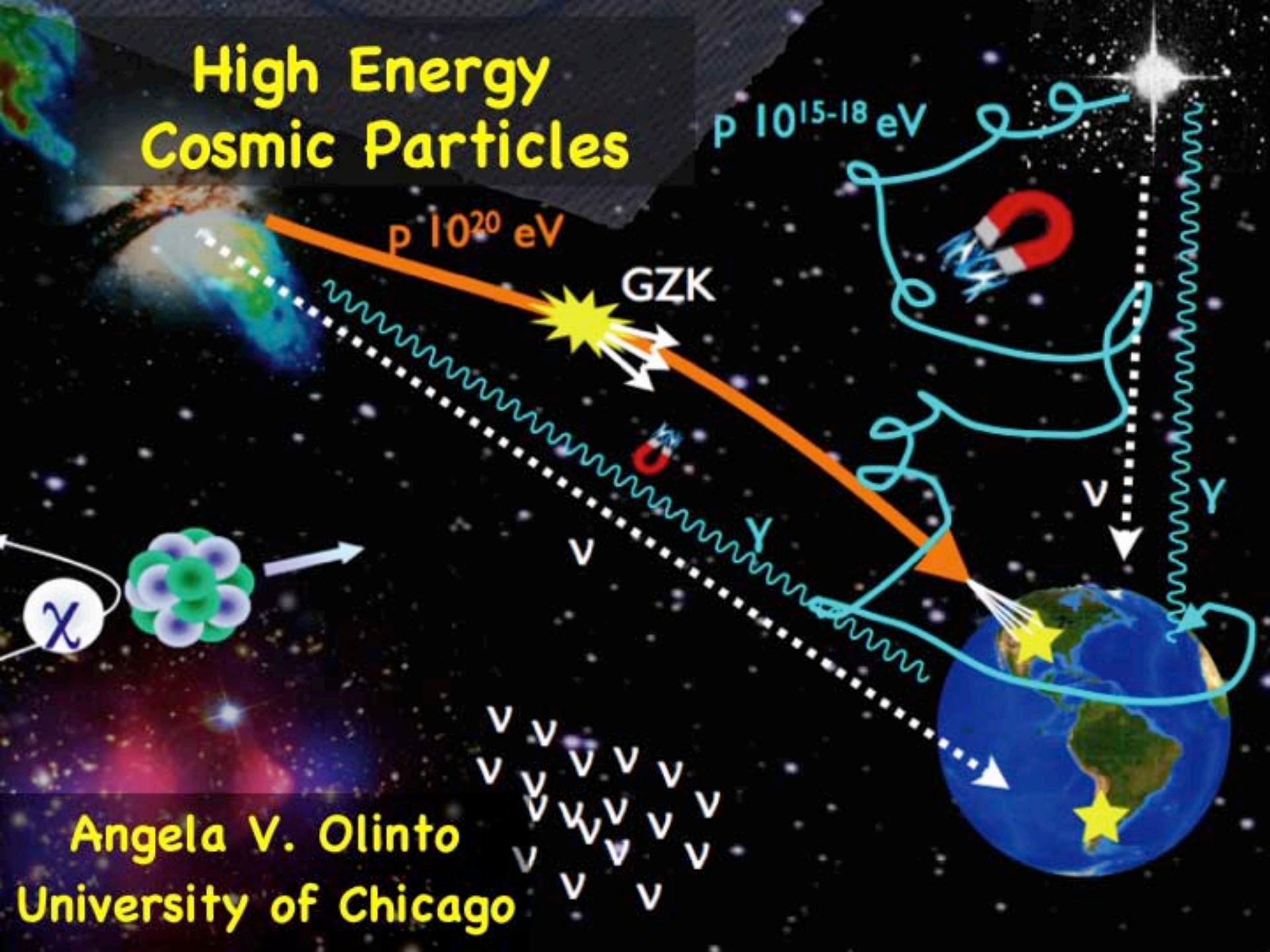
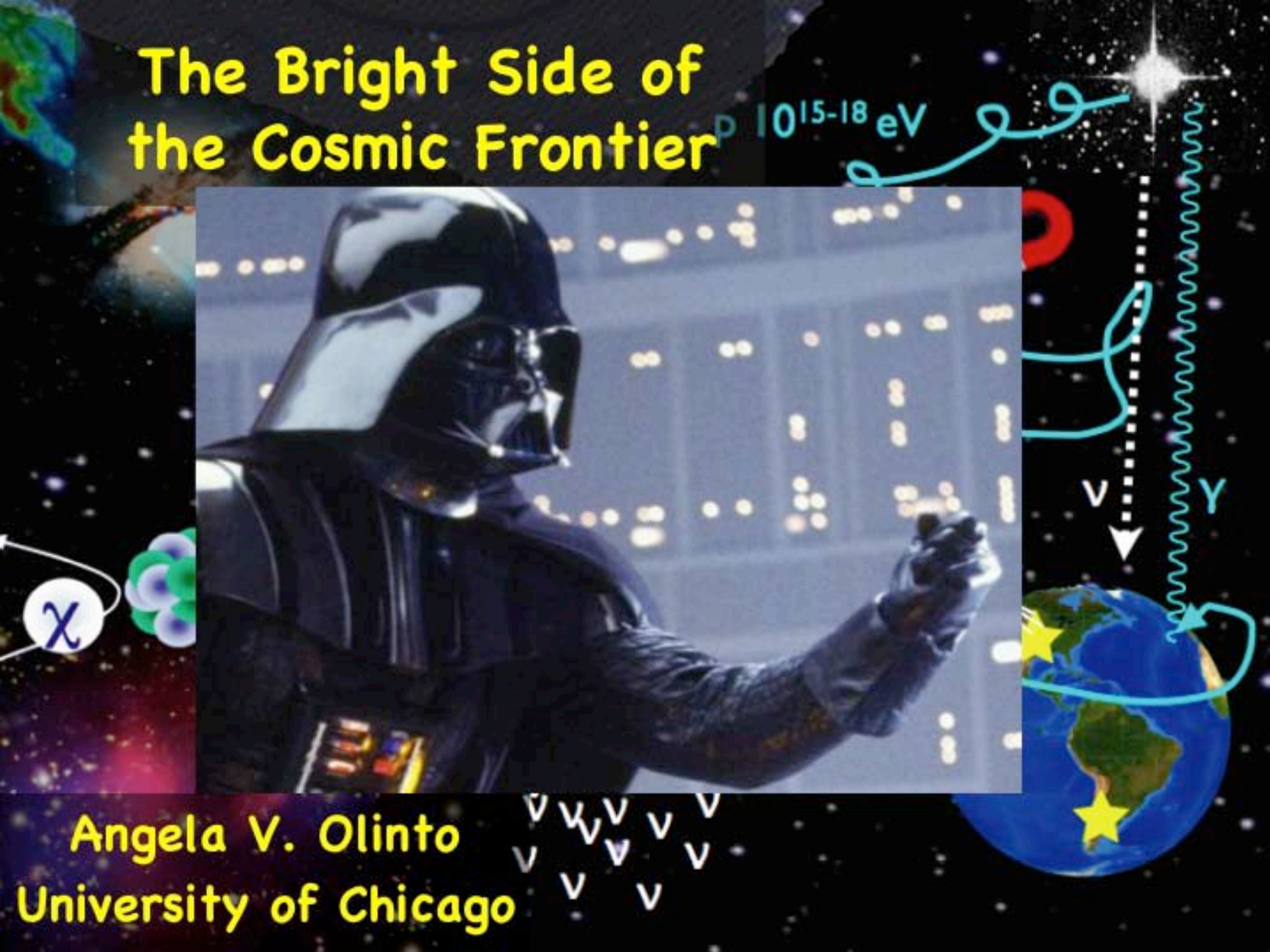
High Energy Cosmic Particles



Angela V. Olinto
University of Chicago

The Bright Side of the Cosmic Frontier



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The Bright Side of the Cosmic Frontier

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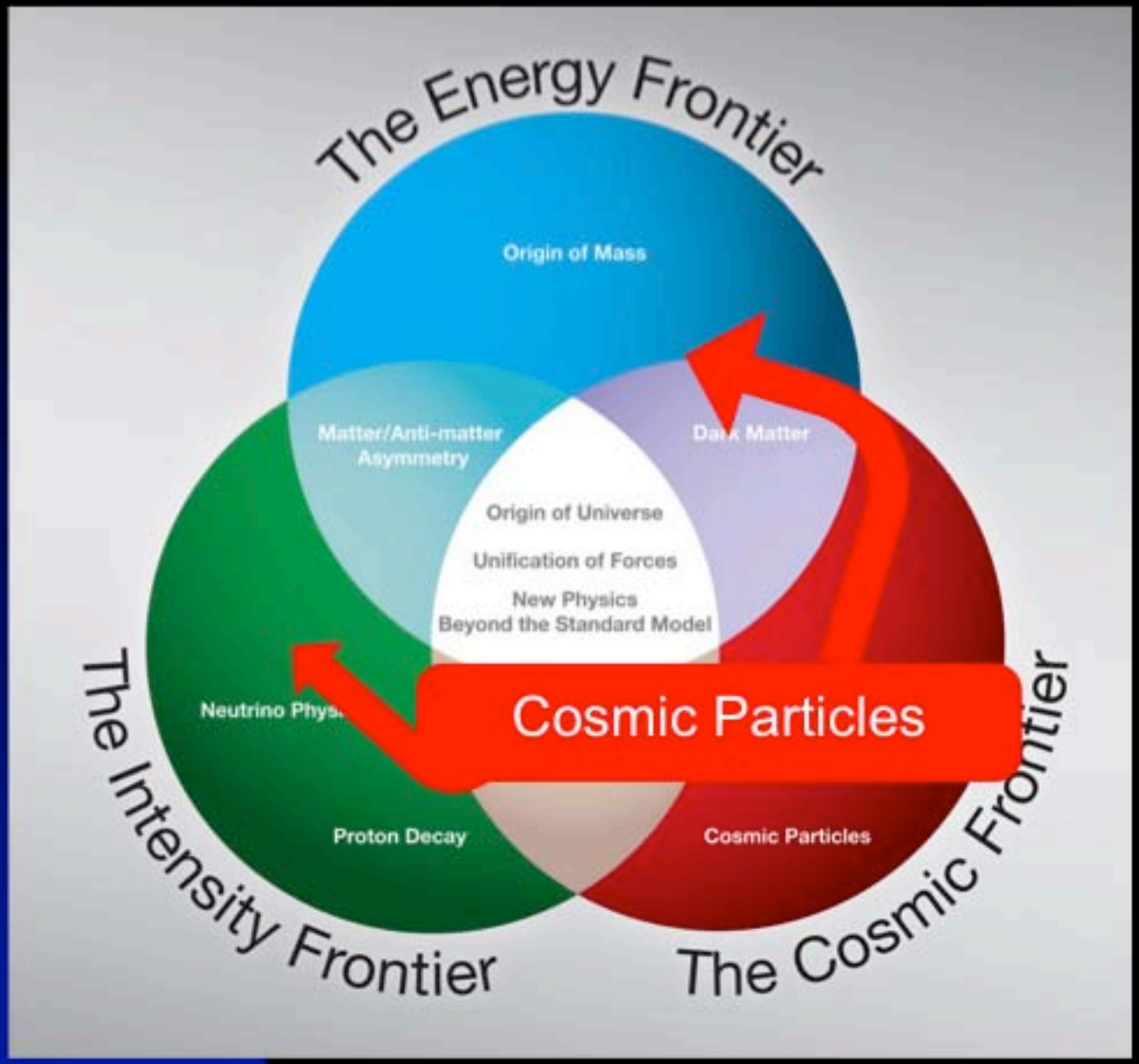
The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Phys.
Proton Decay
Cosmic Particles
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

Big Questions & Unifying themes

What is the origin of Cosmic Particles?

What are the Galactic Accelerators?
What are the Extragalactic Accelerators?
What is the Accelerating Mechanism?
What particles are accelerated?
How do they propagate to Earth?
What are the cosmic Magnetic Fields?
Are there other unknown relic particles?

Probes of High Energy Particle Interactions:

Interactions in source, on the way to Earth, on Earth (Atmosphere, Ice, Ocean) give cross sections, multiplicities, oscillation parameters, etc…) with **E_{CM} > 100 TeV hadrons, 50 TeV photons & neutrinos**

Is Dark Matter a new Particle?
Are there other unknown relic particles?
Is **Lorentz Invariance valid** at the Highest Energies?
Are there detectable departures from the standard model? E.g., **extra dimensions, topological defects, …**

High Energy Cosmic Particles

High Energy Cosmic Particles
(aka AstroParticles)

What is the easiest Cosmic Particle to detect?

What is the easiest Cosmic Particle to detect? Photon!

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In what Energy range do we observe them?

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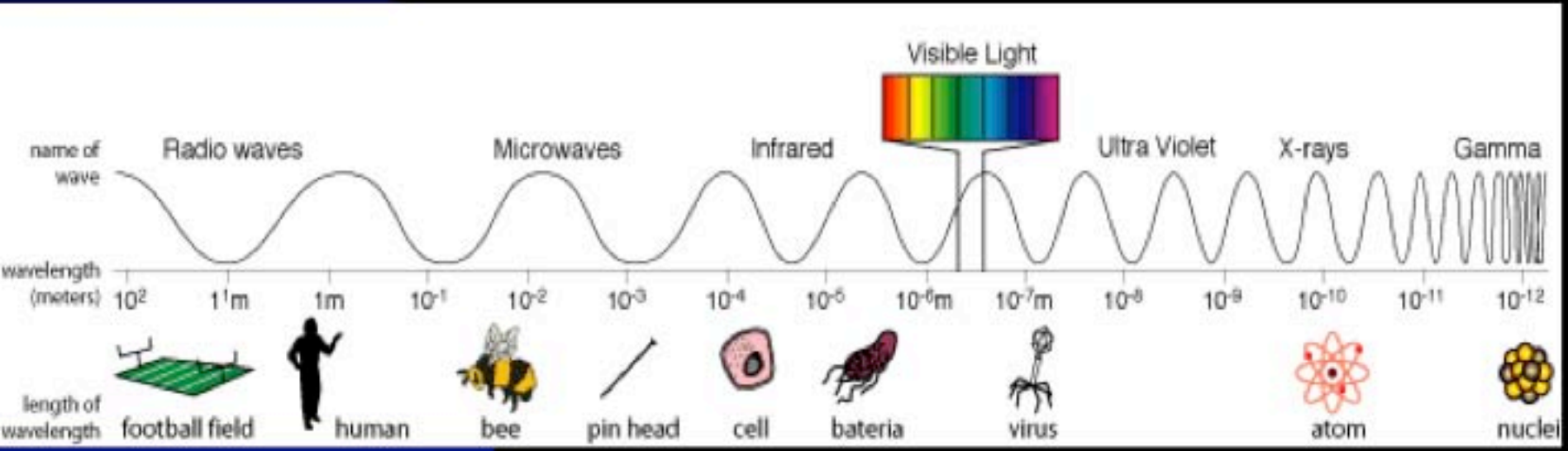
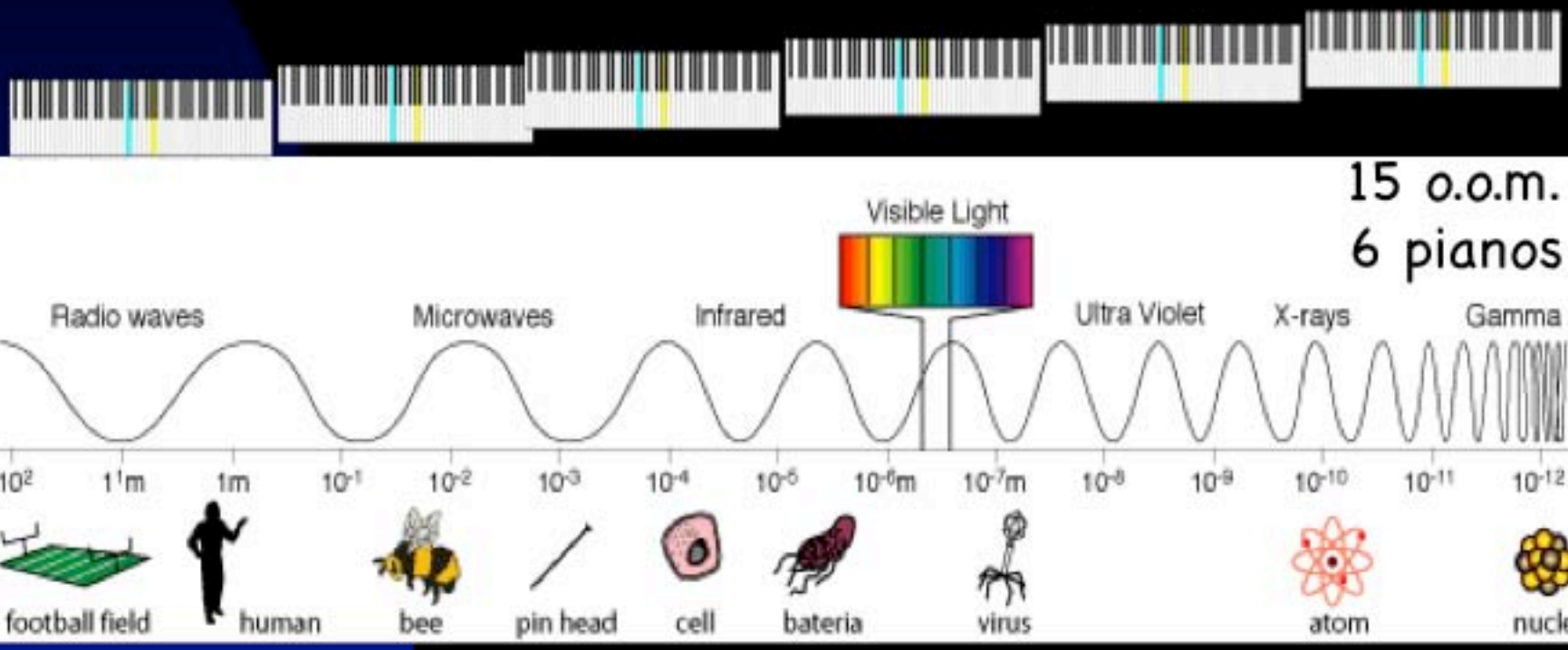


What is the easiest Cosmic Particle to detect? Photon!

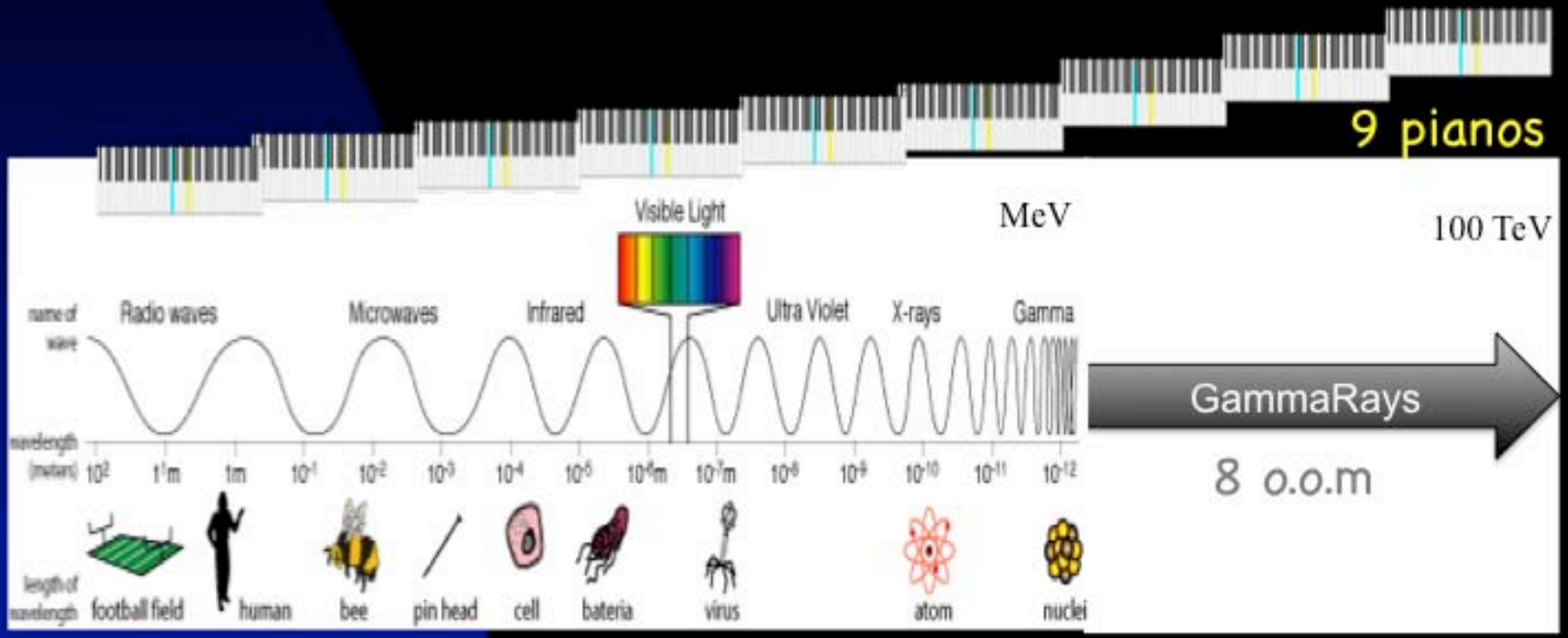
In what Energy range do we observe them?



What is the easiest Cosmic Particle or "Astroparticle" to detect? Photon!

In what Energy range do we observe them?

10^{-9} eV to 10^{14} eV (1 eV = 2.4 10^{14} Hz)

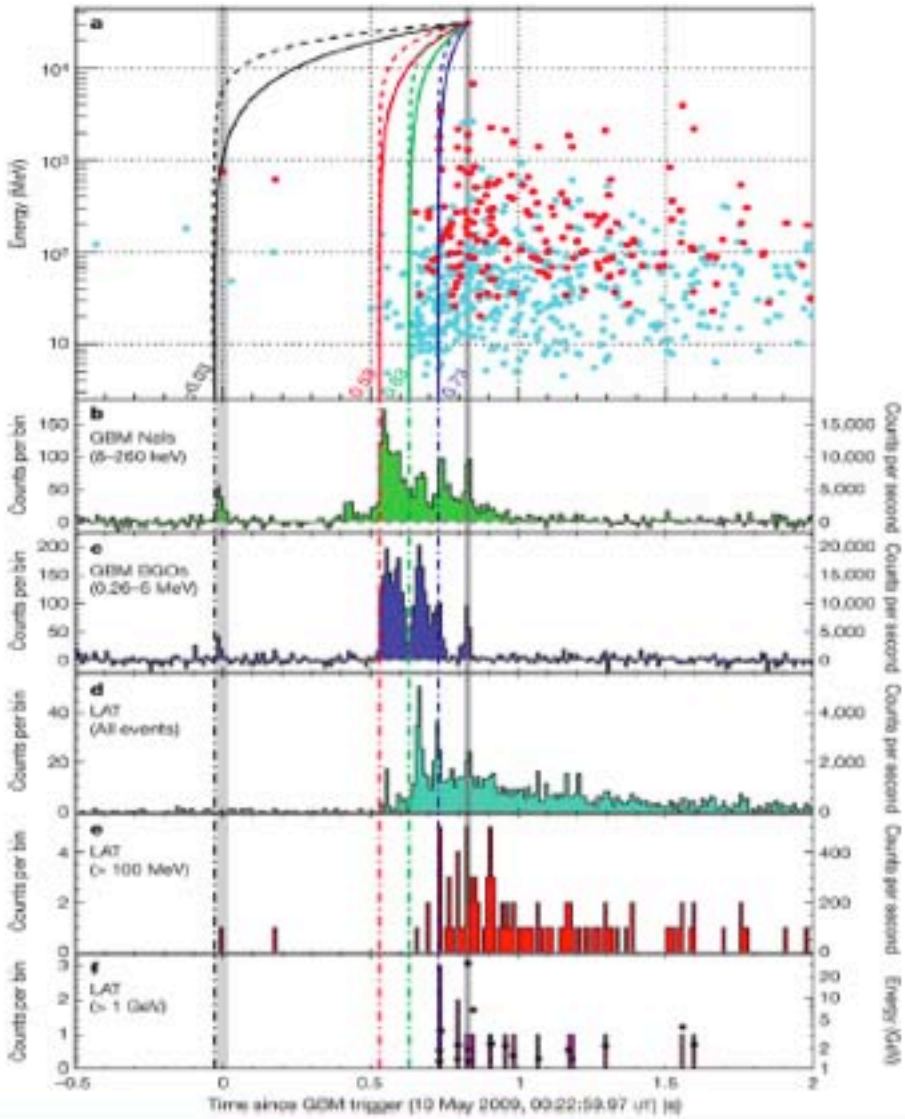


Lorentz Invariance Violation

- Vacuum dispersion relation for photons
- Energy dependent speed of light
- Physics at Planck scale
  - Quantum Gravity
  - String Theory
- Can not directly probe this energy scale

$$\frac{v(p)}{c} = 1 + \zeta_1 \left(\frac{p}{E_{LIV}} \right) + \zeta_2 \left(\frac{p}{E_{LIV}} \right)^2 \qquad \Delta t \approx \frac{1}{\zeta_n} \left(\frac{\Delta E}{E_{LIV}} \right)^n \frac{L}{c}$$

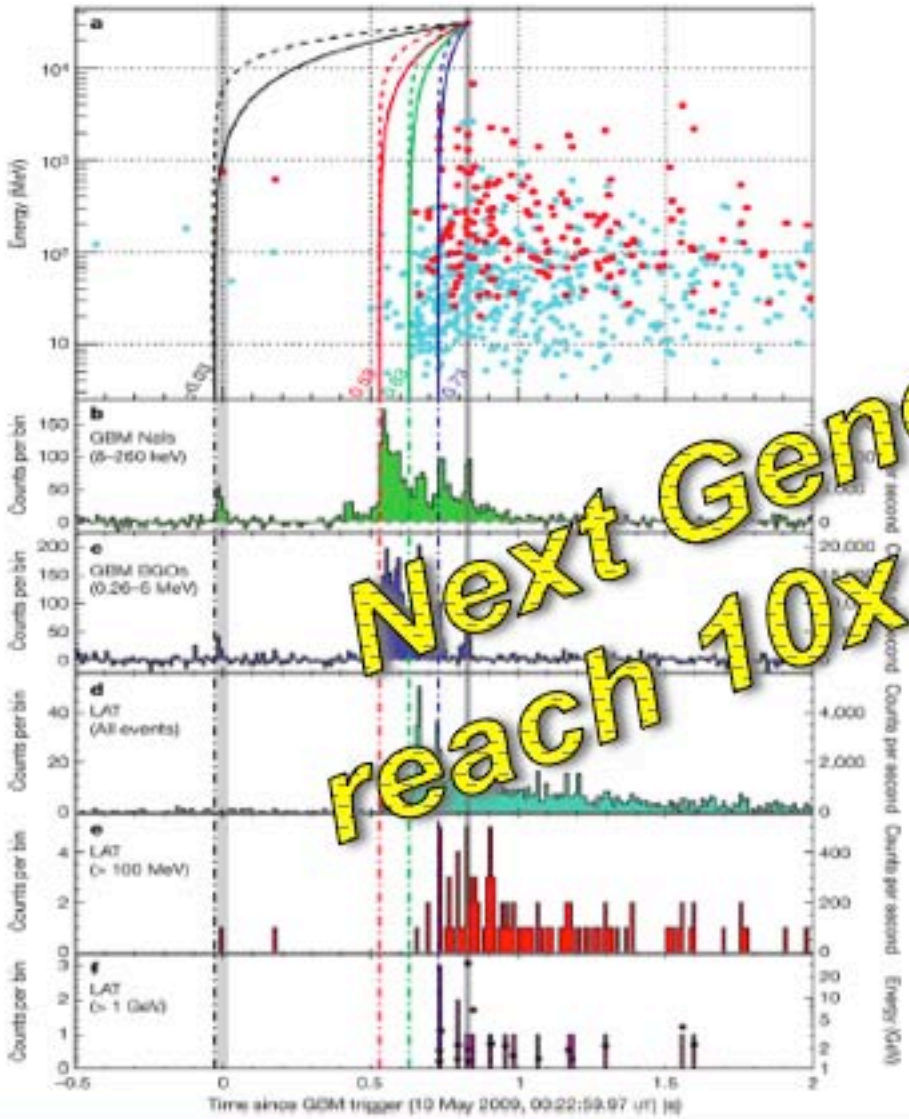
Testing LIV with Gamma-Ray Bursts



- GRB 090510
- Z = 0.9
- Timescale < 1 sec
- **E^1_{LIV}>1.5x10^{19} GeV**
- E^2_{LIV}>3x10^{10} GeV
- Background: Source effects – energy dependent acceleration times

From N. Otte, SLAC meeting

Testing LIV with Gamma-Ray Bursts



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- $E_{LIV} > 1.5 \times 10^{19}$ GeV
- $E_{LIV} > 3 \times 10^{10}$ GeV
- Background: Source effects – energy dependent acceleration times

Next Generation reach 10x past M_{pl}!

From N. Otte, SLAC meeting

Physics	Technique	Background	Solution
LIV	AGN/GRB timing	Acceleration mechanism	Many sources large redshift range particle acceleration

Next Generation
reach 10 x past M_{pl} !

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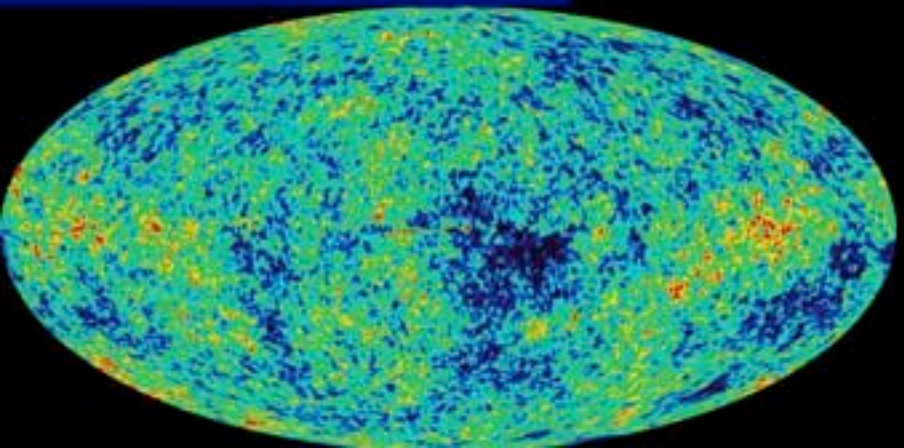
Energy Dependent

z = 1100 (E_{cmb} ~ 10^{-3} eV)

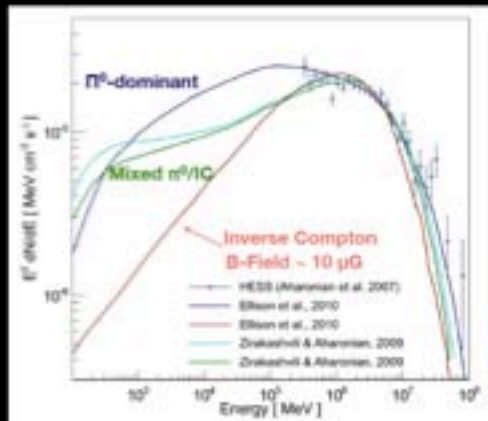
Galactic Sources (E ~ 1 PeV?)

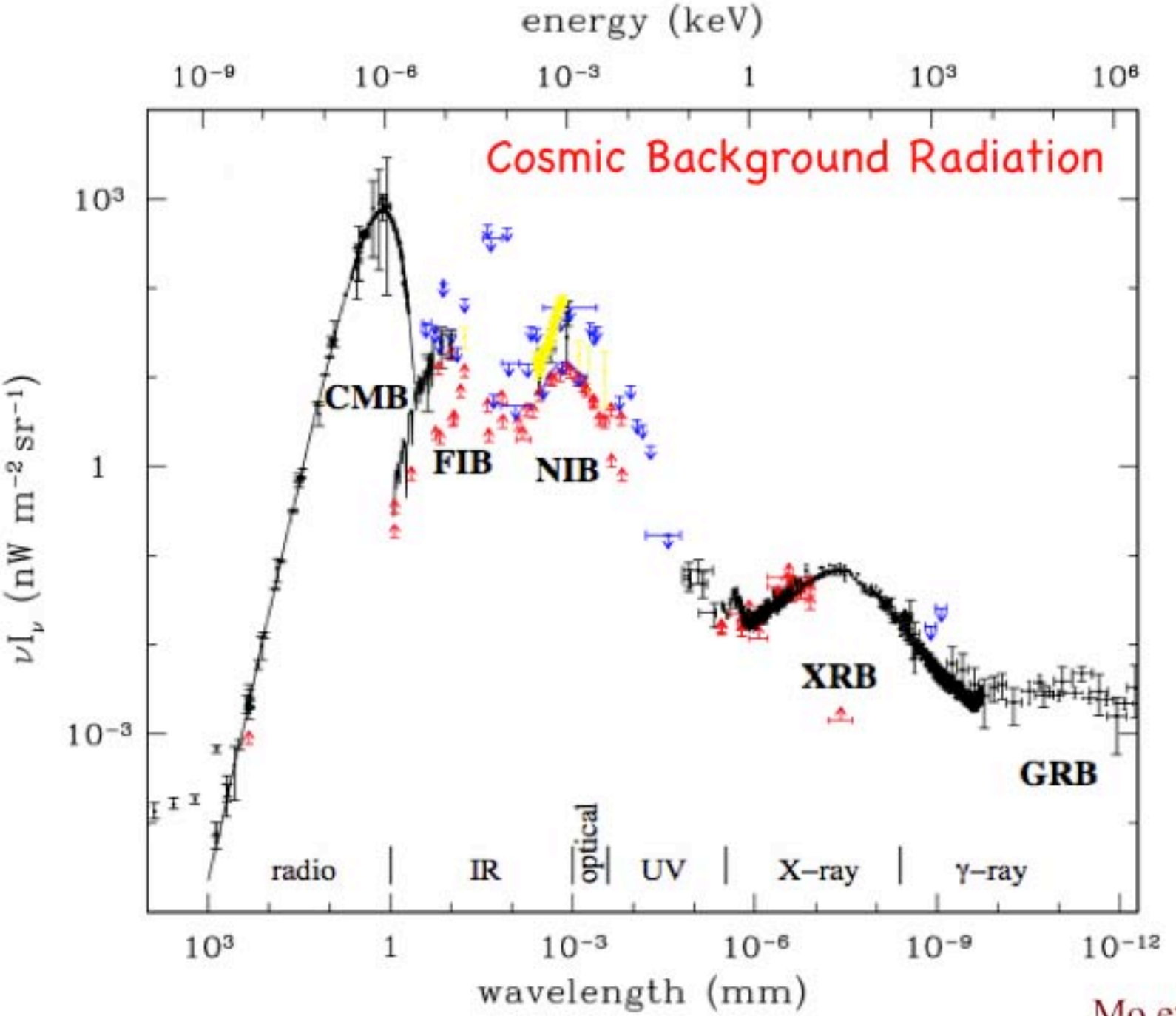
Extragalactic Sources – EBL effect



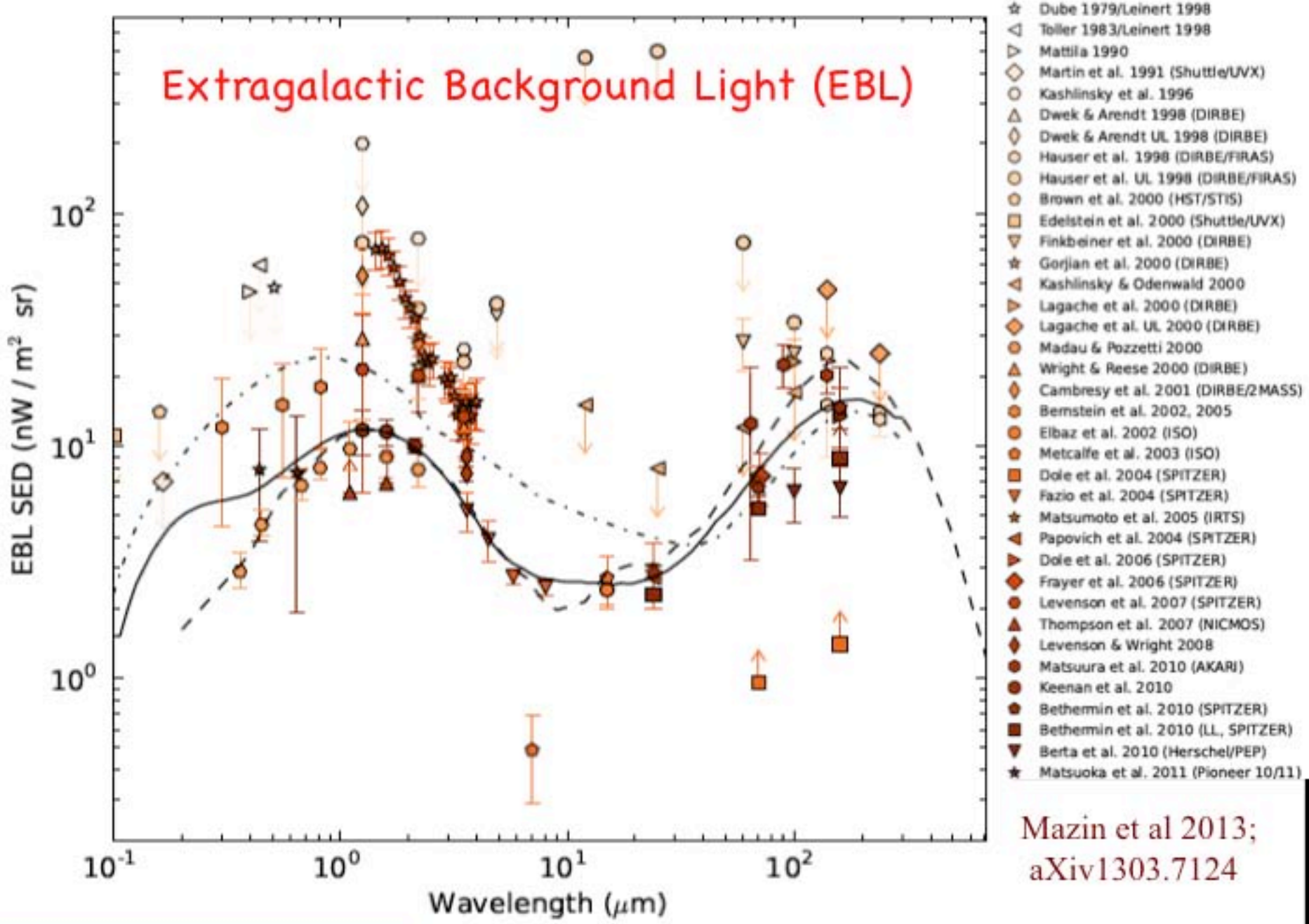
z=10

UDFj-39546284




energy (keV)
10⁻⁹
10⁻⁶
10⁻³
1
10³
10⁶
Cosmic Background Radiation
10³
1
10⁻³
νI_ν (nW m⁻² sr⁻¹)
CMB
FIB
NIB
XRB
GRB
radio
IR
optical
UV
X–ray
γ–ray
10³
1
10⁻³
10⁻⁶
10⁻⁹
10⁻¹²
wavelength (mm)

Mo et al' 10



Mazin et al 2013; aXiv1303.7124

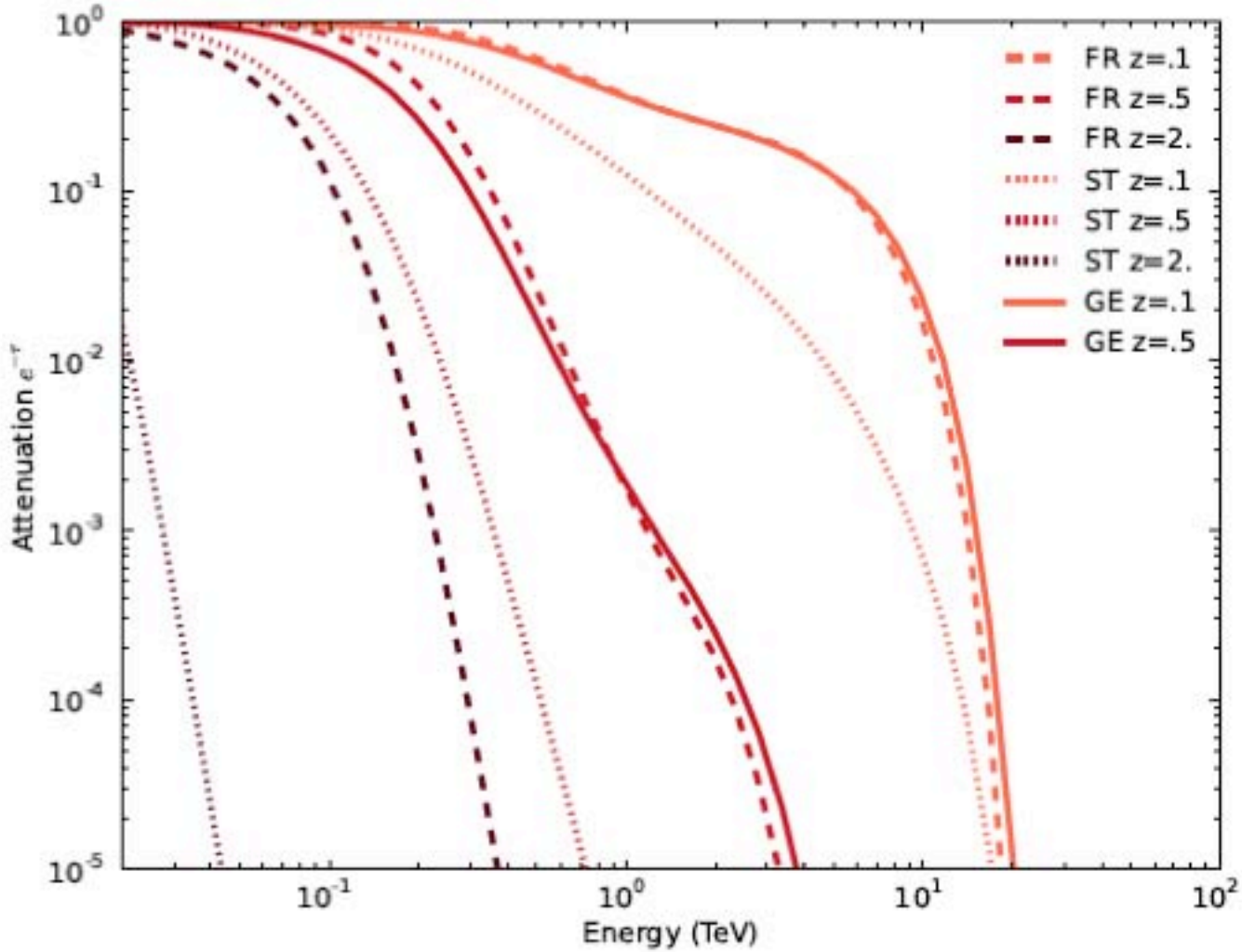
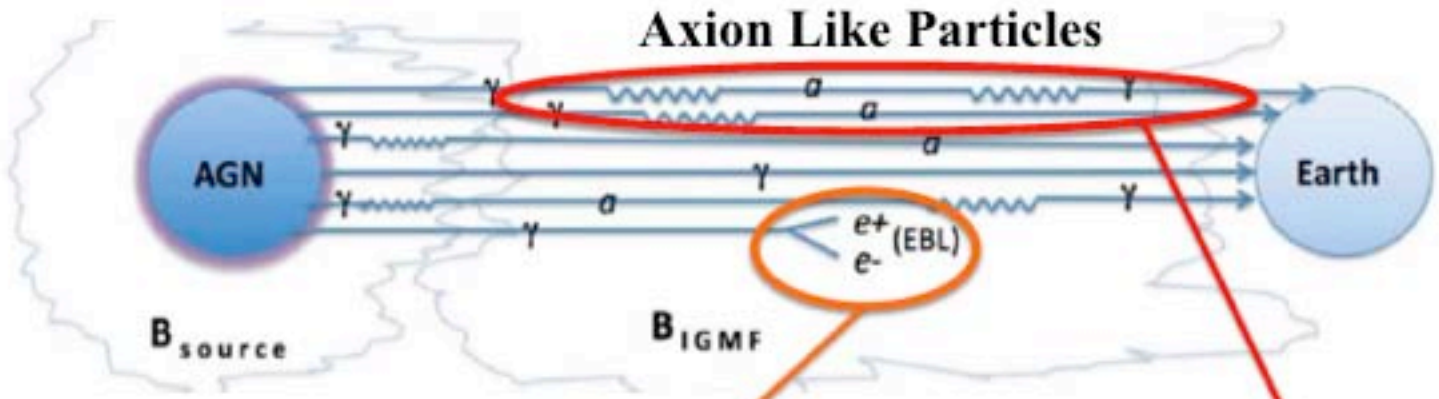
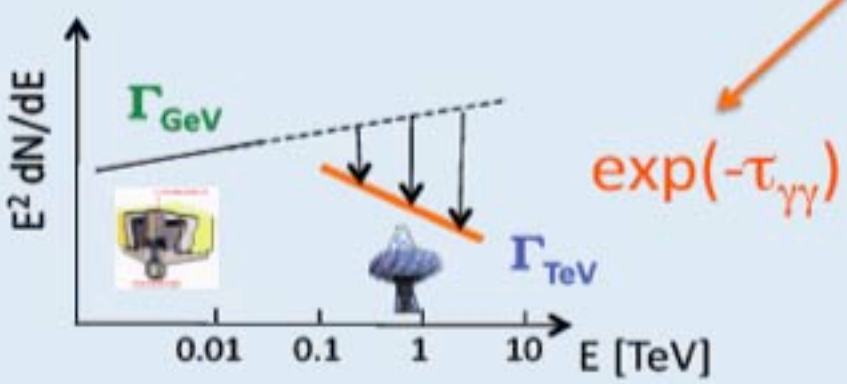


Figure 2: EBL attenuation for VHE γ-rays for different EBL models and redshifts (z) (FR: [5]; ST: fast evolution model from [3]; GE: [4]). Color code of the curves is related to different redshifts (the darker the further away).

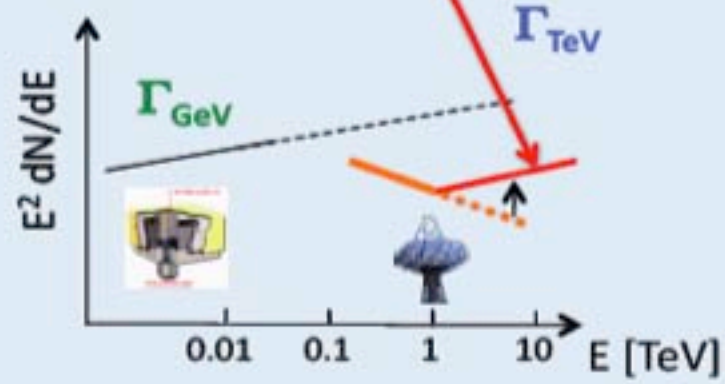
Mazin et al 2013; aXiv1303.7124

Signatures from the EBL & ALP





- Absorption of primary γ-rays by diffuse EBL
- spectra soften
- effect increases with distance (redshift z)



- component arises from **secondary γ-rays** generated by ALP-photon mixing
- spectra harden – characteristic energy
- **but spectral rise** may **not** be unique!

From Krennrich (SLAC meeting)

What is the easiest Cosmic Particle to detect? Photon!

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Galactic Sources (E ~ 100 TeV)

Extragalactic Sources – EBL effect vs **Axion-like Particles**

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Physics	Technique	Background	Solution
Axions	AGN spectra	Intrinsic spectra EBL level UHECR production of secondary gammas	Many AGN large redshift range, precision spectra (100 MeV->TeV) particle acceleration Variability EBL knowledge

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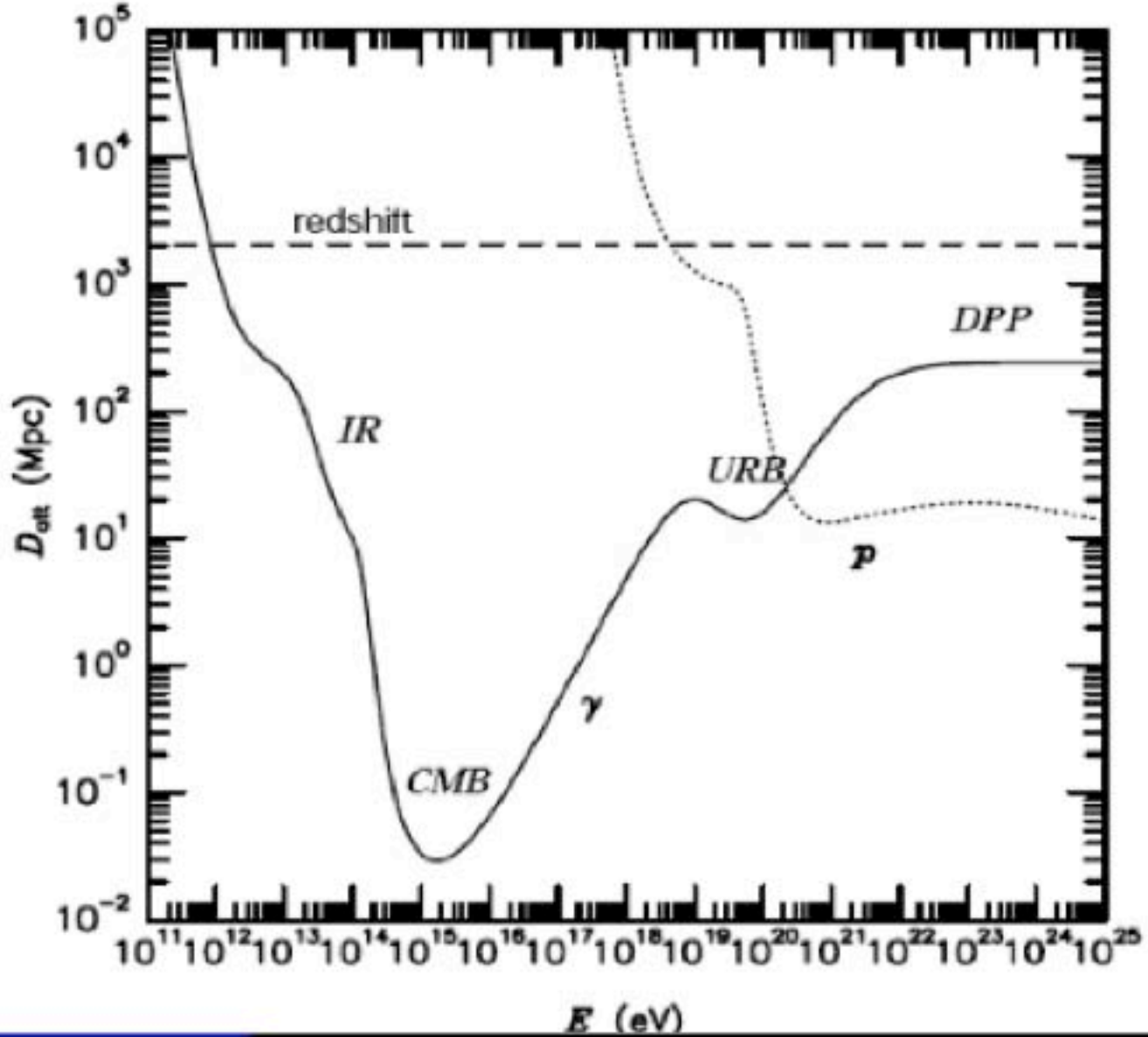
z = 1100 (E_{cmb}~ 10^{-3} eV)

Galactic Sources (E ~ 100 TeV)

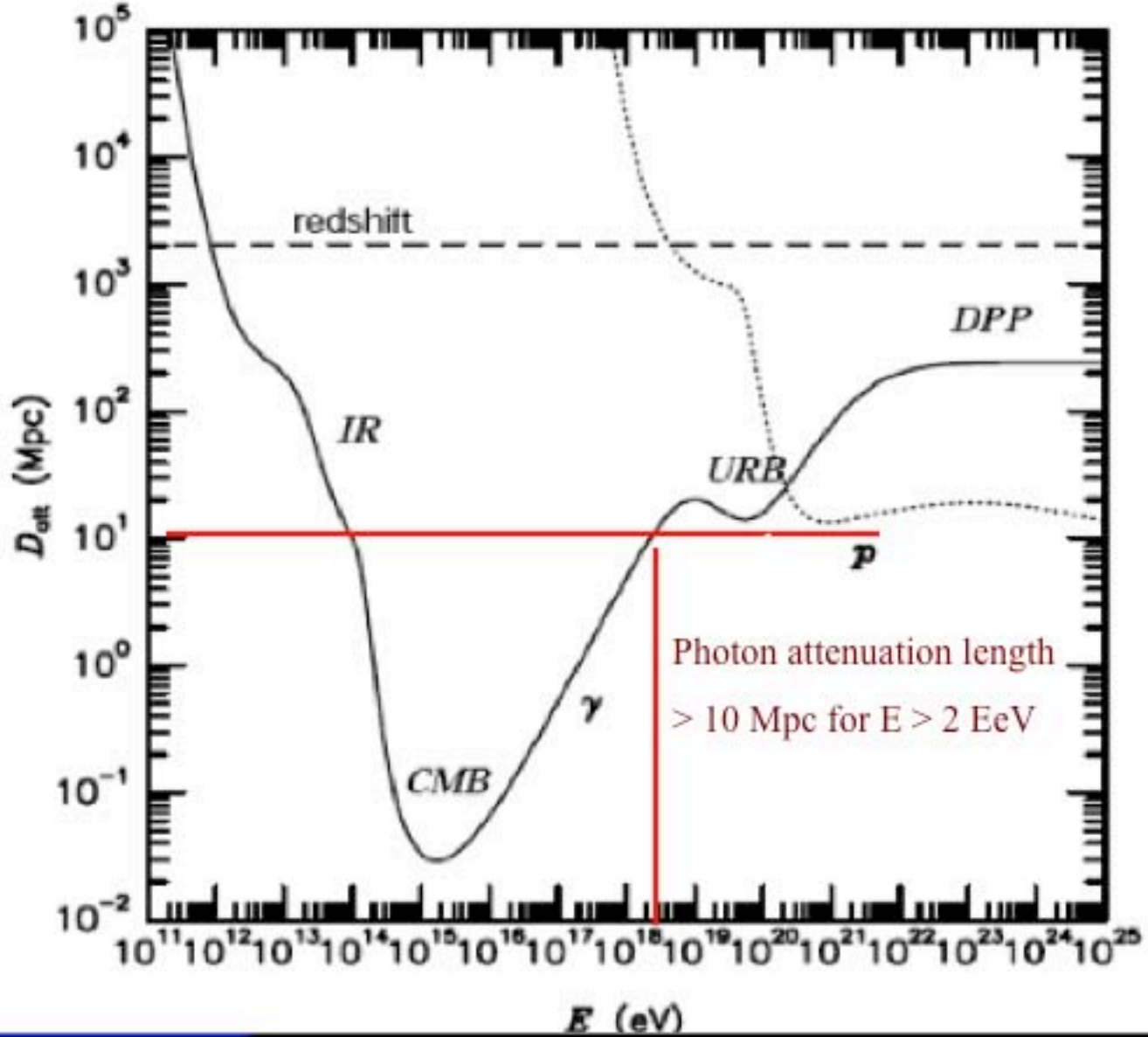
Extragalactic Sources – EBL effect vs **Axion-like Particles**

E > 10^{19} eV from 10 Mpc

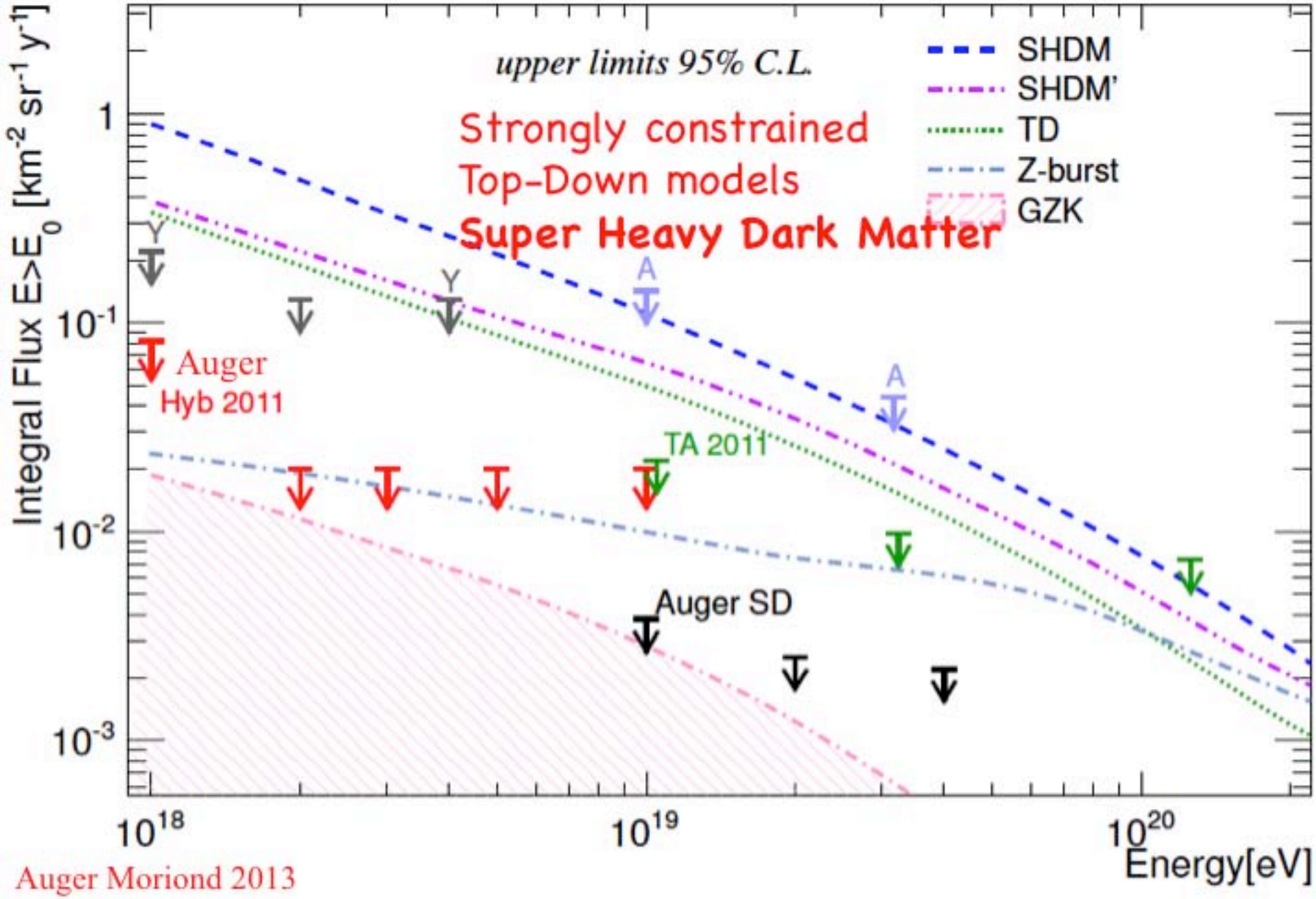
Gamma Ray Attenuation



The UHE Gamma Ray Window

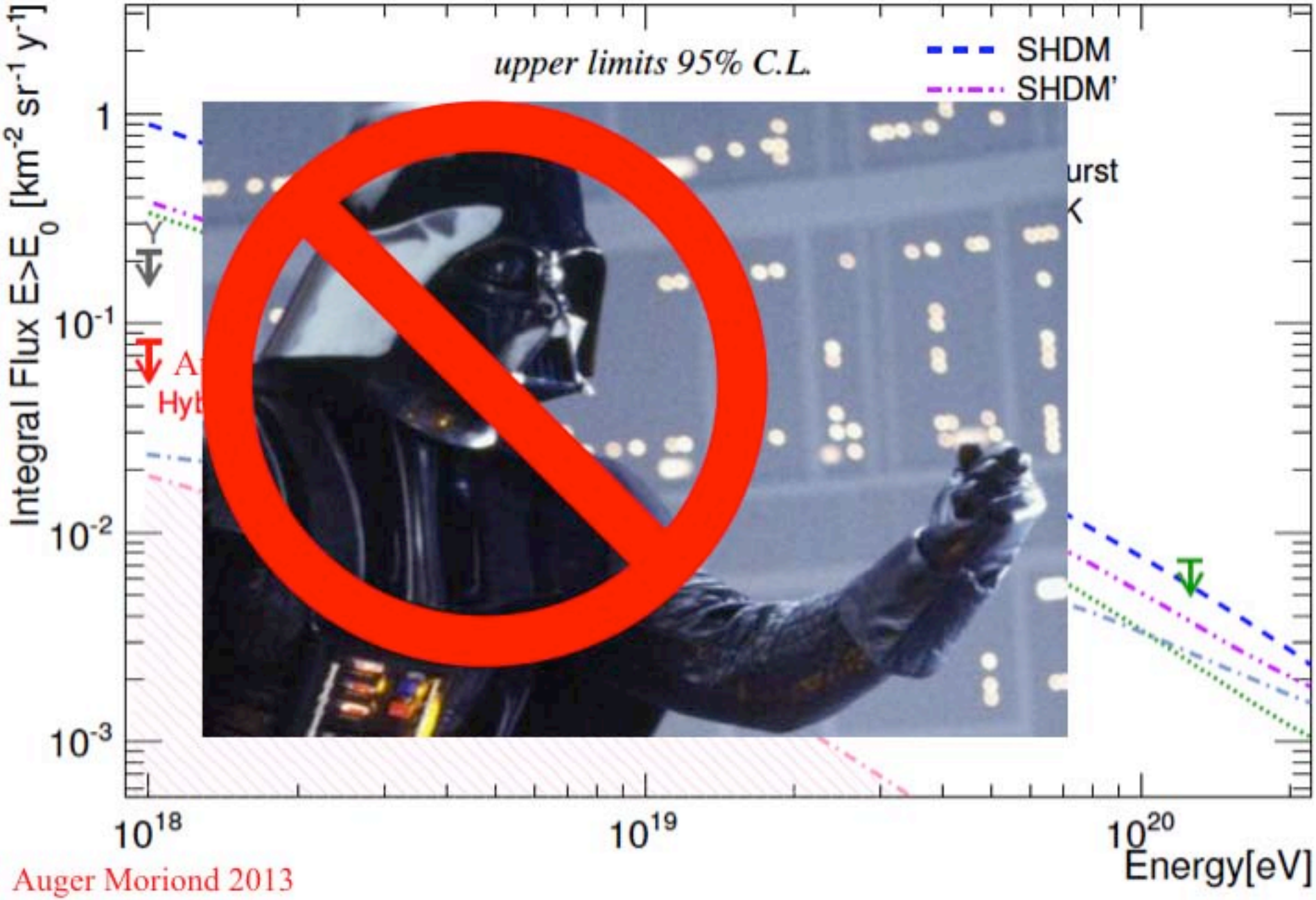


Auger Photon Limits



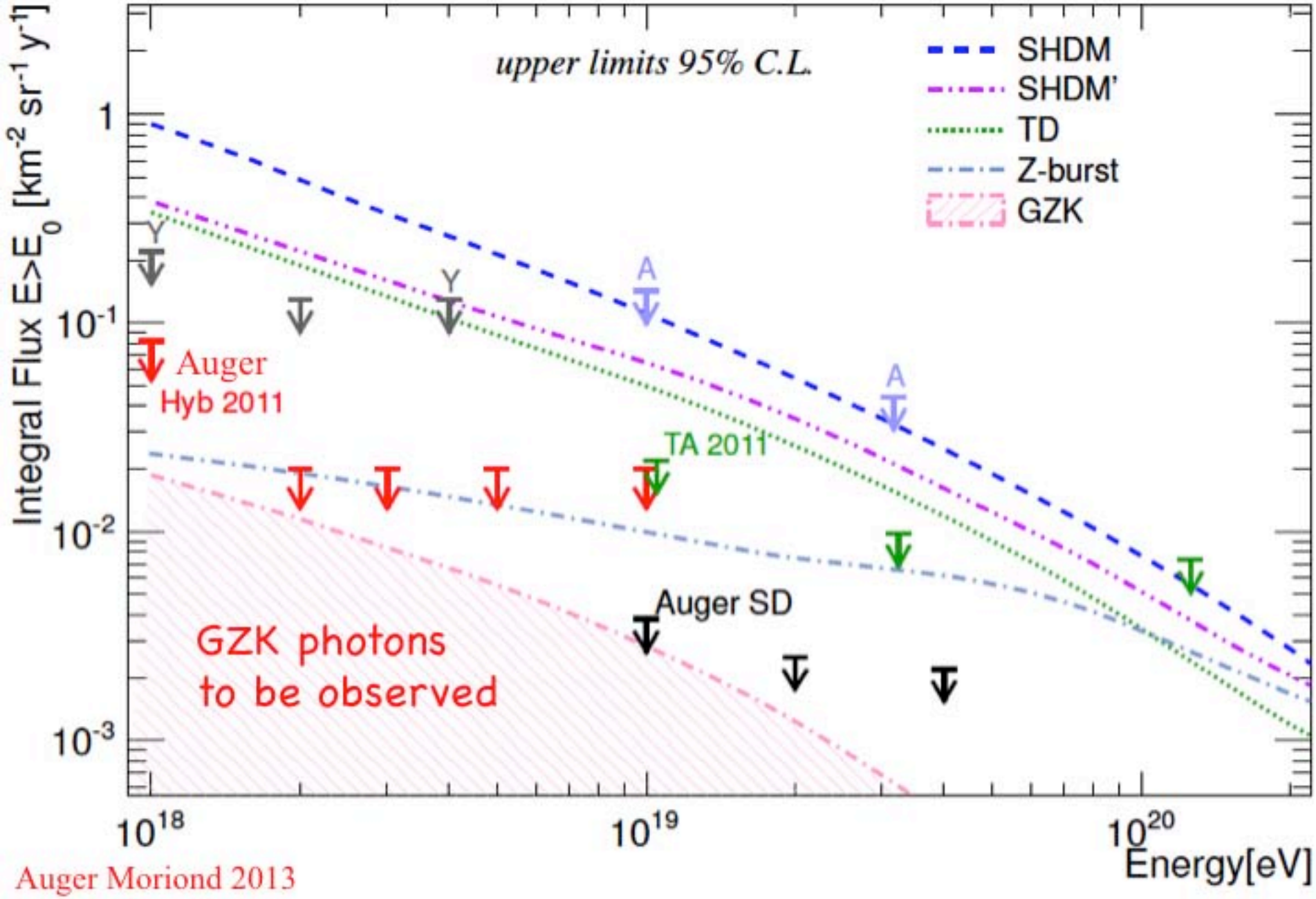
Auger Moriond 2013

Auger Photon Limits



Auger Moriond 2013

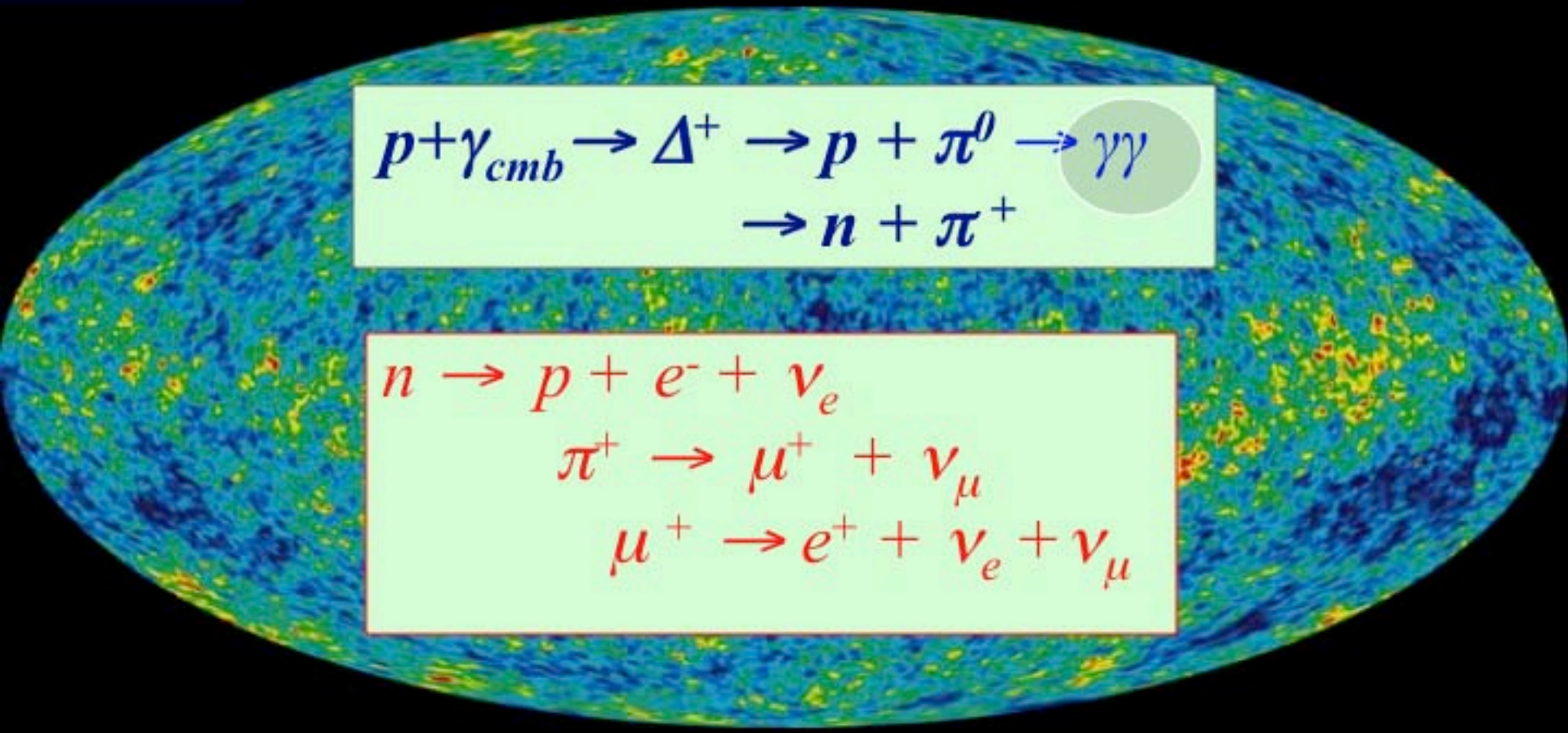
Auger Photon Limits



Auger Moriond 2013

Cosmogenic (GZK) Neutrinos & Photons

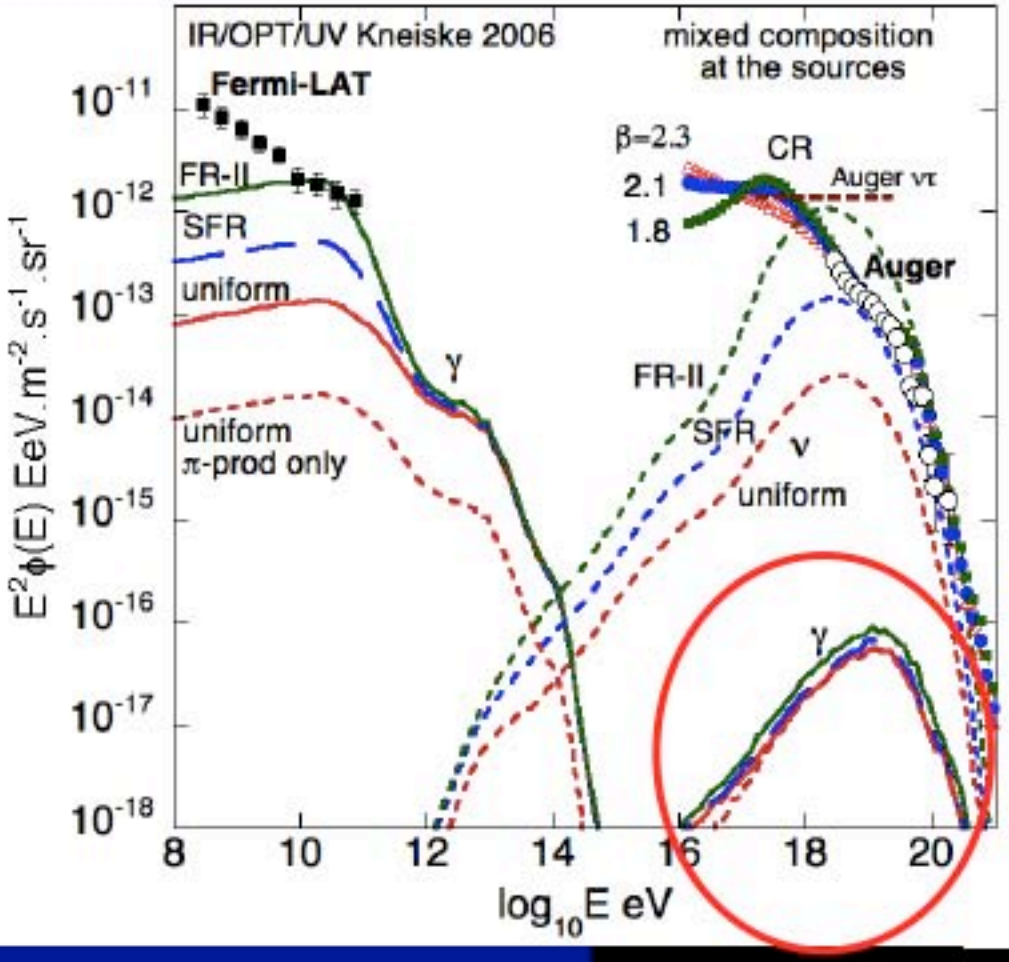
and UHECR composition

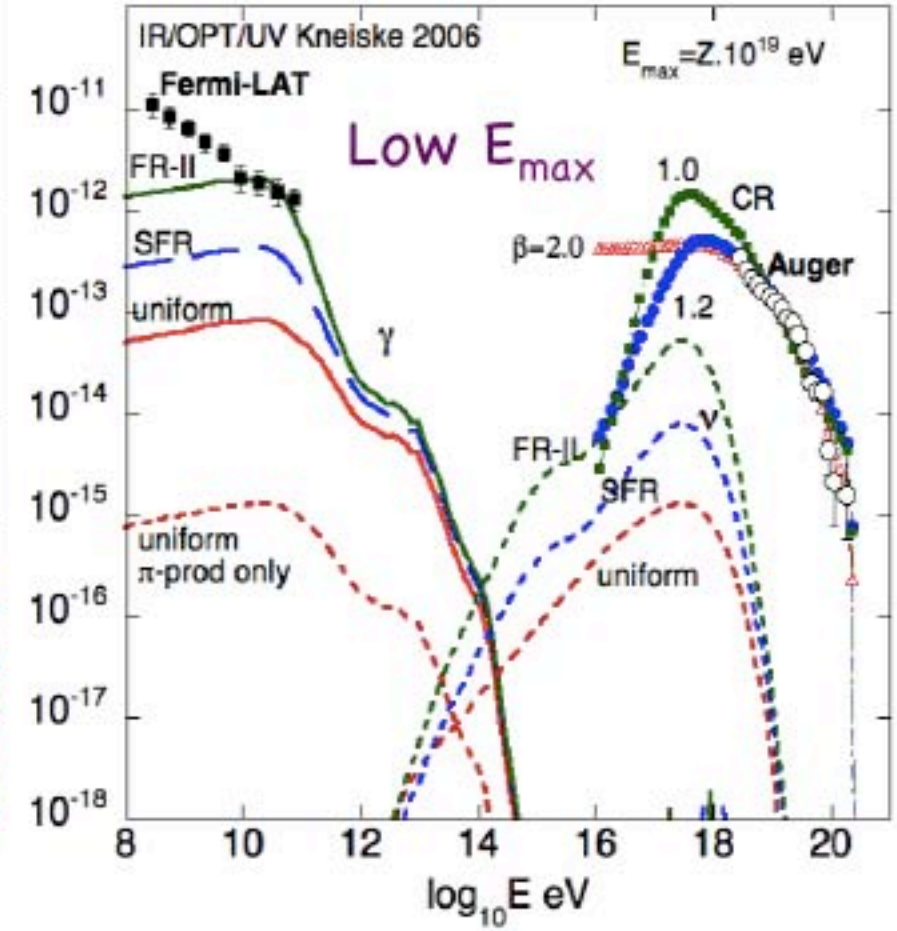


$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^+$$

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

GZK/Cosmogenic Photons E_{max} dependent





Decerprit & Allard 11

At High Energies, how are primary photons generated?

At High Energies, how are primary photons generated?

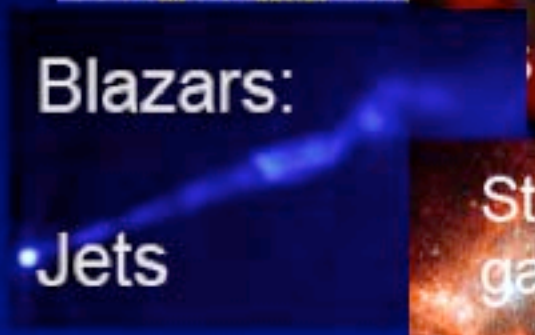
Electromagnetic & Hadronic (π prod) processes

At High Energies, how are primary photons generated?

