Session

Astroparticules

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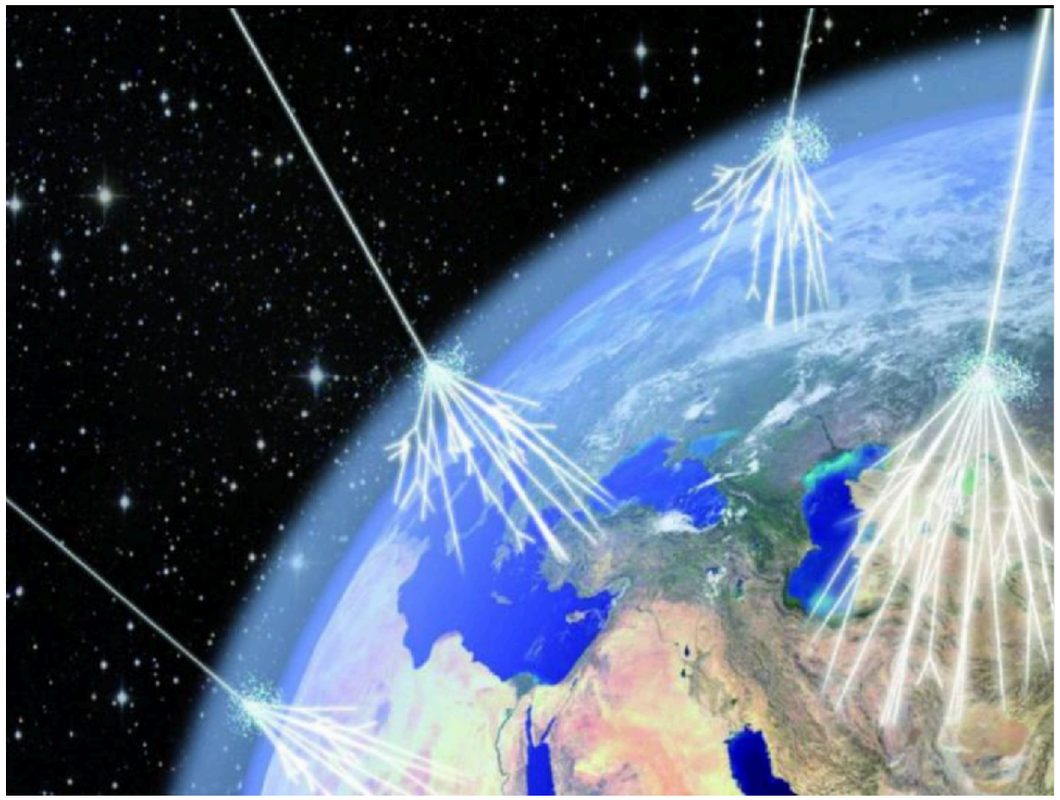
— Journées Rencontre Jeunes Chercheu.se.rs 2024 —

Cosmic Rays

Gamma rays

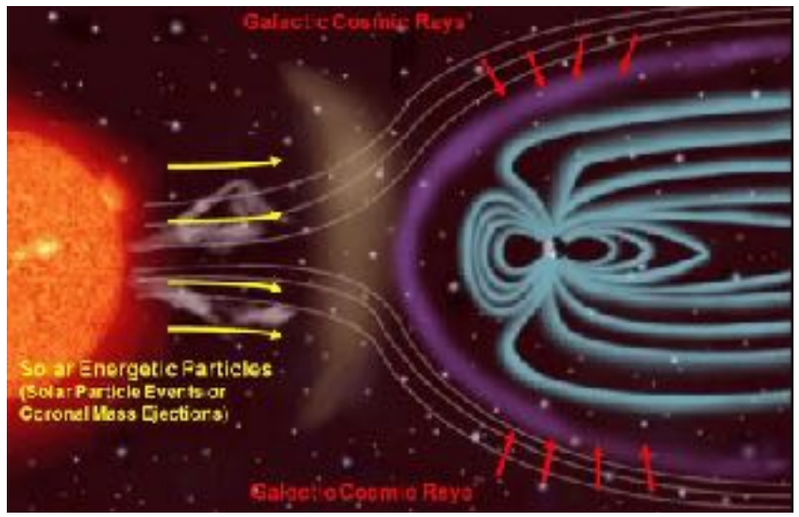
Astrophysical Sources

Discovery of Cosmic Rays



Earth continuously and isotropically strikes by **cosmic particles**

- Terrestrial magnetic field and atmosphere protect us



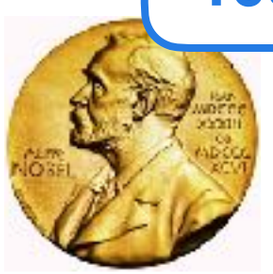
1912

Measure of an increase of the ionization rate with altitude in the atmosphere

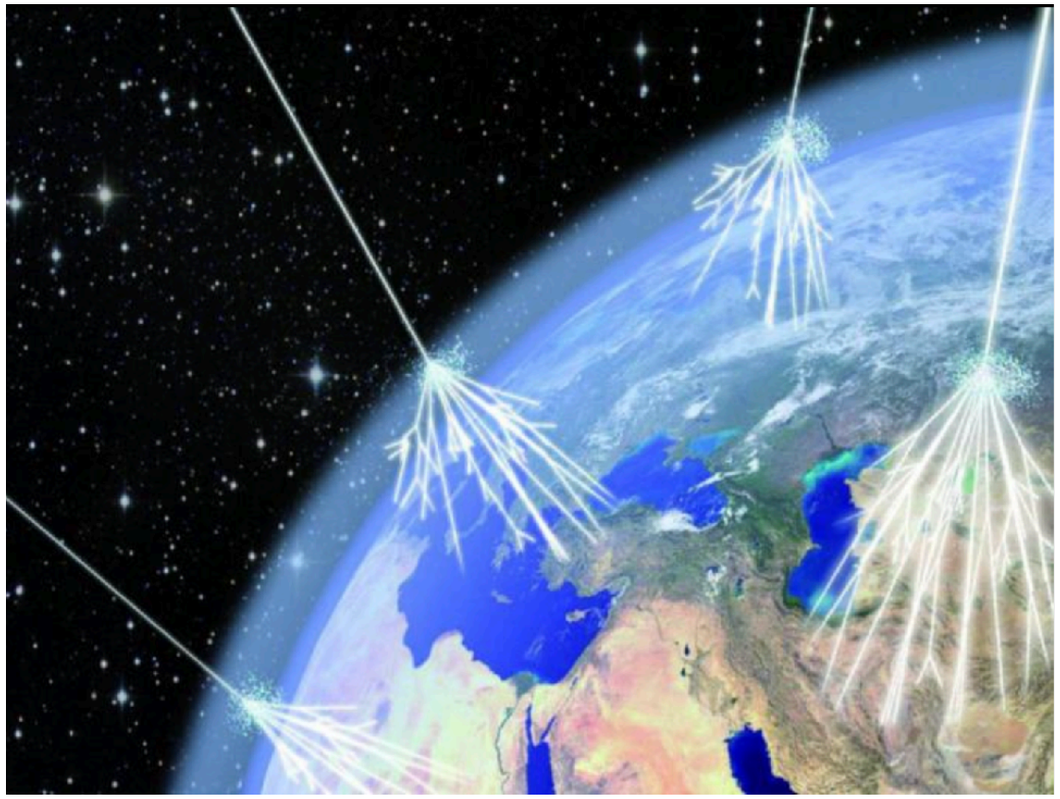
➡ Exists ionizing particles whose origin cannot be terrestrial

1936

DISCOVERY OF COSMIC RAYS



Discovery of Cosmic Rays



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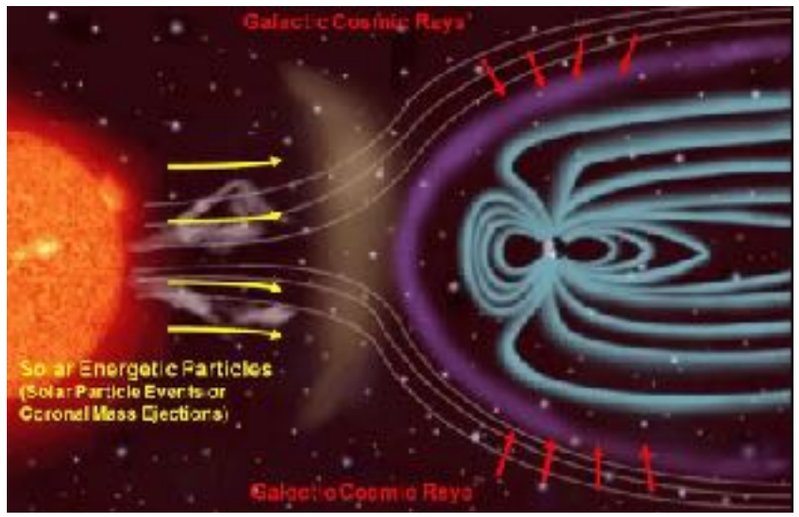

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DISCOVERY OF COSMIC RAYS

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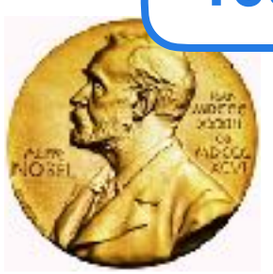
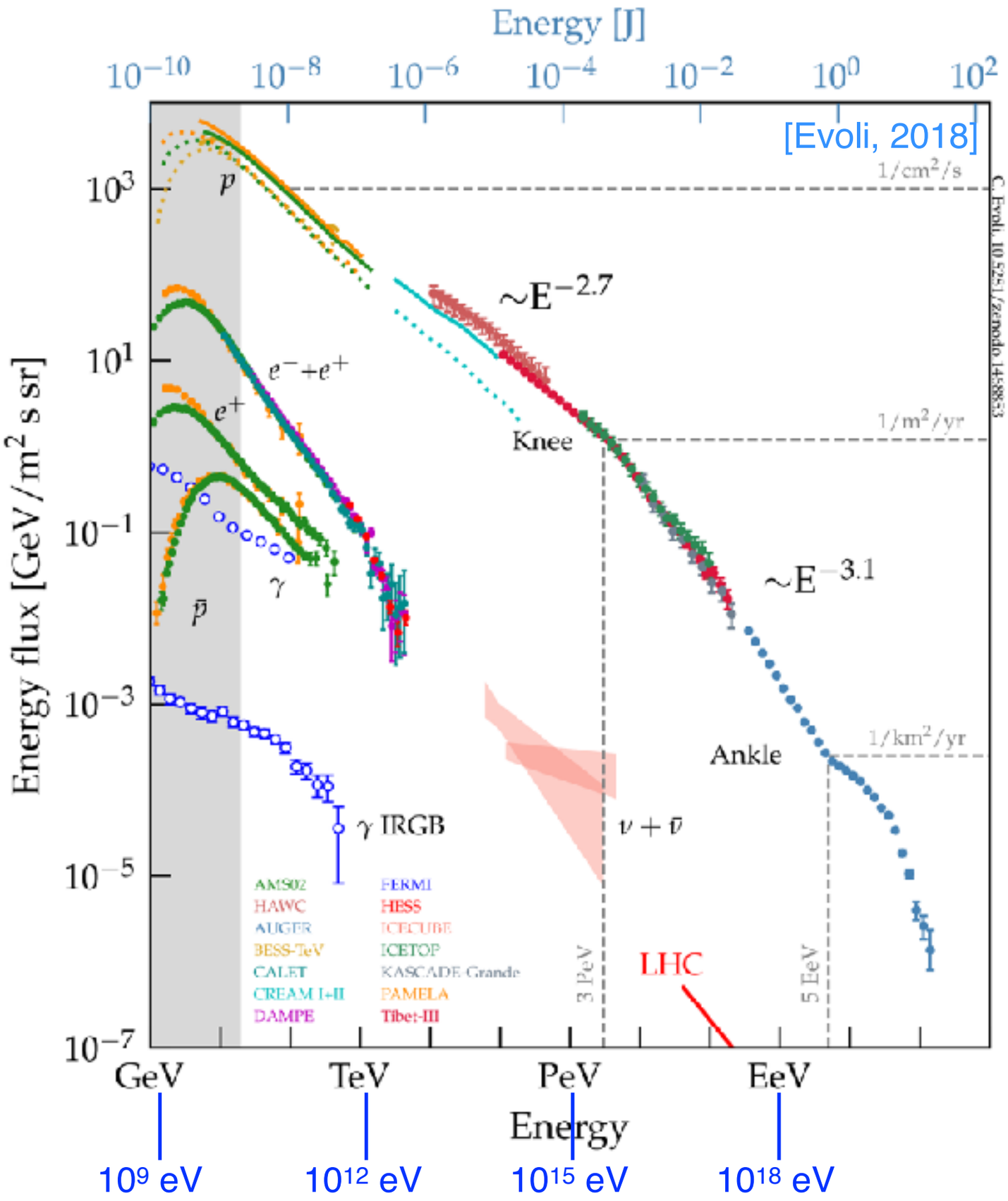


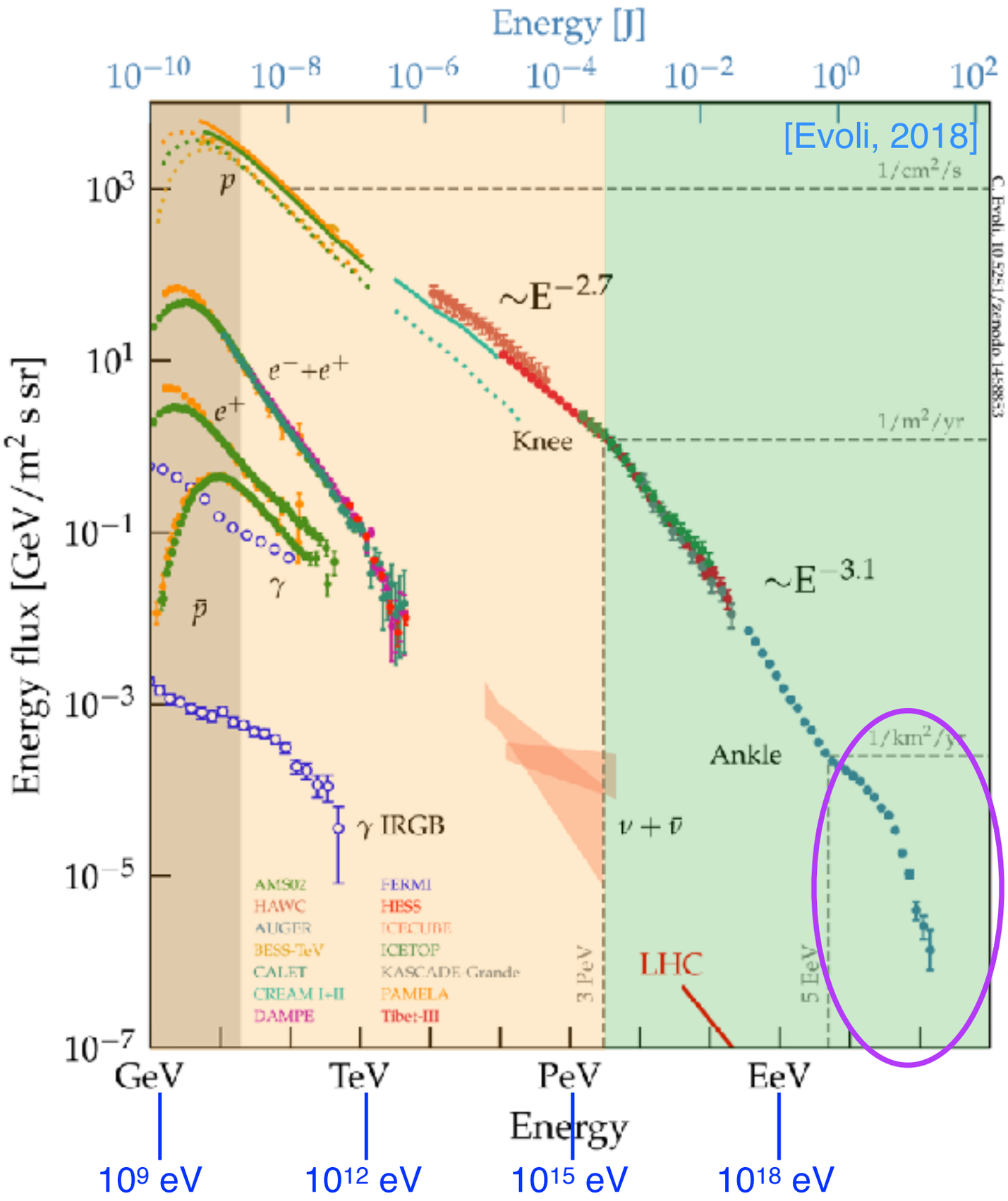
What are cosmic rays?



Composition:

- 90% protons
- 9% heavier nuclei
- 1% electrons

Cosmic-ray spectrum



Origin:

Galactic

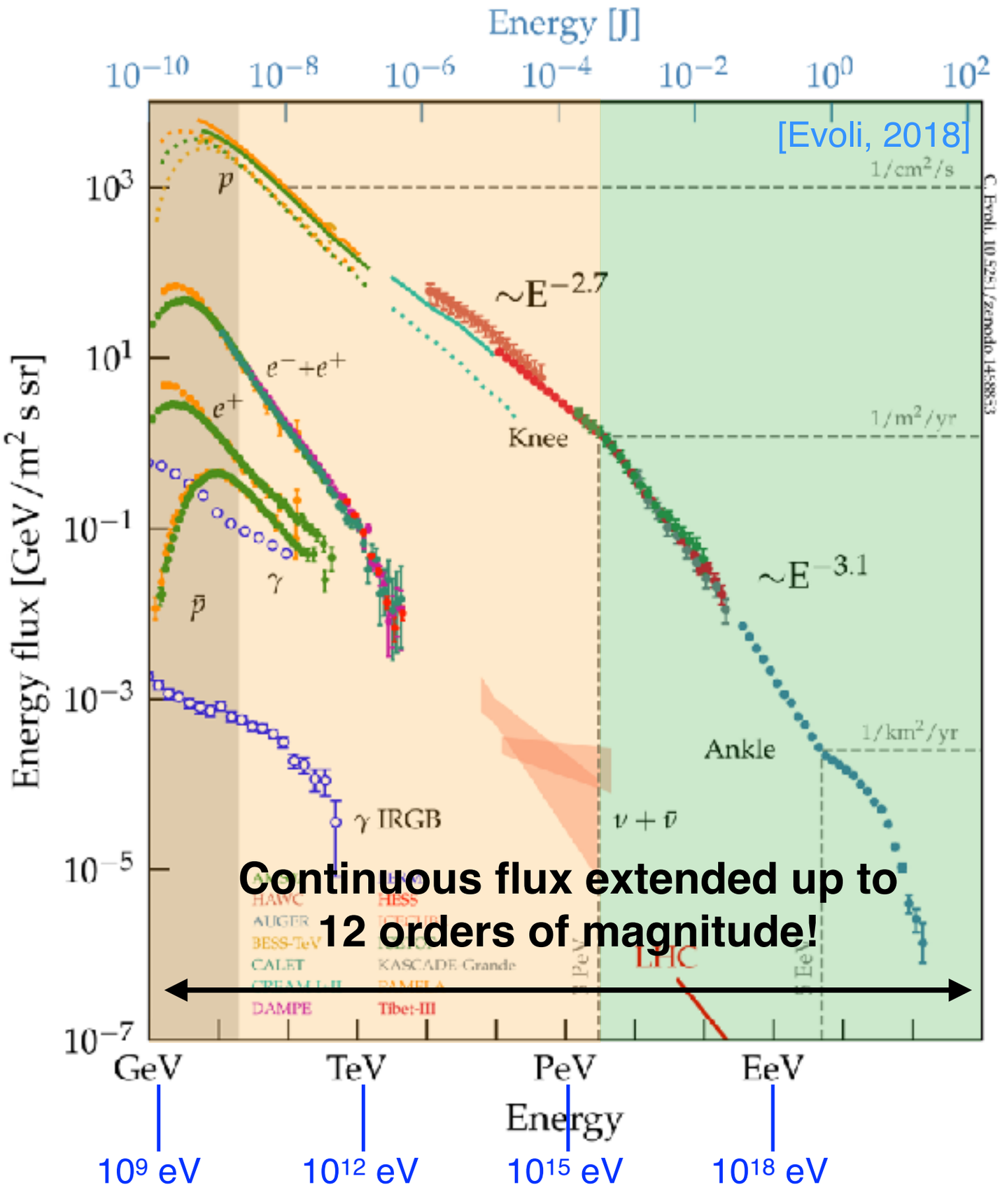
Larmor radius: $r_{\mathrm{L}} = \dfrac{E}{ZeB}$

Confined by the galactic magnetic field

Extragalactic

Opacity: highest-energy CRs interact with CMB photons

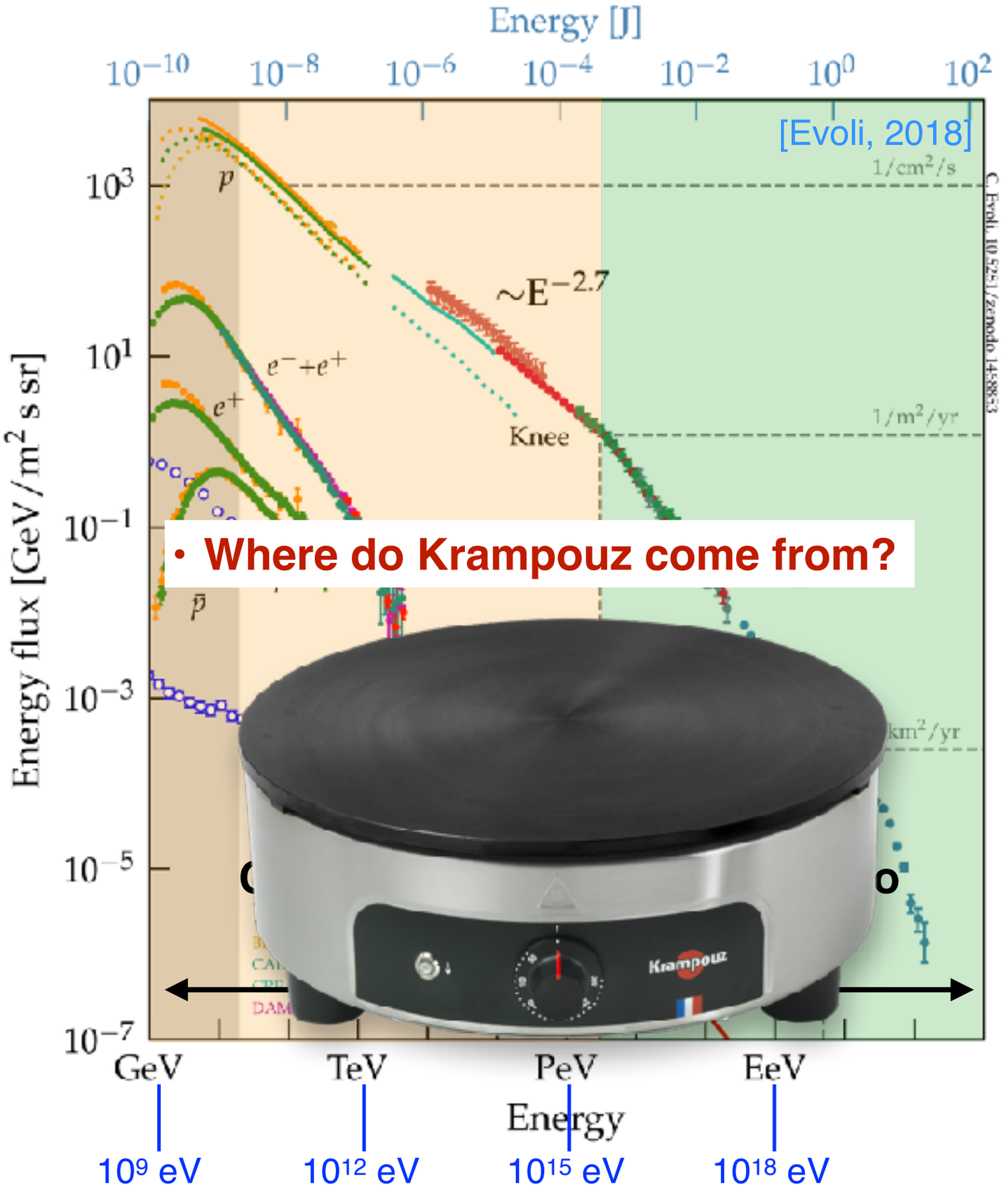
Where do cosmic rays come from?



