Cosmic Ray detection in ground-based and satellite experiments

Dr. Alison Mitchell, 25th March 2020

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Y36 J94

Brief Introduction

Alison Mitchell

Postdoc at UZH since 2018,

previously postdoc at MPIK Heidelberg and
Assistant Project Scientist for CTA,
PhD Heidelberg University 2016,
Undergraduate Warwick University 2013

Research activities:
gamma-ray astronomy and cosmic ray physics with H.E.S.S. and CTA

(Imaging Atmospheric Cherenkov Technique)

Particle acceleration in pulsar wind nebulae

Properties of muons in extensive air showers

Telescope calibration

Outline

- Cosmic Ray power and energy density in the Milky Way
- Hillas Criterion and plausible Cosmic Ray sources
- Diffusion Loss equation
- Inverse Compton scattering, Synchrotron radiation, pion decay
- Search for Galactic PeVatrons
- Cherenkov detection techniques for Air Showers
- Current experiments: H.E.S.S., CTA, HAWC
- Satellites: Fermi-LAT and AMS-02

Cosmic Ray Spectrum

Power law over many orders of magnitude: ~30 in flux, ~ 10 in energy

Key features:

Solar modulation, “Knee”, “Ankle”, GZK effect

Galactic Cosmic Ray energy density:
ε_{CR} ~ 1 eV /cm^3

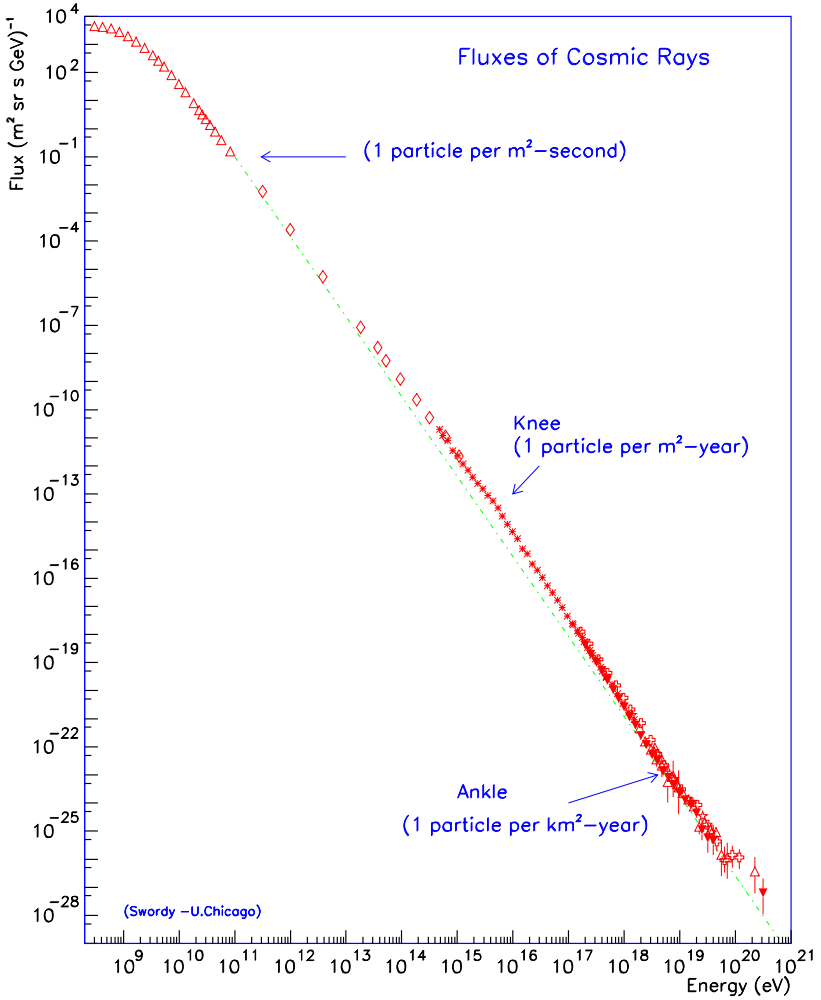
Power needed to sustain:

$$P_{CR} = \frac{\varepsilon_{CR} V_{Gal}}{\tau_{CR}} = 3\times10^{33}\text{W}$$

Galactic volume ~10^{60}m^3 (d ~30kpc, h ~0.3kpc)

c.f. ~ 1 Supernova every 30 yrs = 10^{35} W

→ Few percent of energy from Supernovae is sufficient to sustain the CR power.

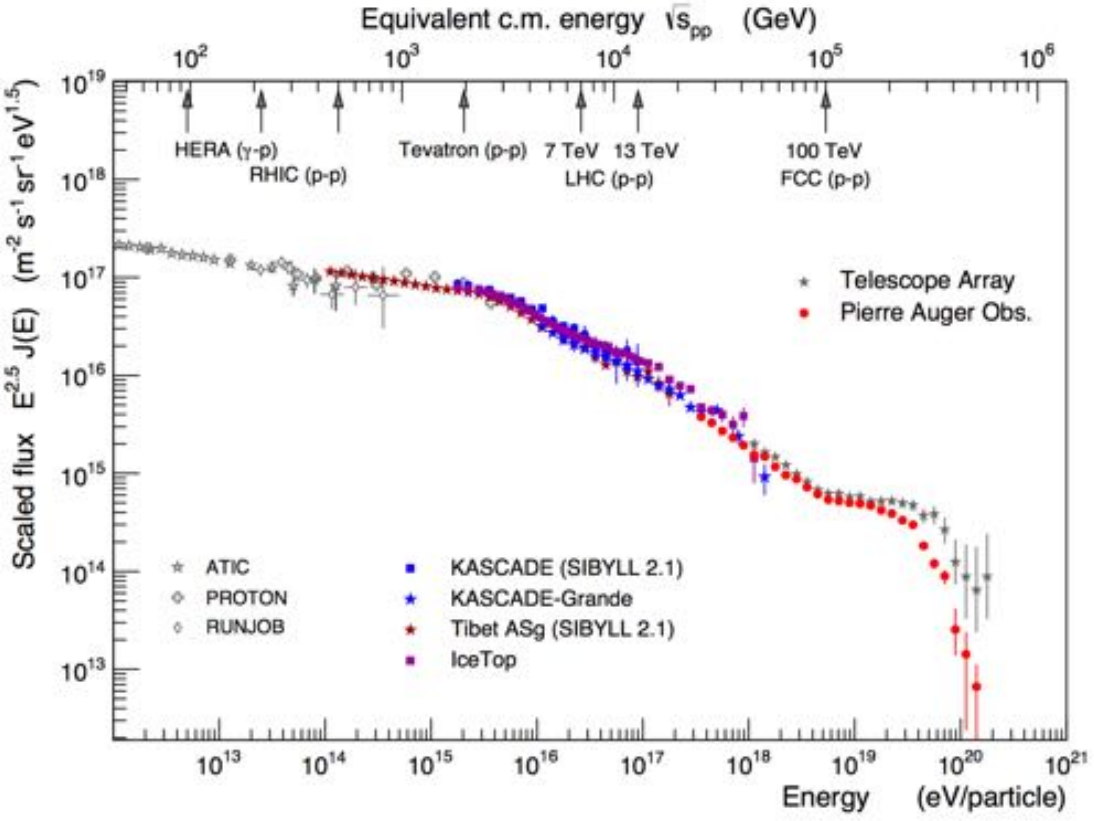


Cosmic Ray Spectrum

Compare centre-of-mass and fixed target collision energy:
14 TeV at LHC <=> 10^{17} eV in cosmic rays

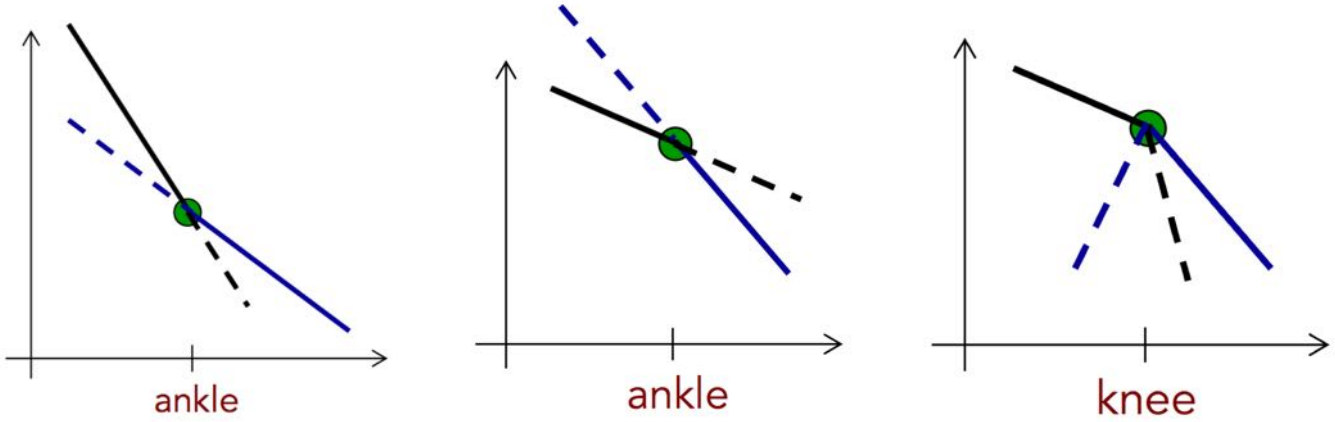
$\sqrt{s} = 2E$ vs $\sqrt{s} = \sqrt{2Em_p}$

- Galactic sources dominate below 10^{15} eV ("knee")
- Extragalactic sources dominate above ~ 10^{18} eV ("ankle")
- Where does the transition occur?



The Galactic – Extragalactic transition

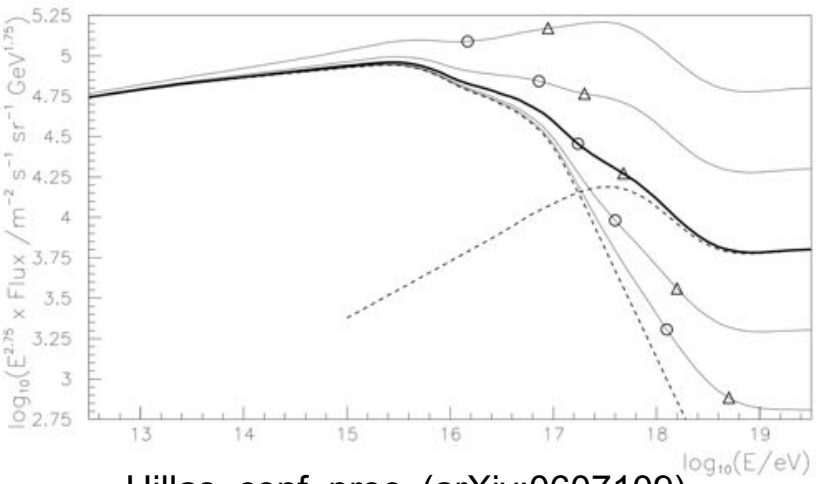
E. Parizot



- A natural transition between power law source components is ankle-like
- Knee can form from propagation / confinement effects
- Implication – particles with higher energies freely escape accelerator

- Change in accelerating mechanism might not be so simplistic…

The Galactic – Extragalactic transition



Hillas, conf. proc. (arXiv:0607109)

- Transition might not be *at* the “ankle”
- An invisible transition between components is also possible

Note how for changing component fractions, the transition is still essentially smooth. Circle = 50% extragalactic; triangle = 80% extragalactic.

Hillas Criterion

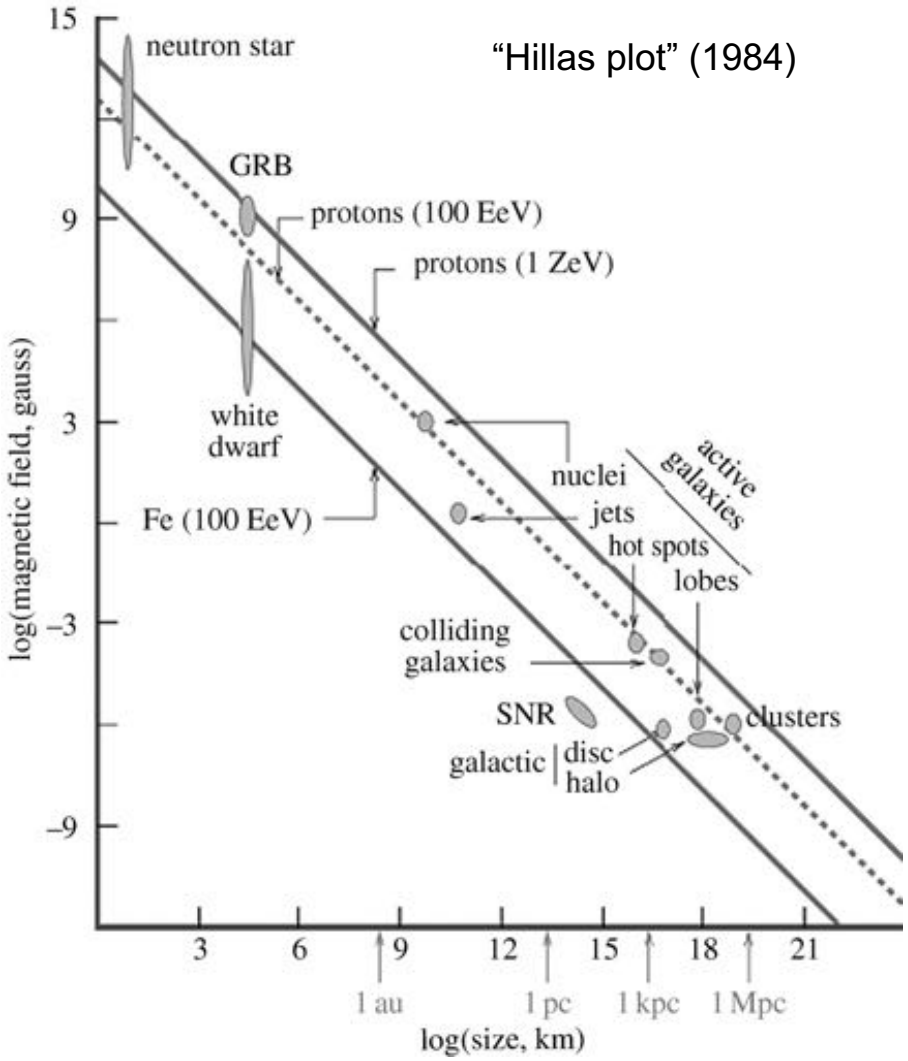
Properties needed for an astrophysical accelerator