Electromagnetic & Hadronic (π prod) processes

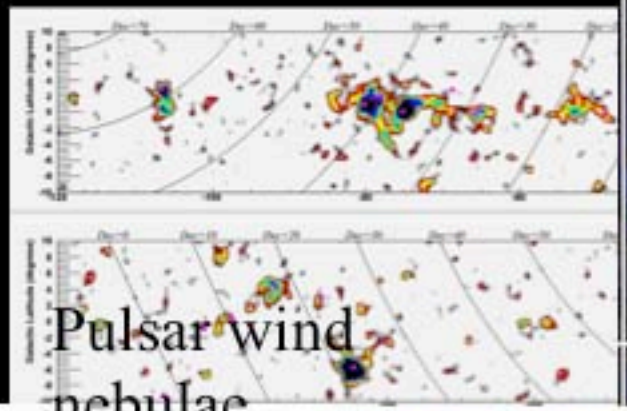
Nature's HE γ Accelerators

Extragalactic

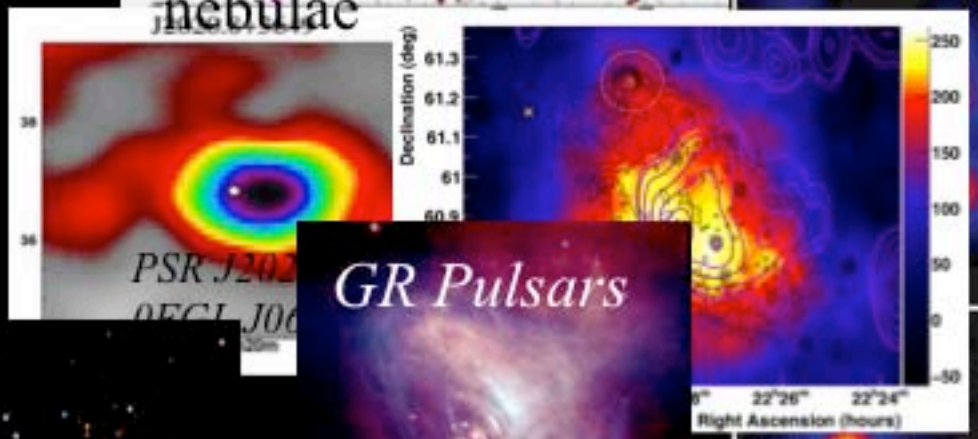


Unidentified

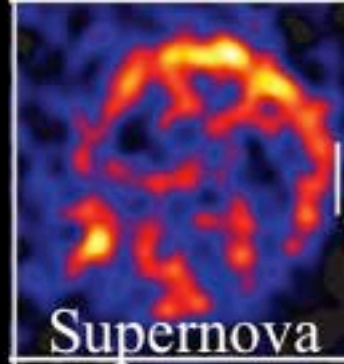
Galactic



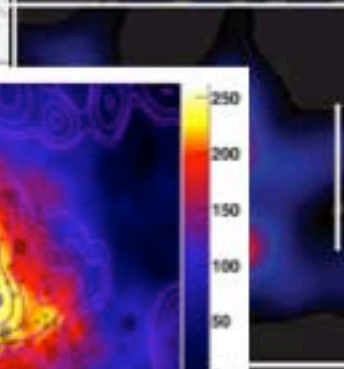
Pulsar wind nebulae

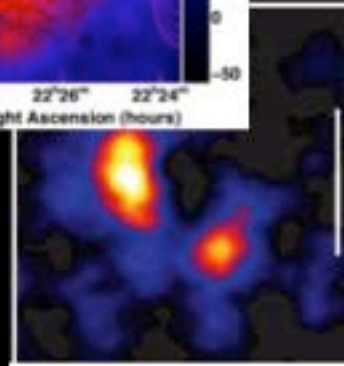


Stellar clusters



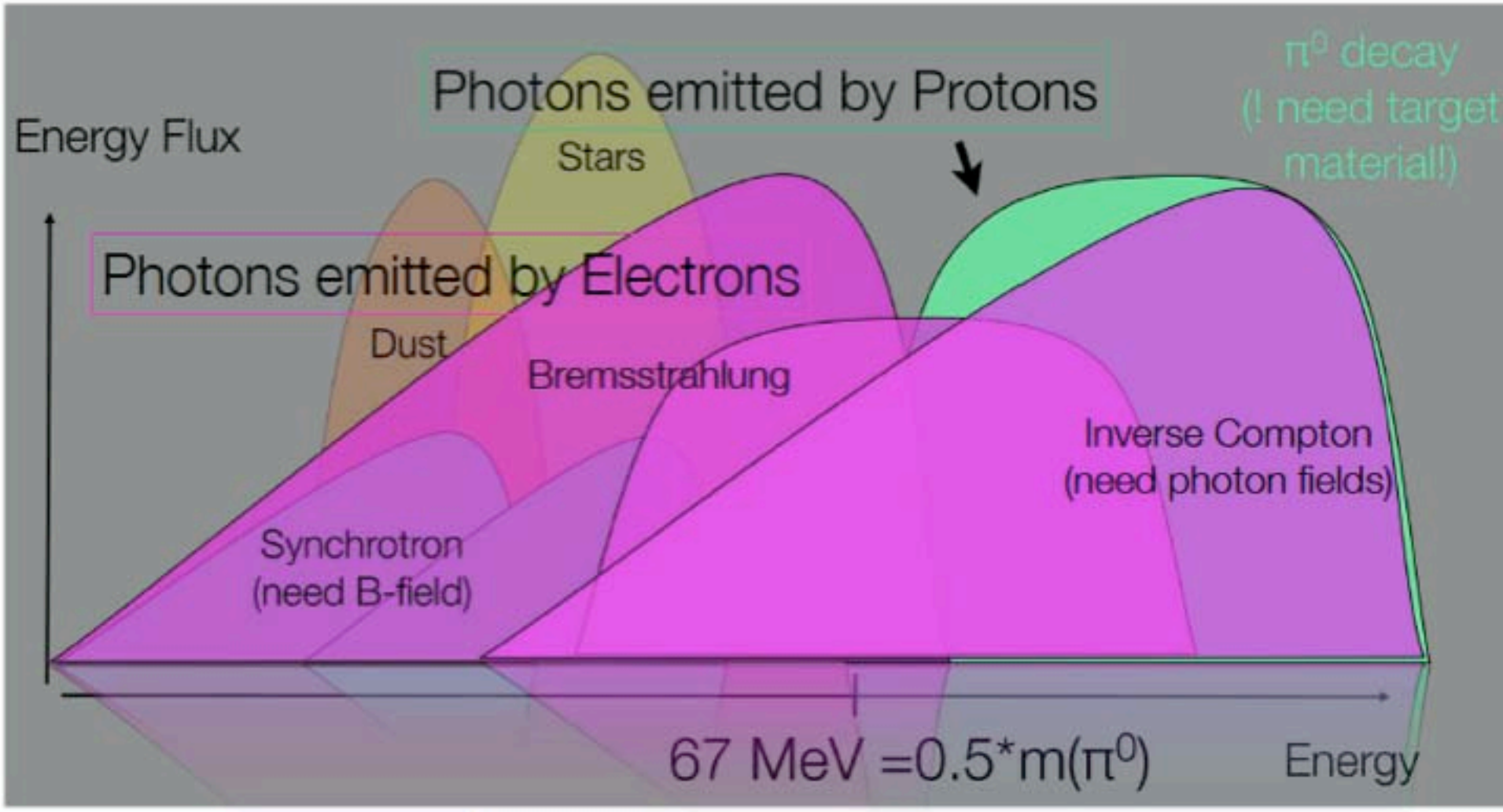
Supernova remnants





Krennrich, Hoffman TeVPA09

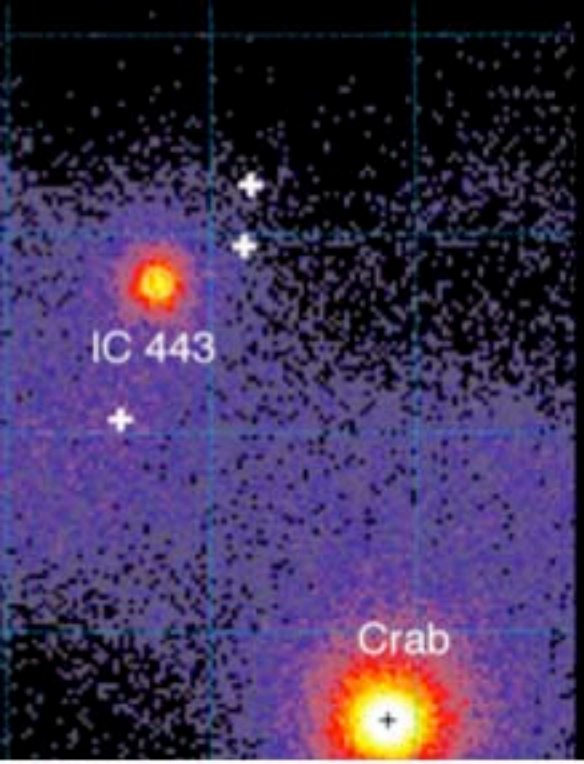
Photon emission by accelerated charged particles

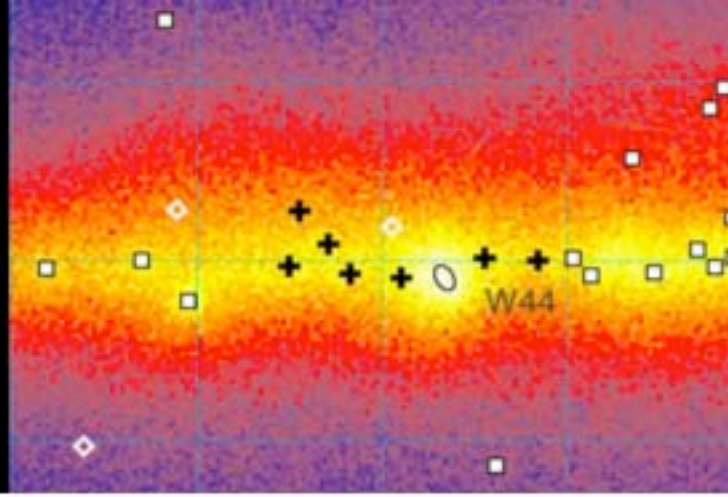


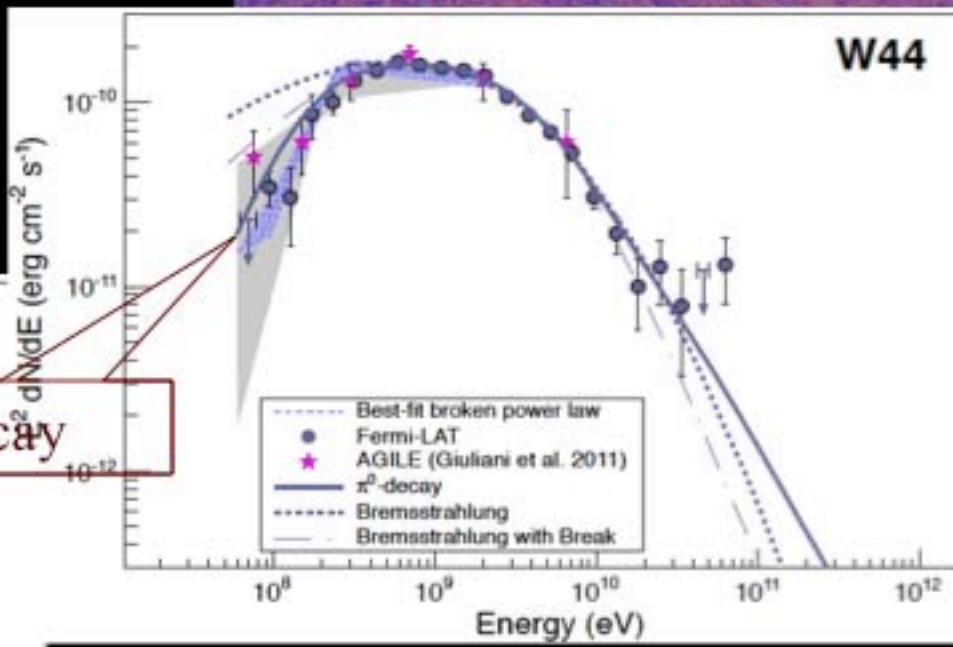
π^0 decay!

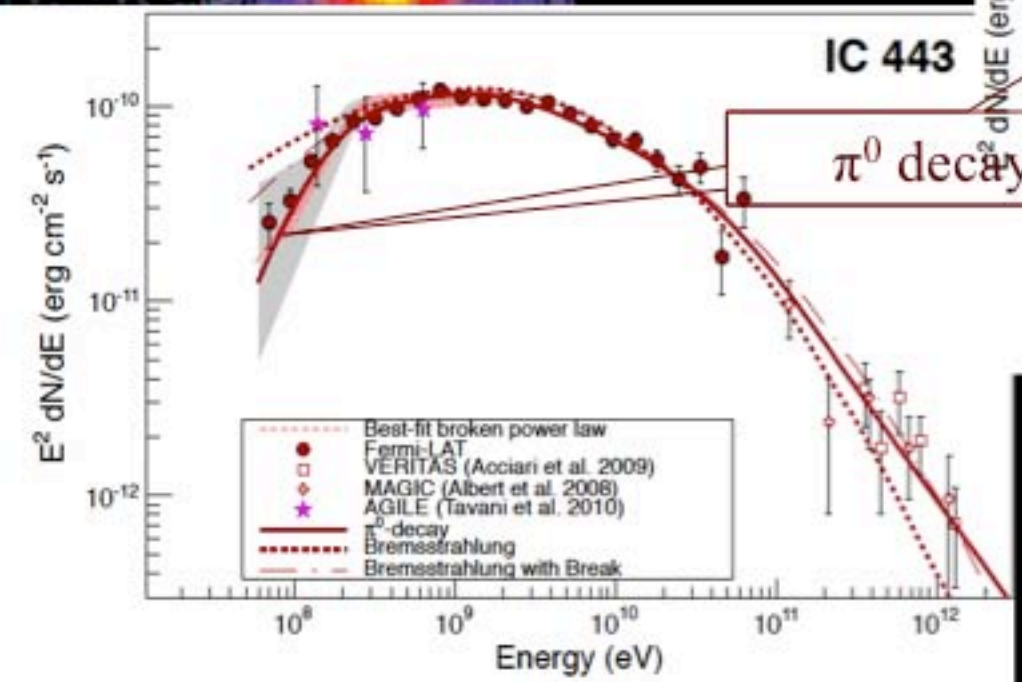
IC 443 & W44

Fermi & AGILE







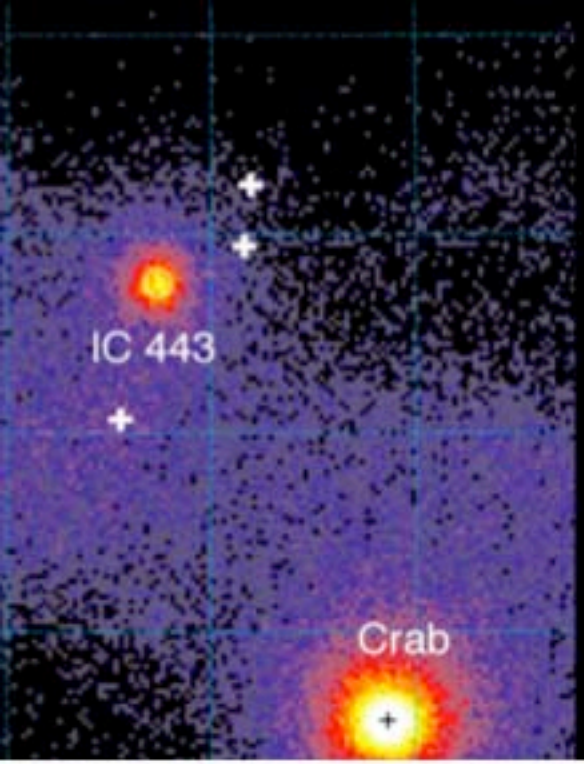


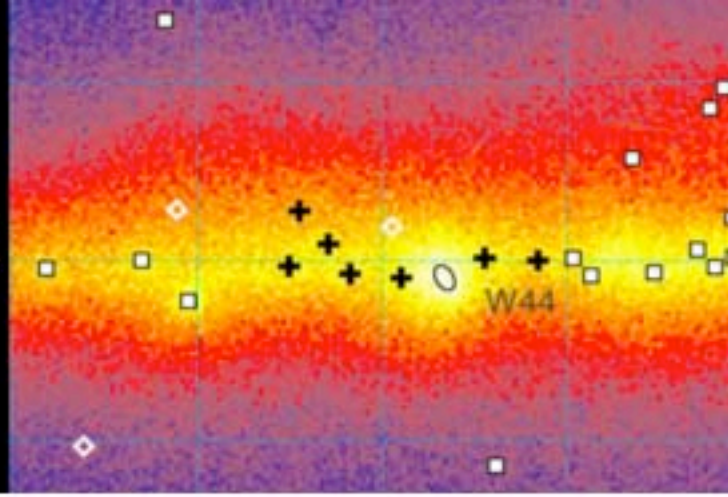
Ackermann et al (Fermi Collab) '13
arXiv:1302.3307

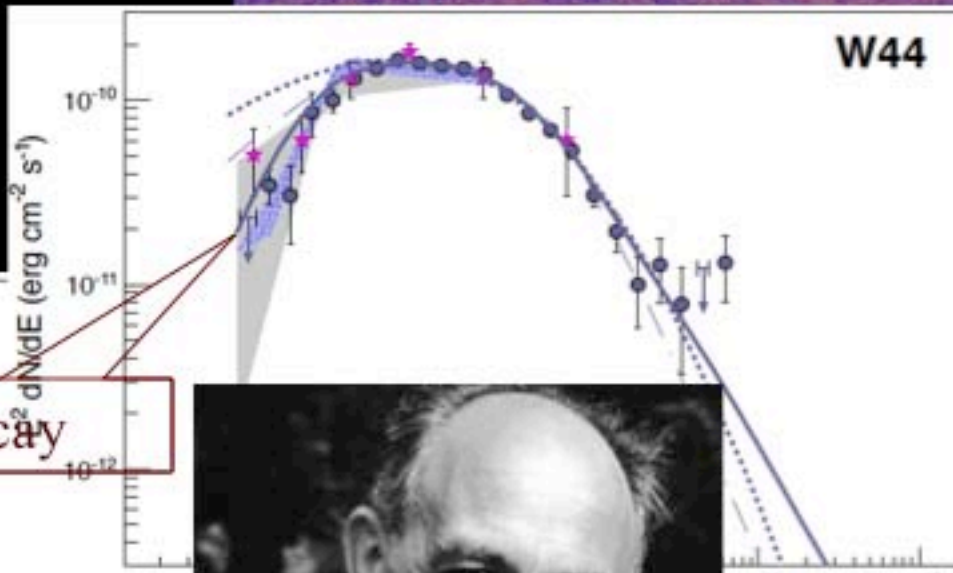
π^0 decay!

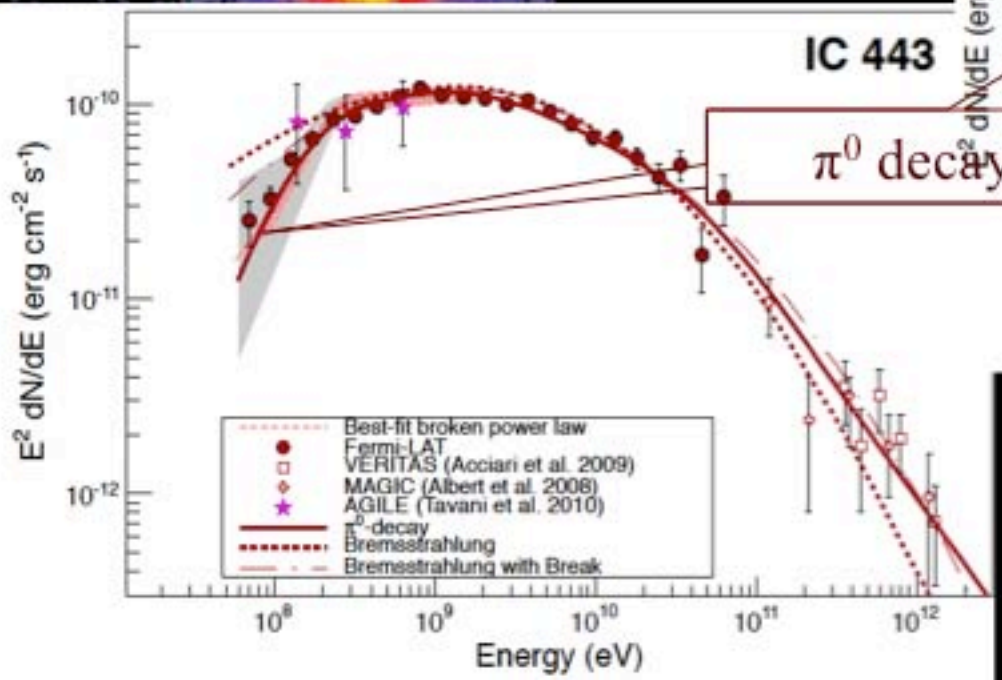
IC 443 & W44

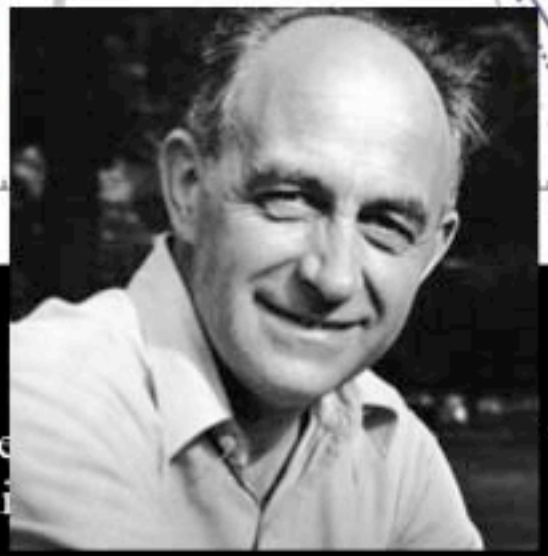
Fermi & AGILE











Acke
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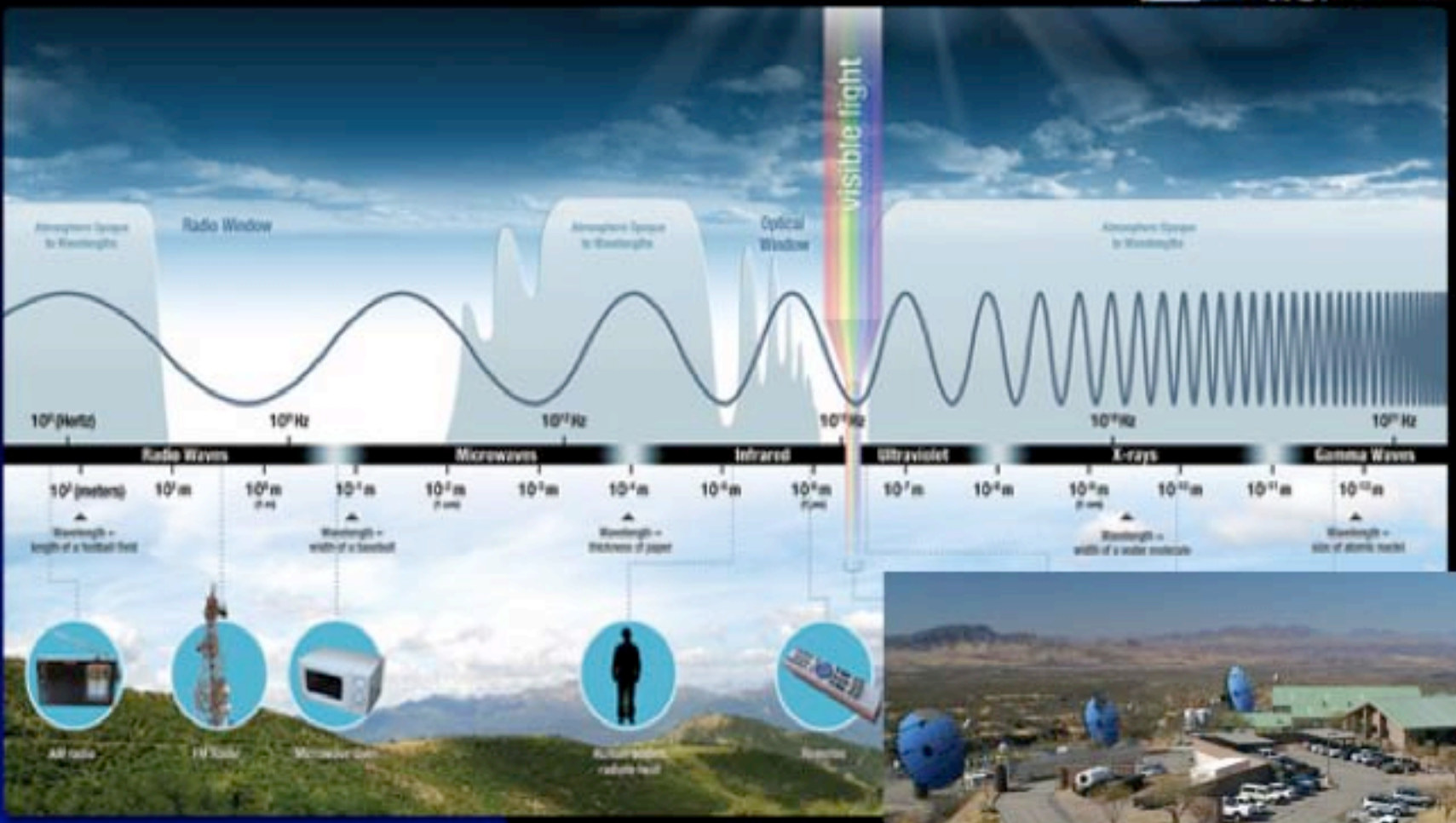
At High Energies, how are primary photons generated?
Electromagnetic & Hadronic (π prod) processes

At High Energies, how are they observed?


visible light
Radio Window
Optical Window
Radio Waves
Microwaves
Infrared
Ultraviolet
X-rays
Gamma Waves

At High Energies, how are primary photons generated?
Electromagnetic & Hadronic (π prod) processes

At High Energies, how are they observed?
Fermi Satellite, IACTs, Water Cherenkov

Gamma-Rays Eyes

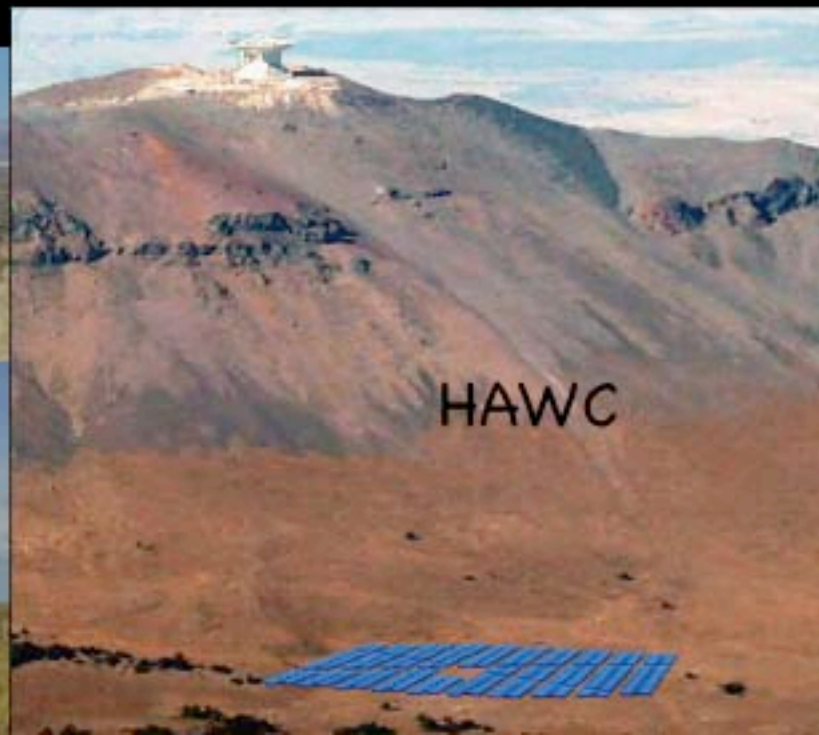
Fermi

MAGIC

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

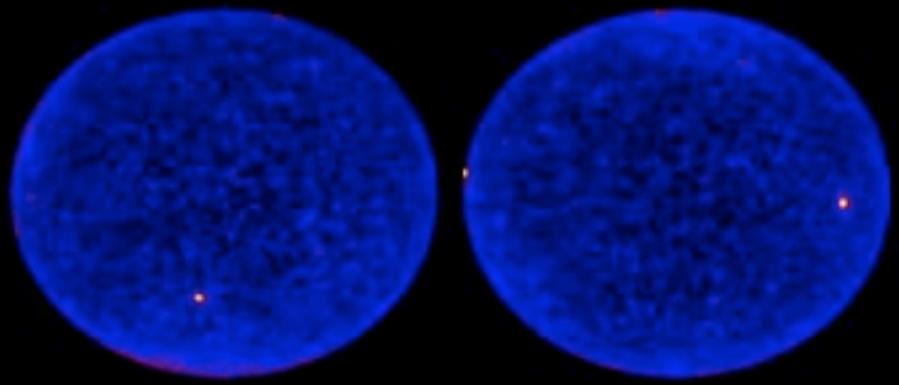
VERITAS

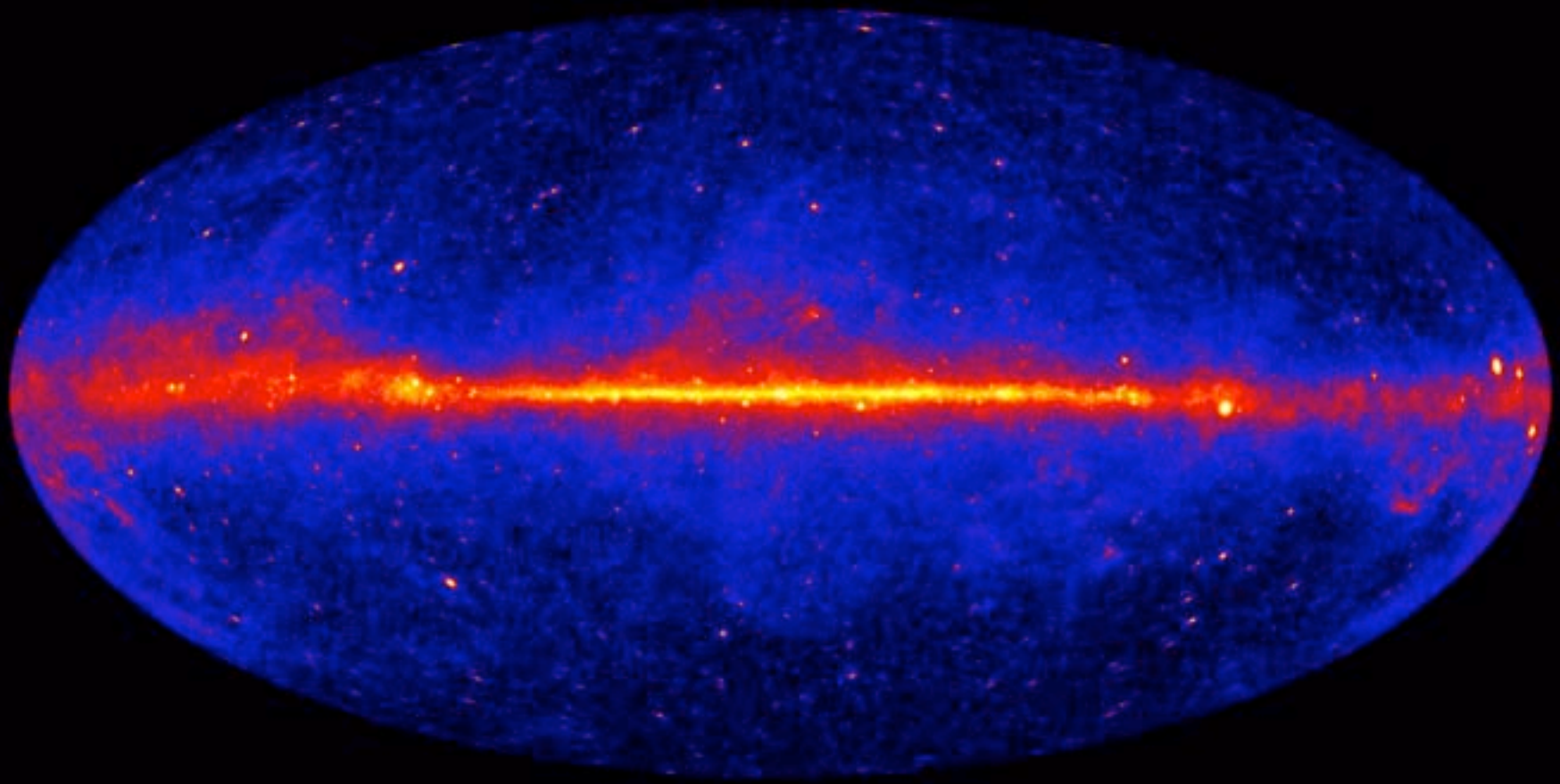
HESS II



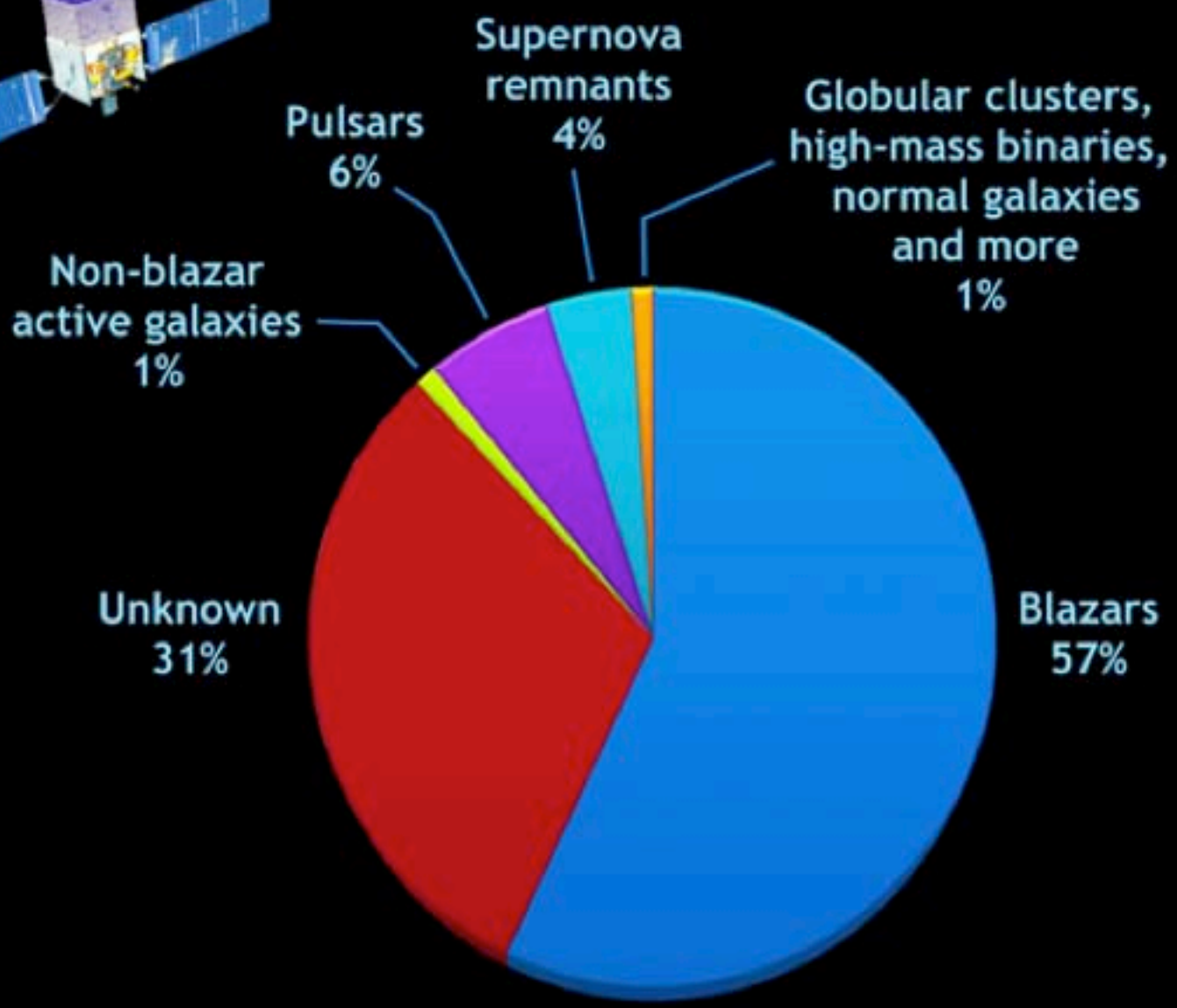
HAWC

Fermi



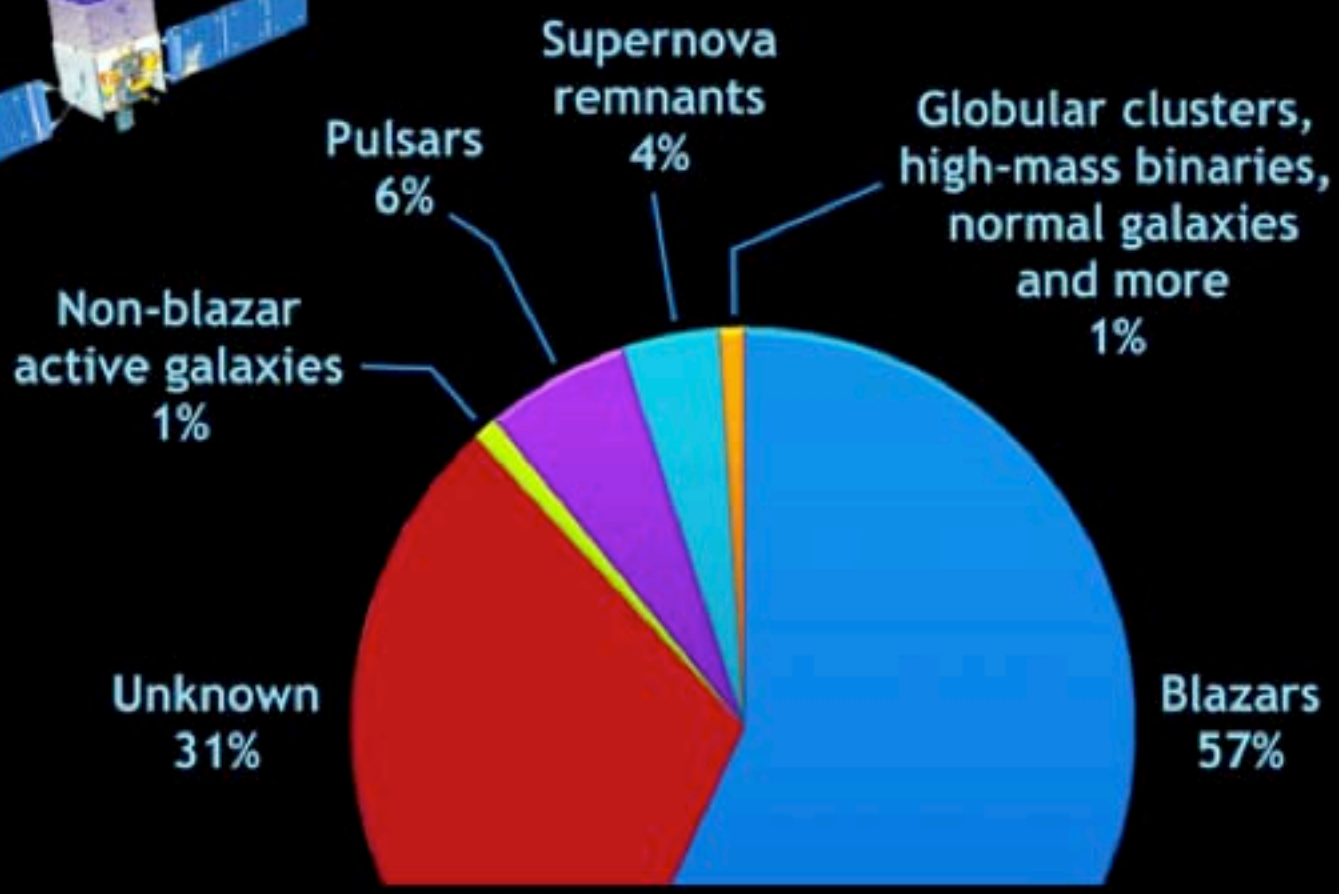


What has Fermi found: The LAT two-year catalog



Credit: NASA/Goddard Space Flight Center

What has Fermi found: The LAT two-year catalog



Limits on DM in GC, Dwarf Galaxies, etc...
Limits on LIV to ~ M_{pl}
Limits on Large Extra Dimensions stronger LHC

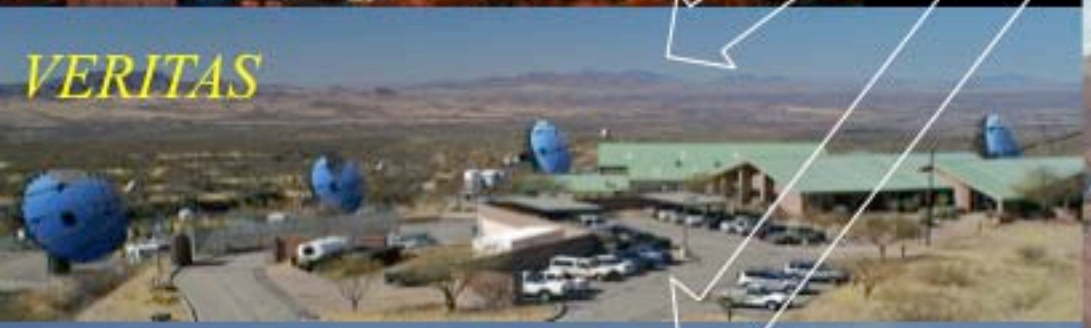
Credit: NASA/Goddard Space Flight Center

Gamma-Rays Eyes

Fermi

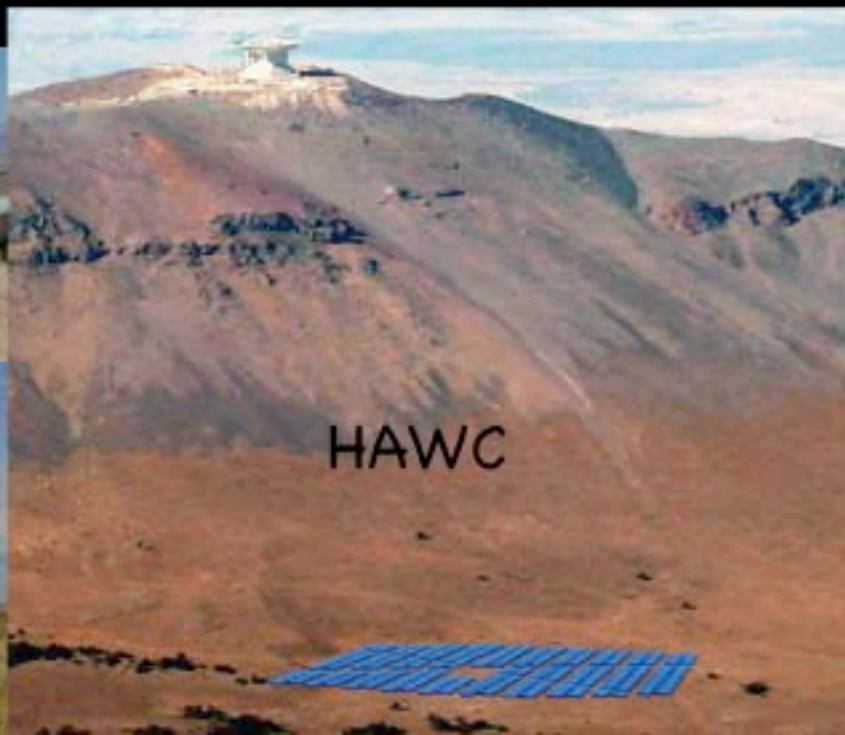
MAGIC

IACT –
Imaging Atmospheric
Cherenkov Telescopes
~10^{10} to <10^{14} eV



VERITAS

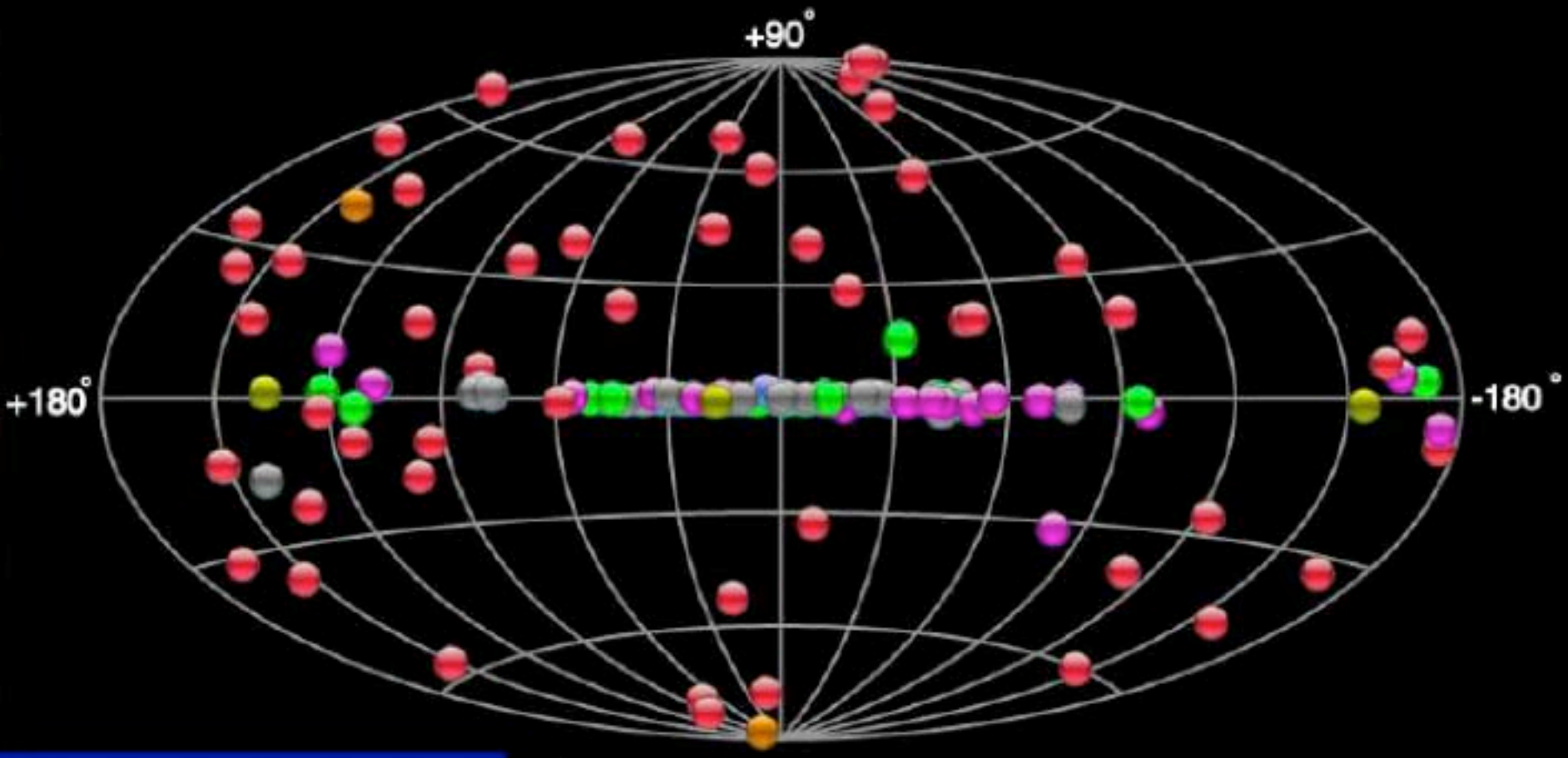
HESS



HAWC

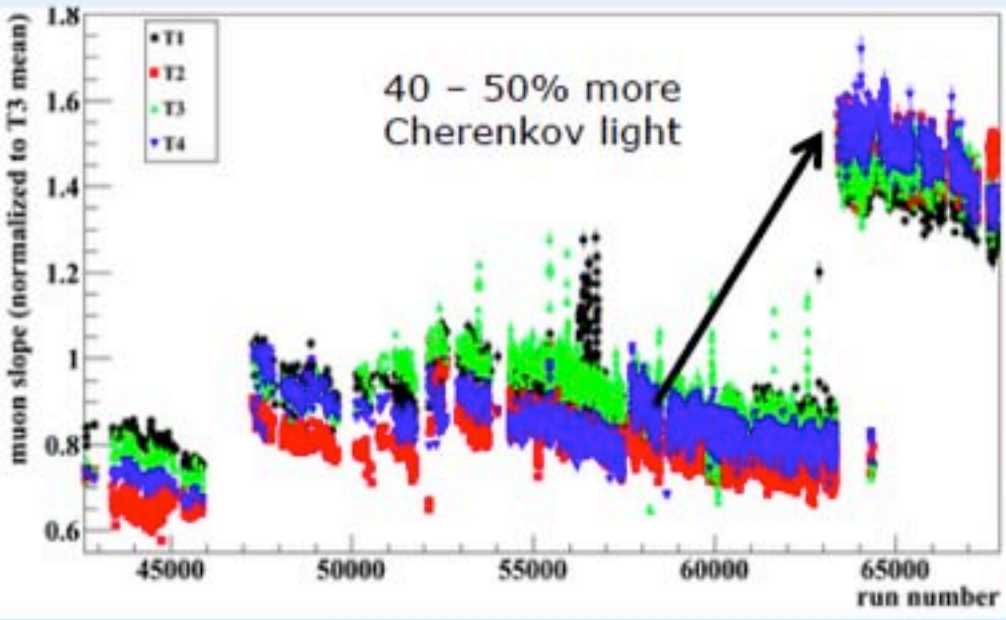
TeV γ Catalog (IACT sky)

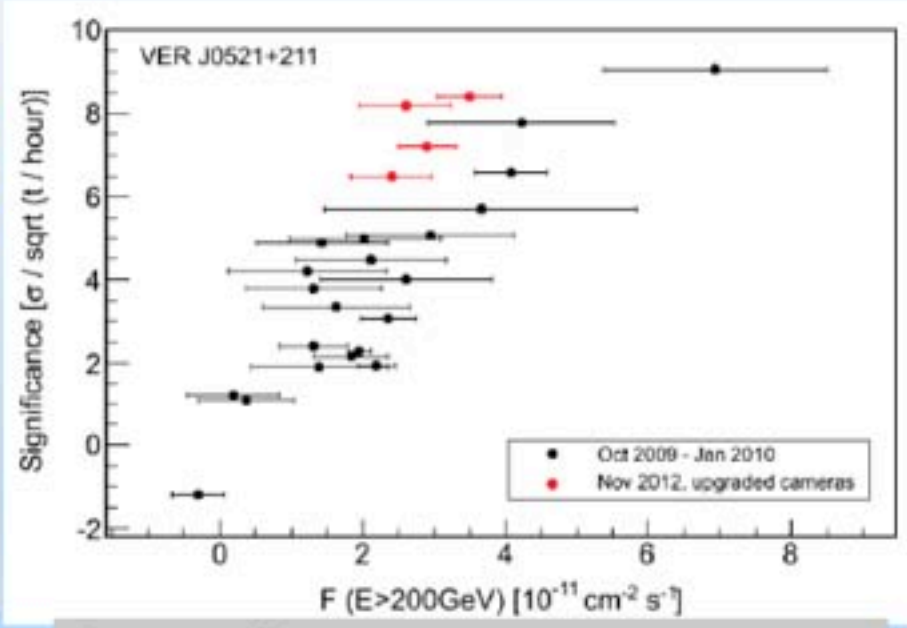
145 sources



tevcat.uchicago.edu

VERITAS



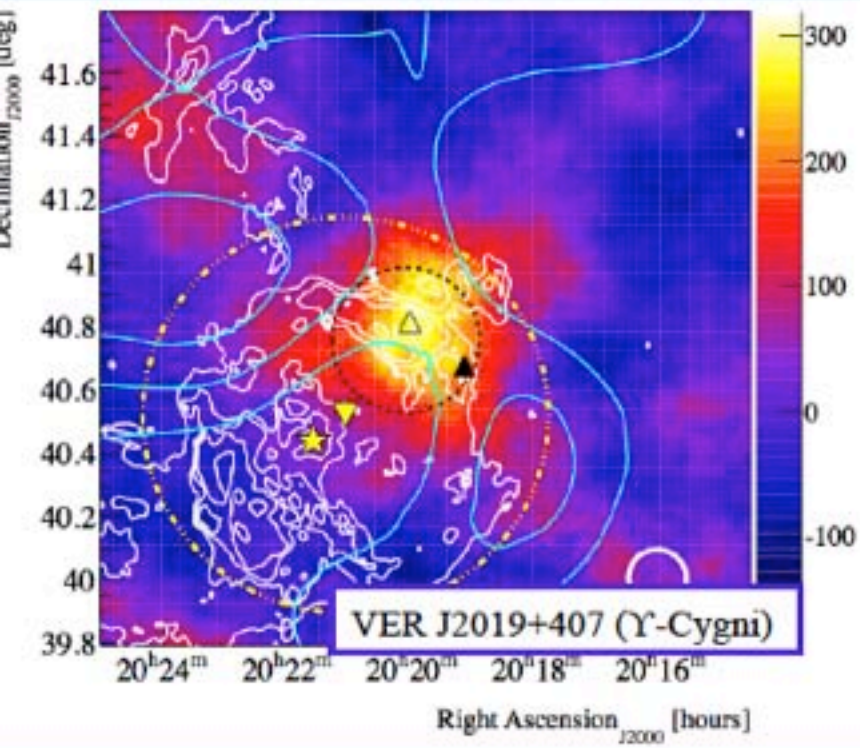


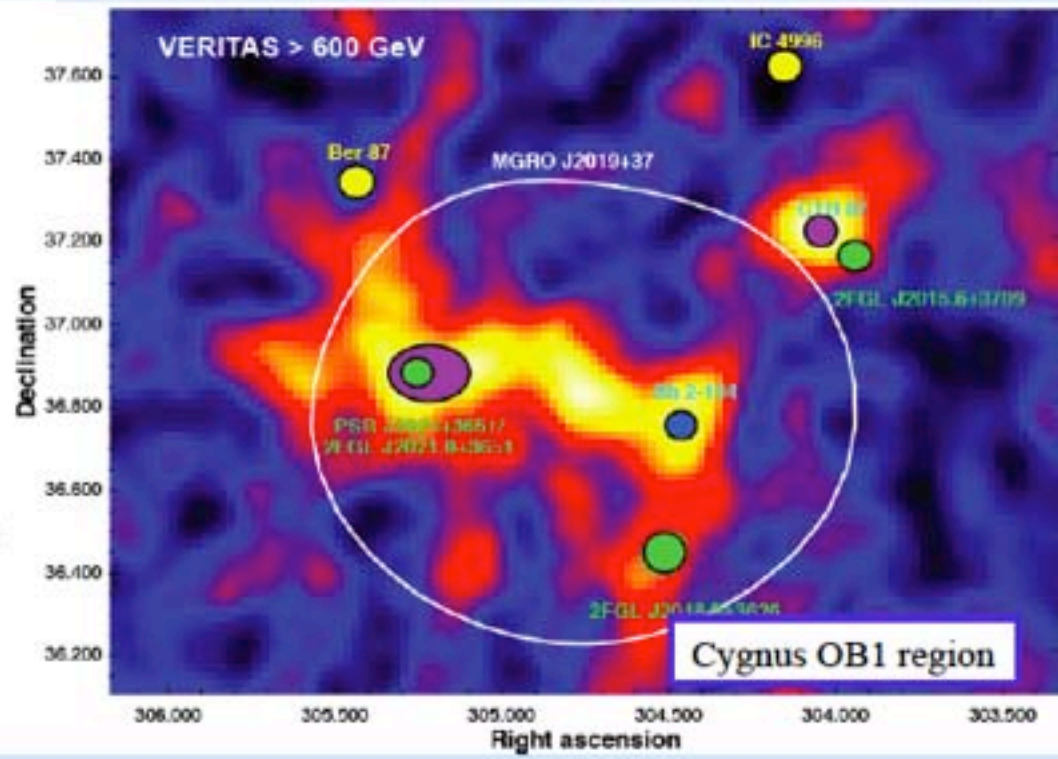
Detect soft spectrum sources twice as fast as in 2009

- Energy range: ~100 GeV - 30 TeV
- Sensitivity: 1% Crab in ~25h
- Energy resolution: 15-25%
- Angular resolution: R_68% < 0.1 deg

from Holder CSS'13

Disentangling CR acceleration regions in our Galaxy





- IACTs such as VERITAS provide good angular resolution (~0.1° / event)
- Allows energy dependent study of complex regions, and deconvolution of multiple overlapping (associated or unassociated) sources.

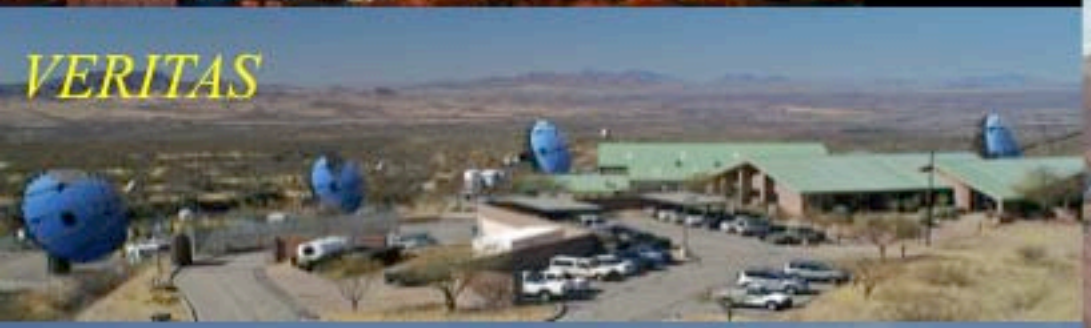
from Holder CSS'13

Next Generation Gamma-ray Detectors

Gamma-Rays Eyes

Fermi

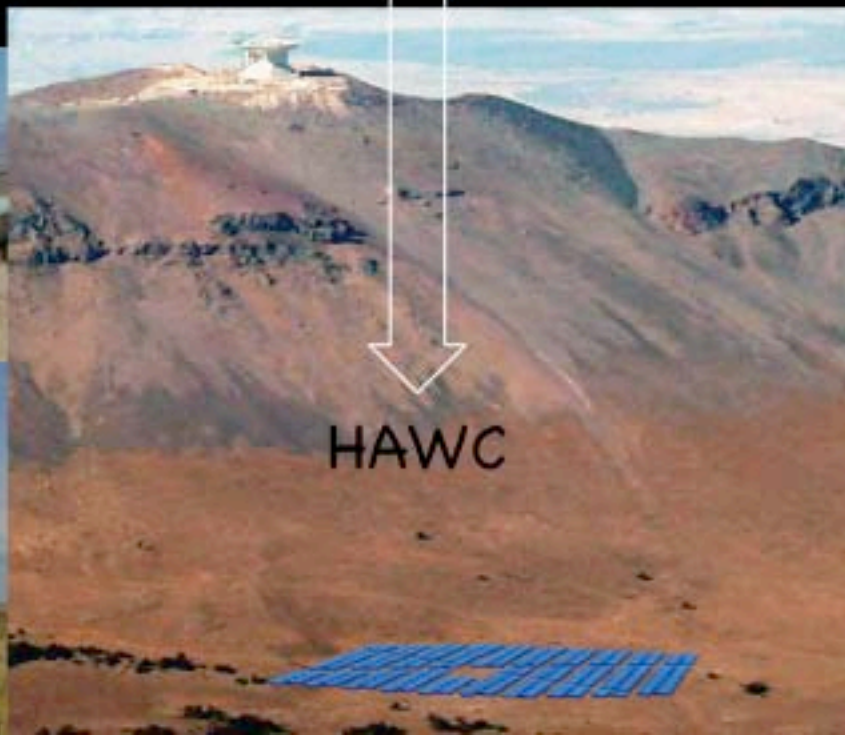
MAGIC



VERITAS

HESS

Water Cherenkov Telescope
Milagro – now HAWC
~10^{11} to 10^{15} eV



HAWC: High Altitude Water Cherenkov

USA:

16 institutions,

57 people

Mexico:

15 institutions

54 people

to be completed in Aug 2014

from Dingus CSS'13

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USA:

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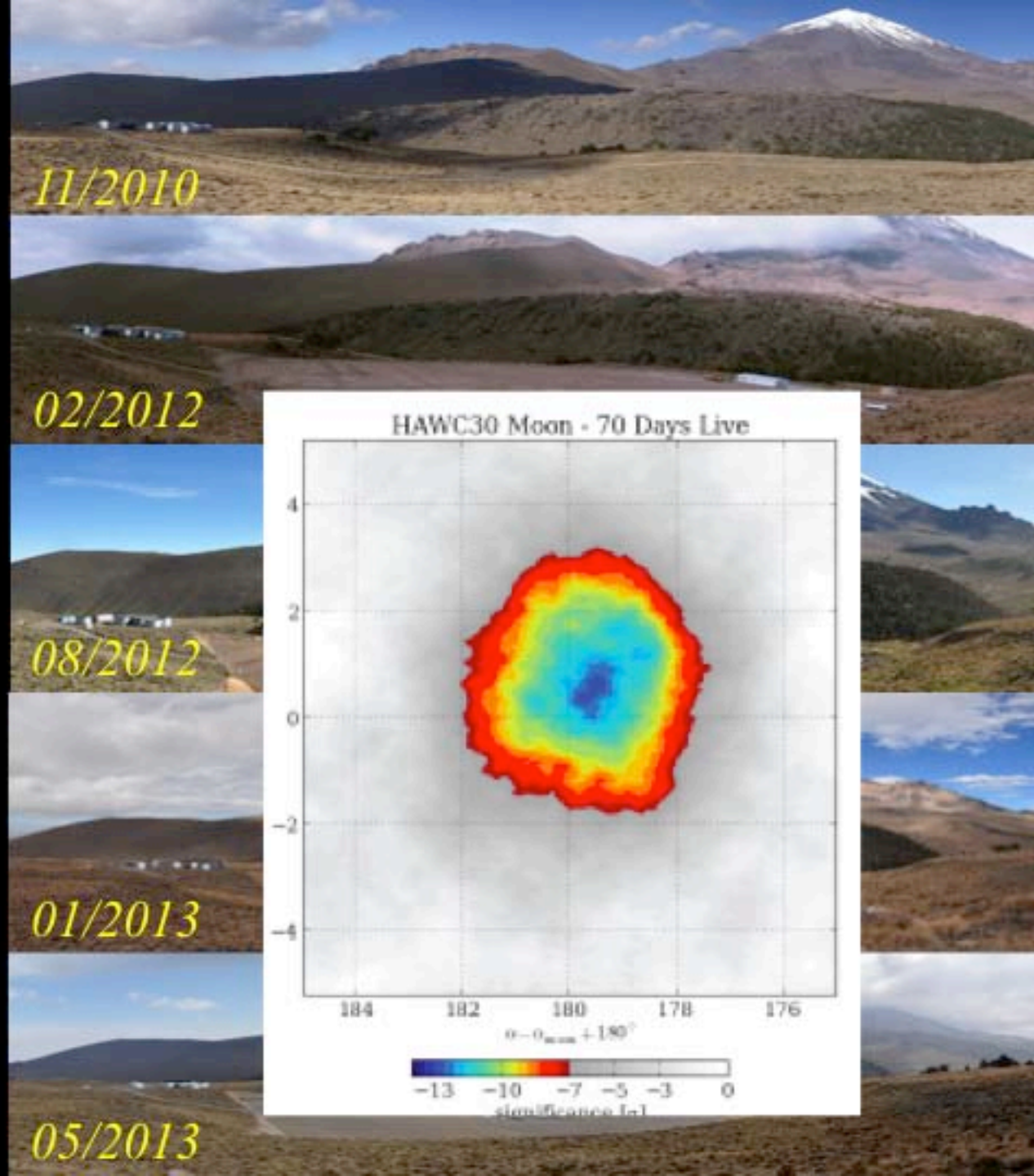
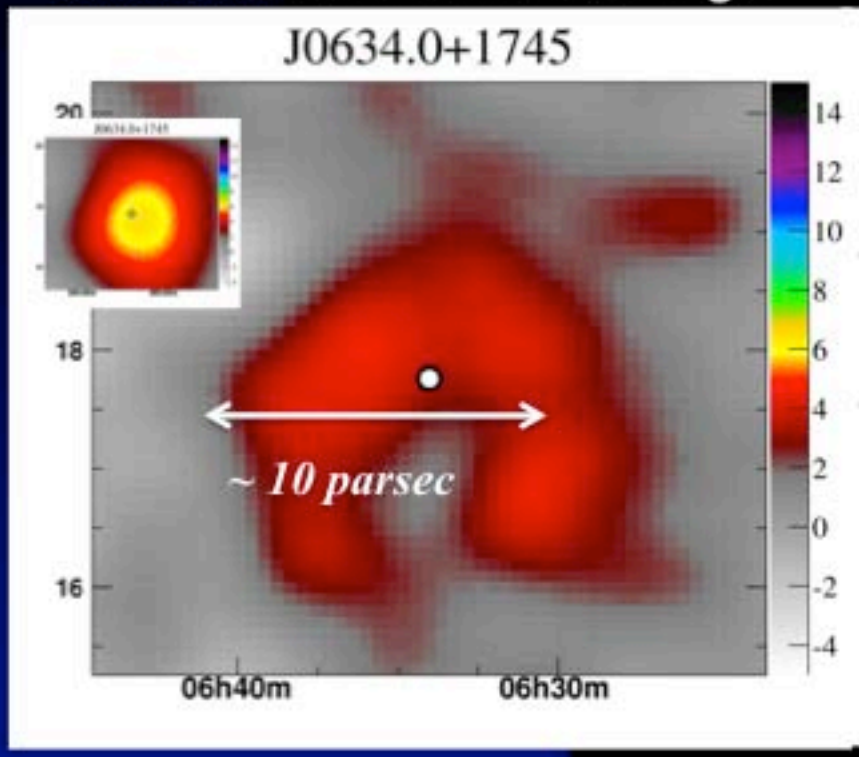


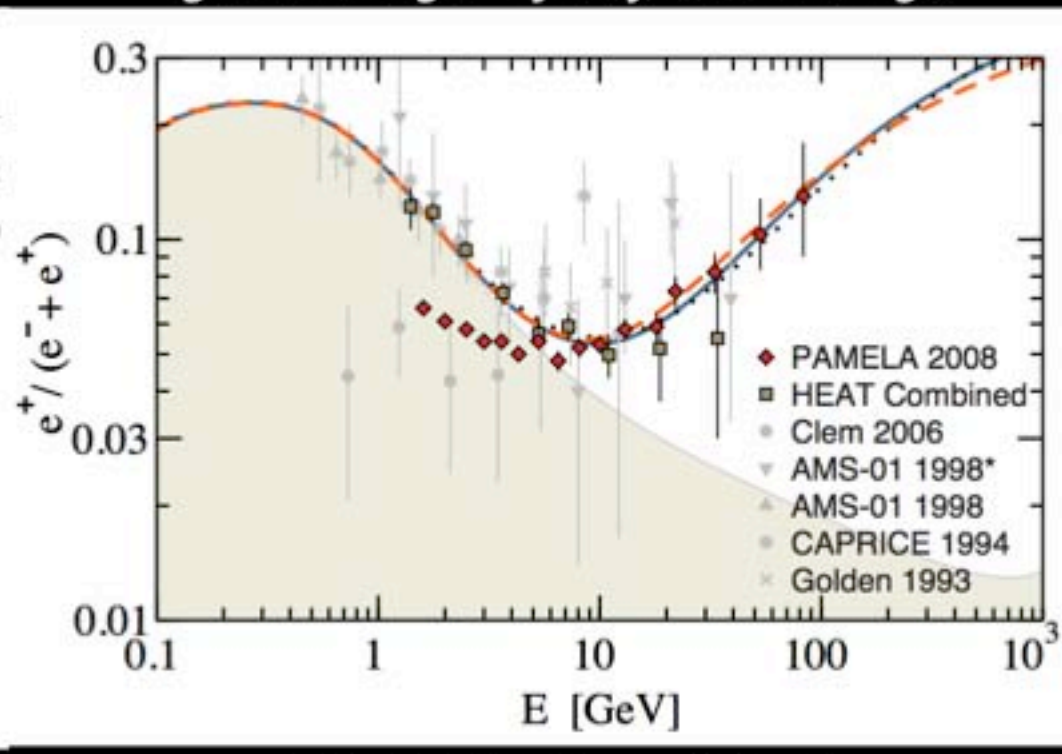
from Dingus CSS'13

HAWC: Extended Sources

Milagro's Detection of an extended excess coincident with Geminga



PAMELA's positron excess is well fit given Milagro's flux from Geminga



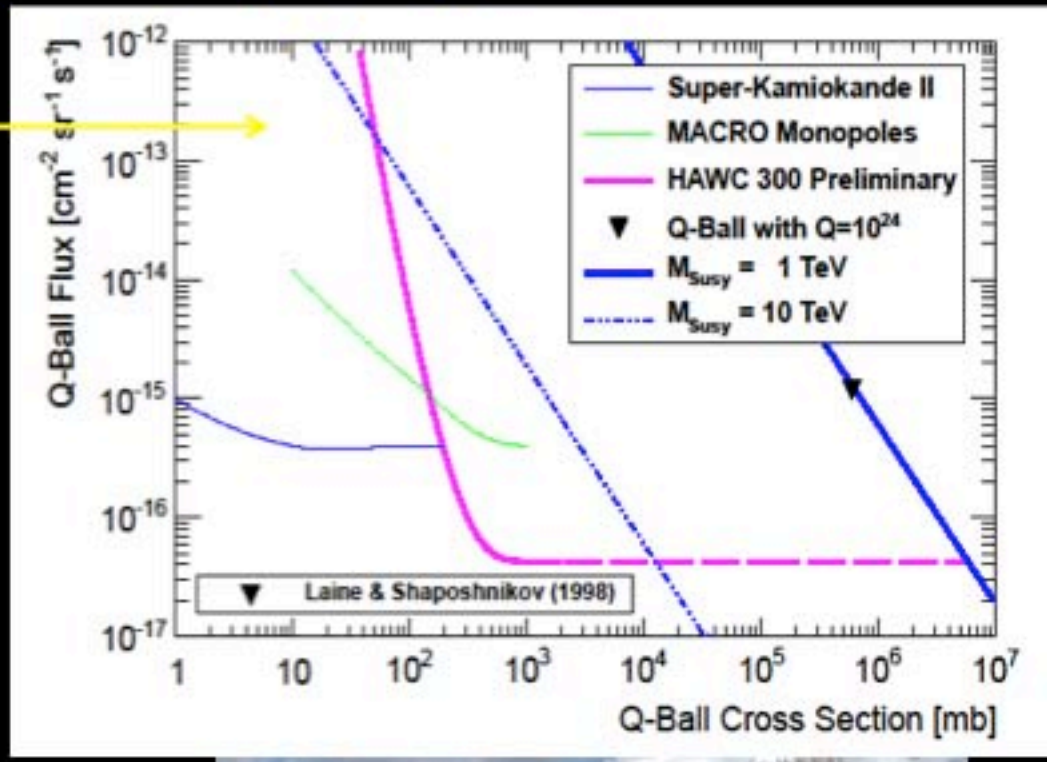
Yüksel, Kistler, Stanev PRL 2009

HAWC will detect Geminga with >50σ
to measure spectra and map diffusion near source.

