Universität Zürich[UZH]

Probevorlesung

Indirect Searches for Weakly Interacting Dark Matter

October 23, 2015

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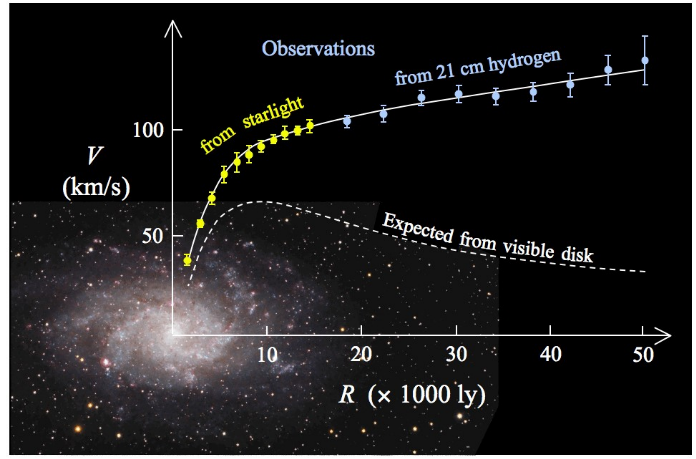
The Need for "Dark Matter"

Galactic rotation curves

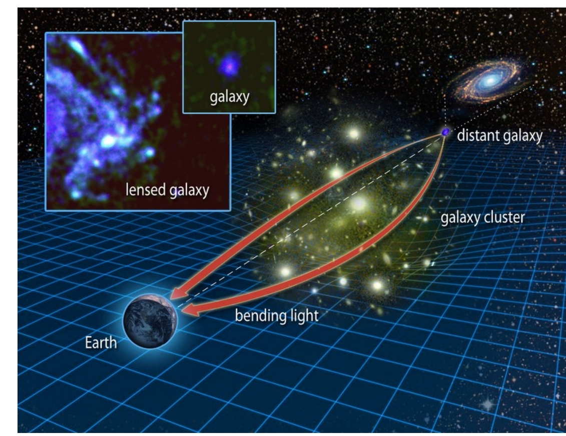
- rotation velocity of stars

$$v^2(r) = \frac{G \cdot M(r)}{r}$$



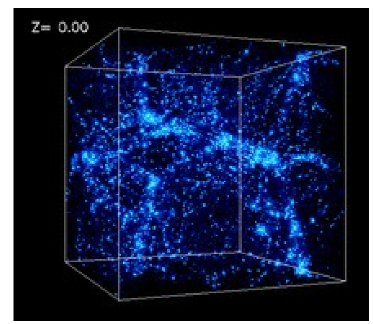
Gravitational lensing

- bending of light from far-away objects



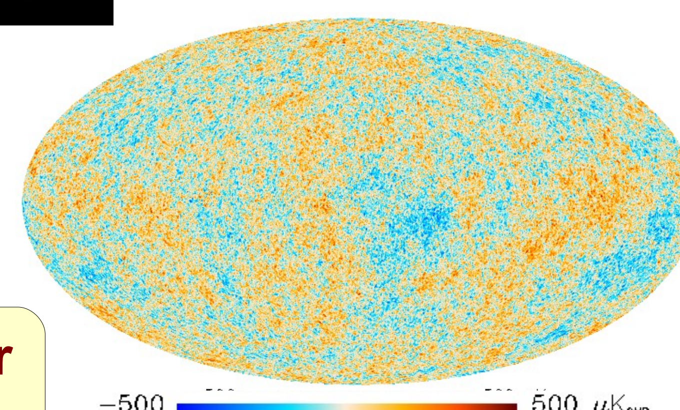
Large-scale structure in the Universe

- distribution and clustering of galaxies



Cosmic Microwave Background Radiation

- angular scale of temperature anisotropies



require ~ 6 × more gravitationally interacting matter than is observed in form of stars, interstellar gas etc.

Dark Matter Candidates

Astrophysical objects – MACHOS (MAssive Compact Halo ObjectS)

- **faint stars**
- **large "Jupiter-like" planets**
- **black holes, neutron stars**

from astronomical observations: can make at most a small fraction of required amount of Dark Matter

As yet unkown elementary particles

- **must be "stable"** (lifetime must be long compared to age of Universe)
- **must be electrically neutral**
- **must be massive** (to explain large-scale structure observed in the Universe)
- **many extentions to Standard Model of particle physics predict such particles**
  - WIMPs ("Weakly Interacting Massive Particles")
  - Axions
  - Sterile Neutrinos

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Astrophysical objects – MACHOS (MAssive Compact Halo ObjectS)

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} from astronomical observations: can make at most a small fraction of required amount of Dark Matter

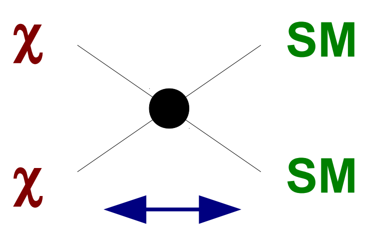
As yet unkown elementary particles

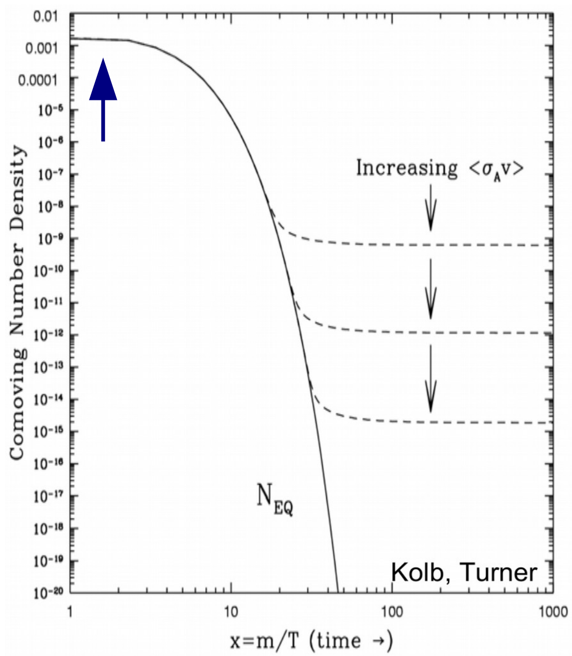
- **must be "stable"** (otherwise would have decayed into lighter particles)
- **must be electrically neutral** (otherwise would not be "dark")
- **must be massive** (otherwise cannot explain observed structure formation)
- **many extentions to Standard Model of particle physics predict such particles**
  - WIMPs ("Weakly Interacting Massive Particles")
  - Axions
  - Sterile Neutrinos

"WIMP Miracle"

"Coincidence" between Particle Physics and Cosmology

- **early Universe: hot and dense**
  - WIMPs and Standard-Model particles in thermal equilibrium
- **as Universe expands and cools down**
  - WIMPs heavy → number density decreases rapidly
  - distance scale increases → interaction rate decreases
- **"freeze out": WIMPs decouple from normal matter**
  - from now on, number of WIMPs stays constant
- **number density determined by time of freeze out**
  - i.e. by strength of interaction with matter, $\langle\sigma_\chi v\rangle$
- **mass density determined by cross section and mass**





m_χ **= 100 GeV** (mass scale of electroweak interaction)
$\langle\sigma_\chi v\rangle$ **= 3×10⁻²⁶ cm³/s** (weak interaction cross section)

} **obtain right mass density to explain Dark Matter**

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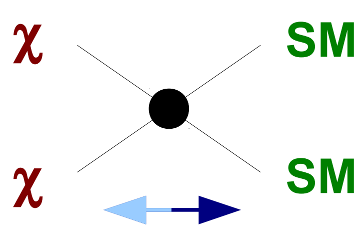

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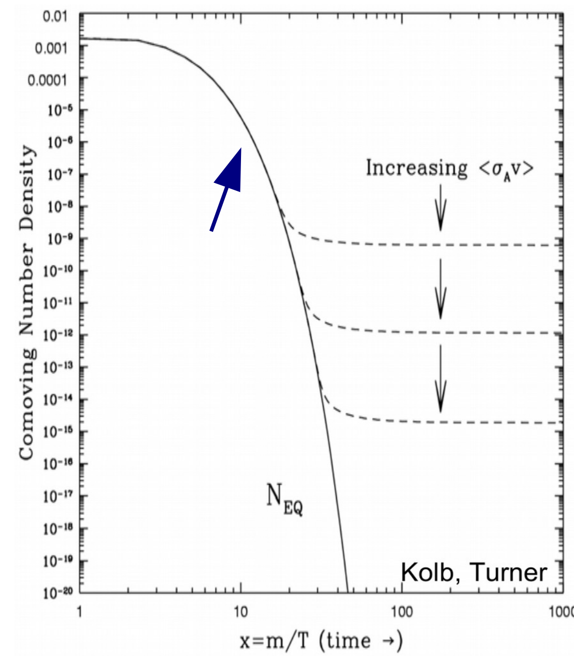

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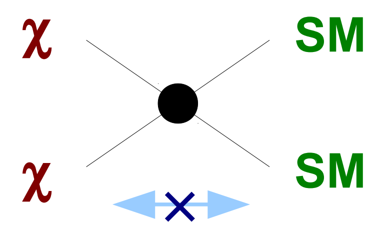

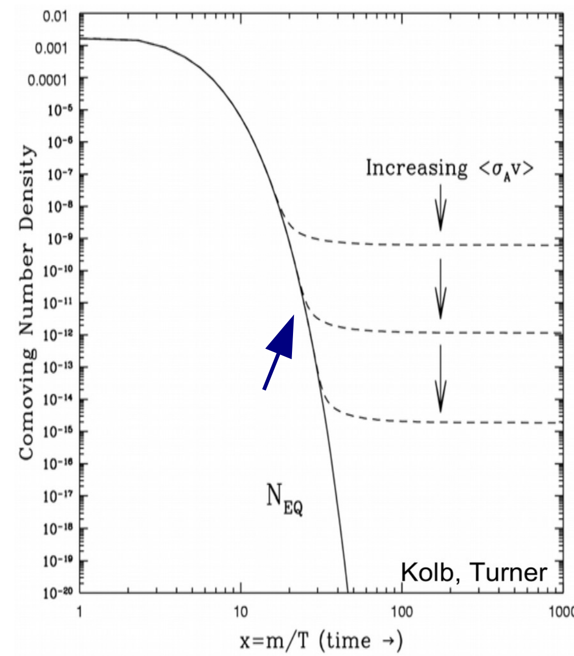

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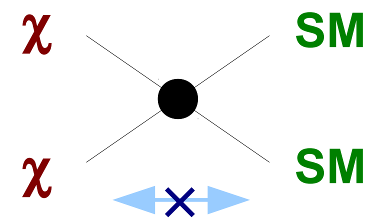

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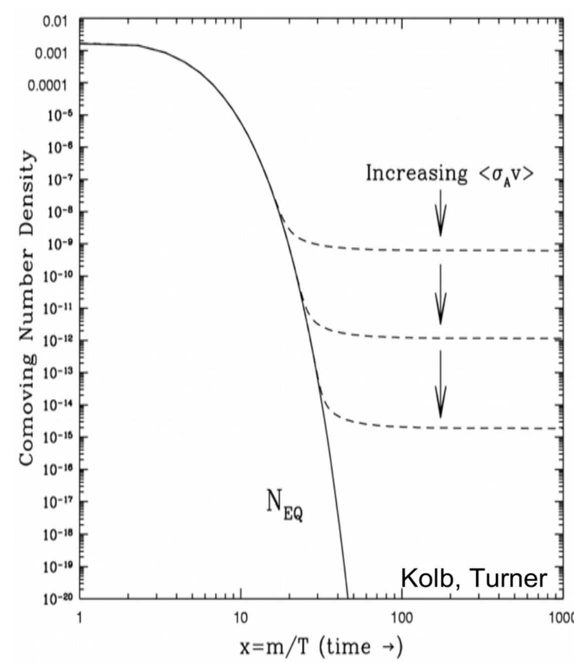

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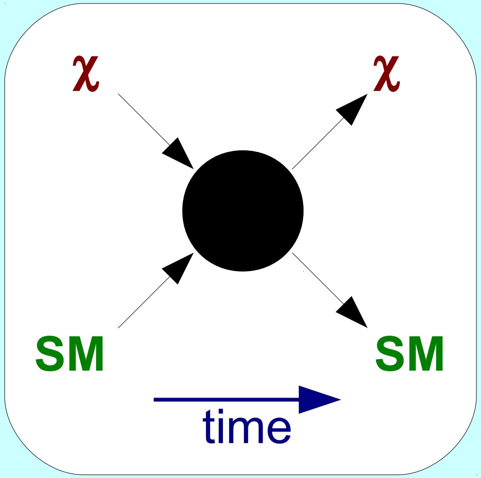
WIMP Searches

Direct Detection

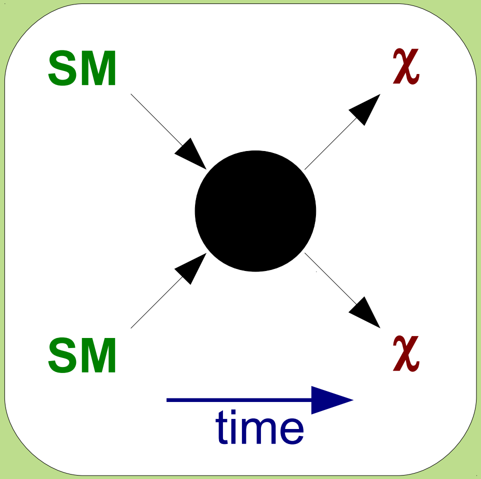
through interaction in detector material



small signals and large backgrounds from Standard-Model processes

Production

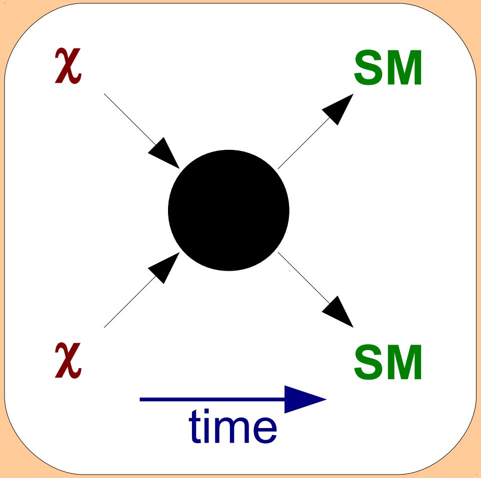
at particle colliders (e.g. LHC at CERN)



if new particle is discovered, how do we know it is what makes Dark Matter ?

Indirect Detection

through observation of annihilation products



most signal signatures can also be explained by astrophysical processes

→ want to see evidence in more than one of the approaches !

WIMP Searches

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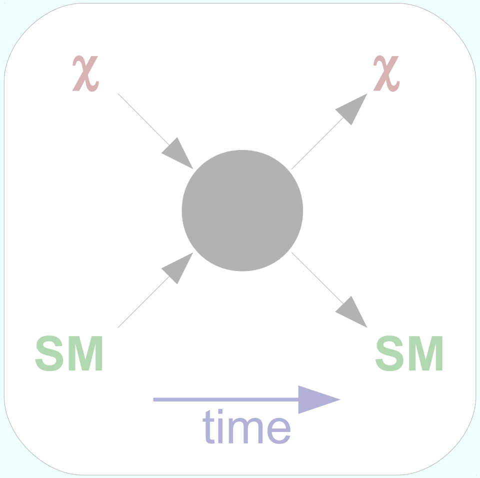

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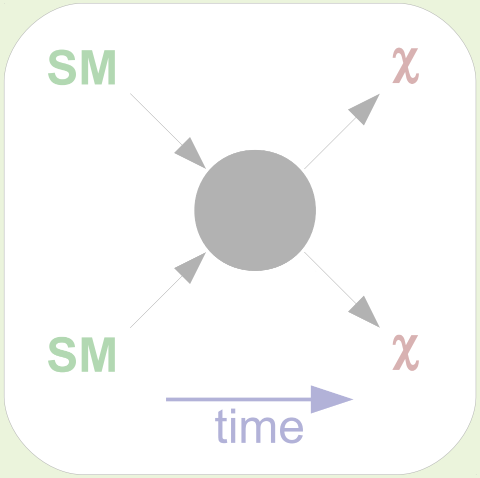

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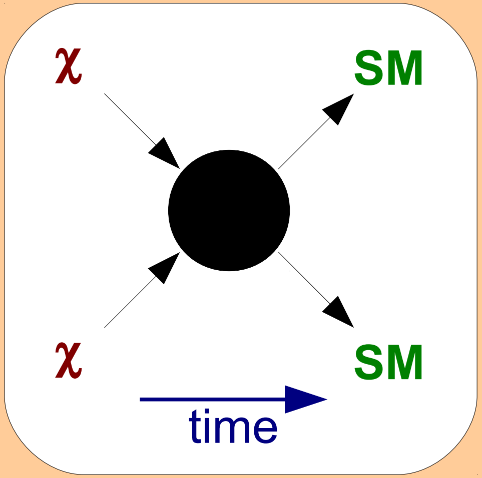

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Indirect WIMP Searches

Dark Matter Madlibs!

Dark matter annihilates in ________________ to
a place

__________ , which are detected by _____________ .
particles an experiment

[J. Feng, UC Irvine]

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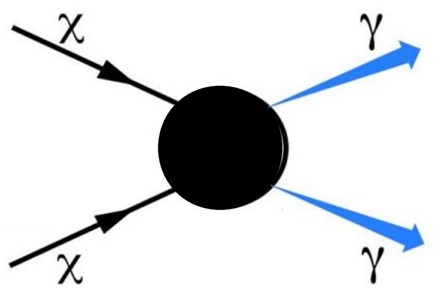
[J. Feng, UC Irvine]

Particles

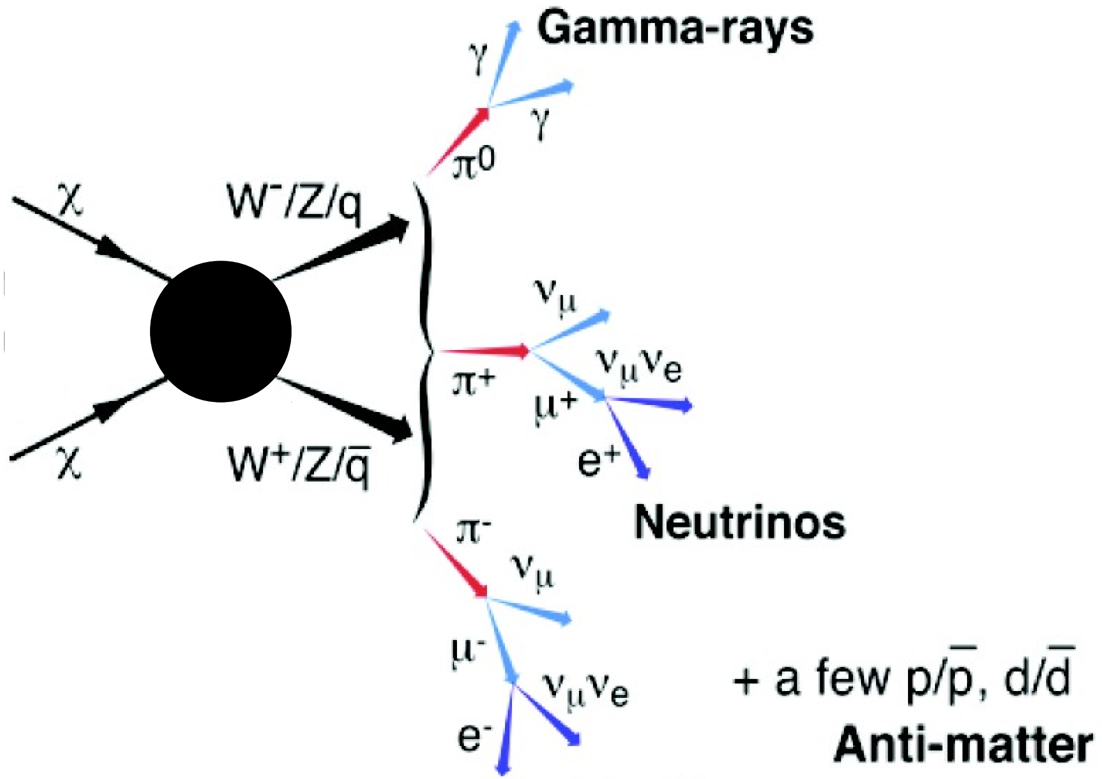
Annihilation to γγ (γH, γZ)

- **energy conservation → fixed photon energy**
- **resonance line in photon energy spectrum**
  - smoking gun signature
  - resonance energy gives WIMP mass



Annihilations to other Standard-Model particles

- ***W*, *Z* bosons, hadrons, … decay to stable particles**
  - **photons**
  - **electrons / positrons**
  - **neutrinos**
  - **protons / antiprotons**



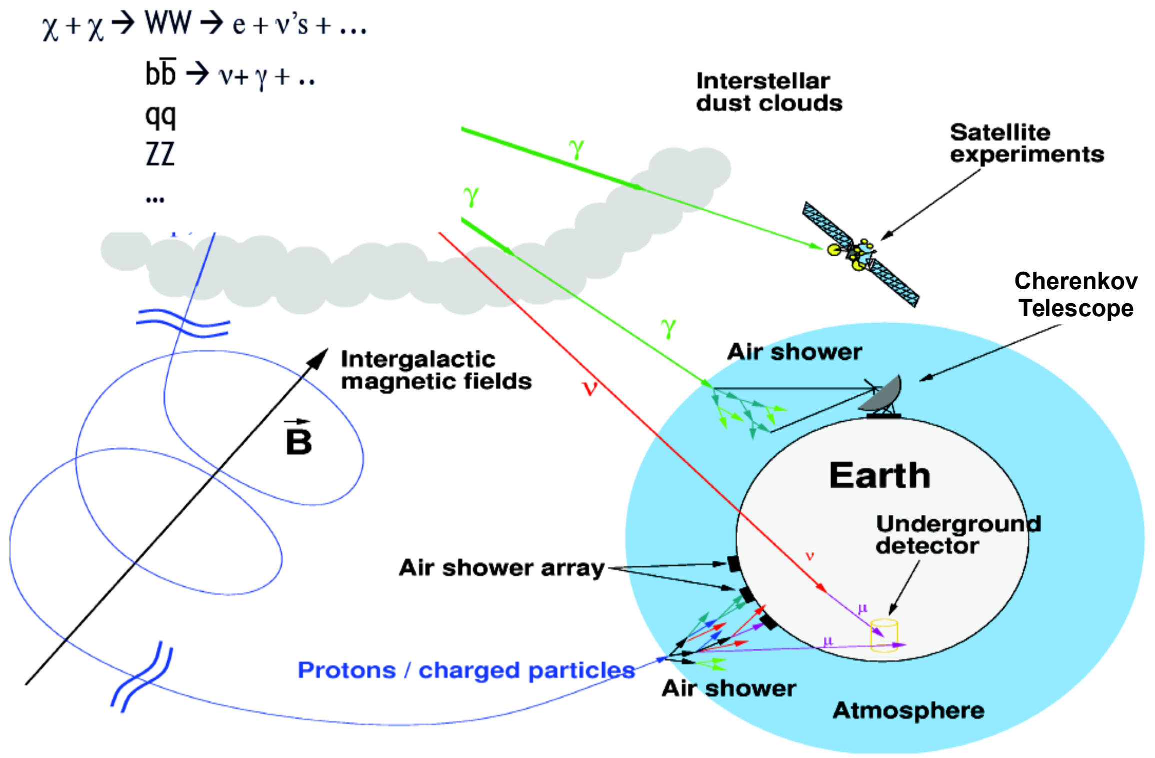
Particles

Gamma-ray photons

- little interaction with Interstellar Medium, point back to source
- but large backgrounds from astrophysical sources

Positrons / antiprotons

- largely unknown backgrounds from astrophysical sources
- get deviated and trapped in (inter-)galactic magnetic fields, do not point back to source



High-energy neutrinos

- very small interaction cross section, point back to source
- difficult to detect, small statistics
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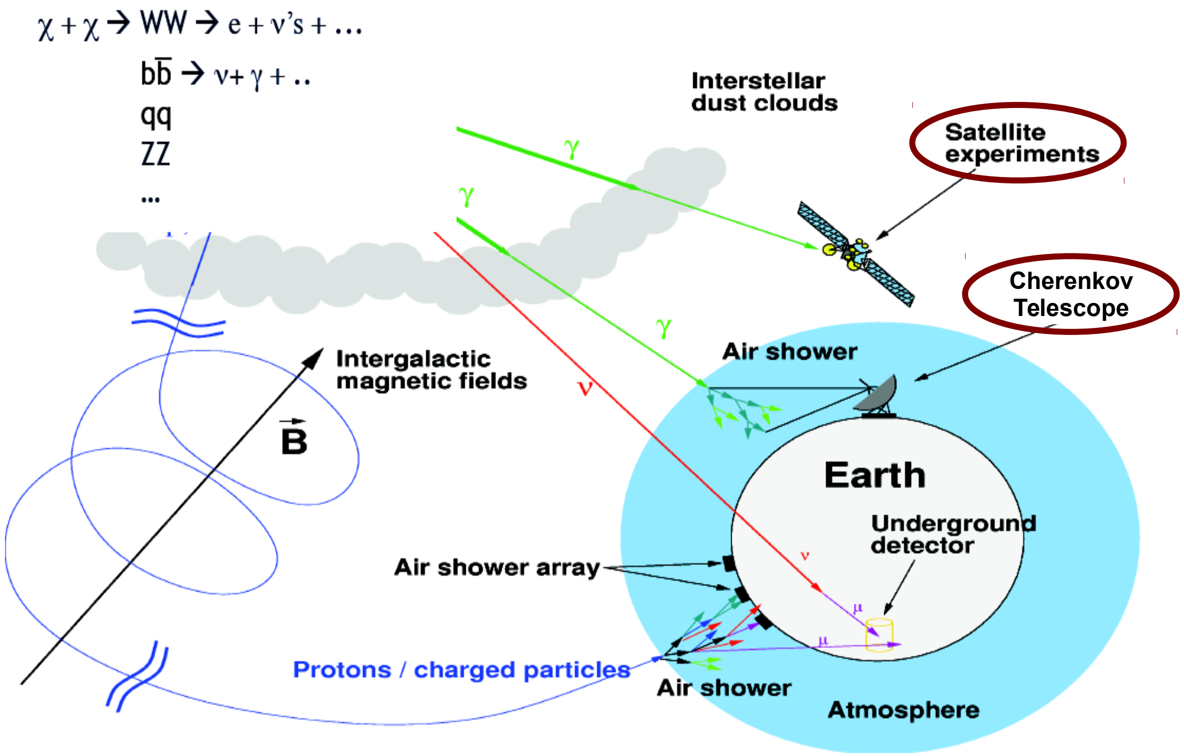

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Indirect WIMP Searches

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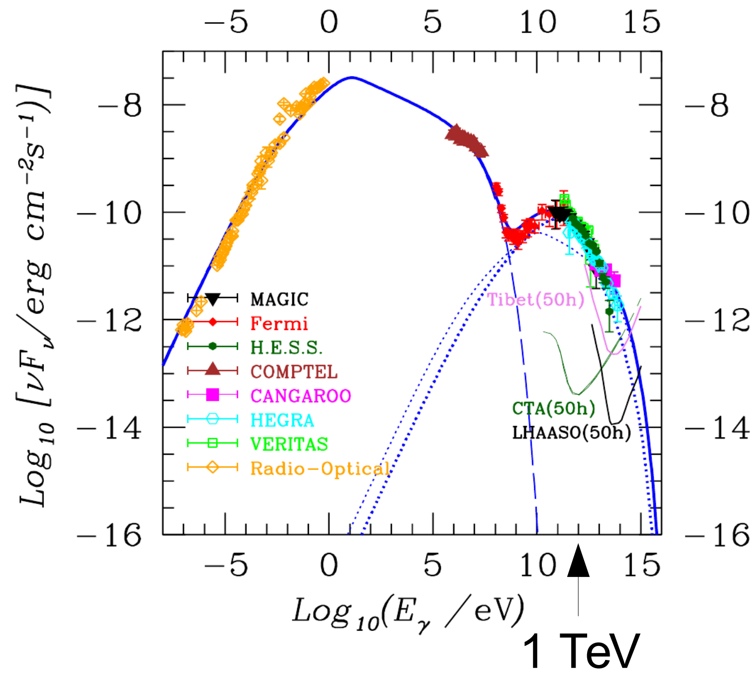
particles an experiment

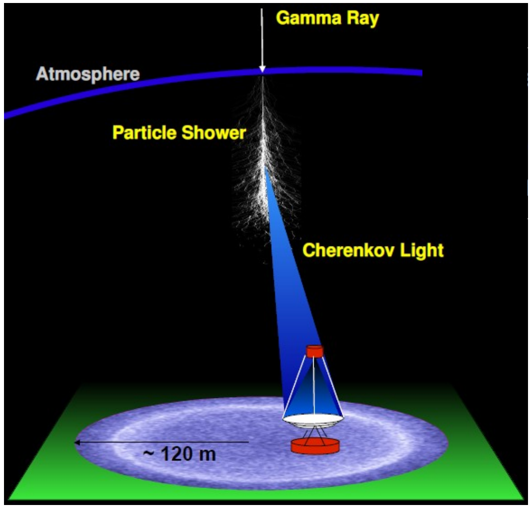
[J. Feng, UC Irvine]

Experiments: γ-rays

Earth's atmosphere opaque for γ-rays

- **interact with atoms in upper atmosphere, create shower of high-energy e^+/e^-**
- **up to $E_\gamma \approx$ 300 GeV: direct detection of γ-rays in balloon or satellite experiments**
  - detection area typically O(1 m²)
- **γ-ray flux drops rapidly with increasing energy**
- **e.g. from Crab nebula (**strong source of γ-rays**):**
  - about 10 γ-rays / m² / year with energy > 1 TeV
  - for 1 event / min: need 50,000 m² detector surface
- **above 300 GeV: indirect detection of γ-ray in ground-based Cherenkov air shower detectors**
  - measure Cherenkov photons produced by high-energy e^+/e^- in the electromagnetic shower

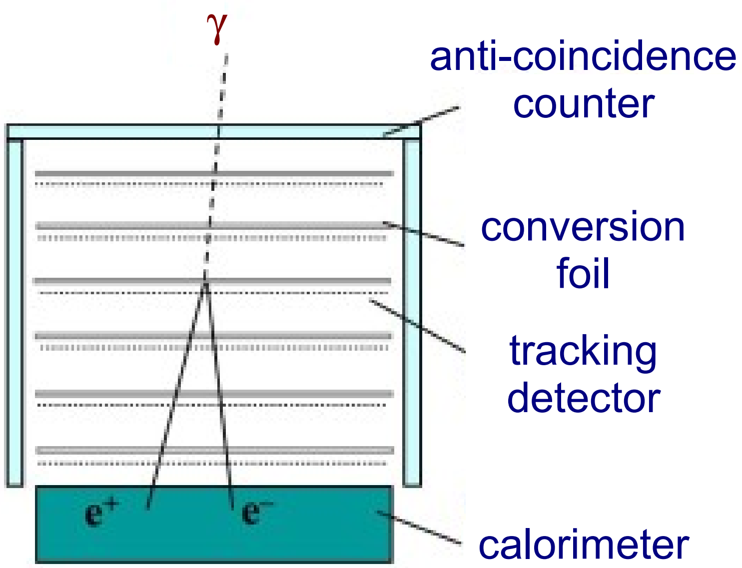




γ-rays: Space-Based Experiments

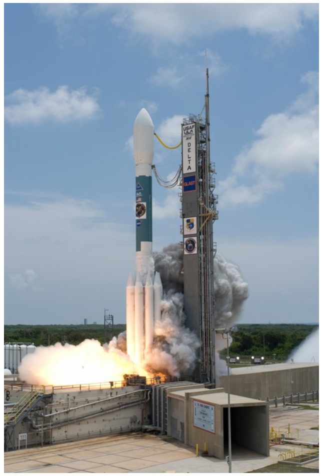
Principle of detection / reconstruction:

- **foils made of a high-*Z* material**
  - pair production $\gamma \to e^+ e^-$
- **tracking detector:** measure e^+ and e^- trajectories
  - reconstruct direction of incident γ
- **calorimeter:** measure e^+ and e^- energies
  - reconstruct energy of incident γ
  - reject hadron background using shower shape
- **anti-coincidence counter:**
  - veto charged incident particles



Limitations by operation in space

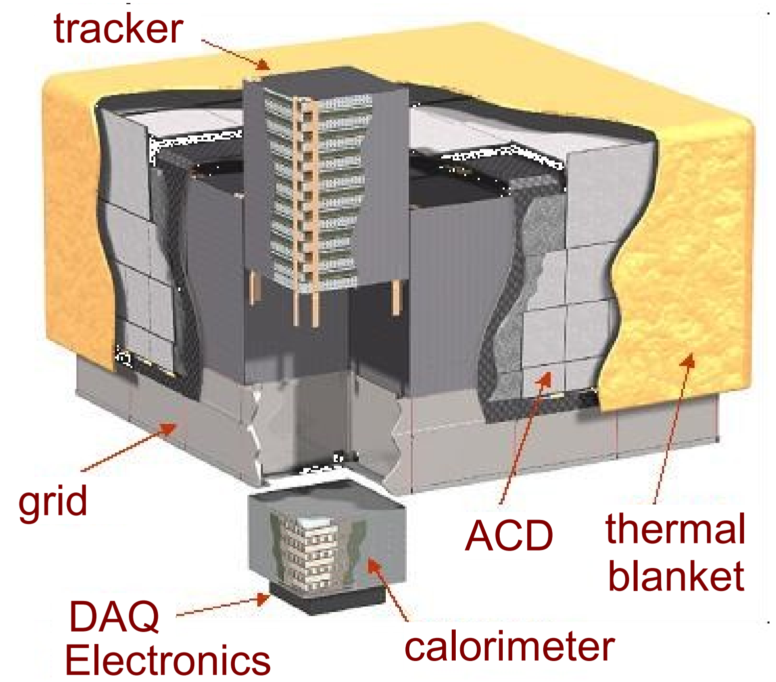
- **e.g. possible detection area limited by size and mass at launch**

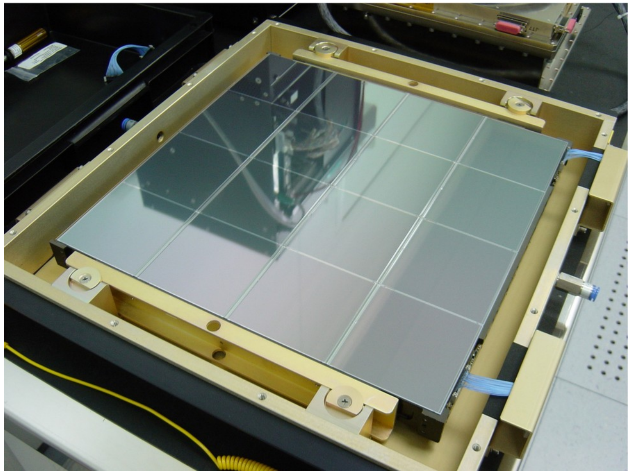


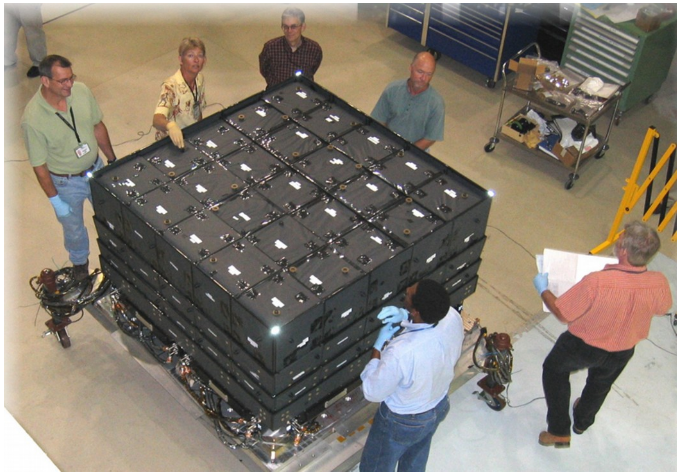
Fermi Large-Angle-Tracker

Launched in 2008

- **tungsten converter foils and silicon micro-strip detectors**
- **segmented CsI(Tl) calorimeter**
- **energy range 20–300 GeV**
- **effective detection area 0.8 m^2**
- **large field of view** (2.4 sr)



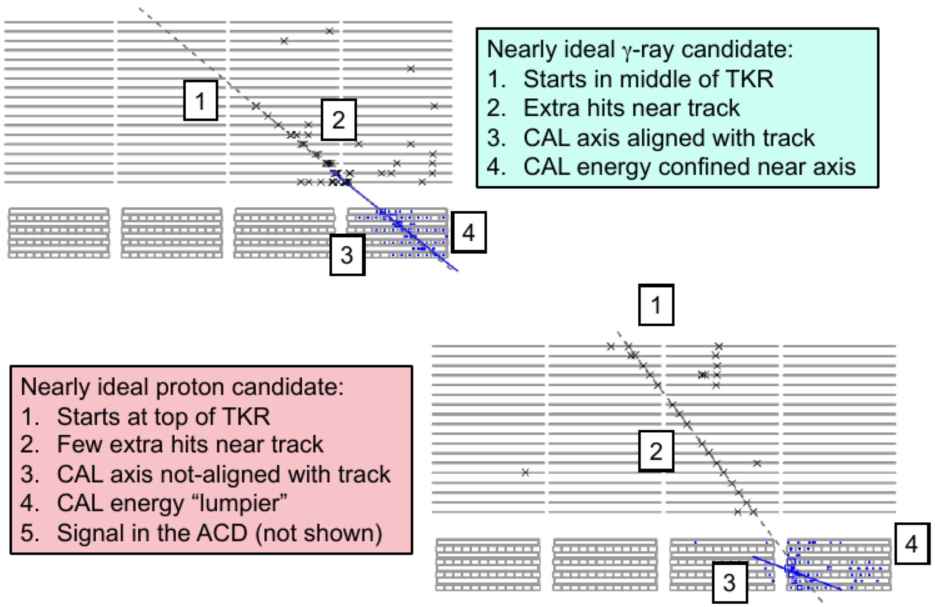




Backgrounds

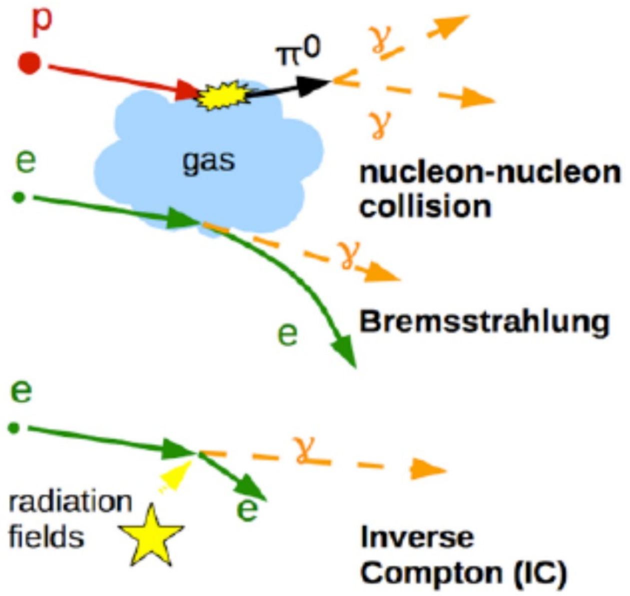
Hadronic cosmic rays

- **1000 × more abundant than γ-rays**
- **anti-coincidence counters**
- **hit distributions in tracking detector**
- **shower-shape in calorimeter**
- **e.g. Fermi: background rejection > 10^5, maintaining 50 % efficiency for γ rays**



Astrophysical sources of γ–rays

- **point sources and diffuse emission**
  - high-energy π^0 from hadronic interactions
  - e^+/e^- bremsstrahlung in interstellar gas
  - Inverse Compton scattering of starlight
- **indistinguishable from possible DM signal**
  - need to model their expected distribution and subtract this from the observed signal



Dark Matter Madlibs!

