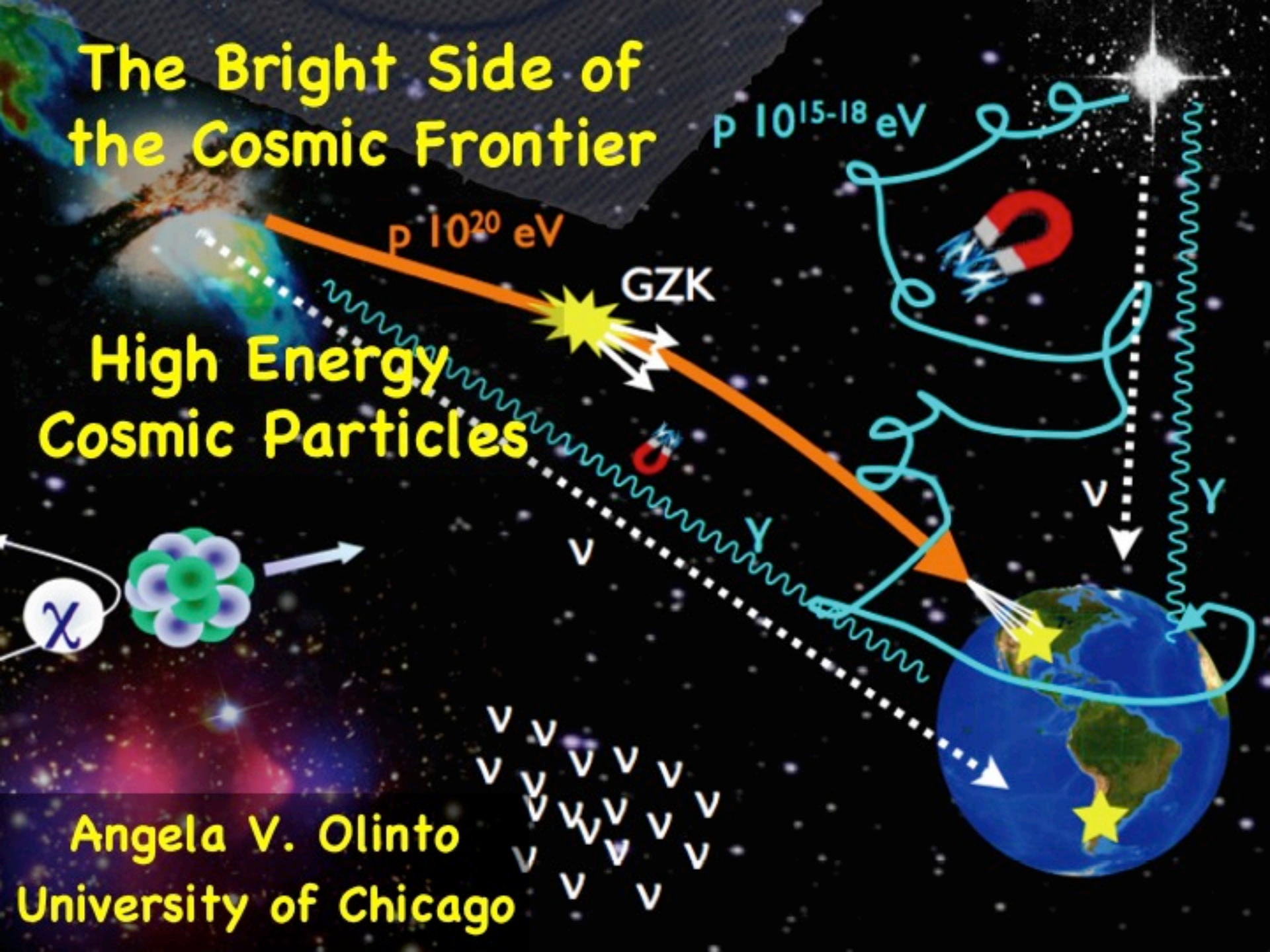
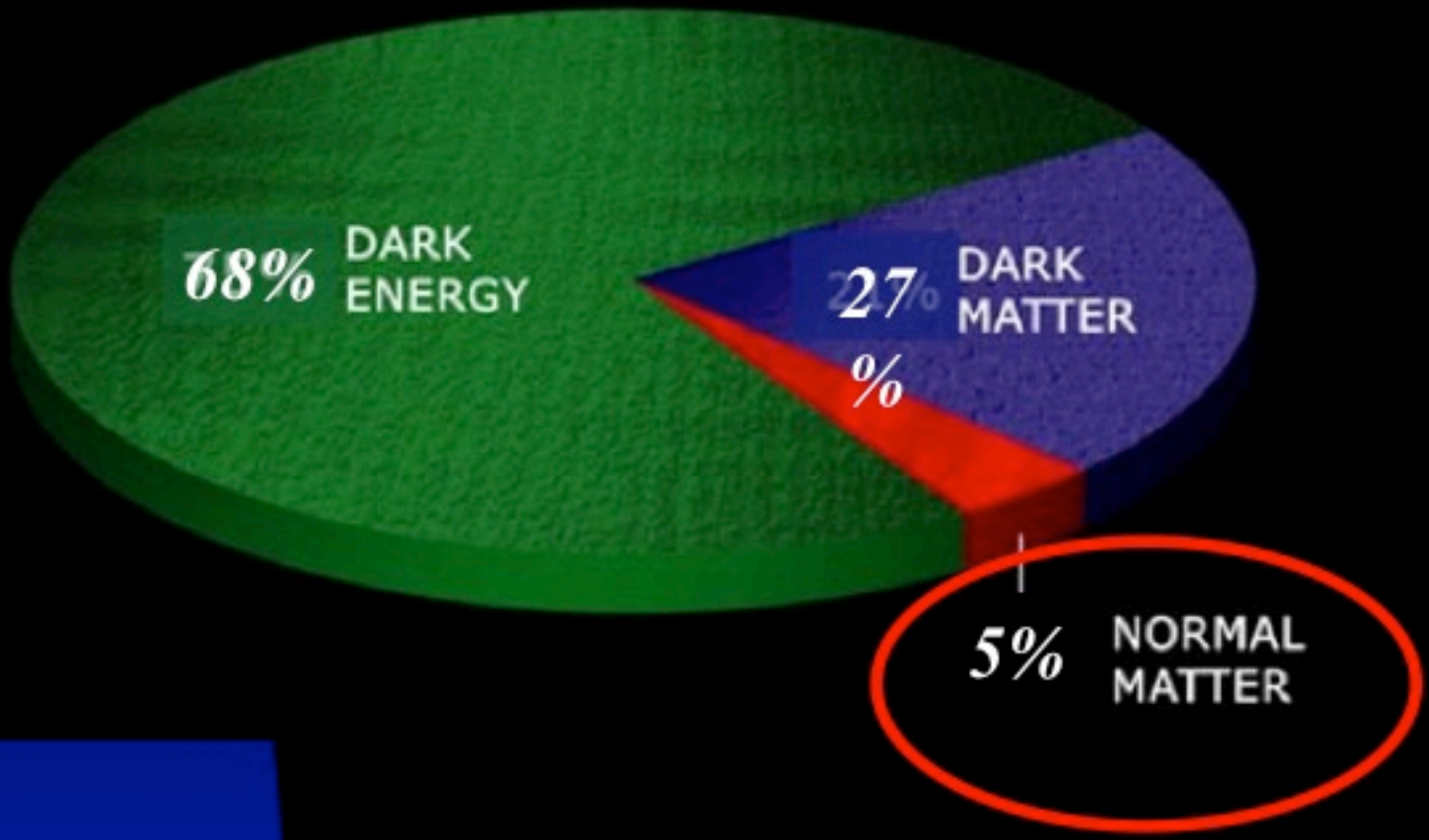
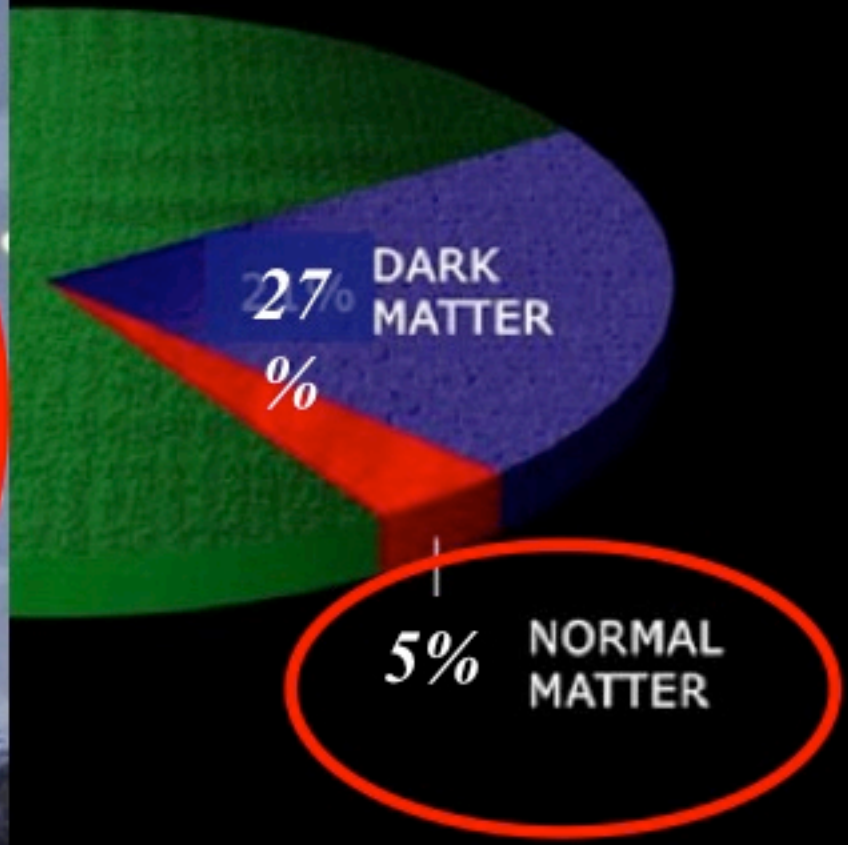

The Bright Side of the Cosmic Frontier
p $10^{15\text{-}18}$ eV
p 10^{20} eV
GZK
High Energy Cosmic Particles
ν
γ
χ
Angela V. Olinto
University of Chicago

5% of MATTER



5% of MATTER

NOT DARK MATTER & NOT DARK ENERGY



5% of MATTER

Why not ~ 0% ??

5% of MATTER

Why not ~ 0% ??

- Cosmological MATTER-ASYMMETRY need physics Beyond the SM (BSM) to explain why 10^8+1 quarks for every 10^8 antiquarks in the early universe

- the New Physics must couple to us

- Cosmology suggests the New Physics is probably at accessible energies

Baryogenesis

Possibilities within popular theories BSM

Leptogenesis: decay of very heavy right handed neutrinos

Electroweak Baryogenesis: new bosons providing 1st order phase transition

Affleck-Dine: evolution and decay of squark/ slepton condensate

many other ideas

- **Need nonstandard CP violation**:

➡ Electric Dipole Moments

➡ CPV in long baseline neutrino oscillations

The 3 Frontiers contribute to solve Problem

CF-6 Summary

Baryogenesis: EDMs, CP violation in neutrino sector, and inflation scale are key measurements

CF-6 Summary

Baryogenesis: EDMs, CP violation in neutrino sector, and inflation scale are key measurements

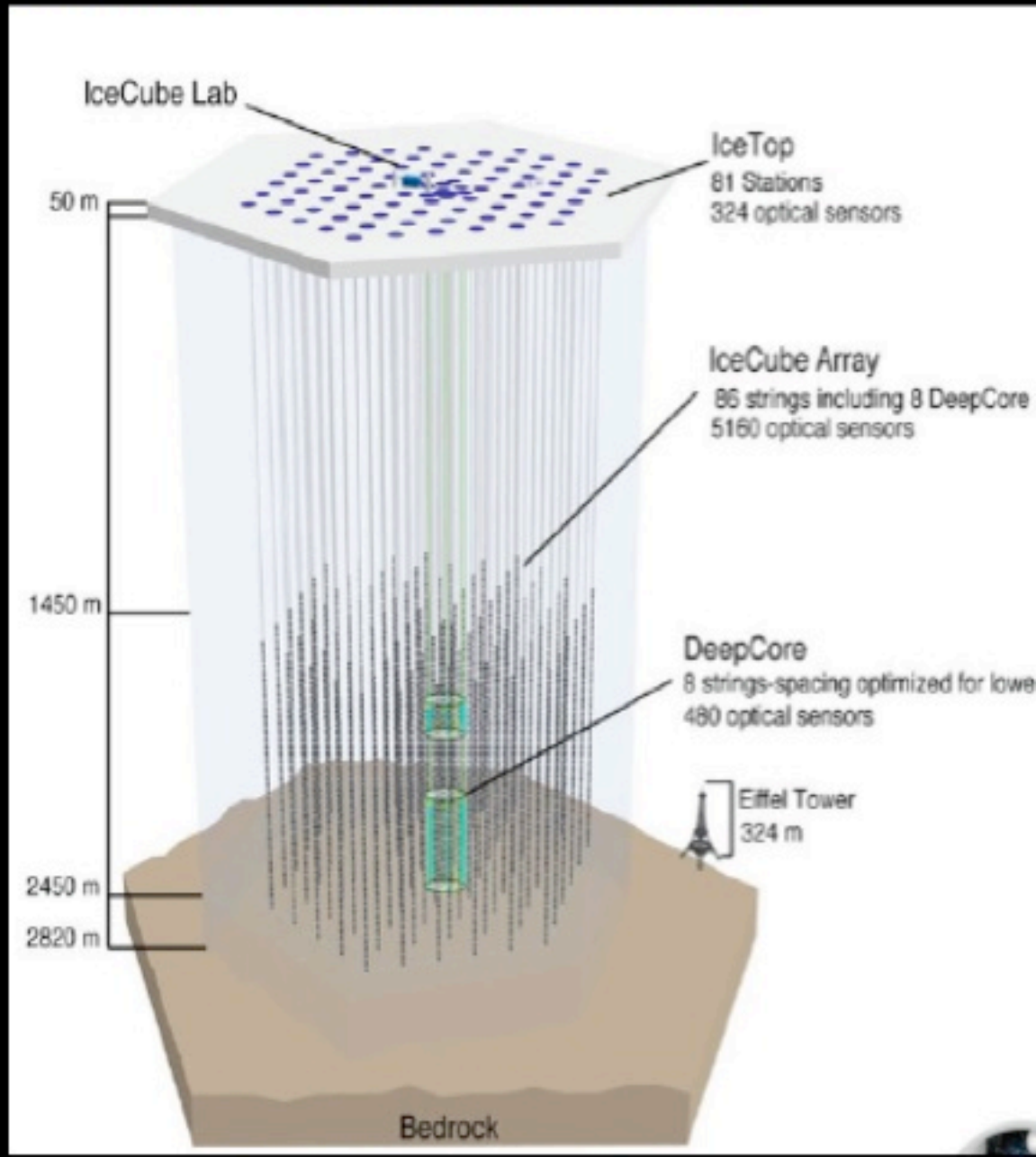
Neutrino mass hierarchy: with SN neutrinos (LBNE) and atmospheric neutrinos (PINGU)

IceCube Detector @ South Pole

First **km-scale**
Neutrino detector
~ 5,000 10" PMTs
78 strings: 125 m apart
depth to 2.8 km

Original Target:
TeV-PeV neutrinos

Now reaches ~ 10 GeV
with Deep Core Infill
8 strings 72m



PINGU

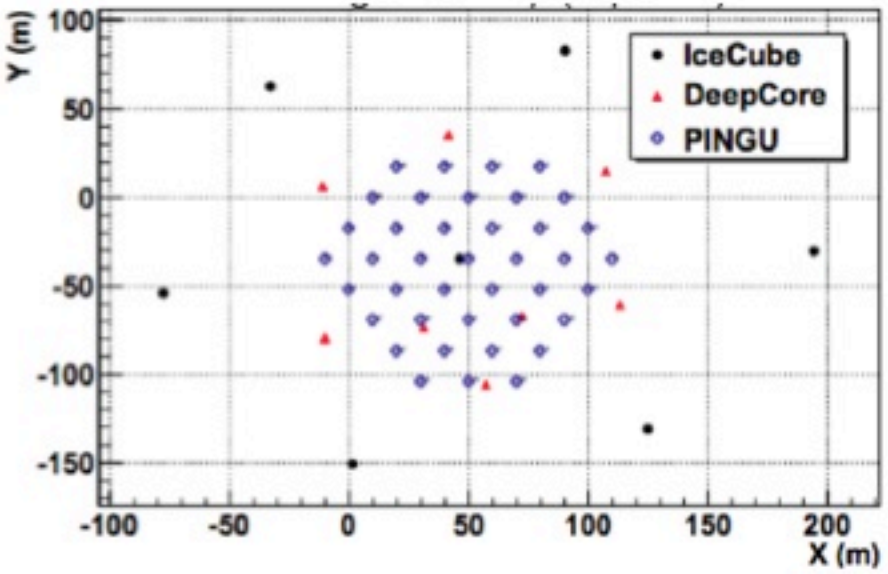
Precision IceCube Next Generation Upgrade

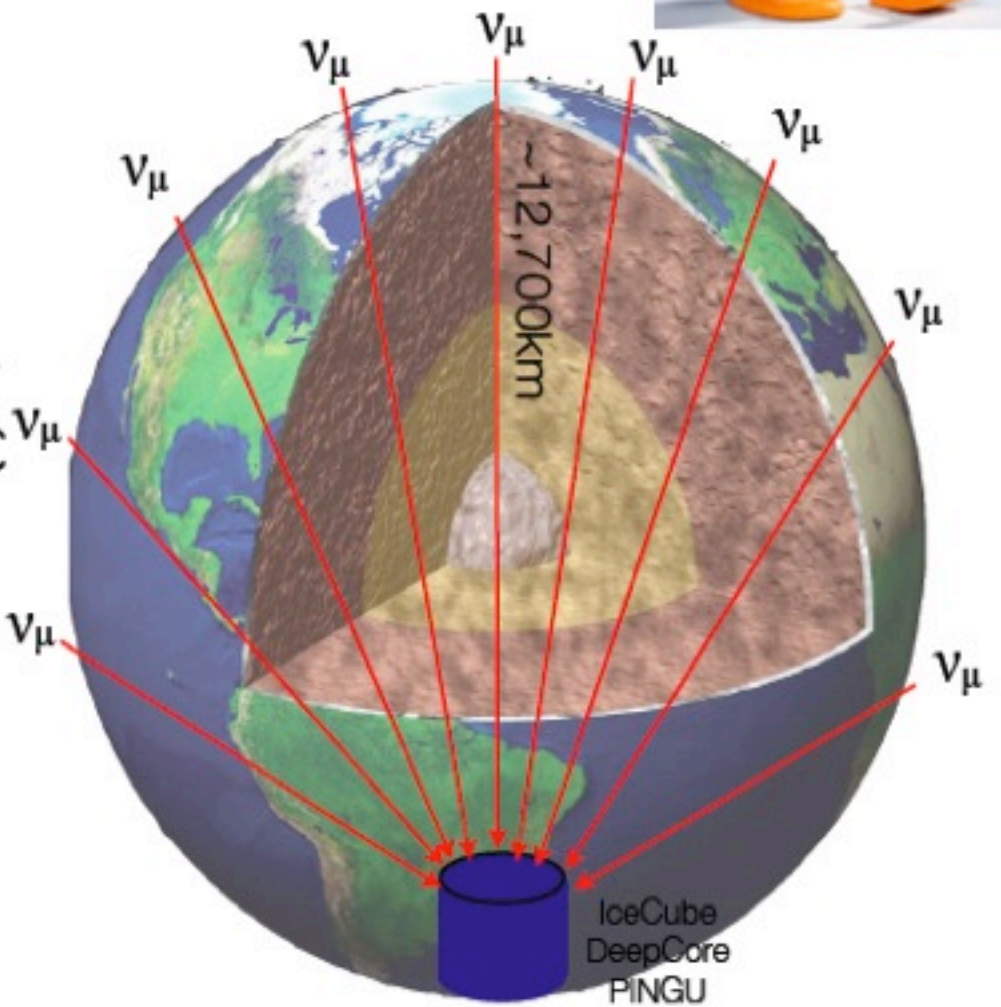
Atmospheric neutrinos provide many values of L and E

Very large baselines for probing matter effects (~12,700 km)

Add ~40 strings inside DeepCore

20-25m string spacing (73 for DC





CF-6 Summary

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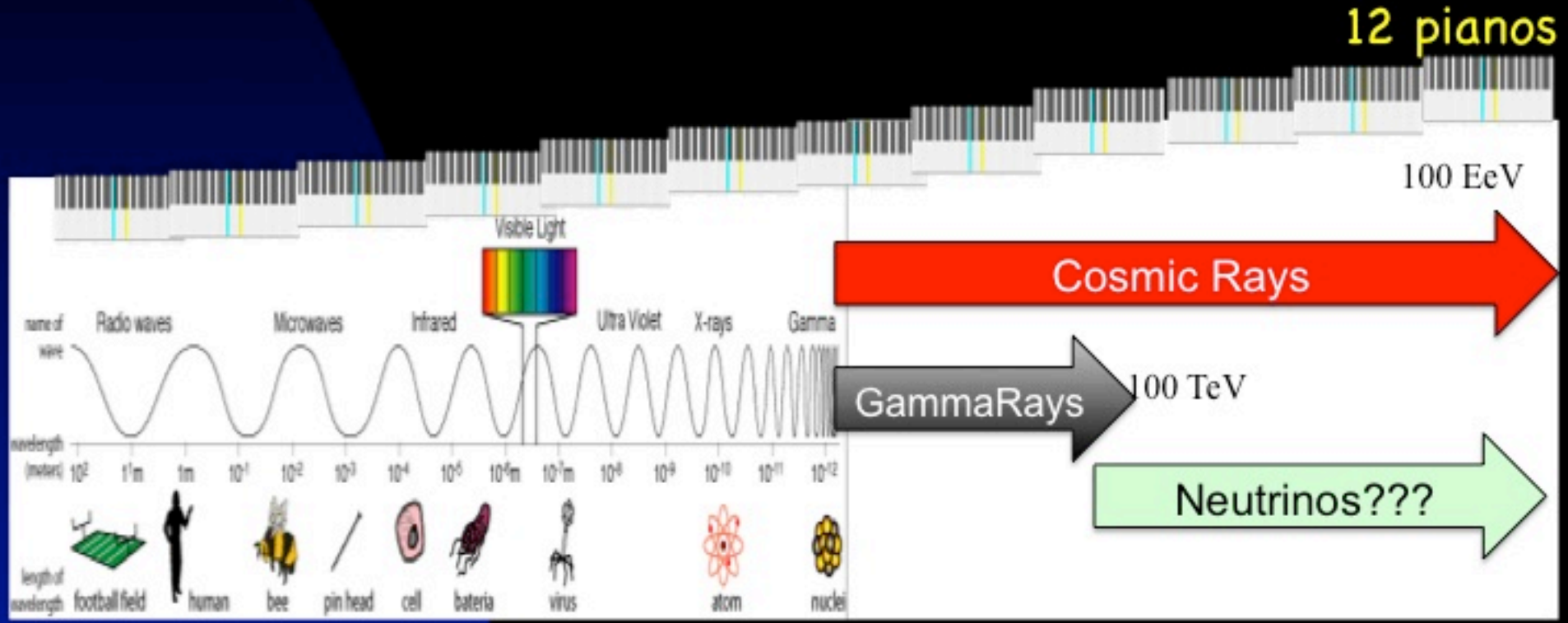
Origin of highest energy particles in the universe (multi-messenger campaign)

+ BSM tests with cosmic particles

Highest Energy Cosmic Particles



CF-6 Summary

Origin of highest energy particles in the universe (multi-messenger campaign)

Fundamental physics accessible with next generation instruments

Control of astrophysical systematics with precision VHE gamma-rays (**CTA**)

Neutrino interactions at high energies to be measured with GZK neutrinos (**ARIANNA, ARA,** ...)

