Laboratoire d'Annecy de Physique des Particules

Gamma-ray astronomy

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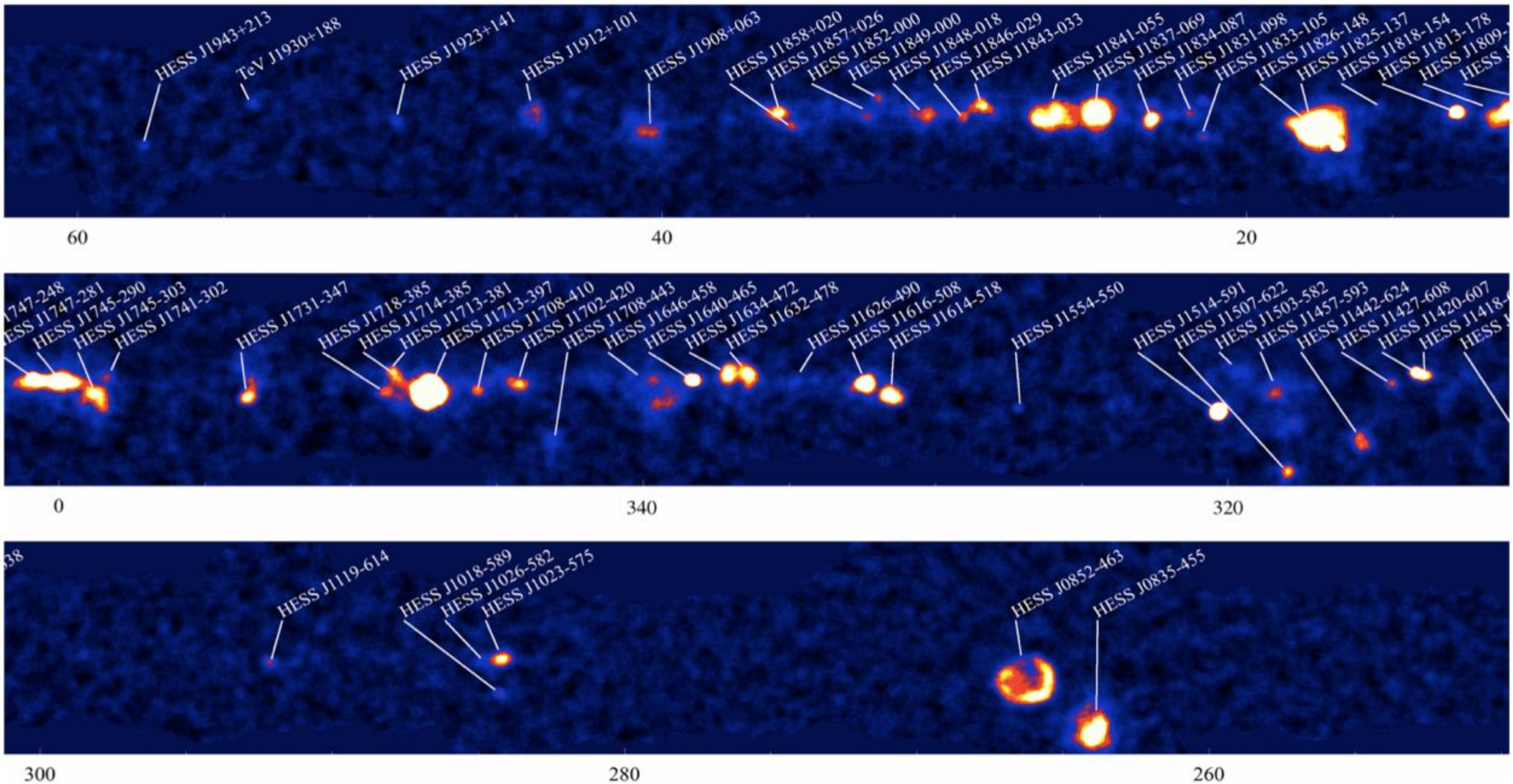
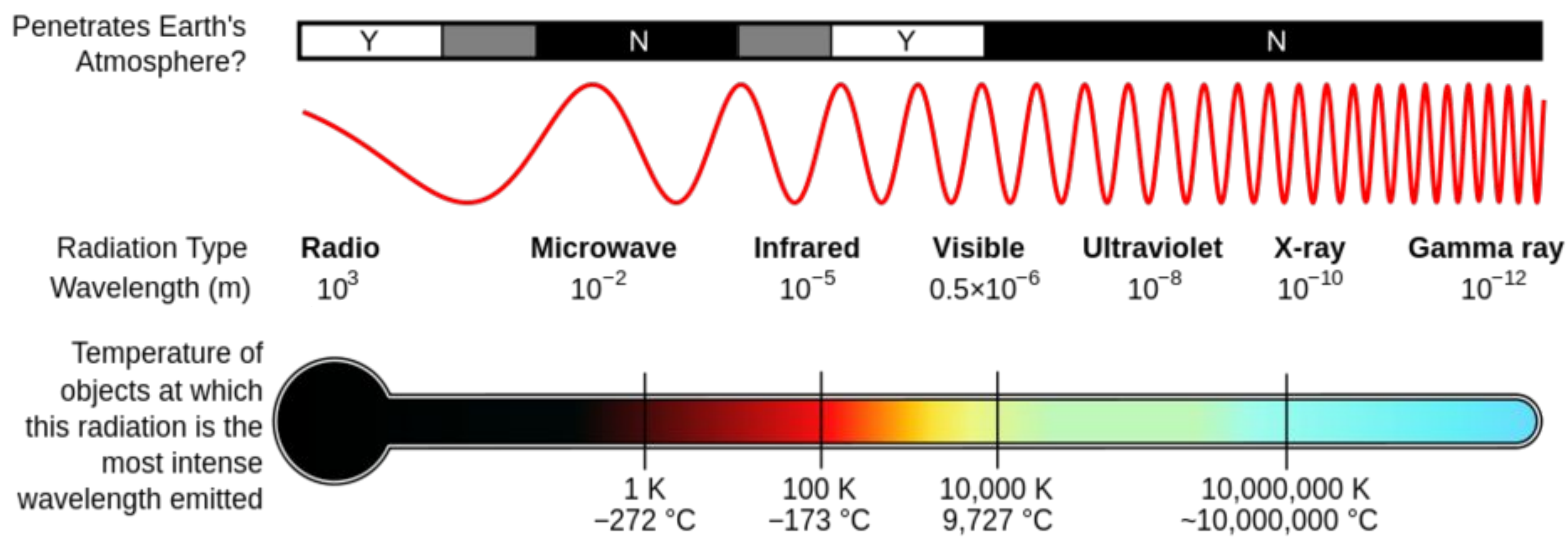
UNIVERSITÉ SAVOIE MONT BLANC

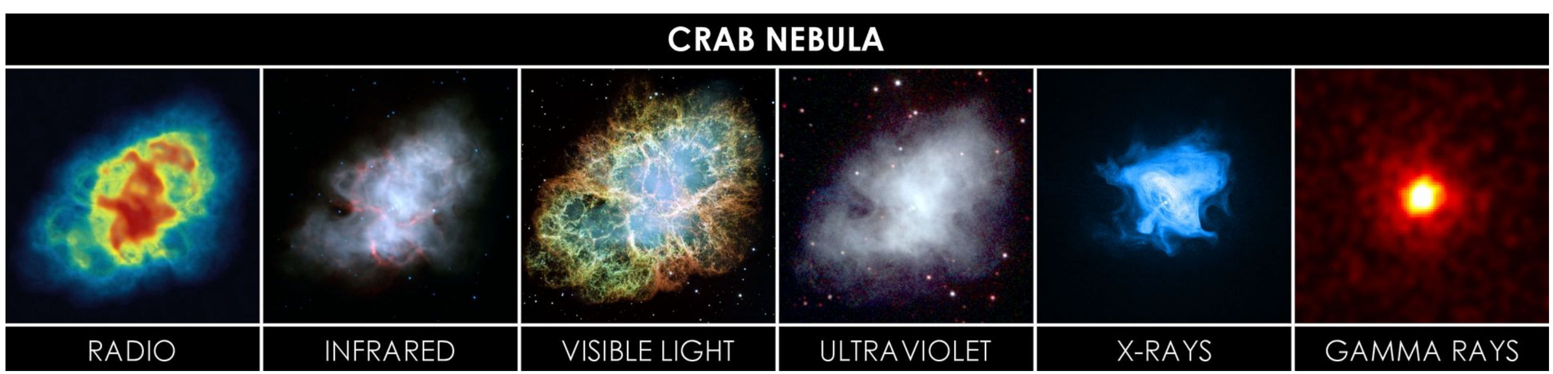
Milky Way at TeV energy



Why do objects emit light?

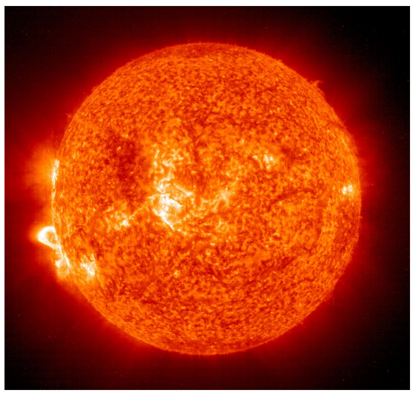
Electromagnetic radiation

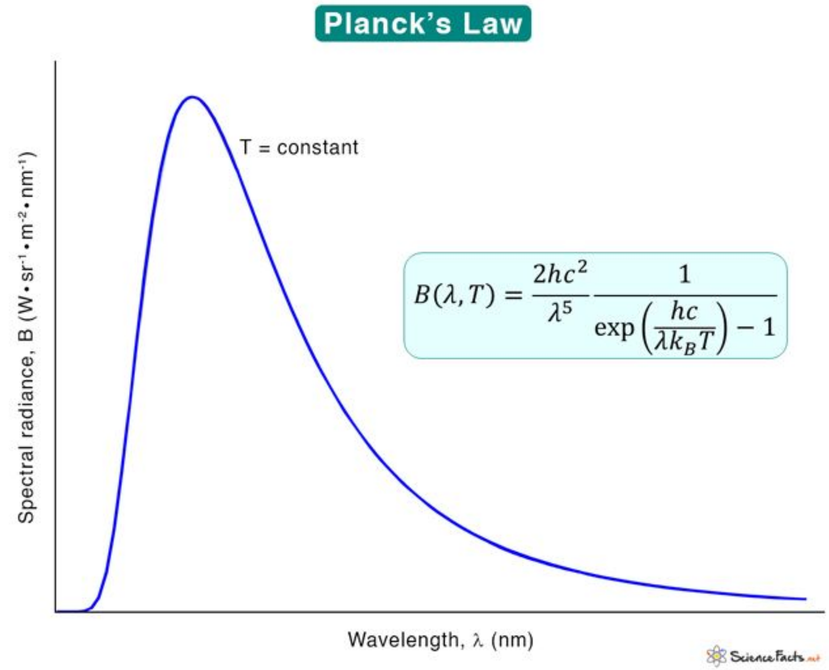




Black-Body radiation

$$u_\nu(\nu, T) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}.$$

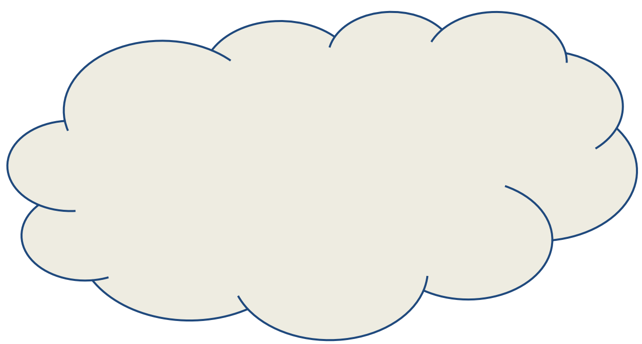


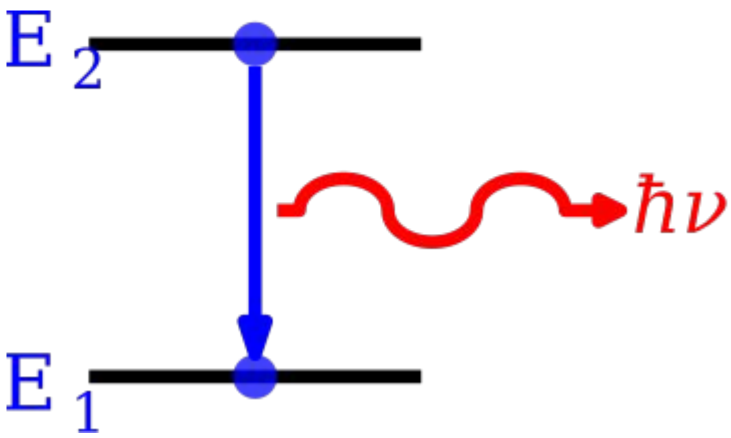


Continuous spectra

Line emission

Spontaneous emission due to transition from high to low energy state

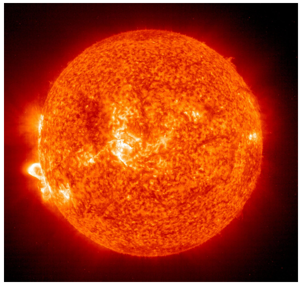


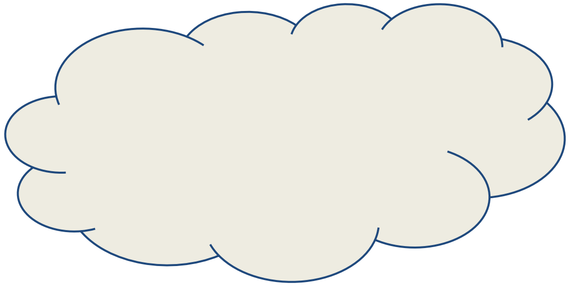


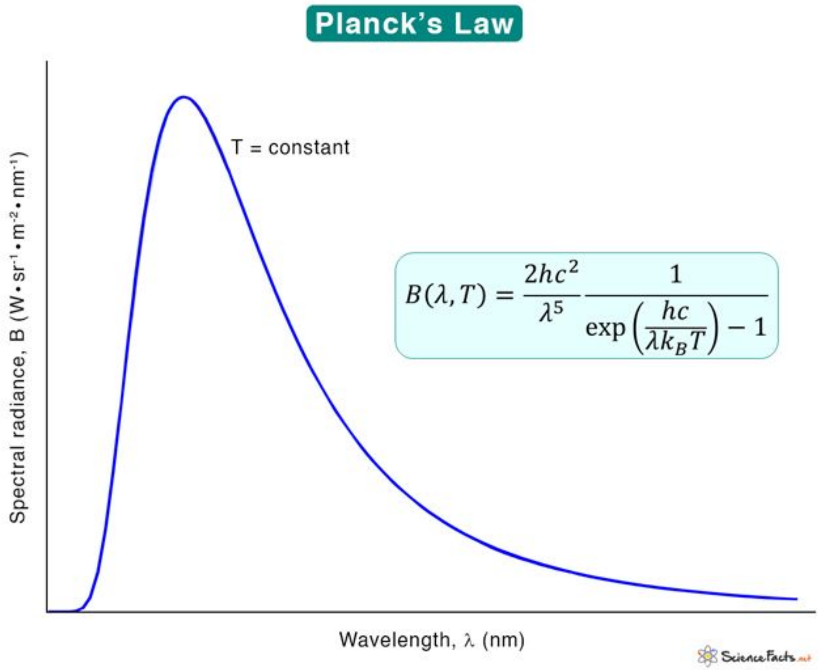
Line spectra

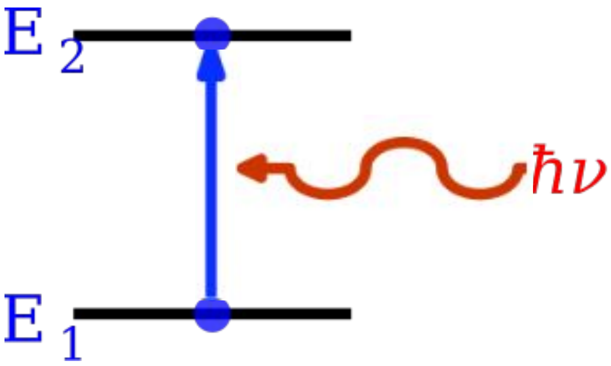
Black-Body radiation + Absorption

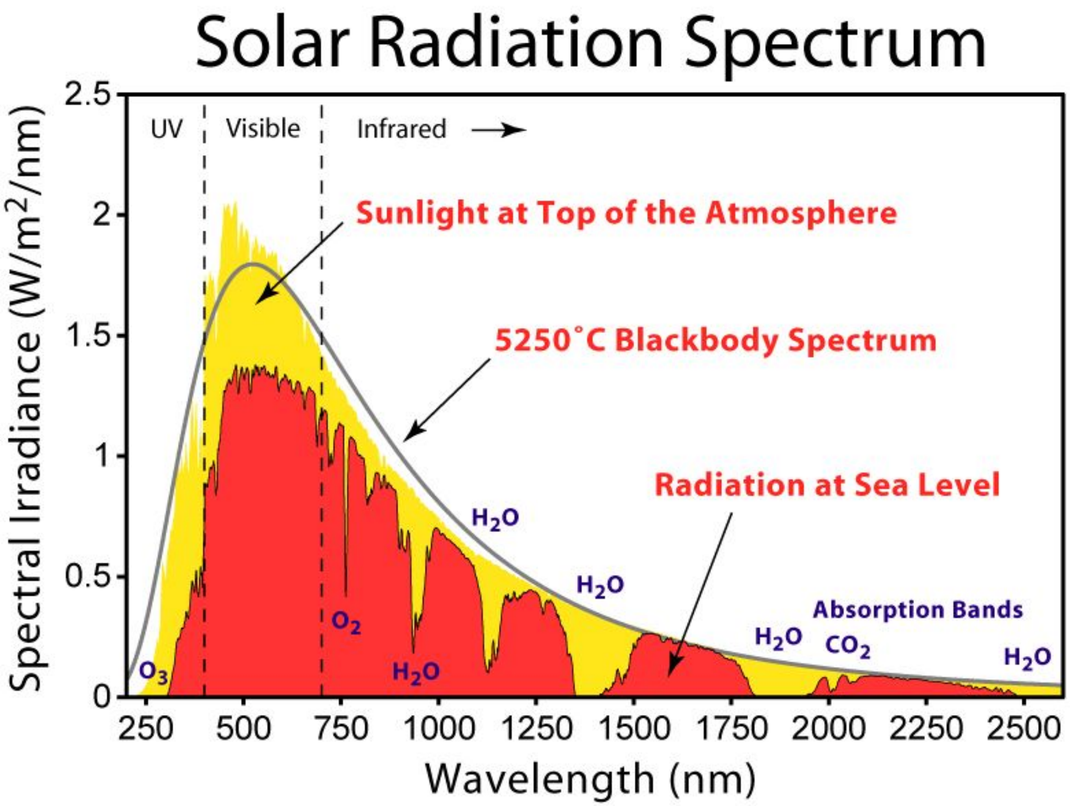
$$u_\nu(\nu,T) = \frac{8\pi h\nu^3}{c^3} \cdot \frac{1}{e^{\frac{h\nu}{k_B T}} - 1}.$$



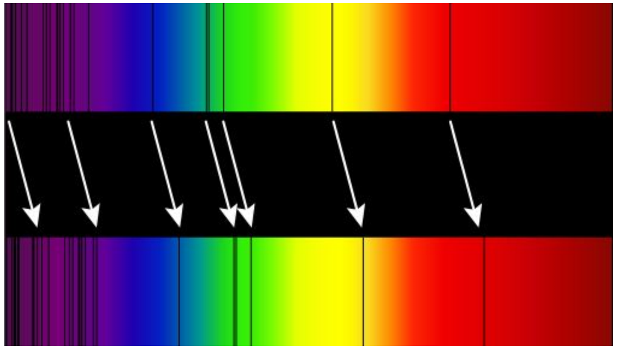






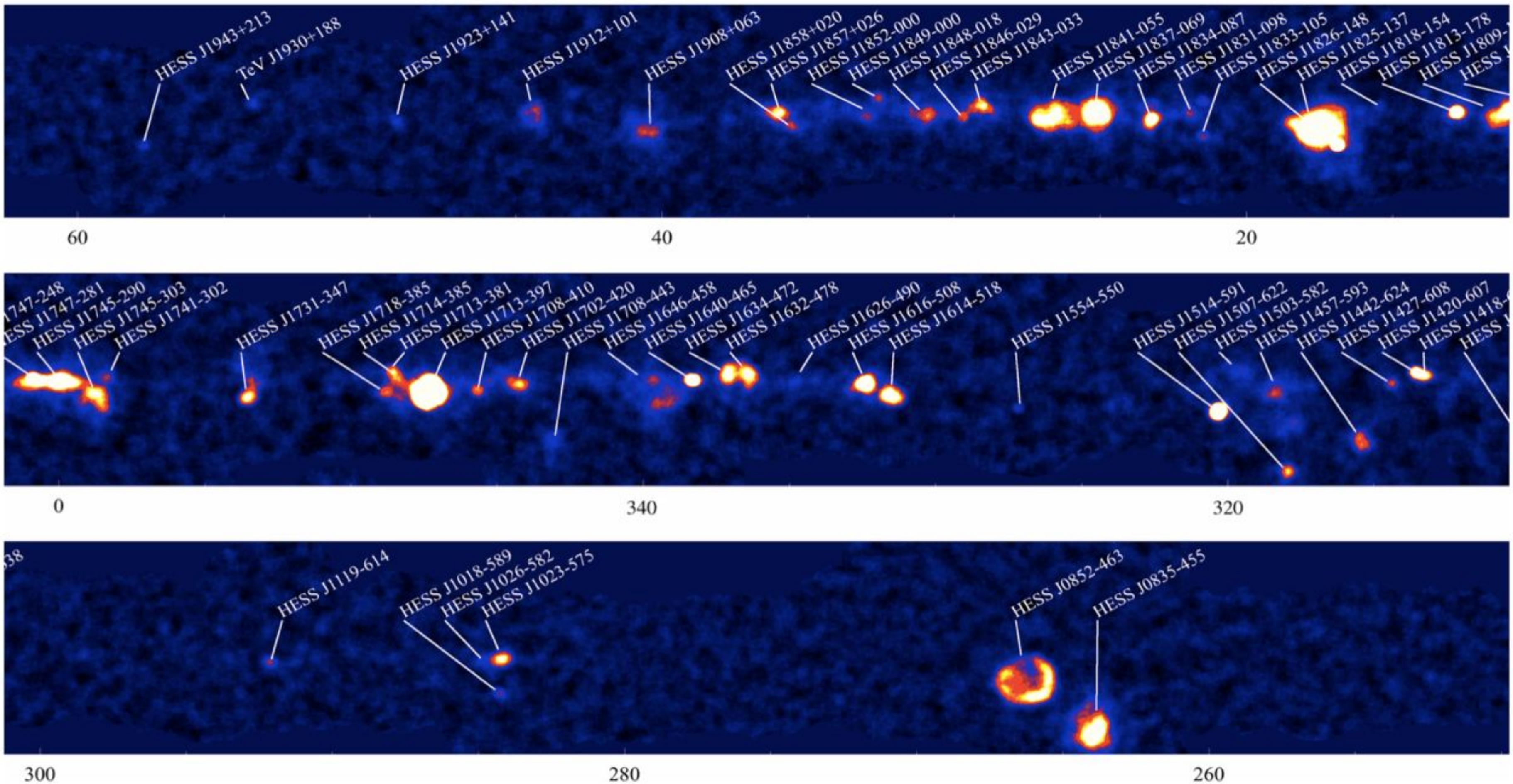


- Temperature of the object photosphere
- Composition of the object vicinity
- Composition of the gas in the line of sight (here the atmosphere !)
- many more :
  - temperature of the gas (doppler broadening)
  - gas pressure
  - redshift



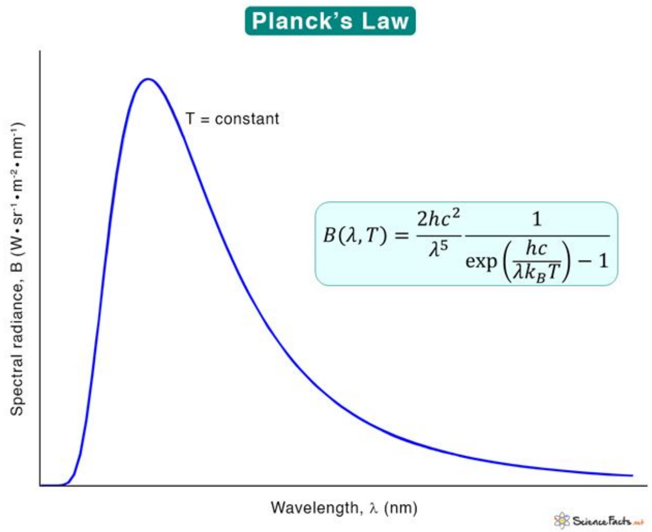
Milky Way at TeV energy

Very hot objects ?



Thermal Gamma-ray ?

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



- 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

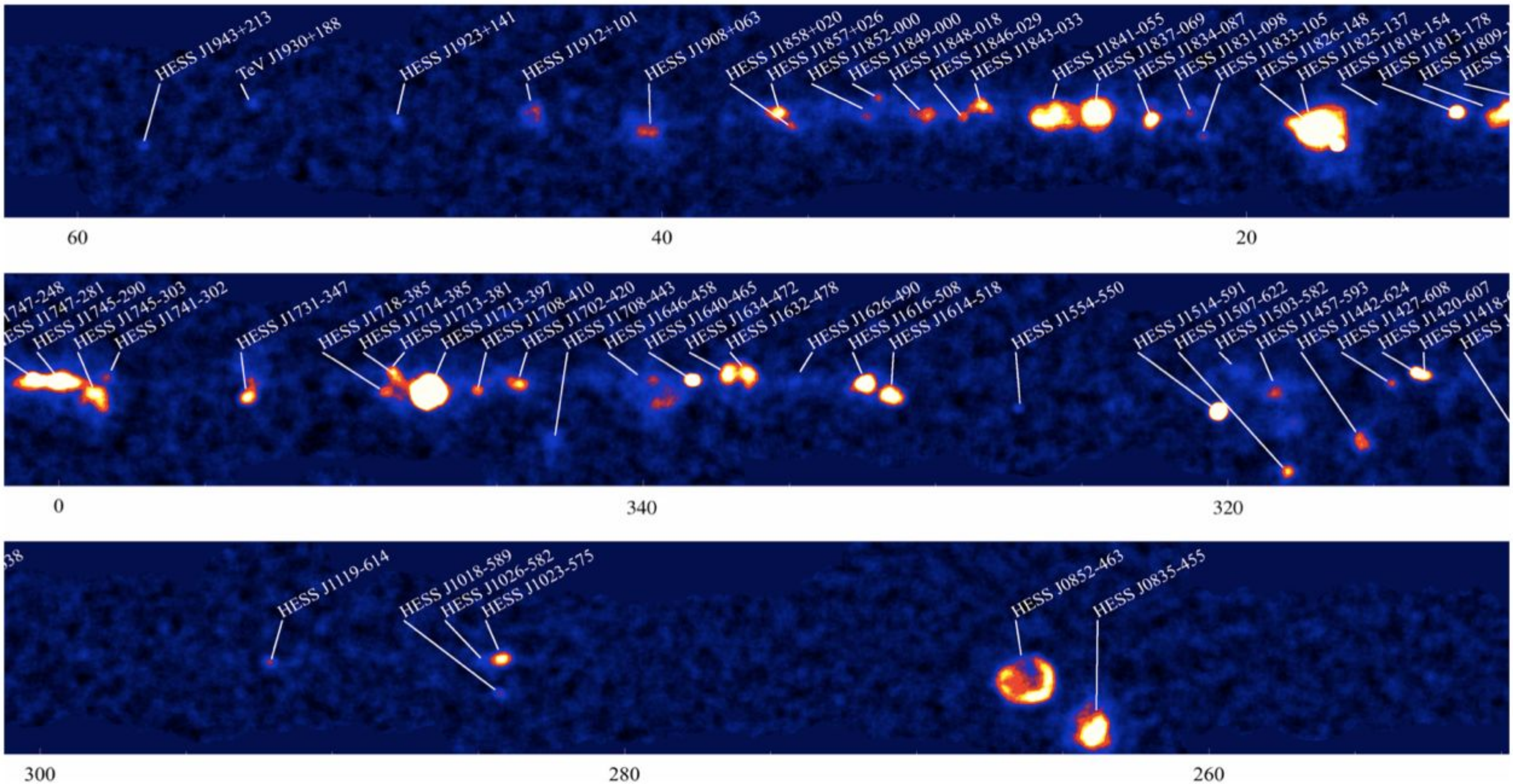
10^{13} Kelvin is the temperature of the universe 1 ms (!!!) after big bang

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

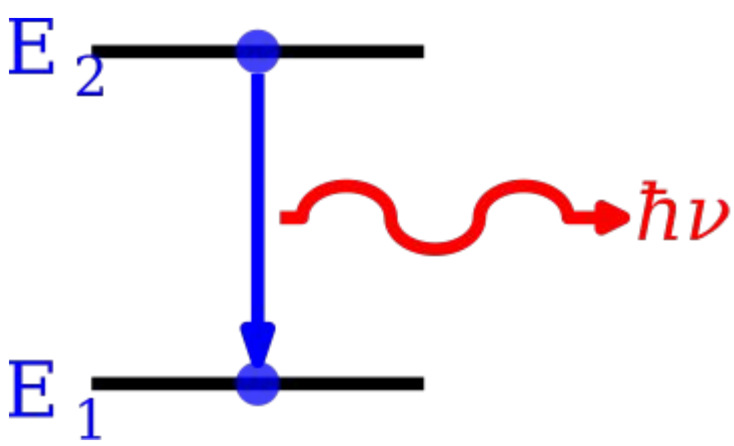
- It looks completely unrealistic to have thermal gamma rays

Milky Way at TeV energy

Spontaneous emission of heavy nuclei ?



Spontaneous emission of gamma rays ?



1 GeV ?

$$E_n = -\frac{13.6\ \mathrm{eV} \cdot Z^2}{n^2}$$

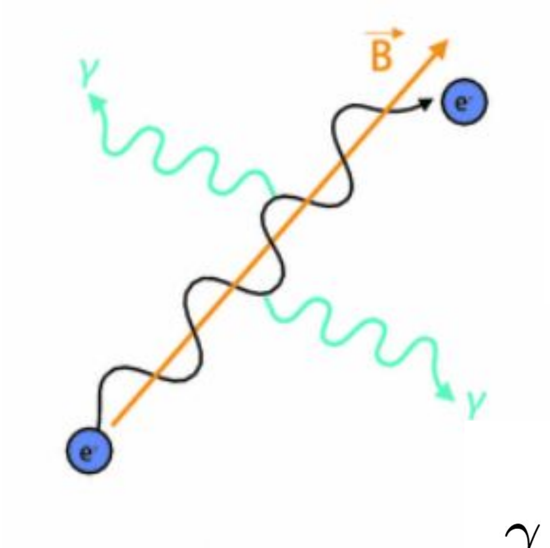
uranium Z = 92

Transition to n = inf -> n = 1

~115 keV << 1 GeV

Gamma-ray production

Synchrotron radiation



(e) Synchrotron.

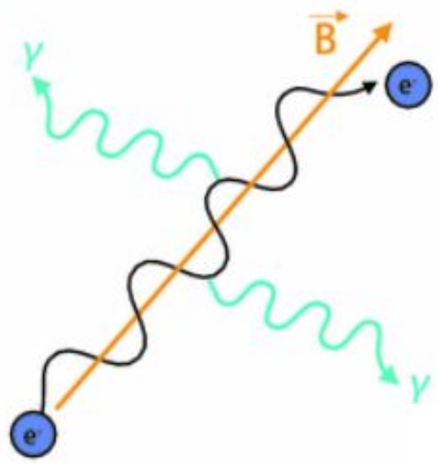
$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c U_B \beta^2 \gamma^2$$

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

$$\gamma = \left(\frac{E_p}{m_p}\right)^2$$

Depend on magnetic field square !

Synchrotron radiation



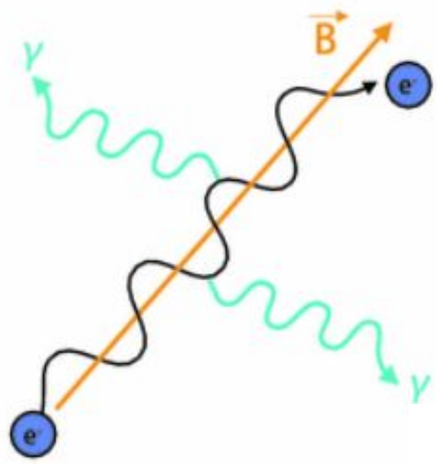
(e) Synchrotron.

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c U_B \beta^2 \gamma^2 \qquad U_B = B^2/2\mu_0$$

$$\gamma = \left(\frac{E_p}{m_p}\right)^2 \qquad \frac{m_p}{m_e} \approx 1800$$

synchrotron energy losses is a way more efficient for electron than protons !

Synchrotron radiation



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$$-\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c U_B \beta^2 \gamma^2 \qquad U_B = B^2/2\mu_0$$

$$\gamma = \left(\frac{E_p}{m_p}\right)^2 \qquad \frac{m_p}{m_e} \approx 1800$$

1 nT ~ Galactic magnetic field

Ec = $1.9 \left(\frac{E}{100\ \mathrm{TeV}}\right)^2 \left(\frac{B}{1\ \mathrm{nT}}\right)\ \mathrm{keV}$

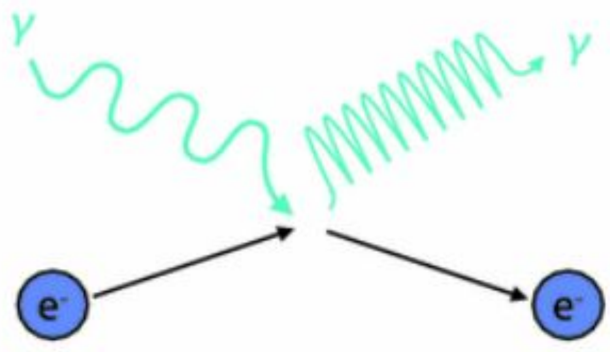
E = 100 TeV, B = 1 nT, E = 1.9 keV

E = 100 TeV, B = 1 mT, E = 1.9 GeV

Inverse Compton radiation

Similar than Synchrotron :

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



(d) Inverse Compton

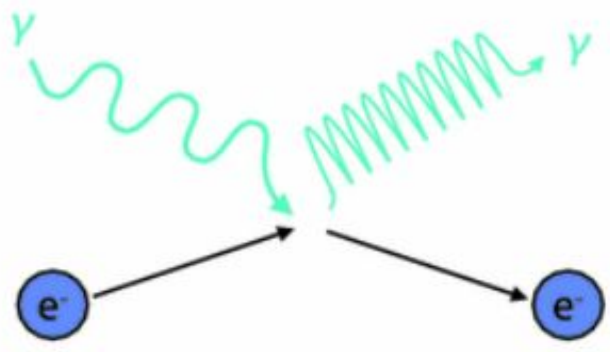
U_R energy density of radiation field

for CMB ~ 0.26 eV/cm^3

Inverse Compton radiation

Similar than Synchrotron :

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



(d) Inverse Compton

U_R energy density of radiation field

for CMB ~ 0.26 eV/cm^3

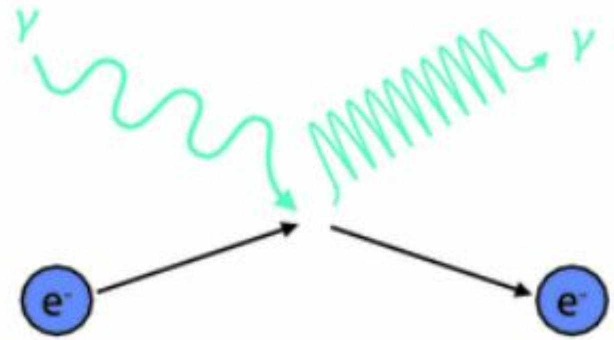
Inverse Compton is a way more efficient for electron than protons !

$$\frac{m_p}{m_e} \approx 1800$$

Inverse Compton radiation

Similar than Synchrotron :

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



(d) Inverse Compton

U_R energy density of radiation field

for CMB ~ 0.26 eV/cm^3

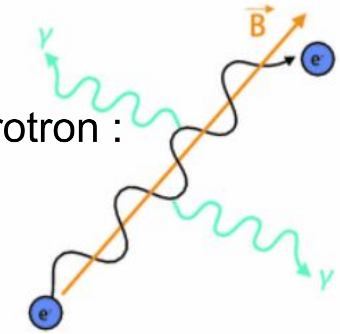
$$\langle E_\gamma^{\mathrm{IC}}\rangle \approx 3.2\ \mathrm{MeV}\cdot\left(\frac{E_e}{1\ \mathrm{TeV}}\right)^2\cdot\left(\frac{\langle\epsilon_{\mathrm{rad}}\rangle}{6.34\times10^{-4}\ \mathrm{eV}}\right)$$

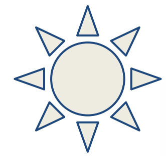
E_e = 100 TeV, CMB, E_{IC} = 32 GeV (10^7 times galactic synchrotron !!)