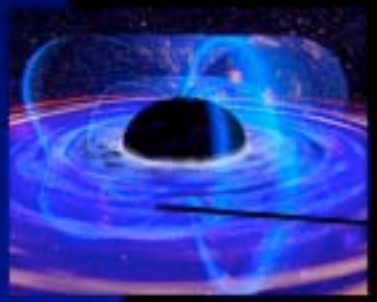
from Dingus CSS'13

HAWC: Exploratory Physics

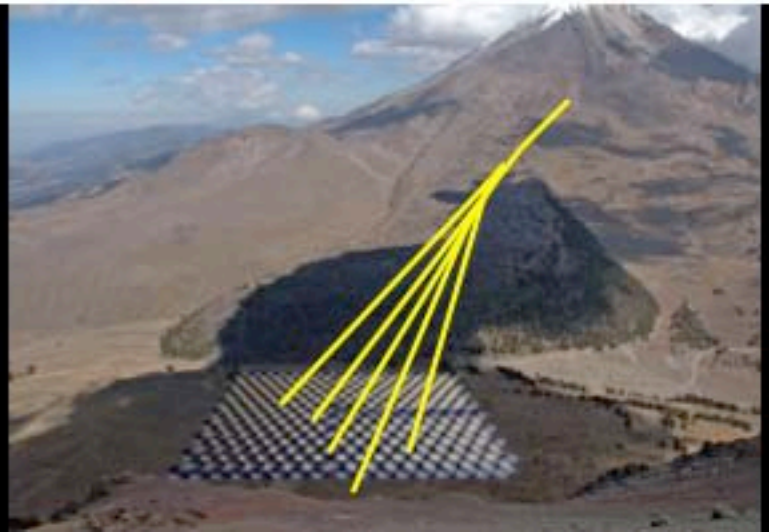
Direct Detection of SUSY Q-balls & Monopoles



Primordial Black Hole Evaporation



Tau neutrino showers



from Dingus CSS'13

CTA: Cherenkov Telescope Array

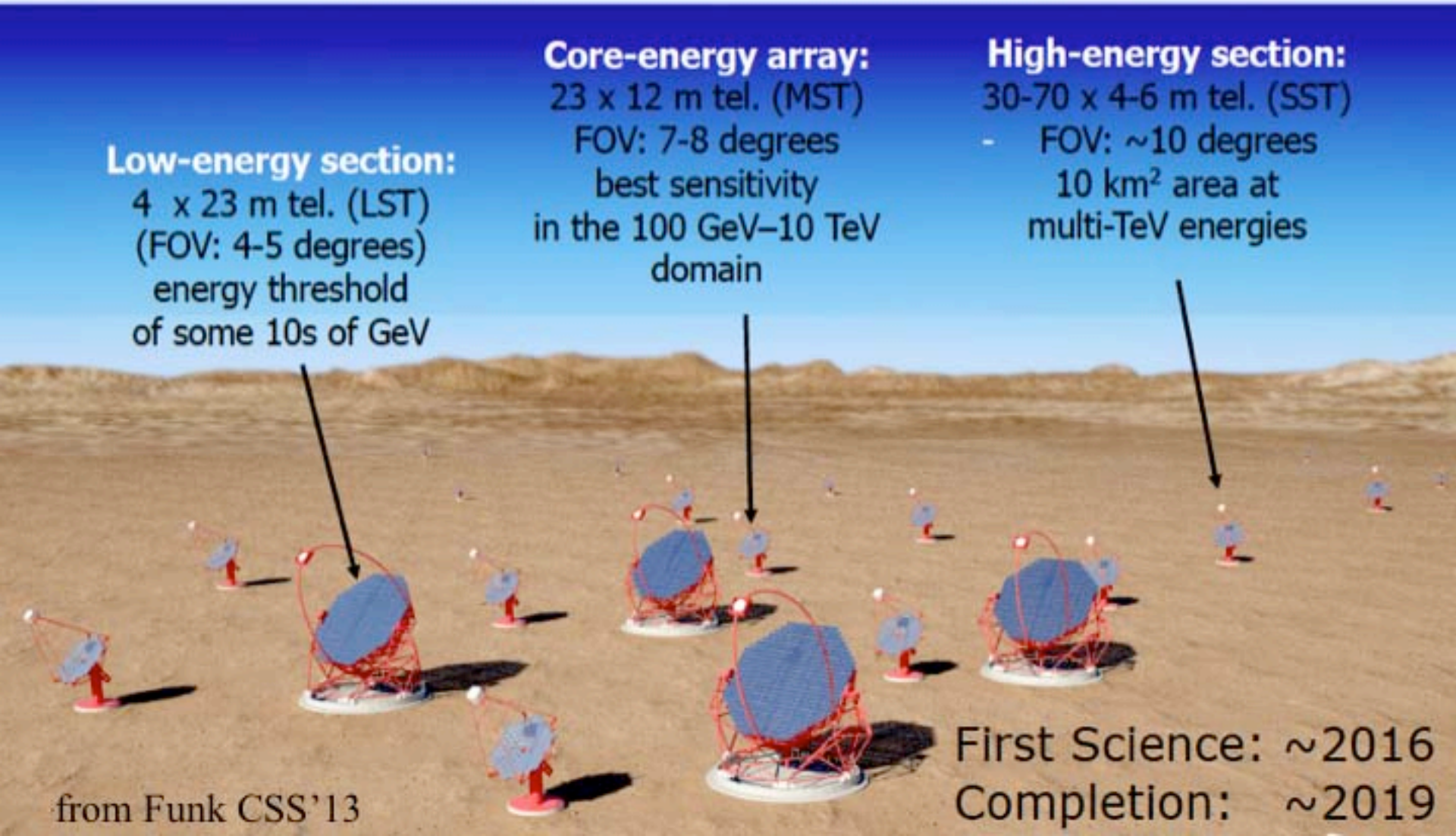
from Funk CSS'13

Key design goals:

- 10-fold increased sensitivity at TeV energies
- 10-fold increased effective energy coverage
- Larger field of view for surveys
- Improved angular resolution
- Full sky coverage: an array in each hemisphere

from Funk CSS'13

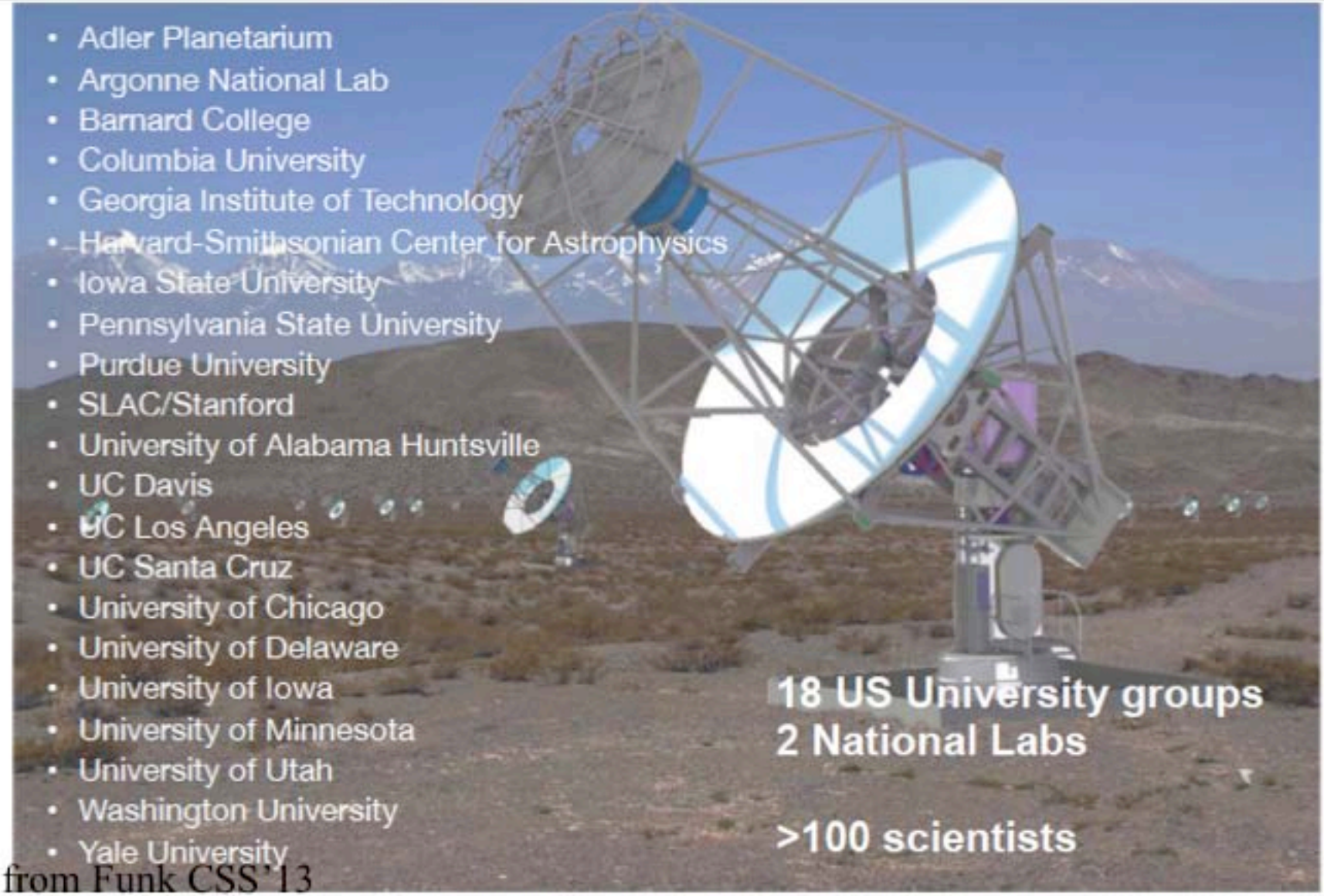
The baseline ...



from Funk CSS'13

The US groups

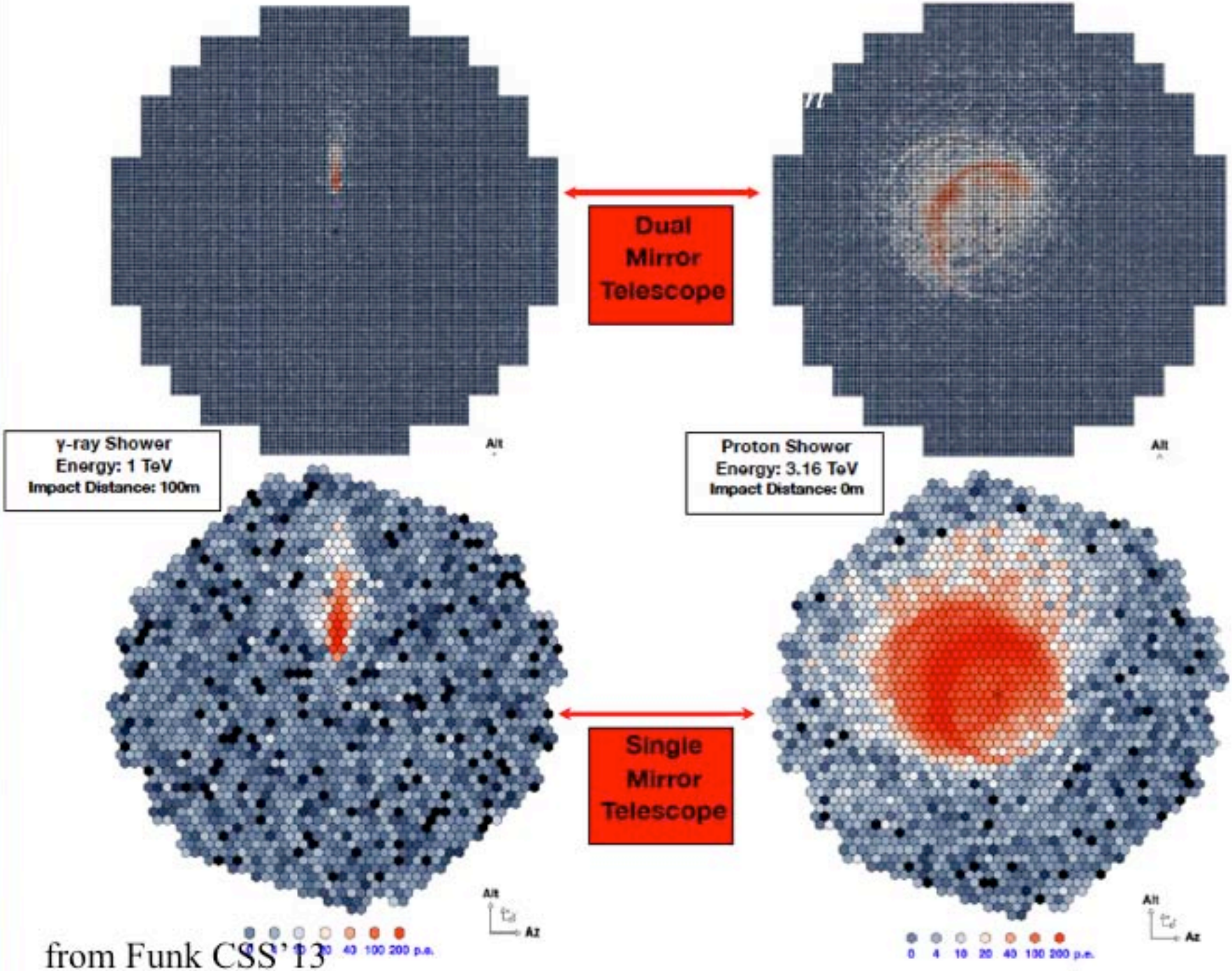
- Adler Planetarium
- Argonne National Lab
- Barnard College
- Columbia University
- Georgia Institute of Technology
- Harvard-Smithsonian Center for Astrophysics
- Iowa State University
- Pennsylvania State University
- Purdue University
- SLAC/Stanford
- University of Alabama Huntsville
- UC Davis
- UC Los Angeles
- UC Santa Cruz
- University of Chicago
- University of Delaware
- University of Iowa
- University of Minnesota
- University of Utah
- Washington University
- Yale University



18 US University groups
2 National Labs

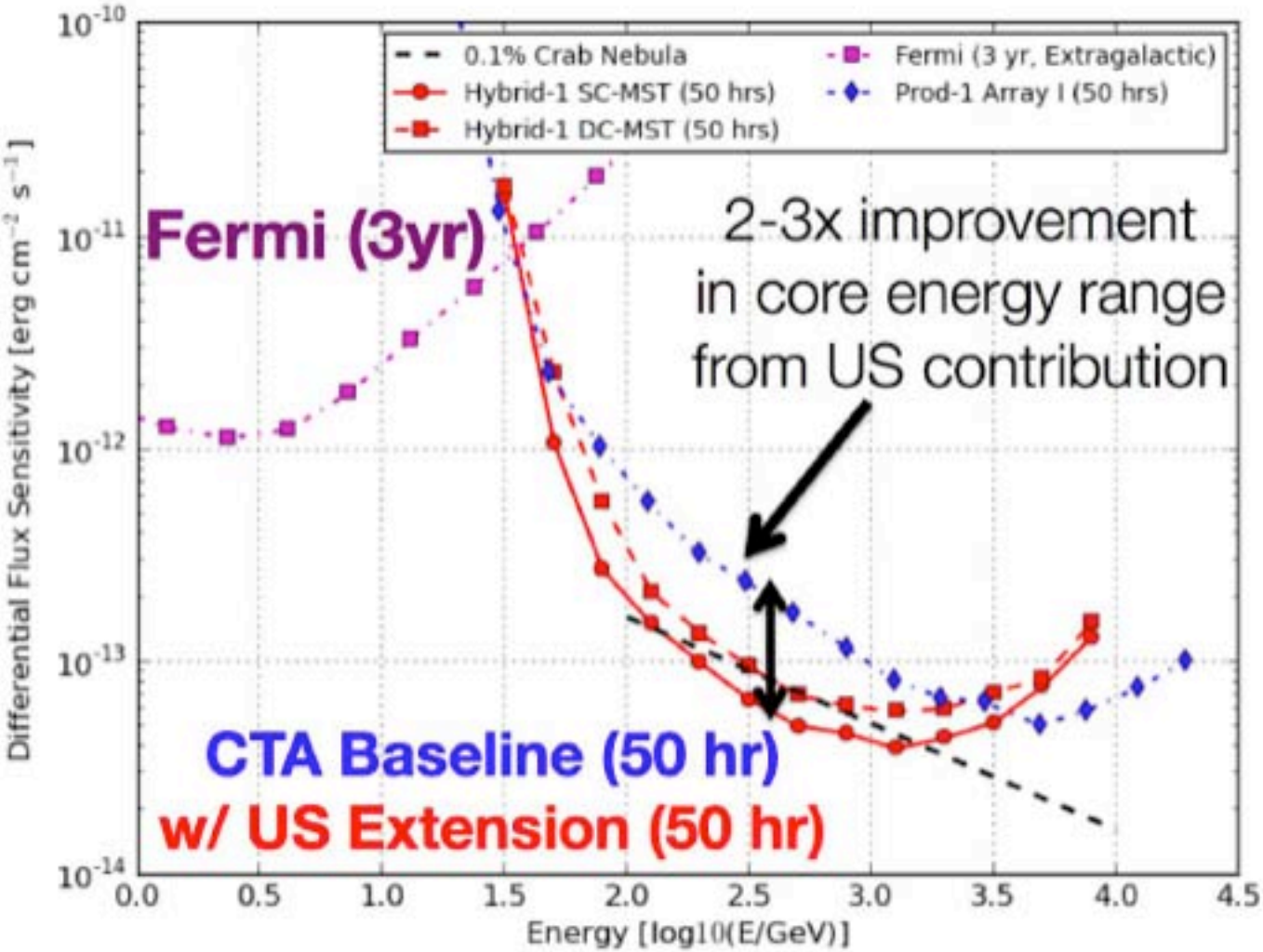
>100 scientists

from Funk CSS'13

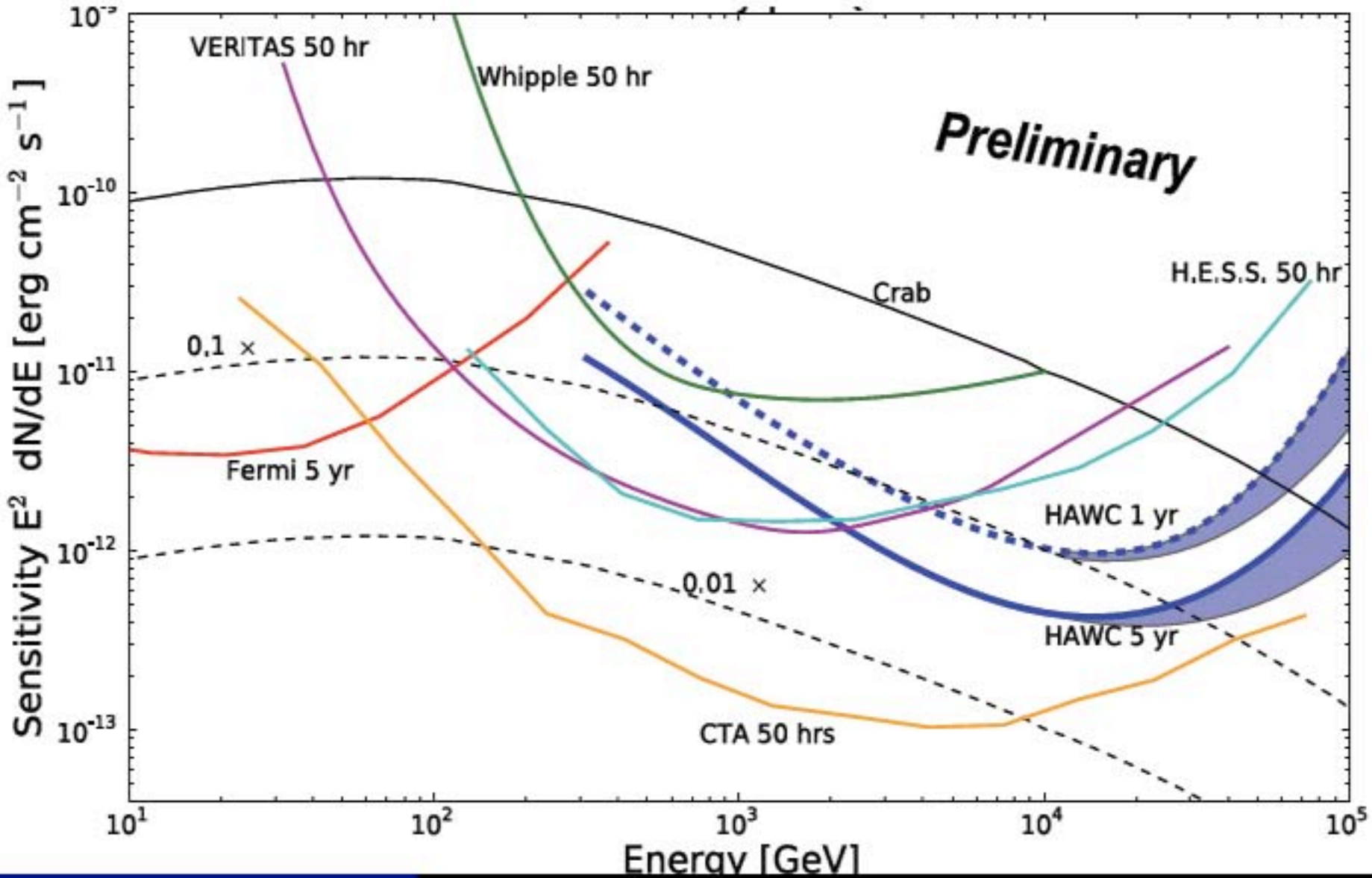


from Funk CSS'13

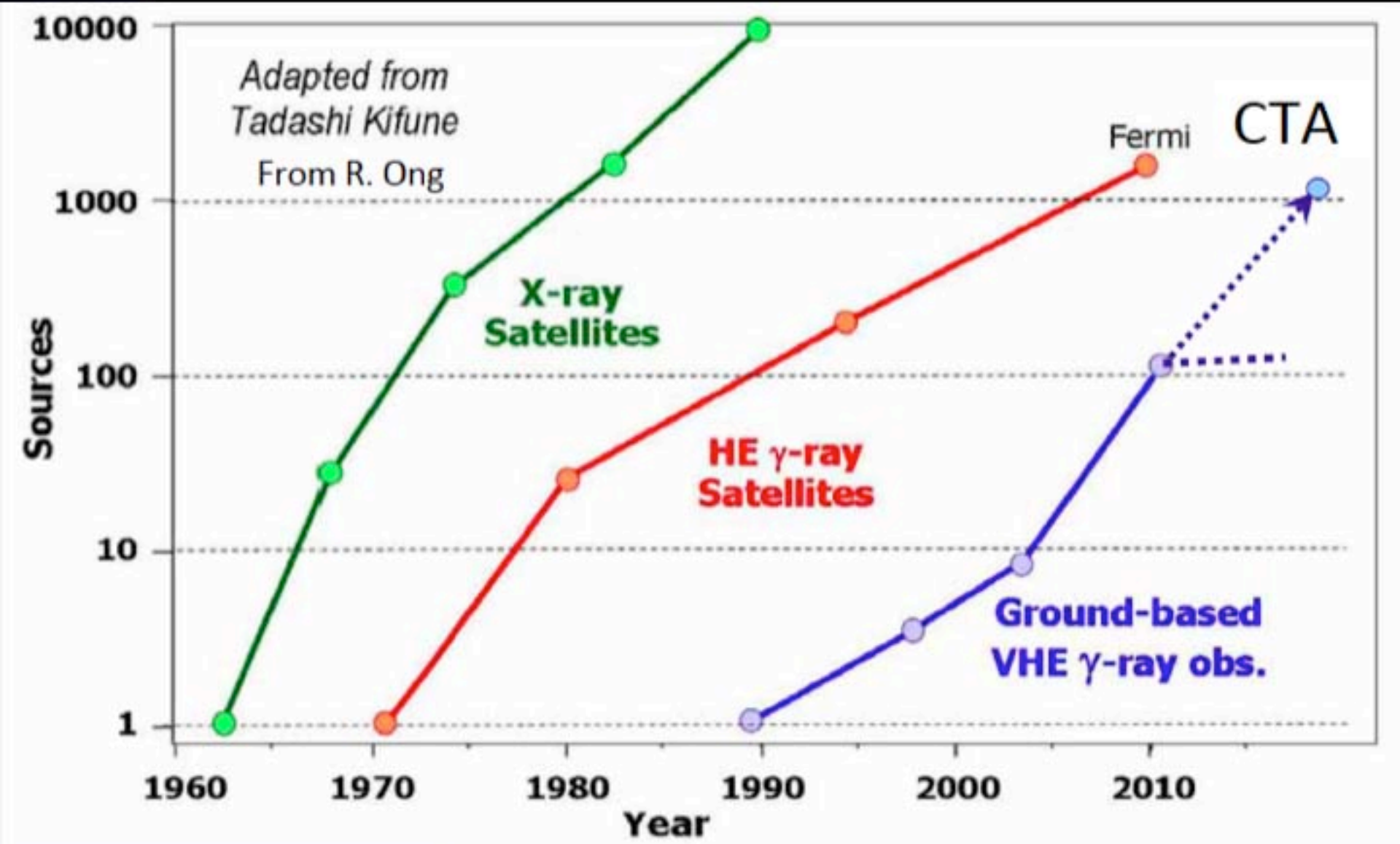
Results in enhanced sensitivity



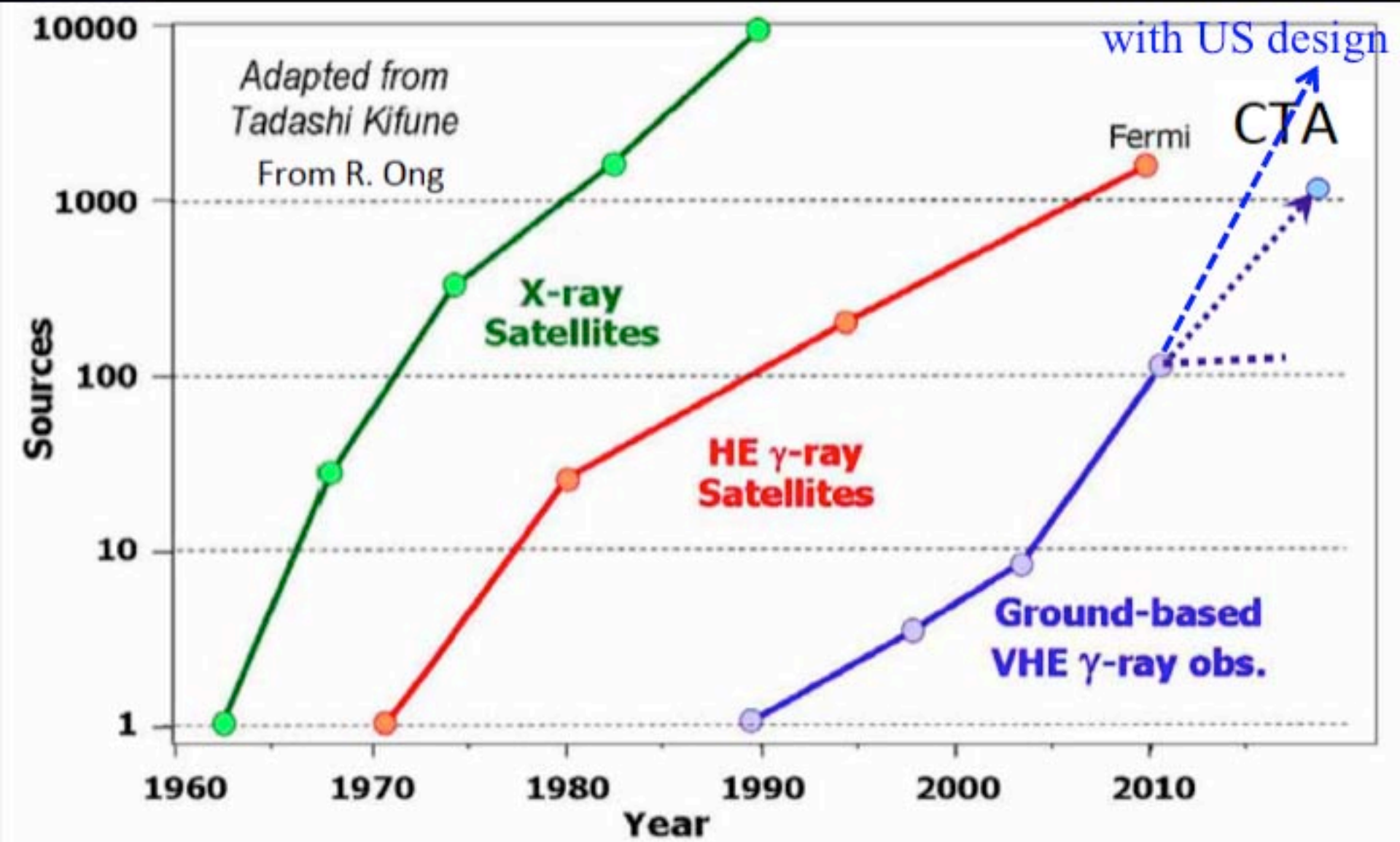
CTA Baseline (Prod-1): See K. Bernlohr et al. 2012, arXiv:1210.3503
w/ US Extension (Hybrid-1): See T. Jogler et al. 2012, arXiv: 1211.3181


VERITAS 50 hr
Whipple 50 hr
Preliminary
Crab
H.E.S.S. 50 hr
0.1 ×
Fermi 5 yr
HAWC 1 yr
0.01 ×
HAWC 5 yr
CTA 50 hrs
Sensitivity E² dN/dE [erg cm⁻² s⁻¹]
Energy [GeV]

Progress Gamma-rays



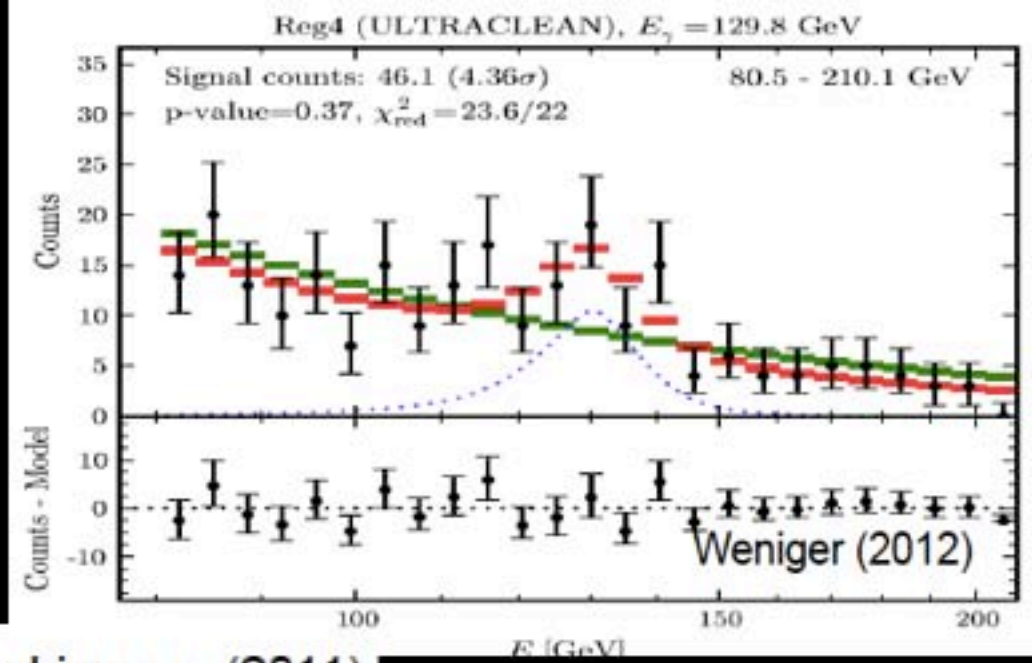
Progress Gamma-rays



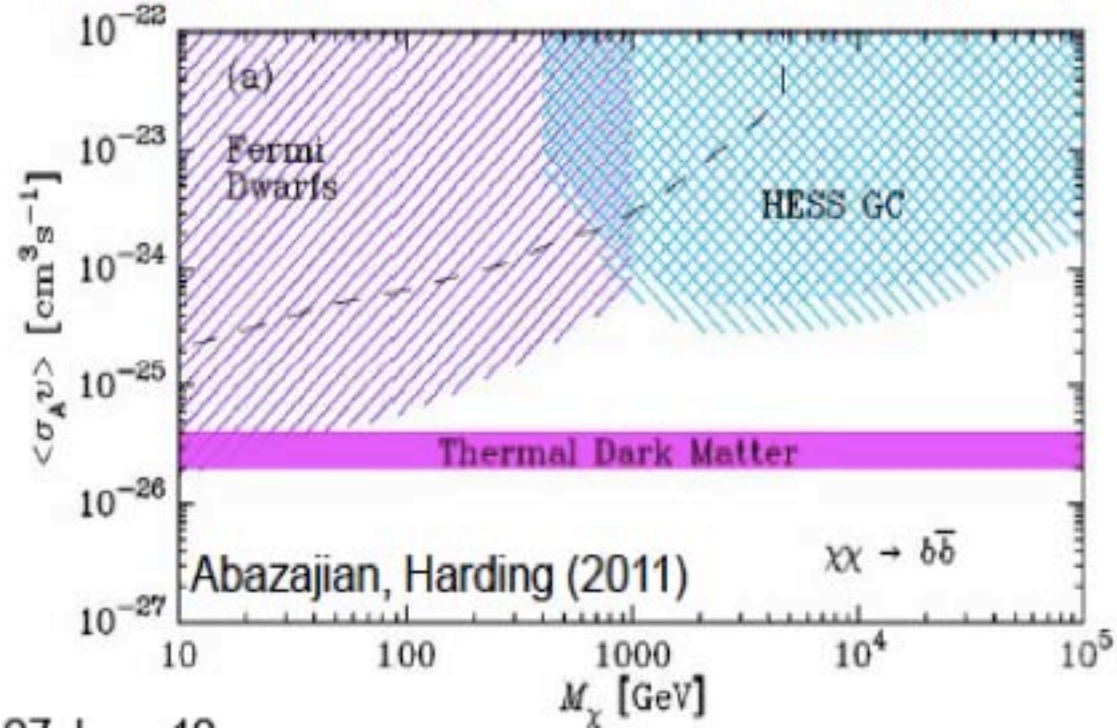
Gamma-rays

Indirect DM searches

For some annihilation channels, bounds exclude light thermal relics



Fermi (2011); Geringer-Sameth, Koushiappas (2011)

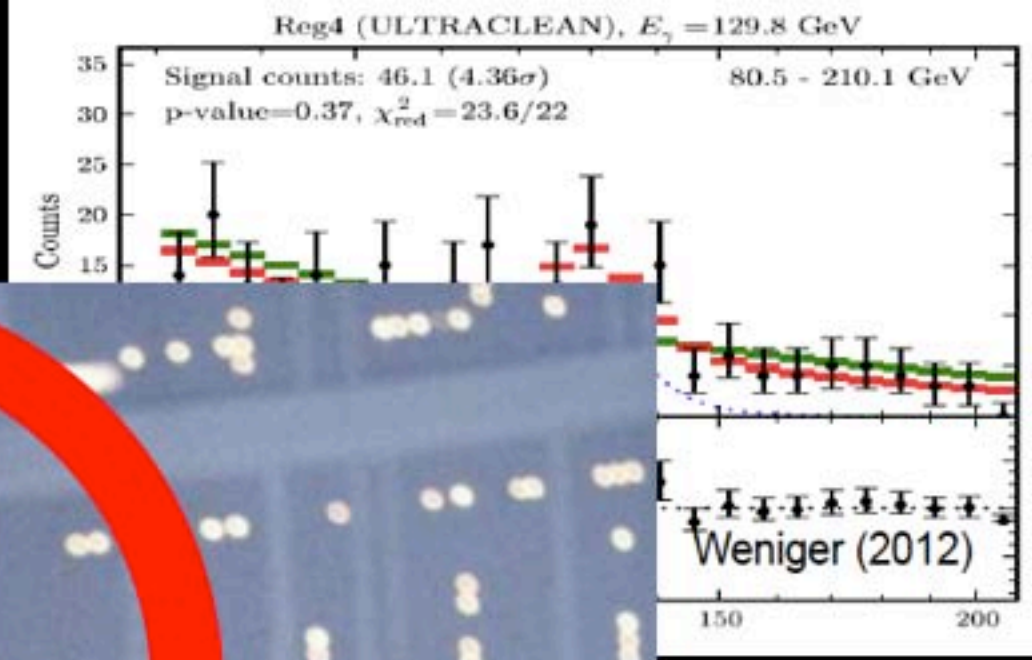


Current interest:
3-5 σ E γ =130 GeV,
⟨σ v⟩ = 10^{-27}cm3/s

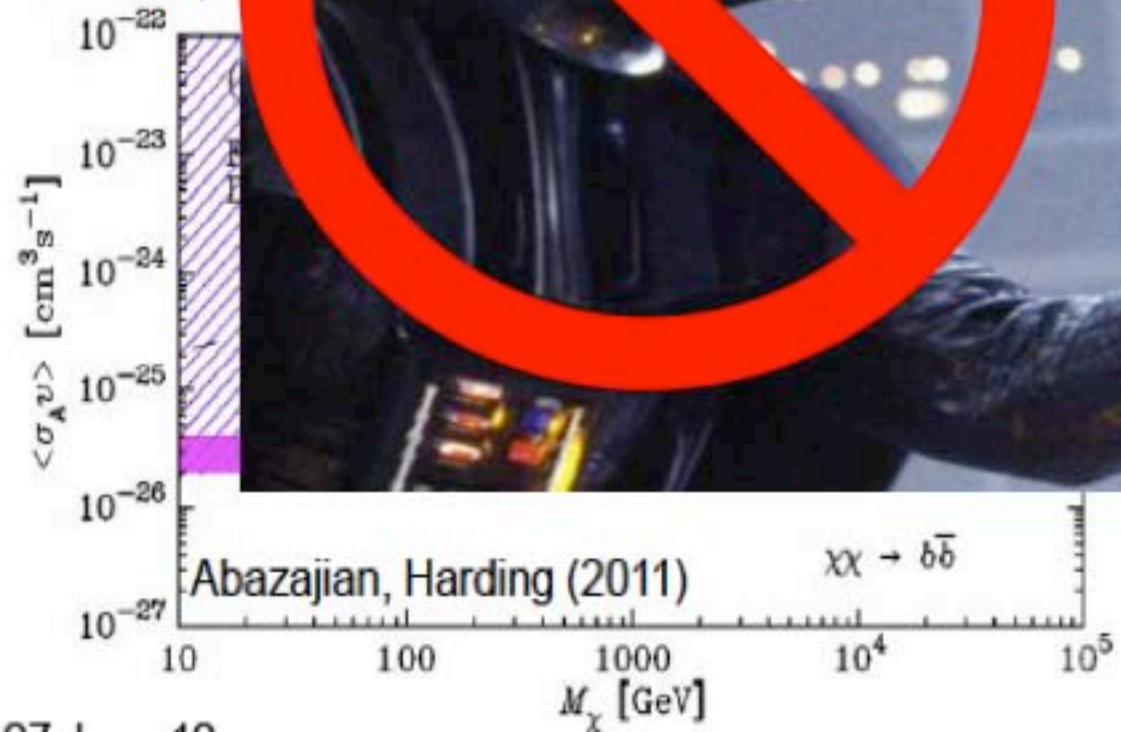
Gamma-rays

Indirect DM se

For some
channels,
light ther



Fermi (2



interest:
γ =130 GeV,
= 10^{-27}cm3/s

What are the most energetic Cosmic Particles ever detected?

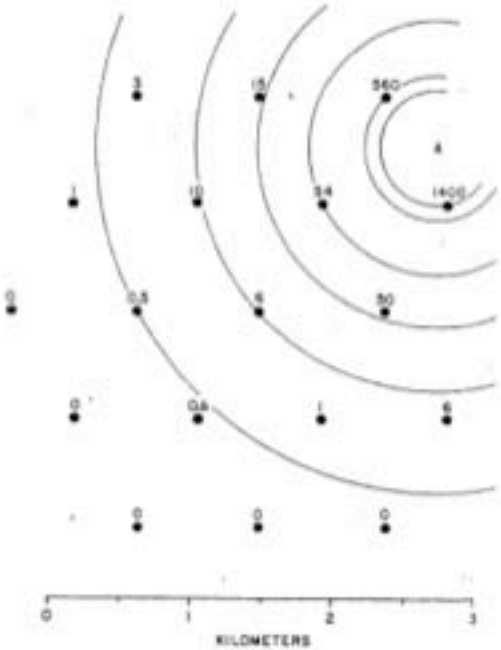
What are the most energetic Cosmic Particles ever detected? Cosmic Rays of Ultra High Energies (UHECRs)

1962 John Linsley's observation of a ~10^{20} eV event

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

point marked "A," assuming only (1) that showe particles are distributed symmetrically about a axis (the "core"), and (2) that the density of par ticles decreases monotonically with increasing distance from the axis. The observed densities



present case, the direction of the shower was nearly vertical (zenith angle 10 ± 5°). The values of shower density registered at the various points

FIG. 1. Plan of the Volcano Ranch array in Febru 1962. The circles represent 3.3-m^2 scintillation de tectors. The numbers near the circles are the show densities (particles/m^2) registered in this event. No

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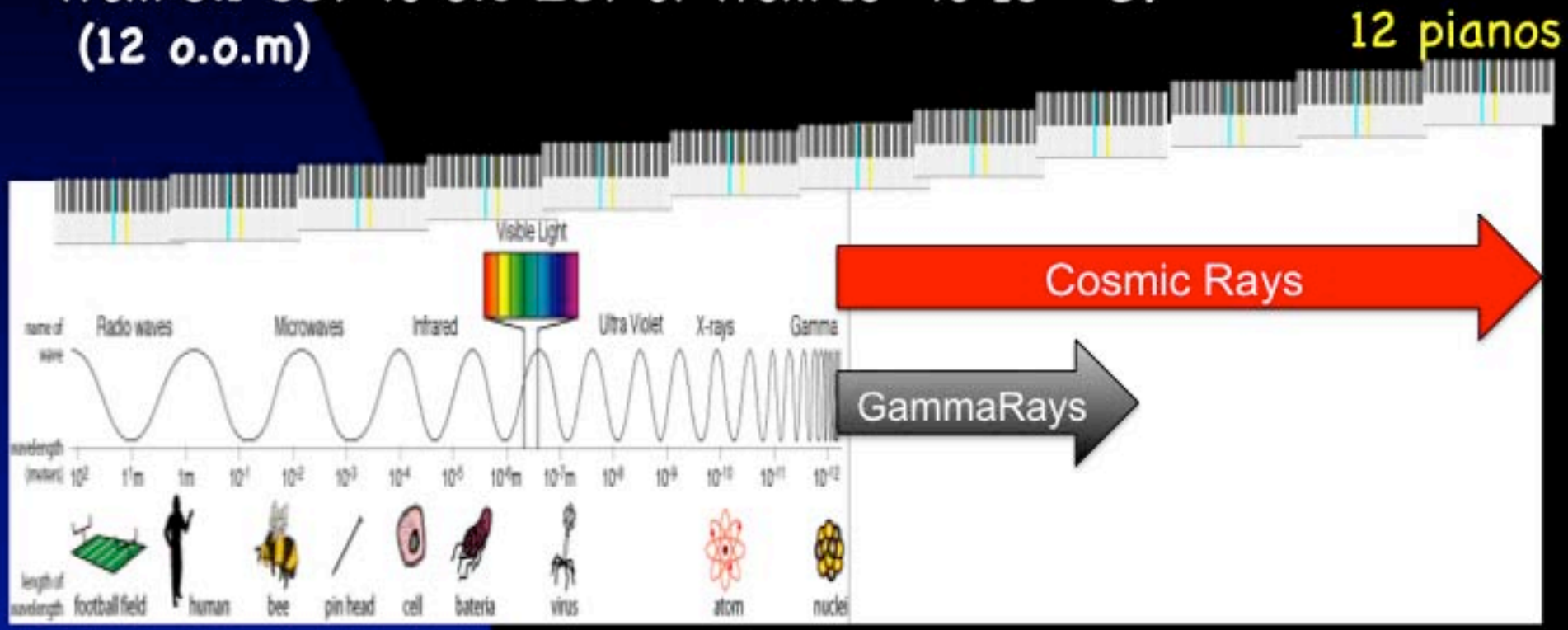
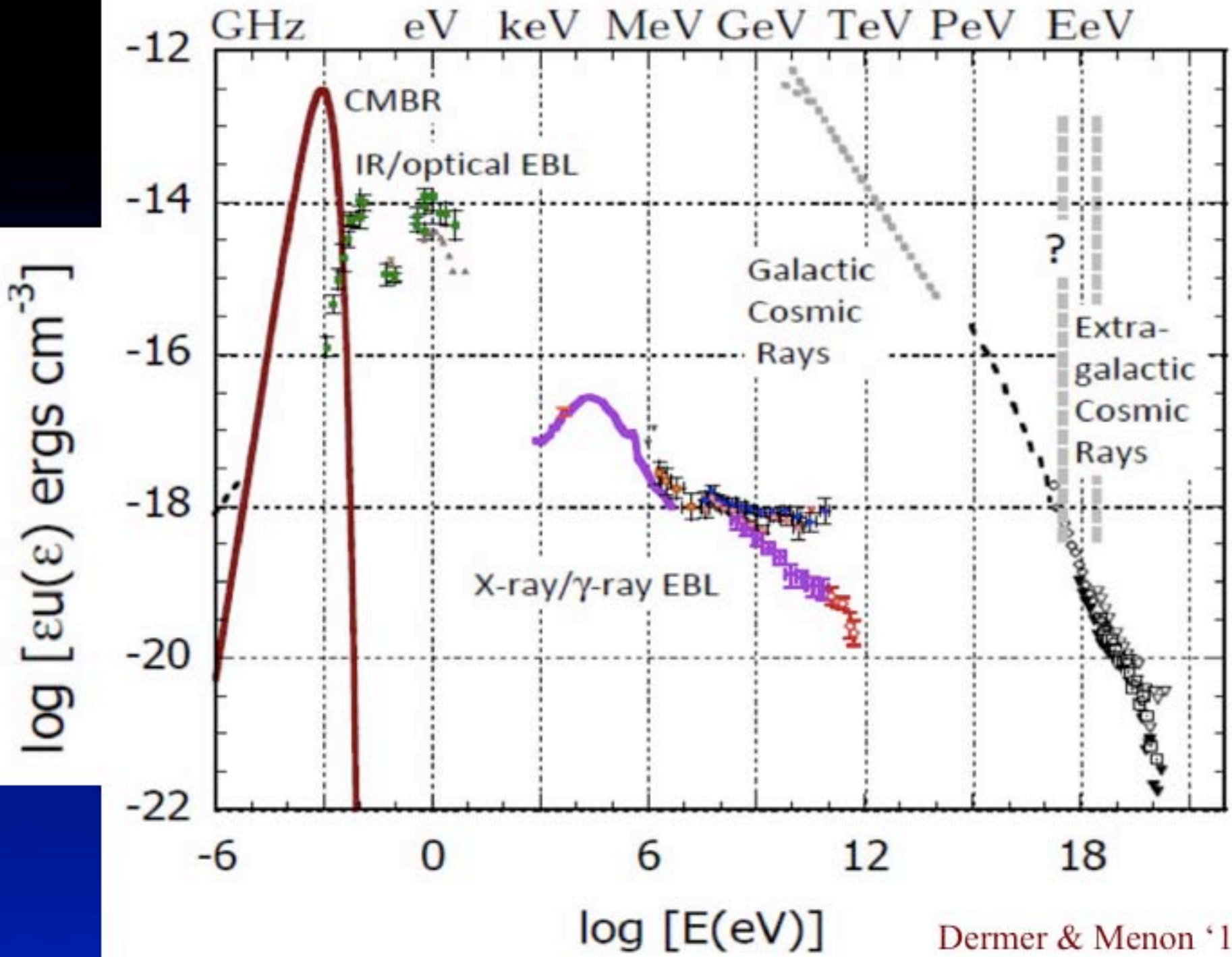
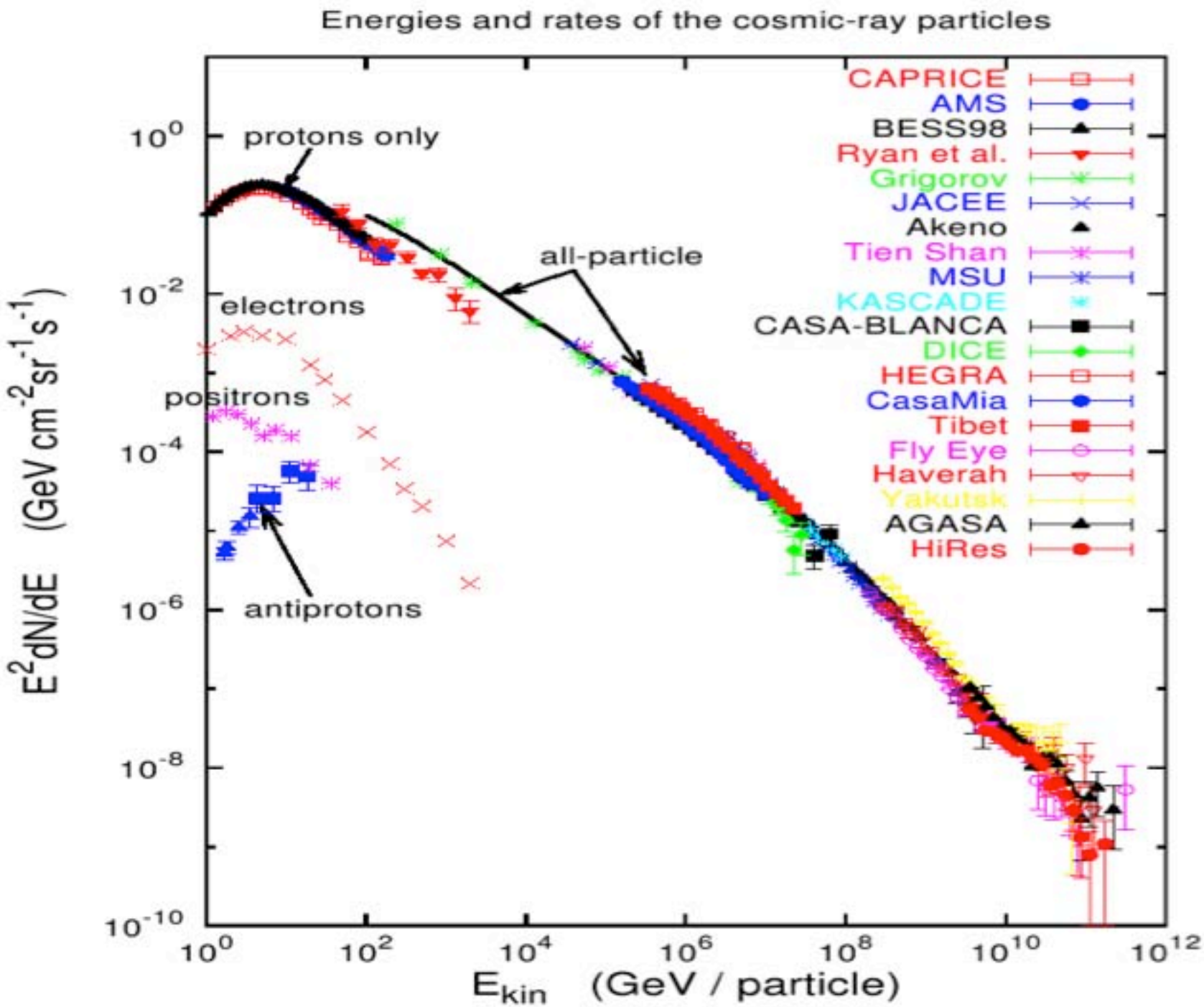
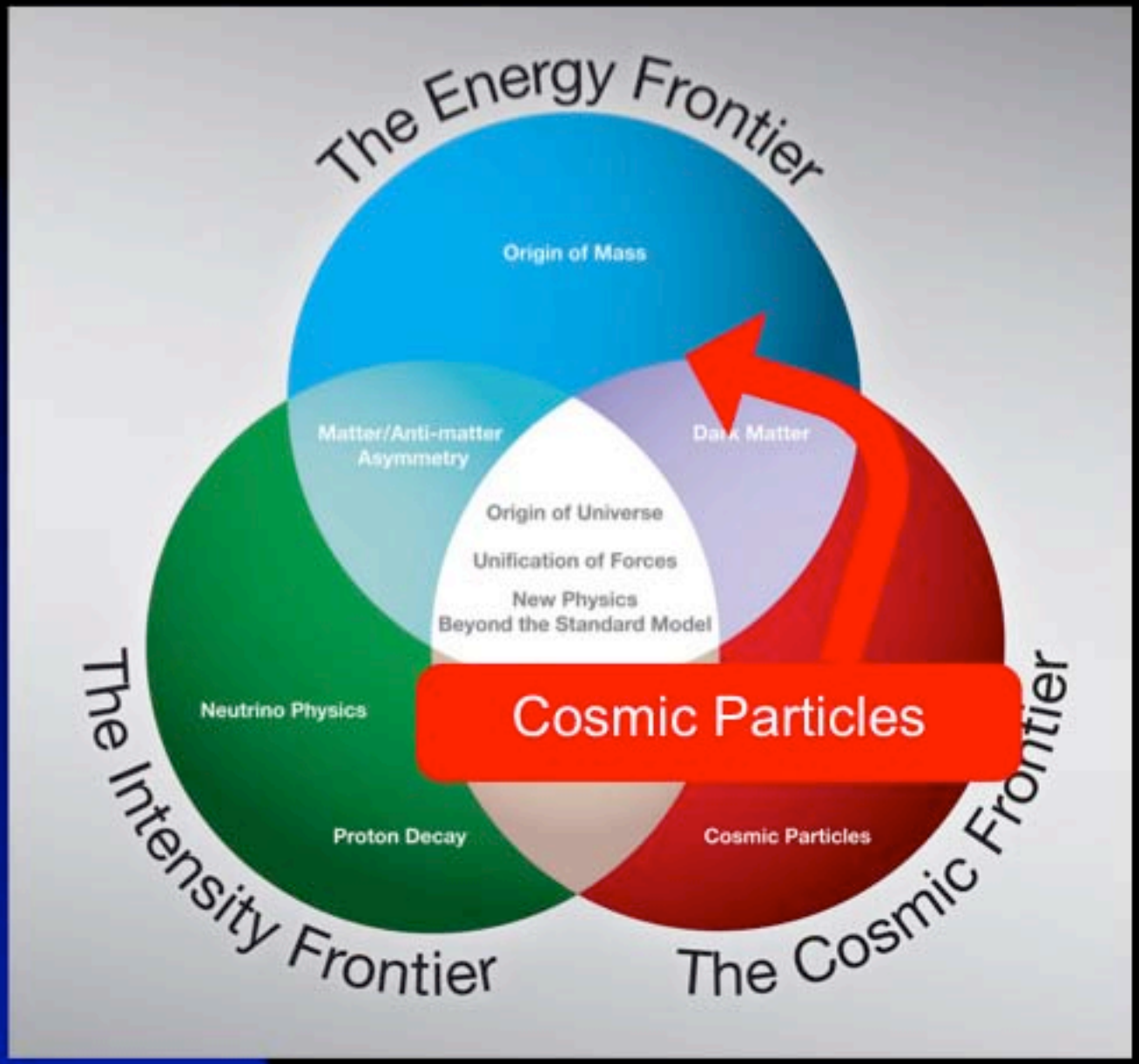
(12 o.o.m)

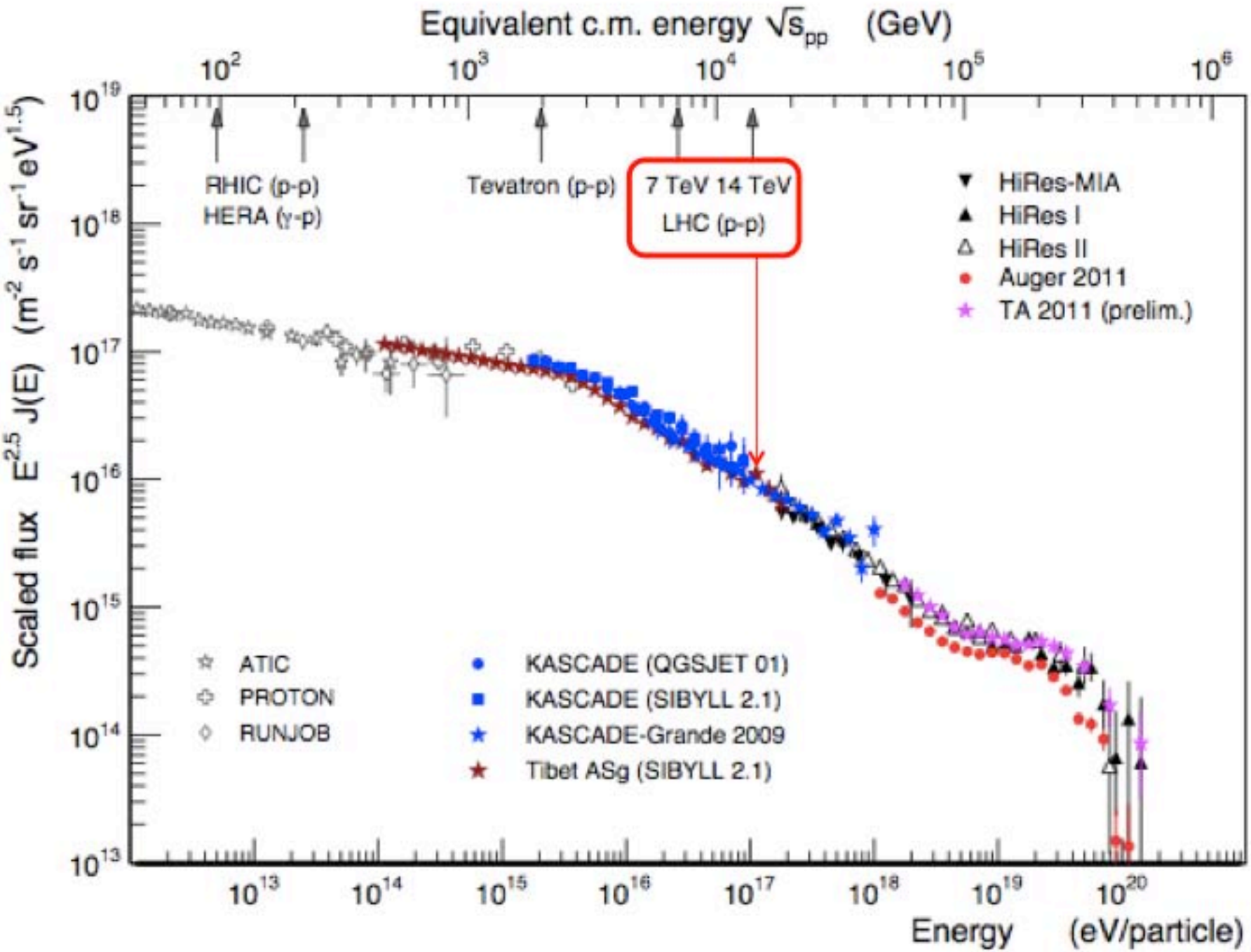




Dermer & Menon '11


Energies and rates of the cosmic-ray particles
protons only
all-particle
electrons
positrons
antiprotons
CAPRICE
AMS
BESS98
Ryan et al.
Grigorov
JACEE
Akeno
Tien Shan
MSU
KASCADE
CASA-BLANCA
DICE
HEGRA
CasaMia
Tibet
Fly Eye
Haverah
Yakutsk
AGASA
HiRes
$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})
E_{kin} (GeV / particle)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Physics
Cosmic Particles
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2011
TA 2011 (prelim.)
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

What are the most energetic Cosmic Particles ever detected?
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In what Energy range do we observe Cosmic Rays?
from 0.1 GeV to 0.3 ZeV or from 10^8 to 10^{20} eV

How far can we observe them from?

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How far can we observe them from?
Galactic $E < 10^{17}$ eV ???

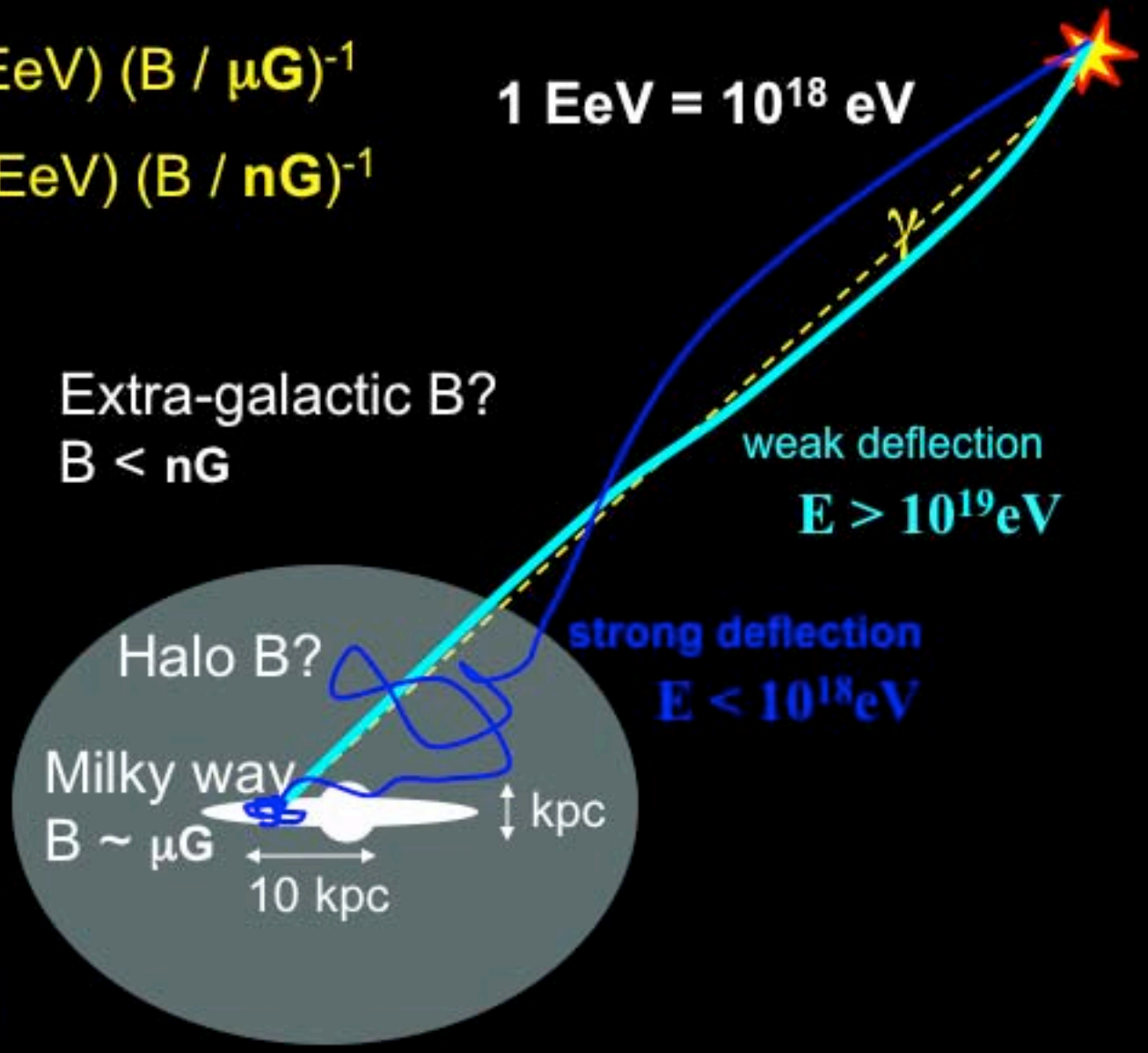
"Known unknown"

Cosmic Magnetic Fields

R_L = **kpc** Z^{-1} (E / EeV) (B / **μG**)$^{-1}$

R_L = **Mpc** Z^{-1} (E / EeV) (B / **nG**)$^{-1}$

1 EeV = 10^{18} eV



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How far can we observe them from?
Galactic $E < 10^{17}$ eV ???
Extragalactic $E >$ EeV $= 10^{18}$ eV; $z_{sources} = 10$??
$E > 50$ EeV, distances of < 100 Mpc

Propagation of UHECRs

Greisen-Zatsepin-Kuzmin (GZK) pioneered the field in 1966

protons & nuclei

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

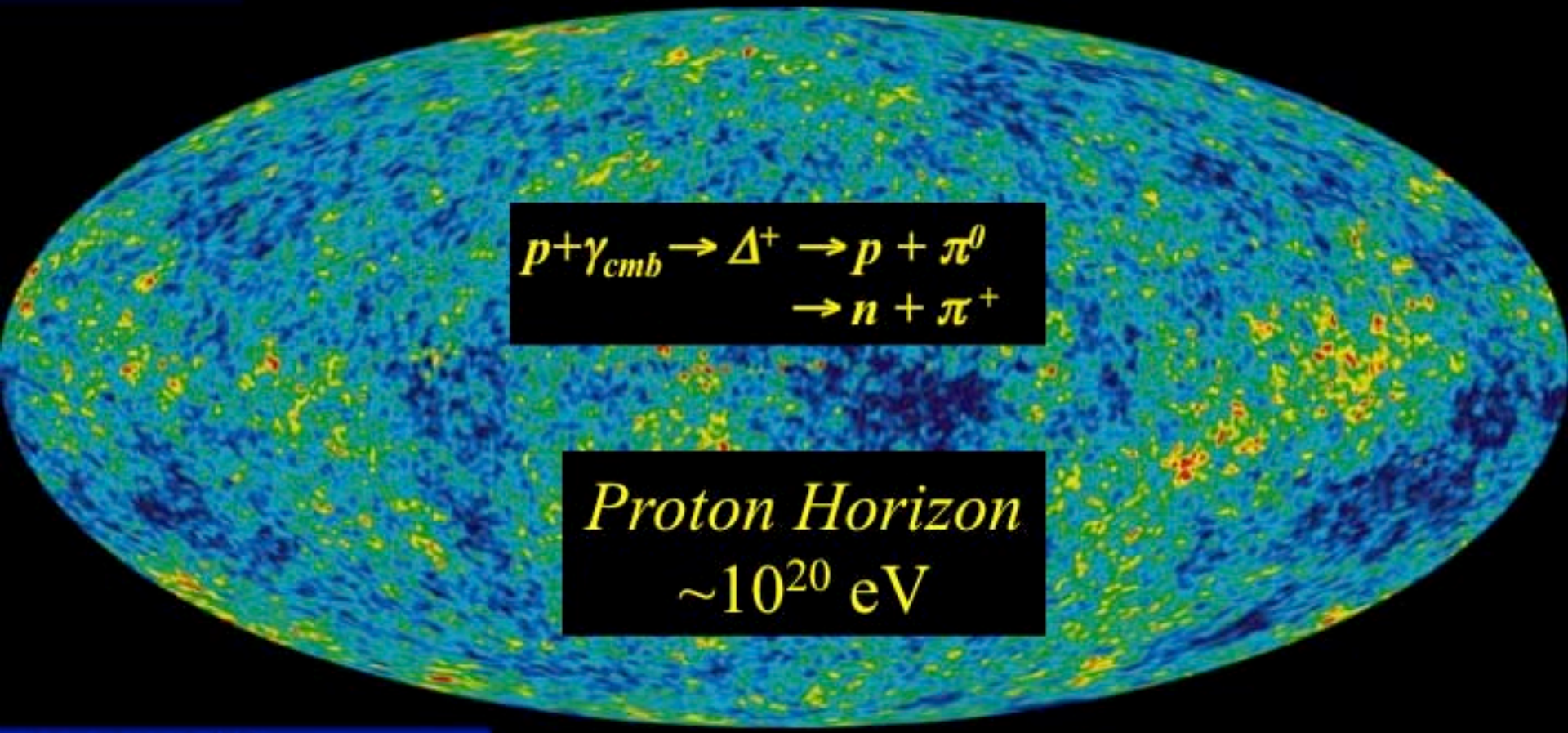
One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is on the order of 10^{-25} cm^2. At this energy the mea

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

Notice should be taken of the disintegration of α particles and other nuclei [6] as they pass through metagalactic space. This occurs at an α-particle energy somewhat lower than the proton energy at which the pion photoproduction process begins. The rather large cross section of this process should lead to total disappearance of the nuclei from the cosmic rays at energies above 10^{19} eV.

"Cosmologically Meaningful Termination"



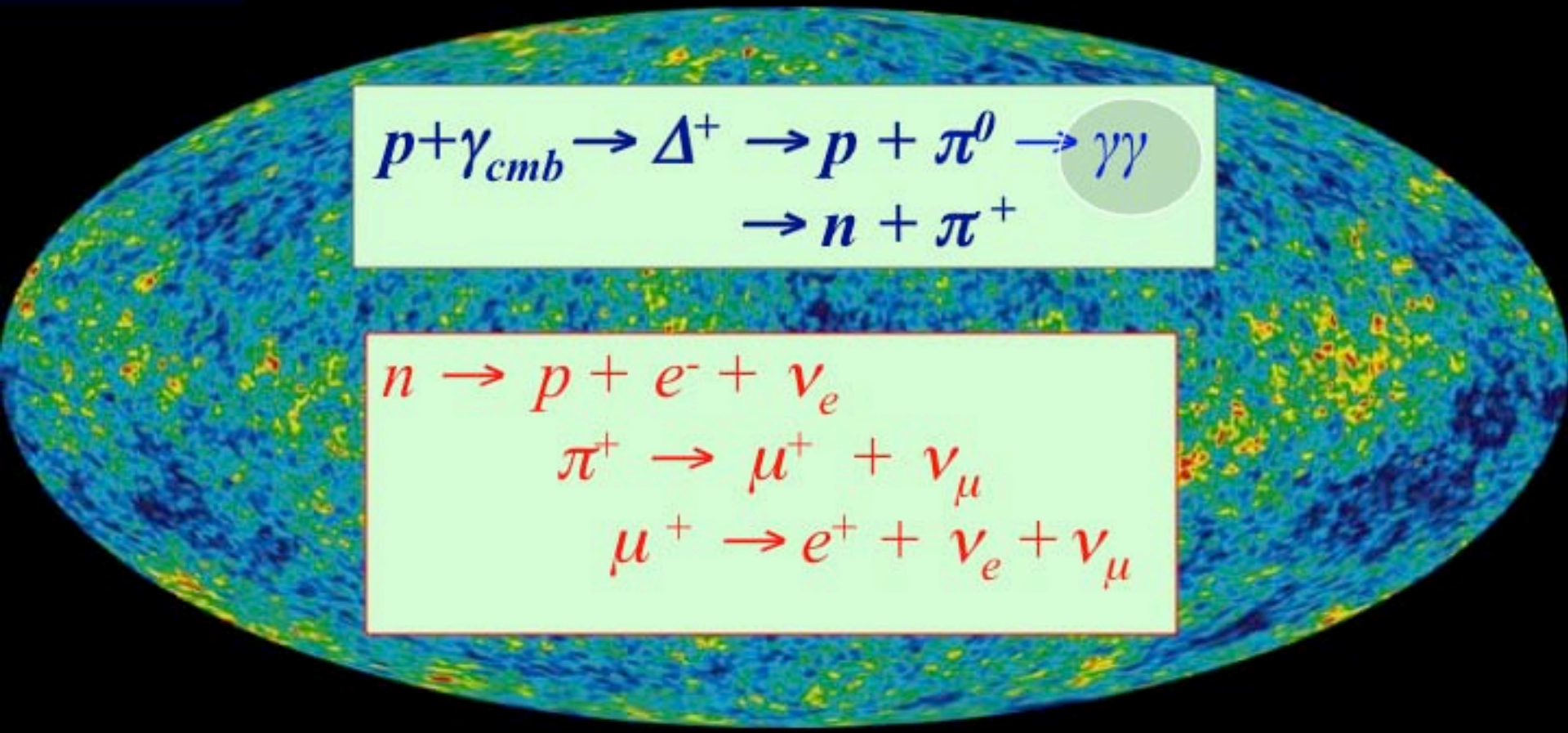
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\rightarrow n + \pi^+$$

Proton Horizon
$\sim 10^{20}$ eV

GZK Cutoff
Greisen, Zatsepin, Kuzmin
1966

Cosmogenic (GZK) Neutrinos & Photons

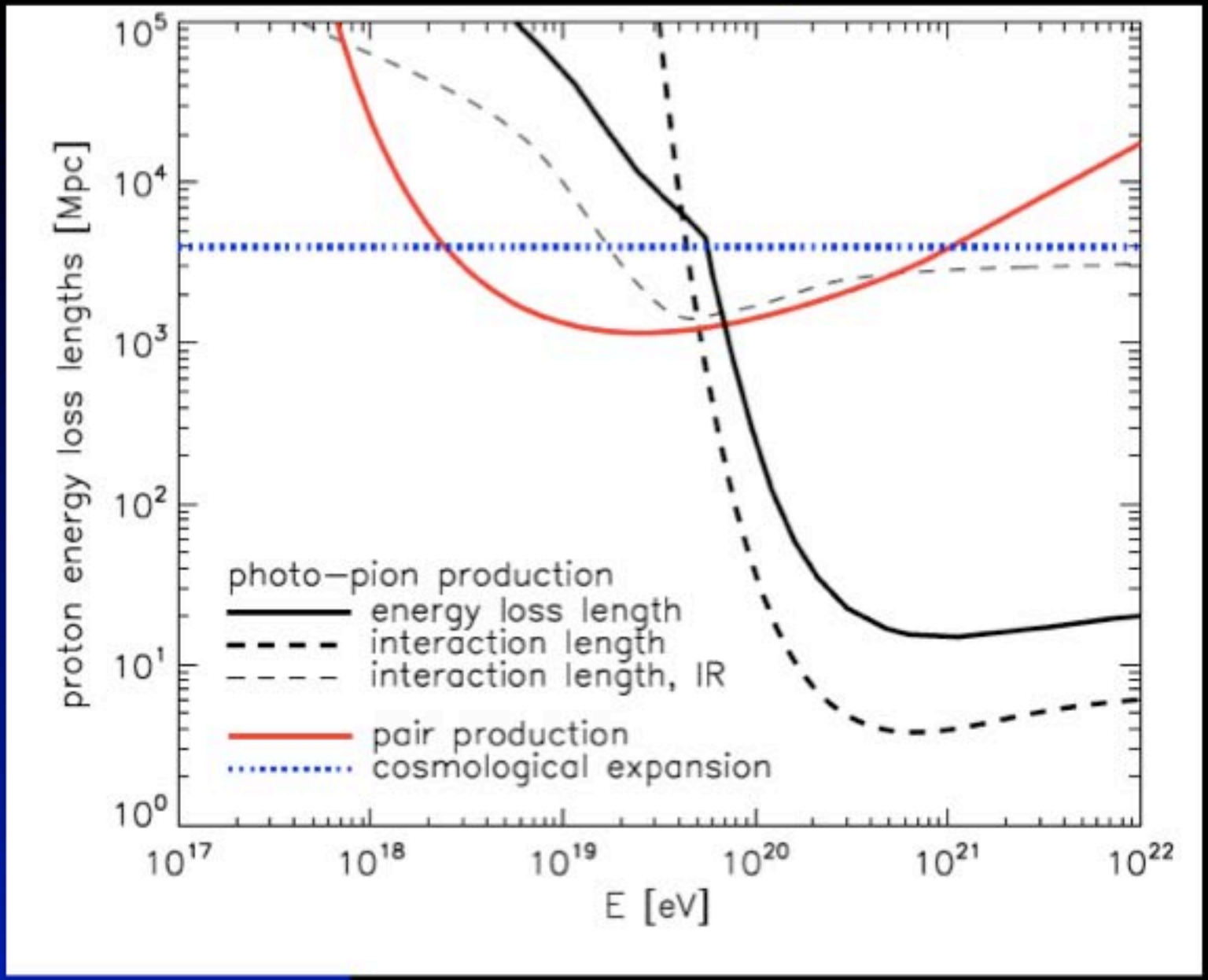
and UHECR composition



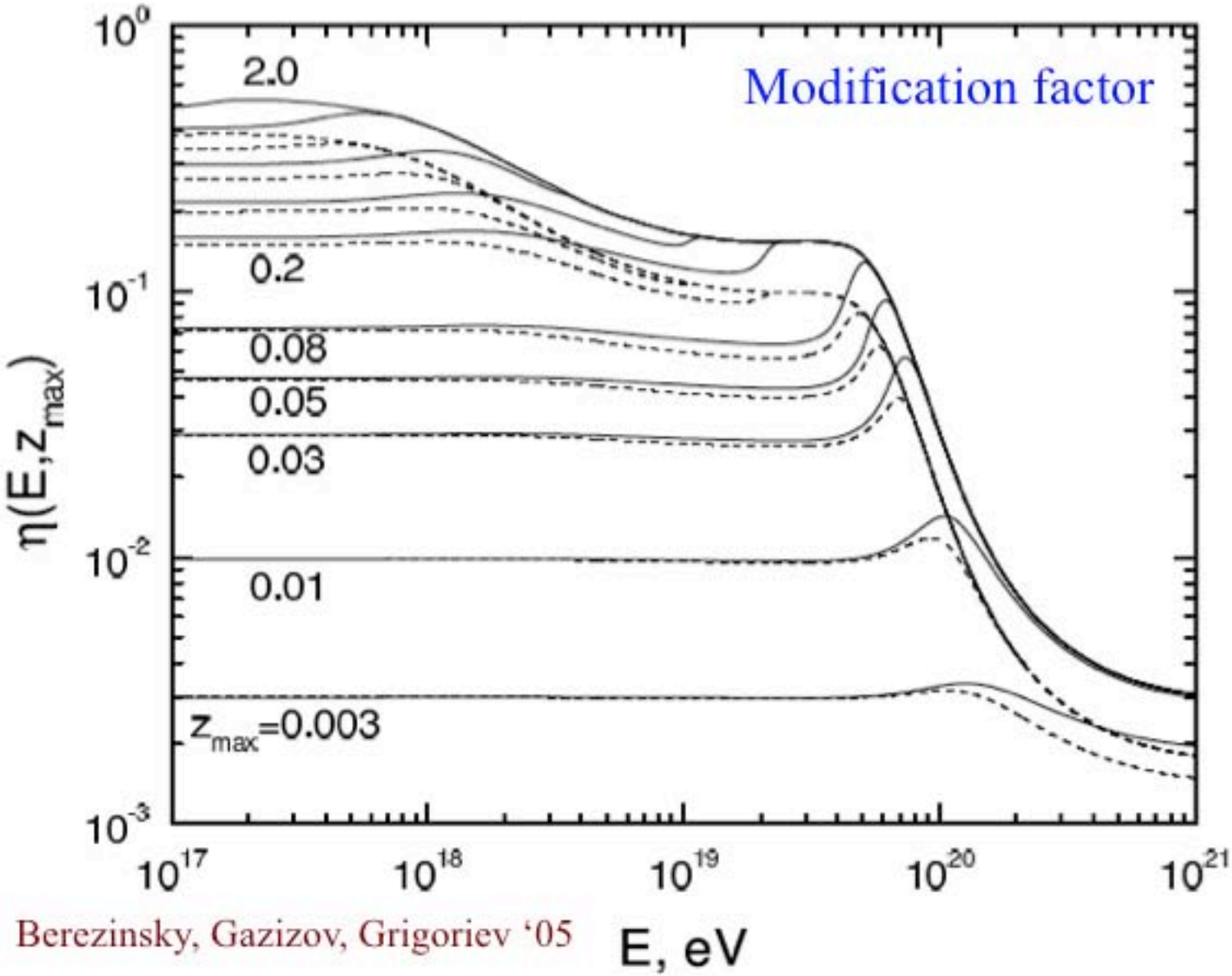
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^+$$

