Gamma ray astronomy (at TeV)

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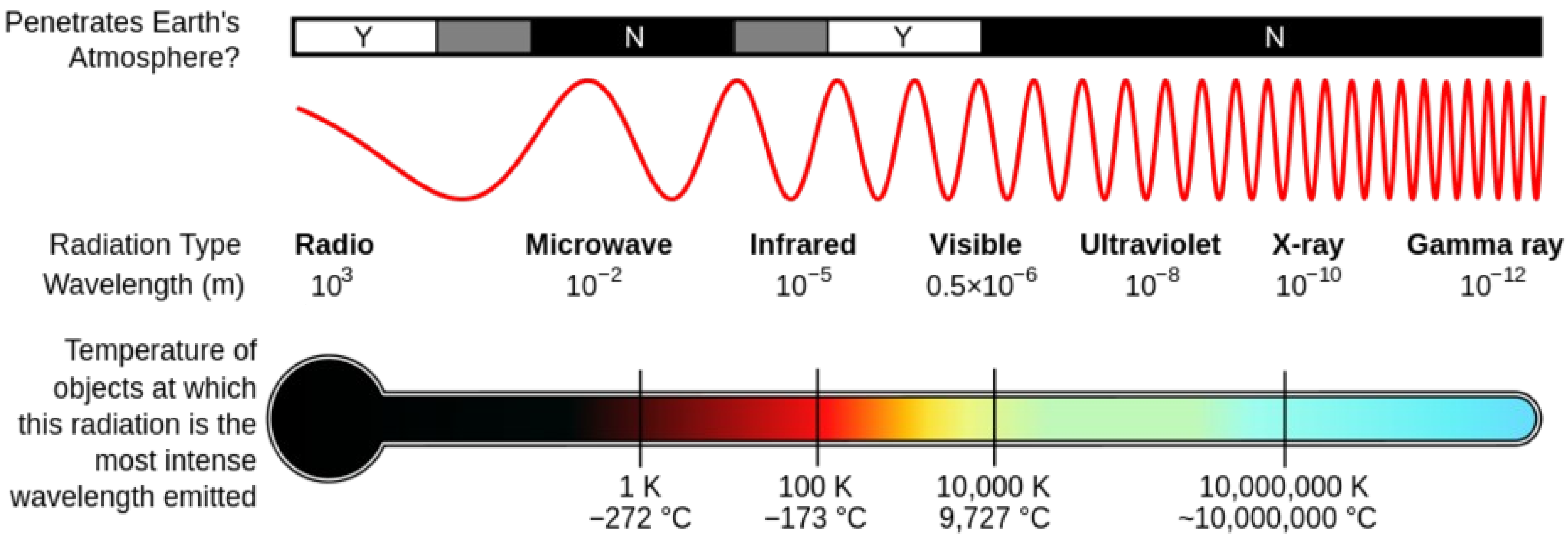
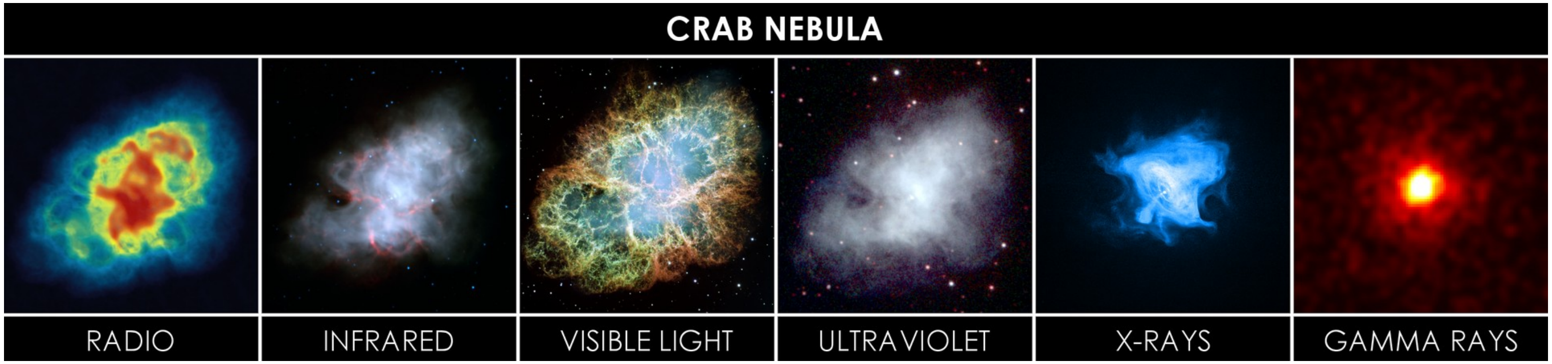
Electromagnetic radiation

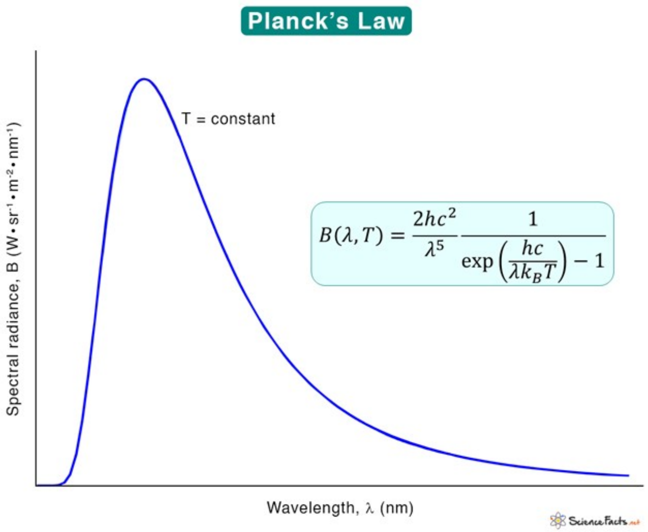




Thermal Gamma-ray ?

$$L^{\circ}_{\Omega,\nu}(\nu,T) = \frac{2h\nu^3}{c^2}\frac{1}{\mathrm{e}^{\frac{h\nu}{kT}}-1}$$

- 1 GeV ~ 10^{13} Kelvin !
- 1 TeV ~ 10^{16} Kelvin !



$$\frac{M}{M_\odot}\frac{M_\odot}{M_p}k_B T$$

~ 10^{50} Joules per solar mass for TeV
~ 10^{47} Joules per solar mass for GeV

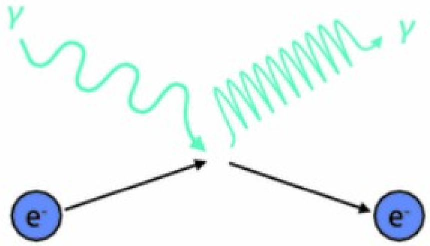
(strongest hypernova ever detected 10^{49} joules !)

- It looks completely unrealistic to have thermal gamma rays, more efficient way of production of gamma rays exists

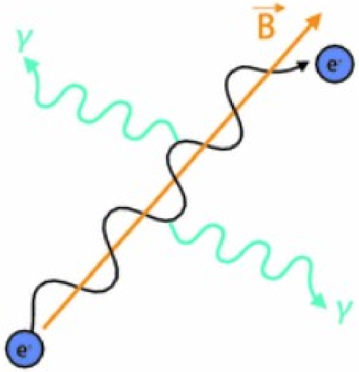
Gamma-ray production

Neutral messenger counterpart : gamma-rays

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c U_R \beta^2\gamma^2$$



(d) Inverse Compton

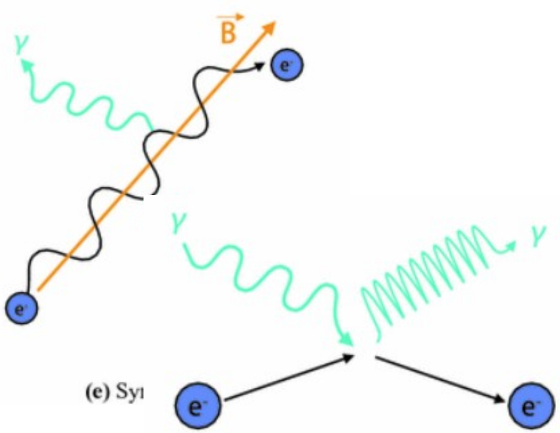


(e) Synchrotron.

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c U_B \beta^2\gamma^2$$

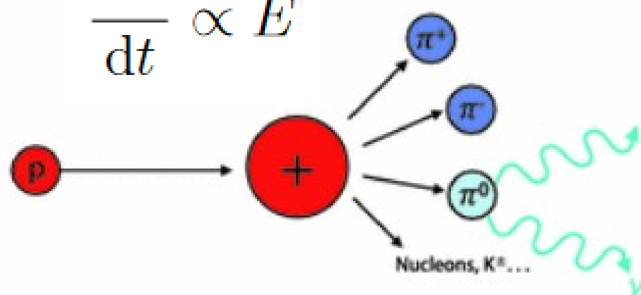
$$U_B = B^2/2\mu_0$$

Synchrotron Self Compton :



(d) Inverse Compton

$$\frac{\mathrm{d}E}{\mathrm{d}t} \propto E$$

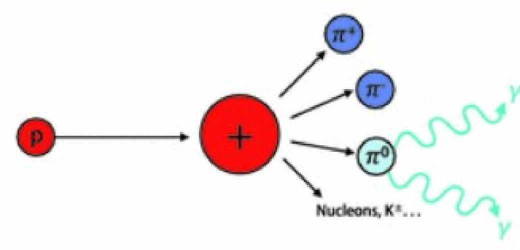


(c) Pion decay

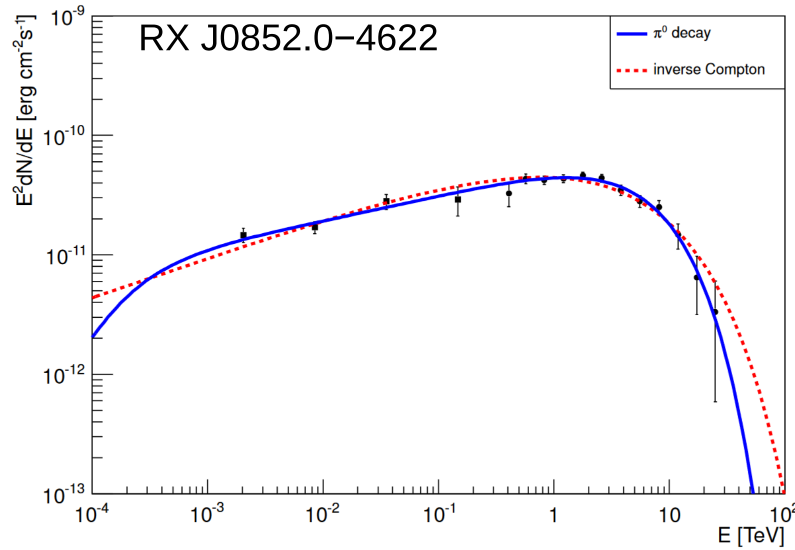
Gamma-ray production

$$\frac{dE}{dt} \propto E$$

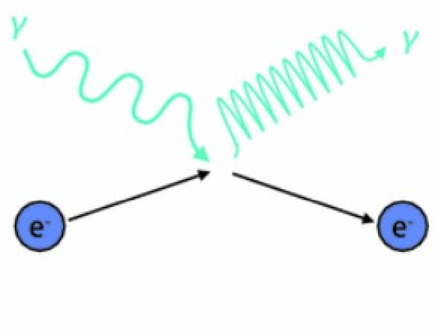
hadronic



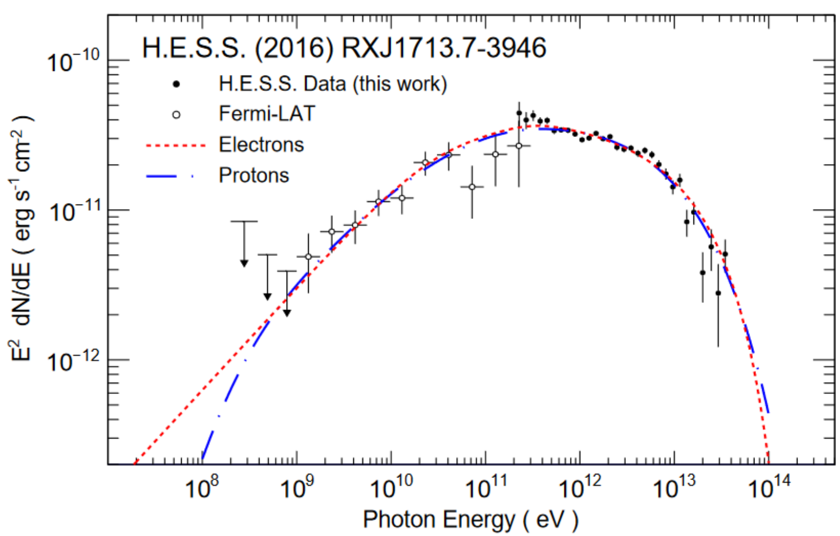
(c) Pion decay



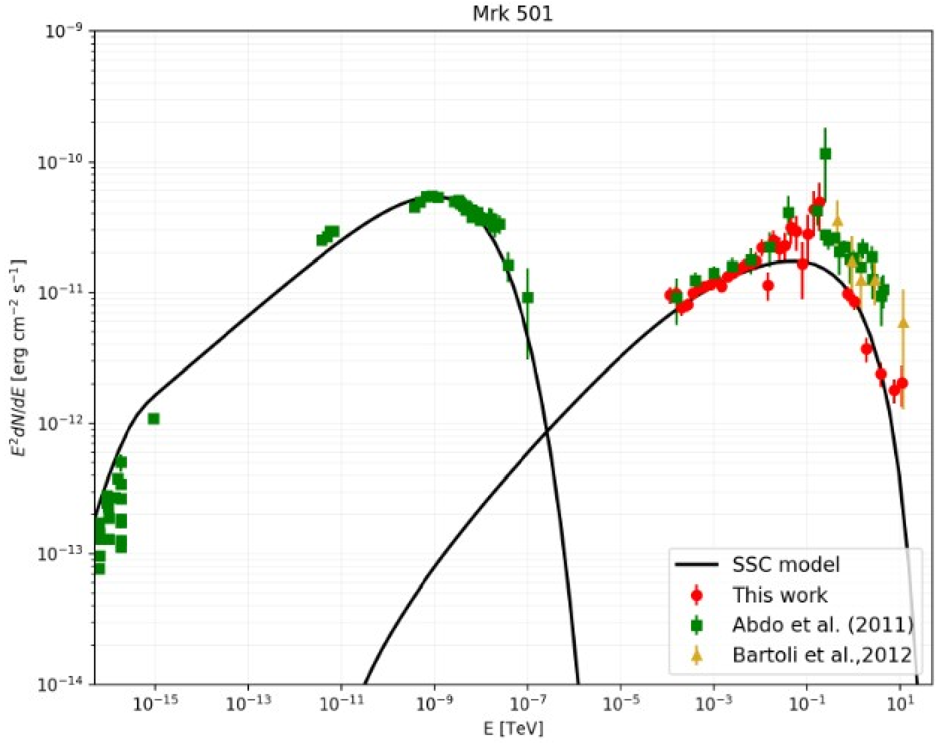
leptonic



(d) Inverse Compton



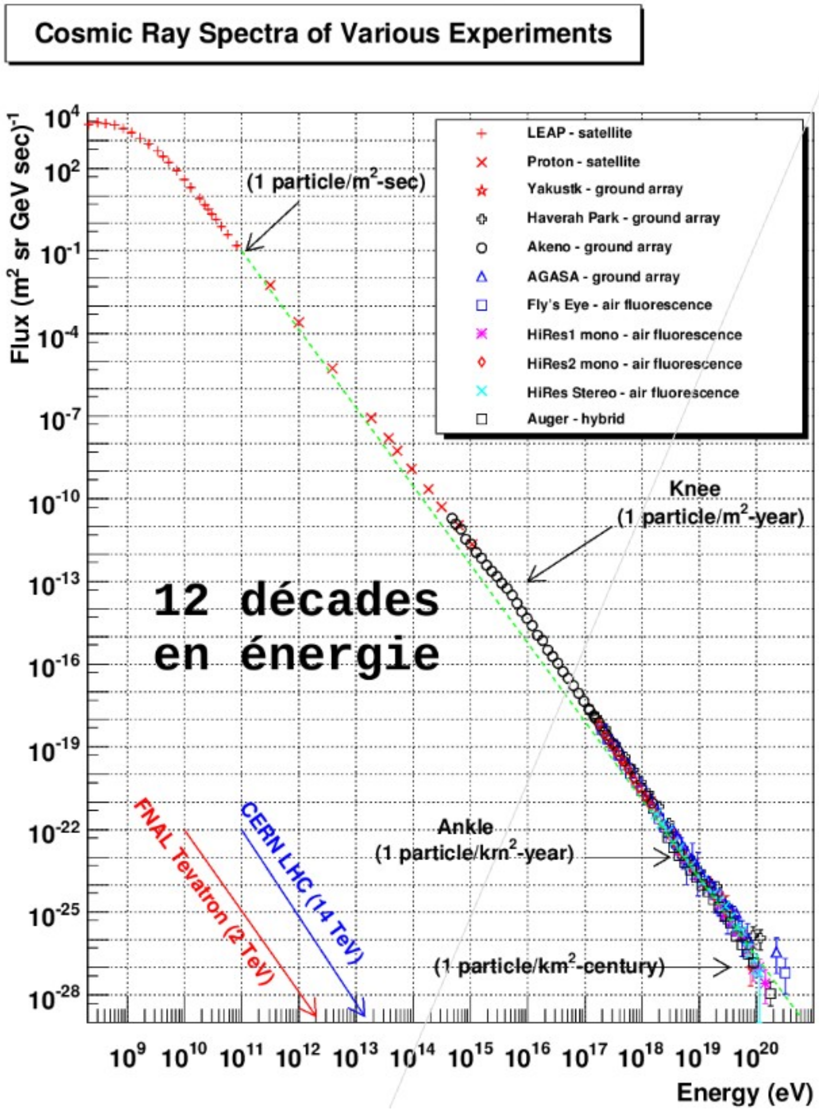
Gamma-ray production



- How to produce gamma rays ?
  - High energetic particles (accelarated charged particles)
  - and/or photon fields (Inverse Compton)
  - and/or magnetic fields (synchrotron)
  - and/or matter (p+p interactions)
- Two types of origin for the gamma-rays
  - Leptonic ($4*E_\gamma \sim E_e$), more efficient because high Lorentz factor (low mass)
  - Hadronic ($10*E_\gamma \sim E_p$), less efficient but should happen in dense regions

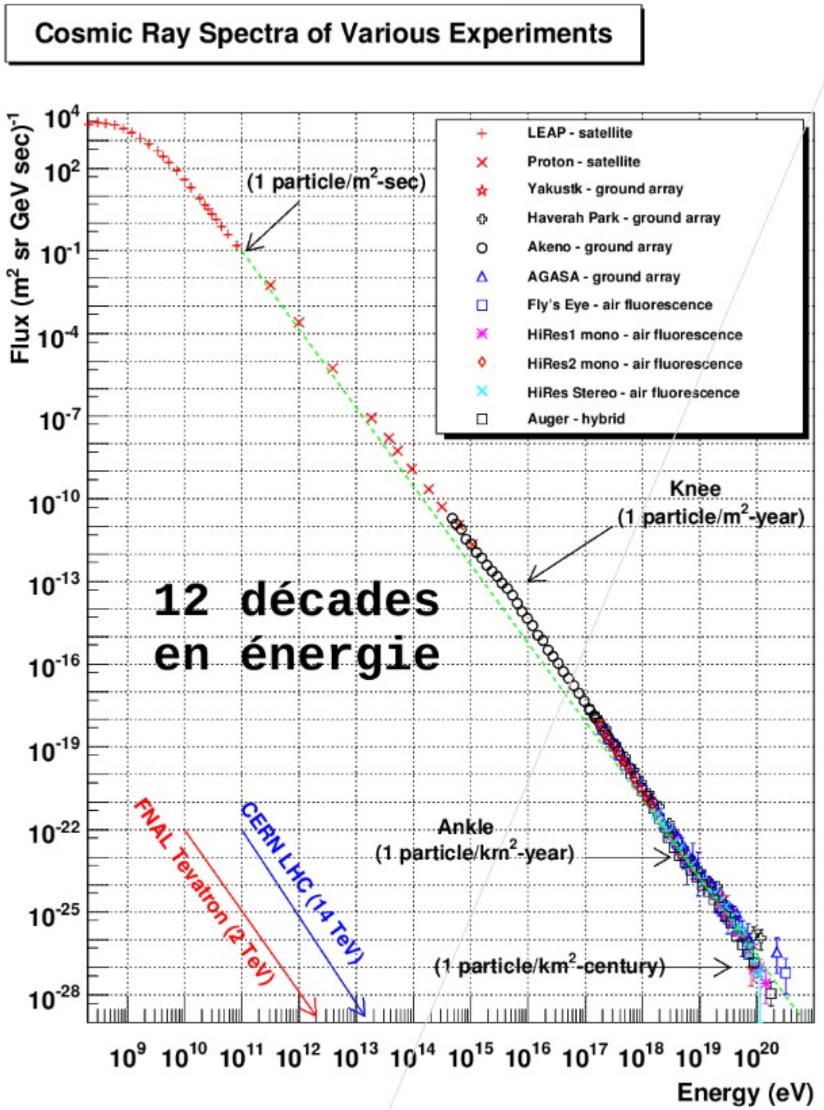
Cosmic rays

Cosmic Rays



- 12 decades in energy
- Power law distribution
- **Galactic origin below the knee**
- Principally hadronic for the galactic part
- **Extra-galactic origin** up to the ankle
- **Charged particles**
- **Isotropic (allmost)**
- Need natural particle accelerators

