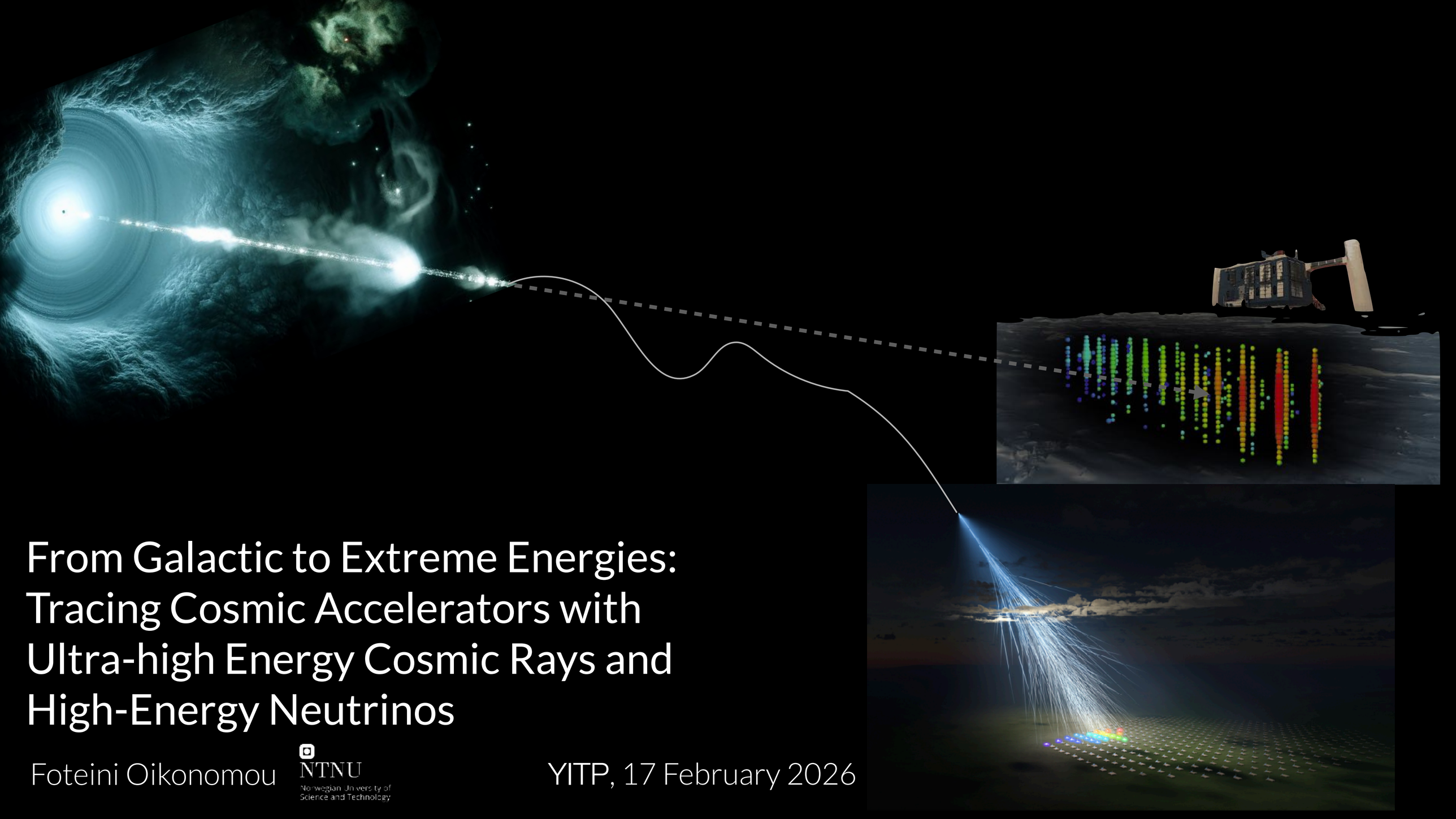


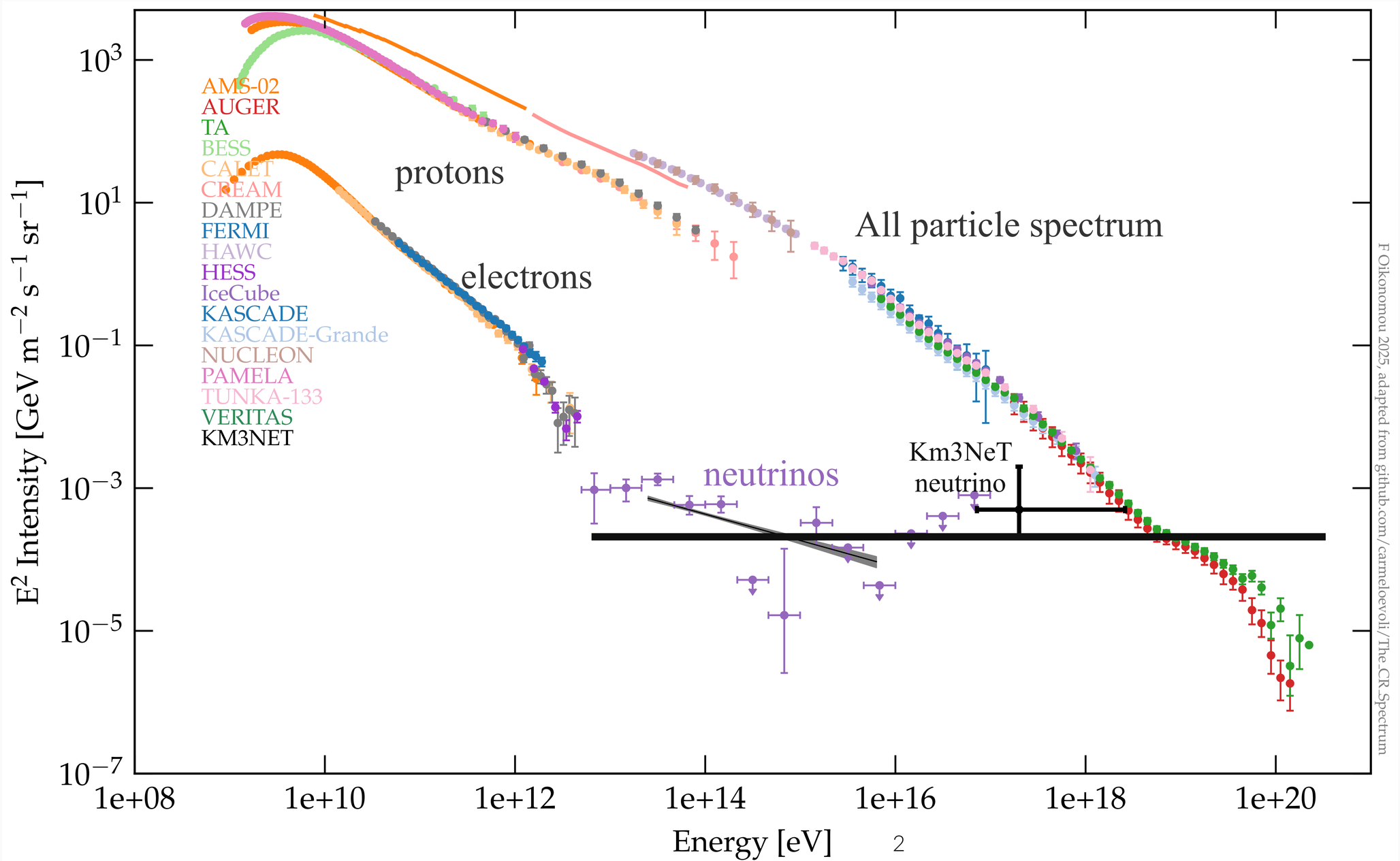
From Galactic to Extreme Energies: Tracing Cosmic Accelerators with Ultra-high Energy Cosmic Rays and High-Energy Neutrinos

Foteini Oikonomou

NTNU
Norwegian University of Science and Technology

YITP, 17 February 2026

Diffuse Particle Spectrum



High-energy messengers

$E > 10^{20}$ eV, $D \sim$ 10-100 Mpc

UHECRs

$$\langle\theta\rangle_{\rm GMF} \sim 3^\circ \times Z \times \left(\frac{E}{10^{20}\ {\rm eV}}\right)^{-1}$$

γ-rays

Hadronic: $p/A + \gamma_{\rm CMB/source} \rightarrow X + \pi^0 \rightarrow 2\gamma$

Leptonic: $e^- + \gamma \rightarrow e^- + \gamma$

$E \lesssim 10^{16}$ eV, $D \sim$ 10 kpc (Galactic)

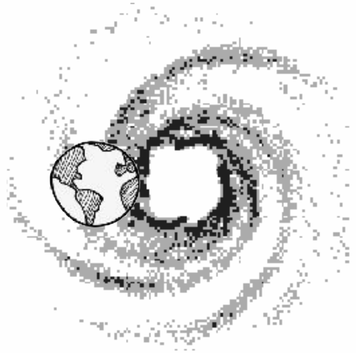
$p/A + \gamma_{\rm CMB/source} \rightarrow X + \pi^+ \rightarrow 3\nu$

$E < 10^{17}$ eV, $D >$ Gpc (cosmological)

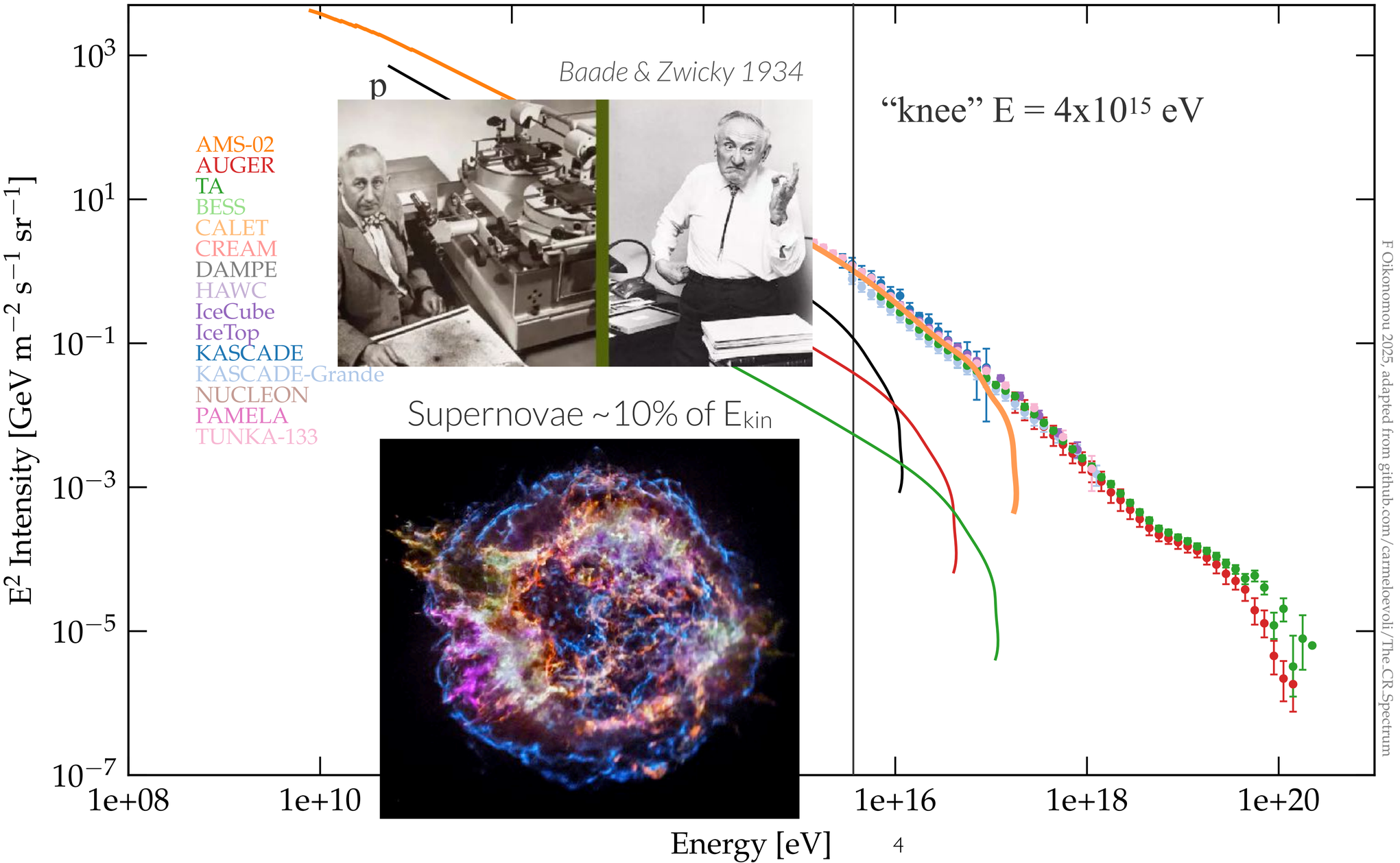
ν

Energy: $E_{CR} : E_\nu : E_\gamma$

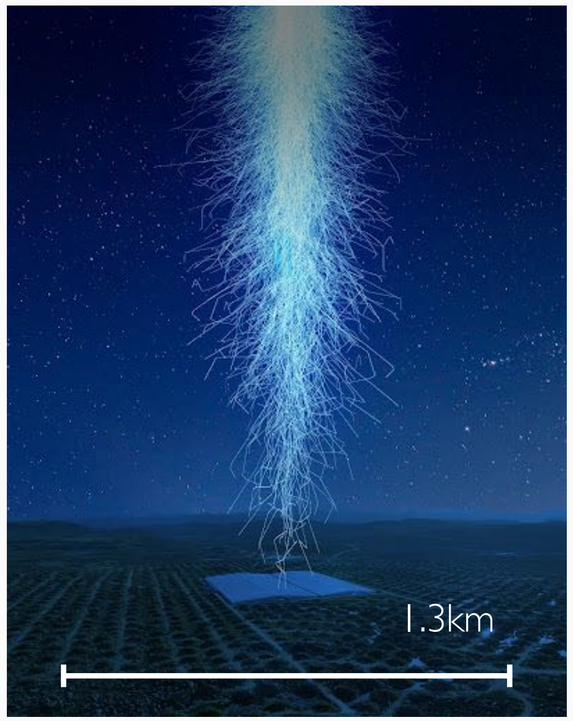
$20 : 1 : 2$

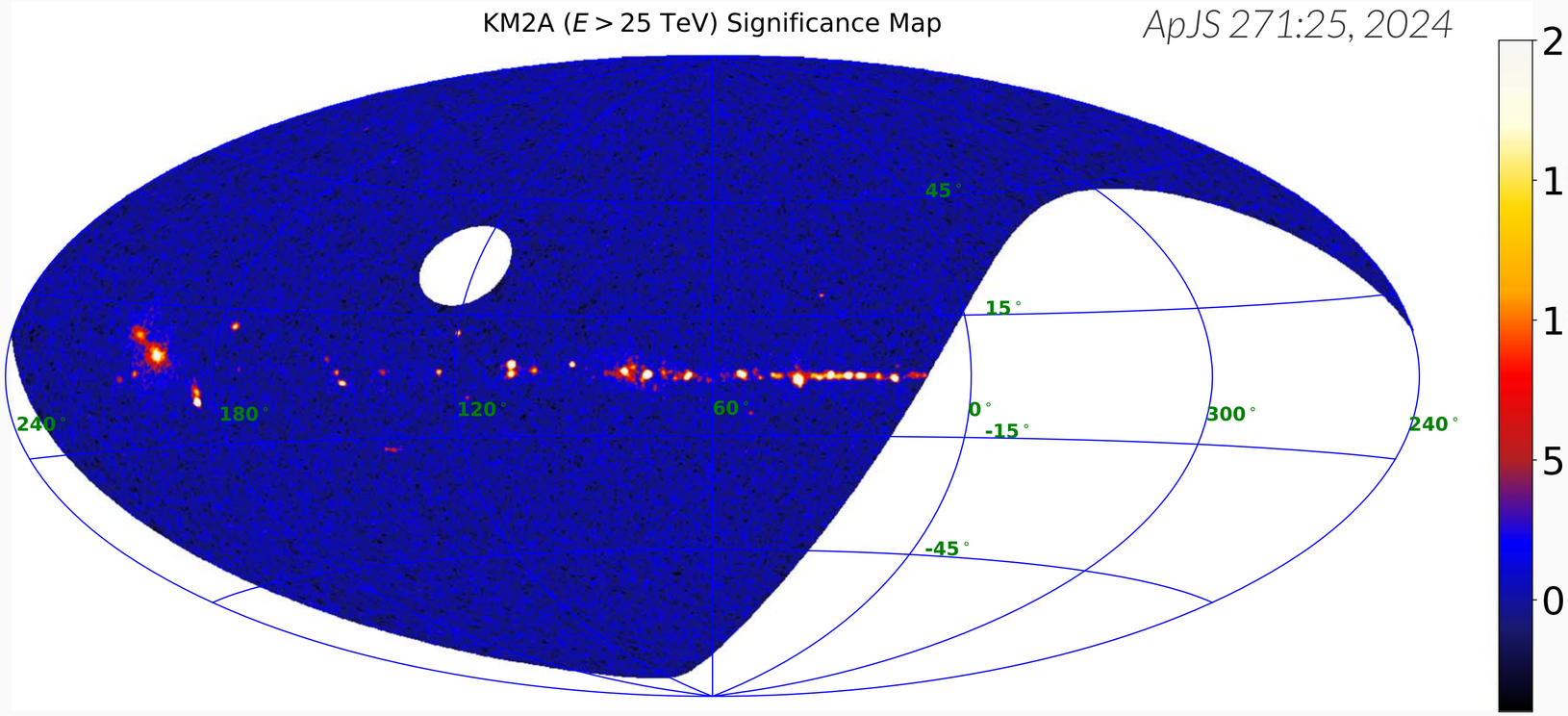


Galactic Cosmic Rays



Learning from Galactic gamma-rays: 1st LHAASO Catalog





Hadronic

$E_{CR} : E_\gamma$

10 : 1

Leptonic

$E_e \sim O(E_\gamma)$

HAWC: 0.1km^2 (2015-)
LHAASO ~1.0 km^2 (2021-)