Dark matter annihilates in ________________ to
(a place)

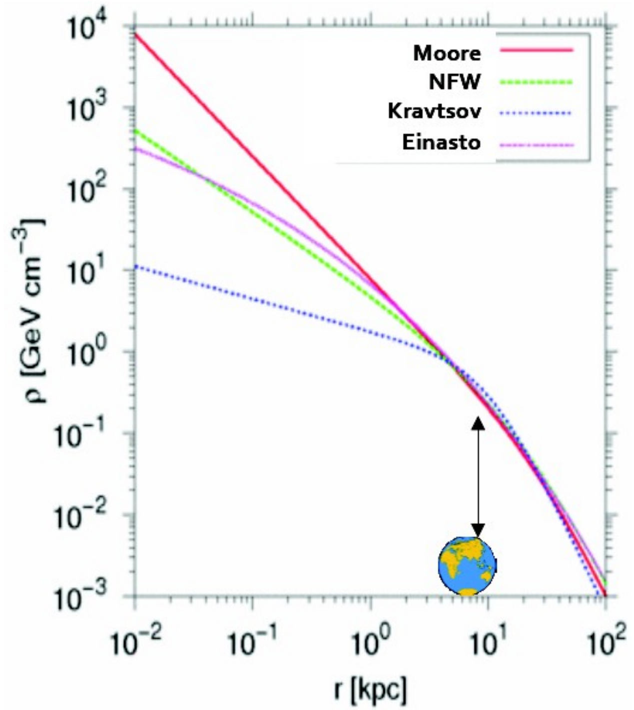
________________ , which are detected by ________________ .
(particles) (an experiment)

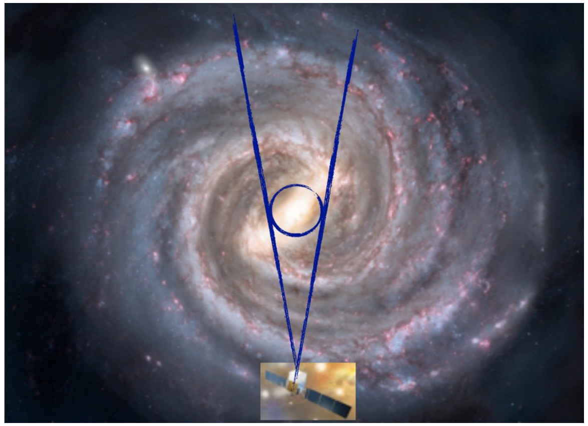
[J. Feng, UC Irvine]

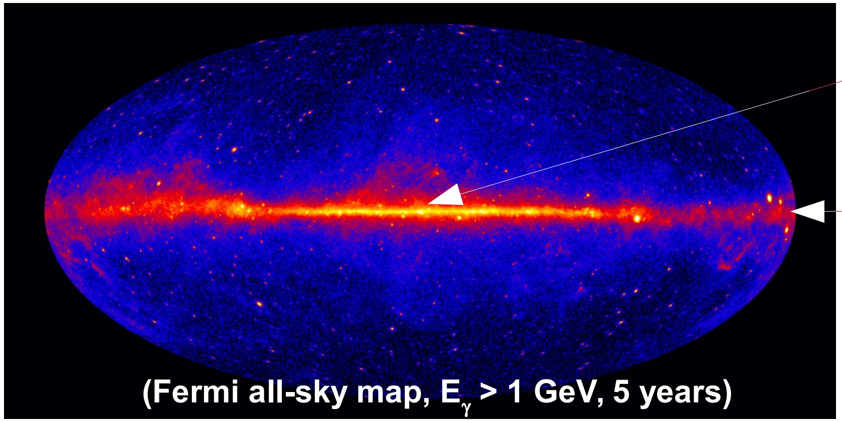
Places

Galactic centre and its halo

- **from models of galaxy formation expect Dark Matter density profile to be peaked towards Galactic centre**
- **WIMP annihilation cross section ∝ density squared**
- **but large backgrounds from astrophysical sources**
  - large number of point sources near Galactic centre and along the line of sight
  - diffuse γ-ray emission from high density of radiation fields and interstellar gas along the line of sight





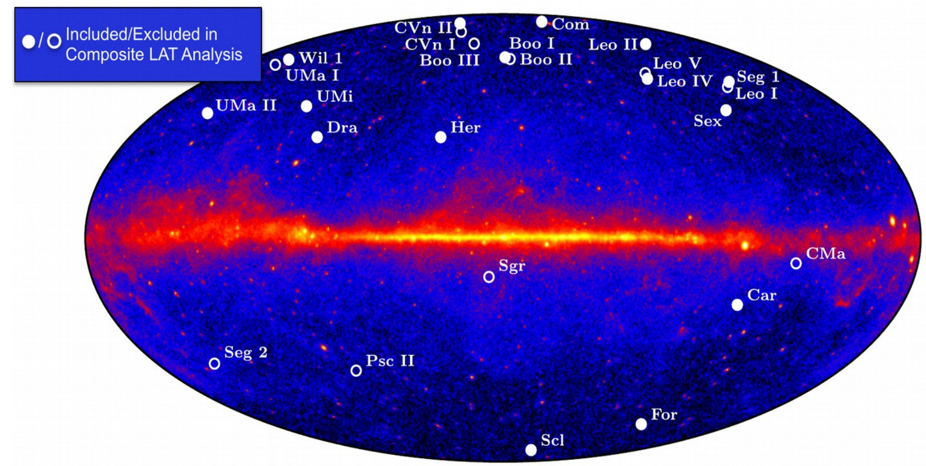


(Fermi all-sky map, E_γ > 1 GeV, 5 years)

Places

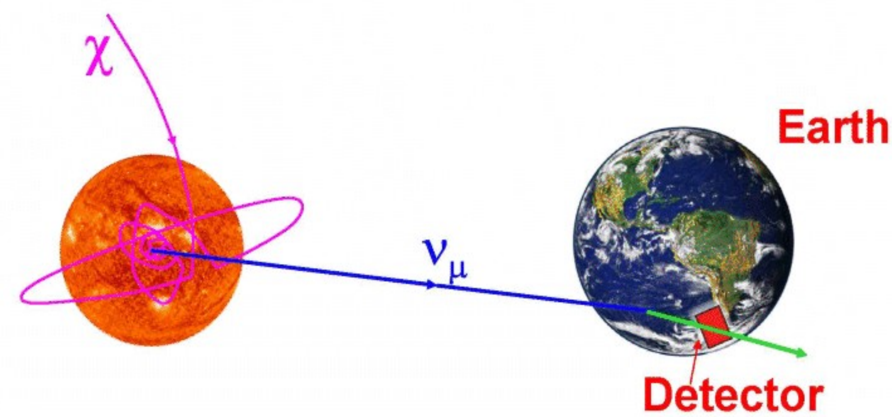
Dwarf Spheroidal Galaxies (satellites of our own galaxy)

- **mass dominated by Dark Matter:**
  - total mass ≈ (10–2000) × luminous mass
- **astrophysical backgrounds small**
  - contain no astrophysical γ sources
  - are located at high galactic latitude
- **but low statistics: faint sources and currently only ~ 25 known candidates**



The core of our Sun

- **Sun "sweeps" through Dark Matter halo of our galaxy → sees "wind" of WIMPs**
- **WIMPs can scatter elastically on nuclei**
  - loose energy → become gravitationally bound → accumulate in Sun's core
- **WIMP annihilation in Sun's core → constant flux of high-energy neutrinos**



Indirect WIMP Searches

Dark Matter Madlibs!

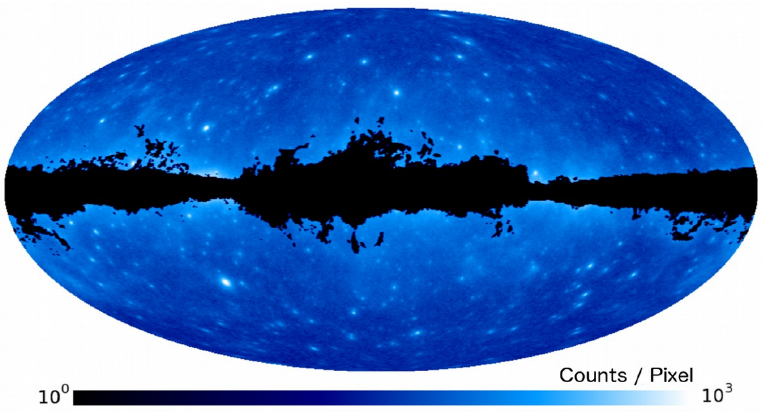
Dark matter annihilates in **the halo of the galactic centre** (a place) to **γ-rays** (particles), which are detected by **Fermi** (an experiment).

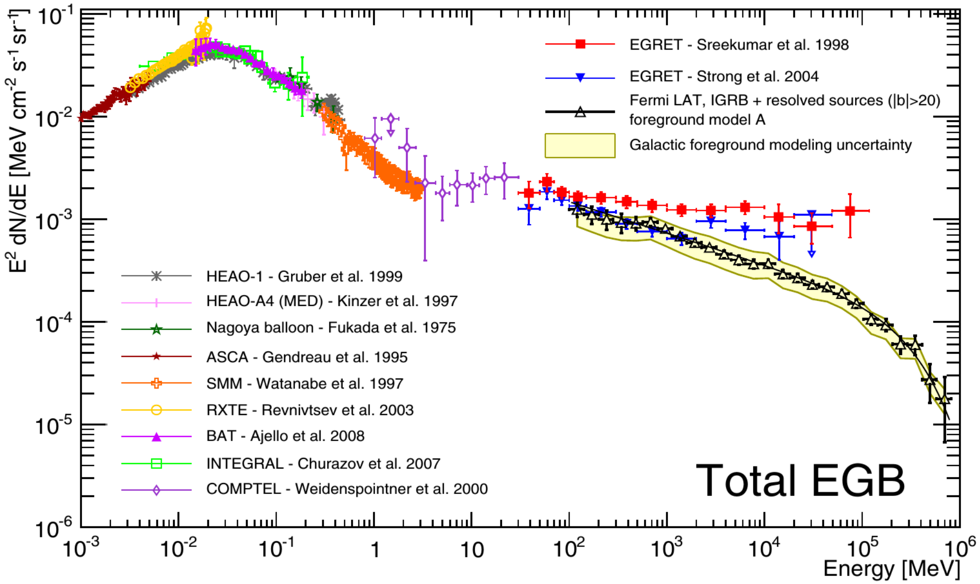
[J. Feng, UC Irvine]

Fermi: Diffuse γ-Spectrum

Measurement based on 50 months of data taking [arxiv:1410.3696]

- **mask region around galactic plane**
- **fit measured energy spectrum with templates for known astrophysical backgrounds**
- **fits can describe observed energy spectrum**
  - do not confirm excess at high γ energies reported by an earlier experiment





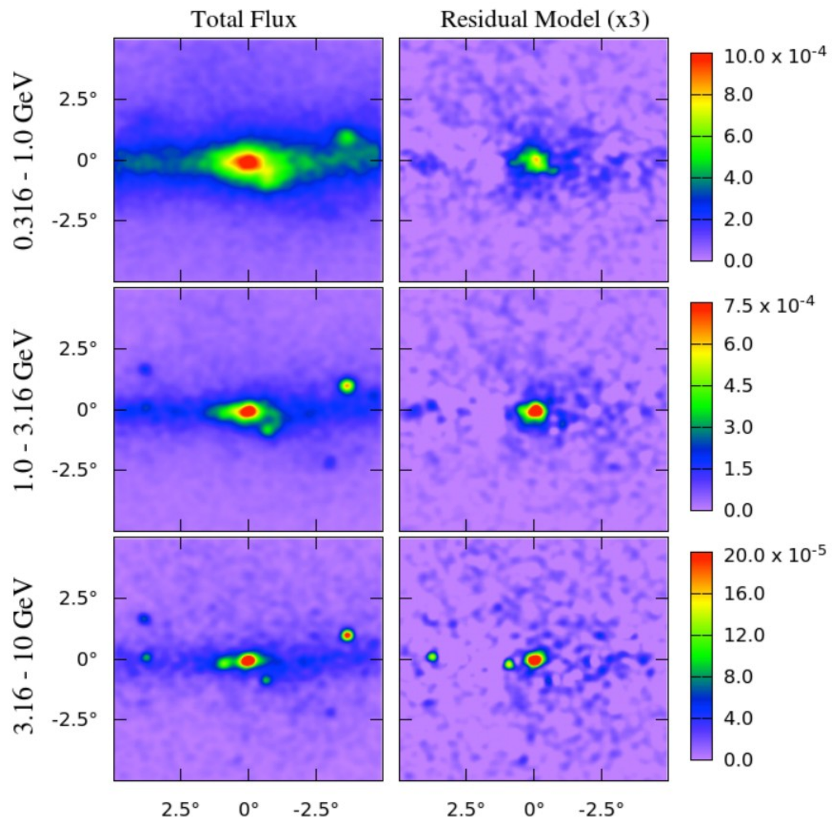
Fermi: Galactic Centre

2014: two independent groups find an excess in γ-ray flux from Fermi data

- **fit data with templates for diffuse emission and known point sources**
- **excess peaking at $E_\gamma \approx 1–3$ GeV**
  - centered on Galactic centre
  - spherically symmetric
  - spatially extended
- "Compelling Case for Annihilating Dark Matter"

  `[arxiv:1402.6703]`
- "... may be explained within the framework of a model where the dark matter annihilates to leptons or a model with unresolved millisecond pulsars in the Galactic Center"

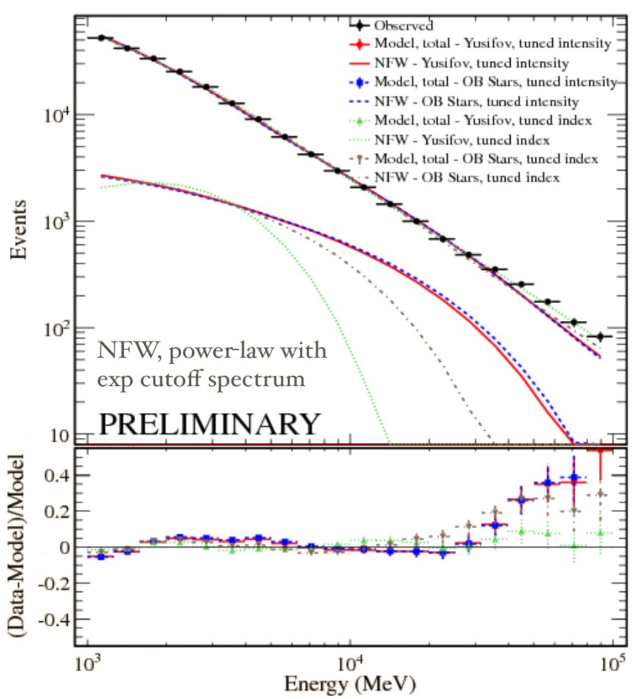
  `[arxiv:1410.6168]`

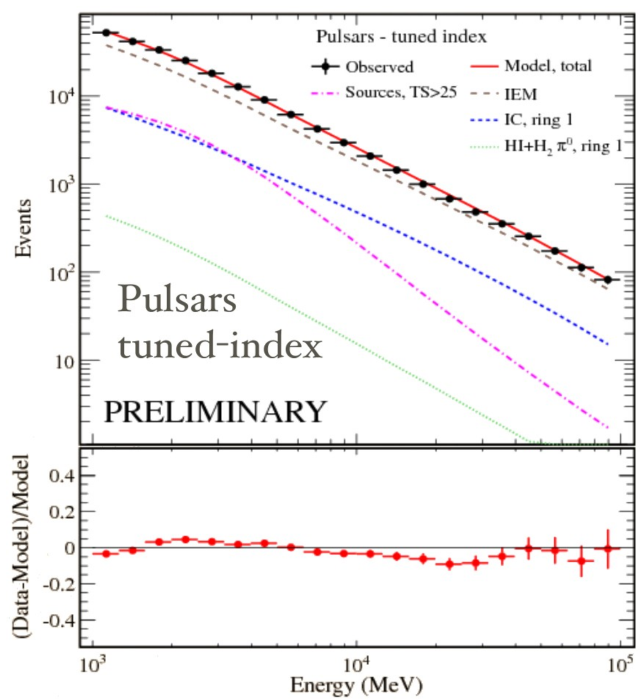


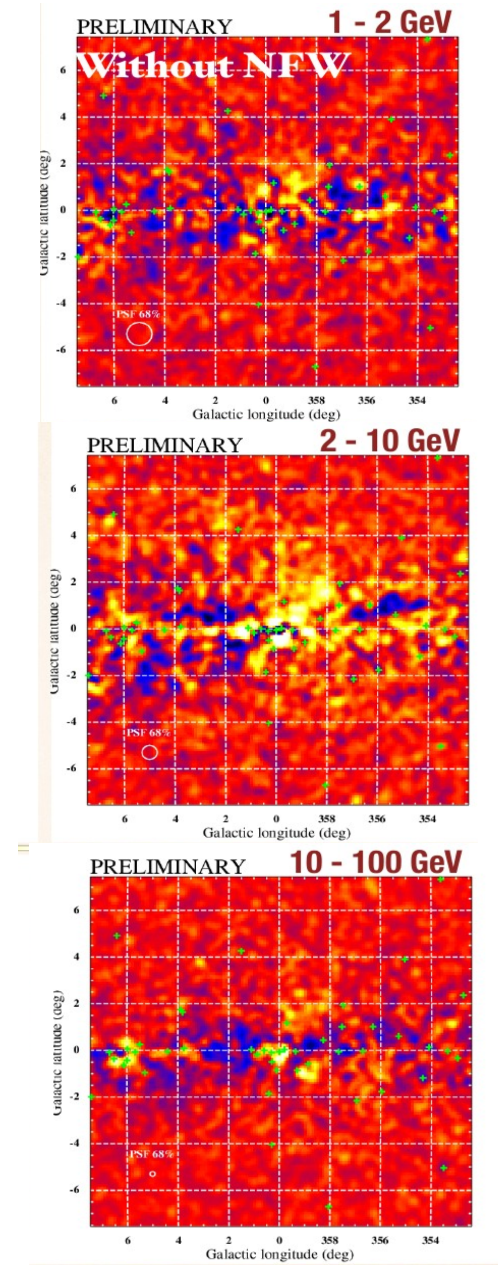
N.B. all Fermi data are made public within 24h; independent groups are free to do their own analysis

Analysis by Fermi collaboration

- **also find enhancement in GeV range, approximately centred on GC**
- **could be explained by Dark-Matter models**
- **but also by astrophysical background** (Pulsars)







[S. Murgia, Fermi Symposium, Oct 24, 2014]

Fermi: Spectral Lines

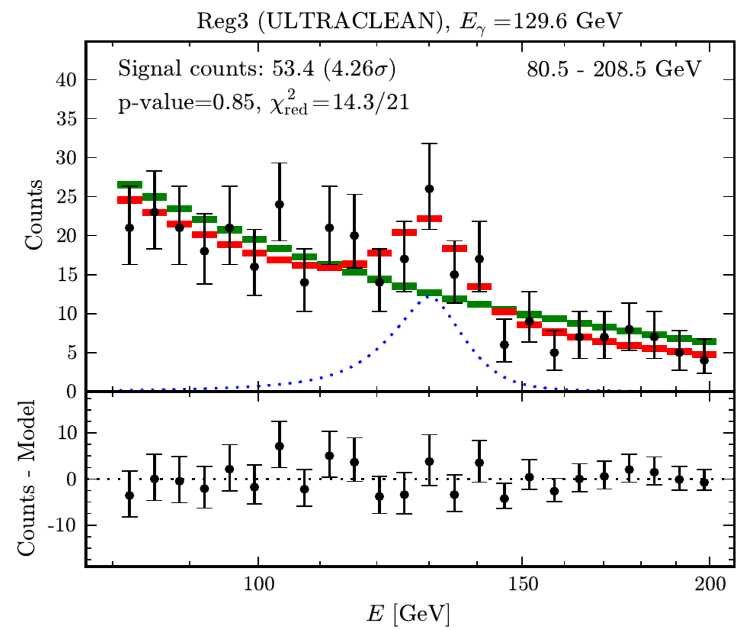
2012: two independent groups claim evidence for a narrow feature in γ energy spectrum from Fermi

- **spectral line = smoking gun signal for WIMP annihilation !**
- **origin of excess close to Galactic centre**
- **E_γ ~ 130 GeV, statistical significance > 4 σ based on data set from 3.7 years**

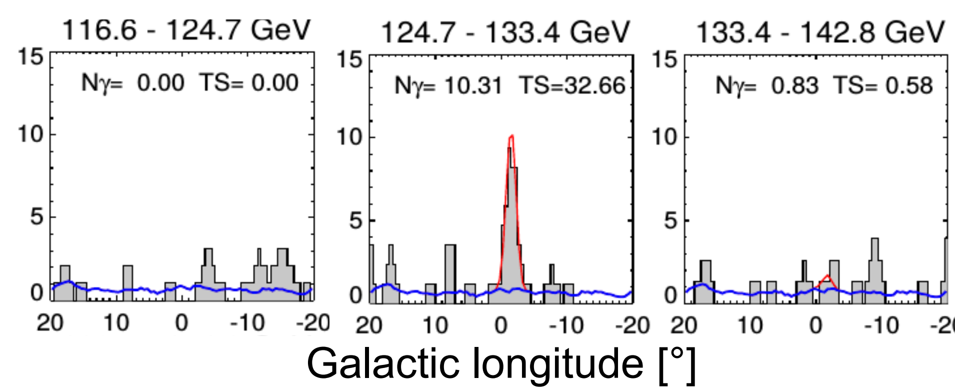
on interpretating significance:

- naively, “4 σ“ corresponds to Gaussian probability of 3×10^{-5} for statistical fluctuation
- but: looking for possible deviations ANYWHERE in the energy spectrum
- probability for finding a 4 σ deviation at ANY energy much larger

[arxiv:1204.2797]



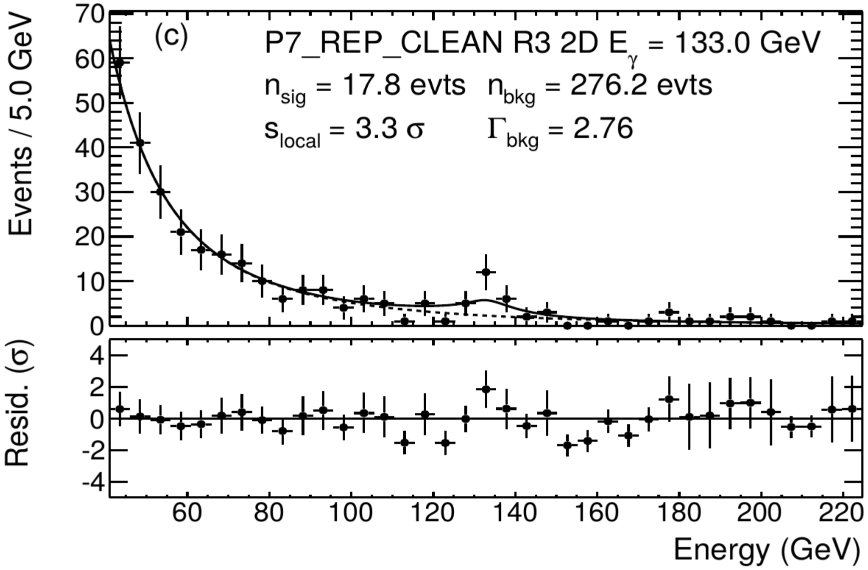
[arxiv:1206.1212]



Analyses by the Fermi collaboration

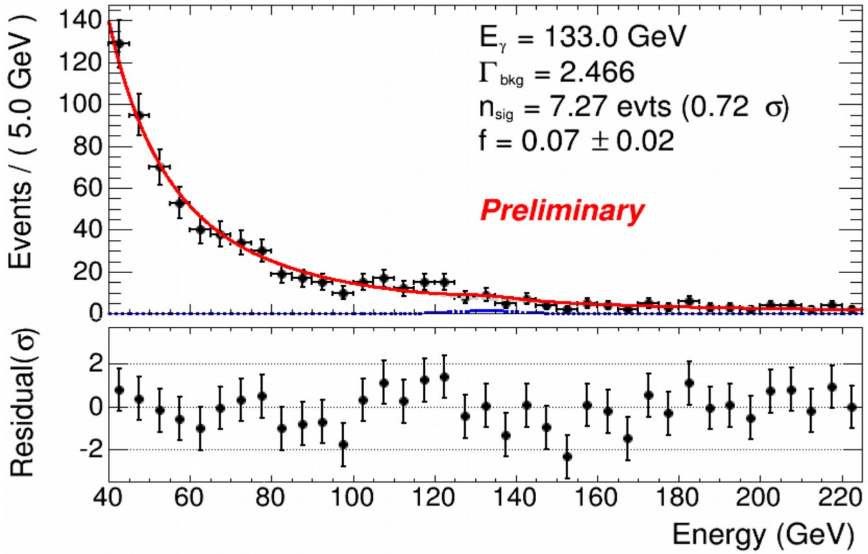
- **using their 3.7-year data set**
  - observe feature at $E_\gamma \sim 133$ GeV with statistical significance of 3.3 σ
  - but note that its width is narrower than the energy resolution of the experiment

`[arxiv:1305.5597]`



- **using larger data set from 5.8 years**
  - no significant signal anymore
  - interpret original feature as a statistical fluctuation

`[A. Albert, Fermi Symposium, Oct 24, 2014]`



Indirect WIMP Searches

Dark Matter Madlibs!

Dark matter annihilates in ___**somewhere**___ to
a place

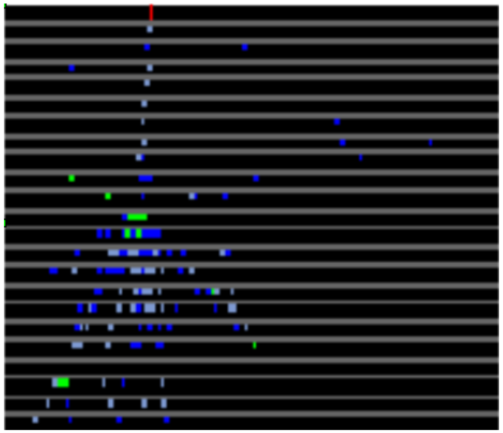
___**positrons**___ , which are detected by ___**Pamela,Fermi,AMS-02**___ .
particles an experiment

[J. Feng, UC Irvine]

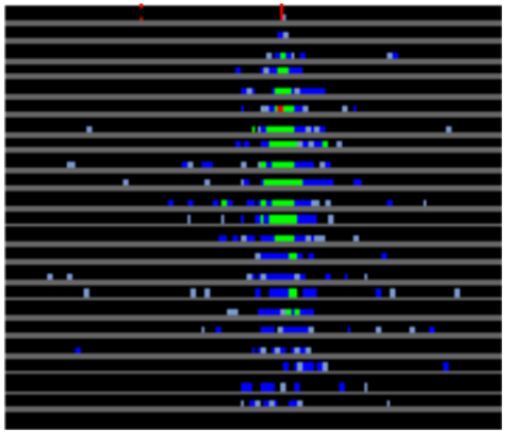
Positrons: Pamela

<u>**Satellite experiment, launched in 2006**</u>

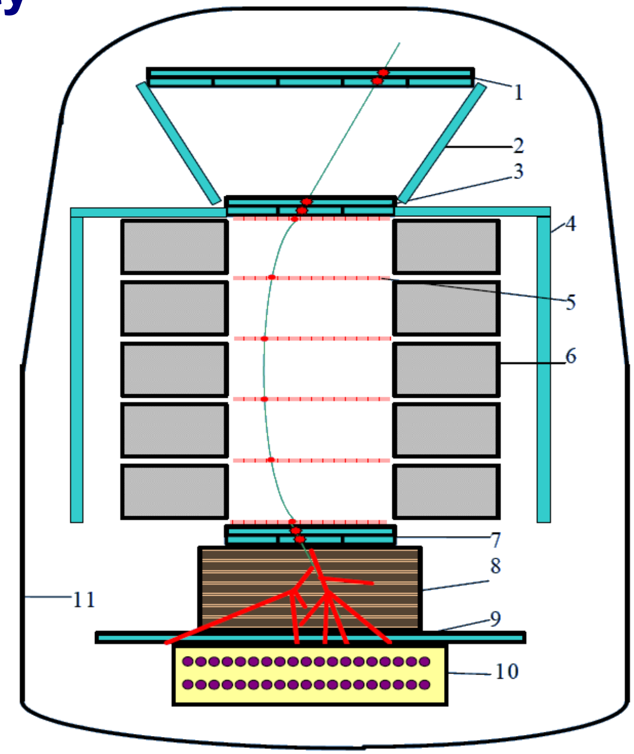
- **time-of-flight counters: particle direction & velocity**
- **tracking detectors and dipole magnet: particle momentum & charge sign**
  - distinguish particle ↔ antiparticle
- **calorimeter: particle energy & shower shape**
  - shower shape: distinguish $(e^+, e^-) \leftrightarrow (p, \bar{p})$



hadron (R=19GV)



electron (R=17GV)

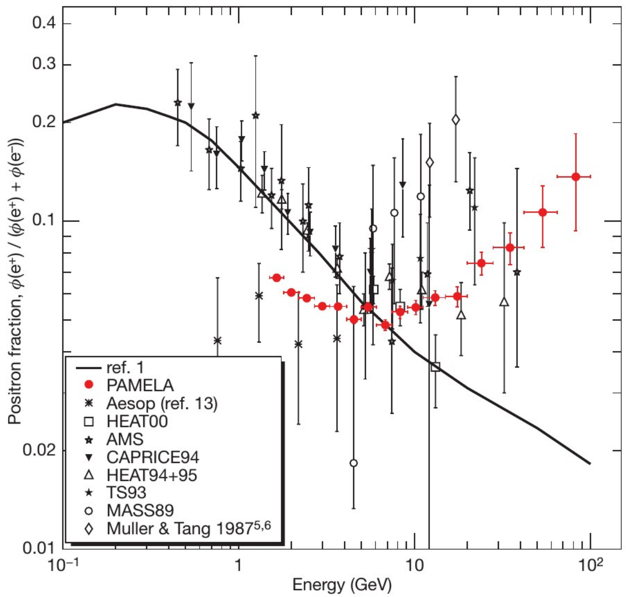


1, 3, 7- TIME OF FLIGHT SYSTEM;
2, 4- ANTICOINCIDENCE SYSTEM;
5- SILICON STRIP TRACKER (SIX DOUBLE PLATES);
6- MAGNET (FIVE SECTIONS);
8- SILICON STRIP IMAGING CALORIMETER;
9- SHOWER TAIL CATCHER SCINTILLATOR;
10- NEUTRON DETECTOR;
11- HERMOCONTAINER.

Positron Fraction

Pamela (from 500 days of data taking)

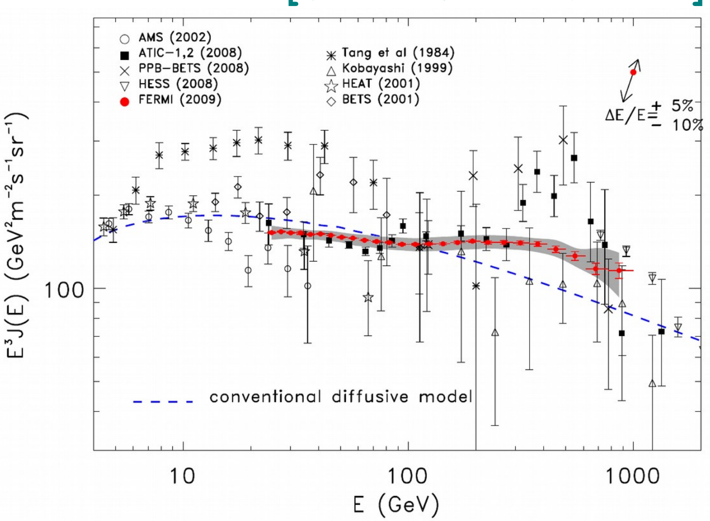
[arxiv:0810.4995]



- **measure positron fraction $N(e^+) / N(e^+ + e^-)$ as a function of the particle energy**
- **observe steep increase above 10 GeV**
- **cannot be explained by models of cosmic-ray propagation**

Fermi

[arxiv:0905.0025]



- **measure the sum of e^+ and e^- fluxes**
  - no magnet → cannot distinguish between electrons and positrons
- **observe smooth energy spectrum**
- **but "harder" than predicted by conventional models of cosmic-ray propagation**

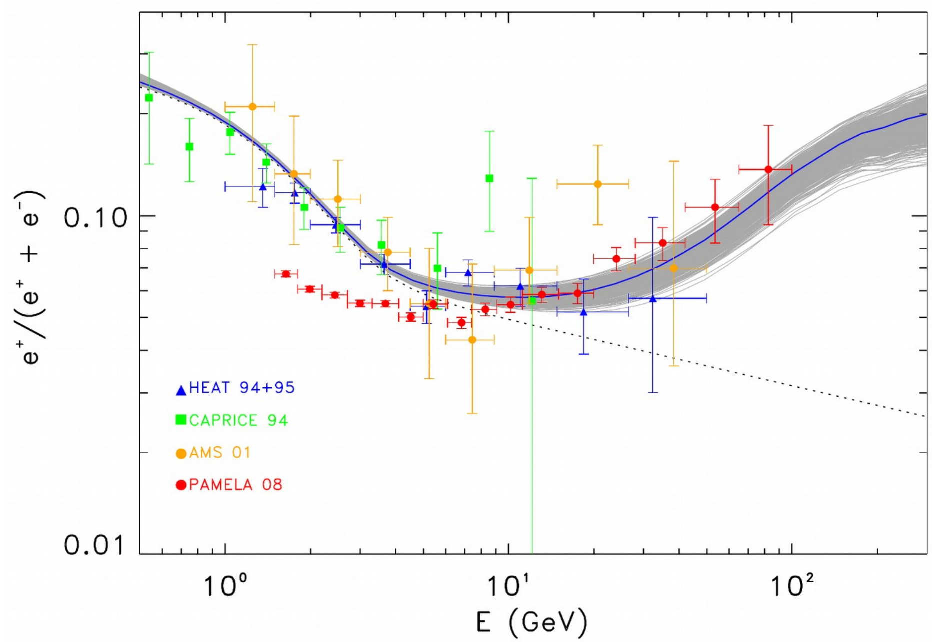
Positron Fraction: Interpretations

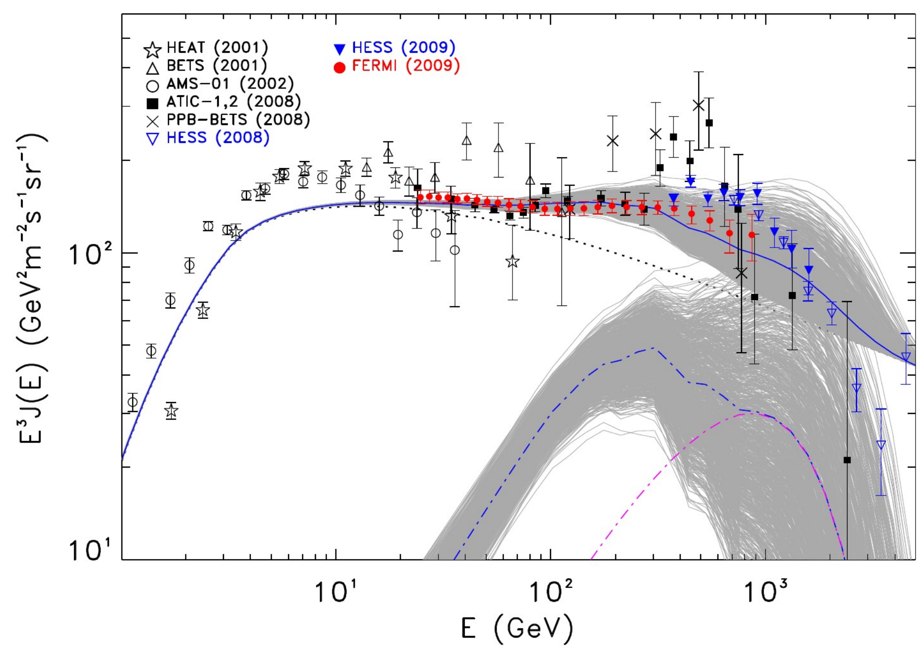
Pamela positron excess triggered ~ 200 theory papers within one year

- **about 170 of them interpretations in terms of various Dark Matter models**
- **but also in terms of possible astrophysical sources**

Most promising candidates: nearby pulsars [arxiv:0905.0636]

- **Monogem (SuperNova Remnant), Geminga (Neutron star)**



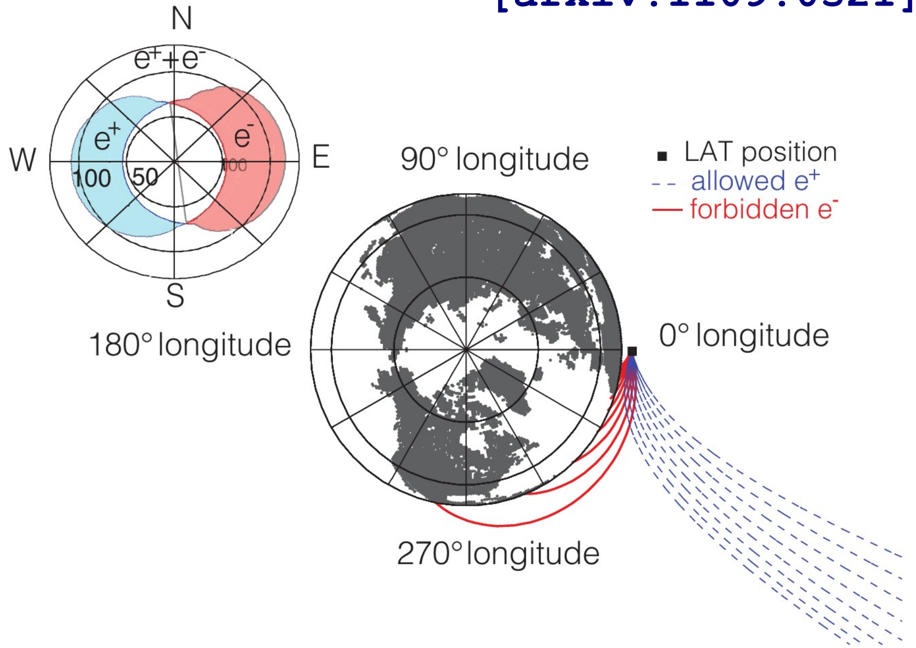


(grey lines in the plots: variation of pulsar model parameters within "reasonable assumptions")

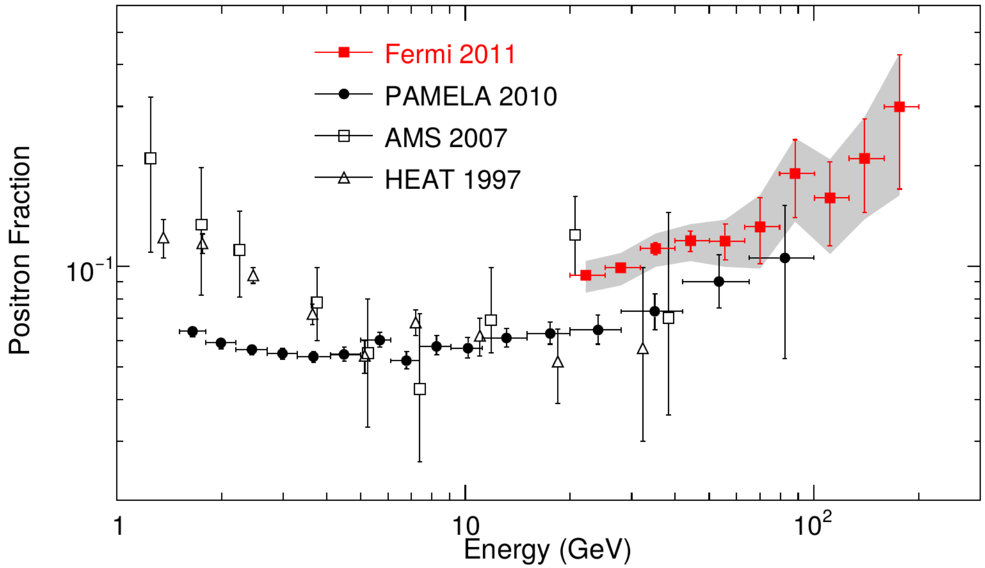
Positron Fraction: Fermi

Exploit magnetic field of the Earth

[arxiv:1109.0521]



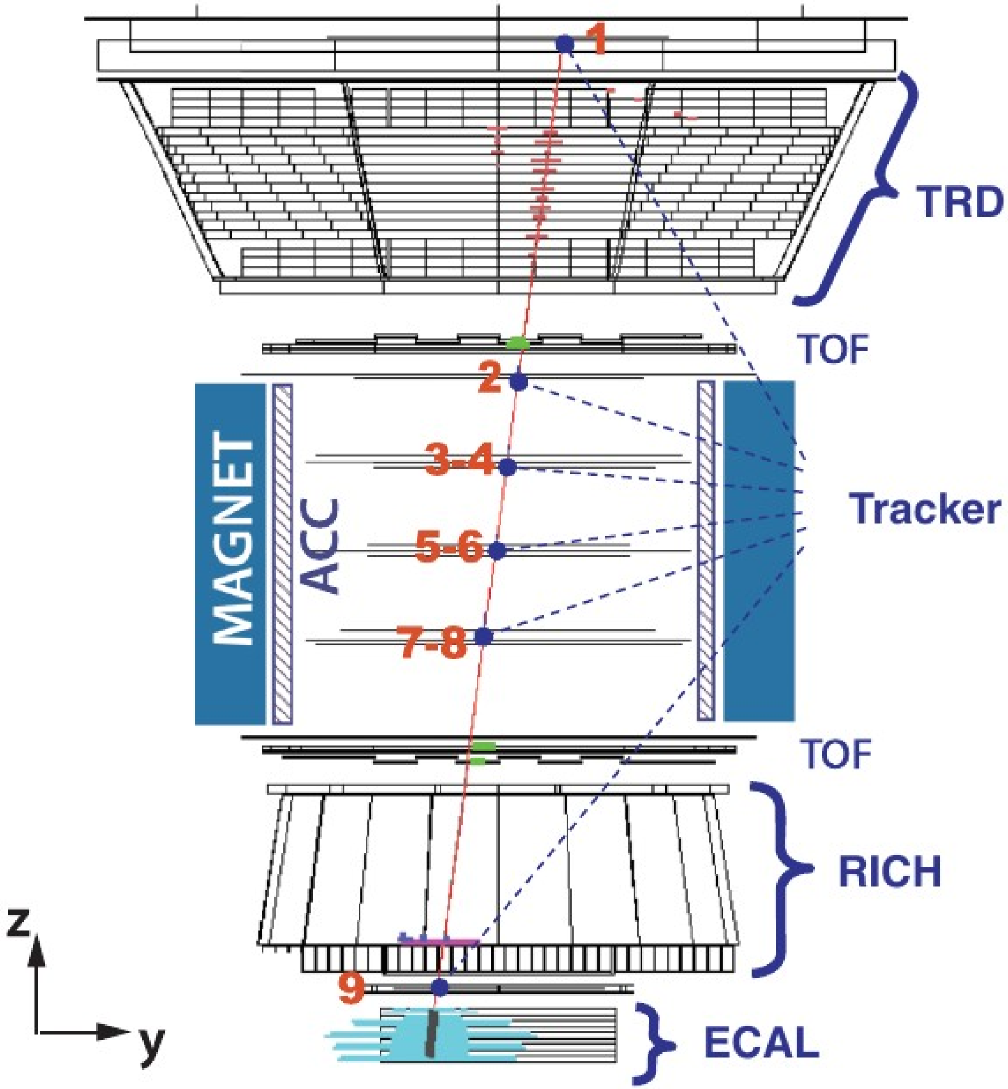
- **trajectories of electrons and positrons are bent in opposite directions**
- **"shadow" of the Earth**
  - blocks trajectories for e^- at certain positions of the satellite
  - blocks trajectories for e^+ at other positions of the satellite
- **allows to measure e^+ and e^- fluxes separately**
- **result agrees with Pamela**
- **increase in positron fraction continues above 100 GeV**



AMS-02

Launched in 2011, installed on ISS

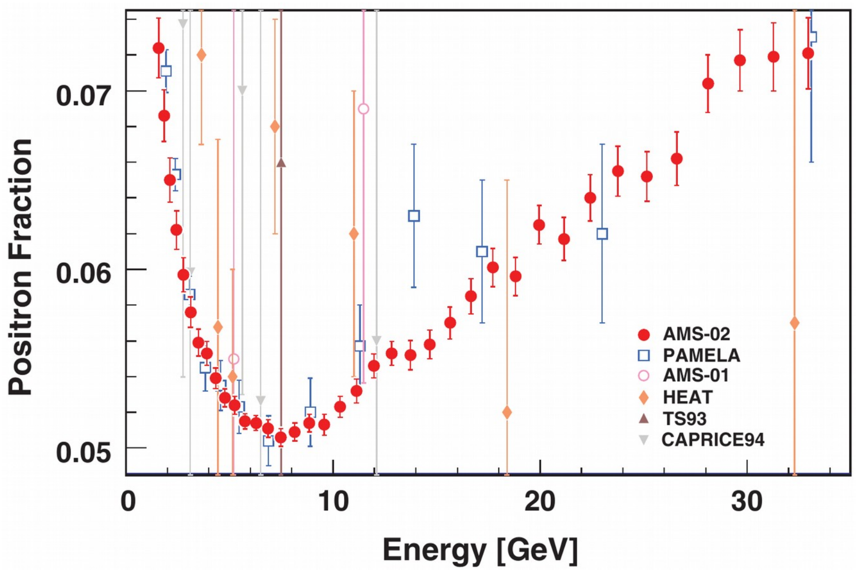
- **silicon micro-strip tracker**
- **electromagnetic calorimeter**
- **anti-coincidence counters**
- **spectrometer magnet**
  - e^+/e^- separation up to ~ 500 GeV
- **Transition Radiation Detector and Ring Imaging Cherenkov Counter**
  - redundant e^+ / p separation

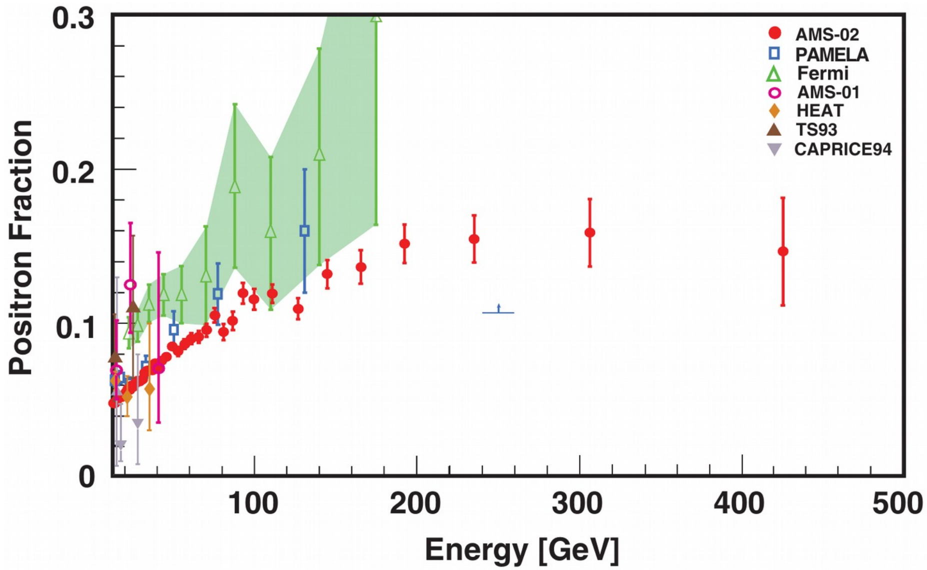


Positron Fraction: AMS-02

AMS-02 measurement using data from 30 months [PRL 113 (2014) 121101]

- **extend energy range up to 500 GeV**
- **observe that positron fraction "flattens out" at highest energies**
  - as expected for both pulsar and DM interpretations





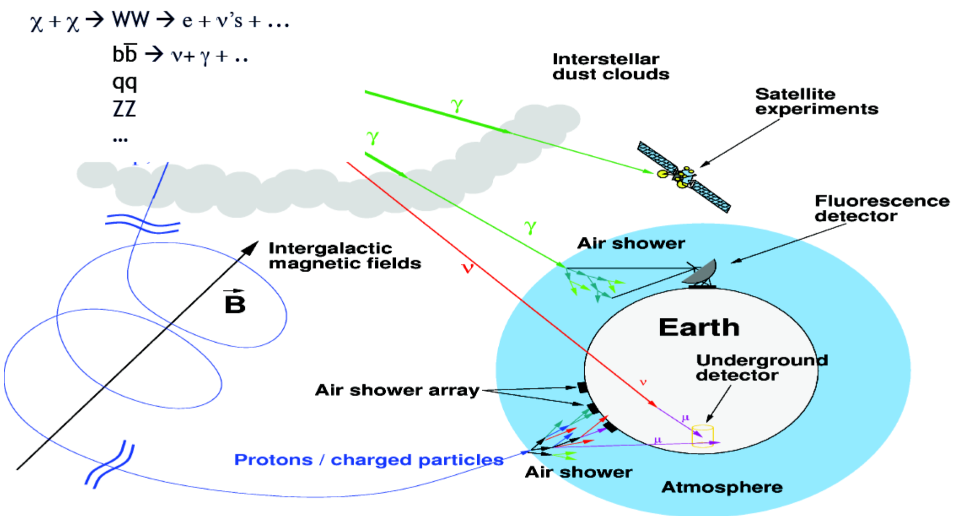
How to distinguish between Pulsar and Dark Matter hypotheses ?