E_e = 10 TeV, IR (50 K), **E_{IC} = 5.7 TeV**

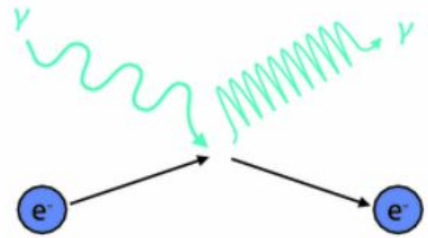
Leptonic induced radiation

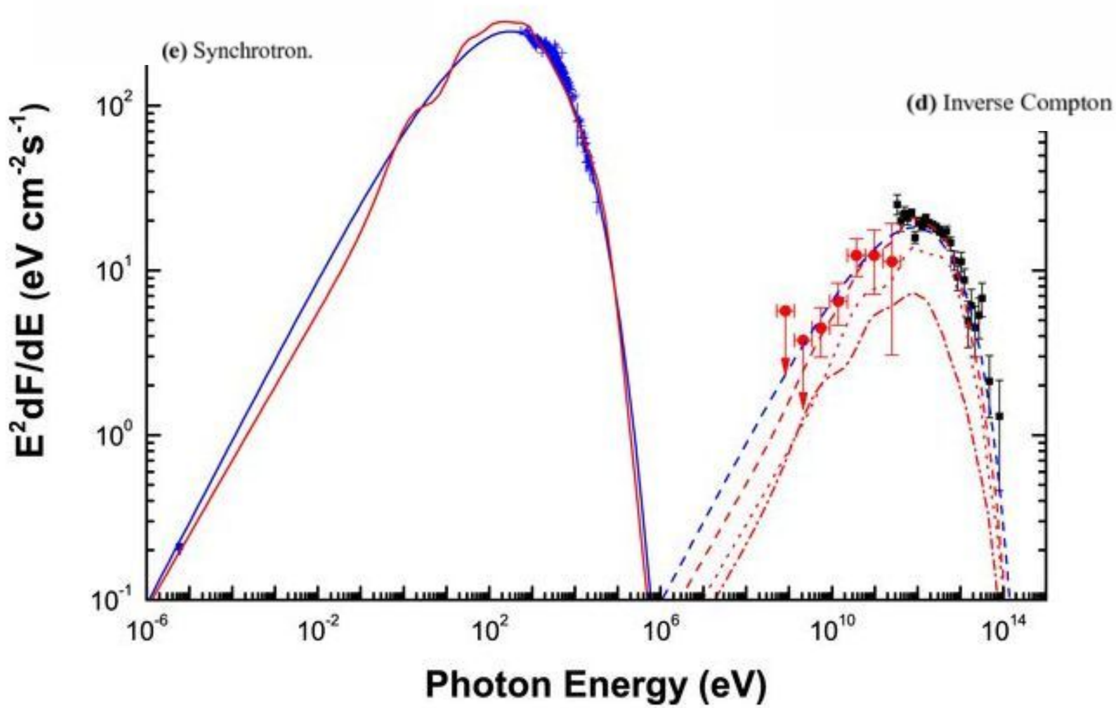
Synchrotron :





External Self Compton :

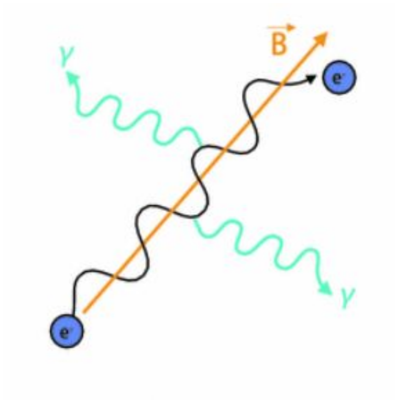




These two peaks are produced by the same population of electrons

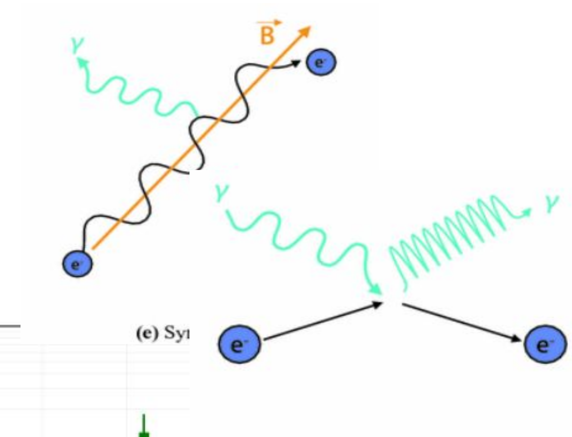
Leptonic induced radiation

Synchrotron :

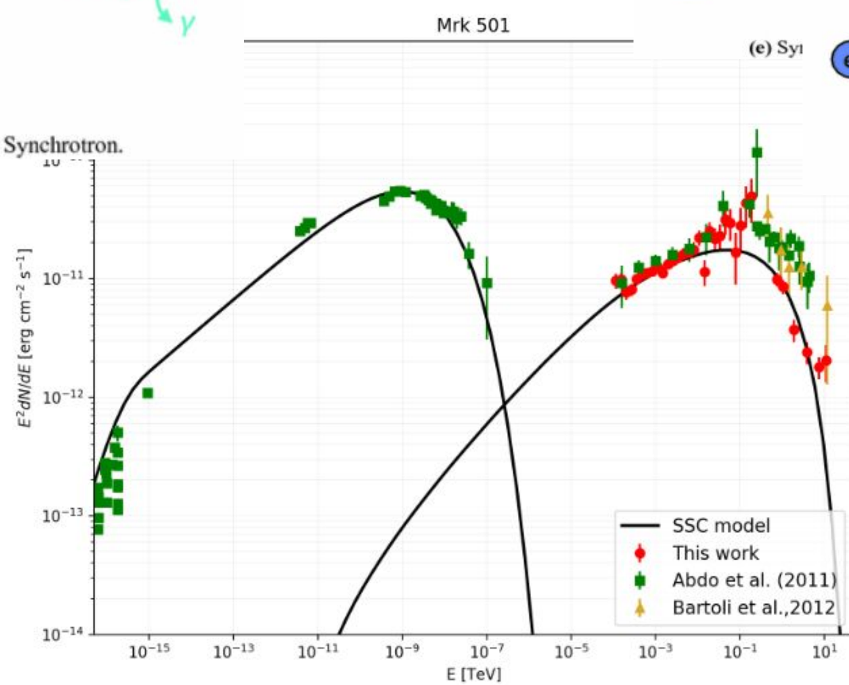


(e) Synchrotron.

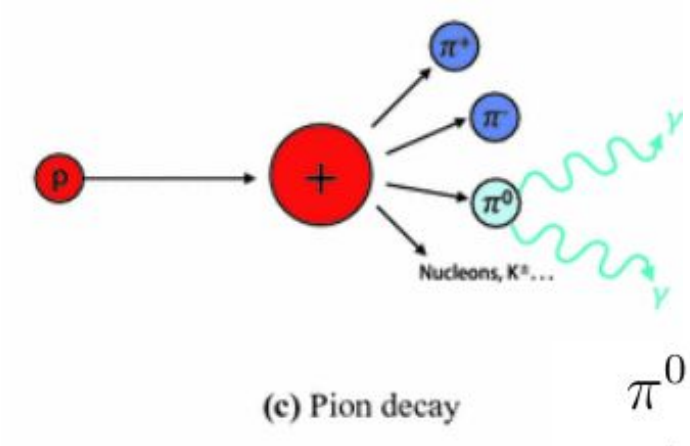
Synchrotron Self Compton :



(d) Inverse Compton



Hadronic interaction



$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow p + n + \pi^+$$
$$p + p \rightarrow p + p + \pi^+ + \pi^-$$

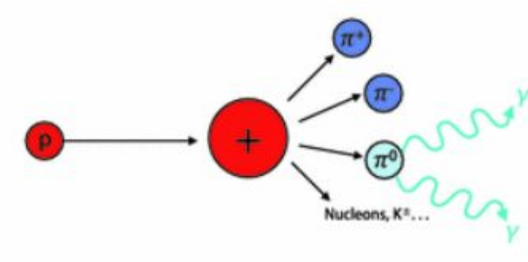
$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \nu_\mu + \bar{\nu}_e + \bar{\nu}_\mu$$

$E_\gamma \sim E_p / 10$
Same spectra than parent population

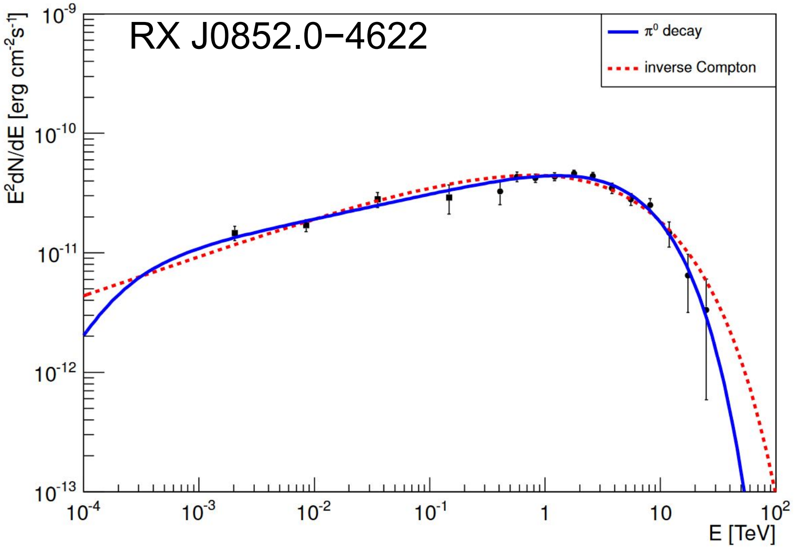
$E_\gamma > \frac{1}{2} m_\pi c^2 = 67.5\ \mathrm{MeV}$

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

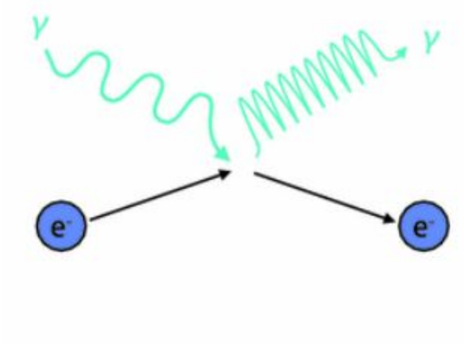
hadronic



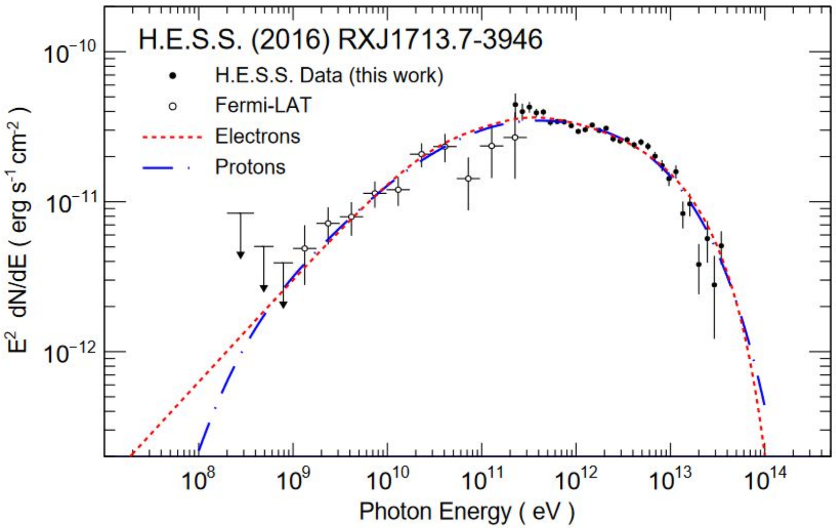
(c) Pion decay



leptonic



(d) Inverse Compton



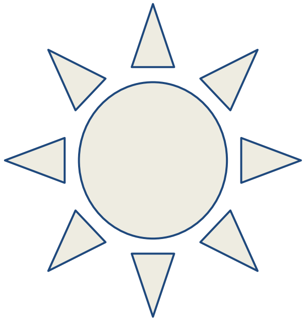
but neutrino production is a smoking gun for hadronic interaction

What do we need to produce gamma-rays ?

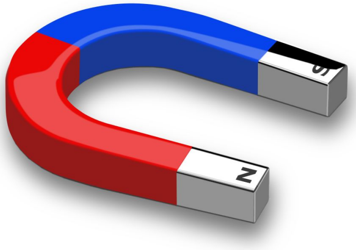
$$\gamma >> 1$$

e-

AND



AND/OR

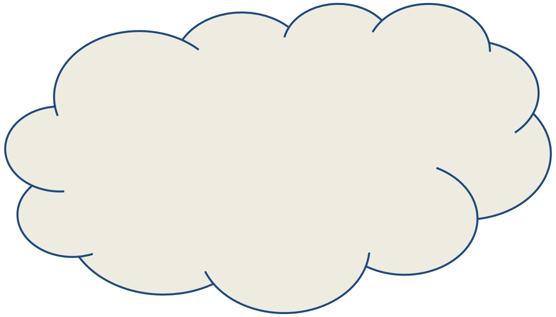


AND/OR

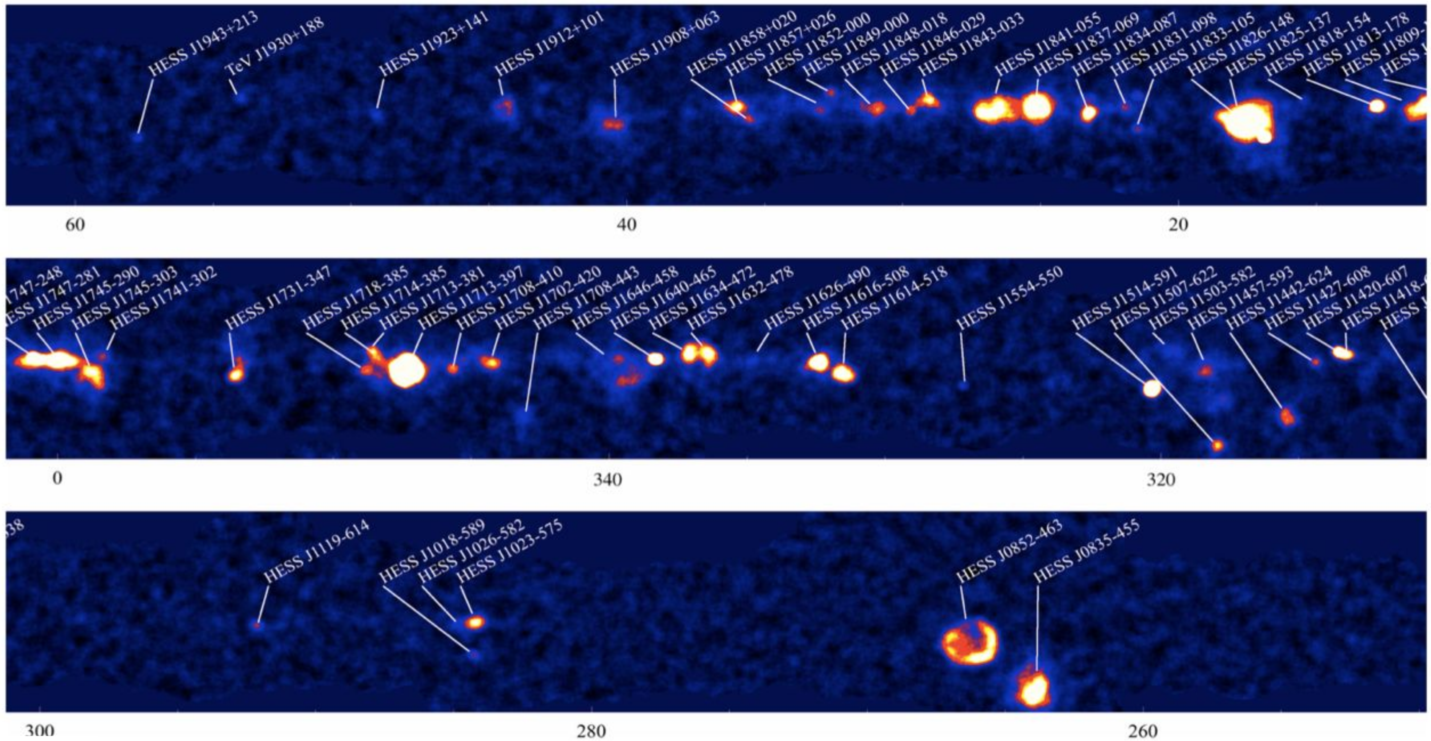
$$\gamma >> 1$$

p

AND



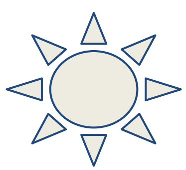
What do we need to produce gamma-rays ?



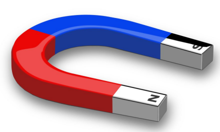
$\gamma >> 1$

e-

AND



AND/OR



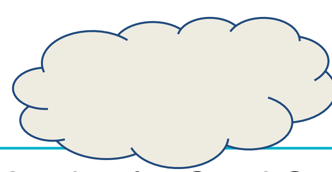
It exists places in our Galaxy (and beyond) that fullfill those criteria

AND/OR

$\gamma >> 1$

p

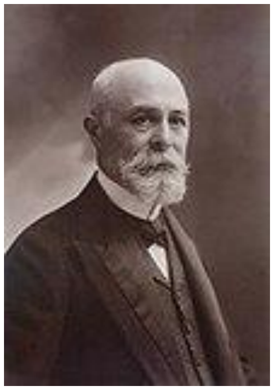
AND



Cosmic rays

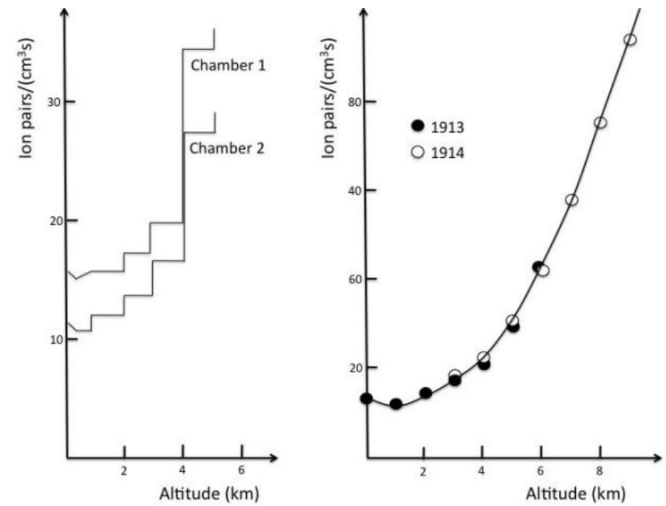
Cosmic rays

1896 : Radioactivity



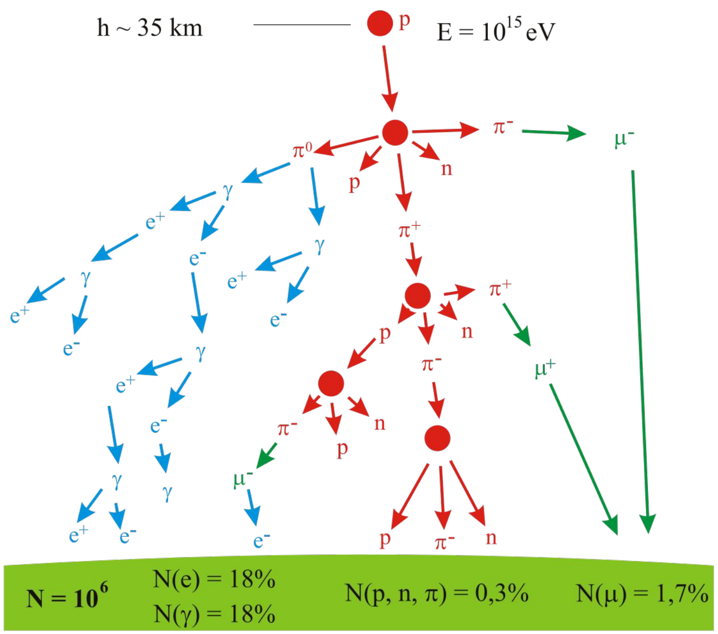
1907-1914 :

cosmic rays are discovered



High energy cosmic rays

- **1939 : Pierre Auger** → detector on ground -> coincidence detector
- Coincidence detection up to ~100m !
- particle of **10^{15} eV** -> ~100 x Large Hadron Collider



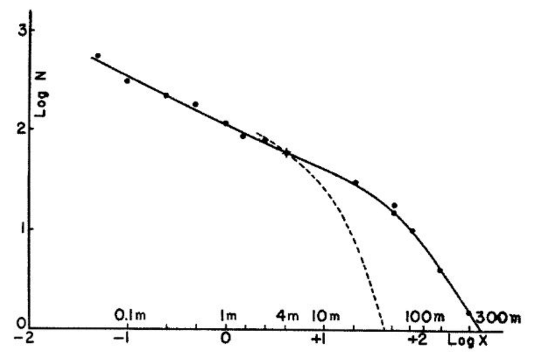
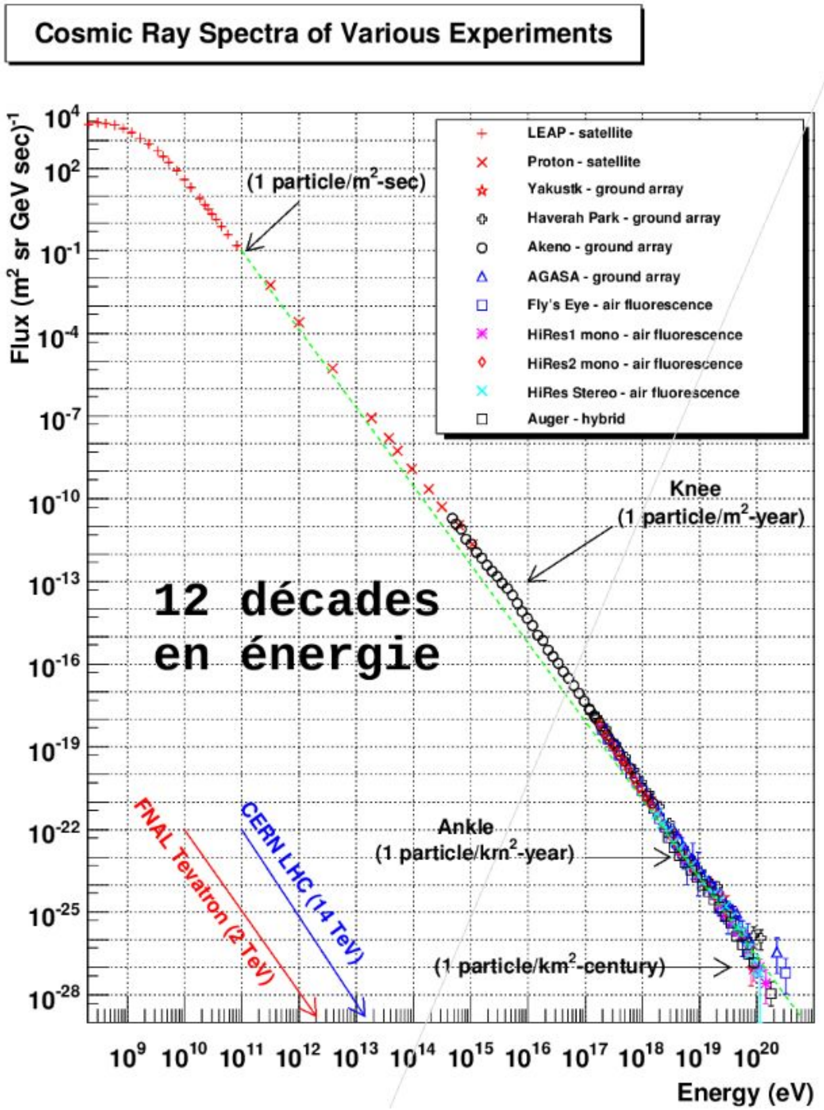


FIG. 1. Results with two parallel and horizontal counters.

CONCLUSION

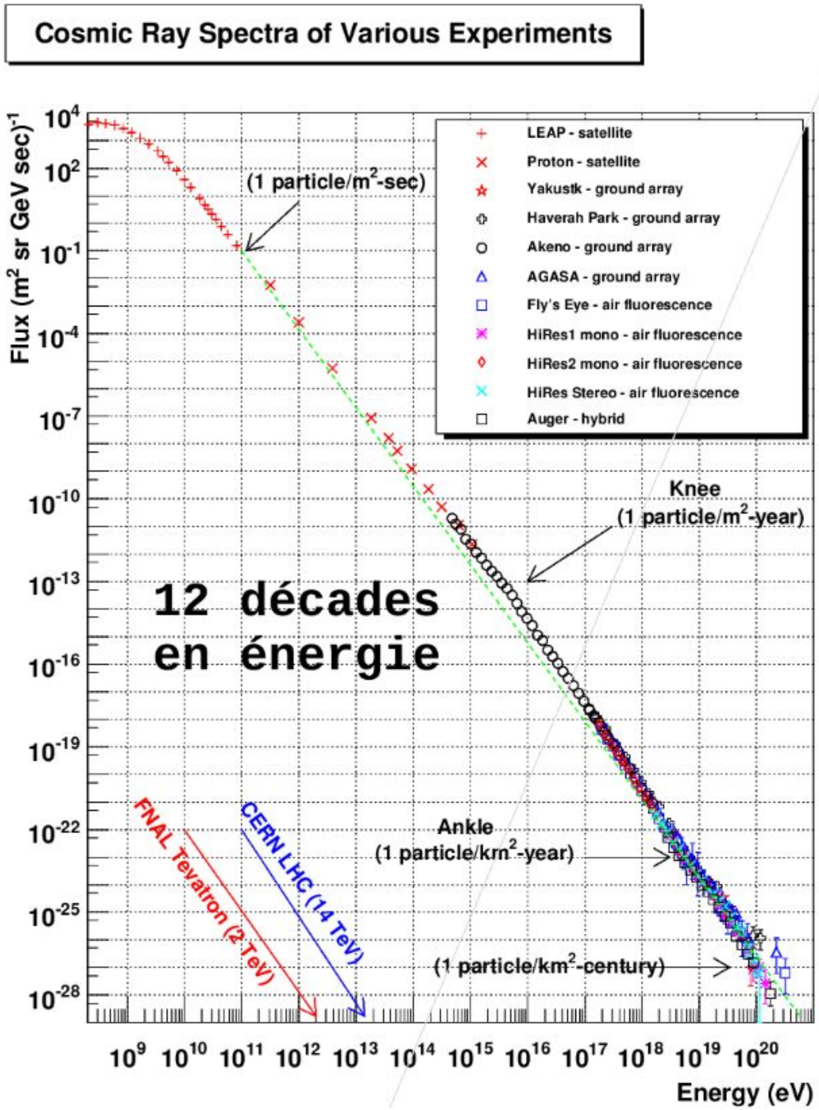
One of the consequences of the extension of the energy spectrum of cosmic rays up to 10^{15} ev is that it is actually impossible to imagine a single process able to give to a particle such an energy.

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 (almost)**
- Need natural particle accelerators

Power law



- Power law spectra :

we suppose a **multiplicative energy increases** after k process

$$E = \beta^k E_0$$

we add a **probability P to escape** after each step

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

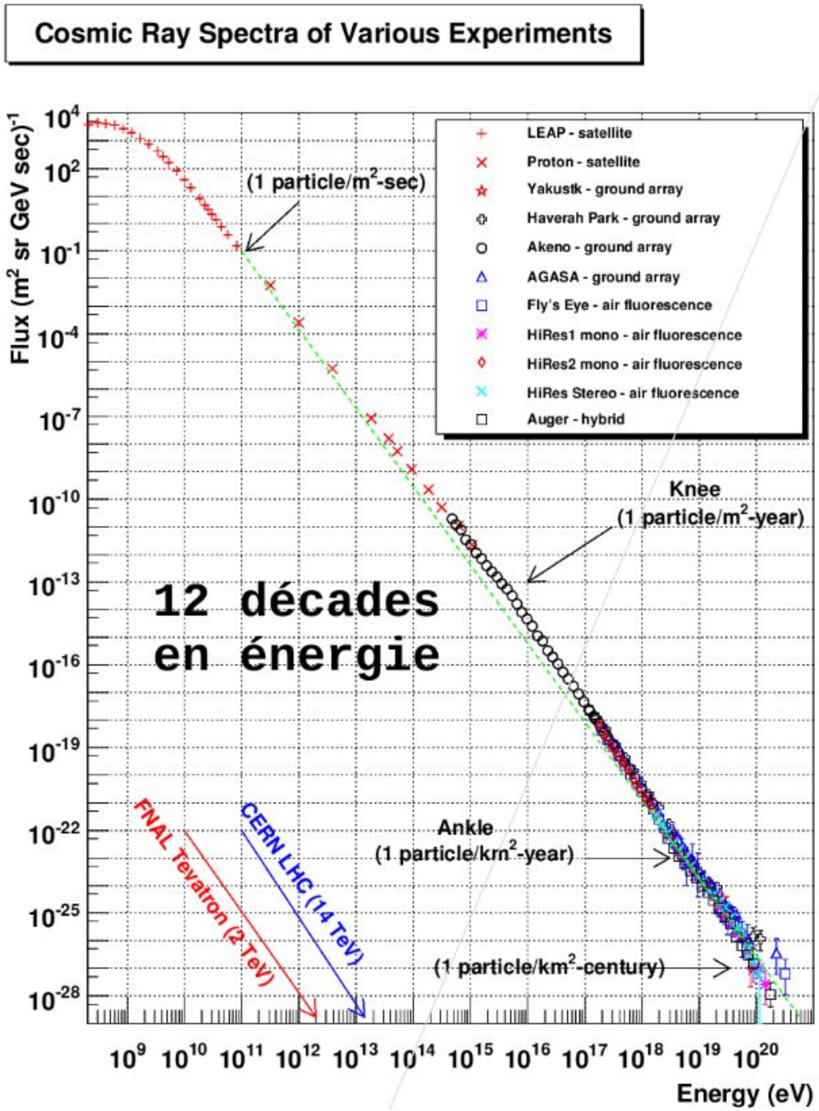
We combine them !

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

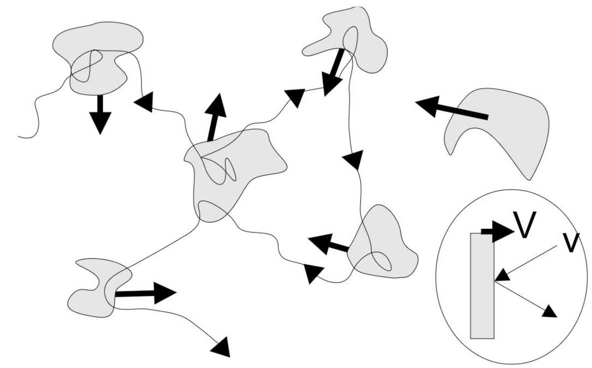
A **power law spectrum** emerges from these very simple assumptions :

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

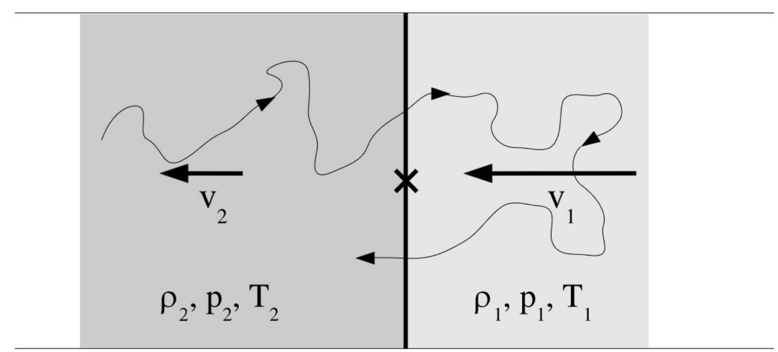
Power law



Second order Fermi acceleration



First order Fermi acceleration



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

Hillas criteria

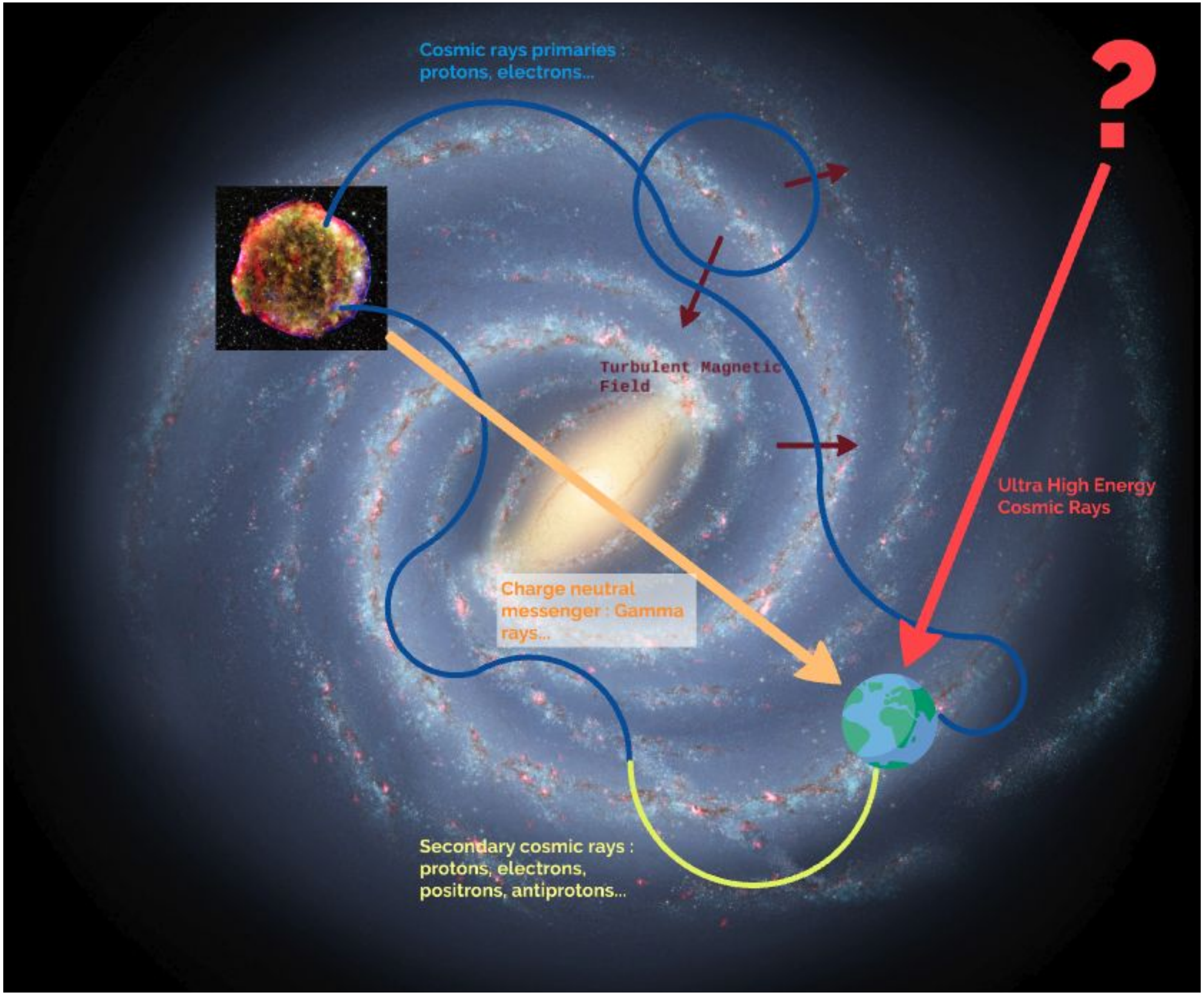
$$Z\left(\frac{r_L}{33km}\right)\left(\frac{B}{1G}\right)=\frac{E_{max}}{1GeV}$$

- 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

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

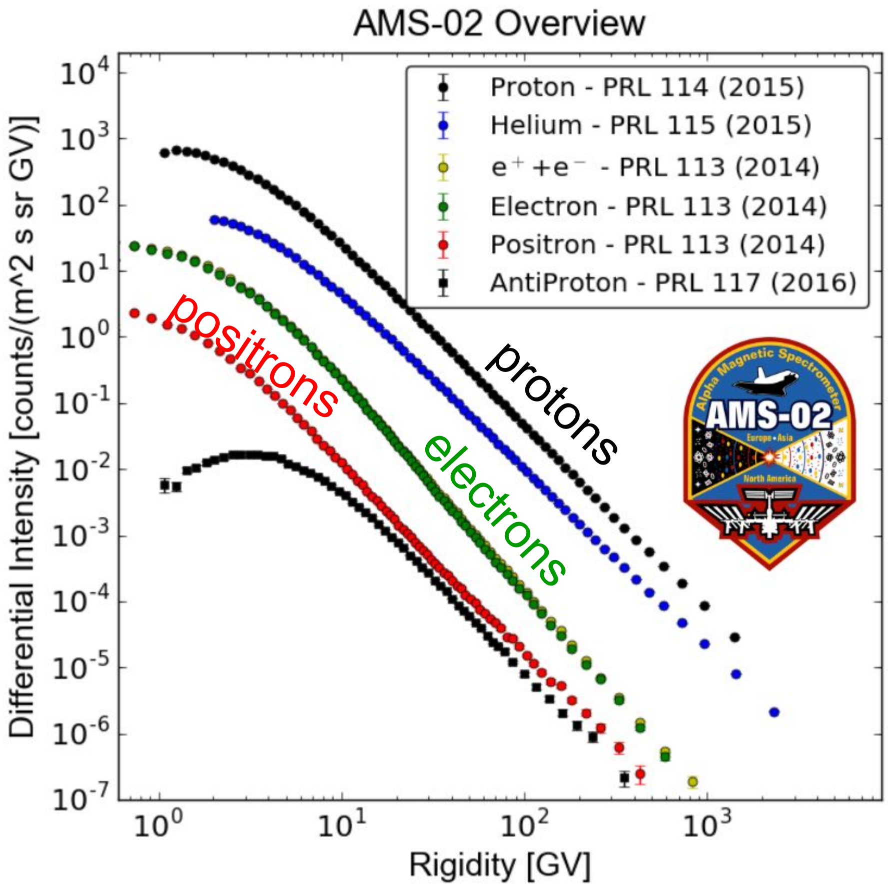
- Let’s take value of the order of our galaxy (1 kpc, 1µG)
  - E = $3*10^{19}$ eV, t = 3.2kyr
- What about a pulsar ? (30 km, 10^{12} G)
  - E = 10^{21} eV, t = 100 µs
- But this formula ignore cooling of charged particle !
- Slow accelerator (galactic halo here) will be more affected by cooling ! Leptonic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

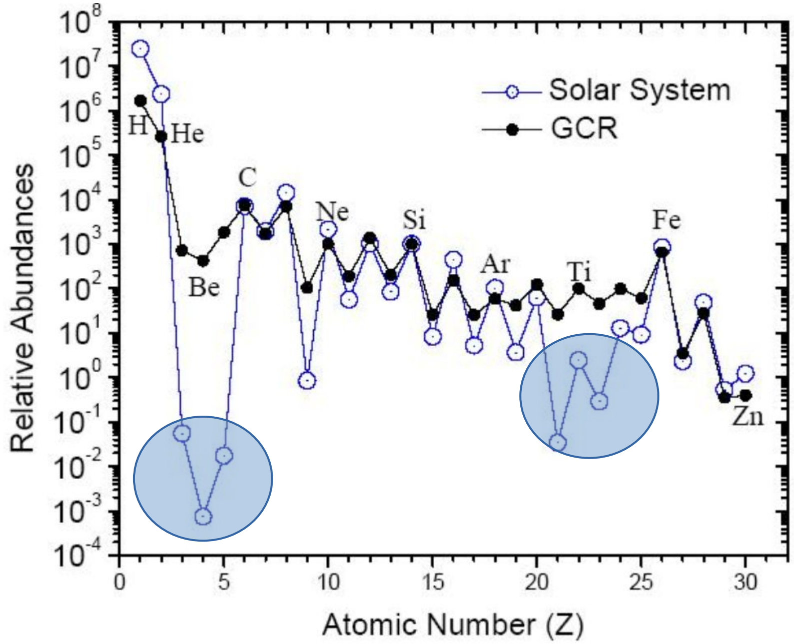
Cosmic messengers



Galactic Cosmic rays

https://ams02.space/collaboration

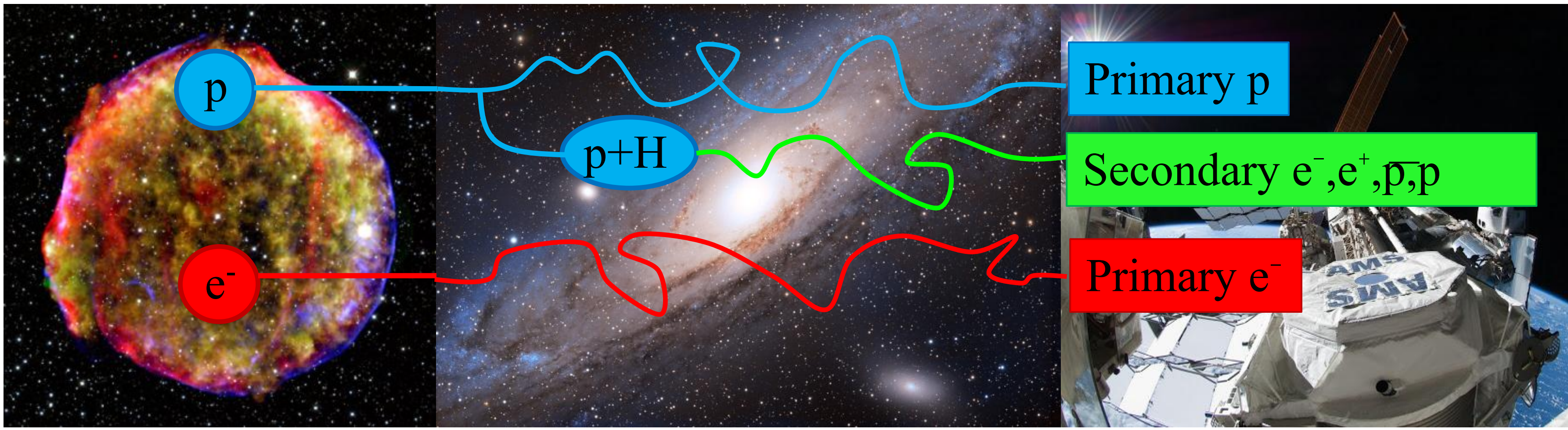




- **Composition** ~90 % protons ~10% helium ~1 % electrons ~0.1 % positrons → dominated by matter
- Difference in abundance compared to GCR due to spallation