90 sources, (43 $E_\gamma > 10^{14}$ eV):

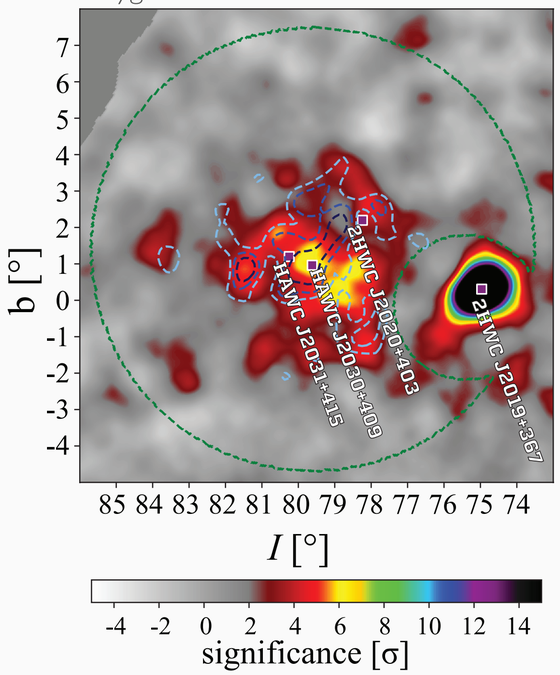
-40% Unidentified sources
- Majority: Pulsar Wind Nebulae (leptonic)
-6 Supernova remnants (old, E < 10^{14} eV)
-2 Young Stellar Clusters, 6 Microquasars

Young Stellar Clusters

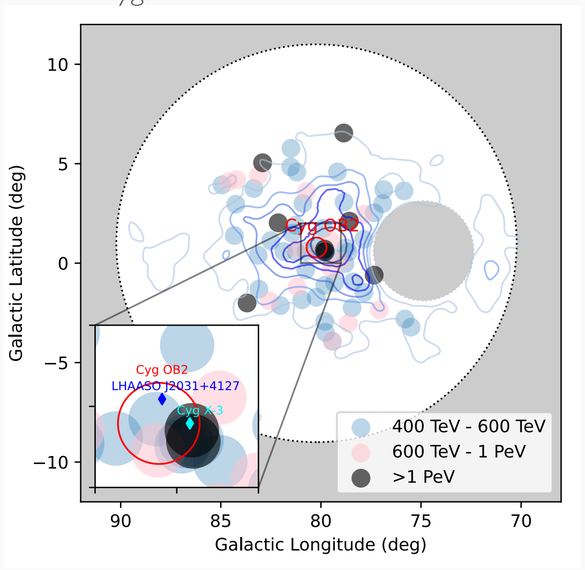
Cygnus OB2: 8 photons with $E_\gamma > 10^{15}$ eV in bubble
W43: $E_\gamma > 4 \times 10^{14}$ eV

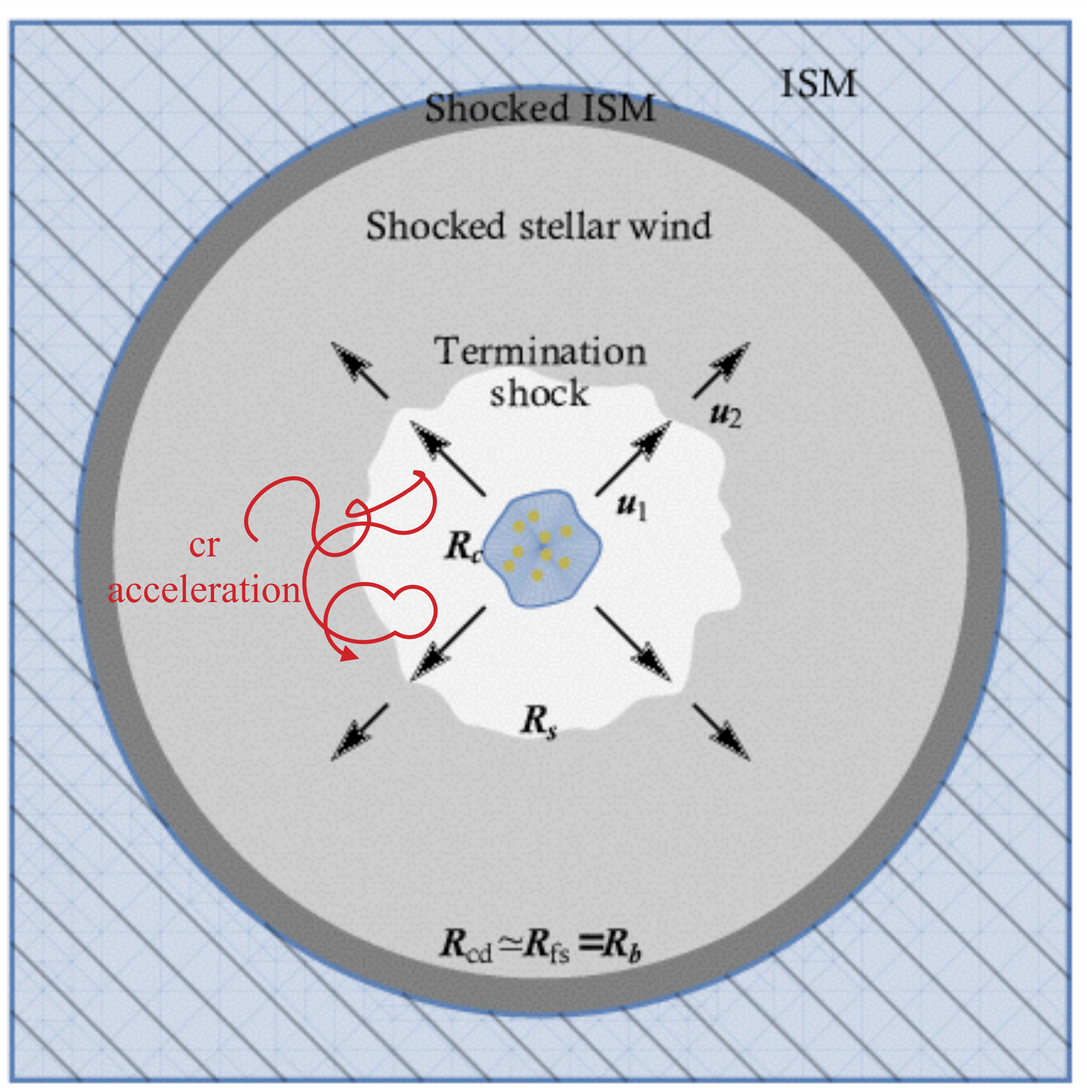
3 consistent with HESS GC: $E_\gamma > 4 \times 10^{14}$ eV
Several more seen with IACTs and Fermi-LAT

Cygnus Cocoon HAWC Coll 2020



Cygnus Cocoon LHAASO Coll 2023





Morlino, Blasi et al, MNRAS 504, 2021, 4

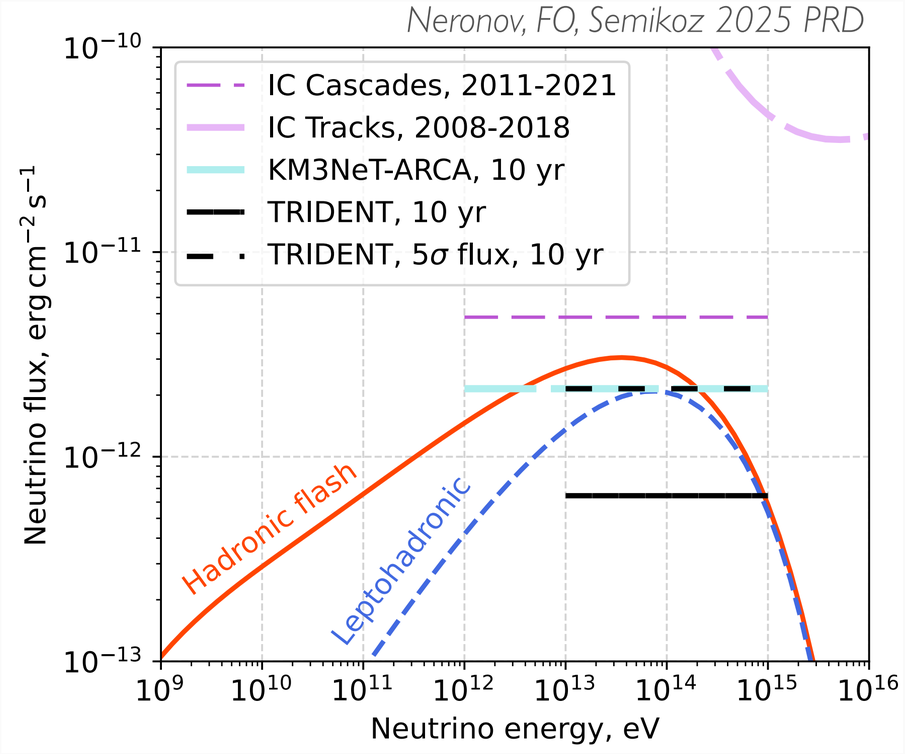
Microquasars

6/12 detected with LHAASO at $E > 10^{14}$ eV

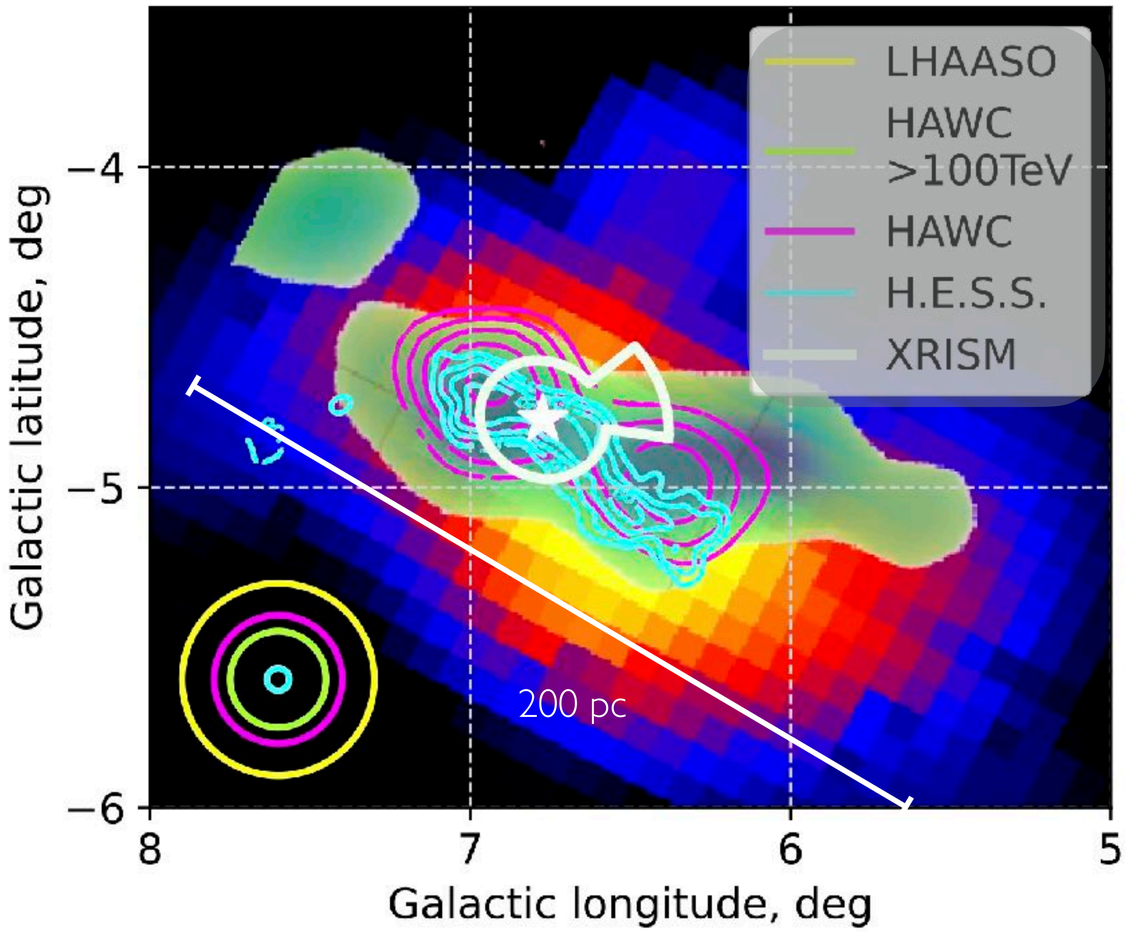
3 extended (jet/wind powered?)

V4641 Sgr: $E_\gamma > 8x10^{14}$ eV (leptonic/hadronic?)

Neronov, FO, Semikoz 2025 PRD

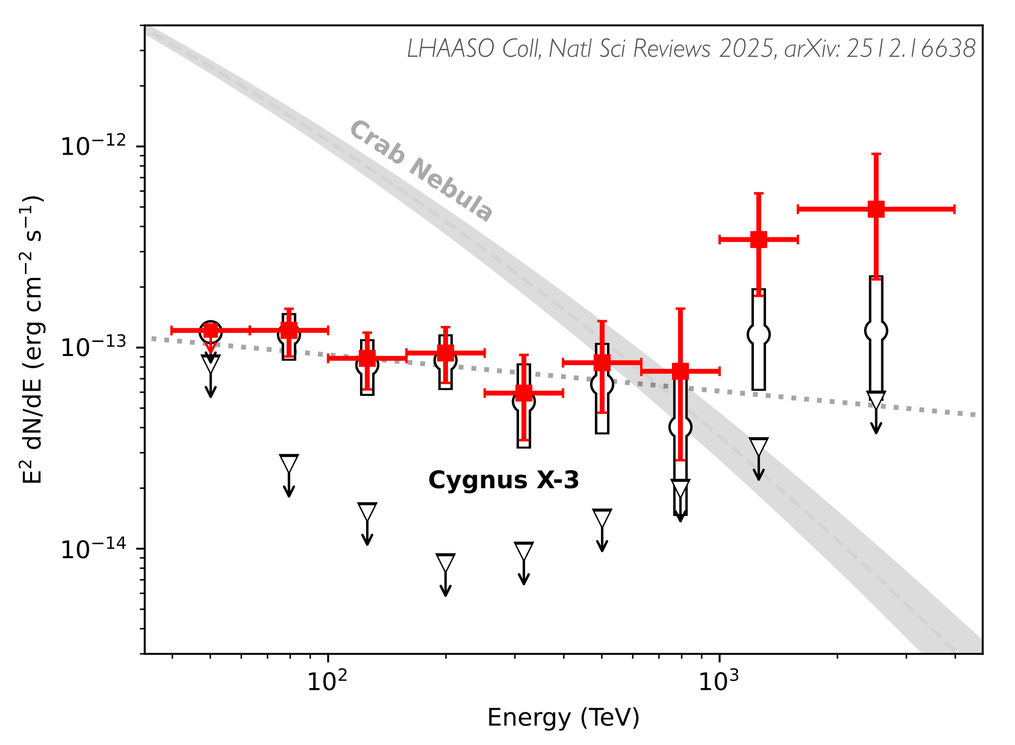


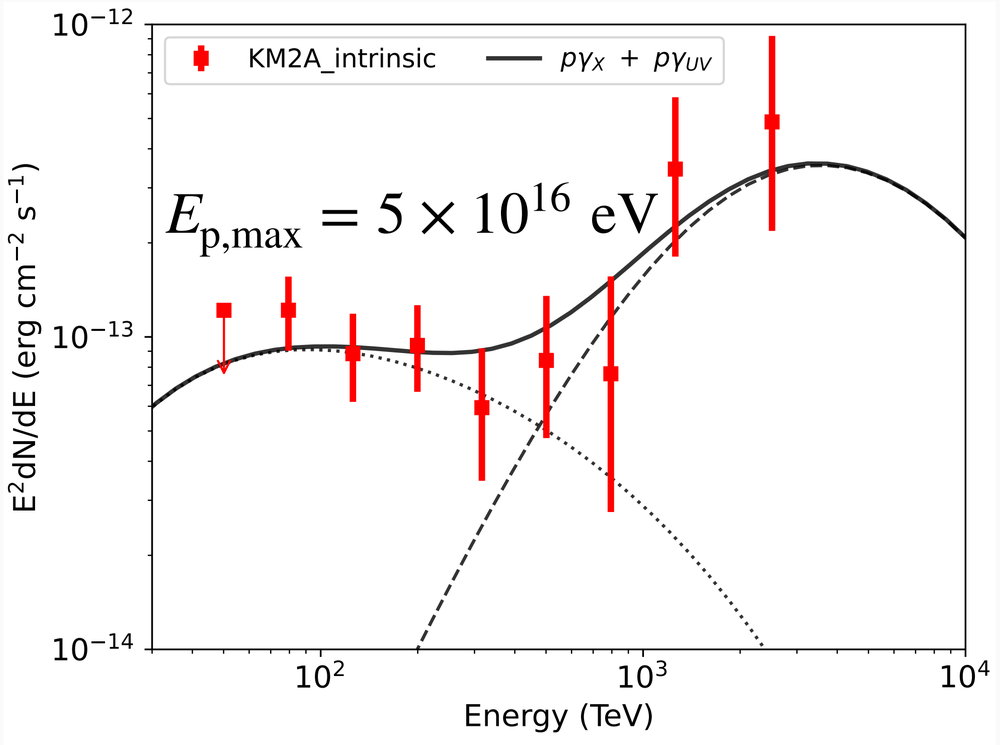
Kleimenov, Neronov, FO, Semikoz,arXiv:2512.13578



