Introduction to Astroparticle Physics

Acceleration and Radiation of high energy particles

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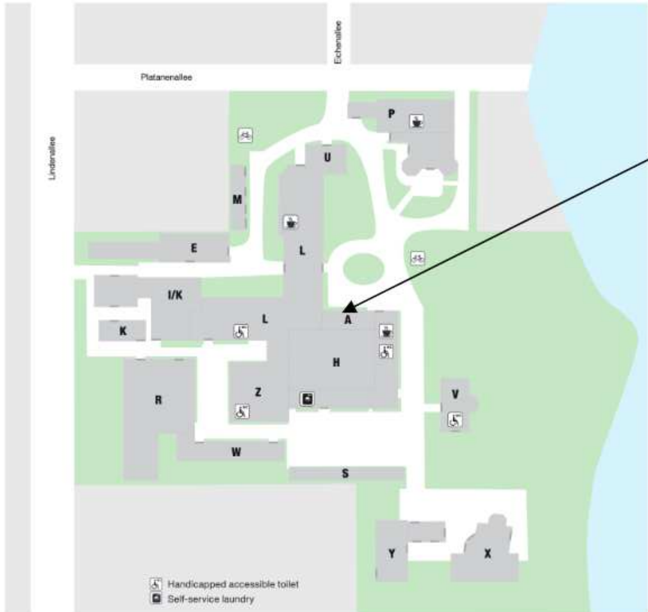


Bibliography

Recommended books and disclaimers

Some books:

- Longair, “**High Energy Astrophysics**”, Cambridge, UK: Cambridge University Press, 2011
- Aharonian, ”**Very High Energy Cosmic Gamma Radiation: A Crucial Window on the Extreme Universe**”. Edited by AHARONIAN FELIX A. Published by World Scientific Publishing Co. Pte. Ltd., . ISBN #9789812561732
- Gaisser, Engel, Resconi, “**Cosmic rays and particle physics**”, Cambridge University Press

Introduction

What are we going to learn

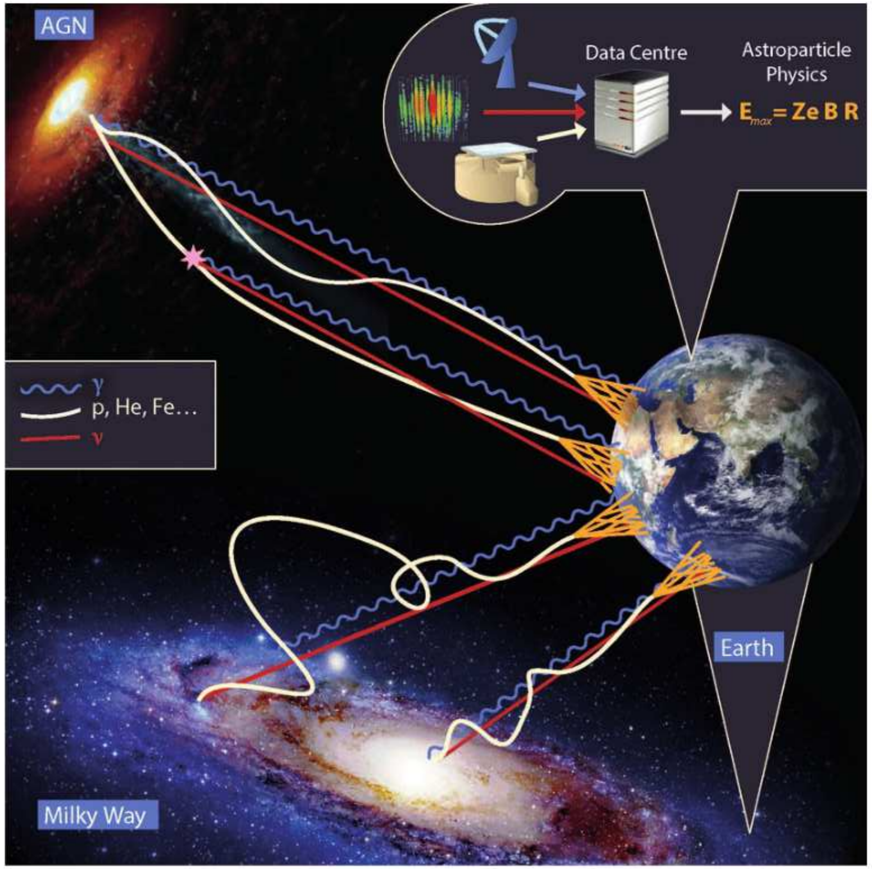
What is Astro-particle physics

- High-energy non-thermal radiation
- Multi-messenger domain
- Where, how, who, what

Cosmic-rays

- History of Cosmic rays
- Radiation processes
- Detection techniques

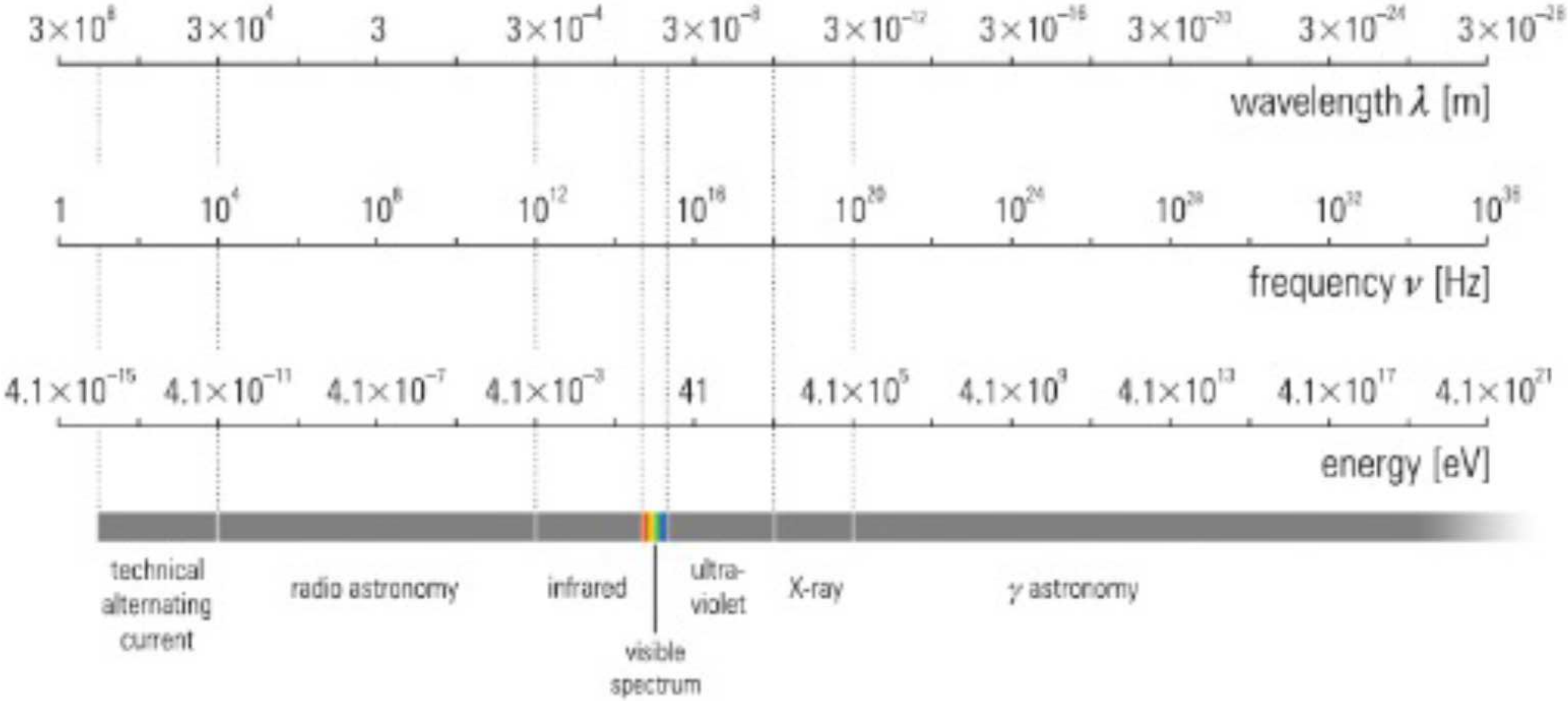
The Universe at high energies



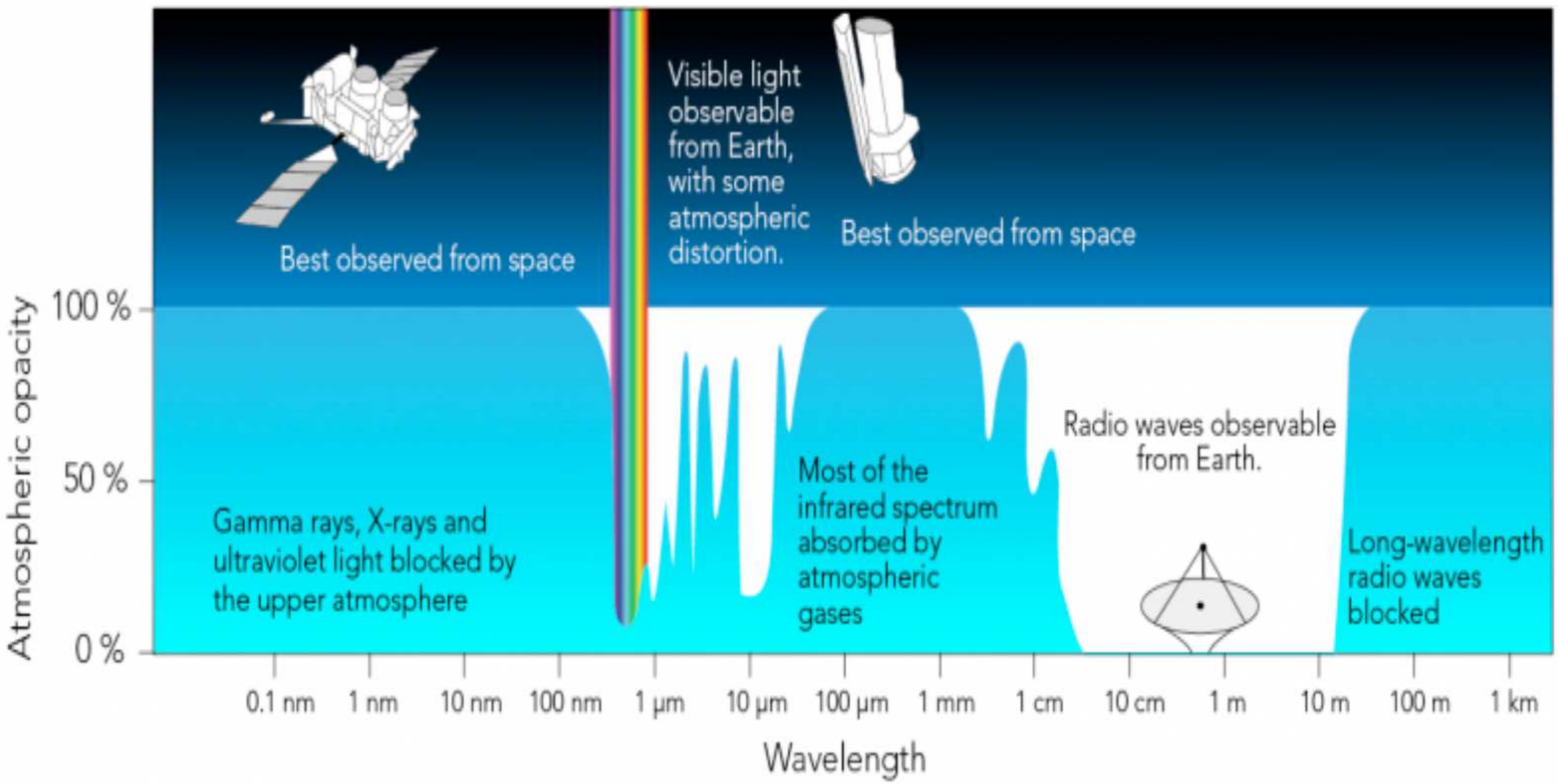
The electromagnetic spectrum

High Energy Astrophysics

$$\nu \leq 3 \times 10^{19}\text{Hz}; \quad \lambda \leq 0.01\text{nm}; \quad \text{E} \geq 100\ \text{keV}$$

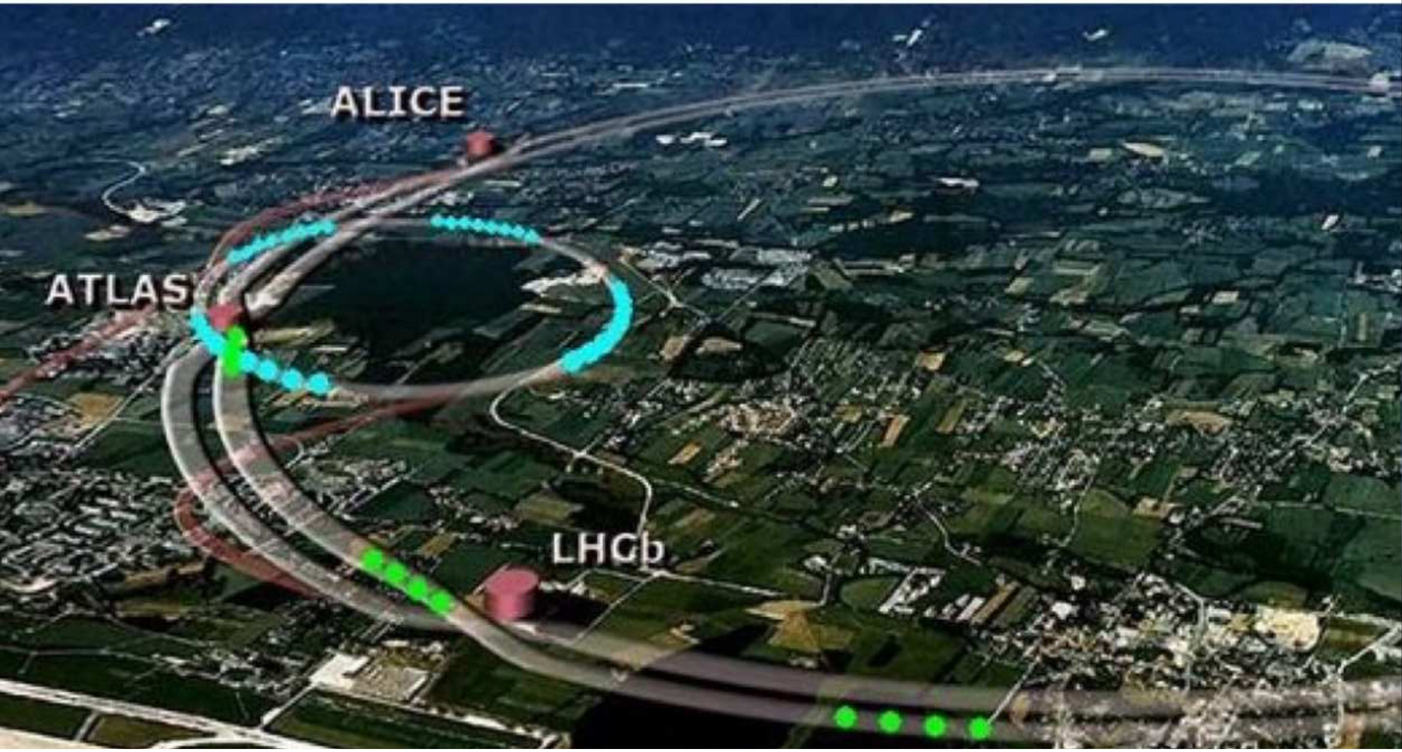


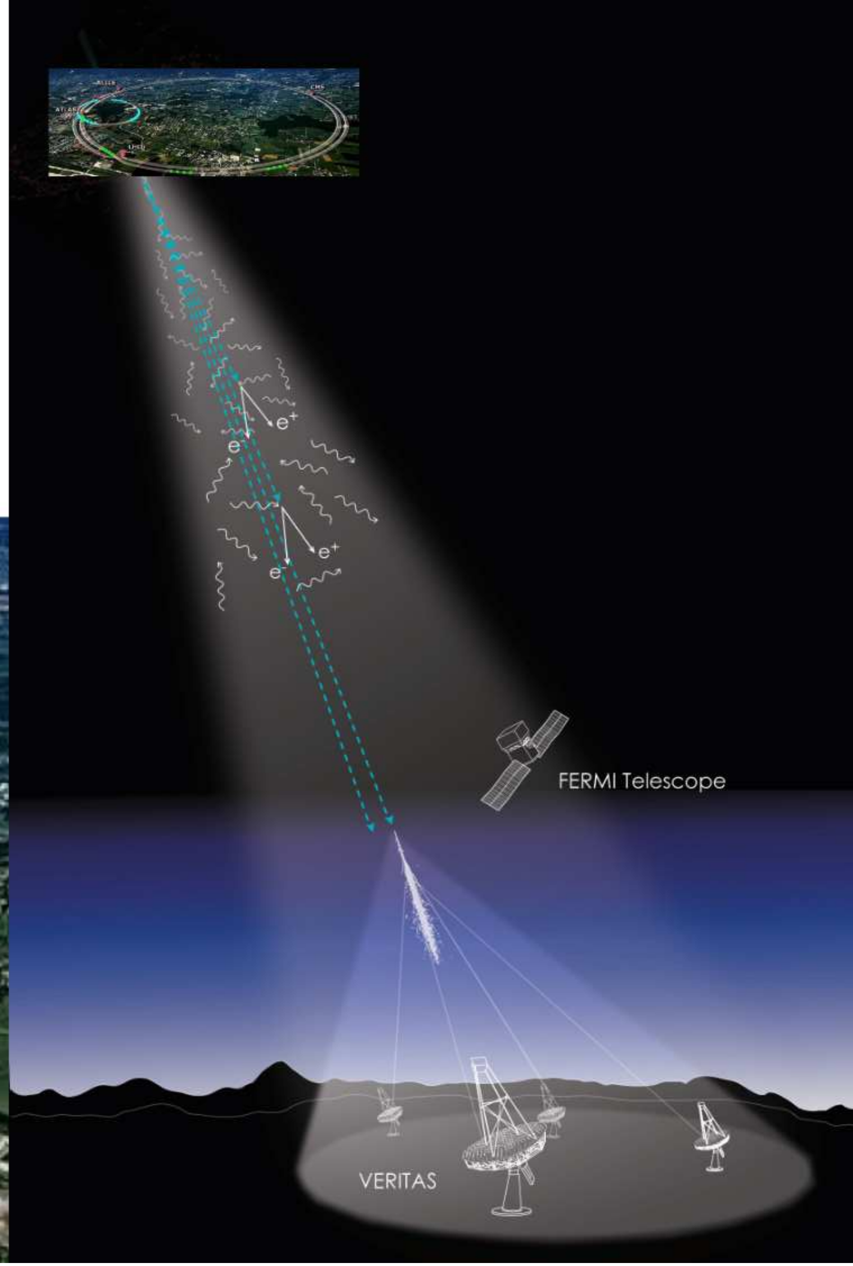
The electromagnetic spectrum



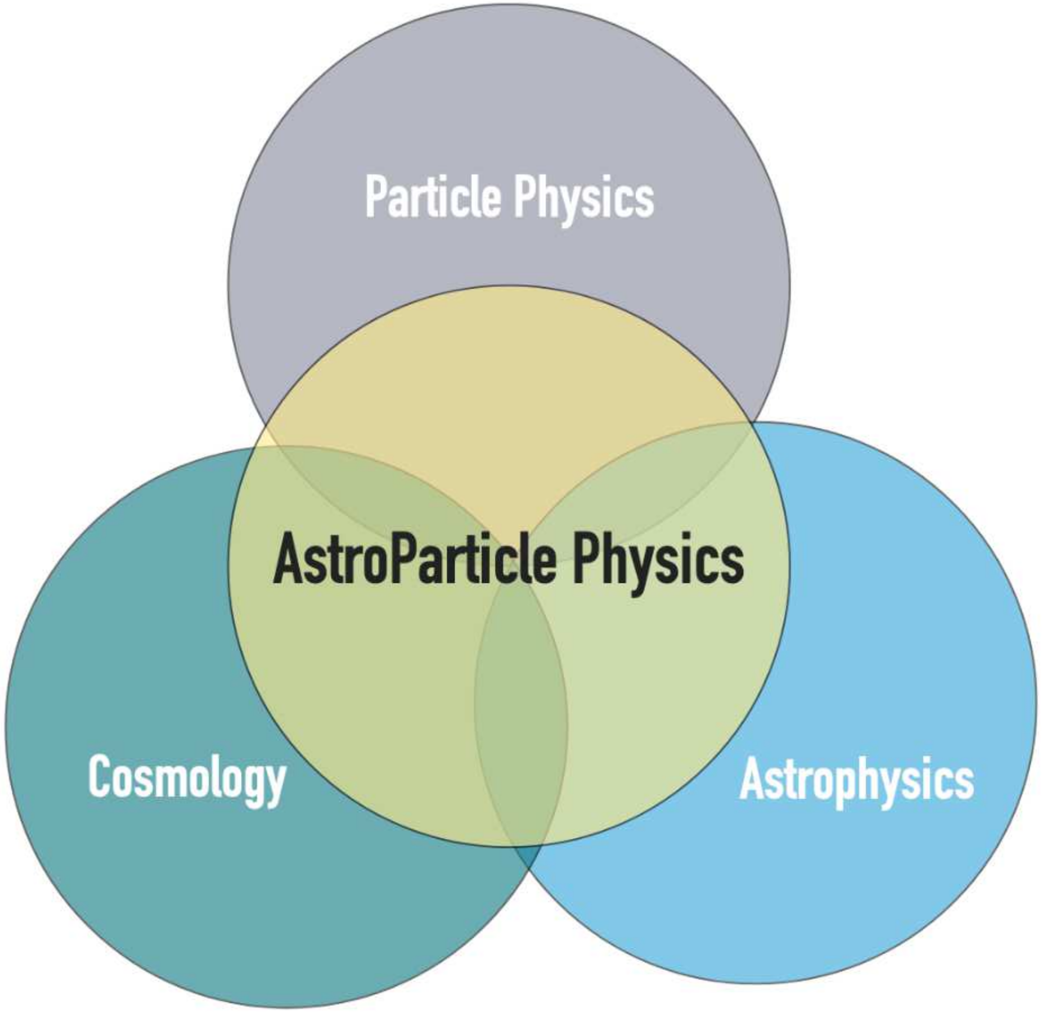
Large Hadron Collider

General properties	
Maximum energy	6.8 TeV per beam (13.6 TeV collision energy)
Maximum luminosity	$1\times10^{34}/(cm^2\cdot s)$
Physical properties	
Circumference	26,659 metres (16.565 miles)

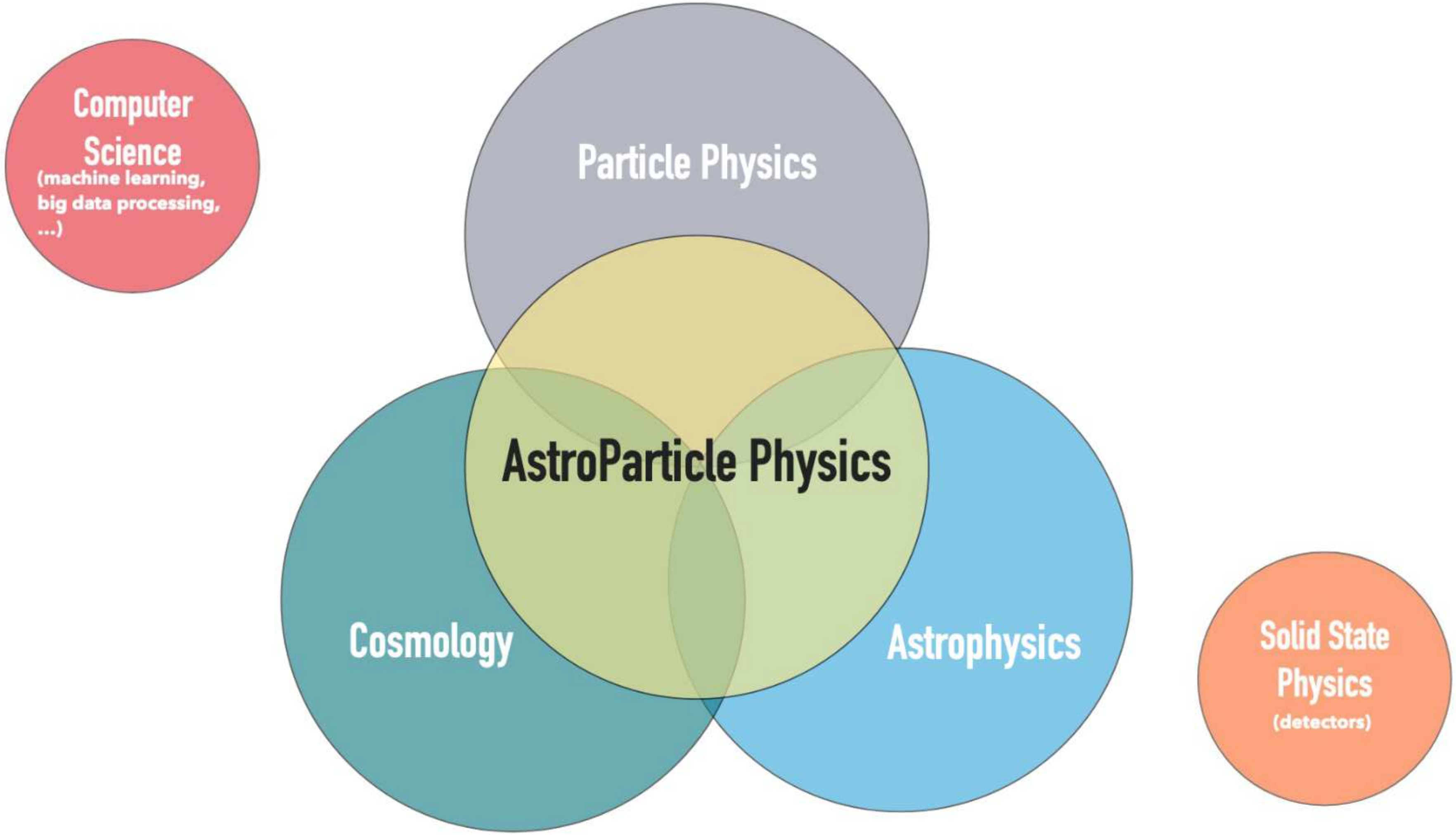




But, what is Astro-particle Physics



But, what is Astro-particle Physics



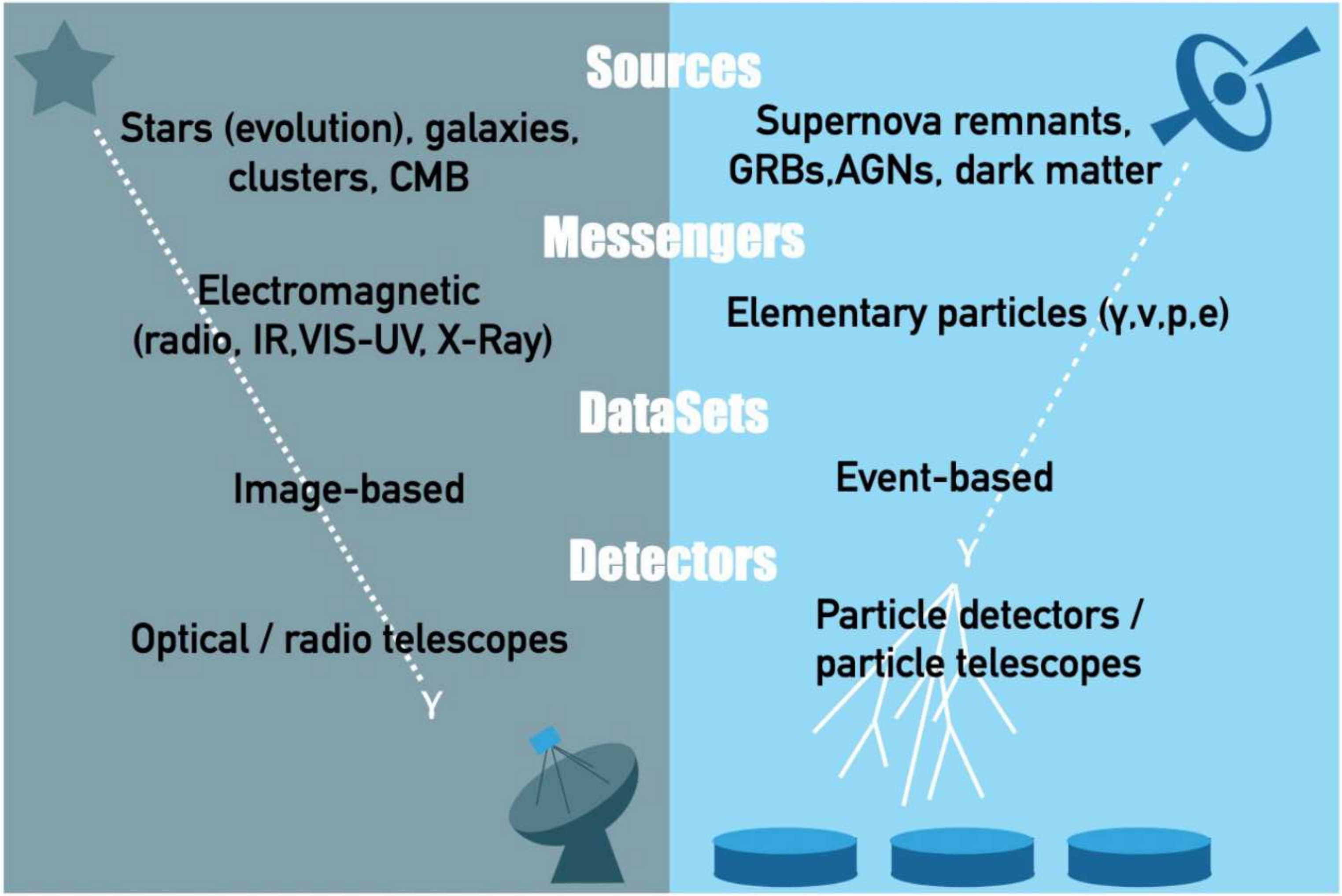
Astro-particle Physics

Characteristics

- Advanced instrumental techniques (optical telescopes, particle detectors) and analysis techniques: the high energy domain is characterized by photon-starved instruments that require powerful statistical tools.
- Multi-messenger approach (neutrino, gamma-ray, gravitational waves) to observe the most energetic phenomena in the Universe
- Particle physics: huge gravitational, magnetic, and electric fields; very dense background radiation; relativistic bulk motions (black hole jets and pulsar winds) shock waves (SNRs), highly excited (turbulent) media, etc. . .

Astrophysics vs Astroparticle

Juan A. Aguilar



Non-thermal radiation

➢ We are dealing with relativist particles, that is, particles with energy E larger than the rest energy

- **For electrons:**

$$E = mec^2 \simeq 5x105\ eV = 0.5\ \mathrm{MeV}$$

- **For protons:**

$$E = mpc^2 \simeq 10^9\ eV = 1\ \mathrm{GeV}$$

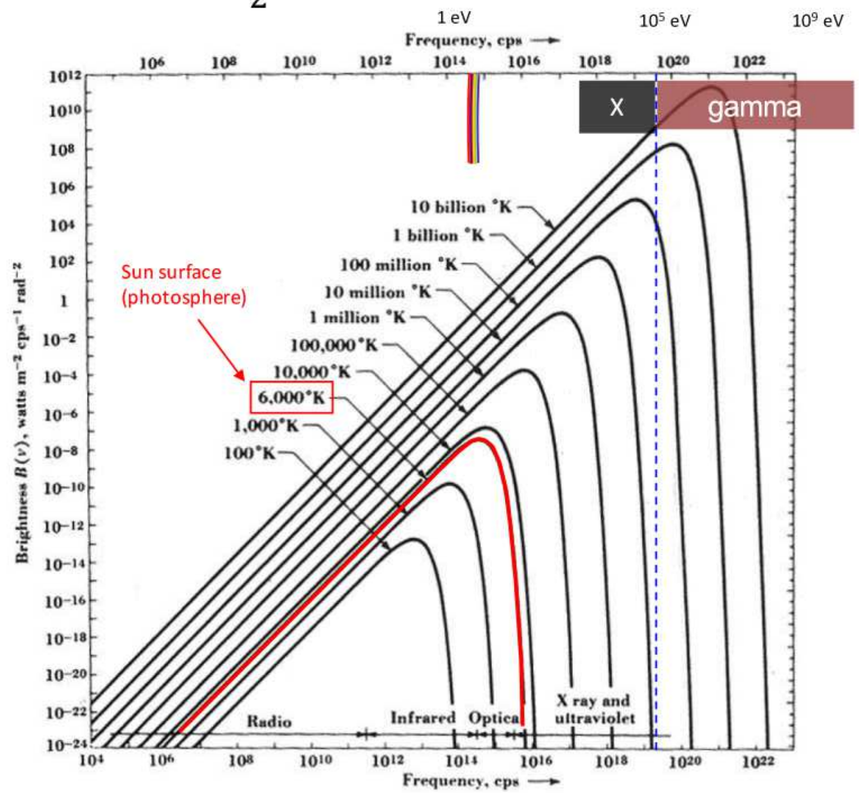
10^3 eV	1 keV (kilo)
10^6 eV	1 MeV (mega)
10^9 eV	1 GeV (giga)
10^{12} eV	1 TeV (tera)
10^{15} eV	1 PeV (peta)
10^{18} eV	1 EeV (exa)
10^{21} eV	1 ZeV (zetta)

Non-thermal radiation

➢ **These particles will loose energy via non-thermal mechanisms**:

Let's calculate the temperature to obtain these energies $< E > = \frac{3}{2} k_B T$

$$T \sim \frac{m_e c^2}{k_B} \sim 0.6 \times 10^{10} K \qquad T \sim \frac{m_p c^2}{k_B} \sim 10^{13} K$$



We need 10^9 K to produce MeV gamma-rays (10^{12} K for GeV gamma-rays)

=> Such objects do exist (inside stars or in SNR explosions), but often screened or red-shifted

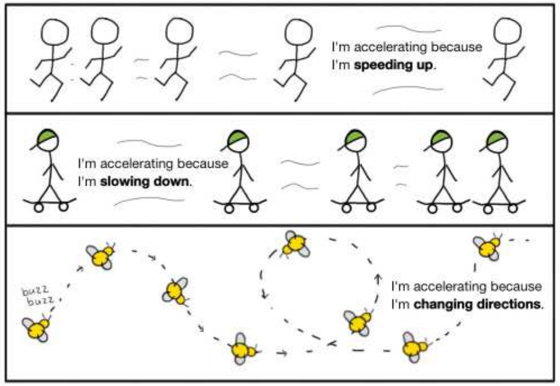
=> **Non-thermal processes dominate MeV - TeV gamma-ray**

High energy Astrophysics

Energy Source

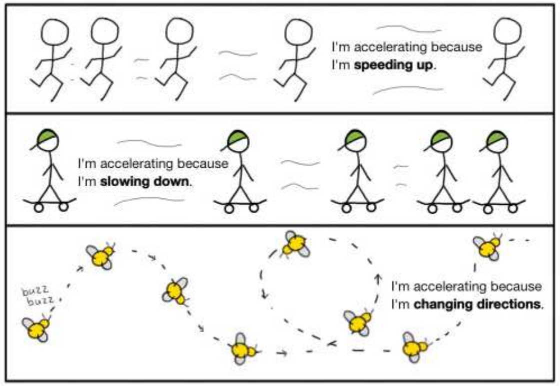
High energy Astrophysics

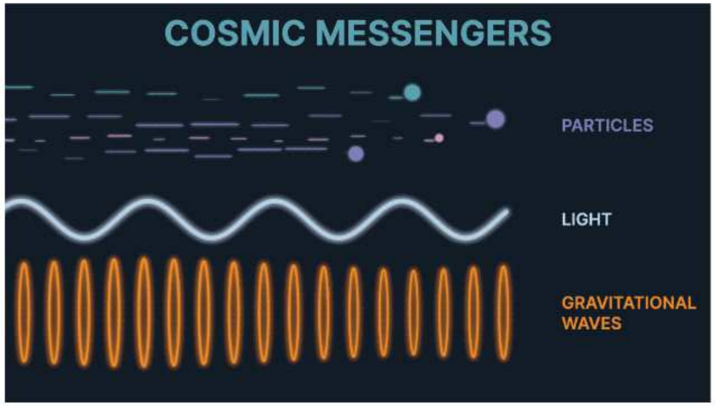
Energy Source



Acceleration Mechanisms

High energy Astrophysics





Energy Source

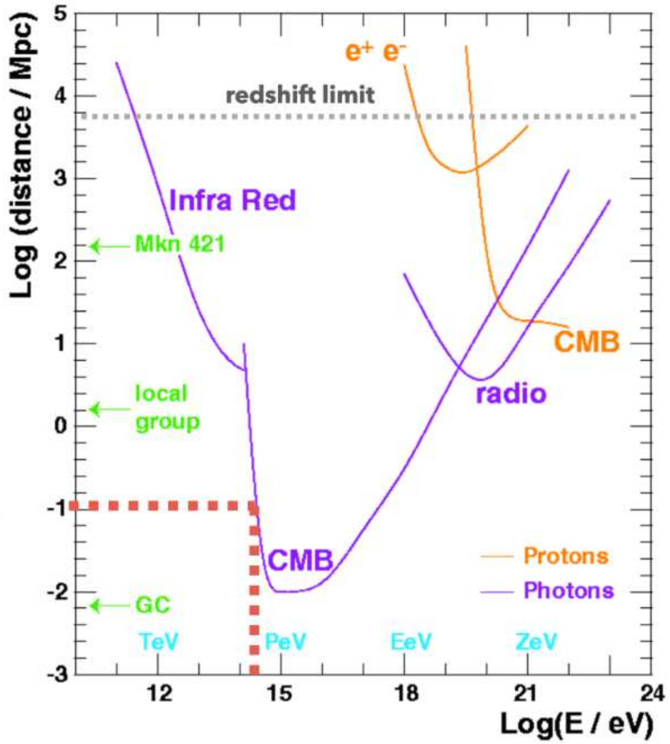
Acceleration Mechanisms

Radiation Processes

High energy Astrophysics

Absorption / Transport

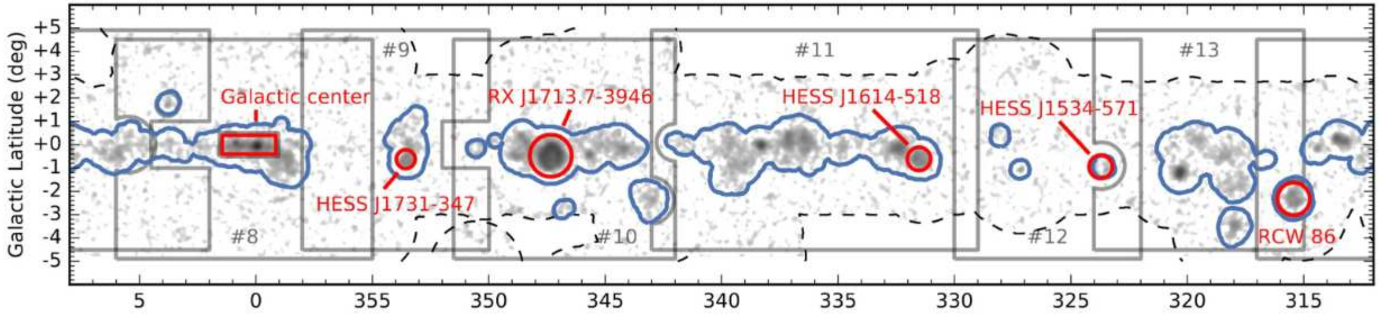
~800 pc



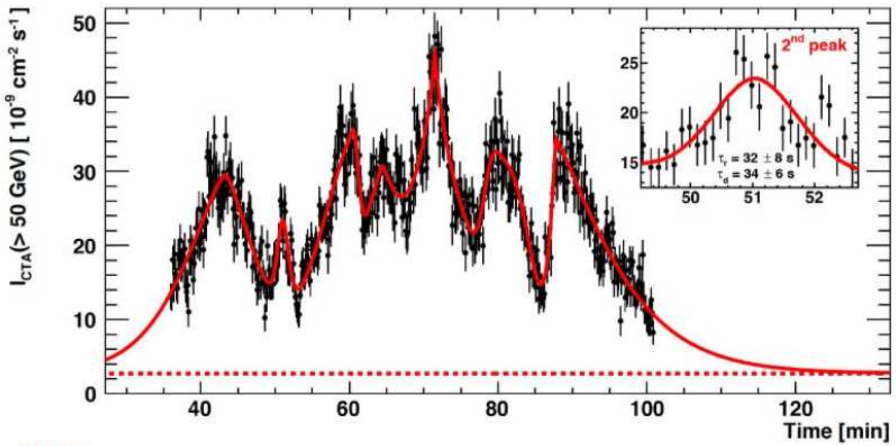
T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)

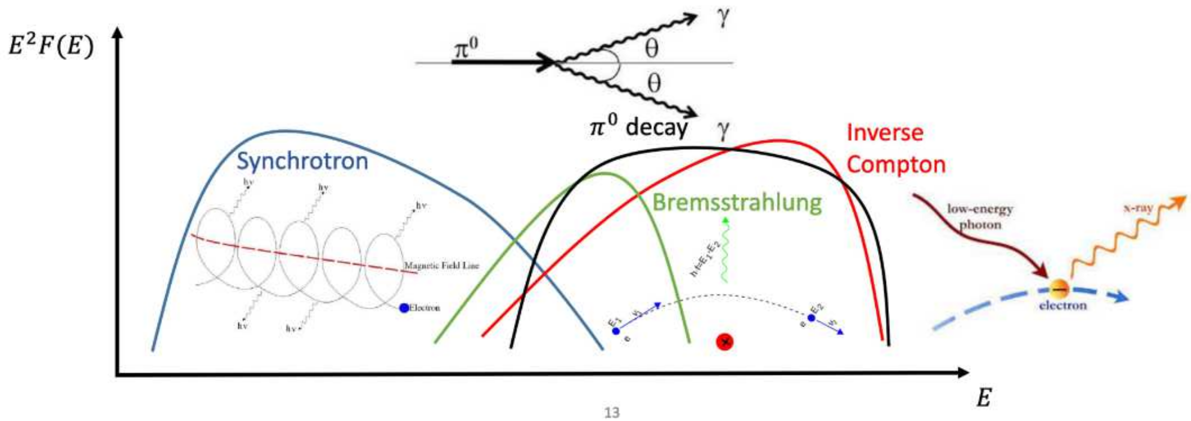
High energy Astrophysics

Measured Flux



- ➢ Spectral Energy Distribution
- ➢ Light curves
- ➢ Morphology / Imaging

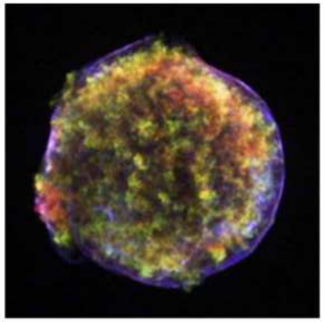




High energy Astrophysics

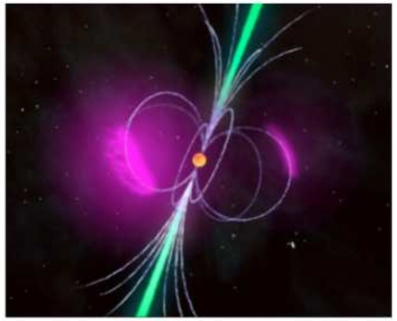
Energy Sources

- Explosions, or shocks with high speed
- Accretion, or accumulation of diffuse gas or matter onto some object under the influence of gravity
- Rotating fields, or twisted magnetic lines
- Exotic particle, or DM particles annihilation

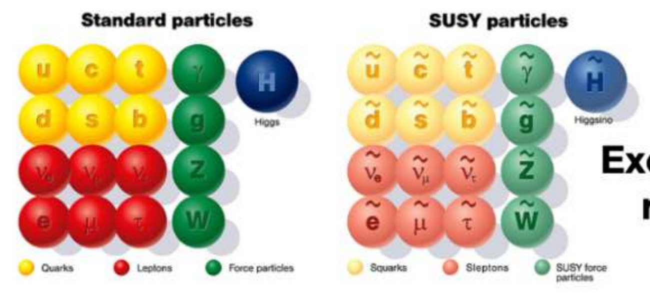


Explosions

Accretion



Rotating Fields



Exotic particle rest mass

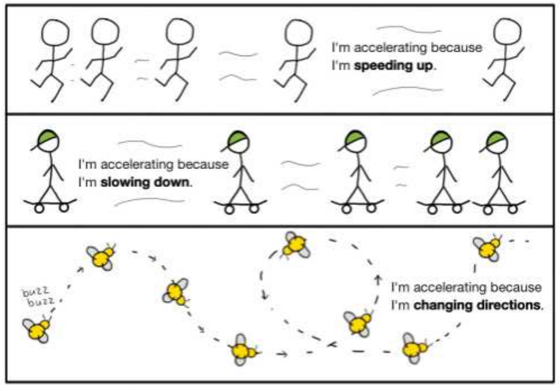
High energy Astrophysics

Energy Sources

The energy is obtained by processes related to explosions, accretion, rotating magnetic fields, or processes related to annihilation of exotic particles

High energy Astrophysics

Acceleration Mechanisms



- Steady magnetic fields cannot accelerate particles
- Static electric fields are quickly neutralized.

