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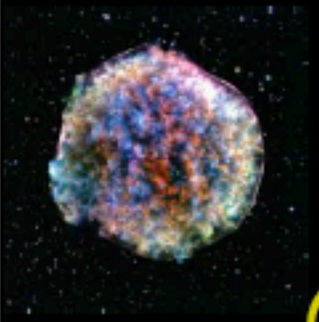
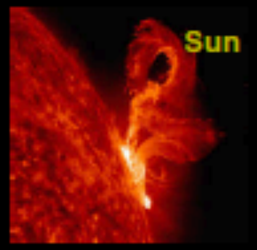
LEARNING FROM GAMMA, COSMIC RAYS AND OTHER MESSENGERS

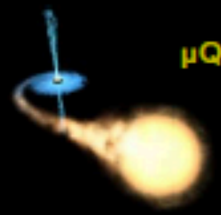
NOW Workshop - Otranto - Sept. 2024

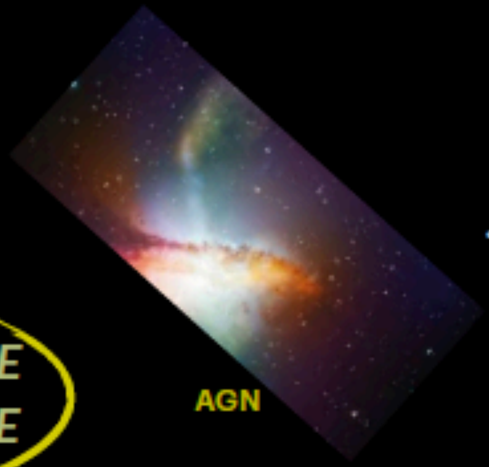
NON THERMAL PARTICLES AND COSMIC RAYS

SNRs









NON THERMAL PARTICLES ARE UBIQUITOUS IN THE UNIVERSE

PWNe

Star Clusters

Starburst galaxies

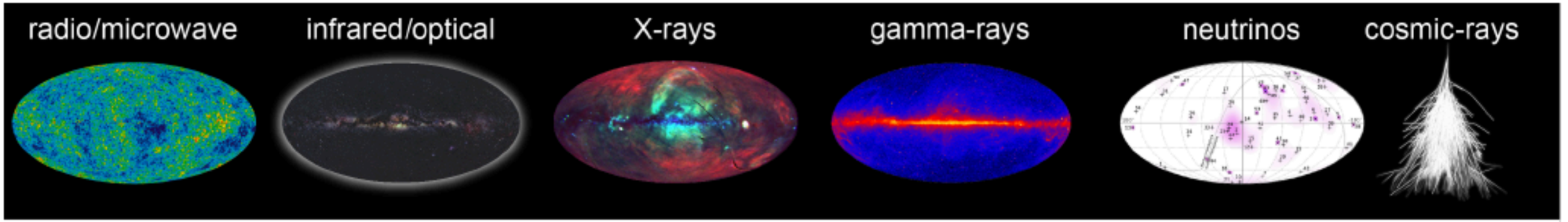
THESE PHENOMENA REQUIRE ACCELERATION MECHANISMS TO BE AT WORK...

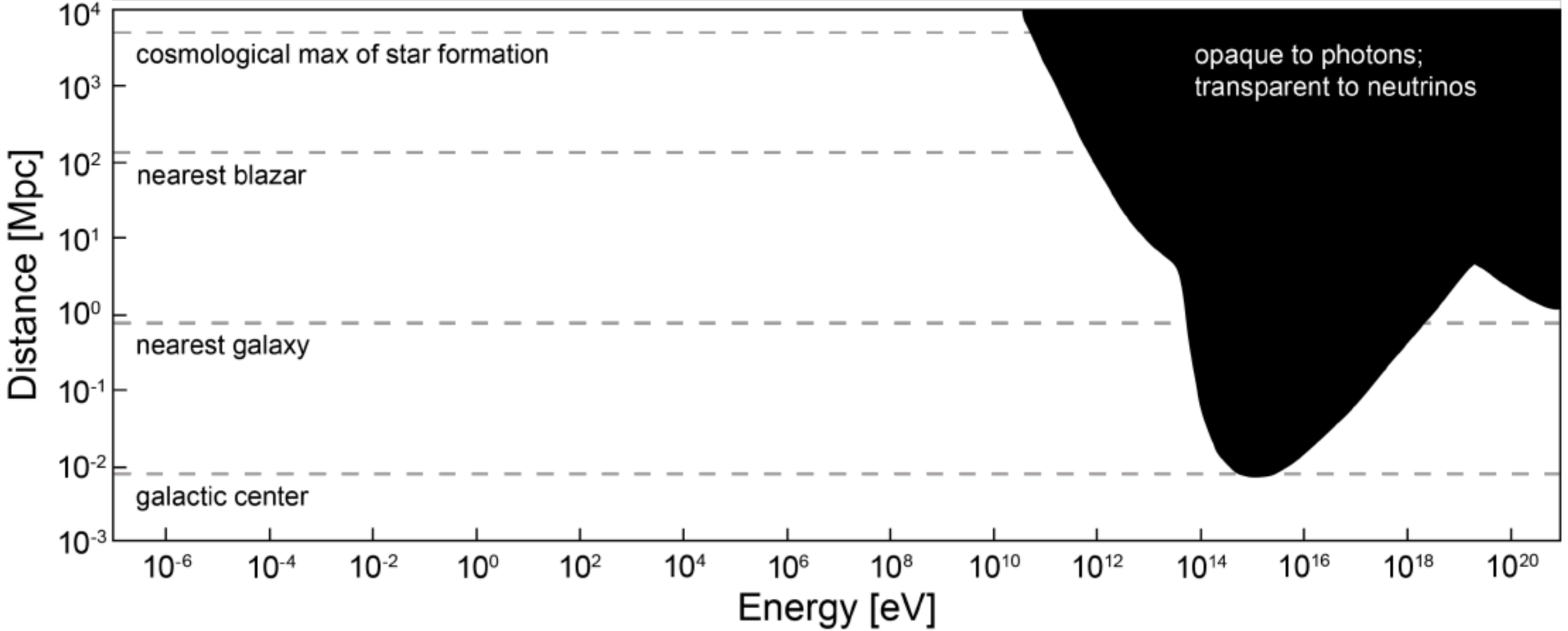
...AND TRANSPORT MECHANISMS THAT TAKE PARTICLES FROM A TO B

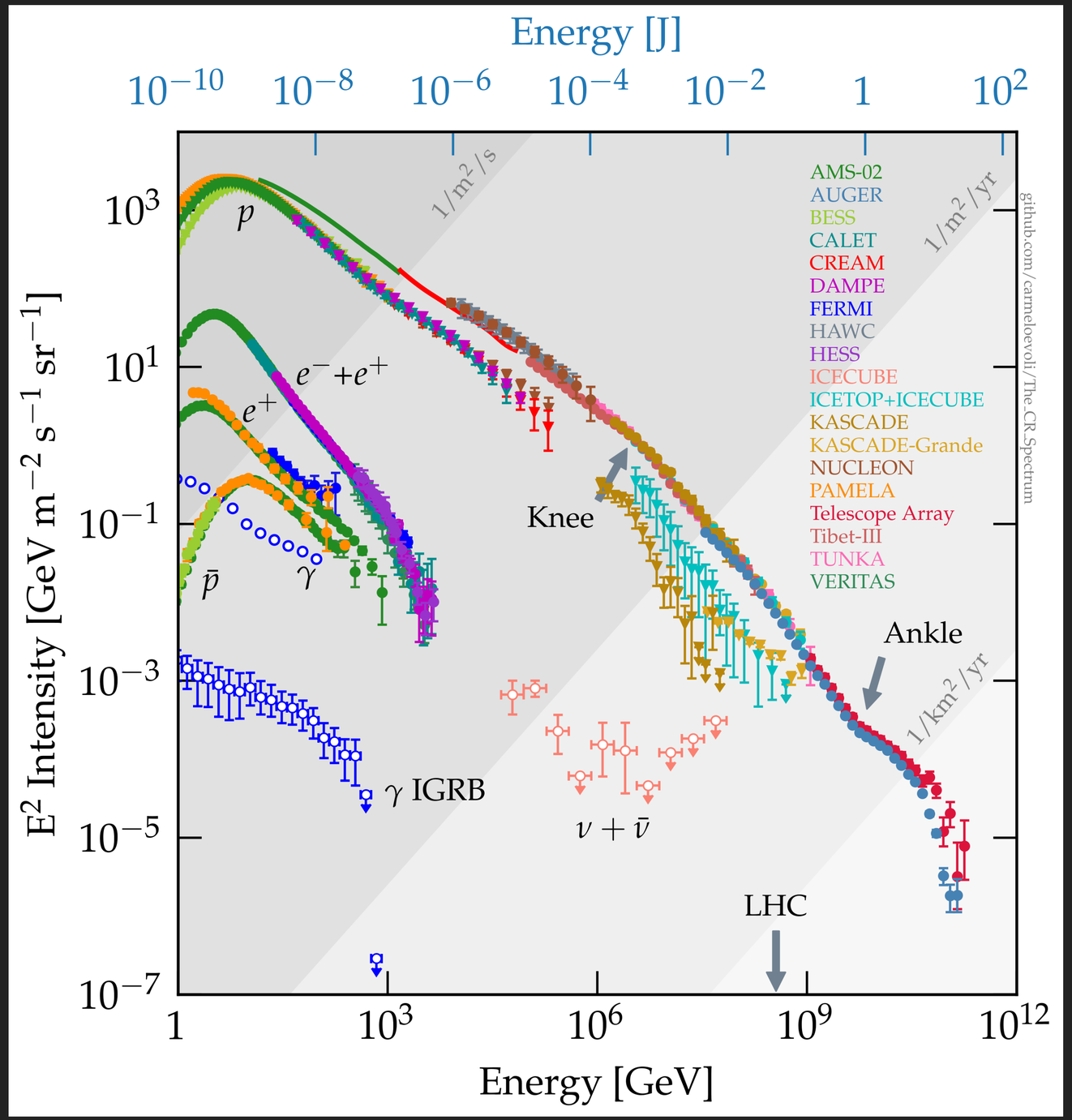
SOMETIMES THE NON-THERMAL PARTICLES PRODUCED IN THESE SOURCES MAKE THEIR WAY TO THE EARTH— AT THAT POINT WE CALL THEM ***COSMIC RAYS***

FOR ALL THESE PROBLEMS, THE CRUCIAL ISSUE IS STILL THE TRANSPORT OF CHARGED PARTICLES IN SPACE AND ENERGY

High-energy messengers of the non-thermal Universe







CR FLUX & COMPOSITION

- Roughly, the all-particle spectrum is a power law **$E^{-\gamma}$** in many orders of magnitude of energy and intensity, with several features:
  - γ = 2,7 until 10^{16} eV ("knee")
  - γ = 3,0 between 10^{16} eV and 10^{18} eV
  - γ = 2,7 until 10^{19} eV ("ankle")
  - γ = 4,2 after 10^{19} eV ("GZK cut-off")

Up to the knee in the CR spectrum **sources are assumed to be Galactic** ! (Galactic Cosmic Rays GCRs)

- *Standard paradigm for GCRs: diffusive shock acceleration in supernova remnants*

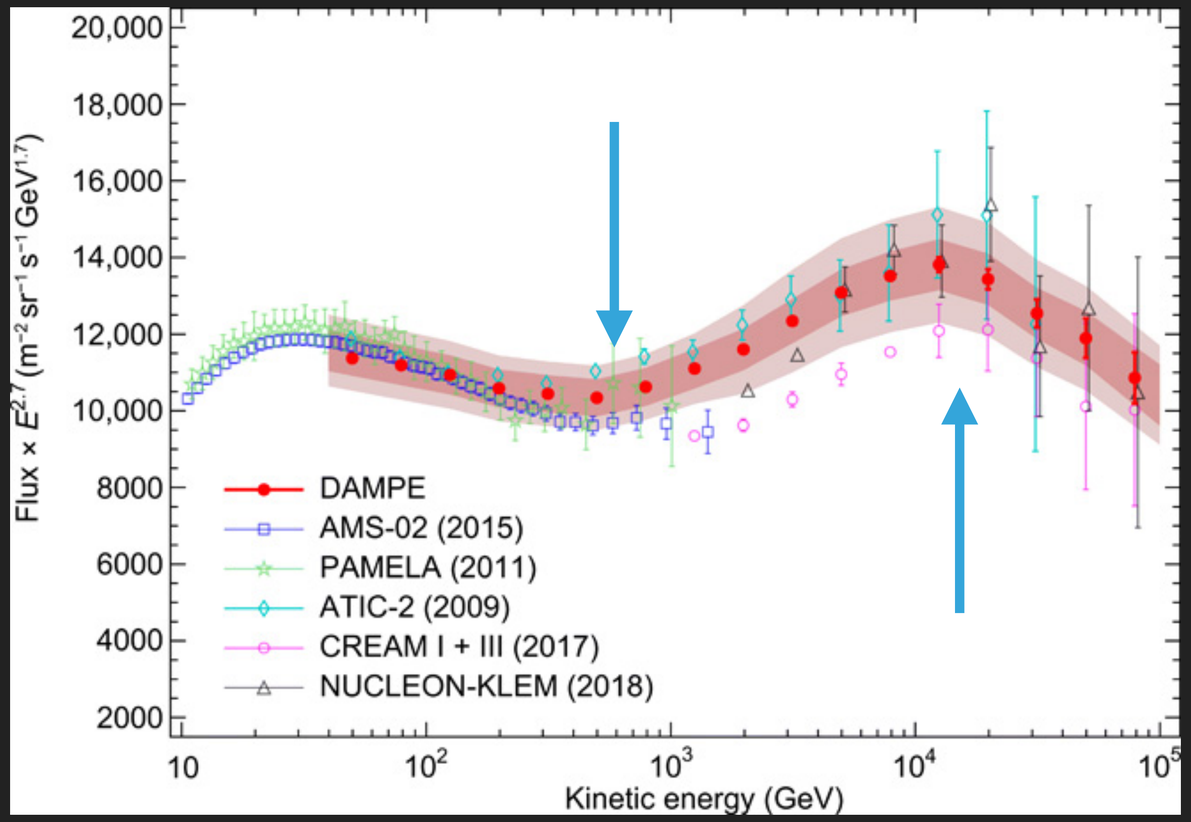
NEWS FROM THE GALAXY

GCRs are mainly detected by “direct measuments” above the atmosphere and in space.