Power law



- Power law spectra :

Let's suppose a **multiplicative energy increases** after k process

$$E = \beta^k E_0$$

Let's add a **probability P to escape** after each step

$$N(\geqslant E) = N_0 P^k$$

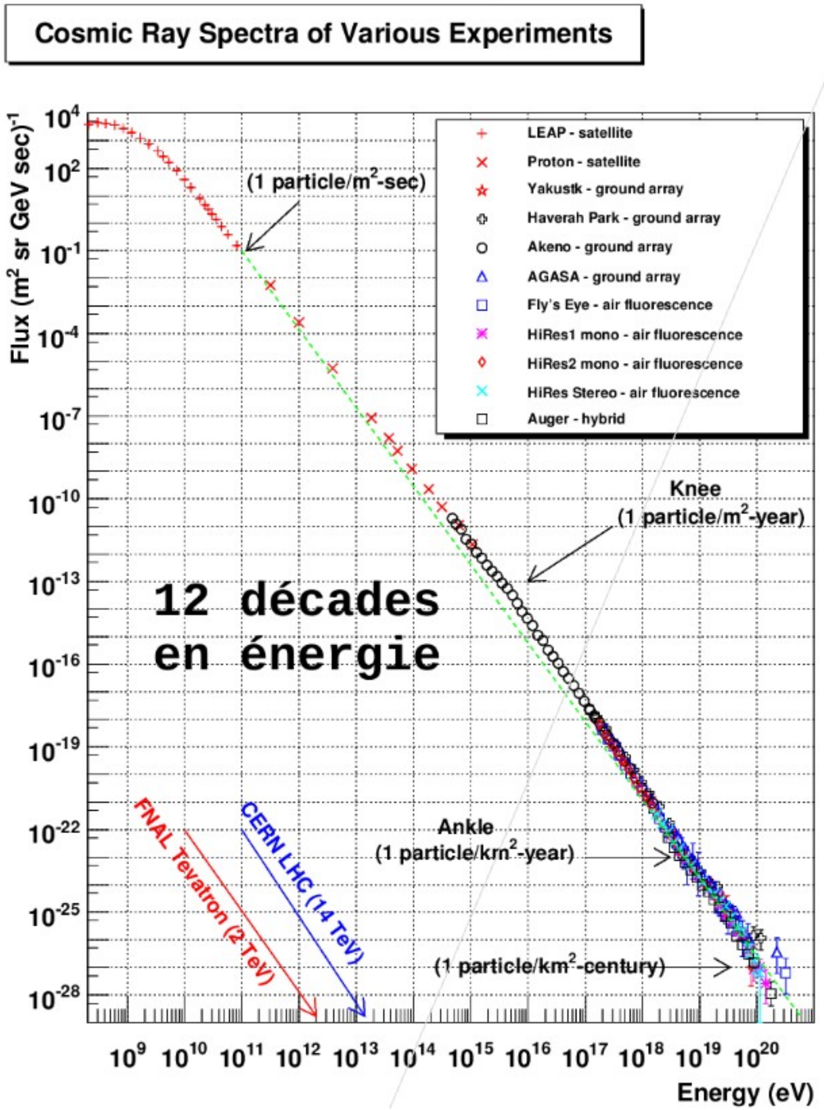
Let's combine them !

$$\frac{N(\geqslant E)}{N_0} = \left(\frac{E}{E_0}\right)^{\ln P / \ln \beta}$$

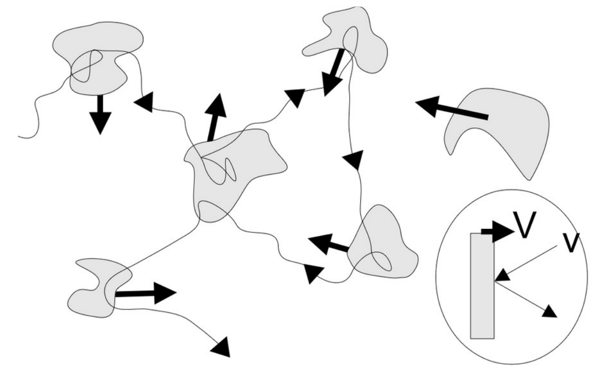
A **power law spectrum** emerges from these very simple assumptions :

- **Fermi acceleration**, stochastic collision with magnetic inhomogeneities or shock waves

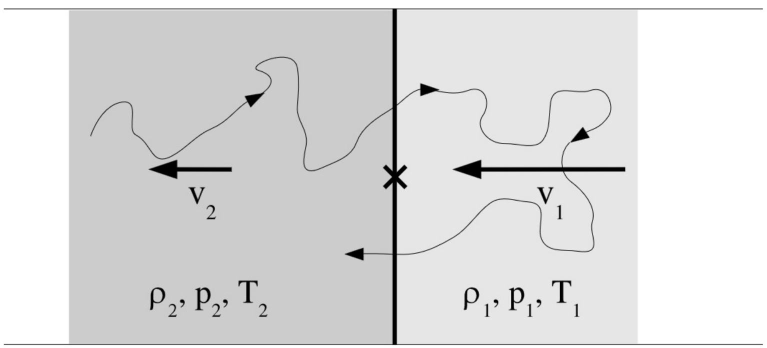
Power law



Second order Fermi acceleration

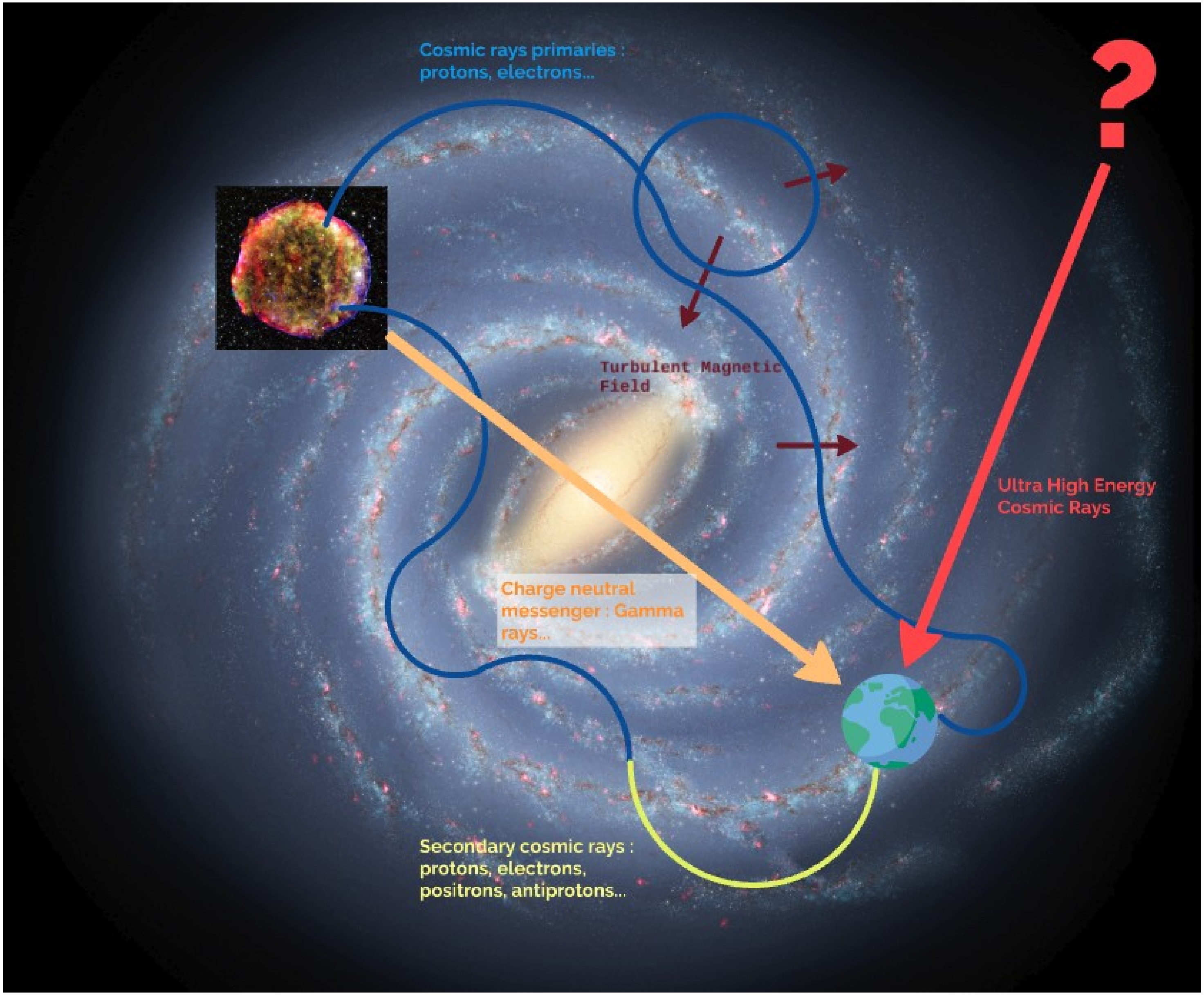


First order Fermi acceleration

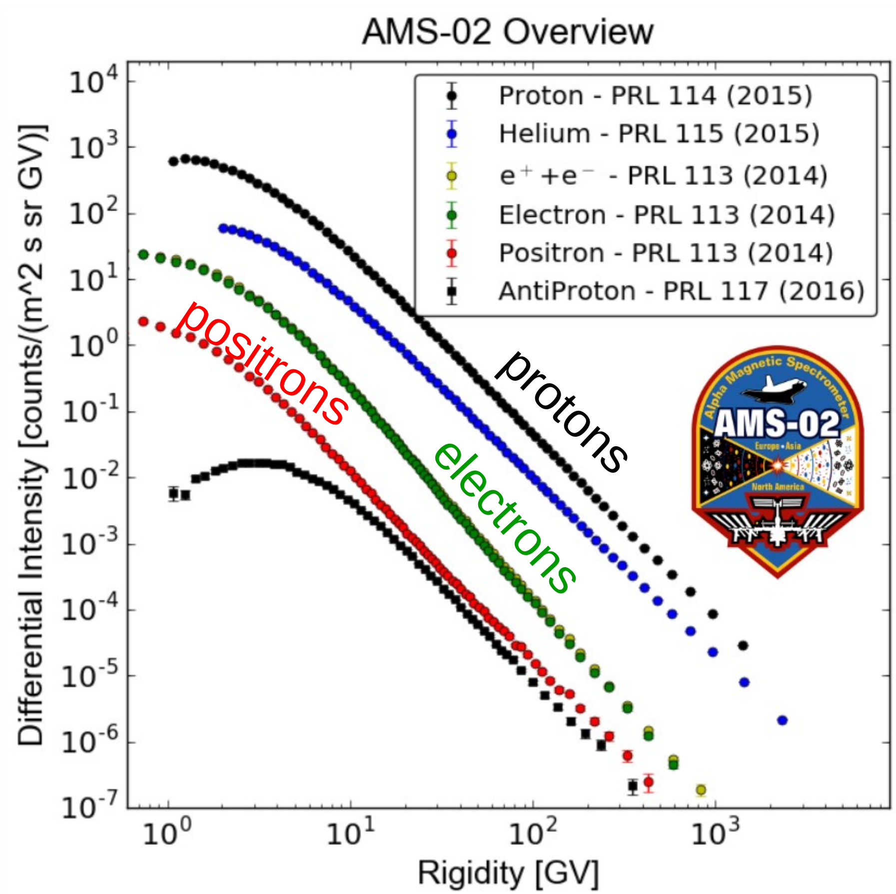


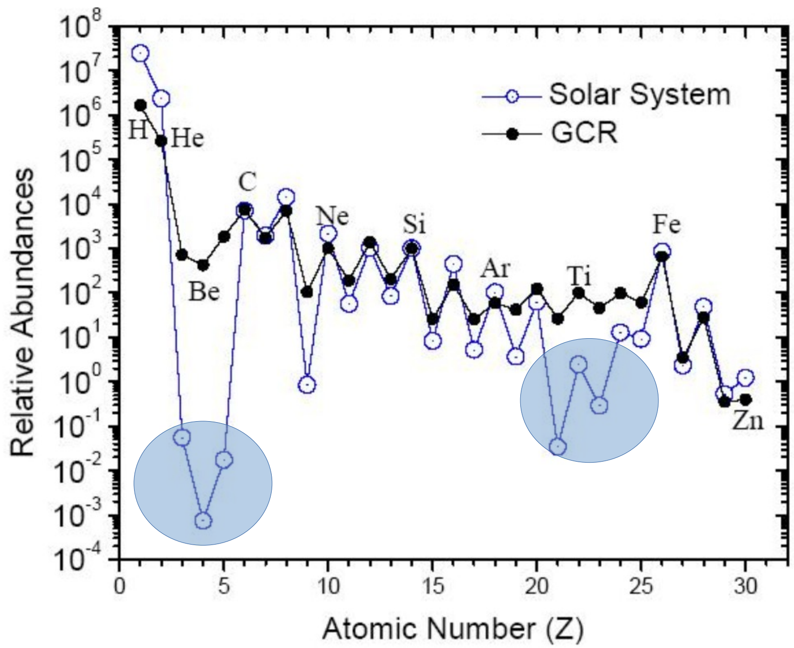
$$\left\langle \frac{\Delta E}{E} \right\rangle \propto \left(\frac{v}{c} \right)^n$$

Cosmic messengers



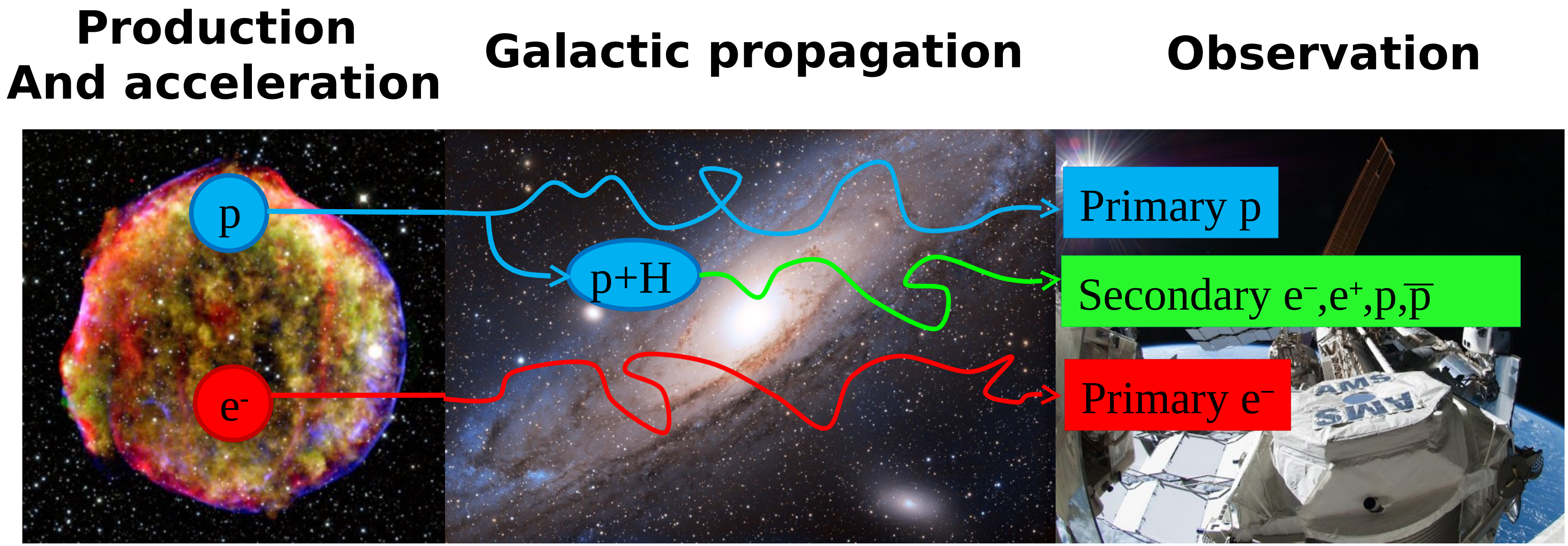
Galactic Cosmic rays





- **Composition** ~90 % protons ~10% helium ~1 % electrons ~0.1 % positrons → dominated by matter
- Difference in abundance compared to GCR due to spallation

Galactic cosmic rays

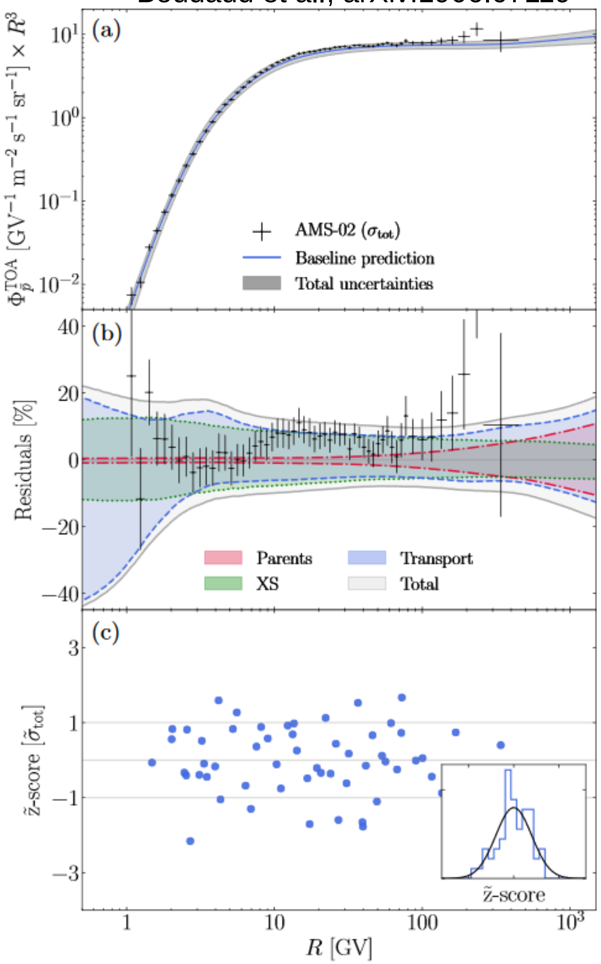


- Accelerator accelerates surrounding **Interstellar medium matter**
- Galactic diffusion due to **turbulent magnetic field**
- Detection at Earth → **primary CR**
- **Interaction with interstellar medium** → production of secondary cosmic ray
- Mainly **p+H collisions** permit to **enrich the cosmic rays with antimatter**

Secondary antimatter flux at Earth

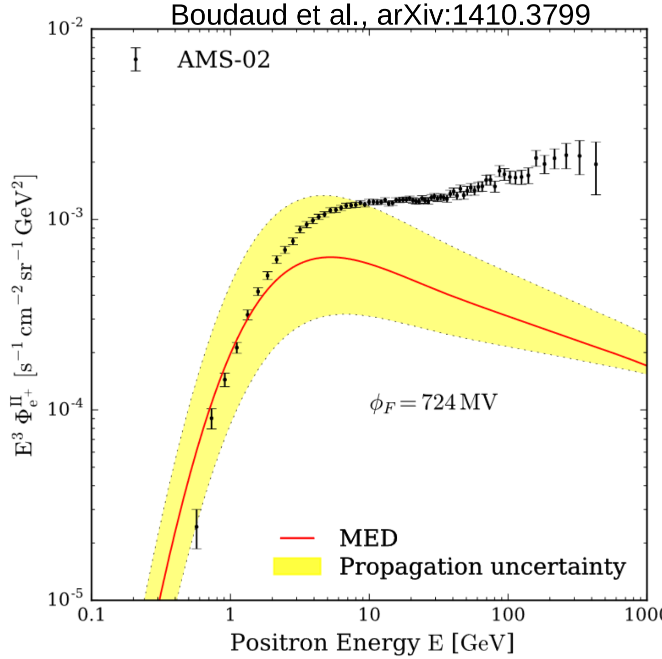
Antiprotons

Boudaud et al., arXiv:1906.07119



Positrons

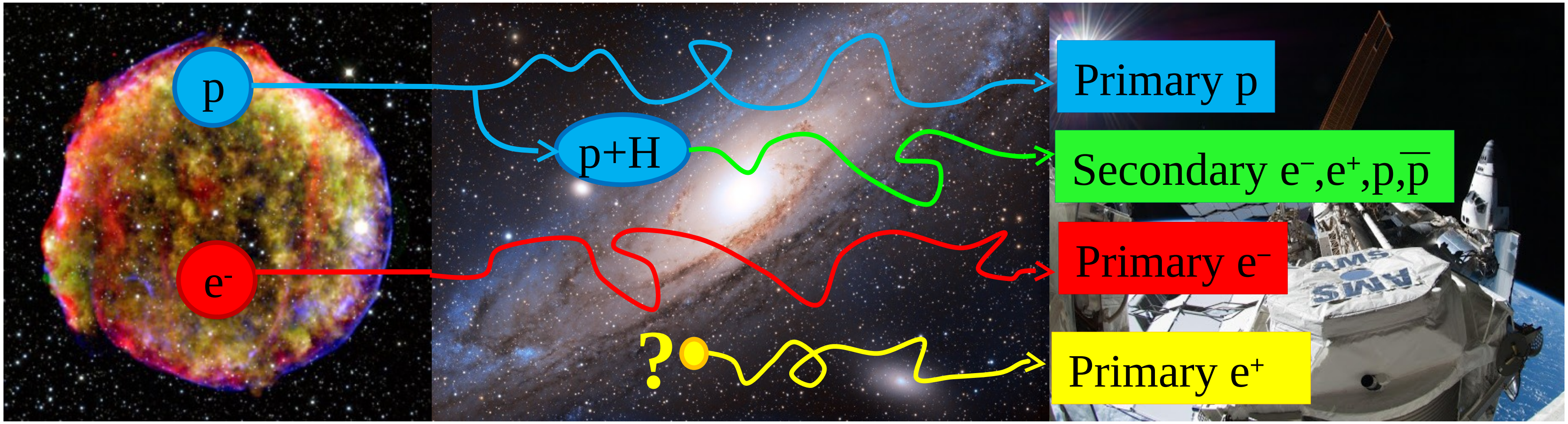
Boudaud et al., arXiv:1410.3799



- Secondary production explain well the amount of antiprotons in the cosmic rays…
- …But fail to explain the amount of positrons for E>10 GeV
- This is the so-called positron excess

Primary positrons ?

