The Extreme Universe in Gamma rays

From Cosmic Accelerators to New Physics

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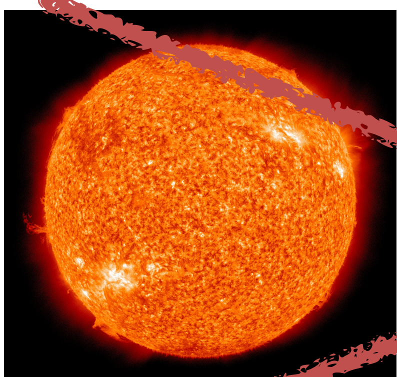
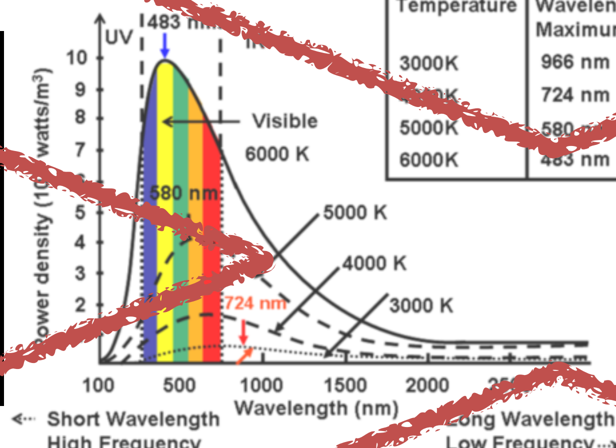
Non-thermal Photons

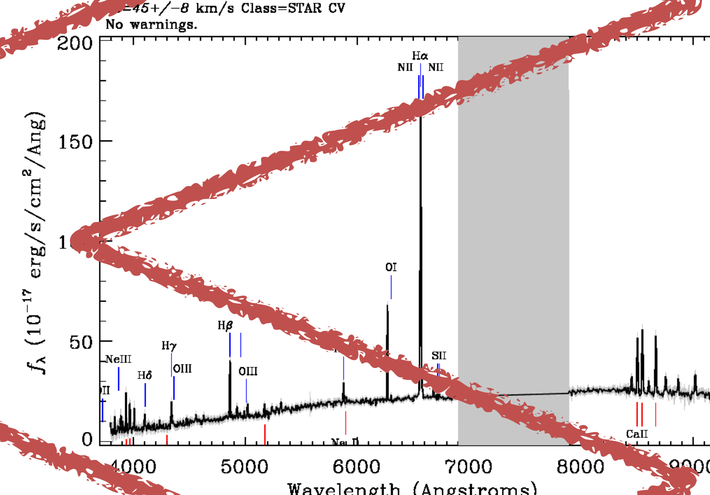
Black-body radiation (continuum)





Temperature	Wavelength for Maximum Intensity	
3000K	966 nm	(IR)
4000K	724 nm	(Red)
5000K	580 nm	(Yellow)
6000K	483 nm	(Blue)

Line emission (strictly not-continuum but usually observed from heated gases)

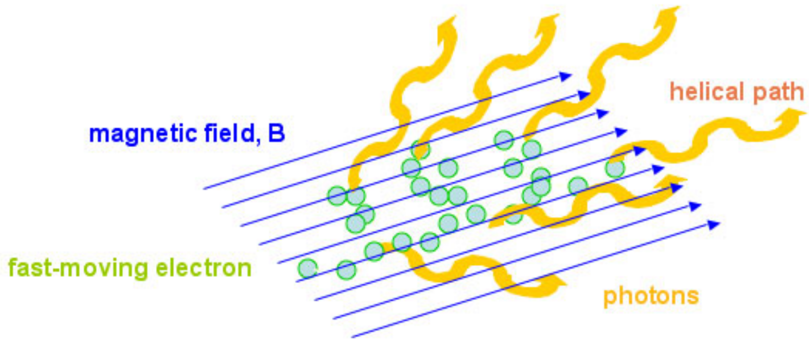


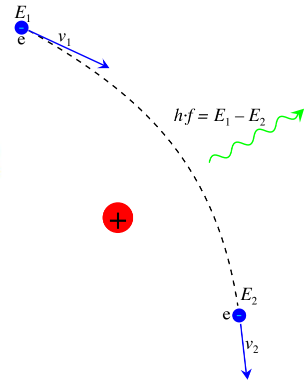
+ Free-free emission (aka thermal bremsstrahlung)

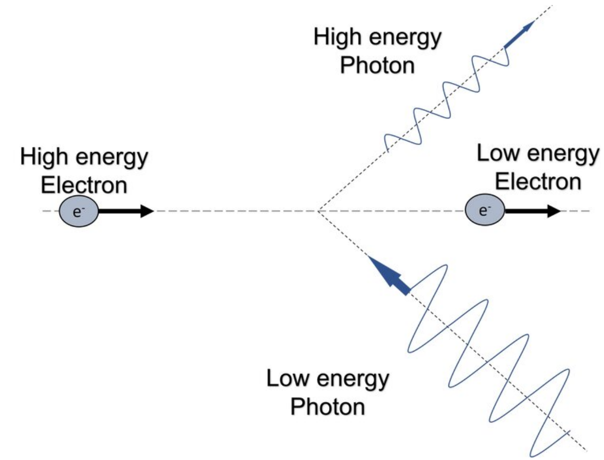
Non-thermal emission

- **Non-thermal**
  - Accelerated particles emit photons
  - Power-law emissions
- **Which particles?**
  - Leptonic (electrons)
  - Hadronic (protons)

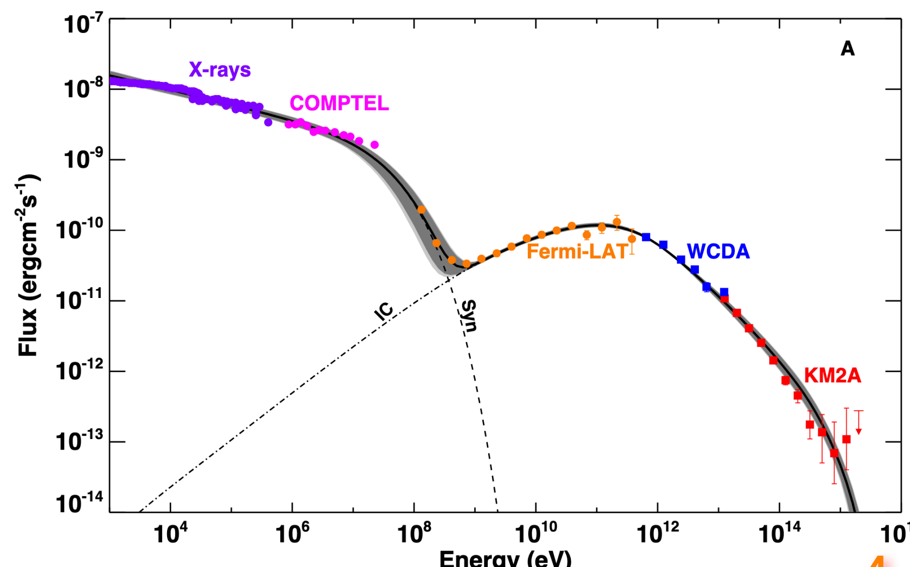
Leptonic Emission



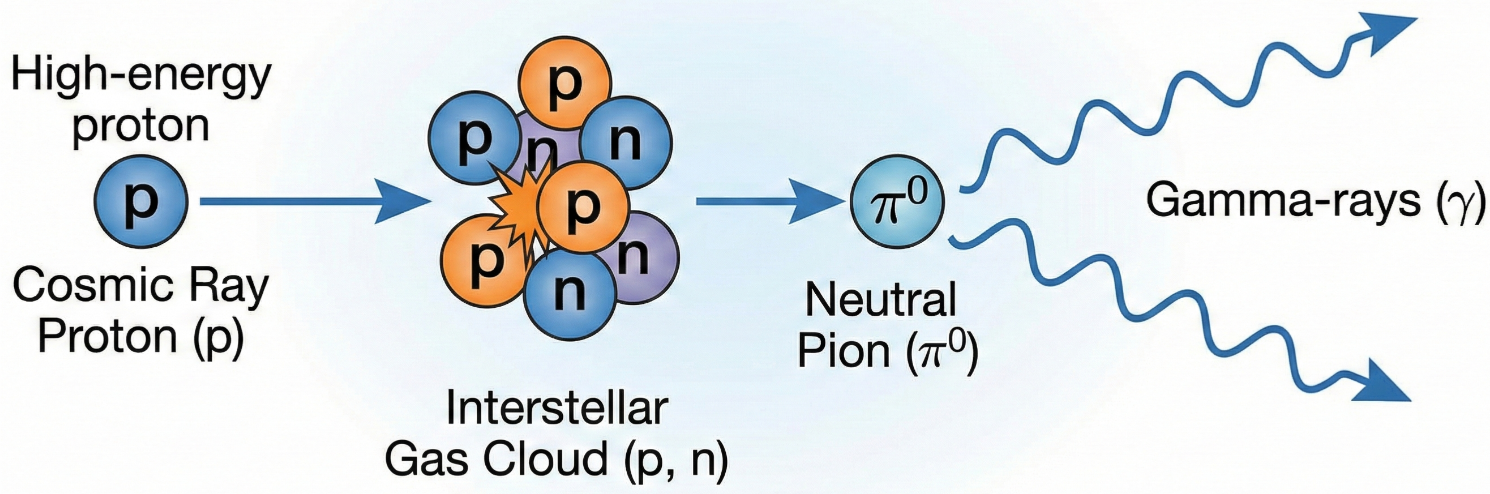




- Synchrotron radiation (radio to X-ray)
- Braking Radiation (Gamma-ray)
  - Negligible if there is not many ambient hadrons.
- Inverse Compton scattering (Gamma-ray)
- Crab Nebula's X-ray-to-Gamma-ray spectrum ->
  - Very young pulsar wind nebula
  - High B-field and extremely energetic rotation
  - Its supernova SN1054 was recorded by medival Chinese and Japanese.



Hadronic Emission

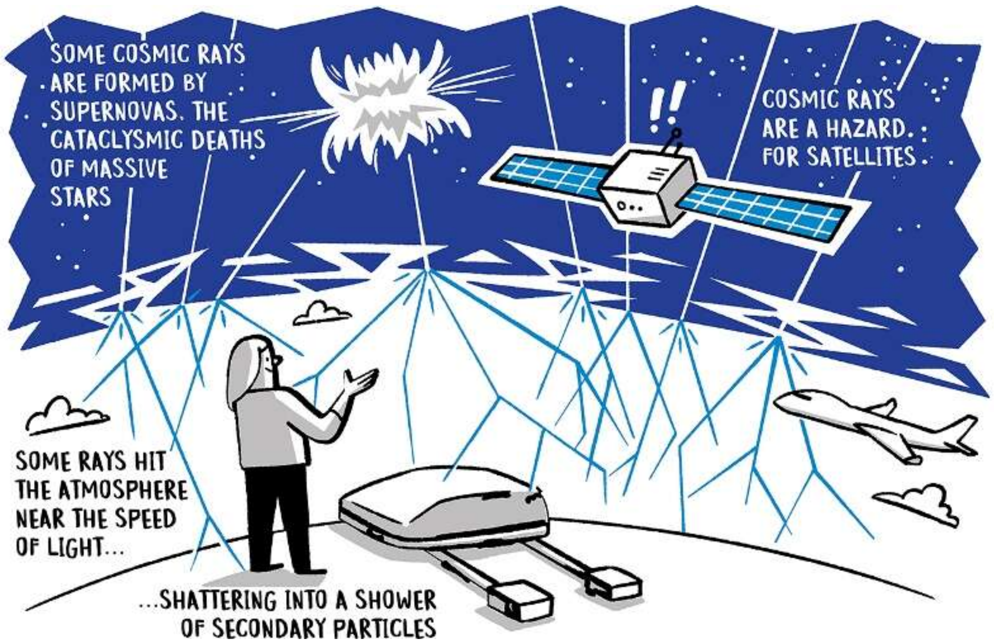


$$p + p \to p + p + \pi^0 + \ldots \to \gamma + \gamma$$

- Inelastic collisions of high-energy cosmic rays and ambient gases produce pions.
- $\pi^0 \to \gamma + \gamma \quad | \quad E_\gamma \approx \frac{1}{12} E_p$
- $\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \quad | \quad E_\nu \approx \frac{1}{24} E_p$

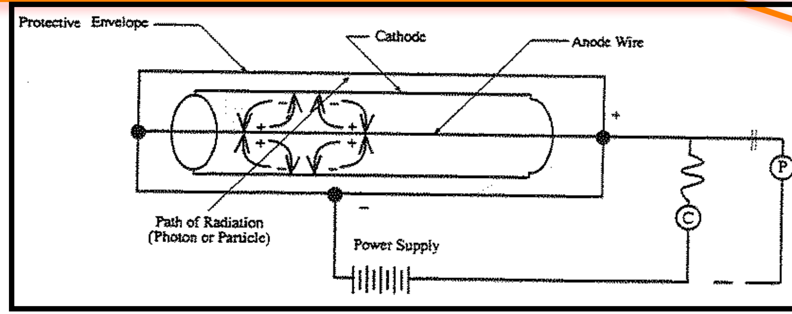
Historical Overview

Cosmic ray physics



https://www.iop.org/explore-physics/physics-around-you/understanding-surroundings/cosmic-rays