- **slow decrease as a function of energy vs. sharp fall-off at WIMP mass ???**
- **anisotropy in angular distribution vs. isotropic distribution ???**

Summary

Choice of potential sources

- **galactic centre and halo**
- **extra-galactic (e.g. dSph)**
- **neutrinos from the Sun**



Choice of messenger particles

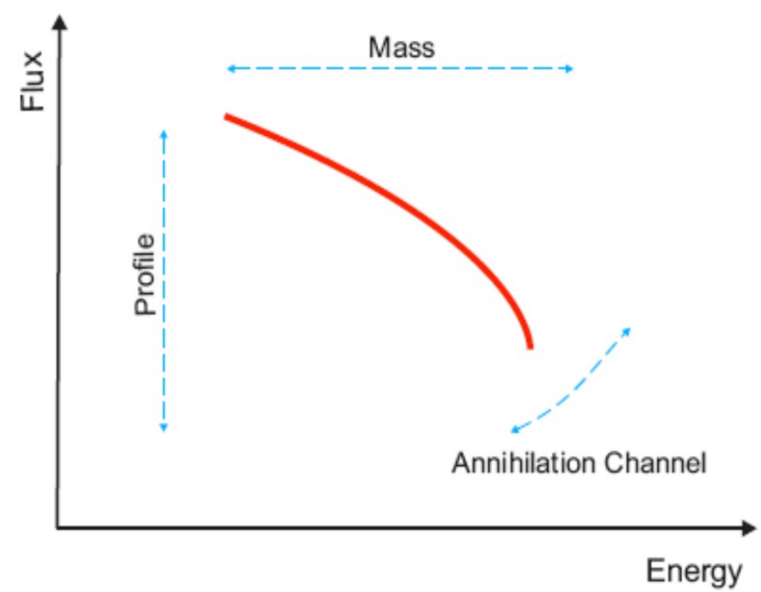
- **photons**
- **neutrinos**

} point back to source

- **anti-particles** – deviated in magnetic fields

Different experimental approaches

- **direct detection in satellite experiments**
- **indirect detection in Cherenkov telescopes**



[Gianfranco Bertone]

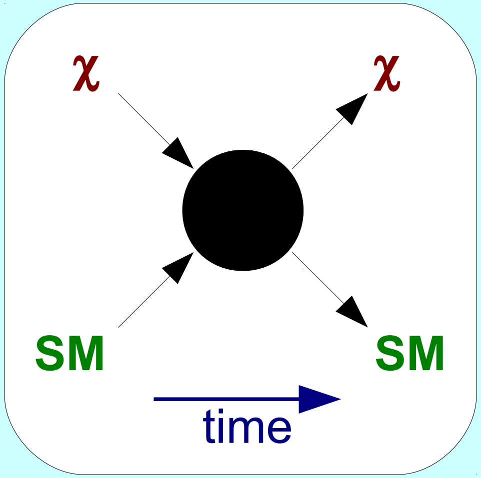
Problem: find an unambiguous signature

- **almost any signal can be interpreted**
  - in terms of Dark Matter annihilations
  - in terms of astro-physical backgrounds

Summary

Direct Detection

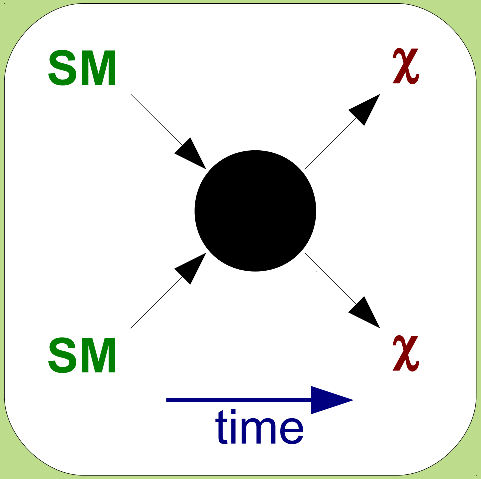
through interaction
in detector material



small signals and large backgrounds from Standard-Model processes

Production

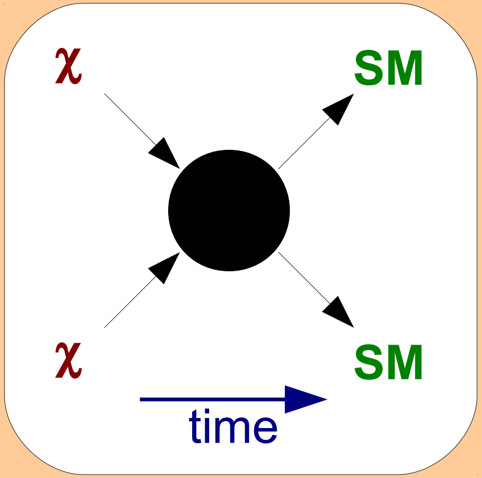
at particle colliders
(e.g. LHC at CERN)



if new particle is discovered, how do we know it is what makes Dark Matter ?

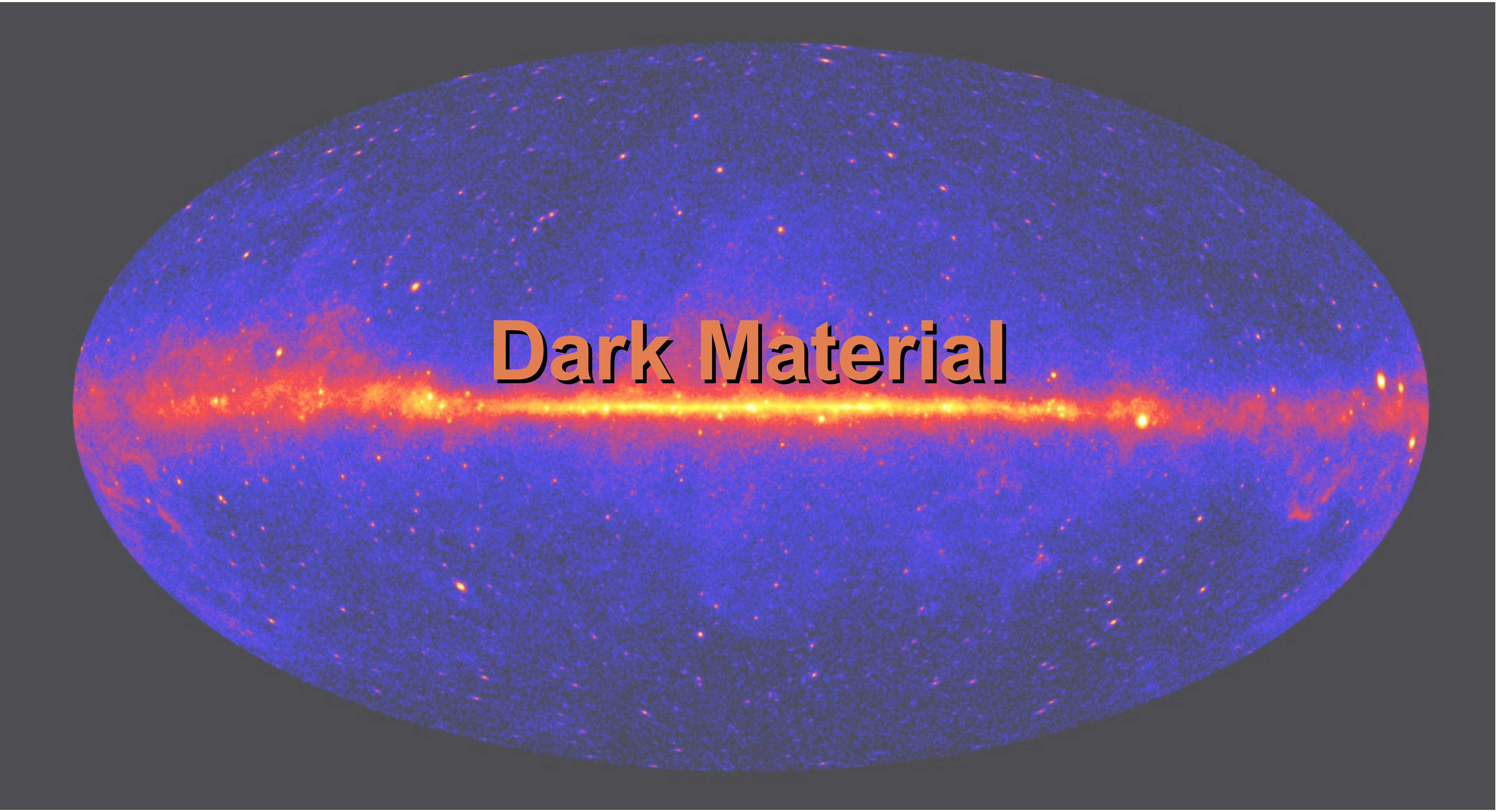
Indirect Detection

through observation
of annihilation products



most signal signatures can also be explained by astrophysical processes

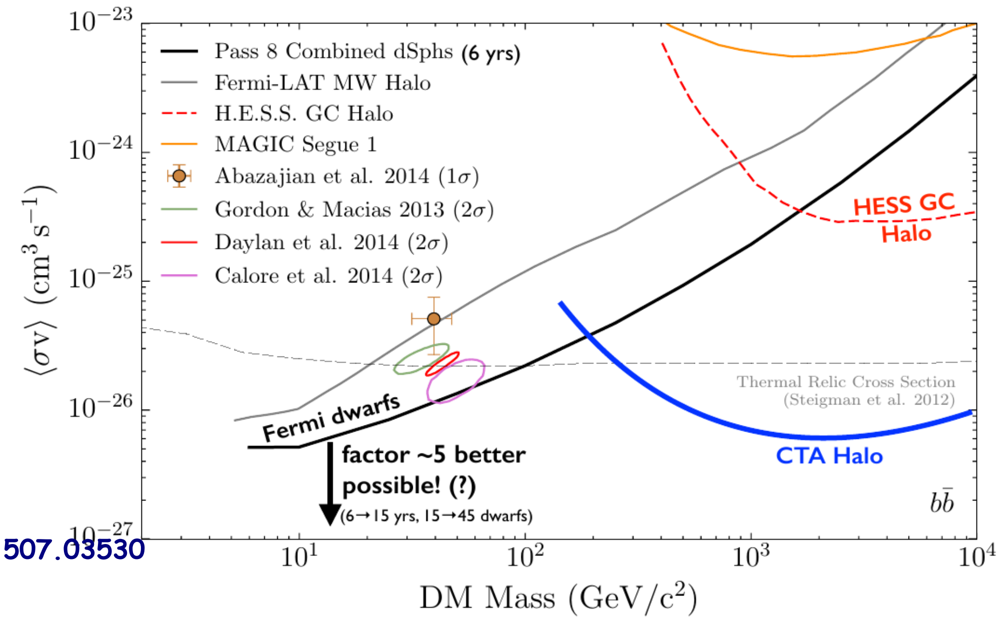
→ need to see evidence in more than one of the approaches !


Dark Material

Limits

- **GeV γ-ray excess around Galactic centre: tension with absence of signal in Fermi measurements of Dwarf Spheroidal Galaxies**

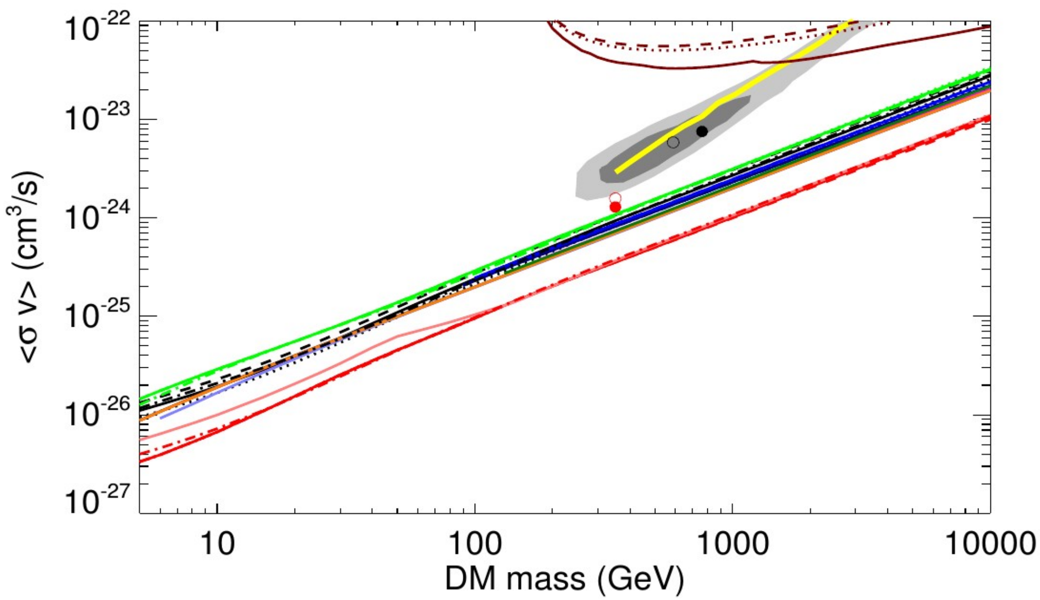
  [arxiv:1507.03530]



1507.03530

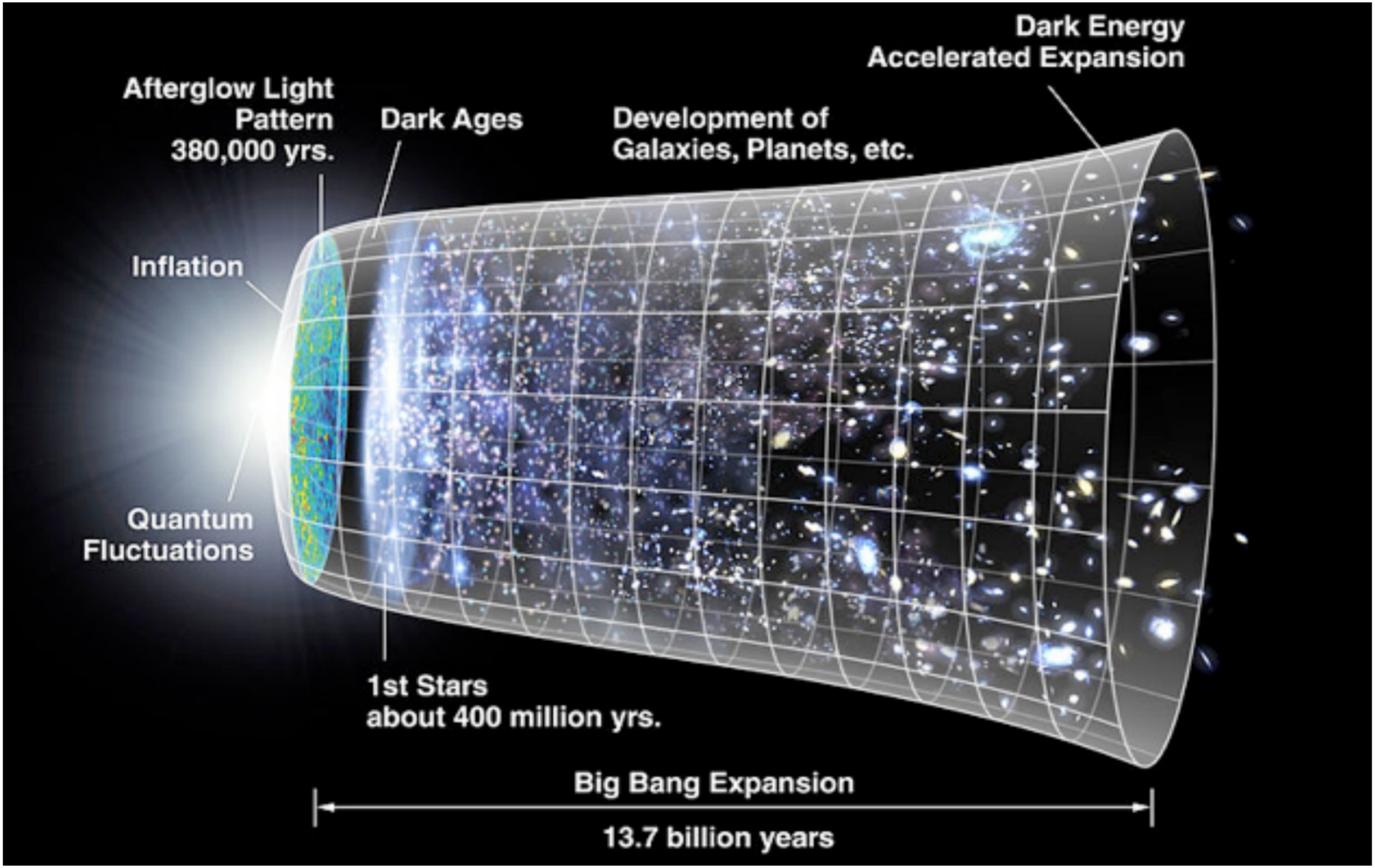
- **positron excess: in conflict with recent Planck measurements of CMBR anisotropy**

  [arxiv:1506.03811]



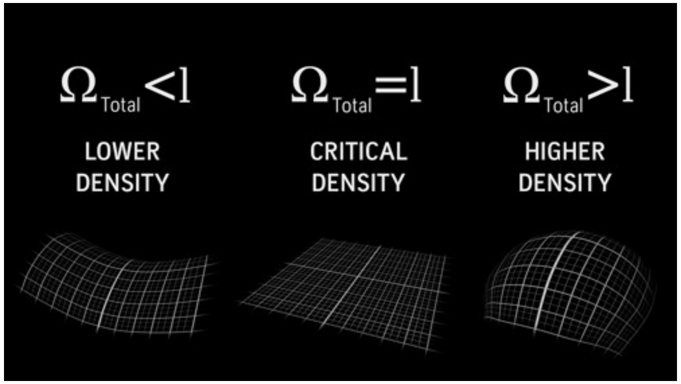
in general, limits seem to depend a lot on the assumed model and on assumed model uncertainties

History of the Universe



Energy density of the Universe

$$\Omega \equiv \frac{\rho}{\rho_{crit}} \equiv \underbrace{\Omega_r}_{\text{radiation}} + \underbrace{\Omega_m}_{\text{matter}} + \underbrace{\Omega_\Lambda}_{\text{vacuum energy}}$$



- $T_{CMBR} \approx 2.7$ K $\Rightarrow$ Ω_r very small

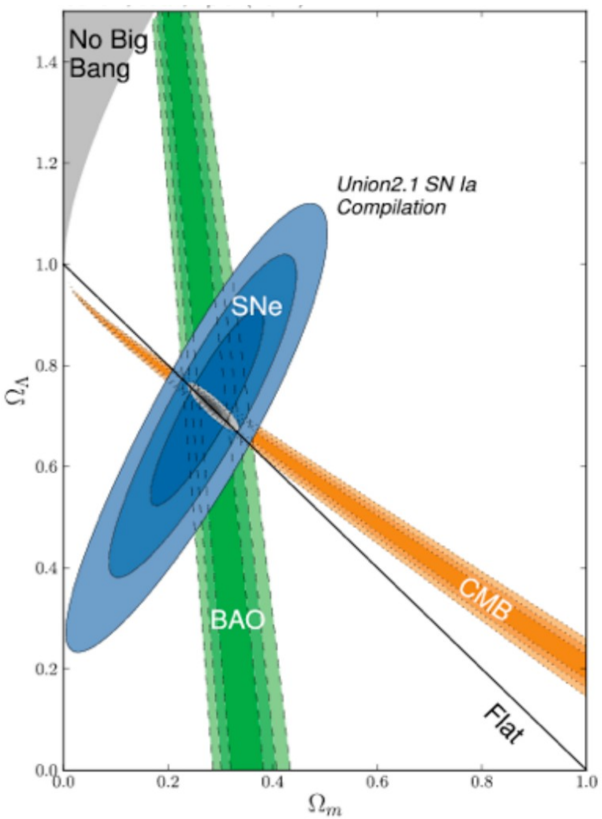
- large-scale structure
- CMBR anisotropy
- red-shift surveys of Type-1a SuperNovae

} $\Omega_\Lambda \approx 0.7$, $\Omega_m \approx 0.3$

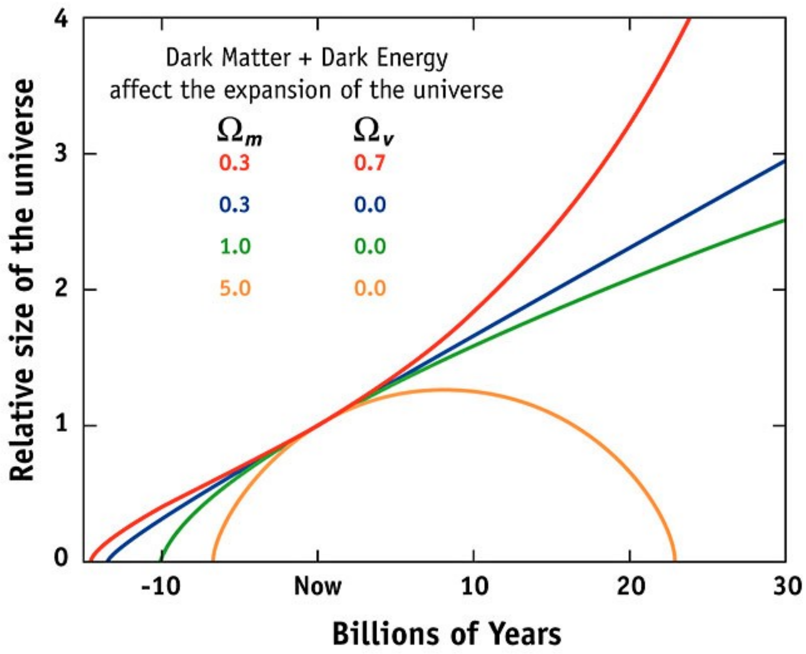
$\Rightarrow$ $\Omega \approx 1$, flat geometry

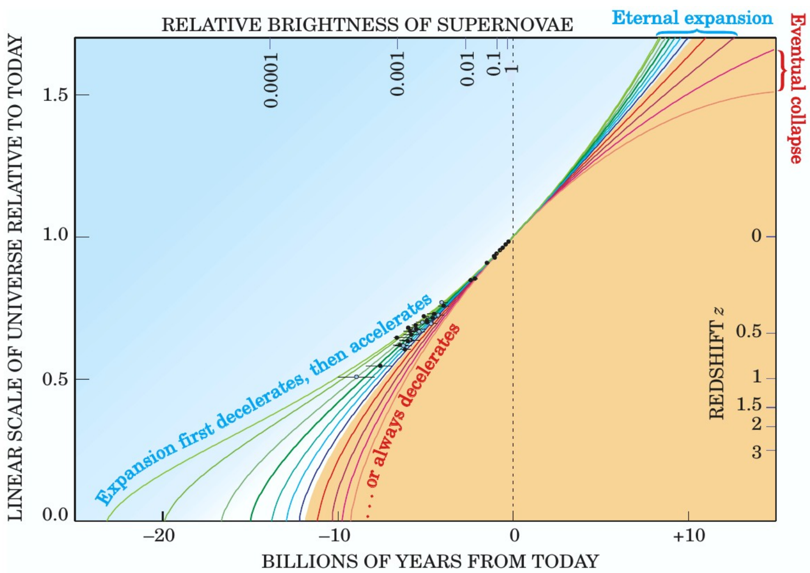
- observed luminous matter:

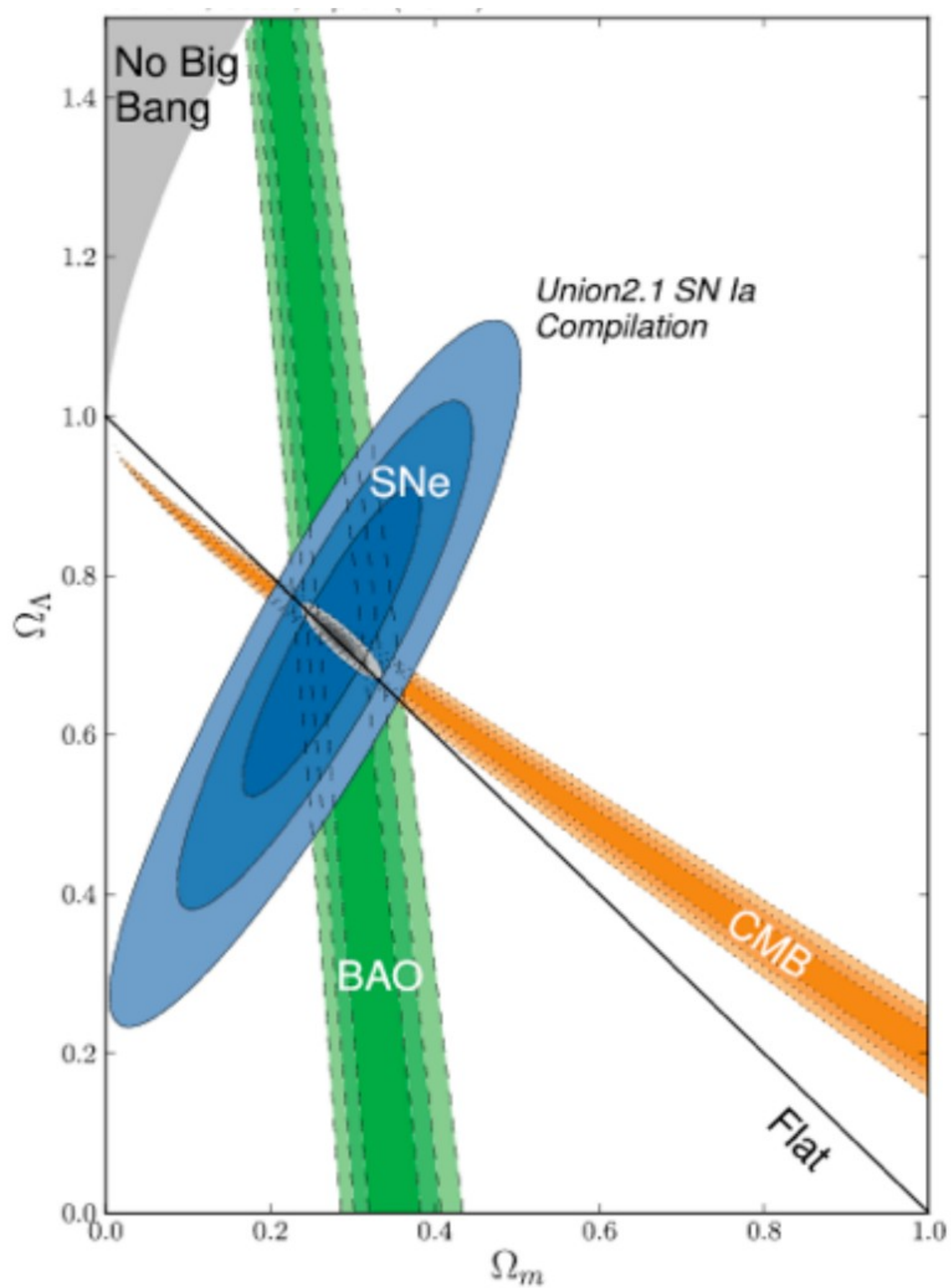
$$\Omega_{lum} \approx 0.05 \ll \Omega_m$$