V4641 Sgr: *LHAASO Coll arXiv:2410.08988,*
HAWC Coll , Nature 634 (2024) 8034
HESS Coll ApJ 2025
SS 433: *HESS Coll, Science383,402-406(2024)*
HAWC Coll. Nature 562, 82–85 (2018)
Microquasars major at the knee? *Kaci, Giacinti et al 2025,*
Zhang, Kimura, Murase, PRD (2025)

Microquasars: Cyg X-3





E_γ up to 3.7 x10^{15} eV

Transient and compact (jet)

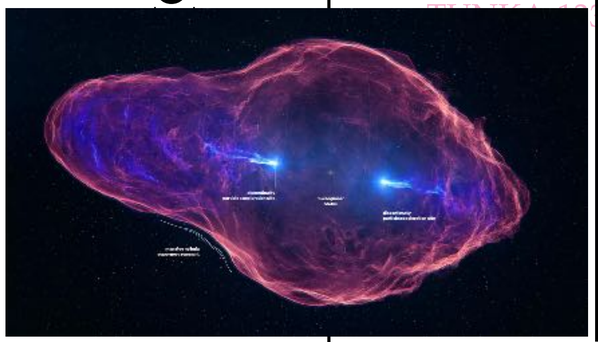
Must be hadronic if as compact

Totally different from V4641 Sgr

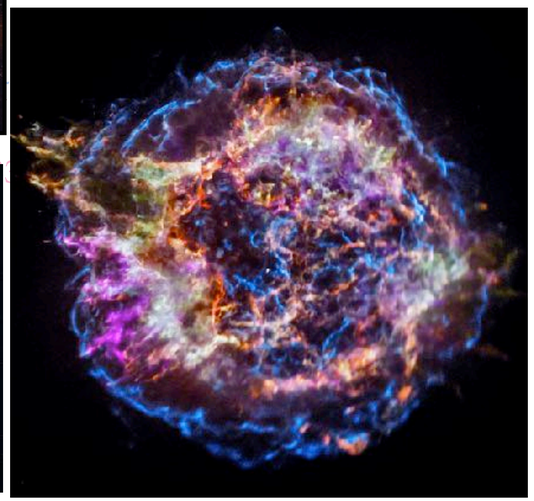
see Wei, Murase, Zhang arXiv:2512.23231 for pp/pγ interpretation

Galactic cosmic rays

Wind bubbles? E_{max} unclear



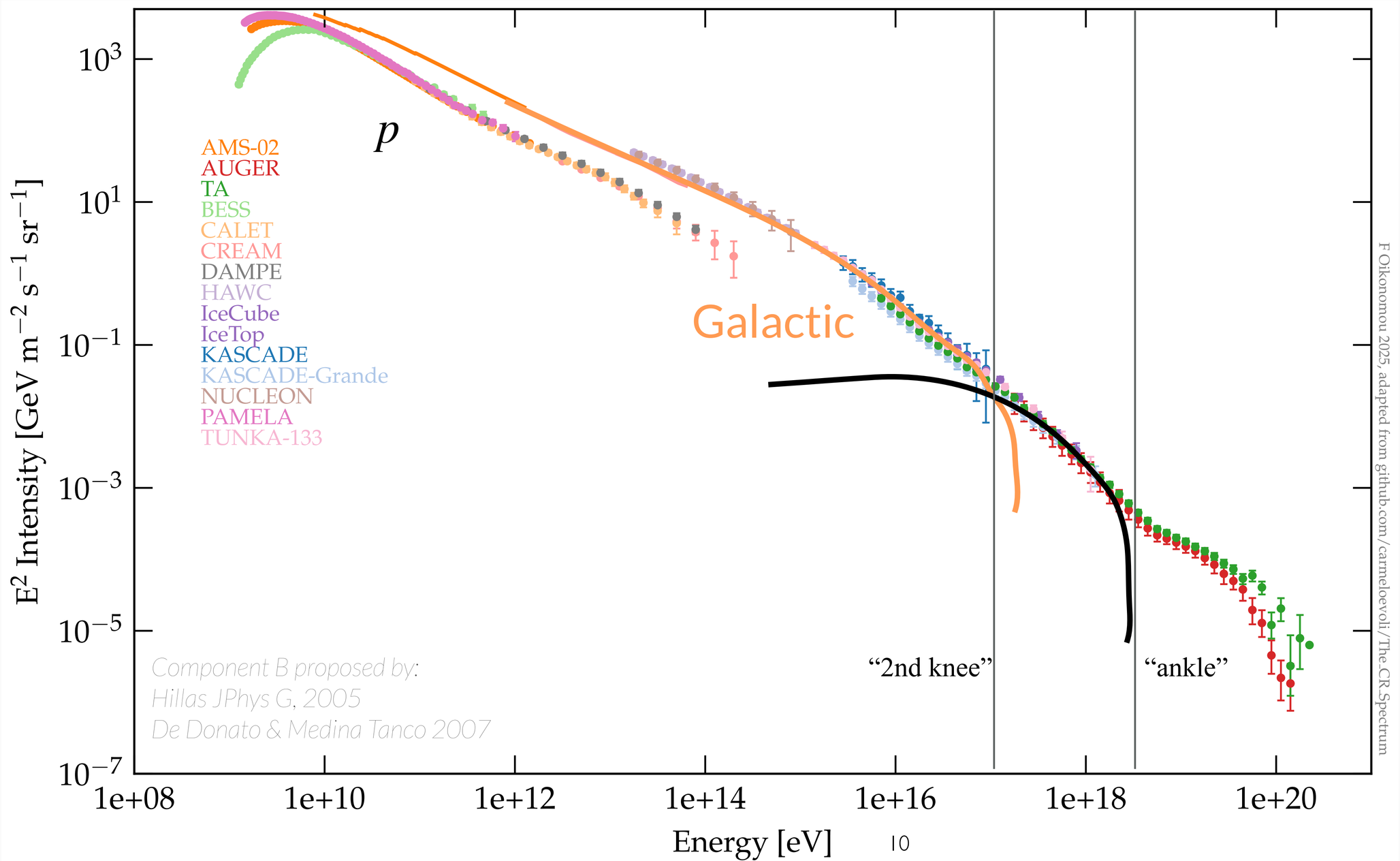
Supernova remnants? E_{max} an issue?



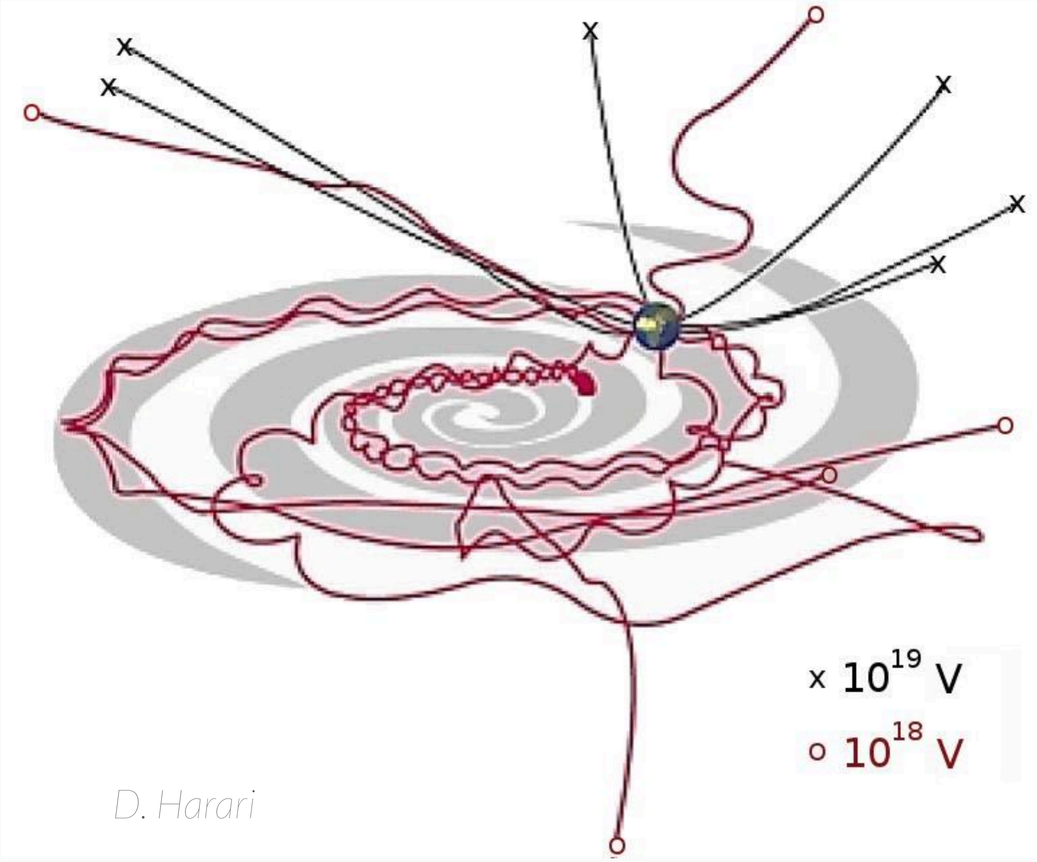
Microquasars? Too few?

F Oikonomou 2025, adapted from github.com/carmeloevoli/The.CR.Spectrum

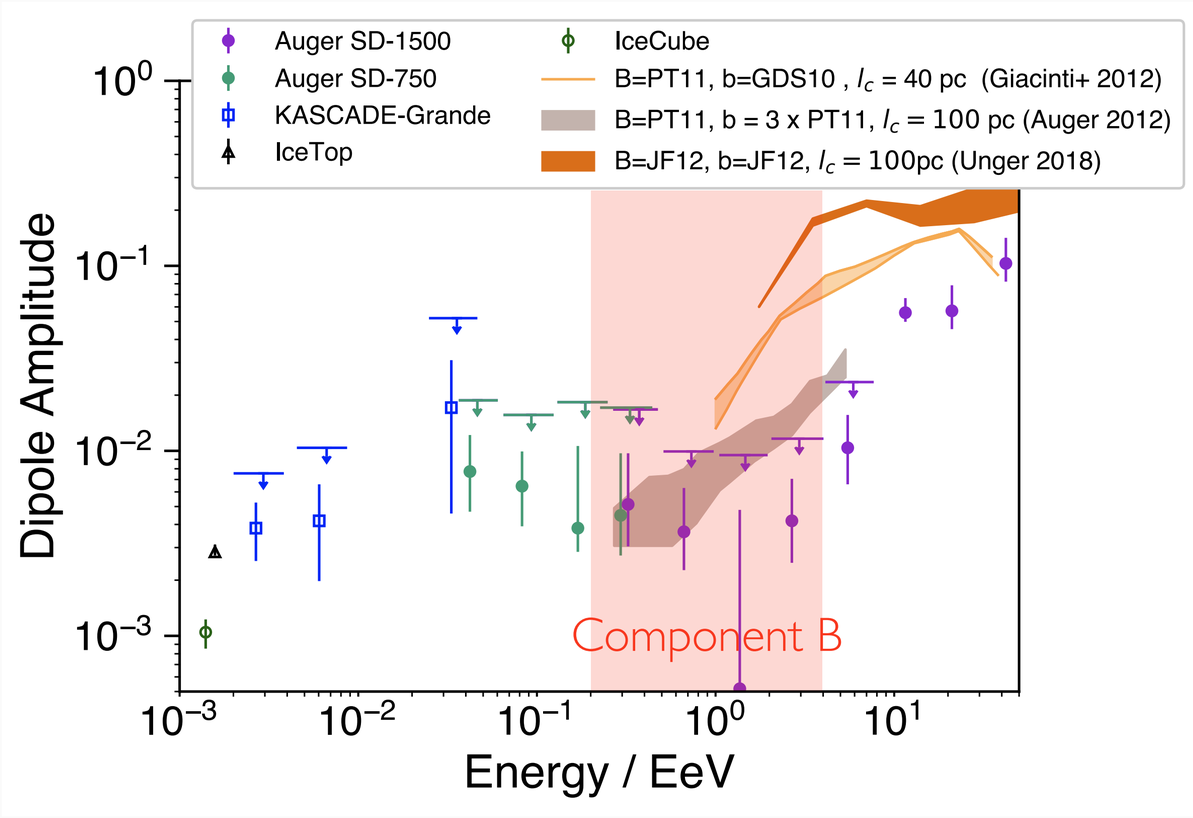
Component B


AMS-02
AUGER
TA
BESS
CALET
CREAM
DAMPE
HAWC
IceCube
IceTop
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
TUNKA-133
p
Galactic
Component B proposed by:
Hillas JPhys G, 2005
De Donato & Medina Tanco 2007
"2nd knee"
"ankle"
E² Intensity [GeV m⁻² s⁻¹ sr⁻¹]
Energy [eV]
10³
10¹
10⁻¹
10⁻³
10⁻⁵
10⁻⁷
1e+08
1e+10
1e+12
1e+14
1e+16
1e+18
1e+20
F Oikonomou 2025, adapted from github.com/carmeloevoli/The.CR.Spectrum

Origin of Component B: Extragalactic?



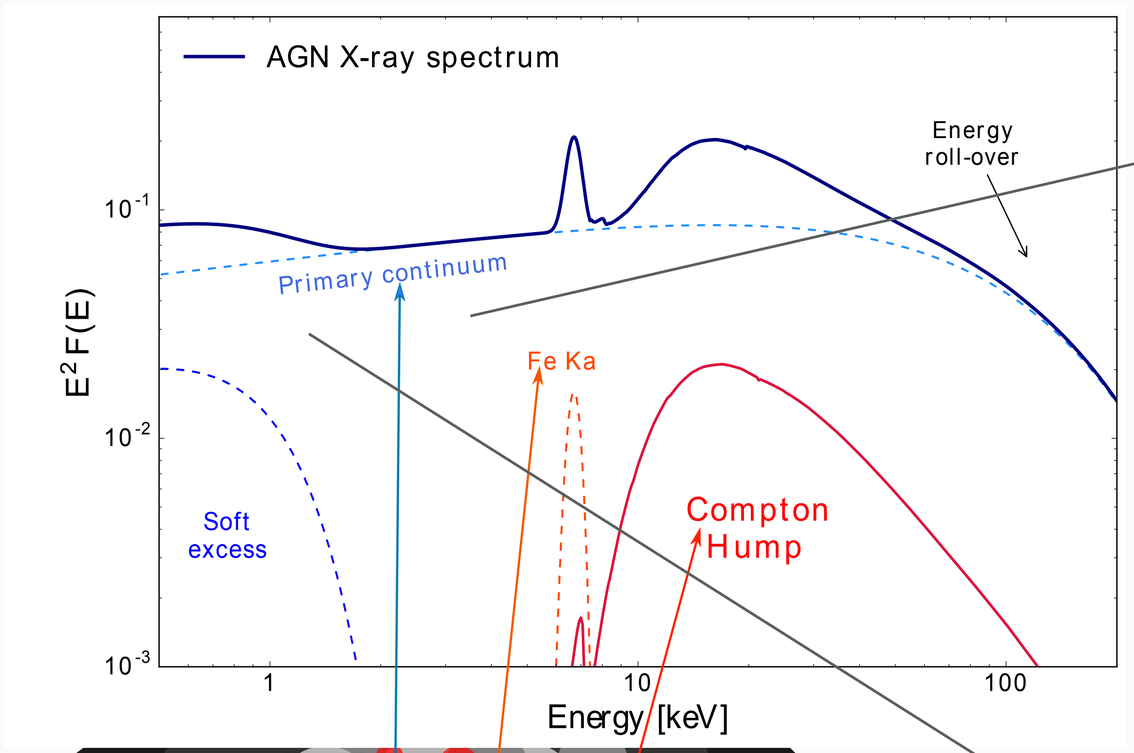
Models of 30% Galactic Carbon

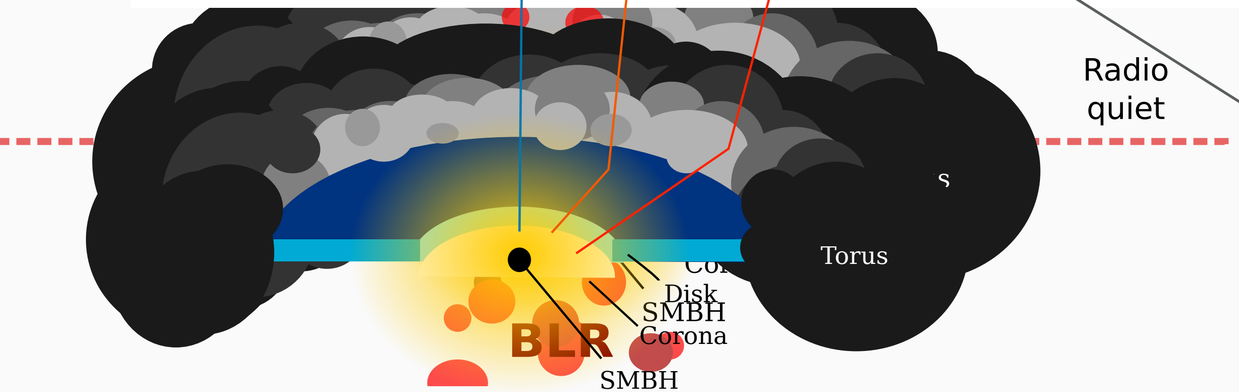


Models assume **population of Galactic sources**
For **single Galactic source**, see e.g. Farrar PoS(ICRC 2021)488

