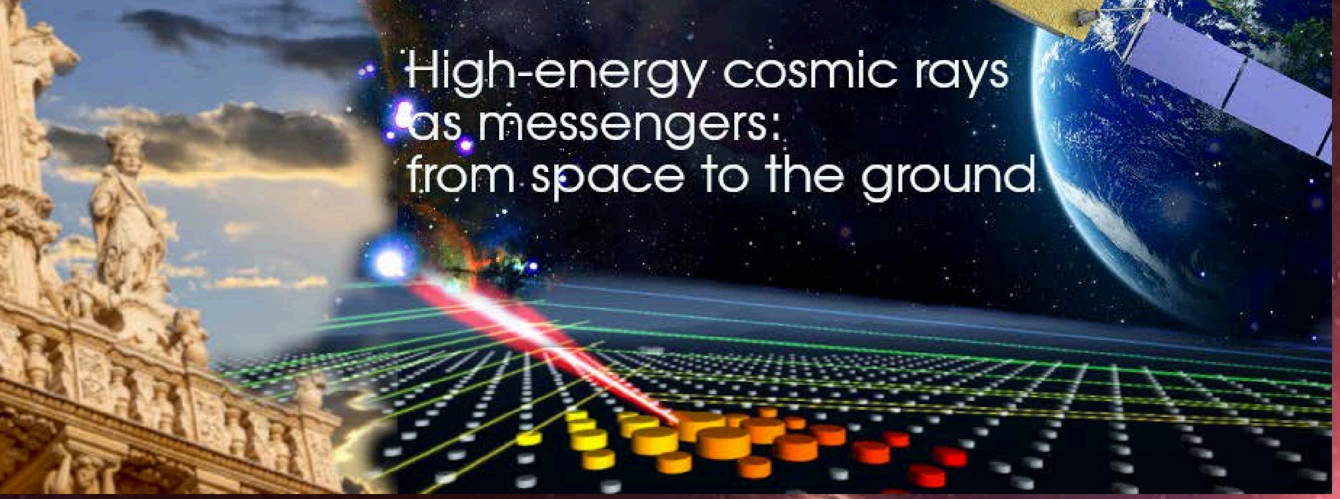
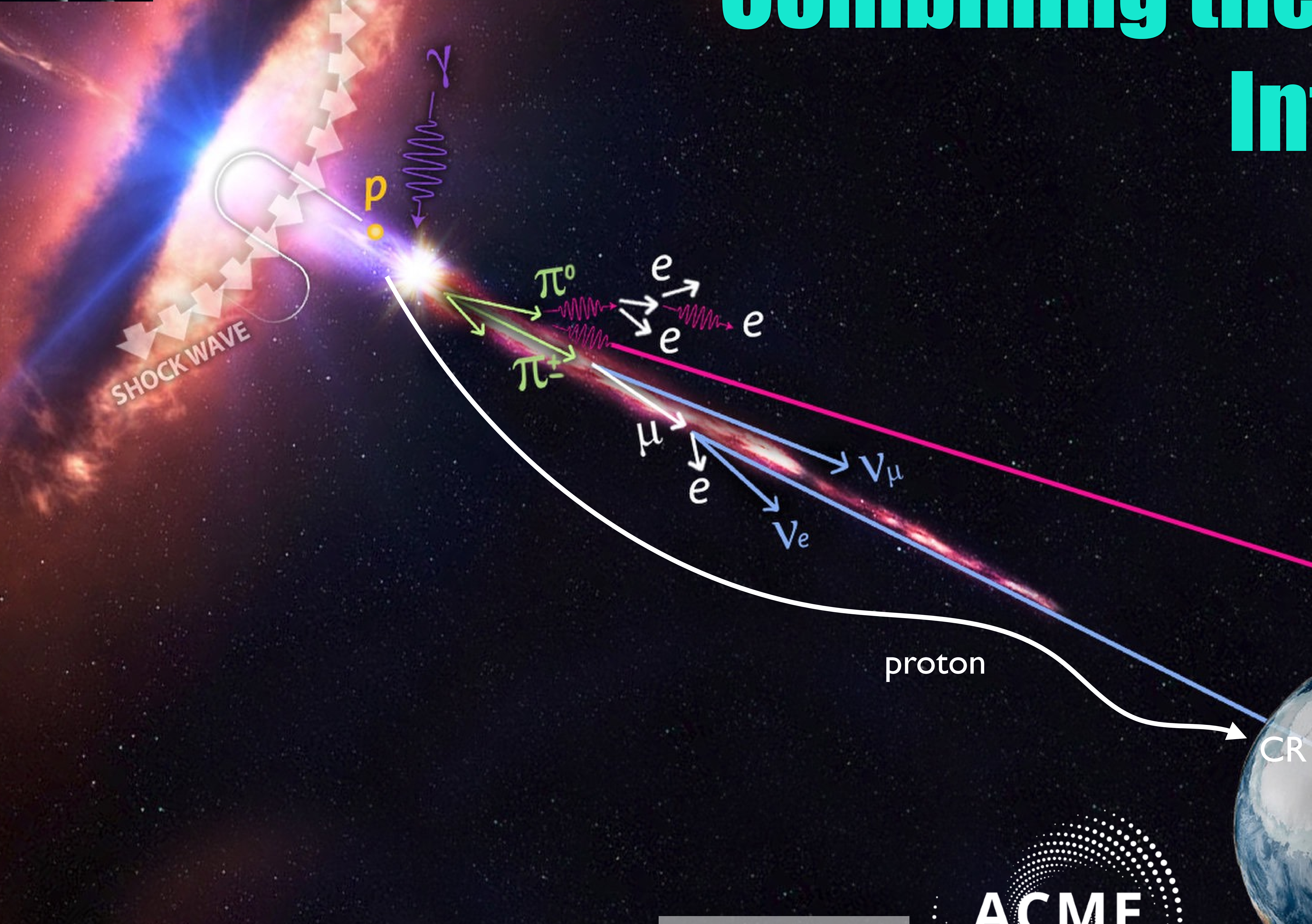


Multi-Messenger Astrophysics:
Combining the Pieces of Information



BERGISCHE UNIVERSITÄT WUPPERTAL

Karl-Heinz Kampert
Bergische Universität Wuppertal

Bundesministerium für Bildung und Forschung

ACME
Astrophysics Centre for Multimessenger studies in Europe

MICRO

SFB1491

High-energy cosmic rays as messengers: from space to the ground
CRs
ν
γ
SHOCK WAVE
p
γ
π⁰
π±
e
μ
νμ
νe
proton
CR
May also be a source of BSM particles
p_{CR} + matter → $\pi^{\pm} + \pi^{0} + X$
a/o radiation fields
↳ $\gamma + \gamma$
↳ $\mu + \nu_\mu + \nu_e$

The High Energy Cosmic Messengers

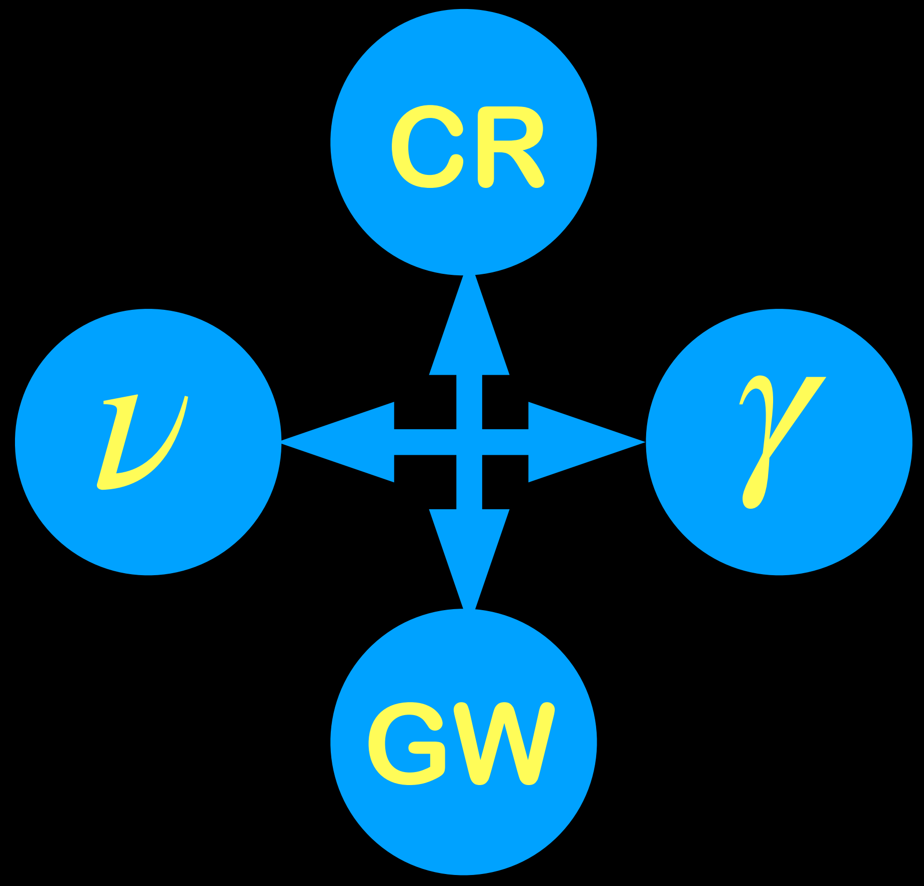
$$p_{CR} + \text{matter} \rightarrow \pi^{\pm} + \pi^{0} + X$$

a/o radiation fields

$$\hookrightarrow \gamma + \gamma$$

$$\hookrightarrow \mu + \nu_{\mu} + \nu_{e}$$

Multi-Messenger Astrophysics



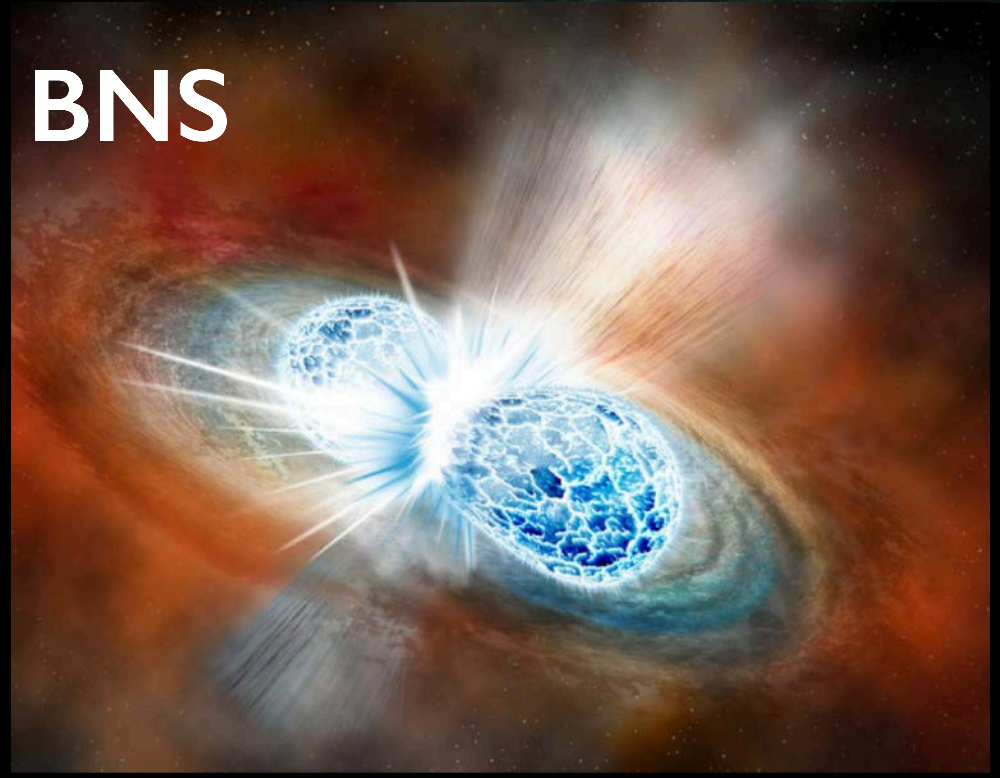
Underlying physics connects the messengers

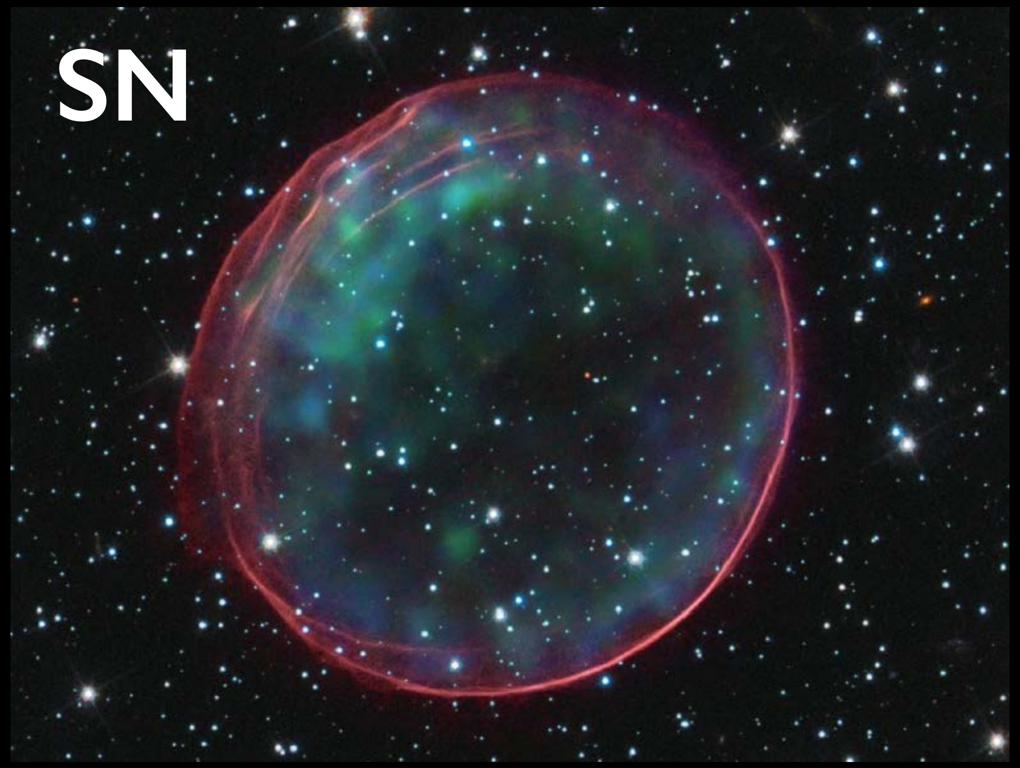
→ Measuring all of them is more than the sum of the individuals !

Adapted from Kumiko Kotera

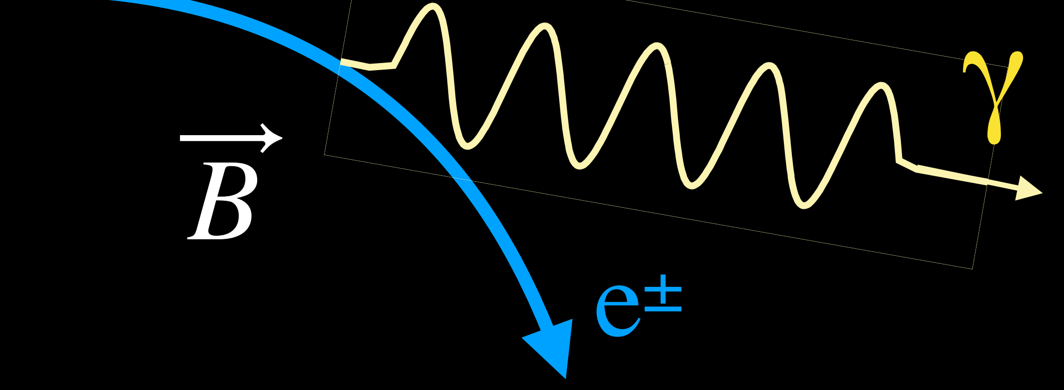
Overarching goal:
learn about the most powerful accelerators in the Universe

Particle Physics in Space

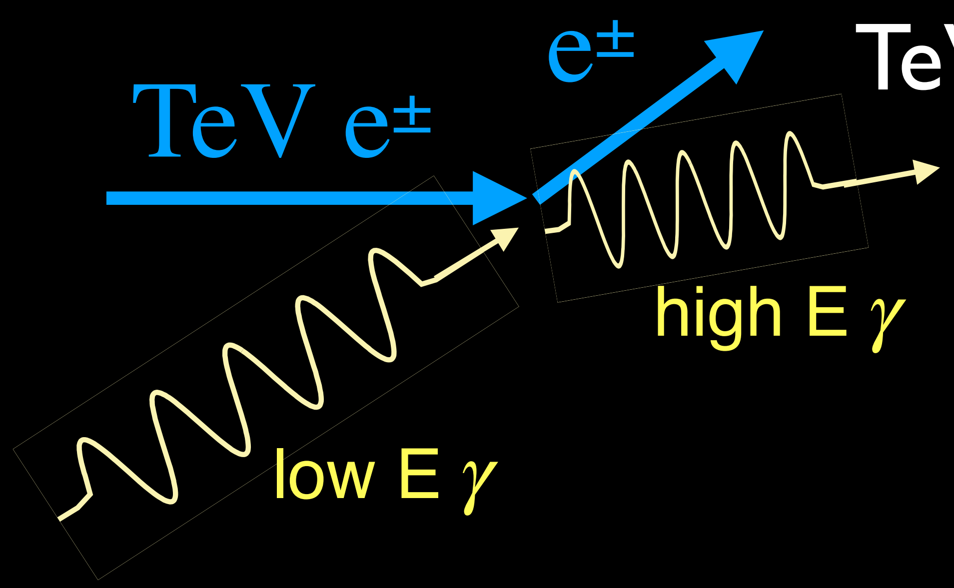


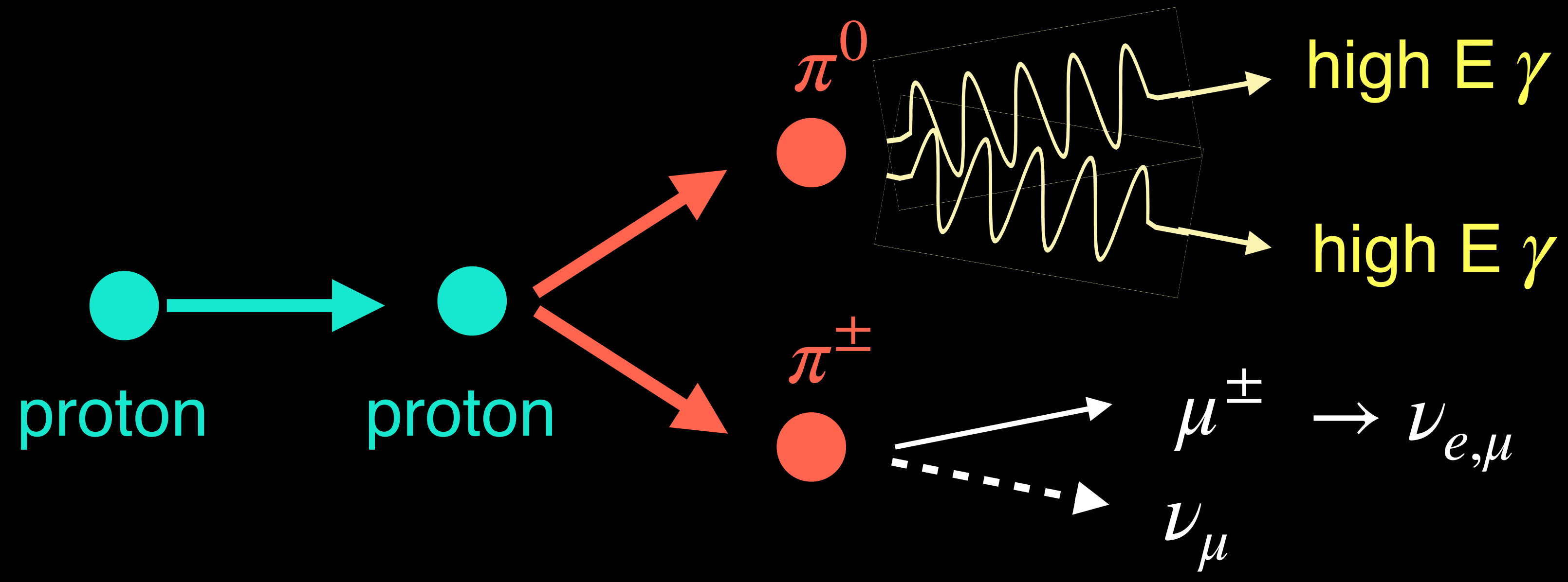


MeV Photons from synchrotron radiation of e±



TeV Photons from inverse Compton scattering

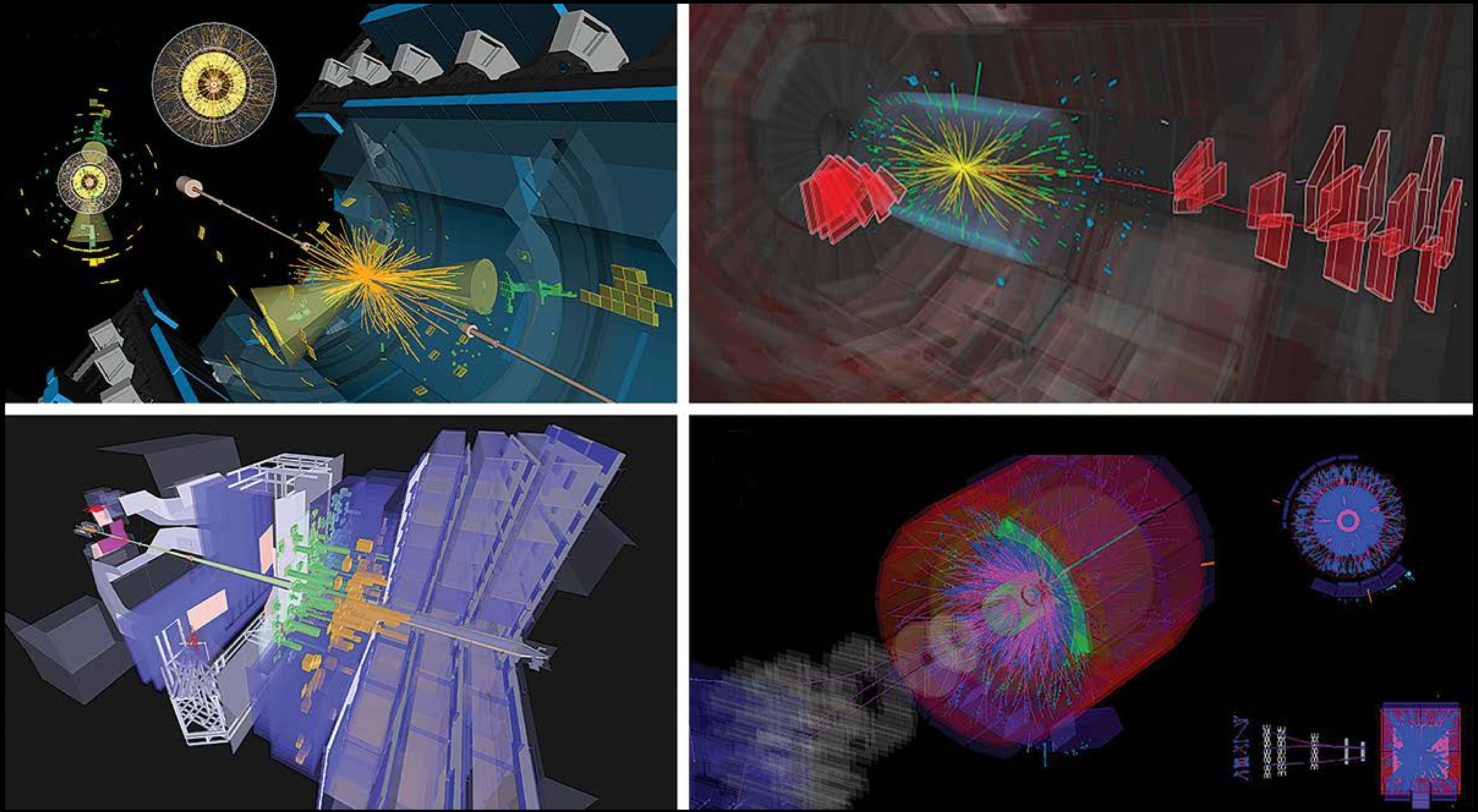




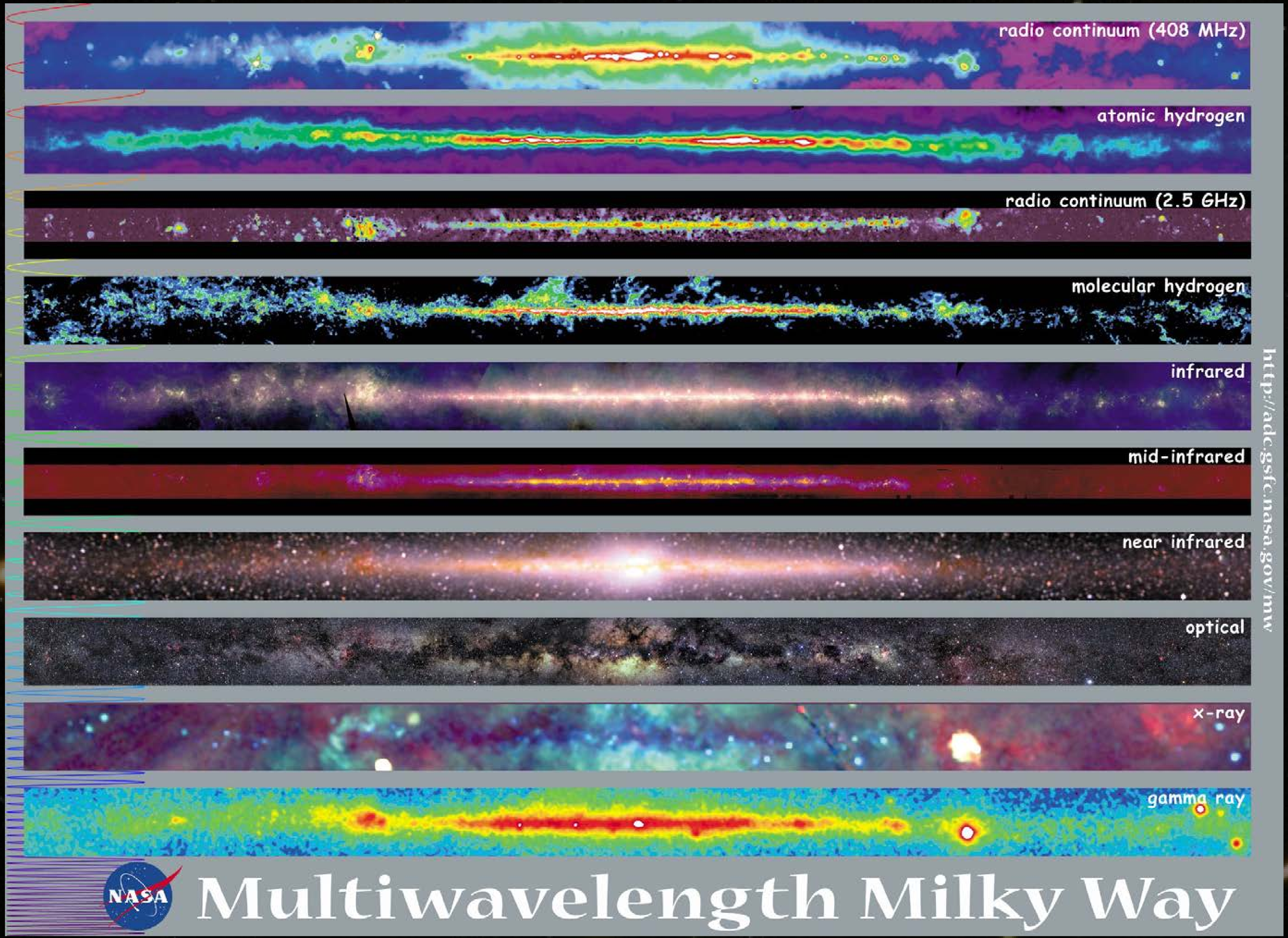
TeV Photons and neutrinos from CR interactions

Multi-Messenger in Particle Physics

Note, particle and nuclear physics experiments also employ a suit of detectors to identify pions, kaons, protons, nuclei, electrons, photons, in the same event….

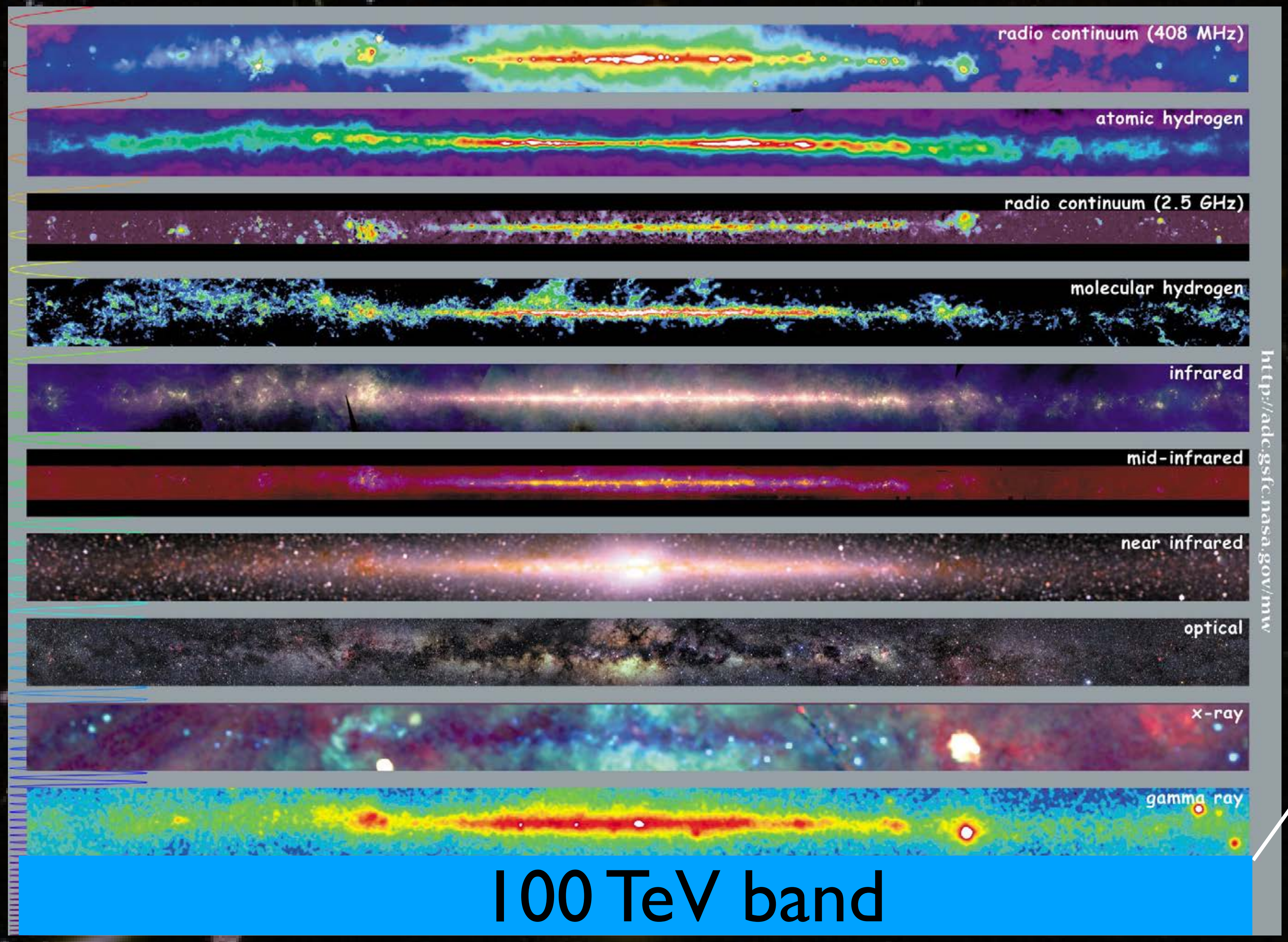


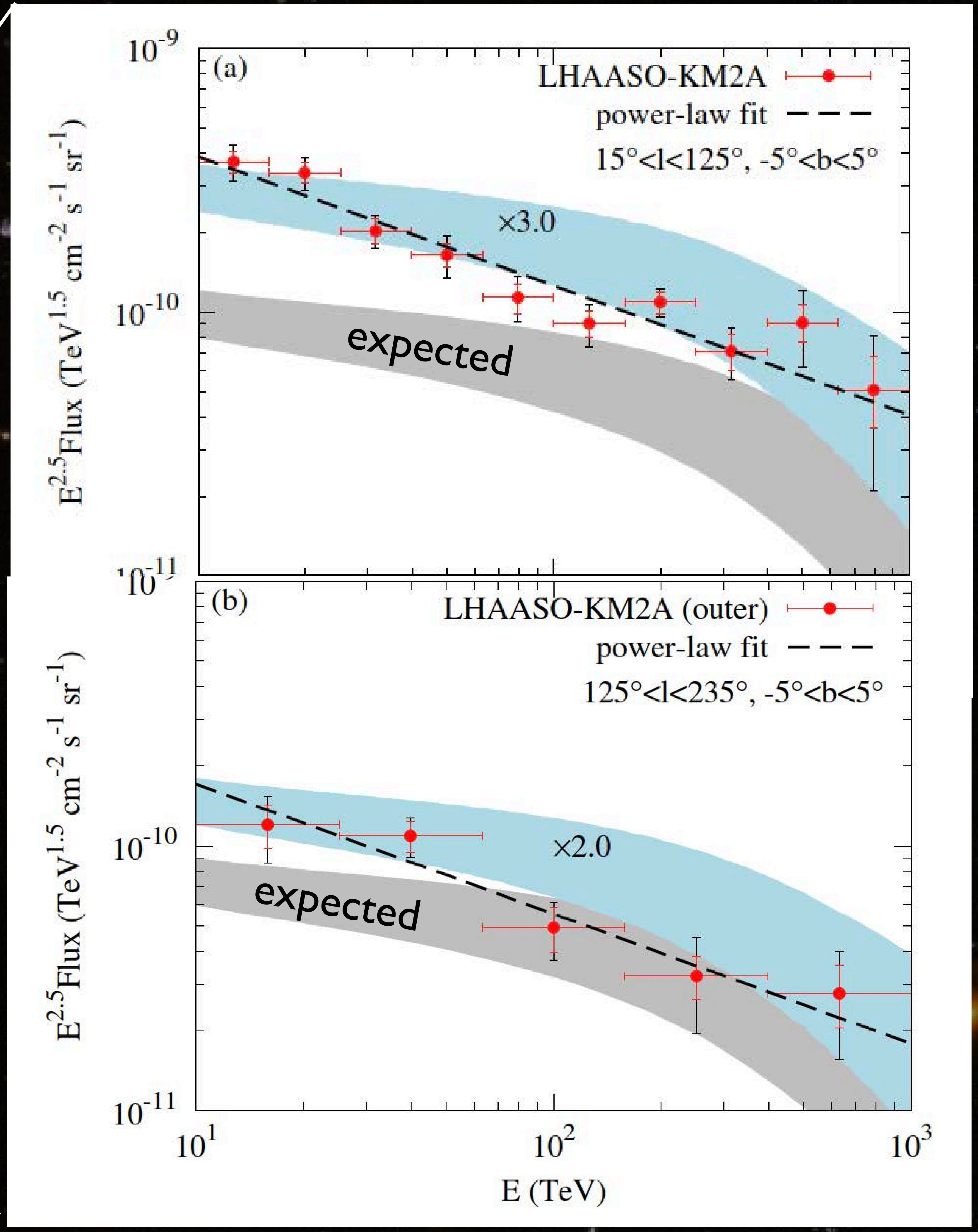
Multi-Wavelength Astronomy



radio 408 MHz	synchron radiation of electrons
H-line 1420 MHz	Ortho⇔ Para hydrogen
radio 2.5 GHz	
molecular H	H_2 transitions
IR	star formation
mid-IR	
near IR	
optical	stars
X-ray	hot gas, CR interactions…
GeV γ-ray	CR interactions with ISM

Multi-Wavelength Astronomy





inner region of GP

outer region of GP

Recently, LHAASO has measured TeV-fluxes in the galactic plane that are higher by a factor of 2~3 than predictions (the local CR interaction with ISM) unresolved sources or propagation effect?

$$p_{CR} + p_{ISM} \rightarrow \pi^0 \rightarrow 2\gamma \quad ?$$

PRL 131:151001 (2023)

Multi Wavelength + Neutrinos

Photons at different wavelength plus neutrinos

optical

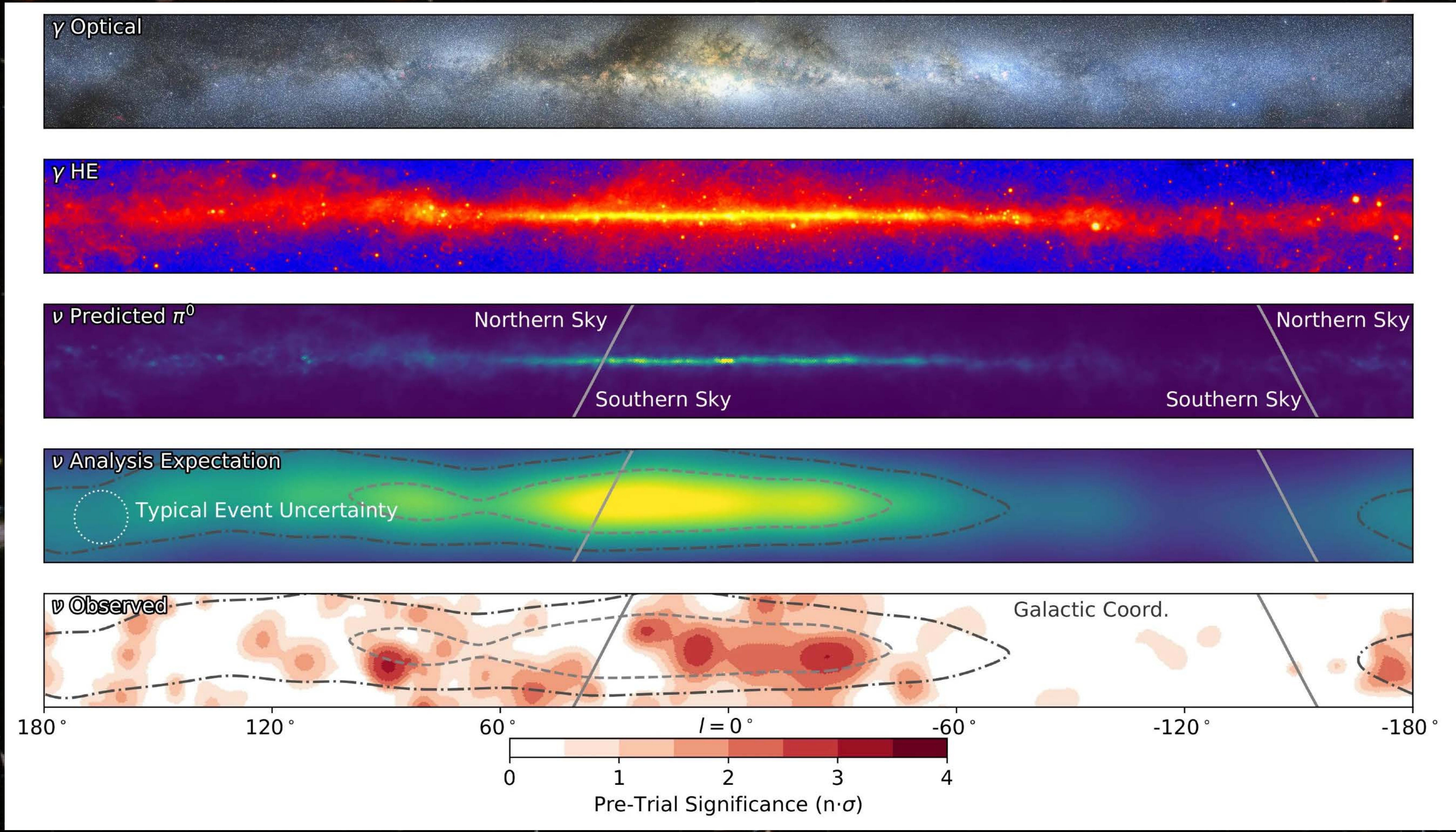
MeV-GeV γ

ν from π^0 predicted

ν analysis expected

ν analysis observed

$p_{CR} + p_{ISM} \rightarrow \pi^{\pm} \rightarrow \nu$



IceCube (Science 2025)

Let's define MM ...

MM is a natural generalisation of Multi-Wavelength Astrophysics to include any other messenger, such as neutrinos, gravitational waves, cosmic rays, …

These messengers may all be produced within the astrophysical source, or may be produced during propagation.

⇒ by doing MM, we learn about environment within the sources and about the medium through with the messengers have propagated

Let's define MM ...

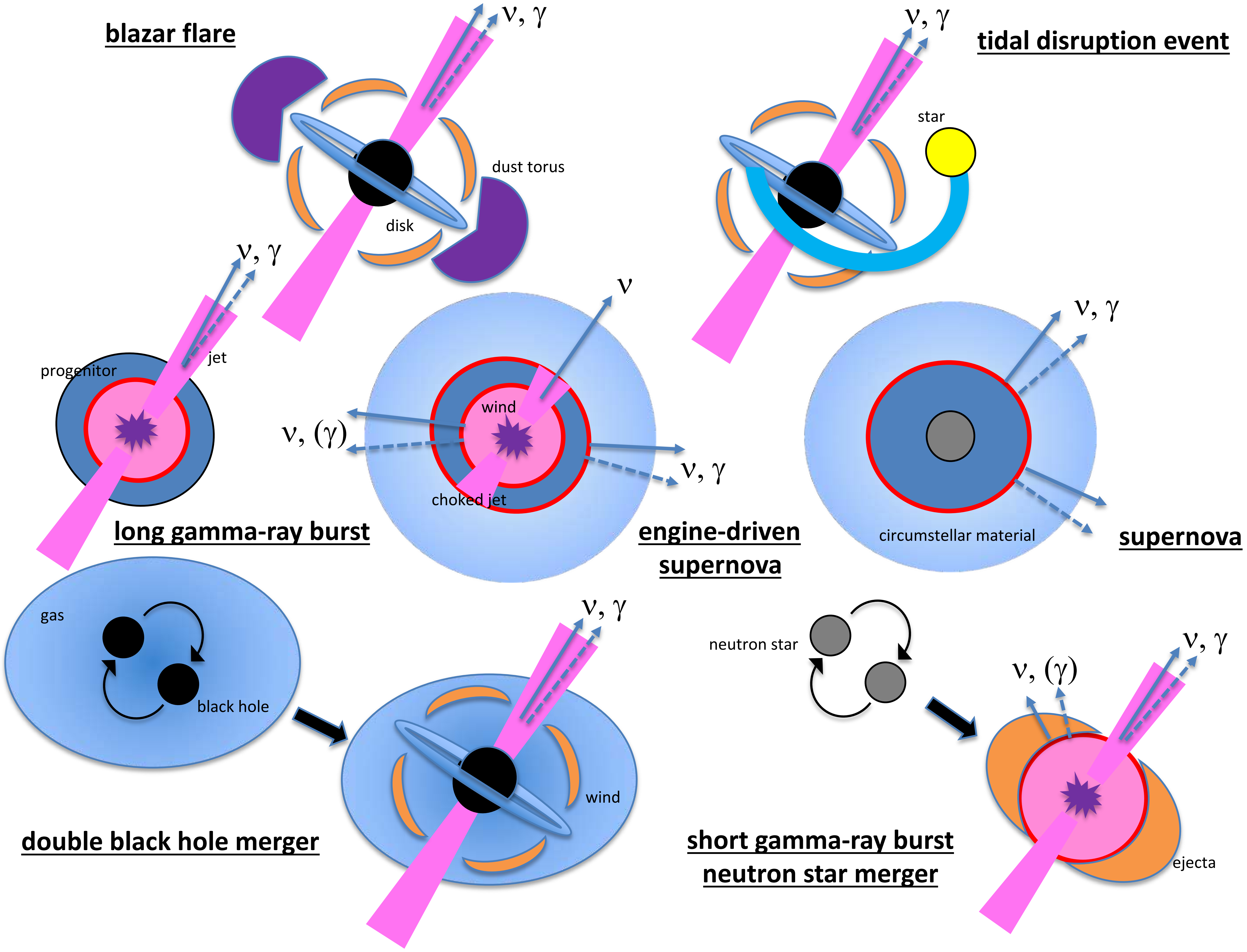
One more level of complexity:

Special case: **transient events** (time-domain studies)
→ relative signal strength as a fct of time
→ different time profiles of messengers
→ different morphologies (also known from MW-Studies)
⇒ Learn about source properties

Further Reading

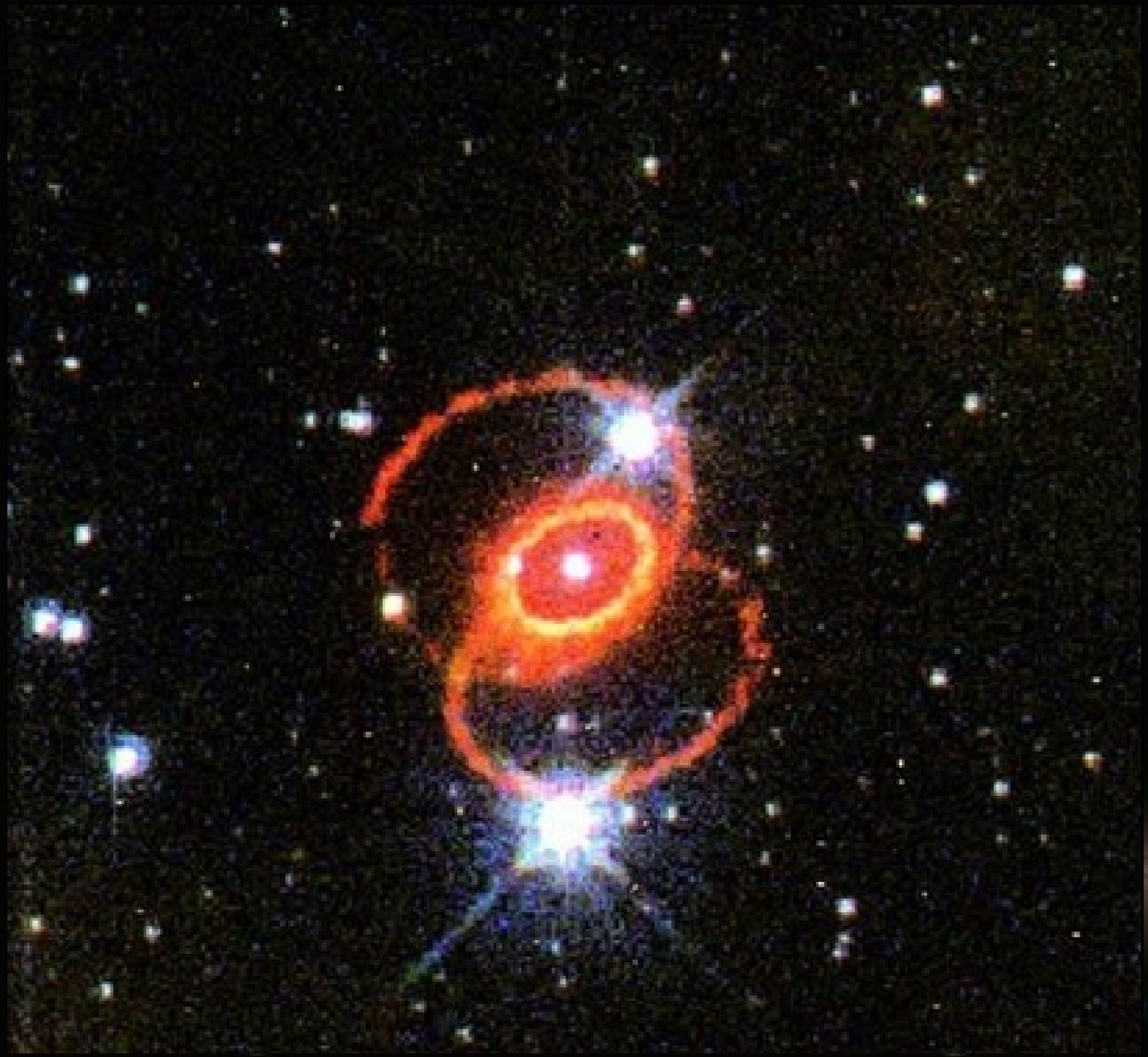
- Kohta Murase & Imre Bartos, „High-Energy Multi-Messenger Transient Astrophysics“, Annu. Rev. Nucl. Part. Sci. 2019 AA:1-36
- Peter Mezaros et al, „Multi-Messenger Astrophysics“, Nature Rev.Phys. 1 (2019) 585-599
- R.A. Batista et al., „Open Questions in Cosmic-Ray Research at Ultrahigh Energies“, Front.Astron.Space Sci. 6 (2019) 23
- G. Ghisellini, „Radiative processes in High Energy Astrophysics“, Springer (2012), https://arxiv.org/abs/1202.5949
- I. Tamborra, Neutrinos from explosive transients at the dawn of multi-messenger astronomy, Nature Rev.Phys. 7 (2025) 6, 285-298

Schematic Picture of MM Transients



Kohta Murase & Imre Bartos; Annu. Rev. Nucl. Part. Sci. 2019 AA:1-36

02/1987: Birth of Multimessenger Astrophysics

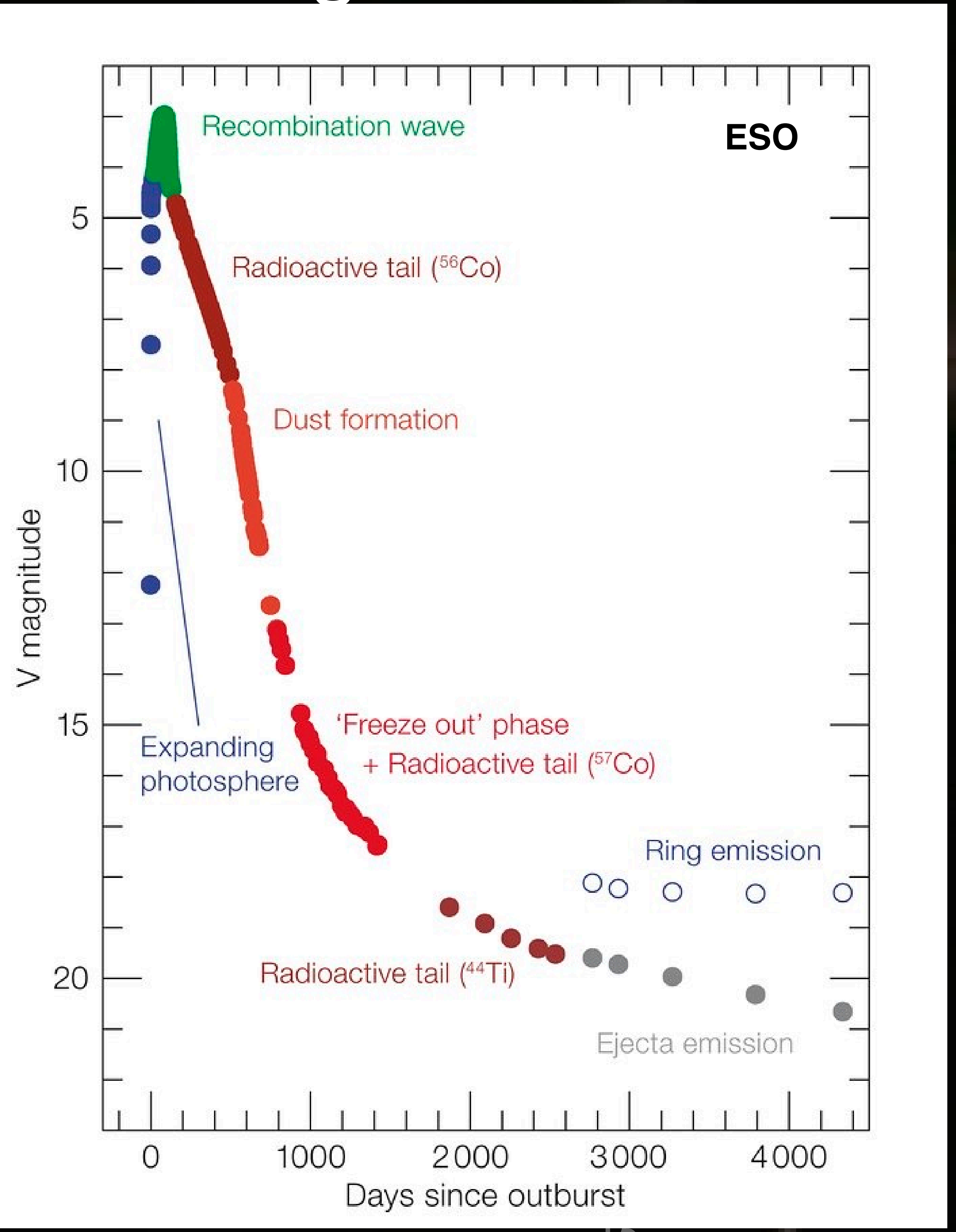


Supernova 1987a

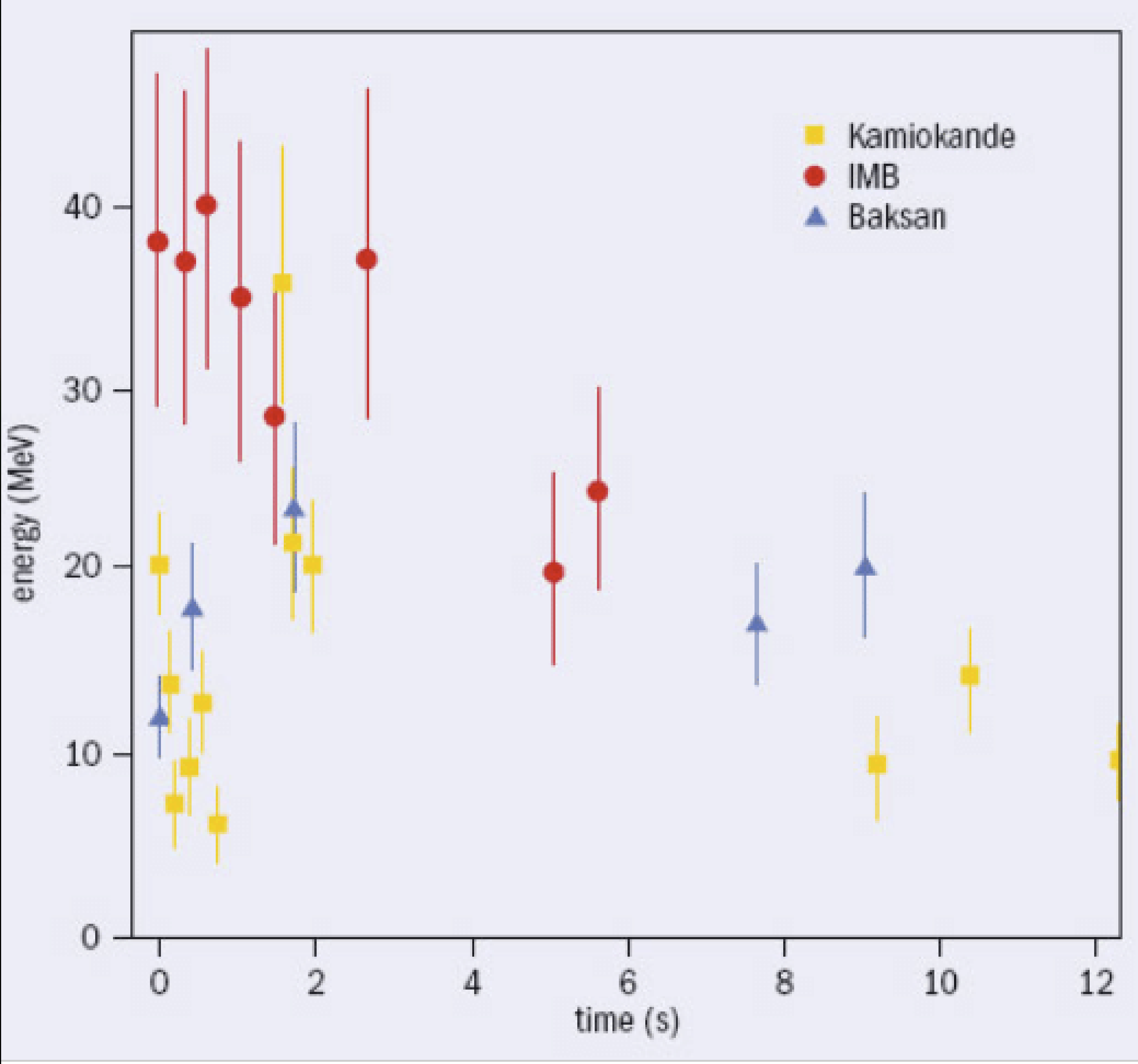
Located in Large Magellanic Cloud @ 50 kpc

~ 17 M_{Solar} → Neutron Star (yet unobserved)

Lightcurve



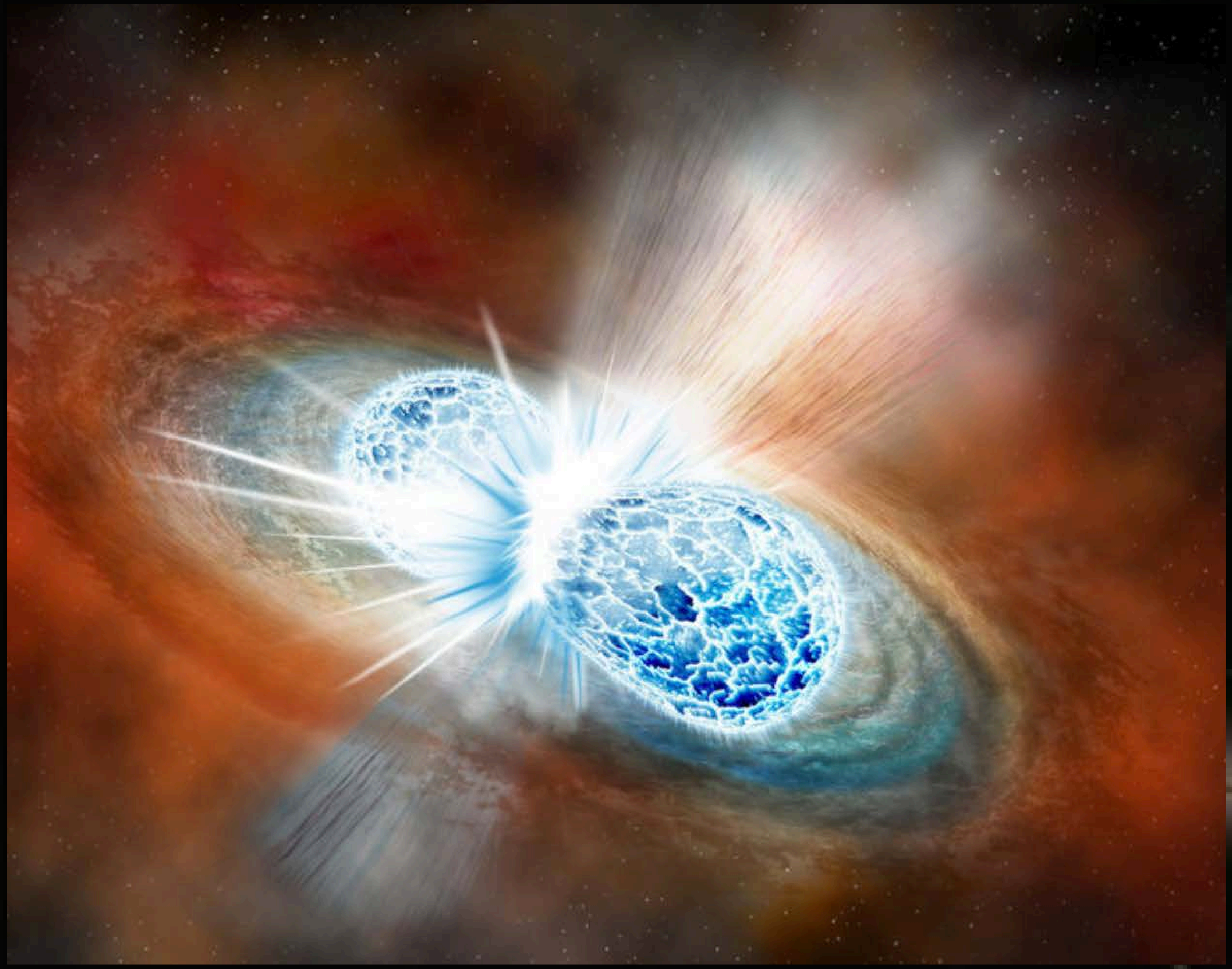
Neutrino-Emission (~19 neutrinos)
~3 hrs before light arrived at Earth



Now a cornerstone of modern astrophysics

- understanding core-collapse SN
- models of stellar evolution
- nucleosynthesis of heavy elements
- expansion of ejecta
- circumstellar material
- ….