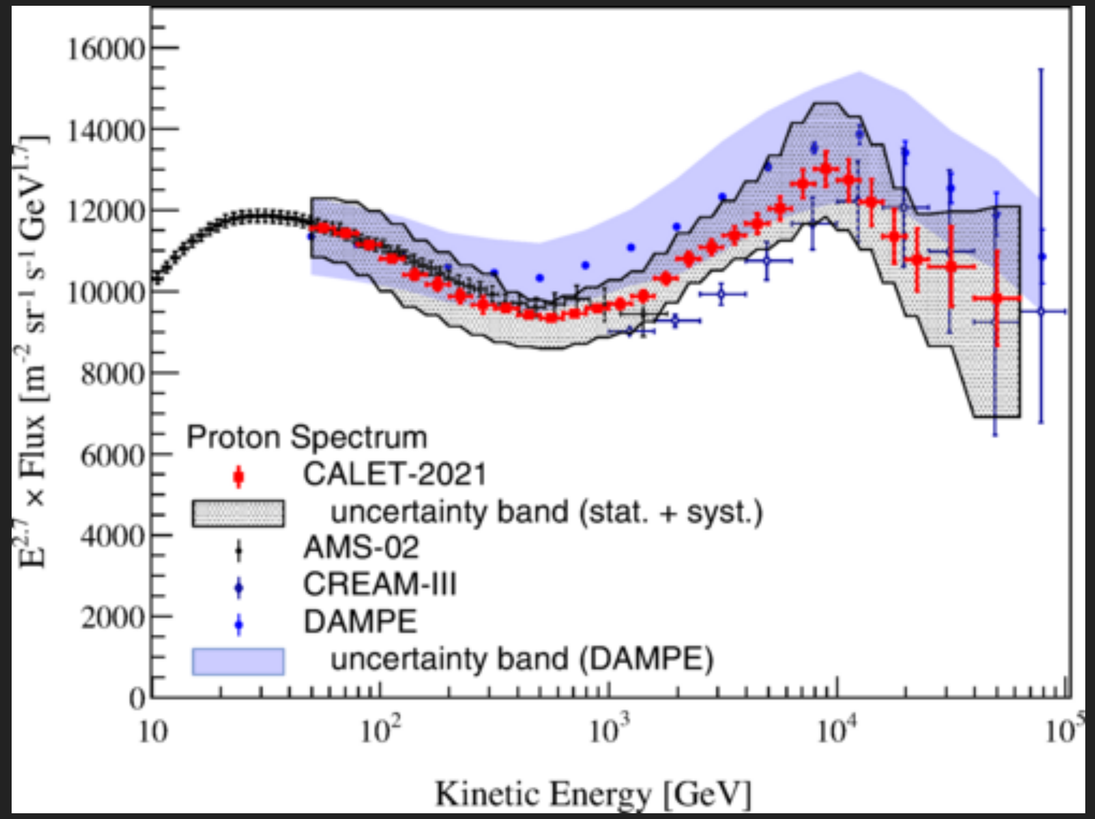
Highlights:

1. Broken power-law spectra of CR’s
2. Positron excess
3. “Pevatrons”

PROTON SPECTRUM (10 GEV–> 100 TEV)



Dampe Collaboration - Science Advances, vol. 5, issue 9, September 2019

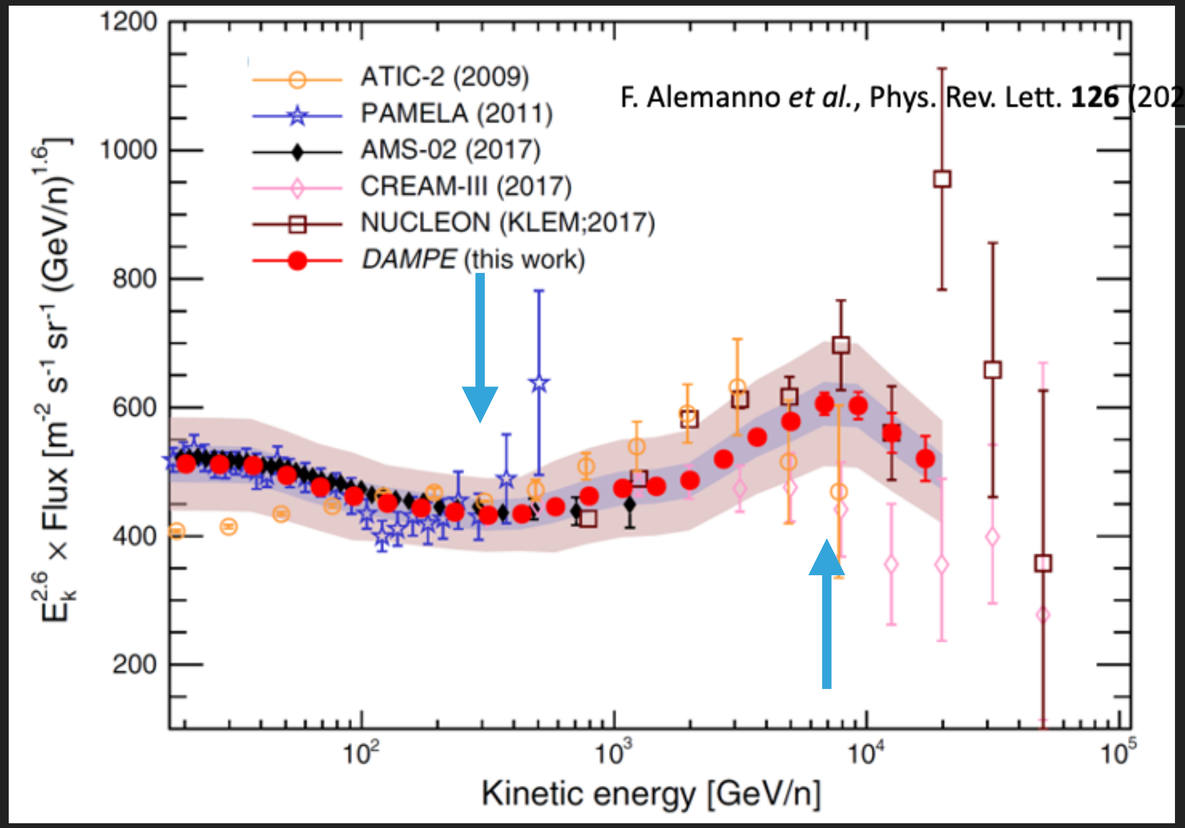


CALET Collaboration - Phys. Rev. Lett. **129**, 101102 - September 2022

Spectra of protons and helium is not a single power law below the knee !!

- **The hardening at R = p/Z ~ 300 – 400 GV is well established since first observation by CREAM and PAMELA**
- **The softening at R = p/Z ~ 10 TV is observed by different experiments, first strong evidence in DAMPE**

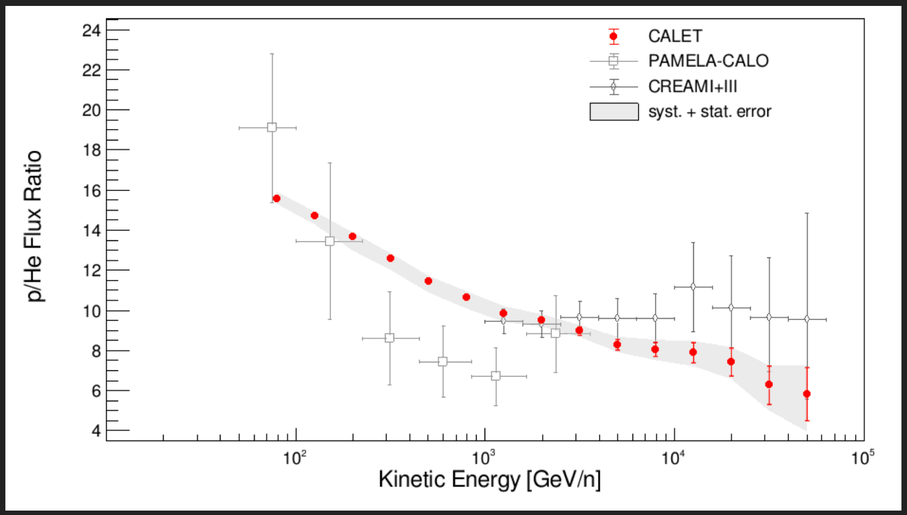
HELIUM SPECTRUM (10 GEV–> 100 TEV)

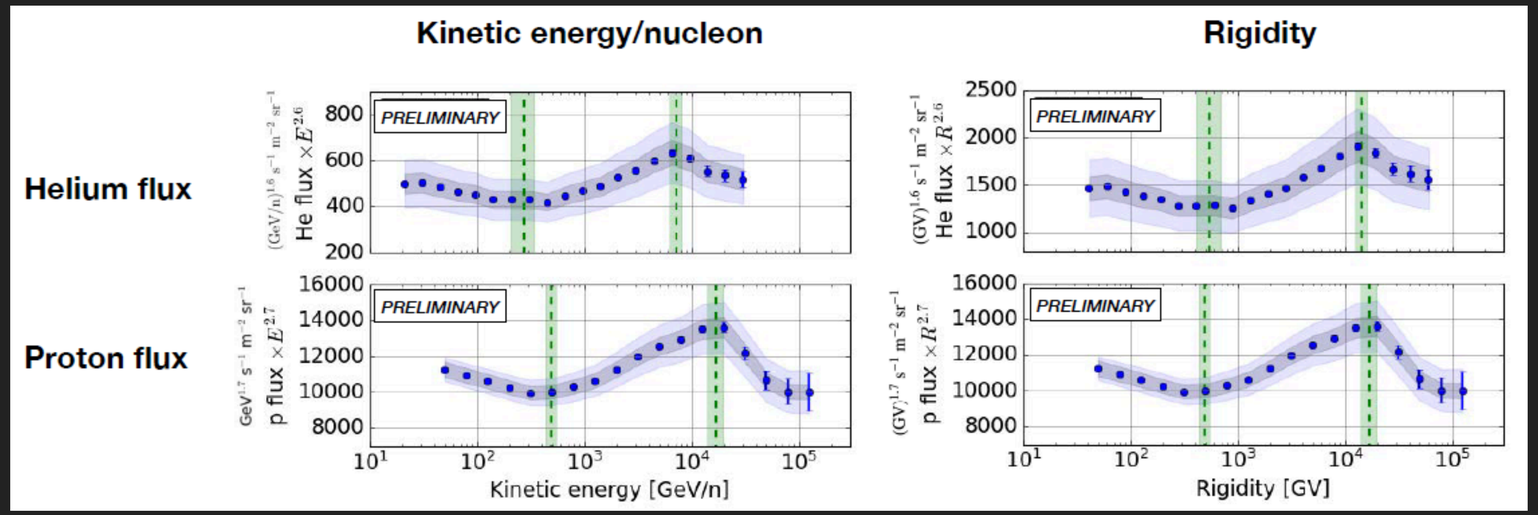


As for protons, helium spectrum shows as well:

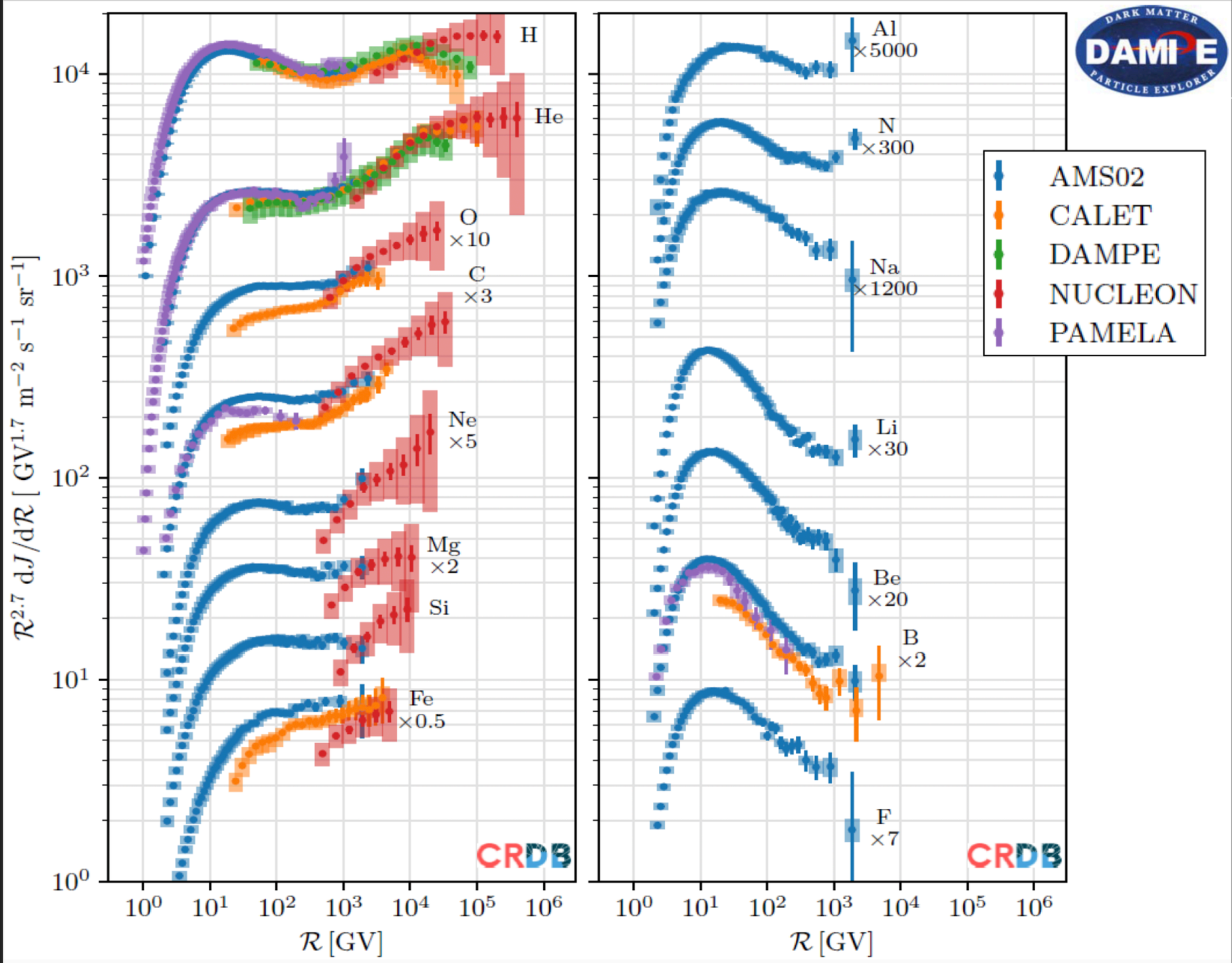
- **A hardening at R = p/Z ~ 300 – 400 GV**
- **A softening at R = p/Z ~ 10 TV**

- **The He spectrum is slightly harder than that of protons (Δγ = 0.1) !!**





Indeed, a **rigidity dependence** of both hardening and softening is favoured by data

