Universität Zürich[UZH]

Physik-Institut

PAUL SCHERRER INSTITUT

PHY213 Kern- und Teilchenphysik II
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Cosmic Frontier: Experimental searches for Dark Matter

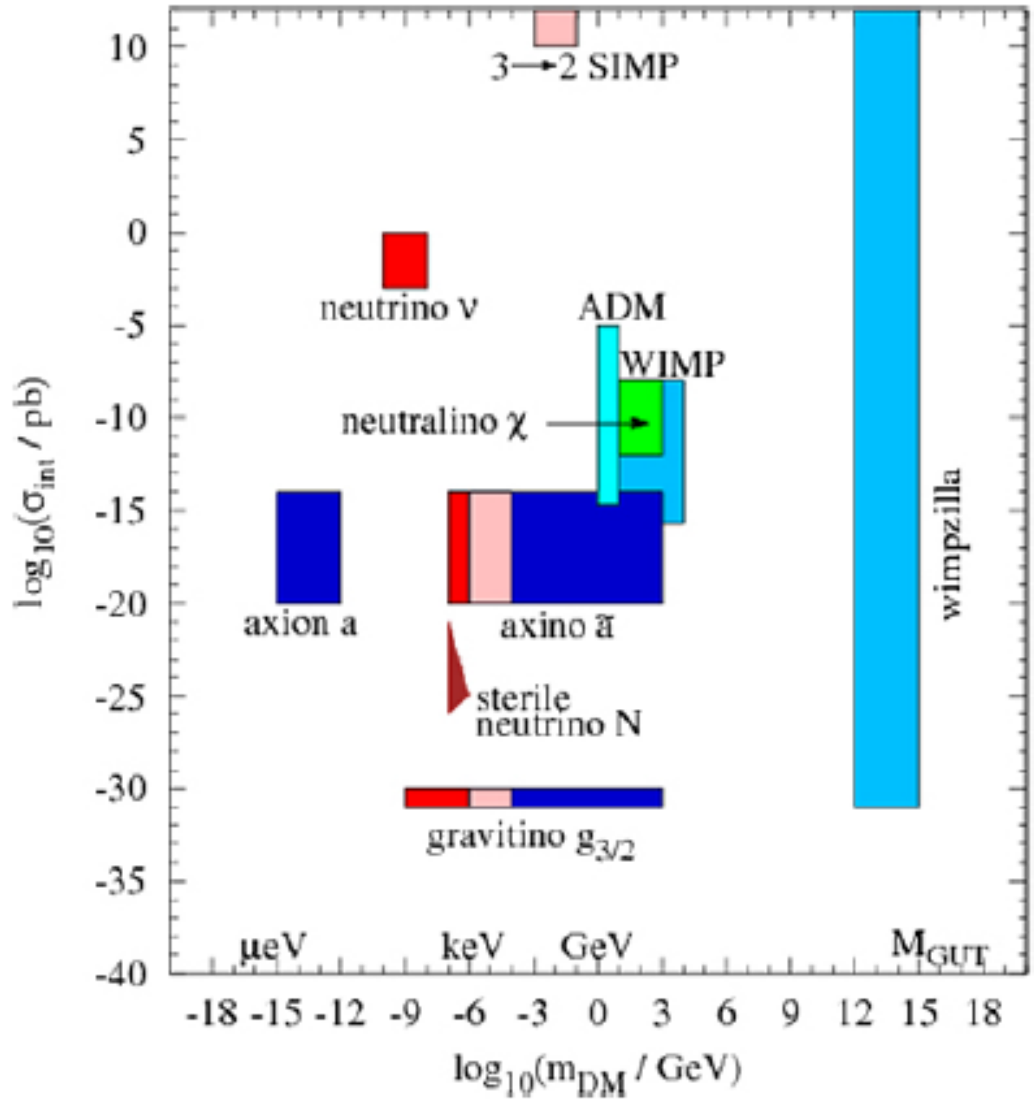
Lea Caminada

lea.caminada@physik.uzh.ch

Overview

- Axion searches
- WIMP – direct searches
- WIMP – indirect searches
- WIMP – searches at colliders

Dark matter candidates



Searching for Dark Matter with Cosmic Gamma RaysAndrea Albert

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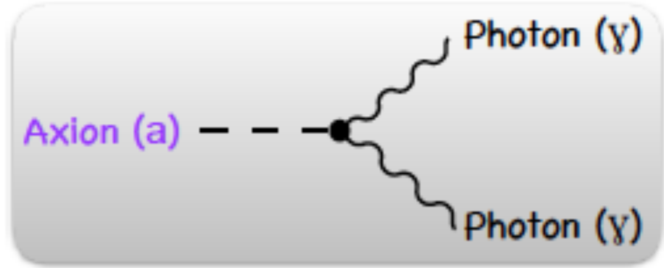
http://iopscience.iop.org/book/978-1-6817-4269-4/chapter/bk978-1-6817-4269-4ch2

Axions as dark matter candidates

- Axion is a very light pseudoscalar particle (spin-parity 0^-) proposed to solve the strong CP problem:
  - Complex CP violating phase can occur in QCD wavefunctions, however strong CP violation not observed experimentally (and thus not in SM)
- Peccei and Quinn (1977) proposed a new global U(1) symmetry, spontaneously broken at some very high energy scale
- Gives rise to Goldstone boson → the axion
  - receives small mass through non-perturbative effects at QCD scale (200 GeV)

Axions as dark matter candidates

- Like the neutral pion π^0, axion can decay to two photons with rate $1/f_a$ (f_a: Peccei-Quinn energy scale)



- Axion mass given by:

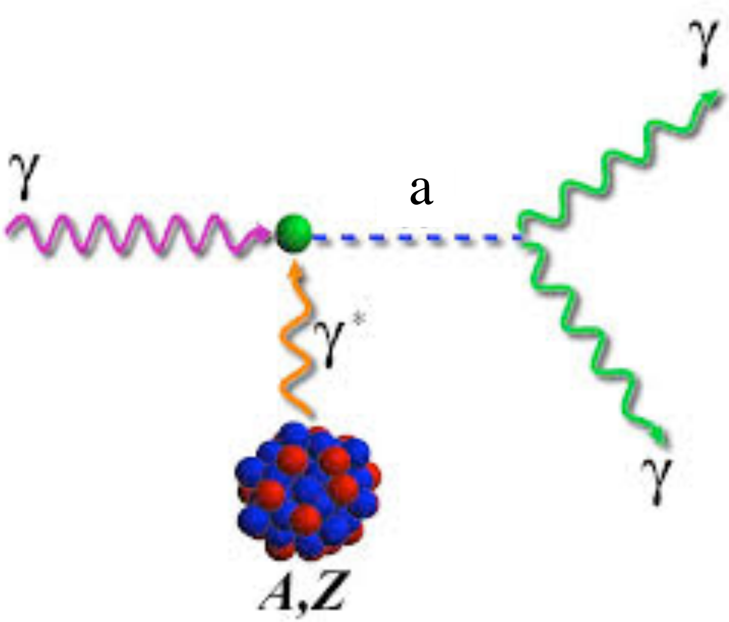
pion mass pion decay constant

$$m_a \approx 0.5 \frac{m_\pi f_\pi}{f_a} \approx \frac{6\,\mathrm{eV}}{[f_a/(10^6\,\mathrm{GeV})]}$$

- Lifetime proportional to $1/m_a^5$ → larger than the age of the universe for $m_a < 10$ eV → would survive as relics from the Big Bang
- Axions never got into thermal equilibrium in early universe → freeze-out arguments for density parameter do not apply

Axions: Constraints from cosmology

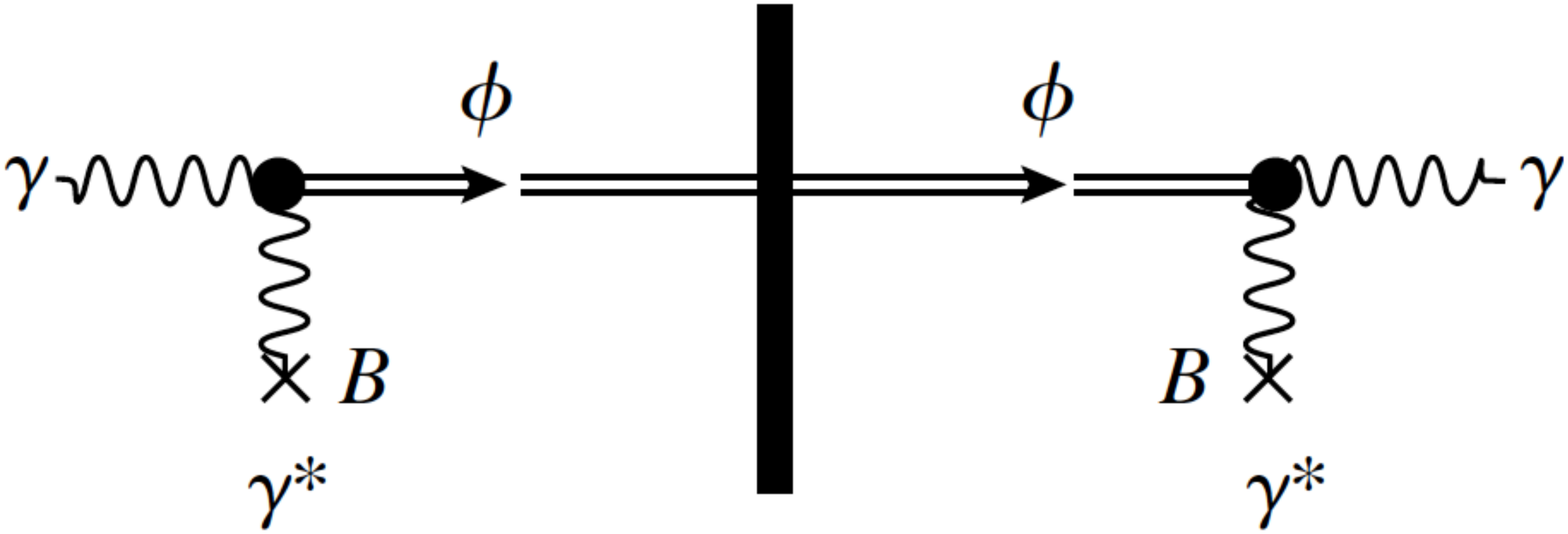
- Axions could be produced in stars by scattering of photon on Coulomb field of a nucleus (Primakoff effect)



- Due to very weak coupling, axions would be emitted from stars and contribute to cooling rate → upper limit on $m_a < 0.01$ eV

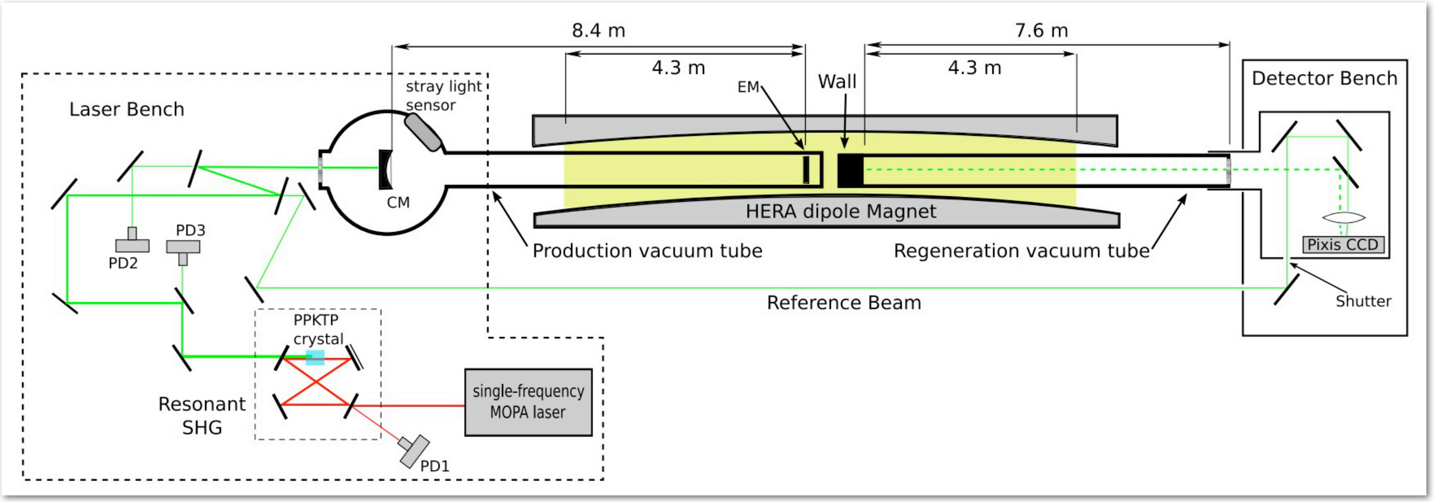
Search for axions: Photon through a wall

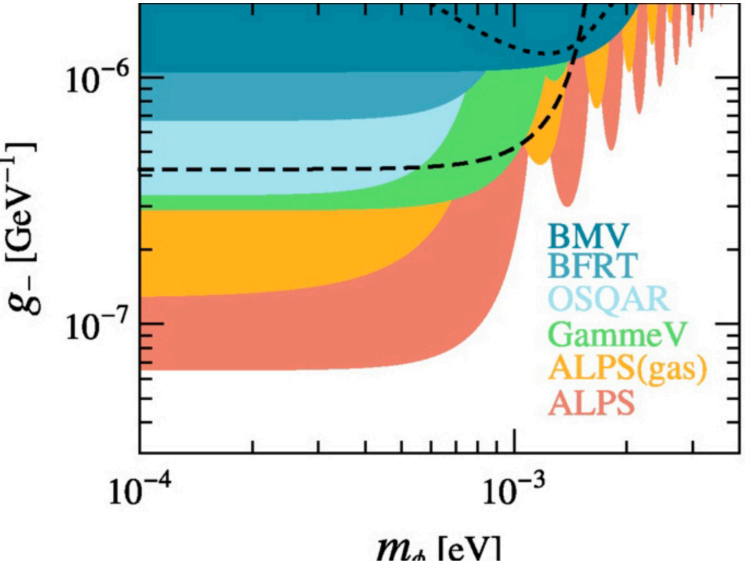
- Incoming photon from a laser interacts with a photon of a very strong magnetic field to produce an axion
- Axion can pass through the wall
- After the wall converts back into a photon in another magnetic field



ALPS experiment at DESY

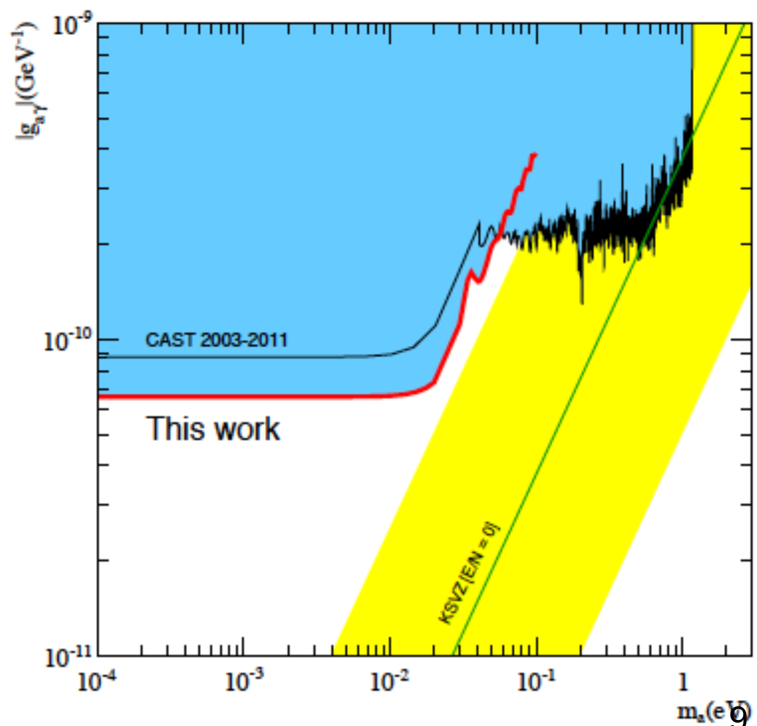
- ALPS – Any light particle search
- Using one of the HERA dipole magnets (5T)





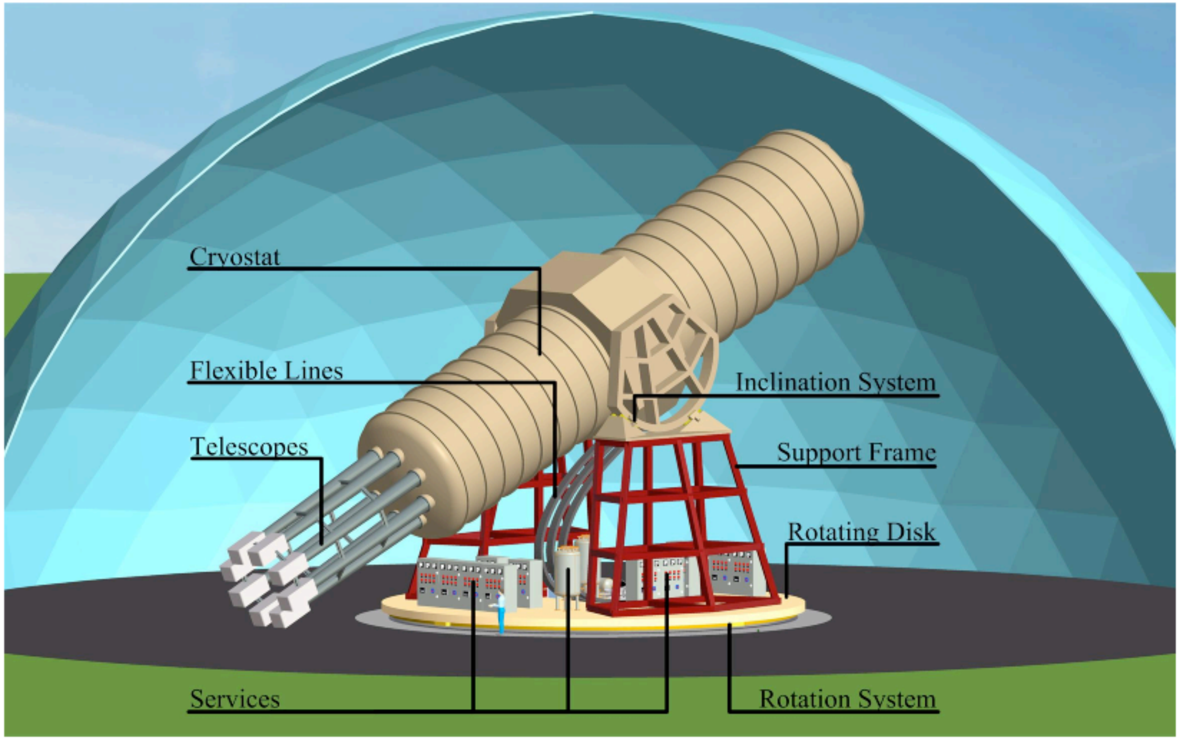
Search for axions: Solar axions

- Look for the decay of axions produced in the sun by the Primakoff effect (excess of x-ray photons)
- Helioscope: Detector that consists of a dipole magnet with bore steered in the direction of the sun and x-ray detectors at the end
- CAST: CERN Axial Solar Telescope – built from 9T LHC magnet
- Set limits on axion mass depending on photon-axion coupling