Maximum energy obtained whilst particle remains in accelerating region minimum size – Larmor radius in magnetic field B

$$E_{\max} = ZecBL$$

e.g. Milky Way: ~3μG, ~15 kpc

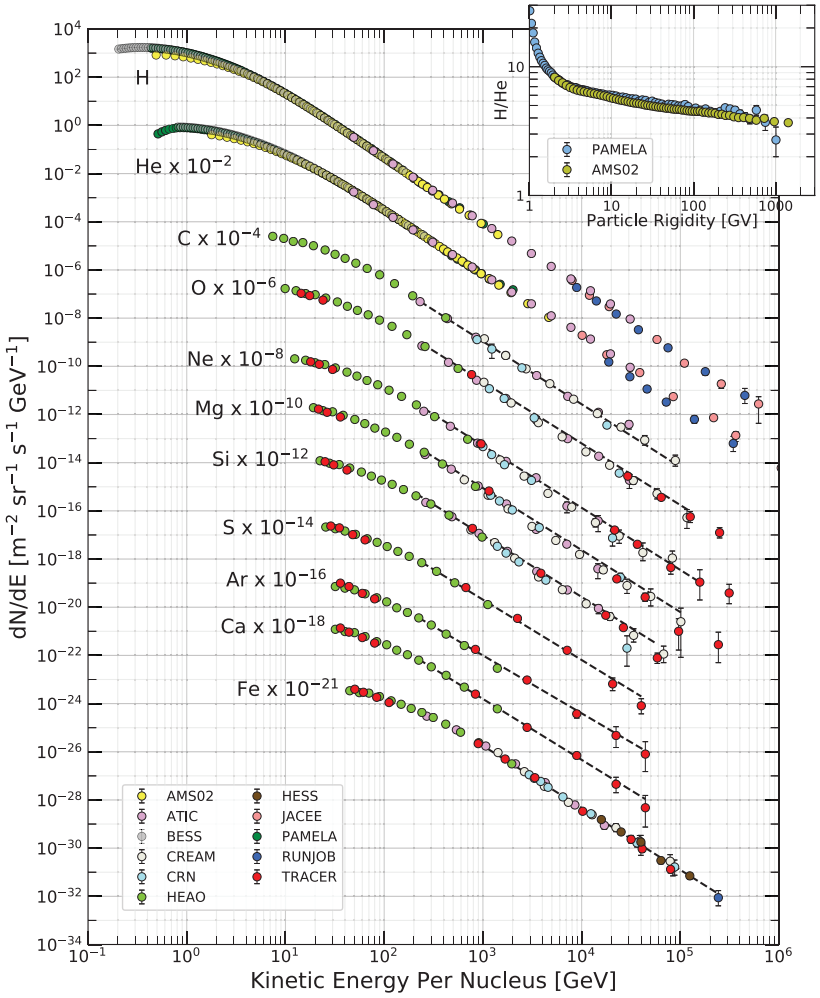
SNR difficult to contain E > 10^{14} eV, need magnetic field amplification
→ Galactic accelerators reach 10^{15}eV (1PeV)
→ Where are the PeVatrons?



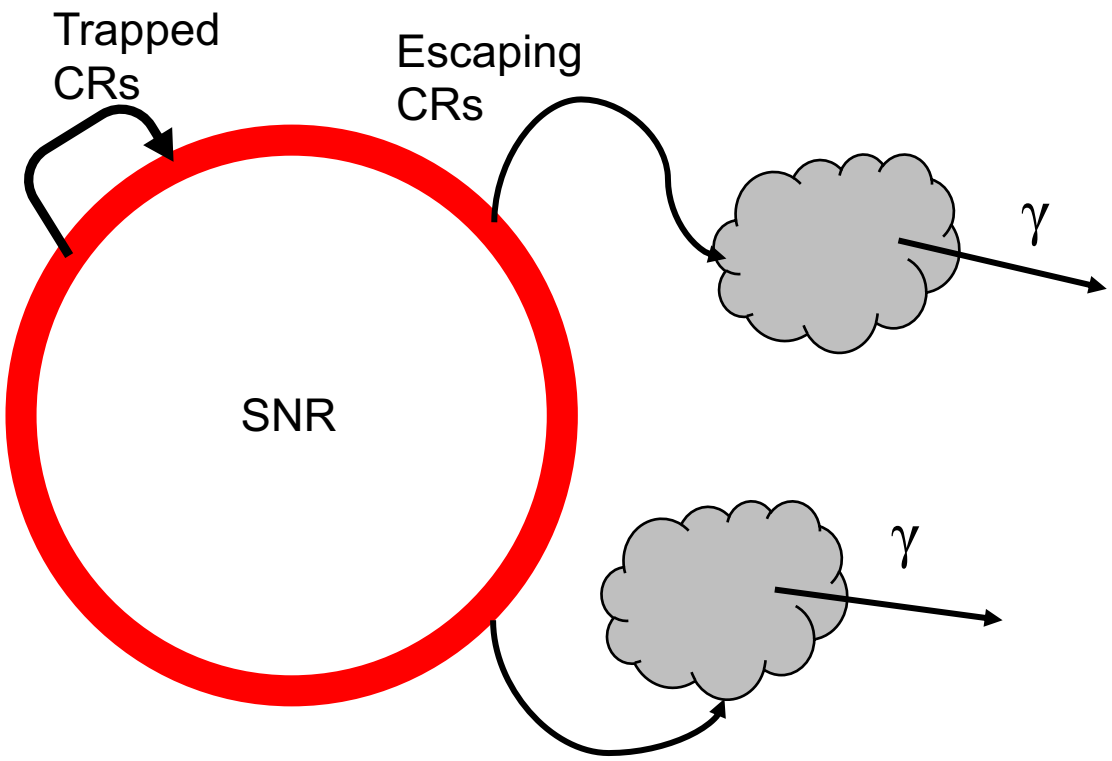
Cosmic Ray Spectrum: Mass Composition

Note Z dependence of Hillas Criterion

The galactic-extragalactic transition may occur at different energies for different species.



Cosmic Ray Escape Conditions



- Cosmic rays with high enough energy escape after a certain time.
- Cosmic ray knee thought to relate to particle escape.
- Hadronic particles generate gamma-ray emission by interacting with nearby target material
- The hunt for PeVatrons is an active area of research.

Cosmic Ray Energy Loss Mechanisms

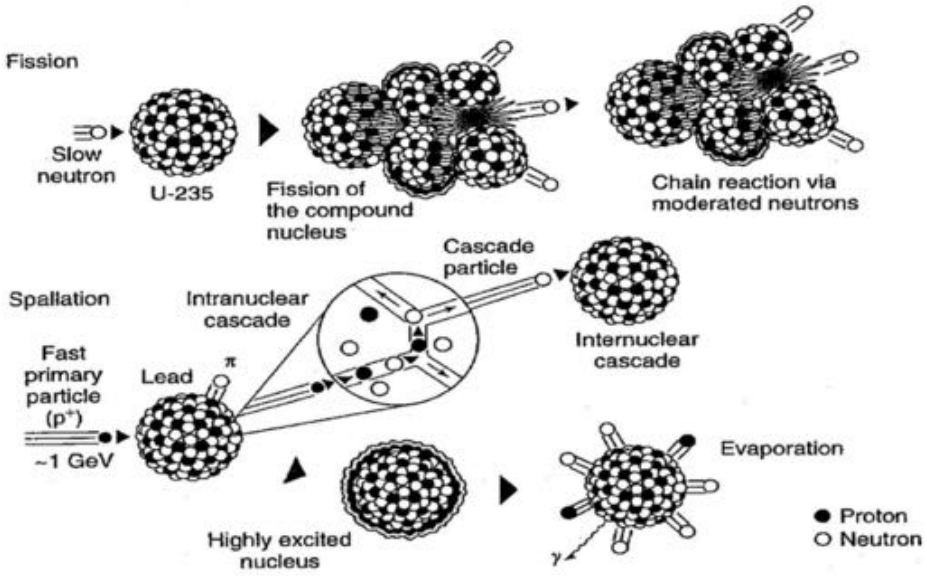
$$\frac{dE}{dt} = A_1 + A_2 E + A_3 E^2$$

Ionisation and adiabatic losses (A_1, A_2)

Synchrotron radiation (A_3): motion in a magnetic field

Inverse Compton Scattering (A_3): kinetic energy loss, photon acceleration

Spallation processes: fragmentation of cosmic ray ions / radioactive decay



i.e. loss terms due to radioactive decay and spallation; spallation also a source term for daughter particles.

Diffusion Loss Equation

Describes the time evolution of the particle energy spectrum based on the primary contributing source and loss terms.

1. Source term due to (e.g.) supernova acceleration: $Q(E) \sim kE^{-p}$
2. Spatial diffusion term with diffusion coefficient D(E)
3. Energy loss term b(E) = -dE/dt

$$\frac{\partial N}{\partial t} = Q + D\nabla^2 N + \frac{\partial}{\partial t}[b(E)N(E)] + \cdots$$

- Note $b(E) = A_1 + A_2E + A_3E^2$ is the sum of contributing processes
- These correspond to 1 ionisation loss, 2 bremsstrahlung / adiabatic losses and 3 synchrotron and inverse Compton losses
- The relative strength depends on the local density and ambient magnetic field strength, the dominant processes governs the spectral index

Ginzburg-Syrovatskii equation

Can add terms to describe other processes
e.g. spallation and radioactive decay (for nuclear species *i*) → "Cosmic Ray clocks"

$$\frac{\partial N}{\partial t} = Q + D\nabla^2 N_i + \frac{\partial}{\partial t}[b(E)N_i] - \frac{N_i}{\tau_i} - \frac{N_i}{\tau_{ri}} + \sum_{j>i} \frac{P_{ji} N_j}{\tau_j}$$

Where for a test volume:

- τ_i is the average lifetime of species *i* against spallation
- τ_{ri} is the average lifetime of species *i* against radioactive decay
- P_{ji} is the probability that in a spallation of *j*, species *i* is created.

Greisen-Zatsepin-Kuzmin Limit

Fundamental limit to the cosmic ray spectrum due to interactions with the CMB (and pair-production).

Energy is reduced to below the GZK cutoff

Cosmic Rays from other Galaxies with higher initial energies will lose energy before arriving at Earth.

Protons, $E_{max} \approx 7 \times 10^{19}$ eV

$$p + \gamma \rightarrow n + \pi^+$$

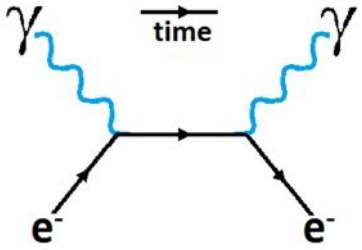
$$p + \gamma \rightarrow p + \pi^0$$

The Oh-My-God particle, $E = 3 \times 10^{20}$ eV (1991)

Since then, many more (> 70) similar events detected

GZK horizon (loss/ interaction length) ~ 70 - 150 Mpc

Production of Gamma-rays and Neutrinos: leptonic - Synchrotron radiation



From a charged particle gyrating in a magnetic field B with energy density U_m

Radiated Power:

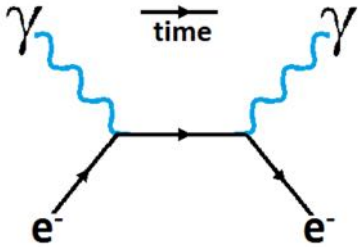
$$P_{synch} = \frac{4}{3} c \left(\frac{v}{c}\right)^2 \gamma^2 \sigma_T U_m$$

Energy loss timescale:

$$\tau_c \approx \frac{1}{\gamma} \left(\frac{\mathrm{B}}{1nT}\right)^{-2} 1.6{\times}10^{11} \text{ yrs}$$

Production of Gamma-rays and Neutrinos: leptonic - Inverse Compton scattering

Transfer of energy from an energetic electron to a photon – boosting photon to gamma-ray energies



Scattering off background radiation fields, energy density U_{rad}

CMB, FIR, NIR, Vis…

i.e. ambient radiation and starlight.

Radiated Power:

$$P_{IC} = \frac{4}{3} c \left(\frac{v}{c}\right)^2 \gamma^2 \sigma_T U_{rad}$$

c.f. Synchrotron – same relation, energy loss rate depends only on the electric field

$\tau_{CMB} \approx \frac{1}{\gamma} 3\times10^{12}$ yrs

Blumenthal & Gould (1970)

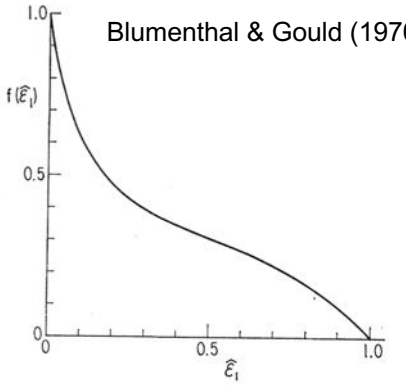


FIG. 3. Scattered photon distribution function in the Thomson limit.

gamma-ray energy factor ~1/9 on average

Production of Gamma-rays and Neutrinos: hadronic - Pion decay

Proton energy loss timescale via p-p interactions:

$\tau_{pp} \approx \frac{1}{n} 6\times10^7$ yrs (n = target material density, cm^{-3})

Charged pion decay:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

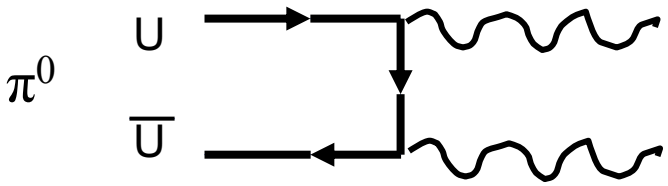
Decay ~ 10^{-8} s

Neutral pion decay:

