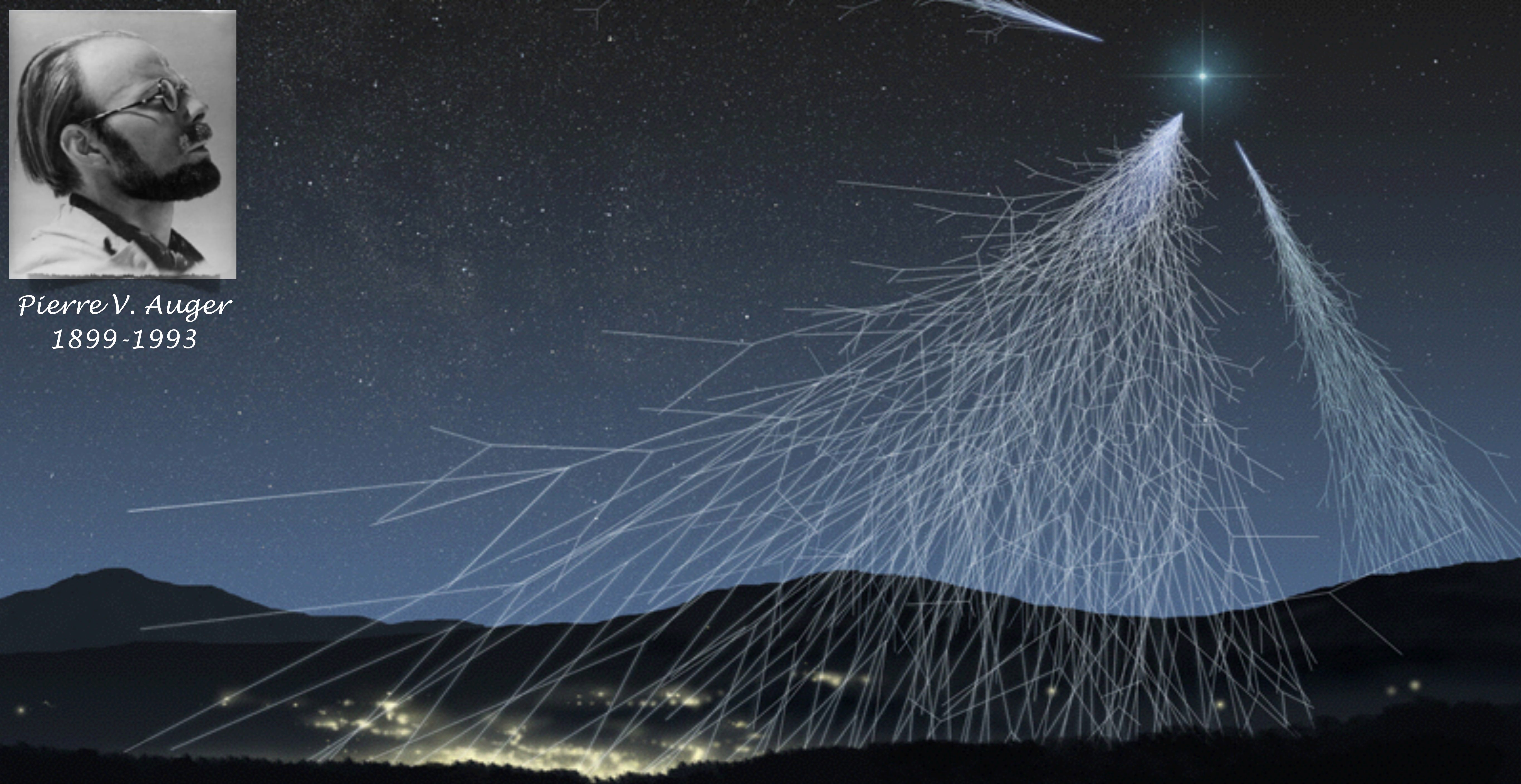


Pierre V. Auger
1899-1993

A multi-messenger quest for the sources of the highest energy cosmic rays

Foteini Oikonomou-*Penn State*

UCL 27/8/15

PIERRE AUGER OBSERVATORY

PENNSTATE Eberly College of Science

NSF

Origin of ultra-high energy cosmic rays? A 50 year old mystery

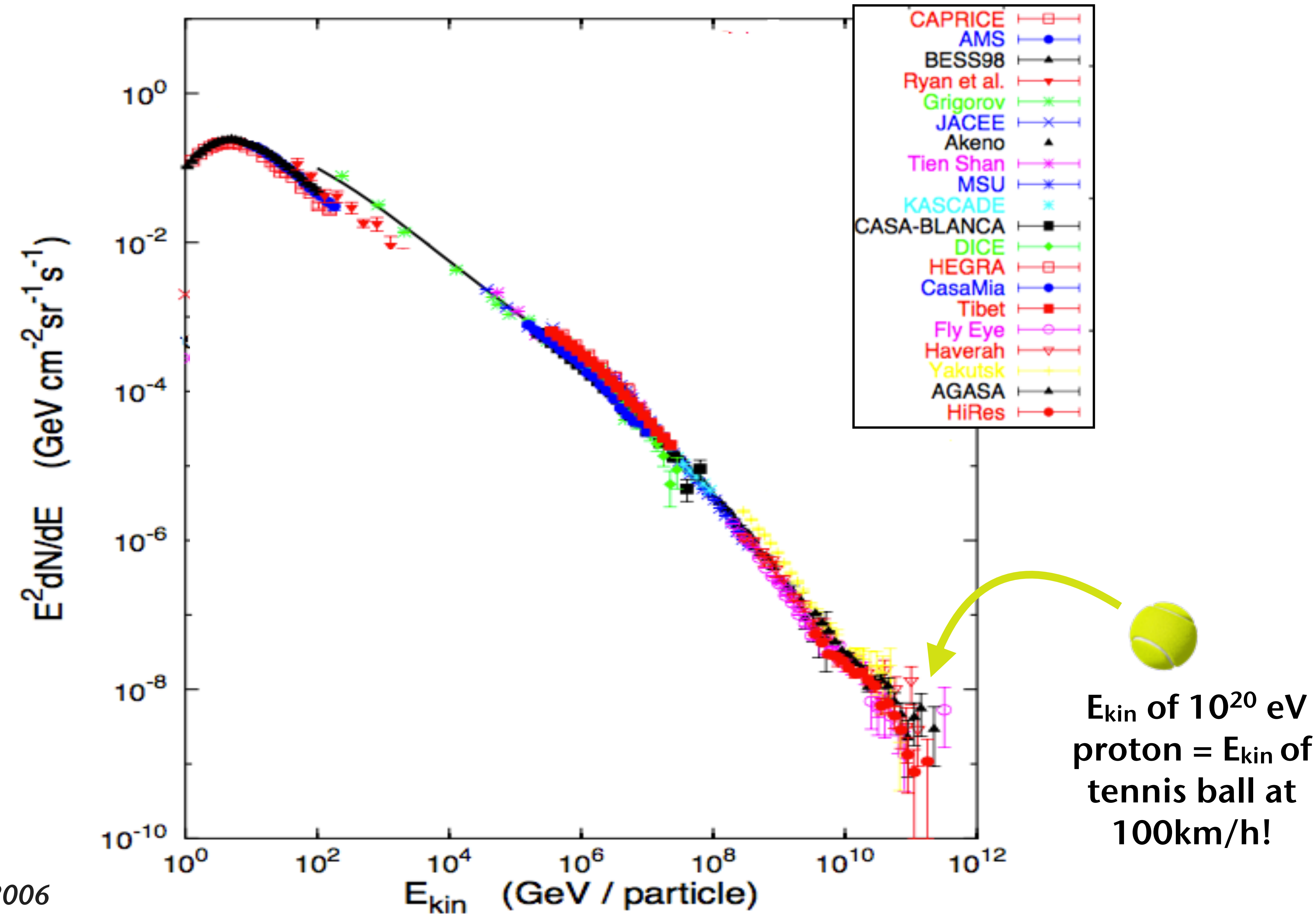
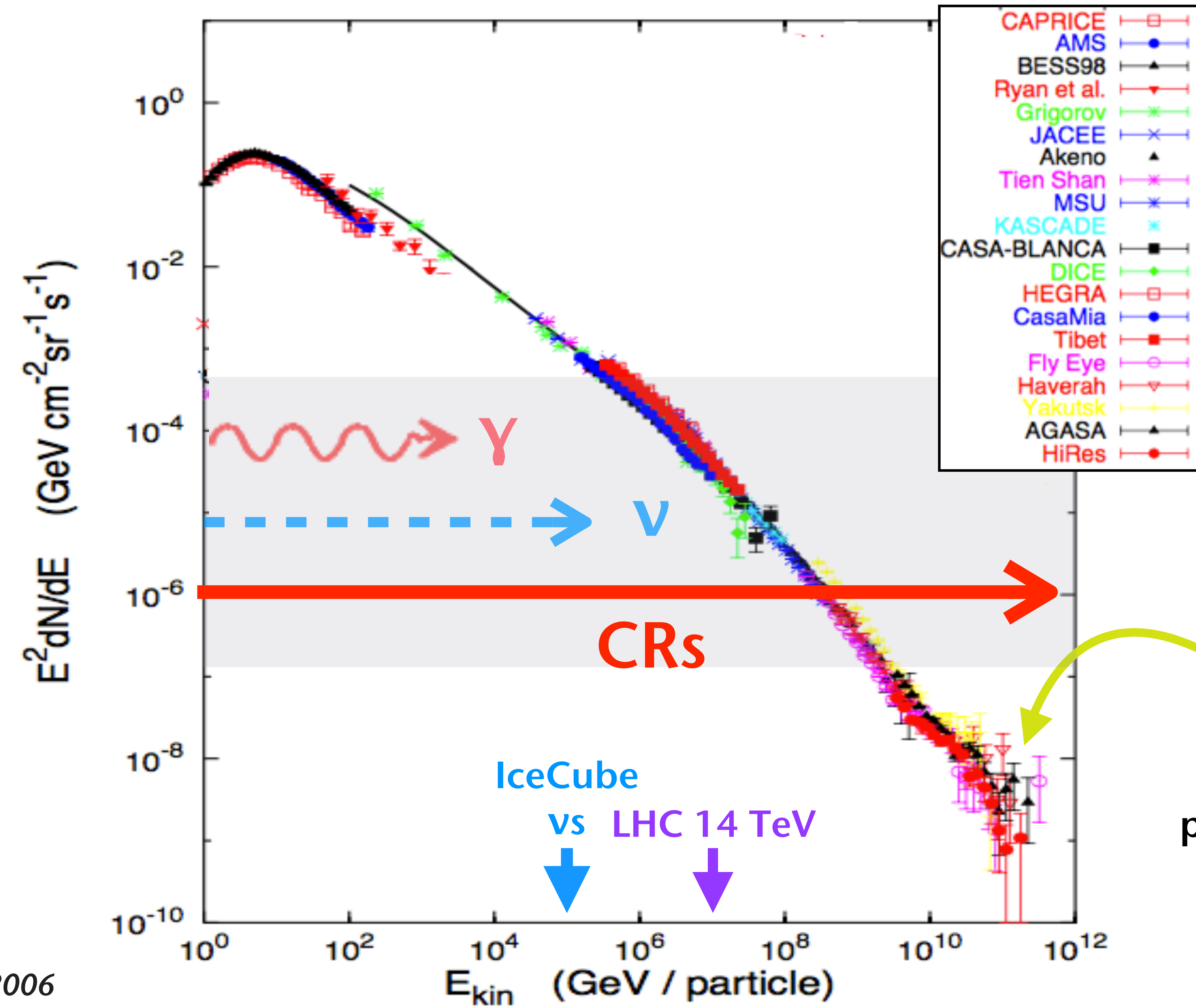


Image: Hillas 2006

Origin of ultra-high energy cosmic rays?
A 50 year old mystery

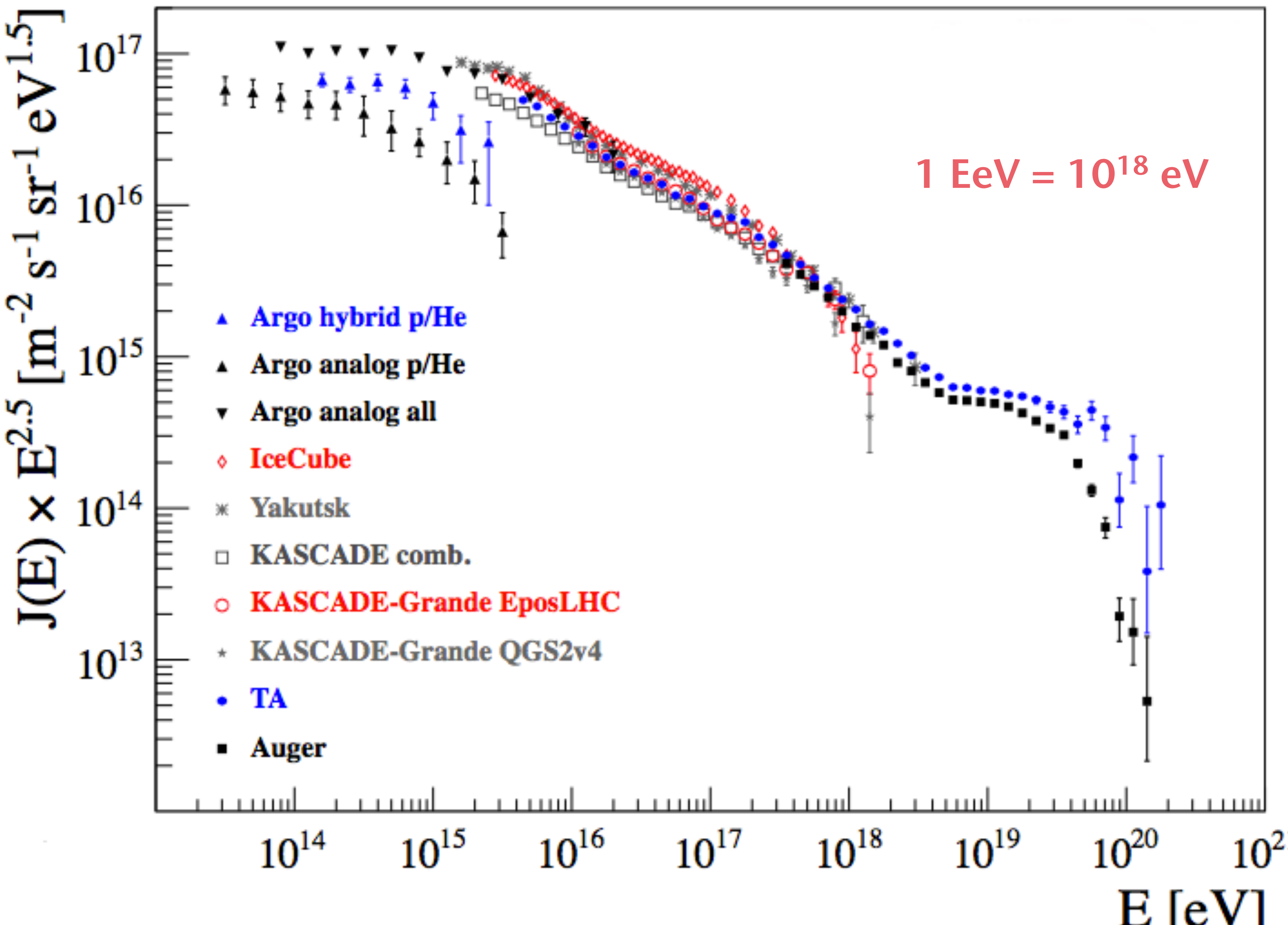


E_{kin} of 10^{20} eV proton = E_{kin} of tennis ball at 100km/h!

Image: Hillas 2006

Origin of ultra-high energy cosmic rays?
A 50 year old mystery

ICRC
The Astroparticle Physics Conference
34th International Cosmic Ray Conference
July 30 - August 6, 2015
The Hague, The Netherlands



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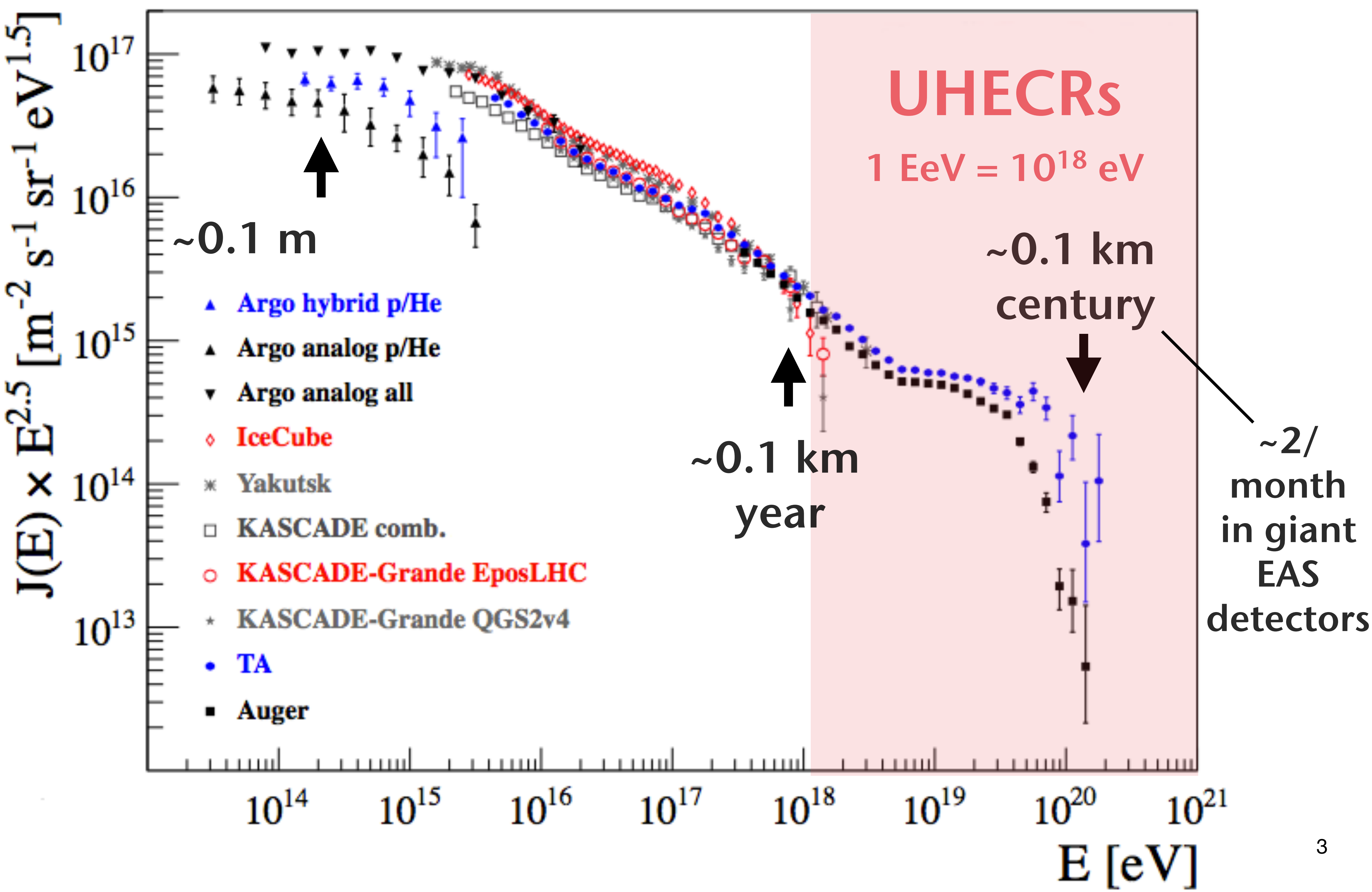

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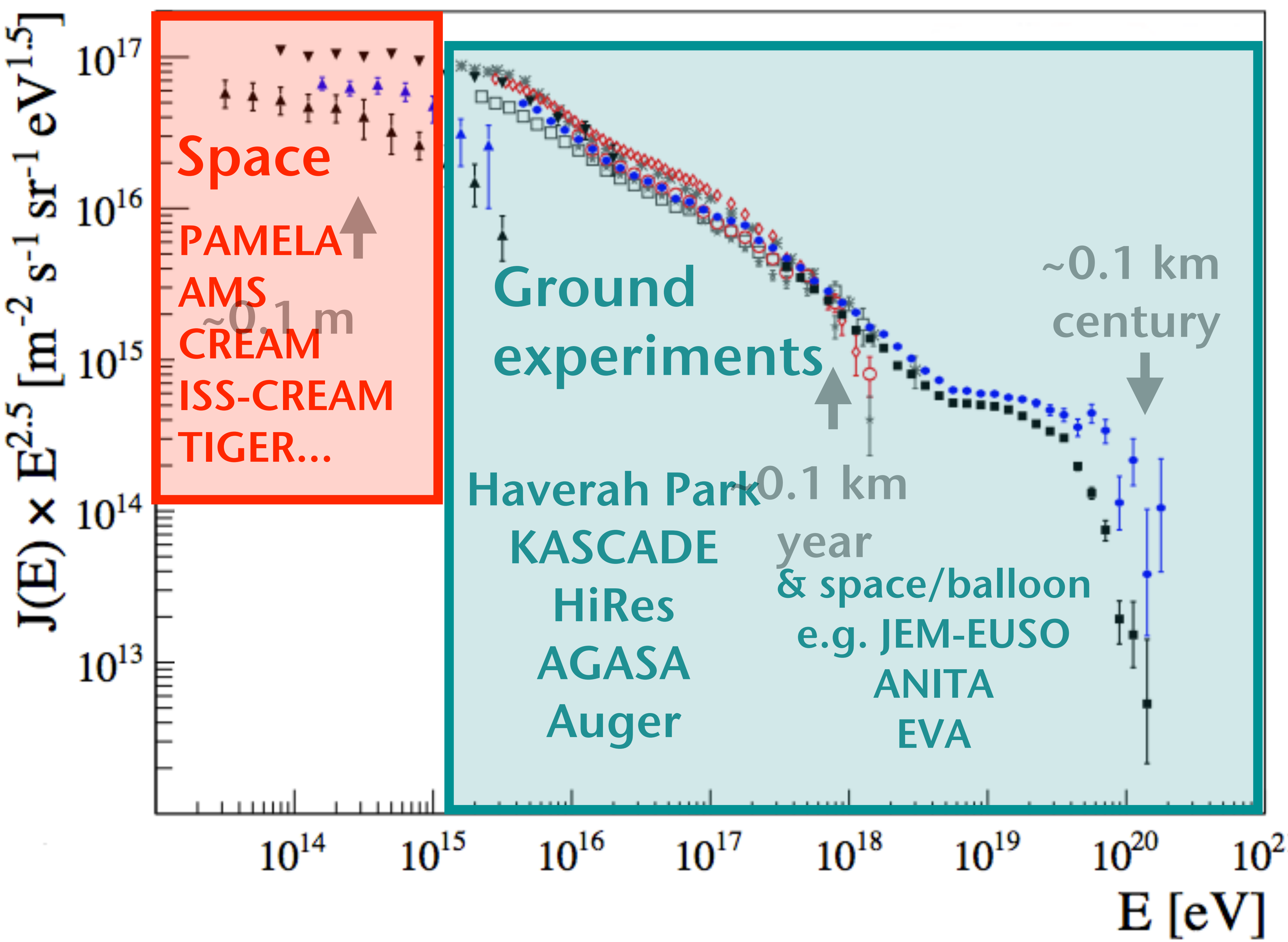

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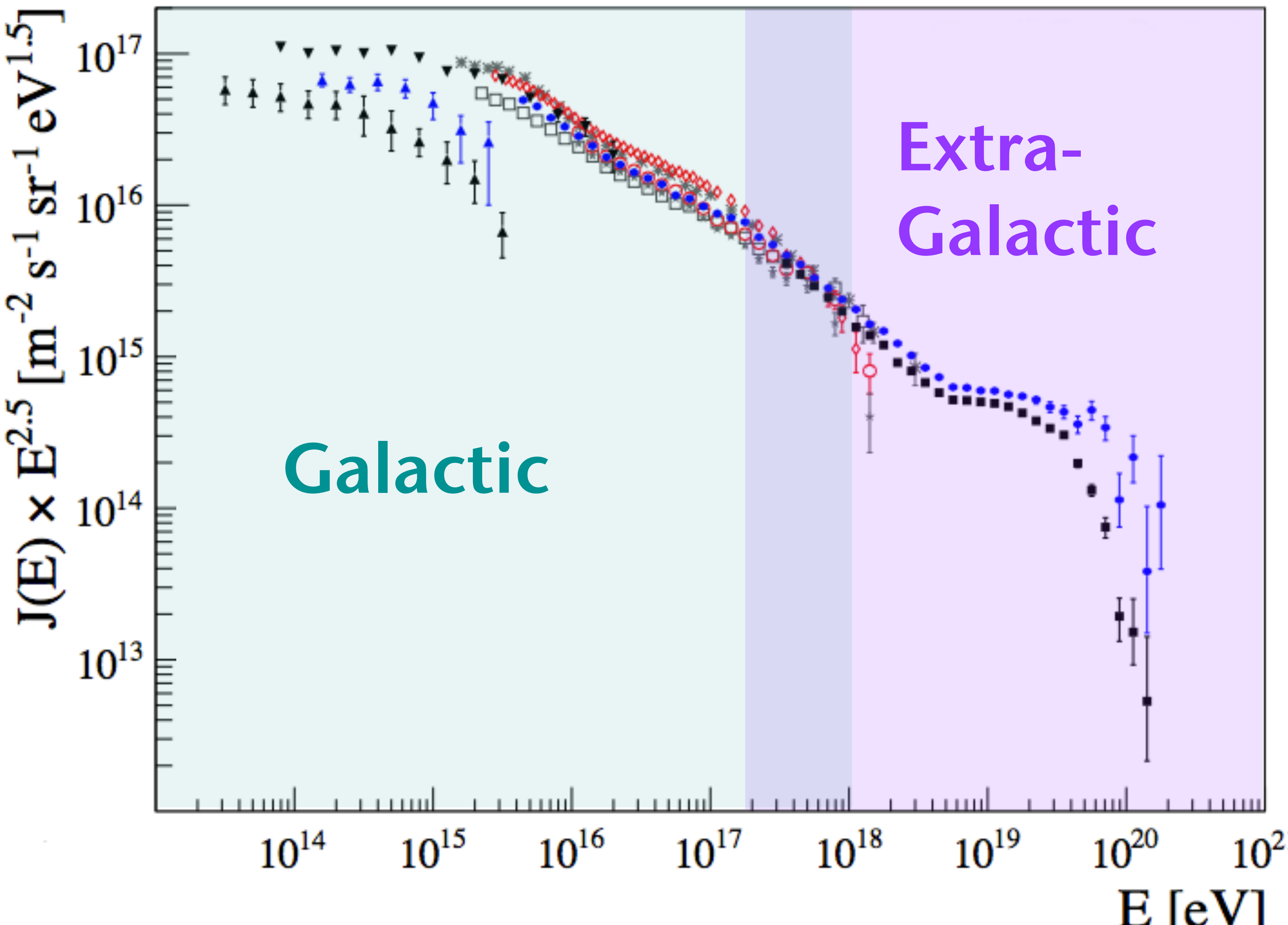

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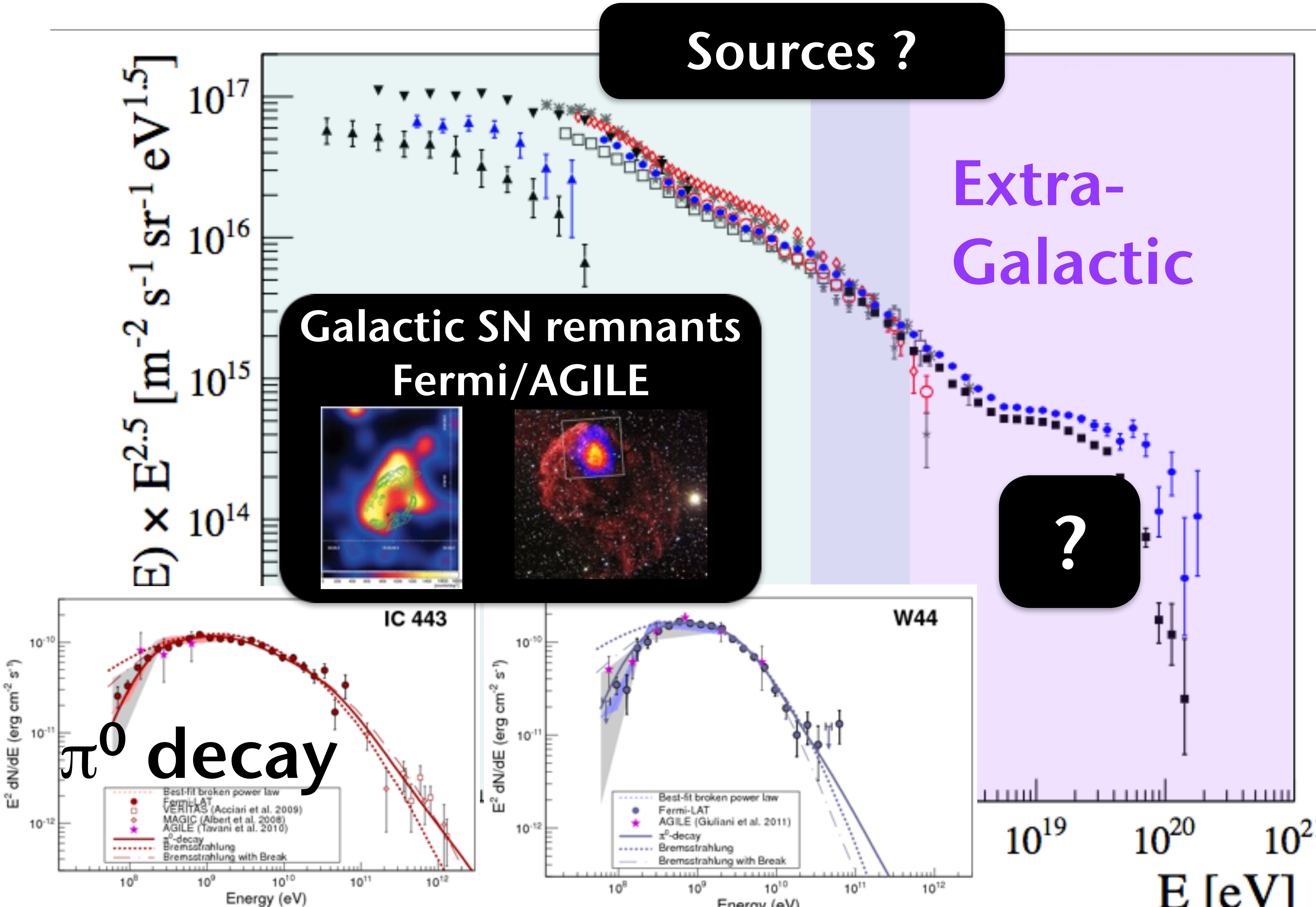
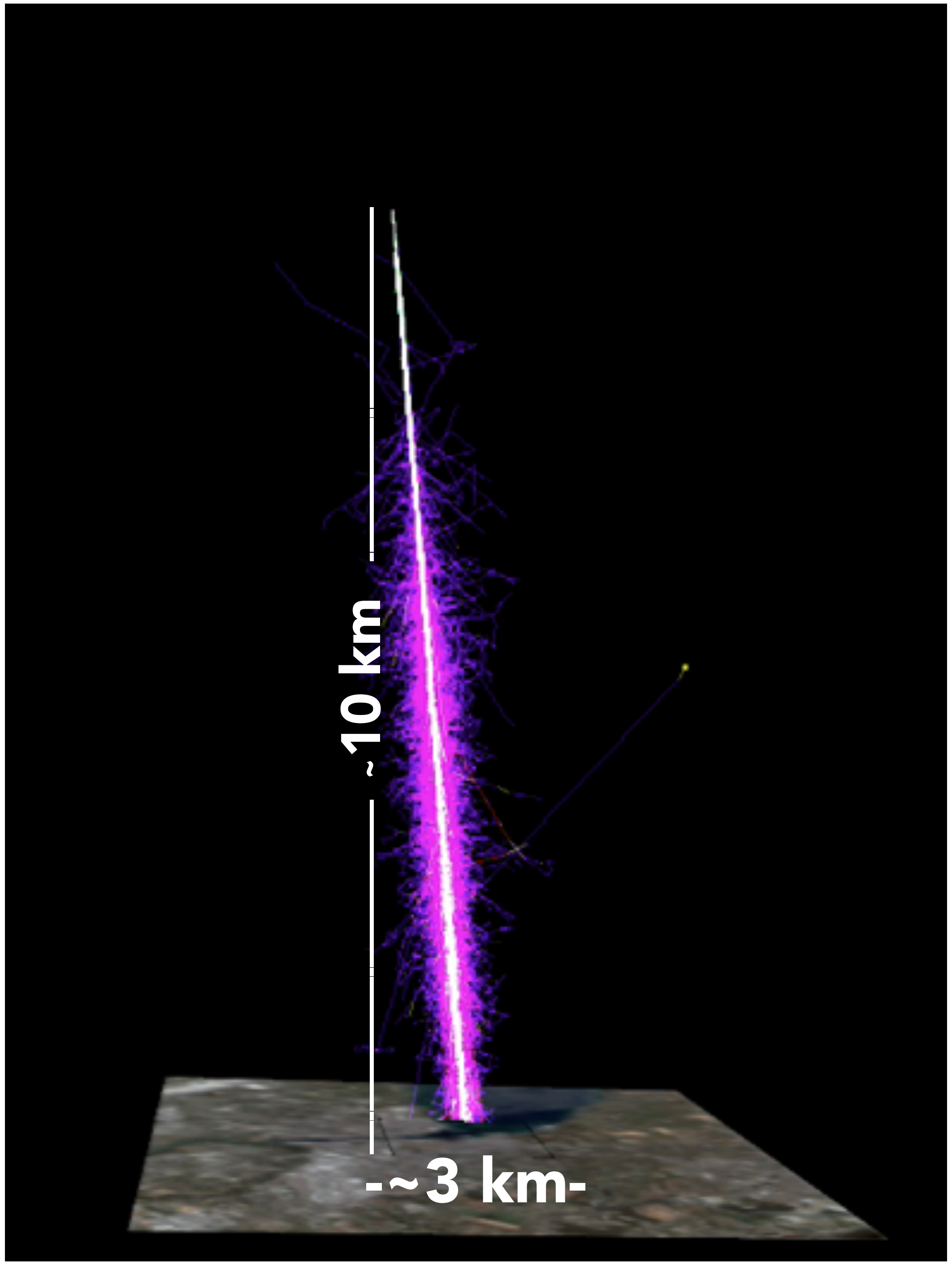
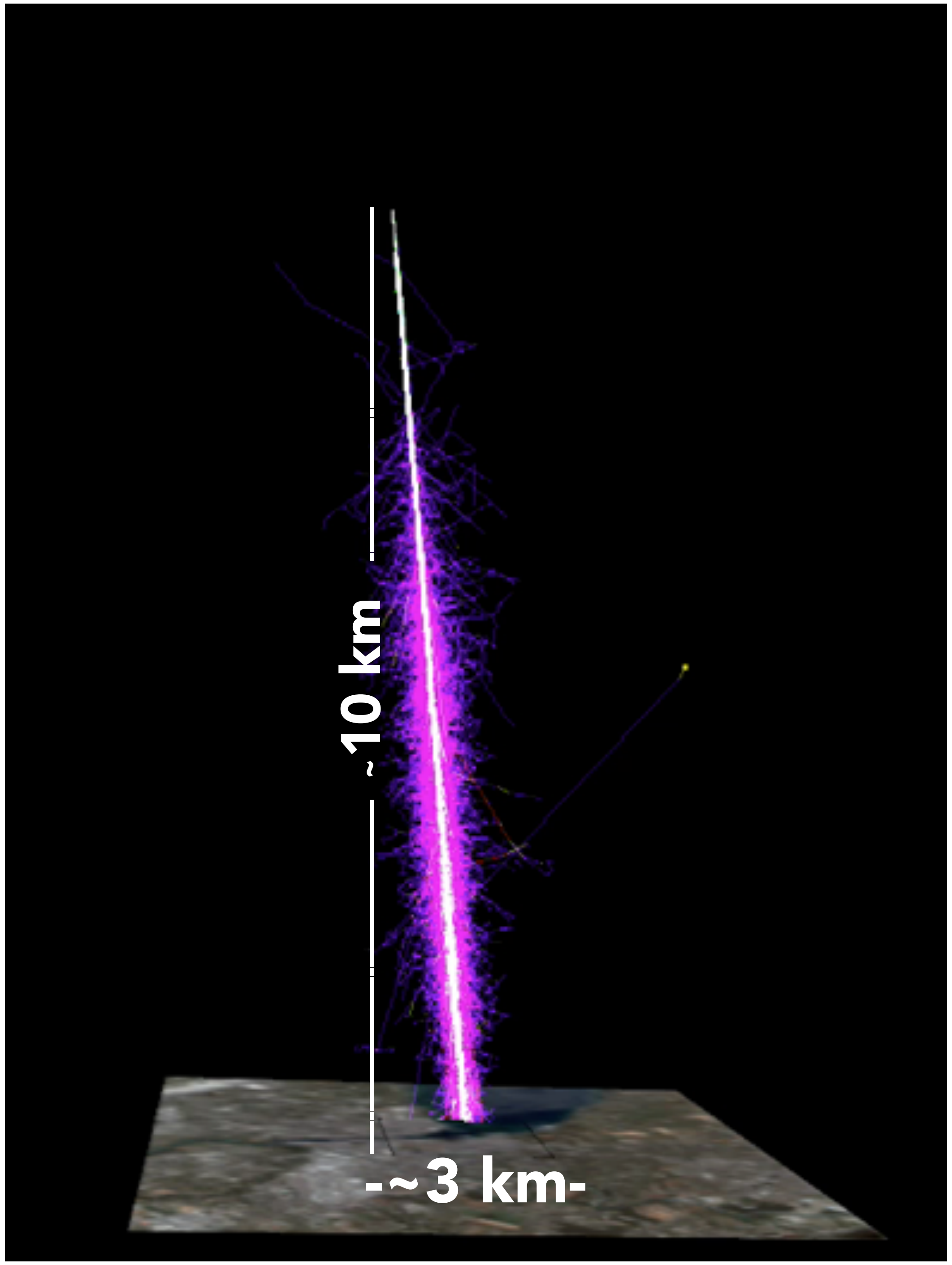
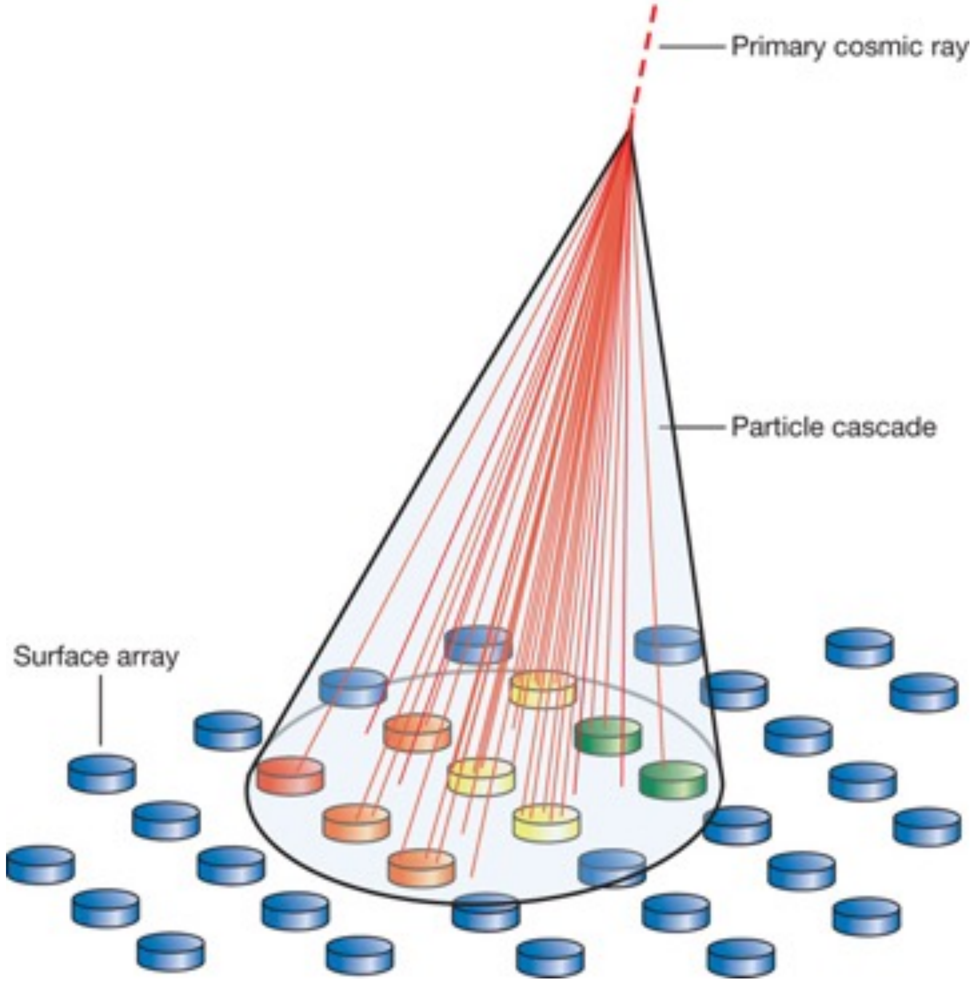


