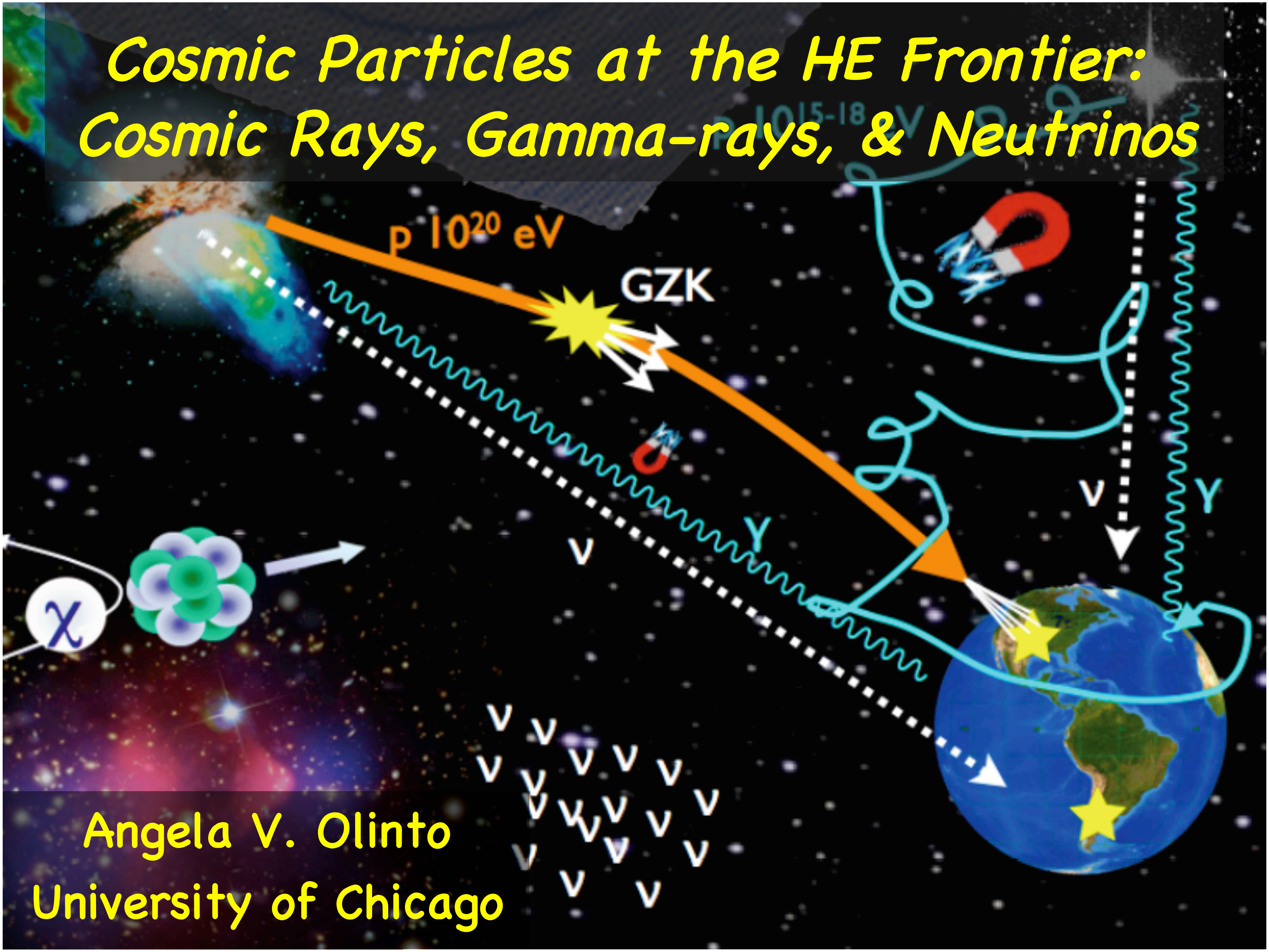
Cosmic Particles at the HE Frontier: Cosmic Rays, Gamma-rays, & Neutrinos



Angela V. Olinto
University of Chicago

TALKS you should have heard - yesterday

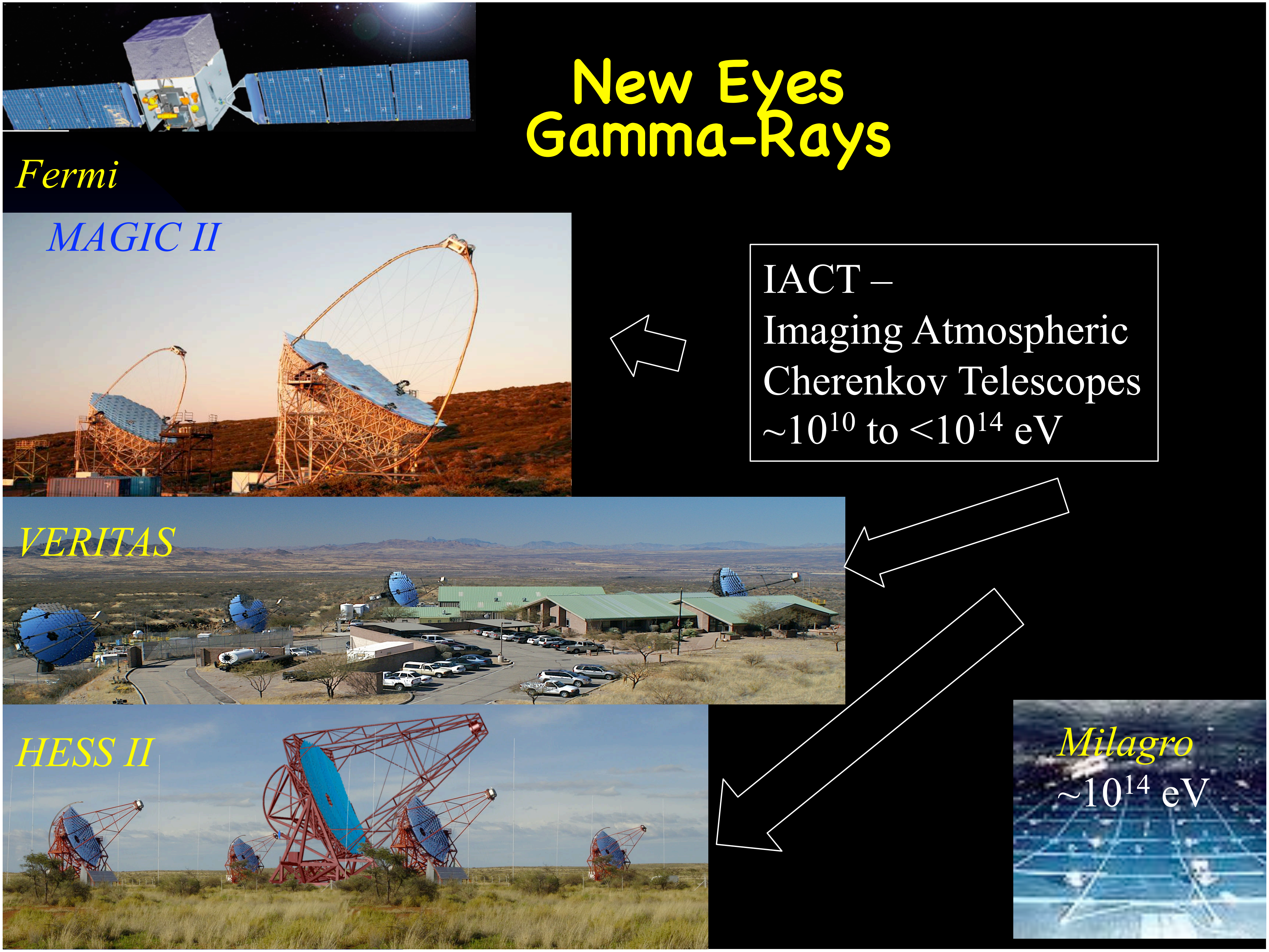
E. HAYS: High Energy Astrophysics with the Fermi LAT
B. HUMENSKY: Highlights of Gamma-ray Astronomy with VERITAS
C. COVAULT: Pierre Auger Observ. South & North: Results & Future
R. HUGHES: Search for Anisotropy in the Flux of CRs w/ Fermi LAT
P. SMITH: Prospects for Measuring CR Proton Spectrum w/ Fermi LAT

TALKS you should hear – this afternoon

R. DICKHERBER: Indirect Dark Matter Search with VERITAS
D. PHALEN: Pulsars and Indirect Signals for Dark Matter
T. DEYOUNG: Recent Results from IceCube and AMANDA

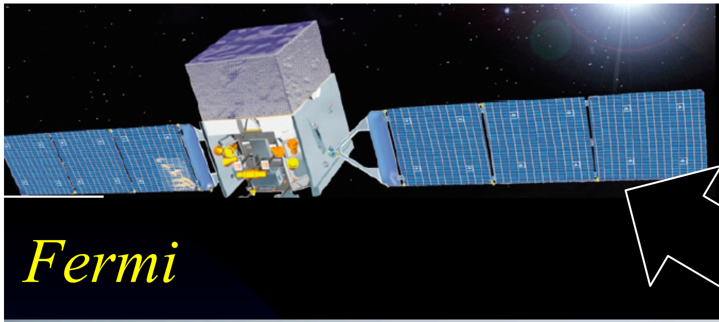
AstroParticles

	Detection	Points to Source	Energy Range Observed (Expected)
γ **Gamma Rays**	Easy	Yes	**10^{-9} eV to 10^{14} eV** (>10^{19} eV)
CR **Cosmic Rays**	Easy	Only above 6 10^{19} eV (?)	**10^{8} eV to 10^{20} eV** (>10^{20} eV)
ν **Neutrinos**	Hard	Yes	(10^{15}eV to 10^{19}eV)

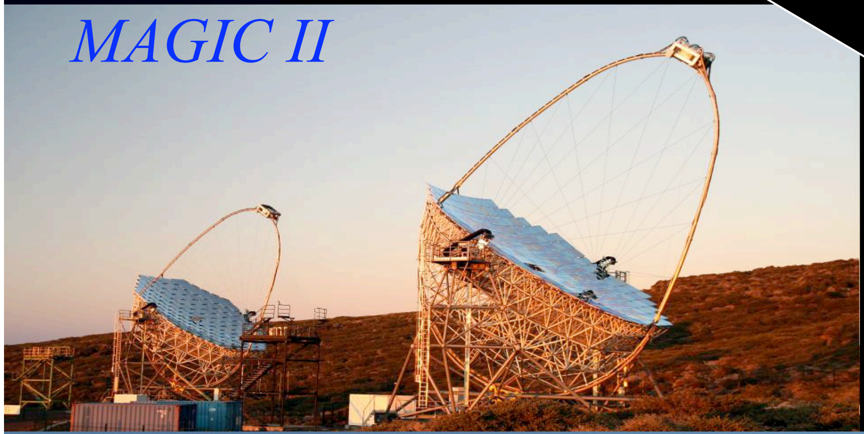


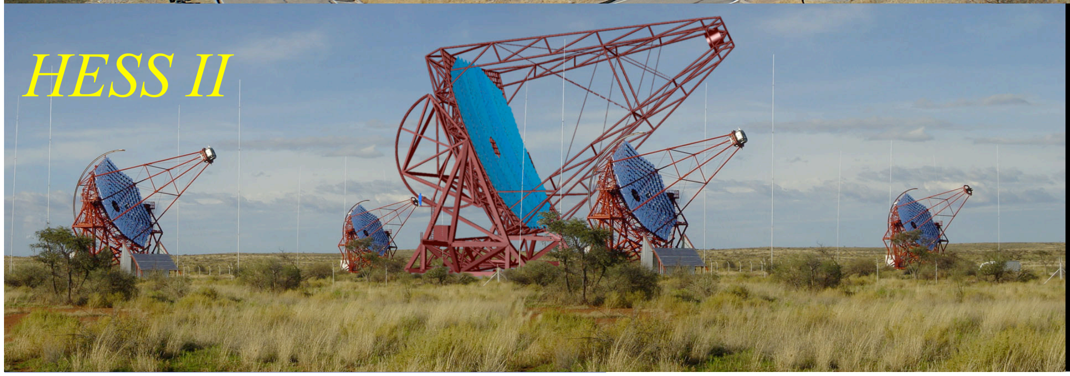
New Eyes
Gamma-Rays
Fermi
MAGIC II
IACT –
Imaging Atmospheric
Cherenkov Telescopes
~10^10 to <10^14 eV
VERITAS
HESS II
Milagro
~10^14 eV

New Eyes Gamma-Rays

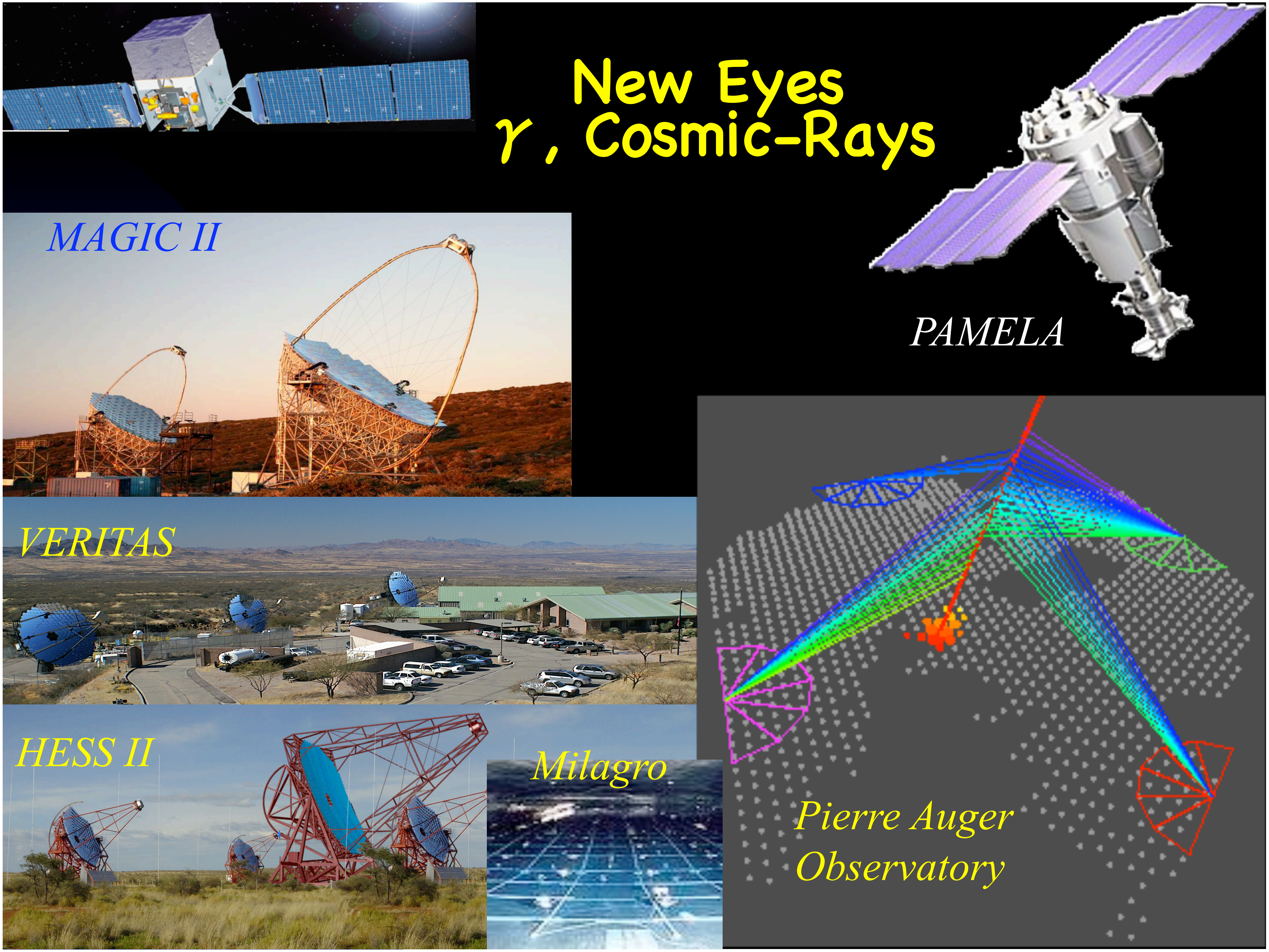


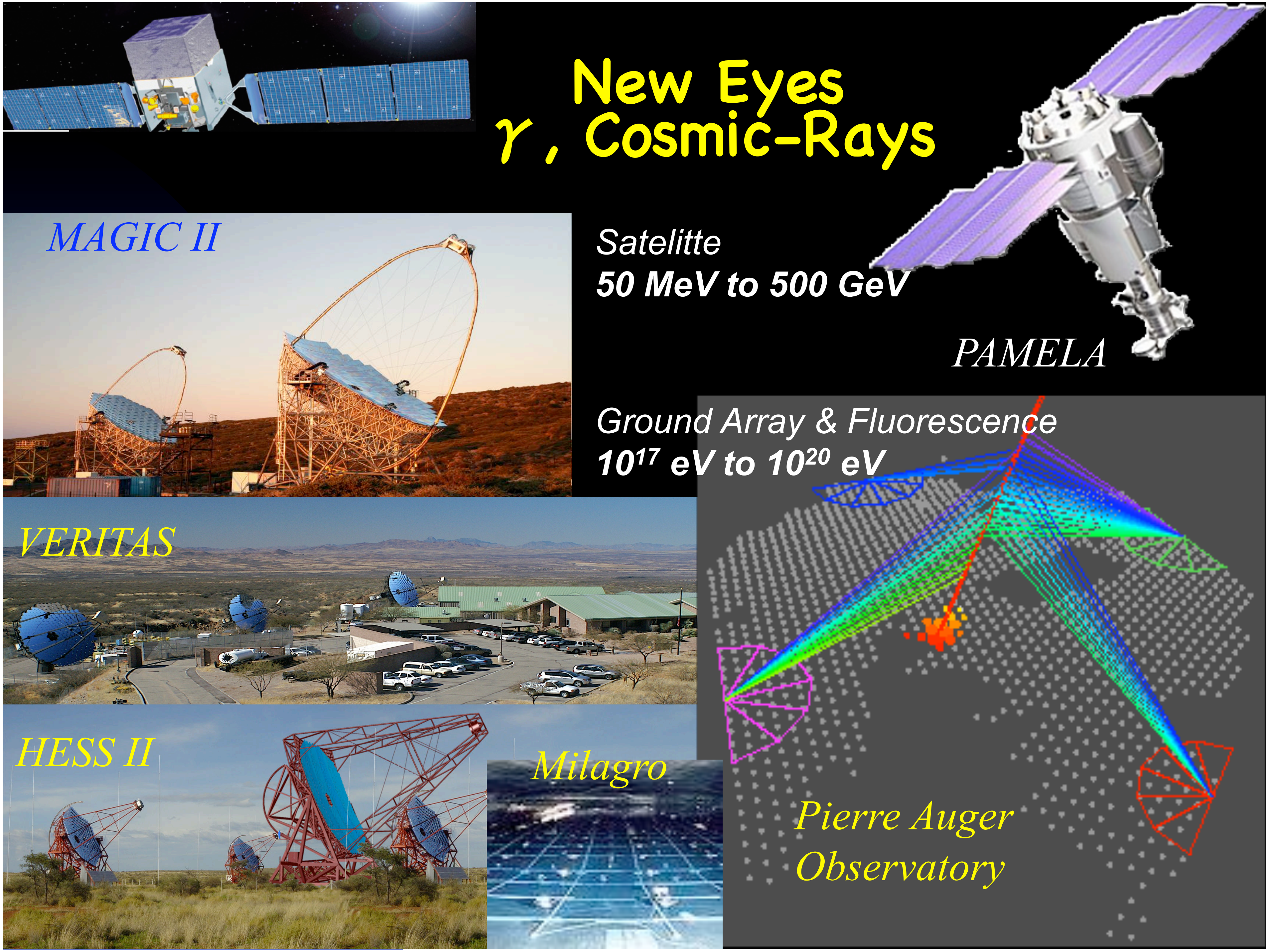
Fermi GST
LAT:
20 MeV - >300 GeV
GBM
8 keV - 40 MeV

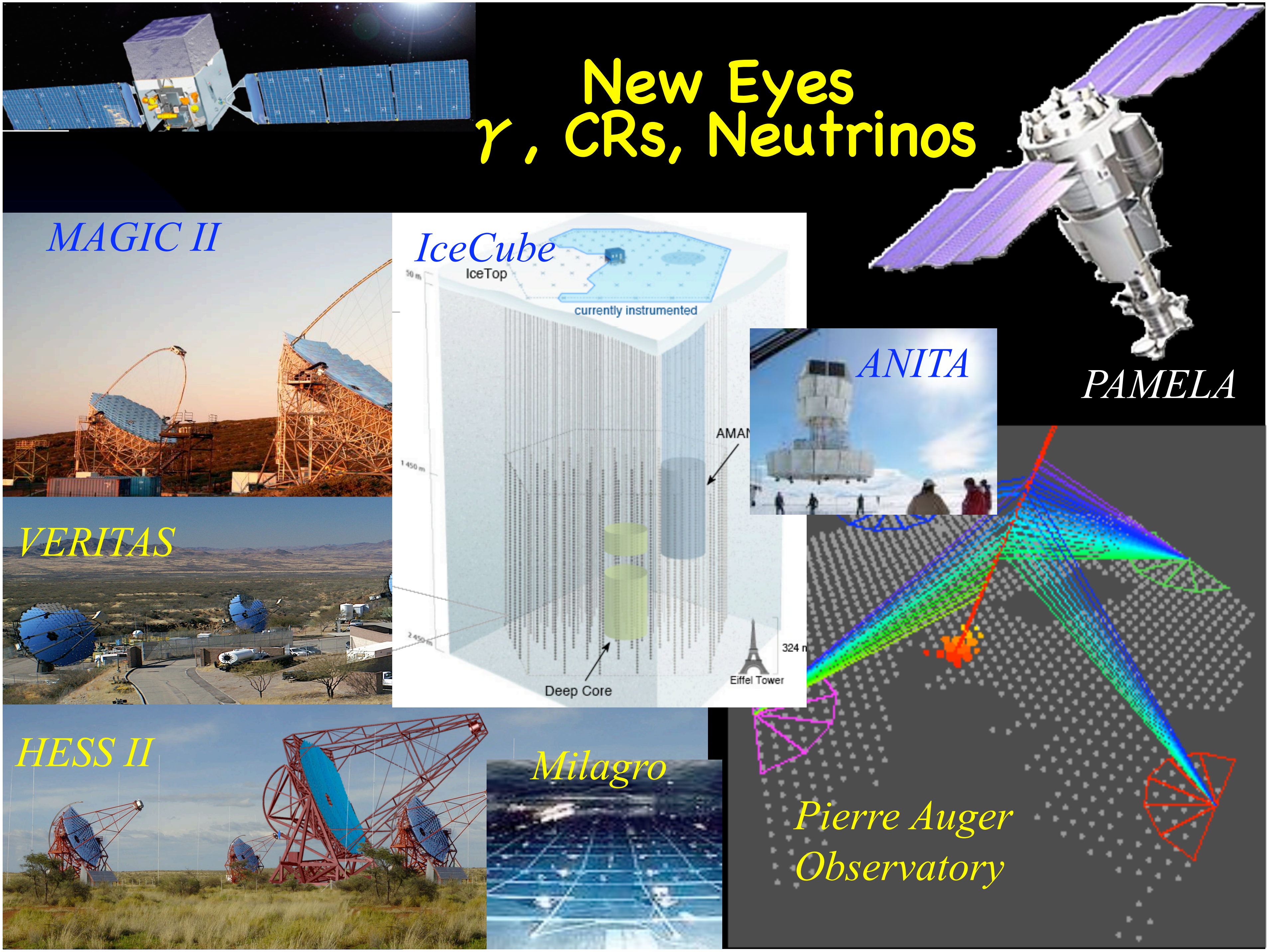




New Eyes
γ, Cosmic-Rays




New Eyes
γ , Cosmic-Rays
MAGIC II
Satelitte
50 MeV to 500 GeV
PAMELA
Ground Array & Fluorescence
10^{17} eV to 10^{20} eV
VERITAS
HESS II
Milagro
Pierre Auger
Observatory


New Eyes
γ, CRs, Neutrinos
MAGIC II
IceCube
IceTop
currently instrumented
Deep Core
Eiffel Tower
ANITA
PAMELA
VERITAS
HESS II
Milagro
Pierre Auger Observatory

Goals of the Field

- To understand Nature's HE Accelerators
- To use Cosmic Particles to study HE interactions

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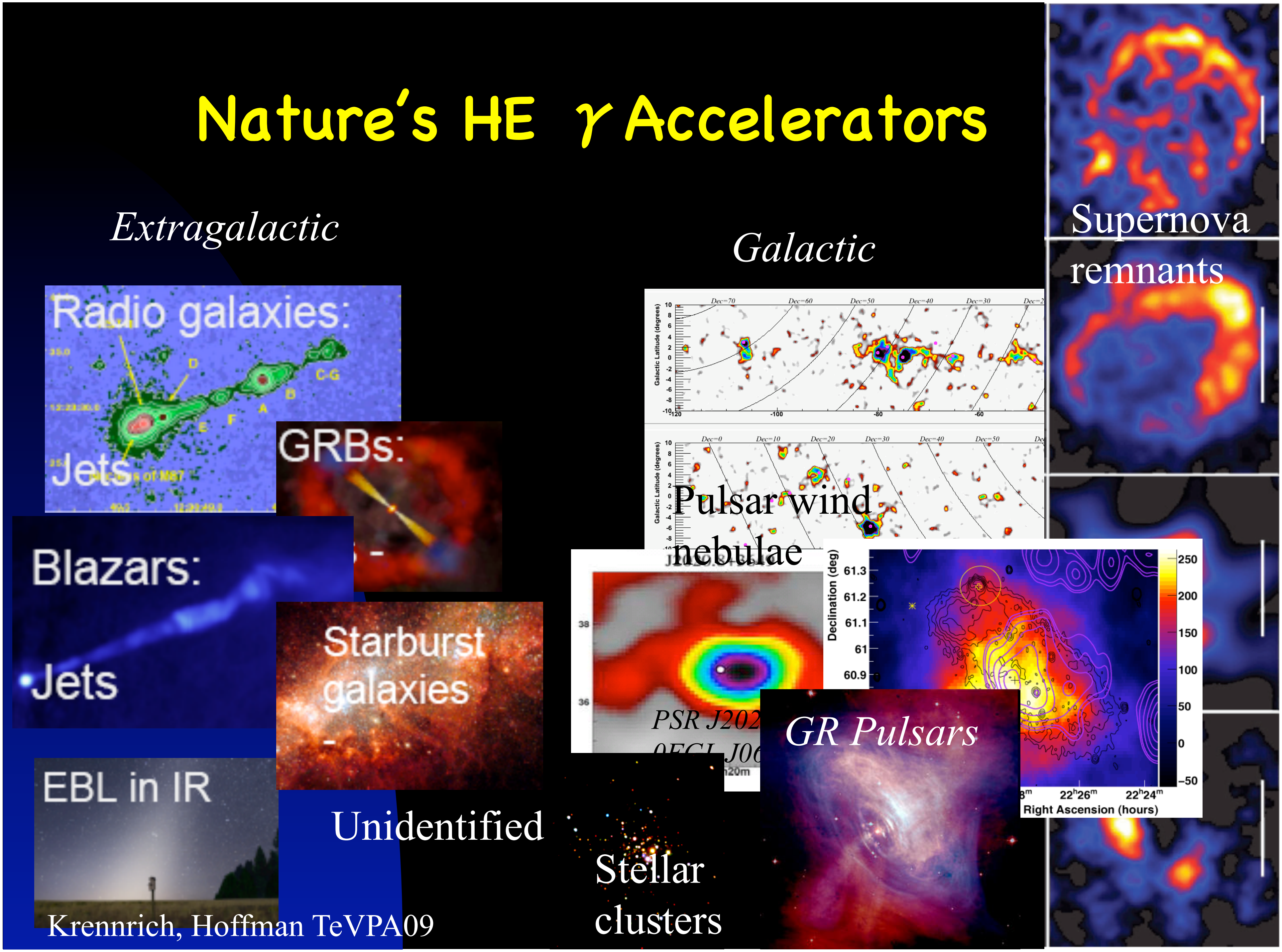
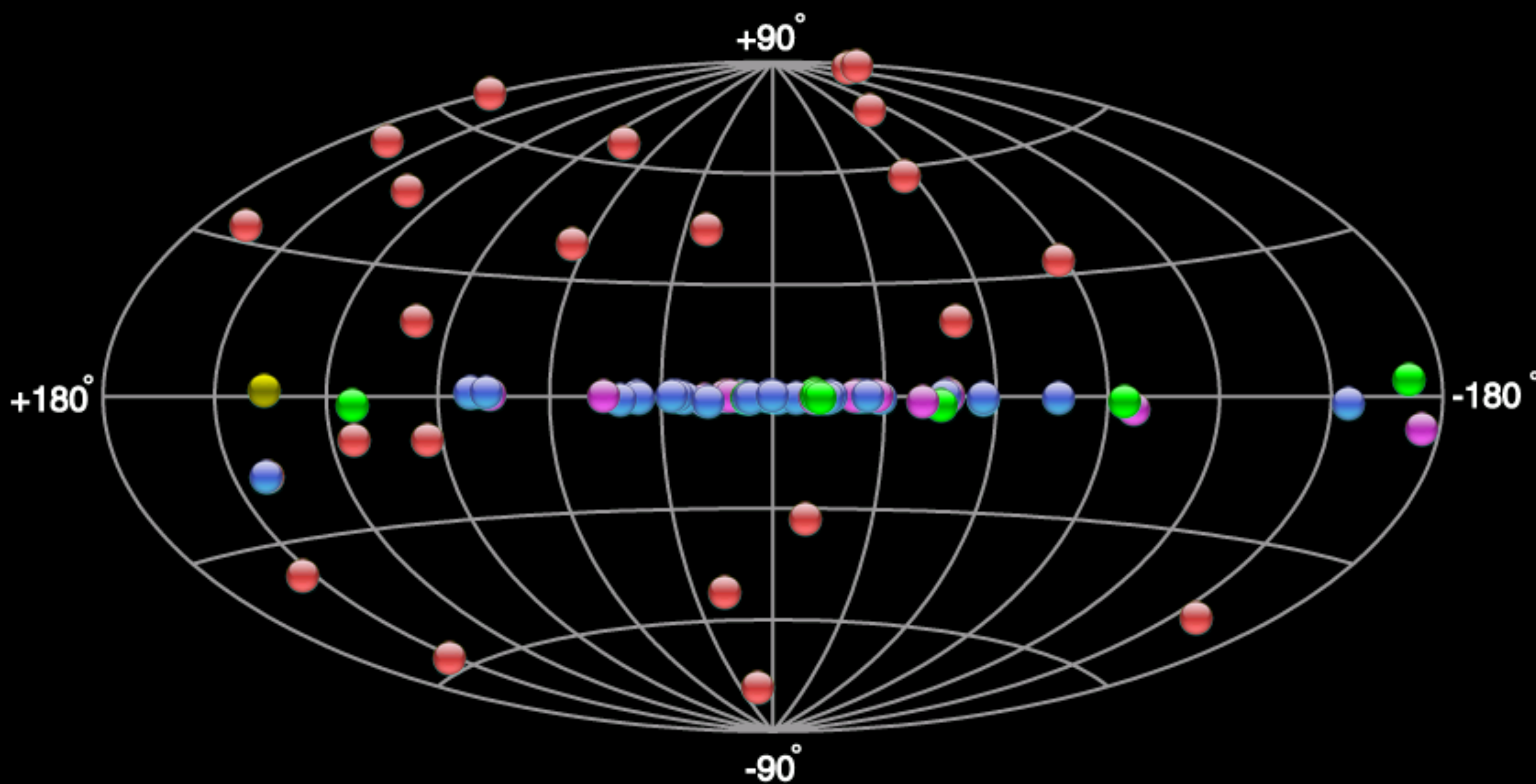
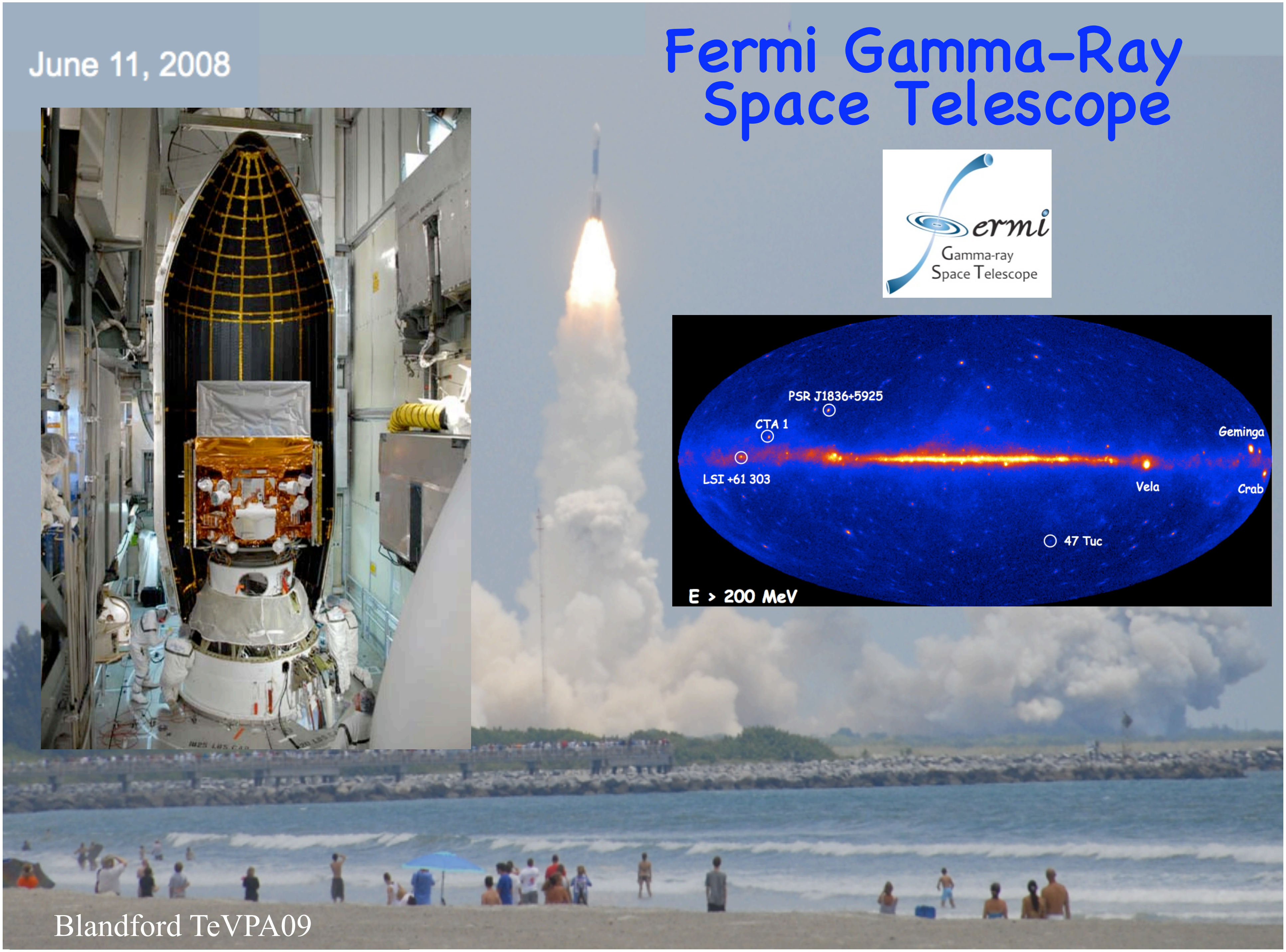