- Where did particles get such energy to become a CRs?
- Where and how are they accelerated in the Universe?

- **Where do they come from?**

Where do cosmic rays come from?



- Where did particles get such energy to become a CRs?
- Where and how are they accelerated in the Universe?

- **Where do they come from?**

- **Where do Krampouz come from?**

Cosmic Rays

Gamma rays

Astrophysical Sources

Our Galaxy: The Milky Way

Several hundreds of billion of stars mostly located on the spiral arms

And orbiting around the supermassive black hole Sagittarius A*

[Event Horizon Telescope 2022]

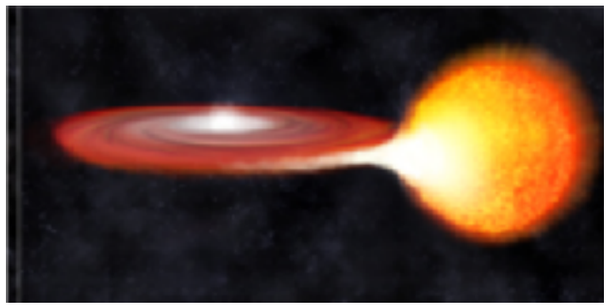
Star forming rate (per year): 1.7 +/- 0.2 Msun [Licquia & Newman 2015]

Large amount of activity in the Galaxy where stars born... and die

Create **Collapse**

Cataclysmic events

- **M < 8 M_{sun} :** white dwarf + companion star

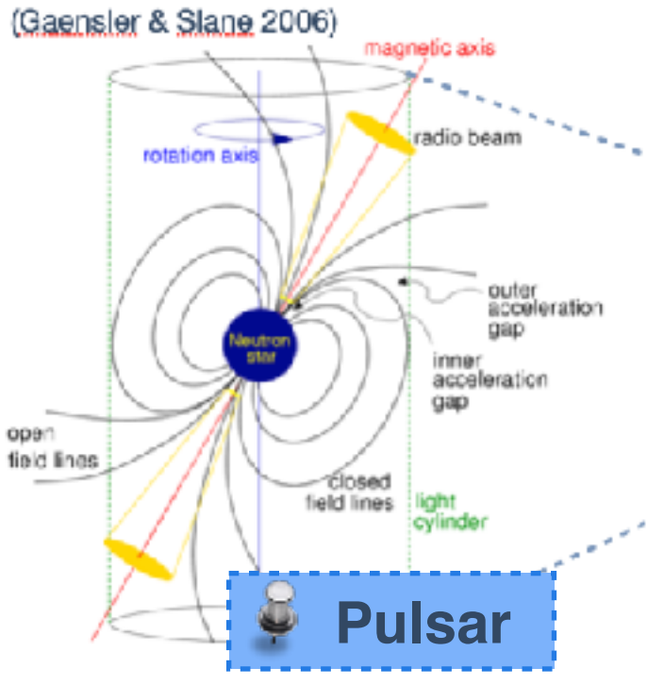


SUPERNOVA

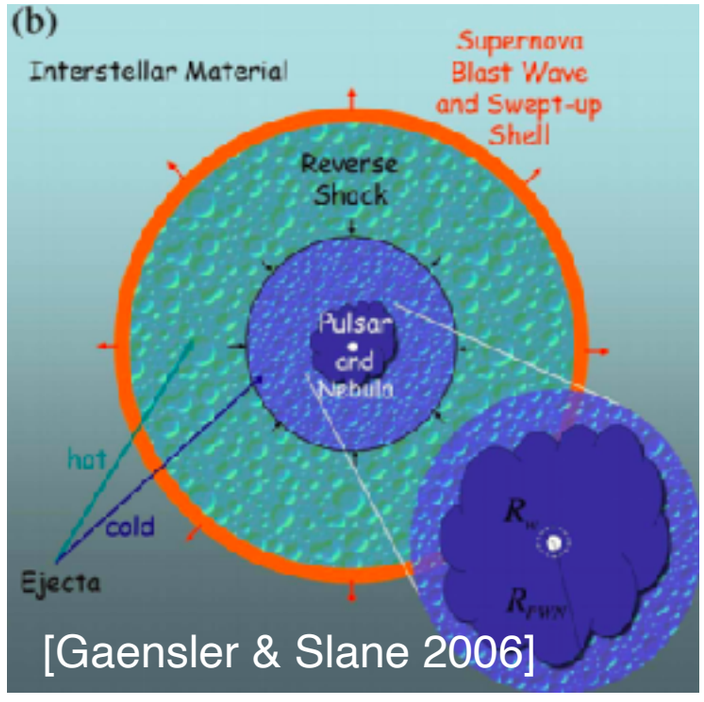
Supernova remnant

- **8 M_{sun} < M < 22 M_{sun} :** neutron star / pulsar

SUPERNOVA



Pulsar



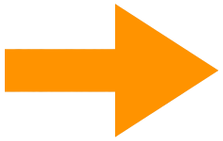
[Gaensler & Slane 2006]

Supernova remnant

Pulsar wind nebula

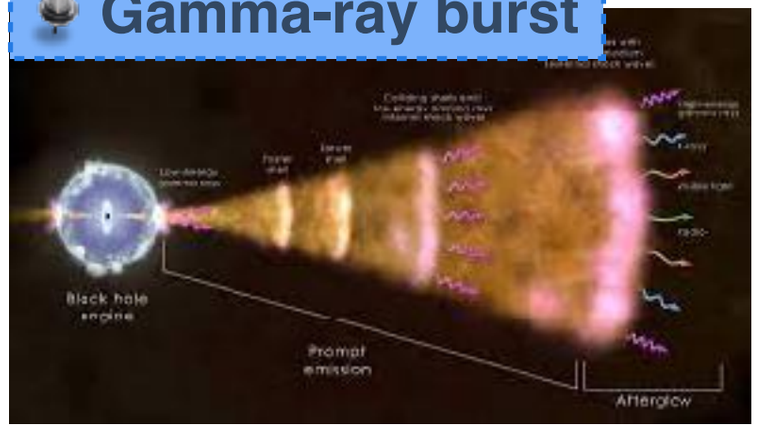
Cataclysmic events

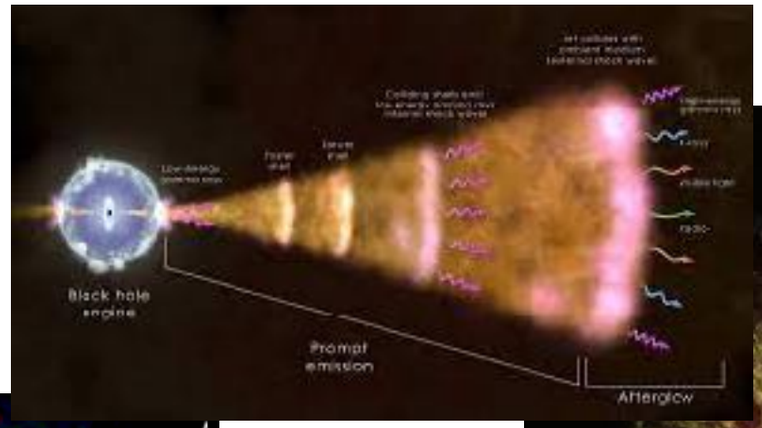
- **M > 22 M_{sun}:** magnetar or black hole

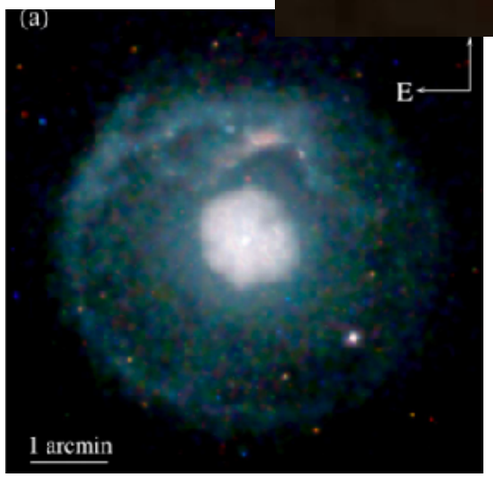


SUPERNOVA

Gamma-ray burst



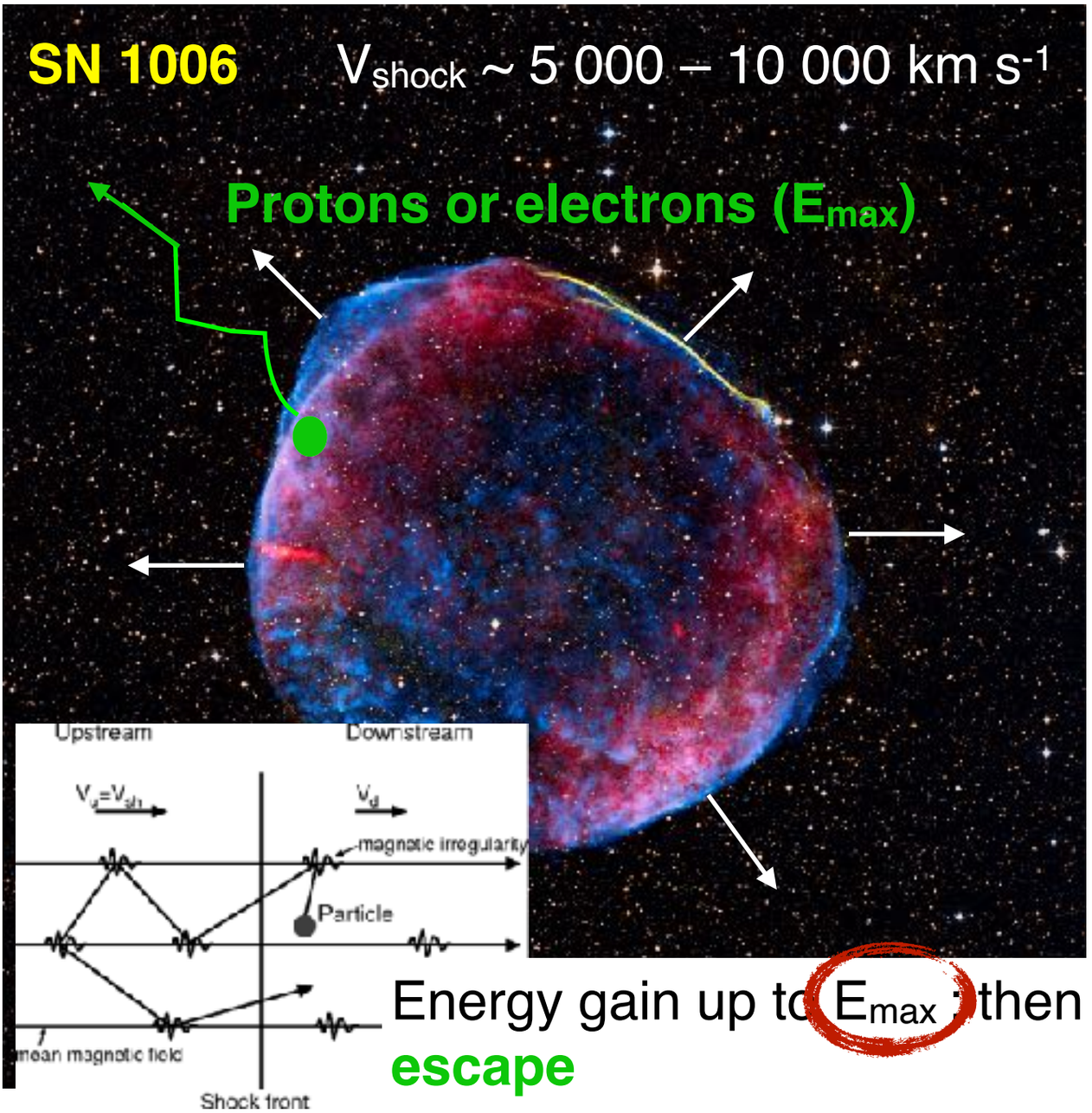




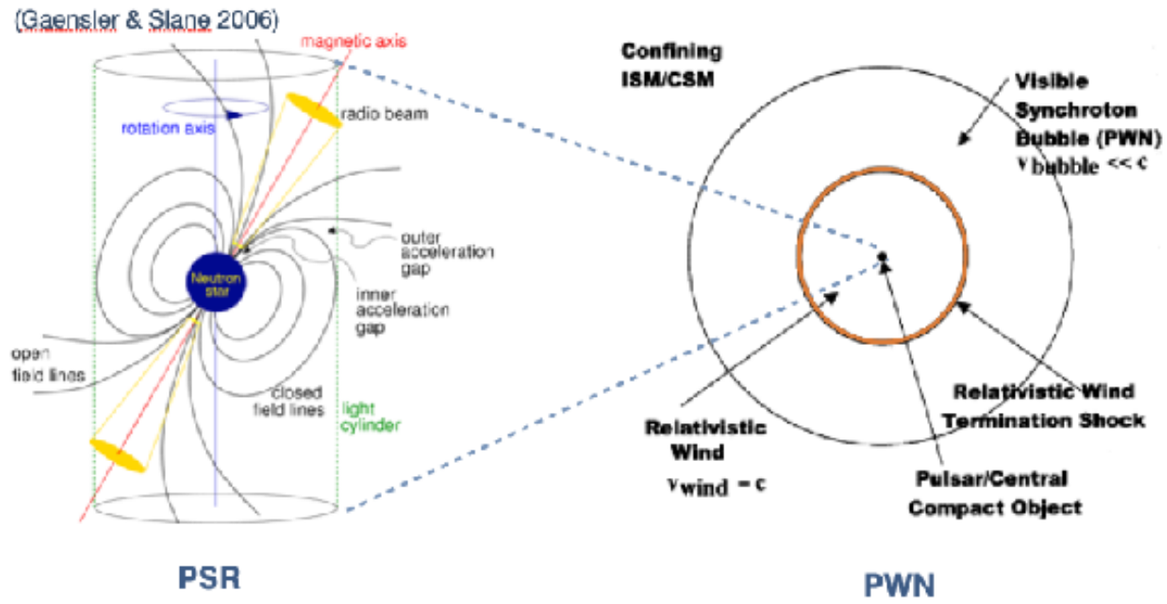
Acceleration of particles must occur within the most violent phenomena