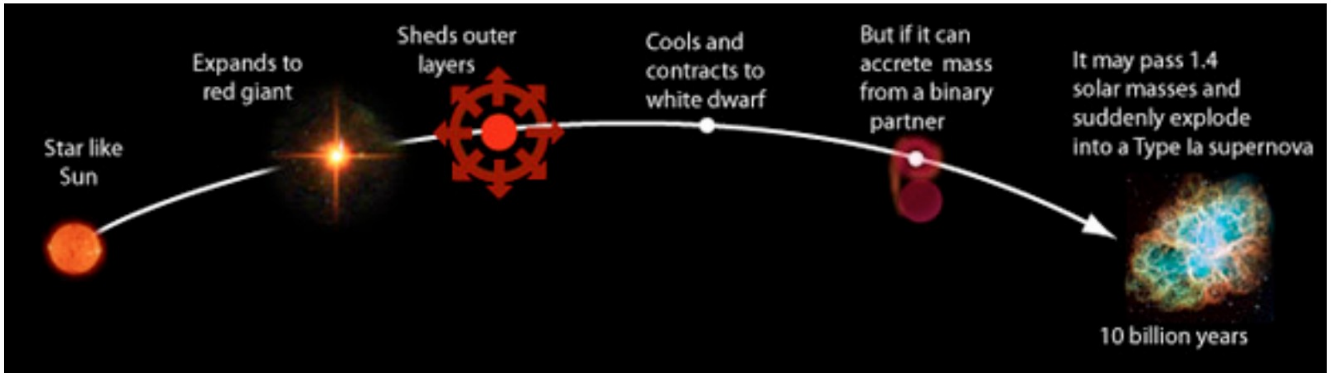
Fate of The Universe

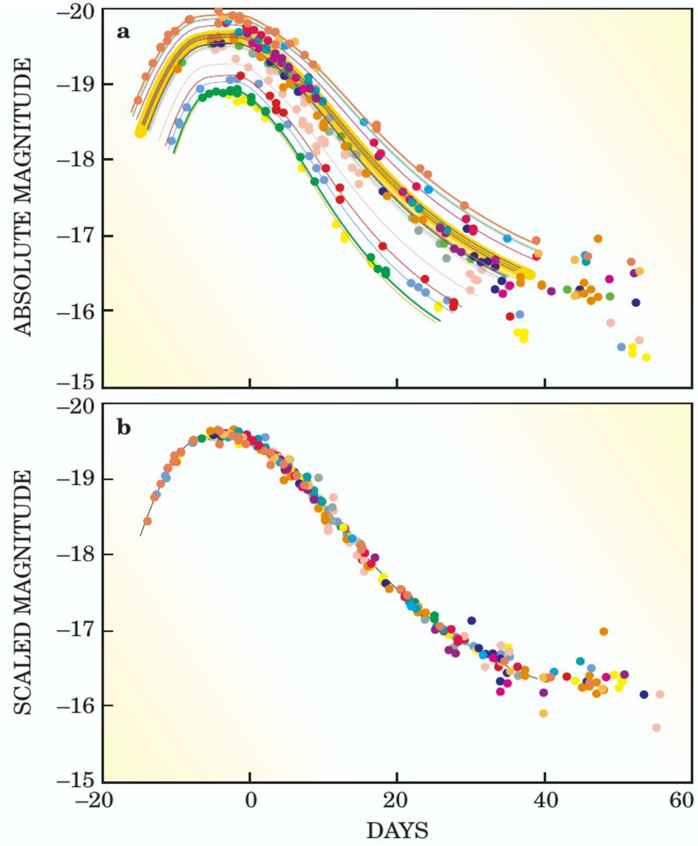


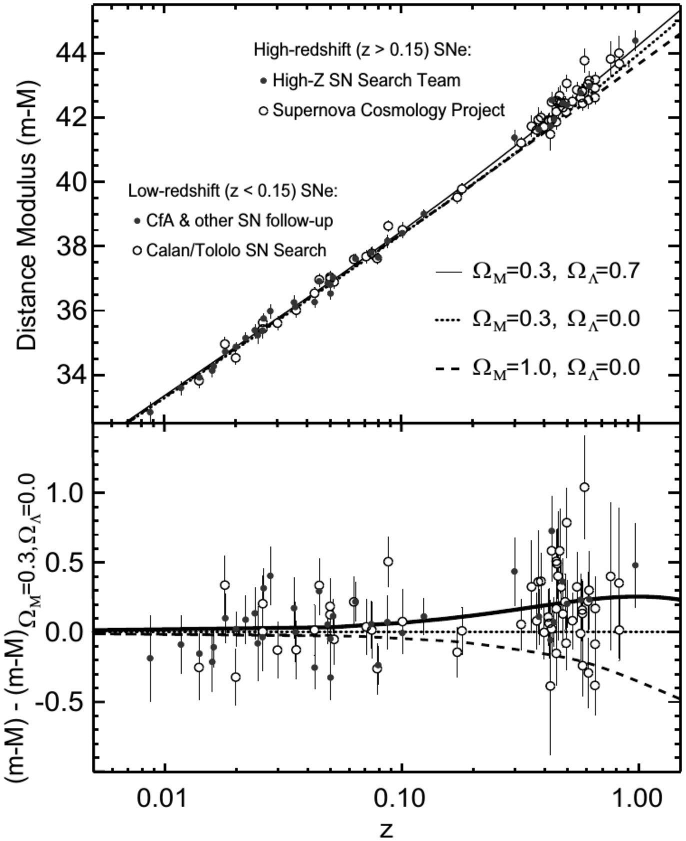




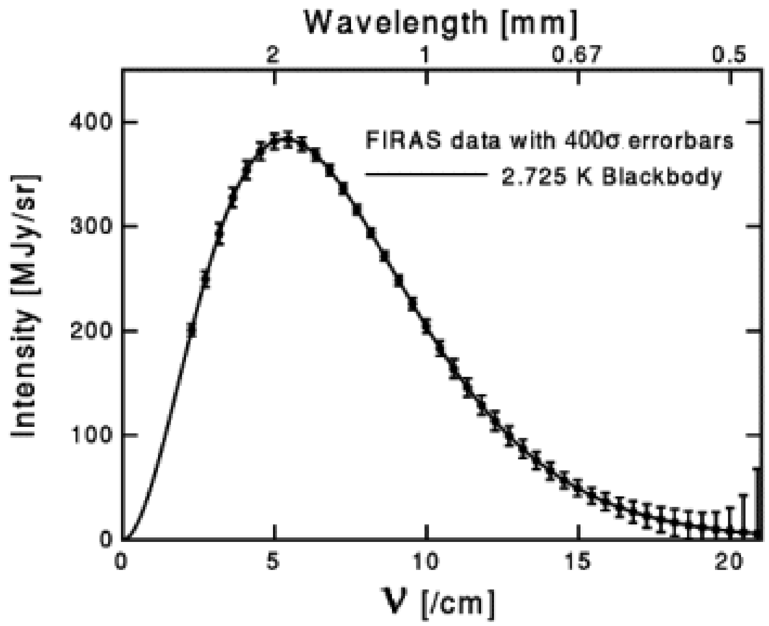
Type-1a Supernovae

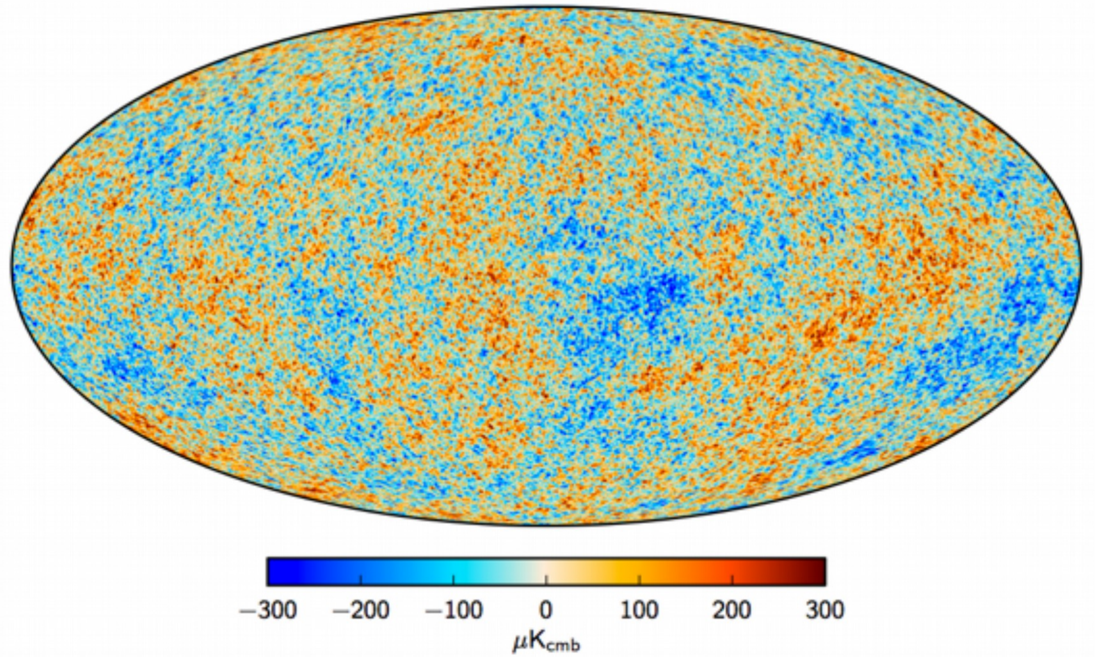


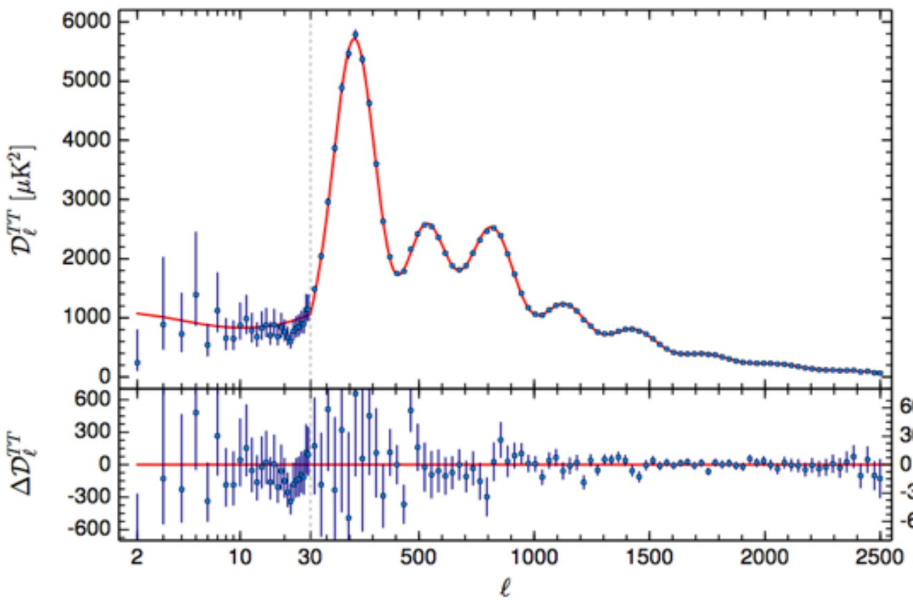




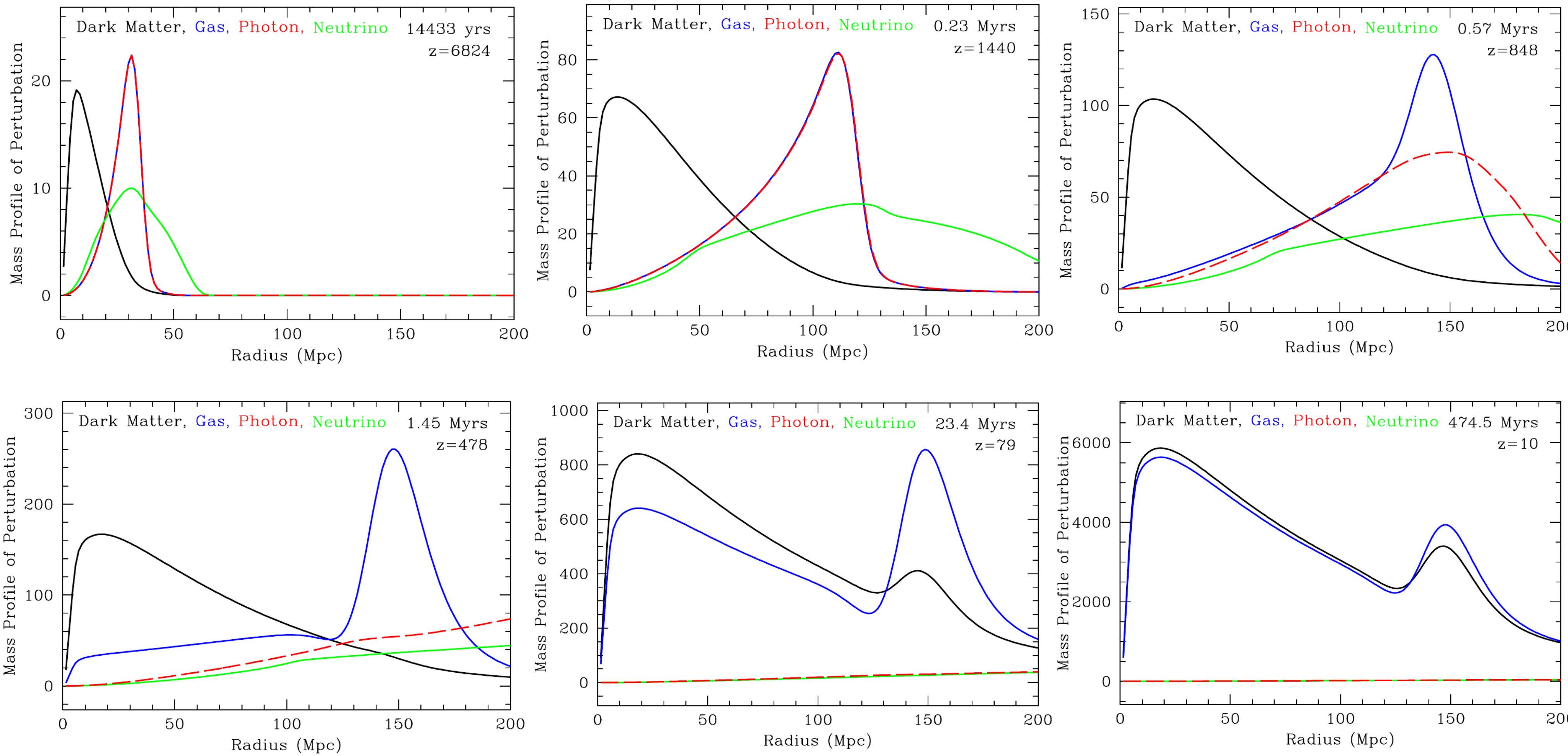
CMBR Anisotropy





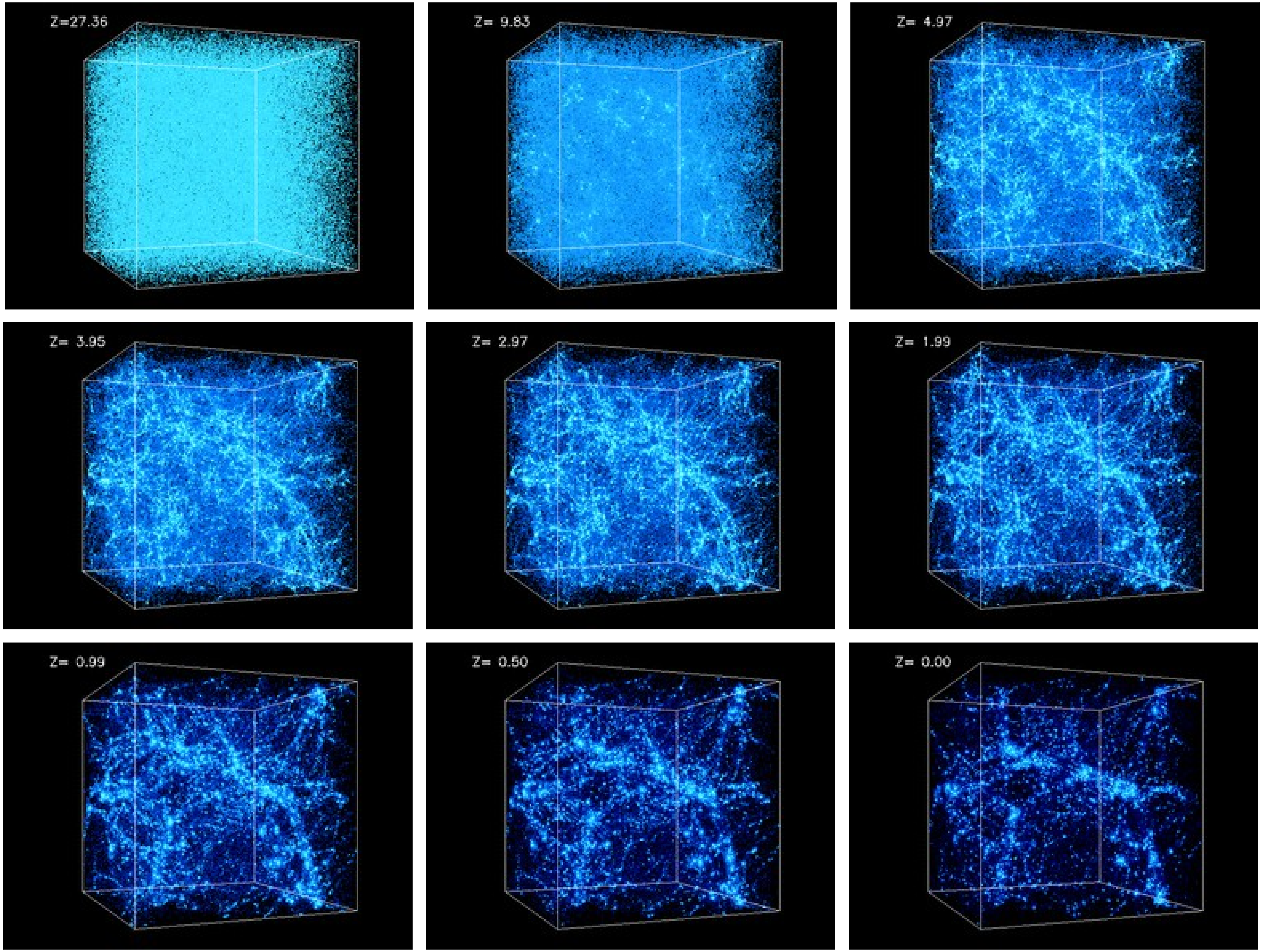


Structure Formation



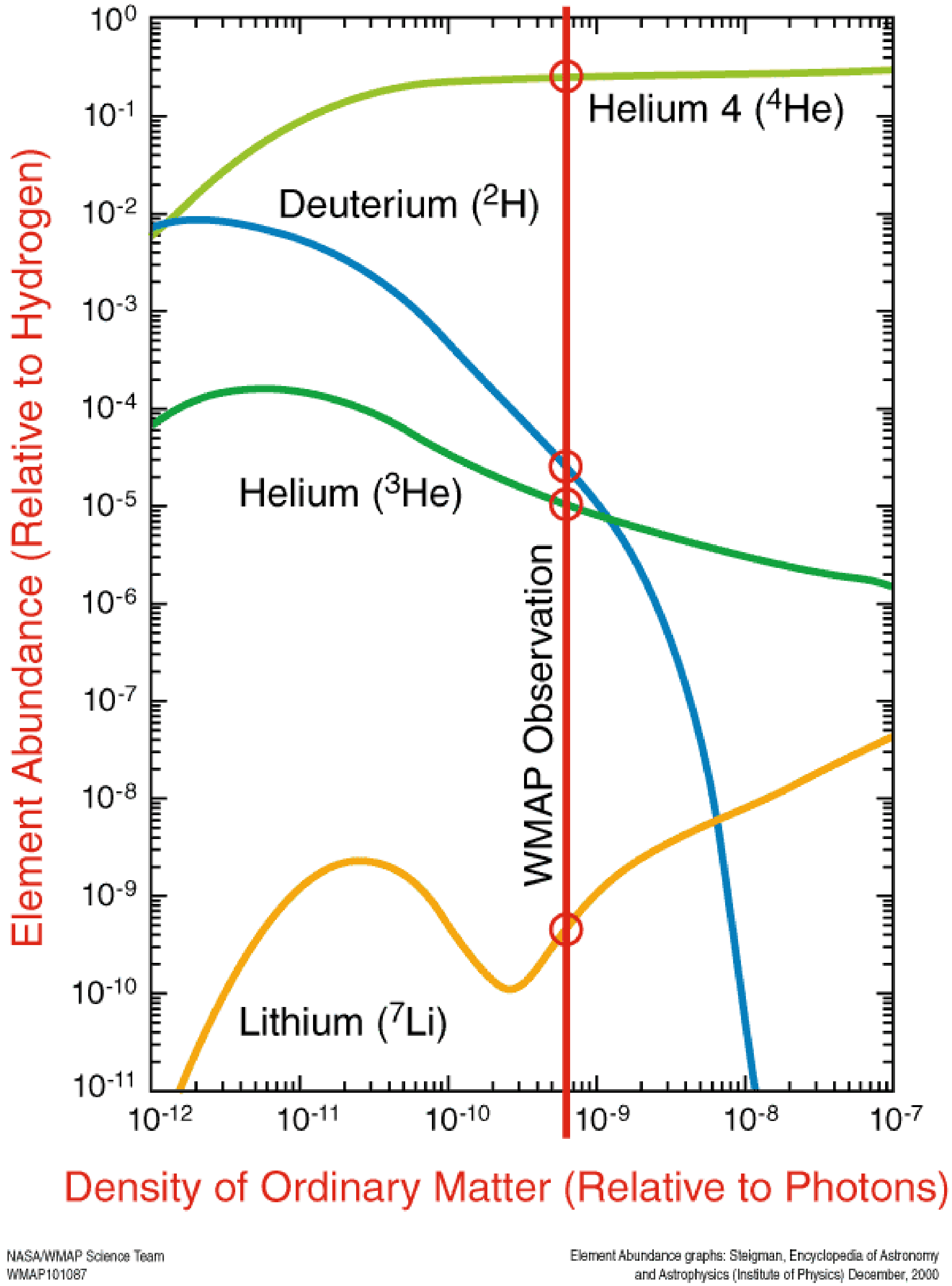
[ApJ 664 (2007) 660-674]

Structure Formation

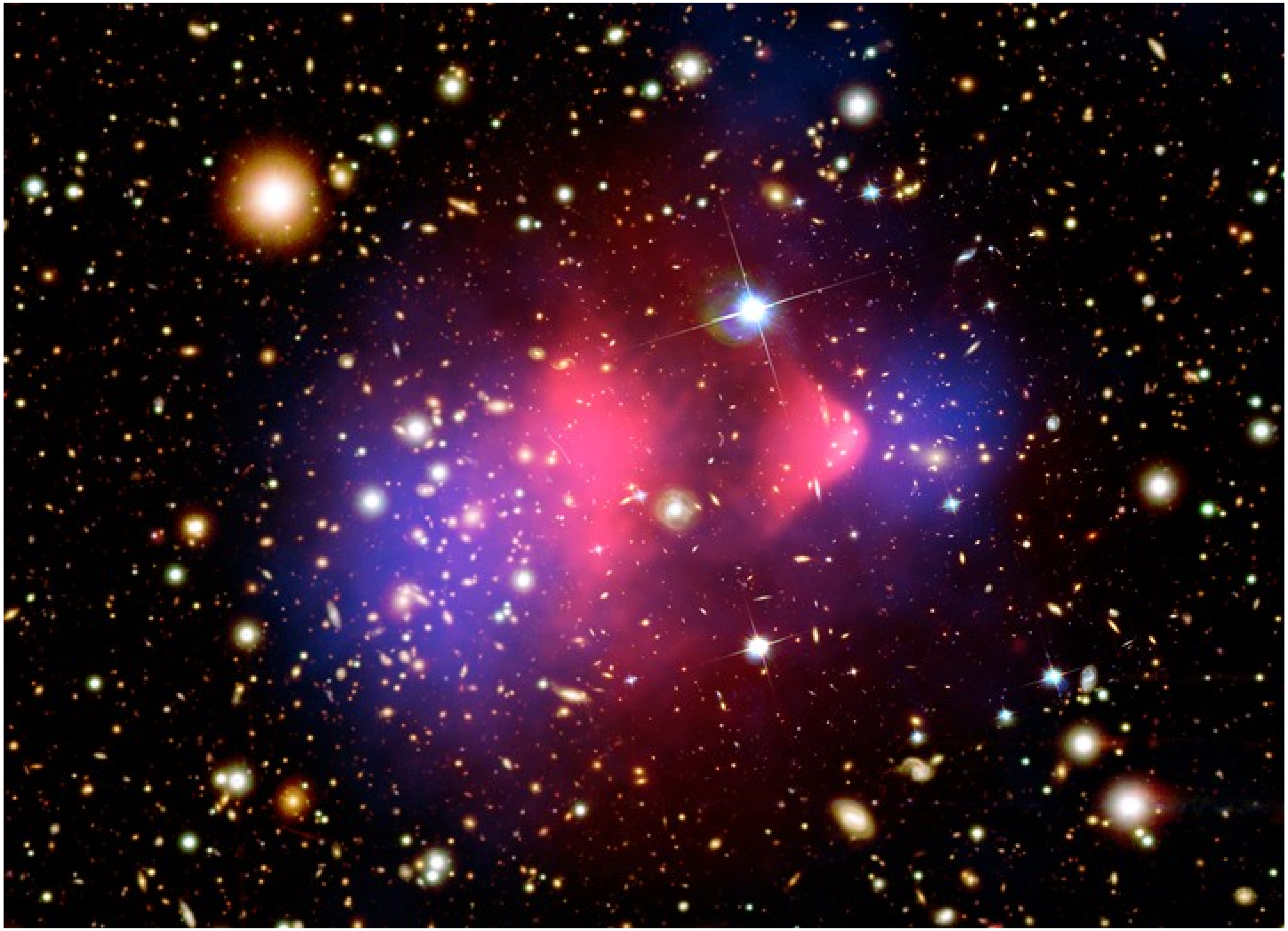


[http://cosmicweb.uchicago.edu/filaments.html]

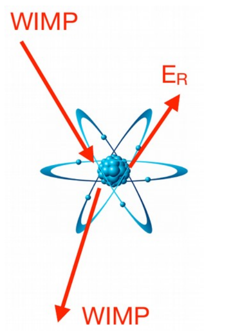
Abundance of Light Elements



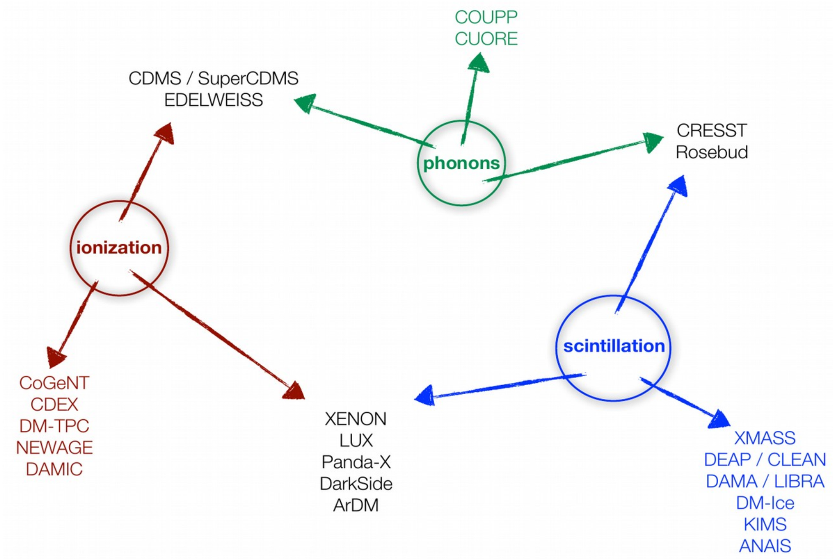
Gravitational Lensing: Bullet Cluster



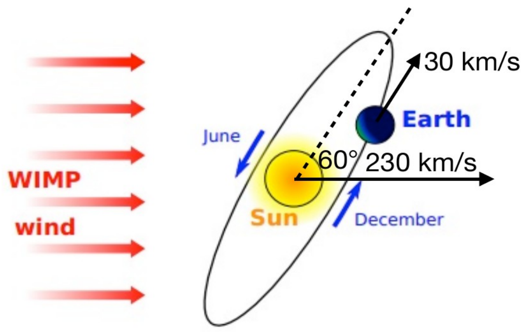
Direct Detection



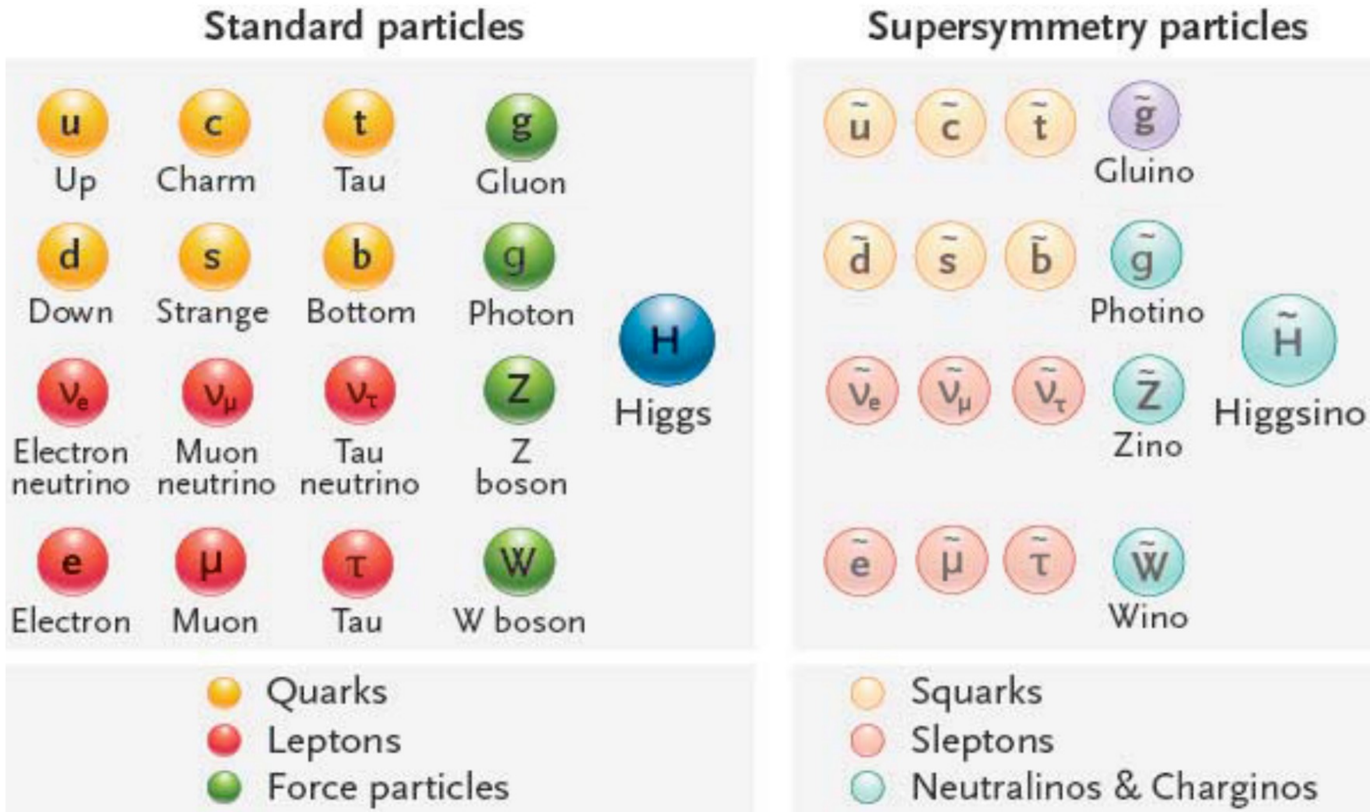
- **search for elastic scattering of WIMPs off atomic nuclei**
- **measure the energy imparted on the recoiling nucleus**
  - small: not more than a few tens of keV
- **large number of experiments**
  - deep underground to suppress backgrounds from cosmics showers
  - using different target materials
  - using different techniques to separate signal from interactions of ionizing particles



- **also: seasonal variation of Earth's velocity relative to galactic rest frame**
  - expect annual modulation of WIMP flux (~3% effect)
  - measure direction of flight of recoiling nucleus ???



SUperSYmmetry

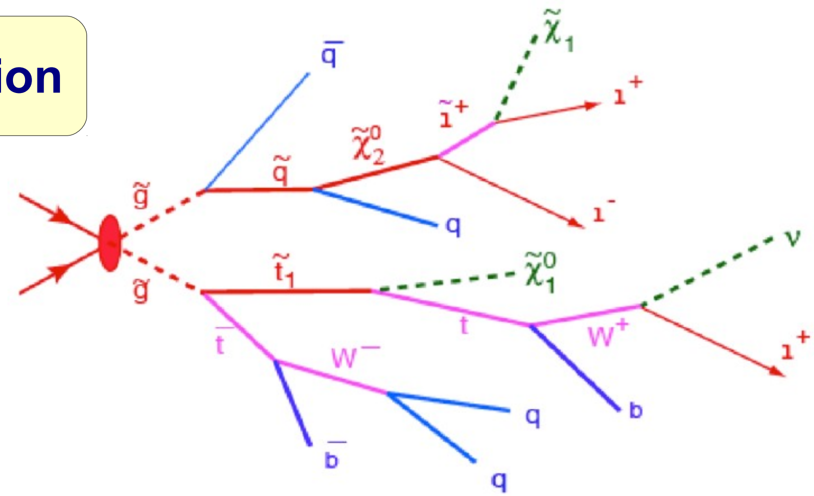


- **class of models that postulates a spin-1 partner for each spin-½ particle of the Standard Model and vice-versa**
- **could solve various "problems" with Standard Model of Particle Physics**
  - e.g. finite mass of Higgs boson ; unification of elm., weak and strong force
- **but introduces many new free model parameters**
- **if lightest SUSY particle stable → WIMP candidate !**

WIMP Production at the LHC

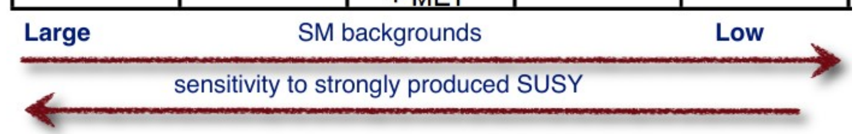
- **pair-production of gluinos / squarks in pp collisions**

strong interaction → large production cross section

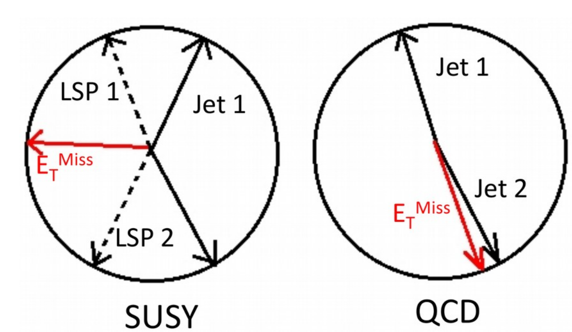


- ***R*-parity conservation: number of SUSY particles conserved in decay**
- **decay cascade:**
  - quarks or leptons produced at each step
- **Lightest Supersymmetric Particle stable**
  - **escapes the detector undetected if it is a neutral particle (WIMP candidate):**
  - large missing transverse energy (E_T)

0-leptons	1-lepton	OSDL	SSDL	≥3 leptons
Jets + MET	Single lepton + Jets + MET	Opposite-sign di-lepton + jets + MET	Same-sign di-lepton + jets + MET	Multi-lepton



clear event signature:
high-p_T jets / leptons + large missing E_T

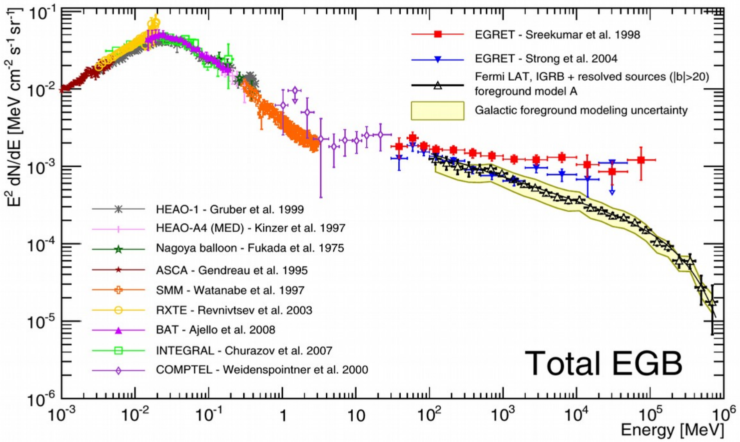


- **use event shape variables to suppress backgrounds from QCD processes**

γ-rays: Surface Experiments

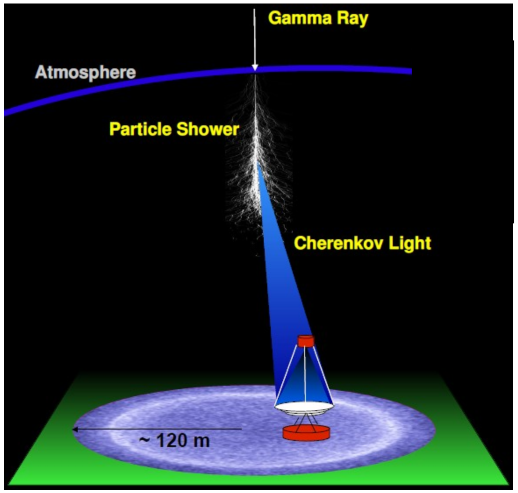
Flux falls steeply with energy (roughly as ~ $E_\gamma^{-2.7}$)

- **above few × 100 GeV: flux too low for observation on small satellite-based detectors**
- **e.g. from Crab nebula** (often used as reference):
  - about 10 γ-rays / m² / year with energy > 1 TeV
  - for 1 event / min: need 50,000 m² detector surface



Indirect detection by surface experiments

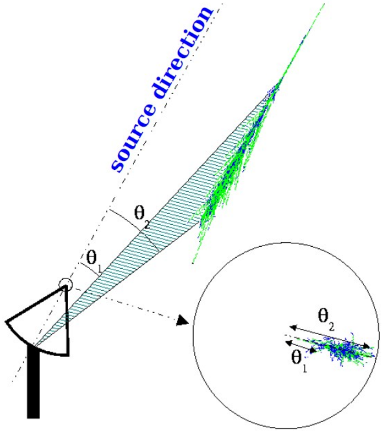
- **γ interacts in upper atmosphere and creates shower**
  - large number of highly relativistic e^+e^- pairs produced
- **e^+/e^- generate Cherenkov photons in air** ($\beta_e > 1 / n$)
  - wavelength around 300-350 nm → penetrate atmosphere
- **observe Cherenkov photons in ground-based telescopes**
  - allows to reconstruct energy and direction of the initial γ-ray

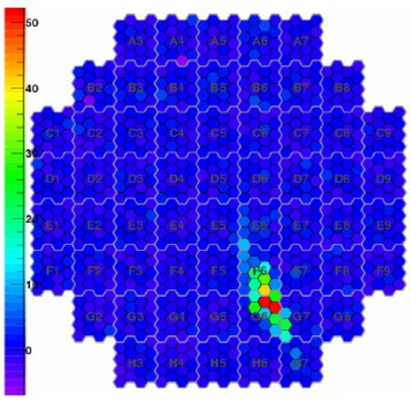


Imaging Telescope Arrays

Imaging Cherenkov Telescope

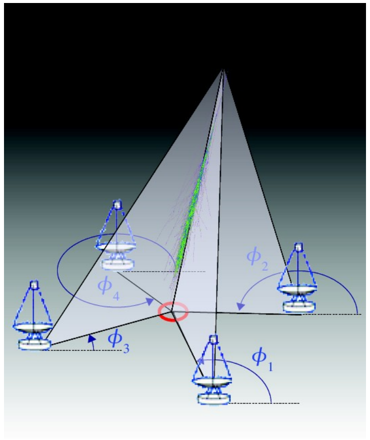
- **large parabolic dish to focus Cherenkov photons onto a segmented camera**
  - position in detection plane → angle of photon
  - orientation of image → 2D direction of shower
- **shape of image → suppress background**

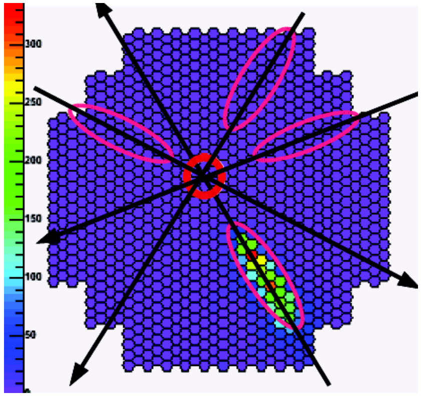




Telescope array

- **view the same shower from different angles**
- **3D reconstruction of shower direction**

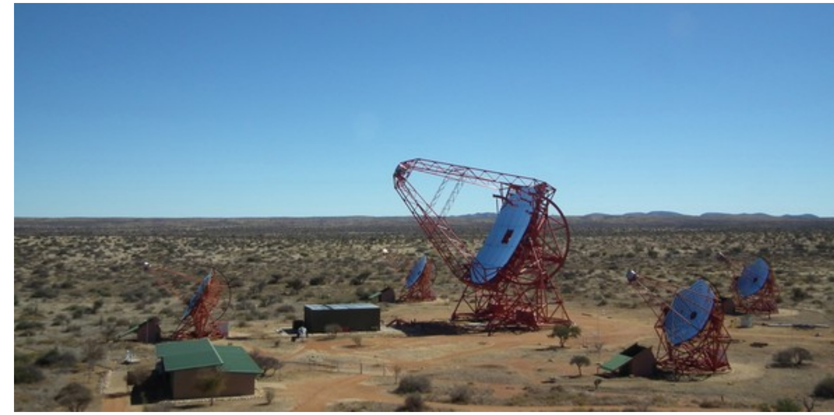




Key parameters

- **size of telescope dishes: number of Cherenkov photons collected per shower**
  - important at lower γ-energies where fewer Cherenkov photons generated
- **surface area over which telescopes are distributed: acceptance for showers**
  - important at highest γ-energies where flux is lowest

H.E.S.S.



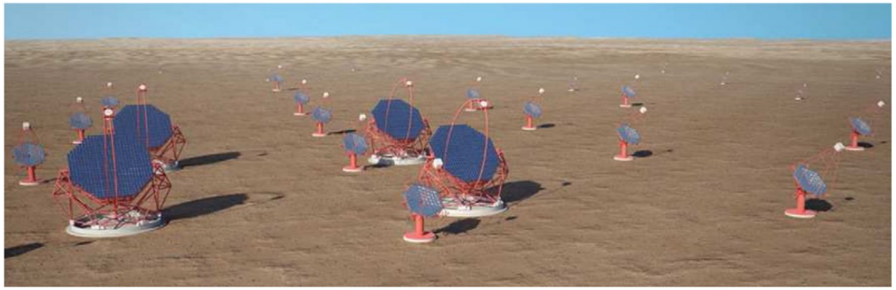
<u>Array of 4 (+1) telescopes</u>

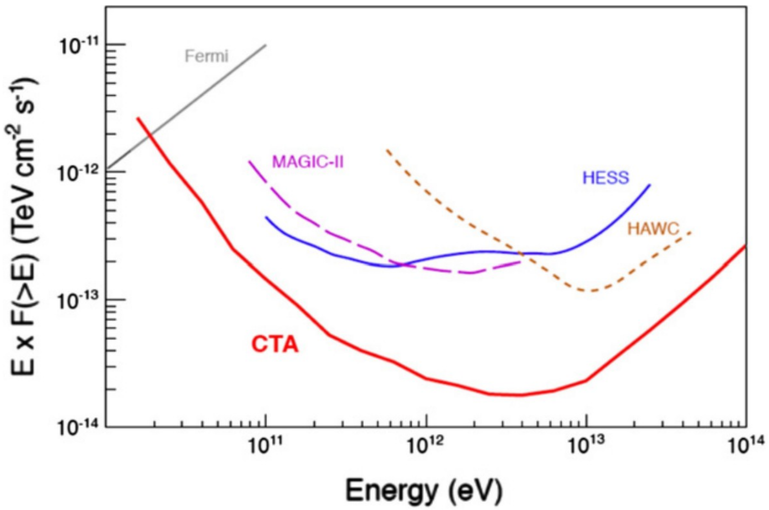
- **located in Namibia → view of GC**
- **four telescopes, 108 m² dish surface each**
  - spacing between telescopes: 120 m
  - **one telescope with 614 m² dish surface**
- **observation time about 1000 hours / year**
  - only clear and "moonless" nights
- **field of view: 5° (c.f. Fermi 2.4 sr)**
- **no e/γ separation → no diffuse γ-ray spectrum**

CTA

Large Cherenkov Telescope Array

- **UZH and ETHZ involvement**
- ***O*(100) telescopes foreseen**
  - large array Southern hemisphere (Chile?)
  - smaller array Northern hemisphere (La Palma?)
- **three different mirror sizes**
  - **a few 24m (**low energies, 10–100 GeV**)**
  - **some 10-12m (**intermediate energies**)**
  - **many 4-6m (**highest energies, > 10 TeV**)**
- **expected energy resolution: 5-10%**
  (c.f. 15% for existing experiments**)**
- **expected angular resolution: 0.03°**
  (c.f. 0.1° for existing experiments**)**





[Astroparticle Physics 43 (2013) 1-356]

Universität Zürich[UZH]

Experimental Astro-Particle Physics

Indirect DM Searches

Spring 2015

Olaf Steinkamp

36-J-22 olafs@physik.uzh.ch 044 63 55763

Exams

Dates:

- **May 28 and 29** **(**last two days of the semester**)**

Format:

- **20 min oral presentation + 5–6 pages "lecture notes" on a chosen topic**
- **10 min questions on presentation (**and anything else from lecture course**)**

Suggested topics: see next slide and handout

- **sign up by email to olafs@physik.uzh.ch or with Michelle on Wednesday**
  - first come, first serve ;-)
- **before you start preparing your presentation, contact corresponding lecturer**
  - short discussion on material to cover, hints for useful literature, …
- **your own suggestion are also welcome, please contact us**

Exam Topics

1. **Cosmology**:
   High-z supernovae and the accelerated expansion of the Universe
2. **Cosmology**:
   Numerical simulations of dark matter distribution in galaxies
3. **Cosmology**:
   Neutrino mass determination from cosmological observations (CMB anisotropy, BAO, LSS)
4. **Cosmic rays**:
   Measurements of the chemical composition of cosmic rays
5. **Cosmic rays**:
   Ultra-high energy cosmic neutrinos and IceCube data
6. **Cosmic rays**:
   Anisotropies in cosmic rays (measurements by IceCube, HAWC, etc)
7. **Indirect dark matter detection**:
   The positron excess and measurements by Fermi and AMS-II
8. **Indirect dark matter detection**:
   The story of the "130 GeV gamma-ray line signal" in the Fermi LAT data
9. **Indirect dark matter detection**:
   Gamma rays from dwarf spheroidal galaxies
10. **Direct dark matter detection**:
    Low-mass WIMP searches with CCDs: DAMIC
11. **Direct dark matter detection**:
    WIMP searches with bubble chambers (COUPP, PICASSO, PICO)
12. **Direct dark matter detection**:
    Axion searches with the ADMX experiment

Introduction

Convincing evidence for existence of Dark Matter (→ Laura)

- **gravitational lensing, galactic rotation curves, cluster formation, CMBR fits**

Standard paradigm: Dark Matter is made up of WIMPs (→ Alex)

- **"WIMP miracle": relic density ≈ compatible with weak cross section**

Three complementary approaches for WIMP searches:

- **direct detection through interaction in detector material** (→ Alex, Laura)
  - cross-sections small; backgrounds from standard particle-physics processes
- **production at colliders** (→ Yong)
  - "reverse problem": how do we know the produced particles (if any) are DM?
- **indirect detection through observation of annihilation products** (→ today)
  - almost any signature can also be explained by astrophysical processes

→ **want to see evidence in more than one of the approaches !**

Indirect Detection

Dark Matter Madlibs!

Dark matter annihilates in ________________ to
(a place)

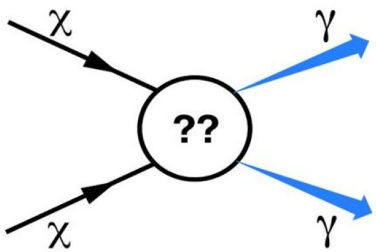
________________ , which are detected by ________________ .
(particles) (an experiment)

[J. Feng, UC Irvine]

Particles (I)

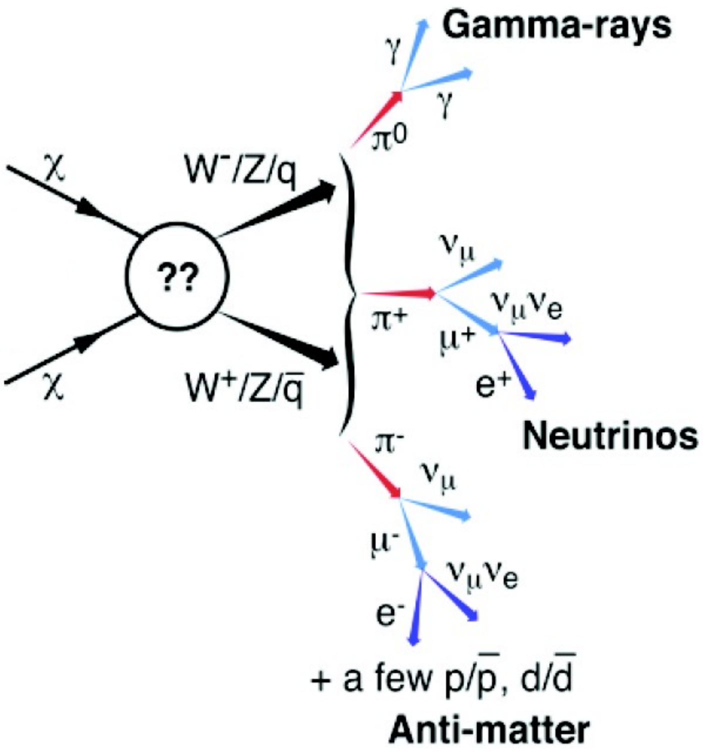
Annihilation of pairs of WIMPs

- $\gamma\gamma$, γ Z, γ H → resonance line in photon spectrum
- heavy fermions, W / Z, H bosons → fragmentation, decay



Fragmentation and decay of annihilation products

- photons (≈ 20–30% of energy)
- electrons/positrons (another 20–30%)
- (anti-)protons, (anti-)deuterium (few %)
- neutrinos (rest)



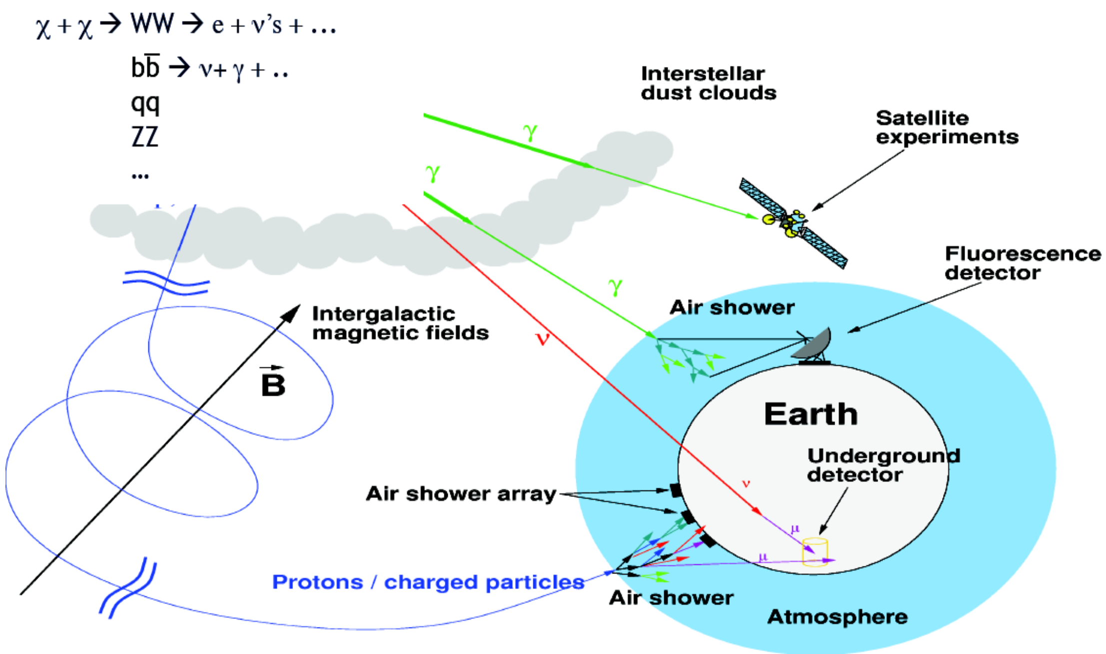
Synchrotron radiation

- radio-wavelength photons from propagation of e^+/e^- through galactic magnetic fields

Inverse Compton Scattering

- MeV to GeV photons from up-scattering of starlight

Particles (II)



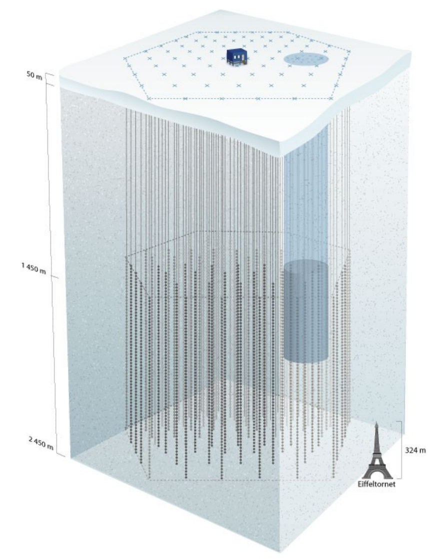
Photons

- **loose energy by Bremsstrahlung and Compton scattering**
- **large and complex backgrounds from astrophysical sources**

Positrons / antiprotons

- **get deviated and trapped in (inter-)galactic magnetic fields**
  - do not point back to source
  - can reach only from nearby sources (≤ 8 kpc)
- **largely unknown backgrounds from astrophysical sources**

High-energy neutrinos



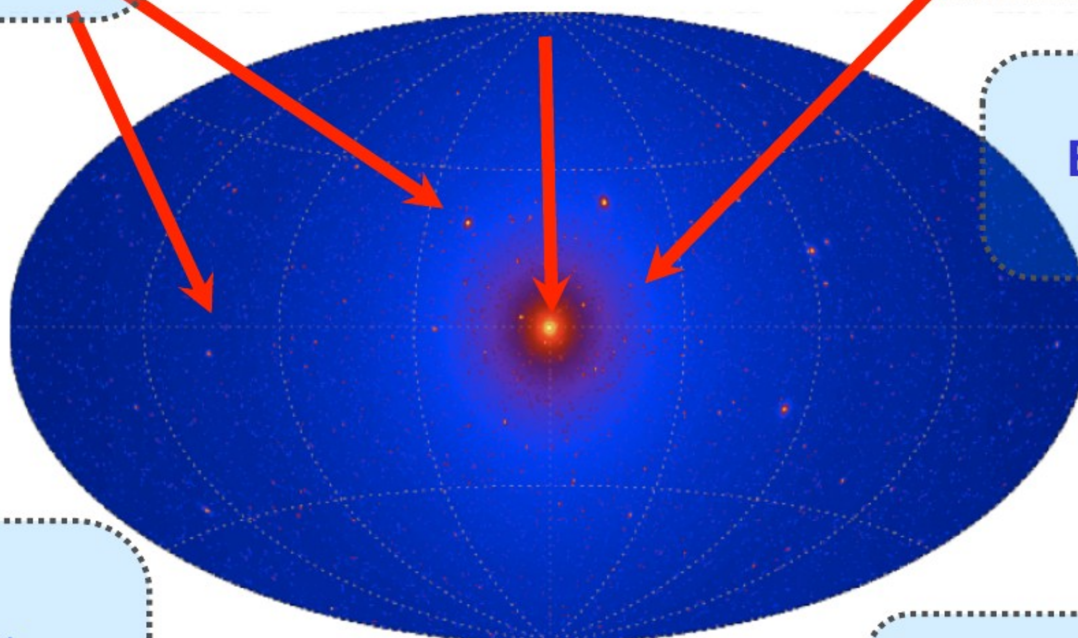
- **very small interaction cross sections → small statistics even with huge detectors**
- **large background from atmospheric neutrinos**

Places (I)

Satellites
Low background and good source id, but low statistics, astrophysical background

Galactic Center
Good Statistics but source confusion/diffuse background

Milky Way Halo
Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

Cosmic-ray Electrons and Positrons

The Sun

Spectral Lines
No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

Galaxy Clusters
Low background, but low statistics

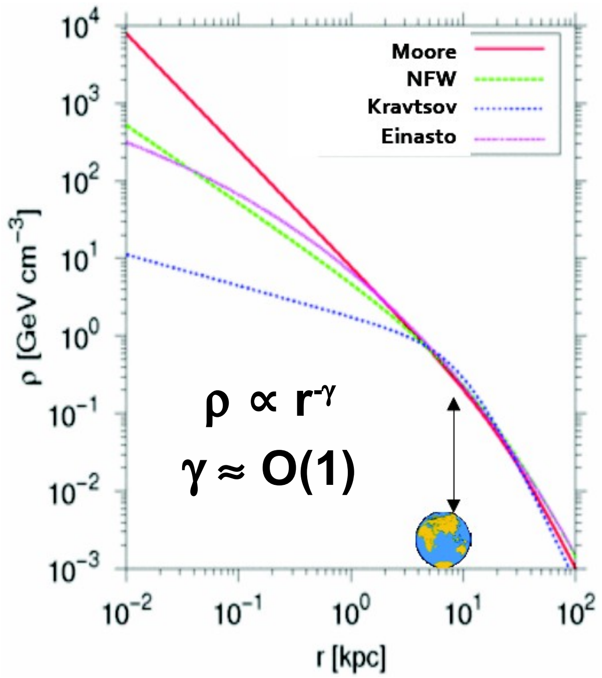
Extragalactic
Large statistics, but astrophysics, galactic diffuse background