$$\pi^0 \rightarrow \gamma + \gamma$$

Decay ~ 10^{-16} s

Signature of hadronic cosmic ray acceleration

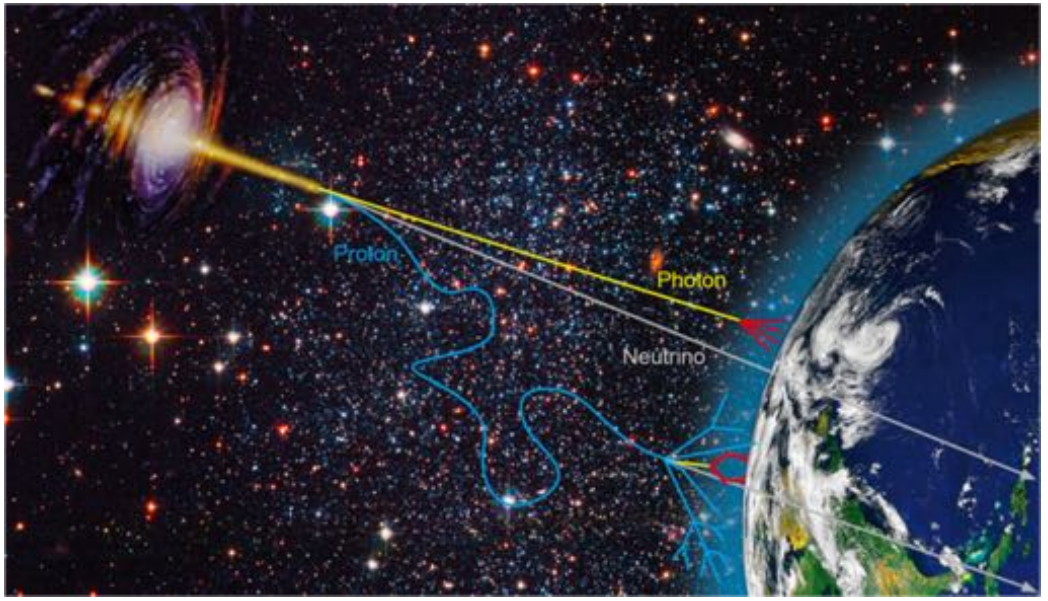


Cosmic Messengers

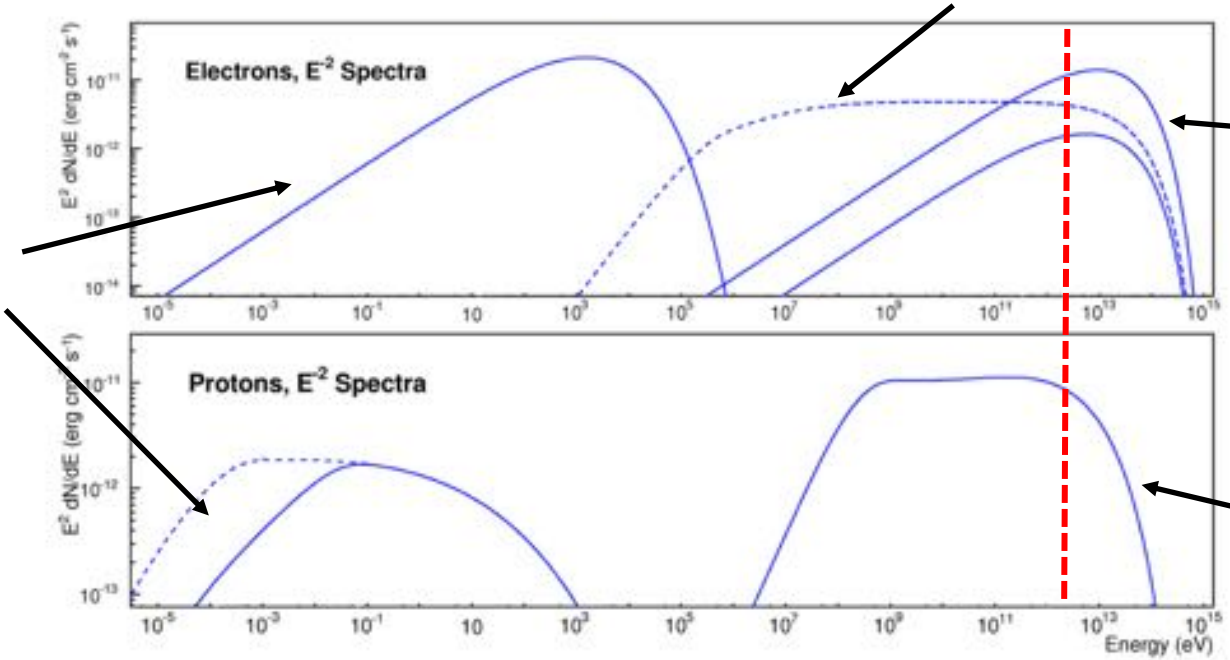
Cosmic rays get deflected by ambient magnetic fields

Neutrinos and gamma-rays, however, are penetrating and travel directly from source to observer

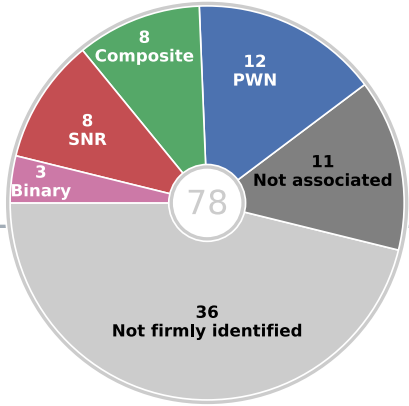
Signature of cosmic ray acceleration is neutrino & gamma-ray



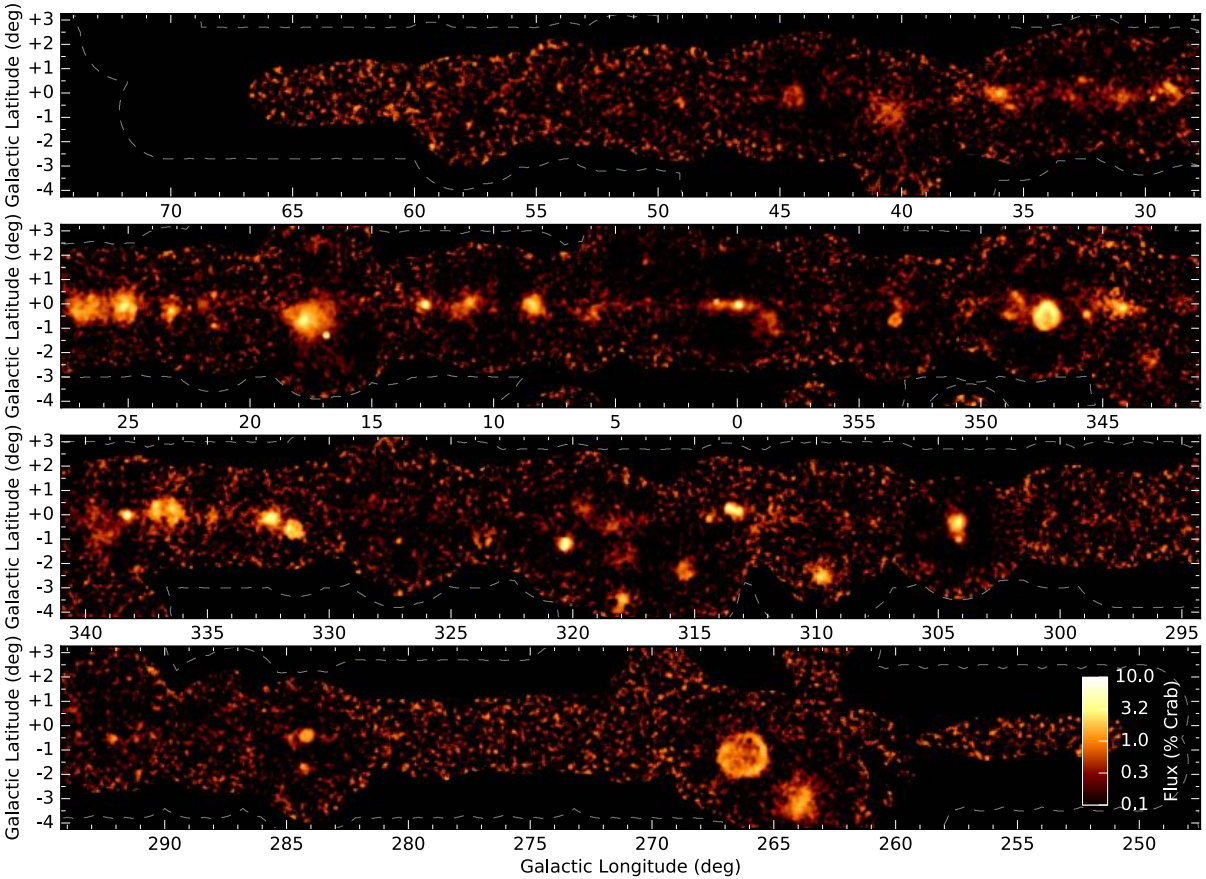
Typical Spectral Energy Distribution (SED)



Hinton & Hofmann (2009)



The Galactic Plane in Gamma-rays

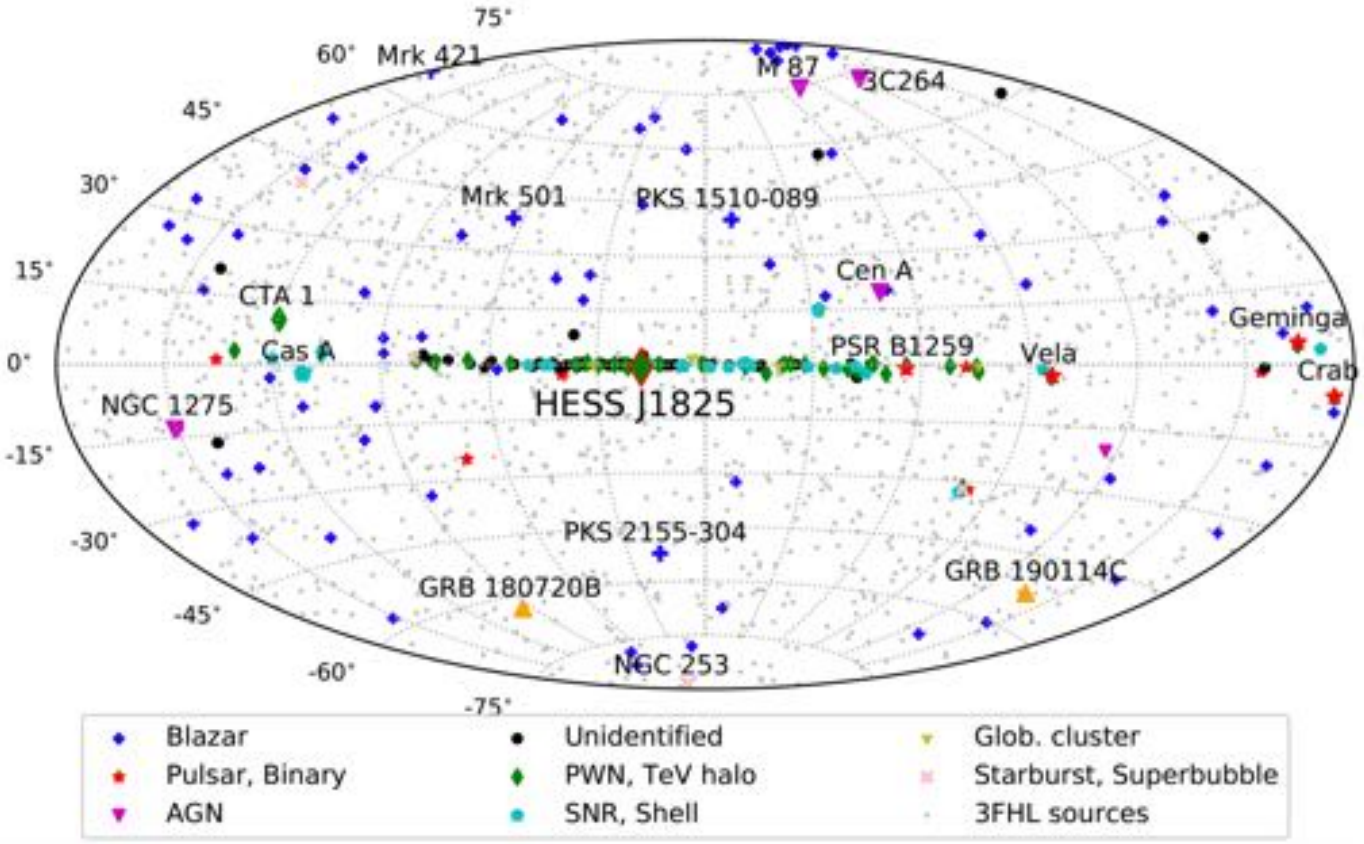


H.E.S.S. Collaboration, A&A 612, (2018) A1 https://www.mpi-hd.mpg.de/hfm/HESS/hgps

The TeV gamma-ray sky

Gamma-rays are a signature of locations of cosmic ray acceleration

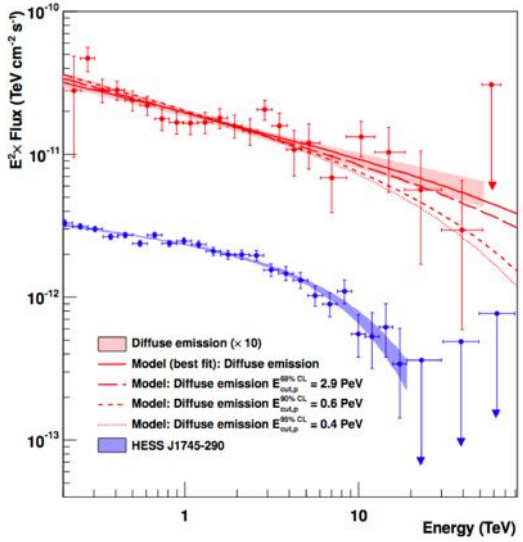
Map of known sources and source classes – many unidentified.

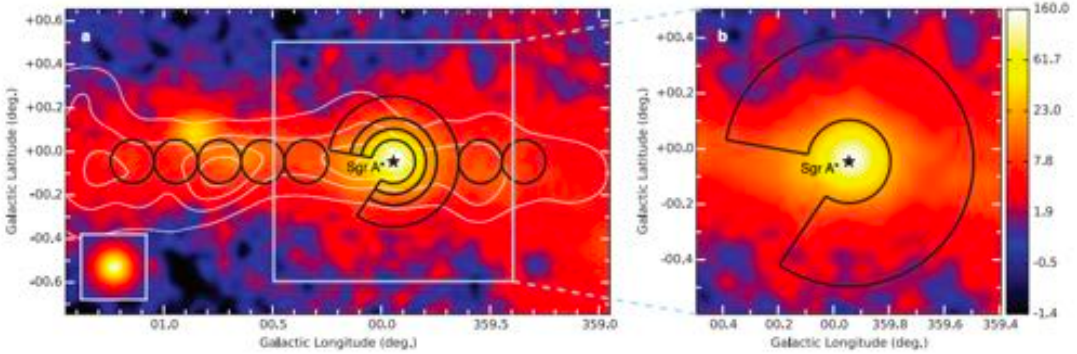


PeVatrons: Galactic accelerators reaching 1 PeV

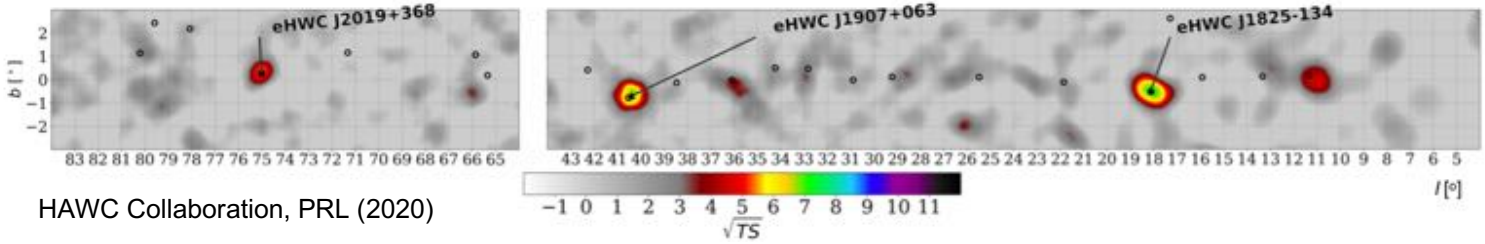
First evidence: Galactic centre – mechanism unknown (HESS, 2016)

First sky maps above 100 TeV → PWNe association? (HAWC, Sep. 2019)





H.E.S.S. Collaboration, Nature (2016)



HAWC Collaboration, PRL (2020)

Cosmic Ray Anisotropy

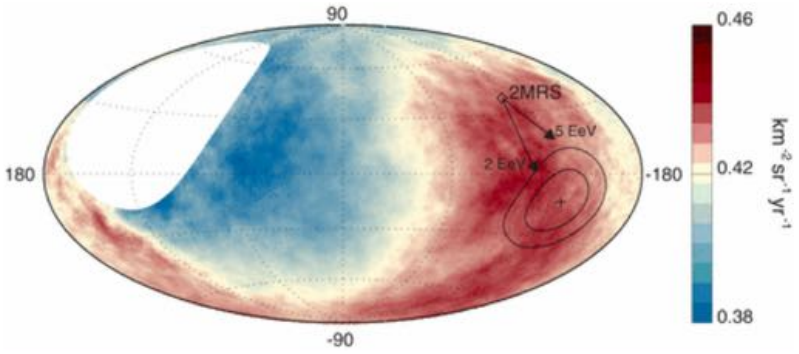
Searching for anisotropies in highest energy cosmic rays