300 TeV C-M interactions to be measured with UHECRs (**JEM-EUSO**)

Probing Planck scale physics is now possible

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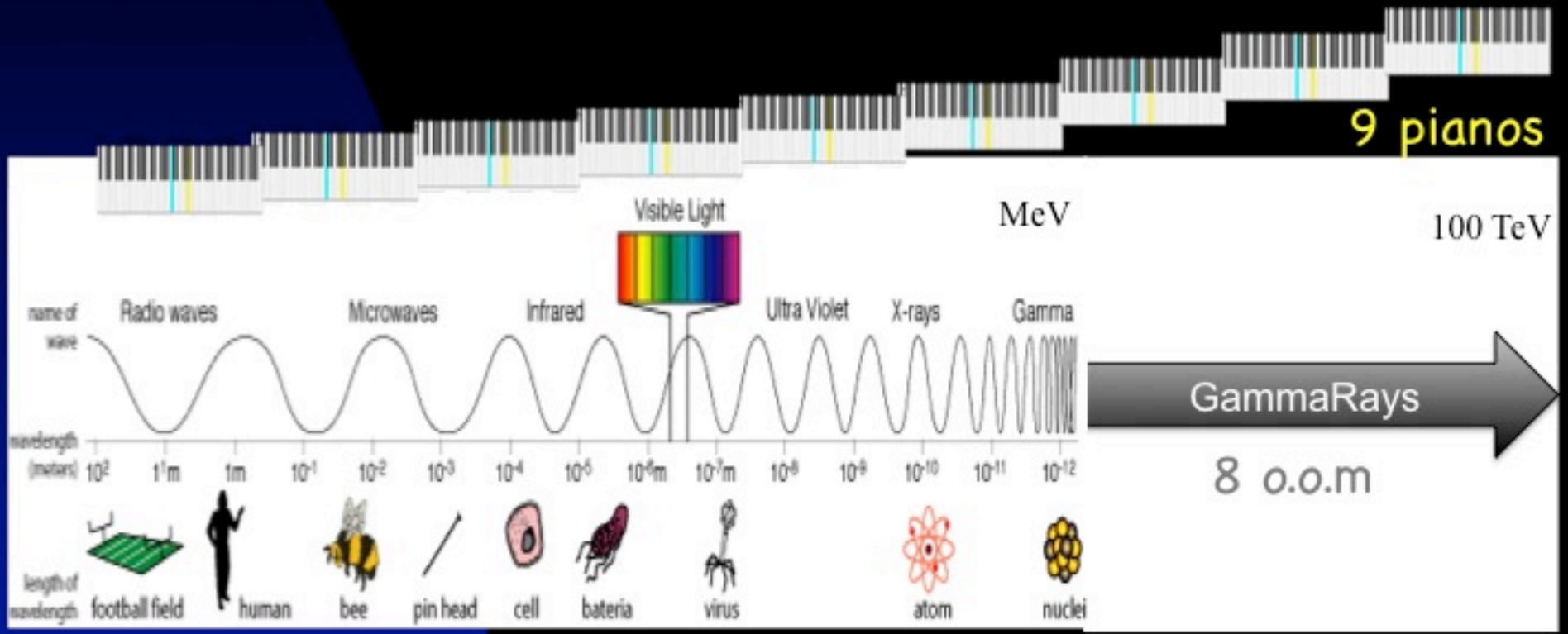
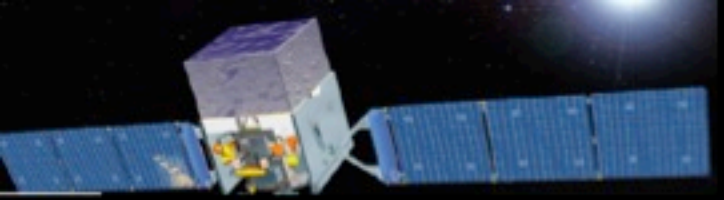
Gamma-ray probe of Planck scale physics



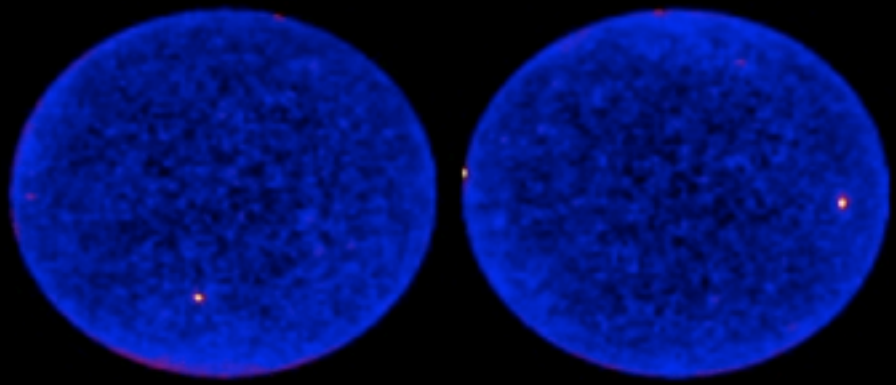
Lorentz Invariance Violation

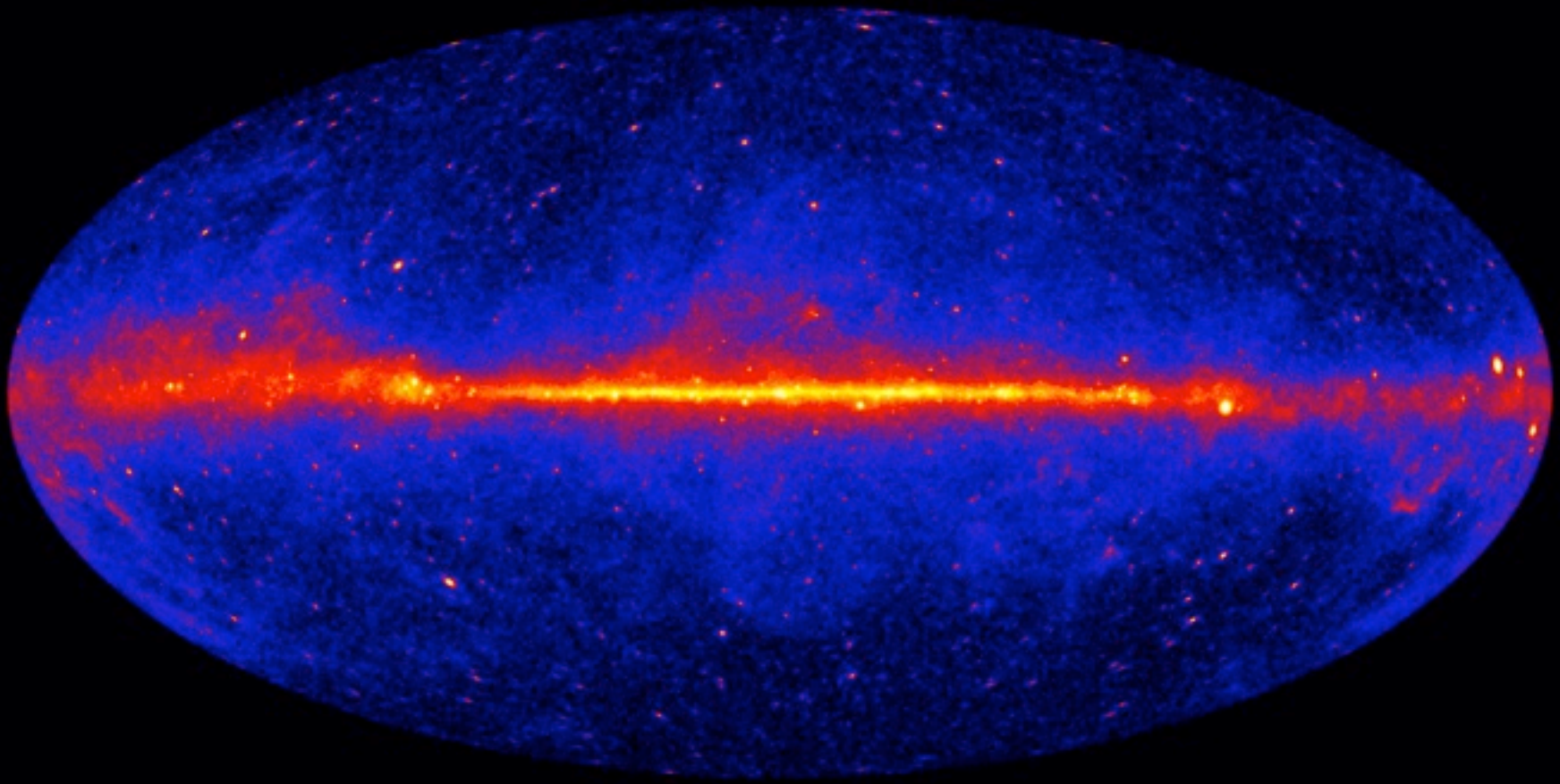
- Vacuum dispersion relation for photons
- Energy dependent speed of light
- Physics at Planck scale
  - Quantum Gravity
  - String Theory
- Can not directly probe this energy scale

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

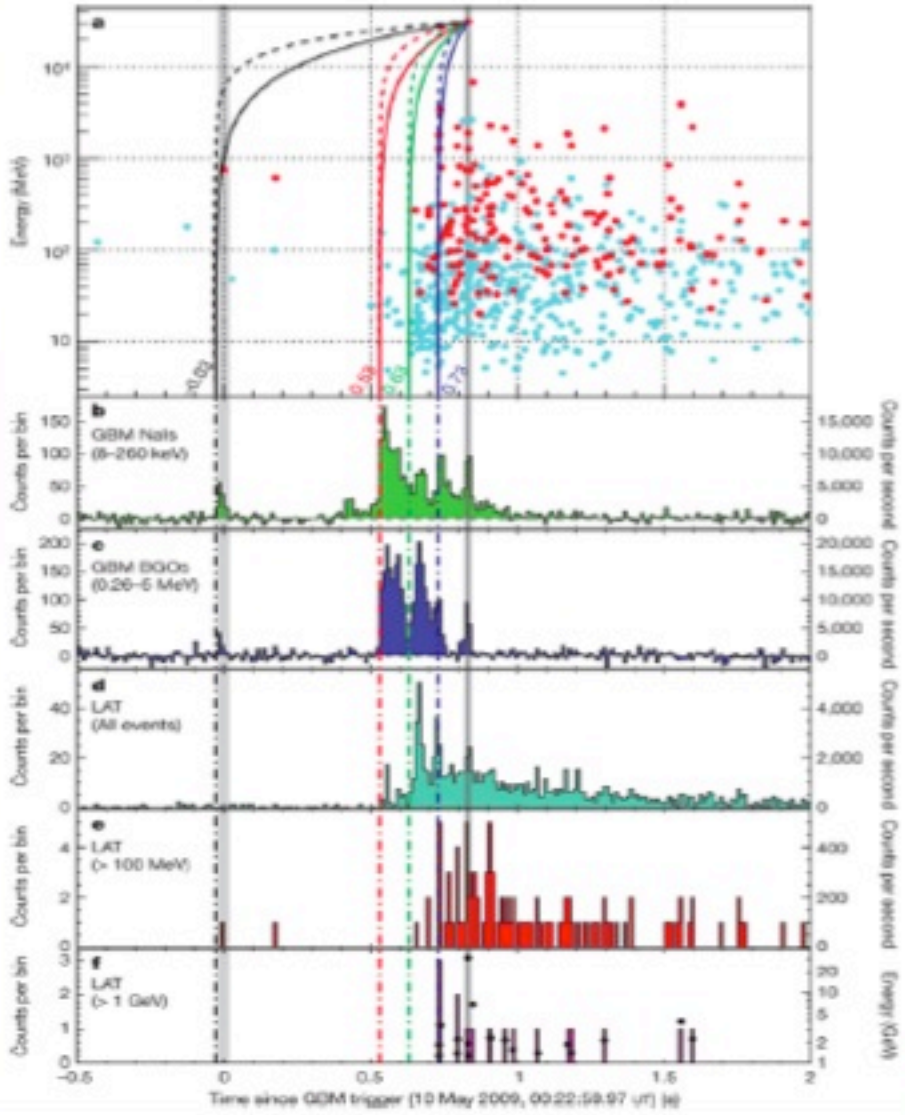


Fermi





Testing LIV with Gamma-Ray Bursts

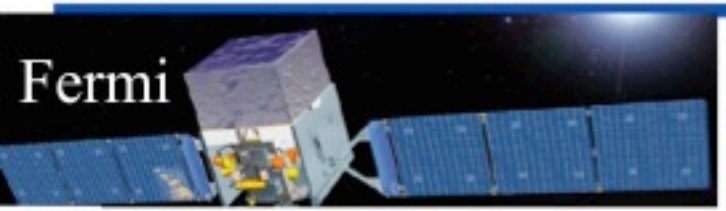


- GRB 090510
- Z = 0.9
- Timescale < 1 sec
- **E^1_{LIV}>1.5x10^{19} GeV**
- E^2_{LIV}>3x10^{10} GeV
- Background: Source effects – energy dependent acceleration times

From N. Otte, SLAC meeting

N. Otte talk DPF:145, 16-Aug-2013, 8:45

Photon Dispersion Limits from GRB 090510



Fermi, Nature, vol 462, p331 (plus comment on p291)

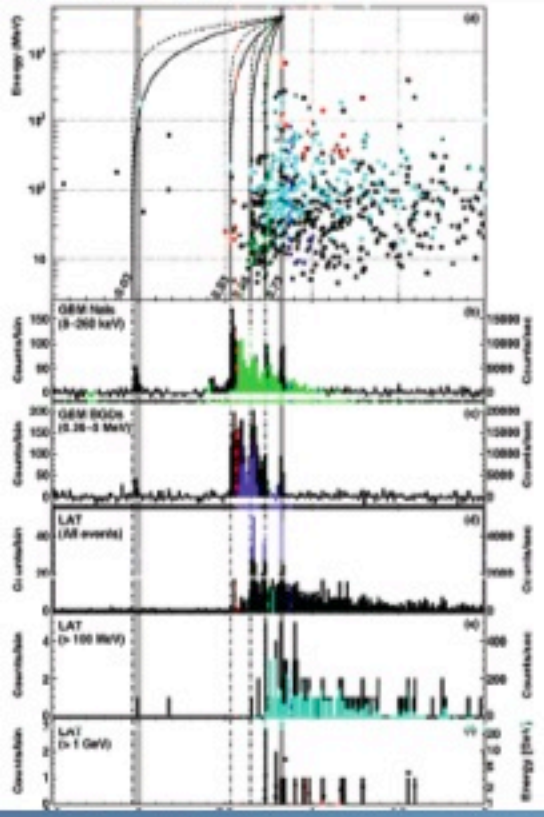
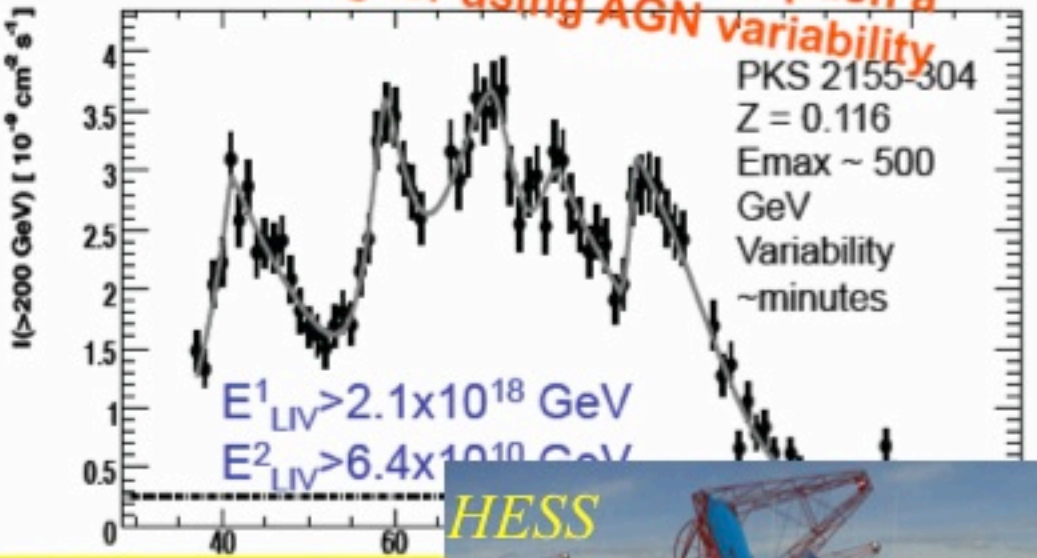


Table 2 | Limits on Lorentz Invariance Violation

#	$t_{start} - T_0$ (ms)	Limit on $\|\Delta t\|$ (ms)	Reasoning for choice of t_{start} or limit on Δt or $\|\Delta t/\Delta E\|$	E_1[†] (MeV)	Valid for s_n*	Lower limit on $M_{QG,1}/M_{Planck}$
(a)°	−30	< 859	start of any < 1 MeV emission	0.1	1	> 1.19
(b)°	530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
(c)°	648	< 181	start of main > 0.1 GeV emission	100	1	> 5.63
(d)°	730	< 99	start of > 1 GeV emission	1000	1	> 10.0
(e)*	—	< 10	association with < 1 MeV spike	0.1	±1	> 102
(f)*	—	< 19	If 0.75 GeV[‡] γ-ray from 1st spike	0.1	−1	> 1.33
(g)*	$\|\Delta t/\Delta E\|$ < 30 ms/GeV		lag analysis of > 1 GeV spikes	—	±1	> 1.22