Nature's HE γ Accelerators
Extragalactic
Galactic
Radio galaxies:
Jets
GRBs:
Blazars:
Jets
Starburst galaxies
EBL in IR
Unidentified
Pulsar wind nebulae
Stellar clusters
GR Pulsars
Supernova remnants
Galactic Latitude (degrees)
Declination (deg)
Right Ascension (hours)
Krennrich, Hoffman TeVPA09

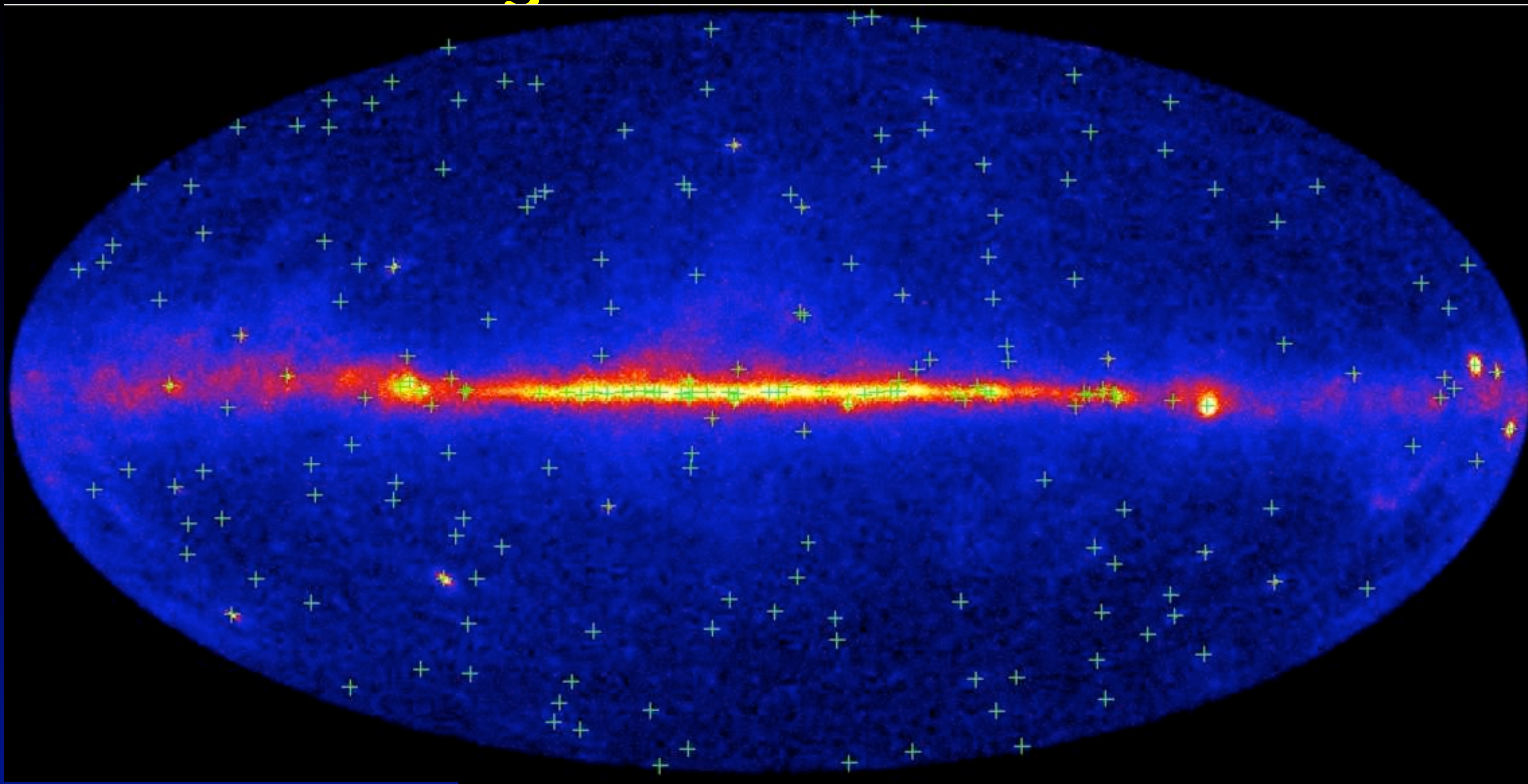
TeV γ Catalog (IACT sky)
> 75 sources



Hoffman TeVPA09


June 11, 2008
Fermi Gamma-Ray
Space Telescope
Fermi
Gamma-ray
Space Telescope
PSR J1836+5925
CTA 1
LSI +61 303
Geminga
Vela
Crab
47 Tuc
E > 200 MeV
Blandford TeVPA09

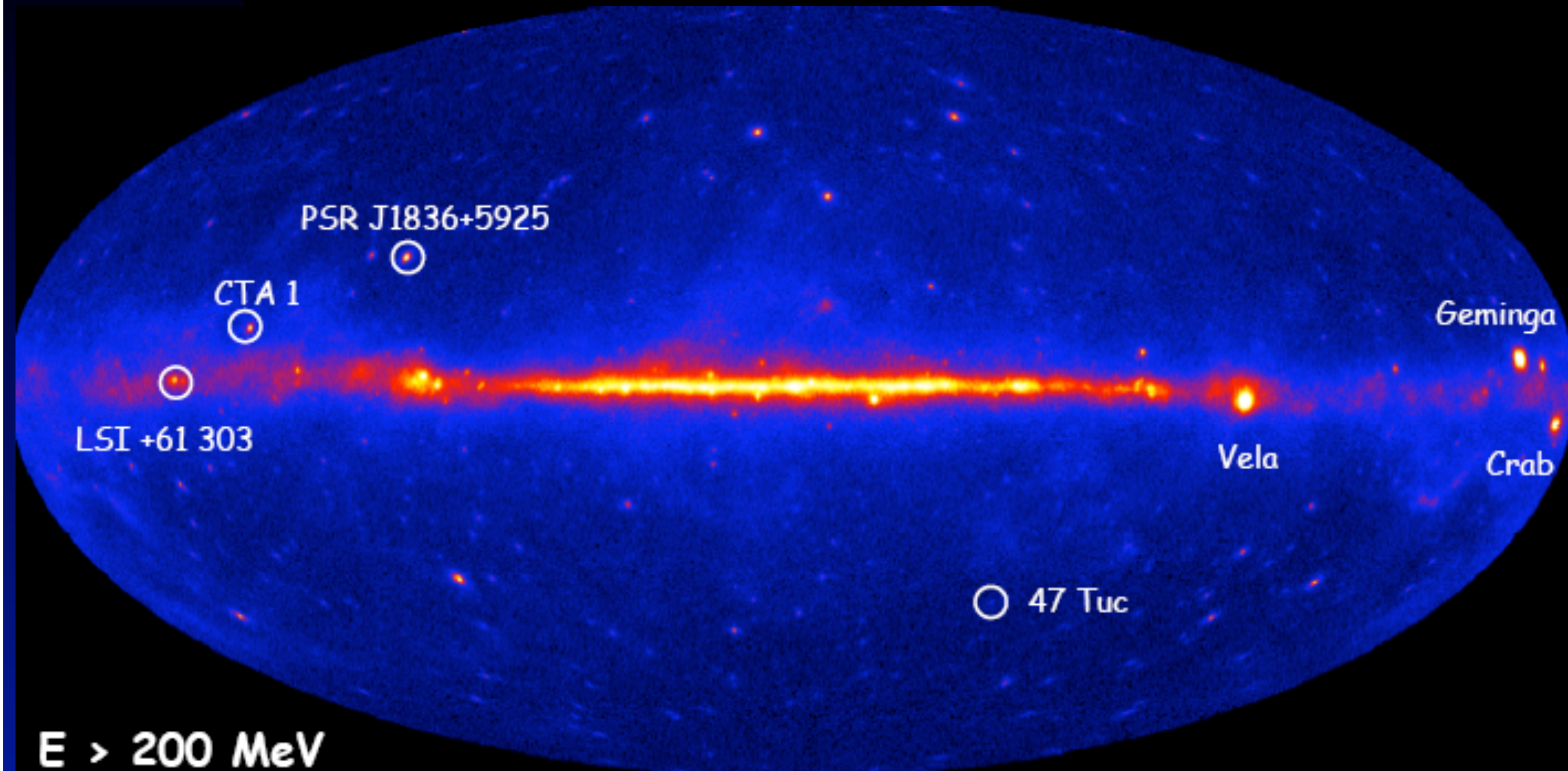
3 Month High Confidence Source List



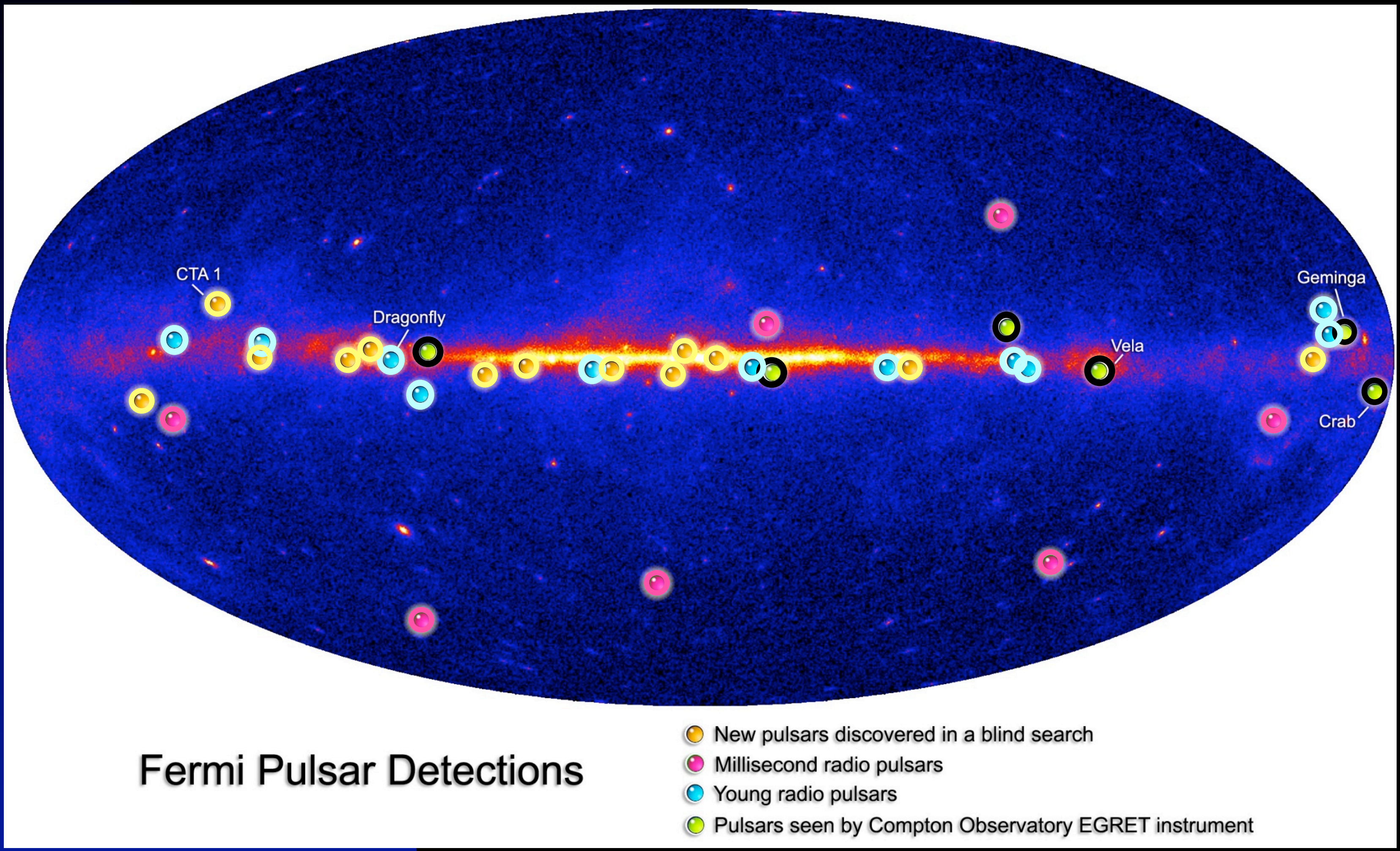
- 205 sources with significance > 10σ (EGRET found fewer than 30)
- Typical 95% CL error radius is <10 arcmin
  (Abdo et al. 2009 ApJS, 183, 46)

Chiang TeVPA09

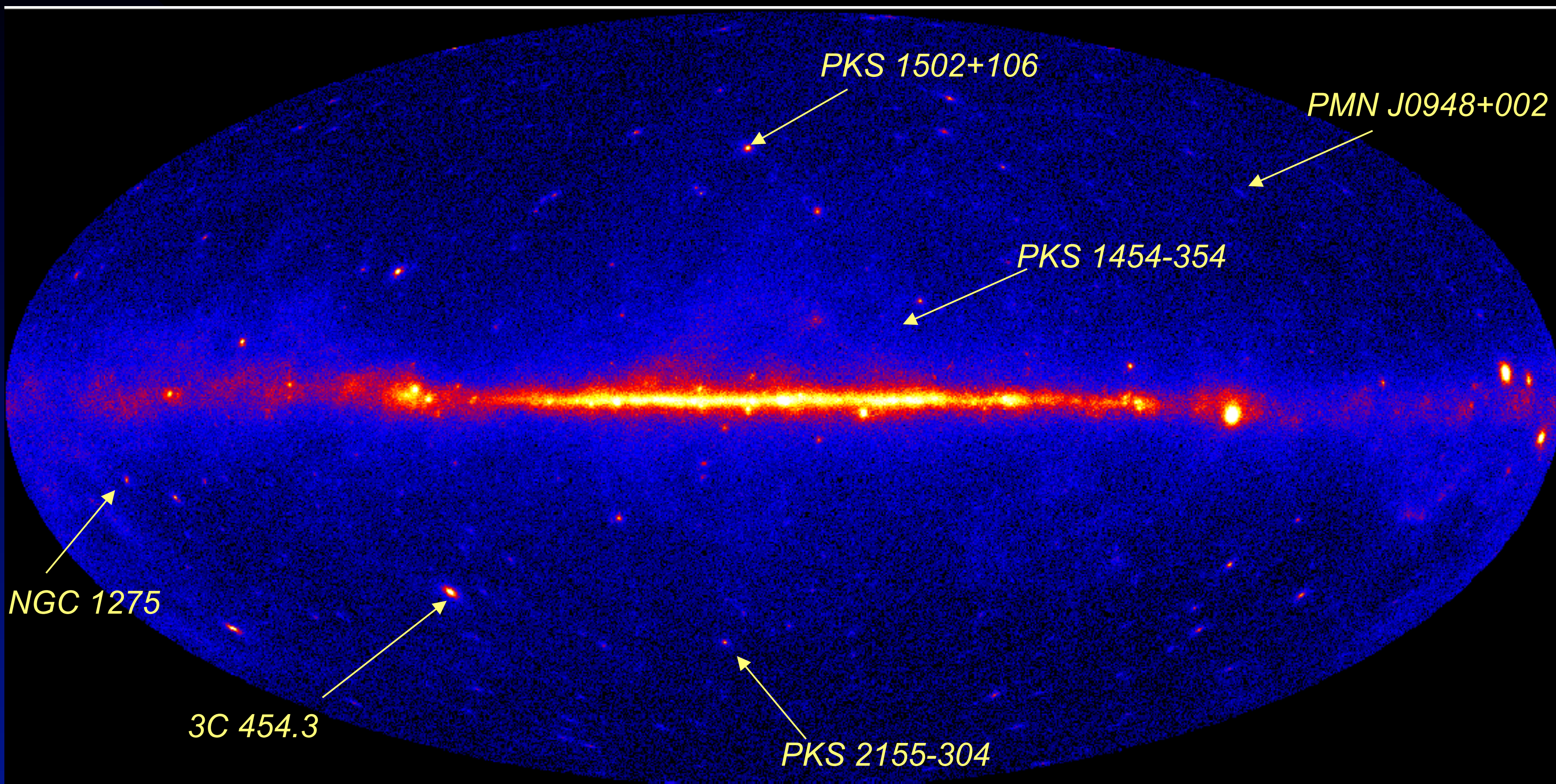
9 months – all sky



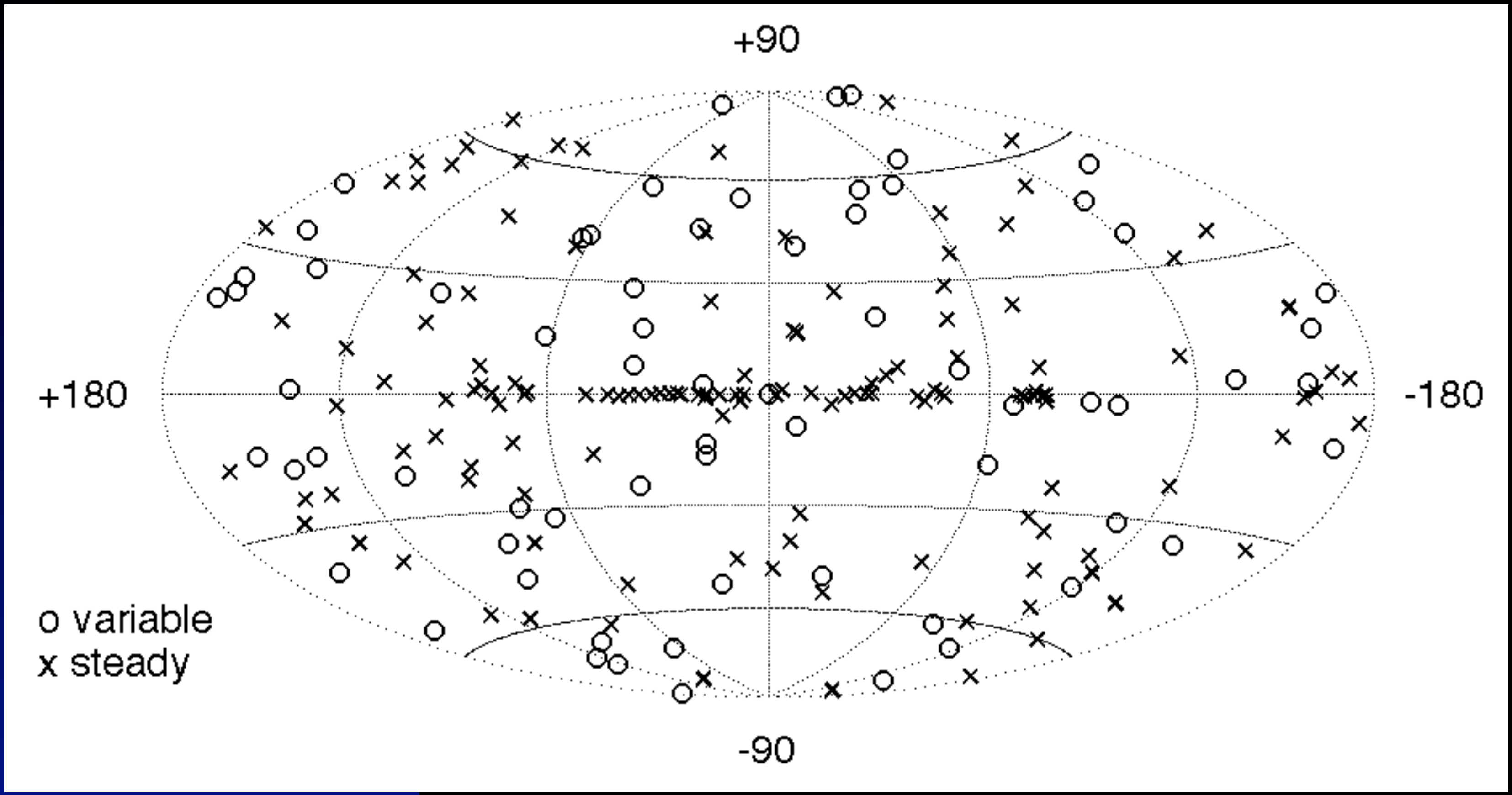
Fermi Pulsars



Fermi - Individual AGNs

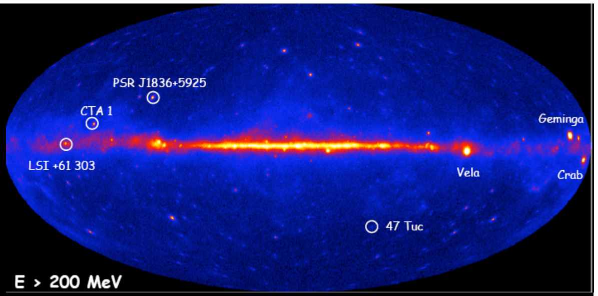


Variable sources in the LAT Bright Source List



- Based on 1 week time scales
- 68/205 show variability with probability > 99%
- Isotropic distribution ⇒ blazars

Fermi + ACT



How do supermassive black holes in Active Galactic Nuclei (AGN) create powerful relativistic jets? What are the jets?

What are the mechanisms of Gamma-ray Bursts?

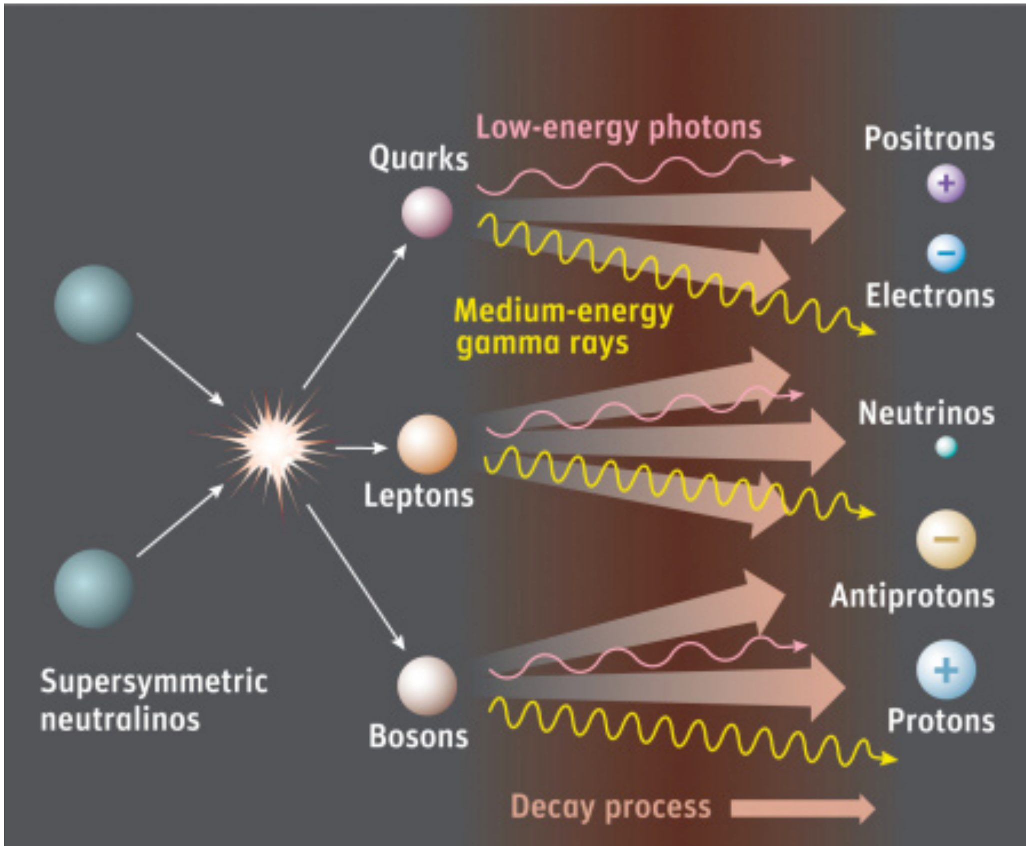
What are the unidentified EGRET sources?

What is the origin of Galactic Cosmic Rays? SNRs? What are the Pevatrons?

What is the Extragalactic background light?