Detection

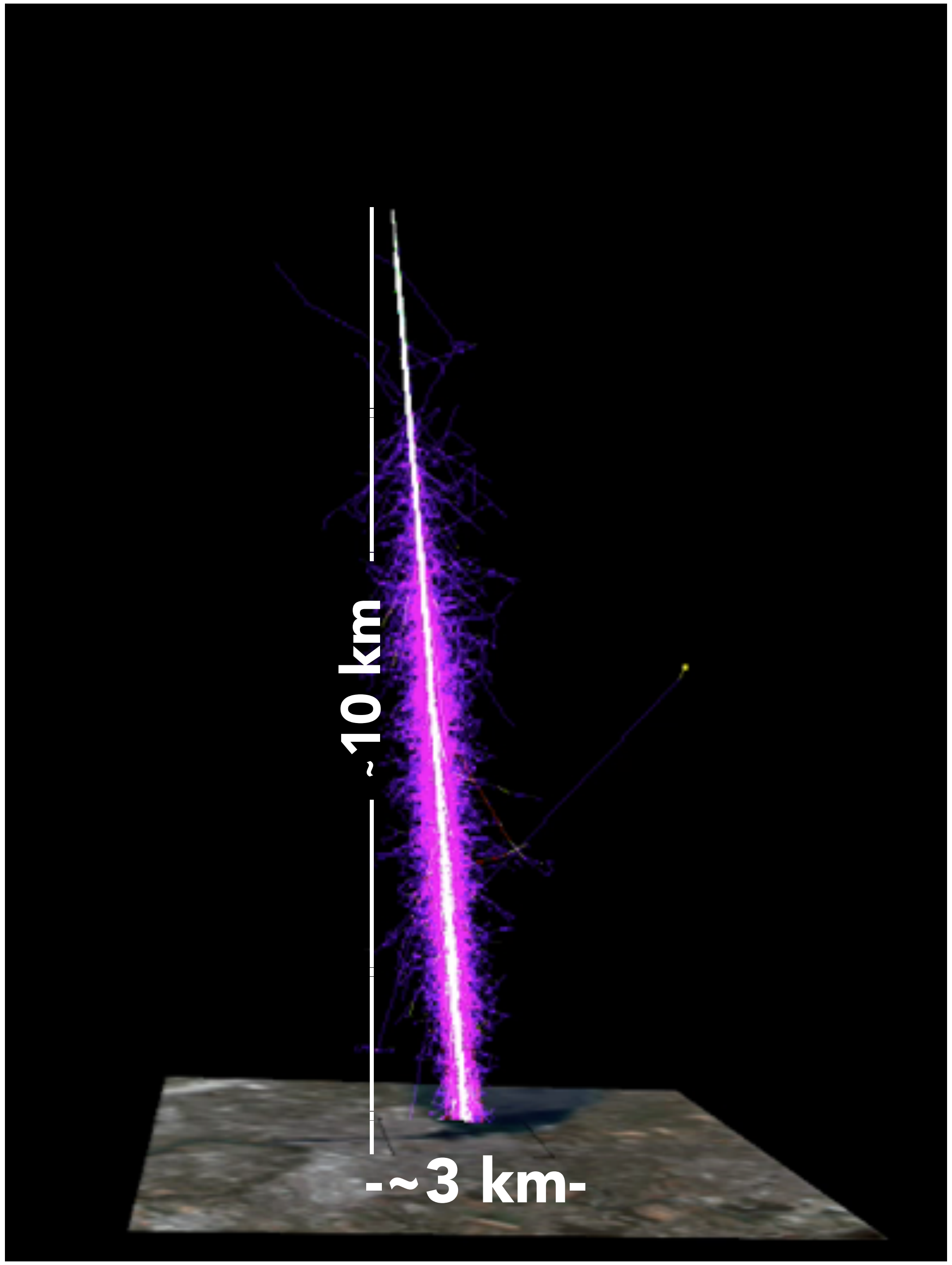


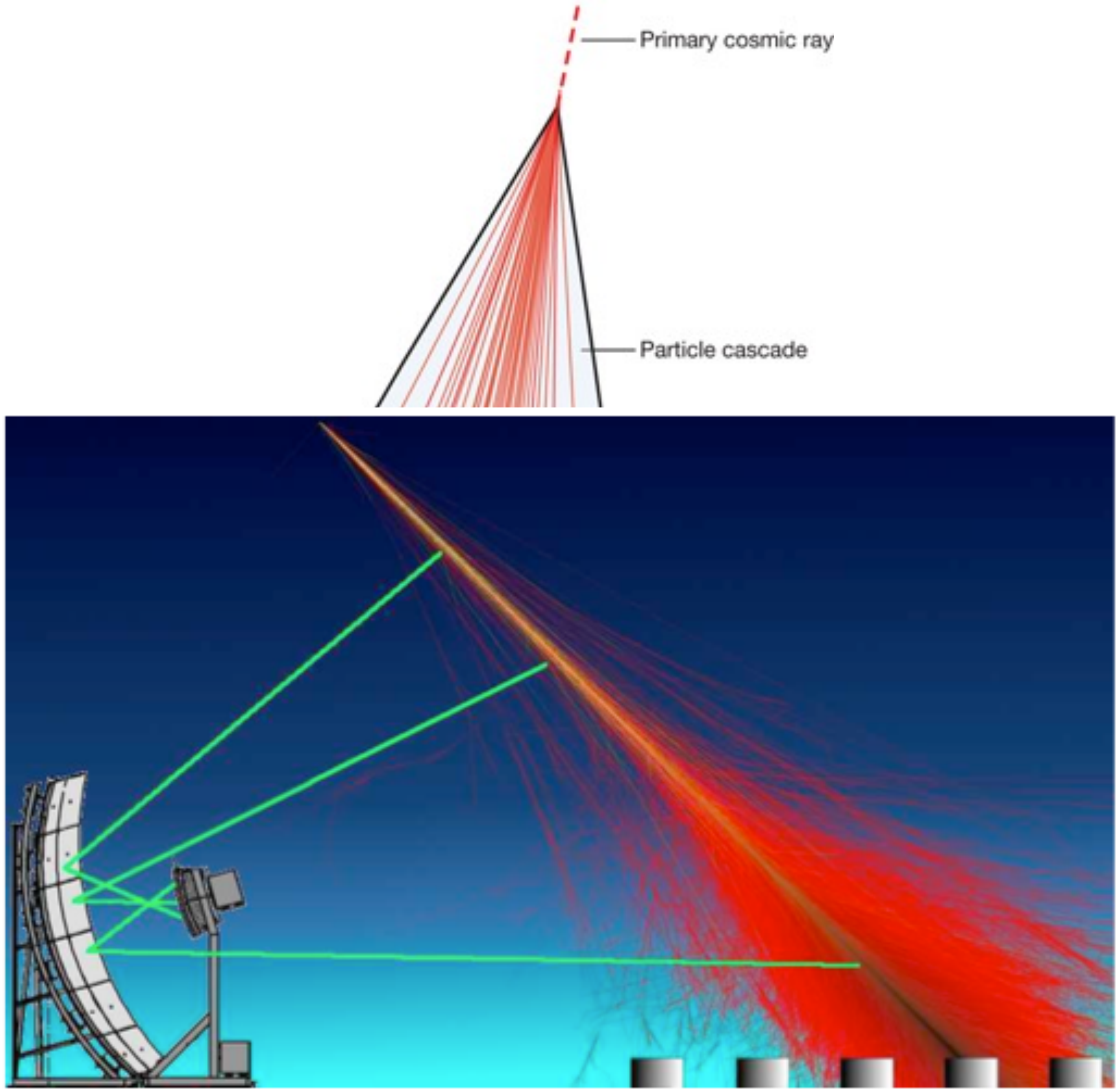
Detection


~10 km
-~3 km-


Primary cosmic ray
Particle cascade
Surface array

Detection



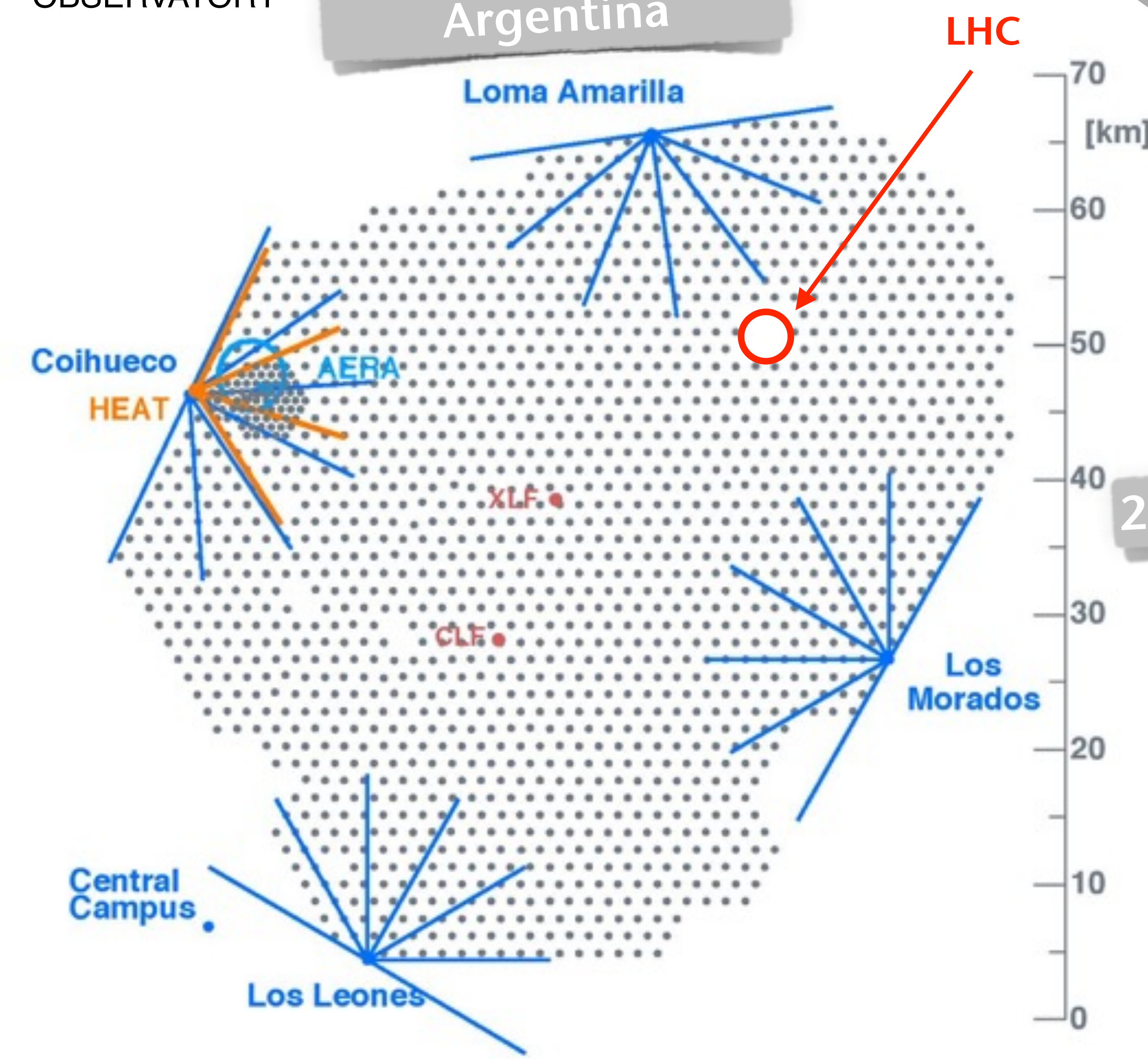


PIERRE AUGER OBSERVATORY

2004 -

3000 km² in Malargue, Argentina

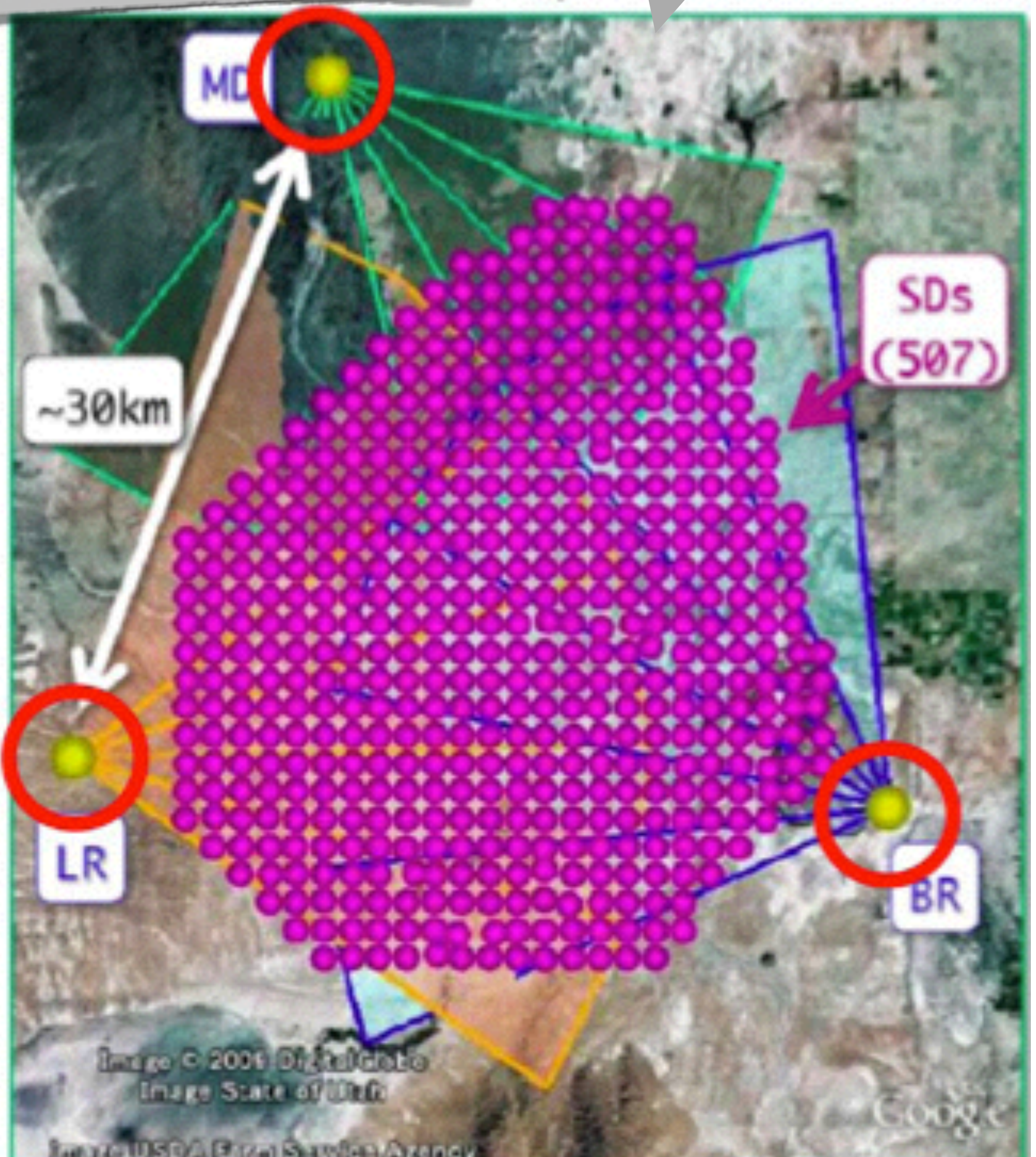
1660 Cherenkov tanks [100% duty cycle]



27 Fluorescence telescopes [~15% duty cycle]

2007 -

680 km² in Utah



507 scintillator counters
(1.2 km spacing)

3 FD Sites [

Candidate sources

Minimum requirement -
Confinement:
$R_{source} > r_{larmor}$

$$E \leq E_{\rm max} \sim 1 \text{ EeV Z } \left(\frac{\rm B}{1\mu\rm G}\right)\left(\frac{\rm R_{source}}{1 \text{ kpc}}\right)$$

Sources must be extragalactic for E > 1-10 EeV

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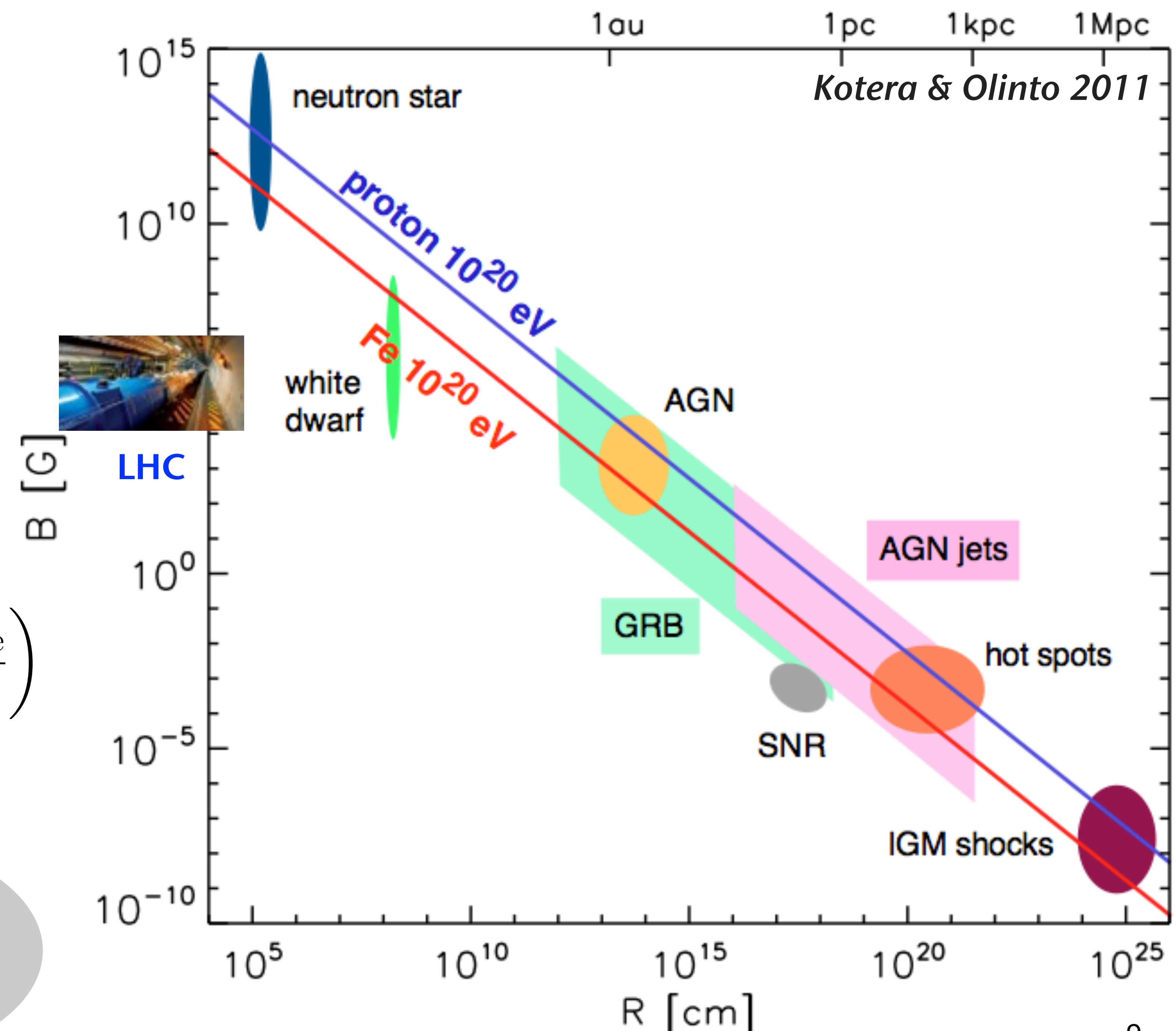
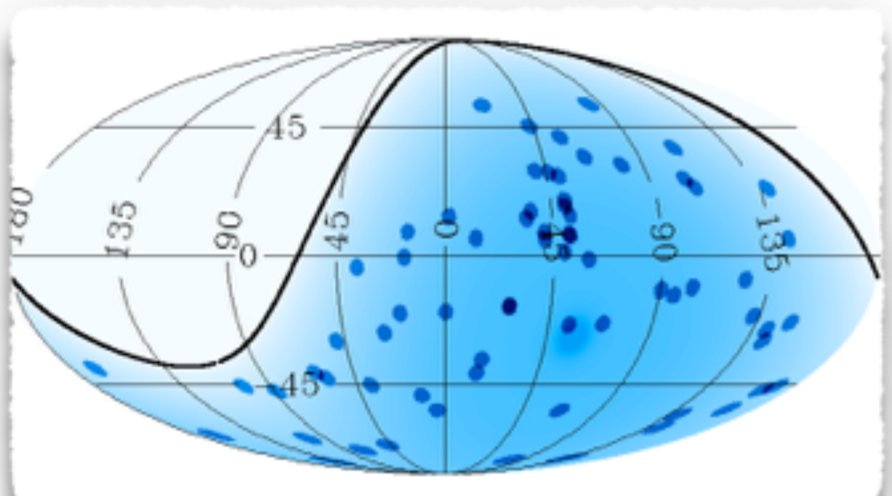
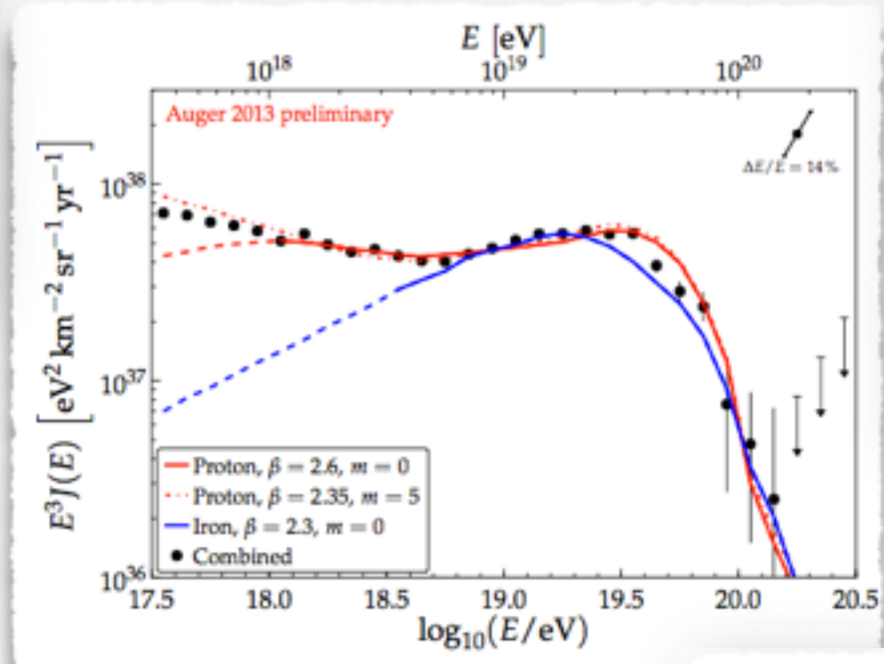


What information do we have?

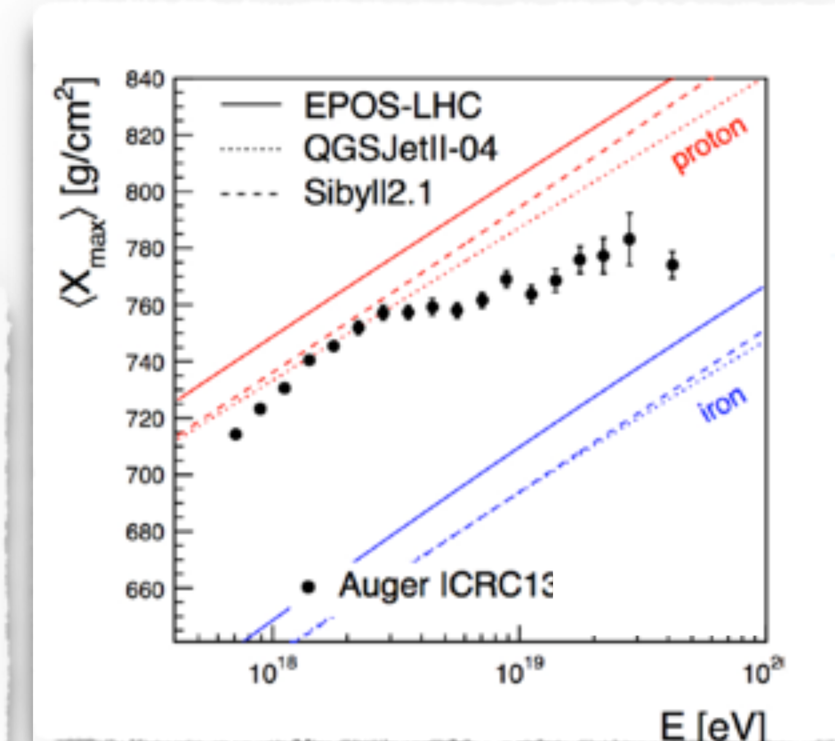
Arrival directions



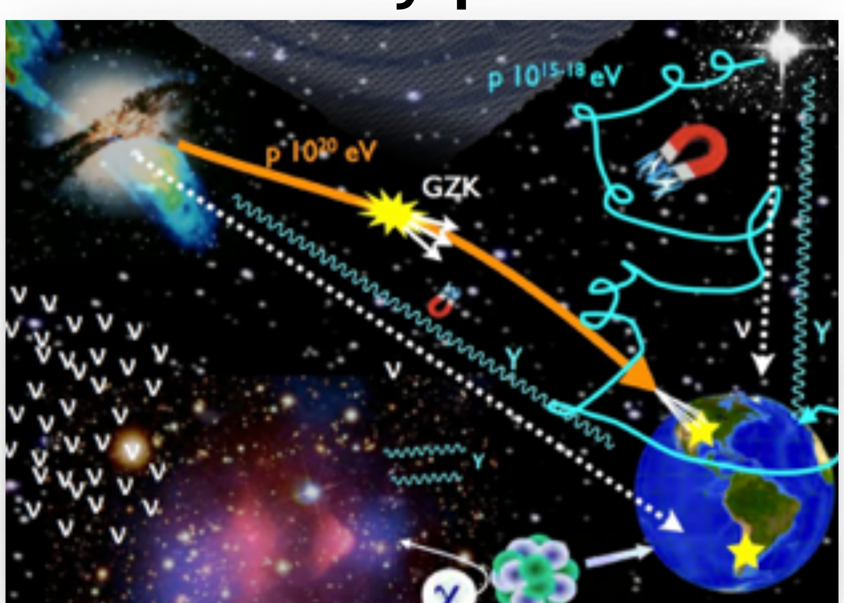
Spectrum/energetics



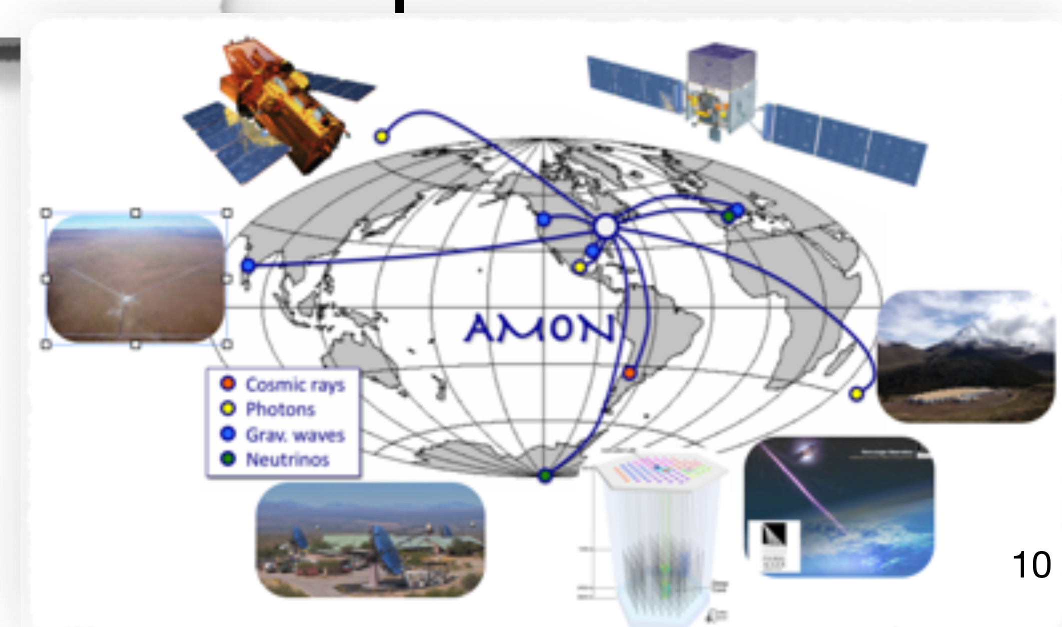
Composition



Secondary products



Multi-messenger temporal coincidences



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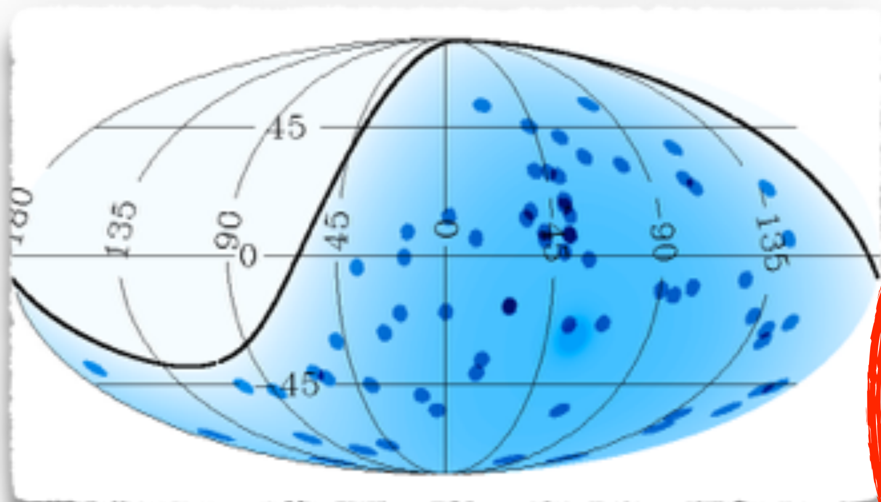