[M. Wood, SLAC Seminar, Oct 14, 2014]

Galactic centre (GC) and halo

- **DM density profiles from numeric simulations of galaxy formation are strongly peaked towards GC**
- **WIMP annihilation cross section ∝ density squared**
  - predicted flux under angle ψ with respect to GC

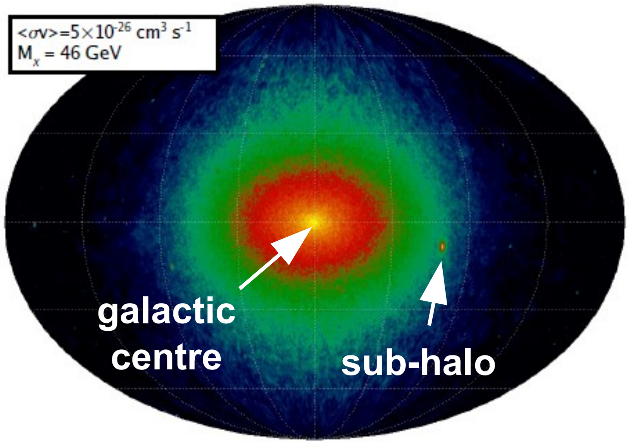
$$\Phi_i(\psi, E) \propto \underbrace{\frac{\langle \sigma v \rangle}{M_\chi} \cdot \frac{dN_i}{dE}}_{\text{particle physics}} \times \underbrace{\int_{\text{line of sight}} \rho^2_{DM}(s)\, ds(\psi)}_{\text{cosmology}}$$



- **simulations of galaxy formation usually result in non-smooth DM density distributions ("sub-halos")**
  - significant enhancement of annihilation rate
  - usually parametrized by "boost factor"

$$B \propto \langle \rho^2 \rangle / \langle \rho \rangle^2$$

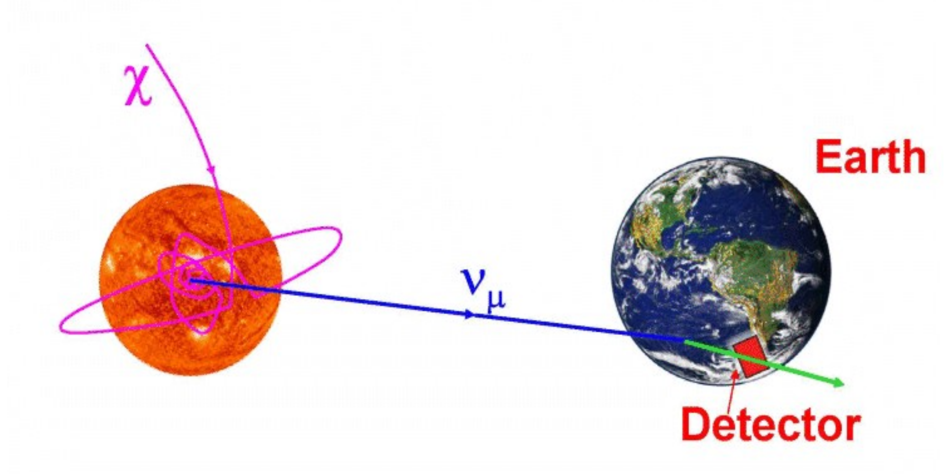
- **sensitivity for indirect detection often relies on large values of such boost factors**



example of the expected γ-ray flux from an N-body galaxy simulation

Places (III)

The core of our Sun

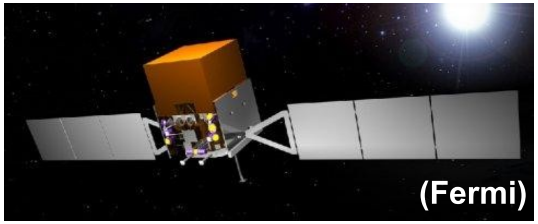


- **Sun "sweeps" through the DM halo of our galaxy**
- **WIMPs scatter elastically on nuclei**
  - loose energy → become gravitationally bound → accumulate in Sun's core
- **WIMP annihilation in Sun's core → constant flux of high-energy neutrinos**
  - annihilation rate ∝ density of trapped WIMPs squared
  - reaches equilibrium with capture rate after a few 10^9 years
- **in equilibrium: neutrino flux ∝ elastic WIMP-nucleon scattering cross section**
  - spin-dependent cross section (WIMP scattering on H nuclei)
  - spin-independent cross section (WIMP scattering on heavier nuclei)
- **predicted neutrino flux potentially large enough to be detected on Earth**

Experiments (I)

Gamma-rays: do not penetrate Earth's atmosphere

- **up to O(100 GeV): direct detection in balloon or satellite experiments**
  - e.g. EGRET, Fermi; planned: GAMMA-400
- **up to TeV energies: indirect detection in ground-based air shower detectors**
  - e.g. H.E.S.S.; planned: CTA

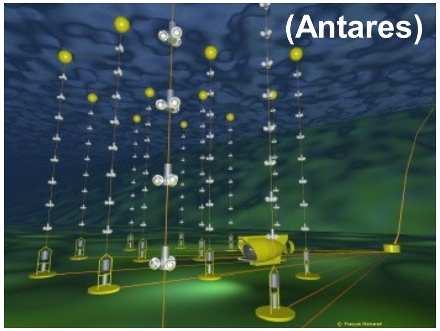


Positrons / antiprotons: backgrounds from air showers

- **balloon or satellite experiments above atmosphere**
  - e.g. Pamela, Fermi, AMS-02

High-energy neutrinos: very low interaction cross section

- **huge, deep underground water Cherenkov detectors**
  - e.g. Super-Kamiokande, SNO
- **neutrino telescopes in deep water, antarctic ice**
  - e.g. Antares; Amanda, IceCube



Experiments (II)

	Space-based experiments			Ground-based experiments		
	Fermi	**AMS-2**	**GAMMA-400**	**H.E.S.S.-II**	**MAGIC**	**CTA**
Energy range, GeV	0.02-300	10-1000	**0.1-3000**	> 30	> 50	> 20
Field-of-view, sr	2.4	0.4	**~1.2**	0.01	0.01	0.1
Effective area, m^2	0.8	0.2	**~0.4**	10^5	10^5	10^6
Angular resolution ($E_\gamma > 100$ GeV)	0.2°	1.0°	**~0.01°**	0.07°	0.05°	0.06°
Energy resolution ($E_\gamma > 100$ GeV)	10%	2%	**~1%**	15%	15%	10%

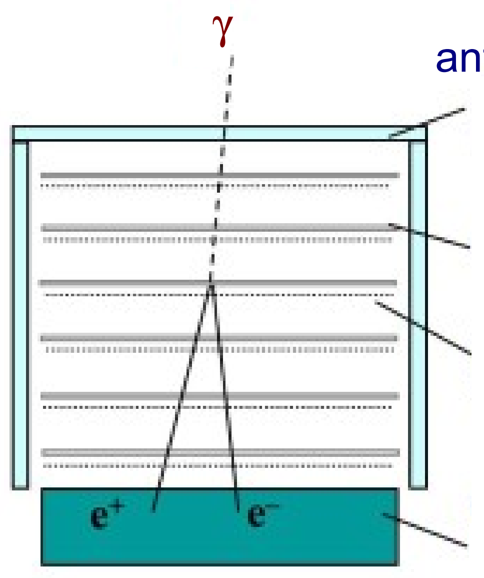
Galper et al. 2012

launch scheduled for 2018

γ-rays: Space-Based Experiments

Principle of detection / reconstruction:

- **layers of conversion foils**
  - pair production $\gamma \rightarrow e^+e^-$
- **tracking detector:** measure e^+ and e^- trajectories
  - reconstruct direction of incident γ
- **calorimeter:** measure e^+ and e^- energies
  - reconstruct energy of incident γ
  - also: hadron rejection from shower shape
- **anti-coincidence counter:**
  - veto charged incident particles



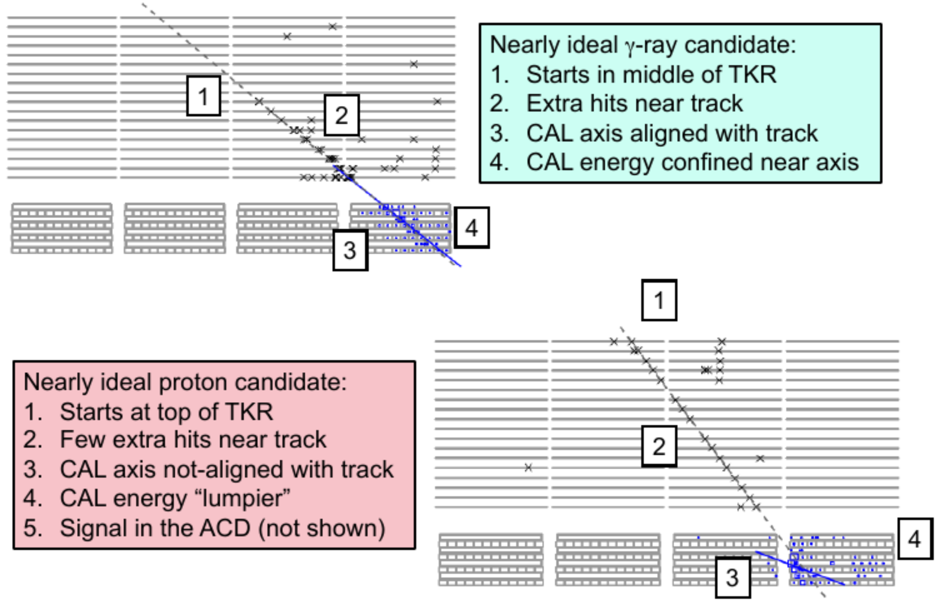
Limitations by operation in space

- **size and mass: detection area limited to O (1 m^2)**
- **power consumption, other consumables** (e.g. gas)
- **cooling, temperature variations, radiation damage**

Backgrounds

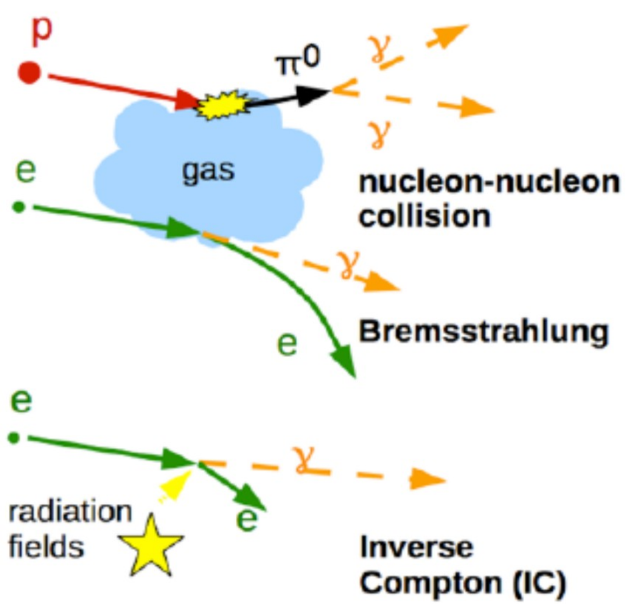
Hadronic cosmic rays

- **1000 × more abundant than γ-rays**
- **anti-coincidence counters**
- **hit distributions in tracking detector**
- **shower-shape in calorimeter**
- **Fermi: background rejection > 10^5, maintaining 50 % efficiency for γ rays**



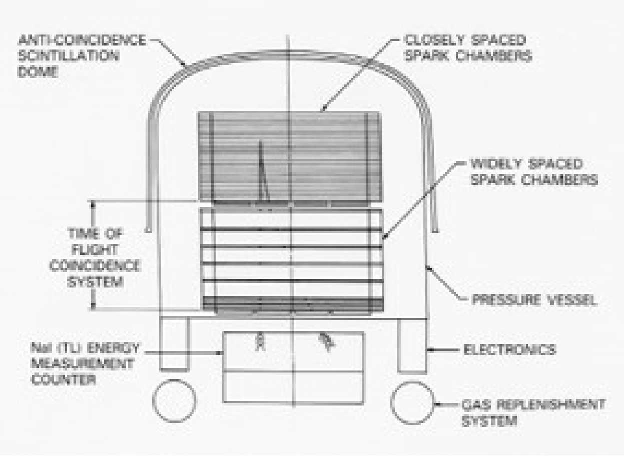
Astrophysical sources of γ–rays

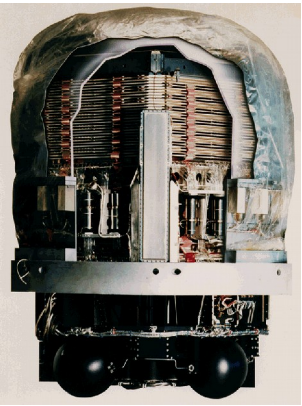
- **point sources and diffuse emission**
  - high-energy π^0 from hadronic interactions
  - e^+/e^- bremsstrahlung in interstellar gas
  - Inverse Compton scattering of starlight
- **indistinguishable from possible DM signal**
- **model their distribution and subtract from the observed signal**



EGRET

In operation from 1991 till 1999



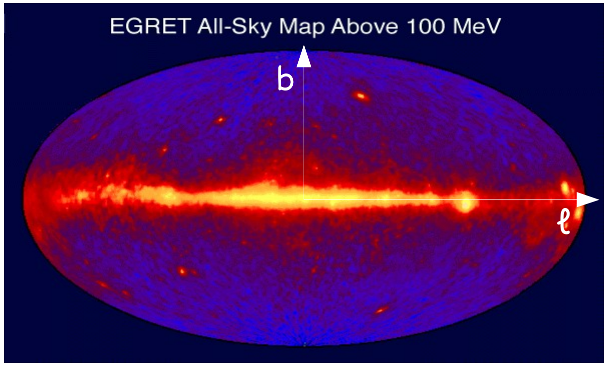


- all-sky γ survey from 30 MeV to 30 GeV
- spark chambers + NaI(Tl) calorimeter

Detected ~270 point sources

- ≈ 1/3 of them identified with known objects

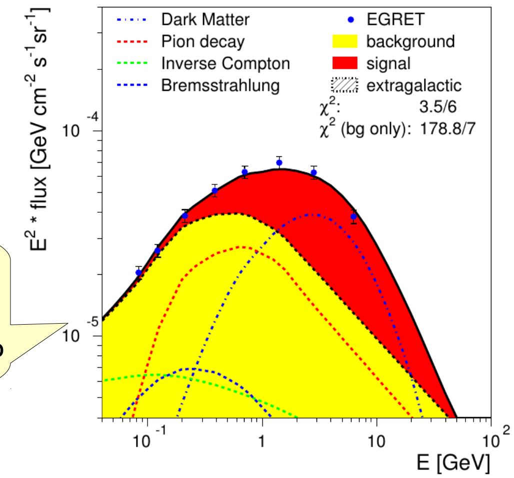
mostly AGNs, Pulsars



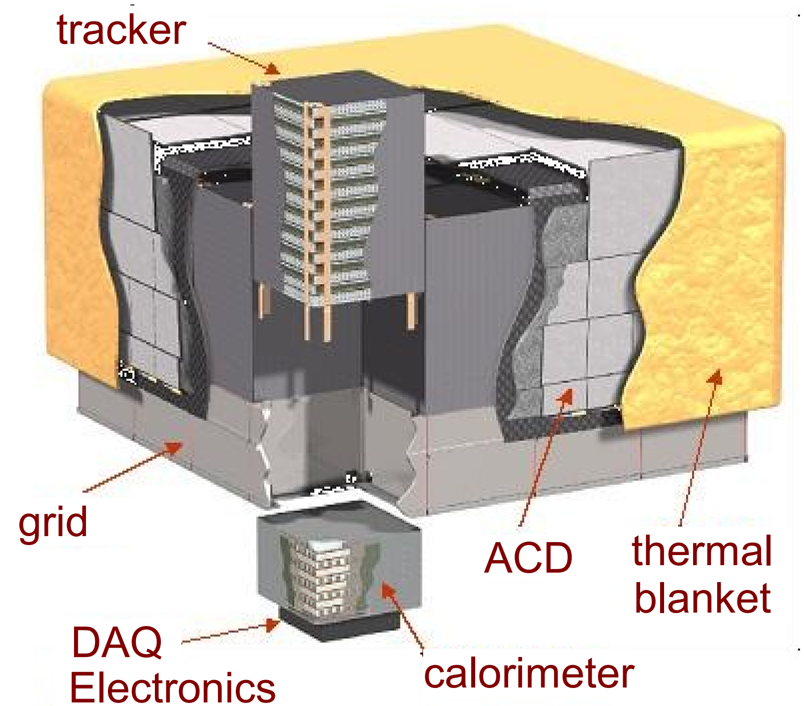
Diffuse emission spectrum

- energy spectrum after subtracting point sources
- observe large excess in flux above $E_\gamma \approx 1$ GeV
- compatible with annihilation signal from a 60 GeV WIMP
  - but would require complicated DM density distribution
  - incompatible with observed anti-proton flux
  - not confirmed by later FERMI measurements
- artefact from imperfect acceptance calibration ?

towards GC:
latitude |b|<5°
longitude |ℓ|<30°

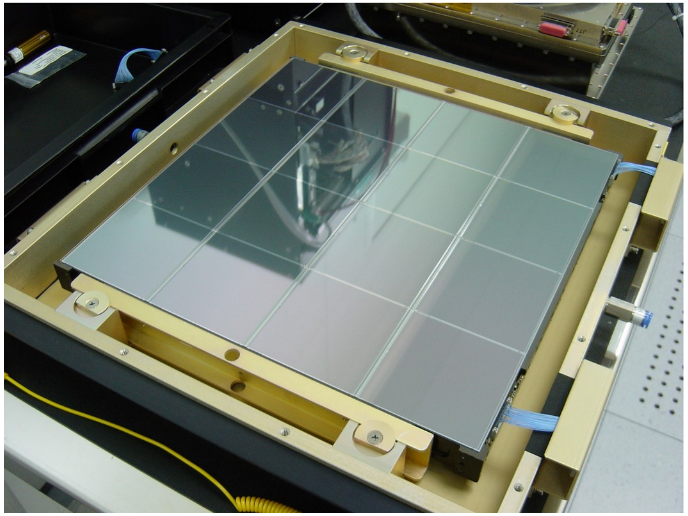


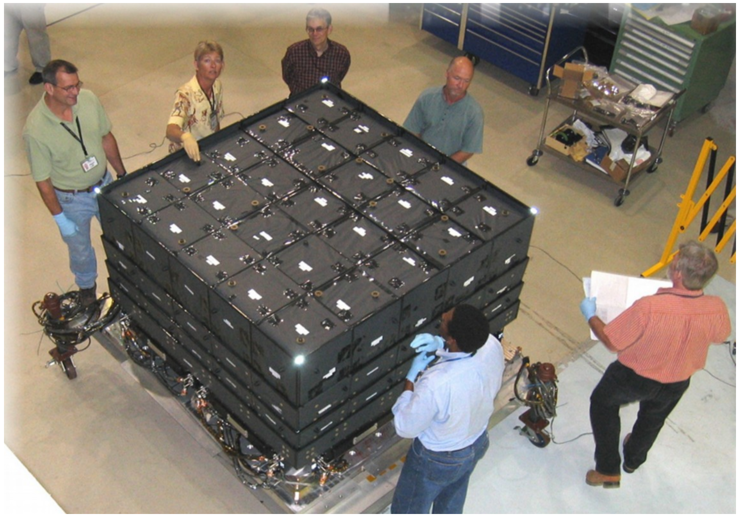
Fermi Large-Angle-Tracker



Launched in 2008

- **energy range 20 MeV – 300 GeV**
- **tungsten converter foils**
- **silicon micro-strip detectors**
  - 18 double layers, 200 μm strip pitch
- **segmented CsI(Tl) calorimeter**
  - about 8.5 radiation lengths

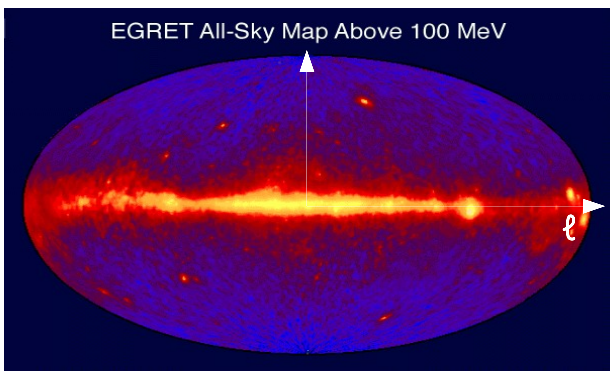


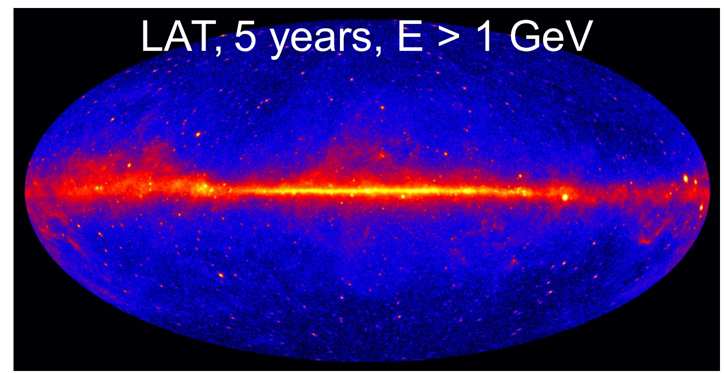


Fermi Large-Angle-Tracker

Performance comparison

	Years	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Eng. Rng. (GeV)	$A_{eff}\,\Omega$ (cm^2 sr)	# γ-rays
EGRET	**1991–00**	**5.8°**	**0.5°**	**0.03–10**	**750**	**1.4 × 10^6/yr**
AGILE	**2007–**	**4.7°**	**0.2°**	**0.03–50**	**1,500**	**4 × 10^6/yr**
Fermi LAT	2008–	3.5°	0.1°	0.02–300	25,000	1 × 10^8/yr

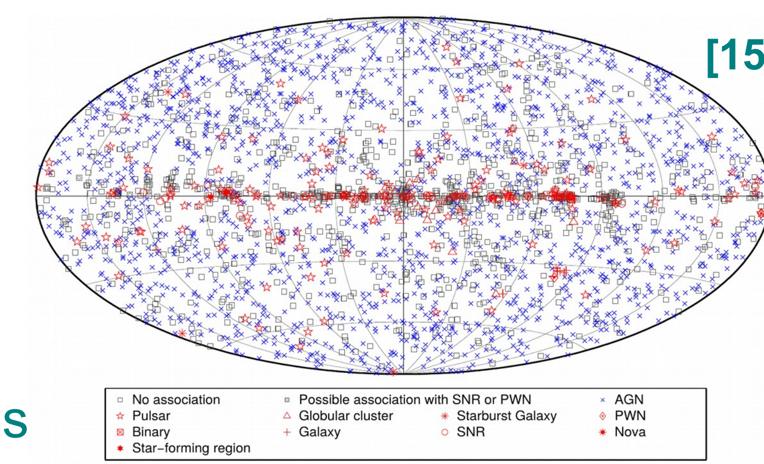




Latest point-source catalogue (3FGL)

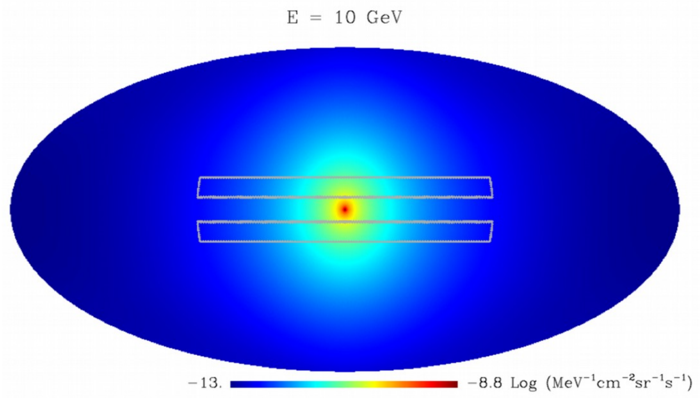
[1501.02003]

- based on data from four years
- 100 MeV – 300 GeV
- 3033 point sources with significance > 4 σ
- ≈ 2/3 of them associated with known sources

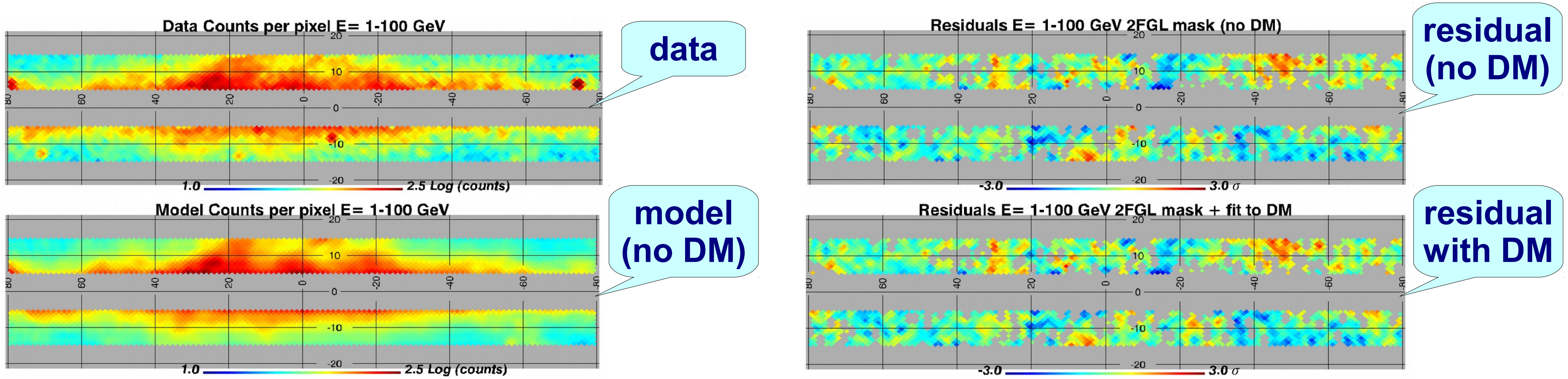


Fermi: Diffuse γ-Spectrum

Measurement based on data from 24 months [1205.6474]



- **investigated region between 5º and 15º in latitude and < 80º deg in longitude**
  - close to GC where DM density is highest
  - but not too close to exclude astrophysical sources near GC
- **mask known point sources, model astrophysical diffuse emission**
  - π^0 decays, bremsstrahlung, Inverse Compton scattering
- **find good agreement between model and data, no need for DM component**

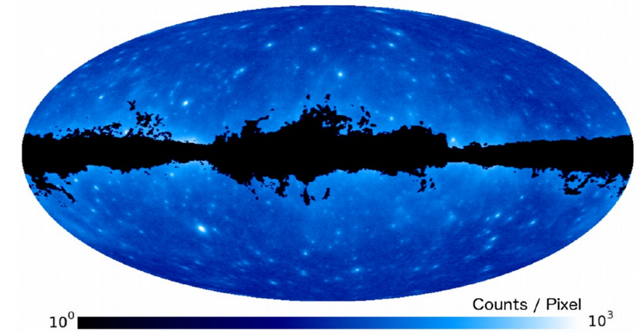


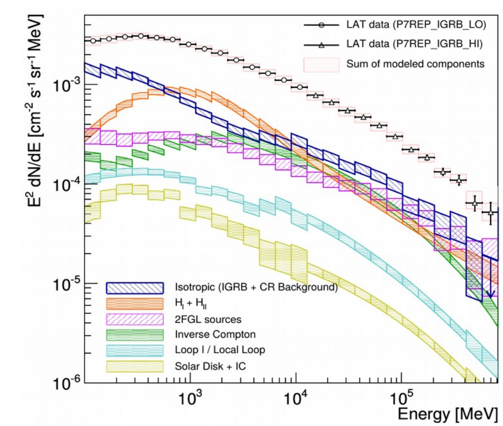
Fermi: Diffuse γ-Spectrum

[1410.3696]

Latest measurement based on data from 50 months

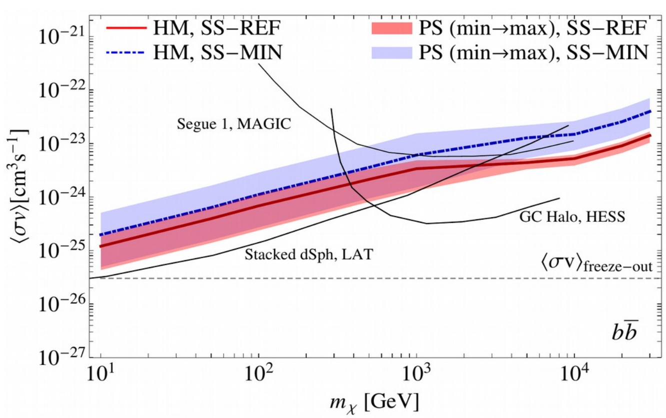
- **mask only small region around galactic plane, fit data with templates for astrophysical sources**
  - known point sources ; π^0 decays
  - IC scattering of photons from starlight and from Sun
  - synchrotron radiation from local magnetic field loops
- **fit describes observed spectrum well**
- **"extragalactic" spectrum (latitude |ℓ| > 20º) matches measurements from experiments at lower energy**

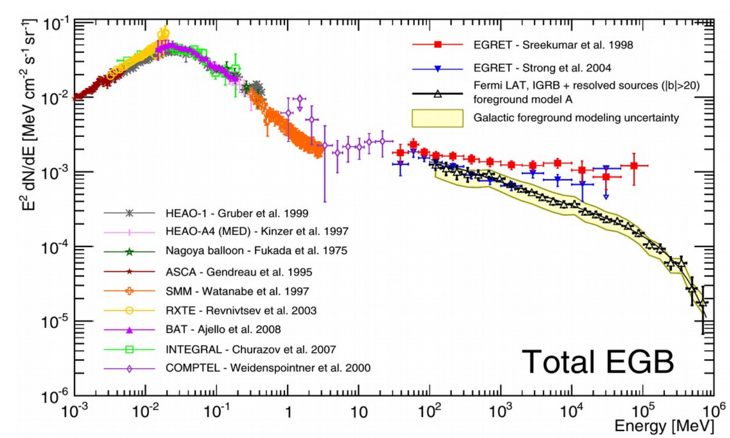




- **use these results to derive constraints on DM parameters**

  [1501.05464]



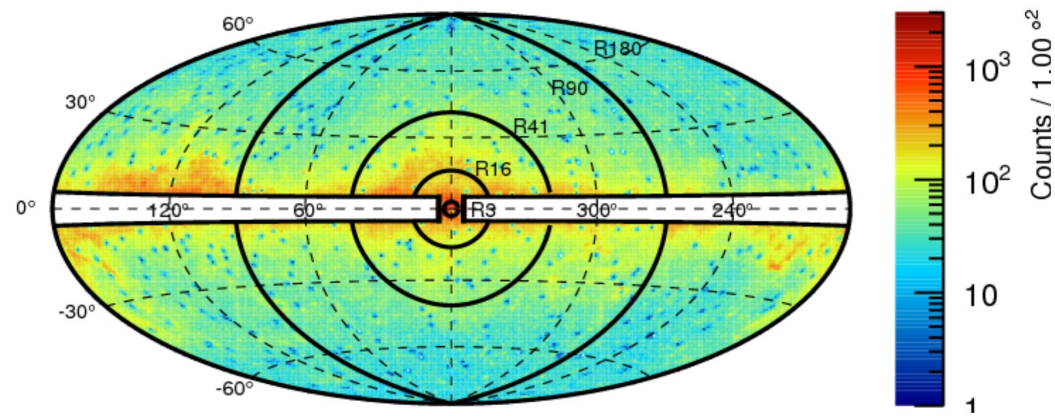


Fermi: Spectral Lines

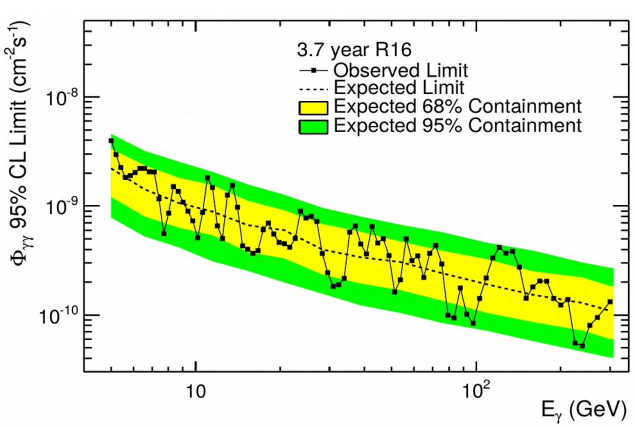
Spectral line = smoking gun signal for WIMP → $\gamma\gamma$ annihilation

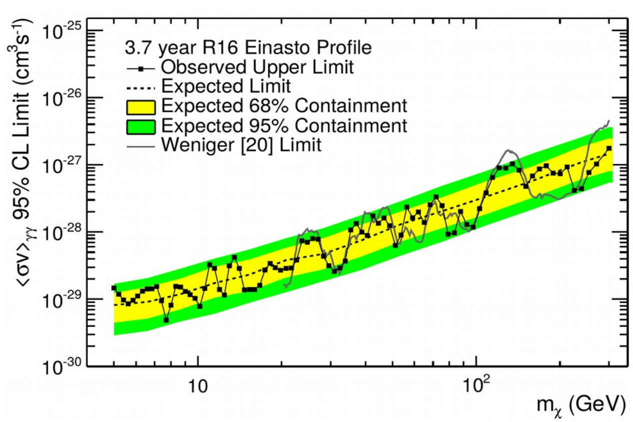
[1305.5597]

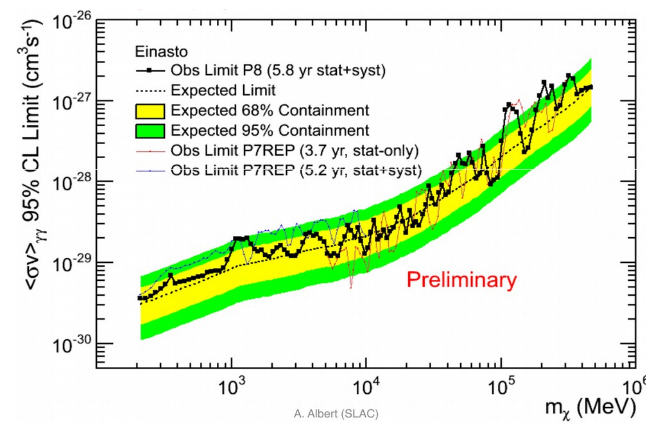
- **Fermi search based on 3.7 years of data**
- **five regions of interest**
  - optimized for different DM models
- **no significant signals found**
  - derive upper limits on DM annihilation cross section



- **preliminary results from search based on 5.8 years of data**
  - also improved energy reconstruction → better acceptance & resolution
  - still no significant signal → improved upper limits





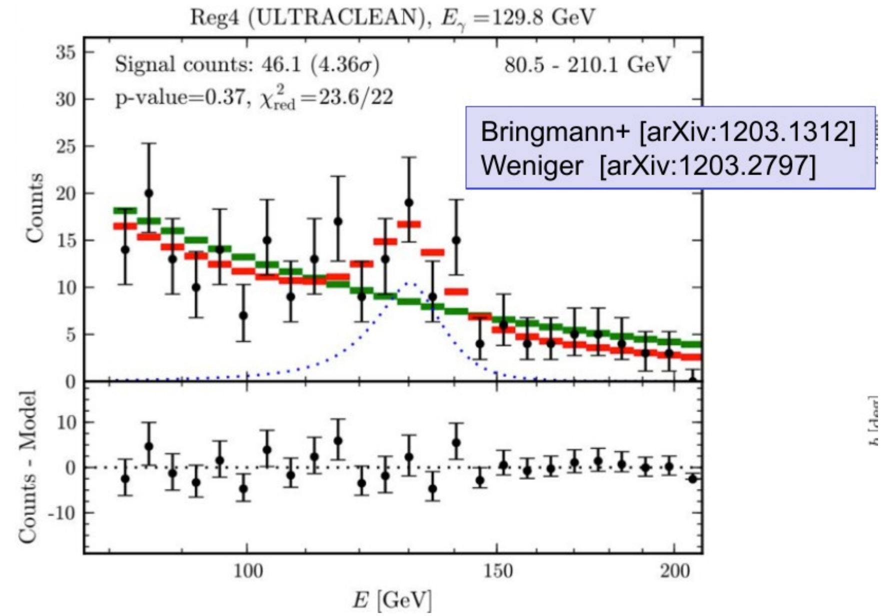


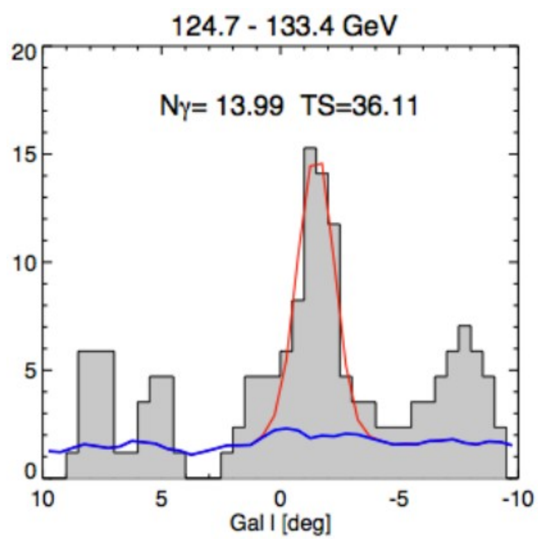
[A. Albert, Fermi Symposium, Oct 24, 2014]

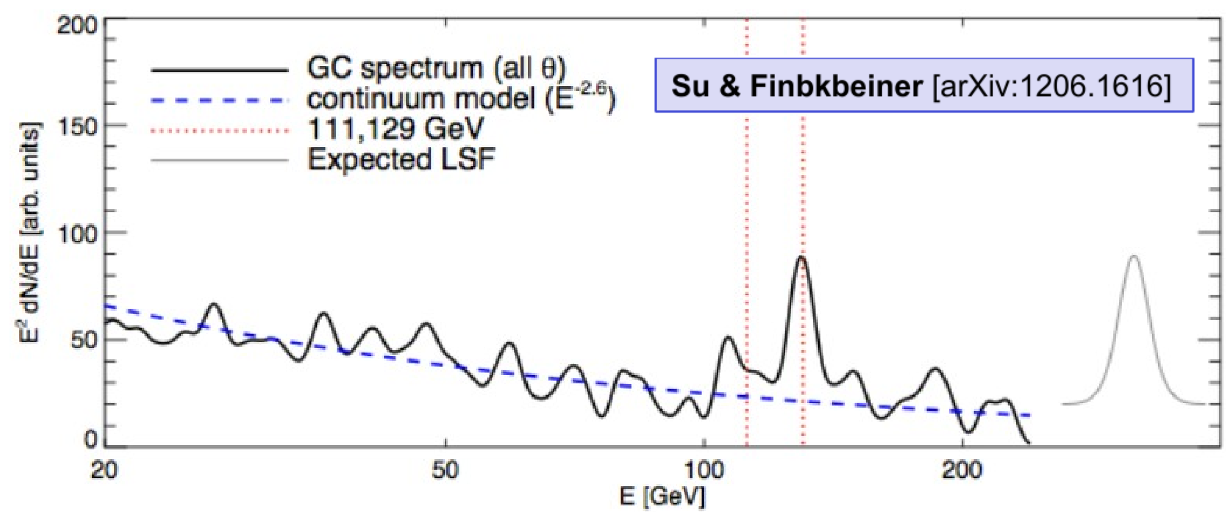
Fermi: Spectral Lines

Spectral line around 130 GeV ???