Galactic cosmic rays

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

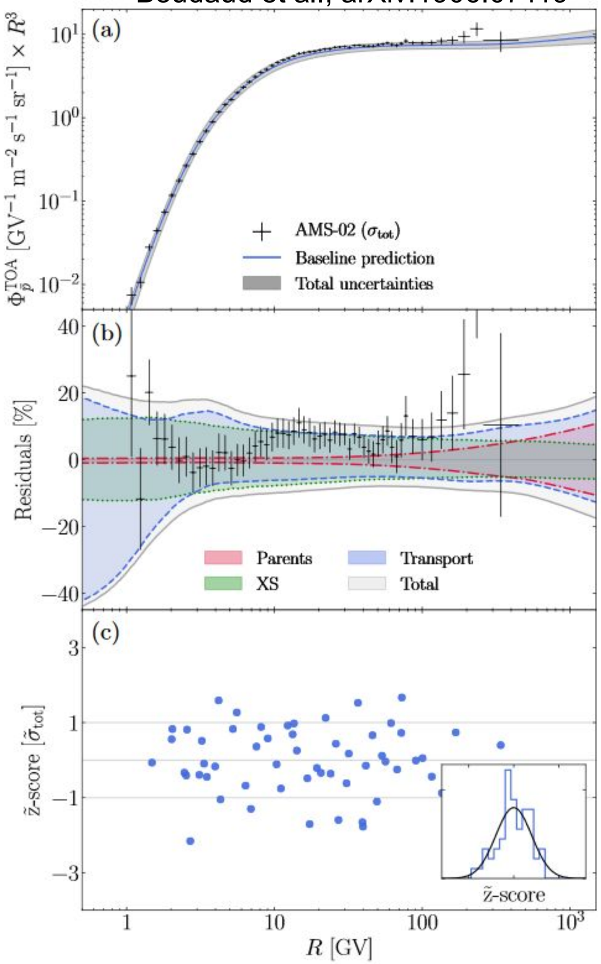


- Accelerator accelerates surrounding **Interstellar medium matter**
- Galactic diffusion due to **turbulent magnetic field**
- Detection at Earth → **primary CR**
- **Interaction with interstellar medium** → production of secondary cosmic ray
- Mainly **p+H collisions** permit to **enrich the cosmic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

Secondary antimatter flux at Earth

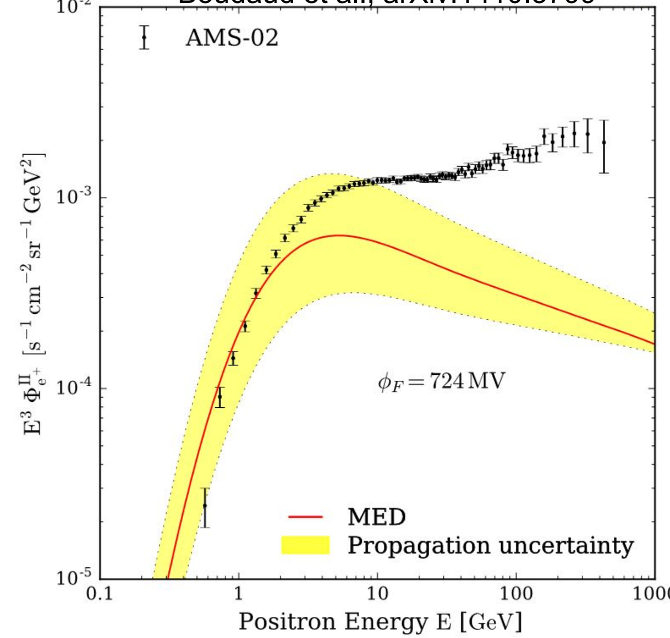
Antiprotons

Boudaud et al., arXiv:1906.07119



Positrons

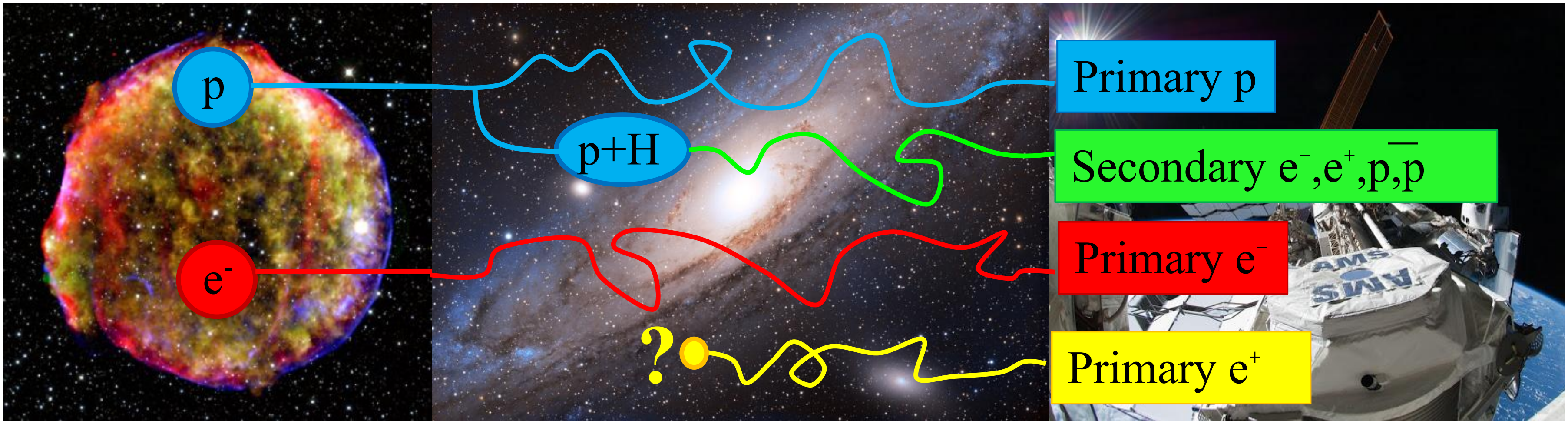
Boudaud et al., arXiv:1410.3799



- 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

Implication for gamma-rays

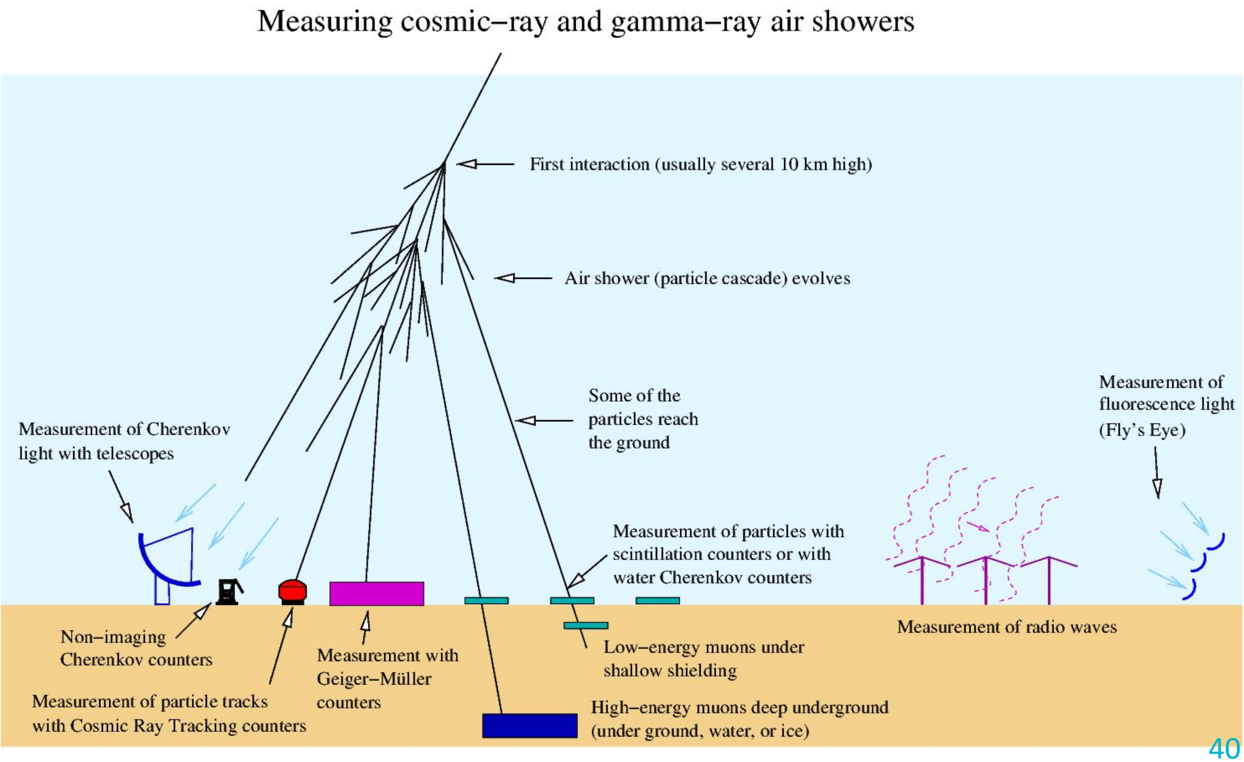
- Leptonic accelerators are believed to be more bright in gamma-rays (Lorentz factor dependency)
- According to galactic cosmic rays, it exists hadronic accelerators in our galaxy, and those accelerators should accelerate up to at least ~1PeV (translated to gamma-ray 100 TeV !)
- It should exists even 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 produce gamma-rays)...
- … of course it is not enough to be compact, we need to have an engine to accelerates the charged particles
- 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

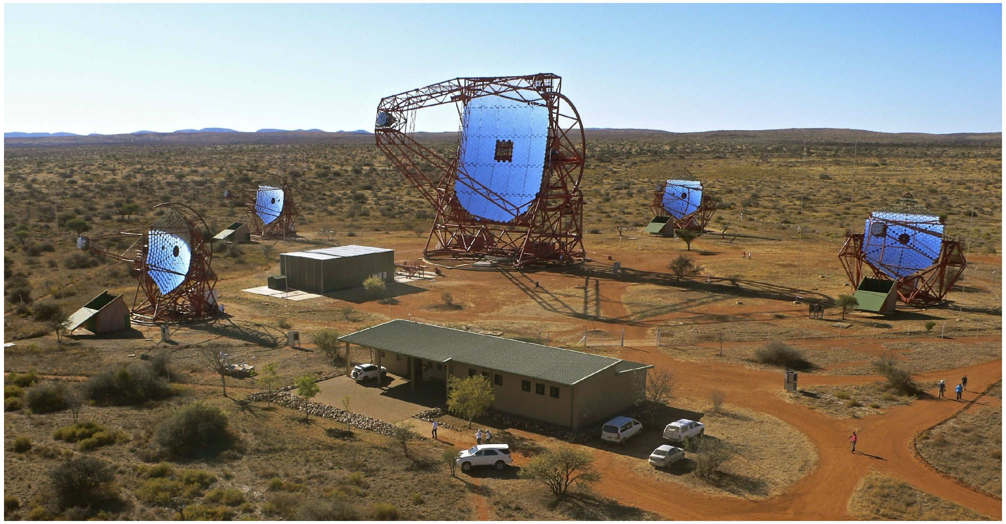
https://fermi.gsfc.nasa.gov/



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

Indirect detection of gamma rays

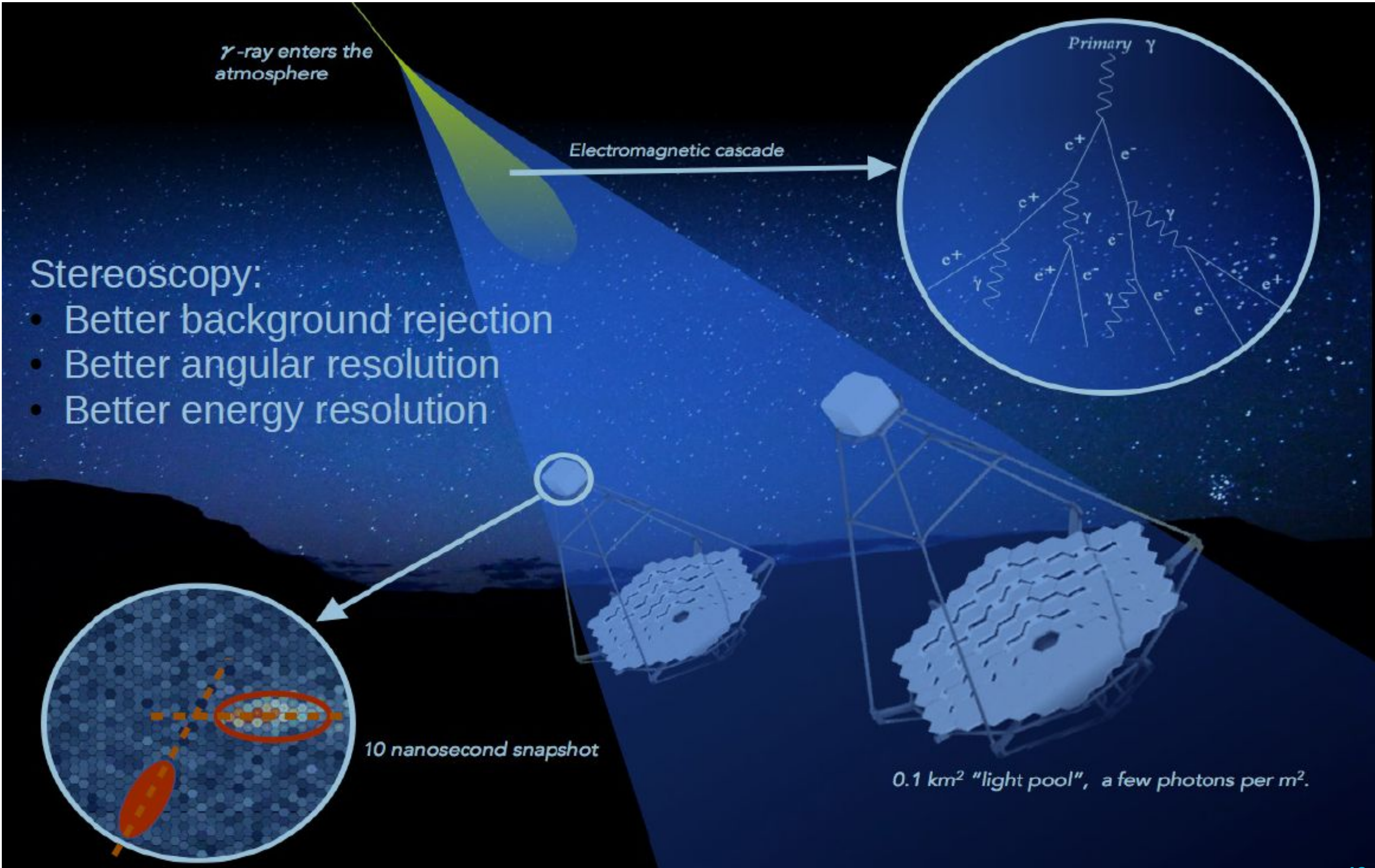
- **IACTs → Imaging Atmospheric Cherenkov Telescope**
- Cherenkov light produced in air
- **Pro :**
  - Good precision in terms of angular resolution (~0.1°) and energy resolution (~10-15%)
- **Cons :**
  - Narrow field of view (~5°)
  - Night observation, affected by weather and full moon (and light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



https://www.hawc-observatory.org/

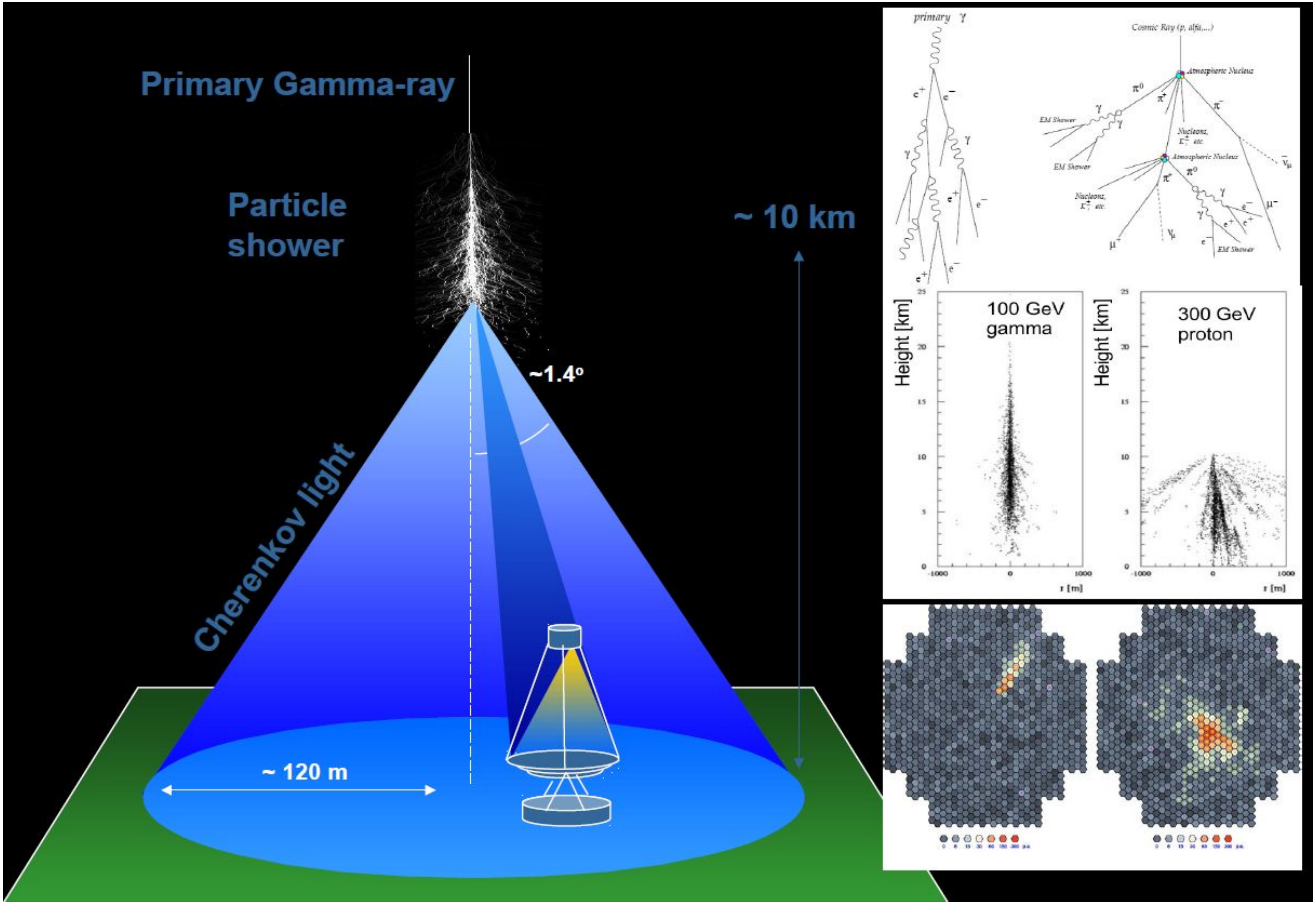
- **Water Cherenkov Array**
- Secondary particles cherenkov in water tank
- **Pro :**
  - Vast field of view (15% of the sky)
  - Can work 24/24 7/7
- **Cons :**
  - Less precise in terms of angular resolution (0.75° @ 1 TeV, 0.3° @ 10TeV) and of energy resolution (95% @ 1TeV, 50% @ 10TeV)

Detection principle



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

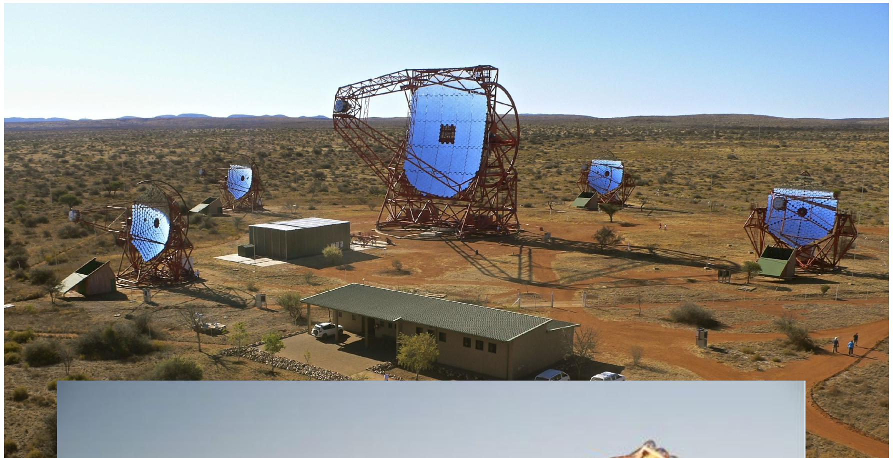
Detection principle



The Gamma Game

https://vuillaut.github.io/gamma-ray-game/game.html

Observatories



H.E.S.S.
- Namibia (South Hemisphere)
- 5 telescopes (28m + 12m)

https://www.mpi-hd.mpg.de/hfm/HESS/

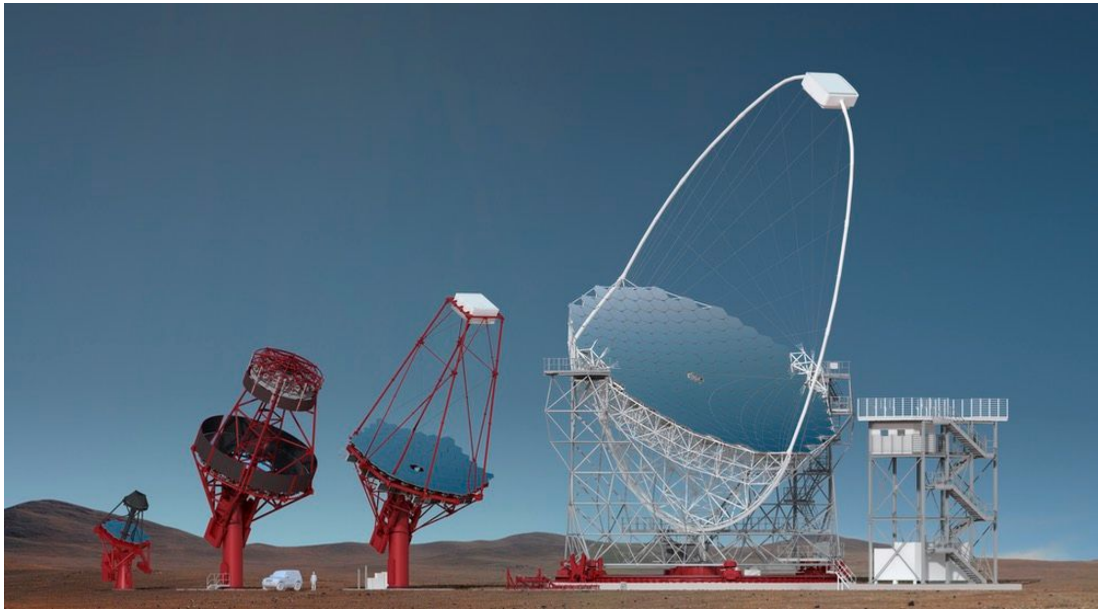
MAGIC
- Canarie Island, La Palma (North Hemisphere)
- 2 telescopes (17m)

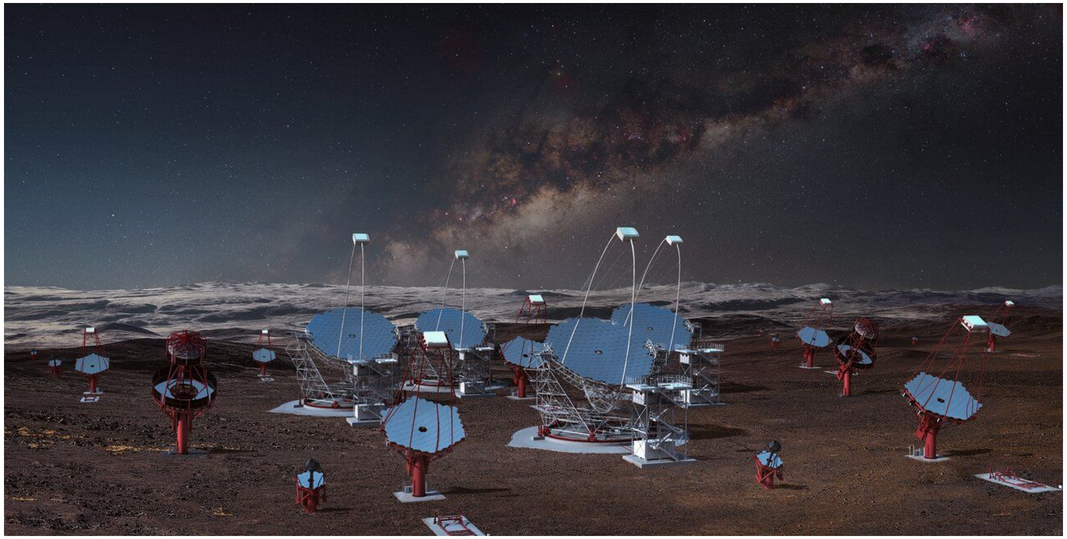
https://magic.mpp.mpg.de/

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

https://veritas.sao.arizona.edu/

Future observatory - CTAO





https://www.cta-observatory.org/

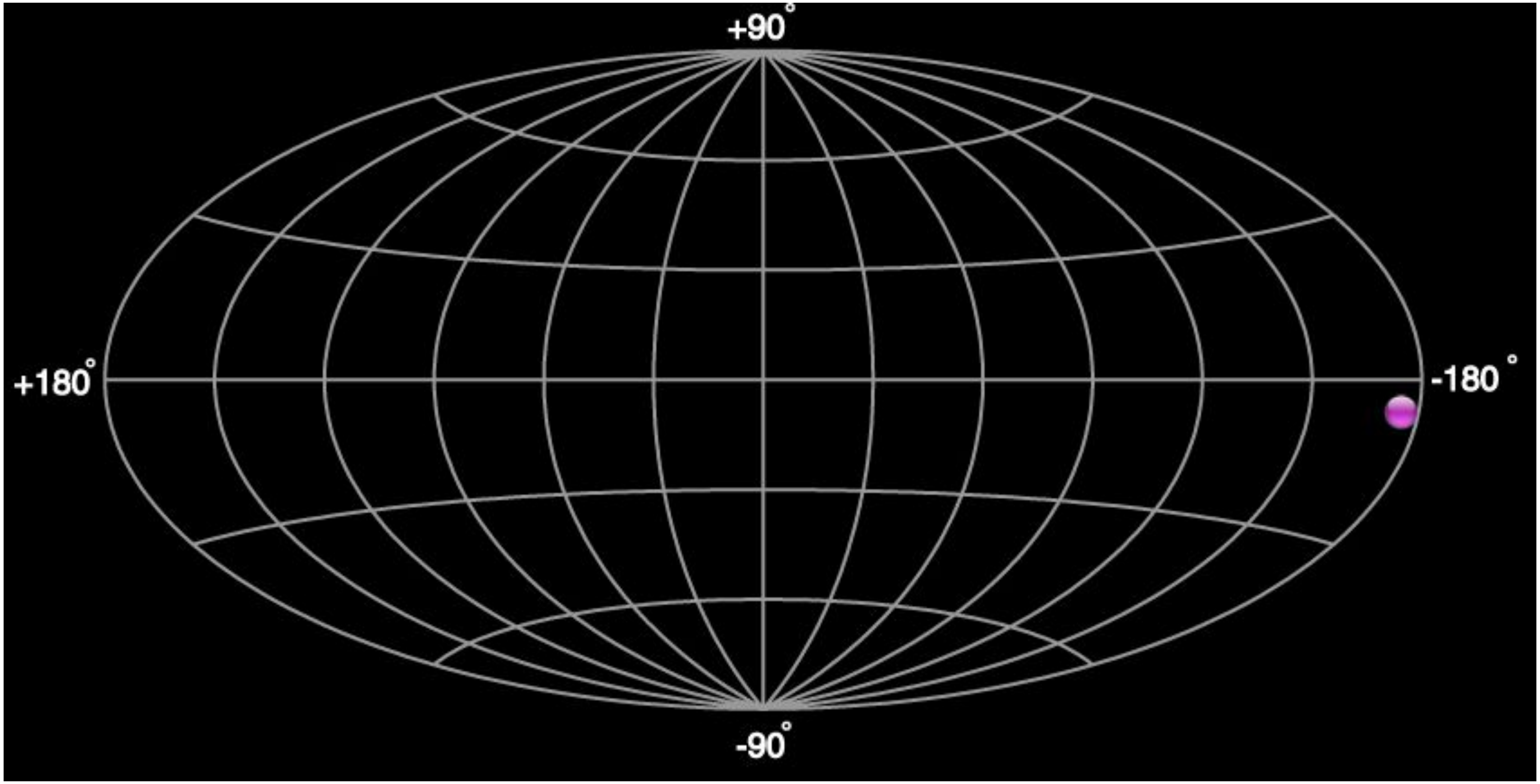
- 3 types of telescopes :
  - LST (23 m)
  - MST (12 m)
  - SST (4.3 m)
- Optimized for various energies :
  - 20 GeV – 3 TeV
  - 80 GeV - 50 TeV
  - 1 TeV - 300 TeV
- ~100 telescopes on two sites :
  - La Palma (hémisphère Nord)
  - Paranal (hémisphère Sud)