08/2017: Big Bang of Multimessenger Astrophysics



Scientific Breakthrough of 2017

Neutron Star Merger GW 170817

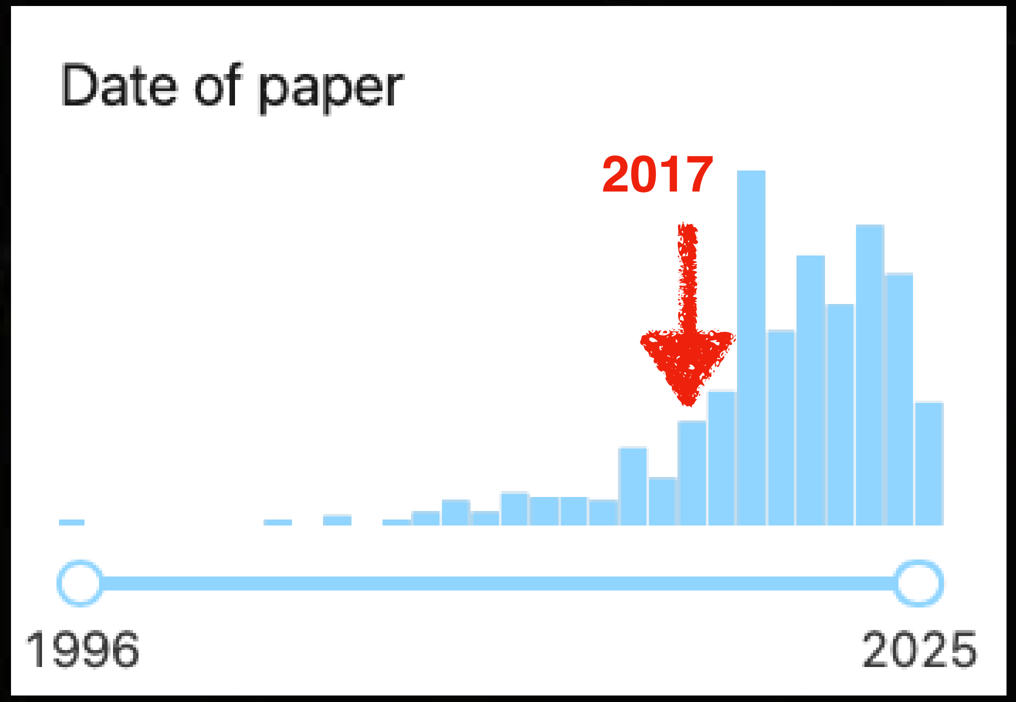
observed in GWs and in a broad range of electromagnetic radiation with strong bounds on HE neutrino emission

Joint publication by > 3000 authors (LHC scale)

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS
CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger



By now ~600 Publications with „Multi-Messenger" in their title
with a total of ~16000 citations
Most cited: ApJL 2017 joint observation paper (~4000 citations by now)

Themes of HE MM-Astrophysics

- **Cosmic Particle Acceleration**
  - How and where are cosmic rays accelerated?
  - Does Nature impose any energy limits?
  - How do CRs propagate through space?
  - What is their impact on the cosmic environment?
- **Probing Extreme Environments**
  - Processes close to supermassive black holes or GRBs?
  - Processes in relativistic jets, winds and radio-lobes?
  - Exploring cosmic magnetic fields
- **Physics Frontiers – beyond the SM**
  - Lorentz invariance violation; Smoothness of Space
  - Particles beyond SM ?
  - New particle physics at $\sqrt{s}$=150 TeV ?

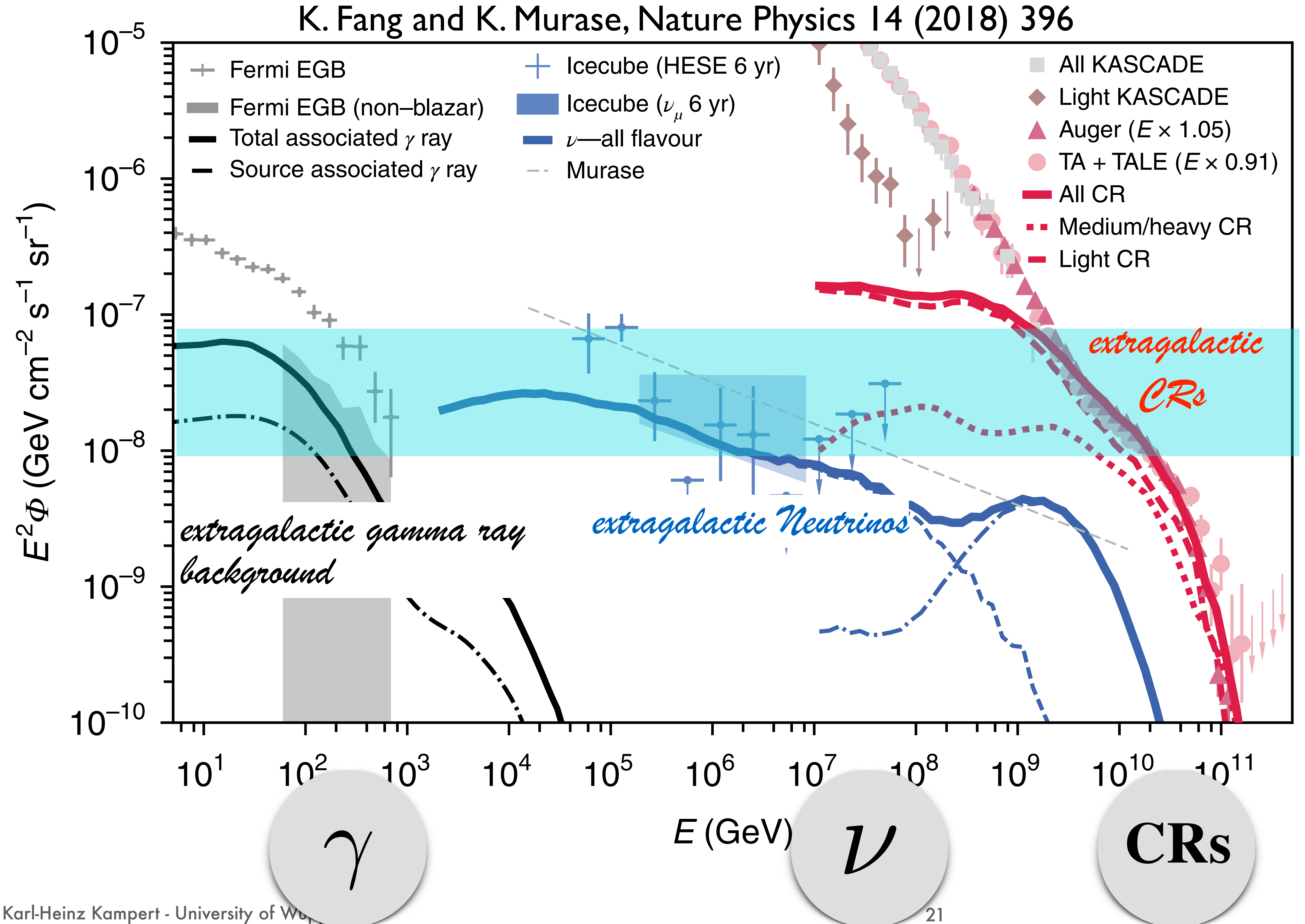
Multi-Messenger Observations
contribute important information
to all of these themes

Outline

Some generalities about MM Astrophysics

- Comparison of messengers and techniques
- GZK-effect and Cosmogenic Photons and Neutrinos
- GW170817
- TXS 0506-056, BNS-Mergers and other transient events
- Upwards-going EAS and new physics ?
- Search for BSM particles
- Prospects

Cosmic Coincidence or Grand Unified Picture ?



10 orders of magnitude in energy, but $E^2 \cdot \Phi$ is about the same in UHECRs, γ's and ν's

→ energy generation rates per decade in E are the same

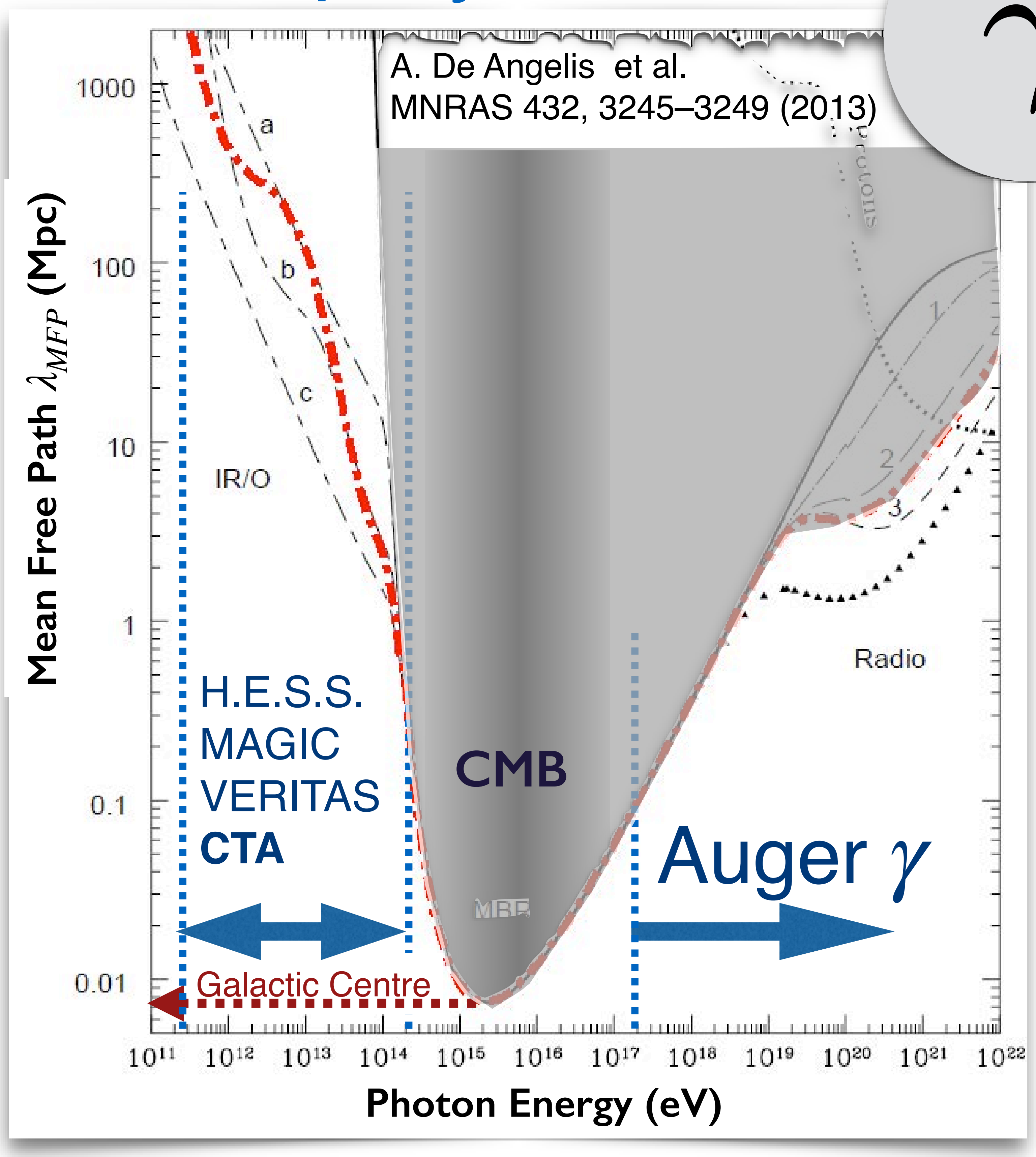
Suggests again a common / related origin

How far can you see?

Andromeda
(700 kpc)

Is there a „Best" Messenger ?

γ-ray horizon



⊕ straight lines

⊕ unexplored at >10^{17} eV

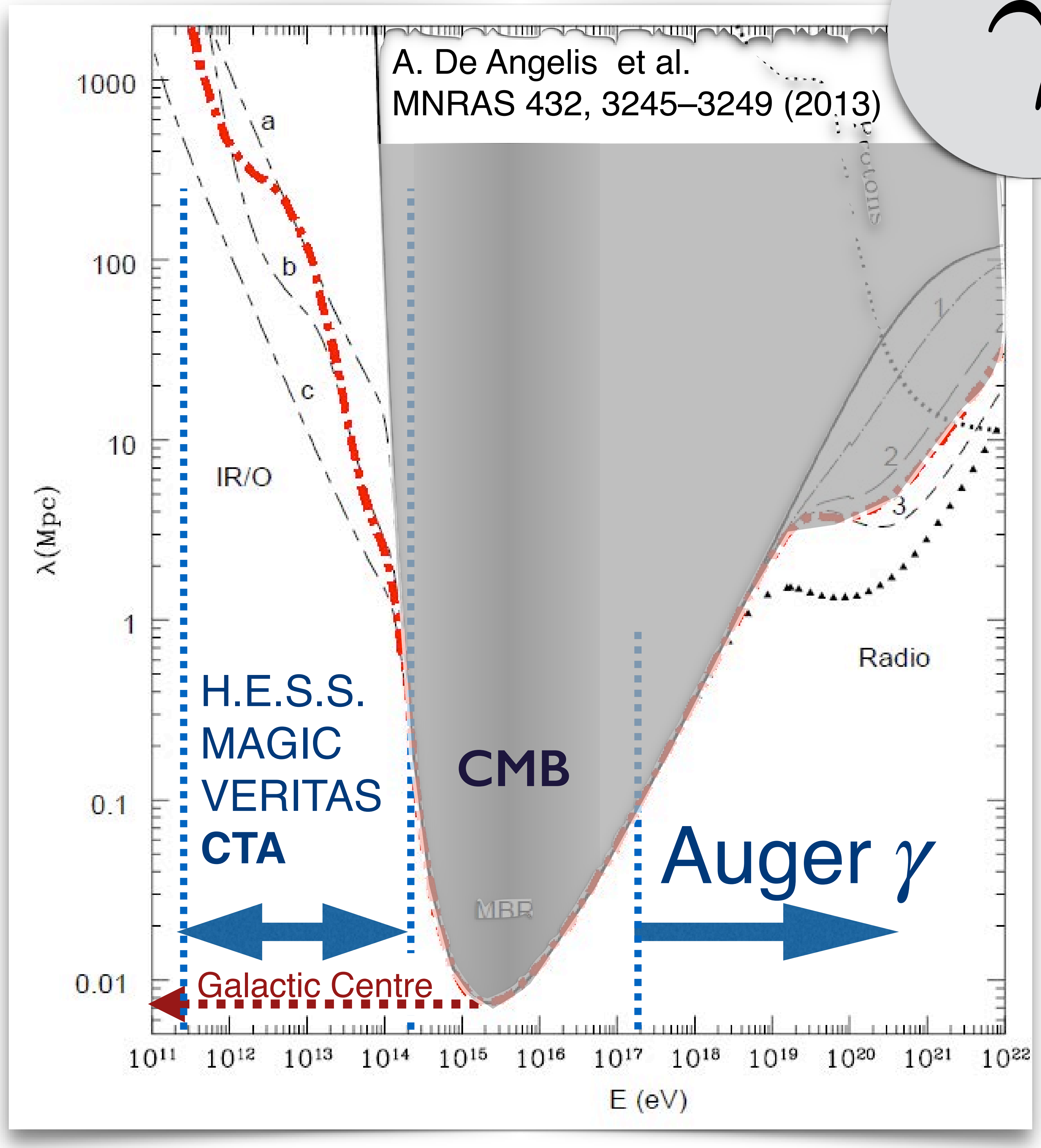
⊖ UHE Horizon < 10 Mpc

⊖ no clean probe of hadron acceleration

- at 2 PeV one can hardly see the galactic centre due to pair production: $\gamma_{HE} + \gamma_{CMB} \rightarrow e^+e^-$
  $\lambda_{MFP}(1\ \text{PeV}) \simeq 10$ kpc
- $\lambda_{MFP}(10\ \text{TeV}) \simeq$ some 10 Mpc
- $\lambda_{MFP}(10\ \text{PeV}) \simeq$ few Mpc

Is there a „Best" Messenger ?

γ-ray horizon



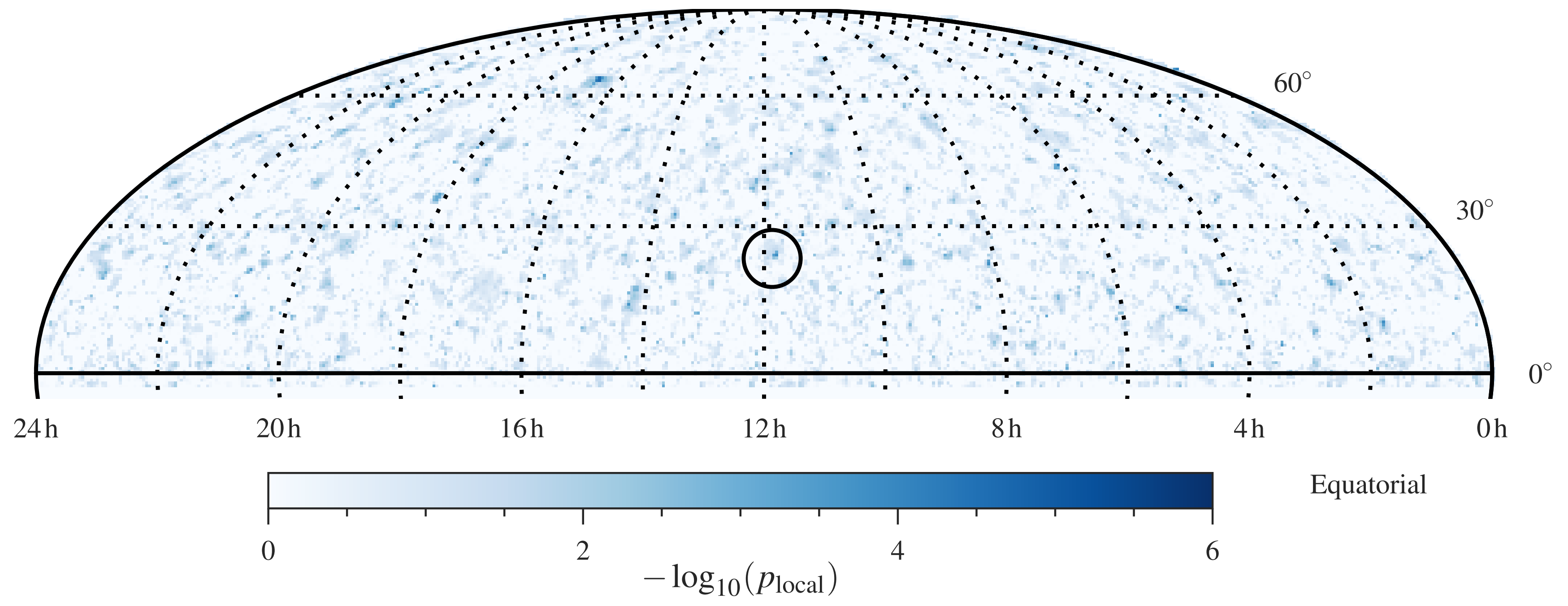
γ

- ⊕ straight lines
- ⊕ unexplored at >10^{17} eV
- ⊖ UHE Horizon < 10 Mpc
- ⊖ no clean probe of hadron acceleration

HE-Neutrino Sky

ν

IceCube, EPJ 2019 (arXiv:1811.07979)



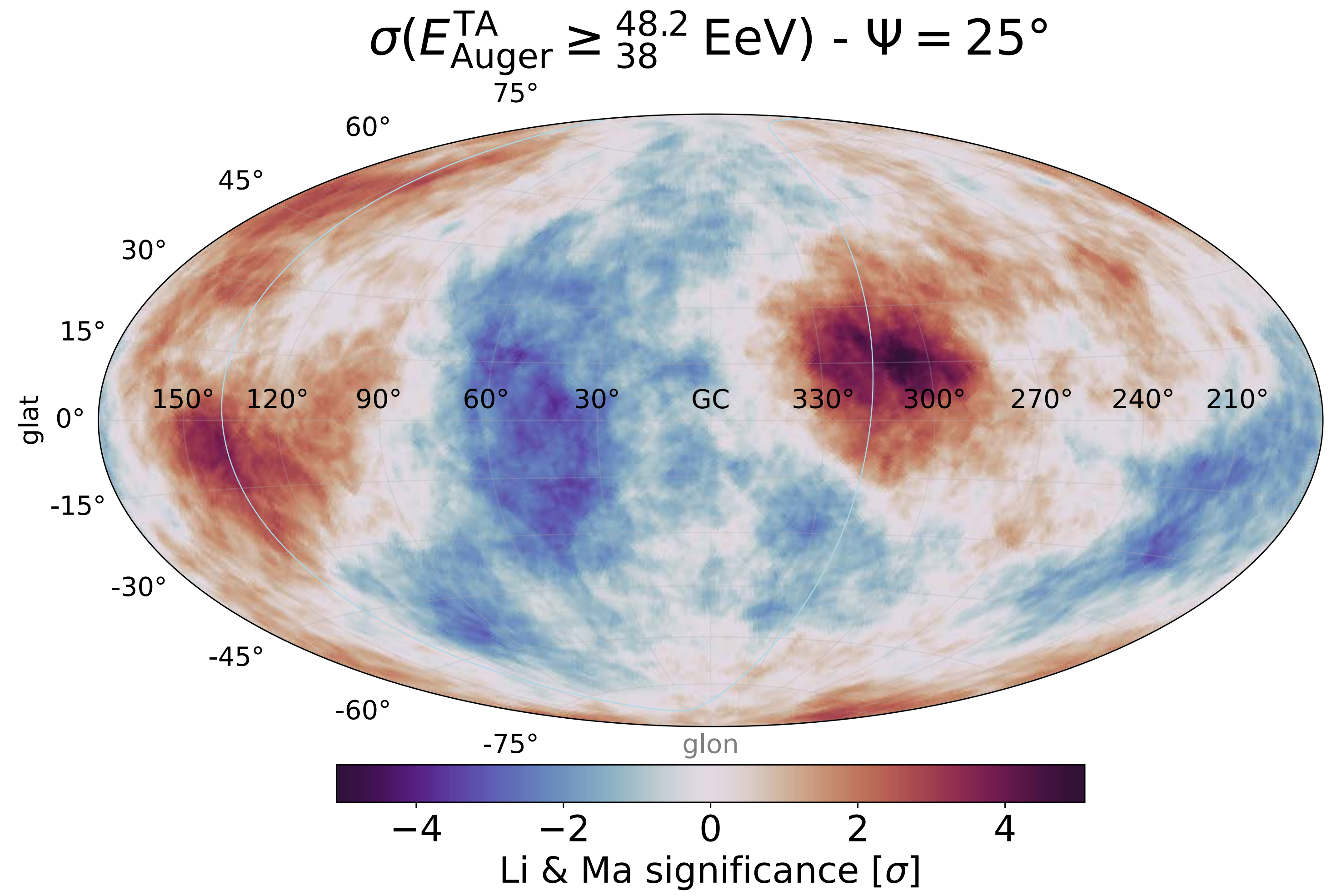
- ⊕ straight lines
- ⊕ clean hadronic probe
- ⊖ Horizon = Hubble ⇒ isotropic
- ⊖ (non bursting) point sources difficult

UHECR Sky

above 40 EeV

CRs

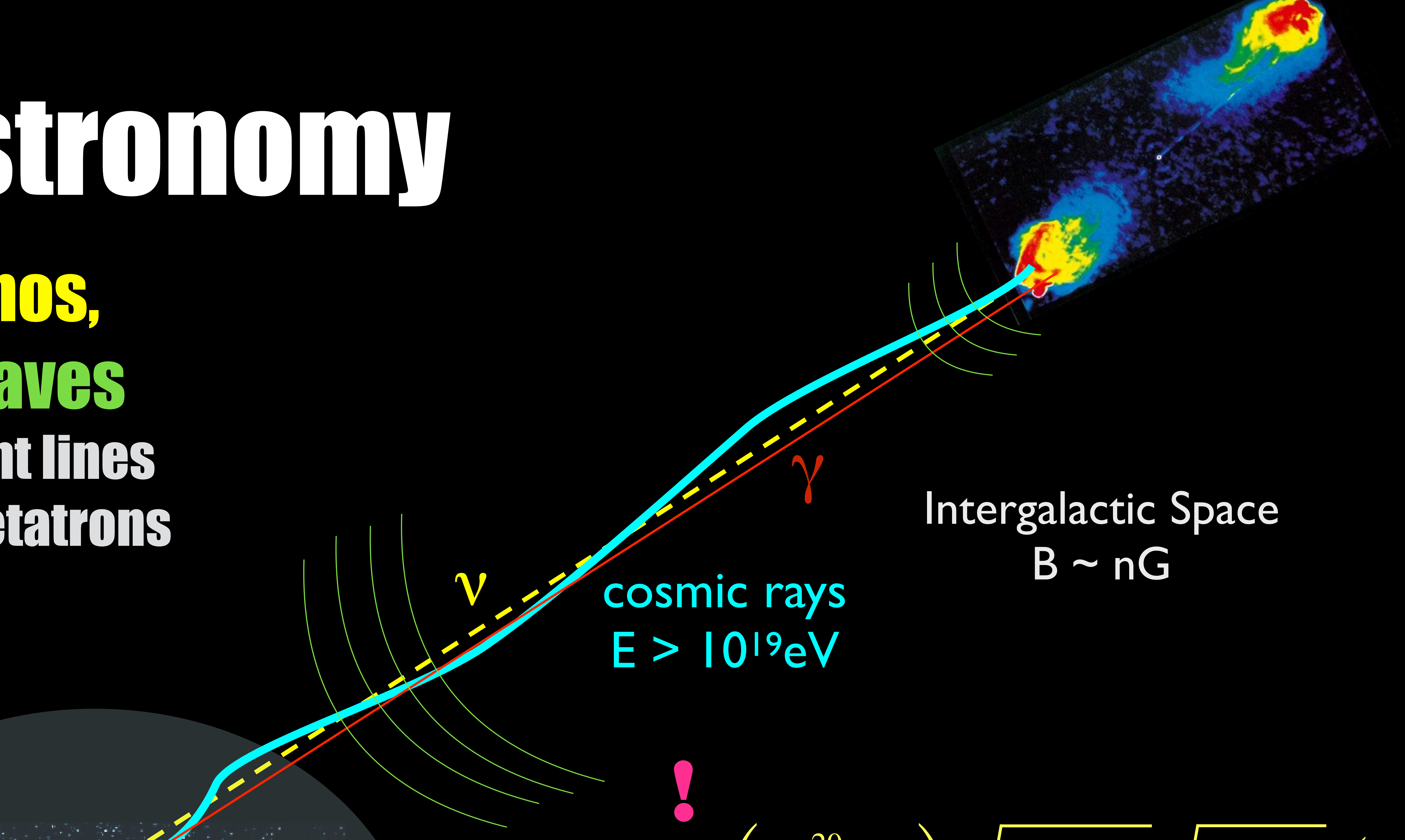
Auger & TA Working Group at ICRC 2023

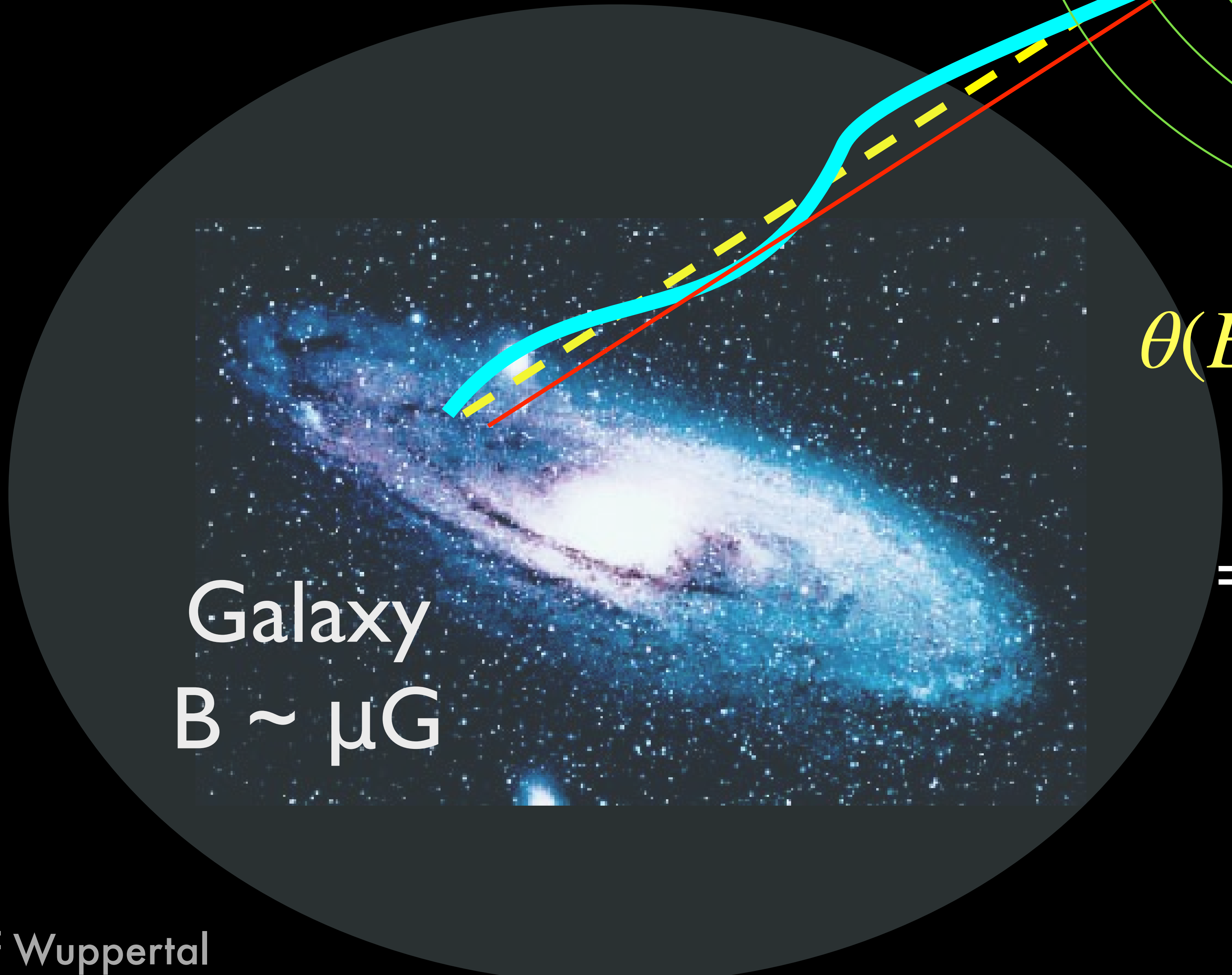


- ⊕ the only direct probe
- ⊕ probes extreme accelerator
- ⊕ chemical composition
- ⊕/⊖ Horizon some 100 Mpc
- ⊖ deflection in magnetic fields

UHECR Astronomy

Photons, Neutrinos, Gravitational Waves
propagate on straight lines
but may not probe Zetatrons





!

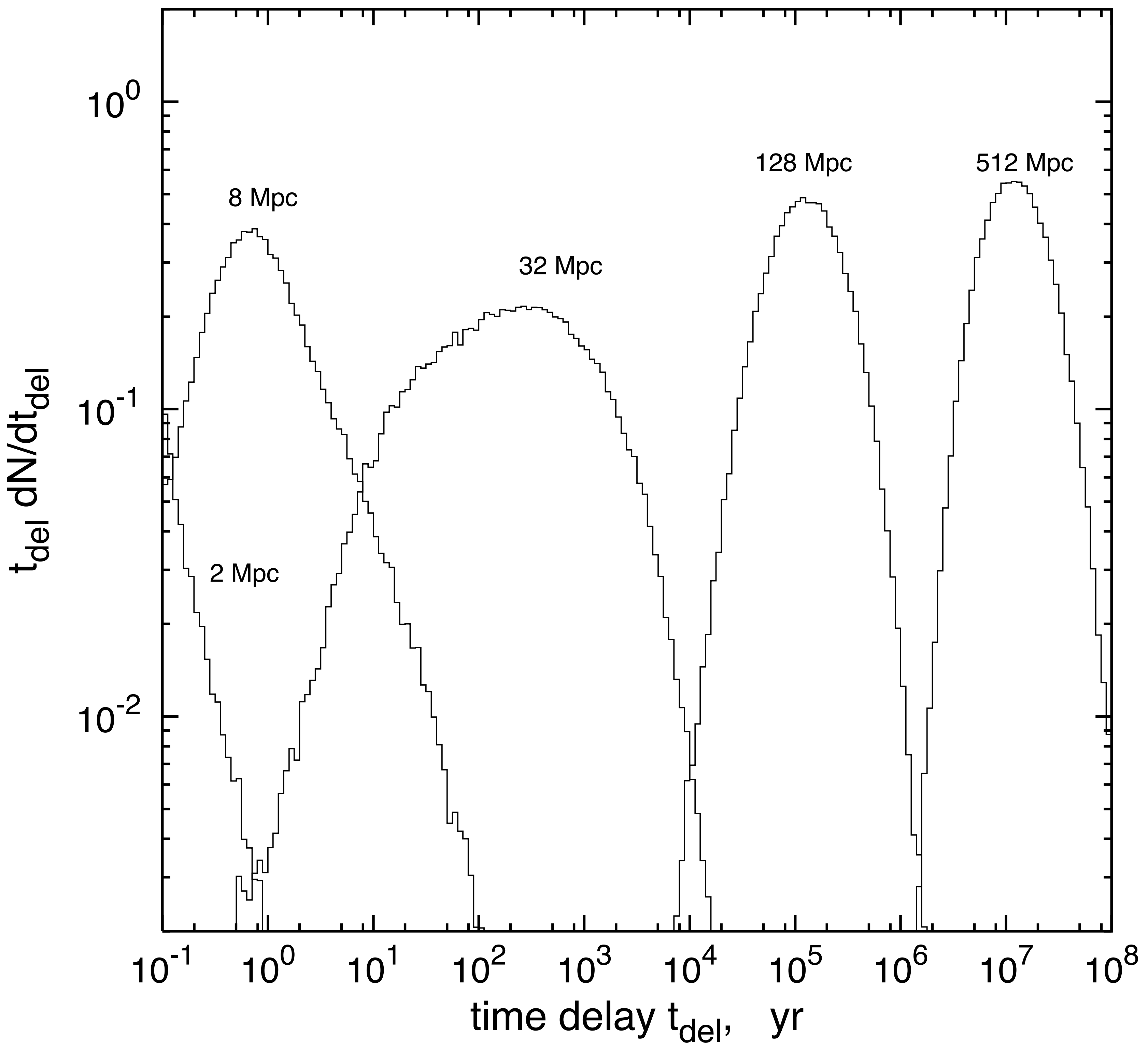
$$\theta(E,Z) \approx 0.8^\circ \cdot Z \times \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)\sqrt{\frac{d}{10\ \mathrm{Mpc}}}\sqrt{\frac{L_{coh}}{1\ \mathrm{Mpc}}}\left(\frac{B}{1\ \mathrm{nG}}\right)$$

⇒ UHECRs arrive delayed wrt to photons and neutrinos

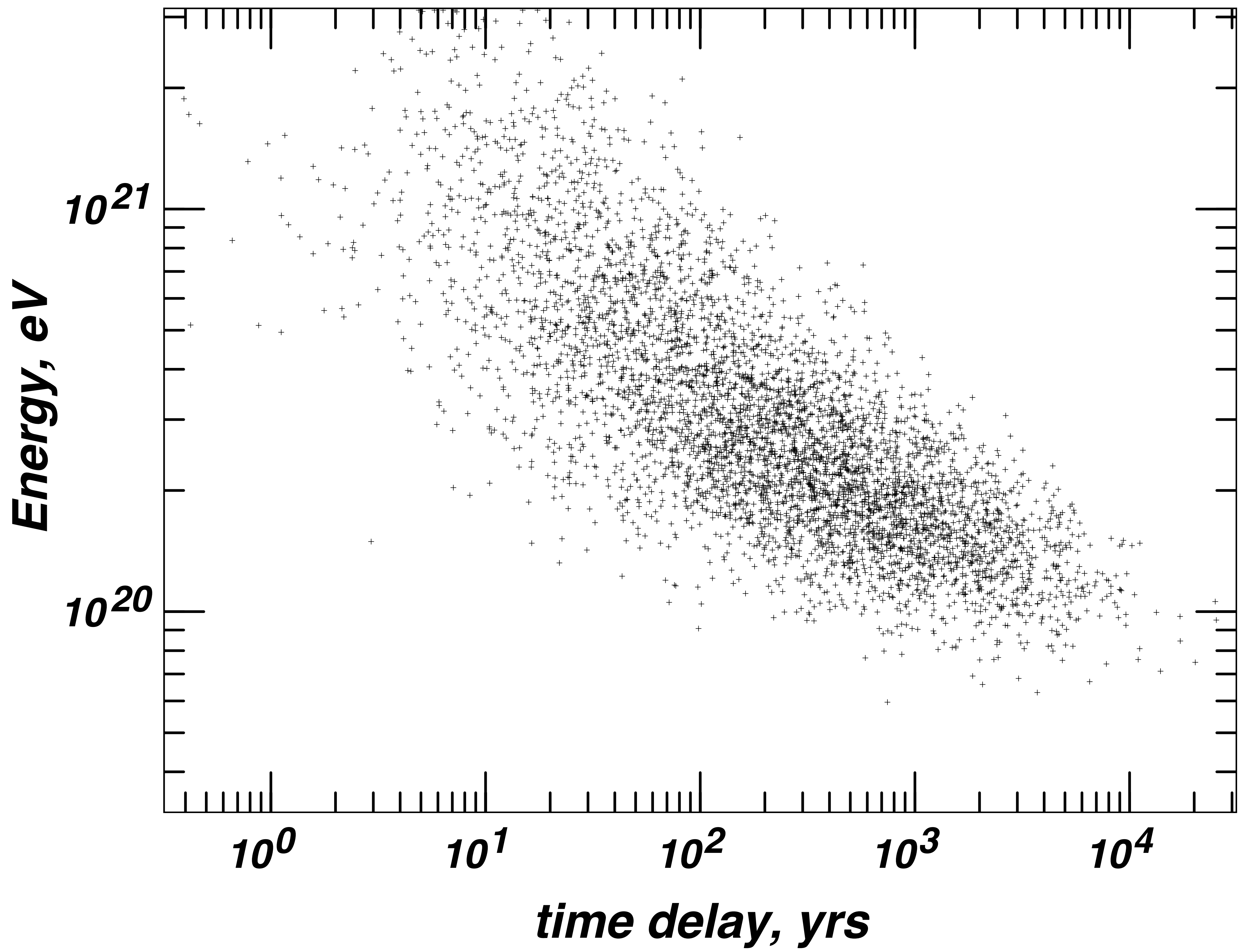
$$\langle t_{delay}\rangle \approx 1.5 \cdot 10^3\ \mathrm{yrs} \times Z^2 \left(\frac{10^{20}\ \mathrm{eV}}{E}\right)^2 \left(\frac{d}{10\ \mathrm{Mpc}}\right)^2 \left(\frac{L_{coh}}{1\ \mathrm{Mpc}}\right)\left(\frac{B_{rms}}{1\ \mathrm{nG}}\right)$$

Time Delay of UHECRs in EGMF

B_{rms}=1 nG ; E_p=$10^{21.5}$ eV



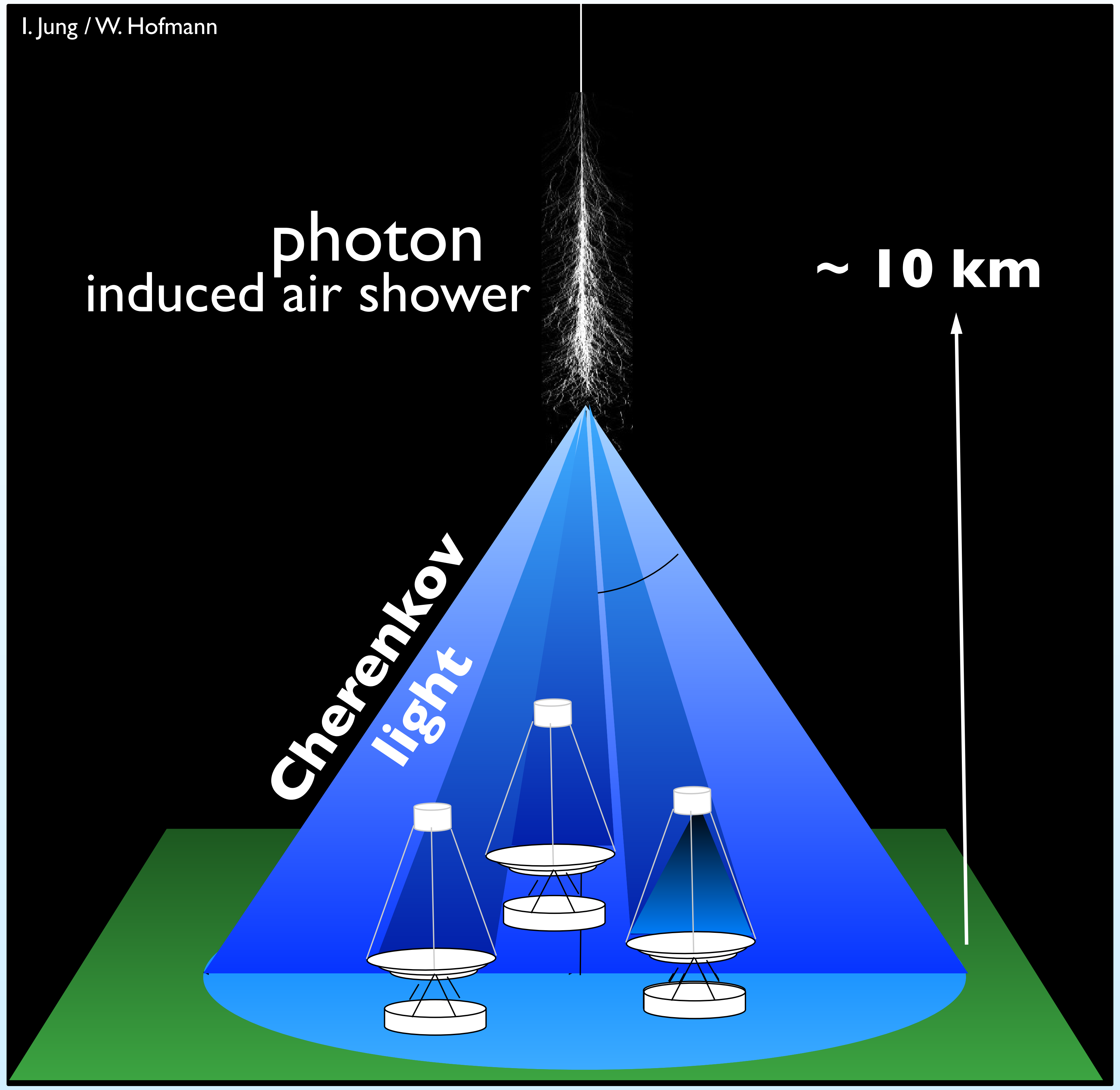
… after propagation over 32 Mpc

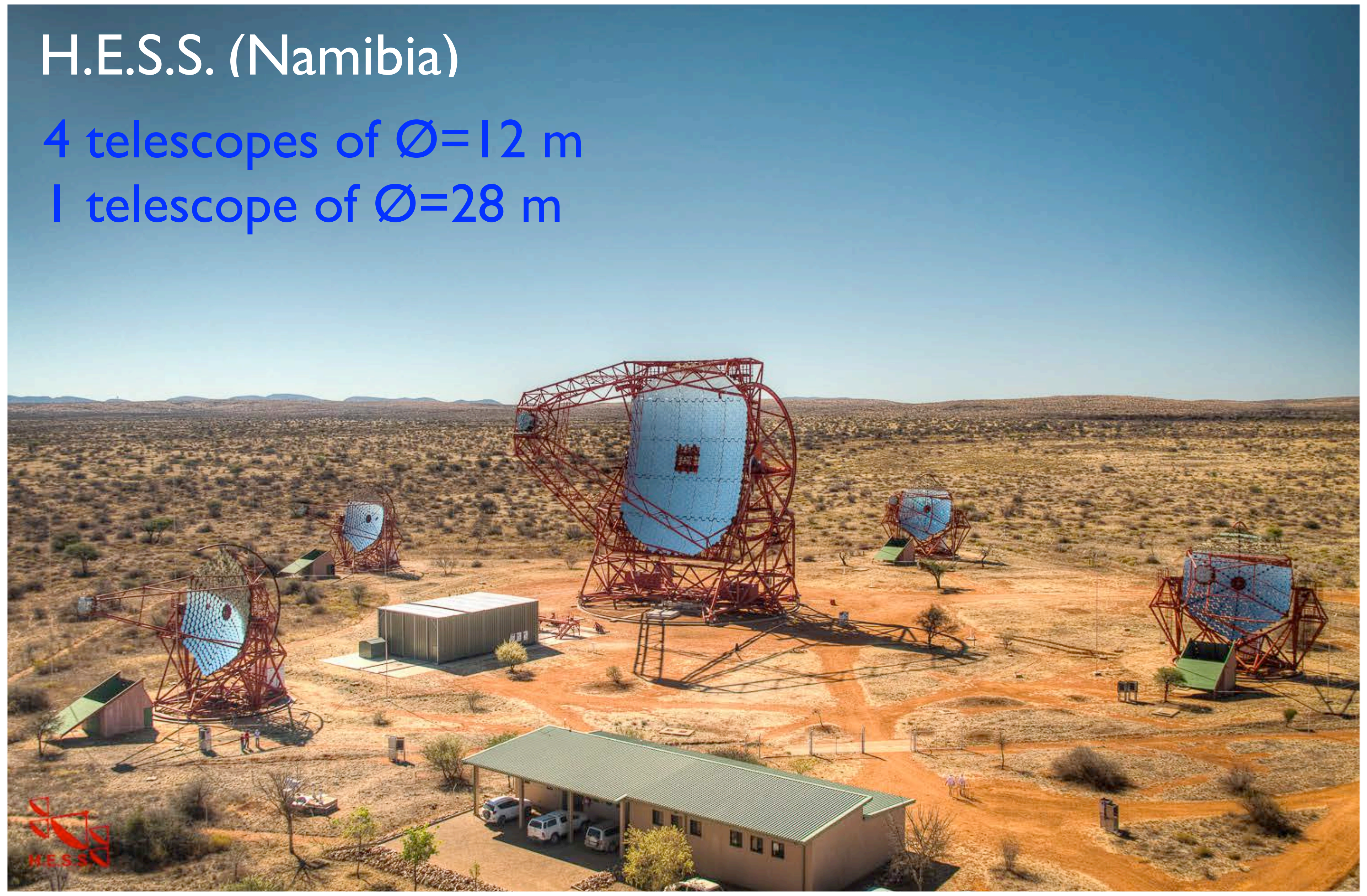


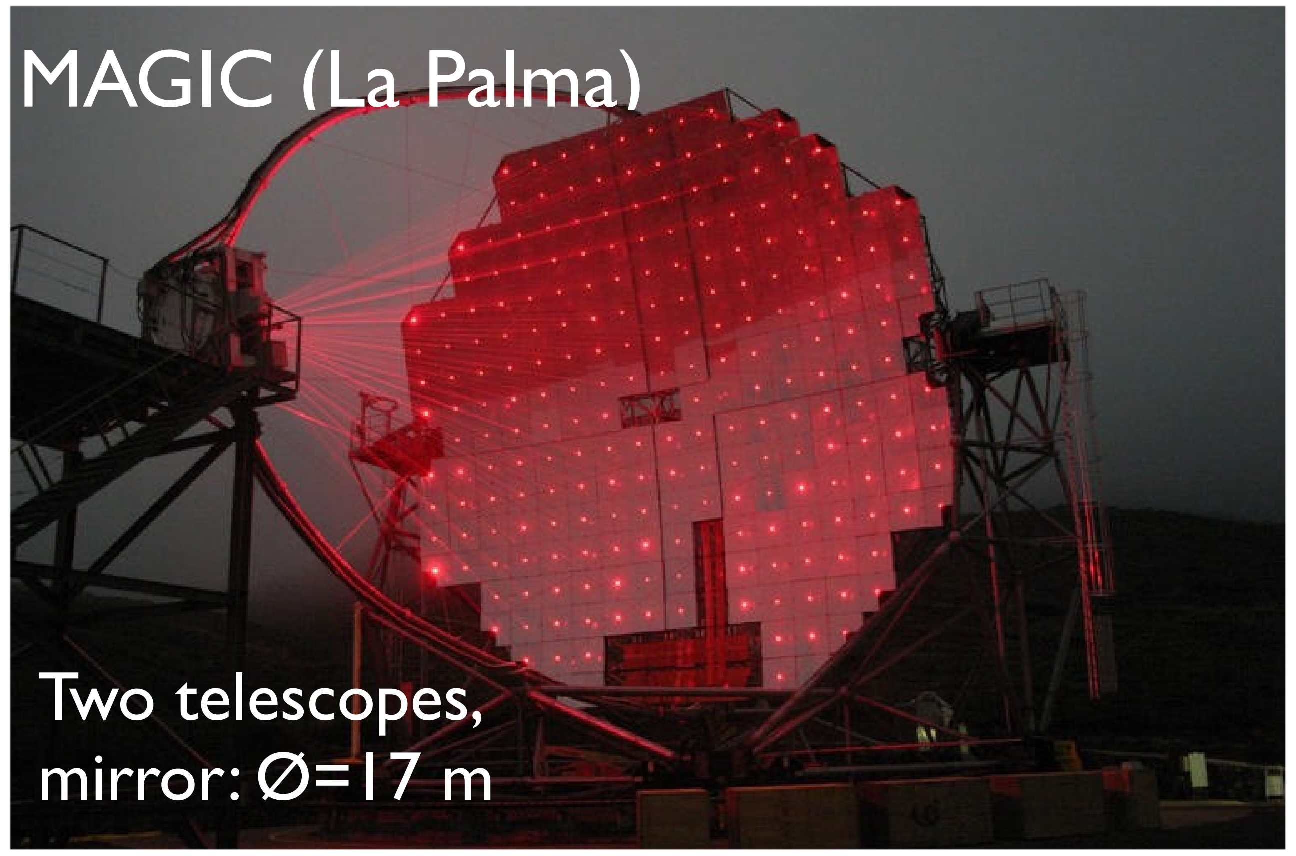
UHECRs cannot (directly) contribute to time-domain studies but provide key information about UHE sources, intergalactic and galactic environment in other ways