- **2012: two independent groups claim evidence for a narrow feature in Fermi's 3.7-year data set**
  - E_γ ~ 130 GeV, statistical significance > 4 σ
  - location of source slightly offset from GC
- N.B.: all Fermi data are made public within ~ 24 h, anyone can do their own analysis





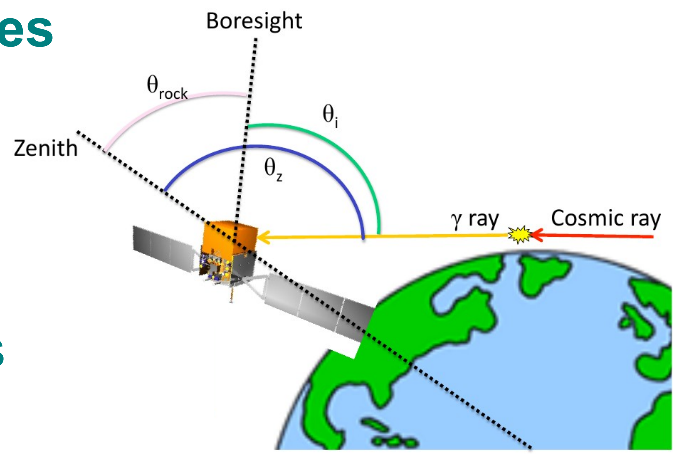


Fermi: Spectral Lines

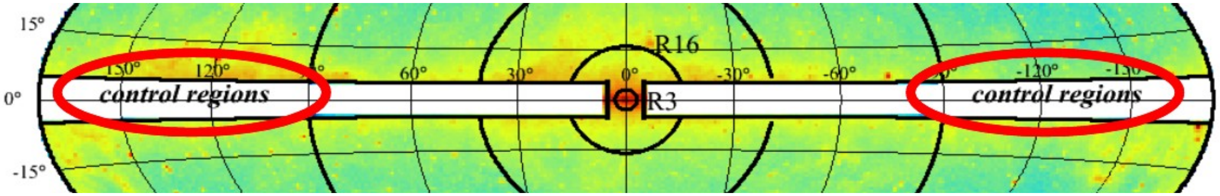
Fermi analysis using their 3.7 year data set

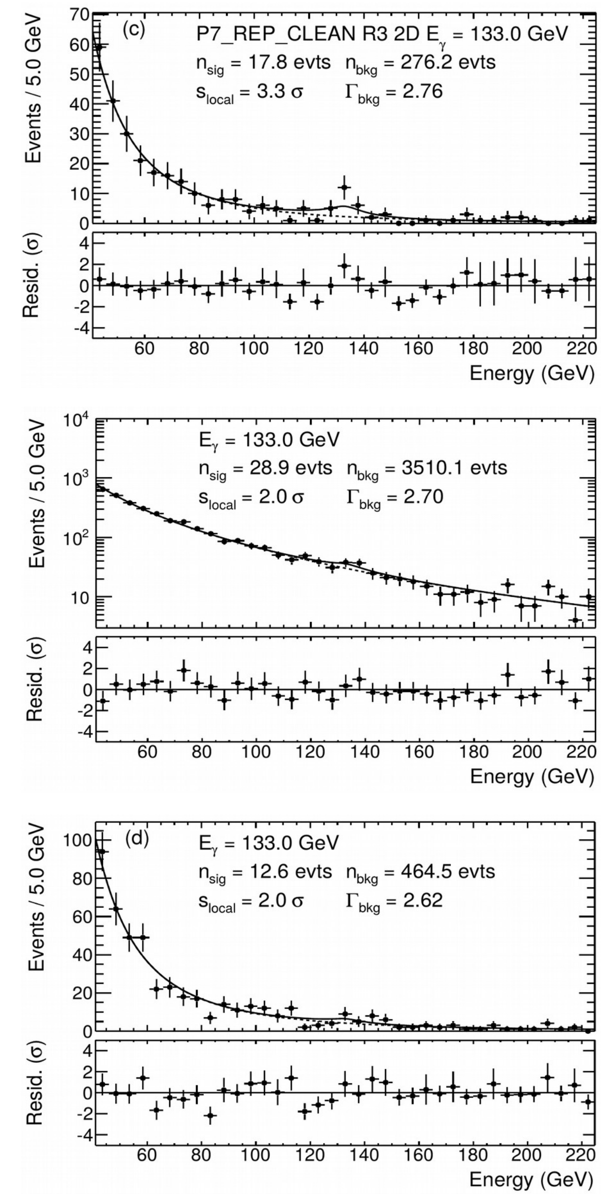
[1305.5597]

- **observe feature at 133 GeV with 3.3 σ significance**
  - but narrower than expected for a DM signal
- **no significant signals found in background-dominated control samples**
  - “Earth limb”: γ -flux dominated by interactions of charged cosmic rays in the Earth's atmosphere



  - region in galactic plane opposite GC: low DM density, but similar astrophysical backgrounds

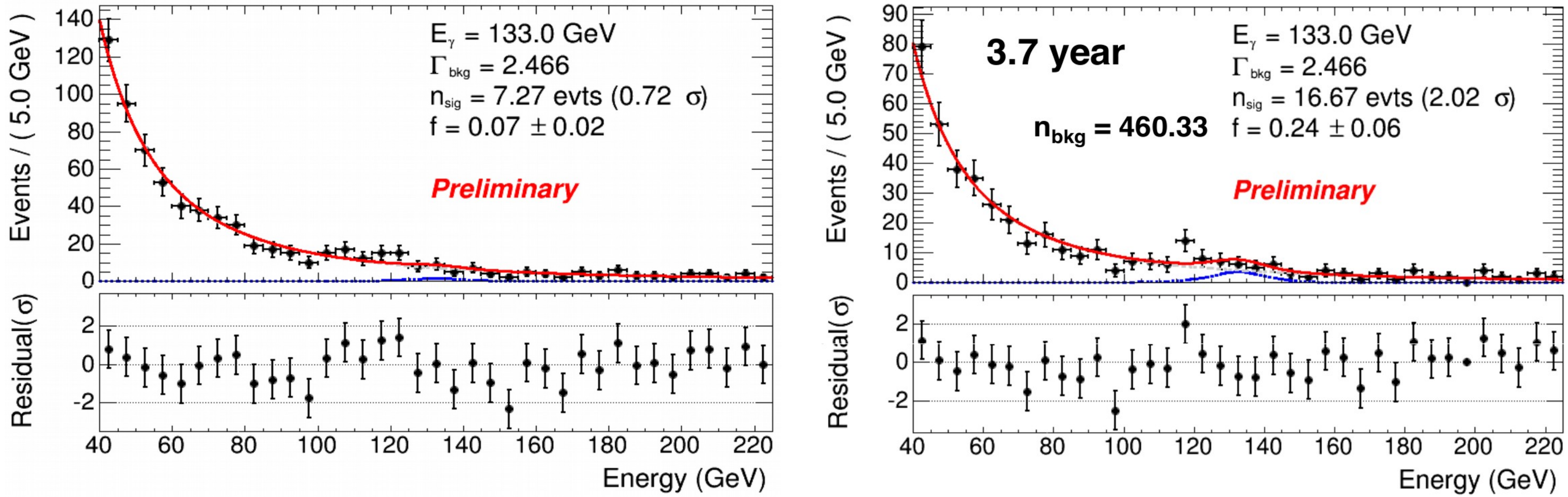




Fermi: Spectral Lines

Preliminary result from new analysis of 5.8 year data set

- also: re-analyzed 3.7 year data set with the improved energy reconstruction
  - in both cases no longer a significant signal



[A. Albert, Fermi Symposium, Oct 24, 2014]

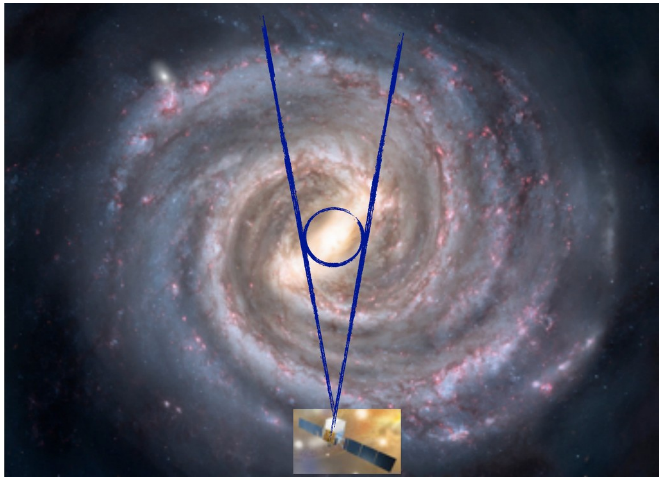
- conclusion from A. Albert's presentation:

original feature consistent with statistical fluctuation

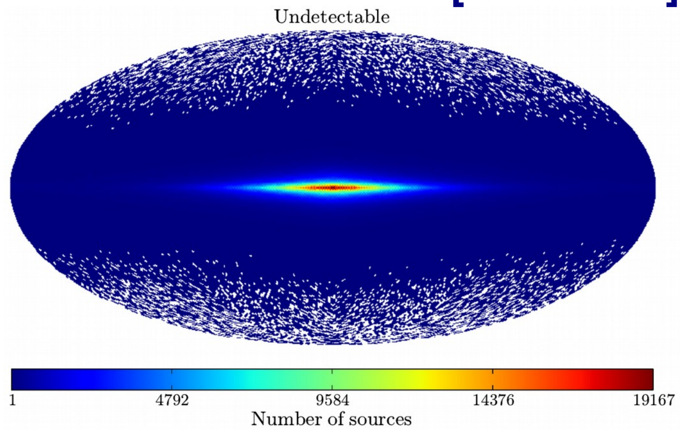
Fermi: Galactic Centre

GC: expext large DM density, but also large astrophysical backgrounds

- **highest CR intensities**
- **highest density of radiation fields and gas**
  - large uncertainties modelling interstellar emission
- **long integration path over the entire Galactic disc**
  - significant foreground and background contribution
- **large density of gamma-ray sources near GC, many energetic sources close to line of sight**
  - difficult to disentangle point sources and interstellar emission
- **also: expect large population of "undetectable" milli-second pulsars close to GC**
  - individual flux below Fermi detection sensitivity
  - additional source of diffuse background



[1305.1584]



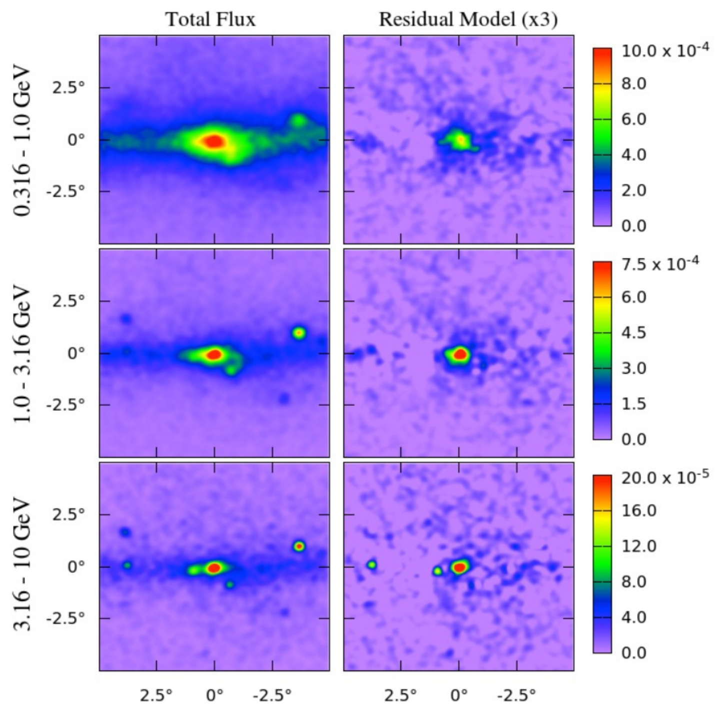
- **various groups have claimed γ-ray excesses with possible DM interpretation**

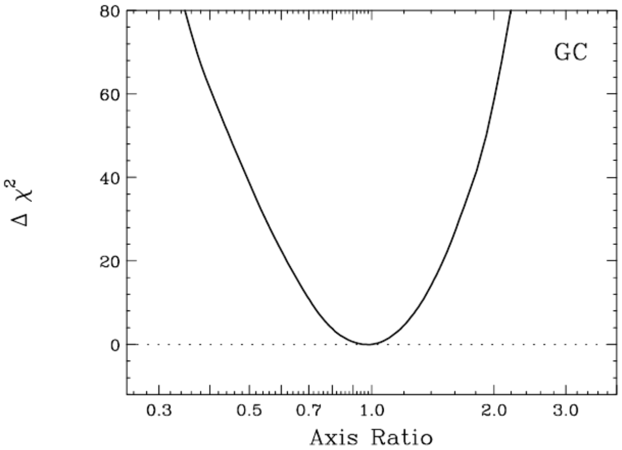
Fermi: Galactic Centre

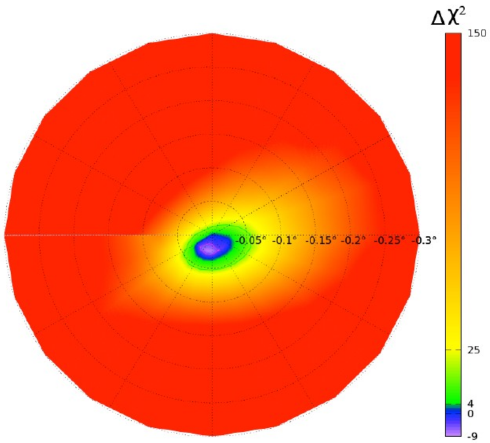
Daylan et al. analyzed Fermi data from 63 months

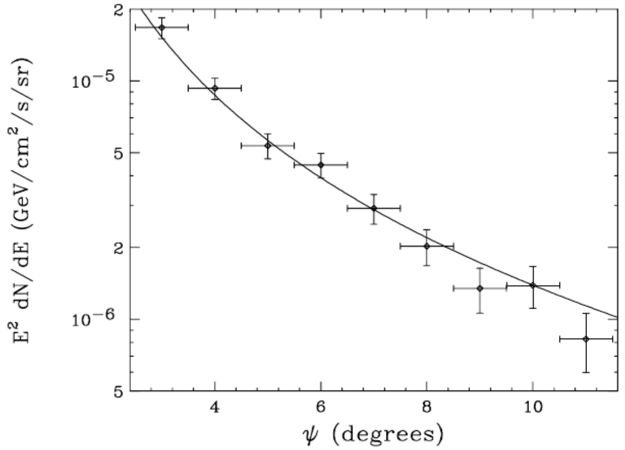
[1402.6703]

- **fit data with templates for isotropic and diffuse galactic emission and known point sources**
- **find excess peaking at E_γ = 1–3 GeV**
  - centered on GC; statistical significance 17 σ
  - spherically symmetric; extending out to ~10º
- **compatible with annihilation of DM candidate with mass around 30–40 GeV**
  - according to the authors, the spatial extention of the excess disfavours other interpretations



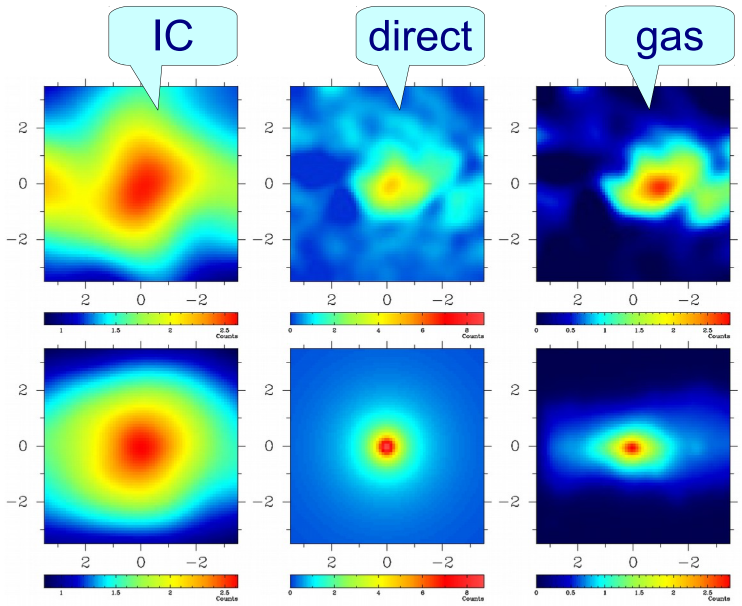


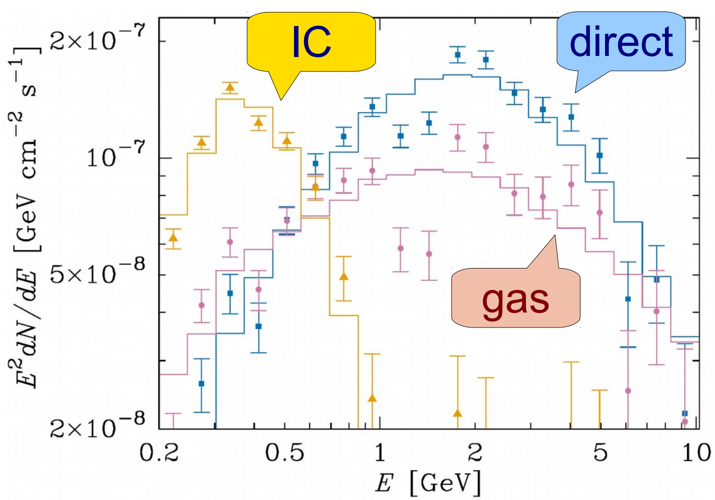




Abazajian et al. analyzed Fermi data from 70 months **[1410.6168]**

- **look at 7° × 7° wide region around GC**
- **again, find spatially extended excess over modelled diffuse emission and point sources**
- **fit energy spectrum and spatial distribution of this excess to separate three components**
  - "direct" ; IC-upscattered starlight ; bremstrahlung
  - spatial templates derived from measurements at 3.4 μm (starlight) and 20 cm (interstellar gas)
- **find IC and bremsstrahlung components compatible with being caused by the same population of CR electrons and positrons**
  - also find that this e^-/e^+ population and the "direct" γ-ray component could be caused by annihilation of a 8 GeV DM candidate to leptons
  - but cannot exclude astrophysical explanation

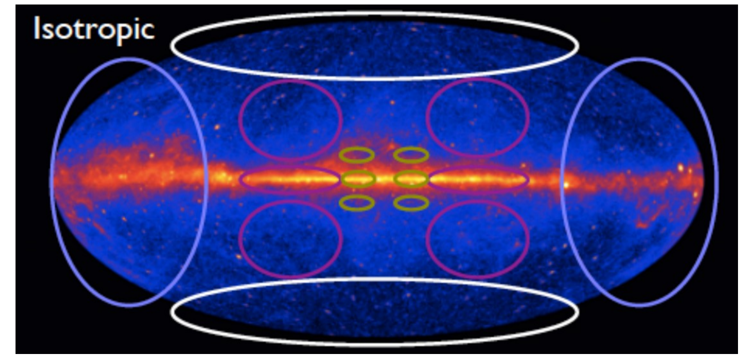




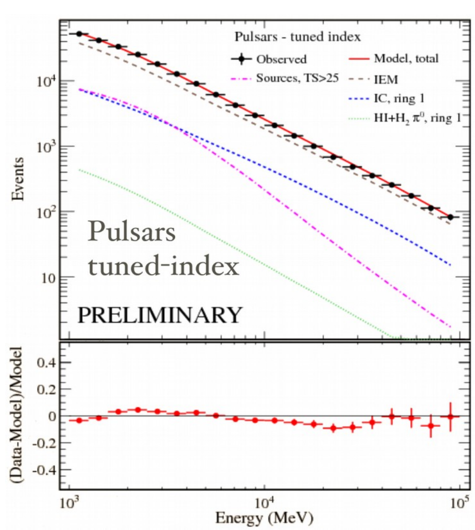
Fermi: Galactic Centre

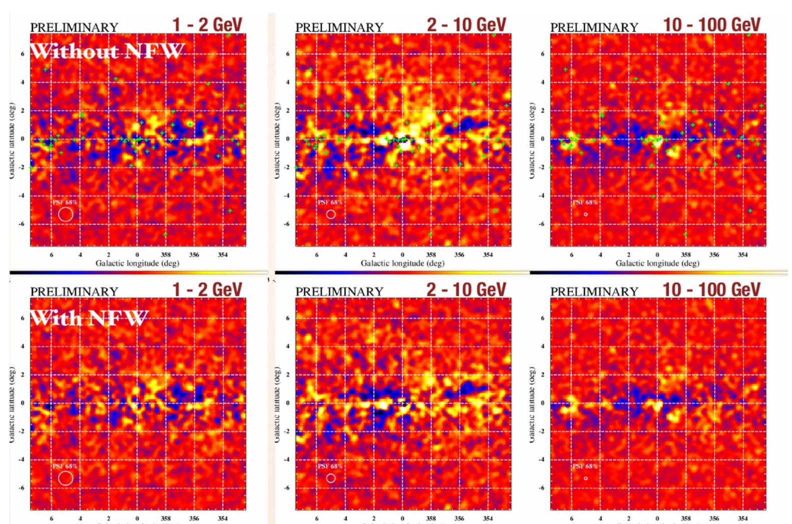
Fermi collaboration focus on 15° × 15° wide region around GC

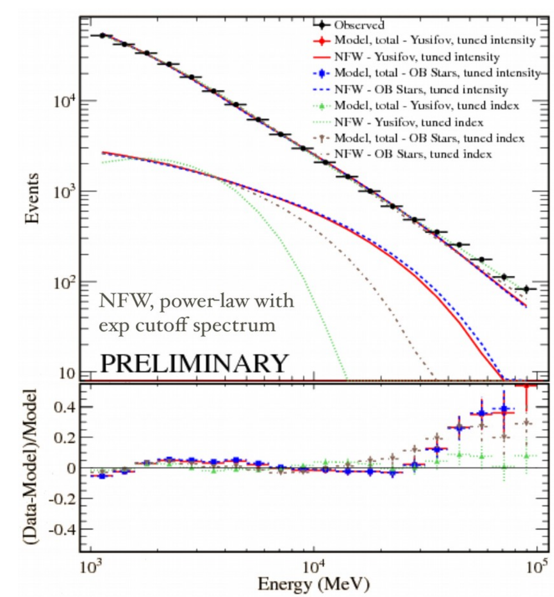
- **model of diffuse emission from**
  - **CR source distributions**
  - **CR propagation**
- **model parameters tuned to observed distributions in various control regions**



- **also find enhancement in GeV range, approximately centred on GC**
  - energy spectrum varies strongly depending on modelling of interstellar emission
  - need better understanding of fore/background emission







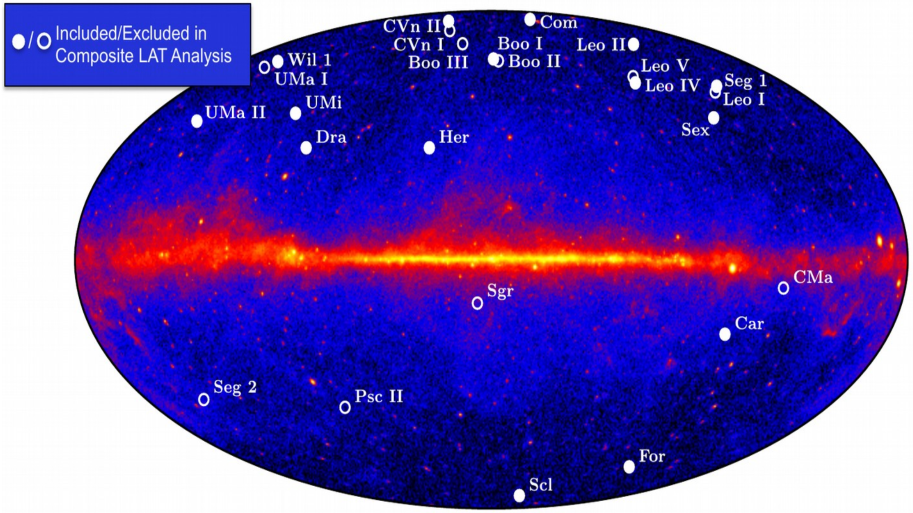
[S. Murgia, Fermi Symposium, Oct 24, 2014]

Fermi: Dwarf Spheroidal Galaxies

Satellites of our galaxy: promising target for DM searches

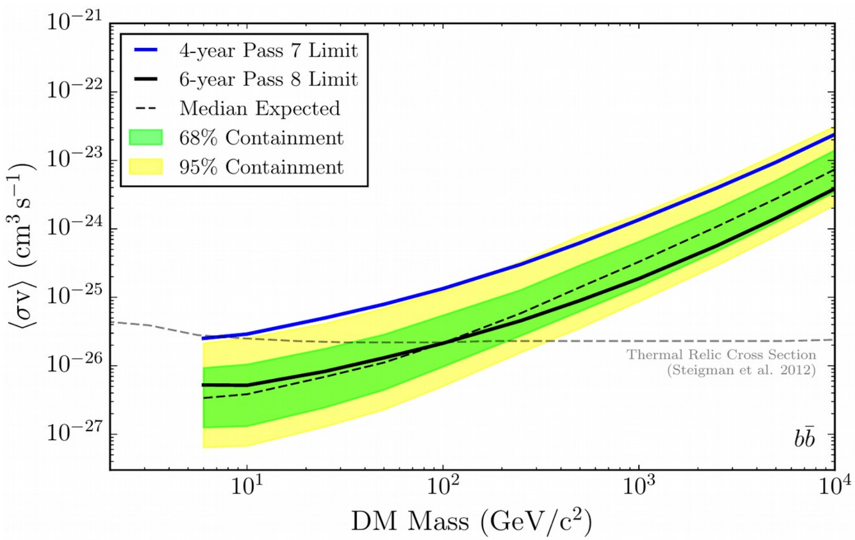
[1503.02641]

- **mass seems strongly dominated by DM**
  - total mass ≈ (10–2000) × luminous mass
- **astrophysical backgrounds small**
  - contain no astrophysical γ sources
  - located at high galactic latitude
- **currently 25 known satellite dSph**



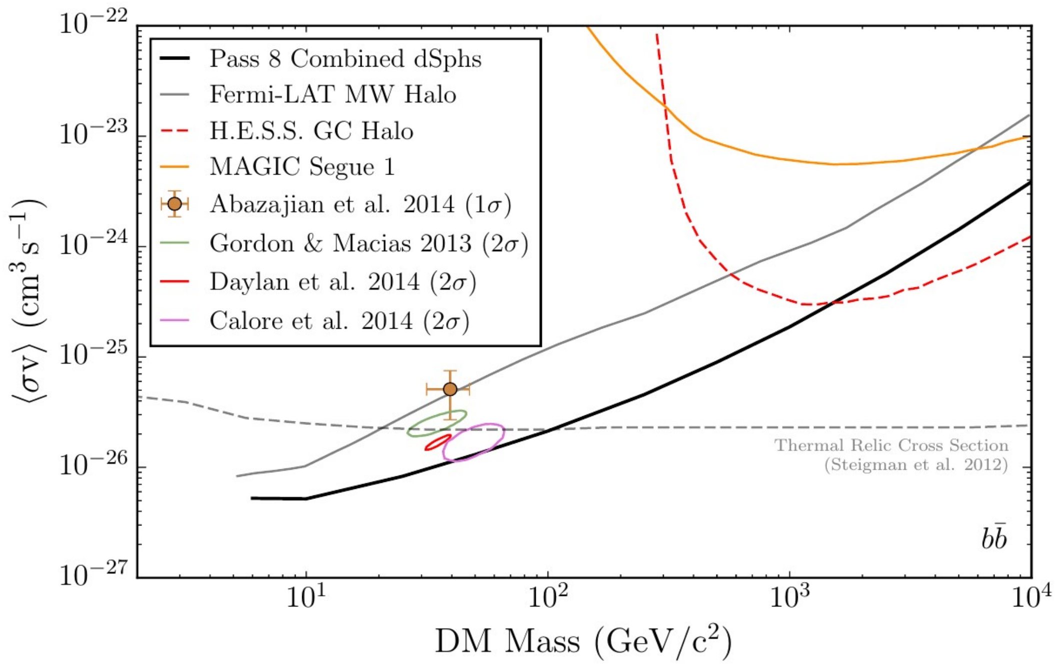
Fermi: combined analysis of 15 dSph

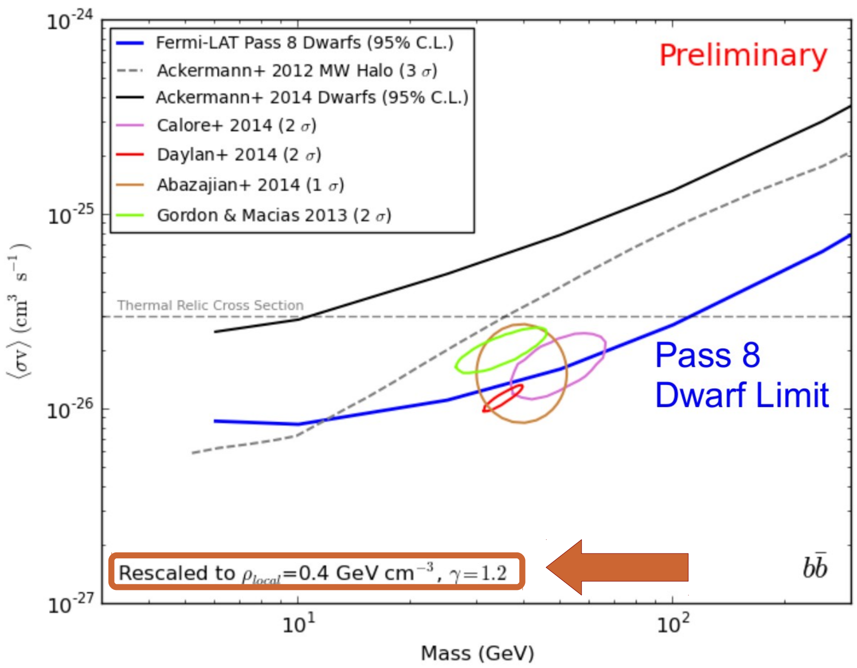
- **based on data from six years**
  - subtract known point sources
  - model & subtract diffuse emission
- **four WIMP annihilation channels considered**
- **no DM signal observed → upper limits start to cut into interesting parameter region**



Fermi: Dwarf Spheroidal Galaxies

- **limits derived from latest dSph analysis start to be in tension with DM interpretations of the Galactic Center excess**
- **but compatibility can still be achieved by tweaking model parameters**
  - e.g. higher local density at position of Earth, steeper slope of inner DM profile

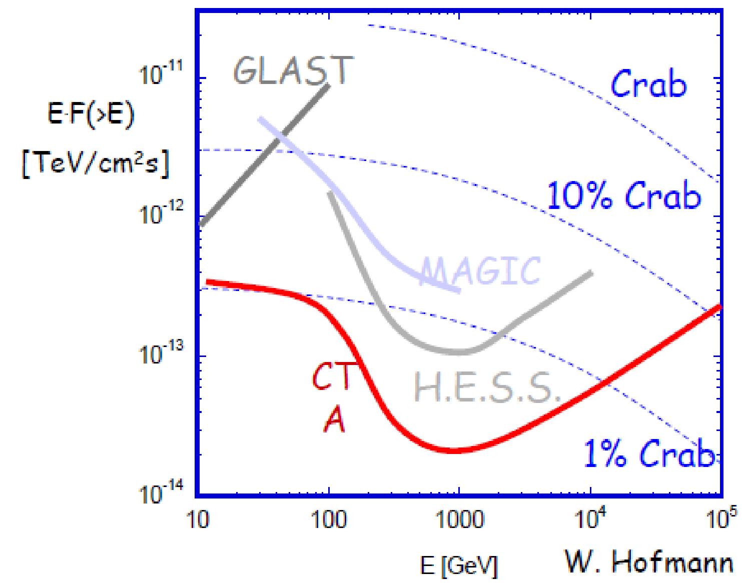




γ-rays: Surface Experiments

Above few × 100 GeV: flux too low for observation on satellites

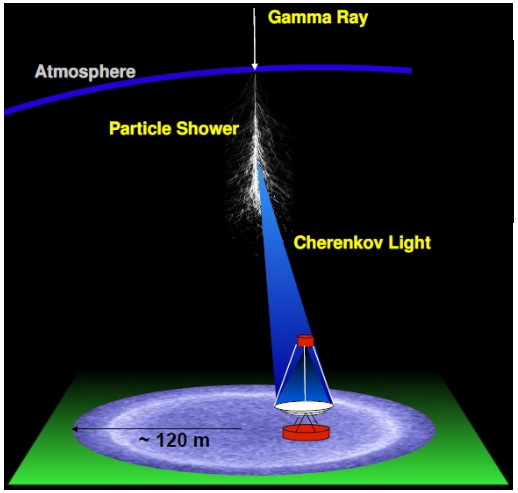
- **e.g. from Crab nebula** (reference):
  - about 10 γ-rays / m^2 / year with E_γ > 1 TeV
  - need 50,000 m^2 detector to observe 1 event / min



But γ-rays do not penetrate the atmosphere

- **radiation length of air: ≈ 38 g / cm²**
- **thickness of atmosphere: ≈ 1030 g / cm² ≙ 27 X_0**

Indirect detection by surface experiments

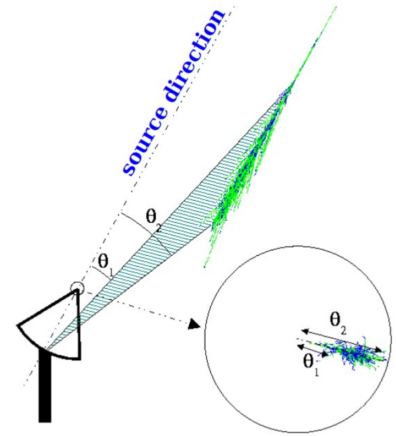


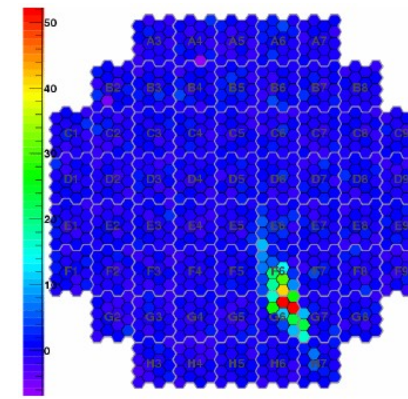
- **γ interacts in upper atmosphere → creates elm. shower**
  - large number of highly relativistic e^+e^- pairs produced
- **e^+/e^- generate Cherenkov photons in air ($\beta > 1 / n$)**
  - wavelength around 300-350 nm → penetrate atmosphere
- **observe Cherenkov photons in ground-based telescopes**
  - allows to reconstruct energy and direction of the initial γ-ray

Imaging Telescope Arrays

Imaging Cherenkov Telescope

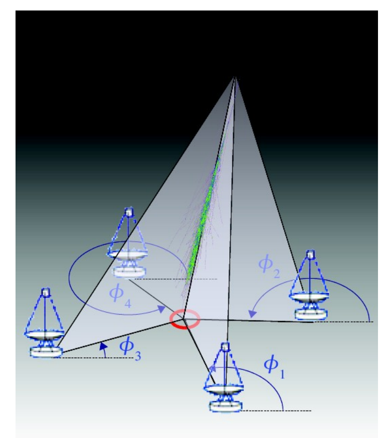
- **large parabolic dish to focus Cherenkov photons onto a segmented camera**
  - position in detection plane → angle of photon
  - orientation of image → 2D direction of shower
- **shape of image → suppress background**

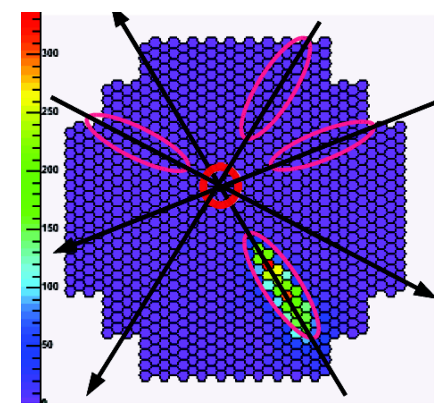




Telescope array

- **stereo-views of the same shower**
- **3D reconstruction of shower direction**





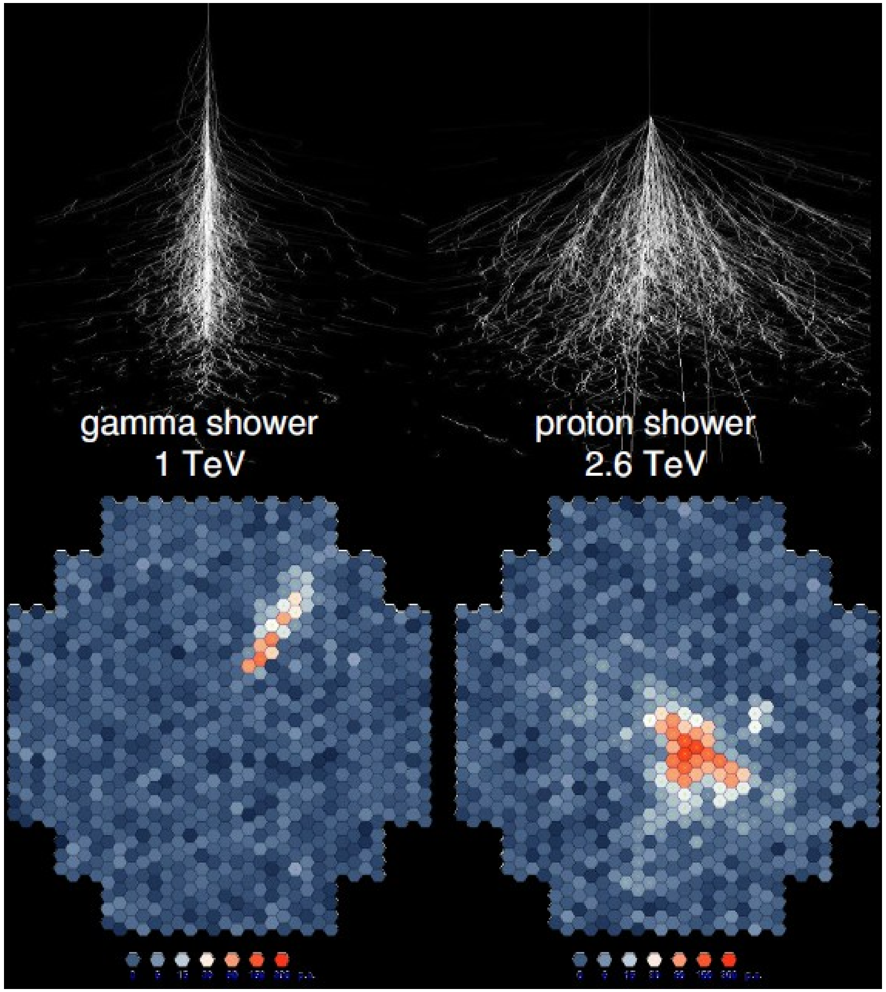
Key parameters for telescope array

- **size of telescope dishes: number of Cherenkov photons collected per shower**
  - important at lower γ-energies where fewer Cherenkov photons generated
- **surface area over which telescopes are distributed: acceptance for showers**
  - important at highest γ-energies where flux is lowest

Hadronic Cosmic Rays

Still the main source of background: 1000 × more abundant than γ-rays

- **hadronic showers: larger lateral extention than electromagnetic showers**
  - results in “fuzzier” shower image
- **achieve ≈ 99.9% background rejection**
  - remaining S/B ≈ 1-10
- **electron showers more difficult to distinguish**
  - but rate much lower at high energies



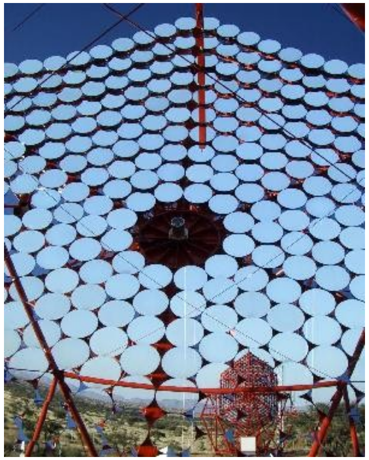
To estimate remaining backgrounds

- **perform “off source” measurements**
- **extrapolate to source position**
- **subtract statistically from “on-source” measurements**

H.E.S.S. (II)

Array of 4 (+1) telescopes

- **located in Namibia → view of GC**
- **four telescopes, 108 m² dish surface each**
  - commissioned 2003/2004
  - spacing between telescopes: 120 m
  - camera: array of 960 photo-multipliers
  - field of view: 5°, resolution: ≈ 0.1°
- **one telescope with 614 m² dish surface**
  - added in summer 2012
  - camera: array of 2048 photo-multipliers
  - field of view: 3.5°, resolution: ≈ 0.4° – 0.1°
- **energy threshold 100 GeV → 30 GeV**
- **observation time about 1000 hours / year**
  - only clear and “moonless” nights
- **no e / γ separation → no diffuse γ-ray spectrum**

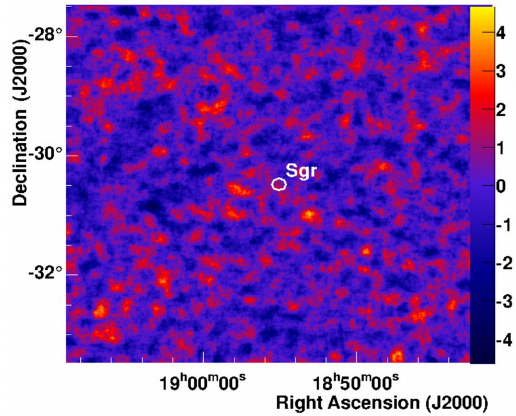


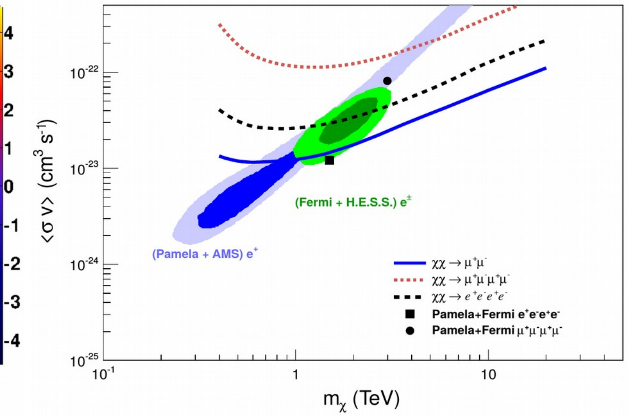
H.E.S.S.: Dwarf Spheroidal Galaxies

Analysis of five Dwarf Spheroidal Galaxies

[1410.2589]

- total observation time 140 hours
- no excess observed, derive limits on DM parameters

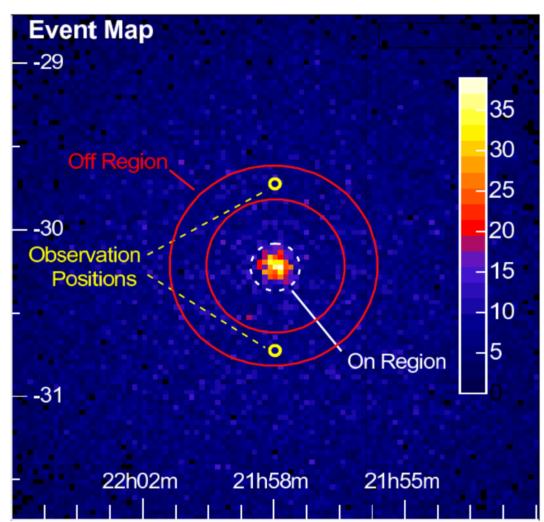


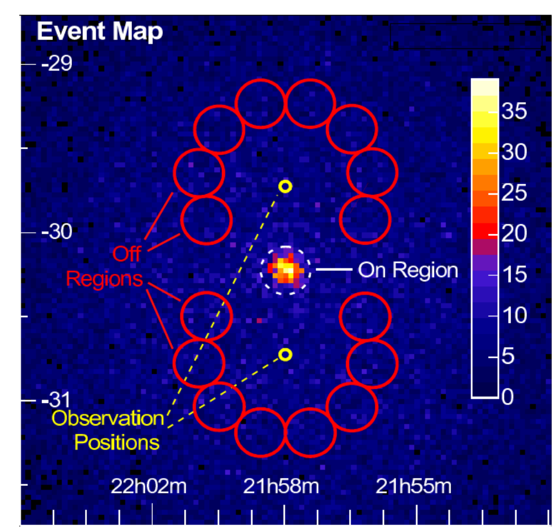


- use “wobble” technique for background subtraction to avoid need for “off-source” data taking:
- size of source smaller than field of vision: can estimate backgrounds from control regions inside field of vision

[astro-ph/0610959]

- but: detection efficiency not uniform across field of vision
  - position source off-centre within the field of vision
  - estimate backgrounds from symmetrically placed control regions inside field of vision

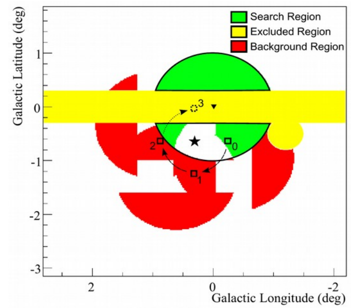


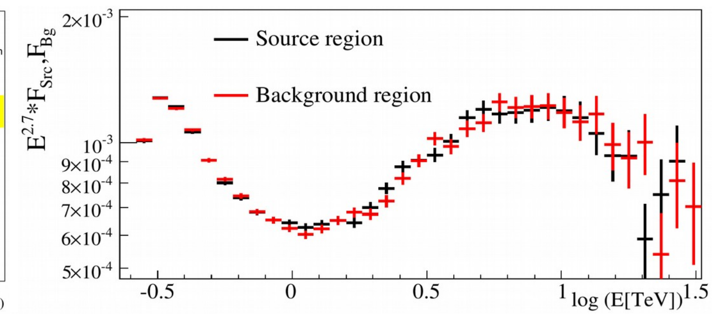


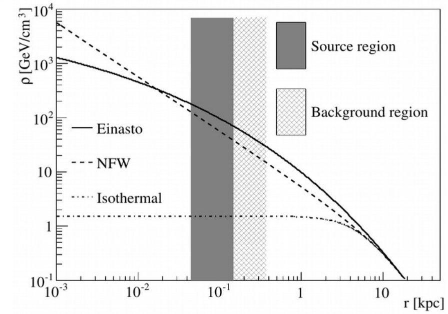
H.E.S.S.: γ-rays from GC

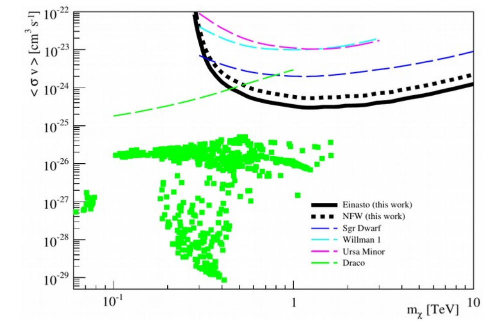
Analysis based on data from 112 hours of observation time [1103.3266]