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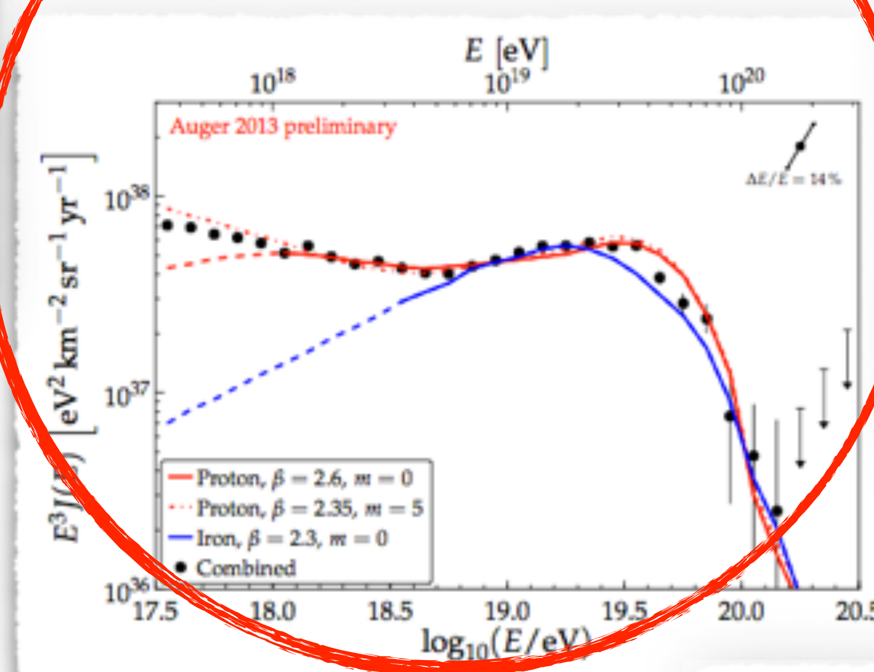
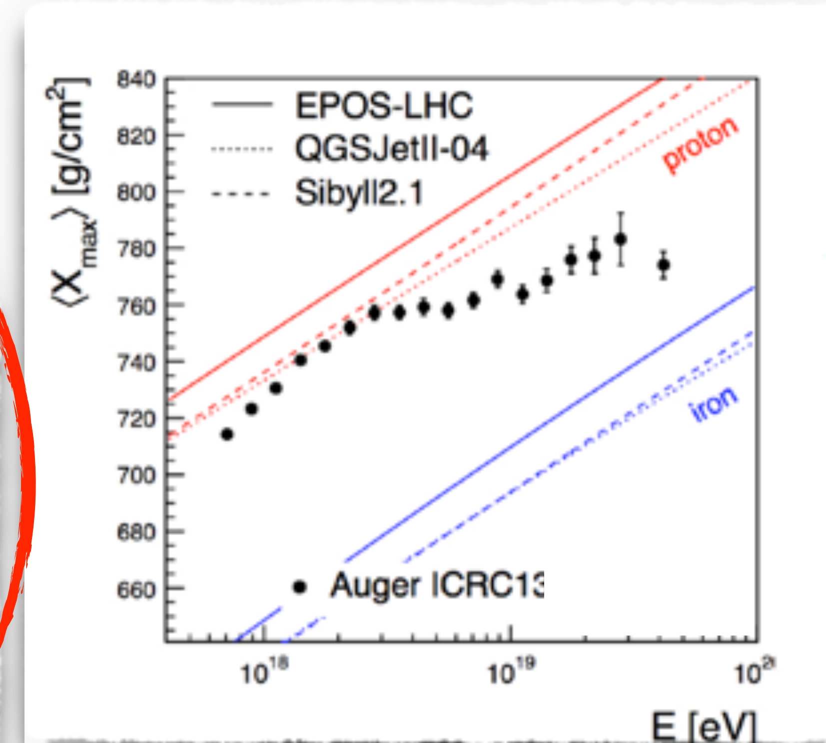


Composition



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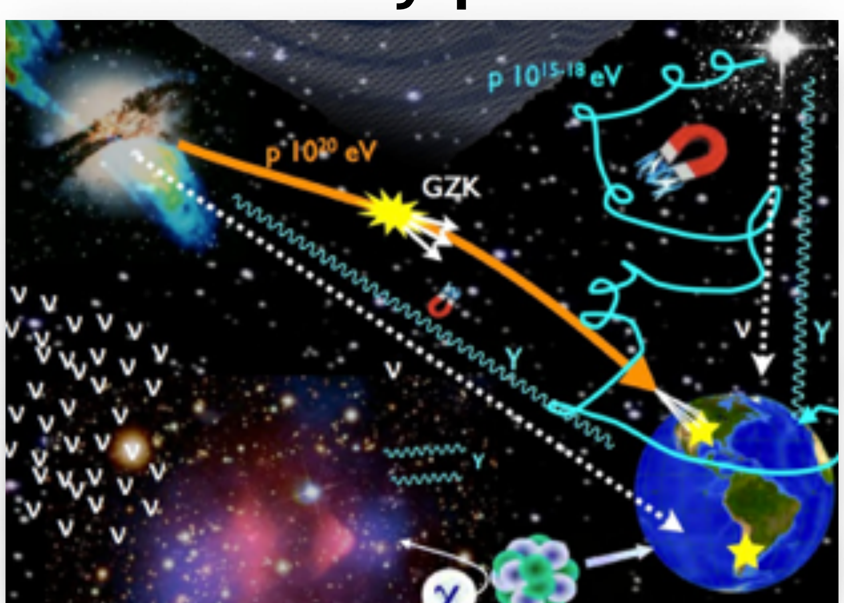

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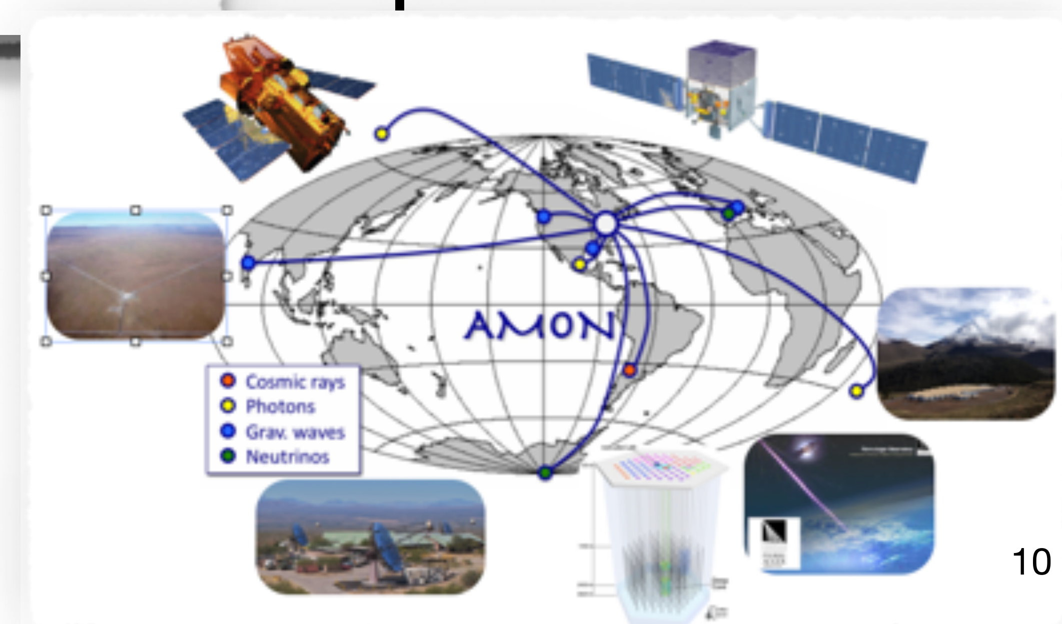
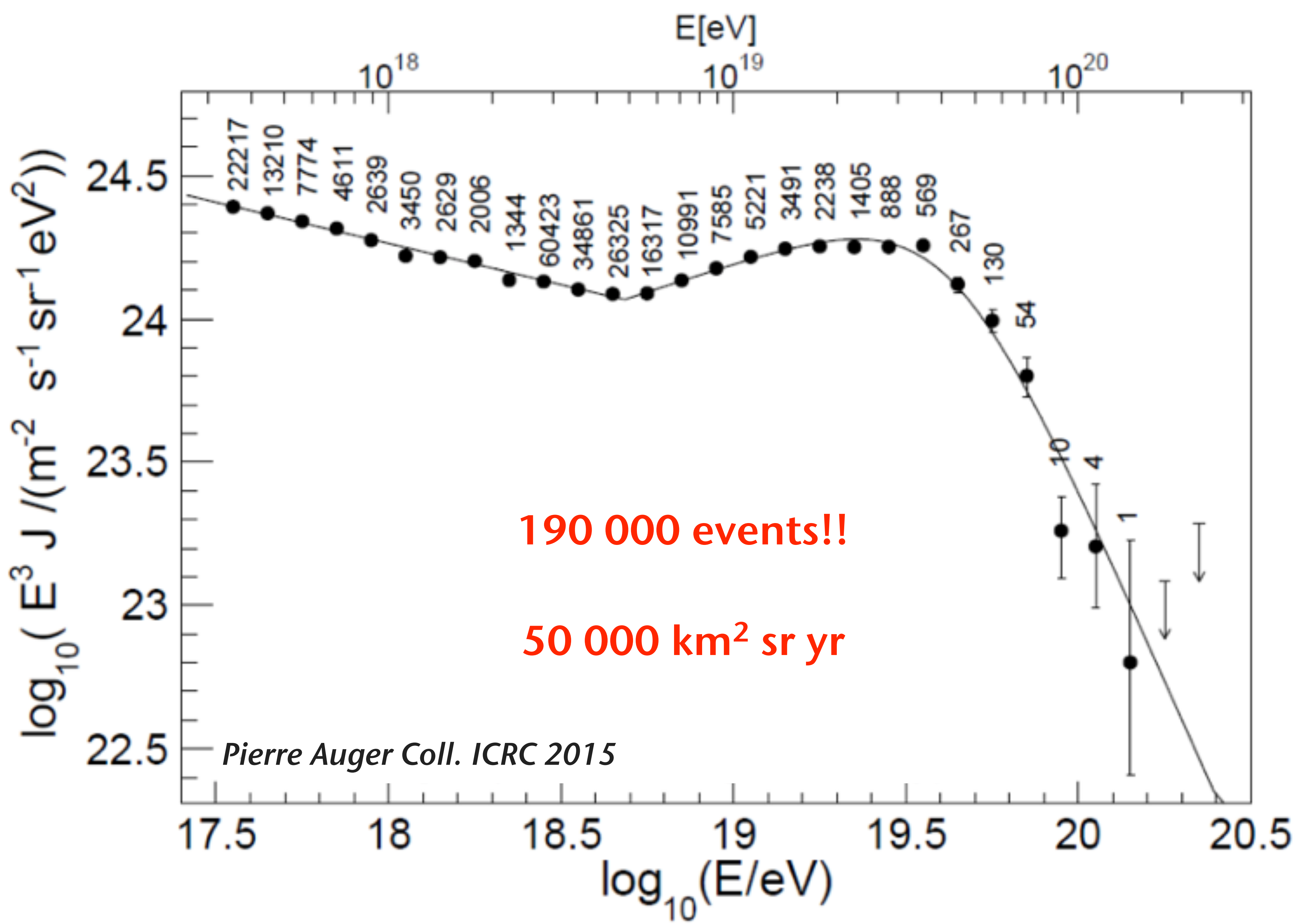


The energy spectrum



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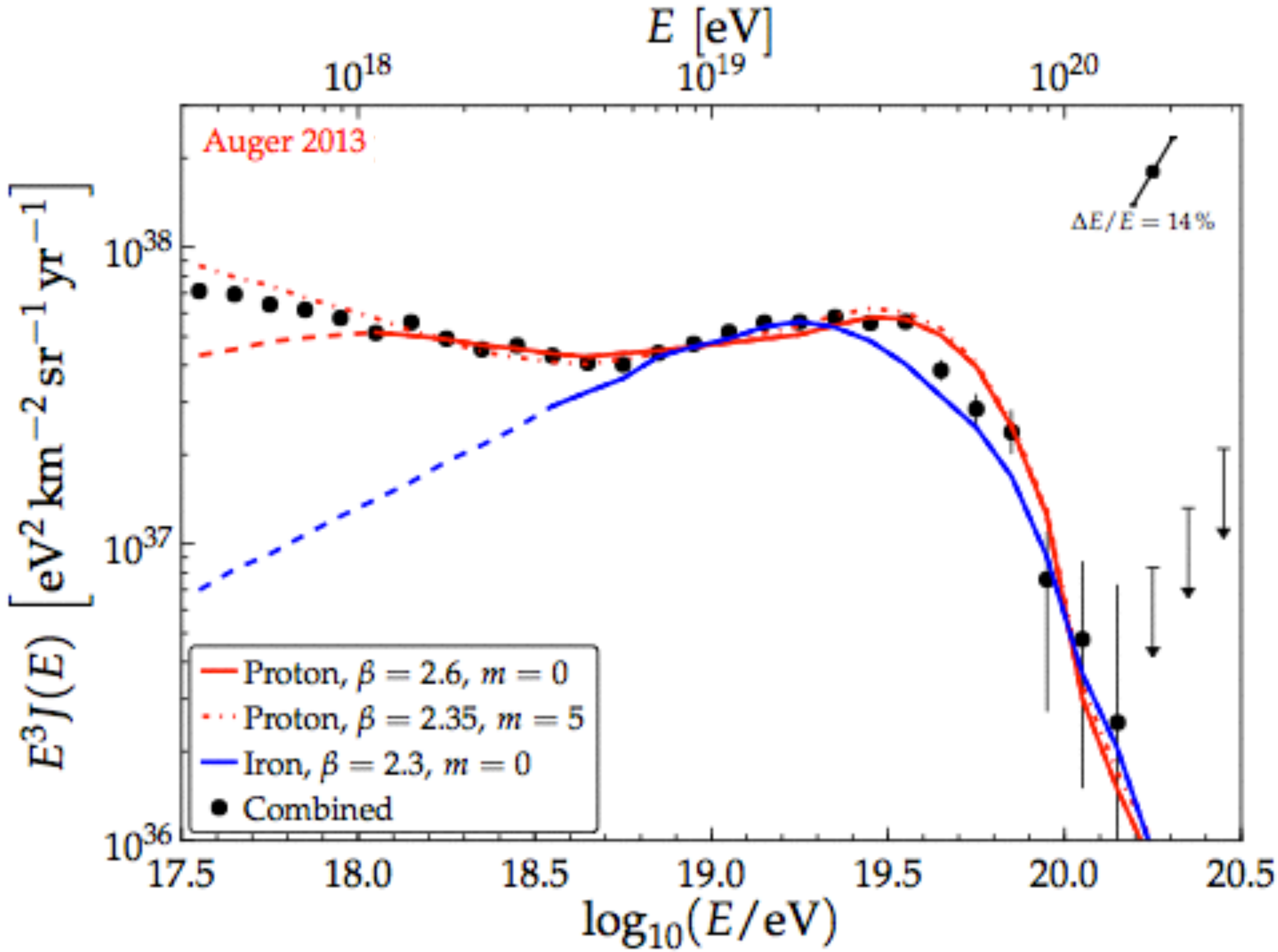

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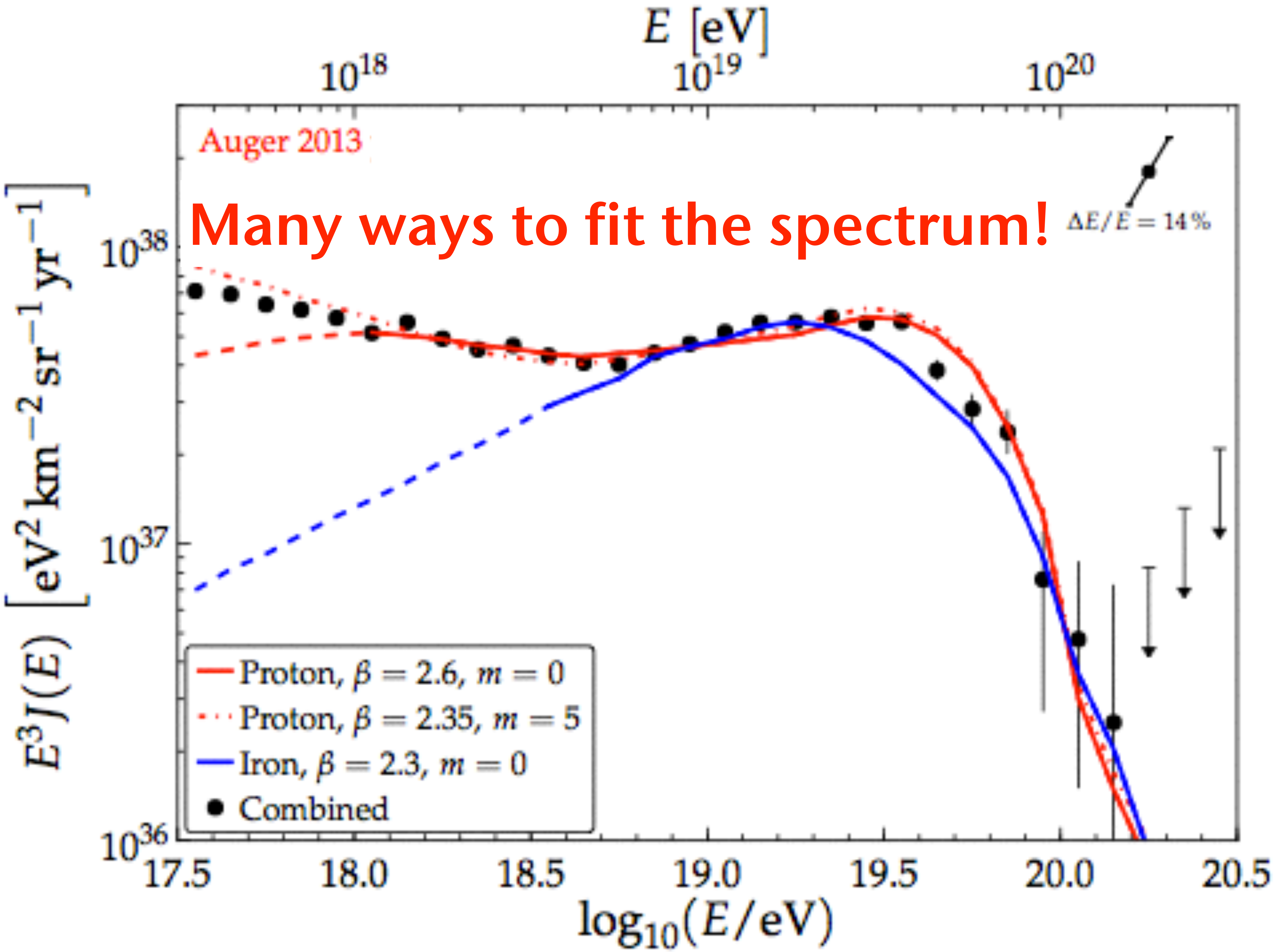

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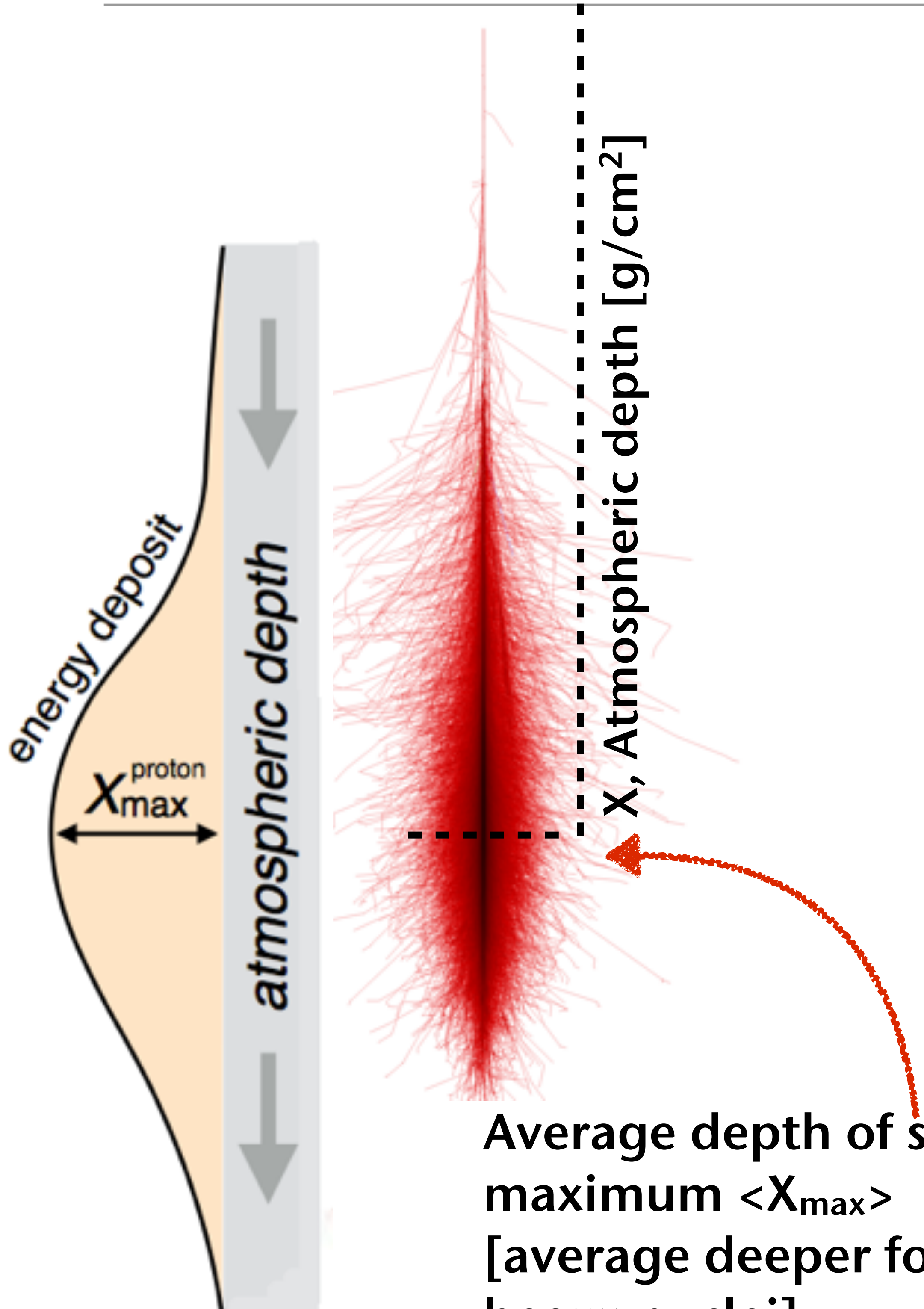
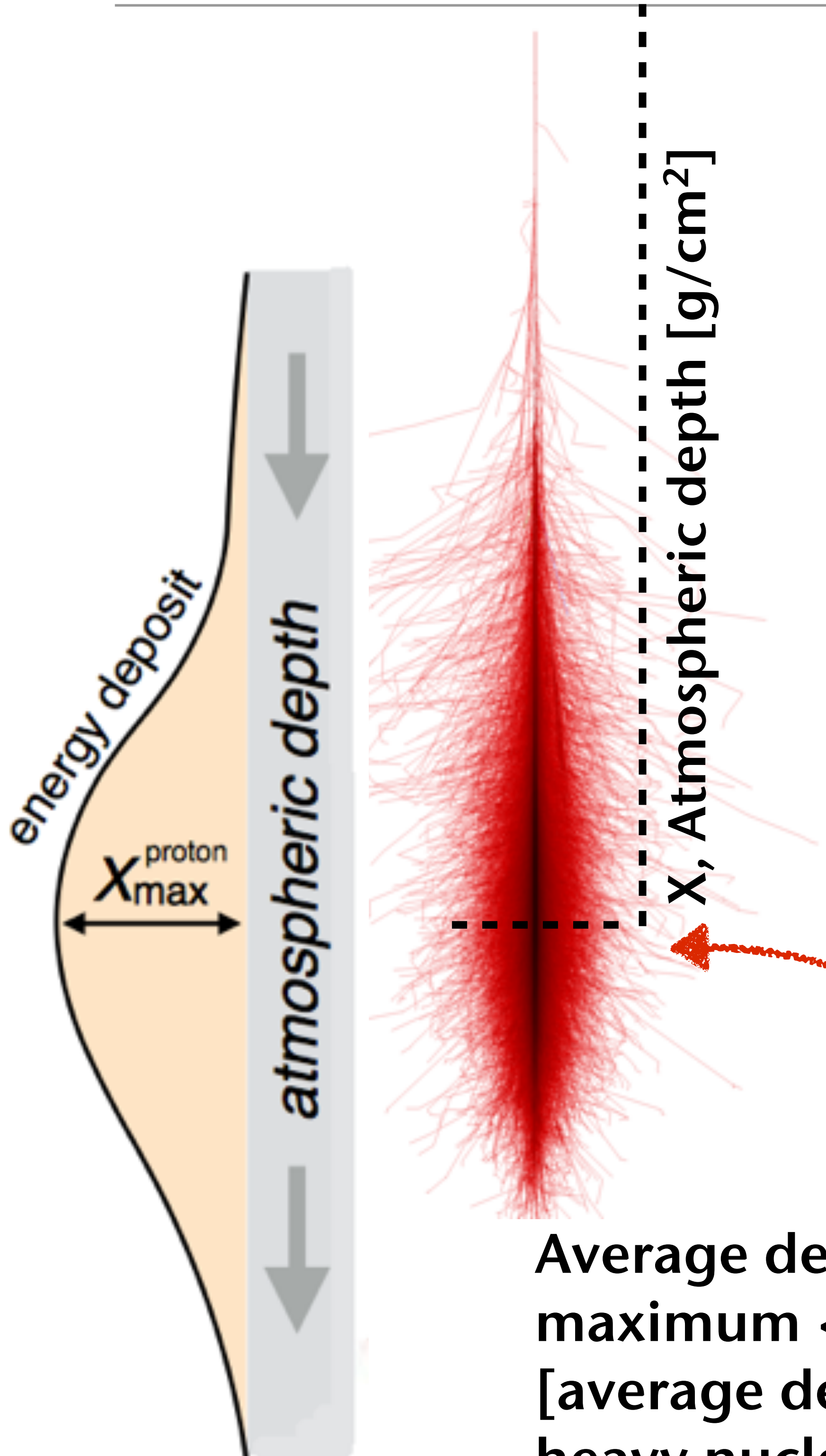


Average depth of shower maximum <X_{max}>
[average deeper for protons than heavy nuclei]

Composition



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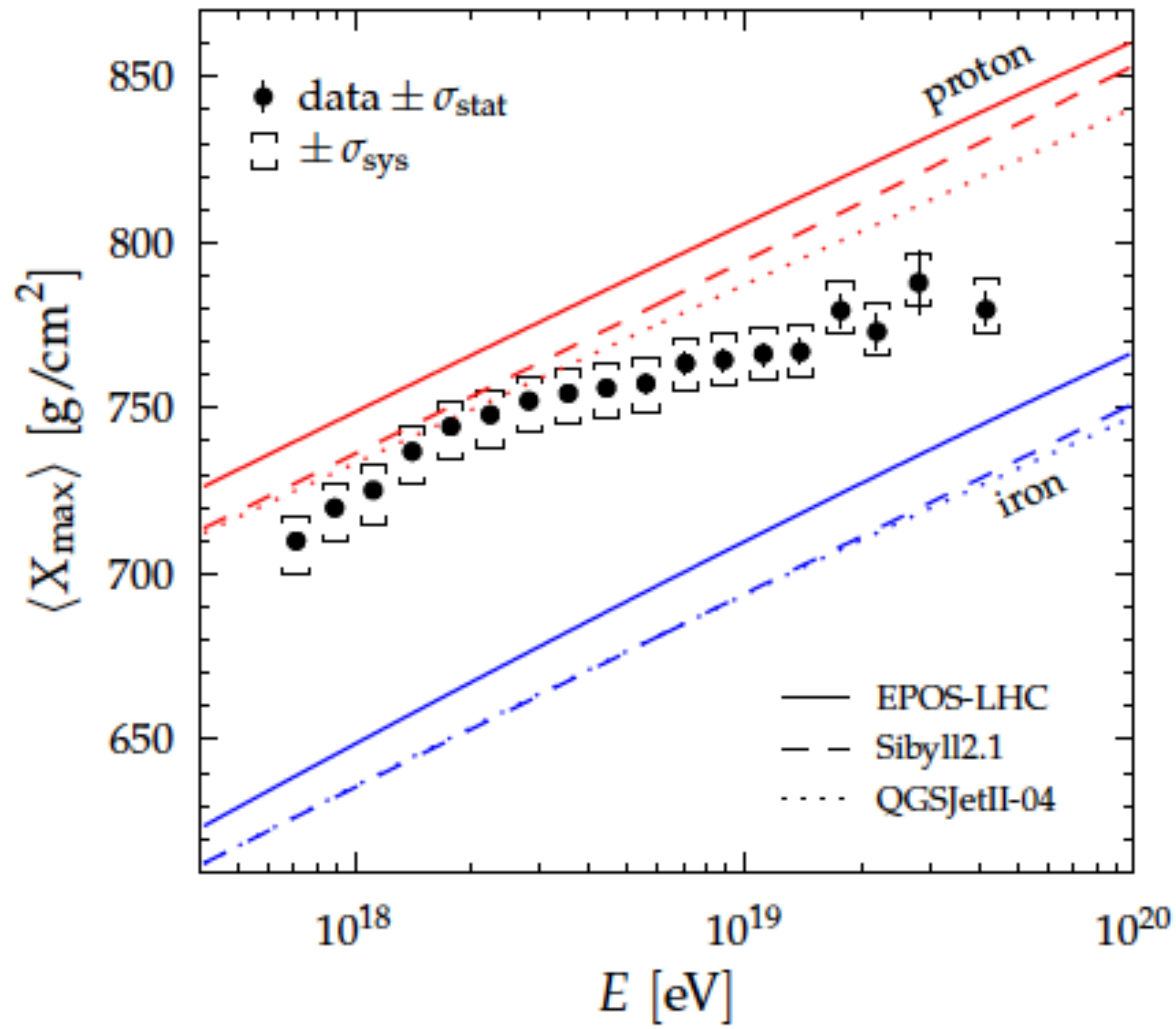
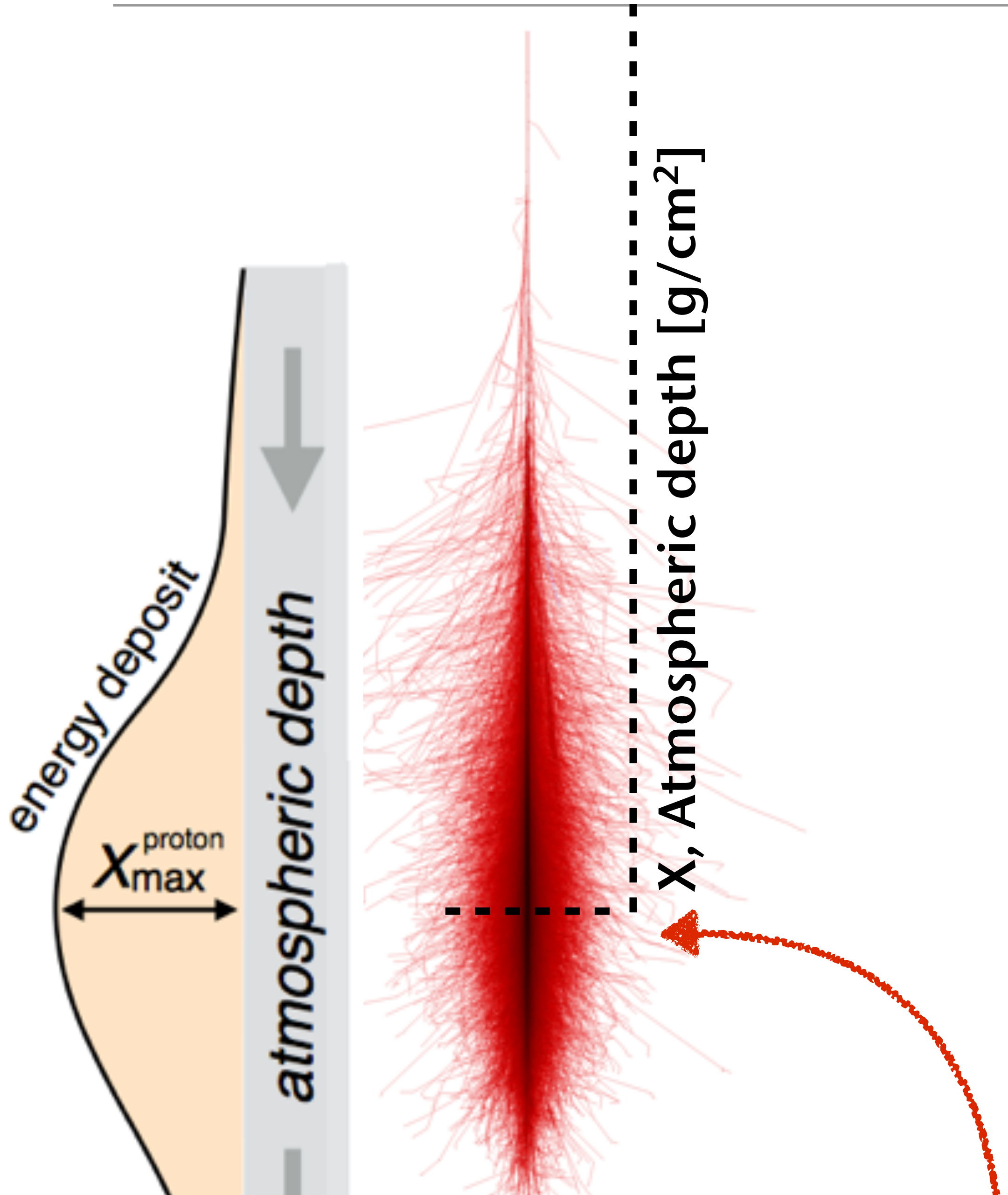
Auger



Composition



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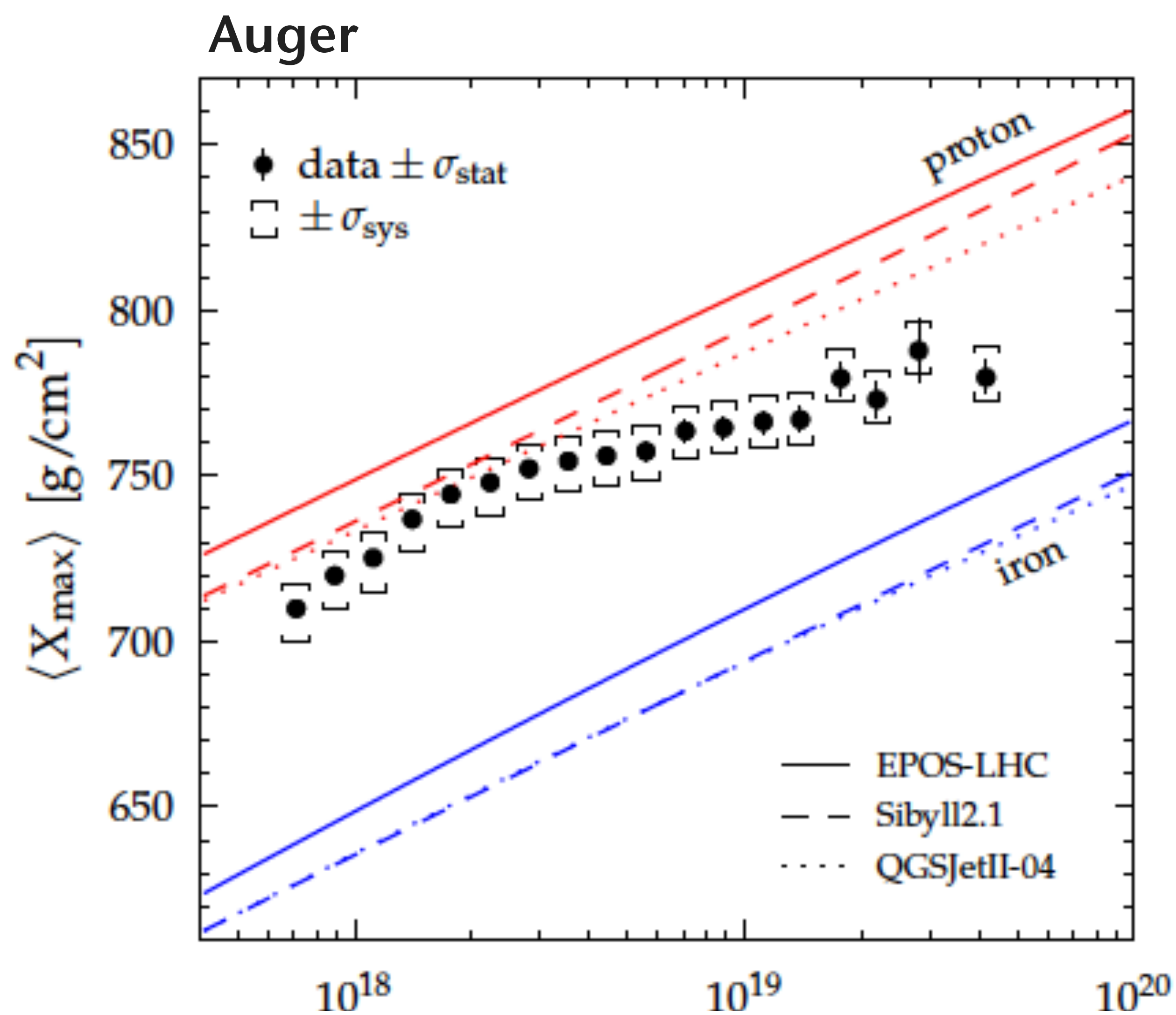