T. Stanev et al., PRD 62 (2000) 093005

γ Eyes to the High Energy Universe: IACT

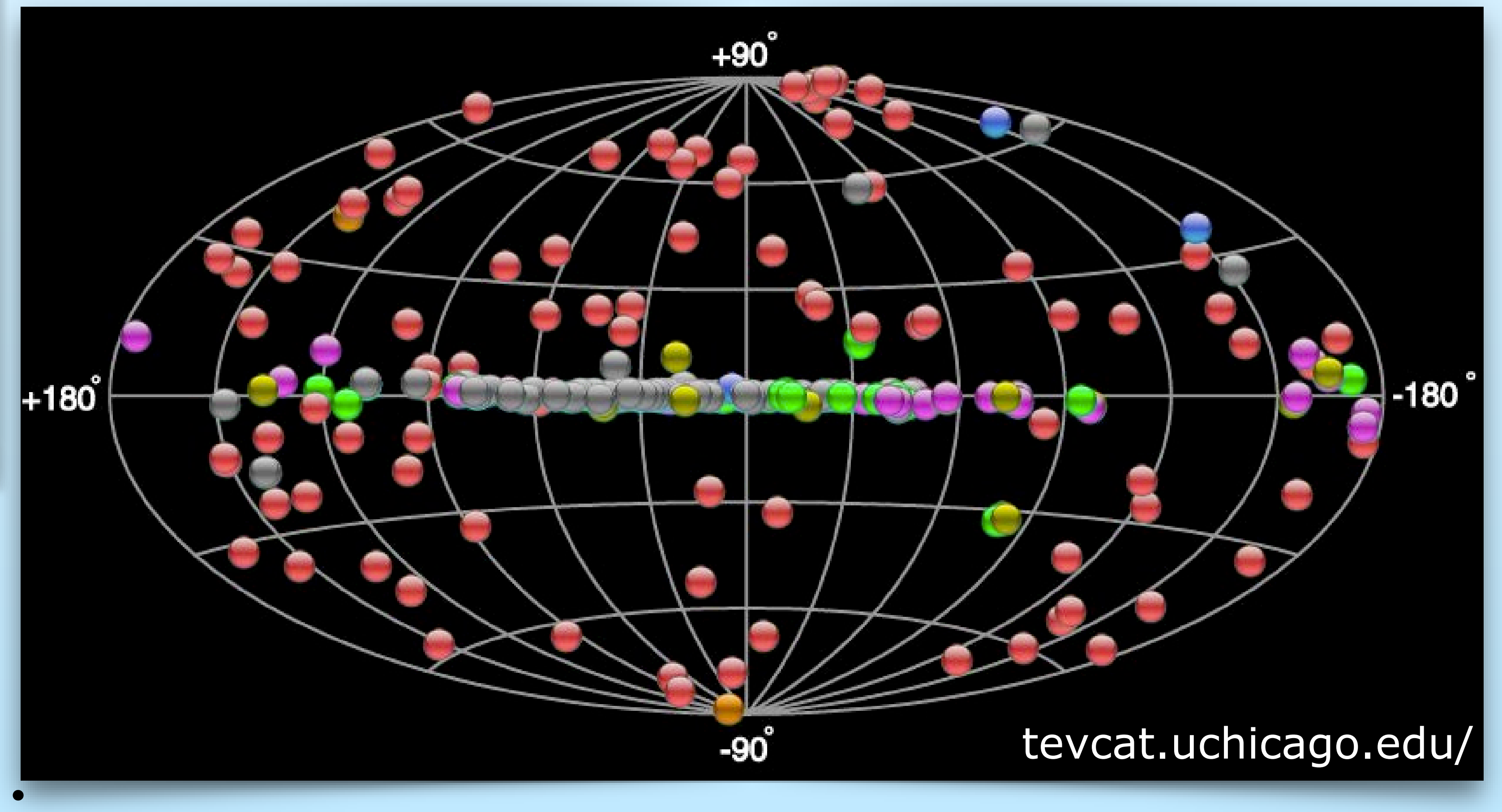


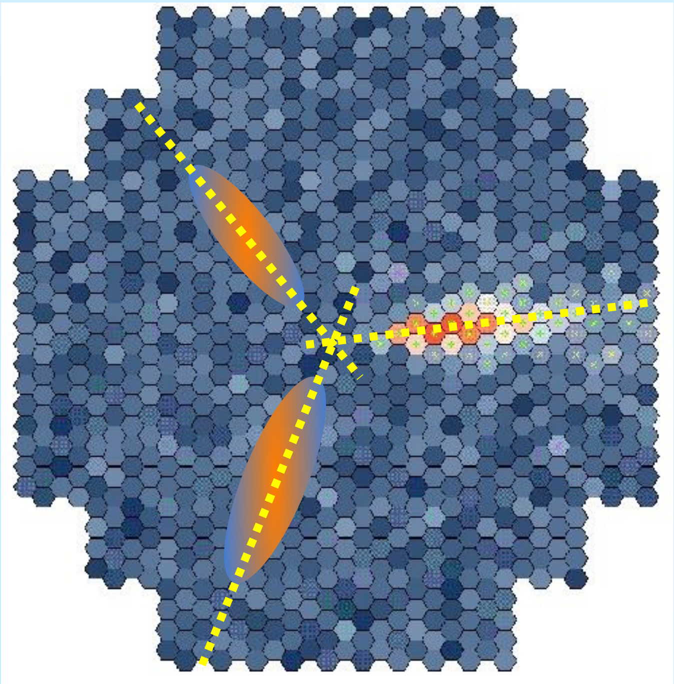




CTA under construction

A new branch of astronomy has emerged





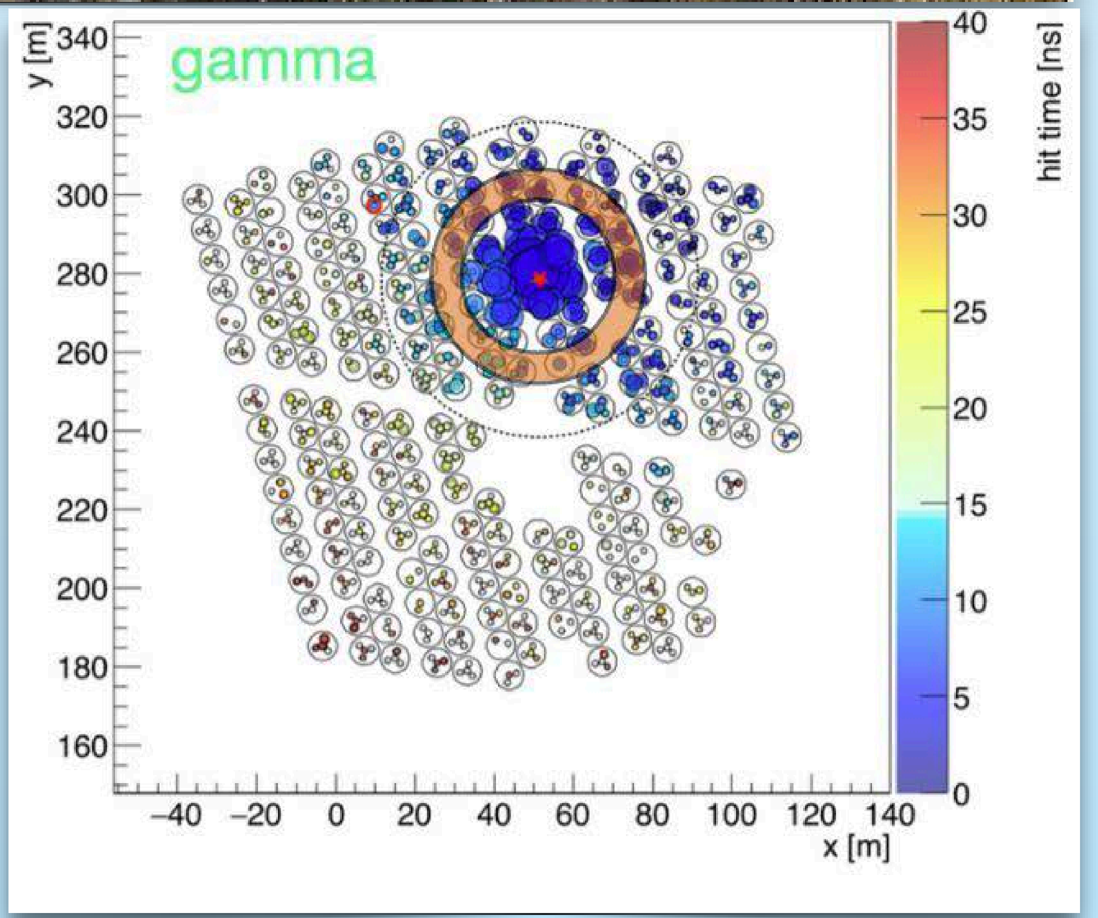
superposition of camera images
- light intensity: energy
- intersection: direction
- shape: primary particle

250 confirmed sources by now:
PWN, starbursts, SNR, AGN, ….

γ Eyes to the High Energy Universe: detector arrays

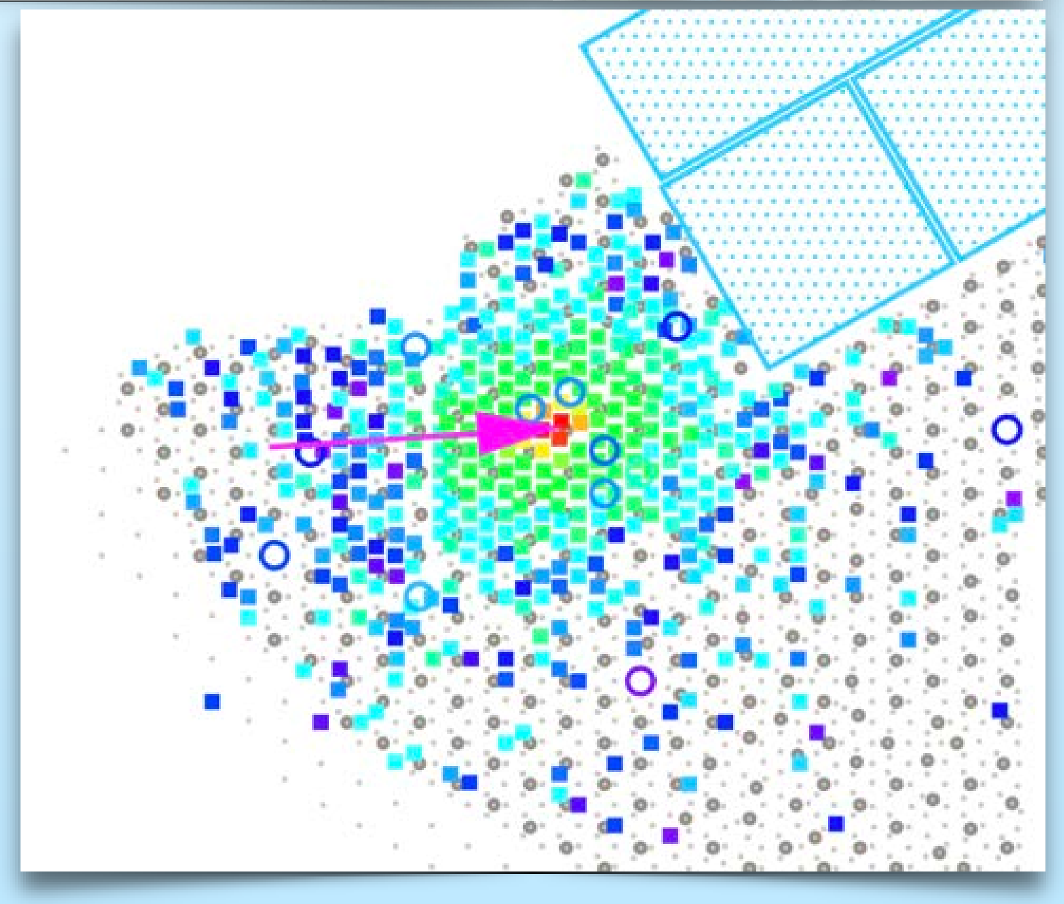
HAWC (Mexico)

Sierra Negra, Mexico
- 4000 m a.s.l.
- ~20,000 m^2
- 300 WCDs
- 345 outrigger detectors

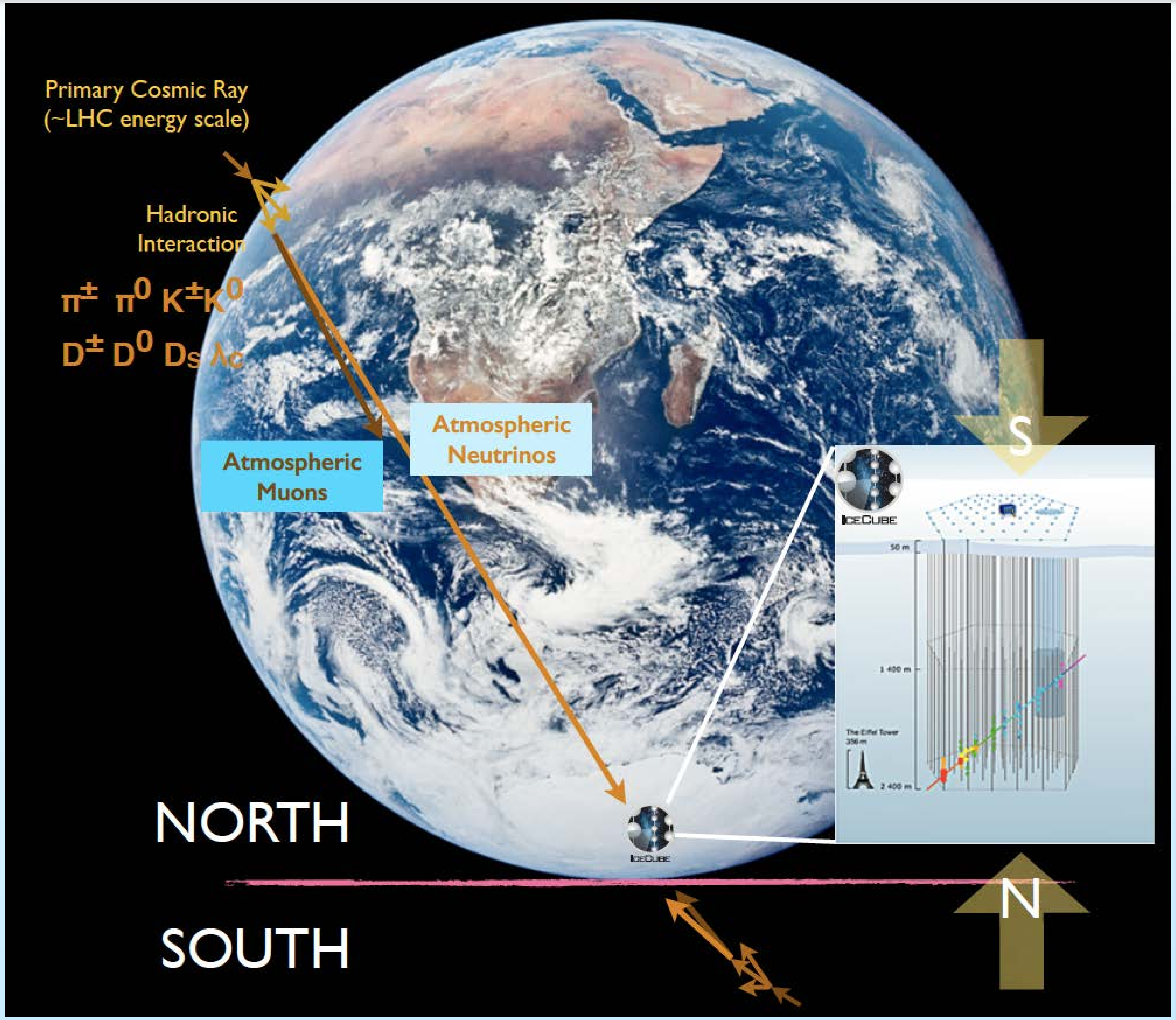


LHAASO (China)

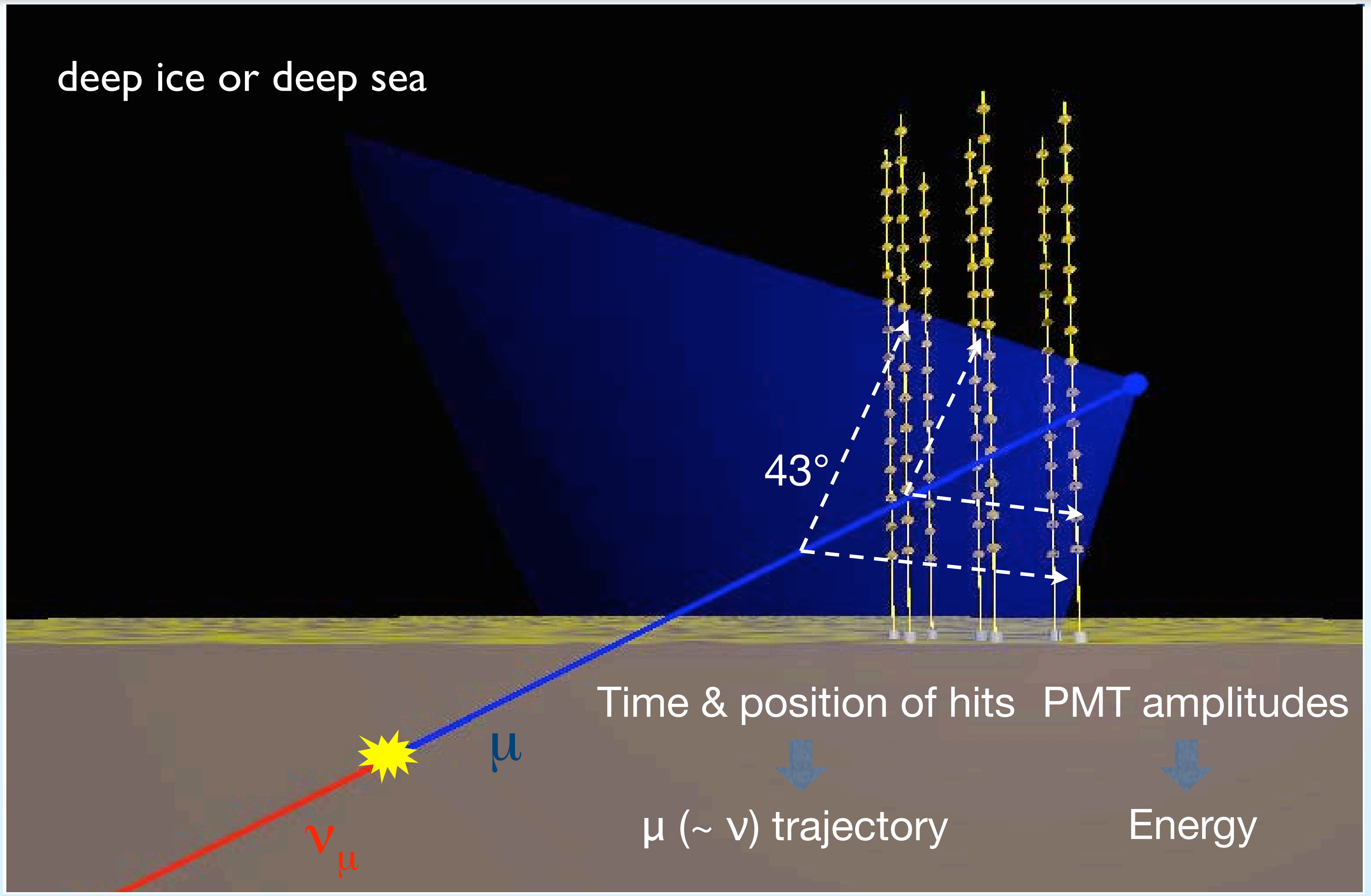
Tibet Area
- 4410 m a.s.l.
- ~78,000 m^2
- 3120 WCDs
- 5242 Scintillators
- 1188 Muon detectors

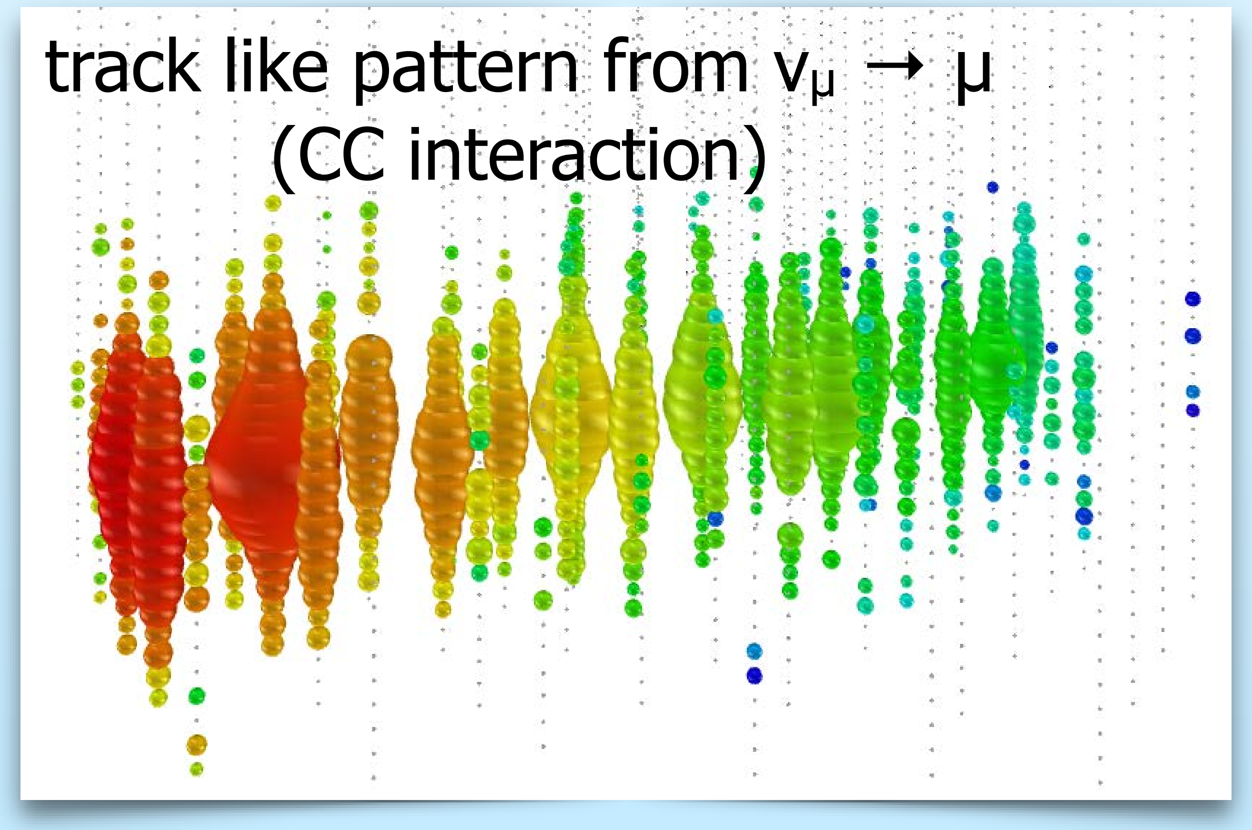


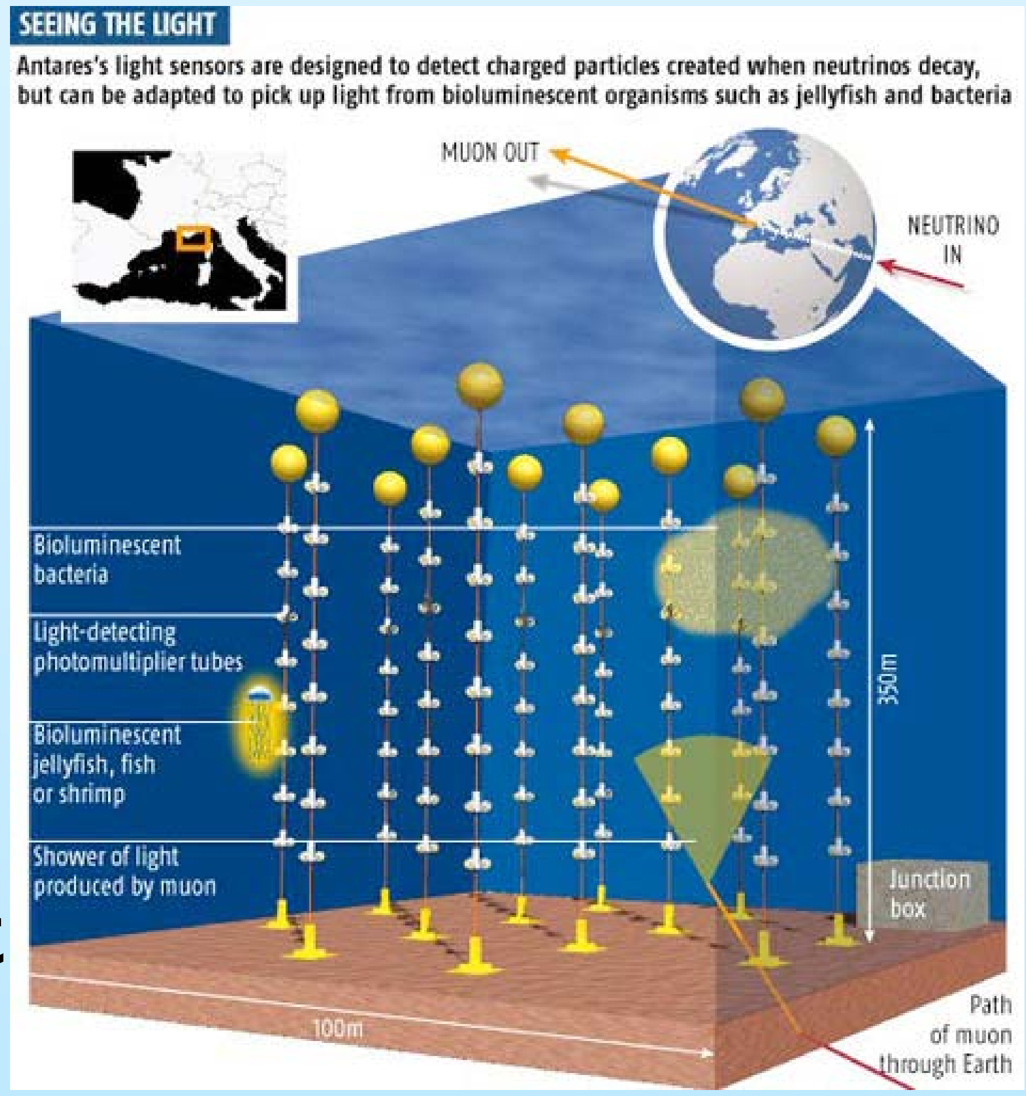
ν Eyes to the High Energy Universe: TeV Neutrinos



IceCube at South Pole







Antares → Km3Net
in mediterranen sea

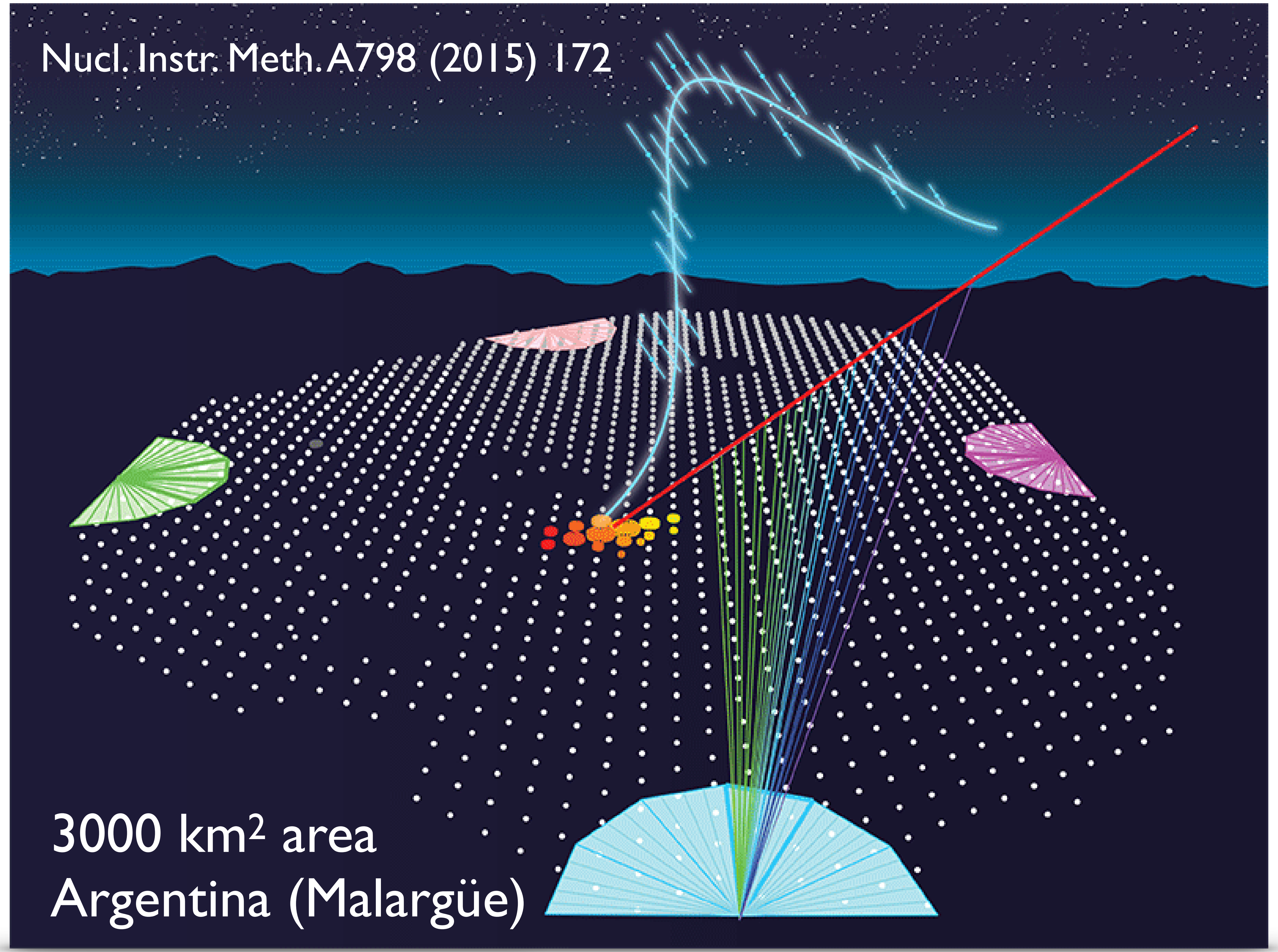
ν Eyes to the High Energy Universe: TeV Neutrinos

Working at IceCube

Deployment of km3net modules


The Observables
direction, time, energy
ν
direction, time, waveform
GW
γ
direction, time, energy
CR
direction, (time), particle type, energy
Note, CRs delayed wrt GW, γ, ν
By construction, a CR observatory is in general also a gamma, neutrino, and neutron-observatory
Moreover, MM physics is more than MWL and more than studying transient events (ToOs)

UHECR Eyes to the High Energy Univserse: Auger



Central campus with visitors center

- 1400 m altitude
- 35° S, 69° W

❶

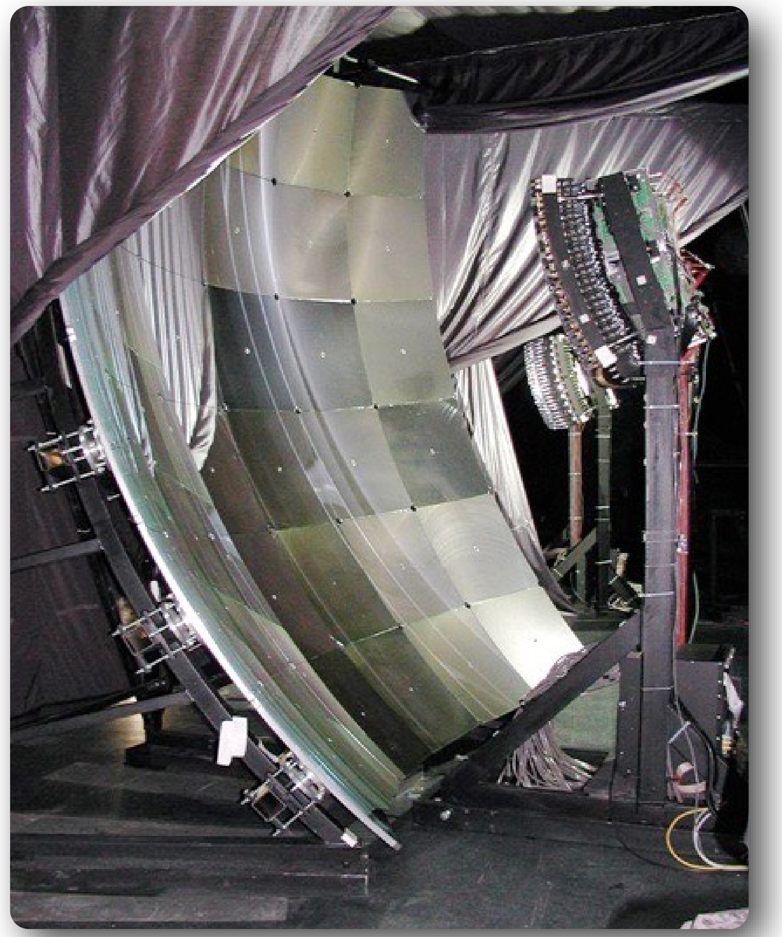
- 27 Telescopes to measure **light trace of EAS** in atmosphere
- integrated light intensity → CR energy
- 13% duty cycle

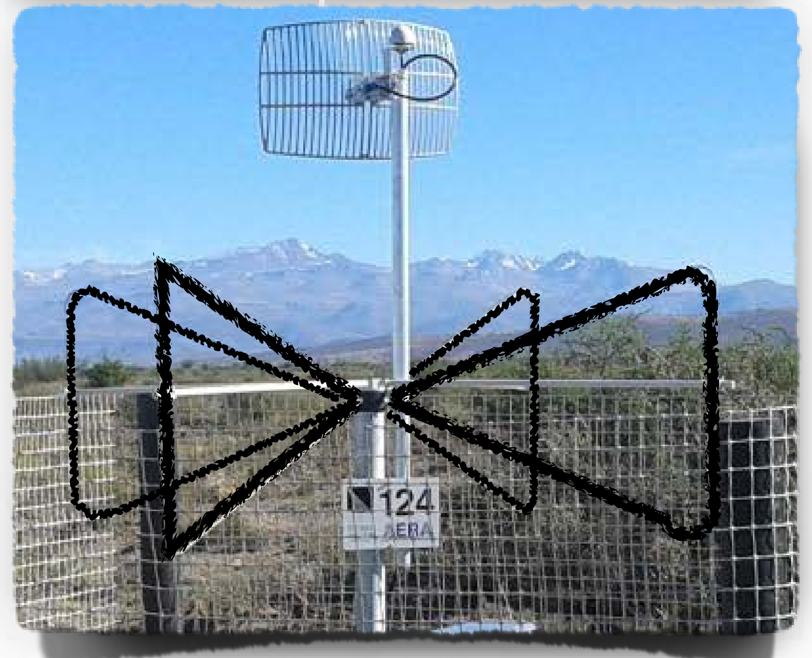
❷

- 1660 Water Cherenkov detectors on 1.5 km grid to measure footprint of **particles at ground**
- 100% duty cycle
- cross calibrated with FD-telescopes with hybrid events

❸

- 153 radio antennas for **em-radiated energy**
- 18 km^2 area
- 100% duty cycle → Now 1500 antennas on 2700 km^2





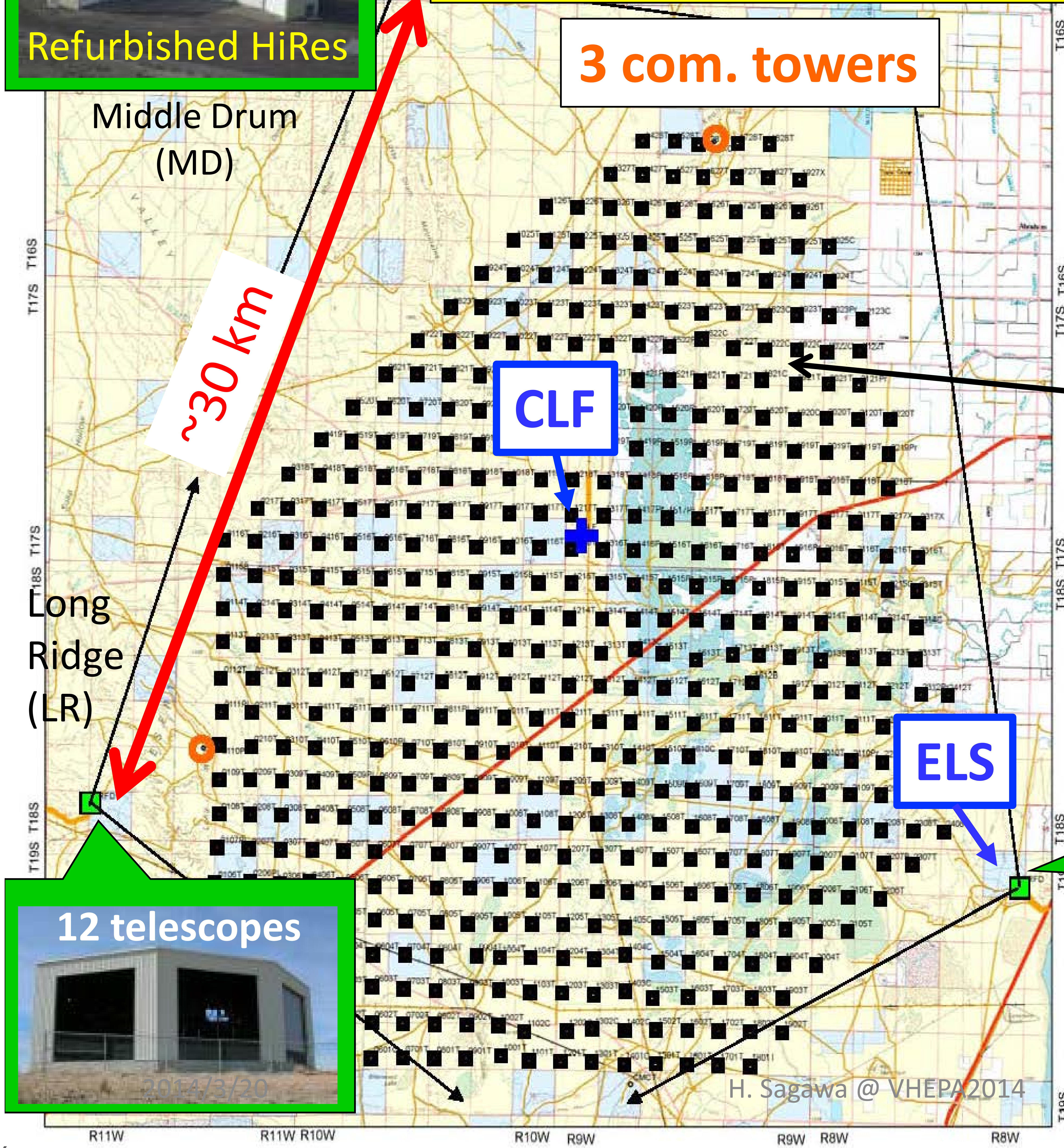
Multi Hybrid Detection of EAS

Fluorescence Light

Particle & Radio Footprint at Ground

TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

507 plastic scintillator SDs
1.2 km spacing
~**700 km²**

Fluorescence Detector(FD)

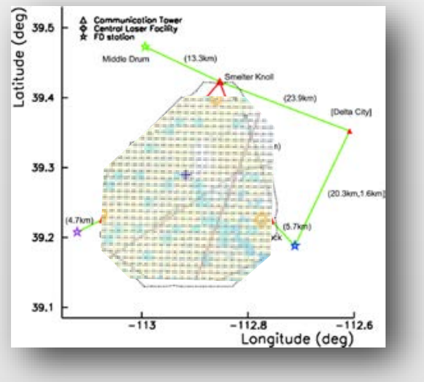
3 stations
38 telescopes

FD and SD: fully operational since 2008/May

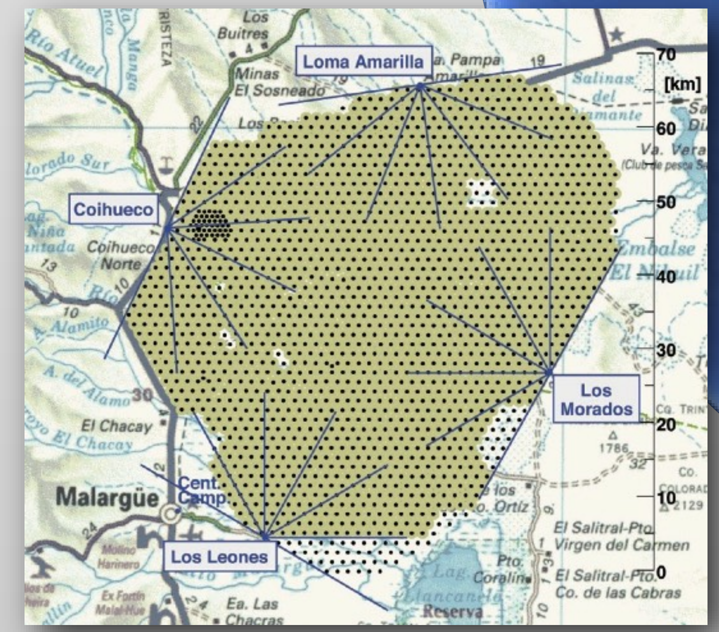
4

Auger and TA

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes



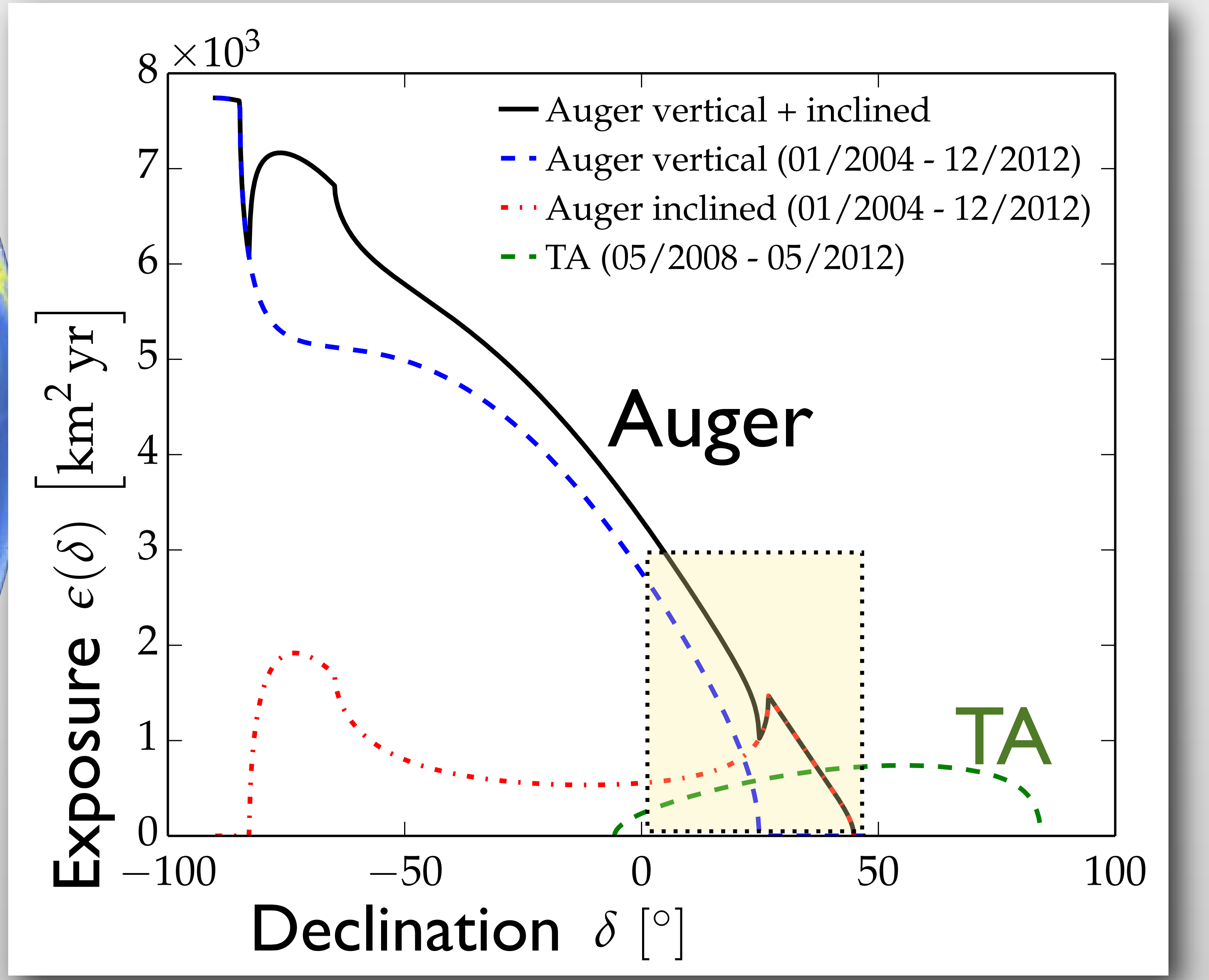
same scale



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

Auger and TA can see the same sky

Auger: started 01/2004
TA: started 05/2008



Auger exposure ~8 times that of TA

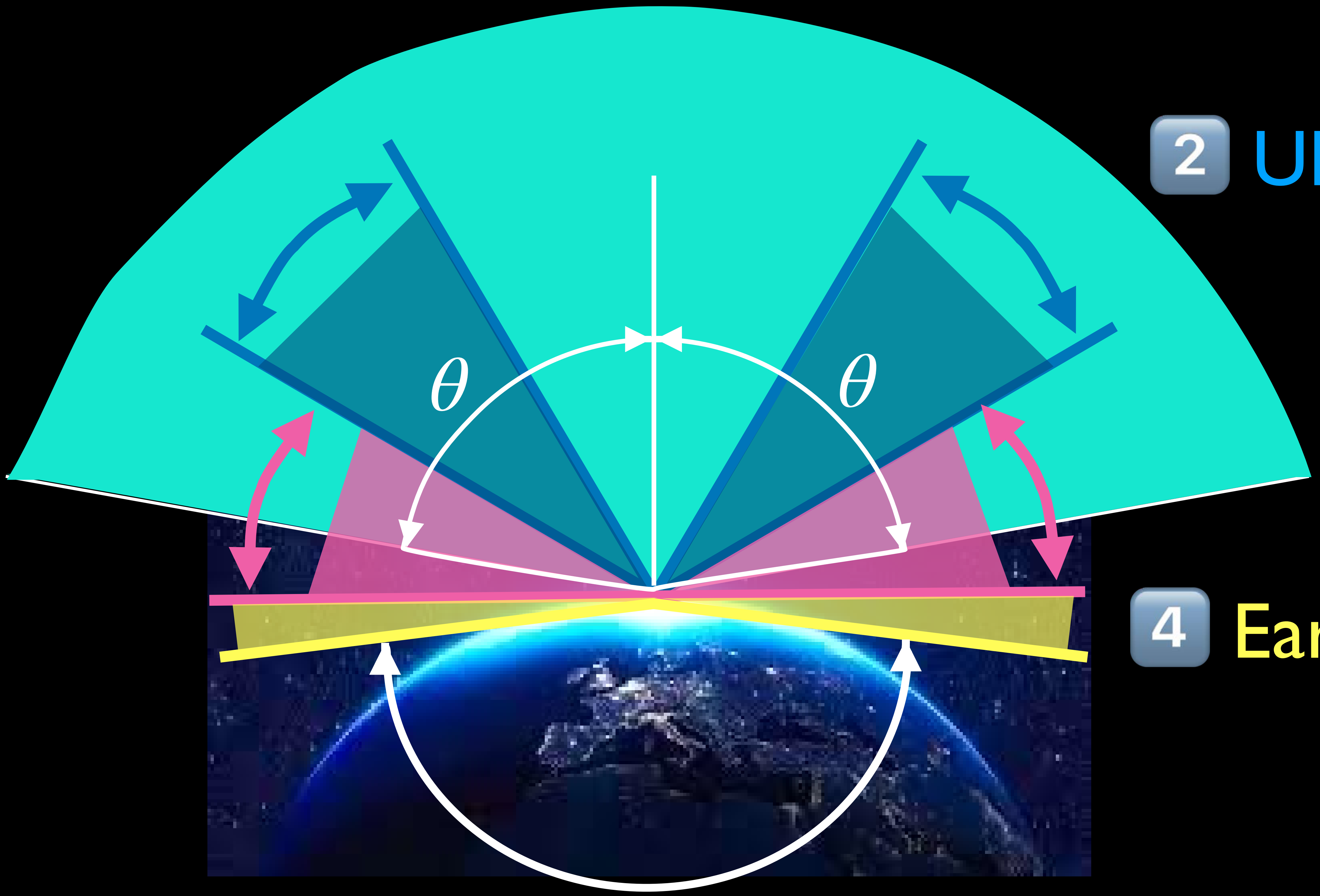
Auger: A 4π MM Observatory

1️⃣ Neutrons and charged CRs: $\Theta \leq 80°$

2️⃣ UHE Photons: $30° \leq \Theta \leq 60°$

3️⃣ Down-Going Neutrinos: $60° \leq \Theta \leq 90°$

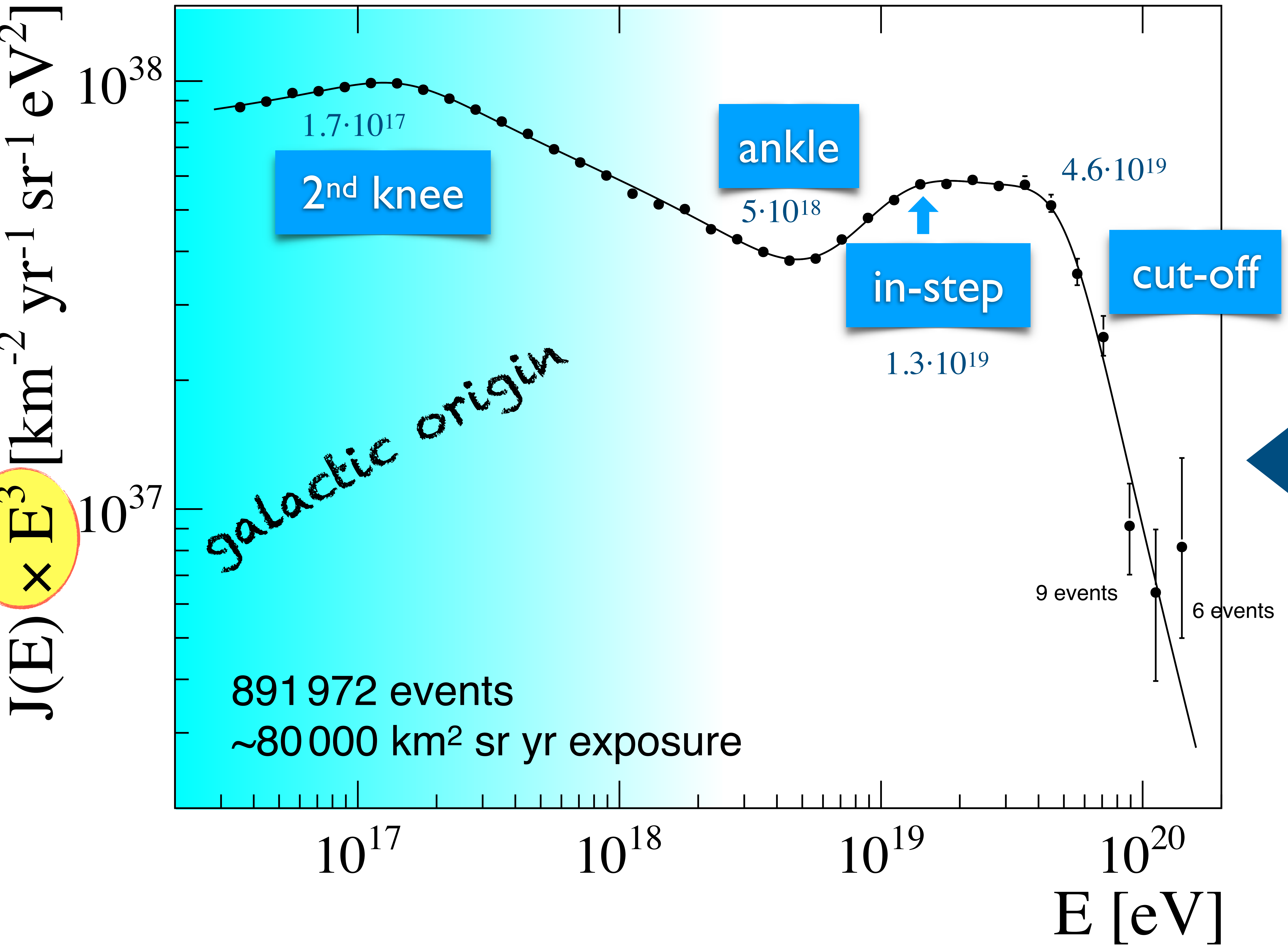
4️⃣ Earth Skimming Neutrinos: $90° \leq \Theta \leq 95°$