Cosmic Ray



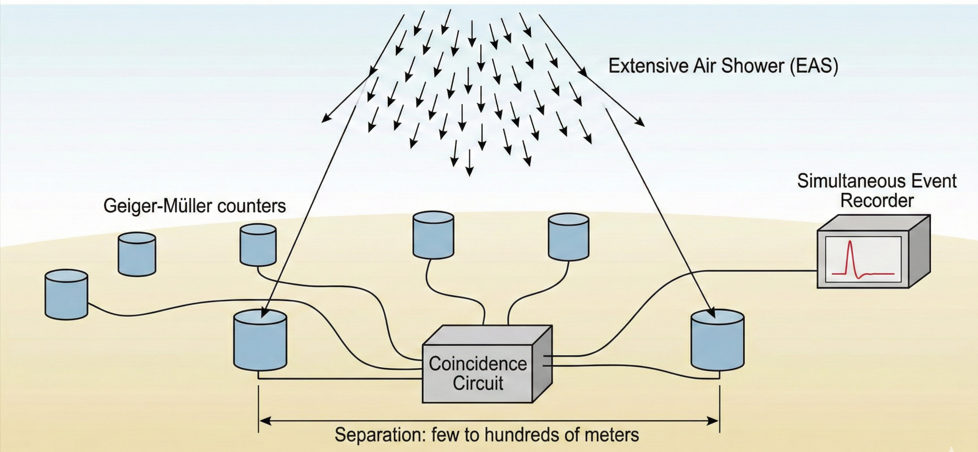
Particle	Discovery
Positron	1932, C. Anderson, First discovery of antimatter cloud chamber. 4 years later from Dirac's prediction
Muon	1936, C. Anderson, First discovery of 2nd gen. cloud chamber. *I. Rabi: "Who ordered that?"*
Pion	1947, C. Powell, First discovery of meson High-altitude nuclear emulsion filmed
Kaon, Lambda	1950, First discovery of 2nd gen quark. Cloud chamber & Bubble chamber

- This field is called "cosmic-ray physics".
- The field started from the measurement of **charged** particles from the upward by Victor Hess. This is cosmic ray.
- And.. it was actually experiemental particle physics til early 1950… Later is the era of accelerators.
- From 50s, cosmic-ray physics became more astrophysical.

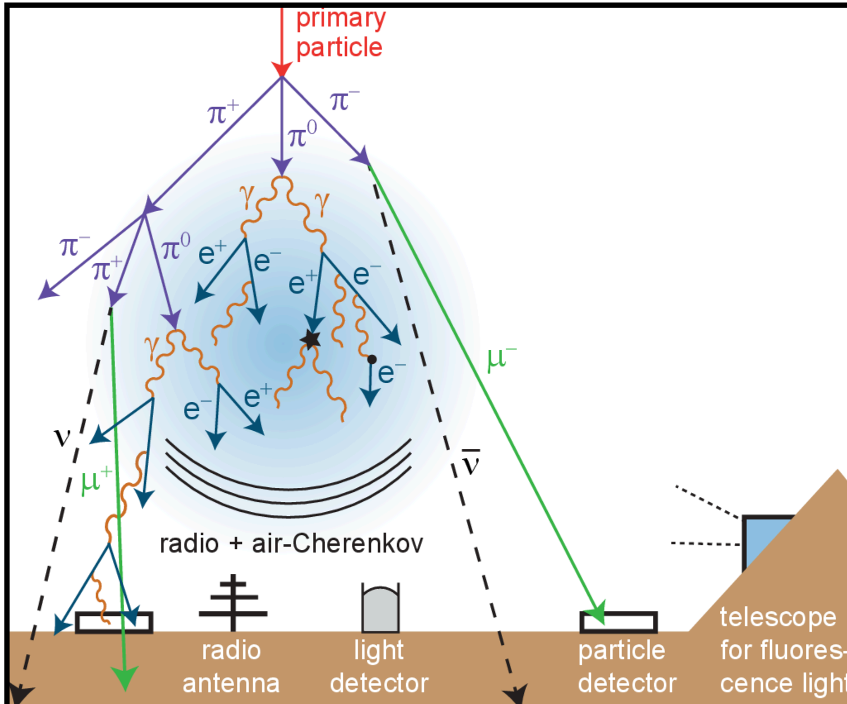
Extensive Air Shower (EAS)

- Pierre Auger found 'extensive air shower' (1938).
- High-energy particles collide with atmosphere and produce EAS, consisting of lots of particles.
- Coincidence circuit with multiple Geiger counters

Pierre Auger's Original Coincidence Experiment (c. 1938) - Discovery of Extensive Air Showers



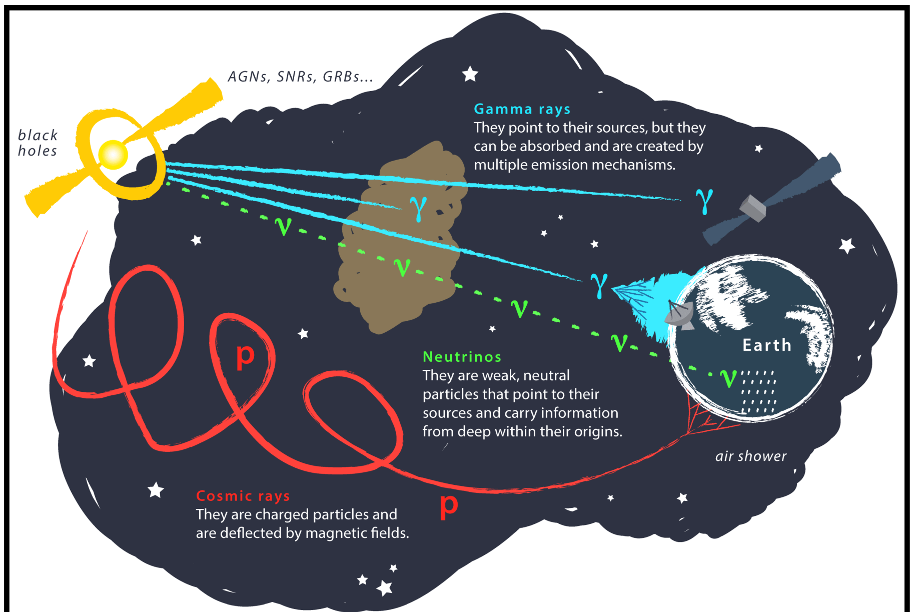
Pierre Auger's Original Coincidence Experiment (c. 1938) - Discovery of Extensive Air Showers

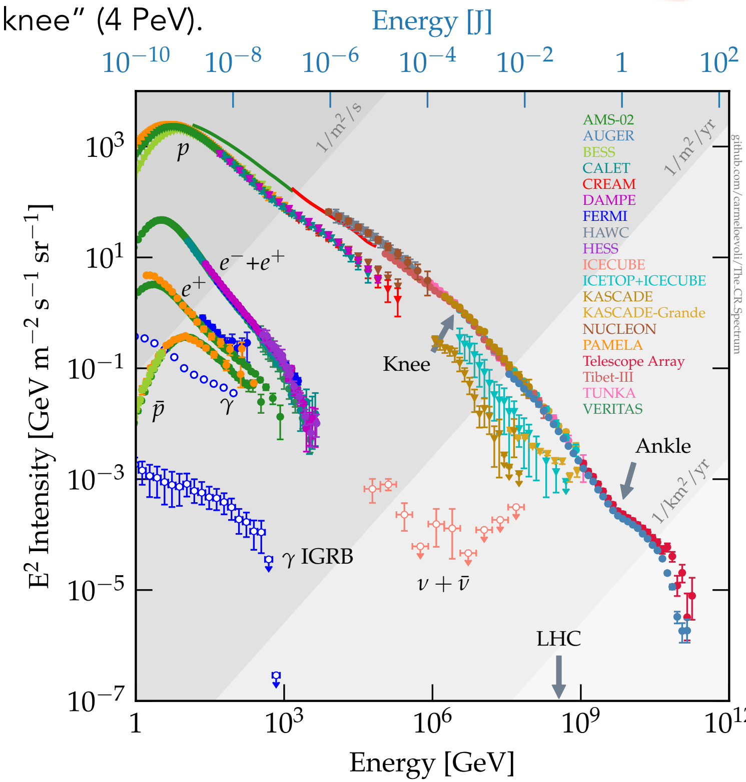


- This idea is still valid! We have two modern EAS observatories:
- *Pierre Auger Observatory (Argentina)*, 3000 km^2 *(5 times bigger than Seoul*, 600 km^2*)*
- *Telescope Array (USA)*, 700 km^2

Cosmic Ray Spectrum

- Precise measurements of cosmic ray spectrum by reconstructing EAS.
- Roughly power-law, but there are some spectral changes. One of them is the “knee” (4 PeV).
- Who accelerate cosmic rays to the knee? We called those as ‘PeVatron’.
- You cannot directly localise them since those are deflected by the B-field.



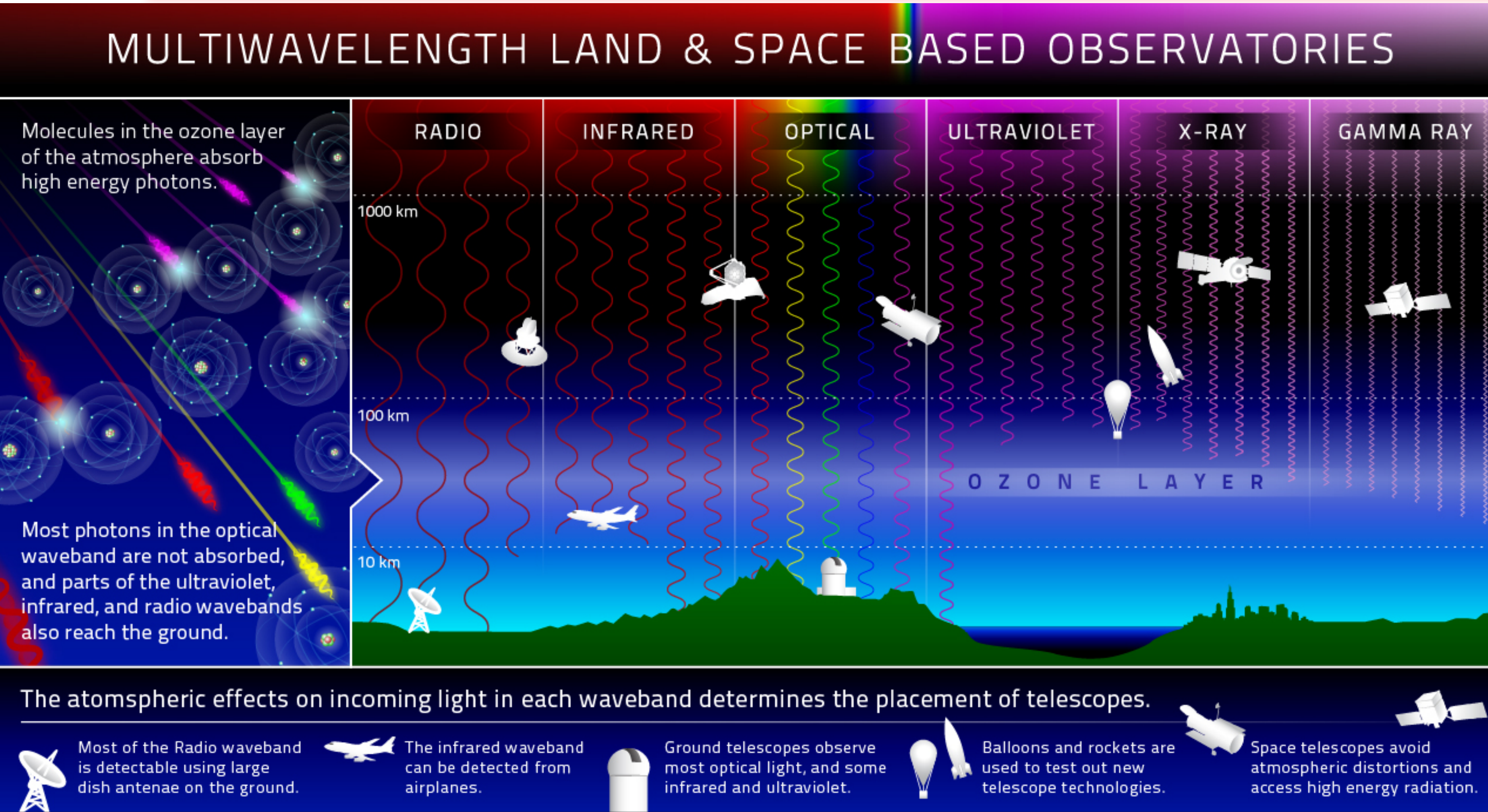


- We can indirectly find them by observing neutral particles from them. Cosmic-ray physics -> Astroparticle physics