Goals of the Field

- To understand Nature's HE Accelerators
- To use Cosmic Particles to study HE interactions



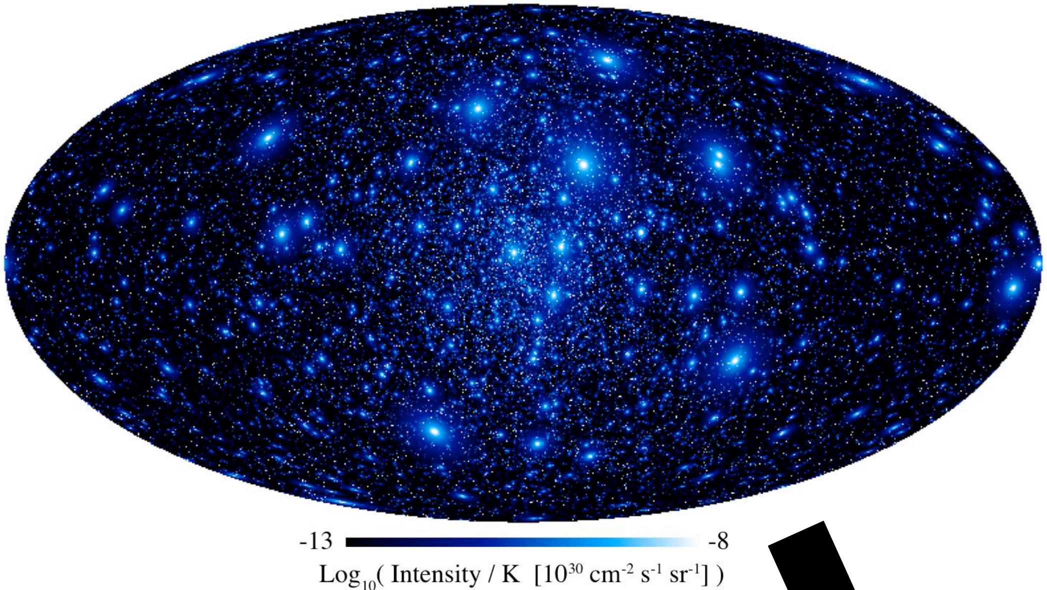
Dark Matter Indirect Searches

Annihilation signal

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

DM distribution



Dark Matter Indirect Searches

γ from DM annihilation in Galactic substructure –

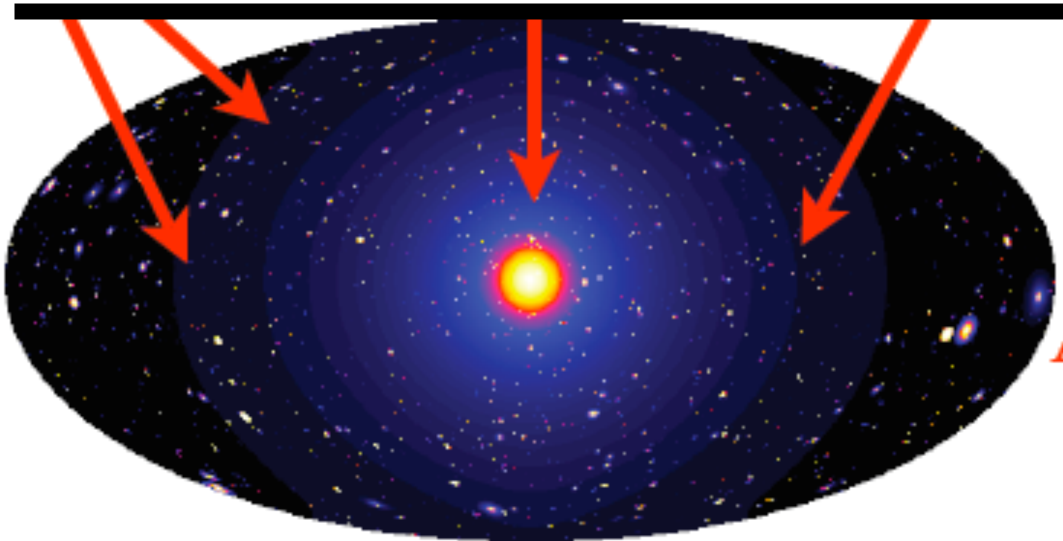
Siegal-Gaskins '08

Annihilation signal

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2(r(l,\phi'))dl(r,\phi')$$

DM distribution



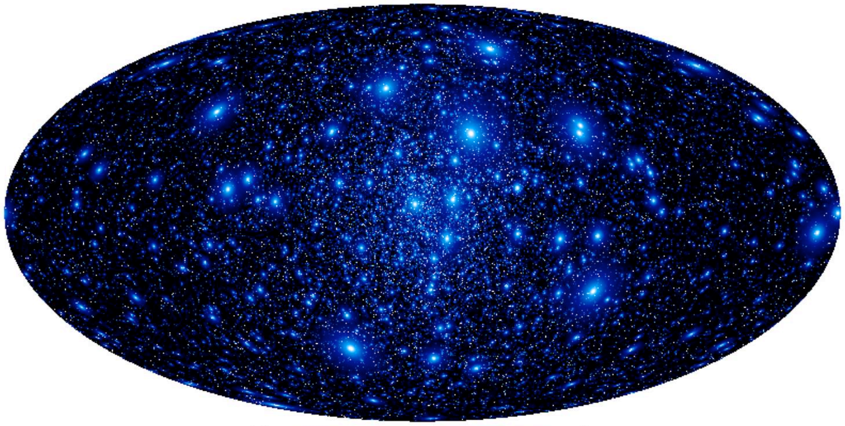
Dark Matter Indirect Searches

Galactic Center

95% CL upper limit (100 MeV-50 GeV)

Flux: $2.43\times10^{-7}\,cm^{-2}s^{-1}$

$\langle\sigma v\rangle$: $3.98\times10^{-25}\,cm^{3}s^{-1}$

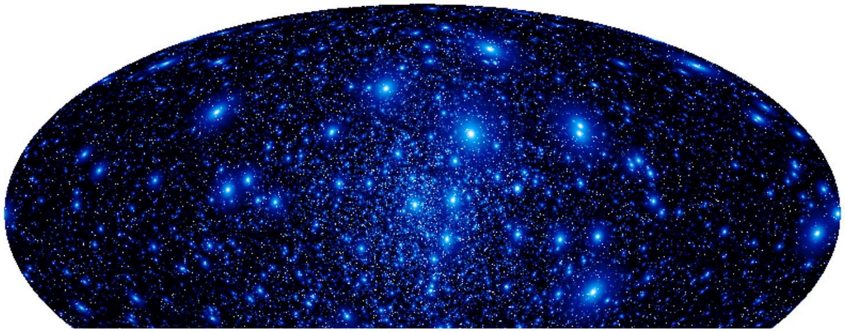


Dark Matter: Dwarf Spheroidals

- Annihilation signal

Name	Distance (kpc)	year of discovery	M/L	l	b
Segue 1	23± 3	2007	1320 ± 2680	220.48	50.42
Ursa Major II	30± 5	2006	1722 ± 1226	152.46	37.44
Segue 2	35	2009	650^{+1300}_{-380}	149.4	-38.01
Willman 1	38± 7	2004	$\sim$500	158.57	56.78
Coma Berenices	44± 4	2006	448 ± 297	241.9	83.6
Usra Minor	66± 3	1954	275 ± 35	104.95	44.80
Sculptor	79± 4	1937	158 ± 33	287.15	-83.16
Draco	76± 5	1954	290 ± 60	86.37	34.72
Sextans	86± 4	1990	70 ± 10	243.4	42.2
Fornax	138± 8	1938	14.8 ± 8.3	237.1	-65.7

Murgia TeVPA09



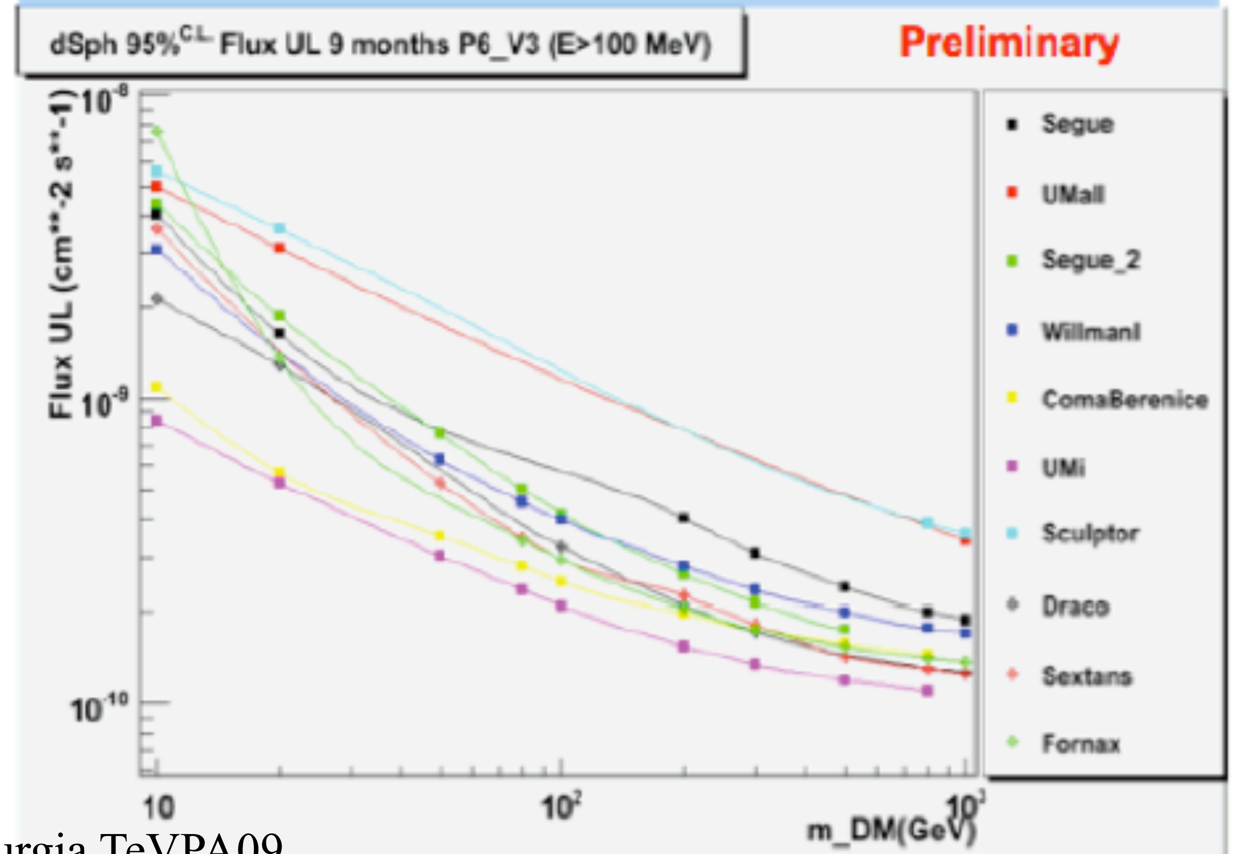
Dark Matter: Dwarf Spheroidal UL

Flux upper limits assuming a point-like source at the dwarf location

power-law with fixed spectral index of $\gamma = -2$

Name **Preliminary**	Flux UL (95%) $(E > 100\ MeV)$ $10^{-9}\ ph/cm^2/s$
Segue I	1.83
UMa II	4.60
Segue II	2.13
Willman I	2.12
Coma Berenice	0.97
UMi	0.72
Sculptor	4.79
Draco	1.16
Sextans	1.33
Fornax	1.67

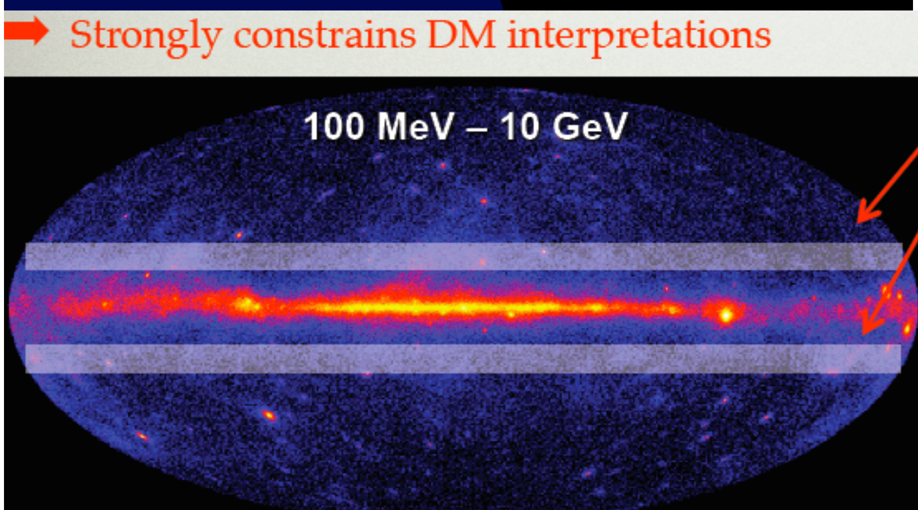
100% b-bbar DM annihilation

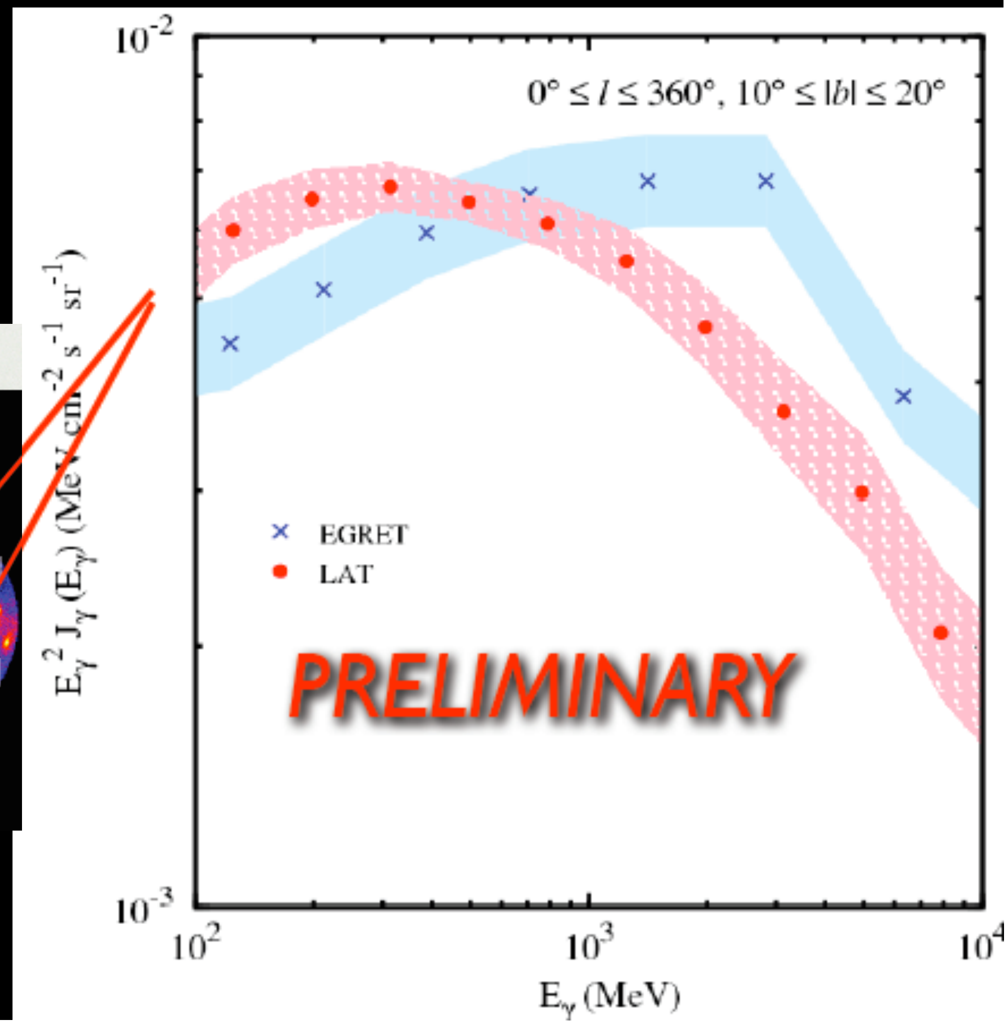


Dark Matter & GeV EGRET excess?

Dark Matter & GeV EGRET excess?

- Fermi says: No





Murgia TeVPA09

Dark Matter & LE Cosmic Rays?

Cosmic Ray Spectrum

10^8 eV < E < 10^{11} eV

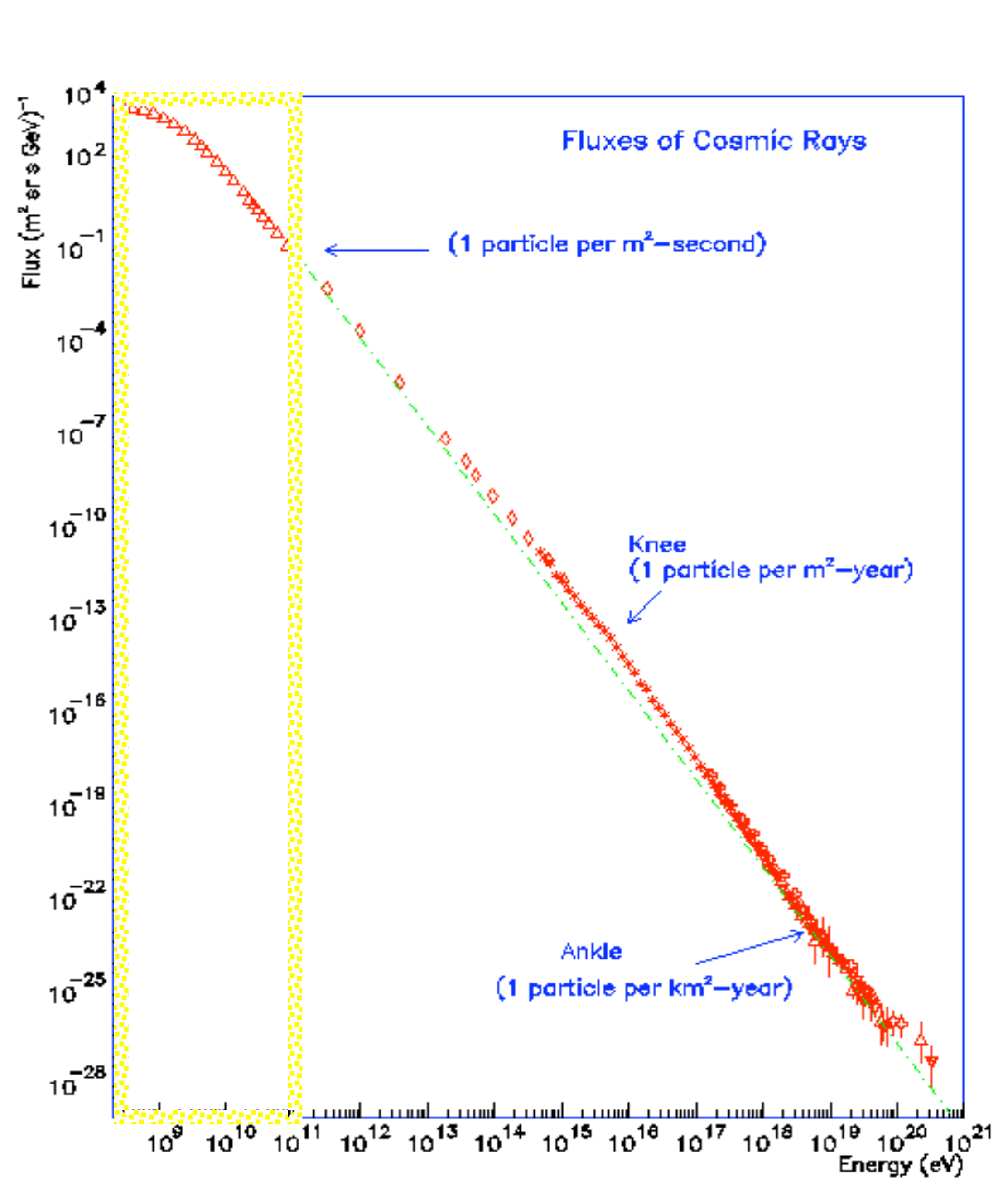
Solar Modulation

10^{11}eV < E < $10^{17.5-18.5?}$ eV

Galactic Propagation

10^{17-19}eV < E < $10^{20-2?}$ eV

Extragalactic Sources



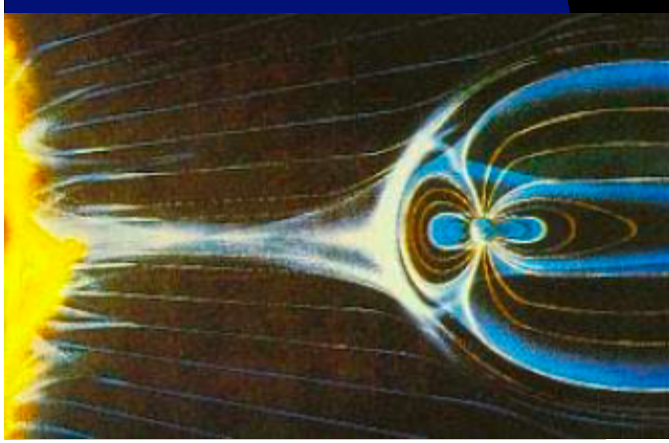
Each Energy range tells its story

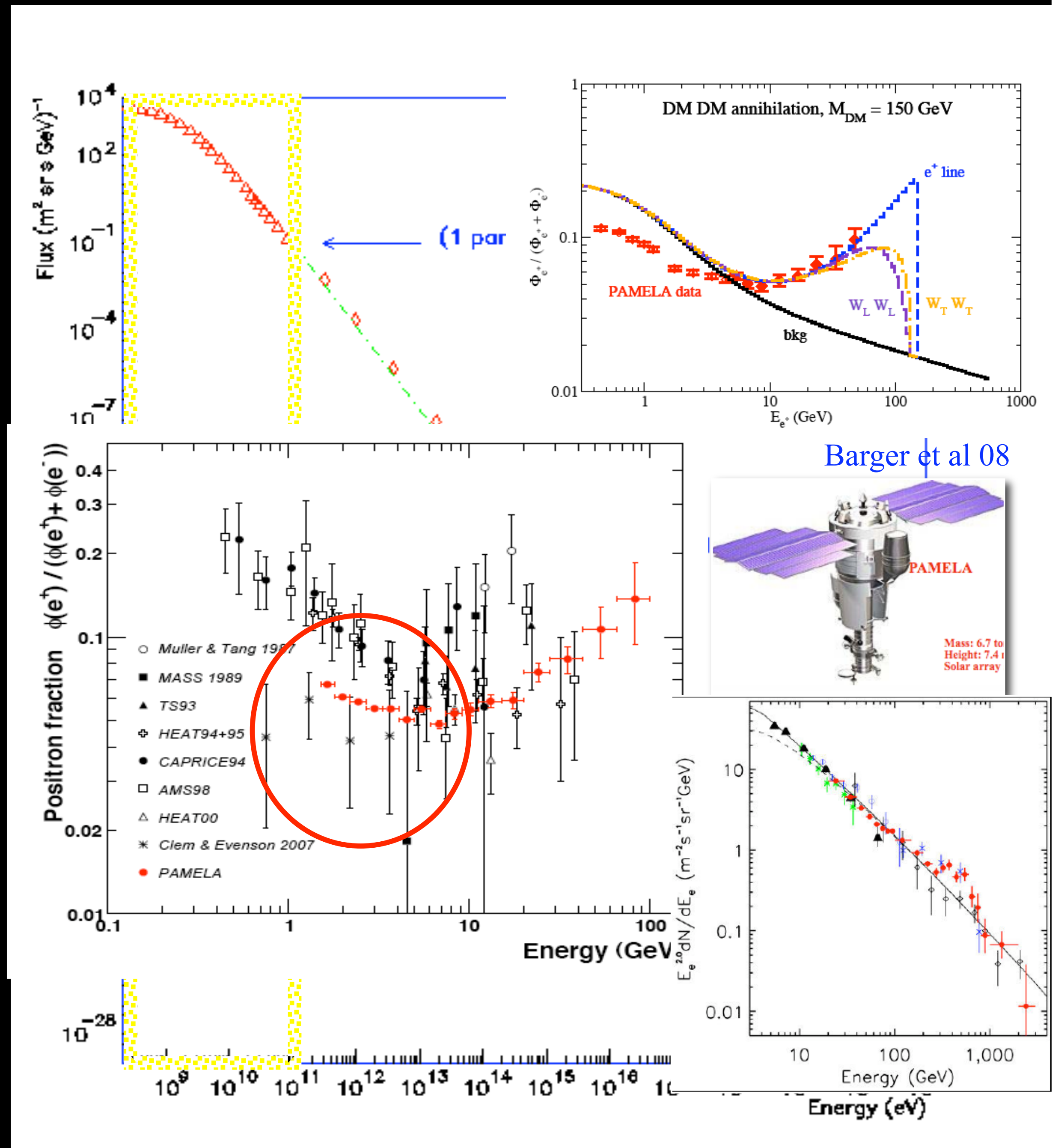
10^8 eV < E < 10^{11} eV

Solar Modulation

Pamela & ATIC

Dark Matter? Pulsars?

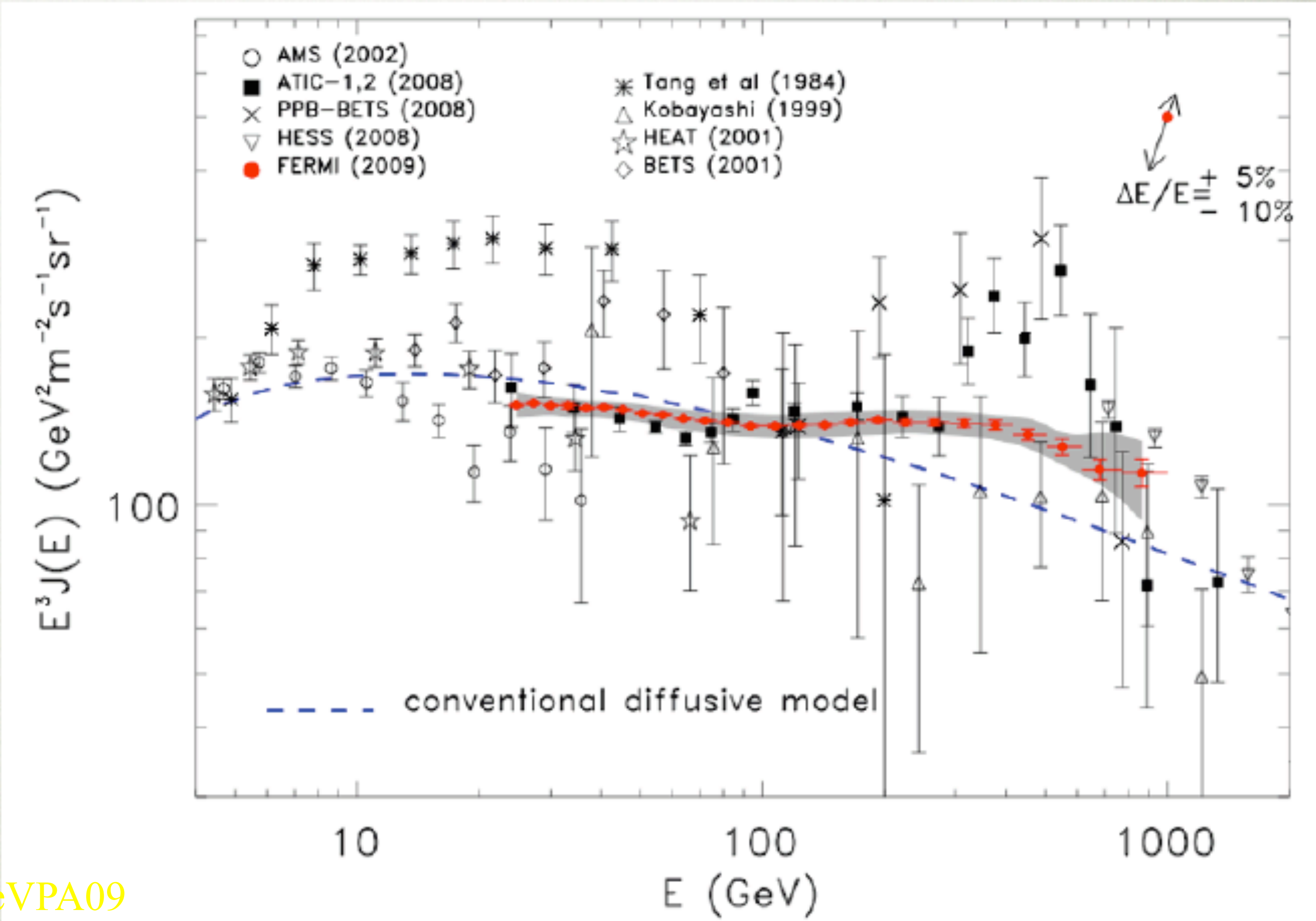




Dark Matter & LE Cosmic Rays?

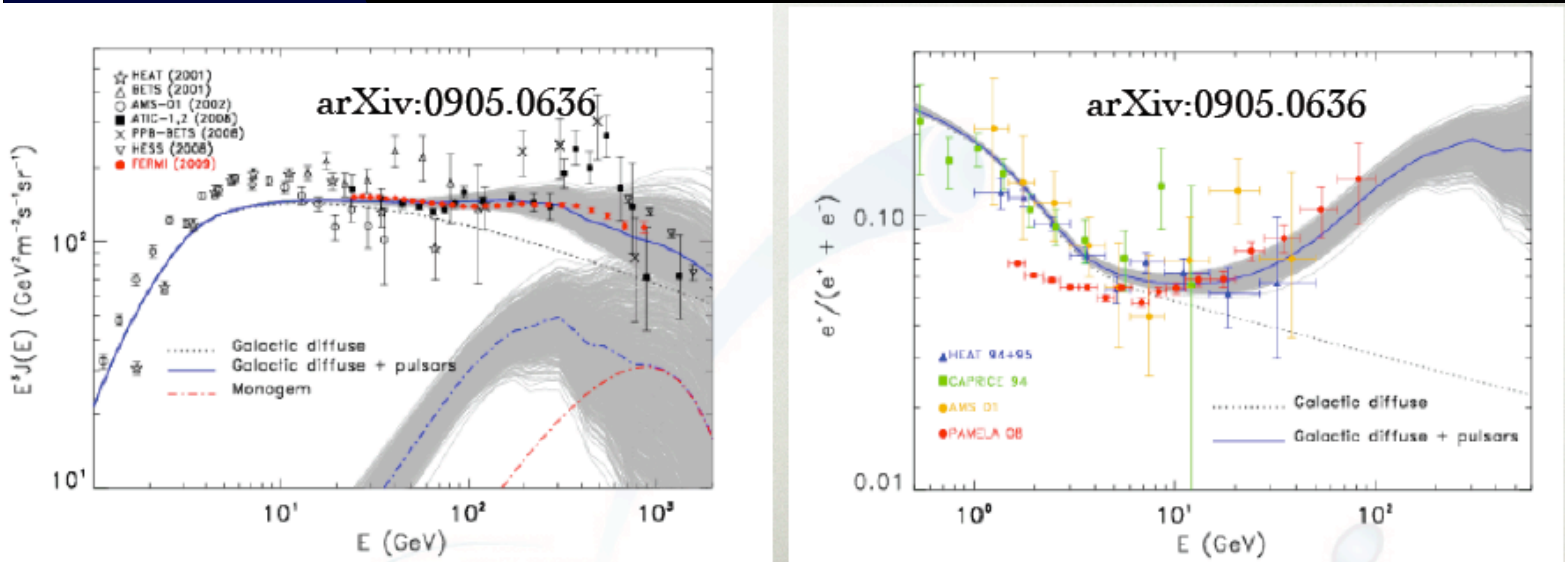
- Fermi says: No to ATIC! CR electron spectrum

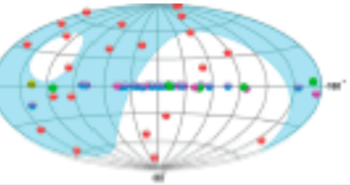
Phys. Rev. Lett. 102, 181101 (2009)



Dark Matter & LE Cosmic Rays?