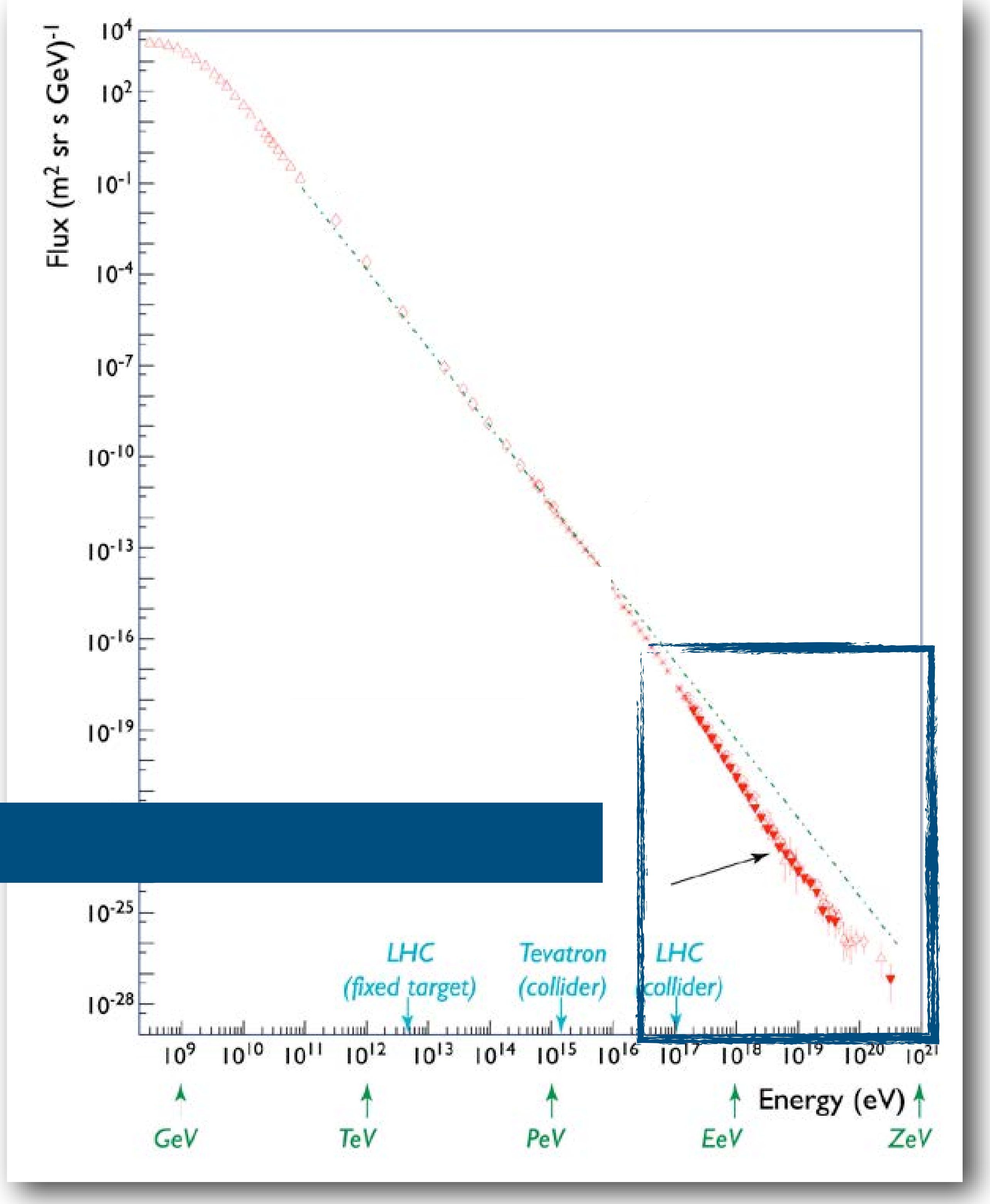


5️⃣ HE BSM Particles: $\Theta > 95°$

Cosmogenic Photons and Neutrinos

The End of the CR Energy Spectrum

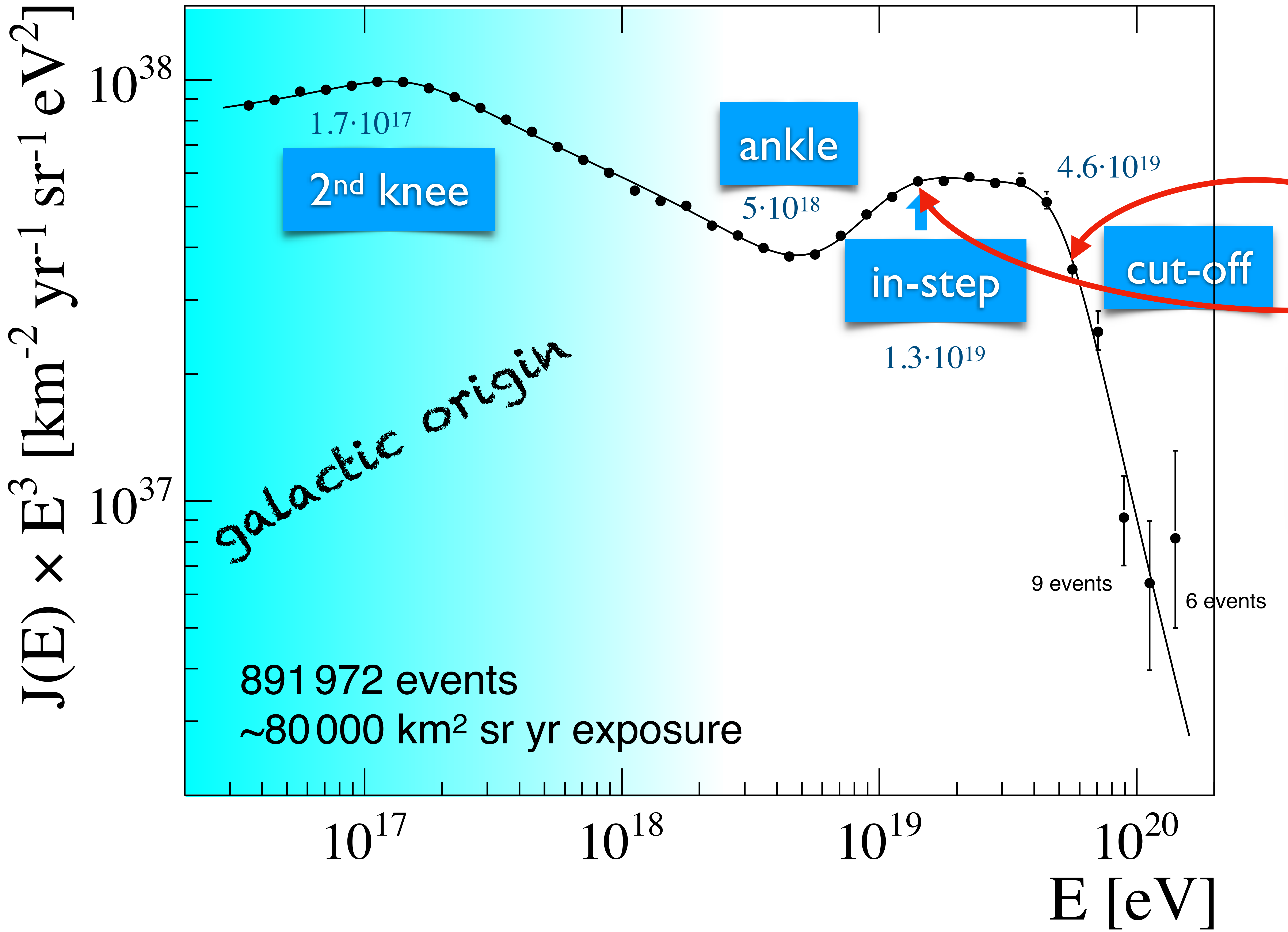




Auger Collaboration

Phys. Rev. Lett. 125, 121106 (2020); Phys. Rev. D 102, 062005 (2020), Eur. Phys. J. C 81 (2021) 966; A. Brichetto, PoS(ICRC2023) 398

The End of the CR Energy Spectrum



very steep and sharp suppression, ~E^{-5}

new feature, not known before

Note, the sharpness of the breaks poses some challenges to their interpretation…

Auger Collaboration

Phys. Rev. Lett. 125, 121106 (2020); Phys. Rev. D 102, 062005 (2020), Eur. Phys. J. C 81 (2021) 966; A. Brichetto, PoS(ICRC2023) 398

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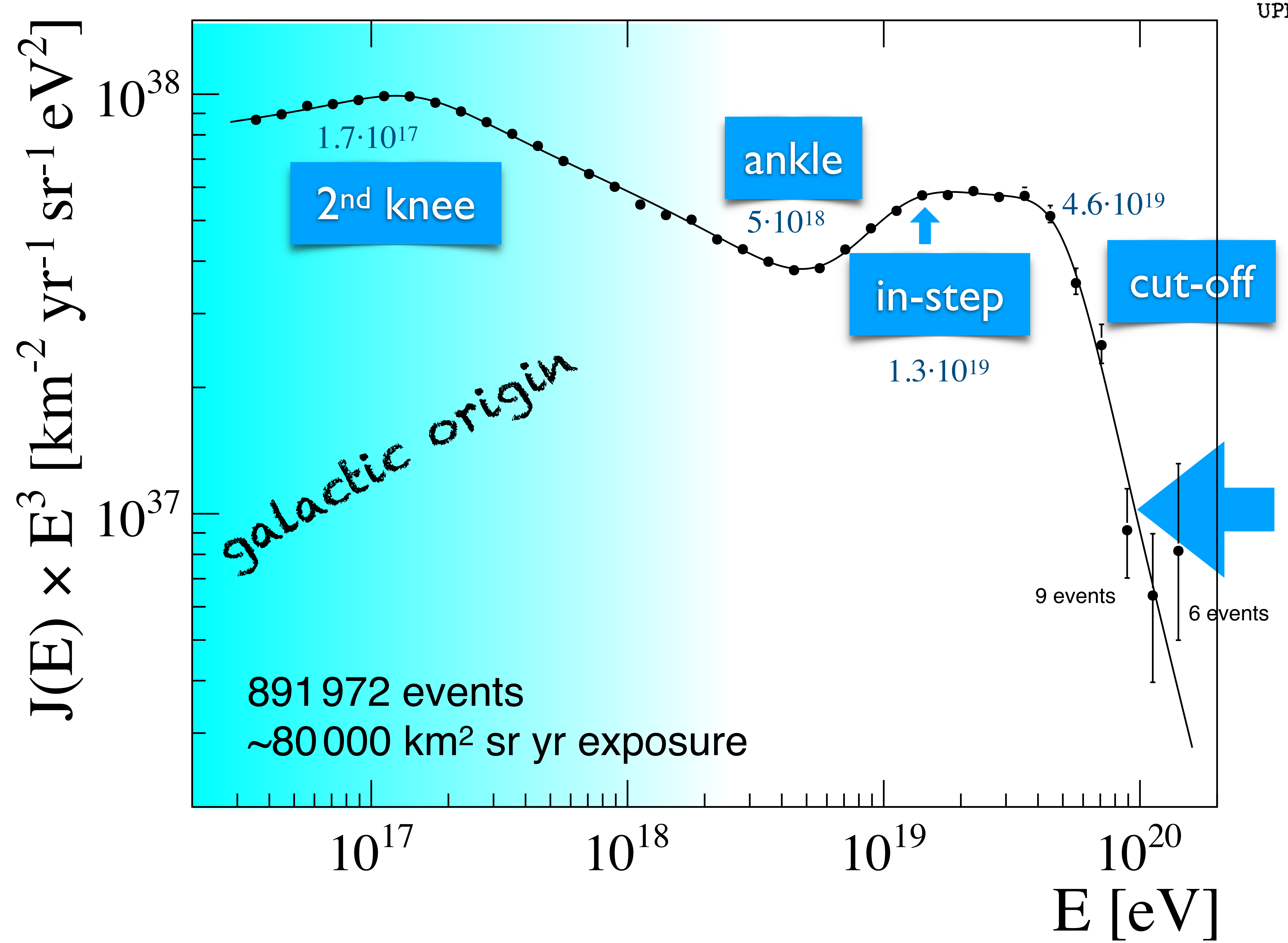
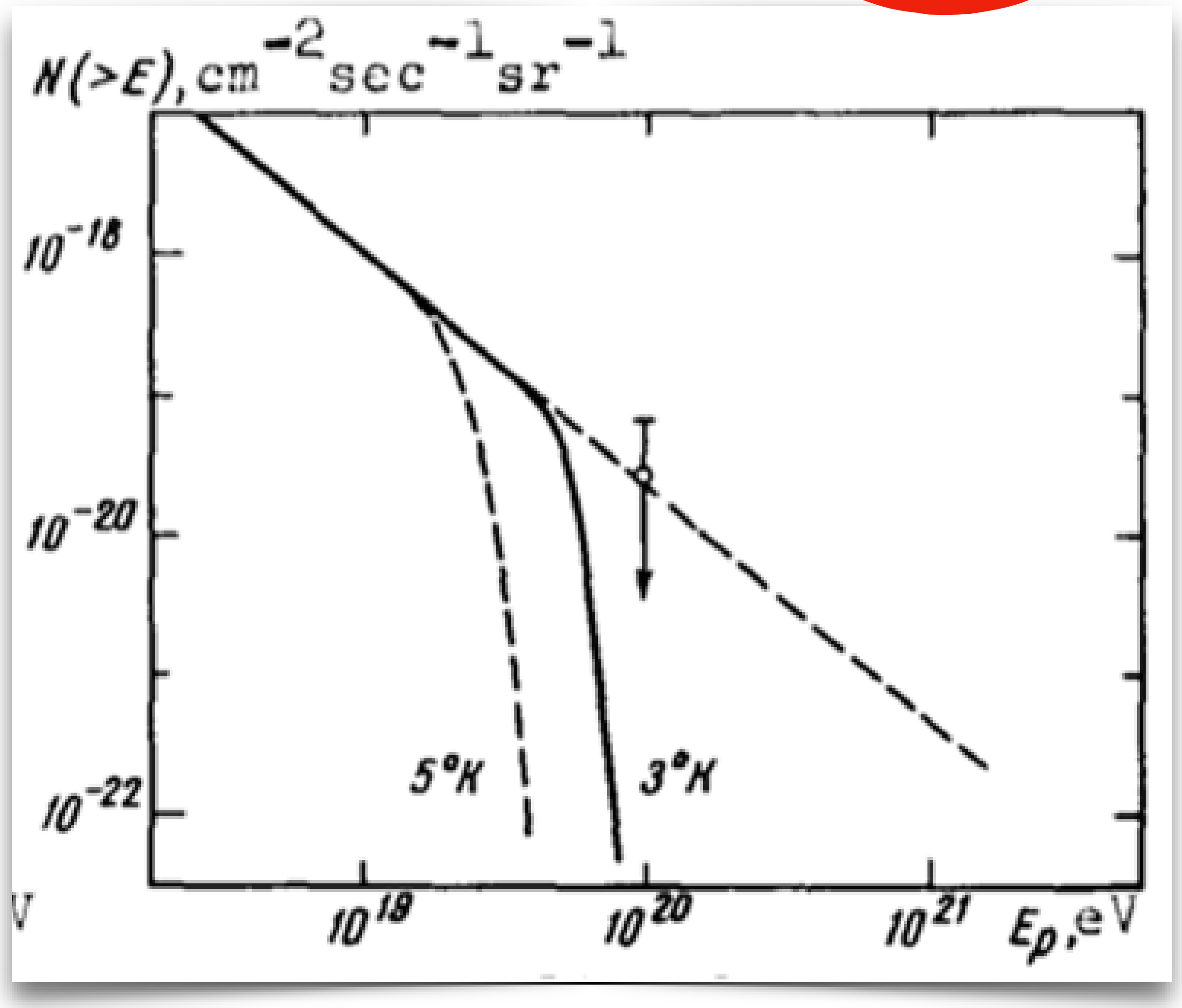


??

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966



Is this the GZK-effect?

Auger Collaboration

Phys. Rev. Lett. 125, 121106 (2020); Phys. Rev. D 102, 062005 (2020), Eur. Phys. J. C 81 (2021) 966; A. Brichetto, PoS(ICRC2023) 398

GZK-effect: Rapid Energy Loss of p & Nuclei in CMB

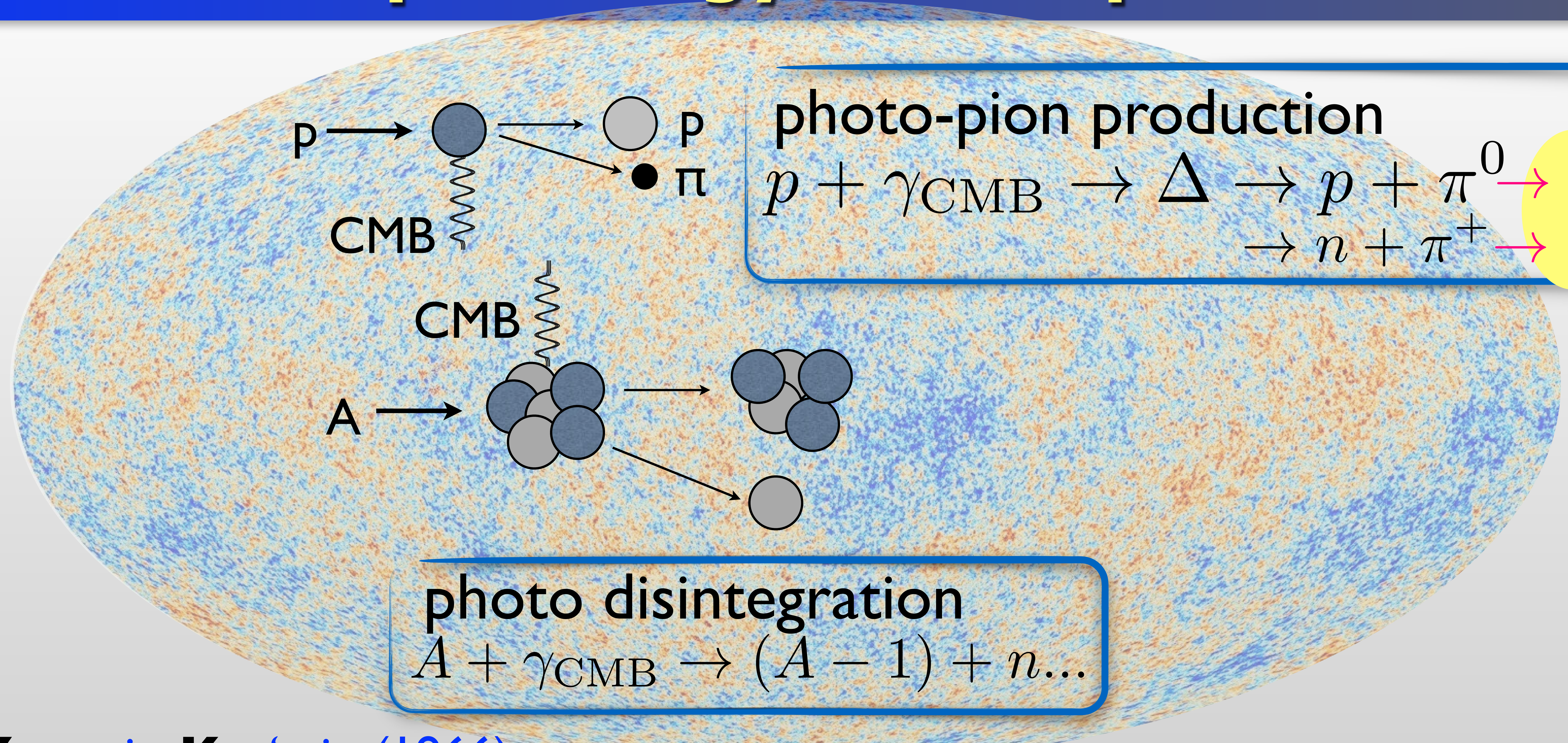


photo-pion production

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta \rightarrow p + \pi^0 \rightarrow \gamma$$
$$\rightarrow n + \pi^+ \rightarrow \nu$$

photo disintegration

$$A + \gamma_{\mathrm{CMB}} \rightarrow (A-1) + n \ldots$$

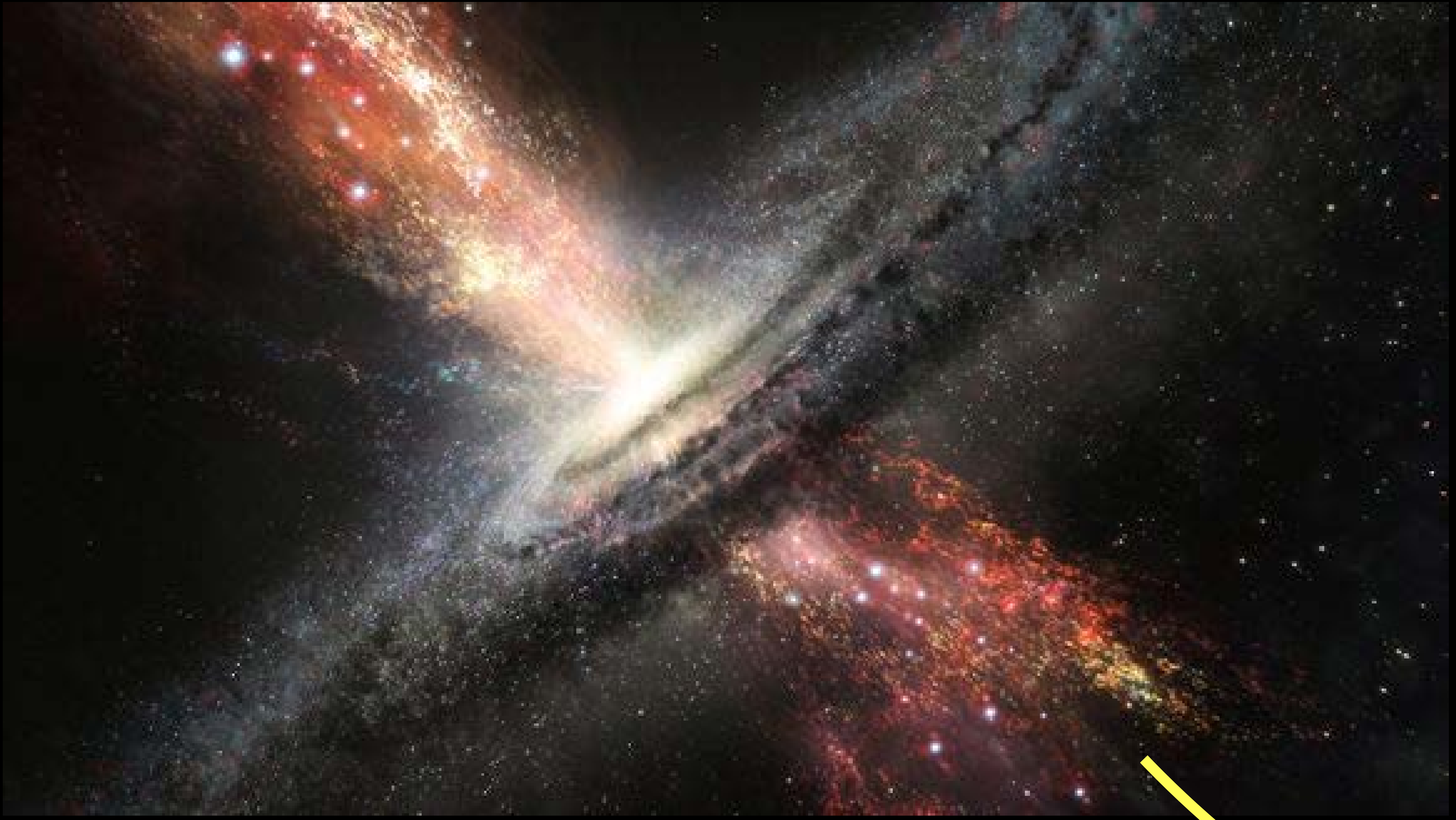
Greisen-**Z**atsepin-**K**uz'min (1966)

threshold: $E_p E_\gamma > (m_\Delta^2 - m_p^2)$

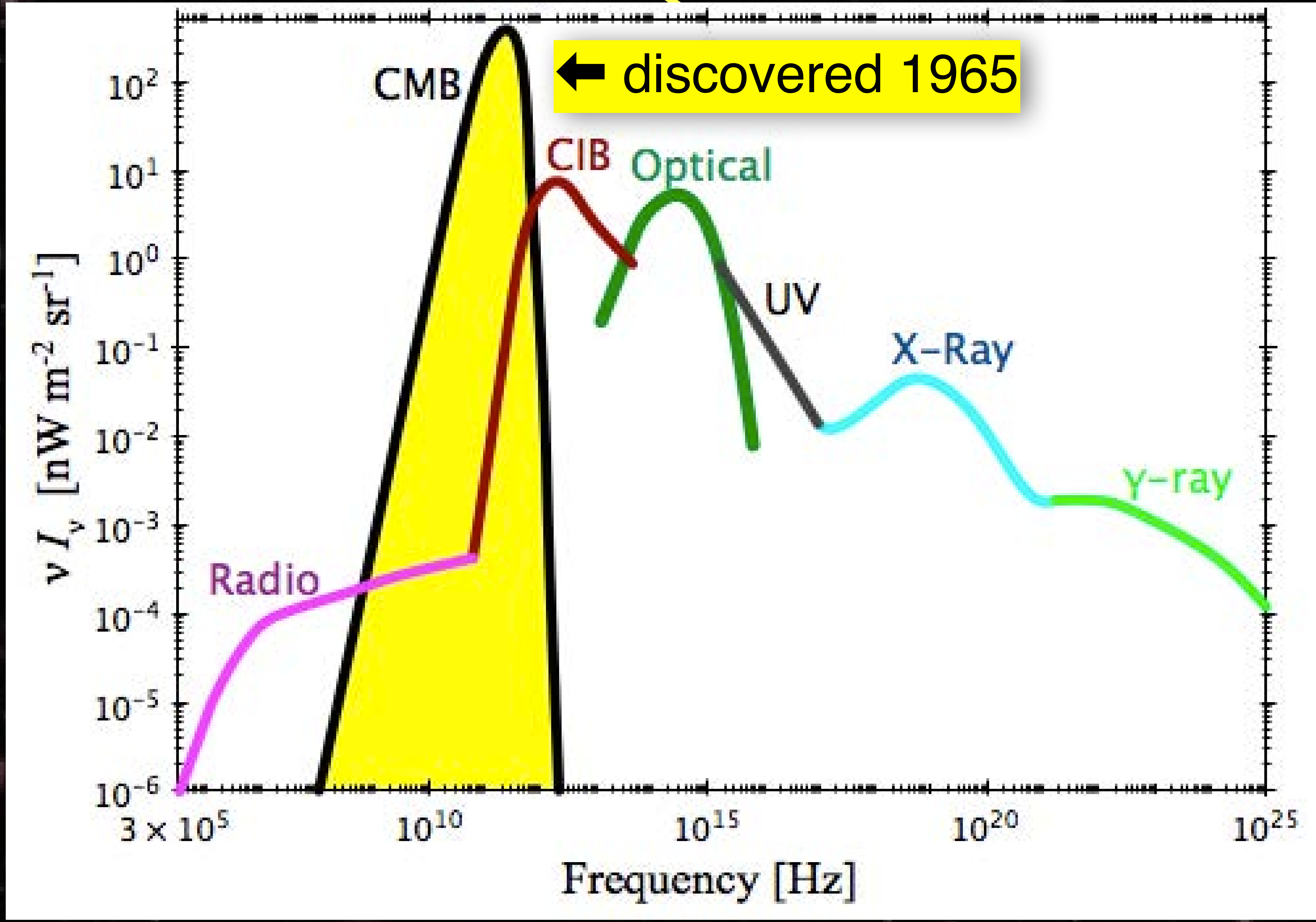
$\Rightarrow E_{\mathrm{GZK}} \approx 6 \cdot 10^{19}$ eV

➙ **GZK-Horizon ~ 60 Mpc**

KHK et al., Astropart. Phys. 42 (2013) 41



Interlude:
Intergalactic Propagation

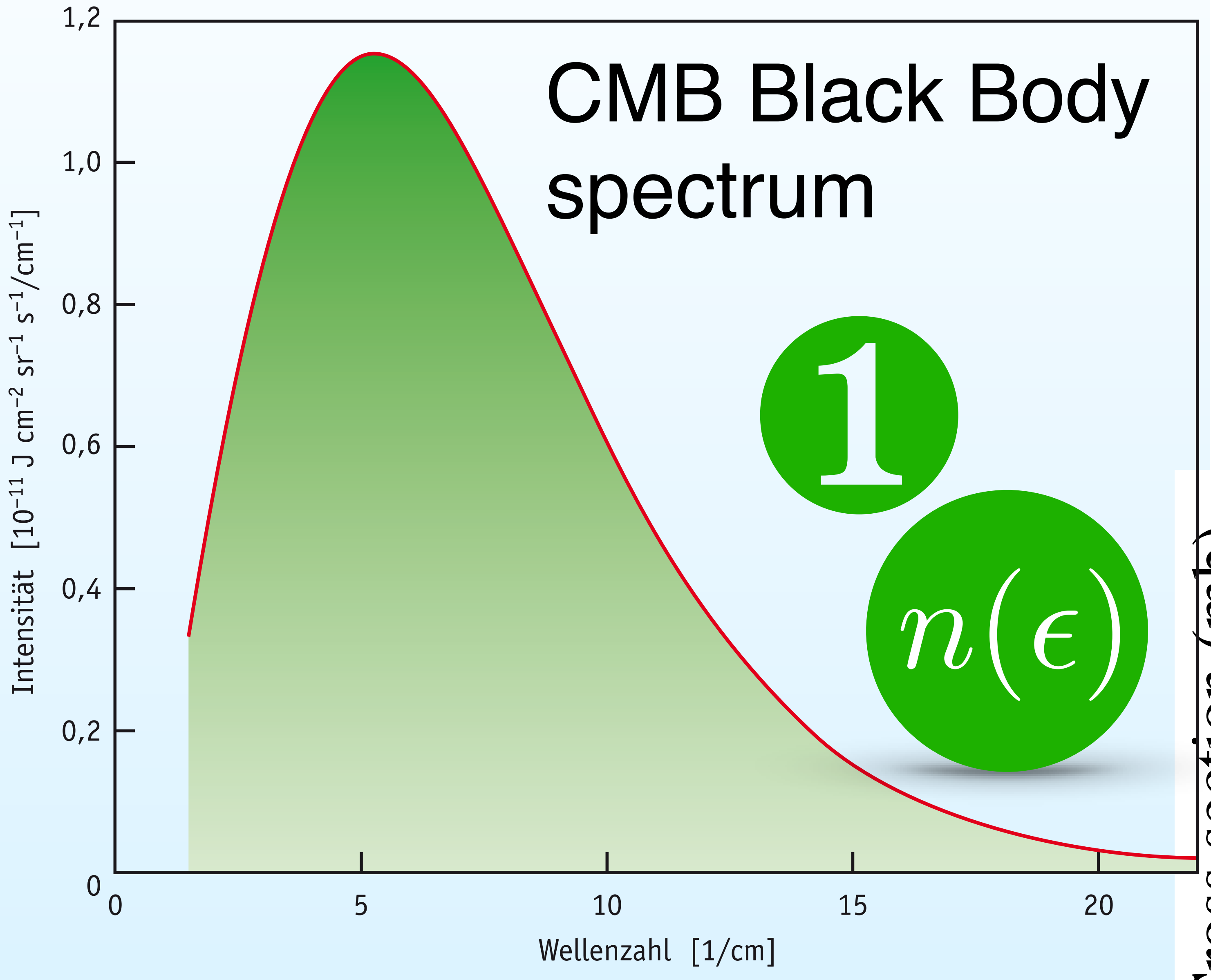


Diffuse Extragalactic Background Radiation

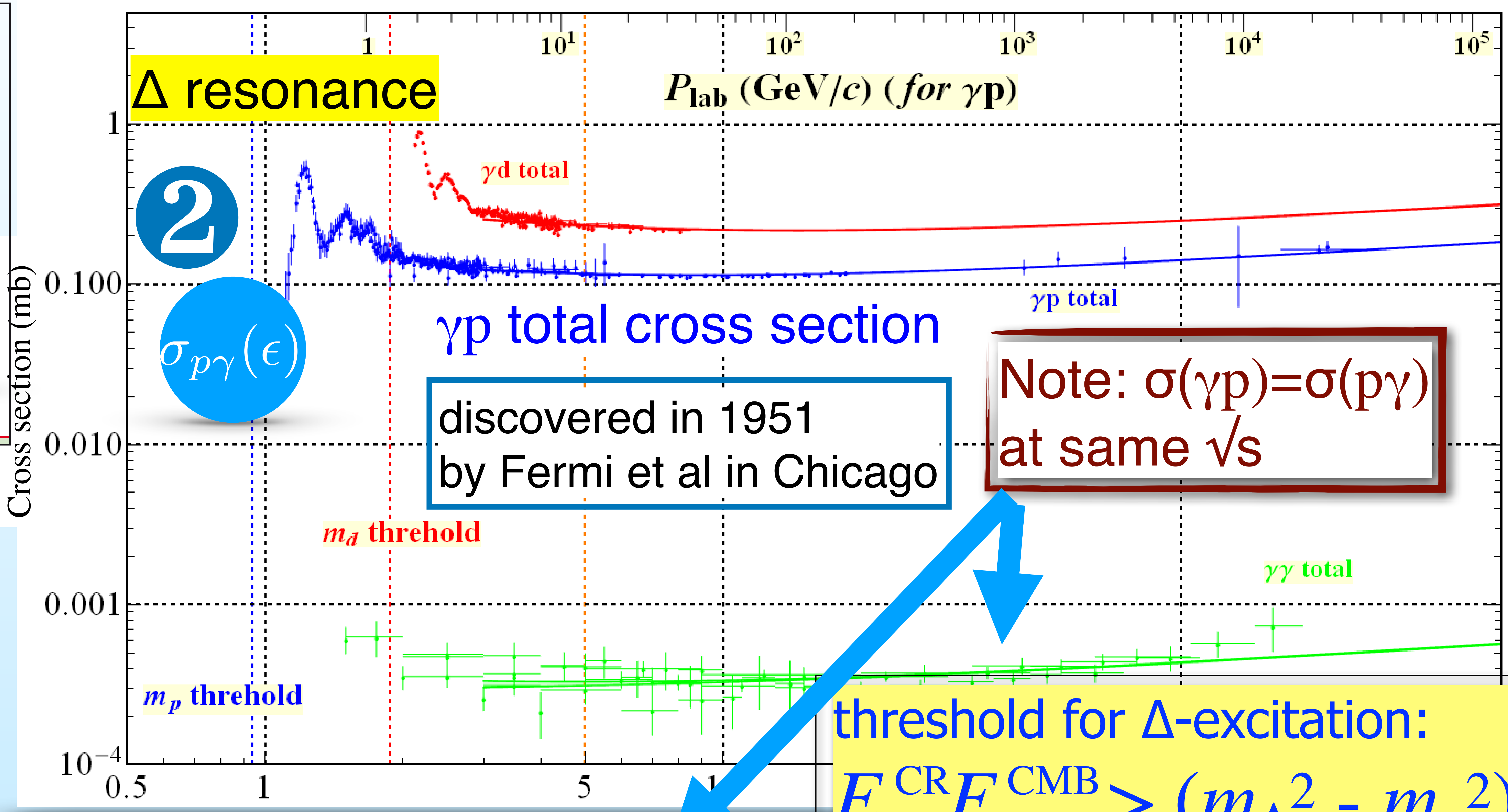
CMB: 412 photons/cm³

for comparison: $\rho_H < 1$ proton/m³

GZK effect for CR protons: The Two Ingredients



discovered in 1965
by Penzias & Wilson



γp total cross section

discovered in 1951
by Fermi et al in Chicago

Note: σ(γp)=σ(pγ)
at same √s

threshold for Δ-excitation:

$E_p^{CR} E_\gamma^{CMB} > (m_\Delta^2 - m_p^2)$

$\Rightarrow E_{GZK} \approx 6 \cdot 10^{19}$ eV

$$\lambda_{eff} = \left(\int n(\epsilon) \cdot \sigma_{\gamma p}(\epsilon) d\epsilon \right)^{-1} \approx 8 \text{ Mpc}$$

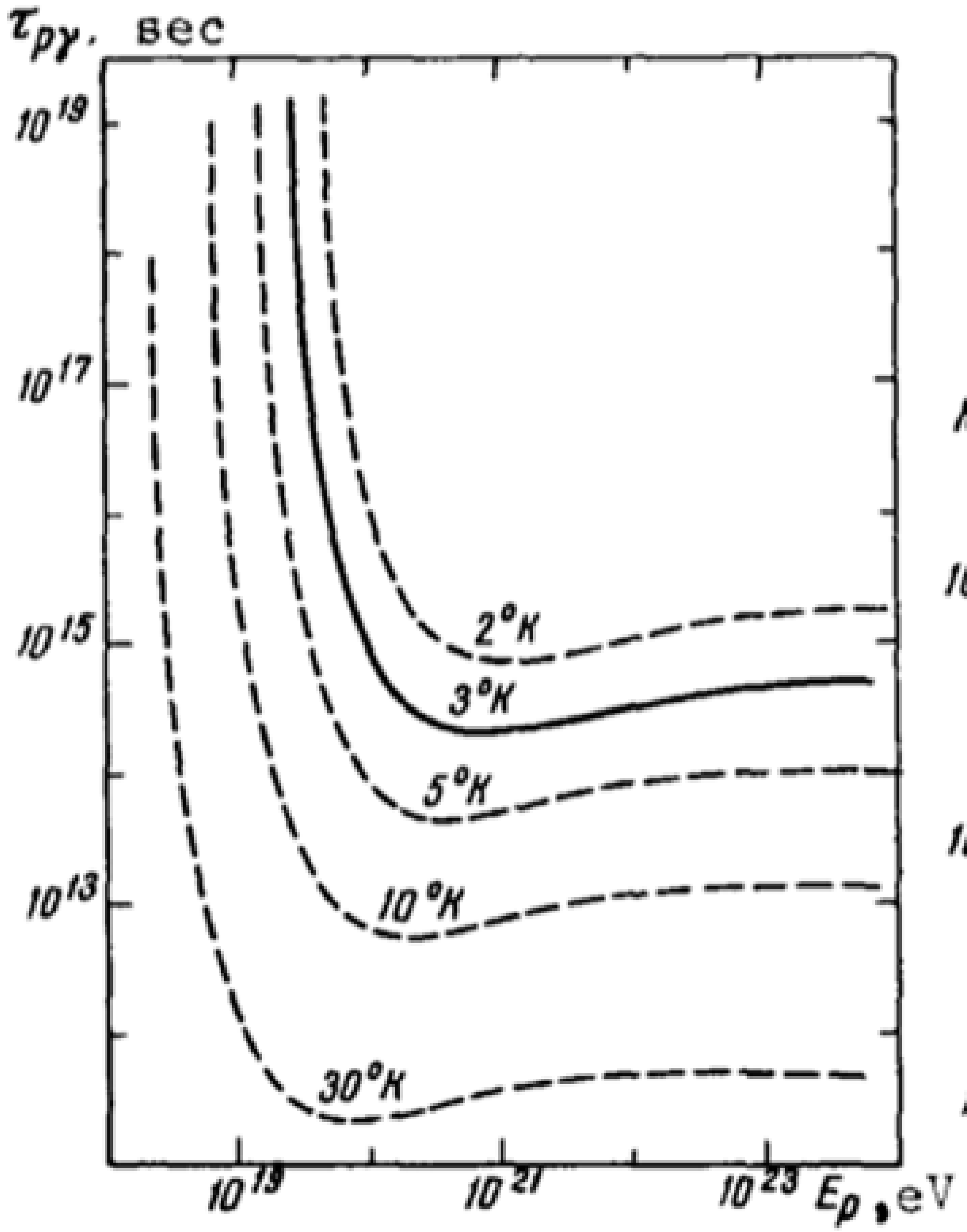
1966: „End to the CR Spectrum ?"

Volume 16, Number 17 PHYSICAL REVIEW LETTERS 25 April 1966

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)



Greisen,
Zatsepin & Kuz'min

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
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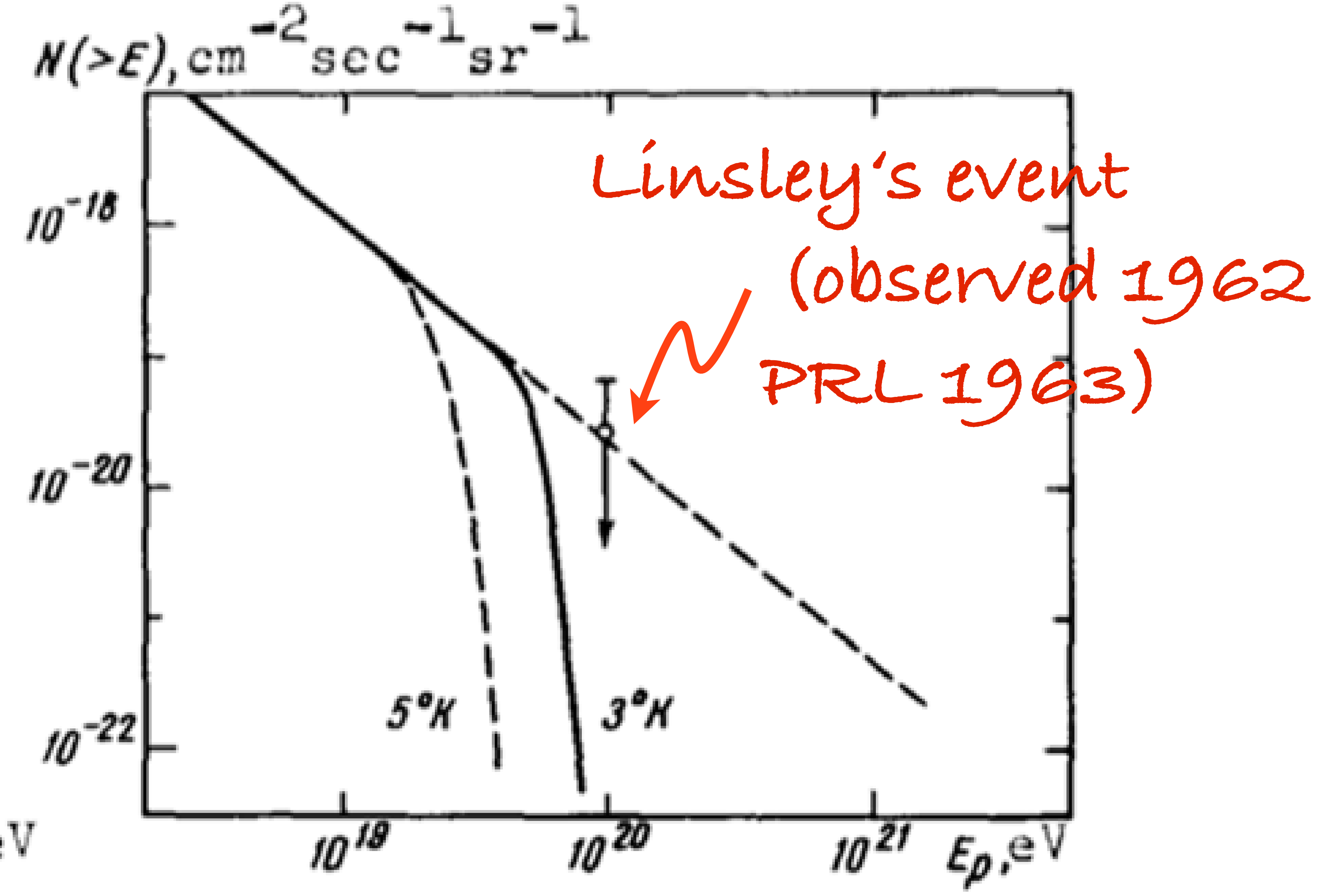
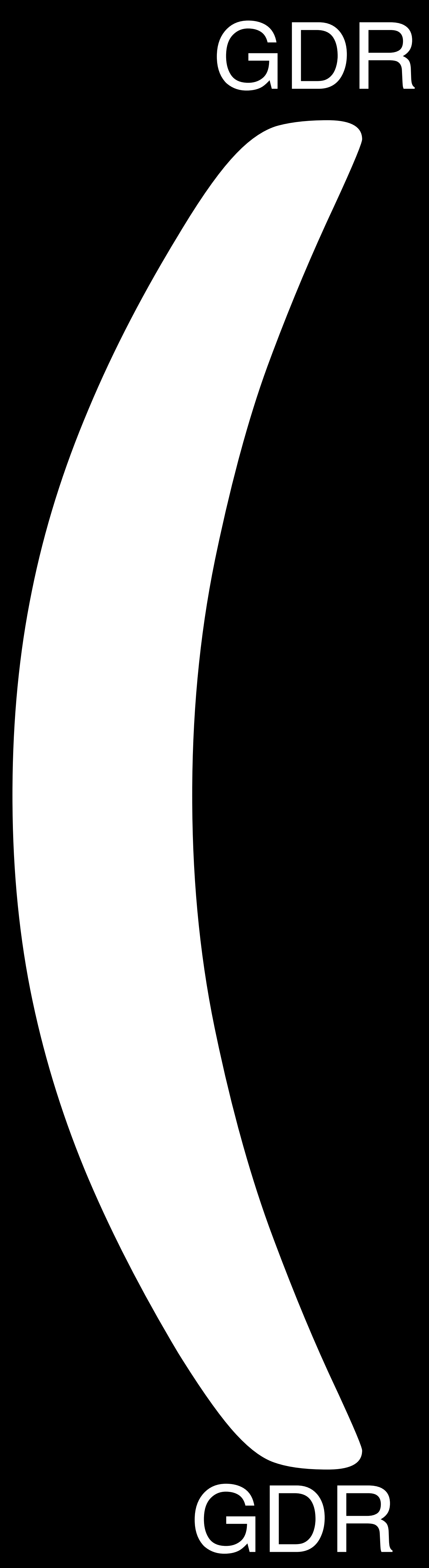
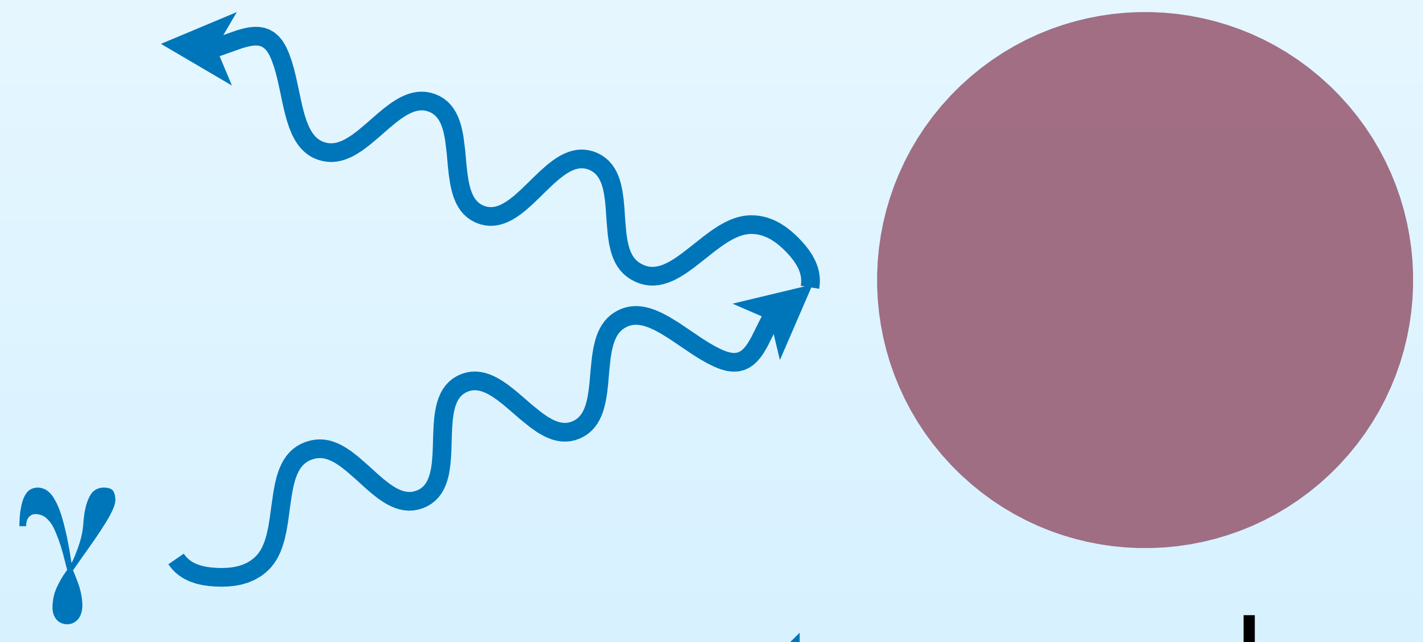


John Linsley @ Volcano Ranch


GDR
GDR

GZK effect for CR Nuclei

interaction with CMB photon may induce a
collective oscillation of neutrons against protons



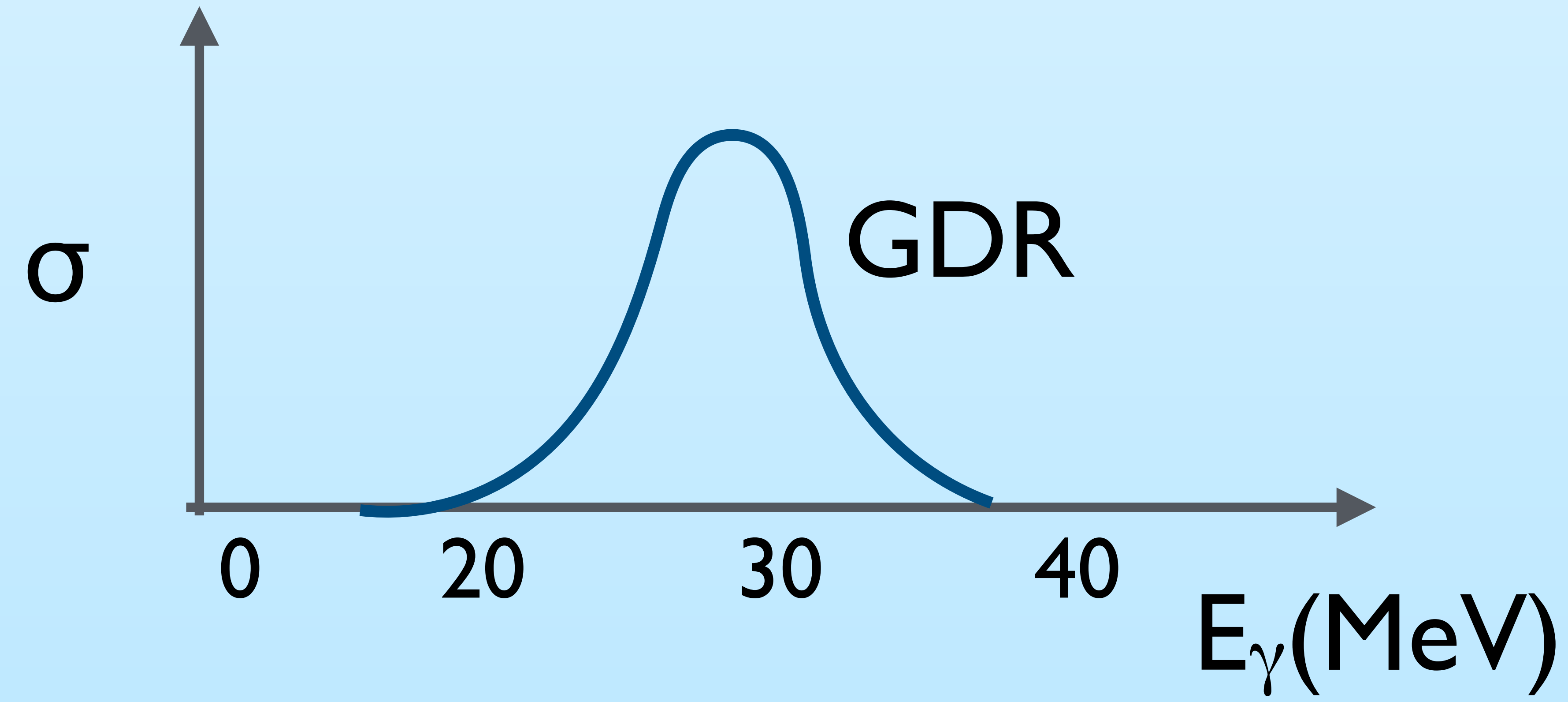
Often, single or multiple nucleons
are lost in this process
→ **photodisintegration**