CRs less affected by deflection

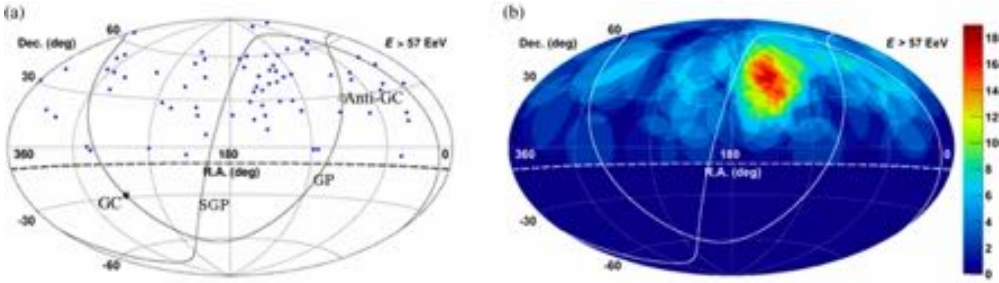
Indicate extragalactic sources of CRs

→ Proof of origin beyond Milky Way

(excess in direction away from Galactic plane)



Pierre Auger Collaboration, Science (2017)



Telescope Array Collaboration, ApJLett (2014)

Extensive Air Showers – Simulations & Observables

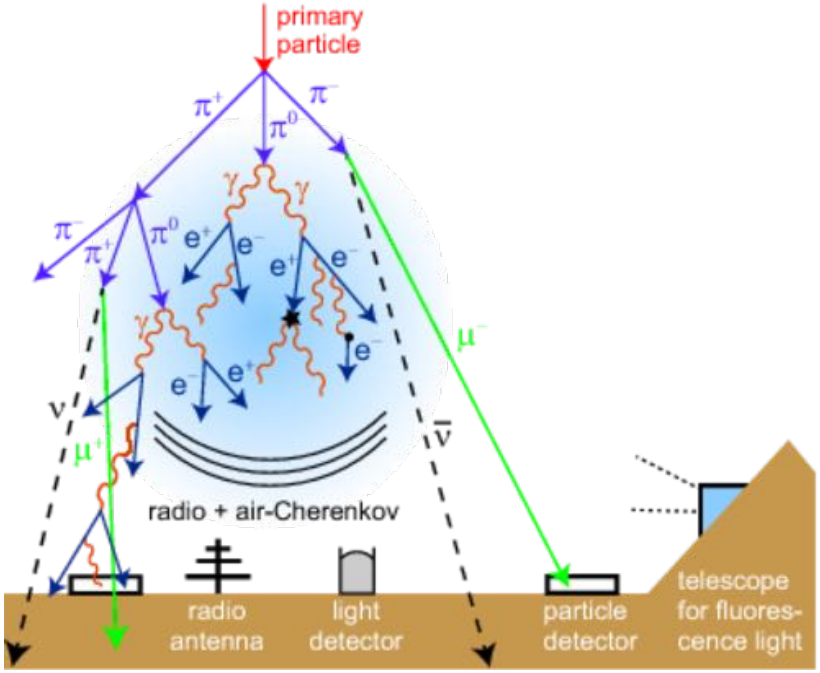
Rely on simulations to describe EAS; assume more energetic EAS can be described as a superposition of less energetic showers.

(number of muons)

Observable properties:

1. Particles at ground
2. Cherenkov radiation
3. Fluorescence emission
4. Radio emission

High energies – CR would pass through satellite (key is detection area)
→ Observe EAS = use atmosphere as part of detector



Cherenkov radiation

Cherenkov radiation is produced when charged particles travel faster than the local speed of light $v > c_m = c/n$

For air: n =1.0003, for water: n = 1.333

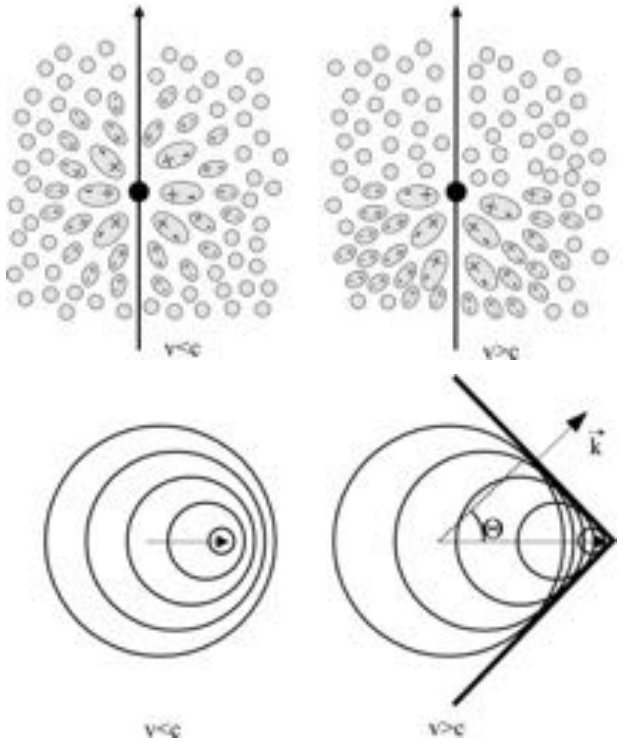
Note: $\mathrm{n(h)} = 1 + n_0 e^{-h/h_0}$

https://www.mpi-hd.mpg.de/hfm/CosmicRay/ChLight/ChLat.html

Cherenkov cone opening angle:

$$\cos\theta_c = \frac{c}{vn}$$

Number of photons produced per unit length is proportional to Z^2

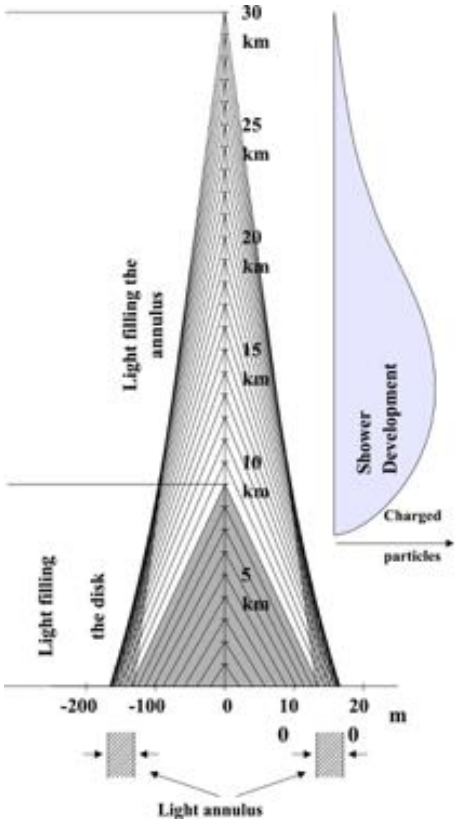


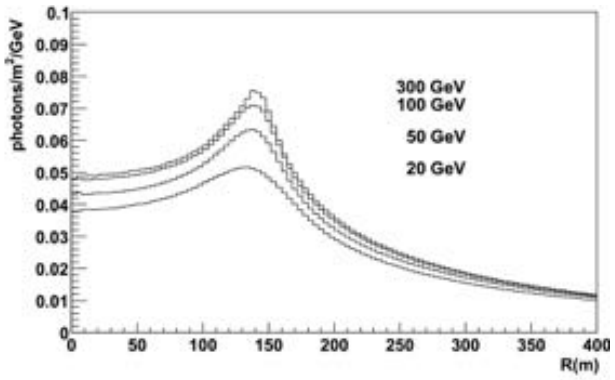
Longitudinal and Lateral shower profiles

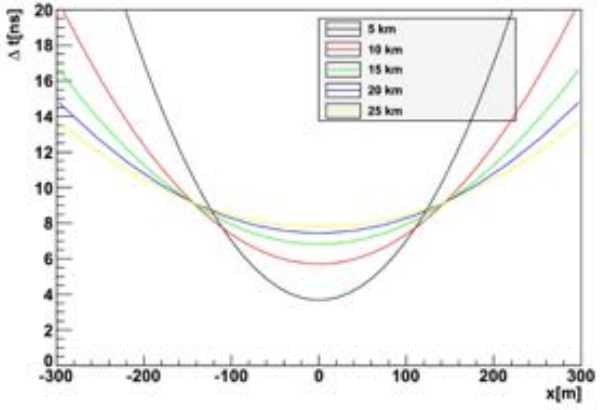
Cherenkov light profile

Peaks in characteristic ring – Cherenkov pool radius ~125 m

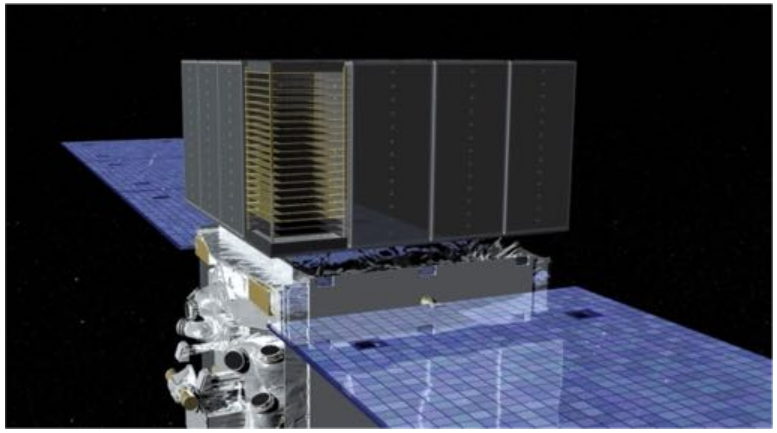
Note – light emitted earlier arrives later

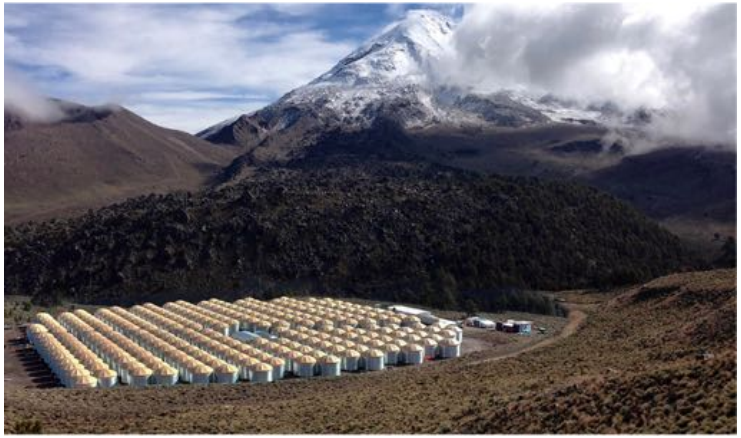






γ-ray Detection Techniques





	Fermi-LAT	IACTs	HAWC
Energy Range	200 MeV – 300 GeV	50 GeV – 50 TeV	1 – 100 TeV
Field of View	20% sky	3º-5º	15% sky
Energy Resolution	10%	10%	100% - 20%
Angular Resolution	6º - 0.3º	0.1º	1º - 0.2º
Effective Area	1 m^2	10^5 m^2	10^5 m^2
Duty Cycle	Full Year	1400 h/yr	Full Year
EAS?	Within detector	Within atmosphere	In water tanks

TeV gamma-rays, IACTs

Electromagnetic showers appear elliptical

Gamma/hadron separation is key to IACT performance – based primarily on image shape

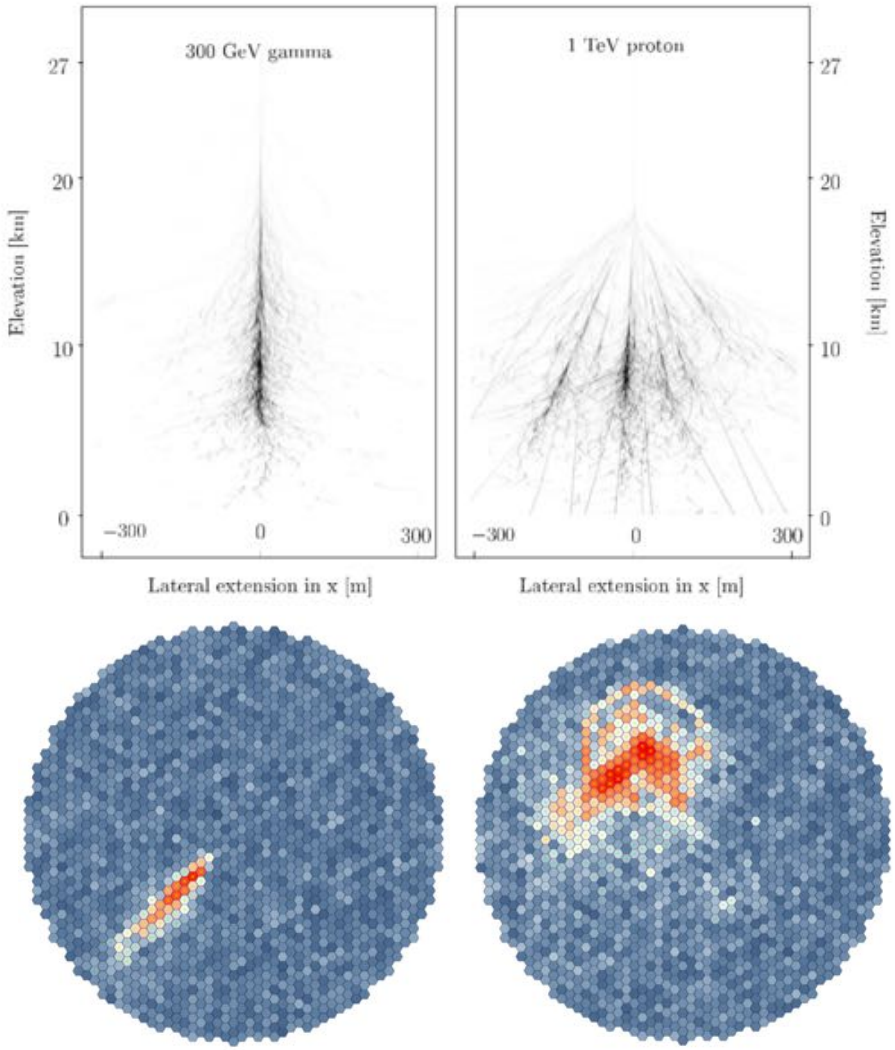
Use stereoscopic imaging to better discriminate and reconstruct

Ideal spacing O(100m)

Current examples:

H.E.S.S., MAGIC, VERITAS

Future: Cherenkov Telescope Array



University of Zurich[UZH]