Gamma ray Galactic sky

Bestiary of gamma ray astronomy

Sources

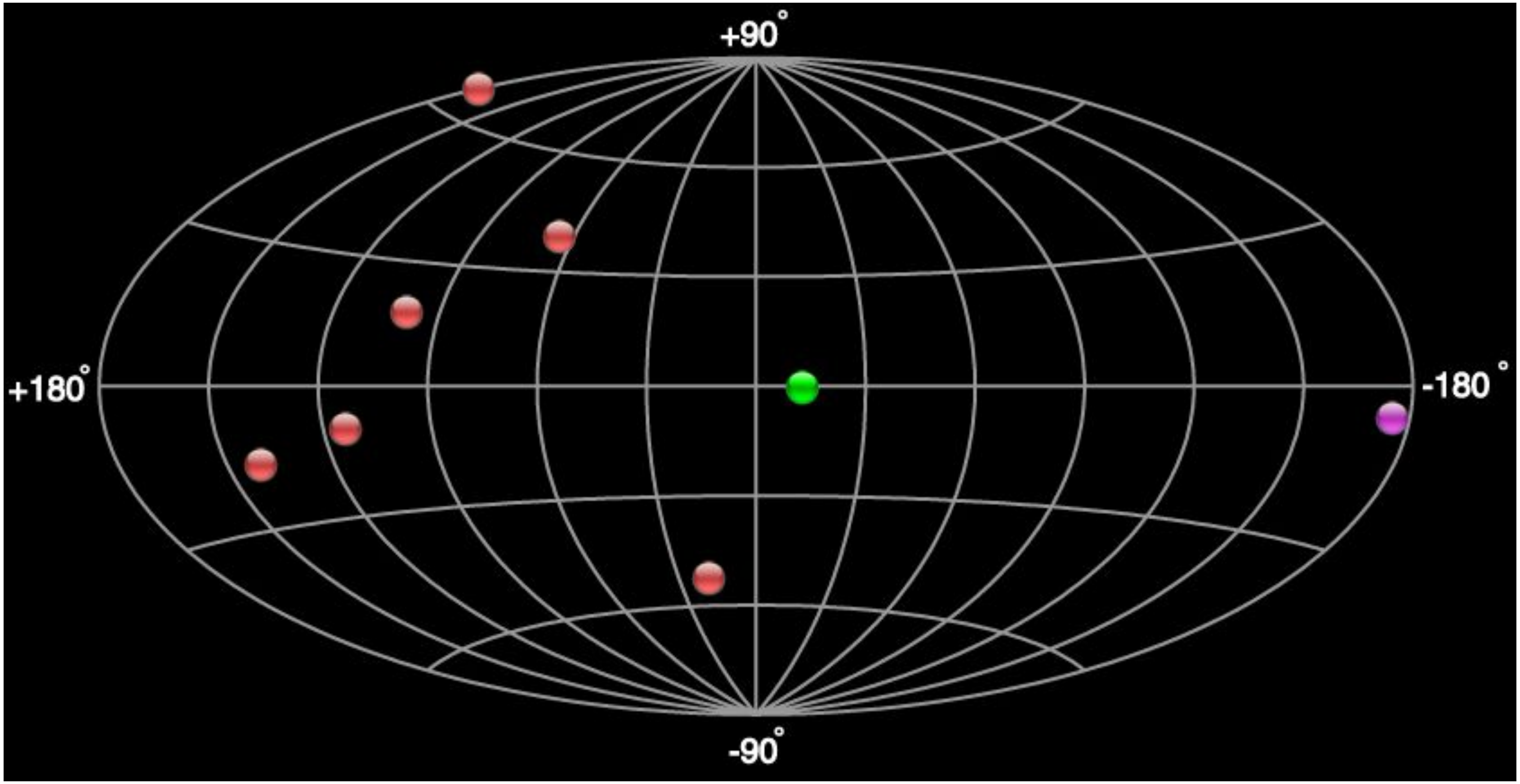
1990



http://tevcat.uchicago.edu/

Sources

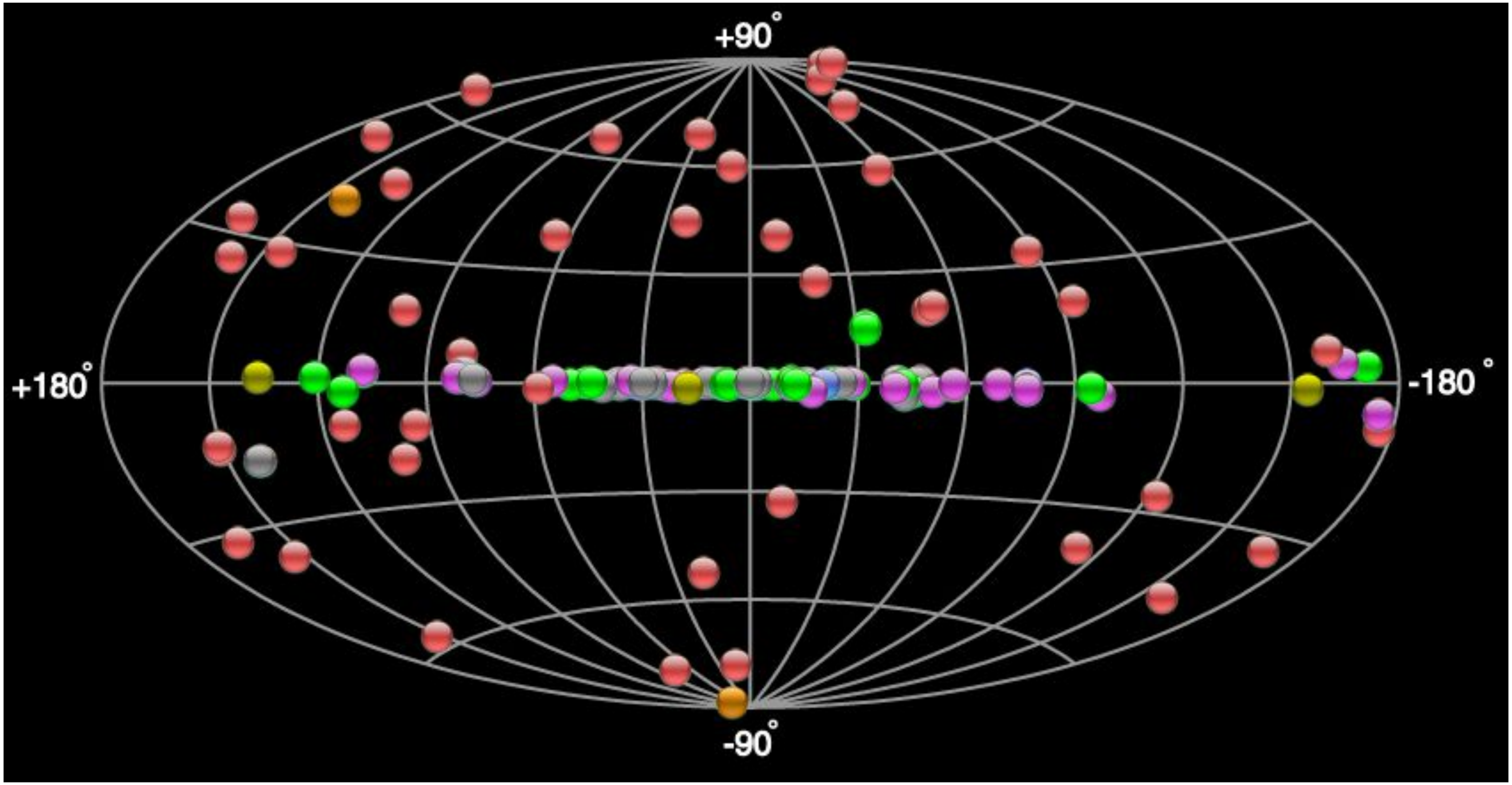
2000



http://tevcat.uchicago.edu/

Sources

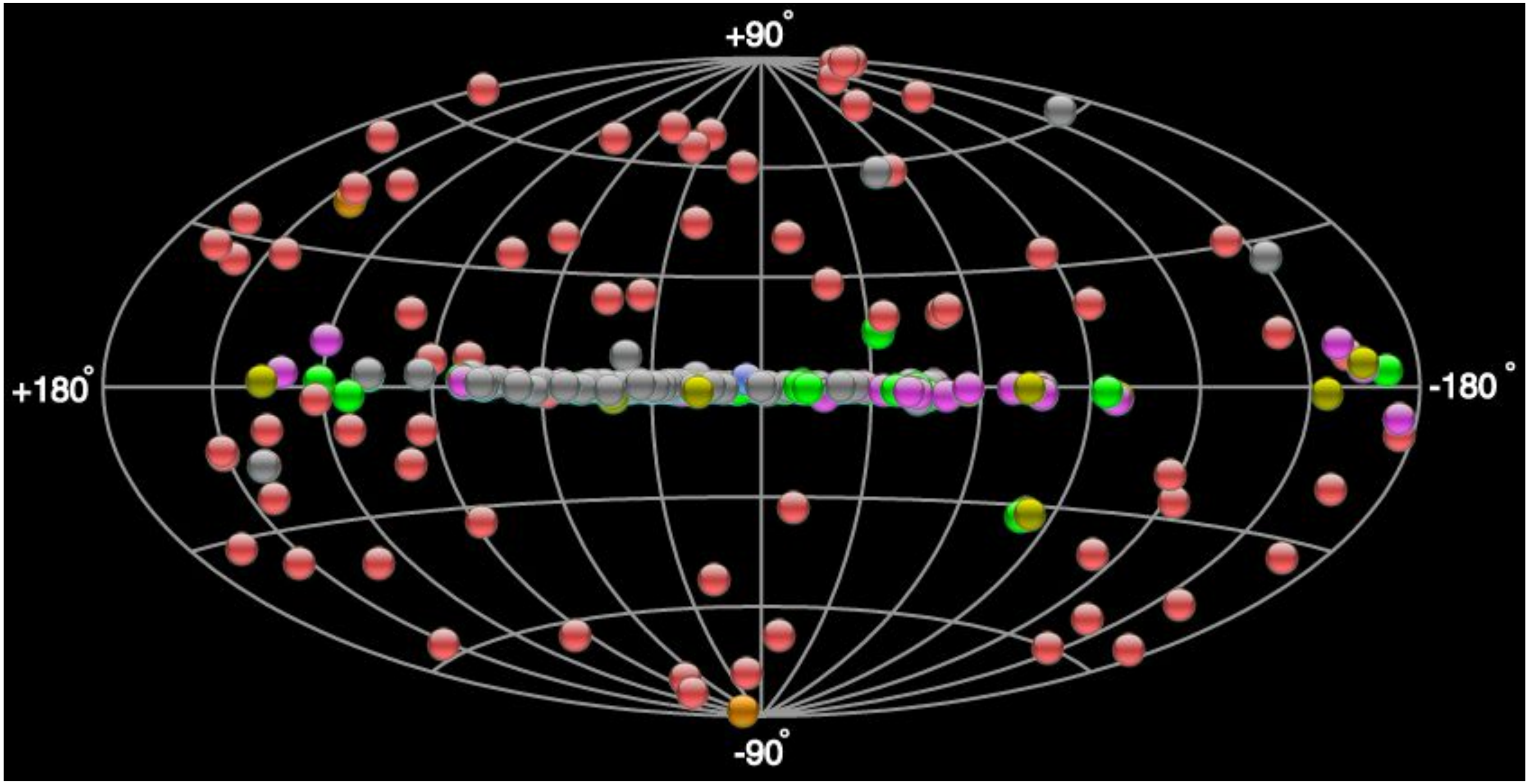
2010



http://tevcat.uchicago.edu/

Sources

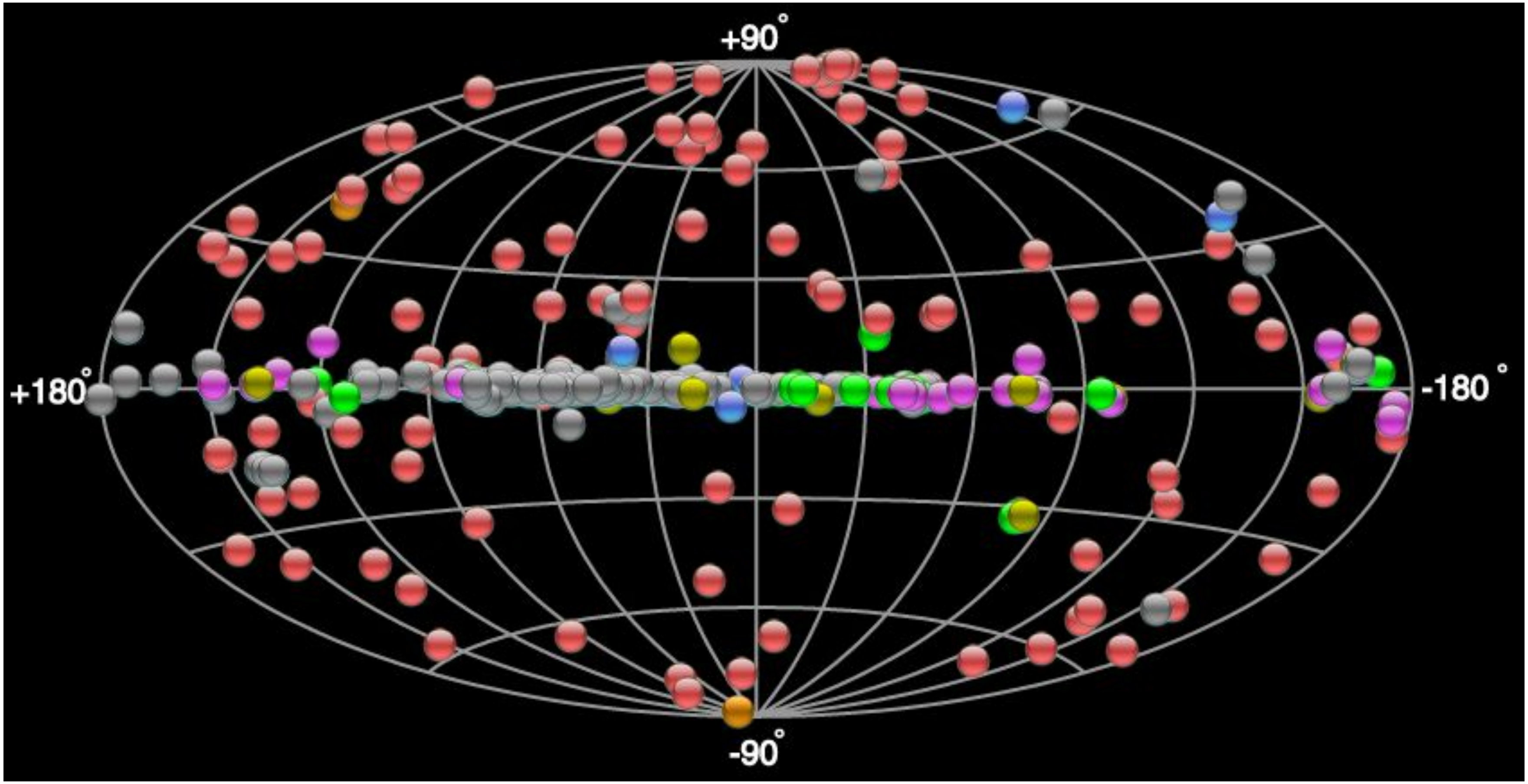
2021



http://tevcat.uchicago.edu/

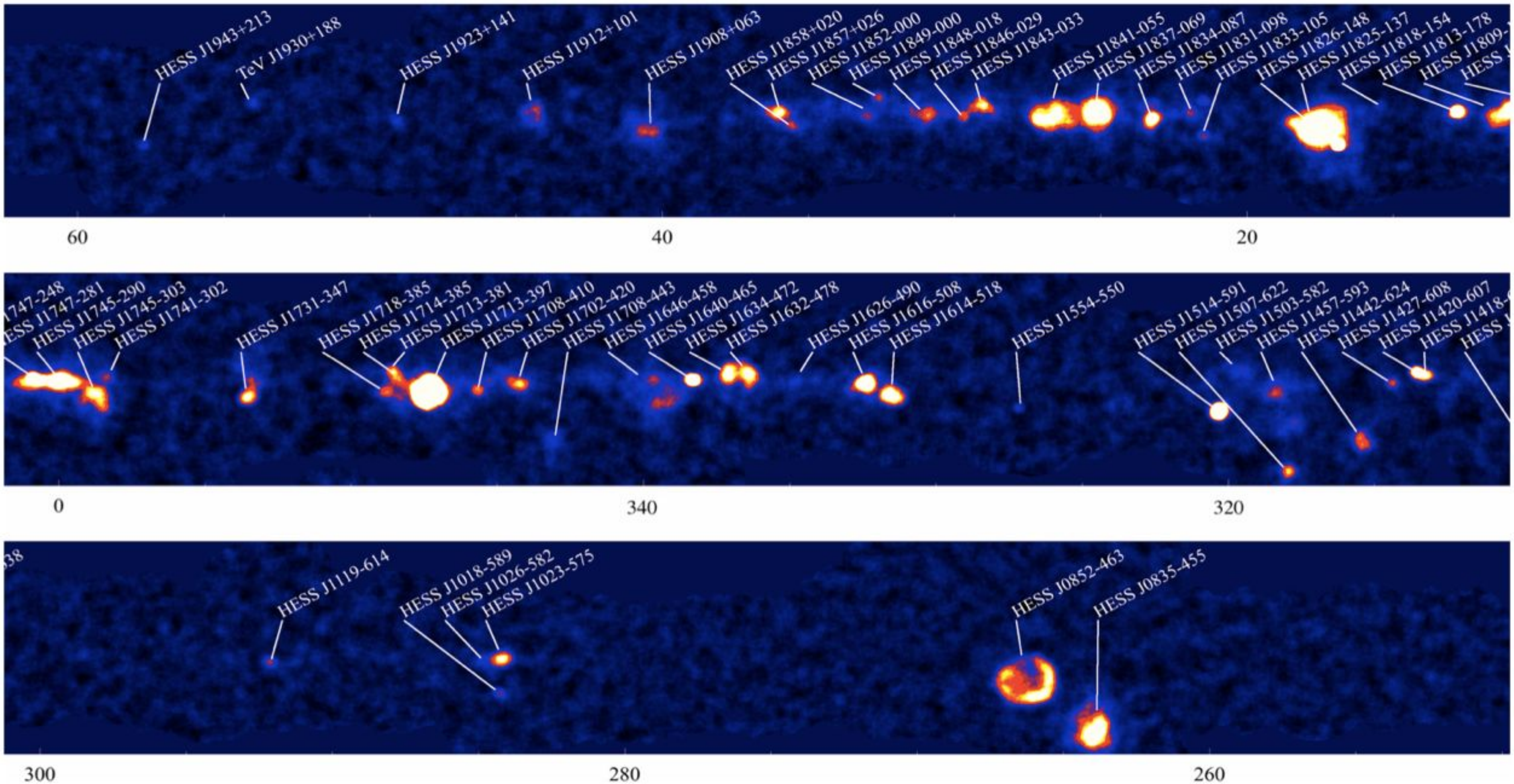
Sources

2025



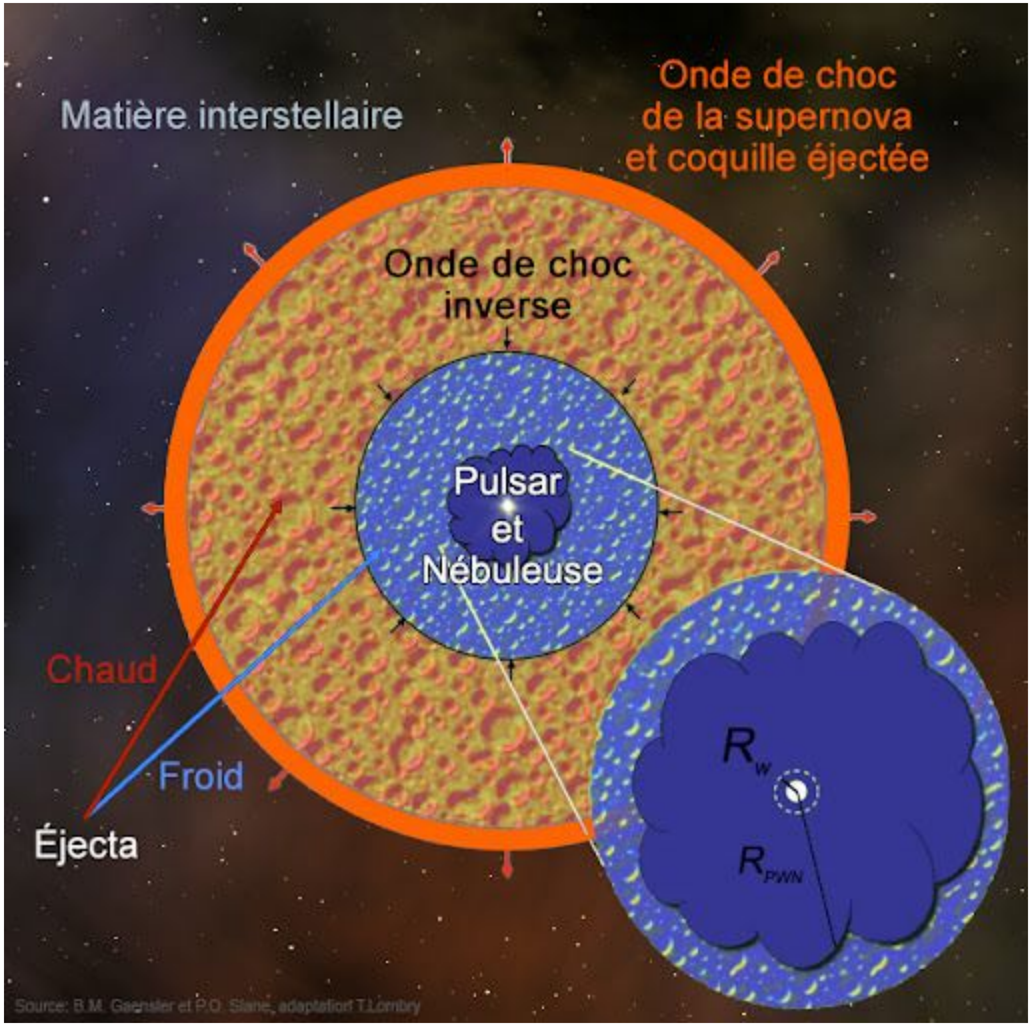
http://tevcat.uchicago.edu/ 315 sources

Galactic sources



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

Supernova remnant and pulsar wind nebula

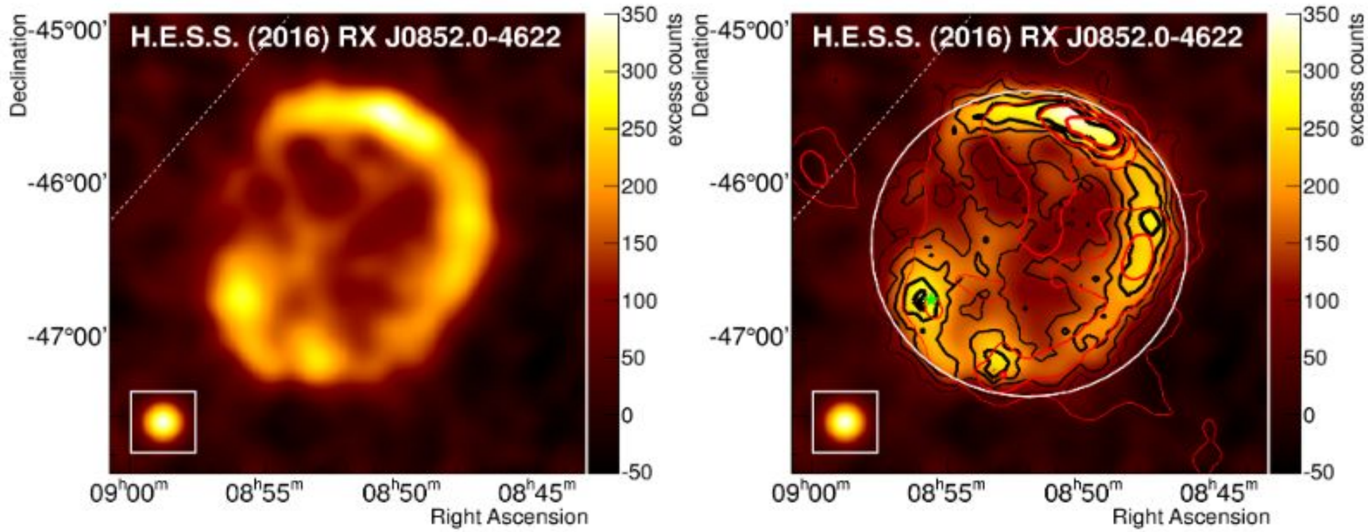


- Explosion of massive star due to exhausted source of energy
- Shock wave + compact core (neutron star)
- Interstellar matter accelerated by shockwave →supernova remnant
- Leptonic production by the pulsar (rotating neutron star + strong magnetic field)→ pulsated emission + pulsar wind nebula

Supernova remnant

RXJ0852.0-4622

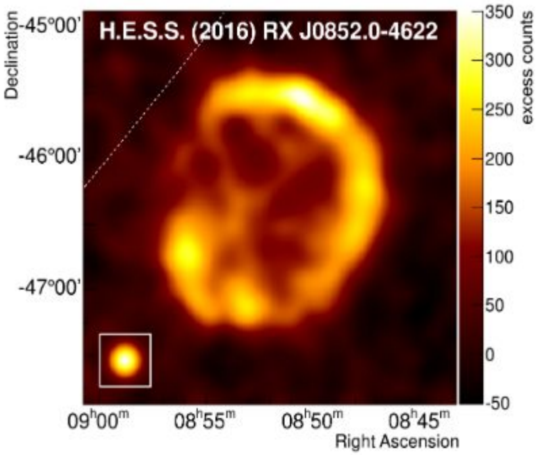
https://hal.archives-ouvertes.fr/hal-02410561/document

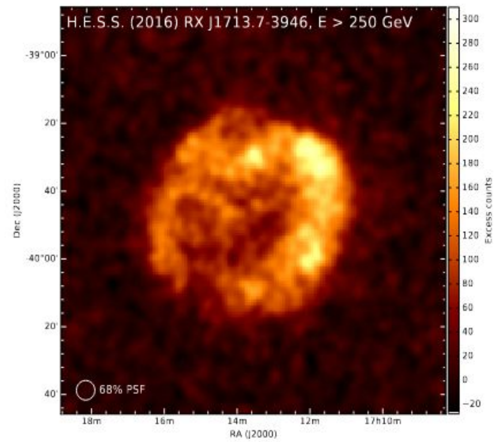


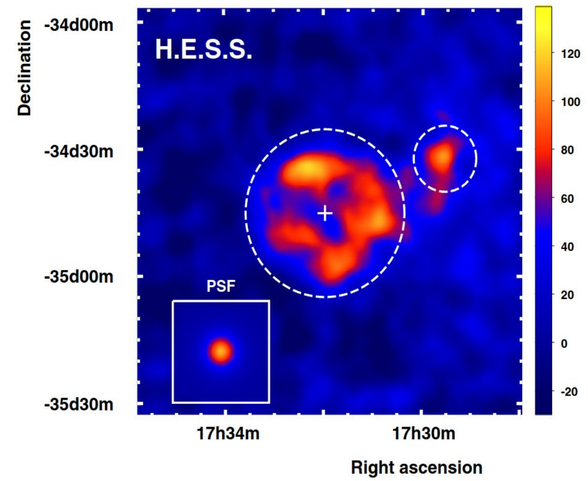
- **Shell like shape smoking gun for supernova remnant (allowed by the good angular resolution of the instrument)**
- **Correlation** of X-ray and gamma-ray (presence of **shock wave** and **highly energetic particles)**
- Open questions :
  - Able to accelerate **up to PeV (100 TeV gamma-rays)** ?
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

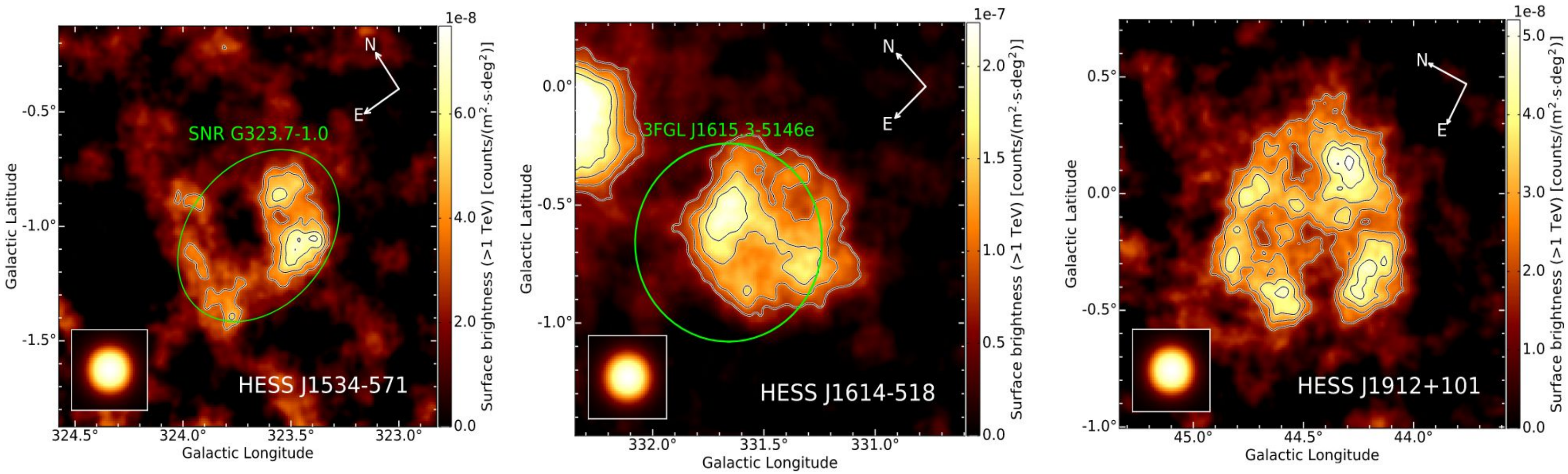
Supernova remnant

http://arxiv.org/abs/1609.08671 https://arxiv.org/abs/1105.3206





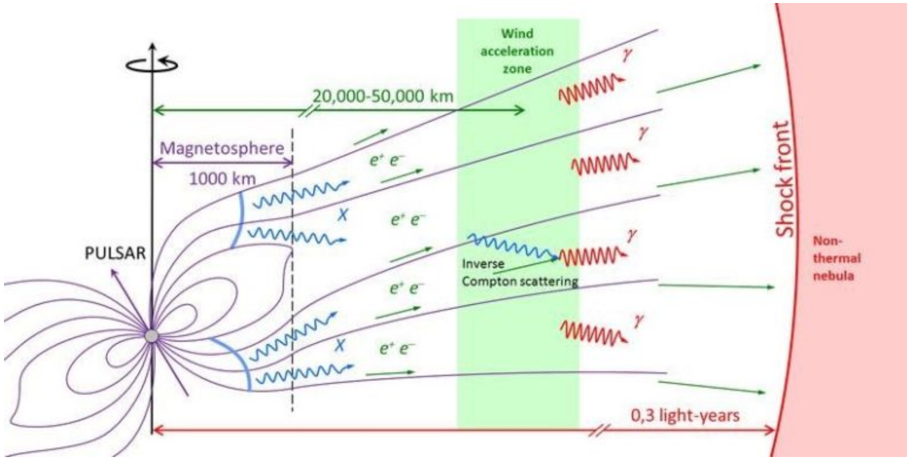




https://arxiv.org/abs/1801.06020

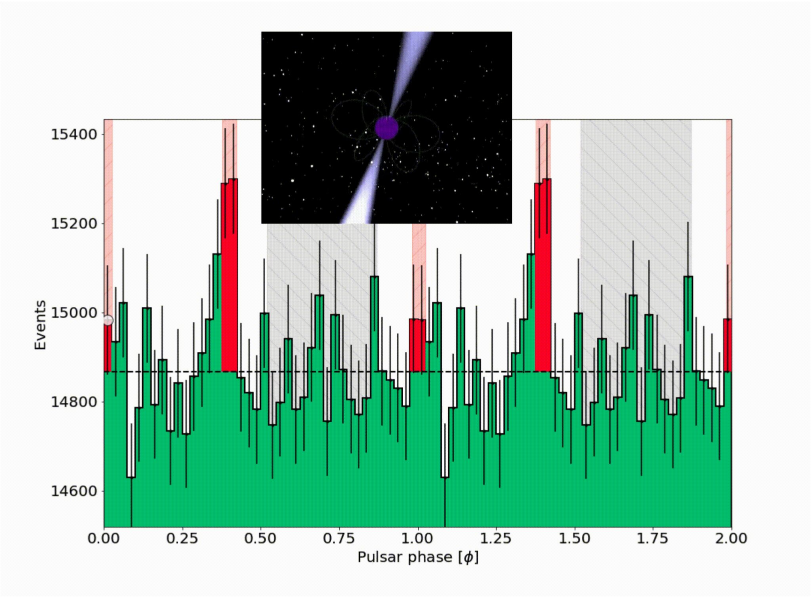
Pulsars

https://arxiv.org/abs/1207.0458

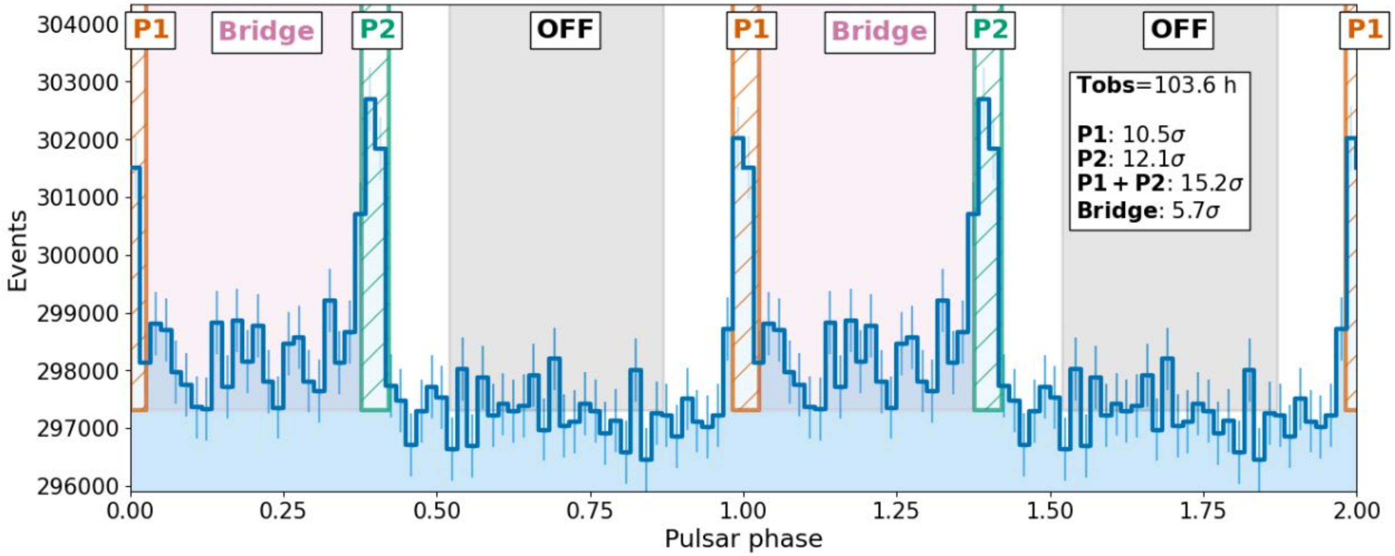


- Strong electric field at the surface of the neutron star due to rotating magnetic field
- Charged particle accelerated, pair production (leptonic)
- Crab pulsar period ~33 ms, pulsated emission permits to compute the rotational speed (and so on the rotational energy of the pulsar for example)

Crab Pulsar



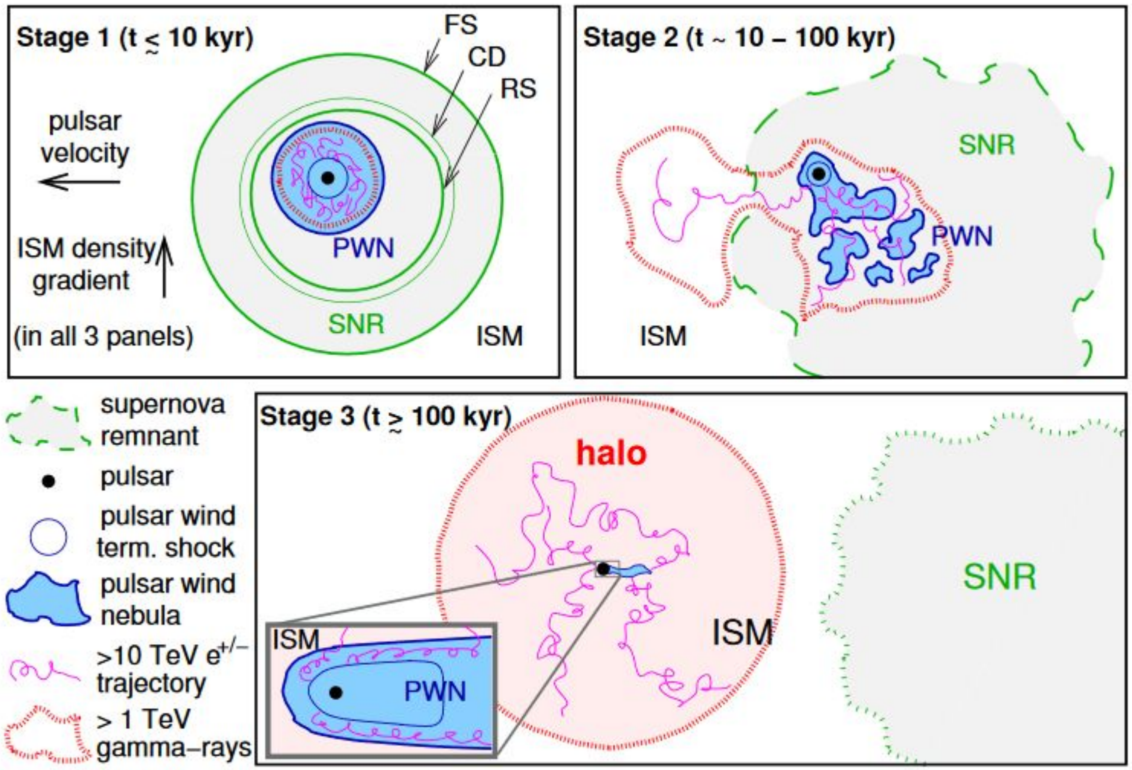
Events
15400
15200
15000
14800
14600
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Pulsar phase [ϕ]



P1
Bridge
P2
OFF
P1
Bridge
P2
OFF
P1
Tobs=103.6 h
P1: 10.5σ
P2: 12.1σ
P1 + P2: 15.2σ
Bridge: 5.7σ
Events
304000
303000
302000
301000
300000
299000
298000
297000
296000
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
Pulsar phase

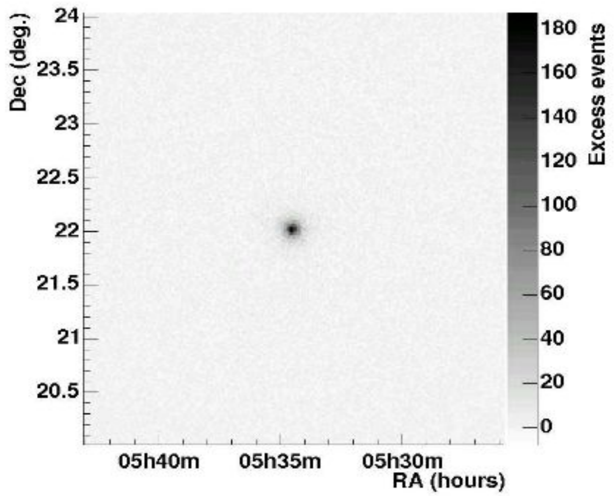
Pulsar wind nebulae - halo

https://arxiv.org/abs/1907.12121

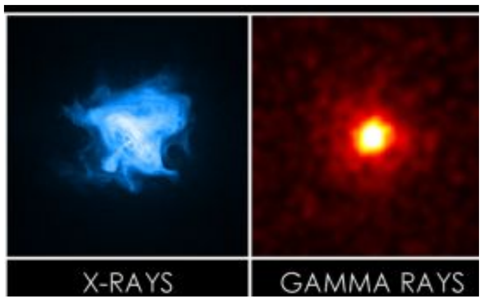


https://arxiv.org/pdf/astro-ph/0607333

Crab Nebula
~1000 years

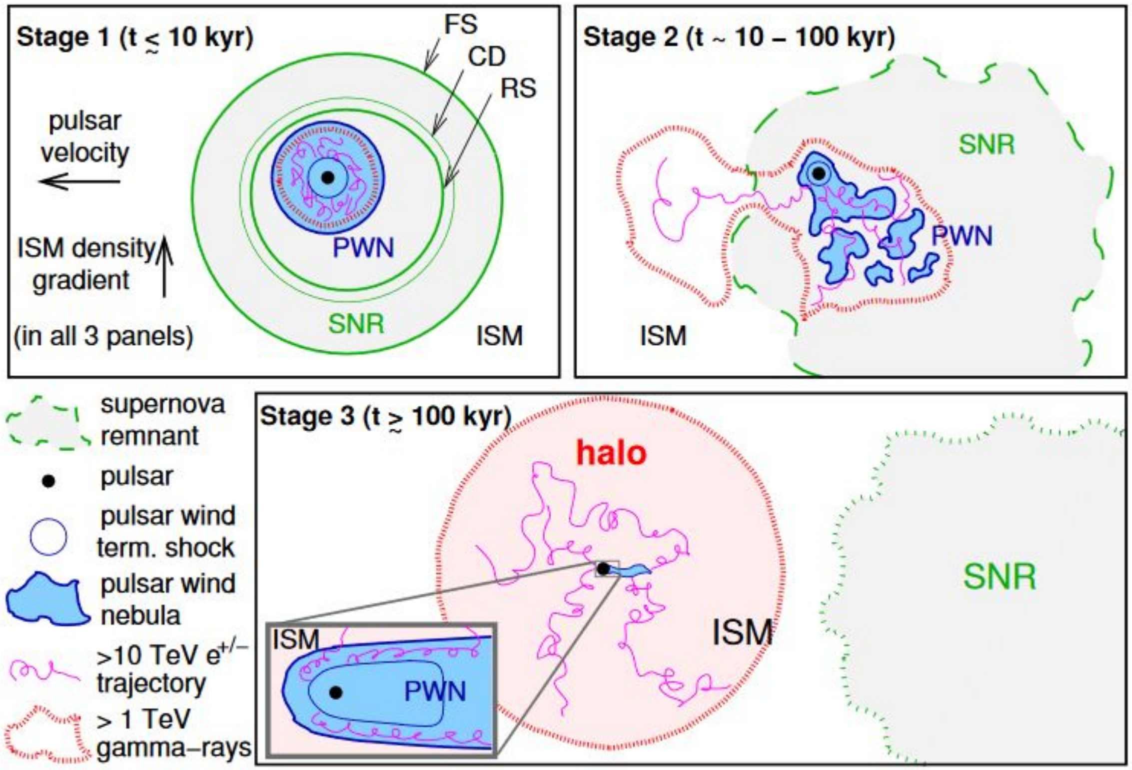


- Associated with the historic supernova SN1054
- Stable and bright
  - Nebula stable because because of its size (11 ly)
  - Bright because leptonic



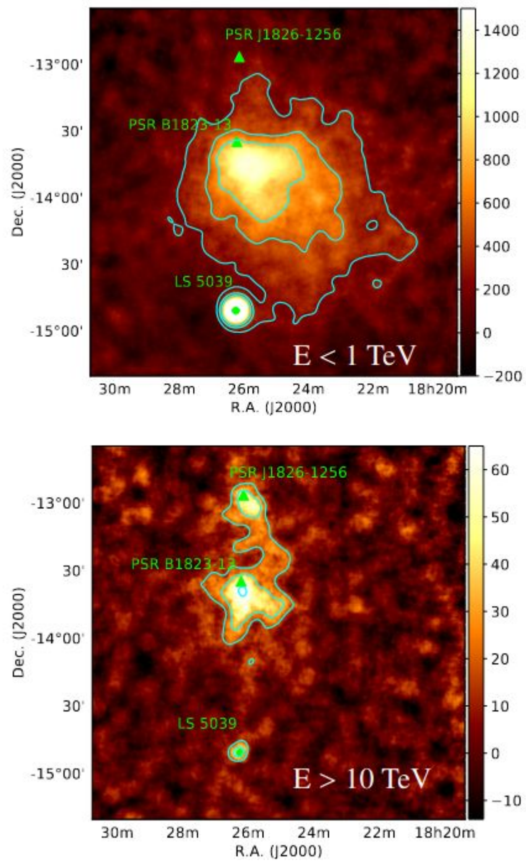
Pulsar wind nebulae - halo

https://arxiv.org/abs/1907.12121



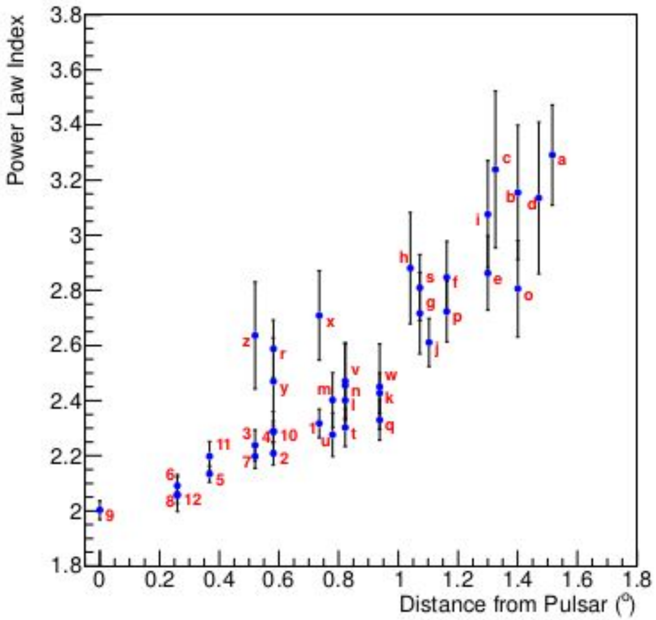
https://arxiv.org/abs/1810.12676

HESS J1825-137
22000 ans

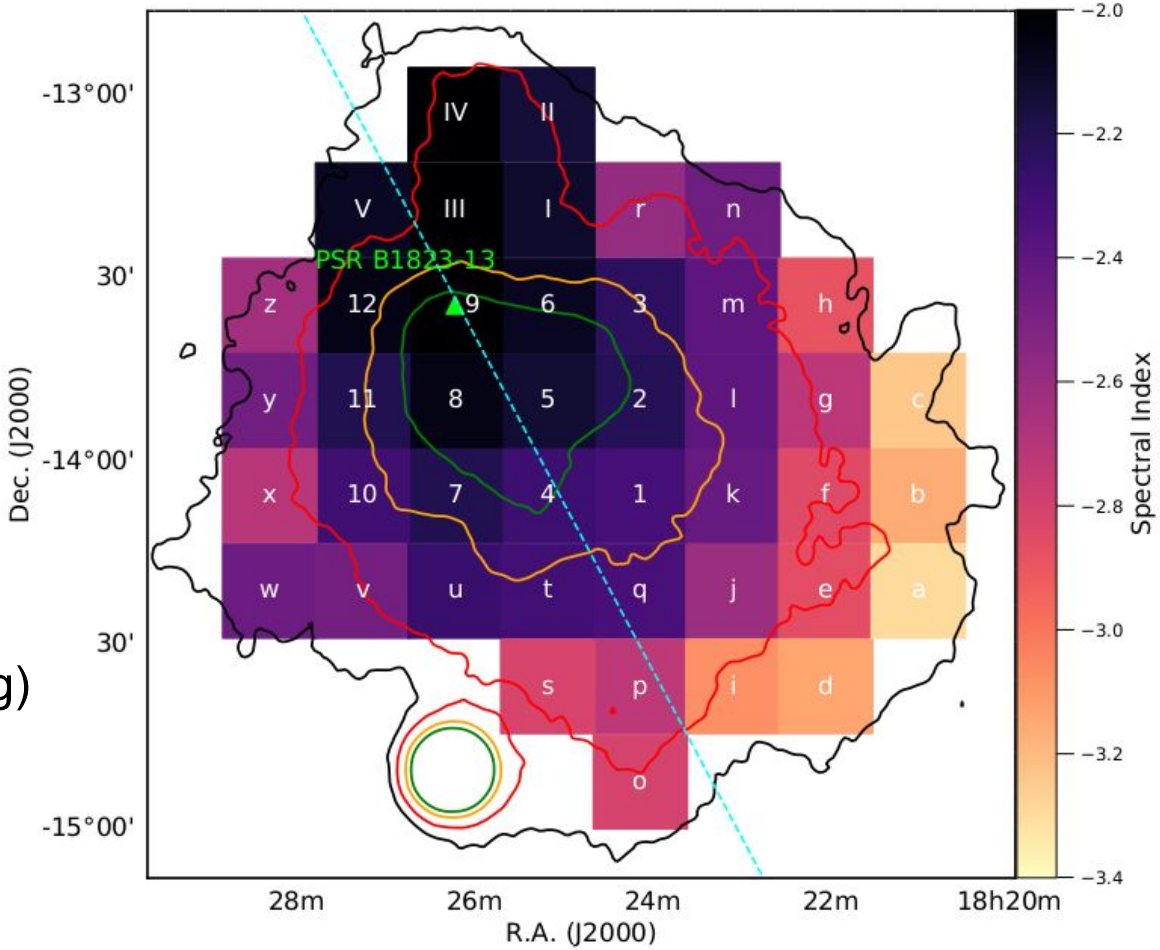


- Cooling of electrons can be observed !