Giant Dipole Resonance

neutrons and protons
in an atomic nucleus

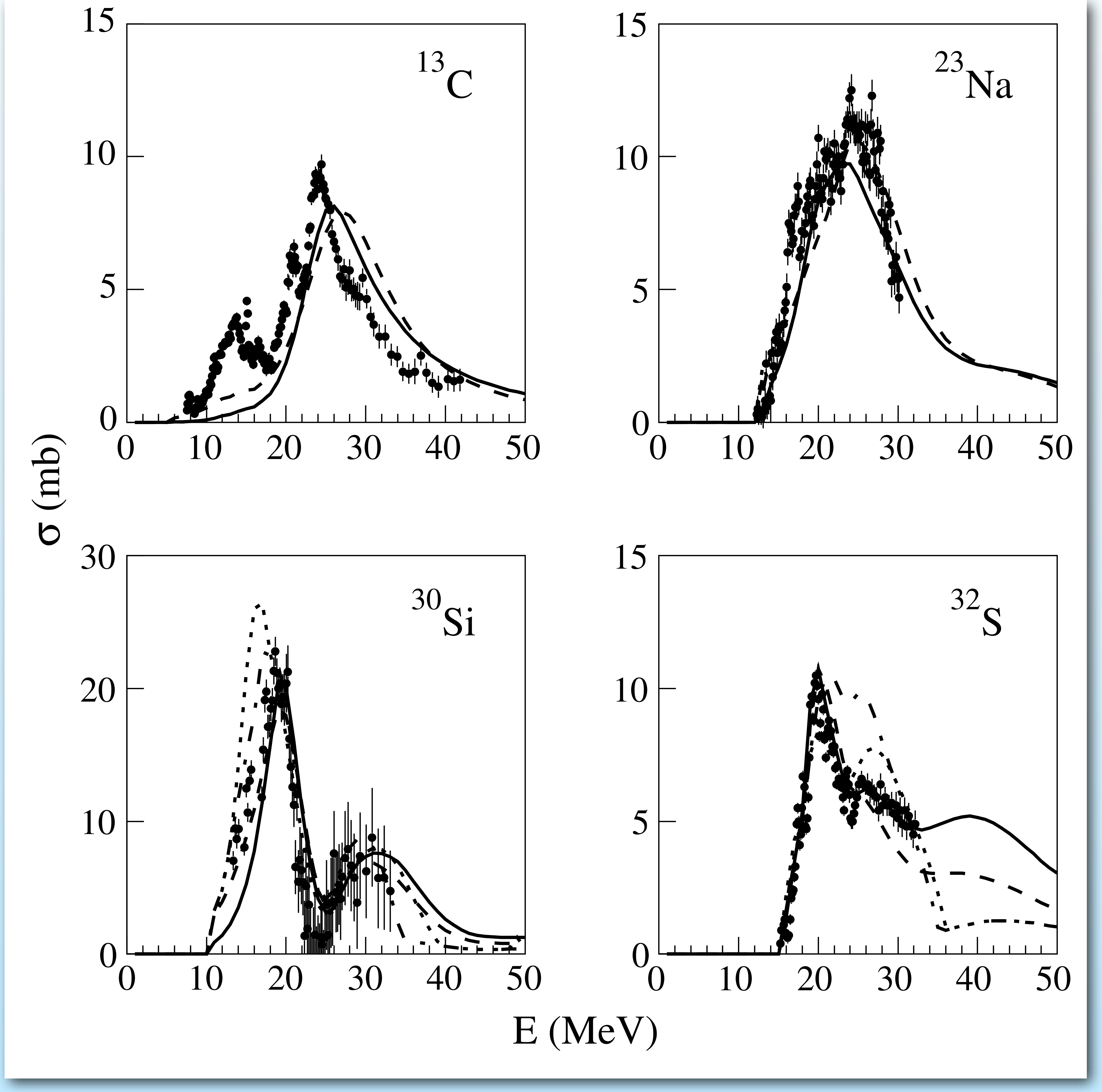
$$(Z,N) + \gamma \rightarrow (Z,N-1) + n$$
$$\rightarrow (Z-1,N) + p$$
$$\rightarrow (Z,N-2) + 2n$$
$$\rightarrow \ldots$$

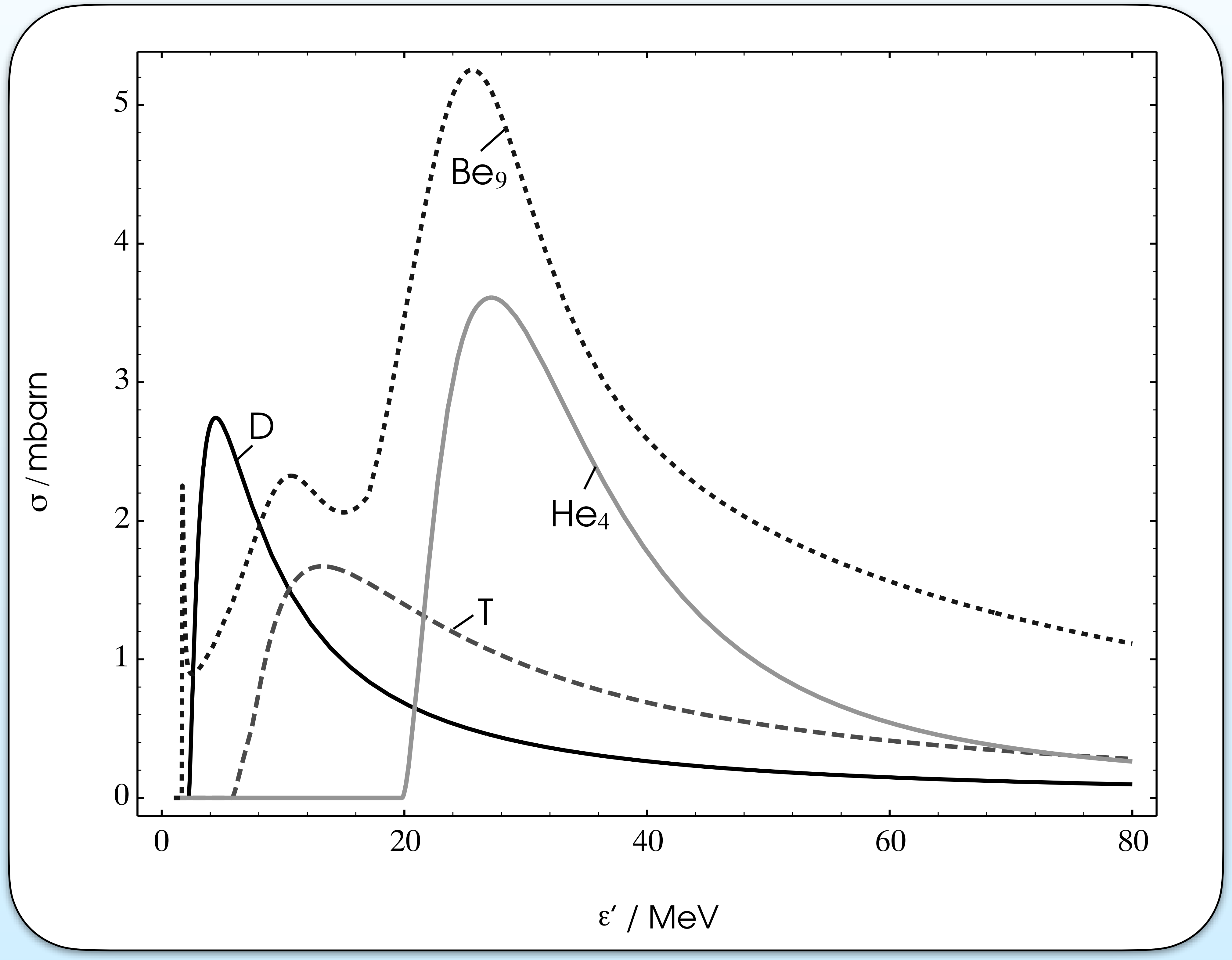
discovered 1947



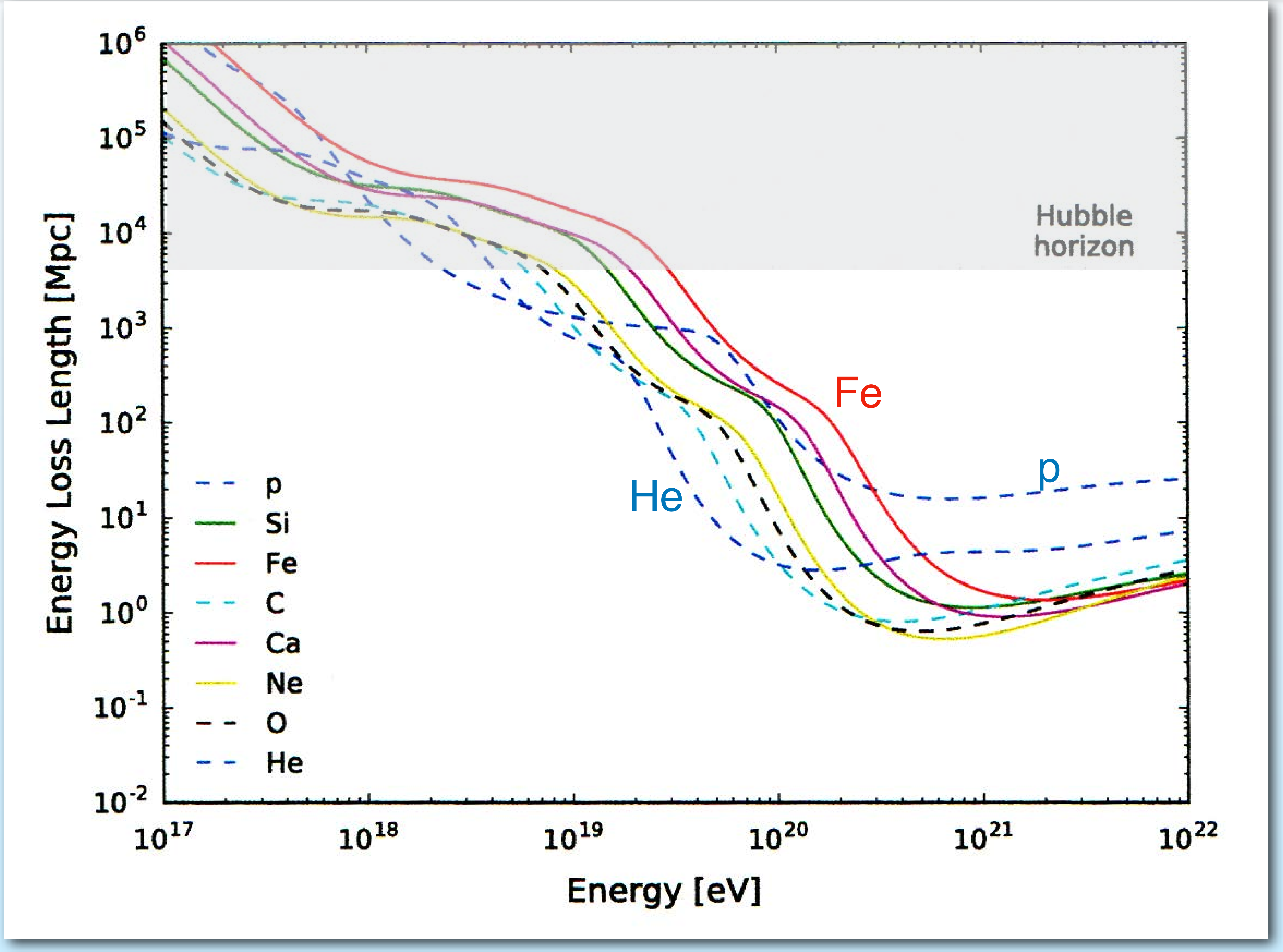
→ **nuclei don't survive propagation if energy is above GDR threshold**

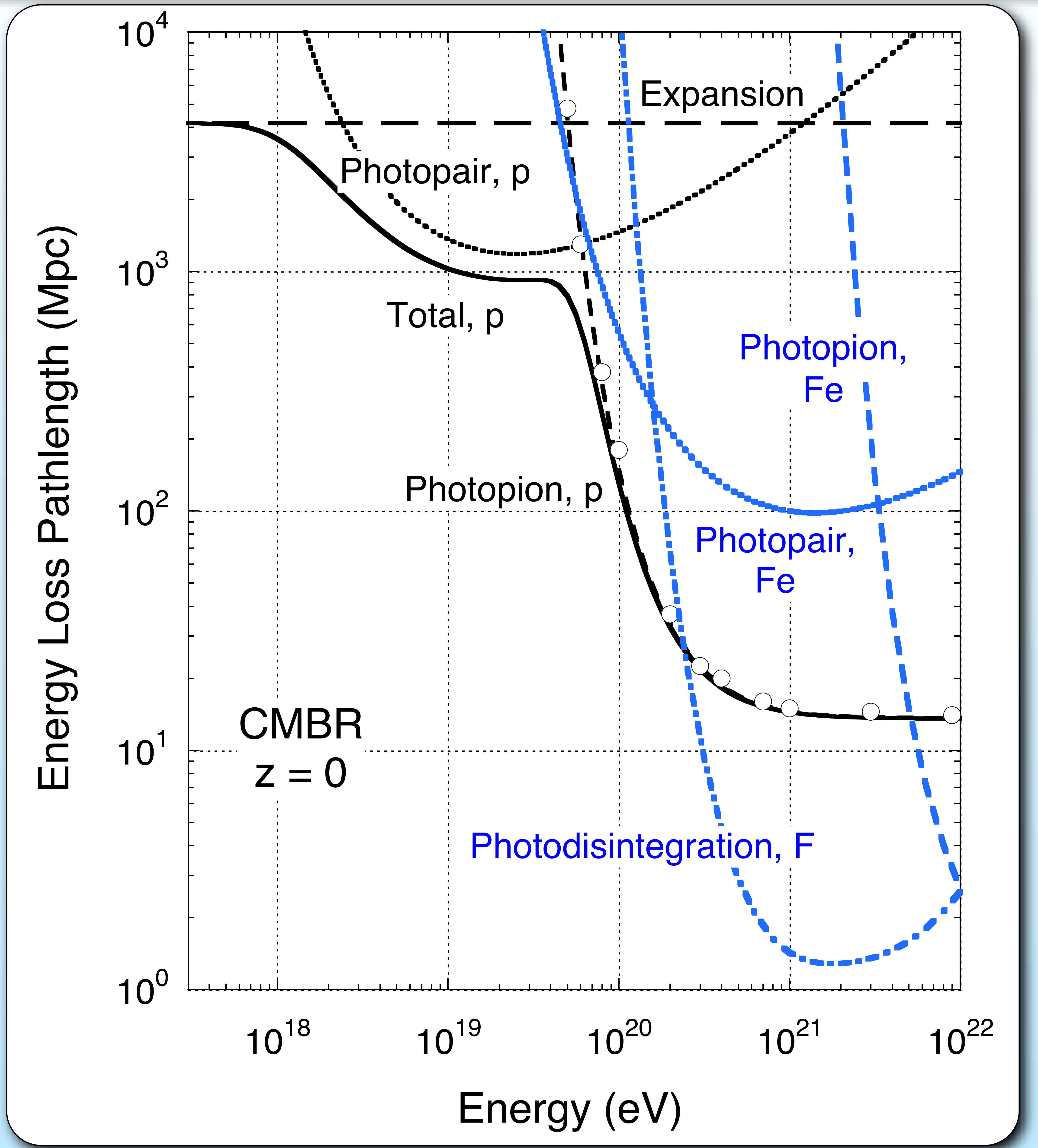
Examples of Giant-Dipole Cross sections





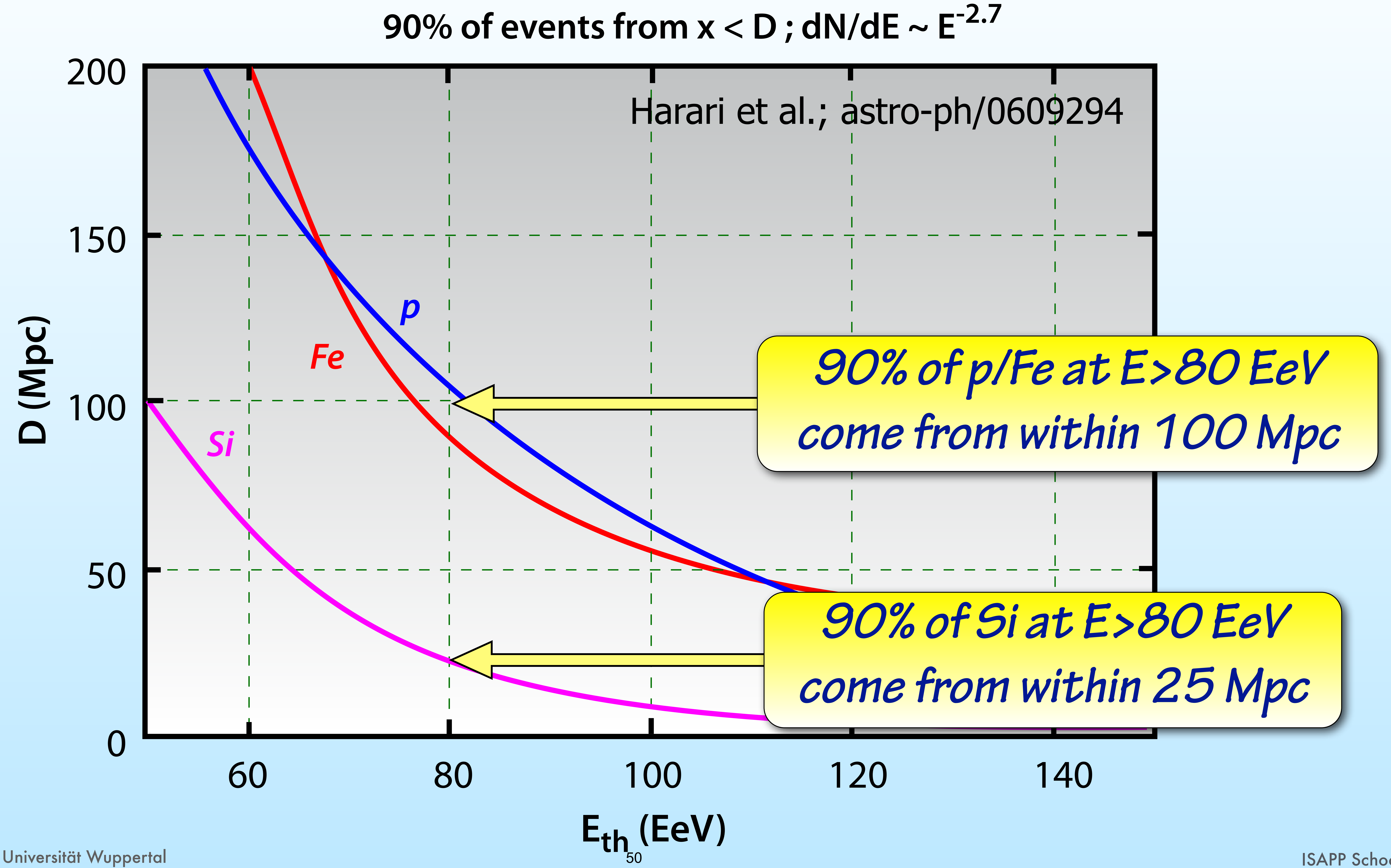
Energy Loss Length for Nuclei





It's a coincidence of nature that the threshold energies for photo-pion production and photodisintegration are about the same

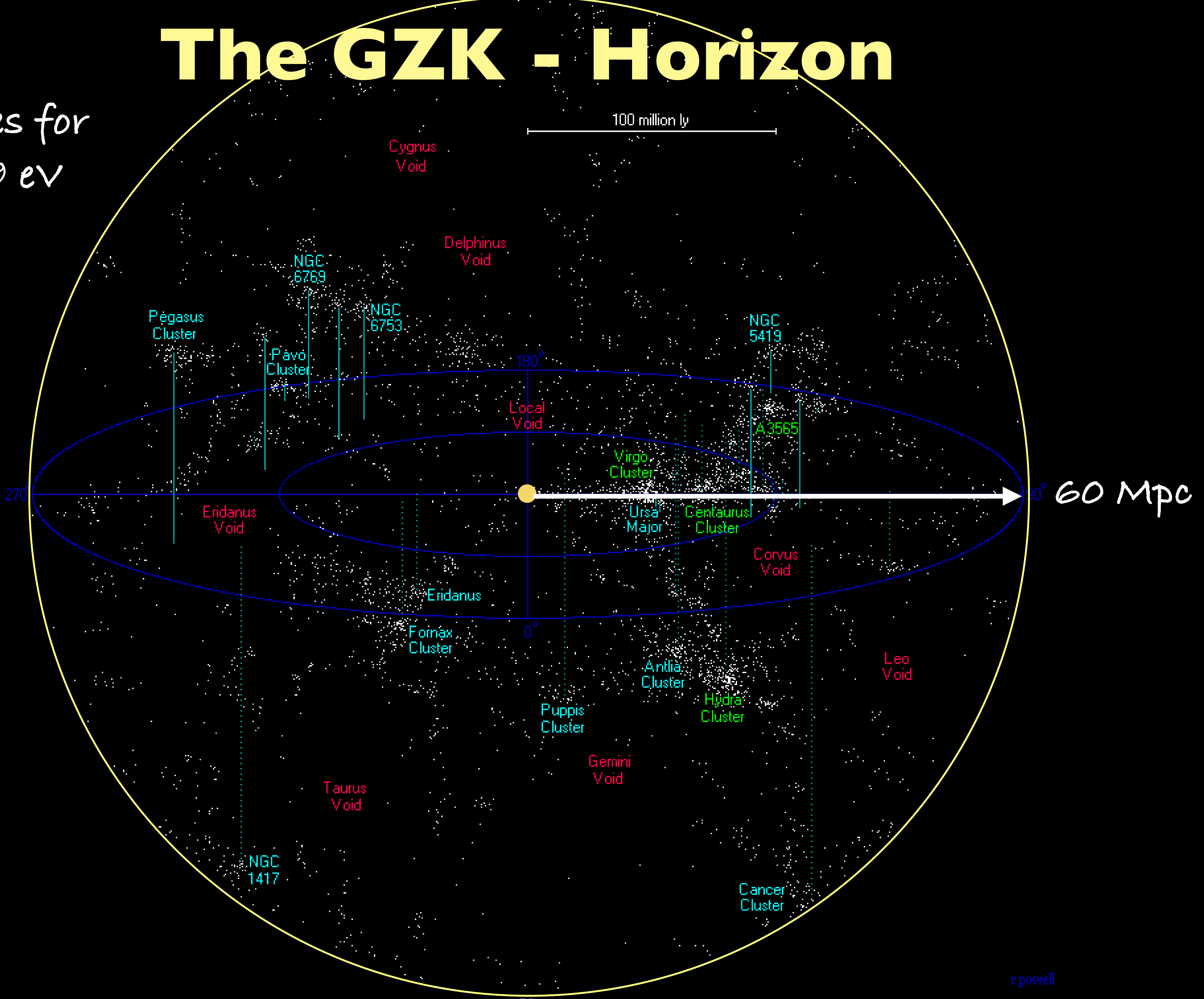
GZK Horizon



90% of events from x < D ; dN/dE ~ E^-2.7
Harari et al.; astro-ph/0609294
D (Mpc)
200
150
100
50
0
60
80
100
120
140
E_th (EeV)
p
Fe
Si
90% of p/Fe at E>80 EeV come from within 100 Mpc
90% of Si at E>80 EeV come from within 25 Mpc

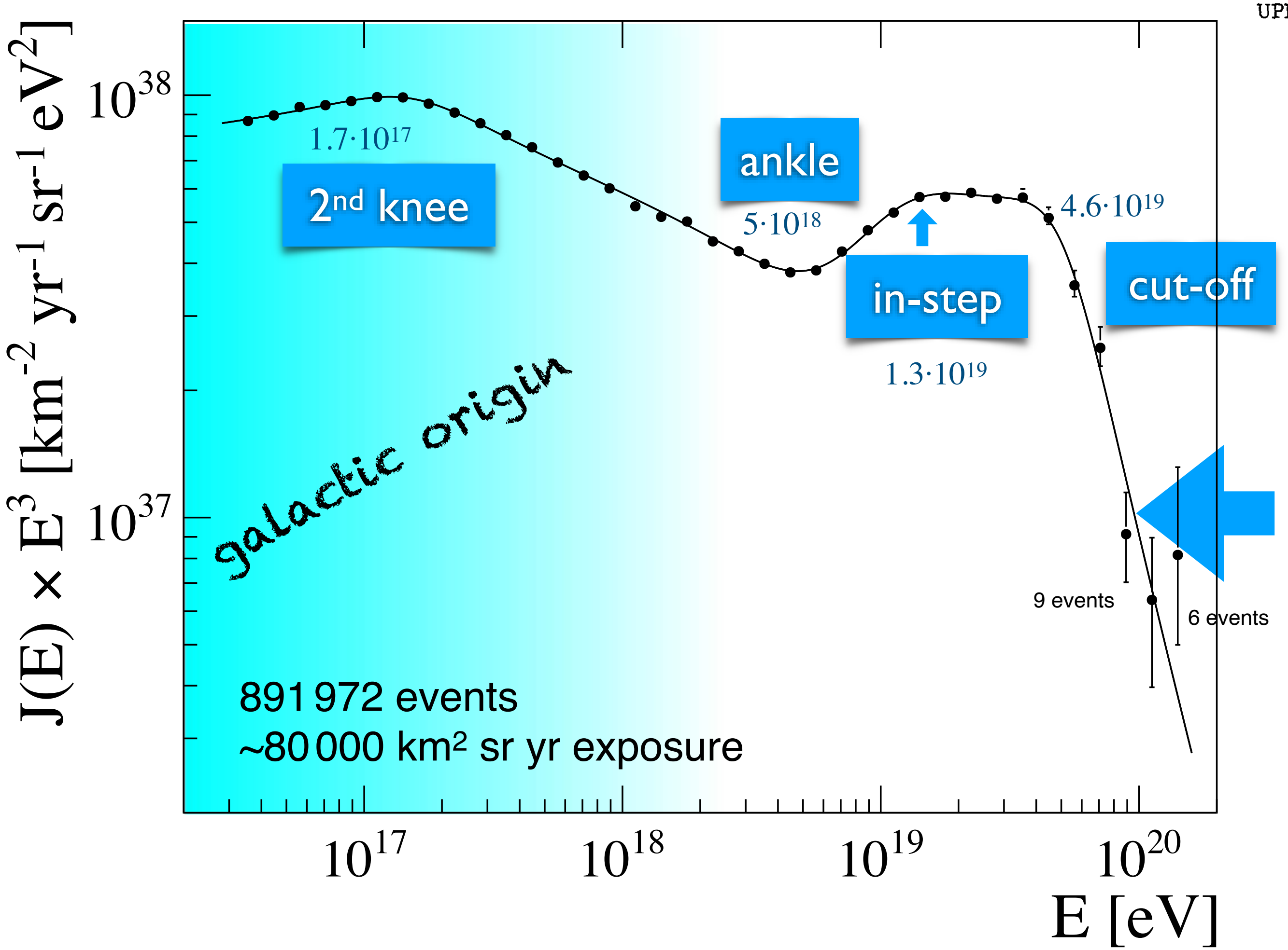
The GZK - Horizon

Expect anisotropies for protons at $E>10^{19}$ eV



)

The End of the CR Energy Spectrum



Auger Collaboration
Phys. Rev. Lett. 125, 121106 (2020); Phys. Rev. D 102, 062005 (2020), Eur. Phys. J. C 81 (2021) 966; A. Br

UPPER LIMIT OF THE SPECTRUM OF COSMIC RAYS

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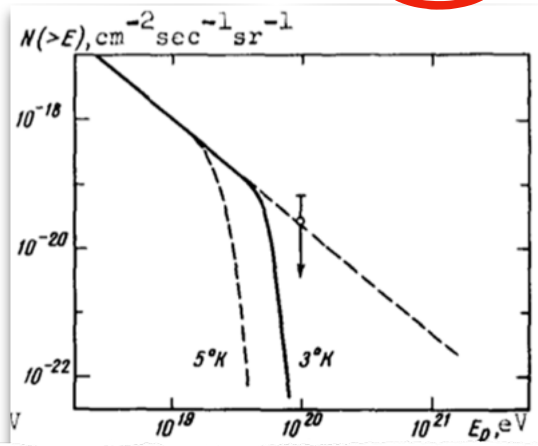
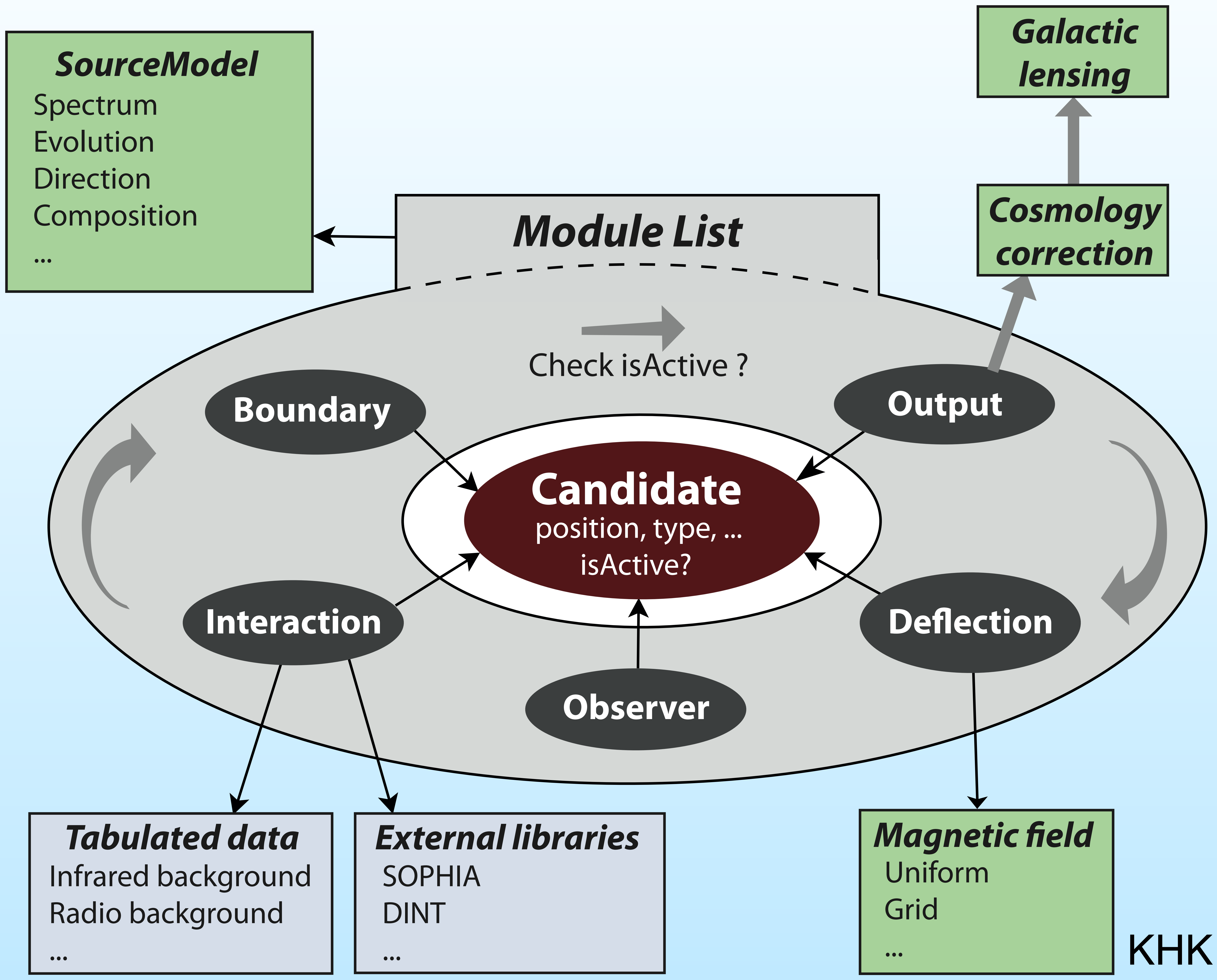


If this is the GZK-effect, we expect a significant flux of cosmogenic γ's and ν's:

$$p + \gamma_{CMB} \rightarrow \Delta \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

CRPropa: Open Source Public CR Propagation Code



Propagates CR particles from source to observer and accounts for all type of interactions in photon fields as well as in magnetic fields.

➥ predict flux of cosmogenic photons and neutrinos

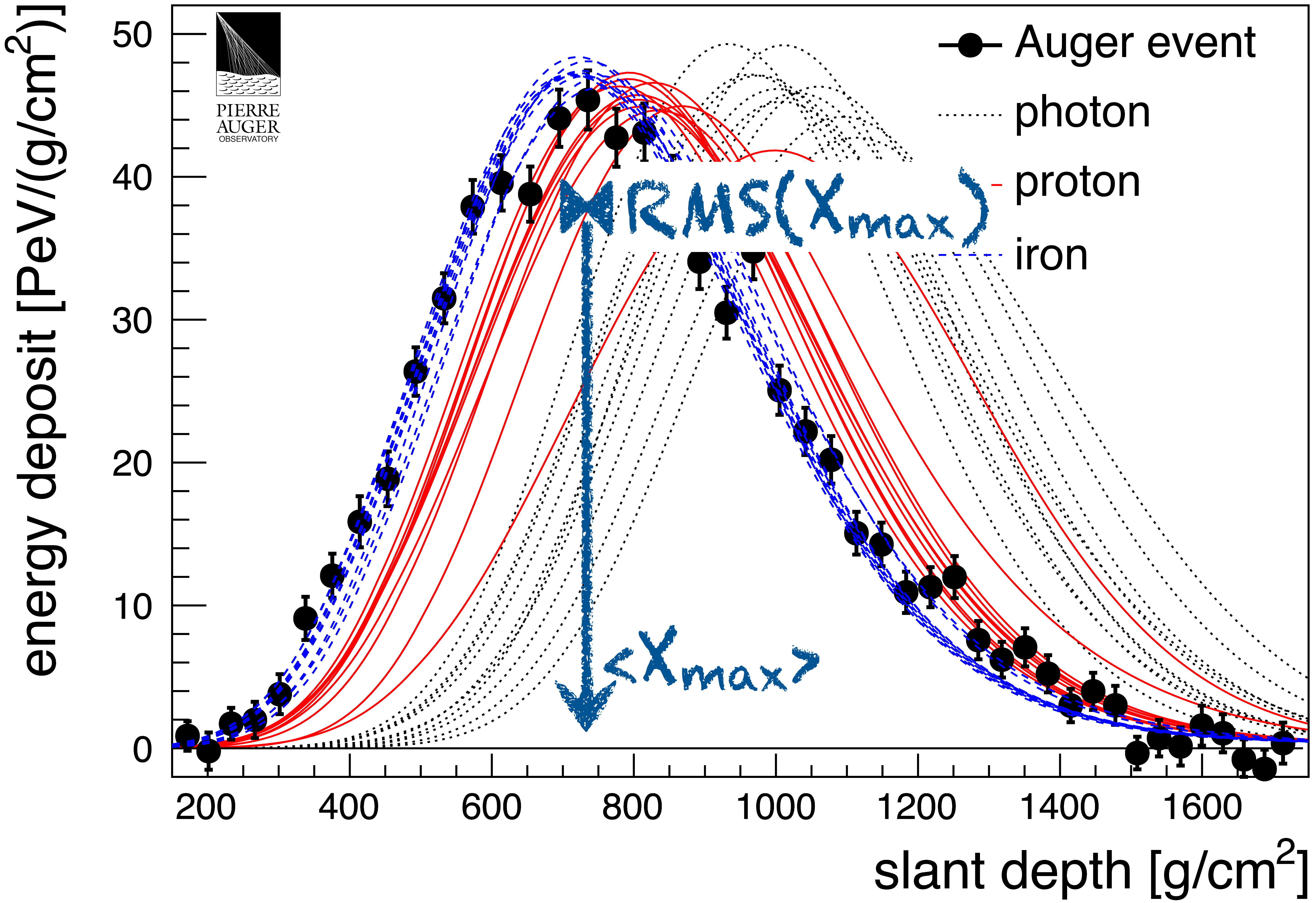
KHK et al, Astropart. Phys. 42 (2013) 41, …
R.A. Batista et al, JCAP 09 (2022) 035

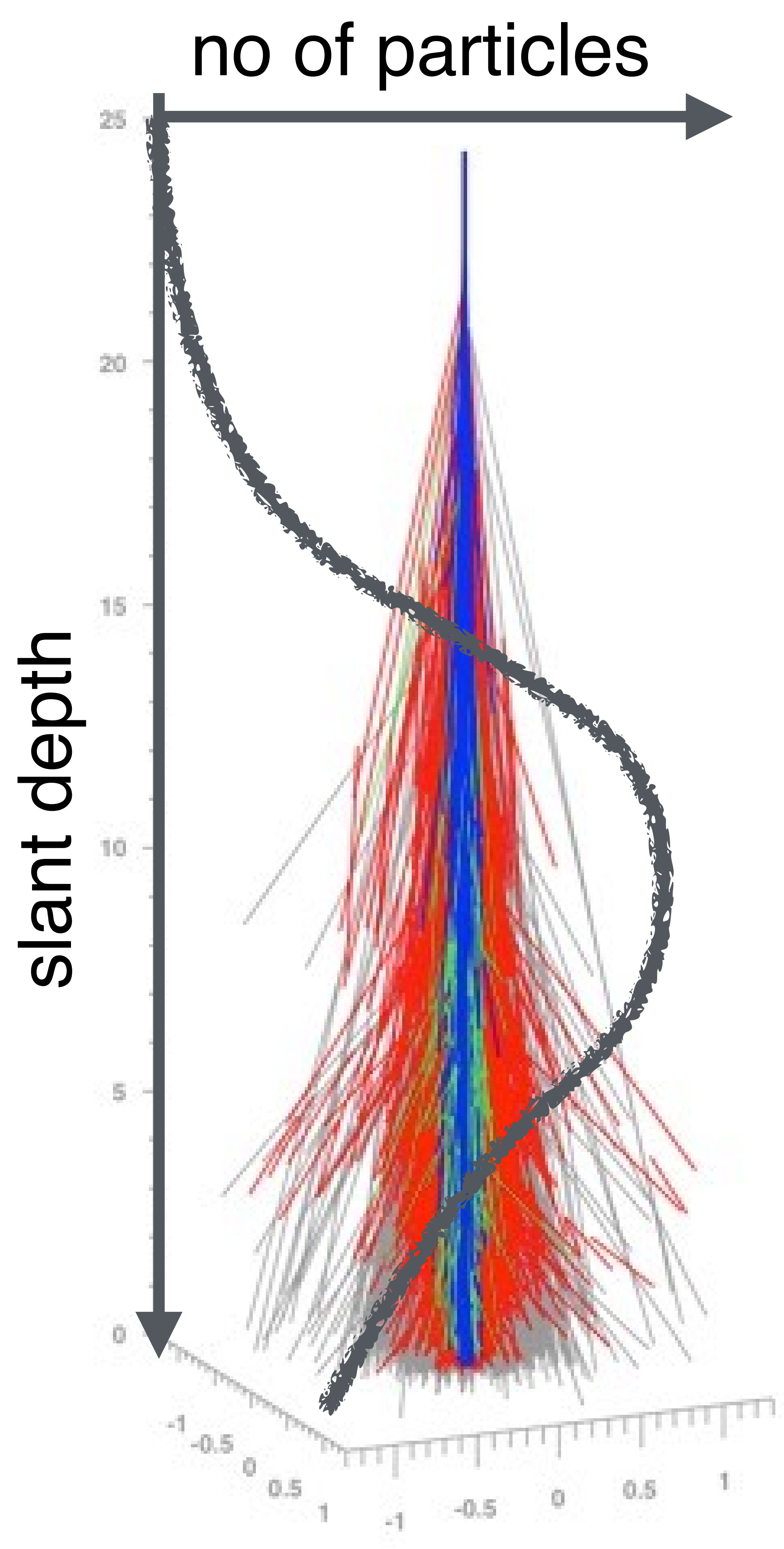
How to Measure UHE photons and neutrinos

Longitudinal Shower Development → Primary Mass

KHK, Unger, APP 35 (2012)
EPOS 1.99 Simulations

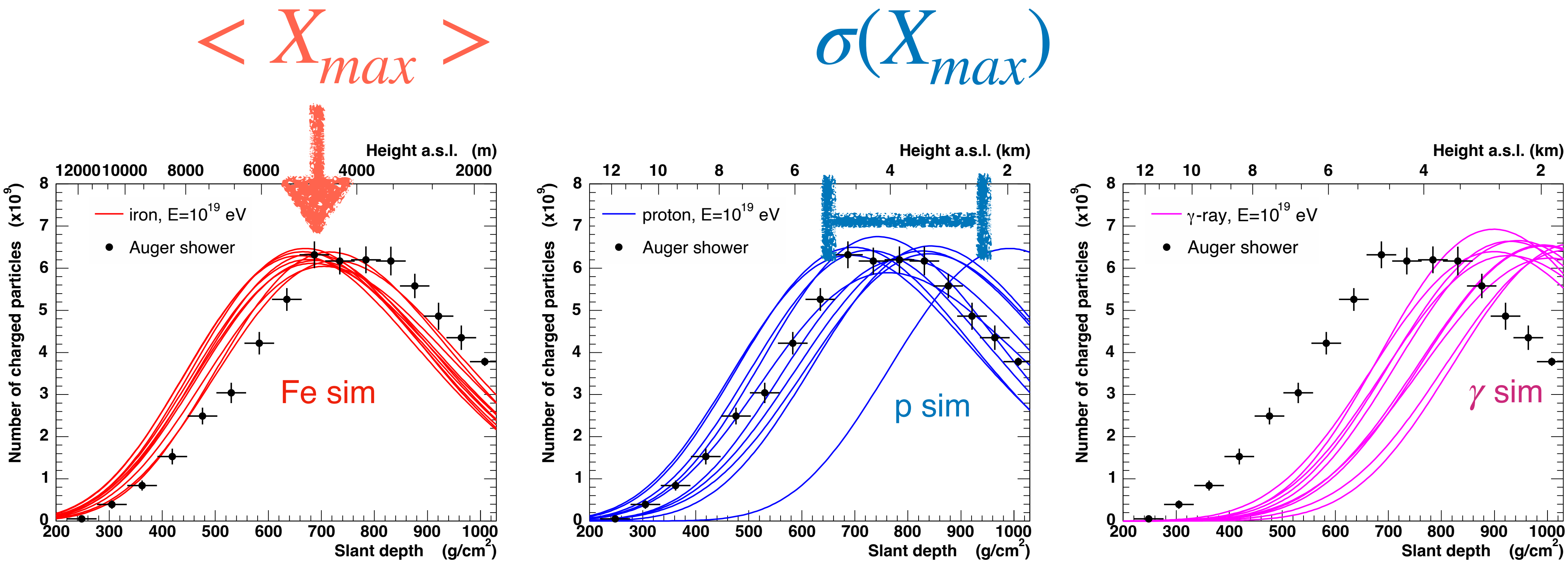
Example of a 3 · 10^19 eV EAS event in FD





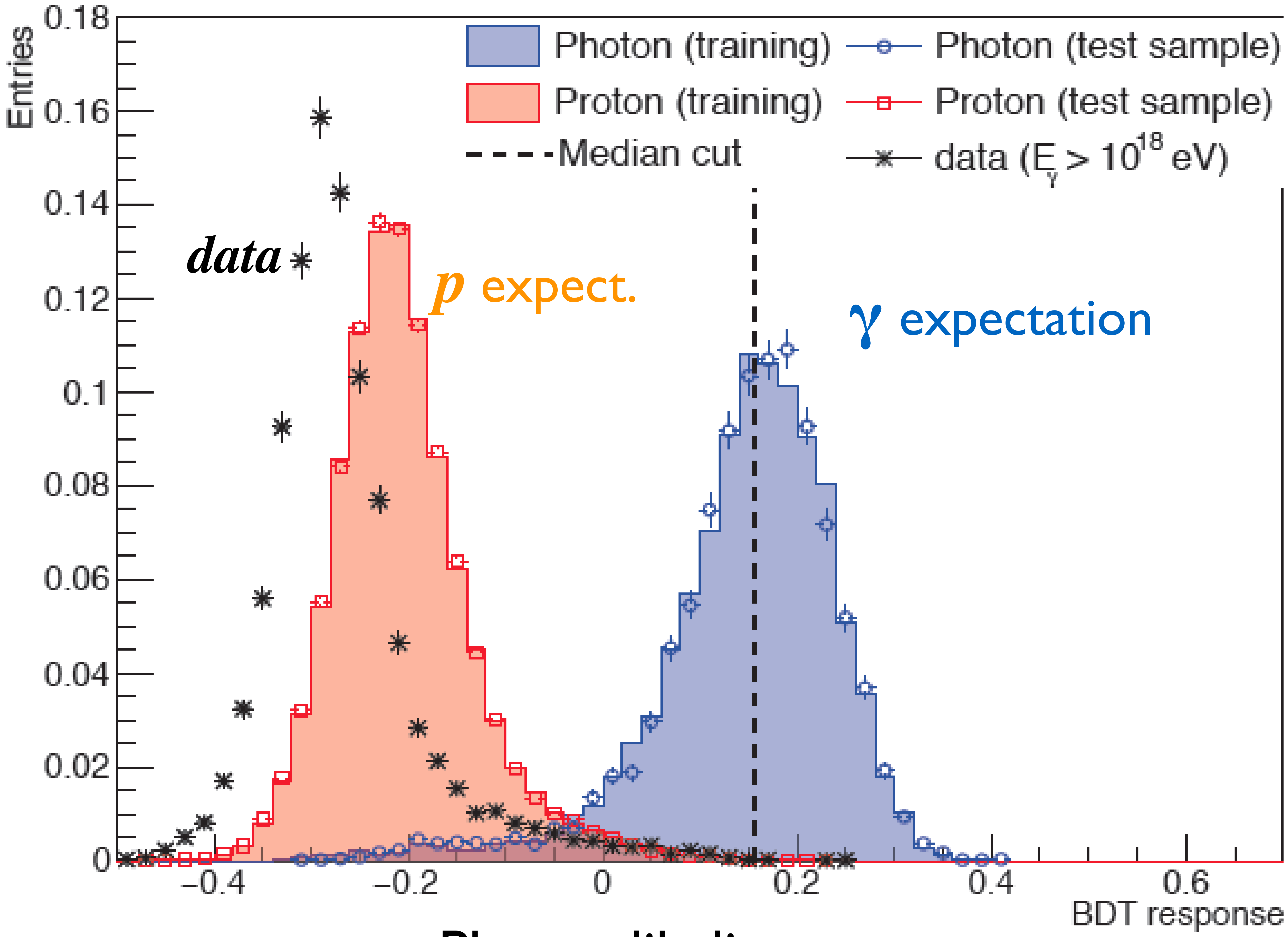
Longitudinal Shower Development (Fluorescence Telescopes)

Two quantities extracted for samples of showers



Search for EeV Photons

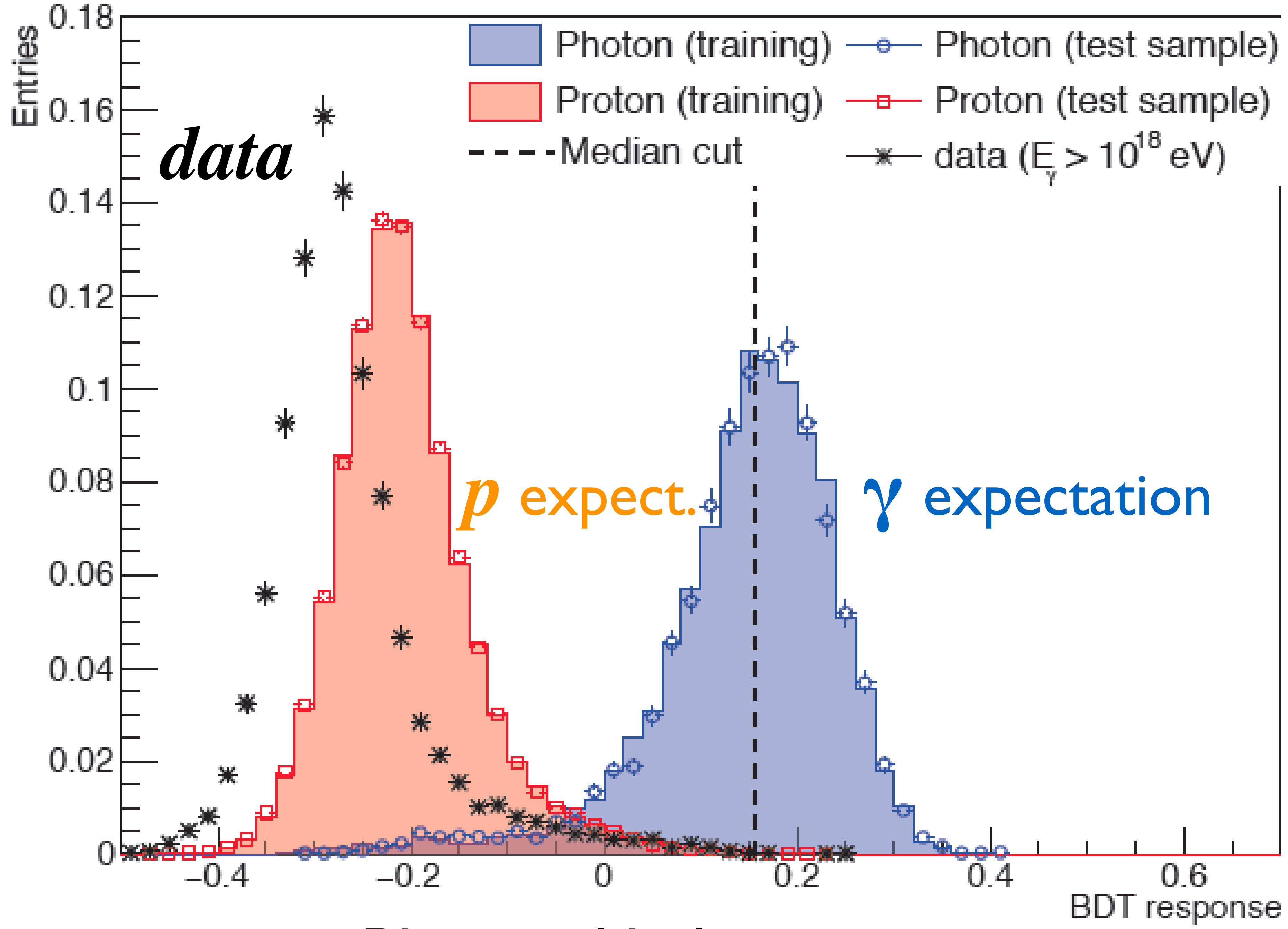
Photons can be identified by deep X_{max} and low muon number



Photon likeliness →

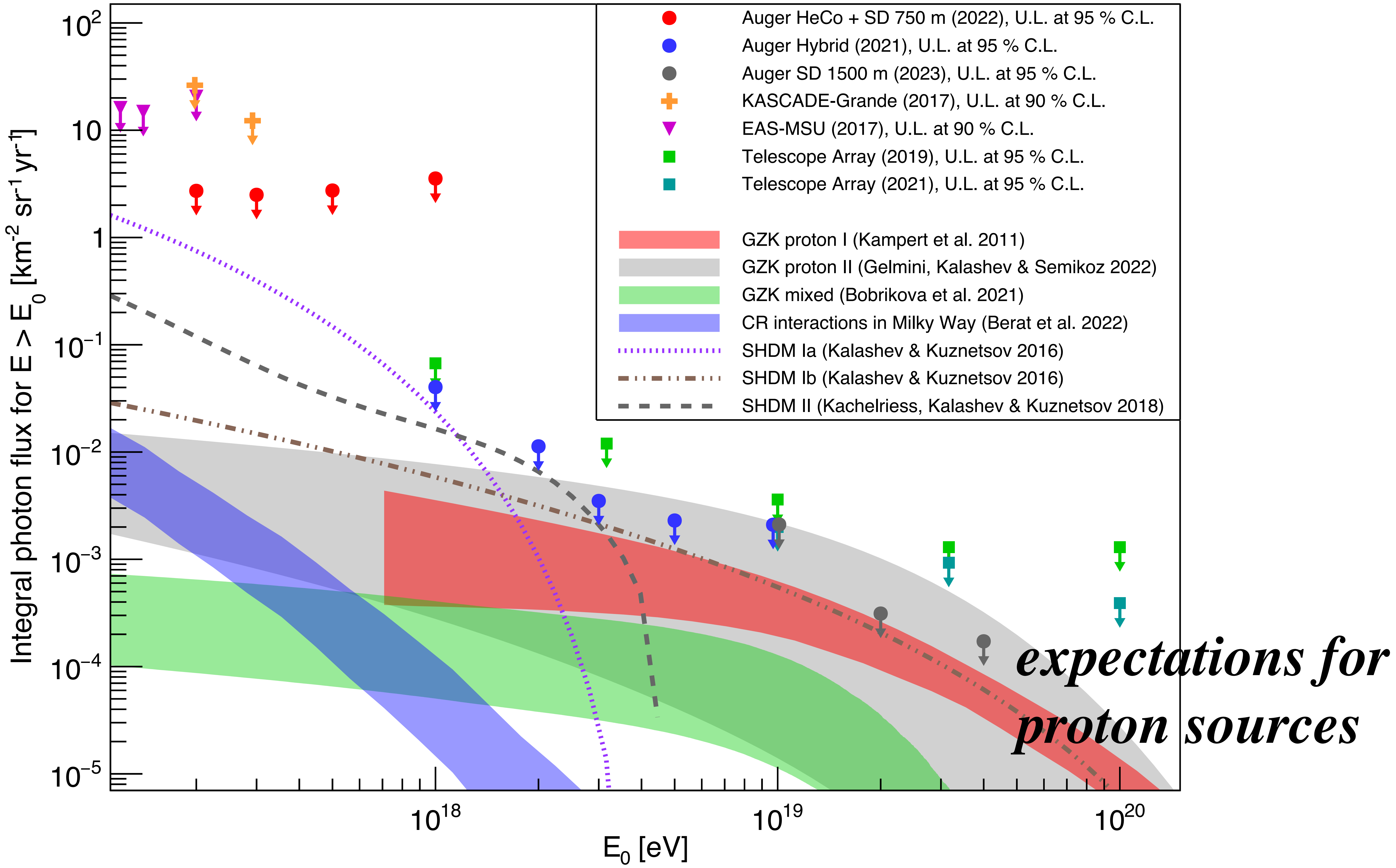
Search for EeV Photons

Photons can be identified by deep X_{max} and low muon number



Photon likeliness →

Auger Collaboration, JCAP04 (2017) 009; Universe (2022) 8, 579; JCAP05 (2023) 021