Gamma-ray Observatory

The Southern Wide-field Gamma-ray Observatory

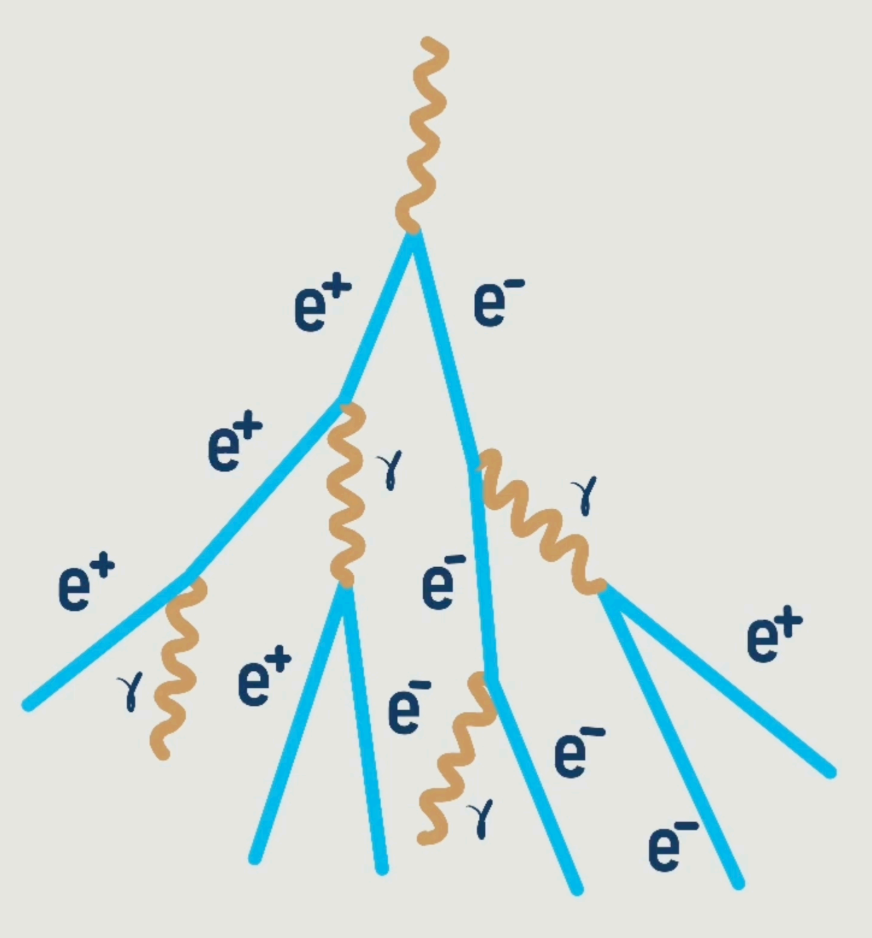
Very-High Energy (VHE; > 300 GeV) astronomy

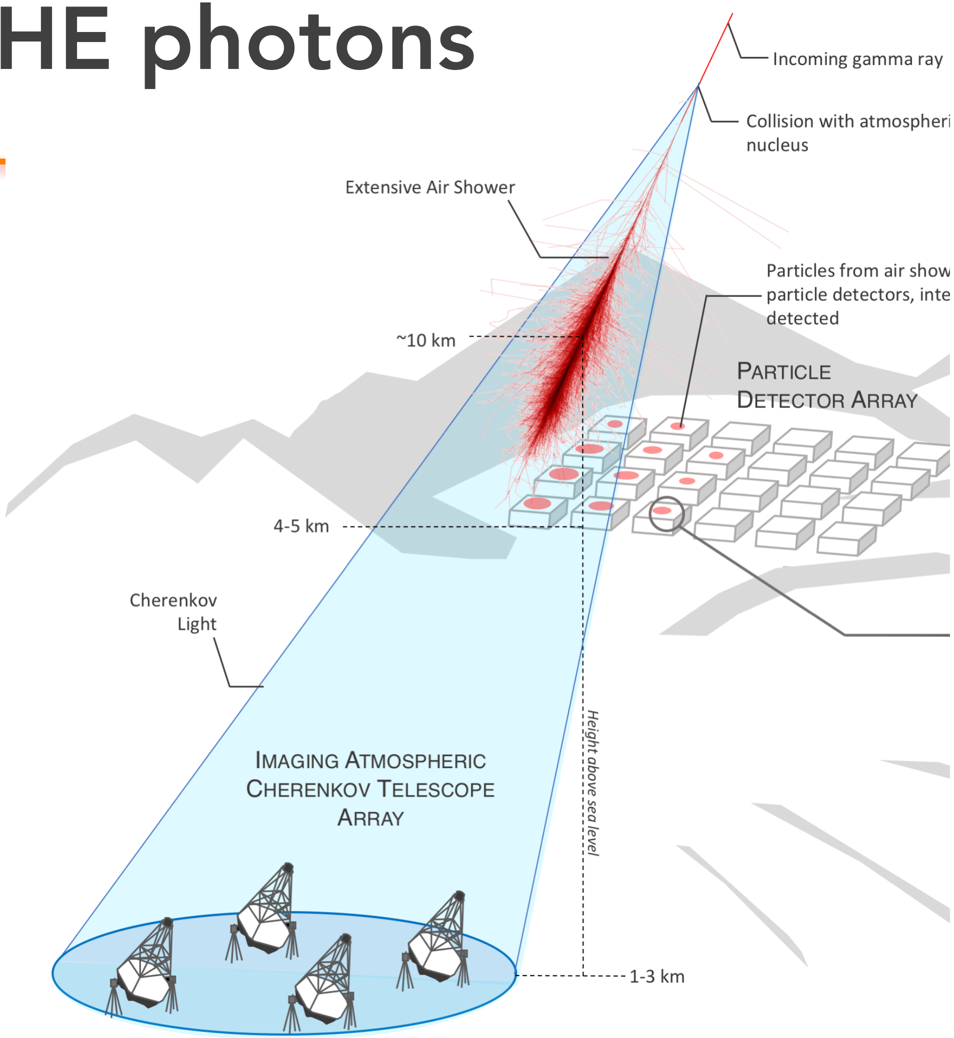


VHE

We are studying here!

Detecting VHE photons





Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

$\gamma - h$ Separation

$$\mathrm{LIC} = \log_{10} \frac{\mathrm{CxPE_{40m}}}{N_{\mathrm{hit}}}$$

$\mathrm{CxPE_{40m}}$ is the largest effective charge far (>40 m) from the shower core.

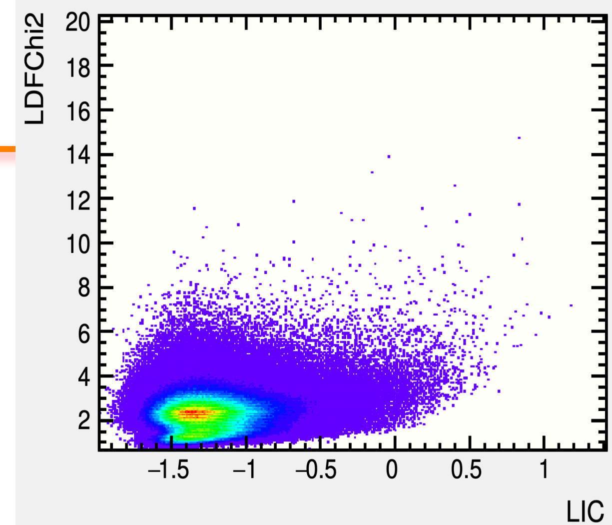
-> Muons (rich in hadronic showers) cause large $\mathrm{CxPE_{40m}}$.

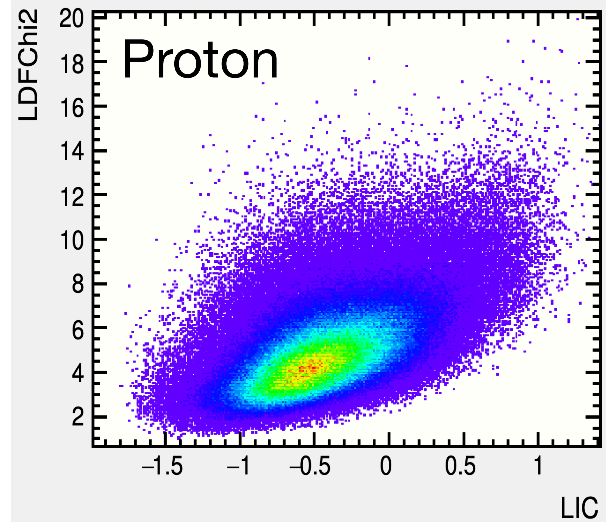
-> High LIC for hadron-induced showers

LDFChi2 is the reduced χ^2 from the lateral distribution function (LDF) fit, describing how the number of particles or radiation varies with the distance from the shower core.

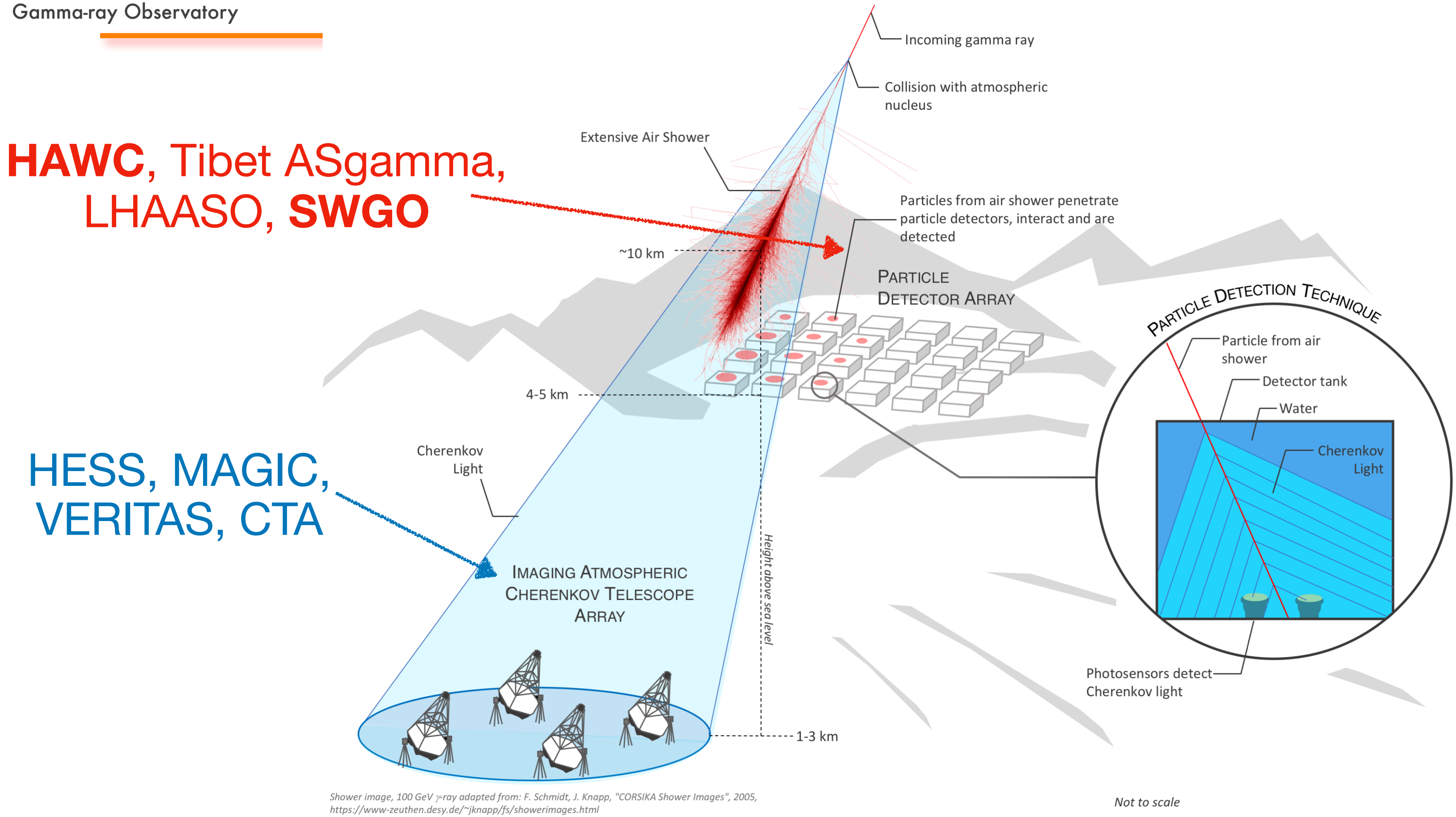
-> Gamma-induced showers are concentrated near the shower axis.