➡ **Supernova remnants: best candidates for acceleration of CRs!**

Theory for acceleration of particles at astrophysical shocks



Energy gain up to E_{max} ; then **escape**

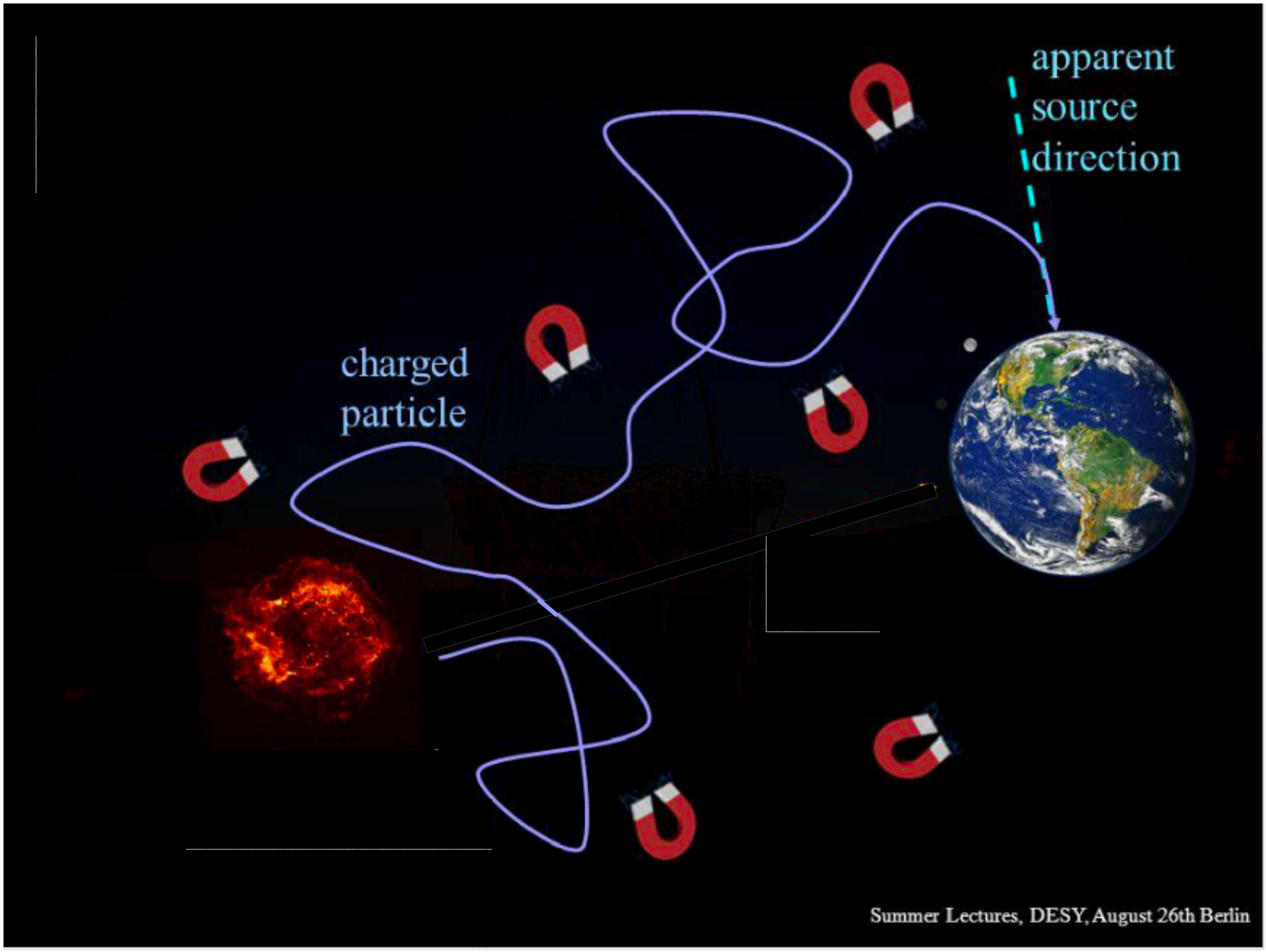


Applicable to any shock front in astrophysical sources

➡ **Can these astrophysical sources be particle accelerators?**

➡ **And to such high energies measured in the CR spectrum?**

Chasing cosmic-ray sources with gamma rays



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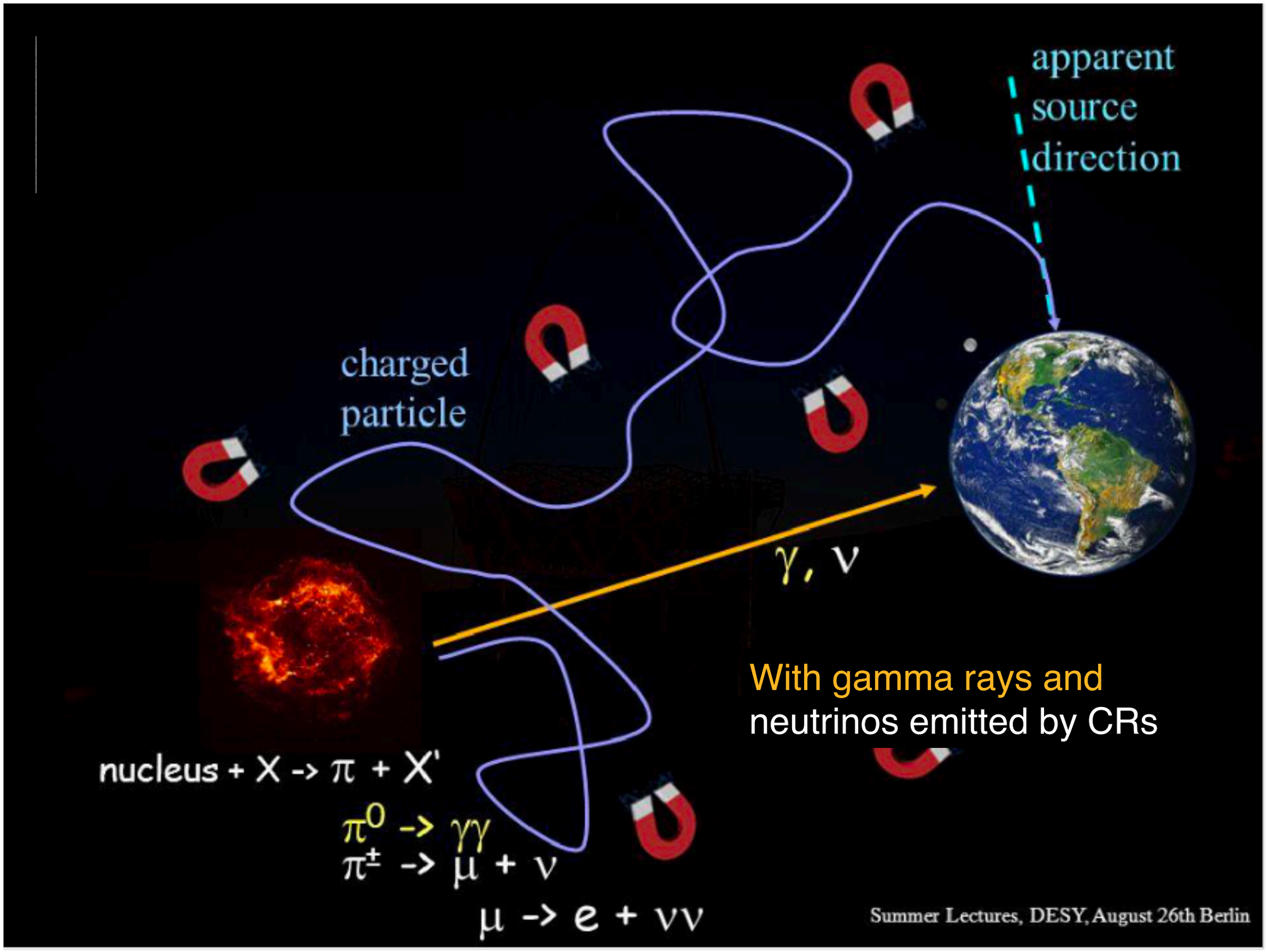
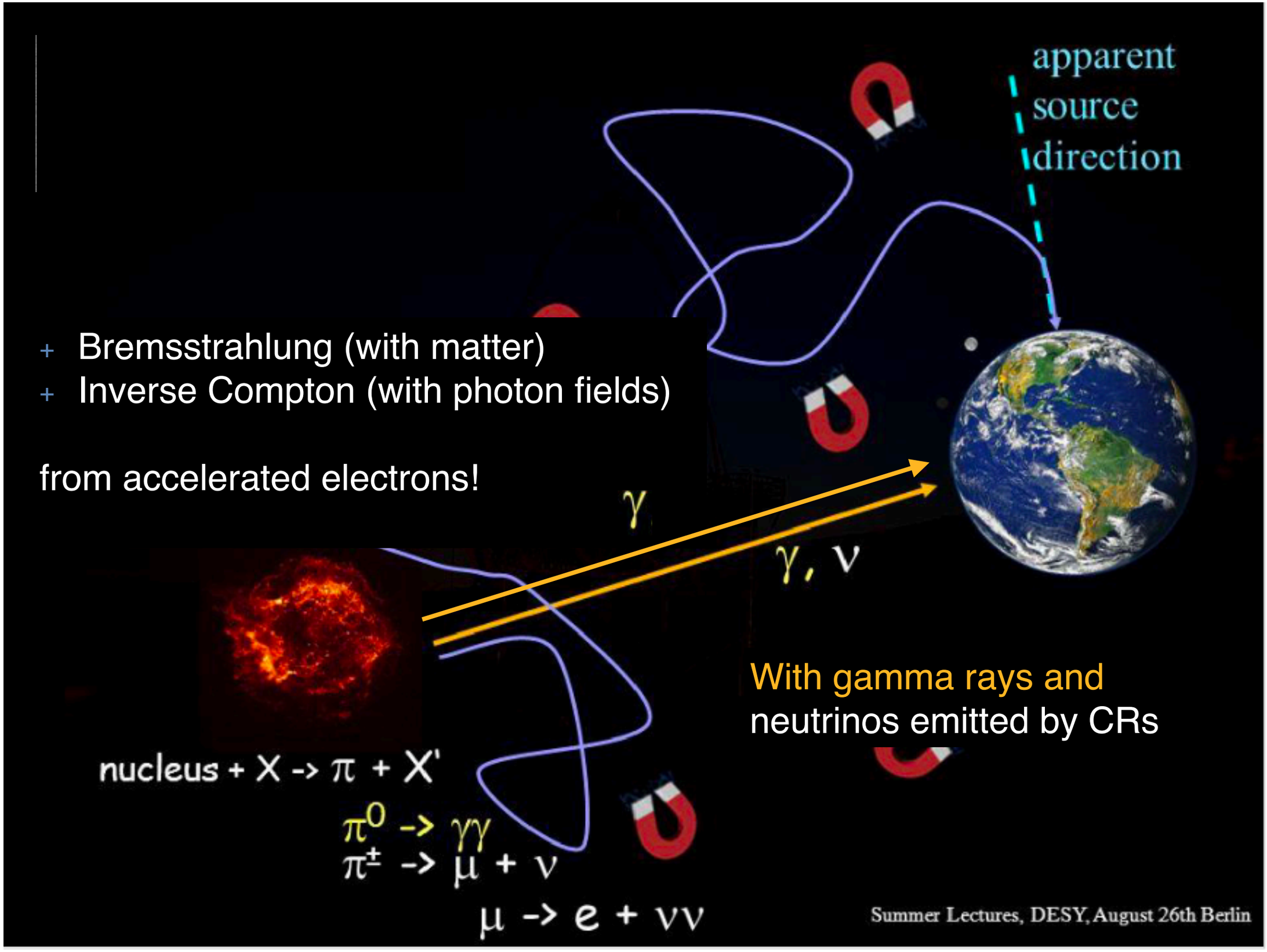
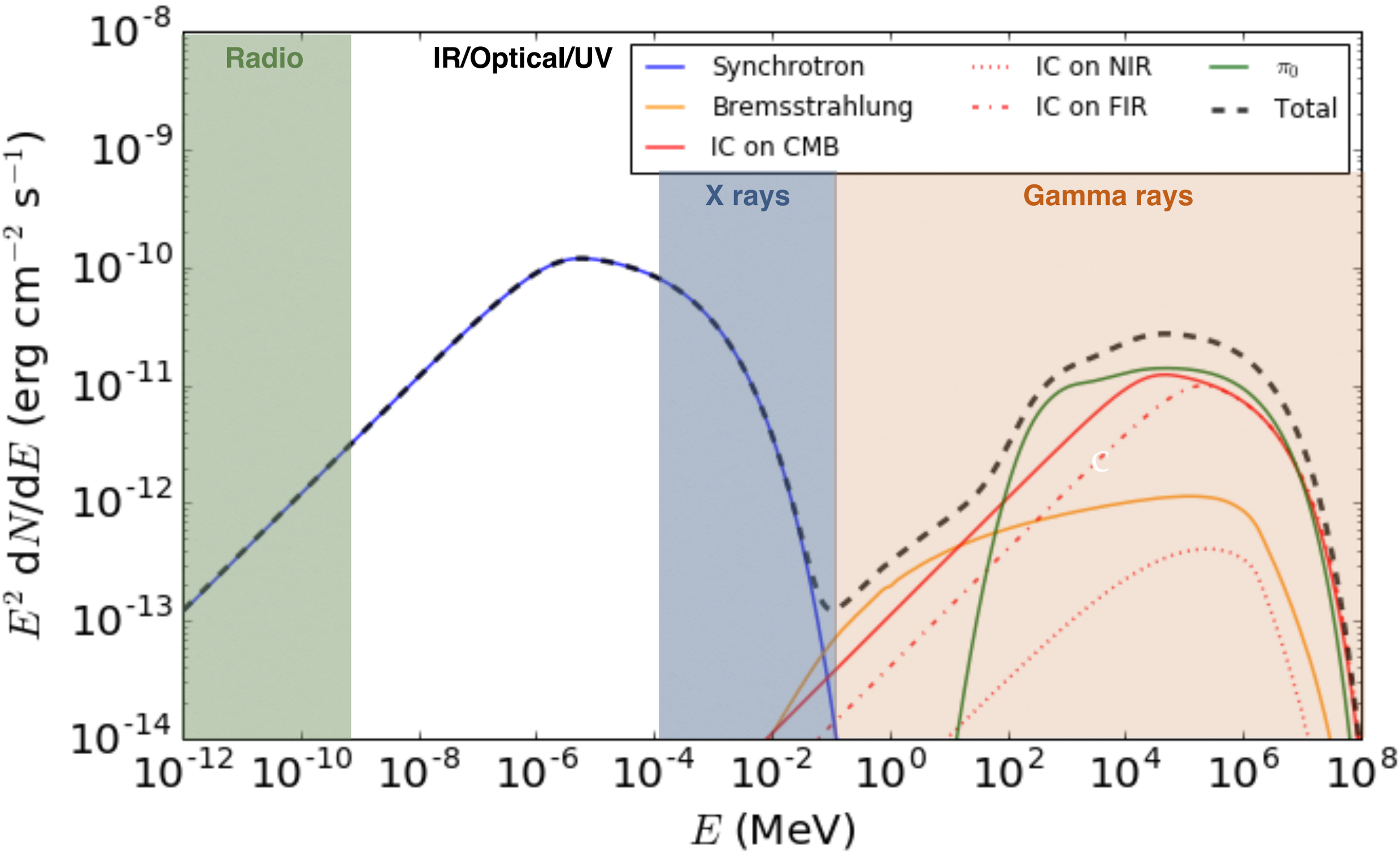


Chasing cosmic-ray sources with gamma rays

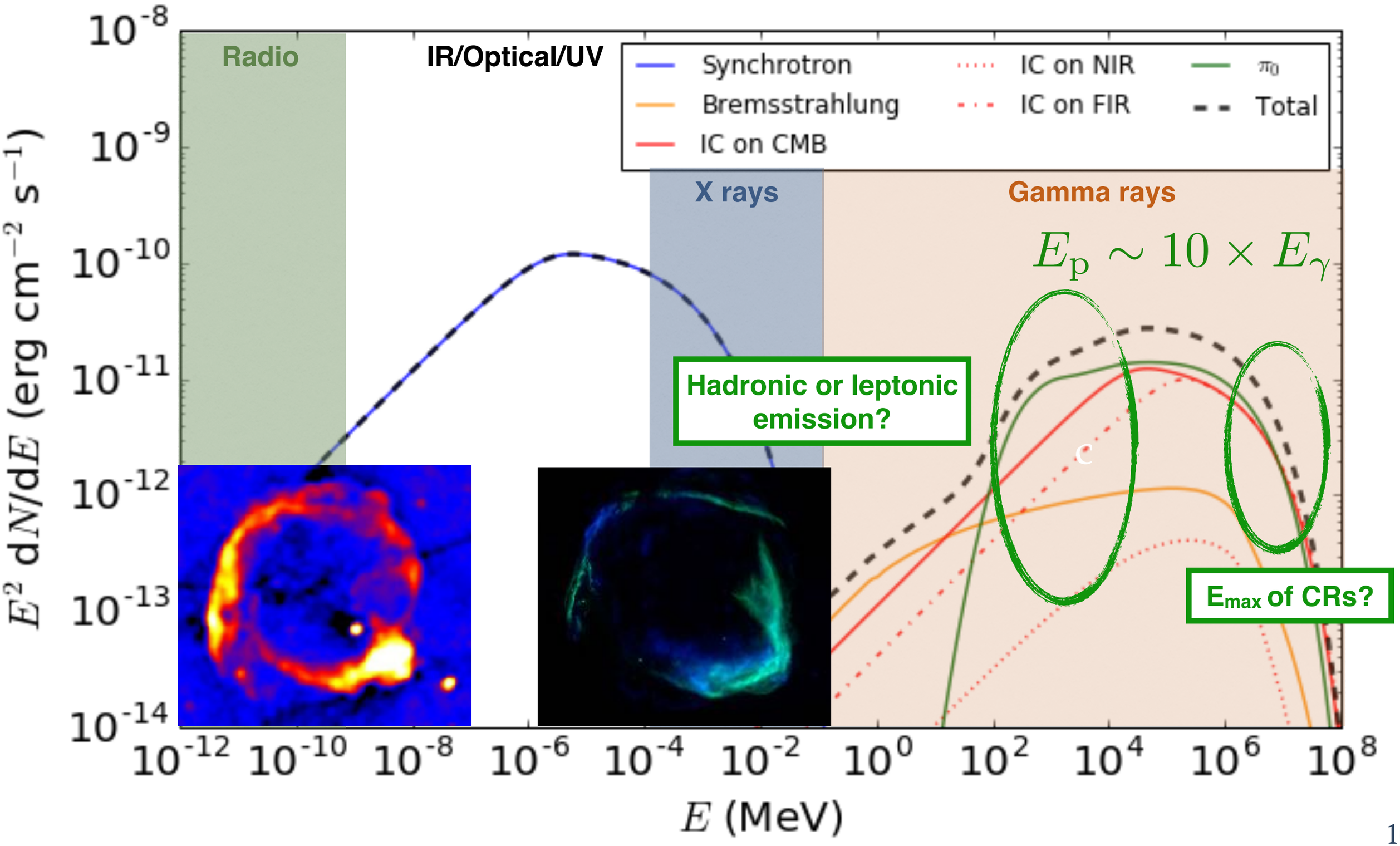


Broadband modeling of the emission



Broadband modeling of the emission

Nature of the accelerated particles (protons or electrons)? E_{max} of accelerated CRs?



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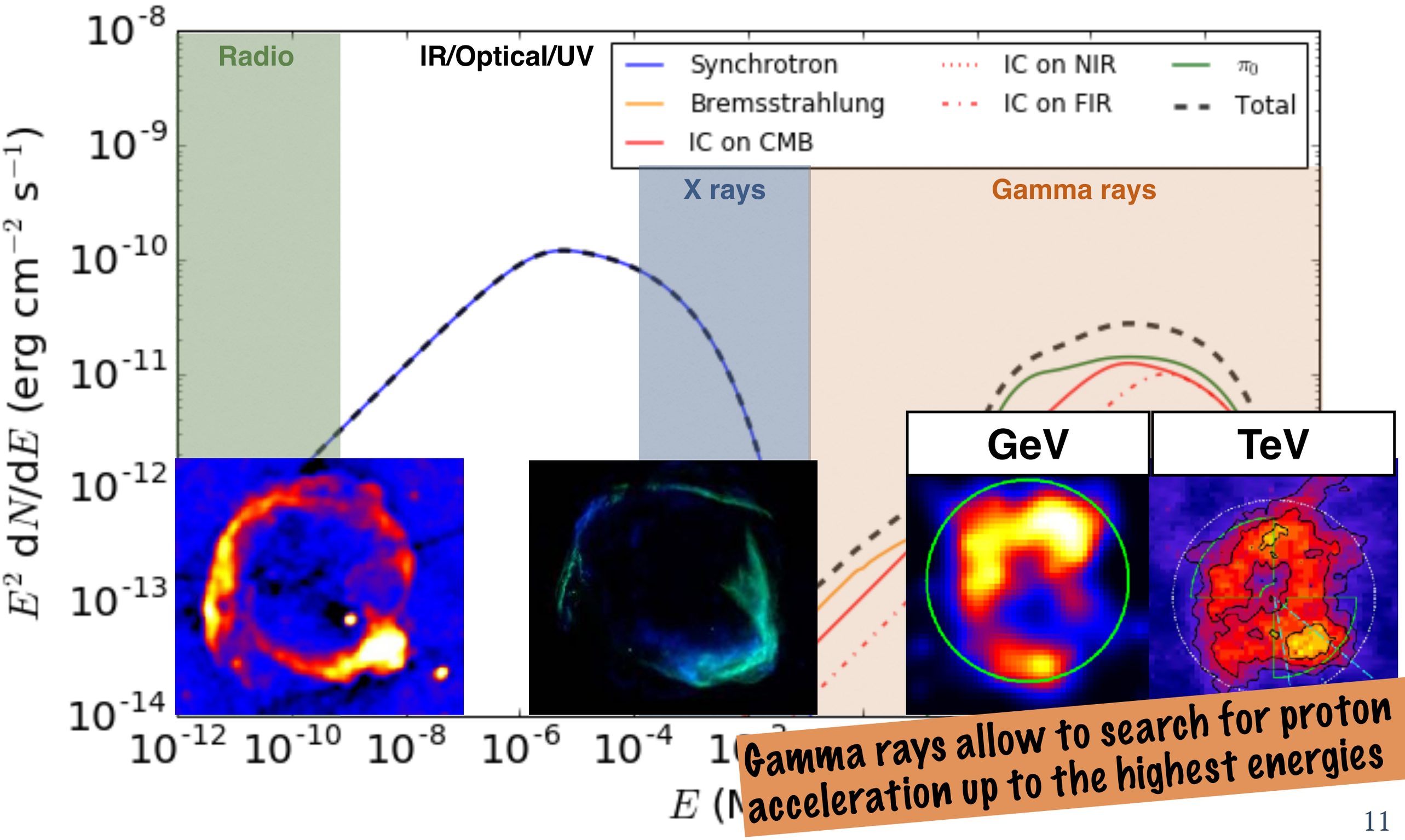
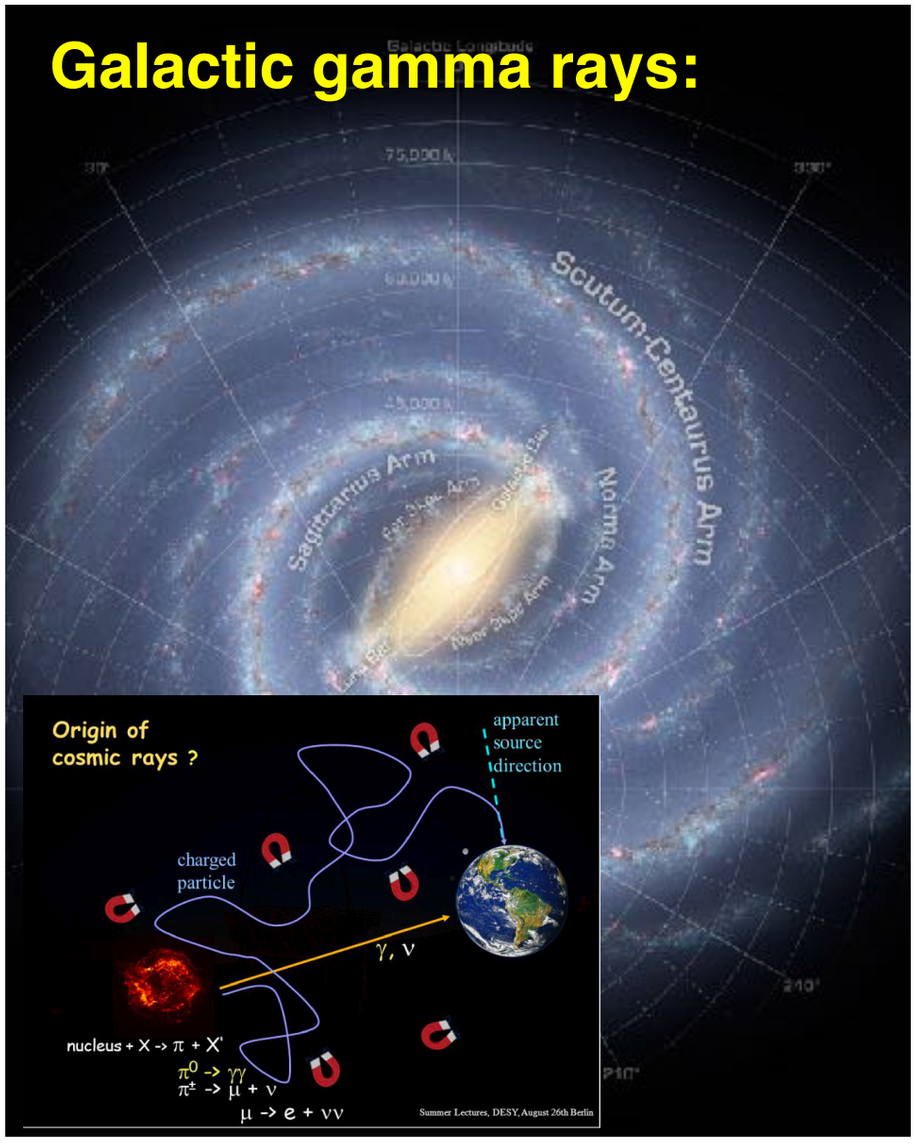
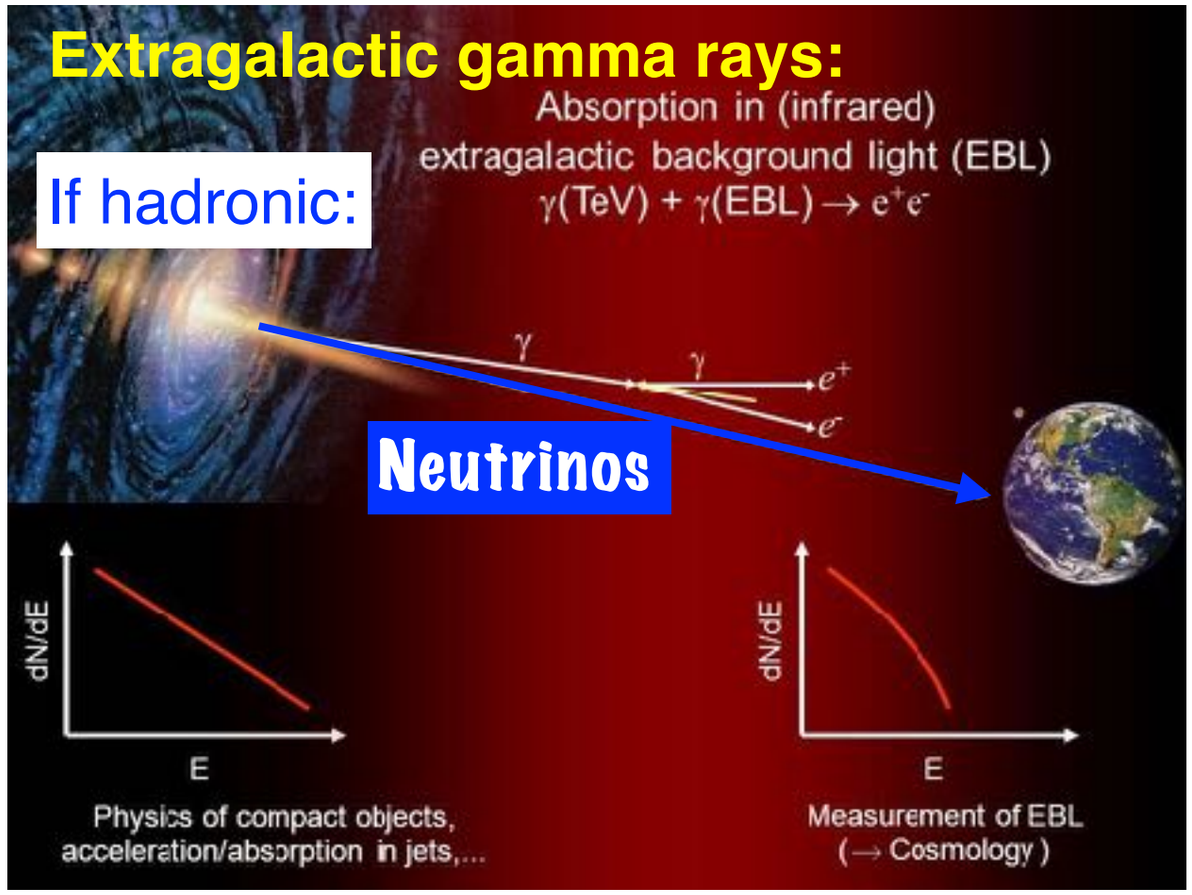


Gamma rays allow to search for proton acceleration up to the highest energies

Extragalactic gamma rays





Extragalactic gamma rays absorbed by the Extragalactic Background Light

Neutrinos are Great!