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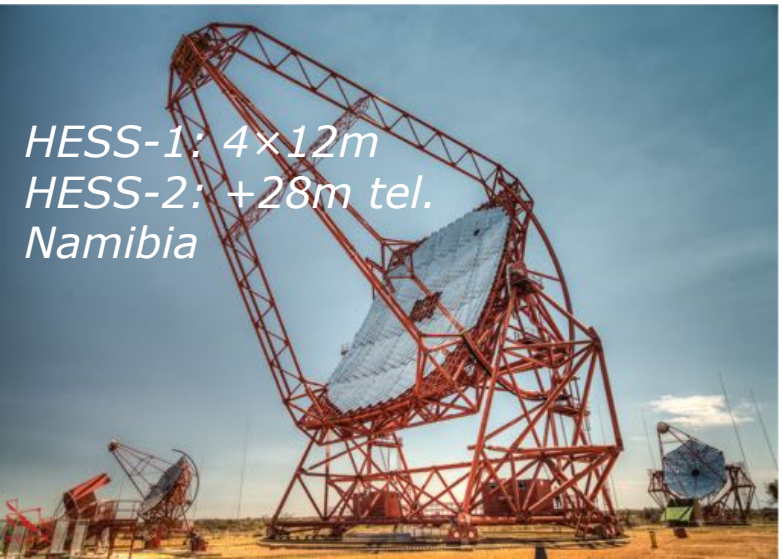
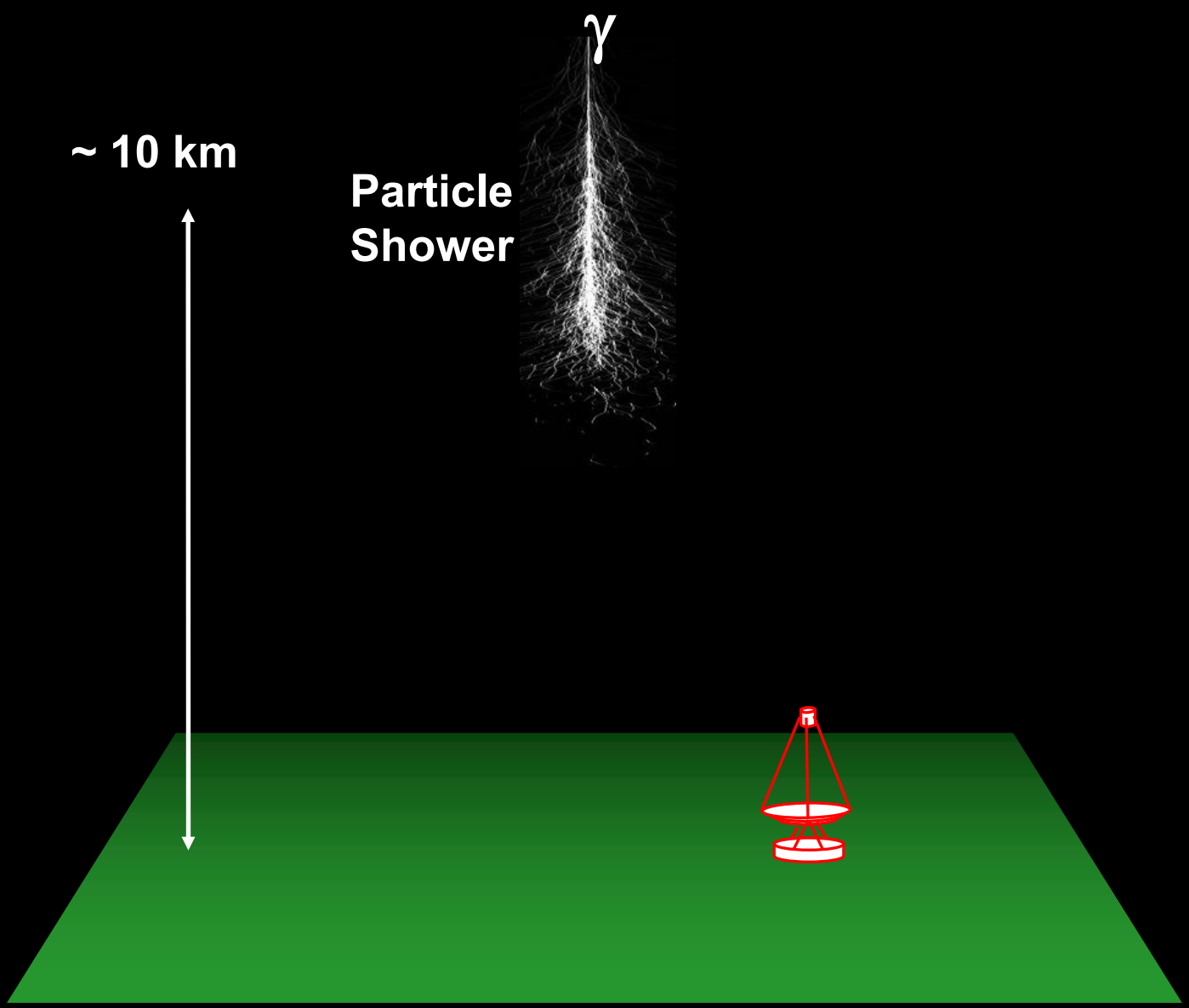
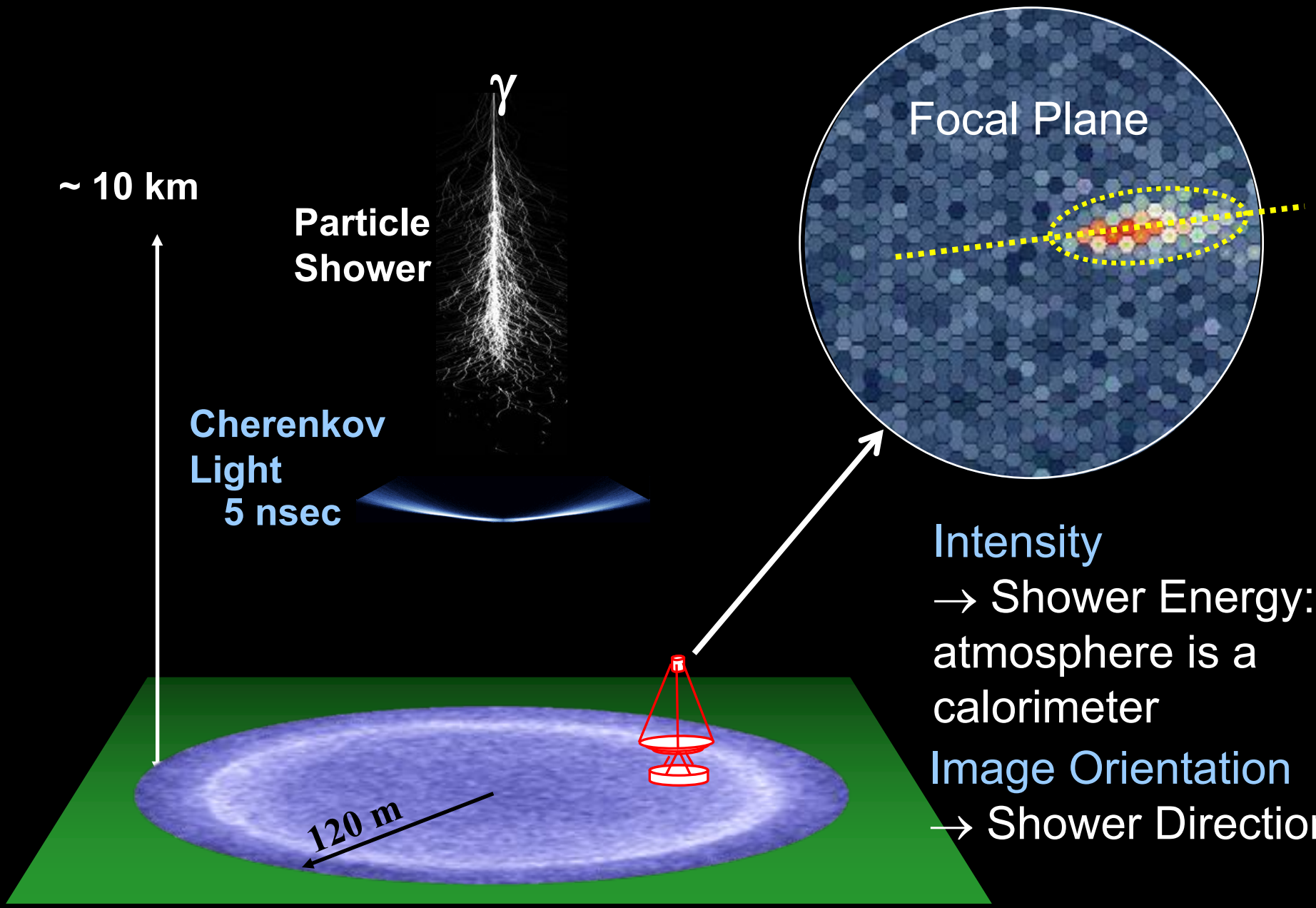
Imaging Atmospheric Cherenkov Telescopes



Detection of Cosmic Rays and Gamma Rays



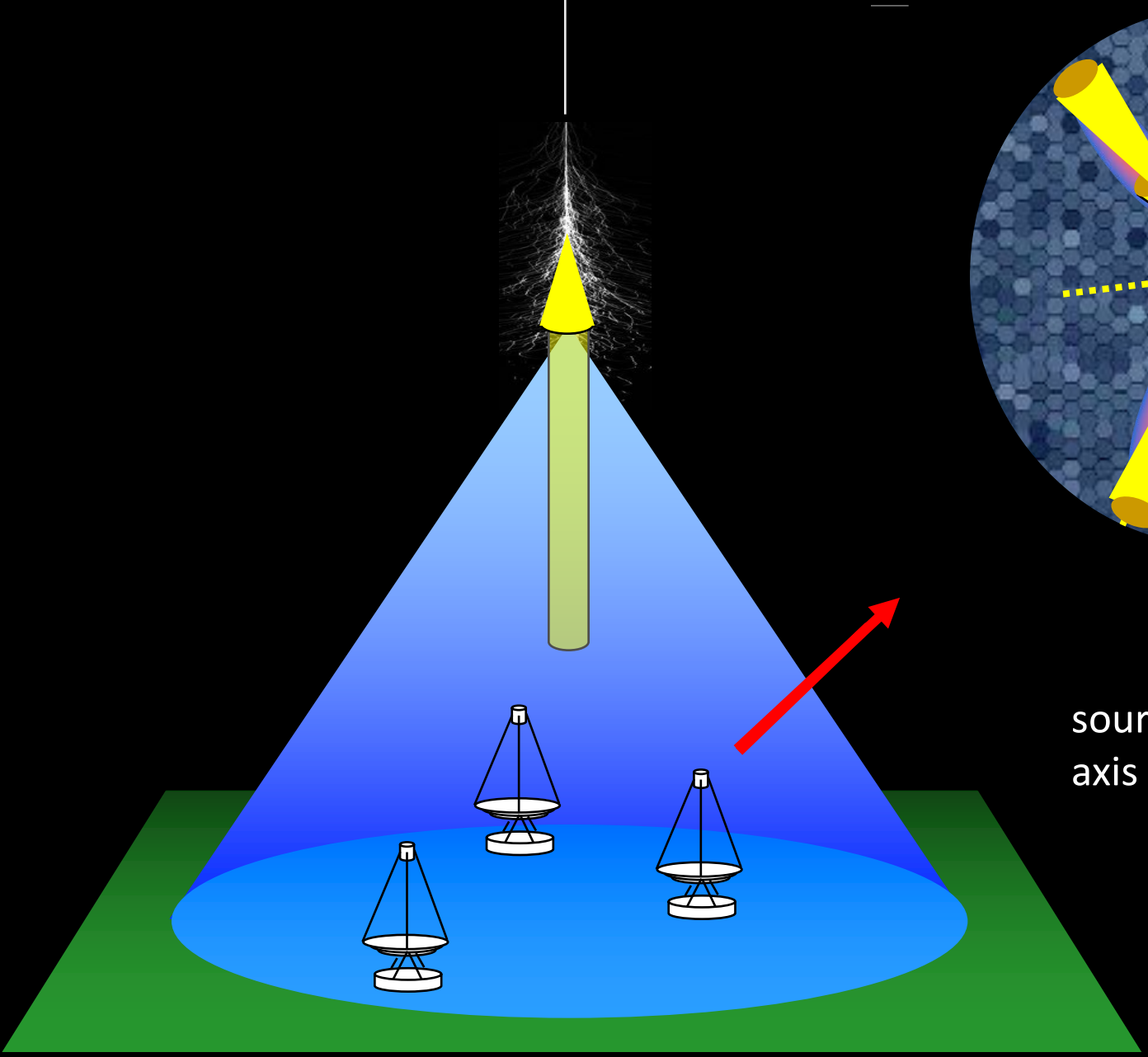
Detection of Cosmic Rays and Gamma Rays

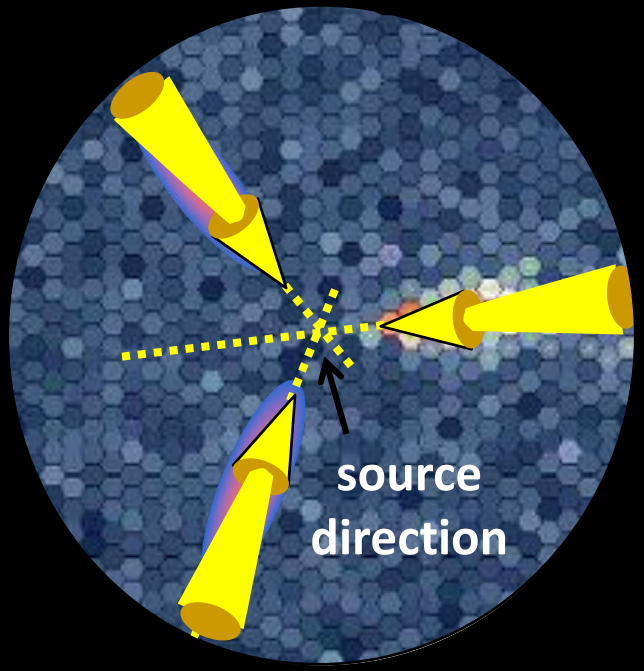


Intensity
→ Shower Energy: atmosphere is a calorimeter

Image Orientation
→ Shower Direction

Stereoscopic Observation Technique





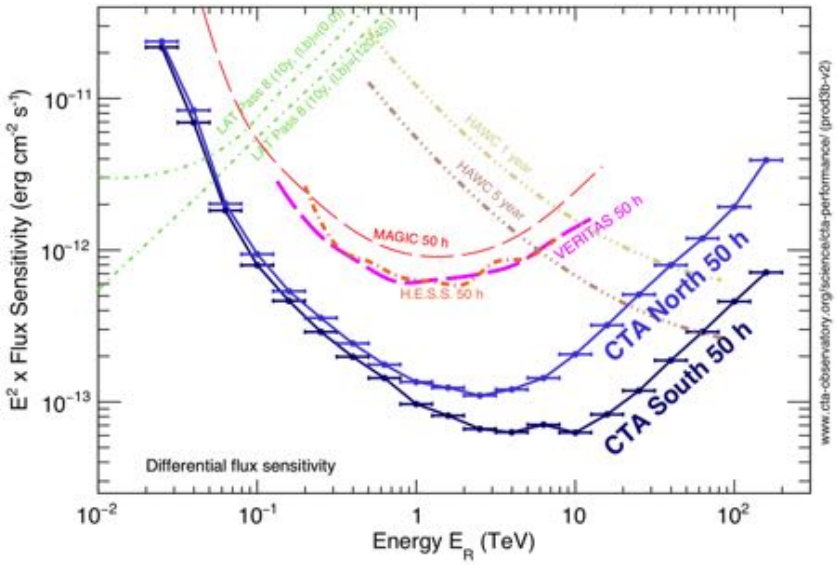
source image is on image axis ⇒

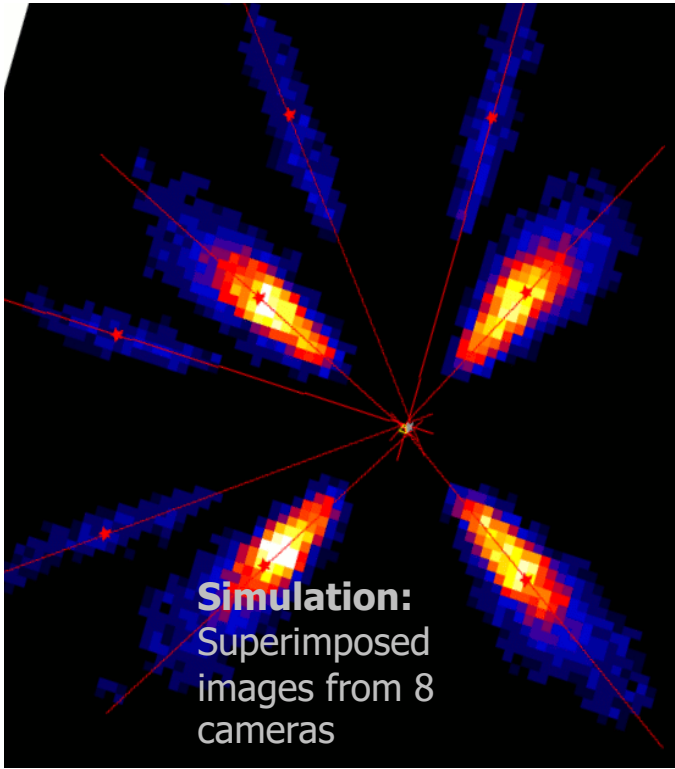
several viewing angles for precise event-by-event source location!