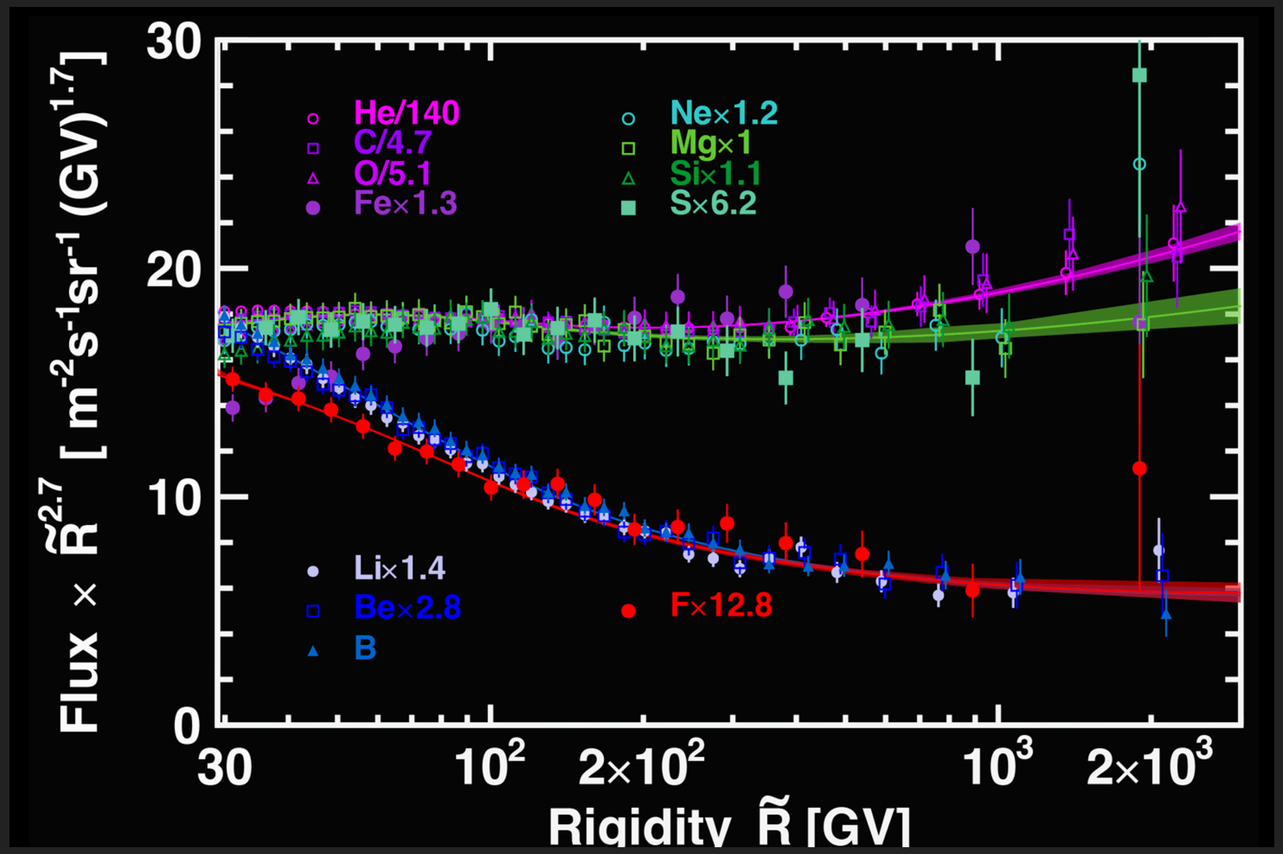


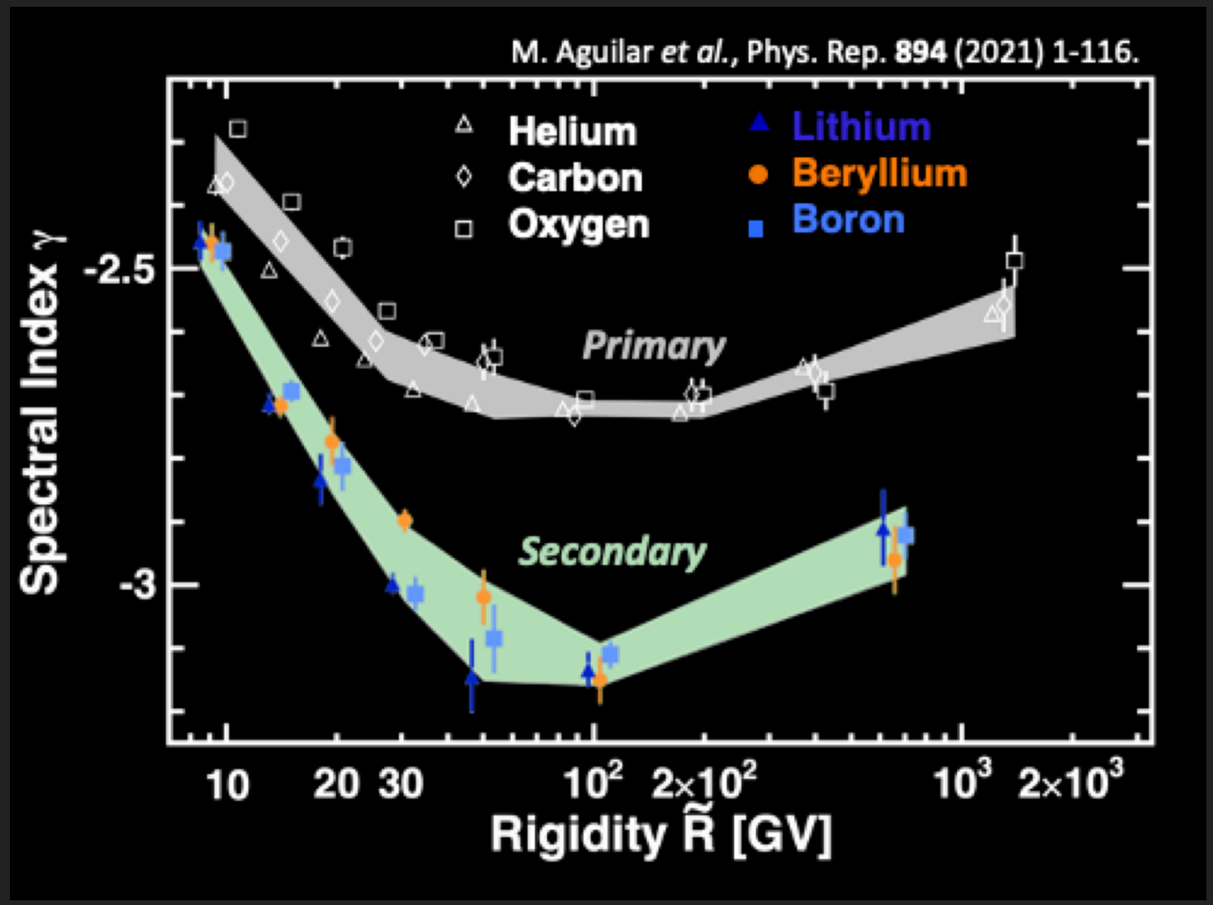
HEAVIER NUCLEI

The spectral hardening is visible in all nuclei !

This seems to be a **universal process**

LIGHT SECONDARY ELEMENTS LI, BE, B





- **Secondary hardening is stronger** –> The flux hardening seems to be a **<u>propagation/diffusion effect.</u>**
- **<u>No clear hints on the softening at 10 TeV</u>**

ANTIMATTER IN COSMIC RAYS

Anti-matter in cosmic rays can be produced by:

1. **Cosmic ray collisions** with the galactic medium;
2. **Astrophysical objects**;
3. **Dark matter annihilations** (e+e-, p, anti-p, D, anti-D, ...);
4. **Primordial origin** (anti-D, anti-He, ...).

Antiprotons are a component of the cosmic radiation being produced in

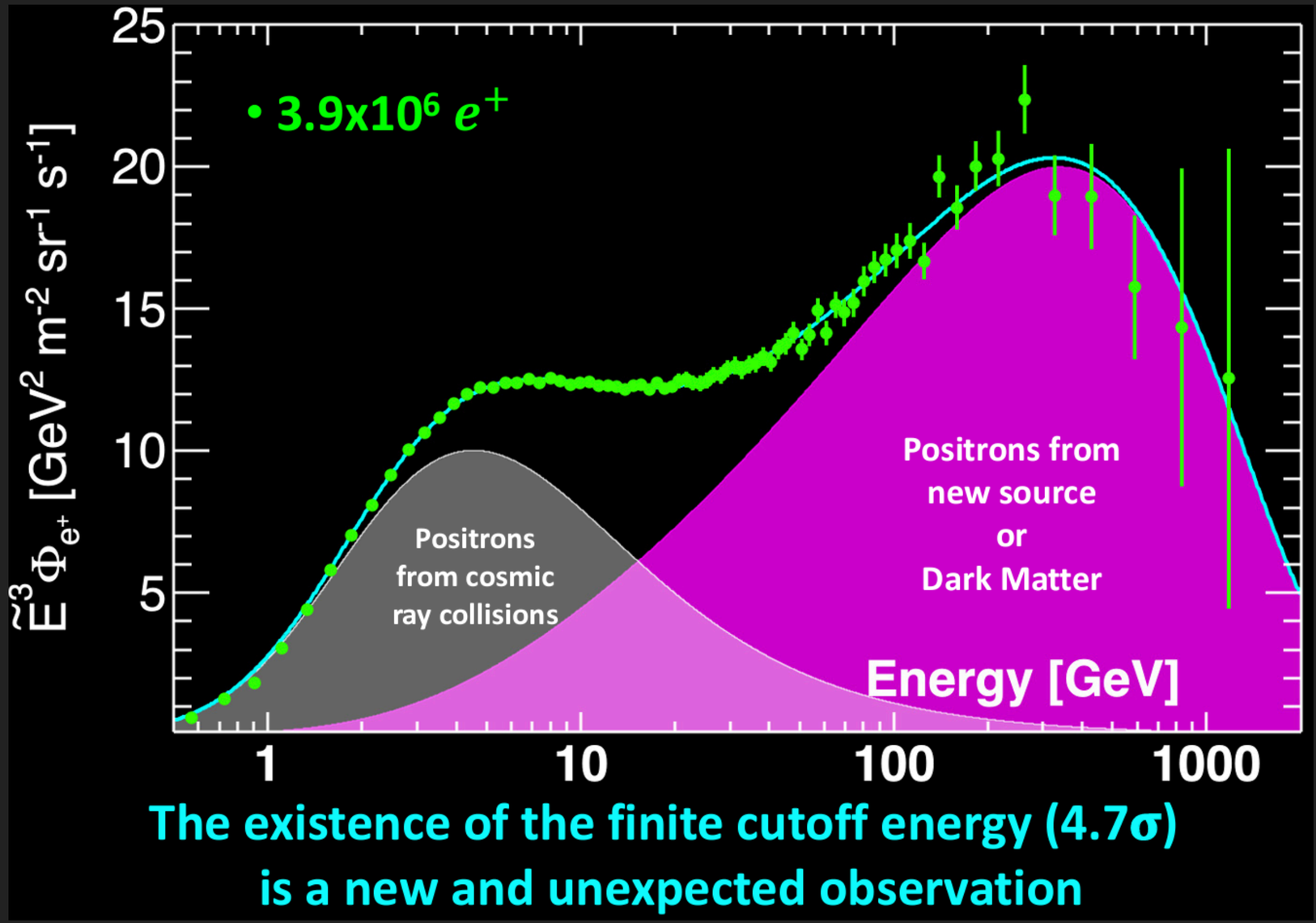
Antiprotons & positrons are produced by the interaction between CRs and the interstellar matter.
For kinematic reasons, no heavier antiparticles can be produced in this way.

POSITRON FLUX

$$\frac{e^+}{e^- + e^+}$$

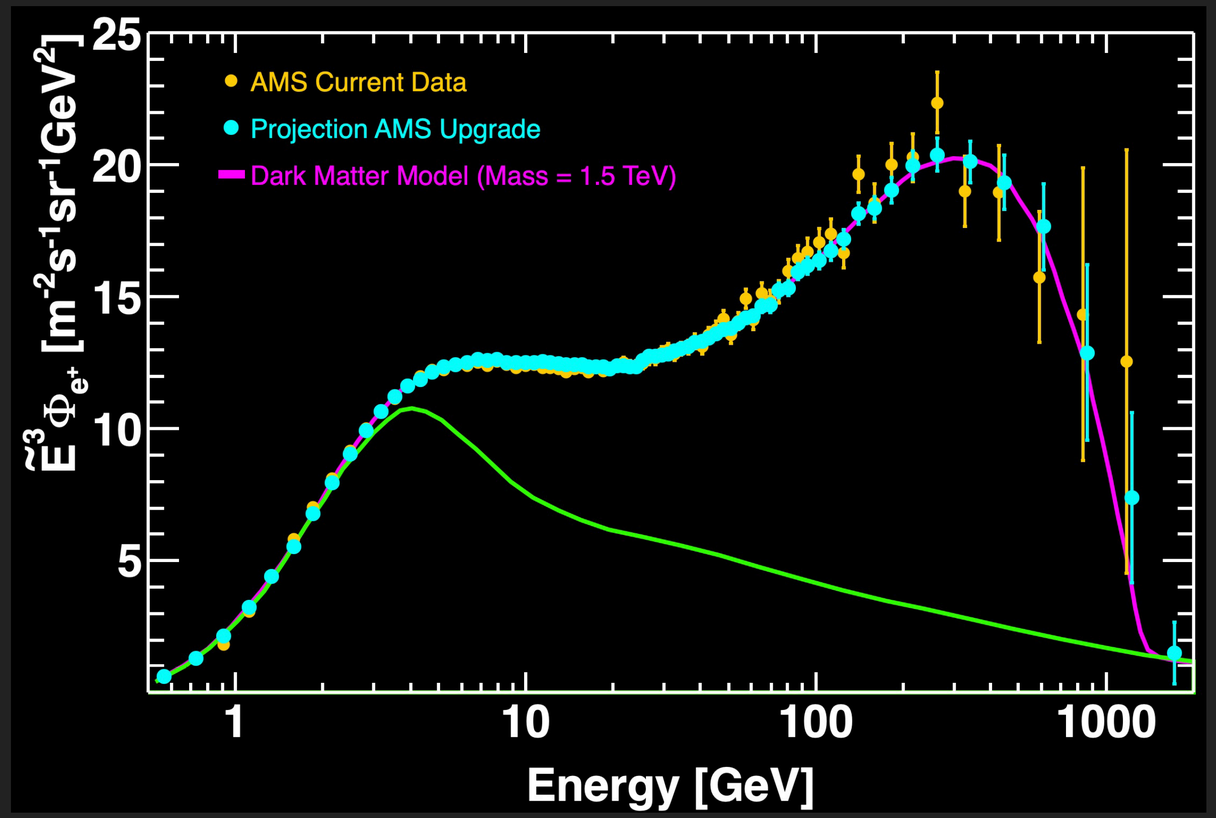
The positron spectrum **steadily increases with energy in the region between 10 and 250 GeV and shows later on a drop-off.**

This increase is **well above that expected** from a model in which all positrons are of secondary origin.