- Irrevocable evidence for hadronic acceleration
- Can constrain the origin of extragalactic CRs (unlike gamma rays)

But hard to detect…! [TXS 0506+056 / NGC 1068, IceCube col.]

Cosmic Rays

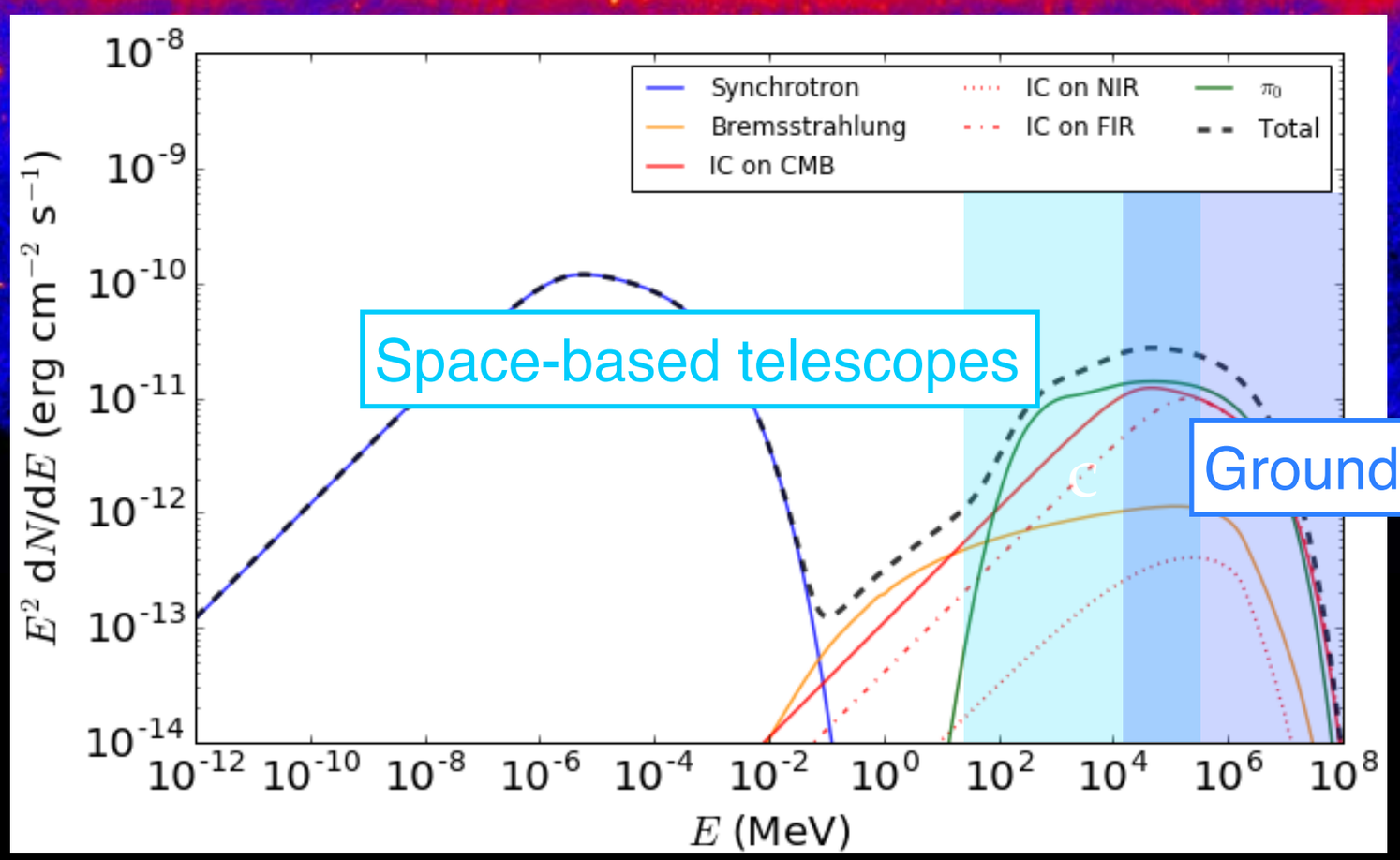
Let's Do Gamma-ray Astronomy!

Astrophysical Sources

Gamma rays

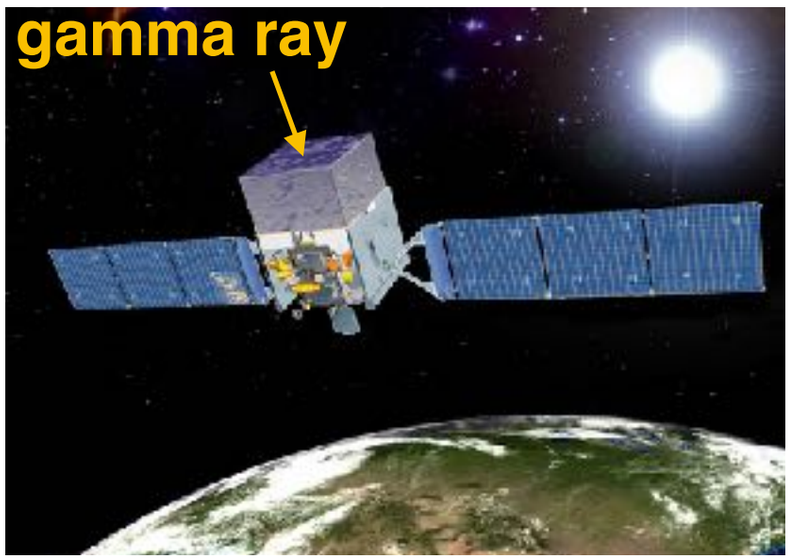
- Origin of Galactic cosmic rays?
- What's going on in these most extreme environments?

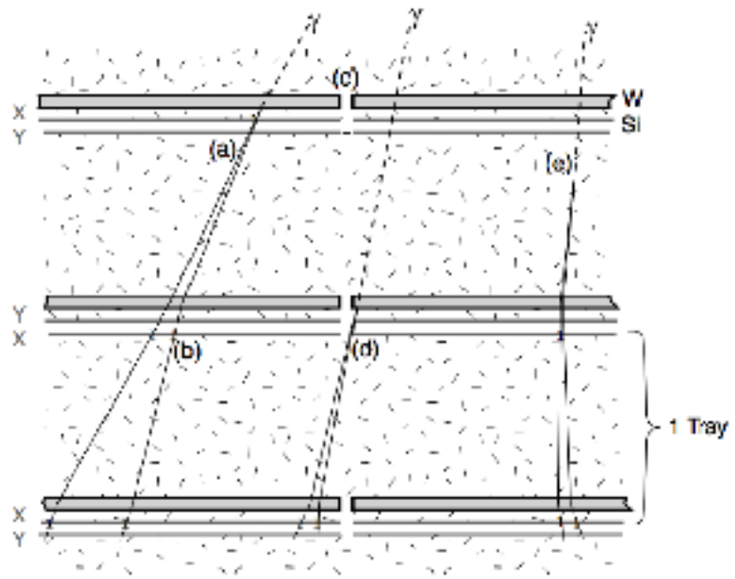
Gamma-ray Astronomy



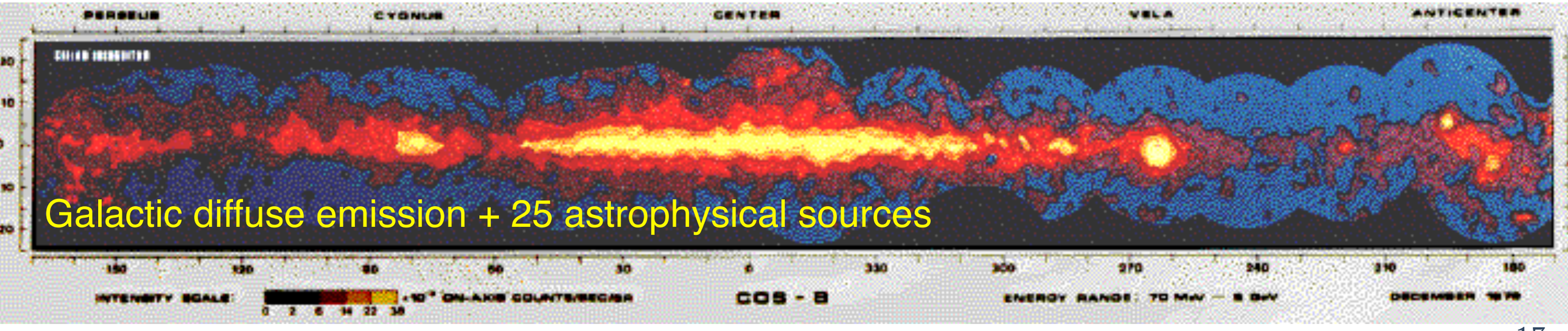
How do we detect gamma rays?

Interaction of gamma rays with the detector (creation of an e—/e+ pair):



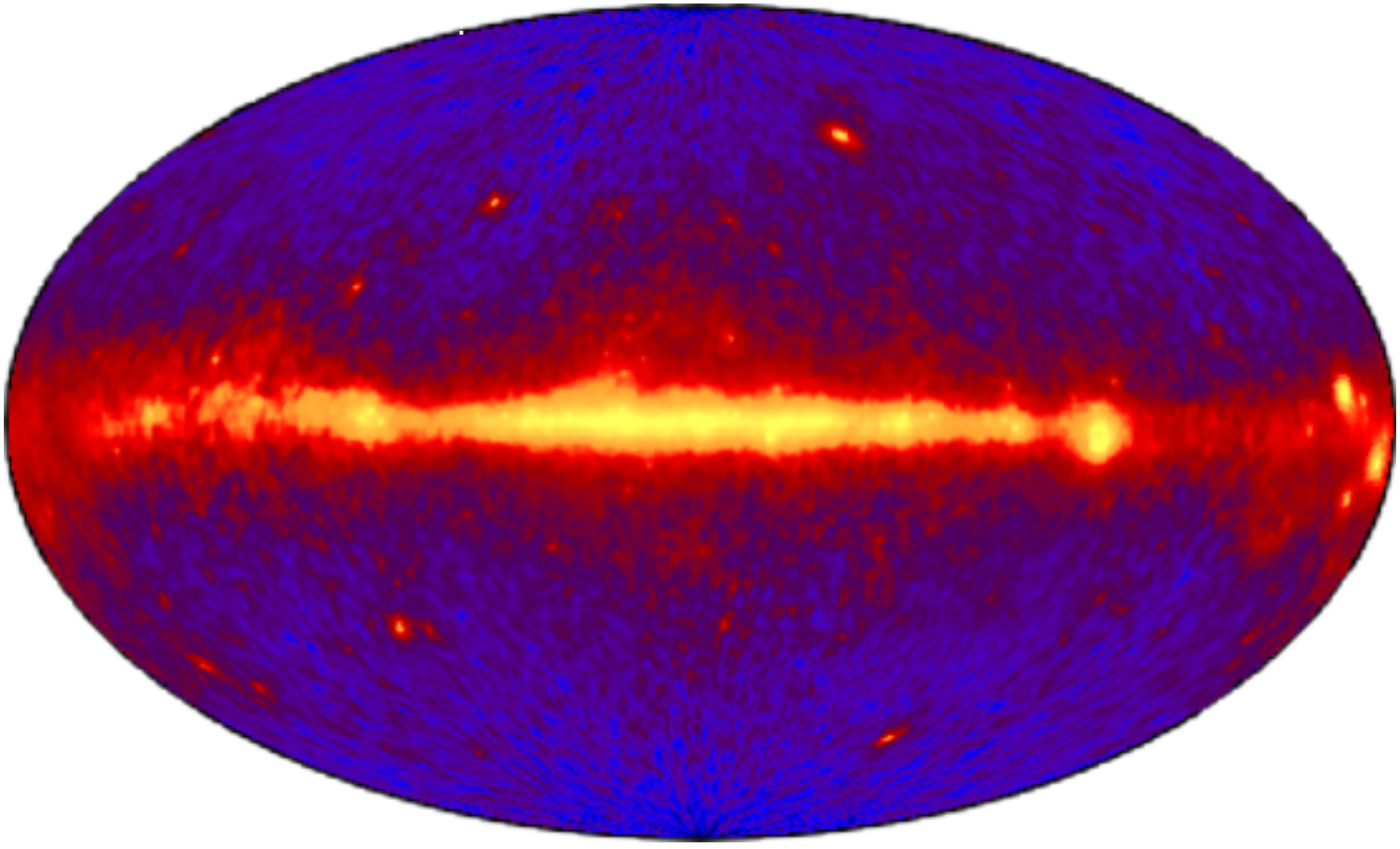


- **1961** : Explorer 11 (22 photons)
- **1968** : Orbiting Solar Observatory (621 photons)
- **1972** : Small Astronomy Satellite (first part of the sky)
- **1975** : COS-B (first full map of the Galaxy)



- **1991:** Compton Gamma-ray Observatory

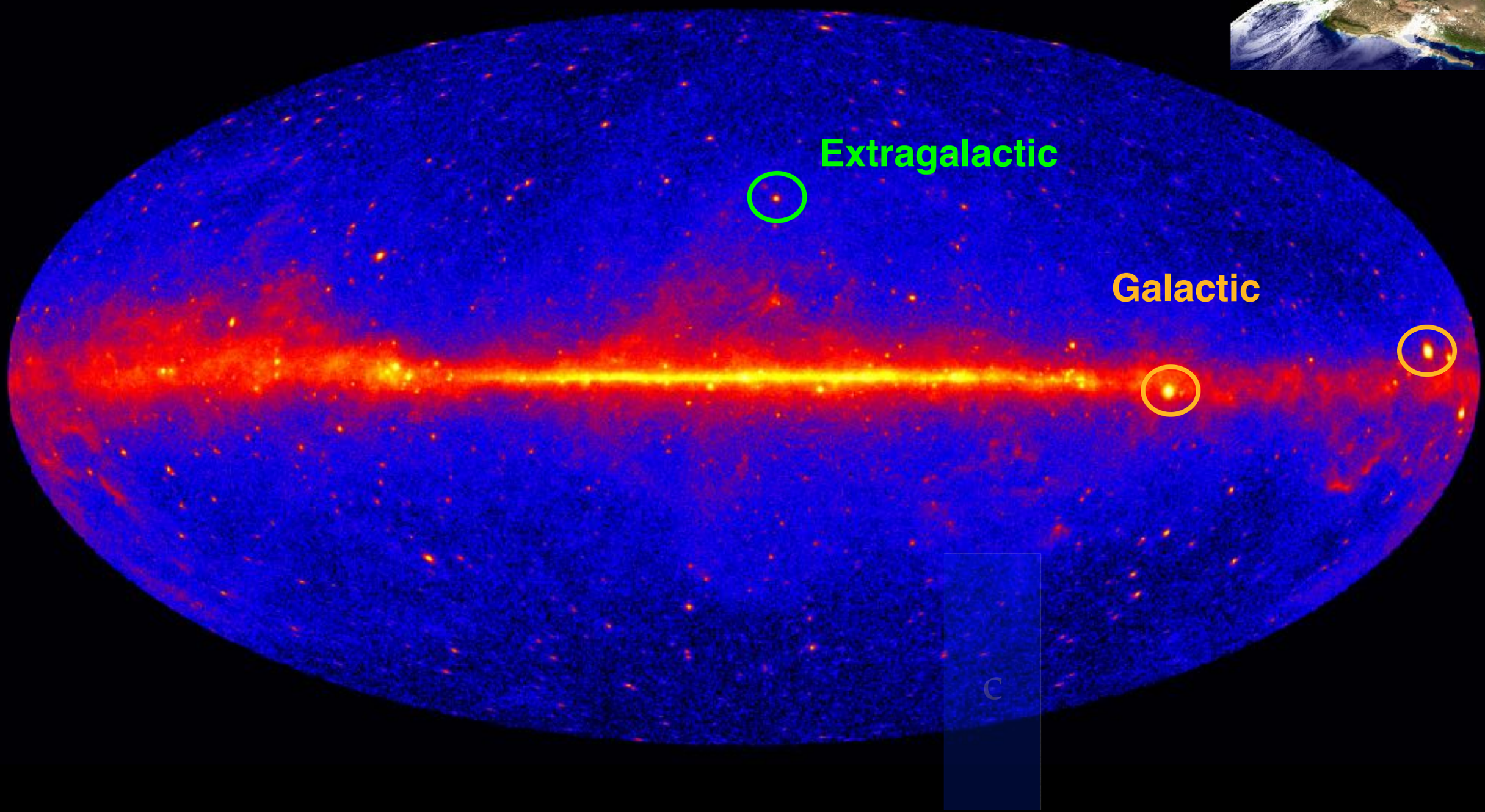
➡ Galactic diffuse emission + 271 astrophysical sources



The GeV Sky Today

- 2008 : Fermi, more than one billion of photons !