Production And acceleration | **Galactic propagation** | **Observation**



- Local source of positrons ?
- Local because of electron cooling

Hillas criteria

$$Z\left(\frac{r_L}{33km}\right)\left(\frac{B}{1G}\right)=\frac{E_{max}}{1GeV}$$

- To accelerate particles, accelerator need to confine magnetically the particle up to the escape energy
- Two types of efficient accelerators :
  - Big accelerator with low magnetic fields
  - Compact accelerators with strong magnetic fields
- Can be translated to a typical time

$$\frac{r_L}{c}=t_L$$

- Let’s take value of the order of our galaxy (1 kpc, 1µG)
  - E = $3*10^{19}$ eV, t = 3.2kyr
- What about a pulsar ? (30 km, 10^{12} G)
  - E = 10^{21} eV, t = 100 µs
- But this formula ignore cooling of charged particle !
- Slow accelerator (galactic halo here) will be more affected by cooling ! Leptonic accelerators as well !
- In general, it make compact objects with strong magnetic fields efficient acceleration sites

Implication for gamma-rays

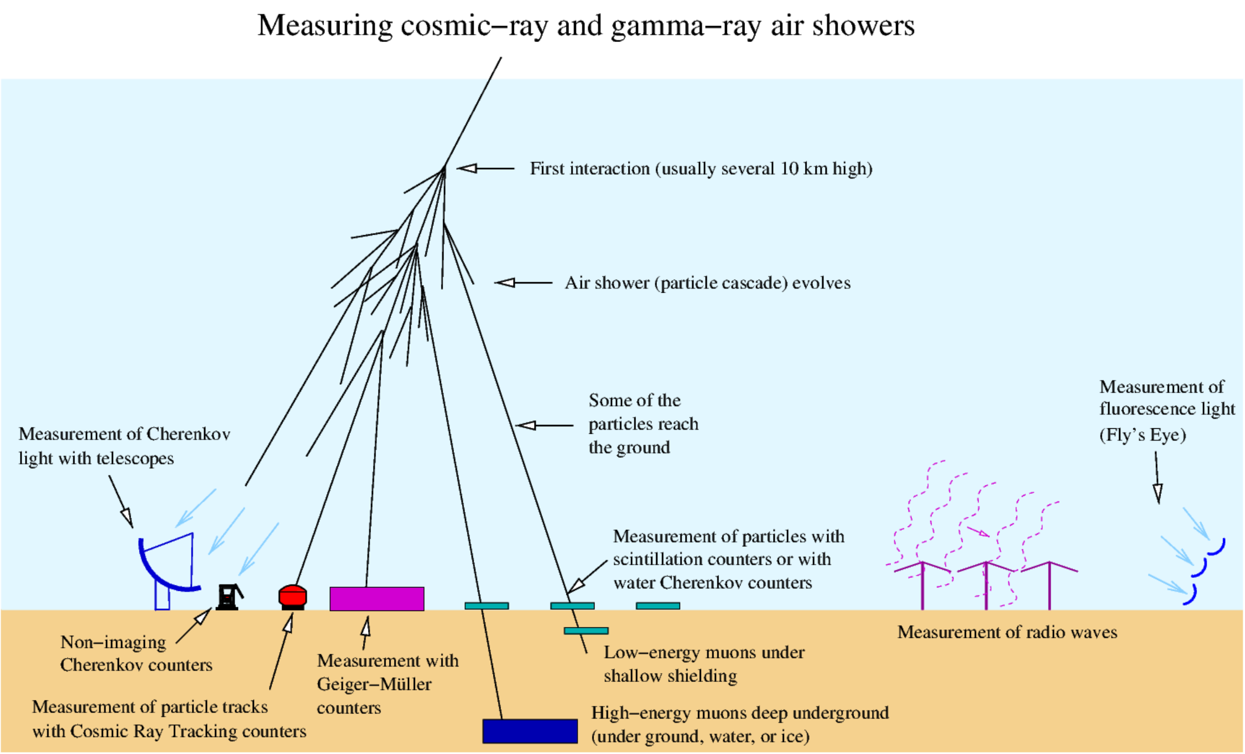
- Leptonic accelerators are believed to be more bright in gamma-rays (Lorentz factor dependency)
- According to galactic cosmic rays, it exists hadronic accelerators in our galaxy, and those accelerators should accelerate up to at least ~1PeV (translated to gamma-ray 100 TeV !)
- According to positron excess in the cosmic rays, it exists leptonic accelerator producing as well antimatter
- It should exists even more extreme accelerators than 1PeV ones (but probably different of the galactic ones)...
- Compact objects with strong magnetic fields can be efficient accelerators (and so should shine in gamma-rays)...
- … of course it is not enough to be compact, we need to have an engine to accelerates the charged particles
- Last but not least, the more compact the acceleration site, the faster acceleration should be (and possibly variability in the gamma ray flux) !
- Direct implication is : compact sources should be more variable, “big” sources should be more static

Gamma-ray observation

Detection methods

- **Direct detection :**
  - Gamma ray interact with atmosphere → only visible in space
  - Power law → Big surface is needed → but limited in space (weight)
  - Fermi Energy range : 20 MeV – 300 GeV

- **Indirect detection** :
  - Atmospheric shower detection
    - **Cherenkov light** (blue, UV)
    - **Radio**
    - **Charged Particle** (scintillation, Water Cherenkov)
    - **Fluorescence** (UV)



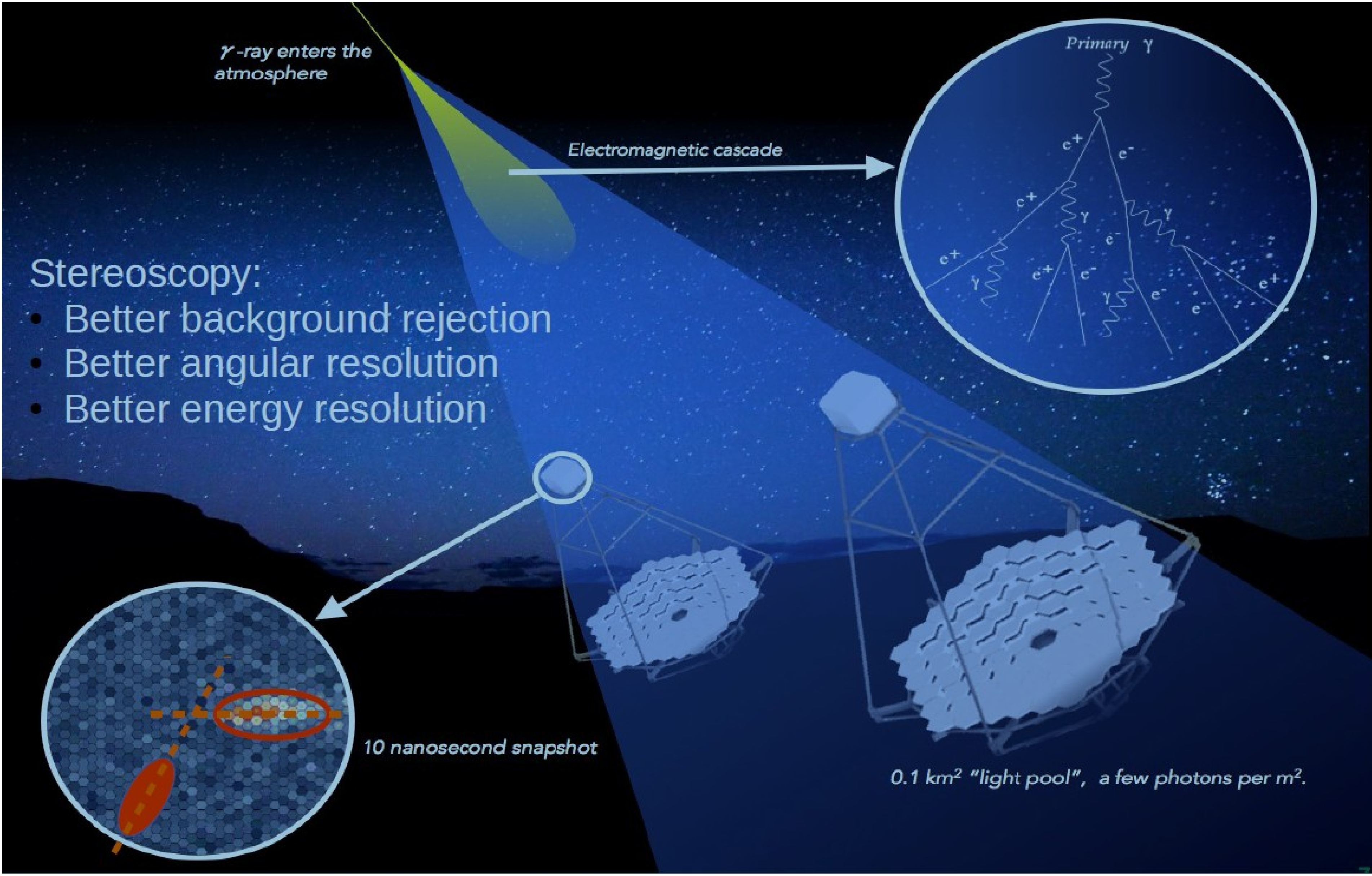
Indirect detection of gamma rays

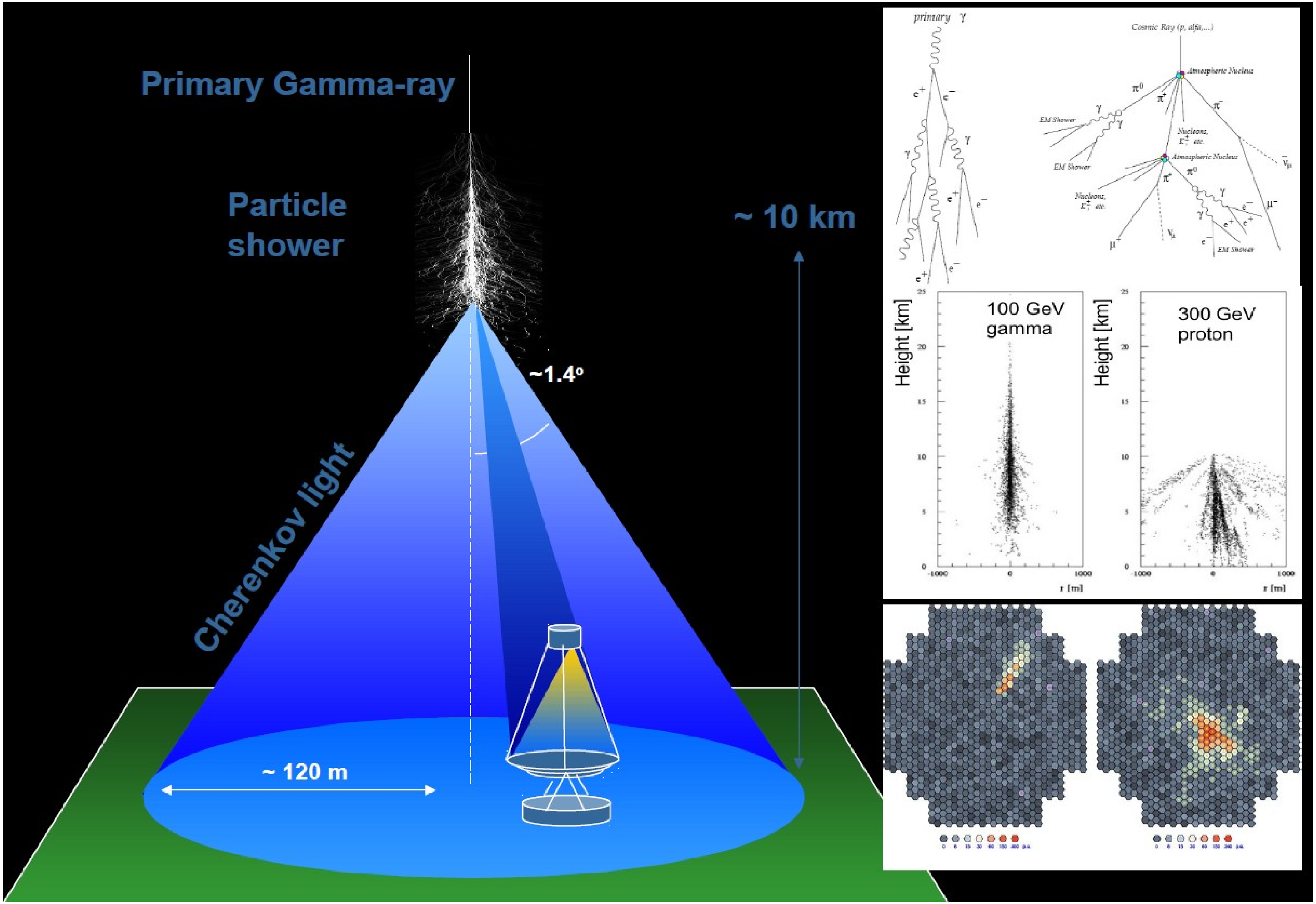
- **IACTs → Imaging Atmospheric Cherenkov Telescope**
- Cherenkov light produced in air
- **Pro :**
  - Good precision in terms of angular resolution (~0.1°) and energy resolution (~10-15%)
- **Cons :**
  - Narrow field of view (~5°)
  - Night observation, affected by weather and full moon (and light pollution in general)

- **Water Cherenkov Array**
- Secondary particles cherenkov in water tank
- **Pro :**
  - Vast field of view (15% of the sky)
  - Can work 24/24 7/7
- **Cons :**
  - Less precise in terms of angular resolution (0.75° @ 1 TeV, 0.3° @ 10TeV) and of energy resolution (95% @ 1TeV, 50% @ 10TeV)

Detection principle

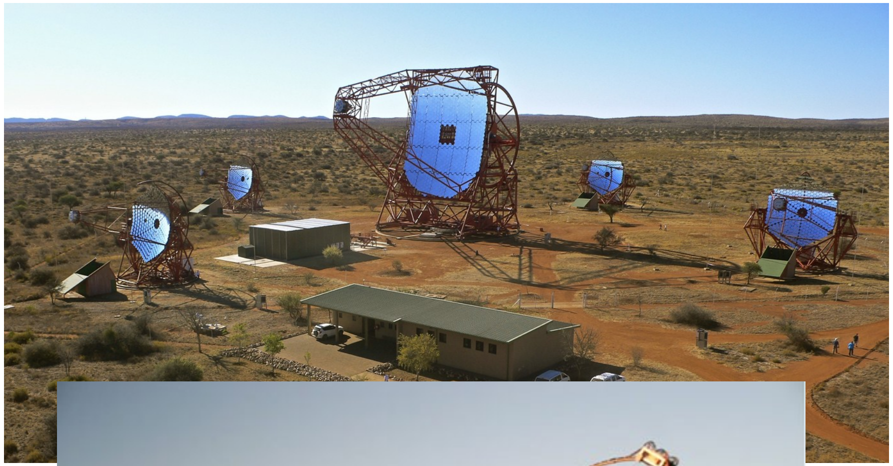
Stereoscopy:
- Better background rejection
- Better angular resolution
- Better energy resolution





Primary Gamma-ray
Particle shower
~ 10 km
~1.4°
Cherenkov light
~ 120 m
100 GeV gamma
300 GeV proton
Height [km]
r [m]

Observatories



H.E.S.S.

- Namibia (South Hemisphere)
- 5 telescopes (28m + 12m)

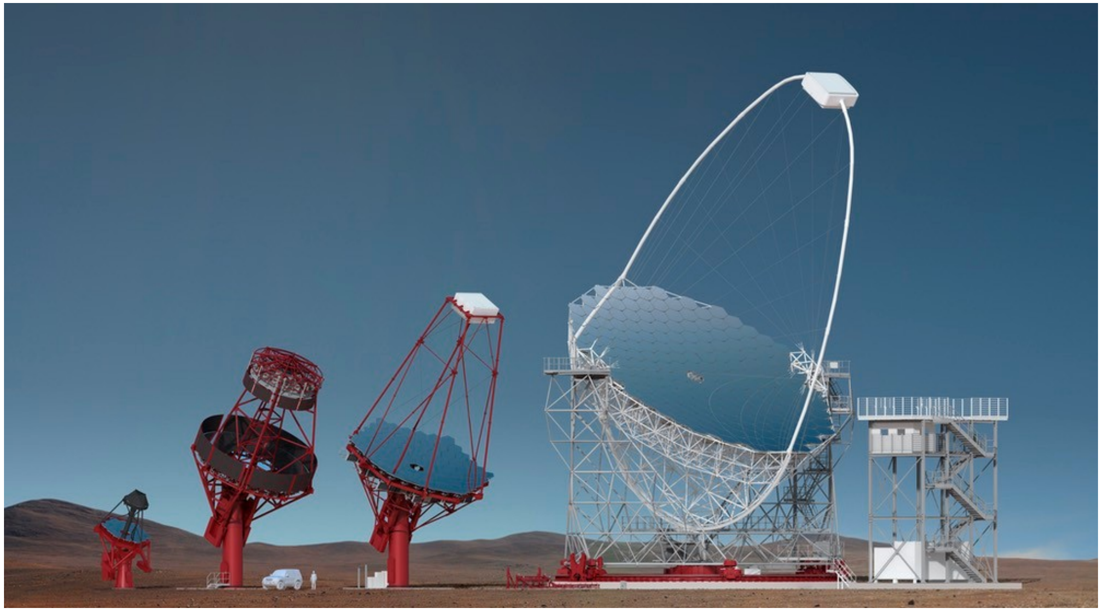
MAGIC

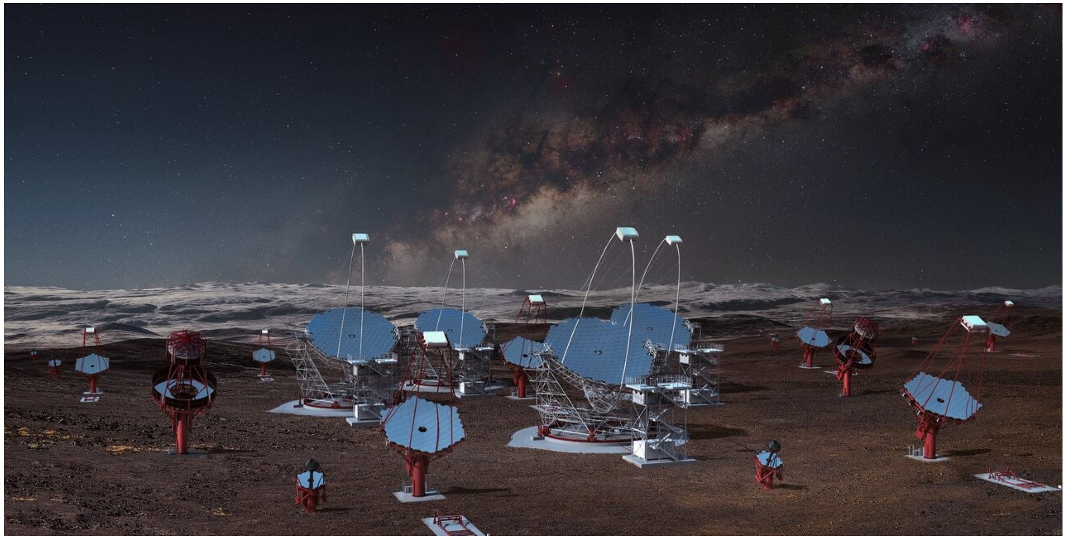
- Canarie Island, La Palma (North Hemisphere)
- 2 telescopes (17m)

VERITAS

- Arizona (North Hemisphere)
- 4 telescopes (12m)