Imaging Atmospheric Cherenkov Telescopes

Stereoscopic imaging for improved angular resolution and energy resolution.

Increased number of telescopes with different sizes.



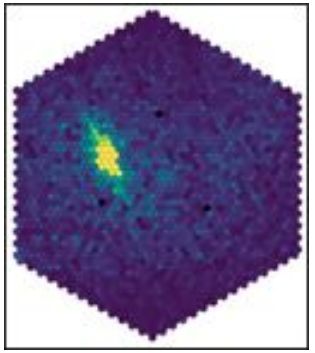


CTA is coming…but plenty happening now

CTA @ UZH:
→ FlashCam: a prototype camera for the Medium Sized Telescopes of CTA
→ Partly constructed at UZH

→First light seen 2018 – successful run on prototype in Berlin

→ Arrival of FlashCam at H.E.S.S. on 4/10/19 – upgrade to largest telescope
→Successful installation and now running smoothly at H.E.S.S.

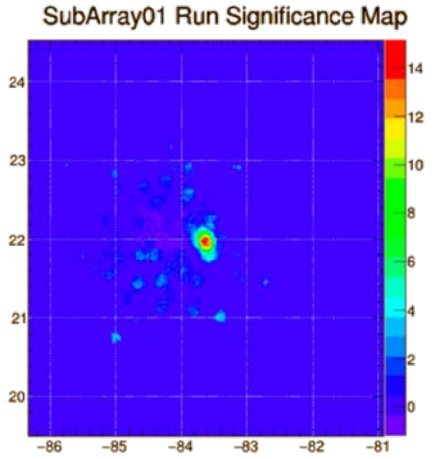


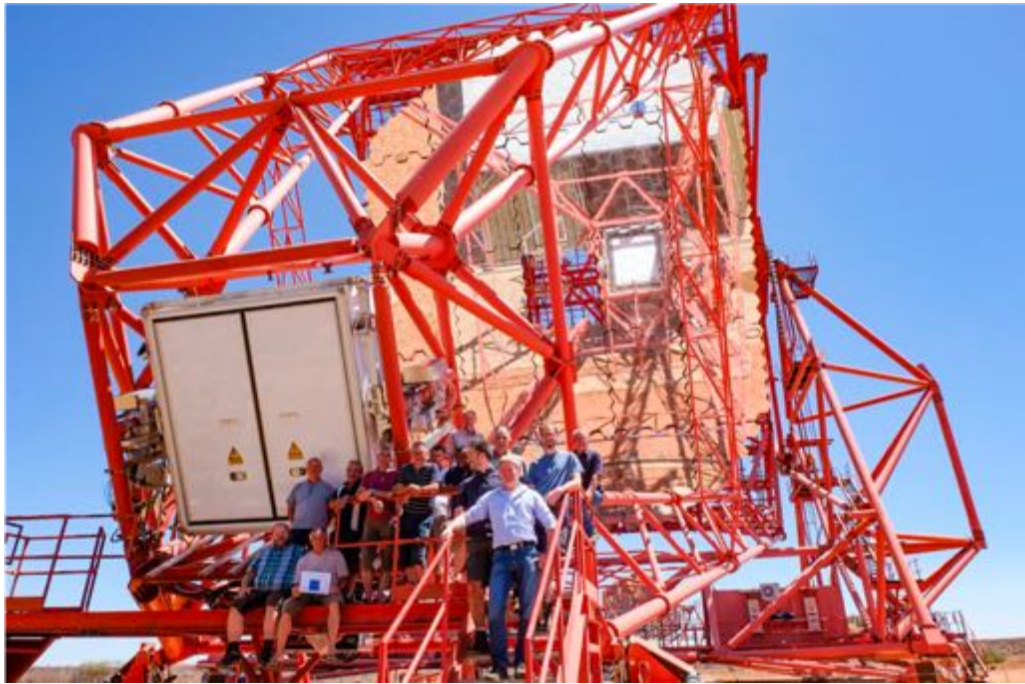
University of Zurich[UZH]
Physik-Institut

CTA is coming…but plenty happening now

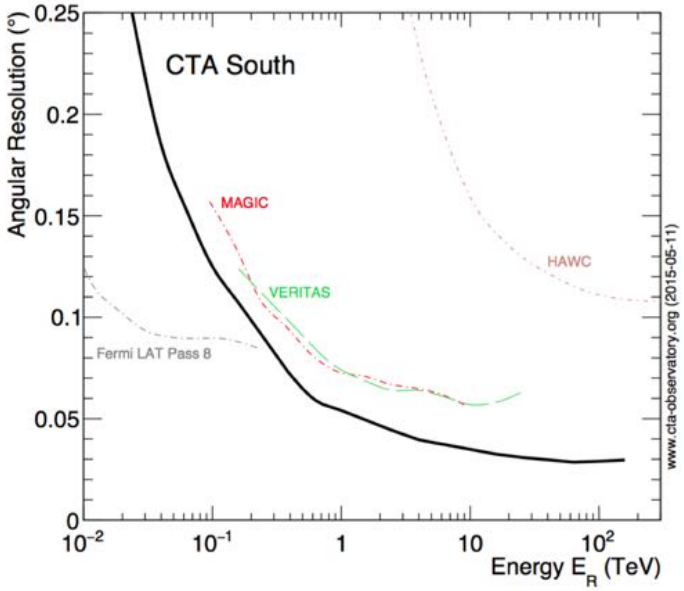
Brightest source detected within first night of observations

Currently learning a lot and exploring new capabilities with FlashCam at H.E.S.S.





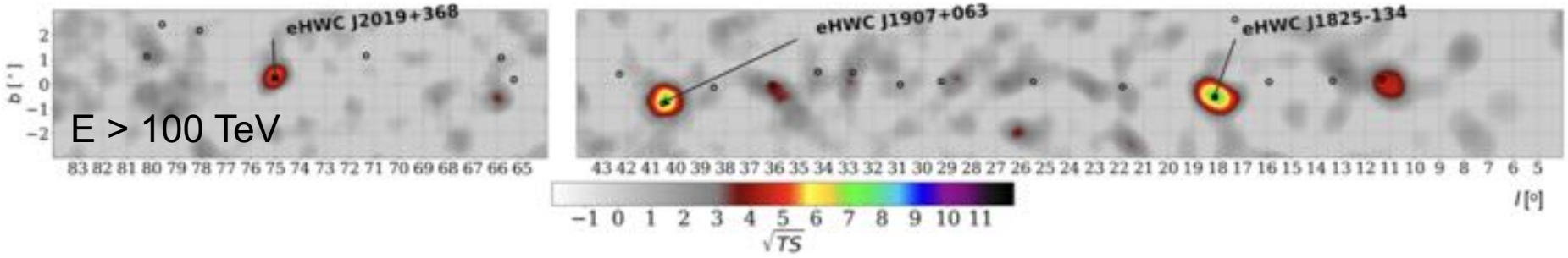
TeV gamma-rays – Water Cherenkov



HAWC (High Altitude Water Cherenkov) Observatory

Detection of EAS through Cherenkov effect in water, higher altitude

High energy, poorer resolution

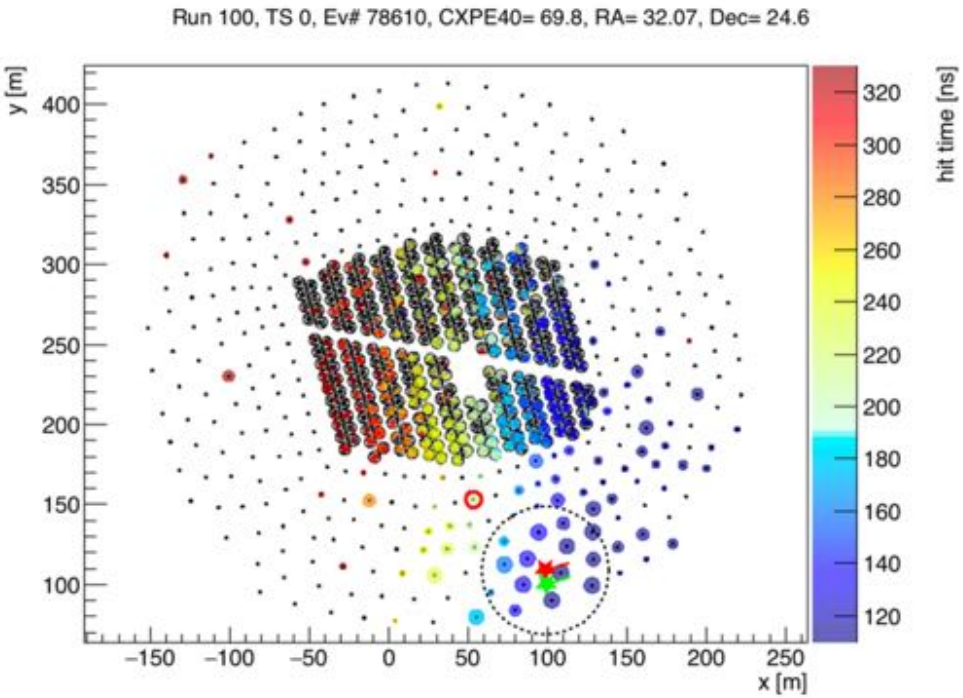


TeV gamma-rays – Water Cherenkov

Tank hit times used to reconstruct the shower and for gamma-hadron separation.

Recall – EAS duration ~ few ns.

Detector density
→ higher density, lower energy threshold.
→ increased separation, higher energy reach.



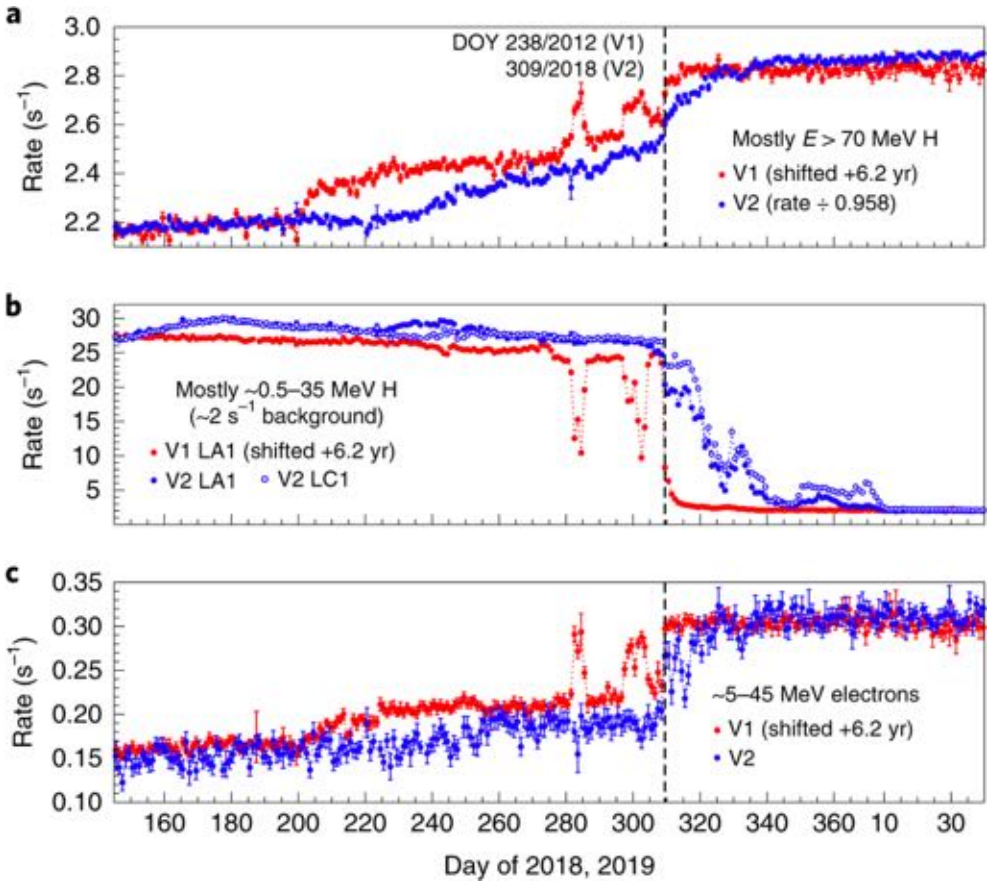
Voyager 1 and 2 satellites

Launched on 05/09/1977 and 20/08/1977 respectively

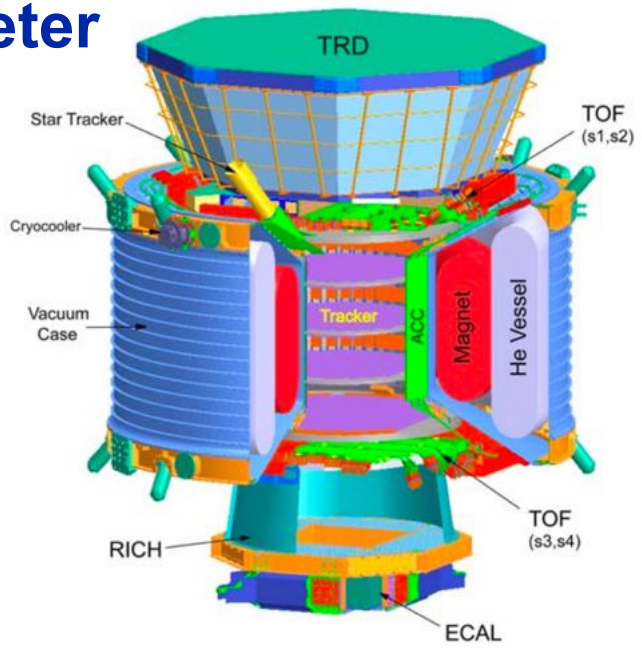
Exited solar system in 2012 and 2018 respectively

Still functioning and relaying data

Clear change in cosmic ray rate (rise) and solar wind rate (drop) as they exit the heliosphere and enter interstellar space.