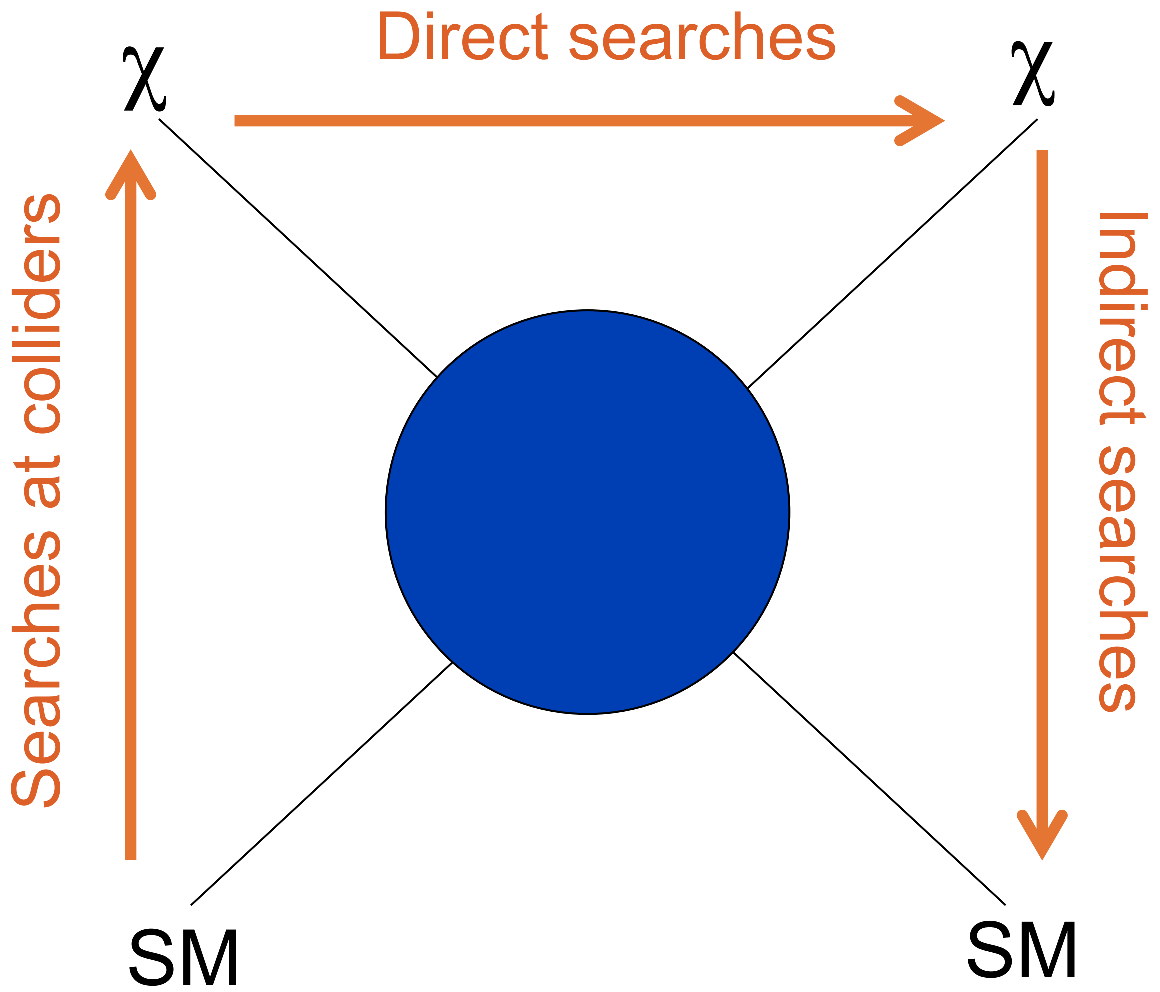


Search for axions: Status

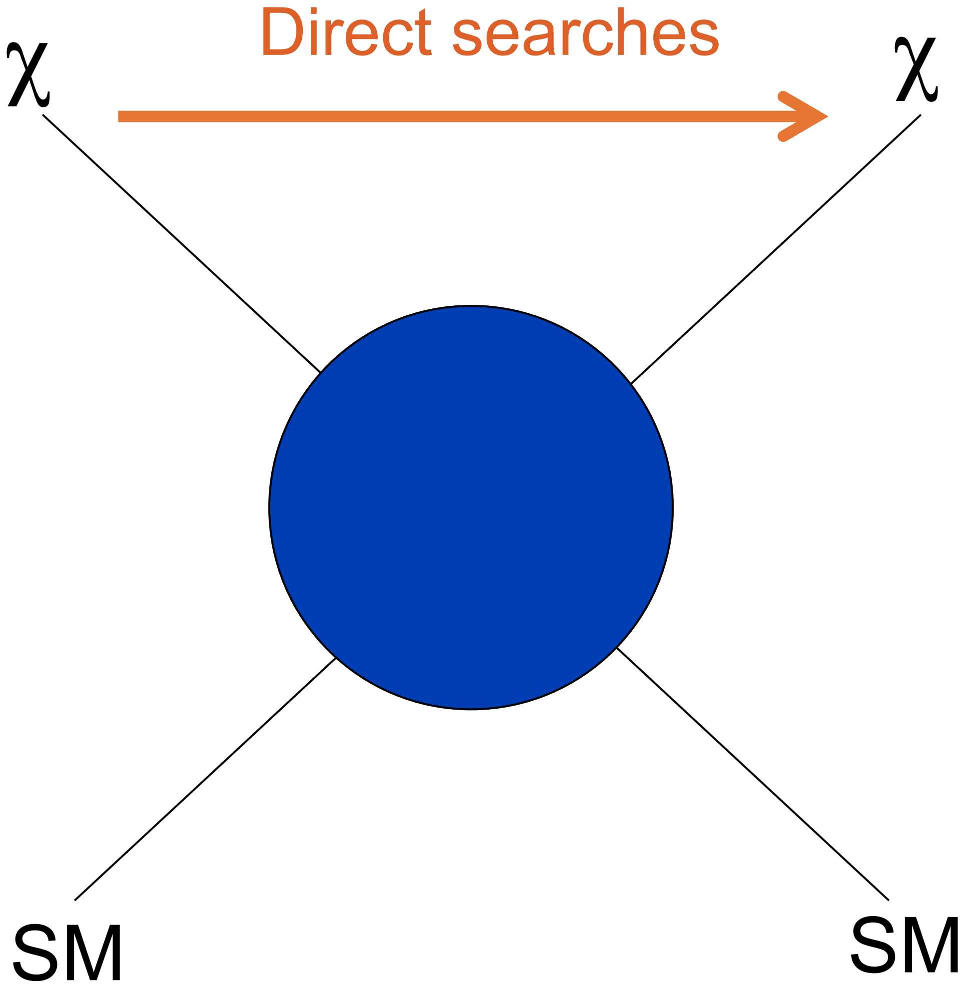
- QCD axion has well bounded parameter space of mass and couplings
- Several models propose axion-like particles (ALP) with slightly different properties → vast and largely unexplored search space
- New experiments proposed: International Axion Observatory IAXO



WIMP searches

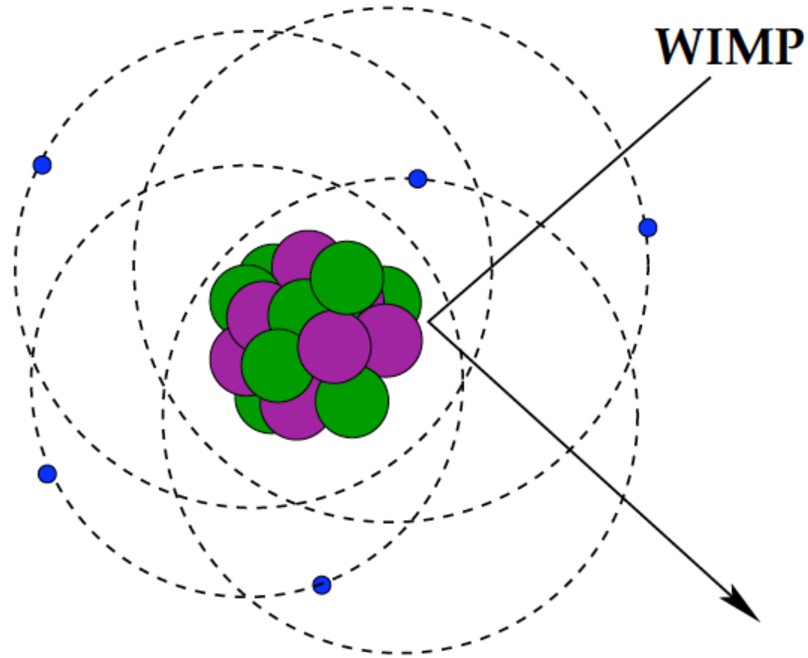


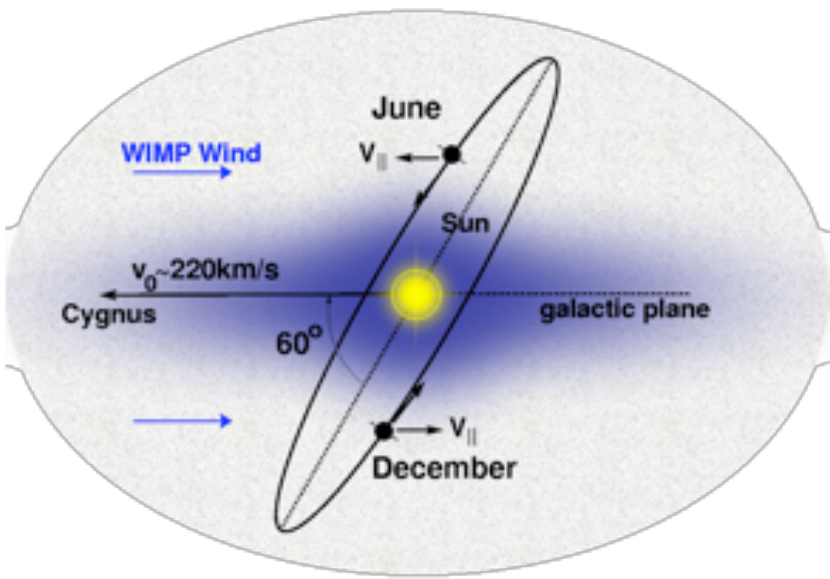
WIMP searches



Principle

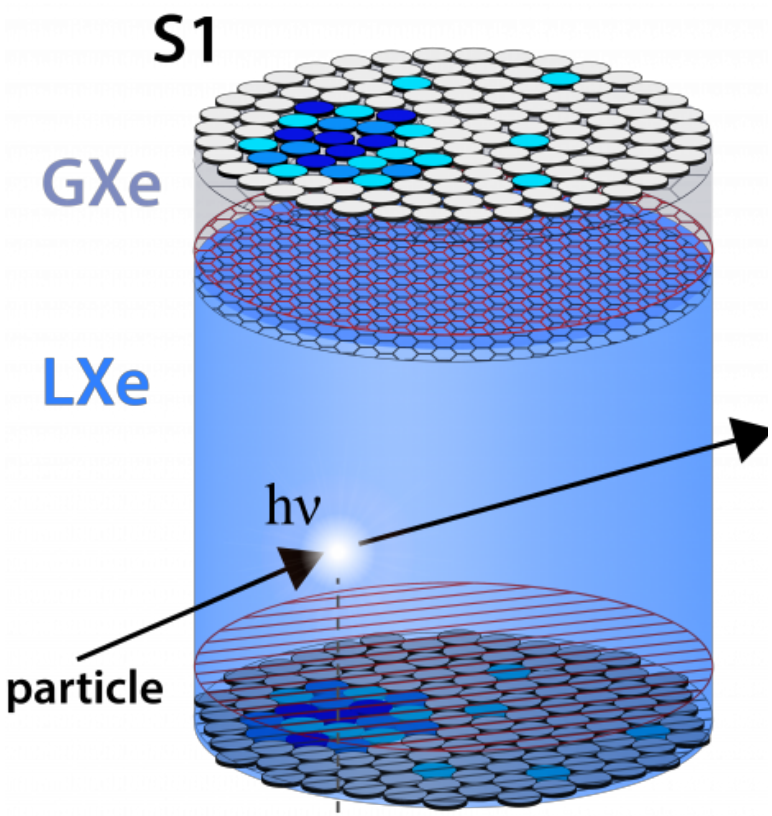
- Dark matter particles present in the solar system scatter with nuclei of detector material
- Expected signature:
- Recoil energy of the nucleus smaller than O(10keV)
- Expect annual modulation of WIMP signature:
- Earth is moving around sun, sun is moving around galactic center→ velocity of the earth relative to galactic rest frame is largest in summer





XENON1T as an example of noble gas detector

- Time projection chamber (TPC) filled with liquid and gaseous xenon
- WIMP interacting with liquid xenon produces scintillation light



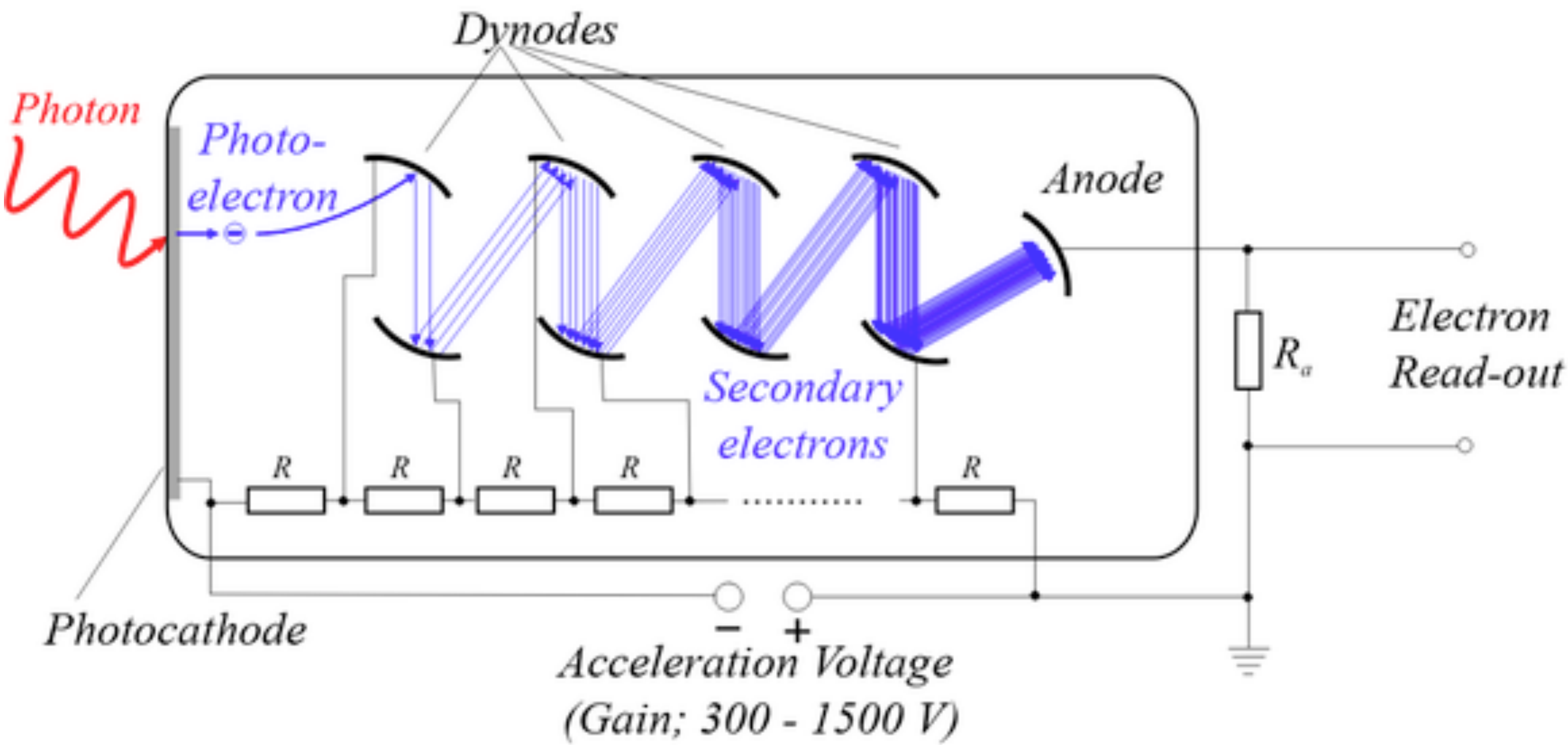
Why Xenon?

$$R \propto \rho_0 \sigma N A^2$$

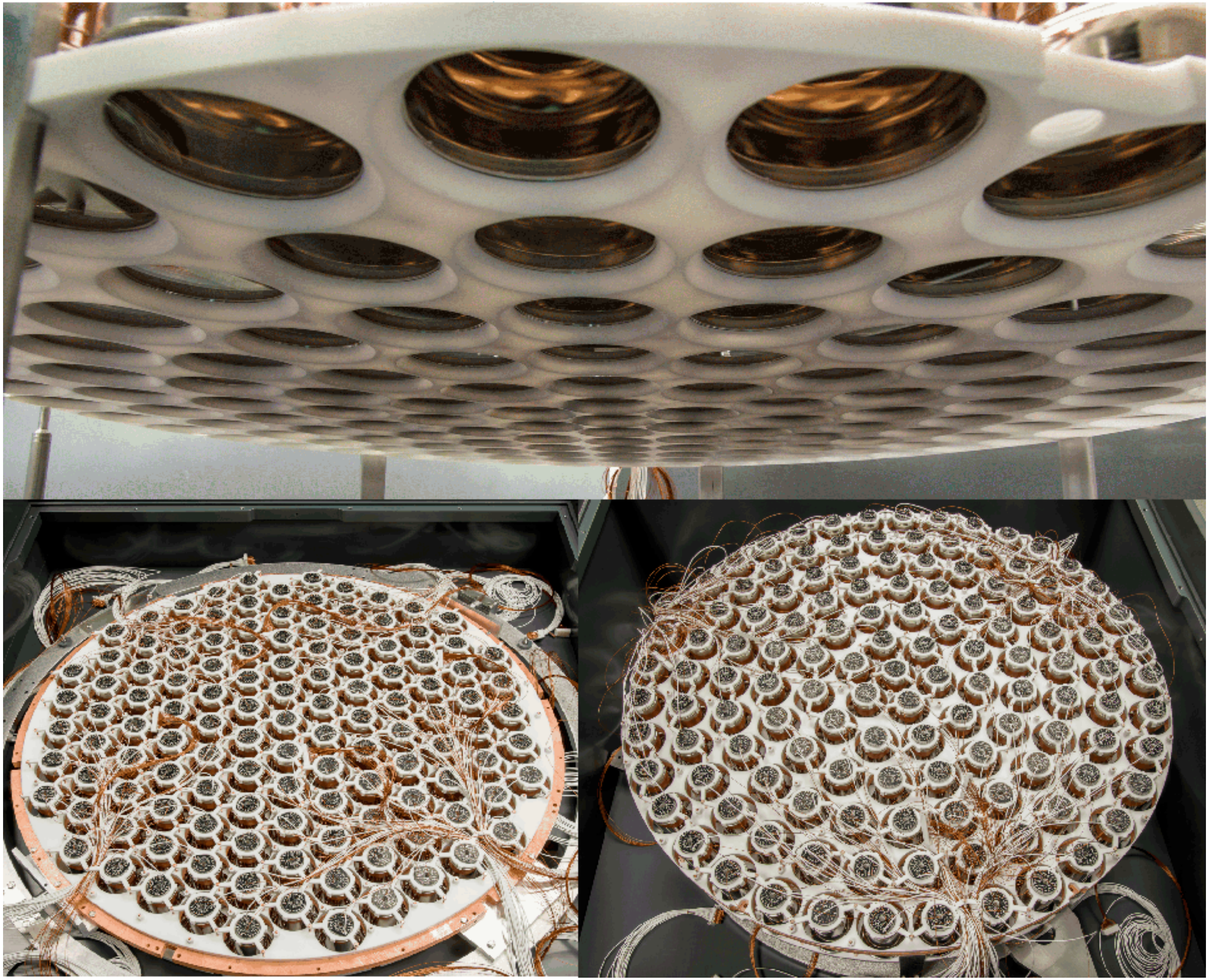
- R – Event rate in the detector
- ρ_0 - Local DM density (0.3 GeV/c^2)
- σ – WIMP-Nucleon cross section
- N – Number of nuclei
- A – Atomic number (~130)