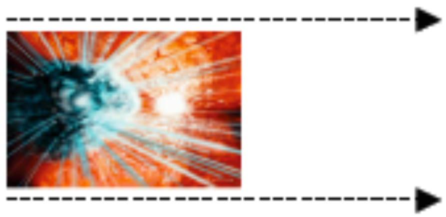
- Data consistent with astrophysical sources (pulsars SNR) + CR propagation.





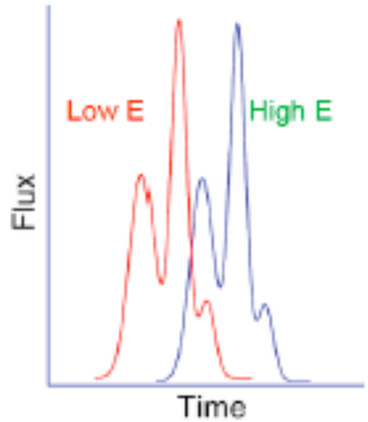
"Time of flight" test: c = const?

E_1



E_2

$E_1 >> E_2$

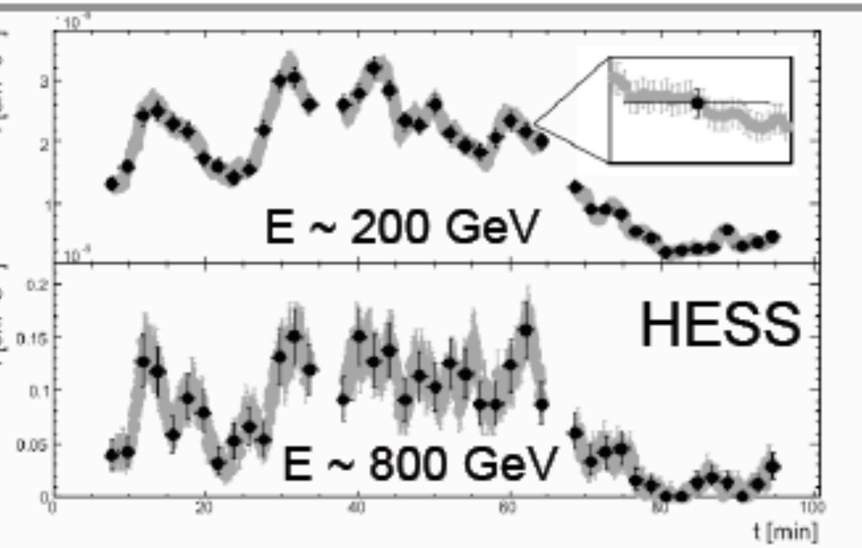


Amelino-Camelia, G., Ellis, J. et al. 1998 , Nature, 395, 525

$$t_1 = \frac{L}{c}\left[1 - \xi \frac{E_1}{E_{QG}}\right]$$

$$t_2 = \frac{L}{c}$$

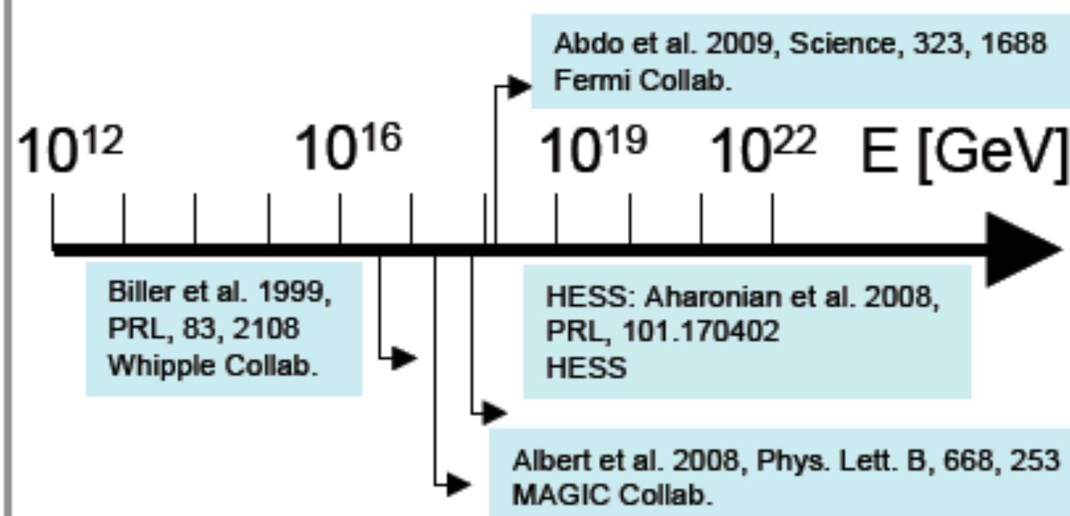
$$\Delta t \approx \left(\frac{L}{c}\right)\left(\xi \frac{E}{E_{QG}}\right)$$



PKS2155-304

Krennrich TeVPA09

$$E_{QG} > 7.2 \times 10^{17}\, GeV$$



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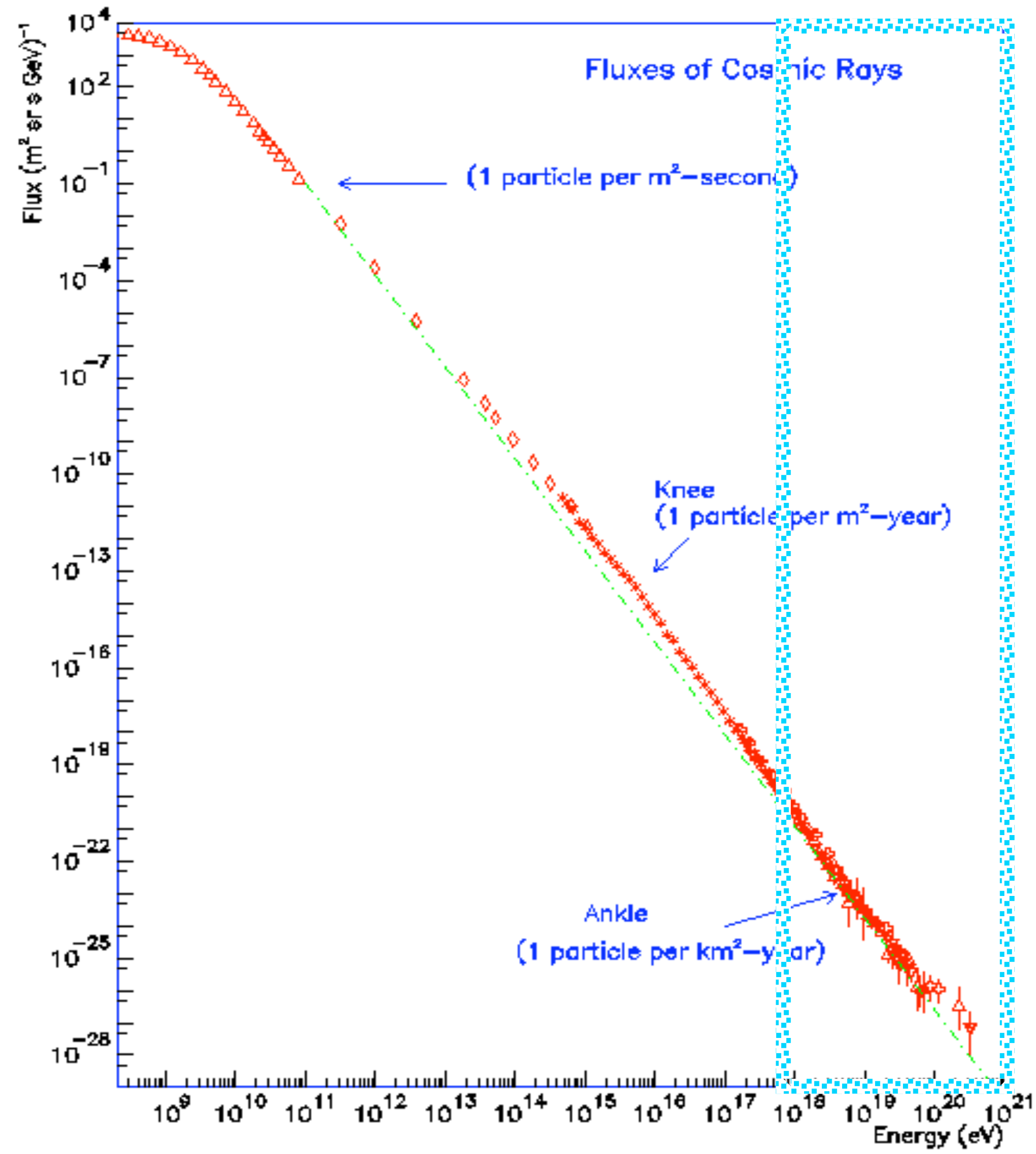
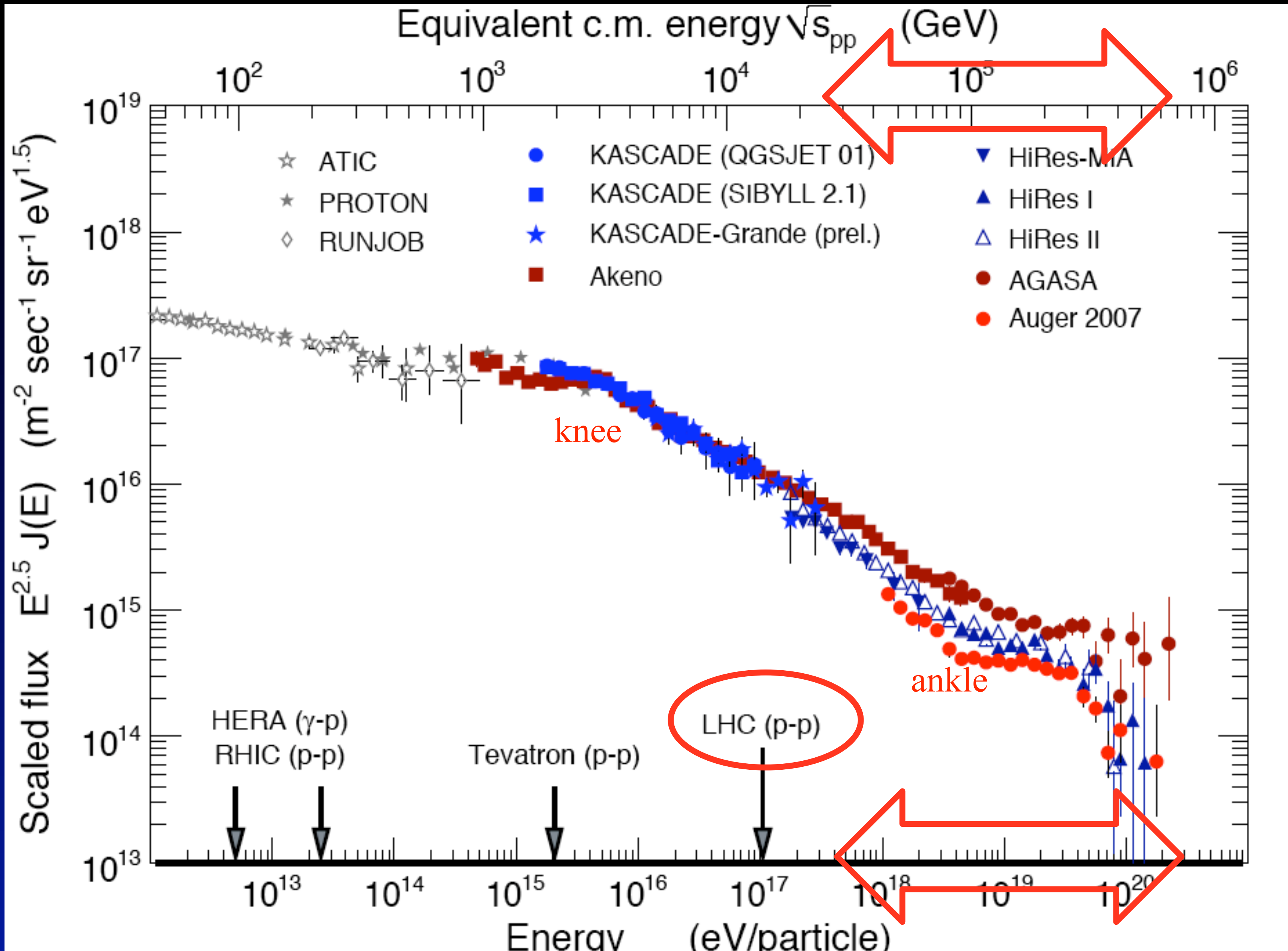
Extragalactic Sources





Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
Scaled flux $E^{2.5}$ J(E) (m^{-2} sec^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2007
knee
ankle
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

Engel'08

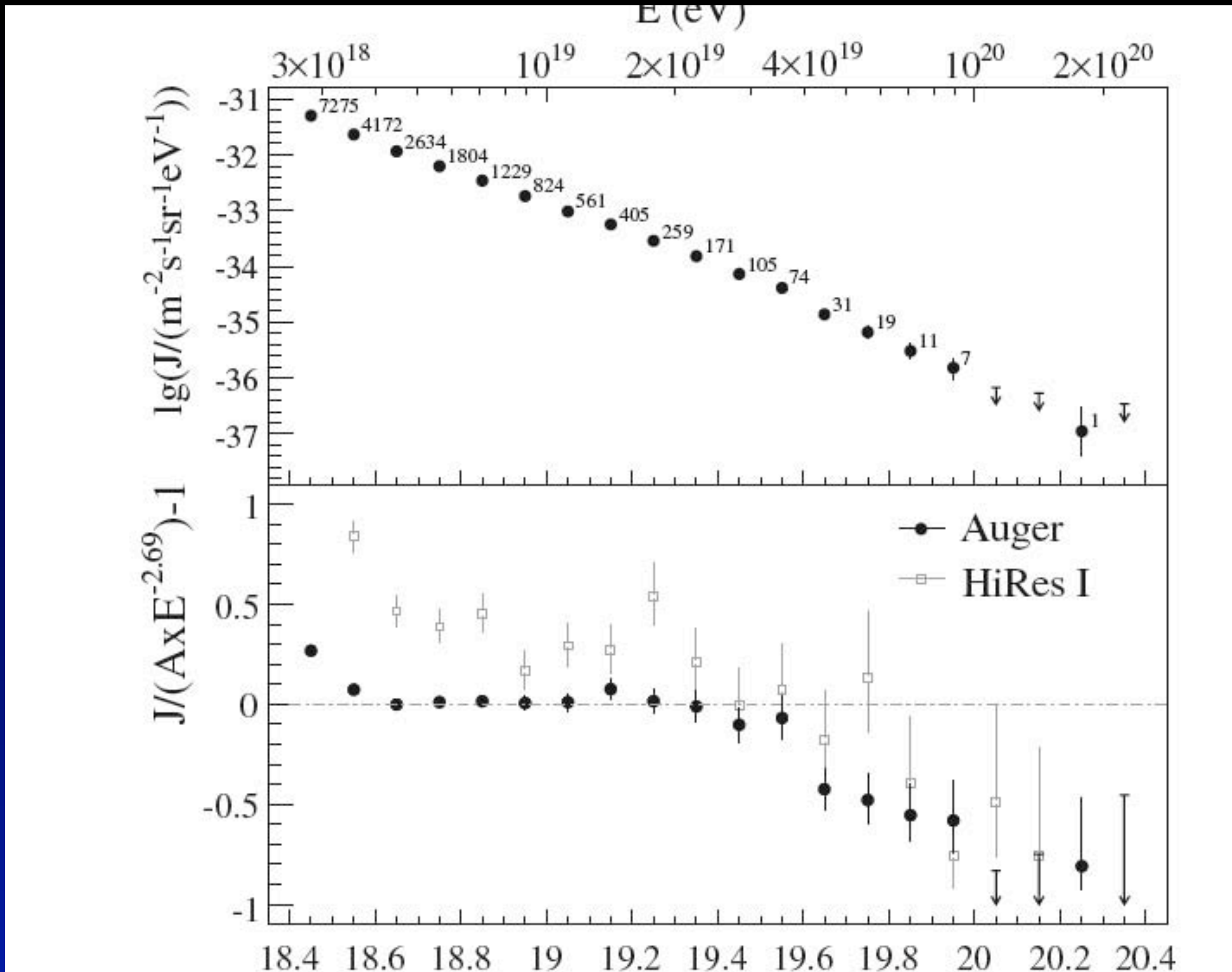
UHE CRs (+ photons & neutrinos)

- To understand Nature's Highest Energy Accelerators (EXTRAGALACTIC)
- To use UHE Cosmic Particles to study HE interactions (~ 350 TeV CM)

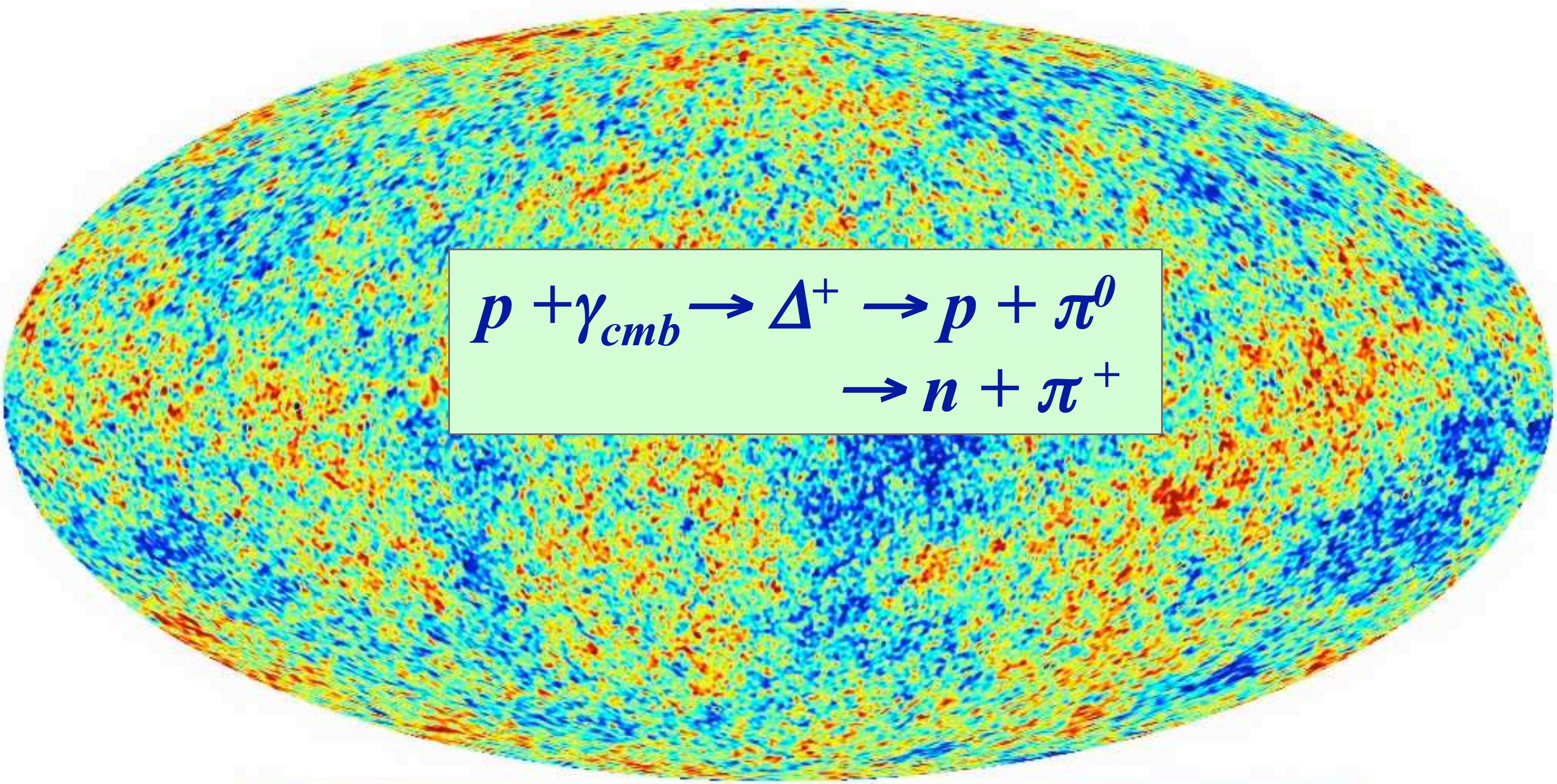
Pierre Auger Observatory

See C Covault's talk

Auger & HiRes spectra (2008)

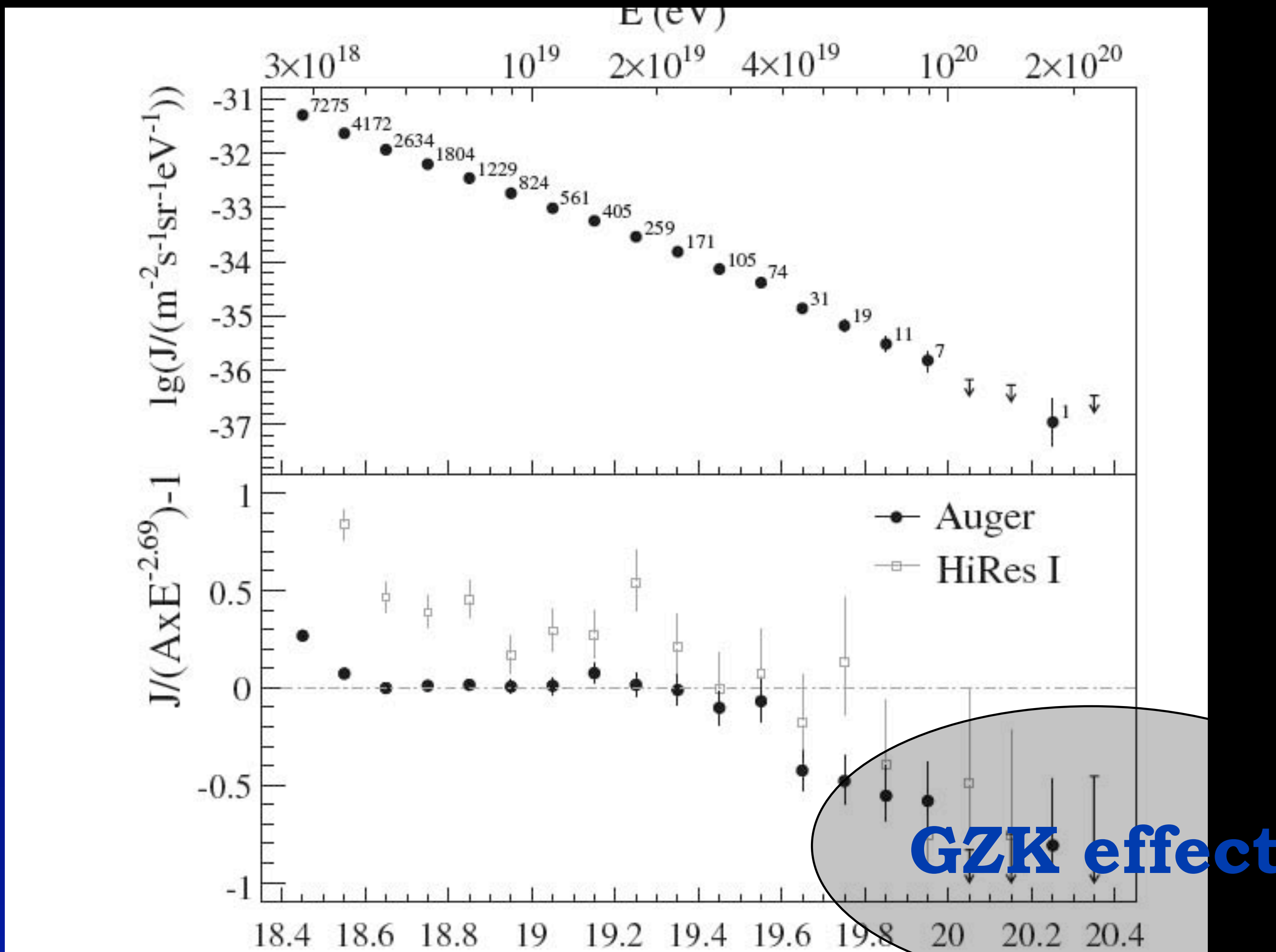


GZK effect
Greisen, Zatsepin, Kuzmin 1966

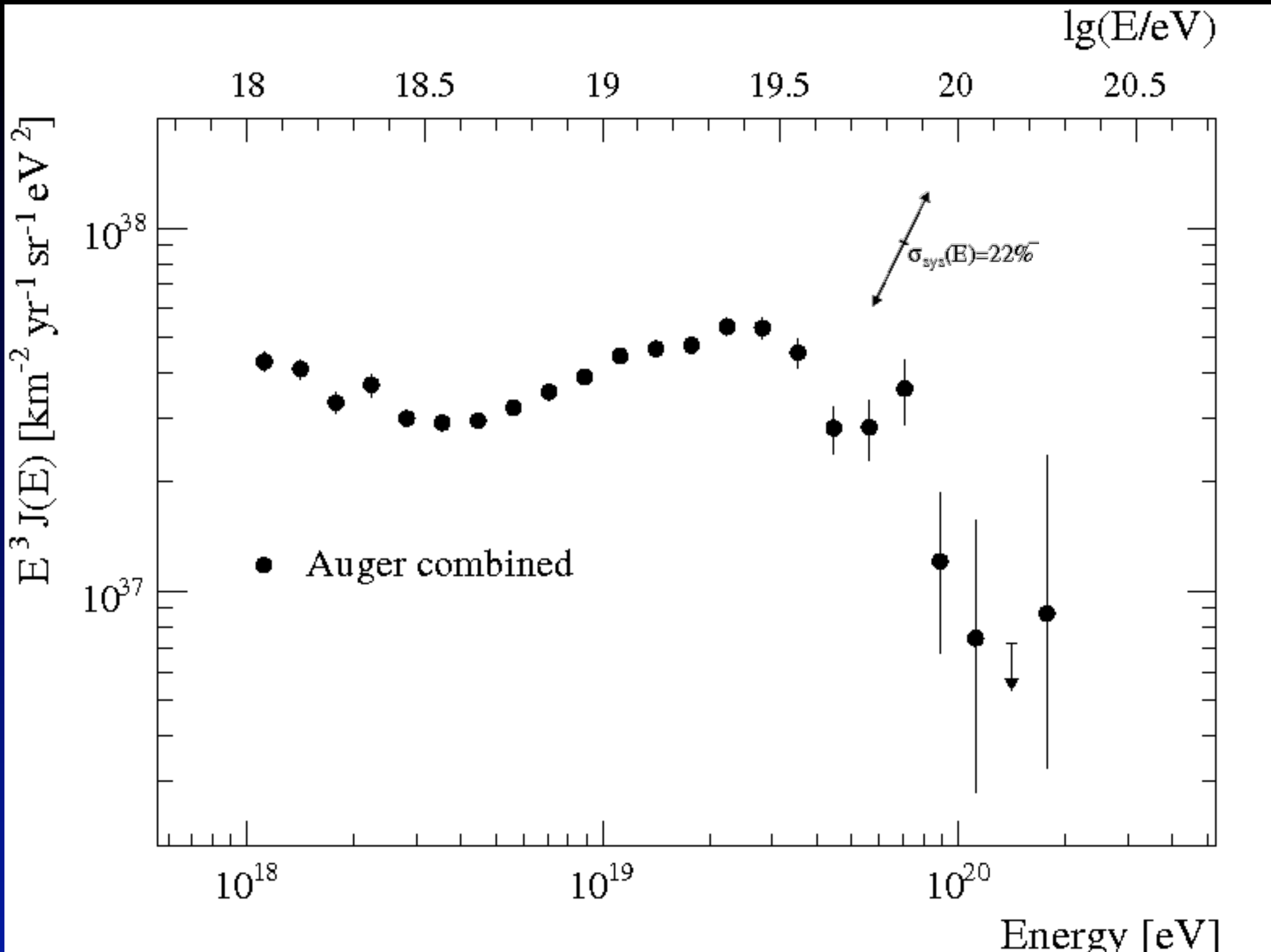


$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Auger & HiRes spectra (2008)