-> Low **LDFChi2** for gamma-induced showers

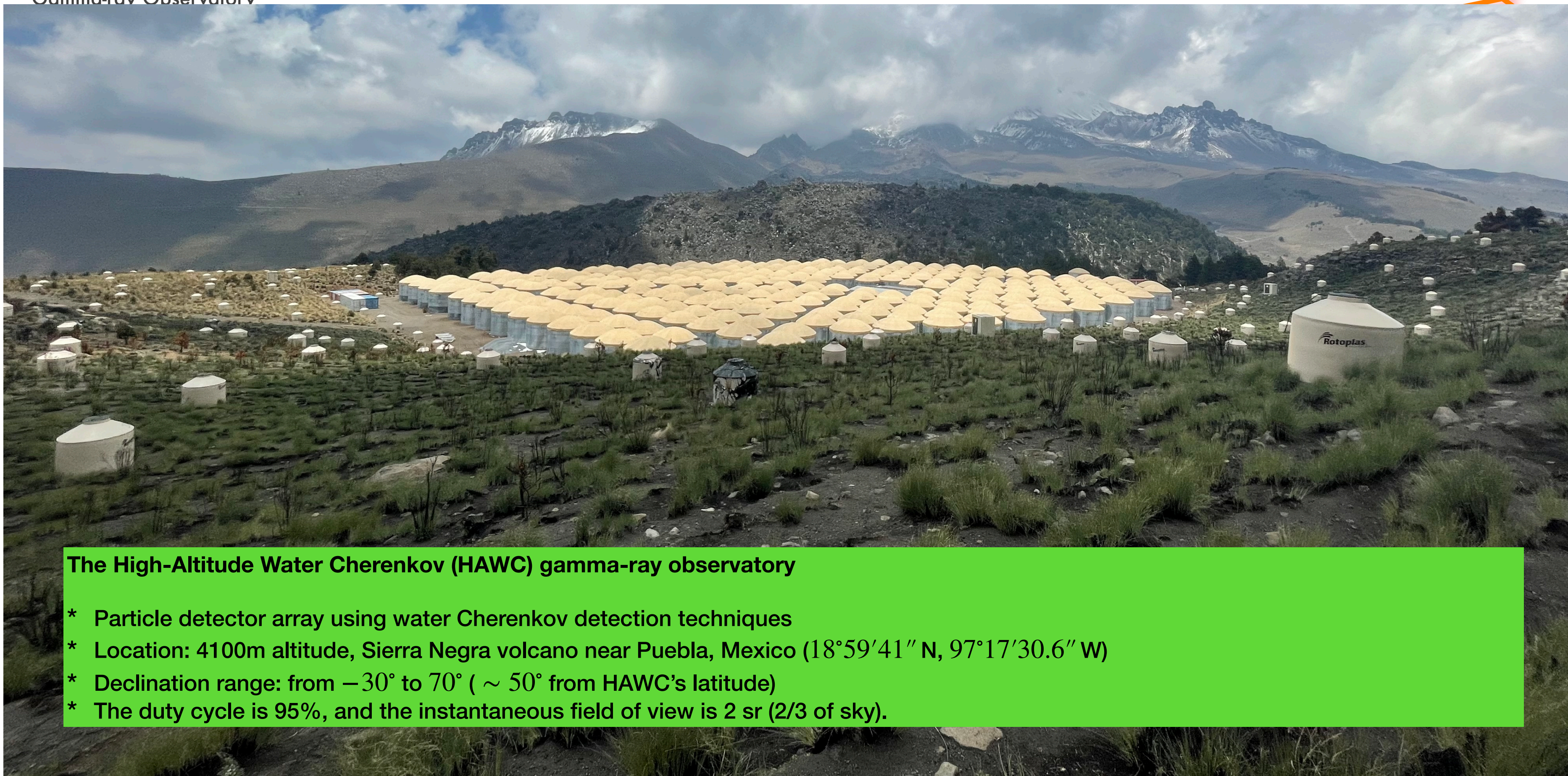




Detecting VHE photons



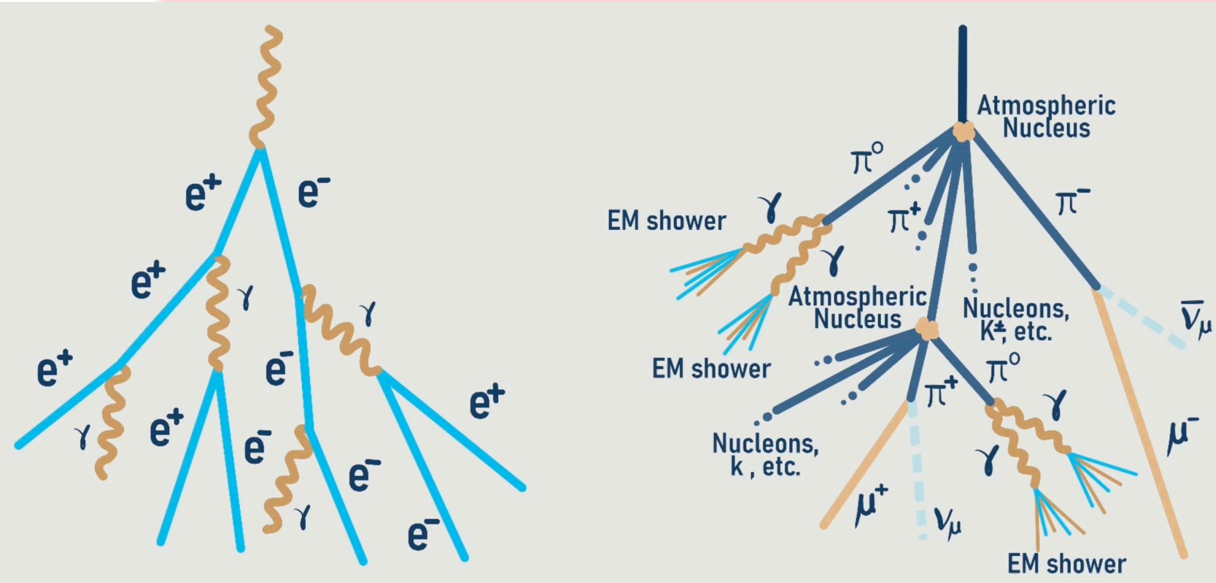
The HAWC Observatory



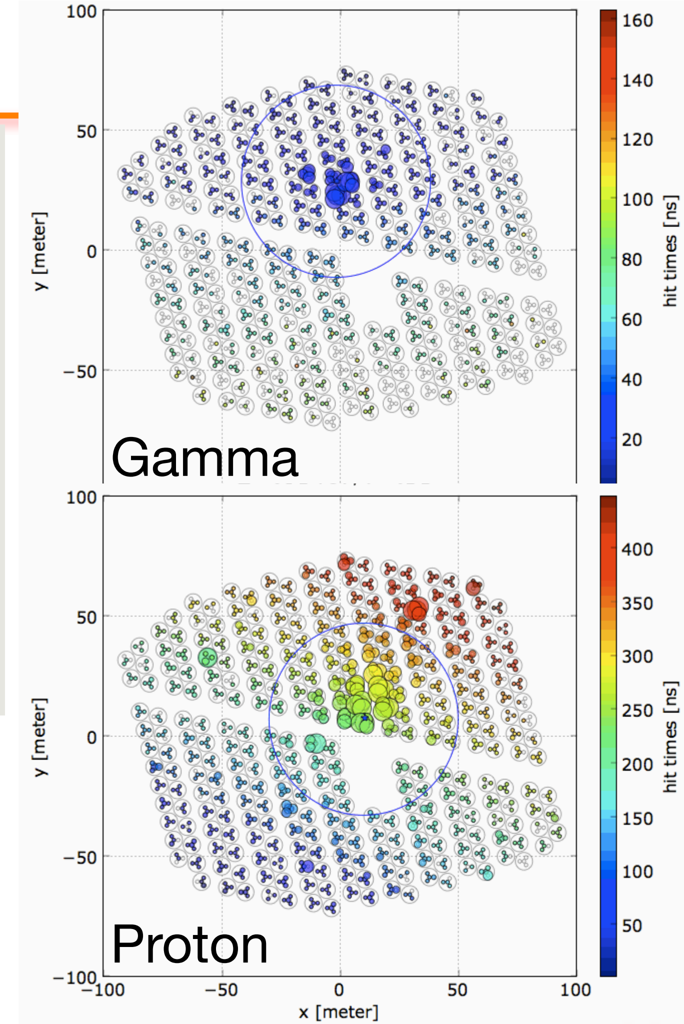
The High-Altitude Water Cherenkov (HAWC) gamma-ray observatory

* Particle detector array using water Cherenkov detection techniques
* Location: 4100m altitude, Sierra Negra volcano near Puebla, Mexico ($18°59'41''$ N, $97°17'30.6''$ W)
* Declination range: from $-30°$ to $70°$ ($\sim 50°$ from HAWC's latitude)
* The duty cycle is 95%, and the instantaneous field of view is 2 sr (2/3 of sky).

$\gamma - h$ Separation



$$\gamma : h \sim 1 : 1000$$



γ Reconstruction

Three main parameters are needed for the high-level analysis:

* Core: Center of the shower -> This affects the reconstruction performance; therefore, it is a main binning variable.

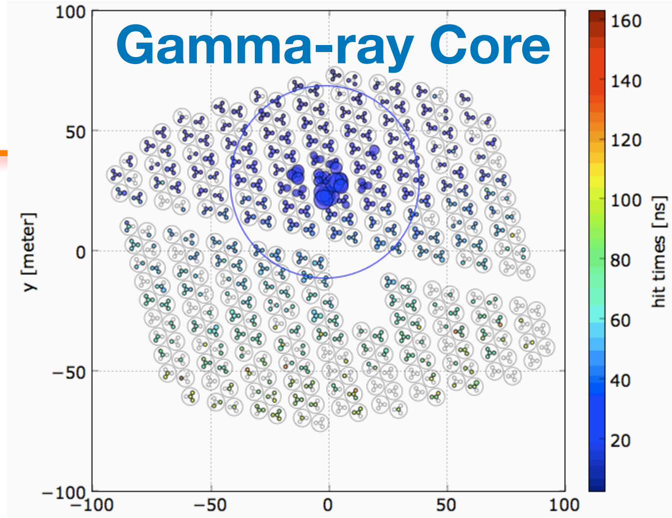
* Primary direction: The directional vector is fitted by minimizing

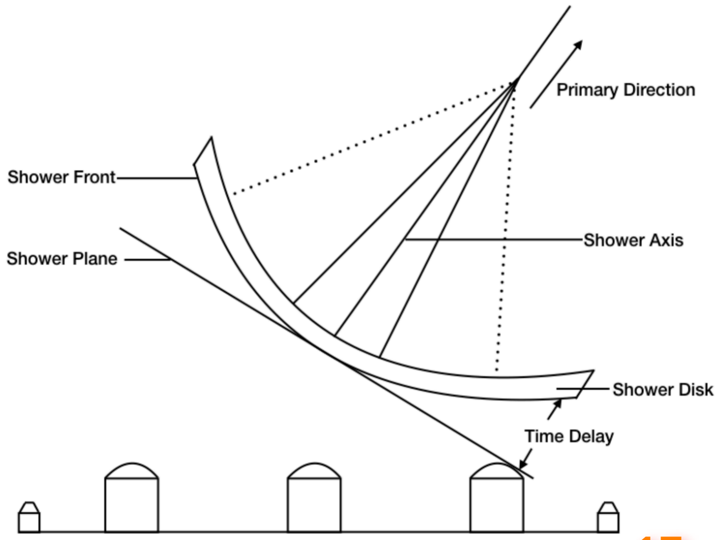
$$\chi^2 = \sum_{n=1}^{N} w_n \left(ct_n - ct_0 + \vec{i}x_n + \vec{j}y_n + \vec{k}z_n \right)^2.$$

For n-th PMT, $c(t_n - t_0)$ is the relative trigger time,
w_n is the weight (inverse log-charge),
(x_n, y_n, z_n) is the PMT position.

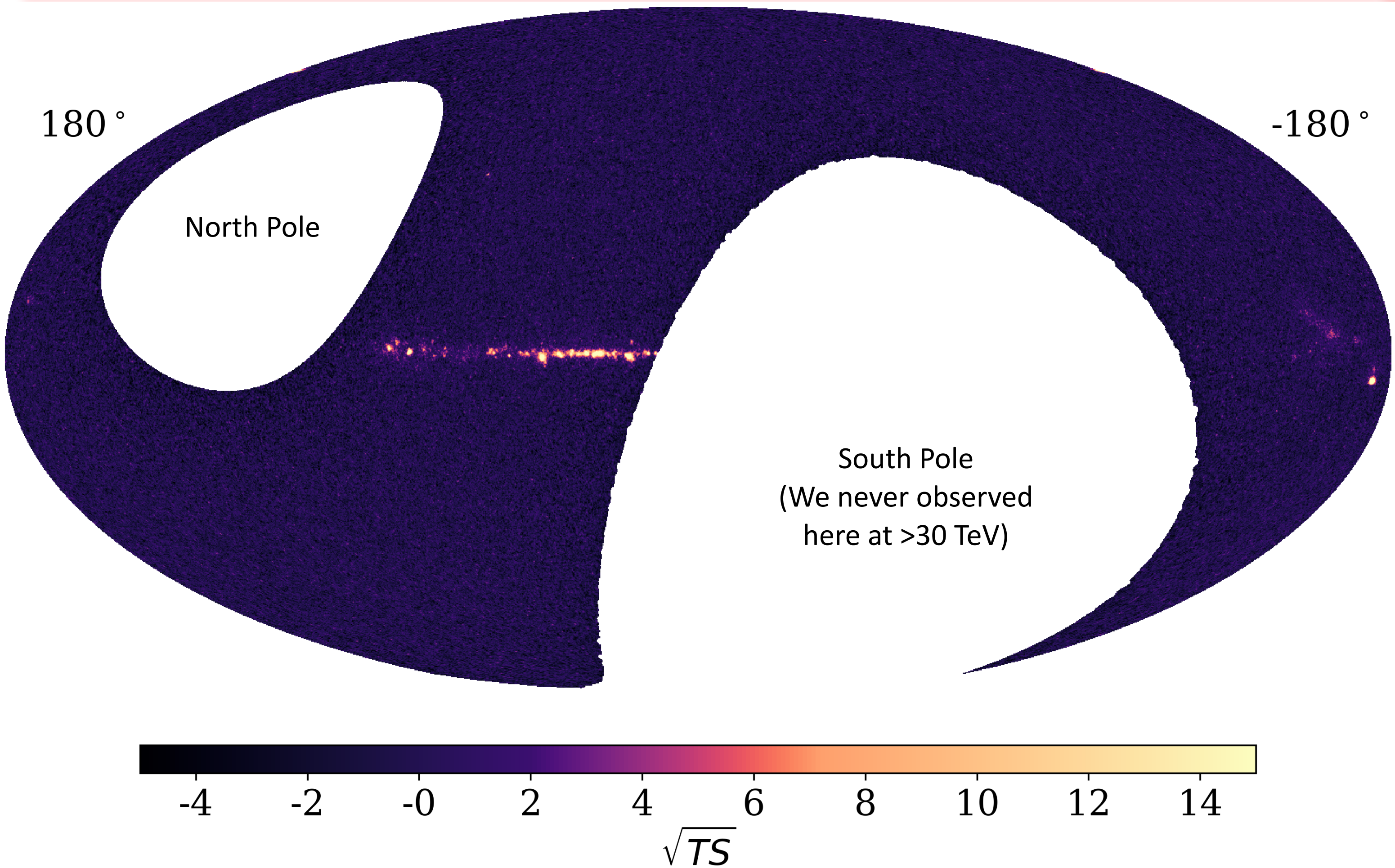
$$(\vec{r} = \cos\theta \sin\phi \vec{i} + \sin\theta \sin\phi \vec{j} + \cos\theta \vec{k})$$