Future observatory - CTAO

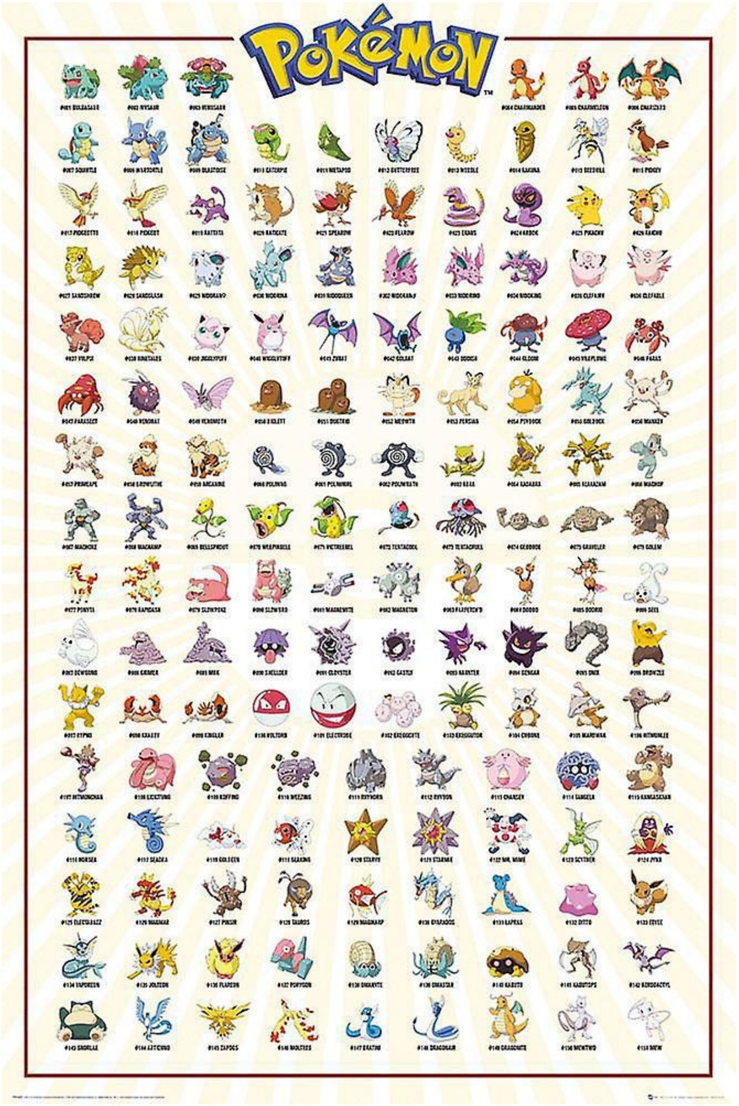




- 3 types of telescopes :
  - LST (23 m)
  - MST (12 m)
  - SST (4.3 m)
- Optimized for various energies :
  - 20 GeV – 3 TeV
  - 80 GeV - 50 TeV
  - 1 TeV - 300 TeV
- ~100 telescopes on two sites :
  - La Palma (hémisphère Nord)
  - Paranal (hémisphère Sud)

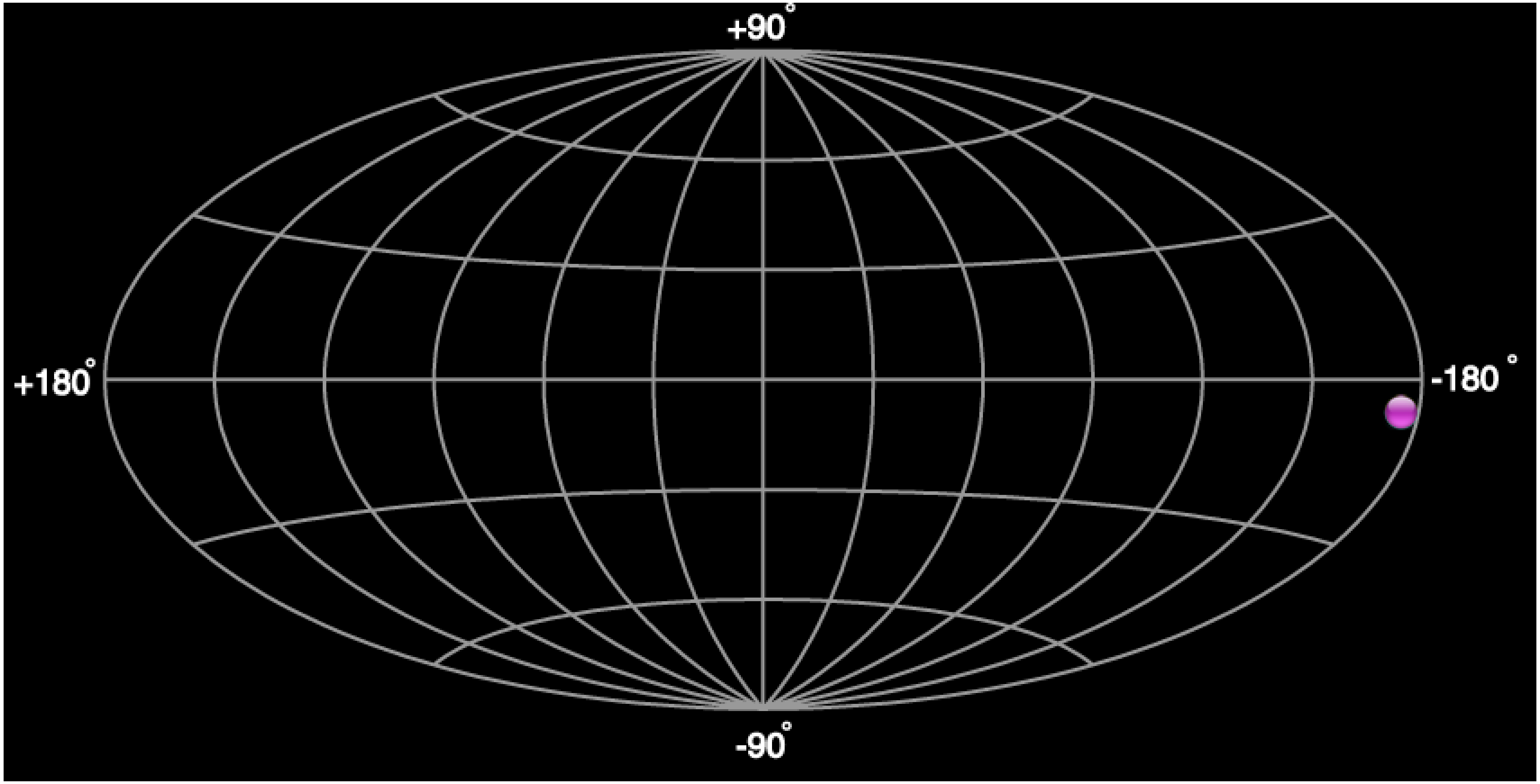
LAPP

Bestiary of gamma ray astronomy



Sources

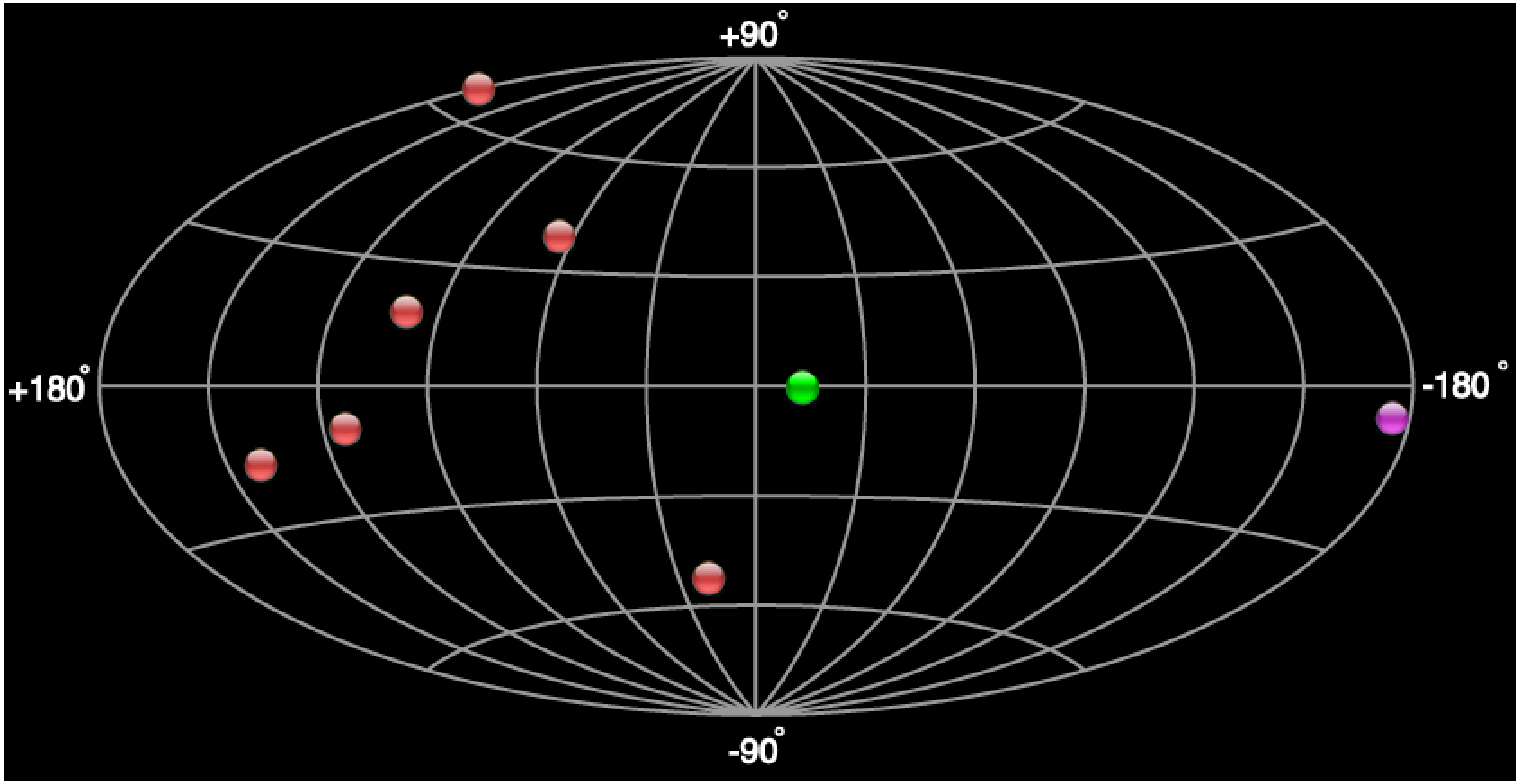
1990



http://tevcat.uchicago.edu/

Sources

2000



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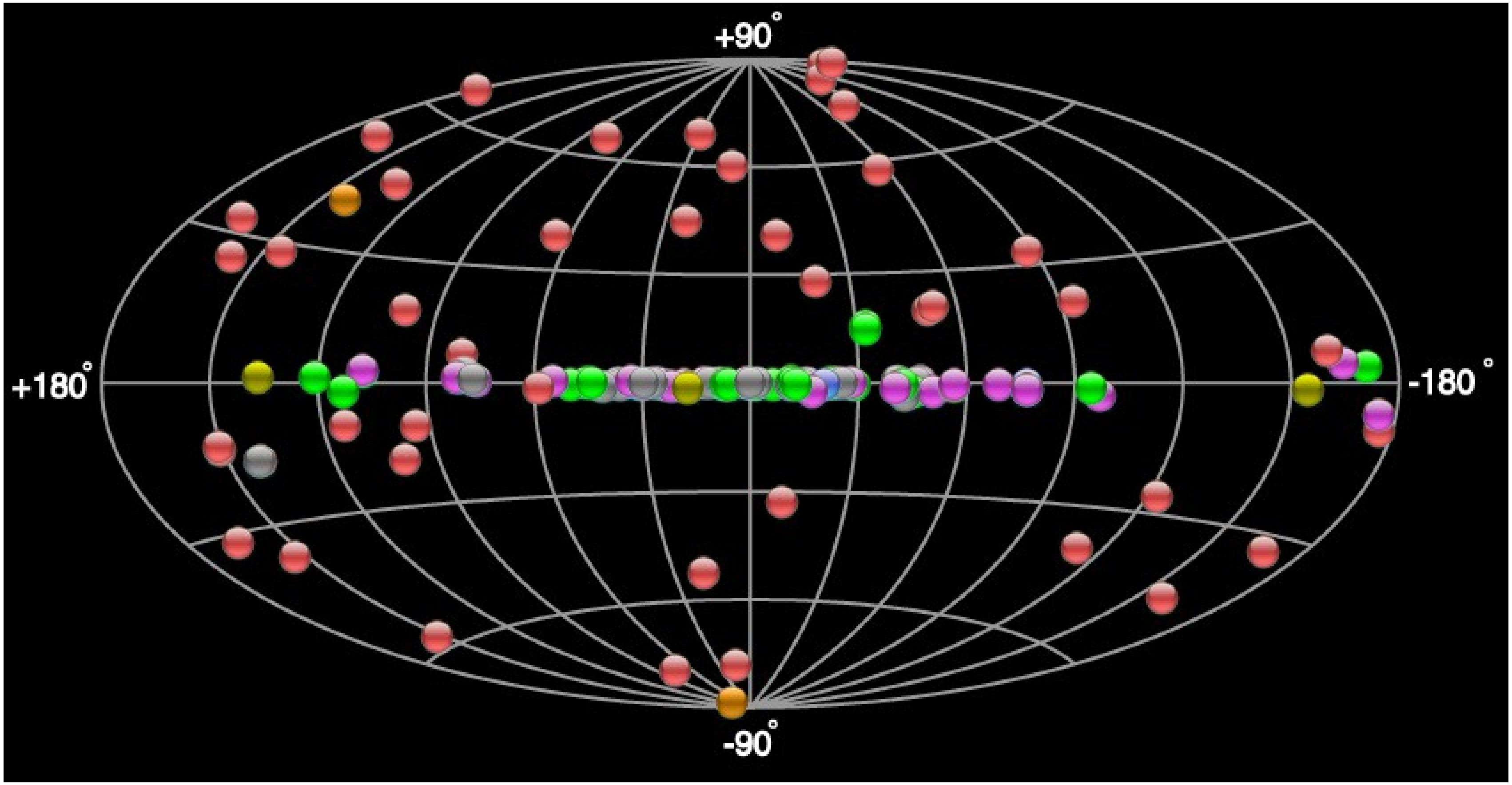
Sources

2010



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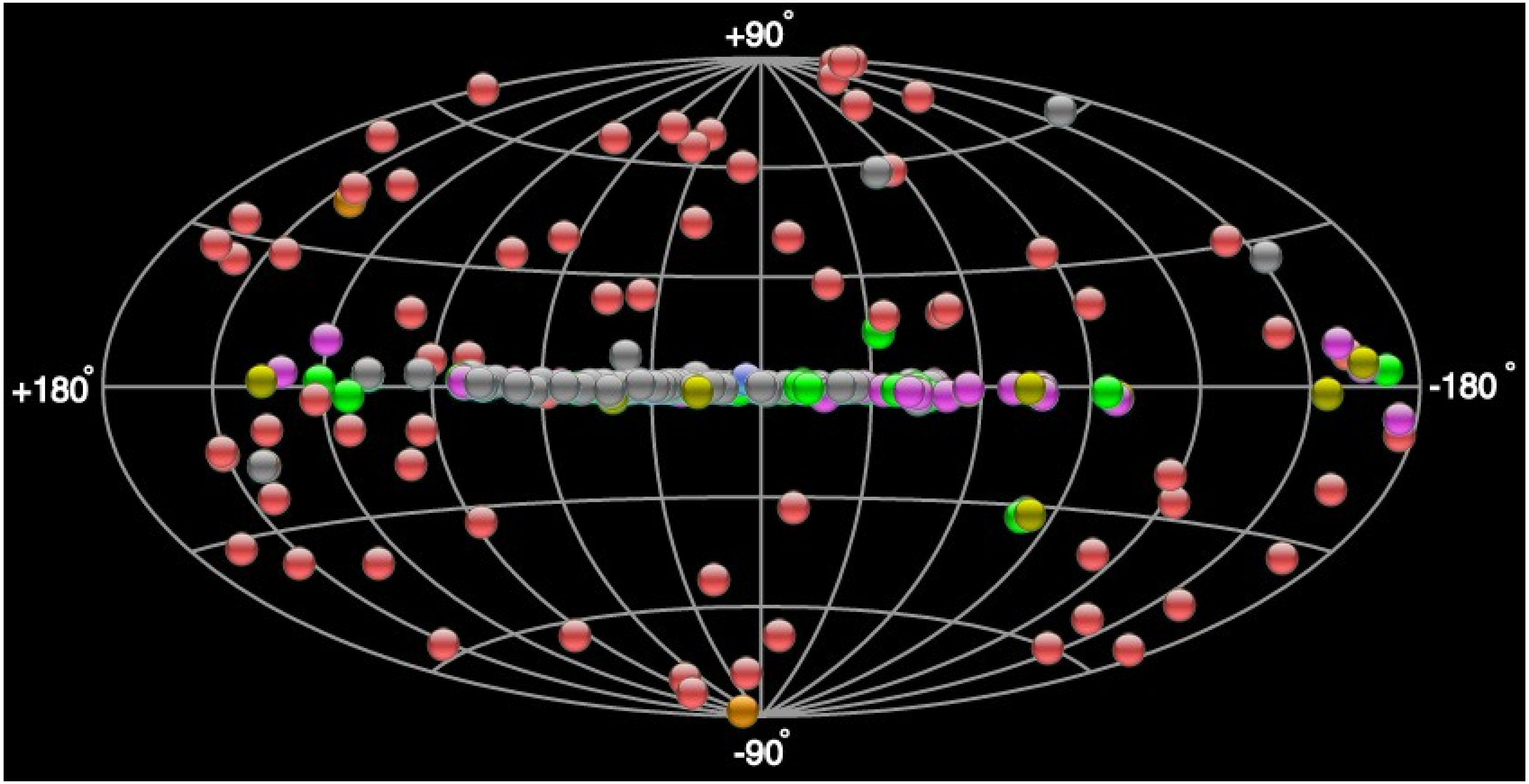
Sources

2021



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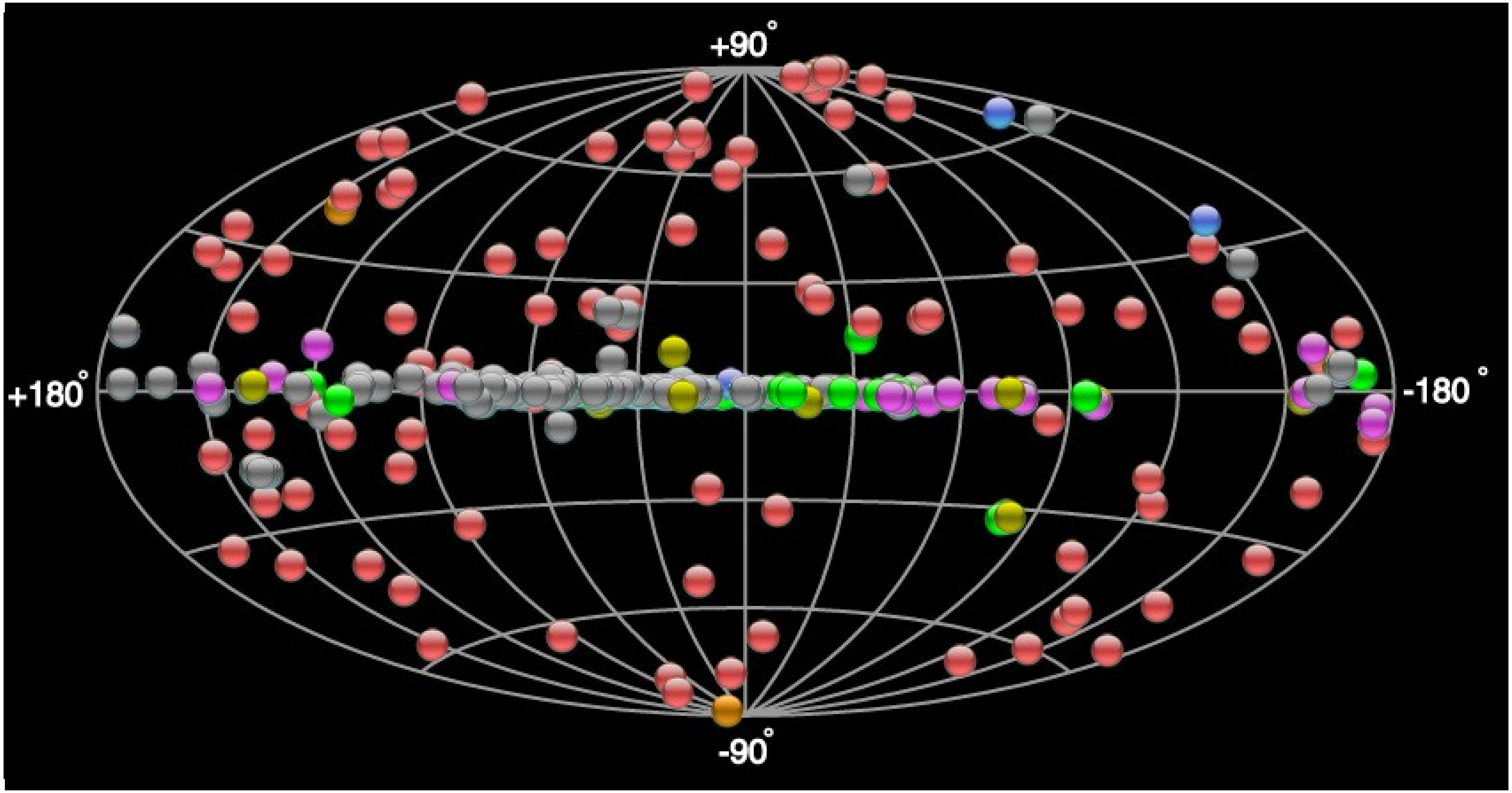
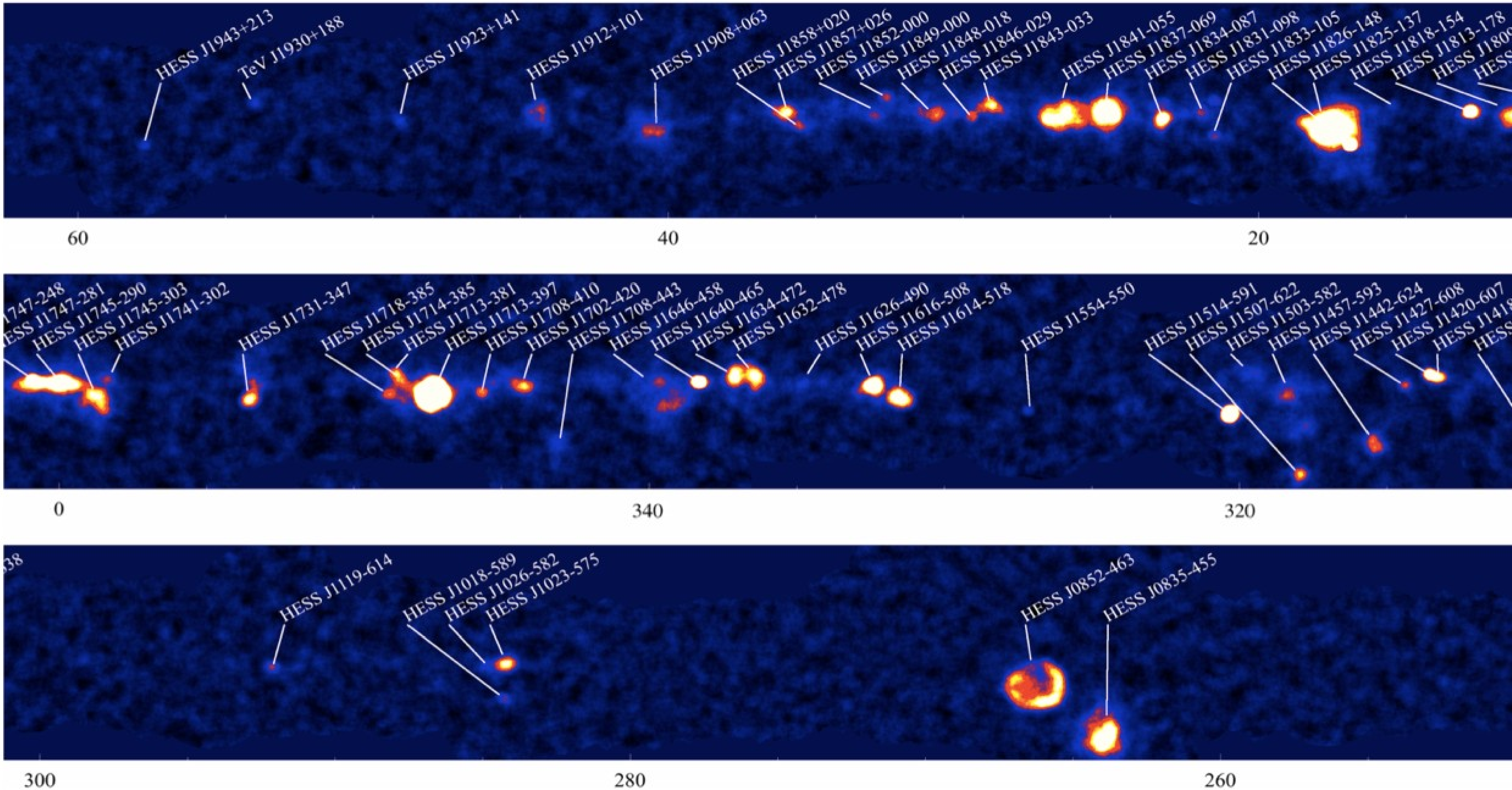
Sources