- define signal region of 1º radius around GC ; symmetric control regions inside field of view
- exclude narrow band around galactic plane to avoid point sources
- observe no excess in signal region
- derive limits on DM parameters



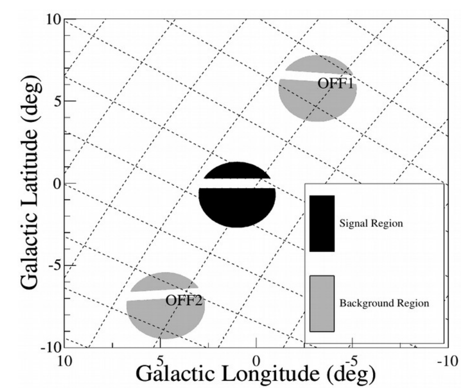


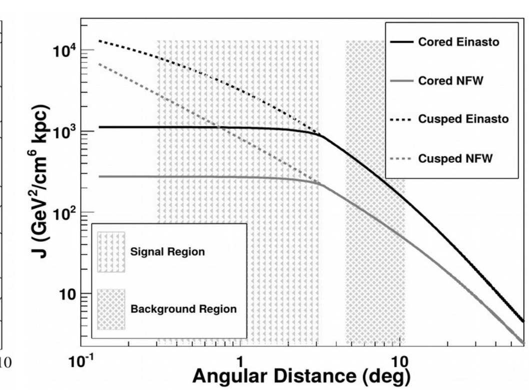




New: test of DM scenarios with flat profile in innermost region

- analysis based on data from 9 hours of observation time [1502.03244]
- "ON/OFF" technique: point at source and at two symmetrically displaced control regions; swap every 33 minutes
- again no excess in signal region
- limits on DM parameters

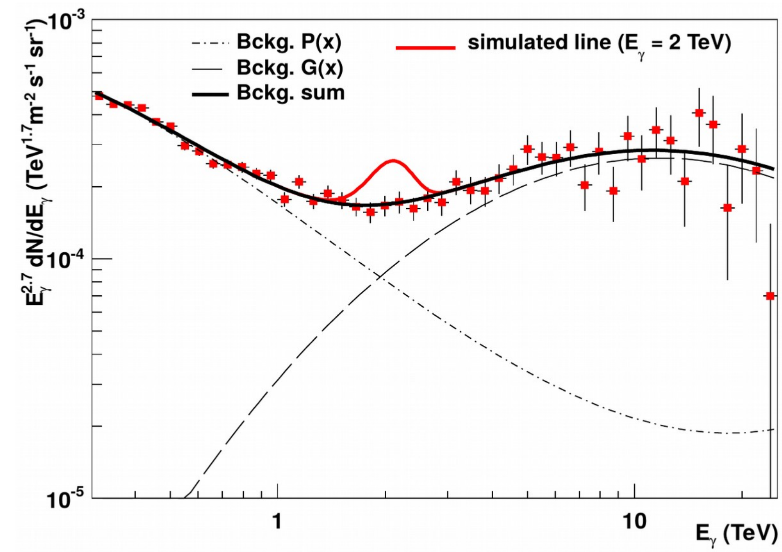




H.E.S.S.: spectral lines

Complementing Fermi searches at higher energies

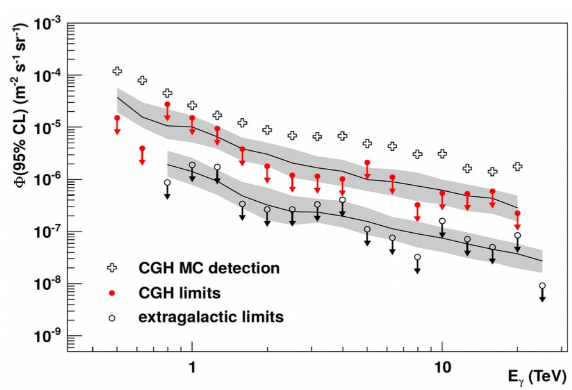
- **analysis of region around GC based on 112 hours of observation time**
  - exclude narrow band around galactic plane
- **combined analysis of data from various measurements of extragalactic objects, total of 1153 hours of observation time**
  - exclude known point sources

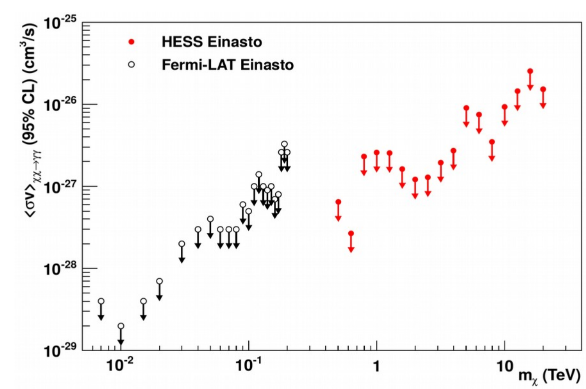


- **null hypothesis (no lines): fit data with smooth empirical function**

power-law term × (3rd-order polynomial + Gaussian term)

- **search for narrow lines: add Gaussian with fixed mean and width**
  - width of Gaussian given by energy resolution of the experiment
- **no significant signal found, upper limits derived**

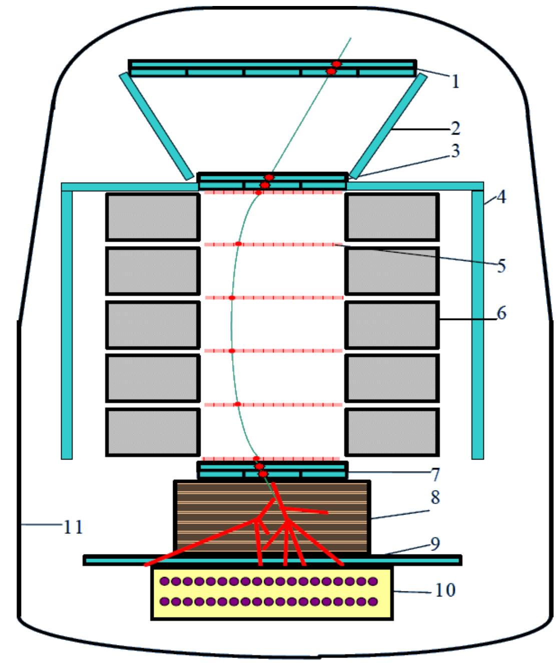




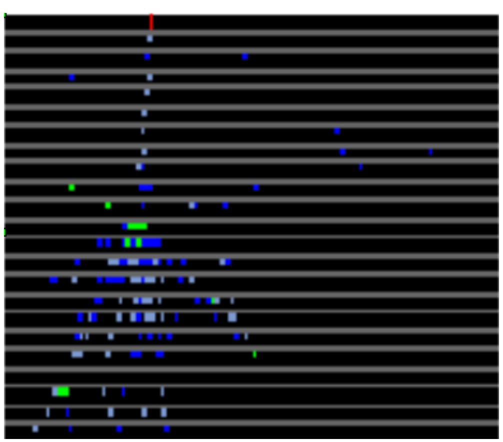
Antiparticles: Pamela

Launched in 2006 – projected lifetime 5 years but still in operation

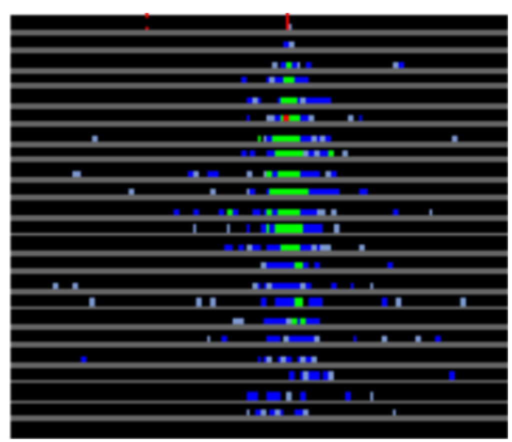
- **time-of-flight counters: particle direction & velocity**
- **magnetic spectrometer: momentum & charge sign**
  - ability to distinguish particle ↔ antiparticle
- **imaging calorimeter: energy & shower shape**
  - shower shape allows to distinguish $(e^+,e^-) \leftrightarrow (p,\bar{p})$
  - (e^+,e^-) rejection power $\approx 10^4$ for 90% $(p,\bar{p})$ efficiency



1, 3, 7- TIME OF FLIGHT SYSTEM;
2, 4- ANTICOINCIDENCE SYSTEM;
5- SILICON STRIP TRACKER (SIX DOUBLE PLATES);
6- MAGNET (FIVE SECTIONS);
8- SILICON STRIP IMAGING CALORIMETER;
9- SHOWER TAIL CATCHER SCINTILLATOR;
10- NEUTRON DETECTOR;
11- HERMOCONTAINER.



hadron (R=19GV)



electron (R=17GV)

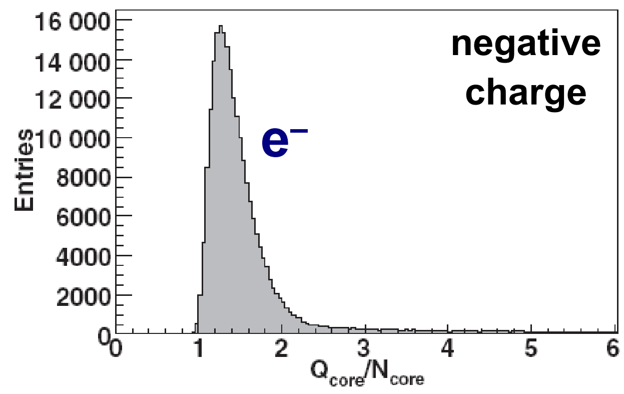
Nominal energy ranges:

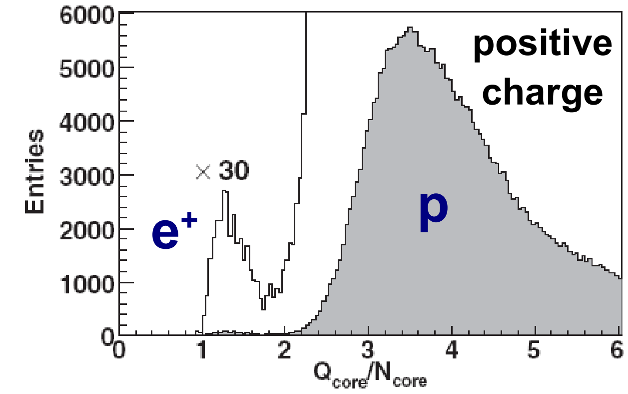
- **anti-protons: 80-190 GeV**
- **positrons: 50-270 GeV**

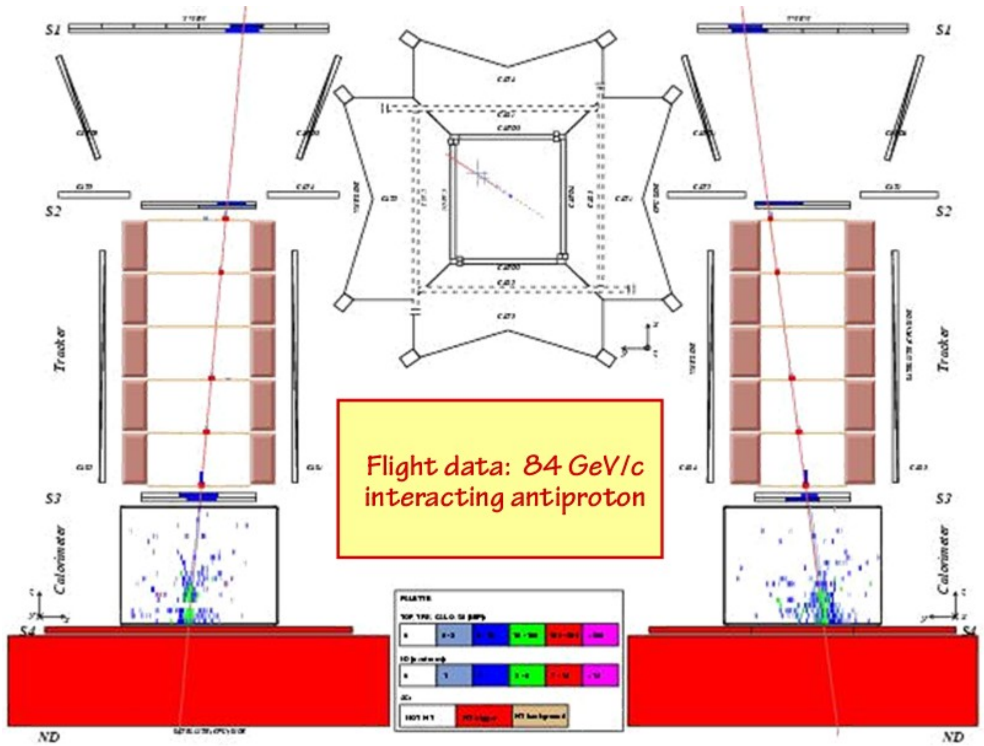
Antiparticles: Pamela

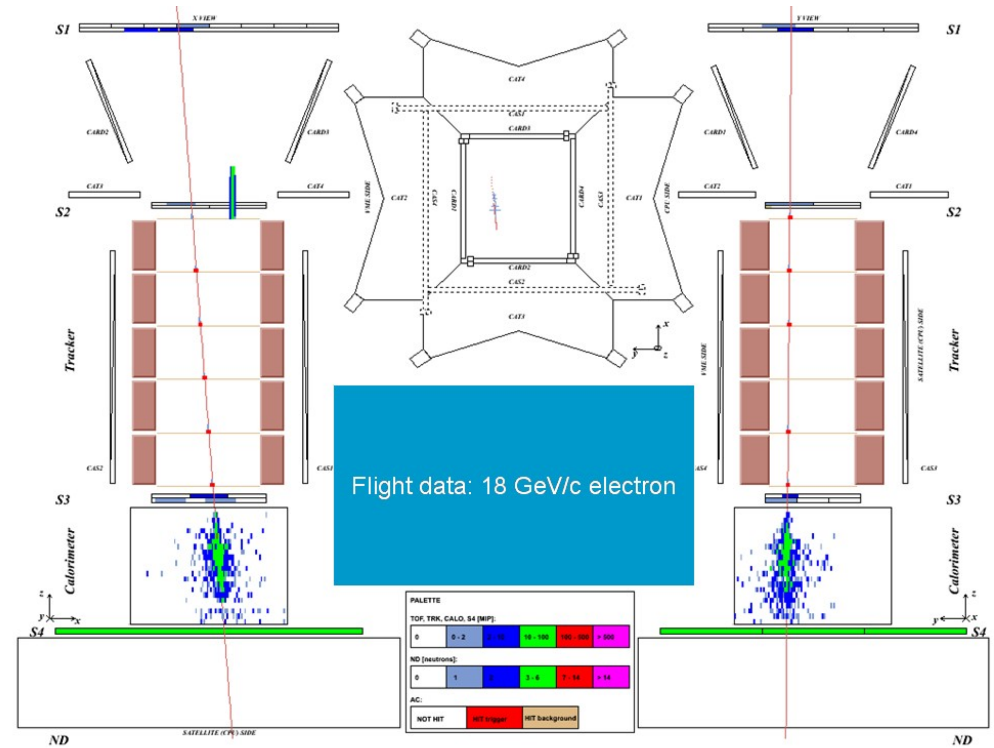
Electron rejection

- e^- flux ≈ $10^3 \times \bar{p}$ flux
- cuts on shower shape allow to reduce this to negligible level





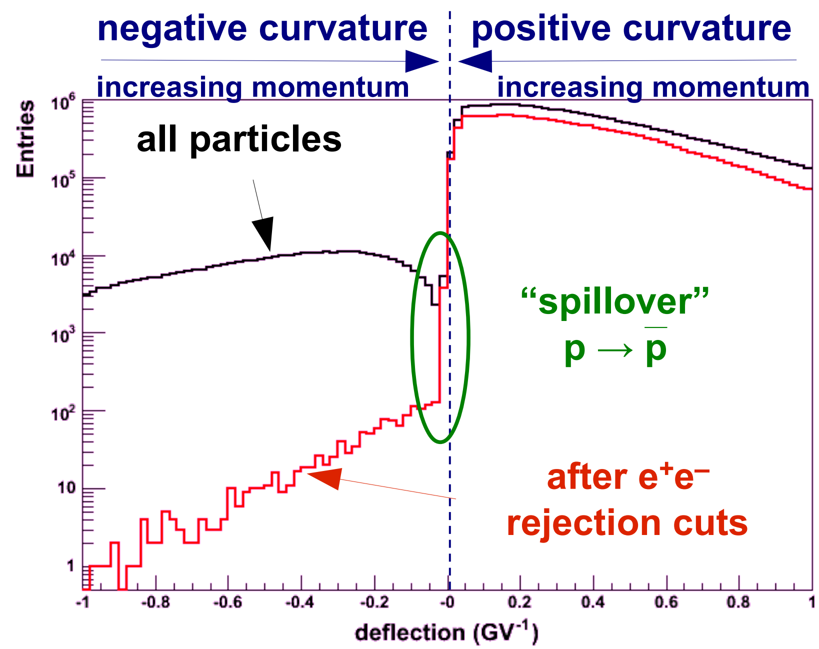




Pamela: Antiprotons

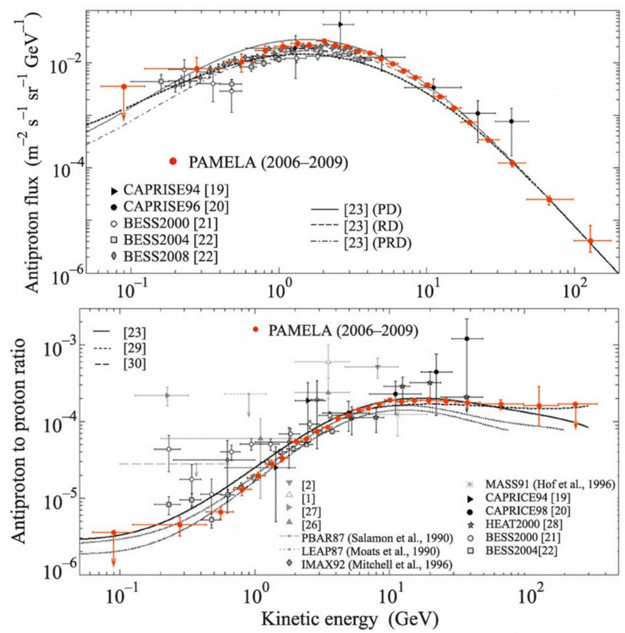
Proton rejection

- **p flux ≈ 10^4 × $\bar{p}$ flux**
- **use track curvature to measure charge sign**
- **accessible momentum range limited by finite position resolution of detector**
  - high momentum → small deflection
  - finite resolution → chance to measure sign of deflection wrong, assign wrong charge sign
- **to improve sensitivity at highest momenta: make use of event-by-event estimate of measurement uncertainty**



Latest analysis based on data from 3½ years

- **selected ~ 2800 $\bar{p}$ from 60 MeV to 350 GeV**
- **measured $\bar{p}$ energy spectrum and $\bar{p}$/p ratio compatible with expectation from cosmic ray models and with earlier measurements**

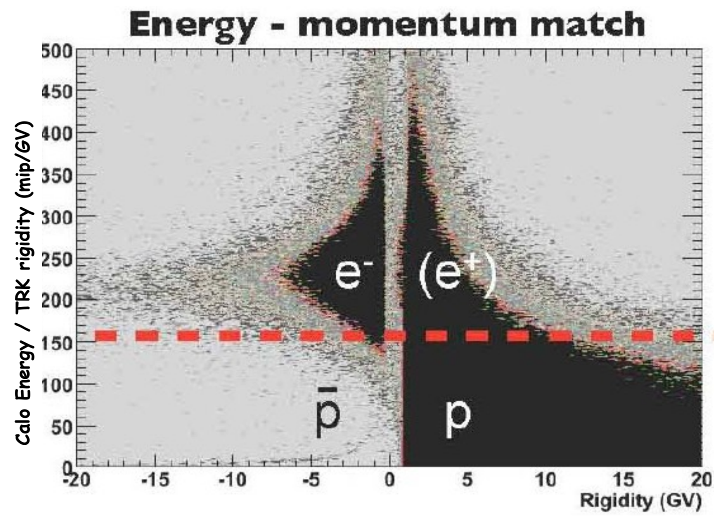


[JETP Lett 96 (2013) 621]

Pamela: Positrons (I)

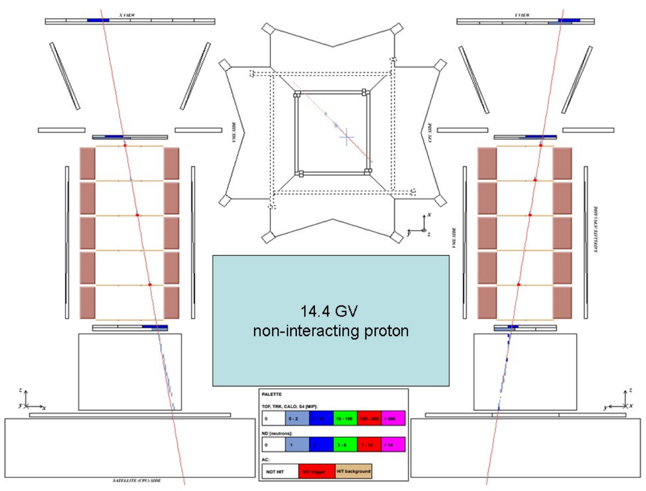
Measure positron fraction = $e^+ / (e^+ + e^-)$ as a function of energy

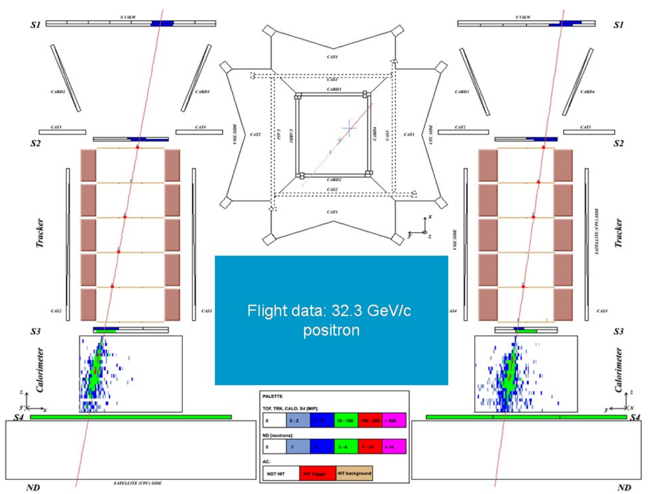
- **basic selection similar to $\bar{p}$/p measurement**
- **“spillover” from e^- not critical**
  - at the highest energies only 10 × more e^- than e^+
- **biggest challenge: p rejection**
  - p/e^+ ratio ~10^3 at 1 GeV and 10^4 at 100 GeV

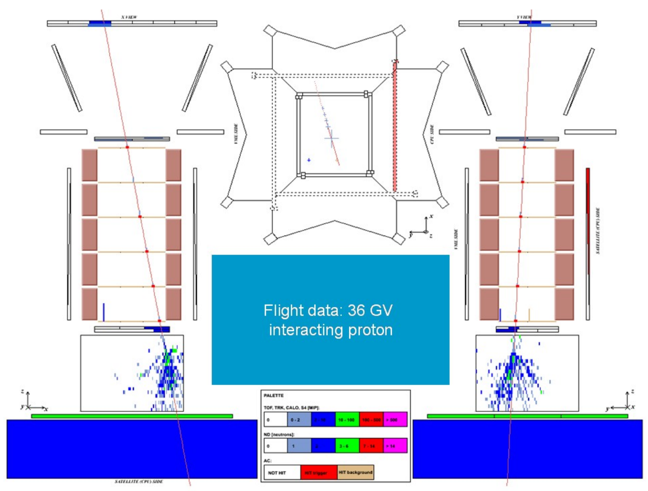


Suppress protons by cutting on:

- **shower energy vs. track curvature** (momentum)
- **longitudinal and transverse shower profile**



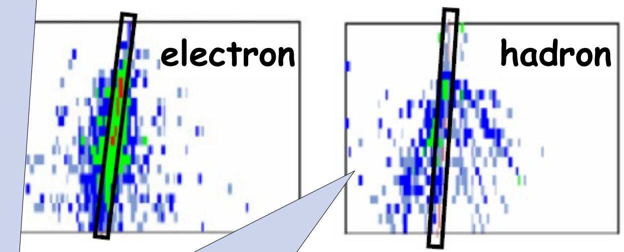




Pamela: Positrons (II)

Transverse shower profile

- fraction of shower energy deposi... within predefined cyl...der around show...



negative curvature

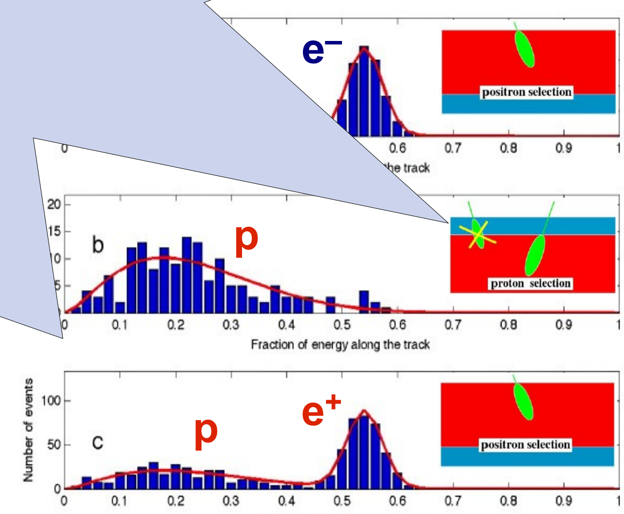
positive curvature

... after b... ...n shower profile

Exercises

F...

- use ... clean sa...
  - e^- s...
  - p sample ... t... ...nd s...e
- fit e^+ sample wi... ...al & ba...kground shapes

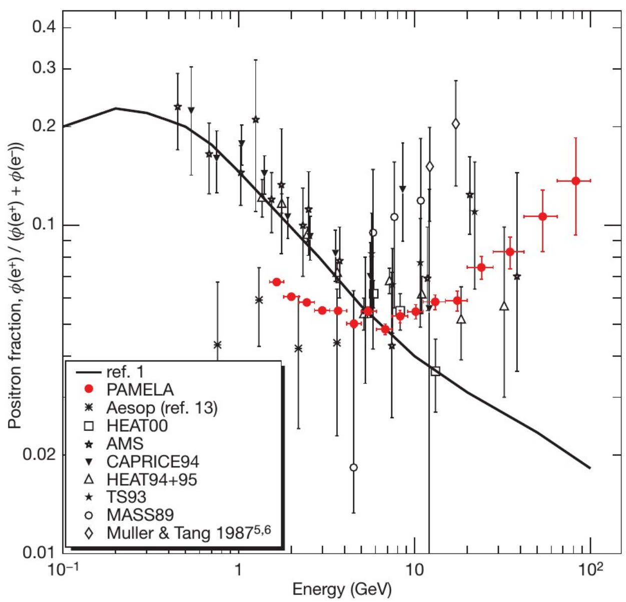


Pamela: Positrons (III)

First analysis based on 500 days of data taking **[0810.4995]**

- **observe steep increase of e^+ fraction above 10 GeV**
  - incompatible with models of secondary e^+ production

    $p + ISM \rightarrow \pi^+ + X$ followed by $\pi^+ \rightarrow \mu^+ \rightarrow e^+$
- **lower e^+ fraction at low end of energy spectrum attributed to modulation effect from solar activity**
  - earlier experiments collected data during maximum of solar activity, Pamela data close to minimum
  - similar effect observed in low-energy $\bar{p}$ flux

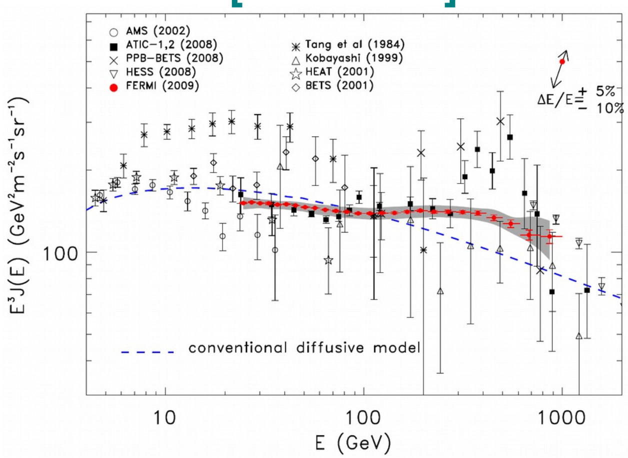


Fermi / H.E.S.S.

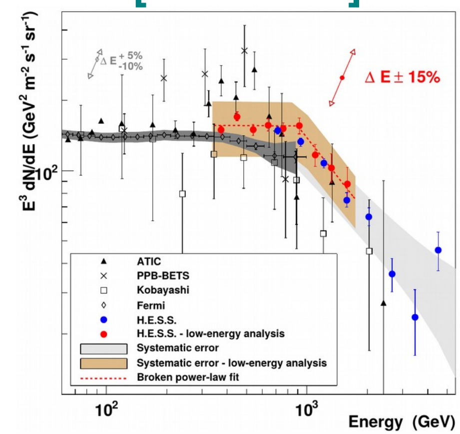
- **cannot measure charge sign**

  $\rightarrow$ sum of e^+ and e^- fluxes
- **smooth spectrum up to ~ 1 TeV**
- **but "harder" than predicted by conventional CR model**

[0905.0025]



[0905.0105]



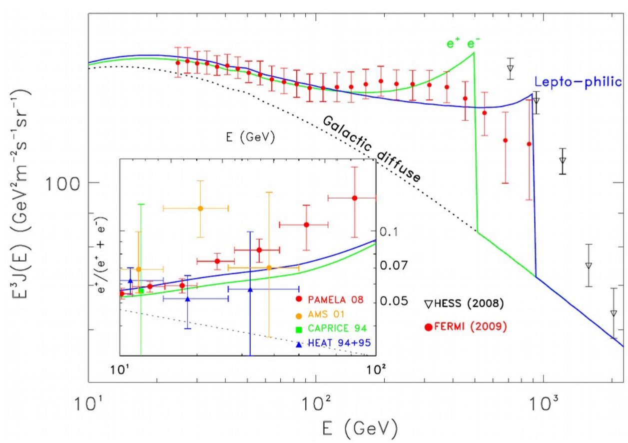
Positrons: Interpretations

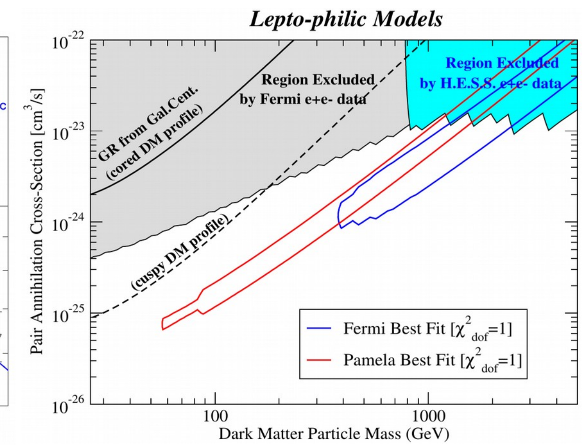
Pamela positron excess triggered ~ 200 theory papers in first year

- **about 170 of them interpretations in terms of various DM models**

DM annihilations [0905.0636]

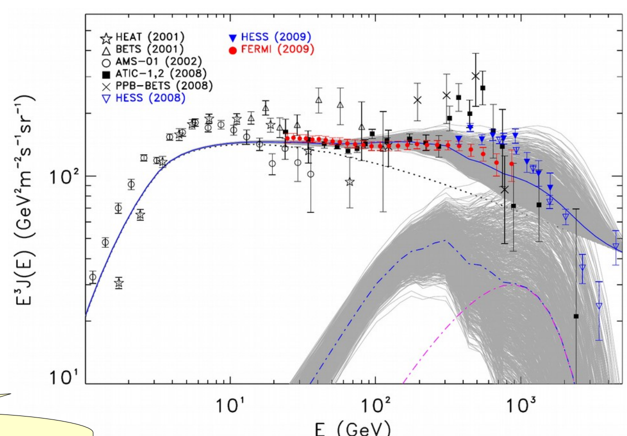
- **WIMP "leptophilic" to explain lack of an excess in $\bar{p}$/p**

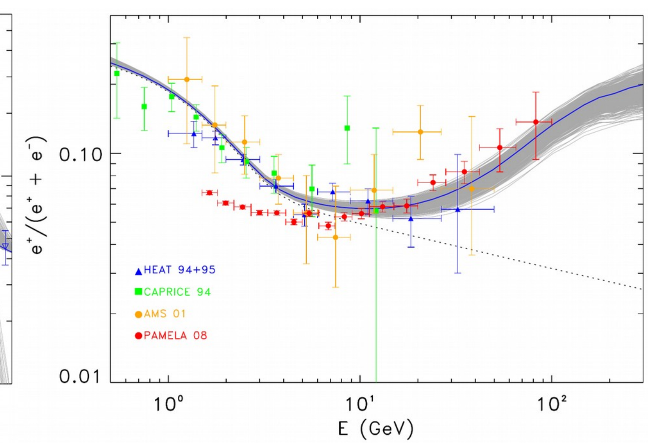




Astrophysical sources

- **e.g. nearby pulsars (d < 1 kpc) [0905.0636]**
  - Monogem (SNR)
  - Geminga (Neutron star)
- **can explain Fermi / H.E.S.S. measurements of e^++e^- flux and Pamela e^+ fraction**





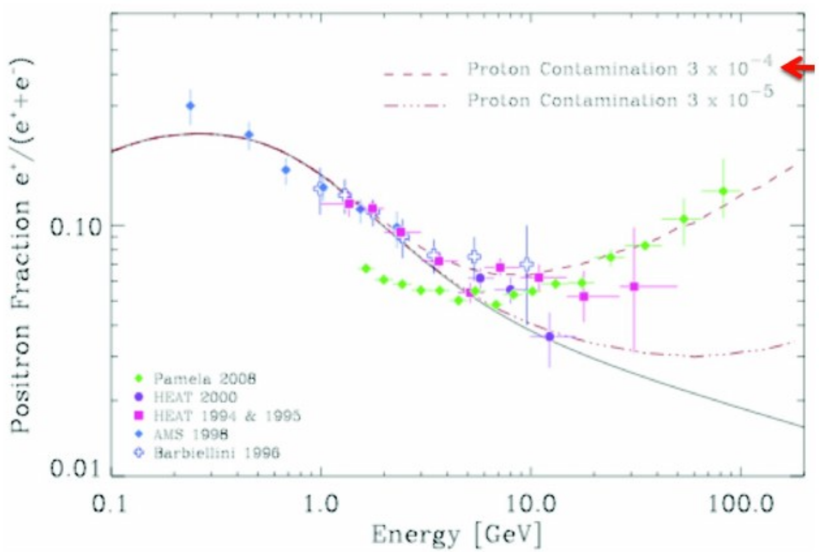
grey lines: variation of pulsar model parameters within "reasonable assumptions"

Pamela: Positrons (IV)

Positrons: Interpretation

Or just an instrumental artifact ?

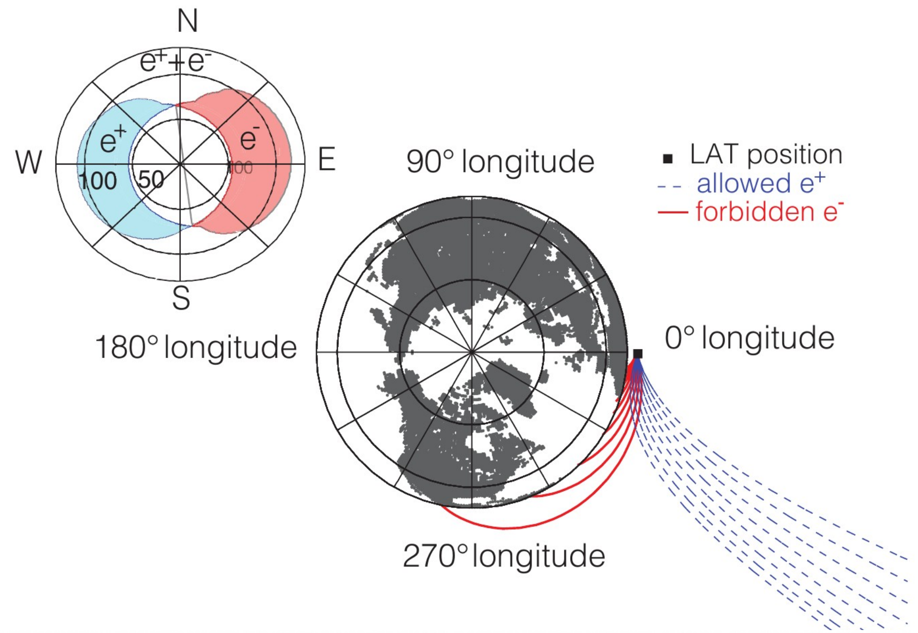
- proton contamination of 3×10^{-4} would explain Pamela rise beautifully
  - remember: positron/proton separation biggest challenge in the analysis
- Pamela claim proton rejection 10^{-5}
  - but not verified using independent technique in-flight
  - Transition Radiation Detector for e^+/e^- identification was orginally foreseen, but then dropped due to lack of space …



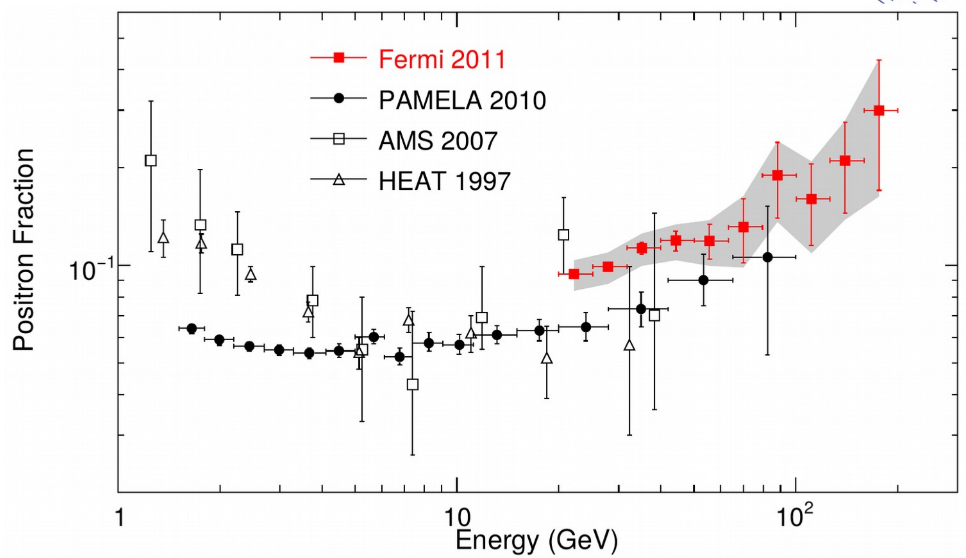
Fermi: Positrons

Measurement exploiting magnetic field of the Earth

[1109.0521]



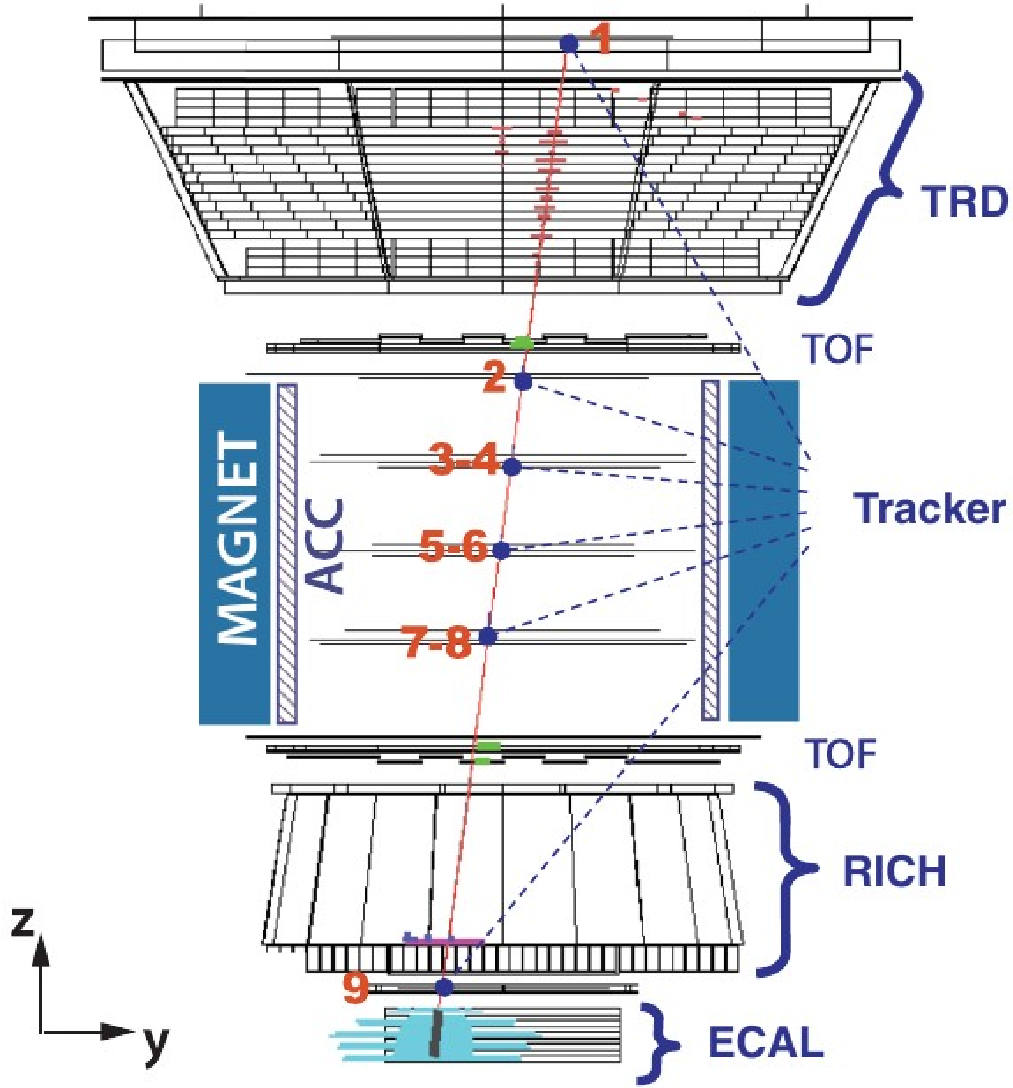
- trajectories of electrons and positrons bent in opposite directions
- at a given position of the satellite, certain trajectories for electrons or for positrons blocked by "shadow" of the Earth
- allows to measure electron and positron fluxes and positron fraction
- result in good agreement with Pamela measurement
- increase continues above 100 GeV



AMS-02

Launched in 2011, installed on ISS

- **silicon strip tracker (**ETHZ contribution**)**
- **electromagnetic calorimeter**
- **anti-coincidence counters**
- **spectrometer magnet**
  - e^+/e^- separation up to ~ 500 GeV
- **Transition Radiation Detector**
  - redundant e^+ / p separation
- **Ring Imaging Cherenkov Counter**