* Primary energy: GP (from shower function fitting) and NN (neural net)



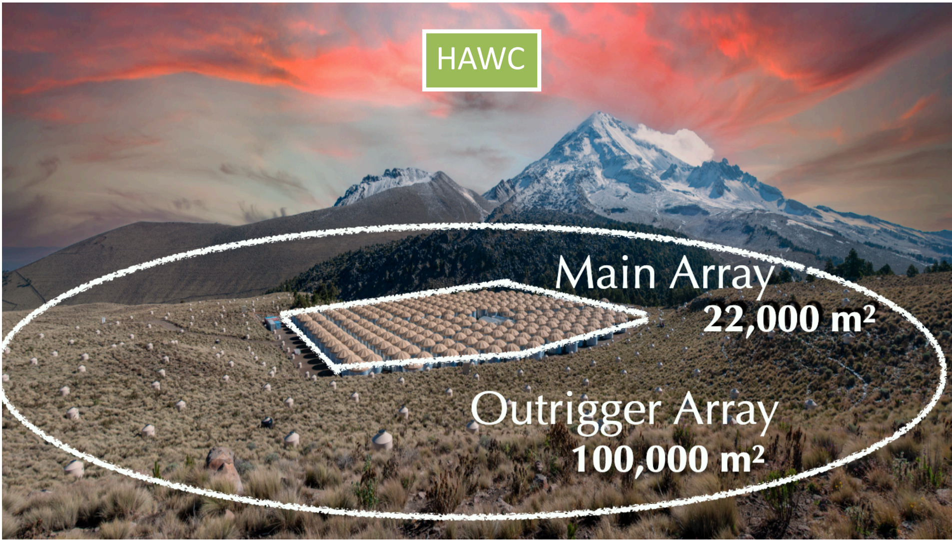


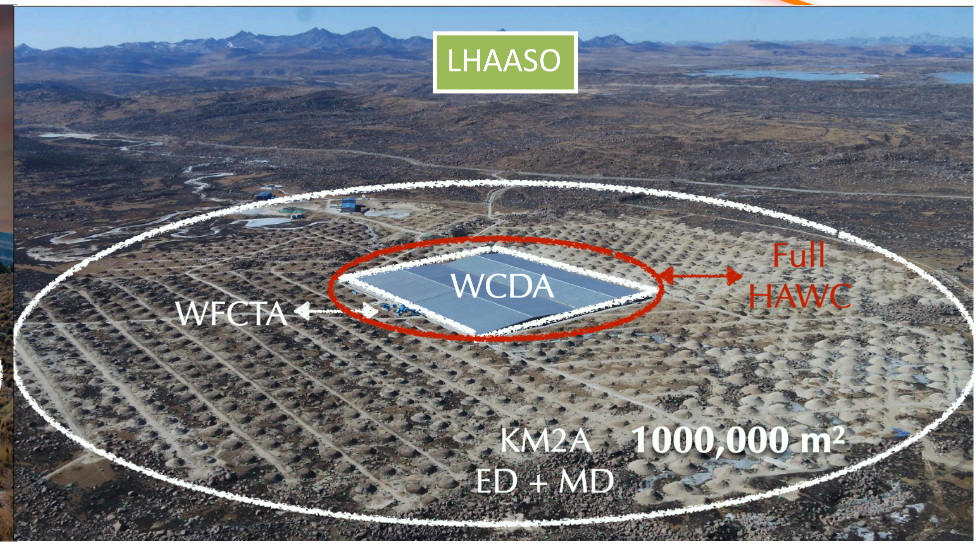
HAWC Sky (1-316 TeV)



LHAASO Era

Large High Altitude Air Shower Observatory

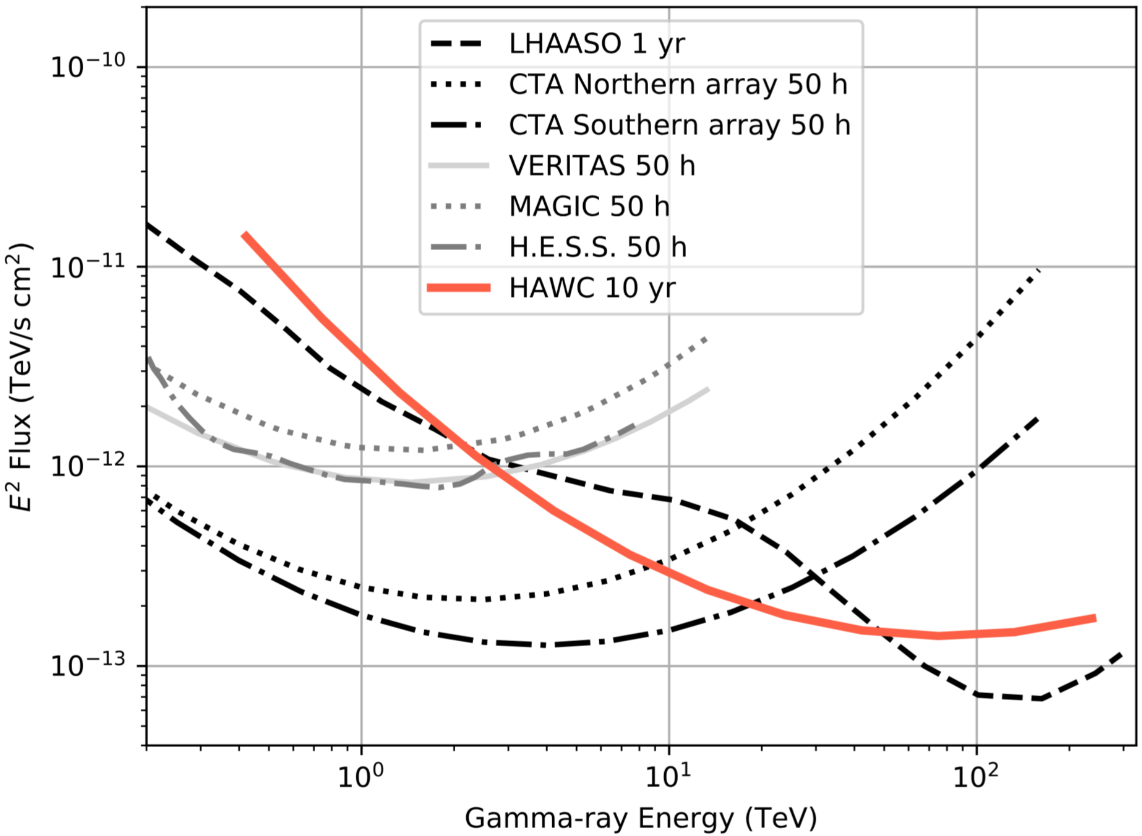




Experiment	Duration	Altitude& Declination coverage	Number of discovered sources
HAWC	Main: March 2015- Outrigger: September 2018-	Altitude: 4100 m a.s.l. Declination: -29-67 deg	85 sources above 4-sigma (7.5 yrs)
LHAASO	WCDA: March 2021- KM2A: January 2020-	Altitude: 4410 m a.s.l. Declination: -20-80 deg	90 sources above 5-sigma (WCDA 1.4 yrs, KM2A 2.5 yrs)

SWGO
The Southern Wide-field Gamma-ray Observatory

LHAASO Era

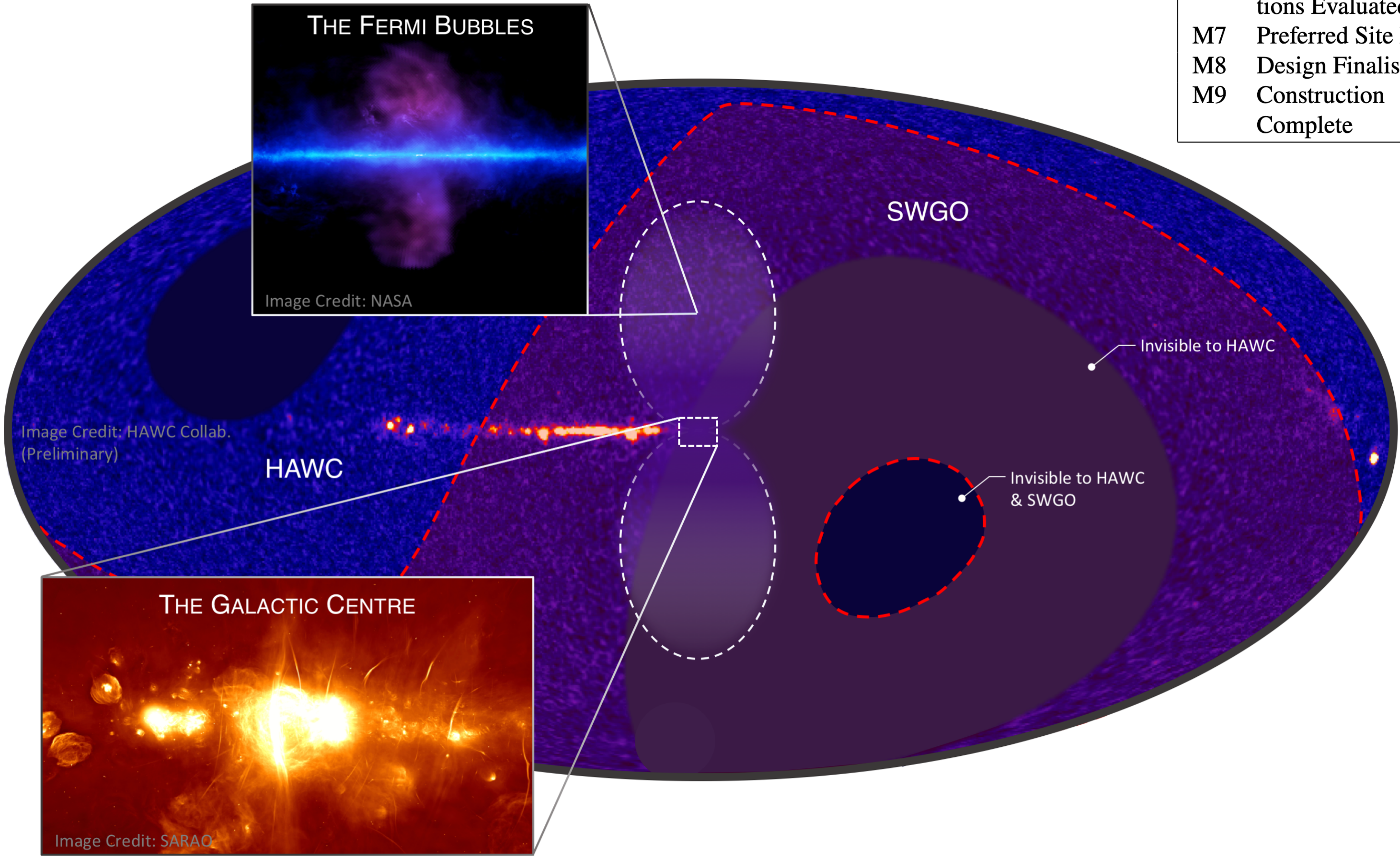


HAWC is too small to compete with LHAASO. But we have a blue ocean, the southern hemisphere.