Photomultiplier Tube (PMT)

- Photon hits photocathode which emits electron due to photoelectric effect
- Electrons are multiplied by the process of secondary emission
- Sharp pulse on anode (ns) detected

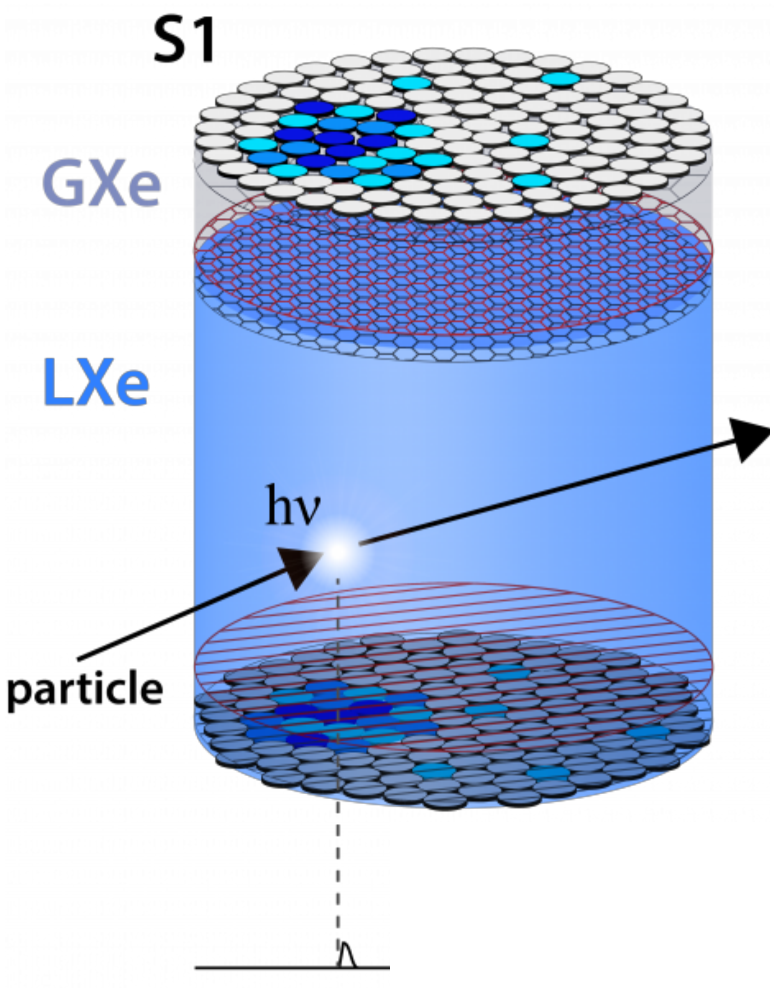


Photomultiplier Tube (PMT)



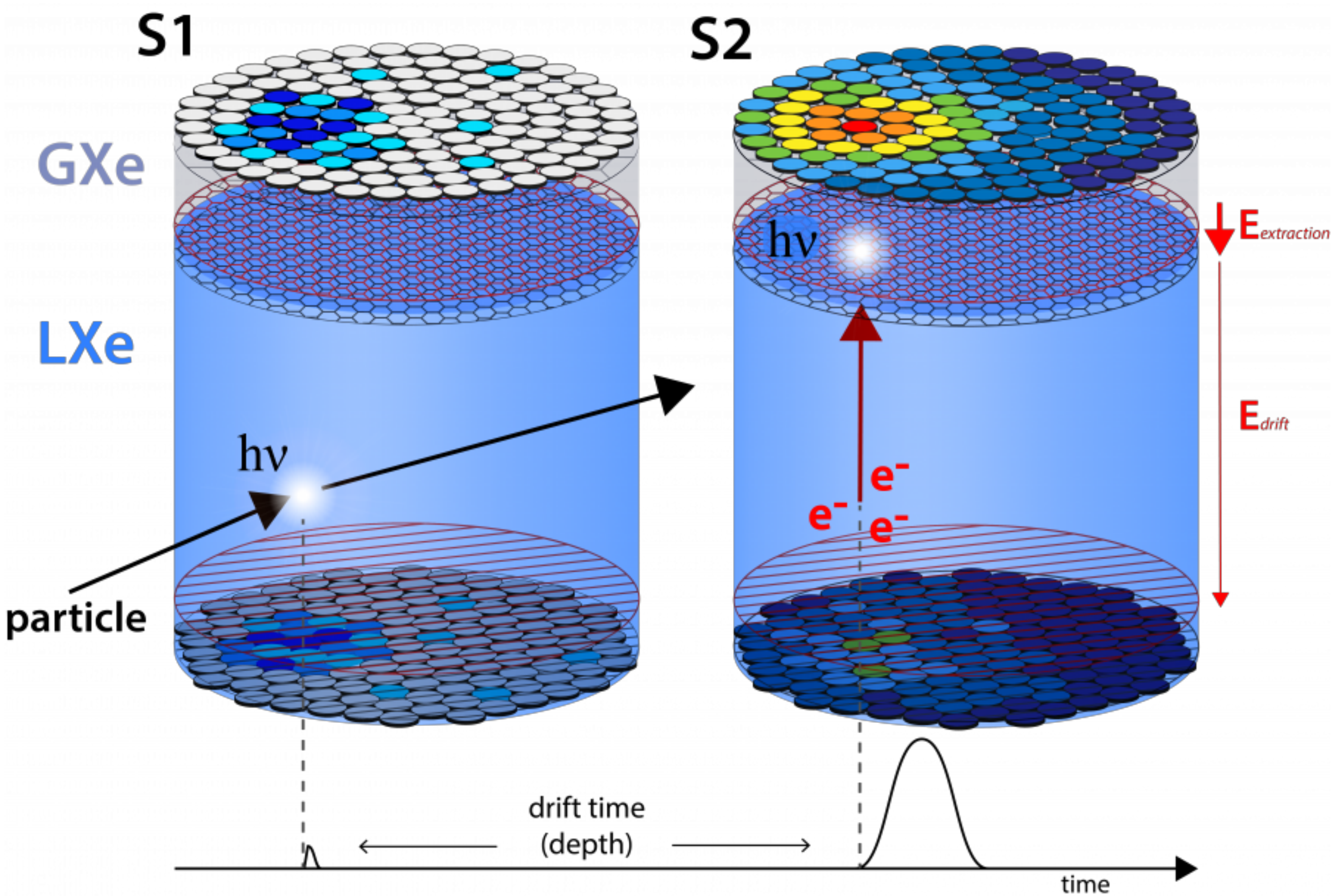
XENON1T as an example of noble gas detector

- S1: Scintillation light measured in top and bottom arrays of PMTs → position in the horizontal plane



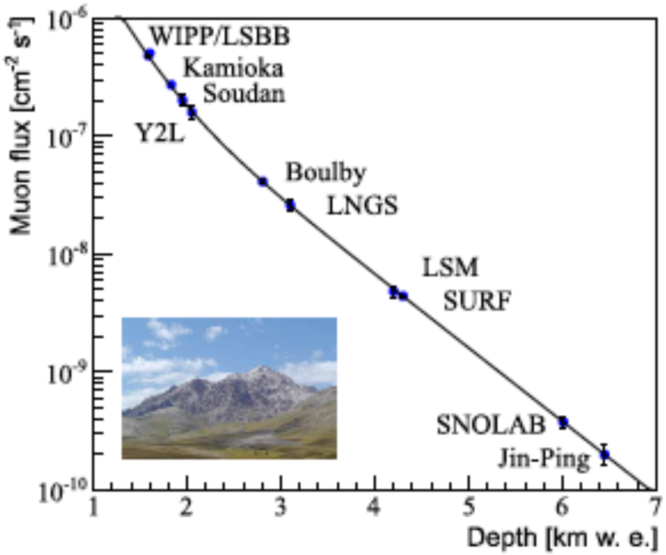
XENON1T as an example of noble gas detector

- WIMP interacting with liquid xenon also produces ionization
  - Two electric fields across detector: E_{drift} and $E_{extraction}$
  - Drift velocity of electrons constant → can extract production depth → 3D information
  - S2-S1 gives characteristic signal

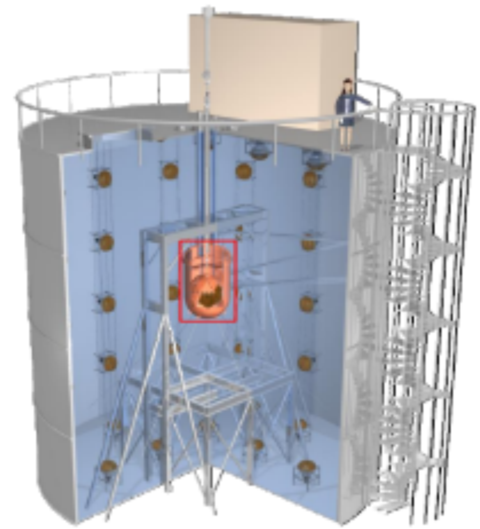


How to deal with backgrounds?