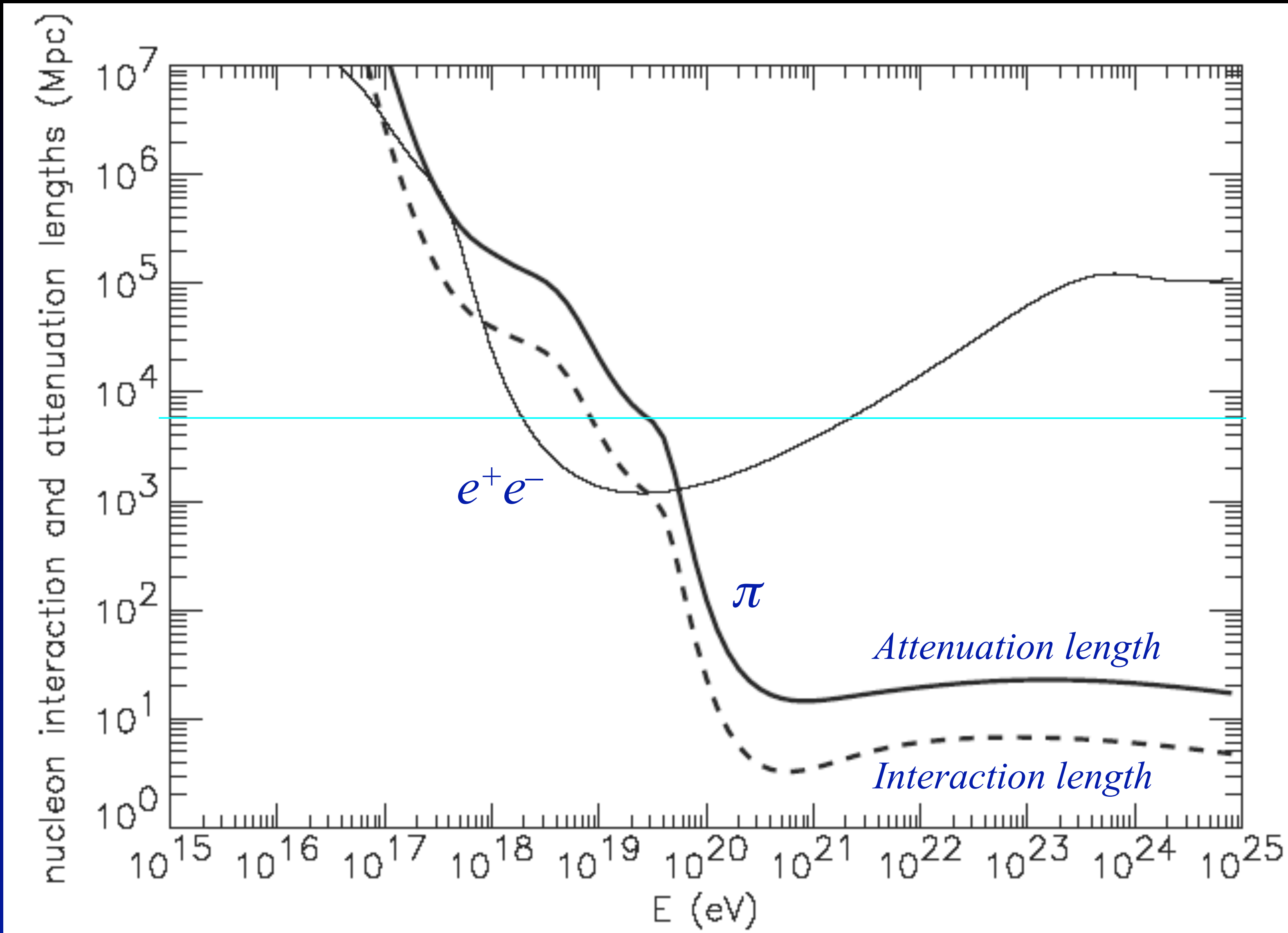


E^3 x Flux

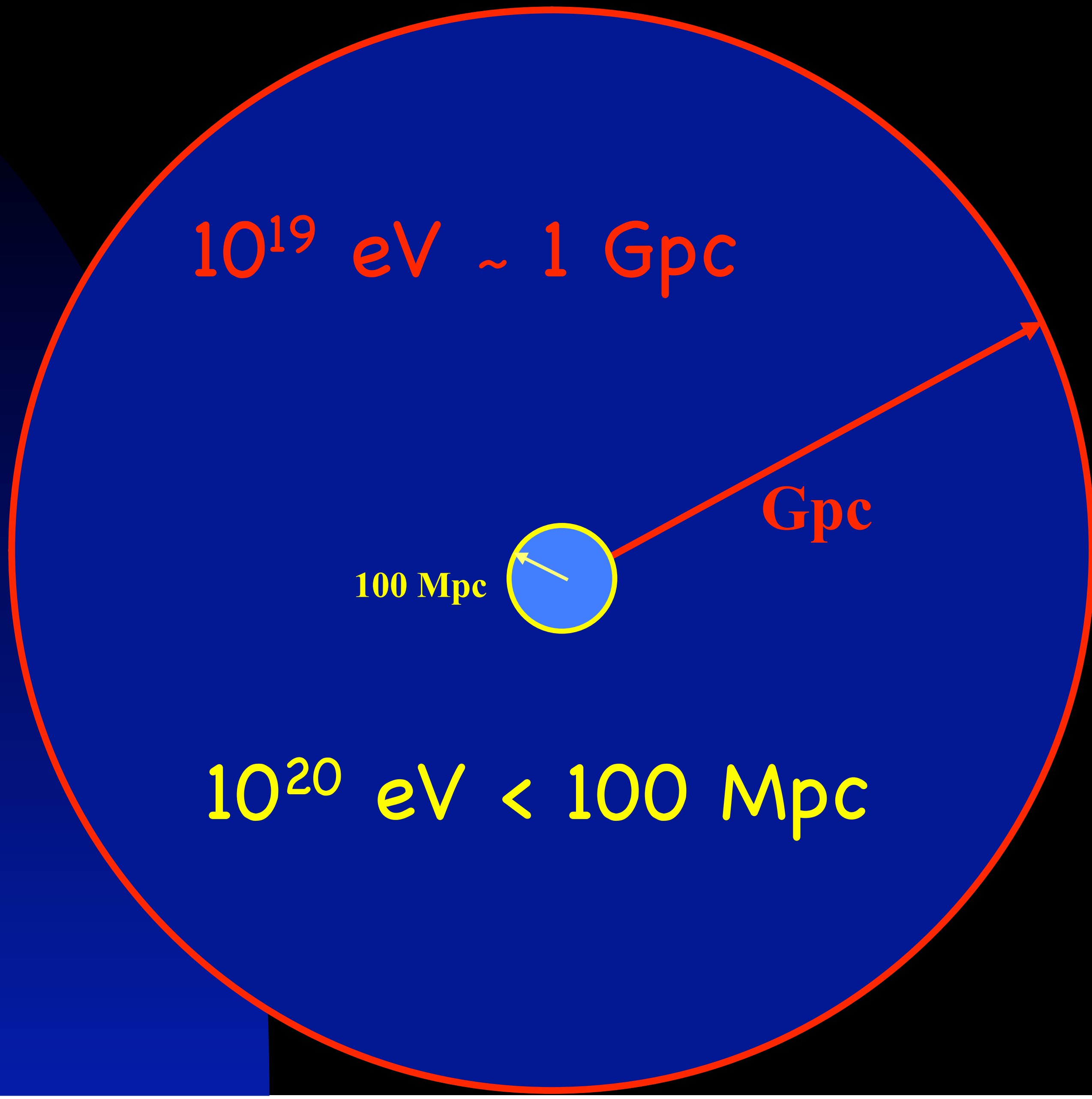


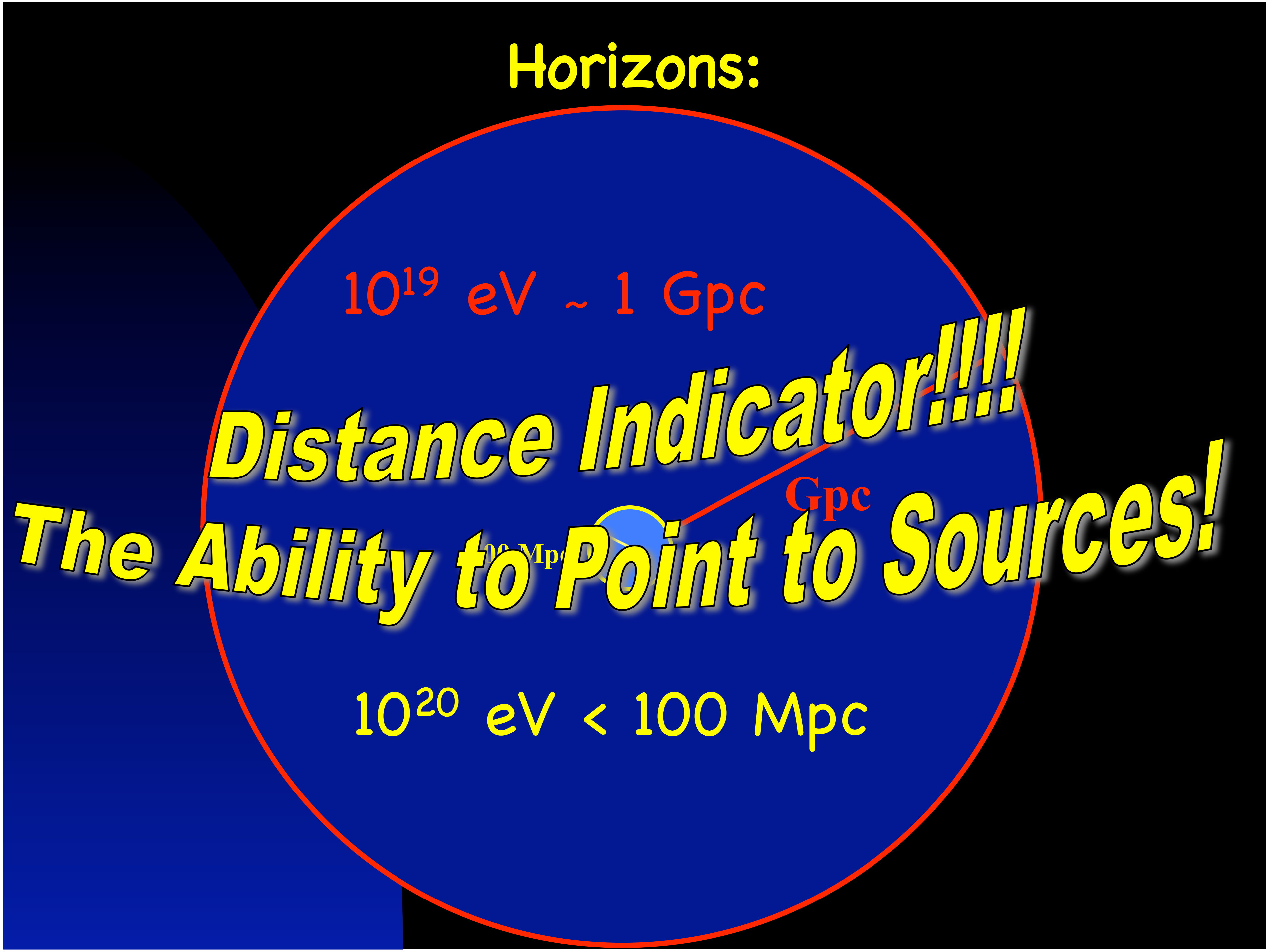
lg(E/eV)
18
18.5
19
19.5
20
20.5
E 3 J(E) [km-2 yr-1 sr-1 eV 2]
10^38
10^37
σsys(E)=22%
Auger combined
10^18
10^19
10^20
Energy [eV]

Attenuation length



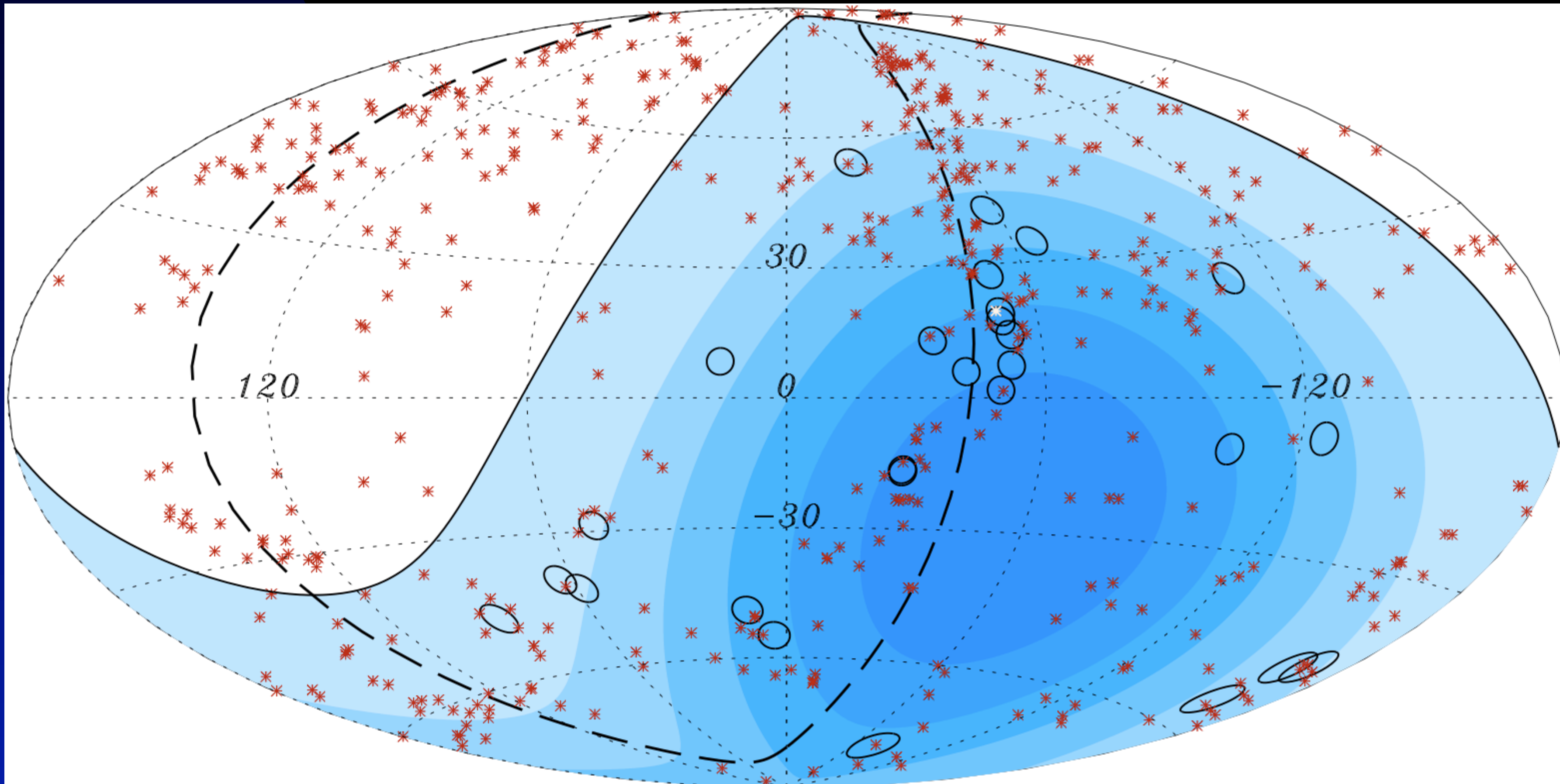
Horizons:



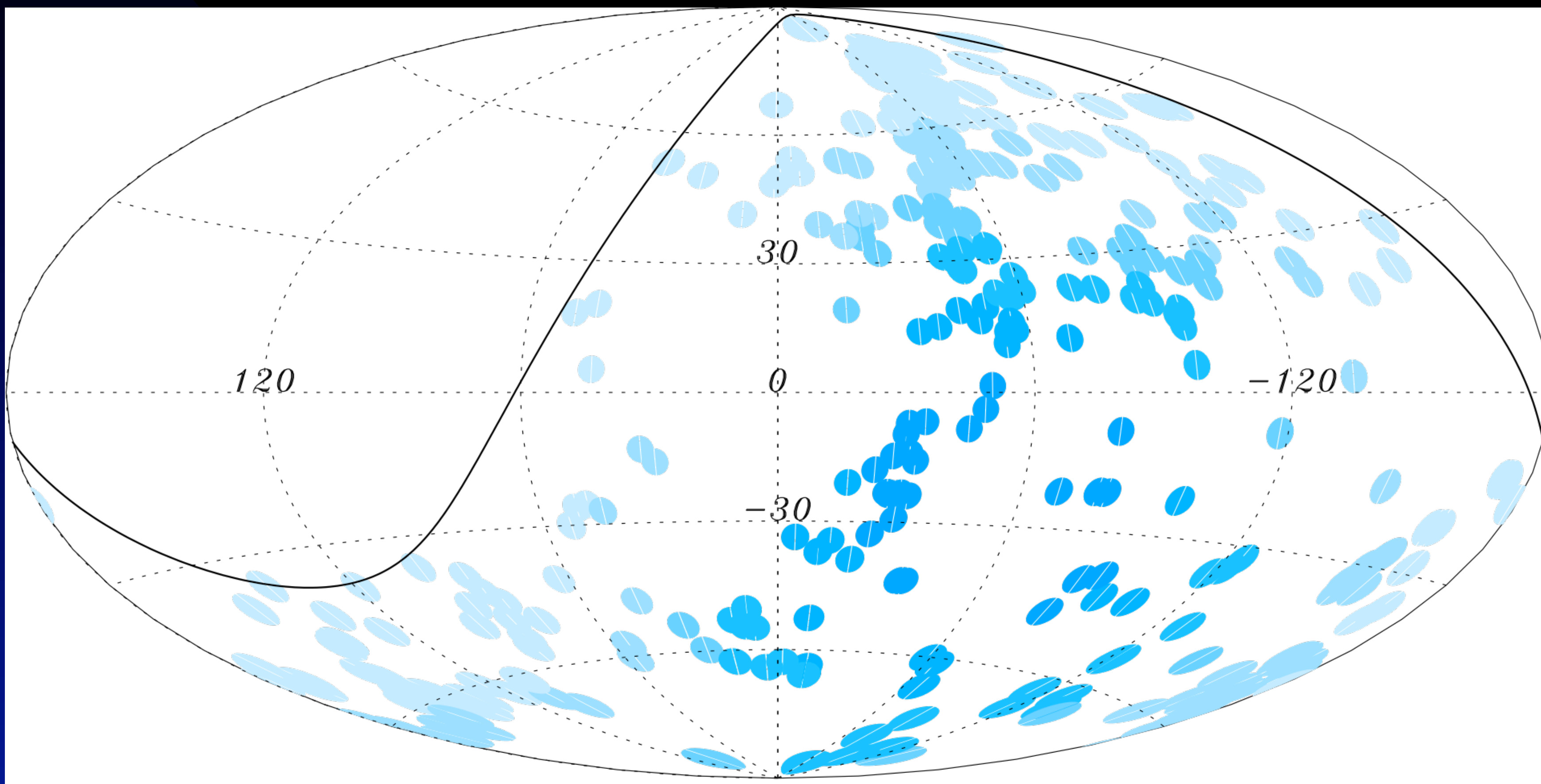

Horizons:
10^19 eV ~ 1 Gpc
Distance Indicator!!!!
Gpc
The Ability to Point to Sources!
10^20 eV < 100 Mpc

Auger VCV correlation

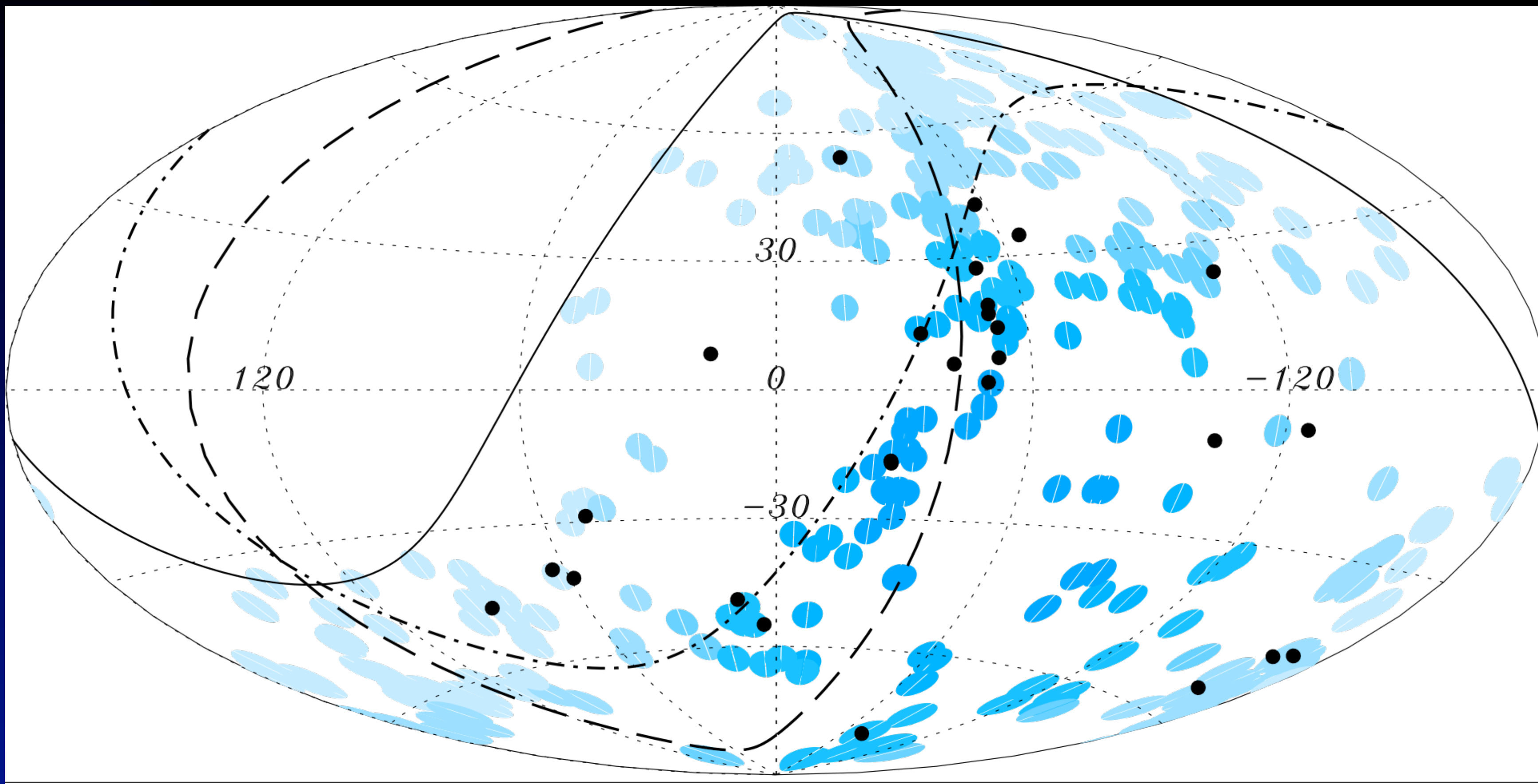
- VCV catalog of AGN: $z < 0.018$, $\theta \sim 3°$, $E > 57$ EeV
- 27 events test prescription: 99% isotropy rejection



Nearby VCV AGN – 21% sky



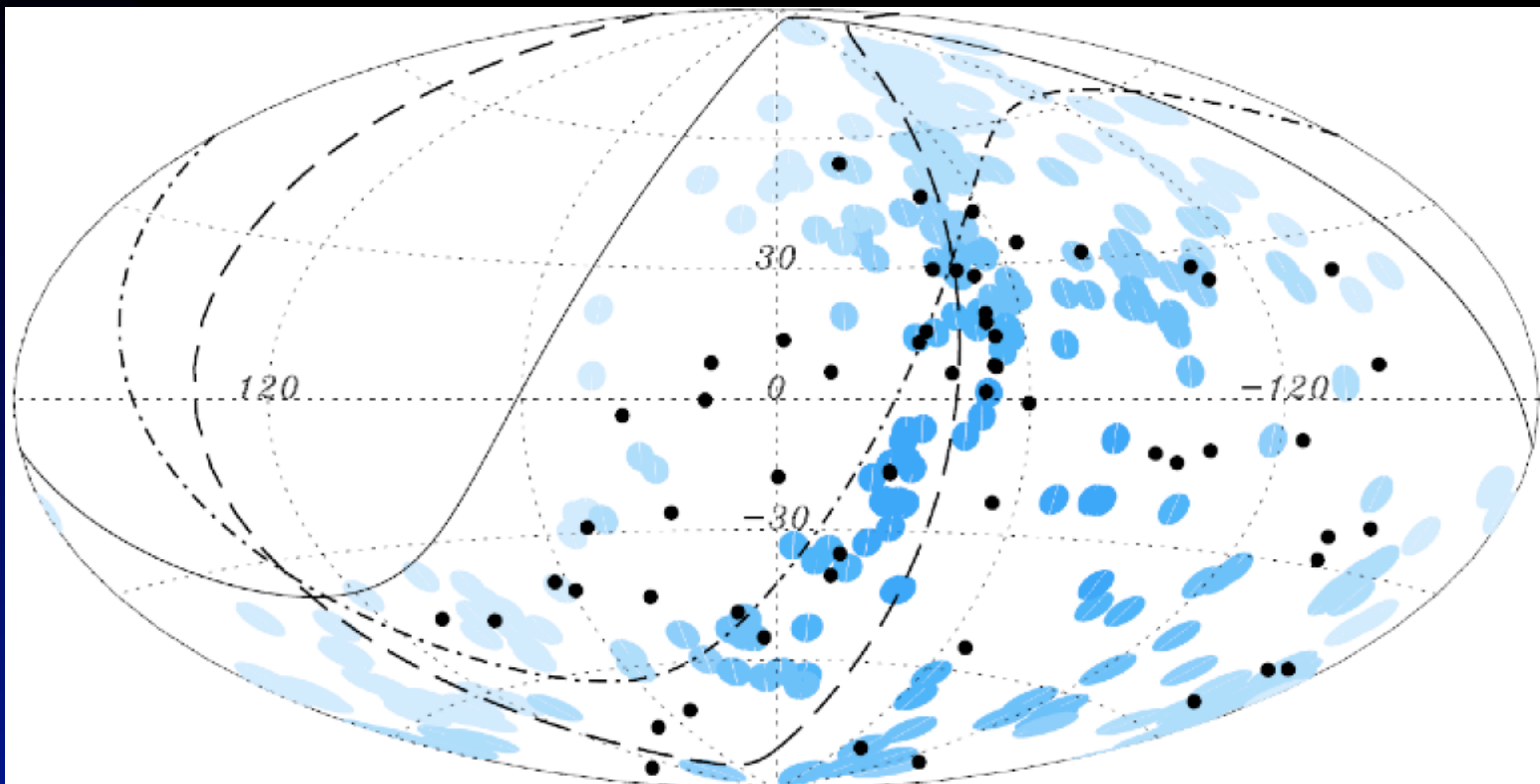
First 27 events



Exploratory scan – 12/15 events correlated (3.2 expected)
Prescription passed when 8/13 correlated (2.7 expected)

Recent Results

58 events above 55 EeV

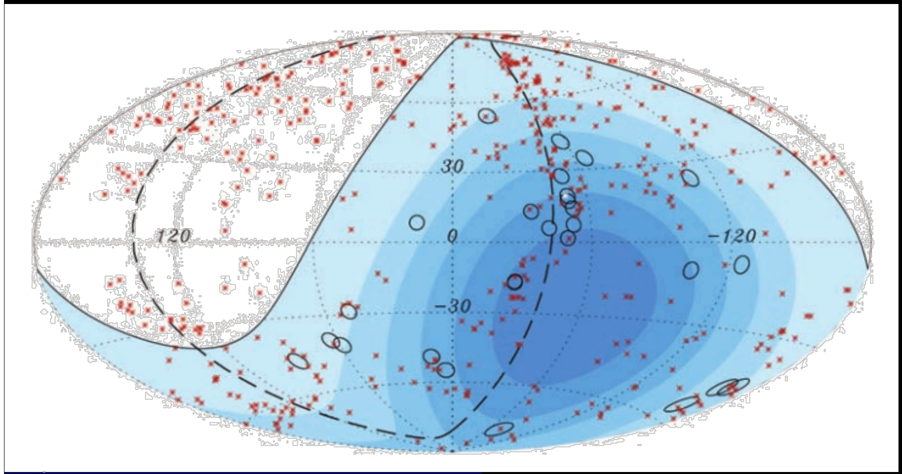


Correlation decreased to 38% (2 s.d from isotropy)

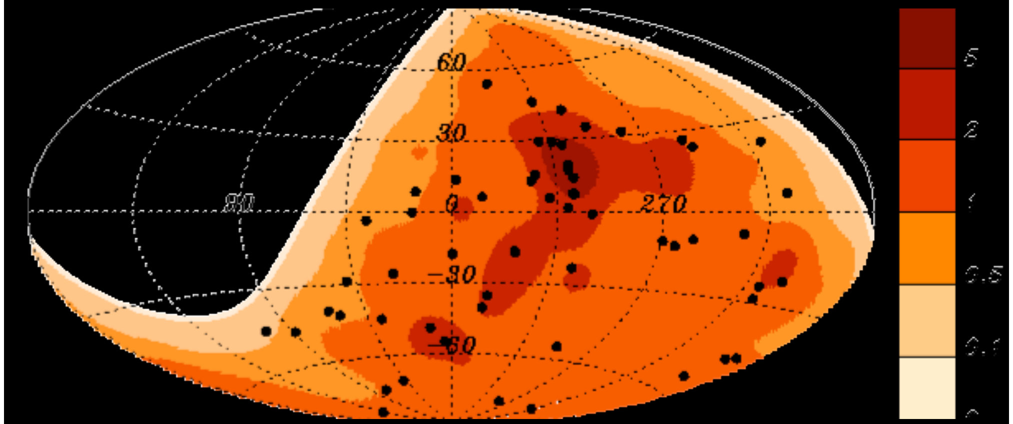
26/58 (iso 12.2) and masked - 25/45 (iso 11.3)

(P ~ (6) 2 10-3 (un) masked events after scan)

The Auger Sky above 60 EeV

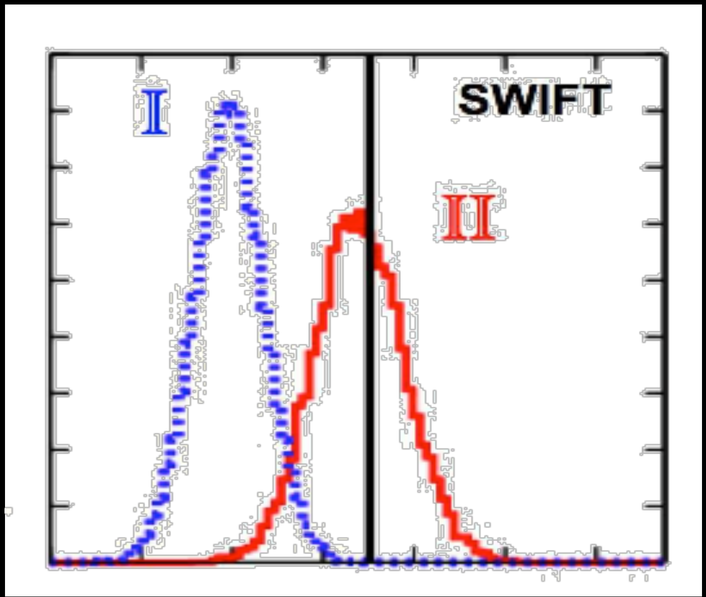


27 events as of November 2007



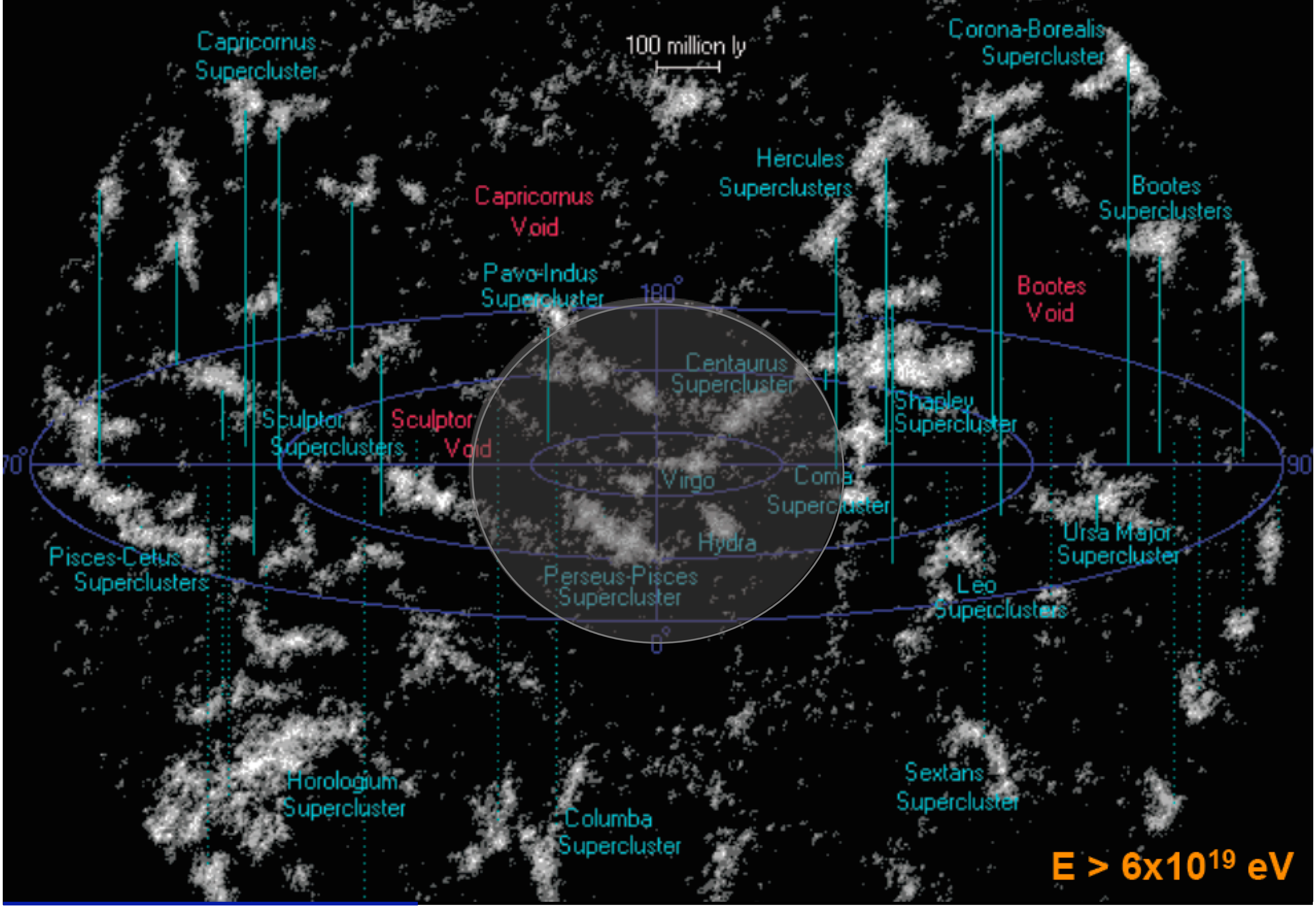
58 events now (with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).