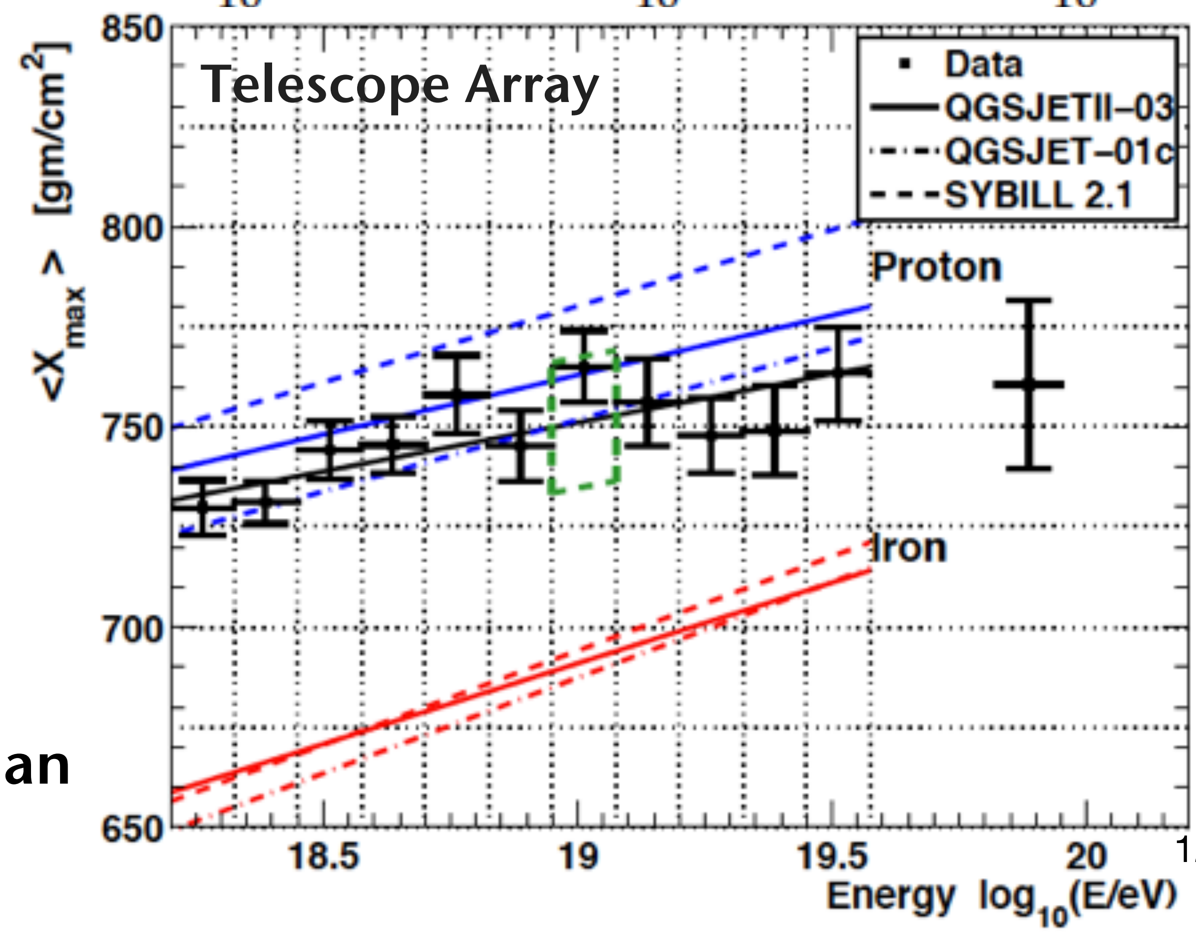

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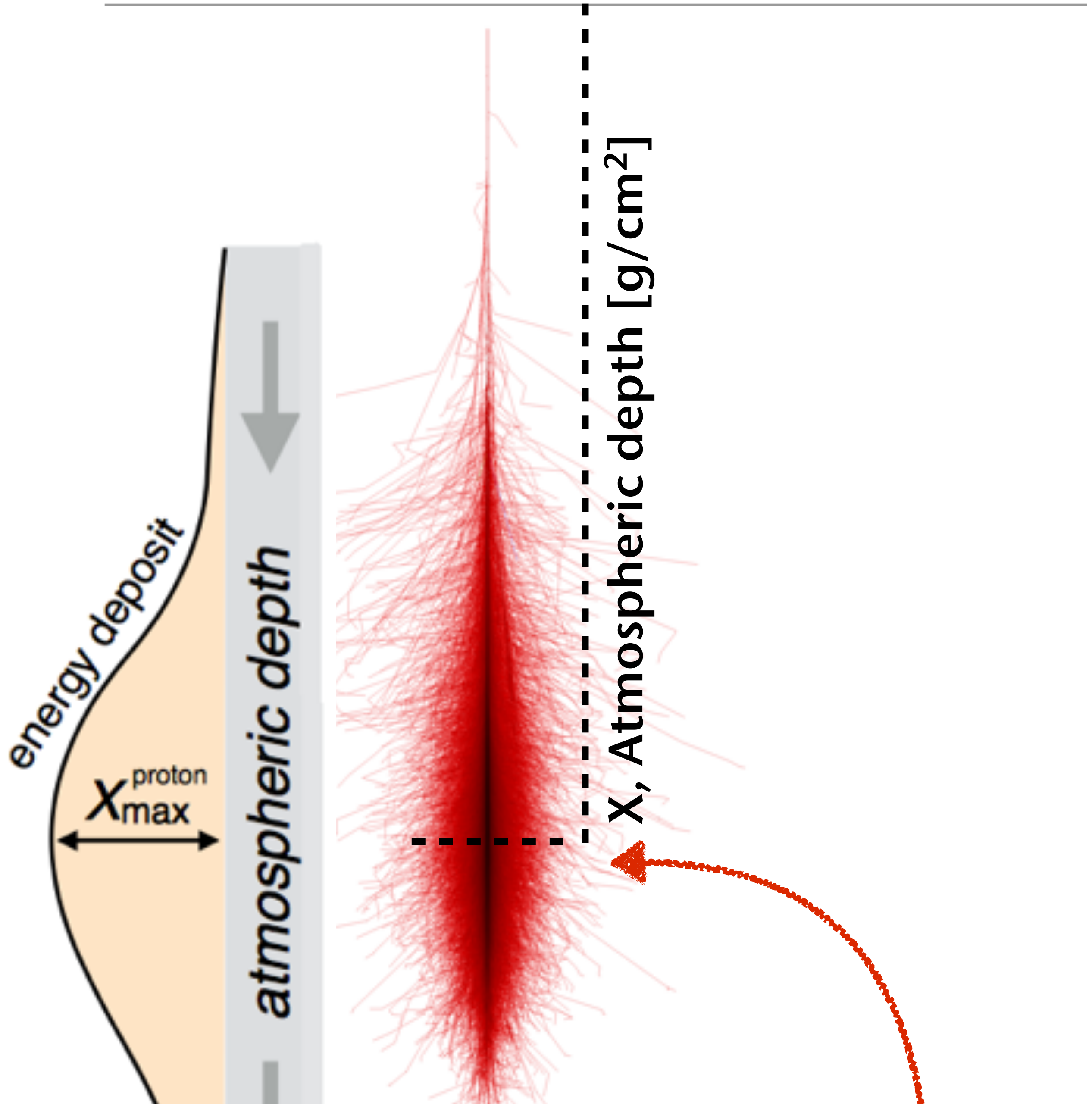

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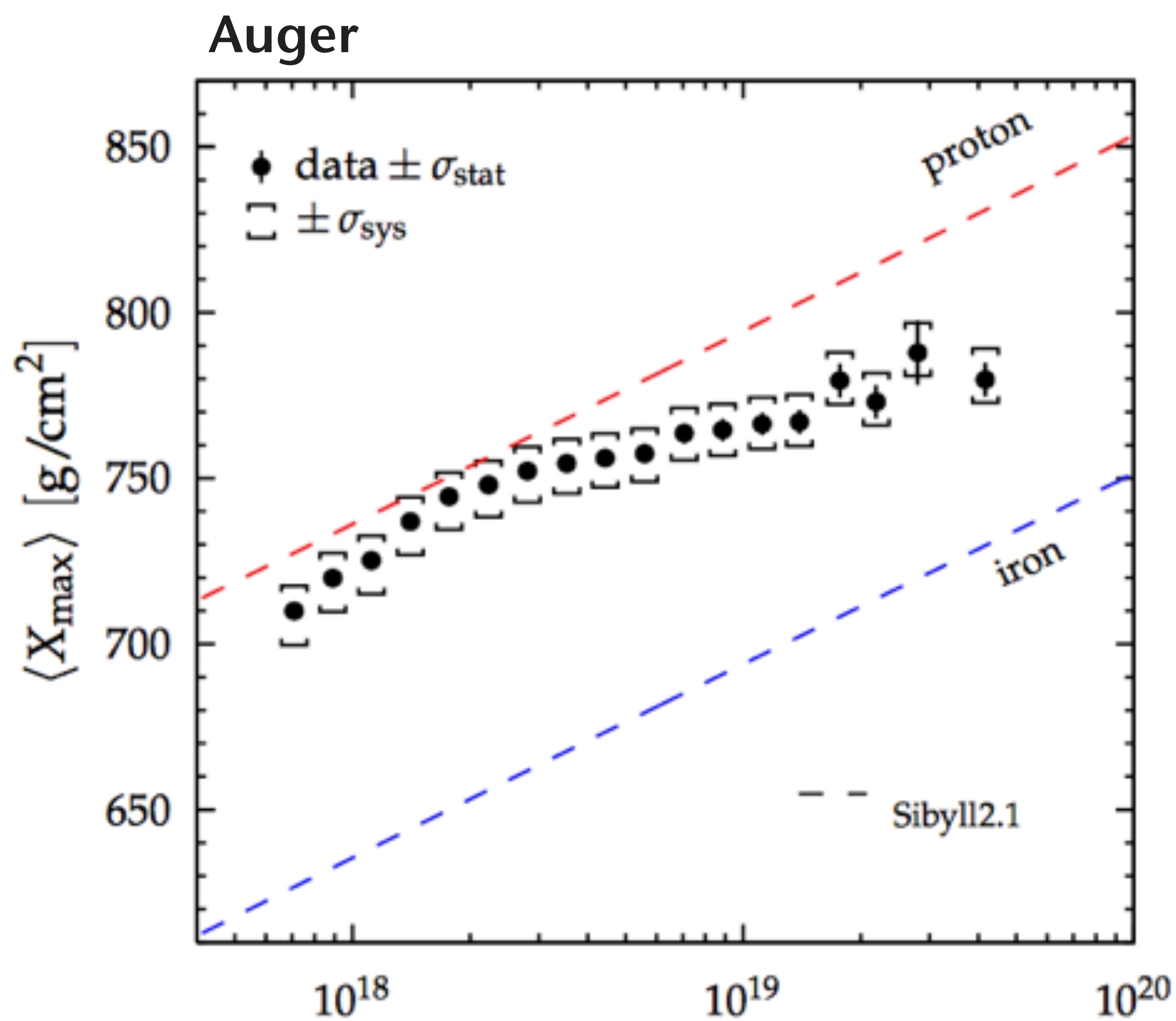

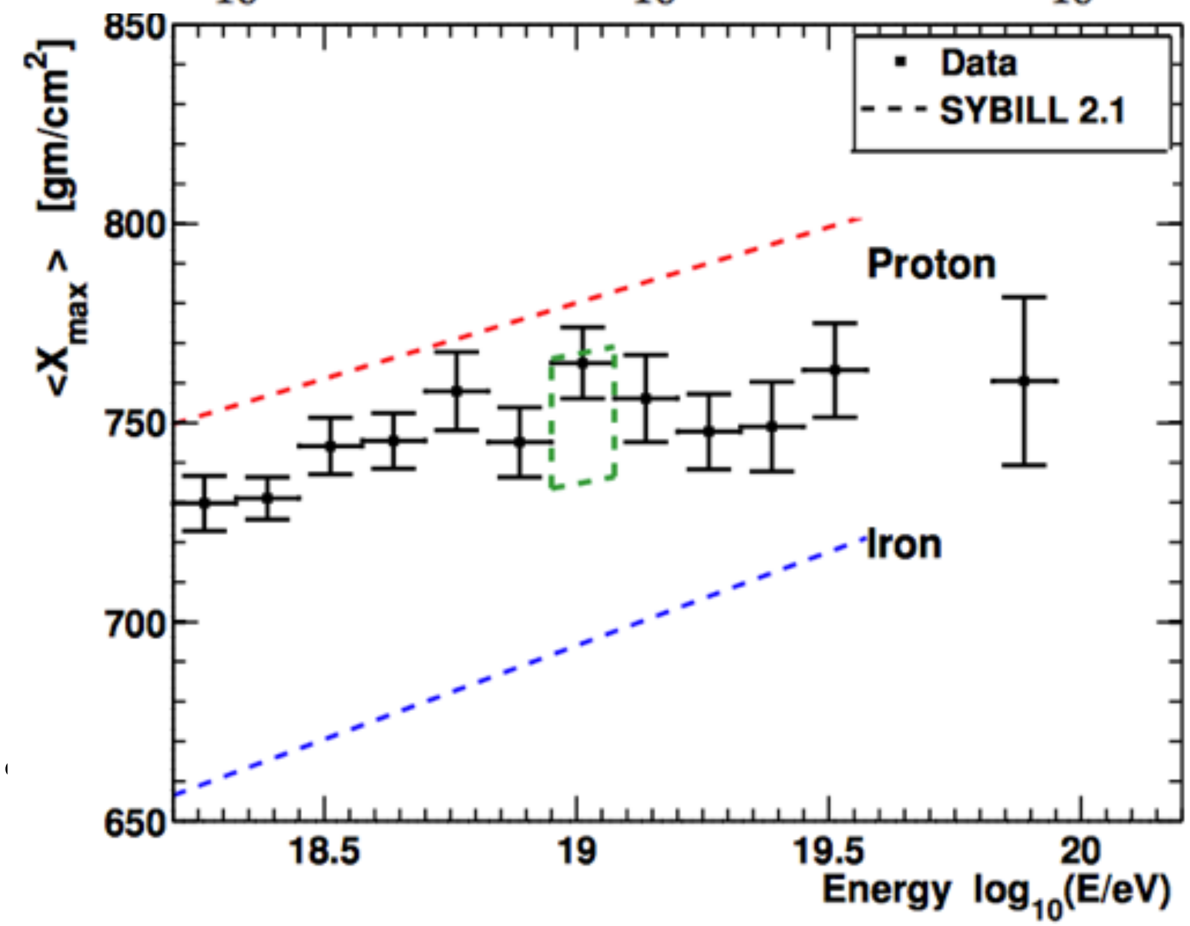

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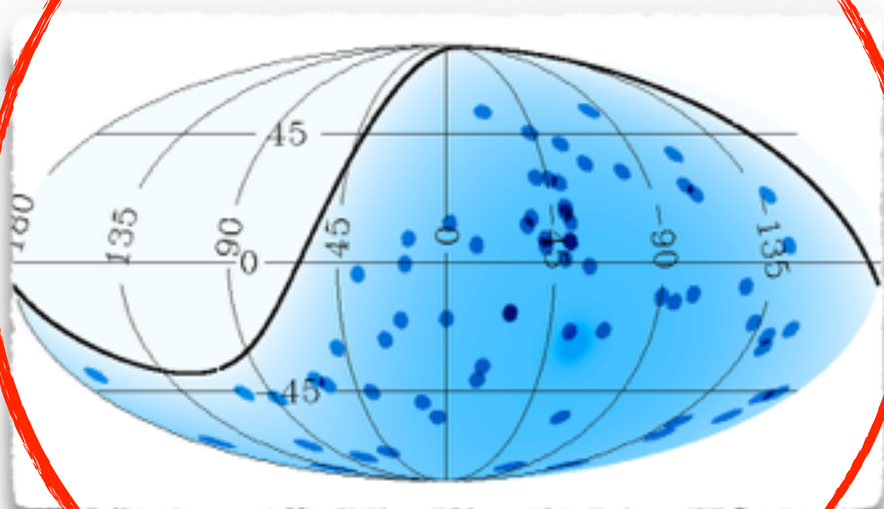

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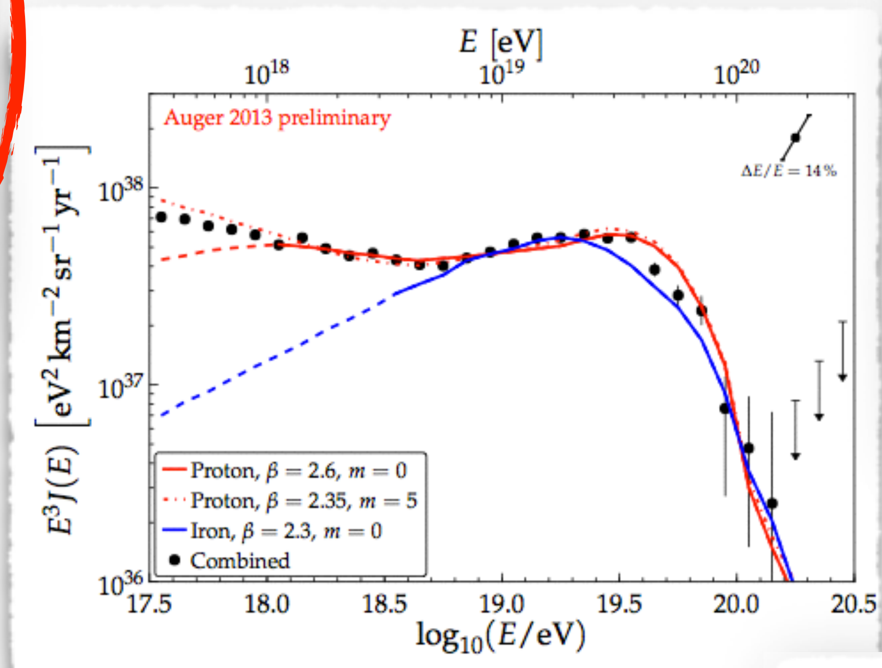

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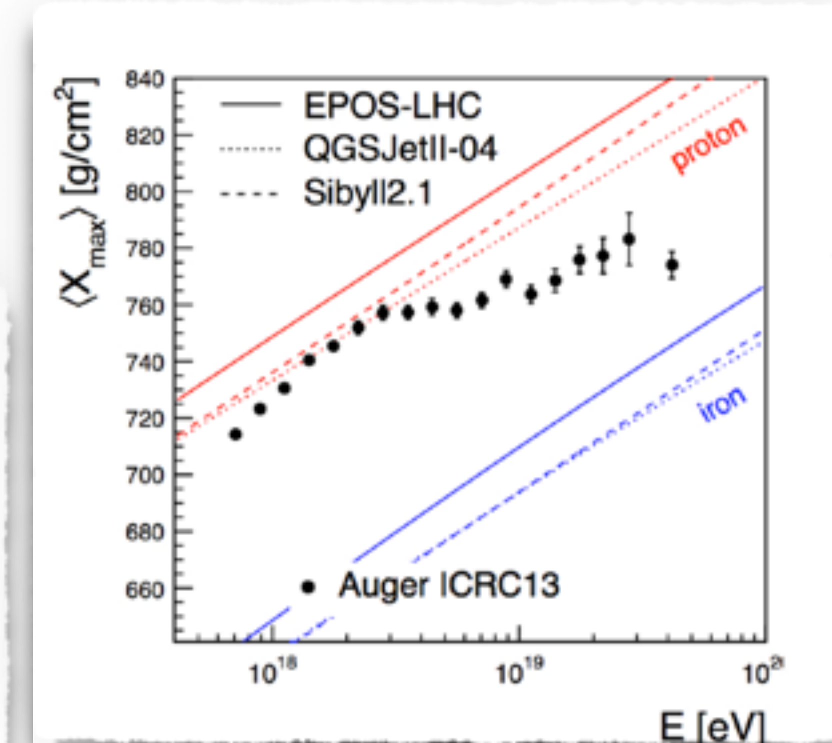

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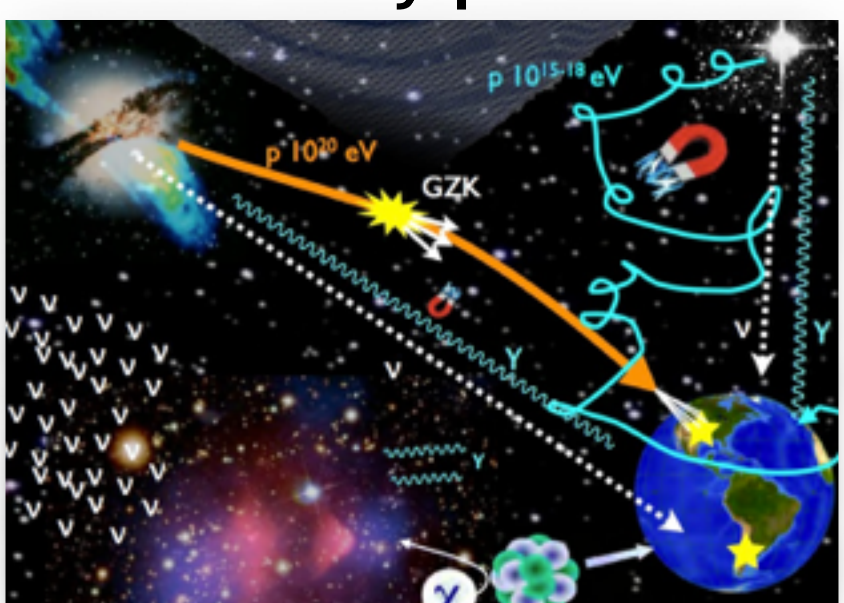

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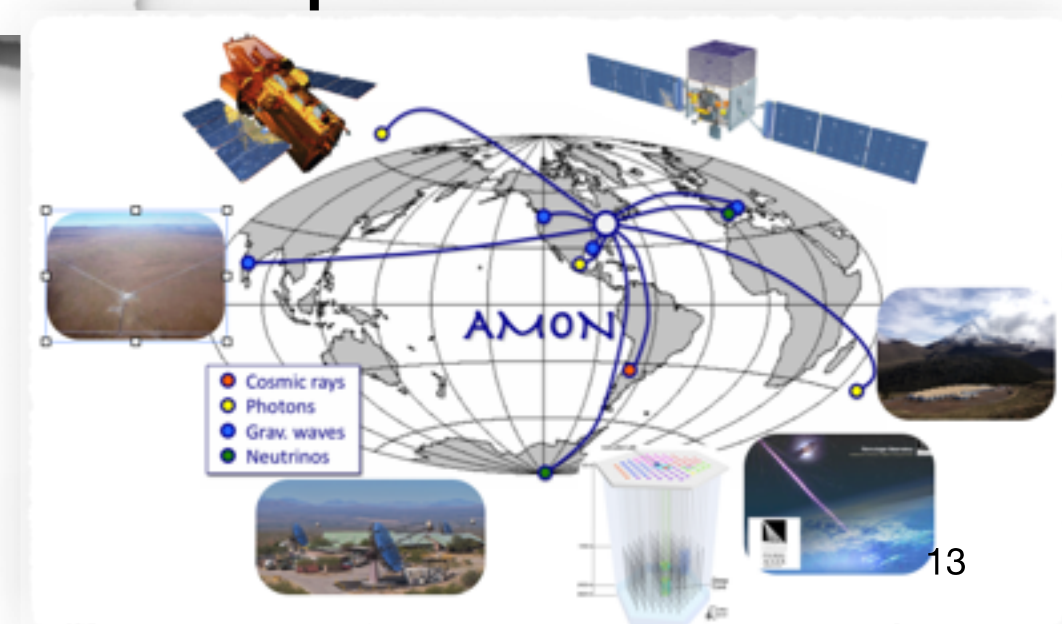
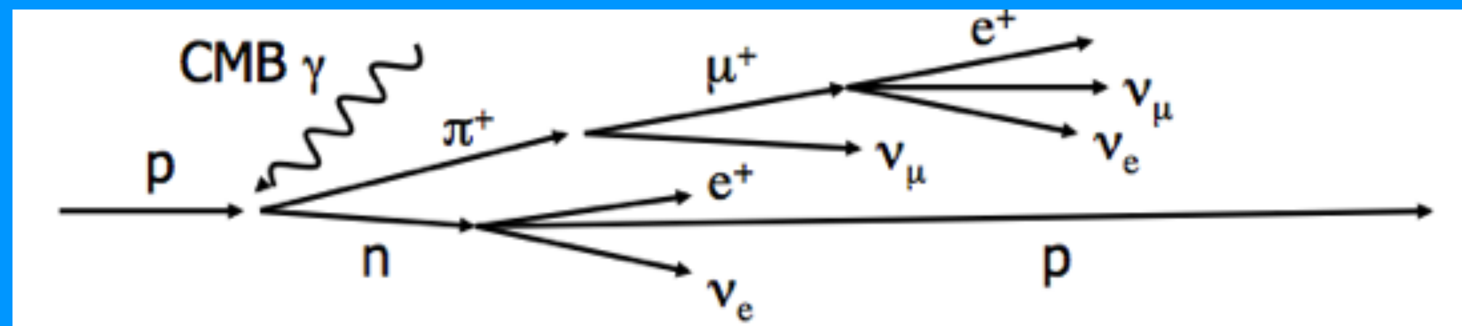


UHECR Interactions

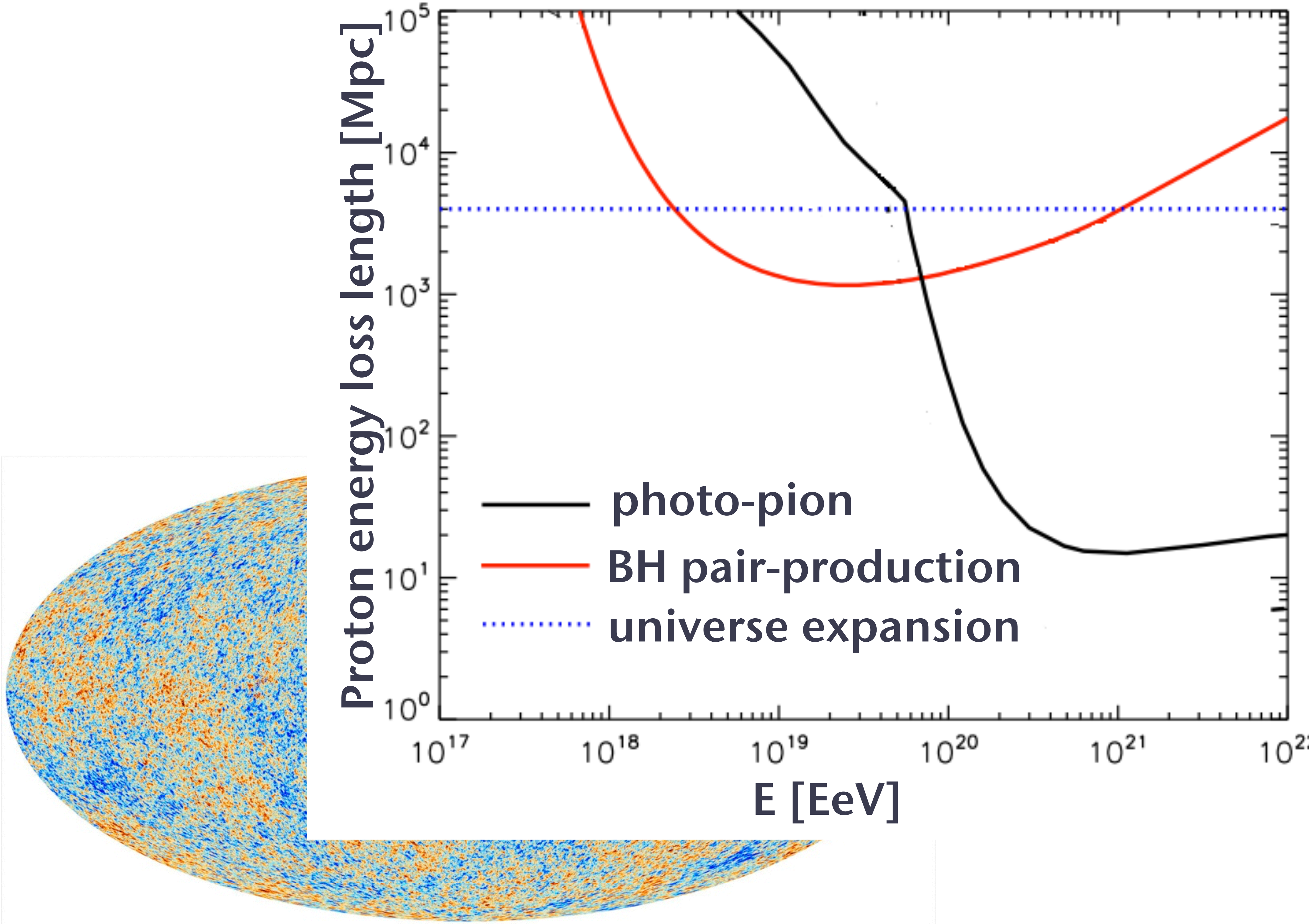
GZK process ($E_p > 6 \times 10^{19}$ eV):



Bethe-Heitler pair creation ($E > 6 \times 10^{16}$ eV):

$$p + \gamma_{\text{CMB}} \rightarrow p e^+ e^-$$

UHECR Interactions



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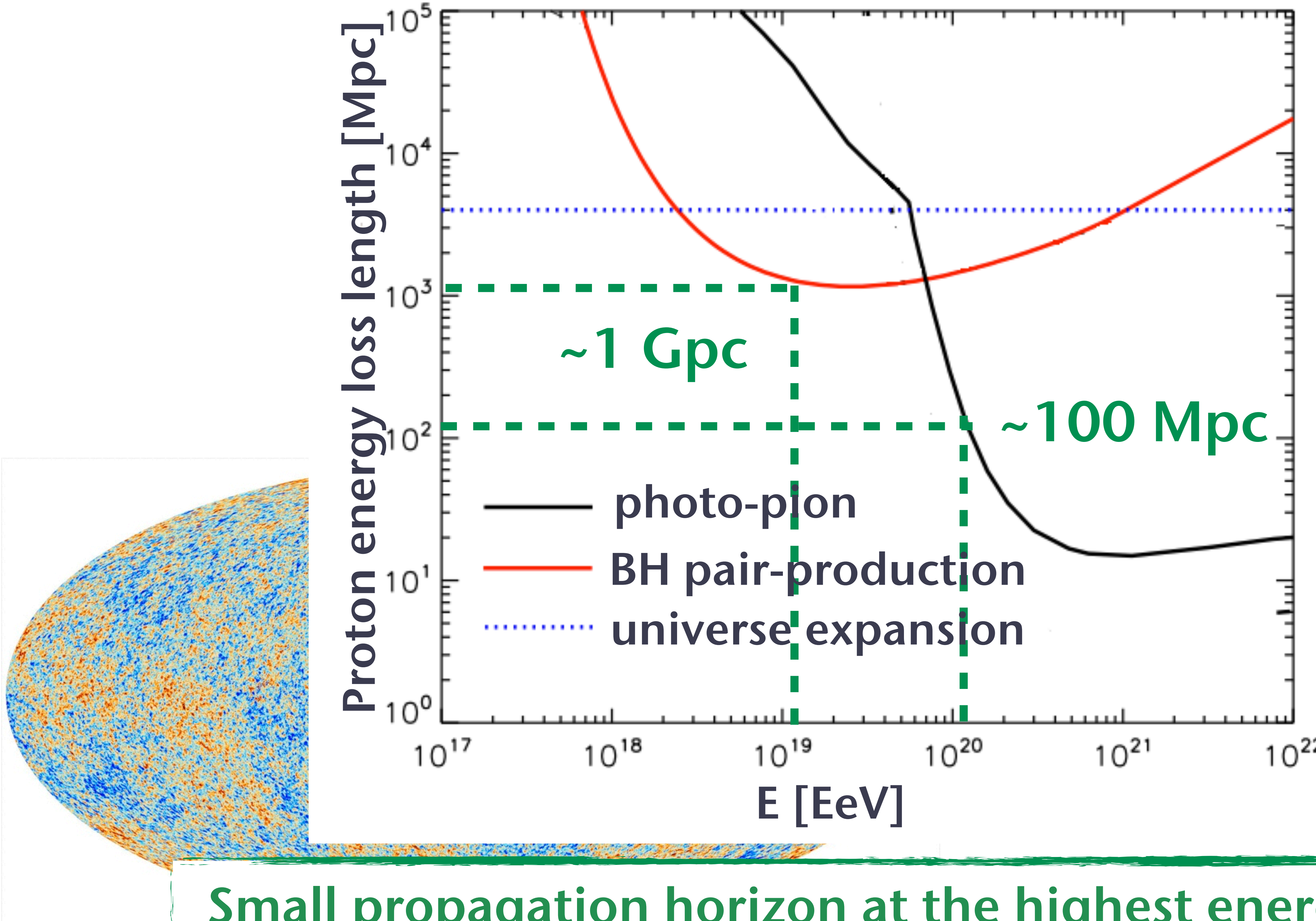
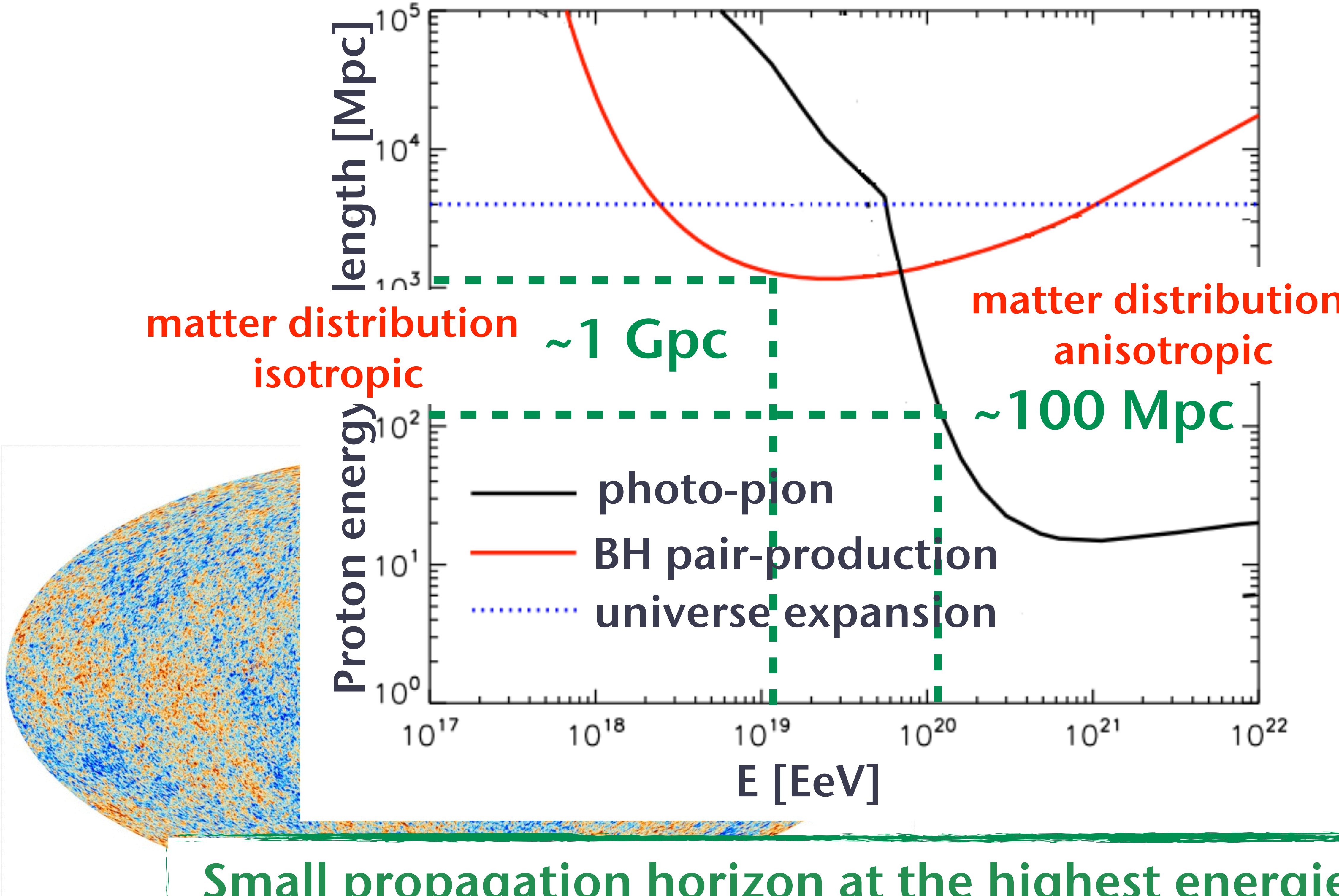


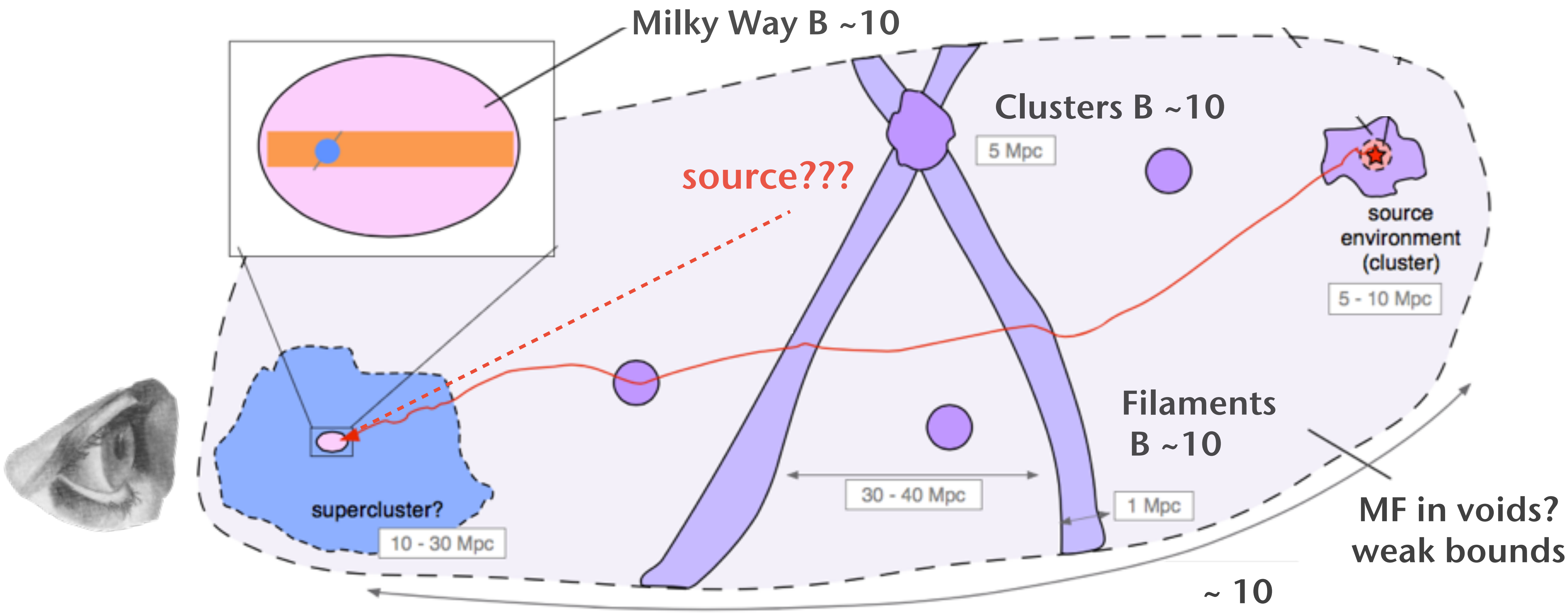
Small propagation horizon at the highest energies!