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

GZK effect for protons

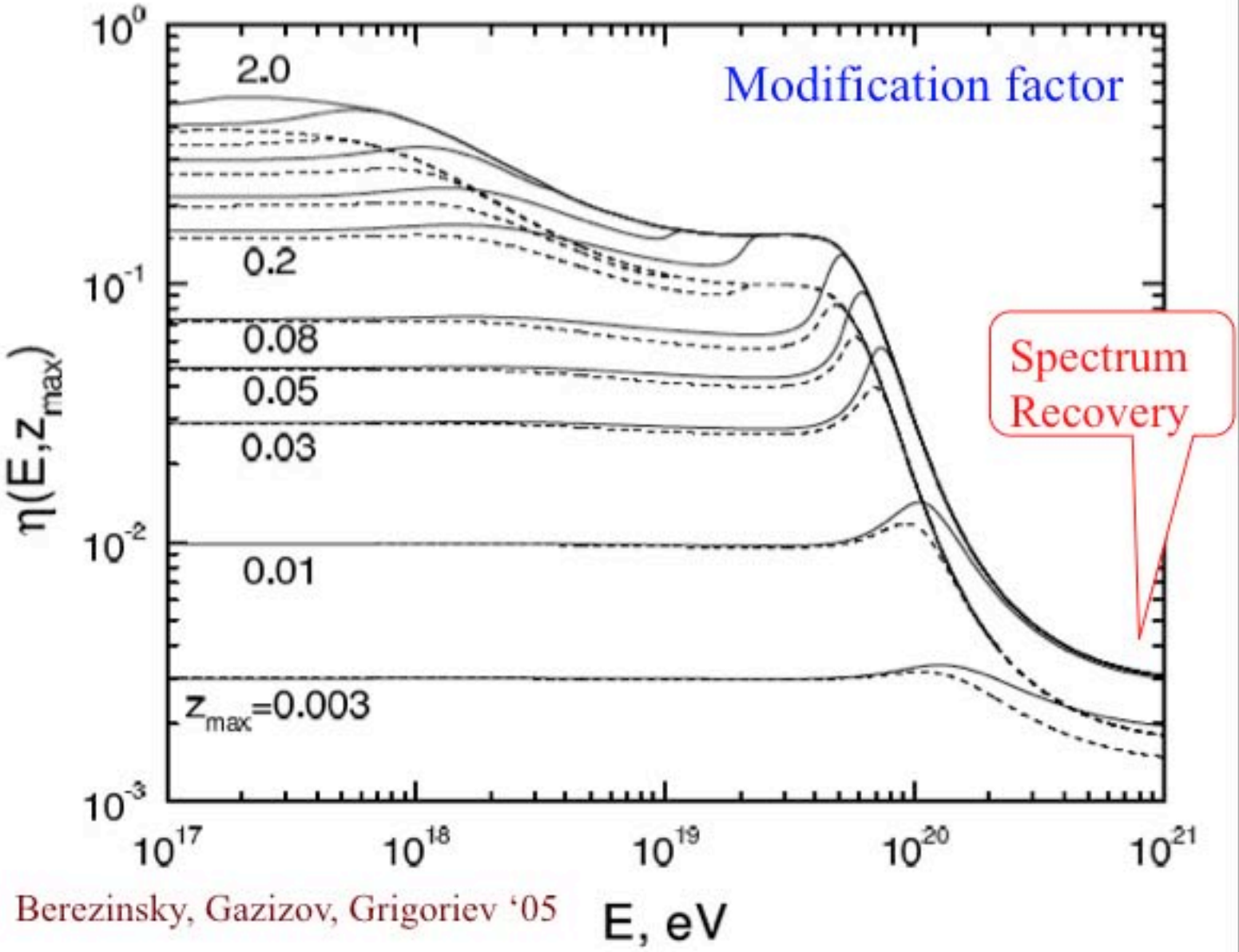


Propagation of UHE protons



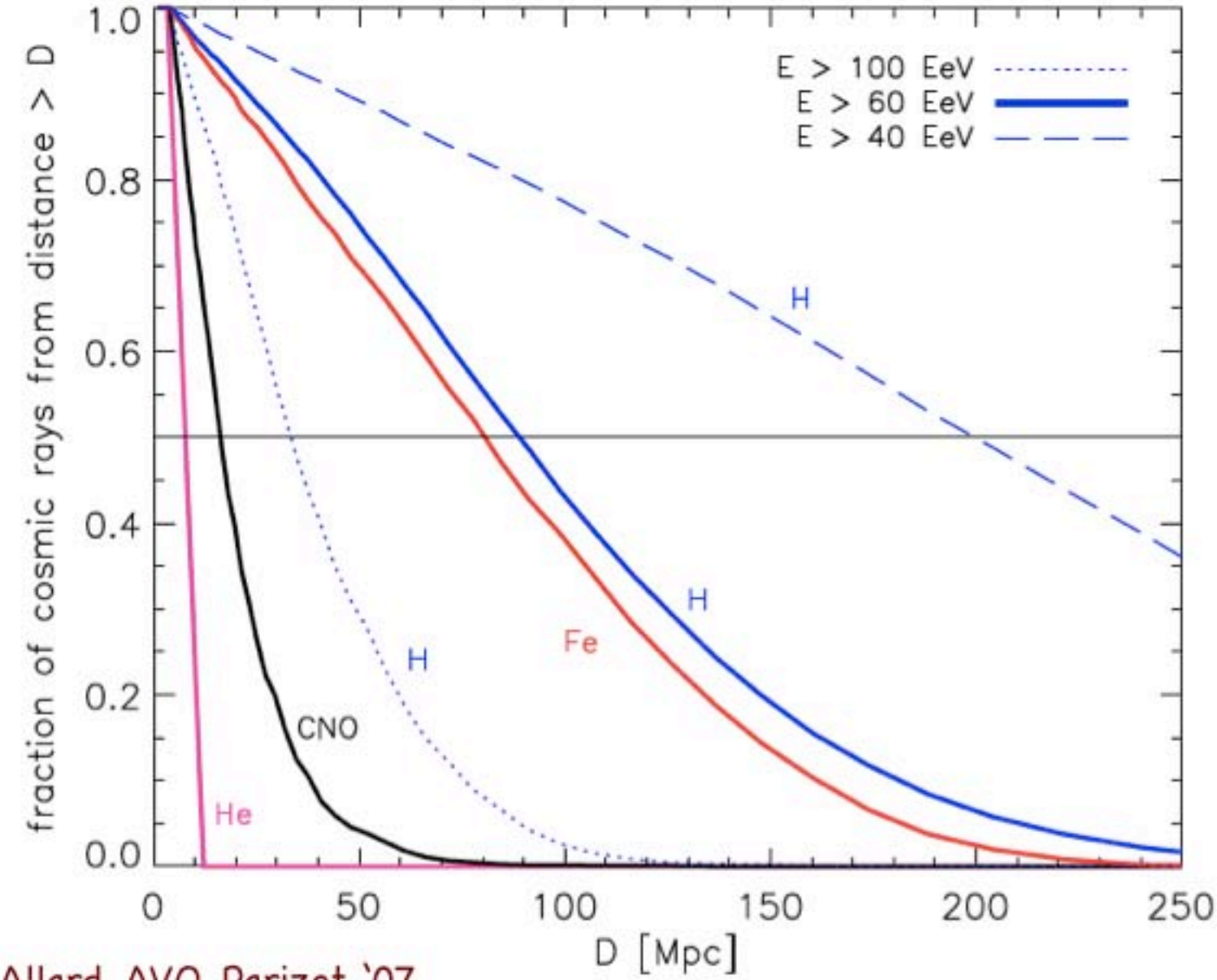
Berezinsky, Gazizov, Grigoriev '05

Propagation of UHE protons



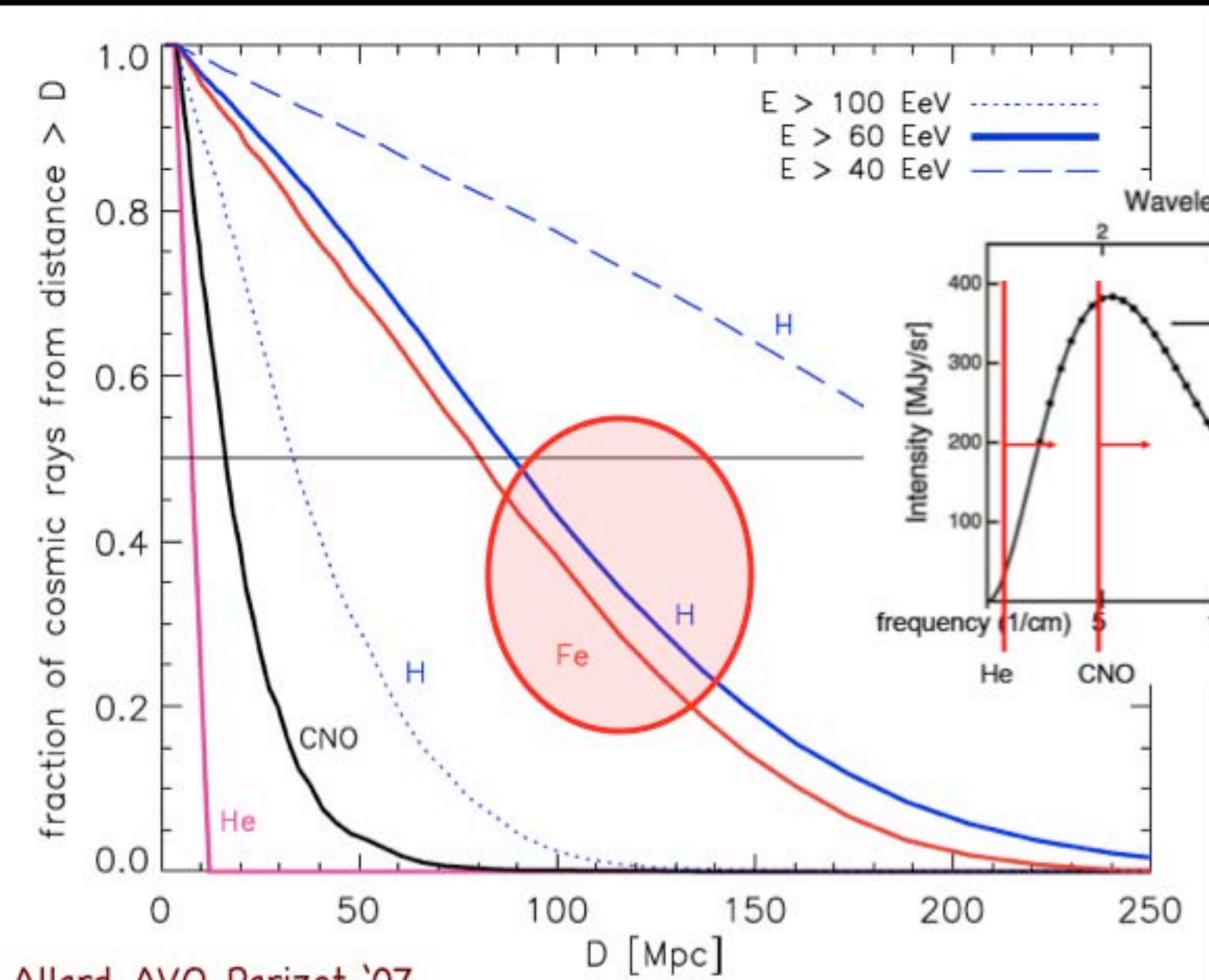
Berezinsky, Gazizov, Grigoriev '05

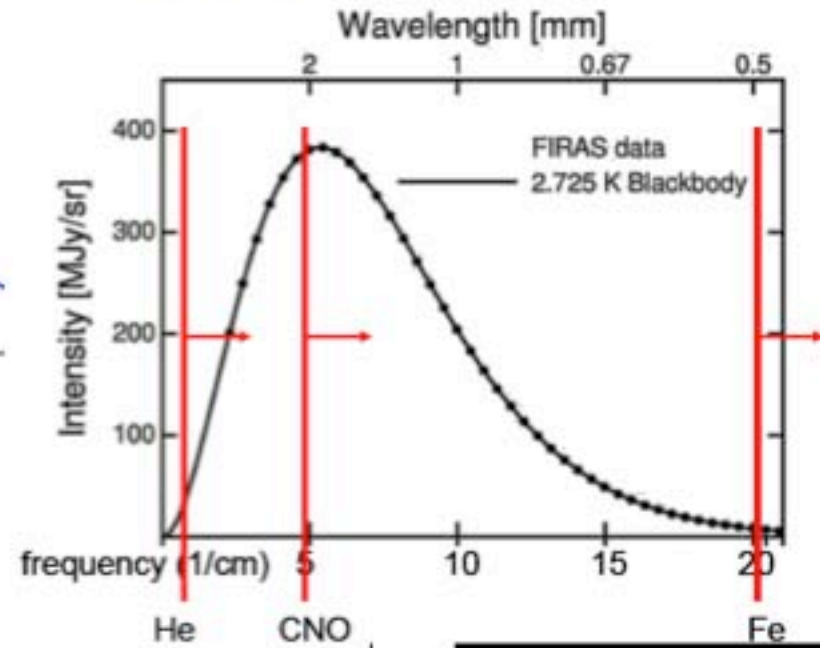
GZK Horizon



Allard, AVO, Parizot '07

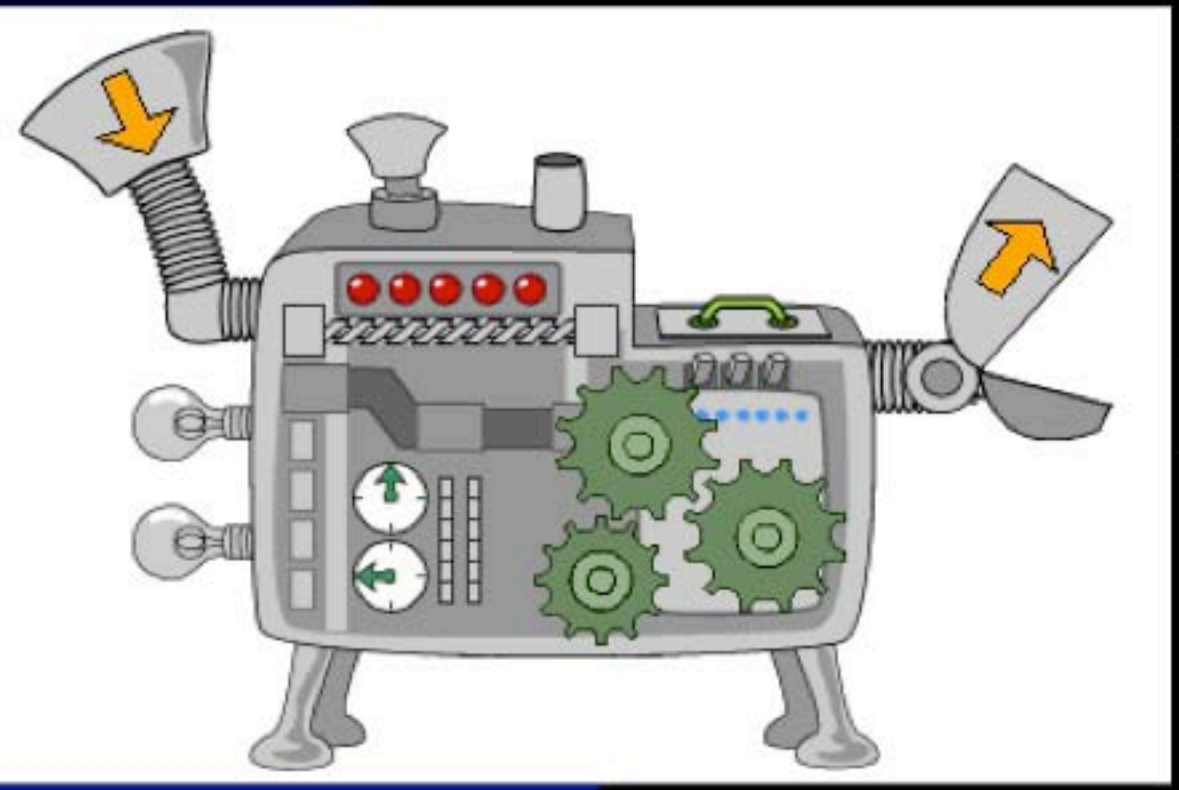
GZK Horizon





Allard, AVO, Parizot '07

Modern Propagation Codes



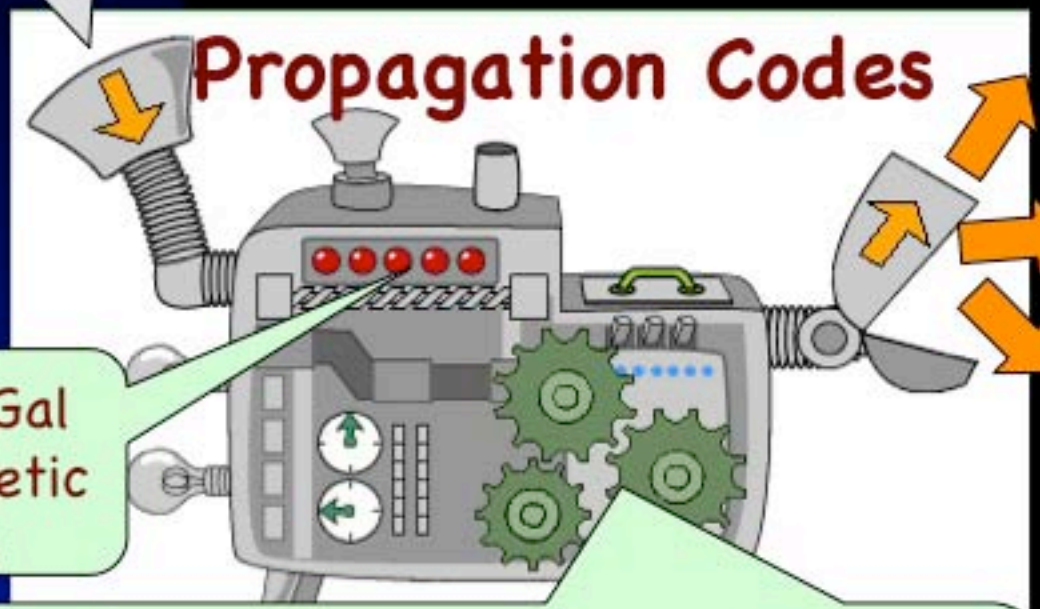
Public:

CRPropa
1.0 Armengaud et al '06
2.0 Kampert et al. '12
3.0 Alvez Batista et al '13
SimProp
Aloisio et al '12

Private:

Allard et al '04
Taylor '07
Ahlers '10
others...

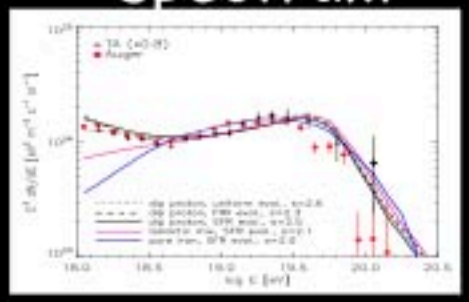
Source Model:
- injection spectrum: E^{-s}
- injected composition
- redshift distribution



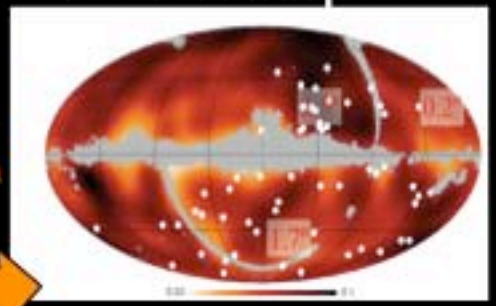
InterGal Magnetic Fields

Interaction Cross Sections, z evolution
Background Fields: CMB, UV/Opt/IR
Primary, Secondary nuclei, nucleons,
e+e-, gamma-rays, neutrinos,...

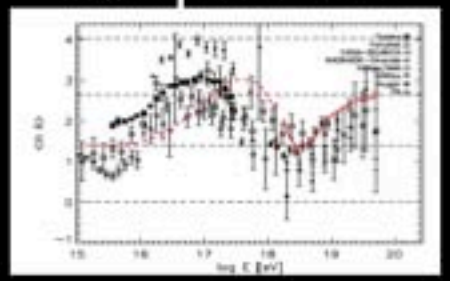
Spectrum



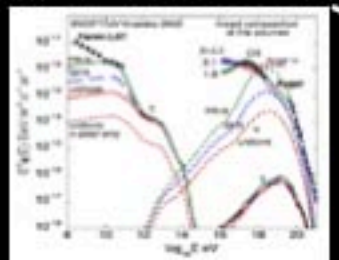
Anisotropies



Composition



Multi-messengers



What are the most energetic Cosmic Particles ever detected?
Cosmic Rays of Ultra High Energies (UHECRs)

In what Energy range do we observe Cosmic Rays?
from 0.1 GeV to 0.3 ZeV or from 10^8 to 10^{20} eV

How far can we observe them from? Galactic E < 10^{17} eV ???
Extragalactic E > EeV = 10^{18} eV; $z_{sources}$ = 10?
E > 50 EeV, distances of < 100 Mpc

How are they observed?

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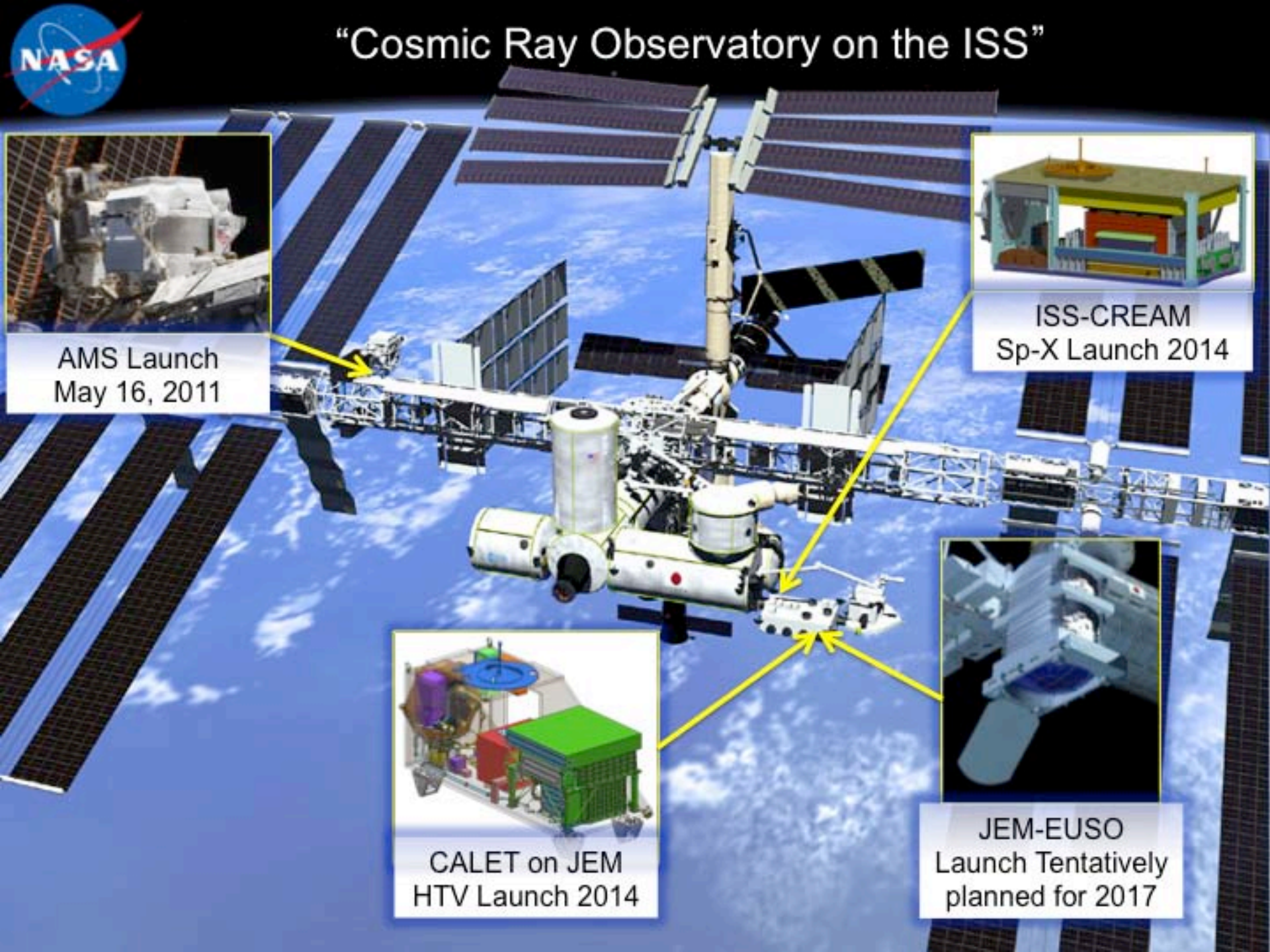
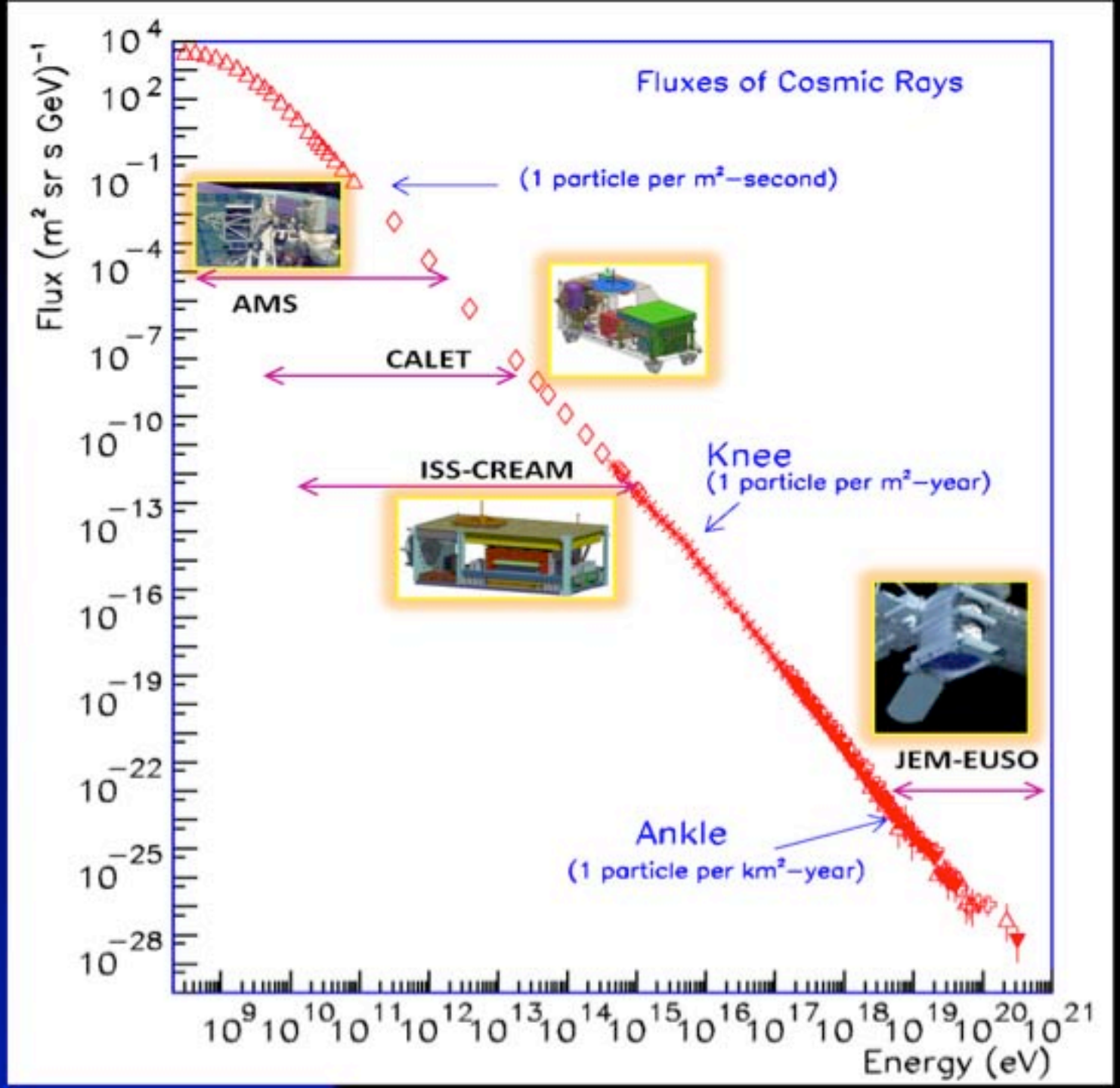
E > 50 EeV, distances of < 100 Mpc

How are they observed?
Detectors in Balloons, Space, Underground, Giant Ground Arrays

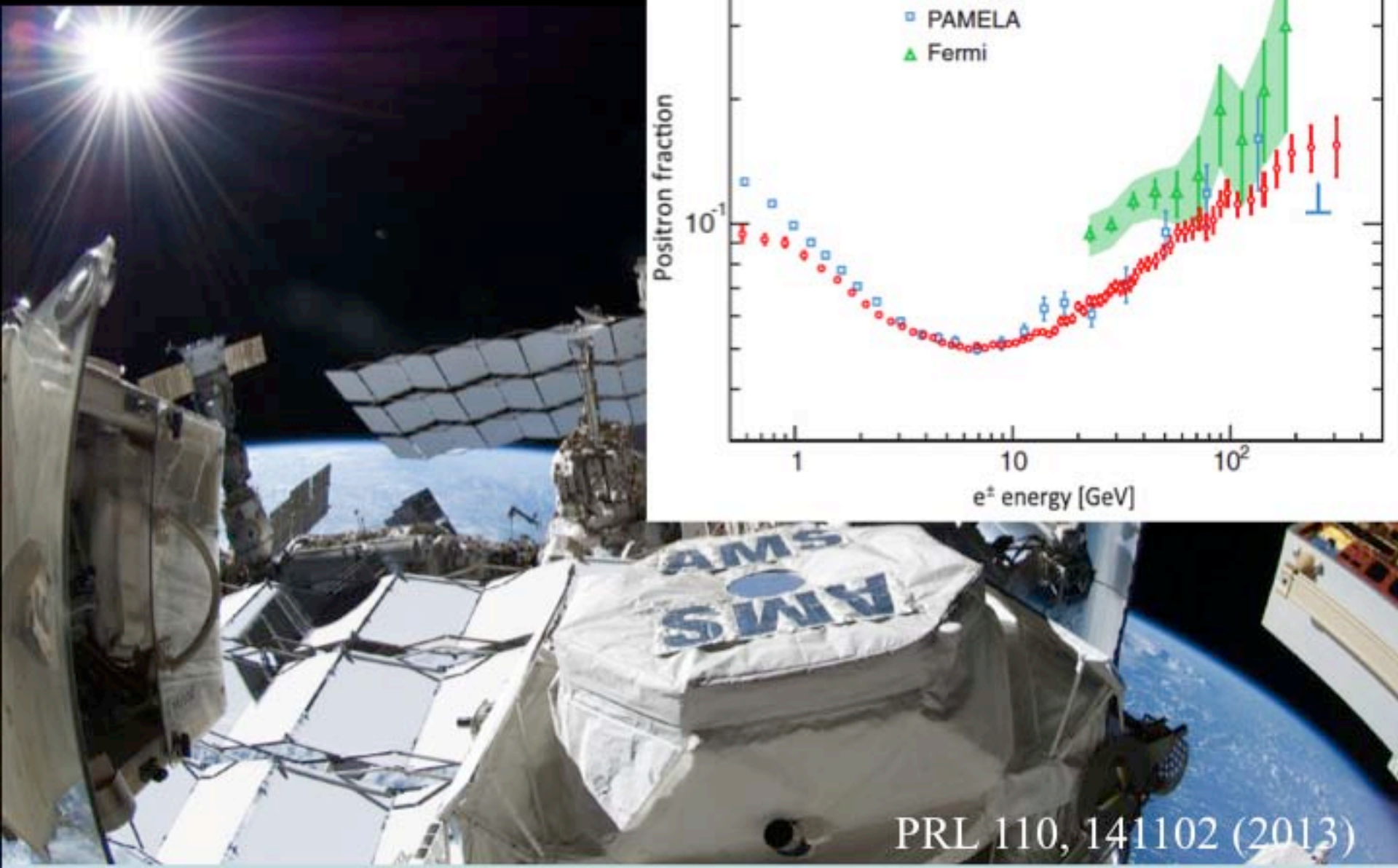
"Cosmic Ray Observatory on the ISS"




Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
Energy (eV)
(1 particle per m²–second)
AMS
CALET
ISS-CREAM
Knee
(1 particle per m²–year)
JEM-EUSO
Ankle
(1 particle per km²–year)

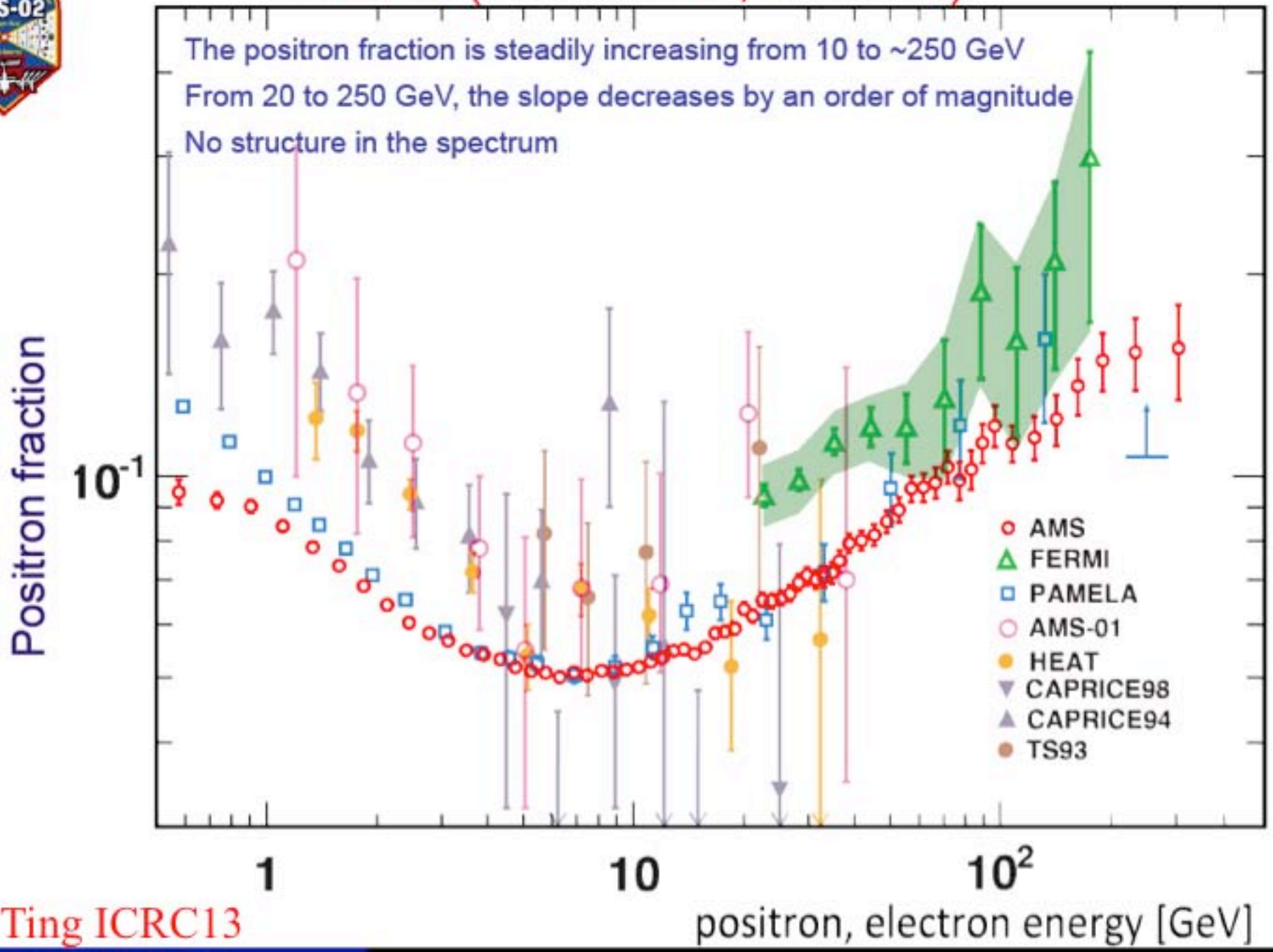
Recent Highlights (April 3, 2013)

AMS first results



PRL 110, 141102 (2013)

AMS-02 (6.8 million e^+, e^- events)



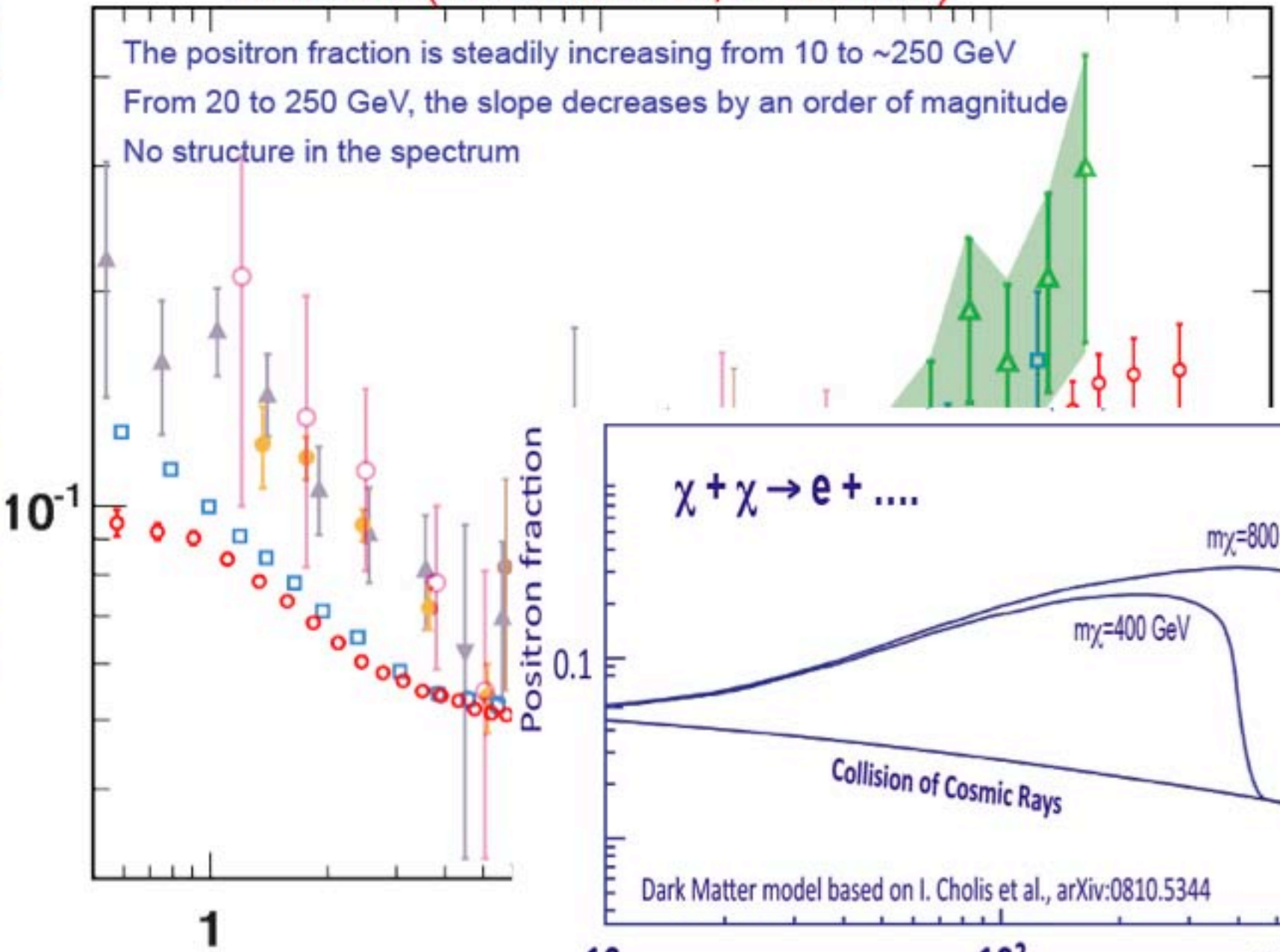
S. Ting ICRC13

AMS-02 (6.8 million e^+, e^- events)

The positron fraction is steadily increasing from 10 to ~250 GeV

From 20 to 250 GeV, the slope decreases by an order of magnitude

No structure in the spectrum



S. Ting ICRC13

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The positron fraction is steadily increasing from 10 to ~250 GeV

From 20 to 250 GeV, the slope decreases by an order of magnitude

No structure in the spectrum

10^{-1}

1

10

10^2

$e^\pm$ energy [GeV]

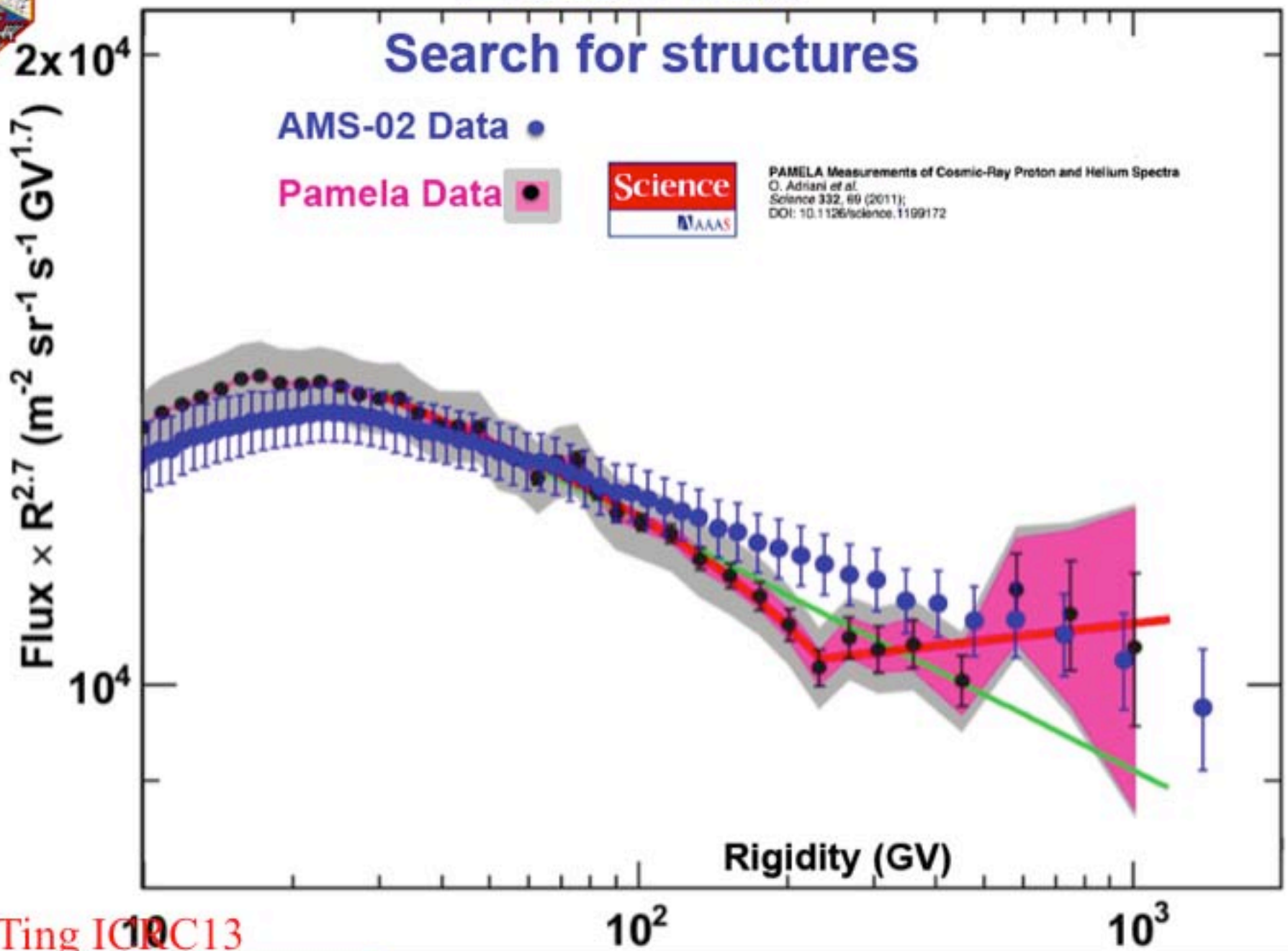
m_χ=800 GeV

00 GeV

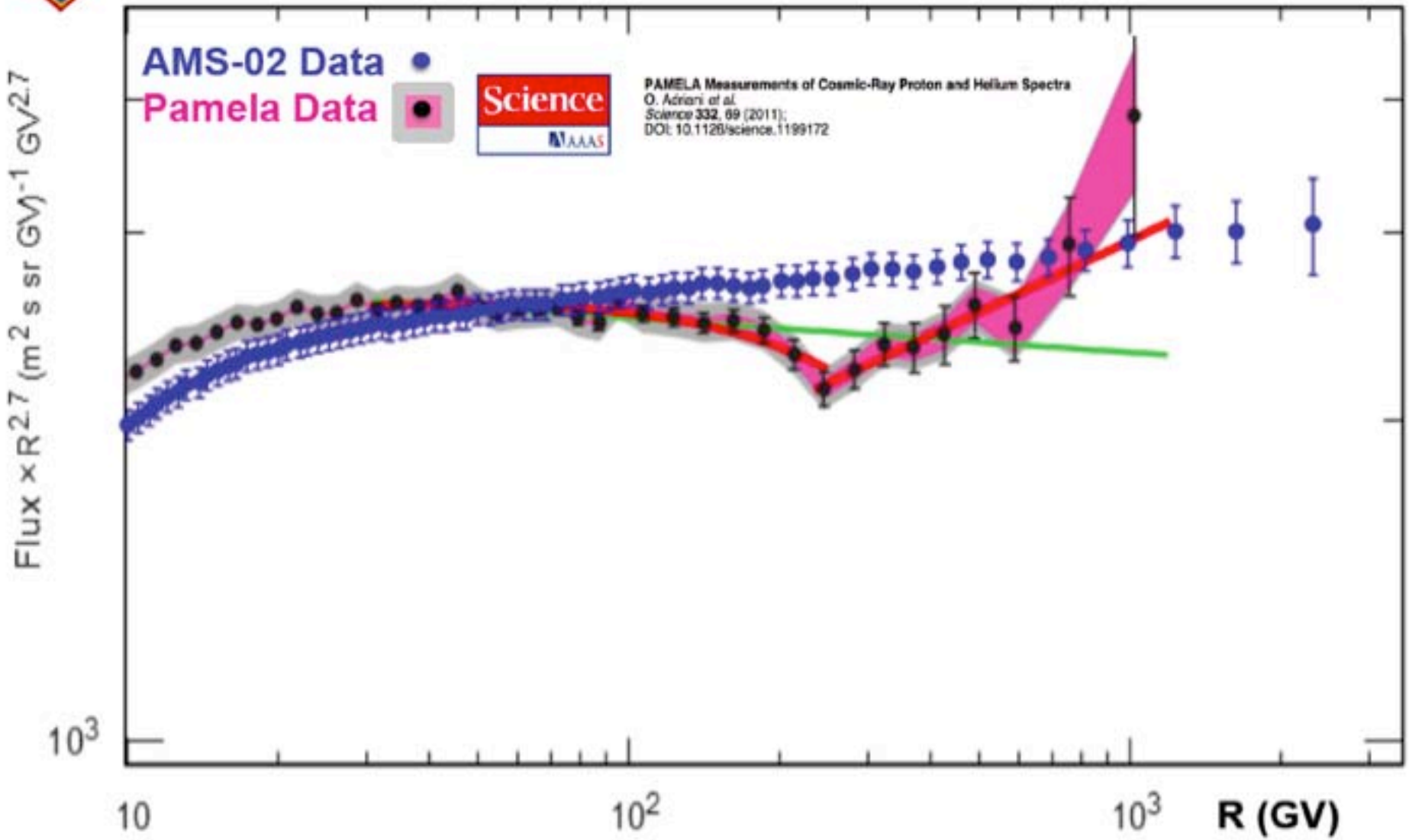
Dark Matter model based on I. Cholis et al., arXiv:0810.5344

S. Ting ICRC13

Proton flux


Search for structures
AMS-02 Data
Pamela Data
Science
AAAS
PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani et al.
Science 332, 69 (2011);
DOI: 10.1126/science.1199172
Flux × R^2.7 (m^-2 sr^-1 s^-1 GV^1.7)
2x10^4
10^4
Rigidity (GV)
10
10^2
10^3

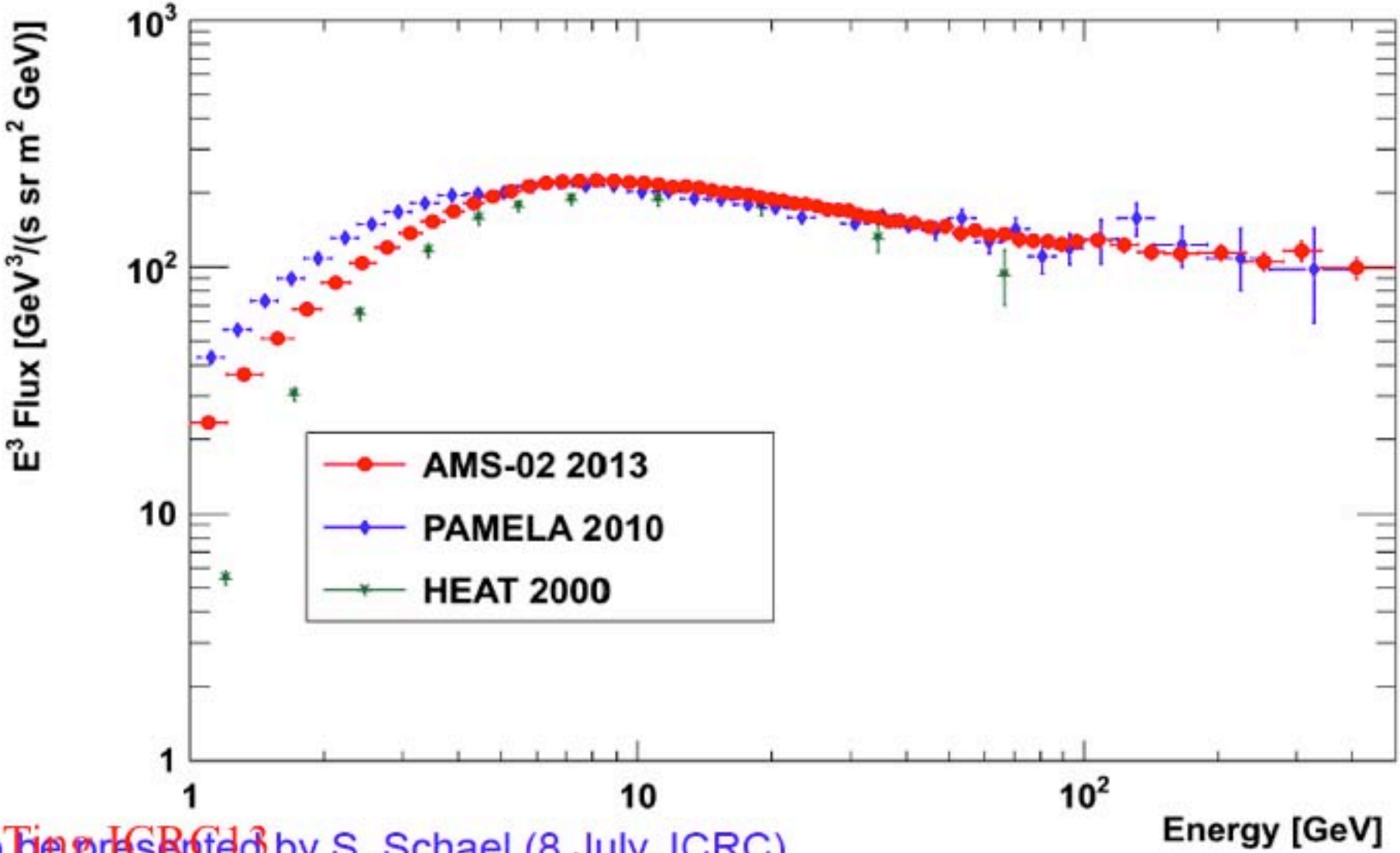
Helium flux
Search for structures



S. Ting ICRC13

To be presented by V. Choutko (8 July, ICRC)

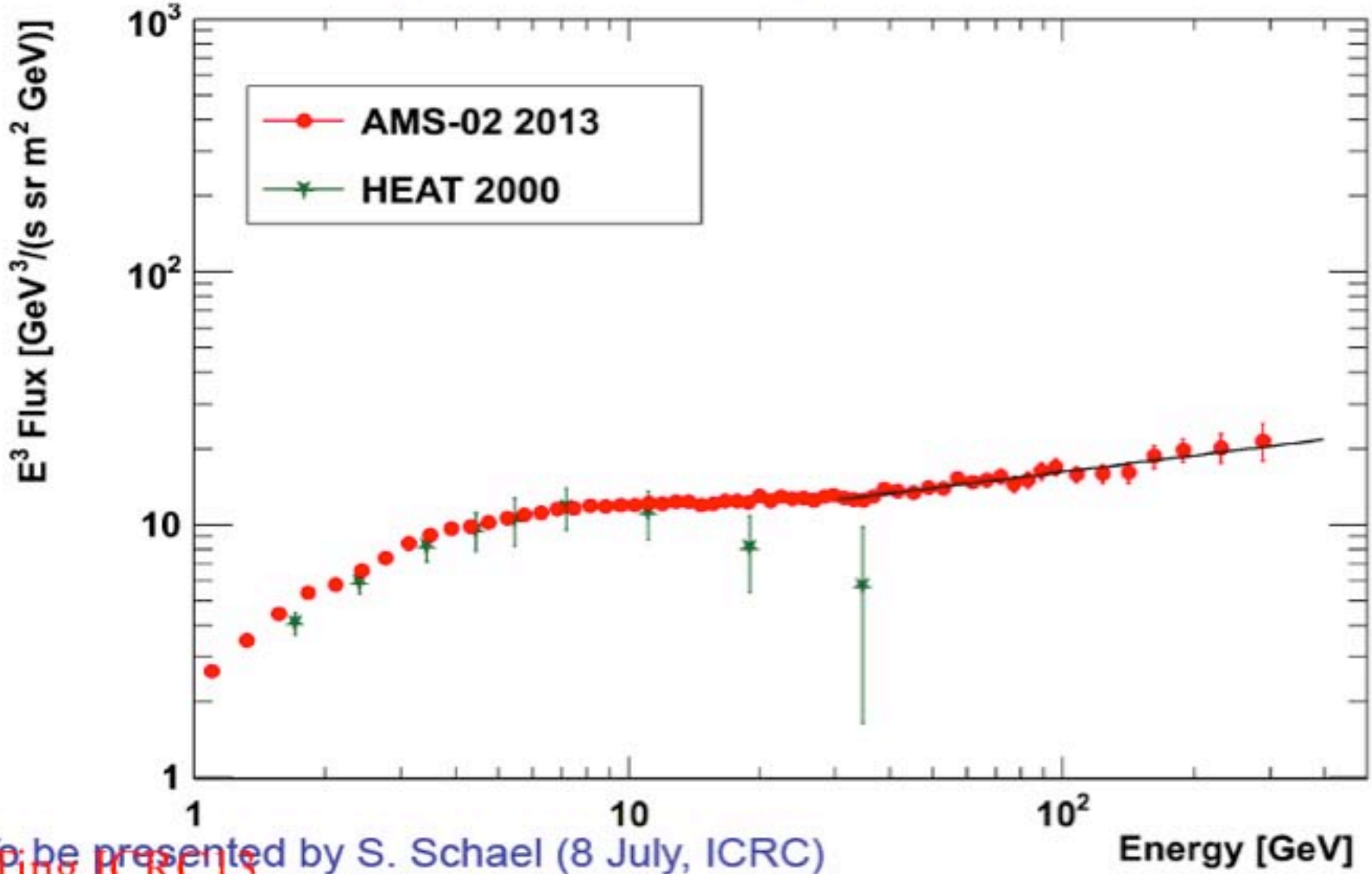
New results from AMS
4) Electron Spectrum



S. Ting ICRC13

To be presented by S. Schael (8 July, ICRC)

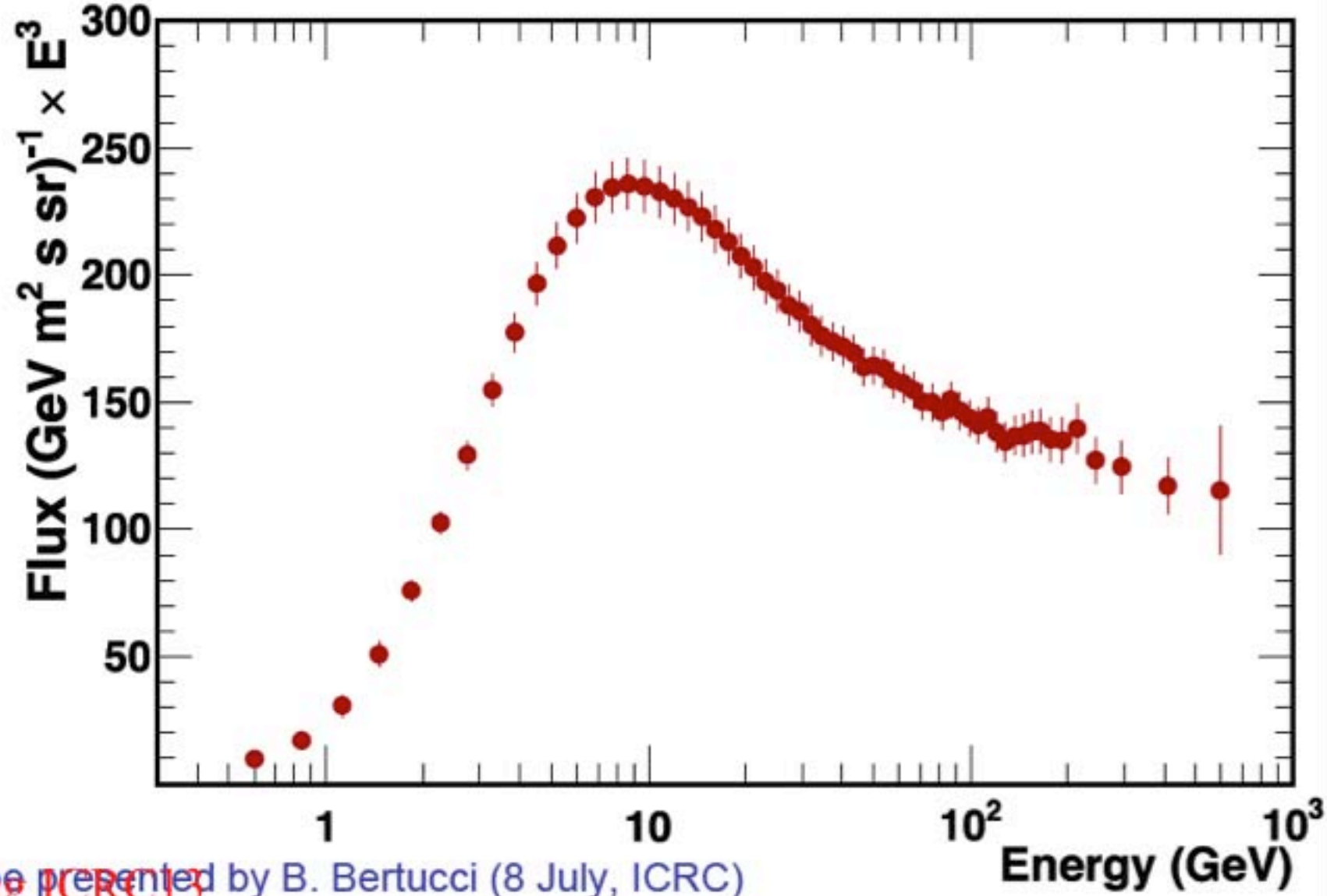
New results from AMS
5) Positron Spectrum



To be presented by S. Schael (8 July, ICRC)

S. Ting ICRC15

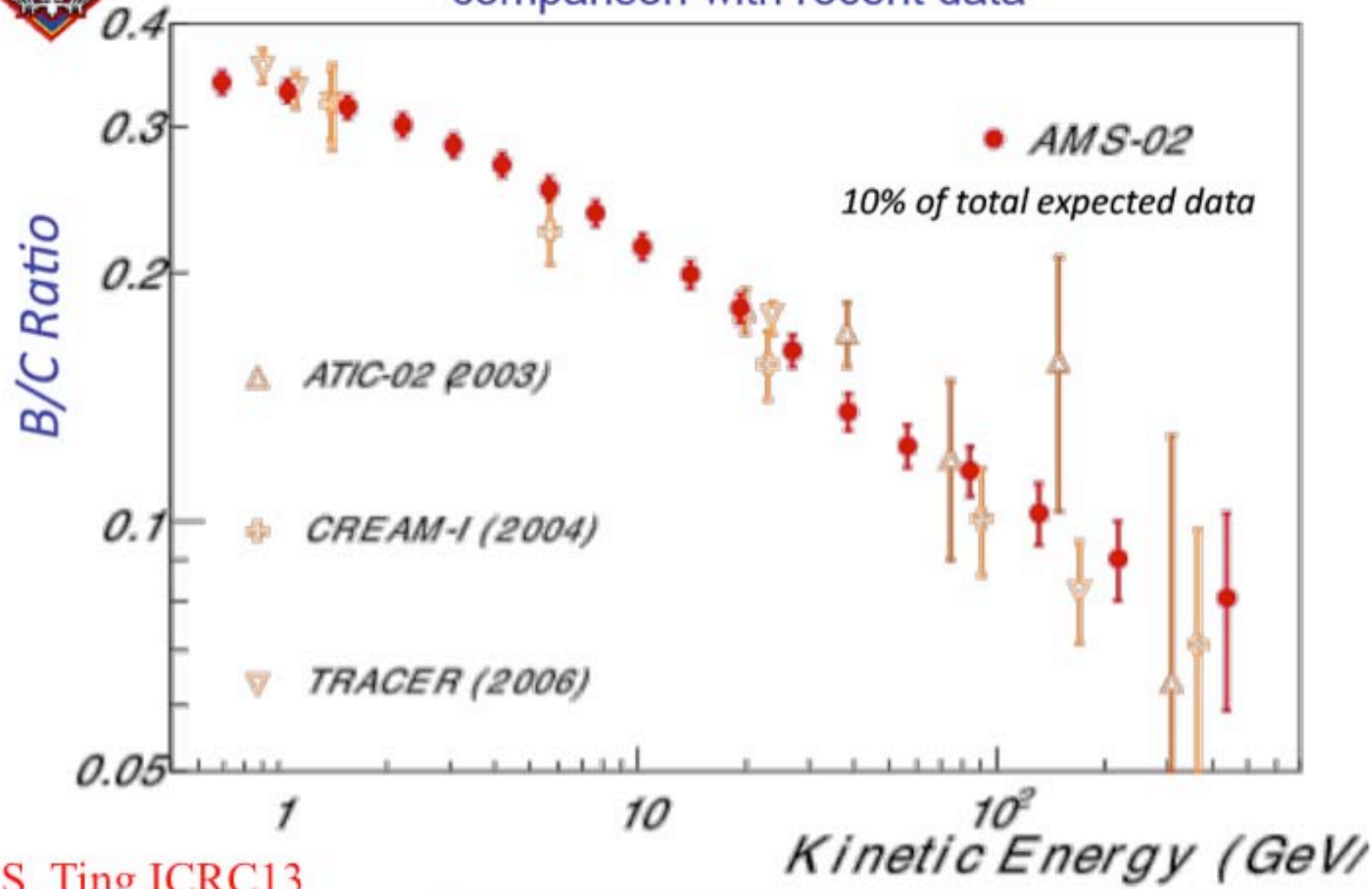
New results from AMS
6) (Electron plus Positron) Spectrum



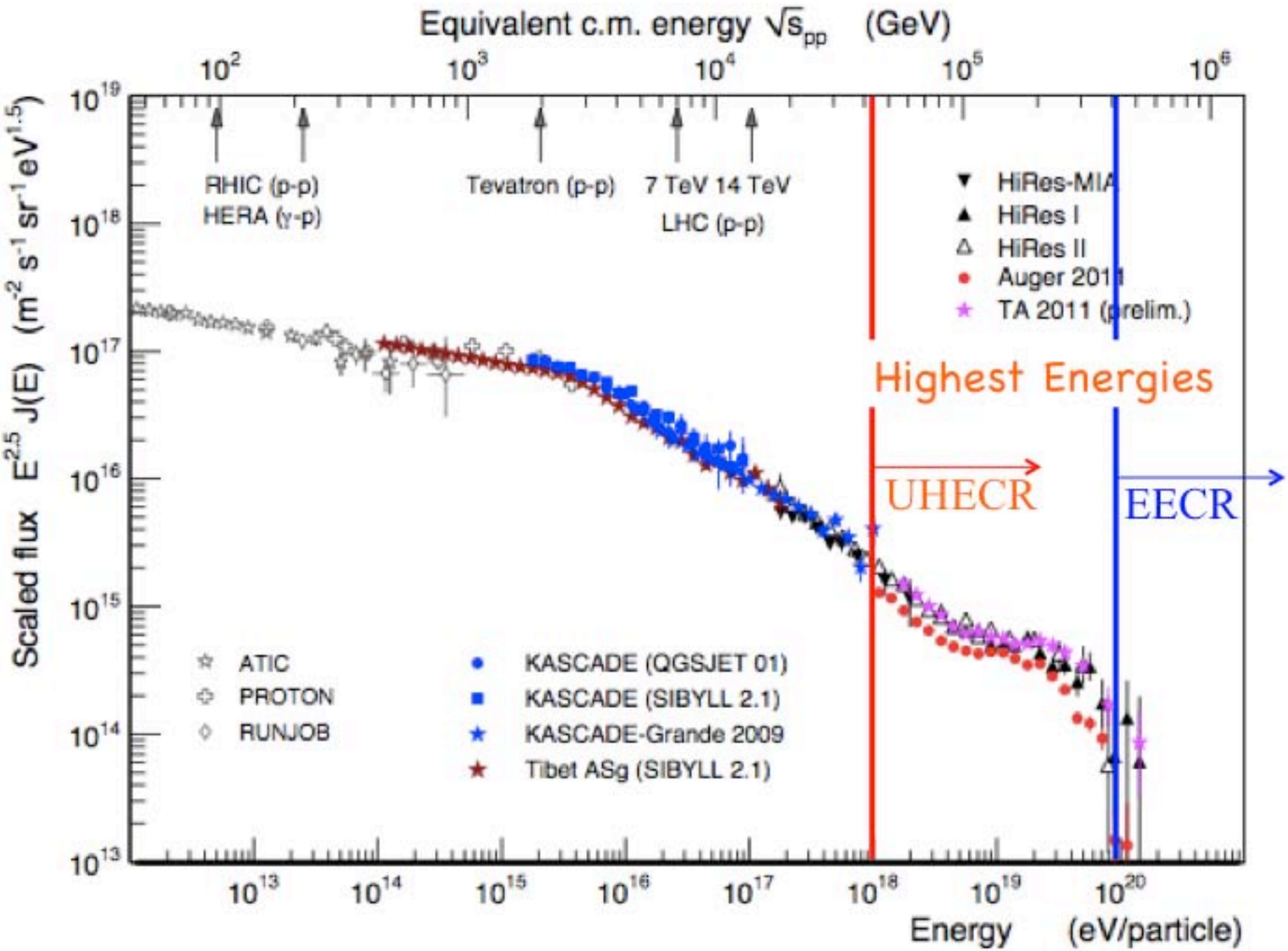
To be presented by B. Bertucci (8 July, ICRC)

Boron-to-Carbon ratio

comparison with recent data



S. Ting ICRC13


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2011
TA 2011 (prelim.)
Highest Energies
UHECR
EECR
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

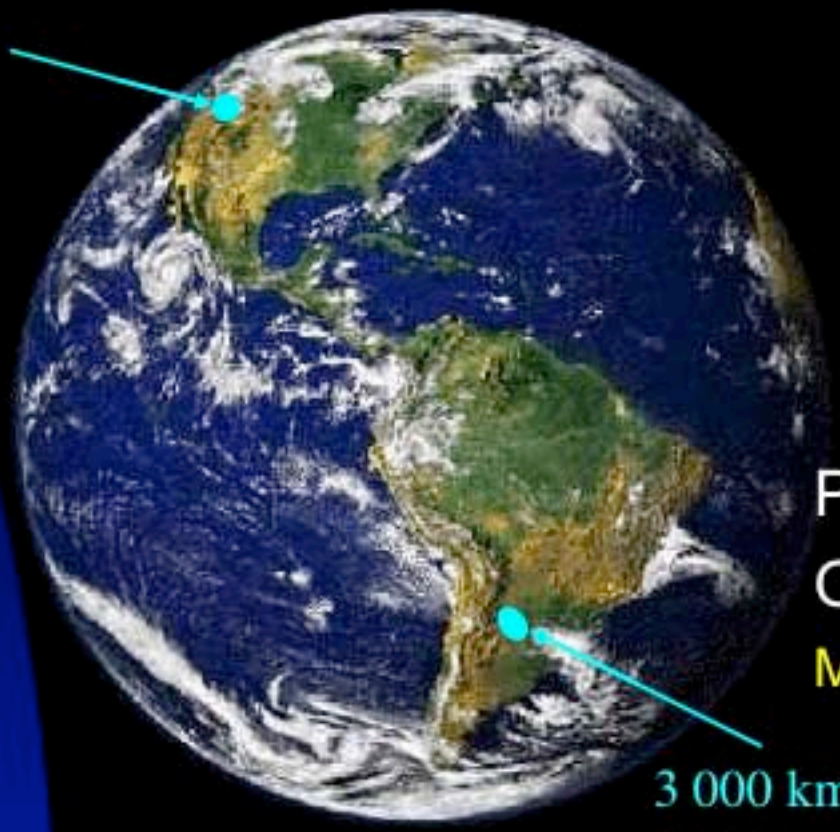
Ultrahigh Energy Cosmic Rays
Leading Observatories

Telescope Array

Utah, USA

700 km^2 array

3 fluorescence sites



Pierre Auger Observatory

Mendoza, Argentina

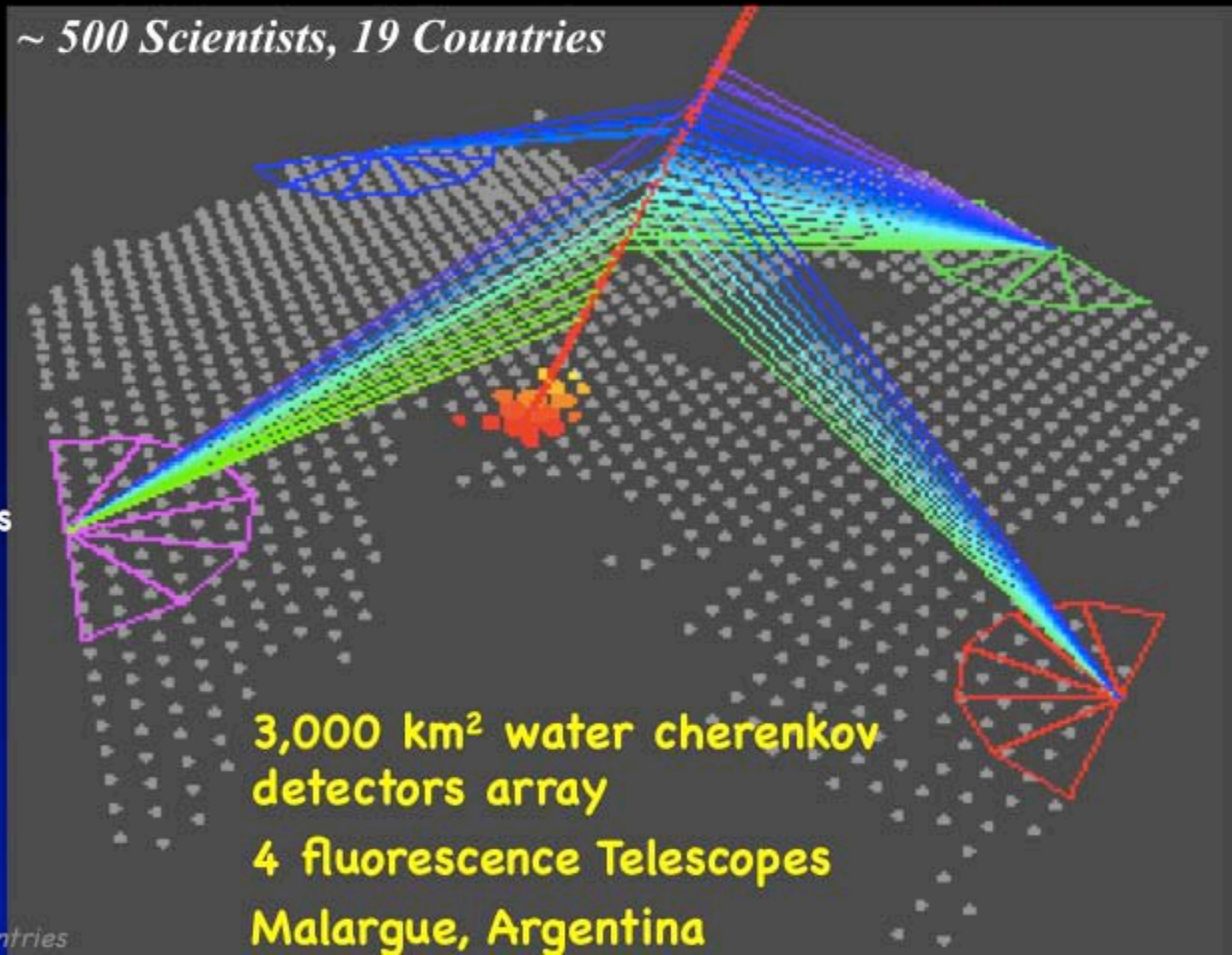
3 000 km^2 array

4 fluorescence sites

The Pierre Auger Observatory

Argentina
Australia
Brasil
Bolivia*
Croatia
Czech Rep.
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania*
Slovenia
Spain
UK
USA
Vietnam*

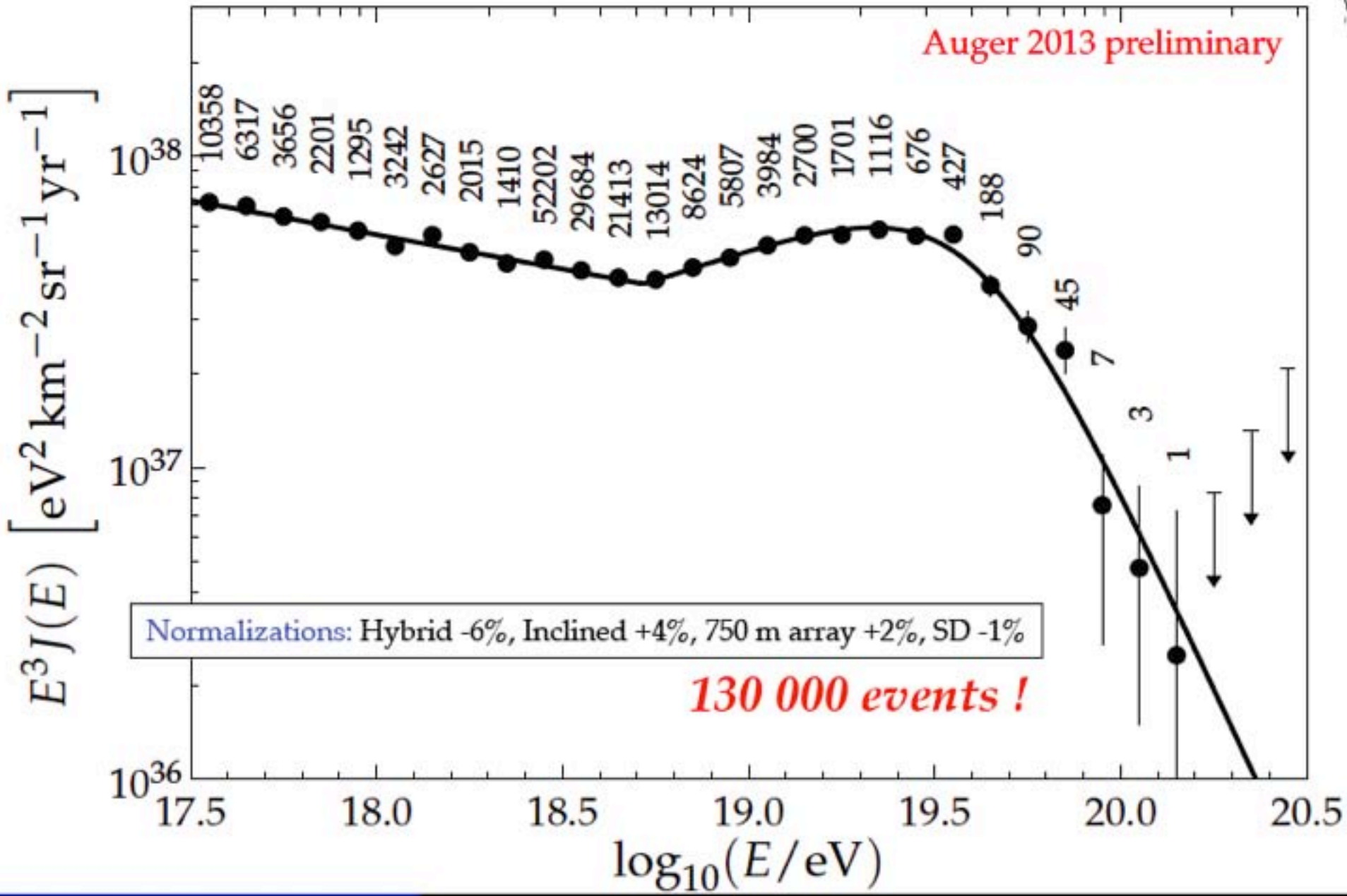
*Associate Countries

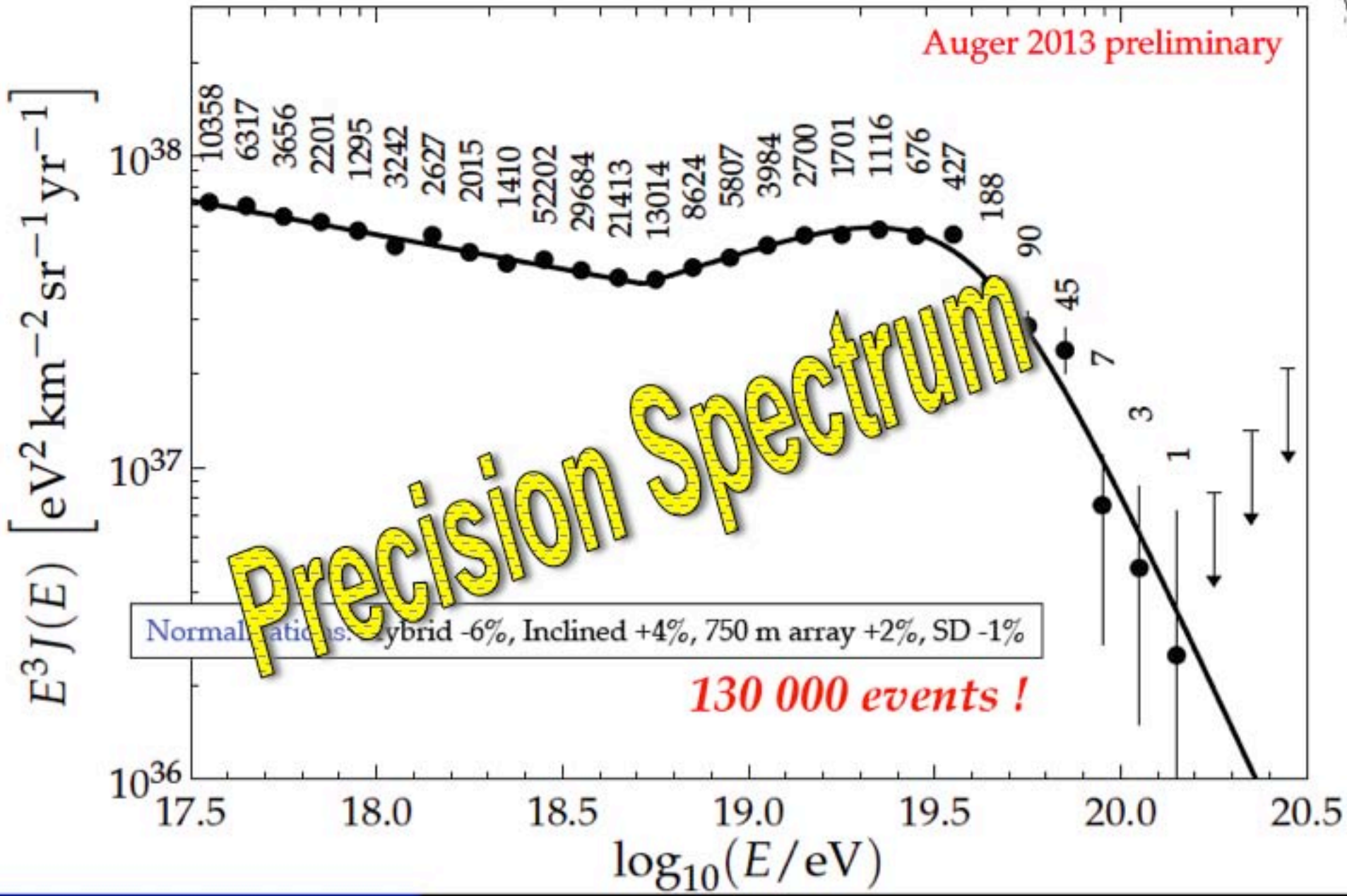


surface detector

array of tanks

4 times 6 telescopes overlooking the site


Auger 2013 preliminary
10358
6317
3656
2201
1295
3242
2627
2015
1410
52202
29684
21413
13014
8624
5807
3984
2700
1701
1116
676
427
188
90
45
7
3
1
Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%
130 000 events !
10^{38}
10^{37}
10^{36}
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$
$E^3 J(E)\ \left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$