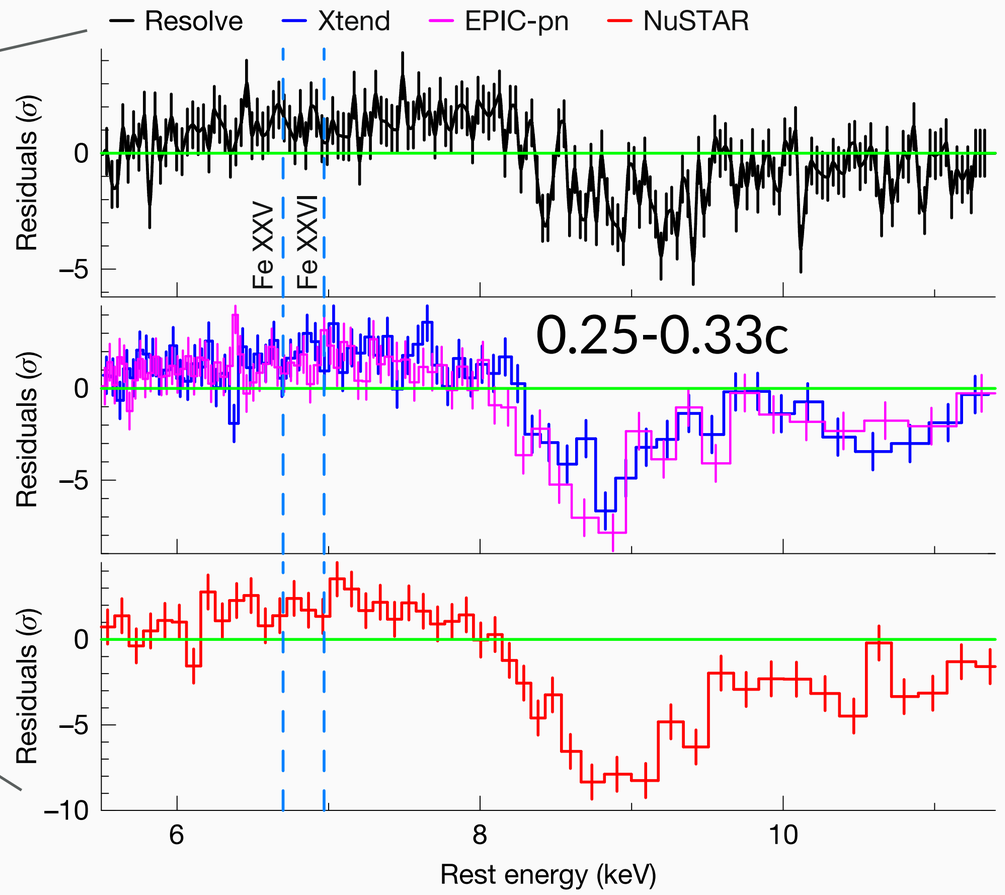
11

Wind bubbles in Active Galactic Nuclei





XRISM Coll, Nature, 2025



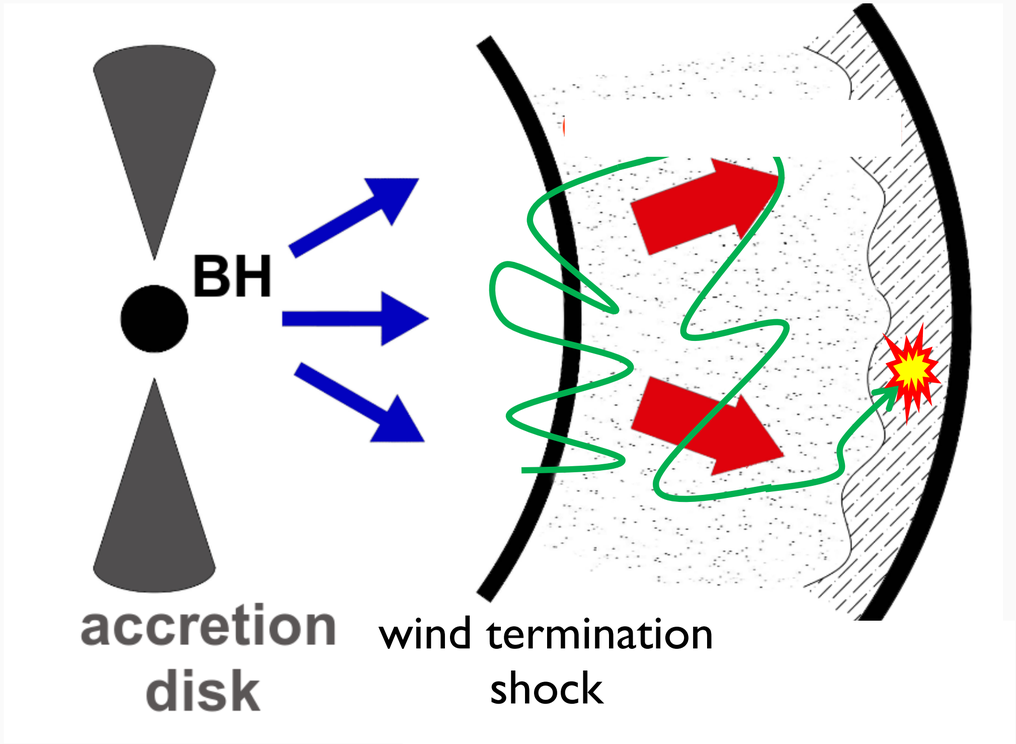
Observed in 30-60% of non-jetted and jetted AGN

(Tombesi et al 2010, 2014, Giannoli 2024)

Cosmic-ray acceleration in AGN Wind Bubbles

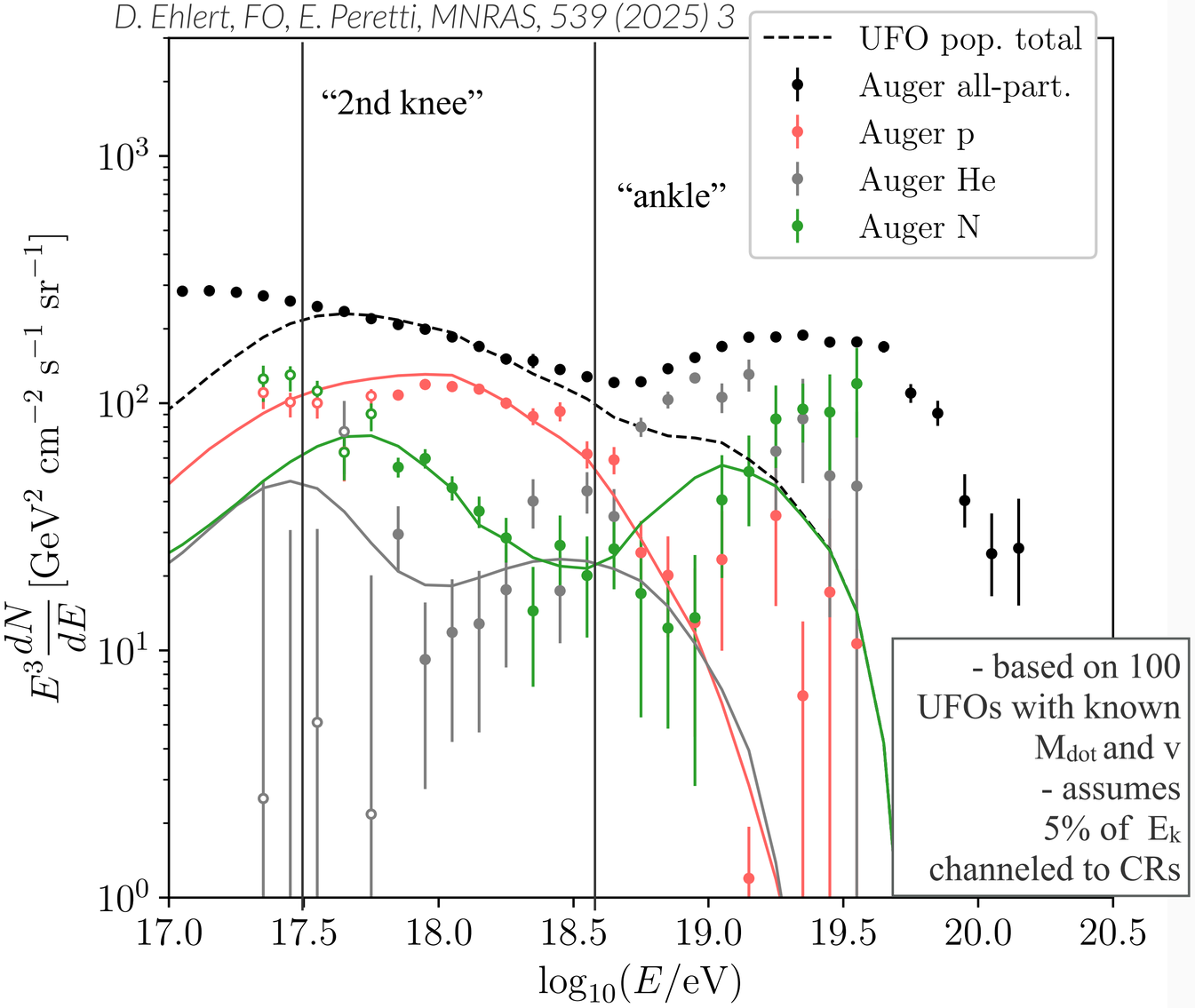
Faucher-Giguere and Quataert 2012,

Peretti, Lamastra, Saturni, Ahlers, Blasi, Morlino & Cristofari 2023

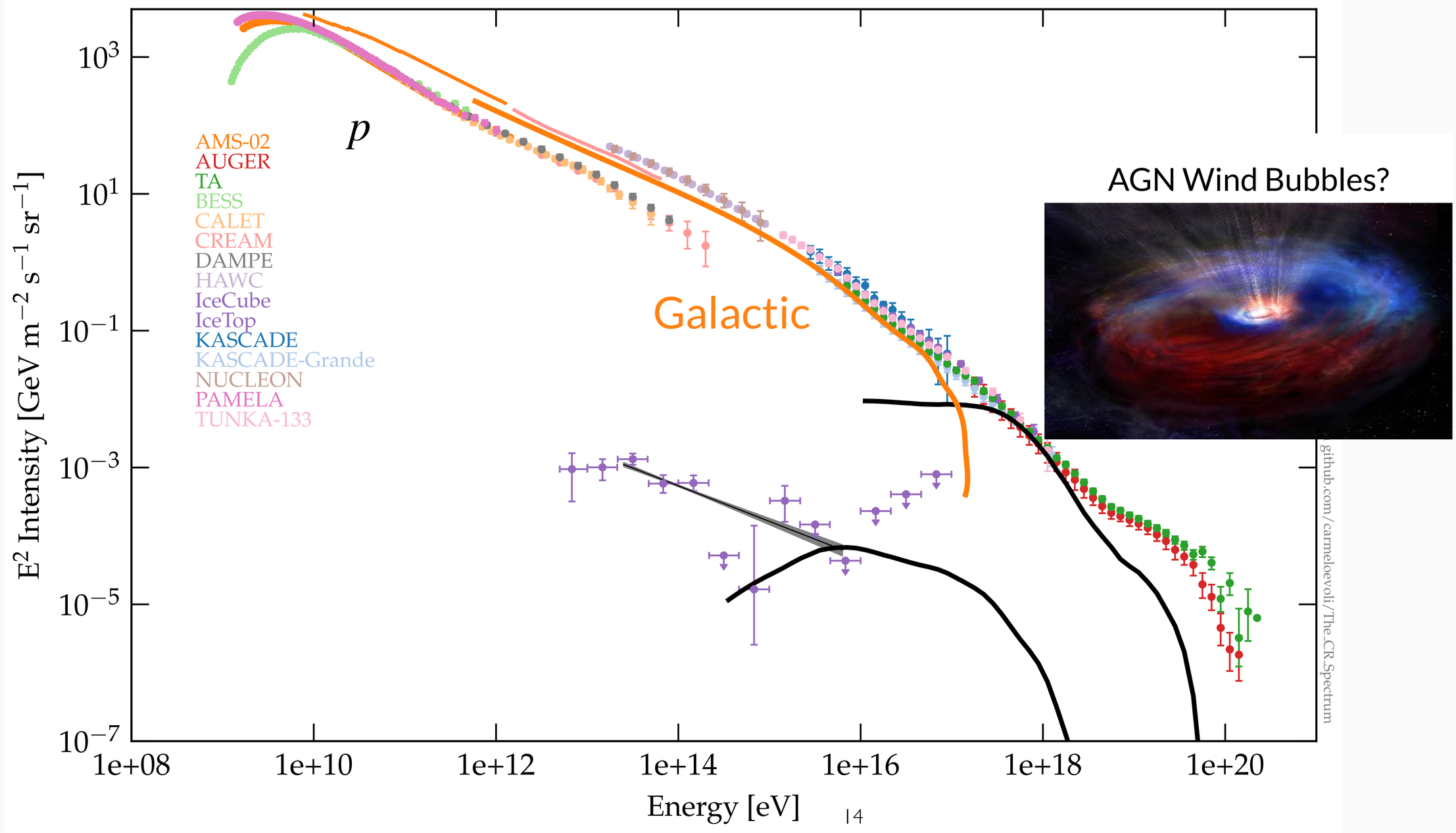


$$E_{p,\max} \sim 1\ \mathrm{EeV} \left(\frac{\dot{M}}{0.1\ M_\odot\ \mathrm{yr}^{-1}} \frac{1\ \mathrm{pc}}{R_{\mathrm{shock}}} \right)^{1/2} \frac{v_{\mathrm{UFO}}}{0.2c}$$

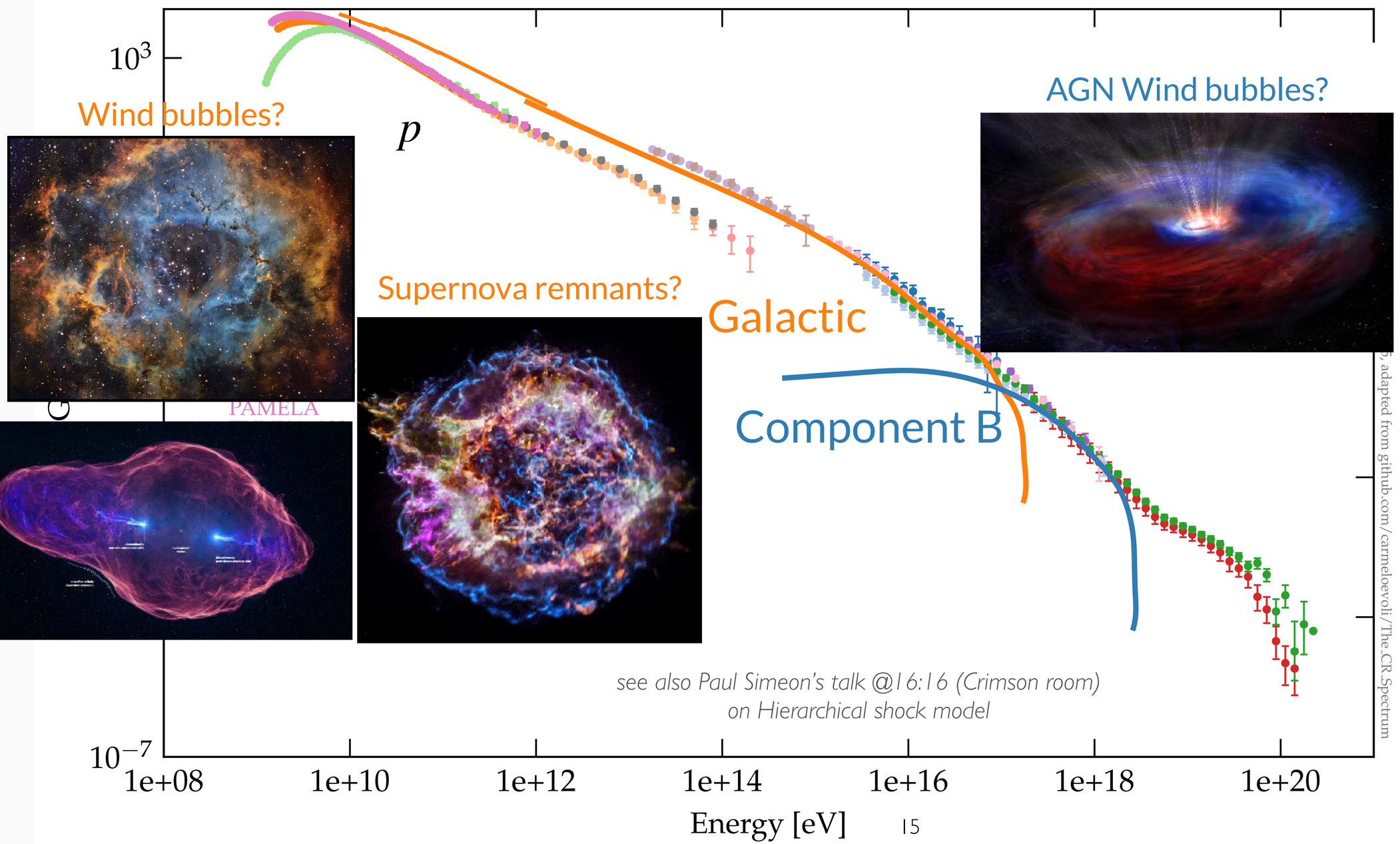
D. Ehlert, FO, E. Peretti, MNRAS, 539 (2025) 3