UHECR Interactions



Small propagation horizon at the highest energies!

UHECR Propagation in the intergalactic medium



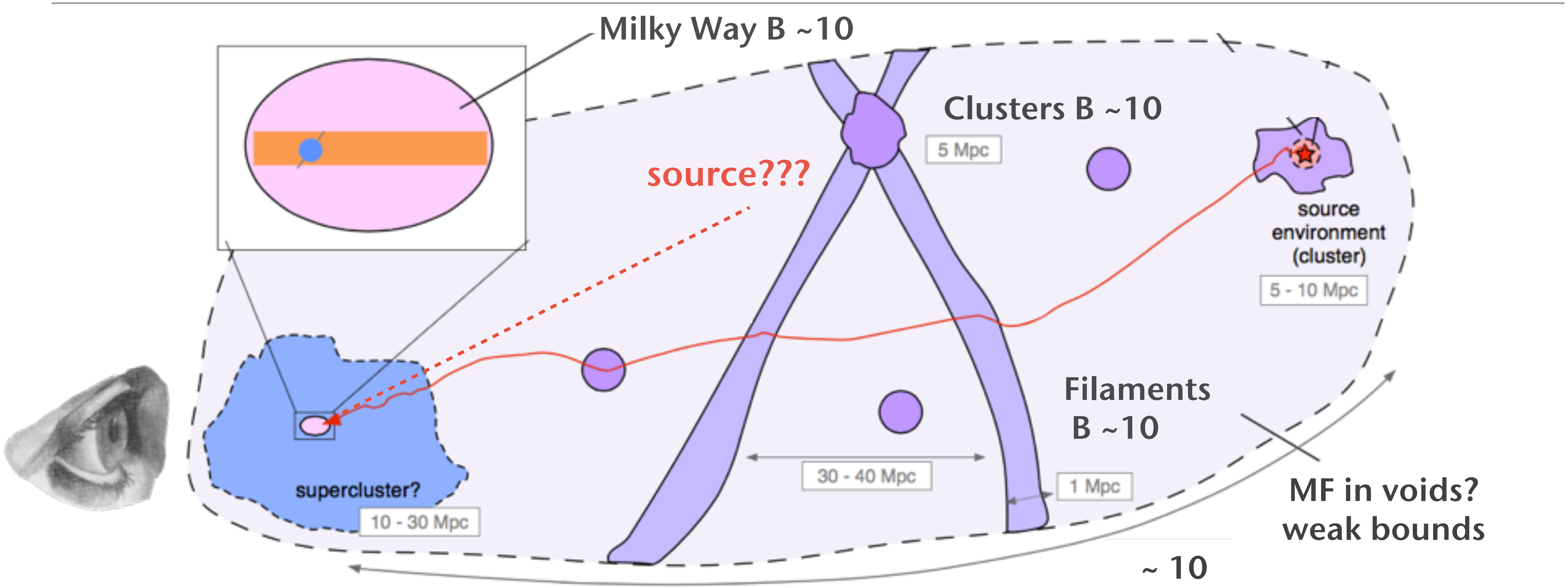
$$\theta(E,L) \simeq 0.22^\circ Z \left(\frac{L}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{E}{10^{20}\ \mathrm{eV}}\right)^{-1} \left(\frac{\lambda}{0.1\ \mathrm{Mpc}}\right) \left(\frac{B}{10^{-9}\ \mathrm{G}}\right)$$

~ 2° for 10^{20} eV proton

Waxman & Miralda-Escude 1995

Image: Kotera & Olinto 2011

UHECR Propagation in the intergalactic medium



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~ 2° for 10^{20} eV proton

Waxman & Miralda-Escude 1995

!! BUT:

-deflection causes time delay

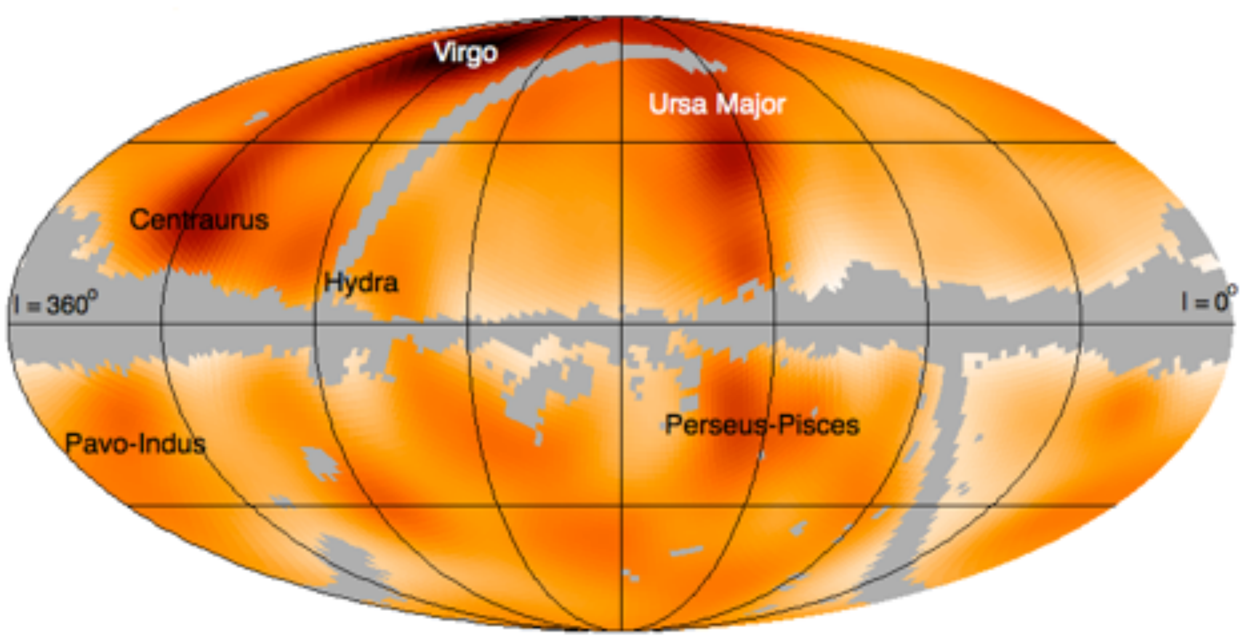
-larger Z -> large deflections

Image: Kotera & Olinto 2011

FO, Connolly, Abdalla, Lahav, Thomas, Waters, Waxman: JCAP05(2013)015

Model of the expected UHECR source distribution: Galaxy surveys

Protons E > 55 EeV, PSCz



IRAS PSCz ~full sky ~ 10000 galaxies, ~far-IR selected: excellent probe of star-formation

Calculations take into account:
- proton energy losses
- galaxy weights as a function of redshift
- Auger exposure
- galaxy survey selection functions

FO, Connolly, Abdalla, Lahav, Thomas, Waters, Waxman: JCAP05(2013)015

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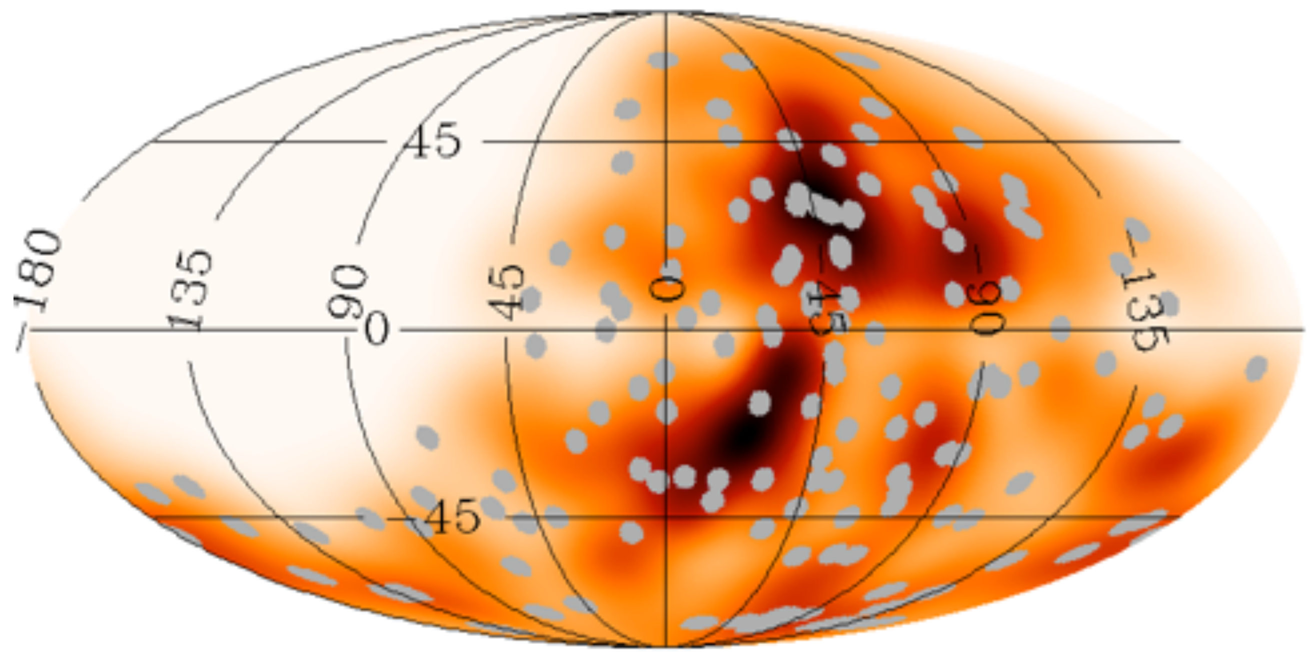


+142 UHECRs with E > 55 EeV detected till April 2014, z<60º

$$X = \sum_i \frac{(N_{\rm CR,i} - N_{\rm iso,i})(N_{\rm M,i} - N_{\rm iso,i})}{N_{\rm iso,i}}$$

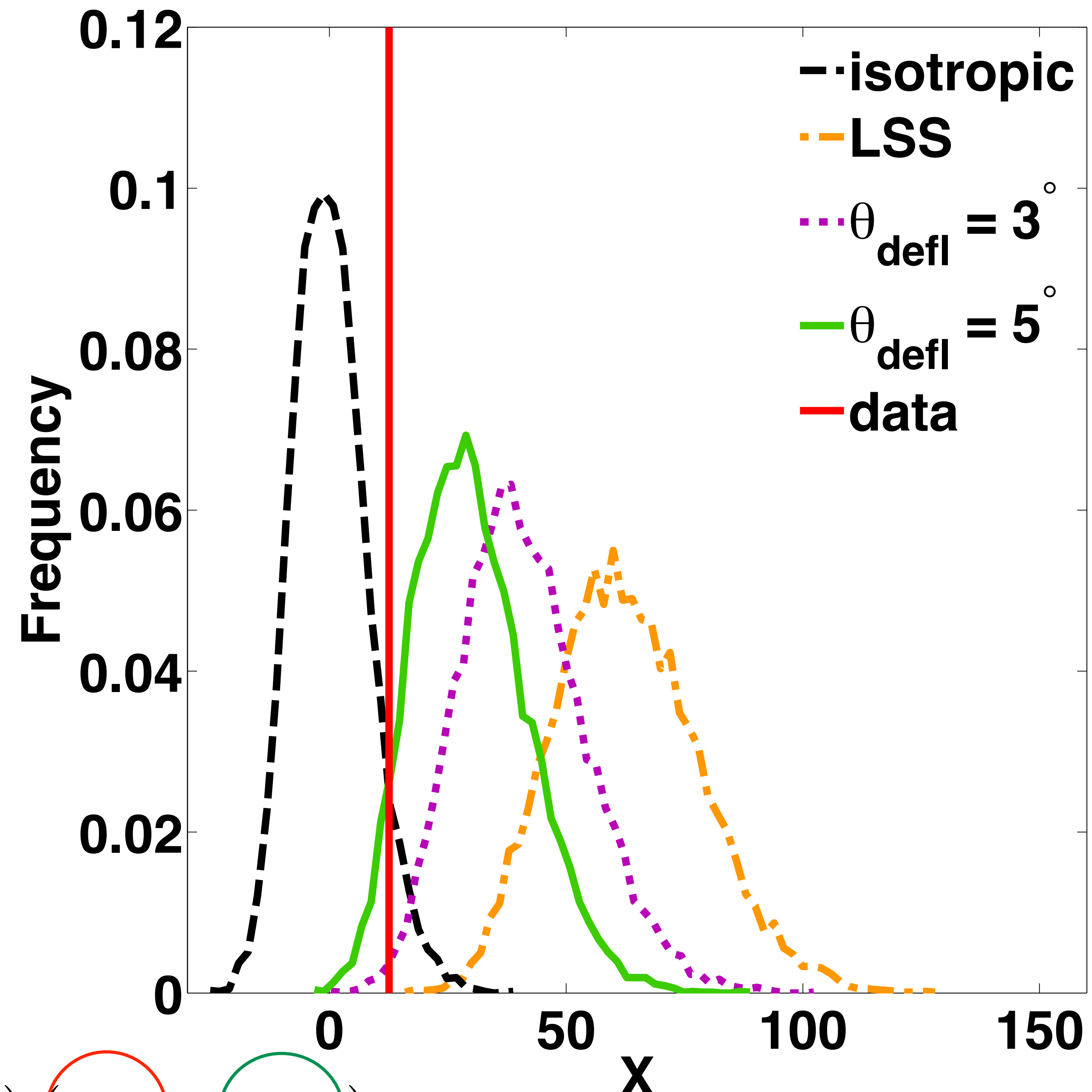
data

LSS model

isotropic expectation

Calculations take into account:
- proton energy losses
- galaxy weights as a function of redshift
- Auger exposure
- galaxy survey selection functions

Correlation with galaxy distribution



Piso = 7%

Pprotons,no deflections

< 0.1%

$$X = \sum_i \frac{(N_{\rm CR,i} - N_{\rm iso,i})(N_{\rm M,i} - N_{\rm iso,i})}{N_{\rm iso,i}}$$

data

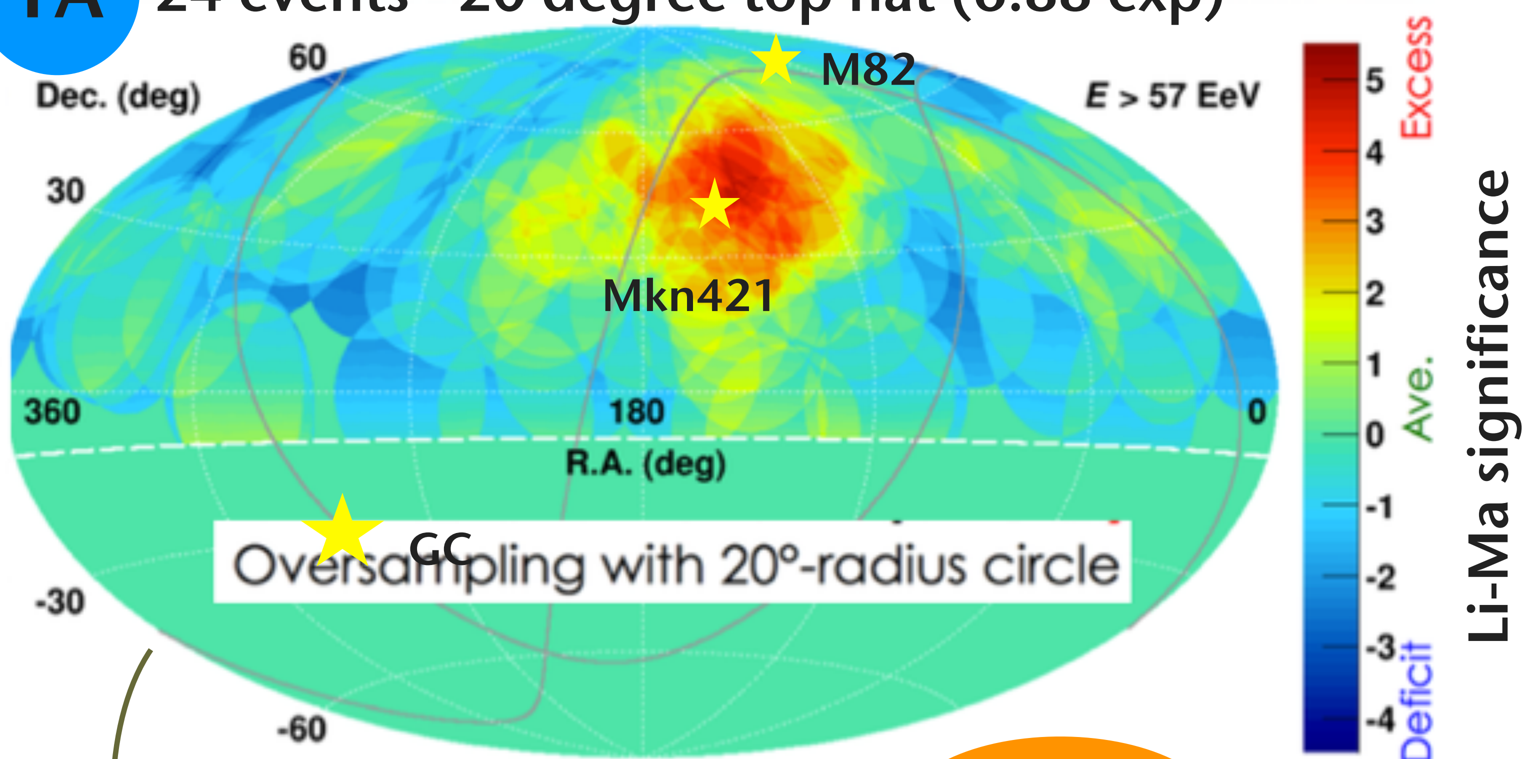
LSS model

isotropic expectation

+consistent results with 6dFGS and 2MRS galaxy surveys

Hotspots in the UHECR sky

TA 24 events - 20 degree top hat (6.88 exp)

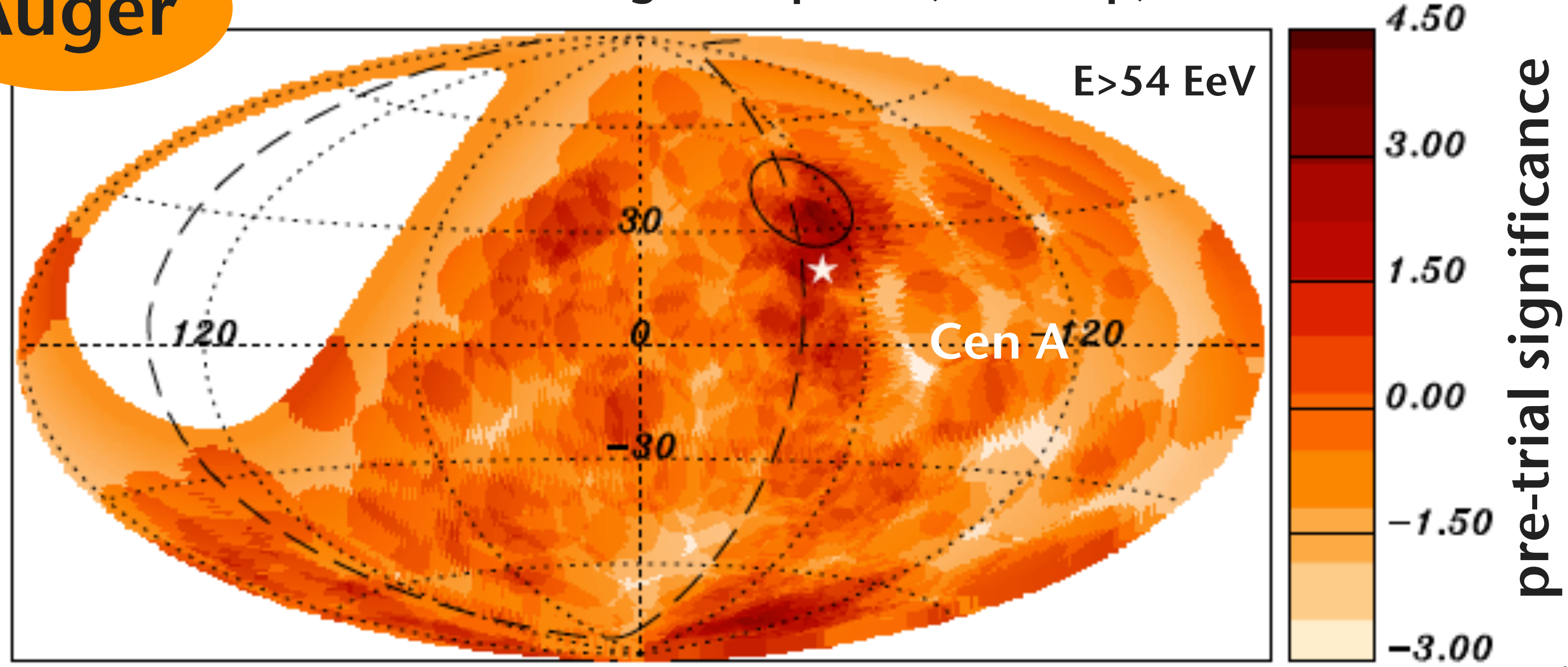


P. Tinyakov for TA Coll, ICRC 2015

post-trial significance ~3.4σ

post-trial: 69%

Auger 14 events - 12 degree top hat (3.23 exp)



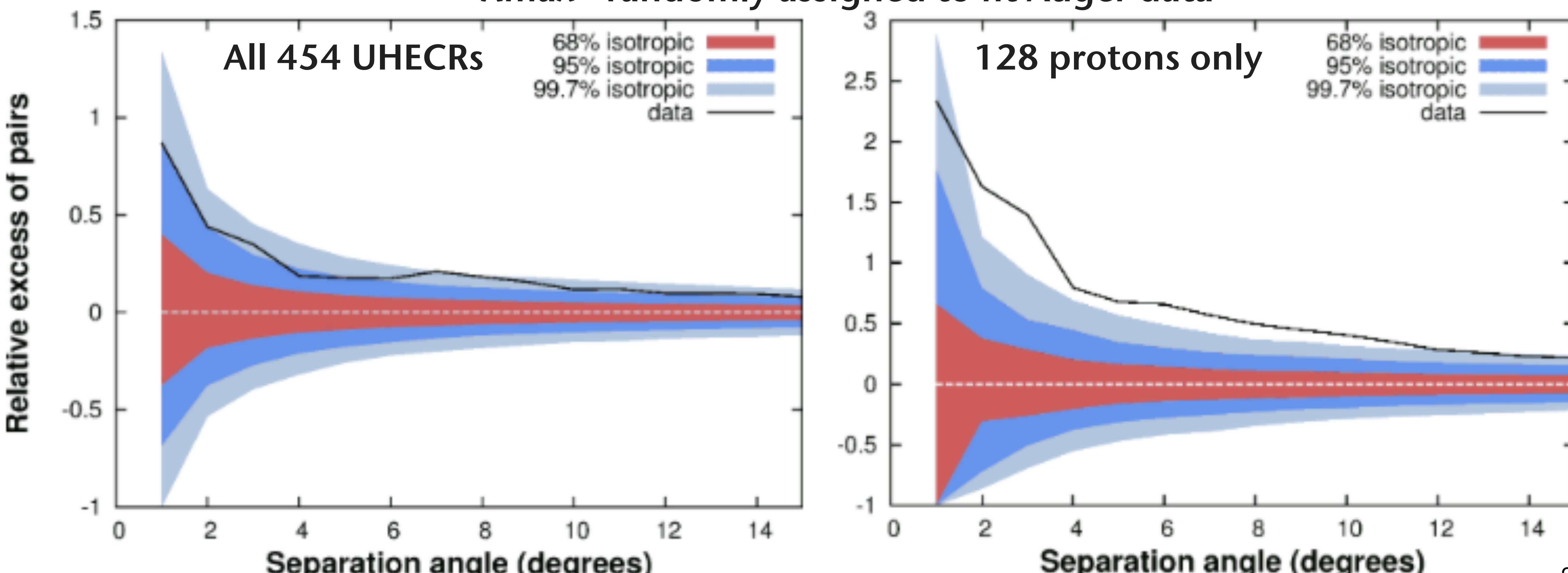
Auger Coll, A. Aab et al. 2015 ApJ, 804, 15

The future: AugerPrime

- Auger surface detector upgrade
- Run 2018-2024
- Composition information shower by shower

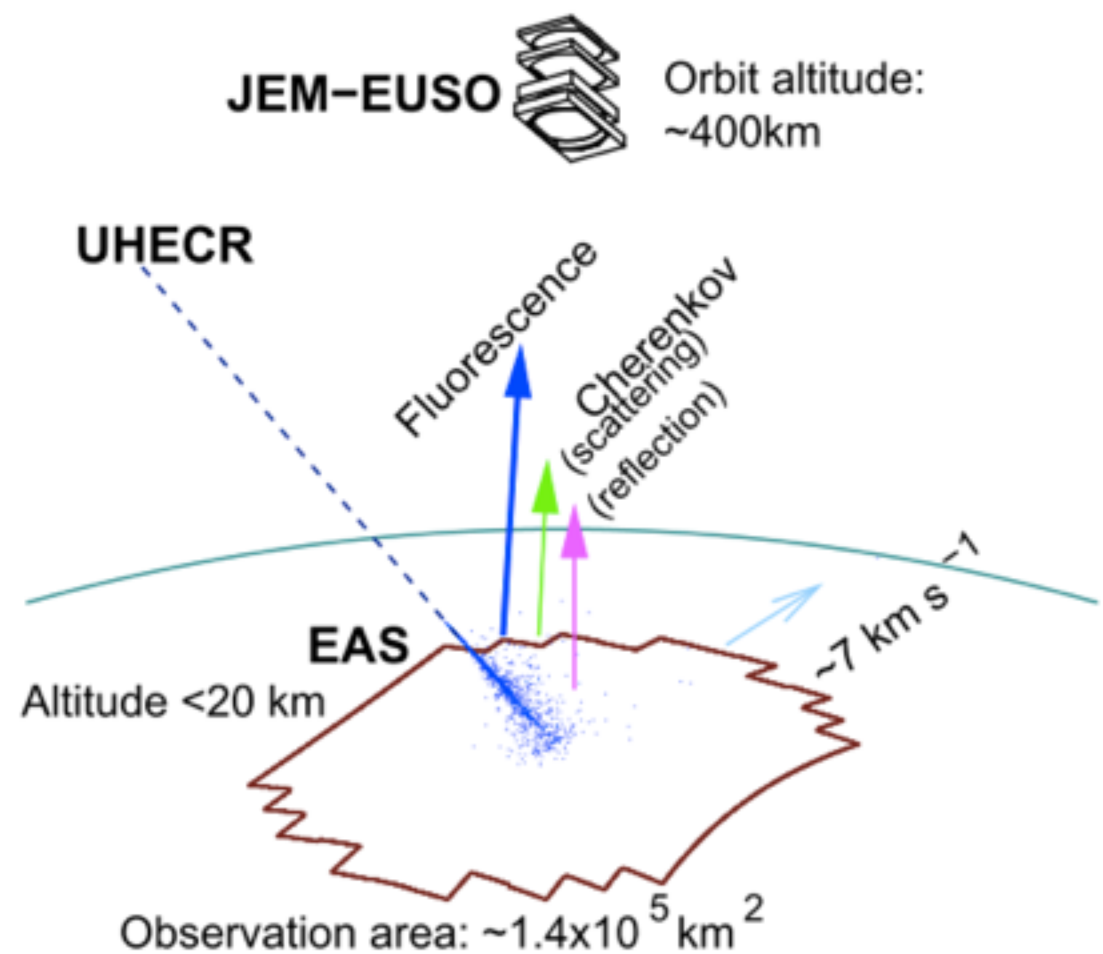
Are we going to detect anisotropy? ?

454 Auger UHECRs E≥40 EeV, 10% proton Xmax, 5% Swift-BAT AGN, θ ≤ 3°, d ≤ 100 Mpc
Xmax - randomly assigned to fit Auger data



The future: Will better statistics help?

e.g., go to space..



JEM-EUSO Coll. 2013-arXiv:1305.2478

Objectives for next generation instrument:

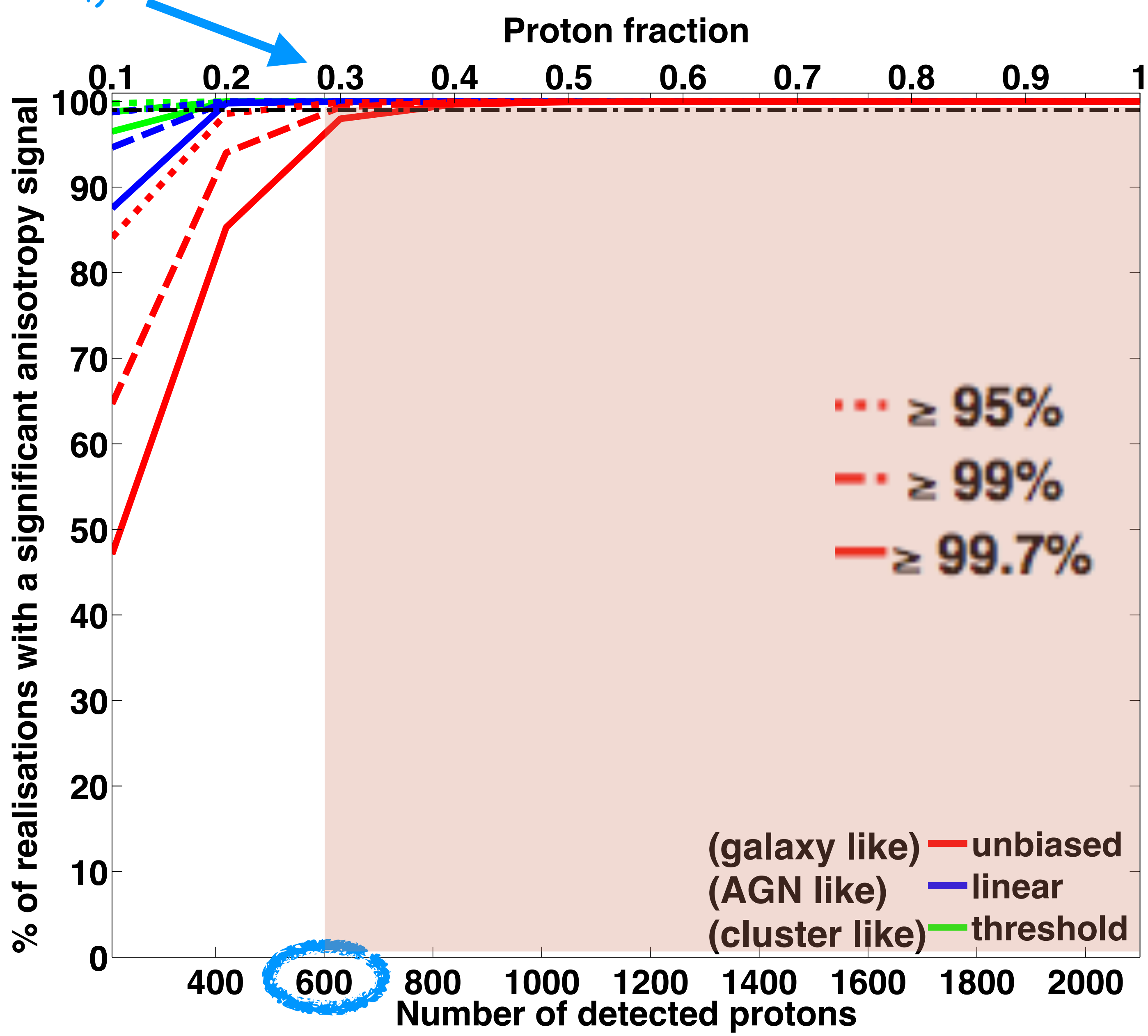
- 10 - 30 x Auger annual exposure
- 40 EeV < E < 1000 EeV
- 1000-2000 events/5 years

JEM-EUSO: Are we going to detect UHECR anisotropy?