Pulsar wind nebulae - halo



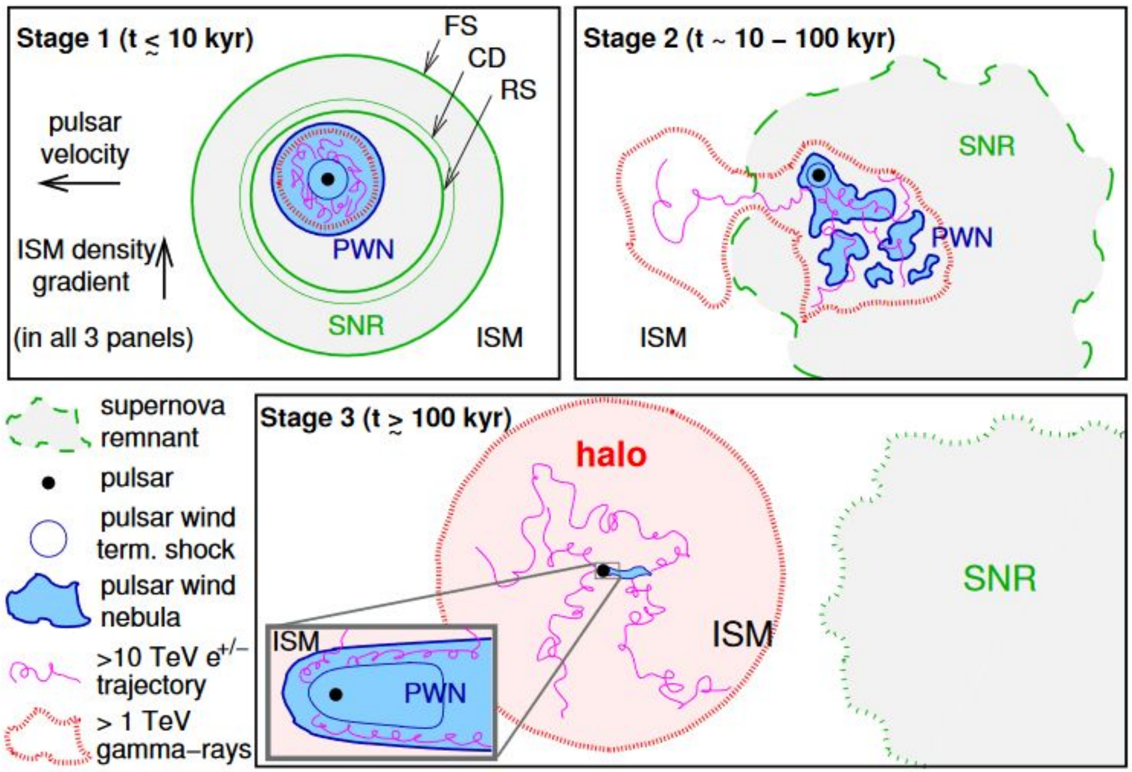
[arXiv:1810.12676](https://arxiv.org/abs/1810.12676)



- 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)

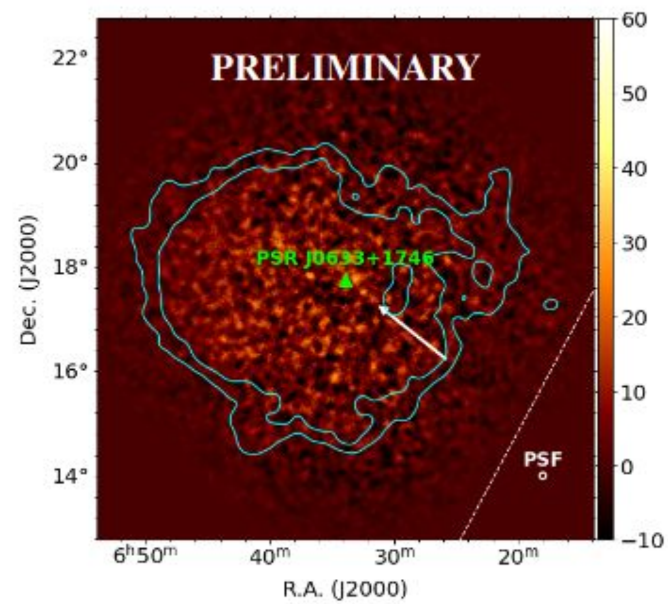
Pulsar wind nebulae - halo

https://arxiv.org/abs/1907.12121



https://arxiv.org/abs/2304.02631

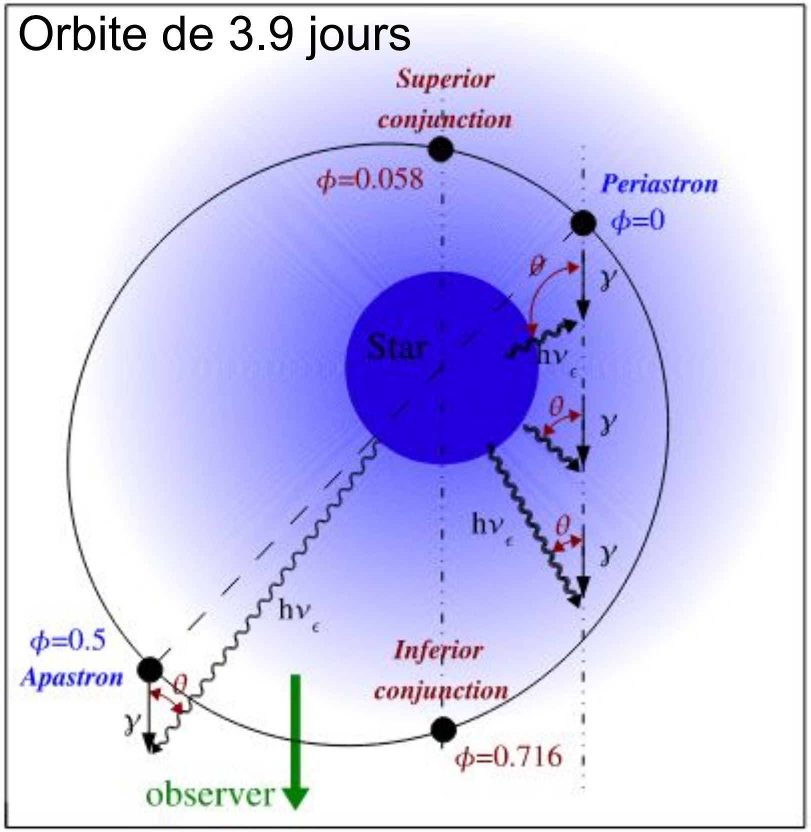
Geminga
340 000 ans

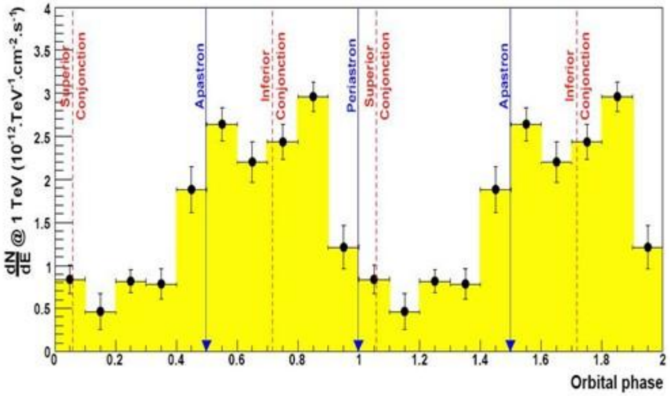


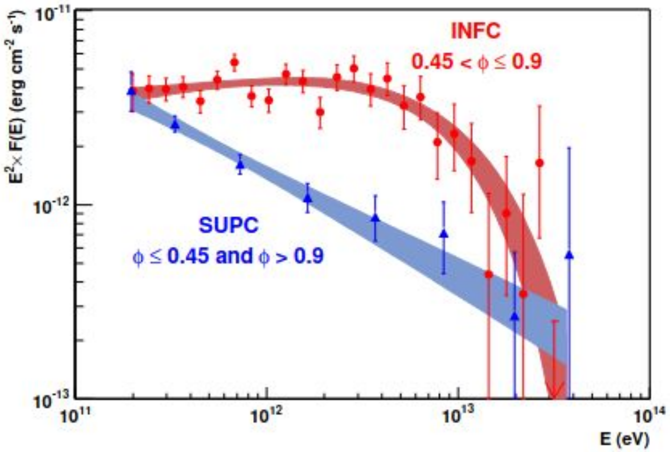
- Data compatible with diffusion (random motion)…
- …But slower than expected, still debate in the community…
- Very plausible origin for the local positrons detected by AMS-02

Binaries

https://arxiv.org/abs/astro-ph/0607192



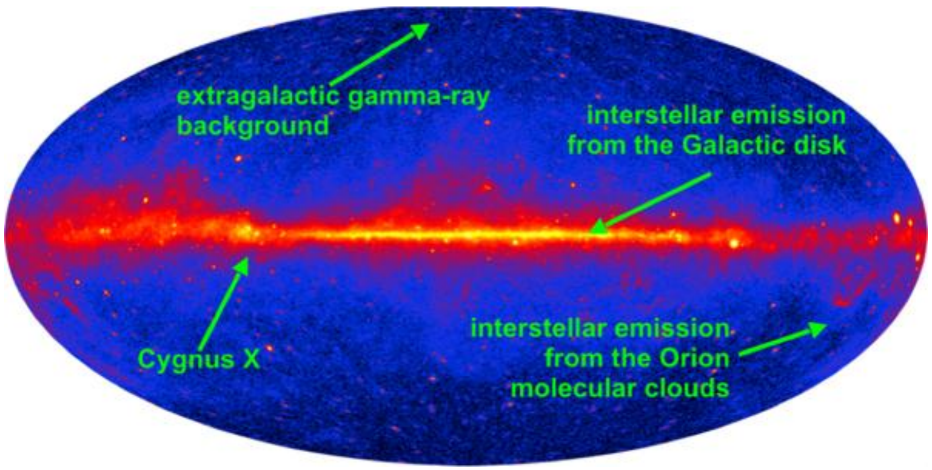




- Star with compact object (black hole or neutron star)
- Modulation of the gamma ray emission due to the photon field of the companion star (absorption et IC)

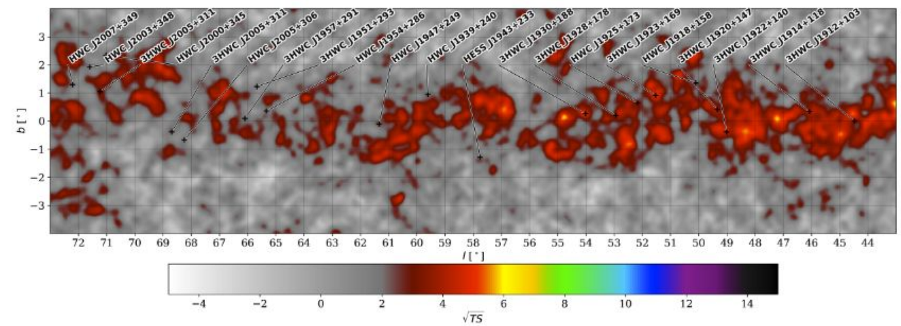
Galactic diffuse emission

GeV

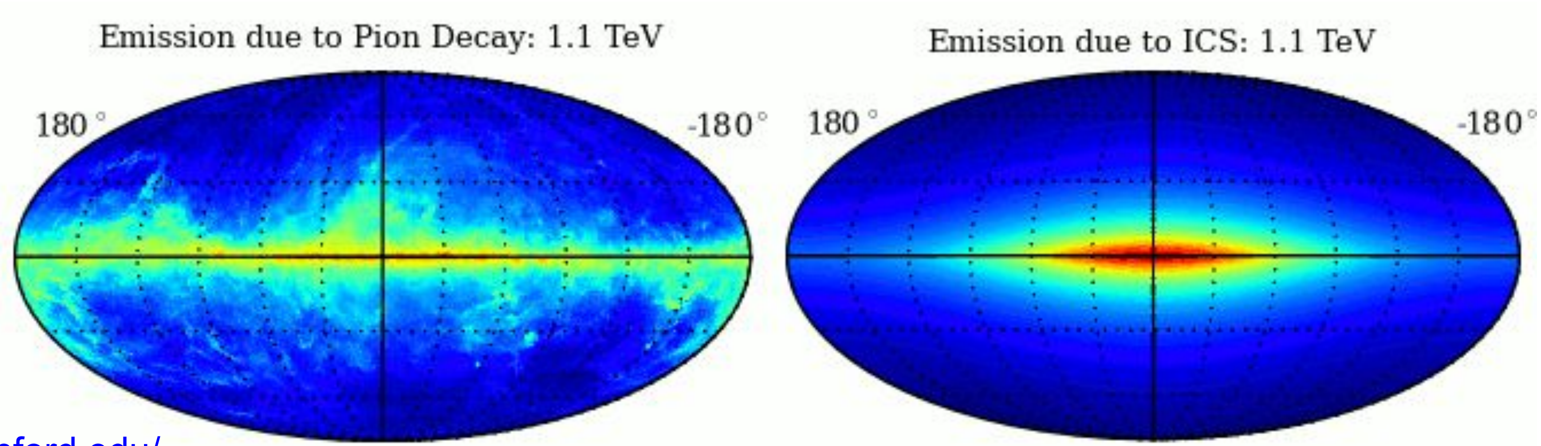


https://fermi.gsfc.nasa.gov/science/eteu/diffuse/

TeV



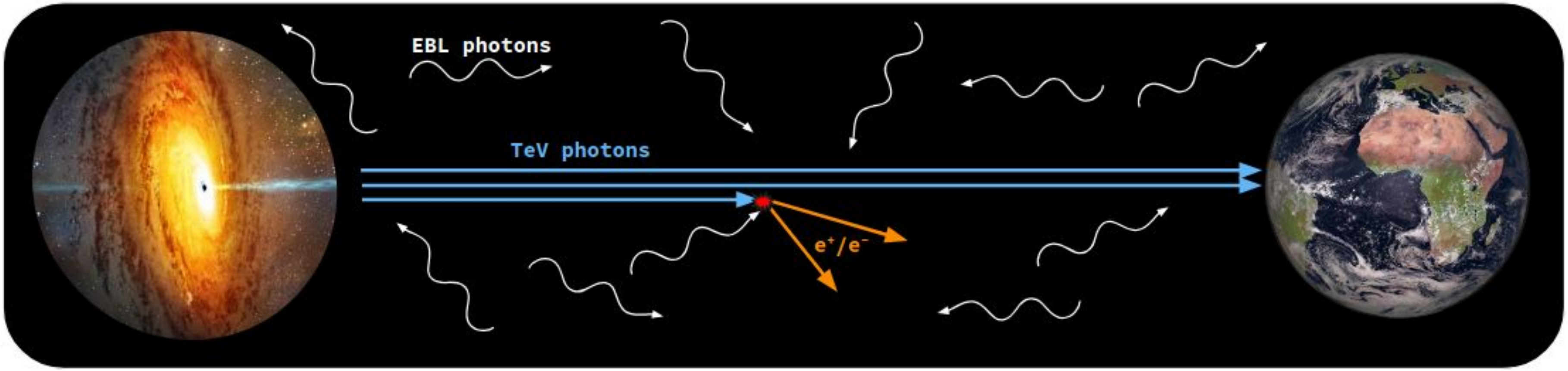
https://arxiv.org/pdf/2310.09117

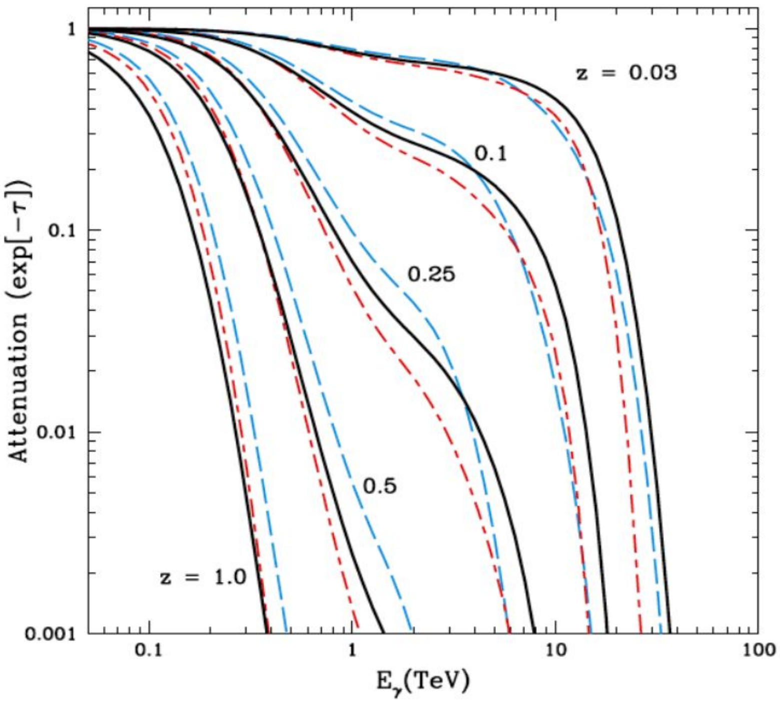


https://galprop.stanford.edu/

Gamma ray Extragalactic sky

Gamma ray attenuation



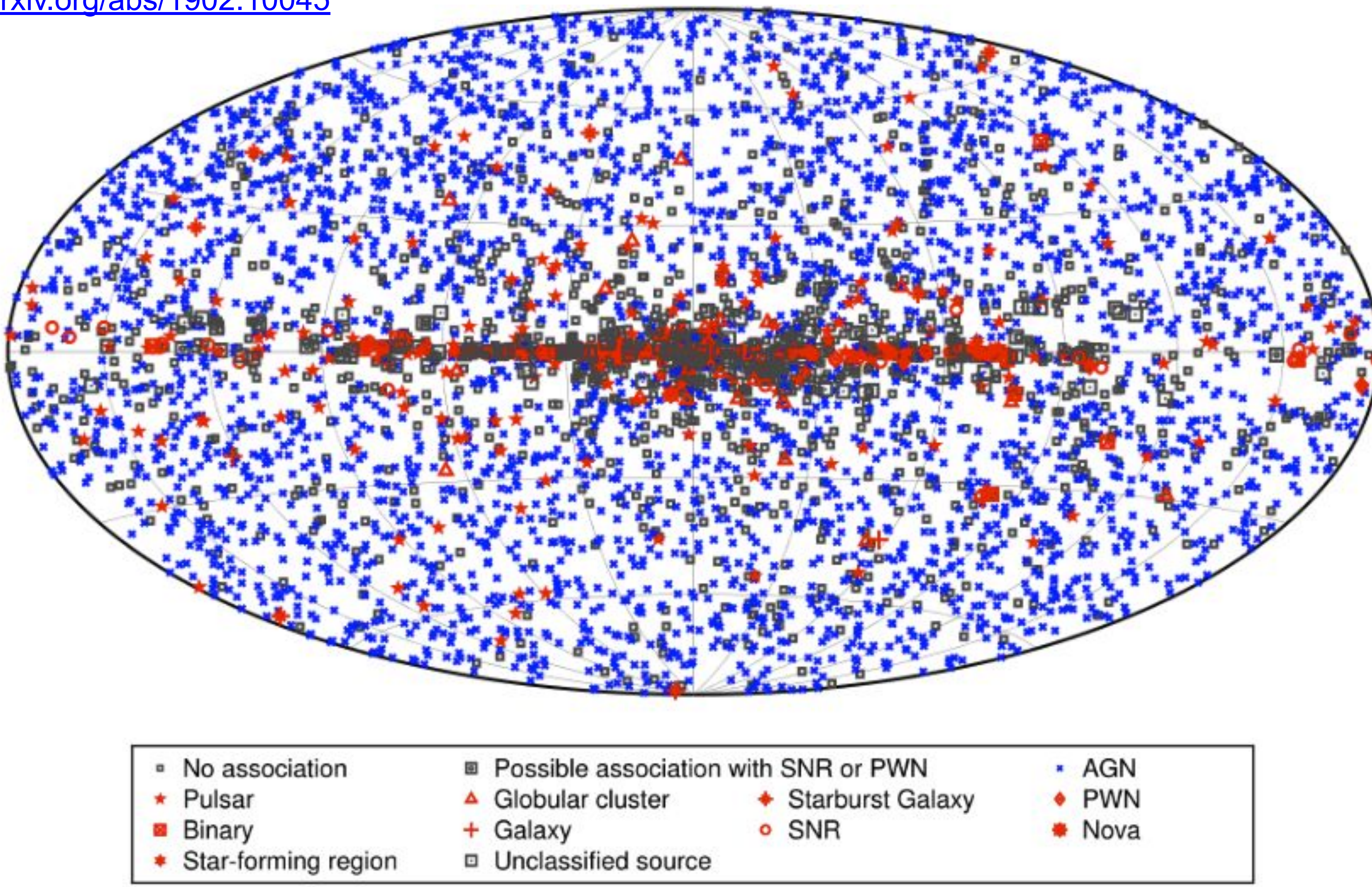


https://arxiv.org/pdf/1104.0671

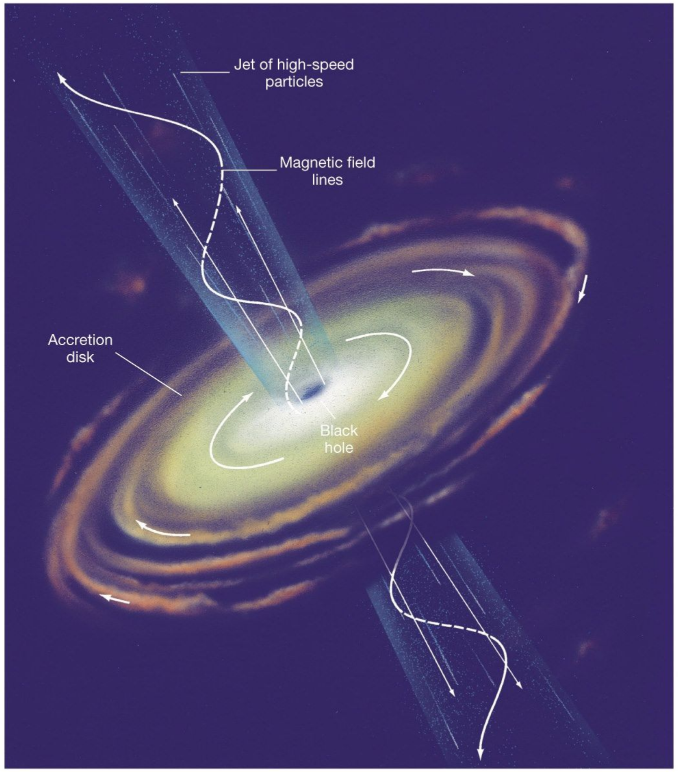
- Pair production with interaction with photons is one of the main limit for the depth of gamma-ray observation
- Recently OP313 (blazar) observed at z=1 (7.8 Billions light years https://www.lapp.in2p3.fr/2024-01-science-4693
- This is why low energy (~100 GeV) are interesting for extragalactic physics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

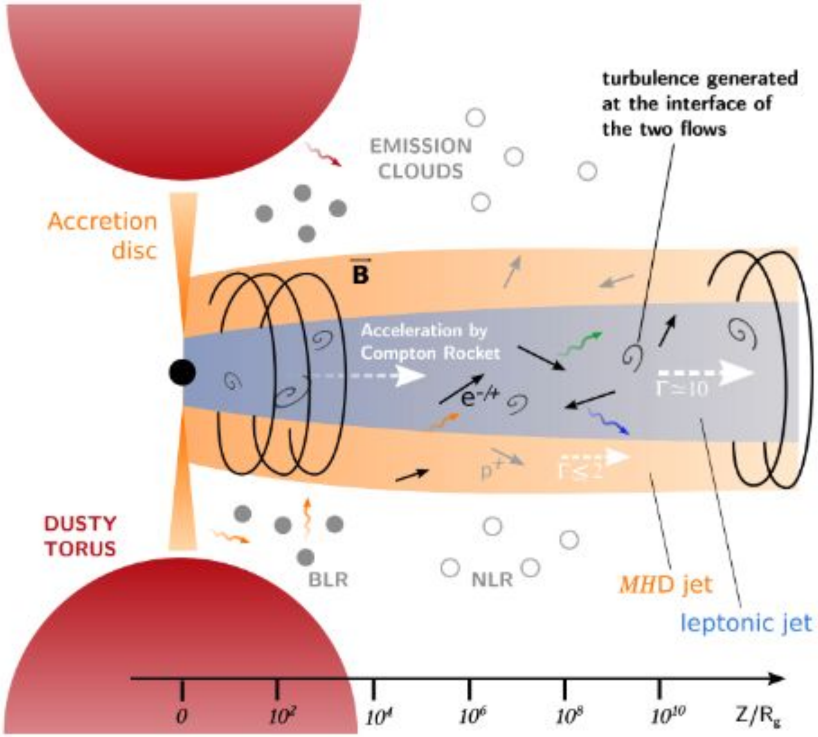
Fermi satellite source catalog

https://arxiv.org/abs/1902.10045



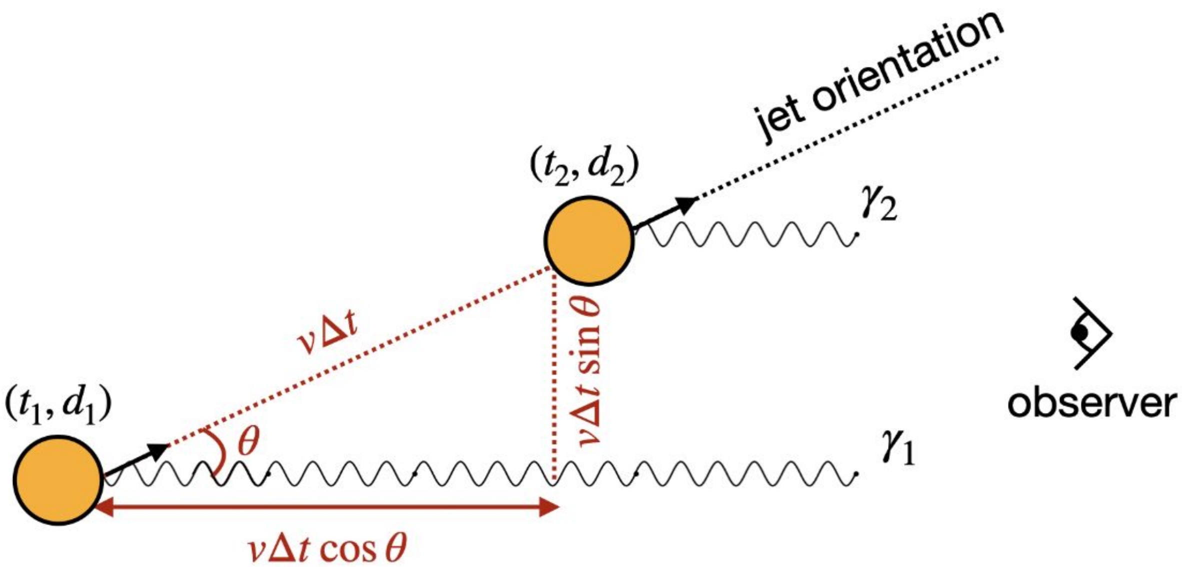
Extragalactic sources

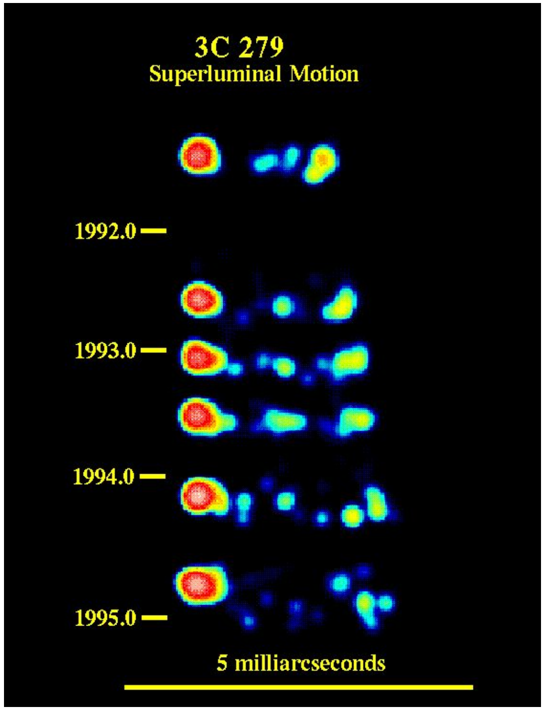




- Vast majority of extragalactic sources are caused by accretion of matter in a black hole vicinity
- Ionised matter rotating → rotating magnetic field→relativistic jets
- Complex acceleration : turbulence in the jet + shock wave between the jet and the external medium
- Significant Lorentz boost in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

Jets variability



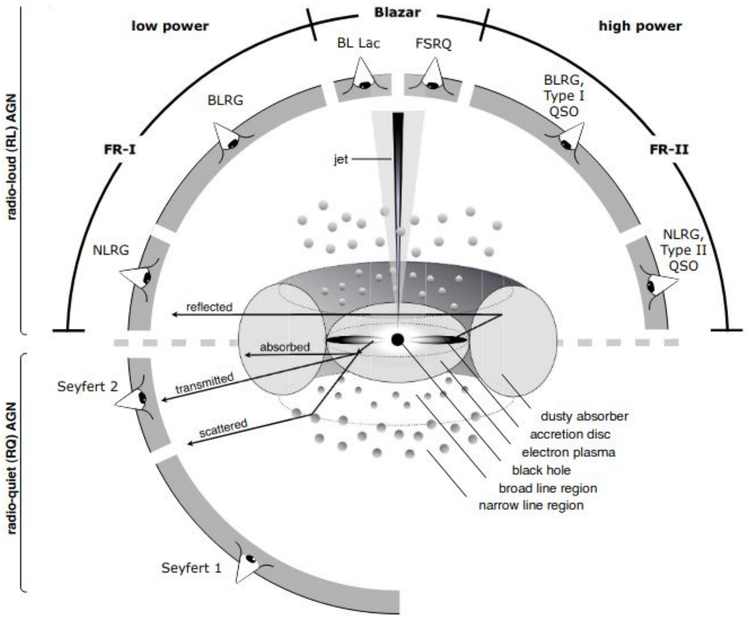


$$\Delta t_{obs} = \frac{c\Delta t - v\Delta t\cos\theta}{c} = \Delta t(1-\beta\cos\theta) < \Delta t$$

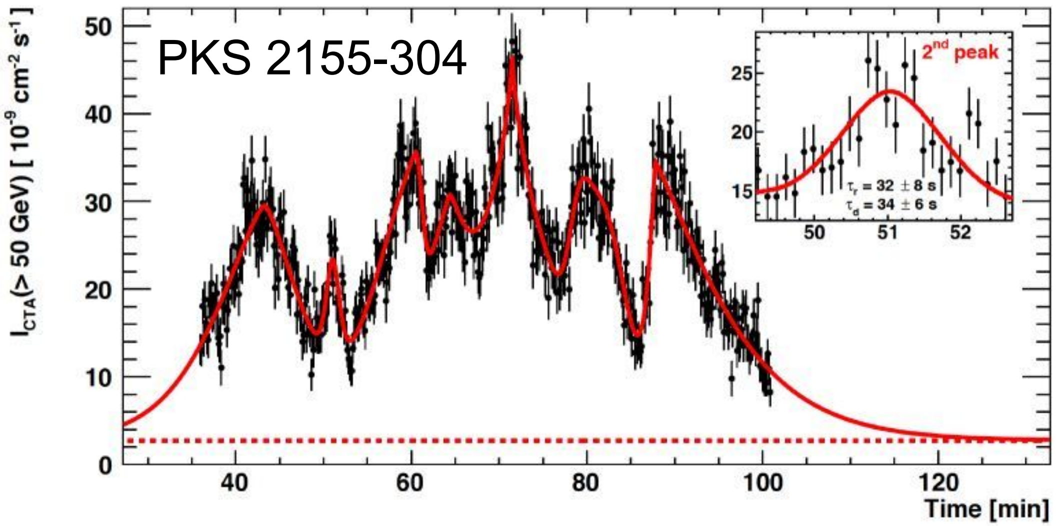
$$v_{obs} = \frac{\Delta d_{obs}}{\Delta t_{obs}} = \frac{v\sin\theta}{1-\beta\cos\theta} > v$$

- 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



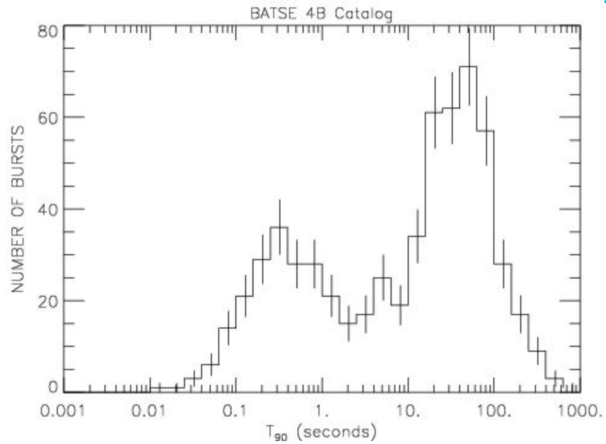
Variability ~ 1 minute



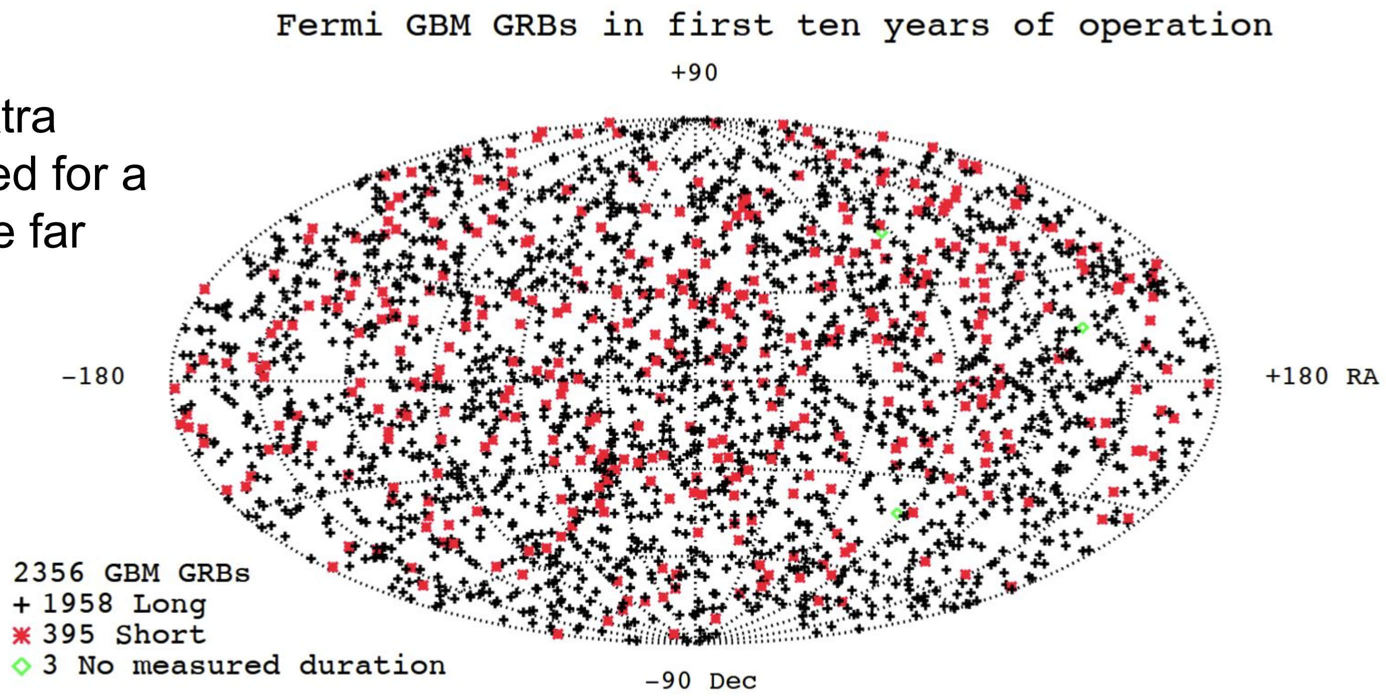
- Jet engine → supermassive black hole in galactic centers
- Very fast variability of the gamma ray flux, due to how compact is the acceleration region
- Naive Acceleration region size : 1.8*10^{10} m
- ~0.01 R_S (supposing a 10^9 Solar mass black hole, R_S = 3 *10^{12} m)
- Taking into account jets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

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

Gamma Ray Burst



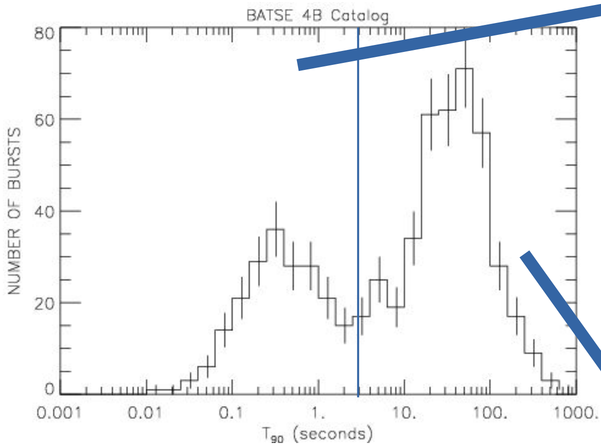
Fast -> compact region
-> black hole ?