➡ Galactic diffuse emission + 5065 astrophysical sources



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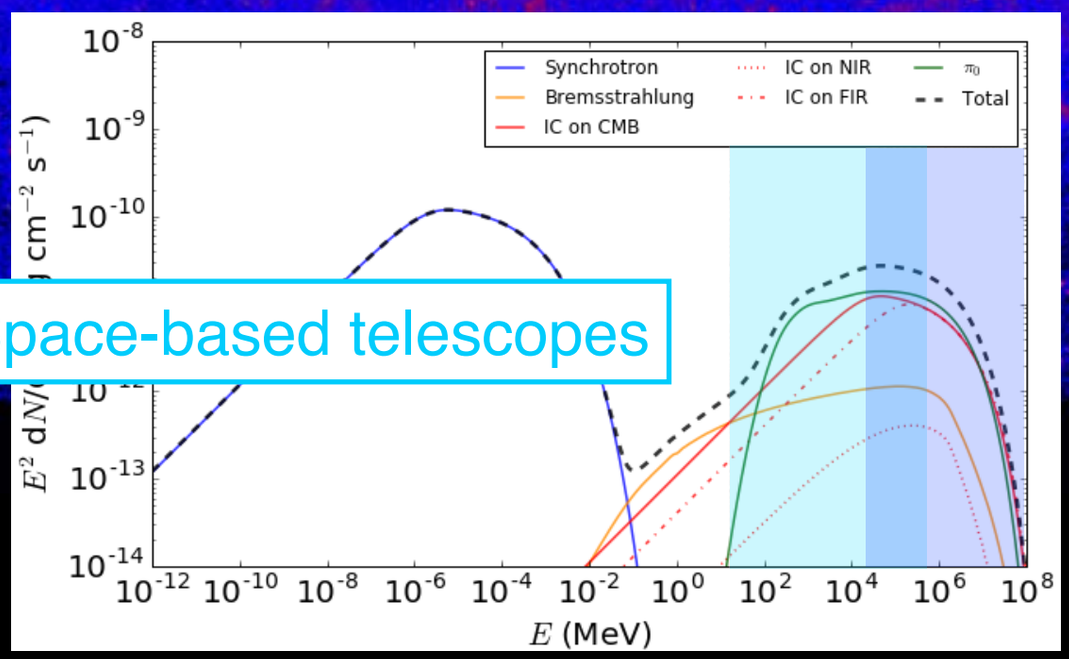
Extragalactic

Galactic

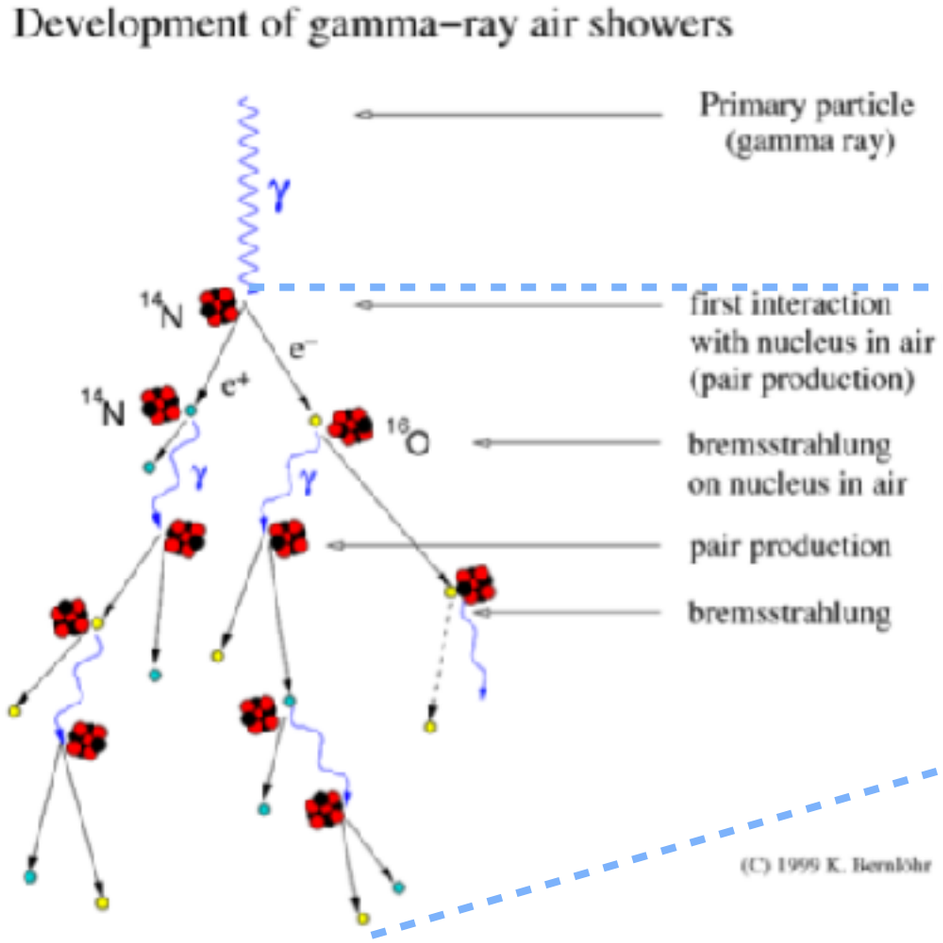


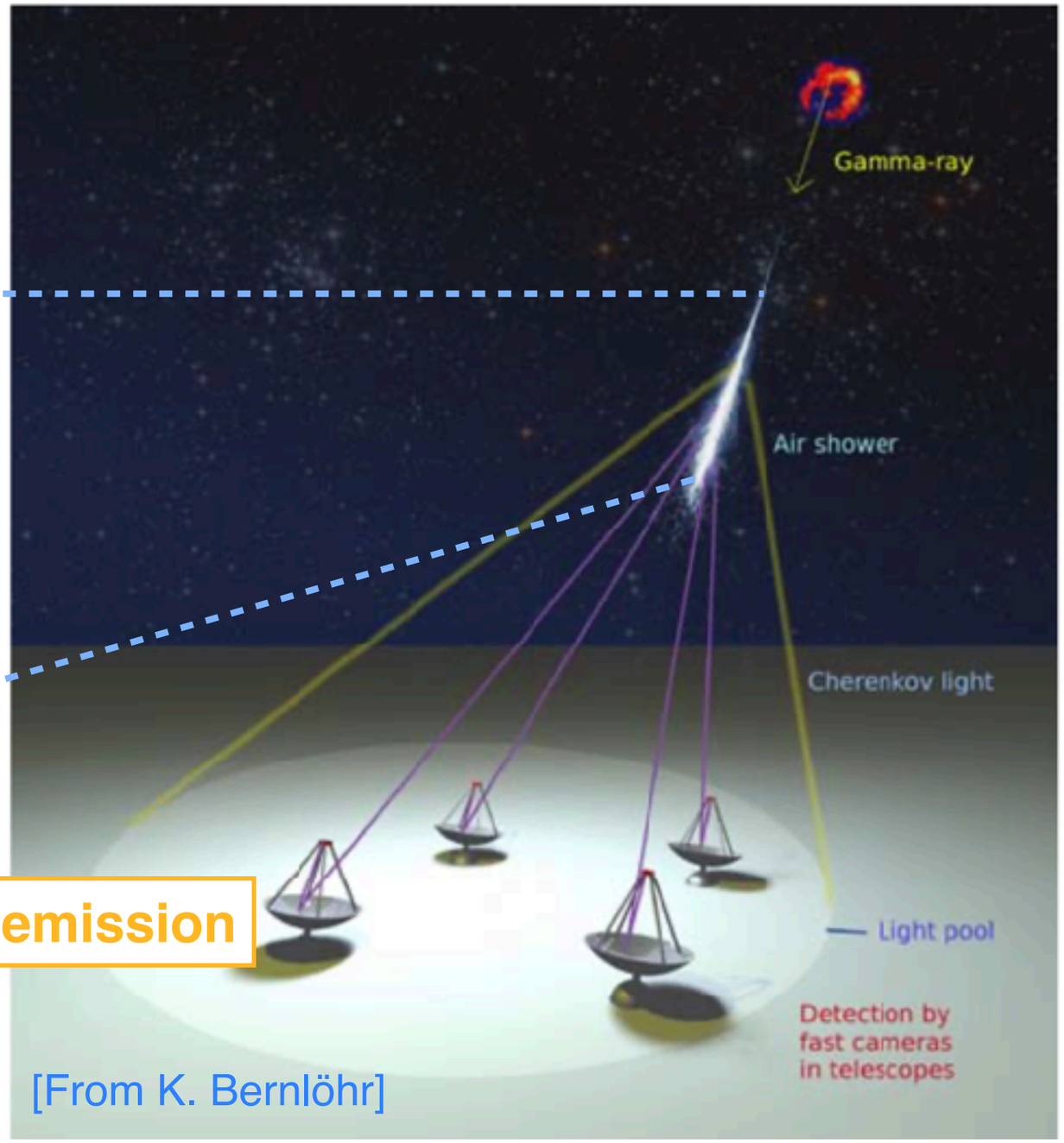
Space-based telescopes

TeV gamma-ray Astronomy

TeV photons more rare than GeV photons: need a larger collection area that can not be boarded on satellite

➡ **The atmosphere is used as a detector**

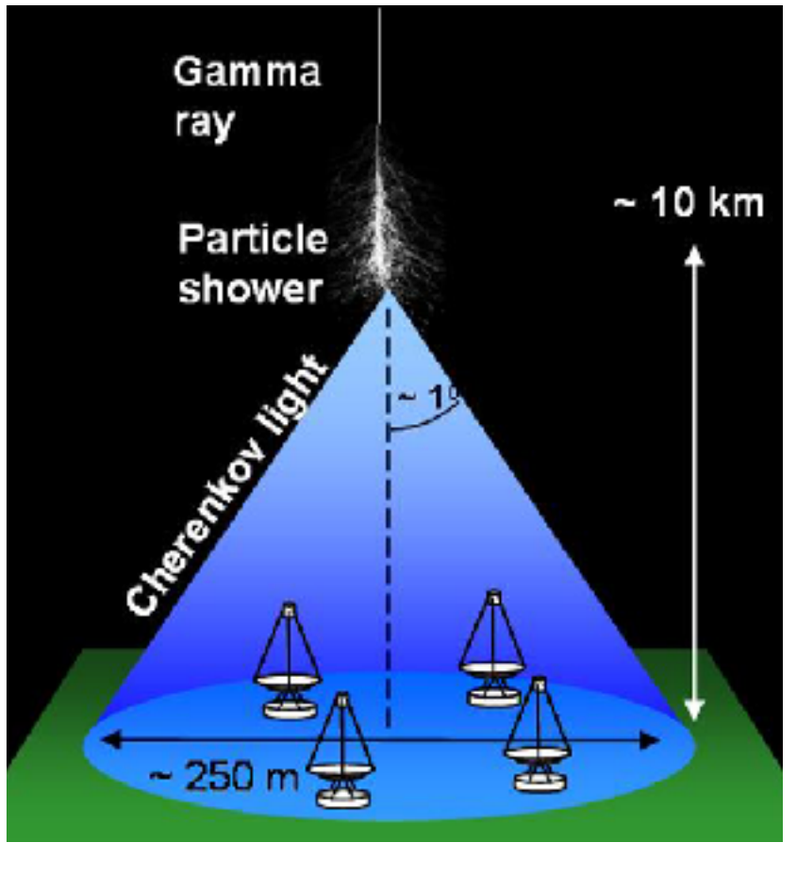


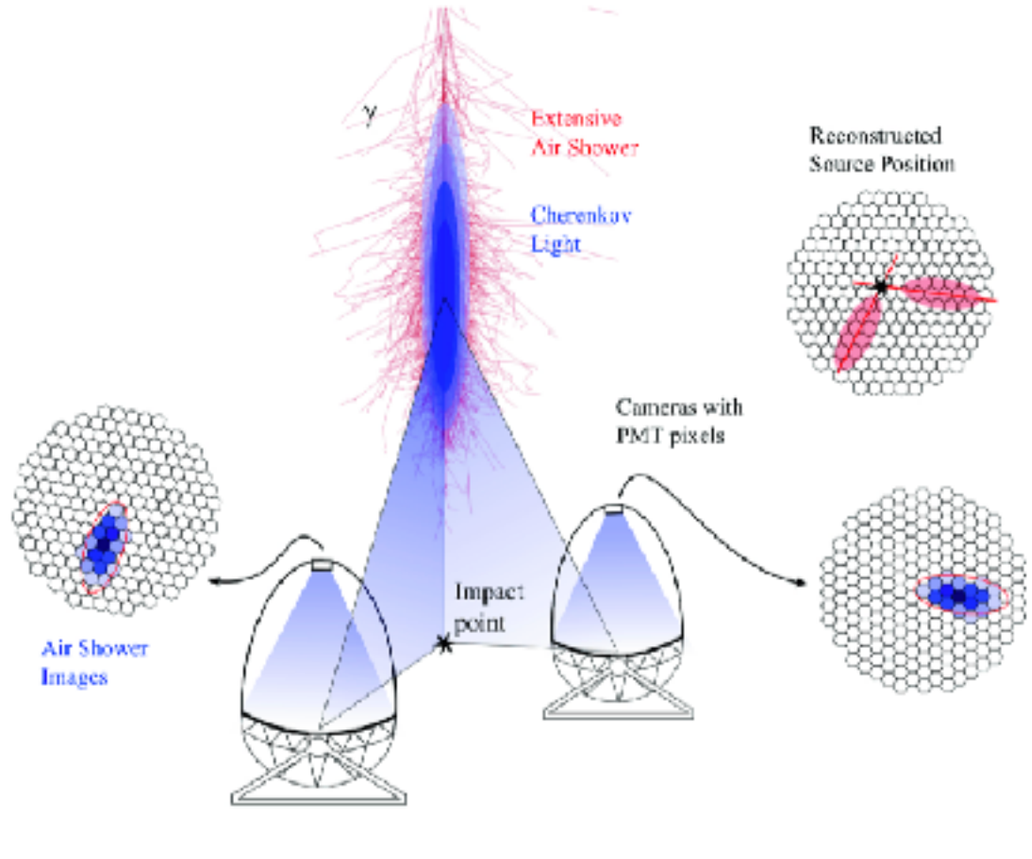


Cherenkov light emission

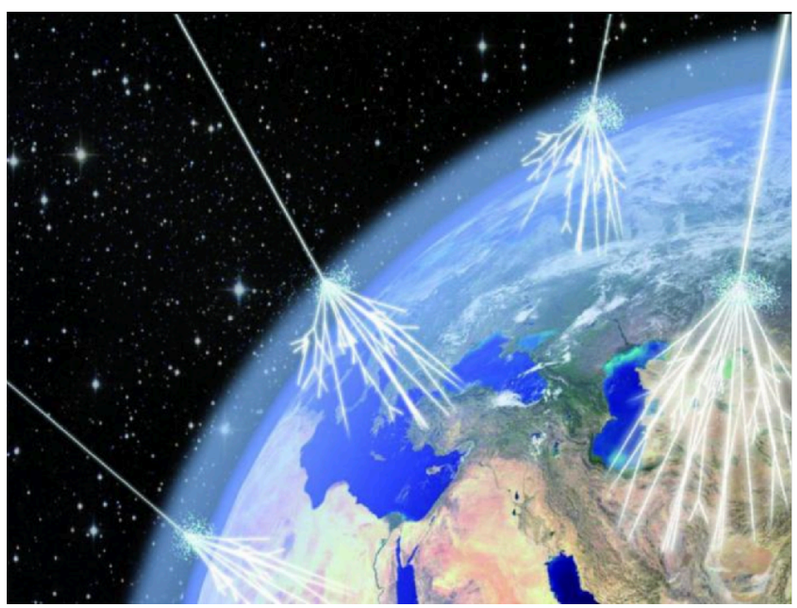
[From K. Bernlöhr]

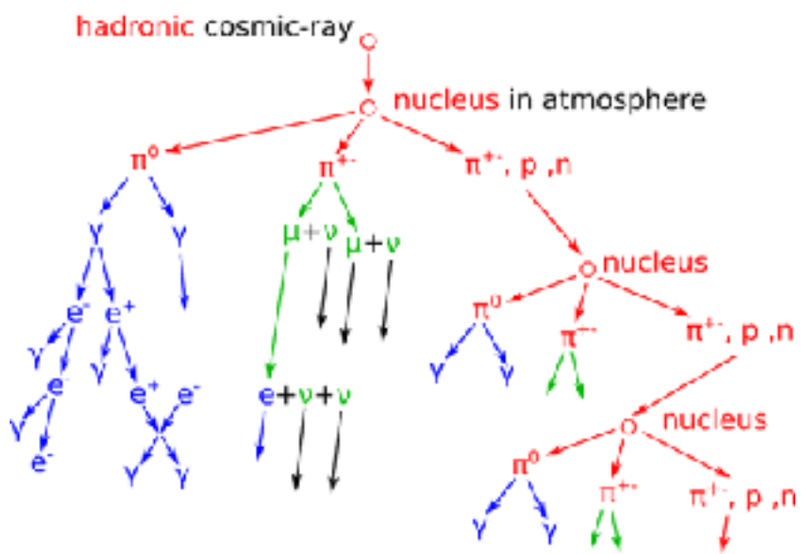
Stereoscopic reconstruction





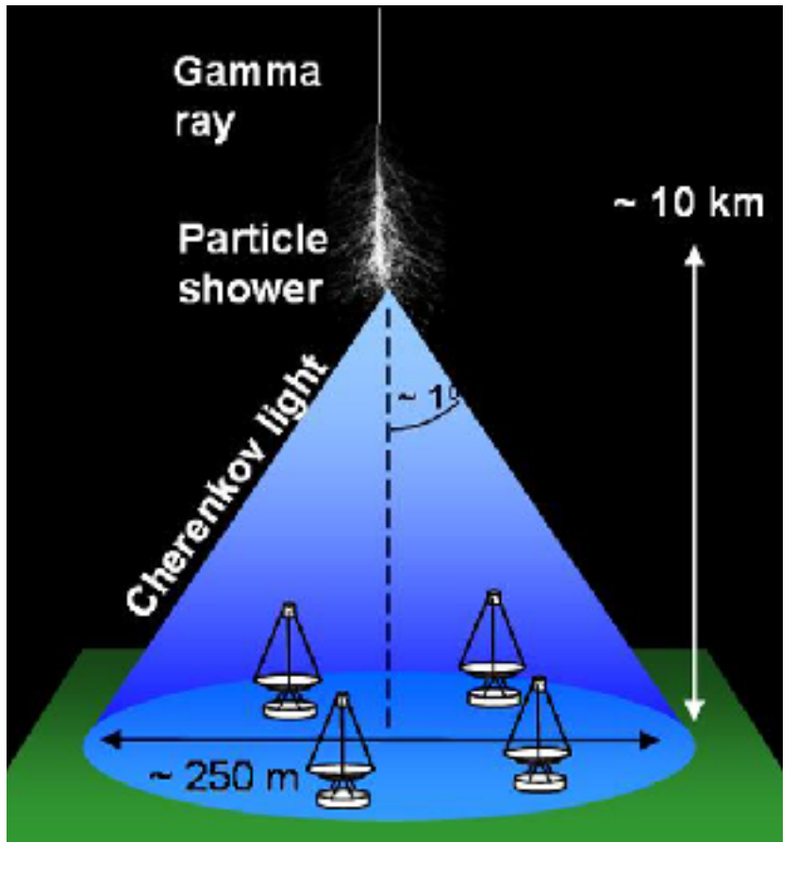
- Reconstructed arrival direction and energy of the primary gamma ray
- Limited field-of-view (~ 3.5–5°): **pointed observations**

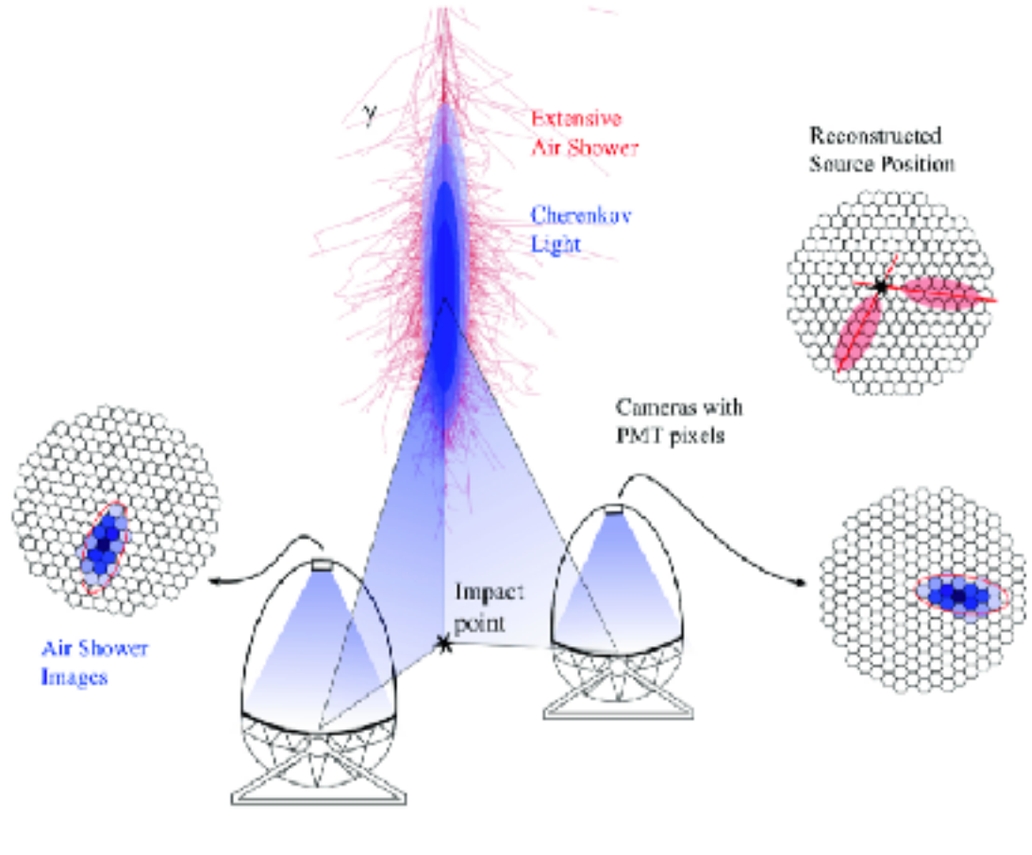




Cosmic rays are Background here!

Stereoscopic reconstruction





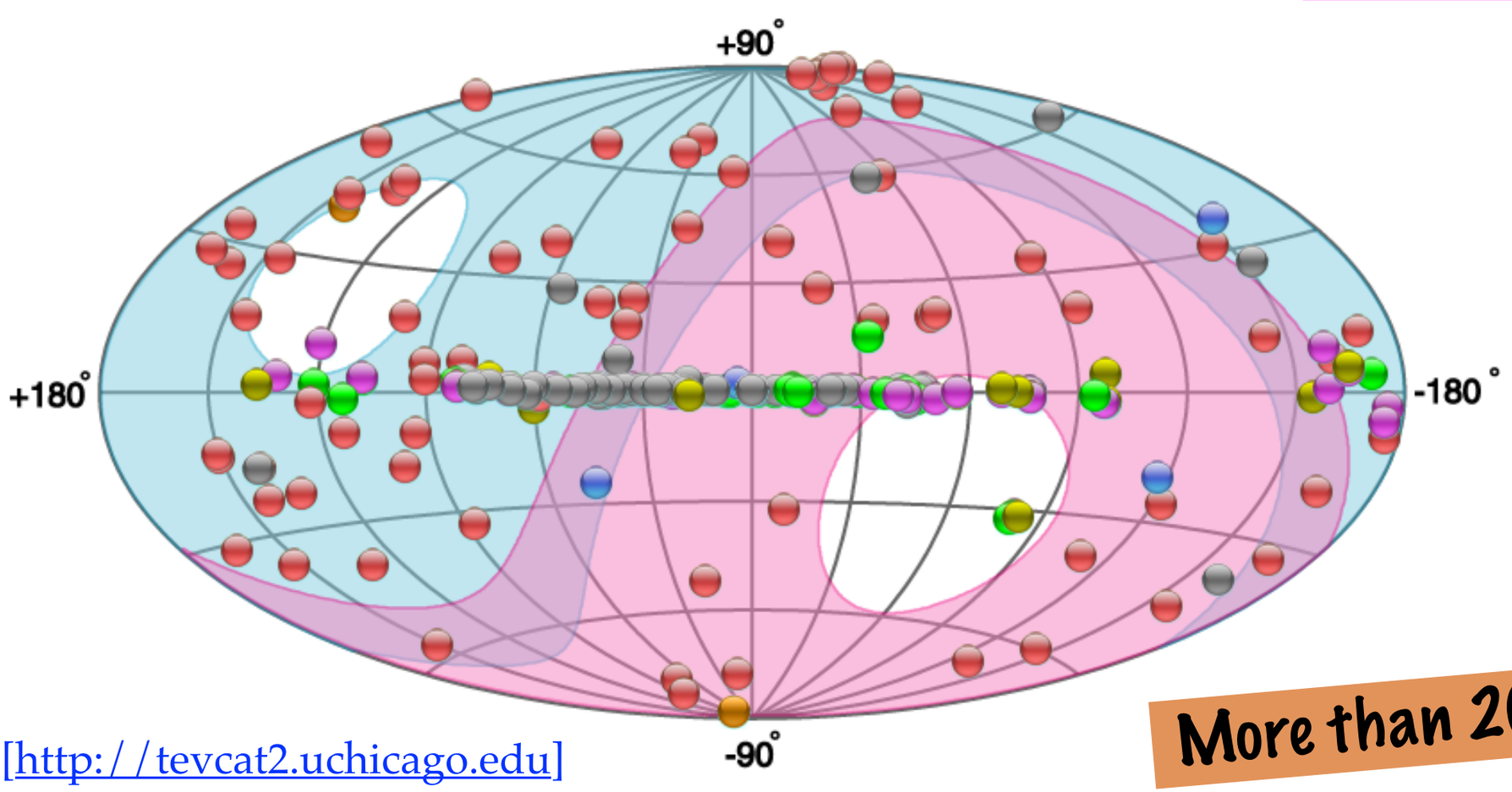
- Reconstructed arrival direction and energy of the primary gamma ray
- Limited field-of-view (~ 3.5–5°): **pointed observations**

The TeV Sky Today

Northern Hemisphere

Southern Hemisphere

Wassim's Talk
New Camera on CT5



Source Types

- Extended TeV Halo PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
- Shell SNR/Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL L...