2100 events, E>50 EeV, n_0 ~ 10^{-2} Mpc^{-3}

P(not isotropic | unbiased)> 99.7%

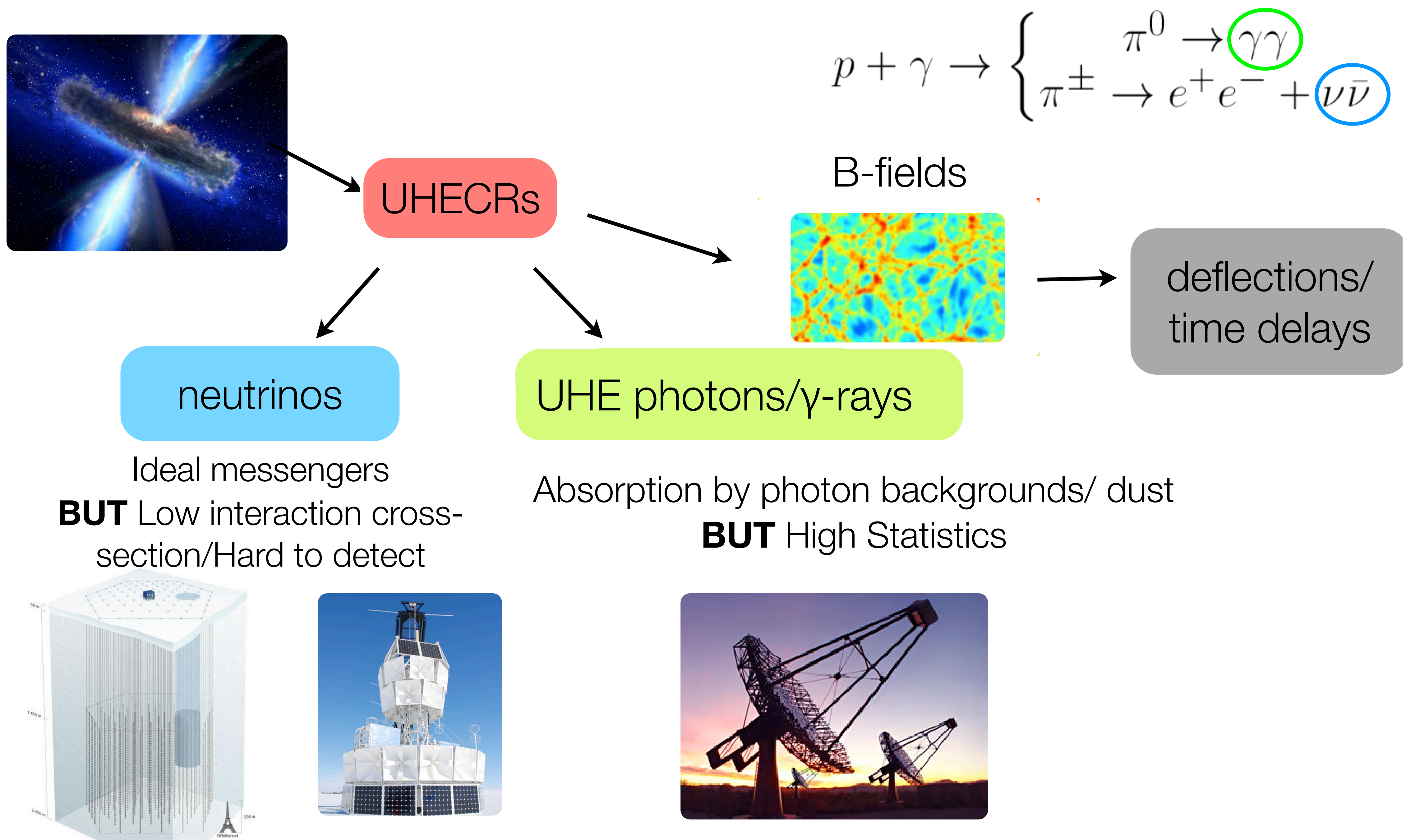
99% CL



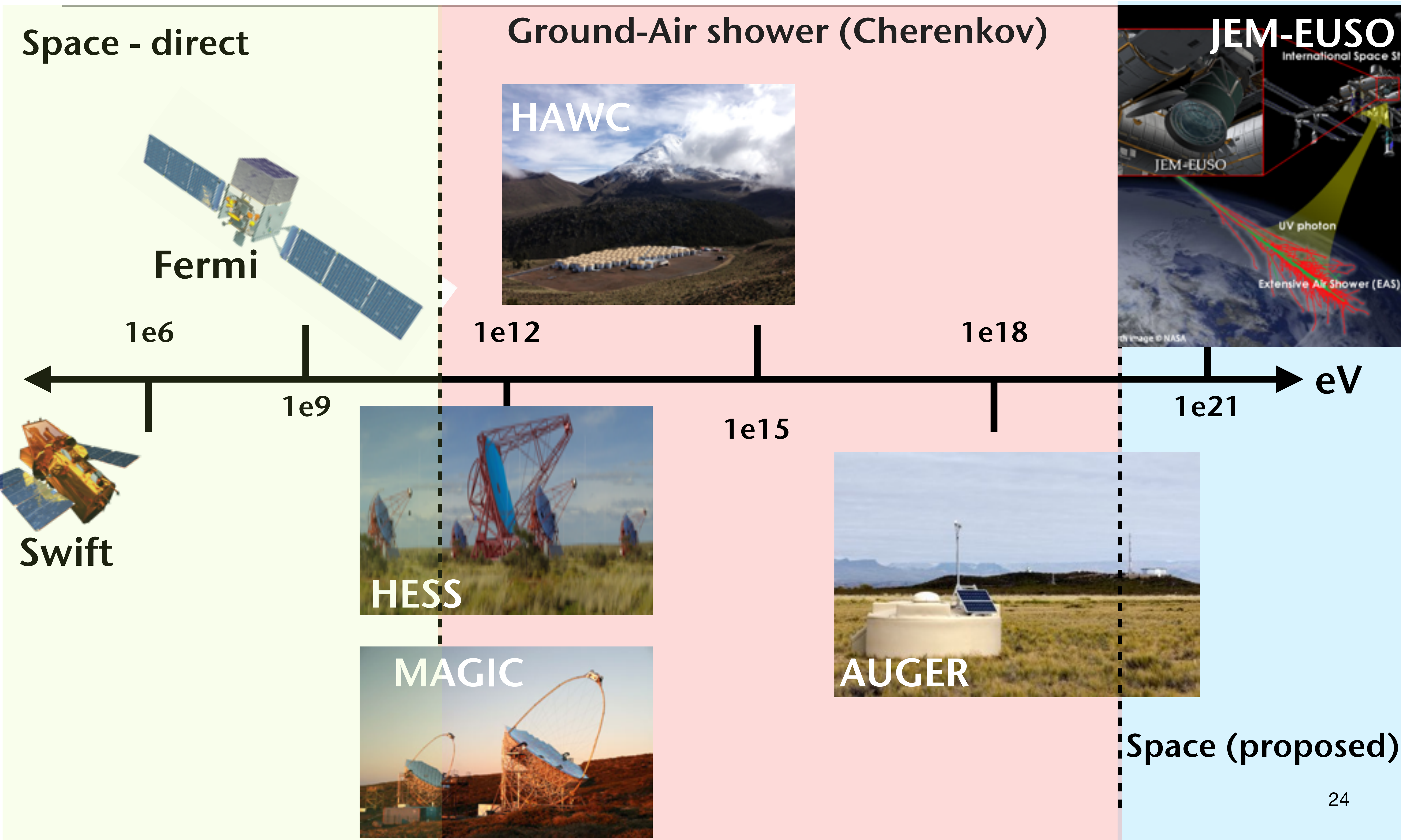
Yes!

With ≥600 protons

Looking for sources at UHE energies: Secondaries

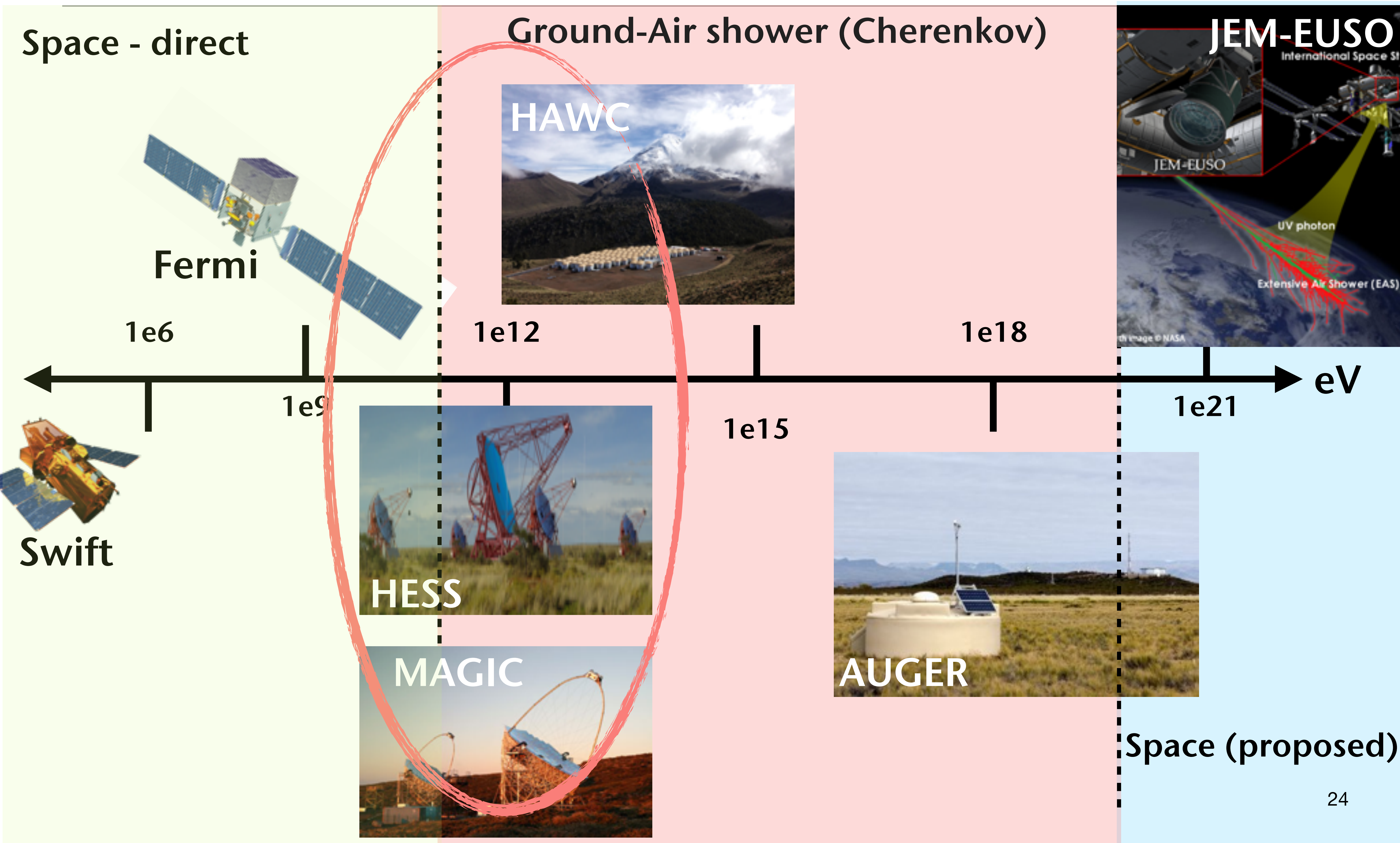


Photons



Space - direct
Ground-Air shower (Cherenkov)
JEM-EUSO
JEM-EUSO
UV photon
Extensive Air Shower (EAS)
HAWC
Fermi
Swift
1e6
1e9
1e12
1e15
1e18
1e21
eV
HESS
MAGIC
AUGER
Space (proposed)

Photons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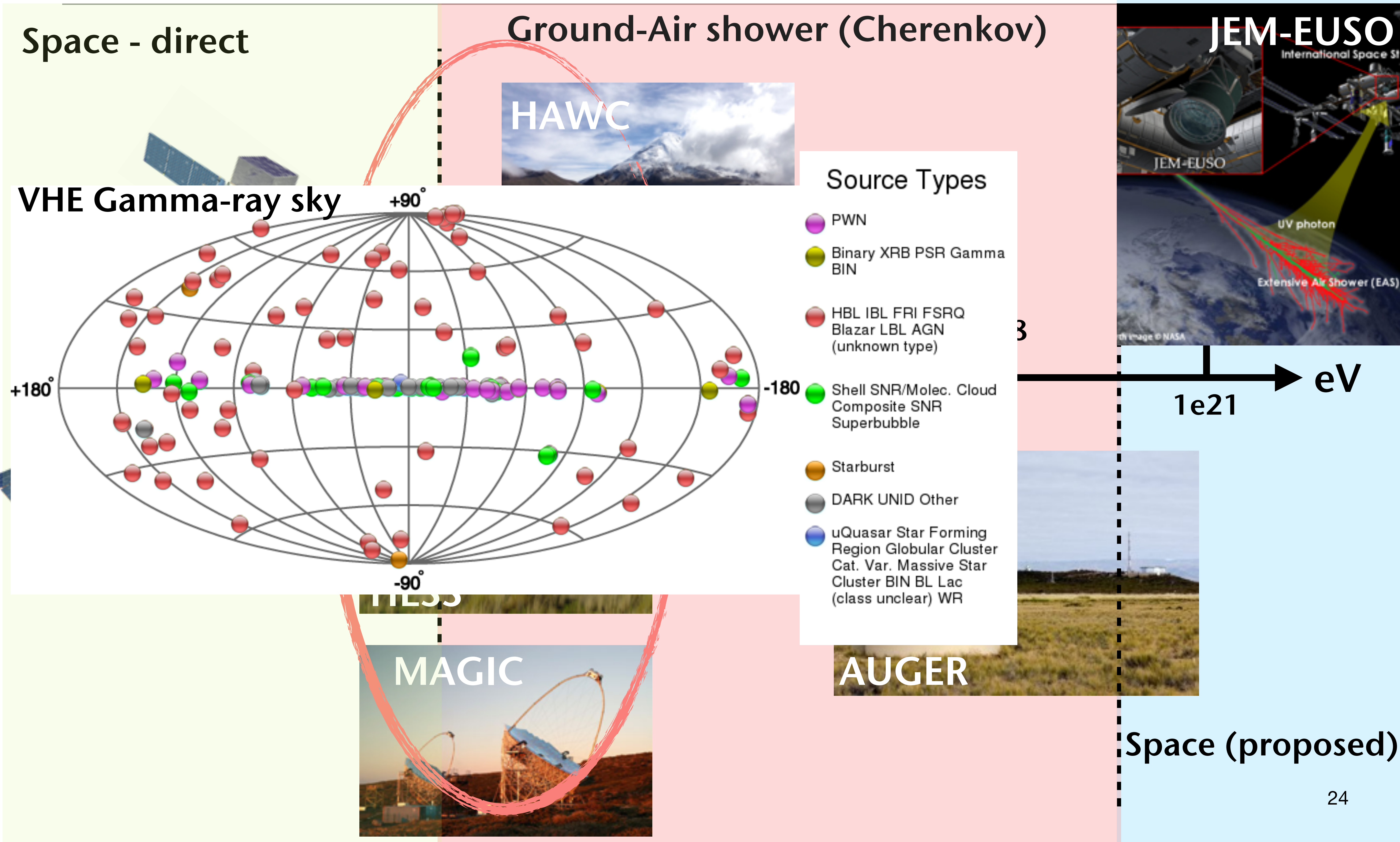
Photons



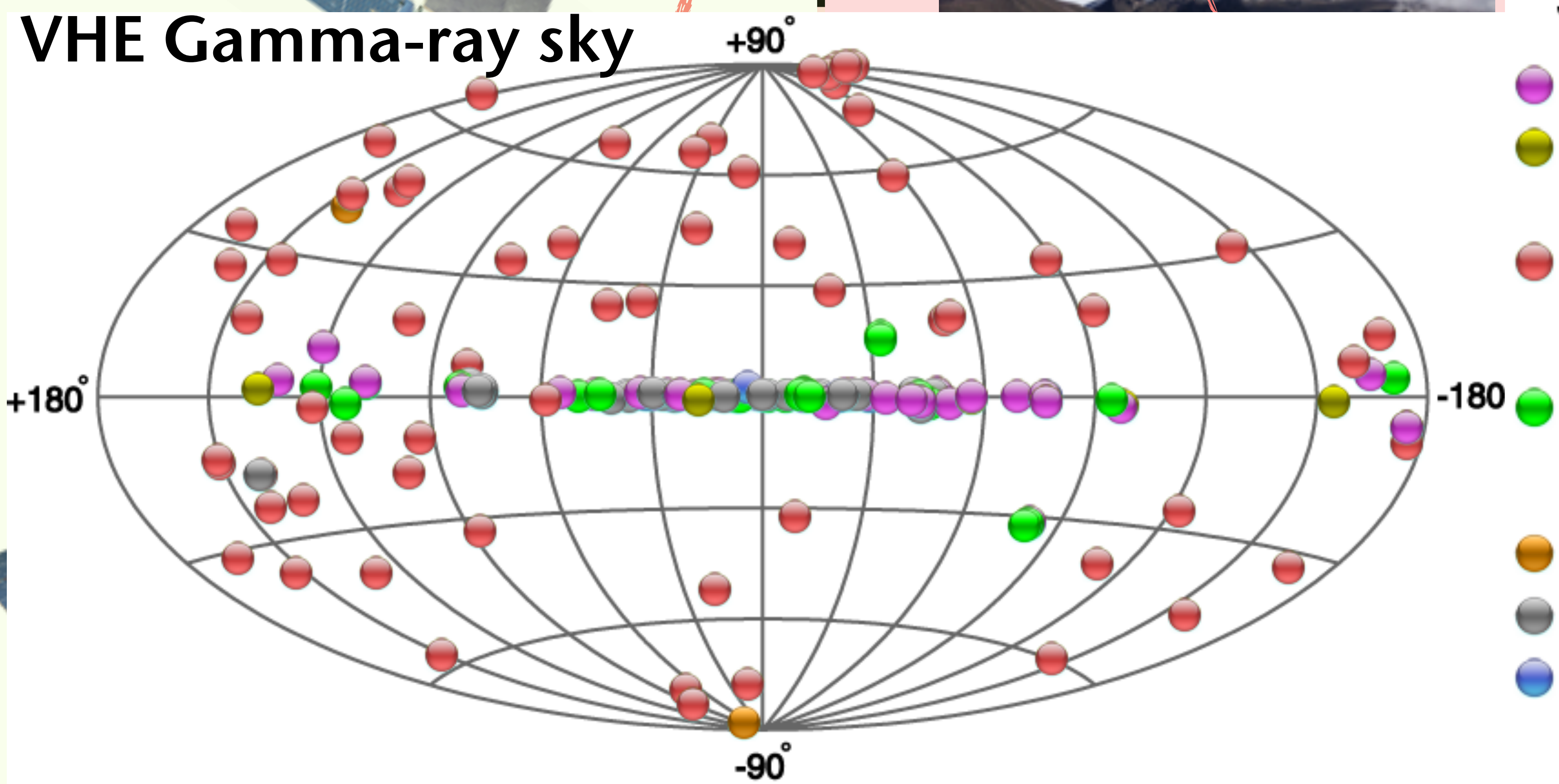
Space - direct
Ground-Air shower (Cherenkov)
JEM-EUSO
International Space St
JEM-EUSO
UV photon
Extensive Air Shower (EAS)
HAWC
VHE Gamma-ray sky
+90°
+180°
-180
-90°
Source Types
PWN
Binary XRB PSR Gamma BIN
HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
Shell SNR/Molec. Cloud Composite SNR Superbubble
Starburst
DARK UNID Other
uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR
eV
1e21
MAGIC
AUGER
Space (proposed)

Photons

Space - direct

Ground-Air shower (Cherenkov)

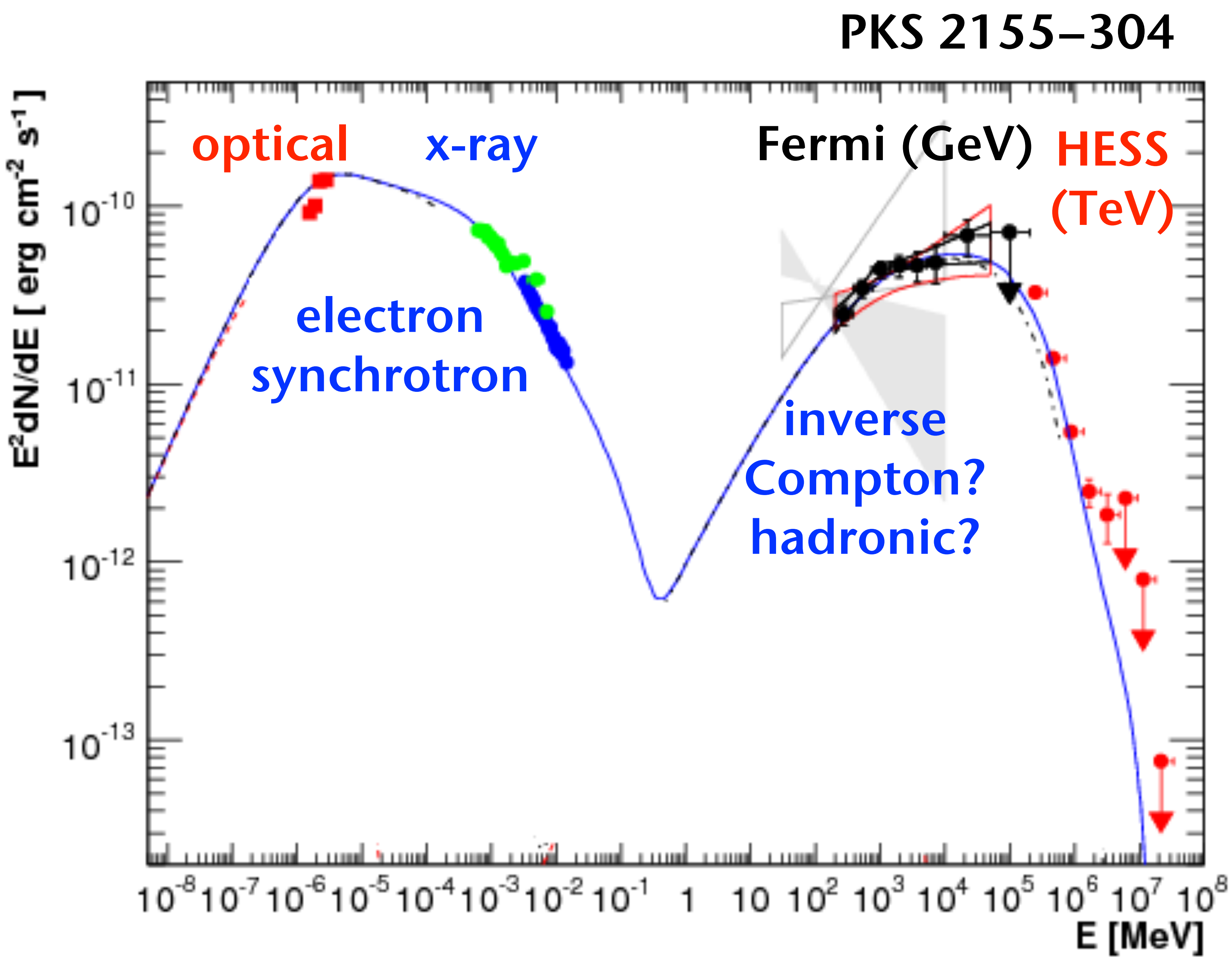
VHE Gamma-ray sky



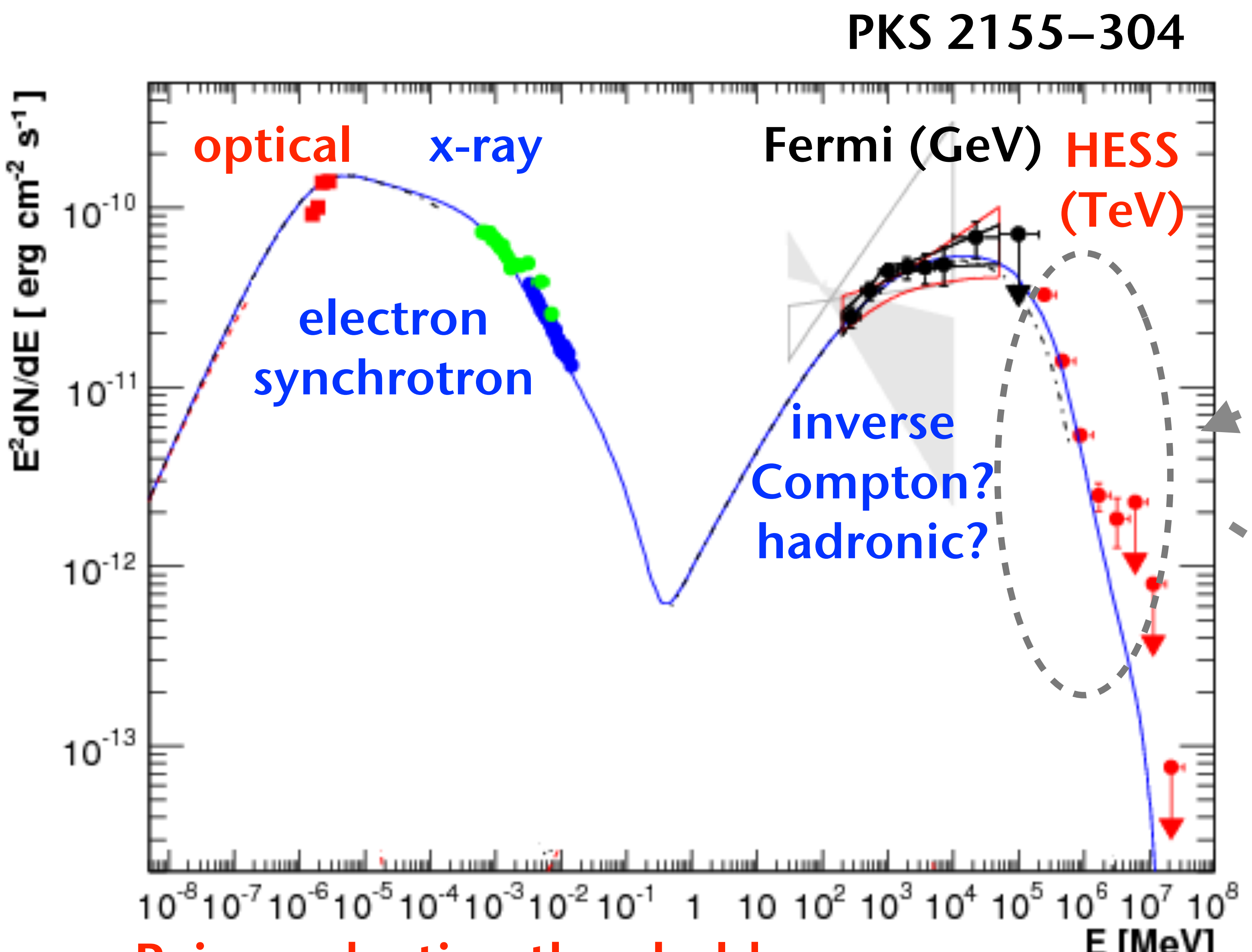
- AGN with jet face-on
- 90% of extragalactic γ-ray sources
- 50+ TeV blazars (see TeVCat)
- 1000+ in GeV [*2LAC, Fermi Coll 2011*]

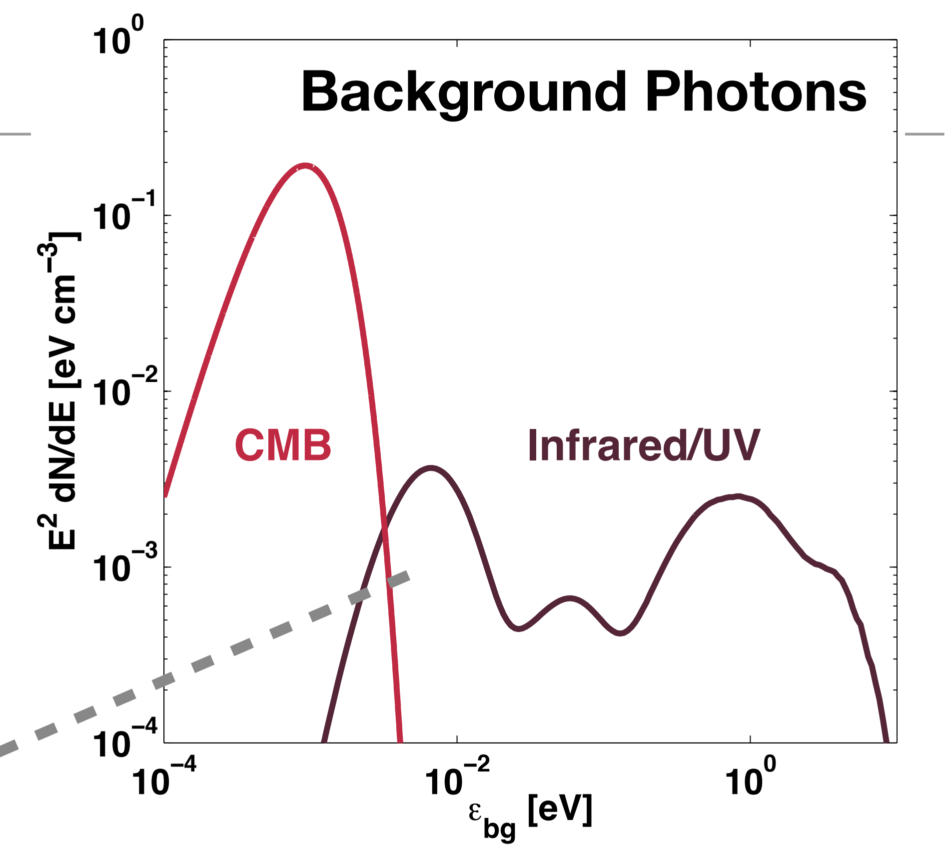
Space (proposed)

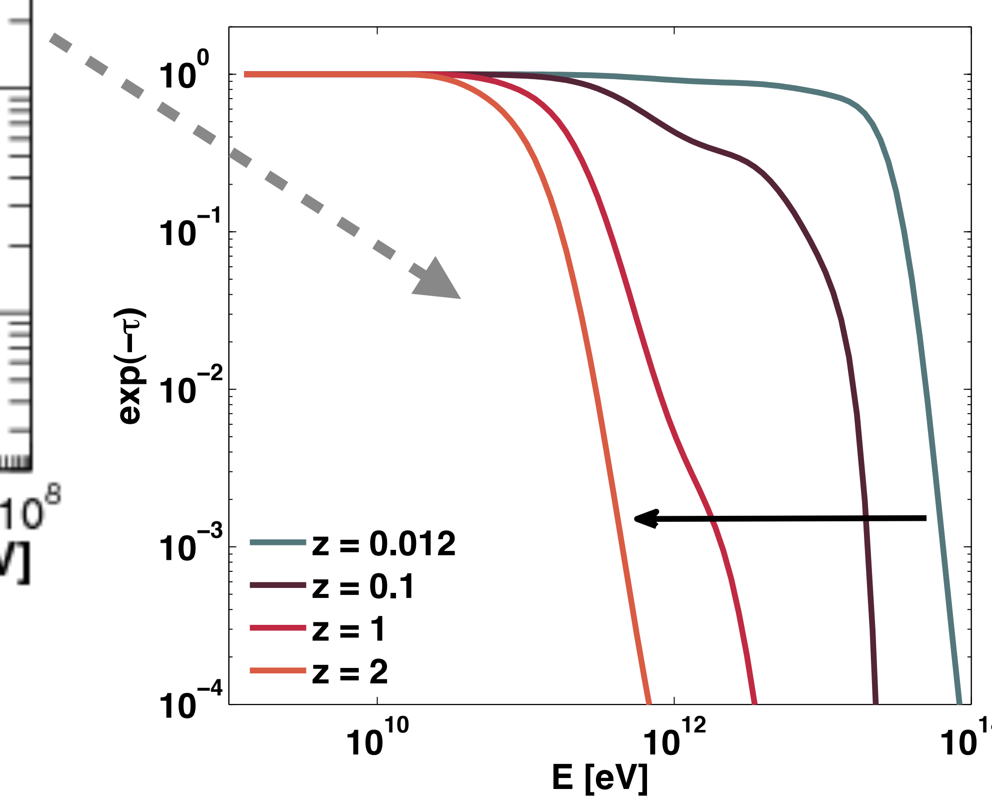
Blazar emission



Blazar emission



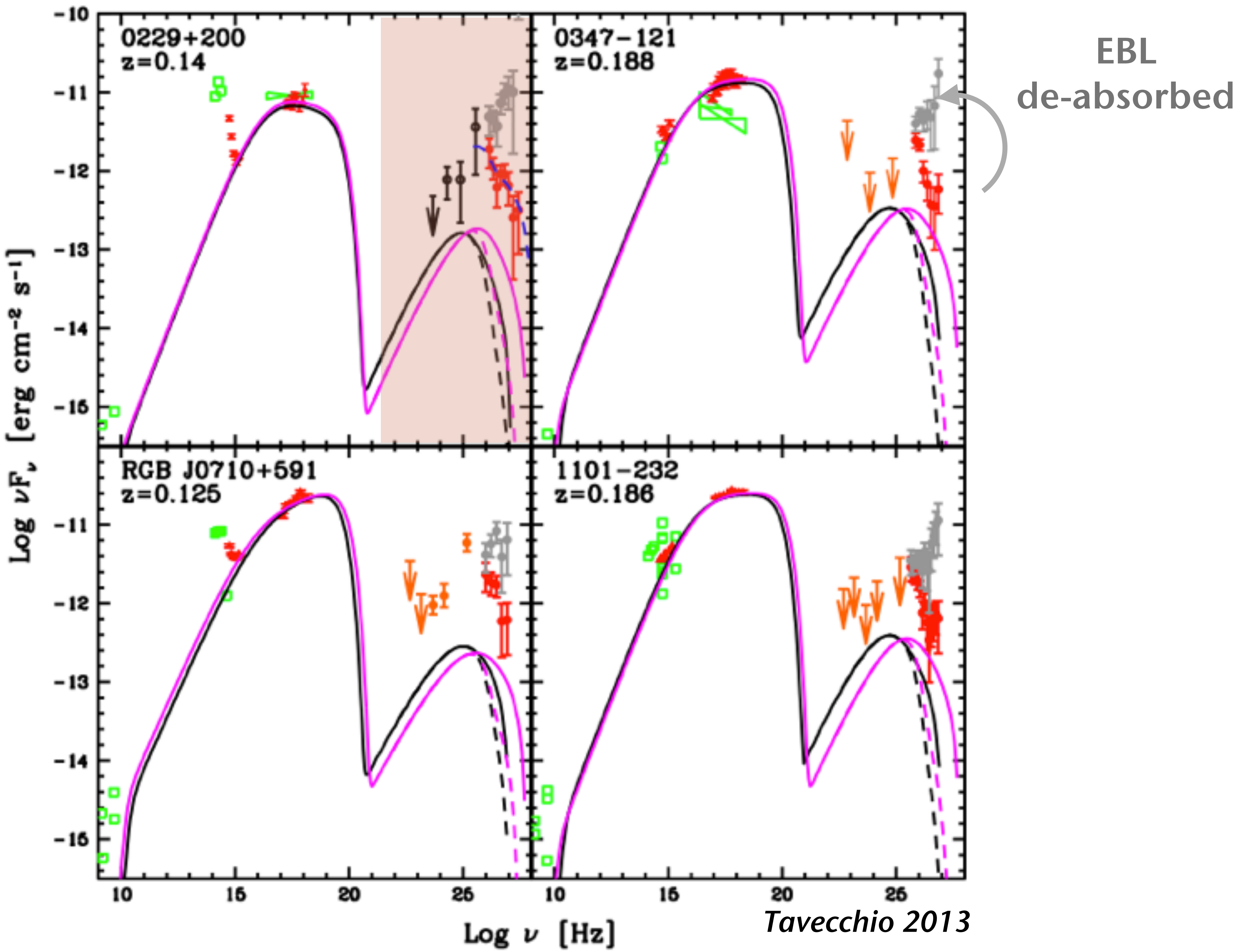




Pair production threshold:

$$E_\gamma = \frac{m_e^2}{\varepsilon_{\mathrm{background}}} \simeq 2.6\times10^{11}\ \mathrm{eV}\left(\frac{\varepsilon_{\mathrm{background}}}{1\ \mathrm{eV}}\right)$$