Auger 2013 preliminary
Precision Spectrum
Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%
130 000 events !
$E^3 J(E)$ $[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}]$
10^{38}
10^{37}
10^{36}
10358
6317
3656
2201
1295
3242
2627
2015
1410
52202
29684
21413
13014
8624
5807
3984
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427
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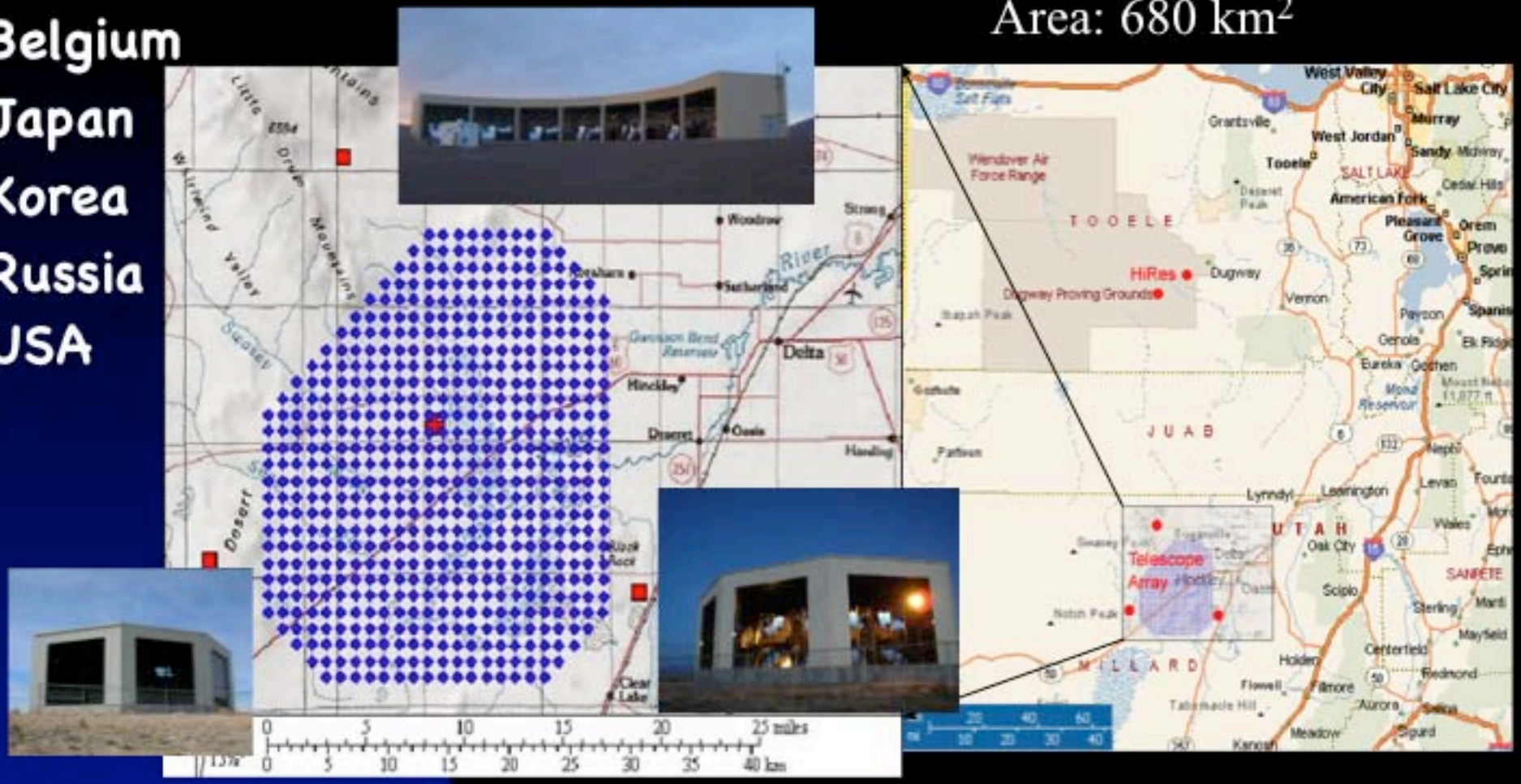
7
3
1
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$

Telescope Array

Belgium
Japan
Korea
Russia
USA

Area: 680 km^2

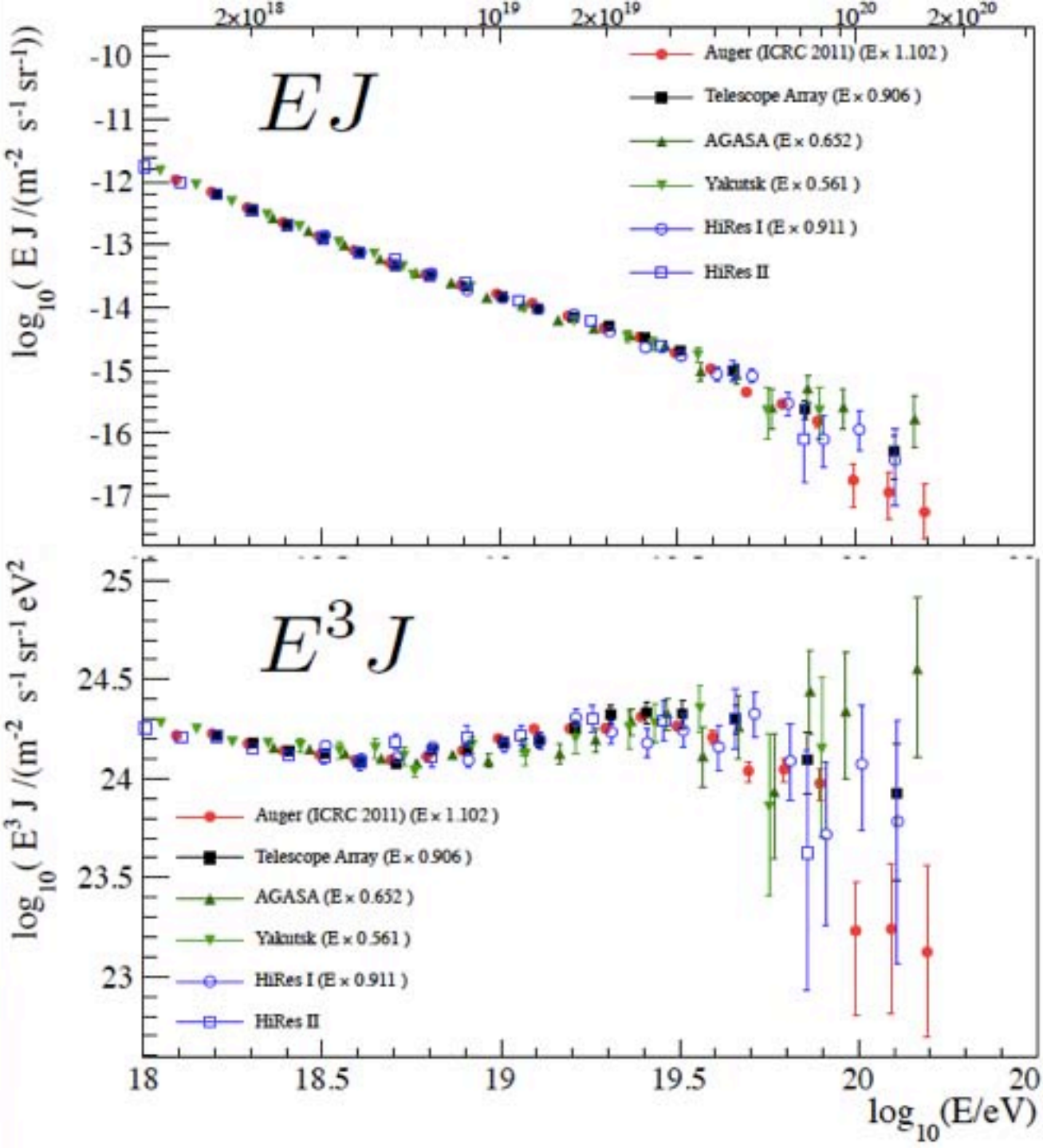


3 FD stations overlooking an array of 507 scintillator surface detectors (SD) complete and operational as of ~1/2008.

Deployment (up to 50/day)
485 SDs: 10/2006 - 3/2007

2012 CERN Working Group

Unified Spectrum



20% absolute energy shifts

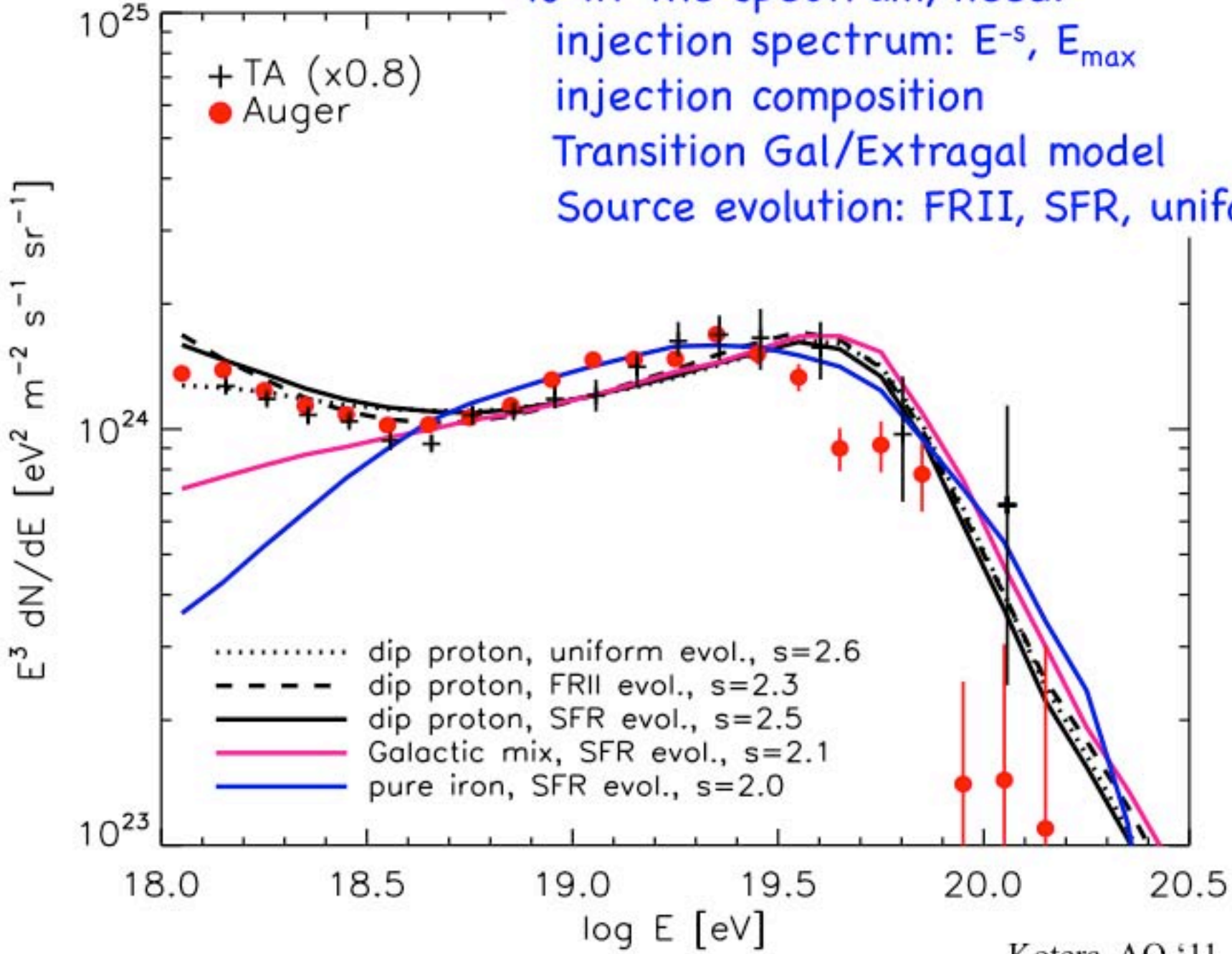
To fit the spectrum, need:

injection spectrum: E^{-s}, E_{max}

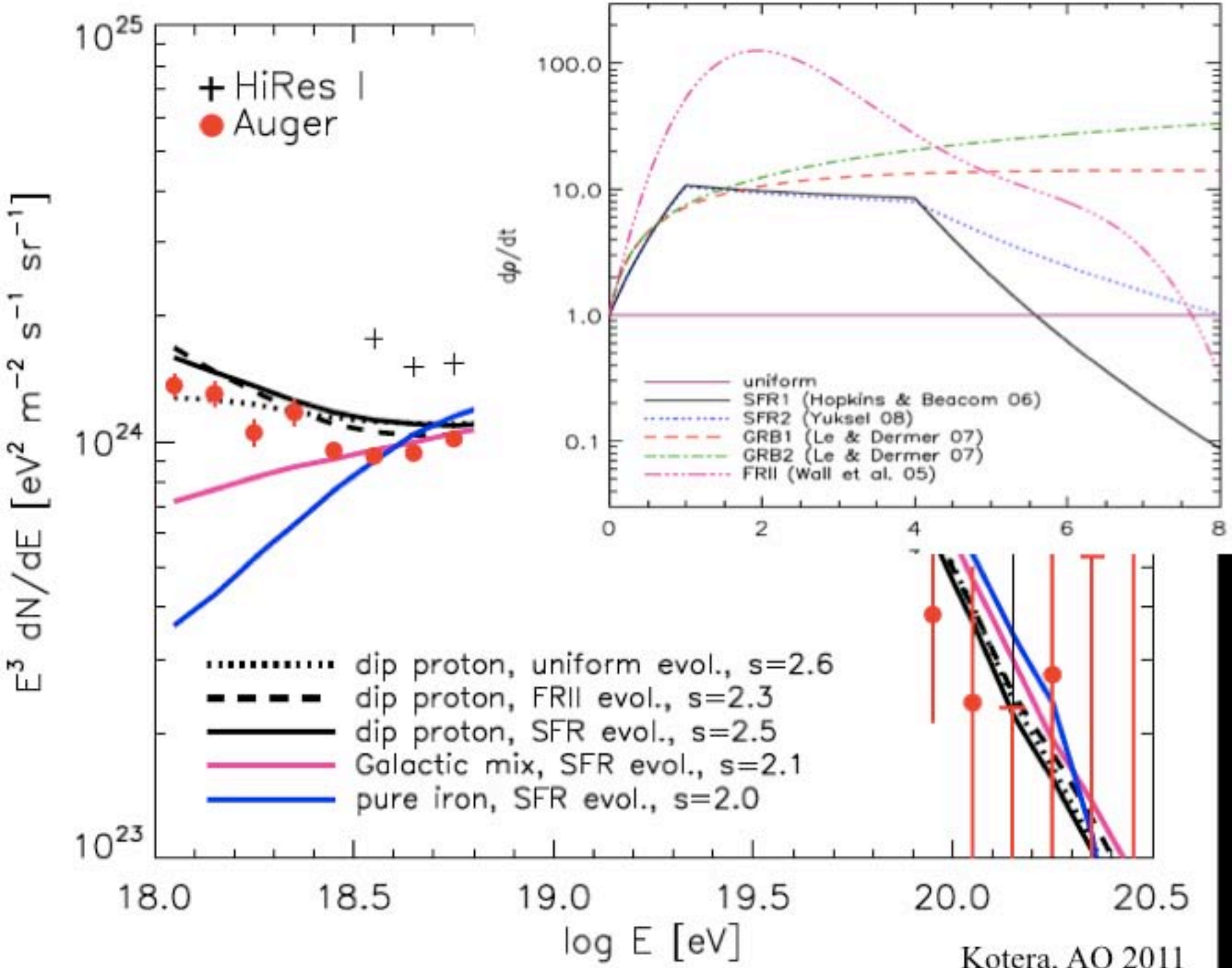
injection composition

Transition Gal/Extragal model

Source evolution: FRII, SFR, uniform

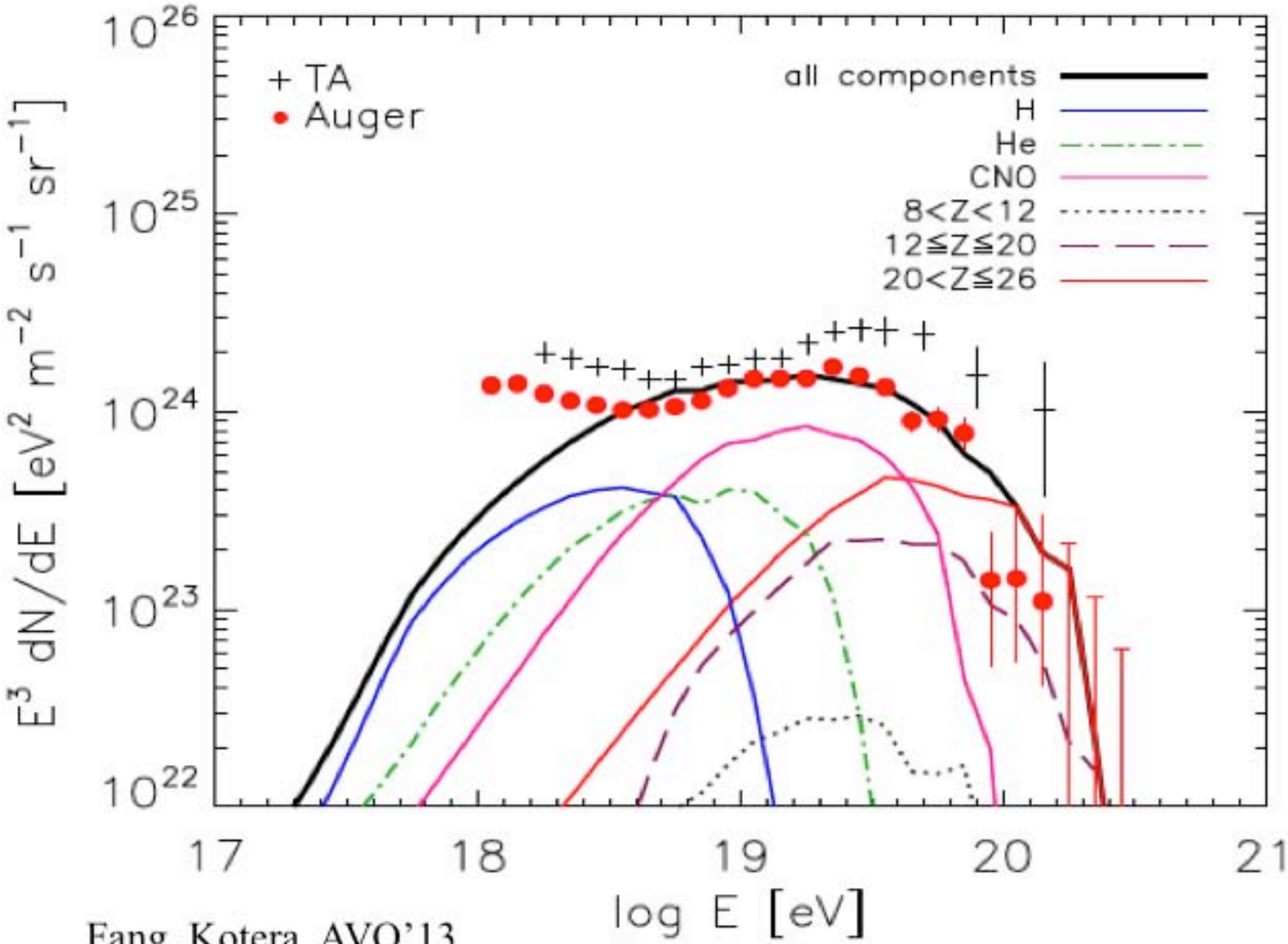


Kotera, AO '11



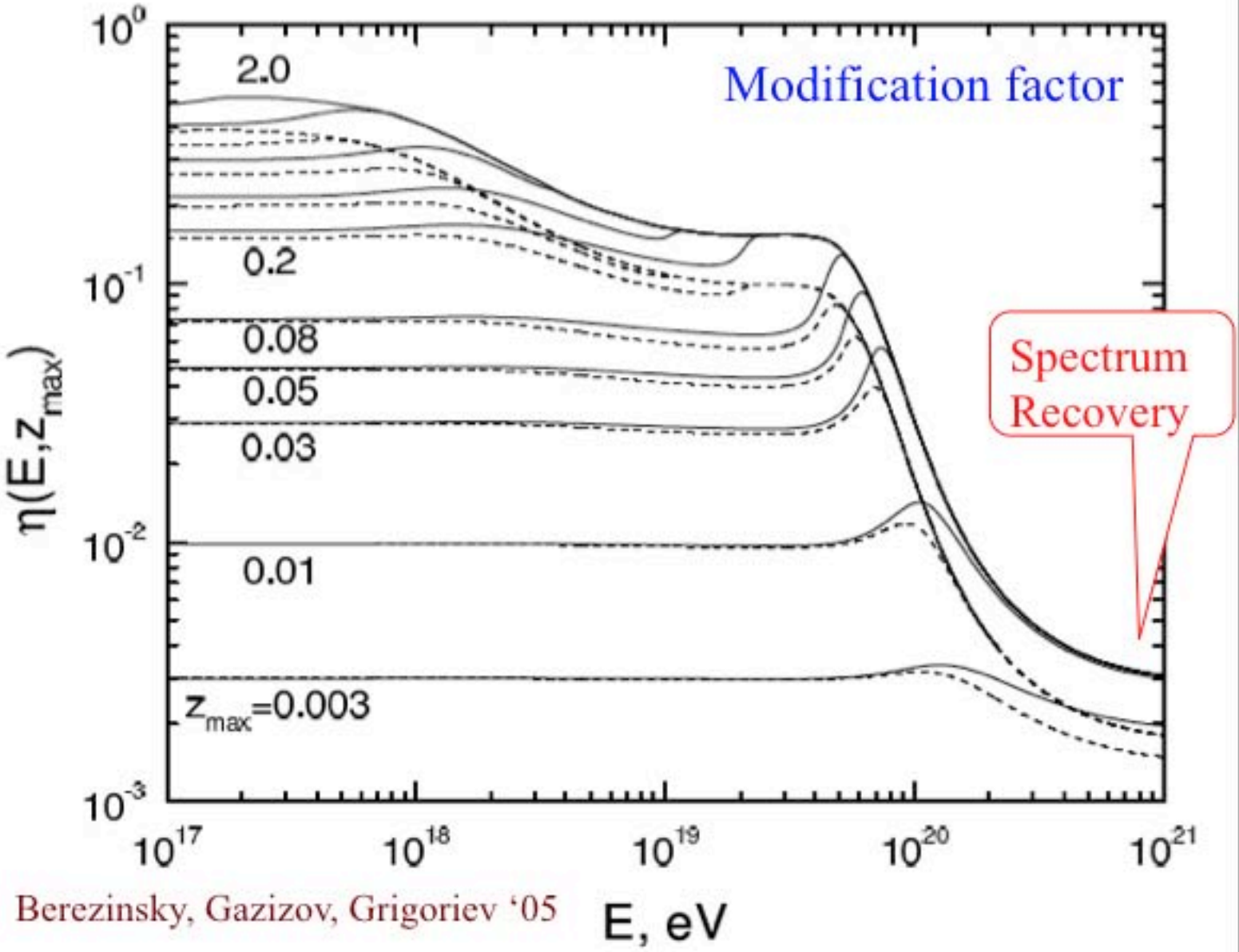
Kotera, AO 2011

Mixed Composition Model (Young Pulsars)



Fang, Kotera, AVO'13

Propagation of UHE protons



Berezinsky, Gazizov, Grigoriev '05

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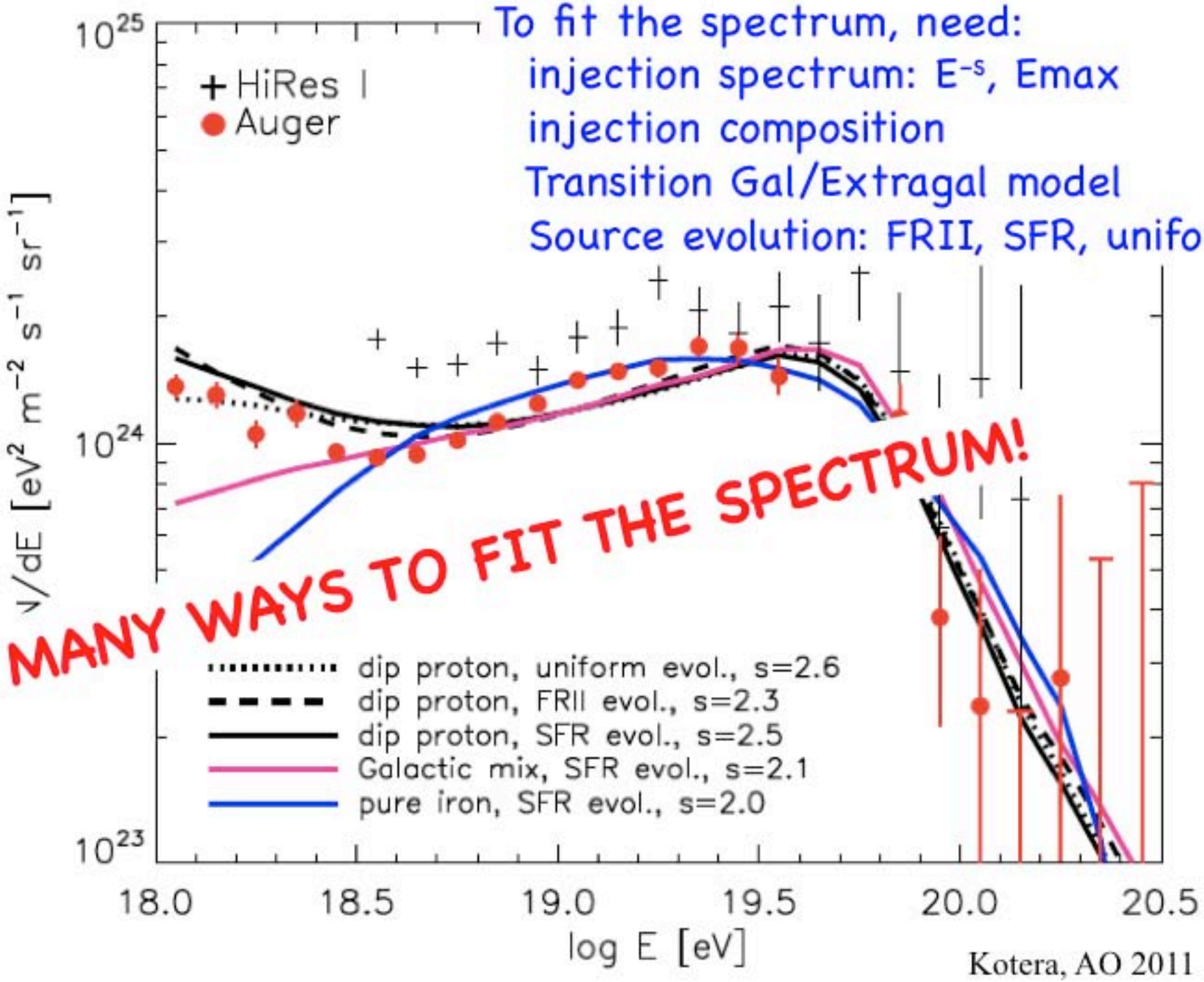
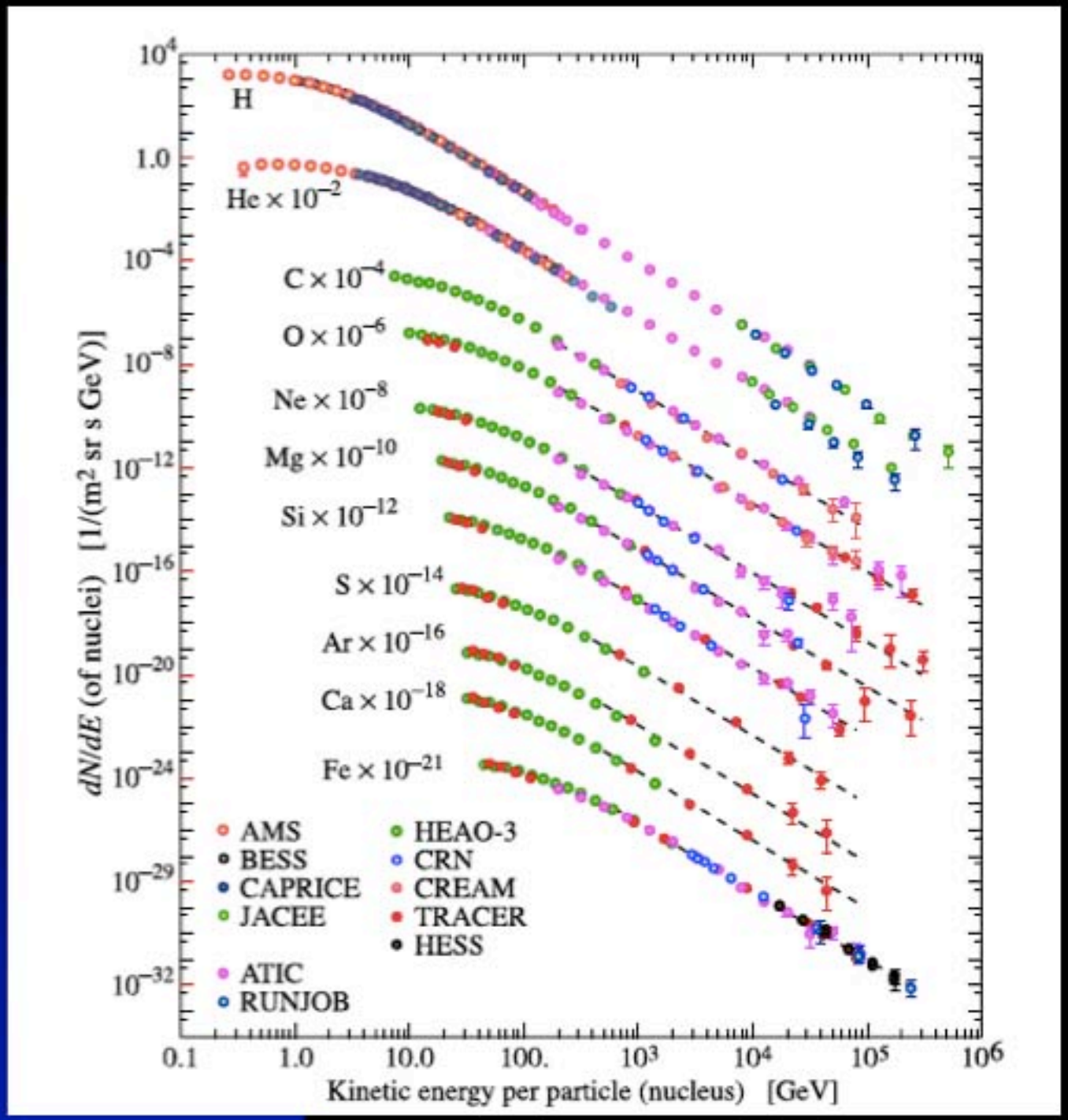


MANY WAYS TO FIT THE SPECTRUM!

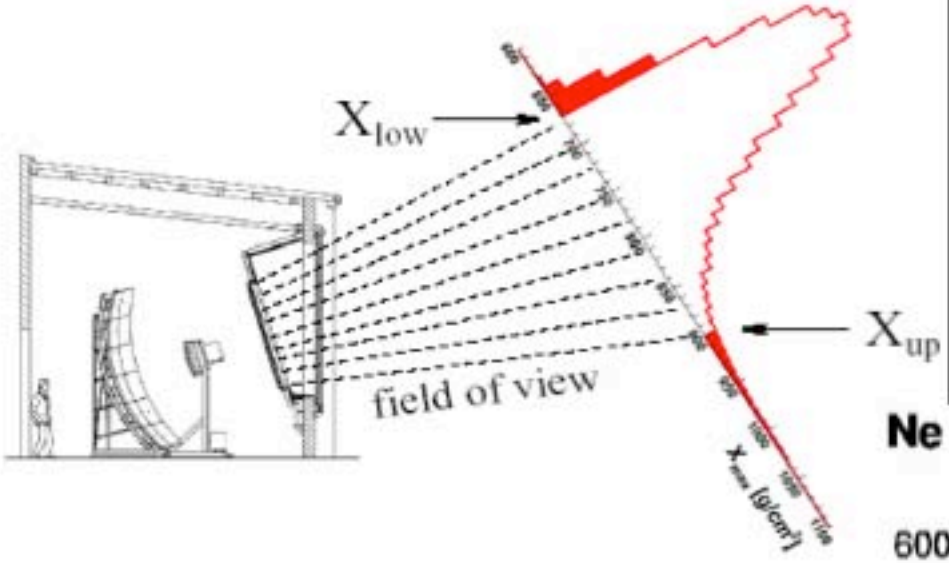
Kotera, AO 2011

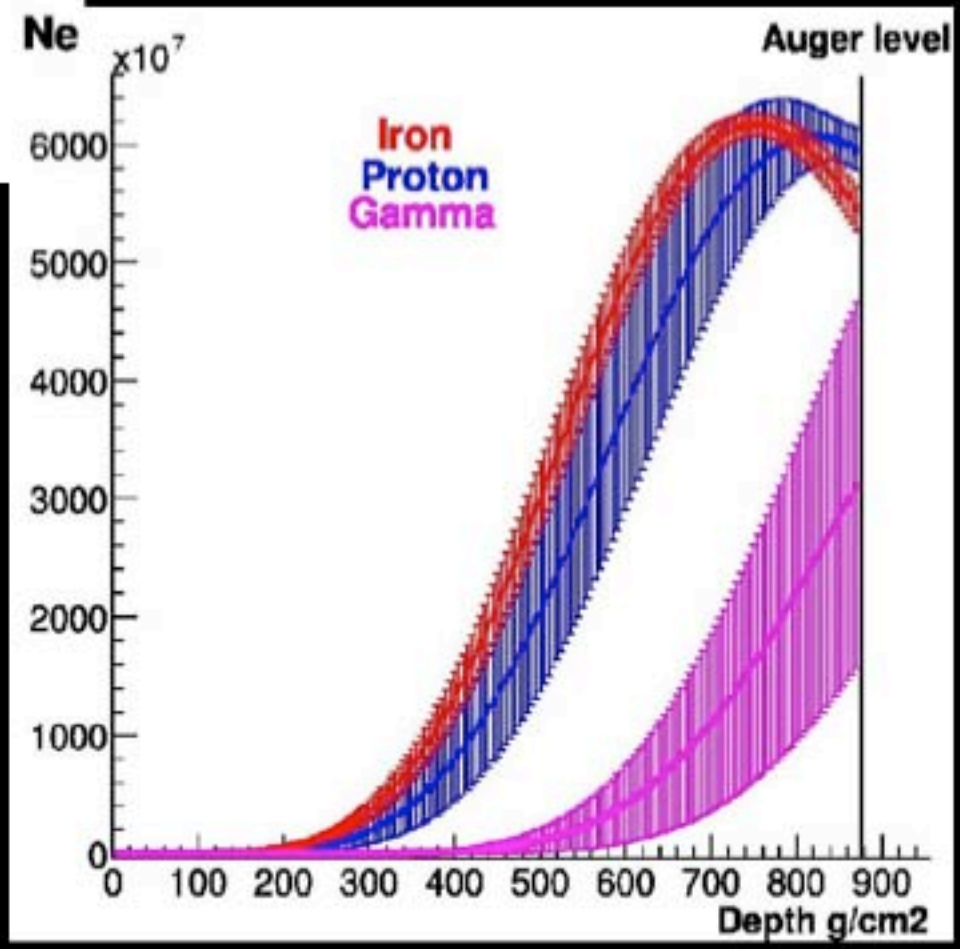
What is the Cosmic Ray composition?

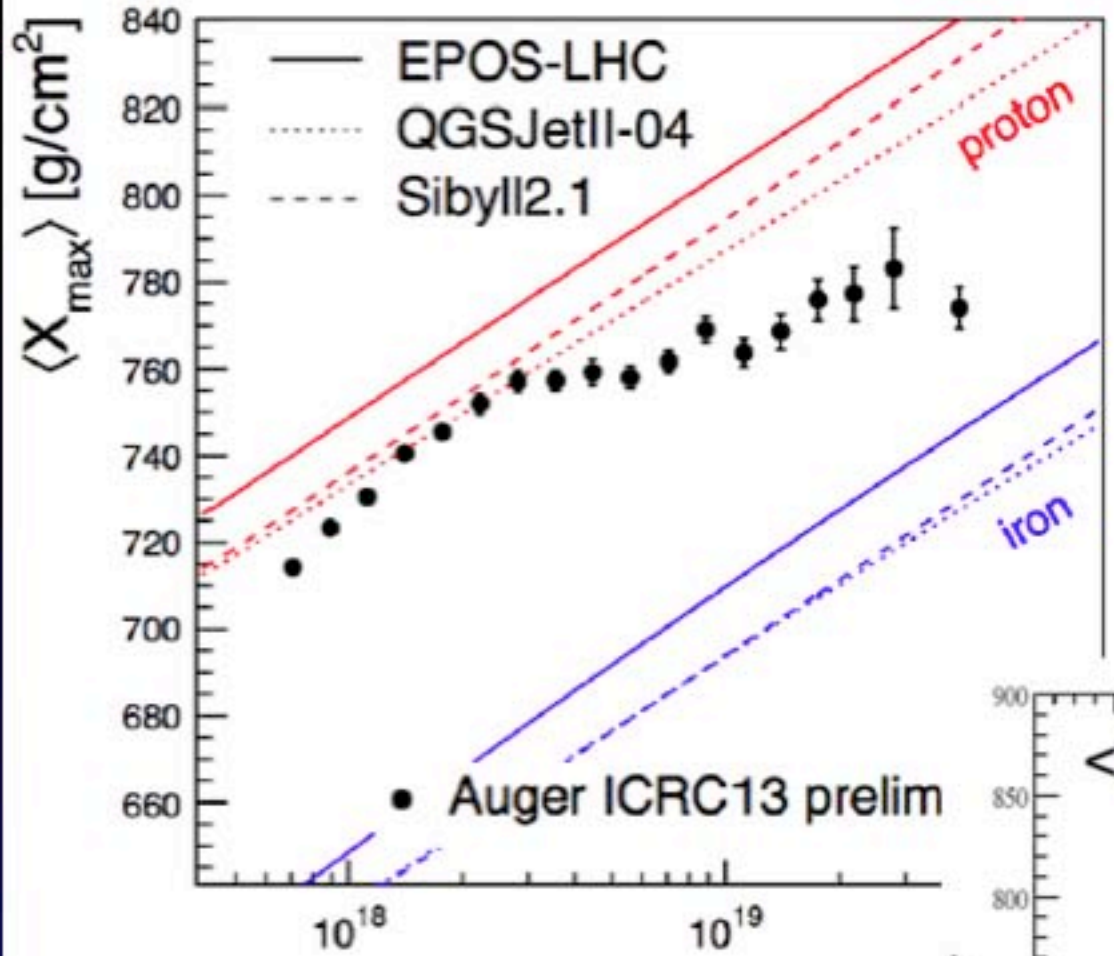
What is the Cosmic Ray composition? Protons Nuclei (e^+ e^-)


H
He × 10^−2
C × 10^−4
O × 10^−6
Ne × 10^−8
Mg × 10^−10
Si × 10^−12
S × 10^−14
Ar × 10^−16
Ca × 10^−18
Fe × 10^−21
AMS
BESS
CAPRICE
JACEE
ATIC
RUNJOB
HEAO-3
CRN
CREAM
TRACER
HESS
dN/dE (of nuclei) [1/(m² sr s GeV)]
Kinetic energy per particle (nucleus) [GeV]

Composition observable: shower maximum

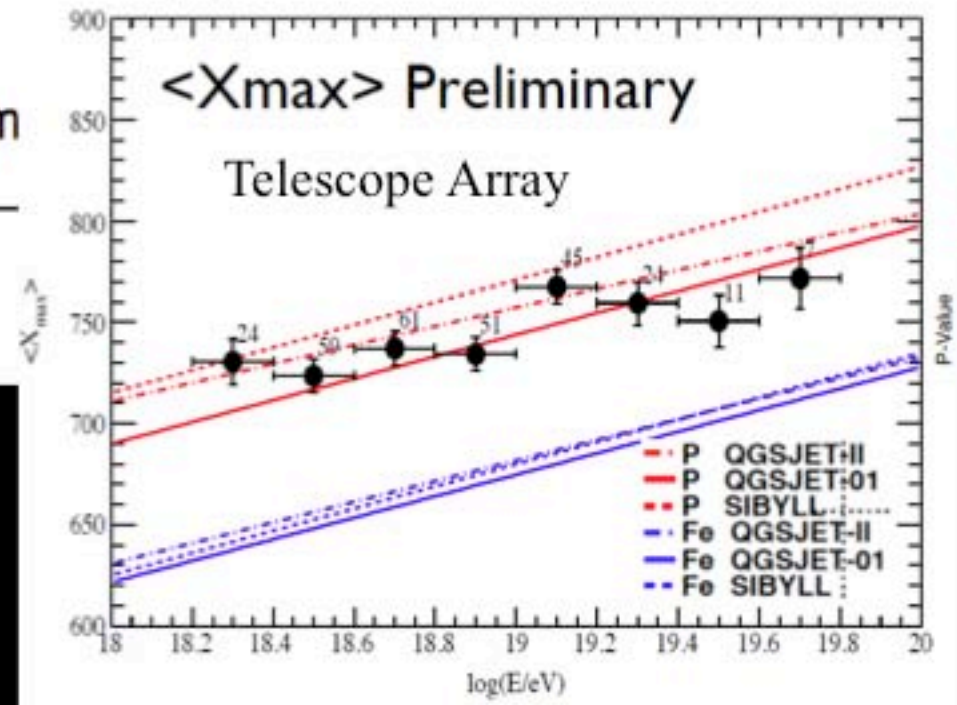


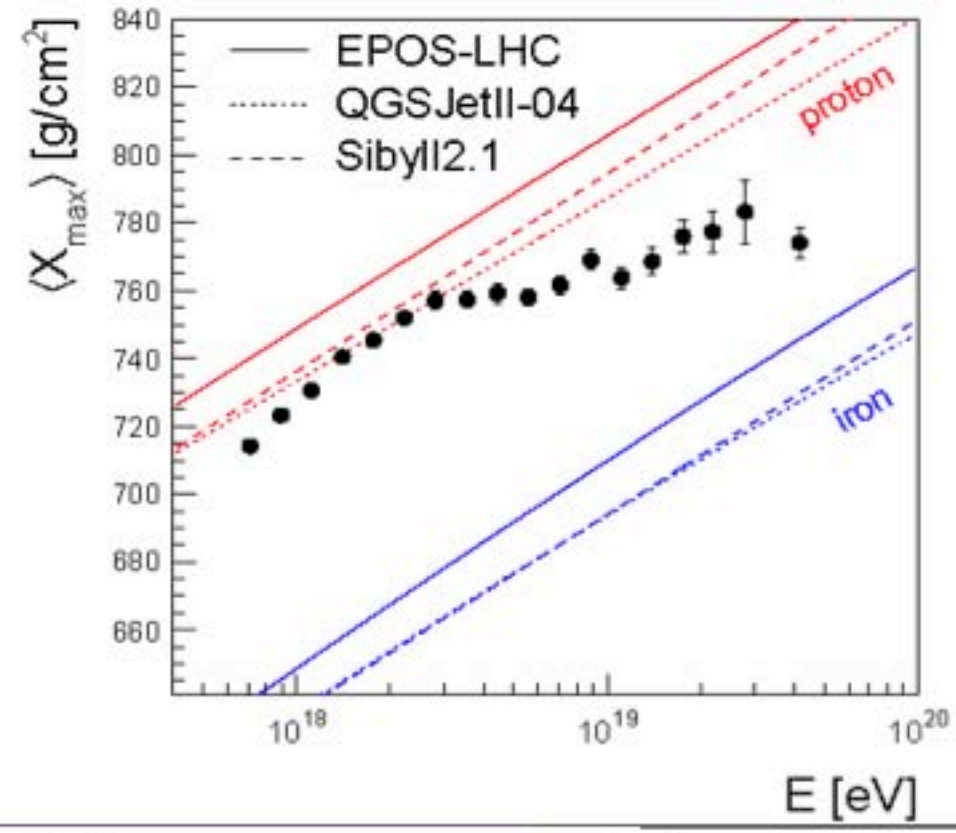


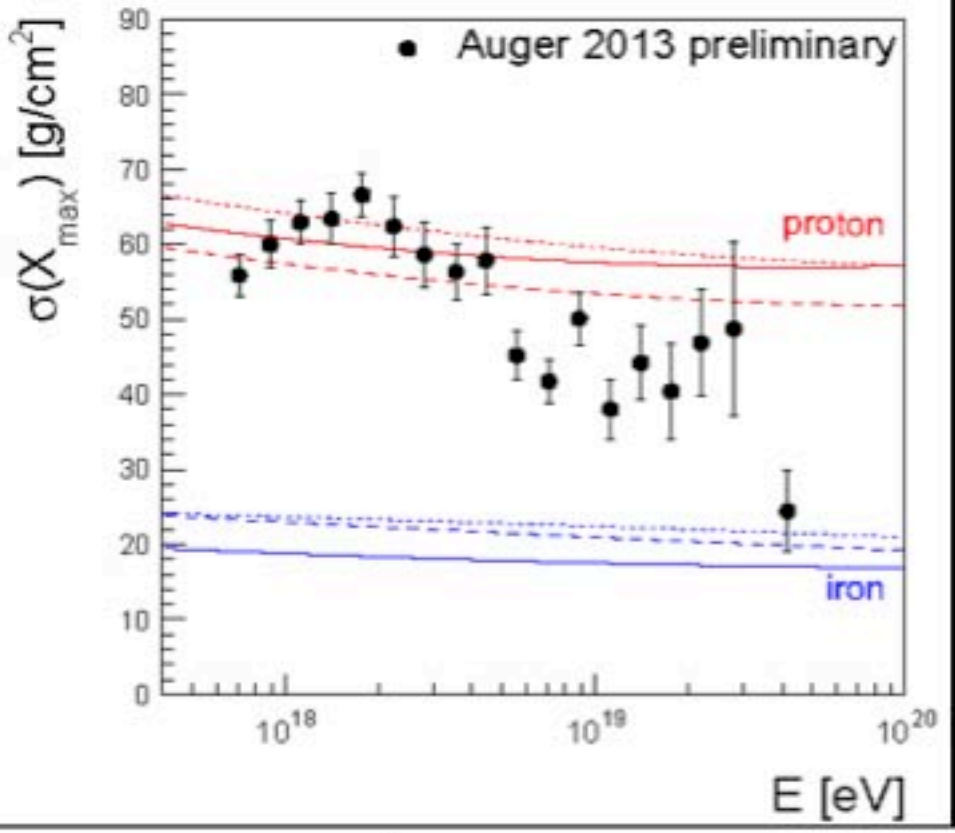


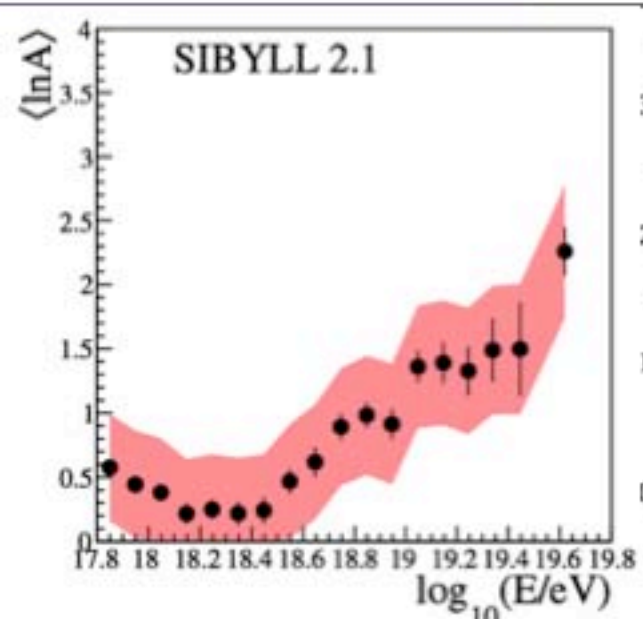
Auger sees change slope: Change in Composition or interactions

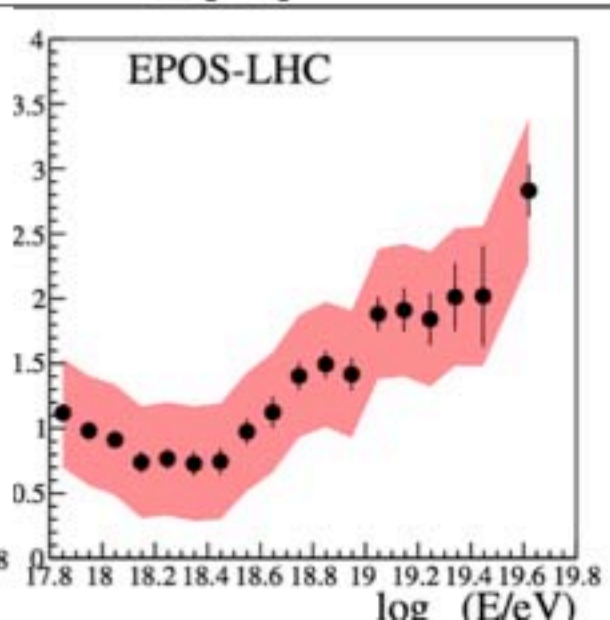
TA: not confirmed yet

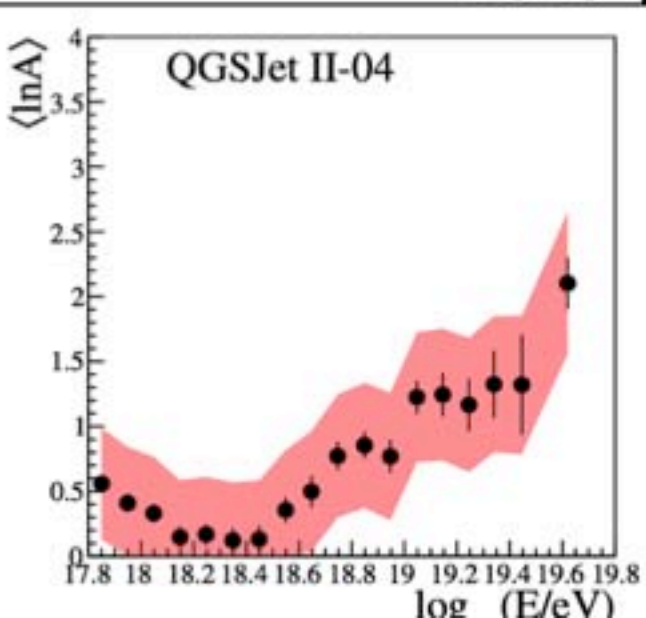



EPOS-LHC
QGSJetII-04
Sibyll2.1
proton
iron
⟨X_max⟩ [g/cm²]
E [eV]

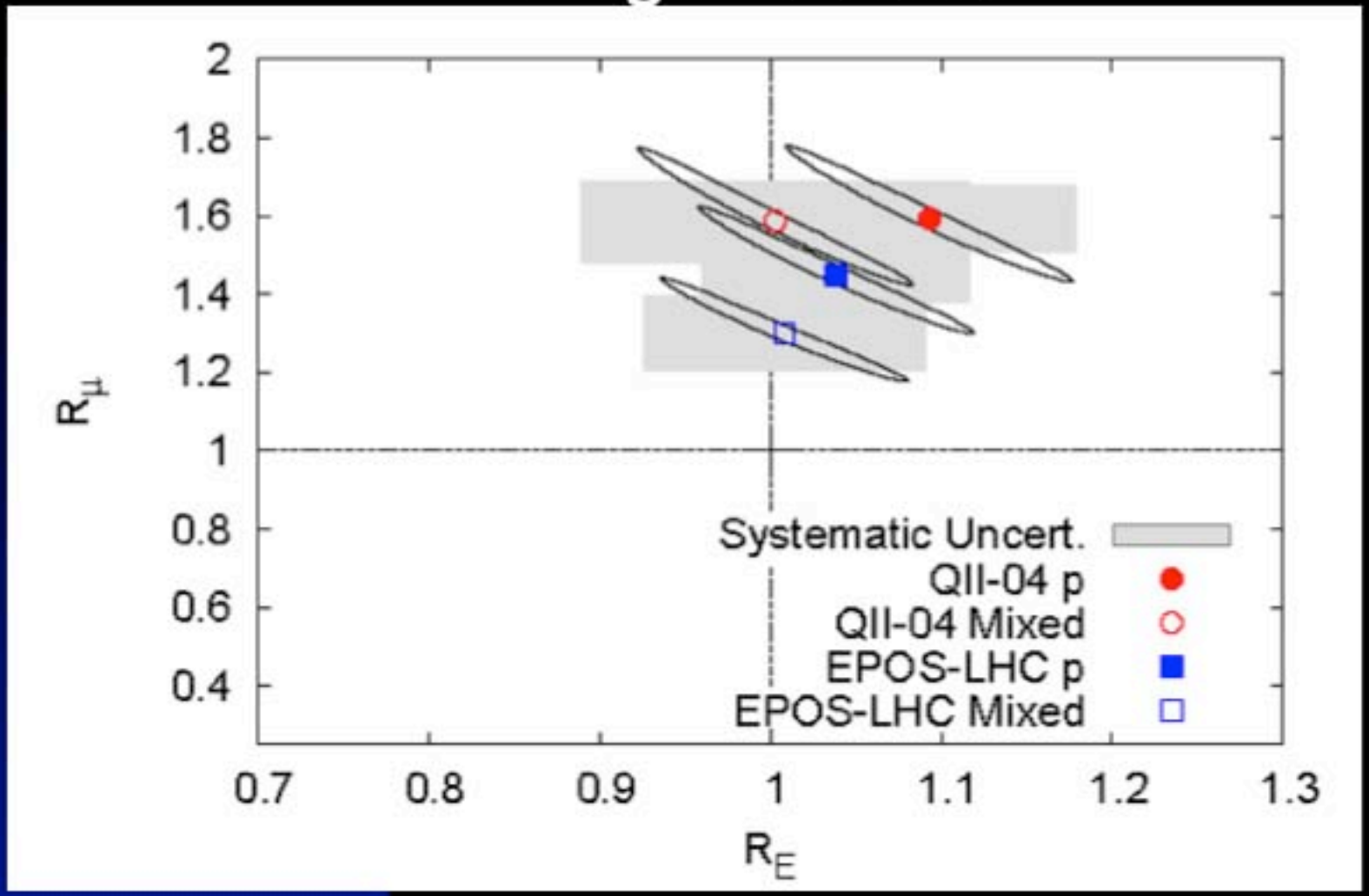

Auger 2013 preliminary
proton
iron
σ(X_max) [g/cm²]
E [eV]


SIBYLL 2.1
⟨lnA⟩
log10(E/eV)


EPOS-LHC
log (E/eV)

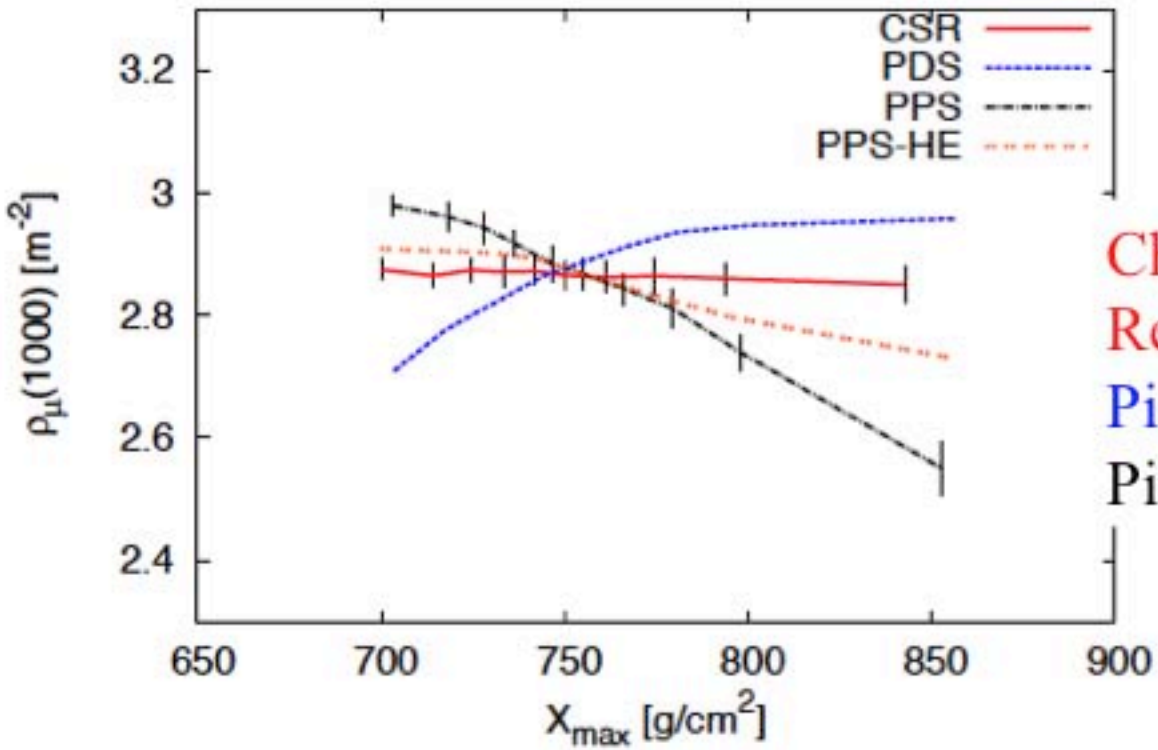

QGSJet II-04
⟨lnA⟩
log (E/eV)

Auger Muons



Observe "too many" muons, even for Mixed Composition!

Inhibit E transfer from hadronic into EM shower, by reducing the production or decay of π^0



Chiral Symmetry Restoration

Pion decay suppression

Pion production suppression

Farrar & Allen ICRC 2013
arXiv:1307.5059,

Property Increased	Change in N_μ	Change in X_{max}
Cross-section	–	Decreased
Elasticity	–	Increased
Multiplicity	Increased	Decreased
Primary Mass	Increased	Decreased
π^0 Eng. Frac.	Decreased	–

How can we tell New Physics from Astrophysics?

Muon Numbers & X_{max}

How can we tell New Physics from Astrophysics?

Muon Numbers & X_{max}

correlation bet. ground signal & X_{max} for individual hybrid events can discriminate between models

How can we tell New Physics from Astrophysics?

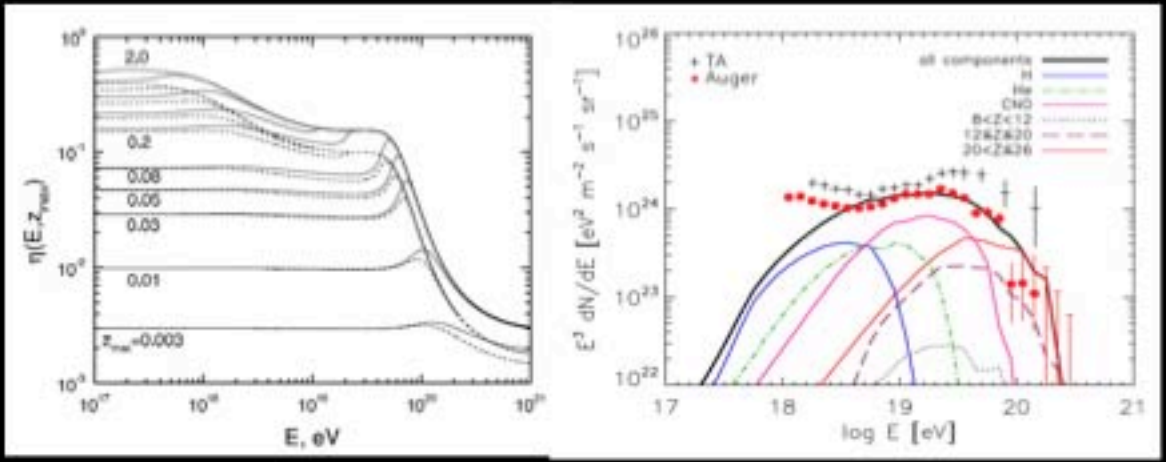
Muon Numbers & X_{max}

correlation bet. ground signal & X_{max} for individual hybrid events can discriminate between models

Auger Upgrade proposal

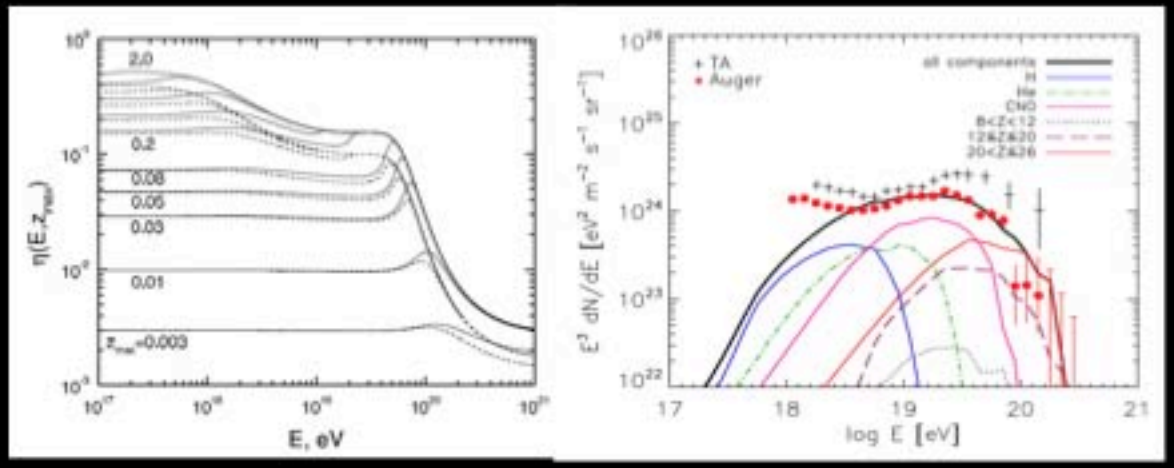
How can we tell New Physics from Astrophysics?

Look for Spectral Recovery – indicate PROTONS



How can we tell New Physics from Astrophysics?

Look for Spectral Recovery – indicate PROTONS



FIND THE SOURCES!!!

How can we tell New Physics from Astrophysics?

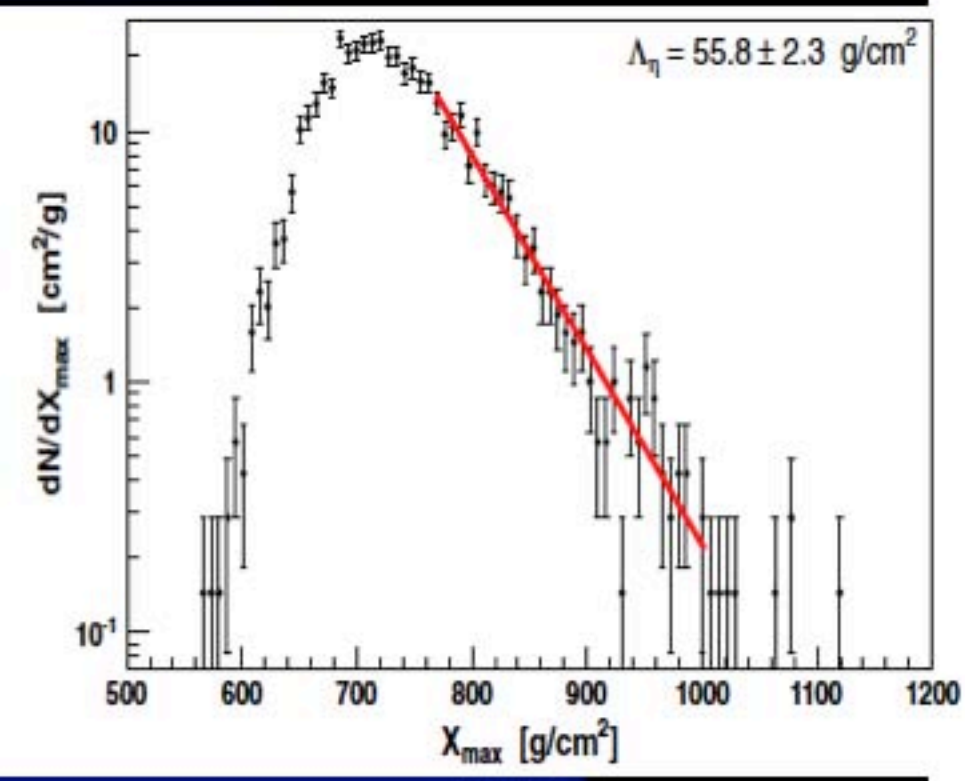
Look for Spectral Recovery –
indicate PROTONS
Increase Statistics by 1 o.o.m. at Highest Energies

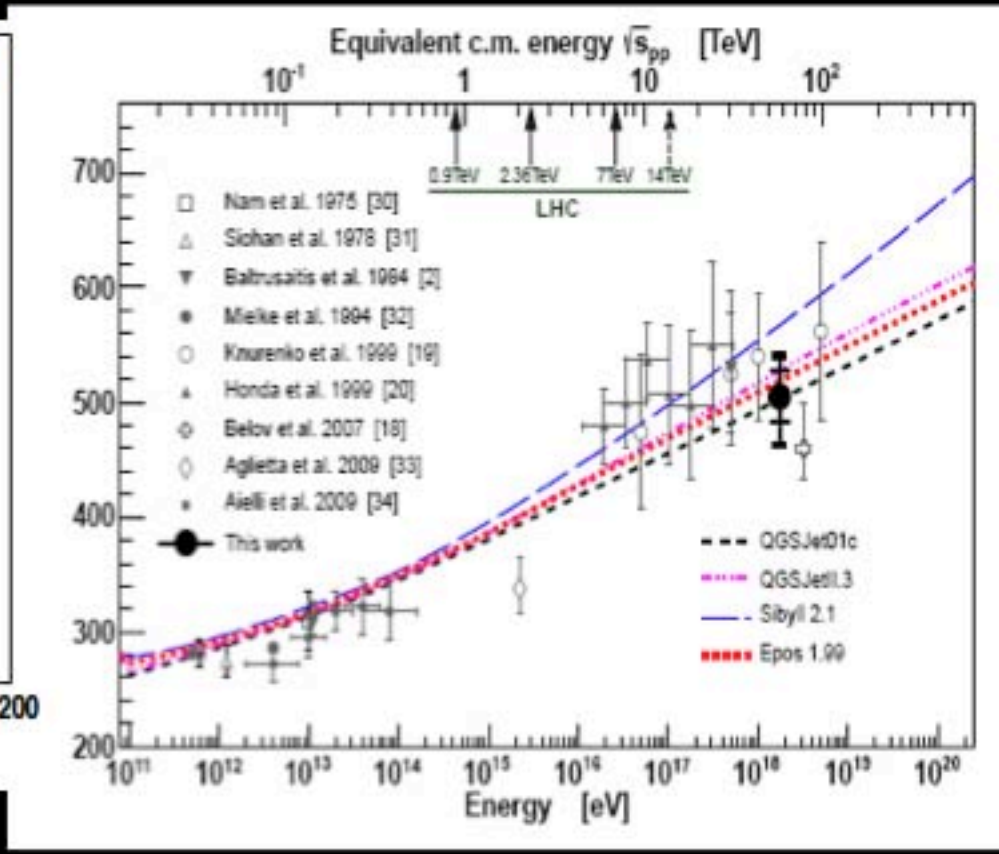
GO TO SPACE!! JEM-EUSO

FIND THE SOURCES!!!
Increase Statistics by 1 o.o.m. at Highest Energies

GO TO SPACE!! JEM-EUSO

p-Air Cross Section at sqrt(s)=57 TeV





Low energy extensions (e.g. TALE) can cross-calibrate with LHC

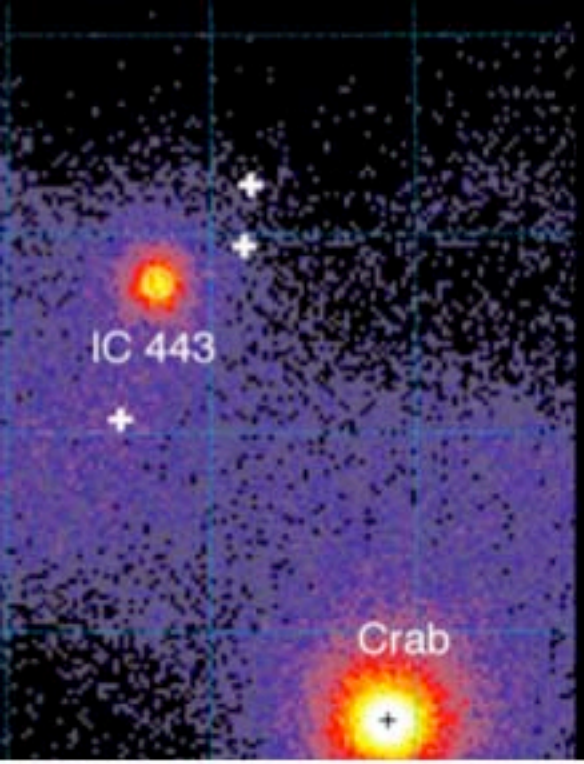
How are UHECRs generated?

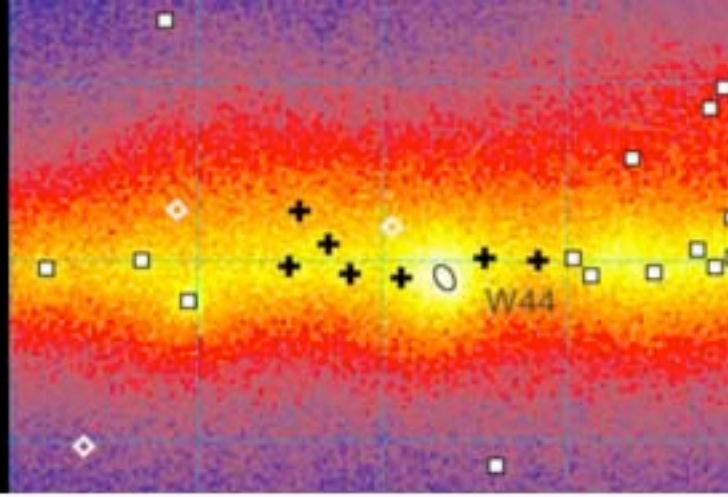
LE: shock acceleration in SNRs!

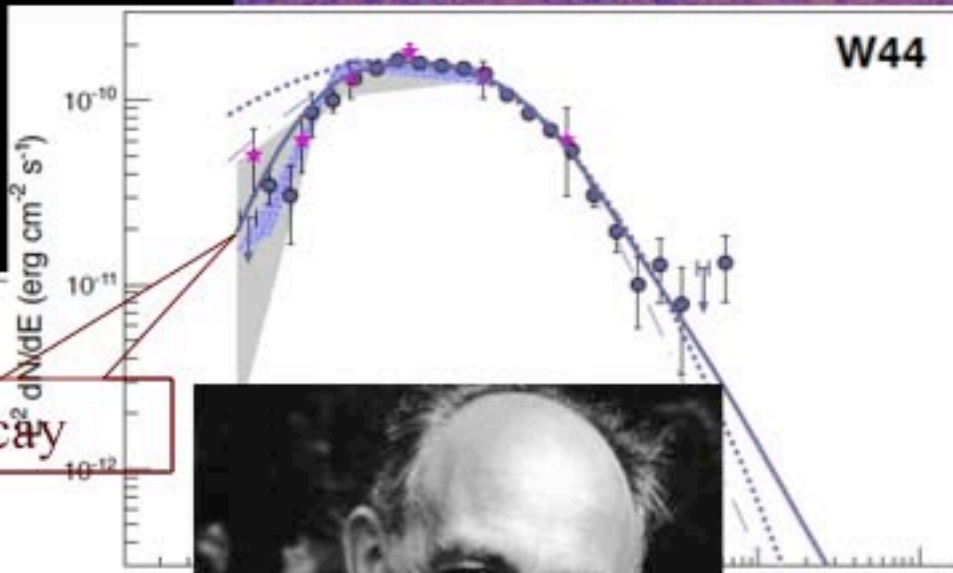
π^0 decay!