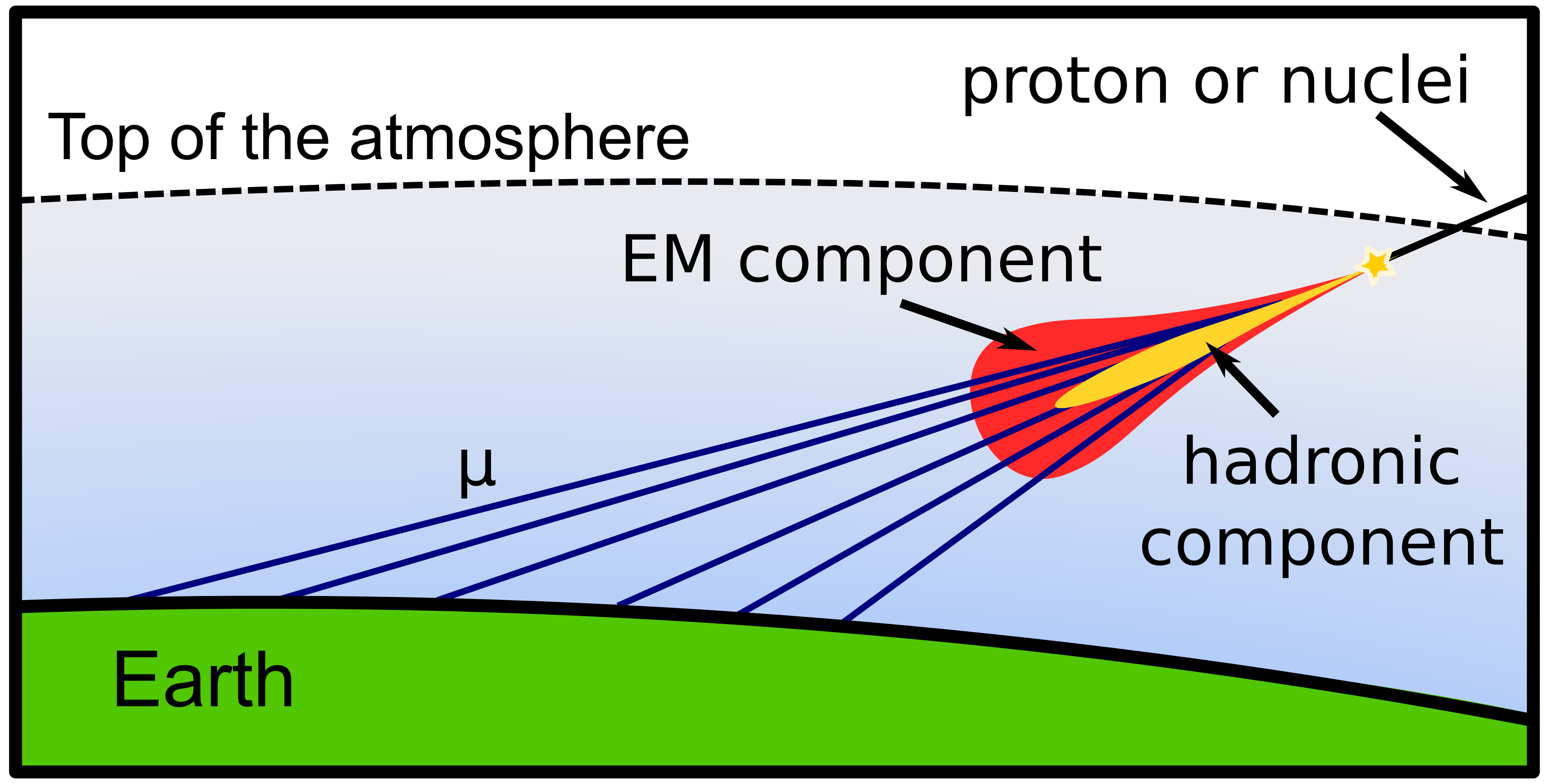


Photon upper limits start to constrain cosmogenic photon fluxes of p-sources

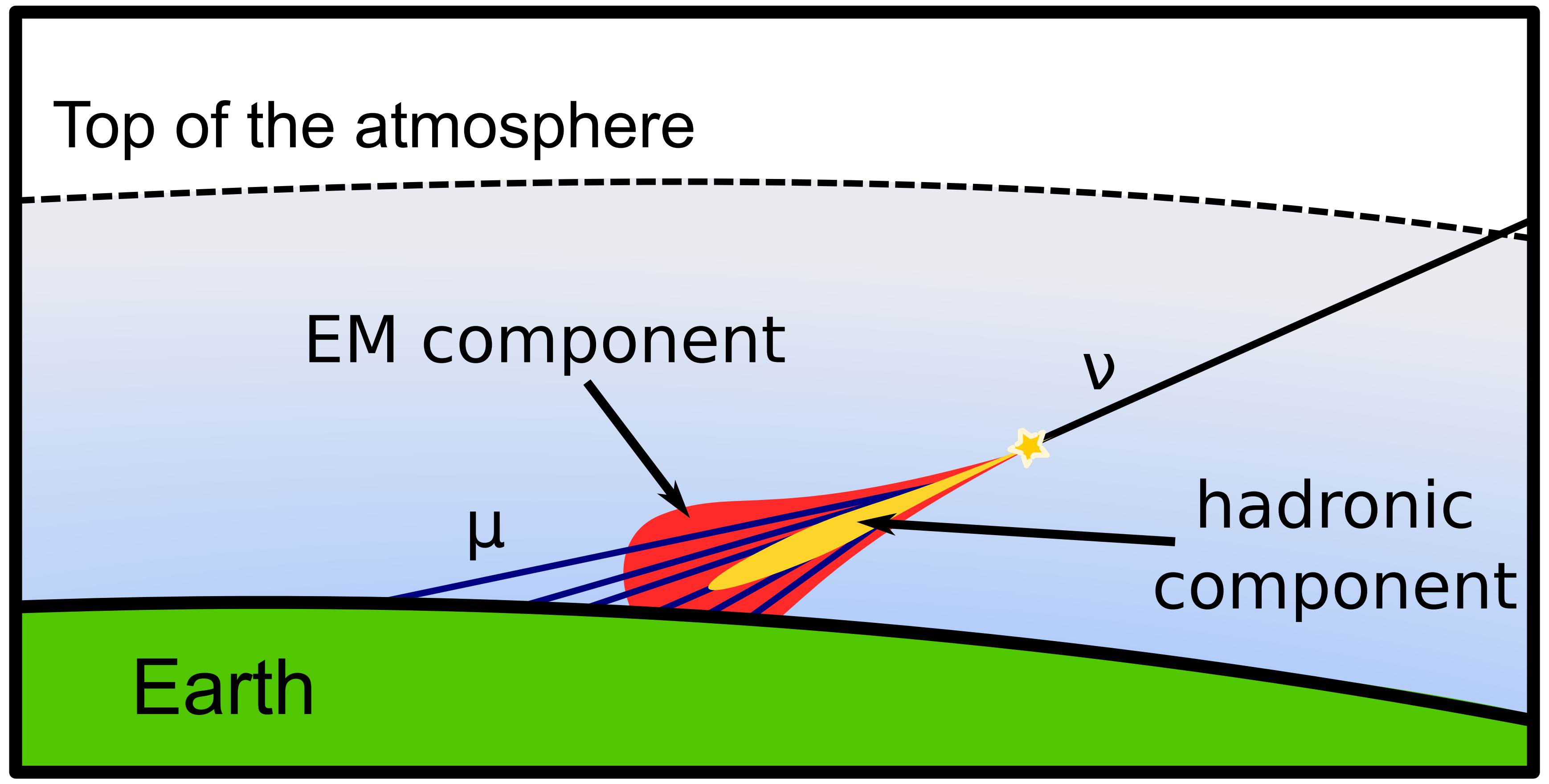
EeV Neutrinos detectable in inclined air showers

- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

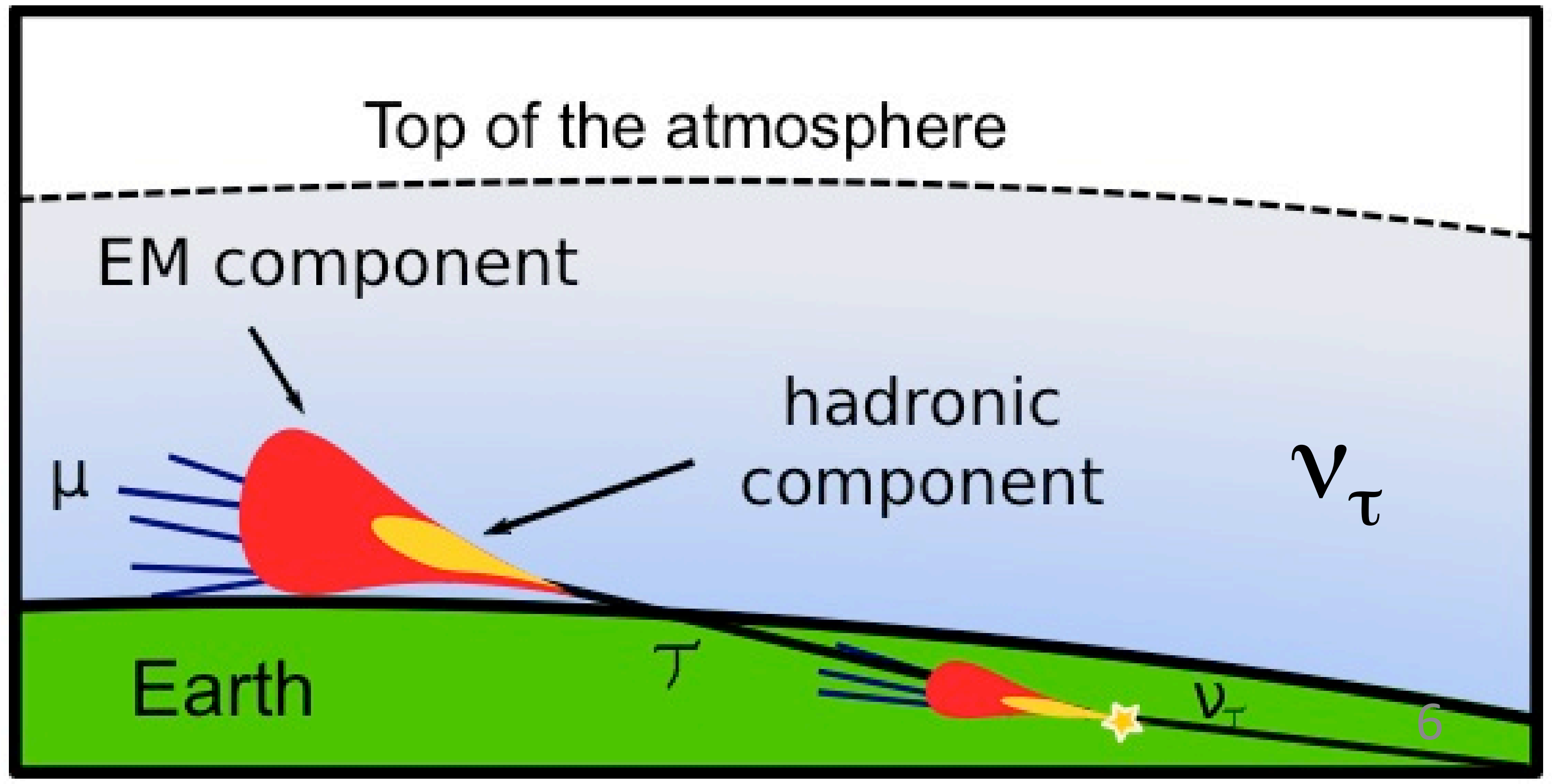
Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component



hadronic induced shower at large zenith angles
→ no em-component („old" shower)



neutrino induced shower at large zenith angles
→ normal em-component („young" shower)



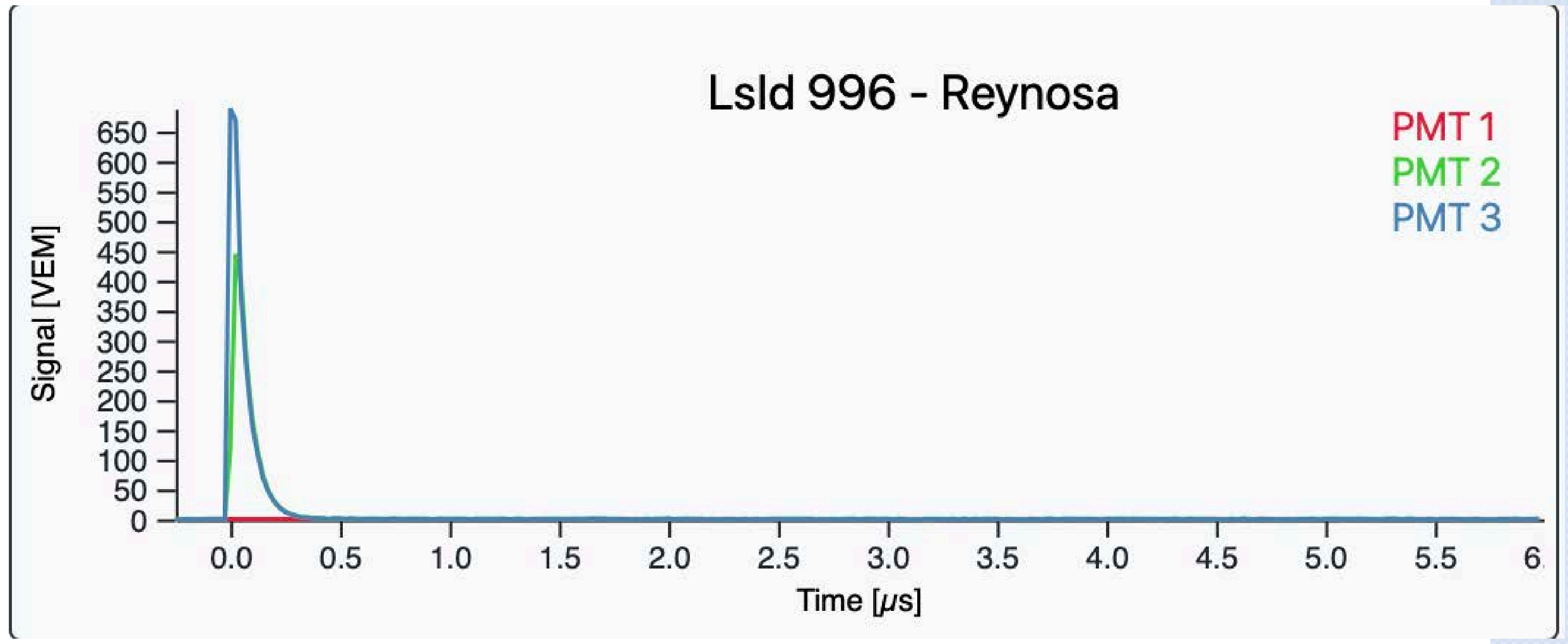
tau-neutrino in Earth skimming event produces up-going young shower

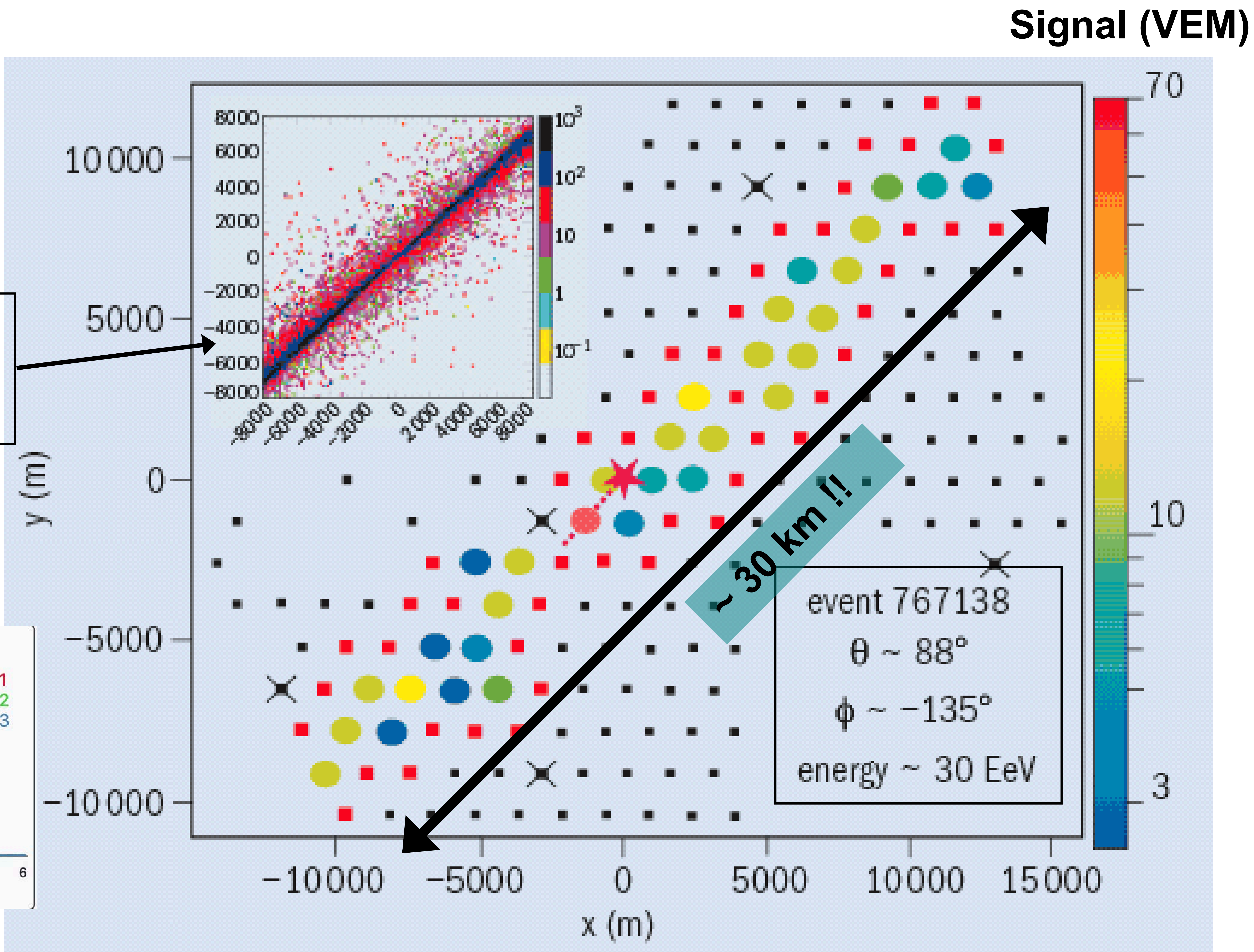
Example of an inclined event seen in Auger

CERN Courier
July 25 2006

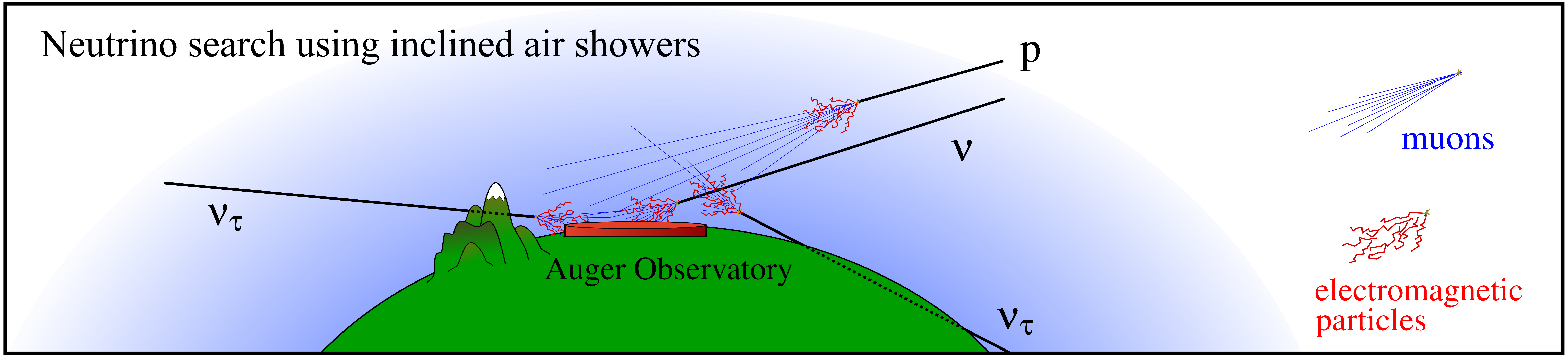
MC simulation of an event with the same angle and energy.

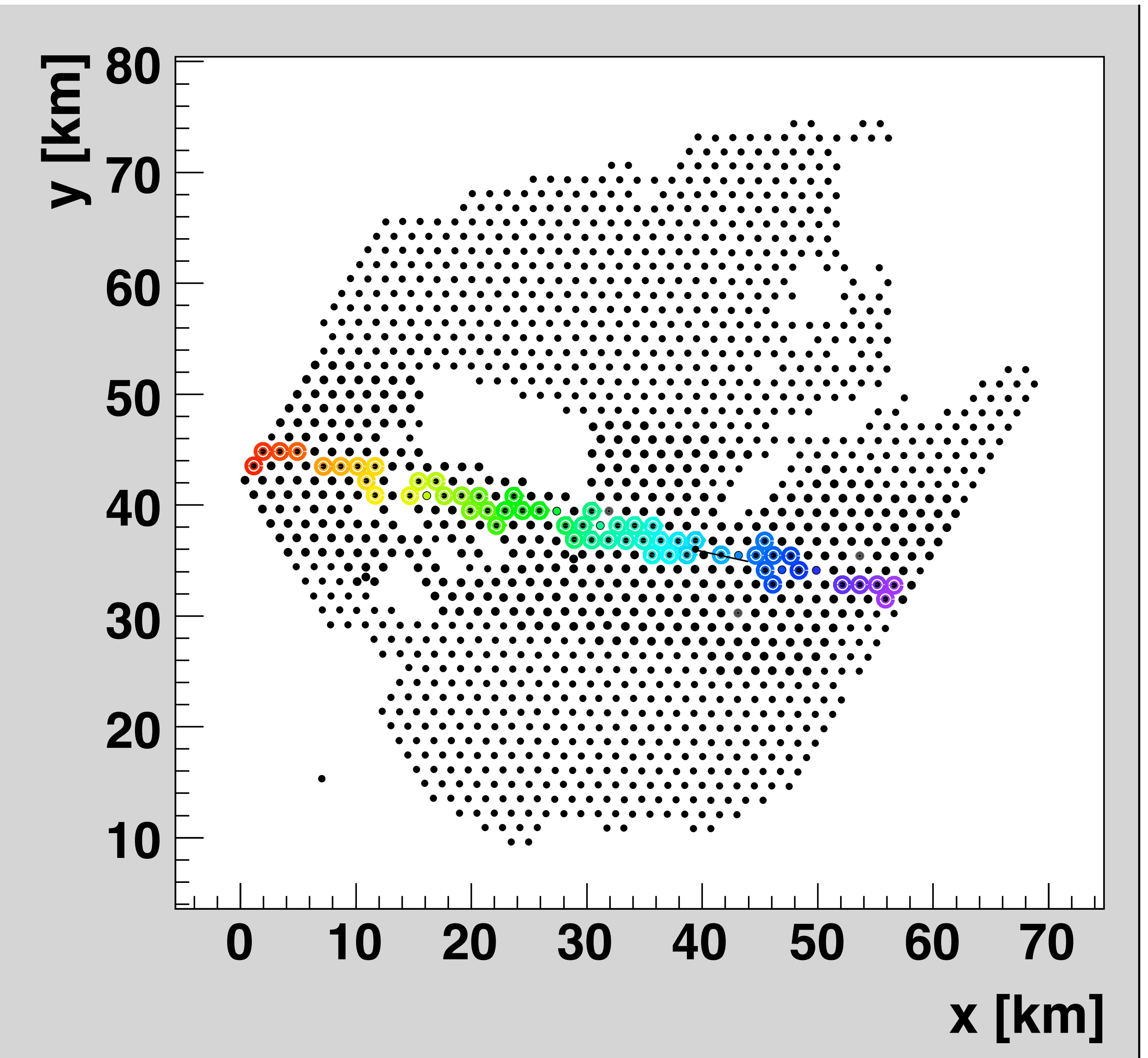
very narrow signal traces





... another example

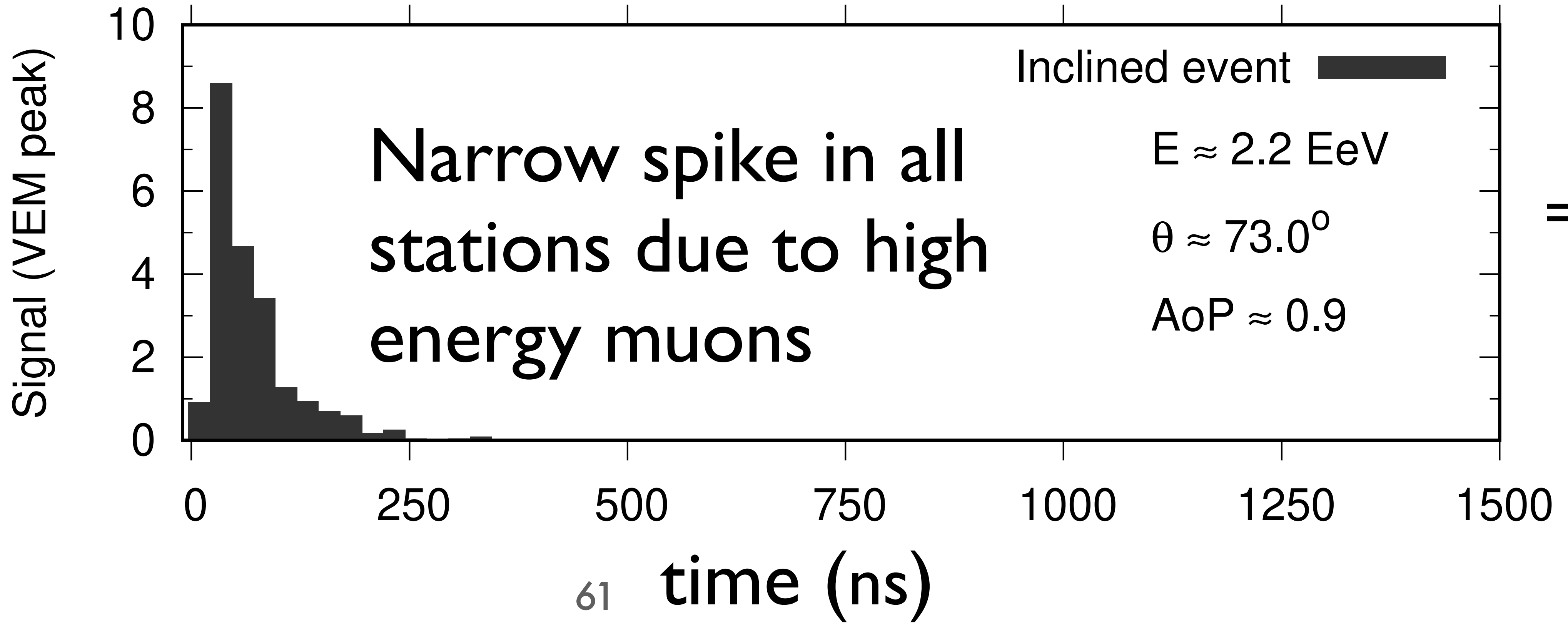




Event 3618809 (25 June 2007): 59 stations,

Example of a very horizontal shower in Auger, extending over ~60 km!

Time traces in Water Cherenkov stations



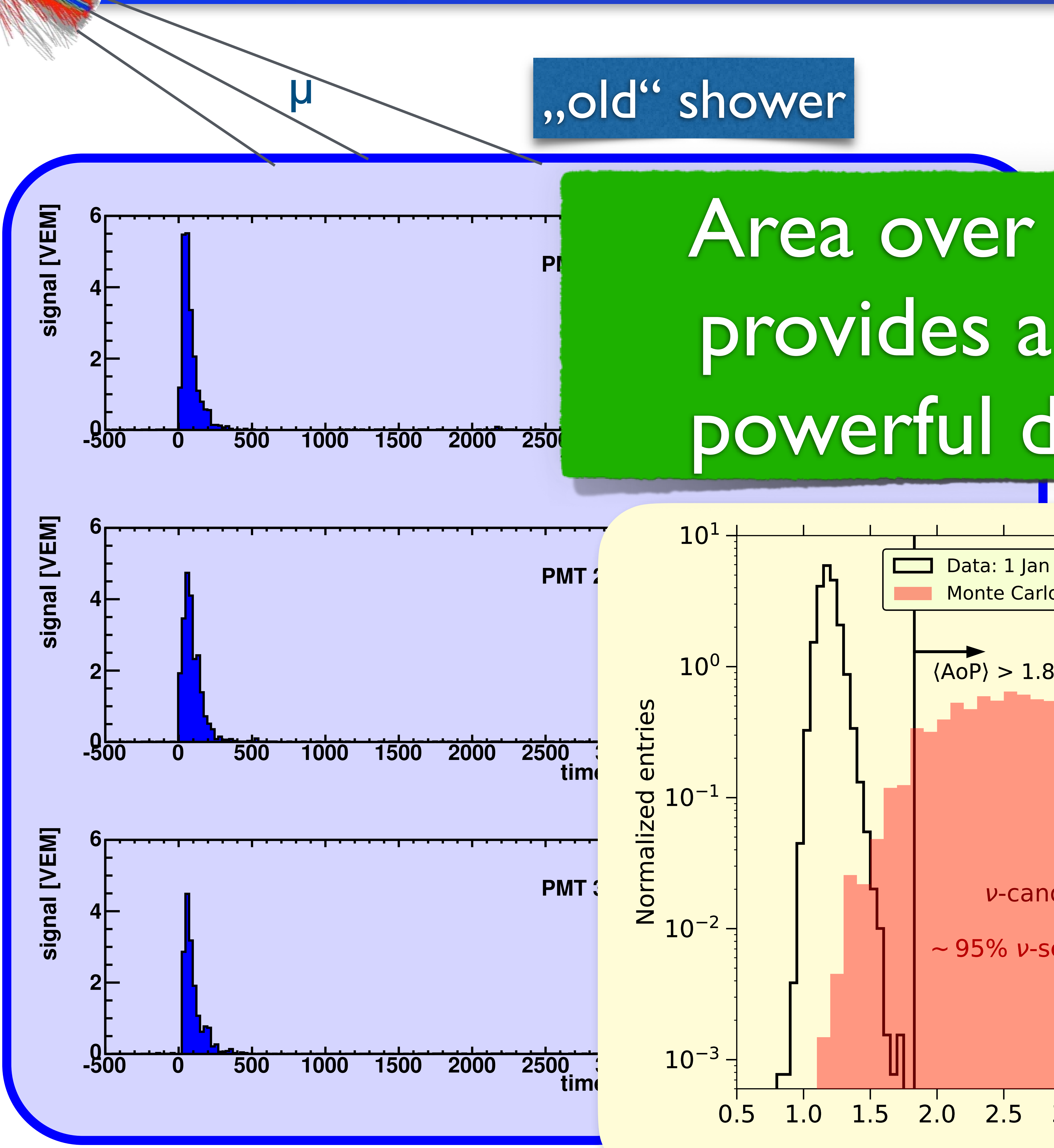
⇒ ordinary hadronic origin, no neutrino

Identifying νs in surface detector data

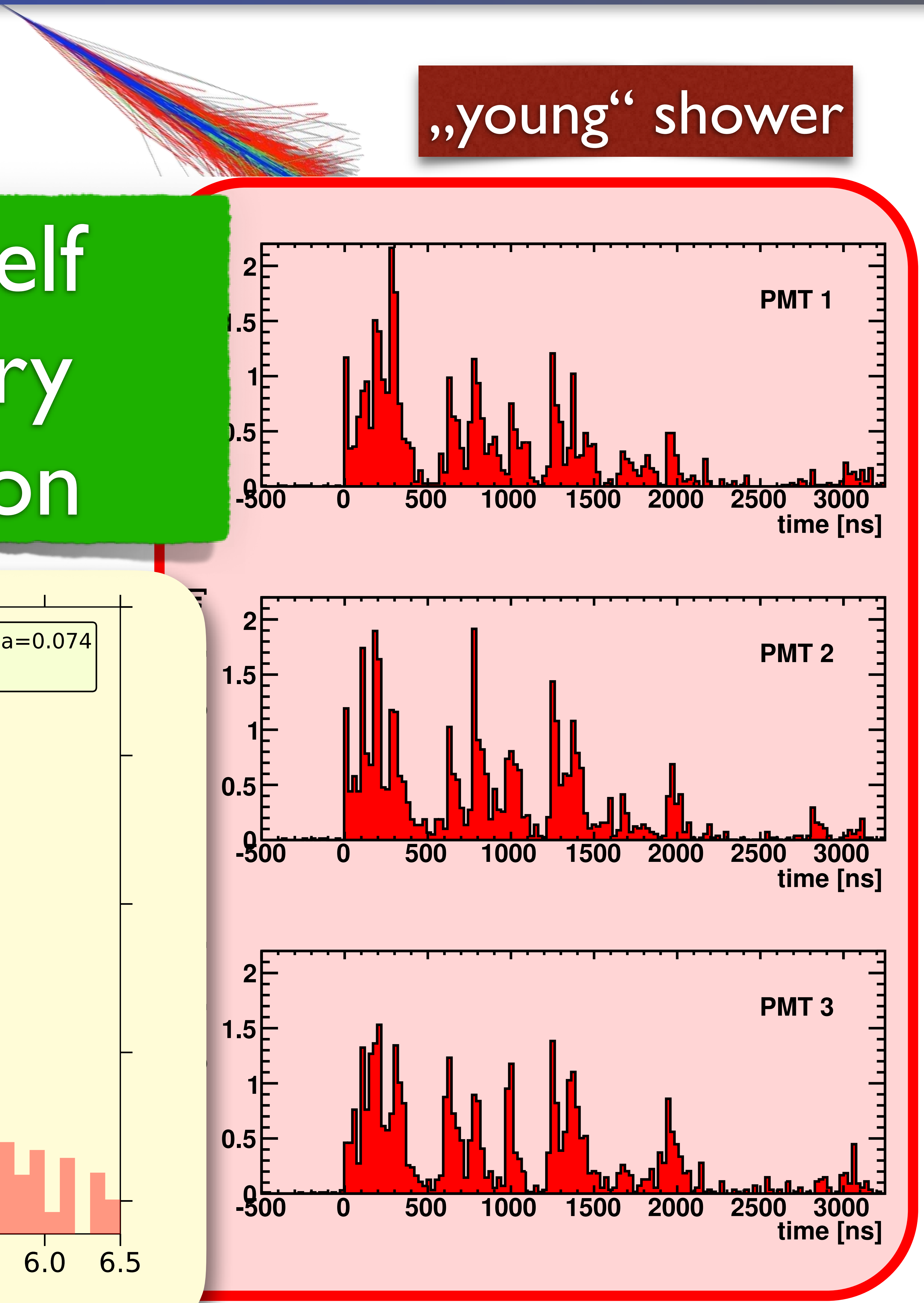
„old“ shower

„young“ shower

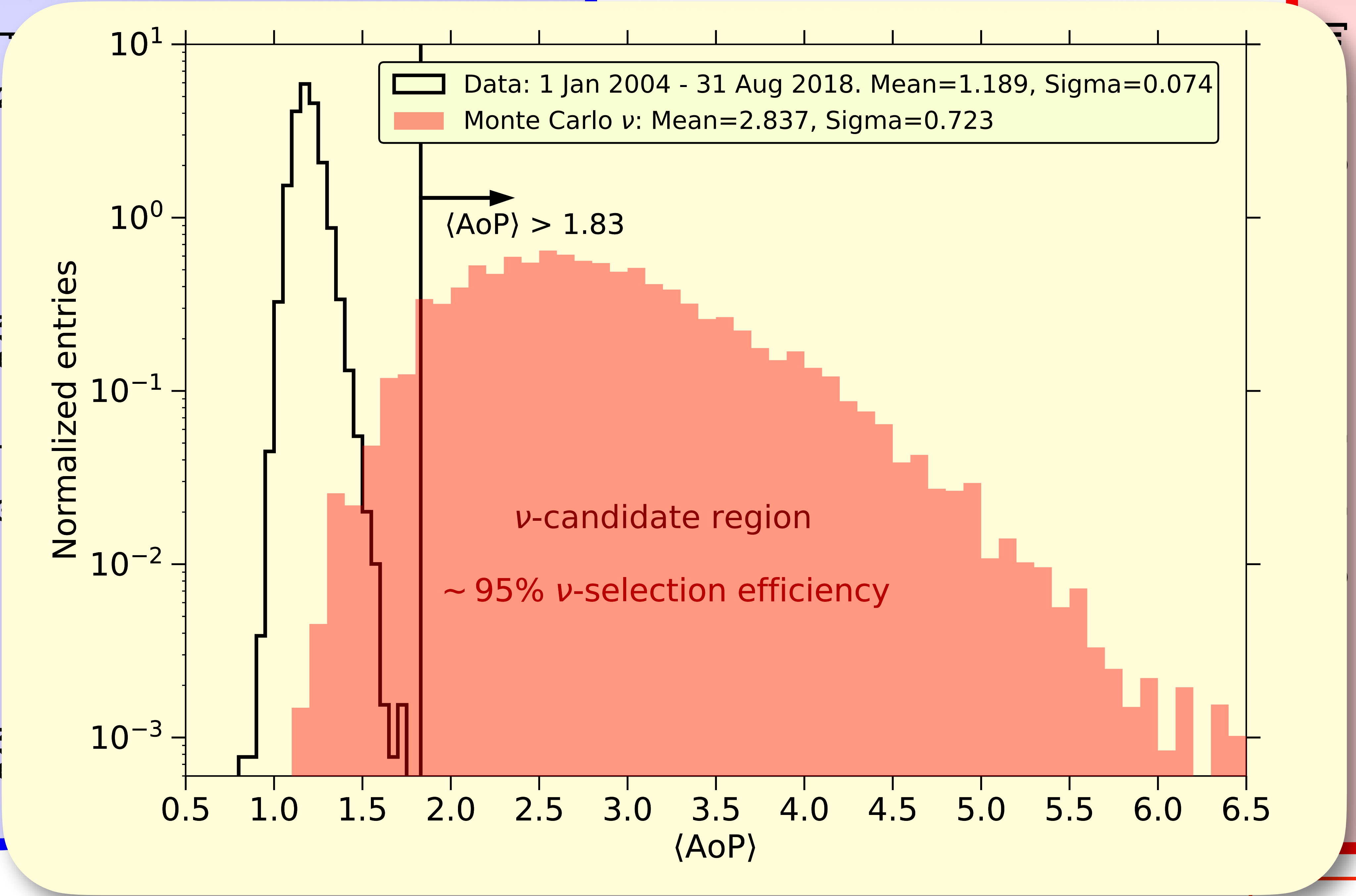
Muonic shower front: narrow signals



EM shower front: broad signals



Area over Peak by itself provides already a very powerful discrimination

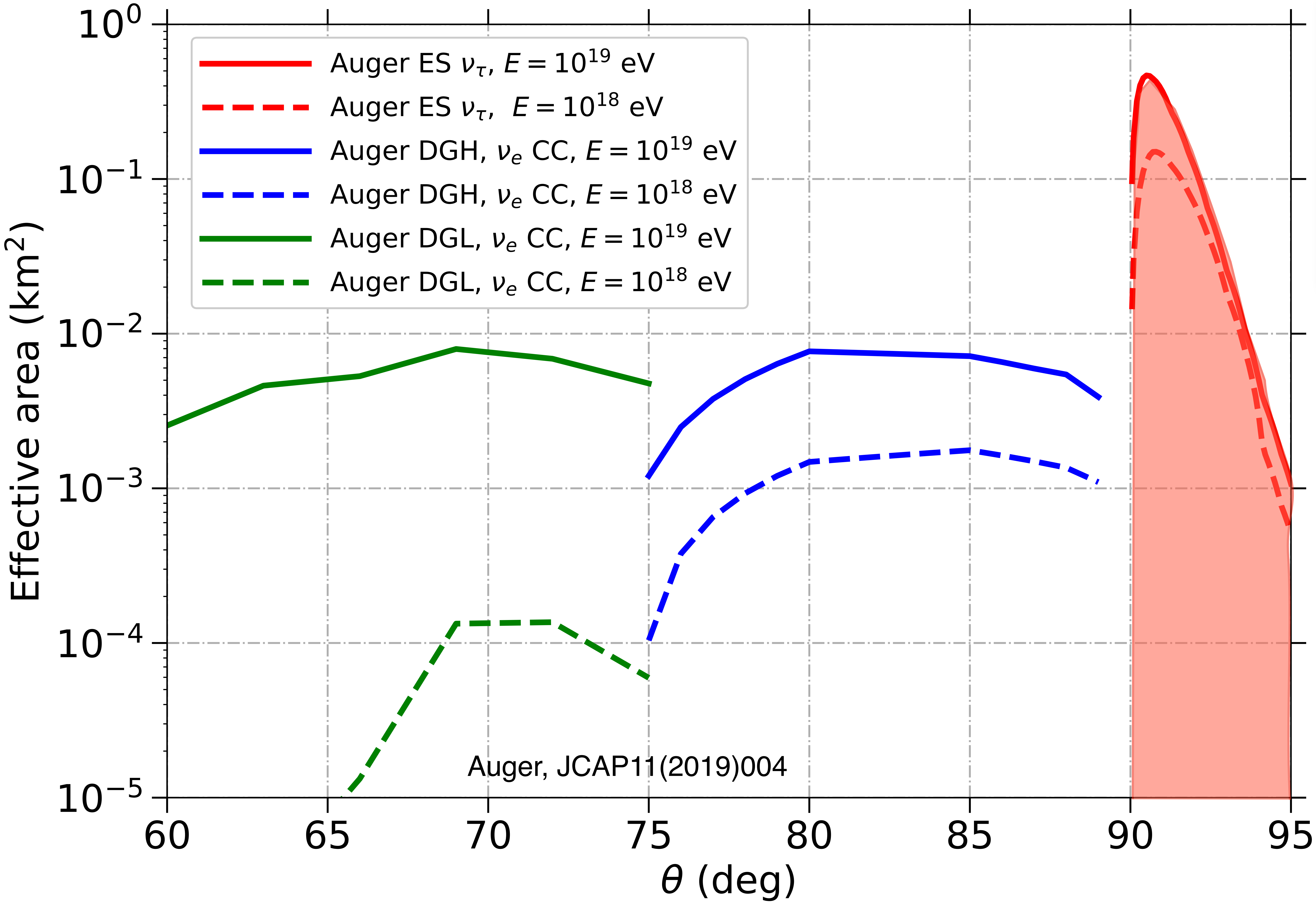


5 EeV, distance to shower axis ~1km
zenith angle ~80°

Area-over-Peak

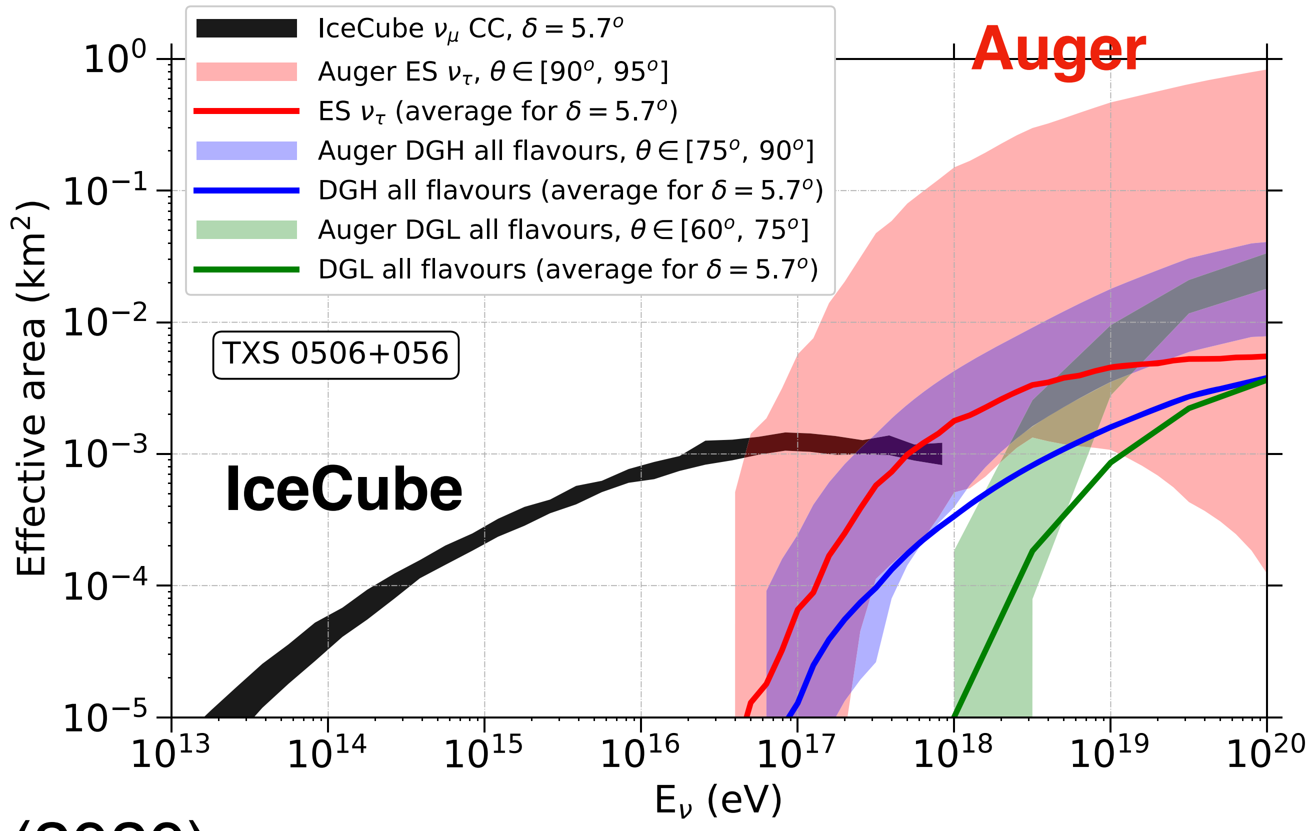
5 EeV, distance to shower axis ~1km
zenith angle ~22°

Neutrino Effective Area of Auger



huge instantaneous effective area in Earth-Skimming channel

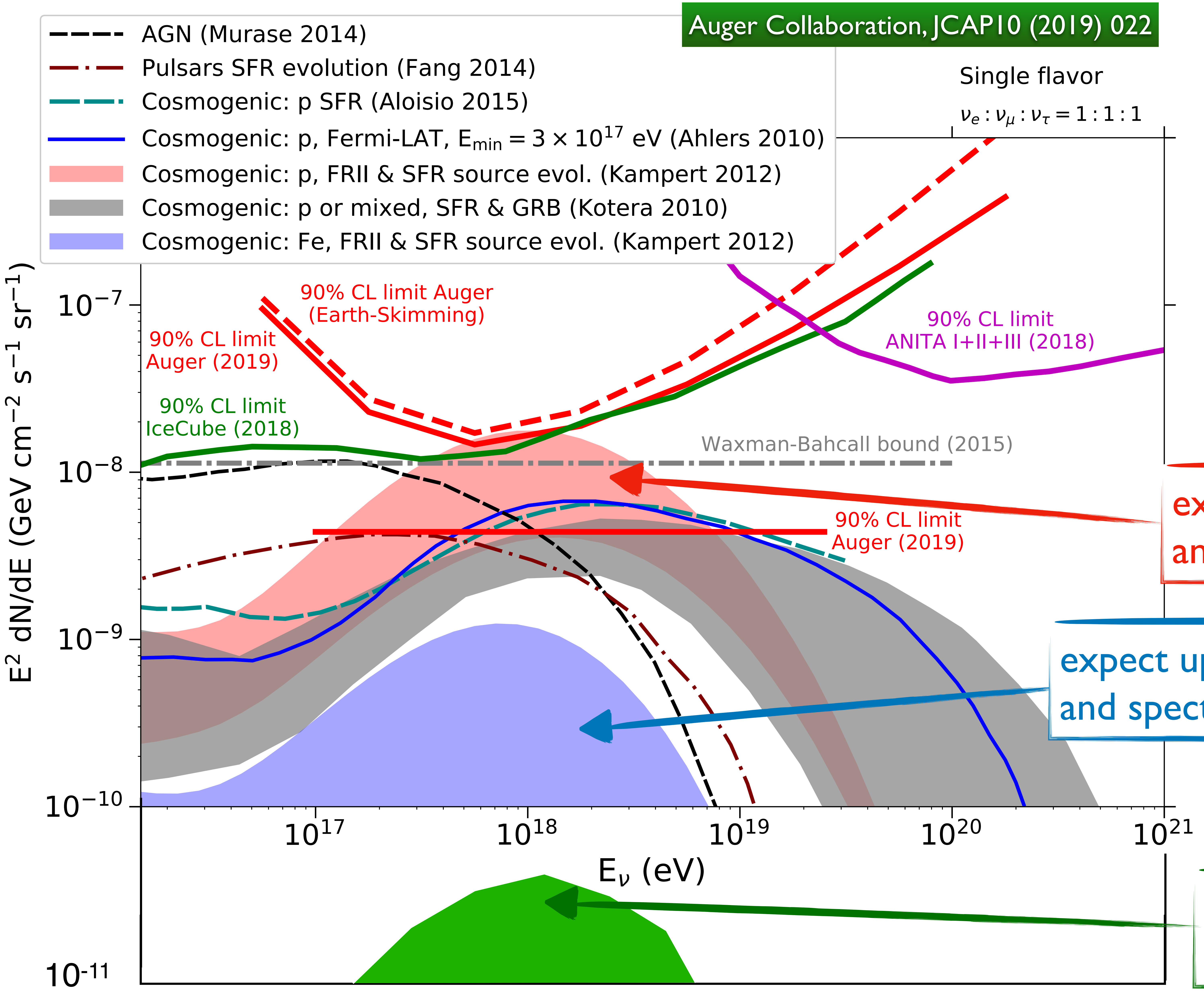
- ~ 100% duty cycle,
- ~ 95% ν_τ selection efficiency at $E_\tau > 10^{17.5}$ eV
- ~ one background event in 50 years

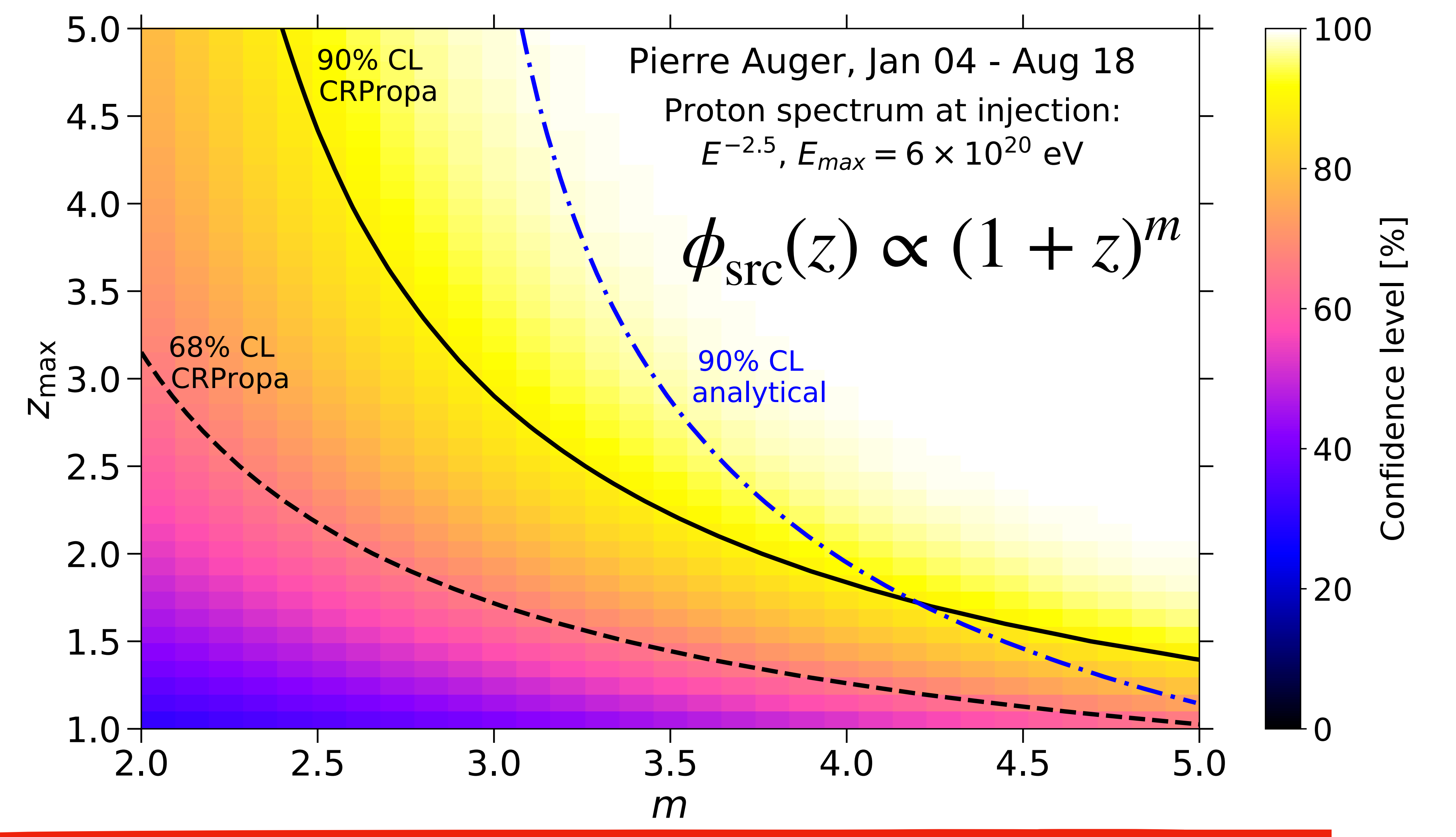


Auger, ApJ 902:105 (2020)

Bounds on cosmogenic neutrino fluxes

Auger Collaboration, JCAP10 (2019) 022





expect up to 6 νs for pure p-composition and spectral cut-off be caused by GZK-effect