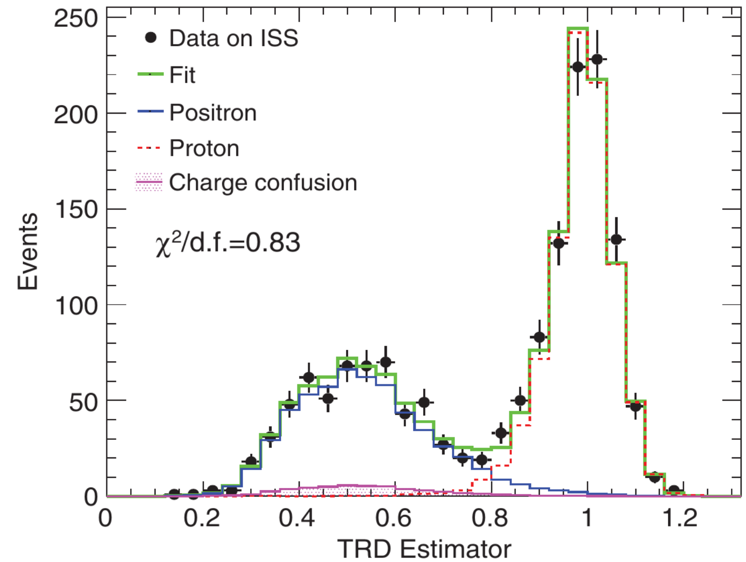
AMS-02: Positrons

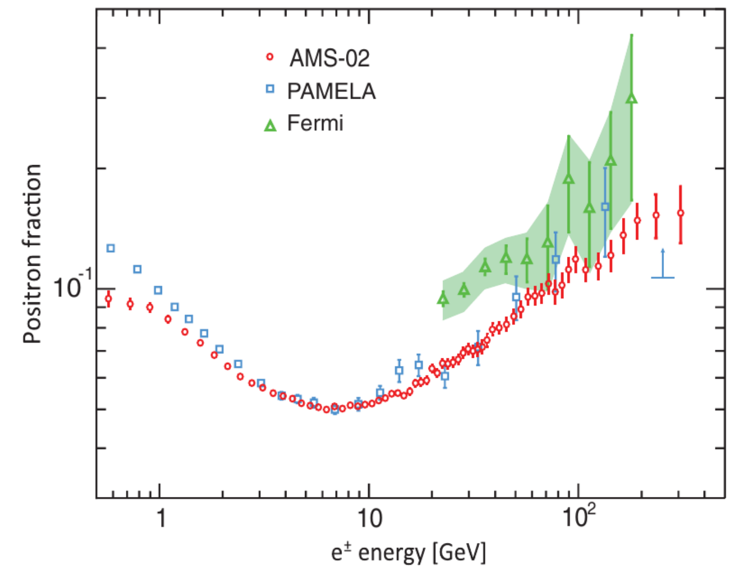
First measurement (data from 18 months) **[PRL 110 (2013) 141102]**

- **6.8 × 10^6 e^+ and e^- candidates**
- **energy range from 0.5 – 350 GeV**
- **proton rejection by**
  - comparison of energy measured in calorimeter and momentum measured in spectrometer
  - 3D shower shape in ECAL

  } factor 10^4
  - transition radiation light produced in TRD

  } factor 10^3–10^4 @ 90% efficiency
- **confirm increase of positron fraction above ~ 8 GeV**

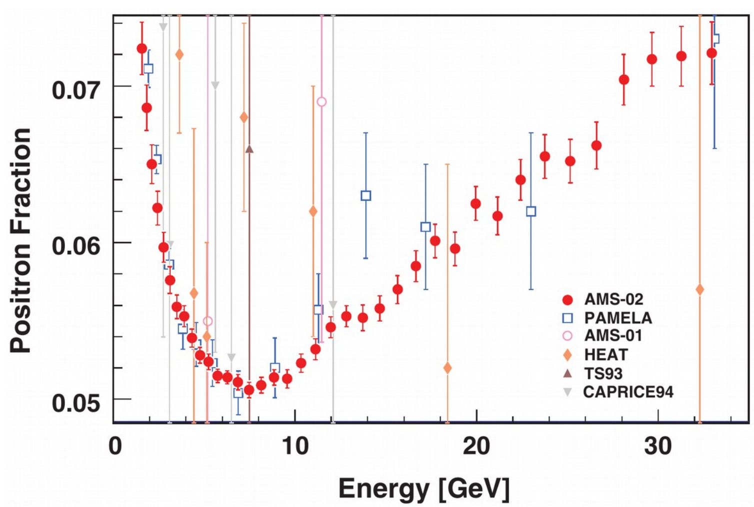


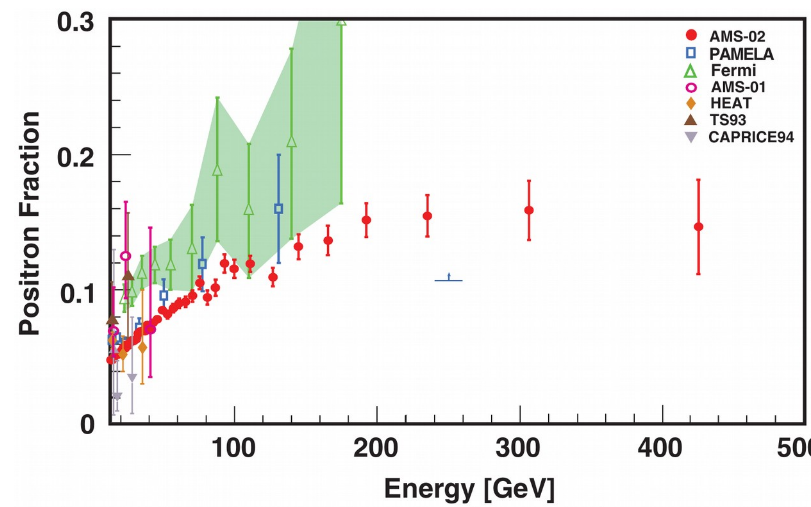


AMS-02: Positrons

Latest result (data from 30 months) **[PRL 113 (2014) 121101]**

- **more data, improved analysis → extend measurement to 500 GeV**
- **find that positron fraction "flattens out" at highest energies**
  - **expected for both pulsar and DM interpretations**





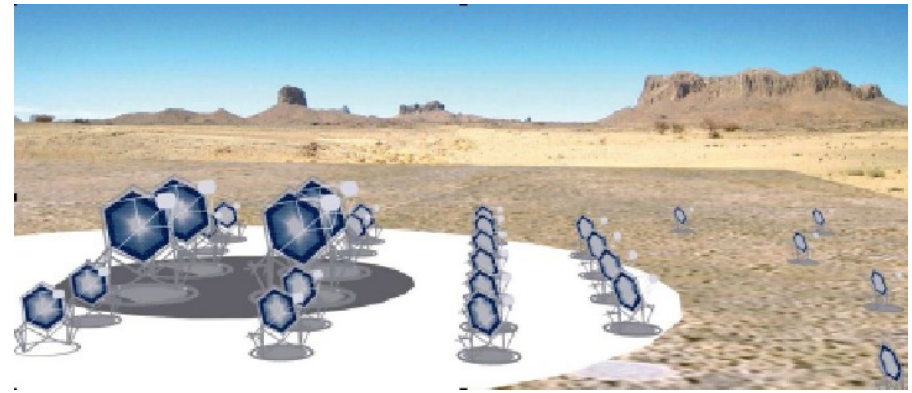
Distinguish between Pulsar and Dark Matter hypotheses ?

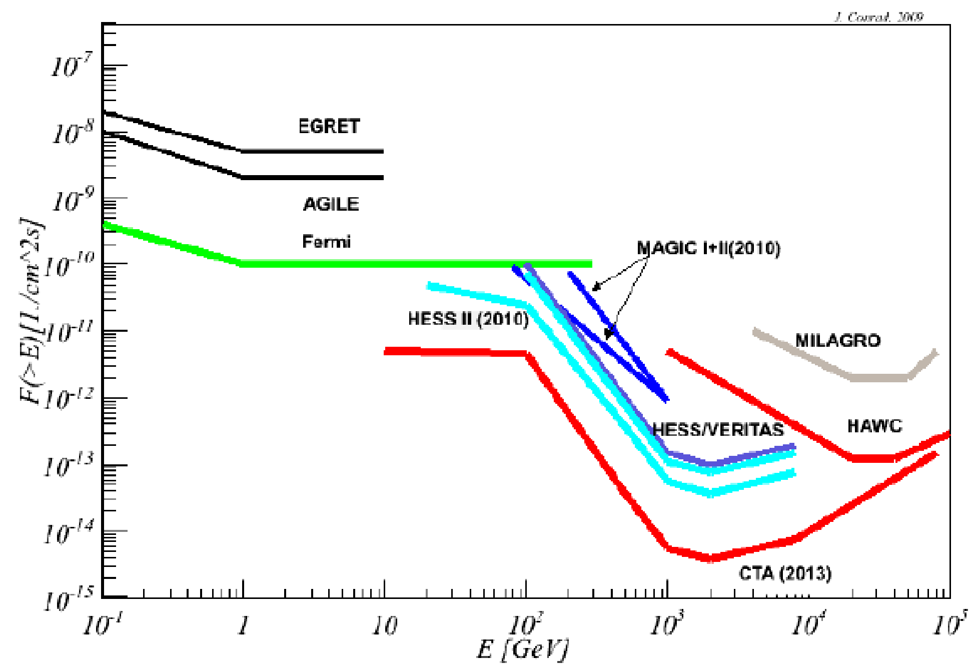
- **slow decrease as function of energy vs. sharp fall-off at WIMP mass**
- **anisotropy in angular distribution vs. isotropic distribution**

→ collect more data to extend energy range and sensitivity

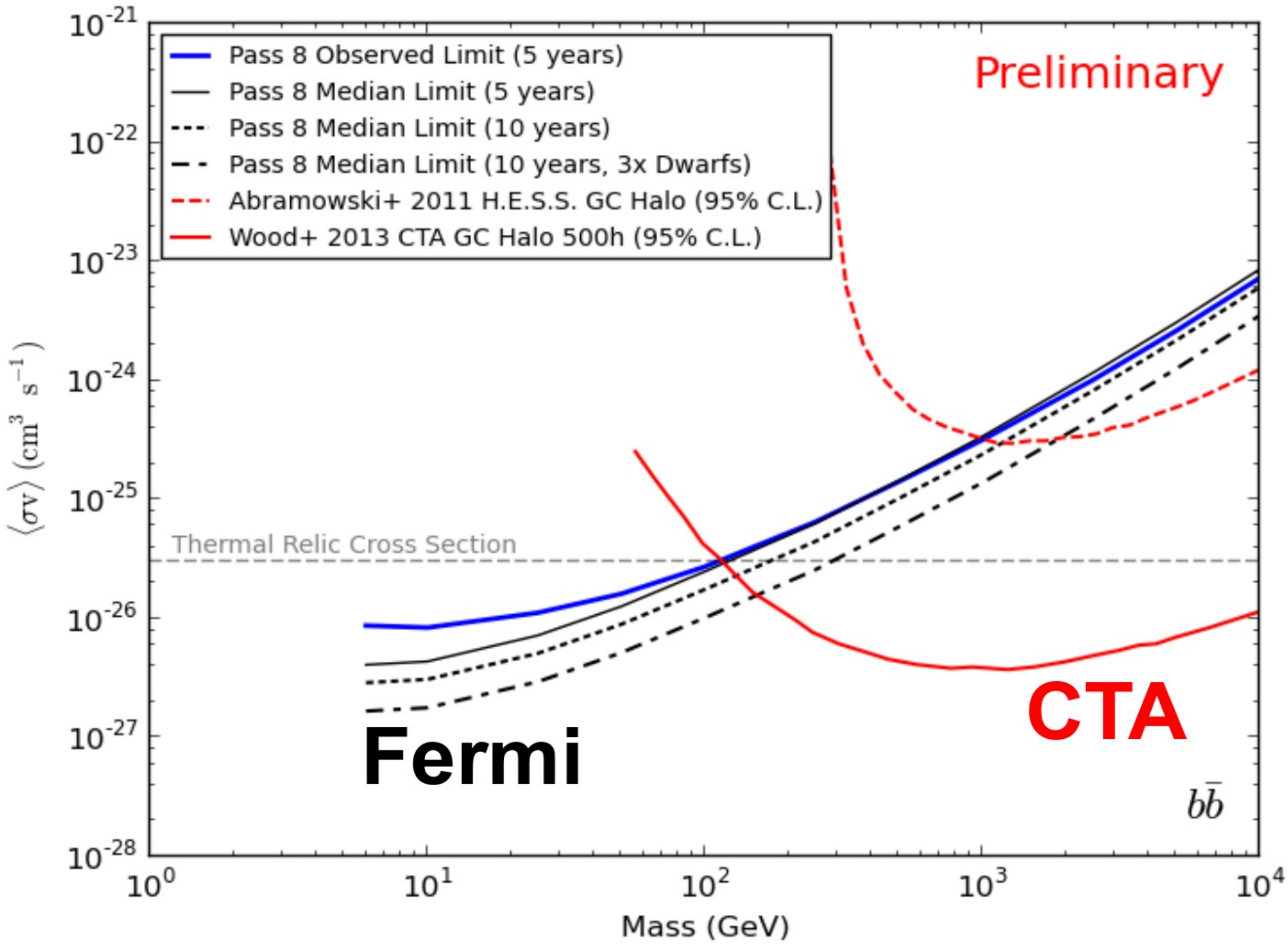
Future: CTA

- **Large Cherenkov Telescope Array**
  (UZH and ETHZ involvement**)**
- **tens of telescopes**
- **three different mirror sizes**
  - **a few 24m (for** 10 < E < 100 GeV**)**
  - **some 10-12m**
    (intermediate energies, 100 GeV-1 TeV**)**
  - **many 4-6m**
    (highest energies, > 10 TeV**)**
- **expected energy resolution: 5-10%**
  (c.f. 15% for existing experiments**)**
- **expected angular resolution: 0.03°**
  (c.f. 0.1° for existing experiments**)**

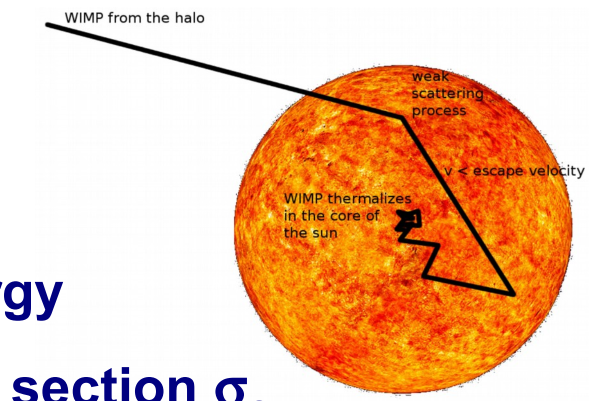




Complementarity Ground-Based vs Space-Based



About 10^{27} WIMPs per second pass through the Sun



- **can scatter elastically off protons and lose energy**
  - same process that is used in direct detection
- **trapped if energy after scatter smaller than escape energy**
- **capture rate for a given WIMP-nucleon scattering cross section σ_{SD}**

$$C \propto \rho_{\mathrm{local}}^{\mathrm{DM}} \cdot M_{\odot} \cdot \sigma_{SD}$$

- **annihilation rate**

$$A \equiv \frac{1}{2} \Gamma_A \cdot N_{\mathrm{DM}}^2 \propto \langle \sigma v \rangle \cdot N_{\mathrm{DM}}^2$$

$$\frac{dN}{dt} = C - 2A$$

- **time evolution**

$$N(t) = \sqrt{\frac{C}{\Gamma_A}} \cdot \tanh\left(\frac{t}{\tau_{\mathrm{eq}}}\right) \quad \Rightarrow \quad A(t) = \frac{1}{2} C \cdot \tanh^2\left(\frac{t}{\tau_{\mathrm{eq}}}\right)$$

- **equilibrium time**

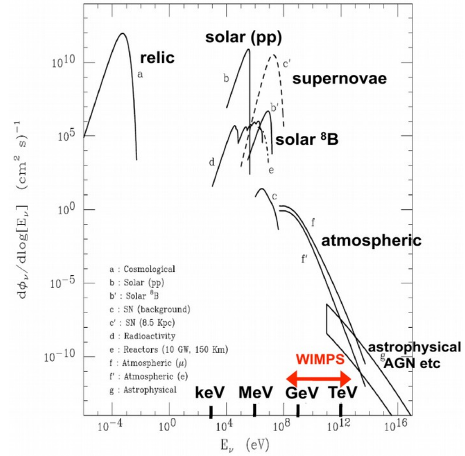
$$\tau_{\mathrm{eq}} = \frac{1}{\sqrt{C\,\Gamma_A}} \propto \frac{1}{\sqrt{\sigma_{\mathrm{SD}} \langle \sigma v \rangle}}$$

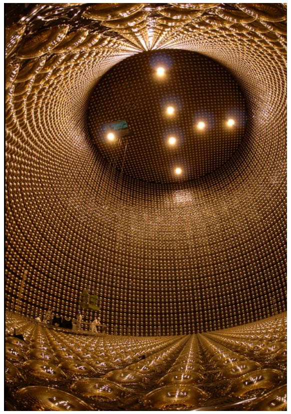
$$\sigma_{\mathrm{SD}} = 10^{-41}\,\mathrm{cm}^2 \Rightarrow \tau_{\mathrm{eq}} = 0.28 \times 10^9\,\mathrm{y} \ll t_{\odot}$$

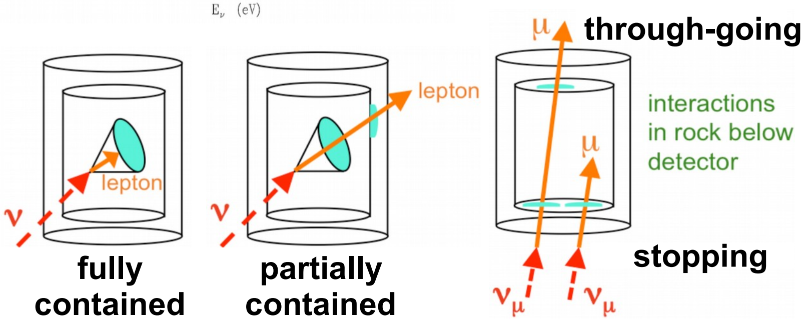
50'000-ton water Cherenkov detector

- fiducial volume 22'500 tons, 11'100 × 20” PMT
- outer part of detector as veto, 1'800 × 8” PMT

- **detect Cherenkov light of charged leptons created by interactions of neutrinos in detector material or surrounding rock**
  - study upward-going events to suppress background from cosmic/atmospheric muons
- **large background from atmospheric neutrinos**

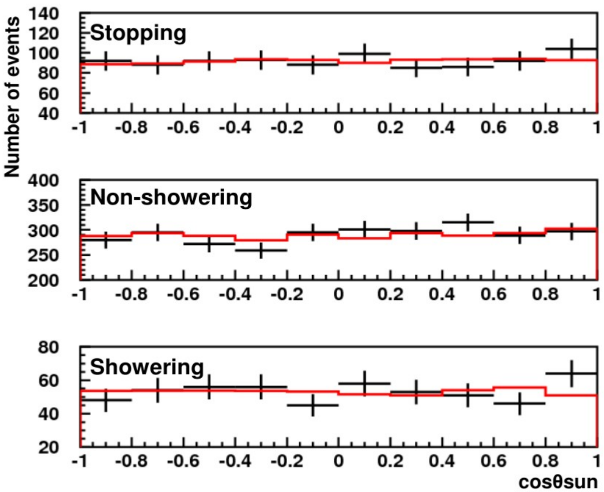






Analysis based on 1996–2008 data (3100 days)

- **look only at stopping and through-going muons**
  - best angular resolution (1 – 1.4)°
- **look for excess in neutrino flux in direction of Sun**
  - no excess found → set upper limits on WIMP scattering cross section

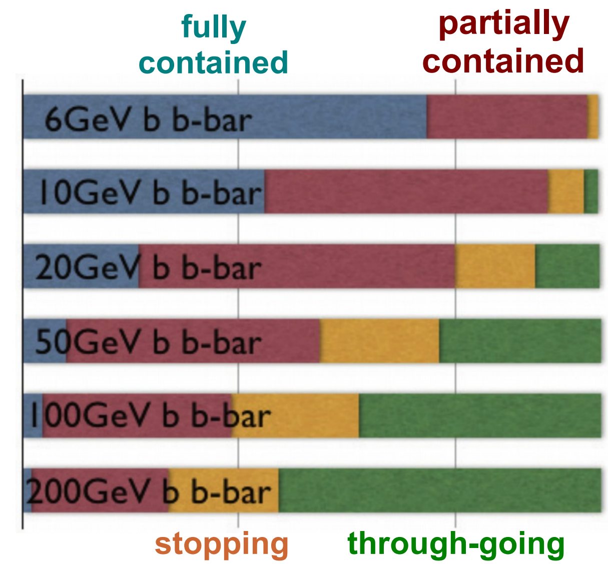


[1108.3384]

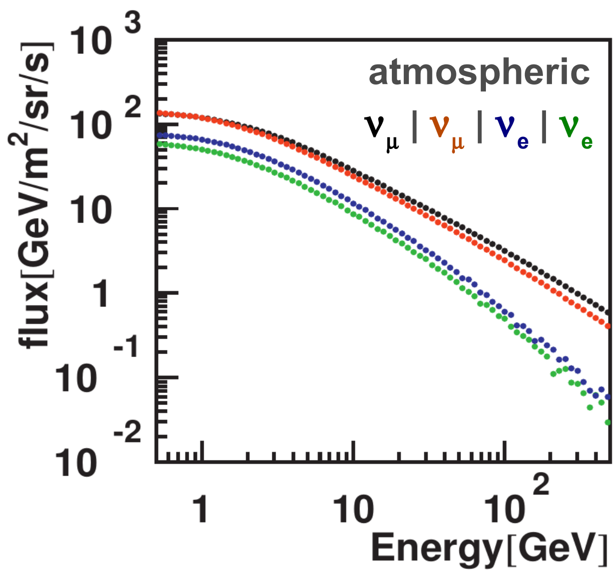
Neutrinos from the Sun: Super-Kamiokande

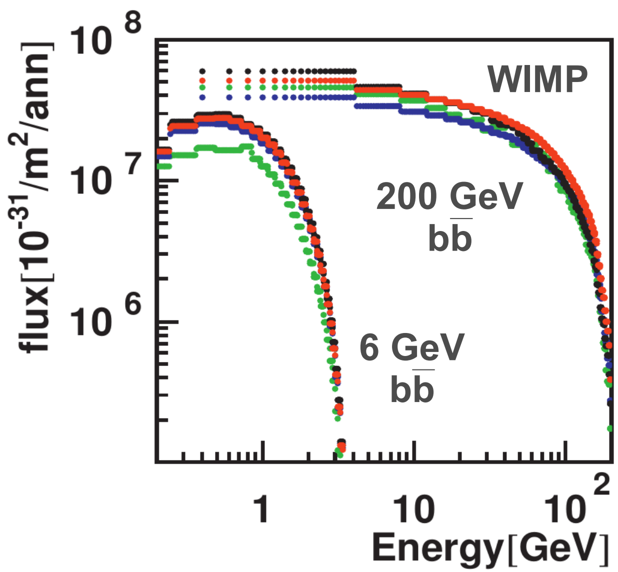
<u>Update adding data till March 2012</u> (+ 1097 days)

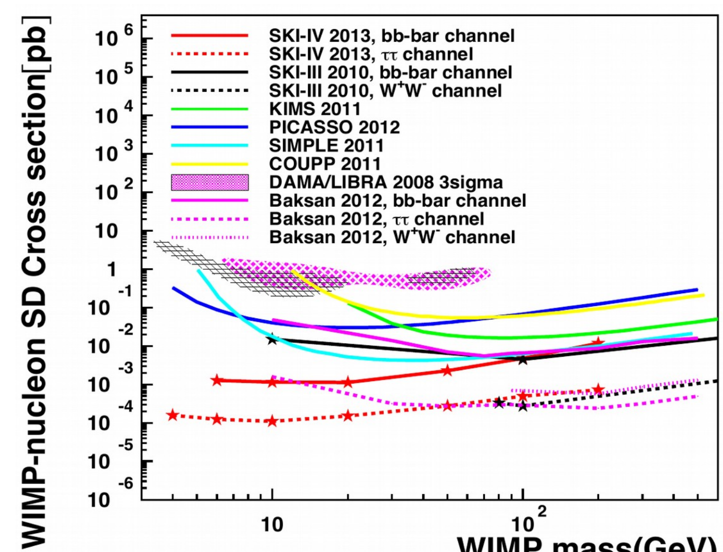
- **use also partially and fully contained events to extend energy range down to 10 GeV**
- **worse angular resolution for contained events**
  - use also energy spectrum and ν_μ / ν_e / $\bar{\nu}_\mu$ / $\bar{\nu}_e$ ratio to discriminate between signal and atmospheric



- **again no excess found, upper limits set on WIMP-nucleon cross section**



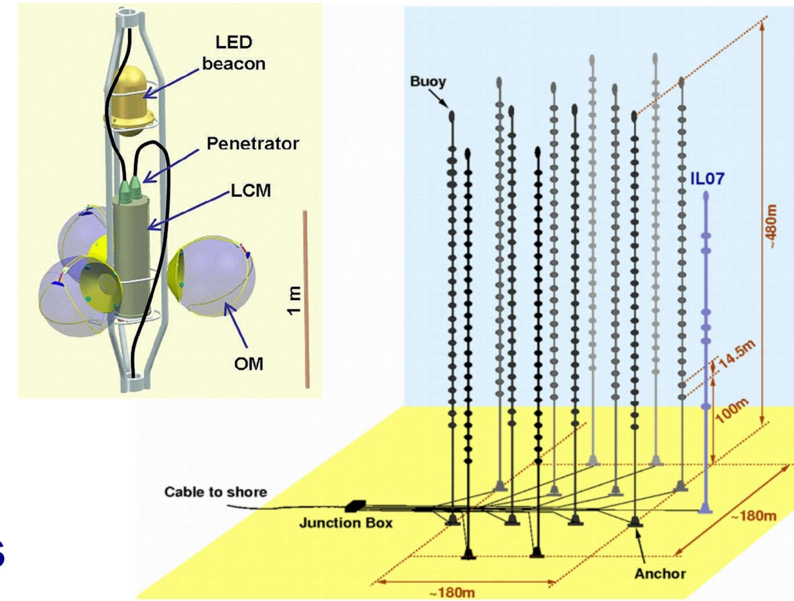


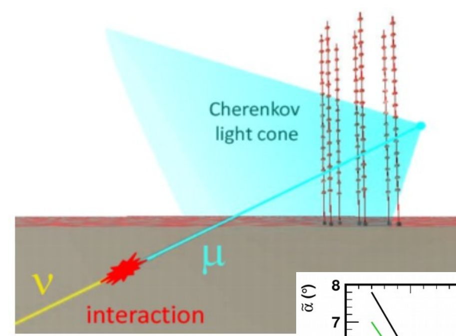


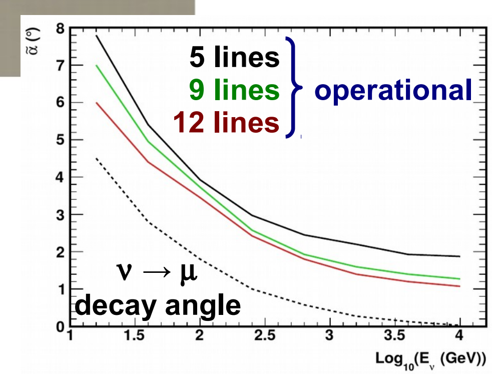
Neutrinos: Antares

Use sea water as Cherenkov radiator

- **installed in Mediterranean sea, near Toulon**
- **12 detection lines, each line 25 storeys, each storey three 10” PMTs**
- **again, study upward-going events**
- **20 MHz clock distribution system to calibrate timing between PMT signals to < 1 ns**
    - monitoring by LED and laser systems
- **positions of lines monitored to < 20 cm**
    - tilt-meter compass system on each storey
    - high-frequency acoustic emitters/transponders at known positions on the sea floor and hydrophones at known positions along each line
- **angular resolution ~ 0.3° for ν_μ with E_ν > 10 TeV**



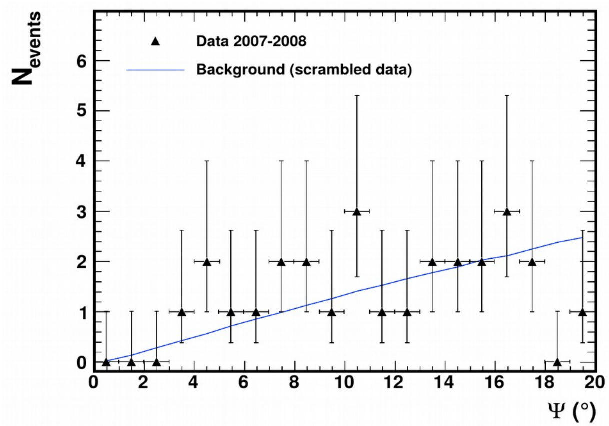


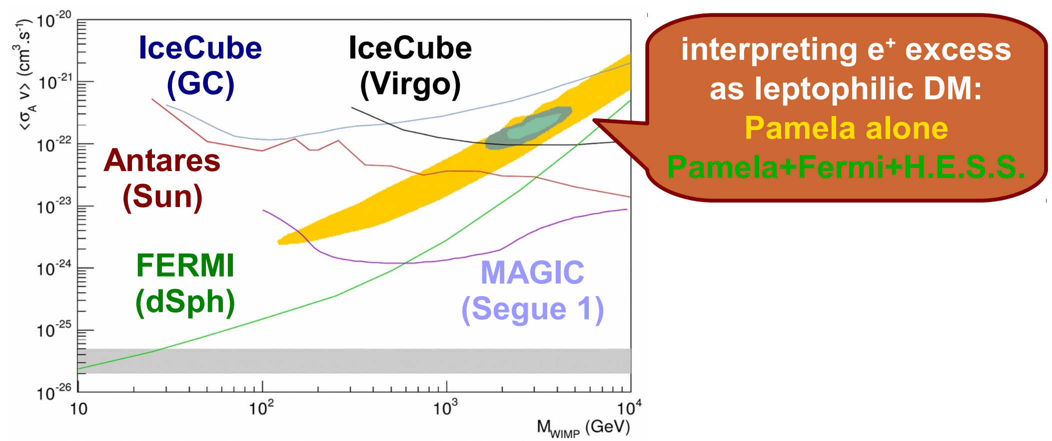


Neutrinos from the Sun

[1302.6516]

- published analysis based on 2007/2008 data, update using 2007-2012 data
- find no excess in direction of Sun, derive upper limits on flux, σ_{SD} and $<\sigma_A v>$

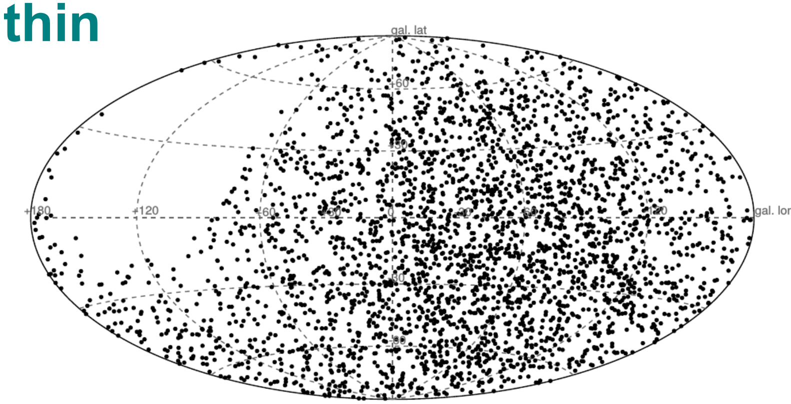




Also: various searches for point sources

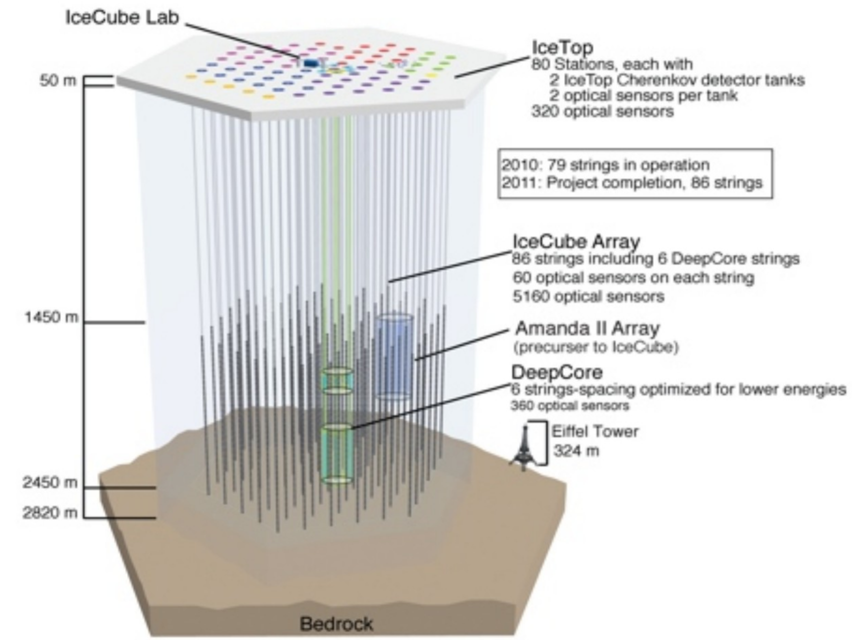
[1402.6182] [1402.2809]

- "full-sky" search: look for clusters of events within a cone of a given diameter (1° or 3°)
- specific search: look for excess of events in the direction of 50 selected candidate sources
- autocorrelation of 3058 neutrino candidates
- no significant excess found, derive upper limits on fluxes

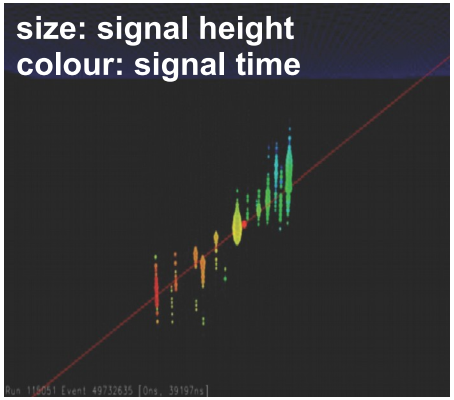


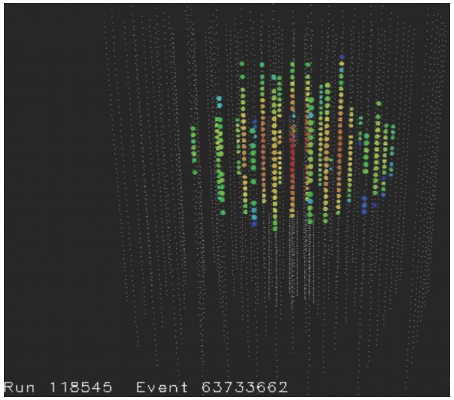
Use polar ice as Cherenkov radiator

- **installed close to South Pole**
  - southern hemisphere: galactic neutrinos cause downward-going events
  - sensitivity affected by large backgrounds from atmospheric muons
- **86 vertical strings, 1.5–2.5 km below surface**
  - each string 60 optical sensors, 10” PMTs
  - strings 125 m apart → 1 km³ detection volume



- **“track-like” events (from muons):**
  - angular resolution ~ 1° but no energy measurement → search for point sources
- **“cluster-like” events:**
  - energy measurement but limited angular resolution → search for diffuse emission

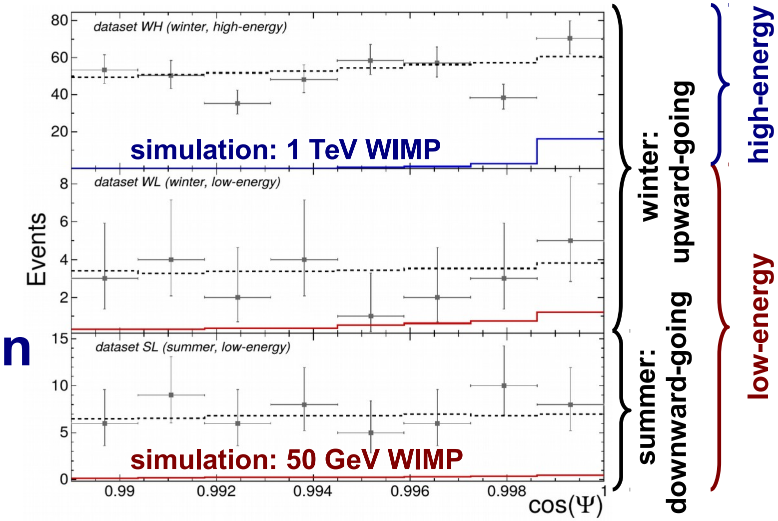


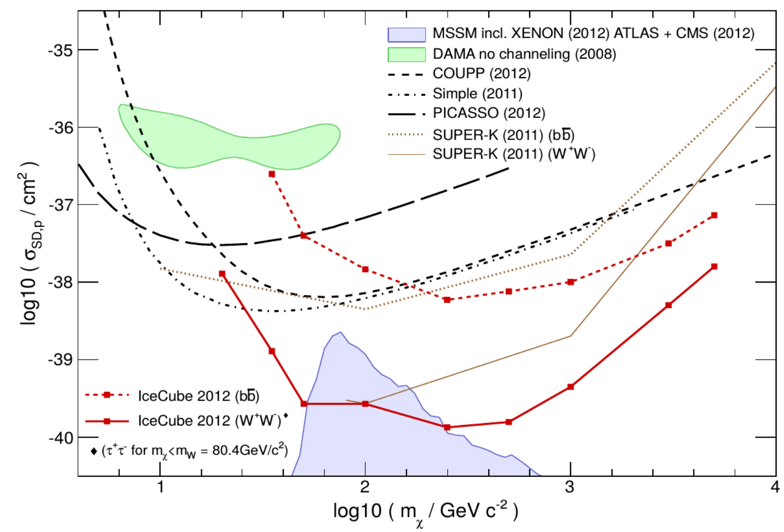


Neutrinos: IceCube

Neutrinos from the Sun (2010/2011, 317 days of data) **[1212.4097]**

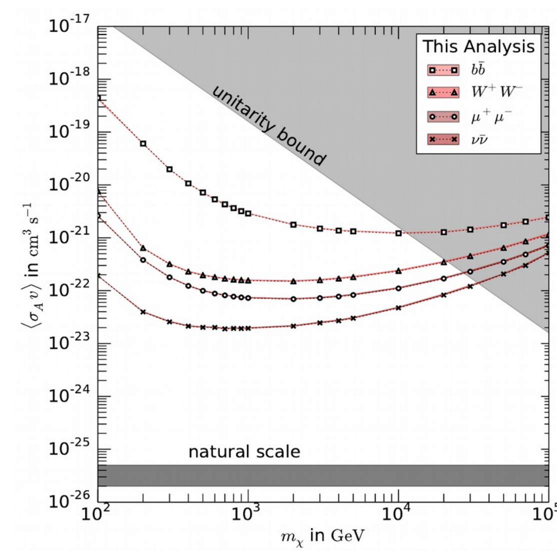
- **no excess over background observed**
- **set upper limits on WIMP-nucleon scattering cross sections**





Various searches for point sources (2008–2011/2 data)

- **look for excess of events in the direction of selected candidate sources** **[1406.6757]**
- **generic searches using auto-correlation and multipole fits of neutrino candidates** **[1408.0634]**
- **multipole analysis to search for DM annihilation in galactic halo** **[1406.6868]**
- **no signals found in any search → derive upper limits**



Summary

Choice of potential sources

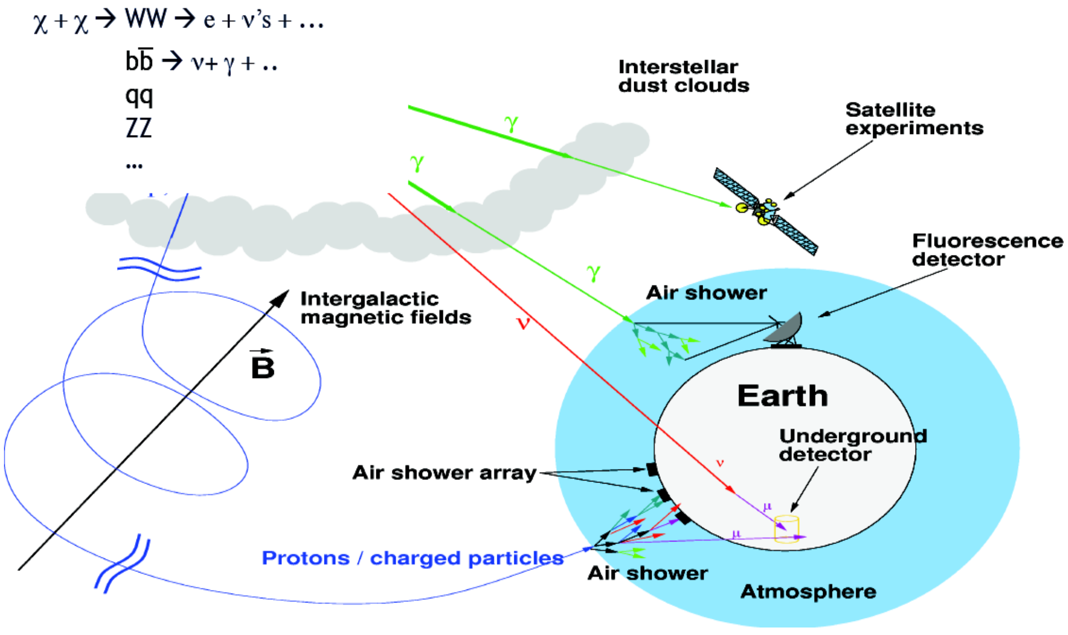
- galactic centre and halo
- extra-galactic (e.g. dSph)
- neutrinos from the Sun

Choice of messenger particles

- photons
- neutrinos

} point back to source

- anti-particles – deviated in magnetic fields

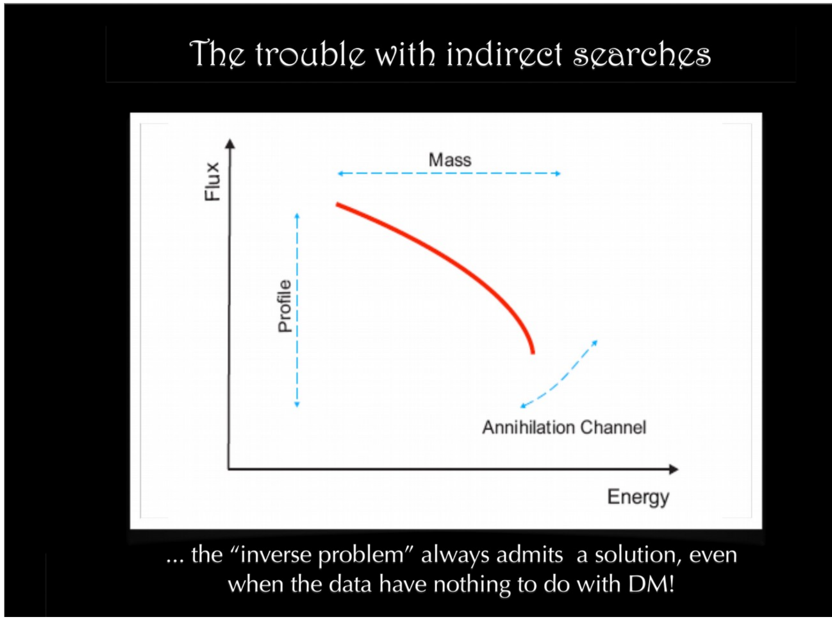


Different experimental approaches

- above atmosphere at lower energies
- ground-based at highest energies

Problem: find an unambiguous signature

- almost any signal can be interpreted in terms of Dark Matter annihilations
- almost any signal can be interpreted in terms of astro-physical backgrounds



[Gianfranco Bertone]