2024

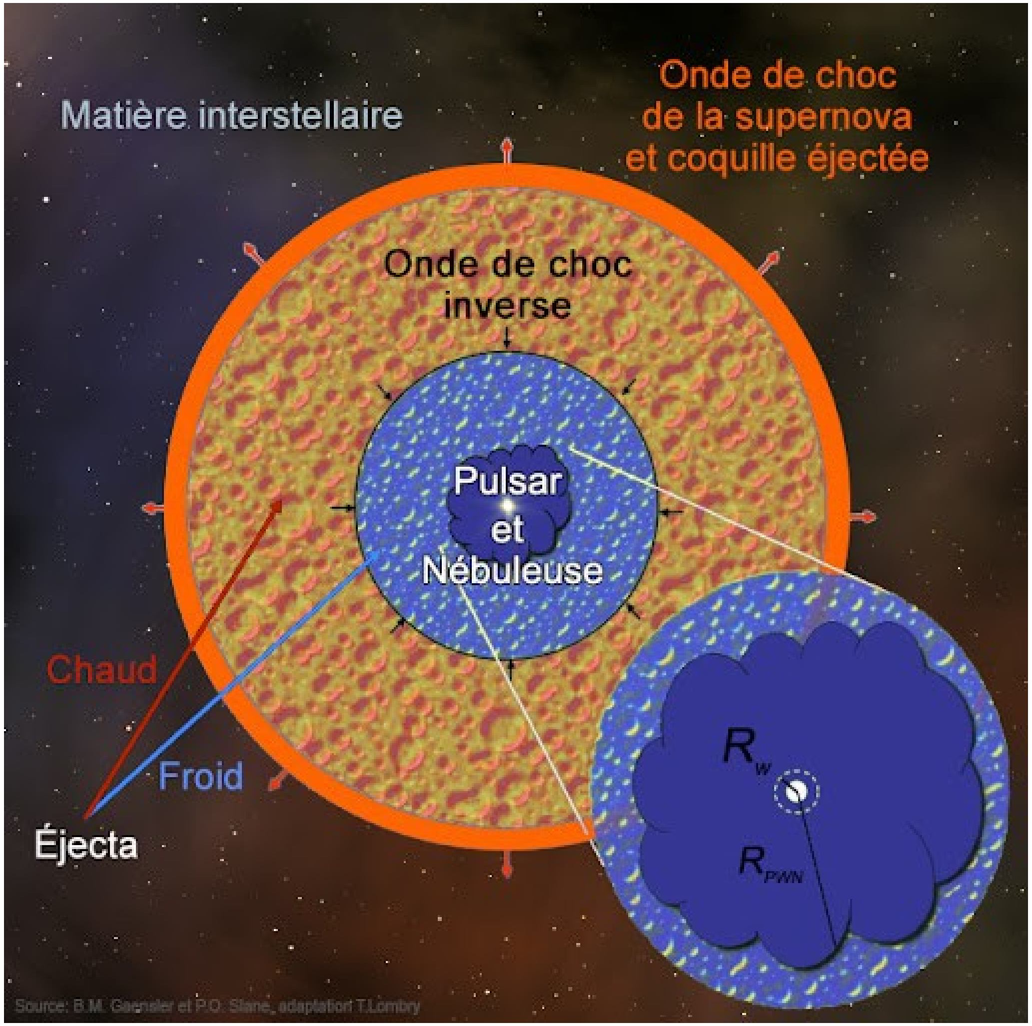


http://tevcat.uchicago.edu/ 308 sources



- **Galactic plane as seen by H.E.S.S.**
- **Direct image of galactic cosmic ray accelerators**

Supernova remnant and pulsar wind nebula

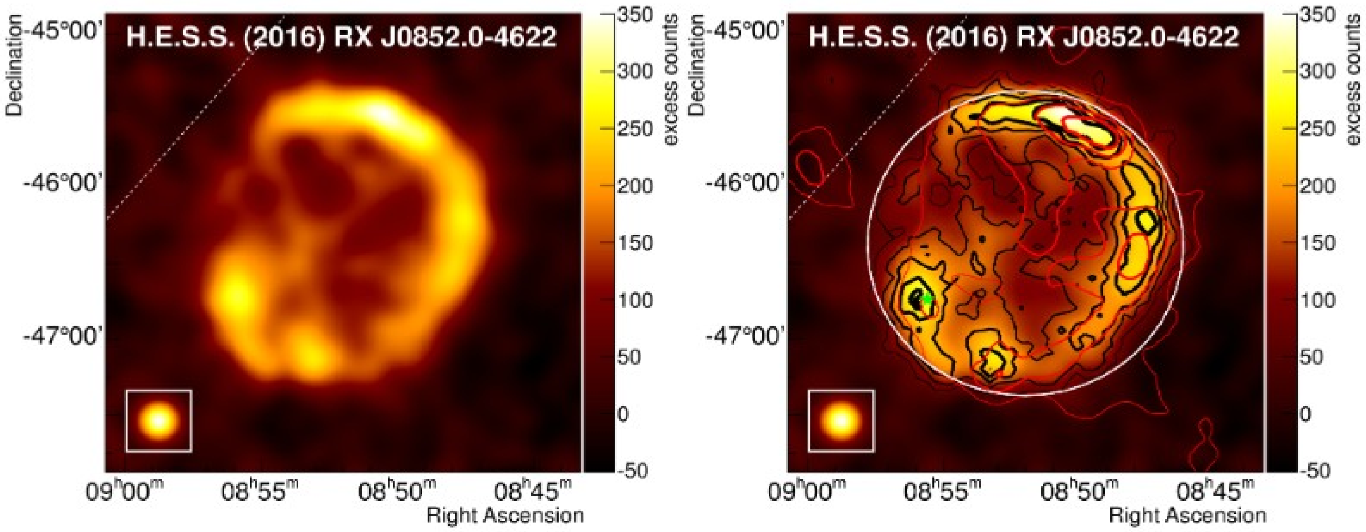


- Explosion of massive star due to exhausted source of energy
- Shock wave + compact core (neutron star)
- Insterstellar matter accelerated by shock wave →supernova remnant
- Leptonic production by the pulsar (rotating neutron star + strong magnetic field)→ pulsated emission + pulsar wind nebula

Supernova remnant

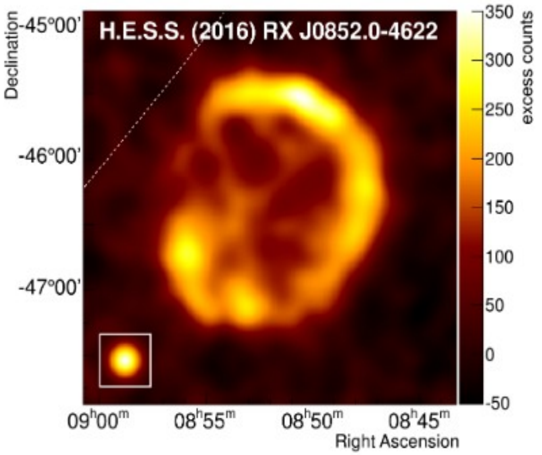
RXJ0852.0-4622

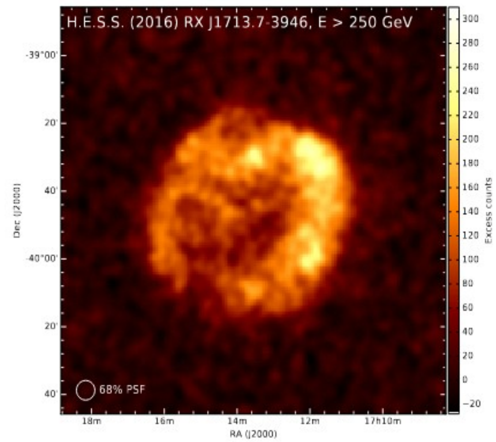
https://hal.archives-ouvertes.fr/hal-02410561/document

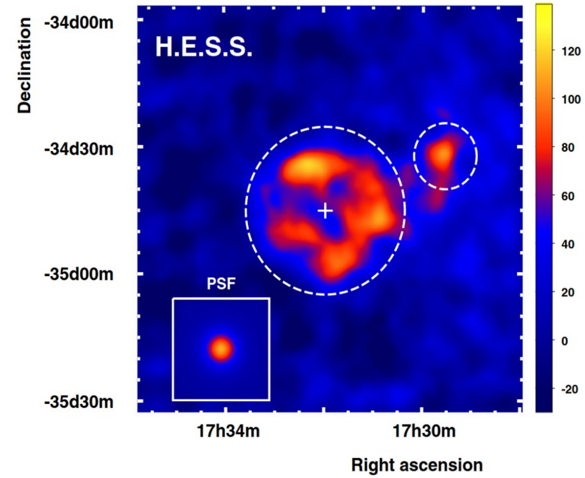


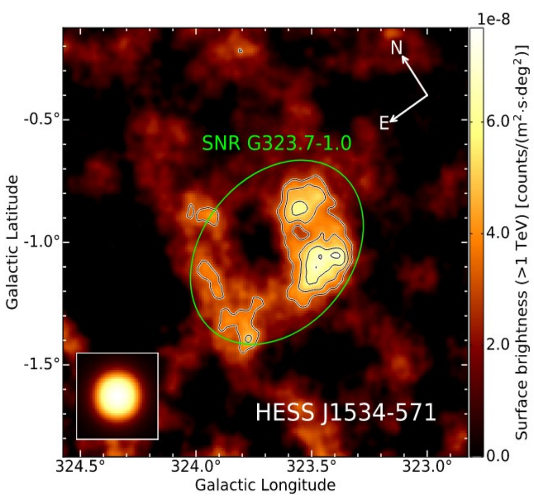
- **Shell like shape smocking gun for supernova remnant (allowed by the good angular resolution of the instrument)**
- **Correlation** of X-ray and gamma-ray (presence of **shock wave** and **highly energetic particles)**
- Open questions :
  - Able to accelerate **up to PeV (100 TeV gamma-rays)** ?
  - Dominance of **leptonic** or **hadronic** ? (cosmic rays are mostly hadronic)
  - Difficult to answer only with gamma-rays, neutrinos can be of great help

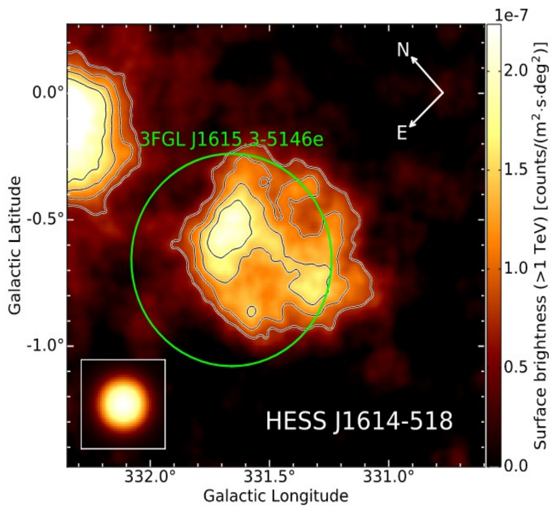
Supernova remnant

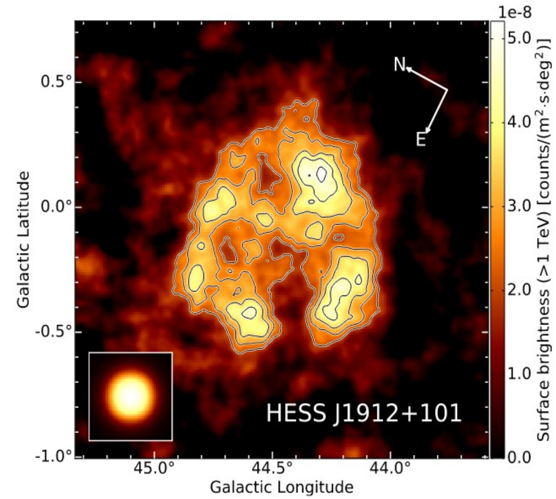




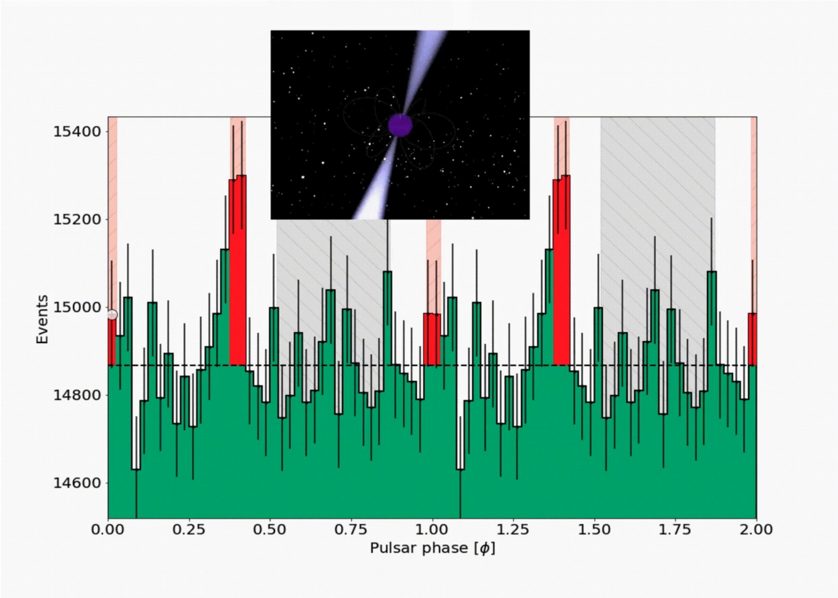


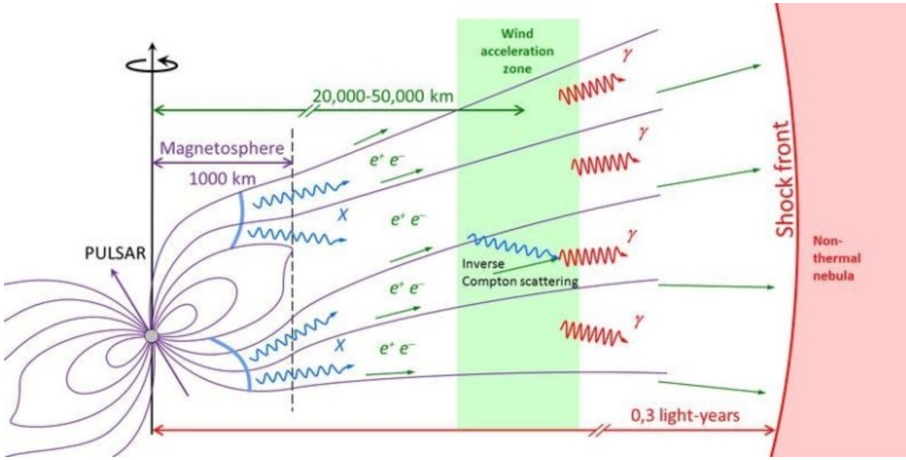






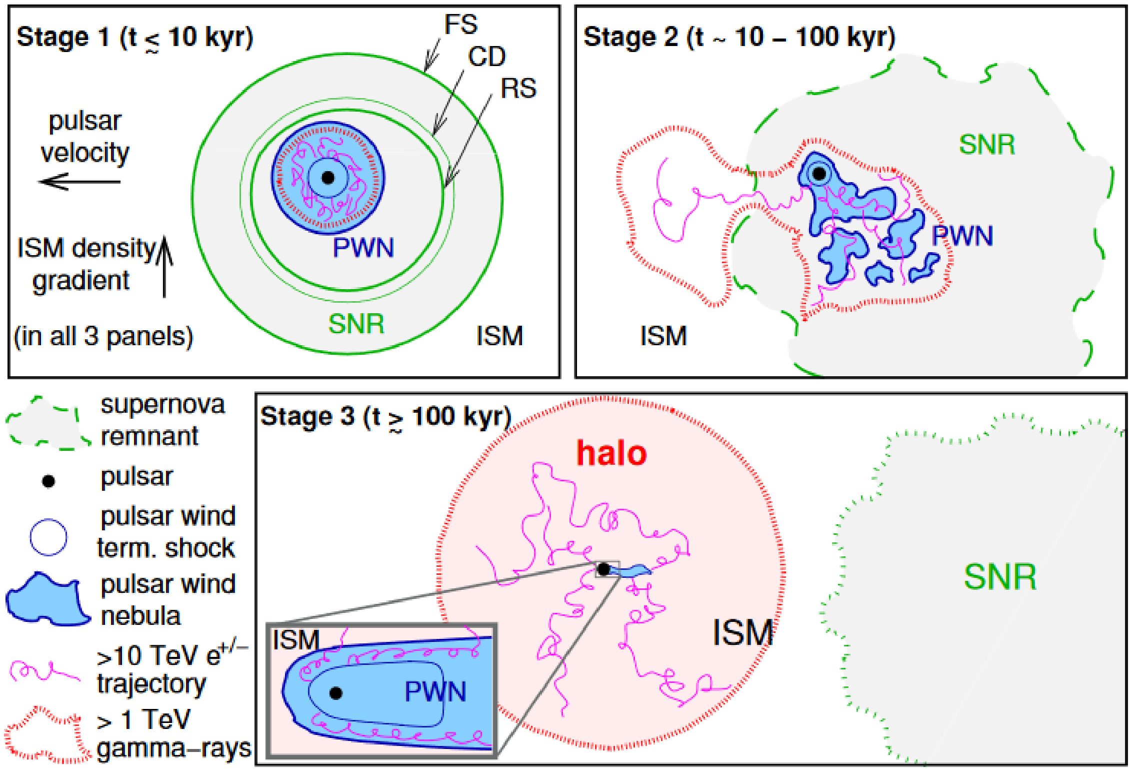
Pulsars



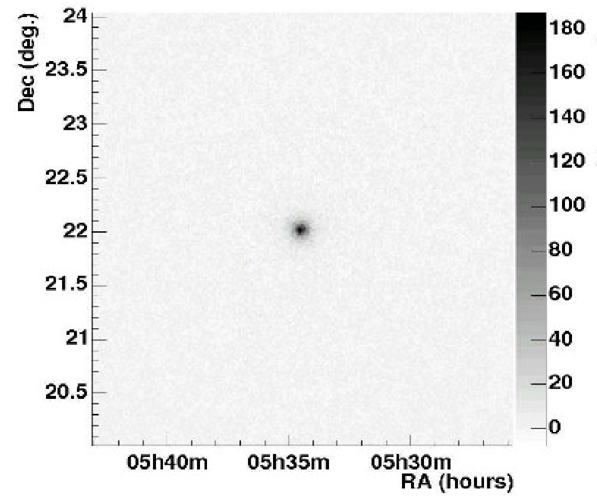


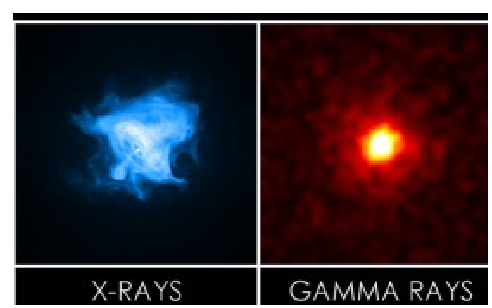
- Strong electric field at the surface of the neutron star due to rotating magnetic field
- Charged particle accelerated, pair production (leptonic)
- Crab pulsar period ~33 ms, pulsated emission permits to compute the rotational speed (and so on the rotational energy of the pulsar for example)