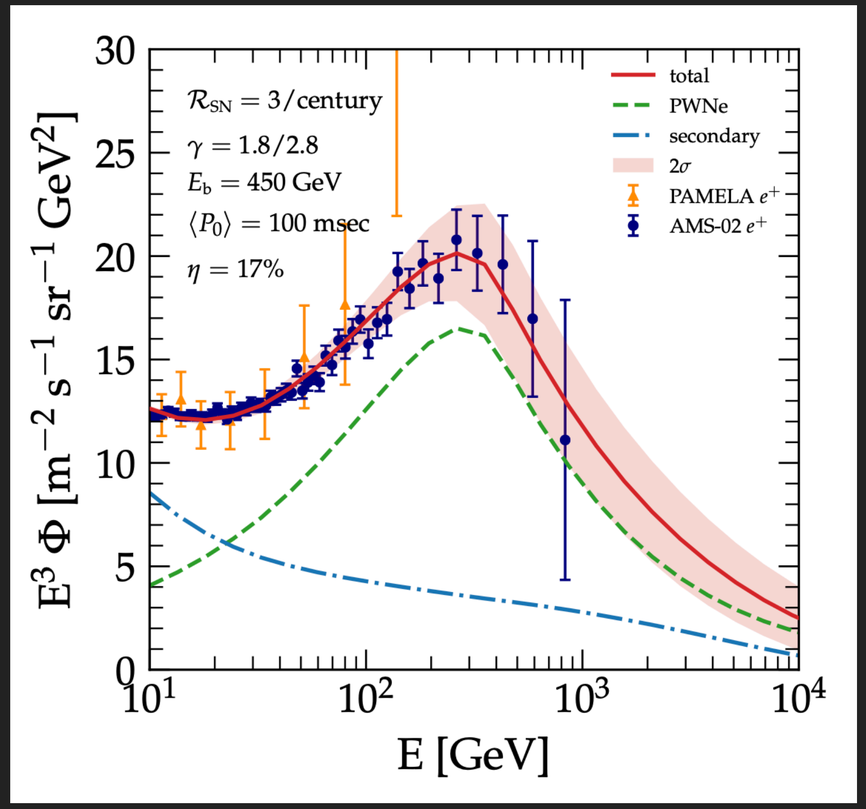


POSSIBLE EXPLANATIONS FOR POSITRON EXCESS

- **Dark Matter annihilation**



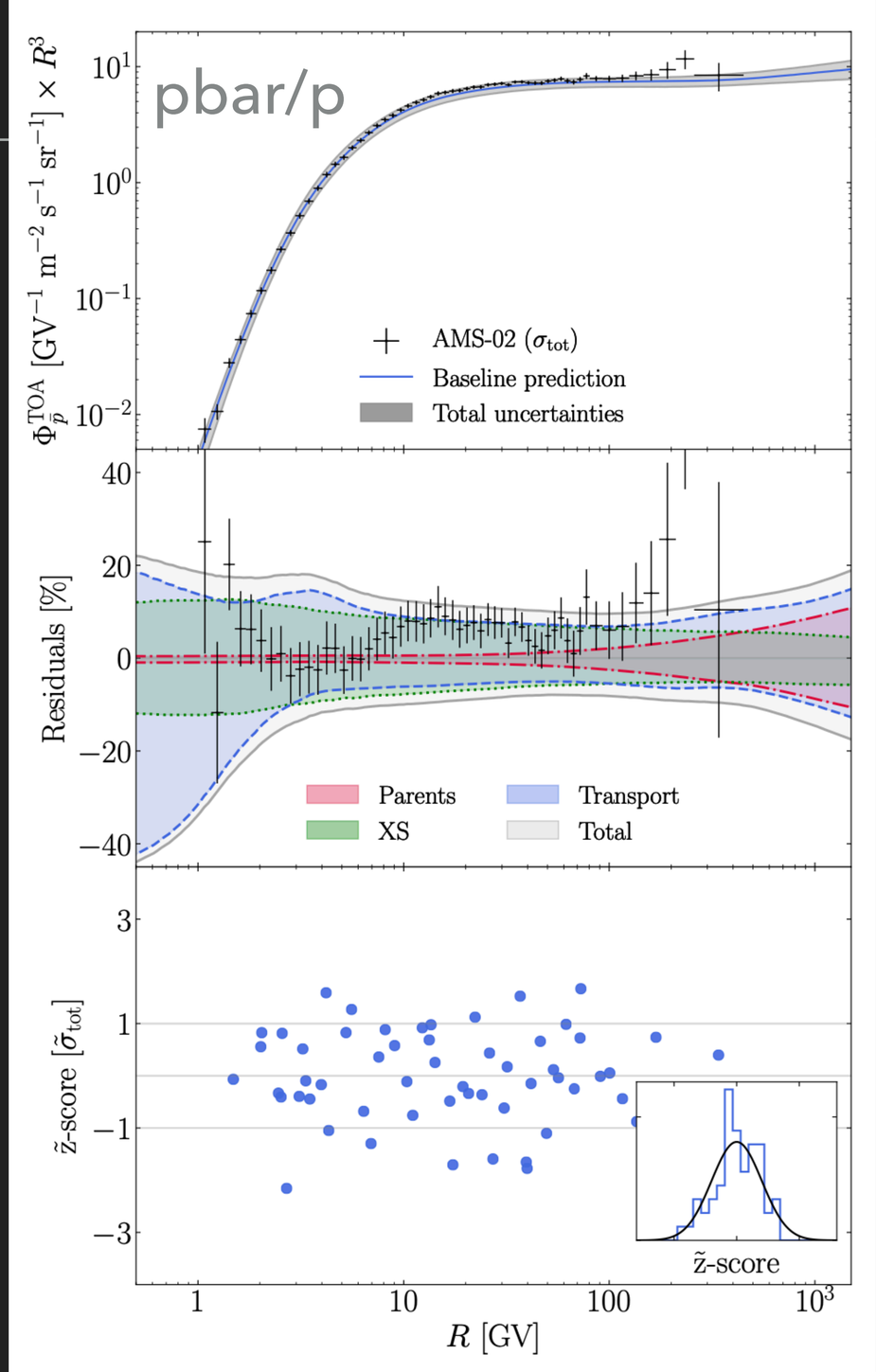
- **Pulsars**



Consistent scenario with the positrons being injected by a population of Galactic Pulsar Wind Nebulae

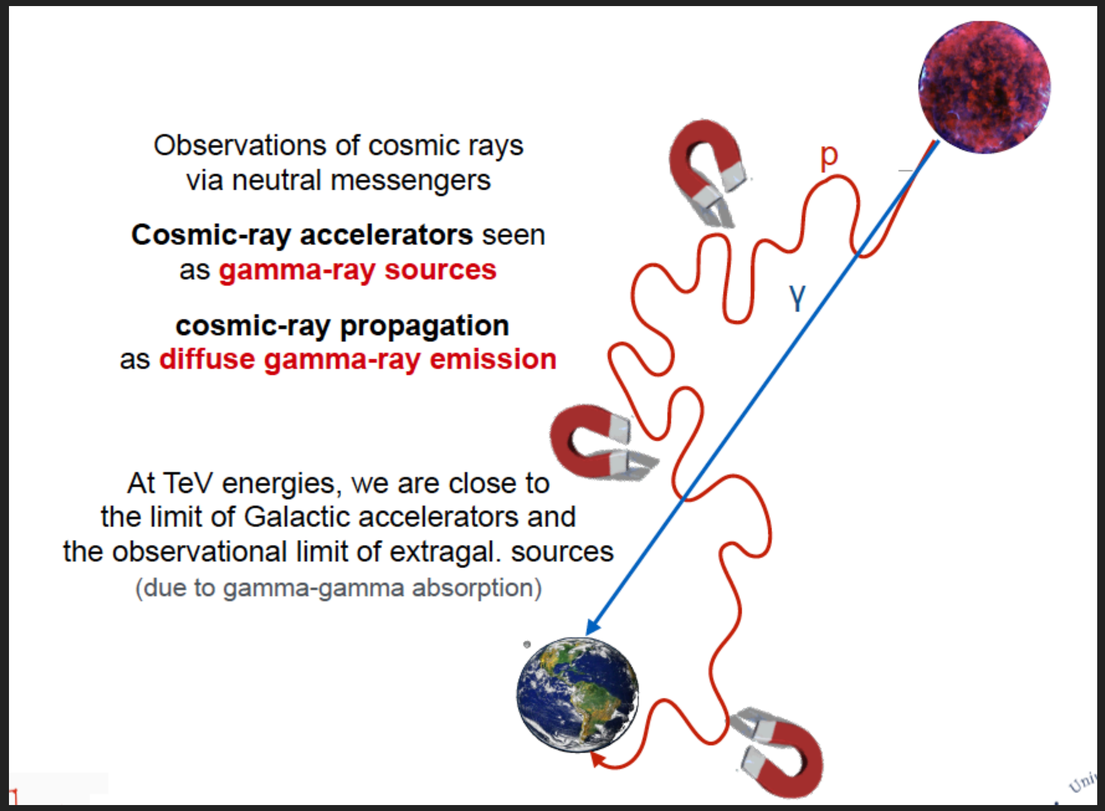
ANTIPROTON/PROTON RATIO

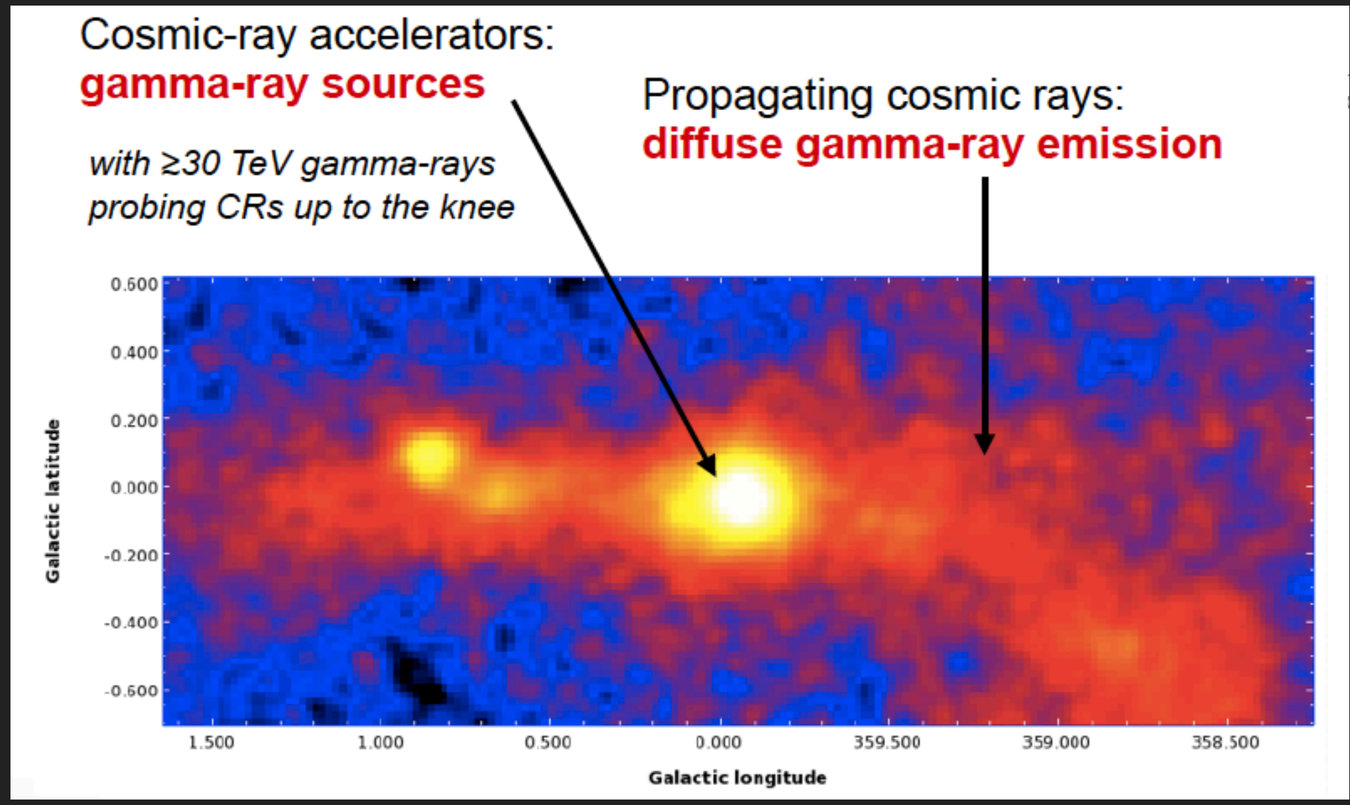
- **No antiproton excess at low or high energies;**
- Antiproton data consistent with a **secondary origin** after accounting for several sources of uncertainties and their correlations



THE GAMMA SKY IN THE GEV & TEV REGION

In order to search for the **cosmic-ray accelerators**, it is necessary to inverstigate the **neutral radiation**, not deflected by the magnetic fields

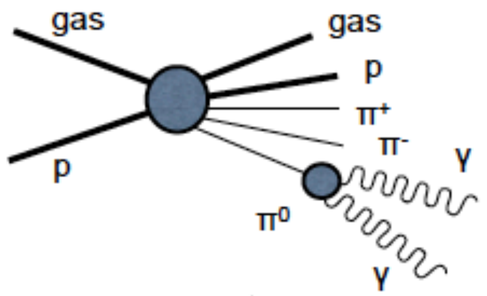




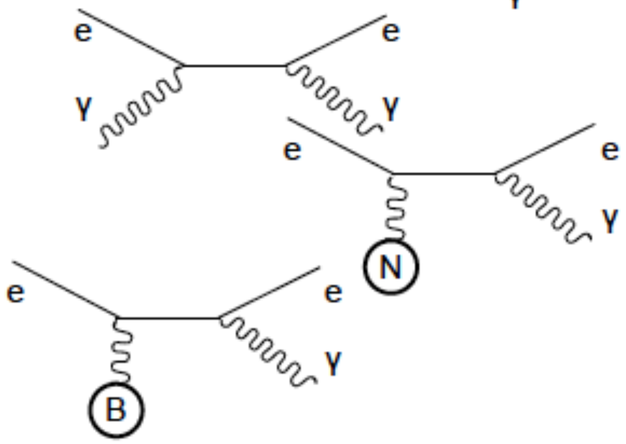
FROM PARTICLES TO RADIATION

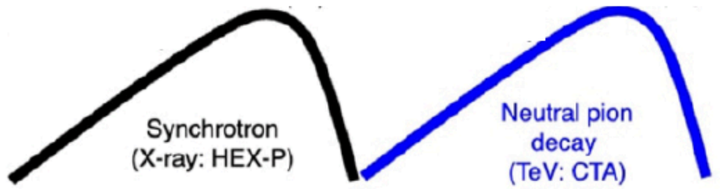
- **Pion production and decay**
  $p + N_{gas} \rightarrow \pi^o + \ldots \rightarrow \gamma\,\gamma$
- **Inverse Compton scattering**
  $e^{\pm} + \gamma_{LE} \rightarrow e^{\pm} + \gamma_{HE}$
- Bremsstrahlung
  $e^{\pm} + N_{gas} \rightarrow e^{\pm} + \gamma$
- Synchrotron radiation
  $e^{\pm} + B \rightarrow e^{\pm} + \gamma$

hadronic mechanism

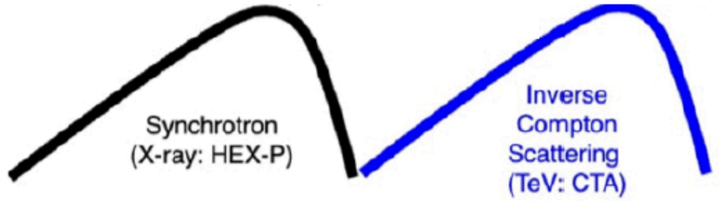


leptonic mechanisms





Hadronic accelerators

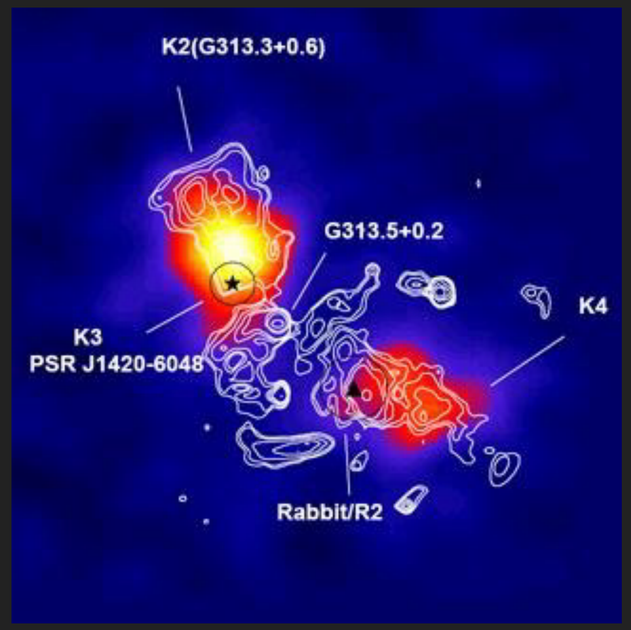


Leptonic accelerators

The discovery of a convincing case of **a cosmic-ray accelerator** through the identification of gamma-rays produced by π^0 decays is **extremely difficult** due to the additional gamma-ray production mechanisms from relativistic electrons.