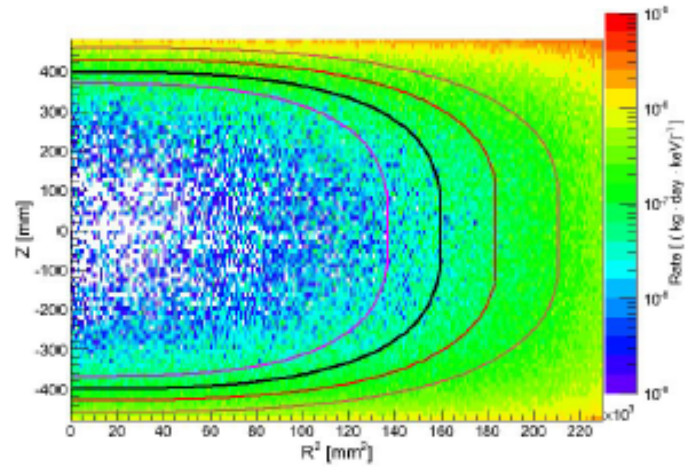
- Go deep underground



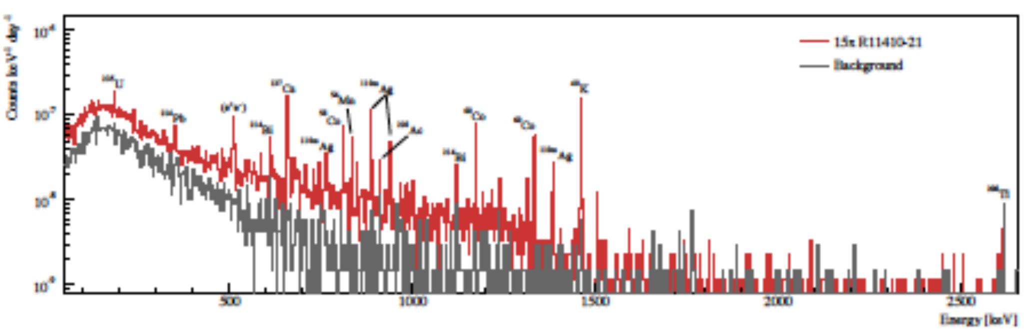
- Use active shields



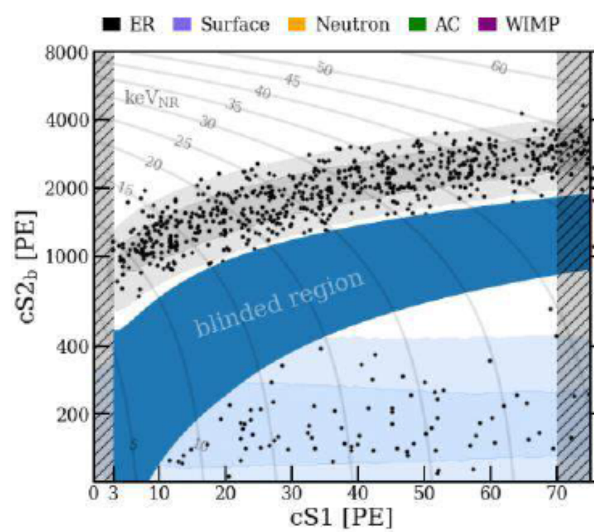
- Fiducialize



- Select low-radioactivity materials

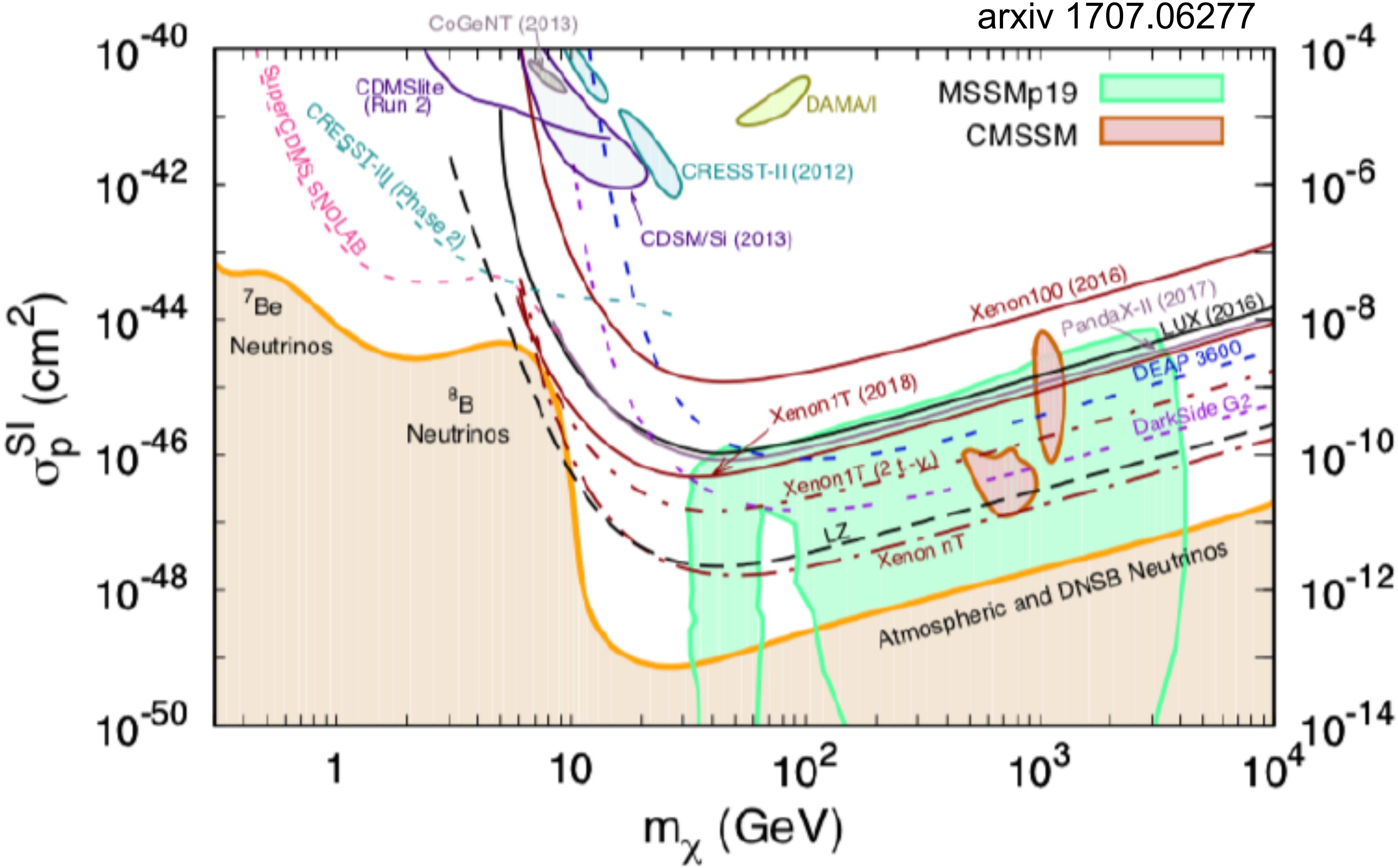


- Discriminate



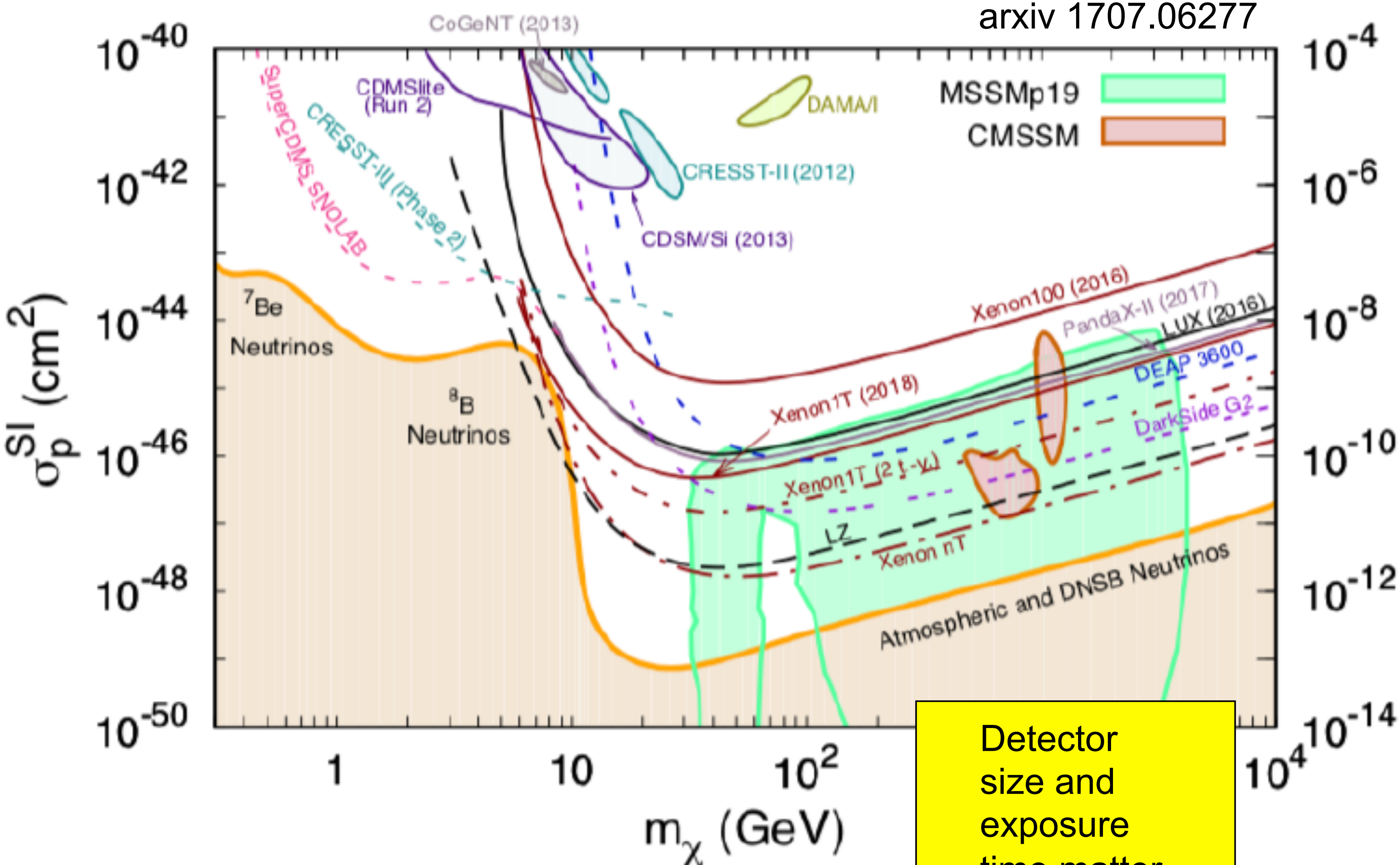
XENON1T results

arxiv 1707.06277



XENON1T results

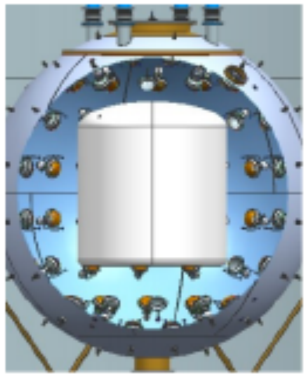
arxiv 1707.06277



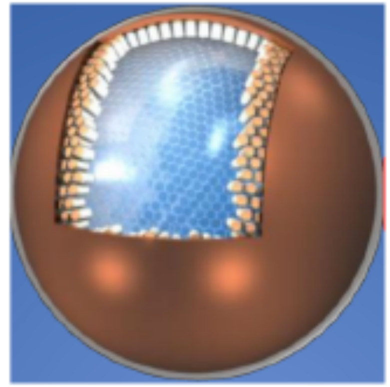
Detector size and exposure time matter

Future noble gas detectors

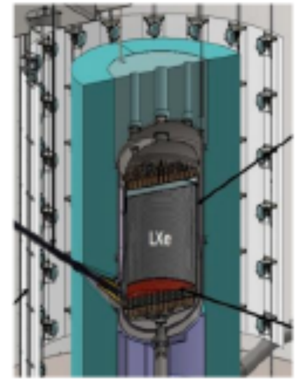
XENONnT: 7t LXe



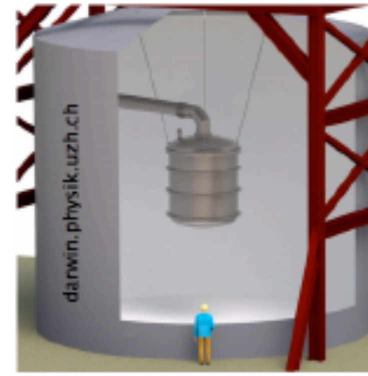
DarkSide: 20 t LAr



XMASS: 5t LXe



LZ: 7t LXe

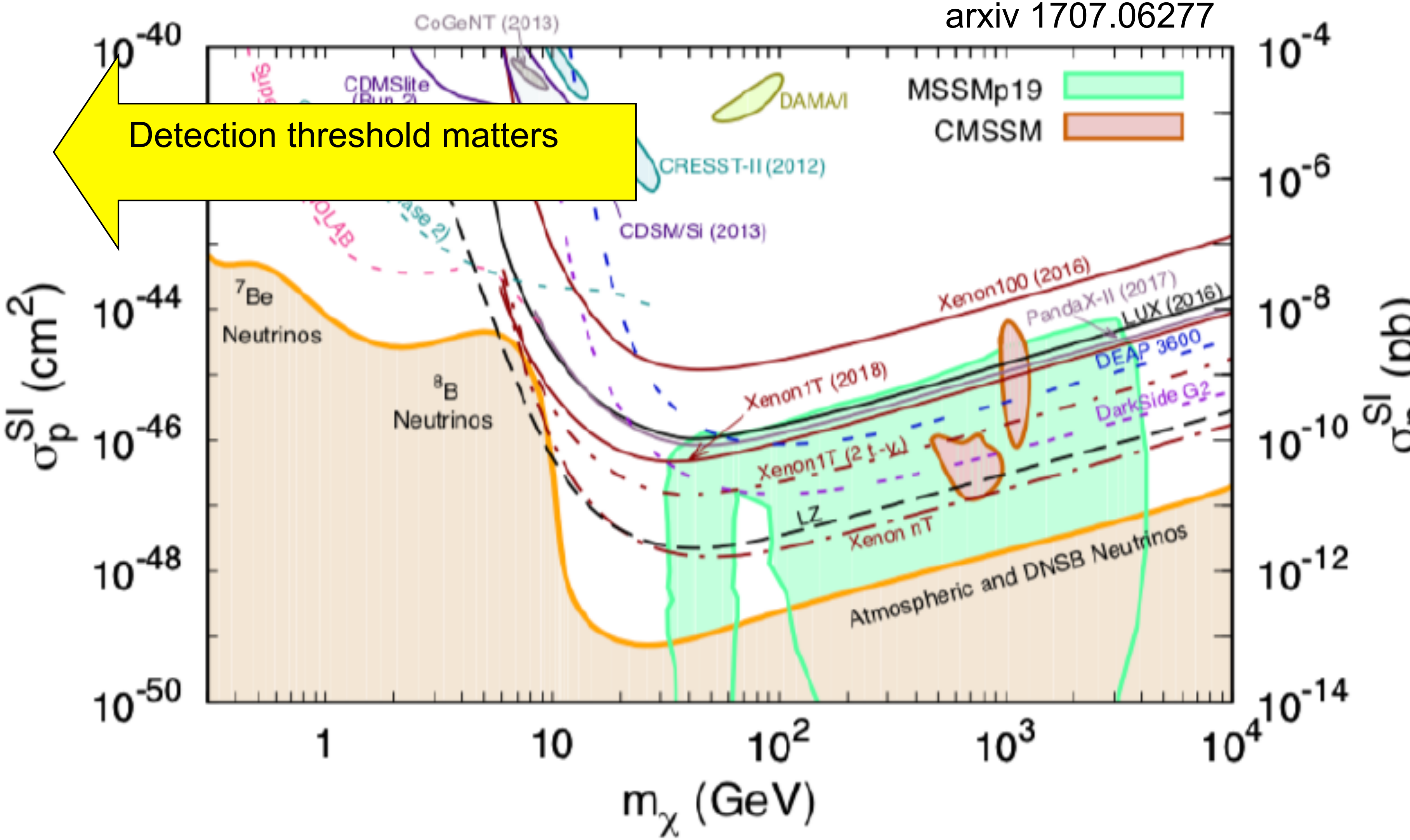


DARWIN: 50 t LXe

- Event rate proportional to the mass, so the challenge is to keep zero background (in some fiducial region) and increase the mass
- Increase in WIMP sensitivity by 2 orders of magnitude in the coming years
- Reach neutrino background in the coming decade

XENON1T results

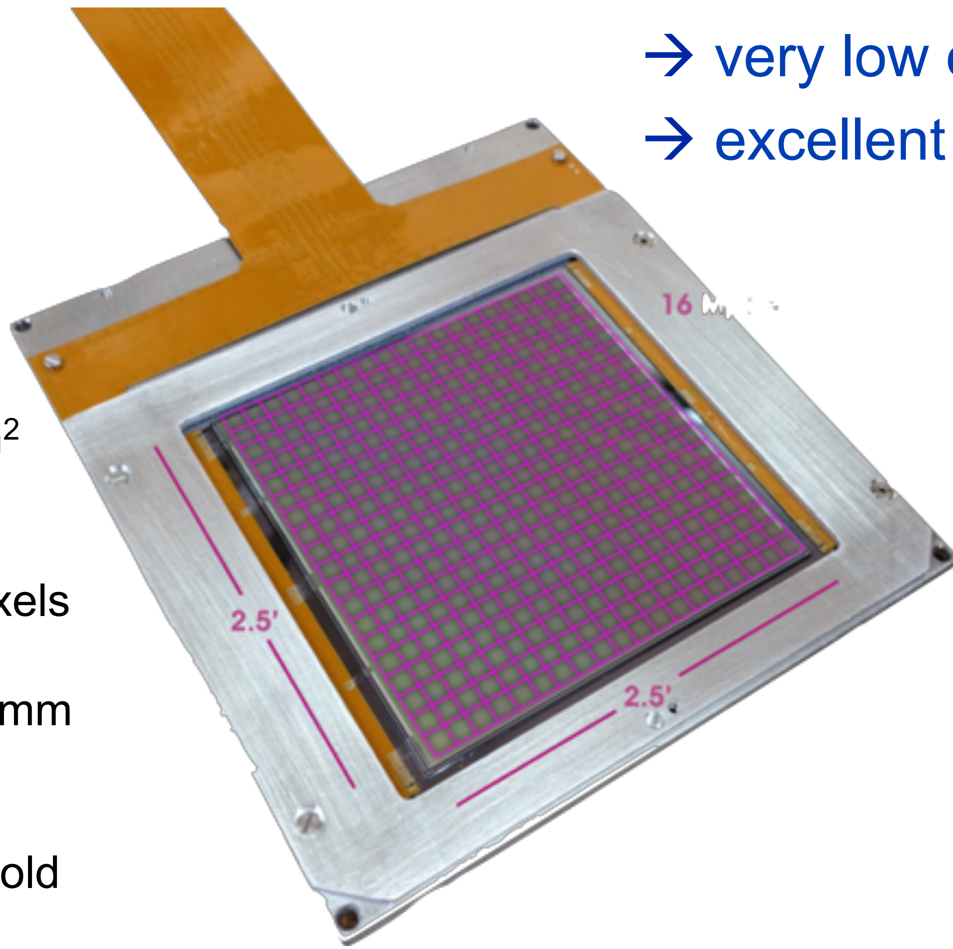
arxiv 1707.06277



DAMIC as an example of low-mass dark matter search experiment

- DAMIC – Dark matter in CCDs
- Use pixelated silicon CCD detectors

→ very low energy threshold
→ excellent spatial resolution



Pixels are 15x15µm^2
Height 650µm

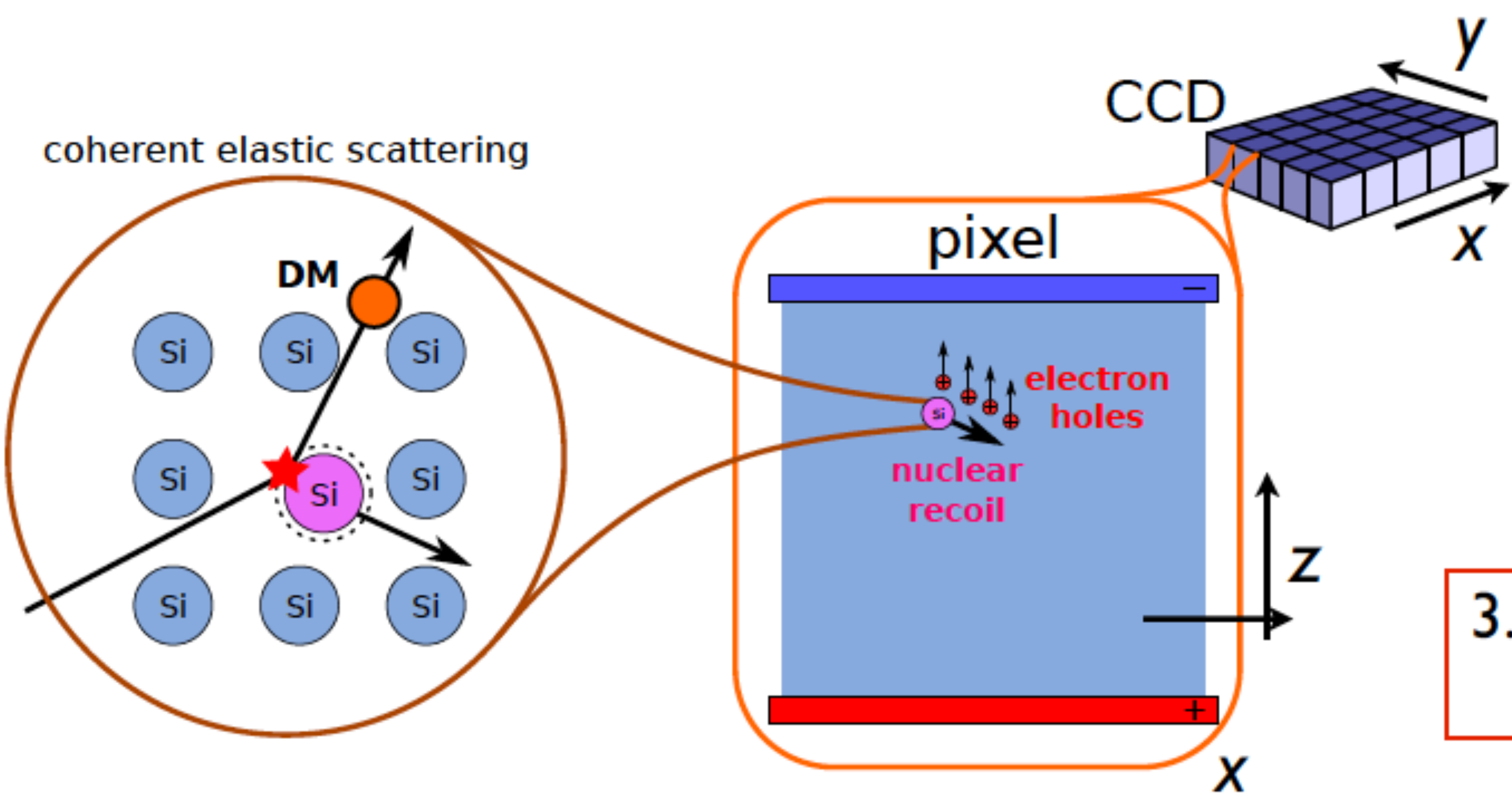
up to 6000x6000 pixels

Size 9cm x 9cm x 1mm
Mass 20g/CCD

35eV energy threshold

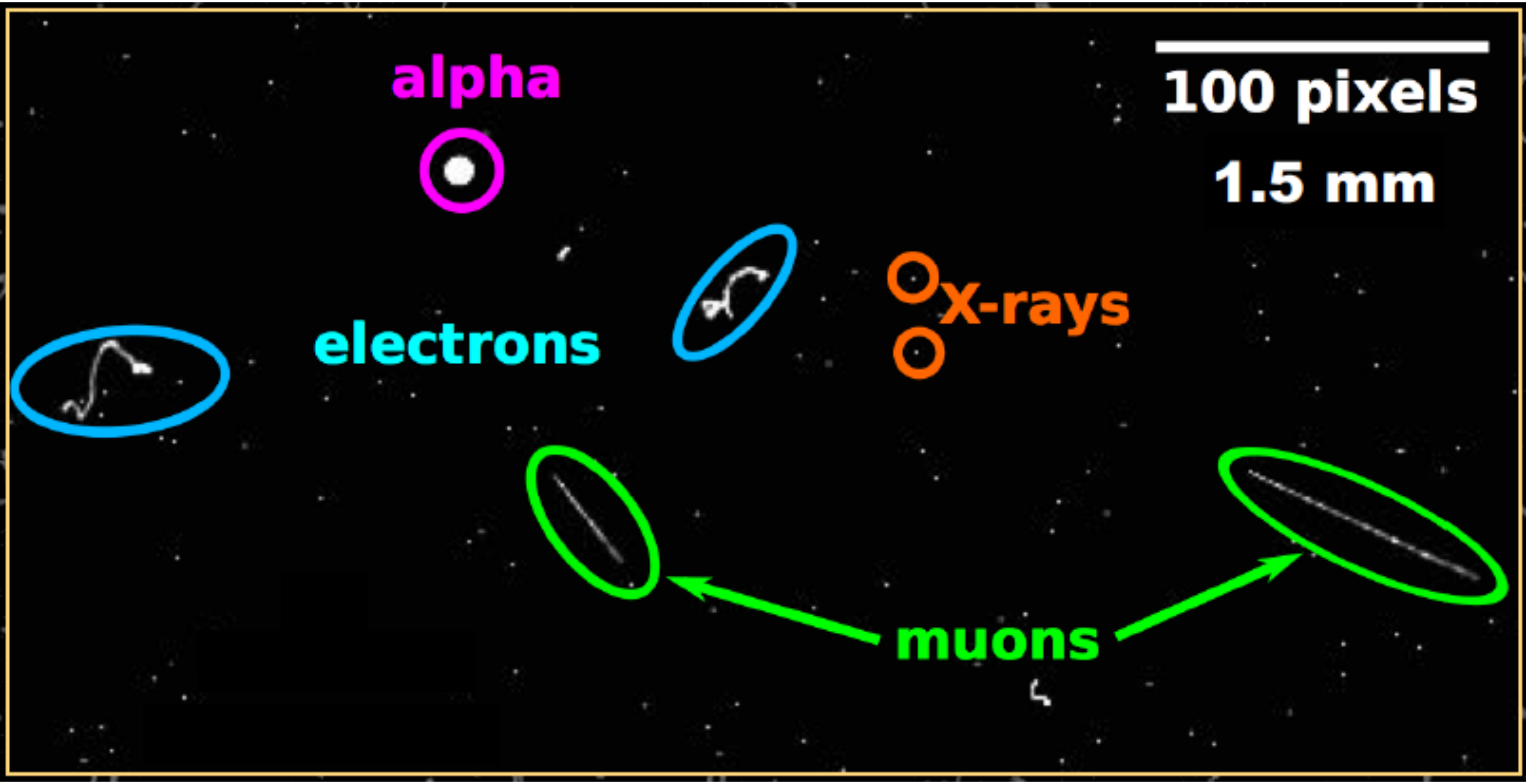
Detecting neutral particles in CCDs

- Neutral particle (dark matter, neutrino, neutron) coherently scatters off nuclei
- Nucleus recoils producing ionization
- Ionization is drifted along electric field, stored on pixels
- To read out charge is shifted from pixel to pixel