AMS-02: Alpha Magnetic Spectrometer



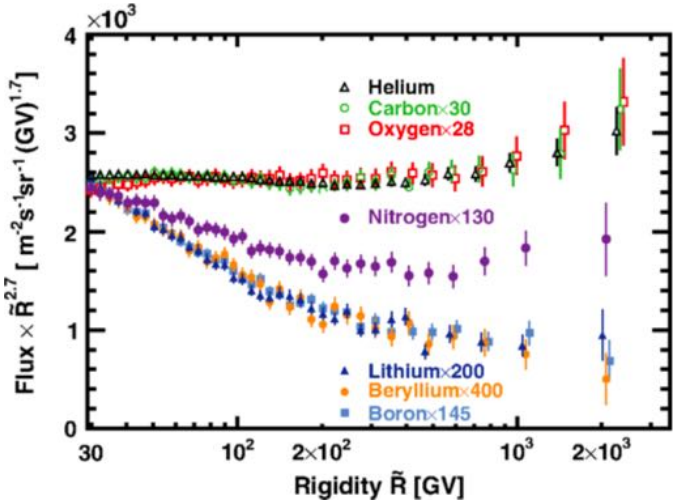
Mounted on the ISS

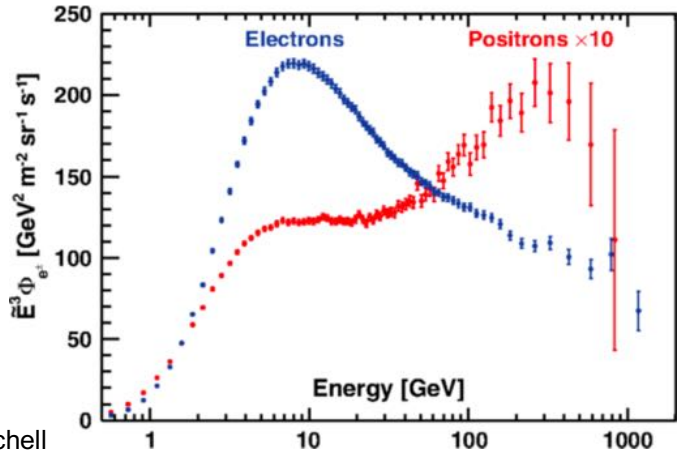
Accurate measurements of CR species spectra

Including unexpected measurements

Different sources of electrons & positrons

https://ams02.space/physics

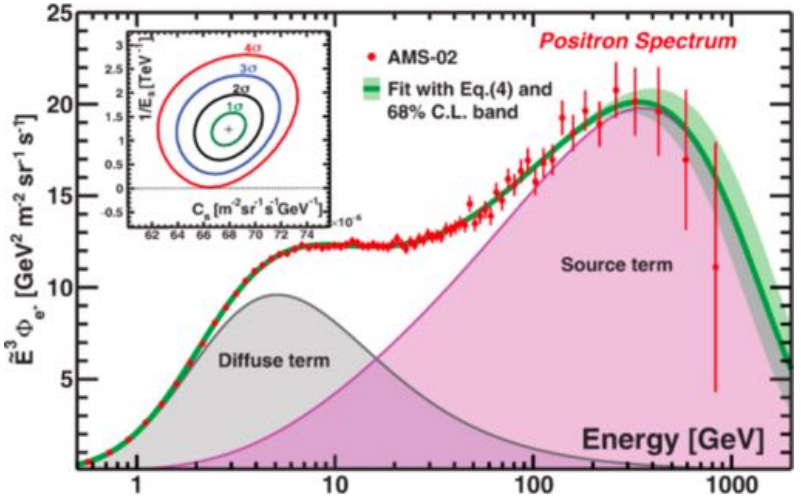




AMS-02: Alpha Magnetic Spectrometer

Positrons and anti-protons have same slope
Pulsars as a source of positrons, but not anti-protons.

Product of dark matter annihilation?
Also: Detection of anti-Helium events
→ no-one predicted that!
(conferences only, not peer-reviewed yet)



CALET: CALorimetric Electron Telescope

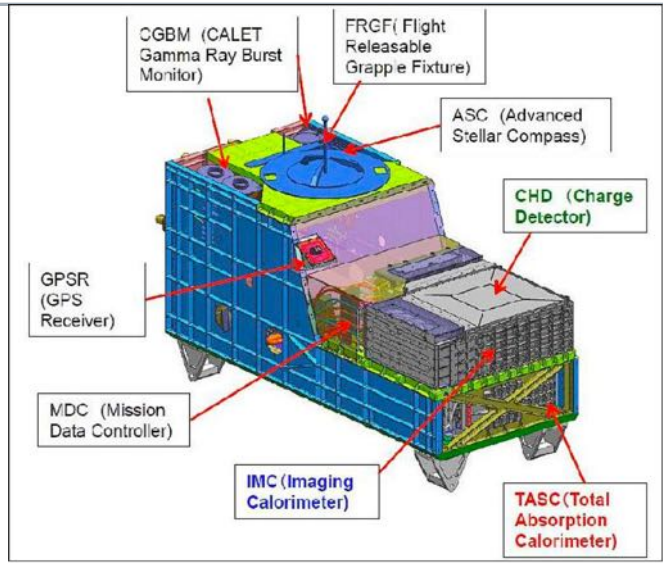
Also mounted on ISS, science since 2015

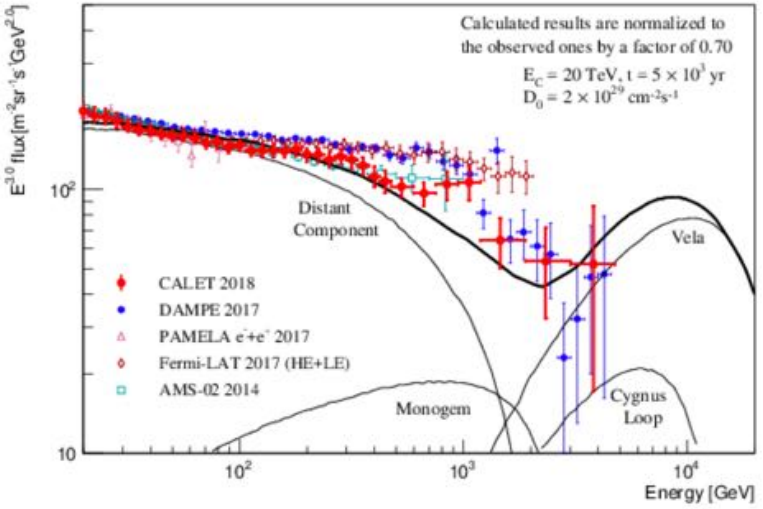
Precision measurements of electron spectrum

Some tension between satellite measurements

Generally modelled with diffuse and source terms.

Induce particle shower within detector





CALET Collaboration, Physical Review Letters 119, 181101 (2017)
https://arxiv.org/abs/1903.07271

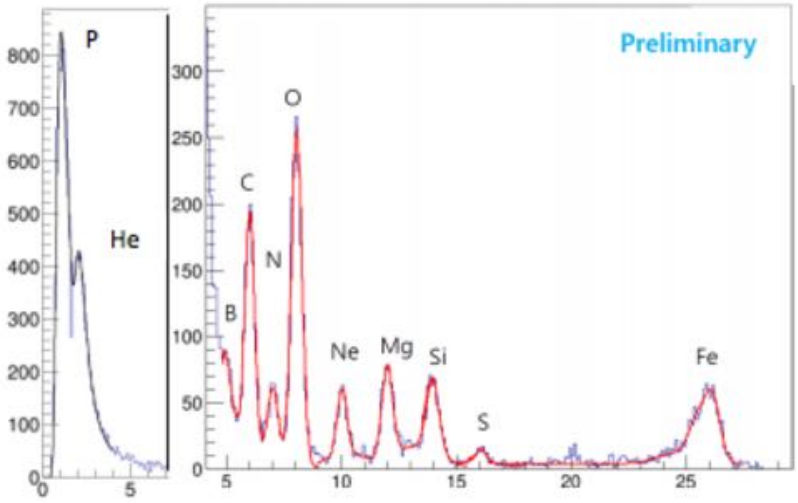
ISS-CREAM (Cosmic Ray Energetics And Mass)

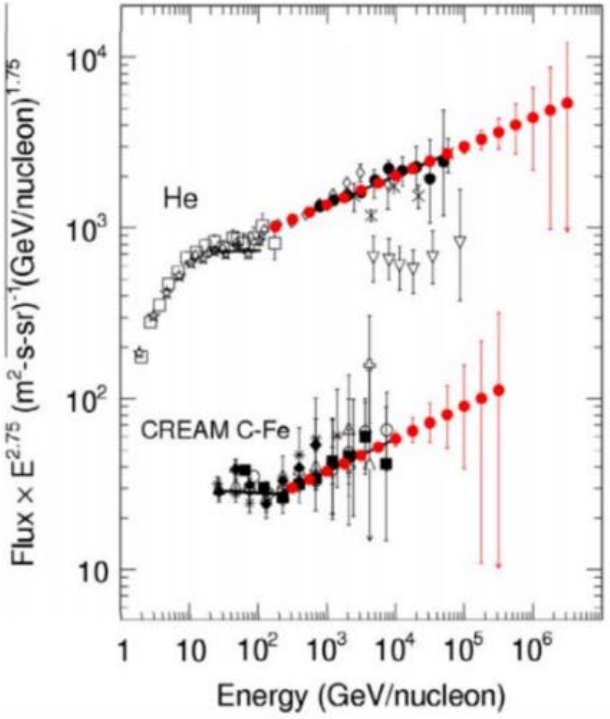
Mounted on ISS, currently shut down by NASA. (Feb 2019, heaters only).

Extremely good charge resolution

TeV – PeV energy range

Projected improvements to existing measurements





DAMPE – Dark Matter Particle Explorer

Launched in 2015

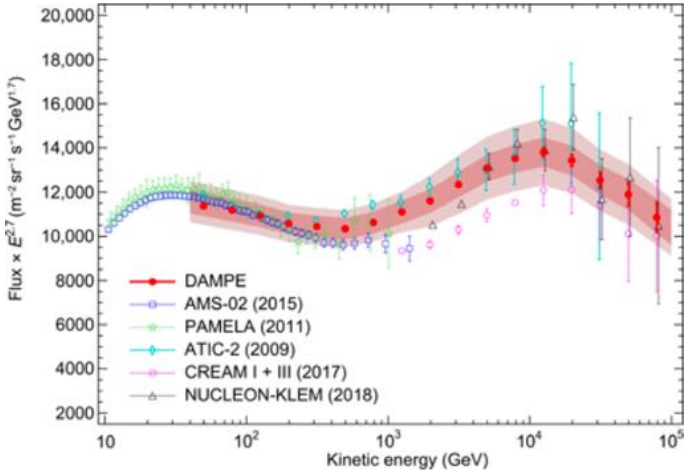
Searching for WIMP annihilation signatures

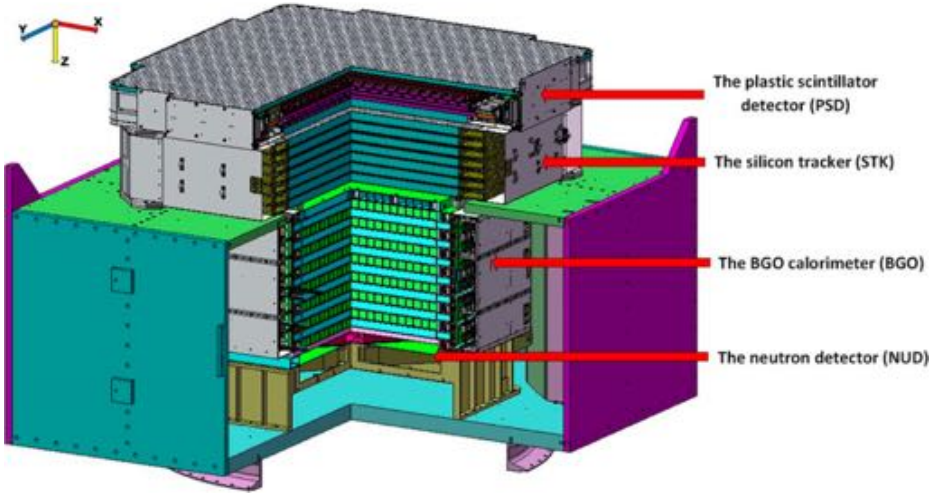
Origin of cosmic rays (TeV)

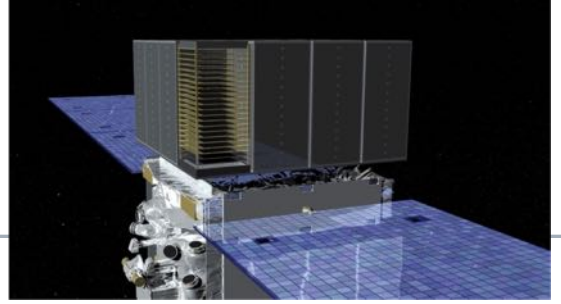
Cosmic ray measurements

Gamma-ray detector

Aims to follow on from Fermi & AMS-02 with higher precision







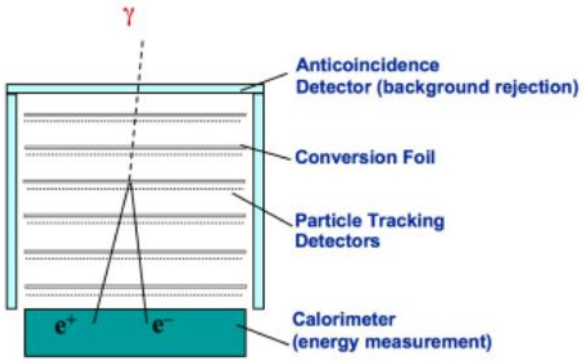
Fermi-LAT (Large Area Telescope)

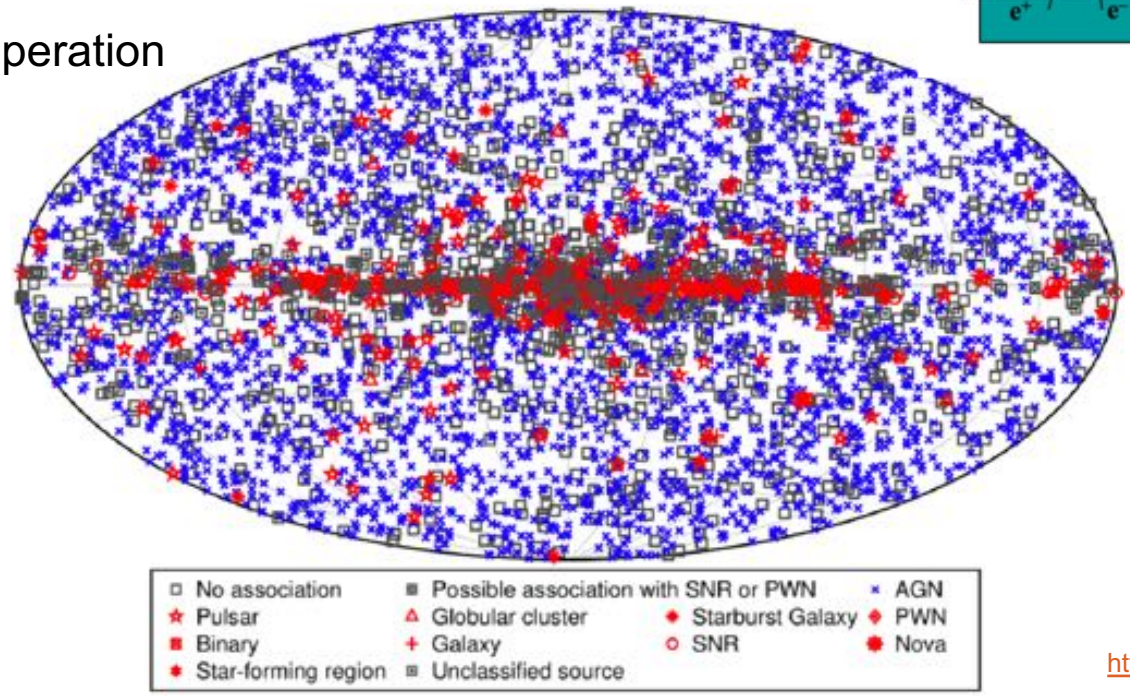
Pair-conversion Technique

Gamma-rays from MeV to ~2 TeV

Large number of sources and variety of source classes detected.