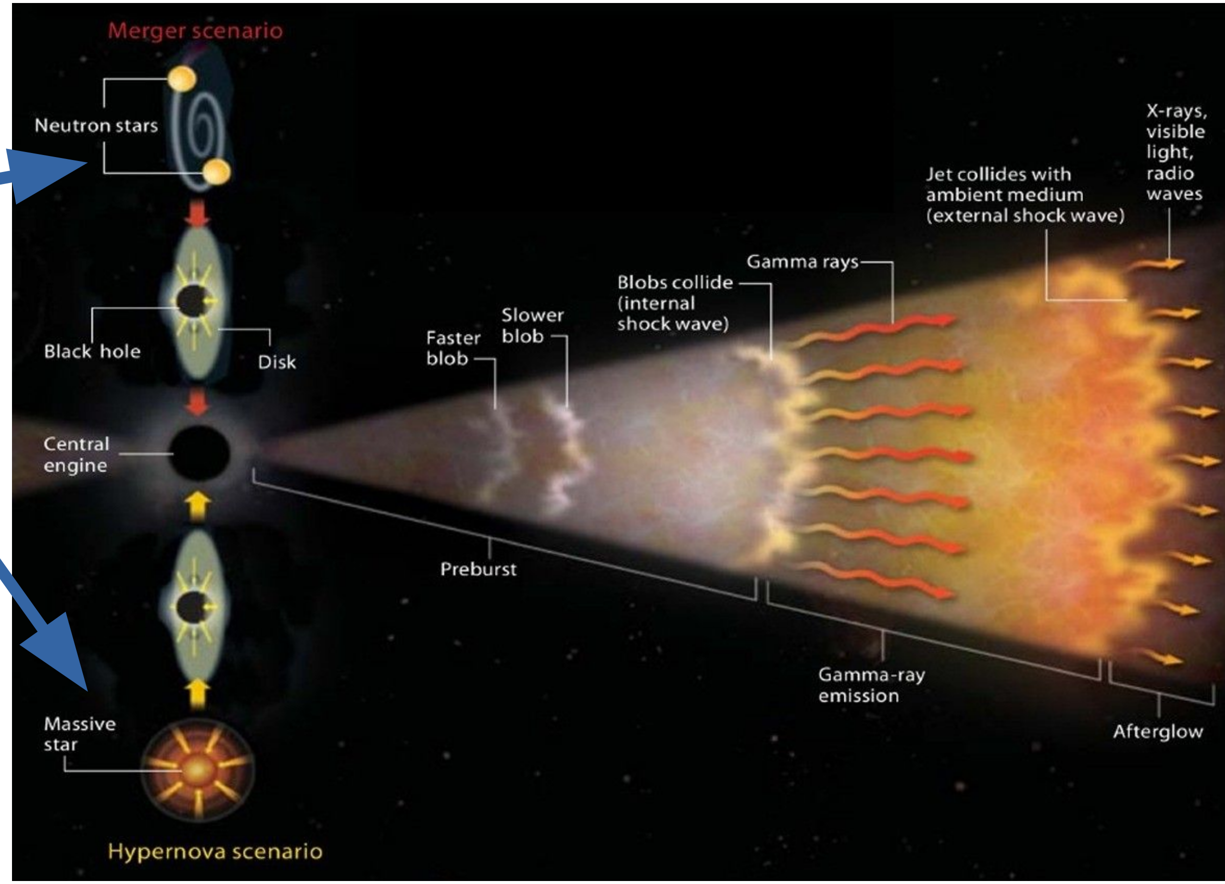
Isotropic -> extra galactic -> need for a jet to be visible far away

Gamma Ray Burst

short burst

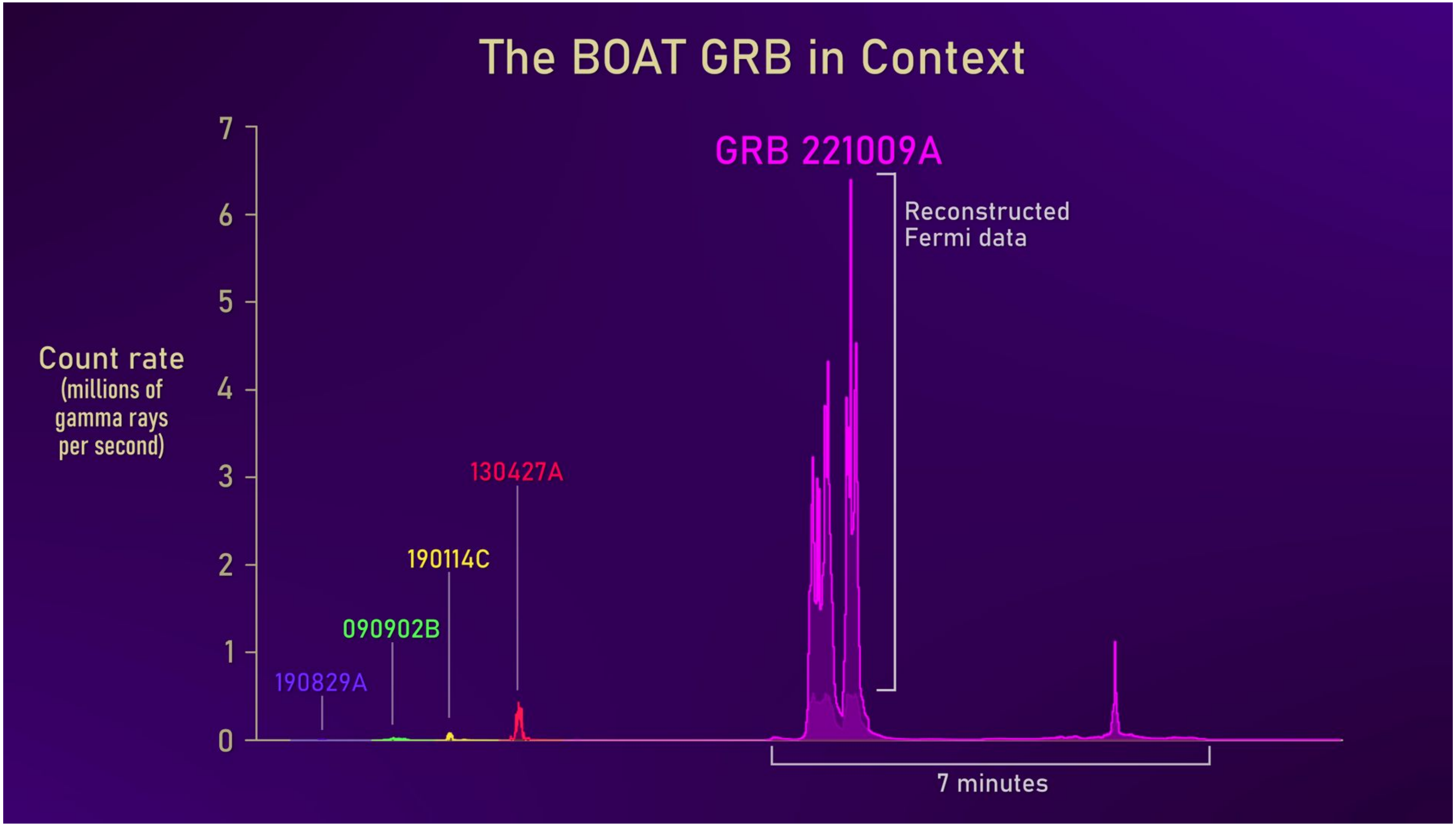


long burst



- 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
  - 4 GRBs detected by cherenkov telescopes so far (~2k in total for Fermi)

The Brightest Of All Time (BOAT)

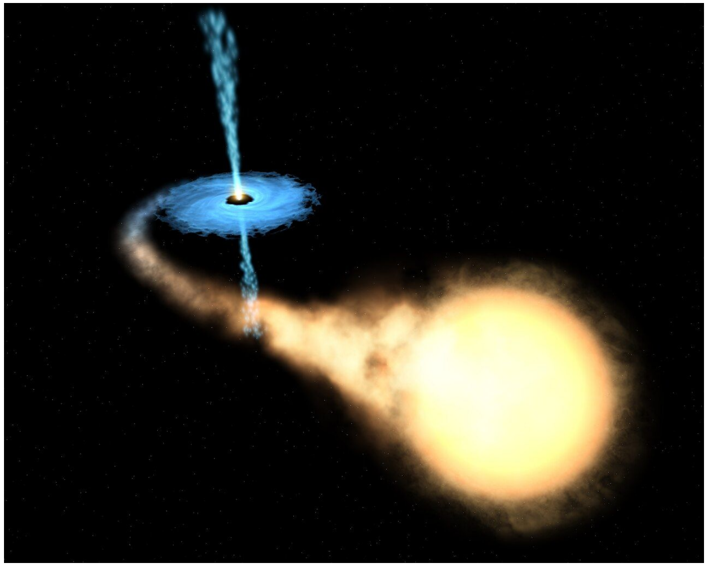


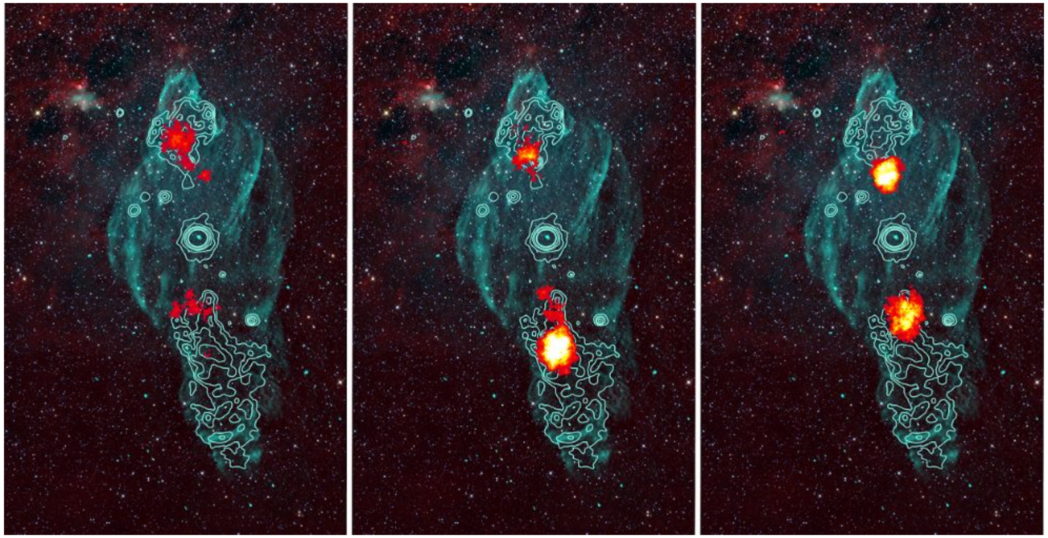
- Combination of "close" (z = 0.15), very energetic (well aligned jets)

https://arxiv.org/pdf/2303.14172

Micro quasars

https://arxiv.org/pdf/2401.16019



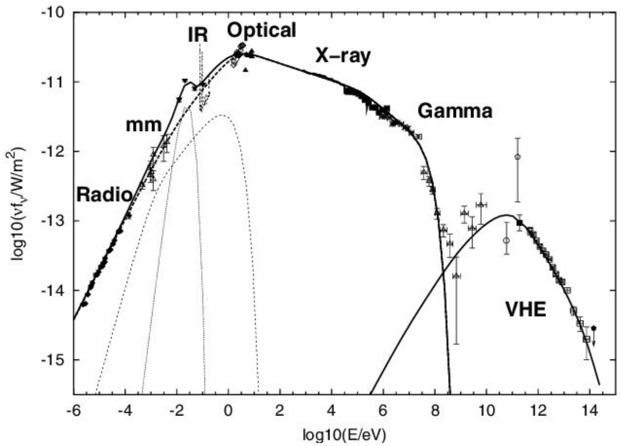


- Micro version of AGNs and GRBs, binary system but with a black hole instead of a pulsar
- Similar physics than AGNs, perpendicular jets are produced
- Since they are close (galactic) we can “easily” observe the jets

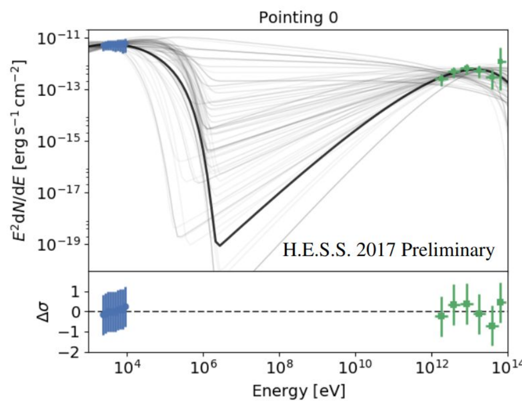
Universality of emission processes

- Besides very various types of accelerators (pulsars, pulsar wind nebula, Supernova remnant, Active Galactic Nuclei, GRBs, micro quasars), the double peak SED is universal due to emission processes

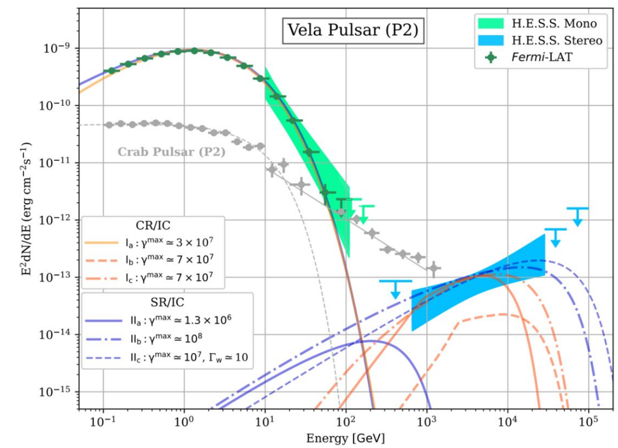
Crab Nebula



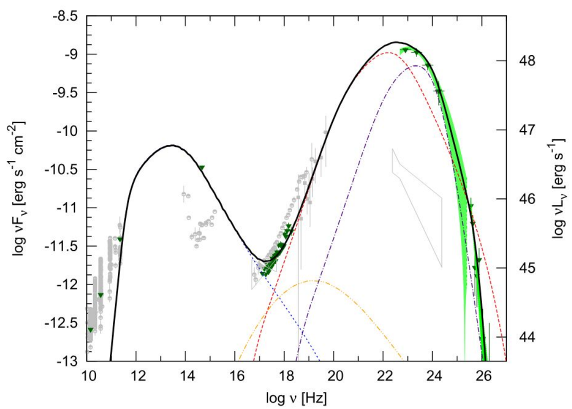
Vela X



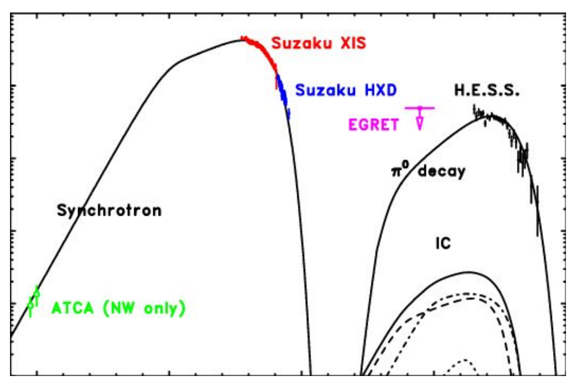
Vela pulsar



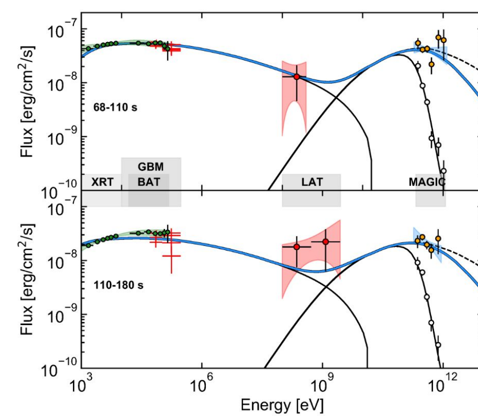
PKS 1510-089



RX J1713.7-3946



GRB 190114C



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, supernova remnant are those type of accelerator, but the hadroness of the accelerator is inconclusive**

- It should exists even more extreme accelerators than 1PeV ones (but probably different of the galactic ones)… → **Yes, AGN / GRB are extreme accelerators, could be observed outside our galaxy**

- 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 (with accretion disk). In case of ultrarelativitic jets, the acceleration is even more boosted**

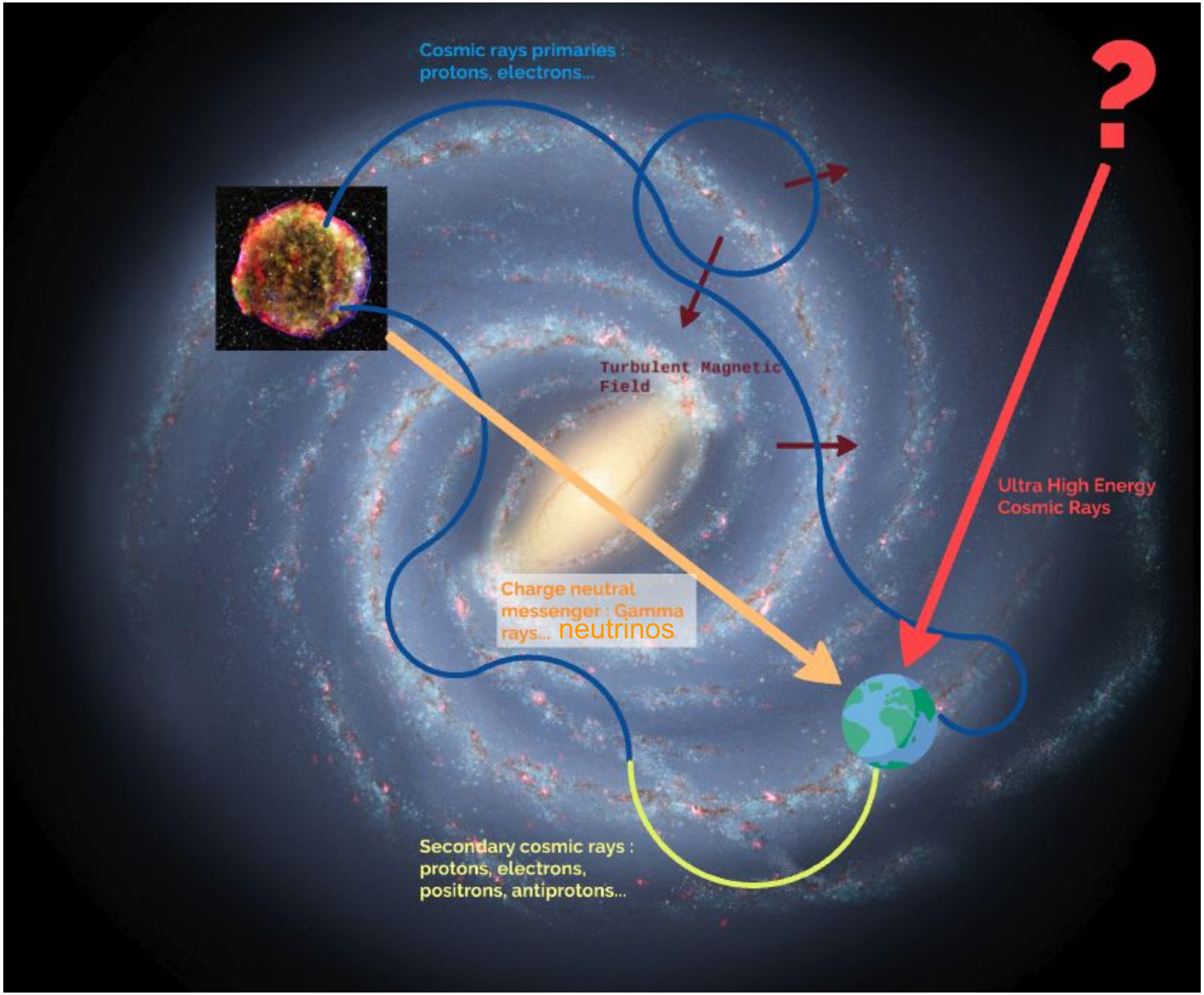
- … of course it is not enough to be compact, we need to have an engine to accelerates the charged particles → **engines are supernova remnants shocks, rotating neutron star, accretion disk around black holes**

- 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 → **True ! Supernova remnant and Pulsar Wind Nebula stable, pulsar and black hole related emission very variable**

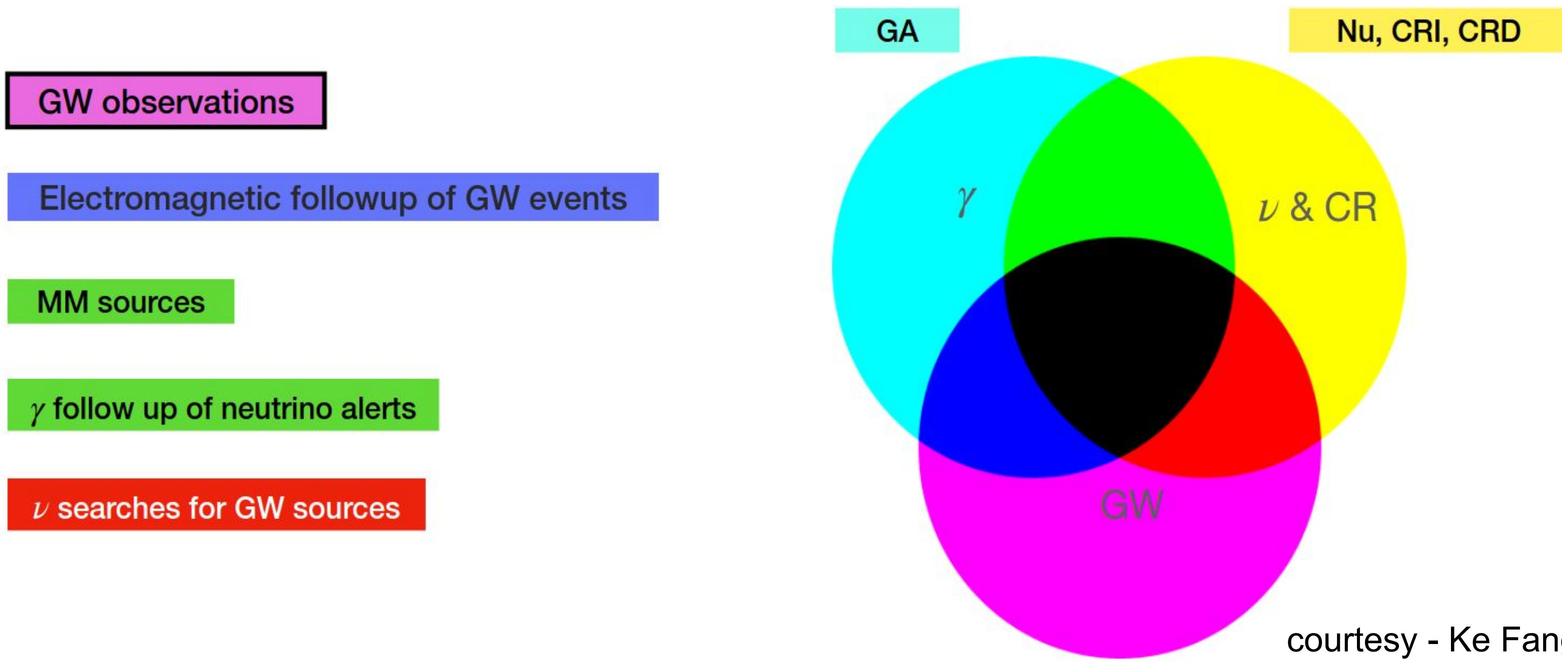
Multi-messenger

Cosmic messengers



- accelerated leptonic and hadronic particles
- B, density, photon field

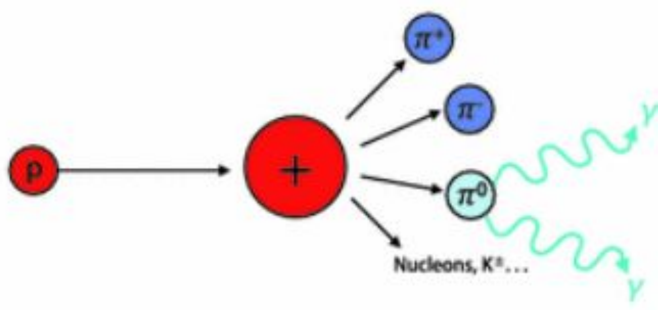
- accelerated hadronic particles
- Density



courtesy - Ke Fang
ICRC 2023

- dense and asymmetric rotating object
- information on the progenitor

Neutrinos



(c) Pion decay

$$
\begin{aligned}
p + p &\rightarrow p + p + \pi^0 \\
p + p &\rightarrow p + n + \pi^+ \\
p + p &\rightarrow p + p + \pi^+ + \pi^-
\end{aligned}
$$

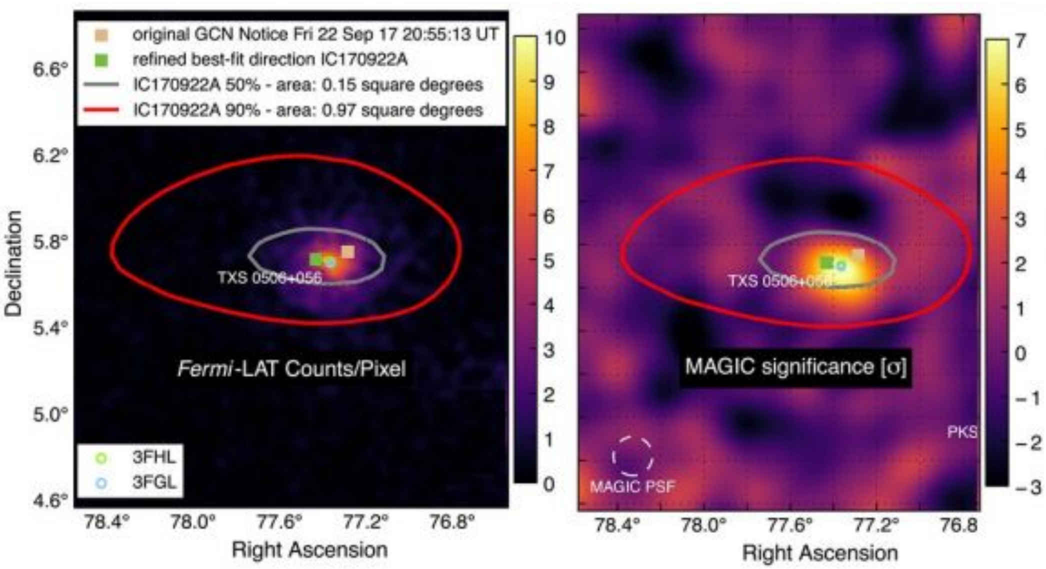
$$
\begin{aligned}
\pi^0 &\rightarrow \gamma + \gamma \\
\pi^+ &\rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \nu_\mu + \bar{\nu}_e + \bar{\nu}_\mu
\end{aligned}
$$

- Neutrinos expected to be a smoking gun for the hadronic processes in sources
- In contrary of gamma rays, neutrinos are unattenuated by pair production
- Interesting to proof acceleration of protons, but as well for far extragalactic sources
- The problem is mainly there (very) poor statistics

Neutrinos sources ?

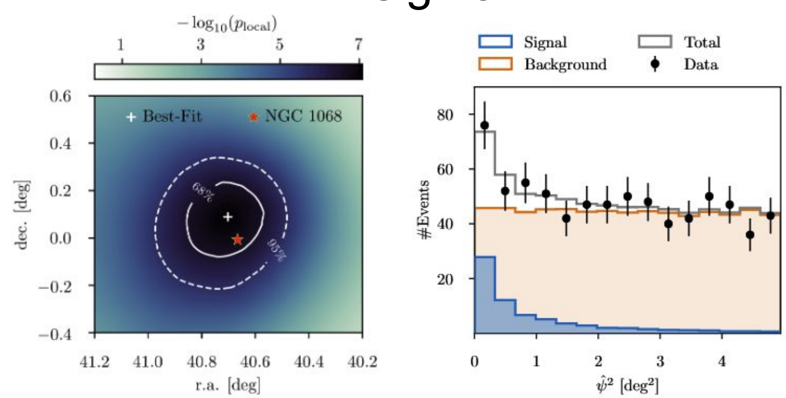
- 290 TeV muon neutrino, IceCube-170922A, a search of counterpart found TXS 0506+056 in the area in a flare

- 4.2 sigma of neutrino excess in vicinity of NGC 1068 with ~10 years of data

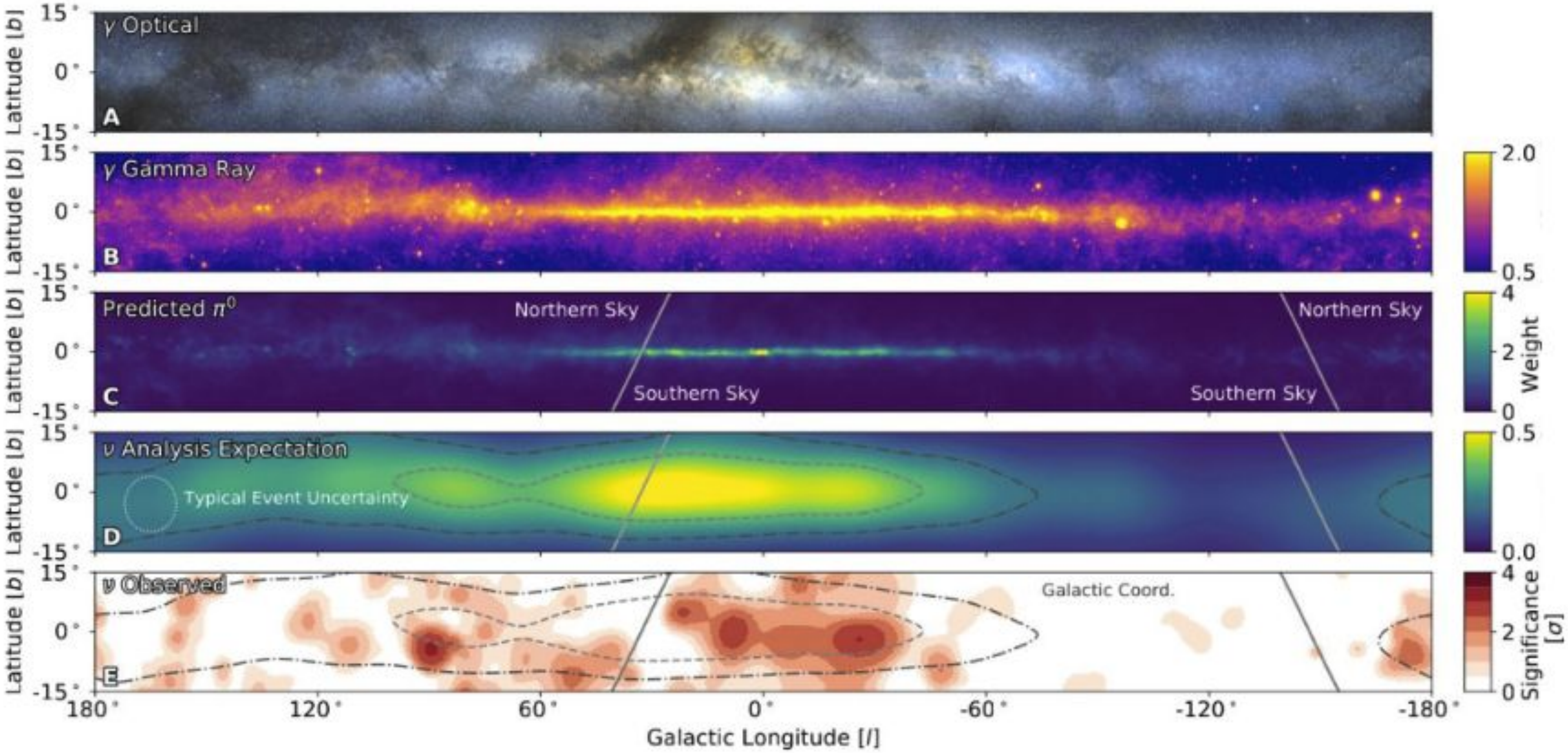


79^{+22}_{-20} **neutrinos**

4.2 sigma

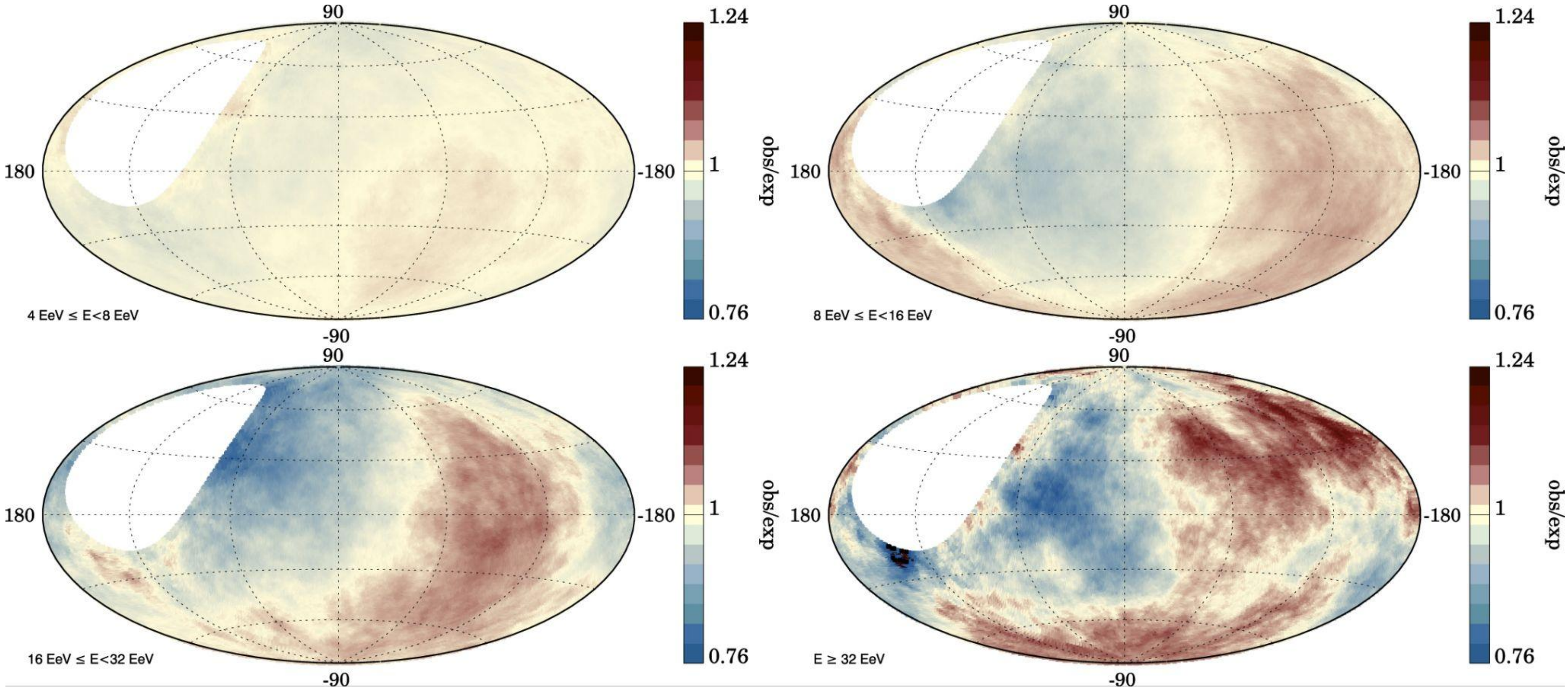


Neutrinos sources ?



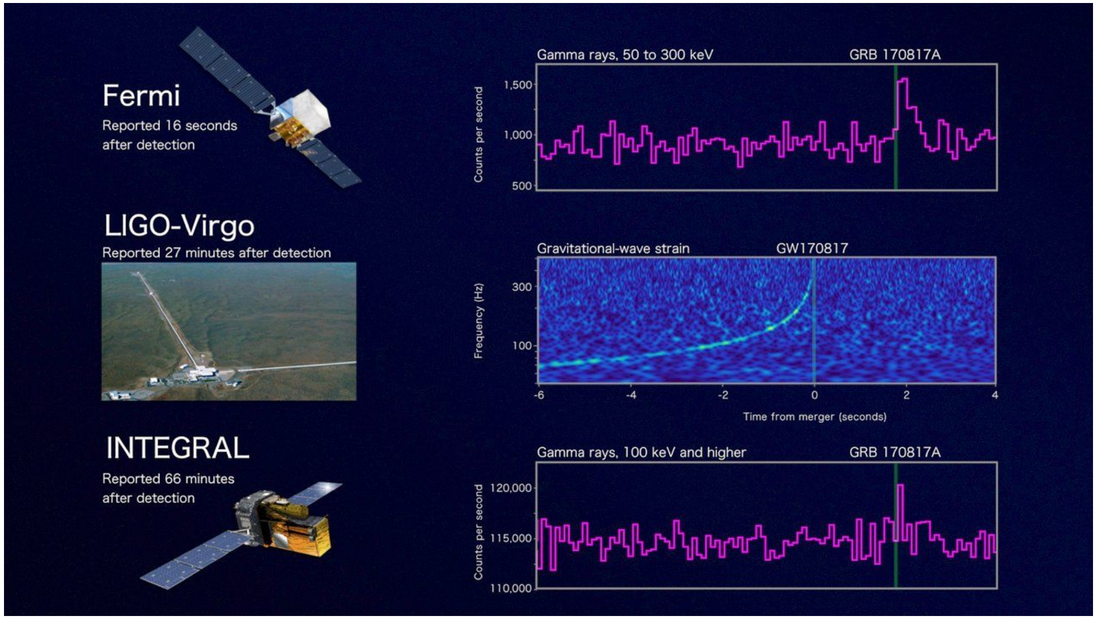
UHECR sources ?

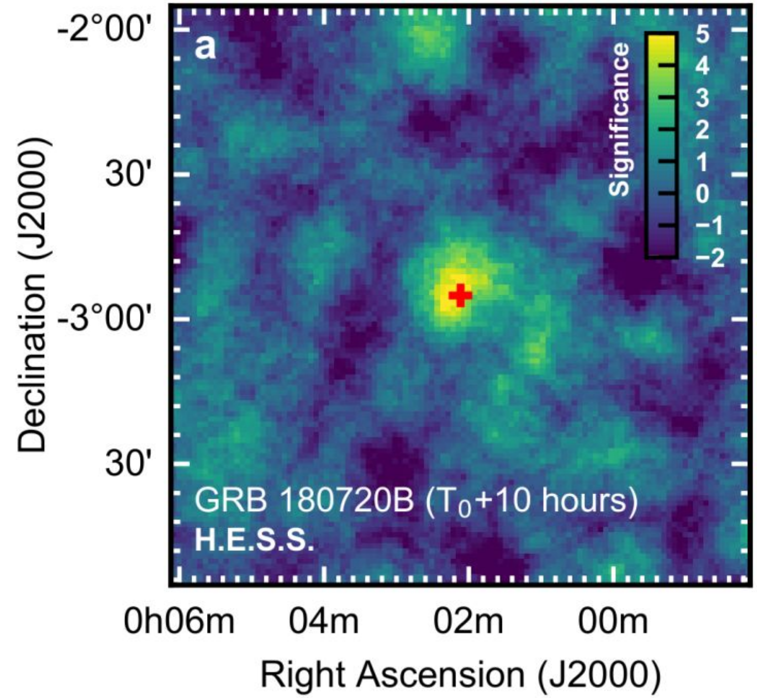
- Large scale dipole for UHECR start to be detected (~4 sigmas)
- Difficult to firmly conclude the dominant source, but galactic origin start to be excluded



https://iopscience.iop.org/article/10.3847/1538-4357/aae689/pdf

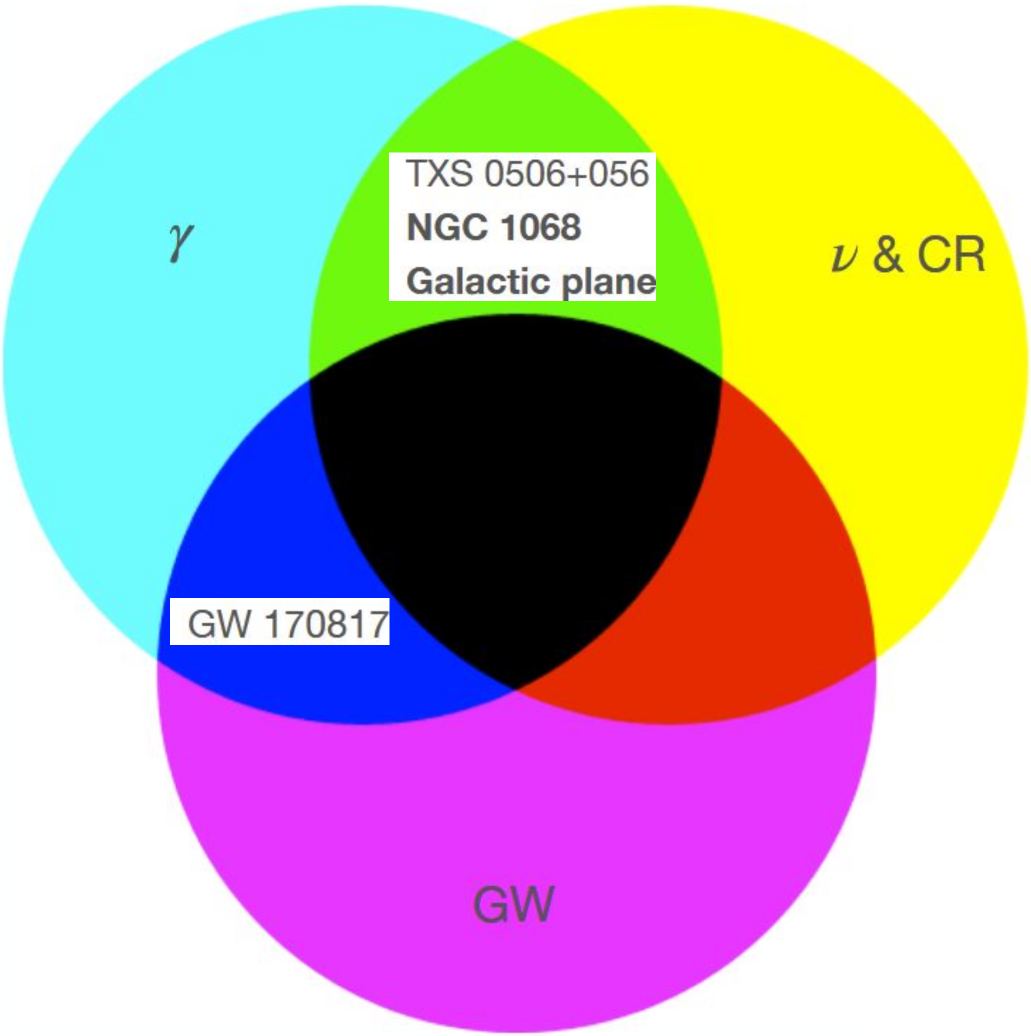
Gamma ray burst multi-messenger observation