Next-generation facilities could push a factor ~10 higher using AGN variability



H.E.S.S.Astrop. Phys

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

P. Karn talk DPF:188, 16-Aug-2013, 9:09

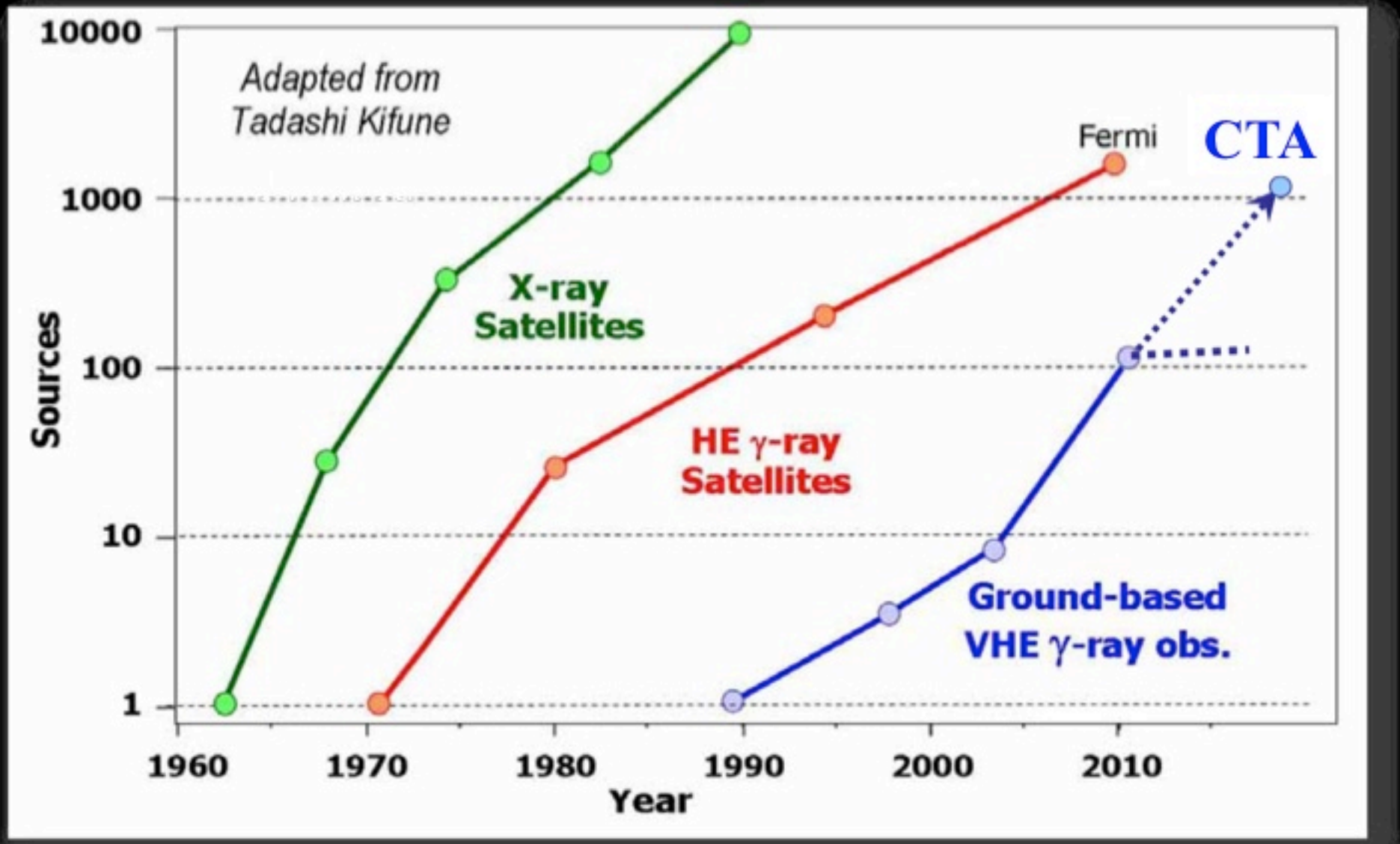
CTA: Cherenkov Telescope Array

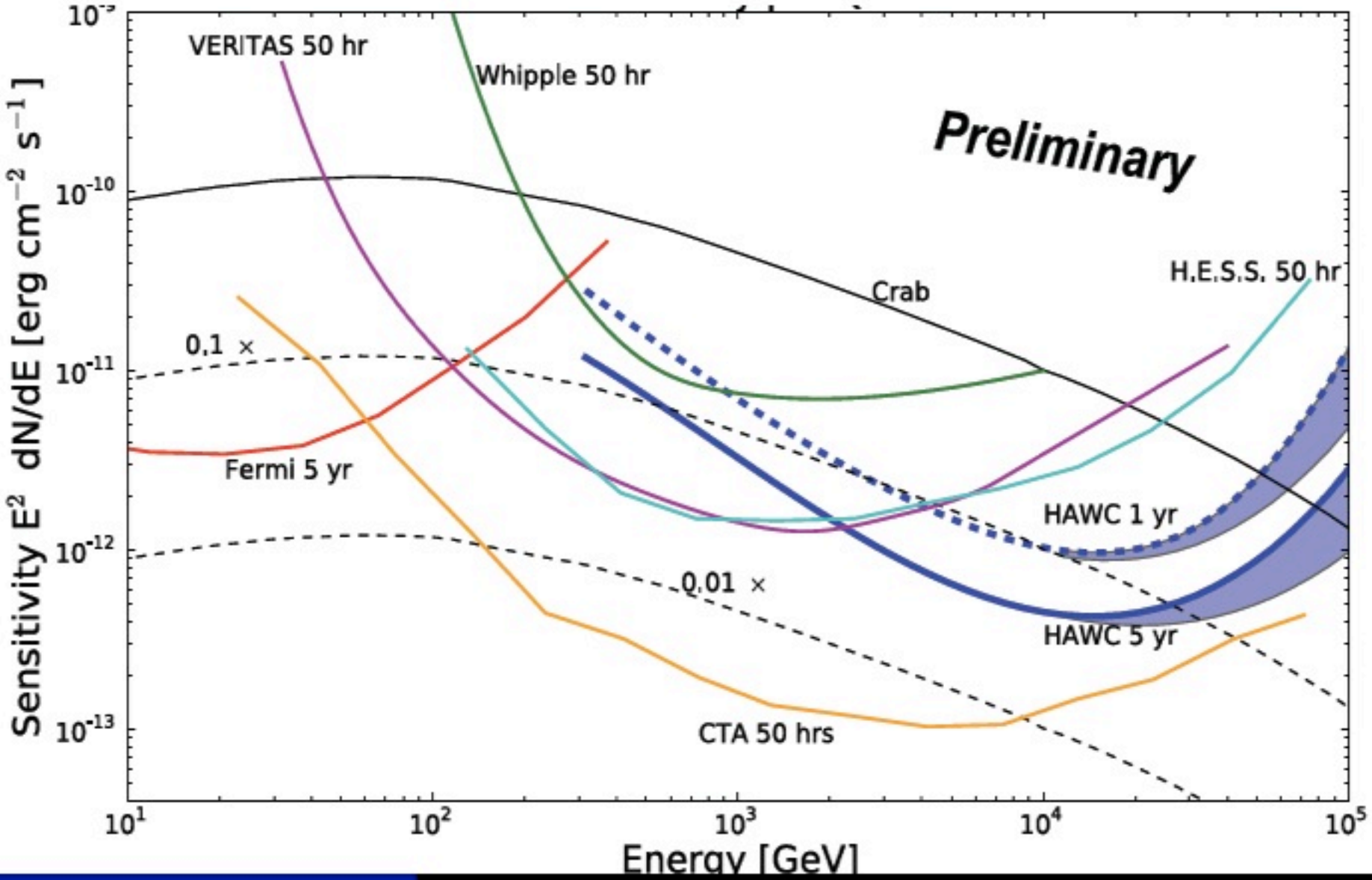
from Funk CSS'13

D. Williams talk DPF:163, 15-Aug-2013 10:30

Control of Astro-Systematics

Dark Matter, Lorentz Invariance Tests




VERITAS 50 hr
Whipple 50 hr
Preliminary
H.E.S.S. 50 hr
Crab
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]
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
10¹
10²
10³
10⁴
10⁵

CF-6 Summary

Origin of highest energy particles in the universe (multi-messenger campaign)

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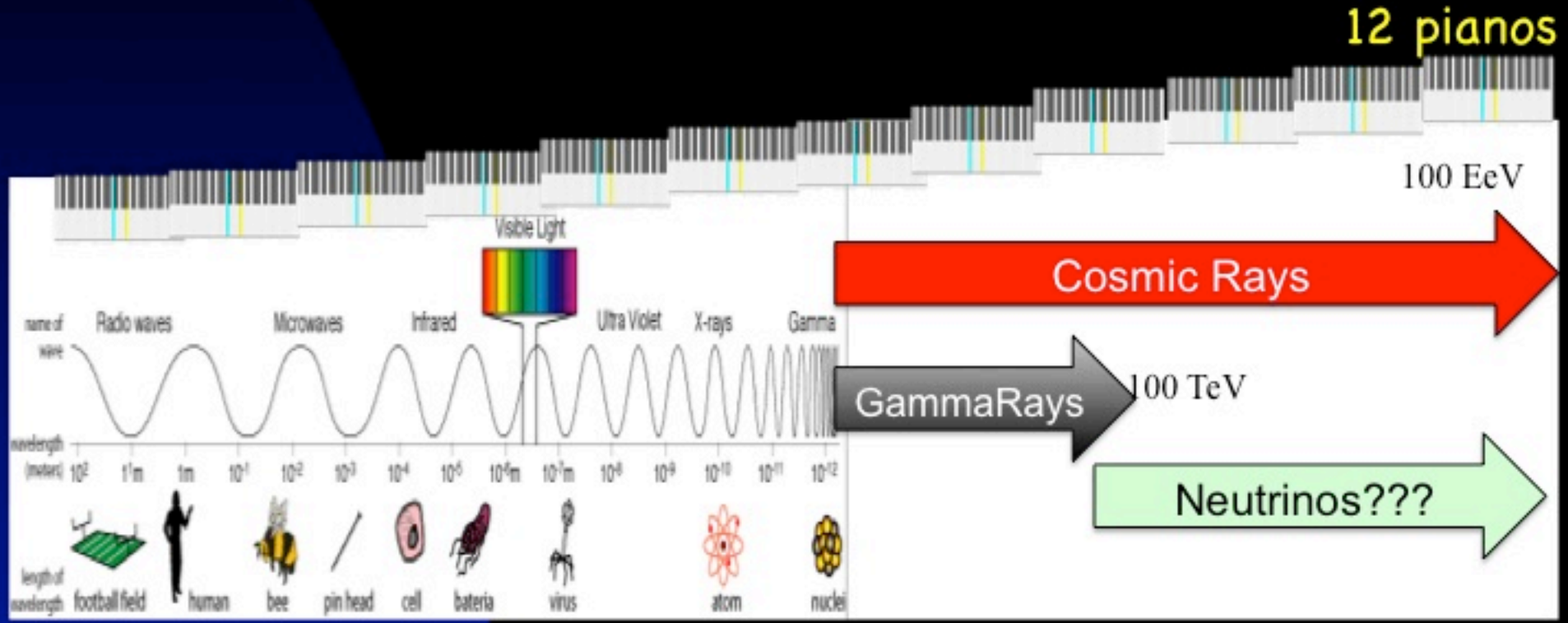
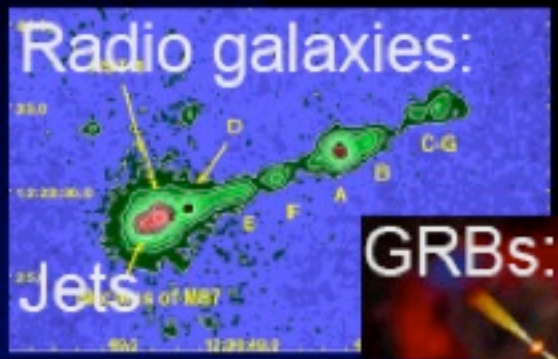
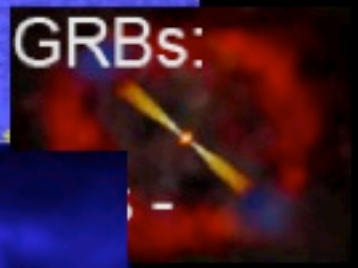


Nature's HE γ Accelerators

Extragalactic

Galactic

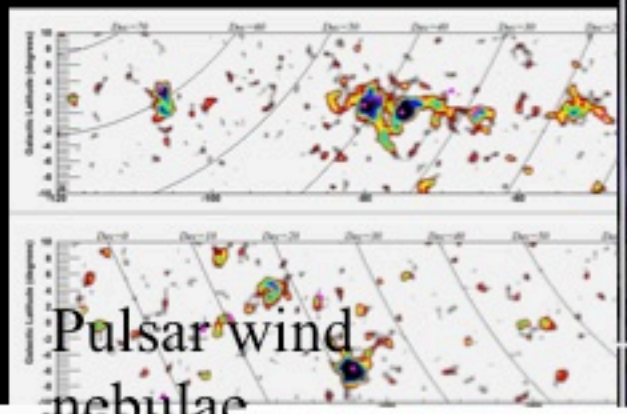




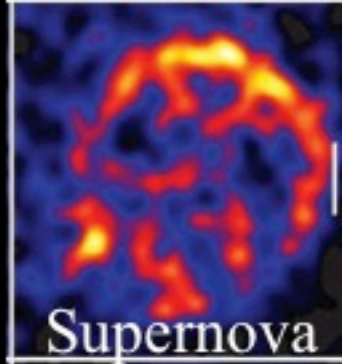
Blazars:

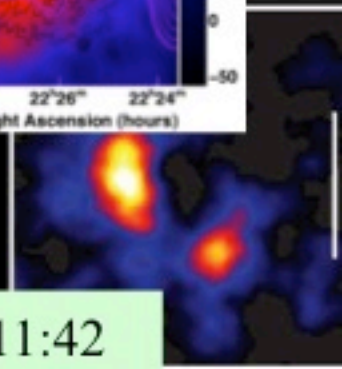
•Jets

Unidentified



Stellar
clusters

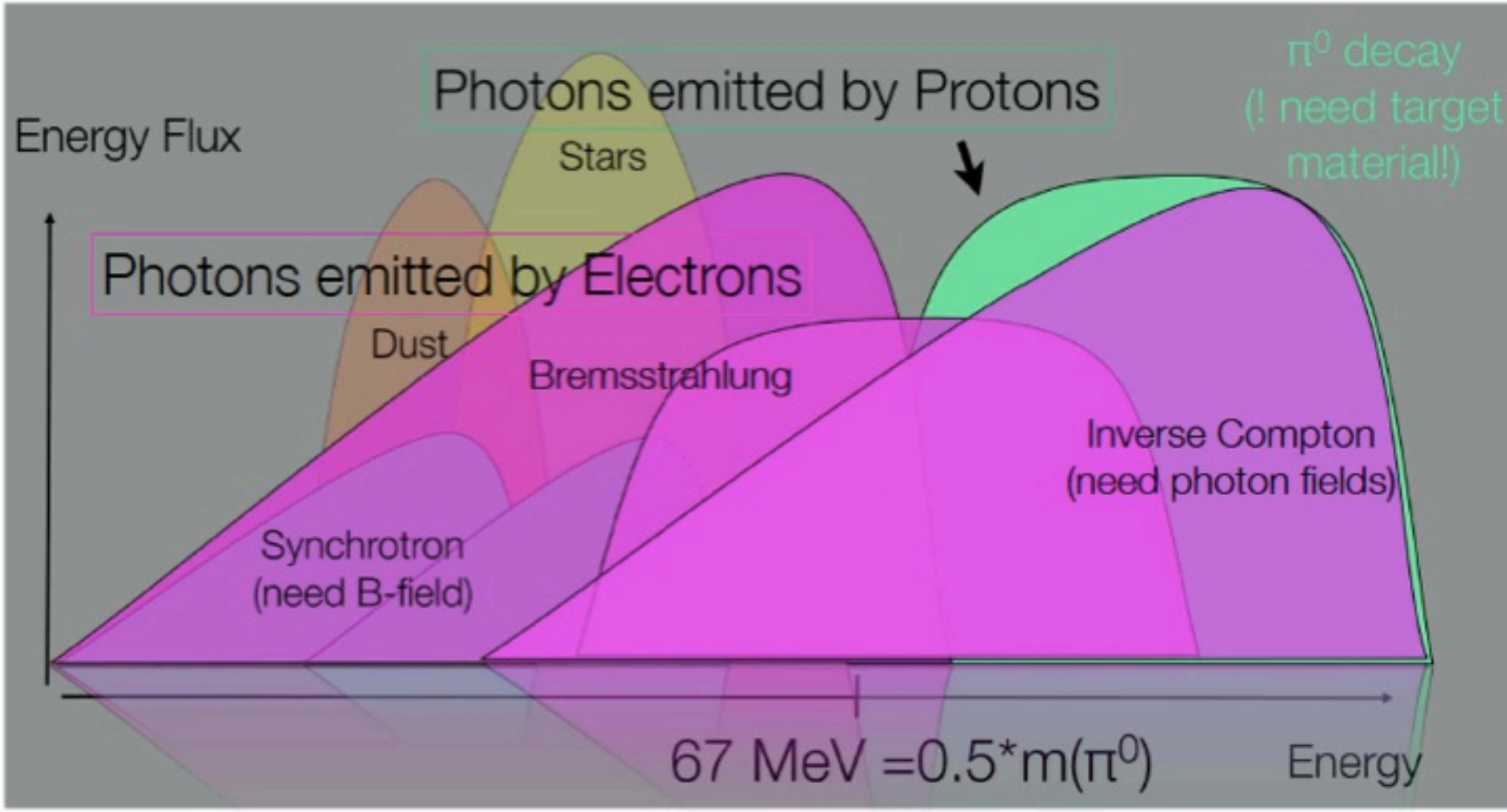




Krennrich, Hoffman TeVPA

R. Mukherjee talk DPF:186, 15-Aug-2013 11:42

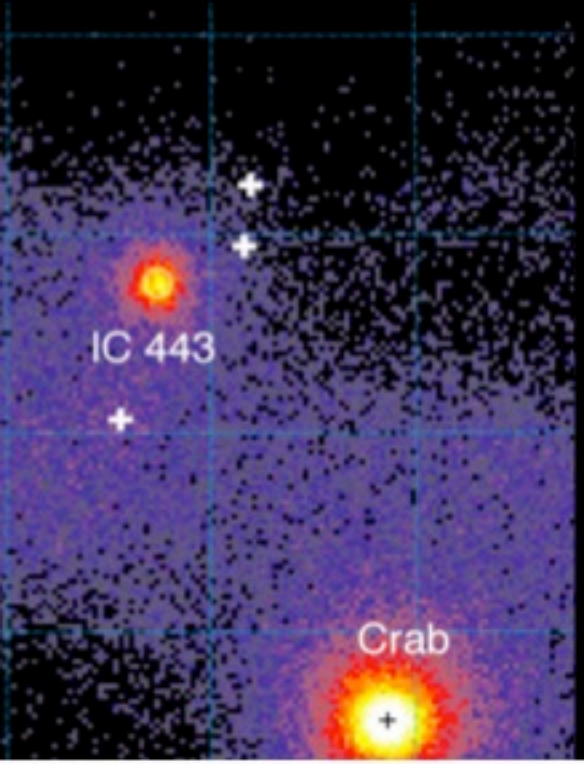
Photon emission by accelerated charged particles

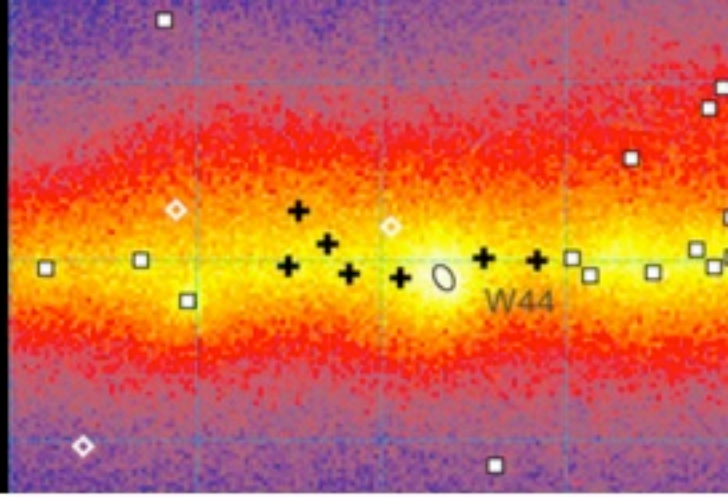


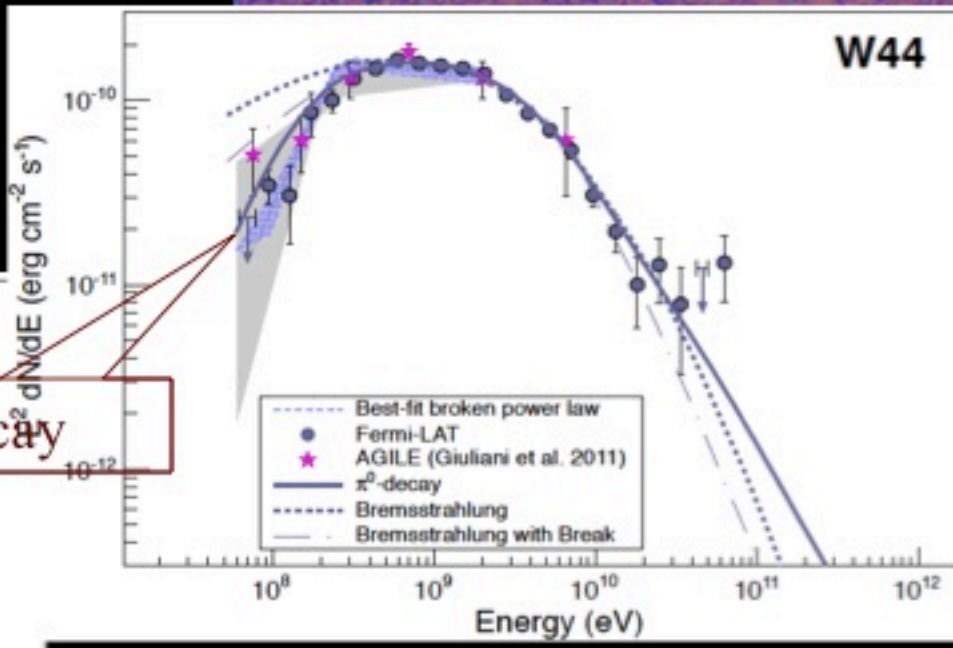
π^0 decay!

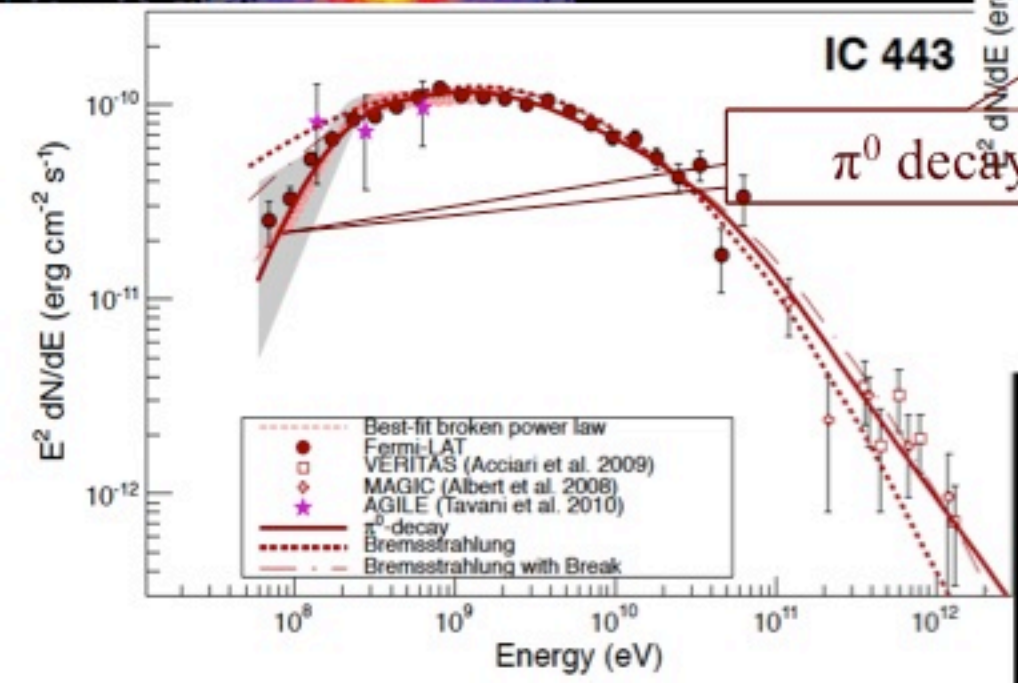
IC 443 & W44

Fermi & AGILE







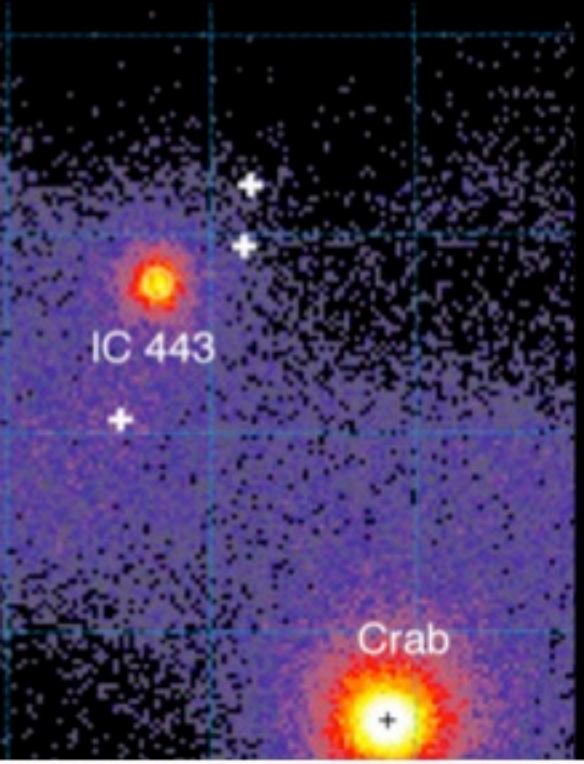


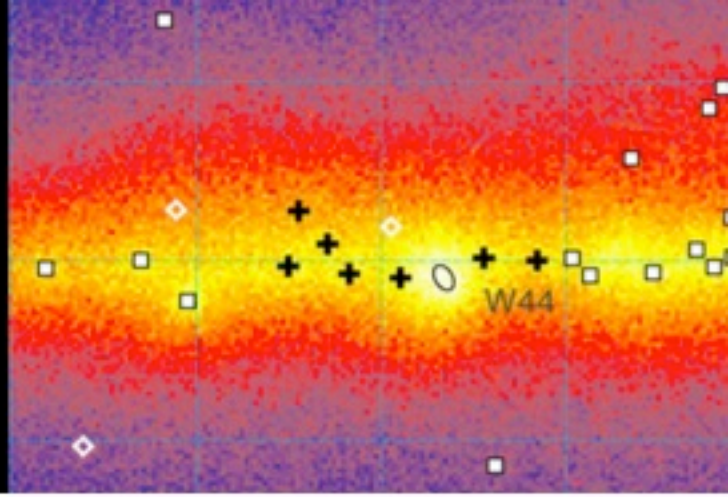
Ackermann et al (Fermi Collab) '13
arXiv:1302.3307

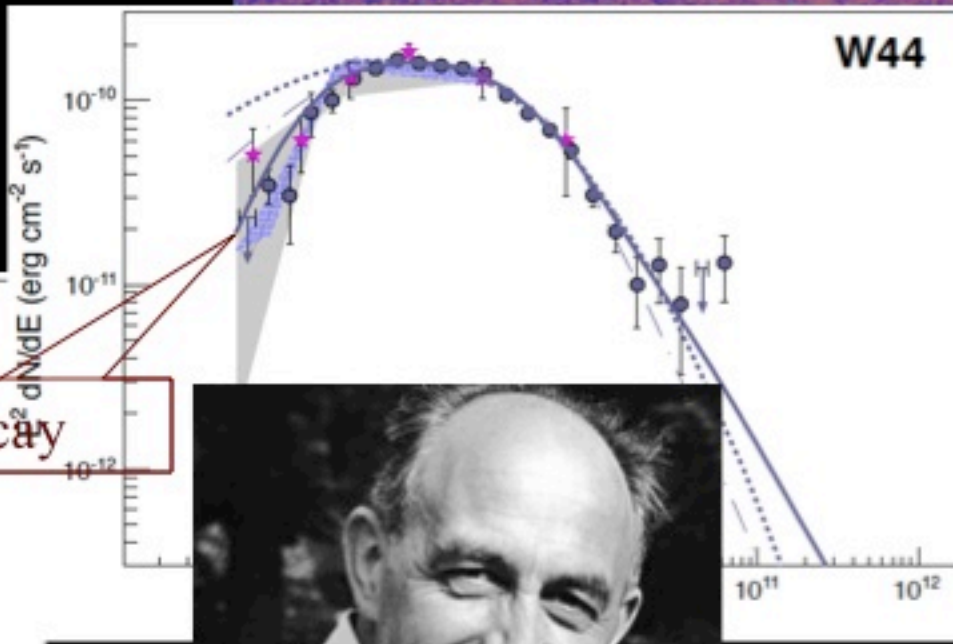
π^0 decay!