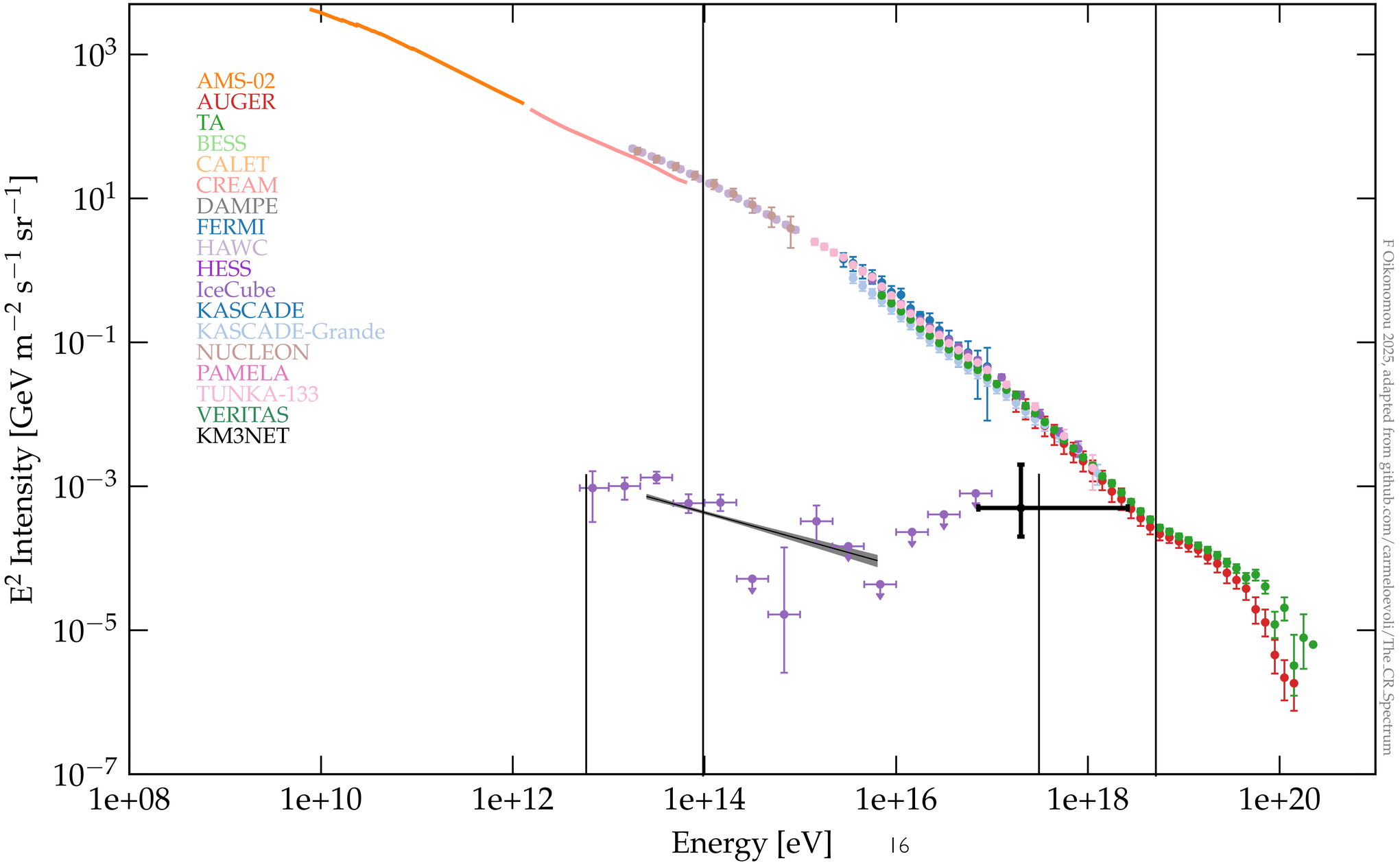
Component B


AMS-02
AUGER
TA
BESS
CALET
CREAM
DAMPE
HAWC
IceCube
IceTop
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
TUNKA-133
p
Galactic
AGN Wind Bubbles?
E² Intensity [GeV m⁻² s⁻¹ sr⁻¹]
Energy [eV]
10³
10¹
10⁻¹
10⁻³
10⁻⁵
10⁻⁷
1e+08
1e+10
1e+12
1e+14
1e+16
1e+18
1e+20
github.com/carmeloevoli/The_CR_Spectrum

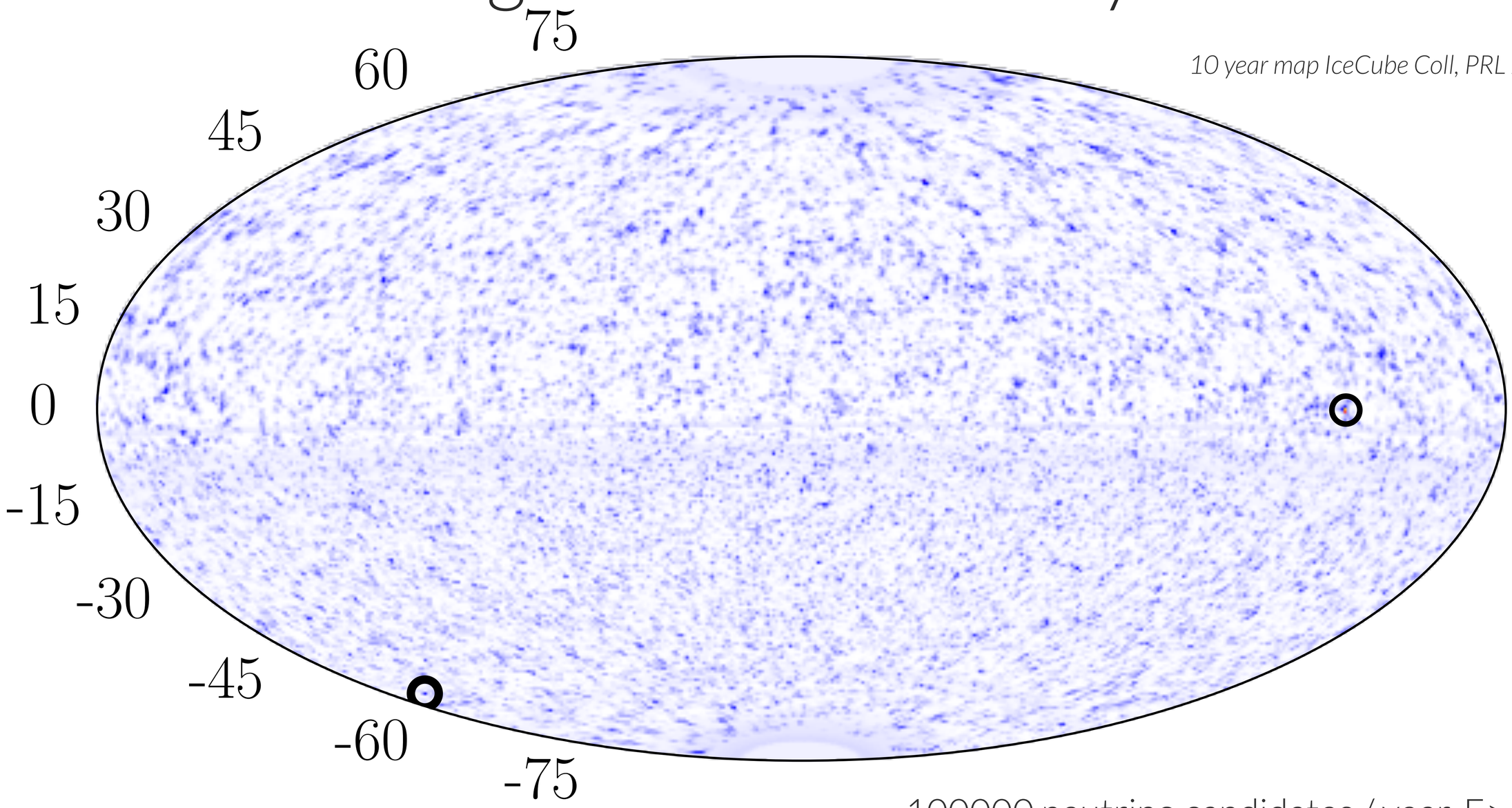
Component B


Wind bubbles?
AGN Wind bubbles?
Supernova remnants?
Galactic
Component B
PAMELA
see also Paul Simeon's talk @16:16 (Crimson room)
on Hierarchical shock model
10^3
10^{-7}
1e+08
1e+10
1e+12
1e+14
1e+16
1e+18
1e+20
Energy [eV]
adapted from github.com/carmeloevoli/The_CR_Spectrum

Neutrinos


AMS-02
AUGER
TA
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
IceCube
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
TUNKA-133
VERITAS
KM3NET
E^2 Intensity [GeV m^{-2} s^{-1} sr^{-1}]
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
1e+08
1e+10
1e+12
1e+14
1e+16
1e+18
1e+20
Energy [eV]
F Oikonomou 2025, adapted from github.com/carmeloevoli/The.CR.Spectrum

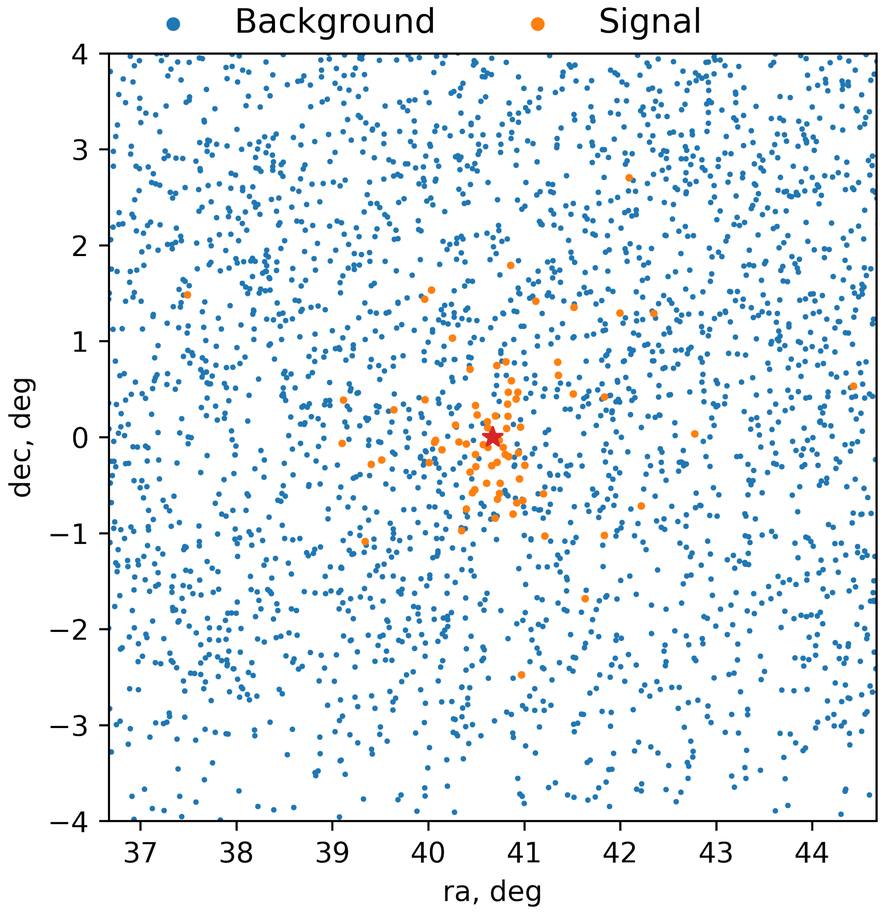
Neutrinos: Looking for a needle in a haystack



10 year map IceCube Coll, PRL 2020

~100000 neutrino candidates / year, E> 100 GeV
> 97% atmospheric

Likelihood stacking analyses

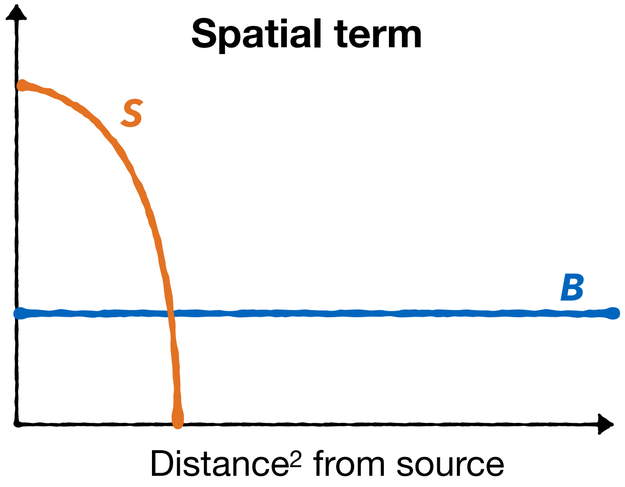


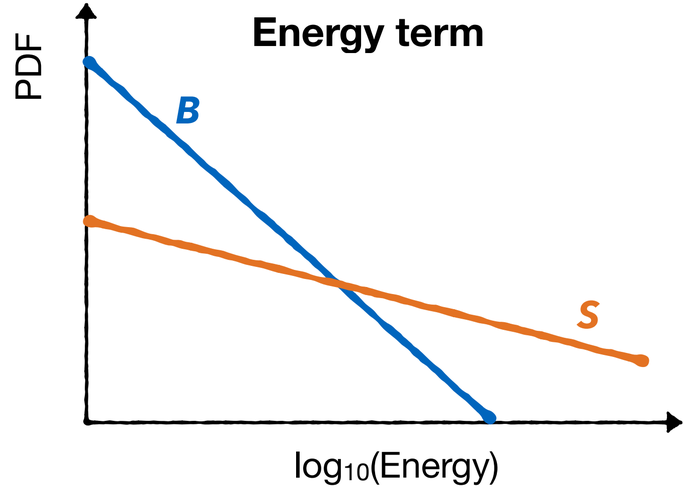
The unbinned likelihood approach:

$$\mathscr{L} = \prod_{i}^{N} \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) \cdot B_i \right]$$

Signal

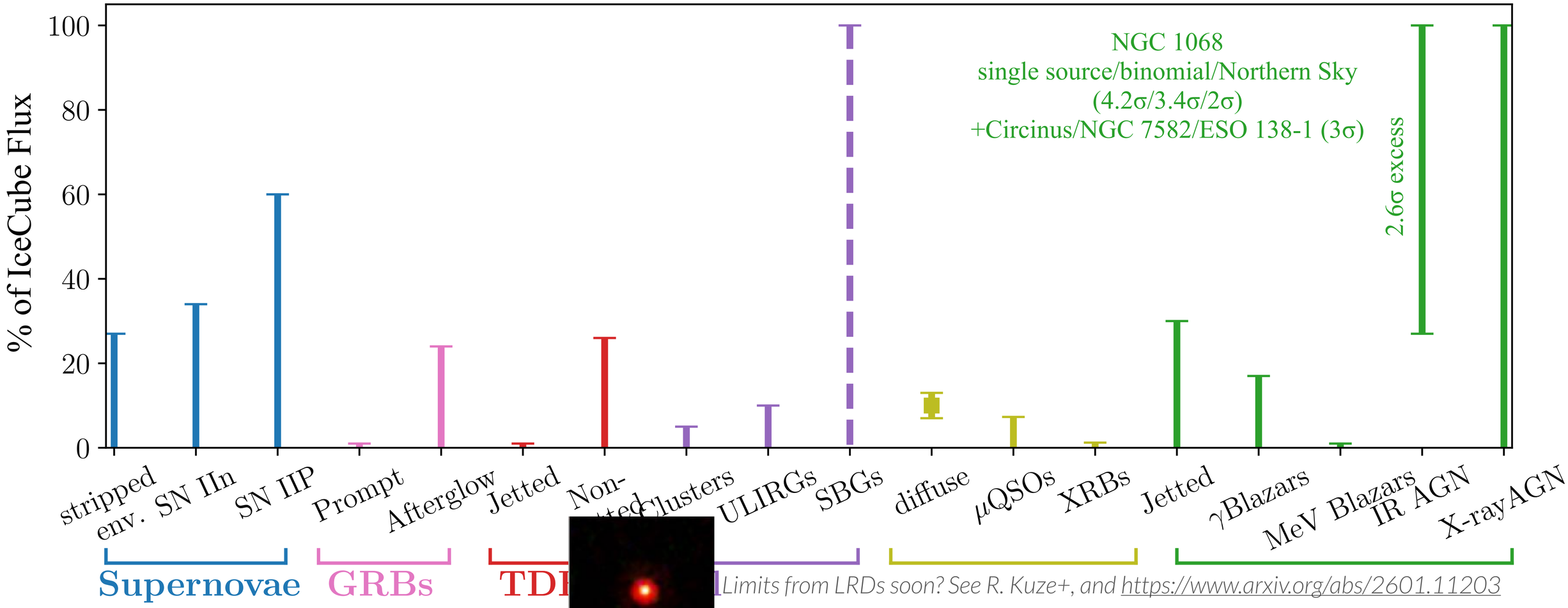
Background





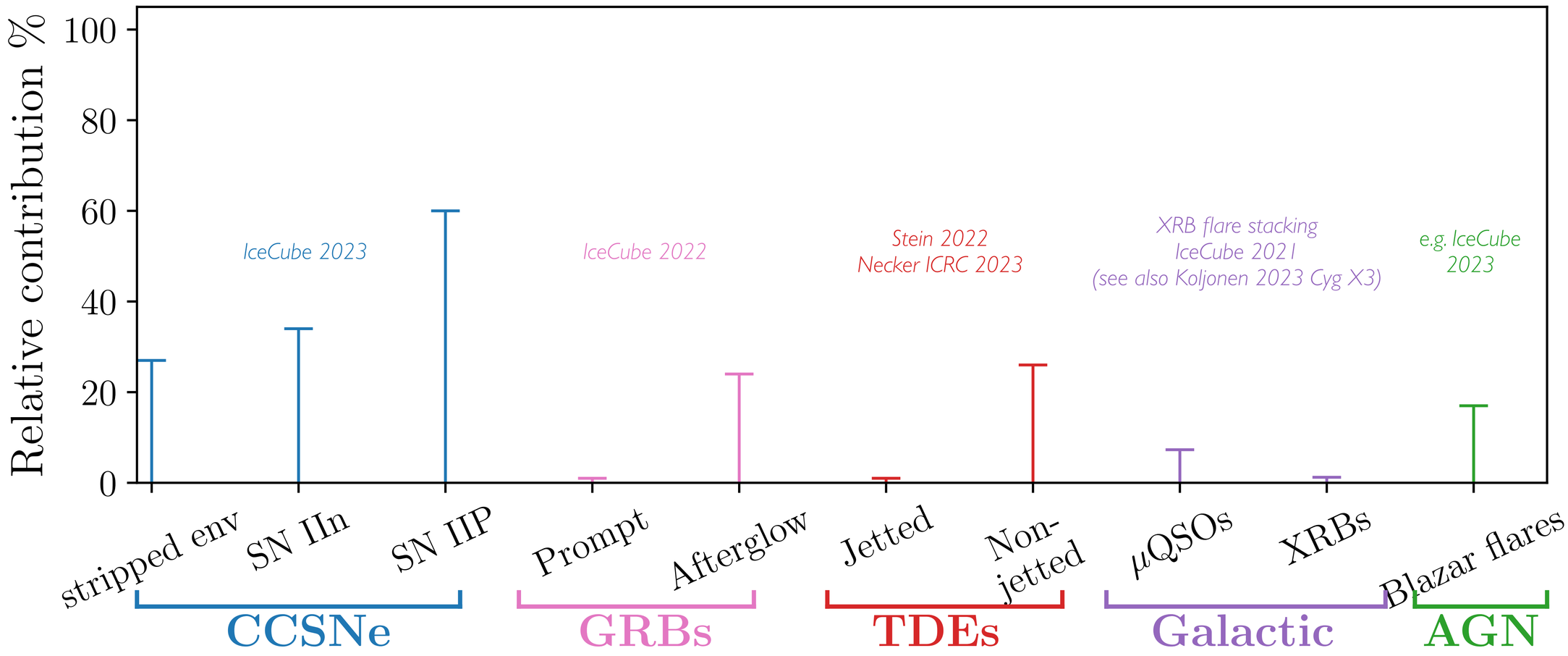
Diffuse neutrino flux: Stacking limits

plot from FO PoS ICRC2021 (2022) 030, based on numerous IceCube analyses, see arXiv:2201.05623 for references