More than 200 sources in total!

[http://tevcat2.uchicago.edu]

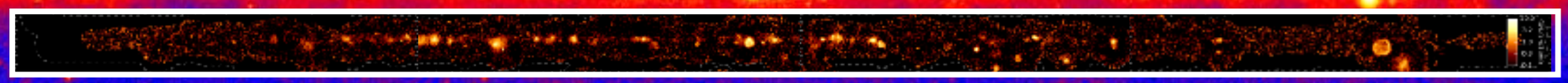
Cosmic Rays

Astrophysical Sources

Gamma rays

The Galactic Zoo in gamma rays

CR acceleration in a large variety of astrophysical sources!

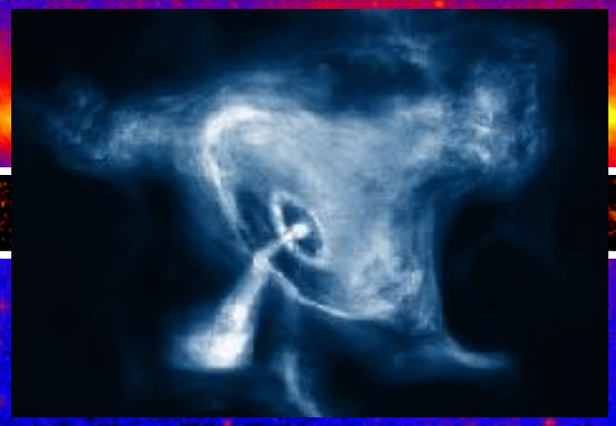


The Galactic Zoo in gamma rays

CR acceleration in a large variety of astrophysical sources!

Supernova remnants

Pulsar and their nebula



Massive Stellar Clusters

Binary systems:
- Microquasar
- Colliding stellar winds
- …

+ A large number of unidentified sources!

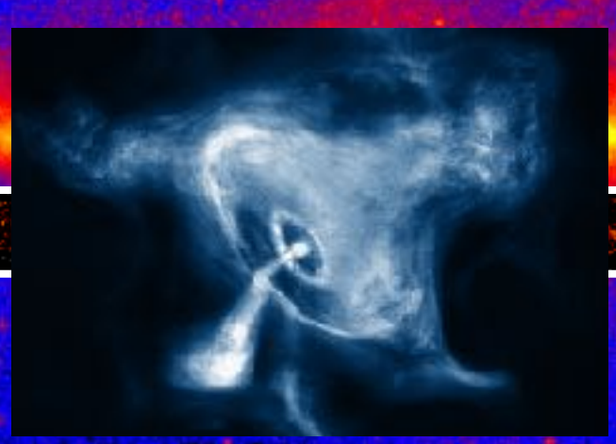
The Galactic Zoo in gamma rays

CR acceleration in a large variety of astrophysical sources!

Maxime's talk:
Pulsars at TeV energies

Supernova remnants

Pulsar and their nebula



HESS col. Nature 2023

Massive Stellar Clusters

HAWC col. Nature 2018

Binary systems:
- Microquasar
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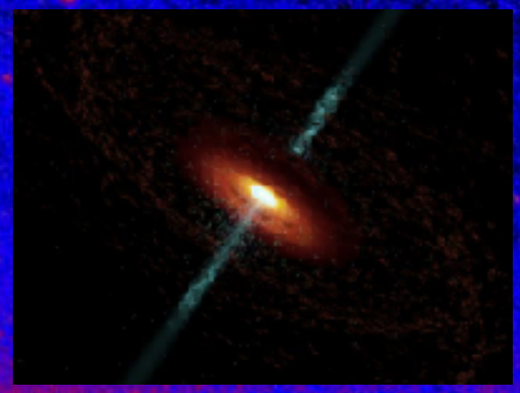
HESS col. Science 2022

+ A large number of unidentified sources!

The Extragalactic Zoo in gamma rays

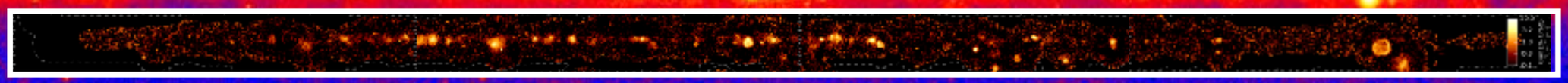
CR acceleration in a large variety of astrophysical sources!

Active Galactic Nuclei

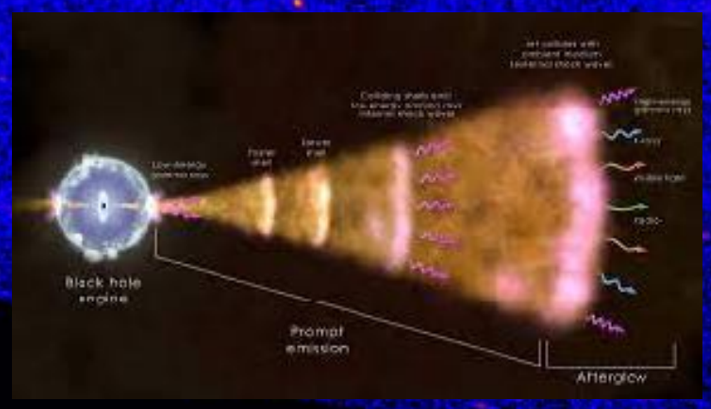


- **Samantha's talk:**
  VER J0521+211 with Fermi-LAT & VERITAS

VER J0521+211



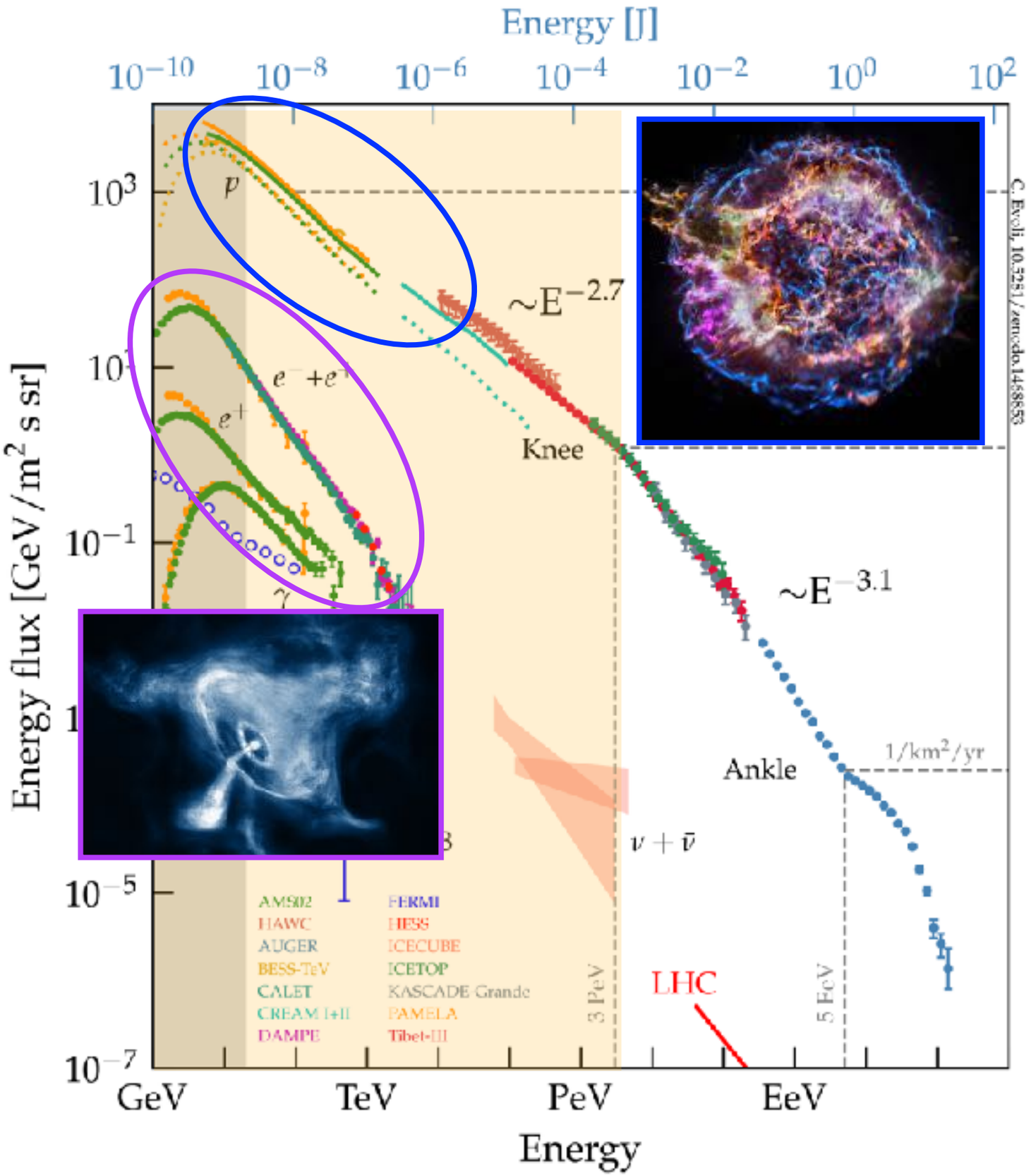
Gamma-ray Bursts



MAGIC col., Nature, 2019
HESS col., Nature, 2019

Emission processes often not clearly understood...

And the Origin of Cosmic rays?



- Electrons can be accelerated in pulsar wind nebulae up to PeV energies

- Accelerated protons seen in our favorite candidates (Supernova remnants) but E_{max} << PeV

➡ Ancient PeVatrons?
➡ Other sources? Massive Stellar Clusters?

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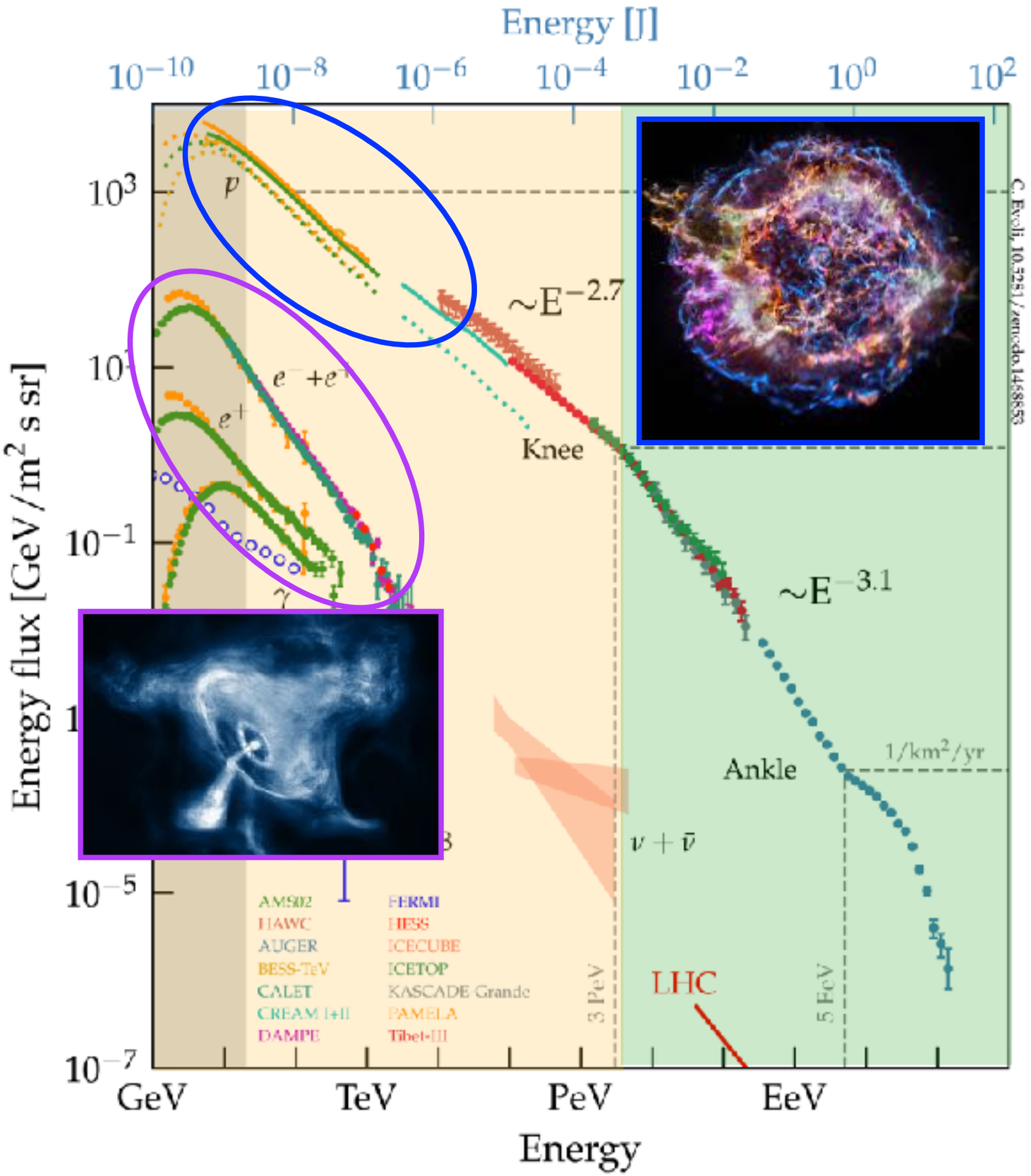

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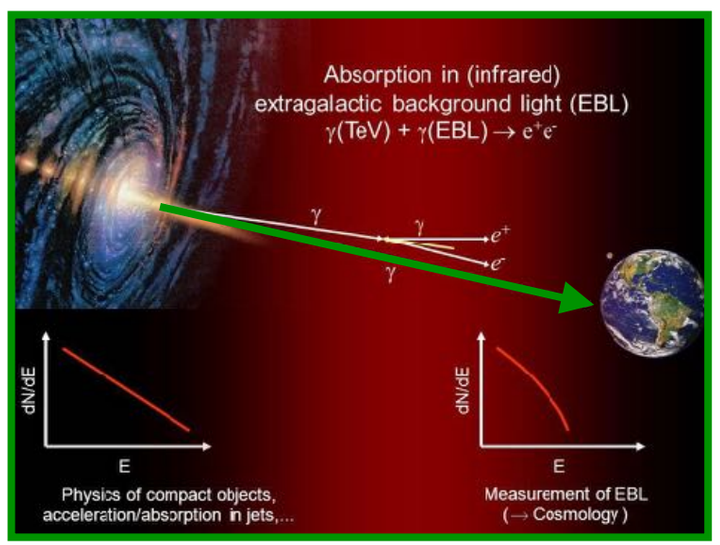
Need some help from neutrinos!



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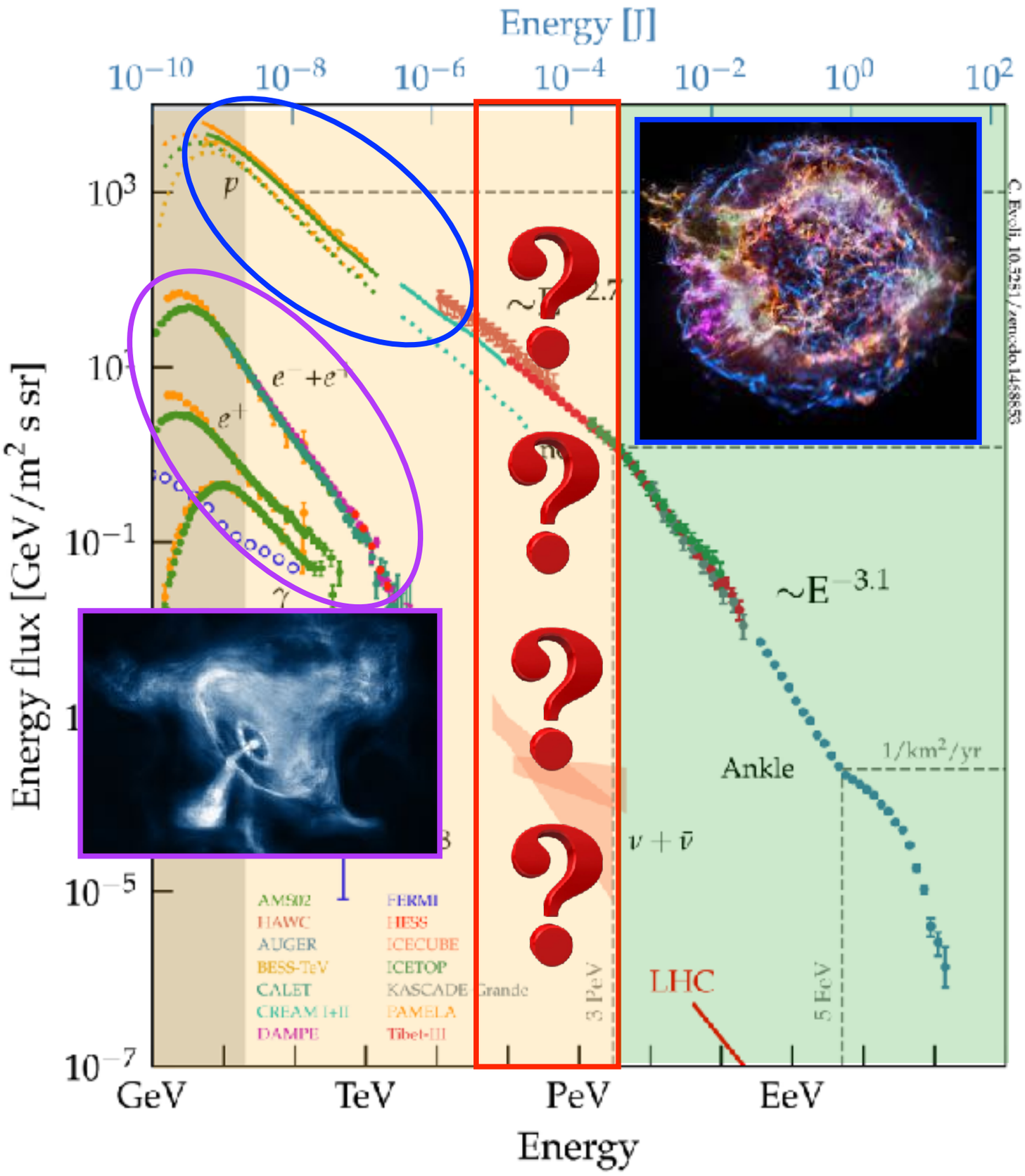

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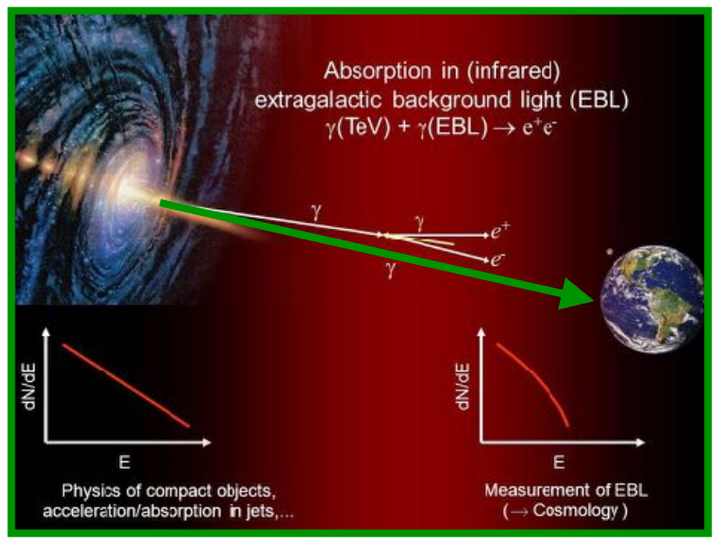
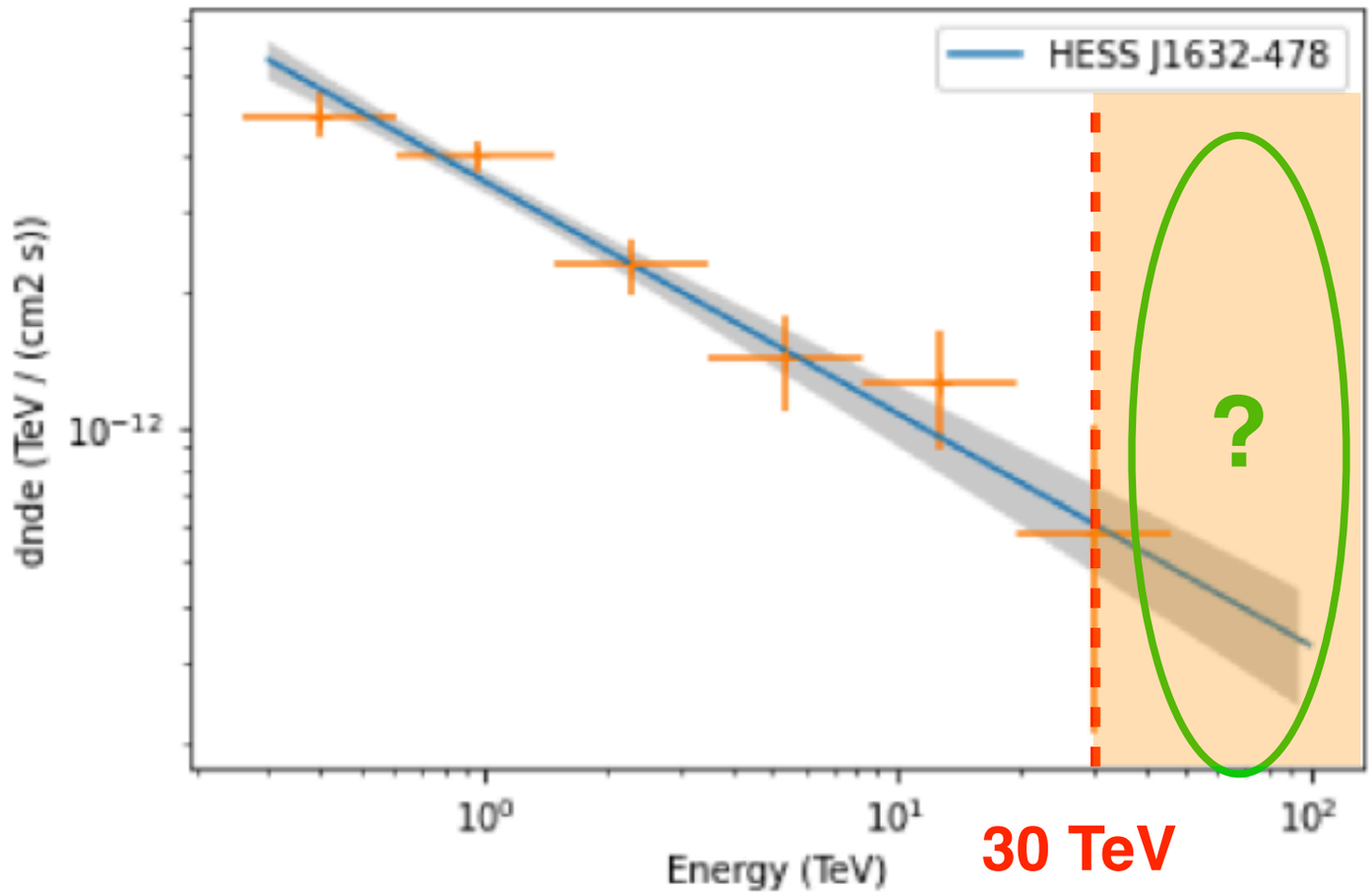


Lack of Statistics!