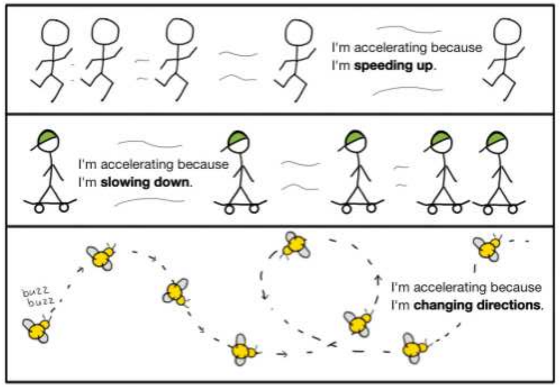
We need strong turbulent magnetic fields, inducing variable electric fields to accelerate particles

and

Particles should be confined for many acceleration cycles.

High energy Astrophysics

Acceleration Mechanisms



- The energy is distributed (mainly) among magnetic energy and kinetic energy
  equipartition: assumption that 50% goes to fields, and 50% to particles

- The basic processes can be well described according to the Lorentz factor or speed of the particle flow (βΓ) and the magnetization parameter

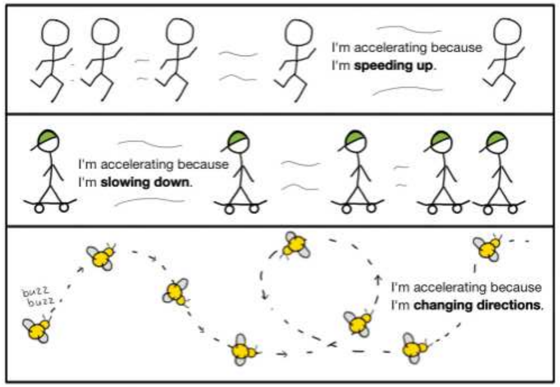
$$\sigma = B^2/4\pi\rho c^2 = B^2/4\pi\rho\Gamma^2 c^2$$

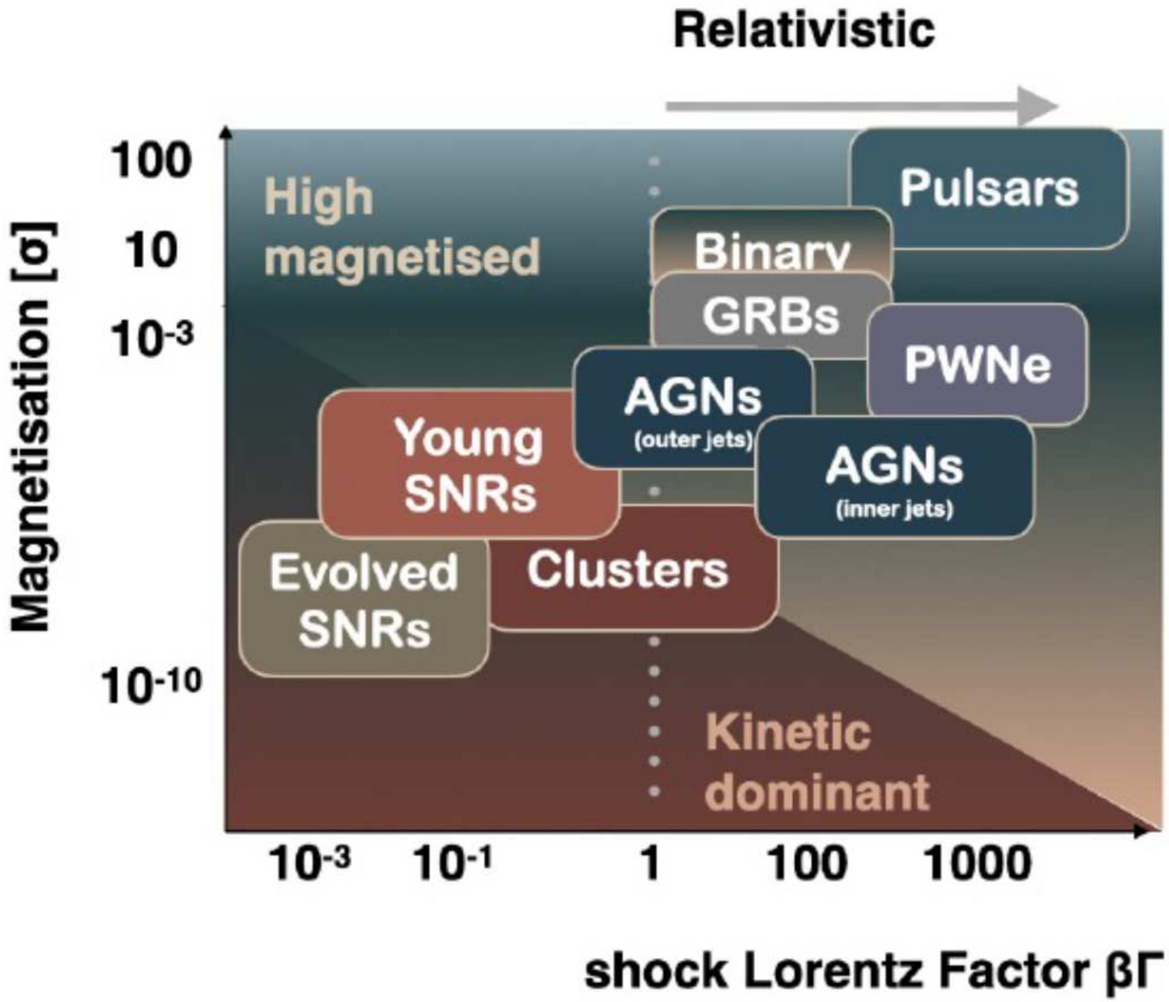
$$\Gamma = (1 - \beta^2)^{-1/2}$$

- To supersede thermal heating (σ>>1), either high magnetization in relativistic flows are needed or efficient Fermi acceleration in supersonic shocks.

High energy Astrophysics

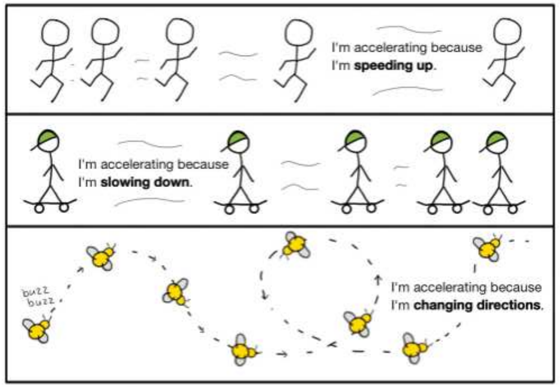
Acceleration Mechanisms





High energy Astrophysics

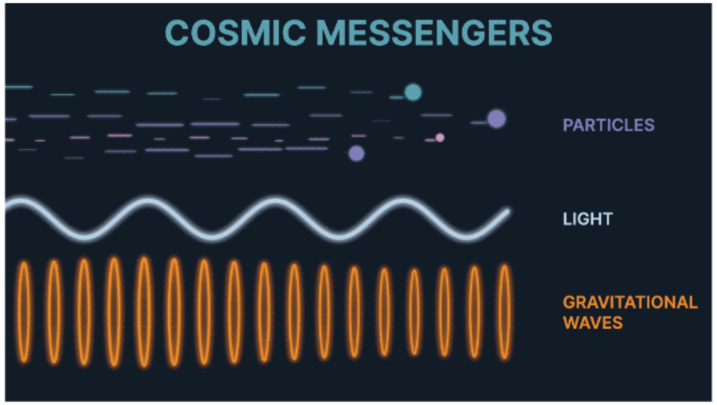
Acceleration Mechanisms



The high energy regime is dominated by non-thermal processes, and they require either high magnetization in relativistic flows or efficient Fermi shock acceleration.

High energy Astrophysics

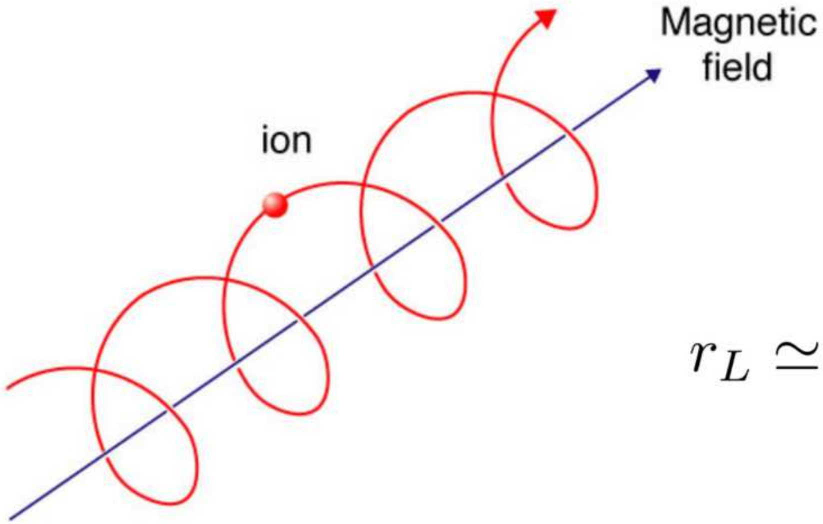
Radiation Processes



- ➢ Elementary particles are injected once they are accelerated and should arrive to us:
  - ➢ Electrons, protons, and heavier nuclei are charged => Deflected by magnetic fields
  - ➢ Neutral messengers bring direct information

The **Larmor radius**, or gyroradius:

- ✓ radius of the orbit of a charged particle (q=Ze) moving in a uniform, perpendicular magnetic field (B)
- ✓ obtained by equating the Lorentz force with the centripetal force:



Source: euro-fusion.org

Lorentz force versus centripetal force

Lamor Radius:

$$qvB = \frac{mv^2}{r_L} \rightarrow r_L = \frac{p}{ZeB}$$

$$r_L \simeq 1\ \text{kpc} \left(\frac{E}{10^{18}\text{eV}}\right)\left(\frac{1}{Z}\right)\left(\frac{\mu\text{G}}{B}\right)$$

Rigidity:

$$R \equiv r_L B c = \frac{pc}{Ze}$$

Larmor radius

Looking at the Larmor radius of a particle we can derive simple but solid conclusions:

1/ How is the trajectory of a charge particle, depending on its energy and the medium in which it propagates

2/ What is the maximum energy / how long can it be confined

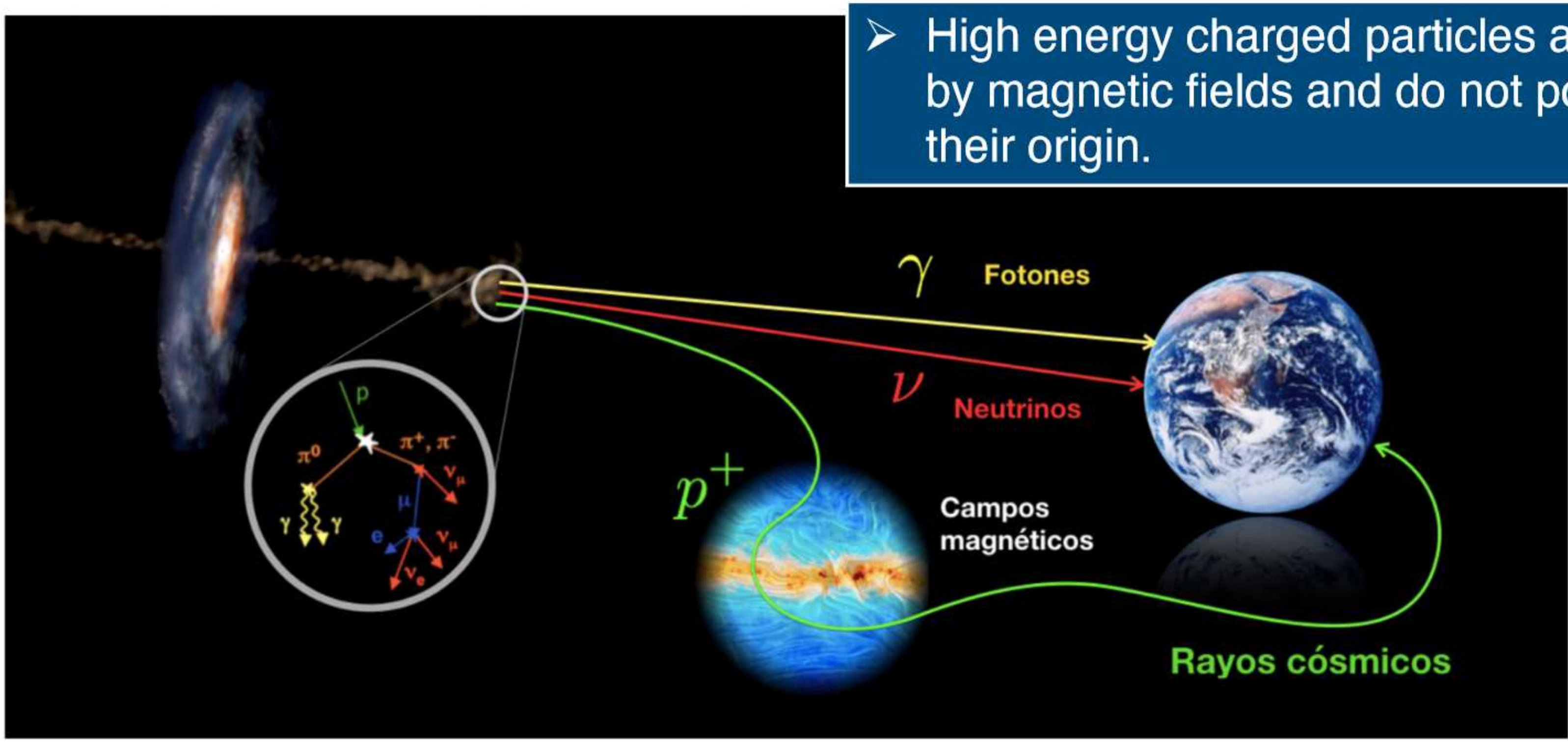
Messengers

Particle trayectories

$$r_L \simeq 1\ \mathrm{kpc} \left(\frac{E}{10^{18}\mathrm{eV}}\right)\left(\frac{1}{Z}\right)\left(\frac{\mu\mathrm{G}}{B}\right)$$

The deflection angle of a 1000 PeV (10^{18} eV) particle, moving in a direction perpendicular to a uniform magnetic field (~uB) after traveling a distance d_{kpc}

- High energy charged particles are deflected by magnetic fields and do not point back to their origin.



Messengers

Particle trayectories

$$r_L \simeq 1\ \mathrm{kpc} \left(\frac{E}{10^{18}\mathrm{eV}}\right)\left(\frac{1}{Z}\right)\left(\frac{\mu\mathrm{G}}{B}\right)$$

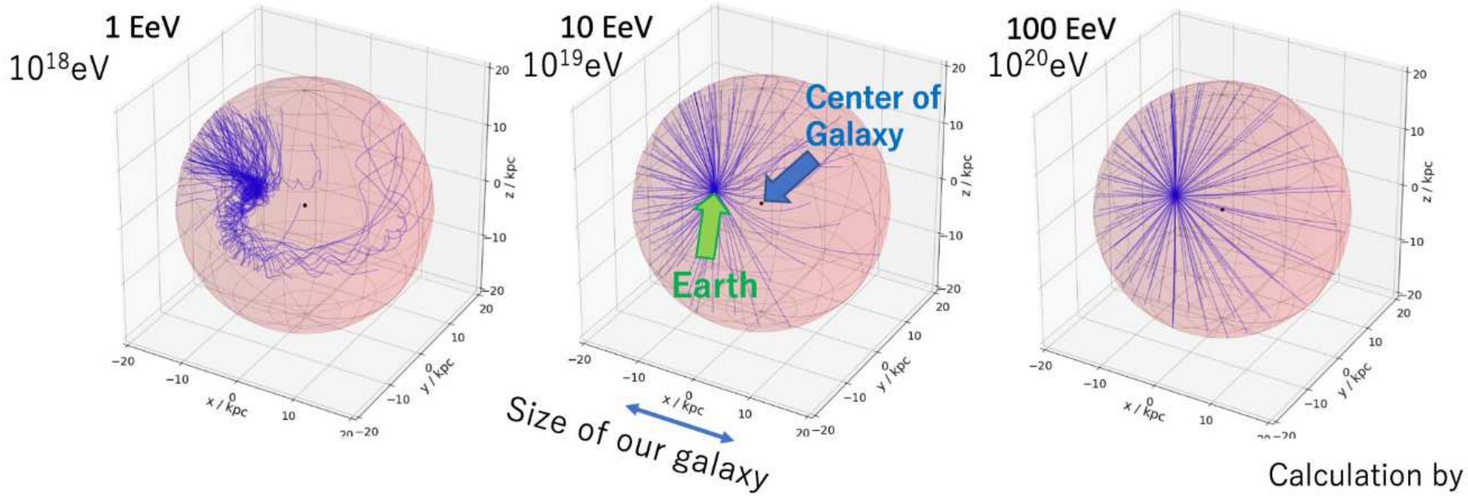
- Astronomical messengers should be neutral & stable
- photons and neutrinos fully satisfy these conditions
- partially also ultra-high energy neutrons and protons

neutrons:

$d < (E_n/mc^2)\ c\ \tau \Rightarrow E_n > 10^{17}$ (d/1 kpc) eV Galactic astronomy with E>10^{17} eV neutrons

protons:

$\Phi \sim 1^o$ if E>10^{20} eV for IGMF B<10^{-9} G Extragalactic astronomy with E>10^{20} eV protons



Calculation by R.Higuchi

Messengers

Maximum energy / confinment

How much can we accelerate a particle on an electric field – how long can we confine it

- Acceleration is always (except for non-ideal cases) carried out by an electric field

- For a particle with charge Z (q), moving a distance L

$$E = q\,|\vec{E}|\,L$$

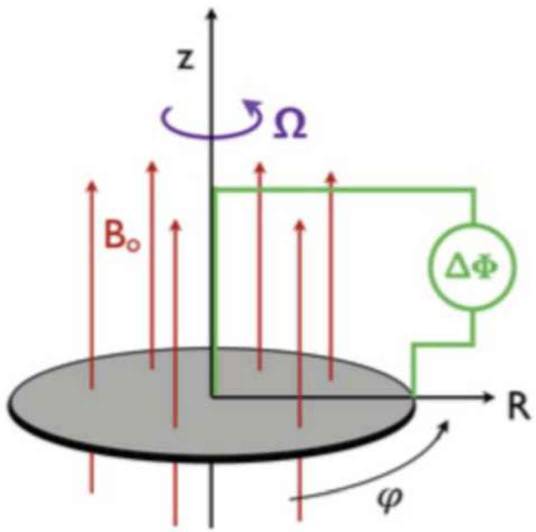
- We can define the acceleration efficiency as:

$$\eta = \vec{B}/\vec{E}$$

then:

$$E = q\eta BL$$

L = Size of the source
B = Magnetic field in the so



**For a particle with charge q at speed of light c (c=1)

Messengers

Maximum energy / confinment

$$r_L \simeq 1\ \mathrm{kpc} \left(\frac{E}{10^{18}\mathrm{eV}}\right)\left(\frac{1}{Z}\right)\left(\frac{\mu\mathrm{G}}{B}\right)$$

We can derive the same condition considering the Larmour radius, considering the maximum total effective electric field that the particle can experience during its passage across the acceleration zone

Energy gain timescale : $t_{\mathrm{acc}} = \eta R_{\mathrm{L}}/c$

$$E_{\mathrm{max}} = qBL/\eta\beta.$$

Escape time:

$$t_{\mathrm{esc}} = L/\beta c,$$

advective flow speed

$$\eta \approx 1/\beta^2,$$

$$E_{\mathrm{max}} = \beta qBL.$$

$$E_{max} \approx 1 \left(\frac{u}{10^3\ \mathrm{km/s}}\right)\left(\frac{R}{\mathrm{pc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{TeV}$$

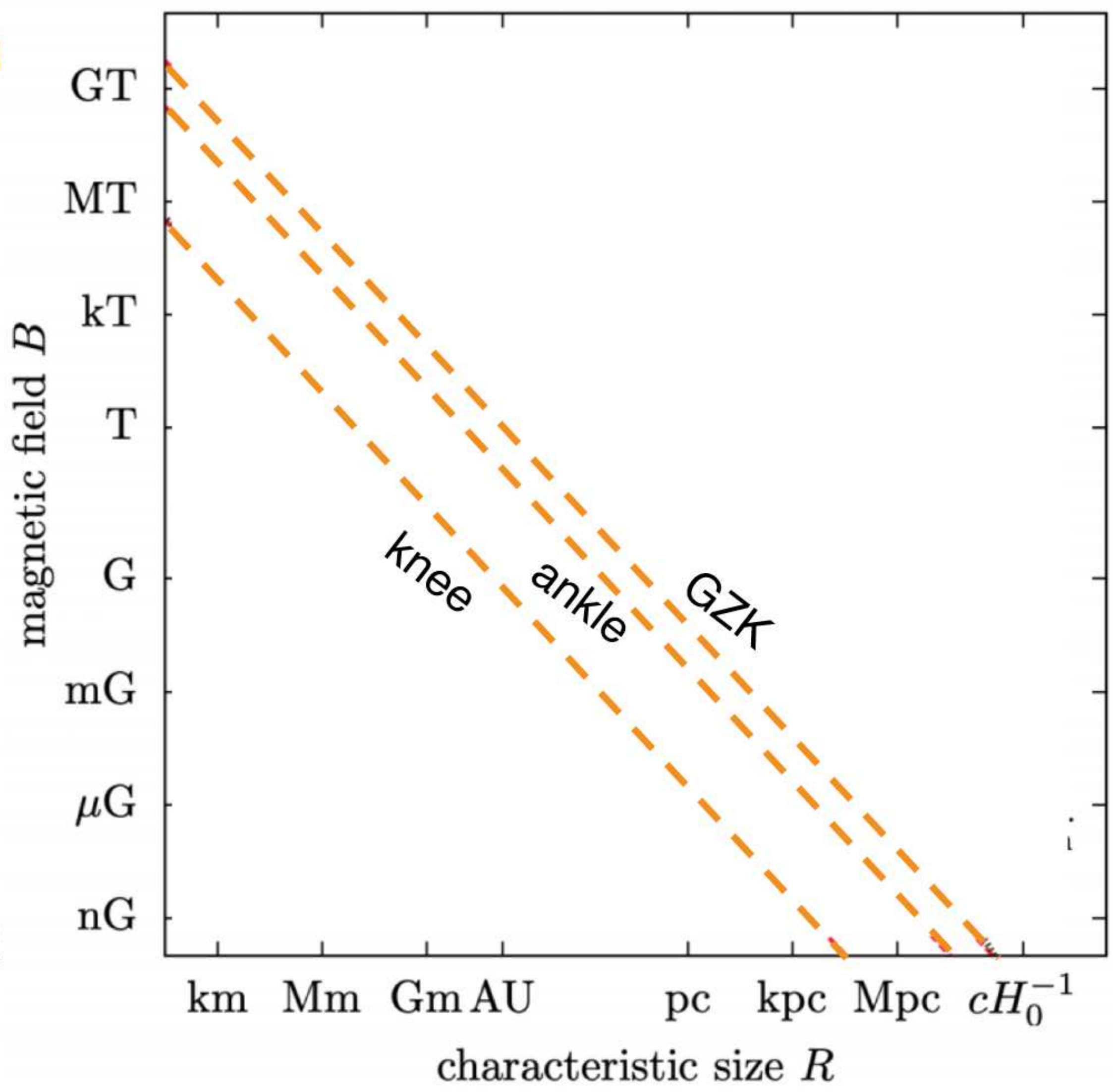
Messengers

Maximum energy / confinmen

SNRs?
GRBs?
Galactic BH?
Pulsars?

R_L (=E/qB) < R => $E_{max} = \Gamma qBR$

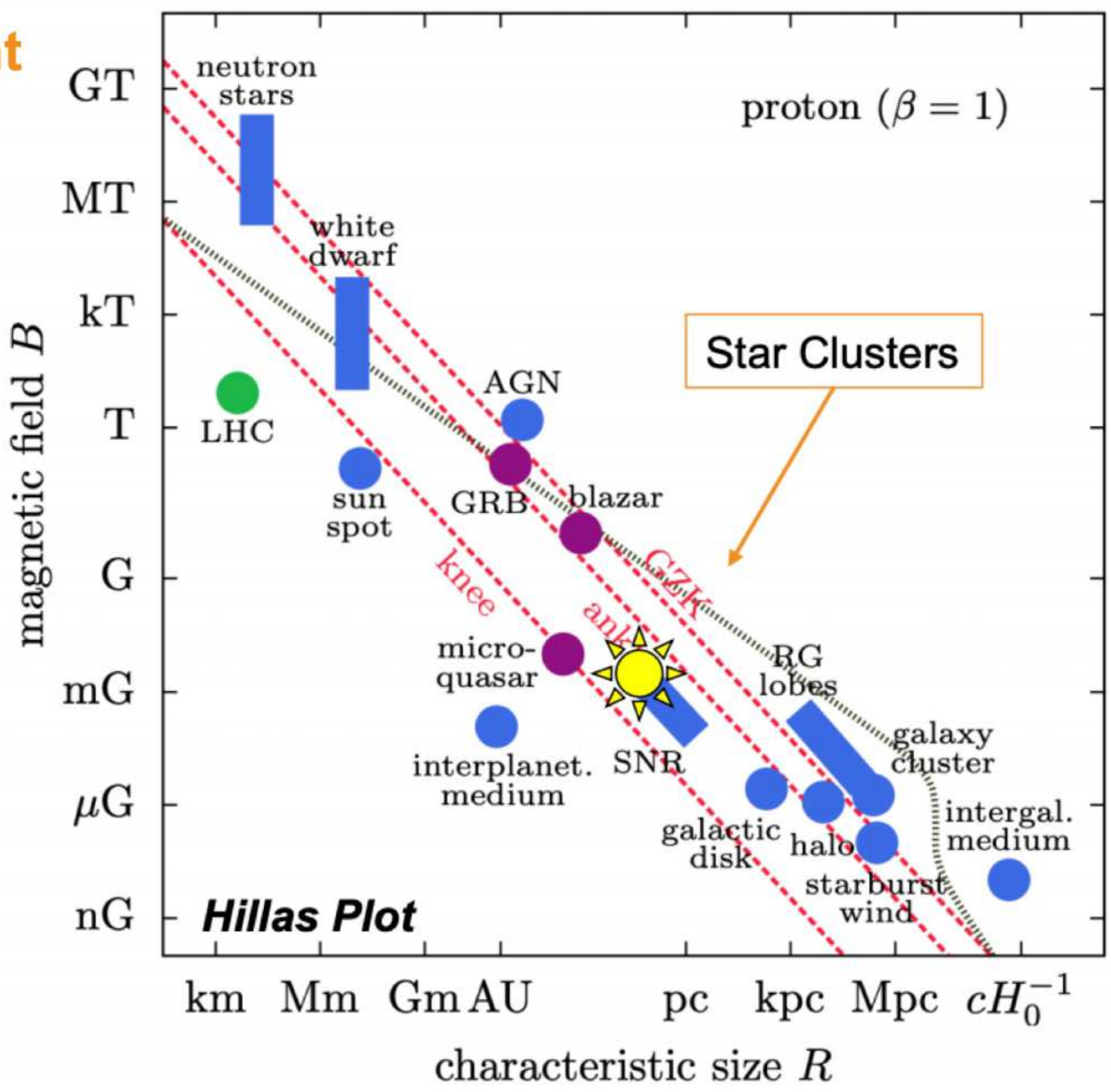
Aartsen et al (IceCUBE) 2017



Messengers

Maximum energy / confinment

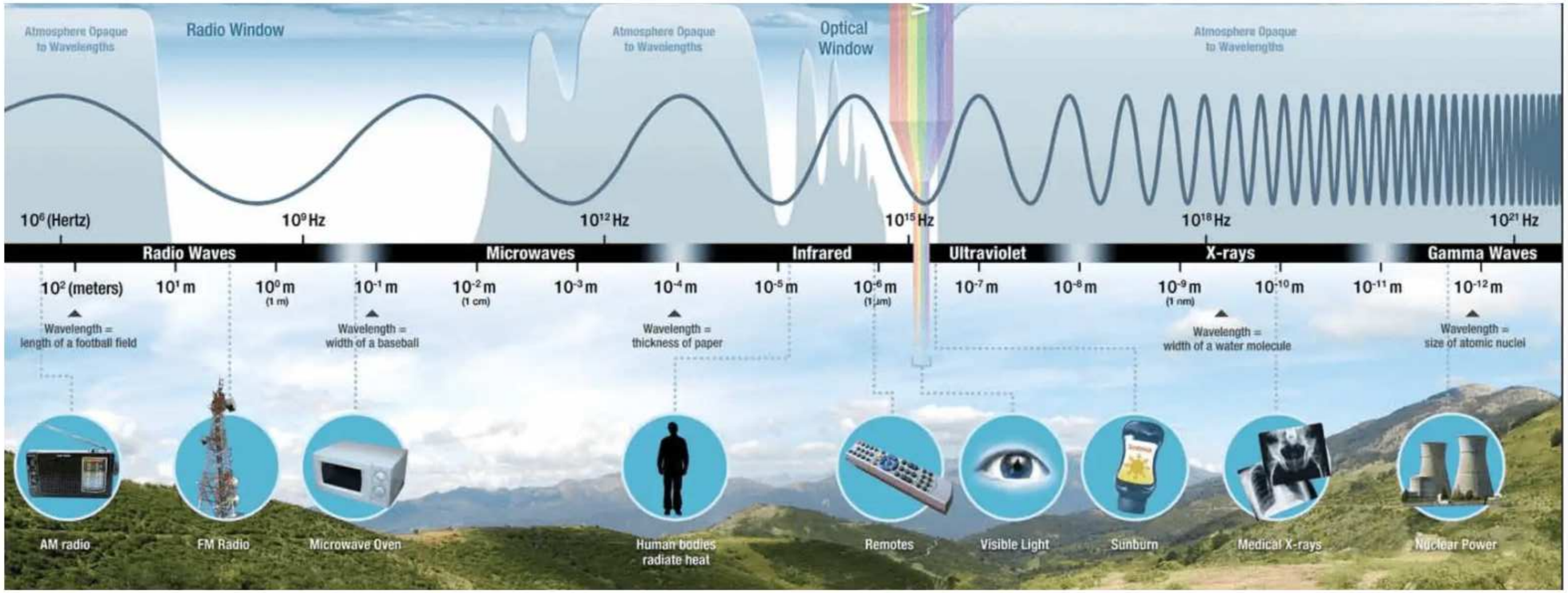
Aartsen et al (IceCUBE) 2017



Messengers

Radiation Processes

- **Gamma rays** are the highest energy form of light
- Produced in leptonic and hadronic radiation processes
- Blocked by the atmosphere

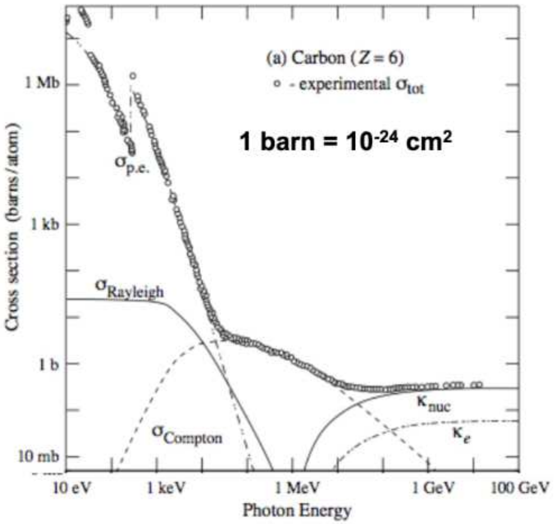


Messengers

Radiation Processes

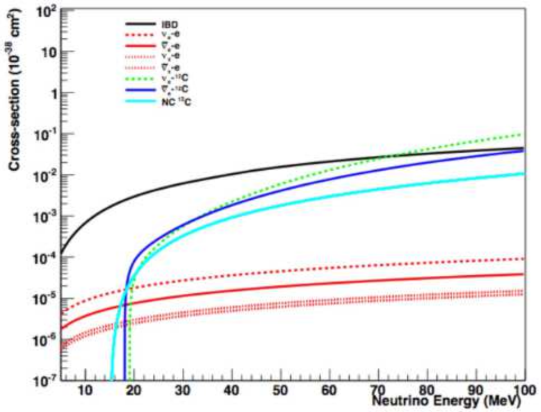
- **Neutrinos** have very large energies and tiny cross-sections => very difficult to detect!
- Produced in hadronic radiation processes

Photon-matter cross-sections



~10^{-24} cm^2

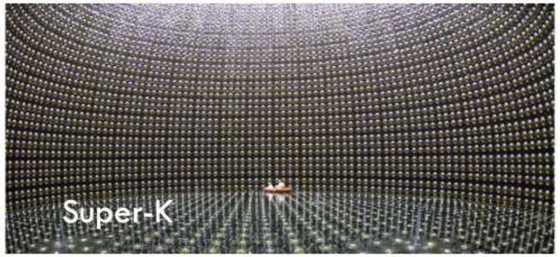
Neutrino-matter cross-sections

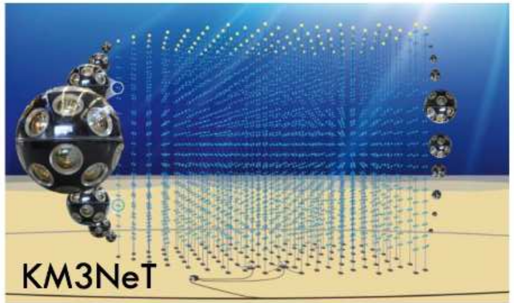


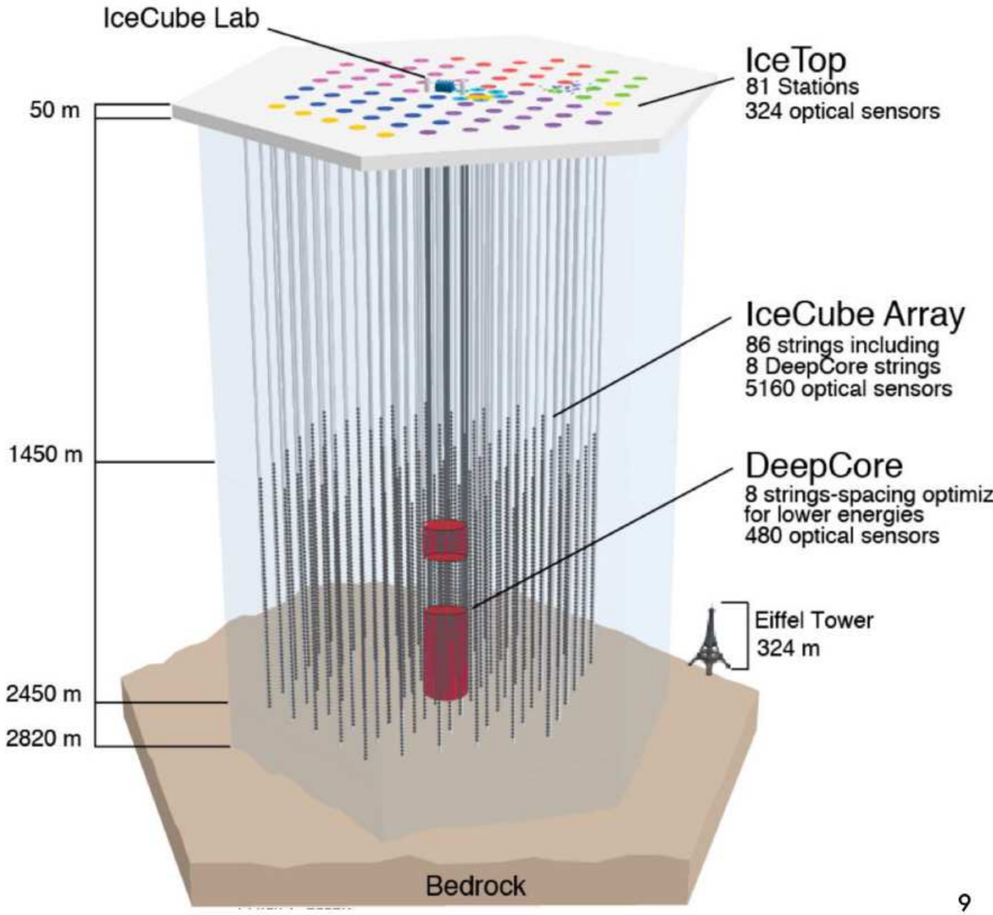
~10^{-40} cm^2

~16-17 orders of magnitude smaller

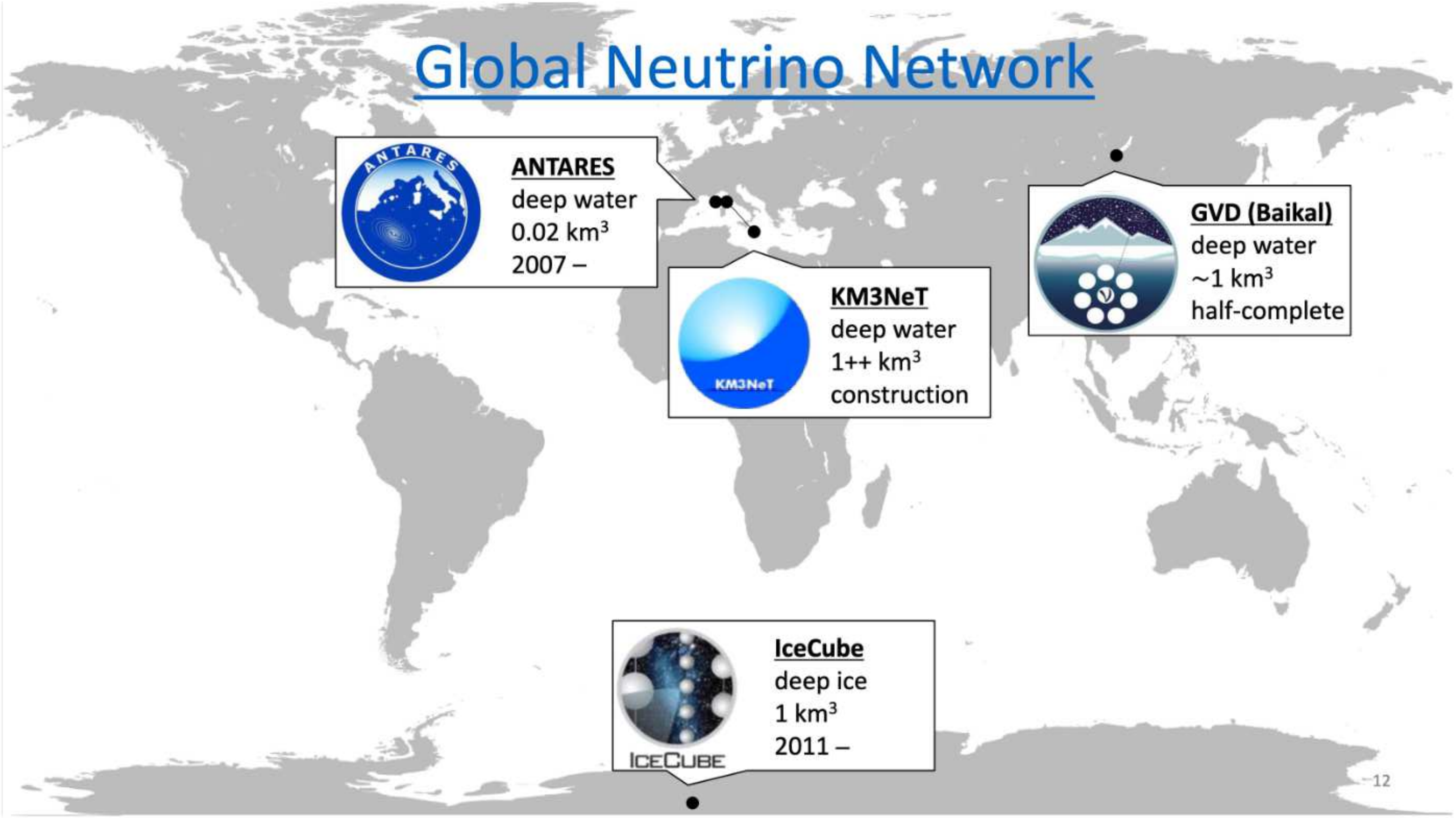
Neutrino experiments need to be large, and hence, made of relatively inexpensive material





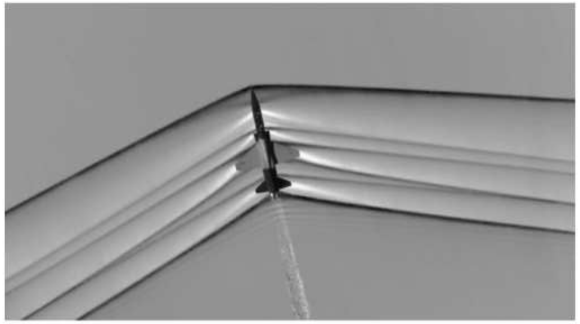


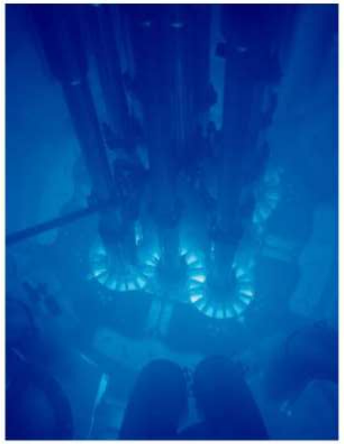
Neutrino experiments need to be large, and hence, made of relatively inexpensive material