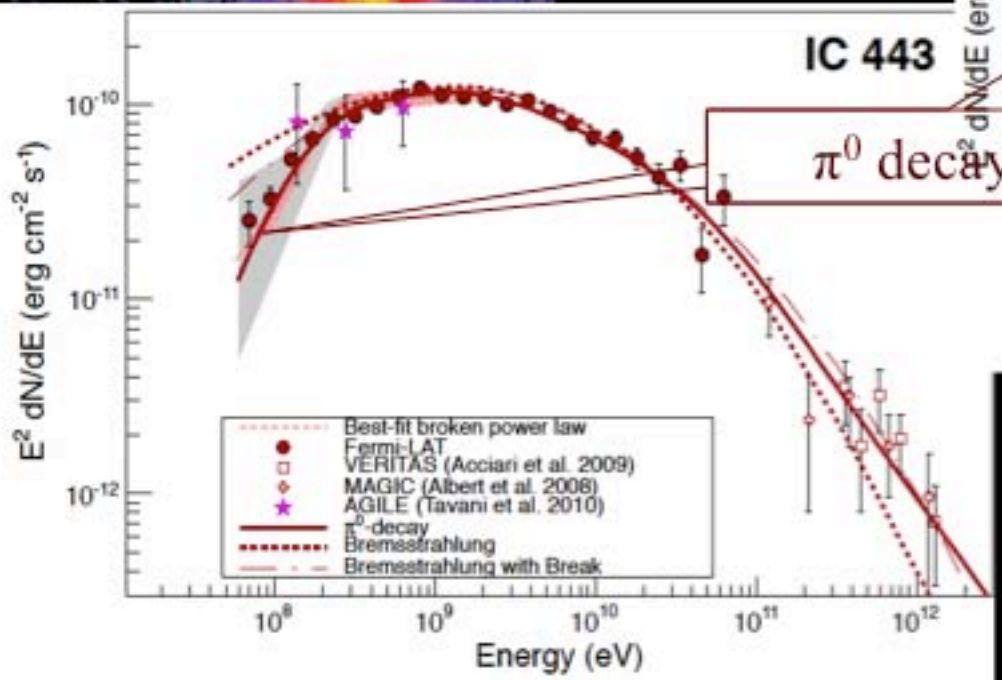
IC 443 & W44

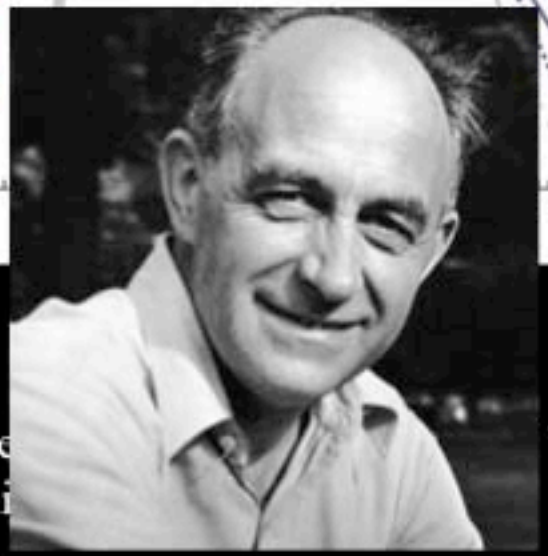
Fermi & AGILE









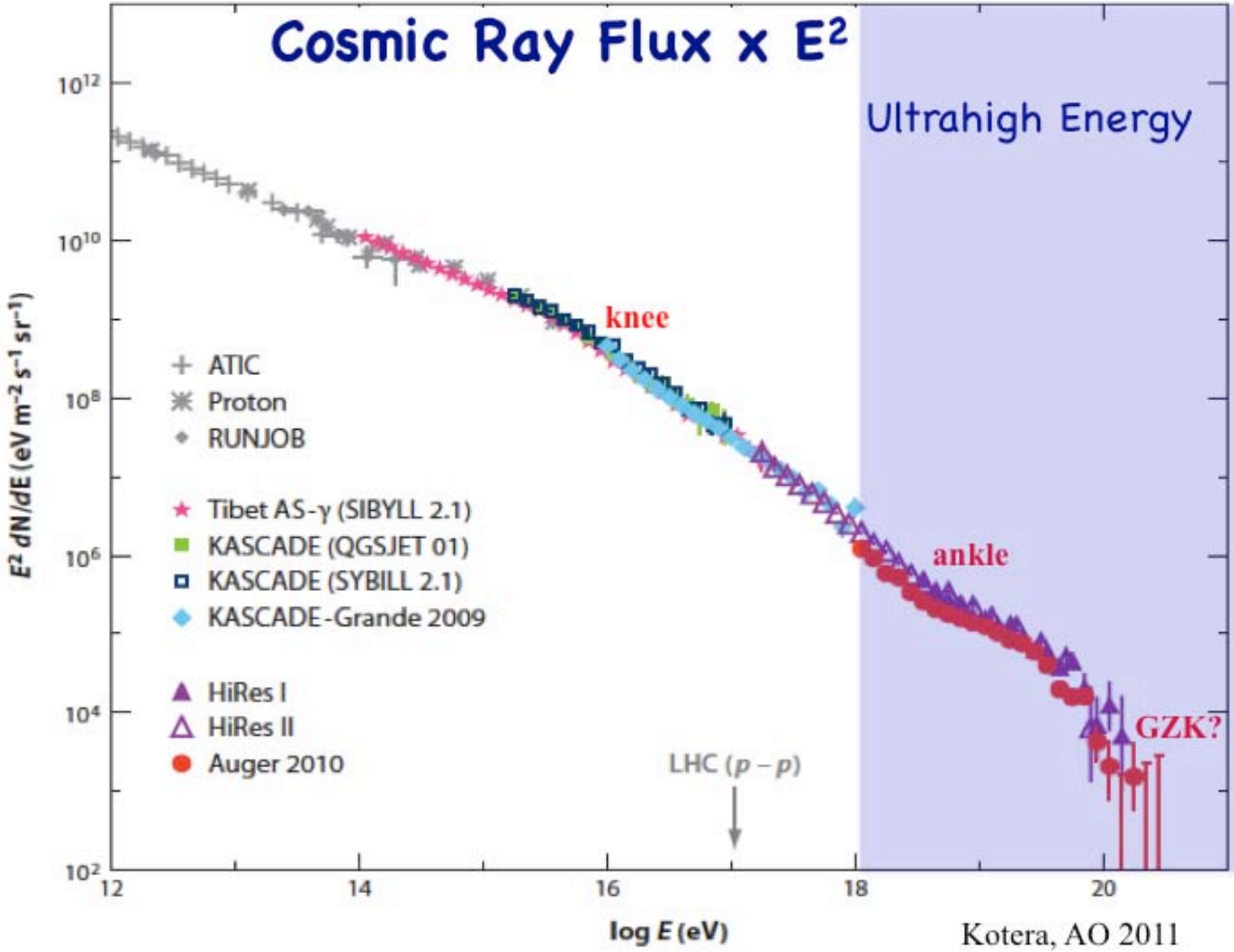


Acke
arXi
'13

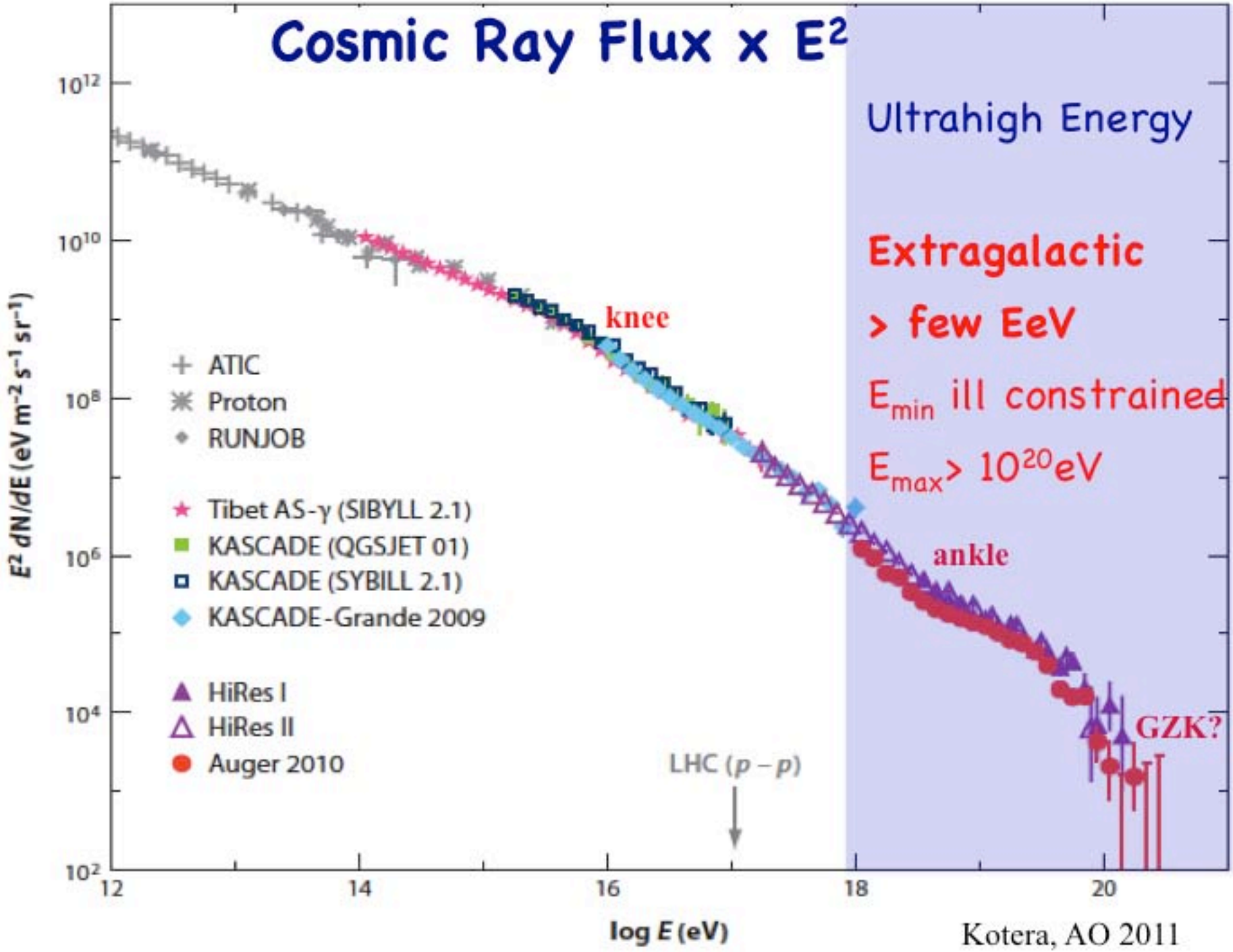
How are UHECRs generated?

LE: shock acceleration in SNRs!

UHEs: unknown extragalactic powerful sources



Kotera, AO 2011

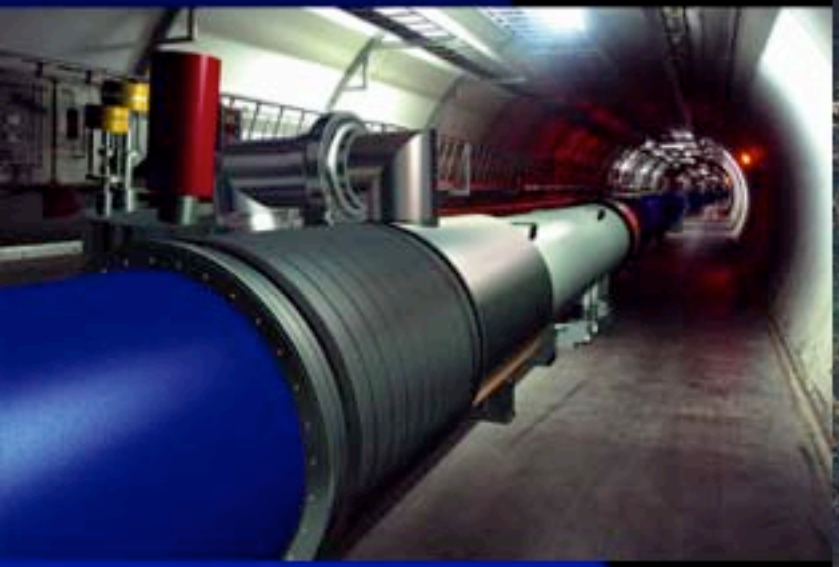


Kotera, AO 2011

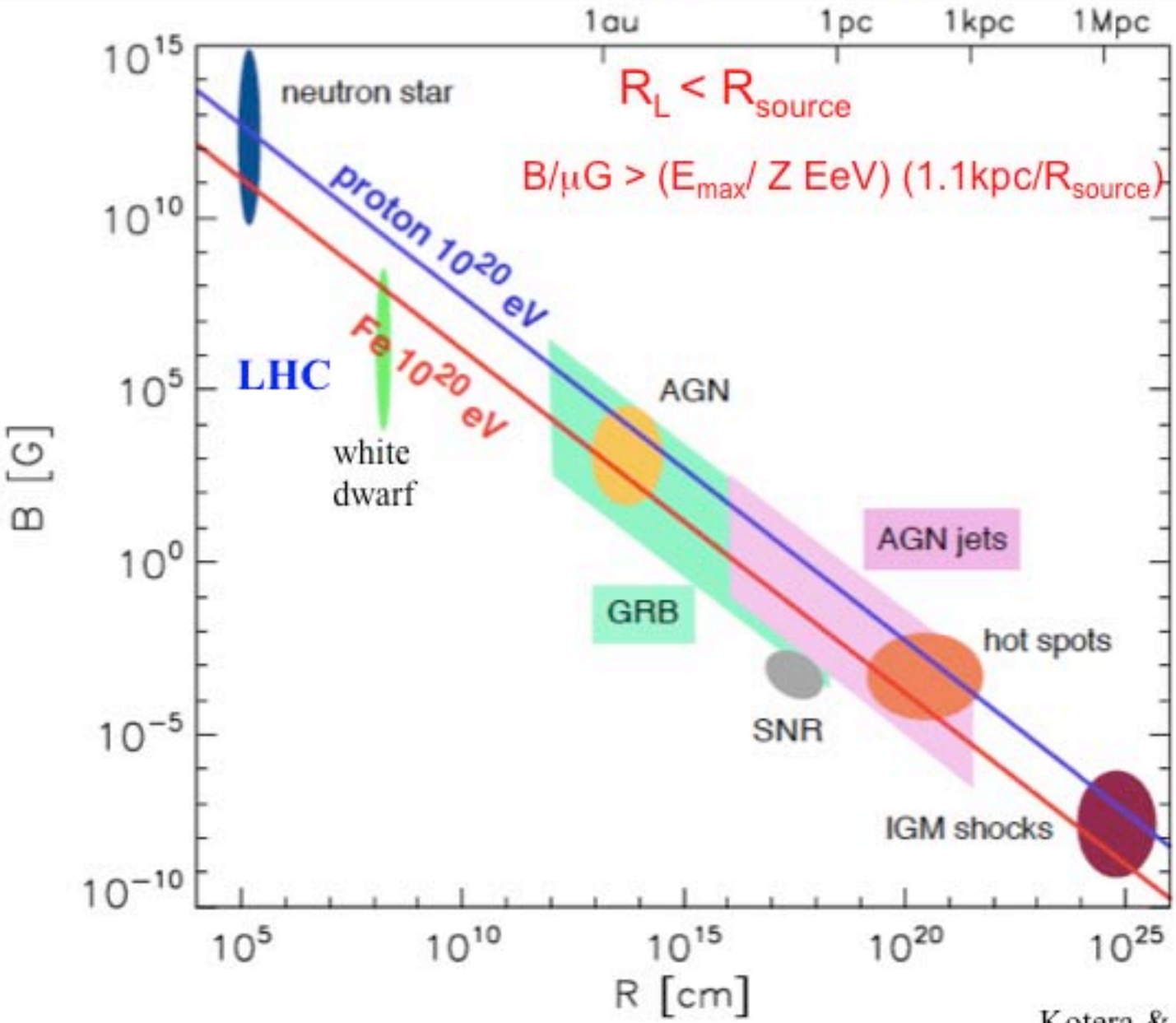
Challenging Accelerators

to reach 10^{20} eV

LHC magnetic field,
radius ~ 10^7 km (Sun - Mercury)
or 10 GT fields!

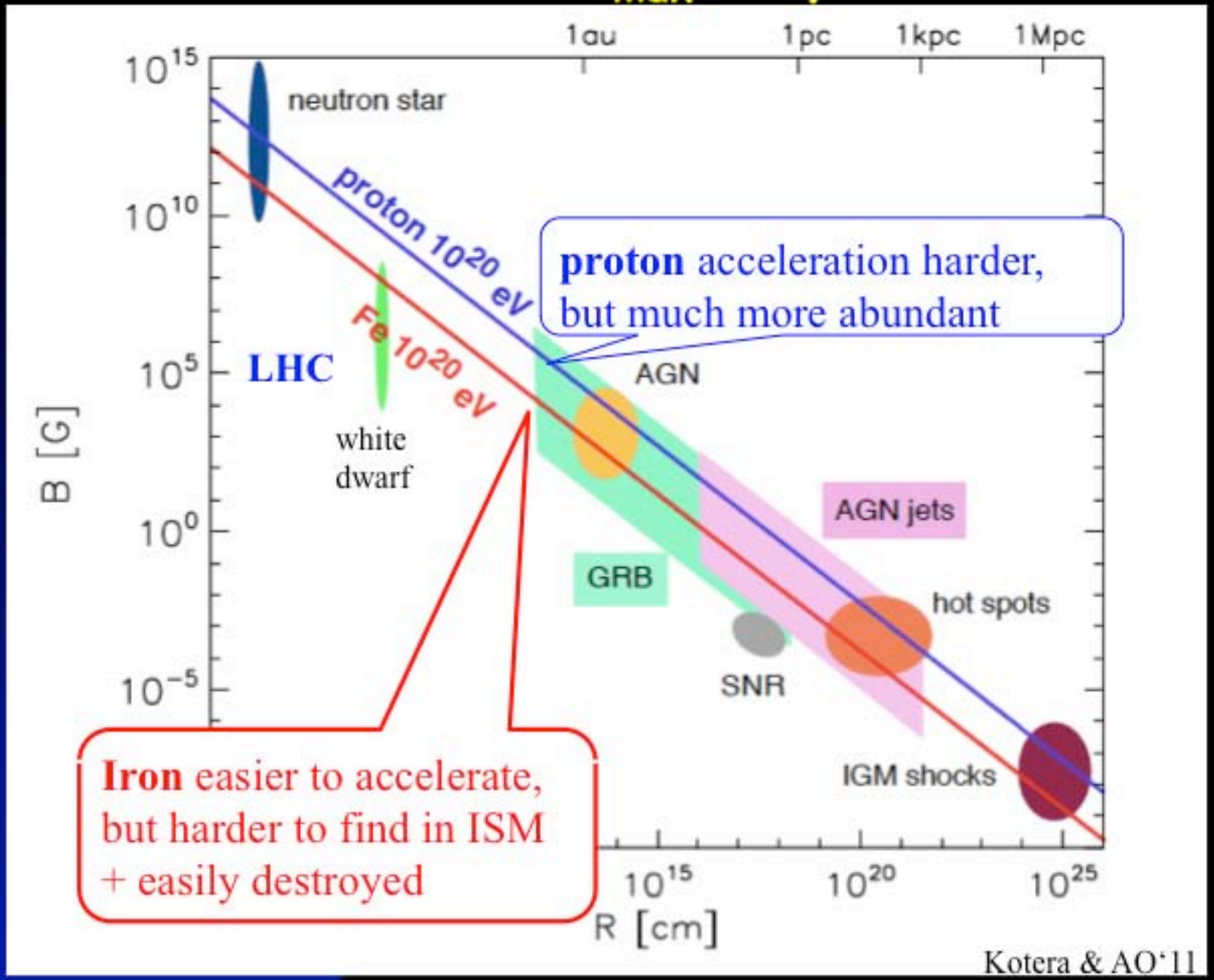


Hillas Plot: E_{max} required



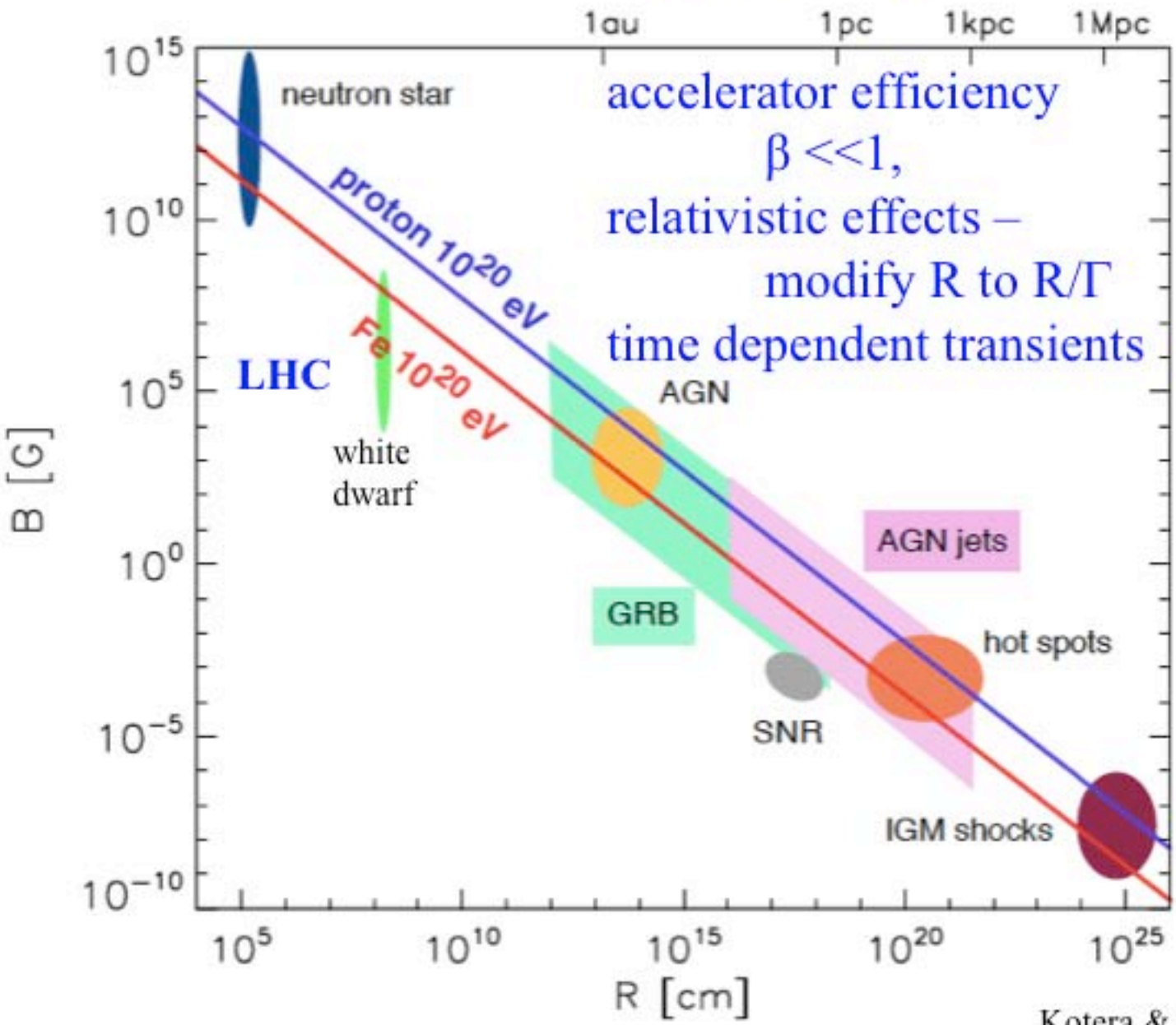
Kotera & AO'11

Hillas Plot: E_{max} required



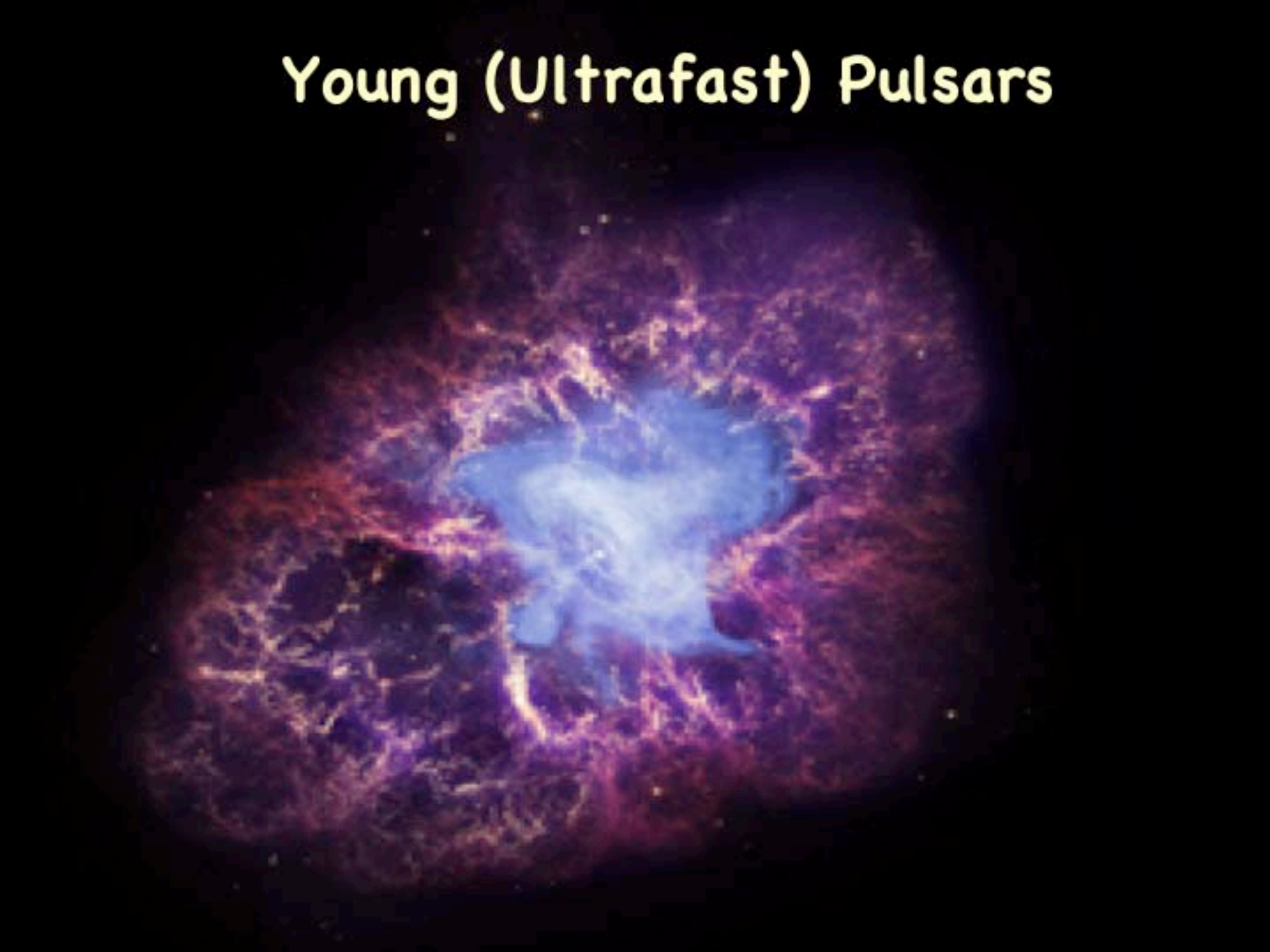
Kotera & AO'11

Hillas Plot: E_{max} required

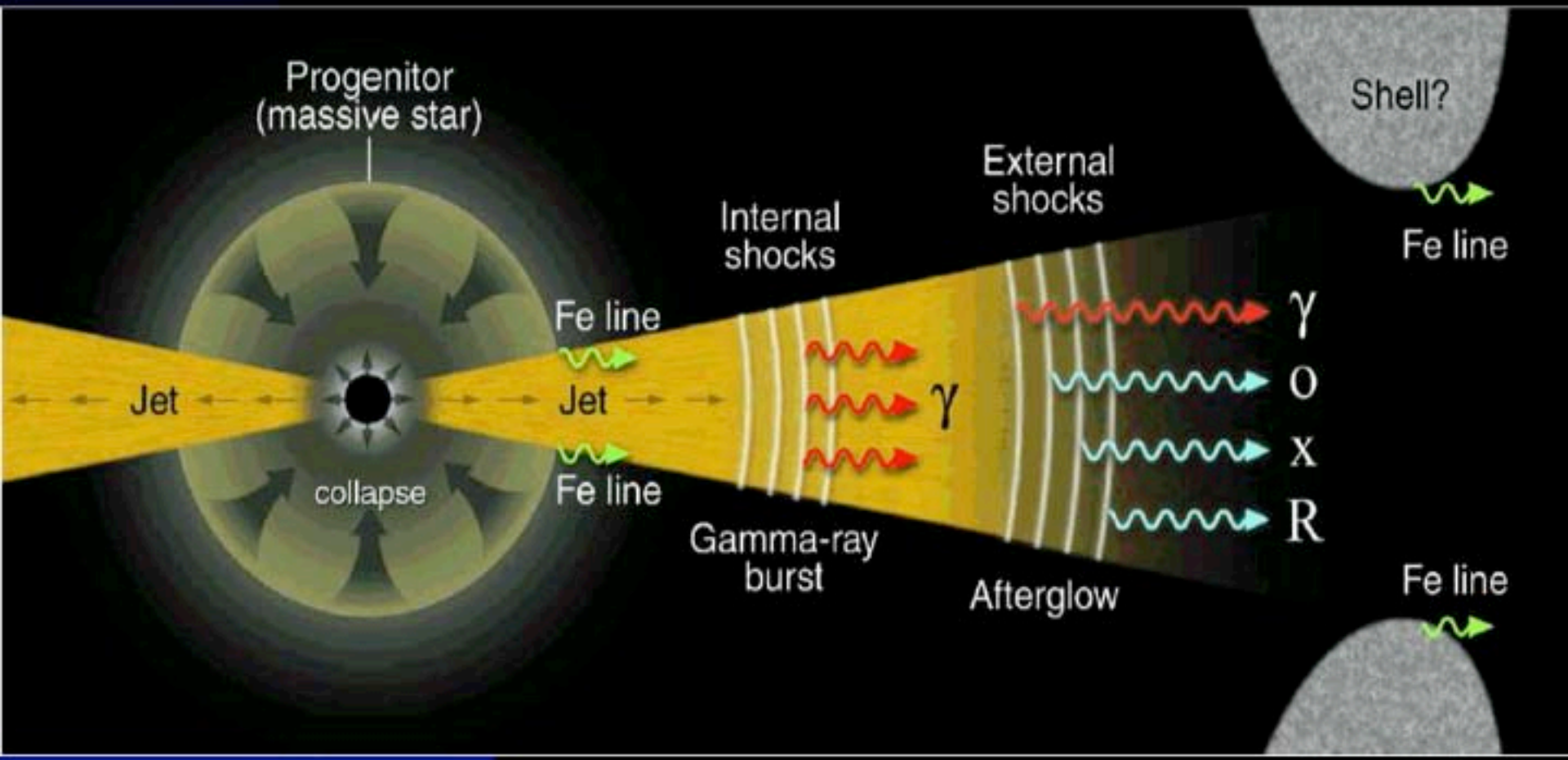


Kotera & AO'11

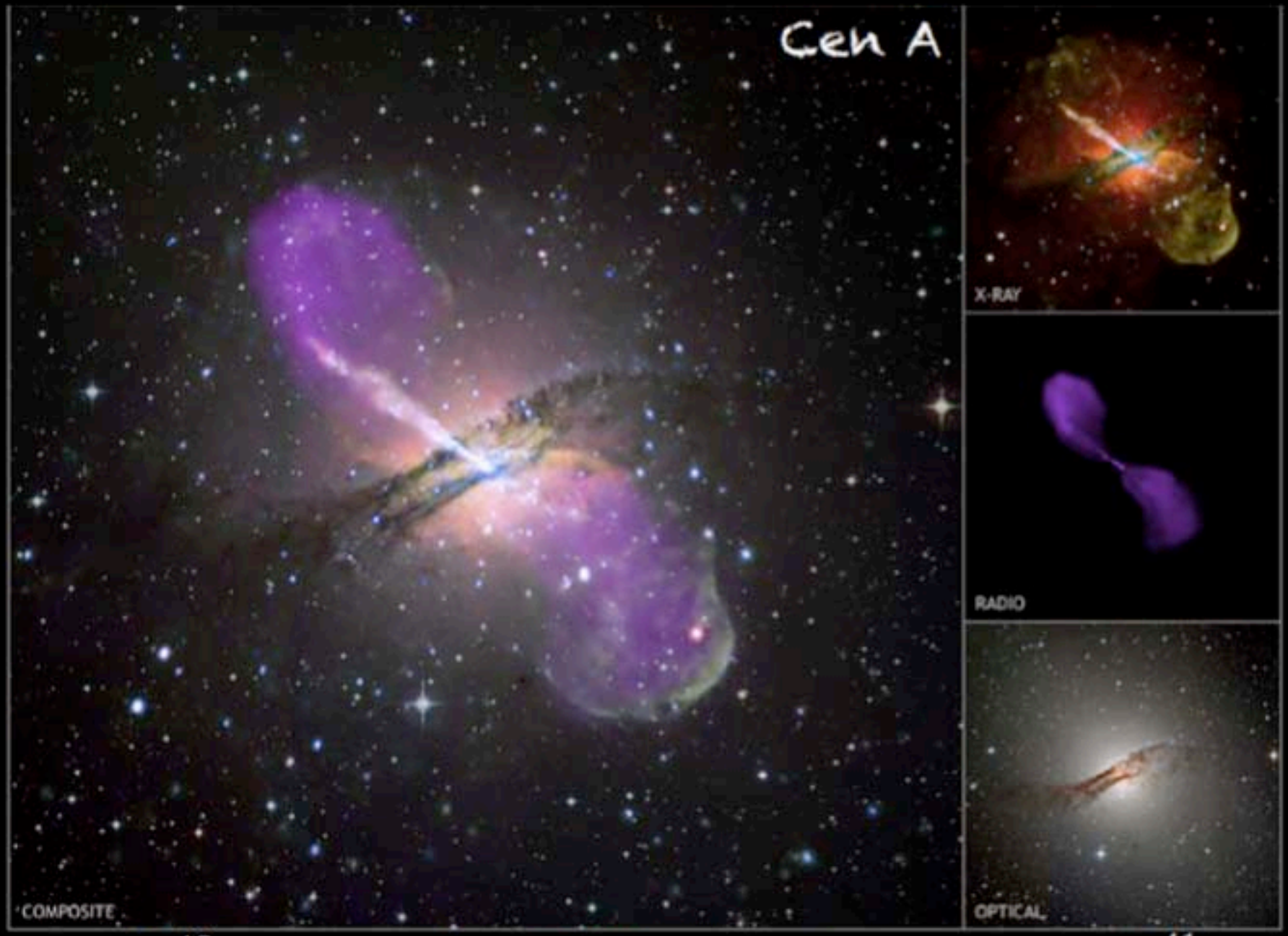
Young (Ultrafast) Pulsars



Gamma-ray Bursts

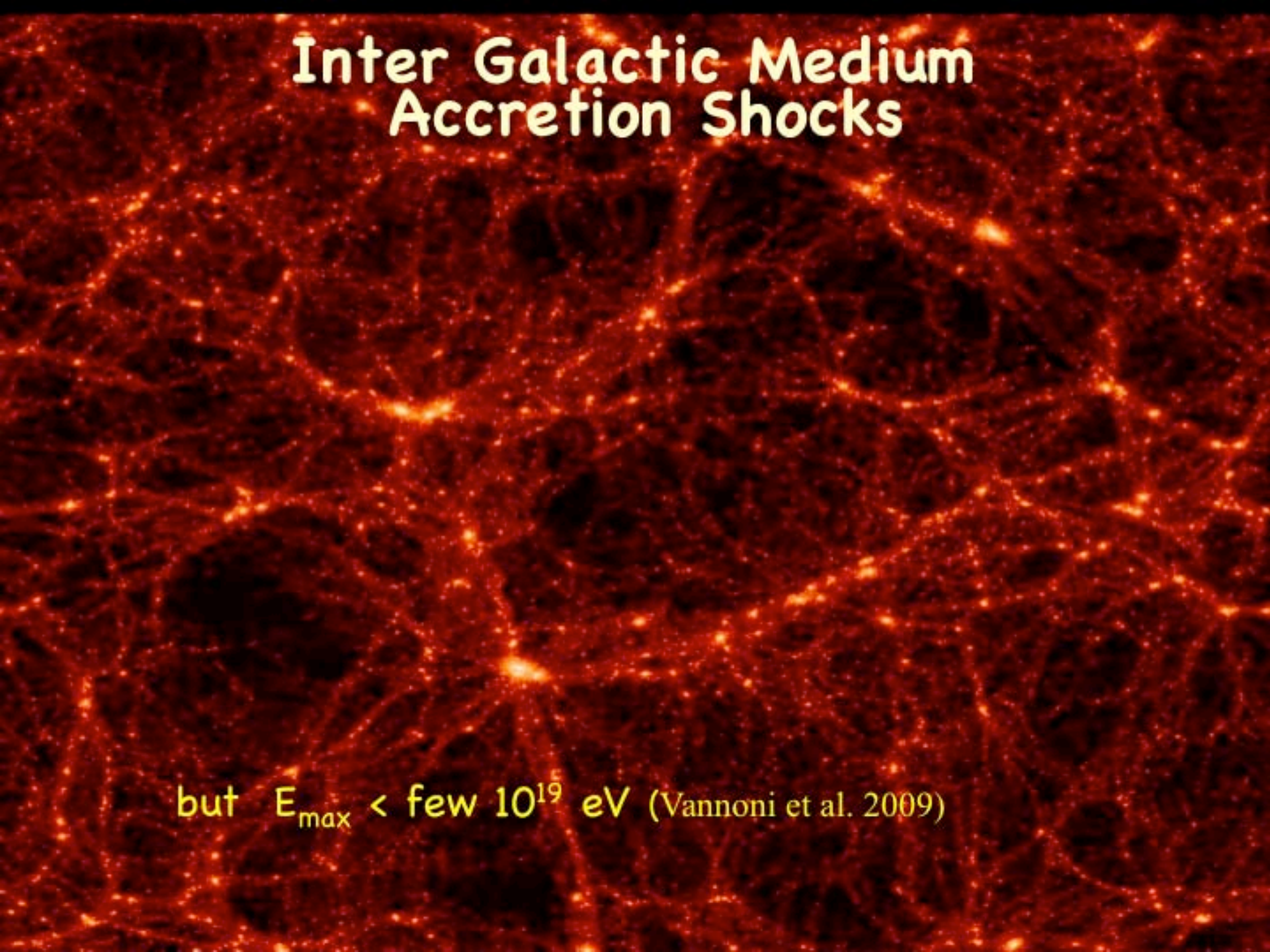


Meszaros '01



$L_{\rm bol} = 10^{43}$ erg/s $\quad d = 3.4\,{\rm Mpc}$ $\quad L_{\gamma>100{\rm MeV}} \approx 10^{41}$ erg/s

Inter Galactic Medium Accretion Shocks

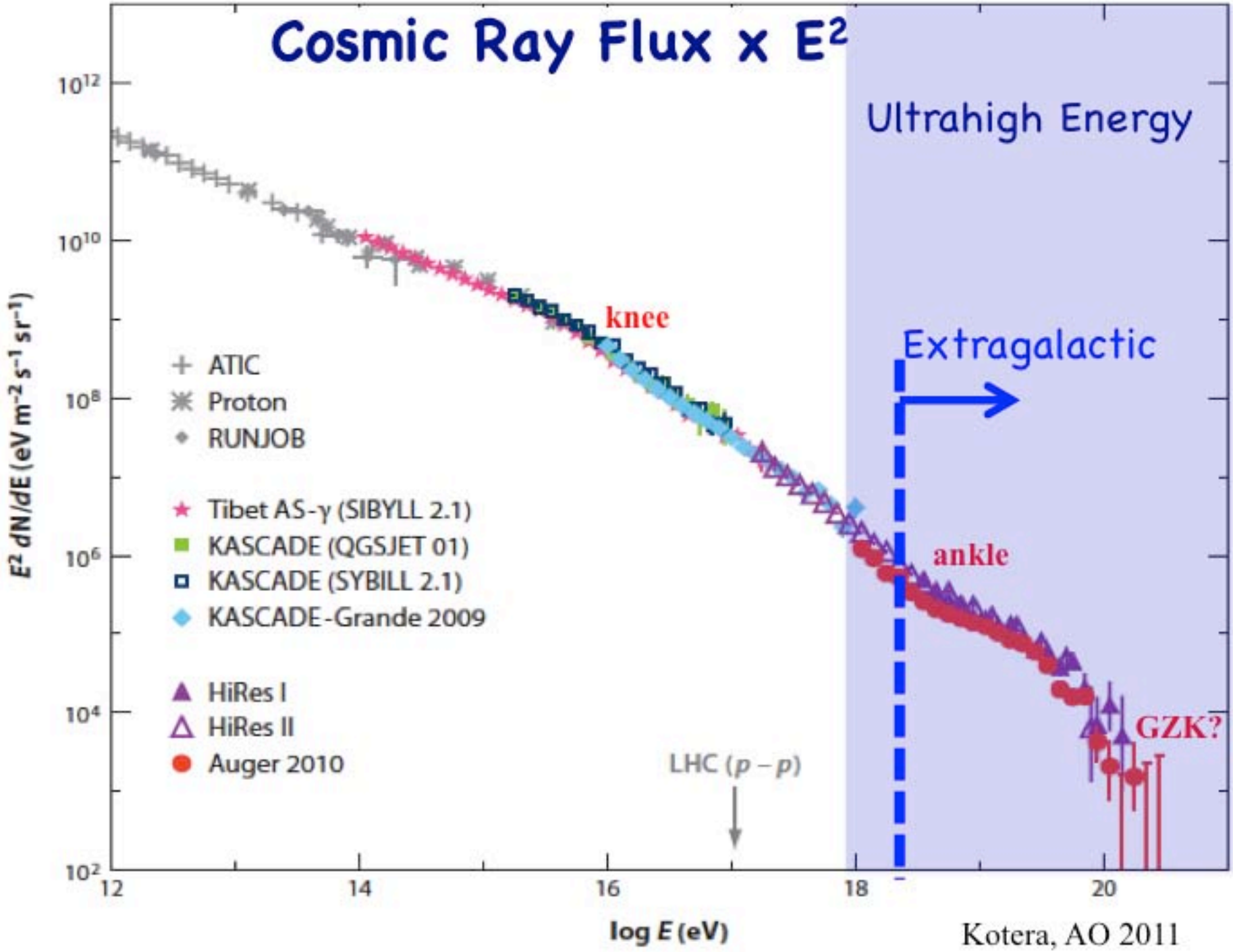


but E_{max} < few 10^{19} eV (Vannoni et al. 2009)

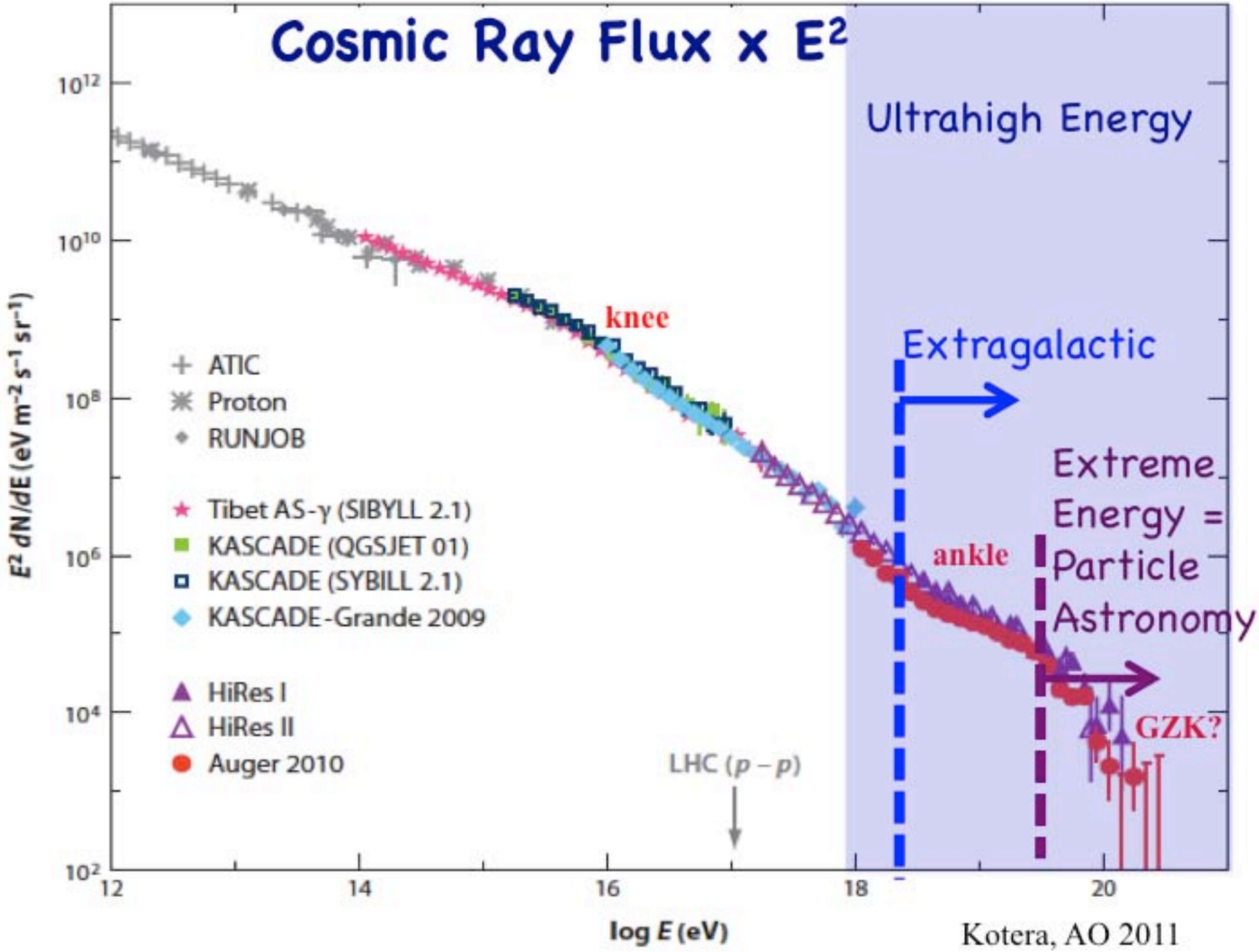
Where are they coming from?

Where are they coming from?

Don't know!



Kotera, AO 2011

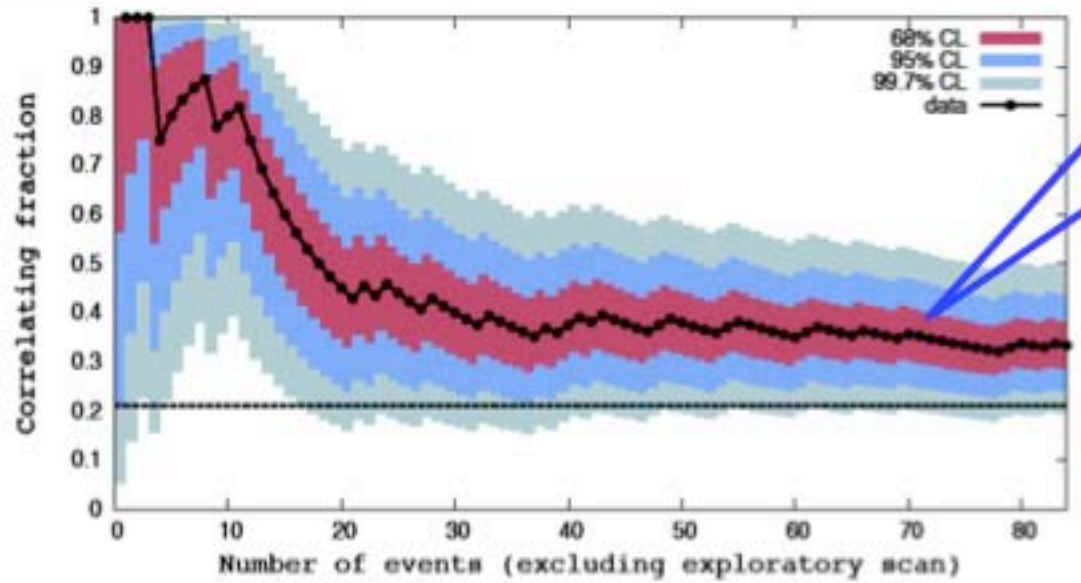


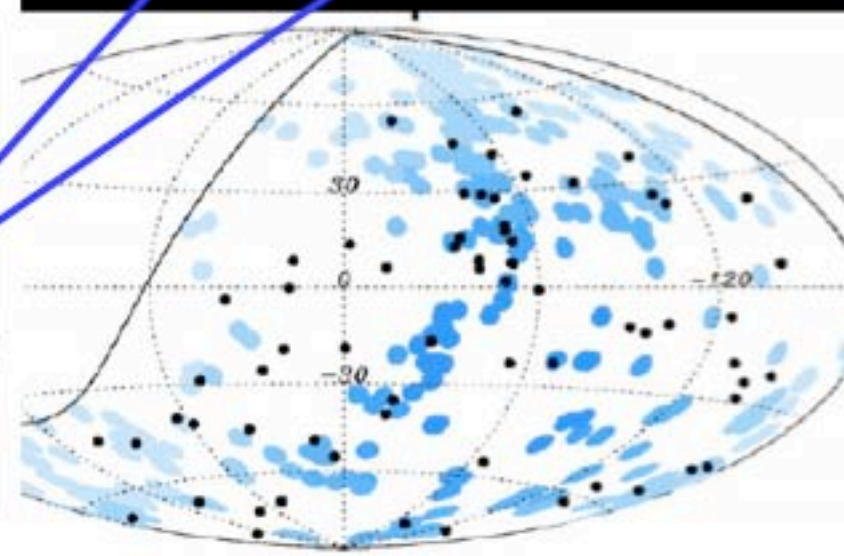
Kotera, AO 2011

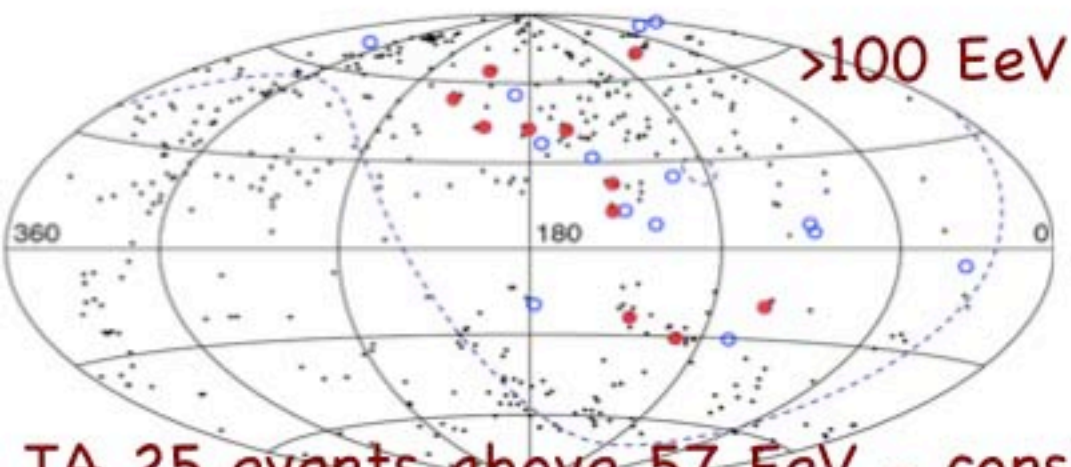
EECR Anisotropy Hints

E > 60 EeV

Mild anisotropy - still dominated by isotropic background at 55 EeV

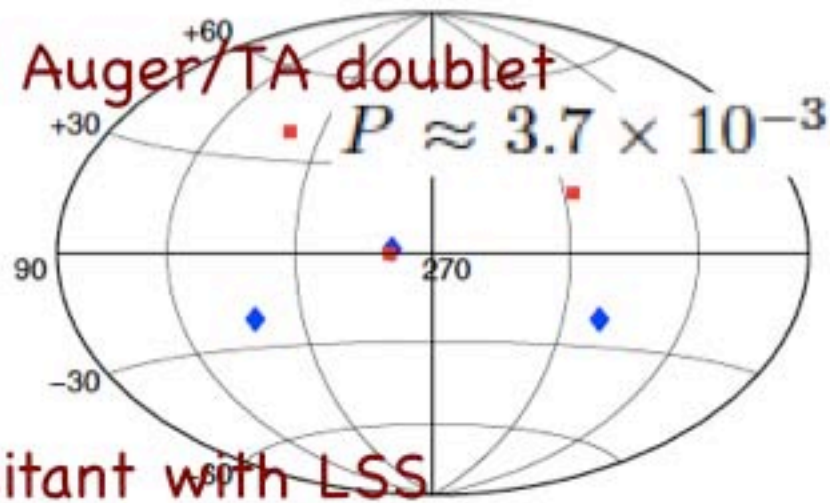






>100 EeV Auger/TA doublet

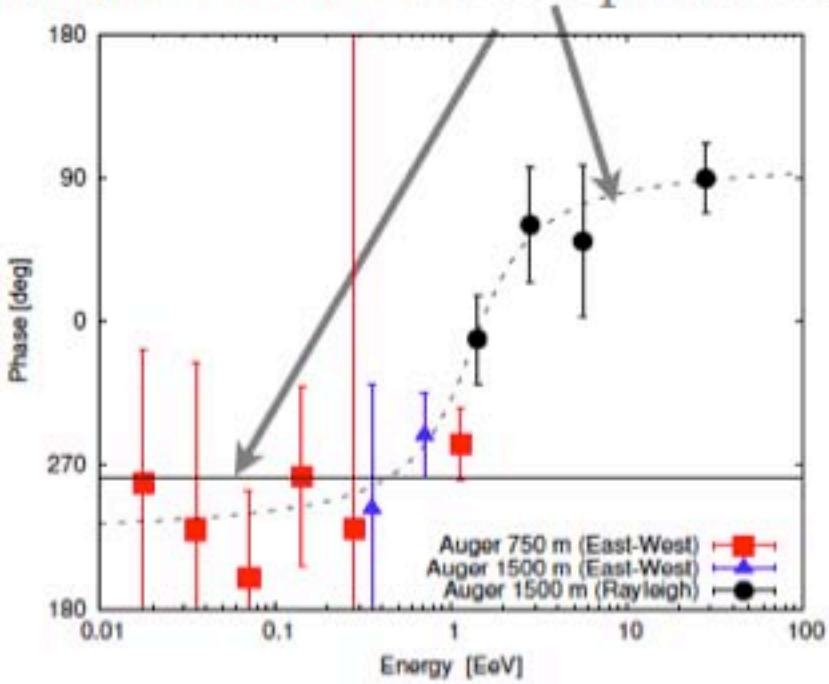
$P \approx 3.7 \times 10^{-3}$



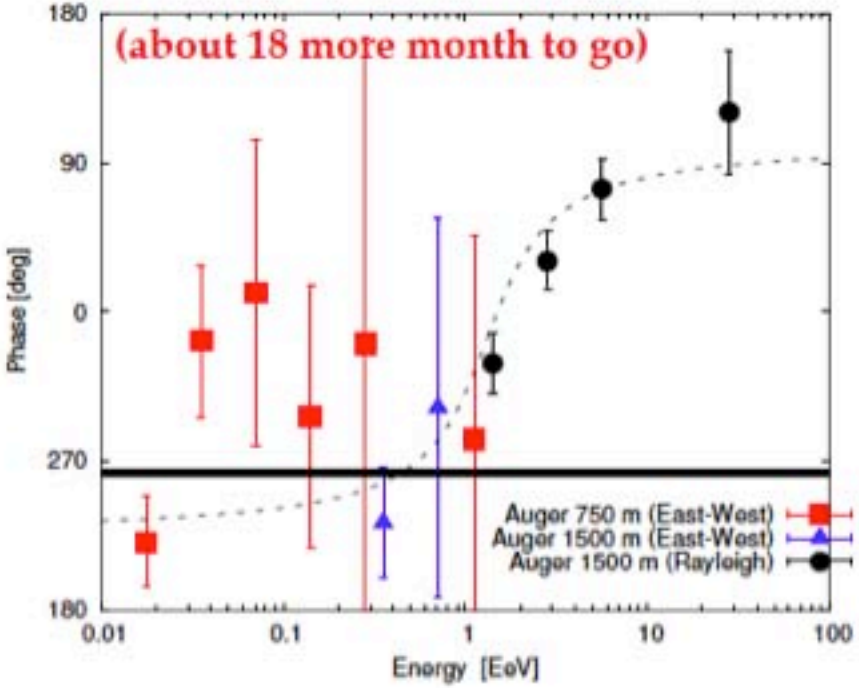
TA 25 events above 57 EeV - consitant with LSS

Auger – First Harmonic Analysis

Data up to December 2010
(April 2011) Prescription set

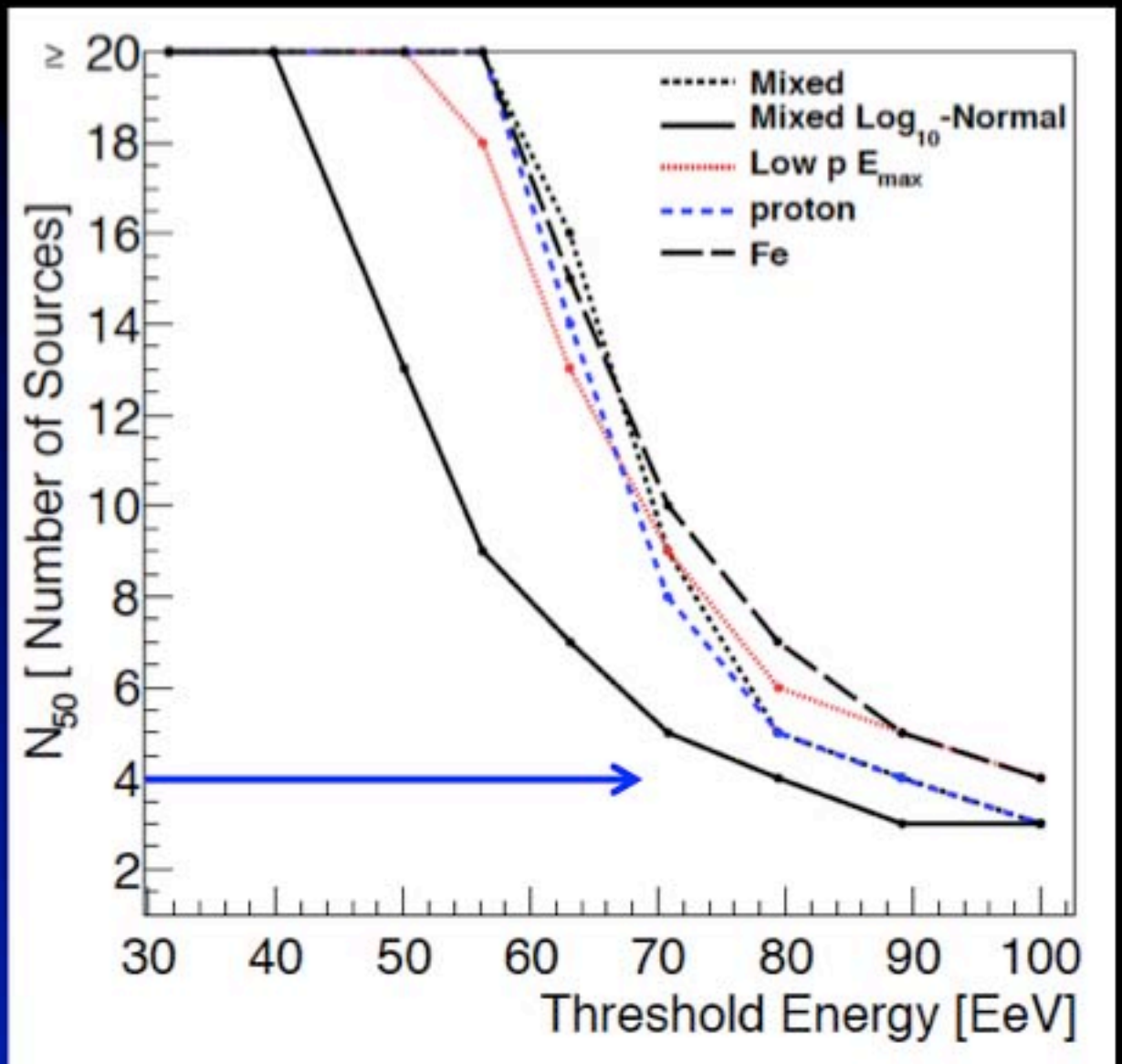


New data Prescription status



To detect sources

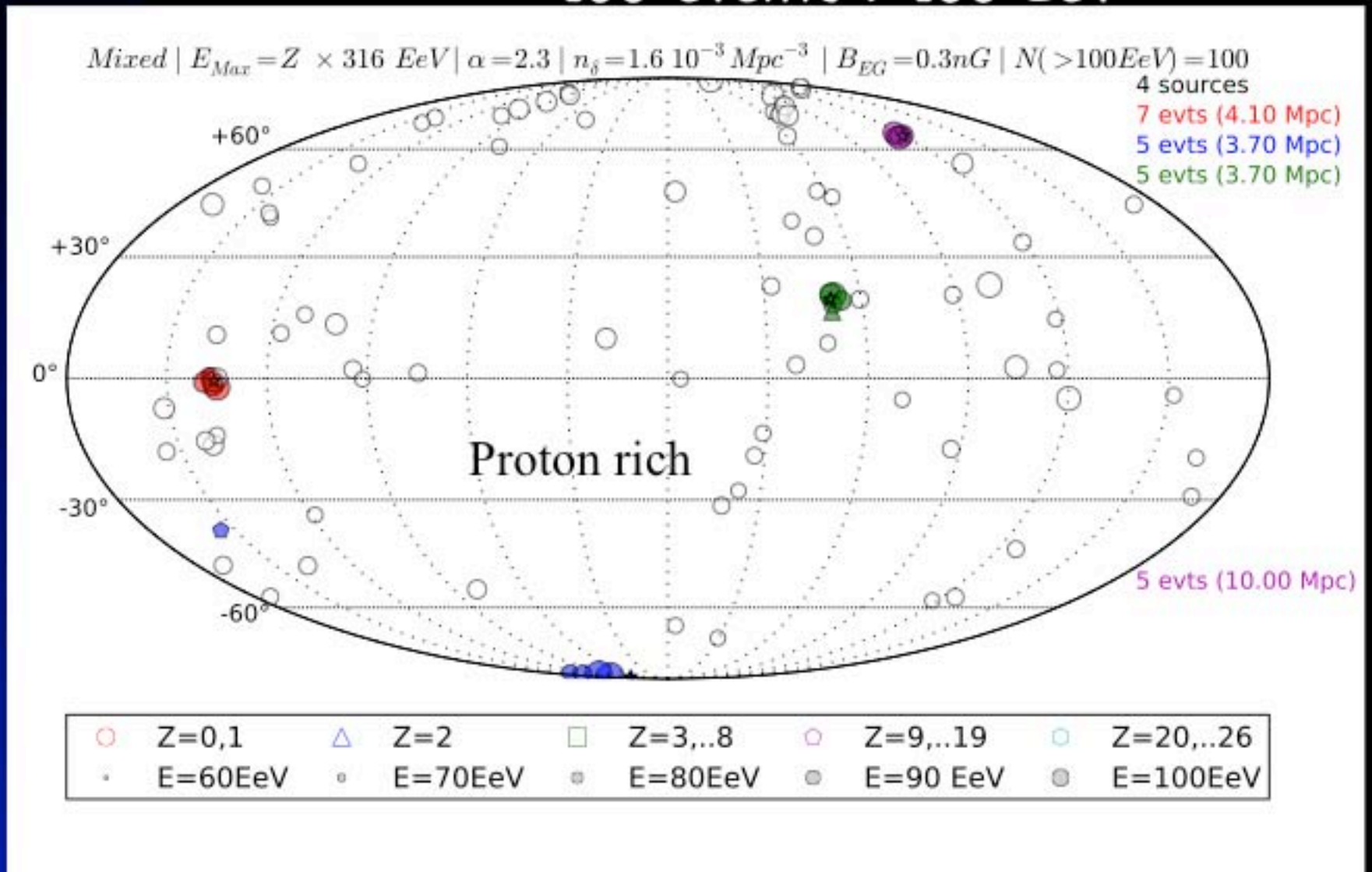
Observe at higher energies – fewer sources



To detect sources

Increase statistics: ~1000 events > 60 EeV

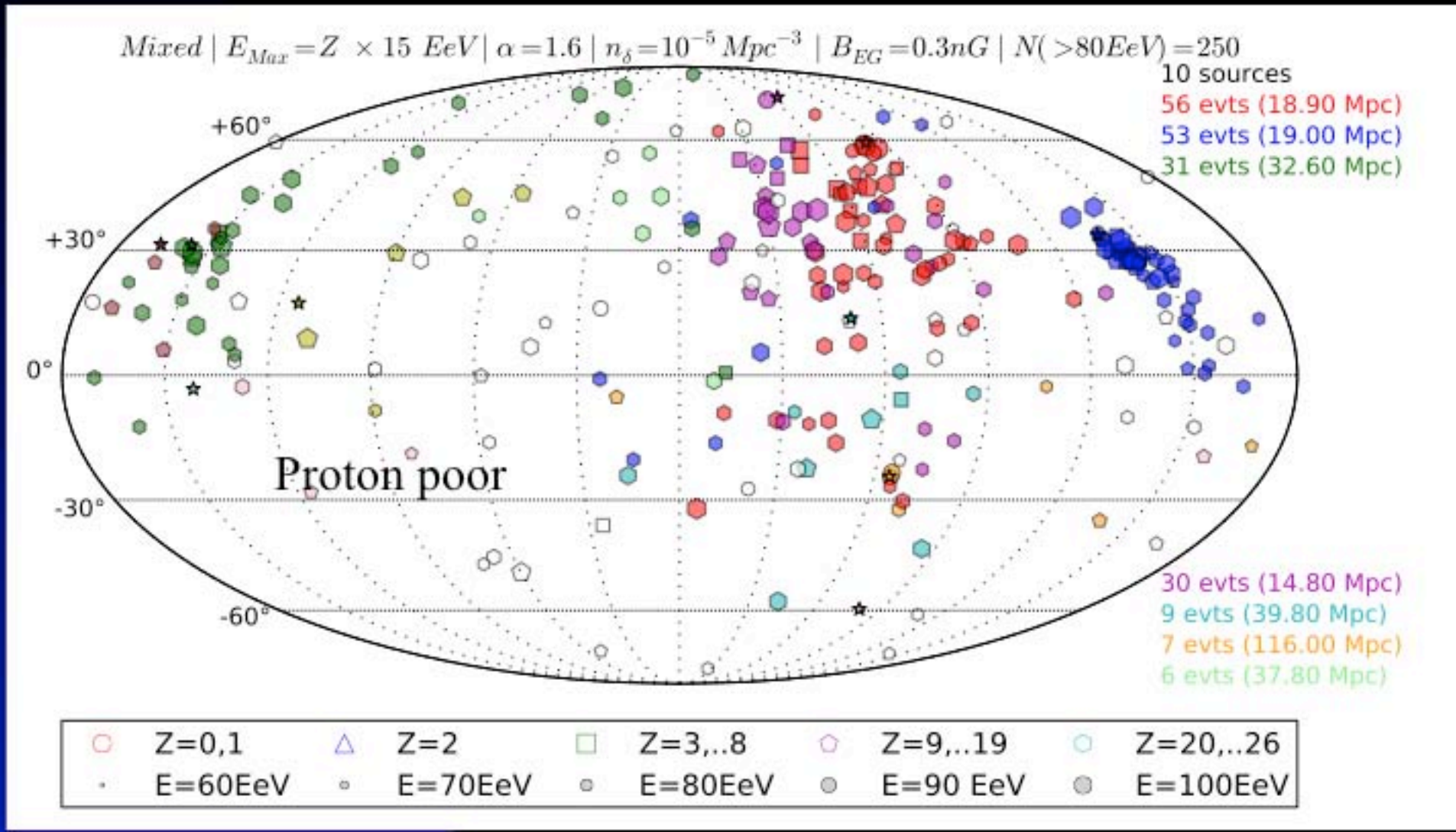
~100 events > 100 EeV



To detect sources

Increase statistics: ~1,000 events > 60 EeV

~100 events > 100 EeV



How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 60 EeV/ yr

Telescope Array w/ 700 km^2

~5 events > 60 EeV/ yr

Auger + TA ~ 25 events/yr > 60 EeV

40 years to reach 1,000!!!

How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 60 EeV/ yr

Telescope Array w/ 700 km^2

~5 events > 60 EeV/ yr

Auger + TA ~ 25 events/yr

40 years to reach 1,000

Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

How many EECRs > 60 EeV?

Auger w/ 3,000 km^2

~20 events > 60 EeV/ yr

Telescope Array w/ 700 km^2

~5 events > 40 EeV/ yr

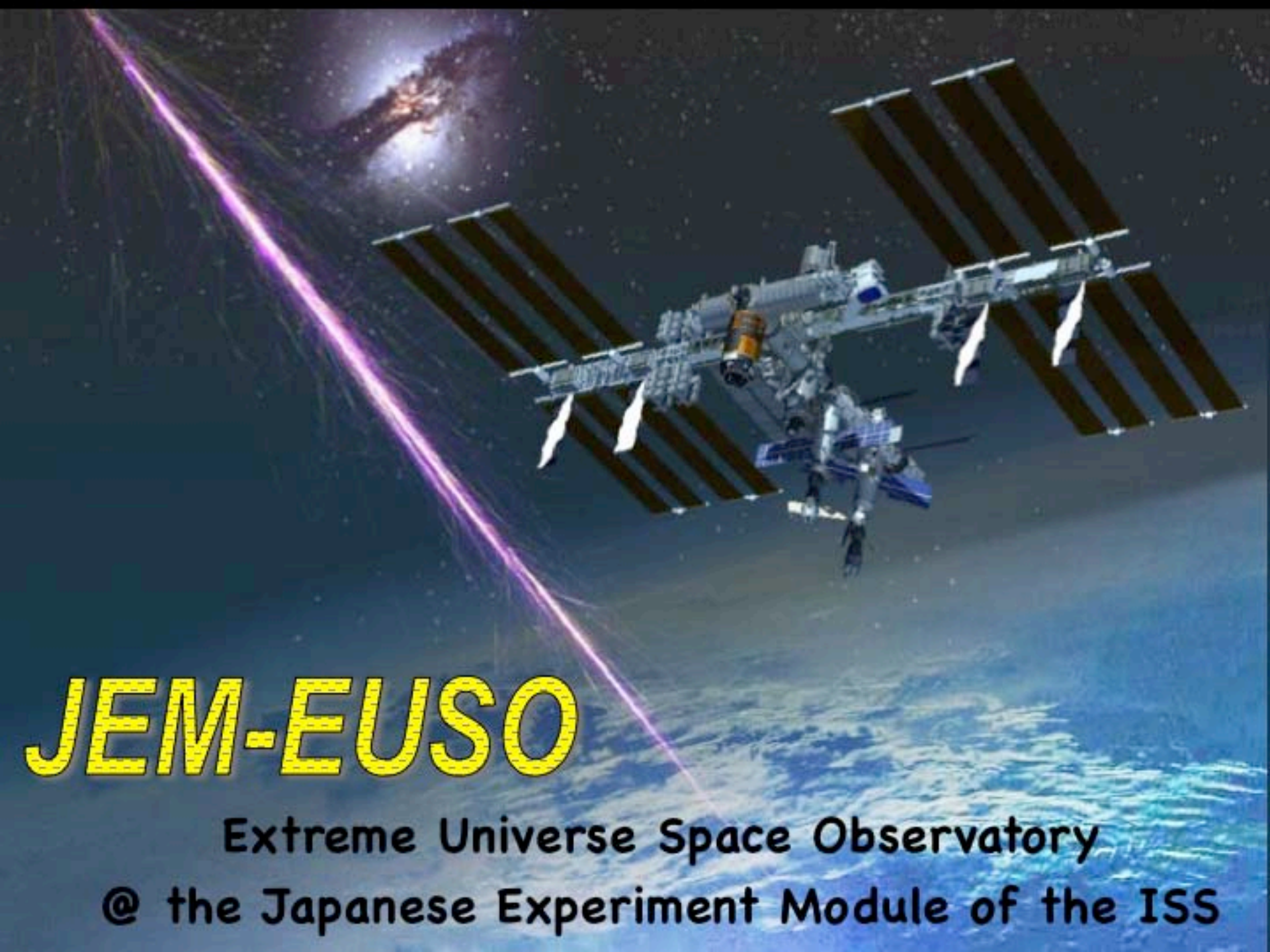
Auger + TA ~ 25 events/ yr

40 years to reach 1,000

5 o.o.m to go!