Pulsar wind nebulae - halo



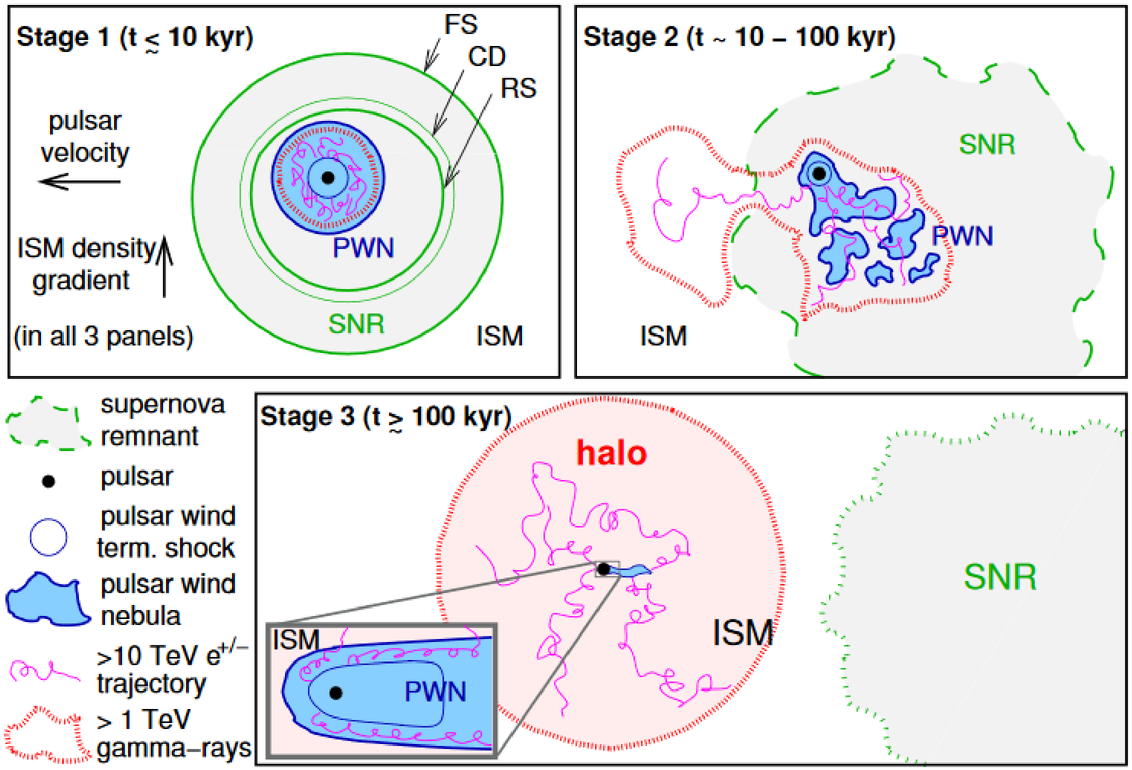
Crab Nebula
~1000 years



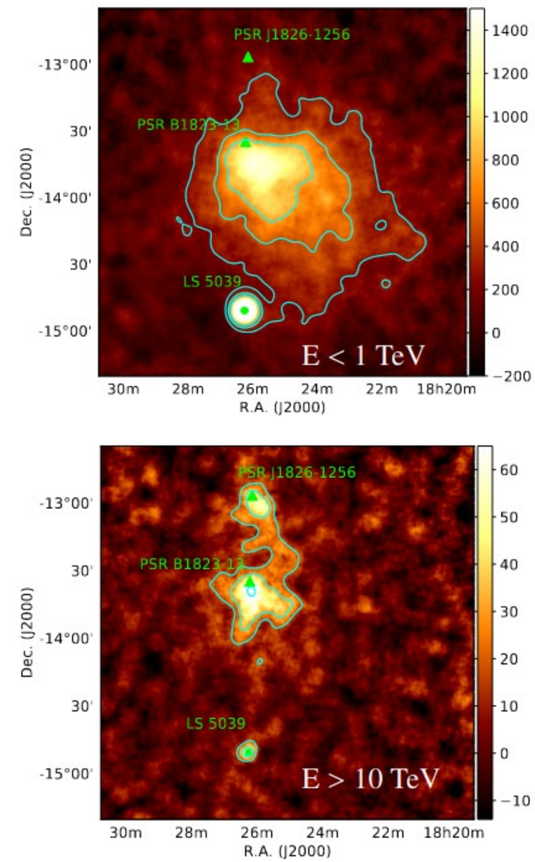


- Associated with the historic supernova SN1054
- Stable and bright
  - Nebula stable because because of its size (11 ly)
  - Bright because leptonic

Pulsar wind nebulae - halo



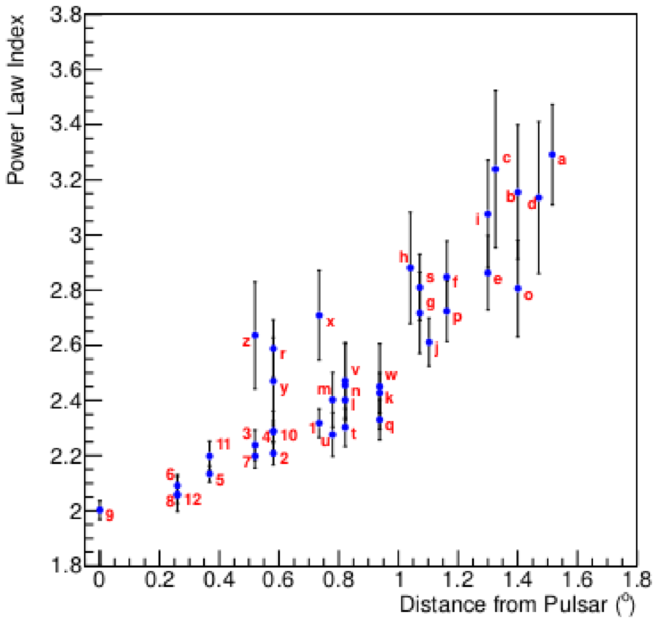
HESS J1825-137
22000 ans

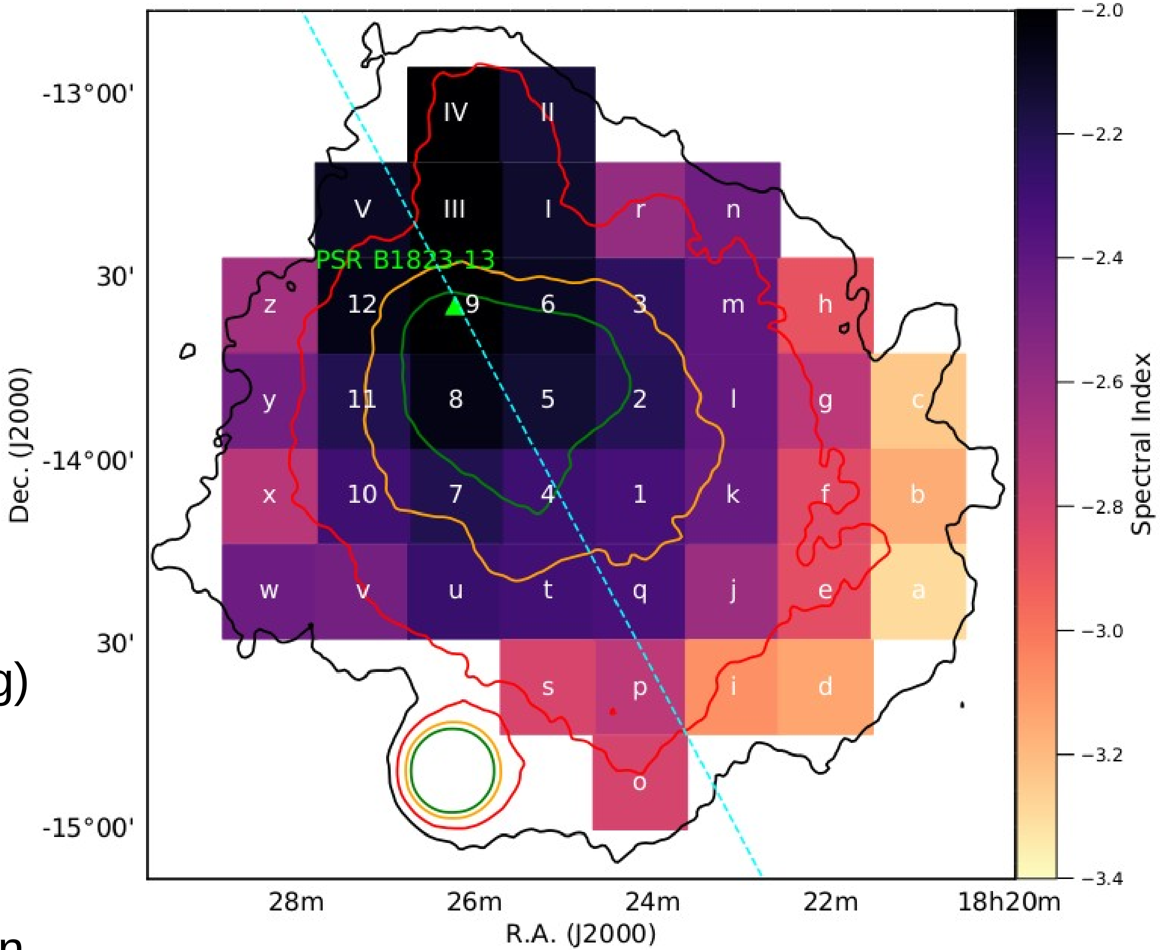


- Cooling of electrons can be observed !

Pulsar wind nebulae - halo

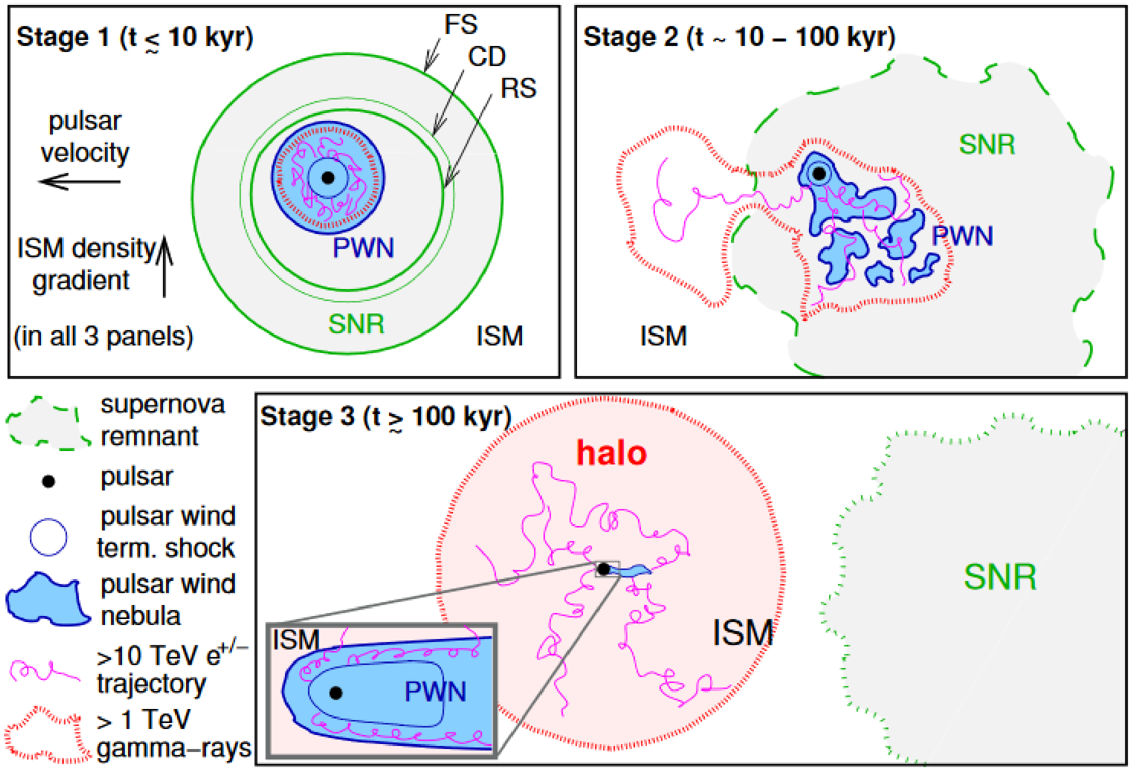
arXiv:1810.12676



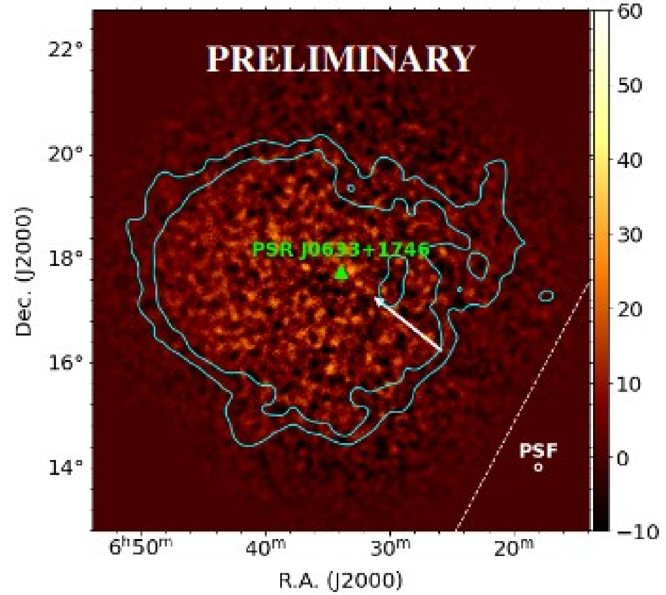


- More energetic electrons are near the pulsars (more young)
  - Proof that the pulsar is the engine that produce those electrons !
  - Cooling is compatible with electrons (leptonic emission by pulsar)

Pulsar wind nebulae - halo

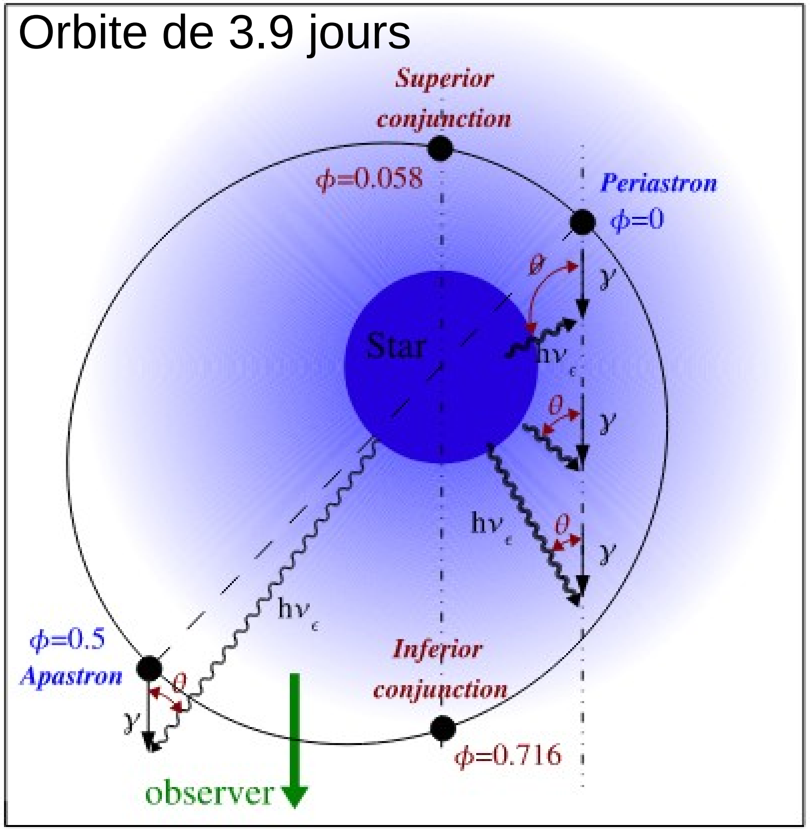


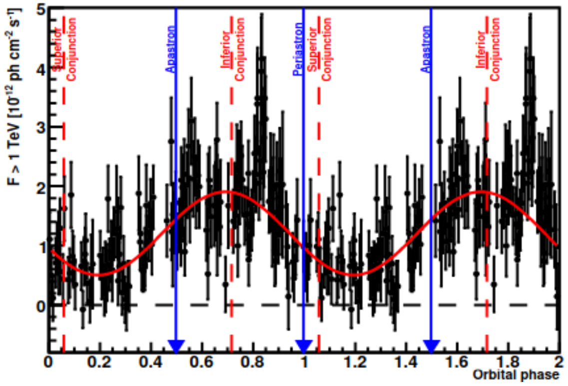
Geminga
340 000 ans

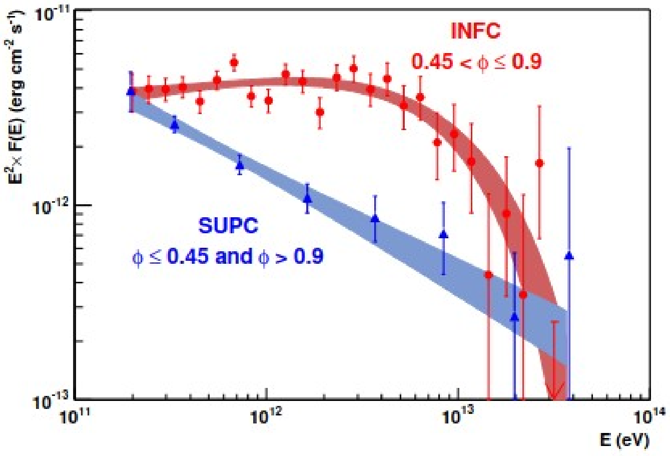


- Data compatible with diffusion (random motion)…
- …But slower than expected, still debate in the community…
- Very plausible origin for the local positrons detected by AMS-02

Binaries



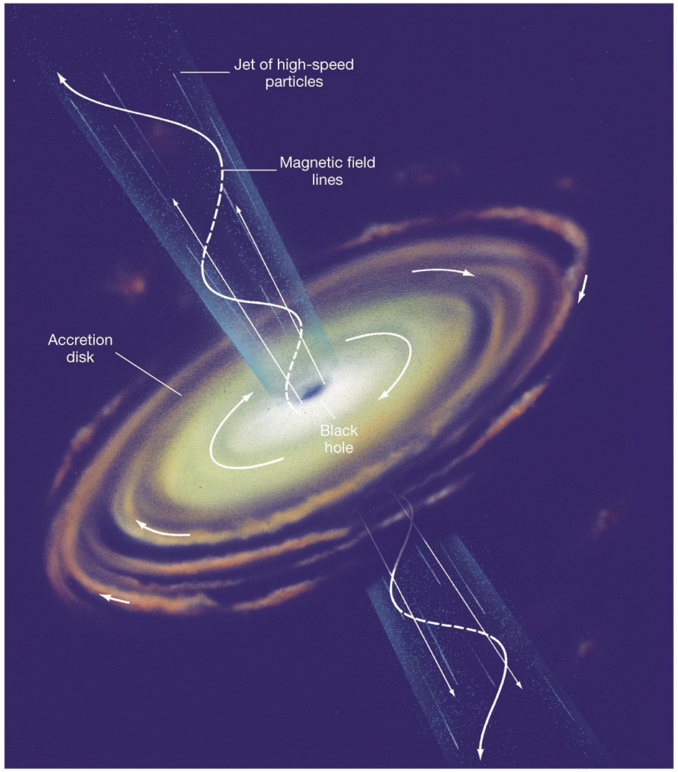


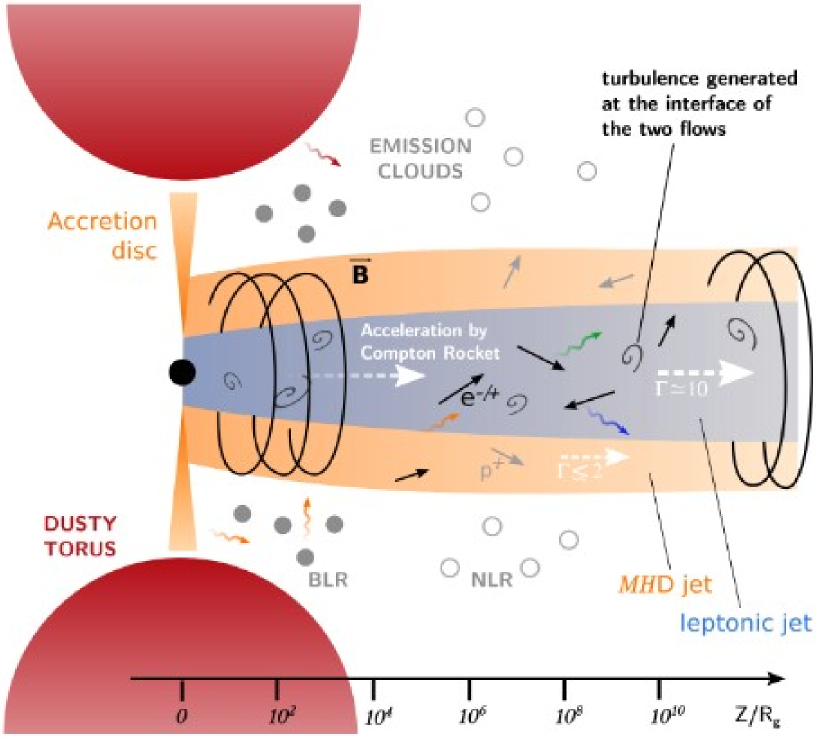


- Star with compact object (black hole or neutron star)
- Modulation of the gamma ray emission due to the photon field of the companion star (absorption et IC)