If $E_p = 3 \times 10^{15}$ eV needed, $E_{g\text{-}ray} \sim 3 \times 10^{14}$ eV (= 300 TeV)

For many TeV sources, we do not know what happens at the highest energy:

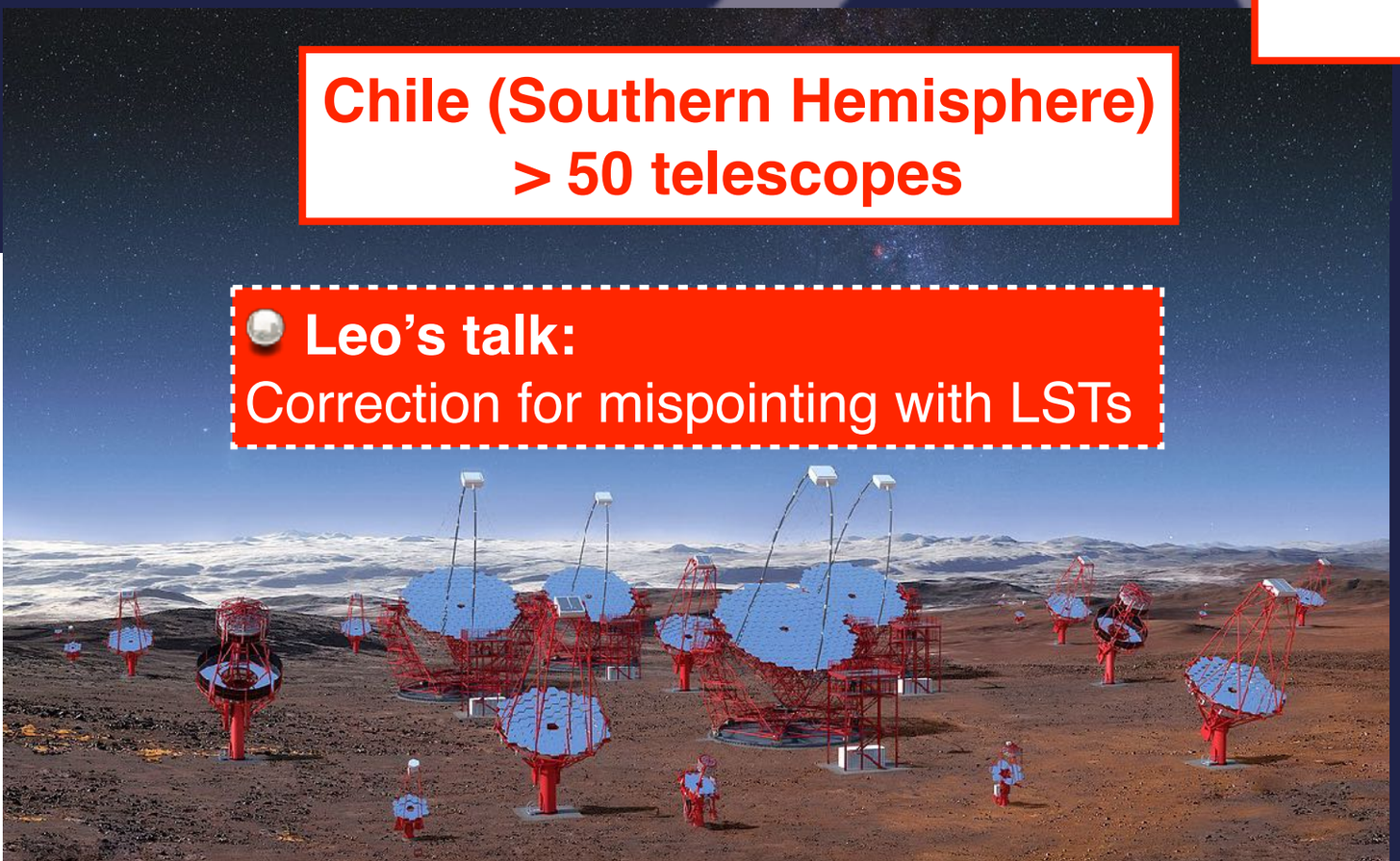


Does the spectrum has a cutoff (E_{max}) or continue up to 300 TeV?

➡ At the sensitivity limit with H.E.S.S.!

The Cherenkov Telescope Array (CTA)

Canary Islands (Northern Hemisphere)
13 telescopes



Chile (Southern Hemisphere)
> 50 telescopes

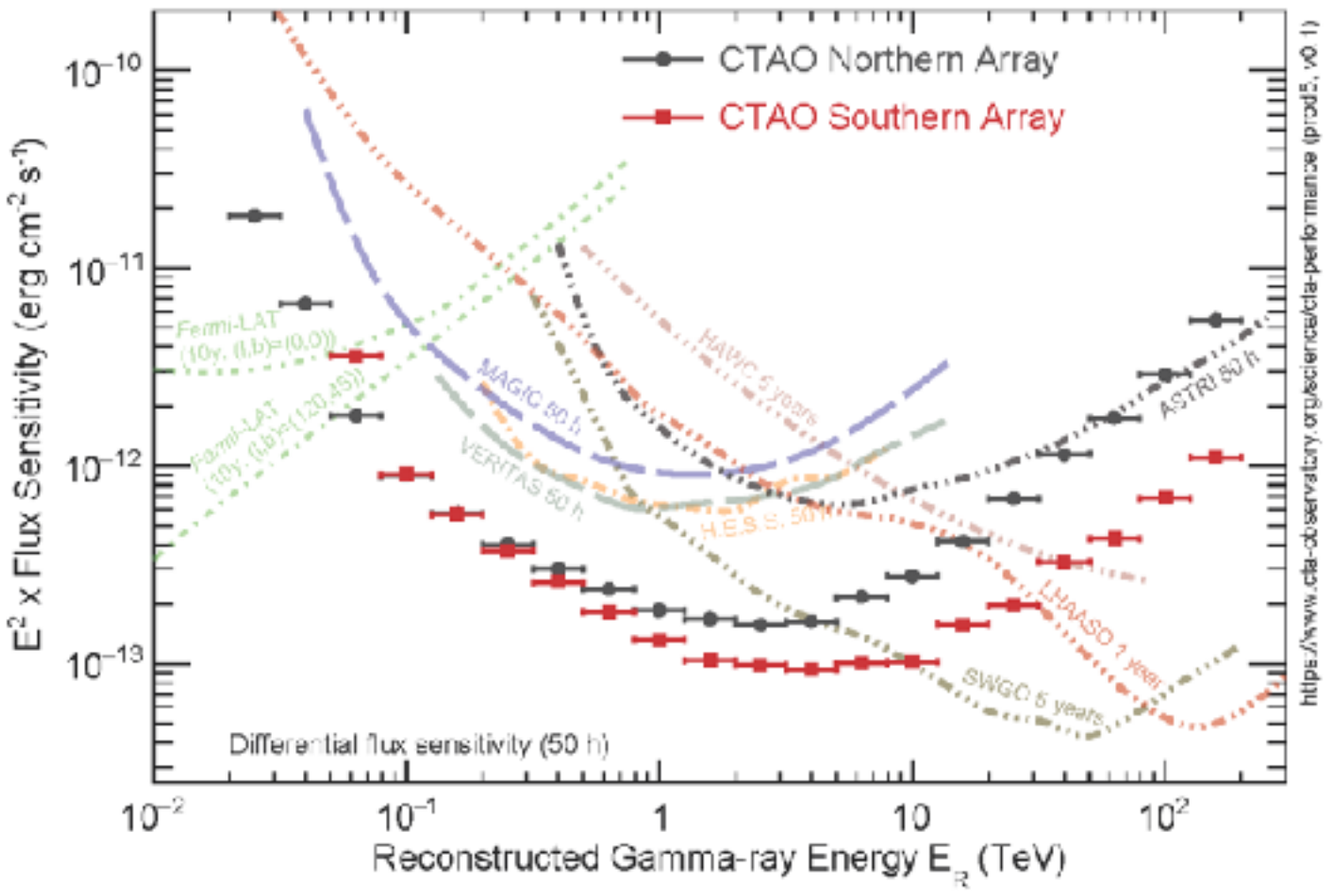
Leo's talk:
Correction for mispointing with LSTs

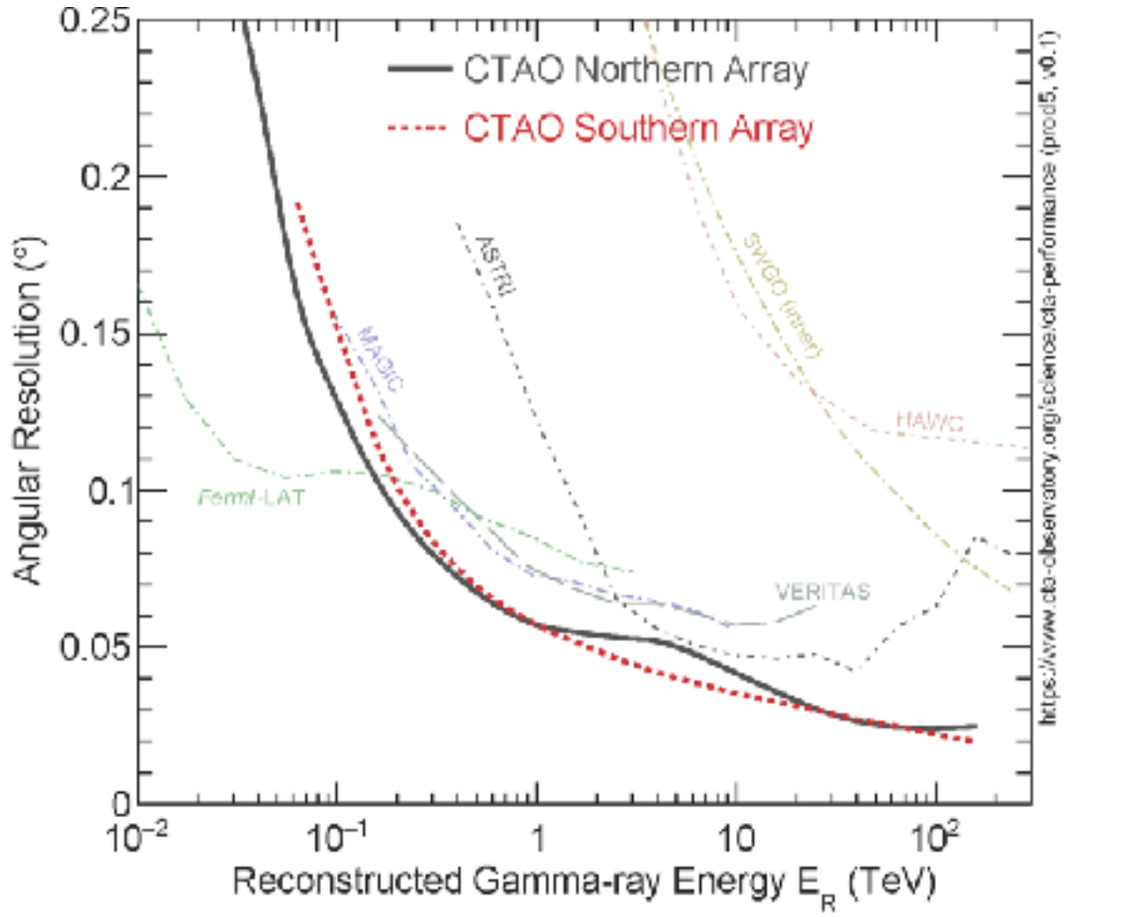
3 different sizes:

- ➡ Large Size Telescopes (LST)
- ➡ Medium Size Telescopes (MST)
- ➡ Small Size Telescopes (SST)

(currently under construction)

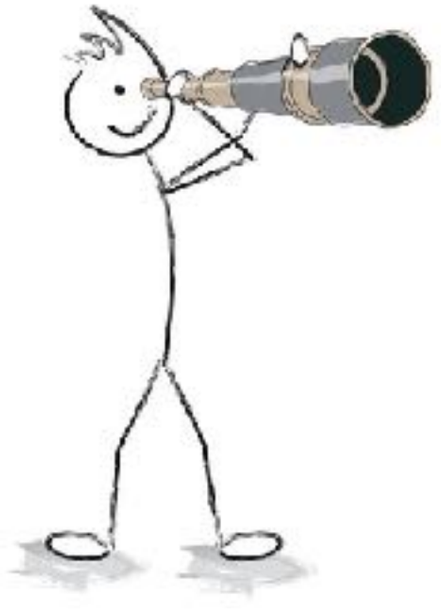
Better sensitivity and angular resolution





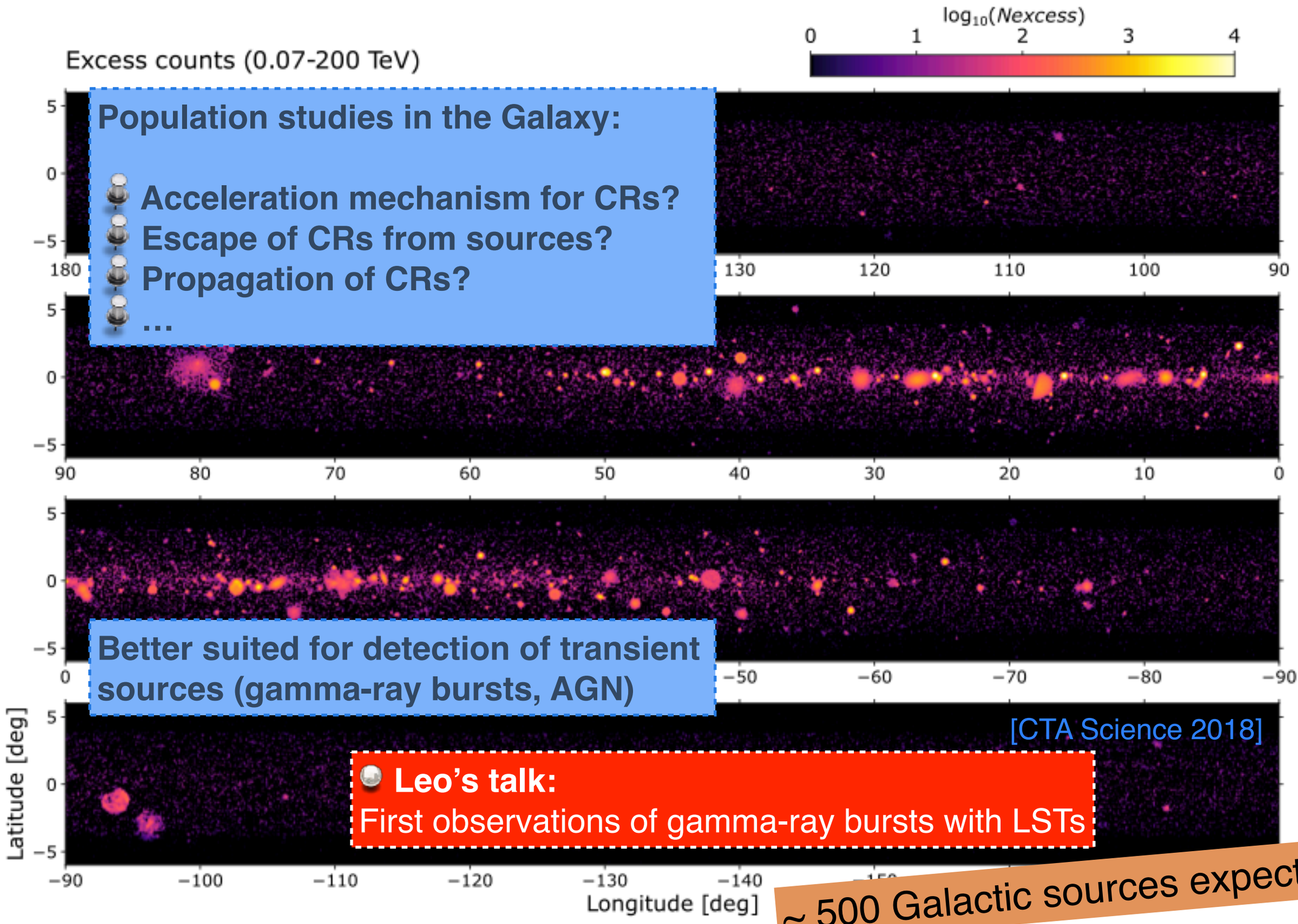
➡ **Detection of fainter signals**

… and farther



= Detection of more sources!

Simulation of the CTA Galactic Plane Survey



Population studies in the Galaxy:

- Acceleration mechanism for CRs?
- Escape of CRs from sources?
- Propagation of CRs?
- …

Better suited for detection of transient sources (gamma-ray bursts, AGN)

- **Leo's talk:** First observations of gamma-ray bursts with LSTs

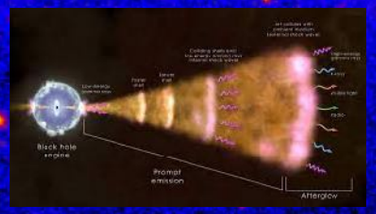
~ 500 Galactic sources expected

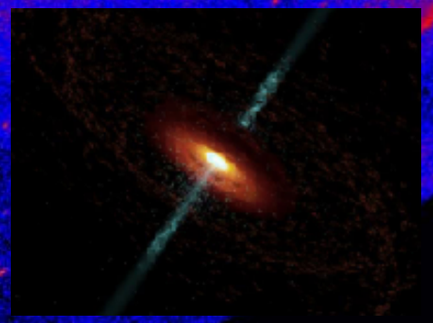
Conclusions

- Cosmic rays **are relativistic charged particles** detected at Earth
  ➡ **We want to address the century-old question of their origin**

- **We use gamma rays (or neutrinos) to pinpoint their acceleration site**

- Gamma-ray astronomy allows to probe:
  ➡ **acceleration, escape and propagation** of cosmic rays
  ➡ a better understanding of the most extreme phenomena





- CTA should be able to answer the question of the origin of cosmic rays and will likely discover unexpected things!

FUTURE IS BRIGHT FOR GALACTIC AND EXTRAGALACTIC SCIENCE WITH GAMMA RAYS!