Earth surface ~ 5 10^8 km^2

~3.4 10^6 events/yr


JEM-EUSO
Extreme Universe Space Observatory
@ the Japanese Experiment Module of the ISS

How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

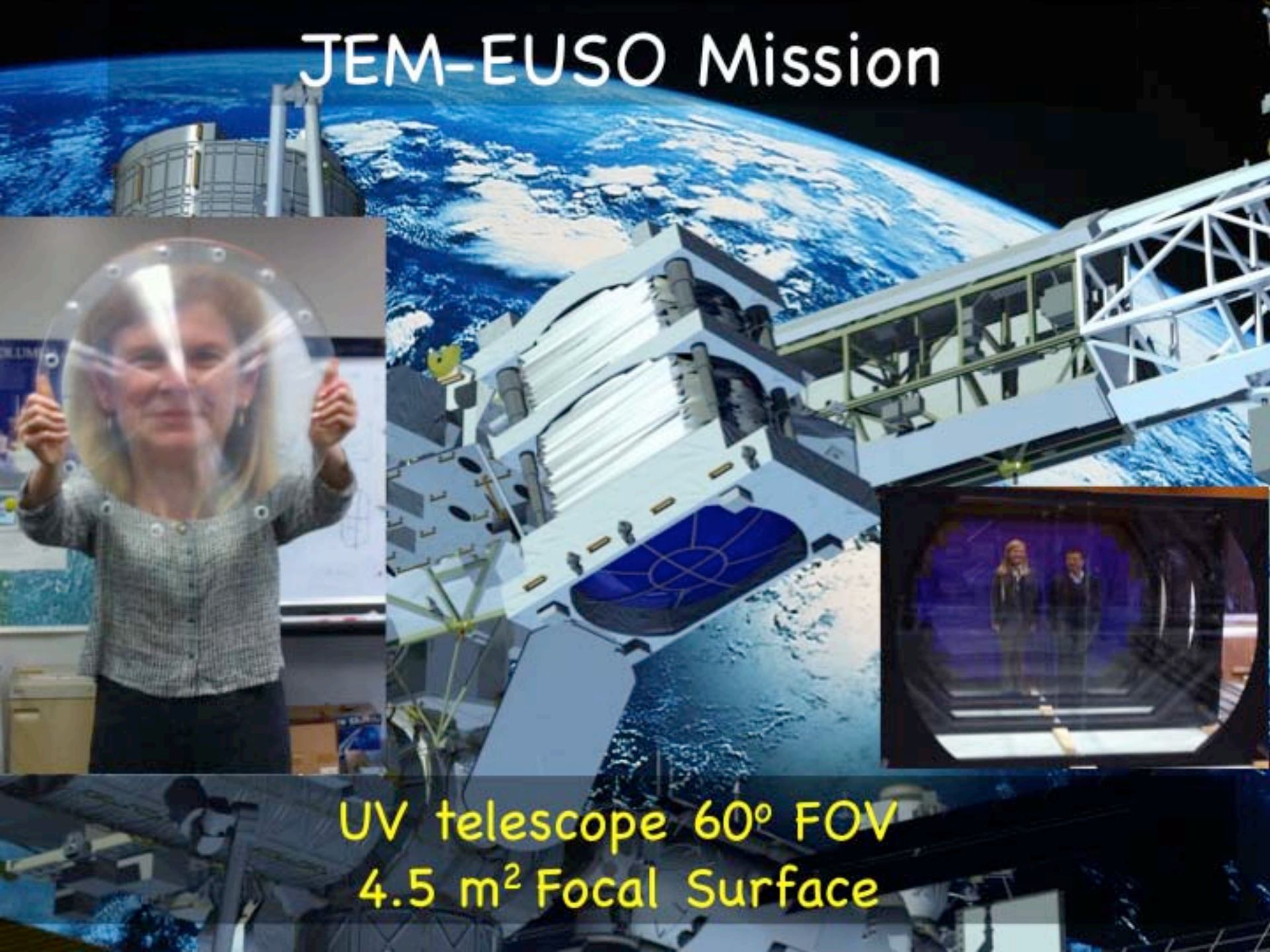
JEM-EUSO

~200 events > 60 EeV/ yr

Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

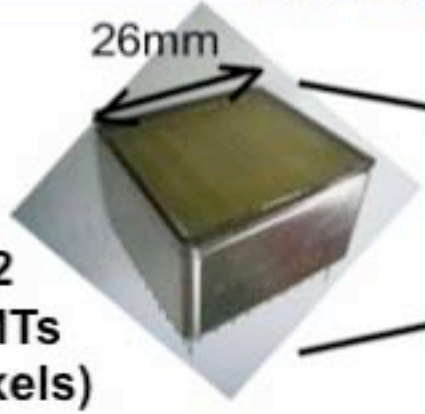
JEM-EUSO Mission



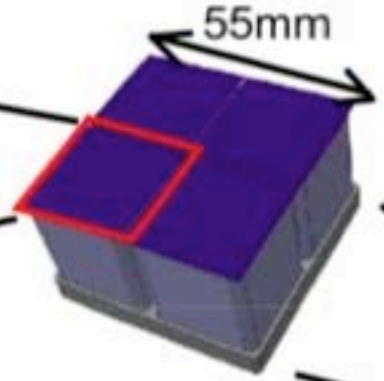
UV telescope 60° FOV
4.5 m^2 Focal Surface

Focal Surface Detector

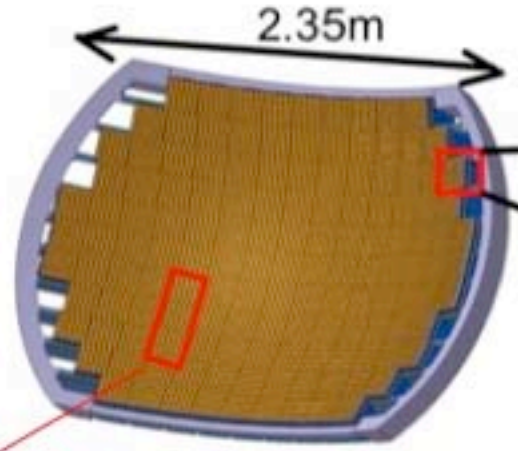
Y. Kawasaki, ID 0472
M. Ricci, ID 0335

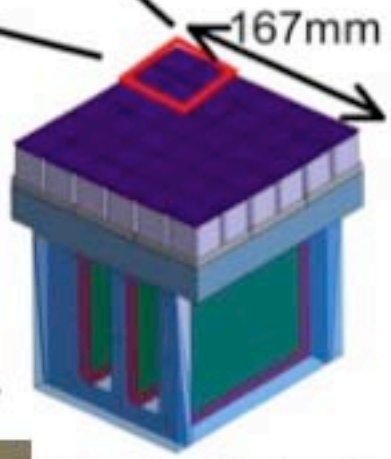


4932 MAPMTs (8x8 pixels)



Elementary Cell (2x2 PMTs = 256 pixels)





Focal Surface detector
137 PDMs
= 0.3M Pixels

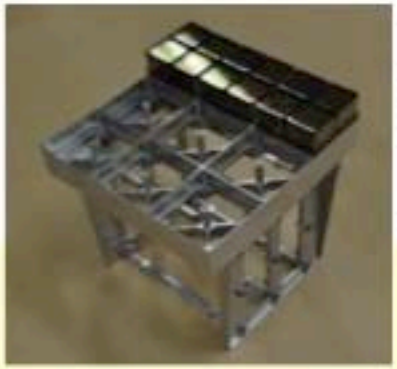
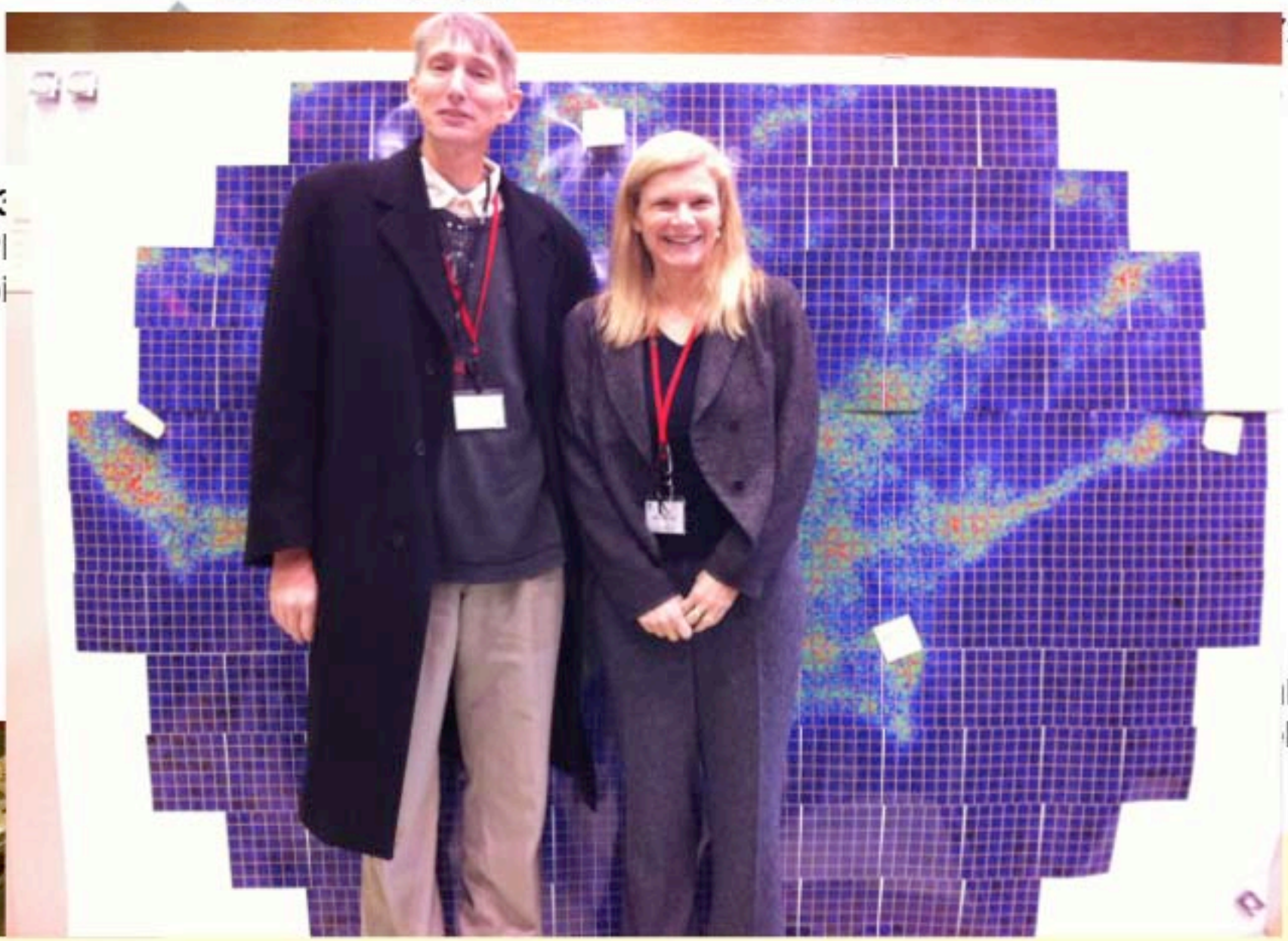


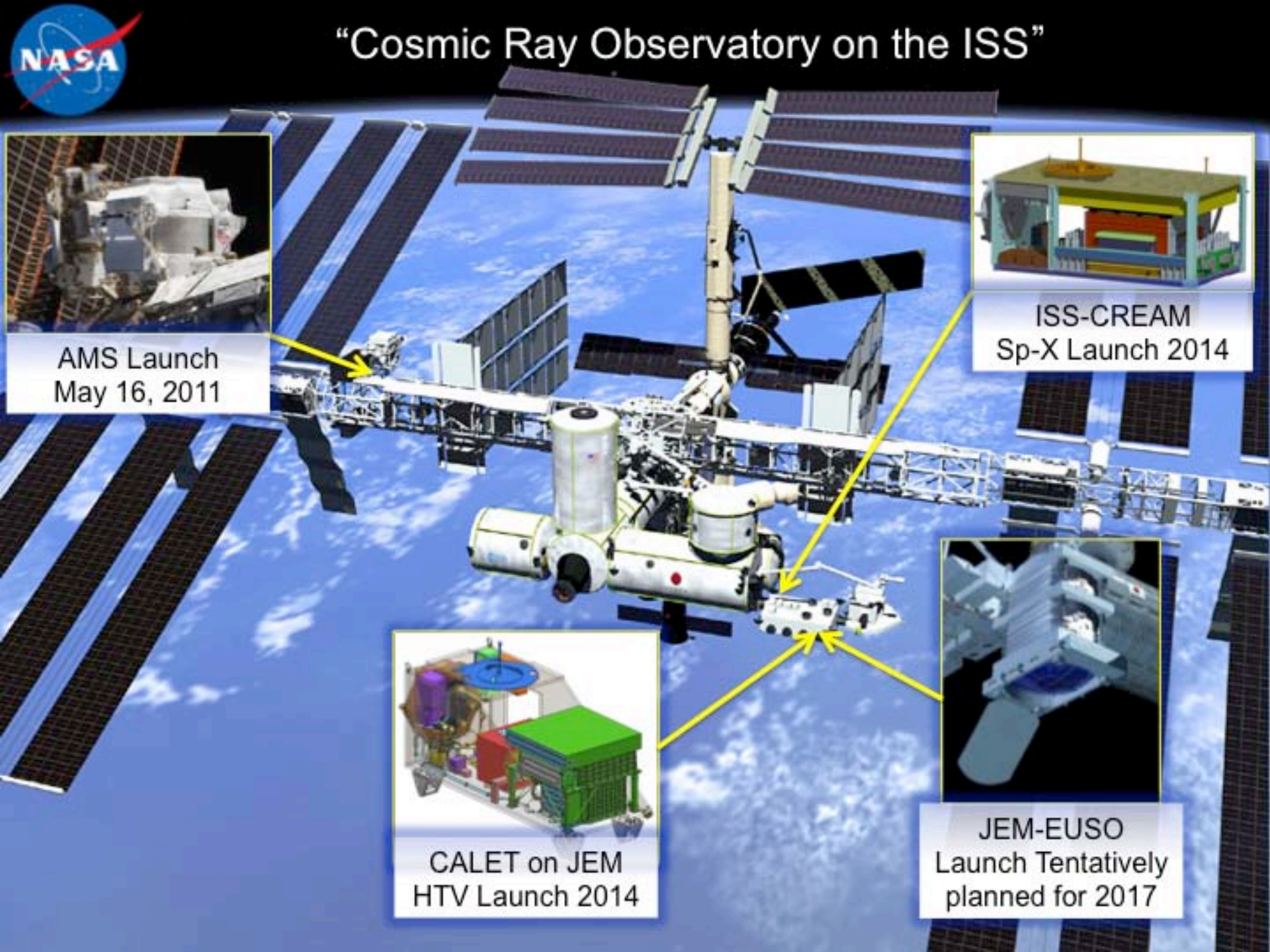
Photo-Detector Module (3x3 ECs = 2,304 pixels

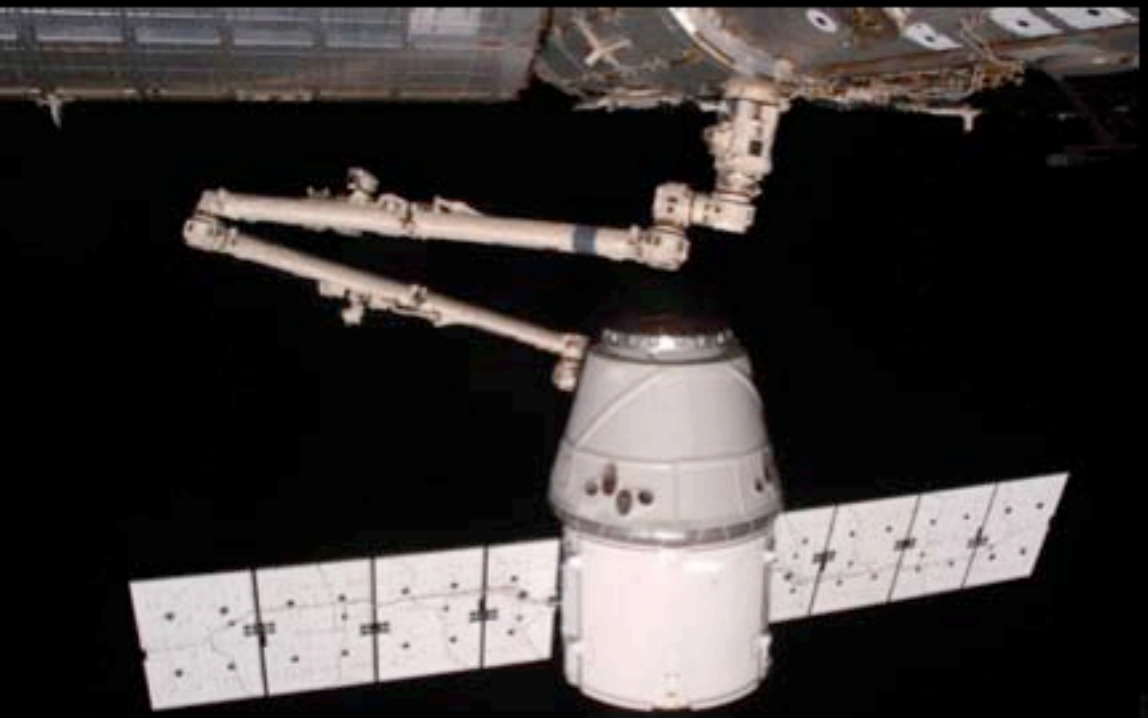
1 High Voltage / PDM

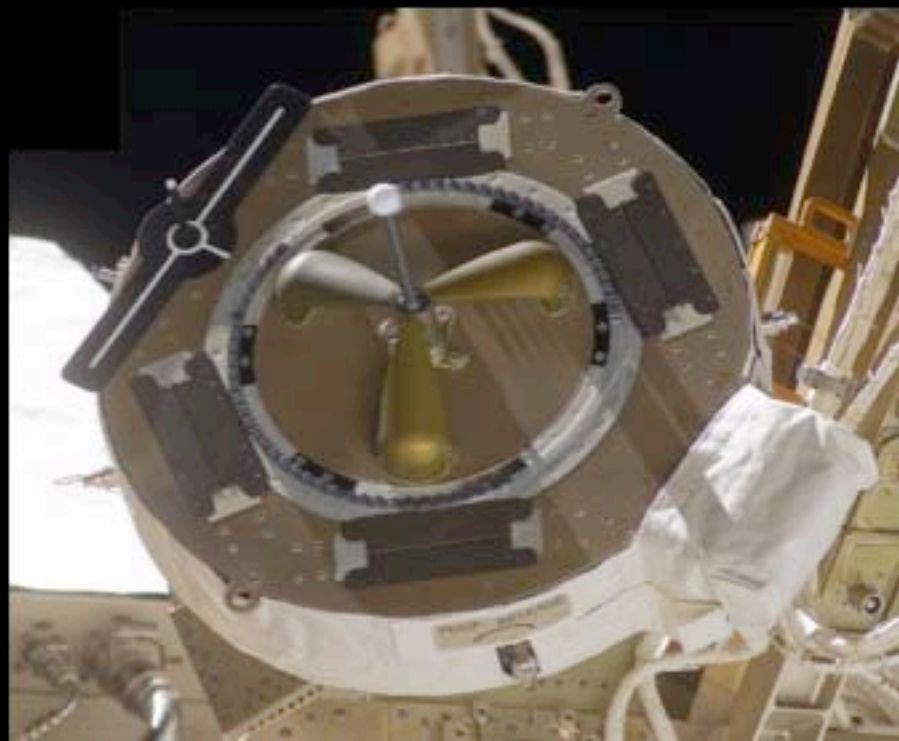
Focal Surface Detector

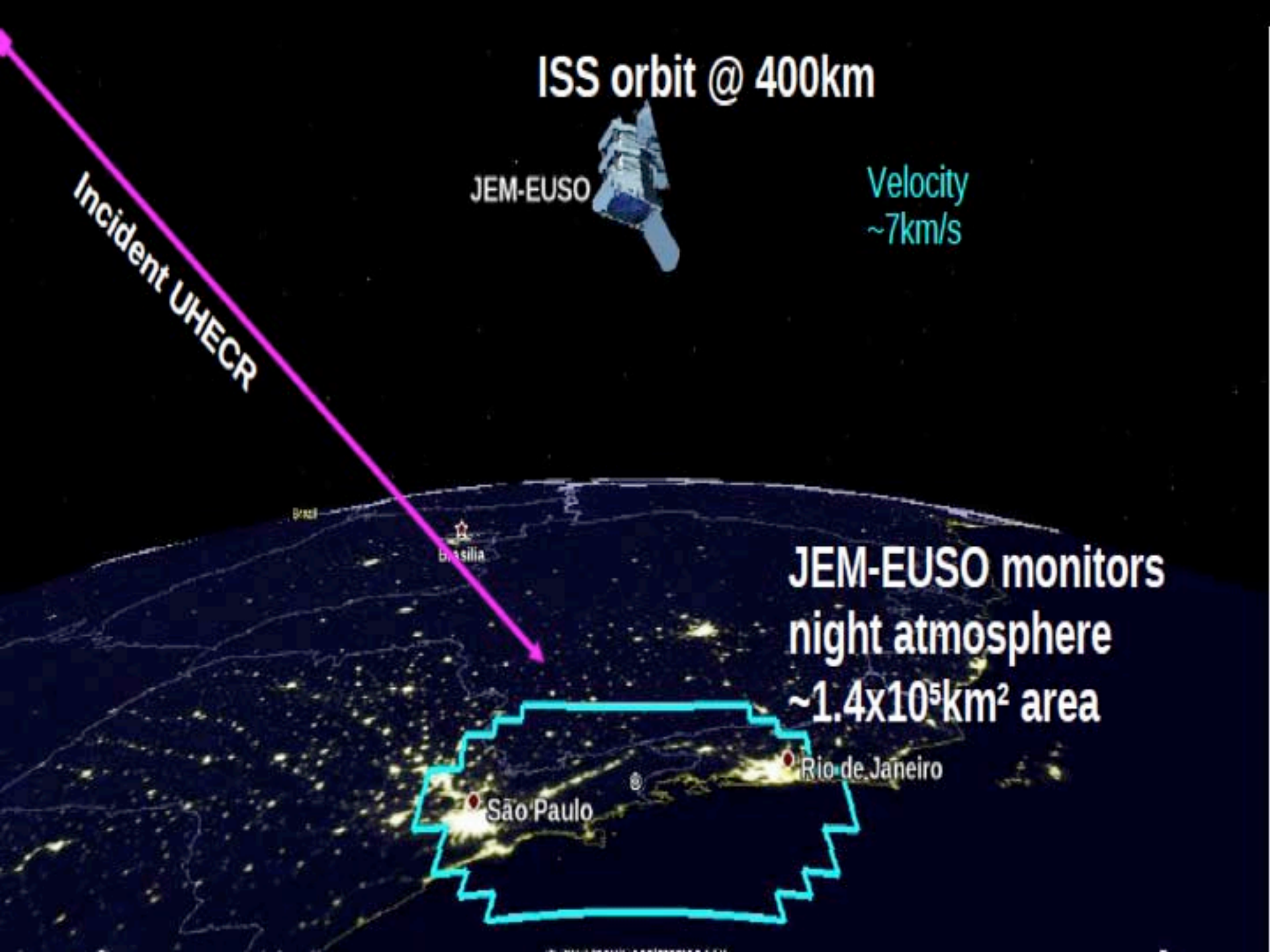


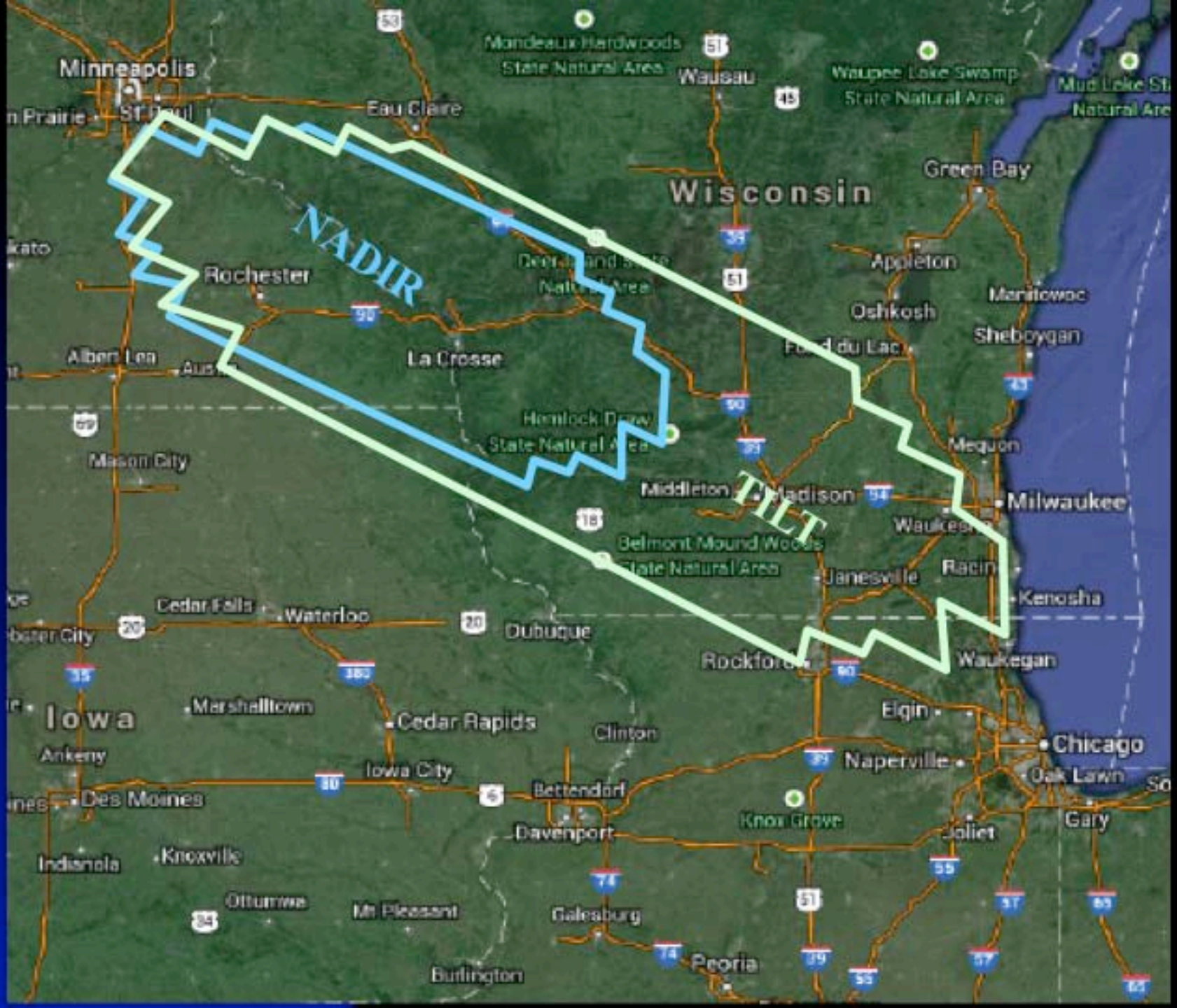
"Cosmic Ray Observatory on the ISS"



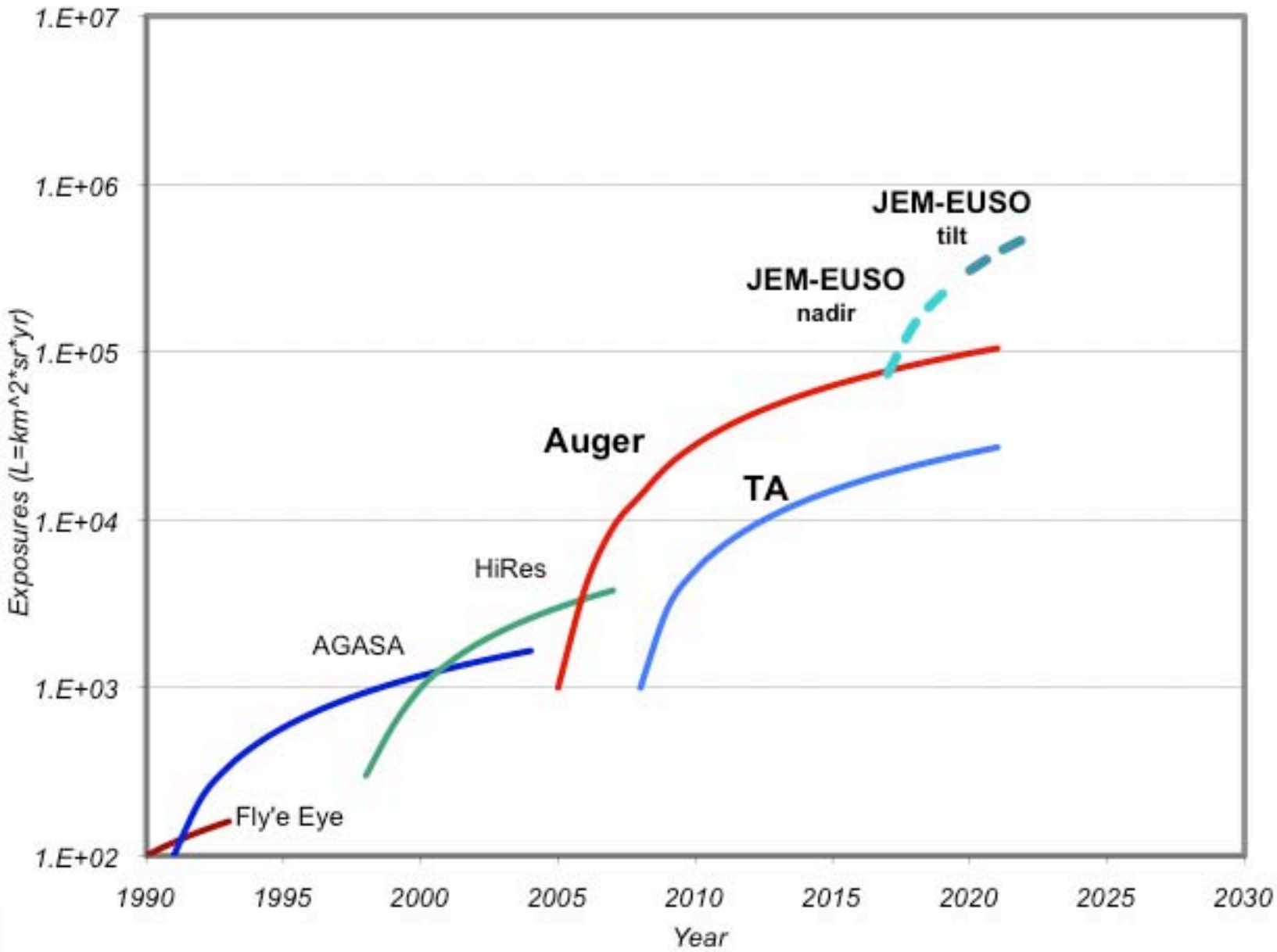





ISS orbit @ 400km
JEM-EUSO
Velocity
~7km/s
Incident UHECR
Brasilia
JEM-EUSO monitors
night atmosphere
~1.4x10⁵km² area
Rio de Janeiro
São Paulo


NADIR
TILT
Minneapolis
St Paul
Eau Claire
Wausau
Mandeaux Hardwoods
State Natural Area
Waupee Lake Swamp
State Natural Area
Wisconsin
Green Bay
Appleton
Oshkosh
Manitowoc
Sheboygan
Fond du Lac
Rochester
La Crosse
Albert Lea
Austin
Hemlock Draw
State Natural Area
Mason City
Middleton
Madison
Milwaukee
Waukesha
Mequon
Belmont Mound Woods
State Natural Area
Janesville
Racine
Kenosha
Cedar Falls
Waterloo
Dubuque
Rockford
Waukegan
Iowa
Marshalltown
Cedar Rapids
Clinton
Elgin
Chicago
Ankeny
Iowa City
Naperville
Oak Lawn
Des Moines
Bettendorf
Davenport
Knox Grove
Joliet
Gary
Indianola
Knoxville
Ottumwa
Mt Pleasant
Galesburg
Peoria
Burlington

Exposure History



In a decade, we can probe
particle interactions at
>300 TeV CM
from Space!!!

How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO

~200 events > 60 EeV/ yr

4 o.o.m to go!

Earth surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

What are the hardest Cosmic Particles to detect?

What are the hardest Cosmic Particles to detect?

Dark Matter??

What are the hardest Cosmic Particles to detect?

Dark Matter??

What are the 2nd hardest Cosmic Particles to detect?

What are the hardest Cosmic Particles to detect?
Dark Matter??

What are the 2nd hardest Cosmic Particles to detect?
Gravitons (Gravity Waves)??

What are the hardest Cosmic Particles to detect?
Dark Matter??

What are the 2nd hardest Cosmic Particles to detect?
Gravitons (Gravity Waves)??

What are the 3rd hardest Cosmic Particles to detect?
NEUTRINOS!

What are the 3rd hardest Cosmic Particles to detect?

Neutrinos

How Abundant are they?

What are the 3rd hardest Cosmic Particles to detect?

Neutrinos

How Abundant are they?

0.3% of the contents of the Universe

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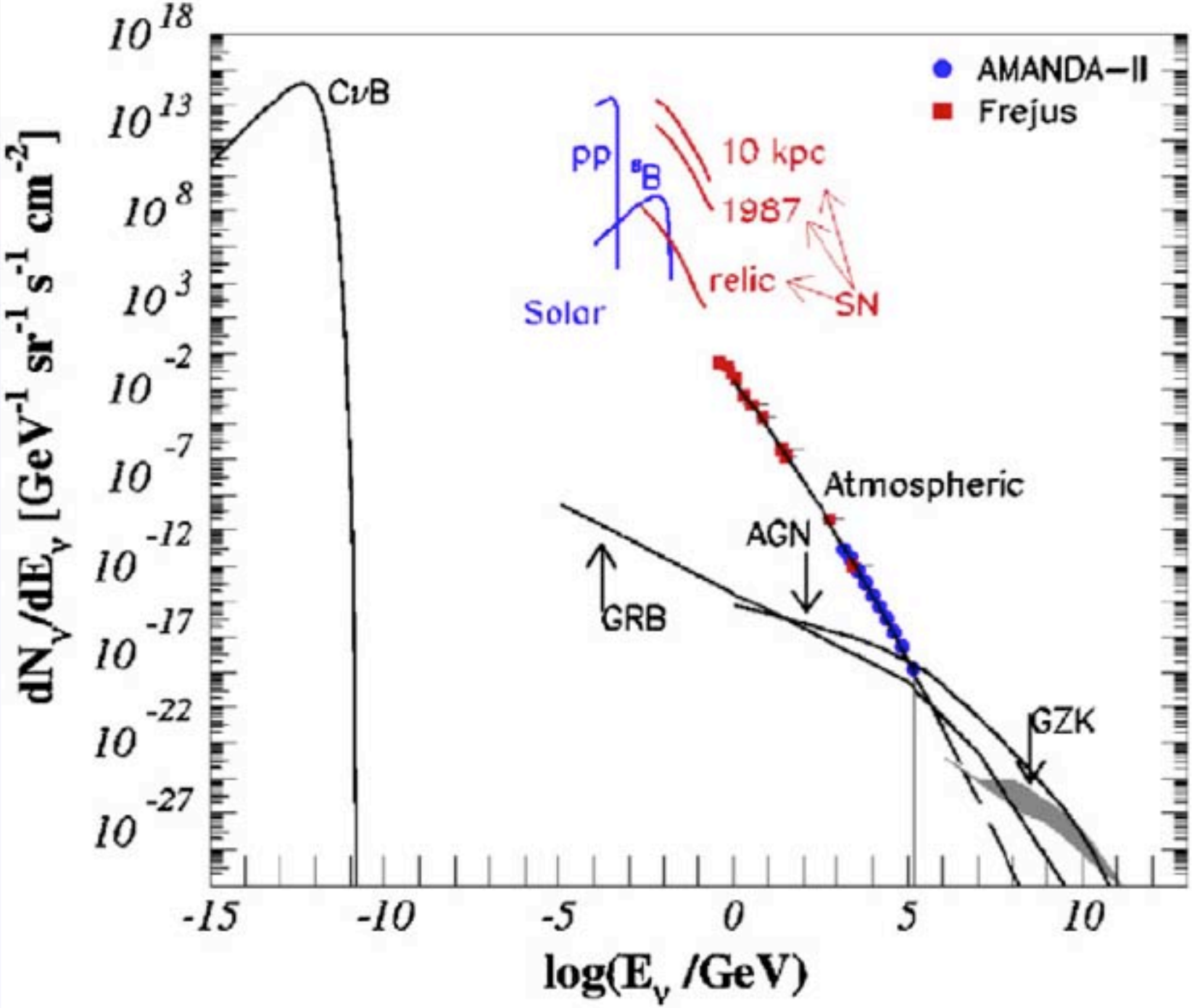
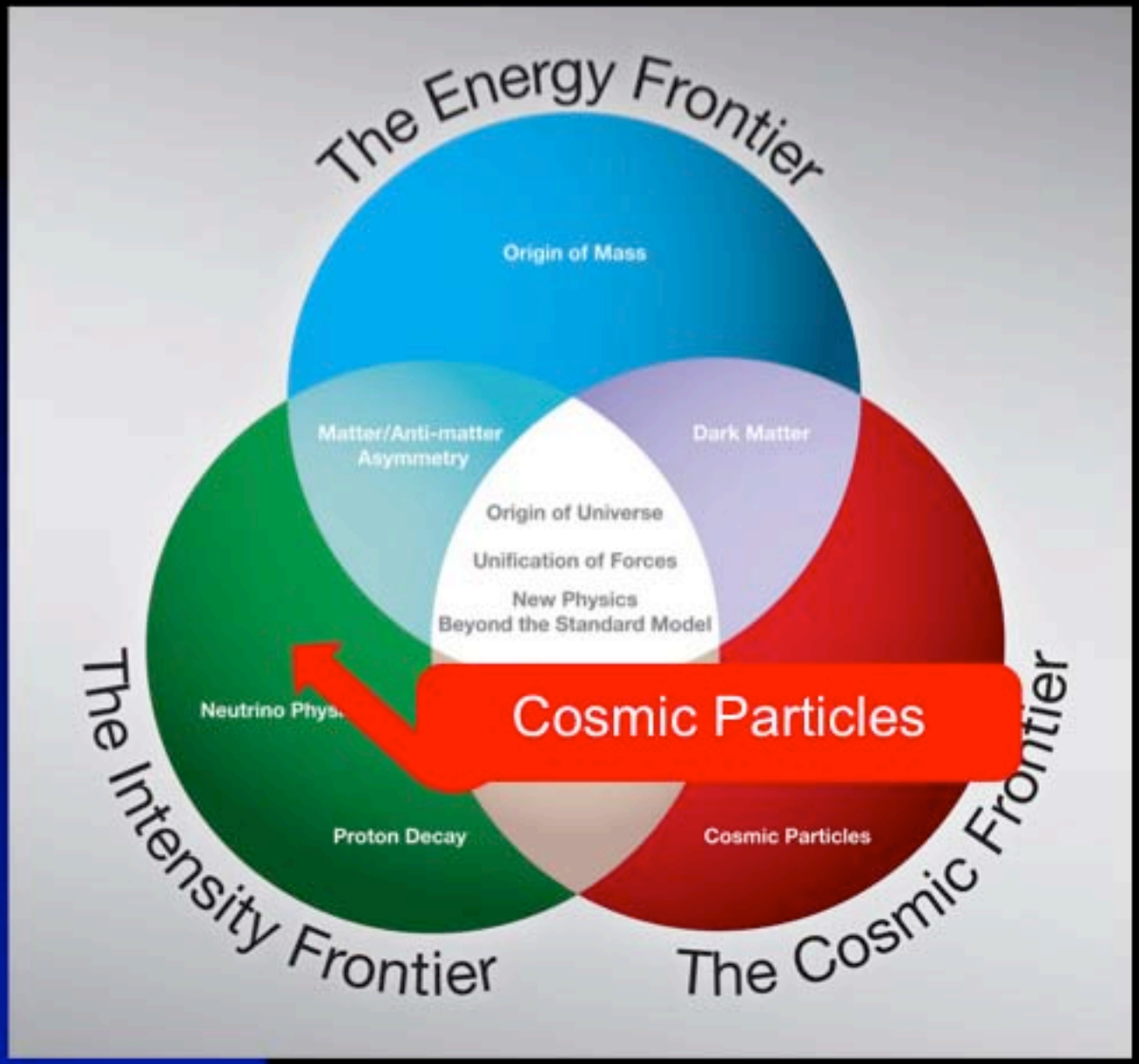
In principle, since neutrino decoupling.

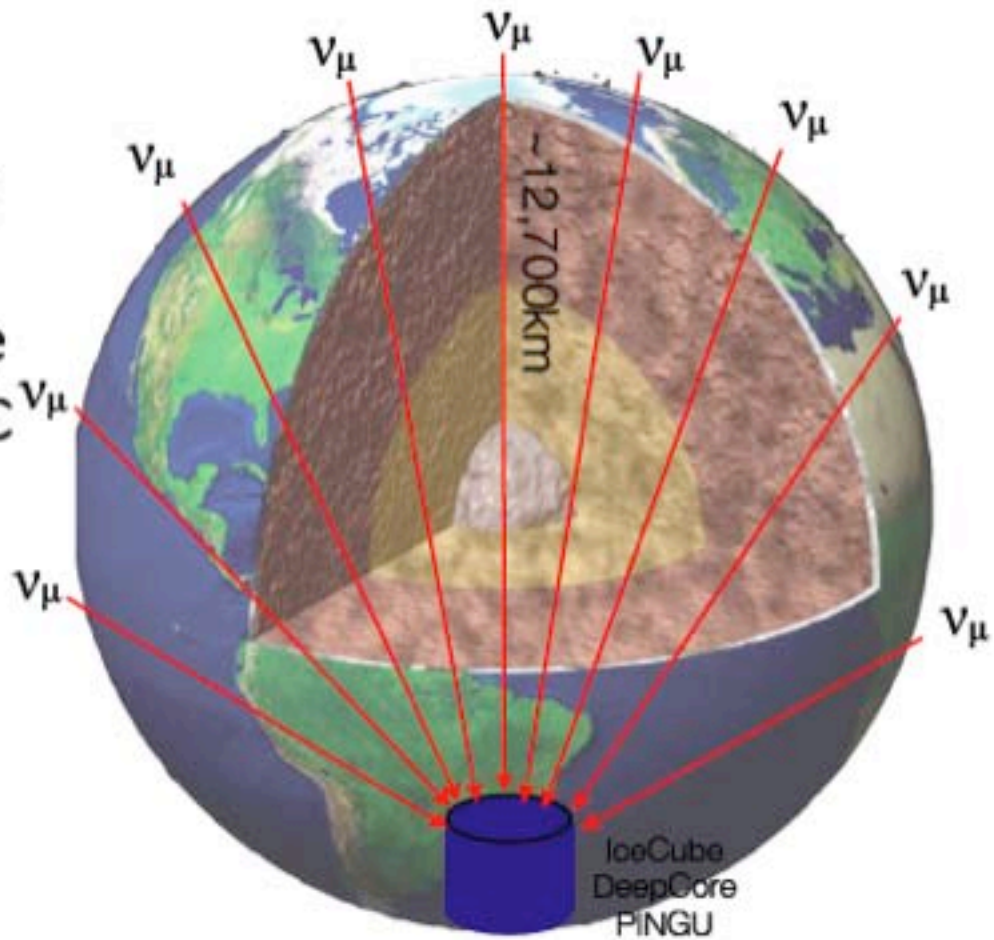
Observed: Sun, Supernova 87a, Atmospheric and IceCube 28 events 100 TeV to PeV !!!!


AMANDA−II
Frejus
CνB
pp
⁸B
Solar
10 kpc
1987
relic
SN
Atmospheric
AGN
GRB
GZK
10^{18}
10^{13}
10^{8}
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
10^{-22}
10^{-27}
-15
-10
-5
0
5
10
dN_ν/dE_ν [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]
$\log(E_\nu/GeV)$


The Energy Frontier
Origin of Mass
Matter/Anti-matter Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics Beyond the Standard Model
Neutrino Phys.
Cosmic Particles
Proton Decay
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier

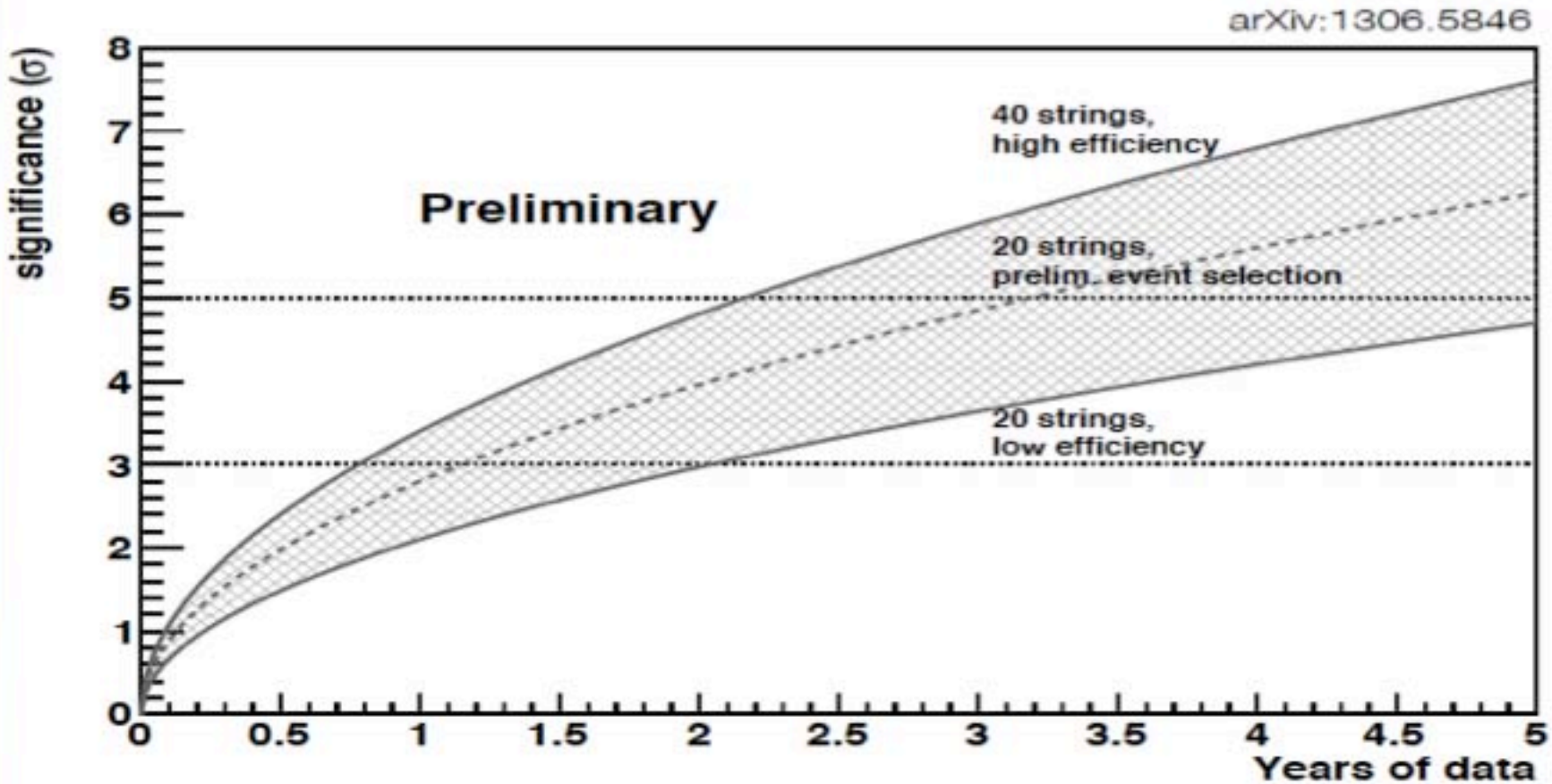
PINGU

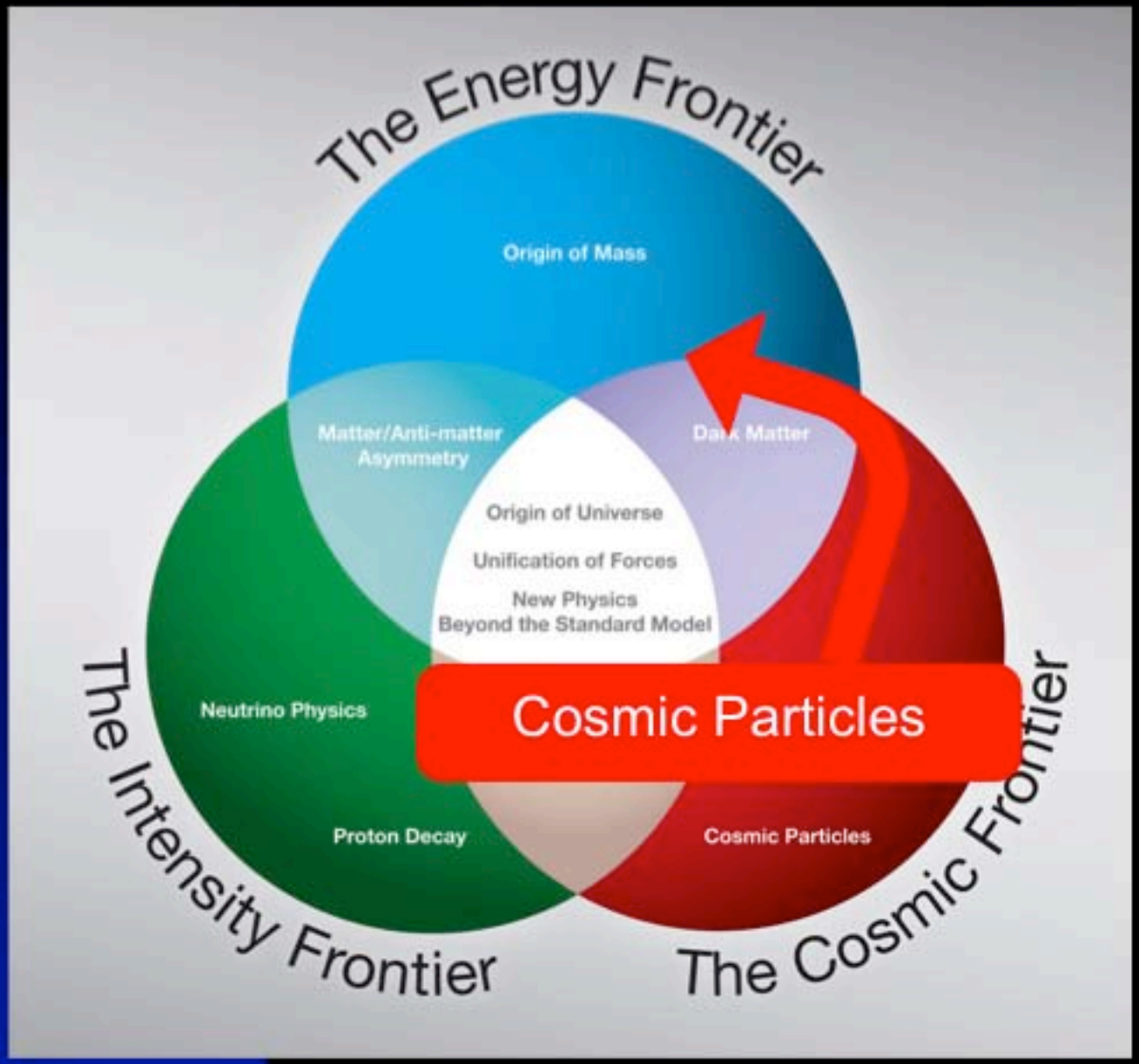
Atmospheric neutrinos provide many values of L and E
Very large baselines for probing matter effects (~12,700 km)
Add ~40 strings inside DeepCore
20-25m string spacing (73 for DC and 125 for IC)
Cost ~$60M



PINGU

- ν_μ disappearance experiment
- 5-20 GeV energy range

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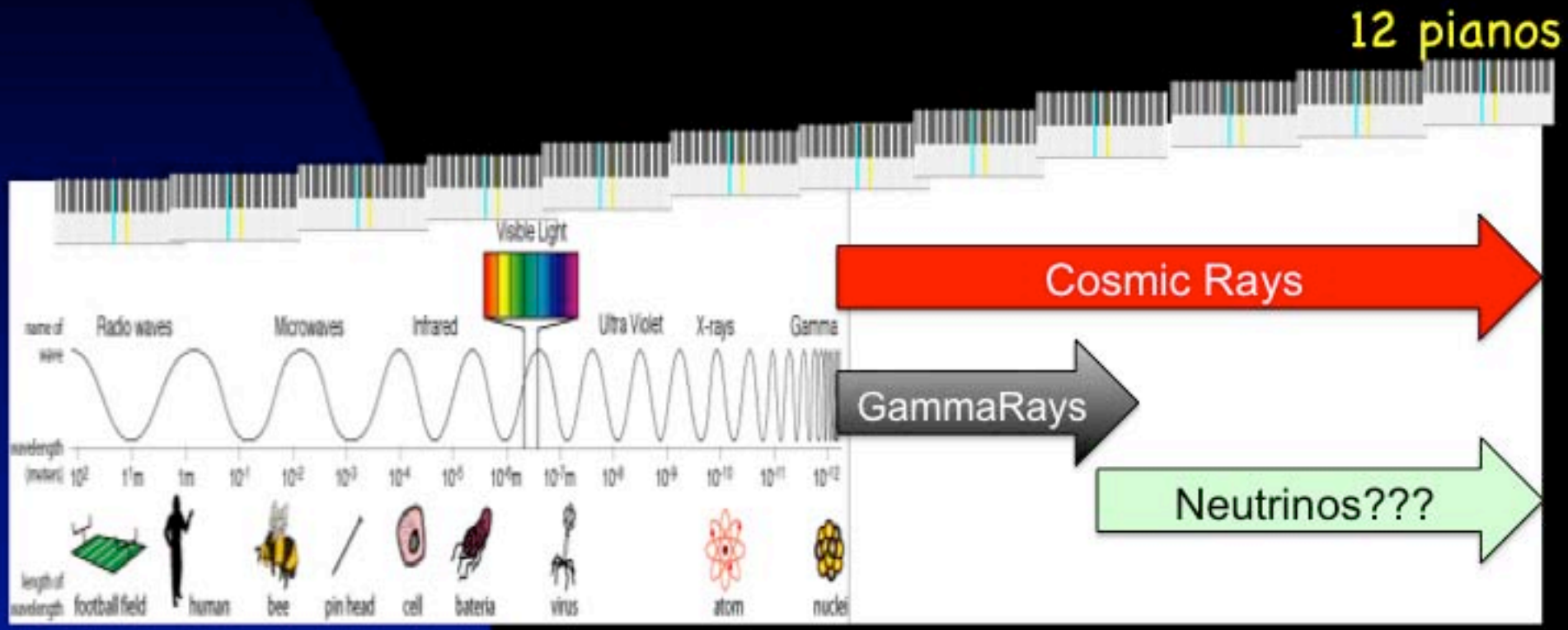
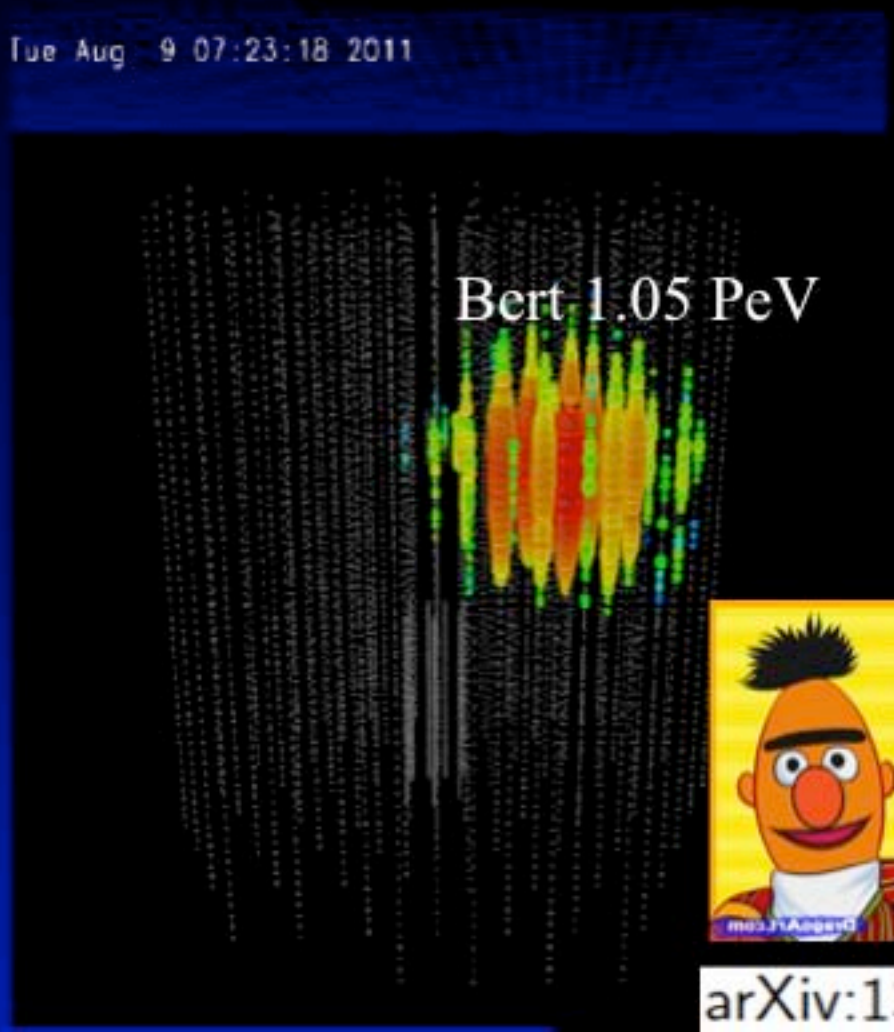
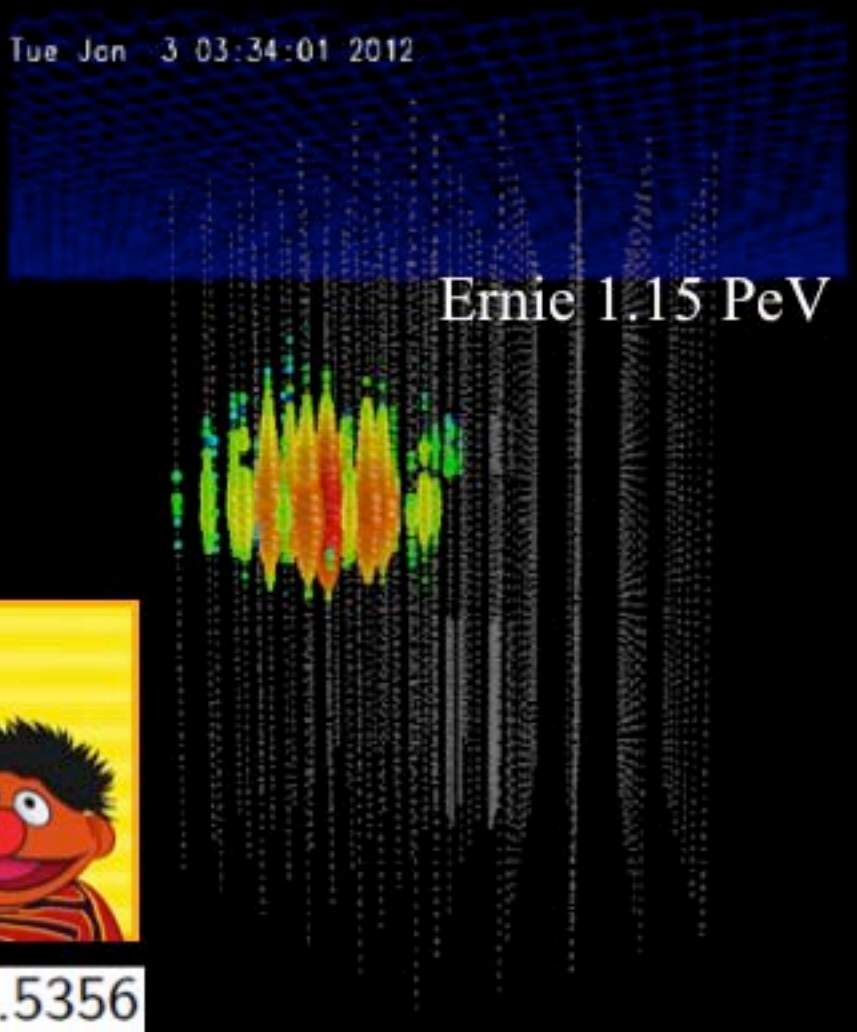

12 pianos
Visible Light
Cosmic Rays
name of wave
Radio waves
Microwaves
Infrared
Ultra Violet
X-rays
Gamma
GammaRays
wavelength (meters)
Neutrinos???
length of wavelength
football field
human
bee
pin head
cell
bateria
virus
atom
nuclei

Neutrino Astronomy Begins

PeV neutrinos first observed by **IceCube** (Apr'13)





arXiv:1304.5356

Neutrino Astronomy Begins

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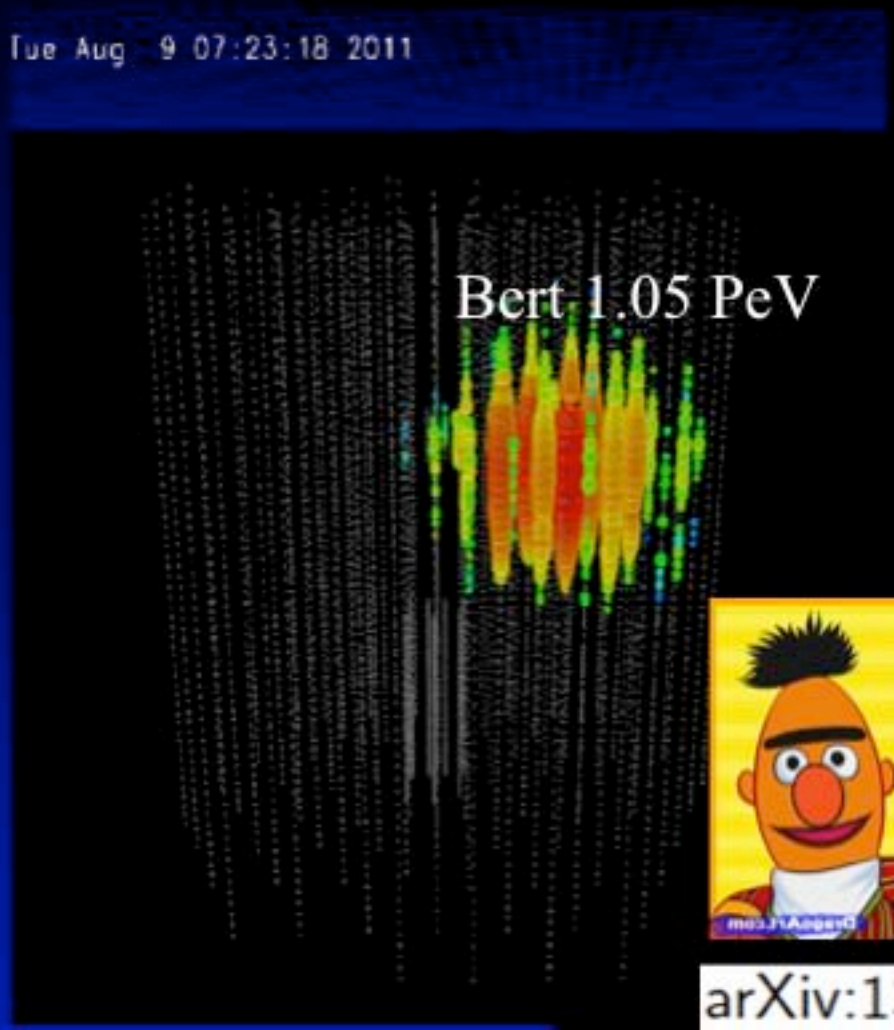
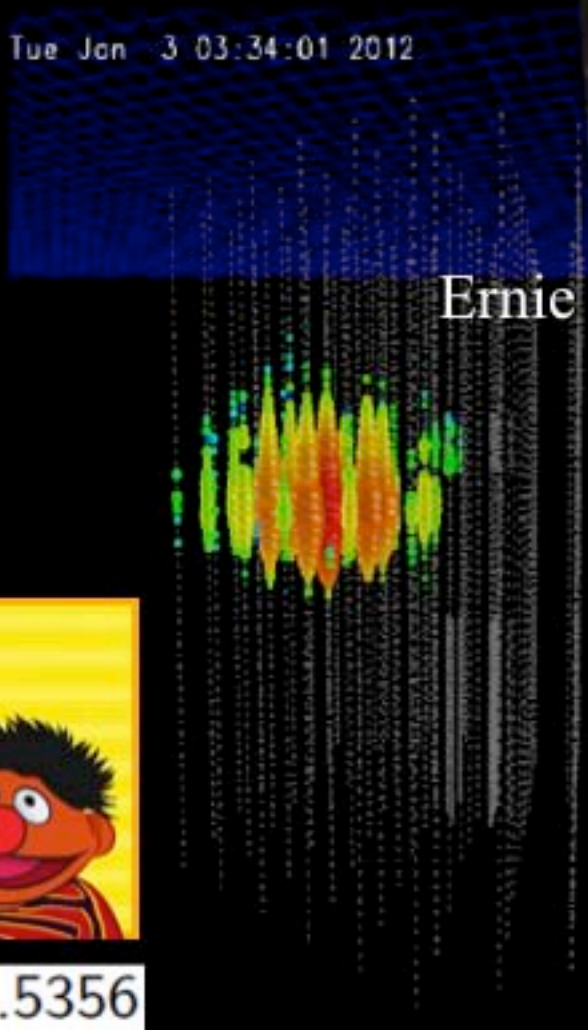
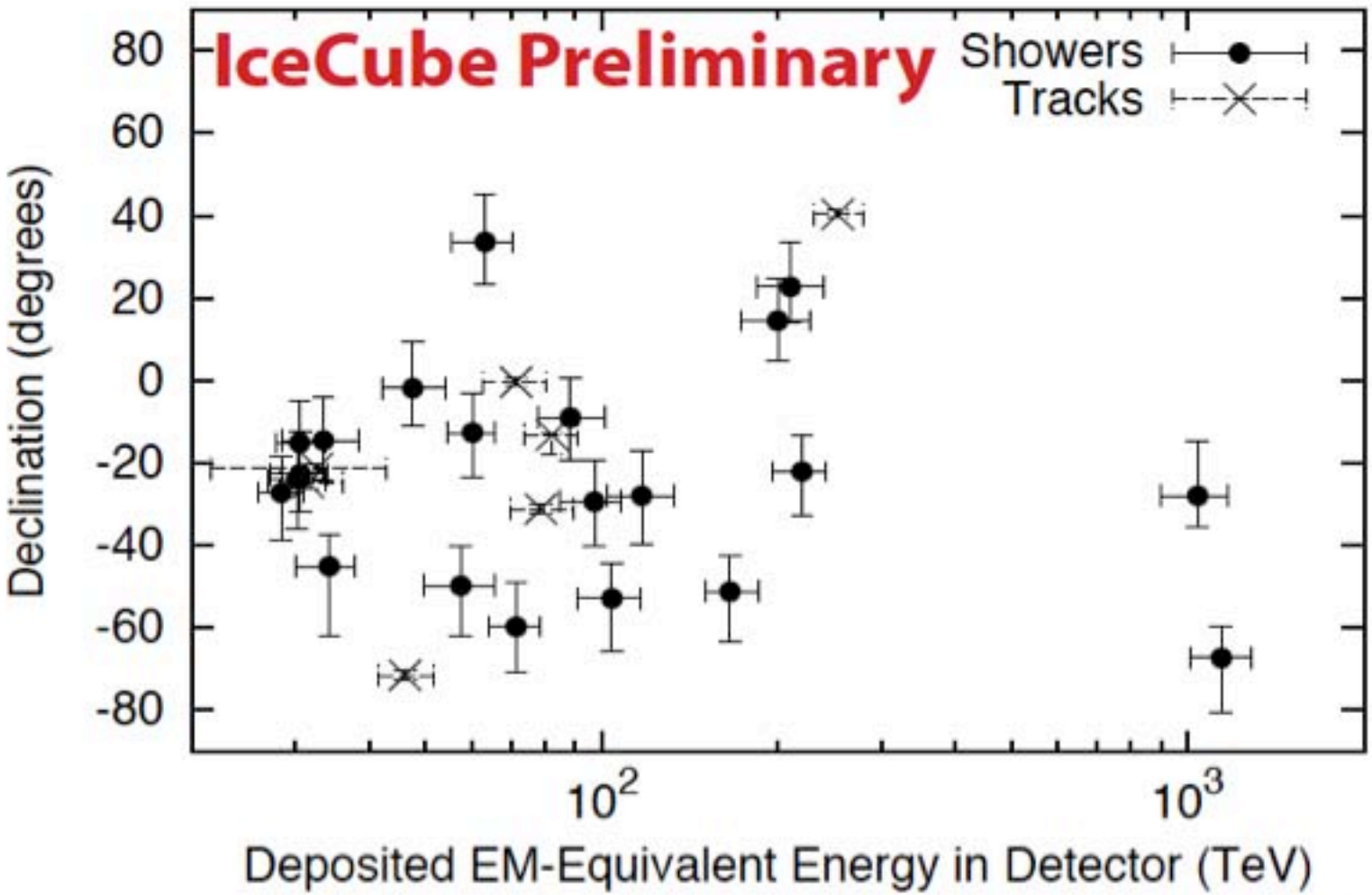




arXiv:1304.5356

Results of Contained Vertex Event Search (4.3σ)



28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

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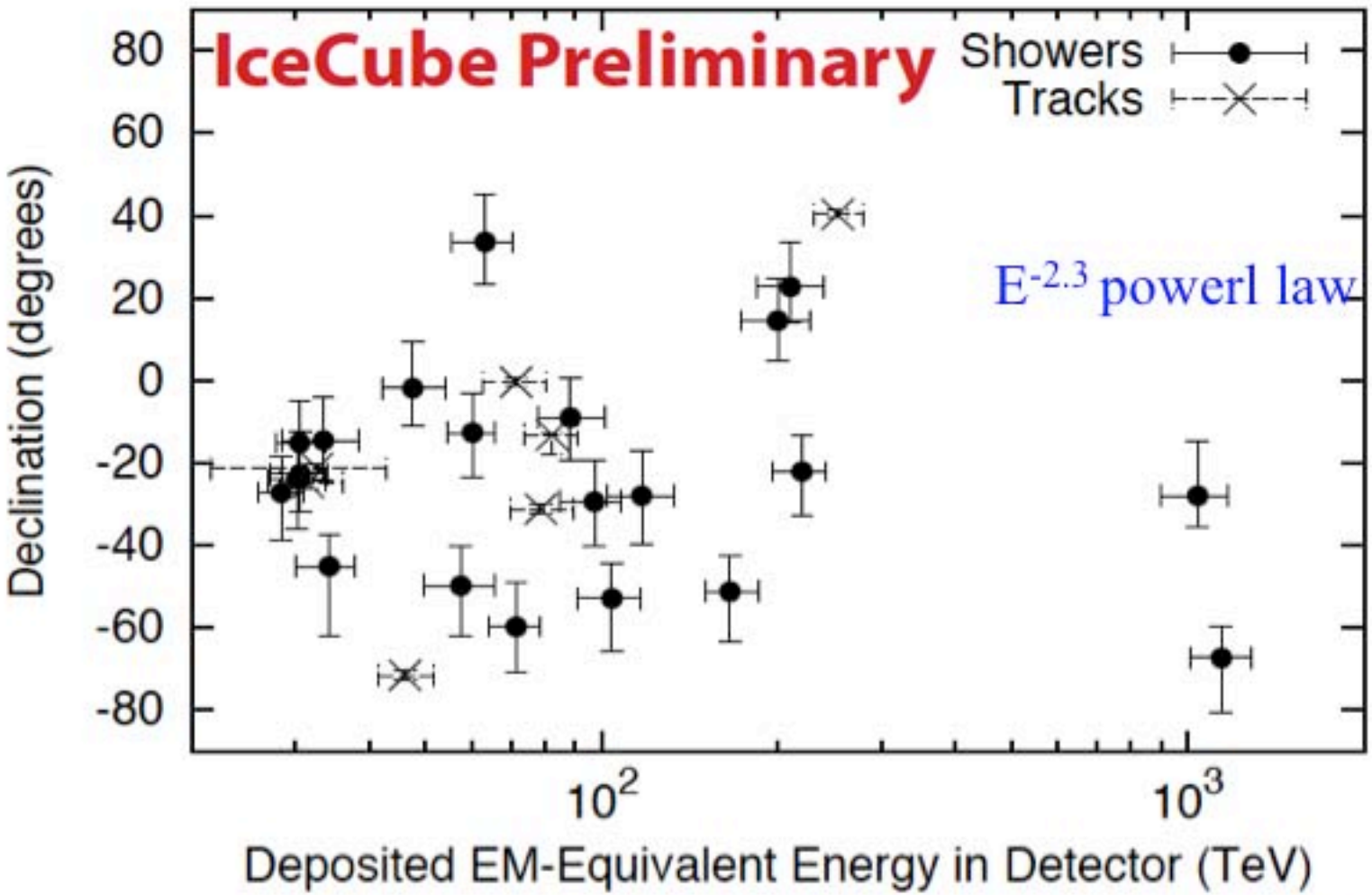

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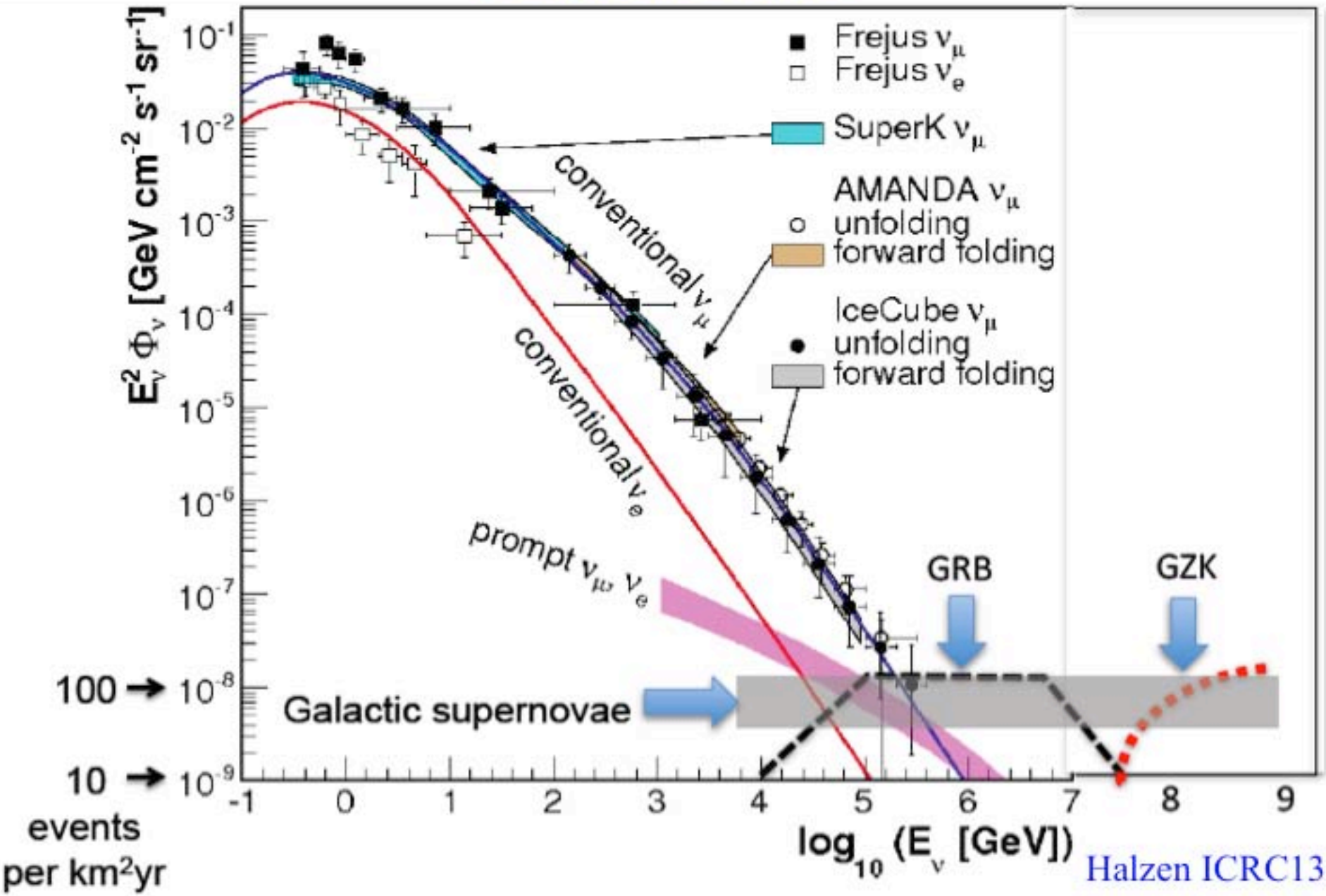
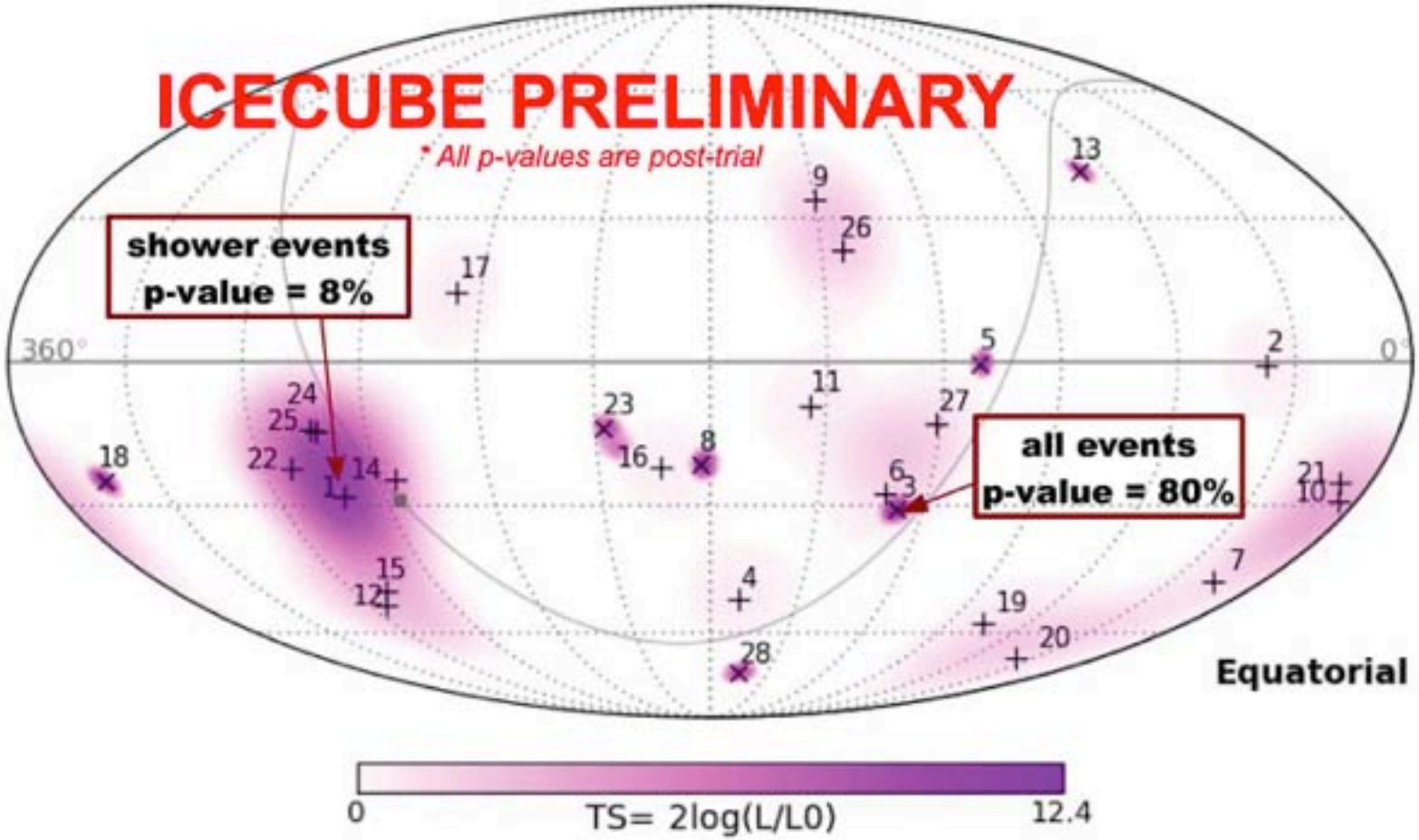
Galactic CRs?