Limits from LRDs soon? See R. Kuze+, and https://www.arxiv.org/abs/2601.11203

What we know so far about transients: IceCube stacking + multiplet searches



[-20, 1000] days optical

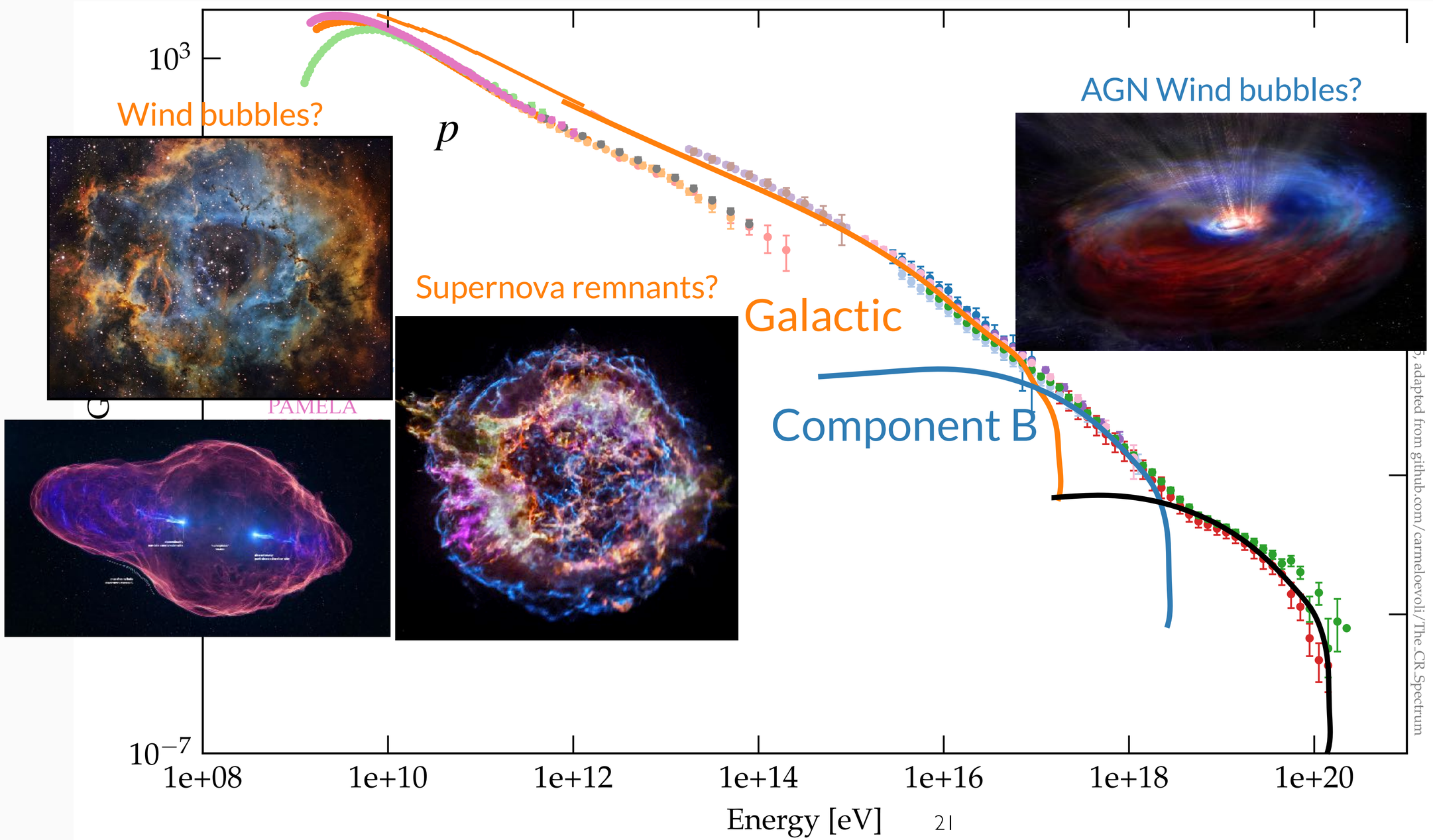
all $<10^4$s trans. w/ GRB-like rate

optical/ IR

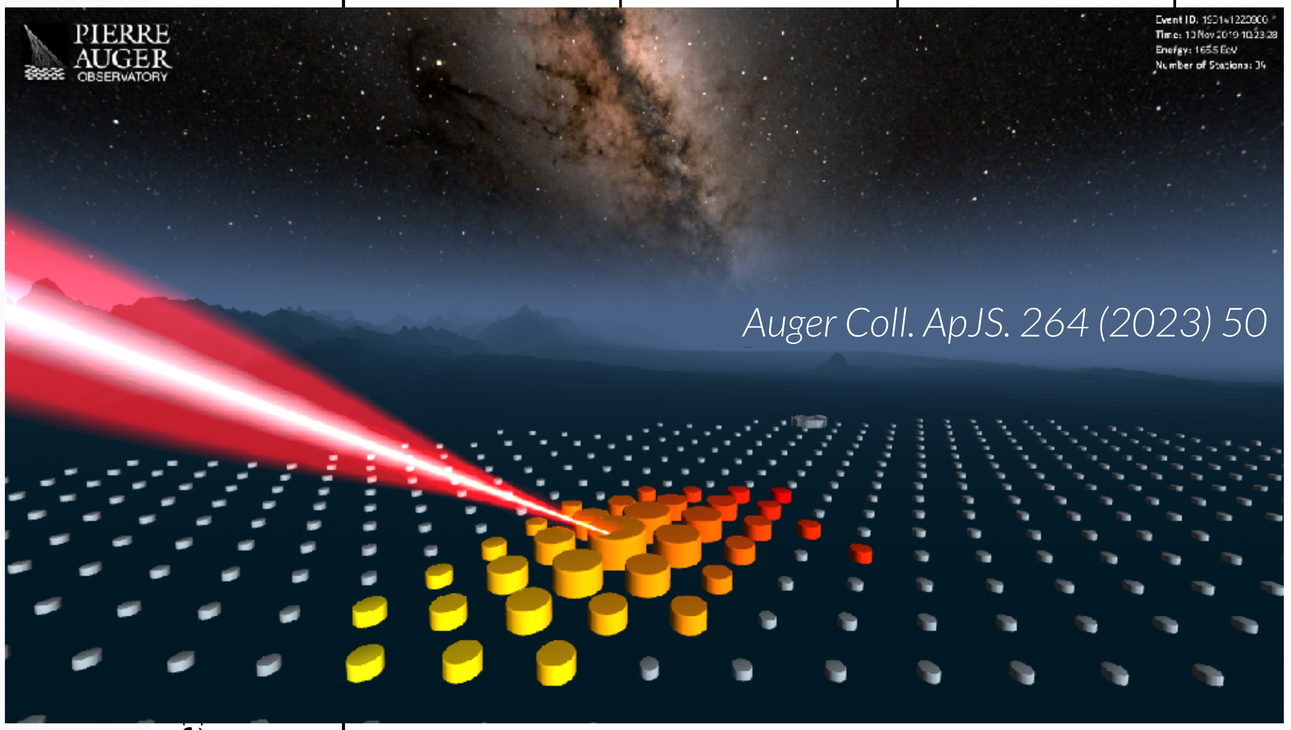
X-ray light curves

Fermi-LAT lightcurves

Ultra-high energy cosmic rays

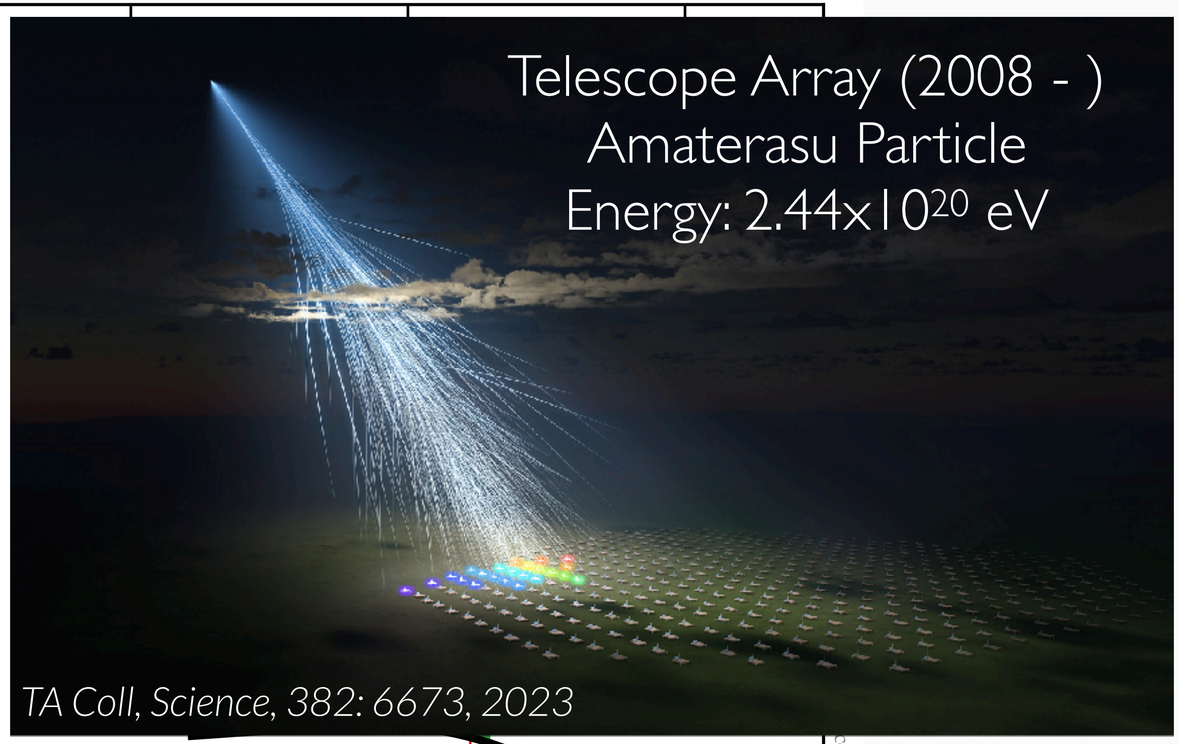


Ultra-high energy cosmic rays



Auger Coll. ApJS. 264 (2023) 50

Pierre Auger Observatory (2004-)
50,000 UHECRs above 8×10^{18} eV
40 UHECRs above 10^{20} eV

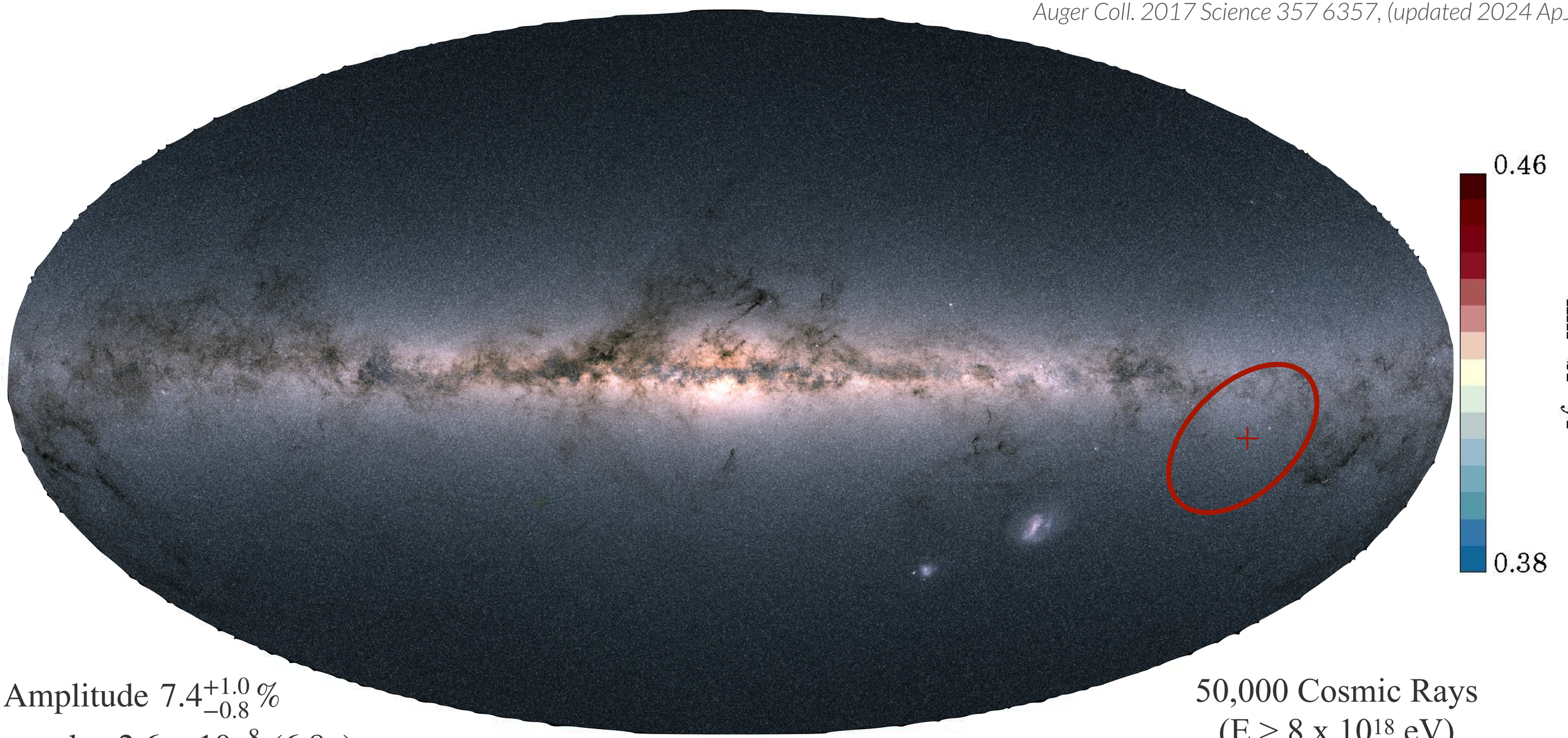


Telescope Array (2008 -)
Amaterasu Particle
Energy: 2.44×10^{20} eV

TA Coll, Science, 382: 6673, 2023

Arrival directions

Auger Coll. 2017 Science 357 6357, (updated 2024 ApJ)

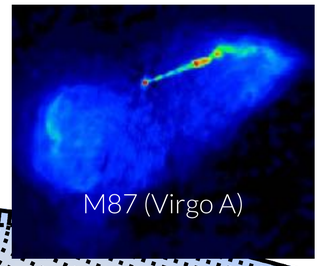


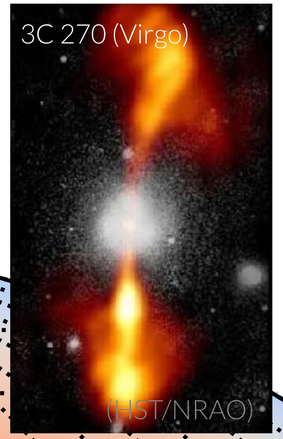
Amplitude $7.4^{+1.0}_{-0.8}$ %

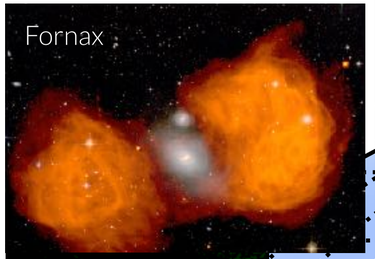
p-val : 2.6×10^{-8} (6.8σ)

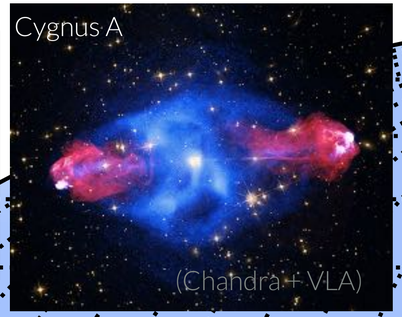
50,000 Cosmic Rays
(E > 8 x 10^{18} eV)