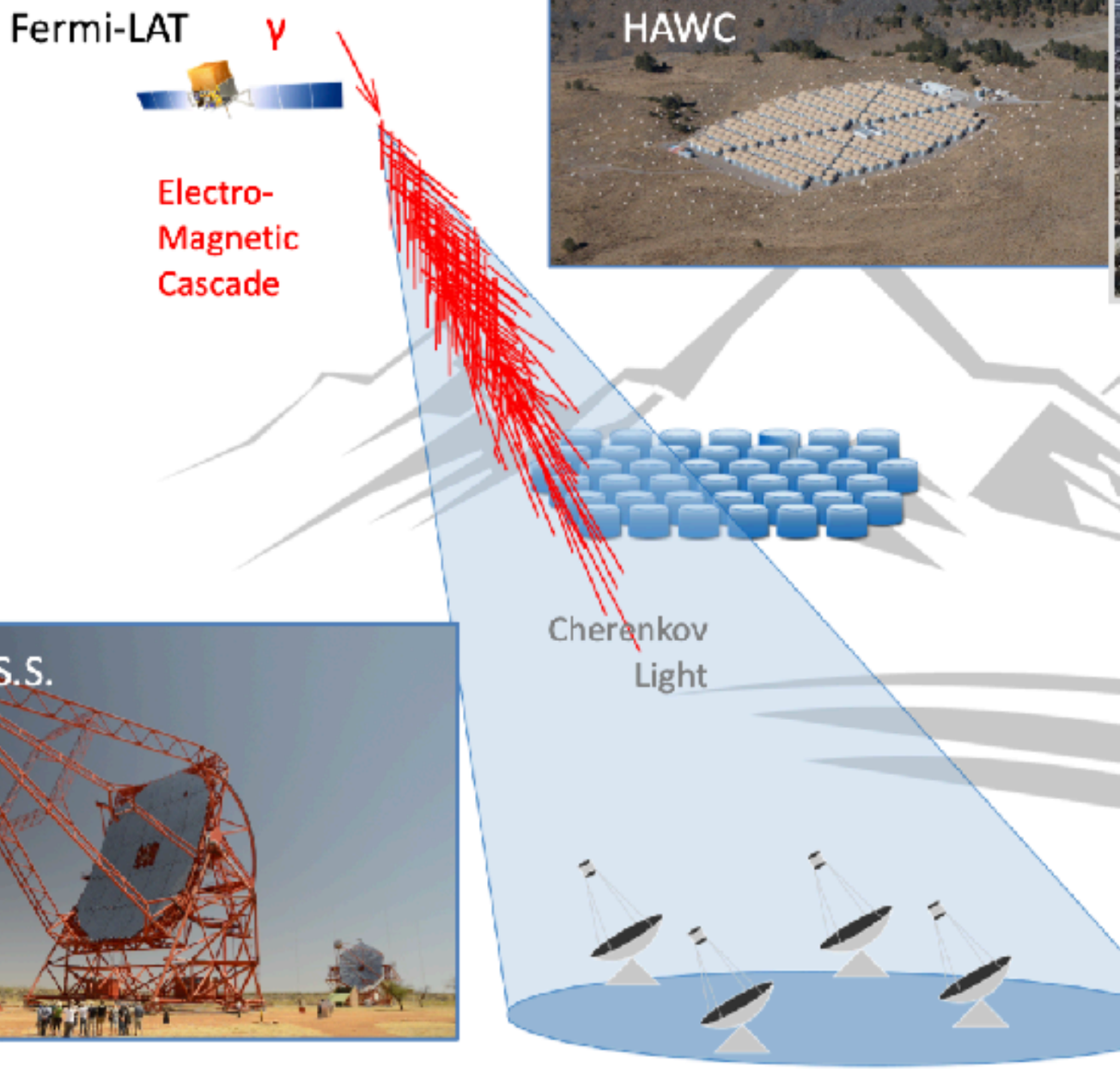
Backup Slides

Detection of gamma rays

HE: 0.3—100 GeV

Extensive Air Shower experiments (EAS)

UHE: 0.1—30 PeV



WCDA,
KM2A

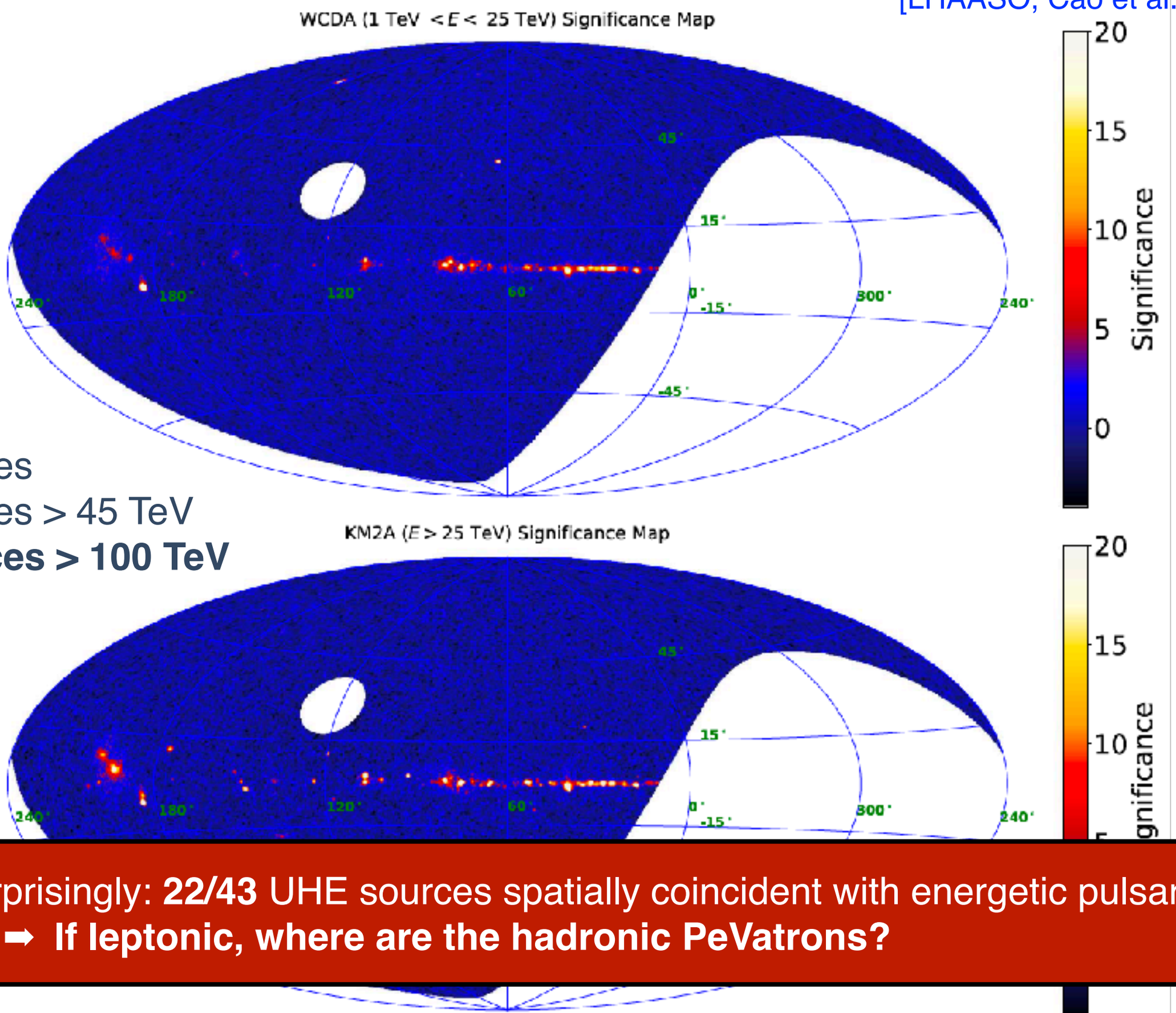
Imaging Atmospheric Cherenkov Telescopes (IACTs)

VHE: 0.1—100 TeV

J. Devin

The 1st LHAASO catalog: a breakthrough

[LHAASO, Cao et al. 2024]



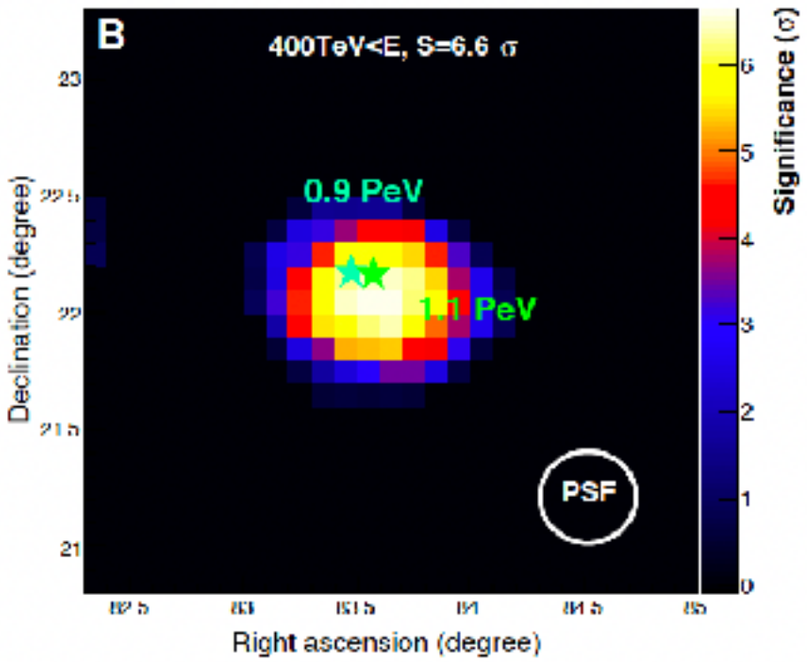
- 90 sources
- 75 sources > 45 TeV
- **43 sources > 100 TeV**

Surprisingly: **22/43** UHE sources spatially coincident with energetic pulsars

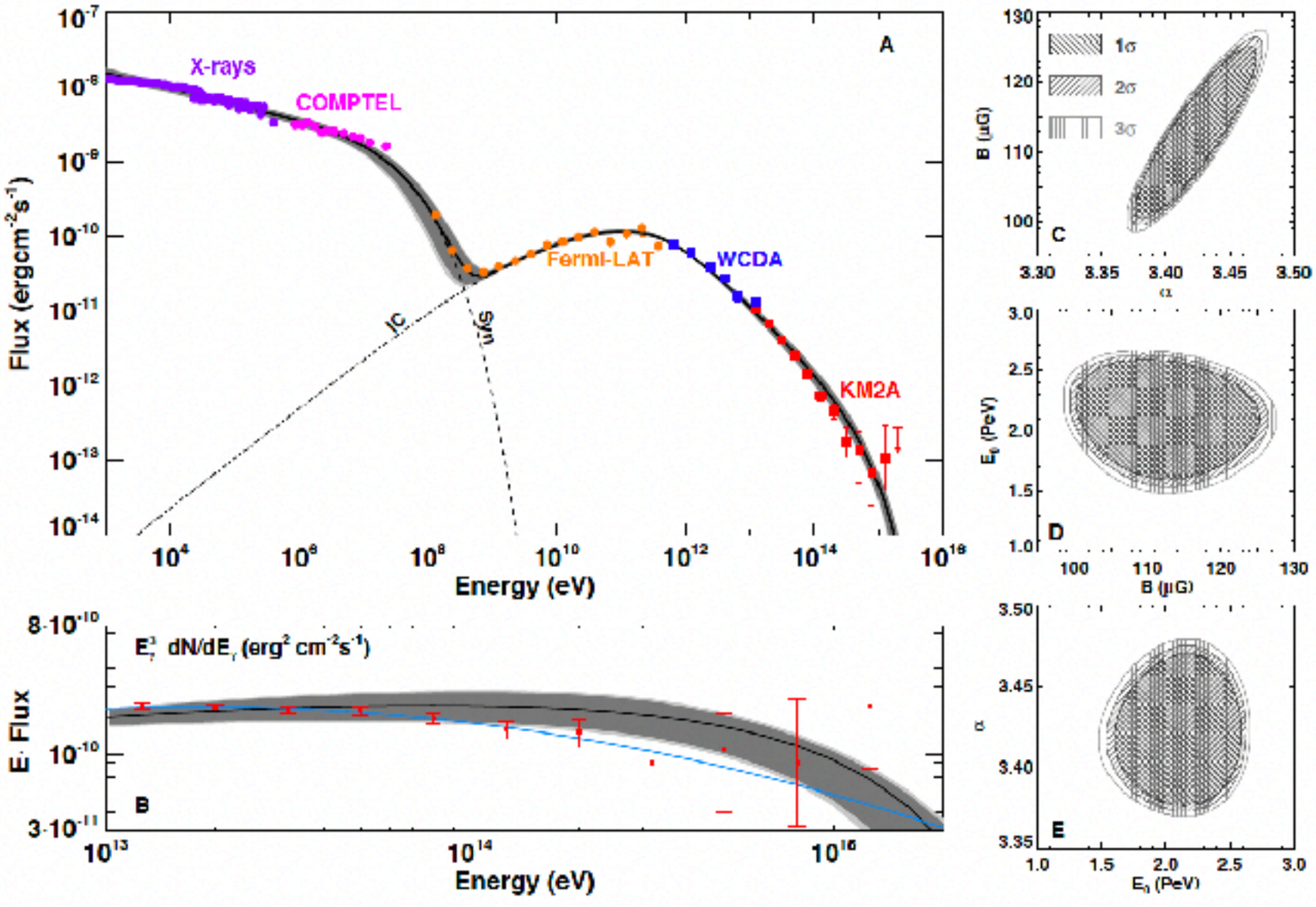
➡ **If leptonic, where are the hadronic PeVatrons?**

The Crab PWN as a likely PeV electron accelerator

Photon of 1.1 PeV !



[LHAASO, Cao et al. 2021]



➡ **Likely leptonic: $E_{max,e}$ = 2.15 PeV**, alpha = 3.42, B = 112 muG **Leptonic PeVatron**

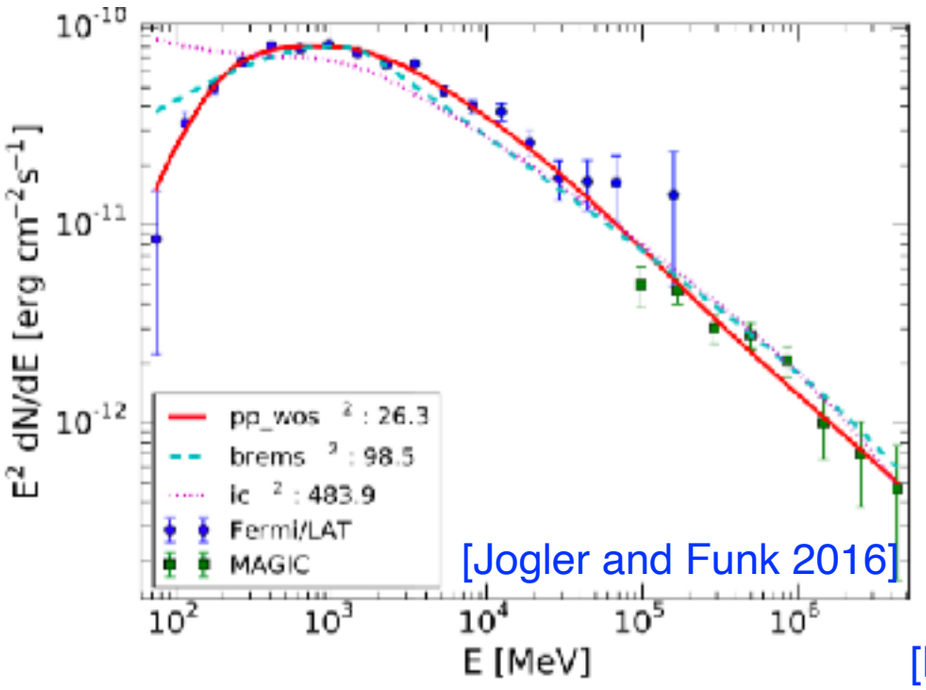
- Steepening of the spectrum between 60 TeV and 500 TeV?
- Hardening of the spectrum at 1 PeV (second population?) ? Clearly not significant at this stage

J. Devin

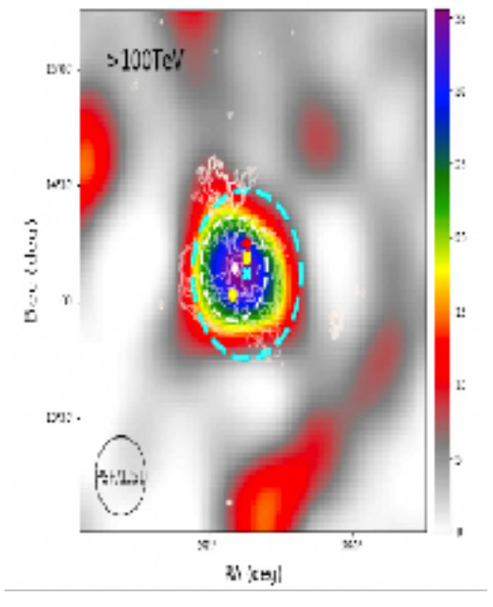
Are SNRs still on the stage?

- **W51C** (t ~ 30 kyr)

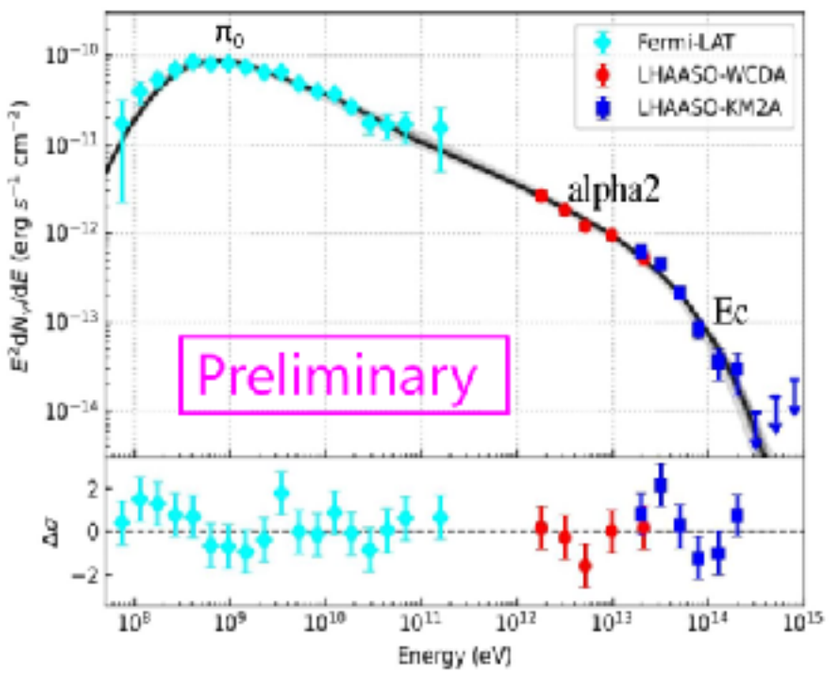
LHAASO detection but $E_{cut,p}$ ~ 400 TeV



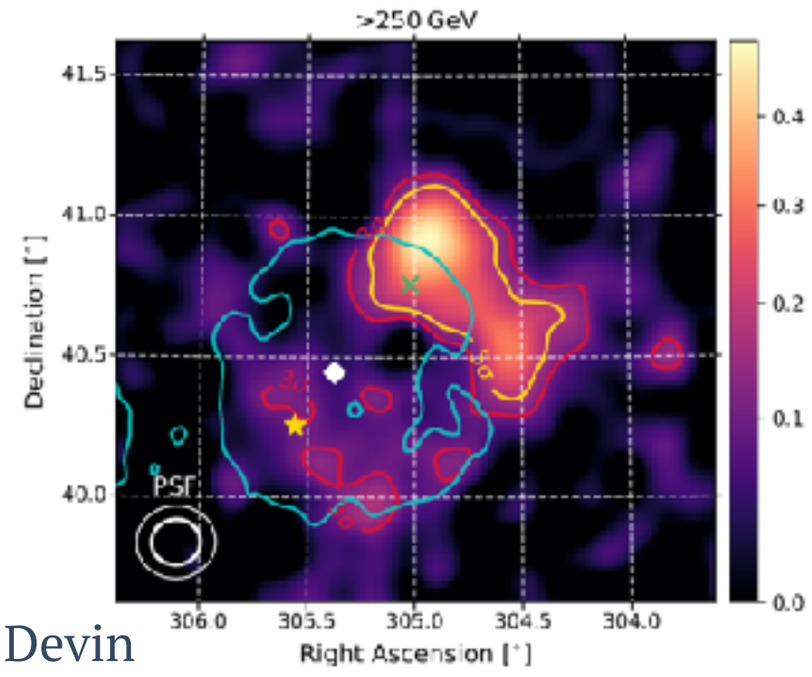
[Jogler and Funk 2016]

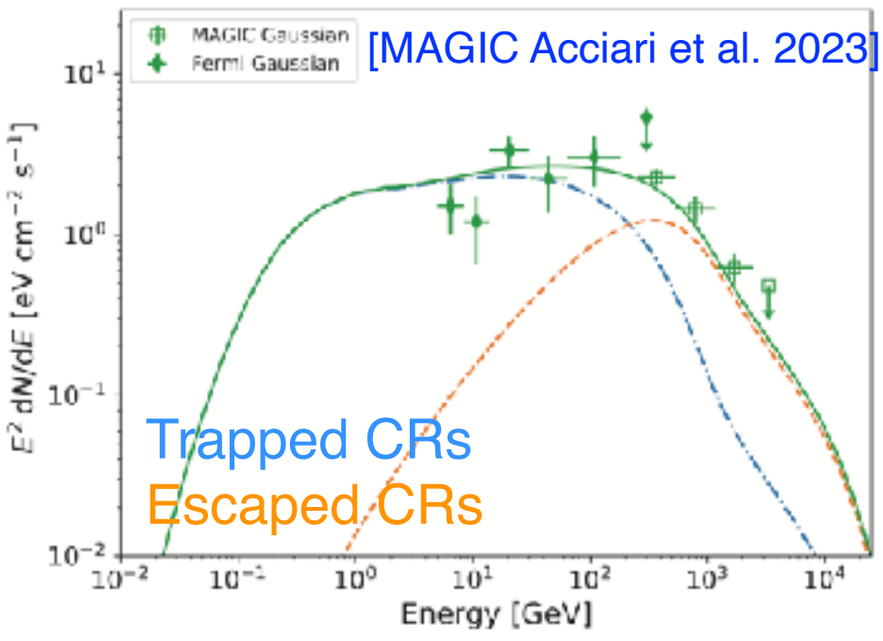


[LHAASO, Fang et al. ICRC 2023]



- **Gamma Cygni SNR** (G78.2+2.1, t ~ 7 kyr)





[MAGIC Acciari et al. 2023]

Ancient PeVatron?

+ observations with LHAASO,
PoS ICRC2023 (2023) 602

IceCube diffuse neutrinos flux