SWGO Project

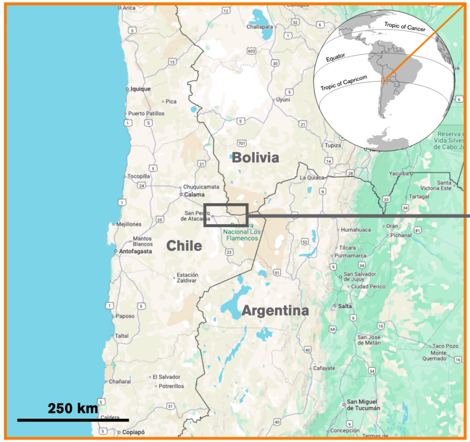
Southern Wide-field Gamma-ray Observatory

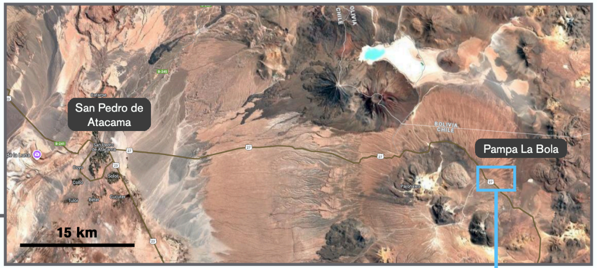
	Milestone	Completed
M1	R&D Phase Plan Established	Q1 2020
M2	Science Benchmarks Defined	Q2 2020
M3	Reference Configuration & Options Defined	Q4 2020
M4	Site Shortlist Complete	Q3 2022
M5	Candidate Configurations Defined	Q1 2022
M6	Performance of Candidate Configurations Evaluated	Q3 2023
M7	Preferred Site Identified	Q2 2024
M8	Design Finalised	-
M9	Construction & Operation Proposal Complete	-

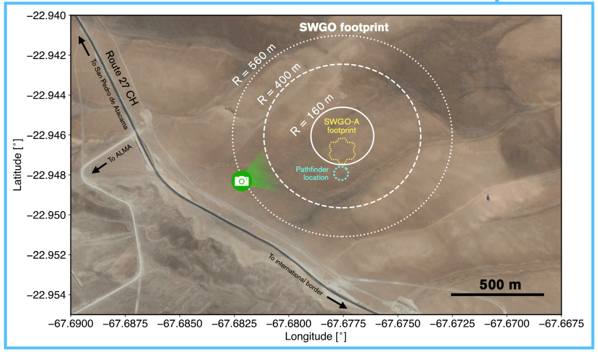


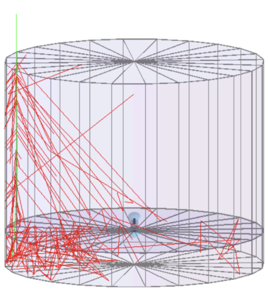
SWGO
The Southern Wide-field Gamma-ray Observatory

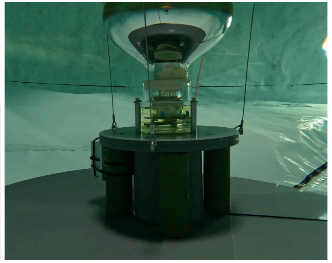
SWGO Project

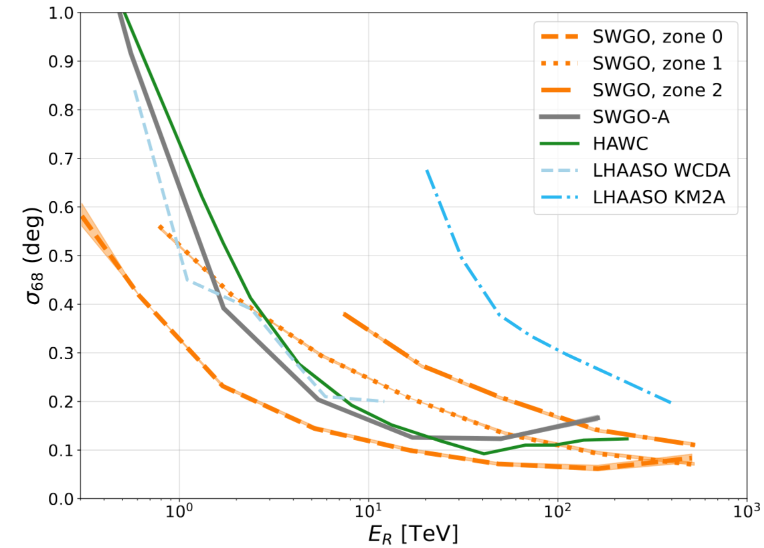


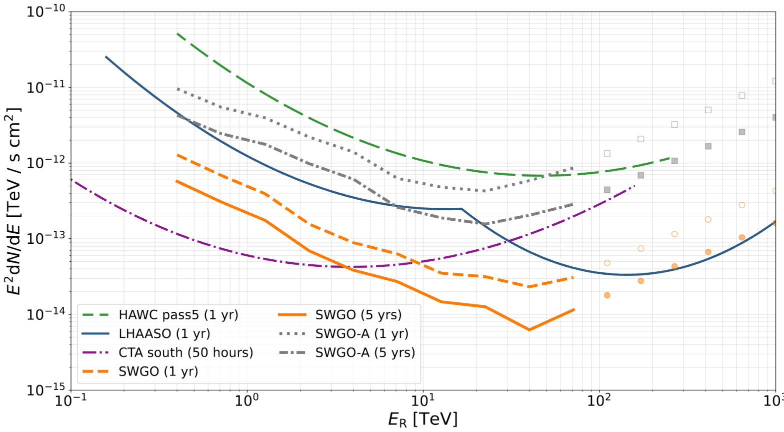








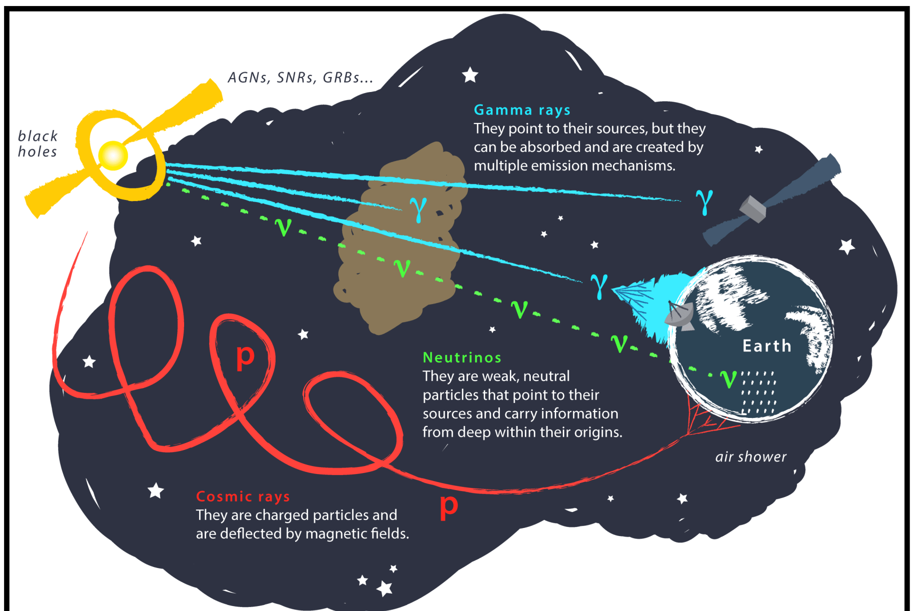


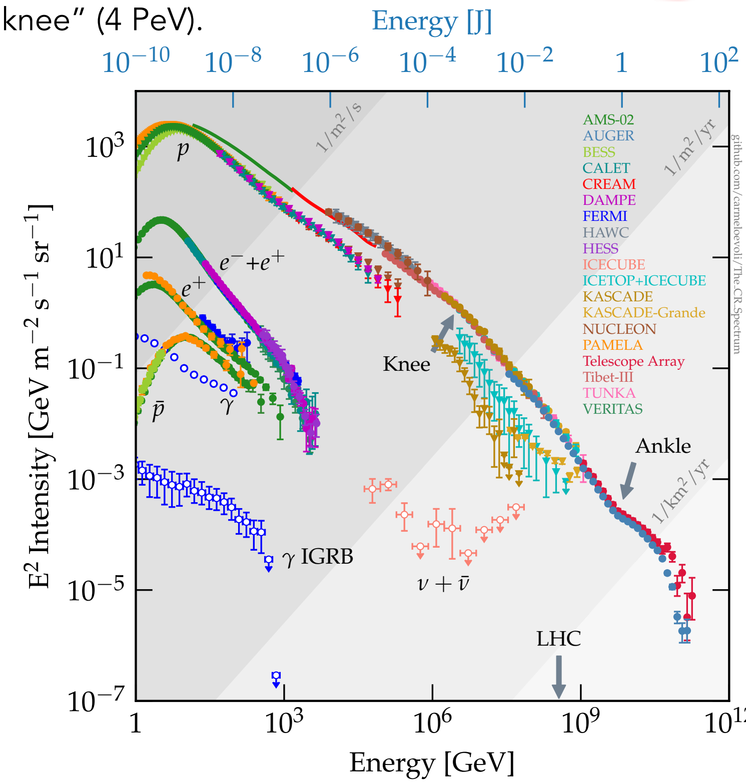


Who can accelarate energetic particles?

PeV Cosmic Ray Knee

- Precise measurements of cosmic ray spectrum by reconstructing EAS.
- Roughly power-law, but there are some spectral changes. One of them is the “knee” (4 PeV).
- Who accelerate cosmic rays to the knee? We called those as ‘PeVatron’.
- You cannot directly localise them since those are deflected by the B-field.

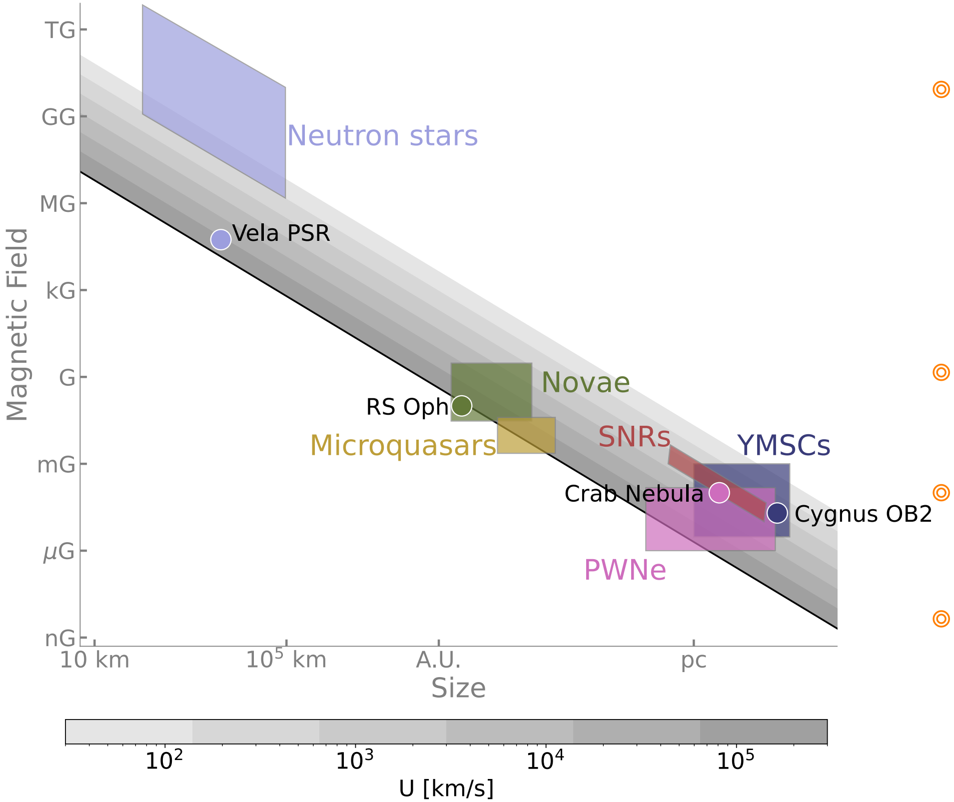




- We can indirectly find them by observing neutral particles from them. Cosmic-ray physics -> Astroparticle physics
- But can we really simply pick those neutral particle sources as a cosmic ray accelerator?

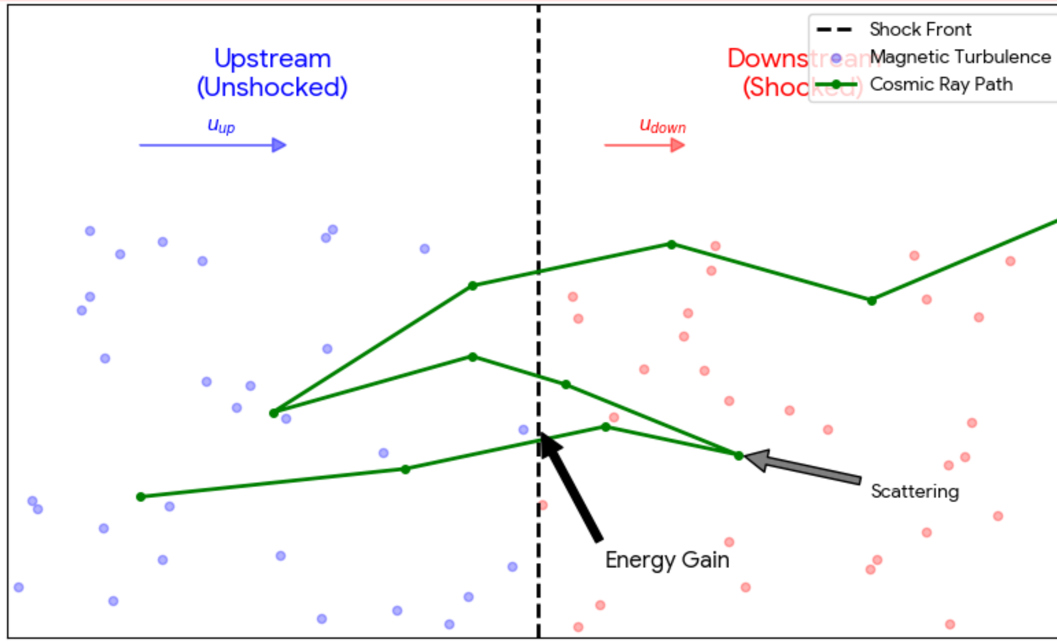
The Hillas Criterion

$$E^{th}_{max} = Z\left(\frac{e}{c}\right) LUB \sim 0.3Z\left(\frac{L}{\text{pc}}\right)\left(\frac{U}{1000\ \text{km/s}}\right)\left(\frac{B}{100\ \mu\text{G}}\right)\ \text{PeV}$$