Extragalactic sky

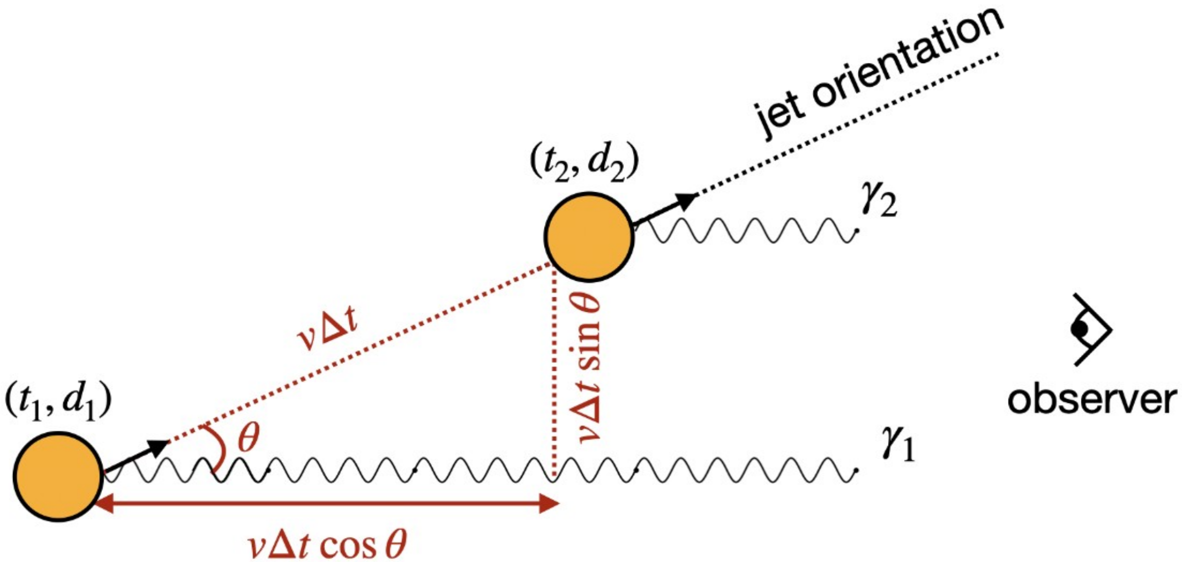
Extragalactic sources

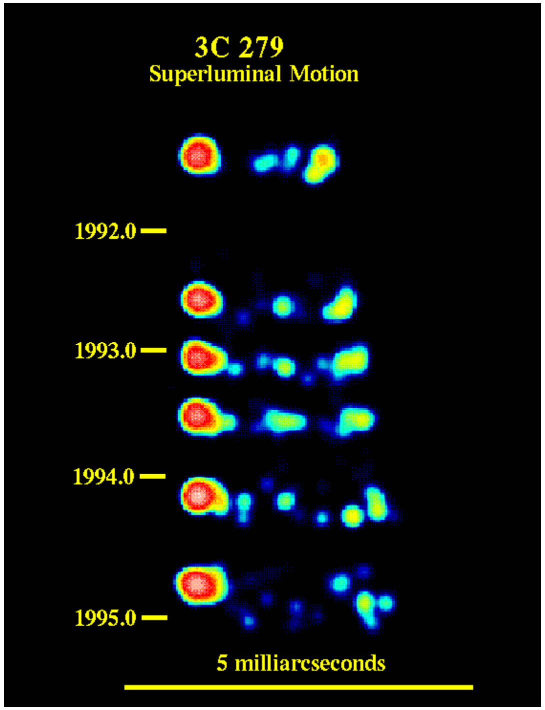




- Vast majority of extragalactic sources are caused by accretion of matter in a black hole vicinity
- Ionised matter rotating → rotating magnetic field→relativistic jets
- Complex acceleration : turbulence in the jet + shock wave between the jet and the external medium
- Significant Lorentz boost in the jet because of energy beaming and doppler effect (blueshift)
- It make those sources very bright sources even at cosmological distances

Jets variability



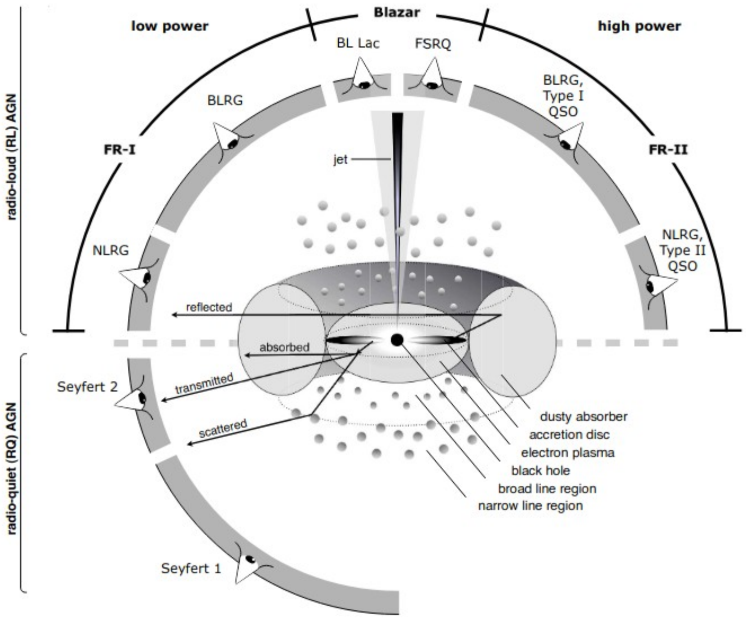


$$\Delta t_{obs} = \frac{c\Delta t - v\Delta t \cos\theta}{c} = \Delta t(1 - \beta\cos\theta) < \Delta t$$

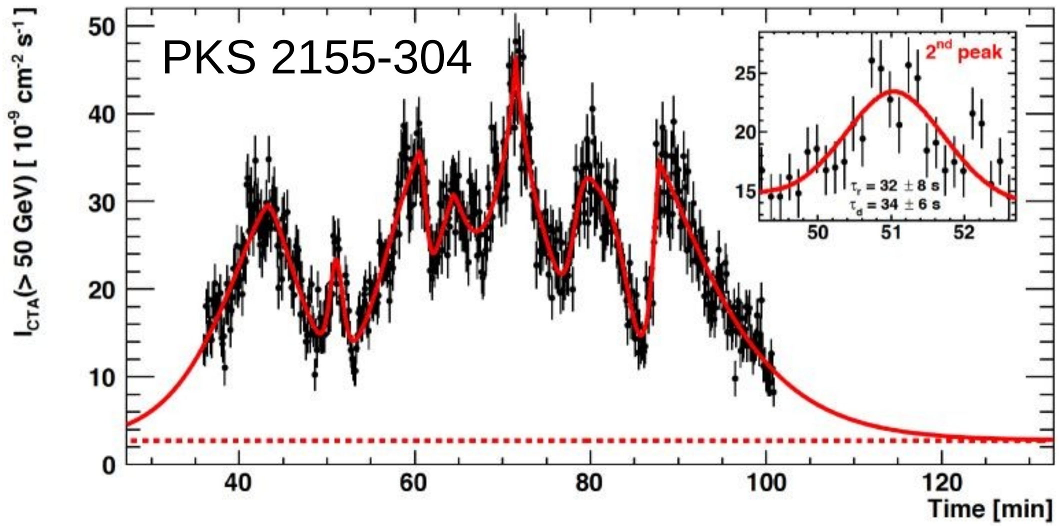
$$v_{obs} = \frac{\Delta d_{obs}}{\Delta t_{obs}} = \frac{v\sin\theta}{1 - \beta\cos\theta} > v$$

- Apparent superluminal velocity is observed in jets
- Variability is as well boosted by the same effect (not only a consequence of the compact acceleration region)

Active galactic nuclei



Variability ~ 1 minute

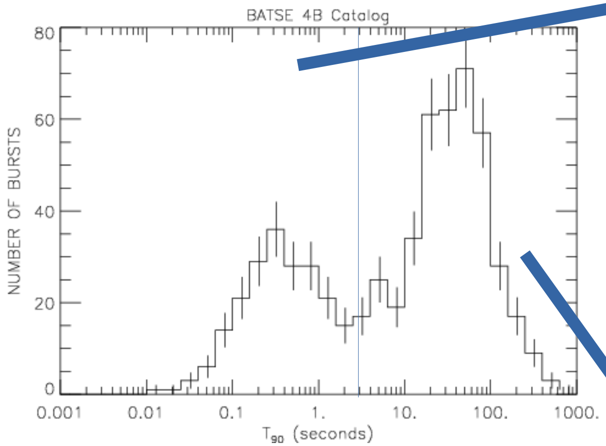


- Jet engine → supermassive black hole in galactic centers
- Very fast variability of the gamma ray flux, due to the compacity of the acceleration region
- Naive Acceleration region size : 1.8*10^{10} m
- ~0.01 R_S (supposing a 10^9 Solar mass black hole, R_S = 3 *10^{12} m)
- Taking into account jets (v = 0.99c), 1.8*10^{12} m

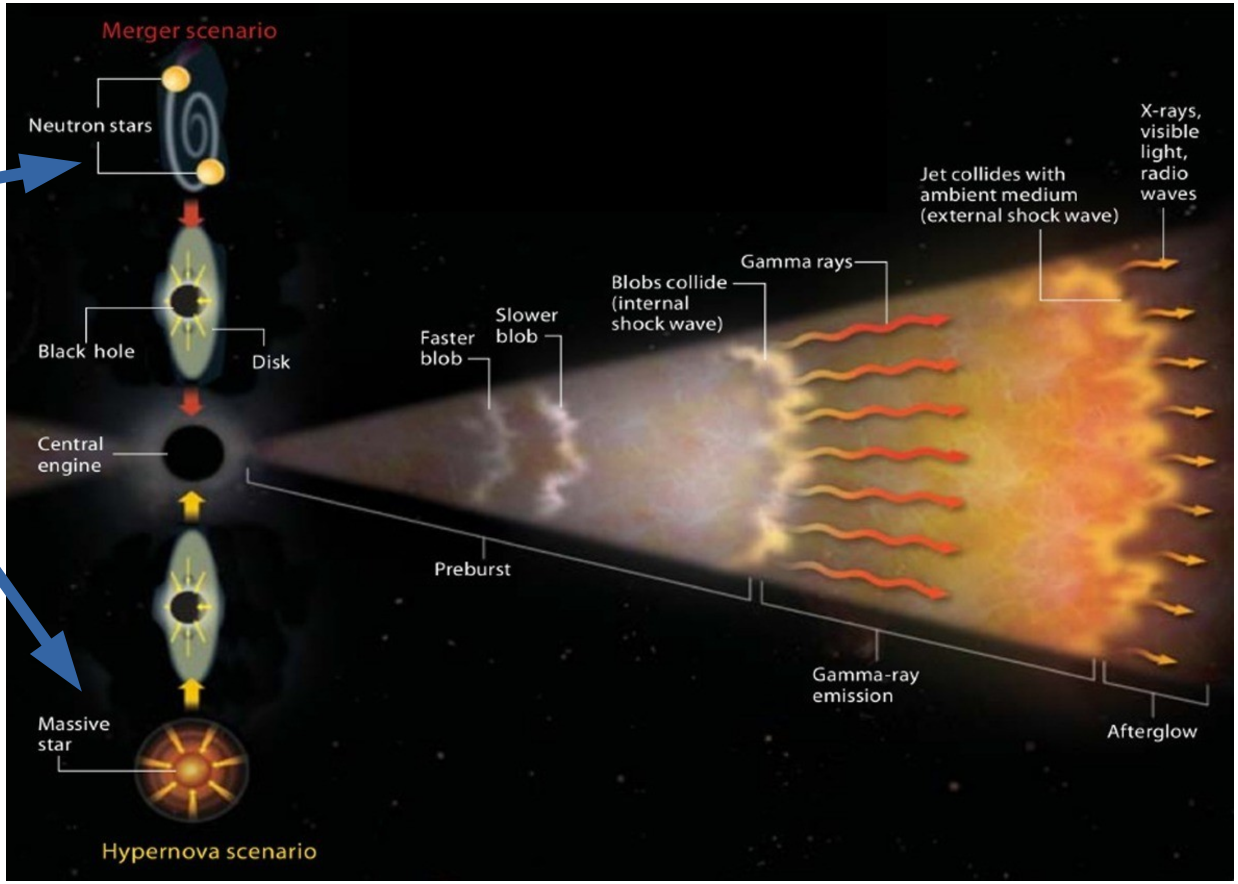
$$r_s = \frac{2GM}{c^2}$$

Gamma Ray Burst

Sursaut court

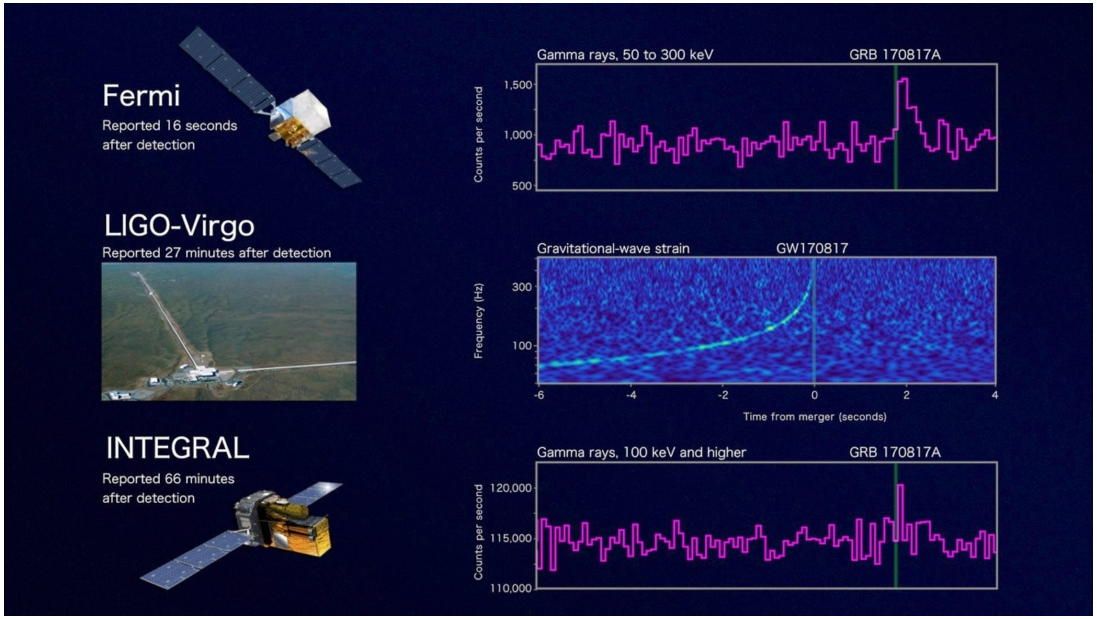


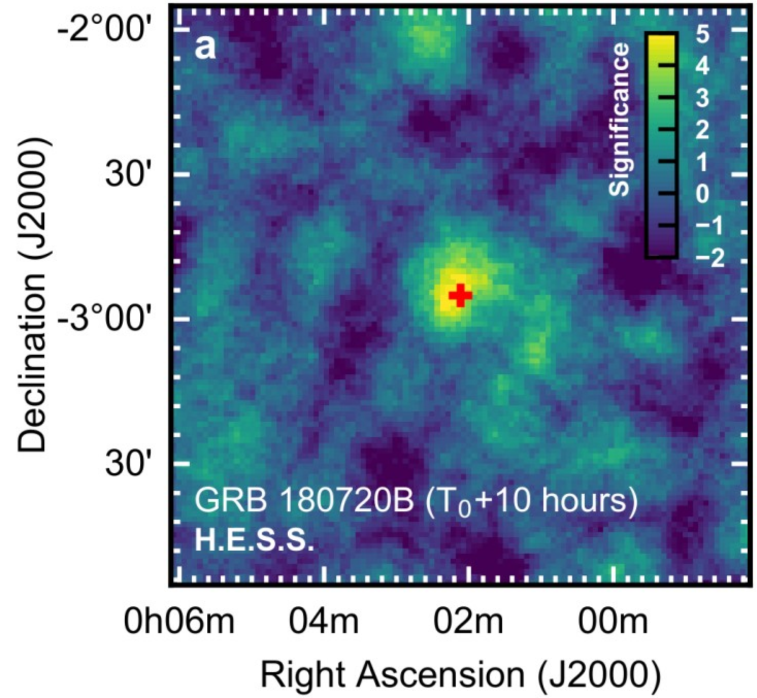
Sursaut long



- Short and bright emission of gamma-rays
- Two populations : short (< 3 s !!!!) and long (> 10 s)
- Prompt emission (shock wave in the jet) than afterglow (choc with external medium)
- Less massive engine than supermassive black hole + faster jet → faster variability than AGNs

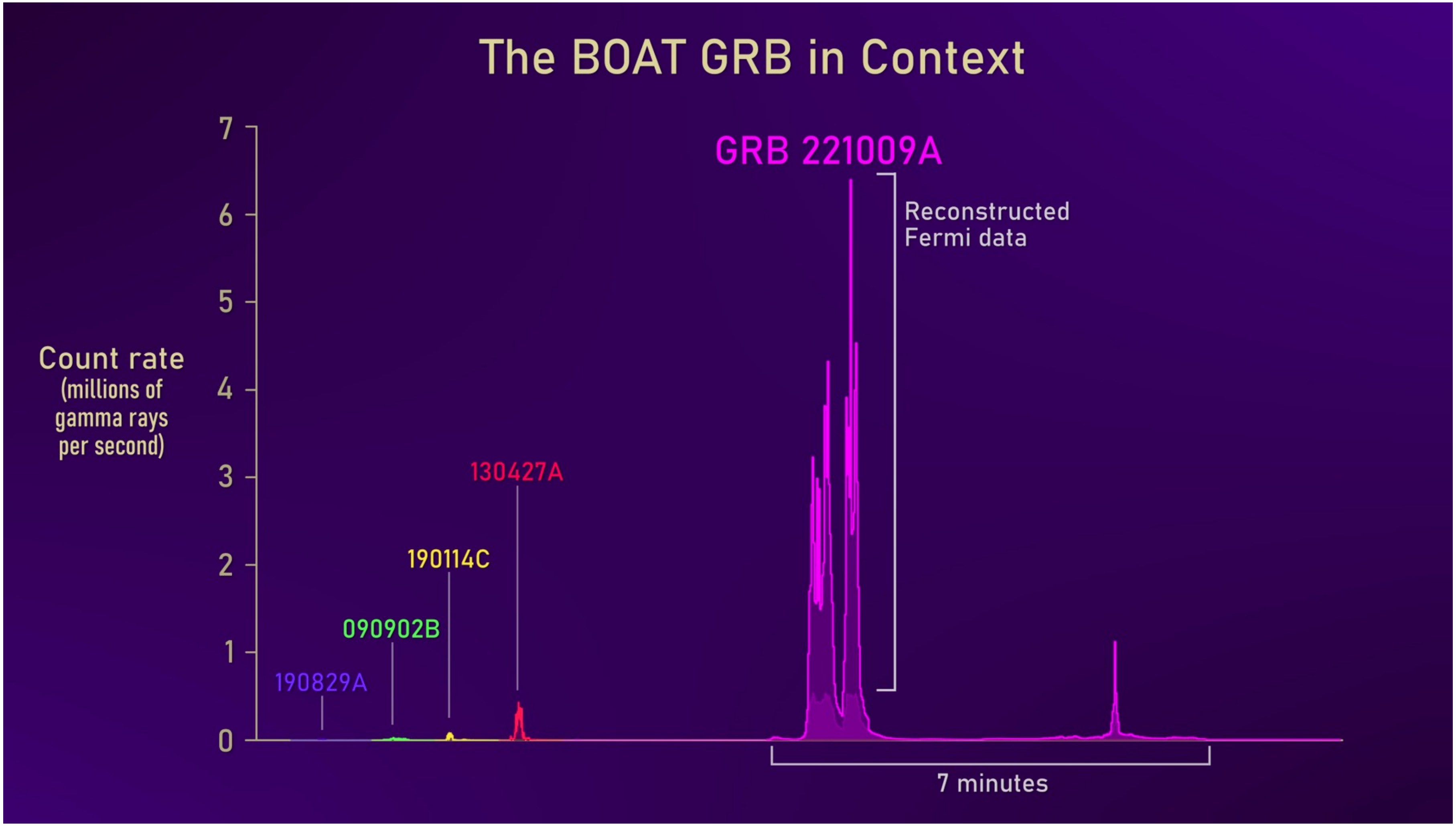
Gamma ray burst multi-messenger observation