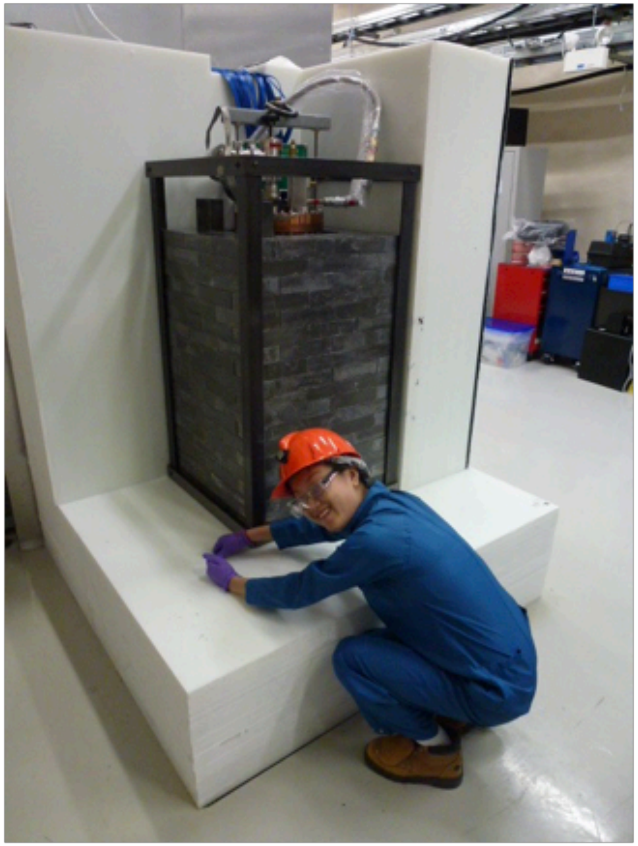
3.62 eV per e & hole

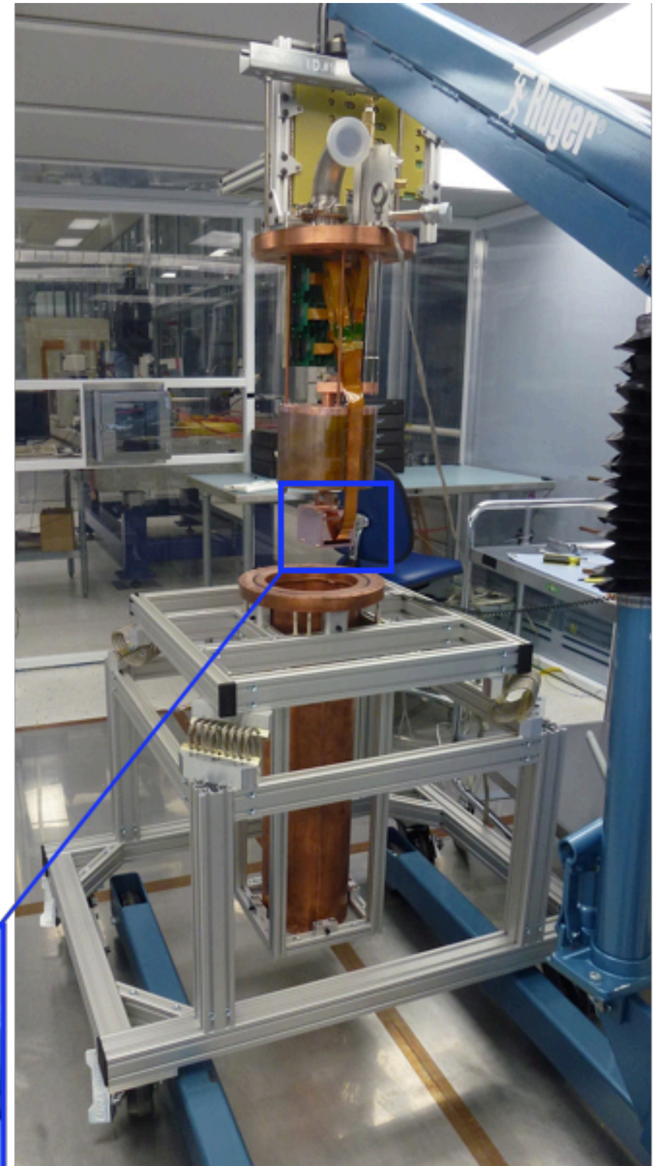
Particle identification in CCD



- Pixel size 15x15μm^2 → single point resolution ~7μm

DAMIC@SNOLAB

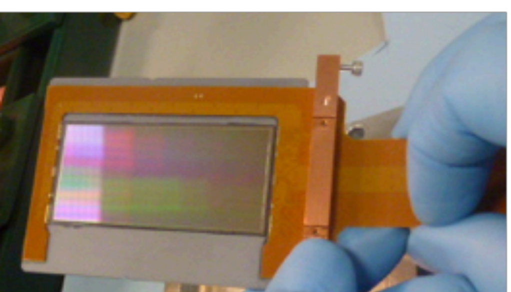


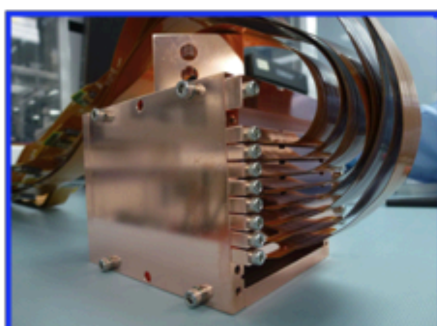


In SNOLAB 6010m water equivalent depth : suppresses cosmics

Currently operating 7 x 6g CCDs = 40g

→ Upgrade and move to Modane ongoing



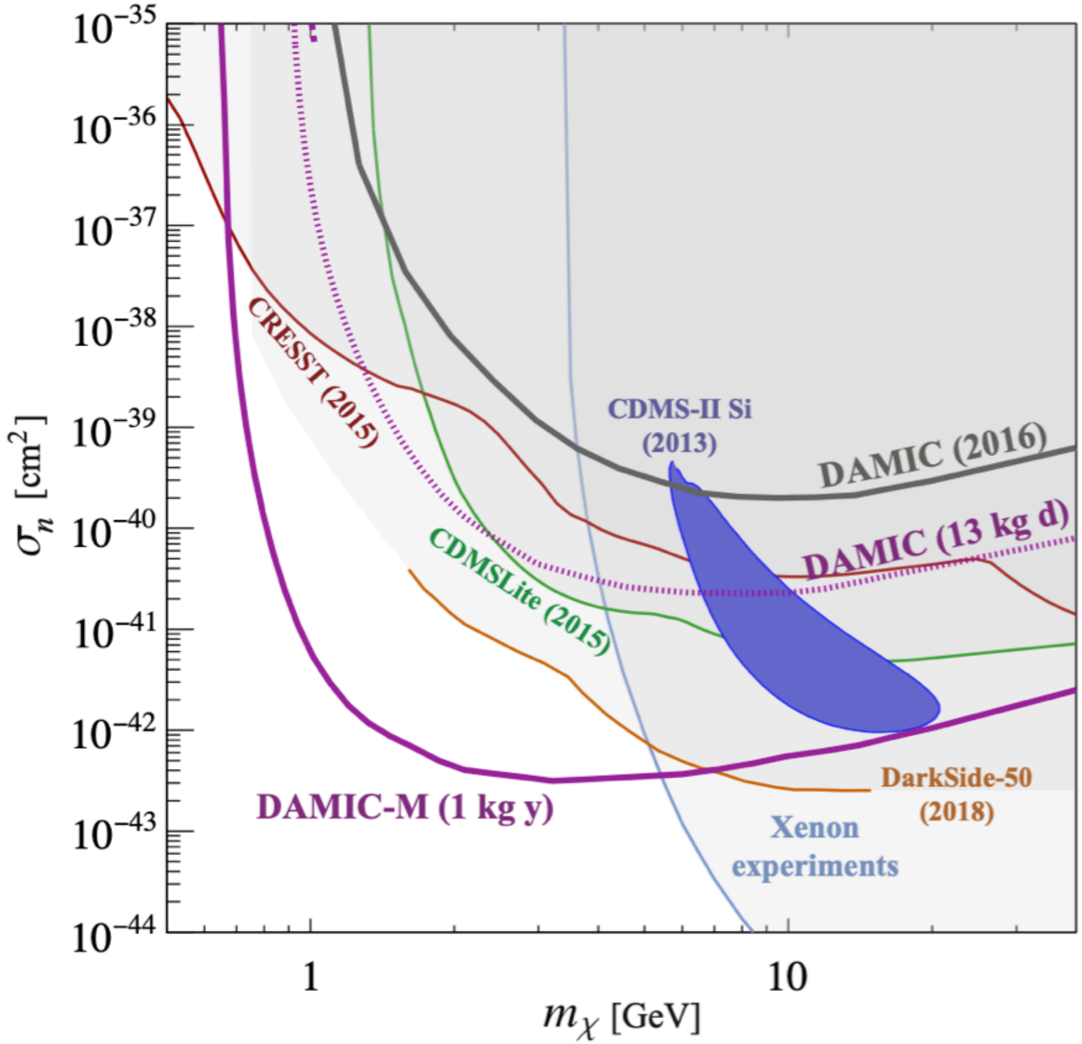


DAMIC results

WIMP nuclear recoil search

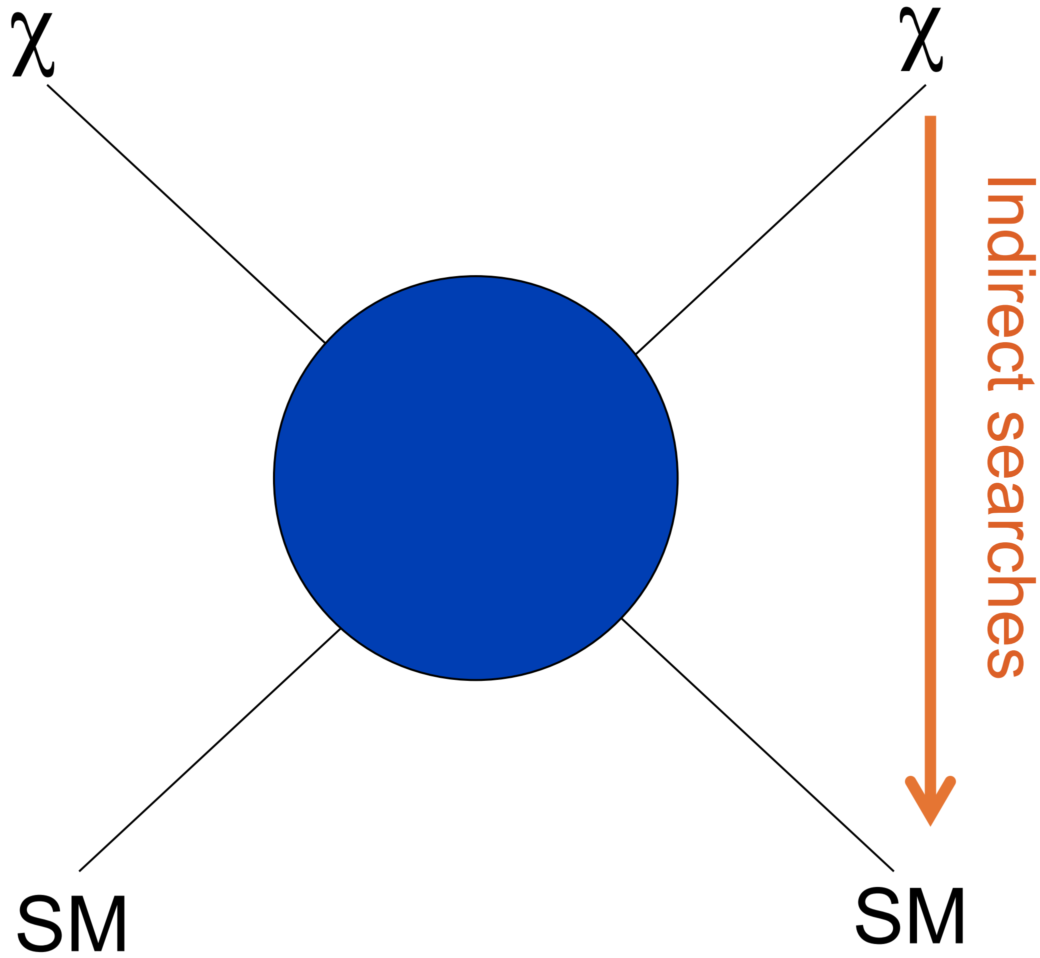
CRESST – Calcium tungstate crystals at cryogenic temperature

CDMS – silicon and germanium detector at cryogenic temperature



- Extends reach of noble gas detectors towards low mass
- Upgrade aims for more mass and lower threshold

WIMP searches



Indirect dark matter searches

Three important components:
dark matter annihilate 'where', into 'what' and it is measured 'how'

- Where? $\rightarrow$ location
  - Galactic center, galactic halo
  - Subhaloes, dwarf spheroidals, the Sun ..
- Into what? $\rightarrow$ particles produced
  - $\chi\chi \rightarrow \gamma\gamma, \gamma Z, \gamma H$
  - $\chi\chi \rightarrow q\overline{q}, W^+W^-$ fragmentation into $\rightarrow e^+e^-, p\overline{p}, \nu$'s
- How measured? $\rightarrow$ detector technology
  - Satellites or balloons measuring charged particles, γ's or X-rays
  - Cherenkov telescopes and large neutrino observatories

Expected particle flux

$$\frac{d\Phi_p}{dE} = \underbrace{\frac{<\sigma_A v>}{4\pi 2 m_\chi^2} \cdot \frac{dN_p}{dE}}_{\text{PPP}} \cdot \underbrace{J(\Delta\Omega)}_{\text{APP}}$$

$<\sigma_A v>$: thermally averaged cross-section

m_χ: dark matter particle mass

$\frac{dN_p}{dE}$: differential particle yield per annihilation

$J(\Delta\Omega)$: Integral over the dark matter density

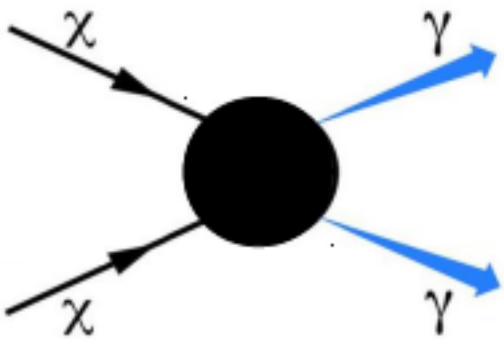
- Particle physics part (PPP): Model for dark matter particle (spin, mass) → cross section, branching ratio and energy distribution for a given final state particle.
- Astrophysical part (APP): Density of dark matter particle at production site (halo model, galactic center, sun)
- Predictions can vary by orders of magnitudes

  → absence of signal cannot be directly converted to a useful limit for particle physics parameters

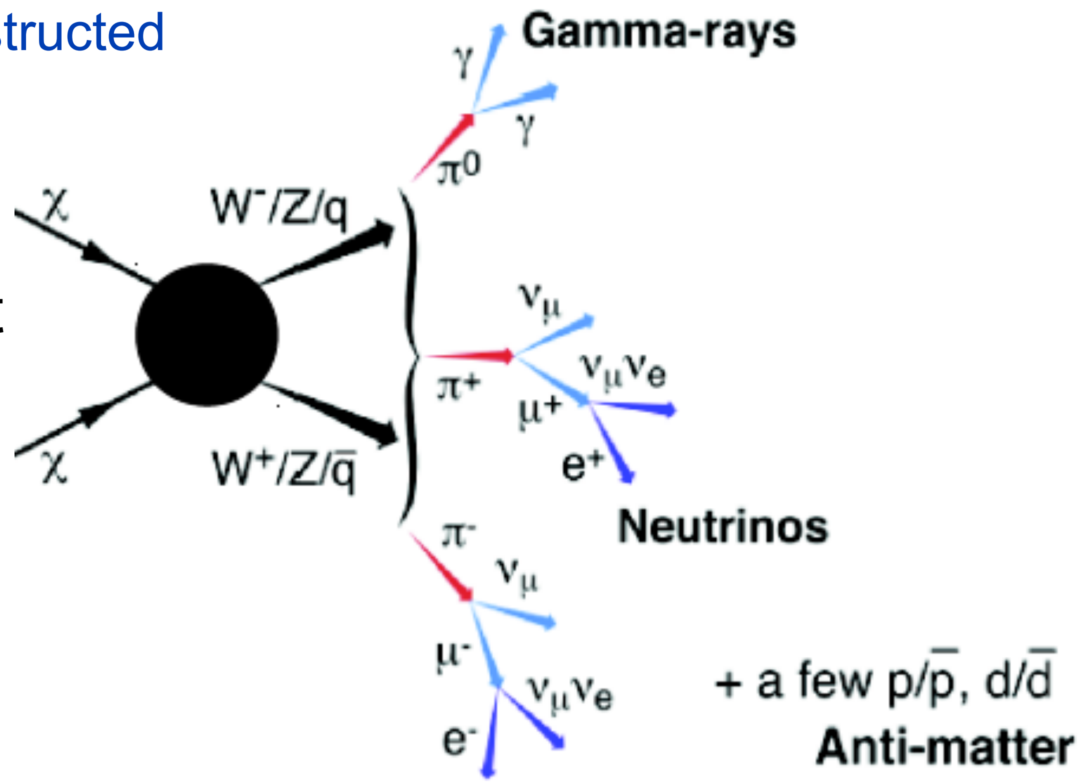
  → if signal is claimed to be found, will need some distinctive feature (e.g. energy or angular distribution) and cross-correlation with different detection method

Particles

- Annihilation to γγ (γH, γZ):
- Two-body decay
  > fixed photon energy
  > Resonance line in energy spectrum
  > Clear signature
  > WIMP mass can be reconstructed



- Annihilation to other SM particles
- Decay chain into different particles (photons, electrons/positrons, neutrinos, protons/ antiprotons)
  > broad energy distribution
  > only partial reconstruction



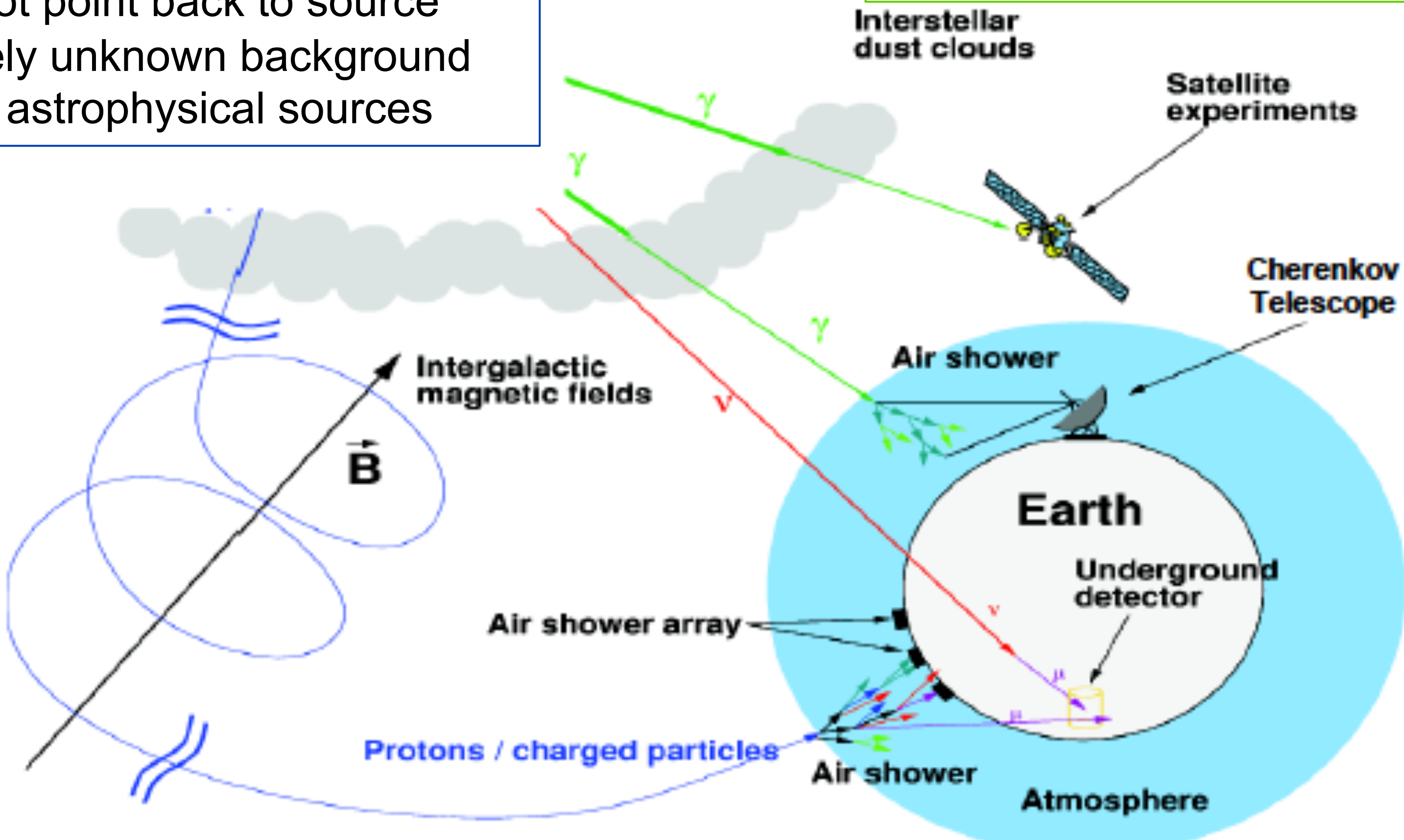
Particle detection

e^+, $\bar{p}$

- get deviated (and trapped) in intergalactic magnetic field
- do not point back to source
- largely unknown background from astrophysical sources