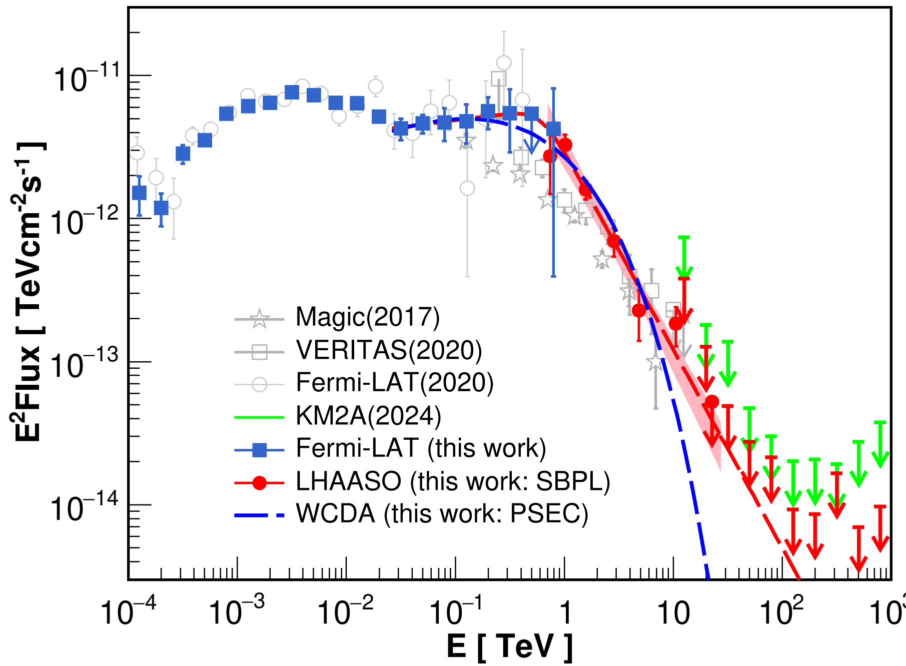
- The left plot is where $E^{th}_{max} = 1$ PeV and $Z = 1$ to produce 100 TeV gamma rays through hadronic. This plot is basically aiming for PeVatron hunting.
  - Electrons have the same acceleration mechanism but suffer synchrotron losses.
- Bigger size L, and bigger magnetic field B to keep particles inside the accelerator.
- U is Plasma speed. Plasma in magnetic field B induce E-field $\varepsilon \sim UB$, which accelerates particles.
- Various environments have different B and L limits, those are presented as boxes in the plot.

Supernova Remnant (SNR)



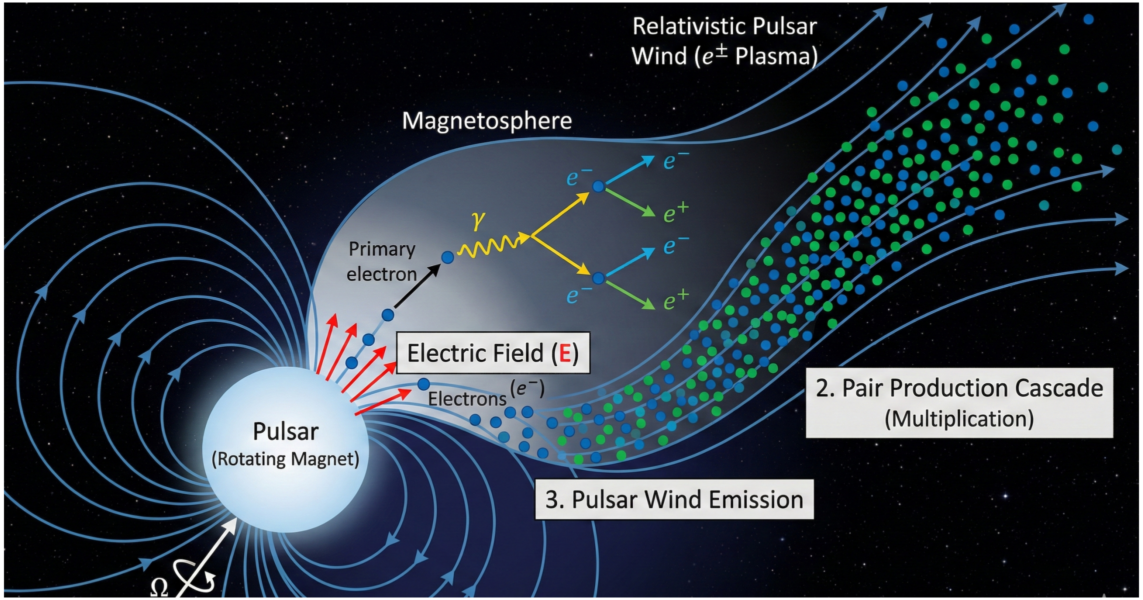
- It is a ping-pong game always smashing. (Diffusive Shock Acceleration)
  Repeatedly gain energy by head-on collision while back-and-forth the shock front (shell of the left plot).
- SNRs have been believed as an accelerator of PeV cosmic rays since explosion energies of $\sim 10^{51}$ erg.
  It means it should emit at least 100 TeV gamma rays.

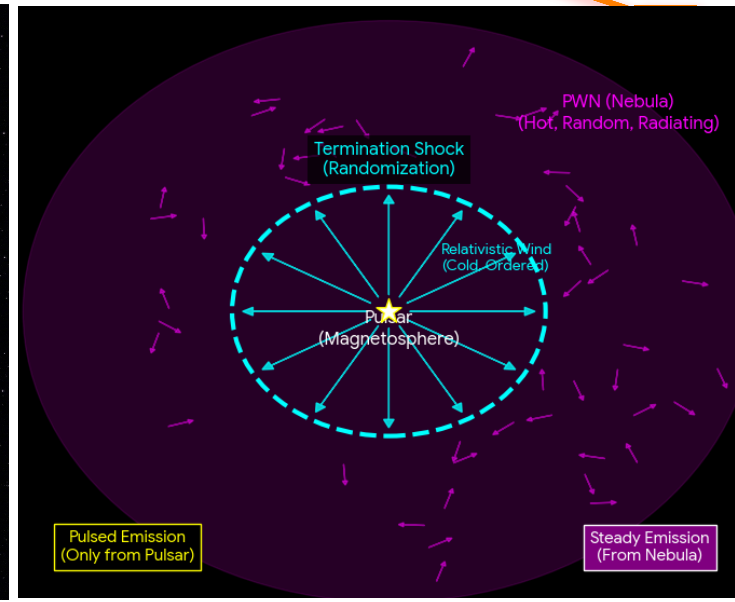
Supernova Remnant (SNR)



- But the recent TeV gamma-ray observation on SNR Cas A found that it has a sharp energy cutoff did not expand above 10 TeV.
- We need another candidate to solve the PeVatron problem.

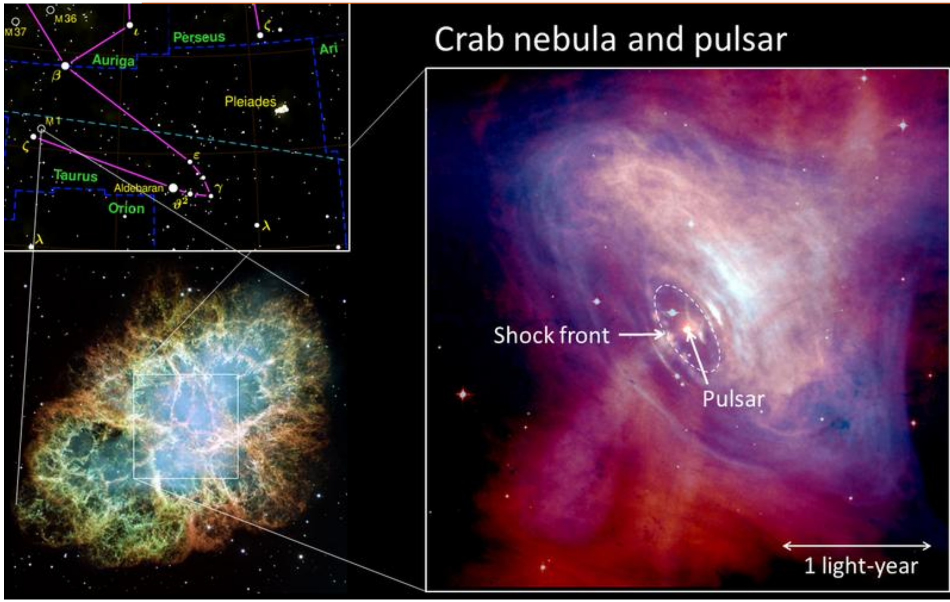
Pulsar Wind Nebula (PWN)

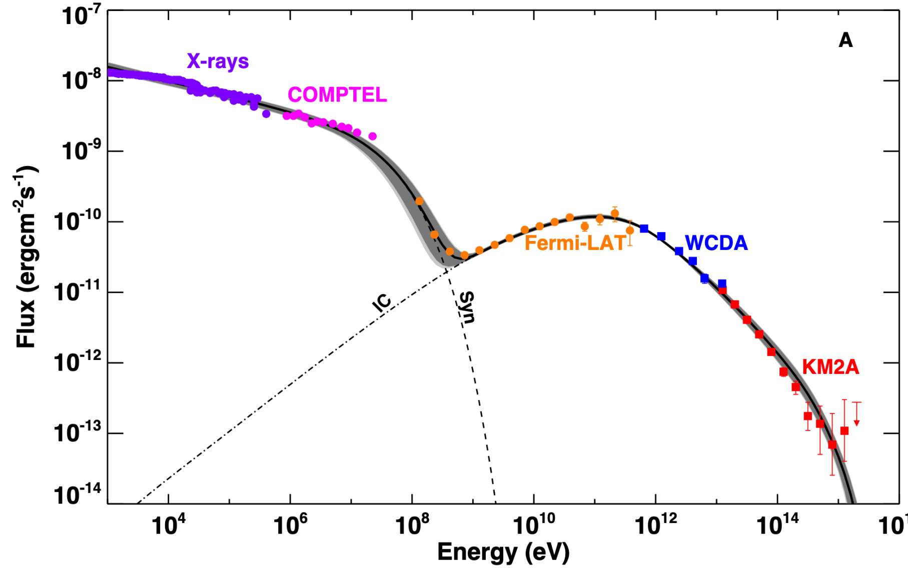




- Pulsar is a fast-rotating neutron star, this rotation produces pulsed emission.
- Electrons (and protons) are extracted from the pulsar's crust escape and the electrons are multiplied.
- The wind meets outside nebula and its pressure induces shockwave, and the particles are accelerated.
- Those accelerated electrons produce Synchrotron (radio-to-X-ray) and IC (gamma-ray).

Pulsar Wind Nebula (PWN)





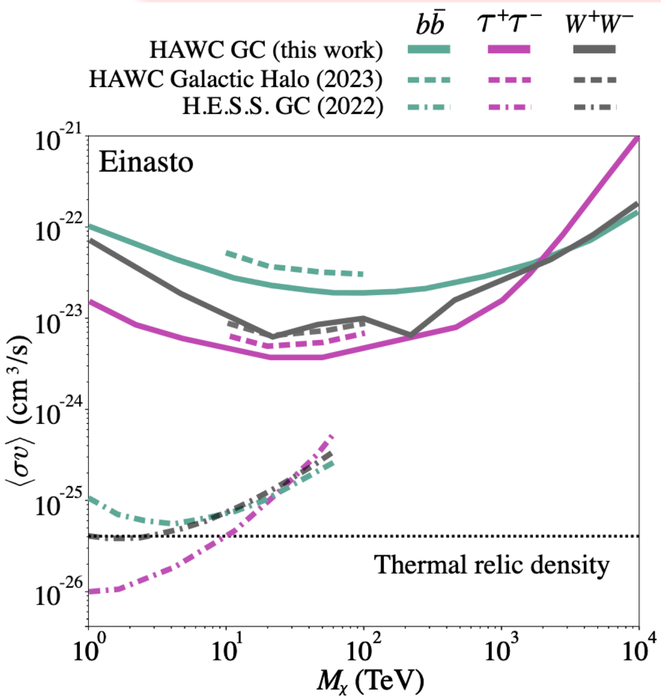
- Crab Nebula has observed in 1.1 PeV photon! It means Crab Nebula can accelerate >PeV particles.
- But, Crab Nebula has been considered as a leptonic source by the electron cascade theory. The electron multiplicity is much bigger than proton multiplicity.
- Also, leptonic scenario is supported by the detection of accompanying synchrotron emissions.
- Nevertheless, it is still necessary to fairly consider the hadronic portion (Still debating).