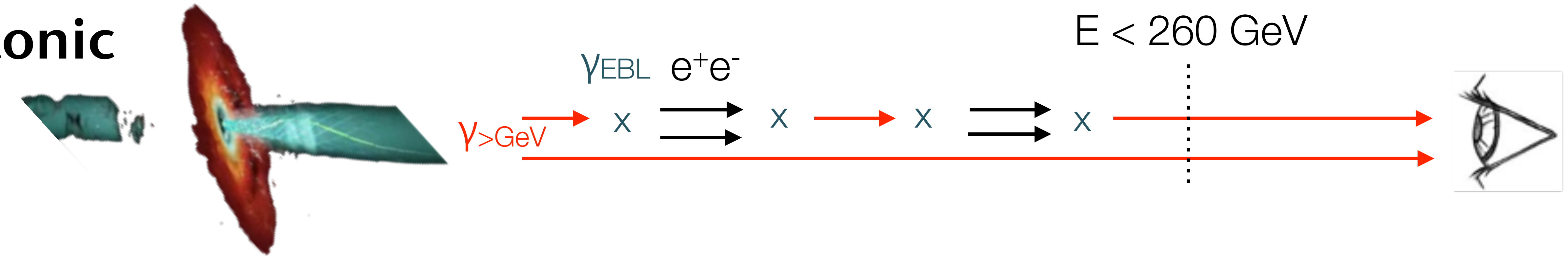
Extreme Hard-Spectrum TeV Blazars



Tavecchio 2013

Blazar TeV emission

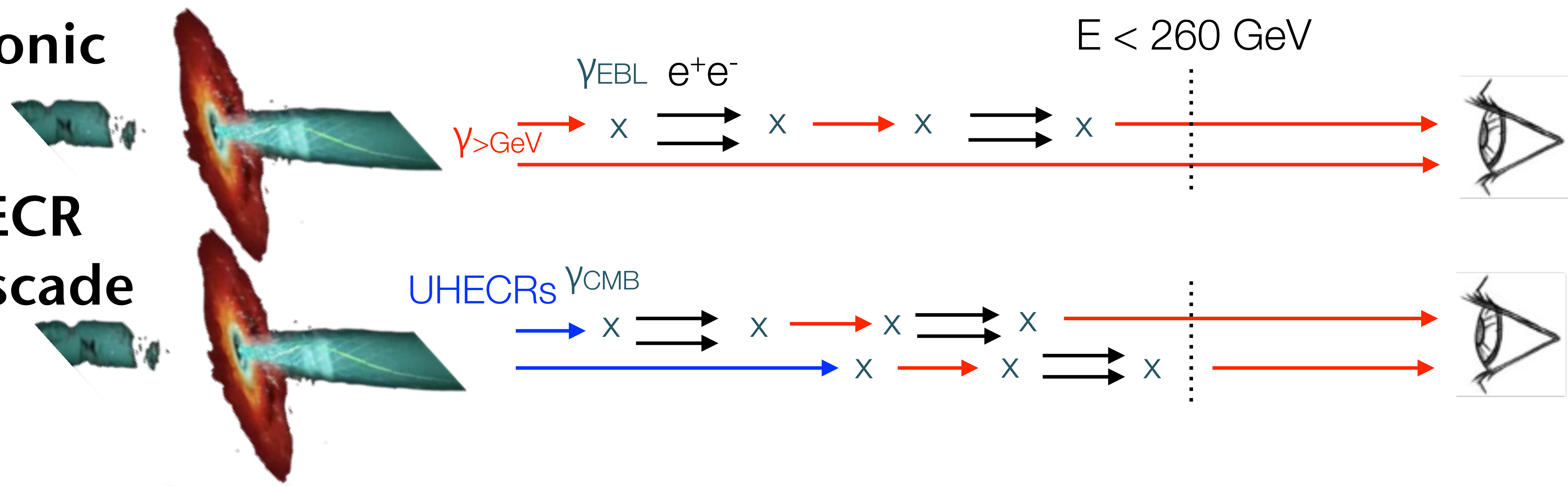
Leptonic



Blazar TeV emission

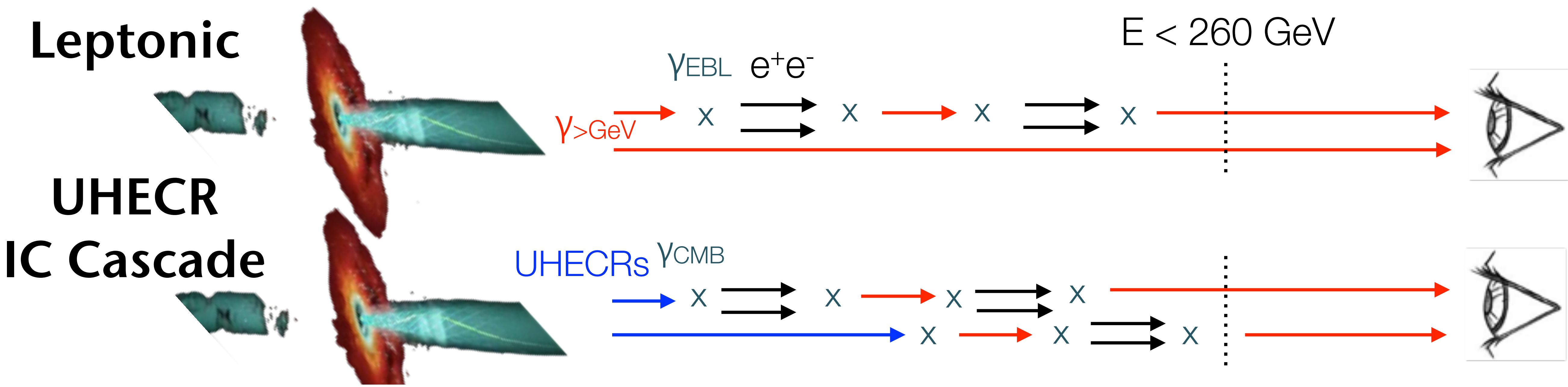
Leptonic

UHECR IC Cascade

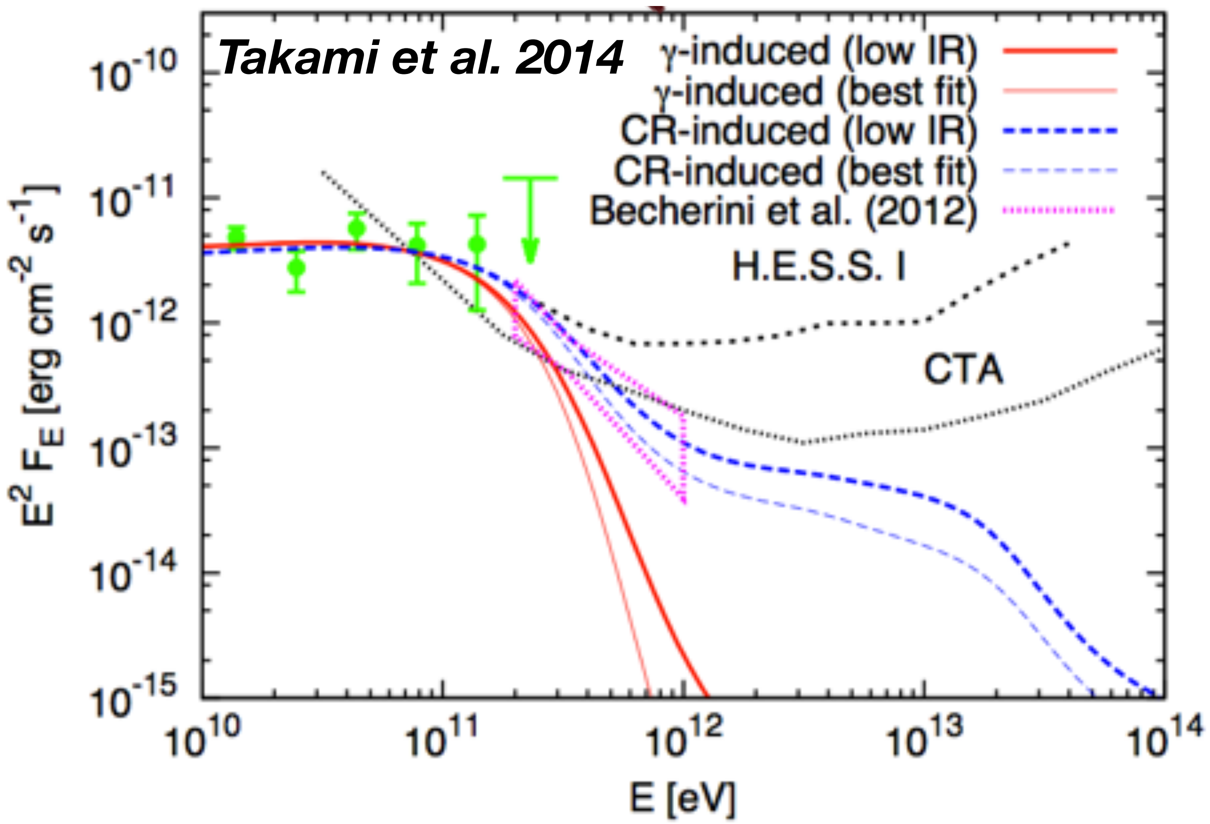


e.g., Essey et al 2010a,b, Murase et al 2012, Tavecchio 2014…

Blazar TeV emission

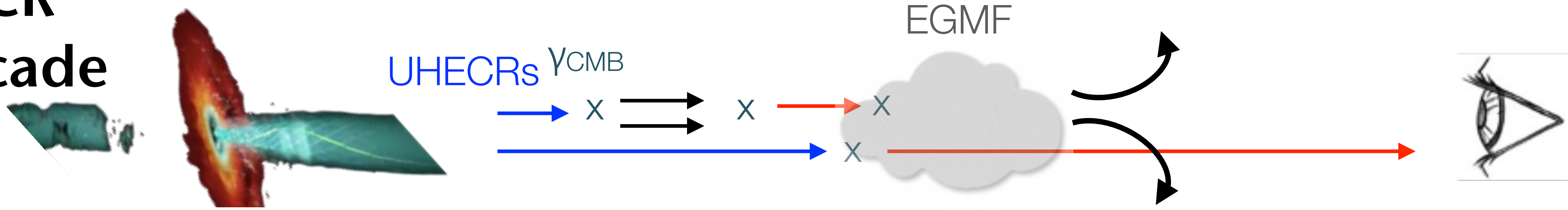


e.g., KUV 00311–1938 (z = 0.61)



Blazar TeV emission

UHECR IC Cascade



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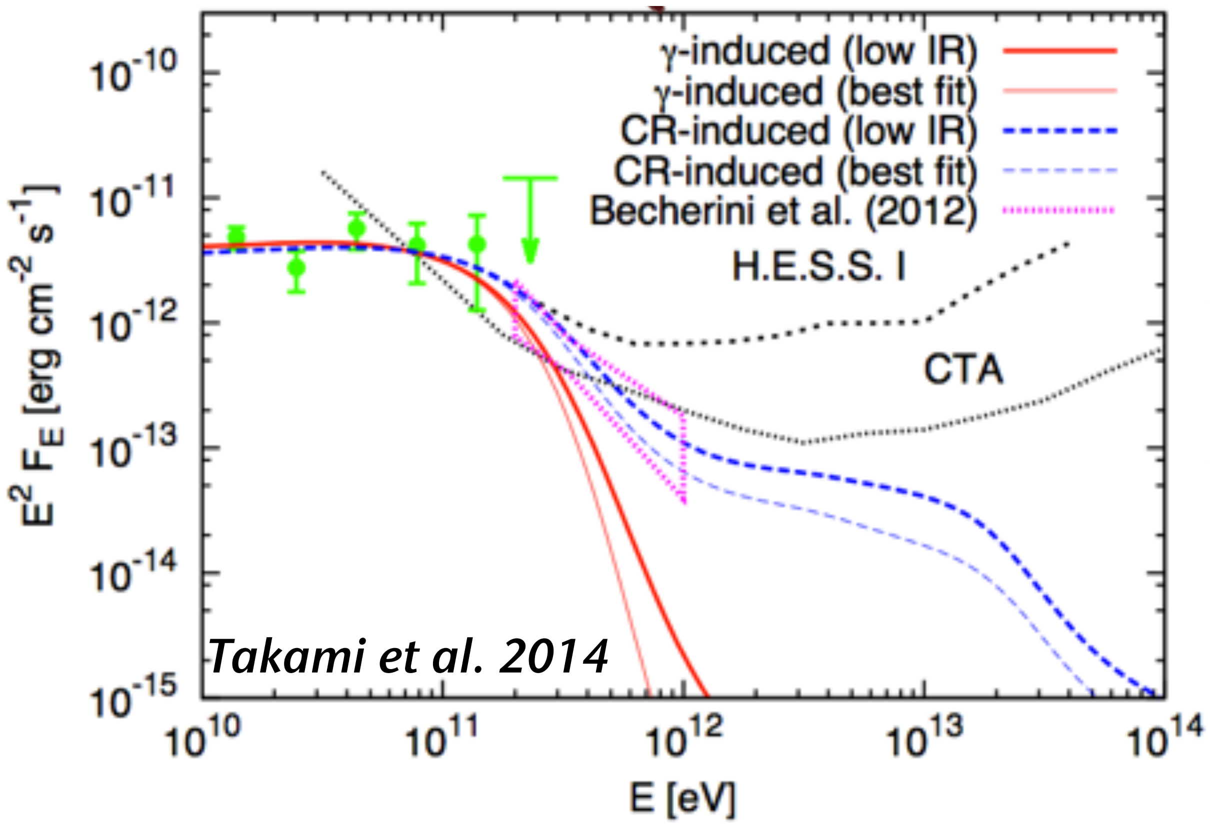


NB **IGMFs may significantly dilute emission!**

$$E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} = f_{1d}(B_\theta)\,\chi_e \frac{L_{\rm cr}}{8\pi d^2}\left(\frac{E_\gamma}{E_{\gamma,\max}}\right)^{1/2}$$

Arriving energy flux, *Kotera, Allard, Lemoine 2011*

Fraction of Universe where $B_{IGMF} \gtrsim 10^{-13}$ G

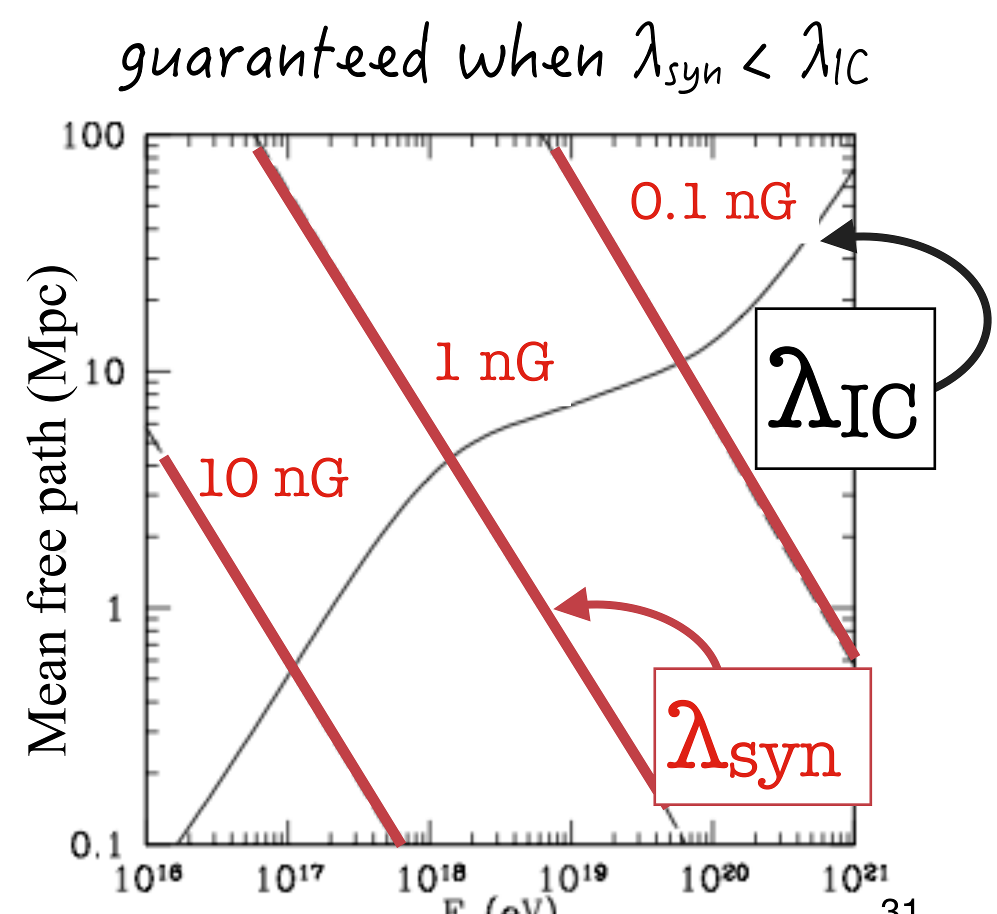
FO, Murase, Kotera, A&A 568, A110 (2014)

Secondary UHECR synchrotron emission

UHECR seeded synchrotron:

Gabici, Aharonian 2005,7
Kotera, Allard, Lemoine 2011

filament/galaxy cluster
B > nG
typically ~few Mpc

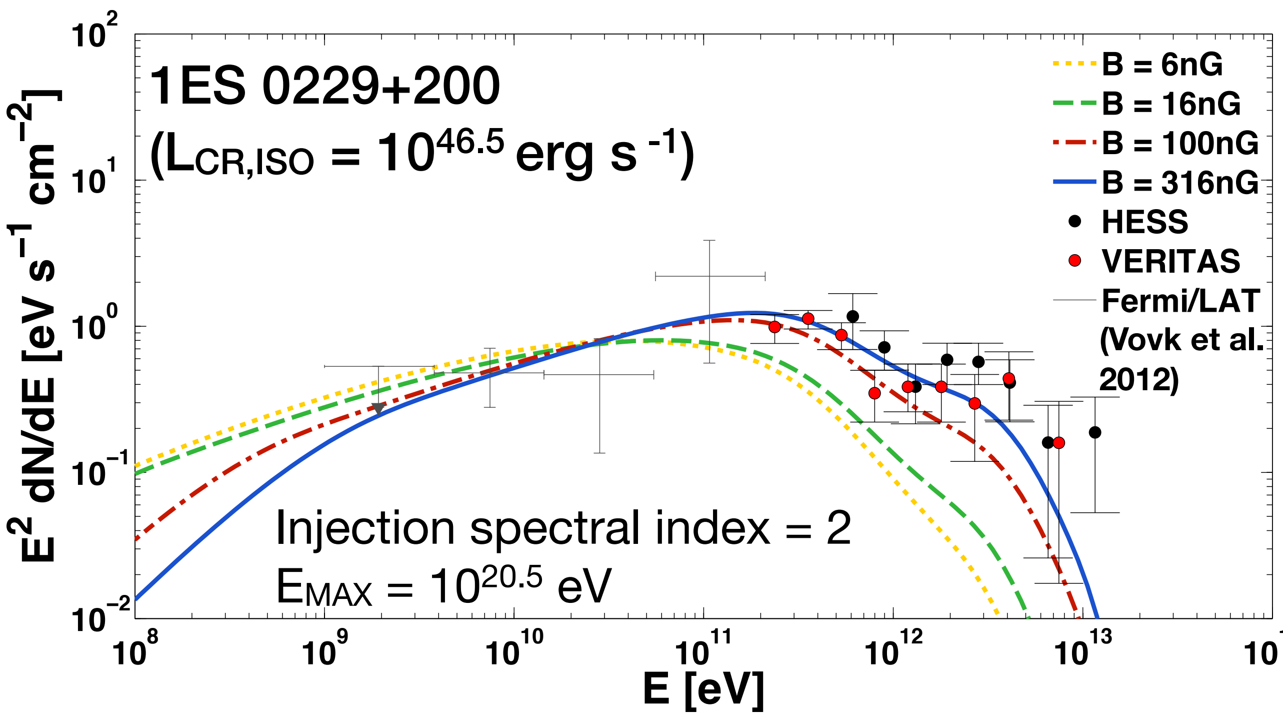


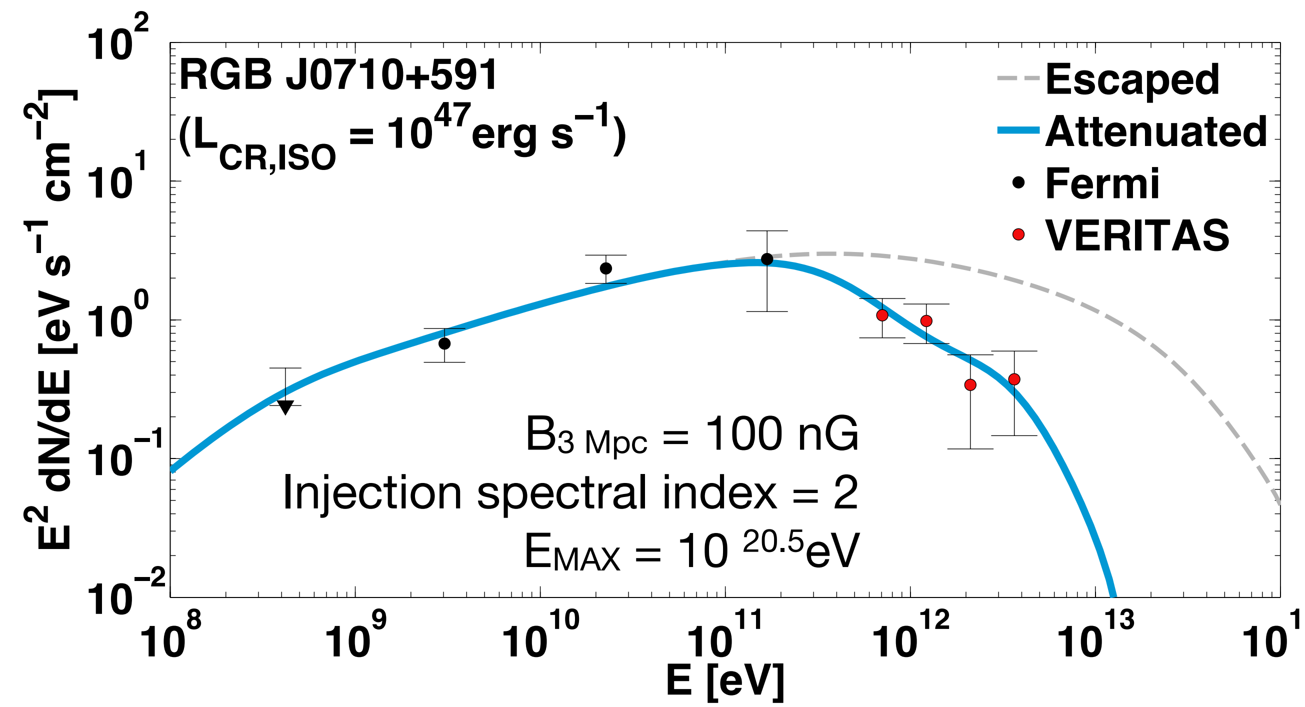
Peak synchrotron energy:

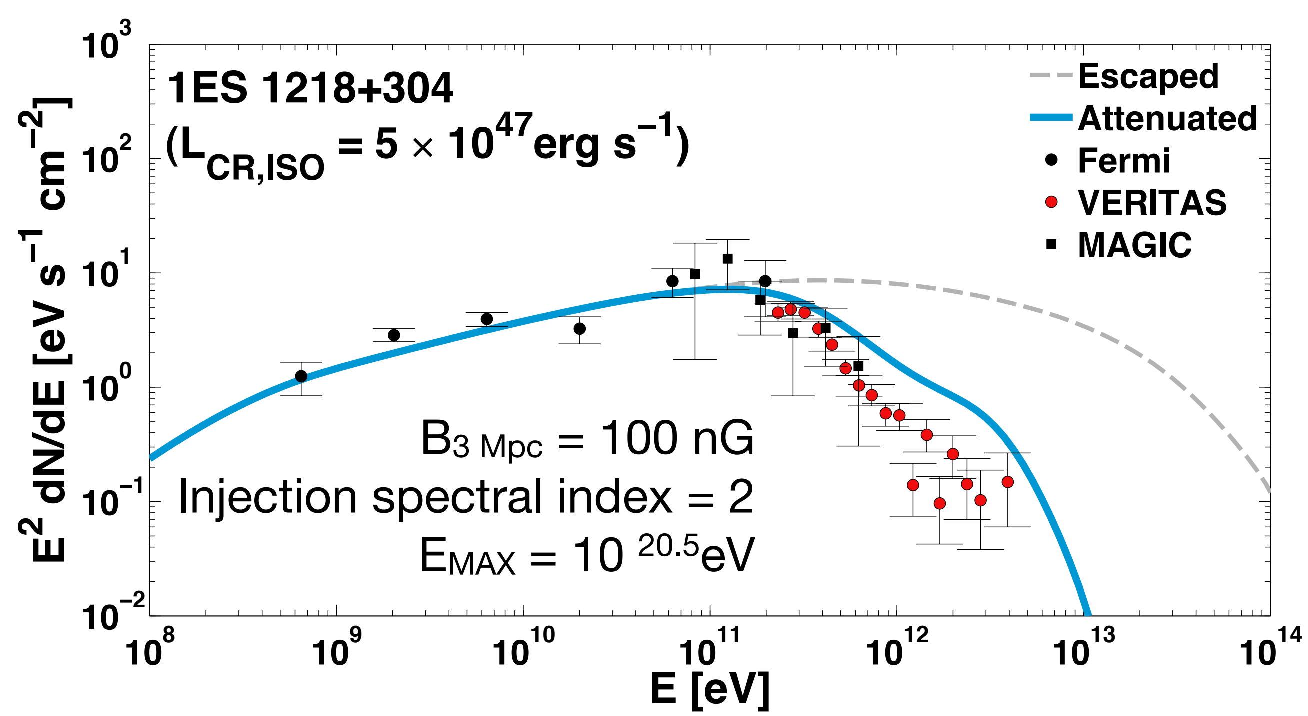
$$E_{\gamma,\mathrm{syn}} \sim 68\ \mathrm{GeV} \left(\frac{\mathrm{B}}{10\ \mathrm{nG}}\right)\left(\frac{\mathrm{E_e}}{10^{19}\ \mathrm{eV}}\right)^2$$

FO, Murase, Kotera, A&A 568, A110 (2014)

UHECR synchrotron pair echo/halo

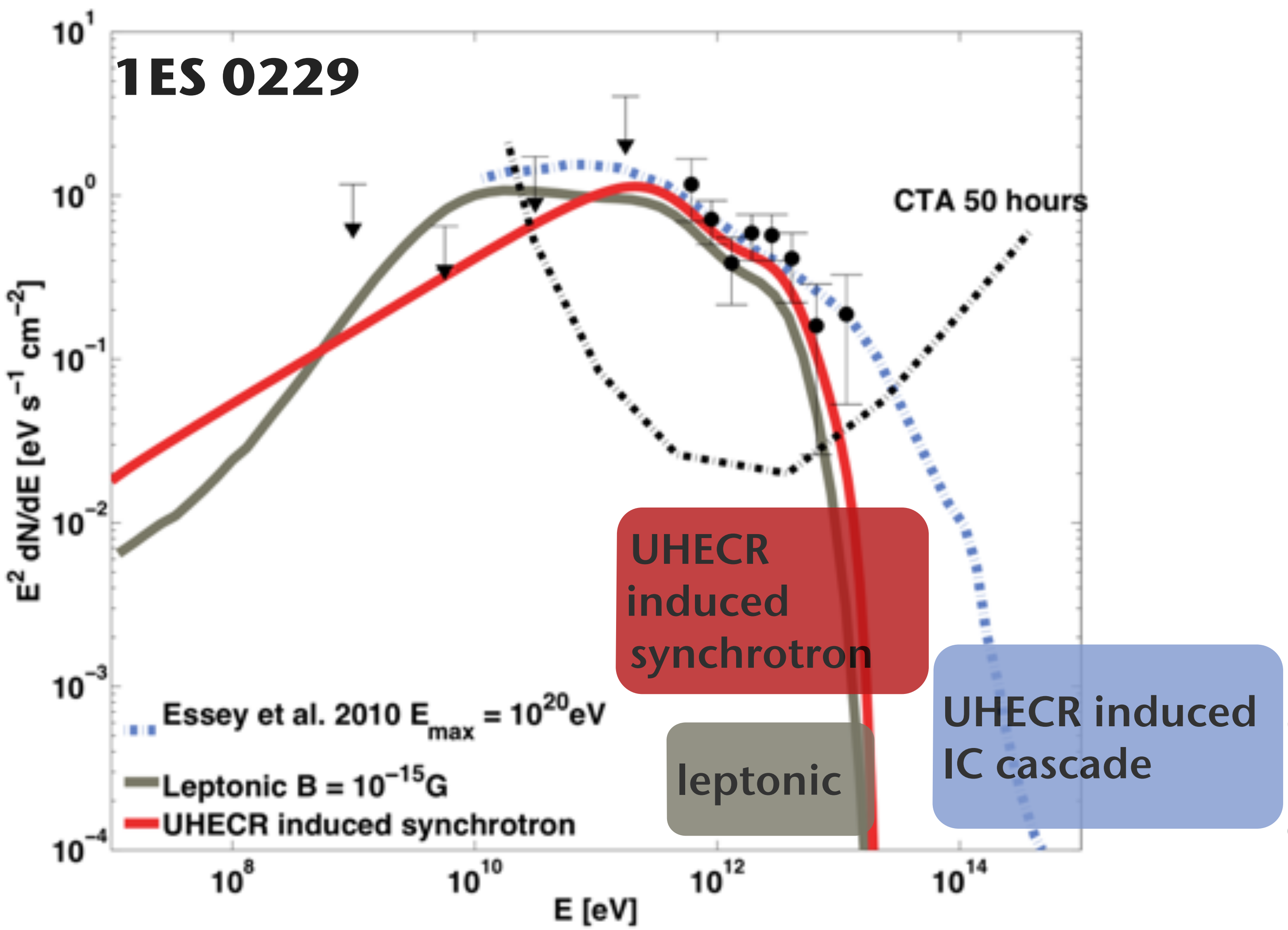




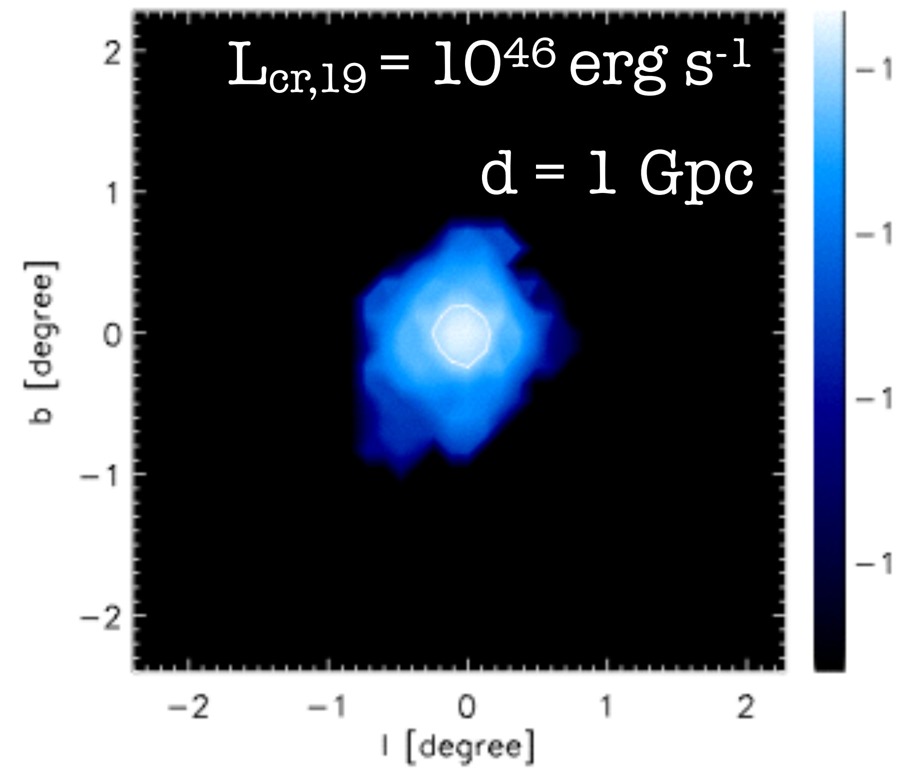


FO, Murase, Kotera, A&A 568, A110 (2014)

How will we establish if UHECR emission?



Kotera, Allard, Lemoine 2011



OR:

Correlated/rapid variability [leptonic/UHE neutral emission]

UHECR signatures:

TeV tail - UHECR IC/high redshift

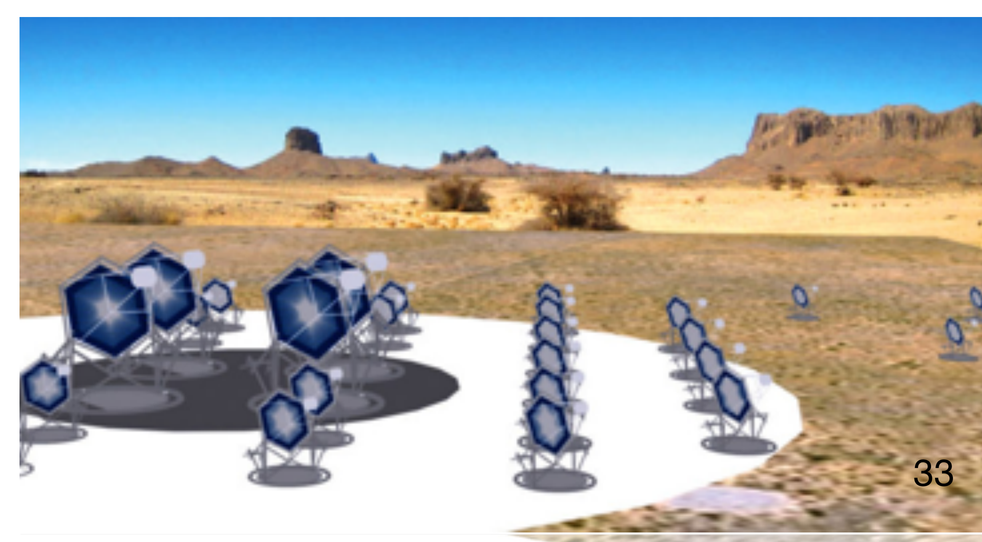
Halo energy dependence/spatial extension

Orphan flares

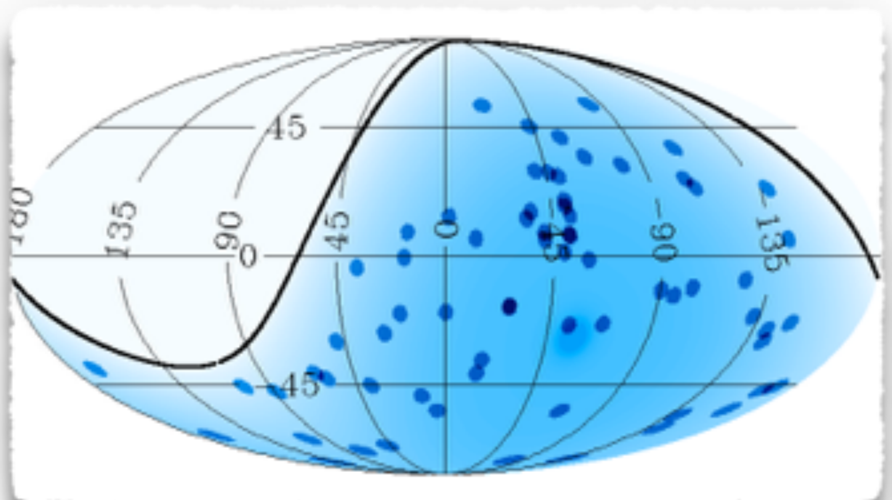
Fermi,

HAWC,

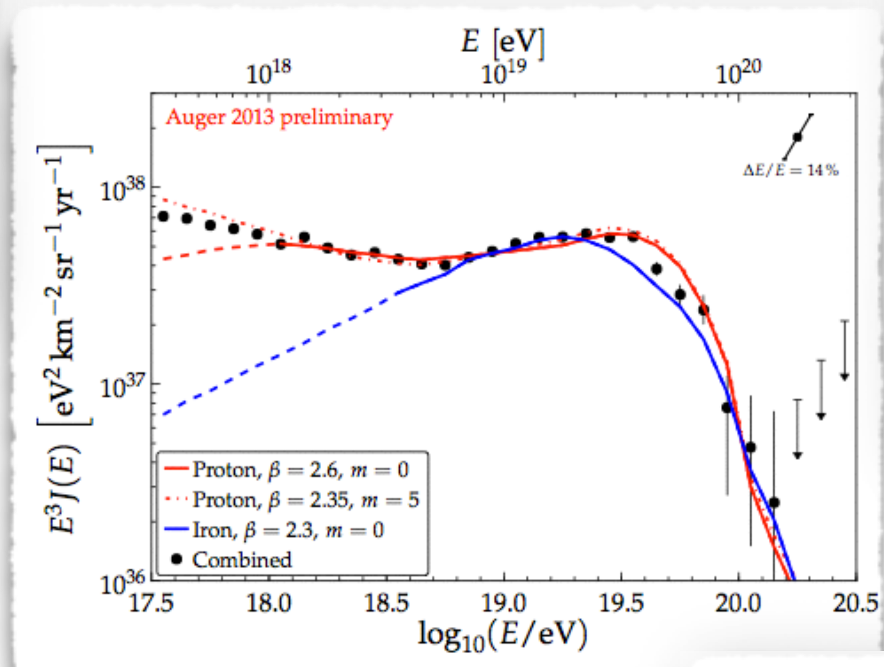
CTA!