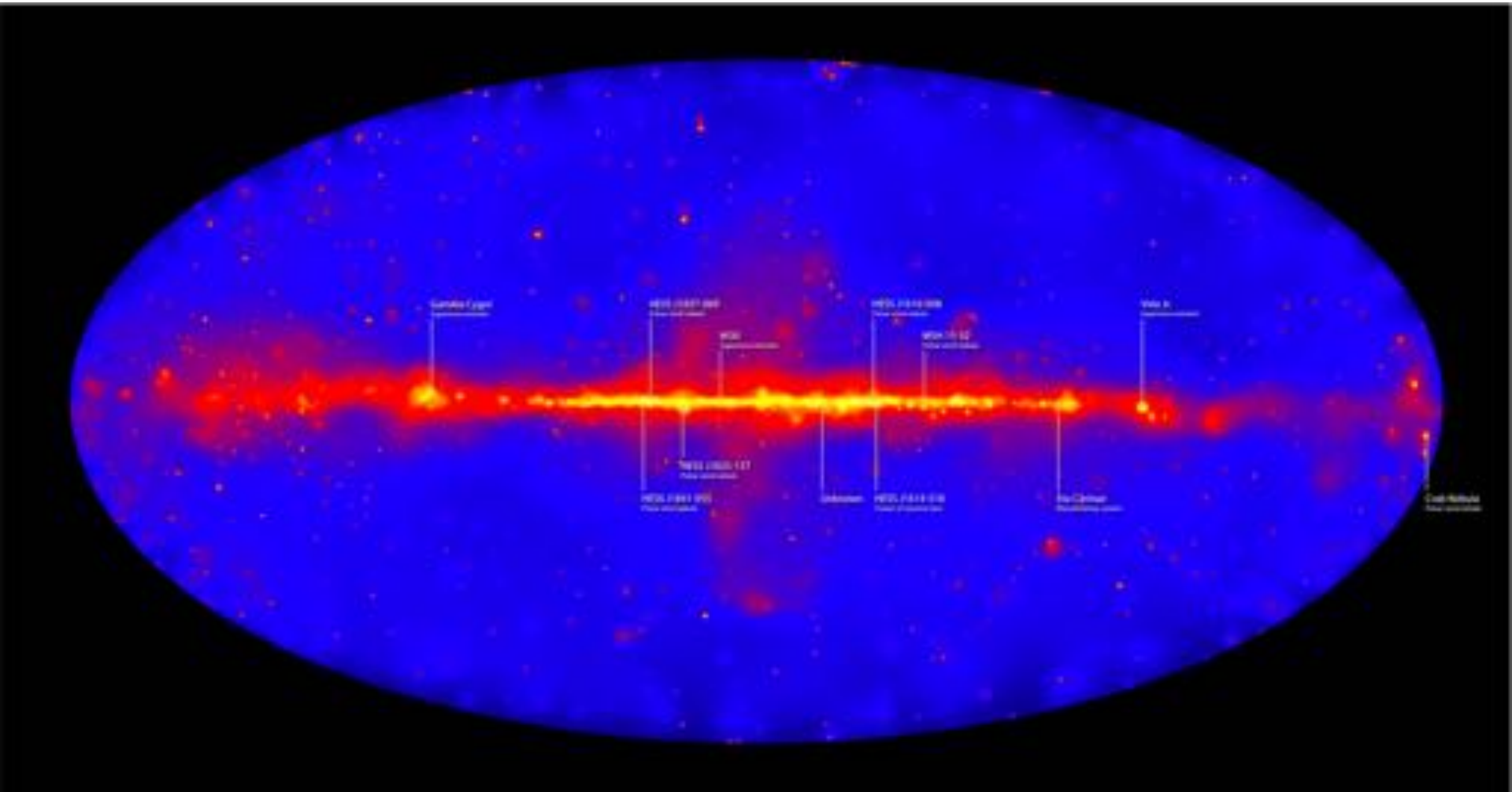
10 years of operation





https://fermi.gsfc.nasa.gov

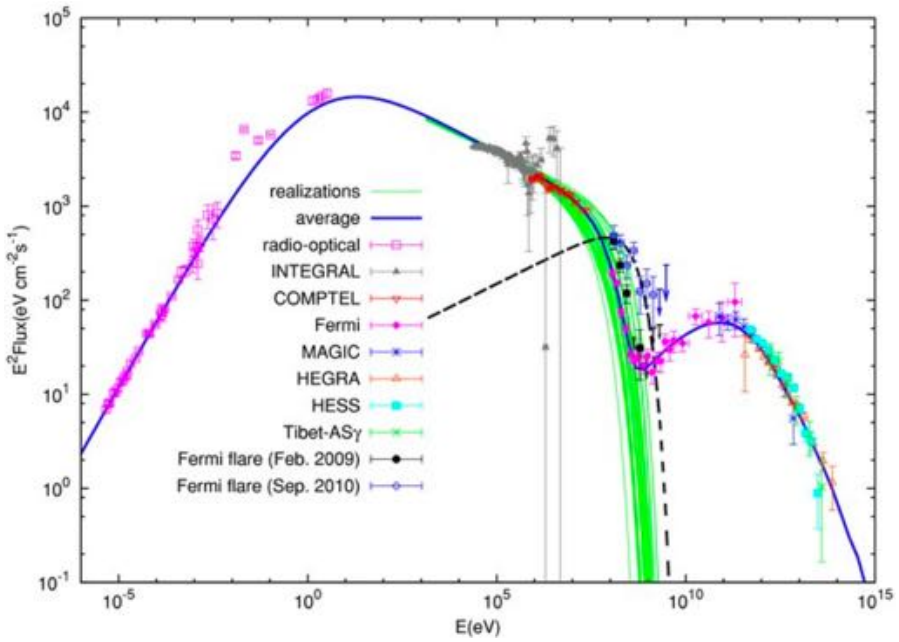
Fermi-LAT All Sky 6 year 50 GeV – 2 TeV

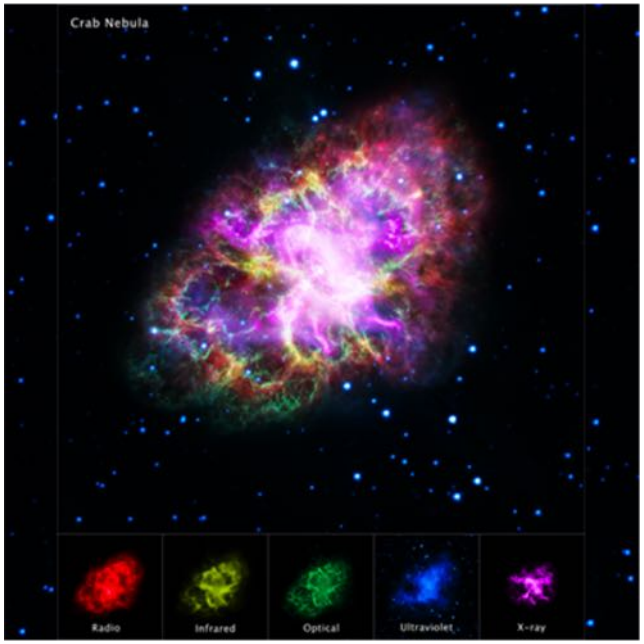


Multi-wavelength astronomy: Crab Nebula

Spectral Energy Distribution – need to combine observations across the full spectrum to build up a full picture.

Very different detection techniques, different standards, different units…



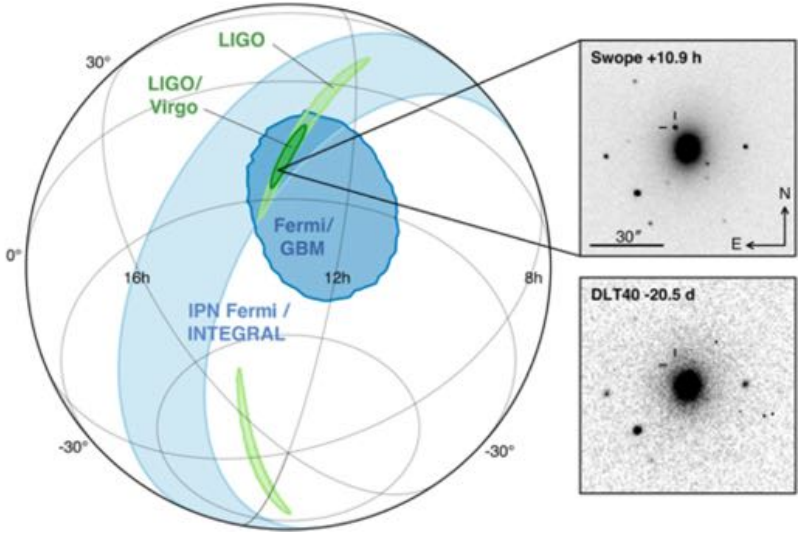


Multi-messenger astronomy: binary NS merger 17/08/17

Alerts need to be issued rapidly

Large position uncertainties problematic for sensitive follow up observations

Use educated guess where to look first, e.g. locations of known galaxies



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9
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OPEN ACCESS

Multi-messenger Observations of a Binary Neutron Star Merger*

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

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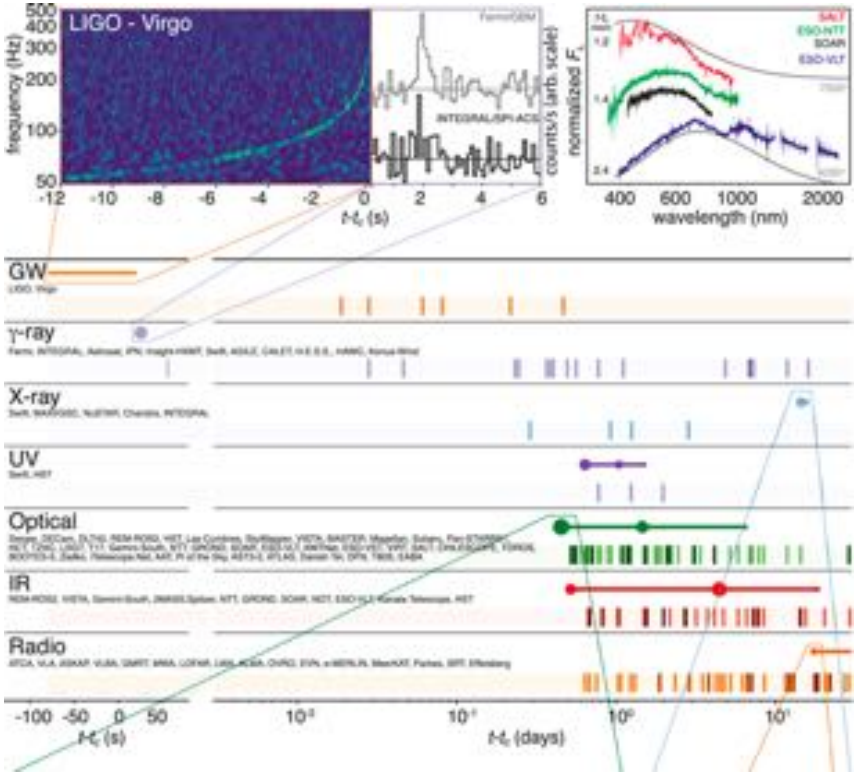
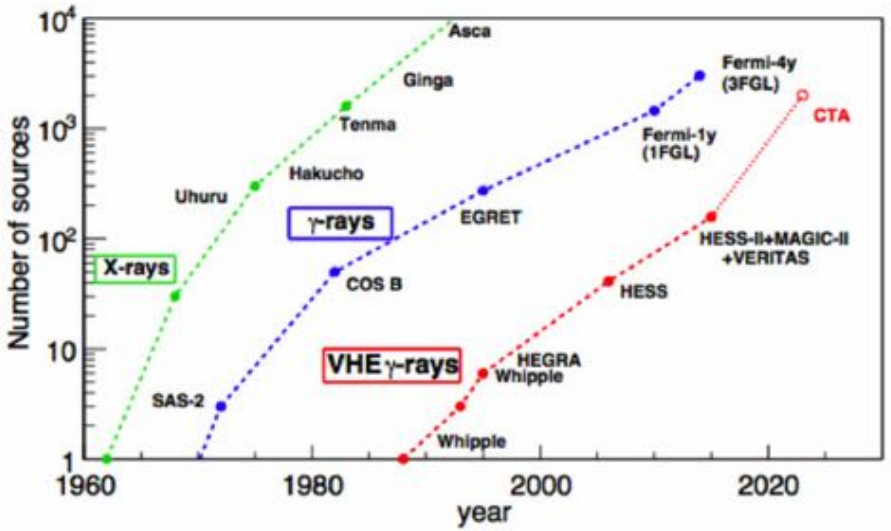


Future Experiments

Particle / Wavelength	Partially exists - ground	Planned - ground	Planned - satellite
Cosmic Ray	Auger-Prime		JEM-EUSO
Neutrino	KM3-NET, IceCube-gen2	GRAND, ARIANNA	
Gamma-ray	CTA	SWGO	
Gravitational Wave	IndIGO, Pulsar Timing Array	Einstein Telescope Cosmic Explorer	LISA, DECIGO



List of unsolved problems

Origin of UHECR beyond the GZK cut-off?

Why are there more muons than expected in UHECR air showers?

Origin of Galactic cosmic rays reaching PeV energies?

What is the nature of the Galactic – extragalactic transition?

What are the unidentified sources of gamma-rays?

What is the cause of the positron excess?

…

Thank you for your attention

Any questions?