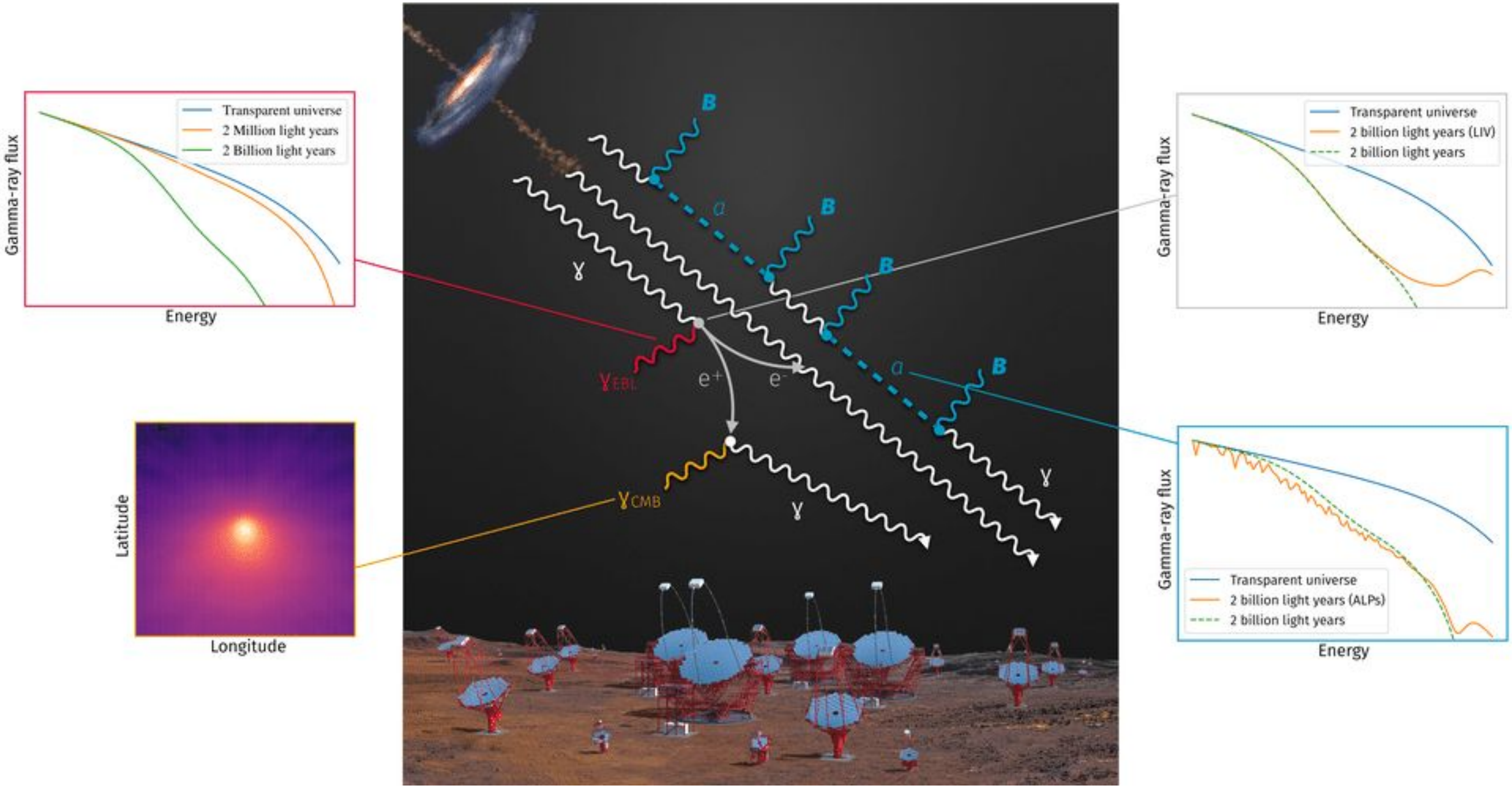
- Cherenkov telescope field of view ~5° (8° for CTA), needs for external alerts (satellites X-ray or GeV gamma rays, GW, neutrinos...)
- For the short burst, production of gravitational wave is expected (asymmetry of the merger precursor)
- Happened in 2017, but missed by Cherenkov telescopes (due to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

Status today



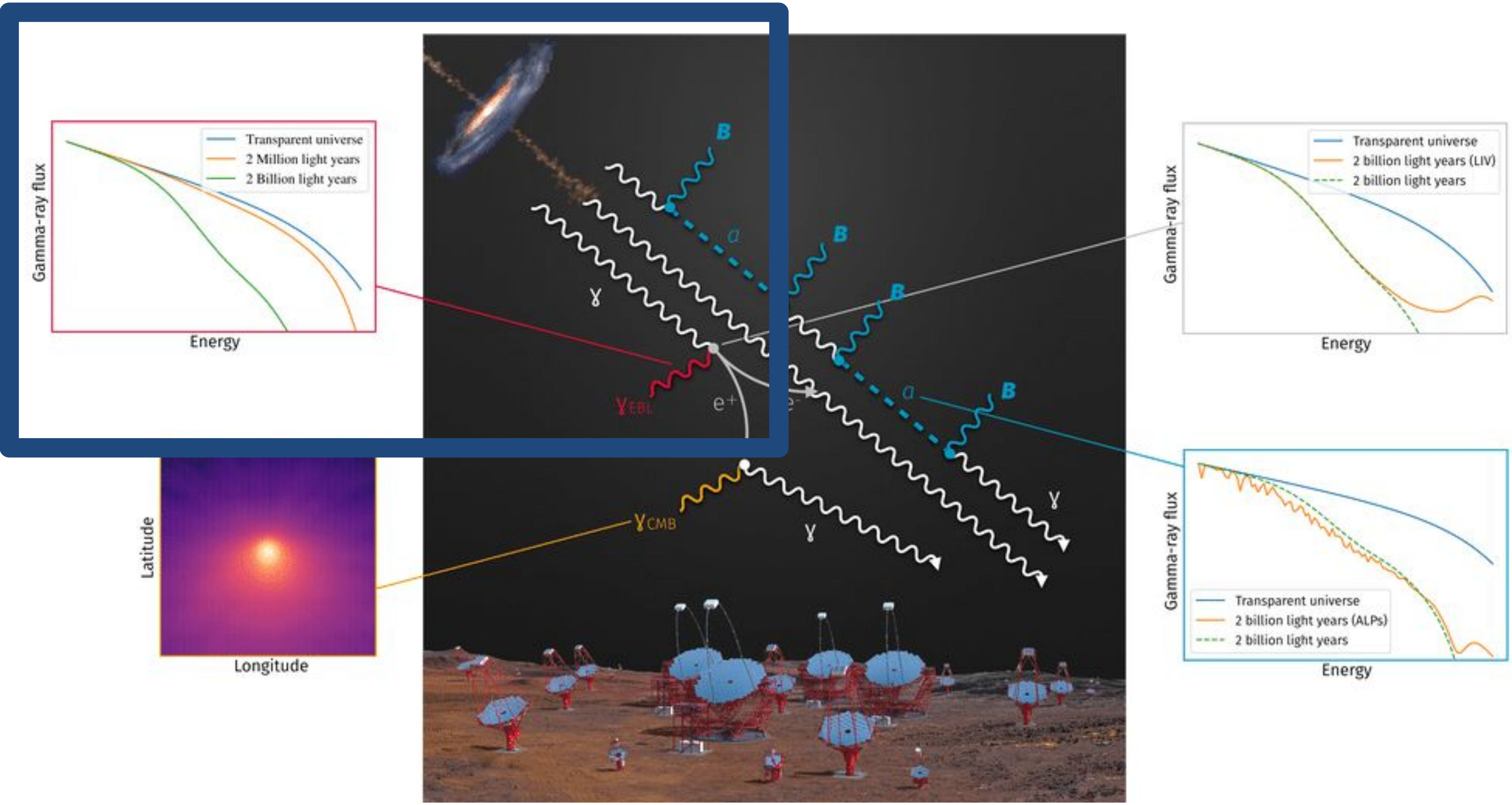
Fundamental physics with gamma rays

Gamma ray propagation



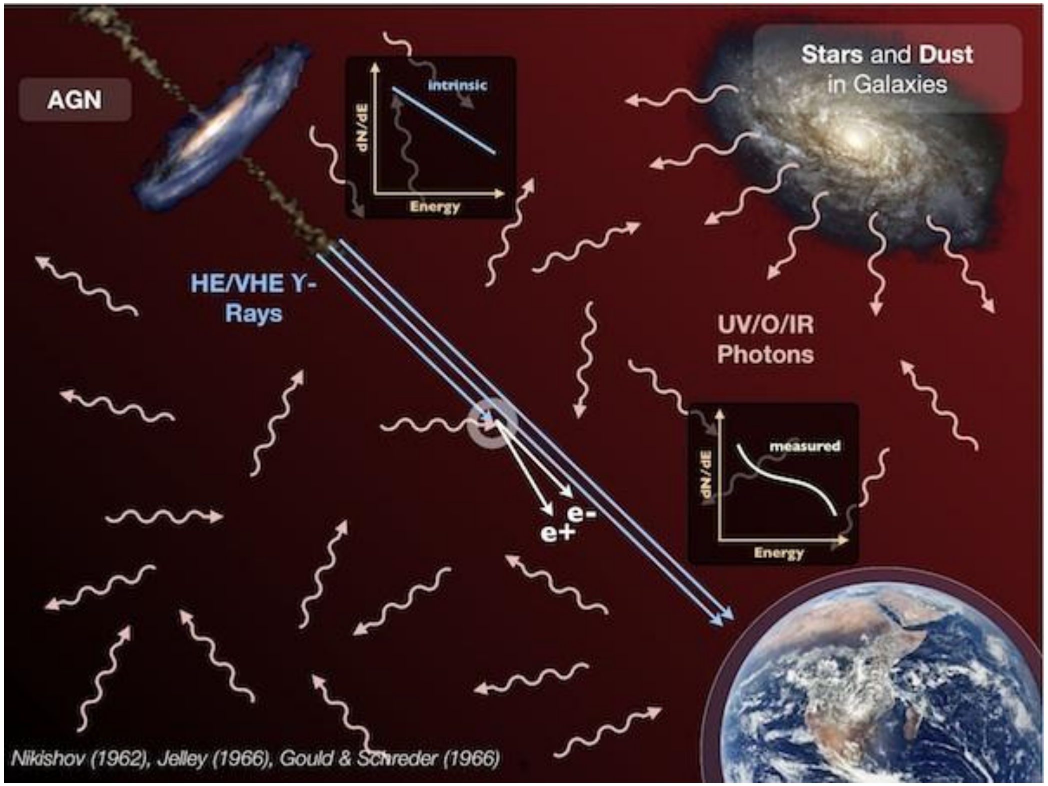
https://www.ctao.org/news/redshift-why-does-distance-matter-to-cta/

Gamma ray propagation

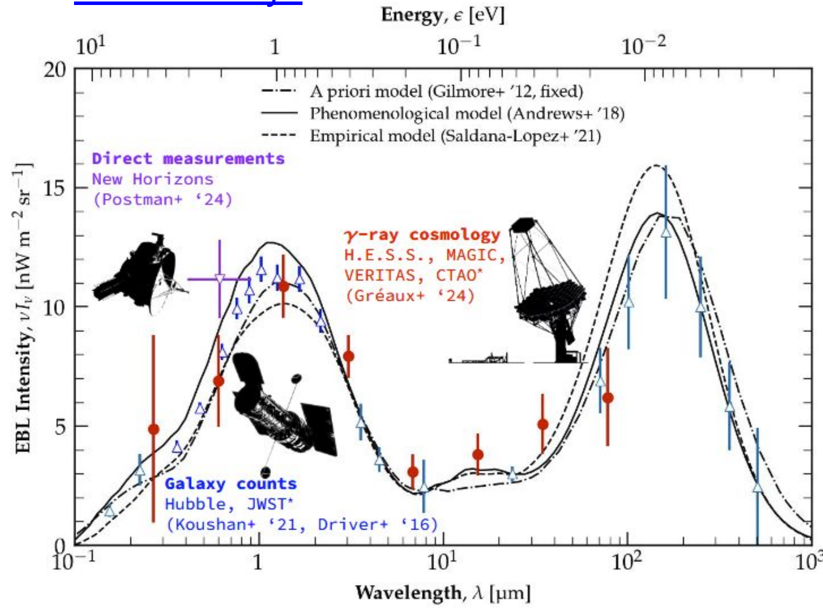


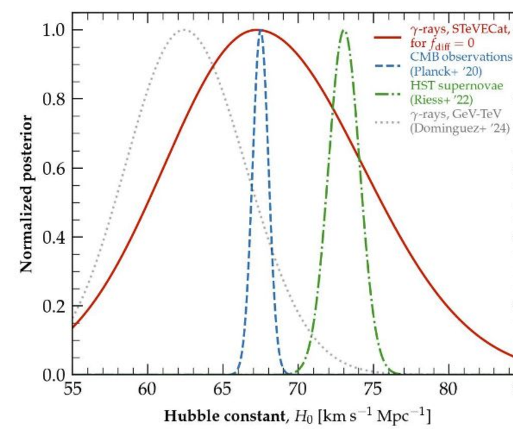
https://www.ctao.org/news/redshift-why-does-distance-matter-to-cta/

Extragalactic background light



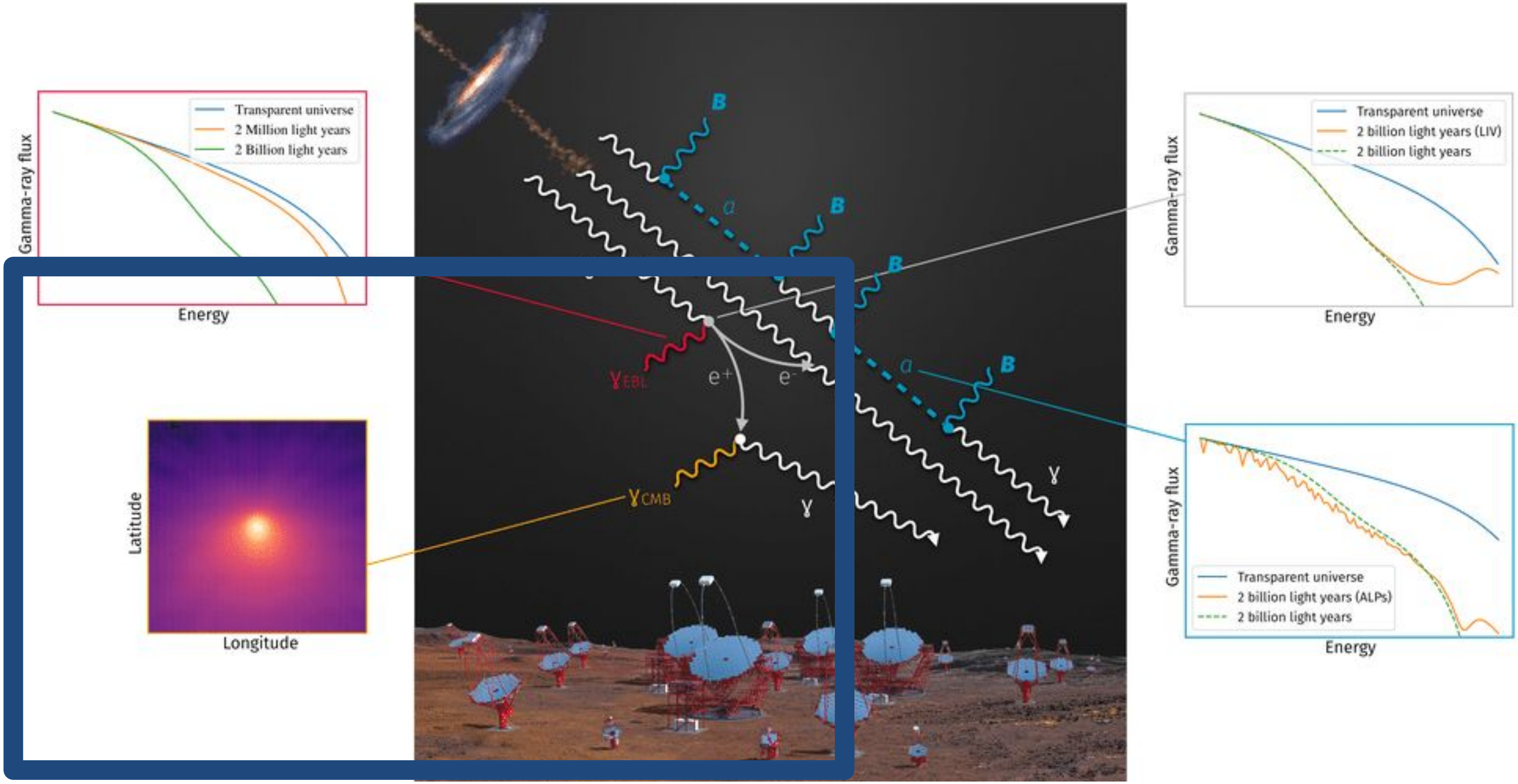
[The Cosmological Optical Convergence: Extragalactic Background Light from TeV Gamma Rays]()



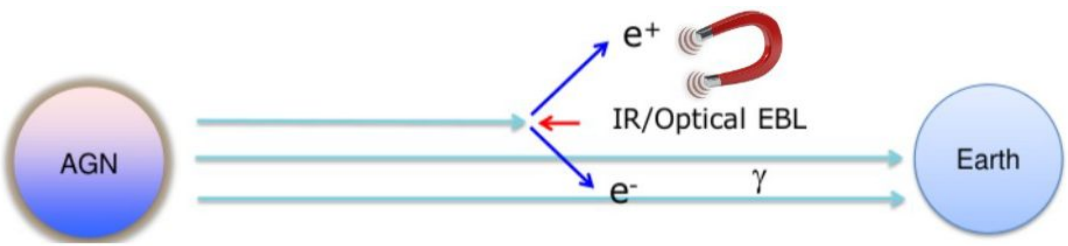


- Gamma ray absorption can be used to indirectly derive the “spectra of our universe”
- This measurement is dependent of the cosmological parameter, measurement of the Hubble constant can be made

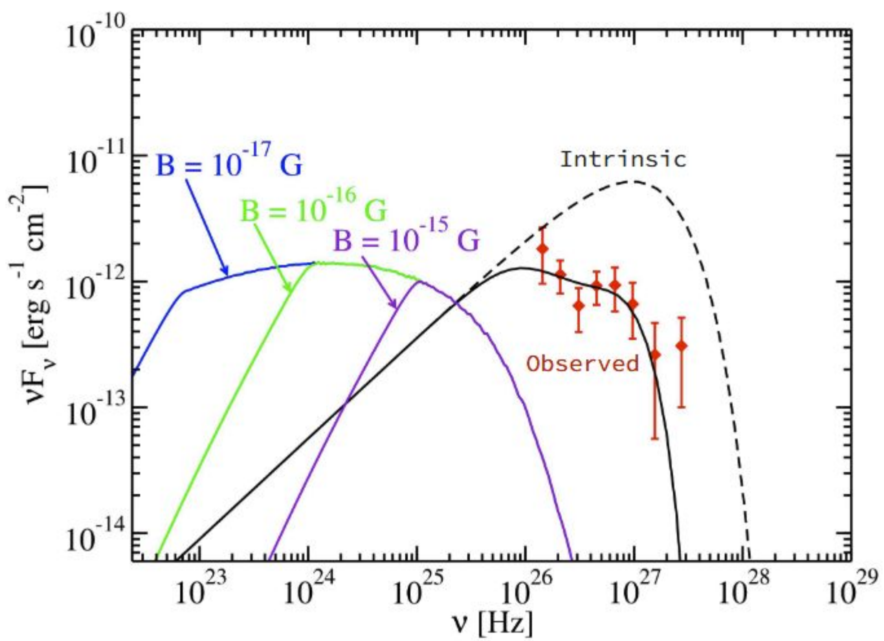
Gamma ray propagation



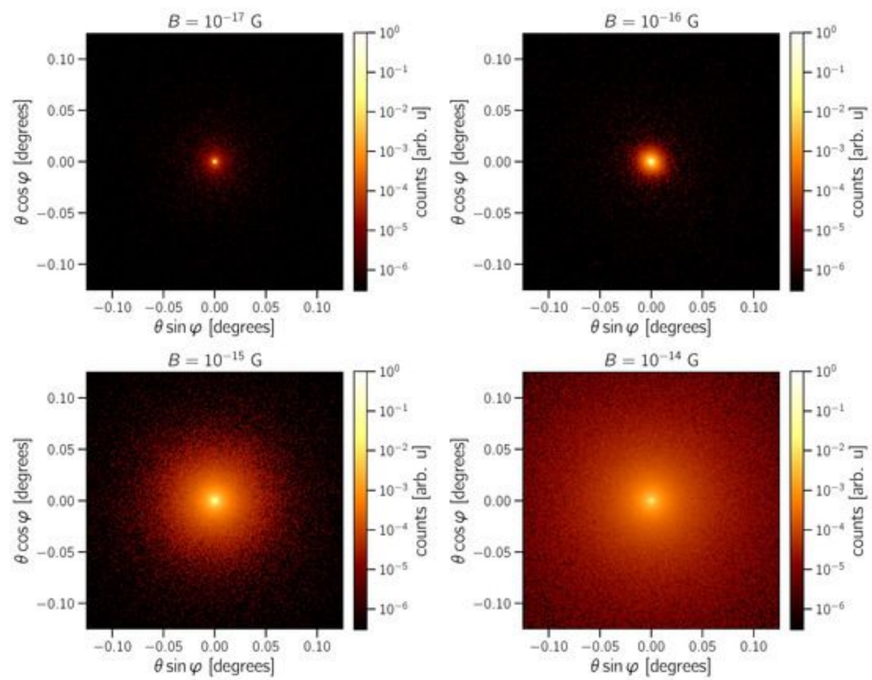
https://www.ctao.org/news/redshift-why-does-distance-matter-to-cta/



- Positrons and electrons can produce gamma-rays (echos)
- Galactic magnetic fields can create extended echos
- Limits B > ~10^-16 G (https://arxiv.org/pdf/2306.05132)

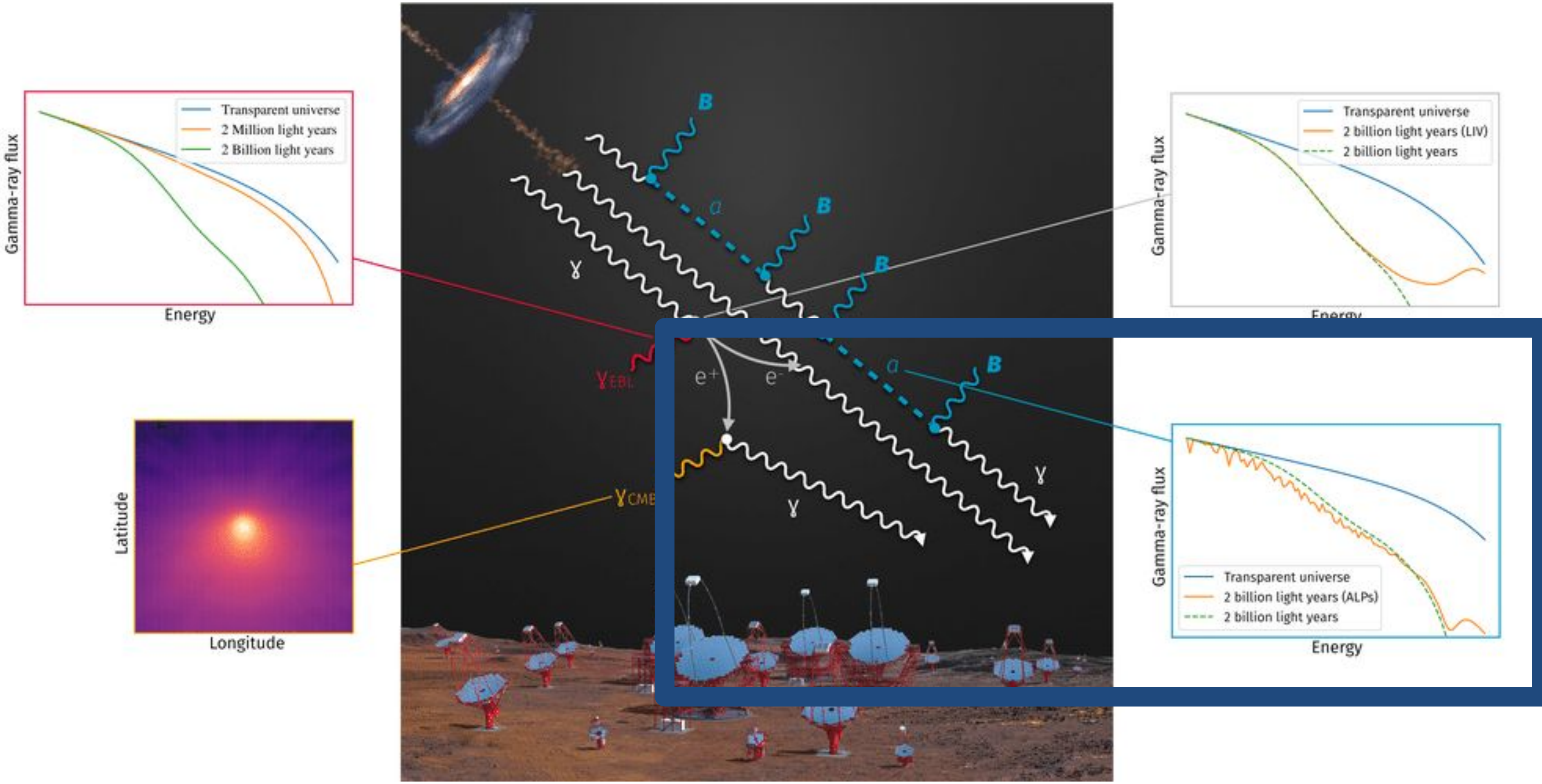


http://dx.doi.org/10.1088/0004-637X/814/1/20



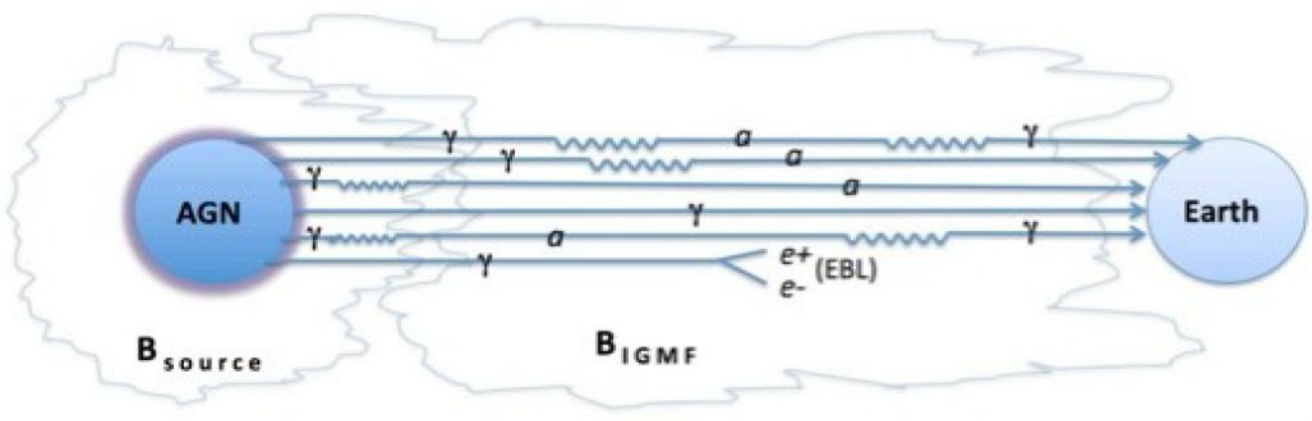
https://arxiv.org/abs/2105.12020

Gamma ray propagation

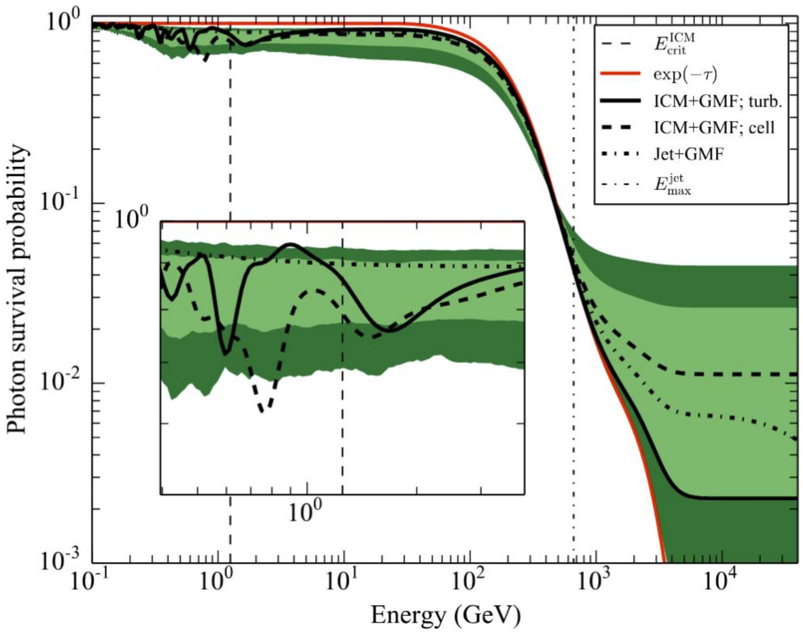


https://www.ctao.org/news/redshift-why-does-distance-matter-to-cta/

Axion Like Particle

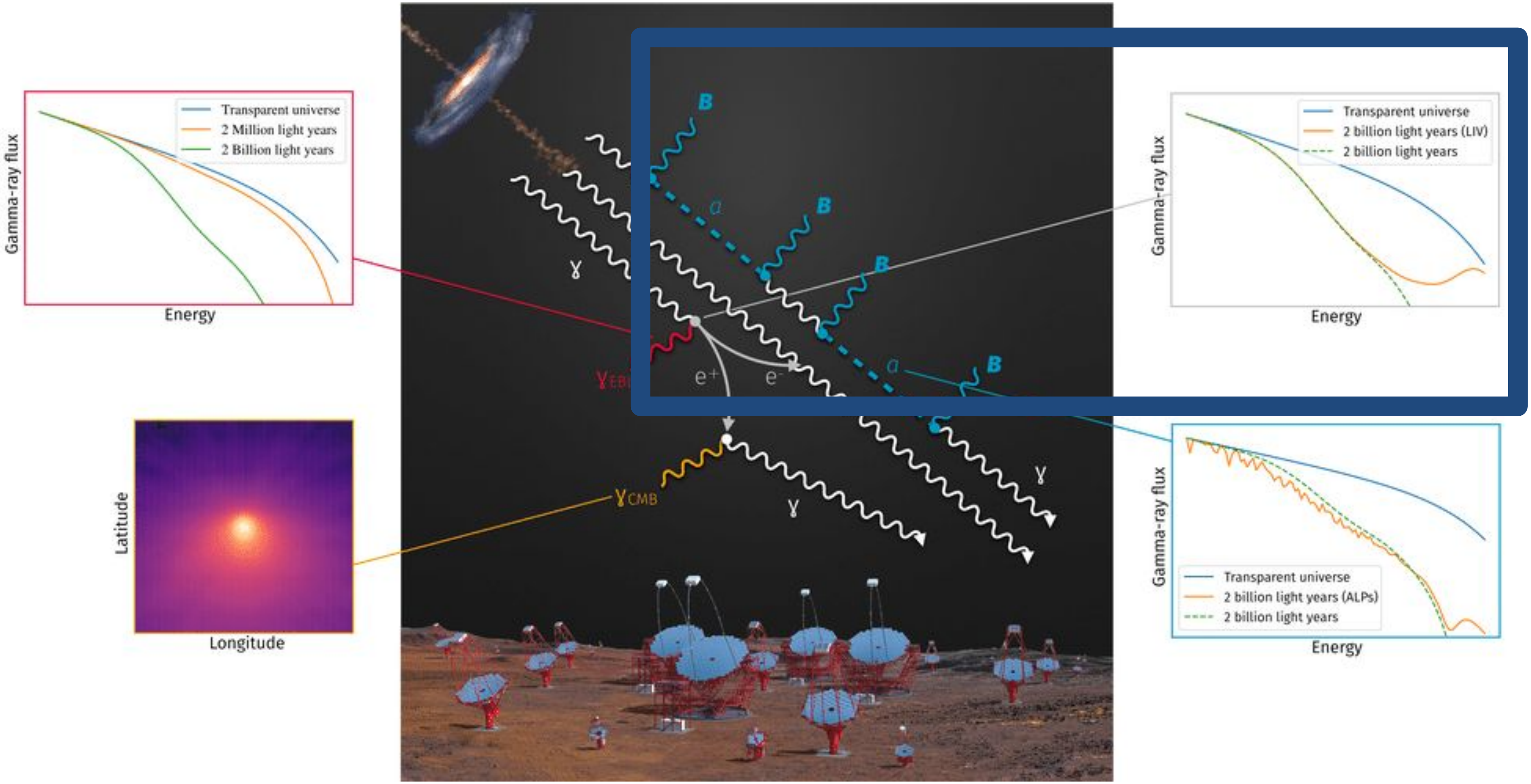


- axion: hypothetical boson introduced to explain the preservation of CP Symmetry in QCD
- It provide a low mass and feably interacting candidate for the Dark Matter
- But strongly weakly couple with photons, allowing conversion from gamma rays to Axions along the travel
- photons can “escape” EBL absorption by conversion to Axions



https://arxiv.org/pdf/1406.5972

Gamma ray propagation



https://www.ctao.org/news/redshift-why-does-distance-matter-to-cta/

Lorentz Invariance basic principles

- Lorentz Invariance Violation (or Deformation) is expected by some candidates theory for Quantum Gravity
- Concept of an invariant, minimal length is a potential manifestation of quantum characteristics of space-time, anticipated to be of the order of Planck length (1.6 10^{-35} m)
- Integrated successfully in special relativistic framework (Doubly Special Relativity https://arXiv.org/abs/hep-th/0112090v2), but as well in classical quantum mechanics (Generalized Uncertainty Principle https://arxiv.org/abs/2308.13788)
- In both cases, leads to a possibly modified dispersion relation, leading to detectable (or constrainable) effects
- Variability of speed of light versus energy is one of them (with an energy scale of the order of Planck Energy ~10^{19} GeV)

- Some cautions :
    - Planck Energy is an extrapolation of the current laws of physics up to 10 order of magnitude, the fact that those effect should happen at this energy should be taken with caution
    - Quantum Gravity is a complete change of paradigm, while what we are looking for is an anomaly in the current paradigm based on theoretical assumptions

Lorentz Invariance basic principles

QG pertubation term

$$E^2 = \frac{p^2c^2}{\boxed{a^2(t)}}\left(1 + \boxed{h_{QG}(E, E_{QG})}\right)$$

Cosmological scale factor

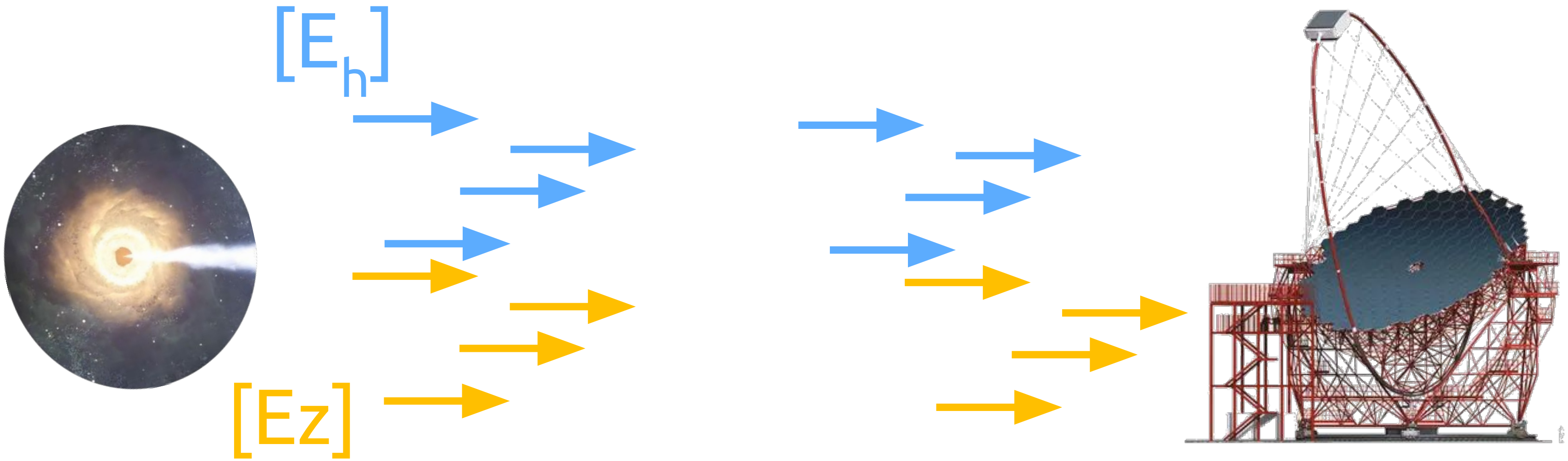
Taylor series expansion

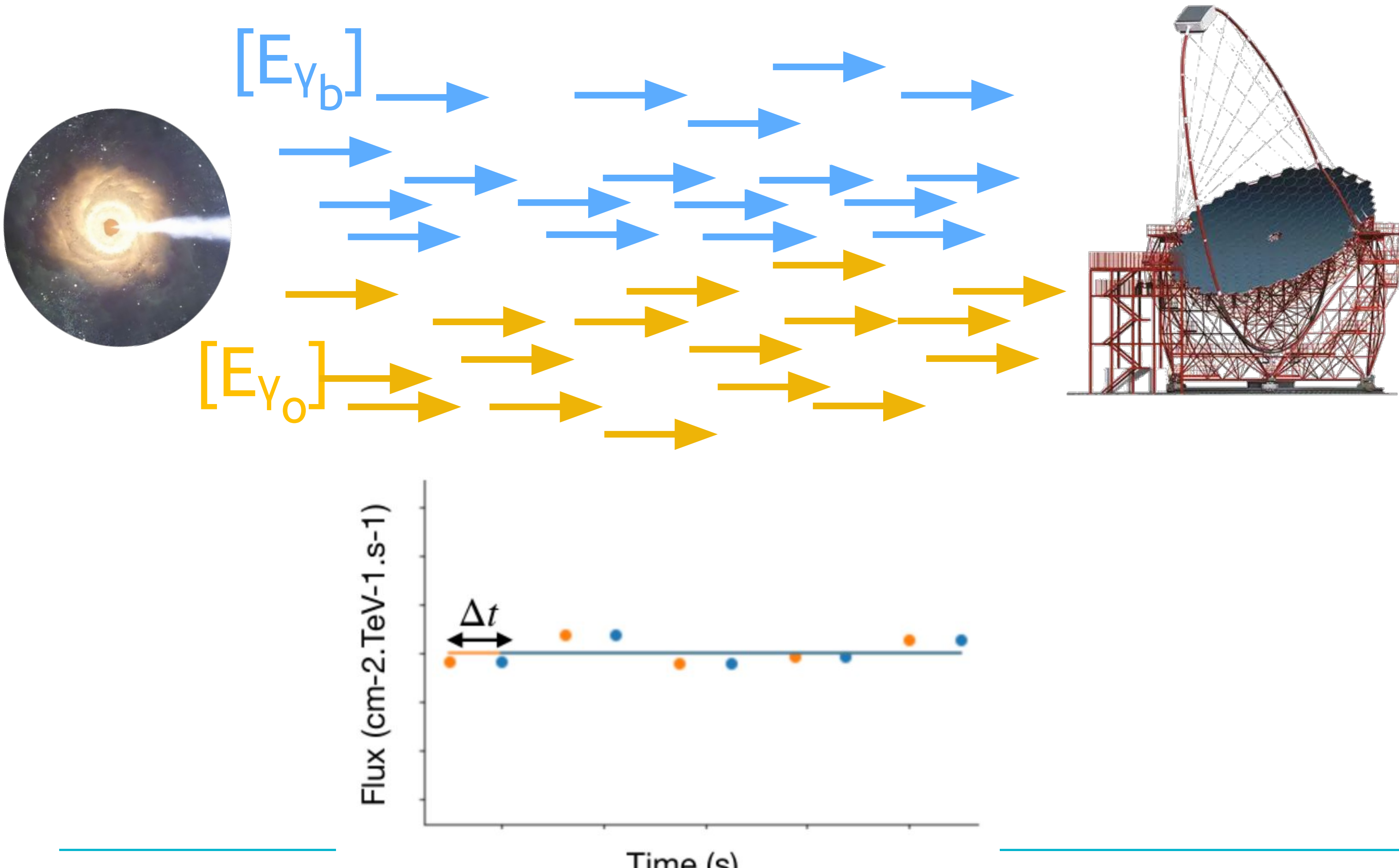
$$E^2 = \frac{p^2c^2}{a^2(t)}\left(1 + \sum_1^n \left(\frac{E}{E_{QG,n}}\right)^n\right)$$