γ

- point back to source
- loose energy by Compton scattering and pair production
- large background from astrophysical sources



ν

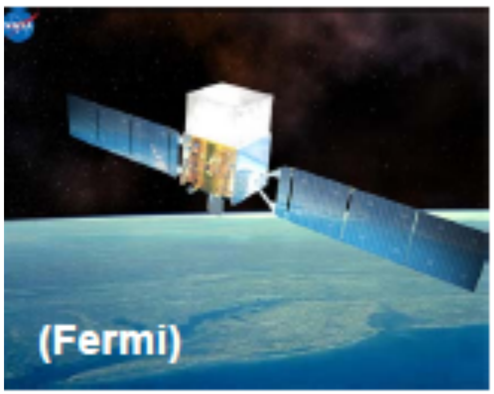
- point back to source
- very little interaction
- difficult to detect, large background from atmospheric ν

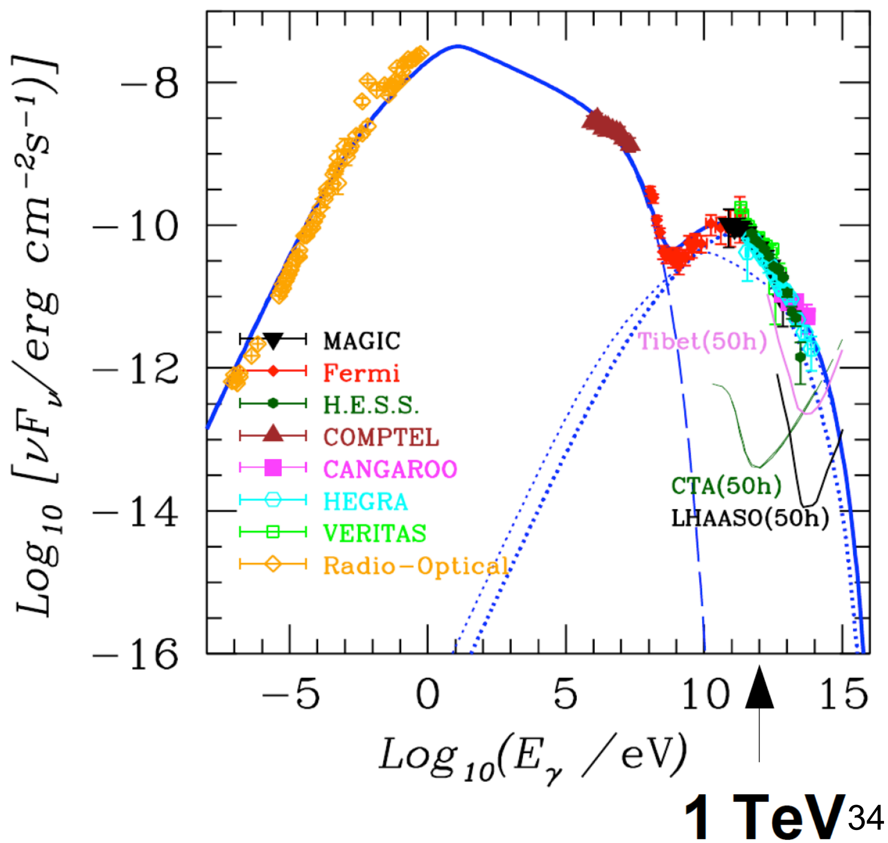
Gamma rays: Experiments

- Atmosphere is opaque for gamma rays

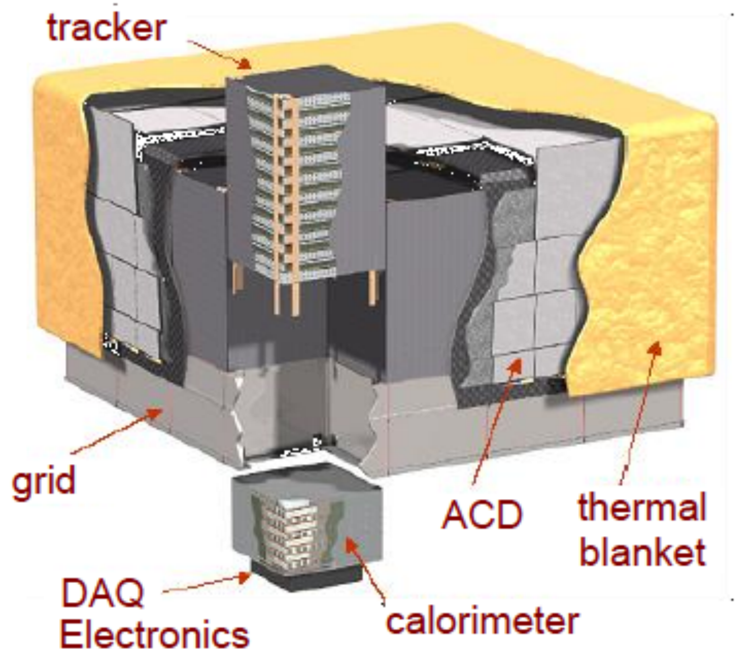
→ up to Eγ ≈ 300 GeV direct detection in balloon or satellite experiments above atmosphere

→ for higher energies: detection of air-showers in ground detector arrays or Cherenkov telescopes (more in Alison Mitchell's lecture)



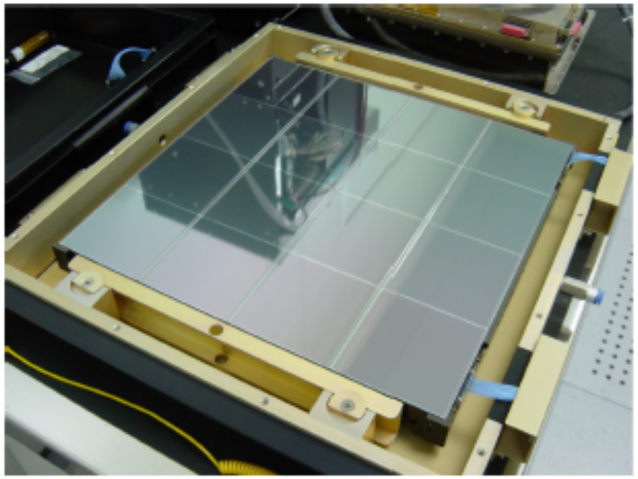


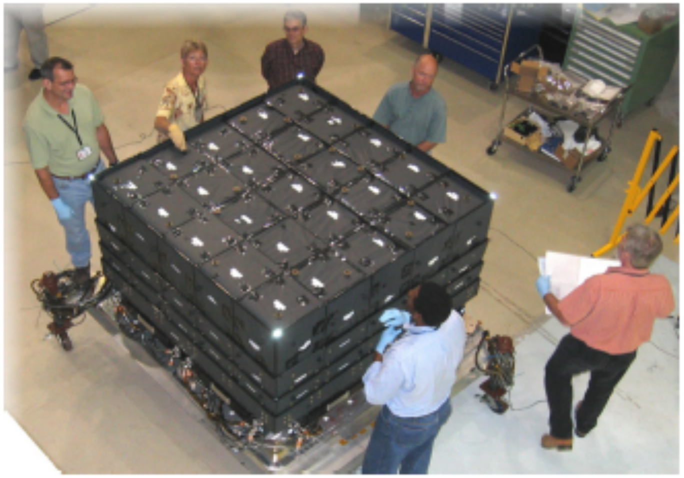
FERMI-Large Angle Tracker (LAT)



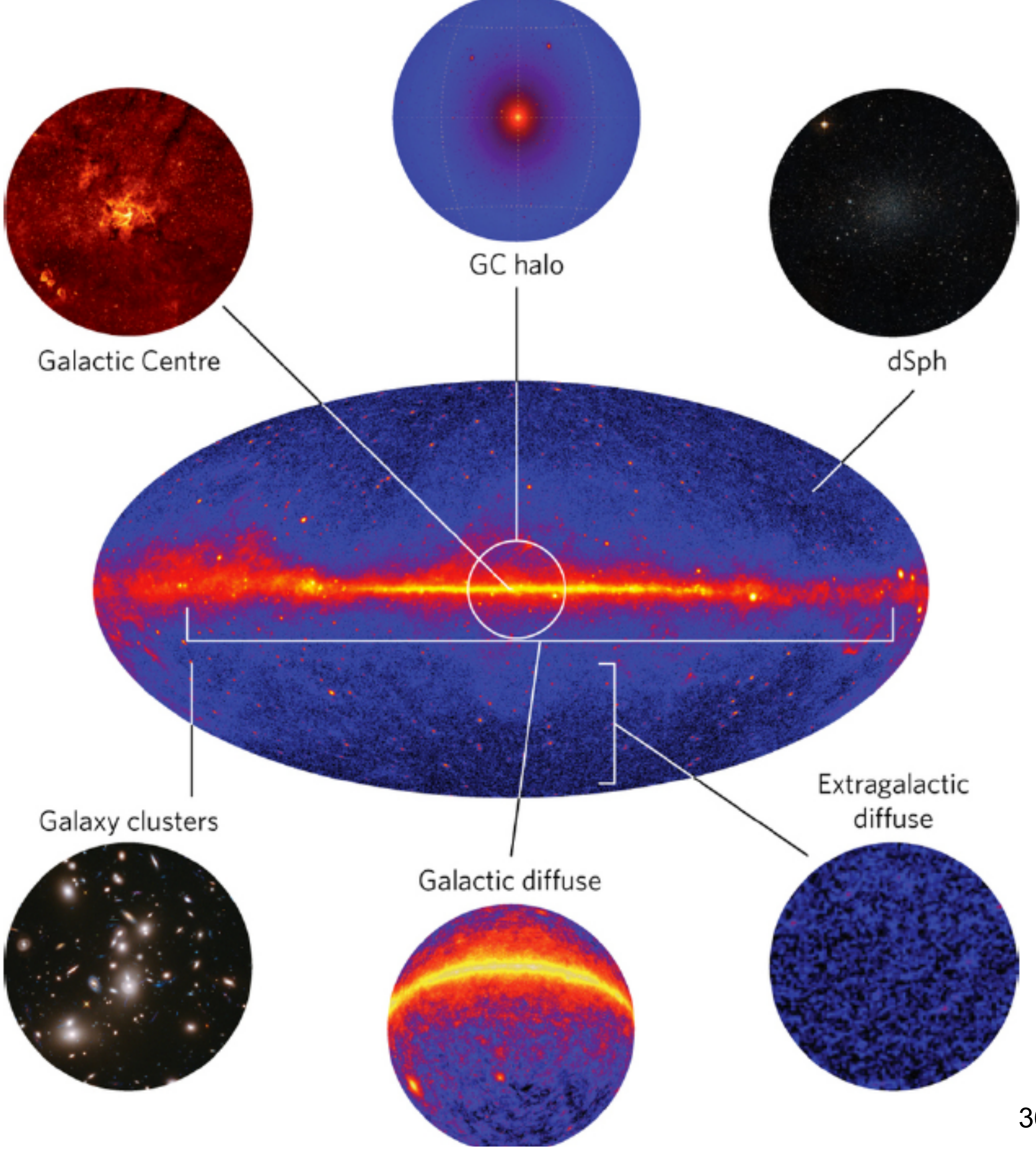
Launched in 2008

- **tungsten converter foils and silicon micro-strip detectors**
- **segmented CsI(Tl) calorimeter**
- **energy range 20 – 300 GeV**
- **effective detection area 0.8 m²**
- **large field of view (2.4 sr)**



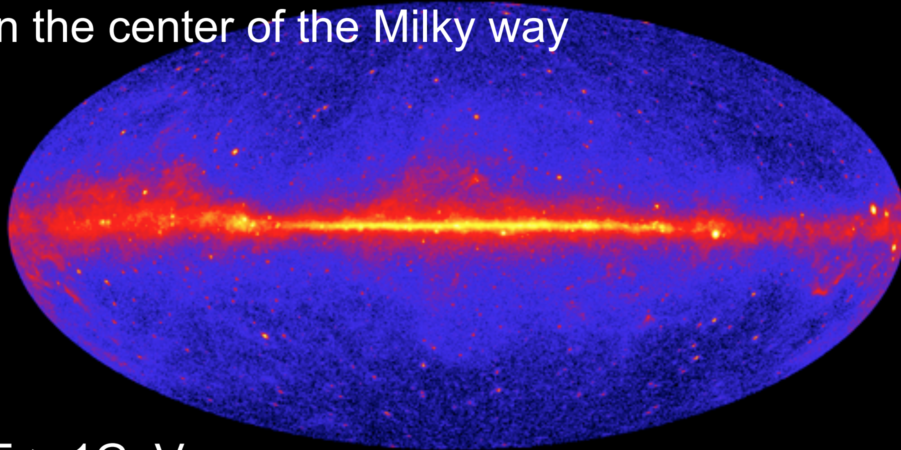


Targets for FERMI-LAT dark matter gamma-ray searches



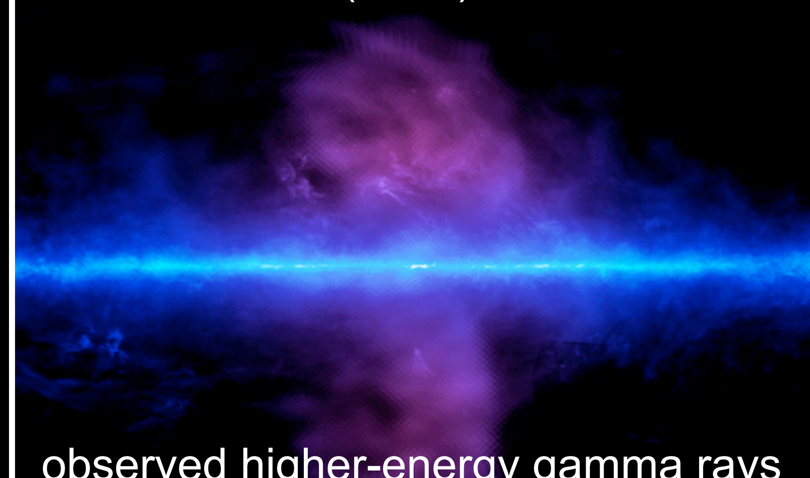
Some gamma-ray anomalies

Galactic center excess (2009-2013)
in the center of the Milky way



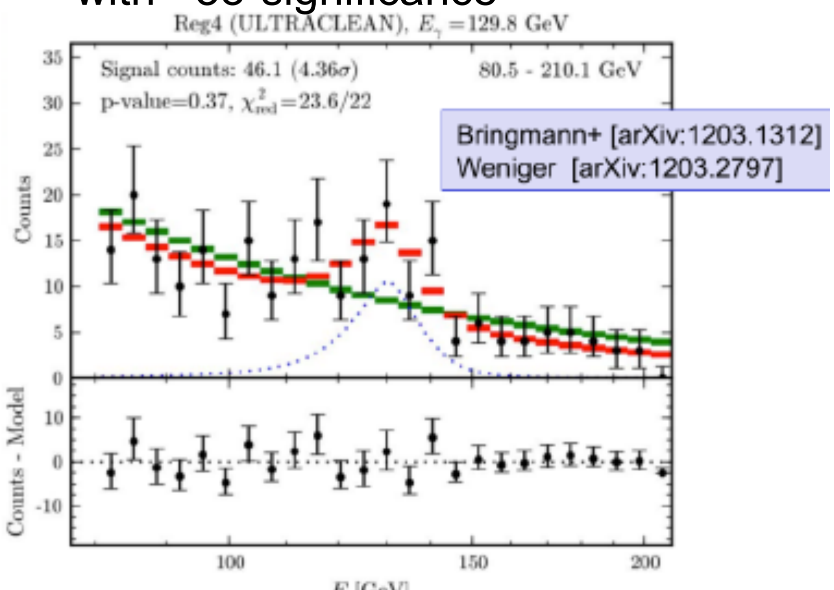
E_γ> 1GeV

Fermi bubbles (2010)

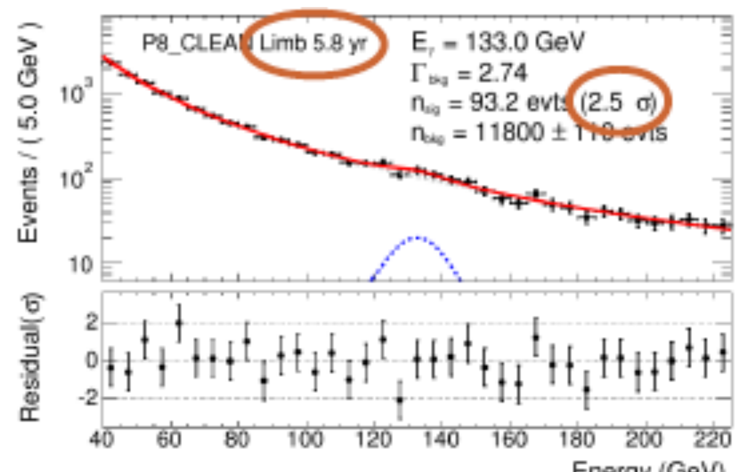


observed higher-energy gamma rays in Fermi bubbles compared to Milky Way galactic disk