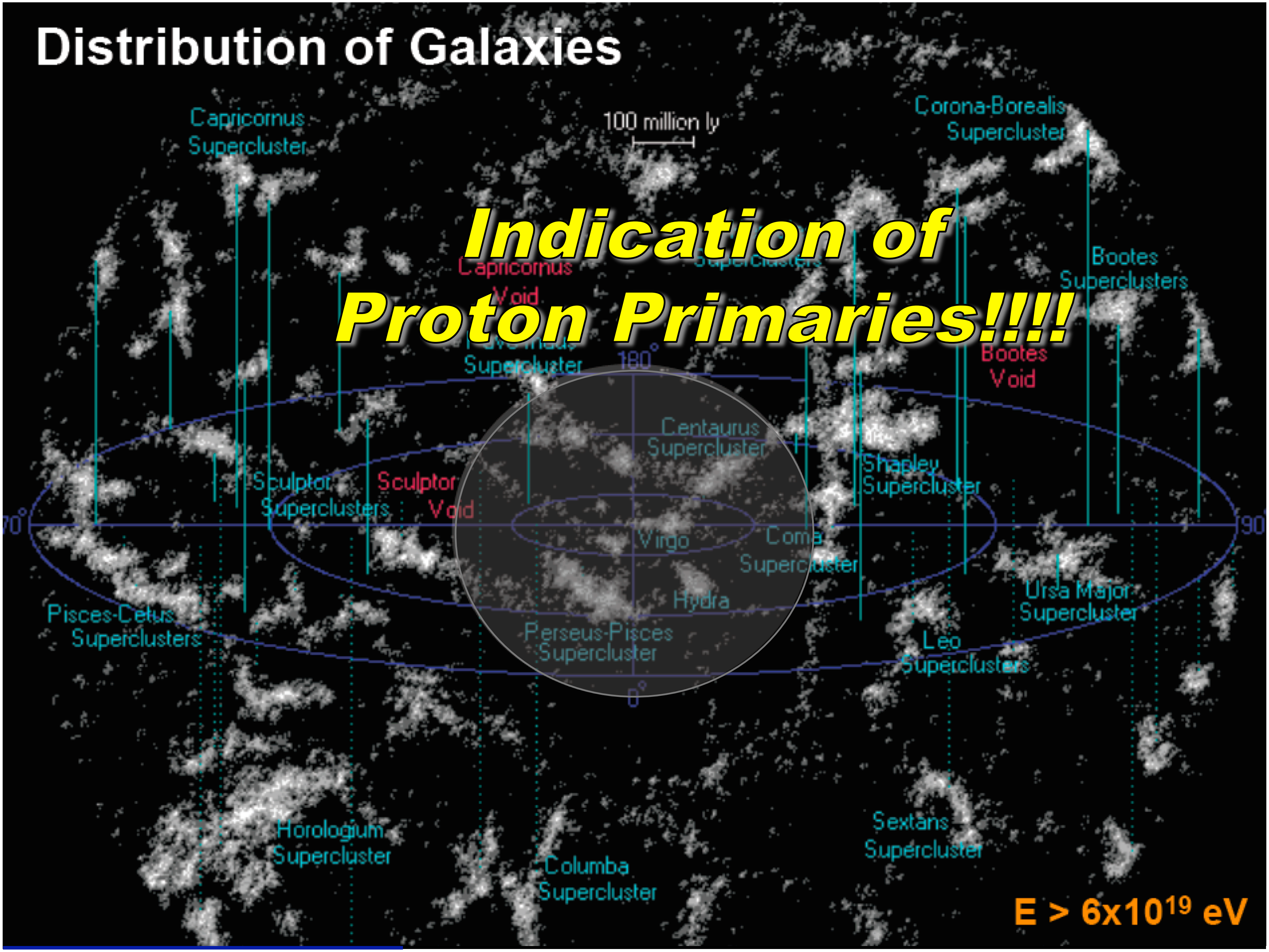


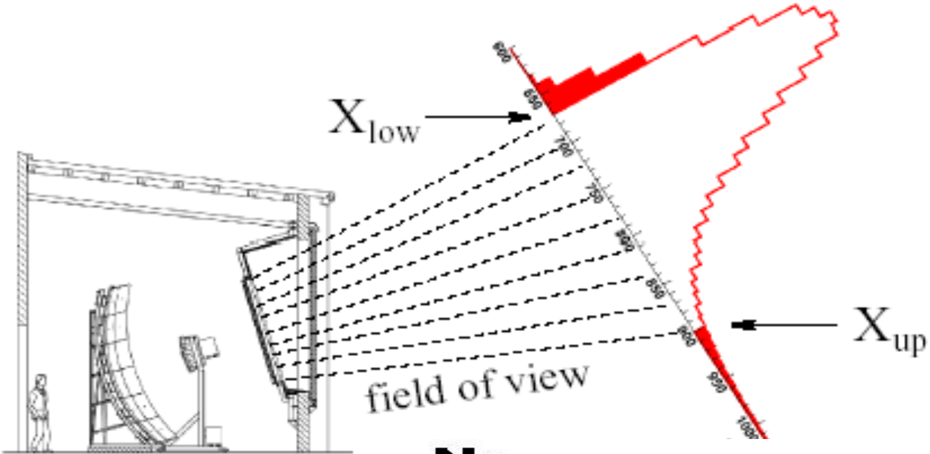
Log(Likelihood)

Distribution of Galaxies

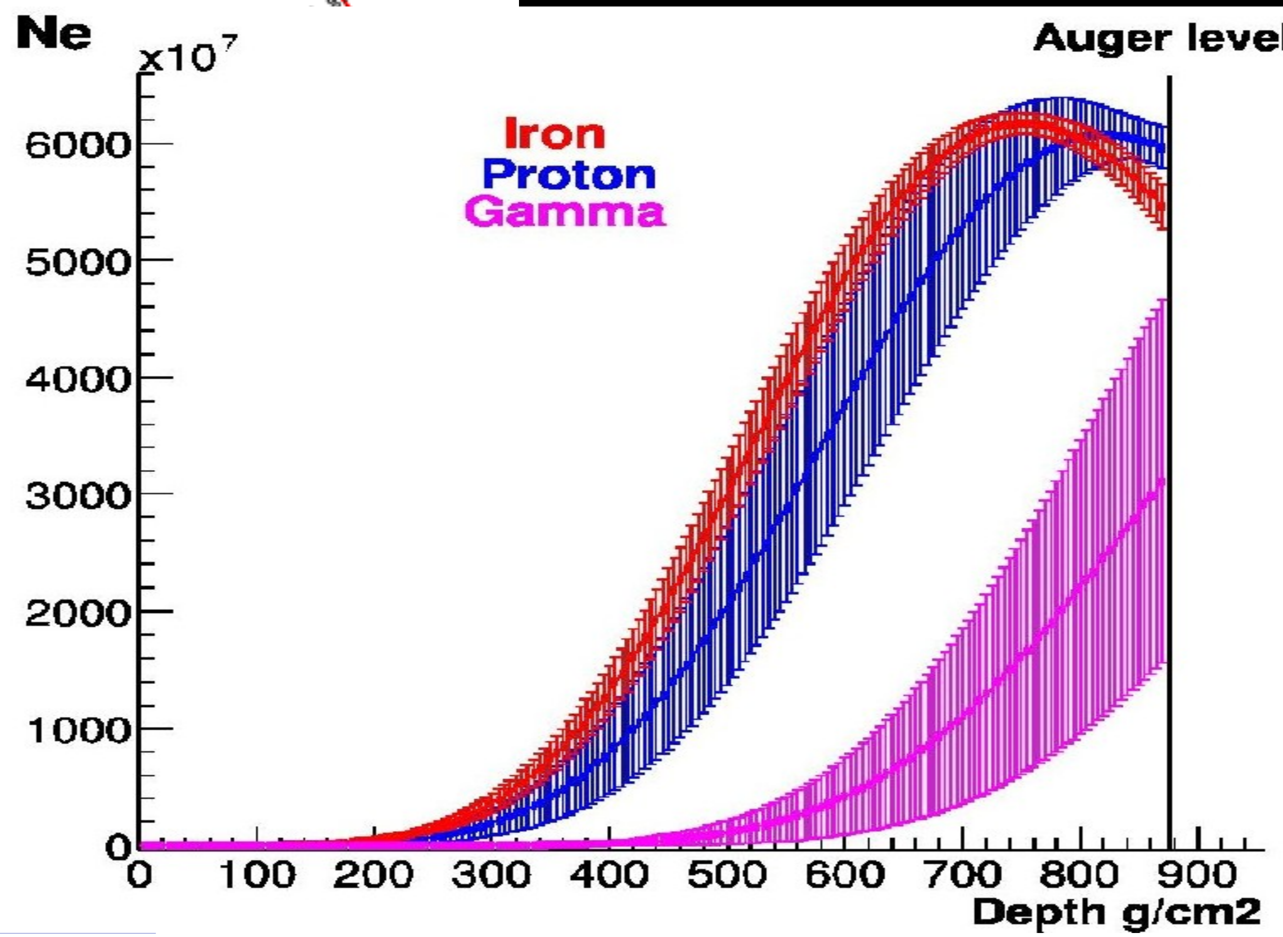


E > $6x10^{19}$ eV


Distribution of Galaxies
Indication of
Proton Primaries!!!!
100 million ly
Capricornus Supercluster
Corona-Borealis Supercluster
Bootes Superclusters
Capricornus Void
Bootes Void
Pavo-Indus Supercluster
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
180°
0°
270°
90°
E > 6x10^19 eV



Composition observable: shower maximum average & RMS

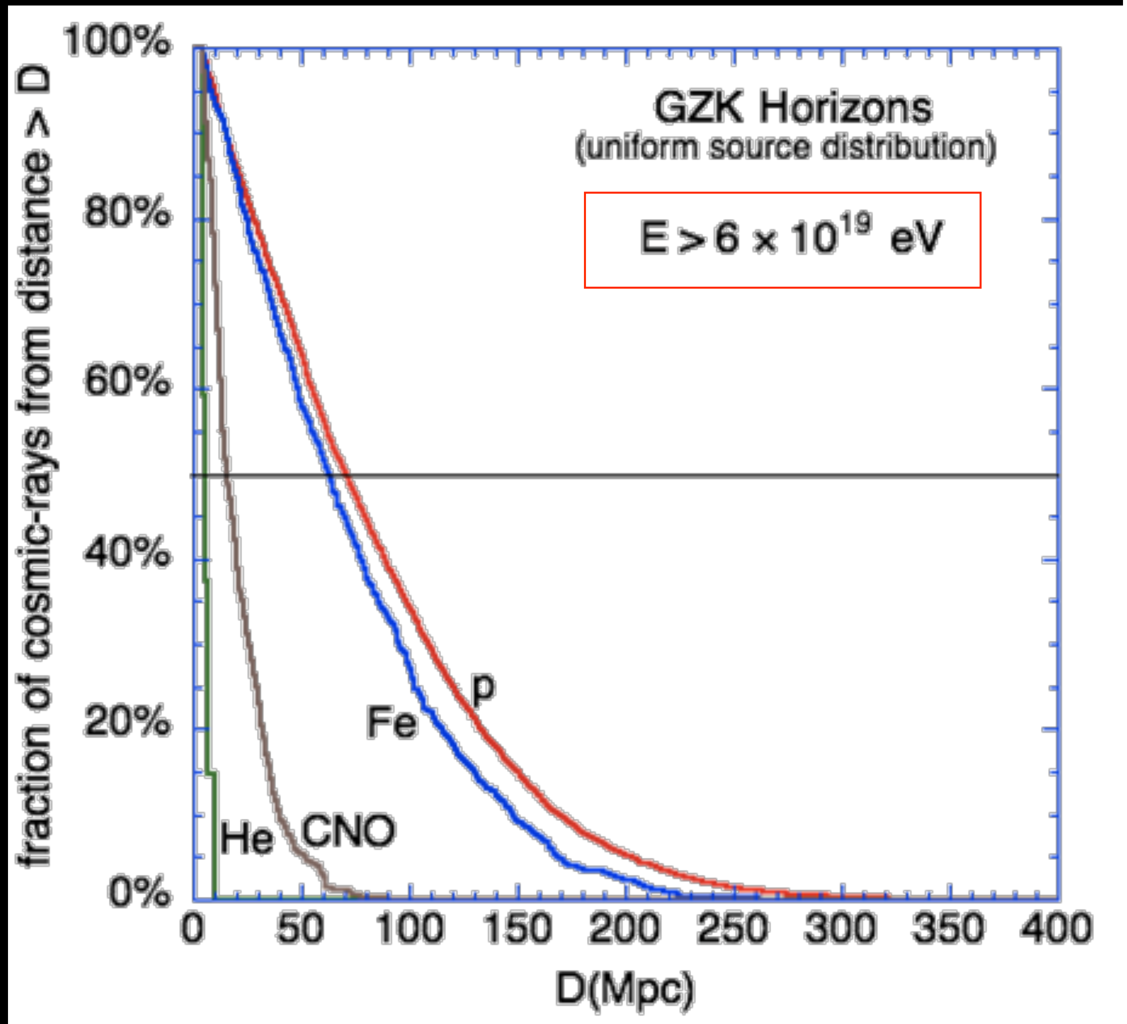


Trans-GZK composition is simpler

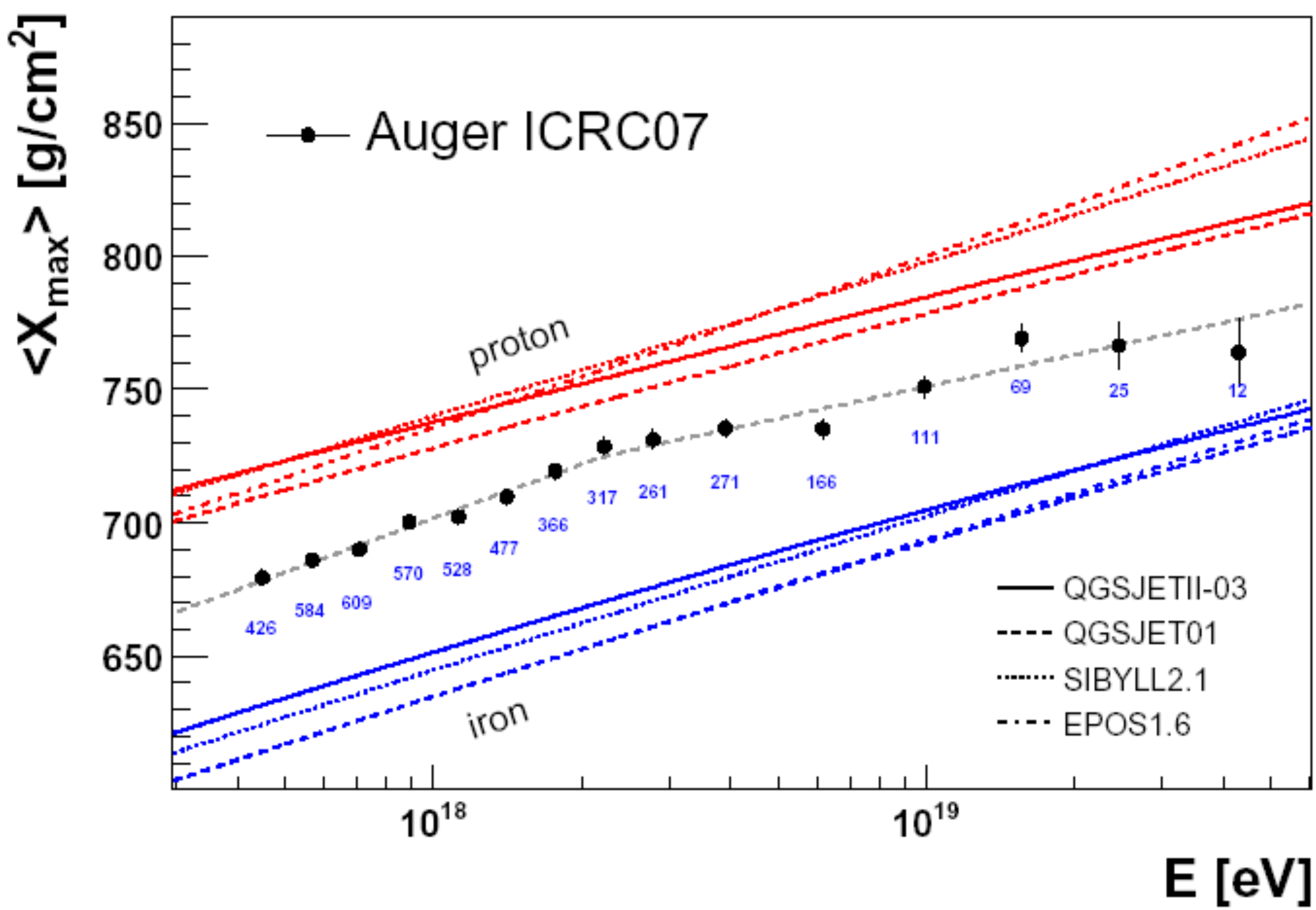
Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

Cosmic magnetic fields should make highly charged nuclei almost isotropic.

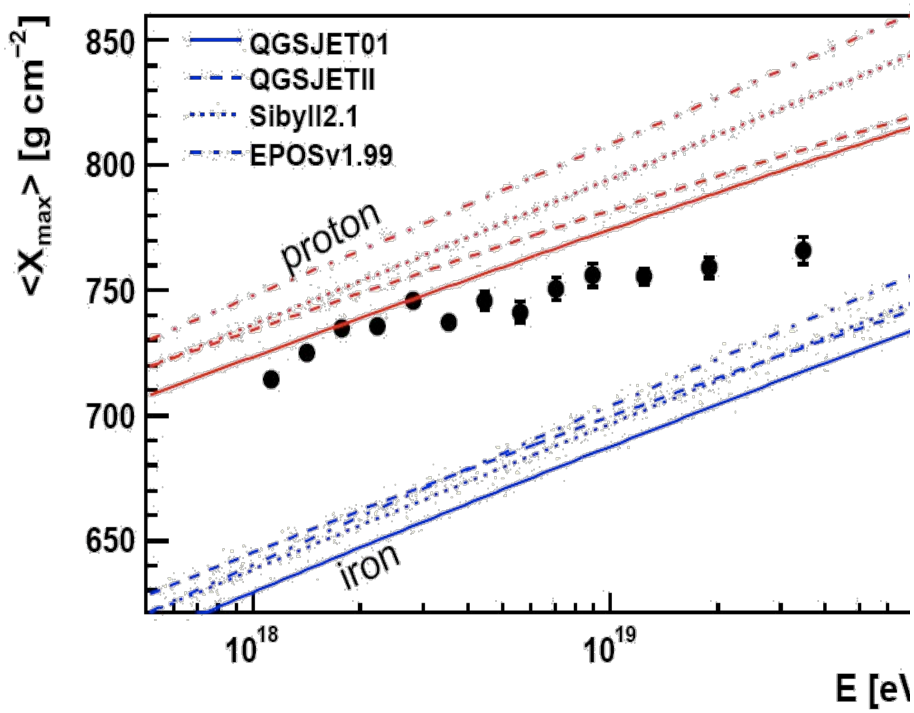


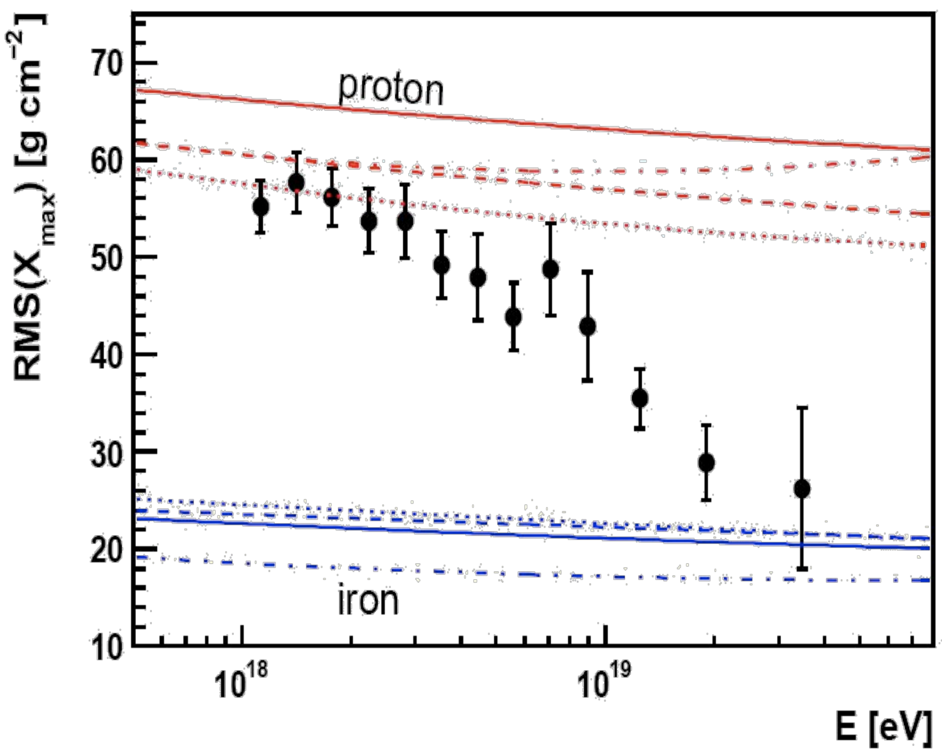
Shower maximum over 2 decades in E



Shower Depths of Maximum X_{max}

Auger ICRC 2009





Heavy nuclei?

Protons? - Higher Cross section and/or high multiplicity at high energy.

Puzzling Composition

- Unexpected Astrophysics:
  - Sources are very Iron rich
  - and have low E_{max}
- Interesting Particle Physics:
  - Hadronic Models do not represent well UHE interactions

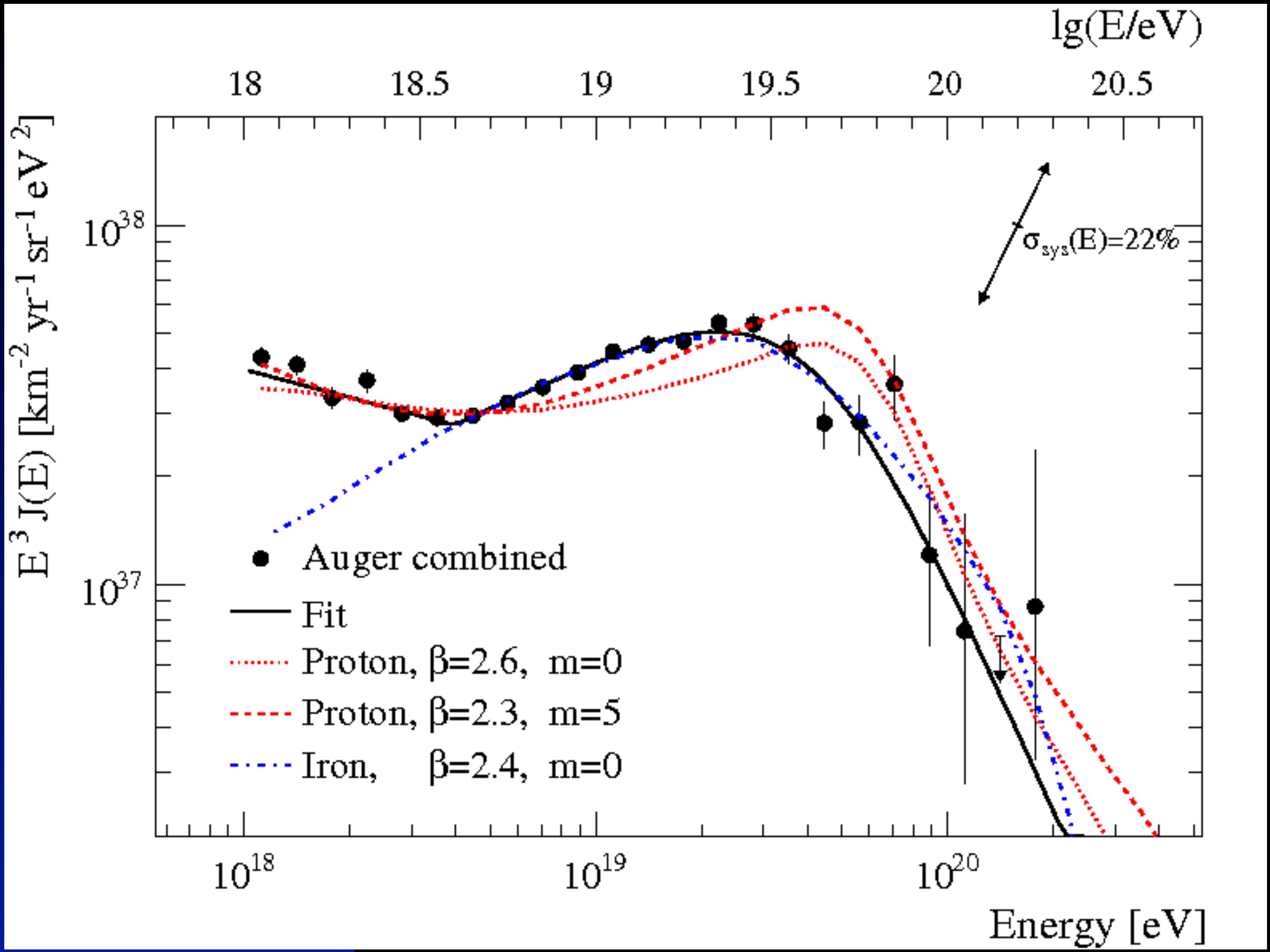
Puzzling Composition

- Unexpected Astrophysics:
  - Sources are very Iron rich
  - and have low E_{max}

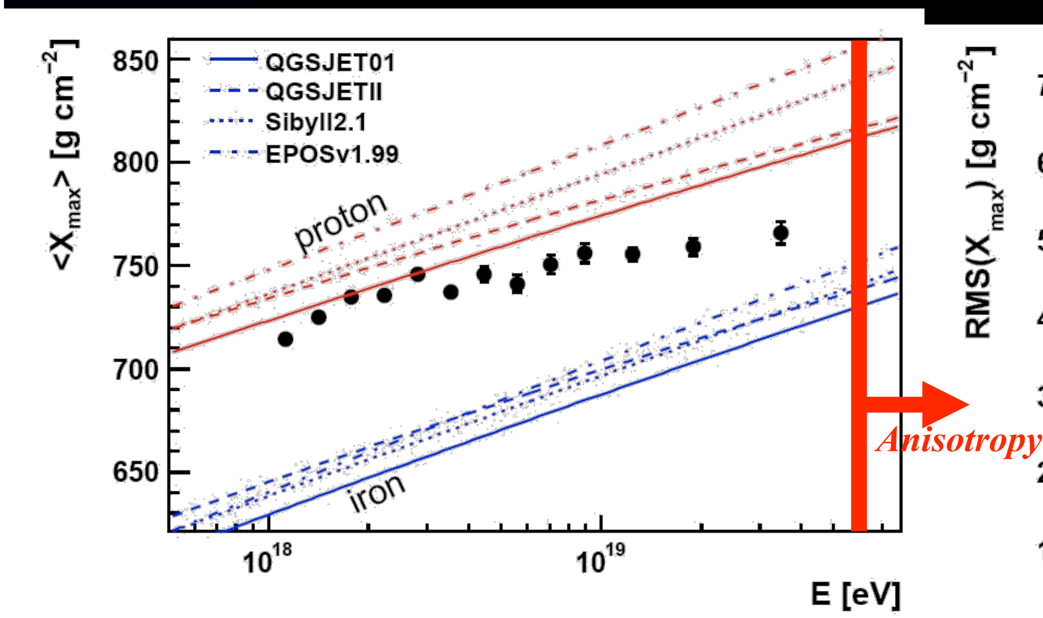
Very Bad News for Neutrino Detectors

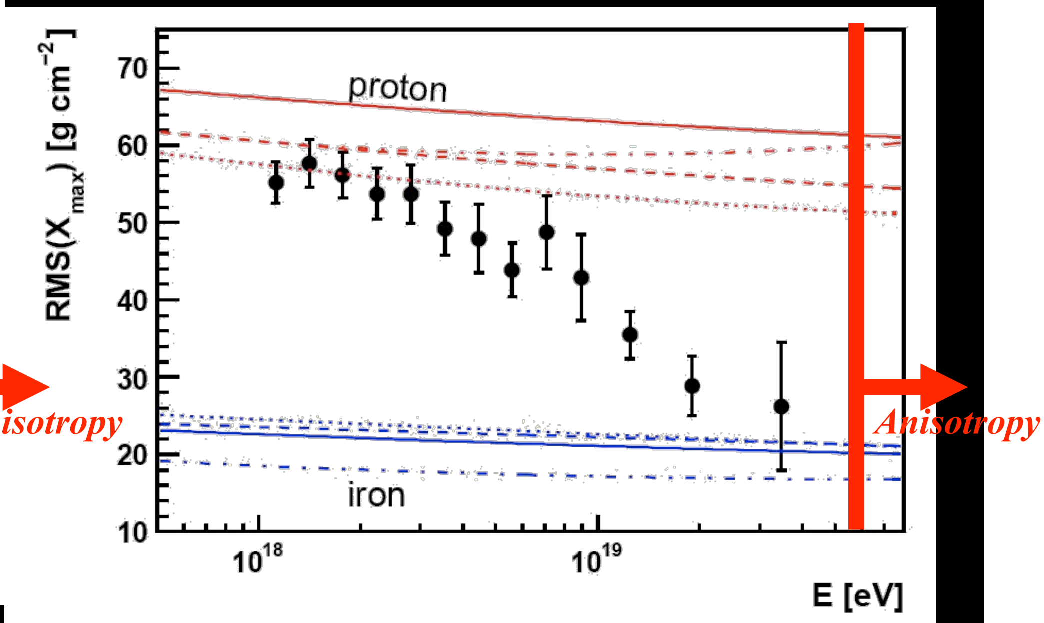
- Interesting Particle Physics:
  - Hadronic Models do not represent well UHE interactions
- ***Higher Cross Sections or Multiplicities***

GZK fits to spectrum



Shower Depths of Maximum X_{max}

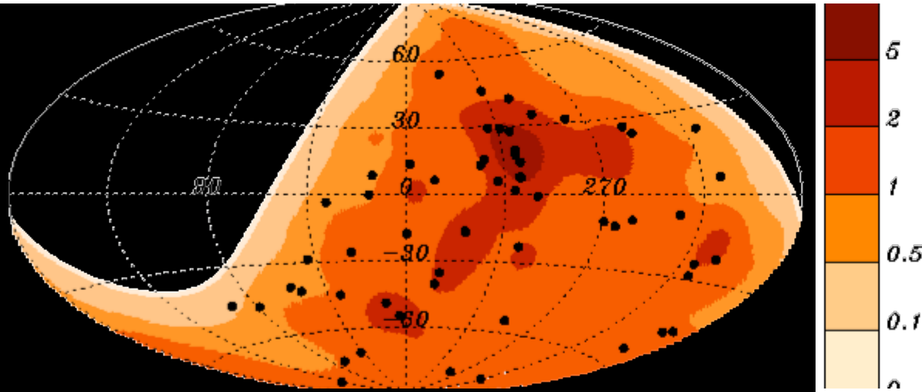




No Information for anisotropic trans-GZK energy regime!