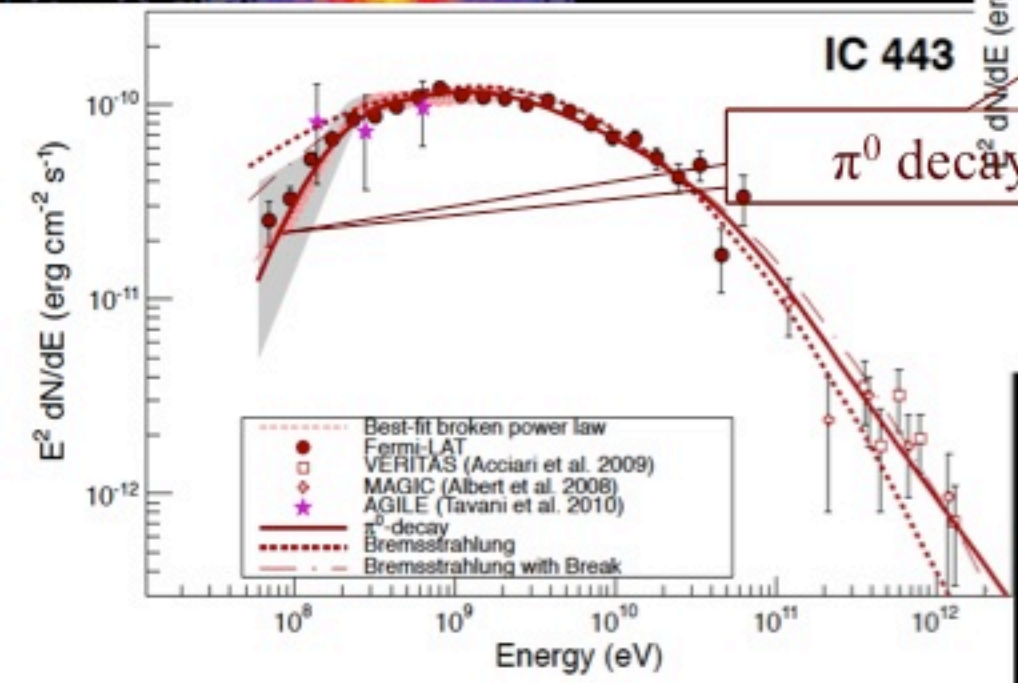
IC 443 & W44

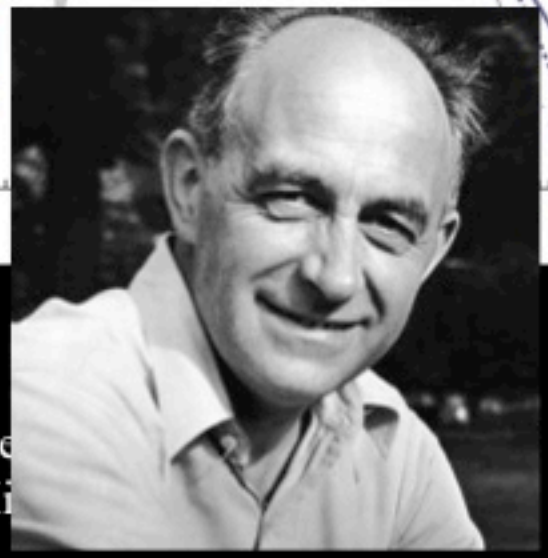
Fermi & AGILE



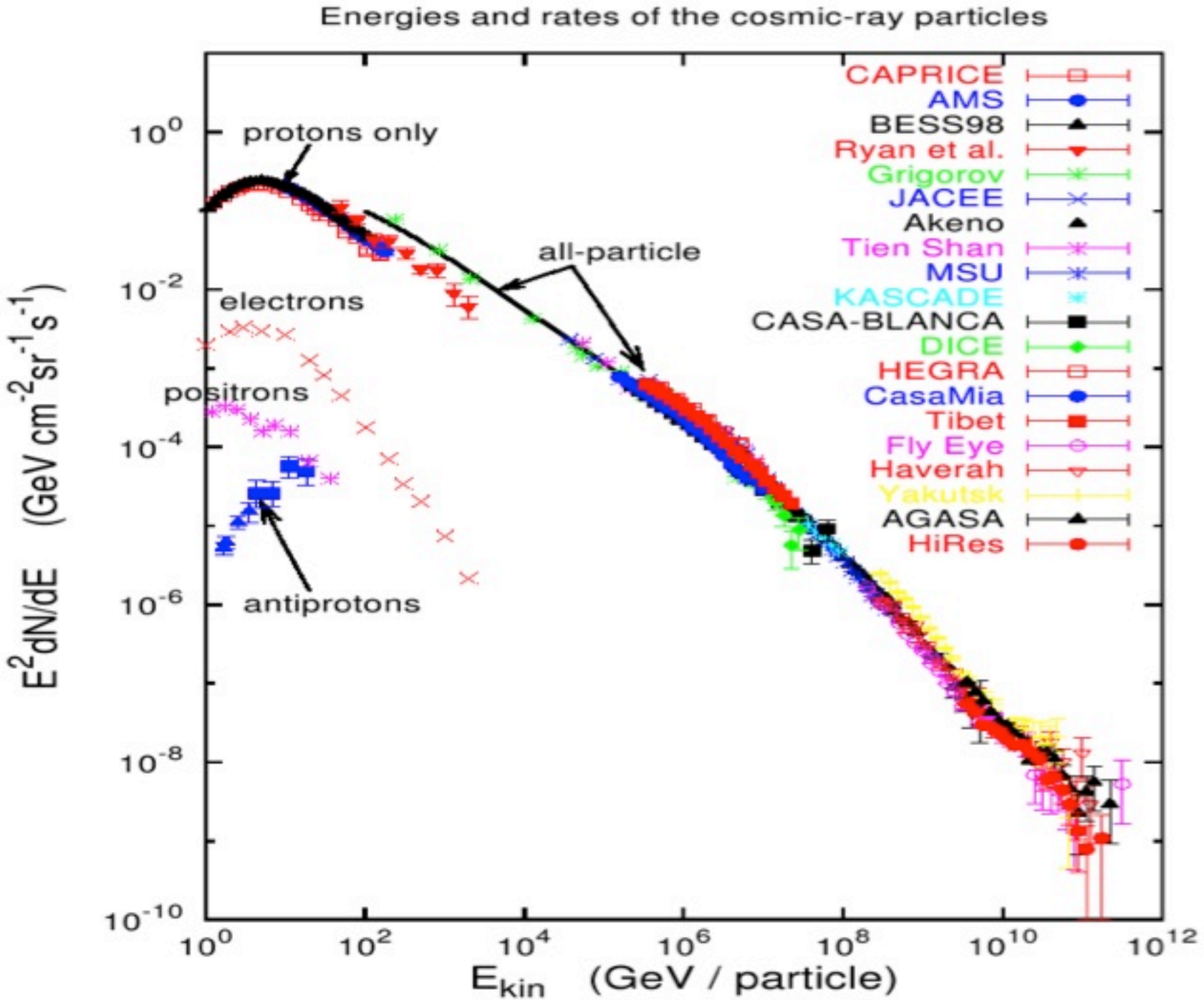


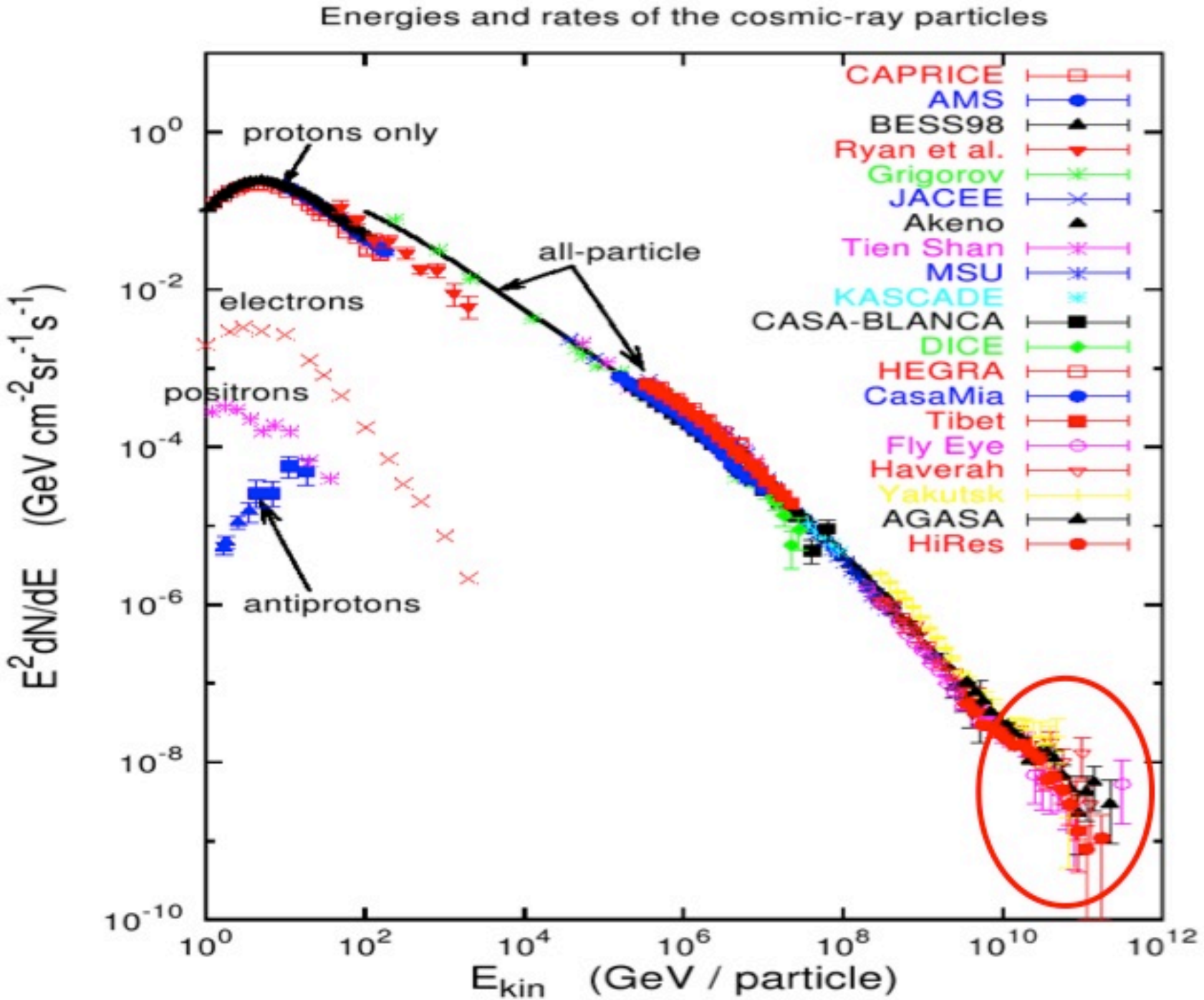






Acke ’13
arXi


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}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$E^2 dN/dE$ (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 most energetic Particles ever detected?

Ultra High Energies Cosmic Rays (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)

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

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

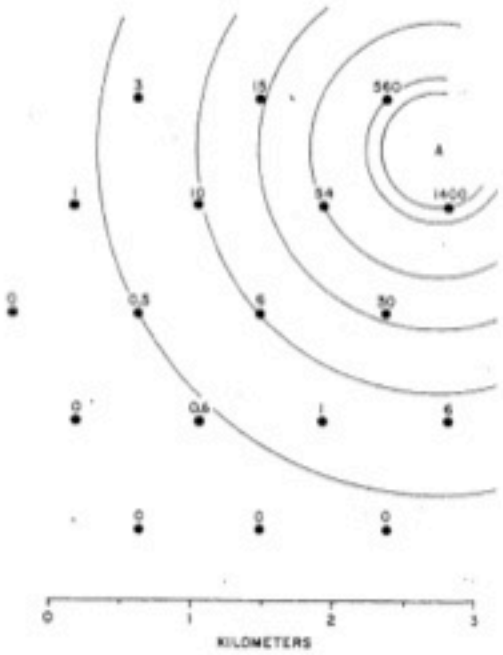
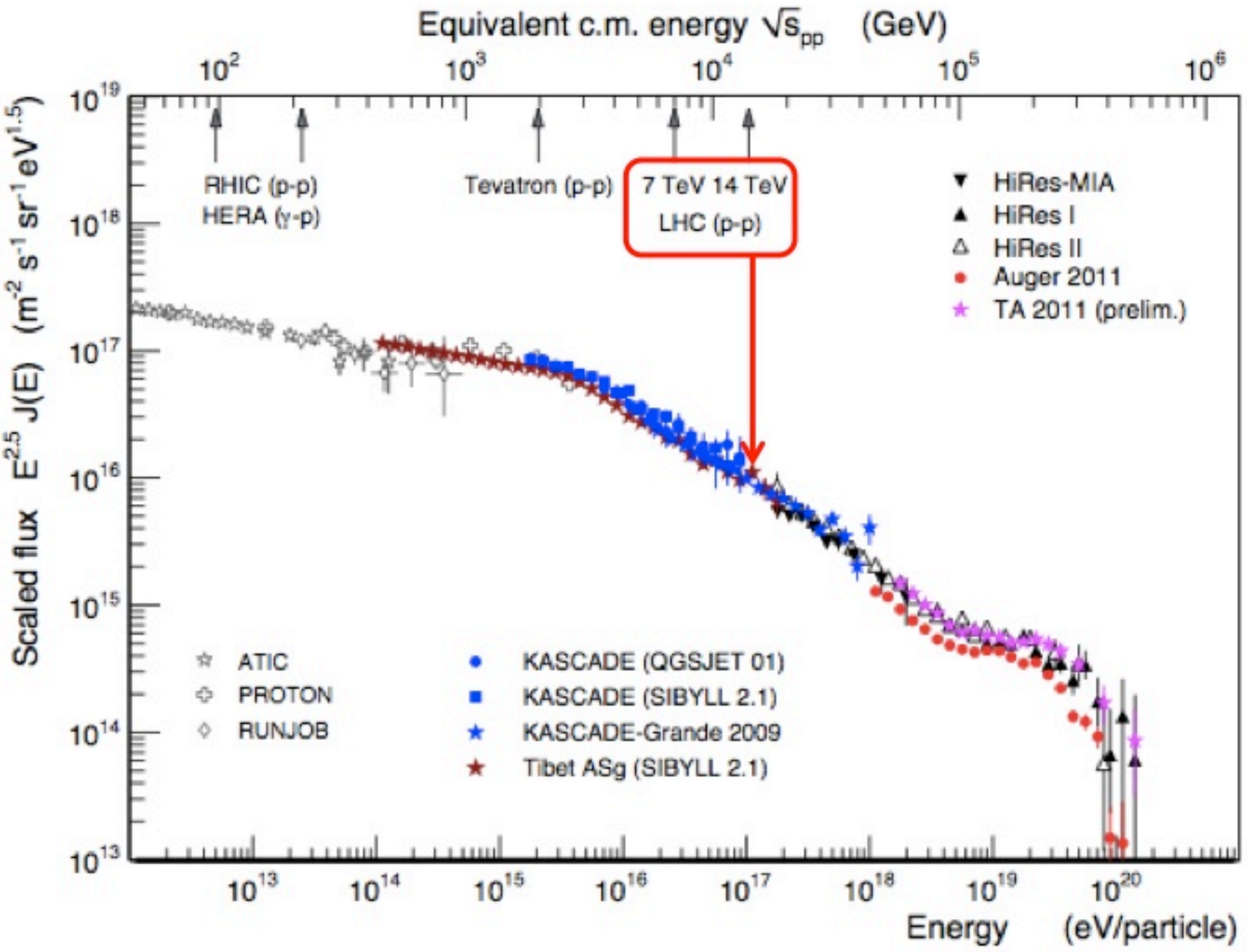
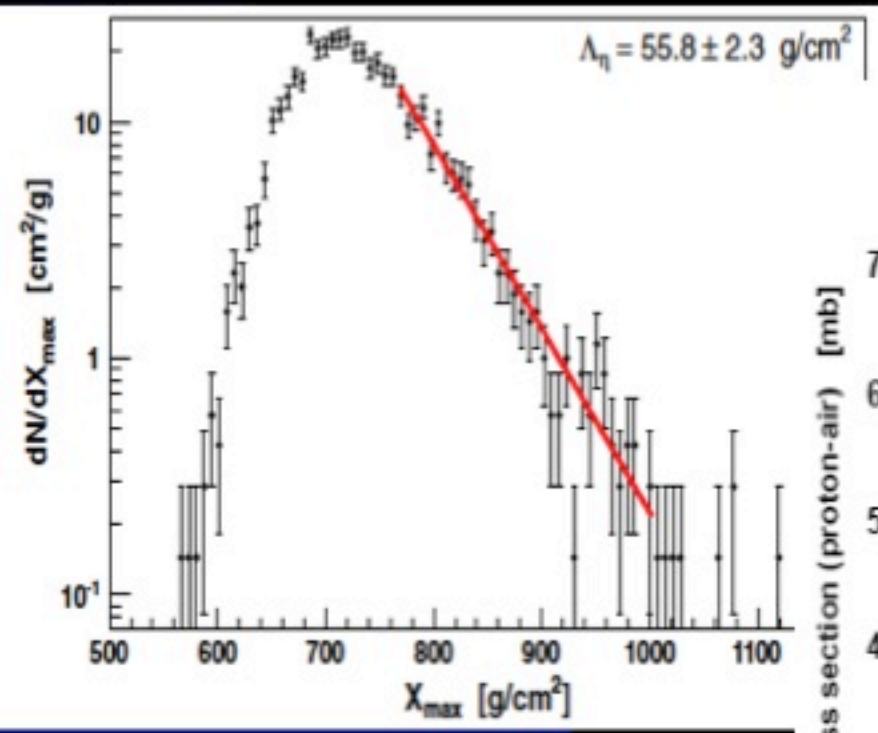
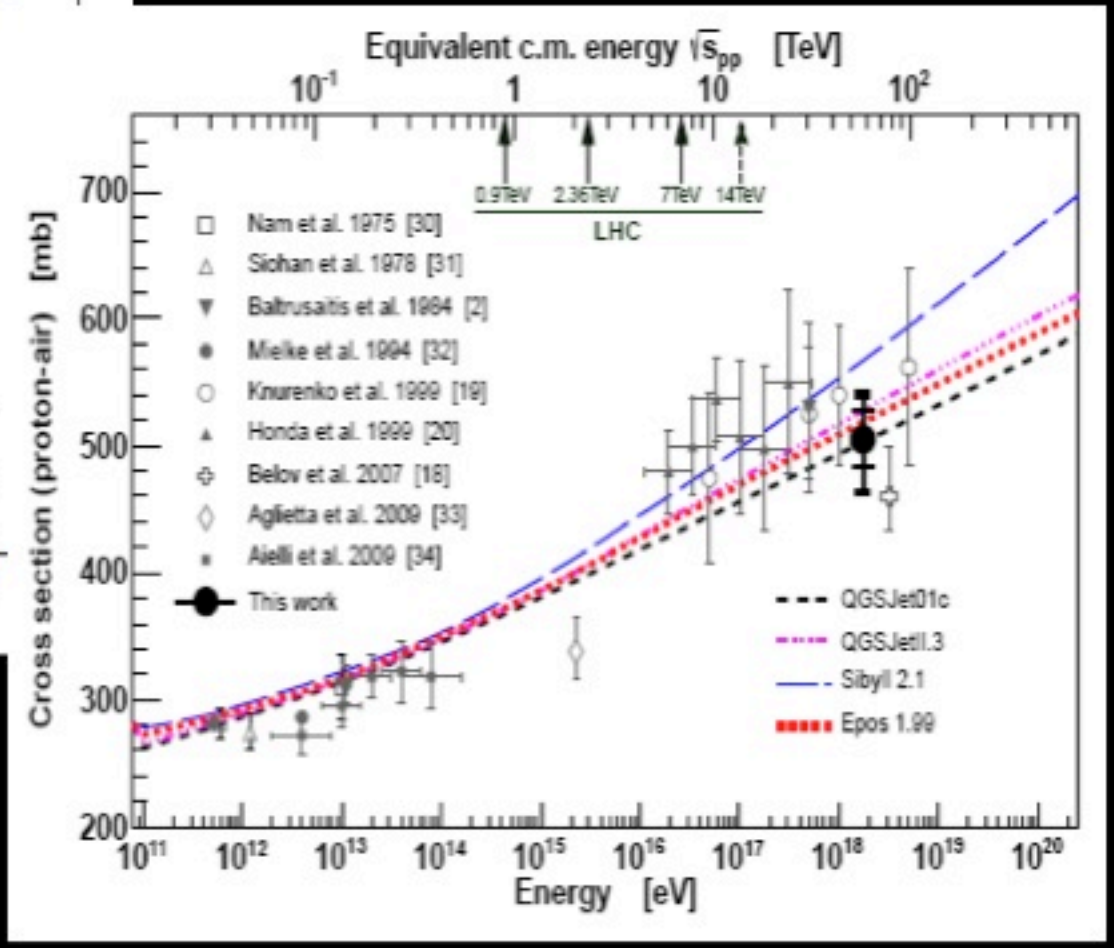