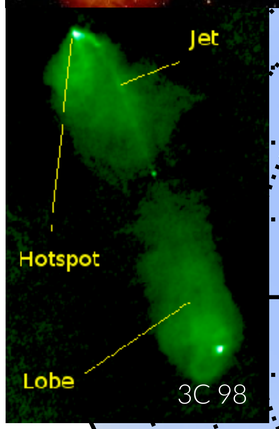
Arrival directions

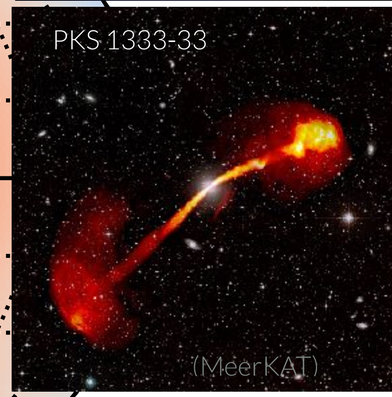


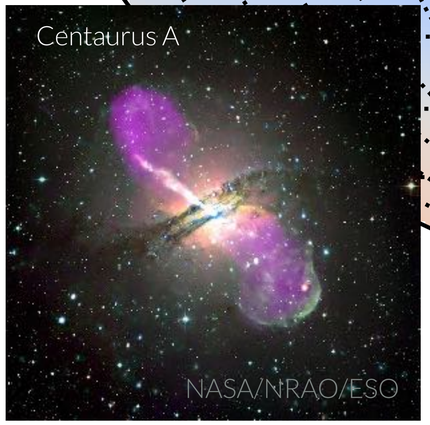


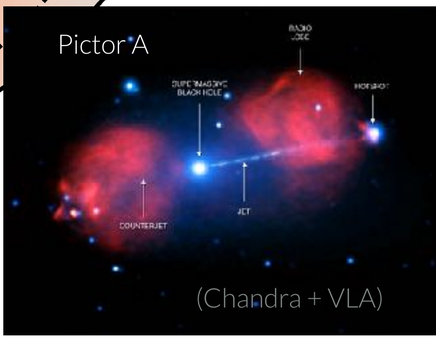






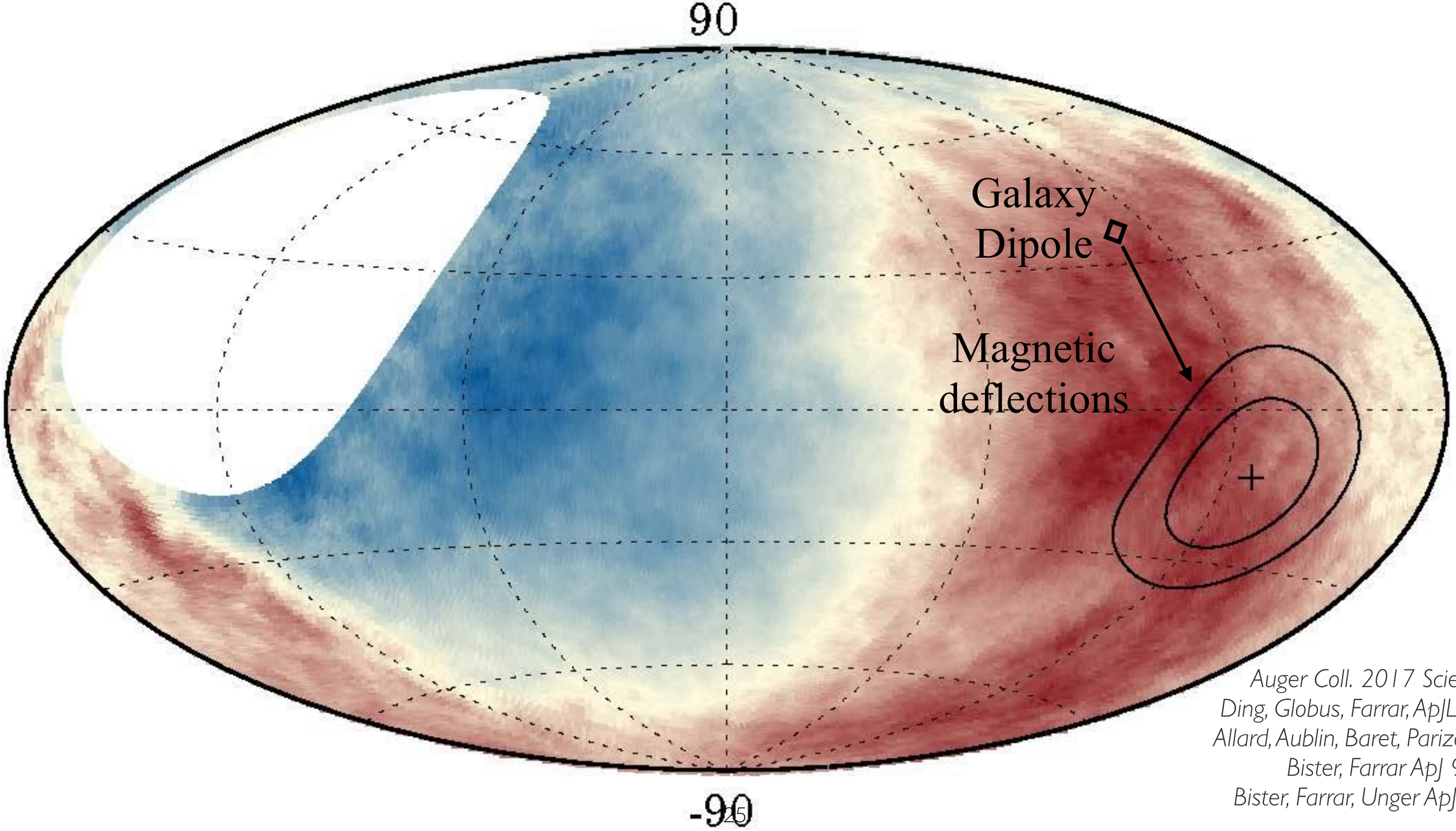






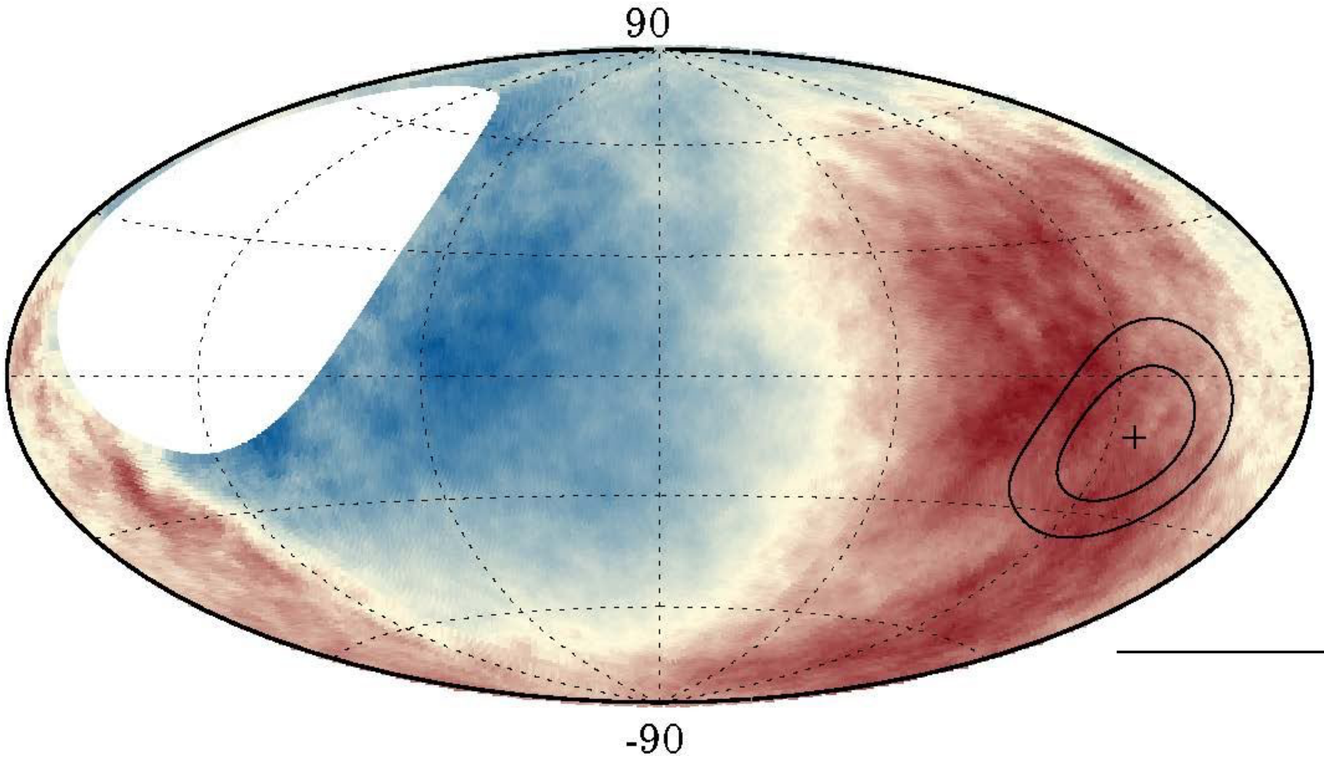
Model based on 26 brightest nearby jetted AGN. From Eichmann, Kachelriess, FO, JCAP07(2022)06
see also Harari et al 2016, Mollerach et al 2019, Mollerach & Roulet 2022, Bister (arXiv:2509.06594)

Arrival directions

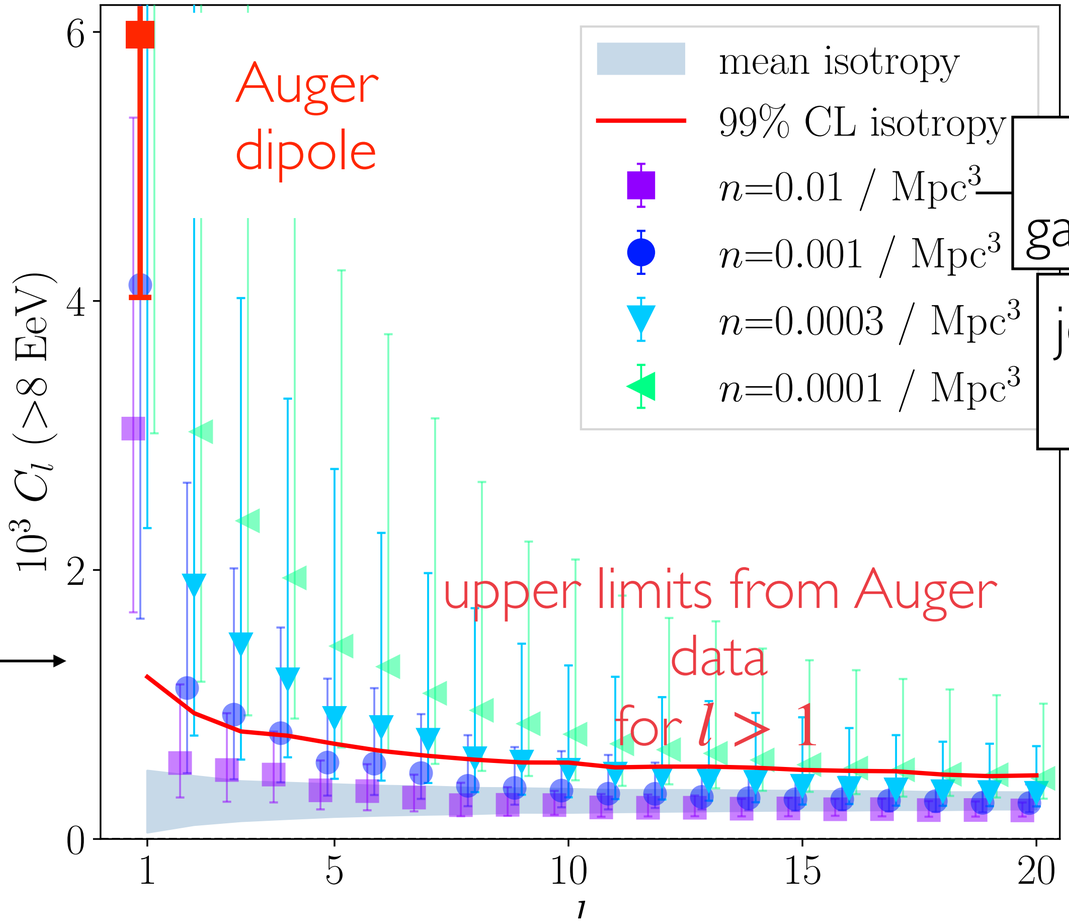


Auger Coll. 2017 Science 357 6357
Ding, Globus, Farrar, ApJL 913 (2021) 1
Allard, Aublin, Baret, Parizot, A&A (2022)
Bister, Farrar ApJ 996 (2024) 71
Bister, Farrar, Unger ApJ 975 (2024) 1