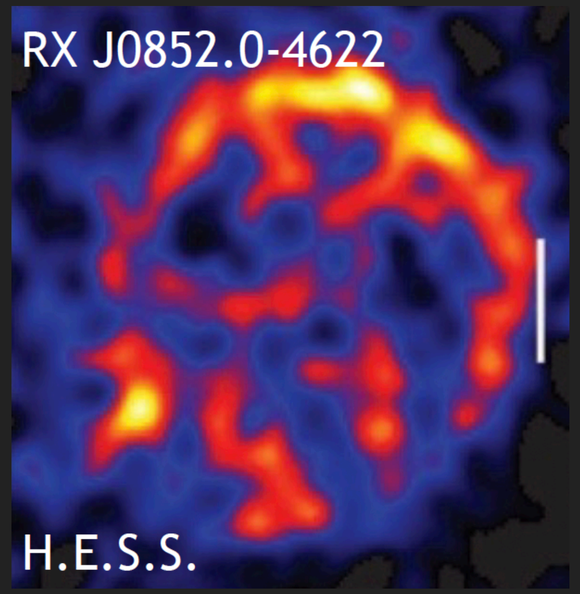
GAMMA-RAY GALACTIC SOURCES IN THE GEV & TEV REGION

Pulsar Wind Nebulae (PWNe)



PWNe and SNRs constitute the majority of gamma Galactic Sources

Supernova Remnants (SNRs)

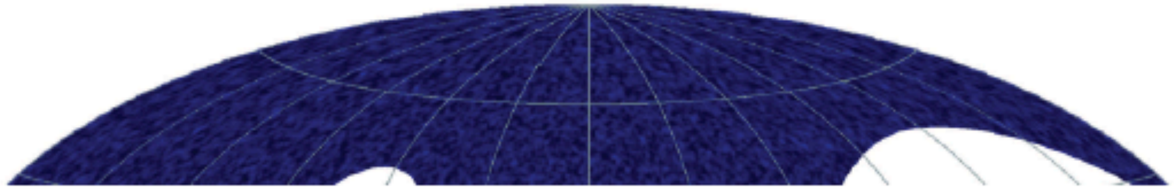


Sources capable of accelerating particles up to at least PeV energies are called **PeVatrons**.

The problem of accelerating cosmic rays to PeV energies in the Galaxy is very serious.
Other classes of sources besides SNR may play a role as cosmic-accelerator.

PeVatrons everywhere!

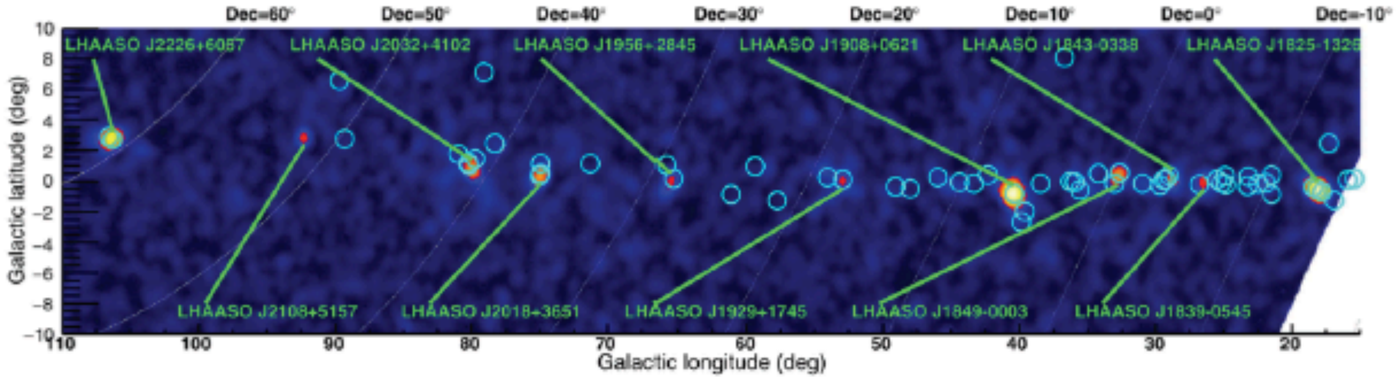
LHAASO Sky @ >100 TeV

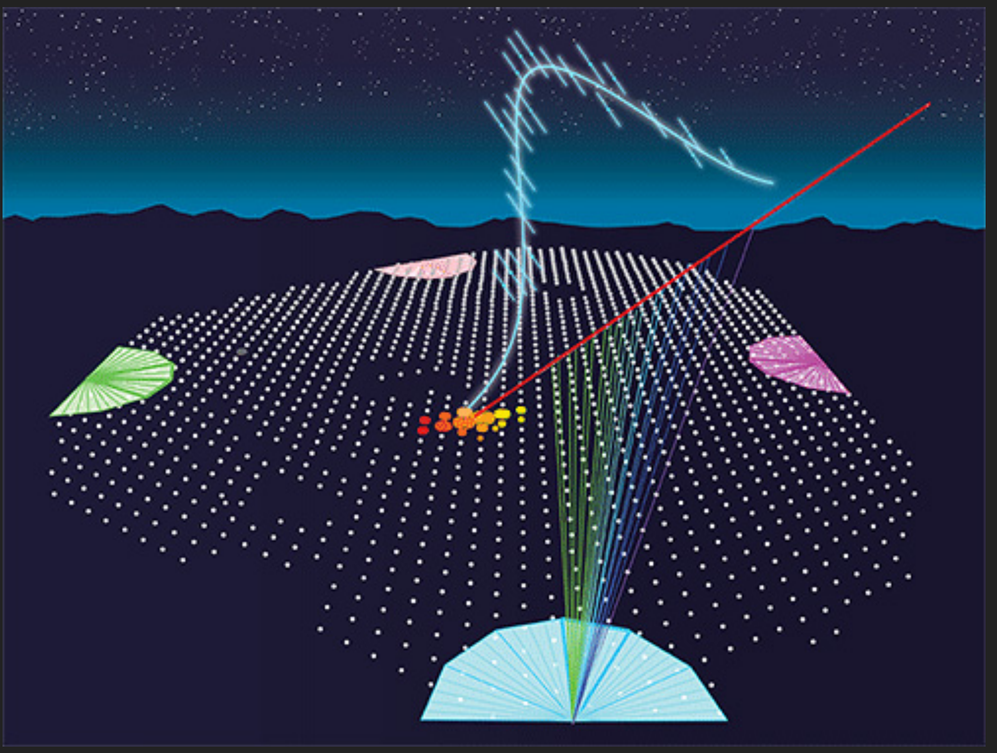


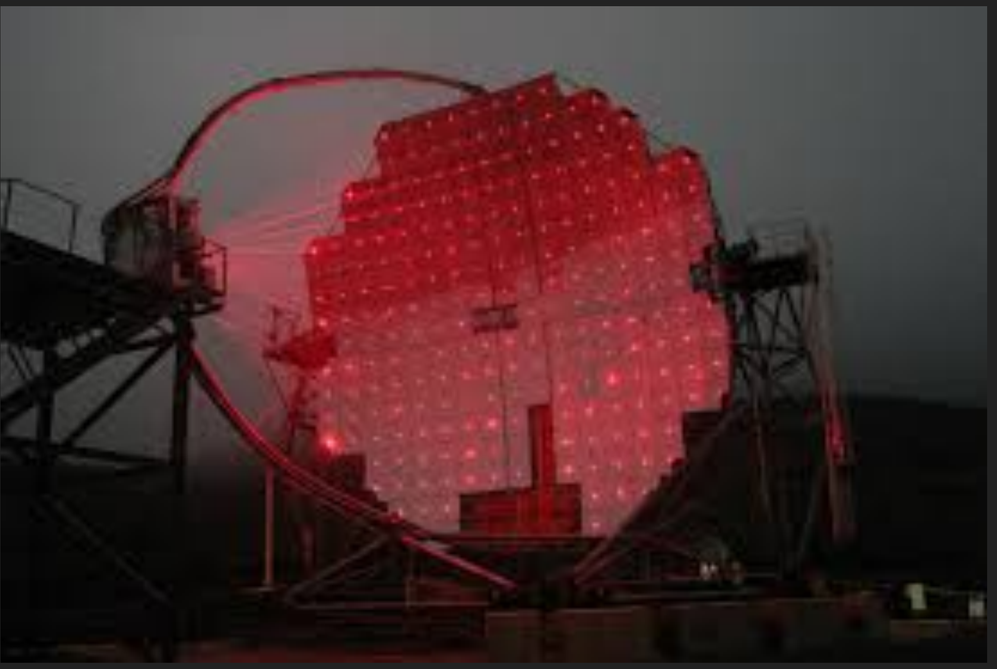
12 sources with energies between 100 TeV and 1.4 PeV!

→ **consequence of the LHAASO sensitivity at E~100 TeV**

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)







EXTRAGALACTIC COSMIC RAYS

UHECRs are detected by “indirect measuments” with instruments on ground

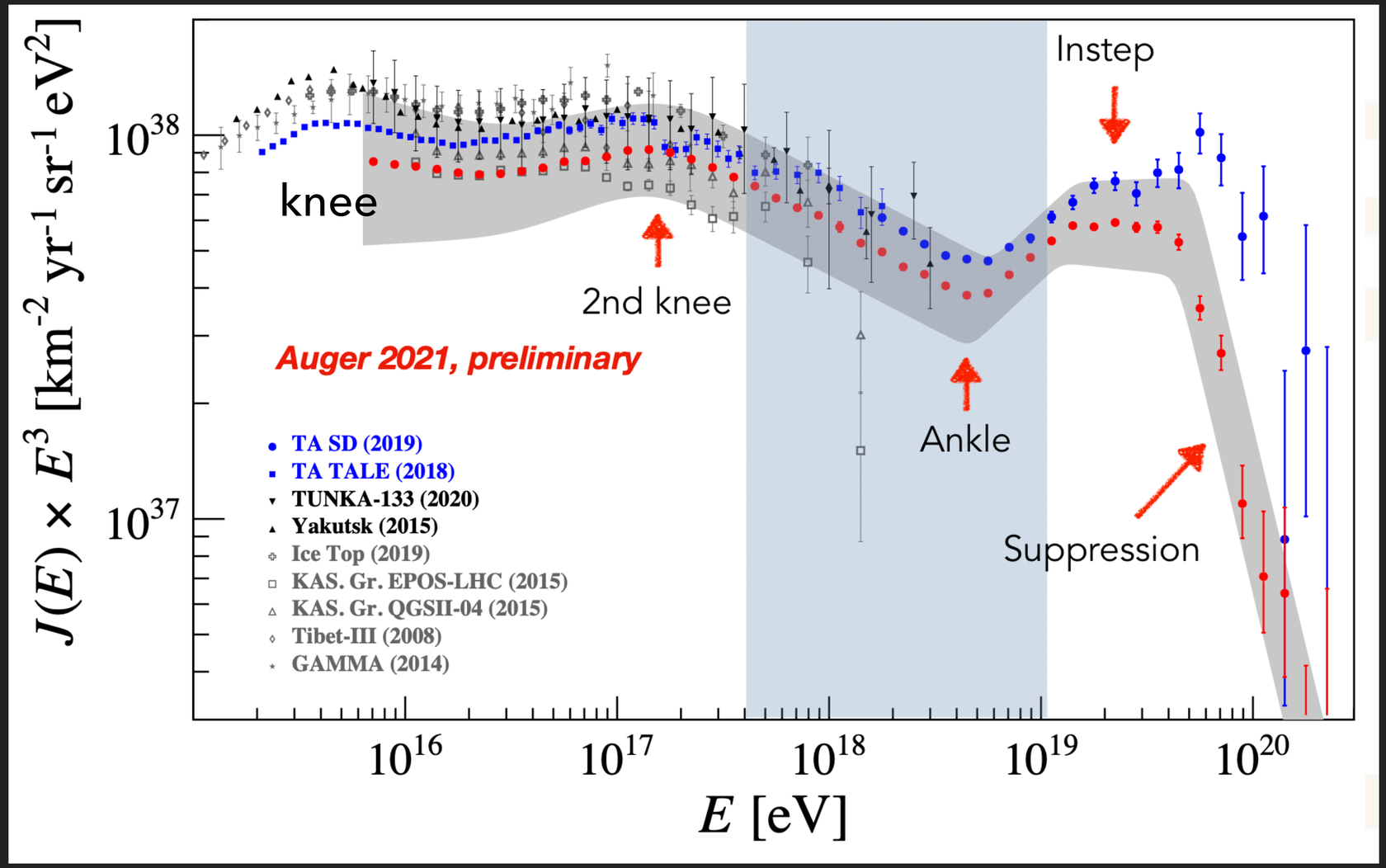
Highlights:

1. Flux determination of UHECRs
2. Composition
3. Anisotropy studies
4. Gamma sources

UHECR'S SPECTRUM: AGREEMENT BETWEEN EXPERIMENTS (PAO AND TA)

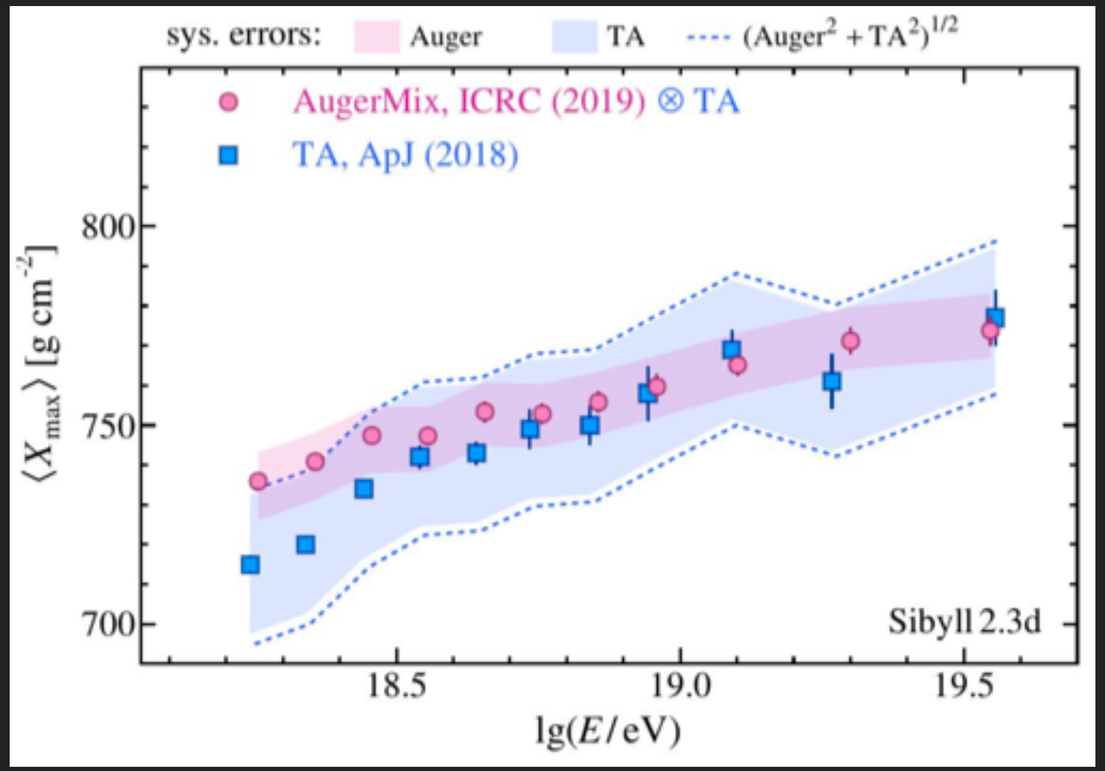
New features appear on UHECRs flux as well:

- a **"2nd knee"**
- an **"instep"** phase between the "ankle" and the final high-energy suppression

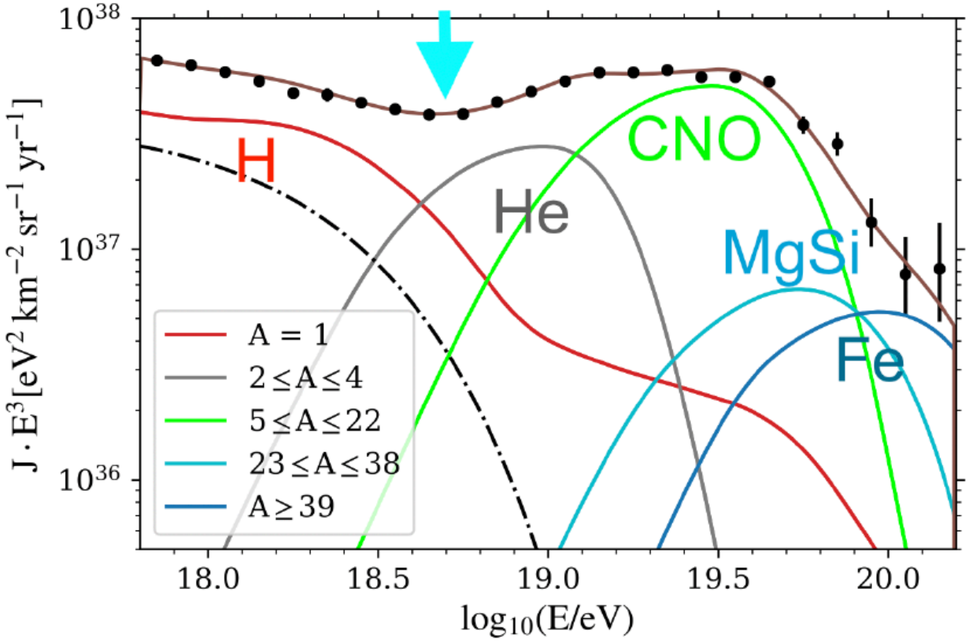


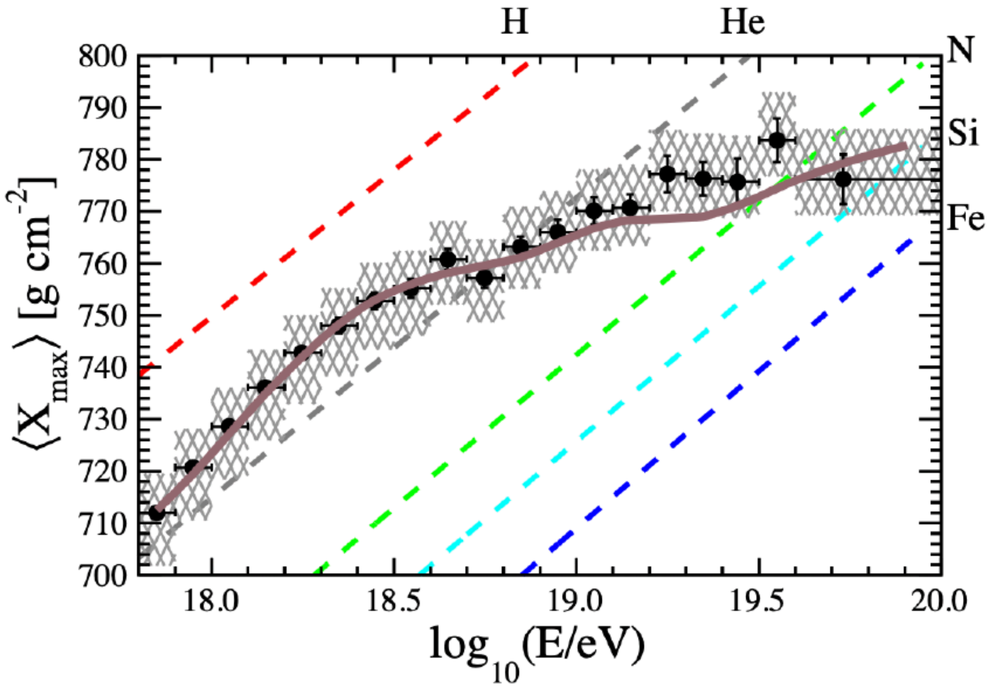
COMPOSITION

The nuclear composition of UHECRs is deduced by observing the **air-shower ⟨Xmax⟩ distributions** and the flux.

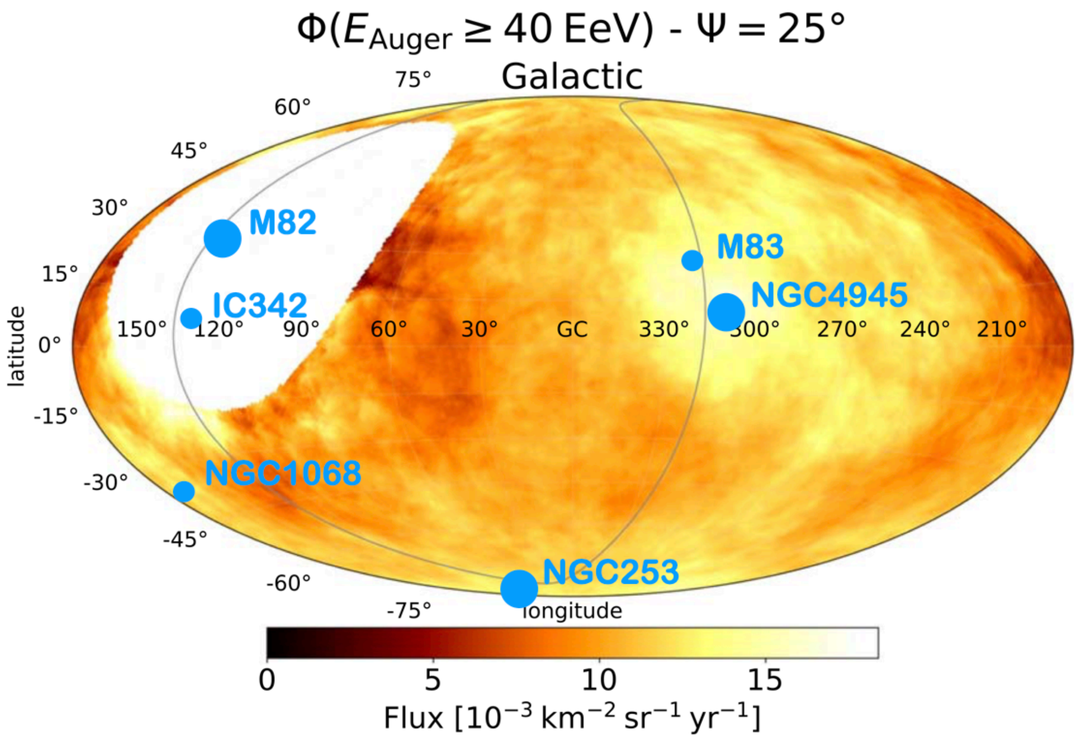


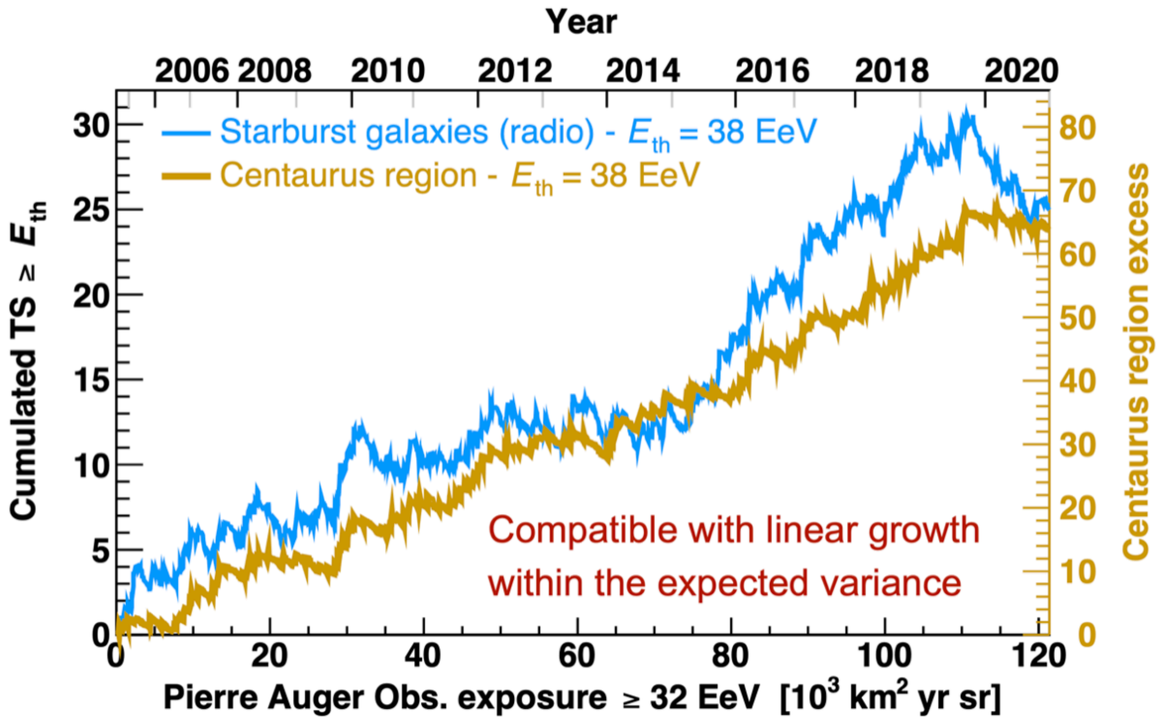
Sources must release a mixed (He + CNO) mass composition





ANISOTROPY



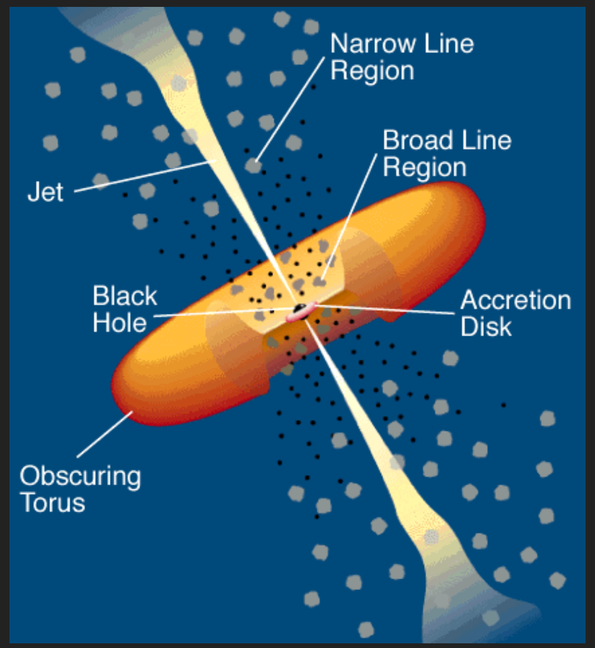


- **Local indication** of departure from isotropy forE ≳ 41 EeV in the direction of the **Centaurus constellation**
- **Global correlation** with Starburst Galaxies

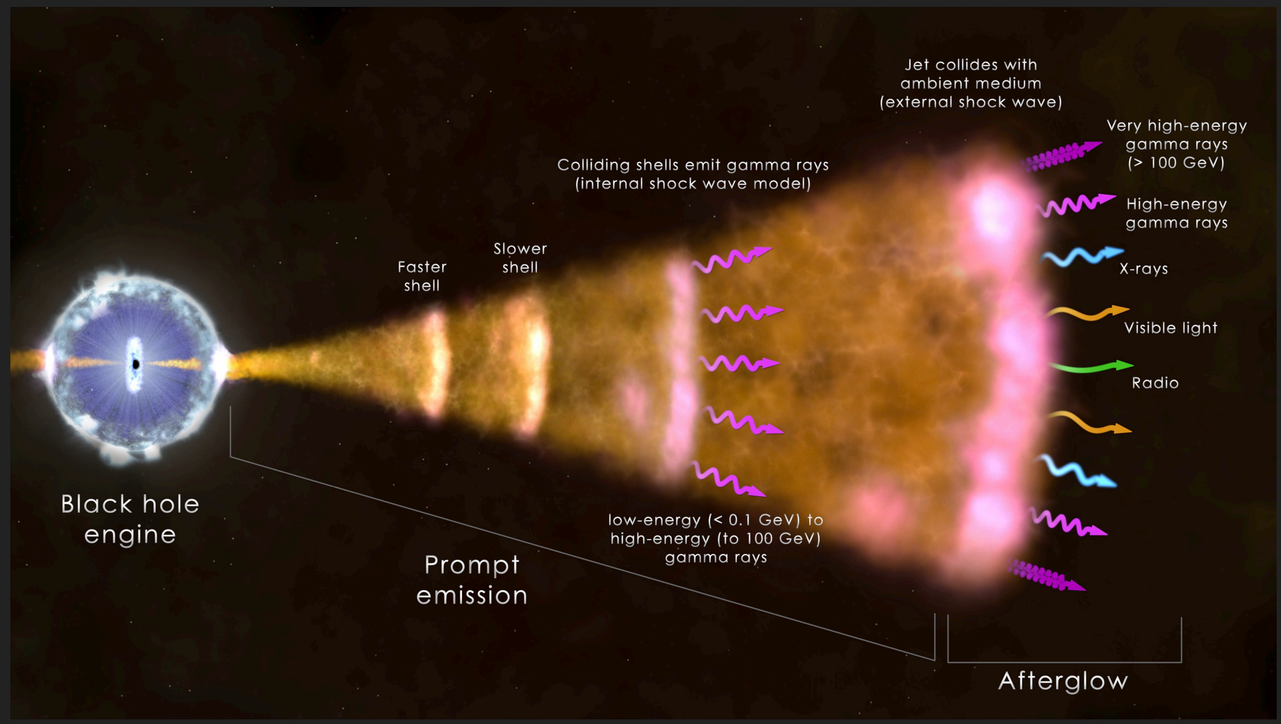
—> **No conclusion about SBGs being the sources of UHECRs**

GAMMA-RAY EXTRAGALACTIC SOURCES IN THE TEV REGION

- **Active Galactic Nuclei (AGNs):** galaxies hosting a compact region at the center that has a much-higher-than-normal luminosity, due to an **accreting black hole**