FIG. 1. Plan of the Volcano Ranch array in Febru 1962. The circles represent 3.3-m² scintillation de tectors. The numbers near the circles are the show densities (particles/m²) registered in this event. No

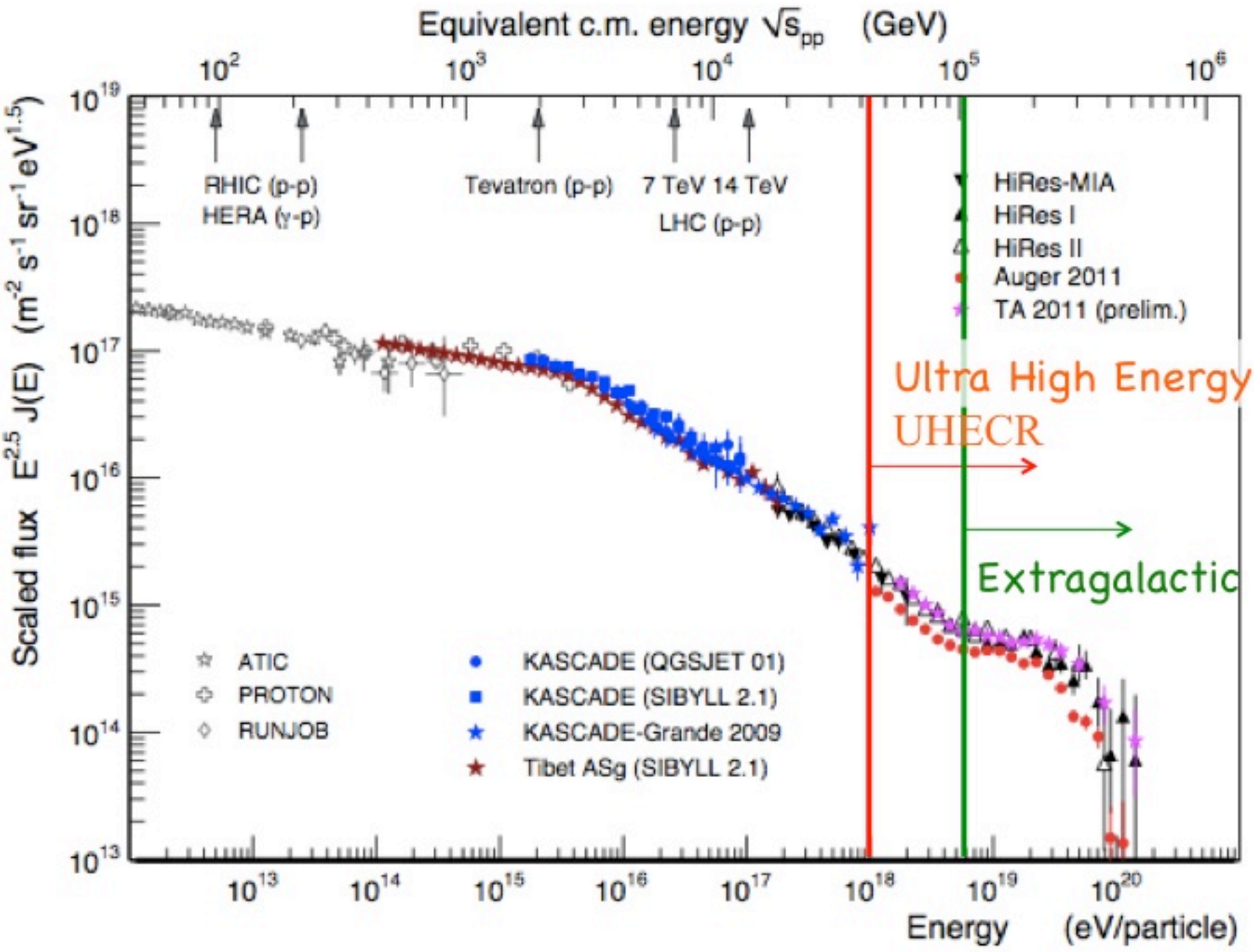

Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger 2011
TA 2011 (prelim.)
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}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

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





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


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.)
Ultra High Energy
UHECR
Extragalactic
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}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

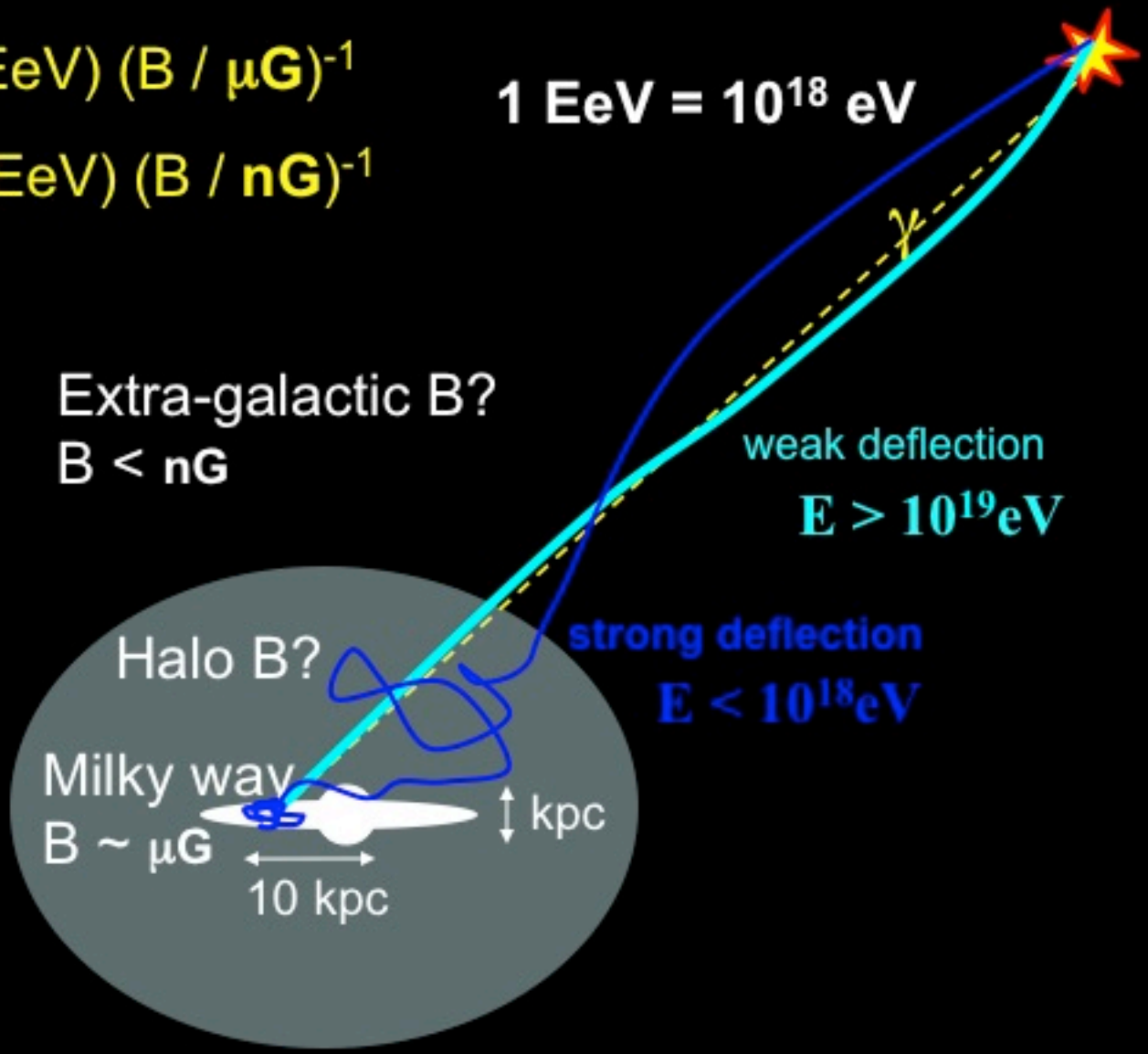
"Known unknown"

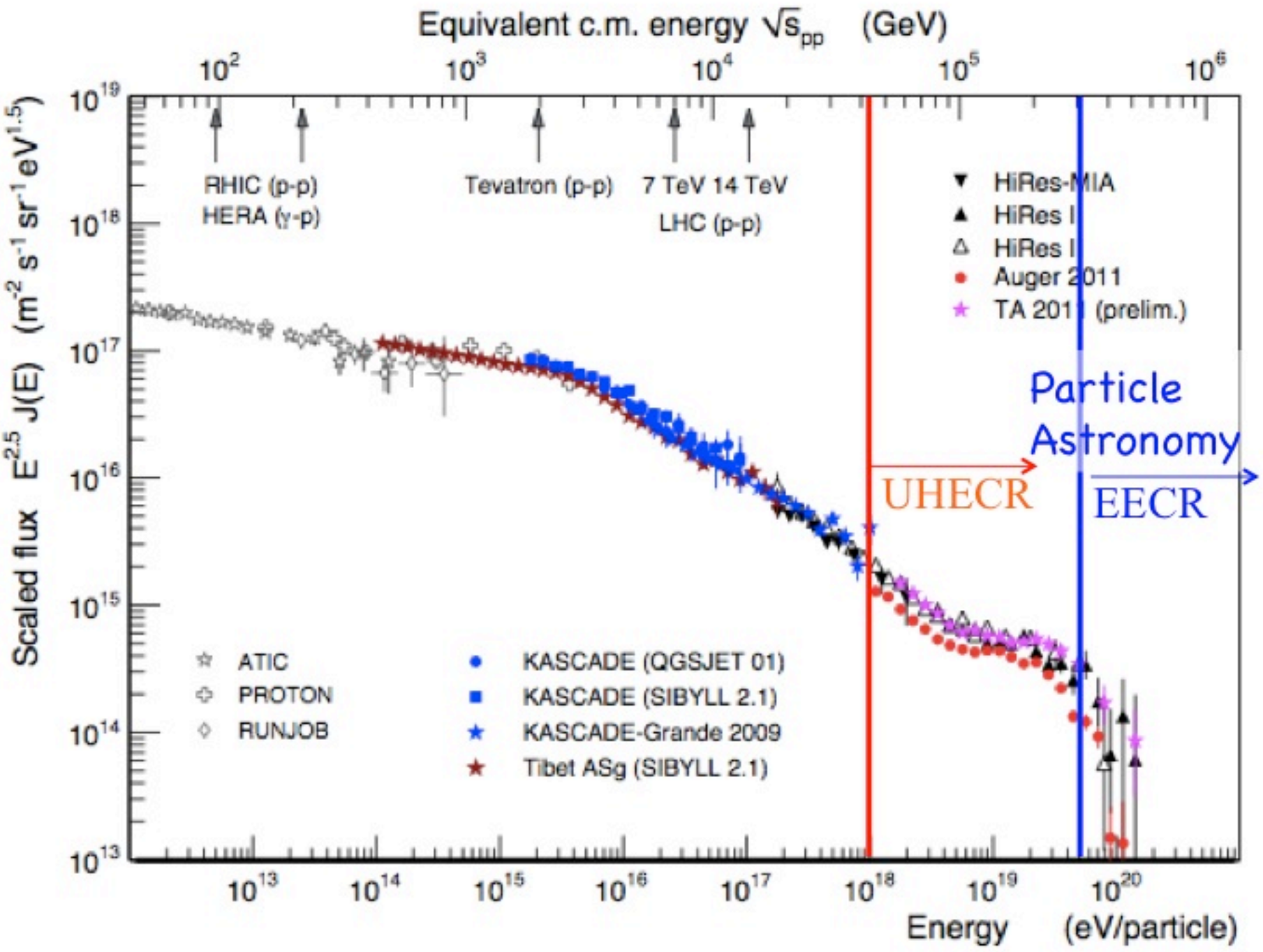
Cosmic Magnetic Fields

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

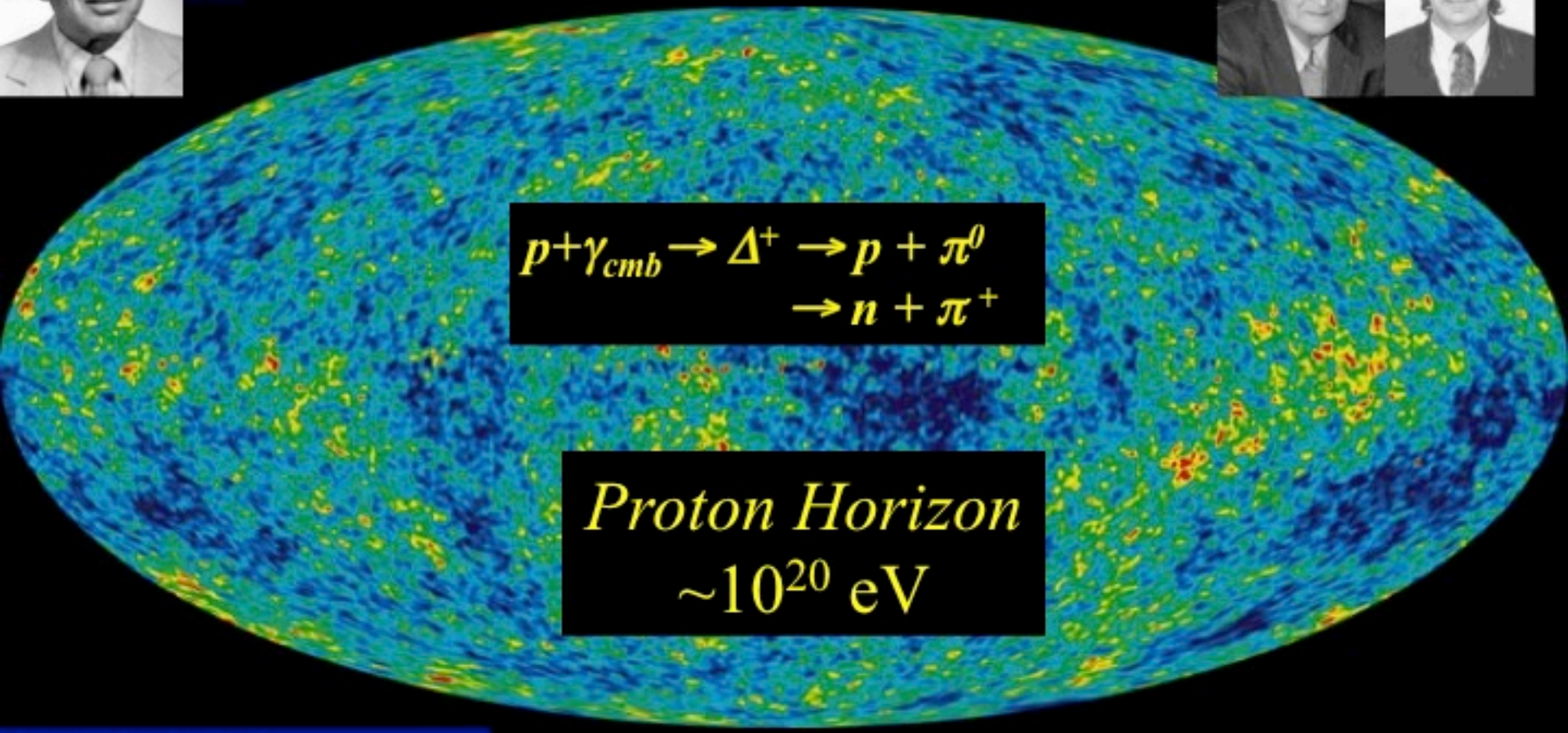
R_L = **Mpc** Z^{-1} (E / EeV) (B / **nG**)$^{-1}$

1 EeV = 10^{18} eV




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 I
Auger 2011
TA 201 (prelim.)
Particle
Astronomy
UHECR
EECR
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}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

"Cosmologically Meaningful Termination"