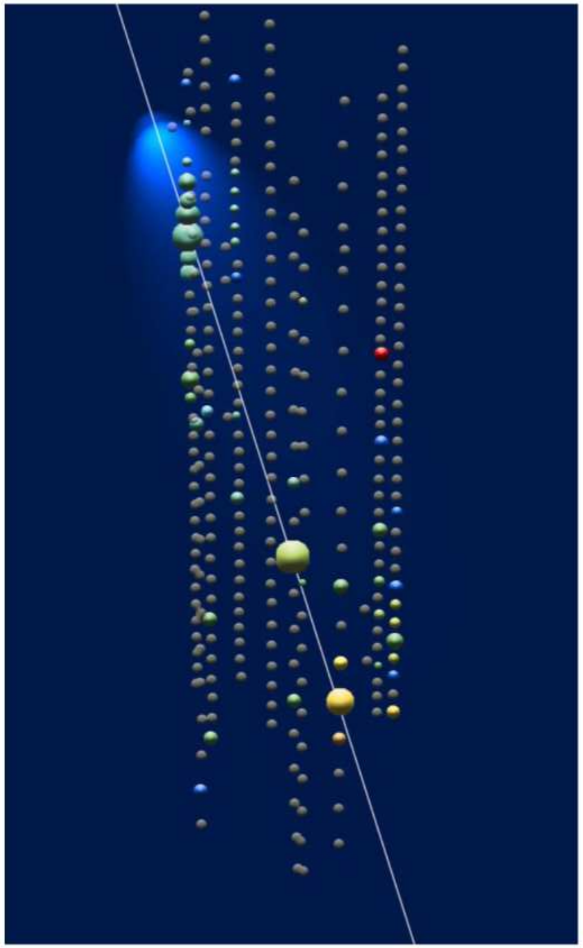


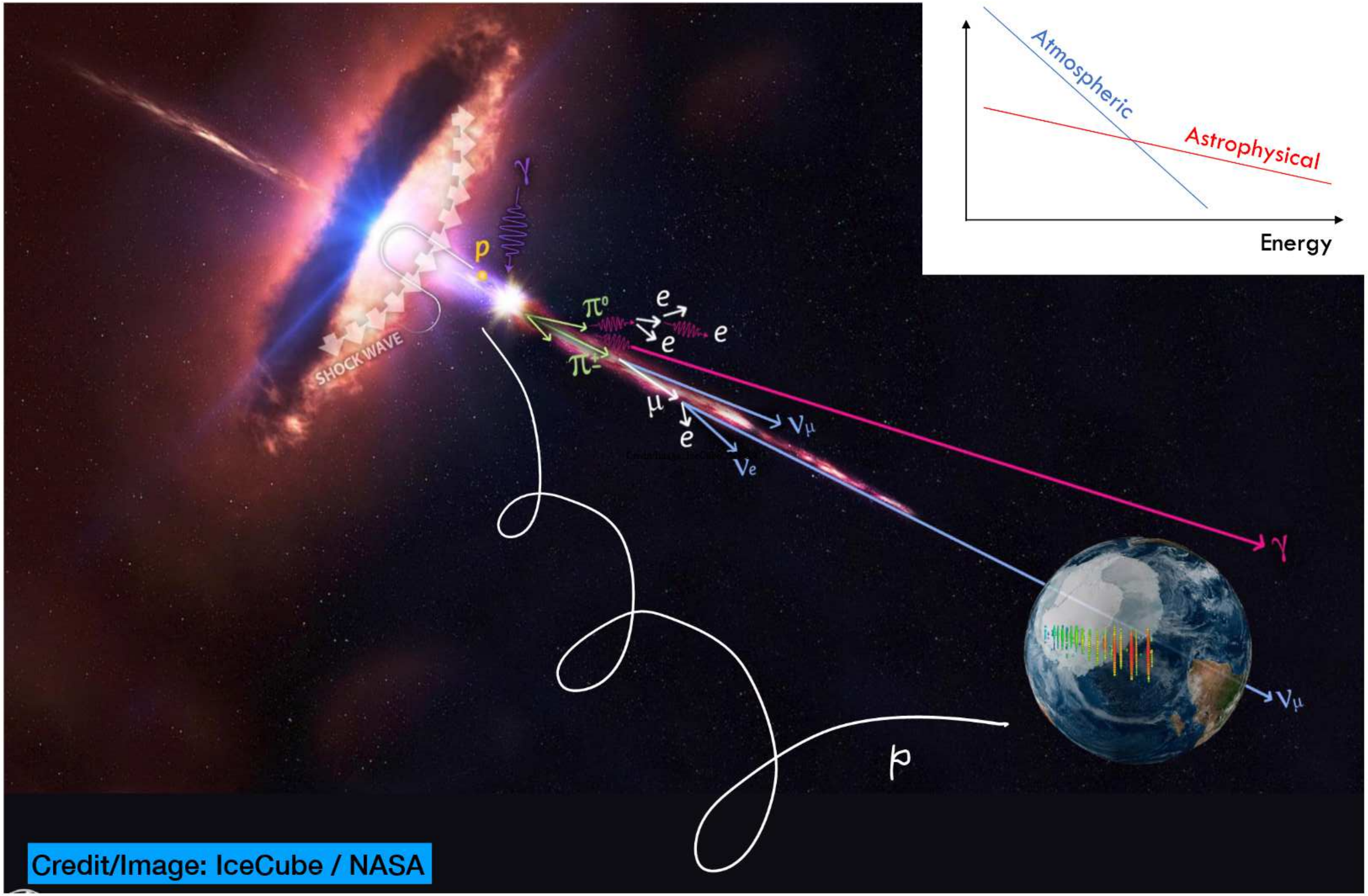
DETECTION PRINCIPLE

- A neutrino interaction will usually create a number of charged particles
- When these travel through the ice faster than light, they emit *Cherenkov* radiation
- This UV/blue light is the same as can be seen in nuclear reactors
- Optically transparent ice allows this light to reach some of the 5160 photosensitive sensors in the ice







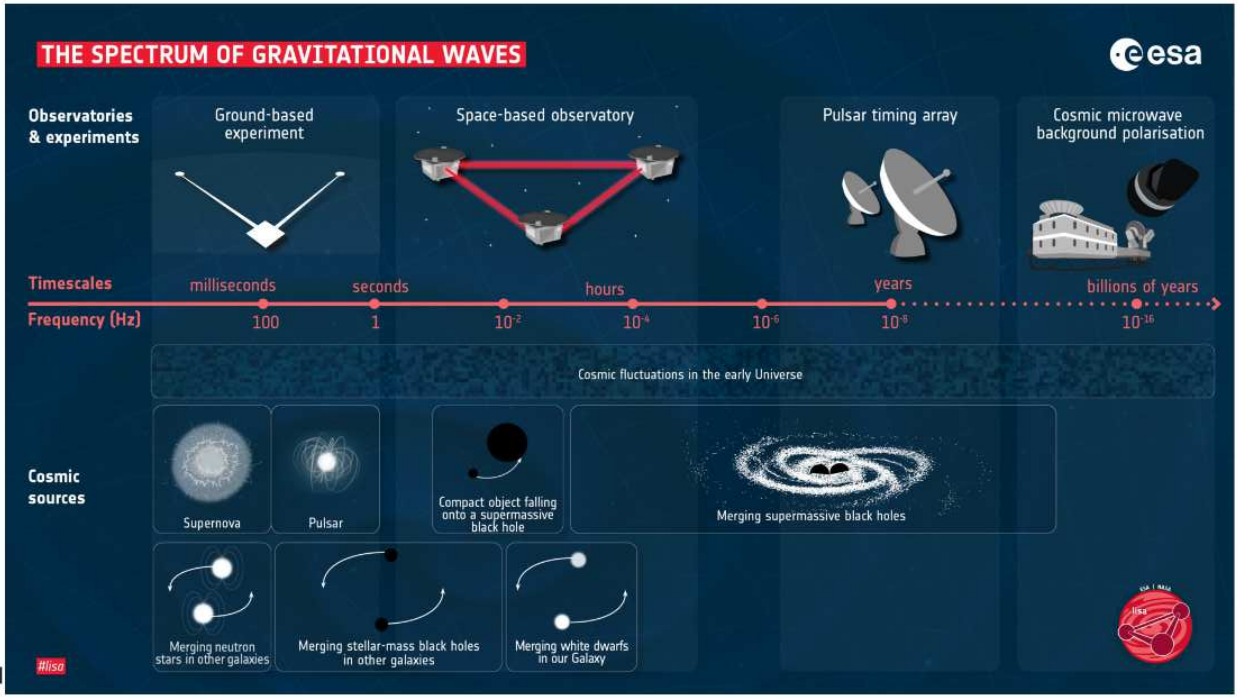


Credit/Image: IceCube / NASA

Messengers

Radiation Processes

- **Gravitational waves** are ripples in space-time produced by accelerated masses.
- They can be detected by interferometers, the pulsar timing array, or their imprint in the CMB polarization.



Recap

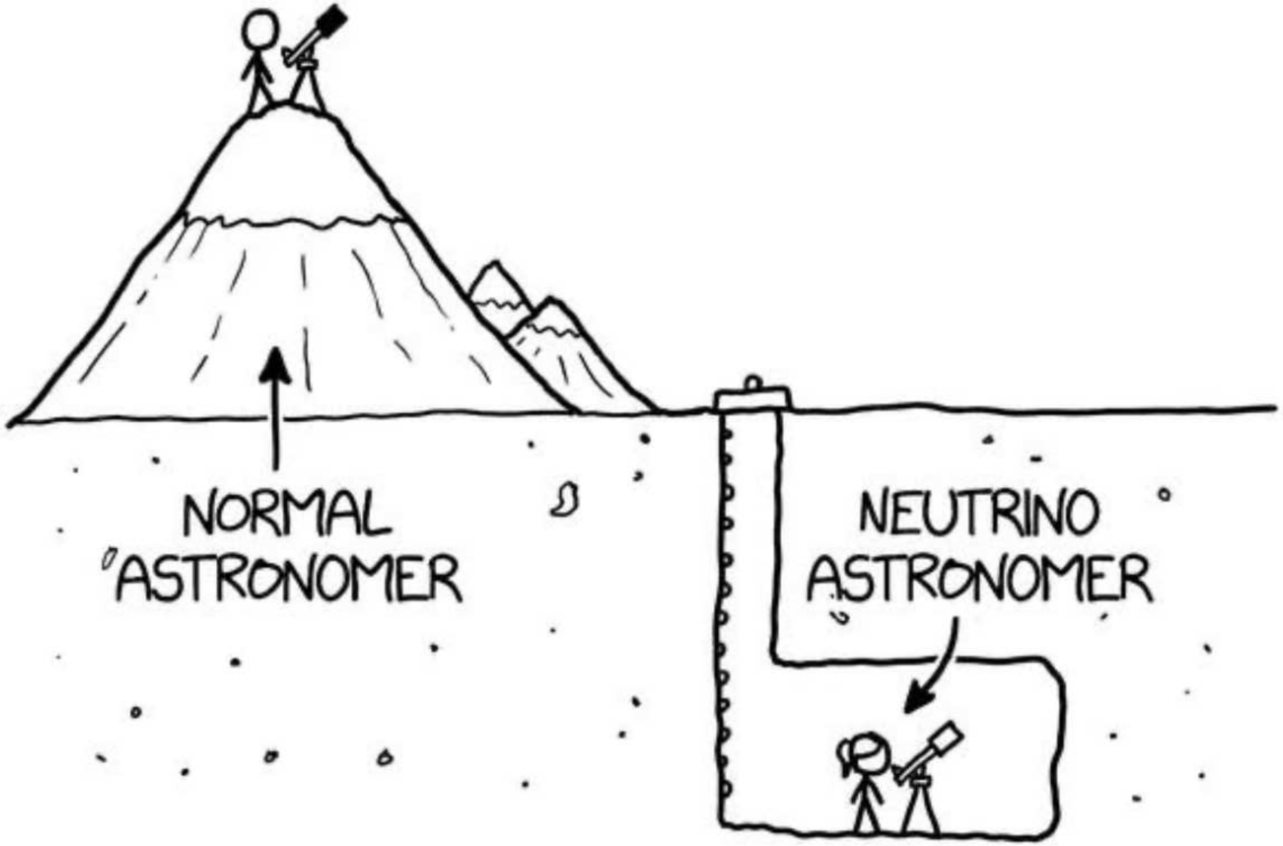
- Astroparticle physics study non-thermal radiation from relativistic particles in extreme environments

$$\nu \leq 3 \times 10^{19}\text{Hz}; \quad \lambda \leq 0.01\text{nm}; \quad \text{E} \geq 100 \text{ keV}$$

- The energy is obtained by processes related to explosions, accretion, rotating magnetic fields, or processes related to annihilation of exotic particles
- The high energy regime is dominated by non-thermal processes, and they require either high magnetization in relativistic flows or efficient Fermi shock acceleration.
- High energy charged particles are deflected by magnetic fields and do not point back to their origin. Neutrinos and gamma rays produced in cosmic-ray interactions can be used to trace back the cosmic-ray sources. Neutrinos are the smoking gun signature for hadronic interactions, while gamma rays can also be produced in leptonic processes.

But what are these high energy particles or *cosmic rays*?

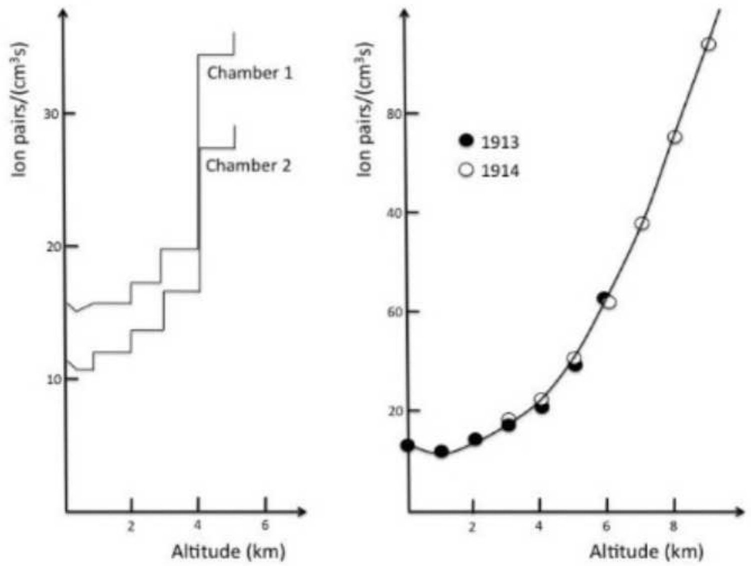
The Cosmic ray see



History of Cosmic Rays

The discovery of Victor Hess

More than 100,000 cosmic rays will hit each of you during this lecture



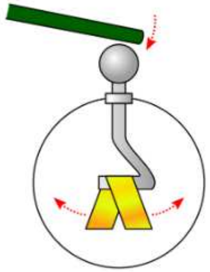


Figure 9: Increase in radiation with altitude as measured by V. Hess in 1912 and then confirmed by Kohlhörster in 1913/14 (Image credit: Wikimedia Commons, `https://commons.wikimedia.org/wiki/File\%3AHessKol.jpg`).

In 1912, after 9 balloon ascents to record ionization levels with charged electroscope, Victor Hess concluded that

"A radiation of very high penetrating power enters our atmosphere from above".

The newly discovered radiation was dubbed "cosmic" by Robert A. Millikan in 1925.

In 1936, Victor Hess was awarded with the Nobel Prize for his discovery.

History of Cosmic Rays

The discovery of Victor Hess

- No day-night variation was detected => No solar origin
- ***East/West effect:*** In 1927 variations of the cosmic-ray intensity with latitude were detected => cosmic-rays are mainly positively charged

- In 1934 / 1937 air showers of secondary cosmic rays were discovered (Bruno Rossi/Pierre Auger)
- In the 1920-1950 studies of cosmic rays led to a revolution in particle physics: discovery of positron, muon, pion, strange particles..

86%	protons
11%	α-particles
1%	heavier elements (up to Uranium)
2%	electrons
	small portion of positions and antiprotons (secondary origin)

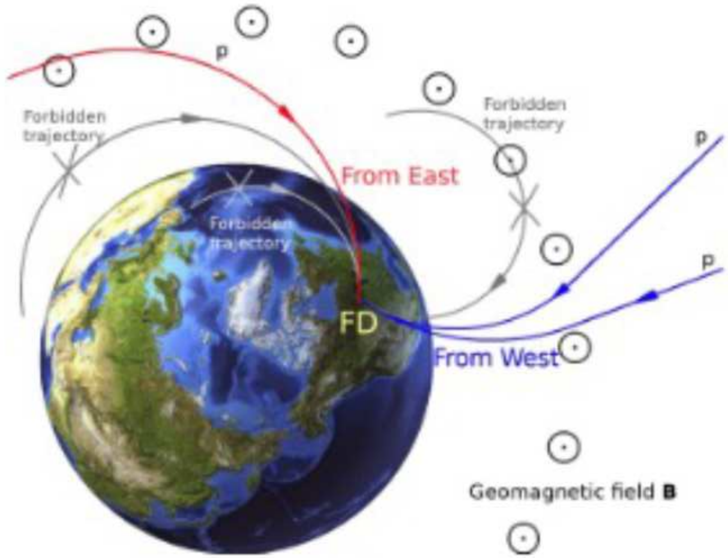
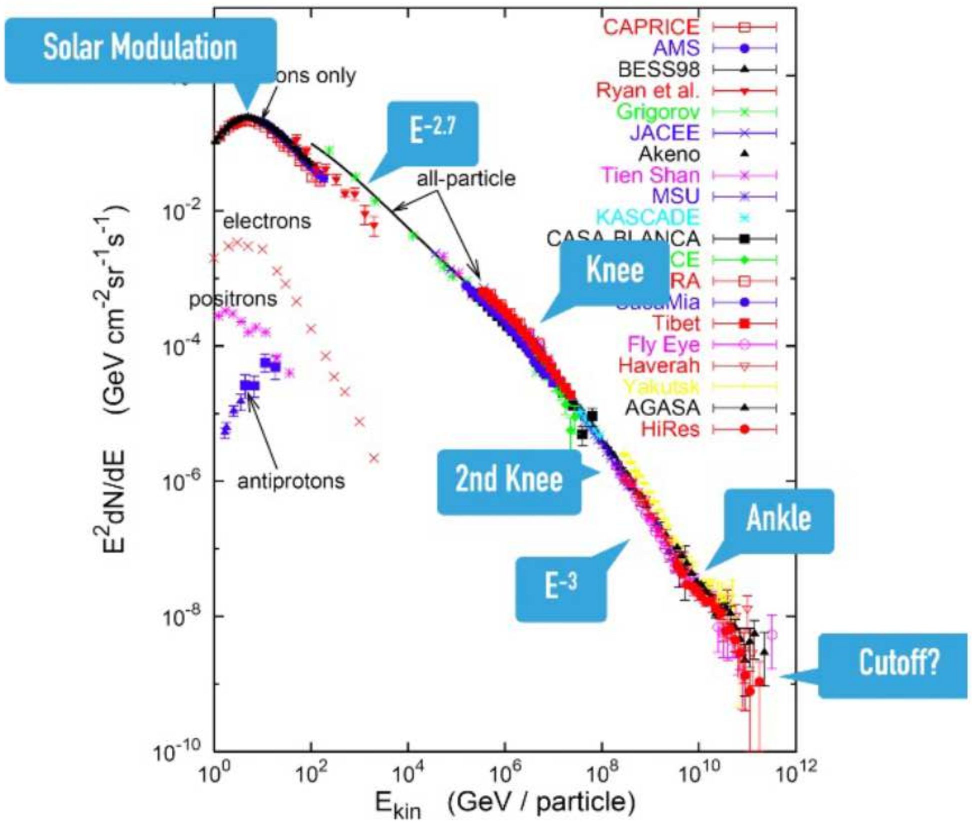


Figure 10: East-West effect.

Cosmic rays

Spectrum

Relativistic particles of cosmic origin hitting the top of the atmosphere at a rate of ~$1 cm^{-2}s^{-1}$



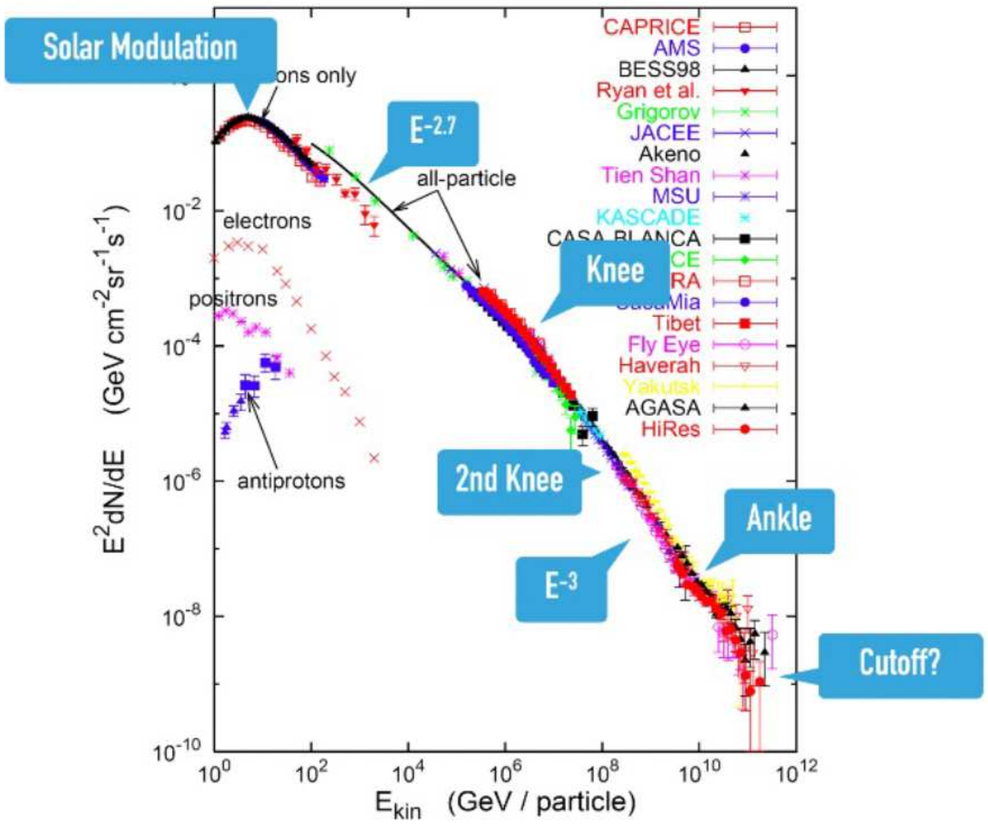
- CRs are charged particles => deflected by magnetic fields
- Statistics! the observed flux is low
- Mainly protons (+electrons and heavier nuclei) coming from beyond the Solar system and extending >10 decades in energy

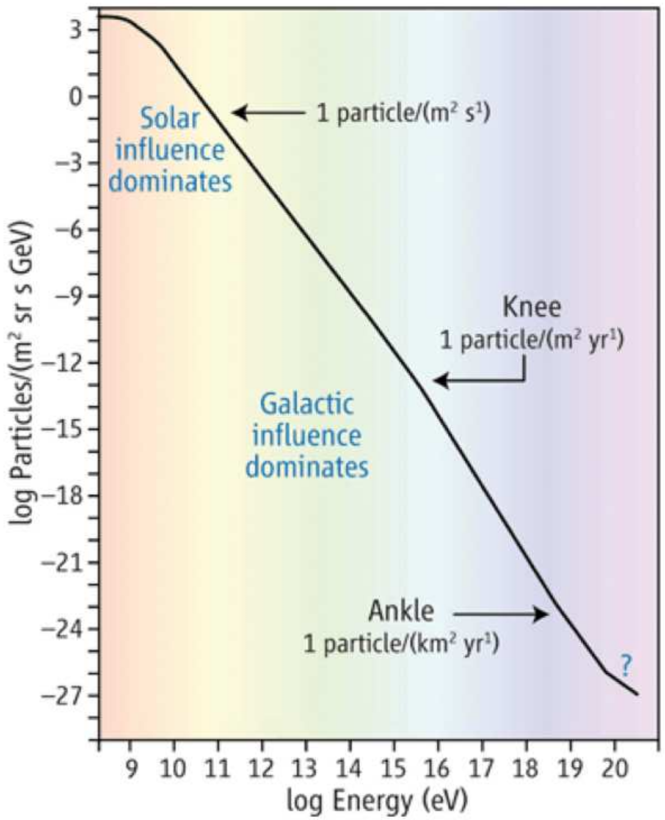
10^3 eV	1 keV (kilo)
10^6 eV	1 MeV (mega)
10^9 eV	1 GeV (giga)
10^{12} eV	1 TeV (tera)
10^{15} eV	1 PeV (peta)
10^{18} eV	1 EeV (exa)
10^{21} eV	1 ZeV (zetta)

Cosmic rays

Spectrum

Relativistic particles of cosmic origin hitting the top of the atmosphere at a rate of ~$1 cm^{-2}s^{-1}$

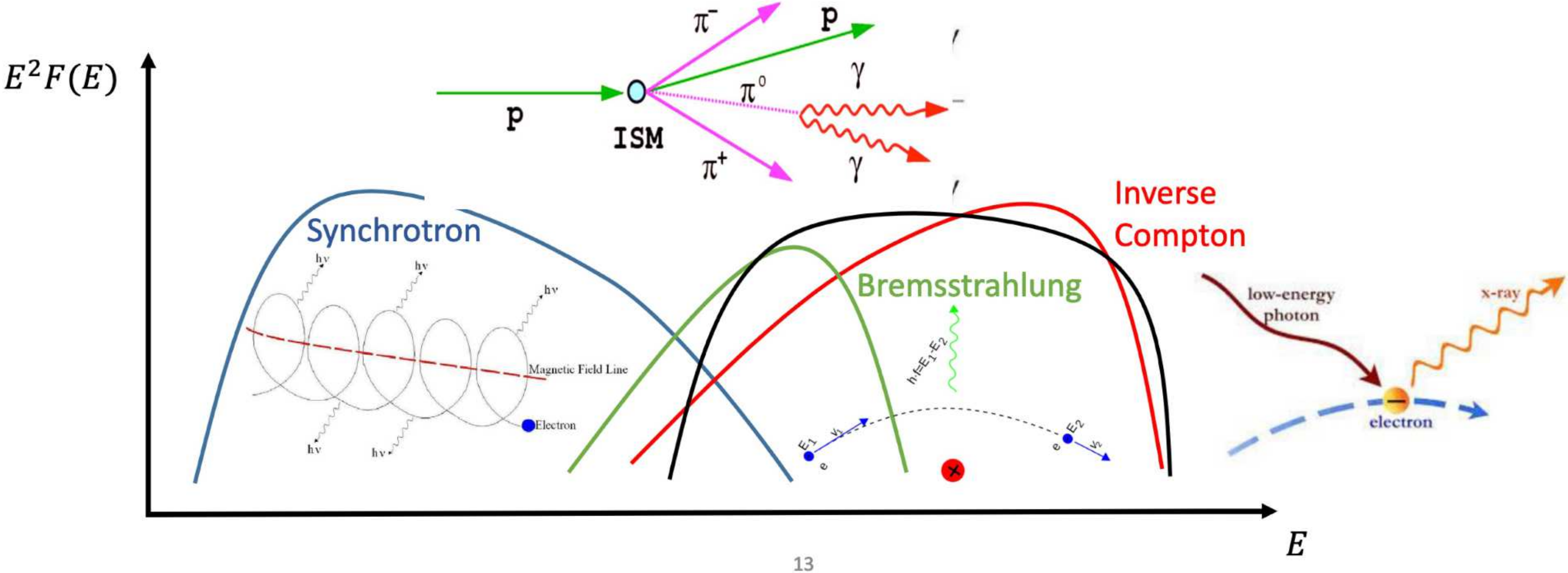




How do we detect them?

Messengers: neutral particles

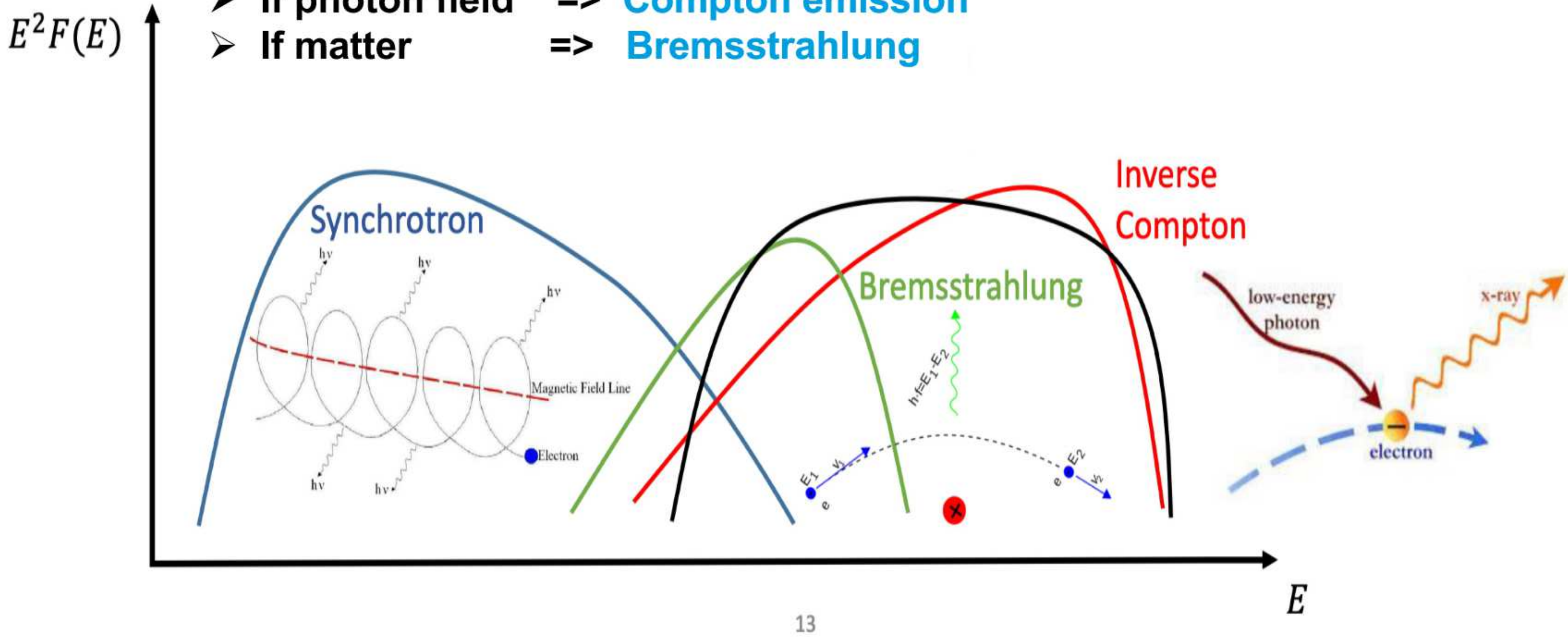
- Hadrons inelastic collisions with matter



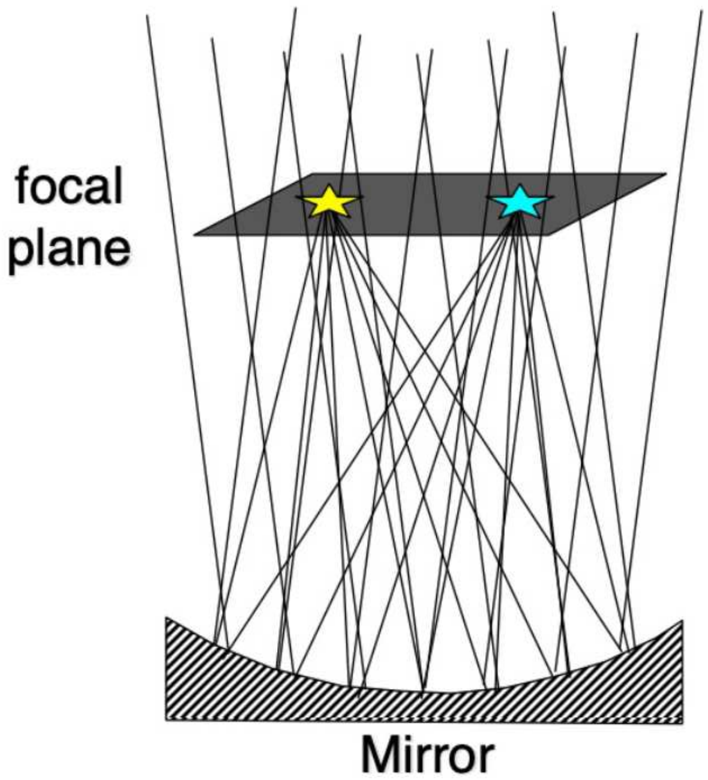
Radiation Processes

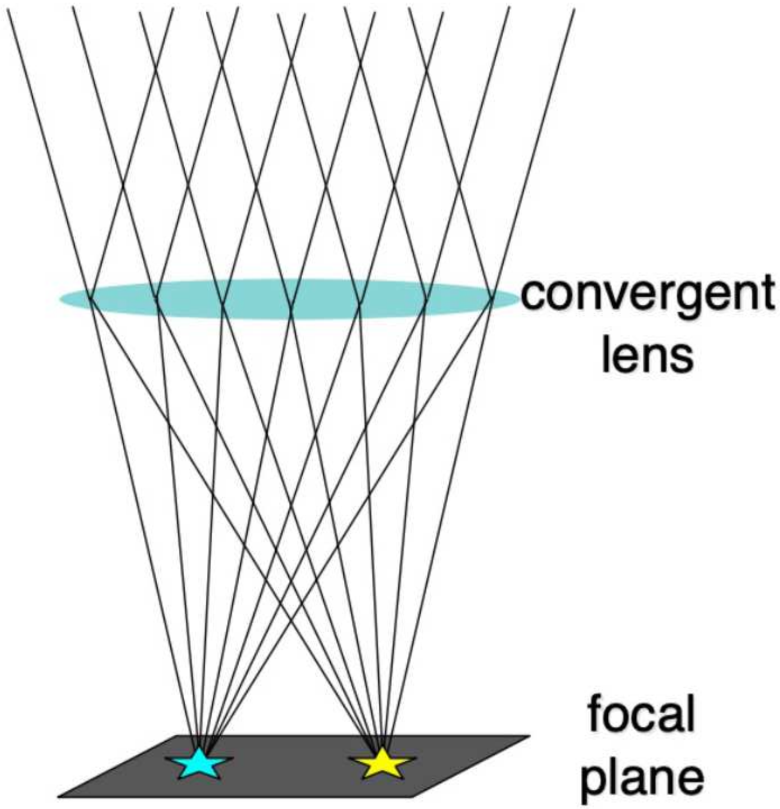
Leptonic Radiation

- Electrons accelerated in the presence of **fields**:
  - **If magnetic field =>** Synchrotron emission
  - **If photon field =>** Compton emission
  - **If matter =>** Bremsstrahlung



- *Imaging:* transform *directions* into *points* in a focal plane
- The photon detector in the focal plane can be a photographic film, the retina or an electronic device





X-ray and γ-ray astronomy

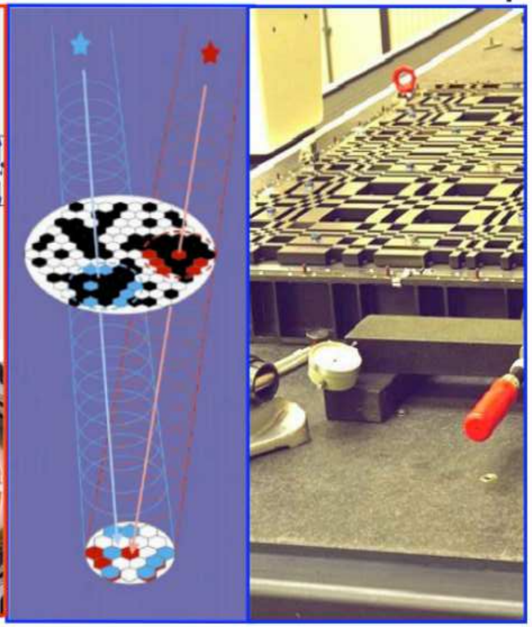
keV MeV GeV

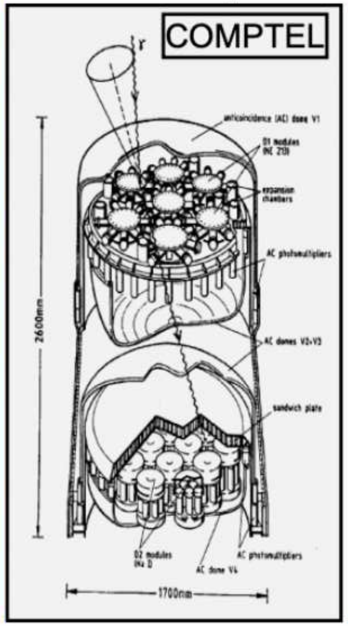
Focusing instruments

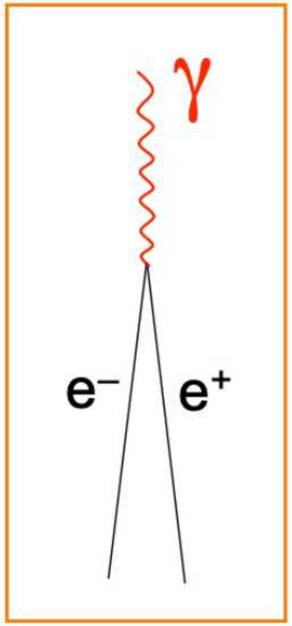
Coded masks, collimators (i.e. INTEGRAL)

Compton telescopes

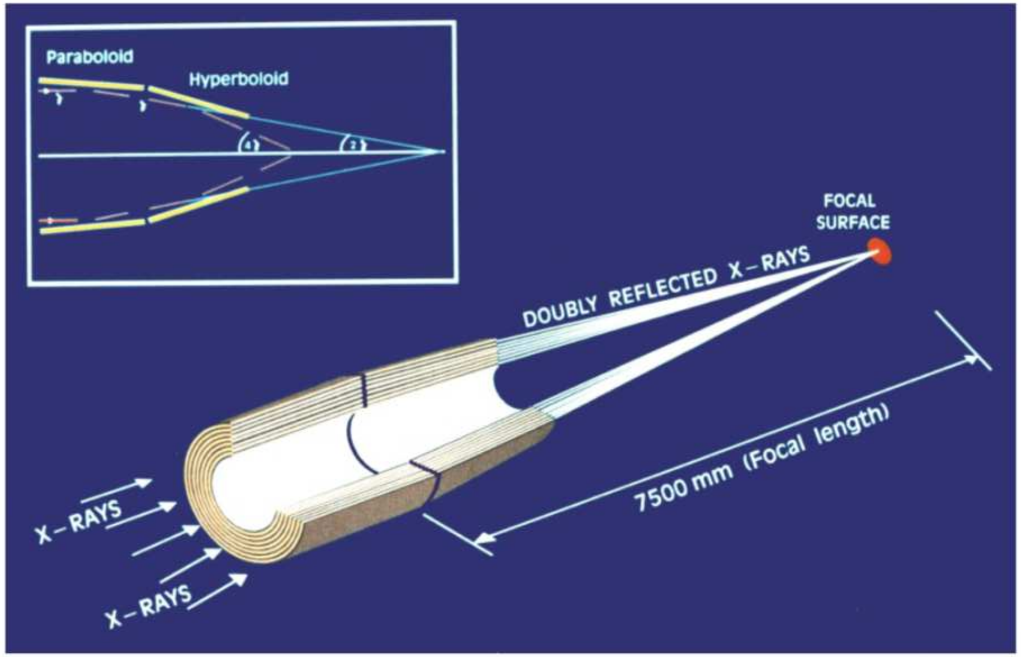
Pair conversion telescopes (until ~300 GeV)







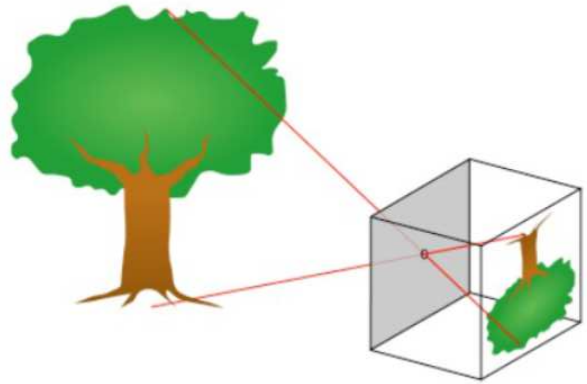
- High energy photons are very *penetrating*... is it possible to build mirrors for them?



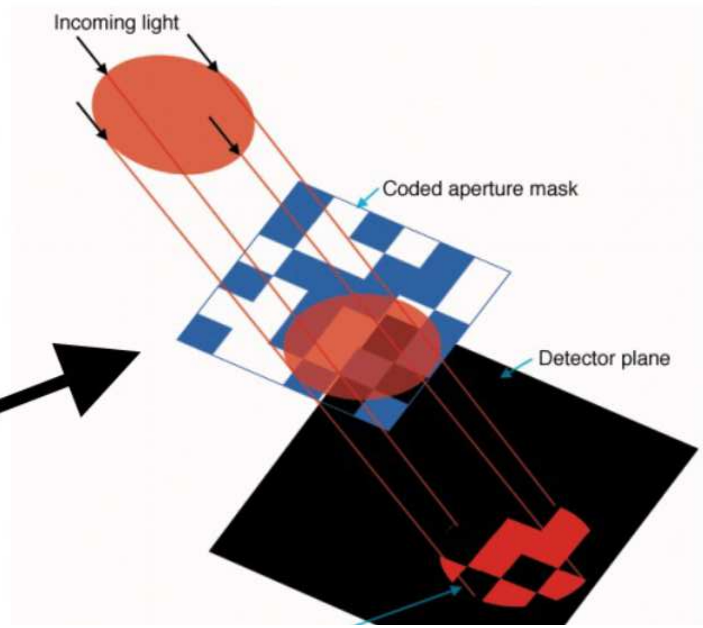
- Grazing incidence mirrors made of heavy metals (Au, Ir) effective up to E~10 keV. What can be done at higher E?