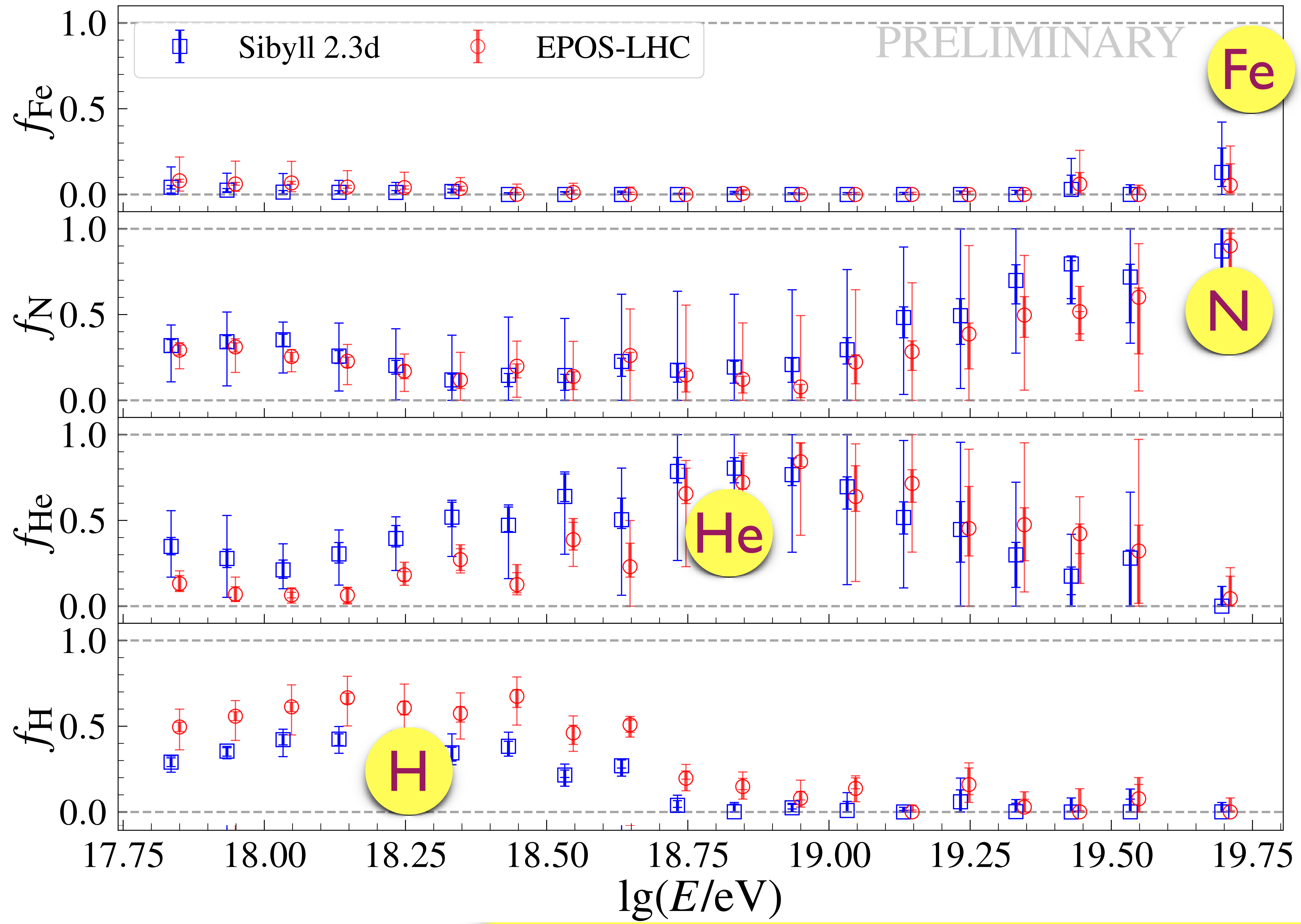
expect up to 0.4 νs for pure Fe-composition and spectral cut-off be caused by GZK-effect

expect up to ~0.001 νs in Auger (& IceCube) for maximum source energy scenario

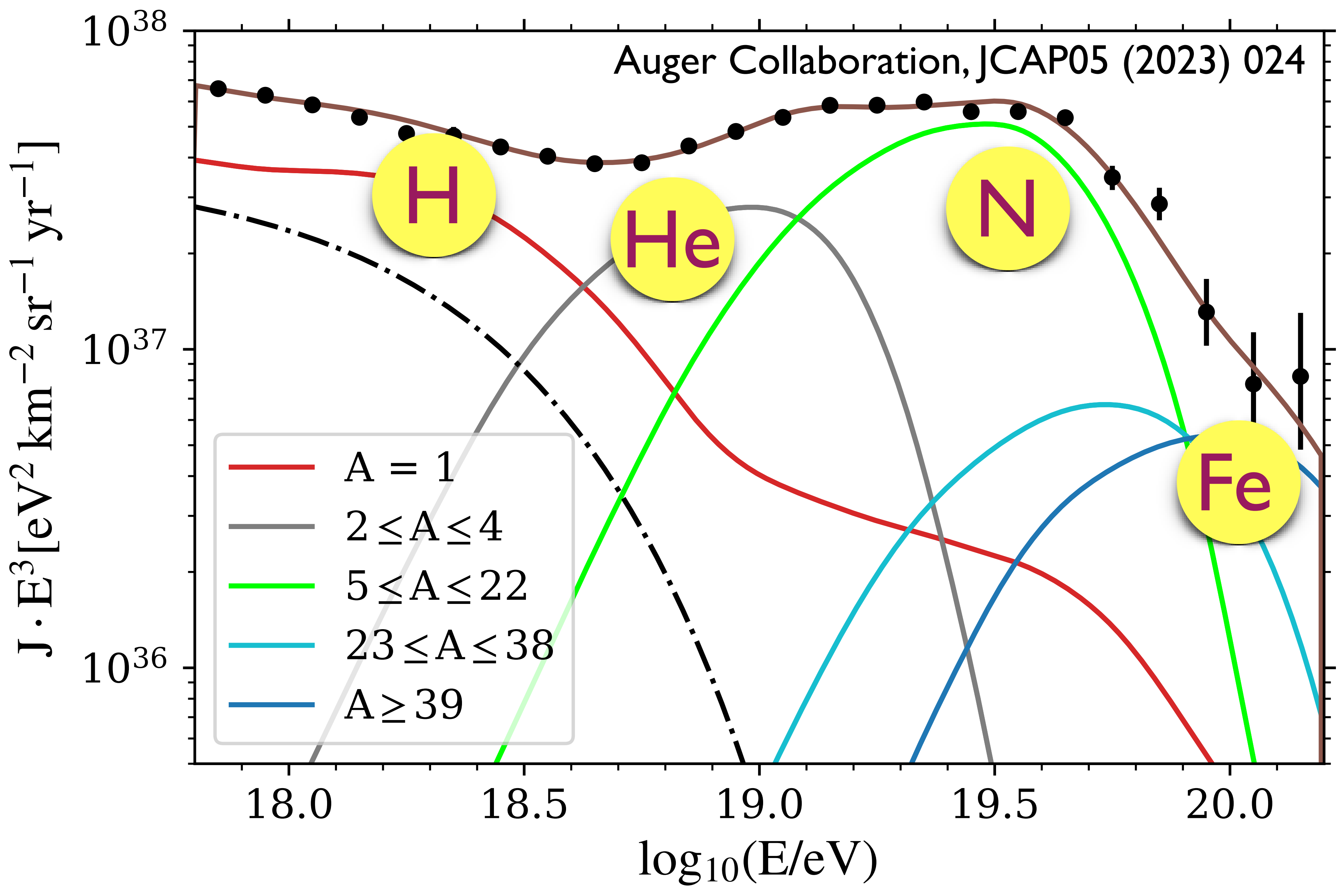
Decomposition of Energy Spectrum into Mass Groups

Auger Collaboration, ICRC 2023

Fractions of H, He, N, Fe



Deconvolution of All-Particle Spectrum



Note: Classical acceleration of charged particles → $E_{max} \propto Z \times R \cdot B$

Combined fit of E-spec & Compositon

→ $E_{max}/Z \simeq 7 \cdot 10^{18}$ V

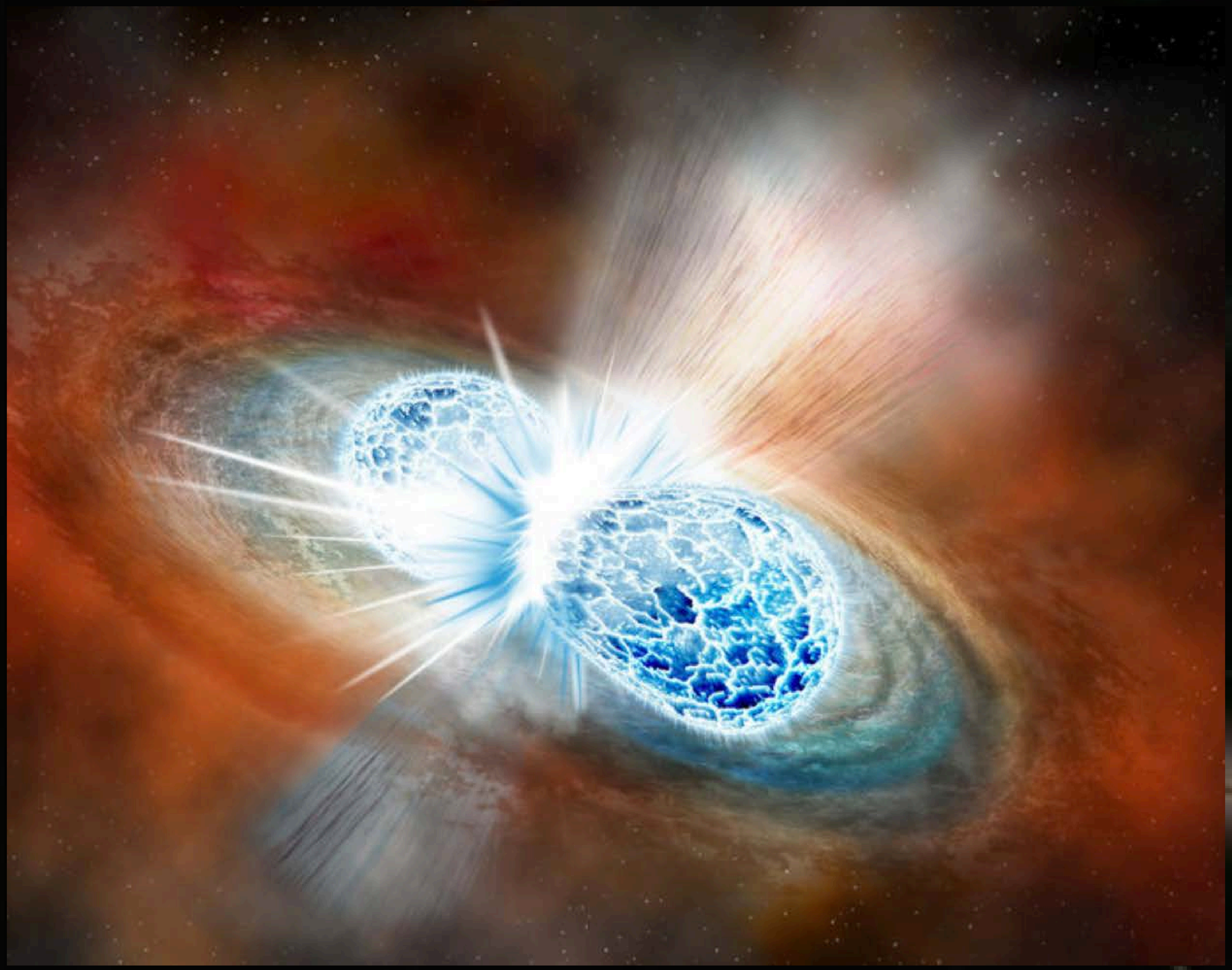
Increasingly heavy composition towards the end of the spectrum

Conclusion

The non-observation of cosmogenic photons and neutrinos supports the interpretation that the spectral cut-off is primarily an effect of the sources rather than an effect of propagation

Back to the Neutron Star Merger GW170817

2017: Big Bang of Multimessenger Astrophysics



Scientific Breakthrough of 2017

Neutron Star Merger GW 170817

observed also in broad range of
electromagnetic radiation
with strong bounds on
HE neutrino emission

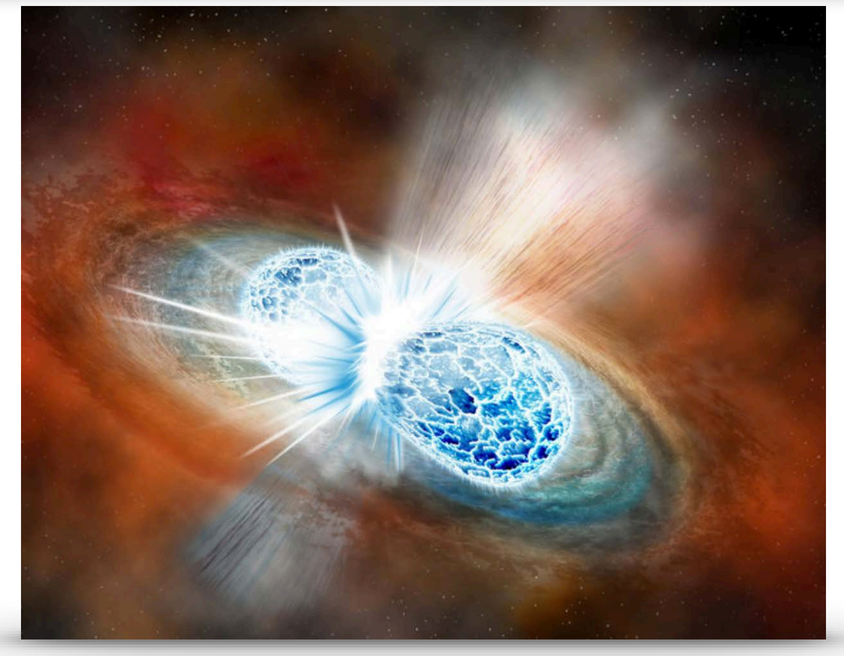
Joint publication by > 3000 authors (LHC scale)

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

This was a very lucky event...!

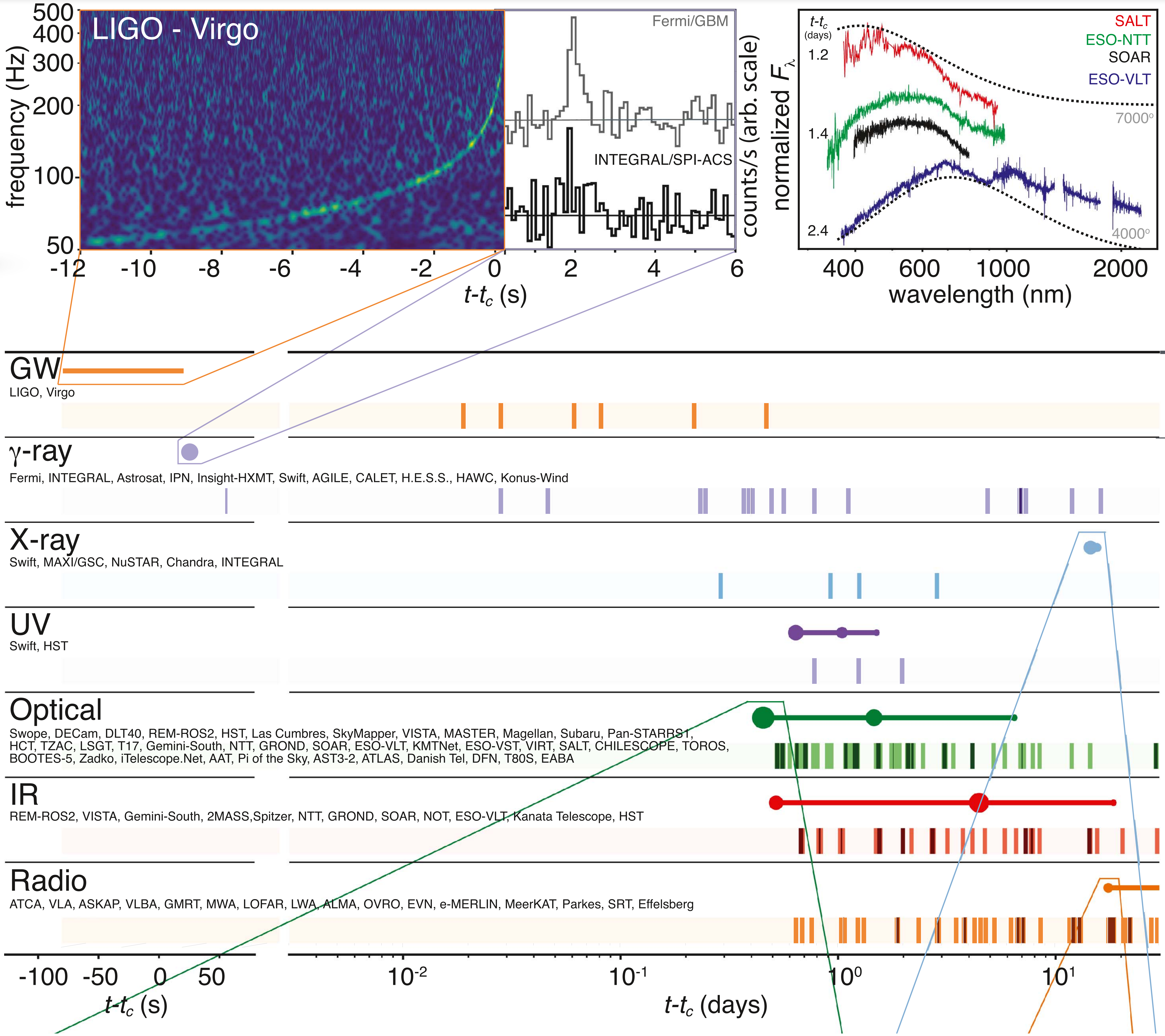
GW170817: Time Sequence



lasted 100 s !

1.7 s after GWs

still after weeks



m_1 = (1.36 - 2.26) M$_\odot$

m_2 = (0.86 - 1.36) M$_\odot$

Host galaxy: NGC 4993

distance: 40 Mpc

optical brightness after one day
10^8 L$_\odot$ → **kilonova** powered by radioactive decays

13:08 UTC LIGO sent a a BNS alert that occurred <2 s before GRB from same direction

Fermi-GBM sent an automated alert of an unspectacular GRB at 12:41 UTC

excessive campaign during next days and weeks

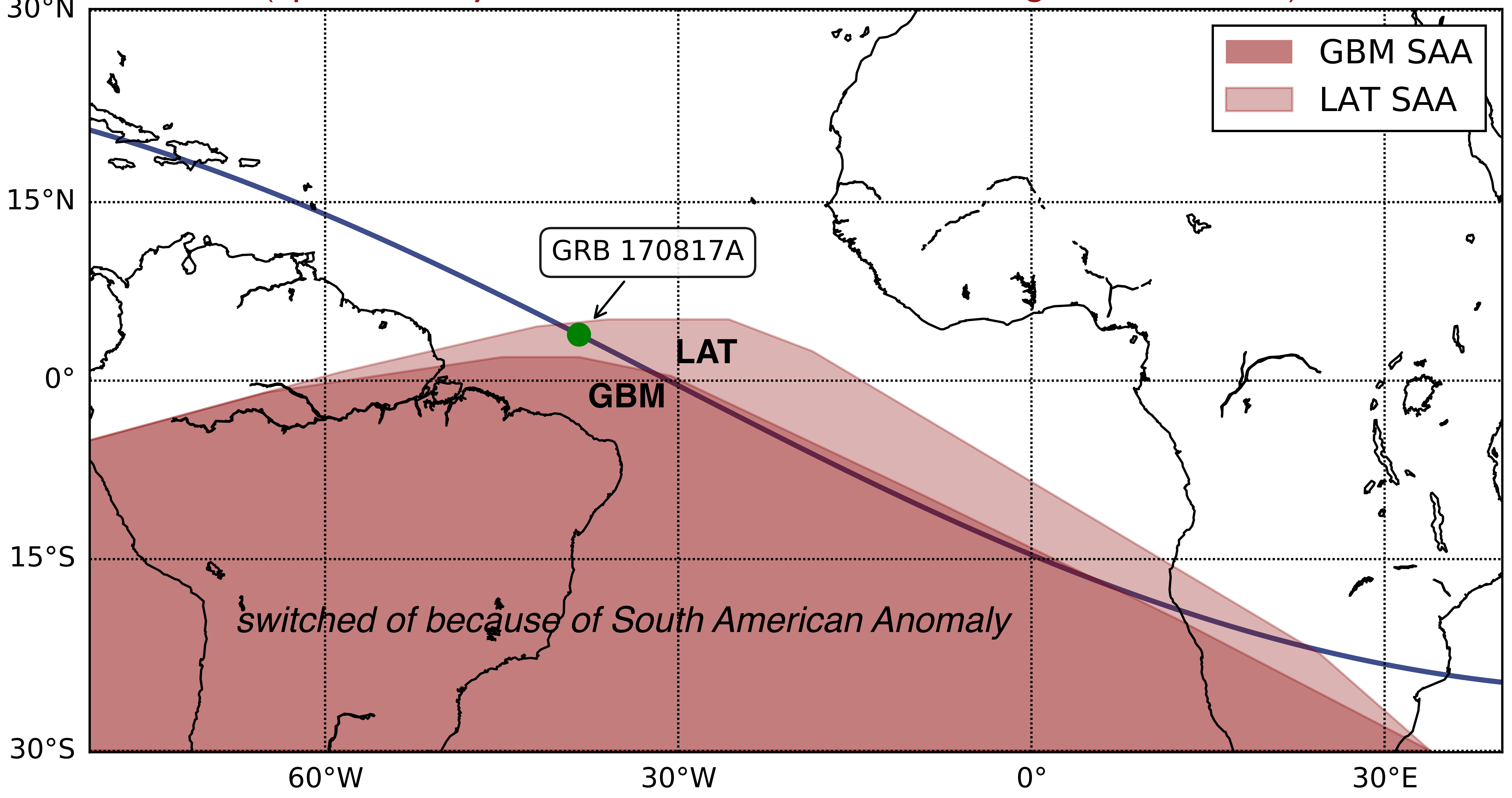
GW170817: Physics across multiple aspects/fields

- **General Relativity**: gravitational waves
- **Cosmology**: independent Hubble constant determination
- **Astronomy**: Follow ups, multiwavelength
- **Astrophysics**: Compact objects, Neutron stars
- **Nuclear Physics**: r-process, equation of state
- **Particle Physics**: Neutrino oscillations
- **Astroparticle Physics**: Particle acceleration, UHE counterparts

Unique Event
→ Brought together different communities

Observation of GRB 170817A was a lucky instance !

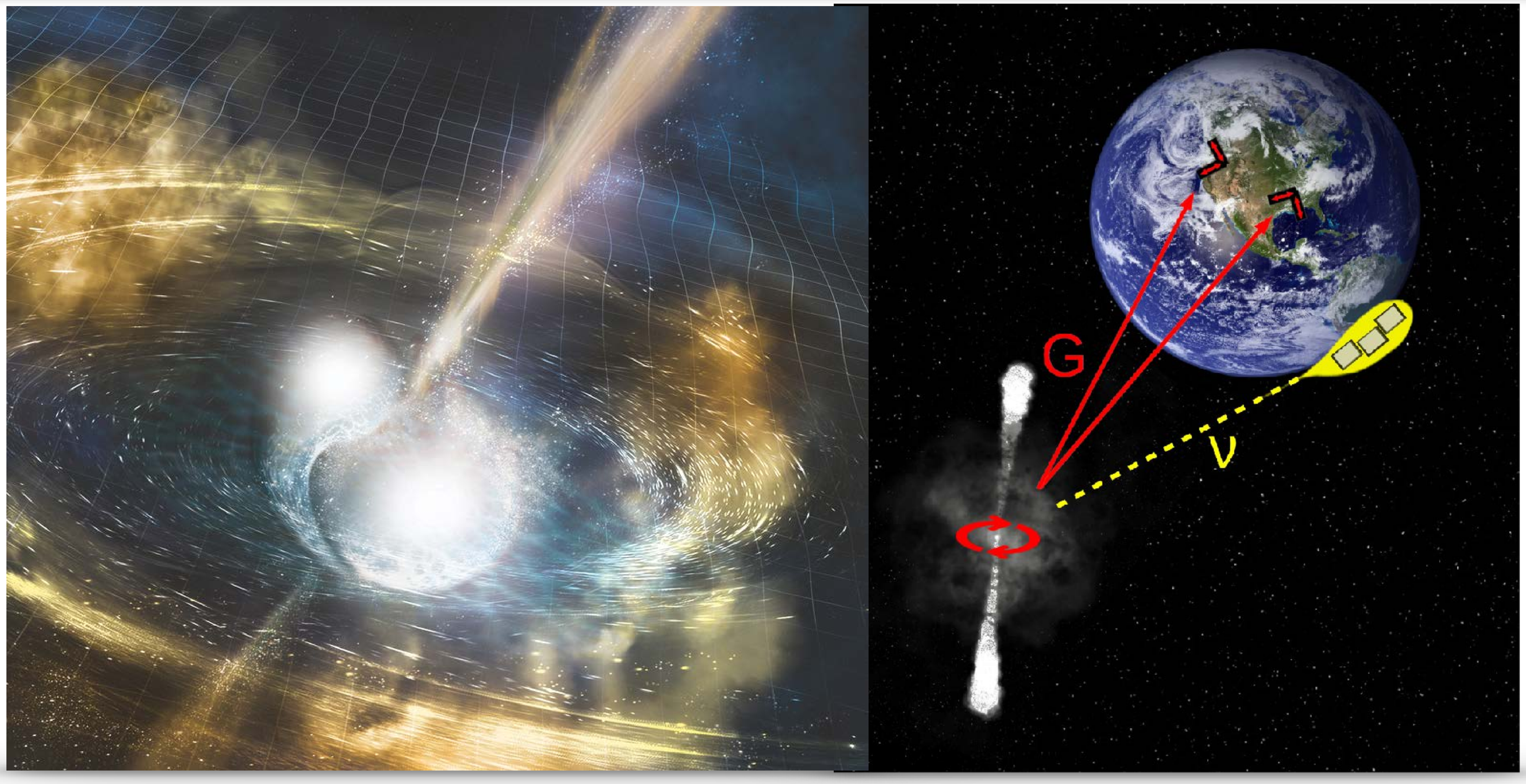
Large Area Telescope (LAT) was switched off 2 seconds before LIGO-Trigger
Luckily, Gamma-Burst Monitor (GBM) was still online
(up to recently, GBM had been switched off/on together with LAT!)

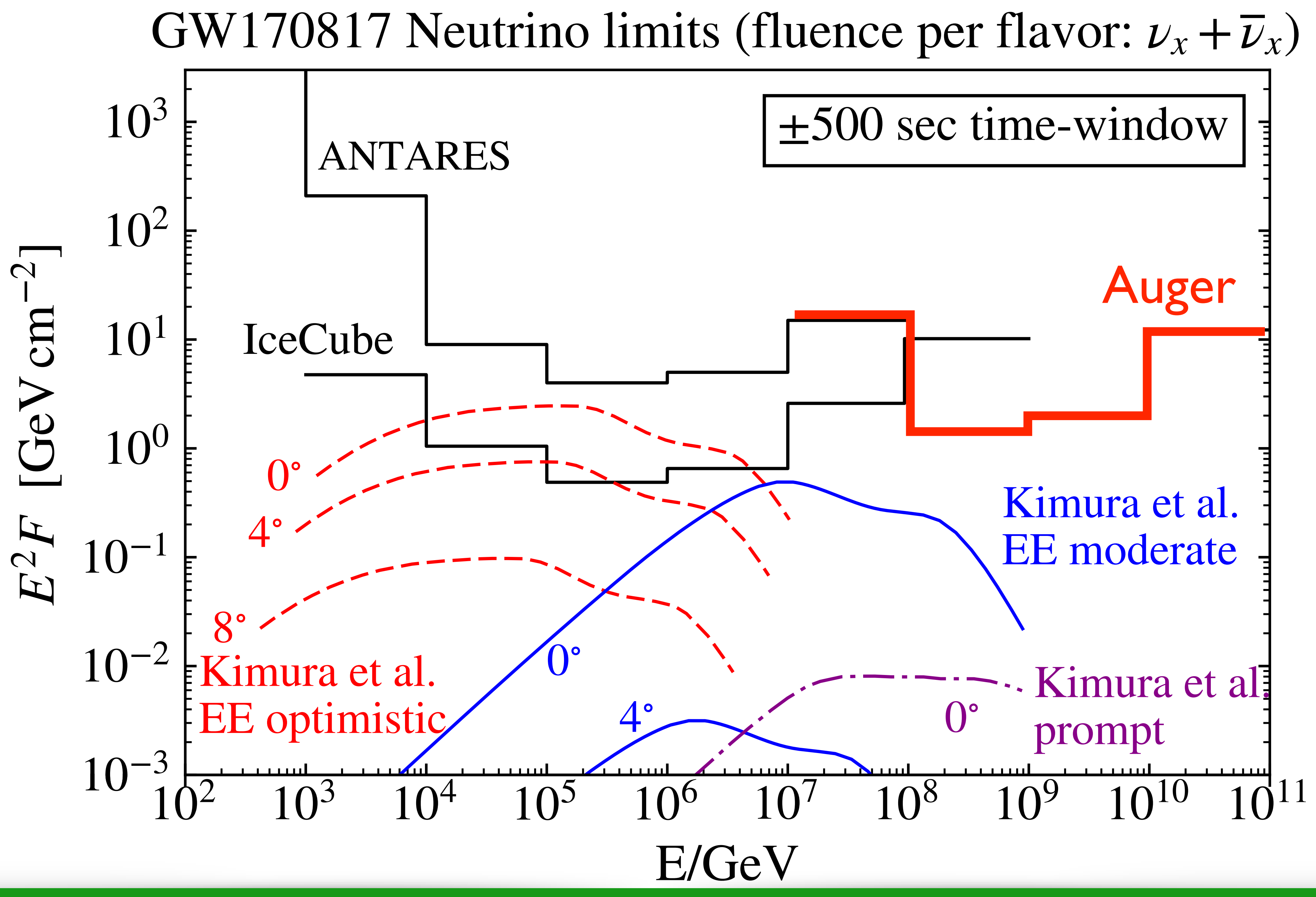


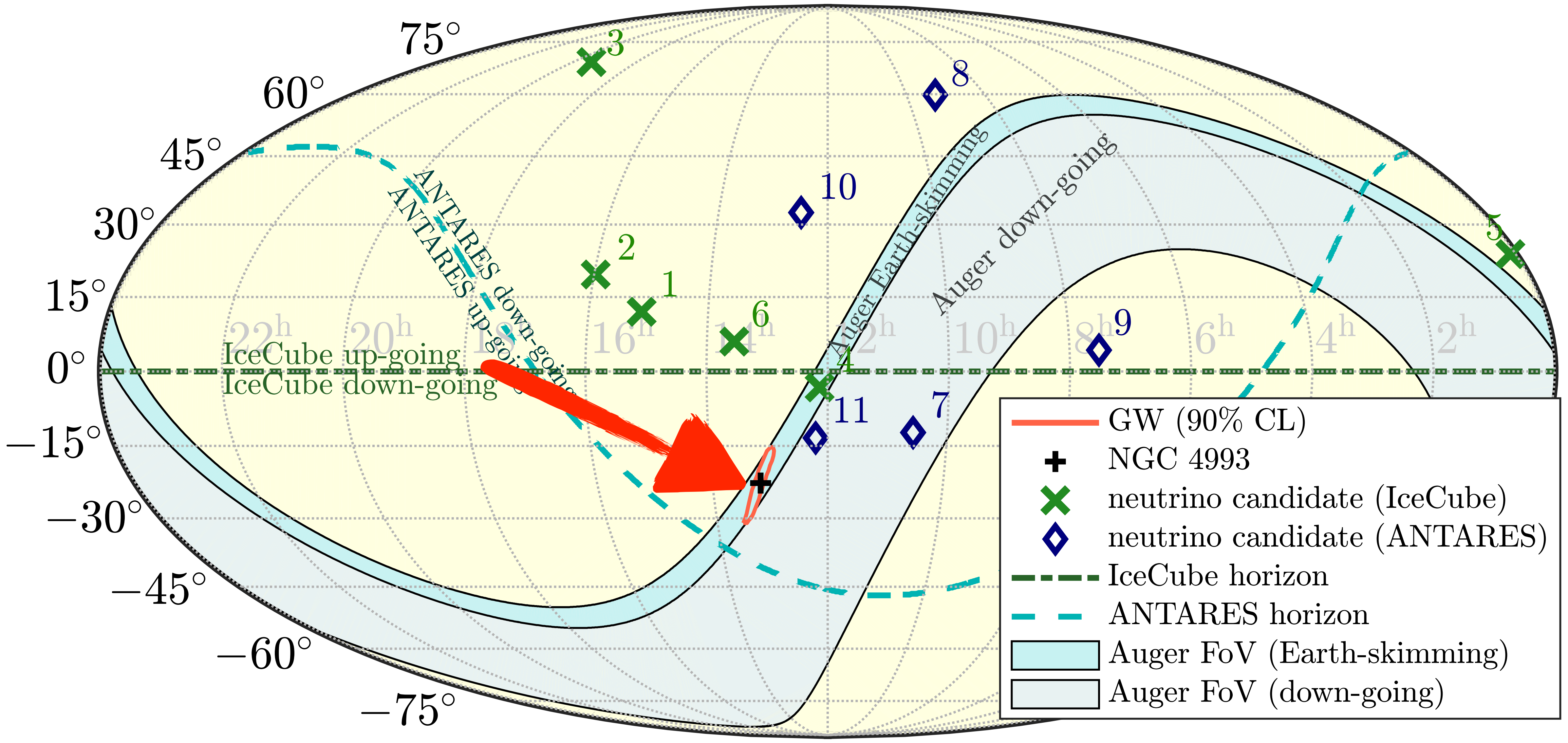
Fermi-LAT Collaboration, arXiv:1710.05450

Message to the young scientists: Never be lazy, always get the very best out of your apparatus !

Neutrino Upper Limits for GW170817







Absence of Neutrino consistent with SGRB viewed at >20° angle

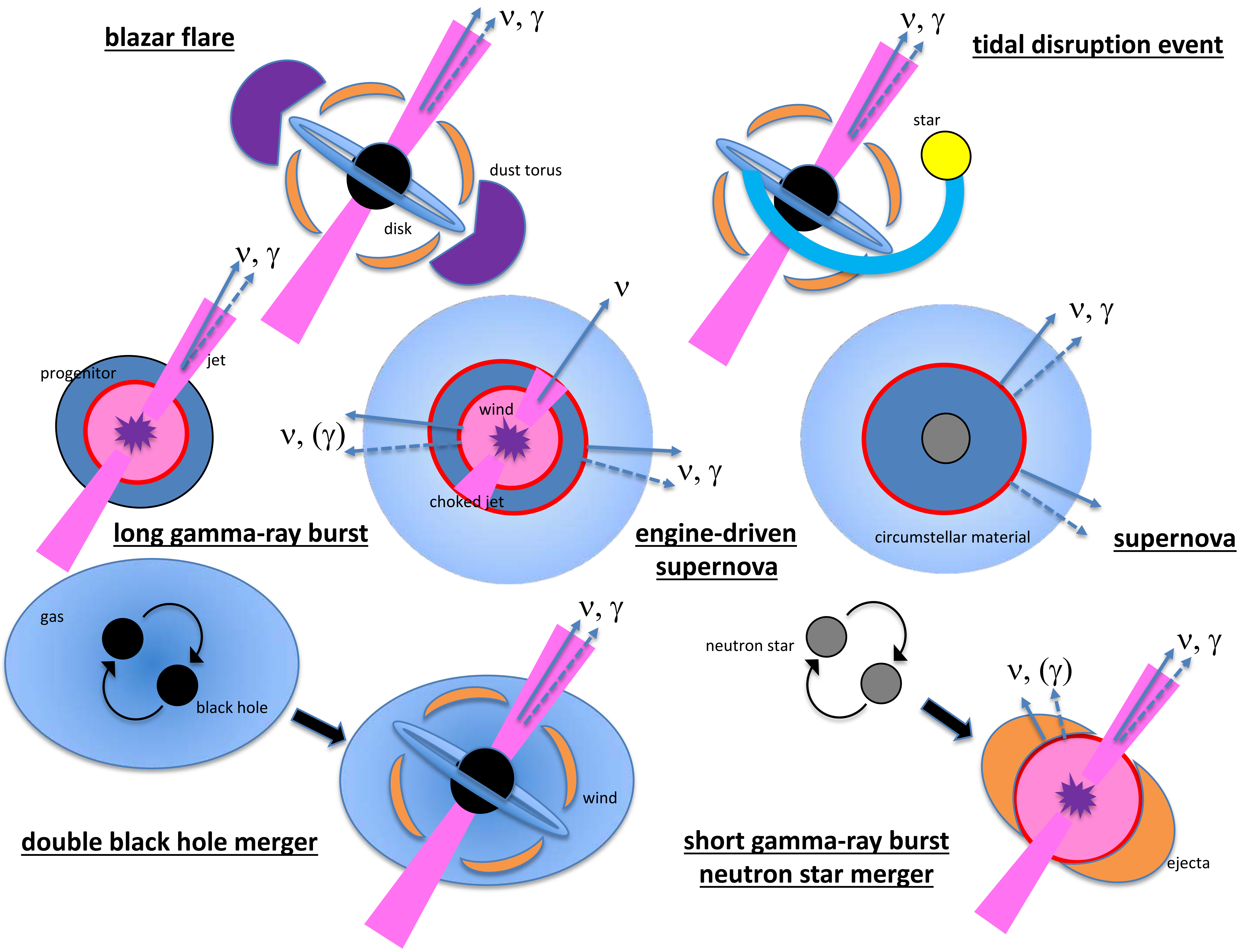
May have seen neutrinos if jet were pointing towards us

LIGO, ANTARES, IceCube, Auger,
The Astrophys. J. Lett. 850 (2017) L35

Follow-Up Observations

of transient sources

Schematic Picture of MM Transients



Kohta Murase & Imre Bartos; Annu. Rev. Nucl. Part. Sci. 2019 AA:1-36

Schematic Picture of MM Transients

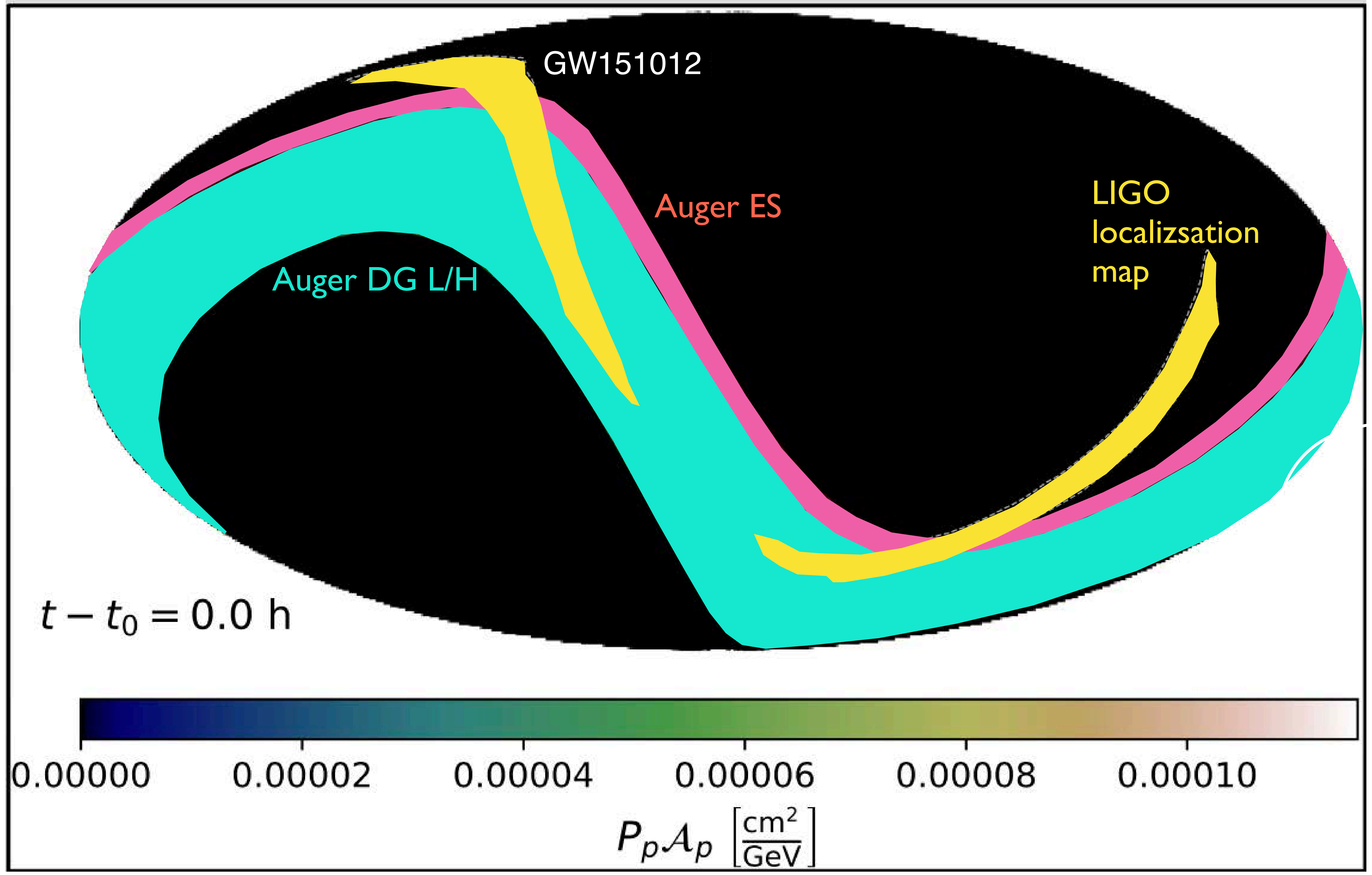
examples discussed here → Blazar flare, NS merger, BH merger

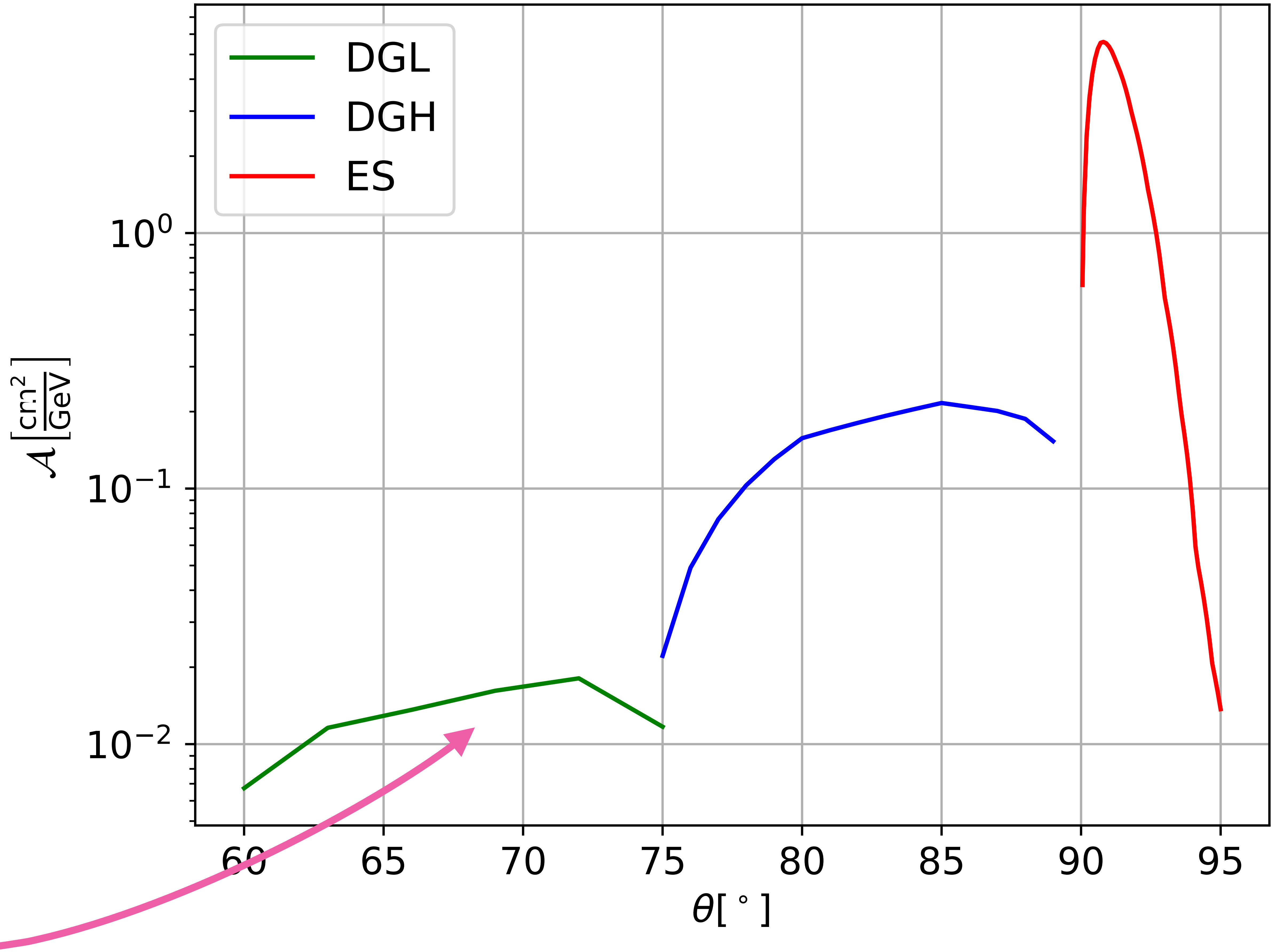
Source	Rate density [Gpc^{-3} yr^{-1}]	EM Luminosity [erg s^{-1}]	Duration [s]	Typical Counterpart
Blazar flare[a]	10 – 100	10^{46} – 10^{48}	10^{6} – 10^{7}	broadband
Tidal disruption event	0.01 – 0.1	10^{47} – 10^{48}	10^{6} – 10^{7}	jetted (X)
	100 – 1000	$10^{43.5}$ – $10^{44.5}$	$> 10^{6}$ – 10^{7}	tidal disruption event (optical,UV)
Long GRB	0.1 – 1	10^{51} – 10^{52}	10 – 100	prompt (X, gamma)
Short GRB	10 – 100	10^{51} – 10^{52}	0.1 – 1	prompt (X, gamma)
Low-luminosity GRB	100 – 1000	10^{46} – 10^{47}	1000 – 10000	prompt (X, gamma)
GRB afterglow		$< 10^{46}$ – 10^{51},	> 1 – 10000	afterglow (broadband)
Supernova (II)	10^{5}	10^{41} – 10^{42}	$> 10^{5}$	supernova (optical)
Supernova (Ibc)	3×10^{4}	10^{41} – 10^{42}	$> 10^{5}$	supernova (optical)
Hypernova	3000	10^{42} – 10^{43}	$> 10^{6}$	supernova (optical)
NS merger	300 – 3000	10^{41} – 10^{42}	$> 10^{5}$	kilonova (optical/IR)
		10^{43}	$> 10^{7}$ – 10^{8}	radio flare (broadband)
BH merger	10 – 100	?	?	?
WD merger	10^{4} – 10^{5}	10^{41} – 10^{42}	$> 10^{5}$	merger nova (optical)

[a]Blazar flares such as the 2017 flare of TXS 0506+056 are assumed for the demonstration.
Abbreviations: BH, black hole; EM, electromagnetic; GRB, gamma-ray burst; NS, neutron star; WD, white dwarf.