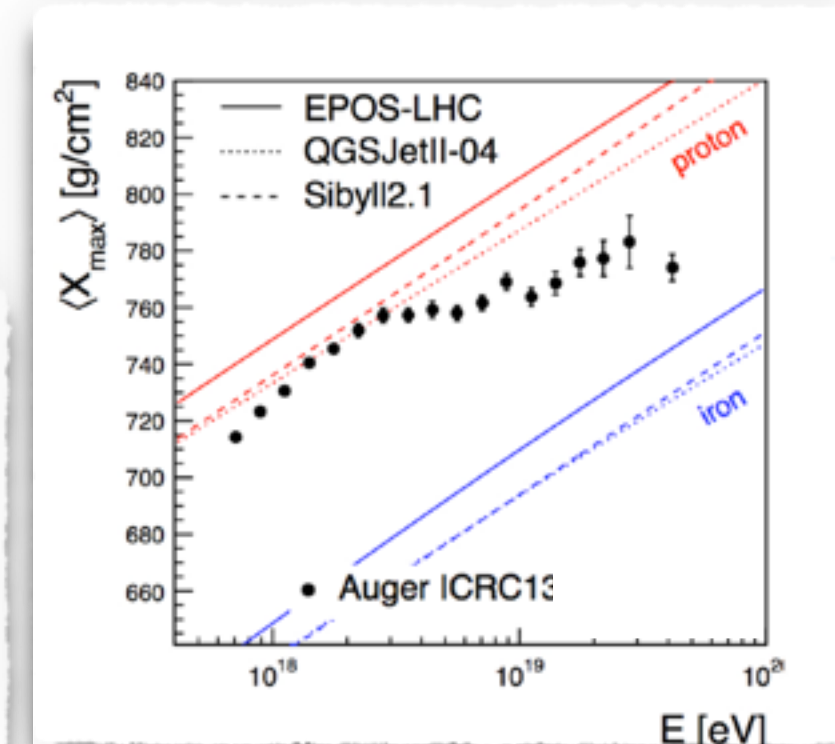
Arrival directions



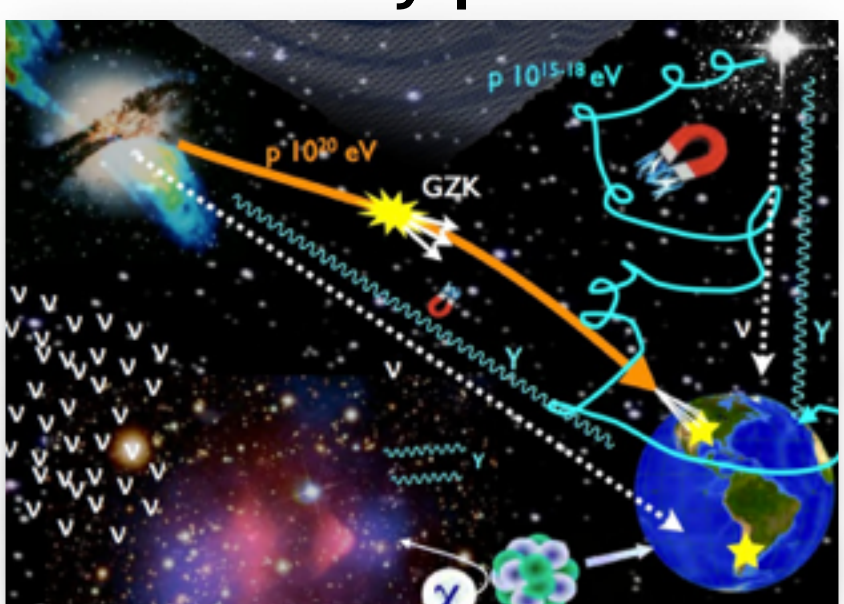
Spectrum/energetics



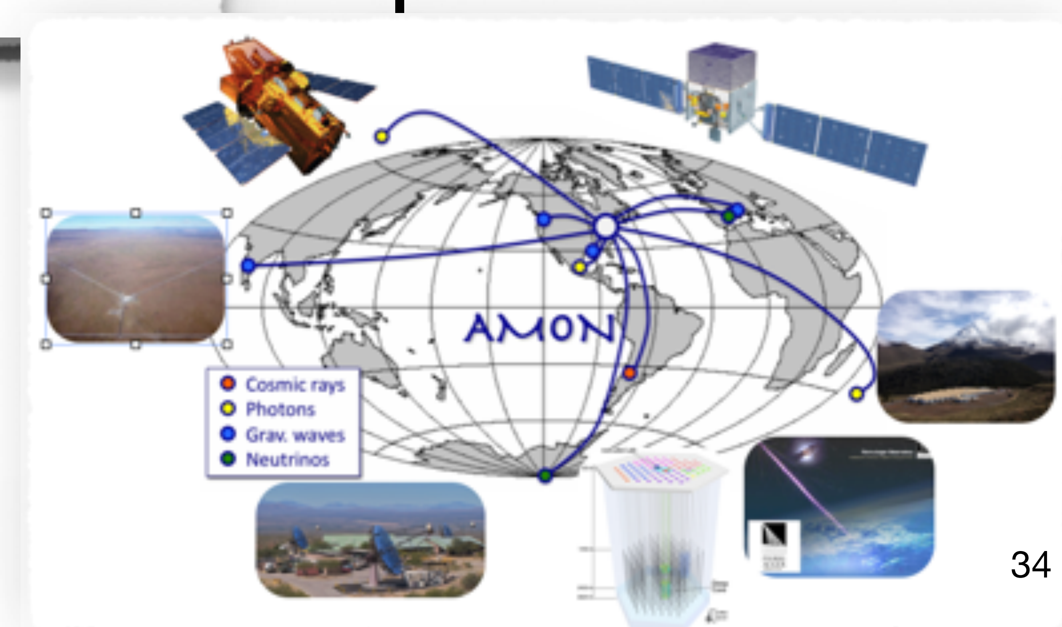
Composition



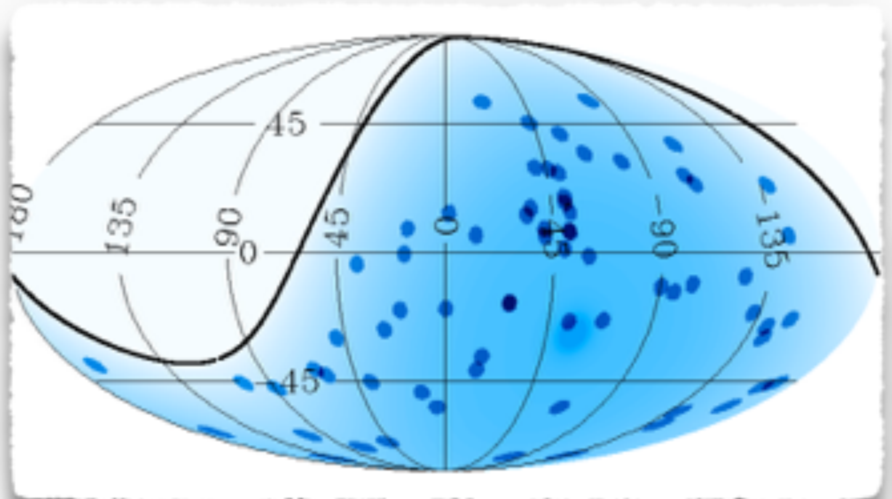
Secondary products



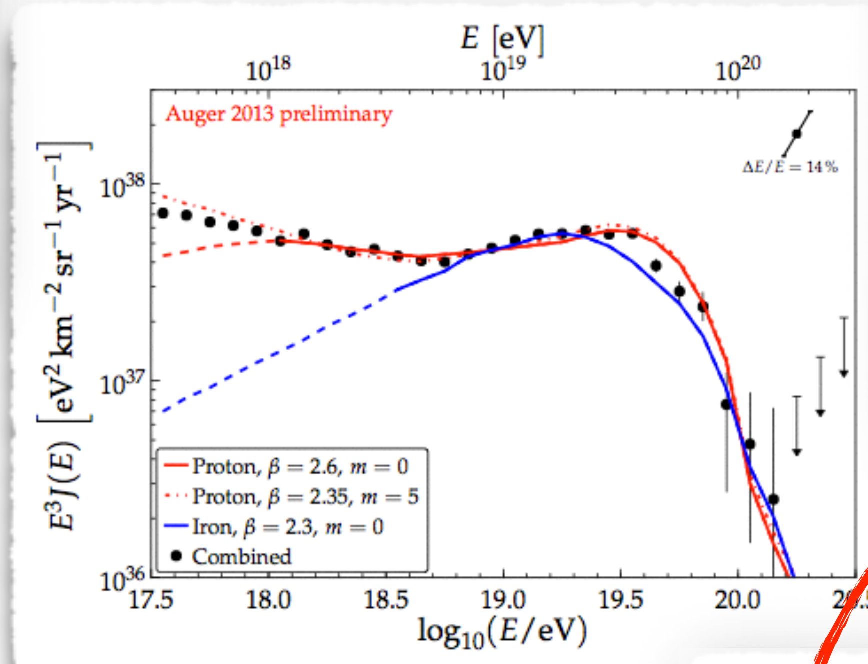
Multi-messenger temporal coincidences



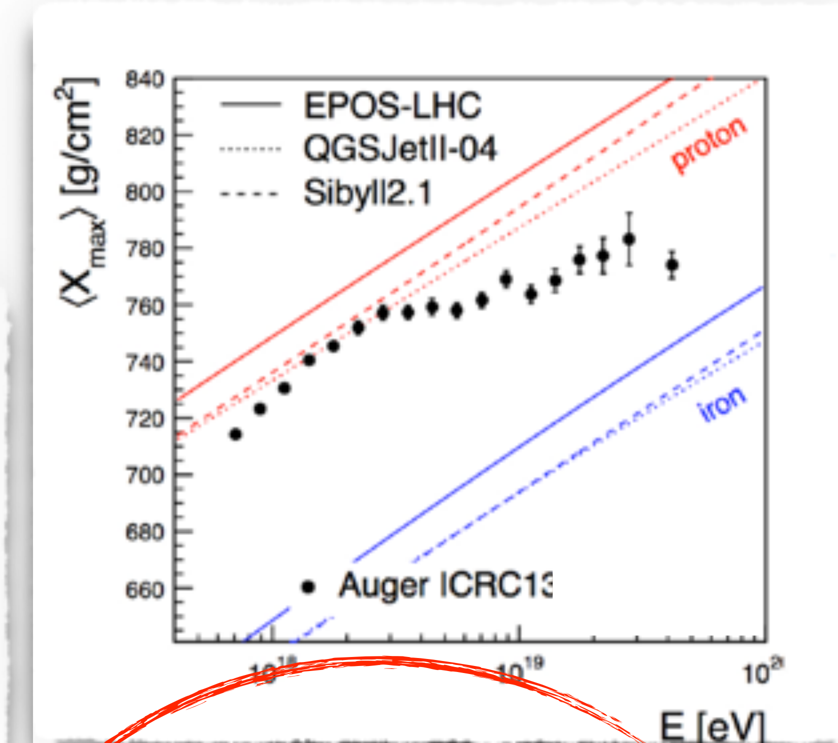
Arrival directions



Spectrum/energetics

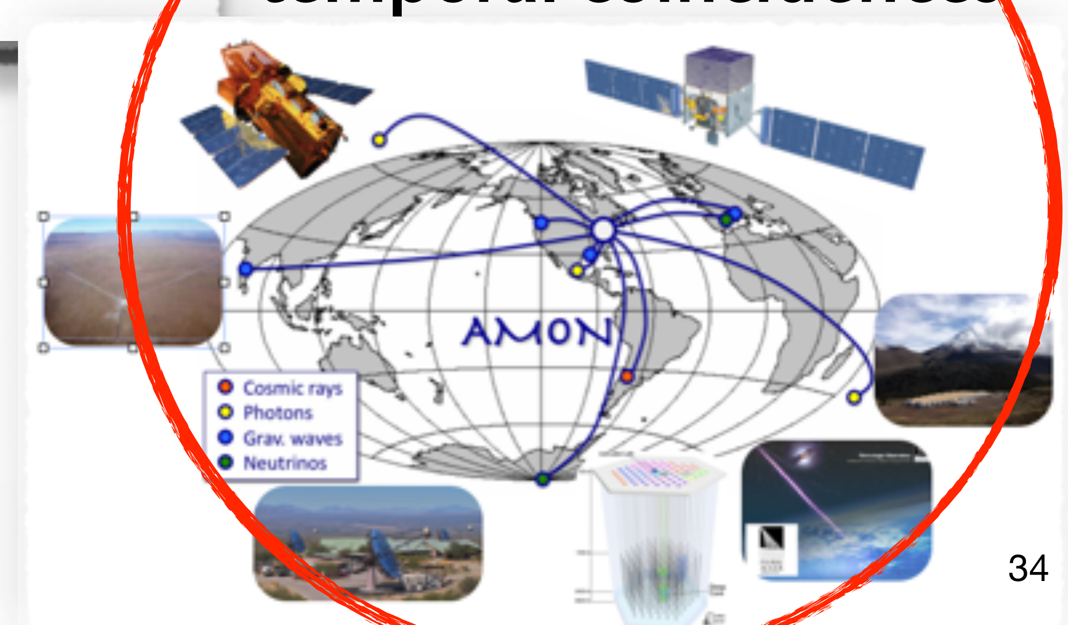


Composition

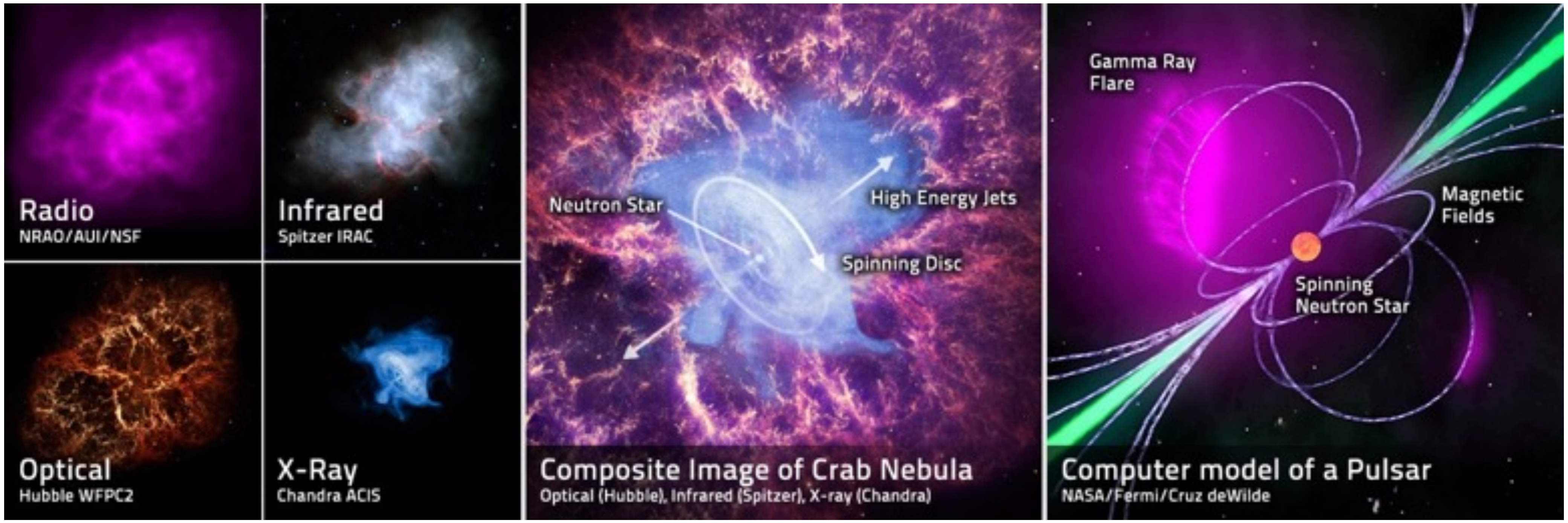


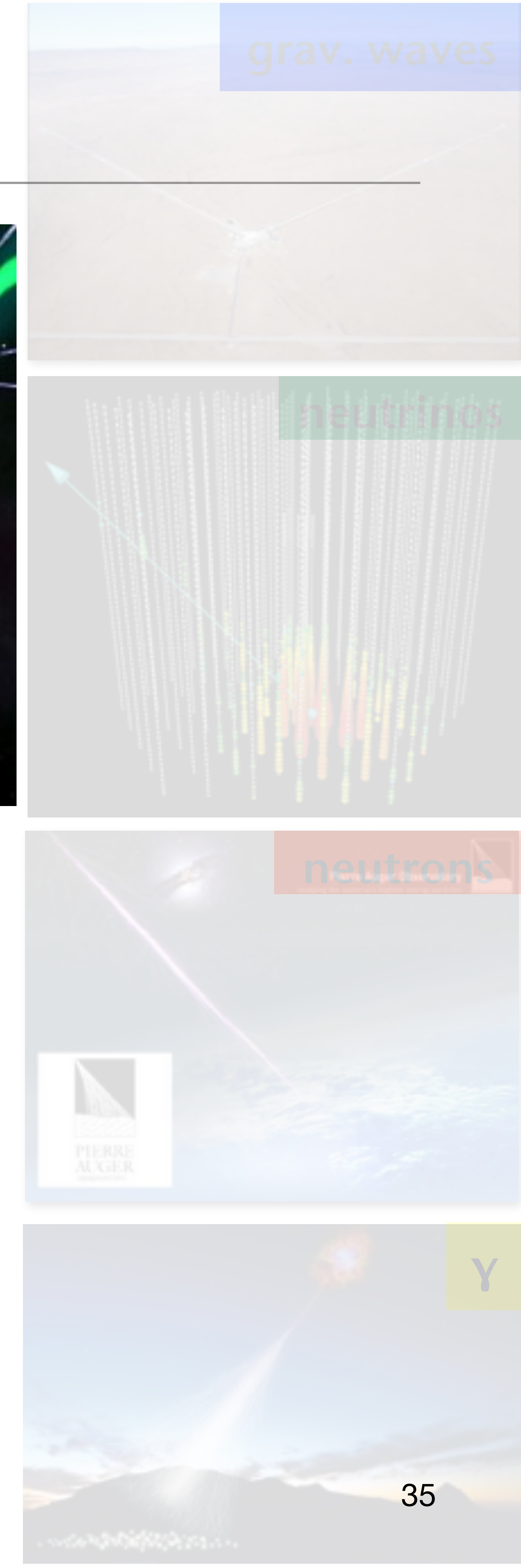
Secondary products

Multi-messenger temporal coincidences



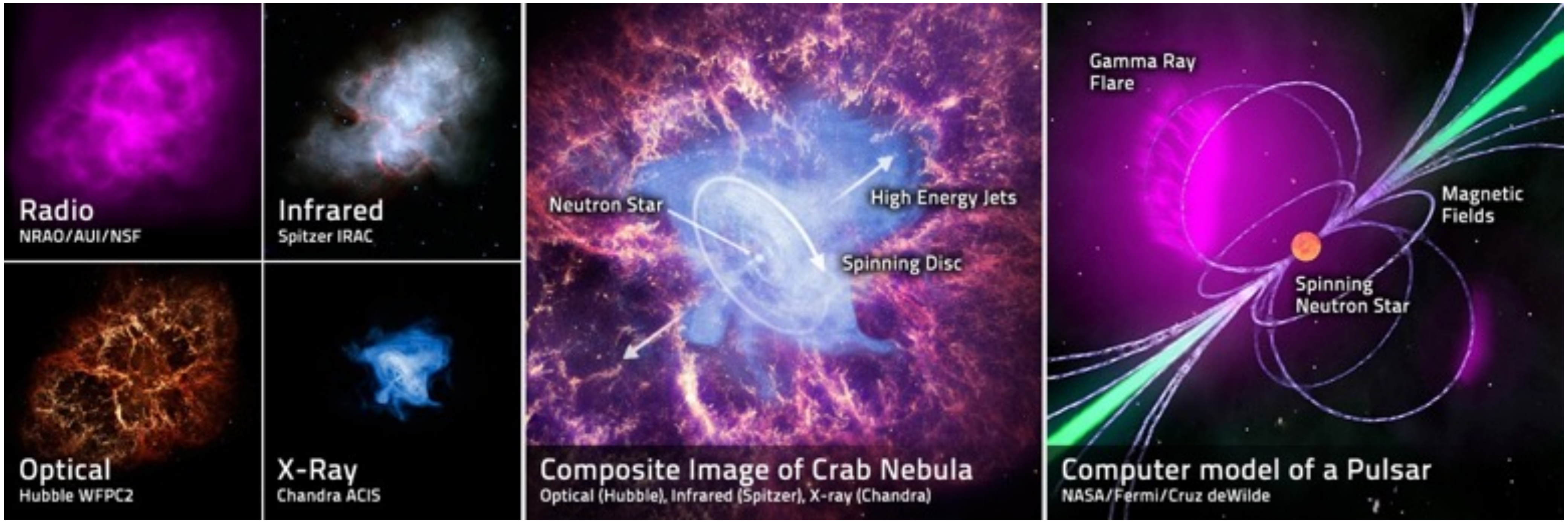
Multimessenger coincidences

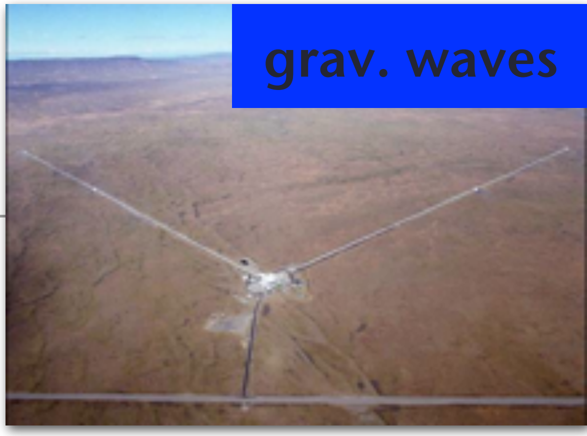


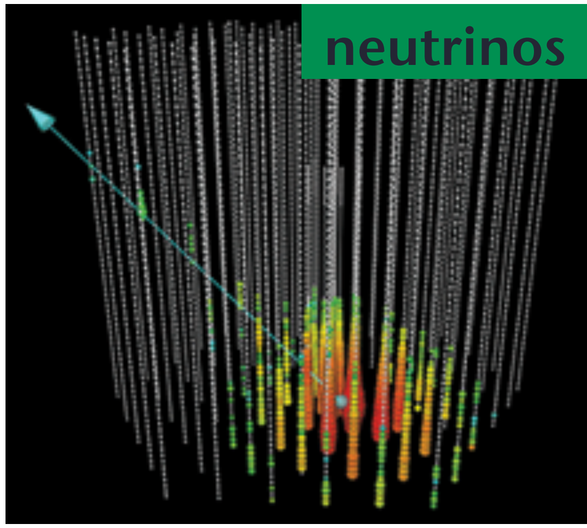


Most violent phenomena must appear at multiple wavelengths-messengers

Multimessenger coincidences



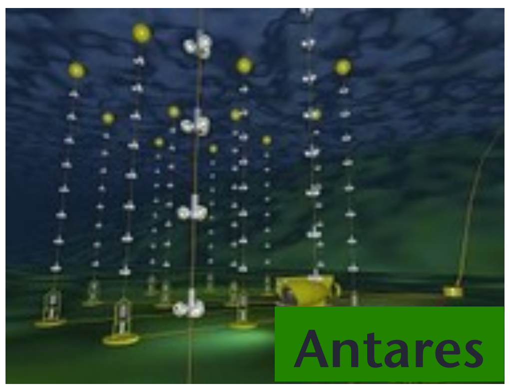


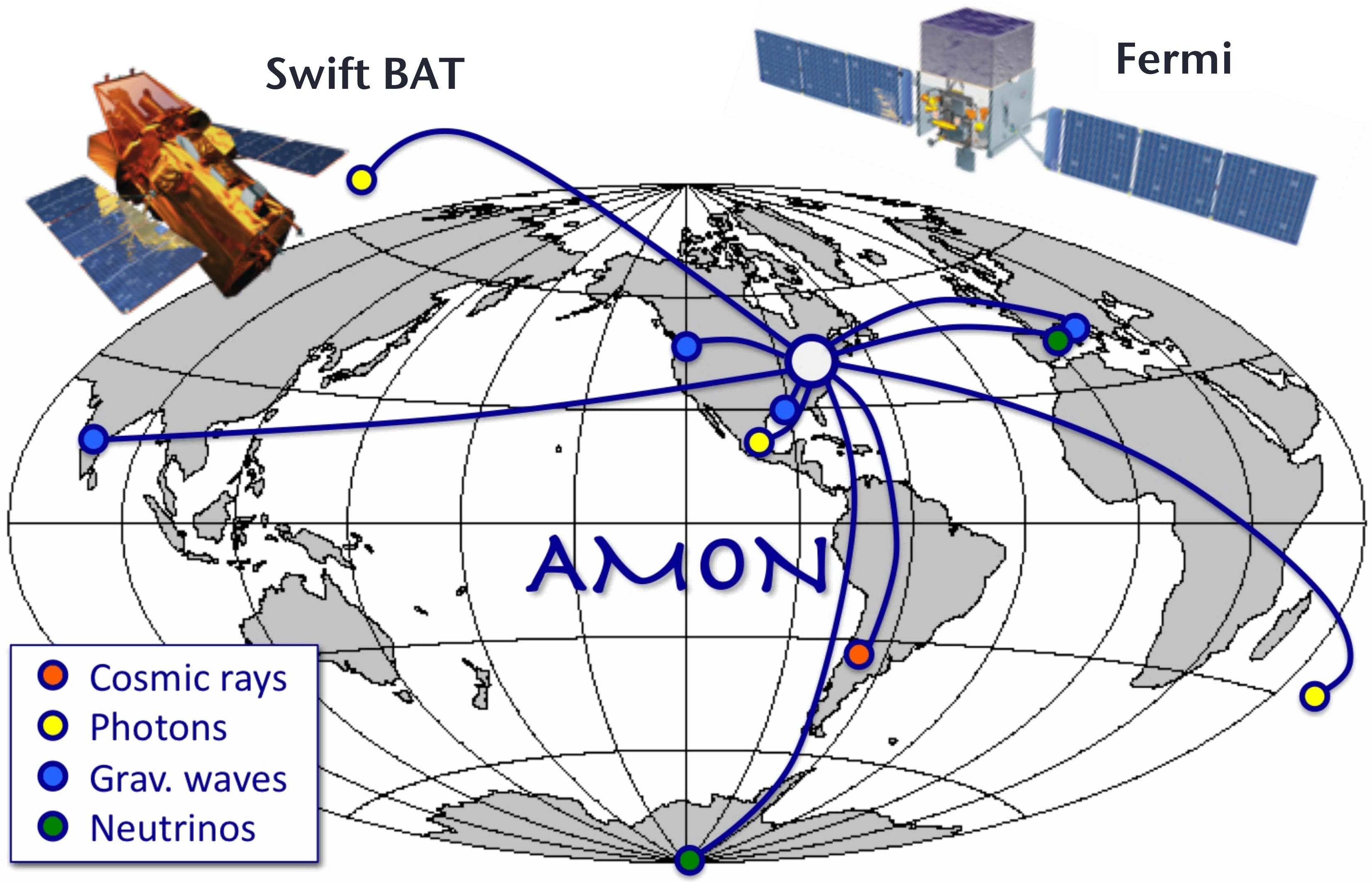


Most violent phenomena must appear at multiple wavelengths-messengers

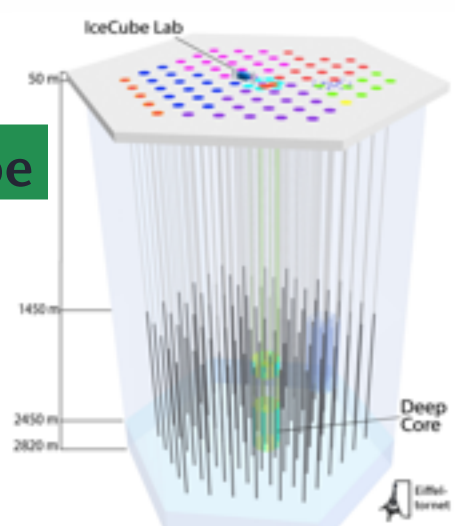
Transient discoveries -> Combine all fundamental forces

The Astrophysical Multimessenger Observatory Network (AMON)





IceCube



+Follow-up:

Swift XRT&UVOT

VERITAS MASTER

http://amon.gravity.psu.edu

Soon to sign MOU:

- HESS
- LIGO
- Large Millimeter Telescope
- MAGIC
- Palomar Transient Factory
- Telescope Array

How can we find UHECR sources with AMON?

Auger datasets suitable for transient searches:

- [ ] **UHE Hadrons [delayed by magnetic fields/directions scrambled]**
- [x] **UHE neutrons**

$$L_n \sim c \cdot \tau_n \cdot \gamma_n \sim 9\ (E_n/1\ \text{EeV})\ \text{kpc}$$

[c.f. MW radius ~ 8 kpc]

Galactic neutrons detectable!

- [x] **UHE Photons** **-loss length up to 30 Mpc**
- [x] **UHE Neutrinos**

How can we find UHECR sources with AMON?

Event class	Prompt				Delayed		
	γ	ν	n	gw	x-ray	IR/O/UV	radio
GRBs	✓	✓		✓	✓	✓	✓
Chocked jet SNe		✓		✓	✓	✓	✓
Core collapse SNe (Galactic)		✓	✓		✓	✓	
AGN flares	✓	✓			✓	✓	✓
Tidal disruption flares	✓	✓			✓	✓	✓
Pulsars/Magnetars	✓	✓✓		✓	✓	✓	✓
Primordial black holes	✓	✓✓	✓				
Other exotica	✓	✓	✓	✓			

*✓✓ UHE neutrinos at flux levels detectable by Auger

How can we find UHECR sources with AMON?

	Prompt				Delayed		
Event class	γ	ν	n	gw	x-ray	IR/O/UV	radio
GRBs	✓	✓		✓	✓	✓	✓
Chocked jet SNe		✓		✓	✓	✓	✓
Core collapse SNe (Galactic)		✓	✓		✓	✓	
AGN flares	✓	✓			✓	✓	✓
Tidal disruption flares	✓	✓			✓	✓	✓
Pulsars/Magnetars	✓	✓✓		✓	✓	✓	✓
Primordial black holes	✓	✓✓	✓				
Other exotica	✓	✓	✓	✓			

UHE γs $\lesssim$few x 10 Mpc

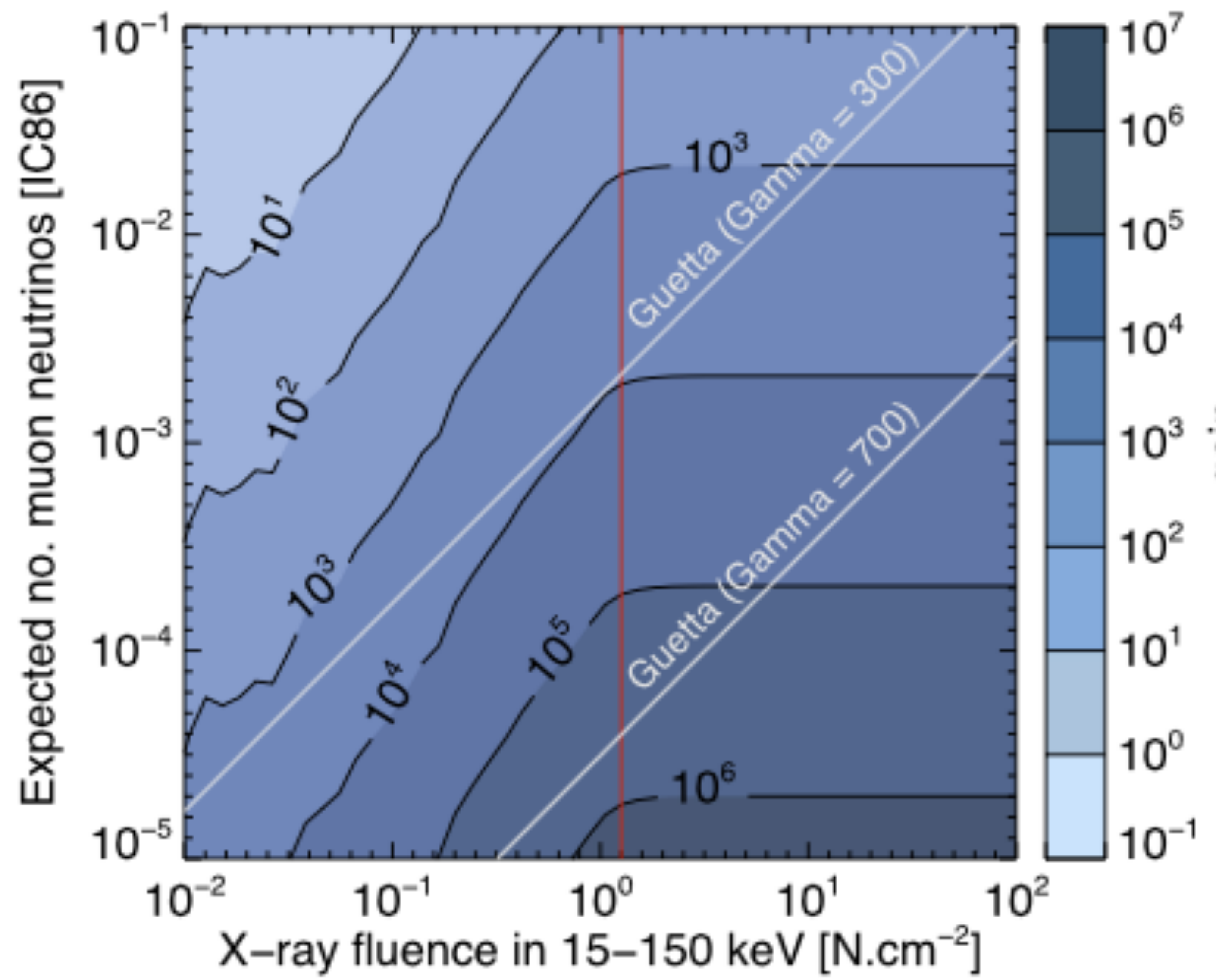
Galactic neutrons

*✓✓ UHE neutrinos at flux levels detectable by Auger

AMON discovery potential: Example
Cosmic Neutrino Sources

	Status quo	AMON
Alert	IceCube "2ν" alerts ($10\ yr^{-1}$)	IceCube 35ν-Nγ* alerts + "2ν" alerts ($5\ yr^{-1}$)
Follow-up (Swift UVOT/ XRT)	70 pointings	70 pointings

AMON Team 2013



***ν-Nγ alerts: coincidence between at least single IceCube/Antares and Fermi-LAT/Swift-BAT/ HAWC**

Outlook

- AugerPrime, TA upgrade, JEM-EUSO
  Anisotropy detection in 5 years, if H ≳10% at highest energies
  (if composition information)

- HAWC, CTA, HESS-2
  Gamma-rays can unambiguously identify UHECR sources - need TeV spectra of high-z sources, timing (flares), angular resolution (halos)

- Multi-messenger astroparticle physics is happening NOW

- AMON
  Subthreshold multi-messenger transients, huge gain in discovery potential