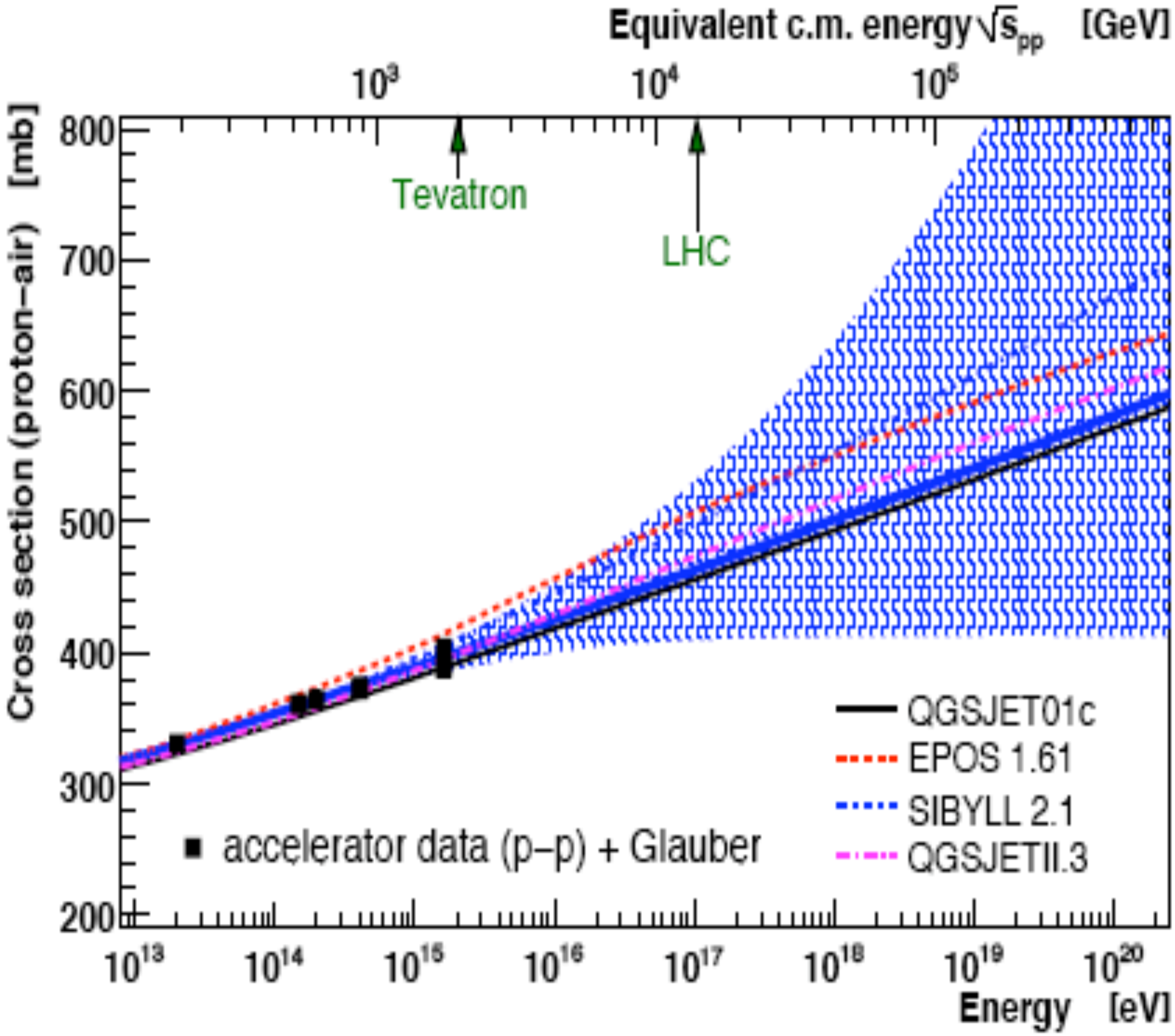
(Crucial for prediction of the diffuse cosmogenic neutrino & photon fluxes)

If Correlated with sources < 10° ➔ protons



- Galactic & ExtraGalactic Magnetic Fields make iron deviate many 10°'s from source position
- If Astrophysically shown to be protons then hadronic models can be tested knowing the primary composition.
- For example, assume current data is protons ➔change the cross section…

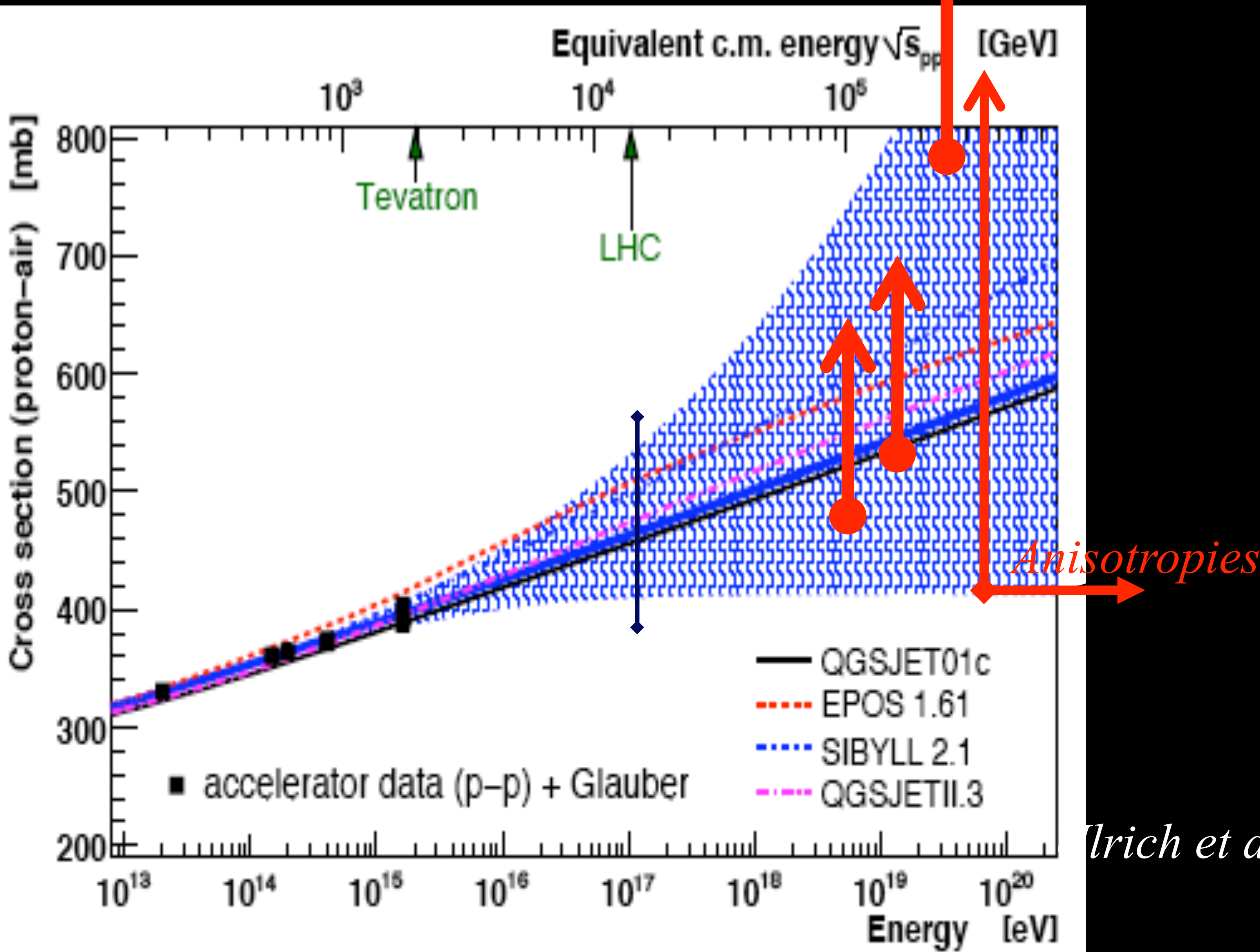
Cross Section Uncertainties



Donnachie &
Landshoff '9

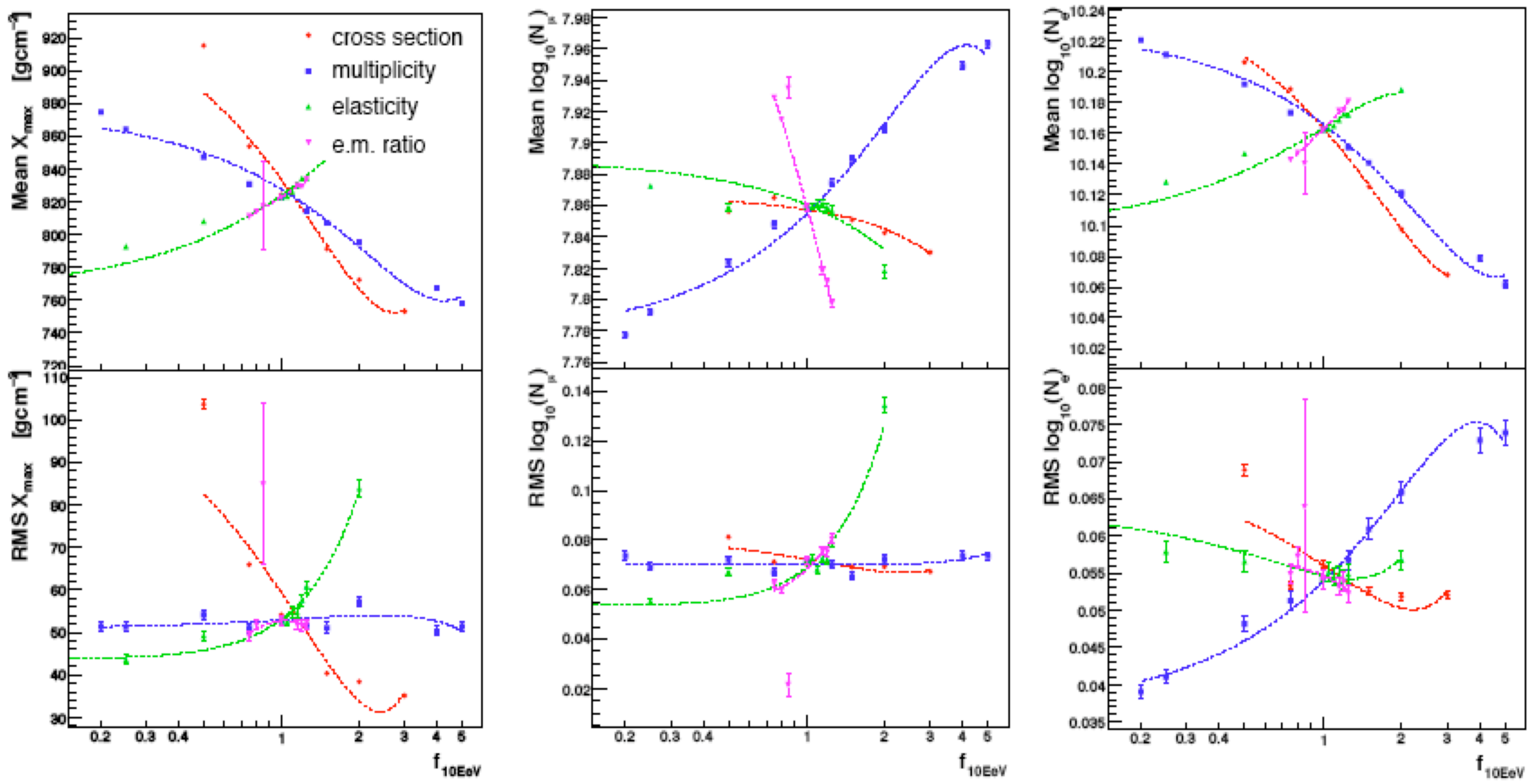
Ulrich et al '09

Cross Section Higher



lrich et al '09

Hadronic Interactions Parameters



Scaling factor at 10^{19} eV

(Ralf Ulrich, 16-Oct-2008)

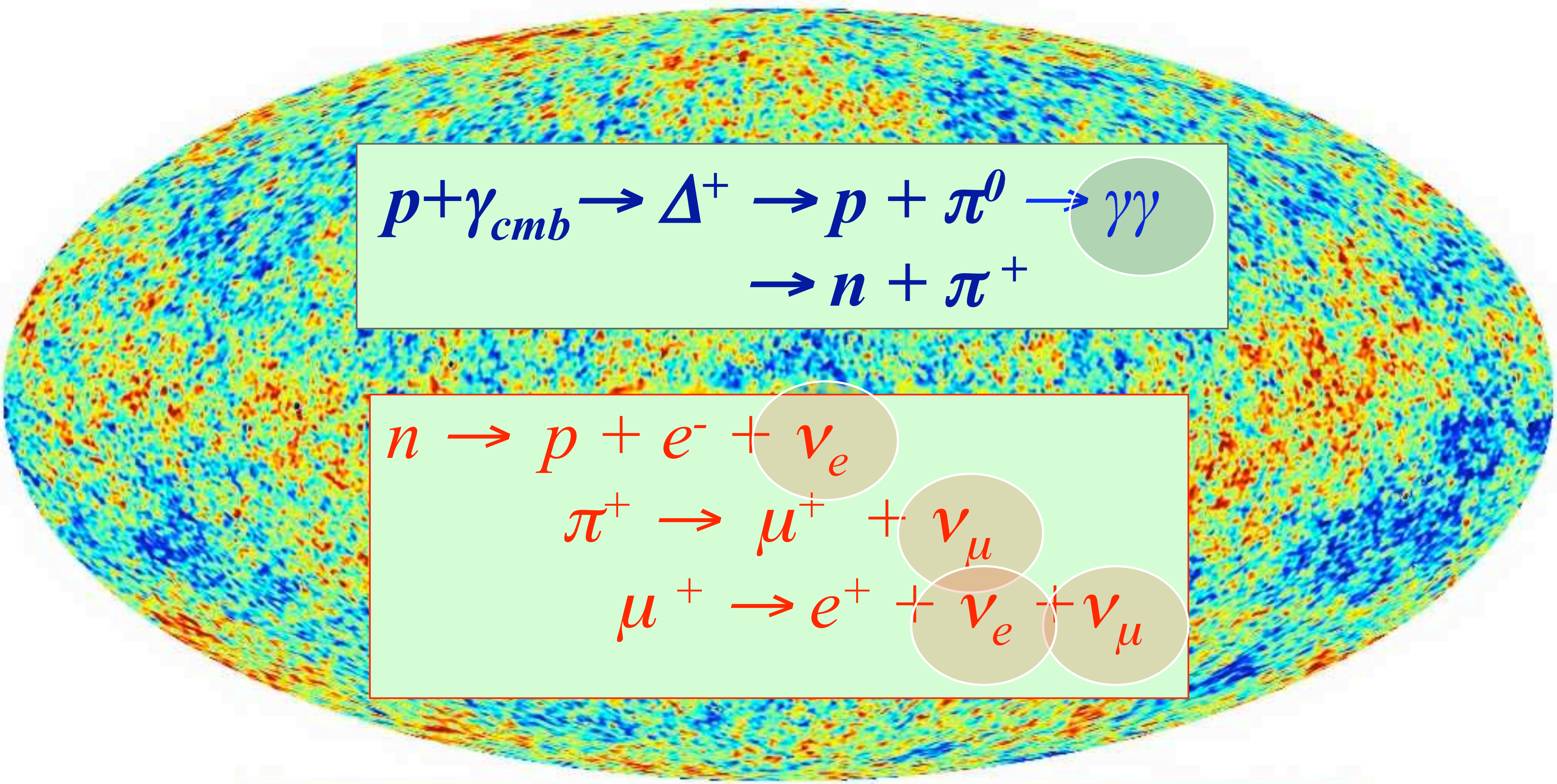
UHE CRs (+ photons & neutrinos)

- To understand Nature's Highest Energy Accelerators (EXTRAGALACTIC):
  - AGNs? GRBs? Acceleration to 10^{21} eV?
  - Propagation: backgrounds, magnetic fields

- To use UHE Cosmic Particles to study HE interactions (~ 350 TeV CM):
  - Hadronic Interactions 350 TeV CM
  - Neutrino cross sections 240 TeV CM

HE & UHE Neutrinos

Cosmogenic (GZK) Neutrinos & Photons



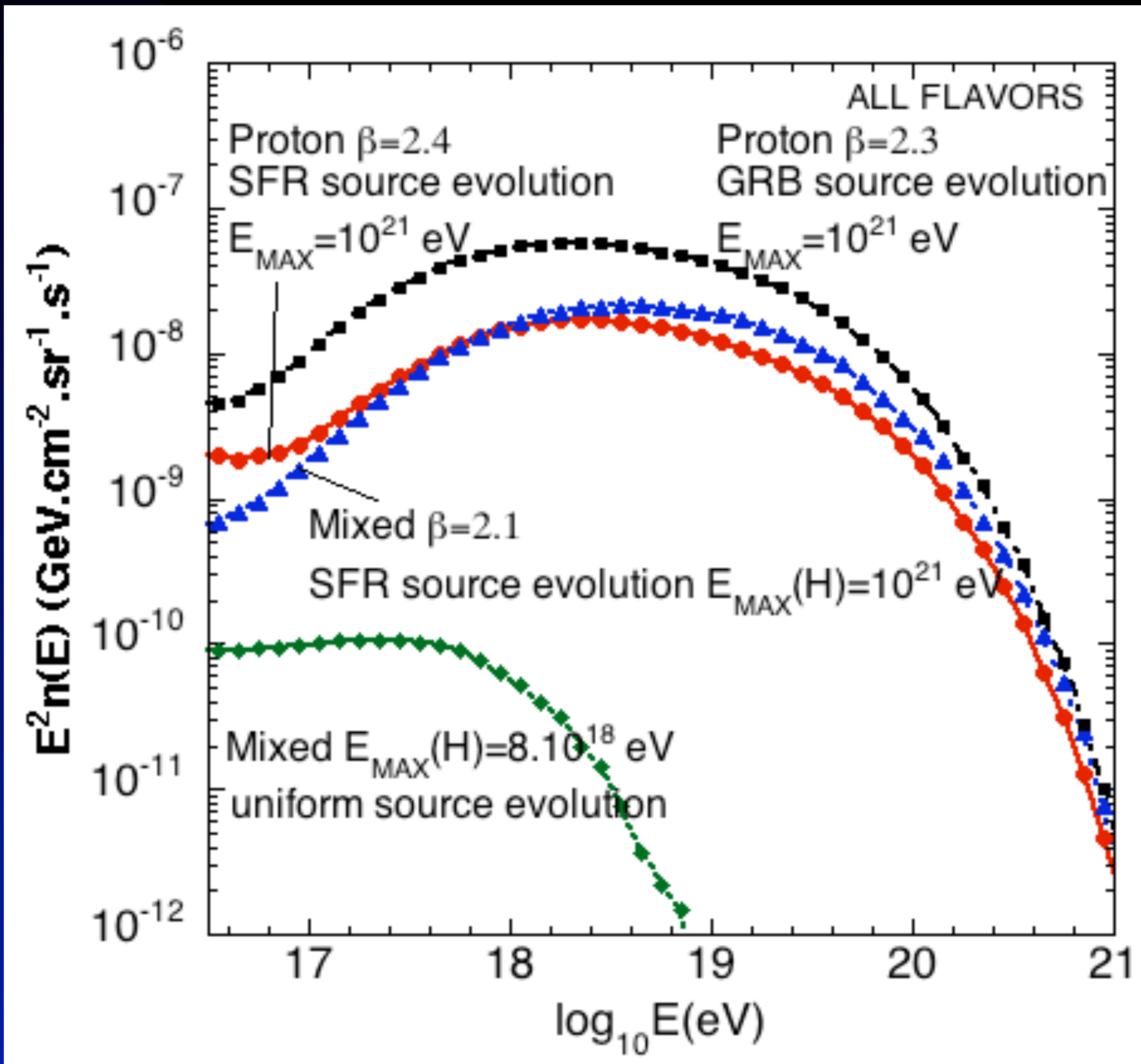
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^+$$

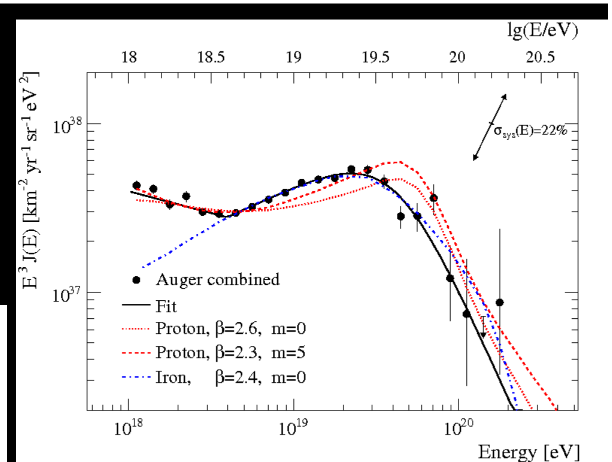
$$n \rightarrow p + e^- + \nu_e$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$