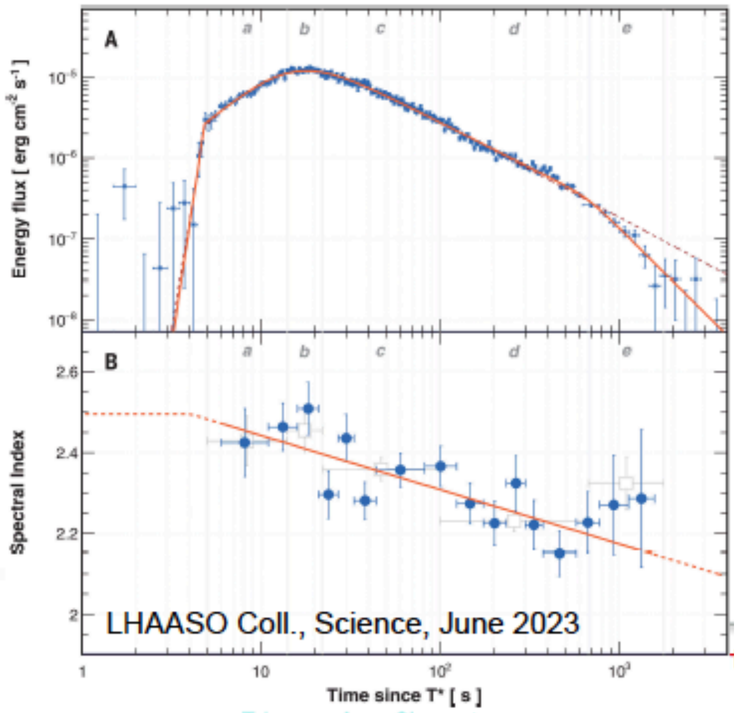


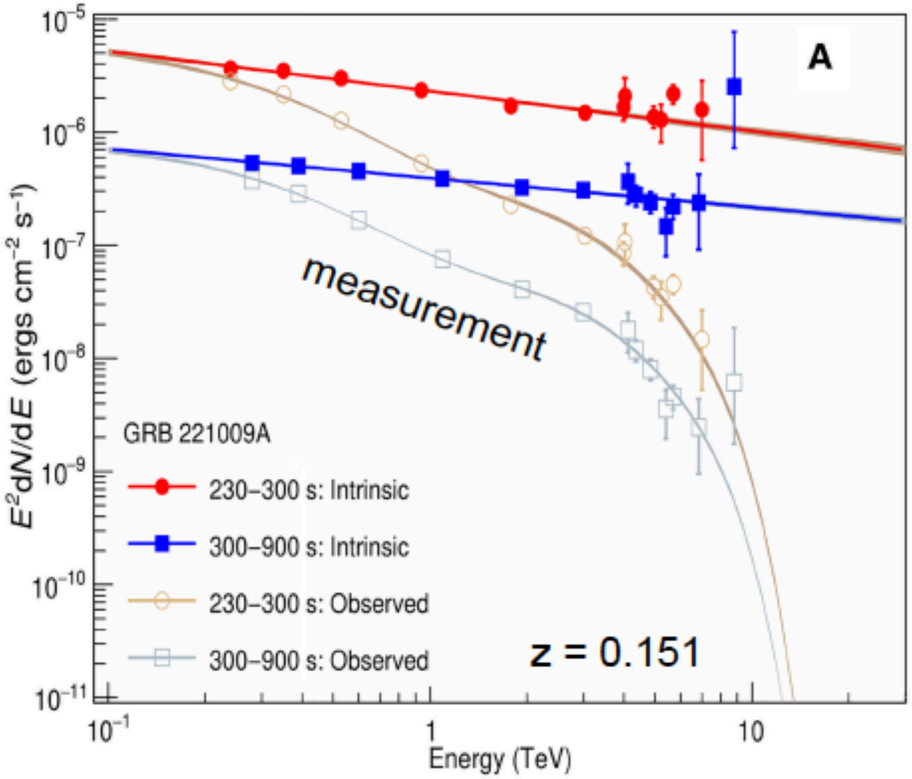
- **Gamma-ray bursts GRBs:** Transient Phenomena ! "Long GRBs" (30 secs) and "Short GRBs" (0.3 secs)



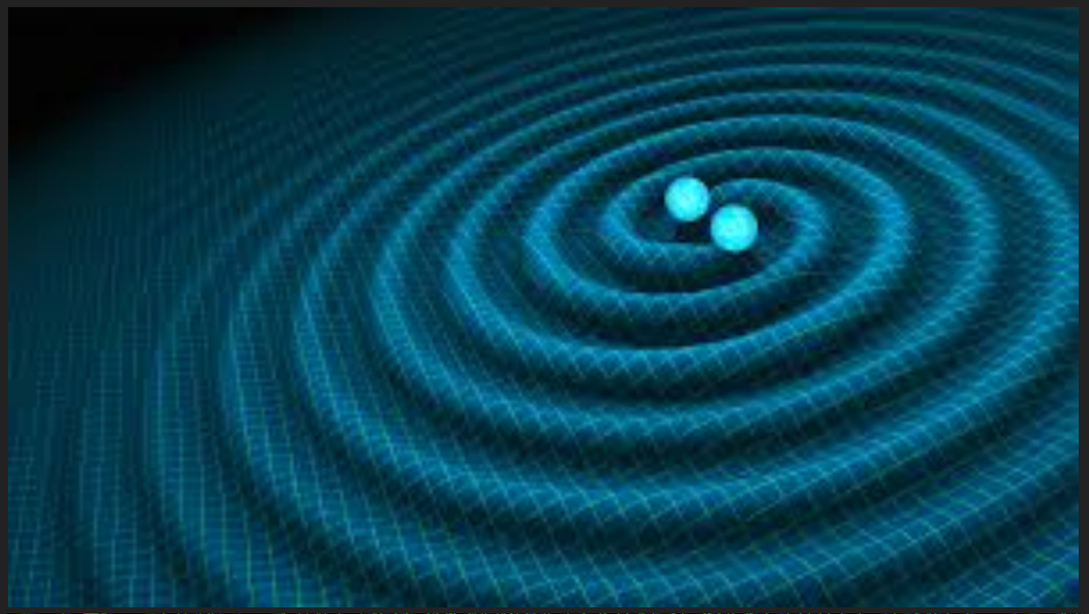
GRB 221009A - The Brightest Of All Times

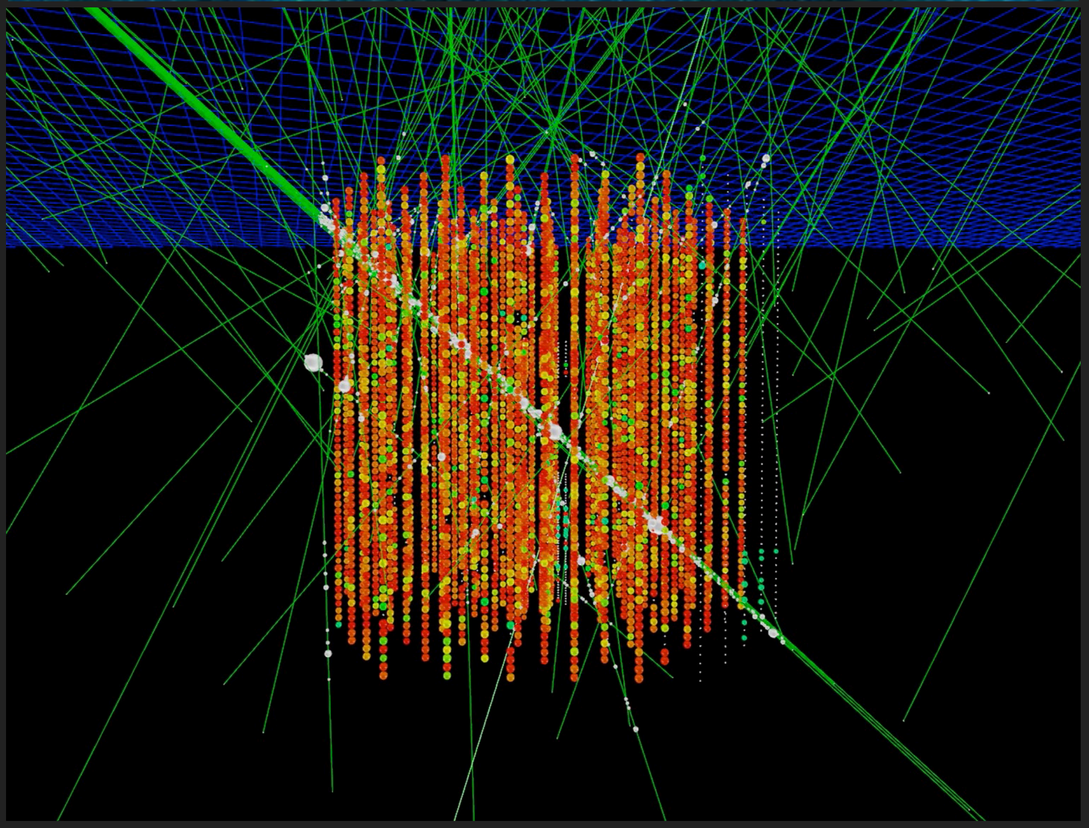
- LHAASO detection >10 TeV
- ~3000 s after the trigger, >64,000 photons with energies between ~200 GeV and ~7 TeV
- EBL absorption by >2 orders of magnitude





LHAASO Coll., Science, Nov 2023





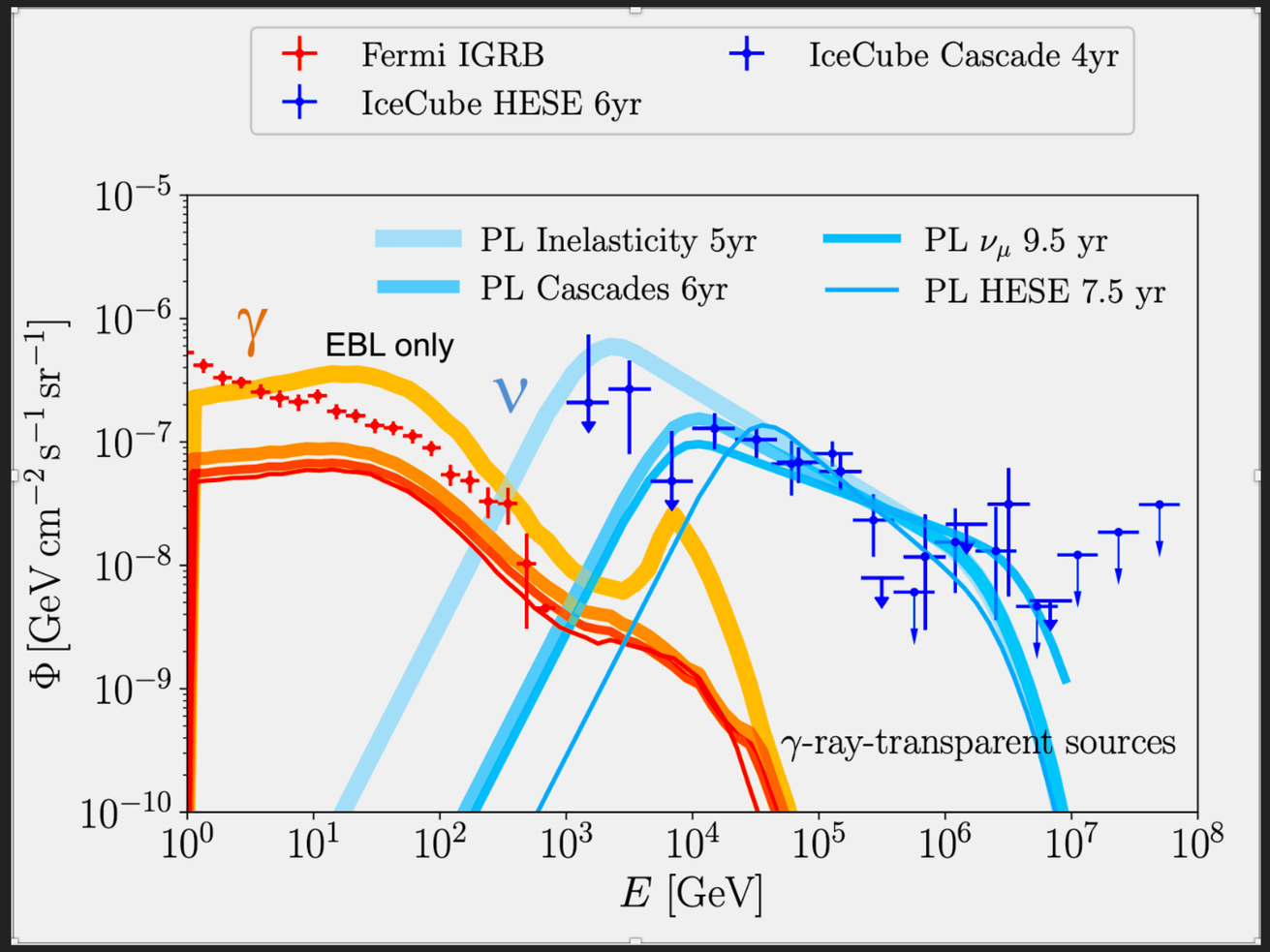
MULTIMESSENGER ASTROPHYSICS

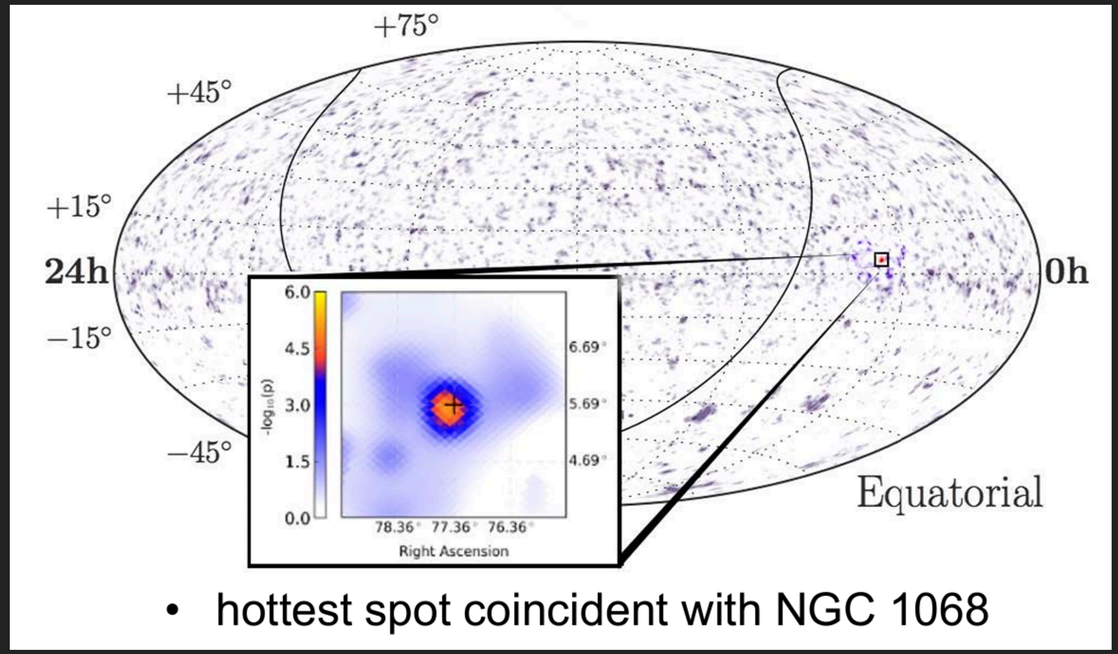
Highlights:

1. A neutrino diffuse flux
2. Multimessenger detections

NEUTRINO SKY

A **diffuse neutrino flux was finally measured**: most of the sources contributing to the diffuse flux must be **obscured to gamma rays**





80 high-energy neutrinos from the direction of the **active galaxy NGC 1068 (a Seyfert 2 type)**

MULTIMESSENGER EVENT: THE CASE OF GW 170817 (08/2017)