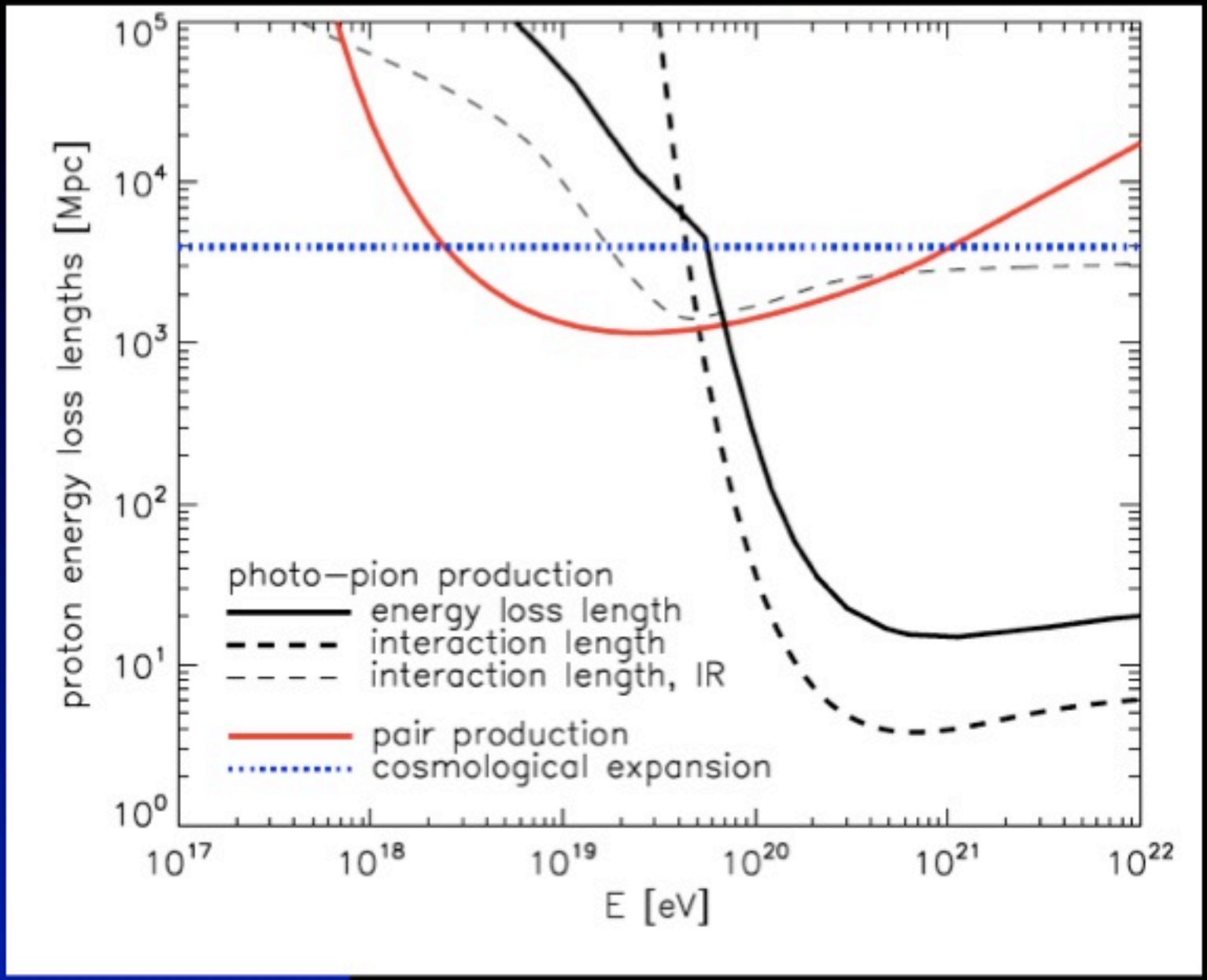


$$p+\gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

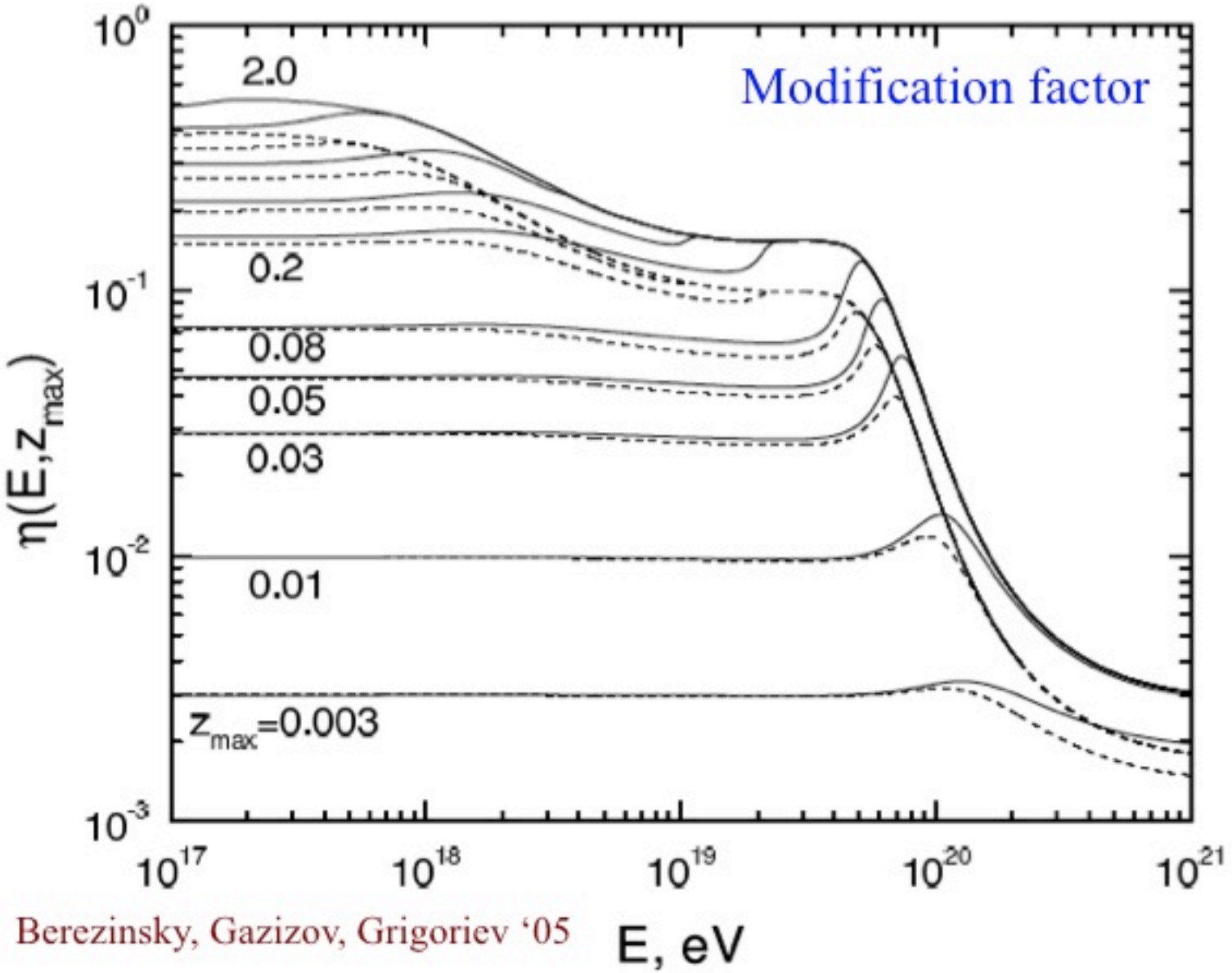
Proton Horizon
$\sim 10^{20}$ eV

GZK Cutoff
Greisen, Zatsepin, Kuzmin
1966

GZK effect for protons

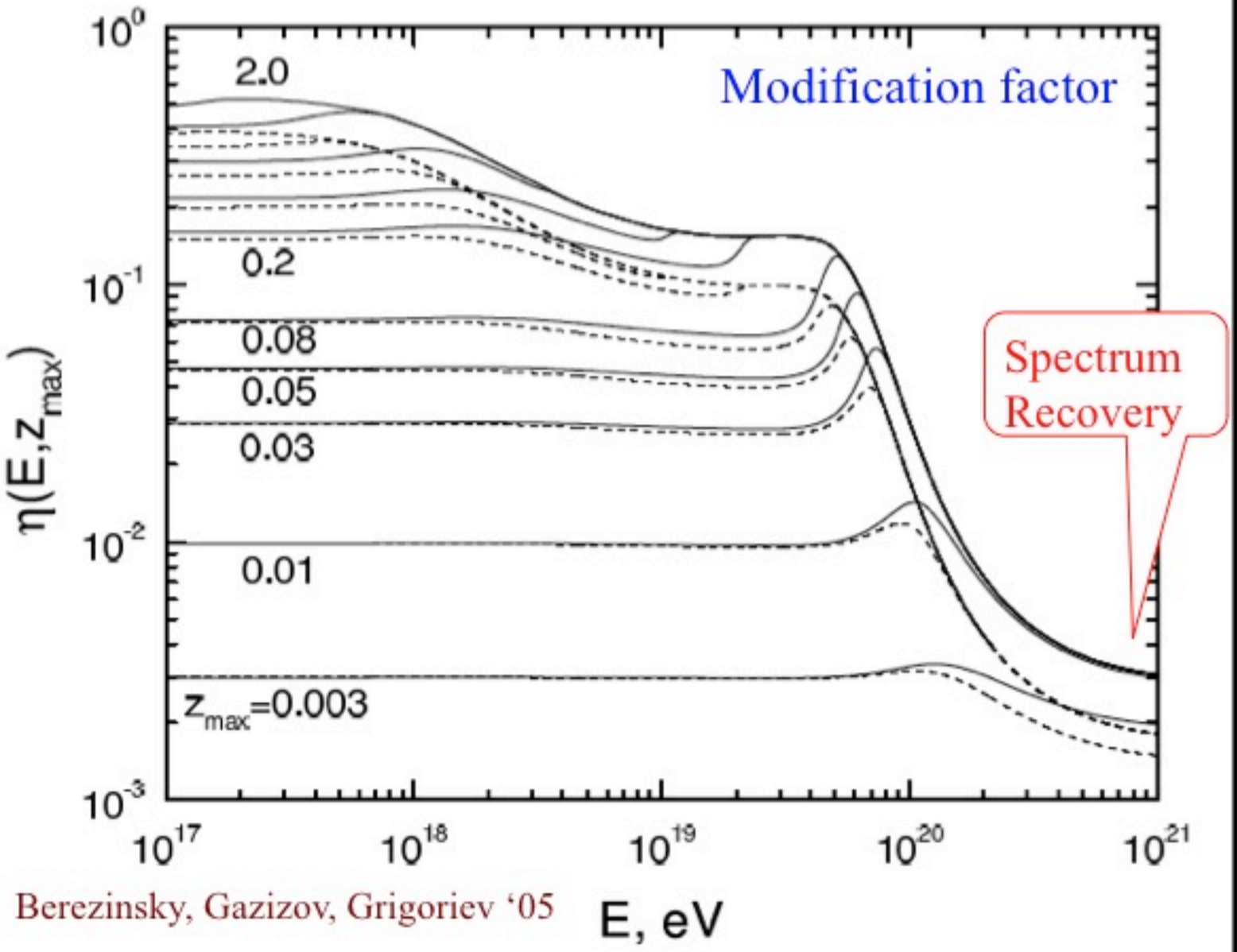


Propagation of UHE protons



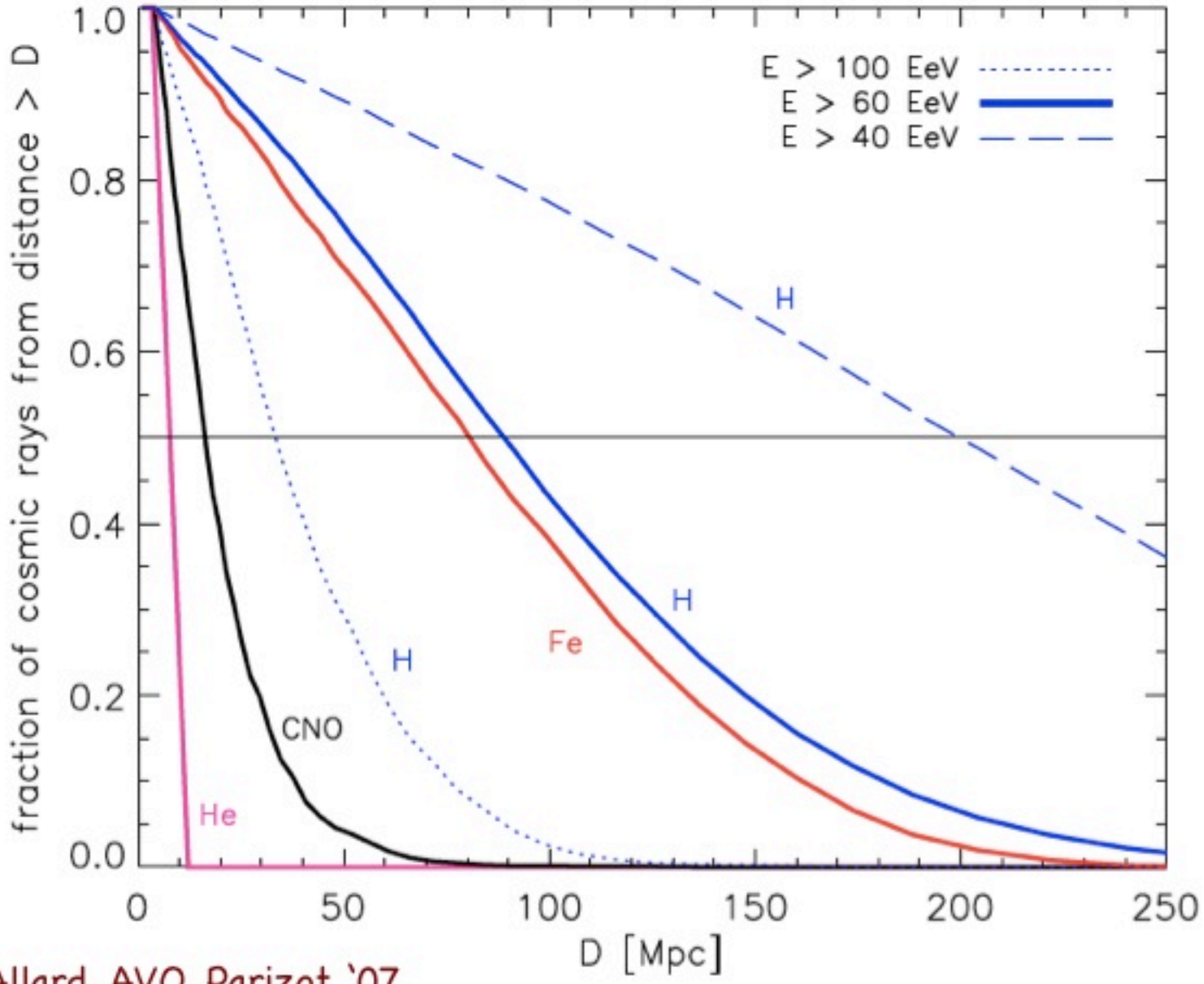
Berezinsky, Gazizov, Grigoriev '05

Propagation of UHE protons



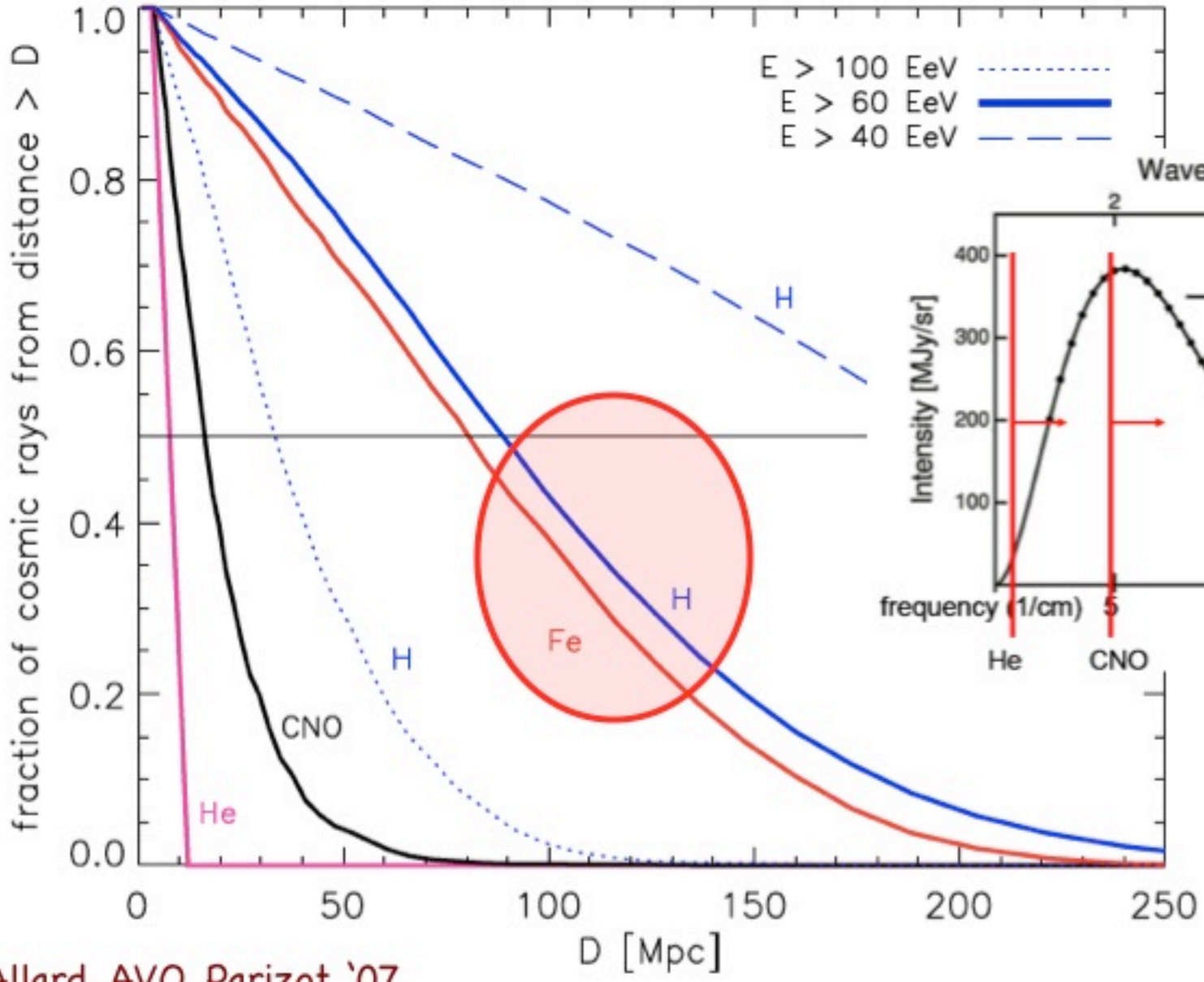
Berezinsky, Gazizov, Grigoriev '05

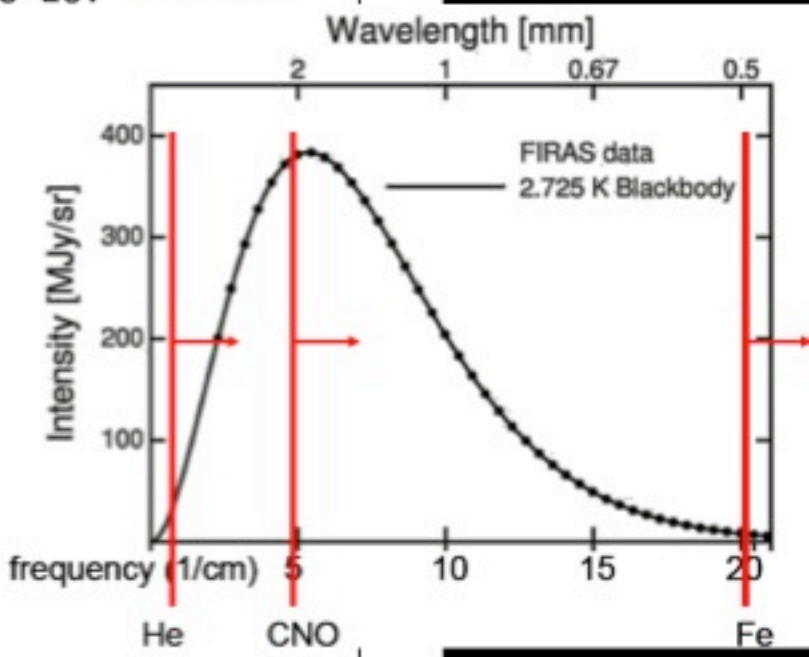
GZK Horizon



Allard, AVO, Parizot '07

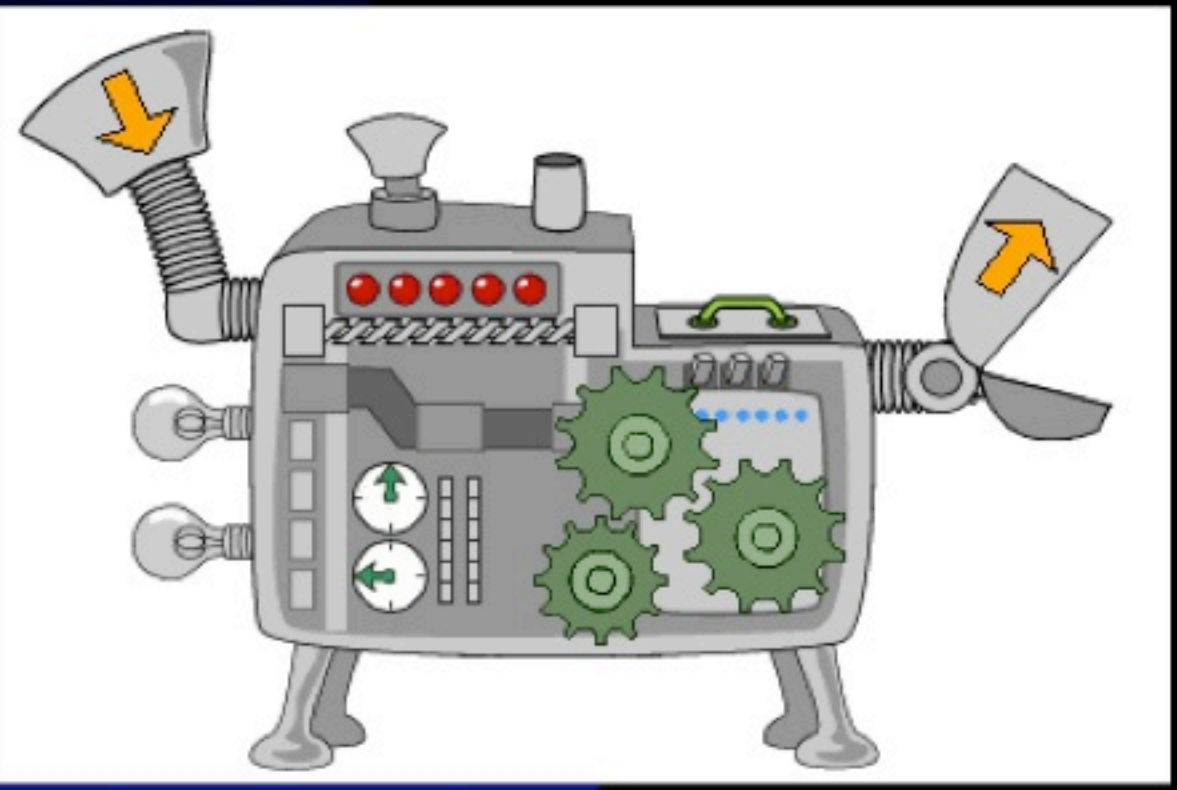
GZK Horizon





Allard, AVO, Parizot '07

Modern Propagation Codes



Public:

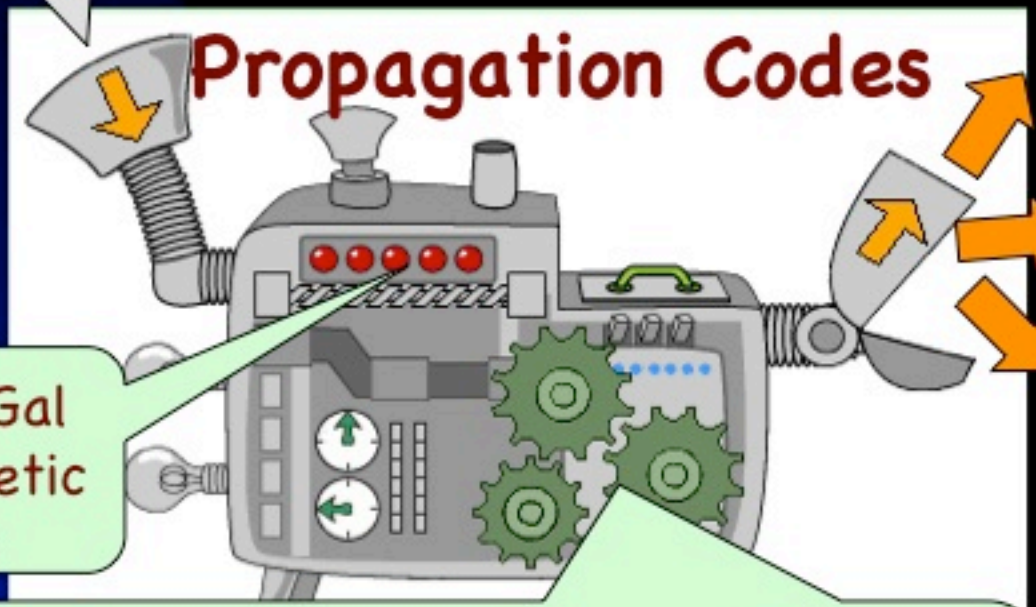
CRPropa
1.0 Armengaud et al `06
2.0 Kampert et al. ‘12
3.0 Alvez Batista et al ‘13
SimProp
Aloisio et al ‘12

Private:

Allard et al ‘04
Taylor ‘07
Ahlers `10
others...

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

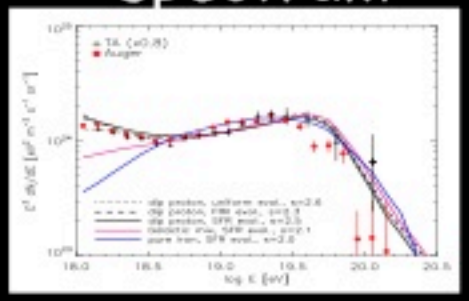
Propagation Codes



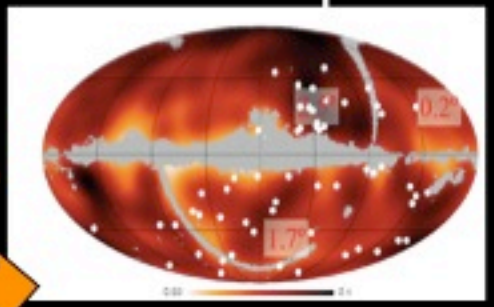
InterGal Magnetic Fields

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

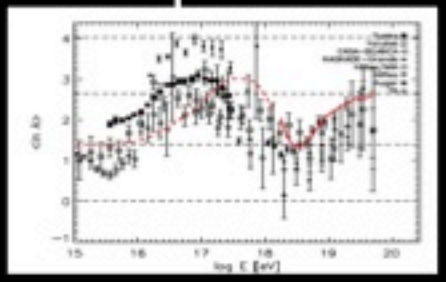
Spectrum



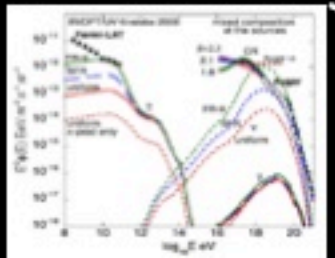
Anisotropies



Composition



Multi-messengers



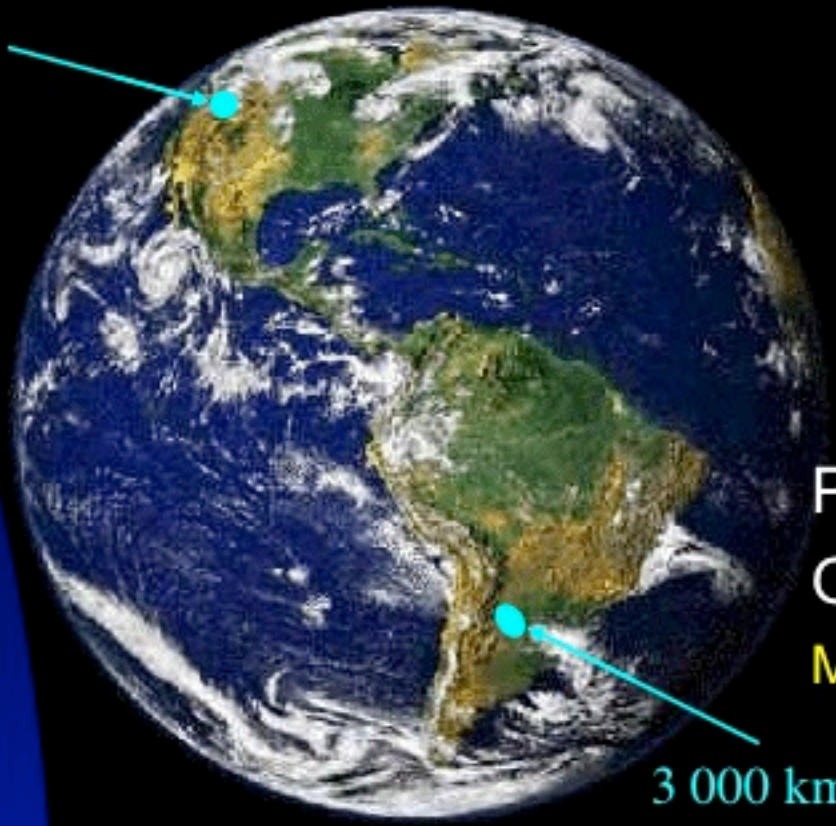
Ultrahigh Energy Cosmic Rays
Leading Observatories