E = 10 keV - 10 MeV

Generalization of the principle of the pinhole camera (the simplest imaging device)

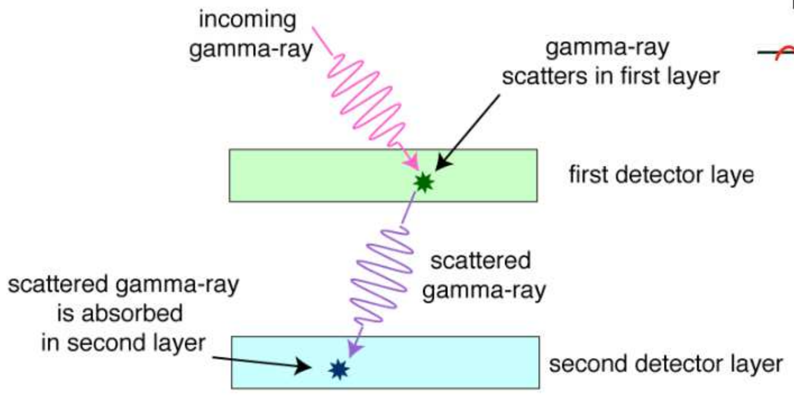


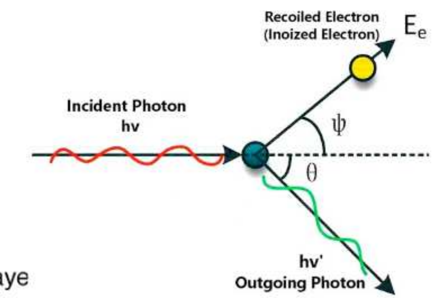
Coded aperture masks:

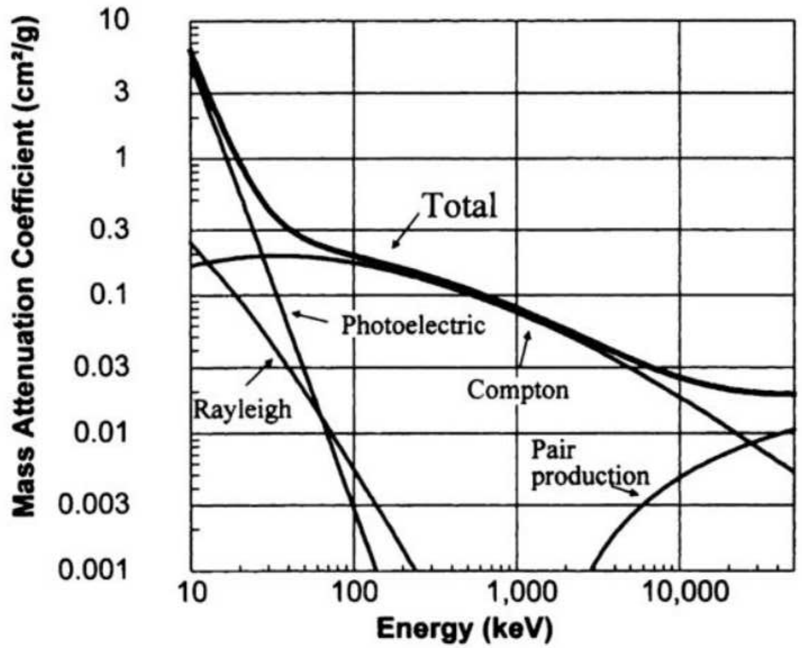


Pair conversion

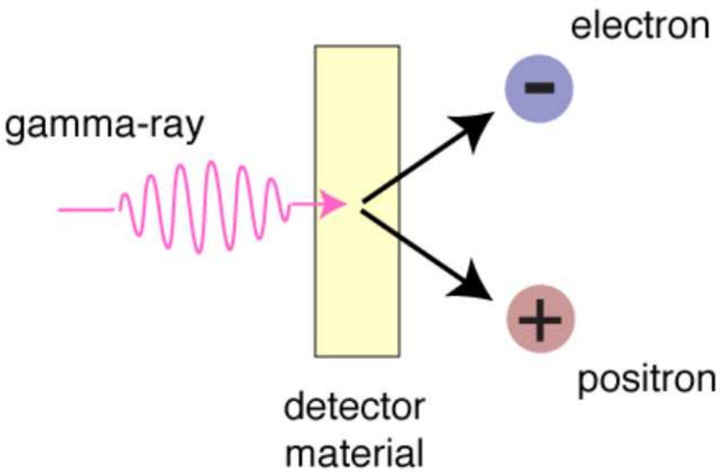
Compton scattering detector.







pair-production telescope



Main idea: To convert photons into electrons that we can measure their current

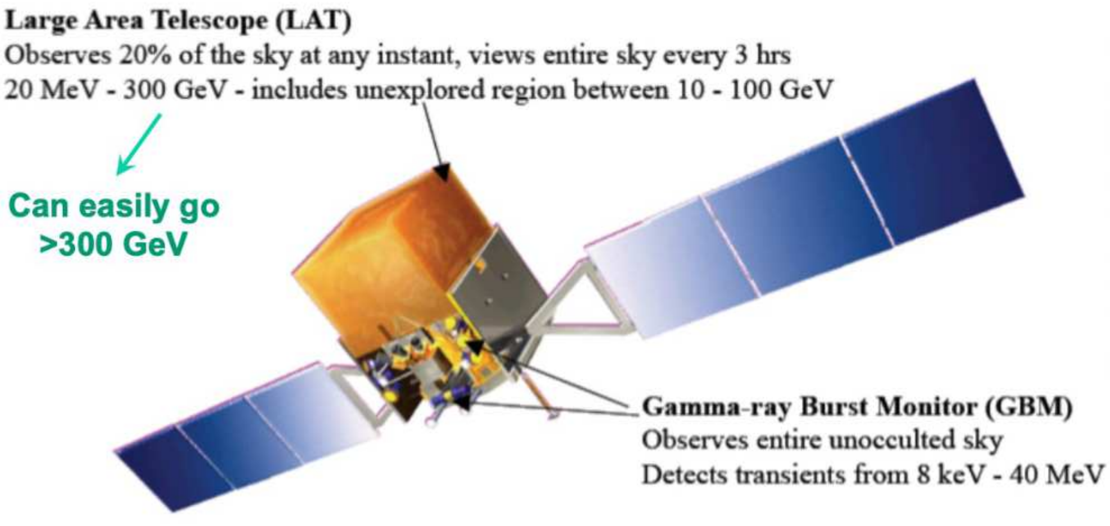
Once the gamma-ray has transferred all or part of its energy to secondary electrons, these have in turn to be detected:

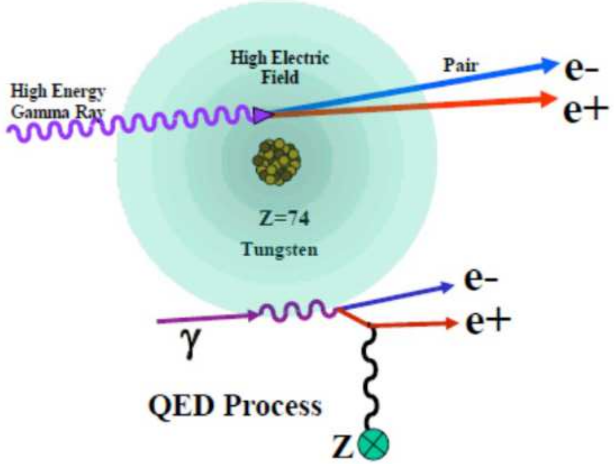
- Gas-filled detectors (i.e. Spark chambers)
- Scintillator + photomultiplier tube
- Semiconductors

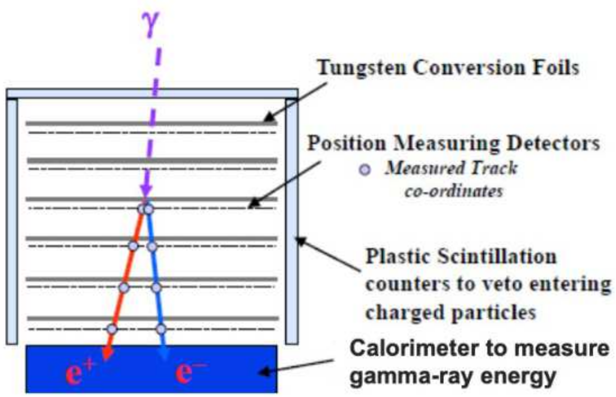
Gamma-ray detection

Satellites (E > 100 MeV)

Based on Pair-Conversion mechanism







4

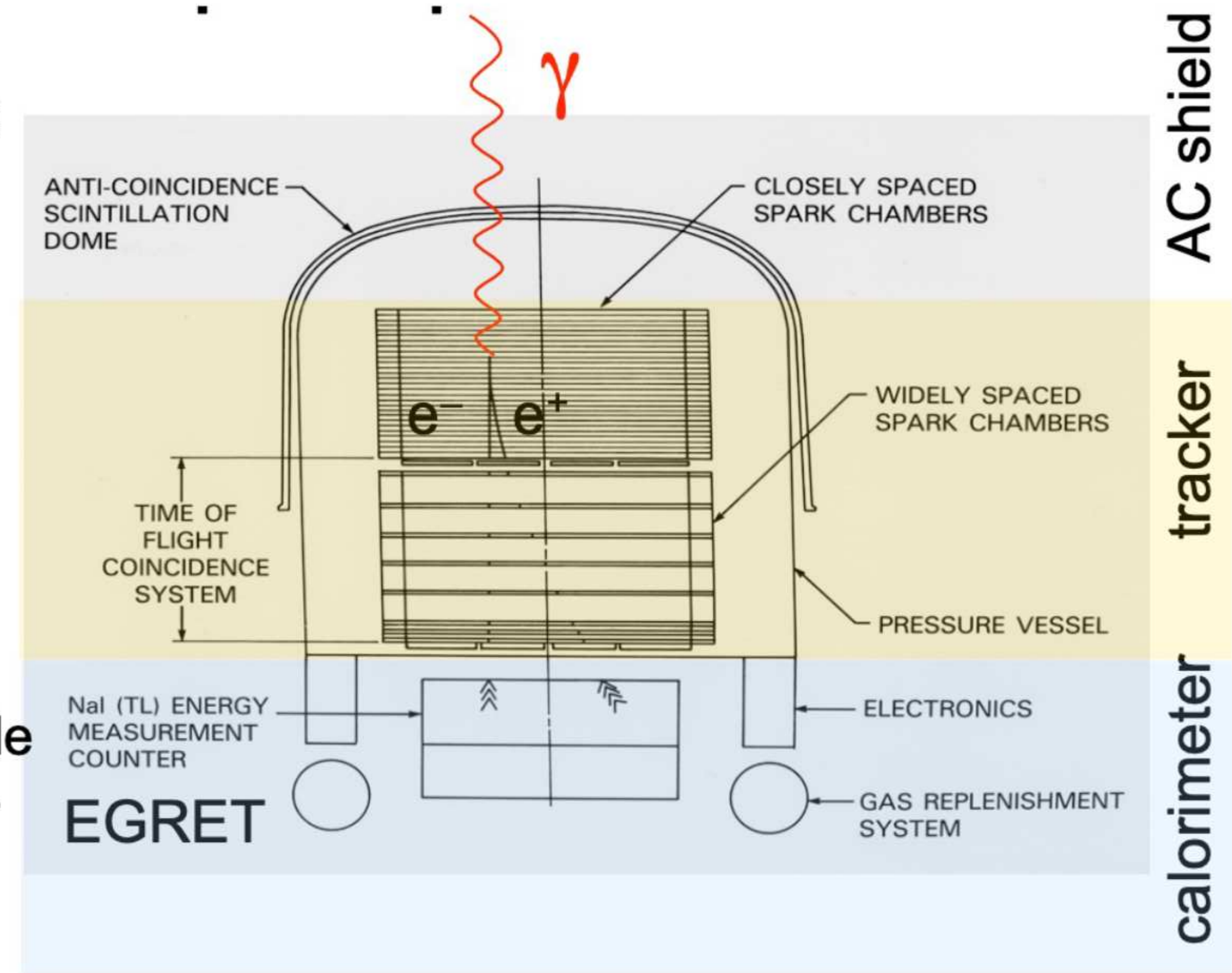
DESY.

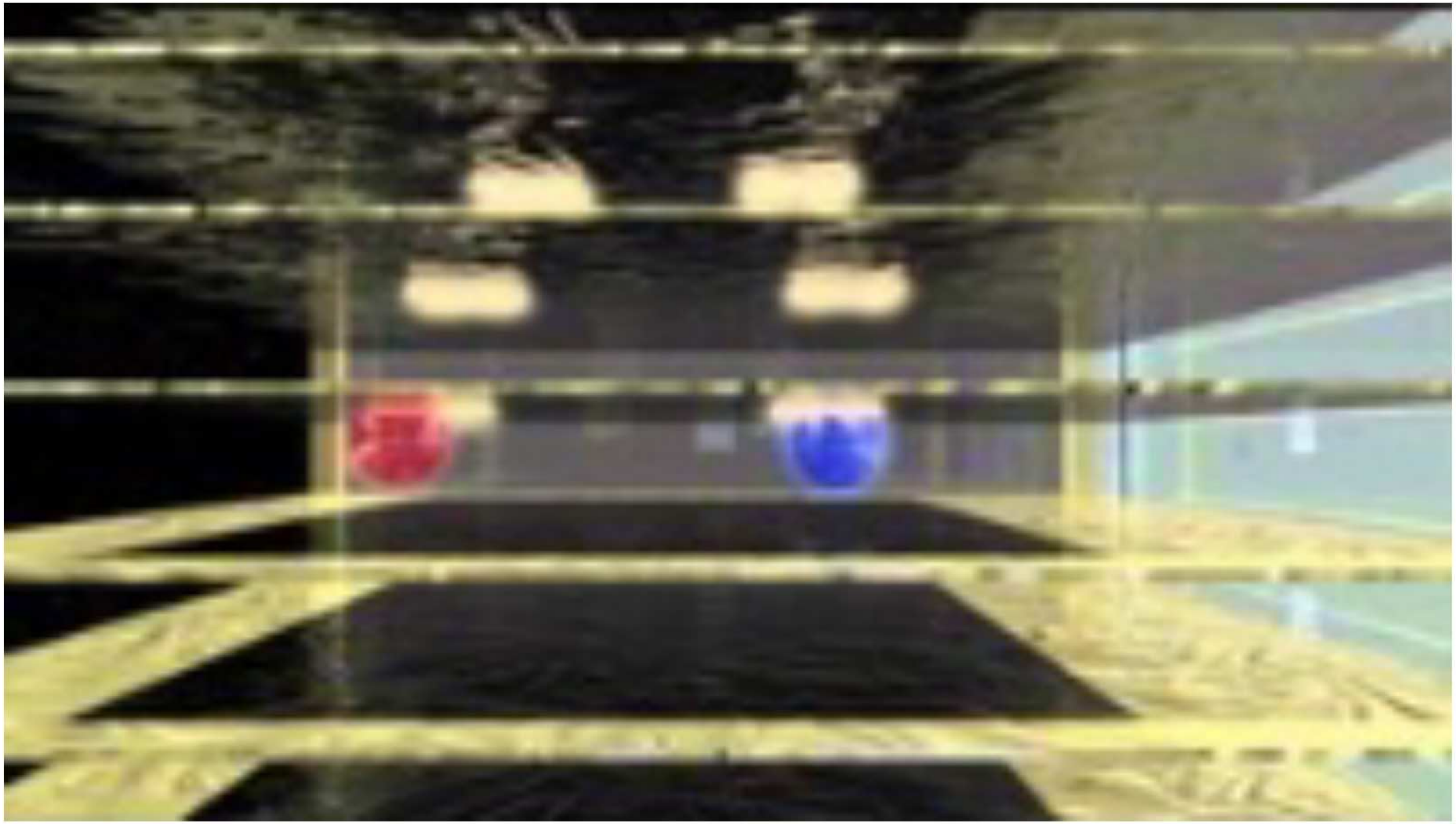
Three main parts:

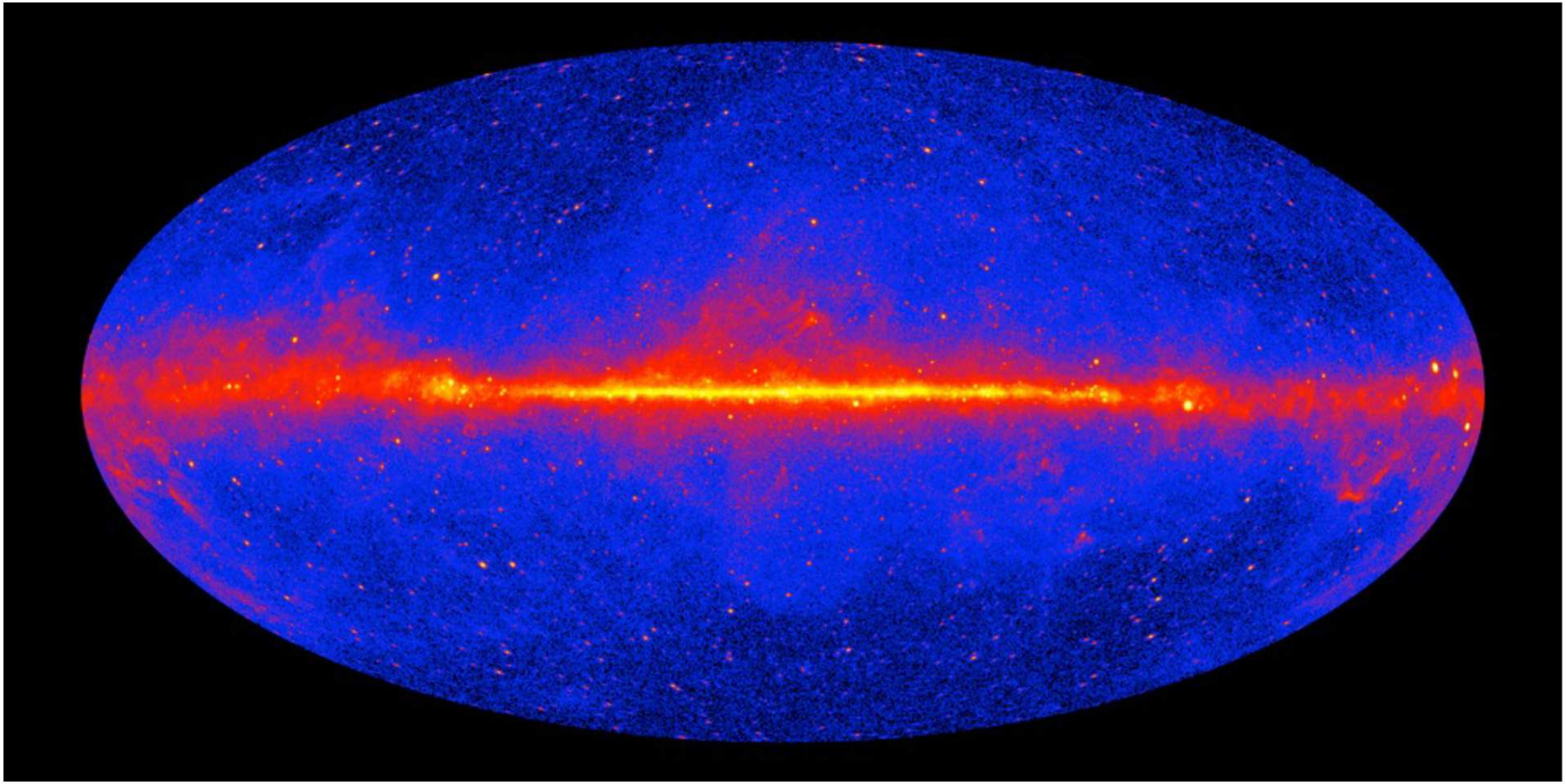
A tracker to determine the trajectory of the $e^{\pm}$

A calorimeter for measuring the energy

An "active shield" against charged cosmic rays (particle detector set in anti-coincidence)







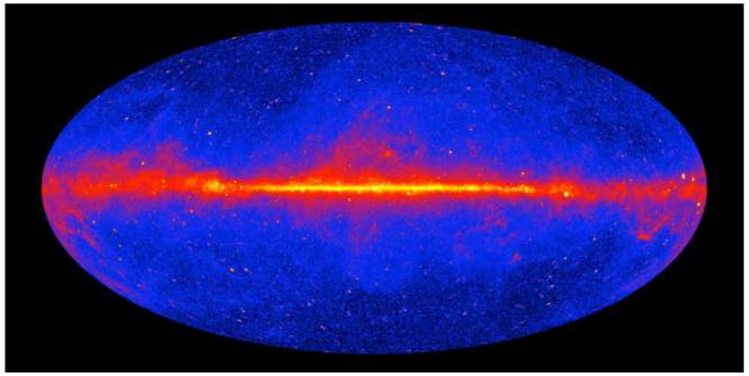
Gamma-ray detection

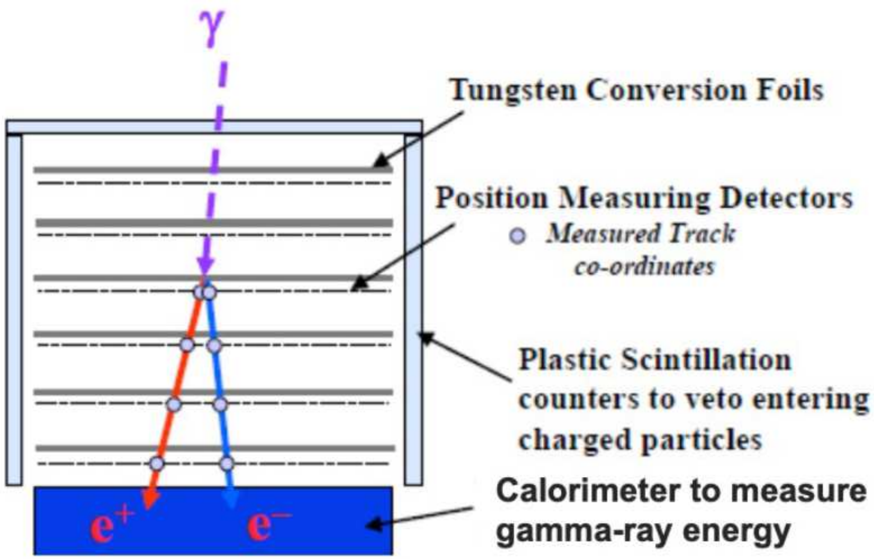
Satellites (E > 100 MeV)

Based on Pair-Conversion mechanism

Signal: Photons from source

Background: Photons from diffuse CR





4

Gamma-ray detection

Satellites (E > 100 MeV)

- Main background => Gamma-ray diffuse emission from the CR sea
- Works very well for low energies (<1 GeV) with limited PSF

- At E few tens of GeV small effective area results in extremely low detection rates, even for strong sources :

$F_{Crab\ Nebula, E>100GeV}$ @ 100 photons/m^2/year

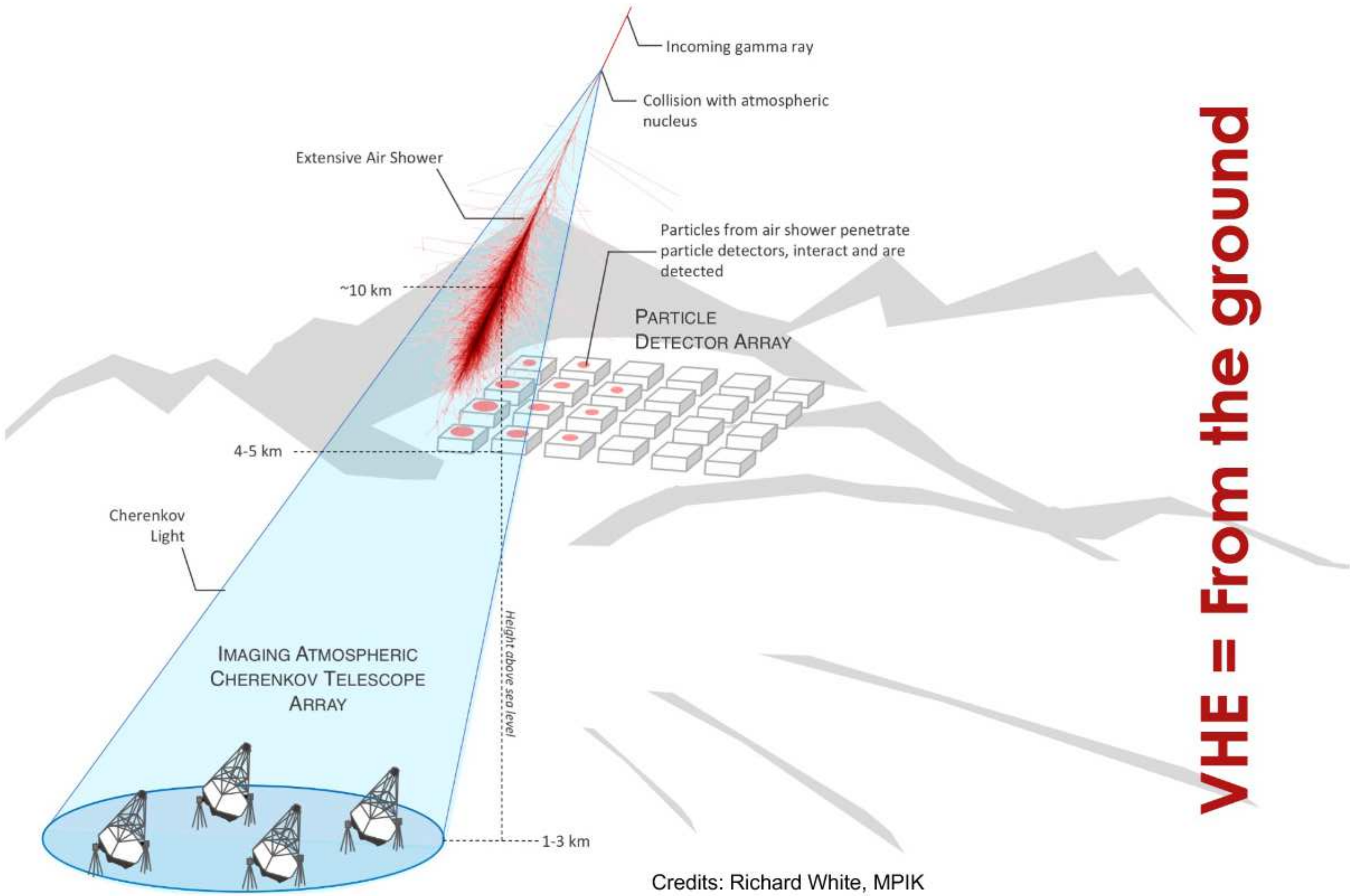
That means: 1 gamma-ray / 3 hours above 30 GeV

- Calorimeter depth ≤ 10 radiation lengths, which corresponds to ~1 ton per m^2 (which is hard to put into orbit) => VHE showers leak out of the calorimeter

=> Solution: a "pair conversion telescope" in which the atmosphere is part of the detector

Gamma-ray detection

Ground-based detectors (E > 50 GeV)



Credits: Richard White, MPIK

VHE = From the ground

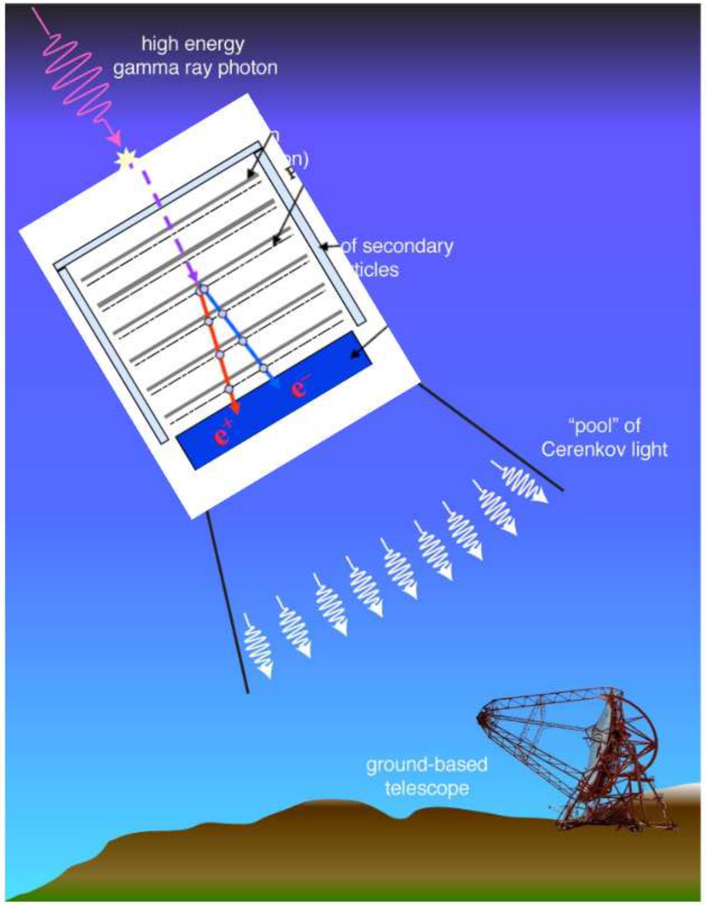
Gamma-ray detection

Extensive Air Showers (EAS)

- Discovered in 1938 by Pierre Auger

Most frequent processes in showers:

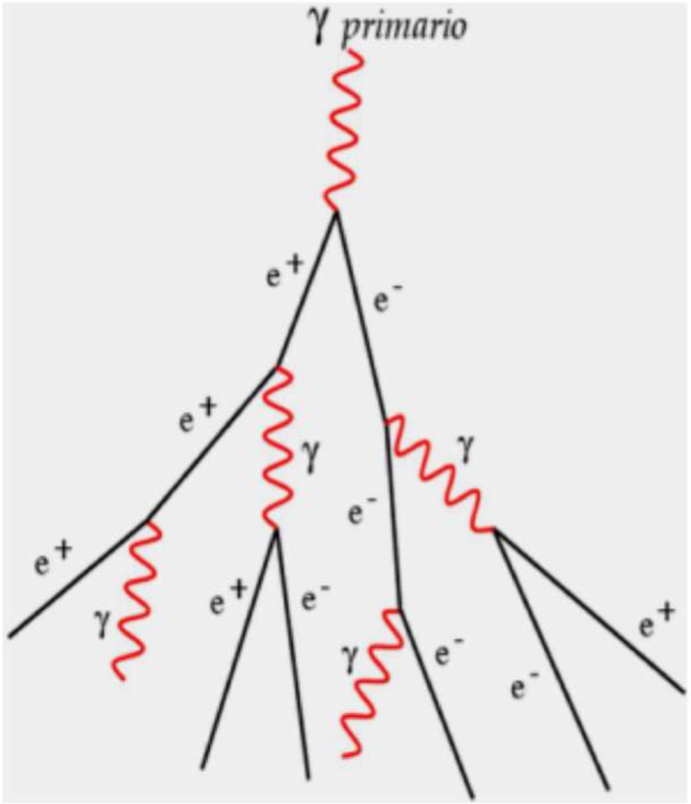
- Electromagnetic showers:
  - $\gamma \longrightarrow e^+ e^-$ (pair production)
  - $e^\pm \longrightarrow \gamma$ (*bremsstrahlung*)
- Hadronic showers:
  - CR + atm. nucleus $\longrightarrow \pi^\circ, \pi^\pm + N^*$
  - $\pi^\pm \longrightarrow \mu^\pm + \nu$
  - $\pi^\circ \longrightarrow \gamma\gamma \longrightarrow$ e.m. showers



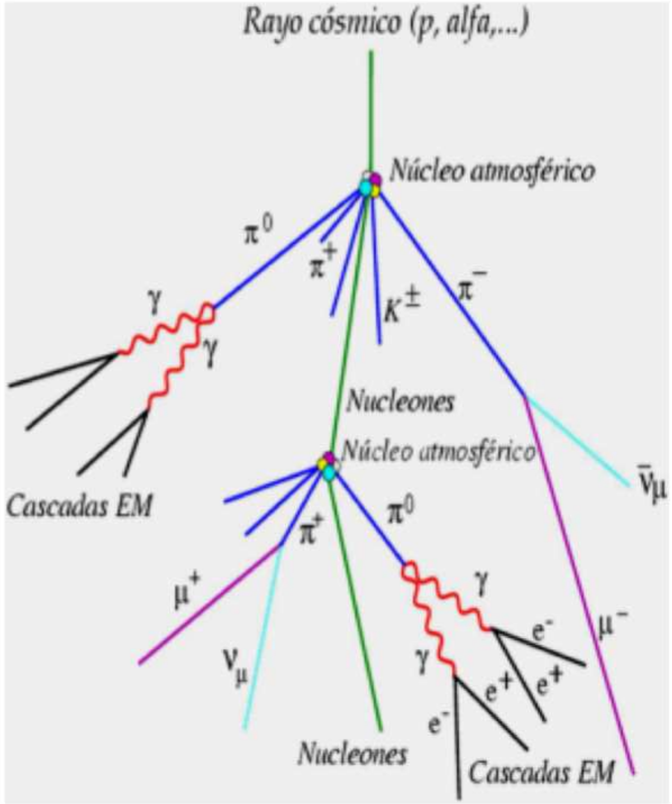
Gamma-ray detection

Extensive Air Showers (EAS)

Electromagnetic

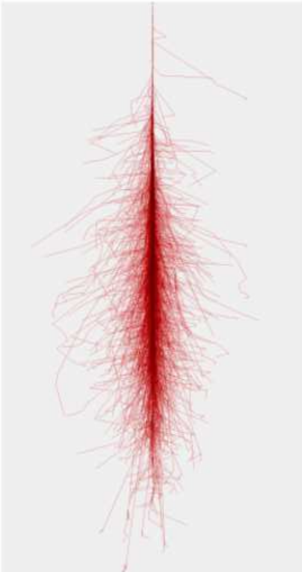


Hadronic

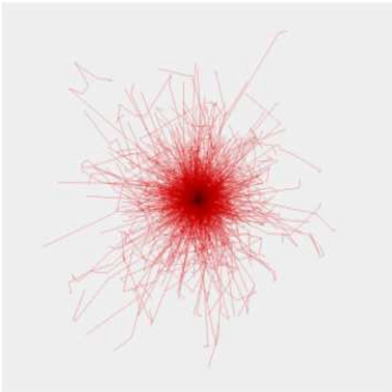


Gamma-ray detection

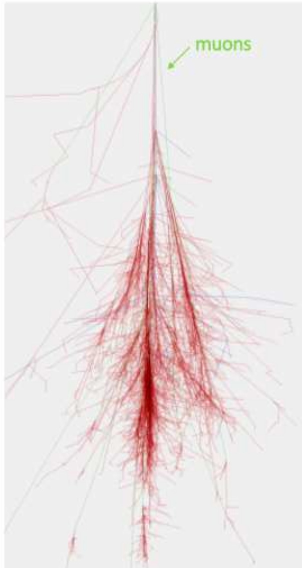
Extensive Air Showers (EAS)



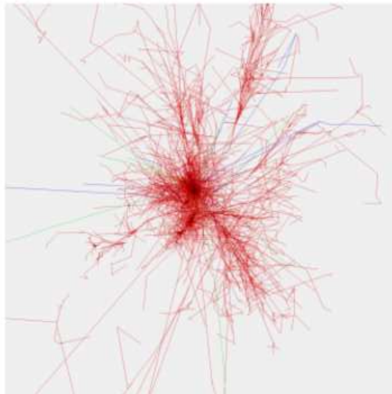
Simulated gamma
50 GeV



Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html



Simulated proton
100 GeV

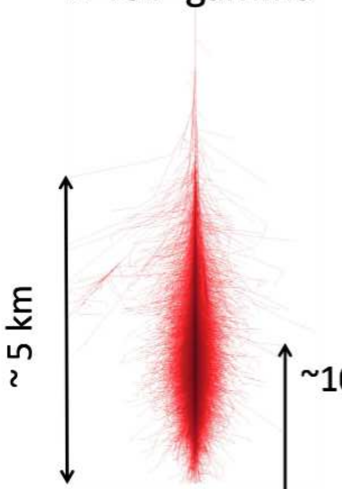


Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html

Gamma-ray detection

Extensive Air Showers (EAS)

1 TeV gamma



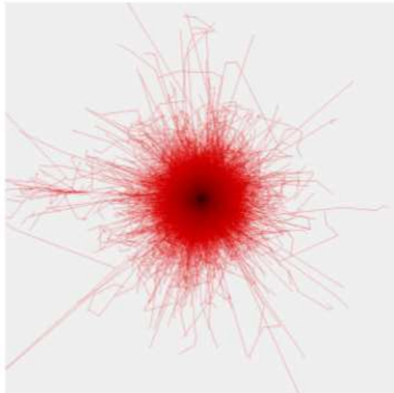
~20 m

Rough dimensions

~10 km above sea level

(note that x-axis scale is always exaggerated for viewing purposes)

Simulated gamma
1 TeV

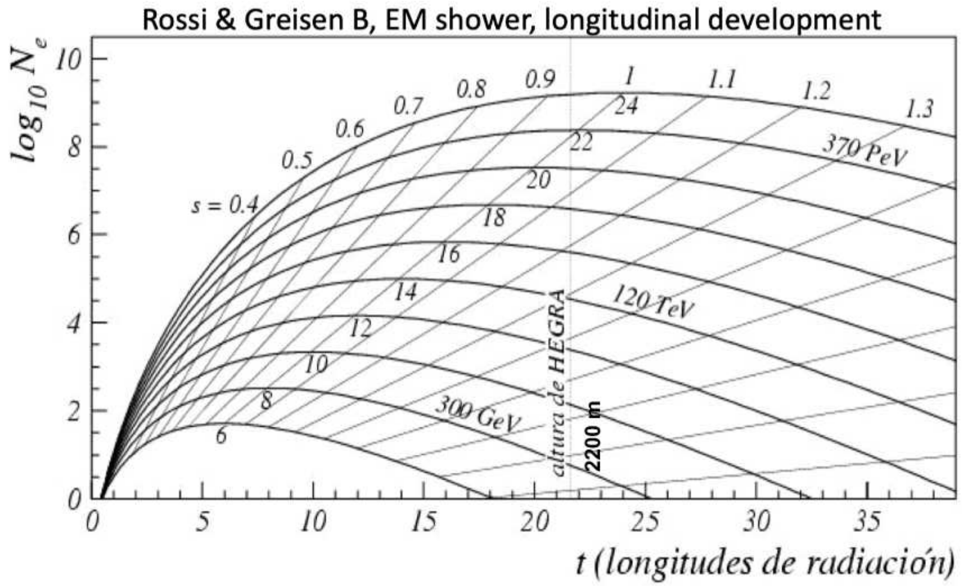


Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html

Gamma-ray detection

Extensive Air Showers (EAS)

- Particle detectors can be scintillators or water tanks (or both)
- The altitude of the detector helps on detecting showers at different energies
- How to detect particles that does not reach the ground? **Cherenkov radiation**

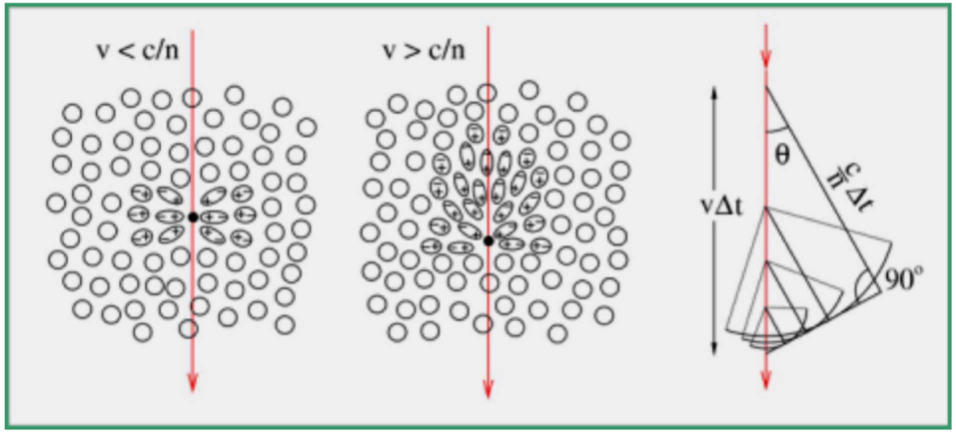


Gamma-ray detection

Cherenkov radiation

- Emitted whenever a charged particle traverses a medium at a speed larger than that of light in the medium

- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When v > c/n the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse

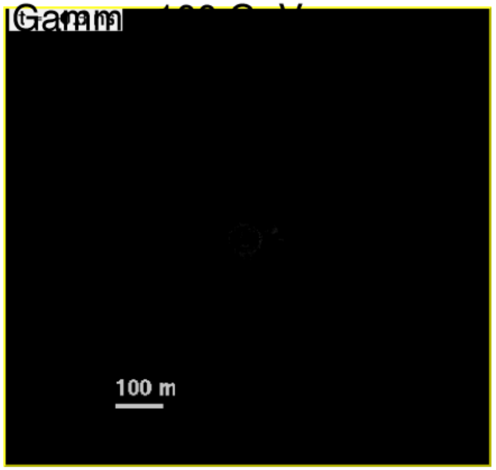


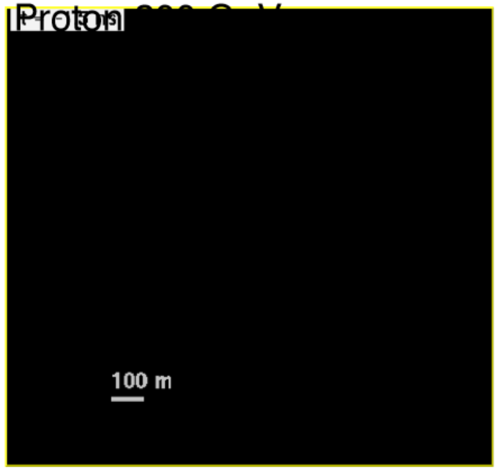
Gamma-ray detection

Cherenkov radiation

Arrival of Cherenkov light on the ground

- Good news: the effects of the interaction of a VHE g-ray in the atmosphere are spread over a large area on the ground
  => very large effective areas are achievable
  => VHE g-ray astronomy is feasible despite the low fluxes

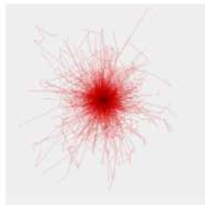


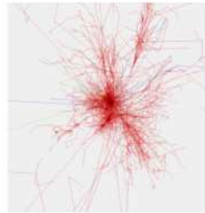


CORSIKA simulation, A. Moralejo

- Problem: CR showers are more numerous and represent an isotropic background

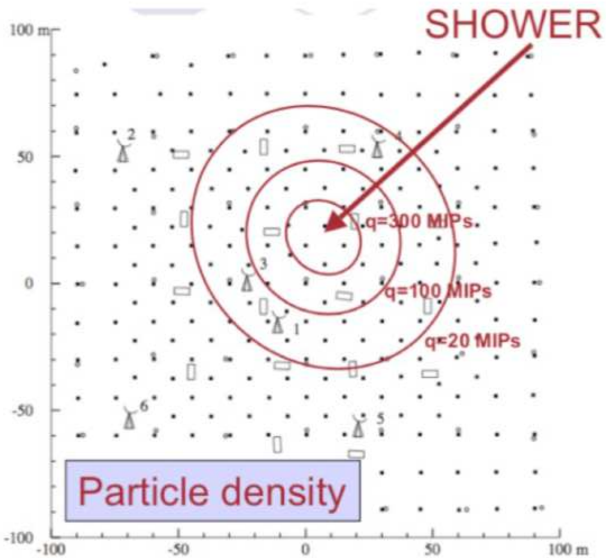
Gamma-ray detection

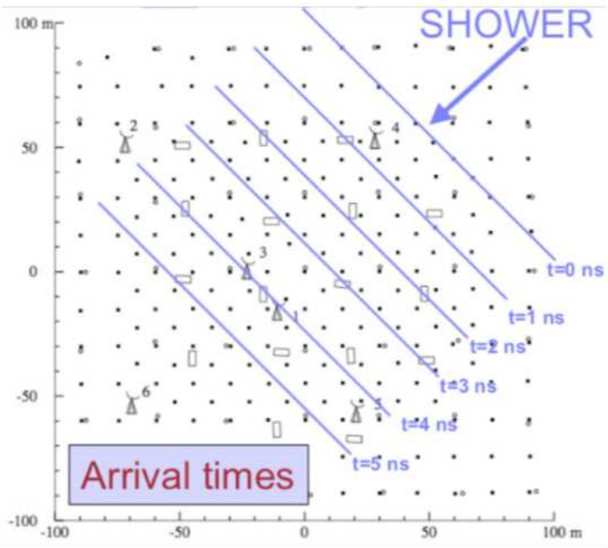




Arrays of particle detectors

- Detectors sample the tail of atmospheric shower that reaches the ground.
- Available information: particle density and arrival time at each detector position.