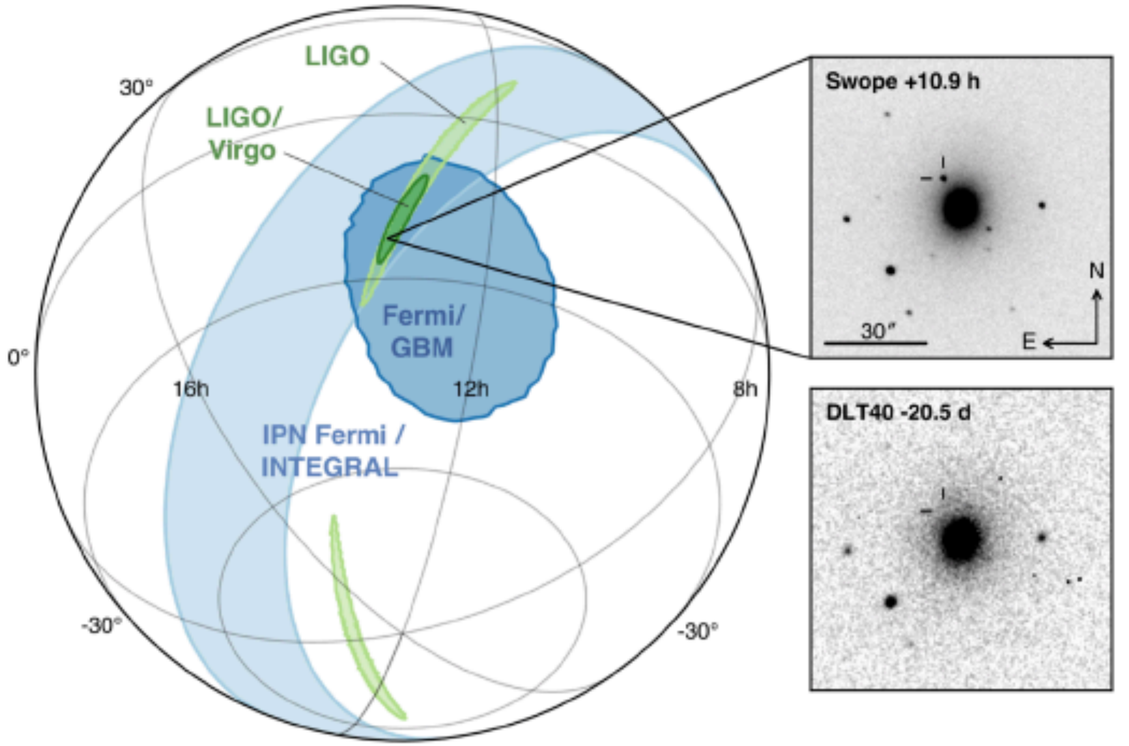
On August 17th, 2017 LIGO and Virgo reported the detection of GWs from the coalescence of a binary neutron star system

Fermi GBM independently detected the sGRB GRB170817A, 1.7s later

An extensive observational campaign localised SGRB in the early type NGC 4993, at d ~ 40 Mpc

GW170817 and GRB170817A confirm binary neutron stars as progenitors of SGRBs (p_{chance} ~10^{-8})

LIGO, Virgo, Fermi Coll+ many others, Astrophys.J. 848 (2017) no.2, L12

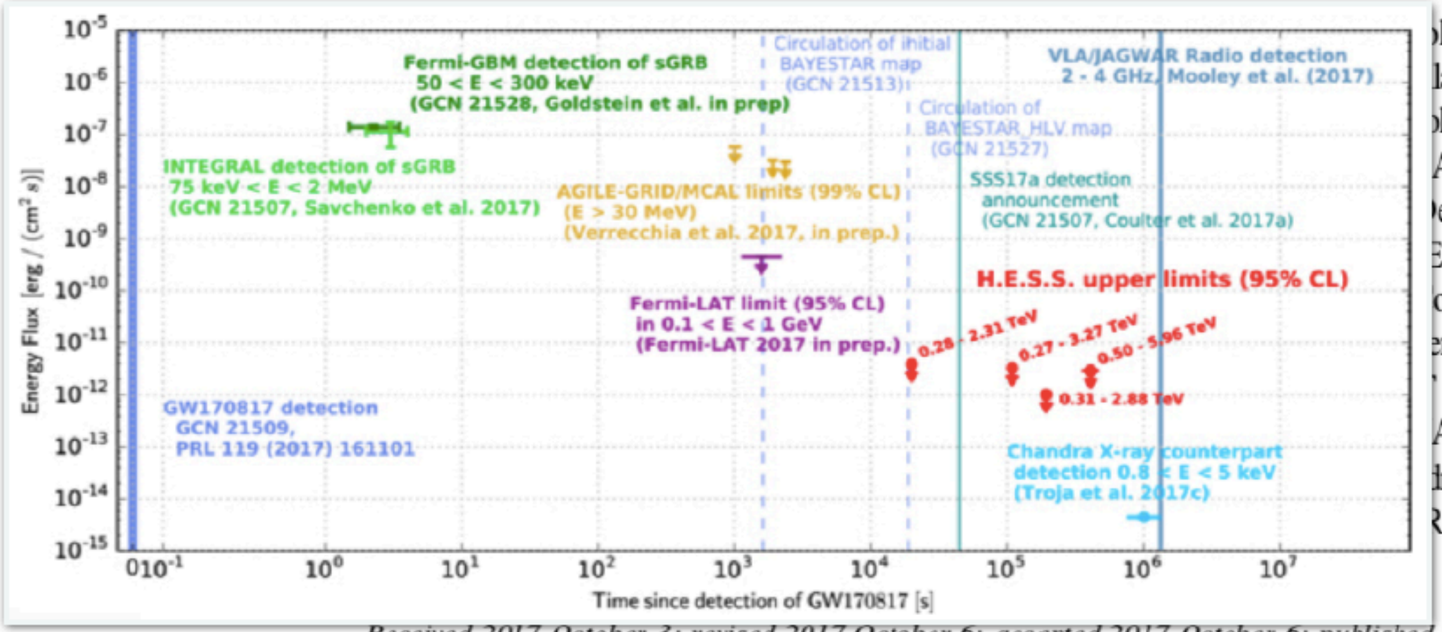


MULTIMESSENGER EVENT: THE CASE OF GW 170817

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20

OPEN ACCESS

Multi-messenger Observations of a Binary Neutron Star Merger*



llaboration, AstroSat Cadmium Zinc
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ATCA: Australia Telescope Compact
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EM, GROWTH, JAGWAR, Caltech-
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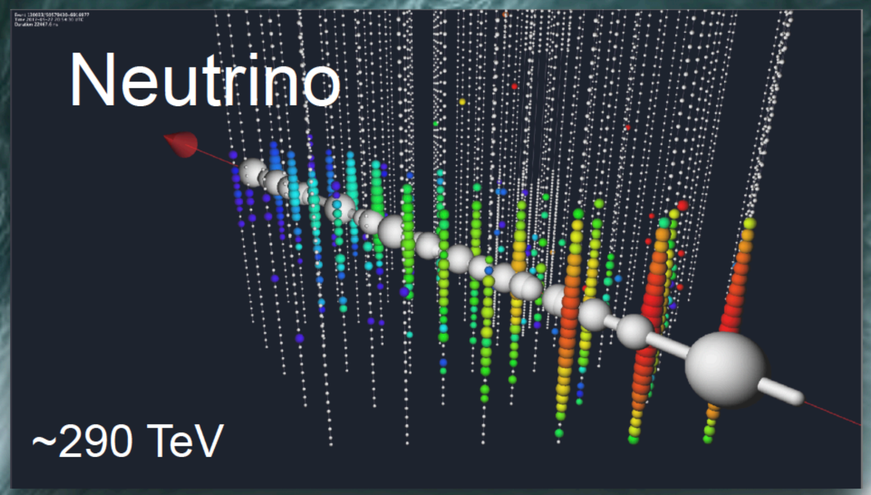
Collaboration, IKI-GW Follow-up
AWC Collaboration, The Pierre Auger
ra Team at McGill University, DFN:
R, and SKA South Africa/MeerKAT

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

A remarkable example of international collaboration!

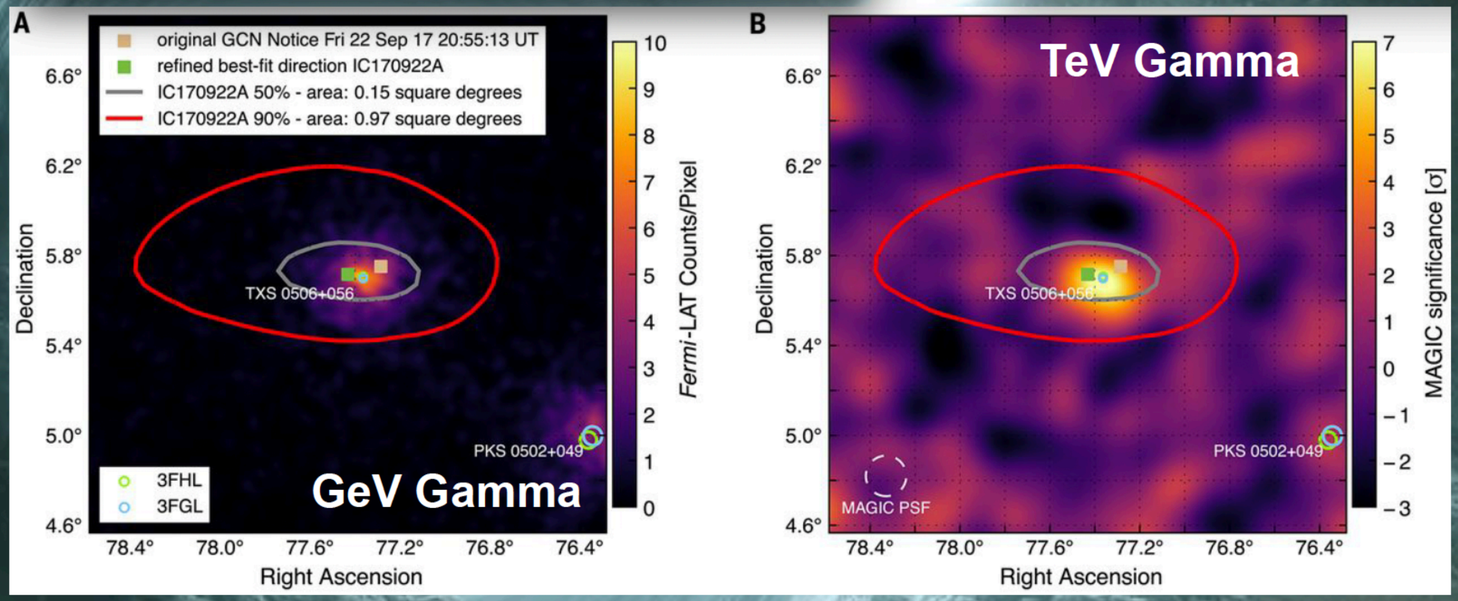
>3500 authors
>70 observatories

MULTIMESSENGER EVENT: THE CASE OF TXS 0506+056 (09/2017)



A high-energy astrophysical neutrino in conjunction with a flaring blazar

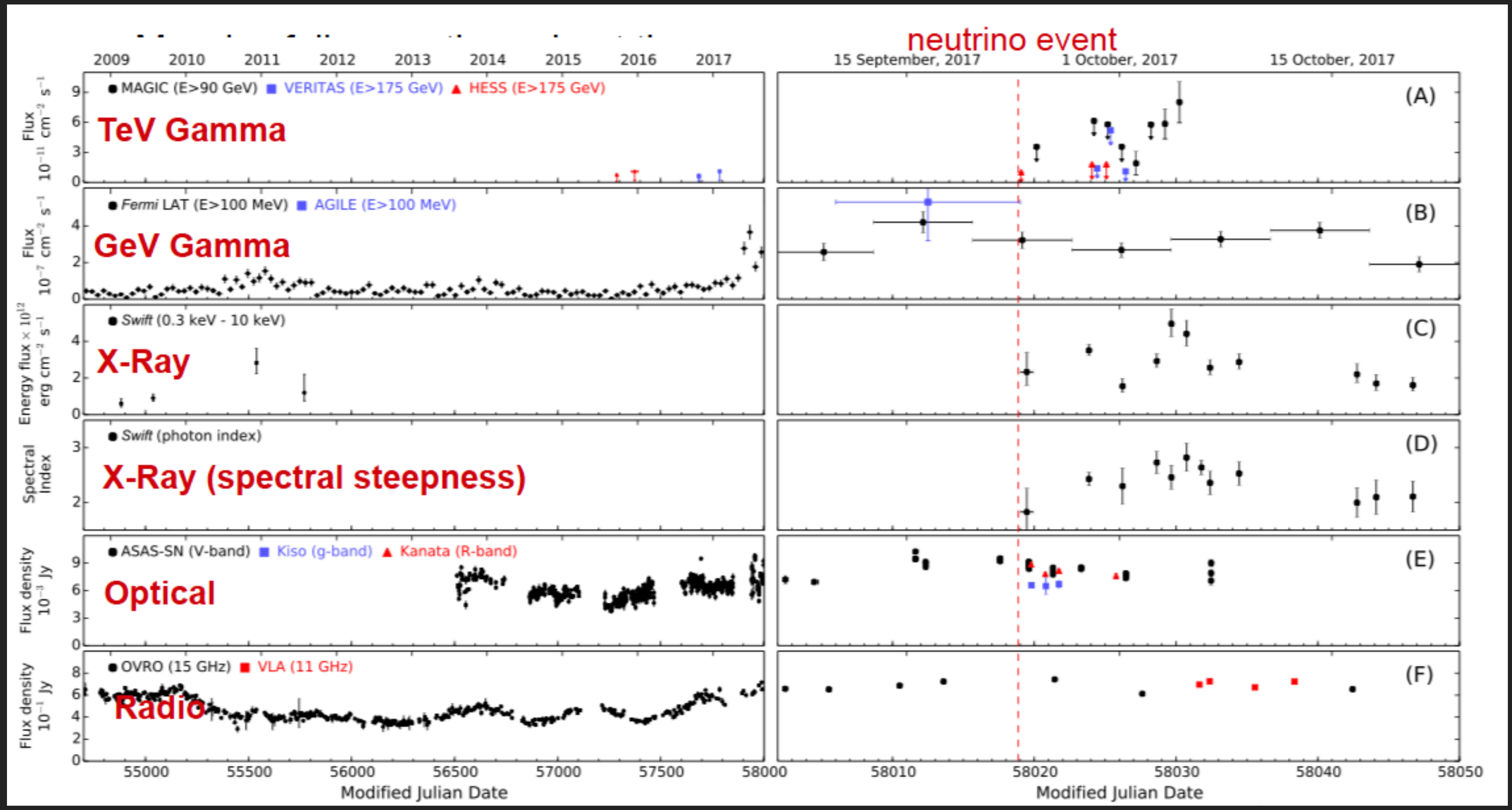
- 4.1 σ (3 σ after trials) correlation
- First known source of HE neutrinos (& first extragalactic source of cosmic rays)



Beginning of neutrino multi-messenger astronomy

… together with a TeV detection!

MULTIMESSENGER EVENT: THE CASE OF TXS 0506+056



CONCLUSIONS: A REVOLUTION IN THE LAST 15 YEARS!

The field of high energy astrophysics has been probably **the most prolific of discoveries in the last 15 years,** thanks to **experiments and observatories of unprecedented capabilities** and a much refined theoretical framework;

I. **Direct detection results** have created a picture of CRs in the Galaxy with a wealth of new insights in CR transport and acceleration;

II. At the same time, **gamma ray telescopes** have led to the detection of sources in 10-100 TeV and to Pevatrons;

III. We have acquired a picture of the **UHECR universe** that starts to be coherent;

IV. The **HE neutrino universe** has now finally been revealed, and the first thing that popped out is a diffuse flux with possible sources;

V. Finally, we started a very efficient **multi-messenger approach** towards astroparticle phonemena.

The implications of astroparticle physics go much beyond astrophysics:

they touch particles & cosmology and - therefore - fundamental physics !