Skymap: No Significant Clustering



See: talk by Naoko Kurahashi Neilson

What are the 3rd hardest Cosmic Particles to detect?
Neutrinos

How Abundant are they?
0.3% of the contents of the Universe

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In principle, since neutrino decoupling. Observed: Sun, Supernova 87a, and IceCube 28 events 100 TeV to PeV

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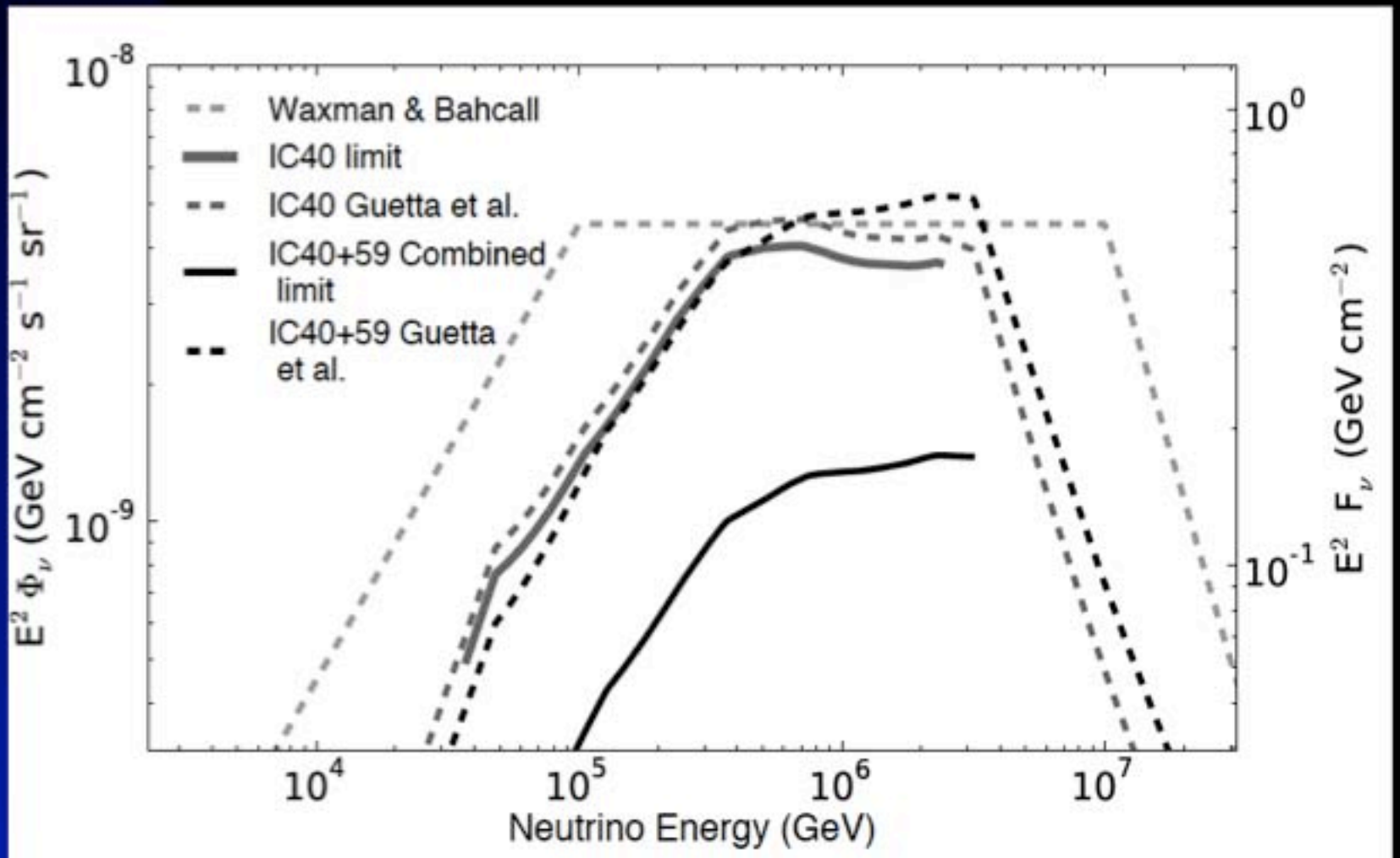
How are they generated?
Early Universe;
Nuclear Reactions (Supernova, Stars…),
Hadronic Interactions;
UHECR propagation

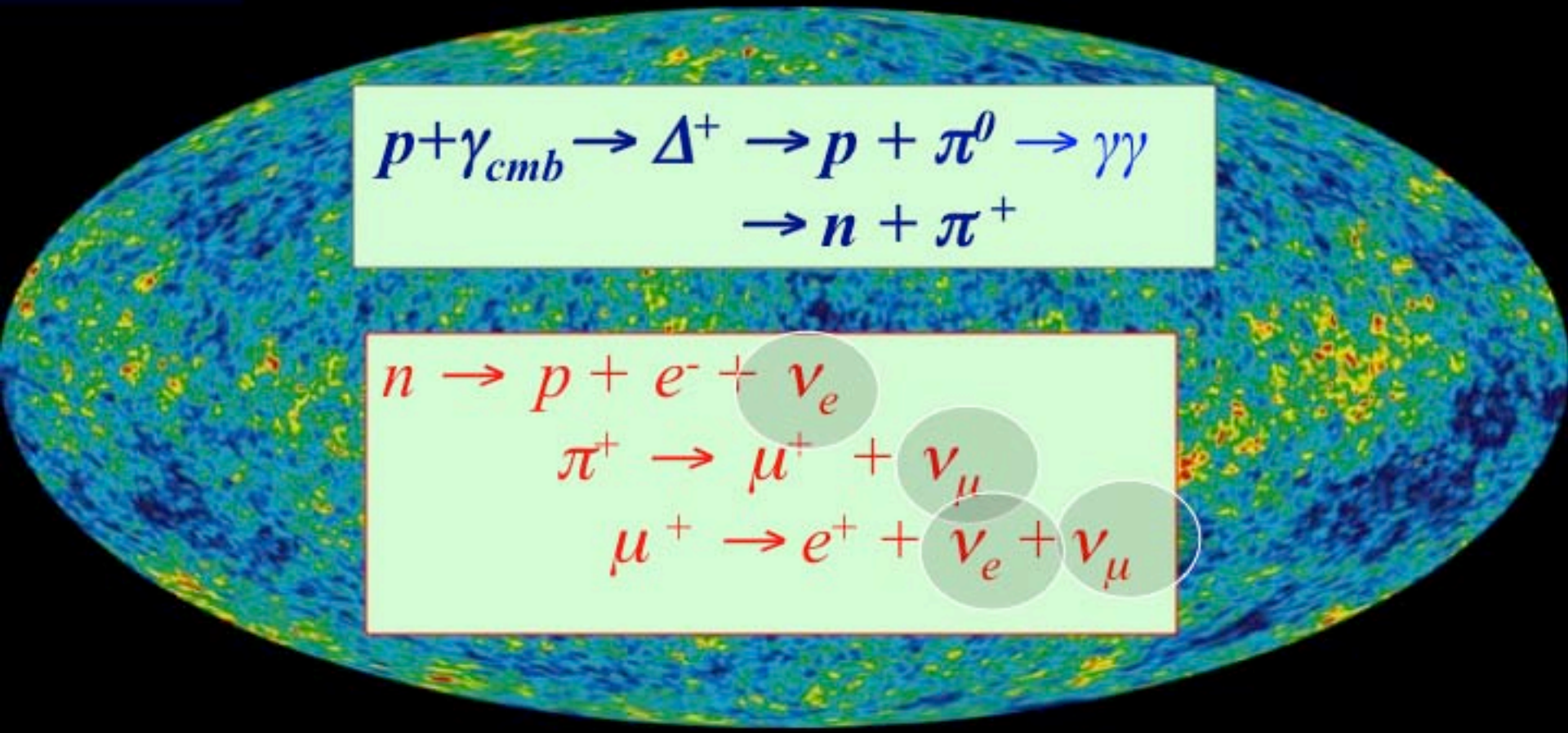
HE Neutrino Limits

IceCube Nature '12 – constraints on (some) Gamma-ray Bursts (GRB) Fireball Models



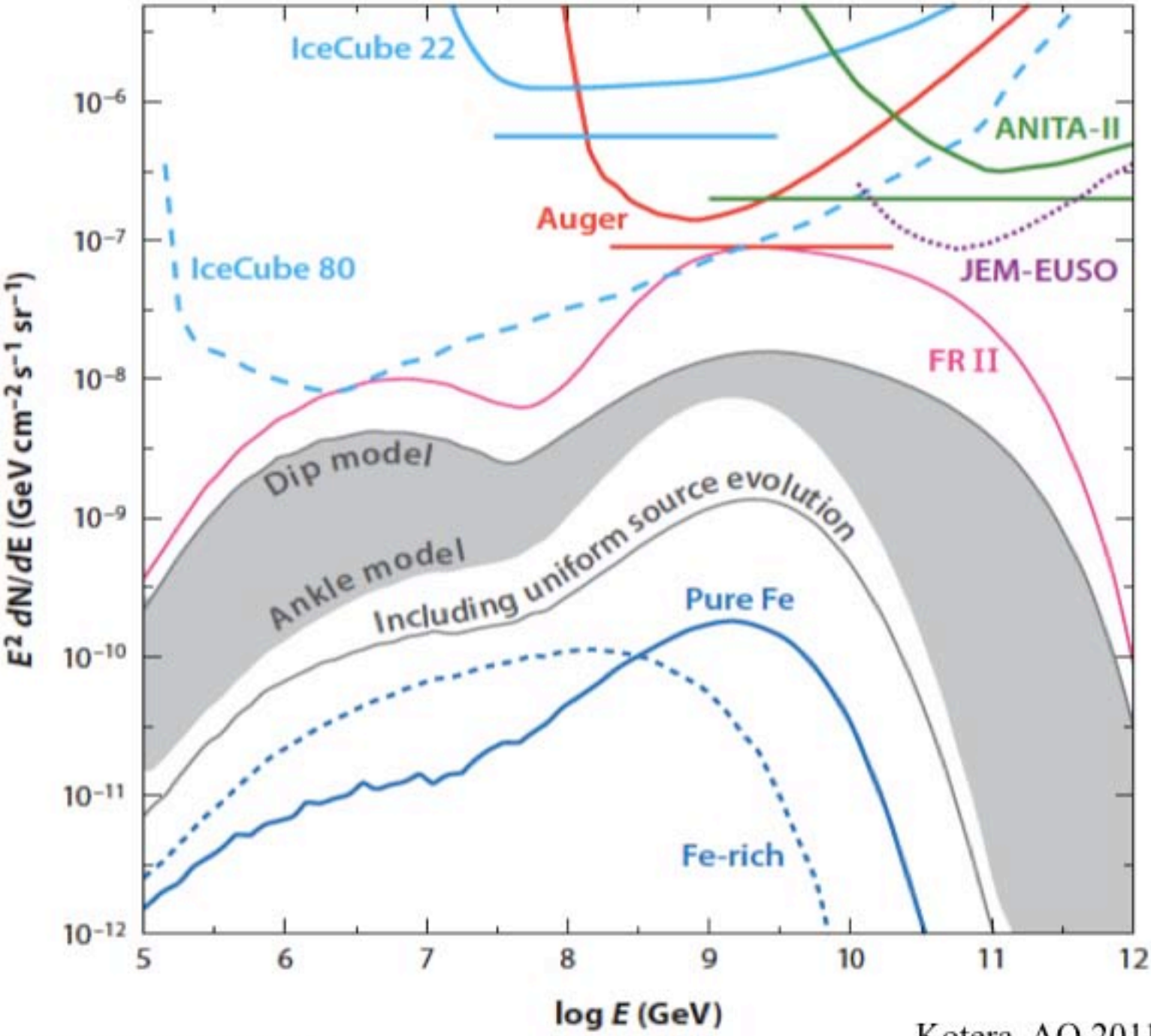
Cosmogenic (GZK) Neutrinos & Photons

and UHECR composition

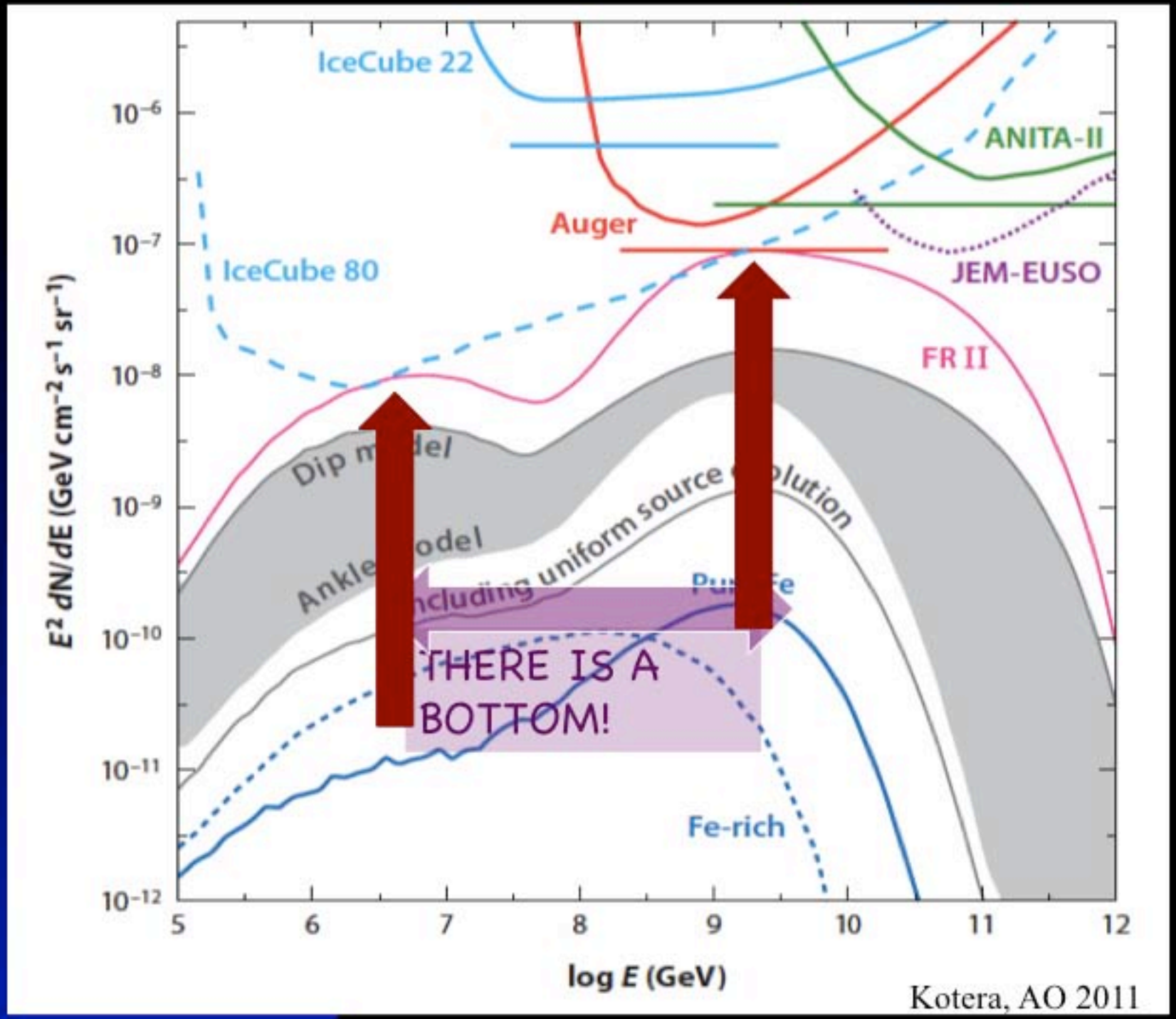


$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^+$$

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

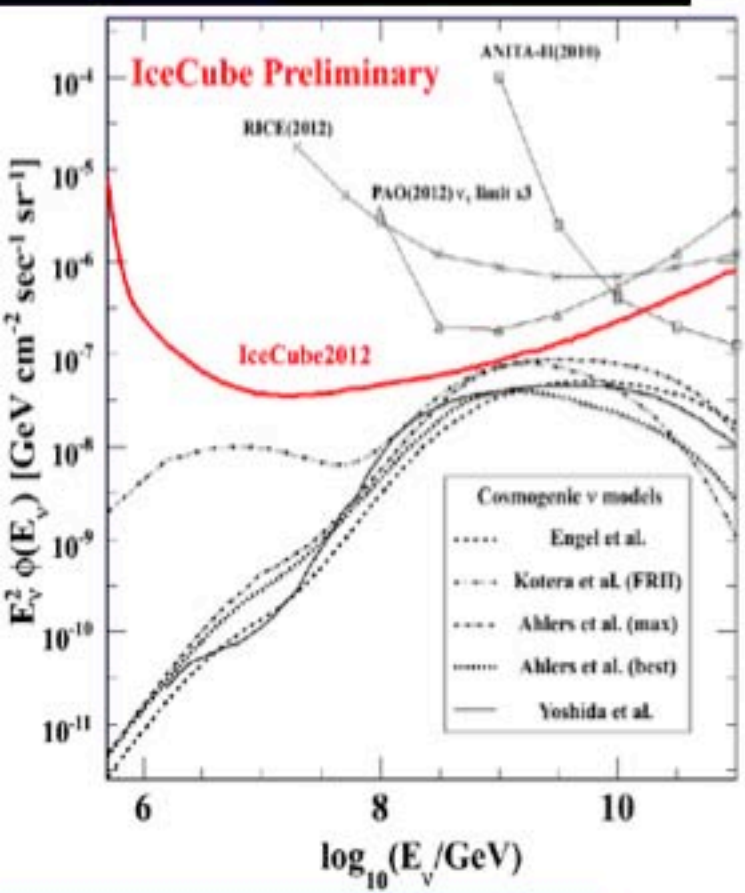


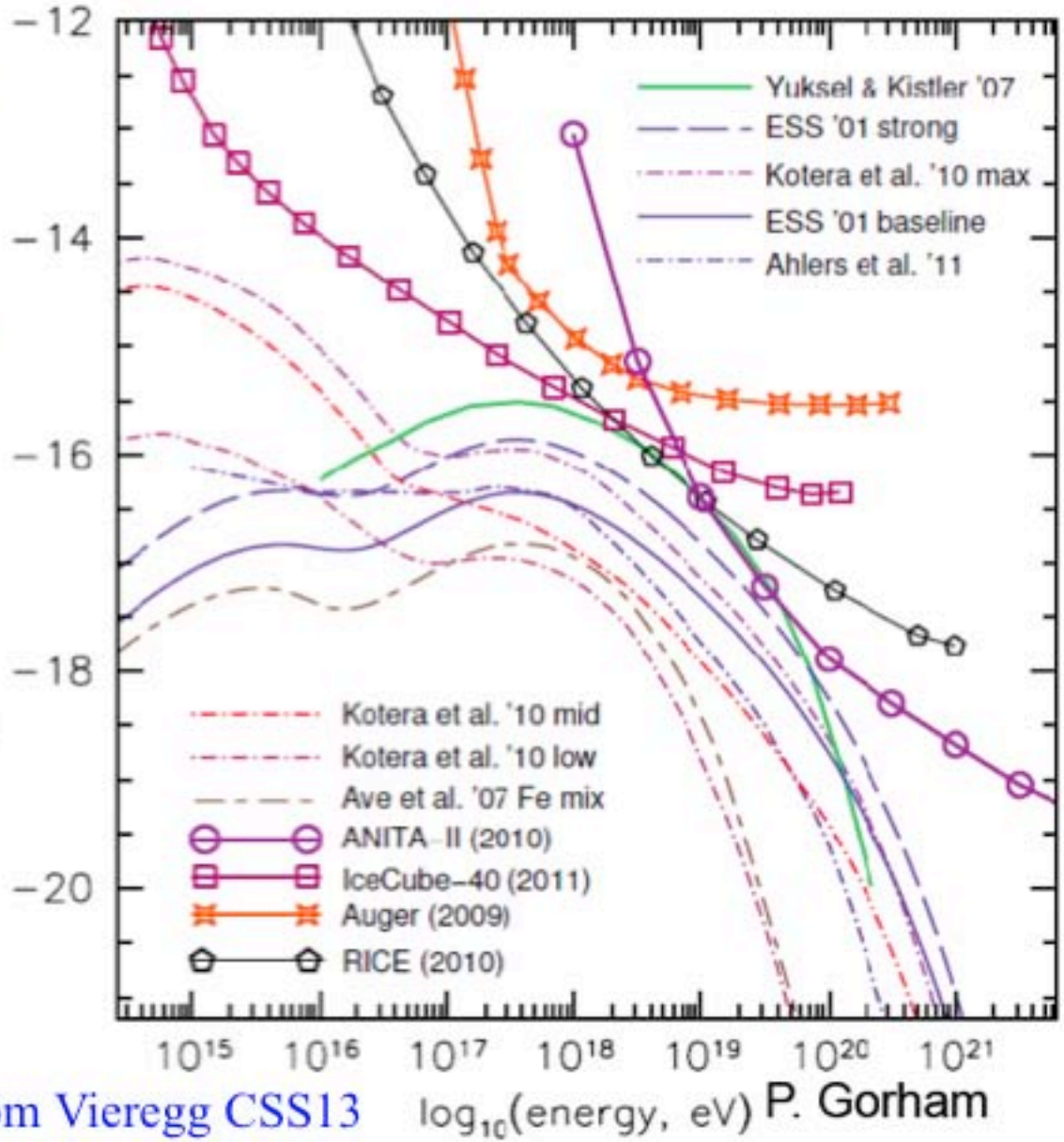
Kotera, AO 2011



Kotera, AO 2011

Current Limits





from Vieregg CSS13

P. Gorham

What is so cool about GZK neutrinos?

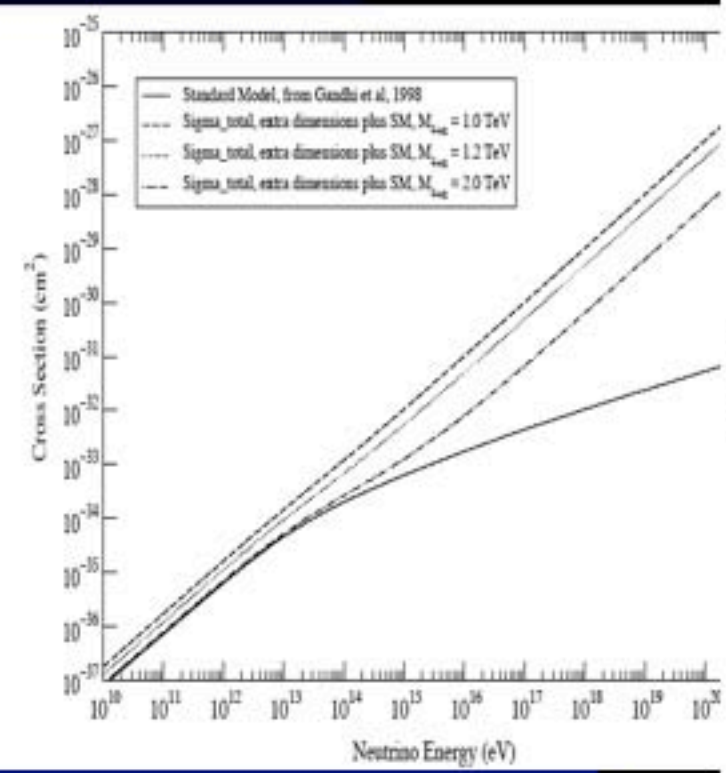
They can answer many questions about the origin of UHECRs

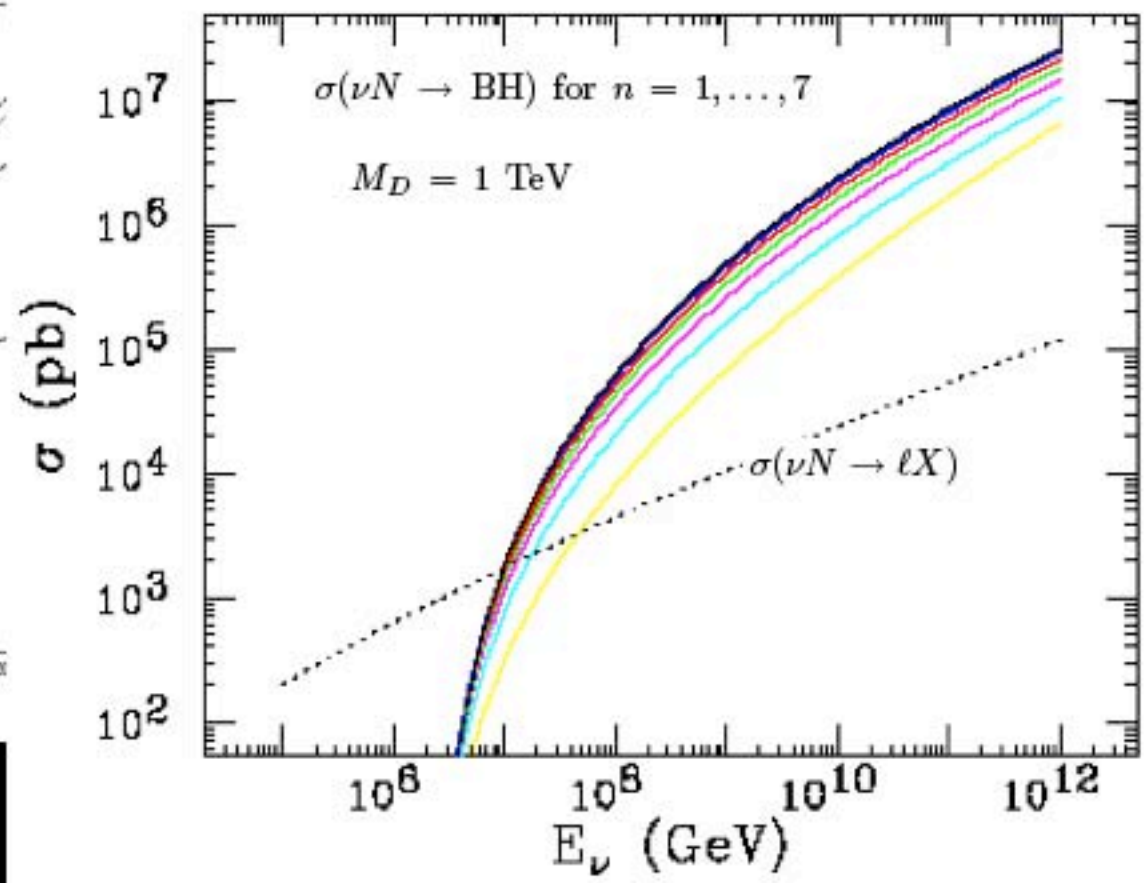
and

Can test BSM physics directly

Tests of UHE Neutrino Interactions

Need to know the expected GZK neutrino flux from UHECRs or...





Tyler, AO, Sigl '01

Anchordoqui et al '03

Observe EarthSkimming & Airshowers ν's

BSM Physics that modifies the neutrino-nucleon cross section at center-of-mass energy up to 245 TeV. ($E_\nu = 3\ 10^{19}$ eV)

Earth-skimming events occur in the Earth's crust $\nu_{\tau\pm} N \to \tau^\pm X$

Air-showers produced deep in the atmosphere $\nu_{\ell\pm} N \to \ell^\pm X$

Ex: leptophobic interaction - suppress the number of Earth-skimming and increase the number of down-going showers.

Earth-skimming τ showers

$$N_{ES} \approx C_{ES} \frac{\Phi^\nu}{\Phi_0^\nu} \frac{\sigma_{CC}^{\nu\,2}}{\left(\sigma_{CC}^\nu + \sigma_{NP}^\nu\right)^2}$$

Down-going (quasi-horizontal) showers

$$N_{QH} = C_{QH} \frac{\Phi^\nu}{\Phi_0^\nu} \frac{\sigma_{CC}^\nu + \sigma_{NP}^\nu}{\sigma_{CC}^\nu}$$

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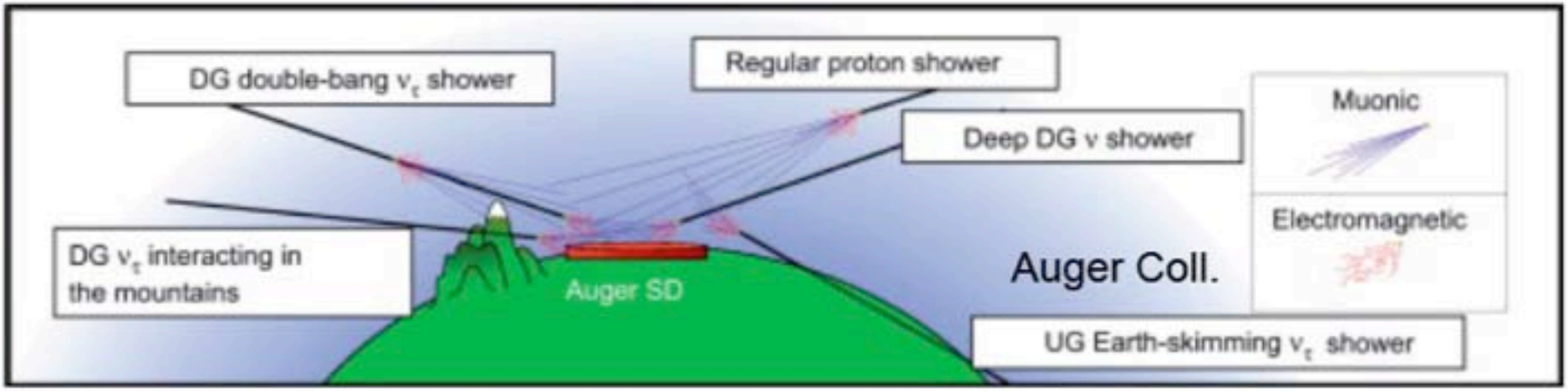
- Auger: Earth-skimming neutrinos and deep downgoing showers



from Vieregg CSS13

How are we trying to observe them?

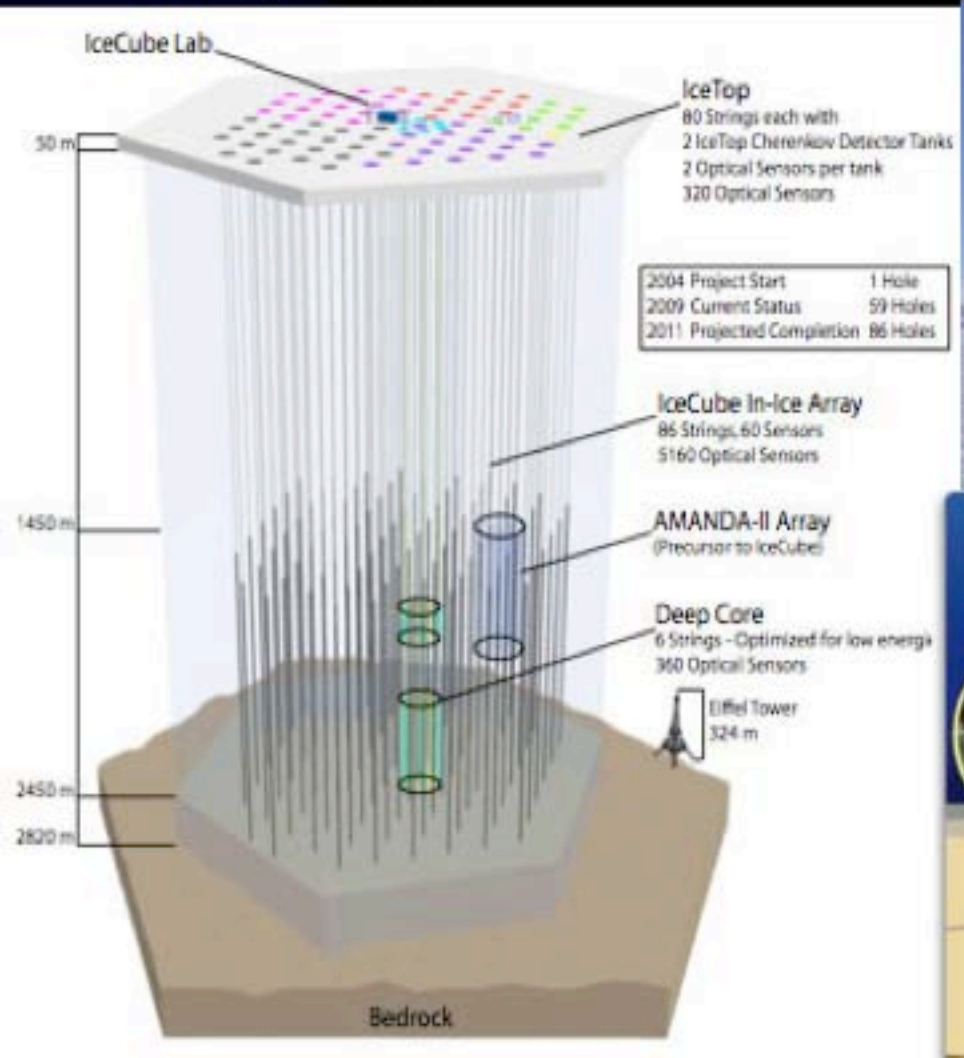
How are we trying to observe them?

Low Energies: underground, reactors, accelerators, CMB

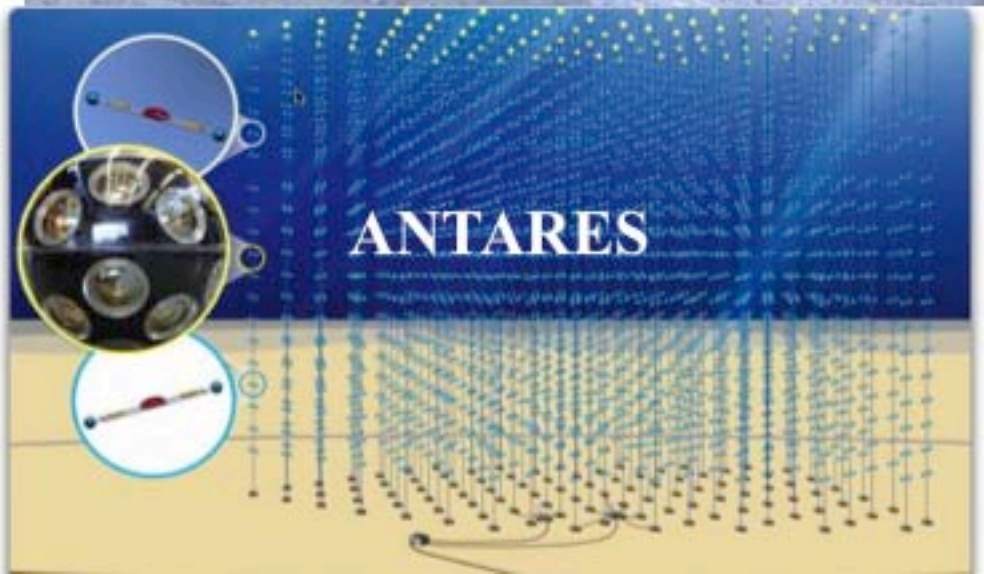
High Energies: air, ice, water km^3 detectors, radio balloons & arrays, future space missions

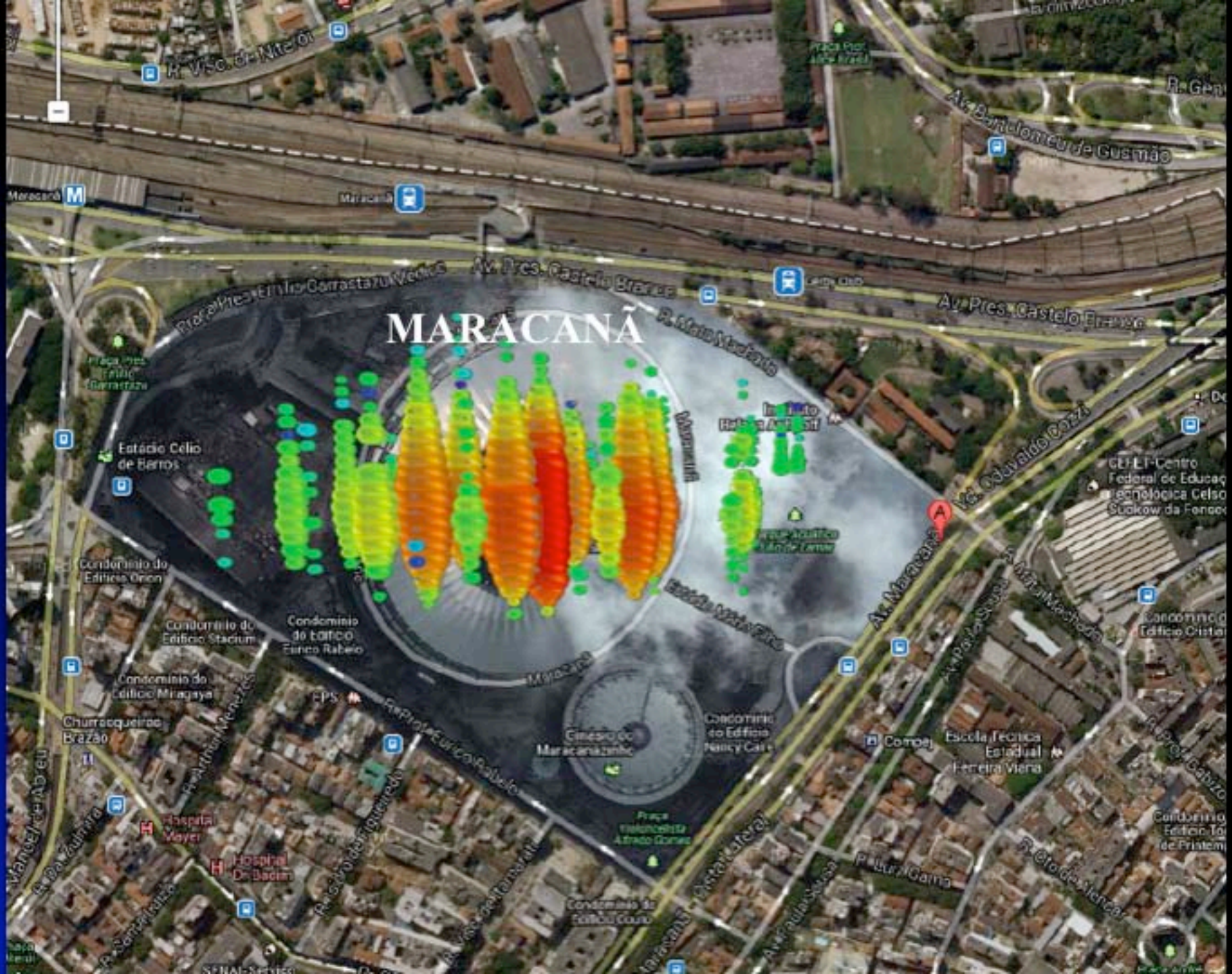
Highest Energy Neutrino Observatories

IceCube

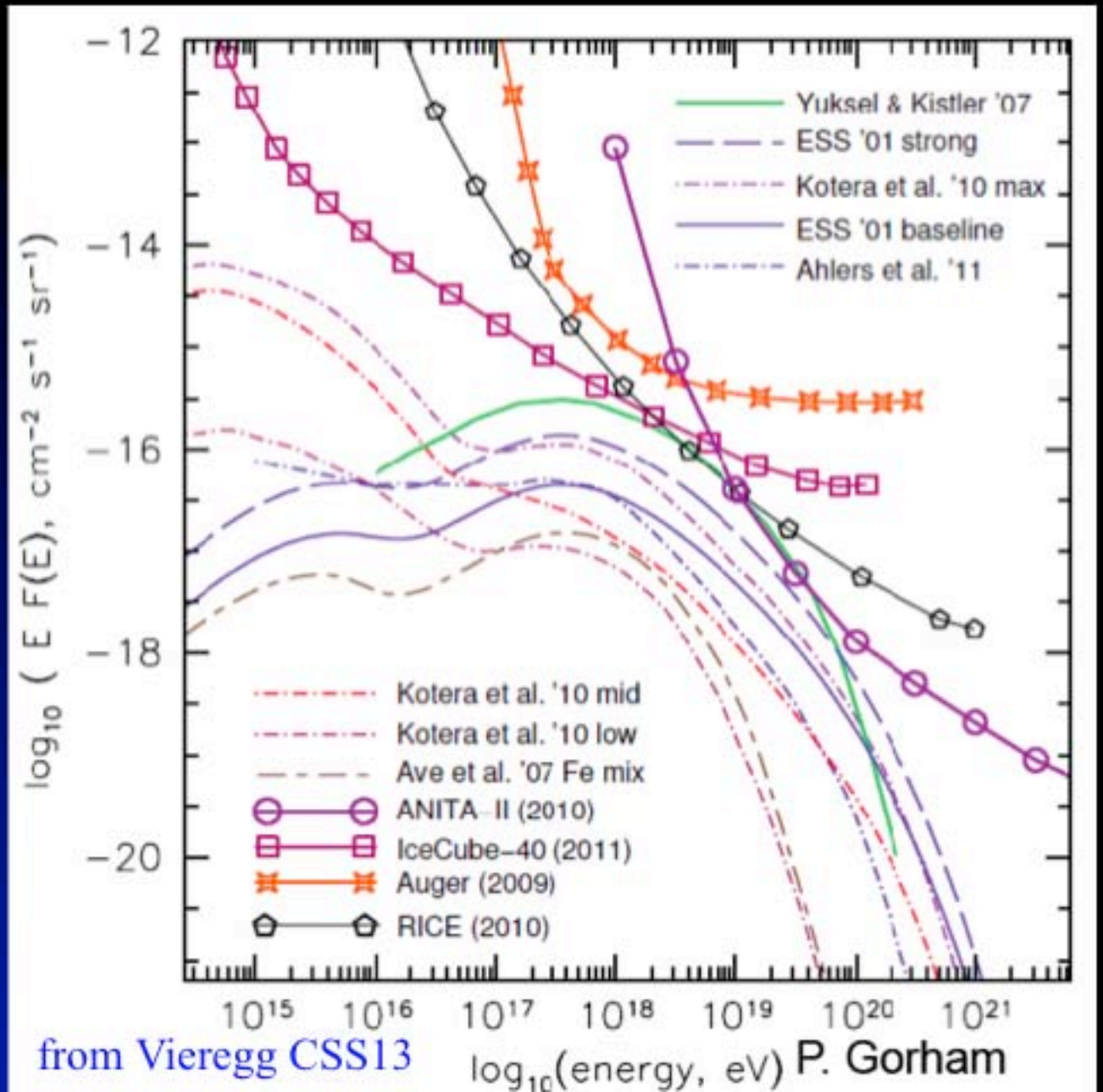


ANITA



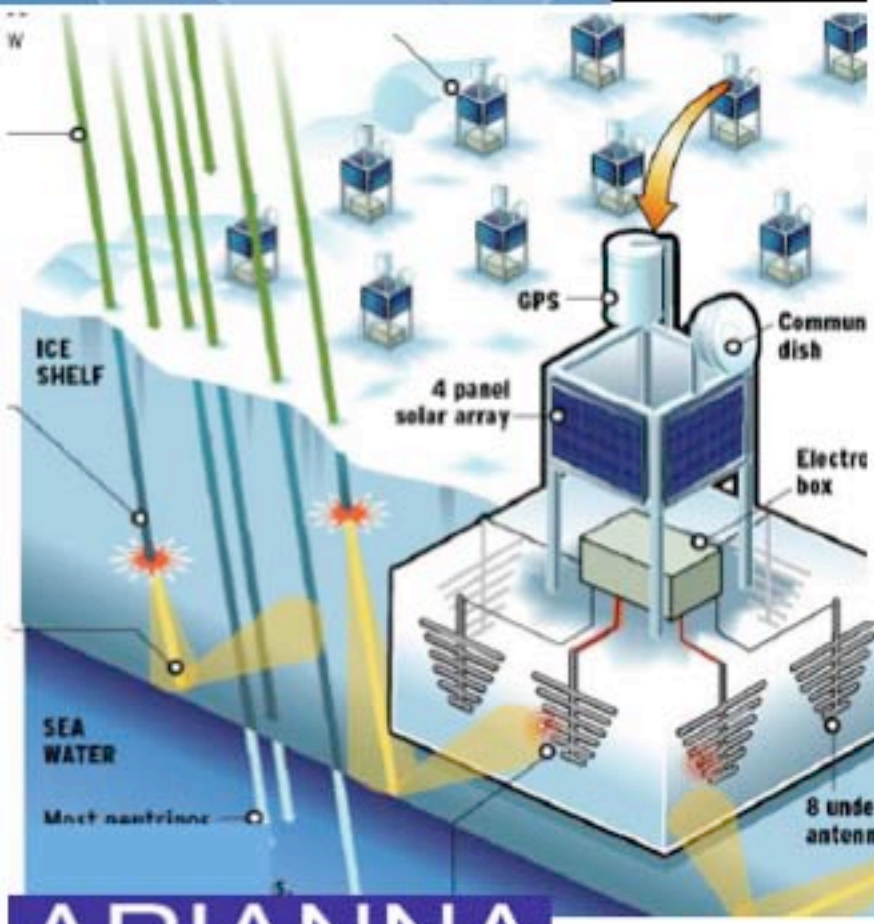

MARACANÃ
Av. Pres. Castelo Branco
Av. Bartolomeu de Guzmão
Estádio Célio de Barros
Condomínio do Edifício Orion
Condomínio do Edifício Stadium
Condomínio do Edifício Enrico Rabelo
Condomínio do Edifício Miragaya
Churrasqueiros Brazão
Hospital Mayer
Hospital Dr. Badim
Ginásio do Maracanãzinho
Condomínio do Edifício Nancy Cassé
Condomínio do Edifício Couto
Escola Técnica Estadual Ferreira Viena
Av. Maracanã
Av. Odovaldo Cozzi
Av. Pedro de Sousa
R. Mata Machado
R. Prof. Eurico Rabelo
R. Luiz Gama
R. Otto de Alencar
Maracanã

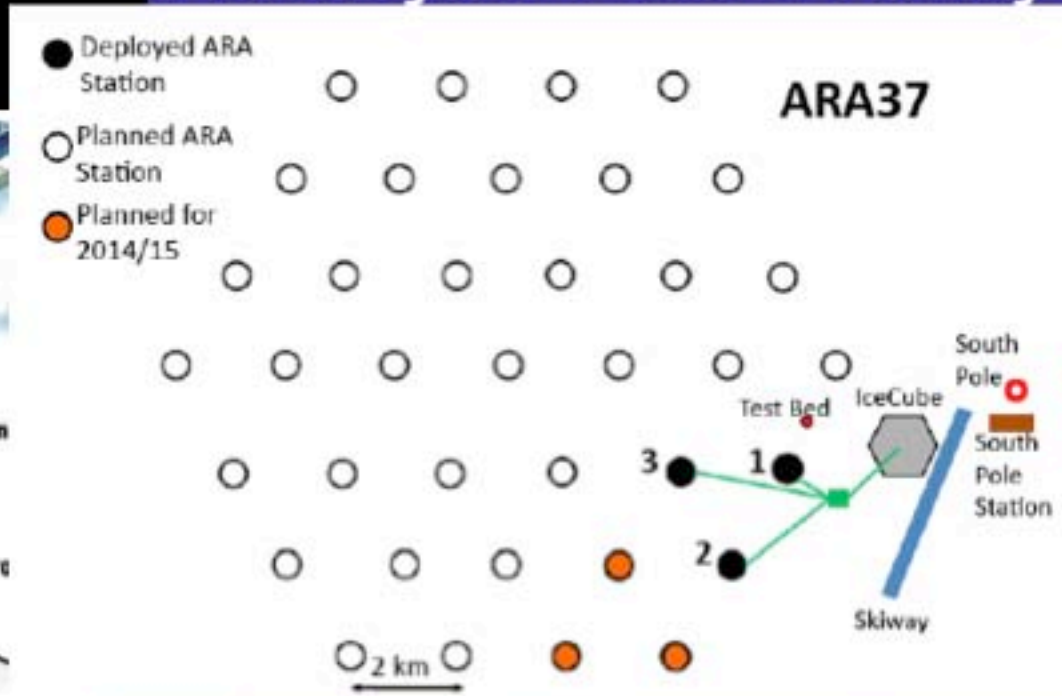
Current Limits



Next Generation

ARA: Askaryan Radio Array

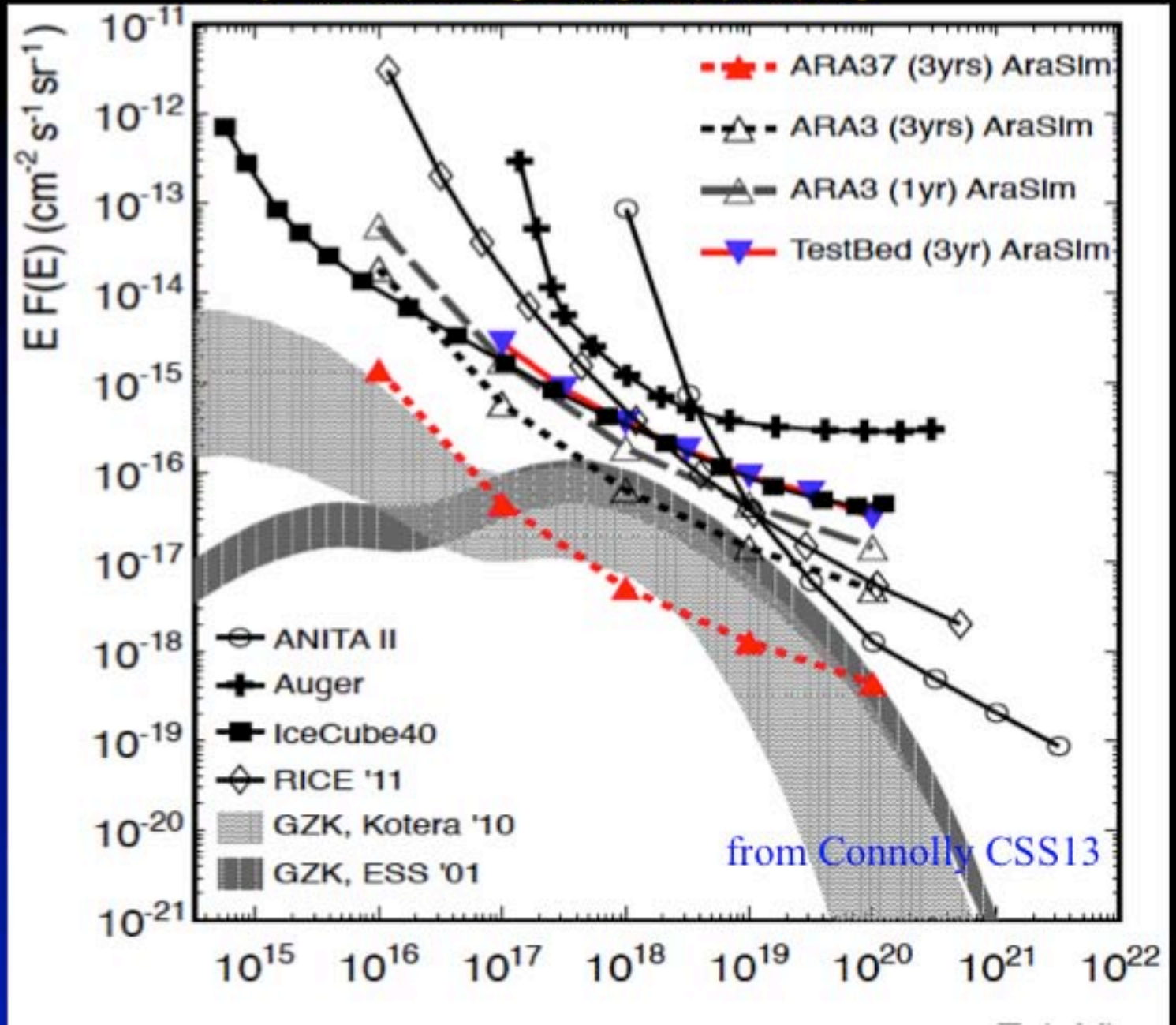




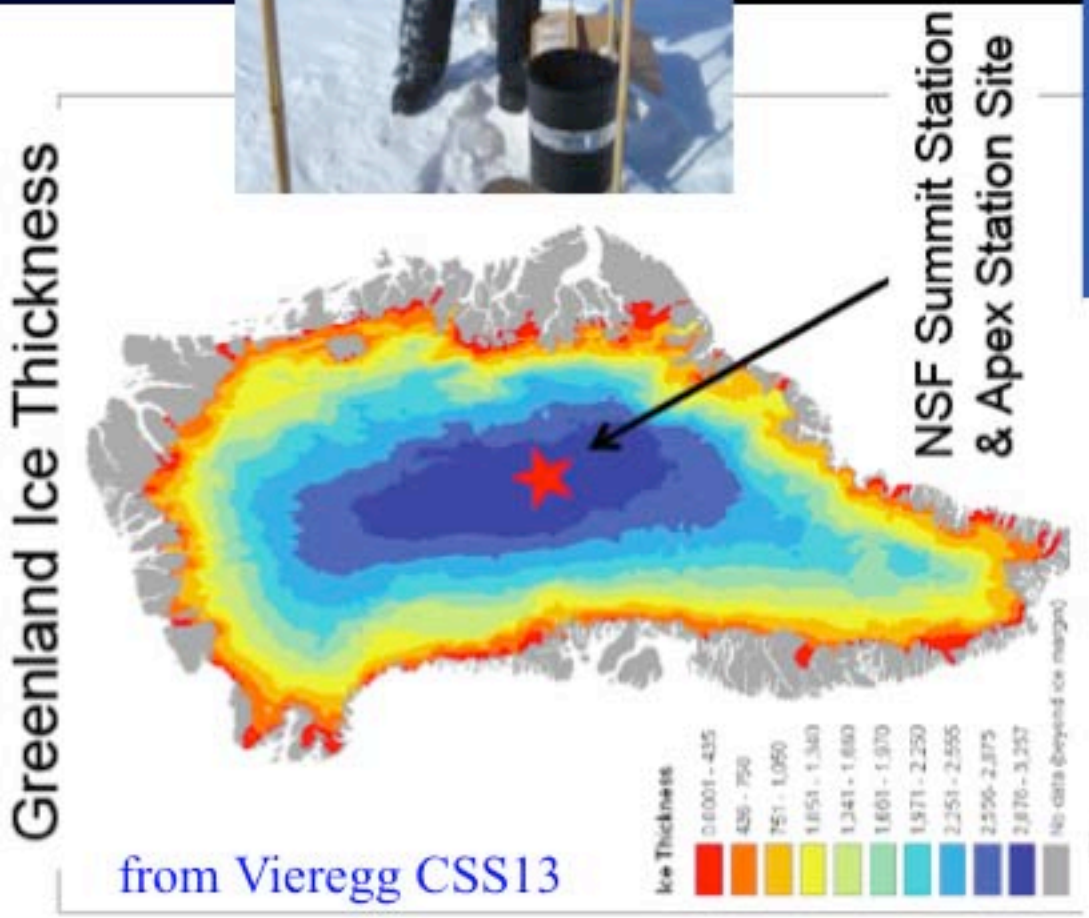
ARIANNA

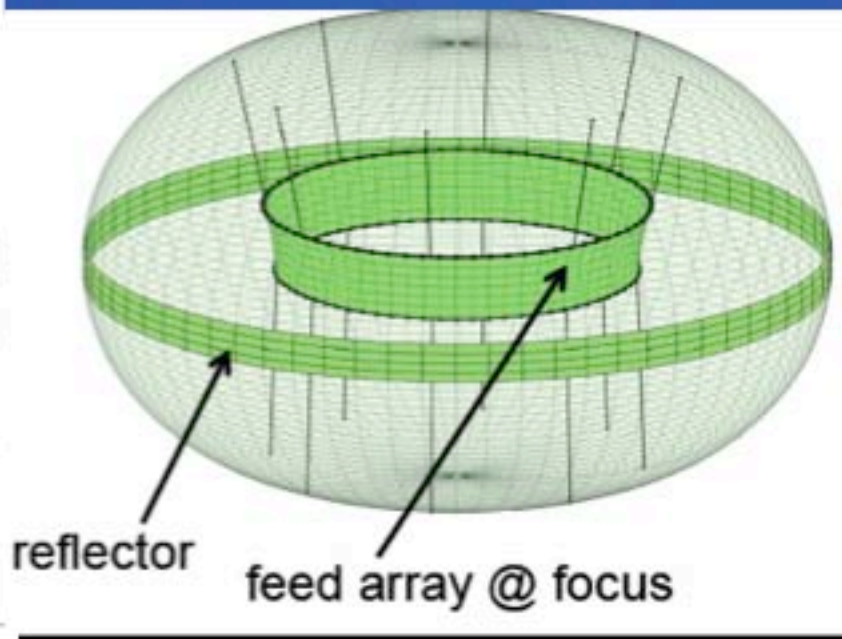
Xiv:1207.3846

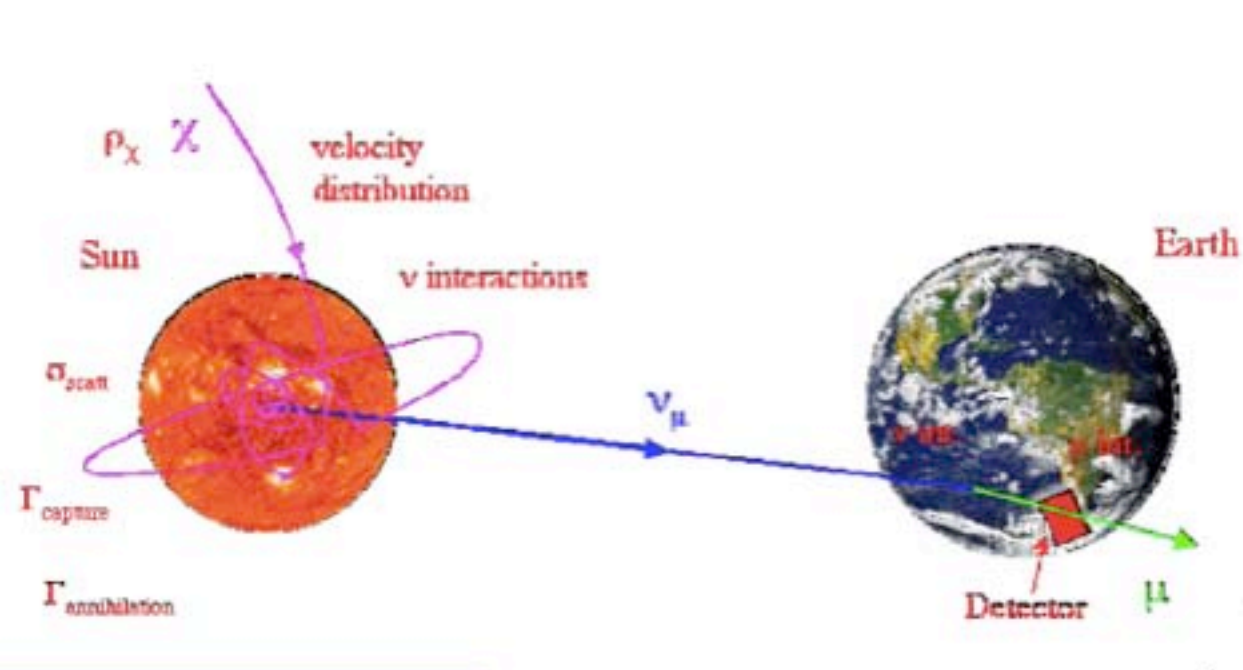
Future Sensitivities

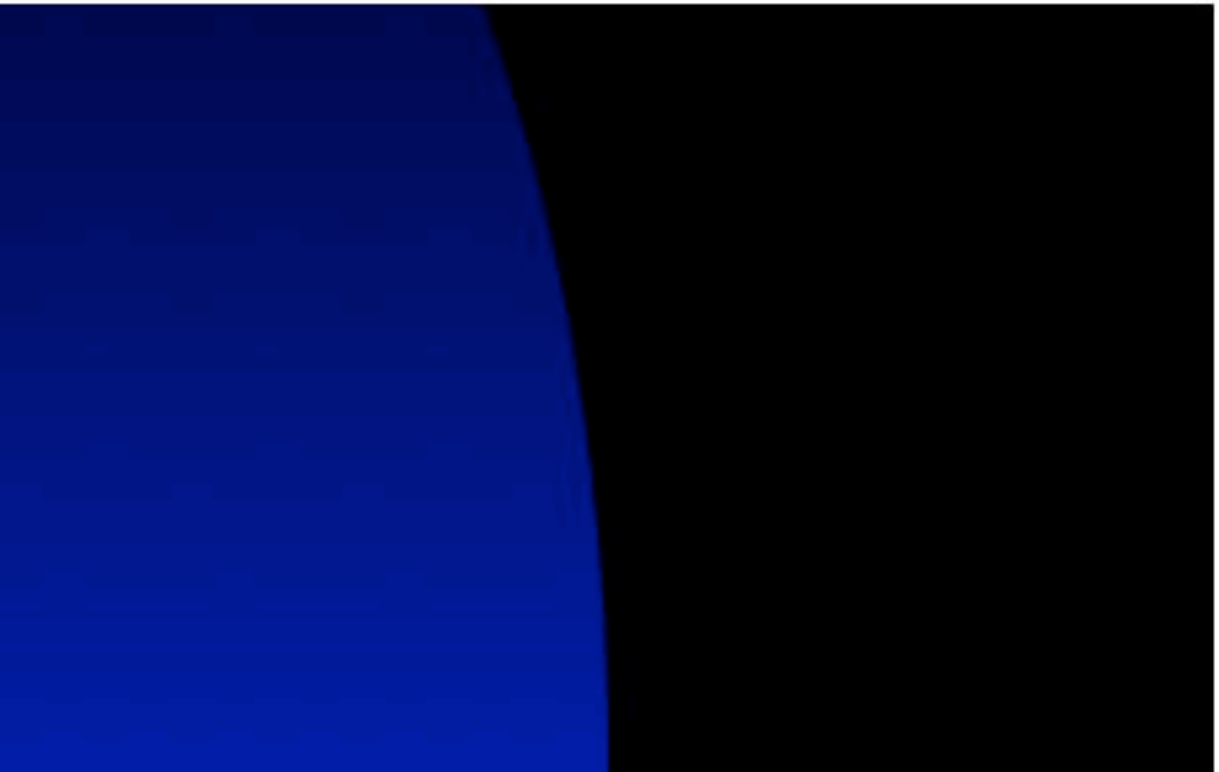


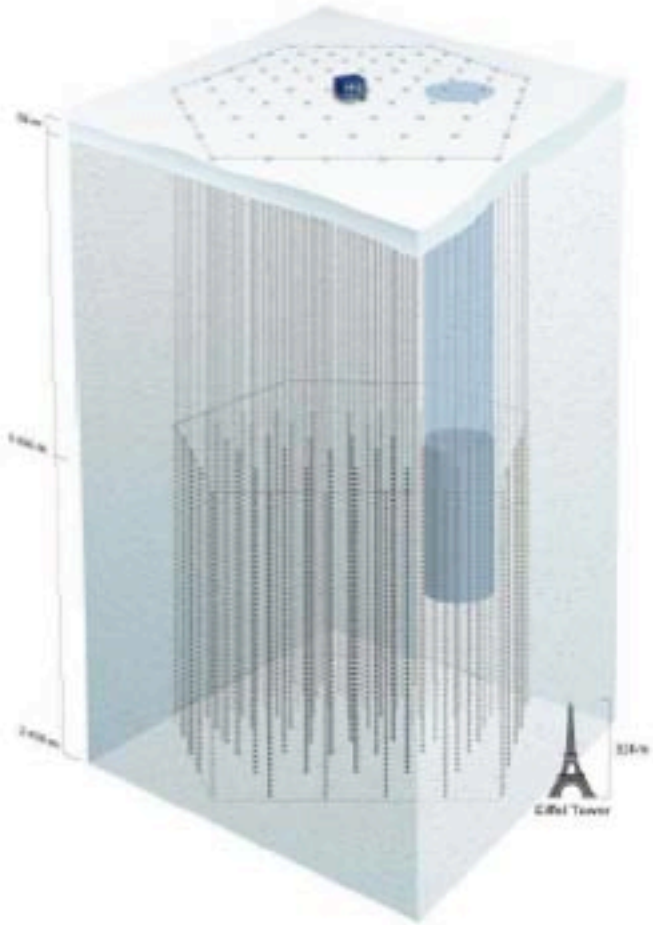
EVA:
ExaVolt Antenna


Greenland Ice Thickness
NSF Summit Station
& Apex Station Site
Ice Thickness
0.0001 - 435
436 - 750
751 - 1,050
1,051 - 1,340
1,341 - 1,600
1,601 - 1,970
1,971 - 2,250
2,251 - 2,555
2,556 - 2,875
2,876 - 3,257
No data (beyond ice margin)
from Vieregg CSS13


reflector
feed array @ focus

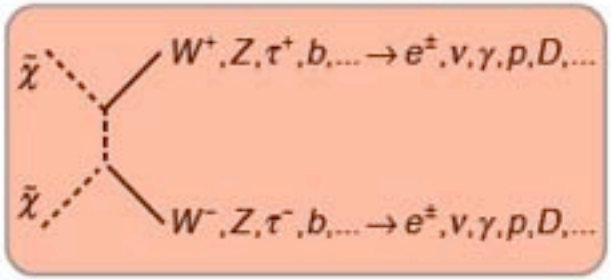

ρ_χ χ
velocity distribution
Sun
ν interactions
Earth
σ_{scatt}
ν_μ
$\Gamma_{capture}$
$\Gamma_{annihilation}$
Detector
μ

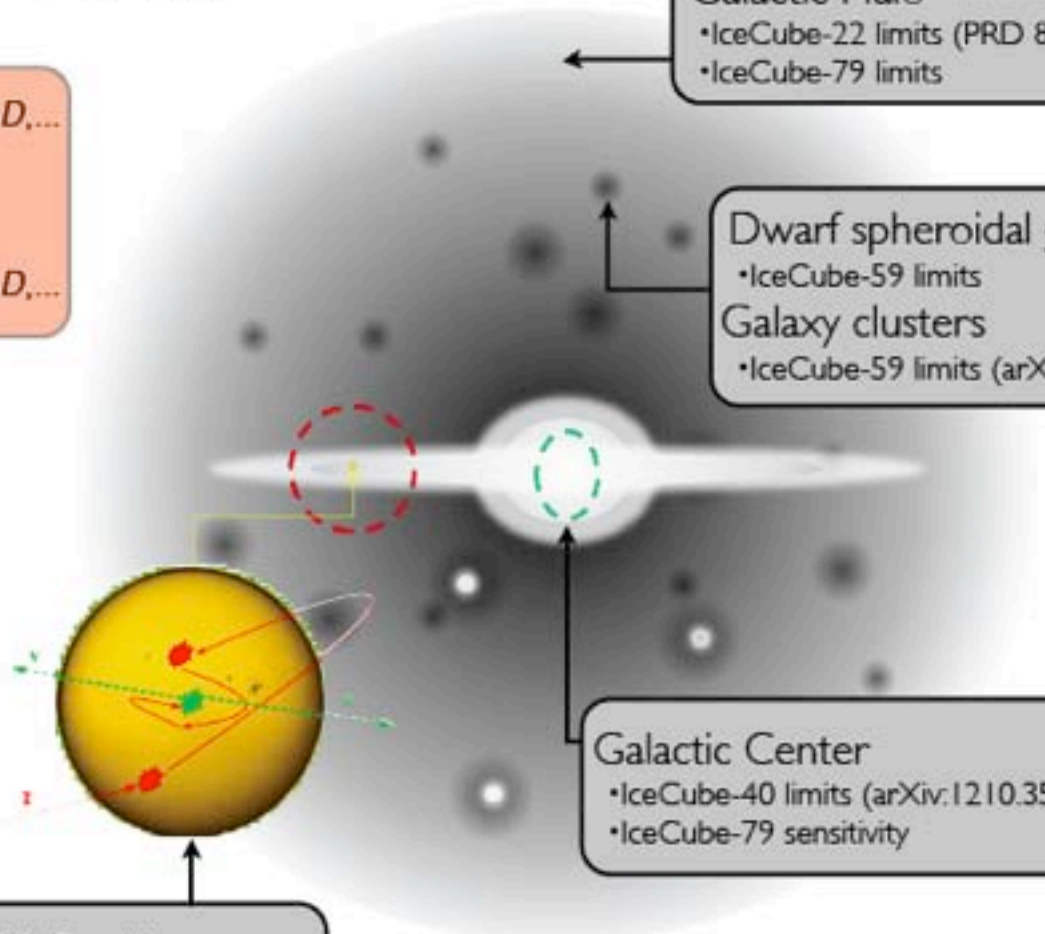




Summary of IceCube Searches

Search for dark matter annihilations to ν at E_ν from 10 GeV – 10 TeV





Galactic Halo
- IceCube-22 limits (PRD 84 (2011) 022004)
- IceCube-79 limits

Dwarf spheroidal galaxies
- IceCube-59 limits

Galaxy clusters
- IceCube-59 limits (arXiv:1210.3557 2012)

Galactic Center
- IceCube-40 limits (arXiv:1210.3557 2012)
- IceCube-79 sensitivity

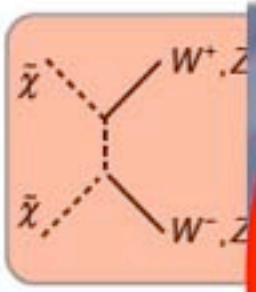
Local sources: Sun (& Earth)
- IceCube-79 limits (PRL 110 (2013) 131302)

Image: M. Strassler

Summary of IceCube Searches

Search for dark matter annihilations to ν at

E_ν from



PRD 84 (2011) 022004)

idal galaxies
ts
rs
ts (arXiv:1210.3557 2012)

210.3557 2012)

Local sources: Sun (& Earth)
- IceCube-79 limits (PRL 110 (2013) 131302)

Image: M. Strassler

What other Astroparticles may we observe?

What other Astroparticles may we observe?

Neutrons? Muons? (Monopoles?)

What other Astroparticles may we observe?

Neutrons? Muons? (Monopoles?)

10 PeV Muons from the Sun

EeV Neutrons from the Galactic Center

Topological defects

Primordial Black Holes

Q-balls

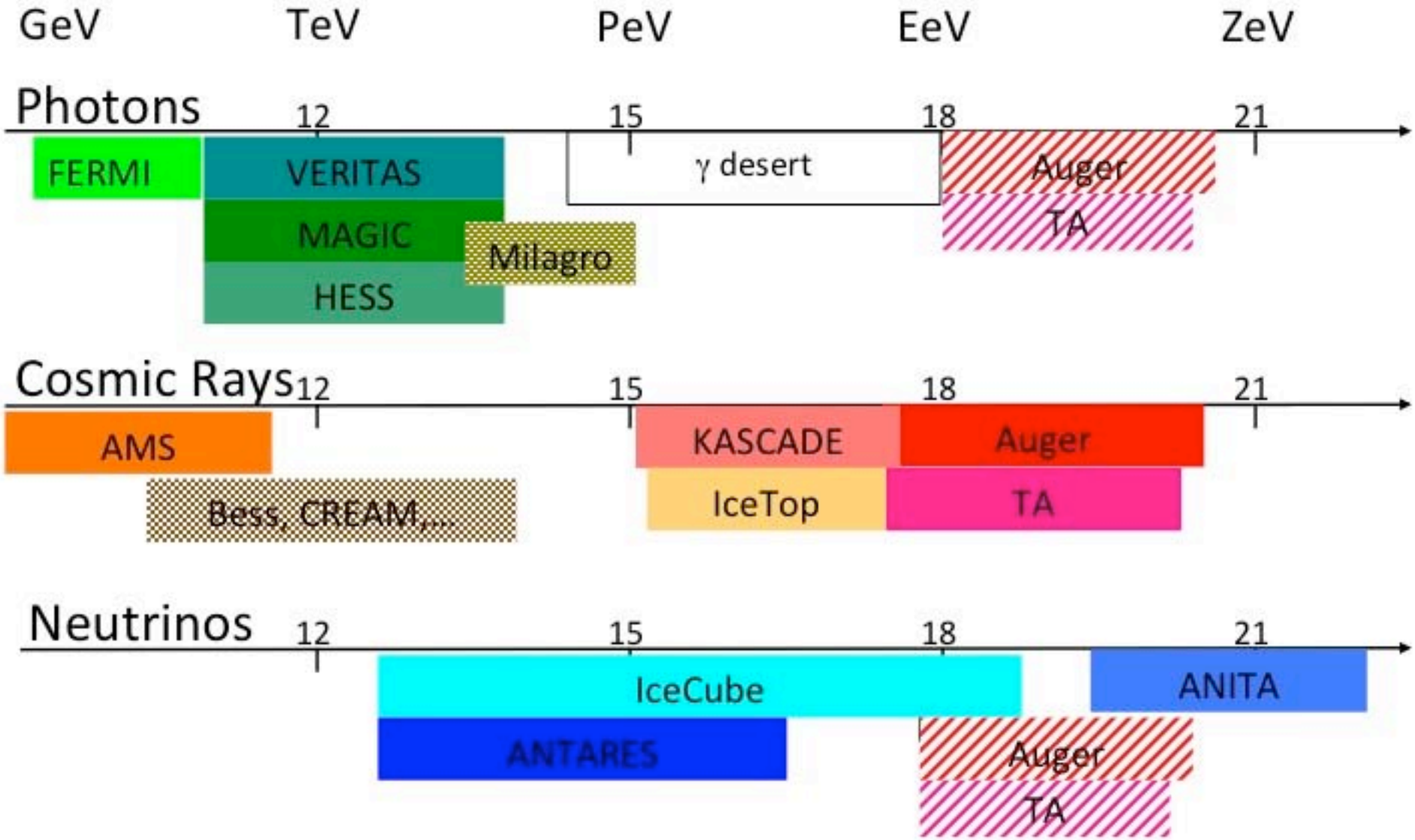
Strangelets

Nucleorites

etc...

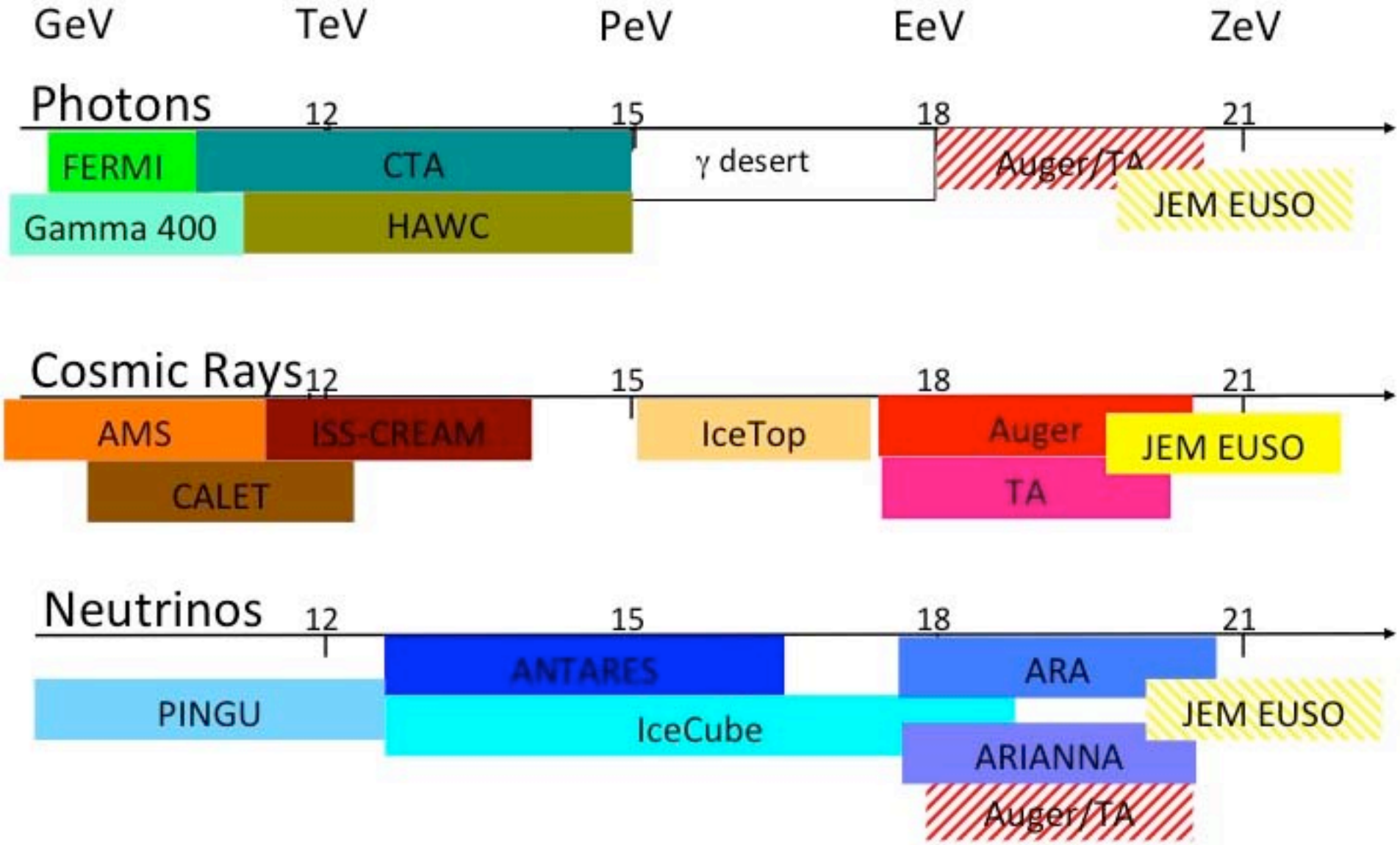
Current Detectors

Cosmic Particles 2013

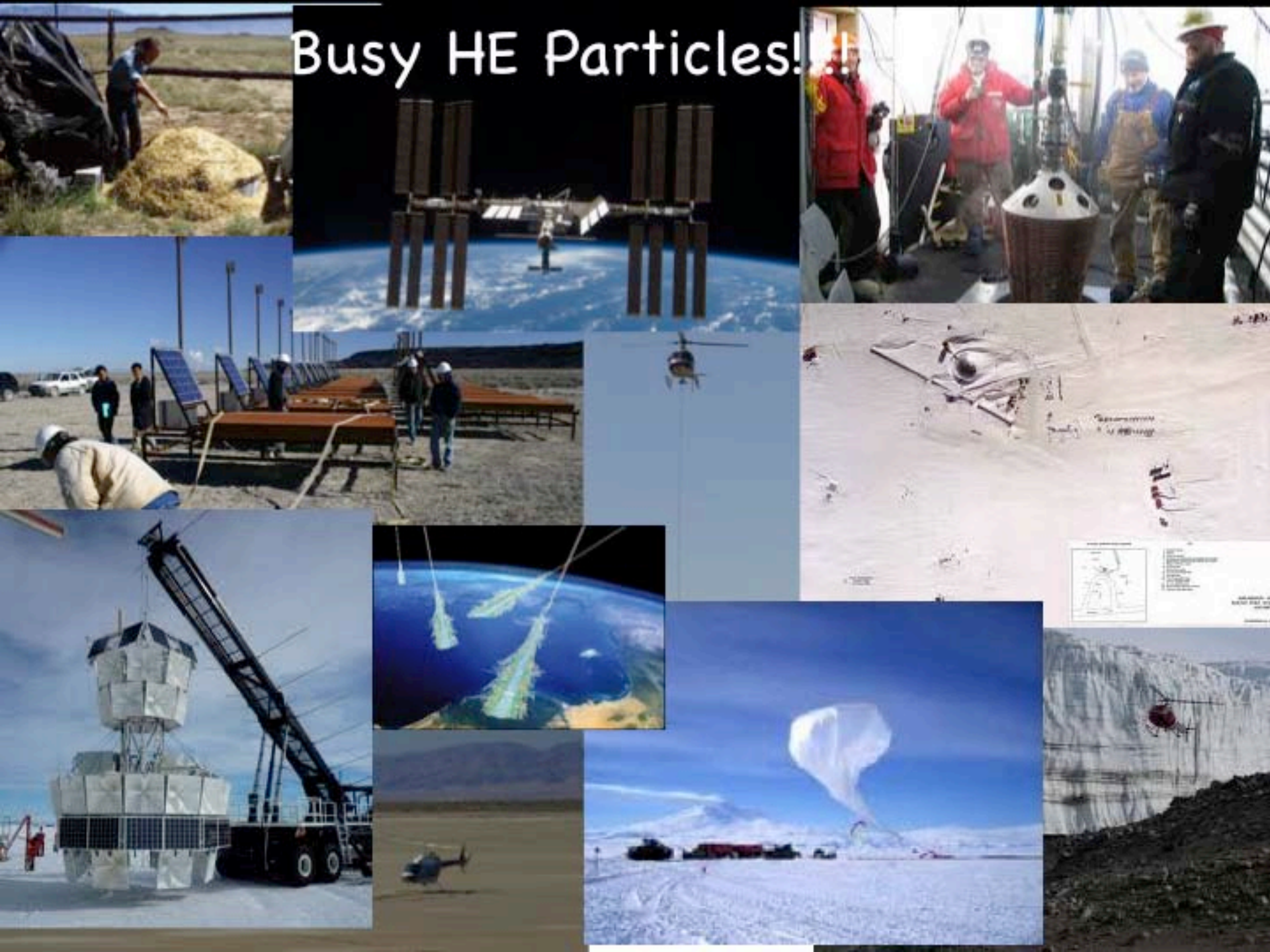


Future Detectors

Cosmic Particles 2020



Busy HE Particles!!!



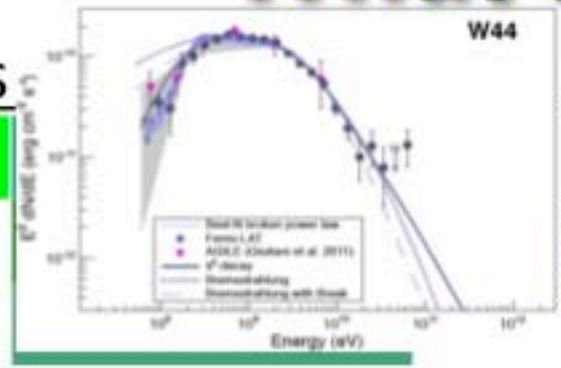
Cosmic Particles 2013

What a great YEAR!

GeV TeV PeV EeV ZeV

Photons

FERMI



5 18 21

γ desert

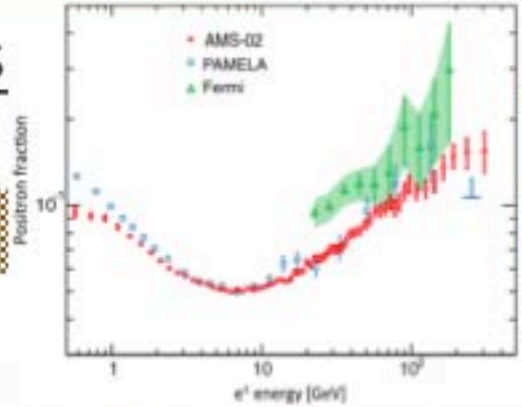
Auger

TA

Cosmic Rays

AMS

Bess,



18 21

KASCADE

Auger

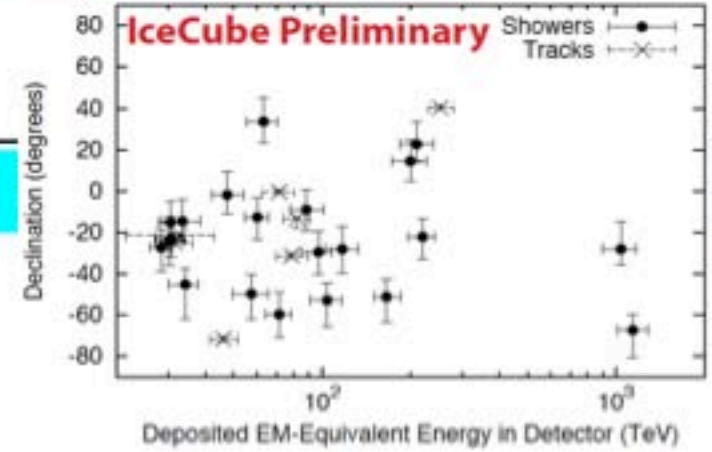
IceTop

TA

Neutrinos

IceCube

ANTARES



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