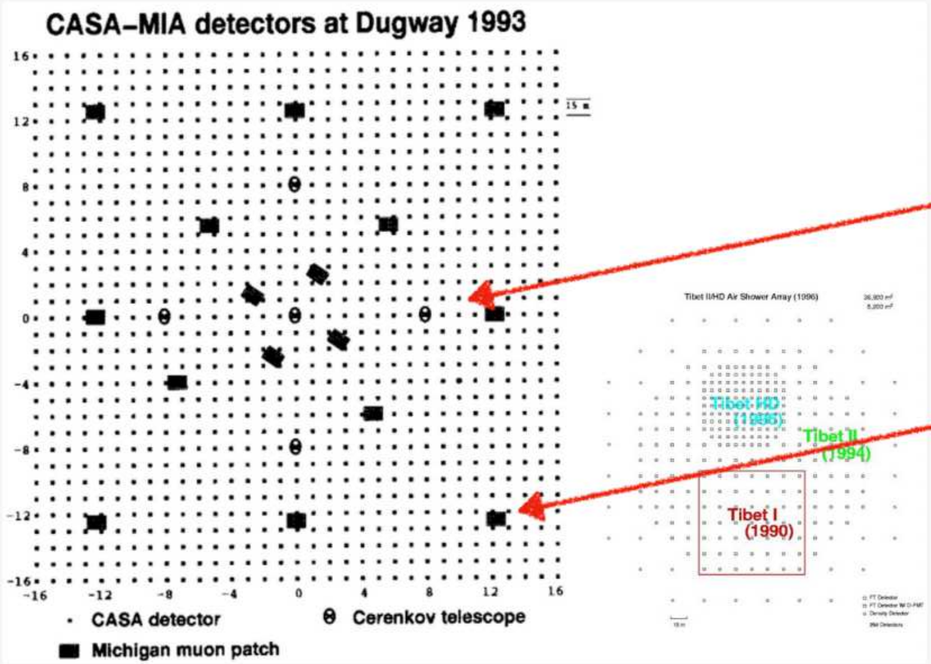
- Angular and energy resolutions are limited: we are only sampling the tail.
- g-hadron separation possible through density inhomogeneities in CR showers, specially “muon tagging.”
- Duty cycle 100%: operate day and night.
- Large FOV: several srad.

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both)

Figure 1. Schematic of layouts of the CASA-MIA array and AS$_\gamma$ in phases before 2002.



- Threshold (CASA-MIA/1600 m) ~ 0.1 PeV
- Threshold (ASg / 4300 m) ~ 10 TeV

Cherenkov telescopes

Muon detectors

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both): MILAGRO

Altitude: 2650m
Size: 60x80 m2

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both): MILAGRO

- Milagro & HAWC
  continuous survey observations

- Increase altitude from 2650m to 4100m
- Increase area from 3600m^2 (pond) to 20000m^2
- Separate tanks instead of a single pond
- Achieve 10-15 x Sensitivity of Milagro (detected Crab in 6h, 5sigma, instead of 3 months)

Gamma-ray detection

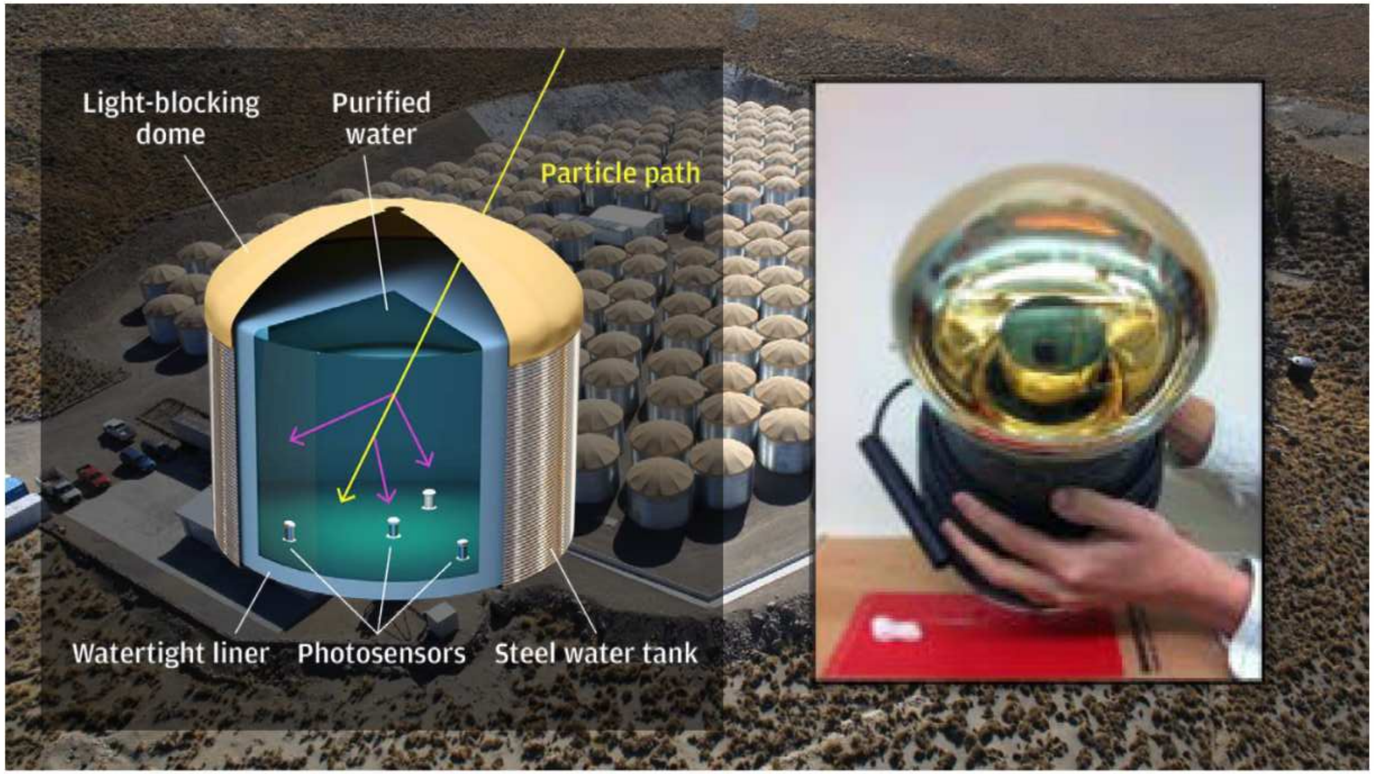
Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both): HAWC

Gamma-ray detection

Arrays of particle detectors

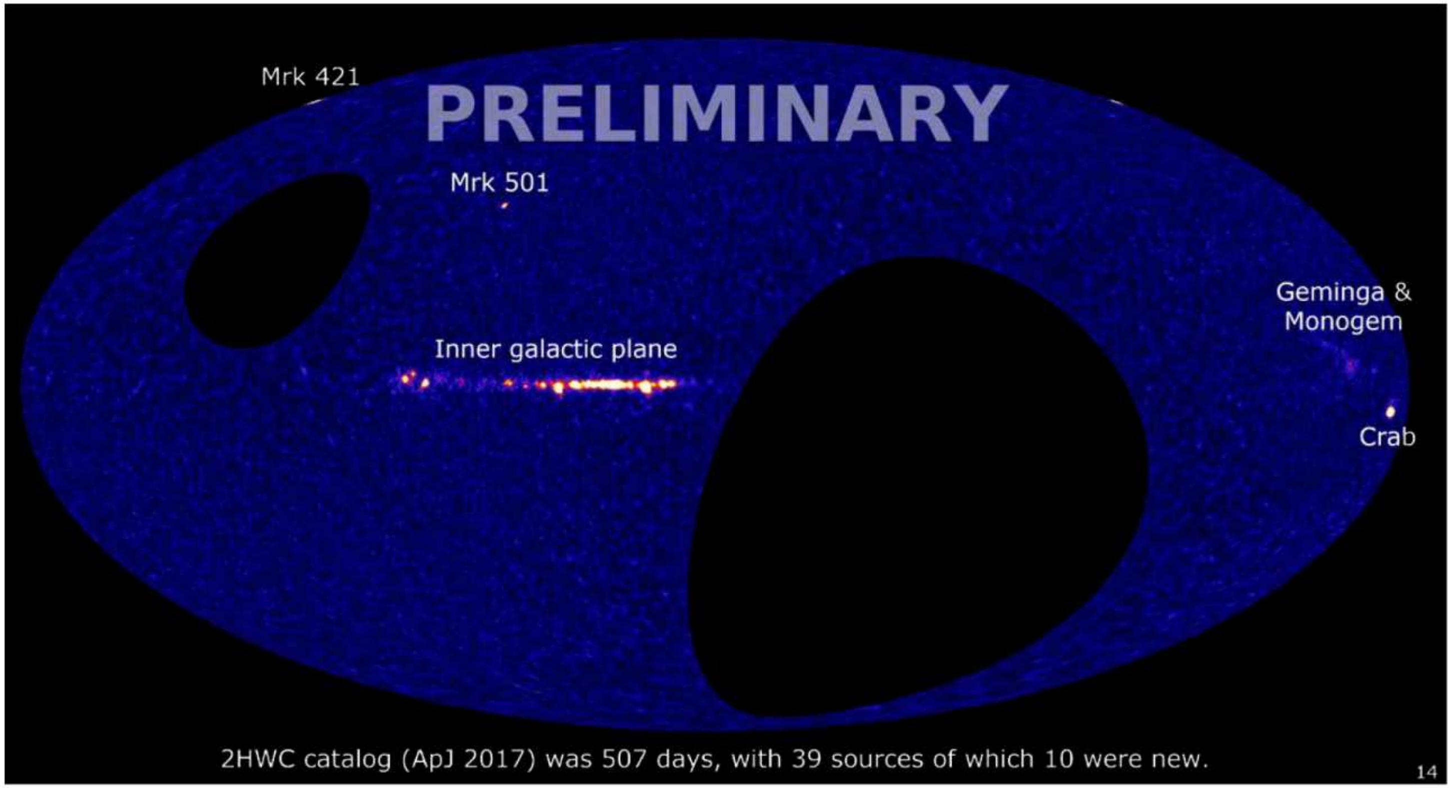
- Particle detectors can be scintillators or water tanks (or both): HAWC



Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both): HAWC



E=[10 - >1000] TeV
PSF ~0.2-0.7°
Aperture > 2 sr
Duty Cycle ~90%

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both) : **LHAASO**

Threshold (LHAASO/4410 m) ~ 30 TeV

~1200 muon detectors

0 scintillator counters

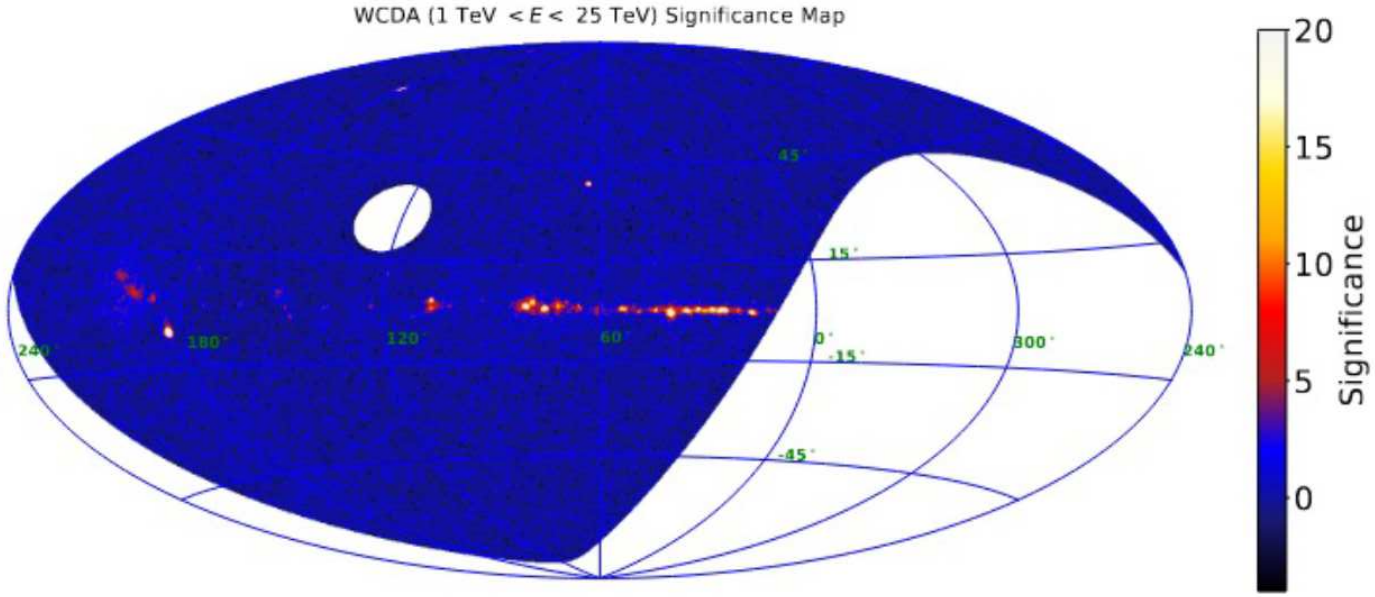
- + 80,000 m2 water Cherenkov
- + Cher/fluorescence telescopes

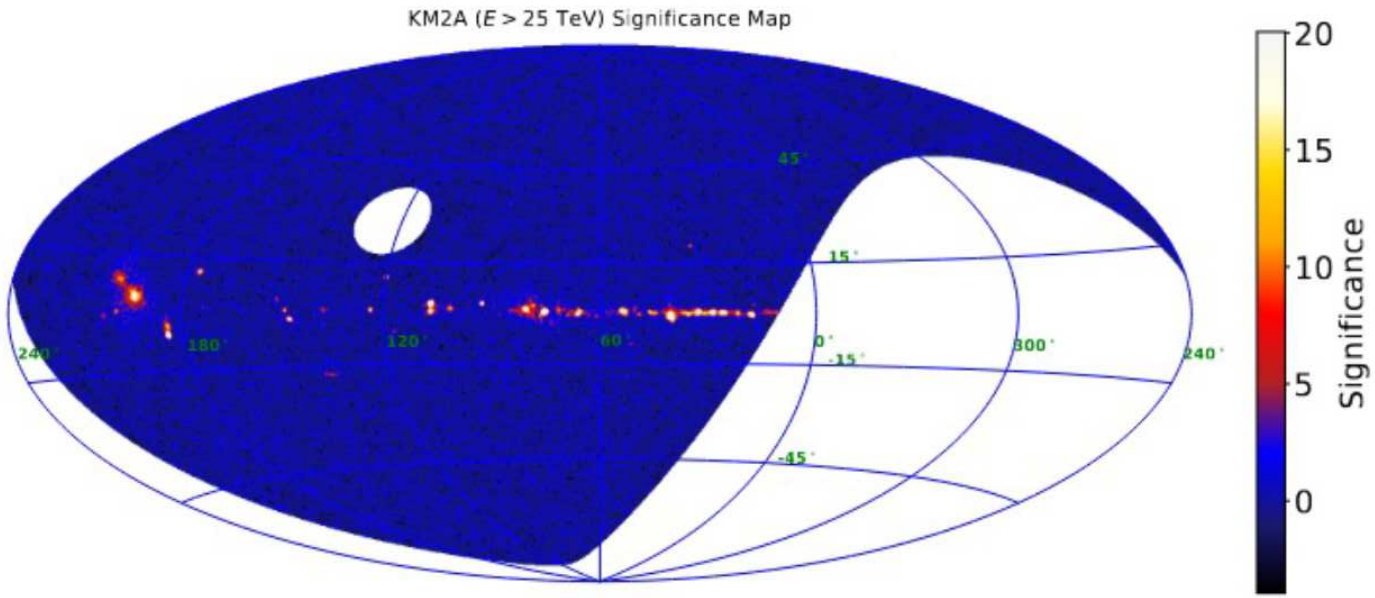
Cao et al 2022

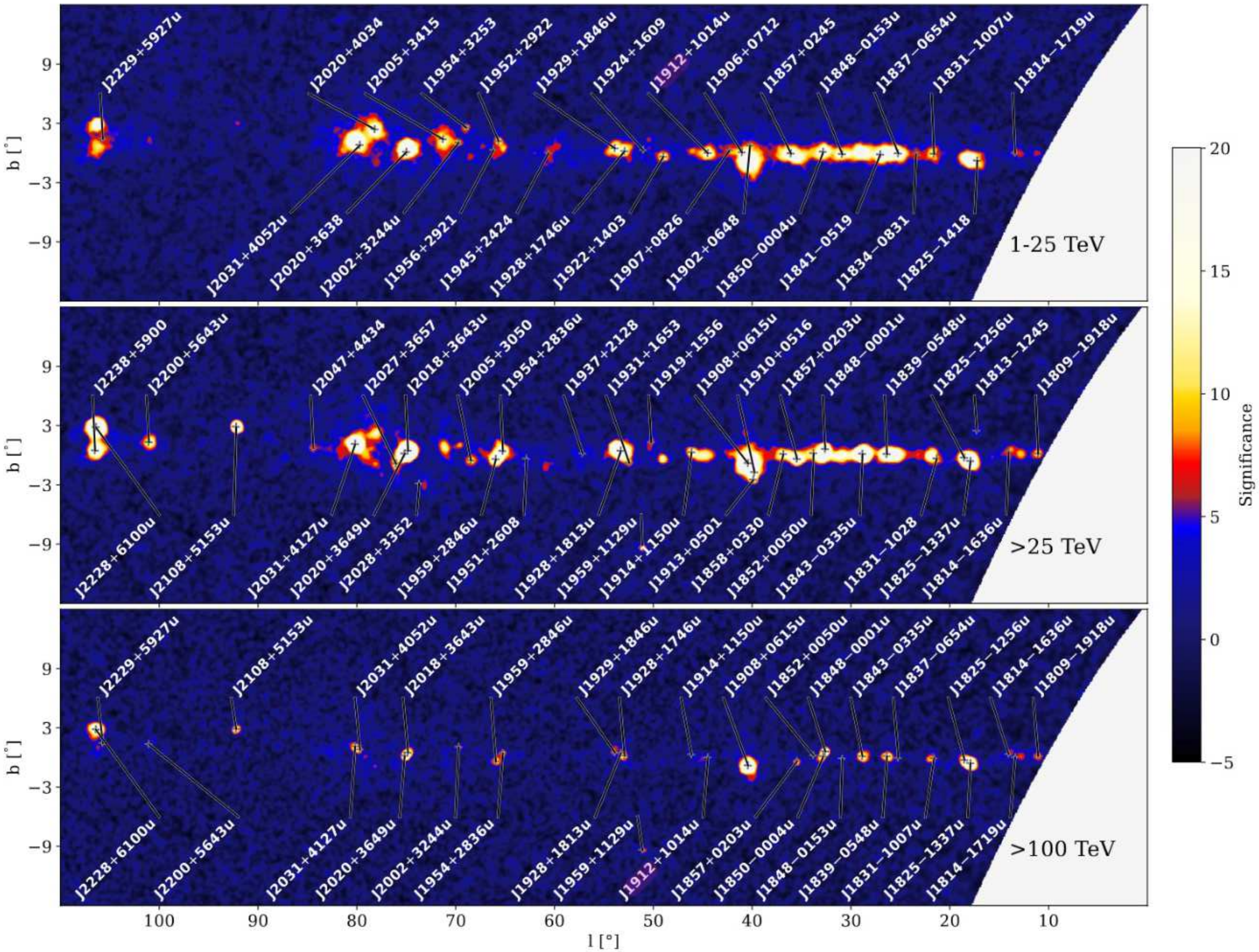
The LHAASO experiment

Array of particle detectors

- Detectors sample the tail of atmospheric shower that reaches the ground:
  - 1 km2 array (LHAASO-KM2A), including 5635 **scintillator detectors**, with 15 m spacing, for electromagnetic particle detection.
  - An overlapping 1 km2 array of 1221, 36 m2 **underground water Cherenkov tanks**, with 30 m spacing**, for muon detection** (total sensitive area 40,000 m 2).
  - A close-packed, **surface water Cherenkov detector** facility with a total area of 90,000 m 2 (LHAASO-WCDA), four times that of HAWC
  - 24 **wide field-of-view air Cherenkov** (and fluorescence) telescopes (LHAASO-WFCTA).
  - 452 **close-packed burst detectors**, located near the centre of the array, for detection of high energy secondary particles in the shower core region (LHAASO-SCDA).


WCDA (1 TeV < E < 25 TeV) Significance Map
45°
15°
-15°
-45°
240°
180°
120°
60°
0°
300°
240°
Significance
20
15
10
5
0


KM2A (E > 25 TeV) Significance Map
45°
15°
-15°
-45°
240°
180°
120°
60°
0°
300°
240°
Significance
20
15
10
5
0

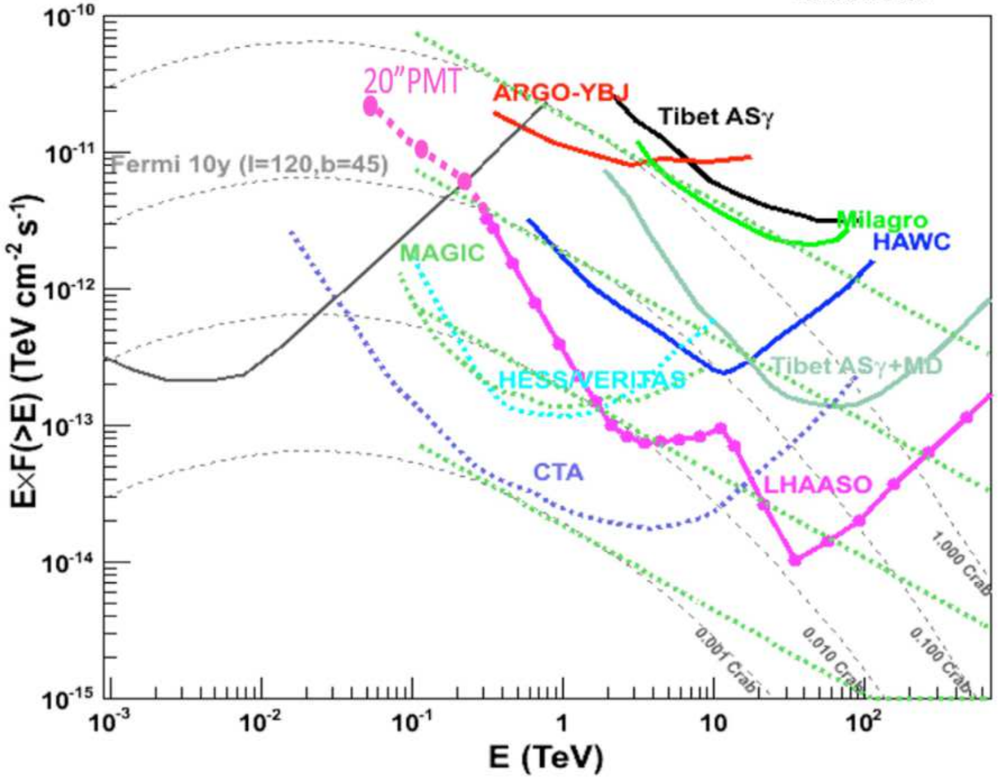

J2229+5927u
J2020+4034
J2005+3415
J1954+3253
J1952+2922
J1929+1846u
J1924+1609
J1912+1014u
J1906+0712
J1857+0245
J1848−0153u
J1837−0654u
J1831−1007u
J1814−1719u
J2031+4052u
J2020+3638
J2002+3244u
J1956+2921
J1945+2424
J1928+1746u
J1922+1403
J1907+0826
J1902+0648
J1850−0004u
J1841−0519
J1834−0831
J1825−1418
1-25 TeV
J2238+5900
J2200+5643u
J2047+4434
J2027+3657
J2018+3643u
J2005+3050
J1954+2836u
J1937+2128
J1931+1653
J1919+1556
J1908+0615u
J1910+0516
J1857+0203u
J1848−0001u
J1839−0548u
J1825−1256u
J1813−1245
J1809−1918u
J2228+6100u
J2108+5153u
J2031+4127u
J2020+3649u
J2028+3352
J1959+2846u
J1951+2608
J1928+1813u
J1959+1129u
J1914+1150u
J1913+0501
J1858+0330
J1852+0050u
J1843−0335u
J1831−1028
J1825−1337u
J1814−1636u
>25 TeV
J2229+5927u
J2108+5153u
J2031+4052u
J2018+3643u
J1959+2846u
J1929+1846u
J1928+1746u
J1914+1150u
J1908+0615u
J1852+0050u
J1848−0001u
J1843−0335u
J1837−0654u
J1825−1256u
J1814−1636u
J1809−1918u
J2228+6100u
J2200+5643u
J2031+4127u
J2020+3649u
J2002+3244u
J1954+2836u
J1928+1813u
J1959+1129u
J1912+1014u
J1857+0203u
J1850−0004u
J1848−0153u
J1839−0548u
J1831−1007u
J1825−1337u
J1814−1719u
>100 TeV
b [°]
9
3
−3
−9
l [°]
100
90
80
70
60
50
40
30
20
10
Significance
20
15
10
5
0
−5

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both) : **LHAASO**

Cao et al 2022

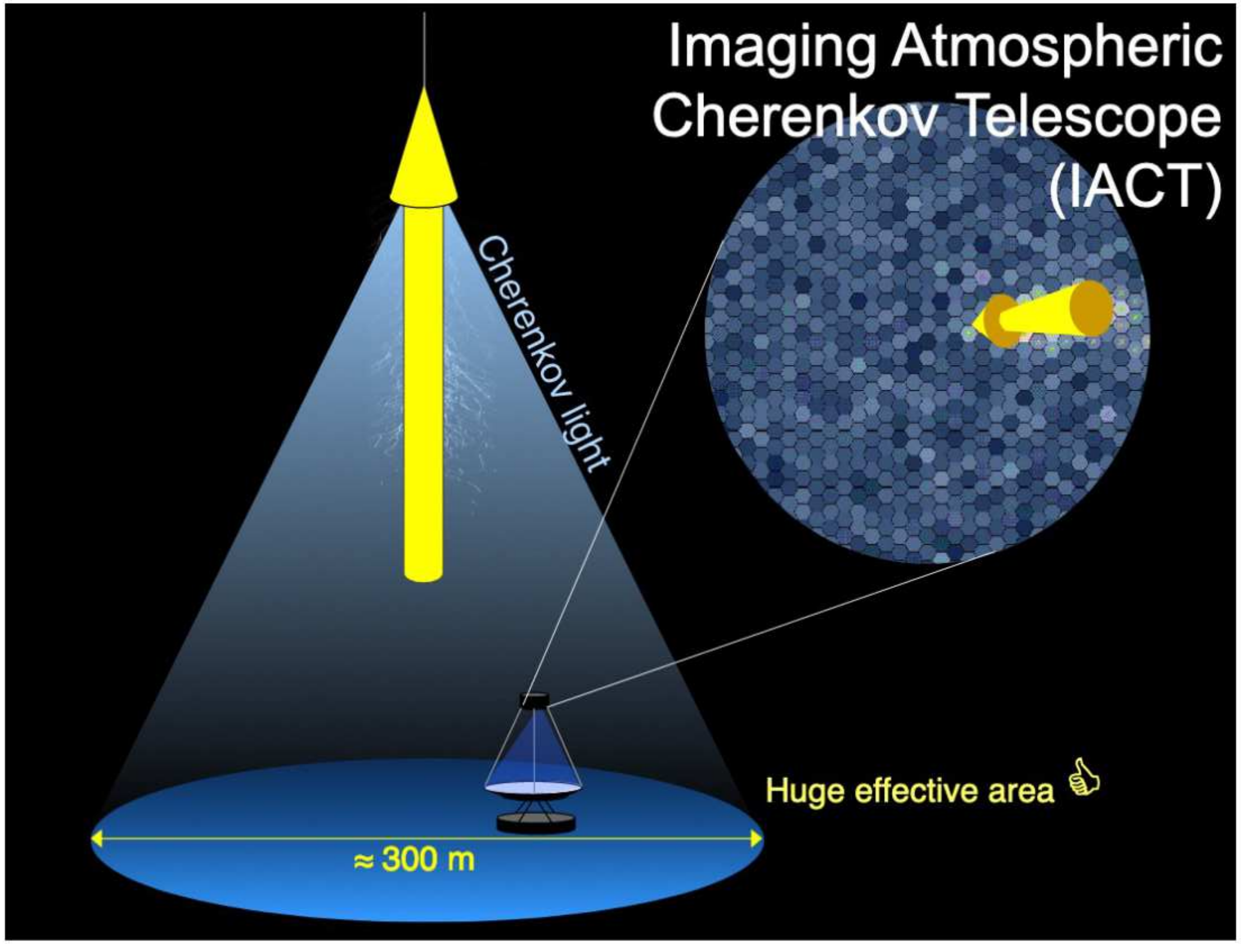


- Extremely sensitivity above 100 TeV
- Opening a new window in gamma-ray observations

- Even on top of the highest mountains, the number of particles reaching the ground for showers initiated by γ's of E < a few hundred GeV is very small $\Rightarrow$ a different technique is needed for γ astronomy, other than the direct detection of shower particles
- The atmospheric Cherenkov light from EAS can be used for this purpose
- Large photon collection areas are desirable (fainter showers $\Rightarrow$ lower energy threshold)
- Caveat: low duty cycle ≈ 10% (clear, dark nights)

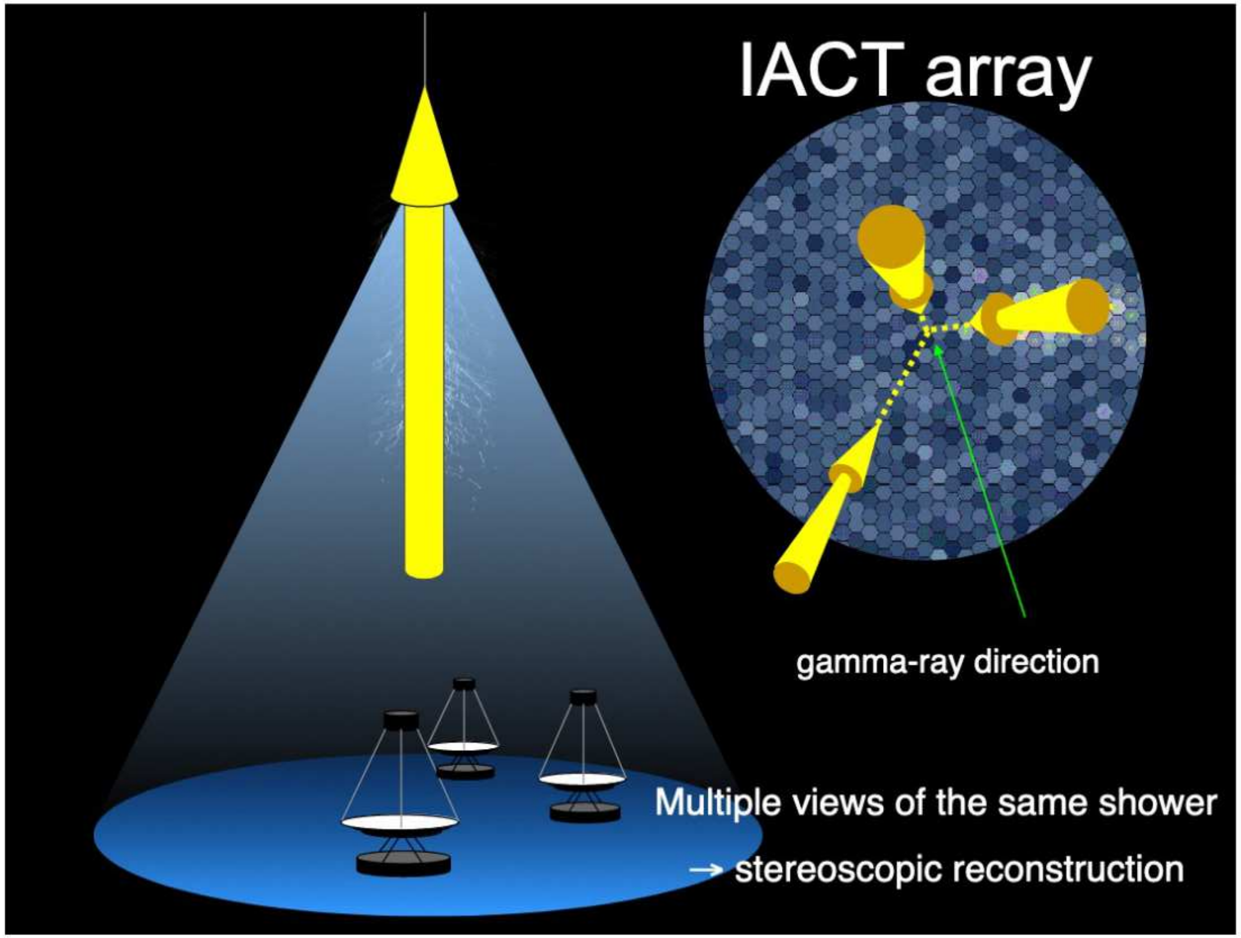
Gamma-ray detection

The Cherenkov Technique



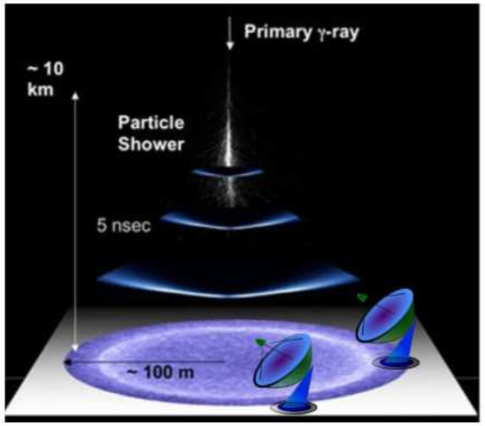
Gamma-ray detection

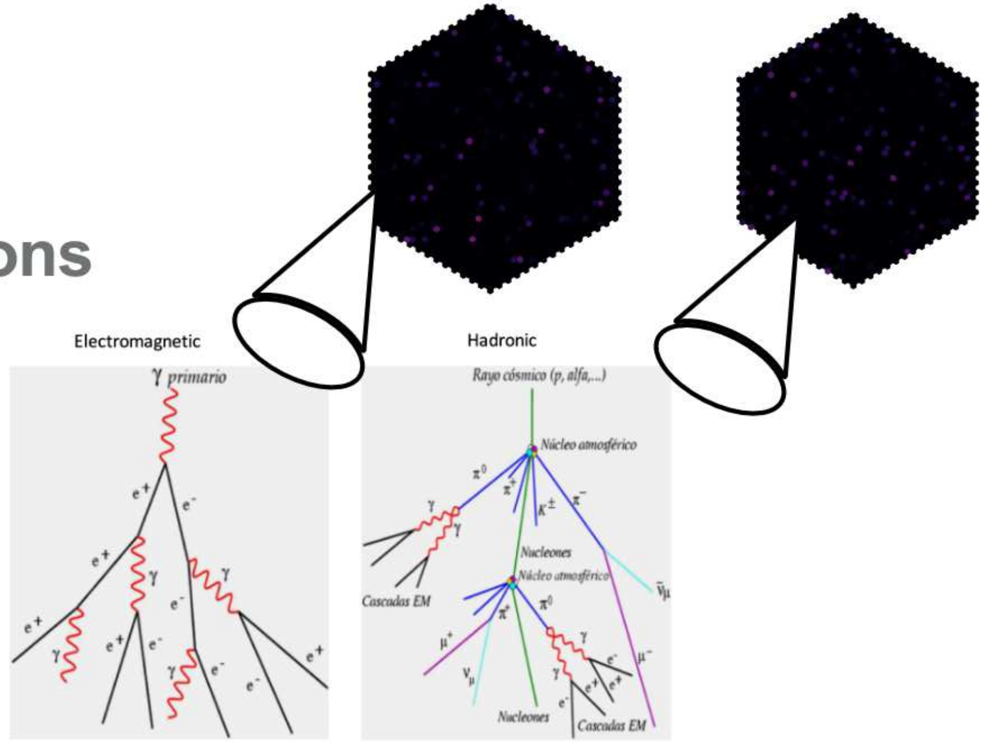
The Cherenkov Technique

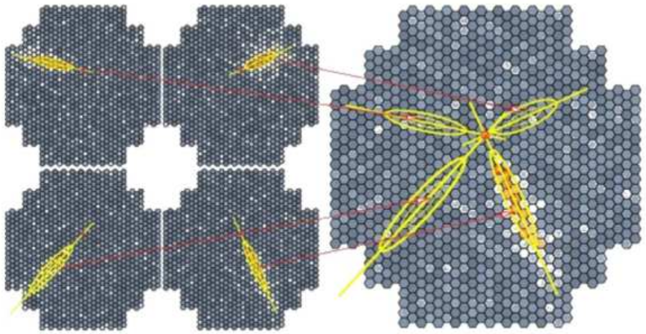


The IACT Technique

Detecting high energy photons





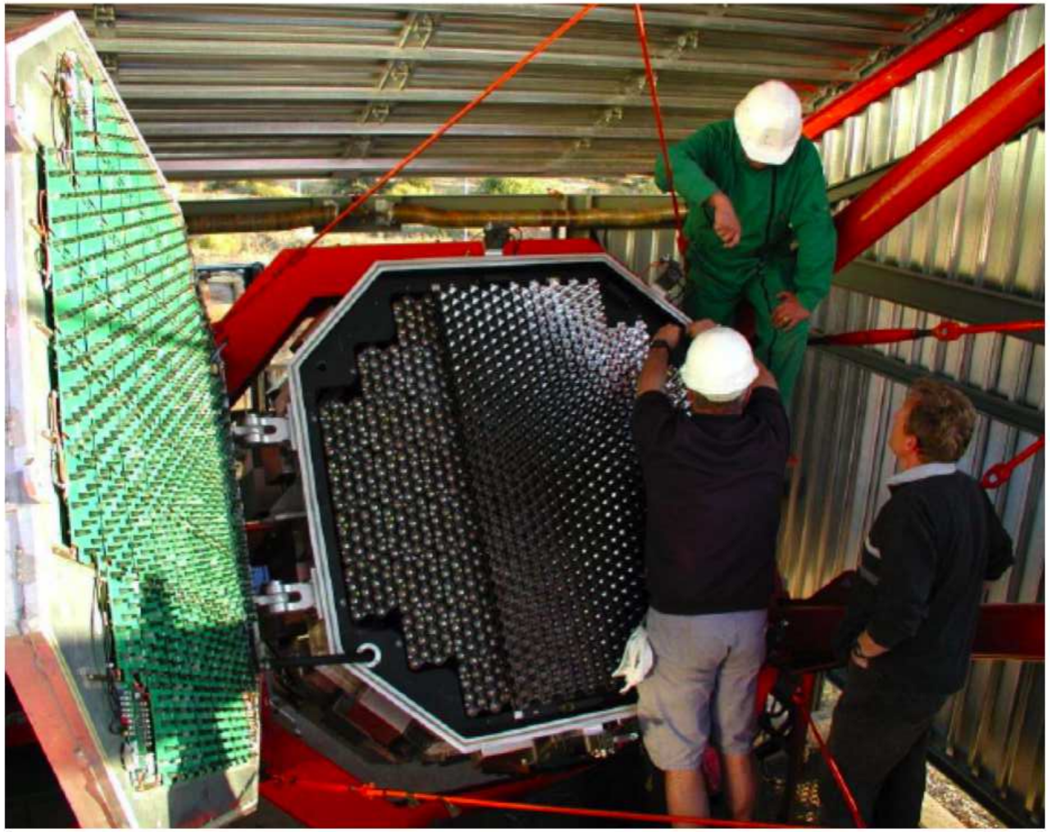


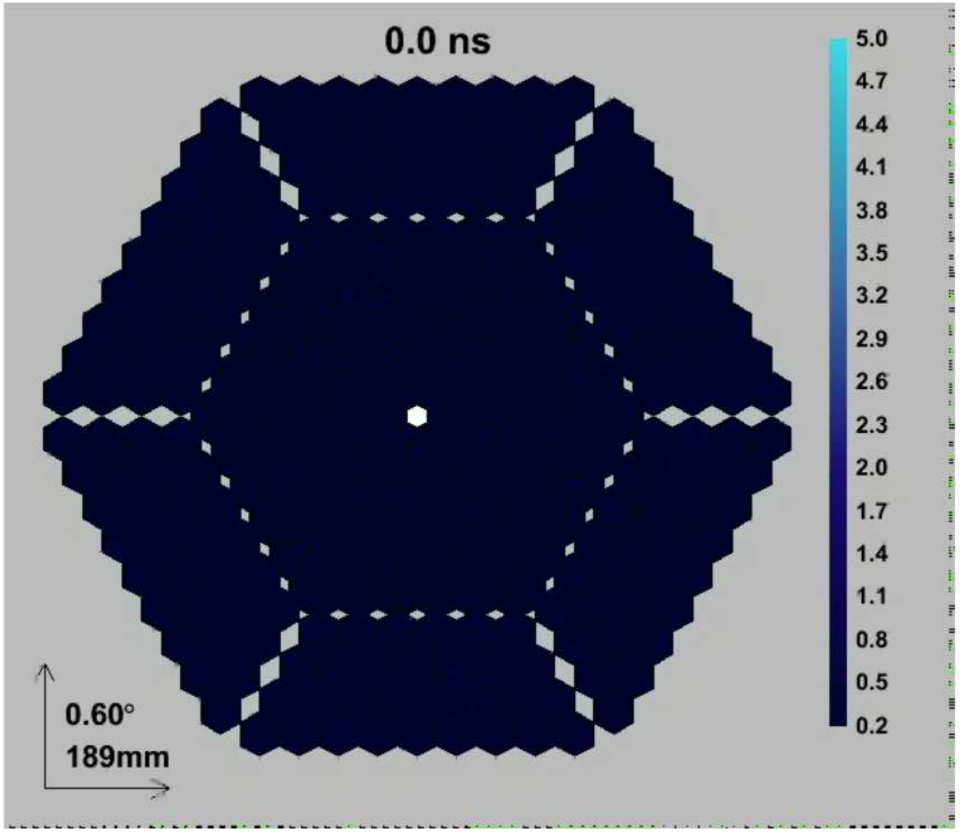
- From the shape => gamma/hadron separation
- From the axis => arrival direction / angular resolution
- From the 'size' => light / energy resolution