Kohta Murase & Imre Bartos; Annu. Rev. Nucl. Part. Sci. 2019 AA:1-36

Combining BBH Mergers





solid angle integration

$$N_{\nu,i} = L_i \, \Delta t \sum_s \frac{\sum_p P_{p,s} \mathscr{A}_{p,s,i}}{d_s^2}$$

sum over all sources

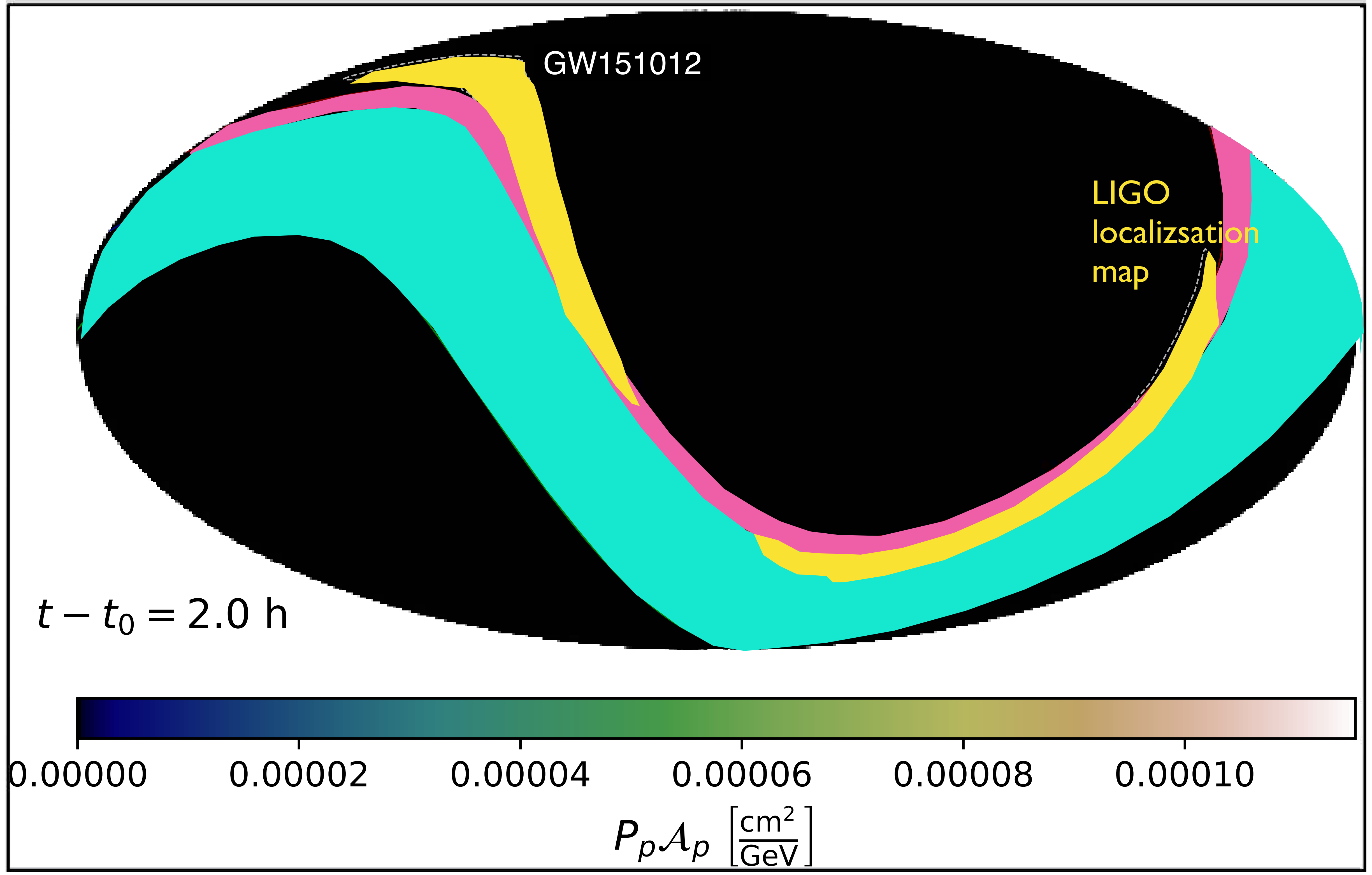
luminosity distance of source

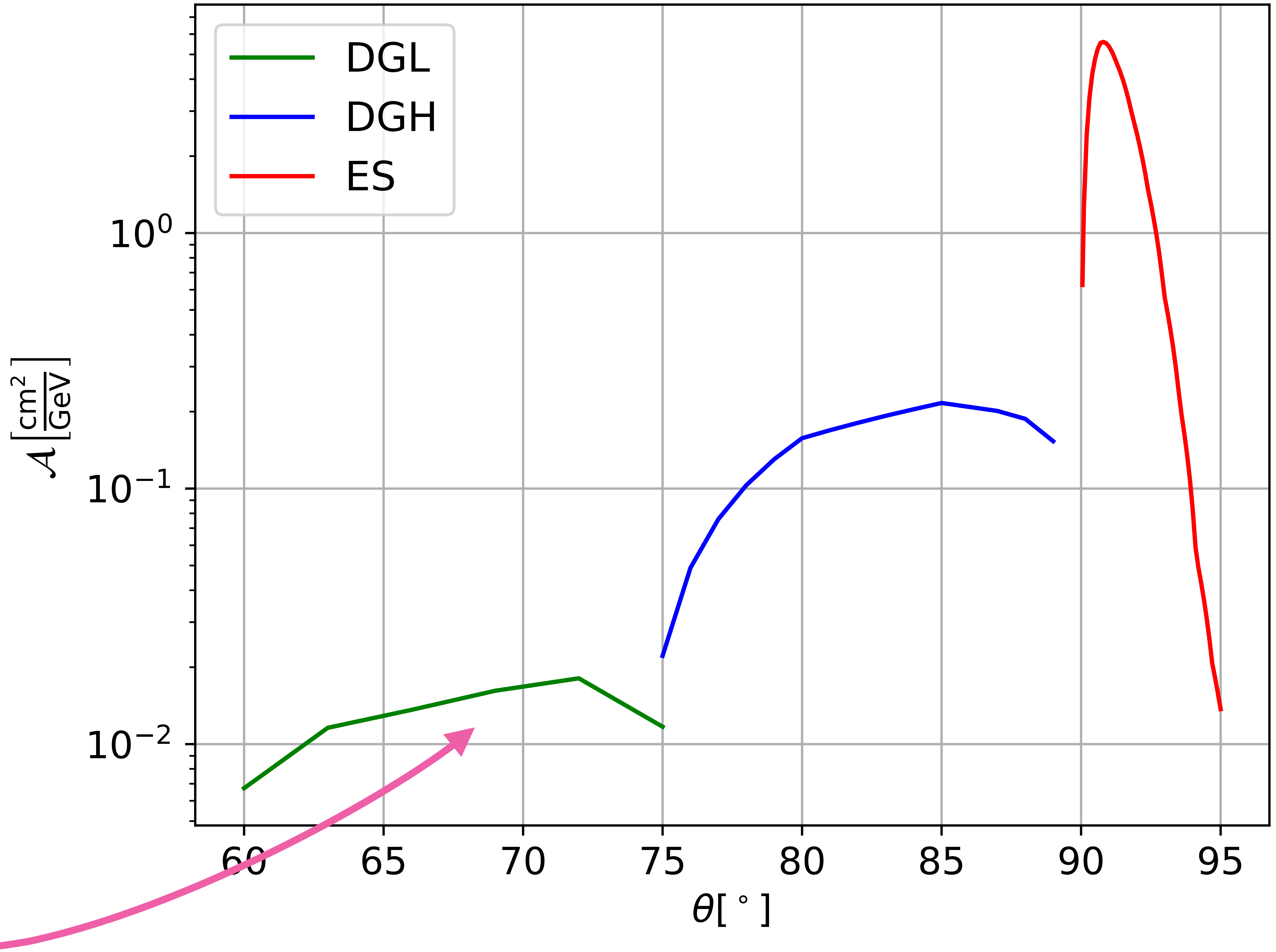
effective area

Number of expected neutrinos per source proportional to weighted overlap area integrated over time time

L_i: Neutrino luminosity (to be constrained)

Combining BBH Mergers





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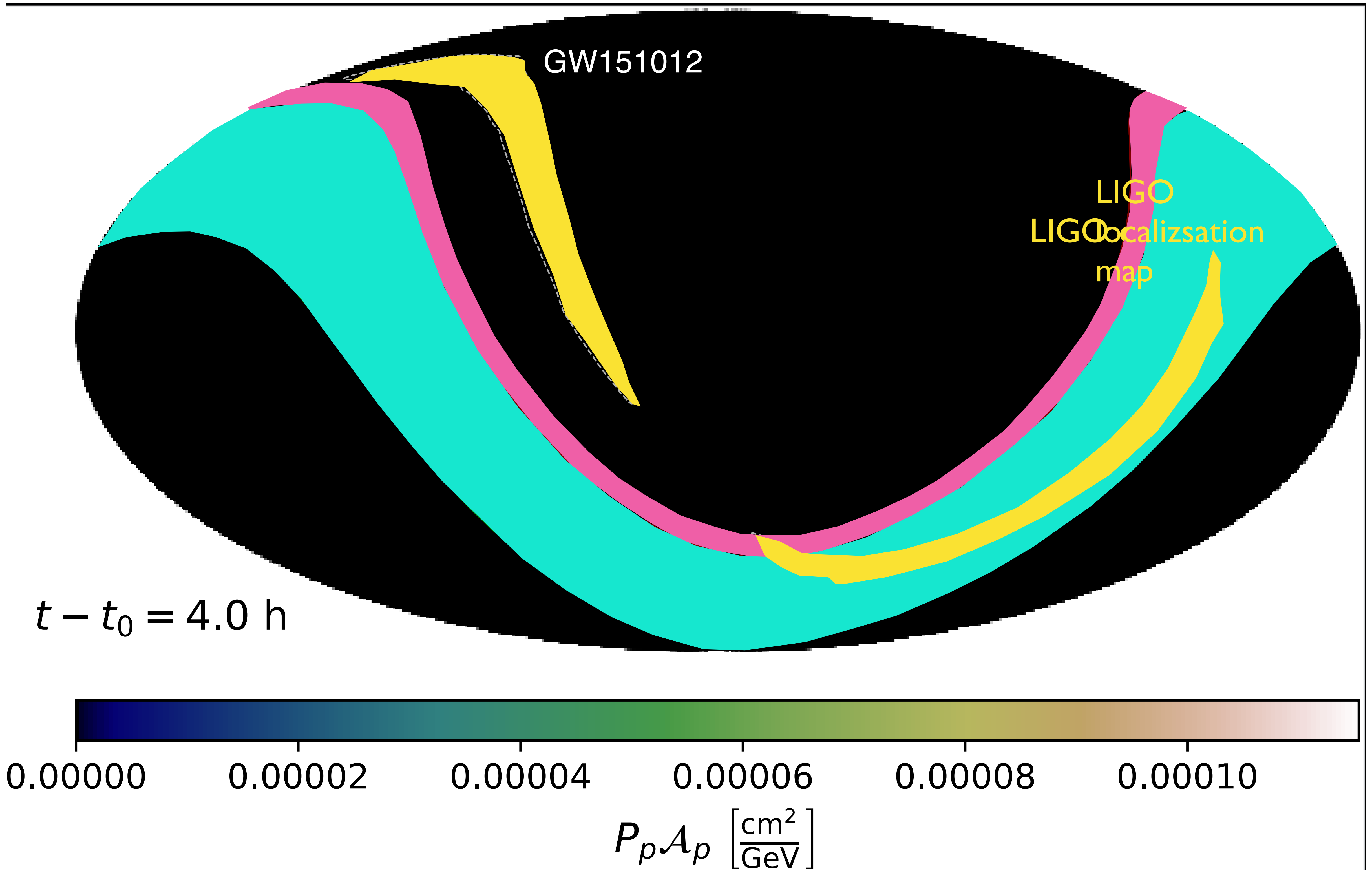

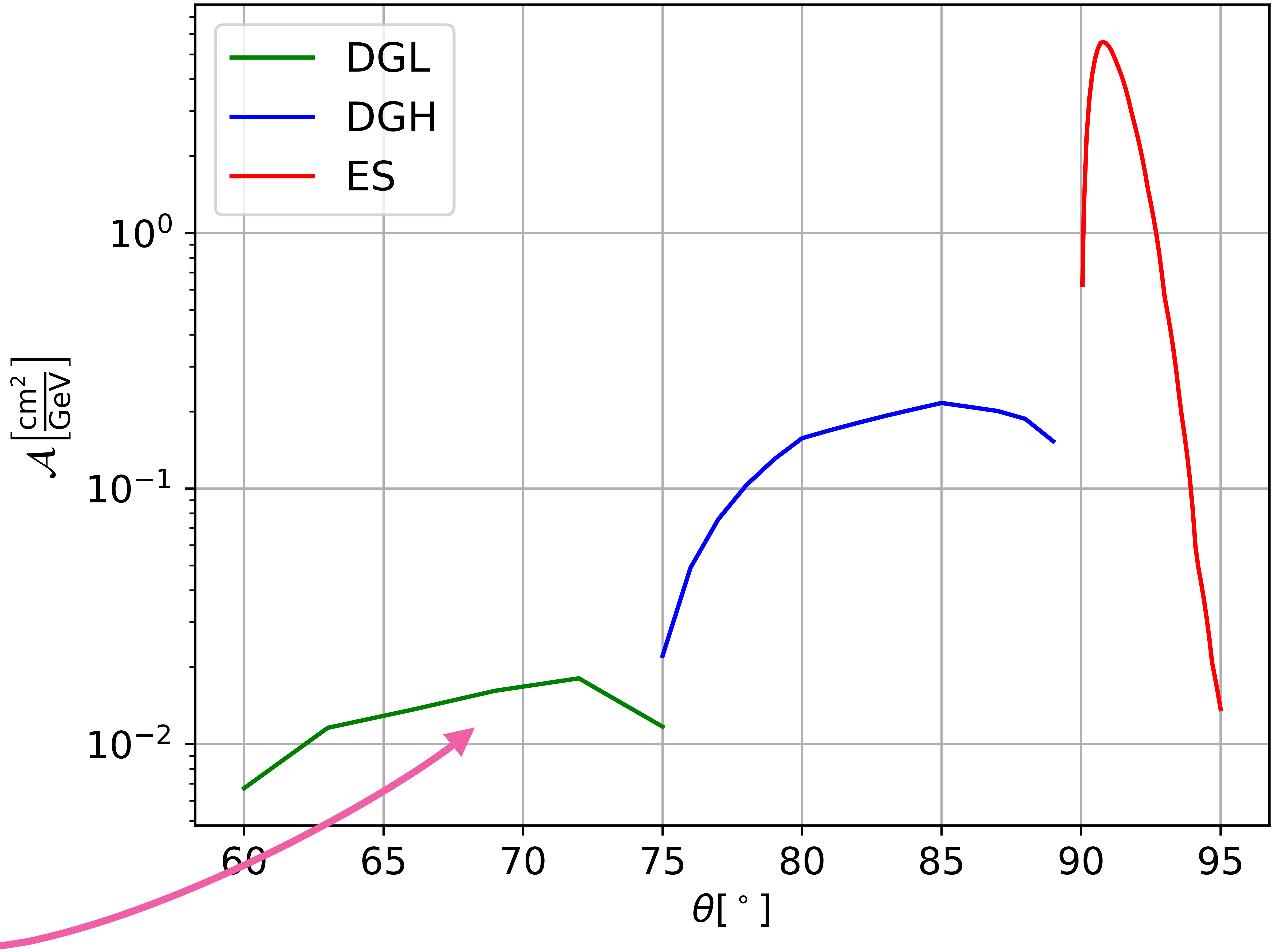

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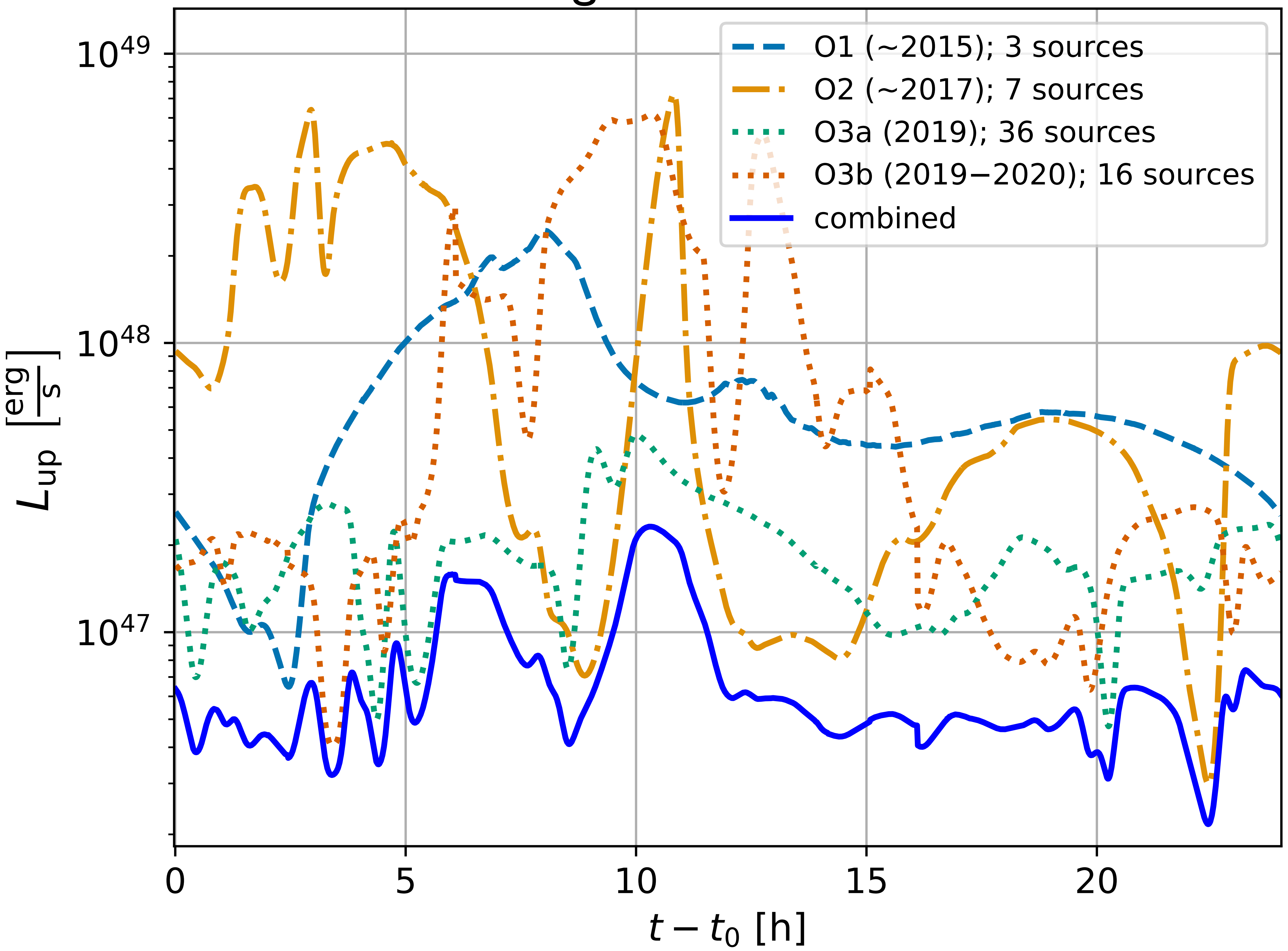
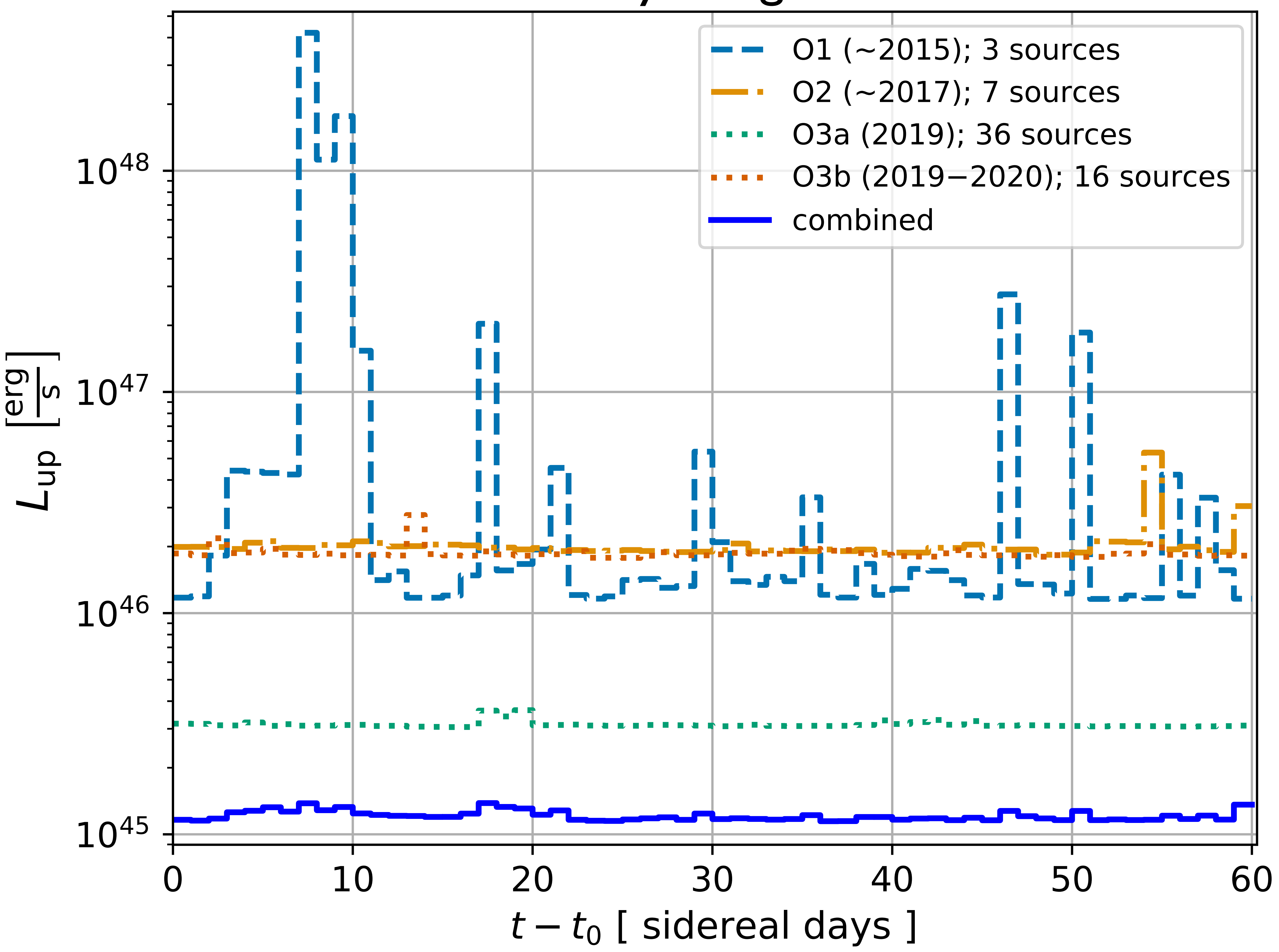
Isotropic Neutrino Luminosity Bound from BBHs

M. Schimp; Auger Collaboration, PoS (ICRC2021) 968

24 hrs stacking limit from 62 GW events



60 day integration

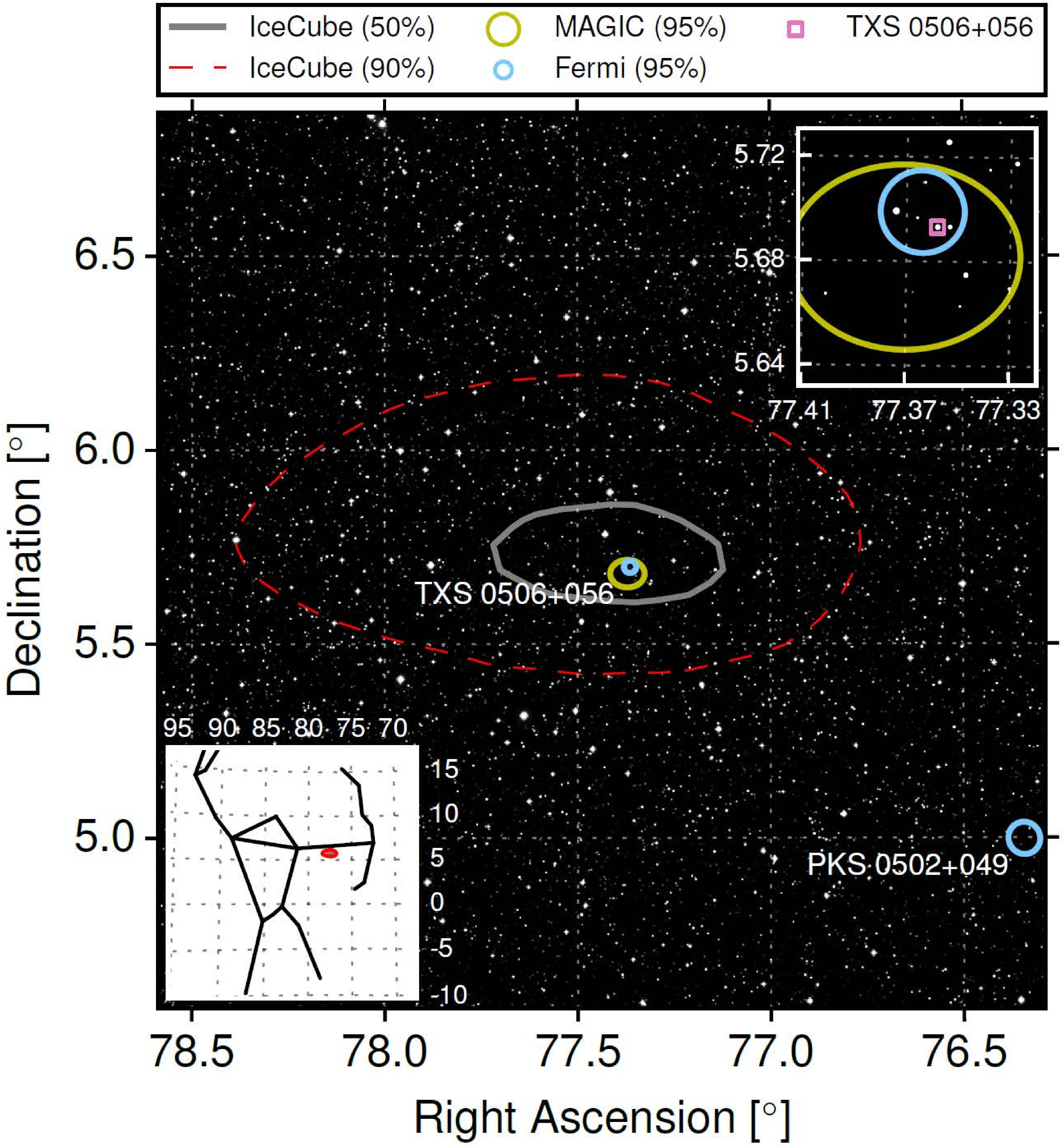


Neutrino emission energy limit $\sim M_\odot c^2/300$ as compared to $\sim M_\odot c^2$ radiated GW energy assuming isotropic emission and E_ν^{-2} flux

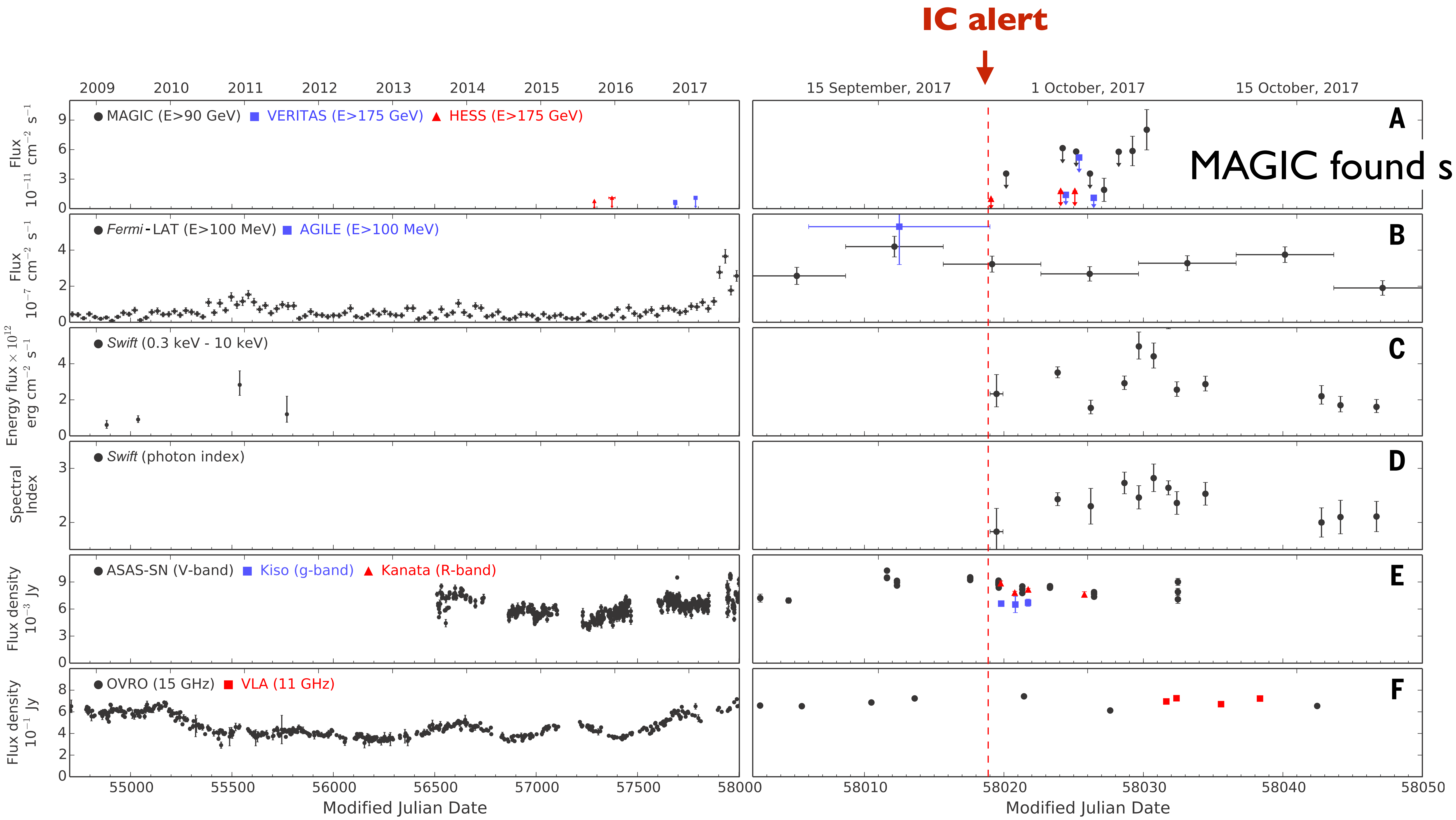
High energy neutrino from direction of TXS 0506-056

Sept. 22, 2017:
290 TeV neutrino from direction TXS 0506-056

IceCube Collaboration
Science 361, 146 (2018)



TXS 0506-056 in flaring state

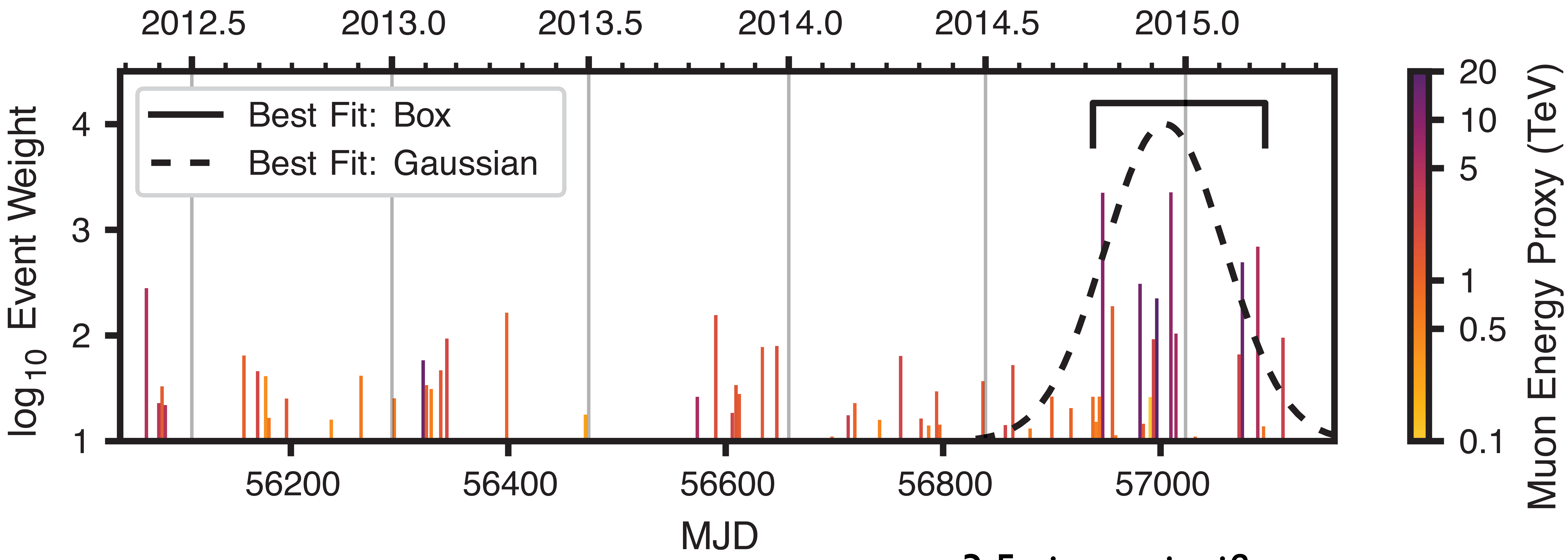


MAGIC found subsequent TeV γ flare

The significance of the association with the gamma-ray flare was ~3σ

TXS 0506-056 Neutrino Flare ?

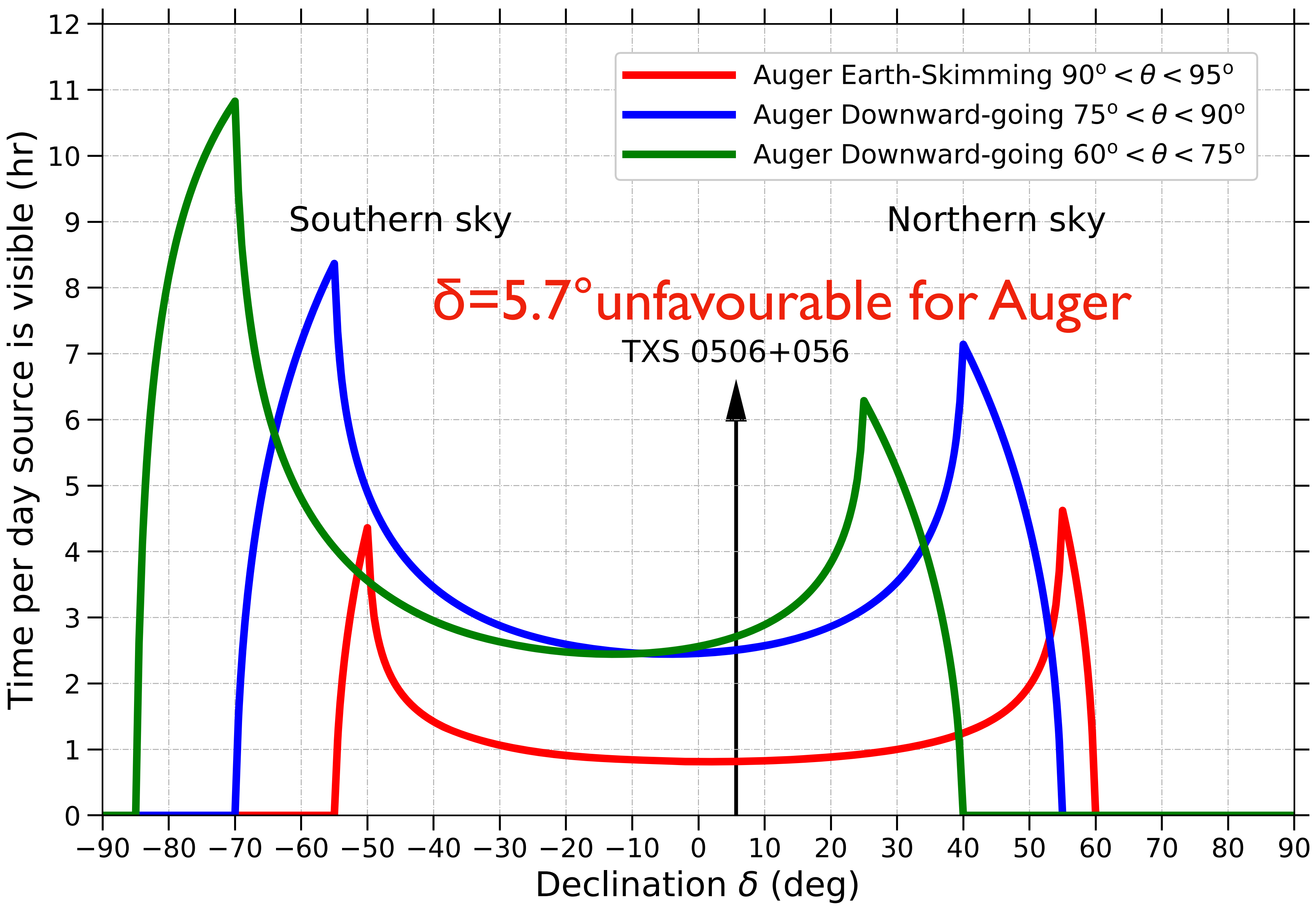
IceCube archival data: possible ν flare (3.5 σ) in 2014-2015
However, no gamma emission found from that direction during that period



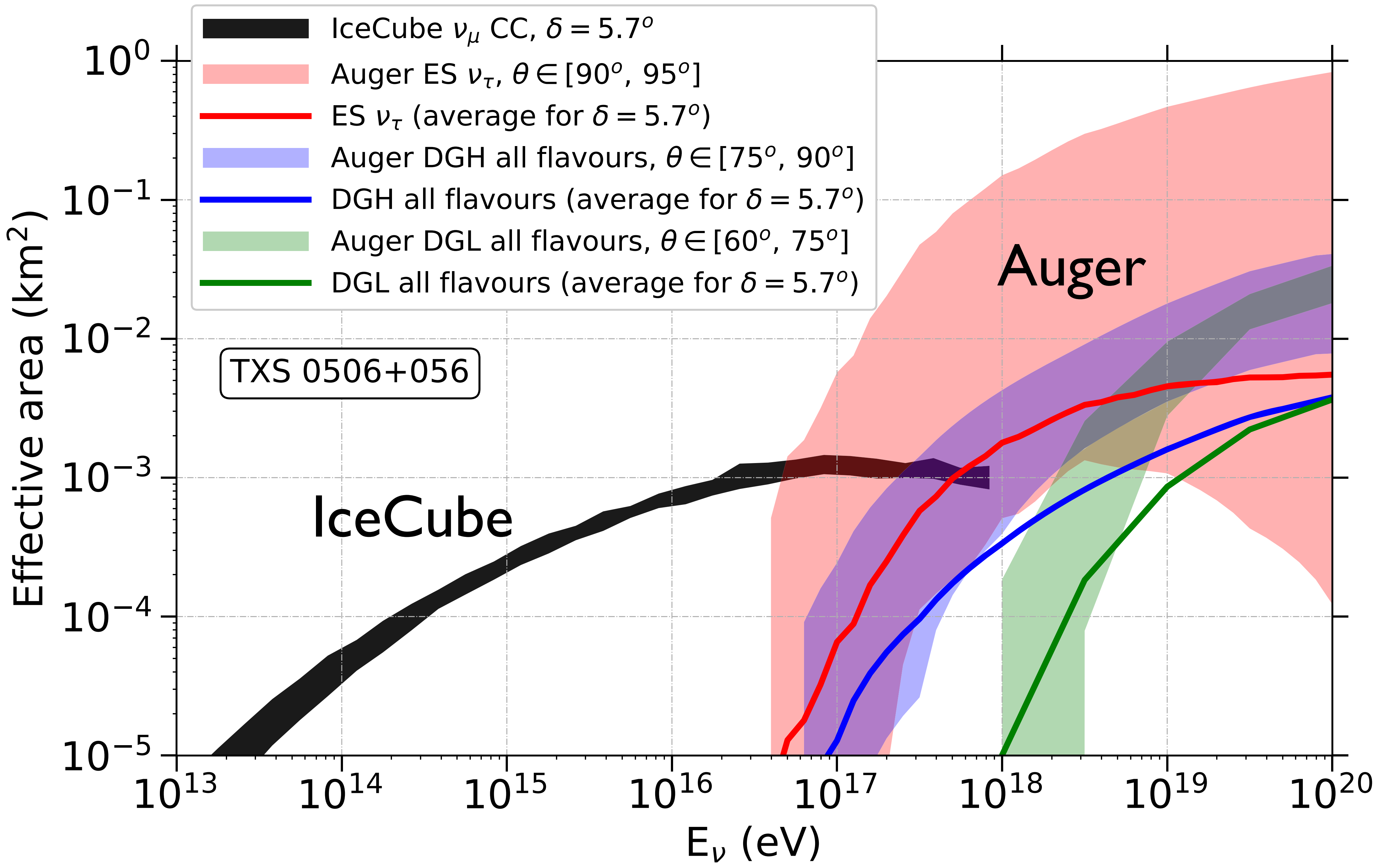
3.5 sigma significance

Search for nu's from TXS 0506+56 with Auger

daily visibility in ES channel of Auger: < 1 hrs



effective area in comparison to IceCube

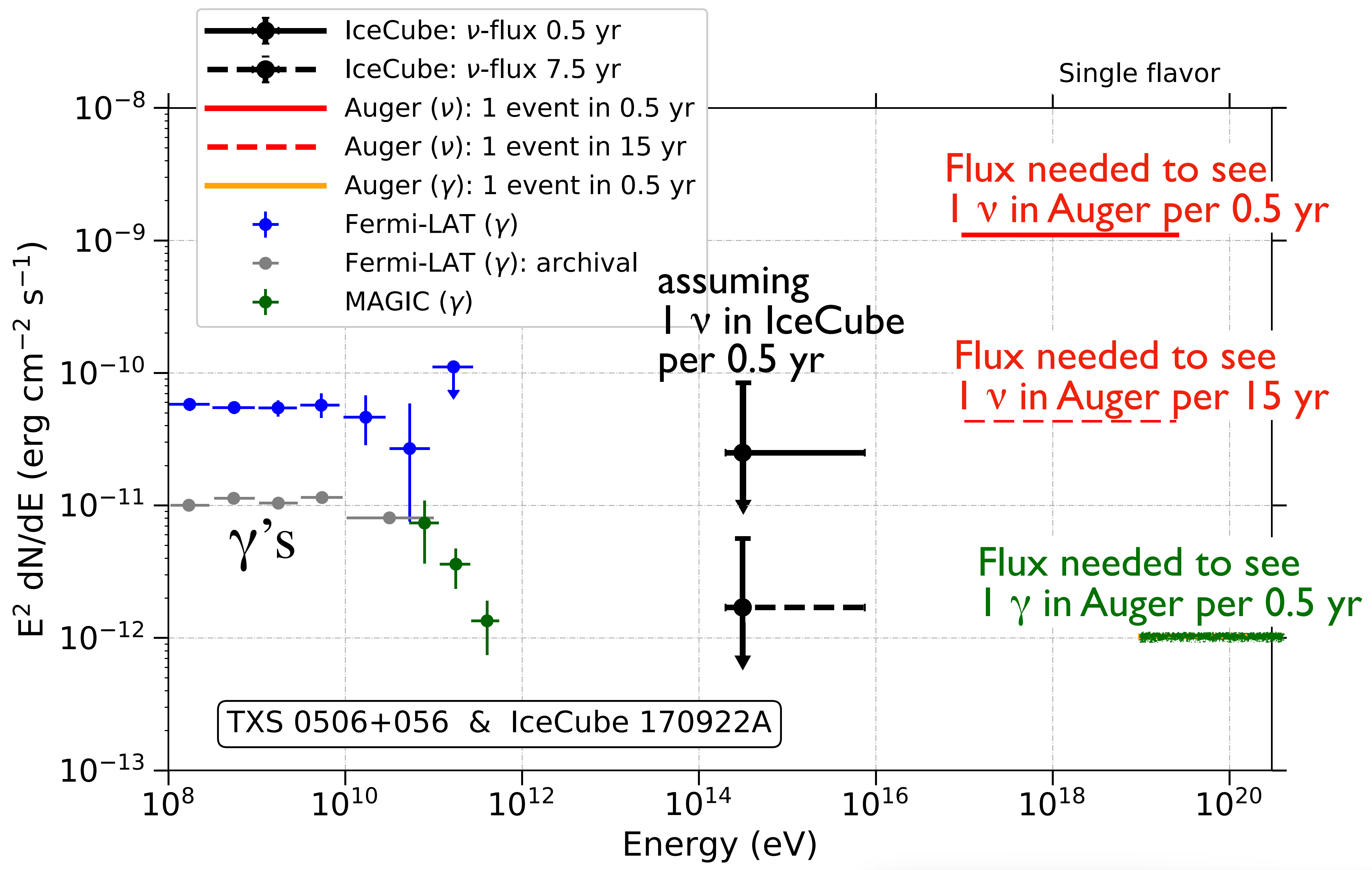


dependent on the spectral neutrino emission, Auger could potentially detect a signal

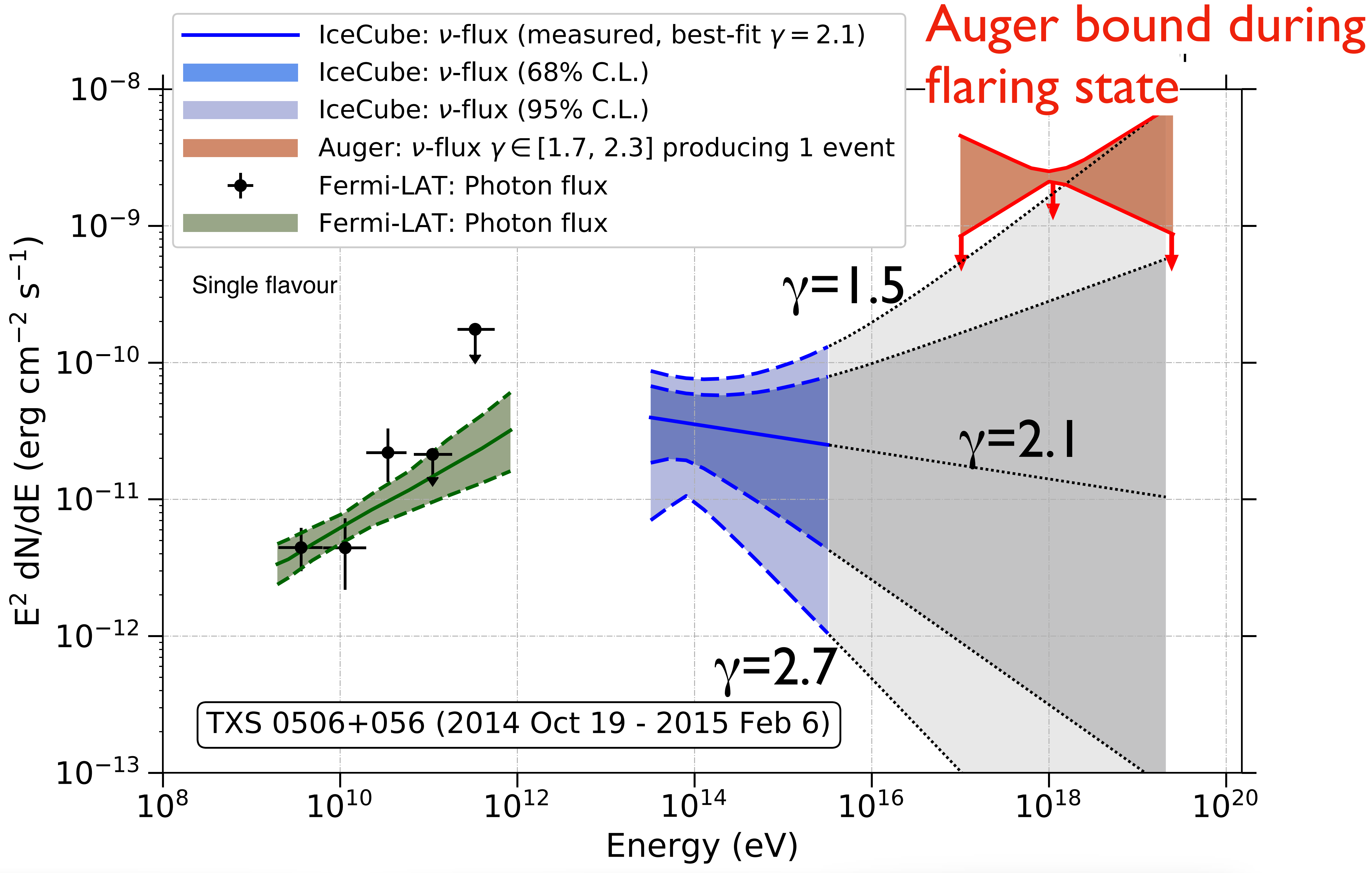
Auger Collaboration, ApJ 902 (2020) 105

Search for nu's from TXS 0506+56 with Auger

Flux comparison from single event assuming E^{-2} spectrum



Sensitivity of Auger to 110 days „ν flaring state"

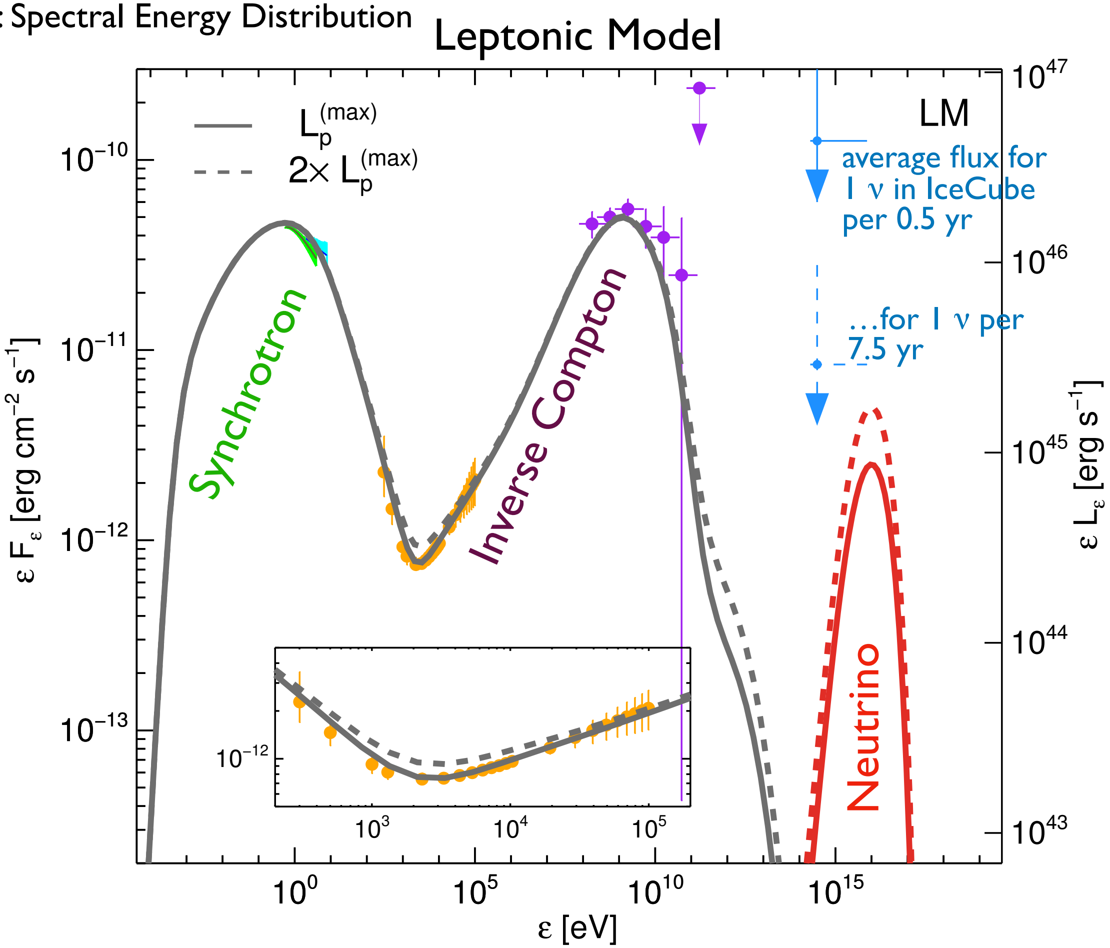


Auger Collaboration, ApJ 902 (2020) 105

Expected to detect a neutrino in Auger only in case of hard neutrino spectra (+2σ allowance of IceCube)

SED of TXS 0506+56 during the flare

SED: Spectral Energy Distribution



Kohta Murase & Imre Bartos;
Annu. Rev. Nucl. Part. Sci. 2019 AA:1-36

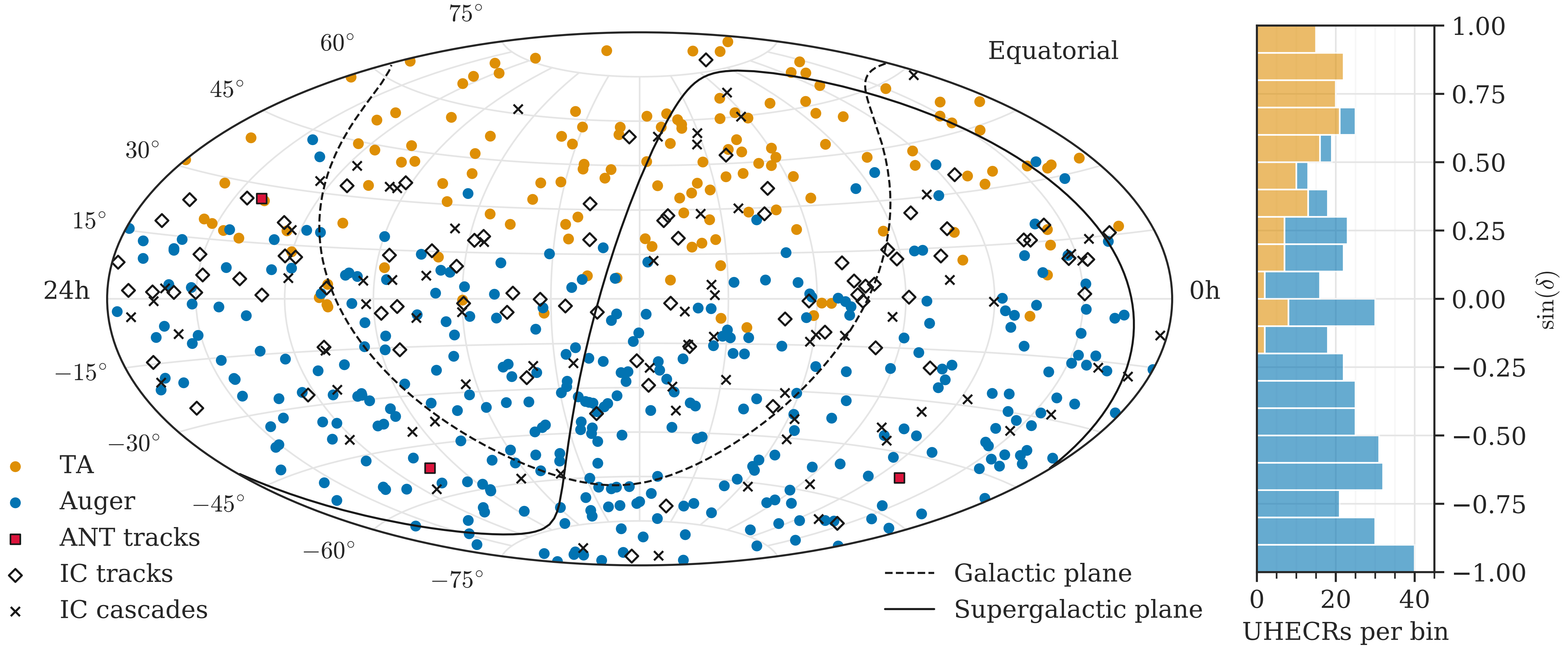
Very challenging to describe neutrino emission of a flaring state !

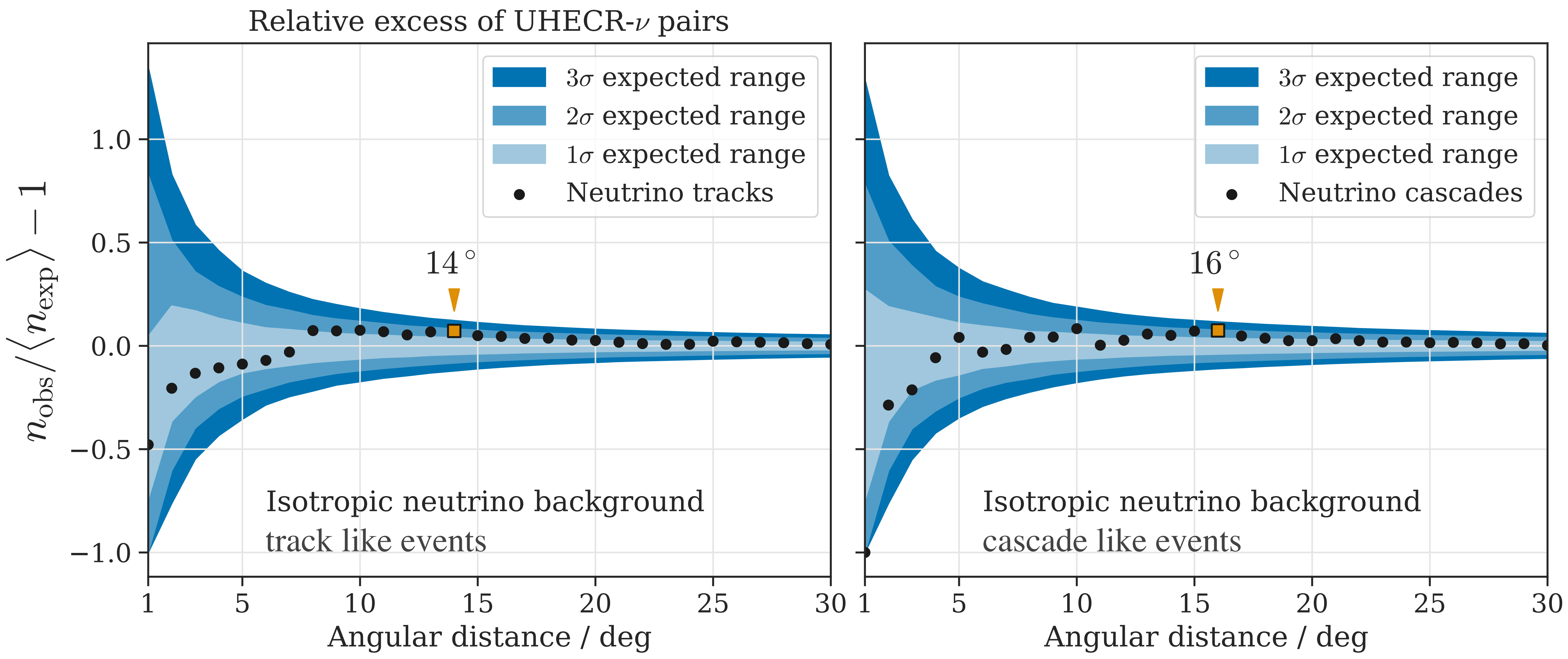
Neutrino emission in Blazar model with protons needs to agree with SED of photons, particularly with inverse Compton peak.
The dashed and full lines show two different fits that agree with the SED and incorporate protons…
but yield much lower neutrino fluxes as would result from the single neutrino observed in IceCube.

Similarly:
Leander Schlegel (Dissertation, Bochum, 2025):
expect $\ll 1\nu$ in IceCube even in an neutrino optimised two zone blazar flare model

Search for Spatial Correlations between UHECR and ν

IceCube, Antares, Auger, TA Collaborations ApJ 934:164 (2022)





2pt-correlation analysis assuming isotropic neutrinos does not yield significant correlations:
p-values ≈ 0.15, 0.23 for track/cascade like event

Not unexpected, given the vastly different horizons for UHECRs and nu's
Also, UHECR and nu-energies different by orders of magnitudes

ACME

https://cordis.europa.eu/project/id/101131928

Astrophysics Center forMultimessenger studies in Europe
(41 Institutes from 14 countries)

Goals:
- Bring together Astrophysics and Astroparticle Physics Communities
- Facilitate Multi Messenger Observations
- Provide data and tools

Messengers & Infrastructures:
- Electromagnetic (Multi-Wavelengths) from radio (LOFAR) … optical (BHTOM) … x- and γ-ray … TeV (CTA…)
- Neutrino (Km3Net, IceCube)
- Cosmic Rays (Pierre Auger Observatory)
- Gravitational waves (LIGO,Virgo, Kagra)

Centres of Expertise to provide support
- currently being setup

Regular calls for proposals for MM access to infrastructures
- young scientists (incl. PhD students) are encouraged

cyber-infrastructures, tools, platforms being developed, training events, …
travel support can be provided

https://www.acme-astro.eu