Line signal at ~ 130 GeV (2012)
with >3σ significance

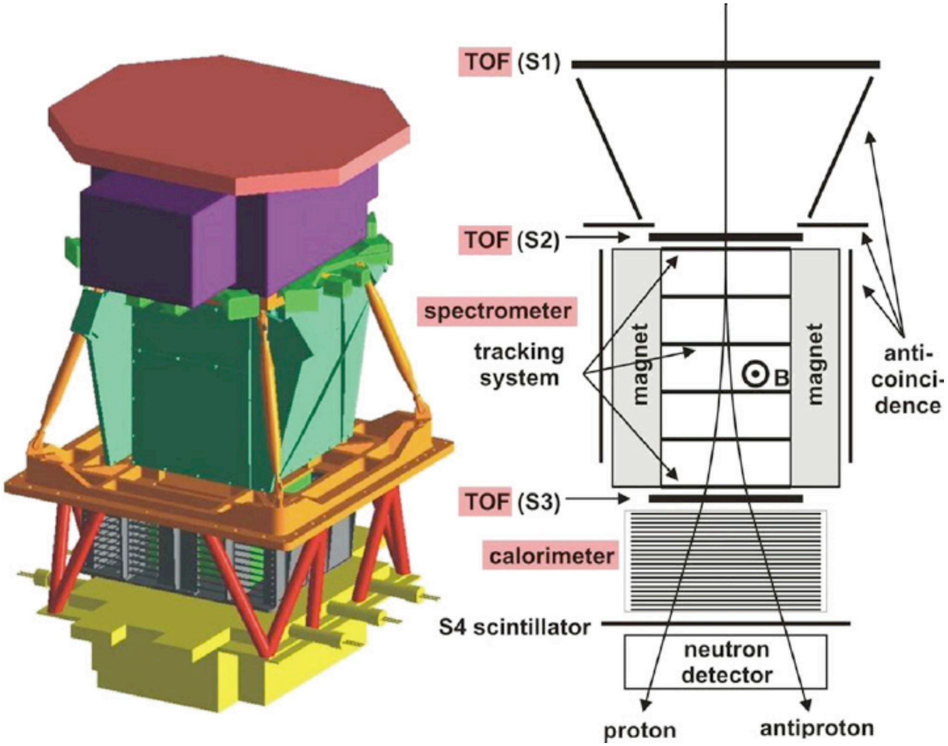


With more data found to be due to statistical fluctuation

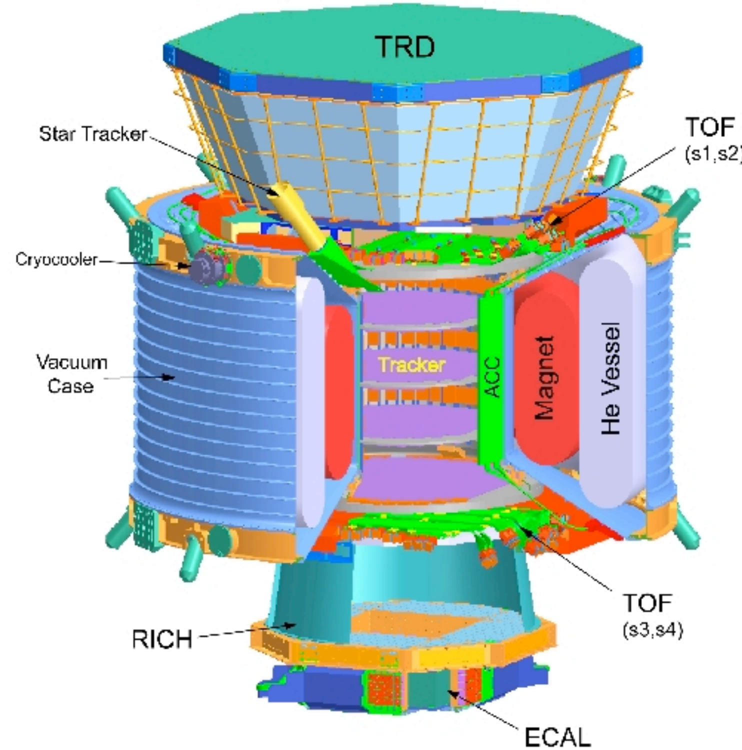


Charged particle experiments

PAMELA (2006-2016)



AMS-02 (since 2011)



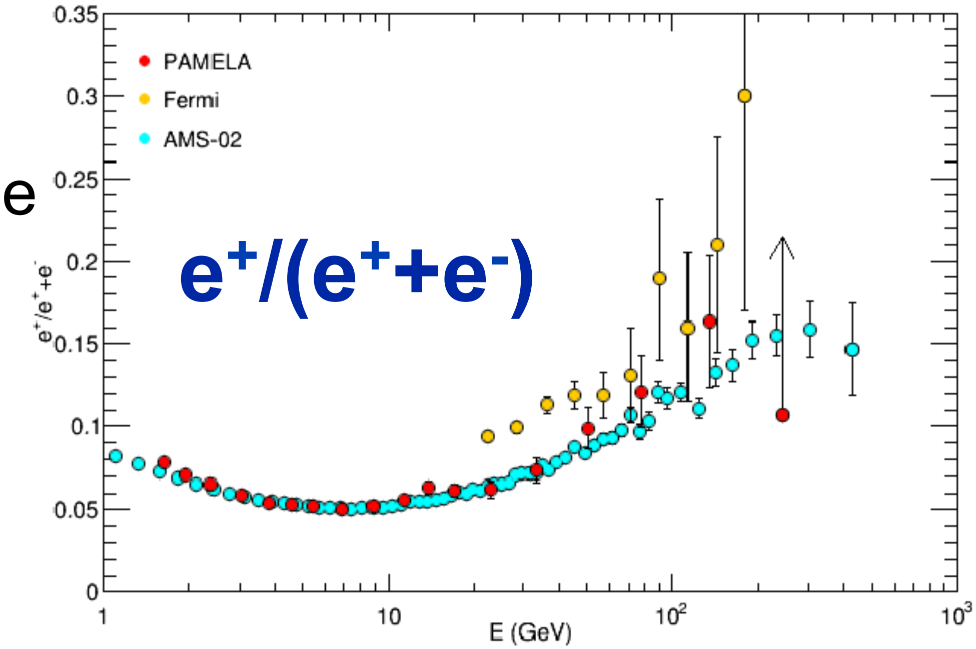
- Time-of-flight (TOF) → velocity
- Silicon microstrip tracker in permanent magnet → momentum, charge, dE/dx
- Calorimeter, scintillators & neutron detector → discriminate leptons and hadrons

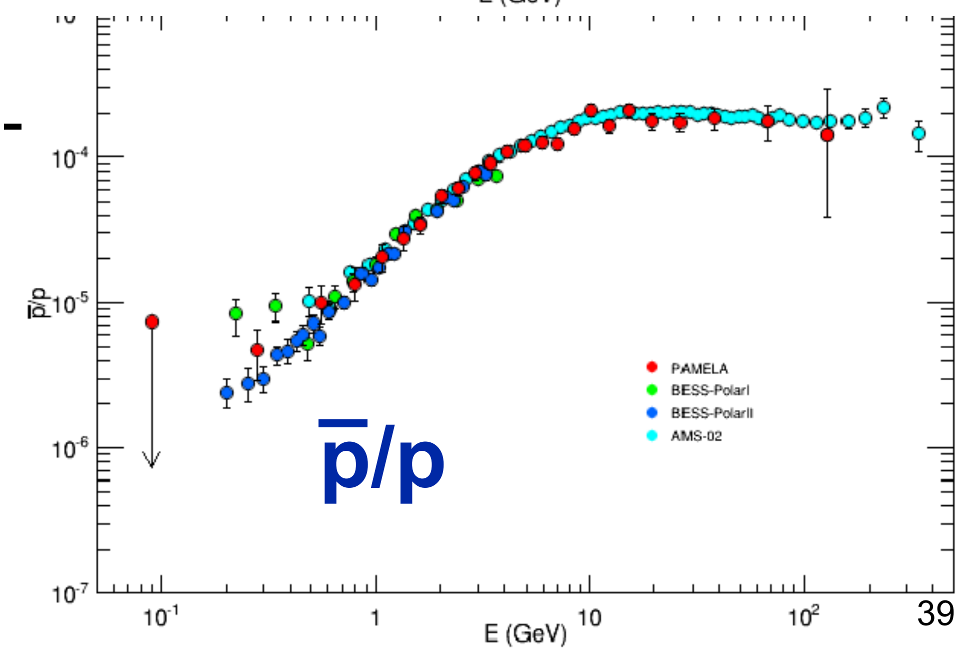
- TOF, silicon strip tracker, calorimeter together with Transition radiation detector (TRD) and Ring Imaging Cherenkov (RICH) detector for improved e/p separation

Observed e^+/e and $\bar{p}/p$ ratios

arvix:1801.10310

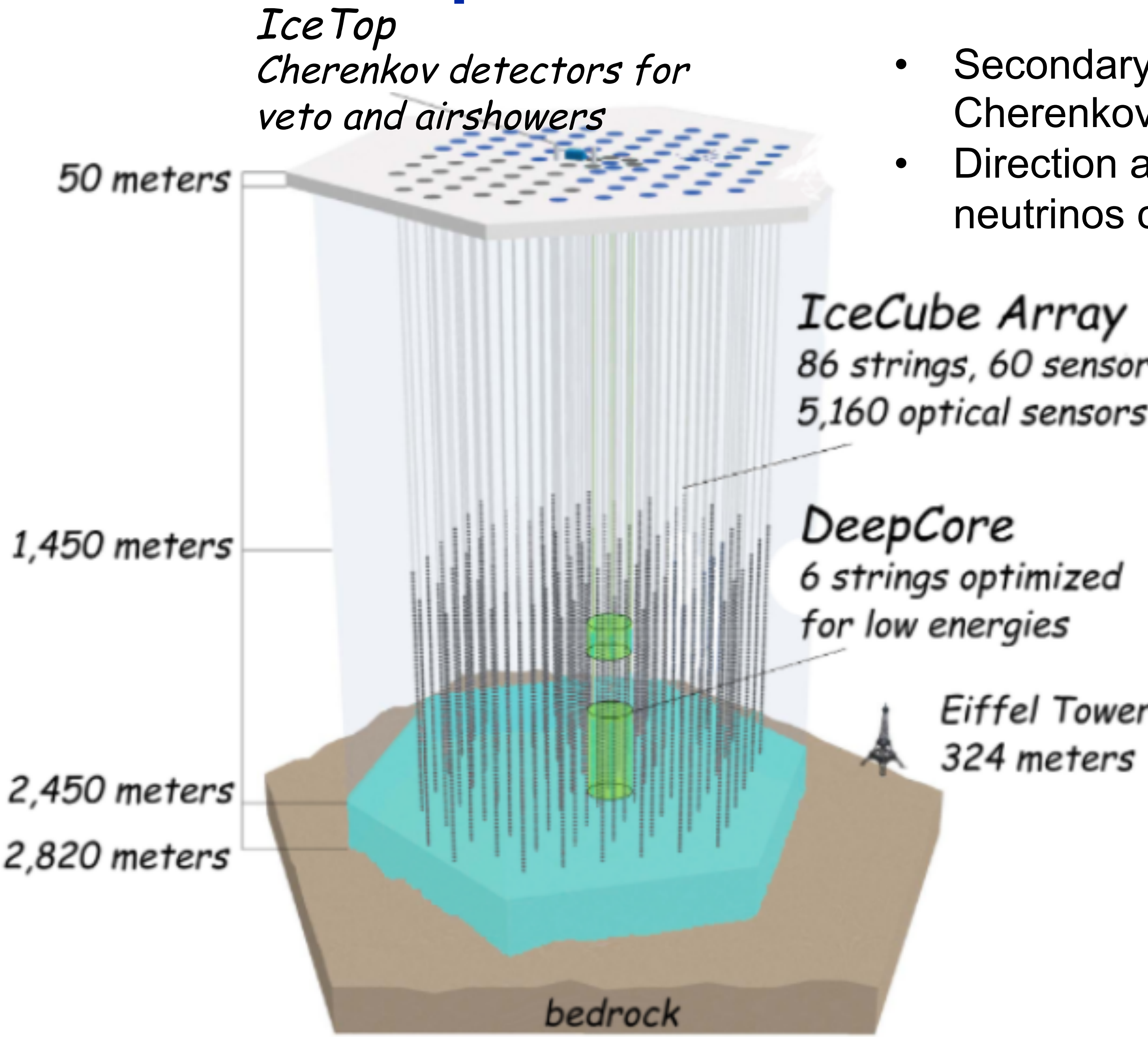
- Unexpected rise in the positron-to-electron ratio at energies above 10 GeV for the first time observed by PAMELA, confirmed by Fermi and AMS-02
- Cannot be explained by production of secondaries → new sources? Dark matter?
- No excess observed in proton-antiproton ration (would be expected for dark matter origin)
- do more measurement → extended energy range, angular dependence, ...





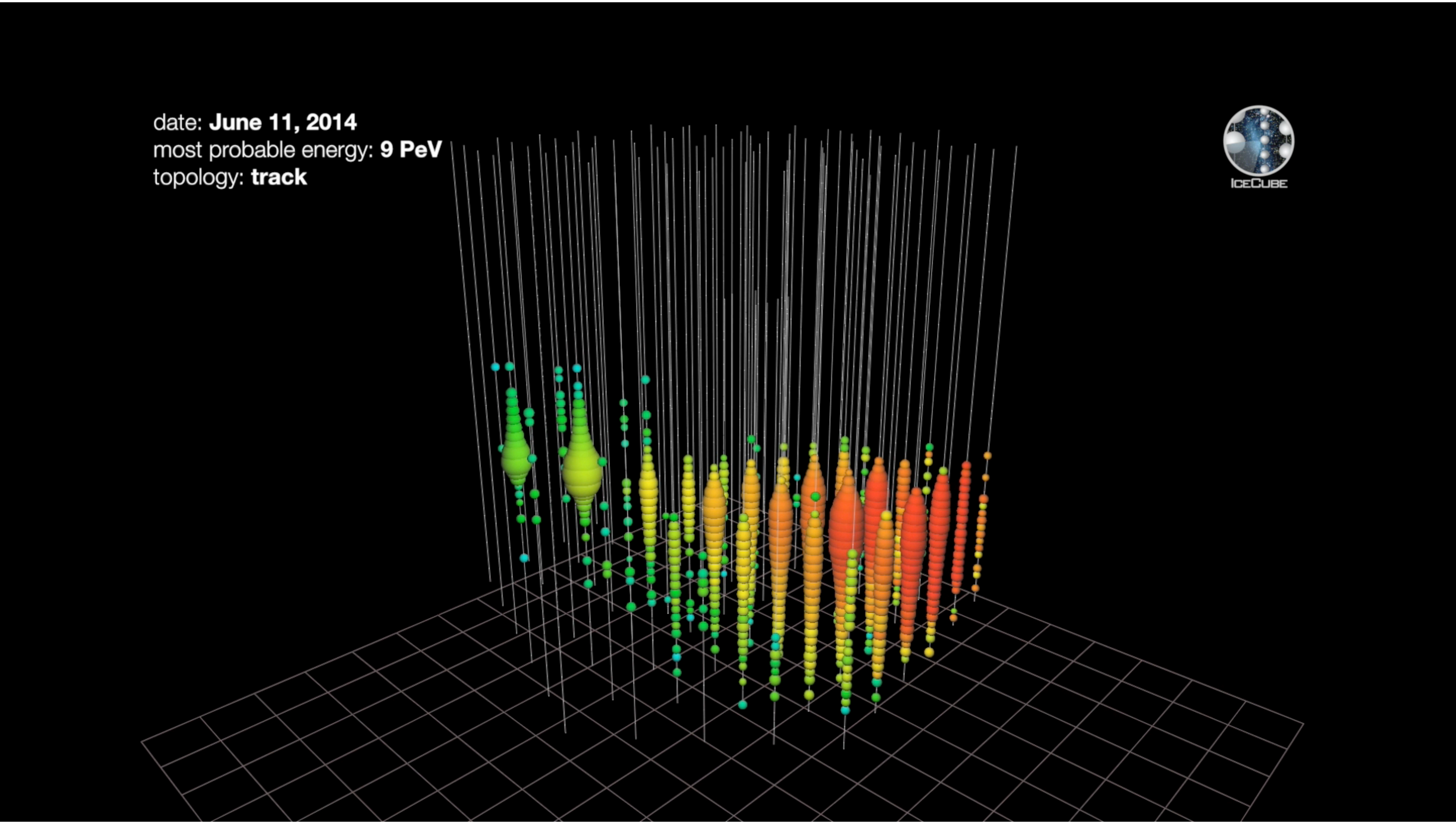
Neutrino experiment: ICE Cube

- Secondary particles create Cherenkov radiation in ice
- Direction and energy of neutrinos can be reconstructed



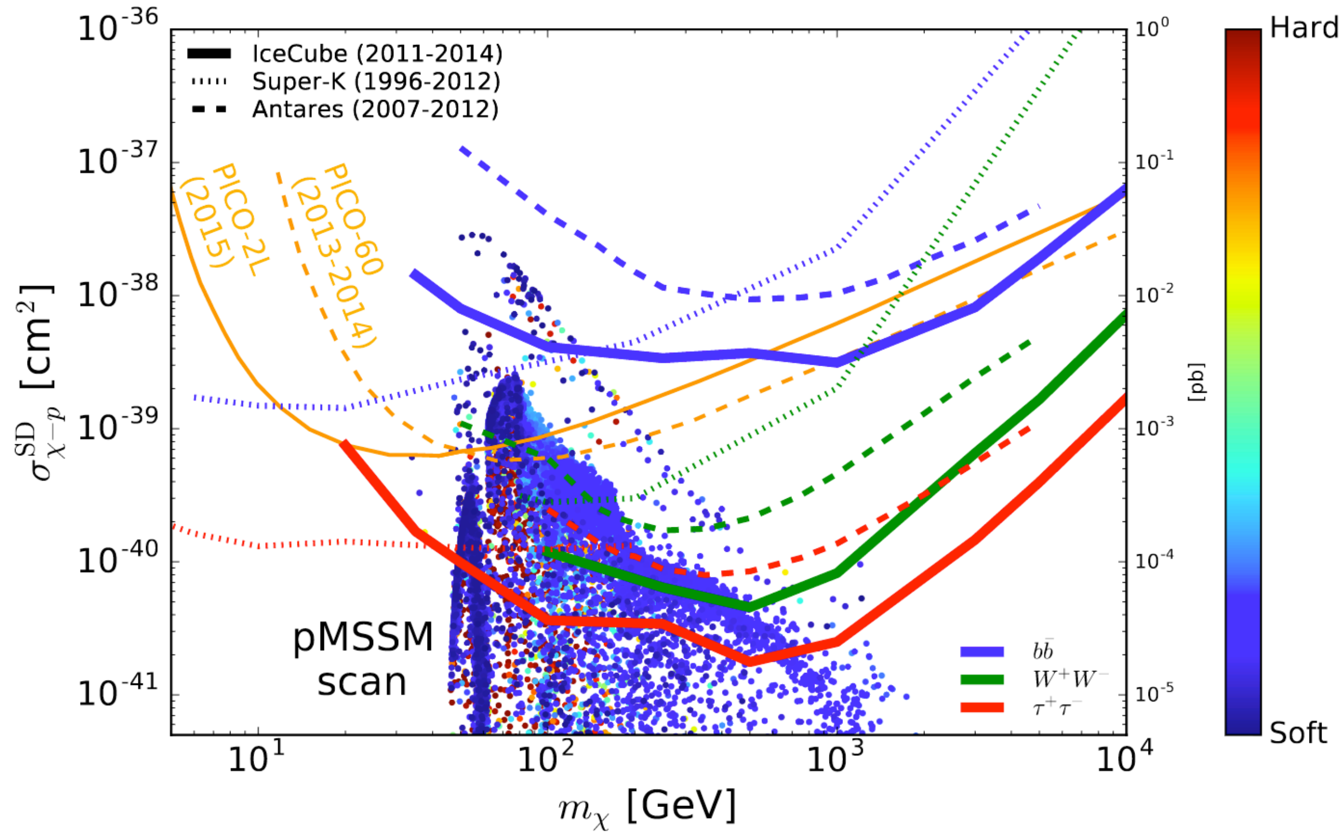
Optical module
PMT

up-going muon track from muon neutrino (9 PeV)