Gamma-ray detection

The Cherenkov Technique

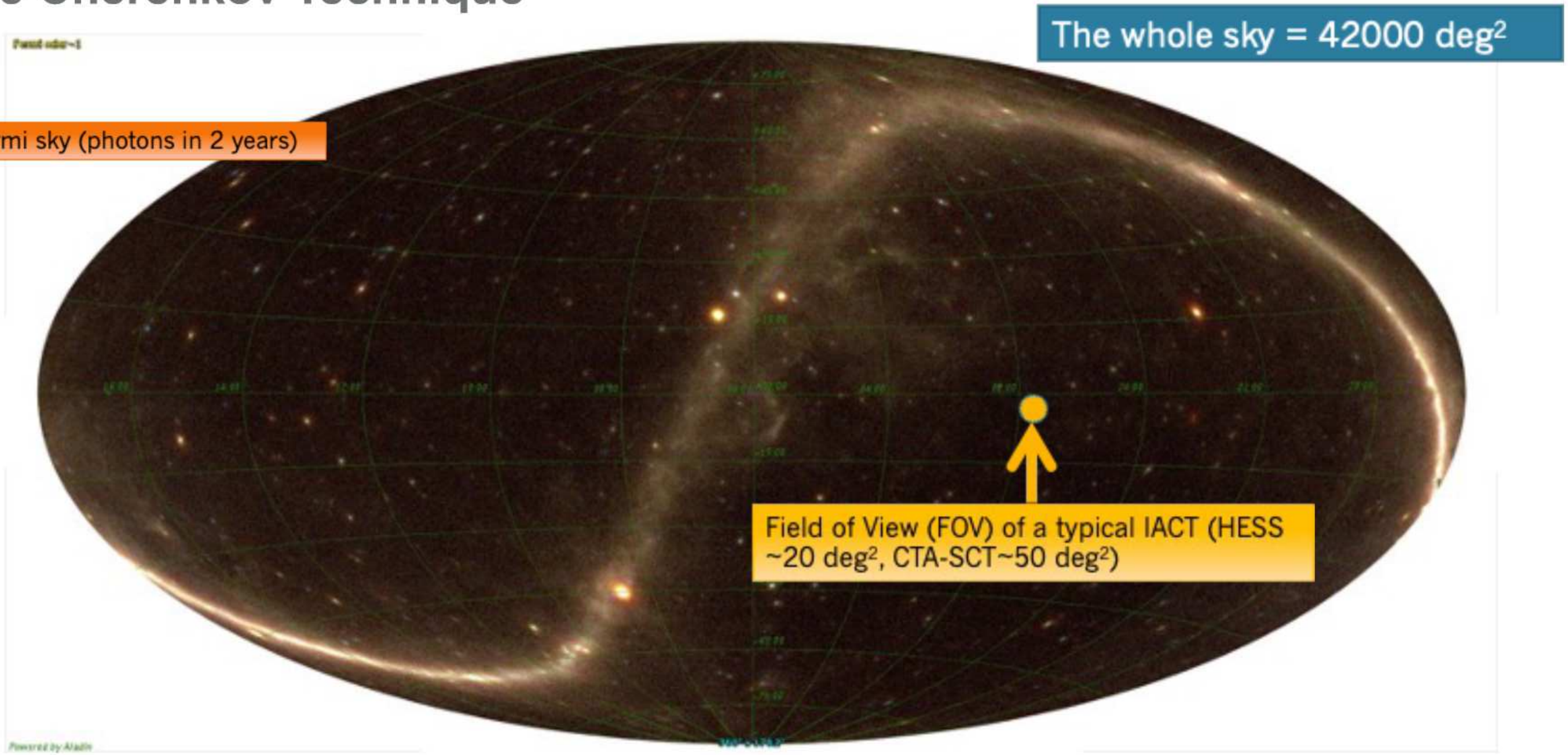
HESS Camera



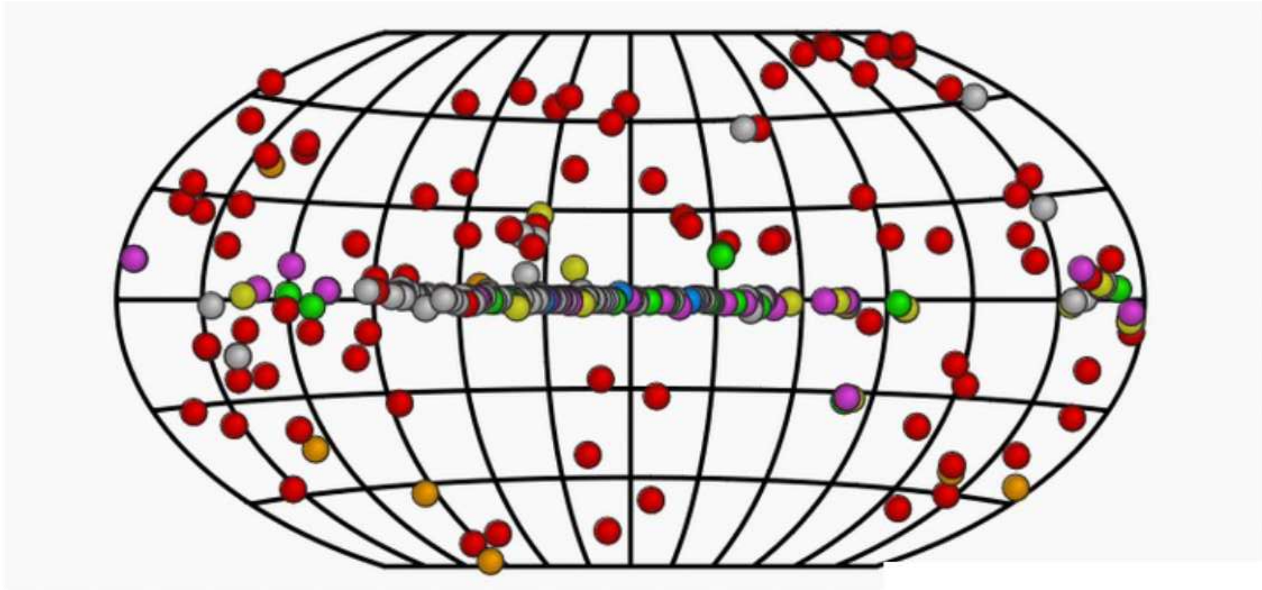


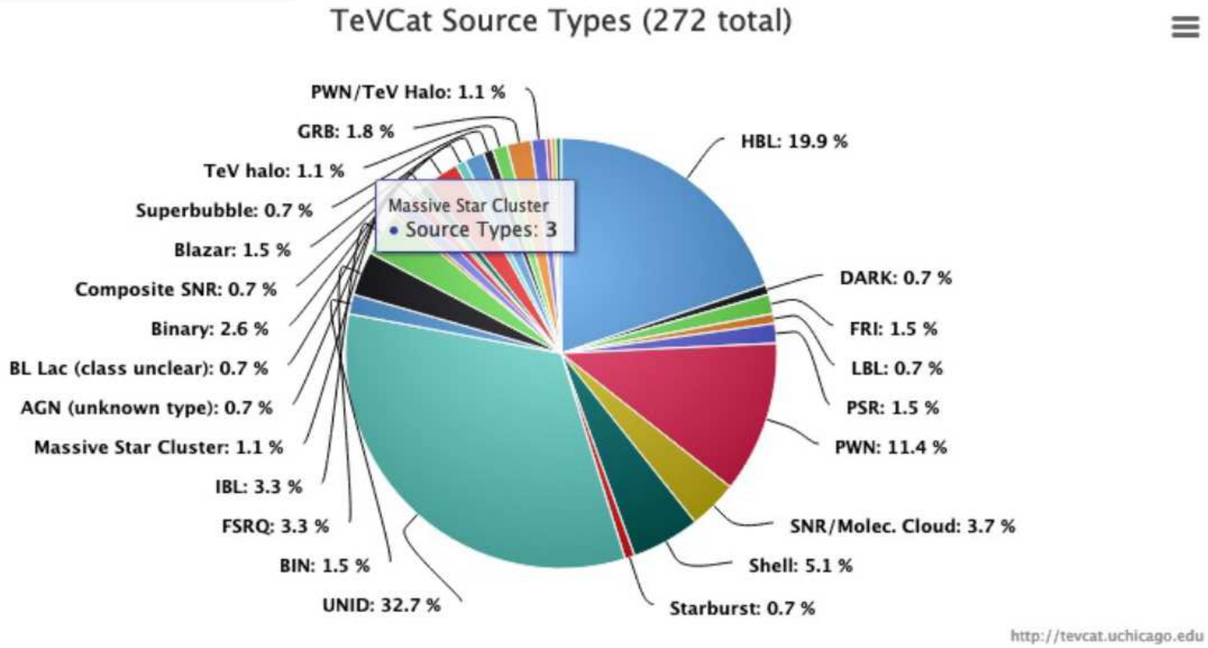
Gamma-ray detection

The Cherenkov Technique



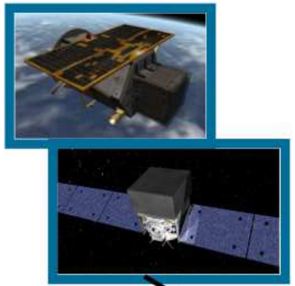

H.E.S.S. (Namibia)
4 x 108 m² (since 2003)
1 x 614 m² (since 2012)
MAGIC (La Palma)
2 x 236 m² (since 2003 / 2009)
VERITAS (Arizona)
4 x 110 m² (since 2007)
Characteristics of current generation of IACT arrays:
• Energy threshold Eγ = 25 to 100 GeV
• Point-source integral flux sensitivity: ~0.6% of the Crab Nebula flux in 50 h (above 200 GeV, 100 times more sensitive than Fermi-LAT in 1 year)
• FoV: 3.5 - 5° diameter ⇒ pointing devices! (unlike e.g. Fermi or HAWC)
• Angular resolution < 0.1°
• Energy resolution ≈ 10 − 15%
Near future: CTA, with 5 − 10 × better sensitivity




TeVCat Source Types (272 total)
PWN/TeV Halo: 1.1 %
GRB: 1.8 %
TeV halo: 1.1 %
Superbubble: 0.7 %
Blazar: 1.5 %
Composite SNR: 0.7 %
Binary: 2.6 %
BL Lac (class unclear): 0.7 %
AGN (unknown type): 0.7 %
Massive Star Cluster: 1.1 %
IBL: 3.3 %
FSRQ: 3.3 %
BIN: 1.5 %
UNID: 32.7 %
Massive Star Cluster
• Source Types: 3
HBL: 19.9 %
DARK: 0.7 %
FRI: 1.5 %
LBL: 0.7 %
PSR: 1.5 %
PWN: 11.4 %
SNR/Molec. Cloud: 3.7 %
Shell: 5.1 %
Starburst: 0.7 %
http://tevcat.uchicago.edu

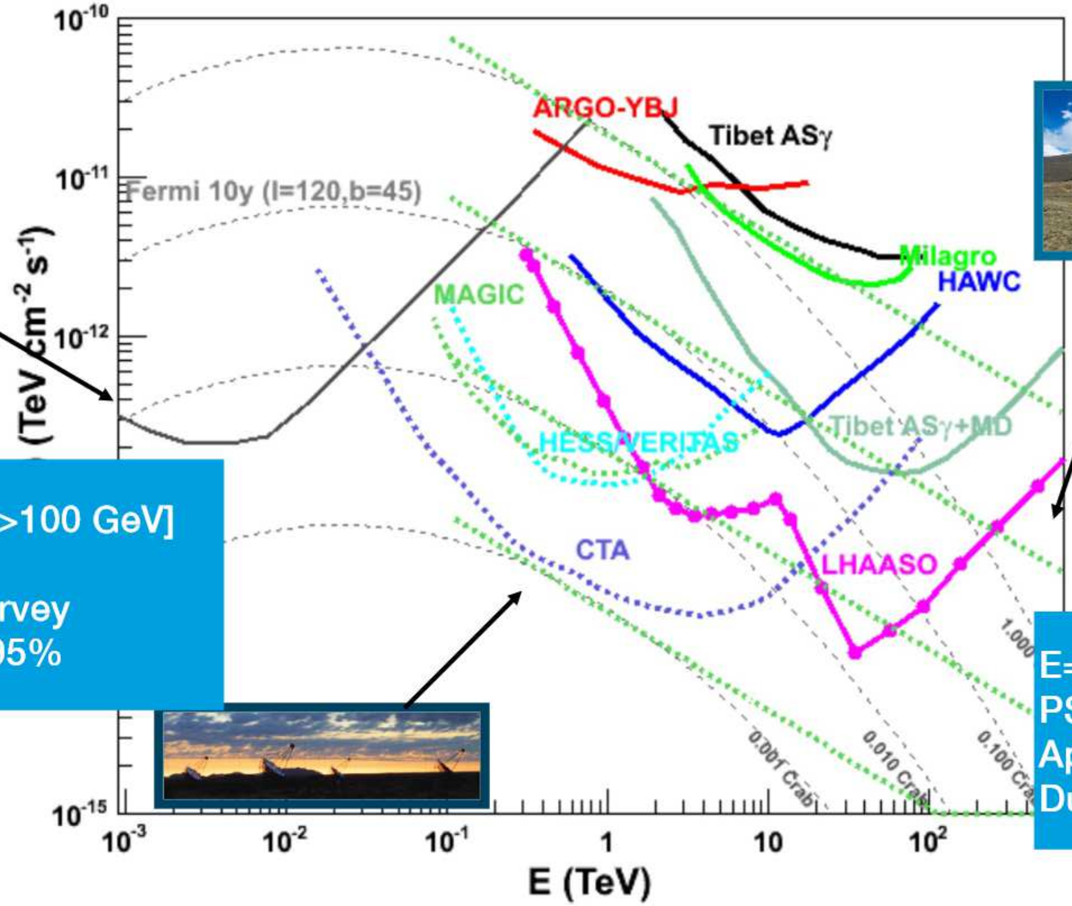
Gamma-ray detection

Pros and Cons



E=[10 - >1000] TeV
PSF ~0.2-0.7°
Aperture > 2 sr
Duty Cycle ~90%

Particle Detectors



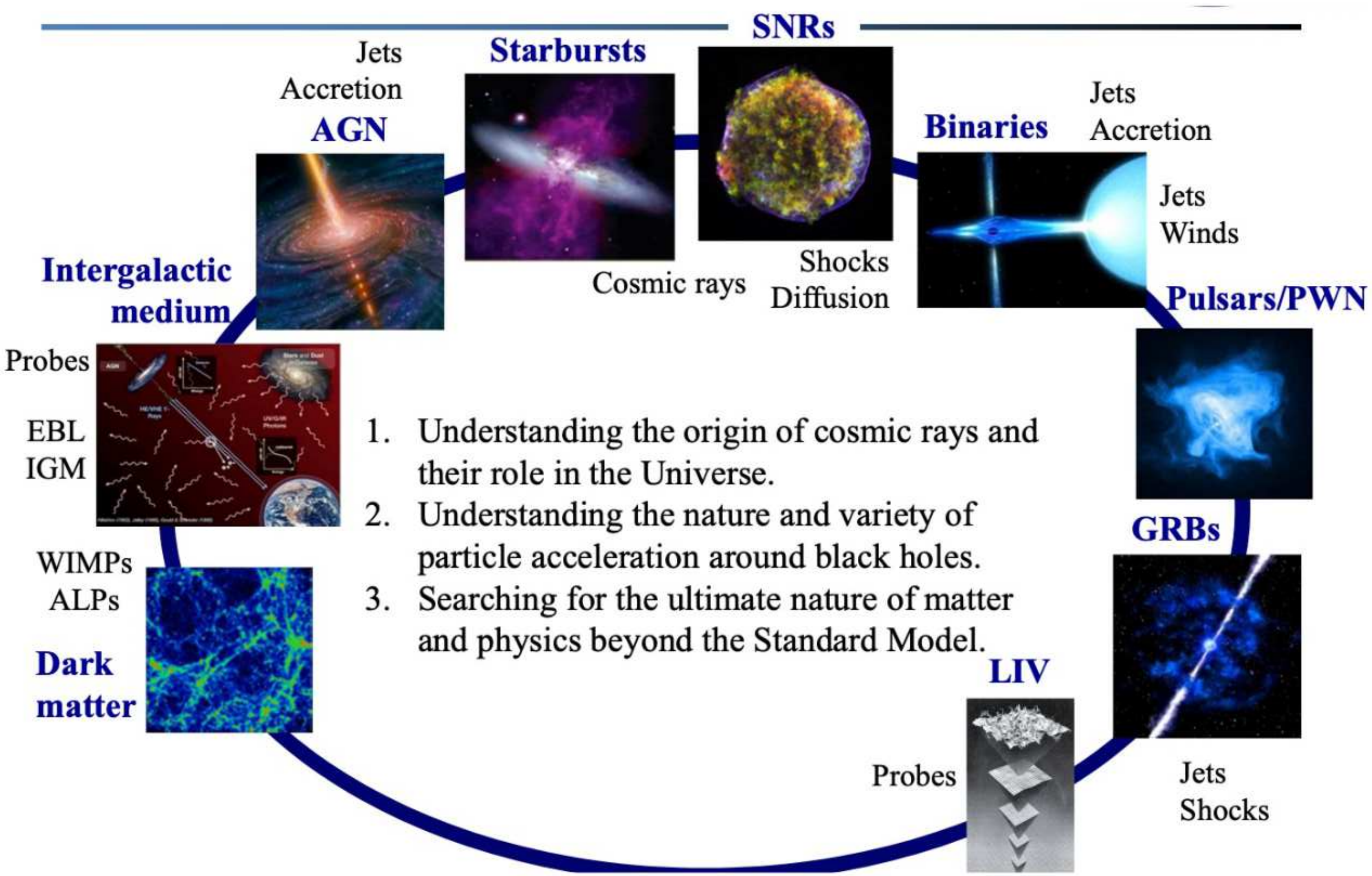
Satellites

E=[100MeV - >100 GeV]
PSF ~0.1-3°
Aperture > survey
Duty Cycle ~95%

IACTs

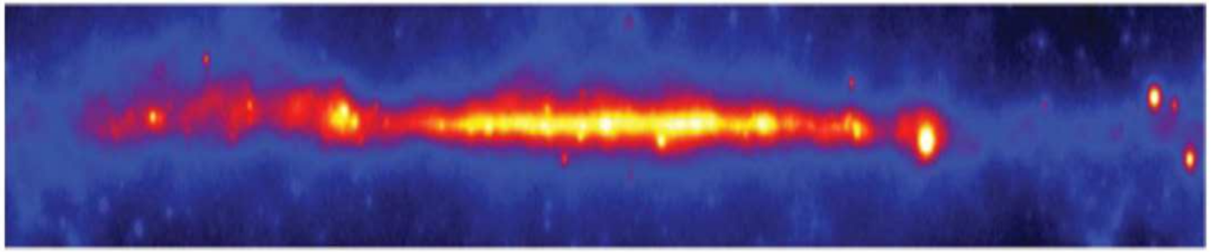
E=[0.02 - 100] TeV
PSF ~0.05°
Aperture ~0.003 sr
Duty Cycle ~10%

The Universe at high energies

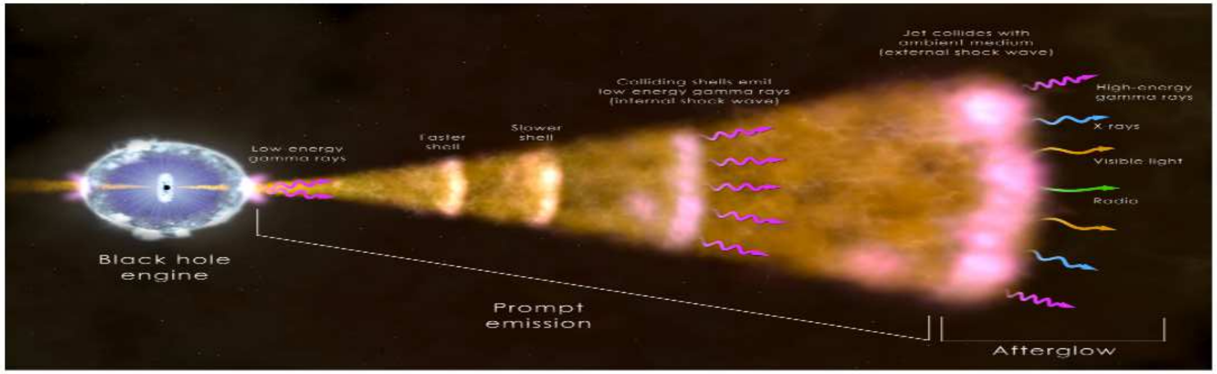


The Universe at high energies

1. Surveys and the Particle acceleration in our Galaxy

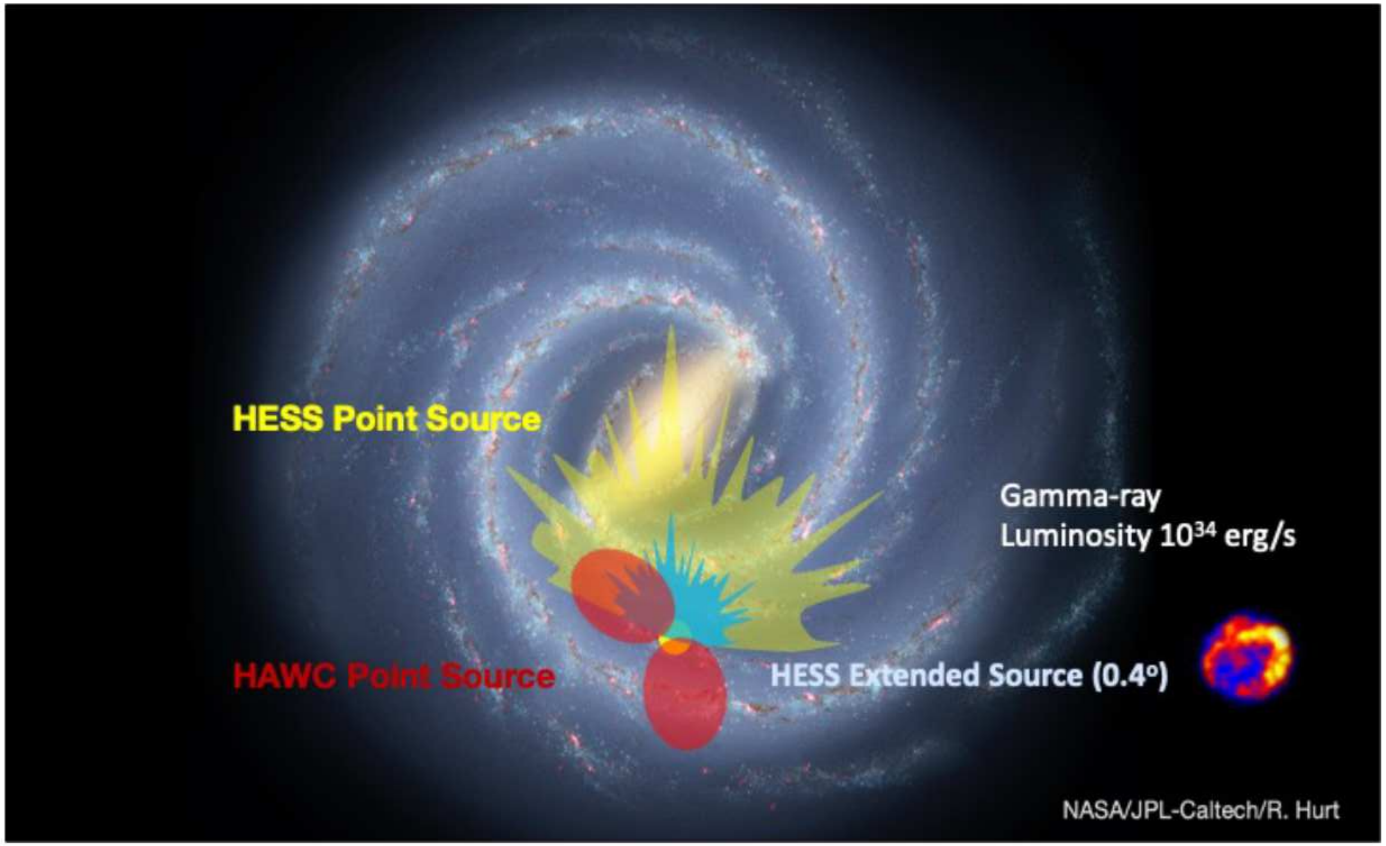


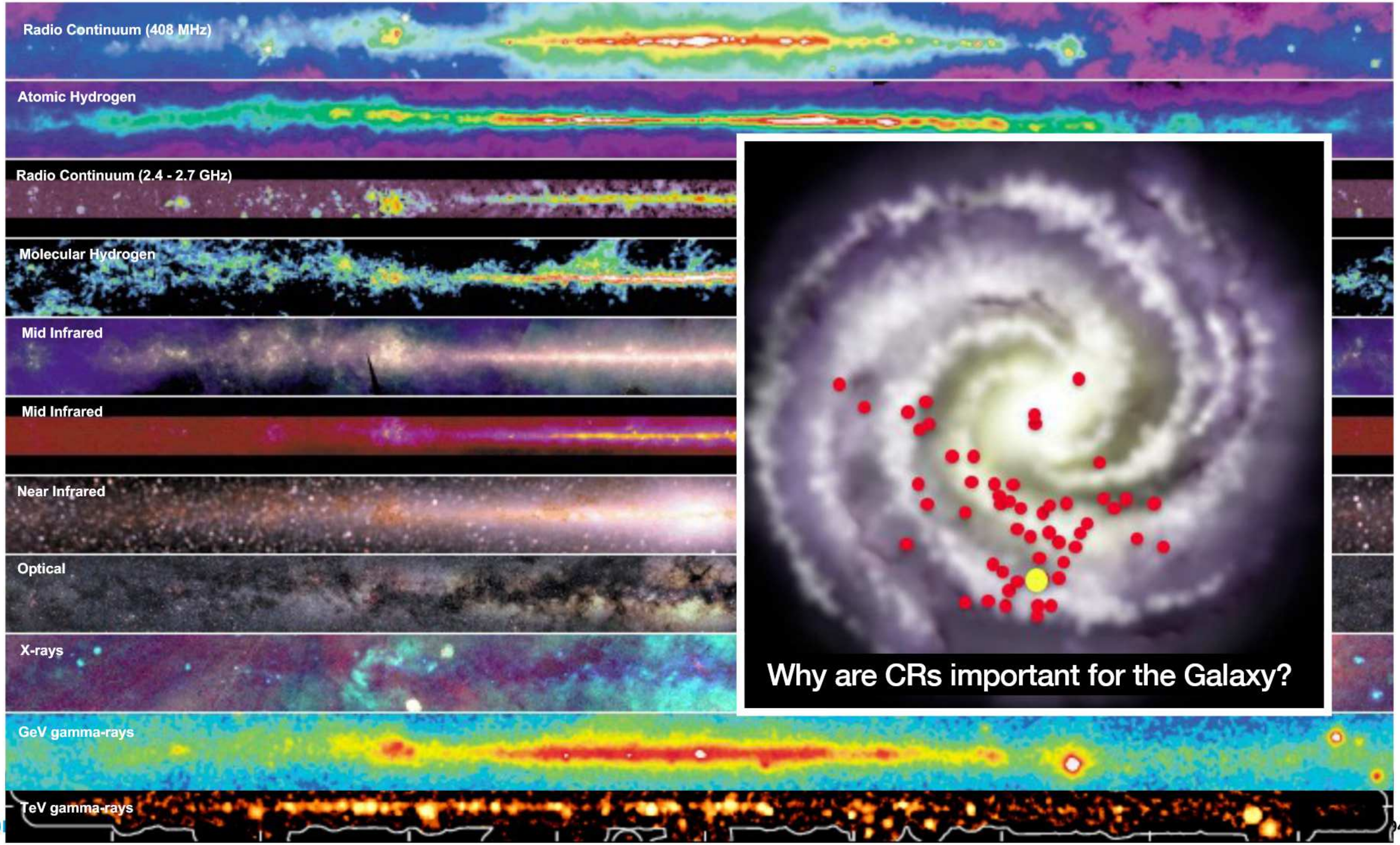
2. The transient extragalactic sky

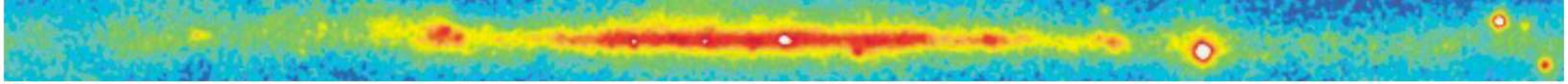


Galactic Surveys

Understanding particle acceleration in our Galaxy

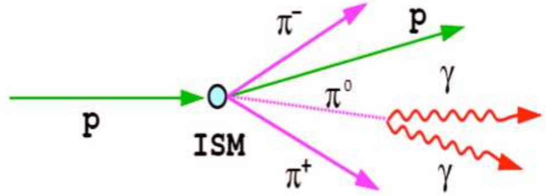



Radio Continuum (408 MHz)
Atomic Hydrogen
Radio Continuum (2.4 - 2.7 GHz)
Molecular Hydrogen
Mid Infrared
Mid Infrared
Near Infrared
Optical
X-rays
GeV gamma-rays
TeV gamma-rays
Why are CRs important for the Galaxy?



Galactic Surveys

Understanding particle acceleration in our Galaxy

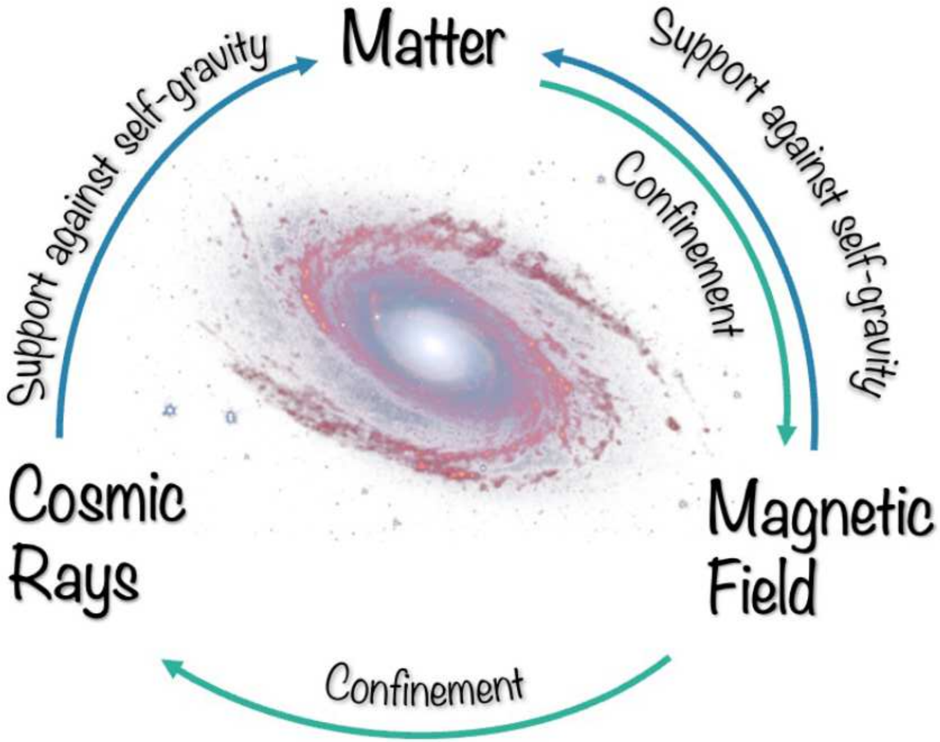


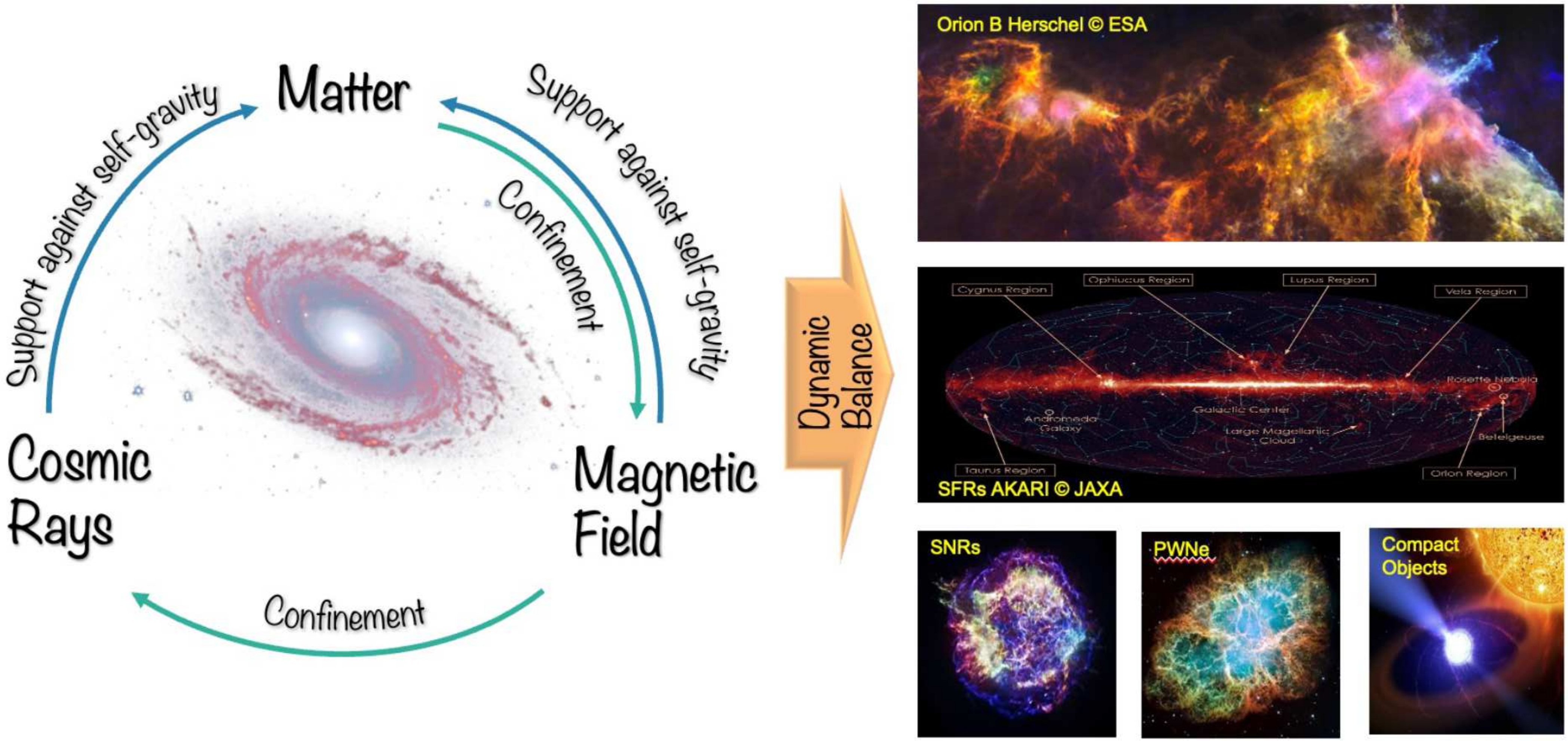
Dynamic balance processes triggers instabilities in the Galaxy structure

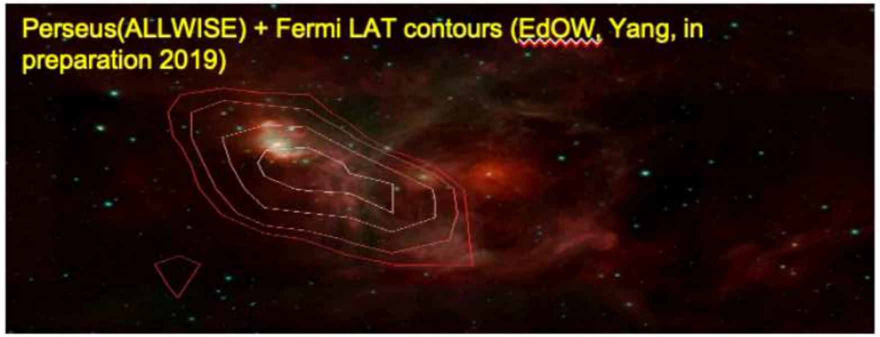
ω_{CR} ~1 eV/cm^3

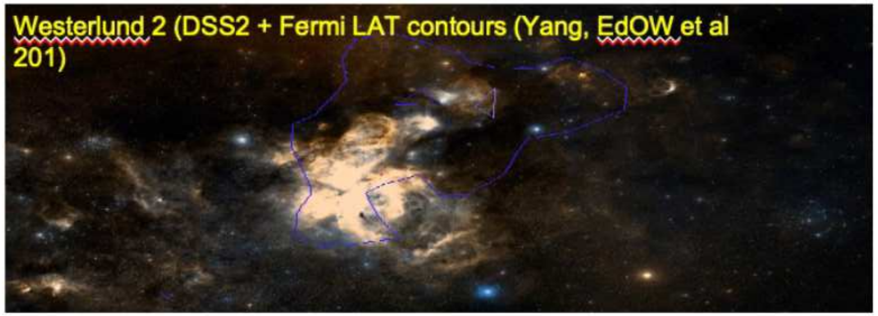
$\omega_B = B^2/8\pi$ ~1 eV/cm^3

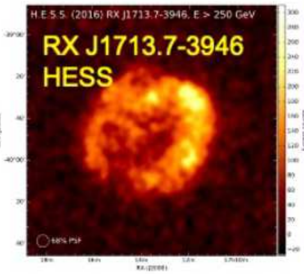
$\omega^{turb}{}_{gas} = \rho_{gas}\, v^2{}_{turb}$ ~1 eV/cm^3

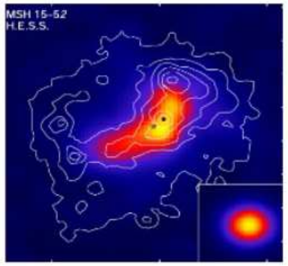


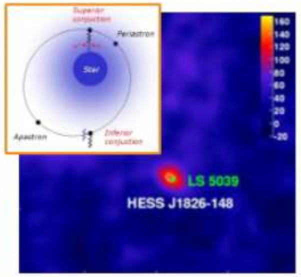

Matter
Support against self-gravity
Support against self-gravity
Confinement
Cosmic Rays
Magnetic Field
Confinement
Dynamic Balance
Orion B Herschel © ESA
Cygnus Region
Ophiucus Region
Lupus Region
Vela Region
Rosette Nebula
Galactic Center
Andromeda Galaxy
Large Magellanic Cloud
Betelgeuse
Taurus Region
Orion Region
SFRs AKARI © JAXA
SNRs
PWNe
Compact Objects


Perseus(ALLWISE) + Fermi LAT contours (EdOW, Yang, in preparation 2019)

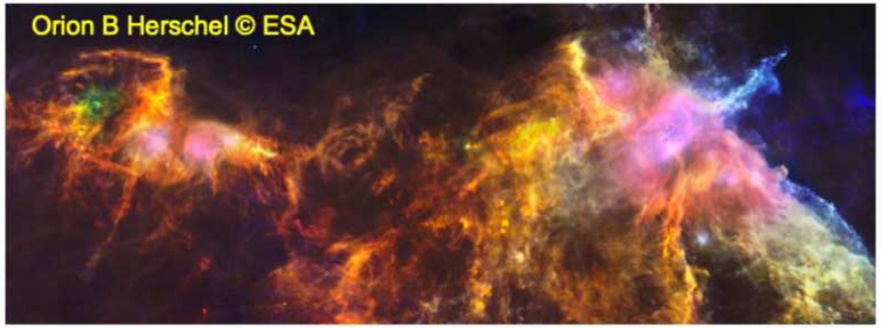

Westerlund 2 (DSS2 + Fermi LAT contours (Yang, EdOW et al 201)

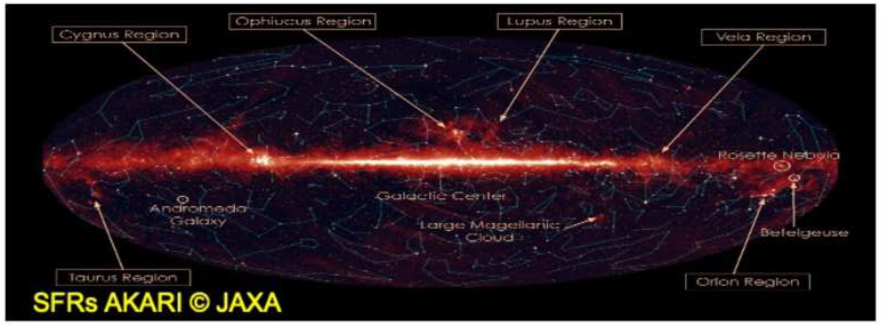

H.E.S.S. (2016) RX J1713.7-3946, E > 250 GeV
RX J1713.7-3946
HESS

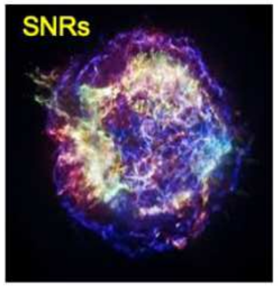

MSH 15-52
H.E.S.S.