Telescope Array

Utah, USA

700 km^2 array

3 fluorescence sites



Pierre Auger Observatory

Mendoza, Argentina

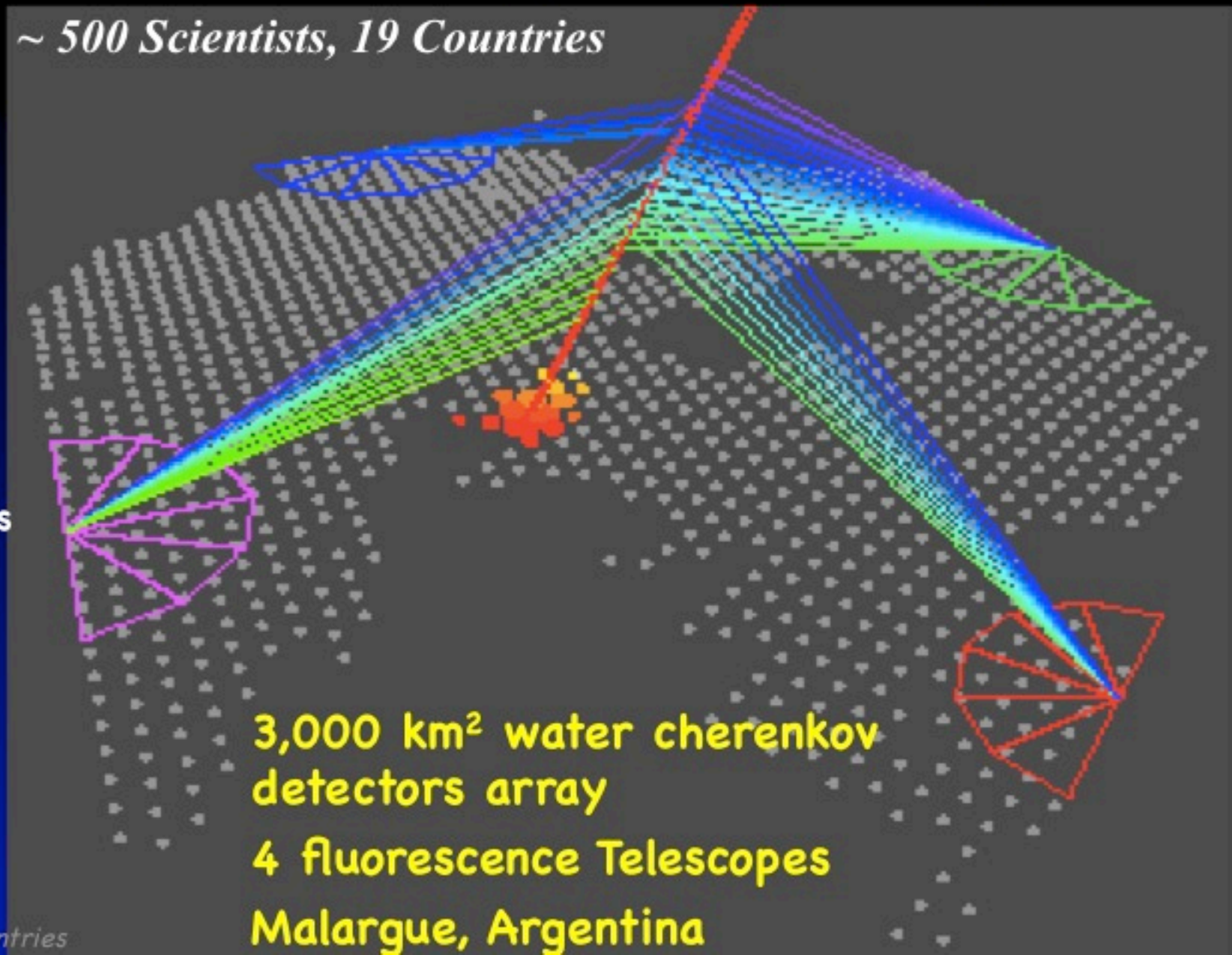
3 000 km^2 array

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*

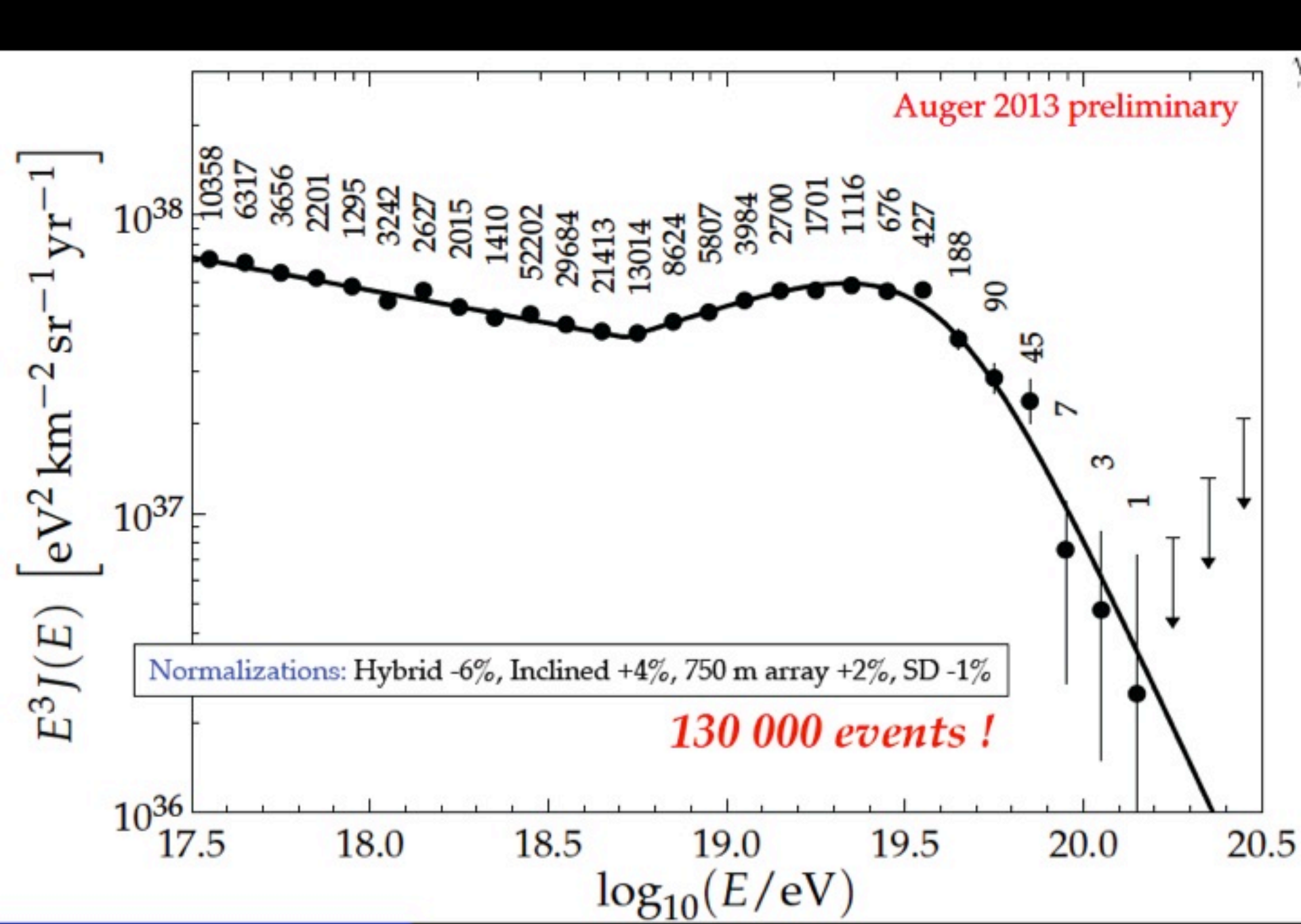
*Associate Countries

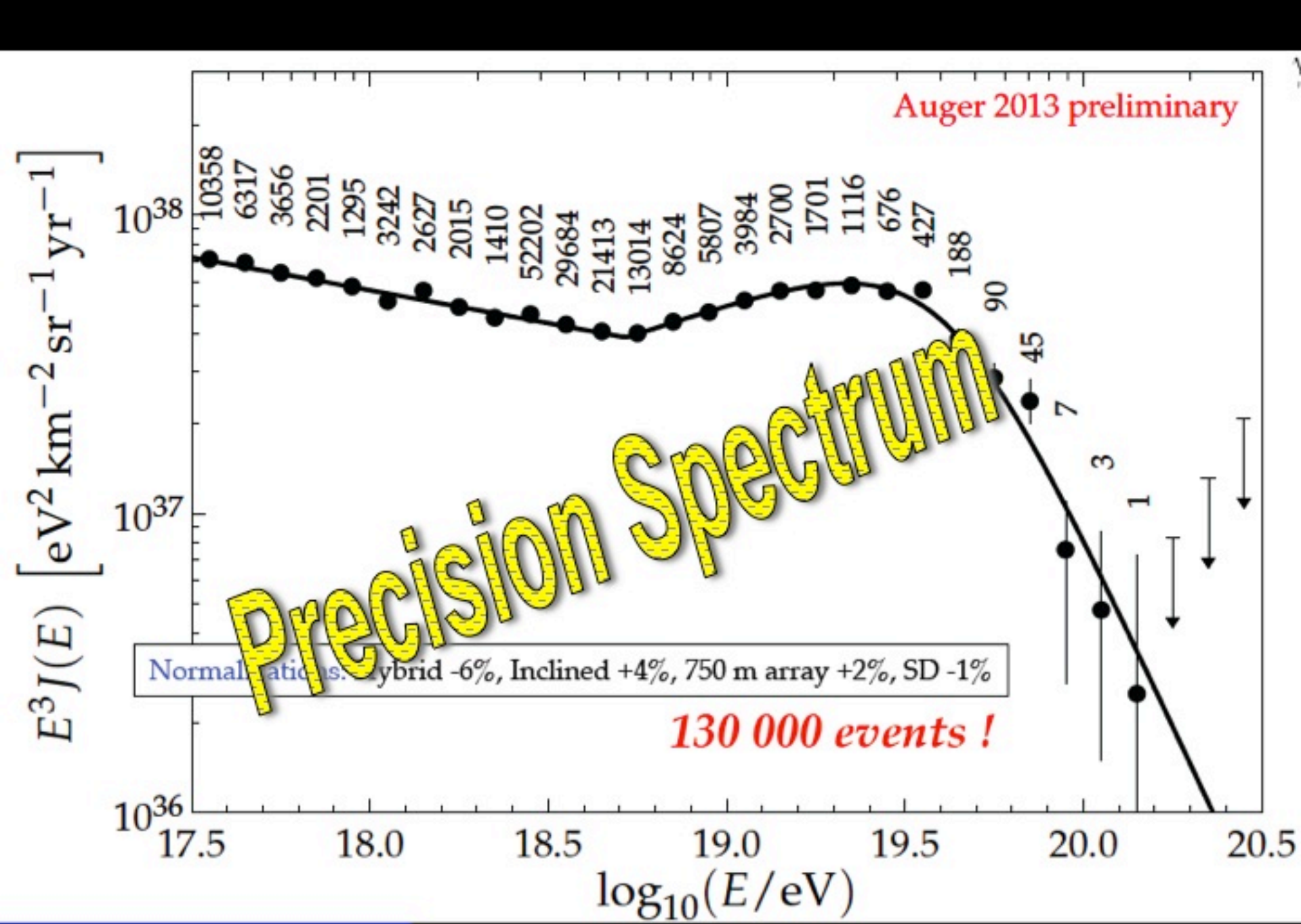


surface detector


array of tanks

4 times 6 telescopes overlooking the site

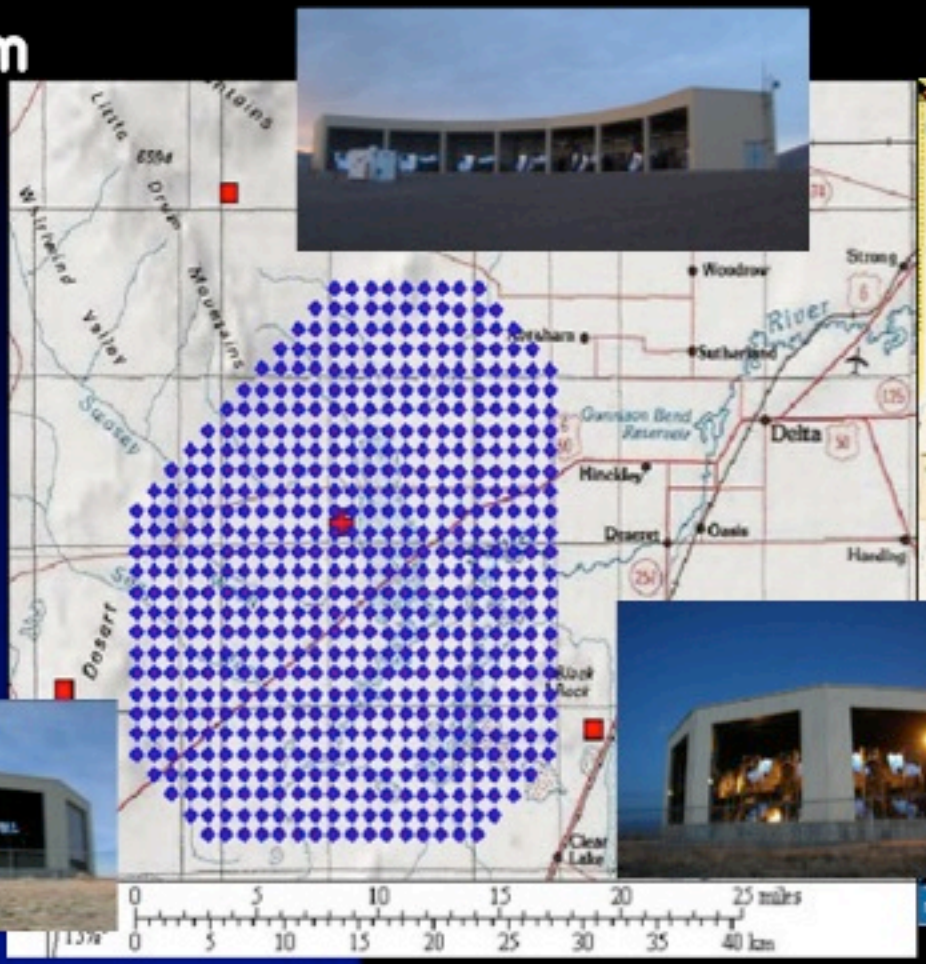

Auger 2013 preliminary
10358
6317
3656
2201
1295
3242
2627
2015
1410
52202
29684
21413
13014
8624
5807
3984
2700
1701
1116
676
427
188
90
45
7
3
1
Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%
130 000 events !
10^{38}
10^{37}
10^{36}
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathr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


Auger 2013 preliminary
Precision Spectrum
Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%
130 000 events !
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
$\log_{10}(E/\mathrm{eV})$
10^{38}
10^{37}
10^{36}
17.5
18.0
18.5
19.0
19.5
20.0
20.5
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

Telescope Array

Belgium
Japan
Korea
Russia
USA

Area: 680 km^2



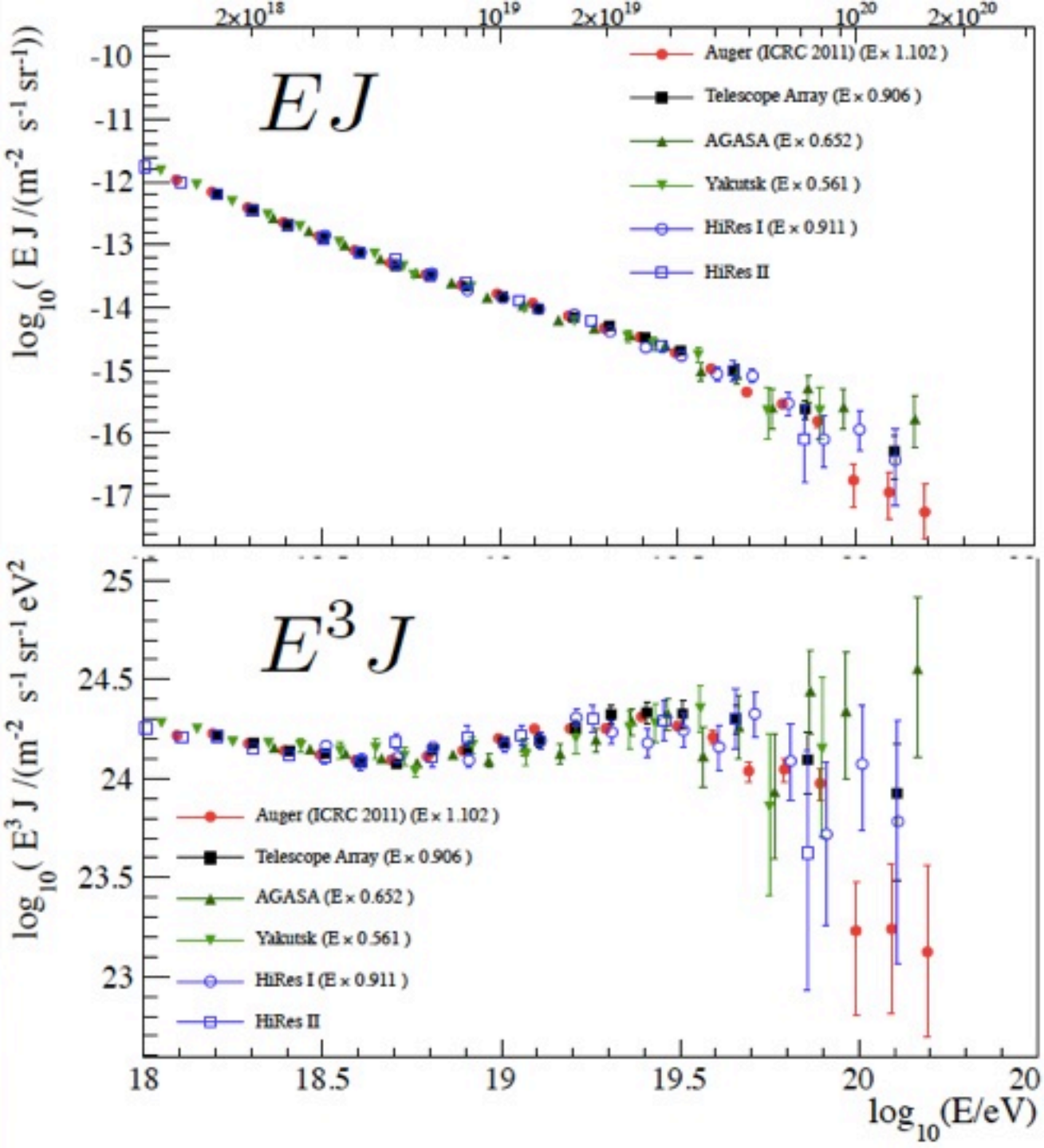
3 FD stations overlooking an array of
507 scintillator surface detectors (SD)
complete and operational as of ~1/2008.