Arrival directions



Bister, Farrar ApJ 996 (2024) 71



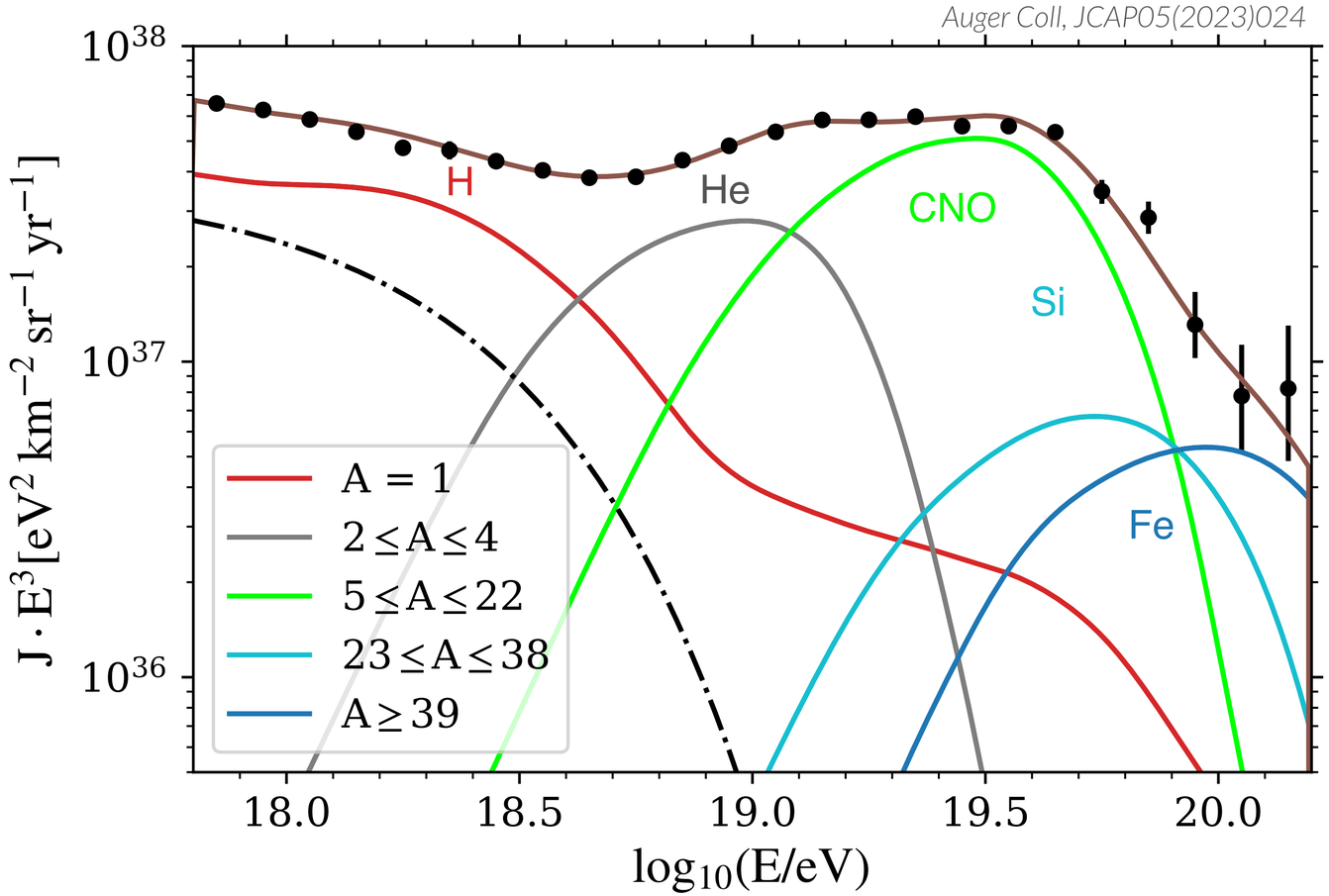
~all galaxies

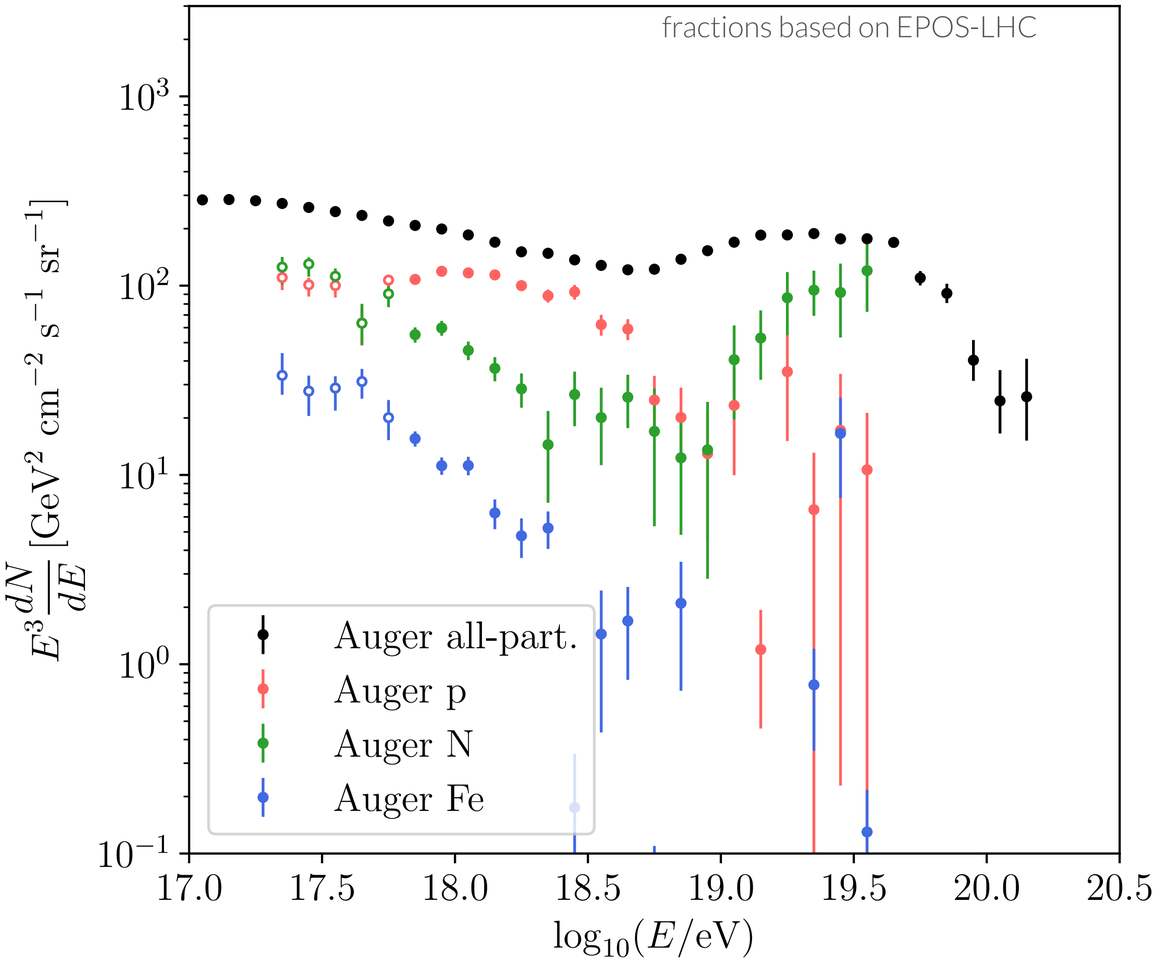
jetted agn

Conclusion #1: UHECR sources are numerous

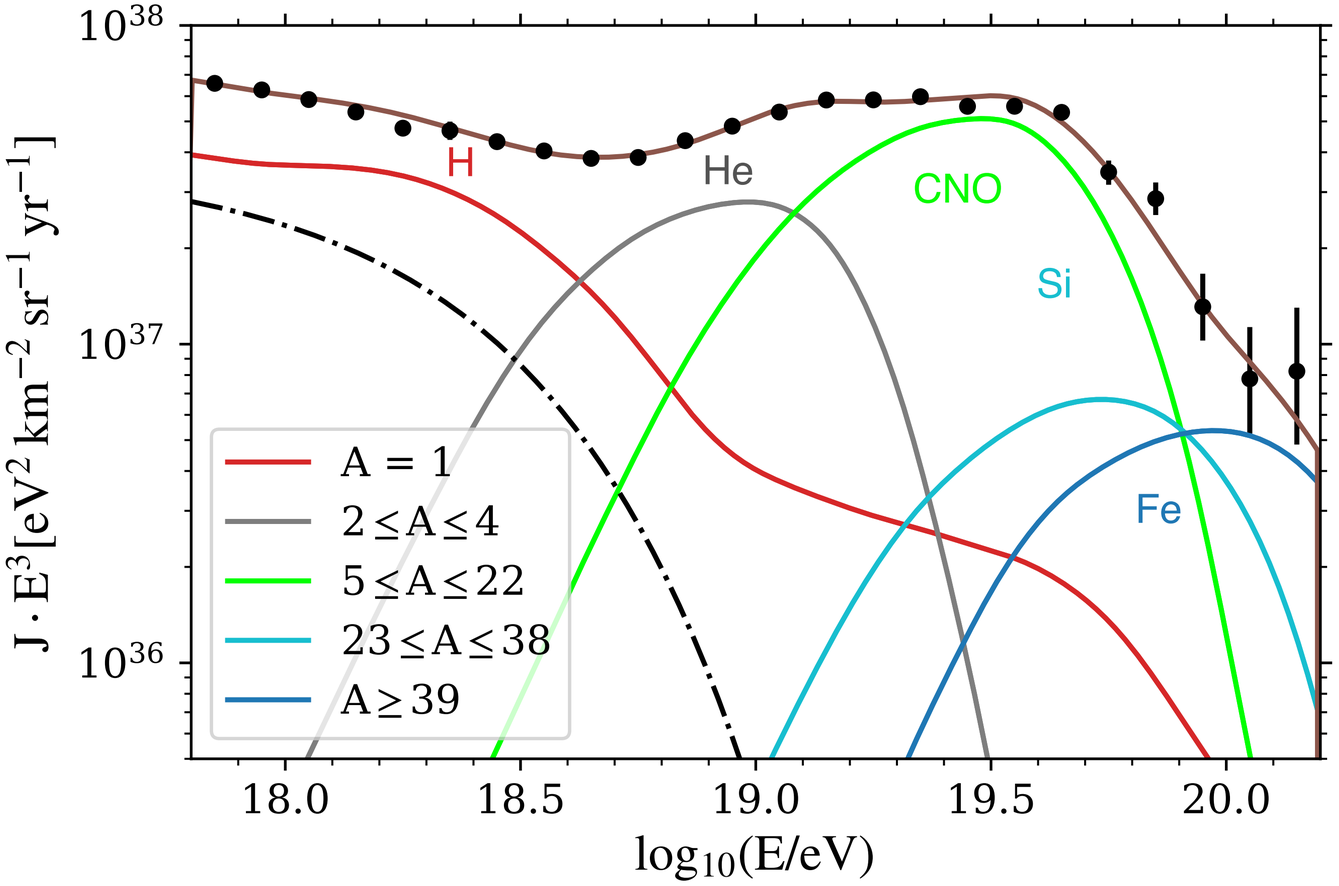
Spectrum and Composition Observables

Auger Coll, PRL, 125, 121106, 2020
Tkachenko for Auger Coll, PoS(ICRC2023)438
Auger Coll, PRL, 134, 021001, 2024

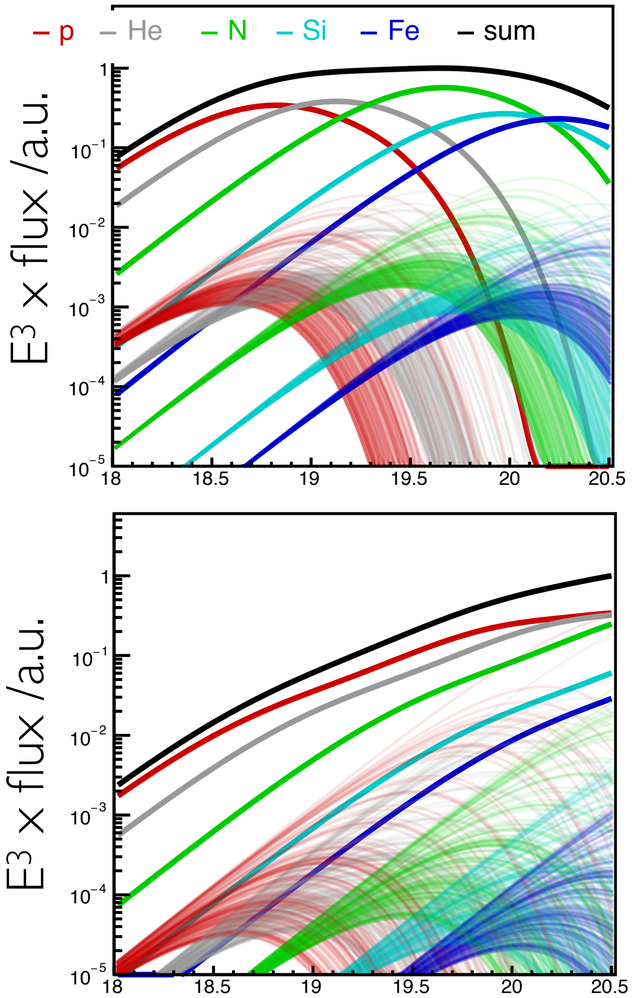




From identical sources to a population



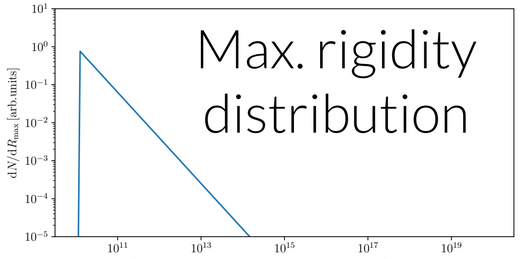
D. Ehlert, FO, M. Unger, PRD 107 (2023) 10



Near-identical sources

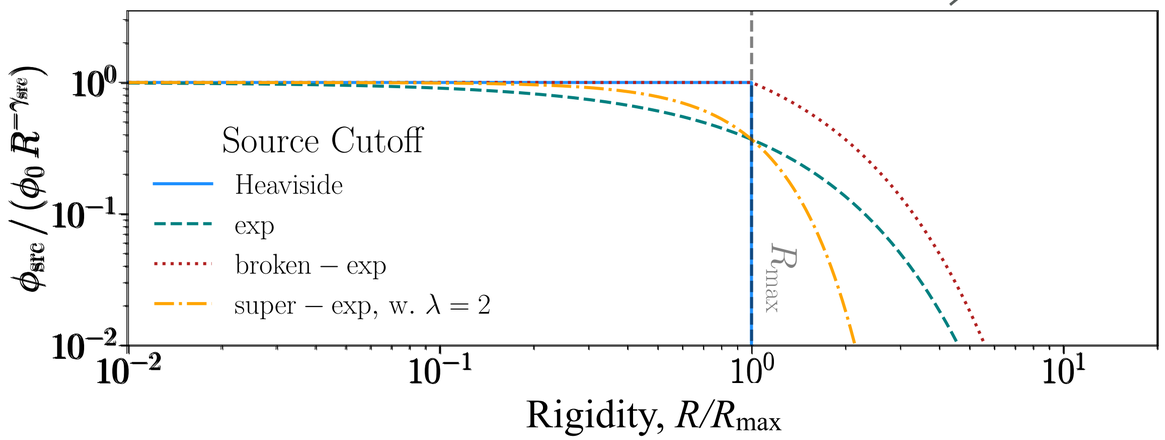
Non-identical sources

From identical sources to a population



$$\frac{\mathrm{d}N}{\mathrm{d}R_{\mathrm{max}}} \propto R_{\mathrm{max}}^{-\beta_{\mathrm{pop}}}$$

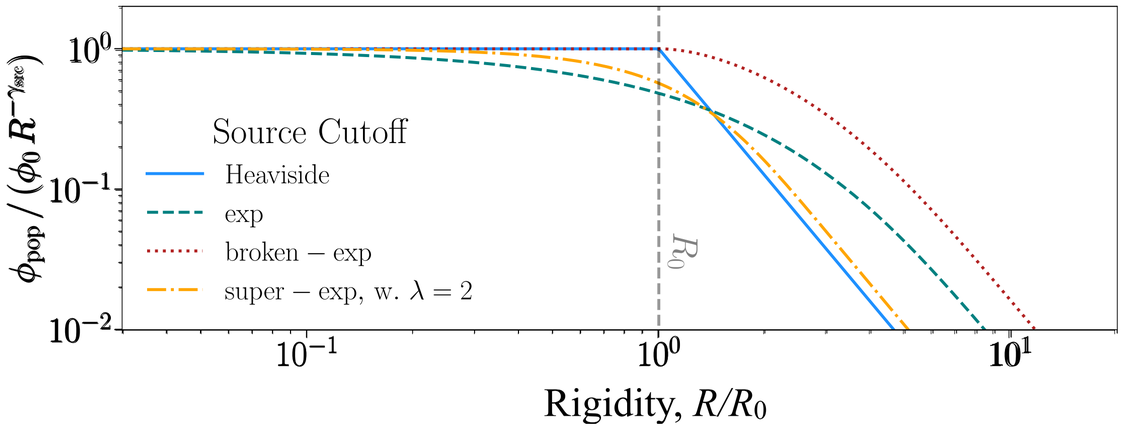
Single Source UHECR Spectrum



$$\frac{\mathrm{d}N}{\mathrm{d}R} \propto R^{-\gamma_{\mathrm{src}}}$$

Population Spectrum

Power-law distributed maximum rigidity

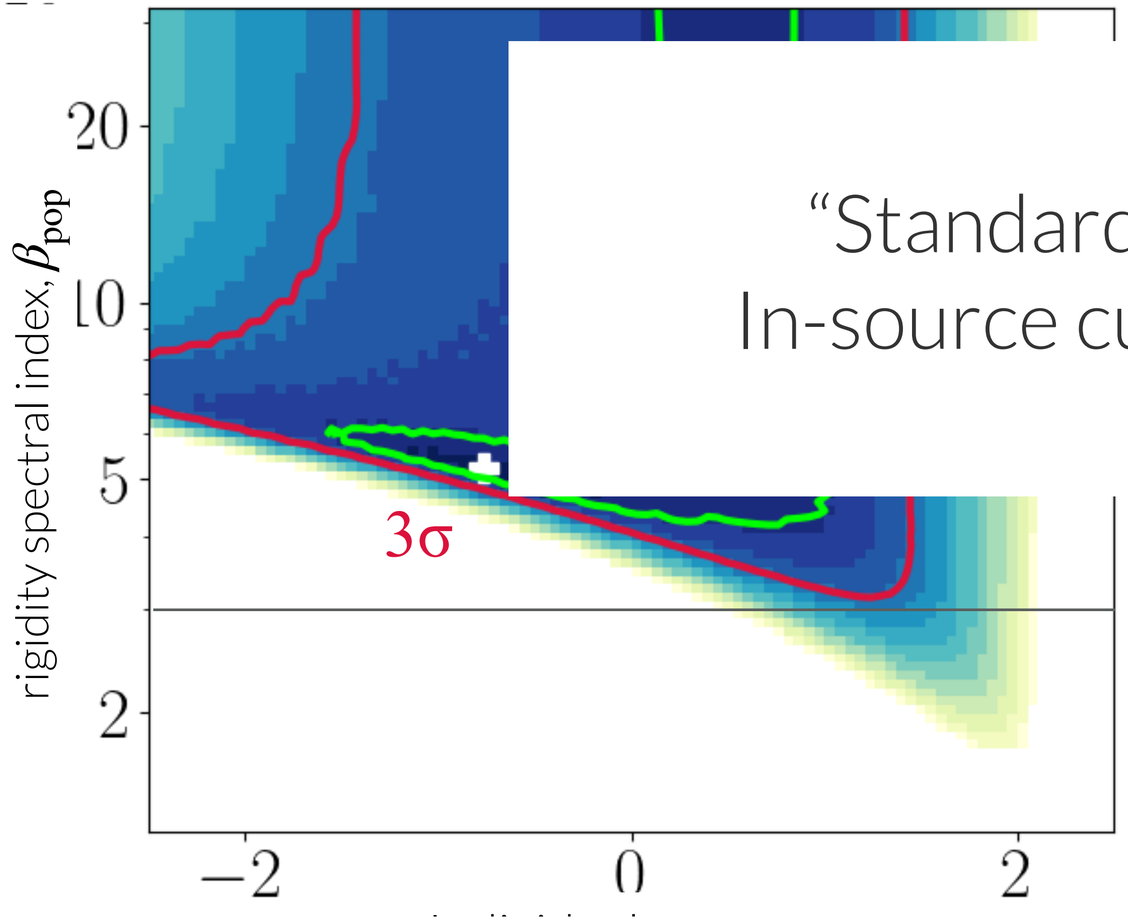


$$\phi_{\mathrm{pop}} \propto \begin{cases} R^{-\gamma_{\mathrm{src}}} & R \ll R_0 \\ R^{-\gamma_{\mathrm{src}}-\beta_{\mathrm{pop}}+1} & R \gg R_0 \end{cases}$$

Broken exponential, e.g. Auger Combined Fit (Aab et al 2017)

Super exponential in case of DSA with synchrotron losses with $\mathrm{d}N/\mathrm{d}R \propto \exp - R^{\lambda}, \lambda = 2$ *e.g. Zirakasvili & Aharonian 2007*

A curious maximum rigidity distribution



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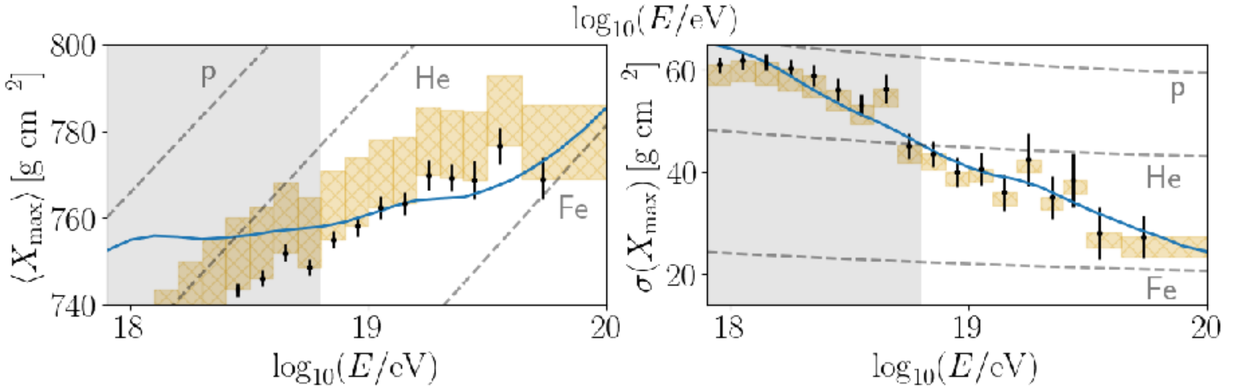
"Standard accelerators"?
In-source cutoff mechanism?



Conclusion #2: UHECR sources are few or near-identical E_{max}

Summary

Galactic cosmic rays

New insights from γ-rays!
Wind bubbles? Stellar clusters? Microquasars?

Component B

AGN “Wind-bubbles” can fill the transition region - consistent with neutrino observations

Neutrinos - probes of Extra-galactic Component B

AGN / Supernovae / Starburst Galaxies main options

New Puzzles at the highest energies

Sources appear to be numerous but near-identical “Standard Candles”? / In-source mechanism?