Superior conjunction
Periastron
Star
Apastron
Inferior conjunction
LS 5039
HESS J1826-148

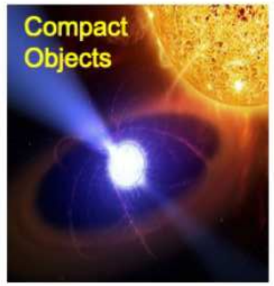

Gamma-ray


Orion B Herschel © ESA

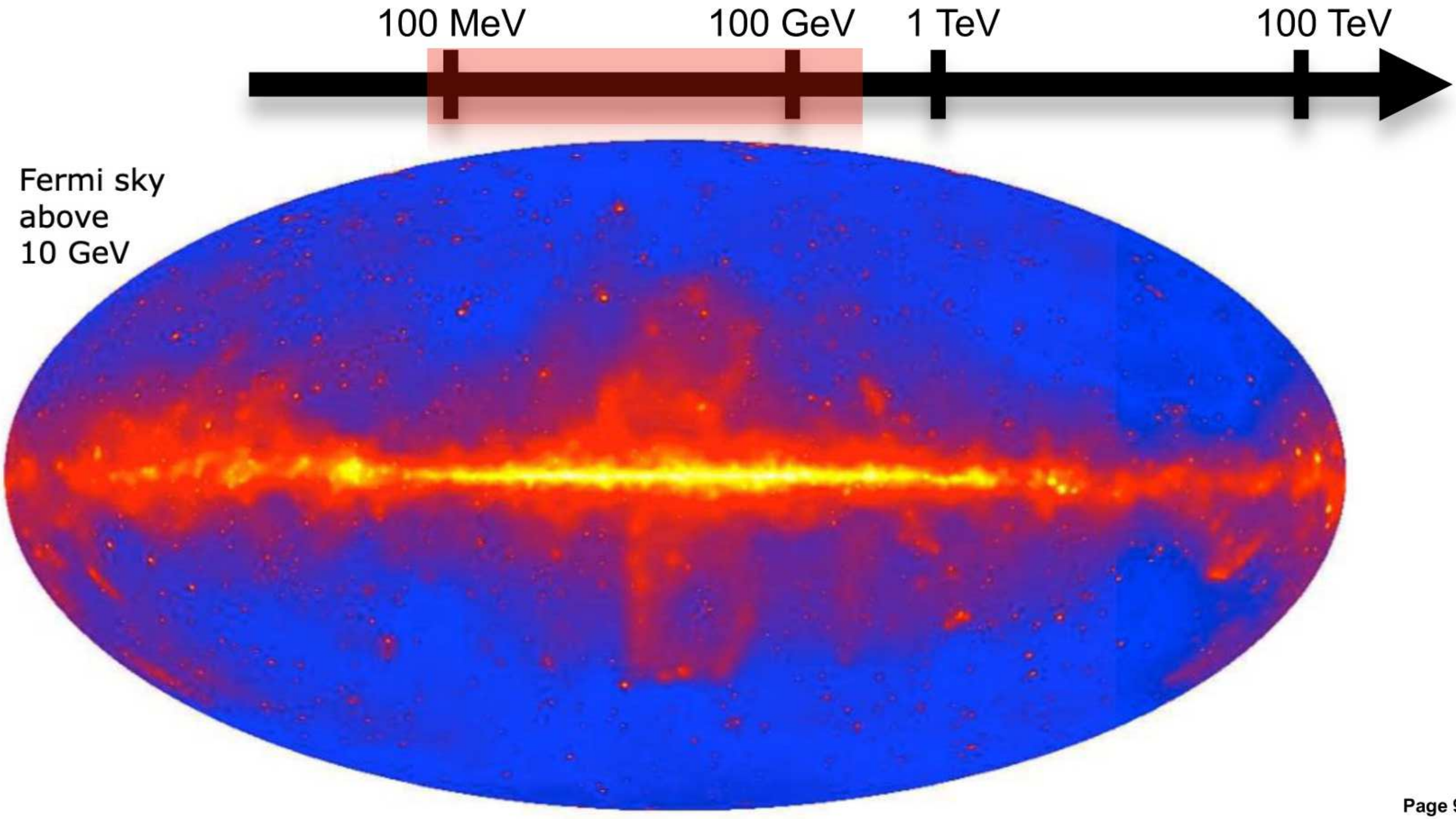

Cygnus Region
Ophiucus Region
Lupus Region
Vela Region
Rosette Nebula
Andromeda Galaxy
Galactic Center
Large Magellanic Cloud
Betelgeuse
Taurus Region
Orion Region
SFRs AKARI © JAXA


SNRs


PWNe


Compact Objects

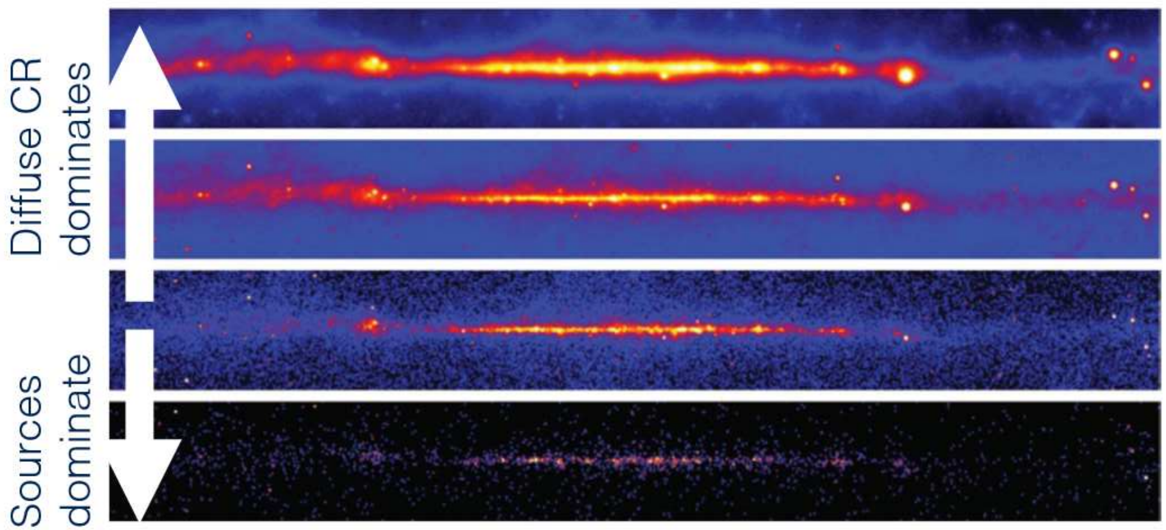
Surveys and Galaxy structures

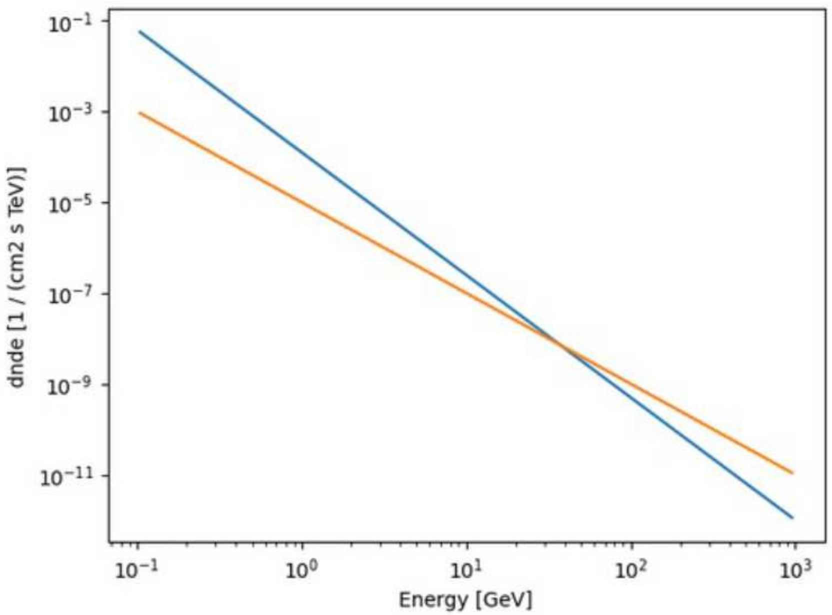


Surveys and Galaxy structures

Mostly due to π^0 production (and subsequent decay) in collisions of CRs with the interstellar medium

If gas density is known (HI: from 21 cm radio line; H_2 traced by CO: 2.6 mm rotational radio line), gamma-rays trace CR density

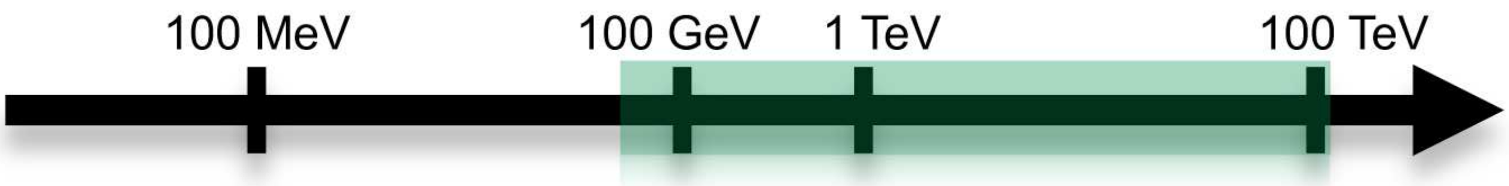




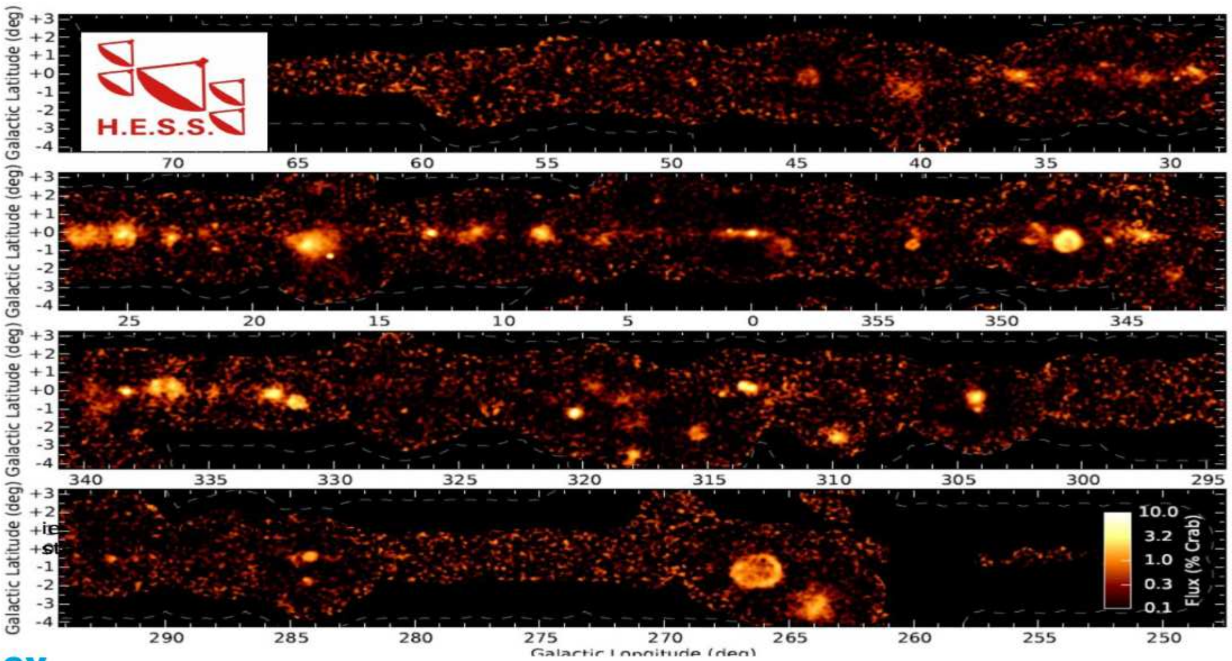

© F. Acero, H. Gast & H.E.S.S. Collaboration

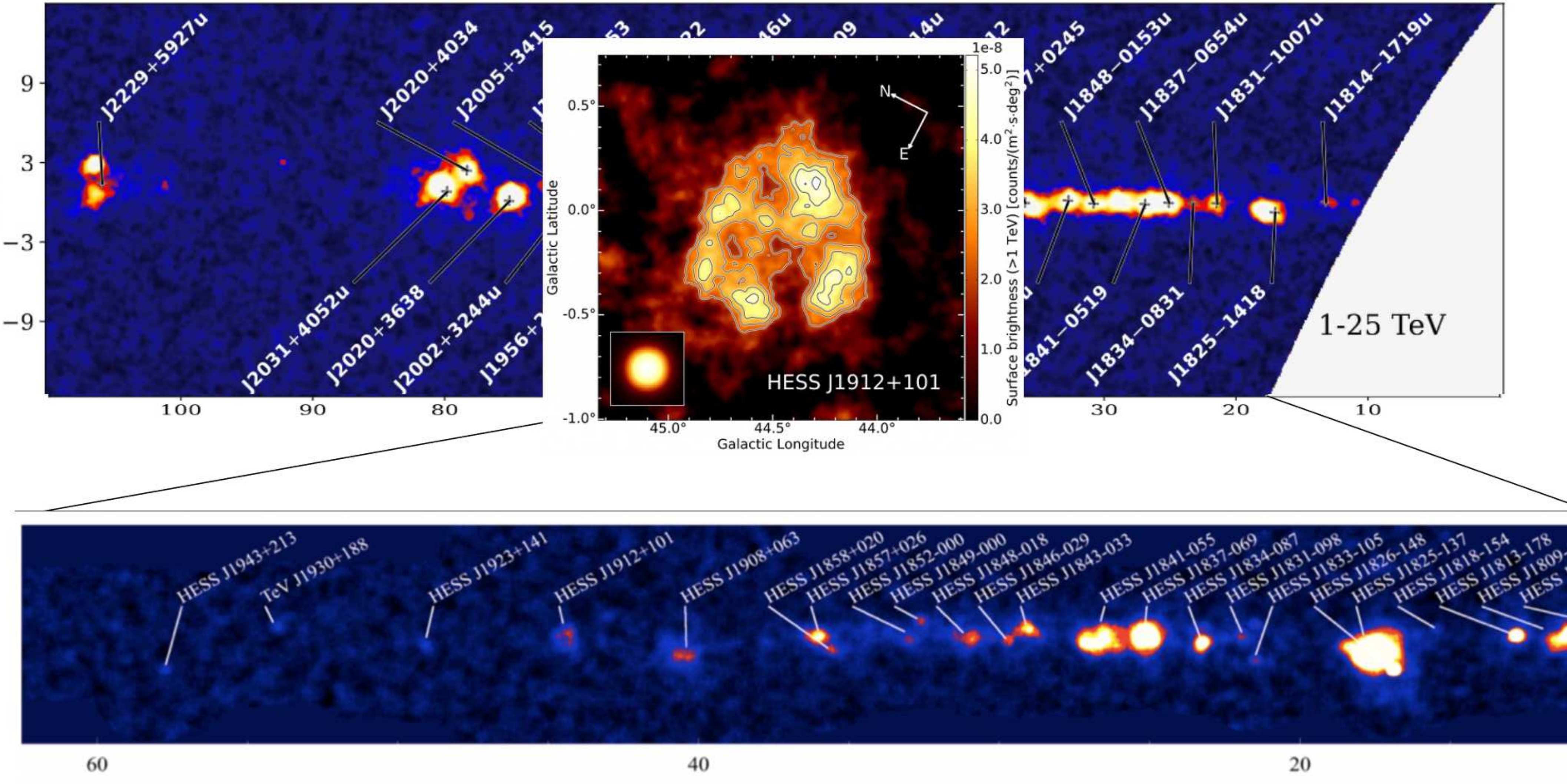
The Galactic Plane in Gamma-rays

H.E.S.S. Galactic Plane Survey (HGPS)



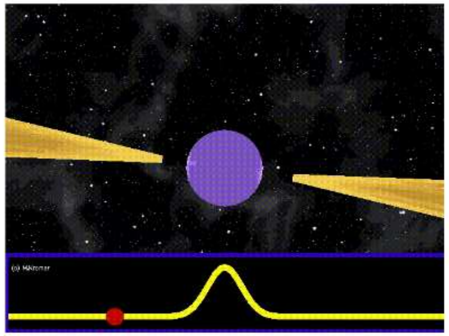
HESS 2018



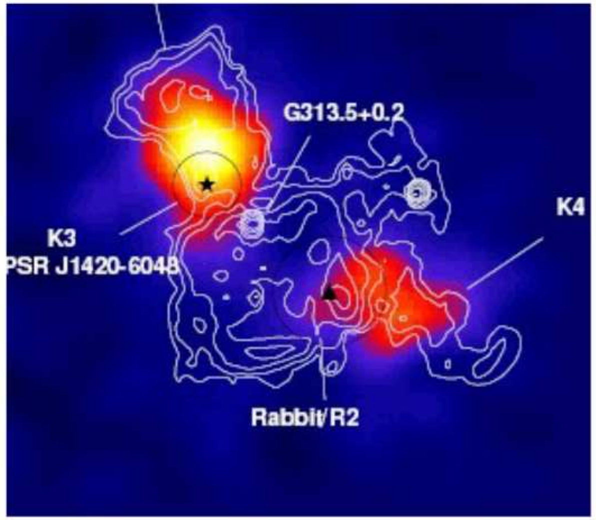


J2229+5927u
J2020+4034
J2005+3415
J2031+4052u
J2020+3638
J2002+3244u
J1848−0153u
J1837−0654u
J1831−1007u
J1814−1719u
J1834−0831
J1825−1418
1-25 TeV
b [°]
HESS J1912+101
Galactic Latitude
Galactic Longitude
Surface brightness (>1 TeV) [counts/(m²·s·deg²)]
N
E
HESS J1943+213
TeV J1930+188
HESS J1923+141
HESS J1912+101
HESS J1908+063
HESS J1858+020
HESS J1857+026
HESS J1852-000
HESS J1849-000
HESS J1848-018
HESS J1846-029
HESS J1843-033
HESS J1841-055
HESS J1837-069
HESS J1834-087
HESS J1831-098
HESS J1833-105
HESS J1826-148
HESS J1825-137
HESS J1818-154
HESS J1813-178

Pulsars

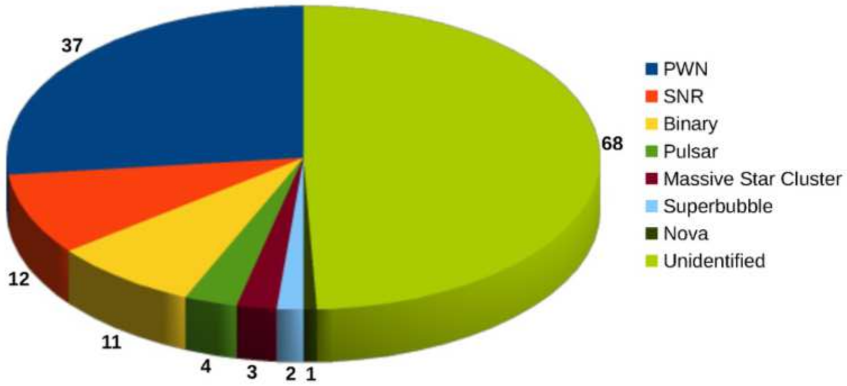


Pulsar Wind Nebulae

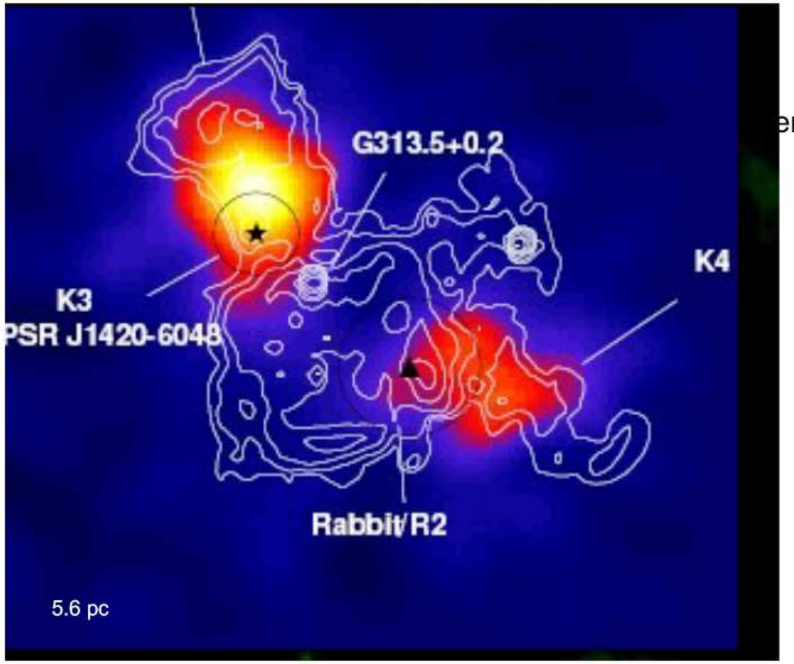


HESS 2006

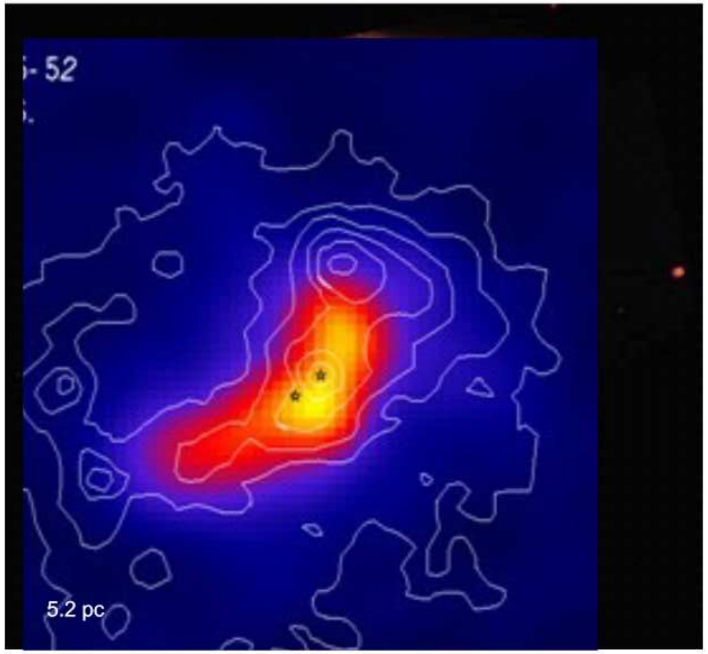
Galactic Sources



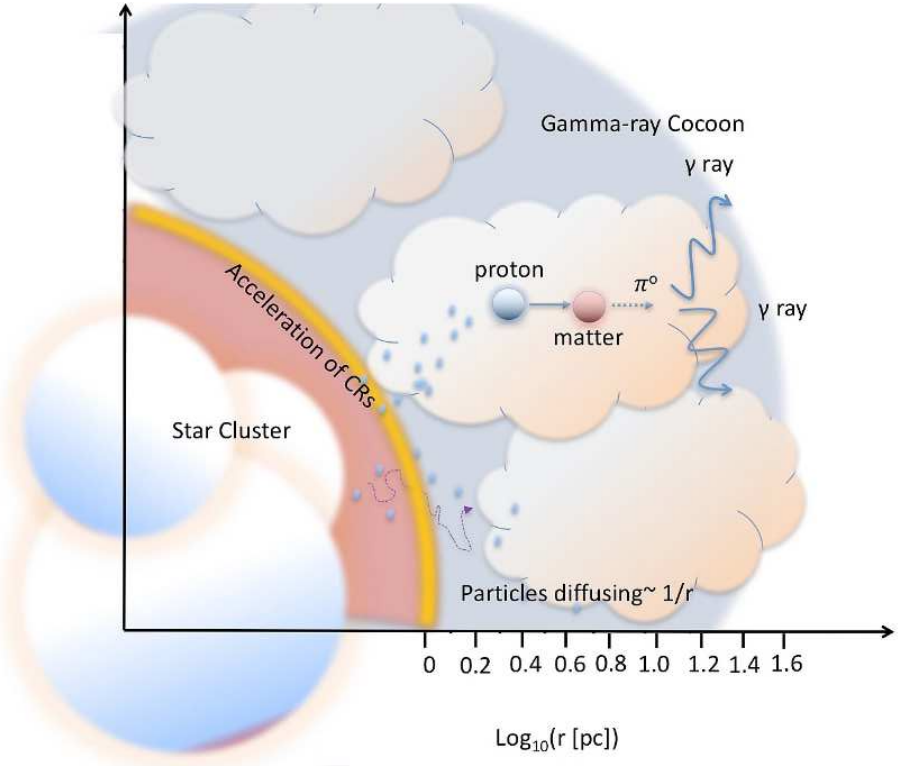
Pulsar Wind Nebulae



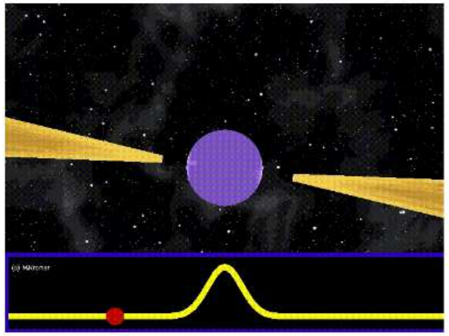
erg



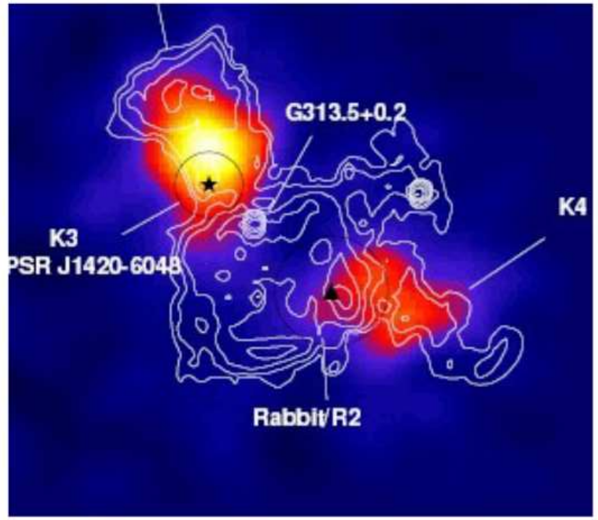
HESS 2007



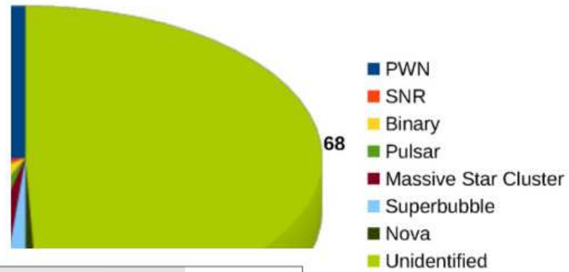
Pulsars



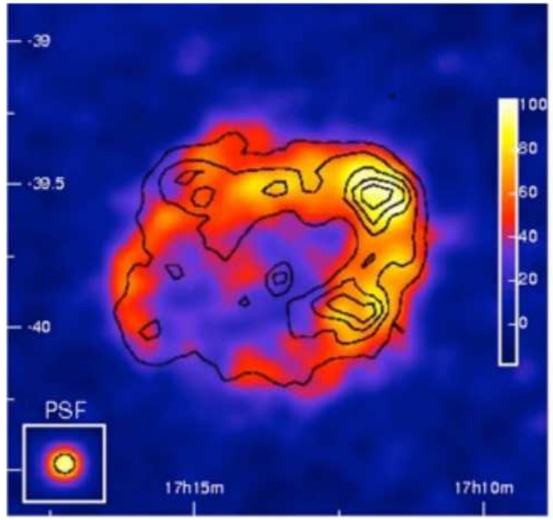
Pulsar Wind Nebulae

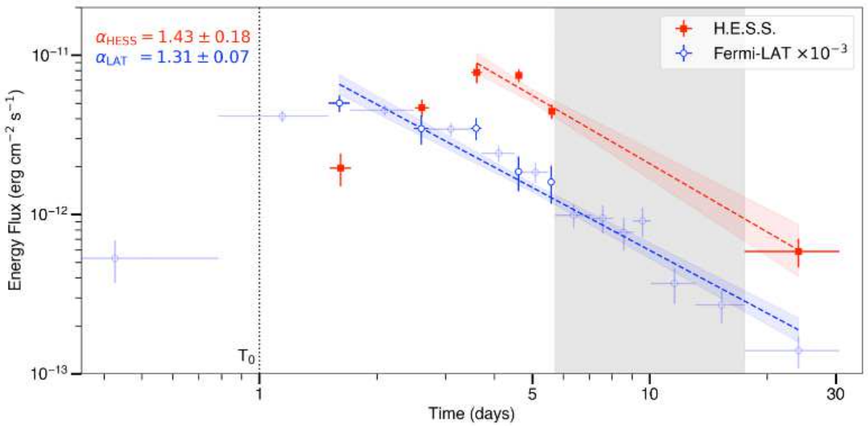


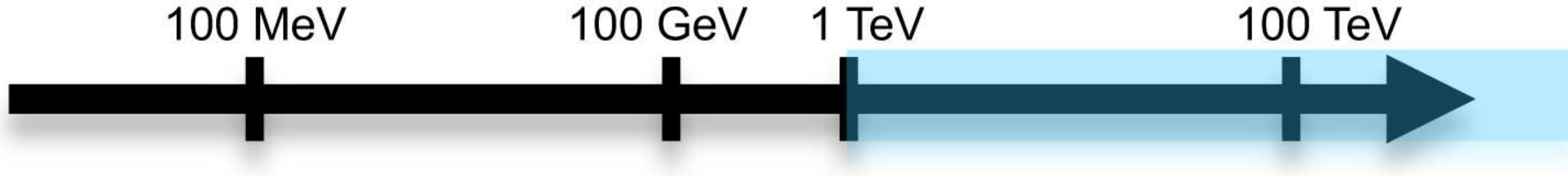
Galactic Sources

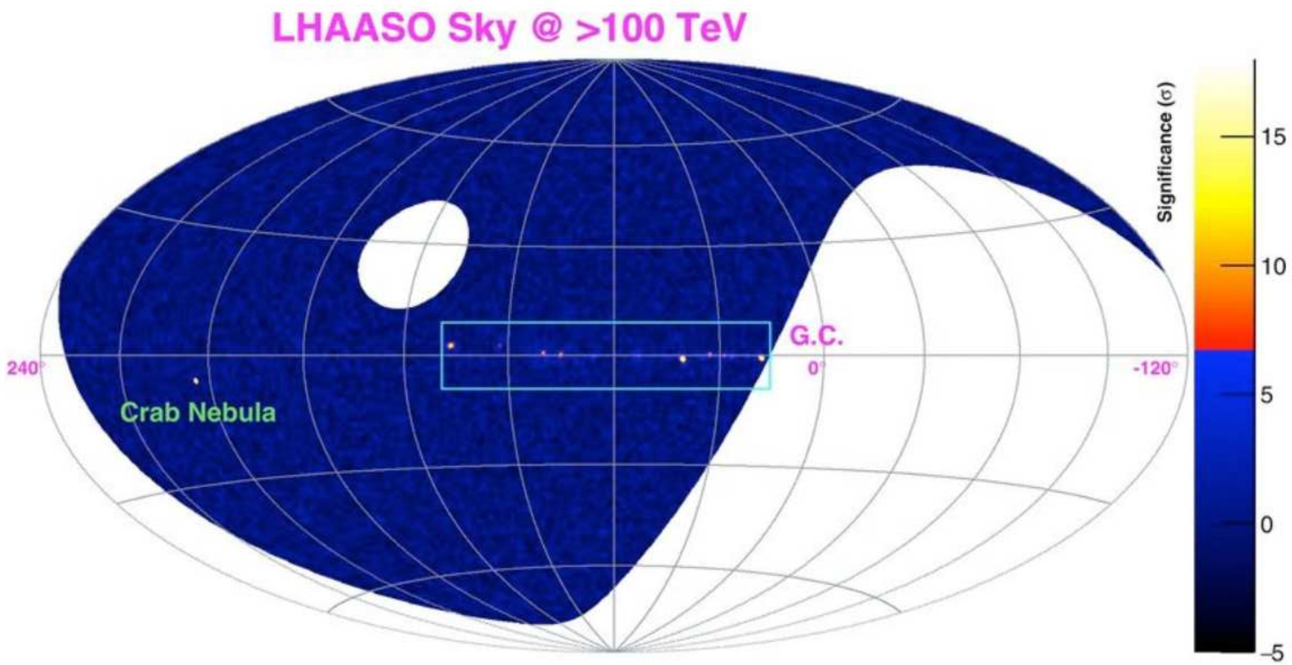


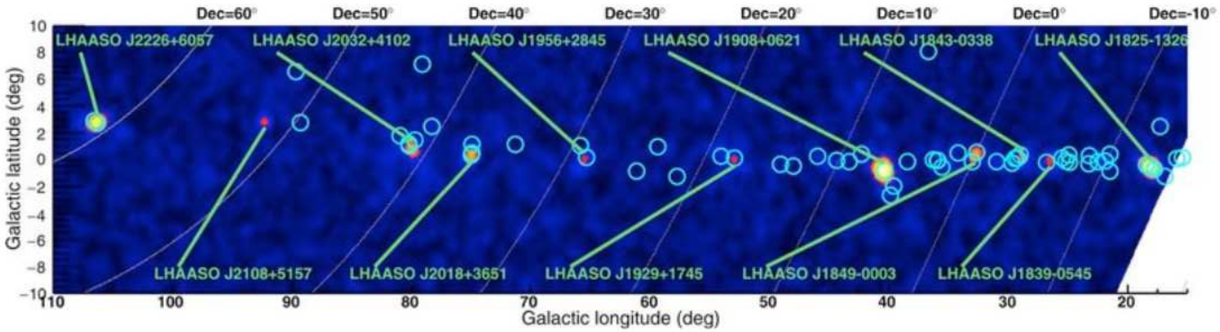
Supernova Remnants

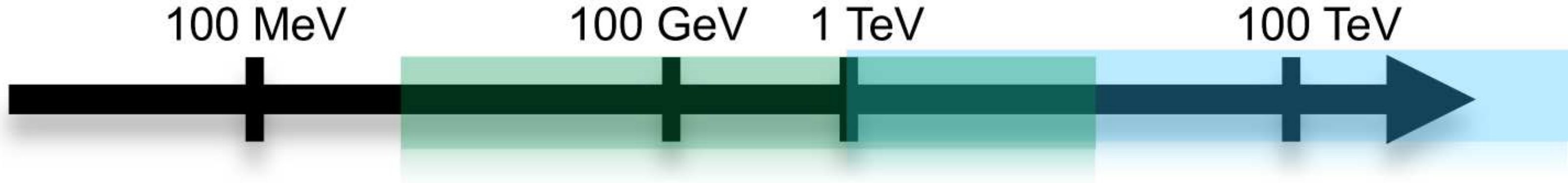


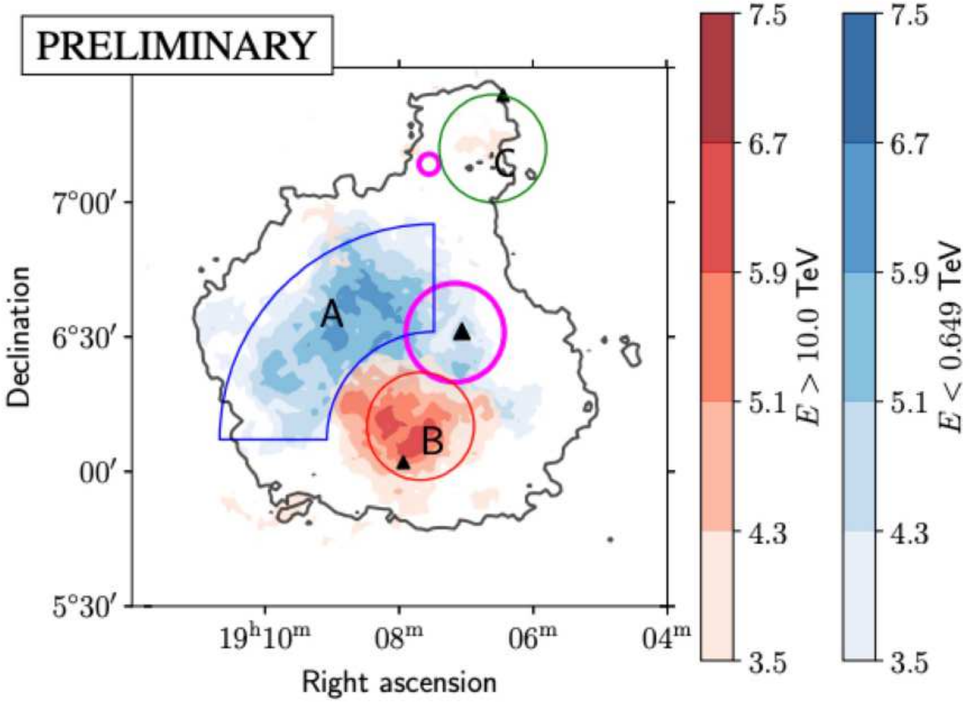


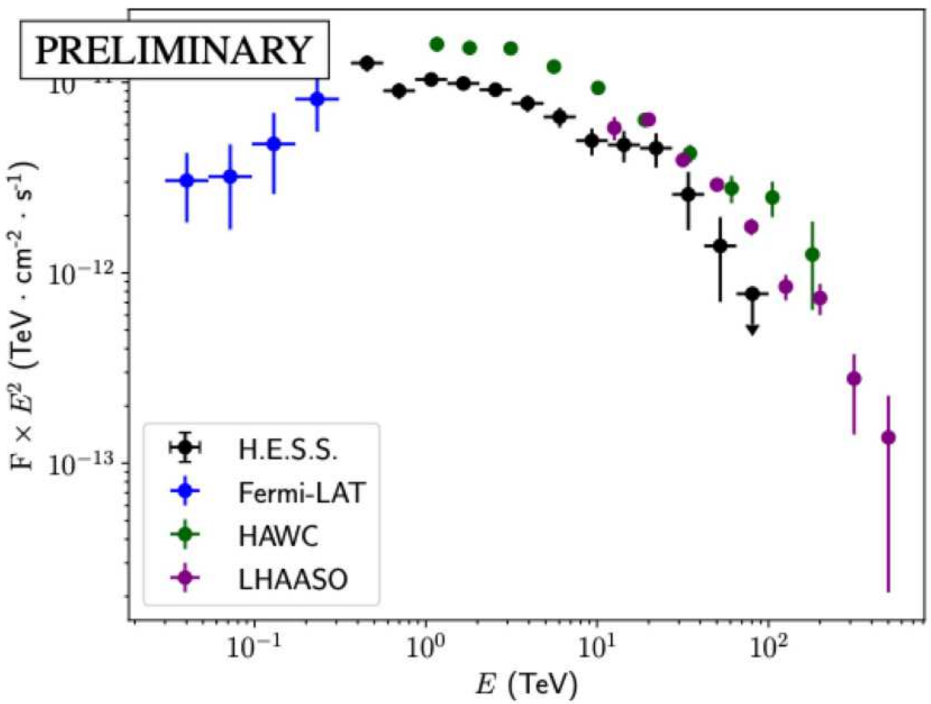

100 MeV
100 GeV
1 TeV
100 TeV


LHAASO Sky @ >100 TeV
G.C.
240°
0°
-120°
Crab Nebula
Significance (σ)
15
10
5
0
−5

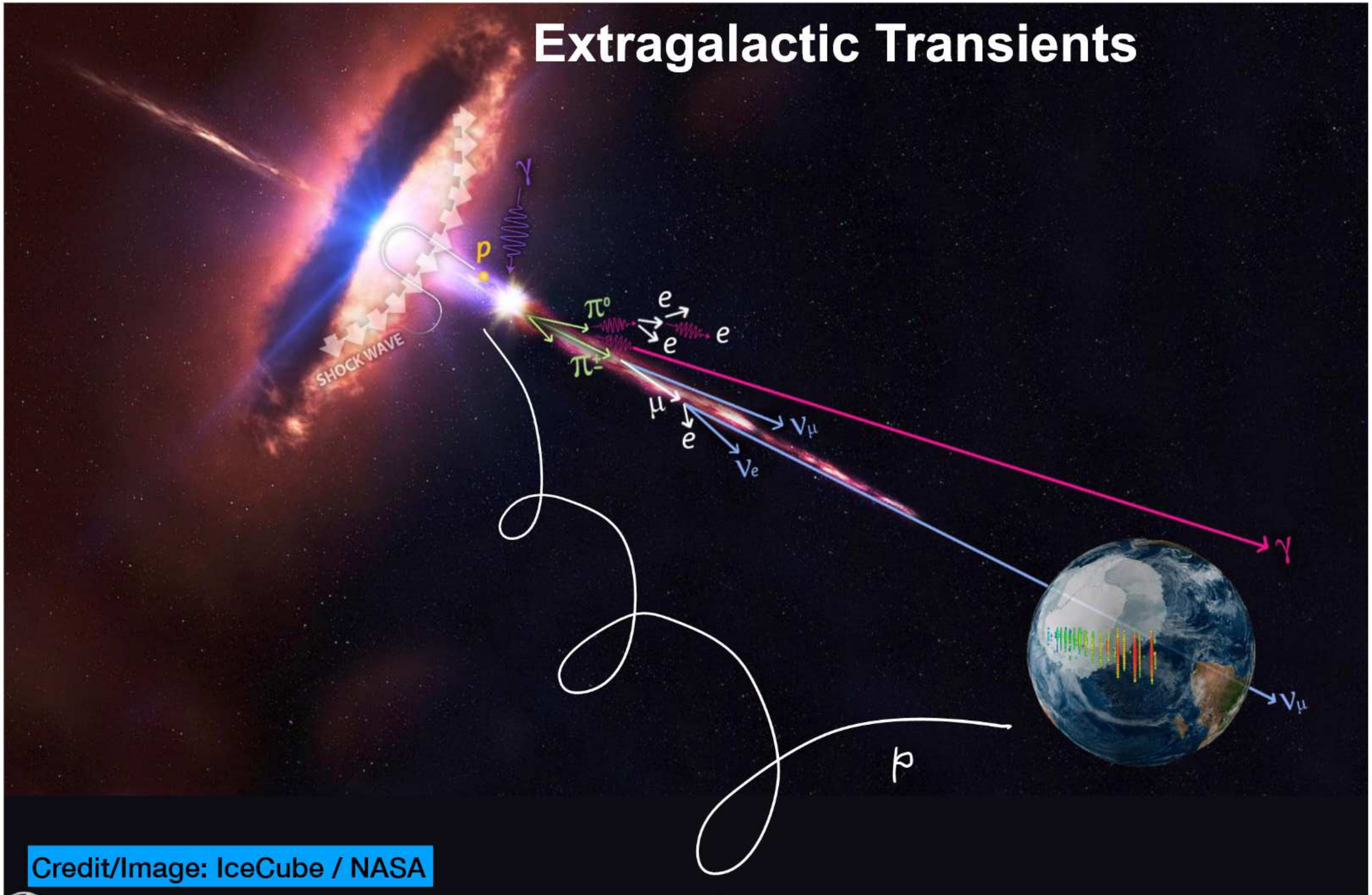

Dec=60°
Dec=50°
Dec=40°
Dec=30°
Dec=20°
Dec=10°
Dec=0°
Dec=-10°
LHAASO J2226+6057
LHAASO J2032+4102
LHAASO J1956+2845
LHAASO J1908+0621
LHAASO J1843-0338
LHAASO J1825-1326
LHAASO J2108+5157
LHAASO J2018+3651
LHAASO J1929+1745
LHAASO J1849-0003
LHAASO J1839-0545
Galactic latitude (deg)
Galactic longitude (deg)


100 MeV
100 GeV
1 TeV
100 TeV


PRELIMINARY
A
B
C
Declination
7°00′
6°30′
00′
5°30′
19h10m
08m
06m
04m
Right ascension
E > 10.0 TeV
E < 0.649 TeV
7.5
6.7
5.9
5.1
4.3
3.5