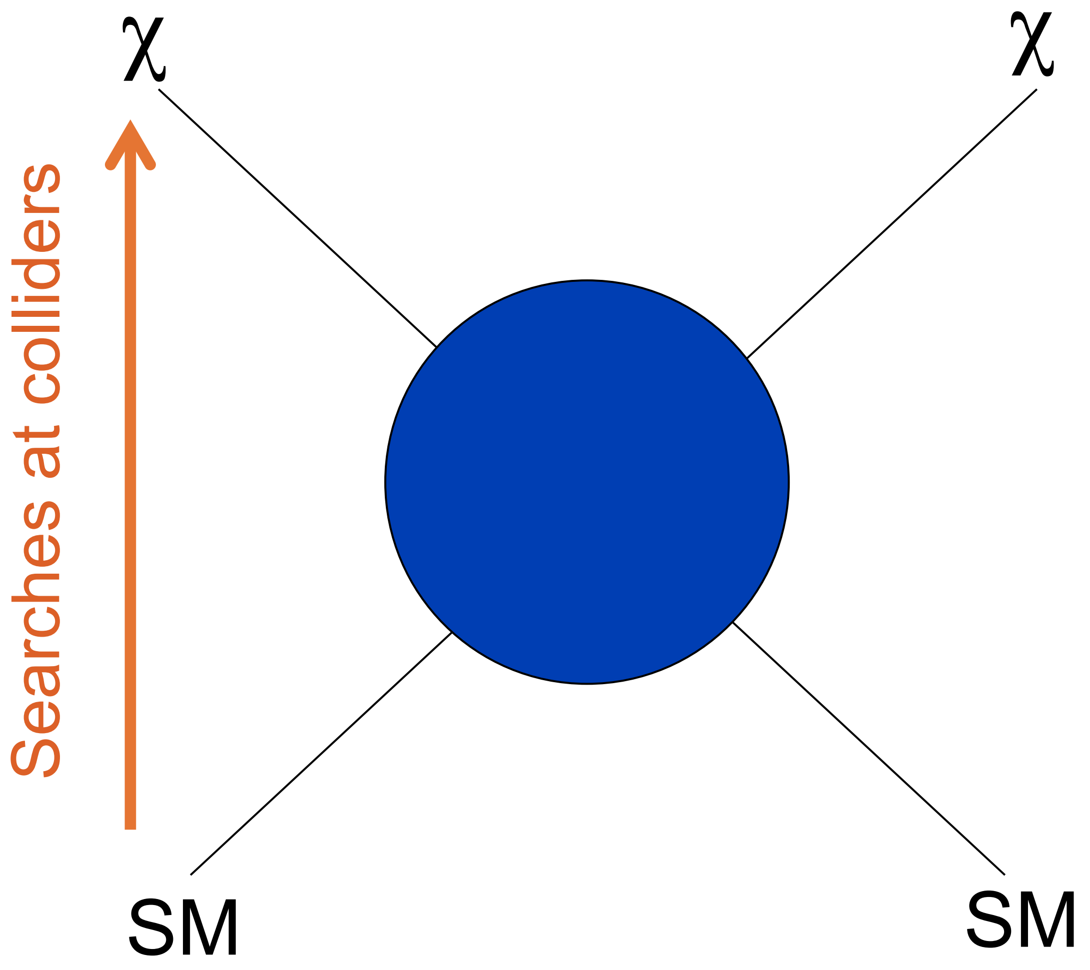


Dark matter at IceCube

- Exploit measurement of direction to study different locations (center of the earth, center of the sun, center of the galaxy)
- e.g search for neutrinos produced as a result of the annihilation of dark matter particles gravitationally trapped by the sun → very stringent limits obtained

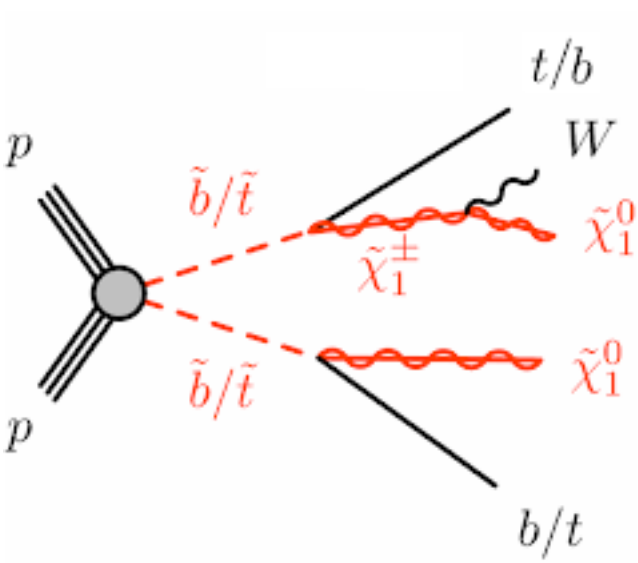


WIMP searches



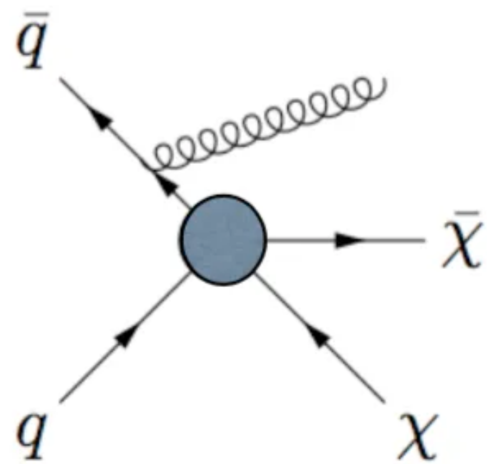
Dark matter particle production at LHC

SUSY PARTICLE DECAYS



MET + X

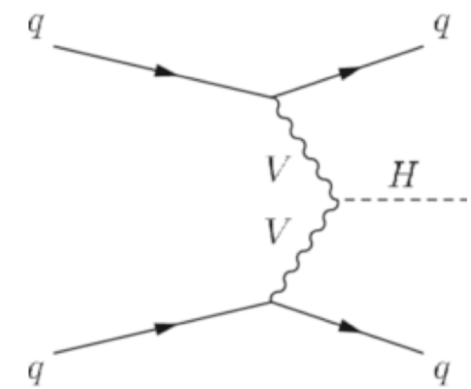
DIRECT PRODUCTION via NEW MEDIATORS

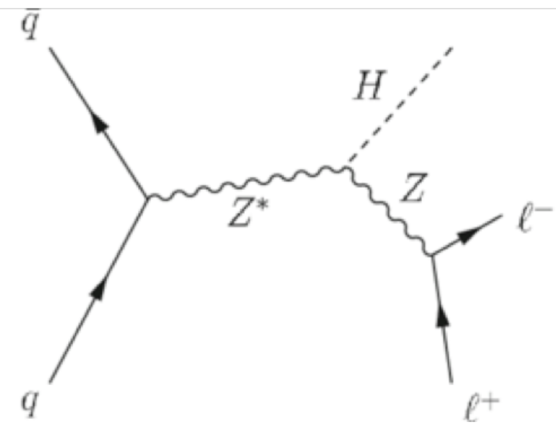


monojet +MET

or
γ+MET,
Z+MET,
bb + MET,
tt + MET, ...

HIGGS BOSON INVISIBLE DECAYS

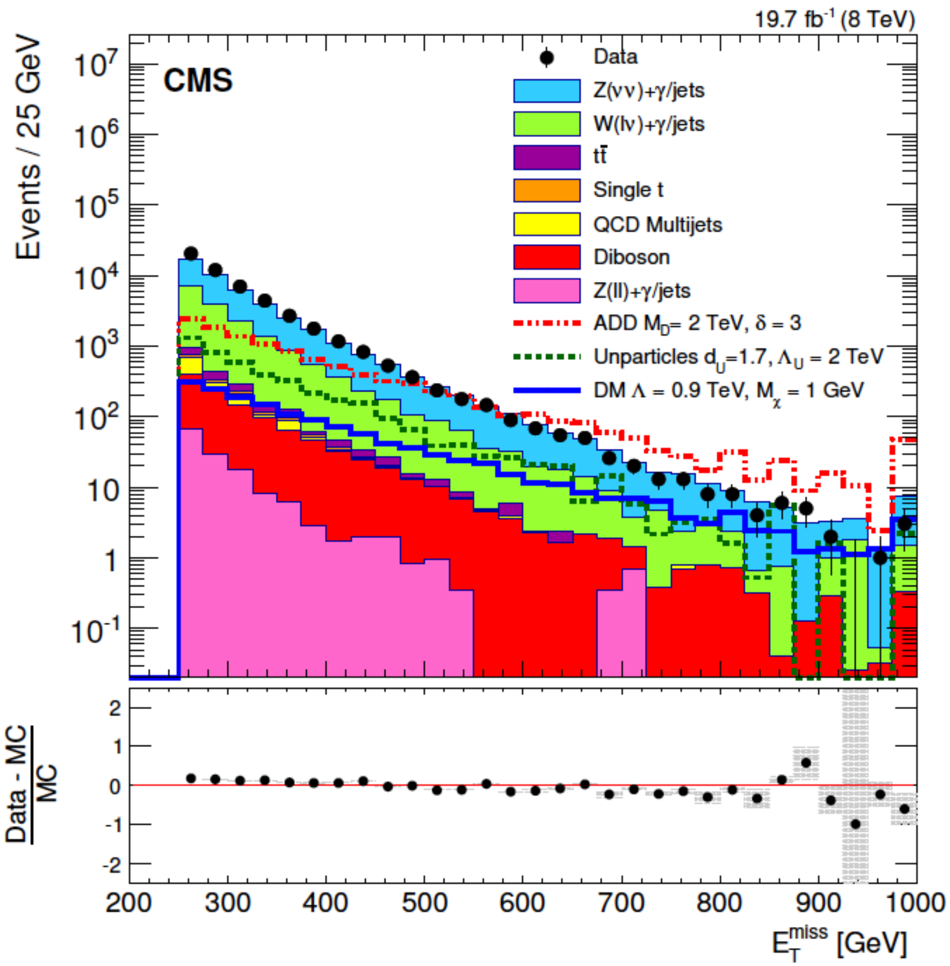


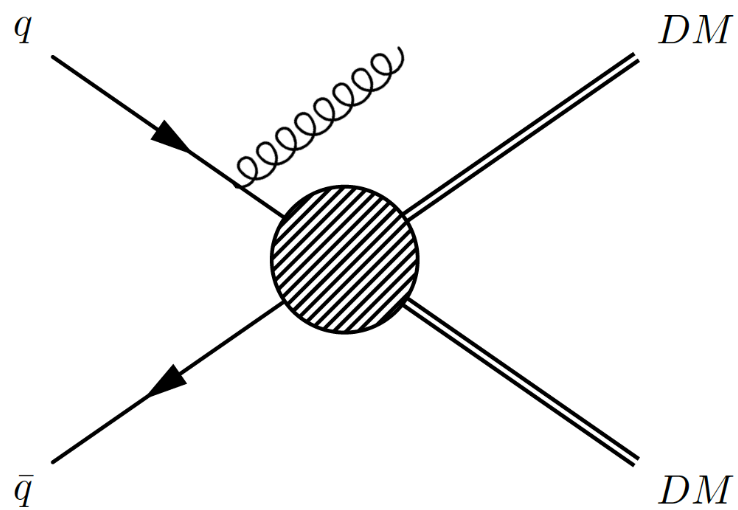


VBF or associated Higgs boson production

CMS result example

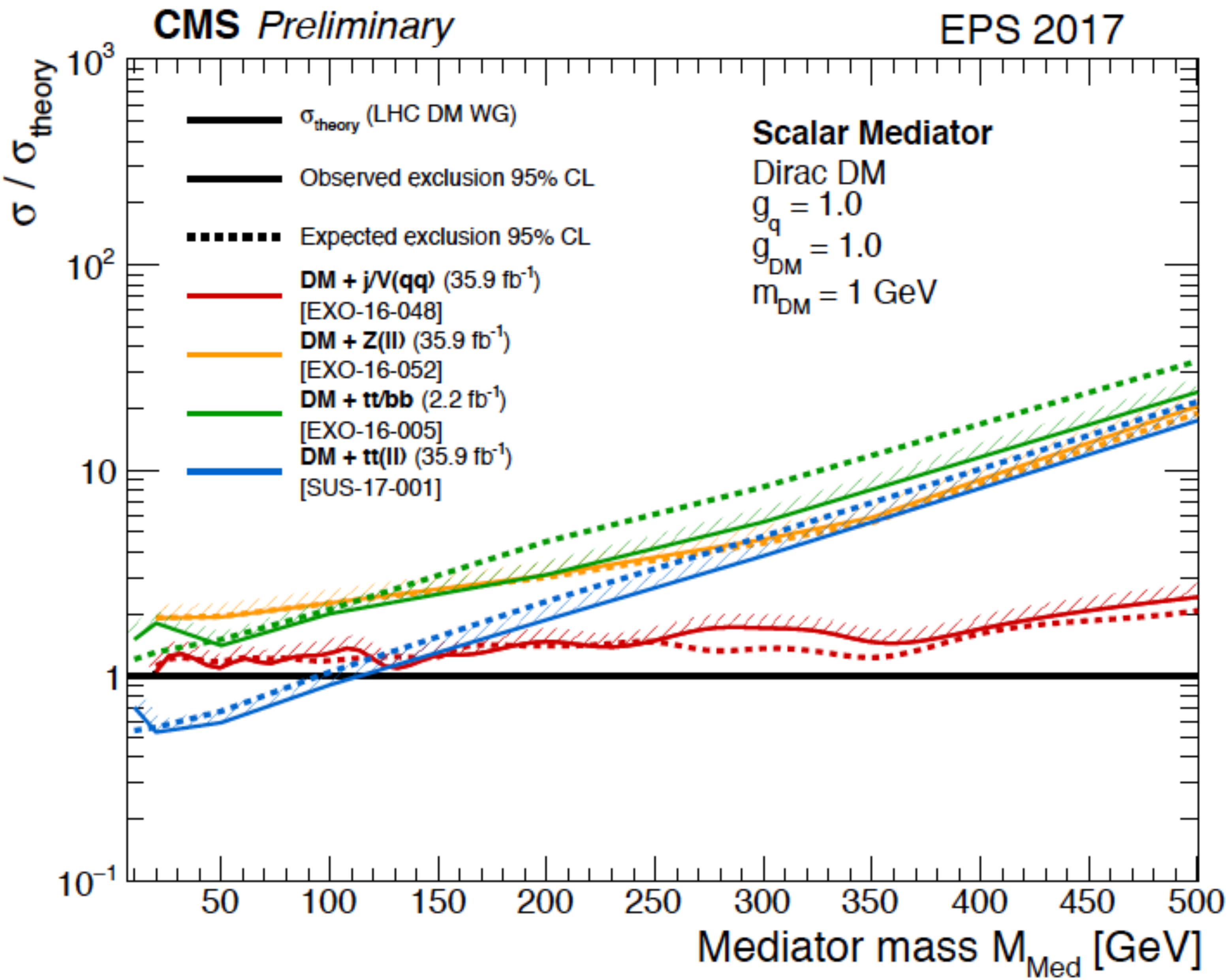
- Dark matter search for monojets with 8 TeV data





- Dark matter would lead to excess at large MET values
- Allows to set limits dependent of dark matter and mediator mass
- Comparison to direct detection is model dependent

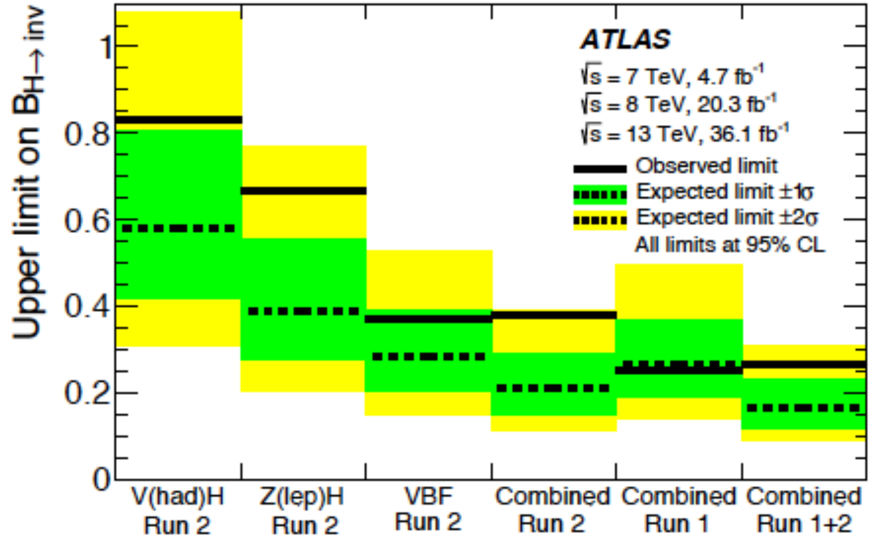
Example of limits for dark matter model

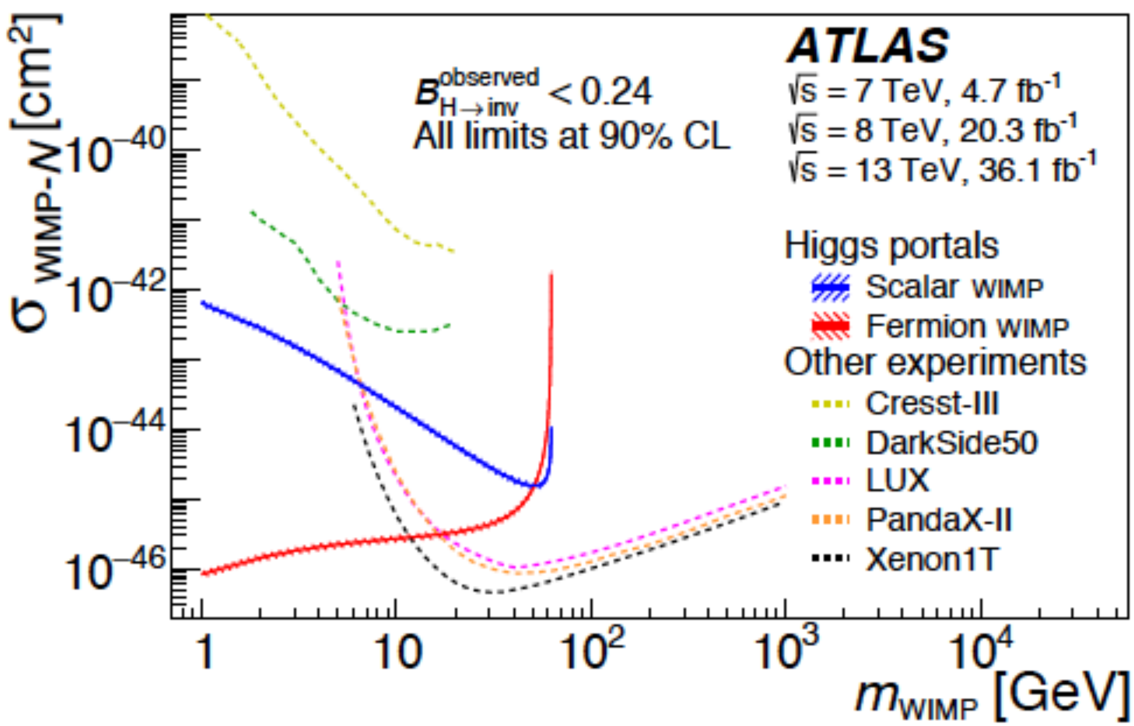


Invisible Higgs decays

arxiv 1904.05105

- Dark matter particles can be produced in the decay of the Higgs boson if they are sufficiently light
- Search for invisible Higgs boson decays performed in different production mechanisms
- Expand reach of direct searches at low mass (again comparison is model dependent)





Summary

- Complementary search strategy for dark matter pursuing direct searches, indirect searches and searches at colliders
- So far no convincing experimental evidence for dark matter particles
- Upgrades and new experiments being prepared and planned
- Expect significant improvements in sensitivity in the coming years

References

- Lecture includes material prepared by L. Baudis, F. Calore, M. Galloway, B. Kilminster, A. Kish, T. Marrodan Undagoitia, O. Steinkamp

Backup