- Cherenkov telescope field of view ~5° (8° for CTA), needs for external alerts (satellites X-ray or GeV gamma rays, GW, neutrinos...)
- For the short burst, production of gravitationnal wave is expected (asymmetry of the merger precursor)
- Happened in 2017, but missed by Cherenkov telescopes (due to day light...)
- But detected by satellites !
- 4 GRBs detected by cherenkov telescopes so far (~2k in total for Fermi)

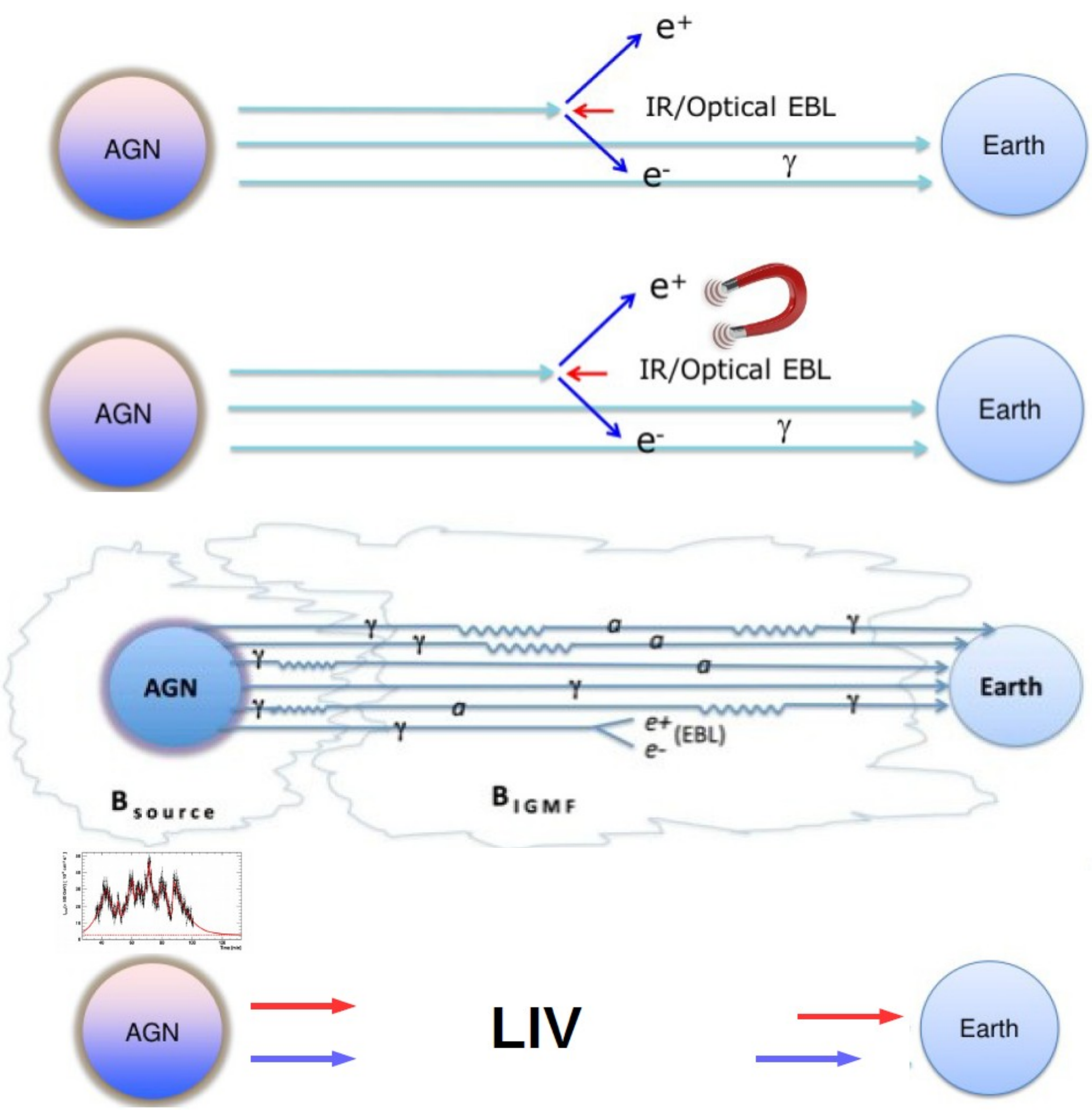
The Brightest Of All Time (BOAT)



- Combination of “close” (z = 0.15), very energetic (well aligned jets)

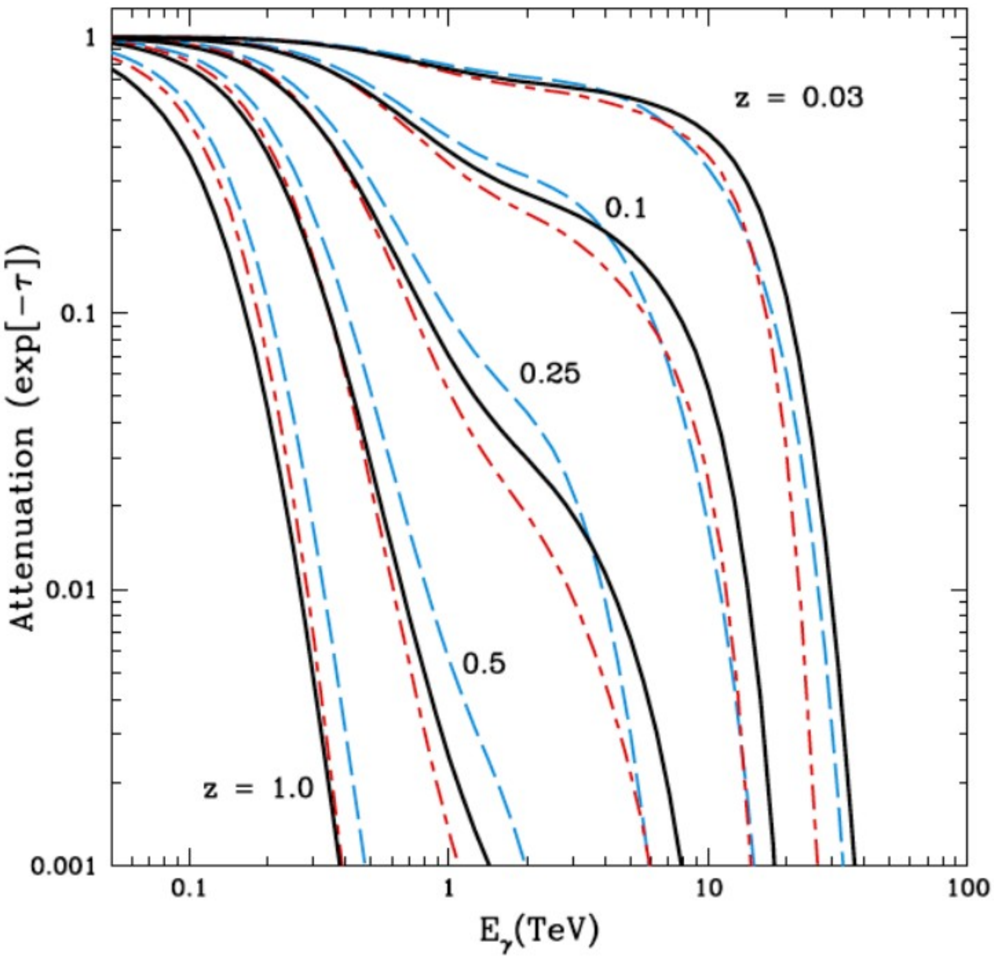
Fundamental physics

Inter-galactic propagation of gamma rays



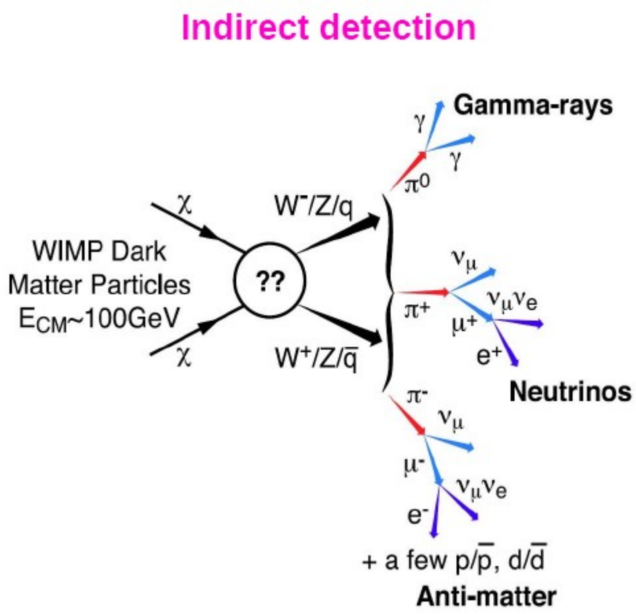
- Gamma-ray absorption due to the amount of light between the sources and the observer
- Positrons and electrons can produce gamma-rays (echos)
- Galactic magnetic fields can create extended echos
- Oscillation between gamma-ray and axion like particles in a magnetic field (absorption)
- Lorentz Invariance Violation is predicted for some Quantum Gravity models at the Planck energy (E~10^{19} GeV), Delay between high and low energy events is expected in such cases

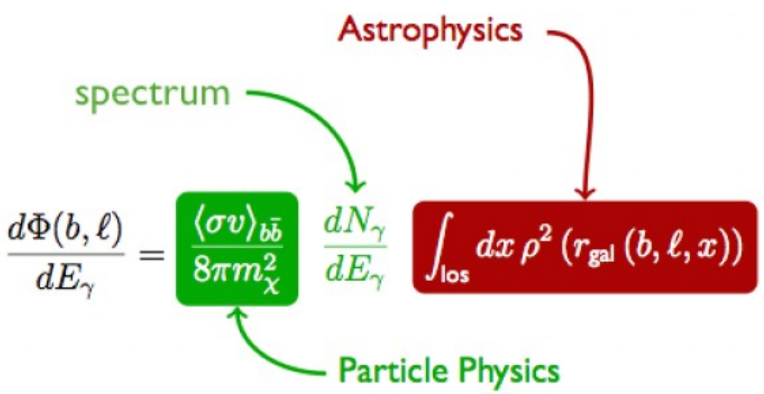
Gamma ray attenuation



- Pair production with interaction with photons is one of the main limit for the depth of gamma-ray observation
- Recently OP313 (blazar) observed at z=1 (7.8 Billions light years https://www.lapp.in2p3.fr/2024-01-science-4693
- This is why low energy (~100 GeV) are interesting for extragalactic physics
- This is what would make neutrinos interesting for astronomy (no interactions)

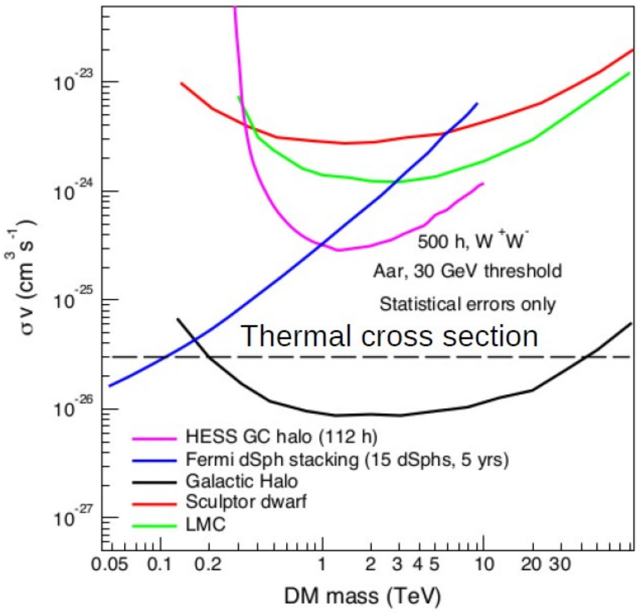
Dark Matter





$$\frac{d\Phi(b,\ell)}{dE_\gamma} = \frac{\langle\sigma v\rangle_{b\bar{b}}}{8\pi m_\chi^2}\frac{dN_\gamma}{dE_\gamma}\int_{los} dx\,\rho^2\left(r_{gal}(b,\ell,x)\right)$$

- Galactic center
  + Large statistics
  - Important astrophysical background
- Dwarf galaxy
  - Low stat
  + Weak astrophysical background
- Spectral lines
  + no background → smoking gun
  - Very low stat



Conclusion

- Leptonic accelerators are believed to be more bright in gamma-rays (Lorentz factor dependency) → **Yes they are, pulsar and pulsar wind nebulae are main class of galactic particle accelerators**

- According to galactic cosmic rays, it exists hadronic accelerators in our galaxy, and those accelerators should accelerate up to at least ~1PeV (translated to gamma-ray 100 TeV !) → **Yes, pulsar and pulsar wind nebulae are important class of gamma ray sources**

- According to positron excess in the cosmic rays, it exists leptonic accelerator producing as well antimatter → **Close and extended leptonic sources are observed in gamma-rays**

- It should exists even more extreme accelerators than 1PeV ones (but probably different of the galactic ones)… → **Yes, Jets are extreme accelerators, but difficult to tell maximal energies due to EBL**

- Compact objects with strong magnetic fields can be efficient accelerators (and so should shine in gamma-rays)… → **Yes, these objects are pulsars (neutron star), and black holes. In case of ultrarelativitic jets, the acceleration is even more boosted**

- … of course it is not enough to be compact, we need to have an engine to accelerates the charged particles → **engines are supernova remnants shocks, rotating neutron star, accretion disk around black holes**

- Last but not least, the more compact the acceleration site, the faster acceleration should be (and possibly variability in the gamma ray flux) ! → **True but ultra relativistic jets as well enhance this**

- Direct implication is : compact sources should be more variable, “big” sources should be more static → **this is more or less true, if we excluded ultra relativistic jet effects**

Back-up slides

Positron sphere

Positron propagation equation

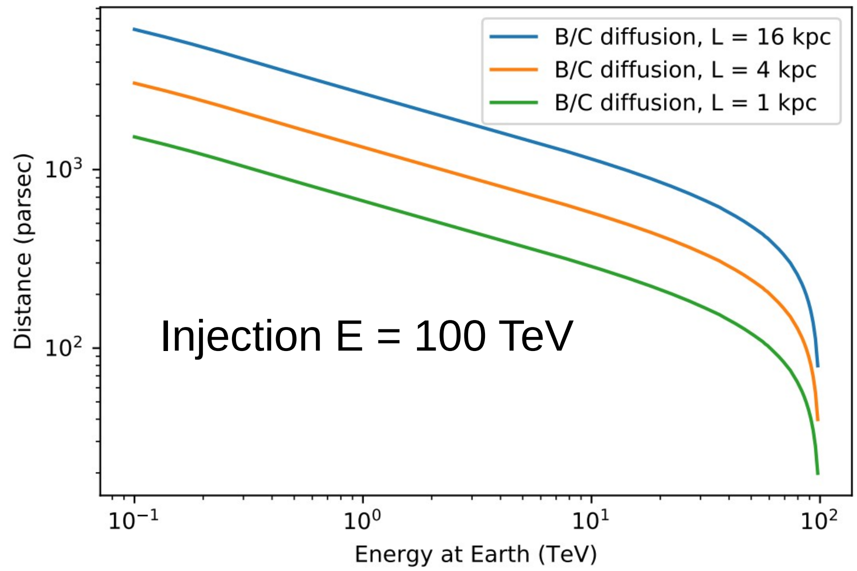
$$-K(E)\Delta\Psi + \frac{\partial}{\partial E}\left(b(E)\Psi\right) = q$$

Solution mono-energetic

$$\psi \propto \exp(-r^2/\lambda(E,E_s)^2)$$

$$\lambda(E,E_s)^2 = 4\int_{E_s}^{E} K(E)/b(E)$$

- For E > 10 GeV, positron propagation can be simplified by a diffusion-energy loss equation
- Energy loss due to synchrotron and IC scaterring
- Scale of propagation can be defined based on diffusion and energy loss
- Positron excess up to ~500 GeV → give a constraint on distance of source
- Positron sphere → ~ < 1-4 kpc
- Positrons are produced locally

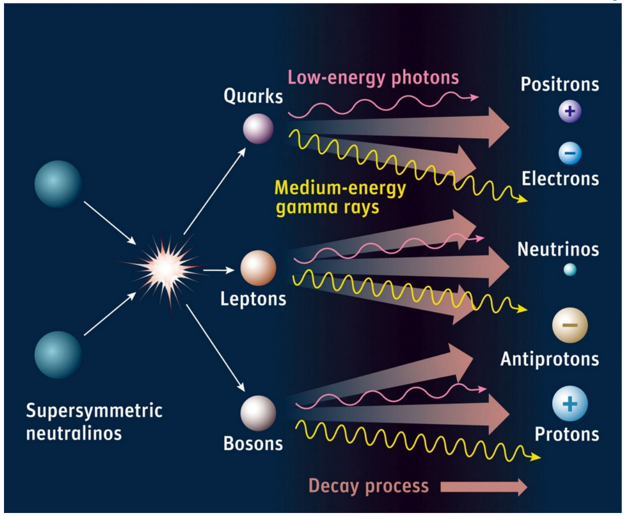


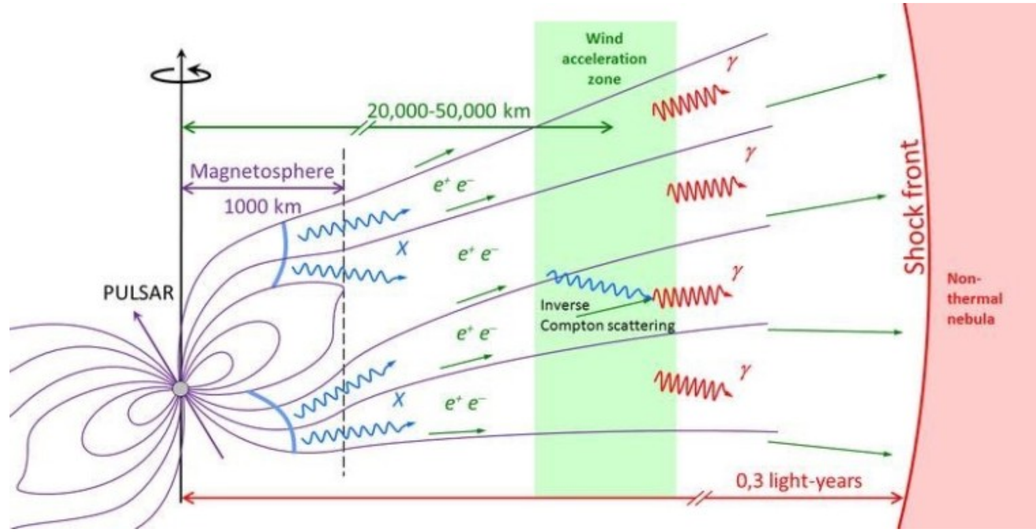
Pulsar or Dark Matter ?

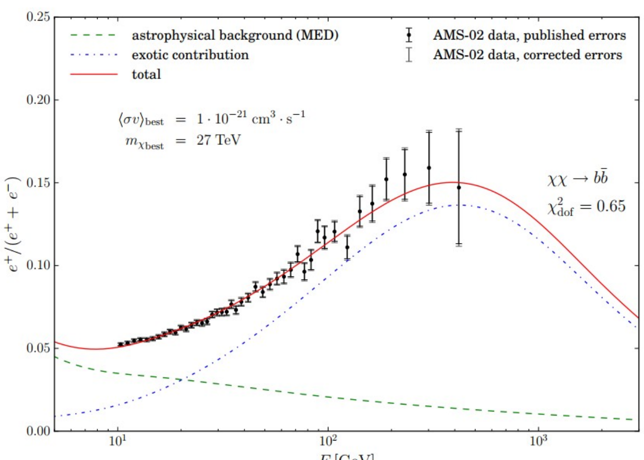
Dark Matter ?

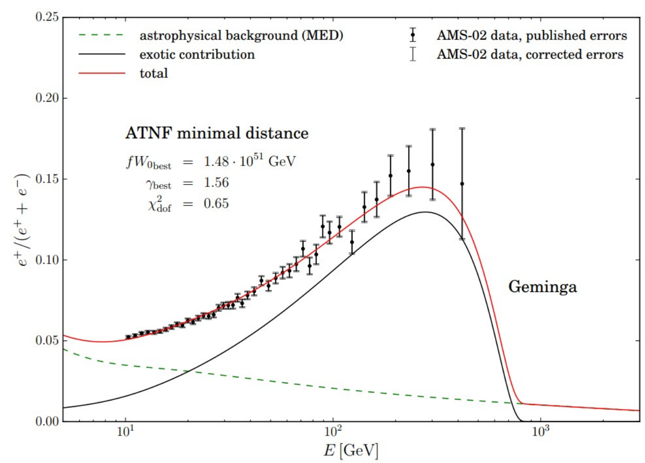
https://arxiv.org/abs/1410.3799

Local pulsar ?









- Dark matter need unrealistic boosting factor of annihilation to explain positron fraction
- Close pulsar is a natural explanation to this excess...