GZK Cutoff - Greisen, Zatsepin, Kuzmin 1966

Neutrino Fluxes

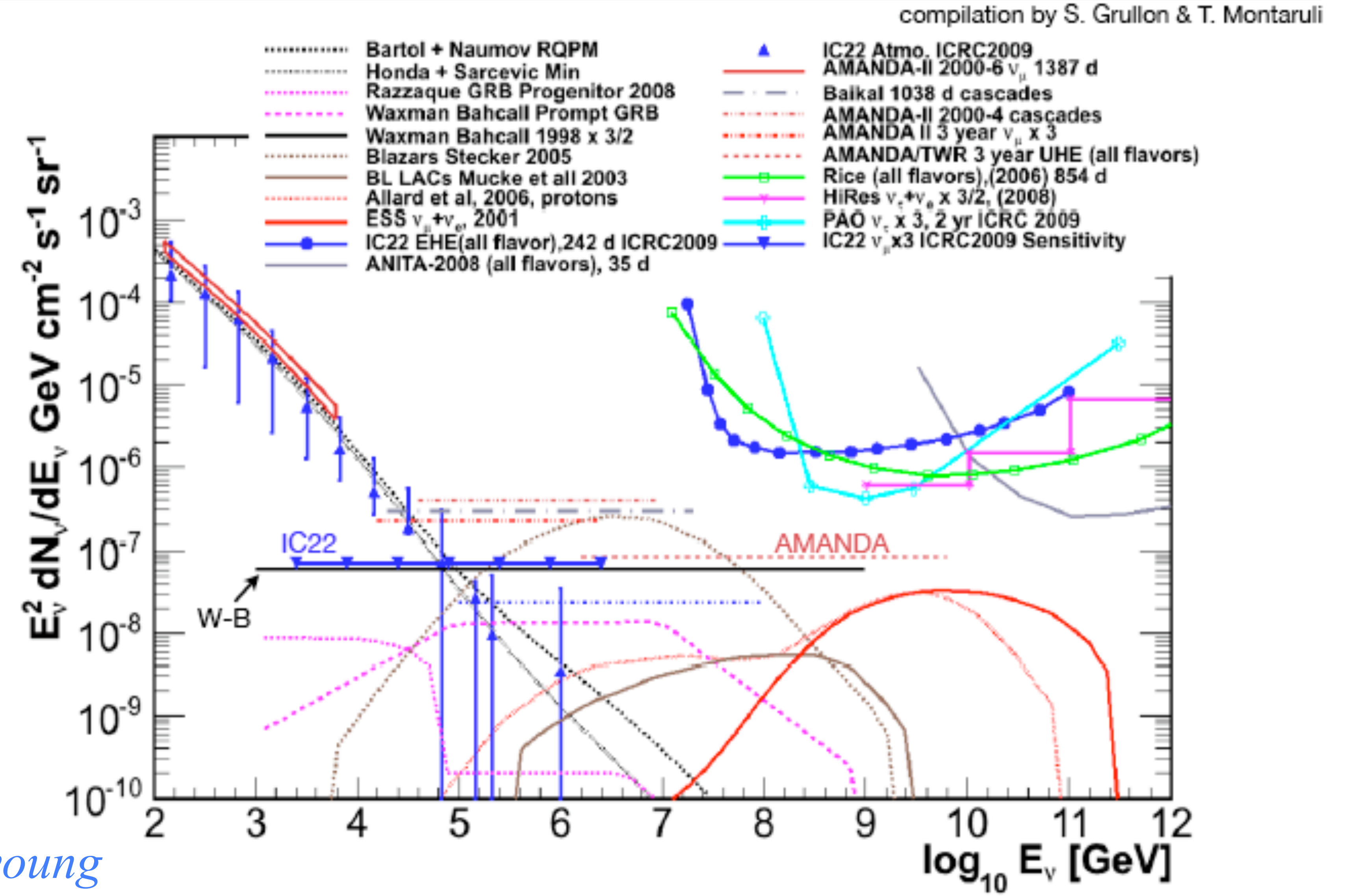
- Highly Composition dependent





Allard et al '09

Neutrinos Limits AMANDA



Deyoung

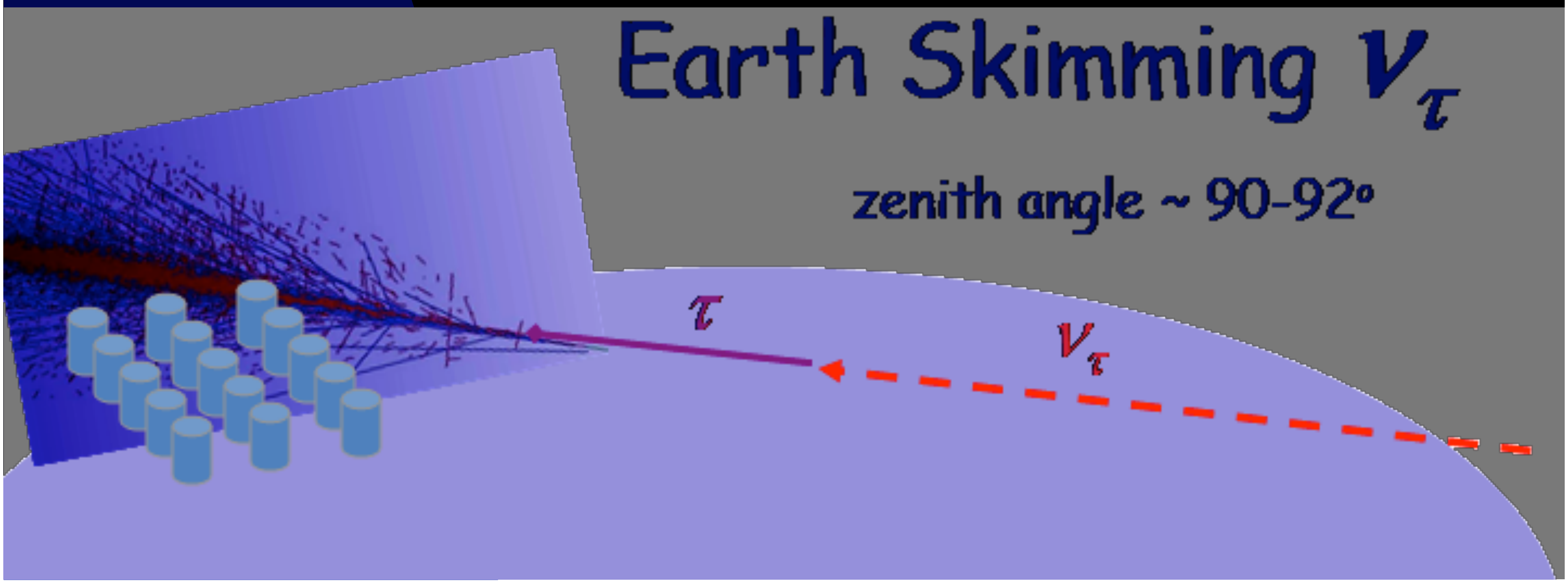
all flavor, assuming 1:1:1 ratio

Note: UHE limits are differential, not directly comparable to integral limits

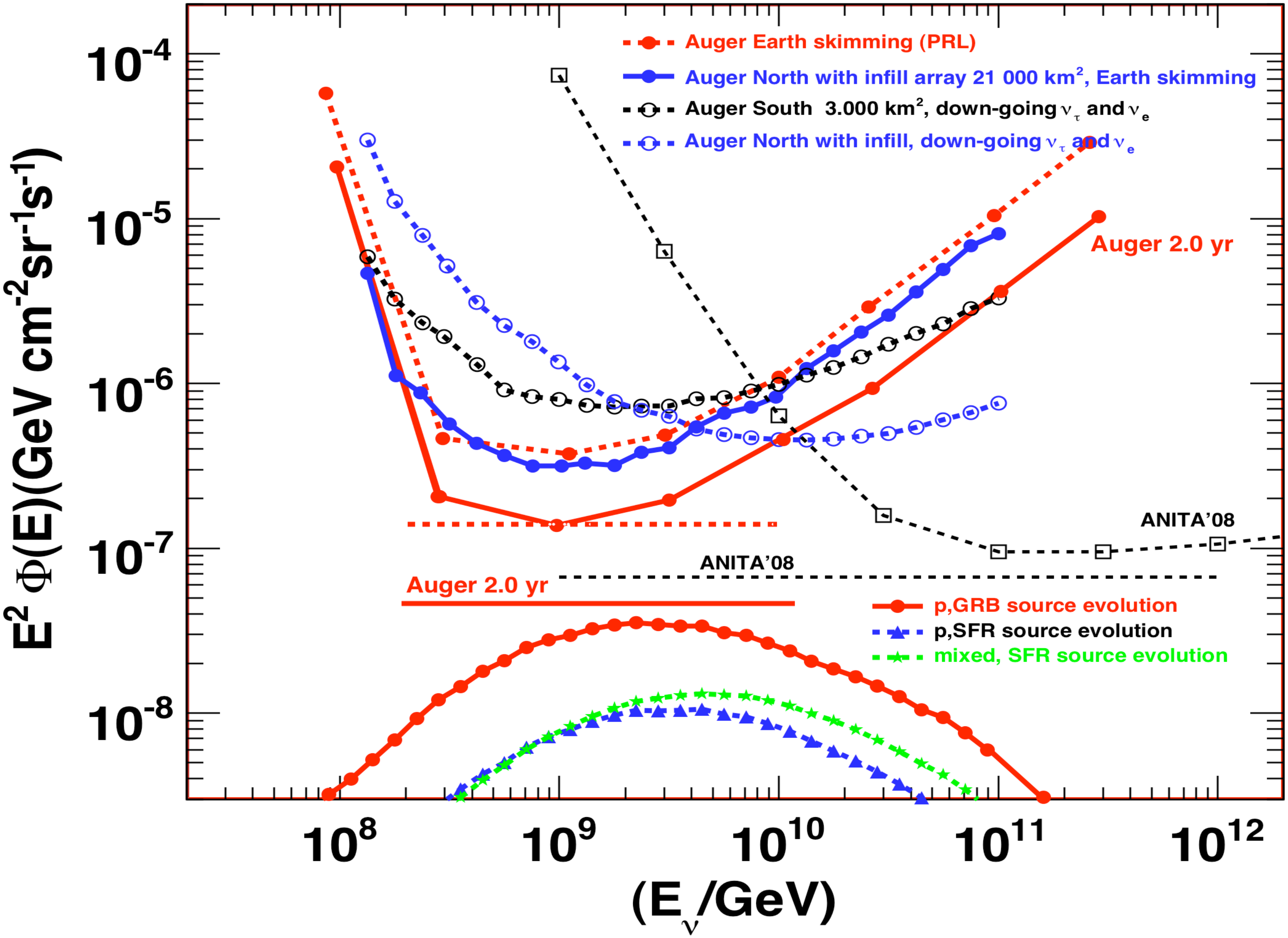
Auger as a UHE Neutrino Observatory

Neutrinos can be identified as "young" showers at very great atmospheric slant depth (either upward or downward).

Auger exposure to tau Neutrinos

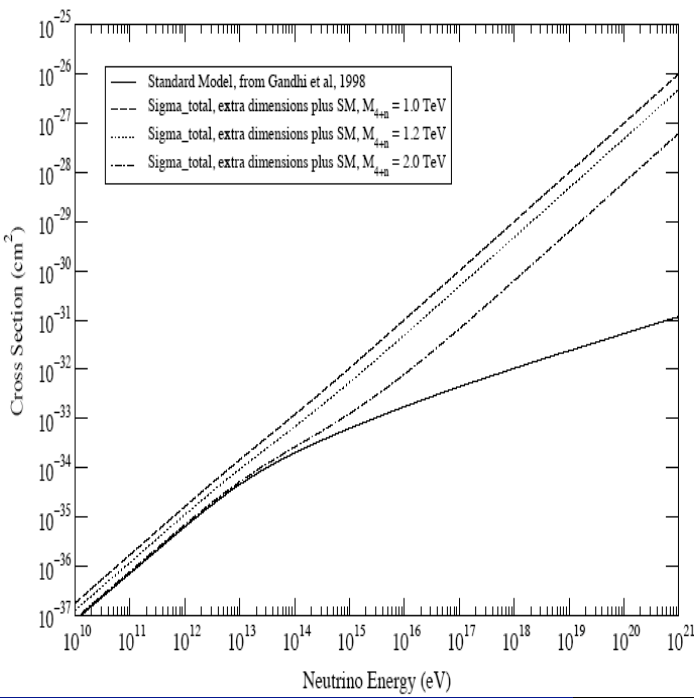


UHE neutrino limit

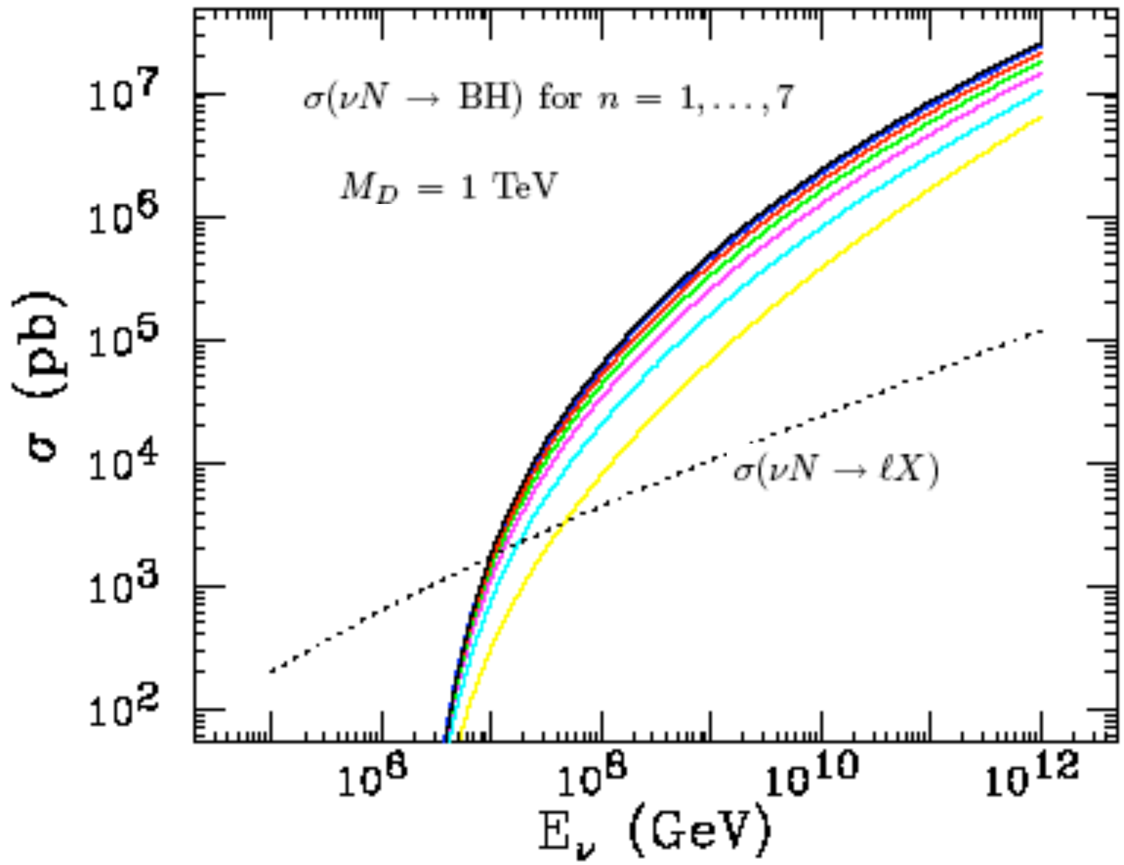


Testing UHE Neutrino Interactions

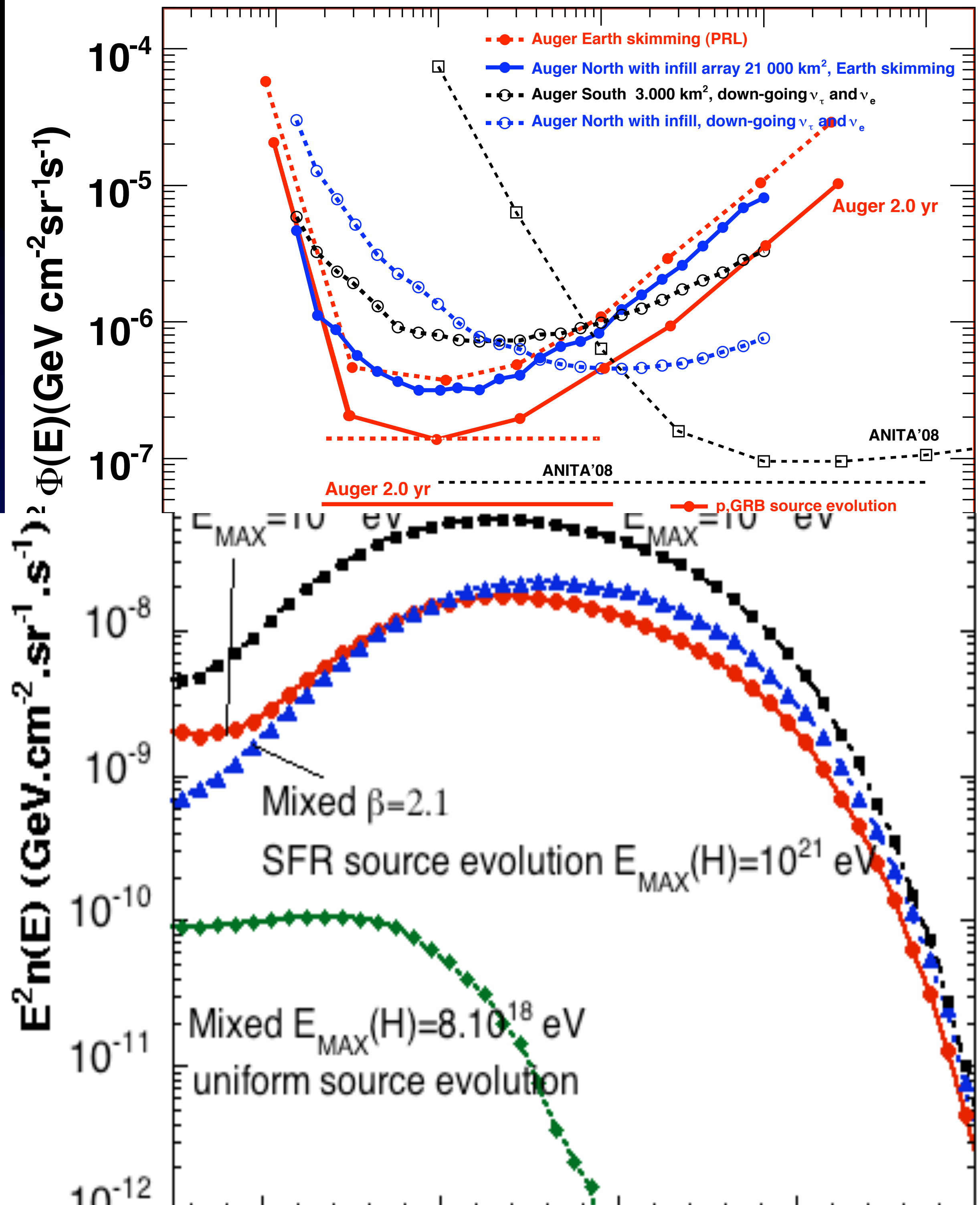
- Need to know the expected GZK
  - neutrino flux from UHECRs



Tyler, AO, Sigl '00

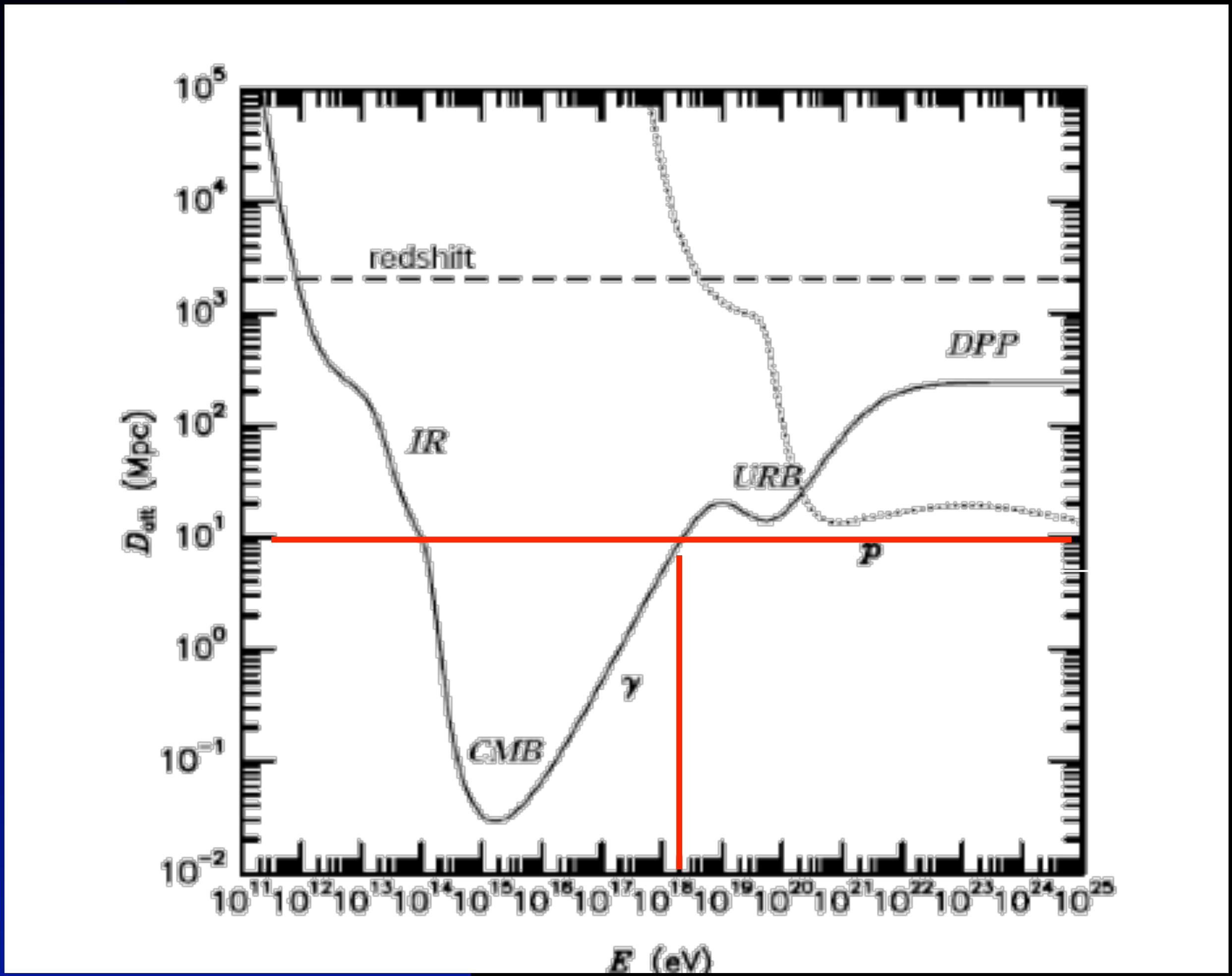


Anchordoqui et al '03



Auger Earth skimming (PRL)
Auger North with infill array 21 000 km^2, Earth skimming
Auger South 3.000 km^2, down-going ν_τ and ν_e
Auger North with infill, down-going ν_τ and ν_e
Auger 2.0 yr
ANITA'08
ANITA'08
Auger 2.0 yr
p,GRB source evolution
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$E^2\Phi(E)$(GeV cm^{-2}sr^{-1}s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$E^2n(E)$ (GeV.cm^{-2}.sr^{-1}.s^{-1})
Mixed β=2.1
SFR source evolution E_{MAX}(H)=10^{21} eV
Mixed E_{MAX}(H)=8.10^{18} eV
uniform source evolution

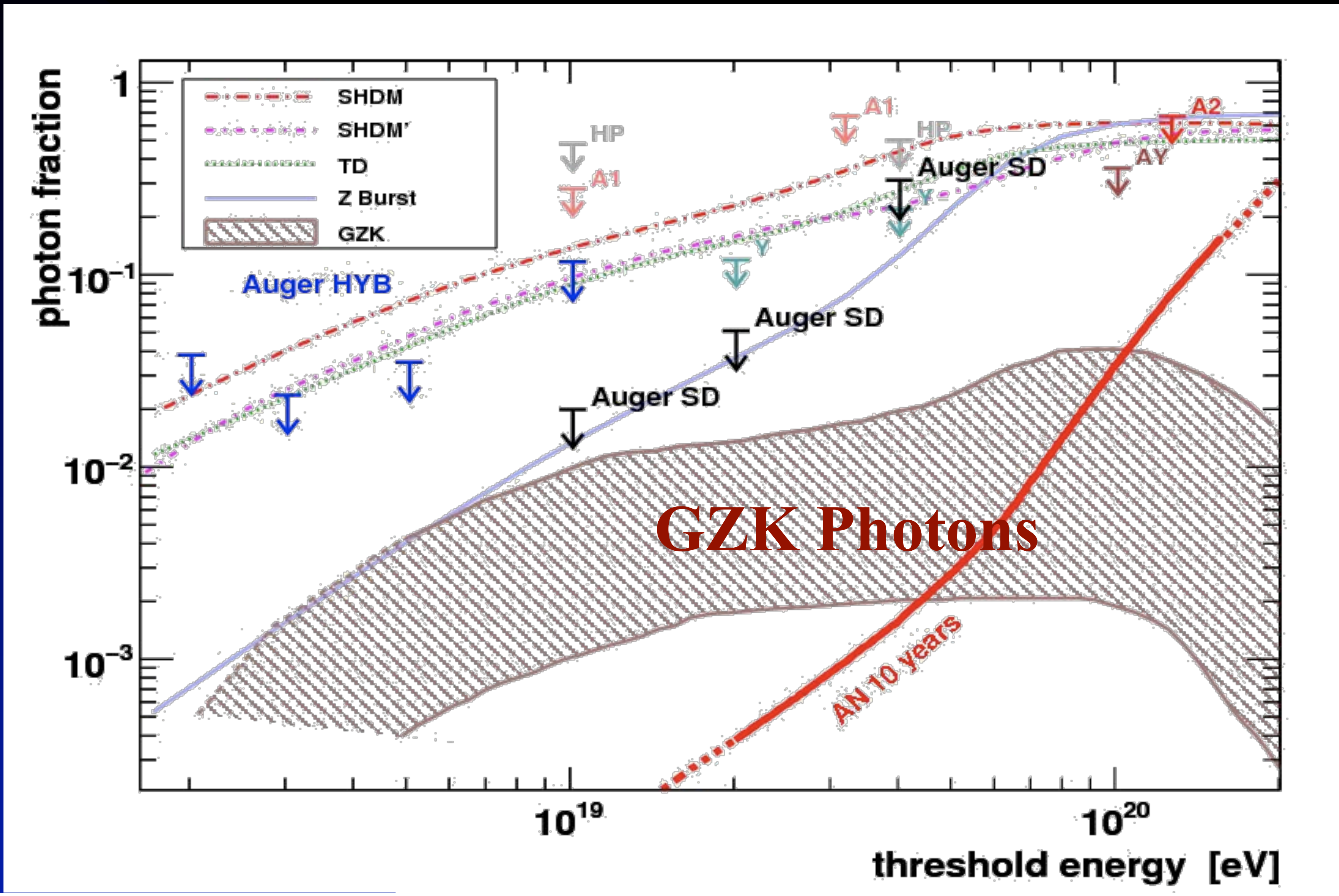
The UHE Gamma Ray Astronomical Window



Photon attenuation length exceeds 10 Mpc for E > 2 EeV

UHE Photon Limits

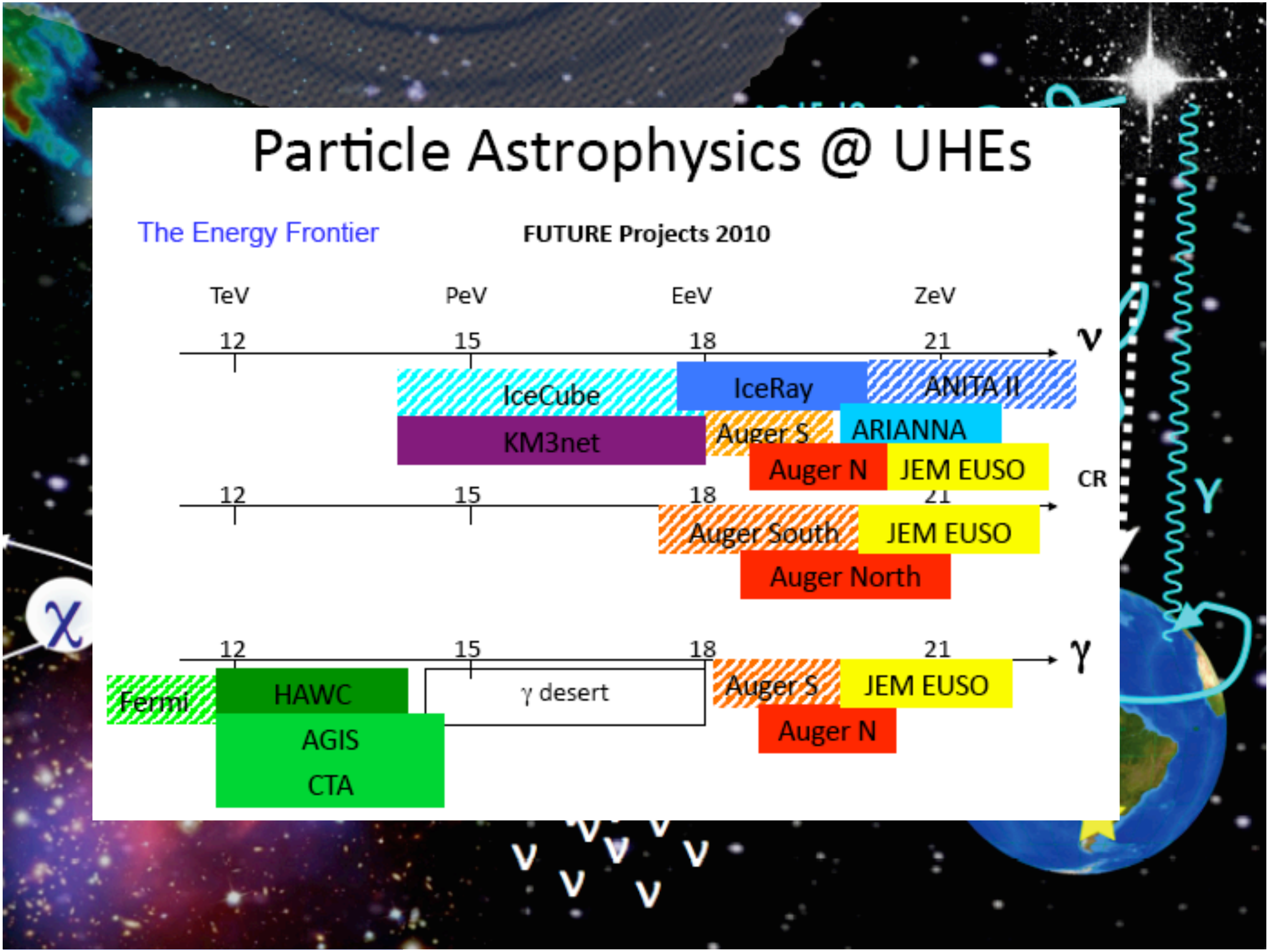
(strongly constrain top-down scenarios)

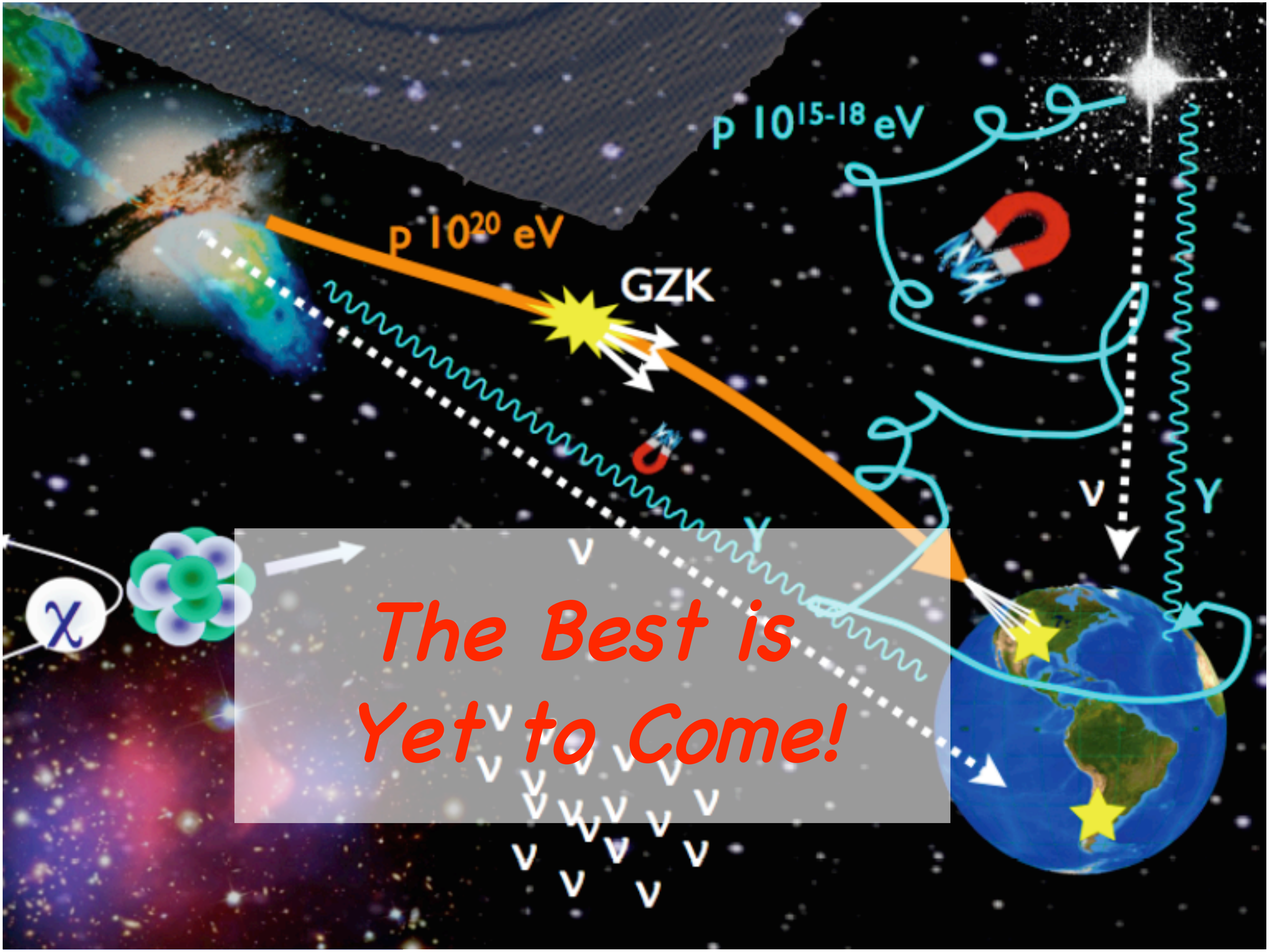


State of Astroparticles

- To understand Nature's HE Accelerators
  - Great Progress from Fermi's 1st year of data: new sources, new views of old sources, precision studies of bright sources and backgrounds
  - Multimessenger & Multiwavelength studies: key in finding hadronic vs leptonic accelarators & underlying mechanisms AGN, GRBs, pulsars, …
- To use Cosmic Particles to study HE interactions
  - Dark Matter not yet needed: Gev excess not there, Atic excess not there, Pamela + Fermi: DM or astrophysical sources (Pulsars, SNR)?
  - UHECRs evidence for large cross sections
  - HE & UHE neutrinos and photons coming soon!

Particle Astrophysics @ UHEs




p 10^{20} eV
GZK
p 10^{15-18} eV
ν
γ
γ
ν
χ
The Best is
Yet to Come!