PRELIMINARY
F × E² (TeV · cm⁻² · s⁻¹)
E (TeV)
H.E.S.S.
Fermi-LAT
HAWC
LHAASO

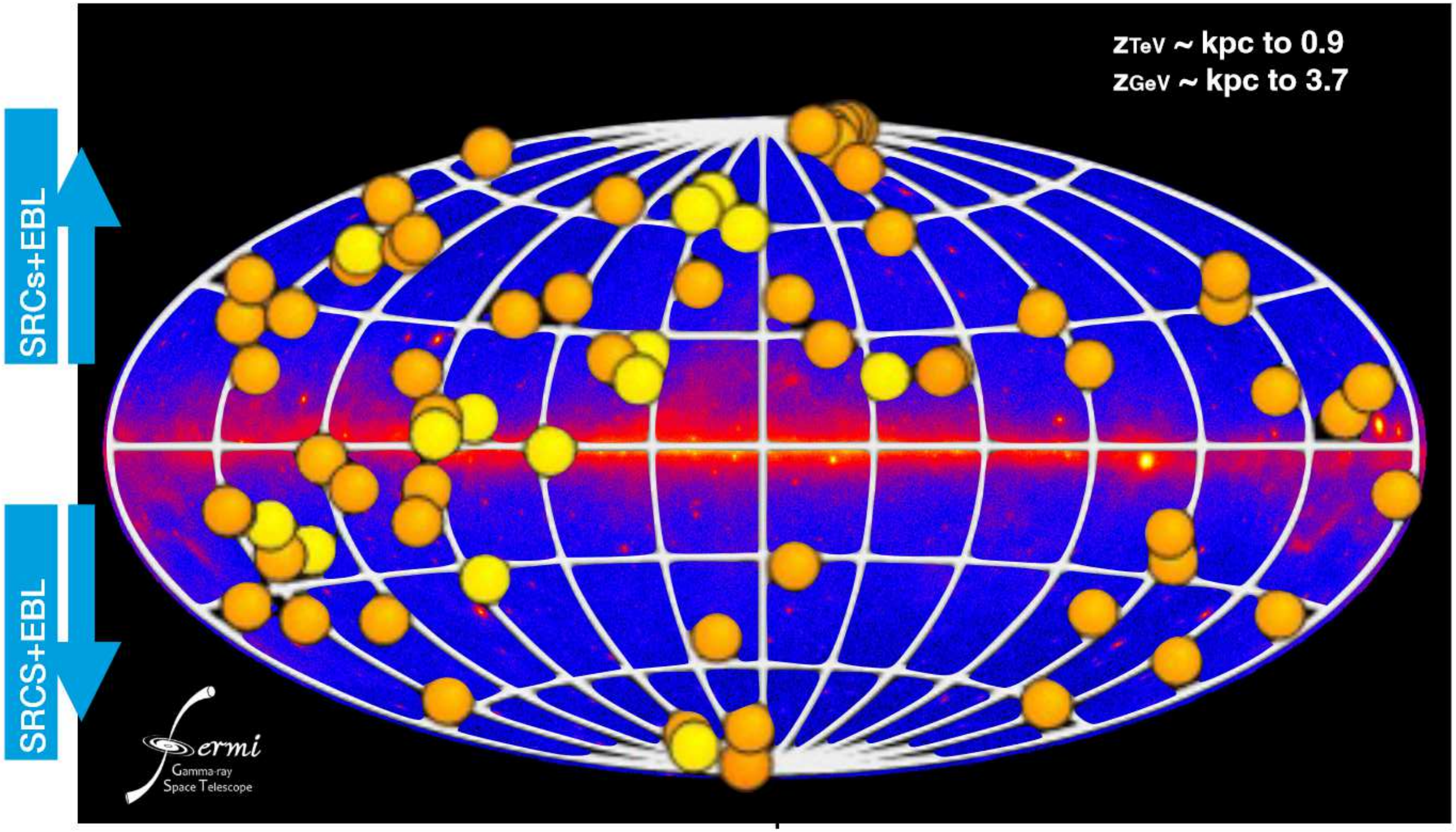
Extragalactic Transients

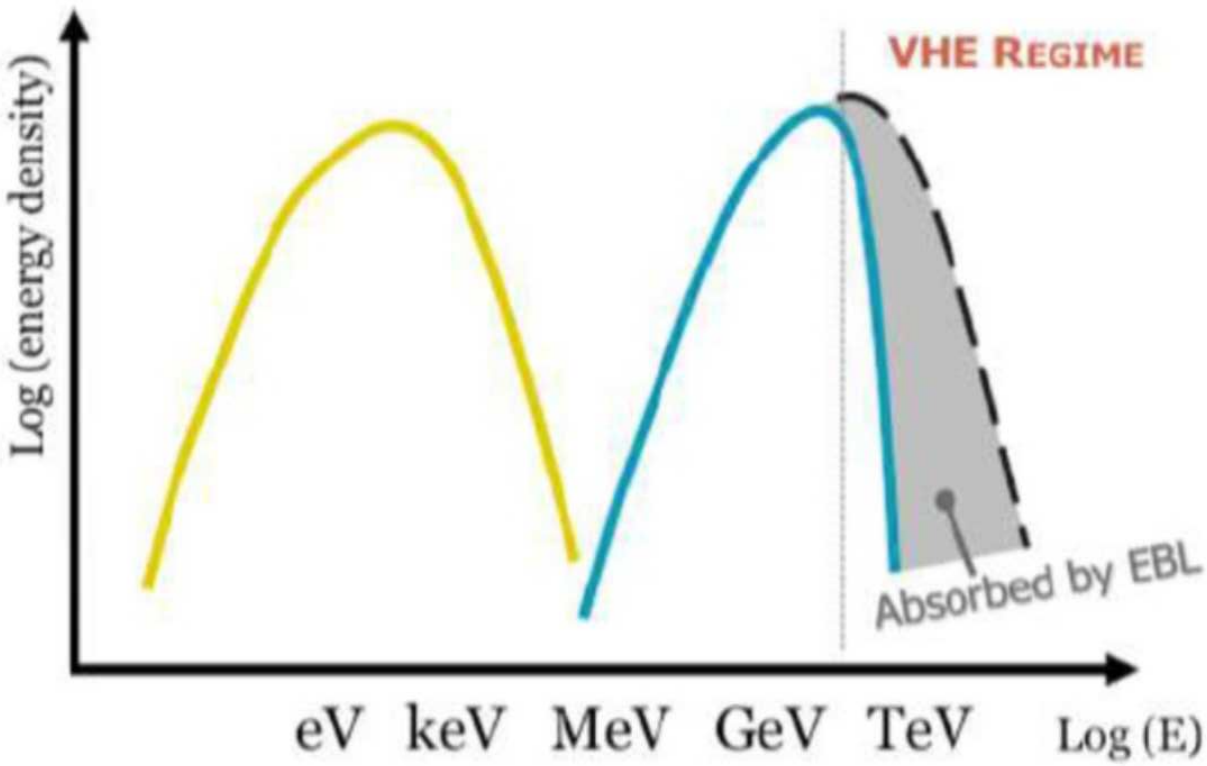


Credit/Image: IceCube / NASA

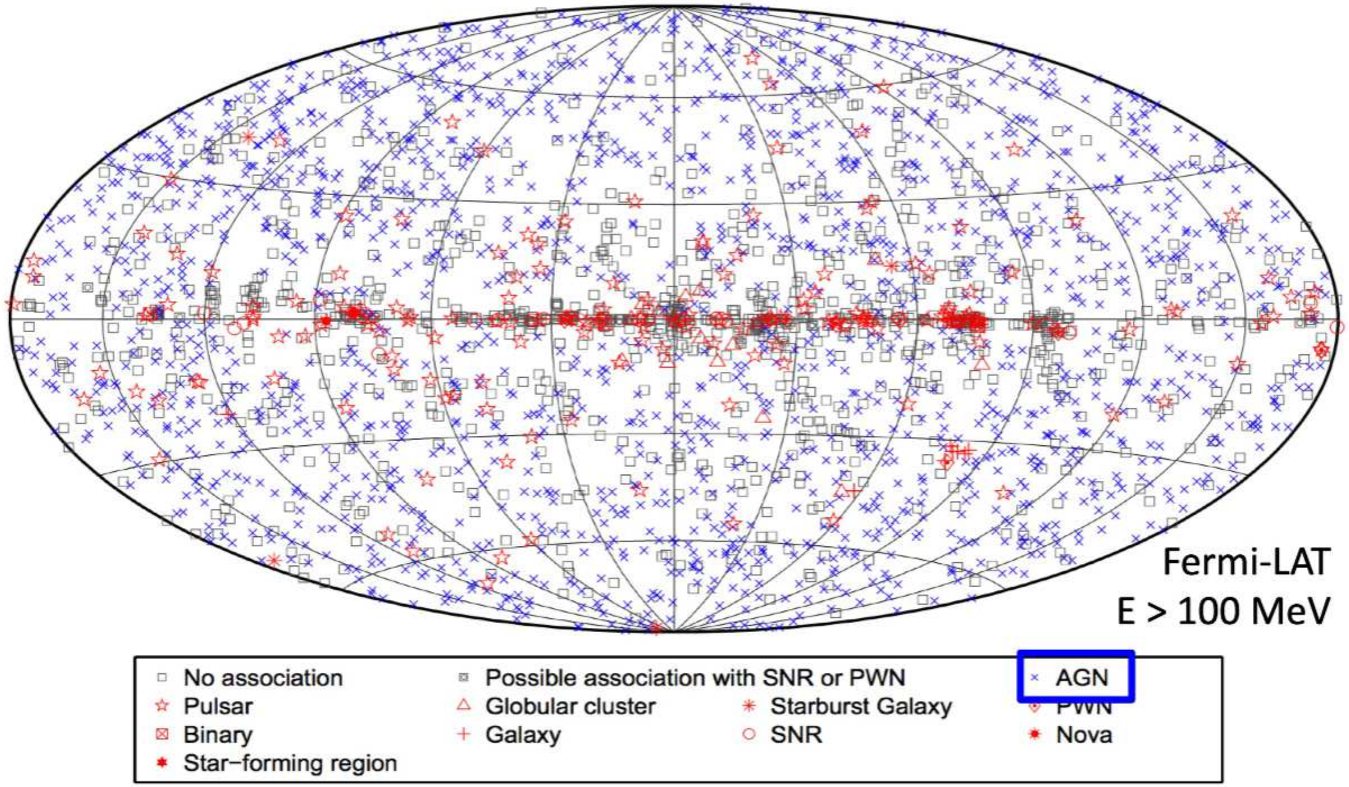
Extragalactic Transients

- Extreme Large Fluxes - Large cosmological distances - Fast Variability




VHE REGIME
Log (energy density)
Absorbed by EBL
eV keV MeV GeV TeV
Log (E)

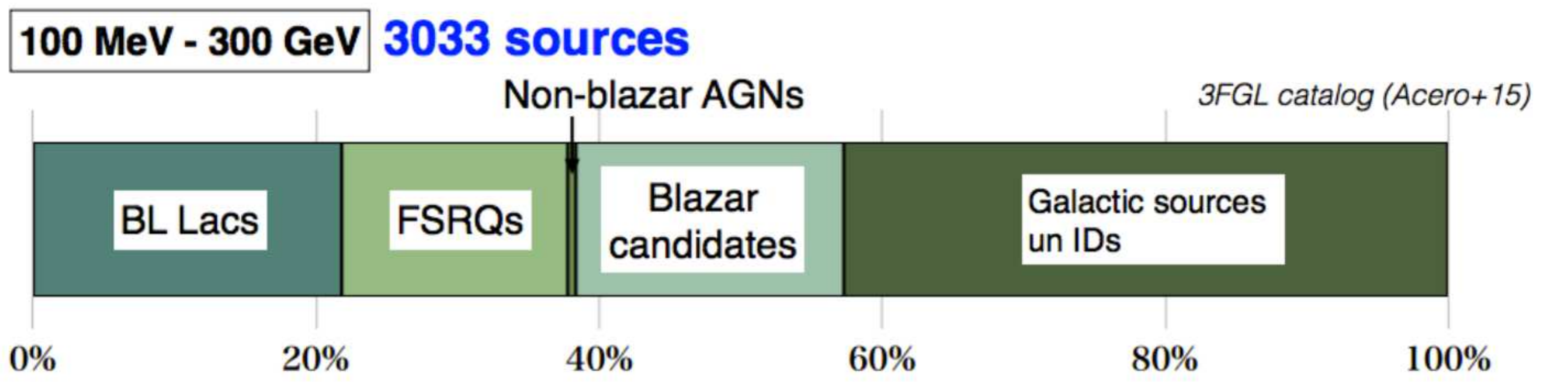
Active Galactic Nuclei

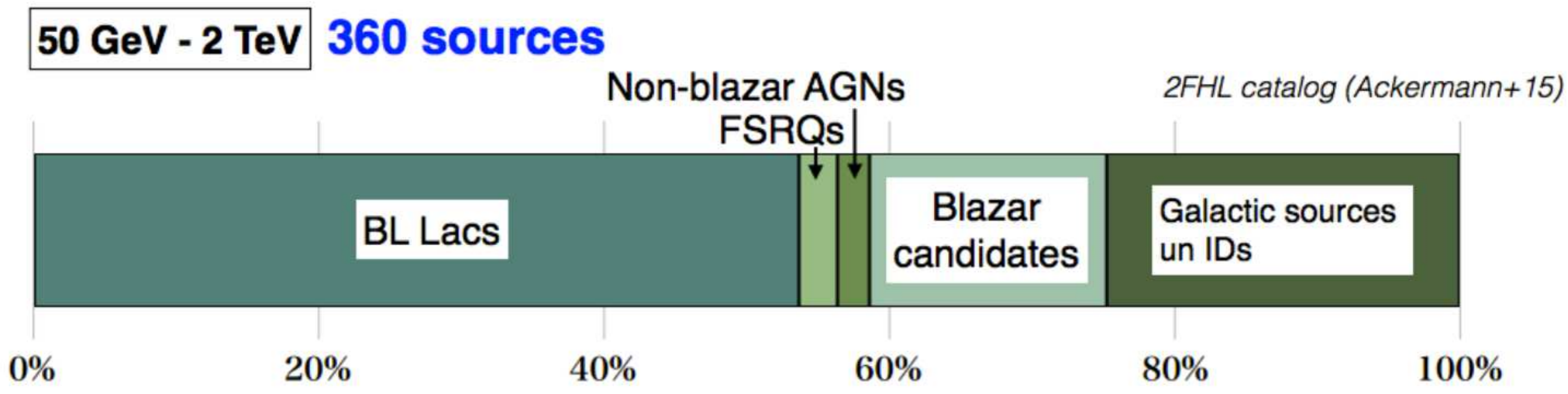


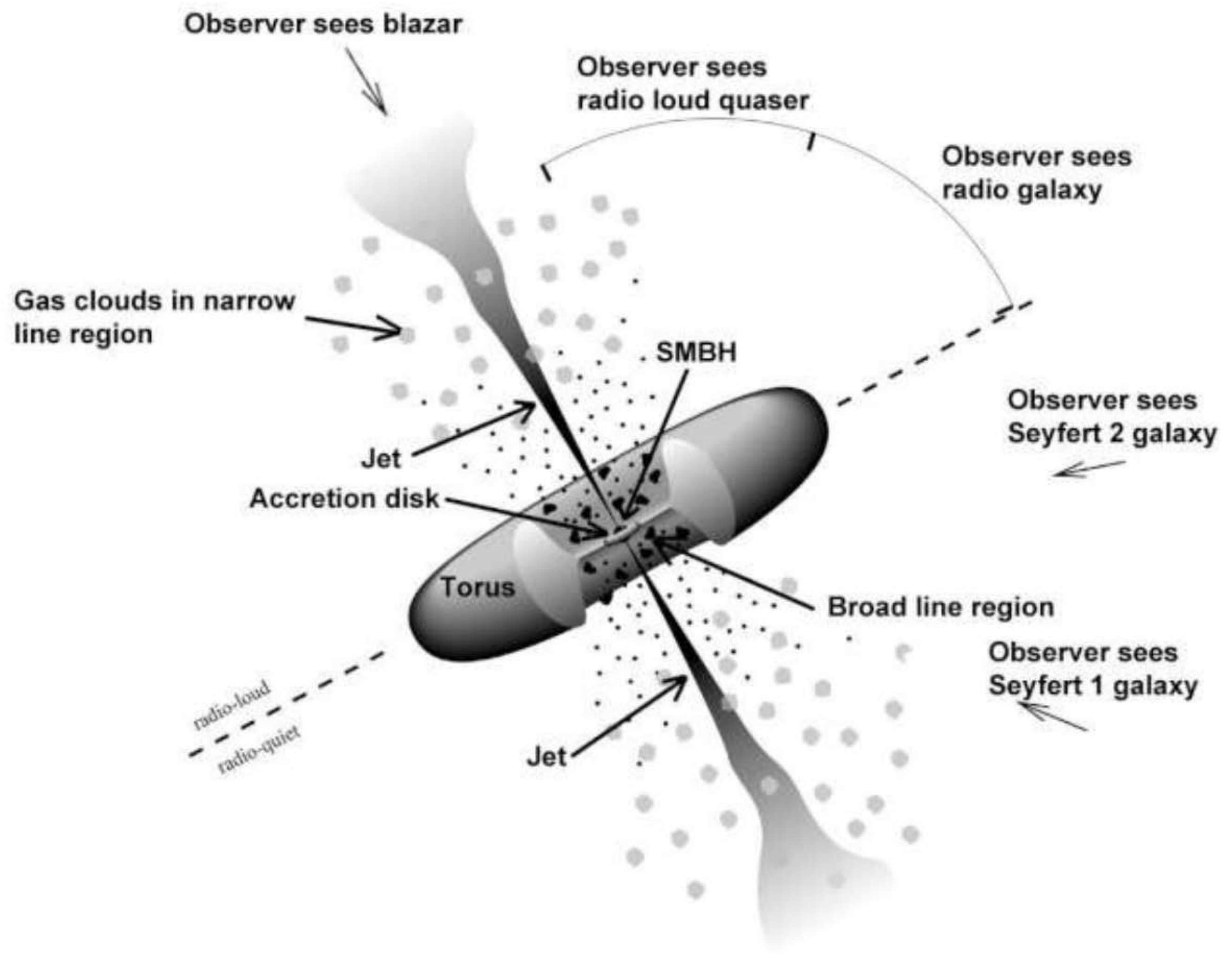
- Nearly all identified persistent** extragalactic γ-ray sources are Active Galactic Nuclei (AGN) of the blazar class, both in the HE (>100 MeV) and VHE (>100 GeV) bands

** does **not** mean *steady*: about half of Fermi AGNs show significant flux variability

The GeV and TeV extragalactic population

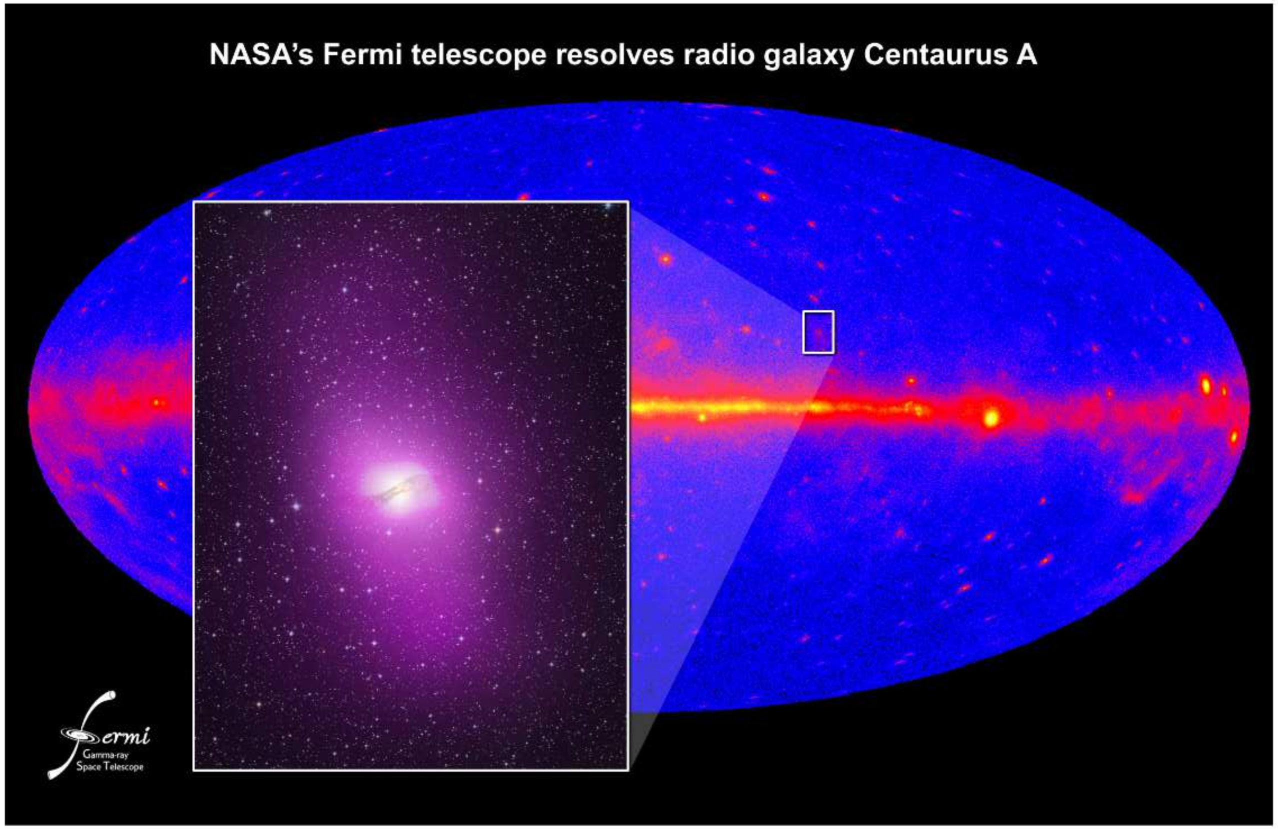





Observer sees blazar
Observer sees
radio loud quaser
Observer sees
radio galaxy
Gas clouds in narrow
line region
SMBH
Observer sees
Seyfert 2 galaxy
Jet
Accretion disk
Torus
Broad line region
Observer sees
Seyfert 1 galaxy
radio-loud
radio-quiet
Jet

Extragalactic sources

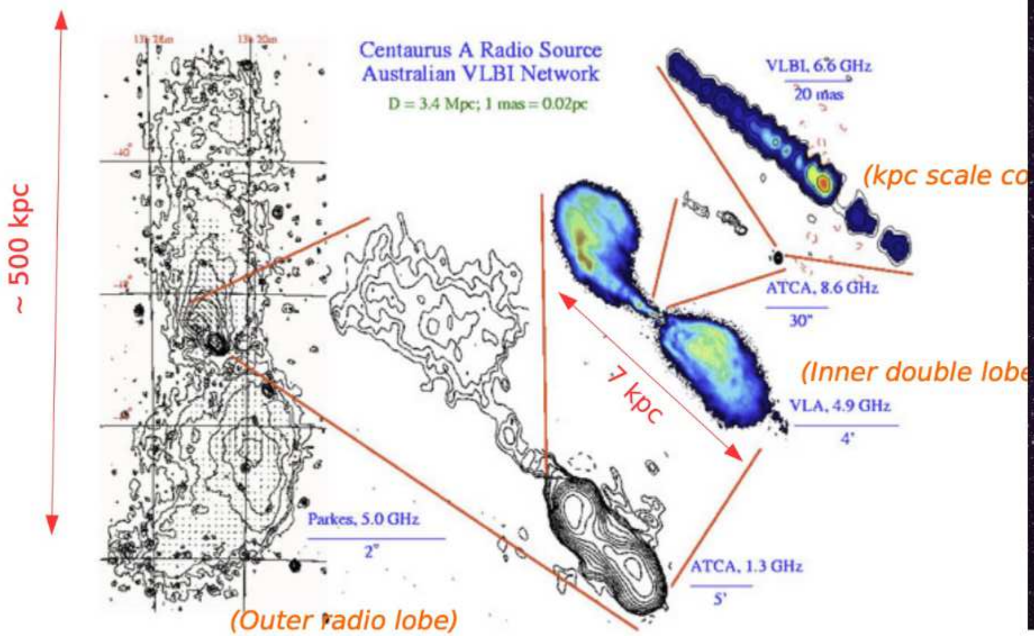
- Sometimes you can resolve them, if they are close enough or are very large



Extragalactic sources

- Sometimes you can resolve them, if they are close enough or are very large

The radio lobes are extended 10 degree on the sky, with orientation in the N-S direction.



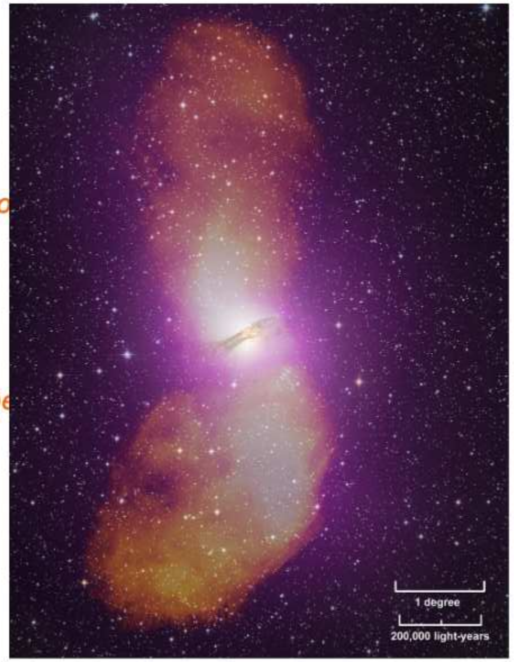
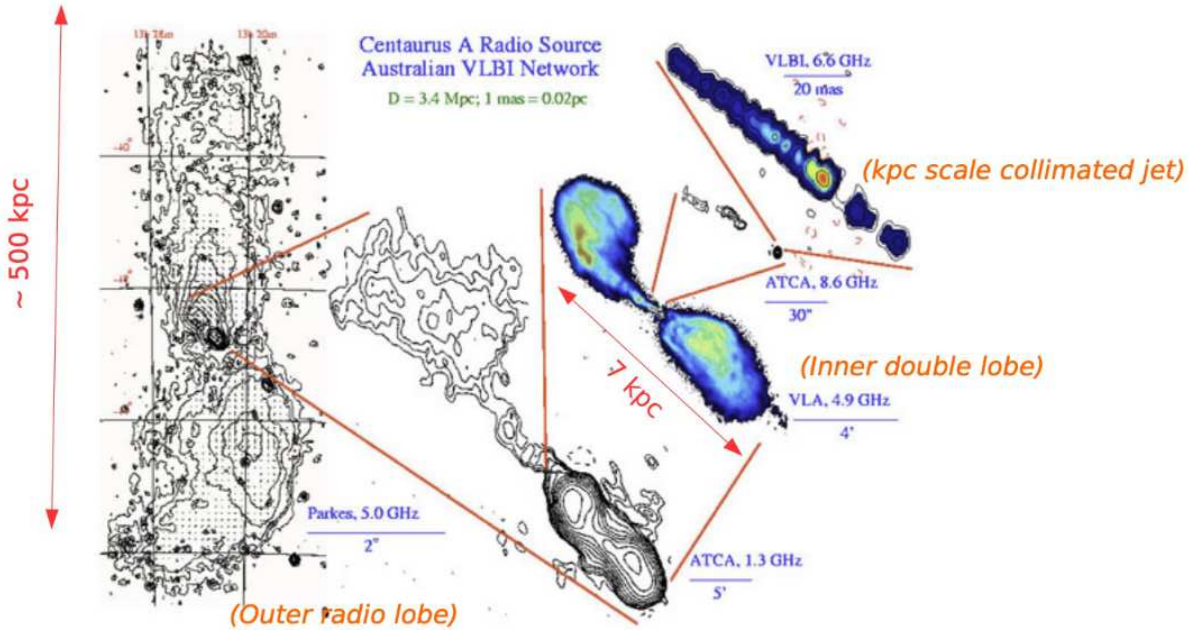


Image credit: ATNF/CSIRO

Extragalactic sources

- Sometimes you can resolve them, if they are close enough or are very large

The radio lobes are extended 10 degree on the sky, with orientation in the N-S direction.



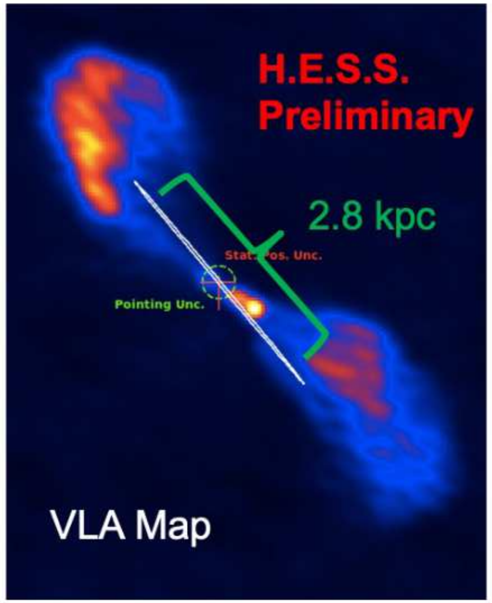
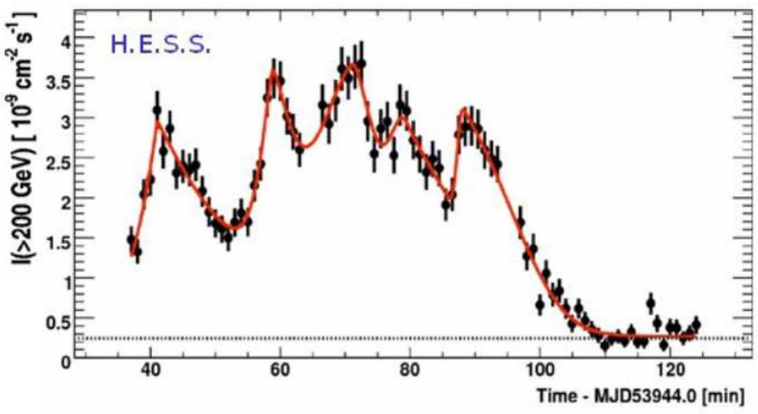
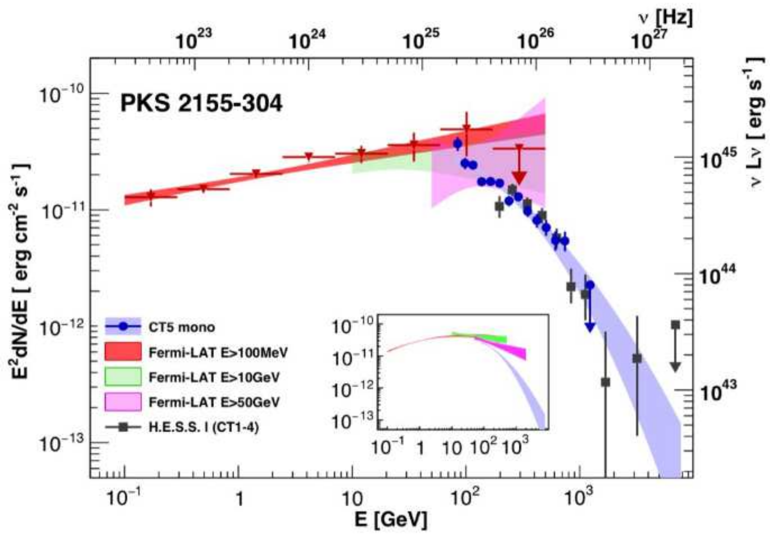


Image credit: ATNF/CSIRO

Extragalactic sources

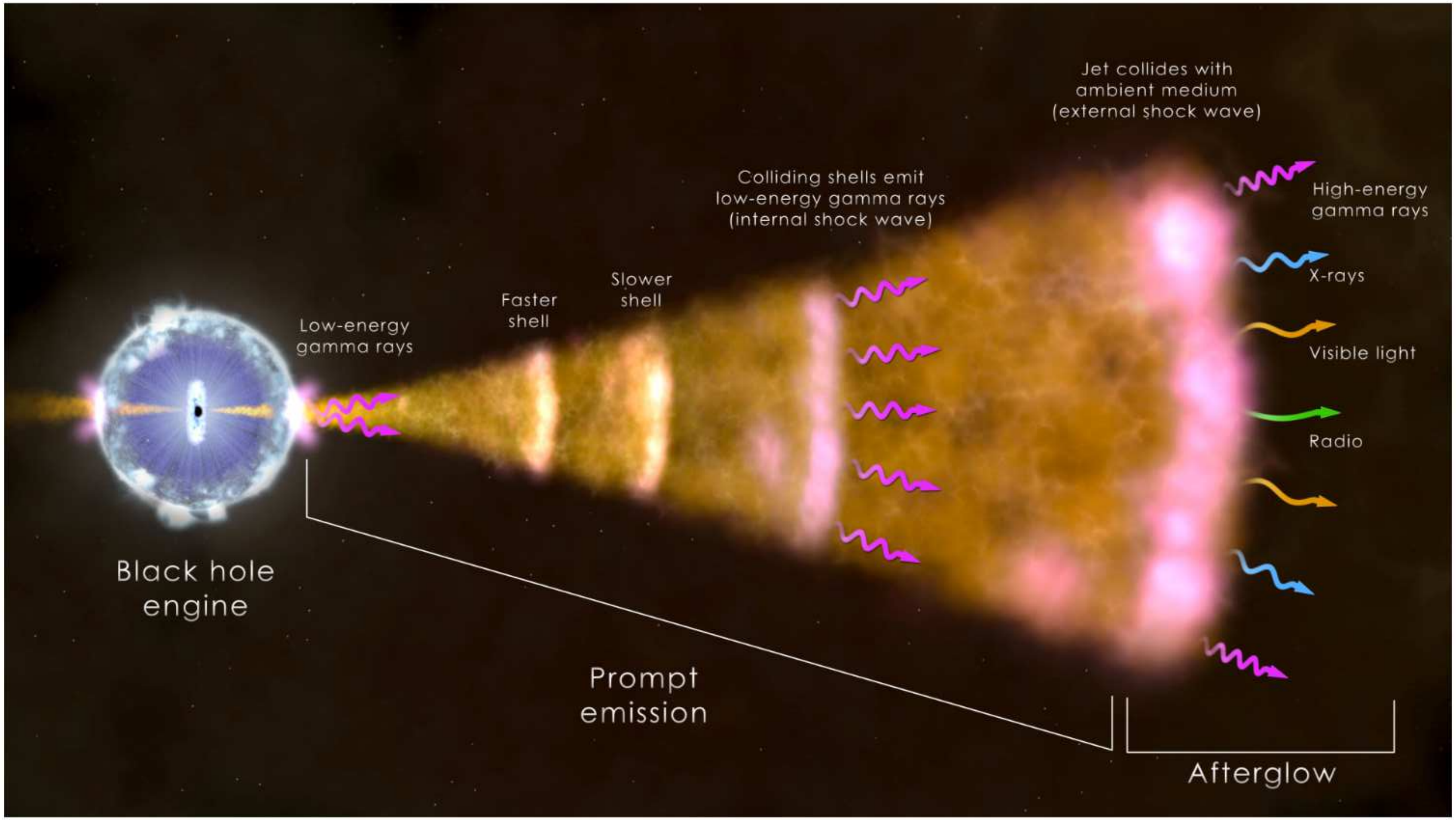
- Sometimes you can resolve them if they are close enough or are very large
- But most of the time, how do we understand what's happening?
  - Variability





Temporal variability down to minutes: $ct \ll r_{Schwarzschild}$

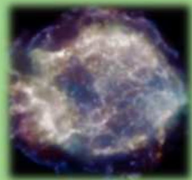
Gamma-ray Burst



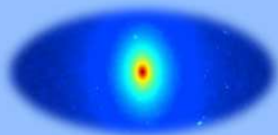
Credit/Image: DESY

What do we expect in the next years?

In-depth understanding of known objects and their mechanisms



Expected discoveries of new object classes

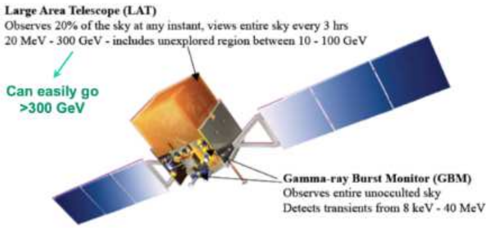


The fun part:
Things we haven't thought of

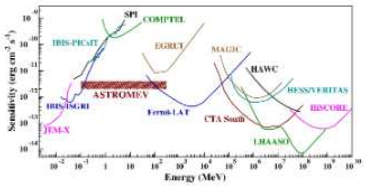
?

1

The Multi-wavelength approach to astrophysics



eASTROGAM
DAMPE
AdePT
HERD
....



SWGO
LHAASO++

MeV - GeV **GeV - > 100 TeV** **PeV**

IceCube-Gen2

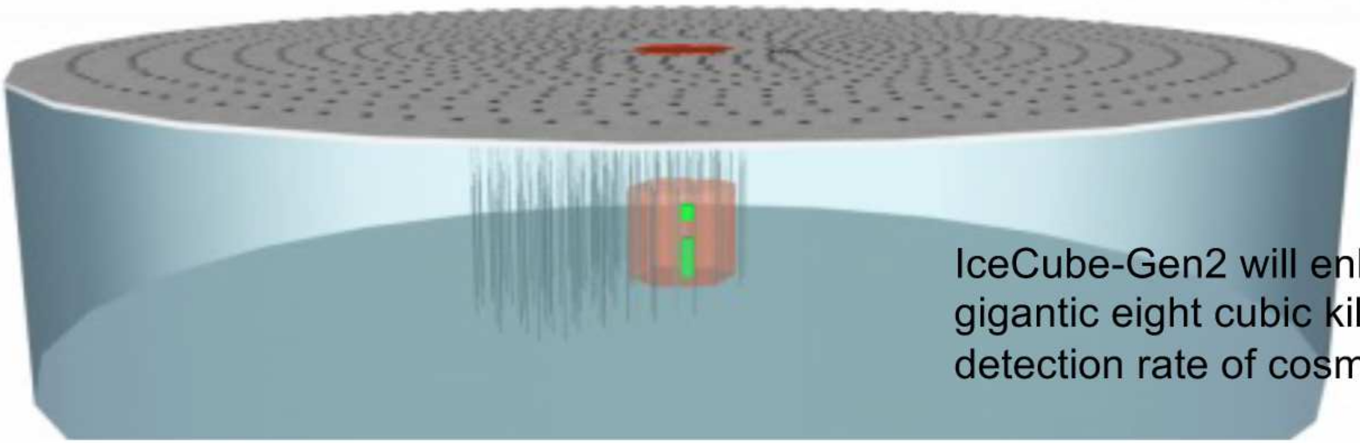
A vision for the future of neutrino astroparticle physics at the South Pole

High energy

- Find (more) neutrino point sources
- Characterise spectrum, flux, and flavour composition of astrophysical neutrinos with higher precision
- GZK neutrinos
- Continue search for BSM physics

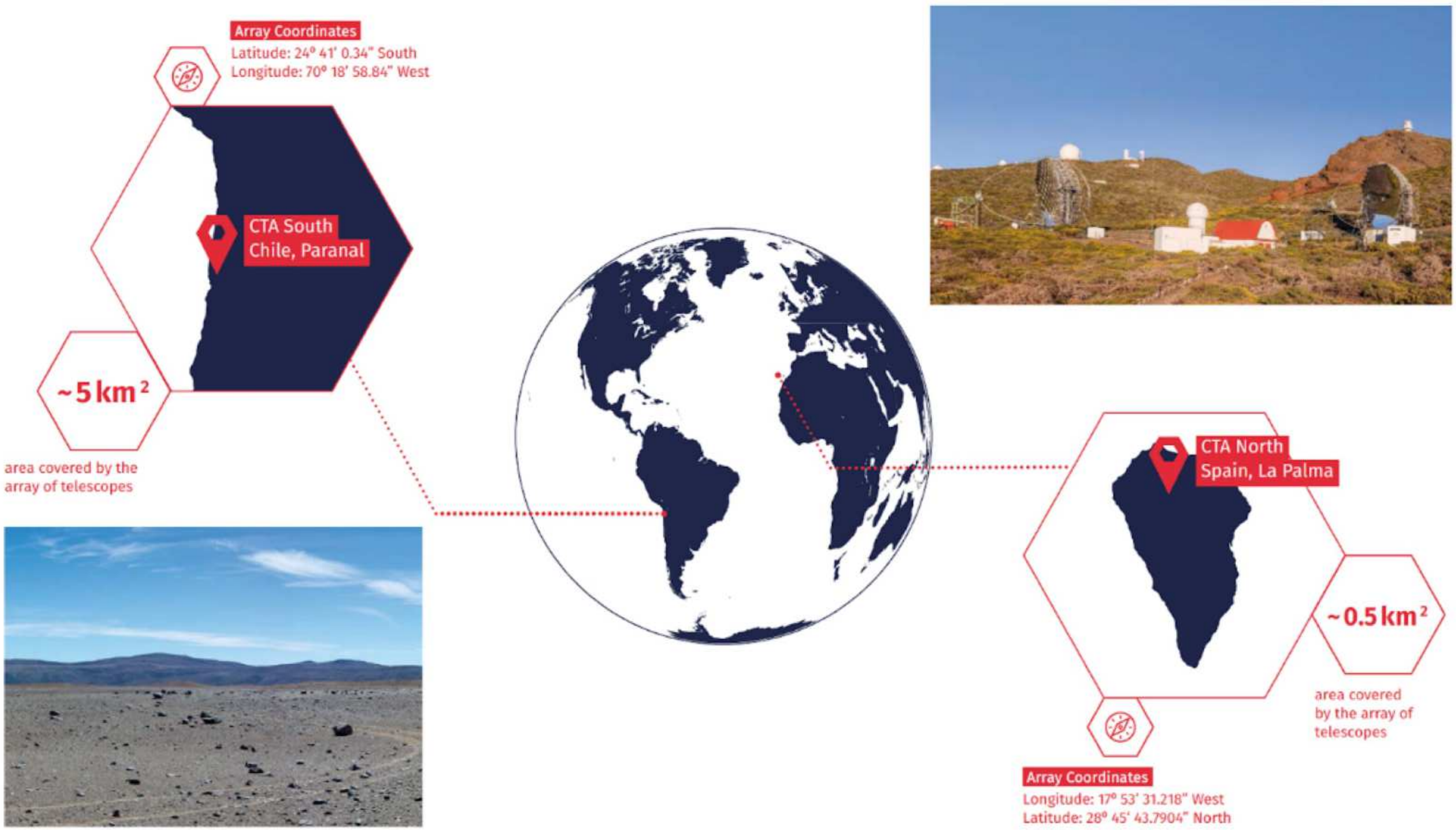
Low energy

- Precision measurements of atmospheric neutrino oscillations:
  - $\nu_\mu \rightarrow \nu_\tau$
  - Neutrino mass ordering
- Characterise atmospheric flux (hadronic interactions)
- Also continue search for BSM physics

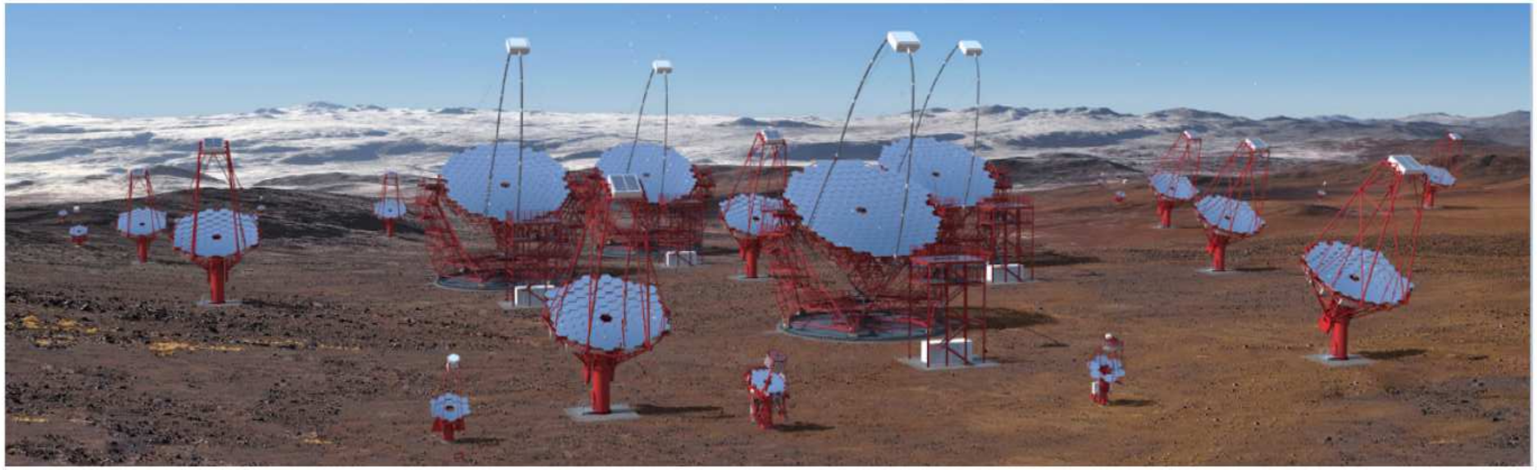


IceCube-Gen2 will enlarge the detector’s volume to a gigantic eight cubic kilometers. This will increase the detection rate of cosmic neutrinos by a factor of ten.

The Cherenkov Telescope Array



South: 99 telescopes spread out over ~5 km2 (70 SSTs, 25 MSTs, 4 LSTs)



North: 19 telescopes spread out over ~1 km2 (15 MSTs, 4 LSTs)

Summary

Astroparticle physics focus on the study of highly relativist particles accelerated to very high energies via:

- huge gravitational, magnetic and electric fields
- very dense background radiation
- relativistic bulk motions (black hole jets and pulsar winds) shock waves (SNRs), highly excited (turbulent) media, etc…

Involves rich interdisciplinary teams

Generates new statistical problems (very large and very small number of events)

Is one of the most attractive topics to reach the general public

Includes: X-ray astronomy, g-ray astronomy (MeV-TeV), neutrino astronomy, gravitational wave astronomy, cosmic ray astrophysics, and cosmology => Join us!