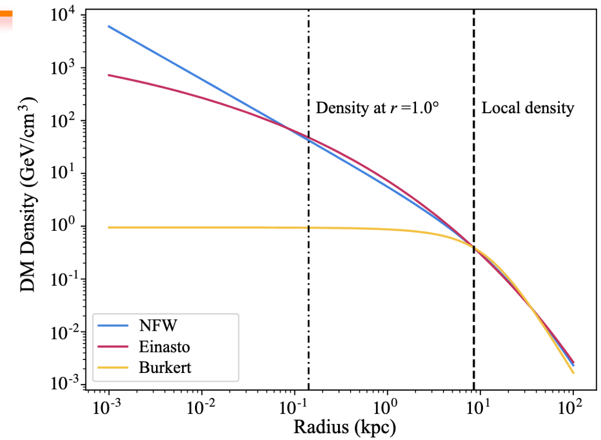
Beyond the Standard Model Studies

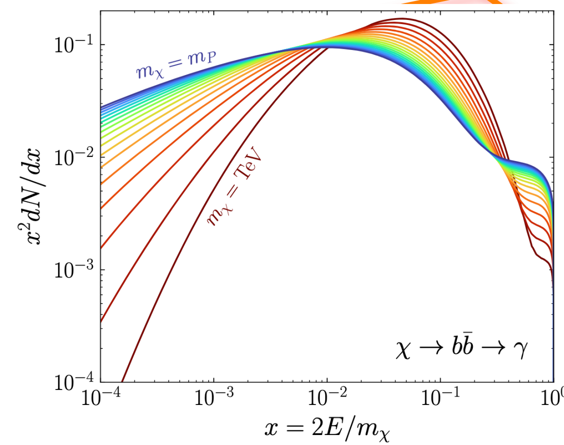
WIMPs

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi M_\chi^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{\text{l.o.s.}} \rho_\chi^2 dl(r,\theta')$$

https://arxiv.org/pdf/2509.06210



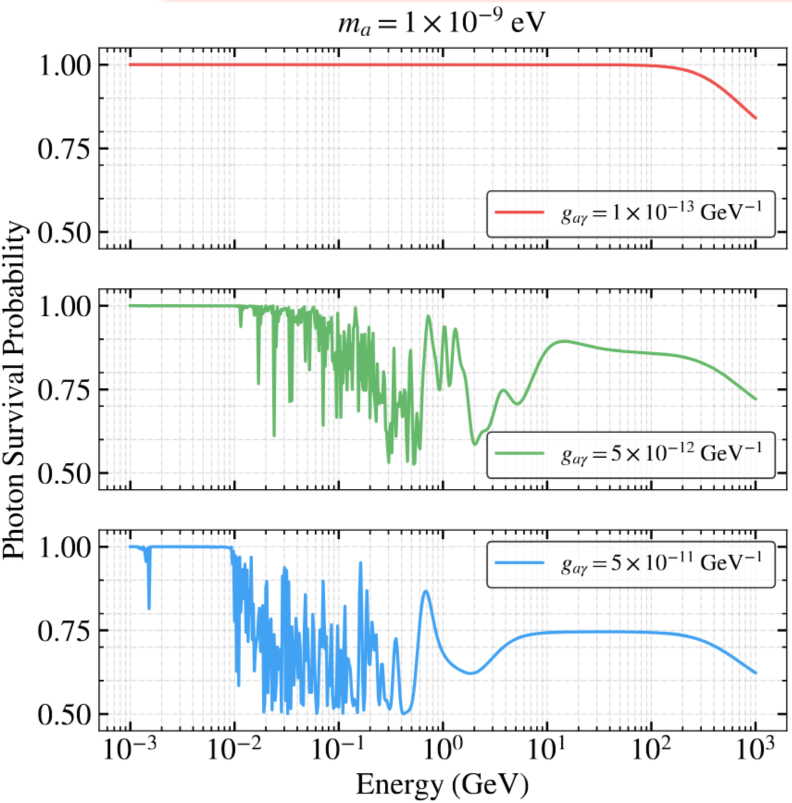


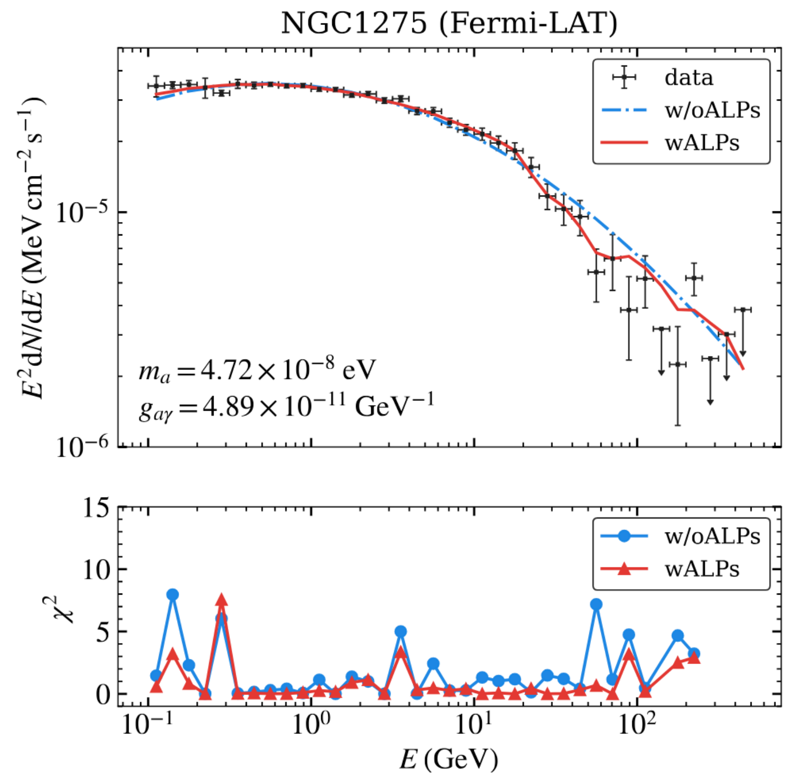


- We can model how the dark matters are distributed (ρ_χ).
- We can model the gamma ray shape from DM annihilation.
- We can expect gamma-ray morphology and spectrum from DM annihilation.

- $\langle\sigma v\rangle$ is velocity-weighted annihilation cross section (rate at which DM particles annihilate into SM particles per unit density)
- Thermal relic density refers to the abundance of a DM that remains in the universe today after it decoupled from the primordial thermal bath in the early universe. (Freeze-out)

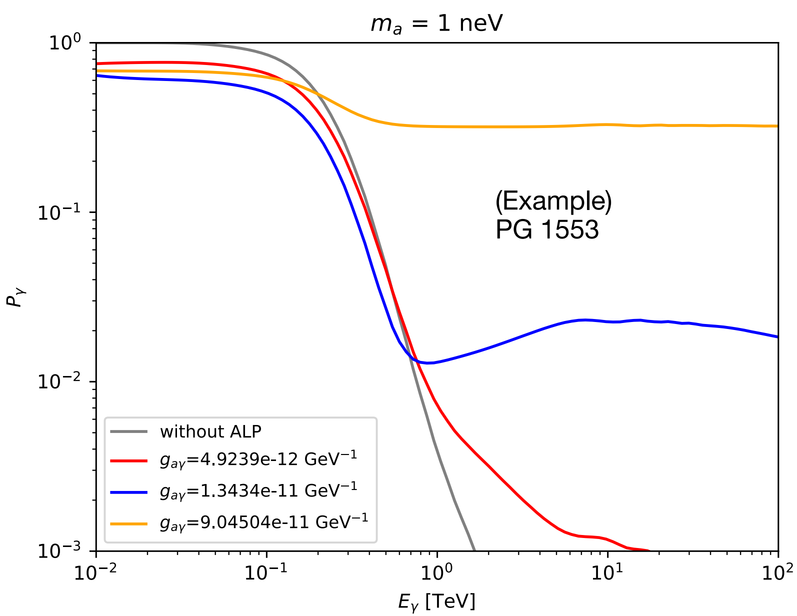
Axion-like Particle





- ALP-photon oscillation: ALP can be converted into photon (also vice versa) in the external B-field.
- This can produce 'wiggle' in the spectrum. Also, it can enhance transparency of gamma-ray sky.

Axion-like Particle



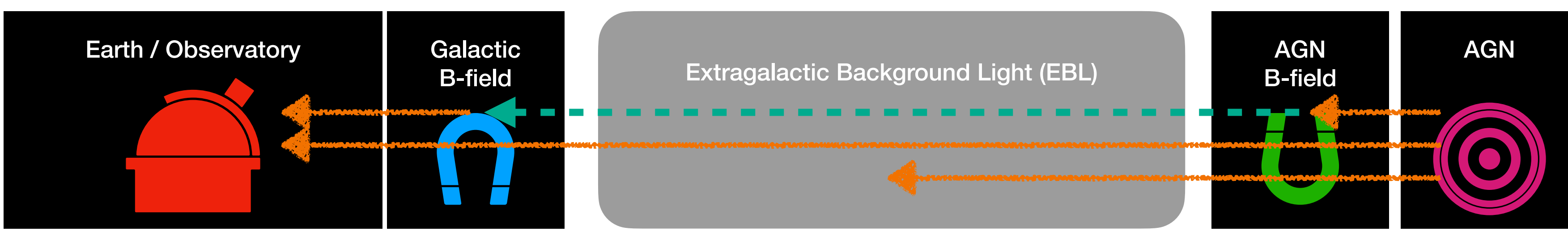
Simulate photon survival probabilities

$$P_\gamma(E_\gamma, m_a, g_{a\gamma\gamma}, z, B_{\mathrm{src}}, B_{\mathrm{GMF}})$$

Planck's Estimate
arXiv:1601.00546

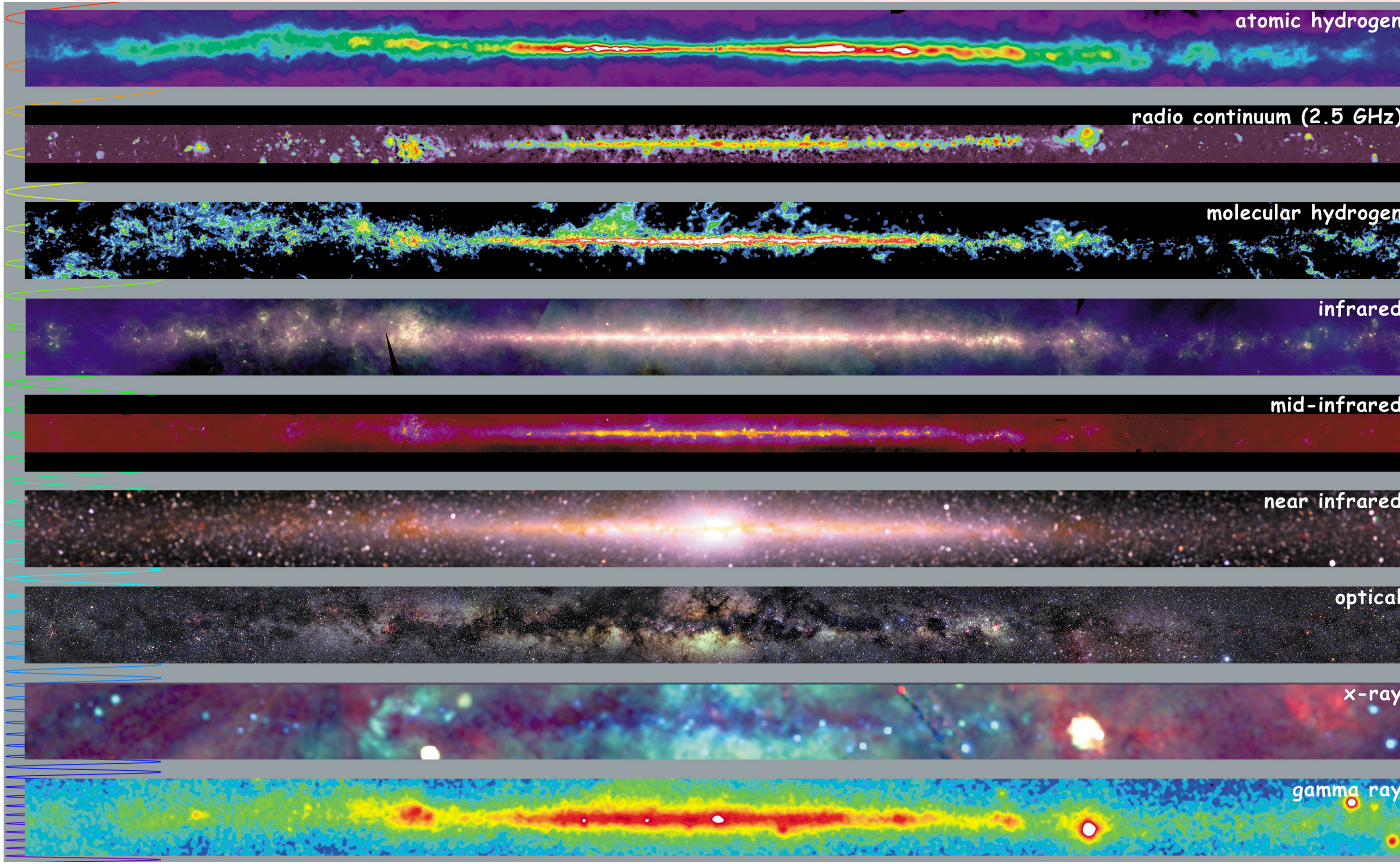
$$P_\gamma = \frac{N_\gamma^{\mathrm{Earth}}}{N_\gamma^{\mathrm{AGN}}}$$

Source	1ES 0229	PG 1553
R.A.(J2000)	02h32m53.2s	15h55m44.7s
Dec.(J2000)	+20d16m21s	+11d11m41s
z	0.14	≥ 0.4
Var. index [67]	6.799	107.2
Data	H.E.S.S [61]	VERITAS
B-field scenario	ICMF+GMF	Jet+ICMF+GMF
B_0^{Jet} [G]		0.5
n_0^{Jet}		5.35×10^3
β^{Jet}		2
δ		35
θ_{obs}		1°
r_{VHE} [pc]		0.063
$r_{\max}$ [kpc]		1



Backup

Milky Way Galaxy



SWGO
The Southern Wide-field Gamma-ray Observatory

Non-thermal Milky Way

Following Galctic magnetic field

ISRF is more widely spreaded than gas