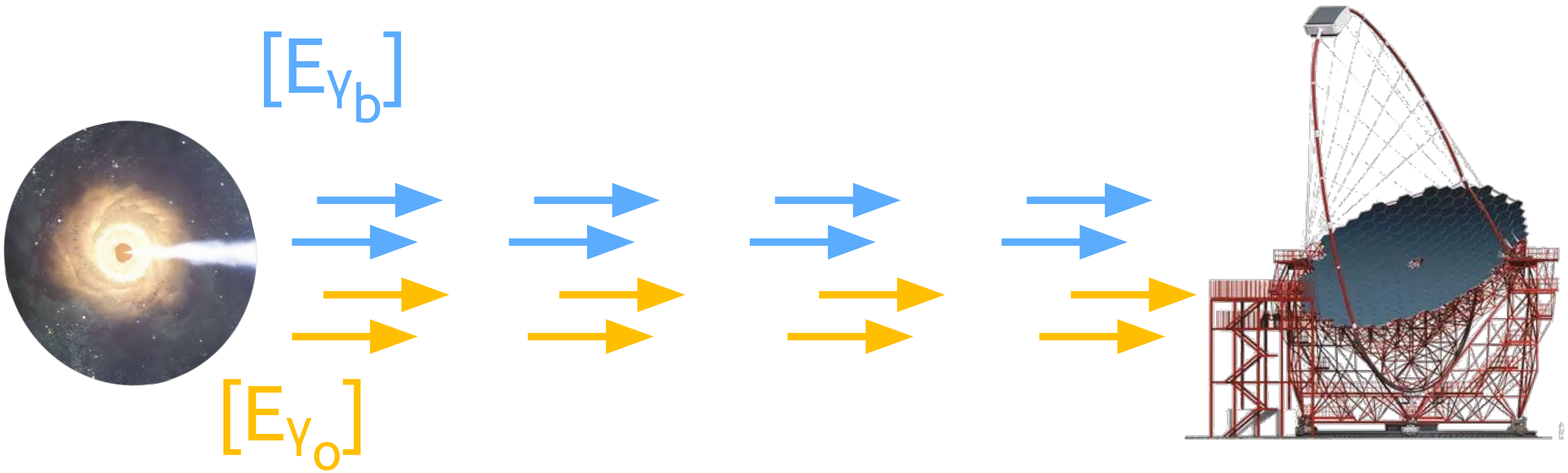
Speed for a given order

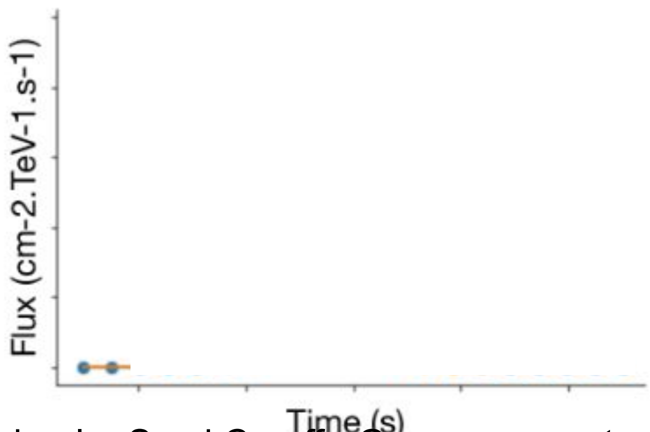
E(t) because of scale factor (redshift)

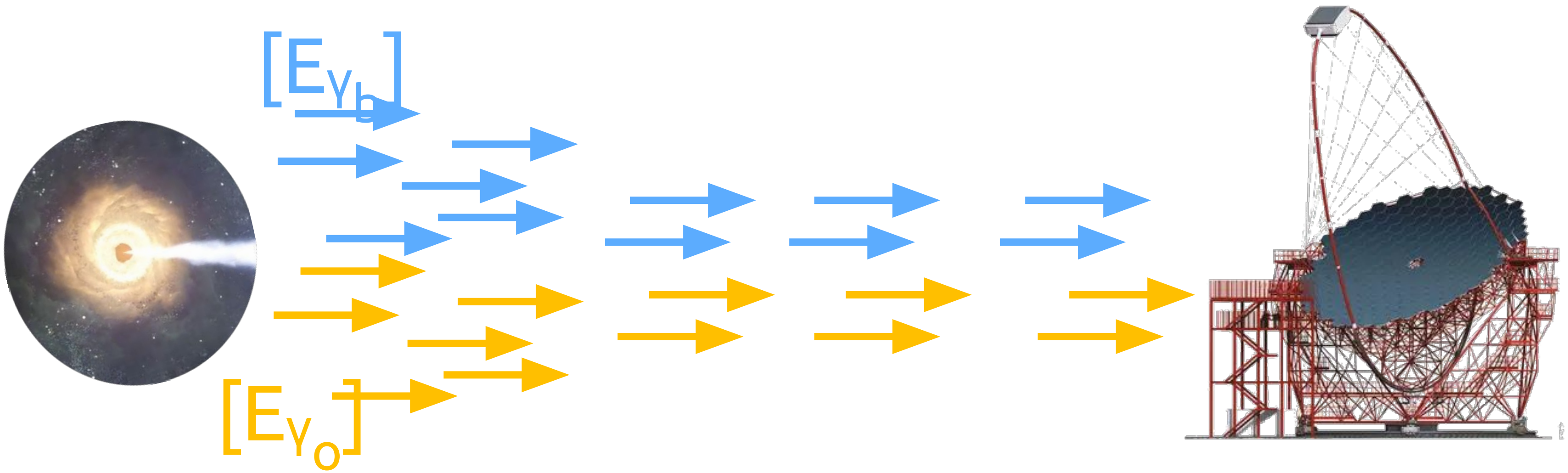
$$v(E,t) = \frac{\partial E}{\partial p} \simeq \frac{c}{a(t)}\left(1 + \frac{n+1}{2}\left(\frac{\boxed{E(t)}}{E_{QG,n}}\right)^n\right) \qquad \left(\frac{E(t)}{E_{QG,n}}\right)^n \simeq \left(\frac{pc}{a(t)E_{QG,n}}\right)^n$$

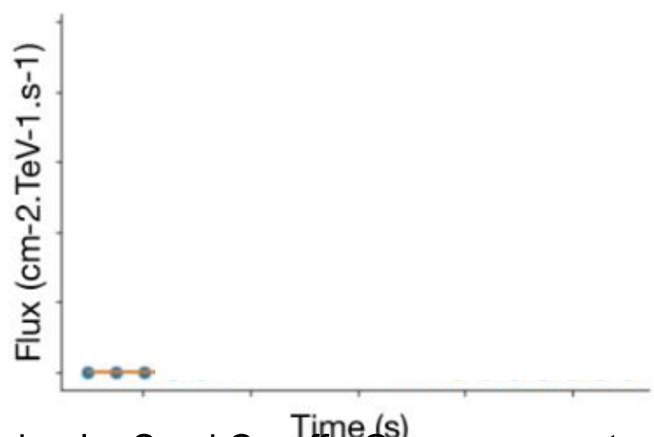

[E_h]
[Ez]

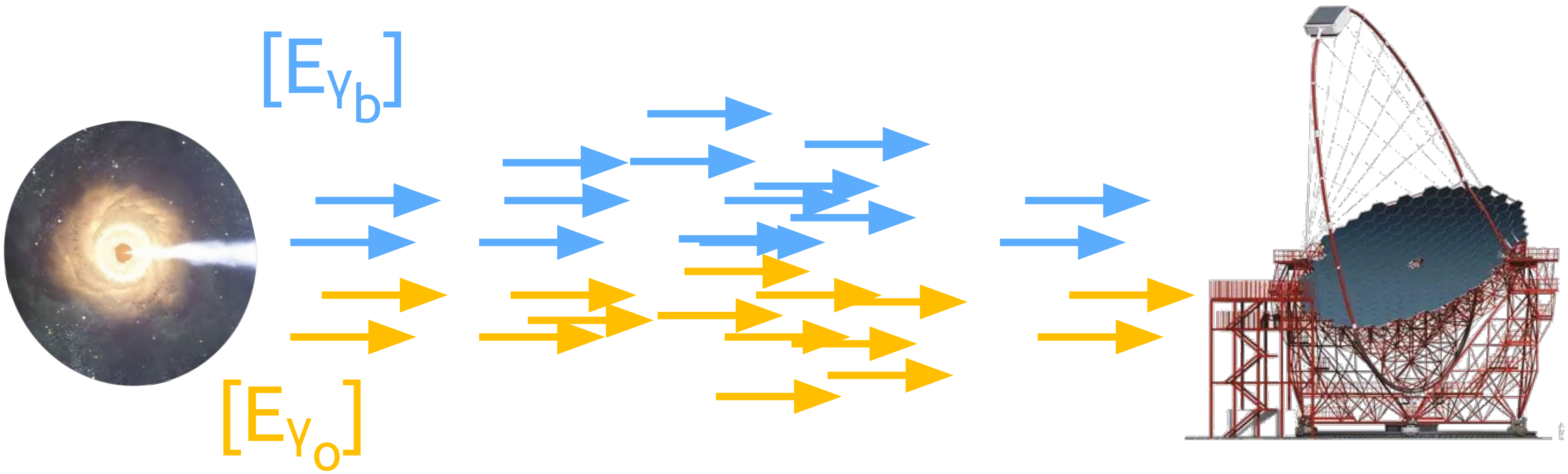

[Eγb]
[Eγo]
Δt
Flux (cm-2.TeV-1.s-1)
Time (s)

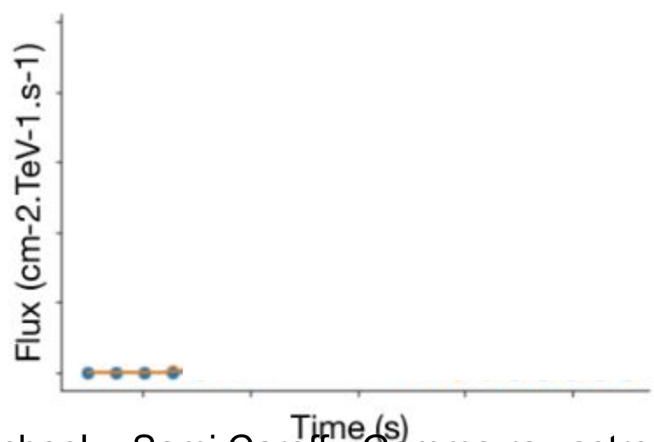

[Eγb]
[Eγo]

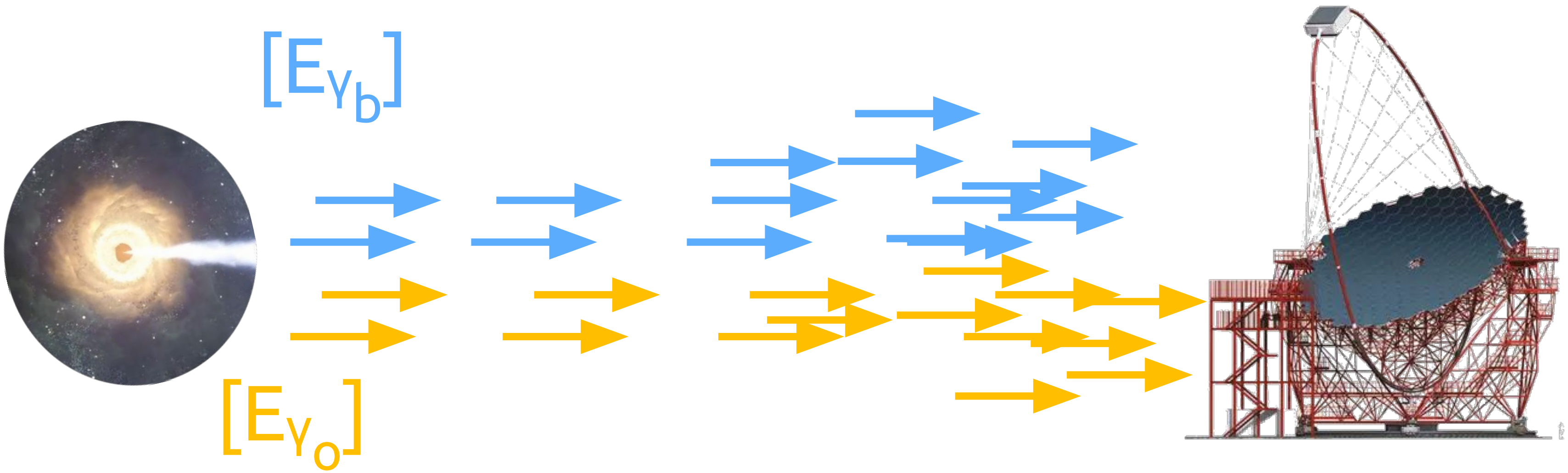

Flux (cm-2.TeV-1.s-1)
Time (s)

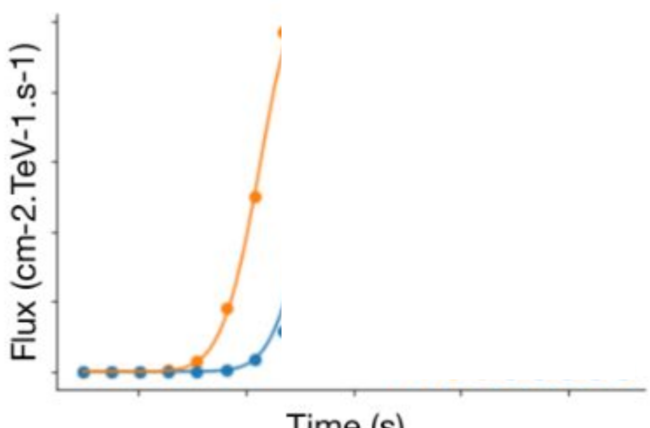

$[E_{\gamma_b}]$
$[E_{\gamma_o}]$

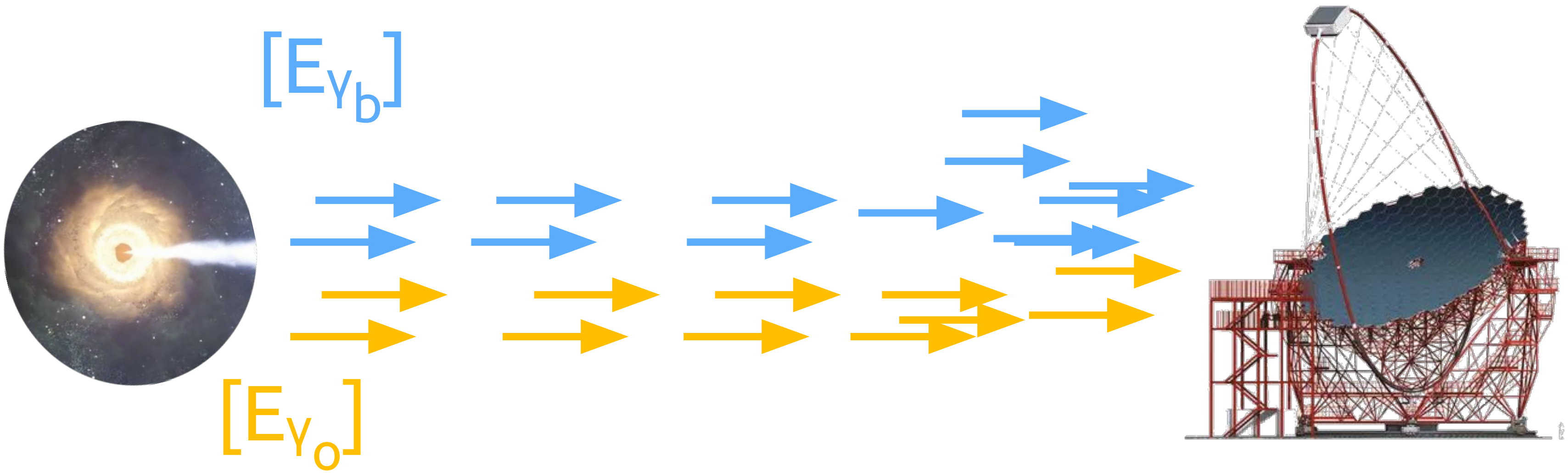

Flux (cm-2.TeV-1.s-1)
Time (s)

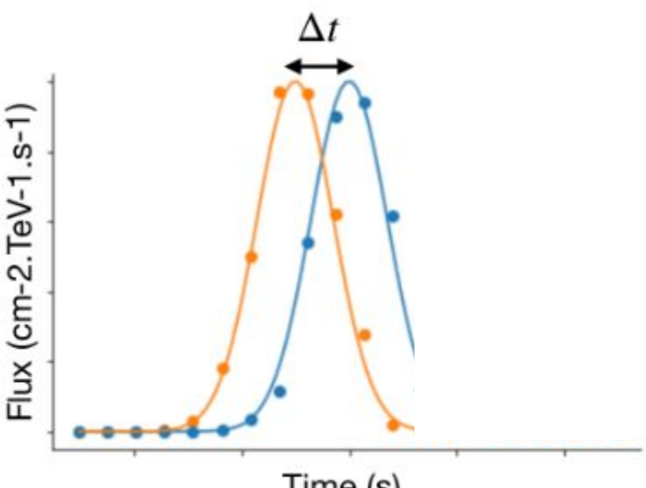

[E_{γ_b}]
[E_{γ_o}]

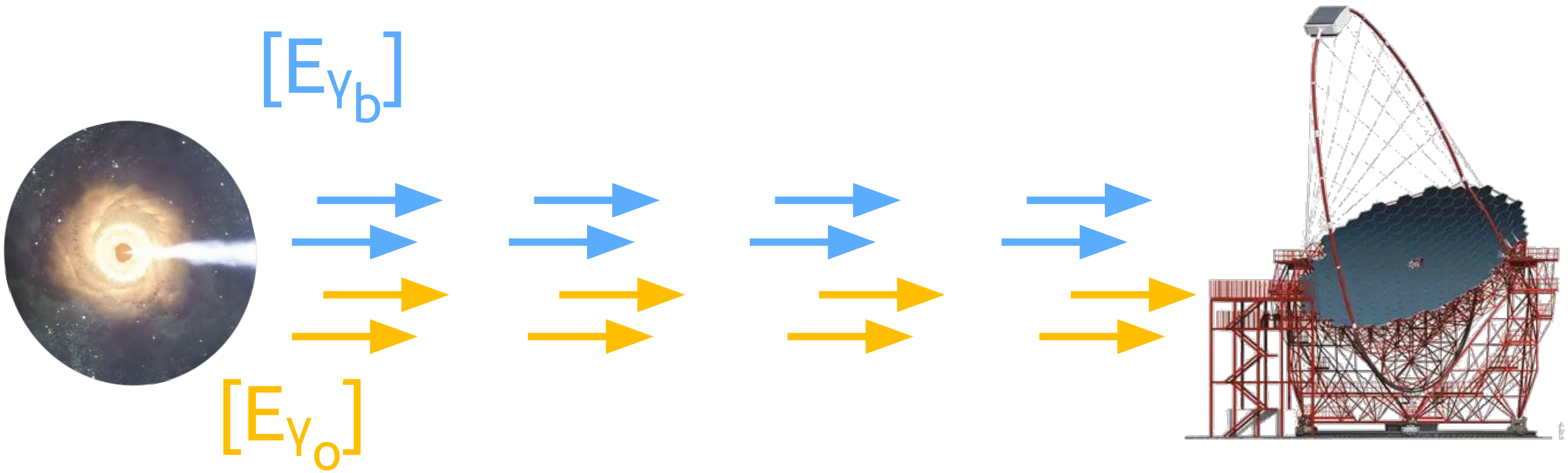

Flux (cm-2.TeV-1.s-1)
Time (s)


$[E_{\gamma_b}]$
$[E_{\gamma_o}]$

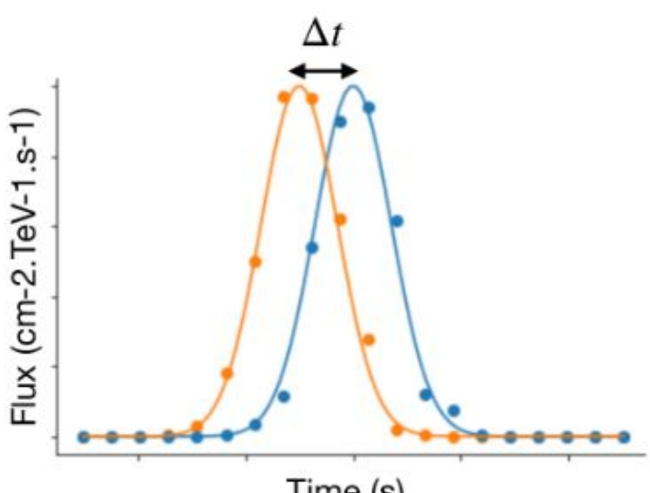

Flux (cm-2.TeV-1.s-1)
Time (s)


[E_{γ_b}]
[E_{γ_o}]


Δt
Flux (cm-2.TeV-1.s-1)
Time (s)

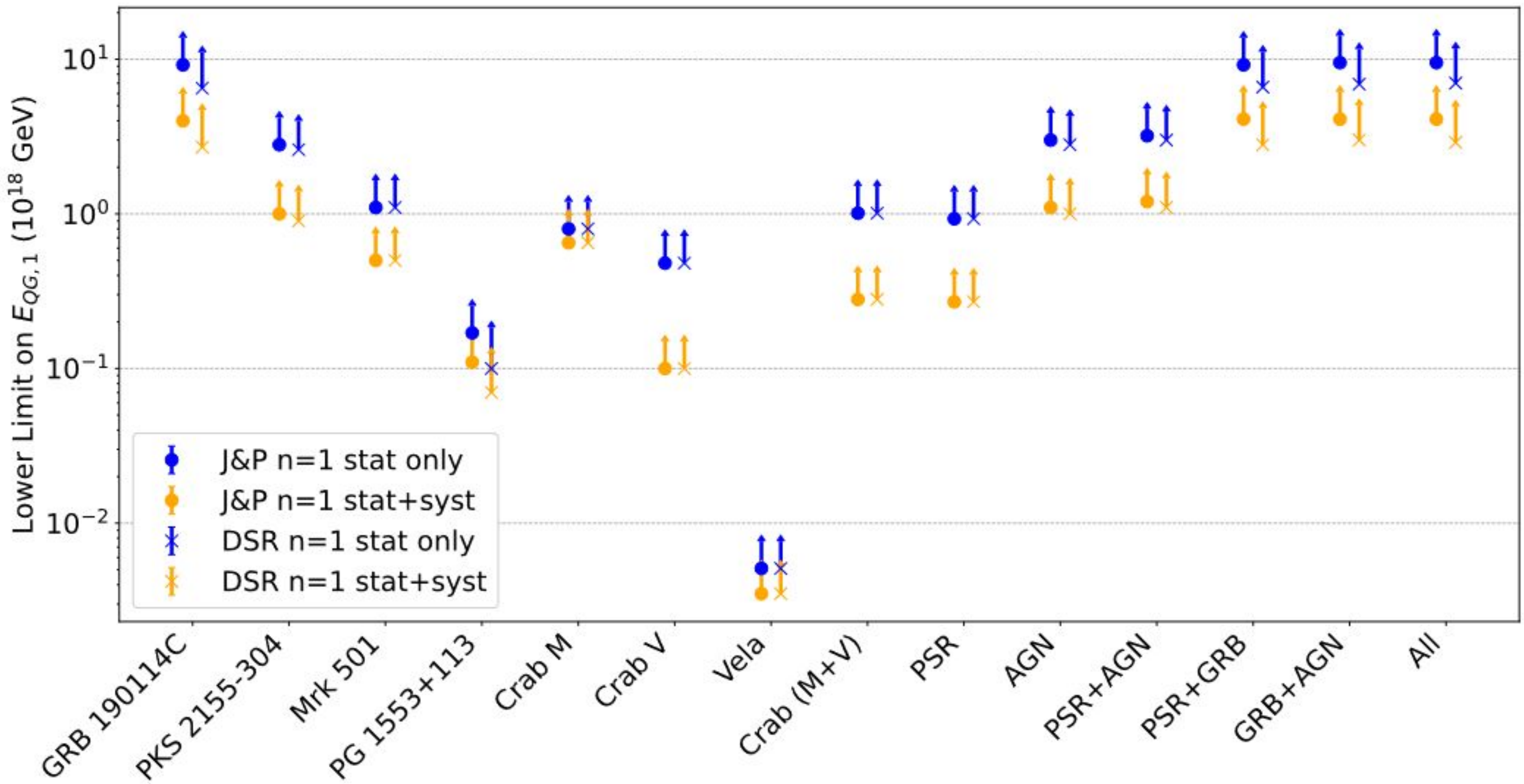


$[E_{\gamma_b}]$
$[E_{\gamma_o}]$



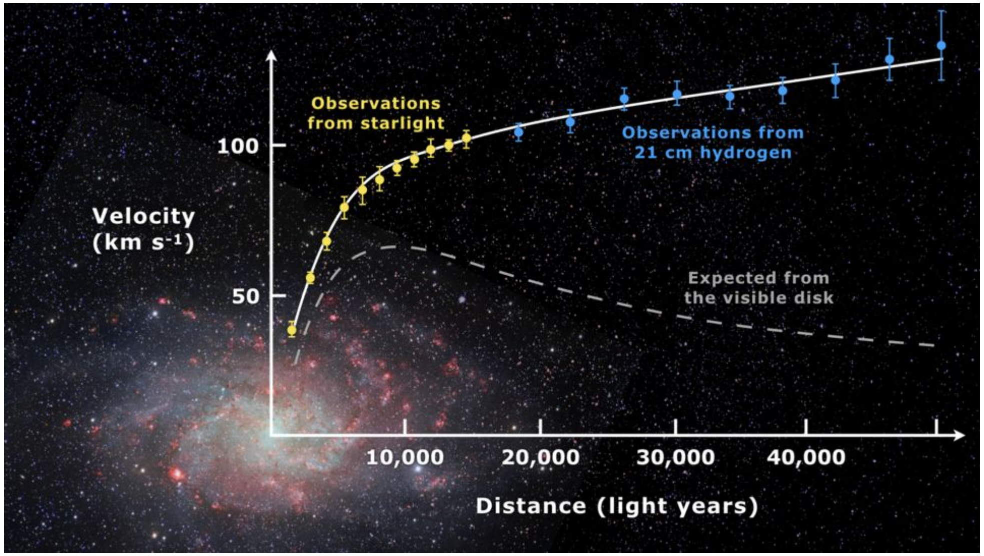
Δt
Flux (cm-2.TeV-1.s-1)
Time (s)

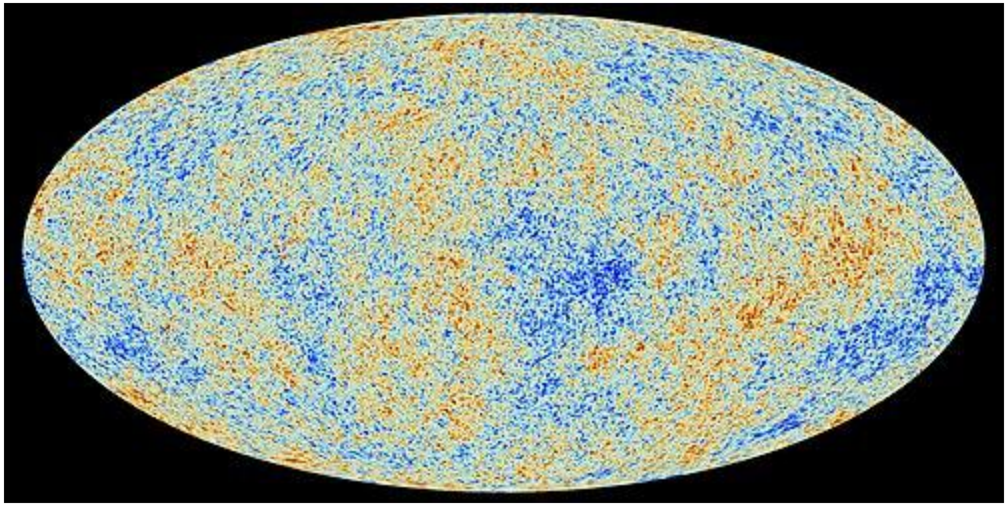
https://arxiv.org/abs/2201.02087



Dark matter

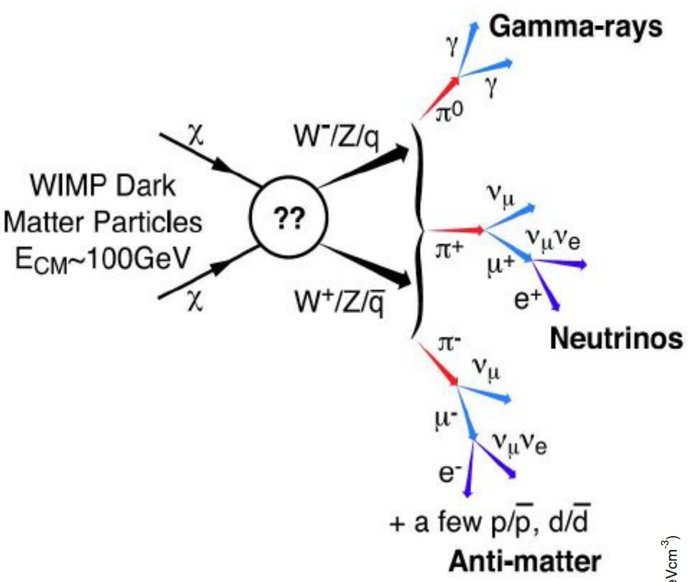
- Needed at various scale to explain various observations
  - Galaxy flat rotation curves
  - Imprint in the Cosmic Microwave background inhomogeneities
  - Needed to explain structure formation
  - Bullet cluster…
- Main candidates studied so far :
  - Axion Like Particle
  - Weakly interacting massive particle

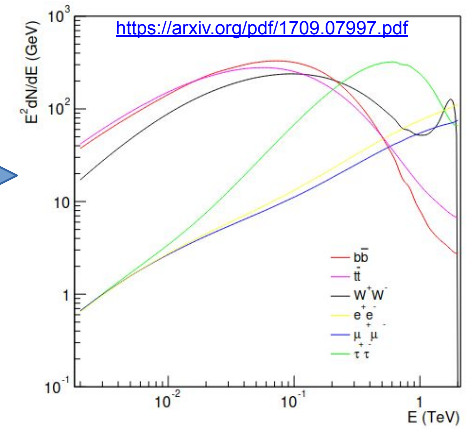


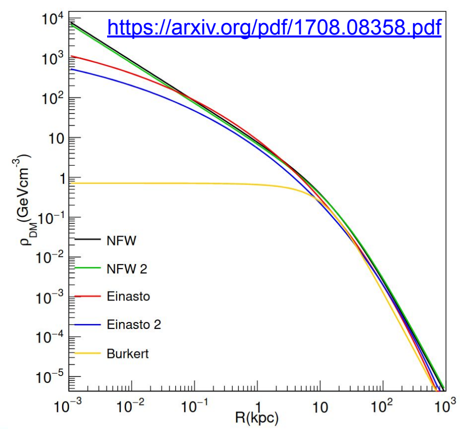


Dark matter indirect detection

Indirect detection







Astrophysics

spectrum

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

Particle Physics

- Galactic center
- + Large DM density, nearby
- - Astrophysical background
- Only visible for ground based observatory in the South Hemisphere (CTA-South, SWGO)

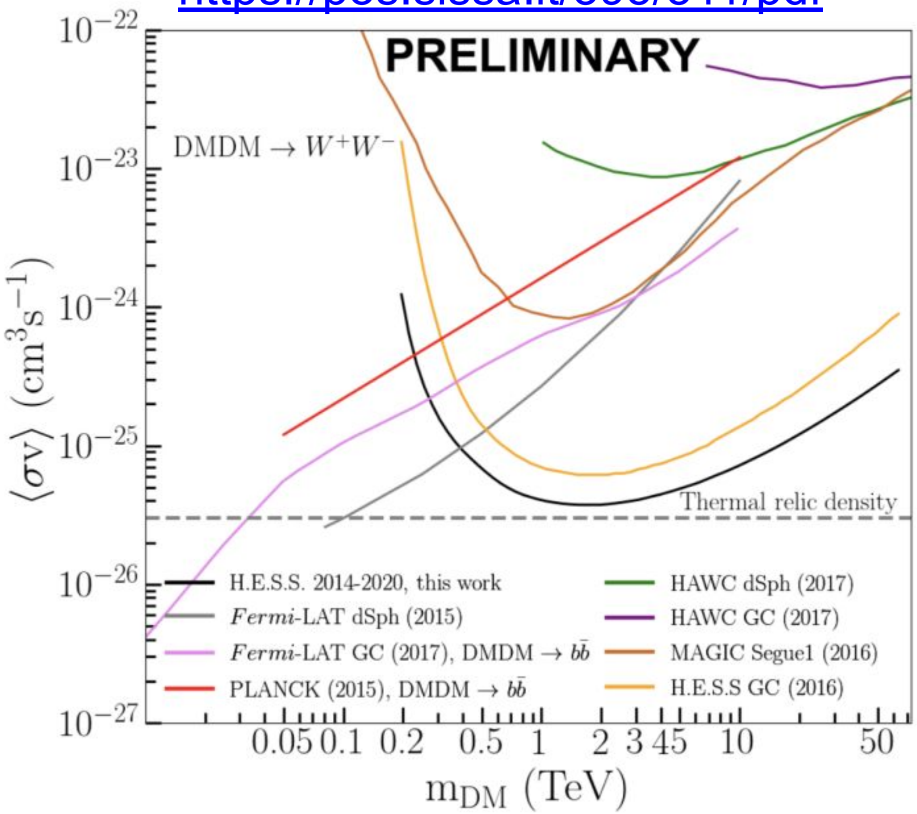
- Satellite galaxie (LMC)
- + Medium stat (distance)
- - Astrophysical background

- Dwarf Galaxies
- - low stat (distance and DM density)
- + Low astrophysical background

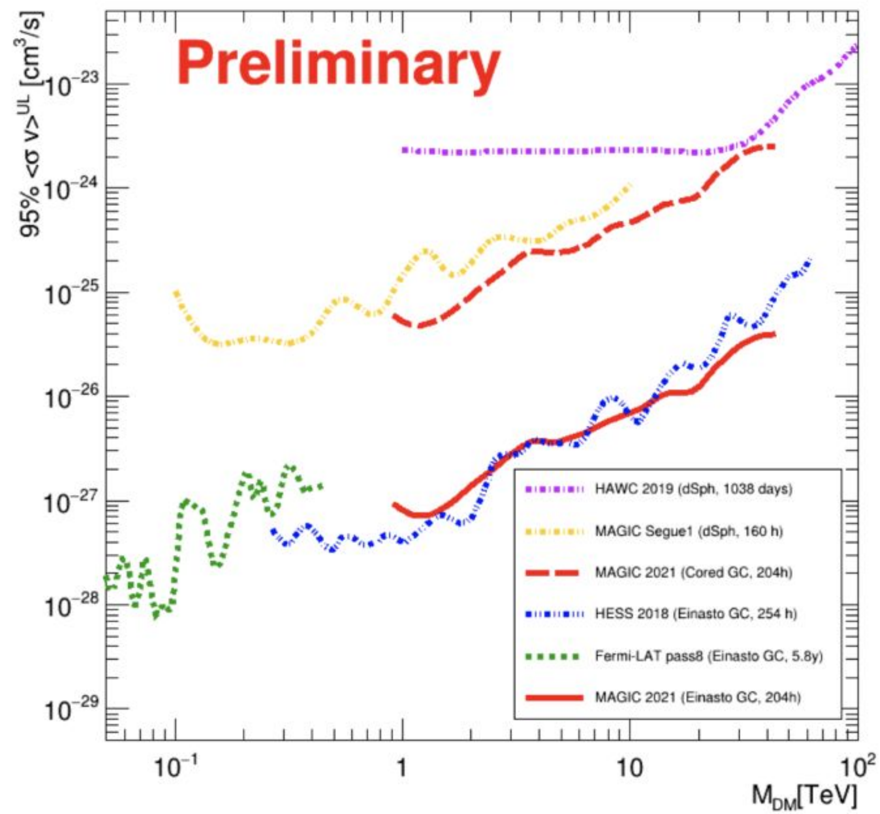
- Spectral lines
- + no background→ smoking gun
- - Low stat

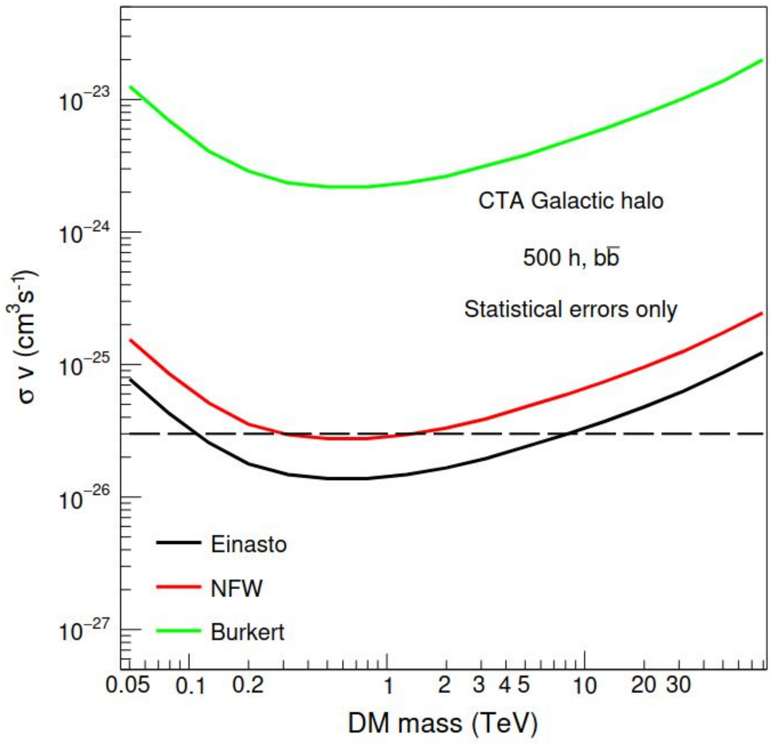
Limits overview (current observatories)

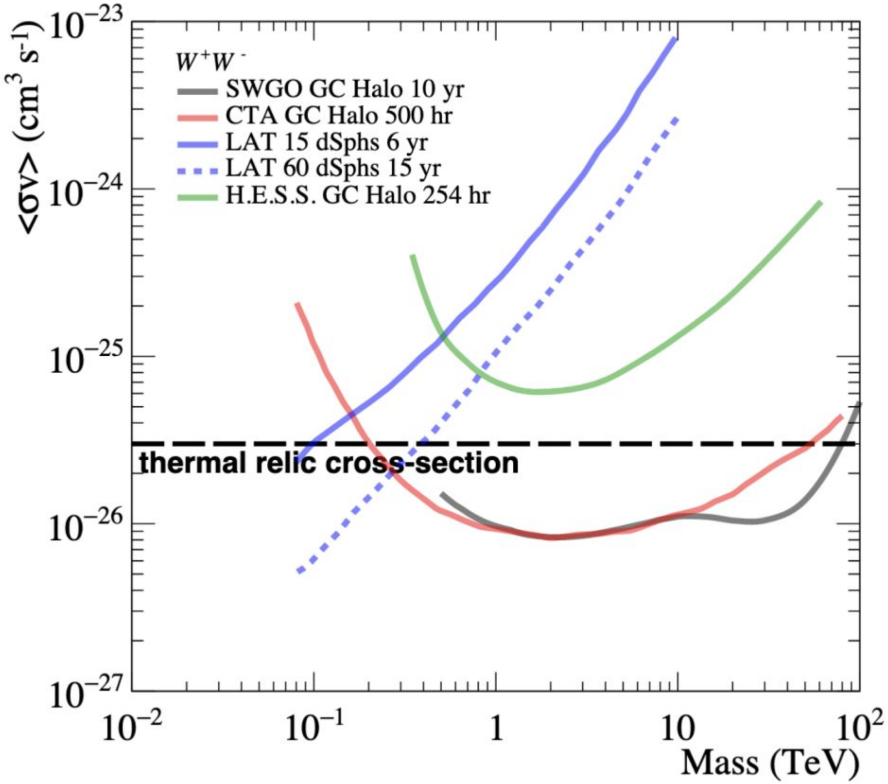
https://pos.sissa.it/395/511/pdf



https://pos.sissa.it/395/520/pdf







- GC best source for CTA (and southern observatories in general) but large uncertainty on the density profile
- Best case scenario, full exclusion of E < 100 TeV mass range (or even better a detection…)