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

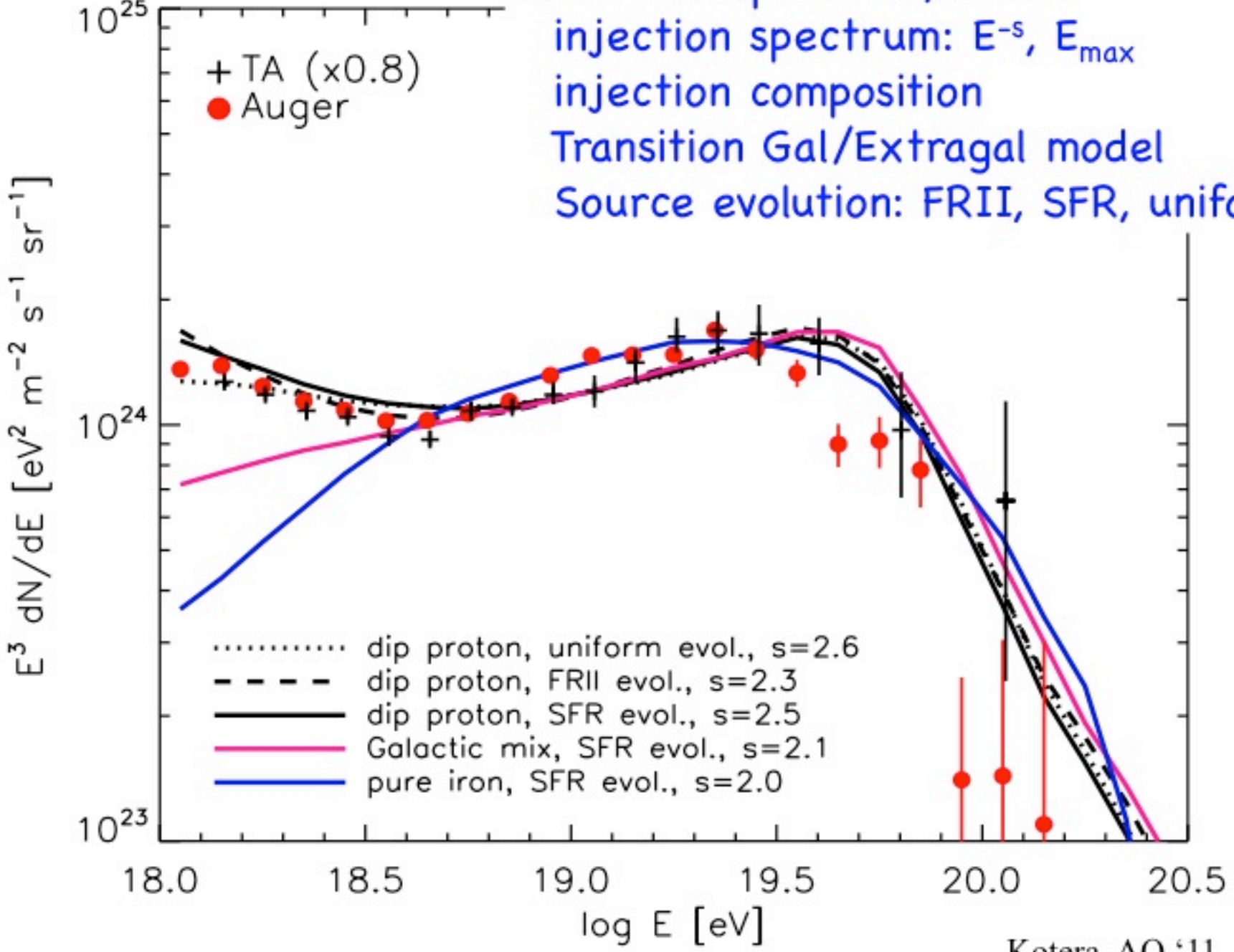
2012 CERN Working Group

Unified Spectrum

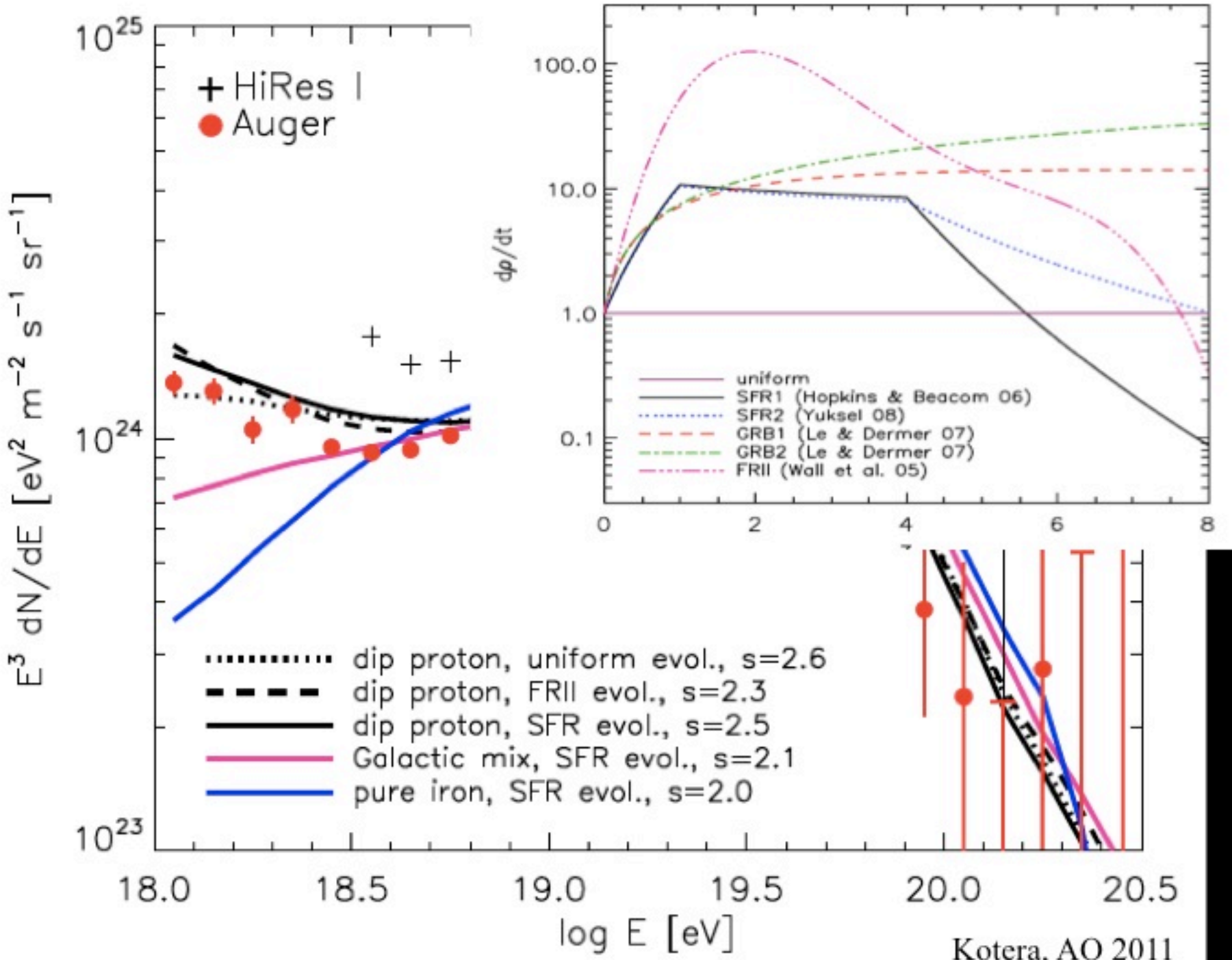
~10% absolute energy shifts



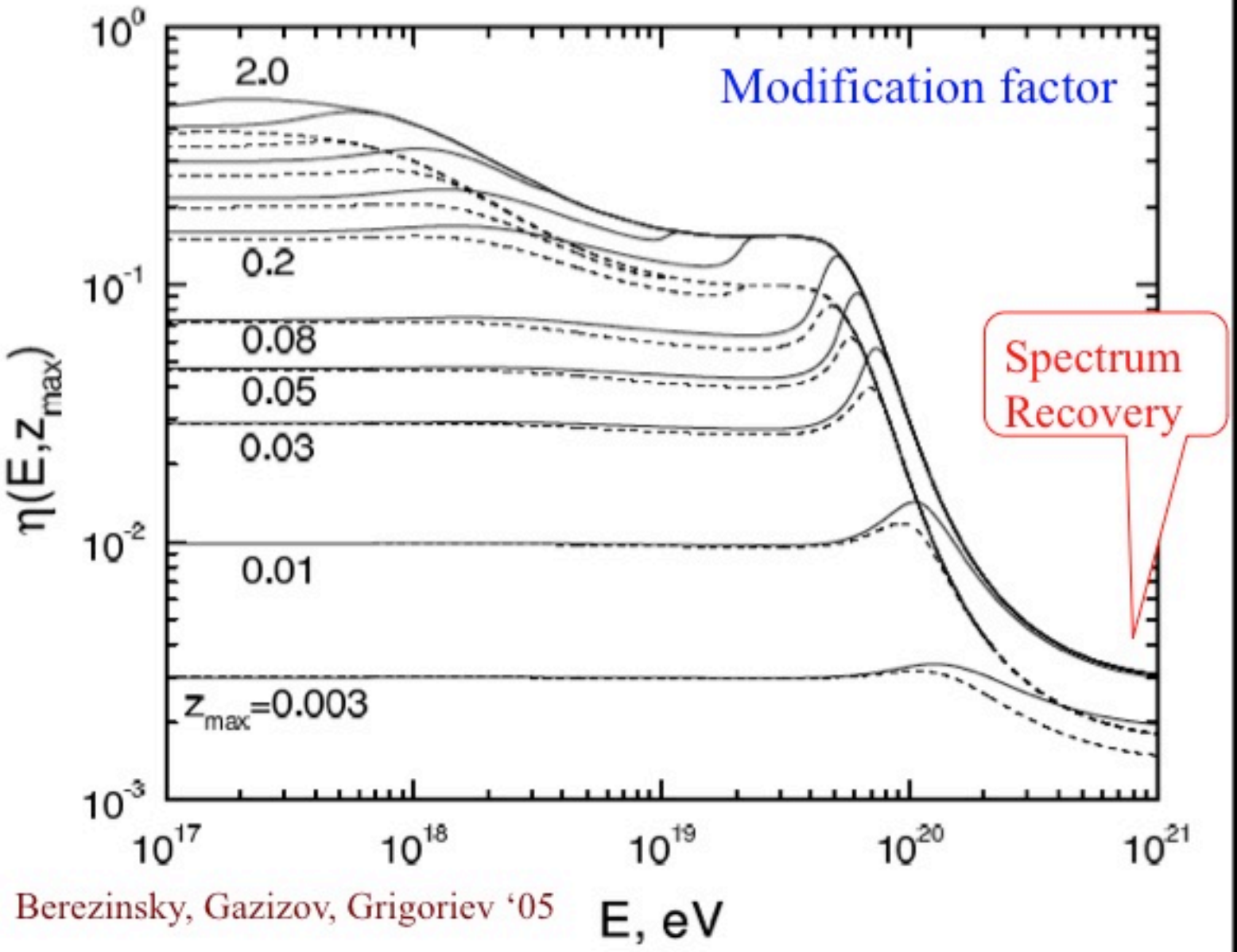
To fit the spectrum, need:
injection spectrum: E^{-s}, E_{max}
injection composition
Transition Gal/Extragal model
Source evolution: FRII, SFR, uniform



Kotera, AO '11

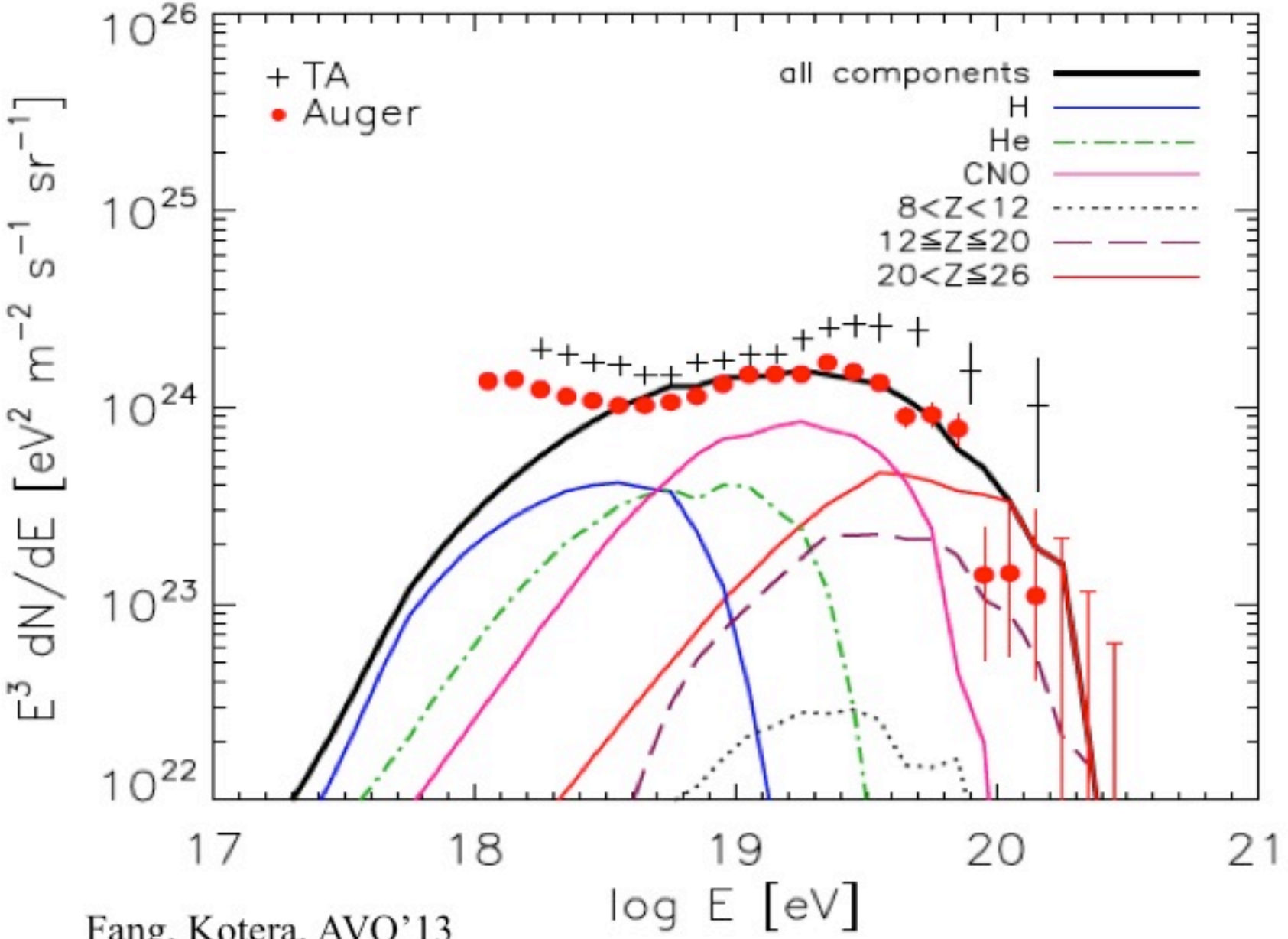

HiRes I
Auger
$E^3\ dN/dE\ [eV^2\ m^{-2}\ s^{-1}\ sr^{-1}]$
10^{25}
10^{24}
10^{23}
dip proton, uniform evol., s=2.6
dip proton, FRII evol., s=2.3
dip proton, SFR evol., s=2.5
Galactic mix, SFR evol., s=2.1
pure iron, SFR evol., s=2.0
18.0
18.5
19.0
19.5
20.0
20.5
log E [eV]
$d\dot{n}/dt$
100.0
10.0
1.0
0.1
uniform
SFR1 (Hopkins & Beacom 06)
SFR2 (Yuksel 08)
GRB1 (Le & Dermer 07)
GRB2 (Le & Dermer 07)
FRII (Wall et al. 05)
0
2
4
6
8
Kotera, AO 2011

Propagation of UHE protons

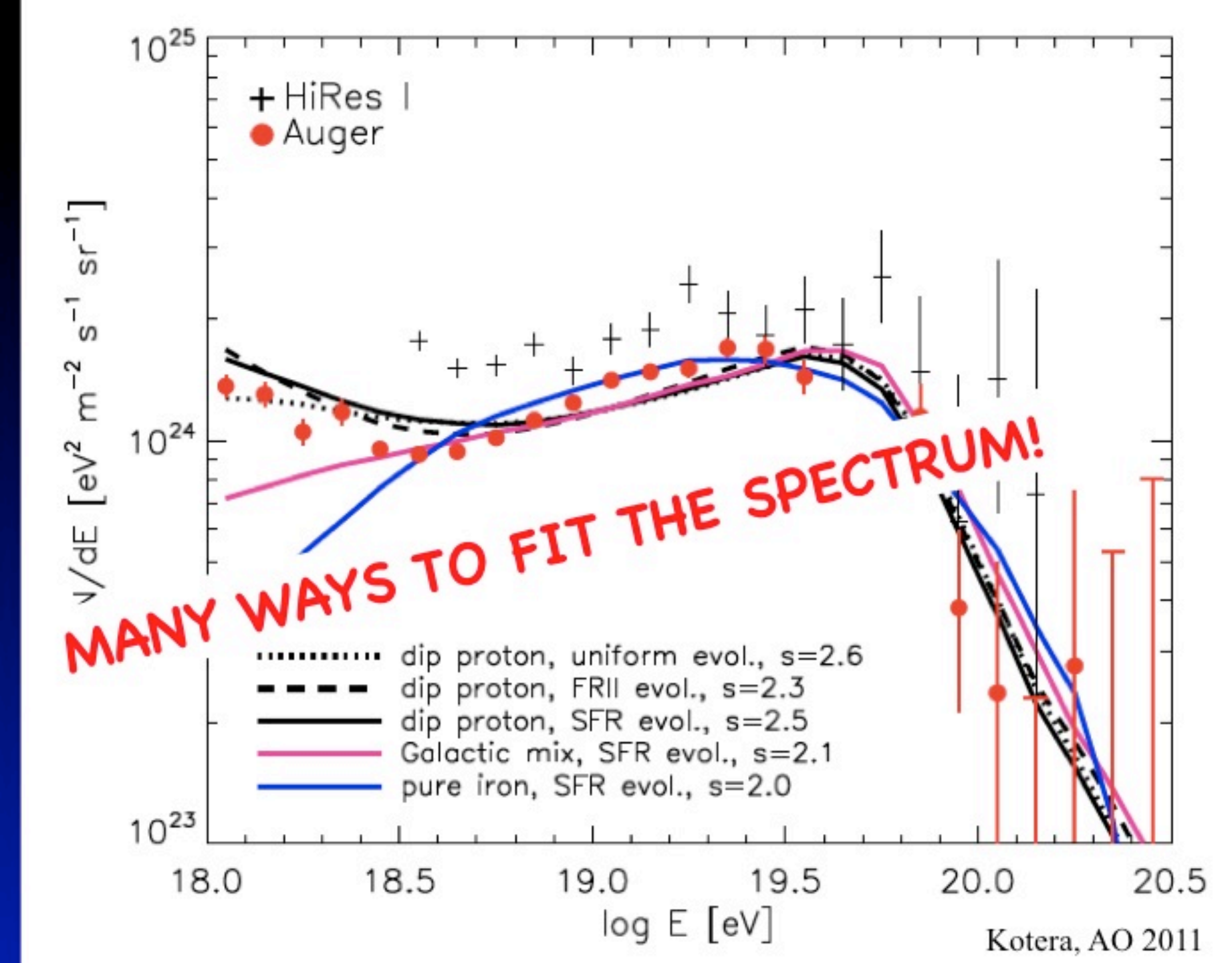


Berezinsky, Gazizov, Grigoriev '05

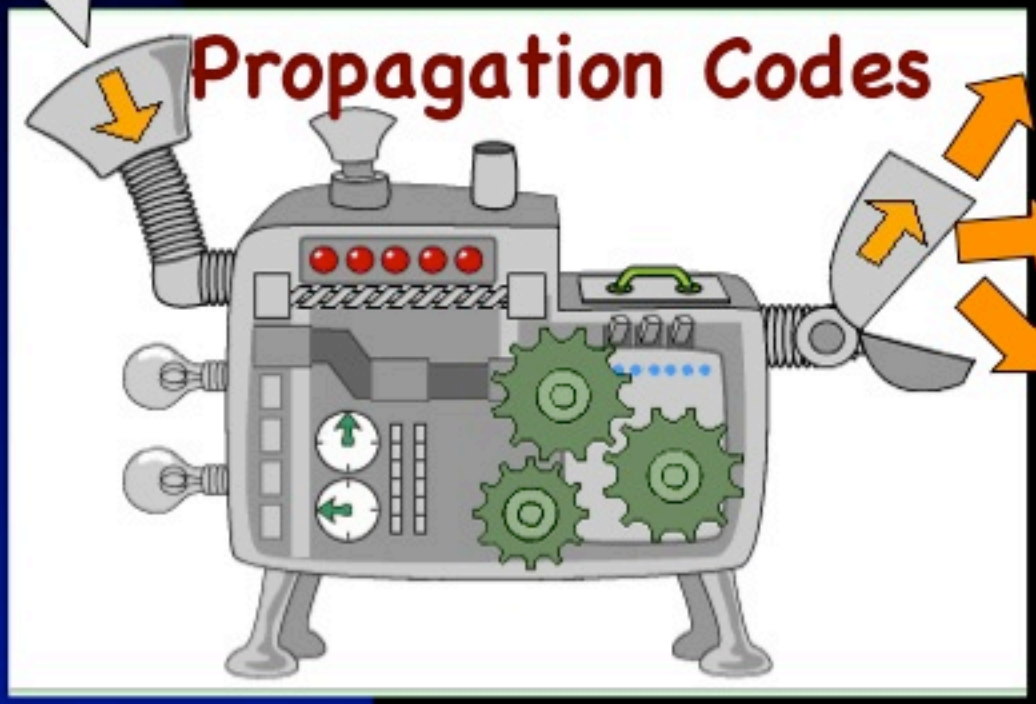
Mixed Composition Model (Young Pulsars)



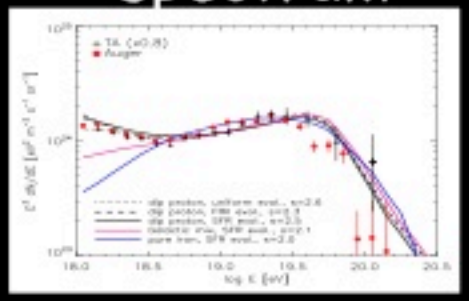
Fang, Kotera, AVO'13


HiRes I
Auger
MANY WAYS TO FIT THE SPECTRUM!
dip proton, uniform evol., s=2.6
dip proton, FRII evol., s=2.3
dip proton, SFR evol., s=2.5
Galactic mix, SFR evol., s=2.1
pure iron, SFR evol., s=2.0
J/dE [eV² m⁻² s⁻¹ sr⁻¹]
log E [eV]
Kotera, AO 2011

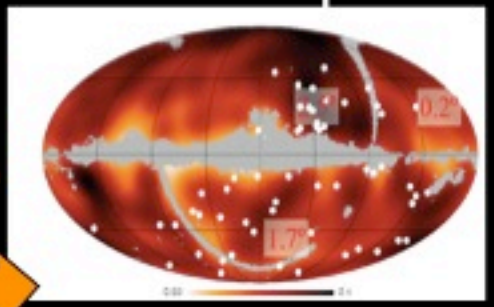
Source Model:
- injection spectrum: E^{-s}
- injected composition
- redshift distribution



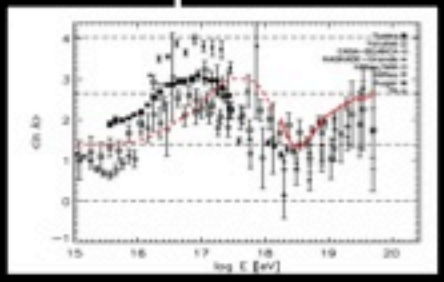
Spectrum



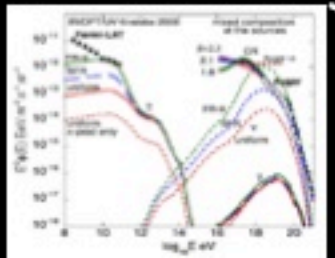
Anisotropies

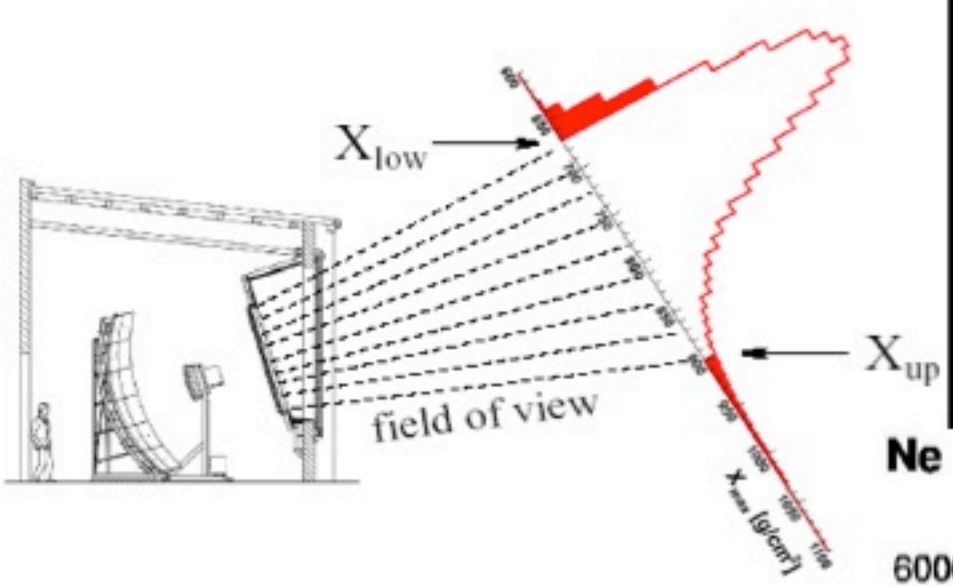


Composition

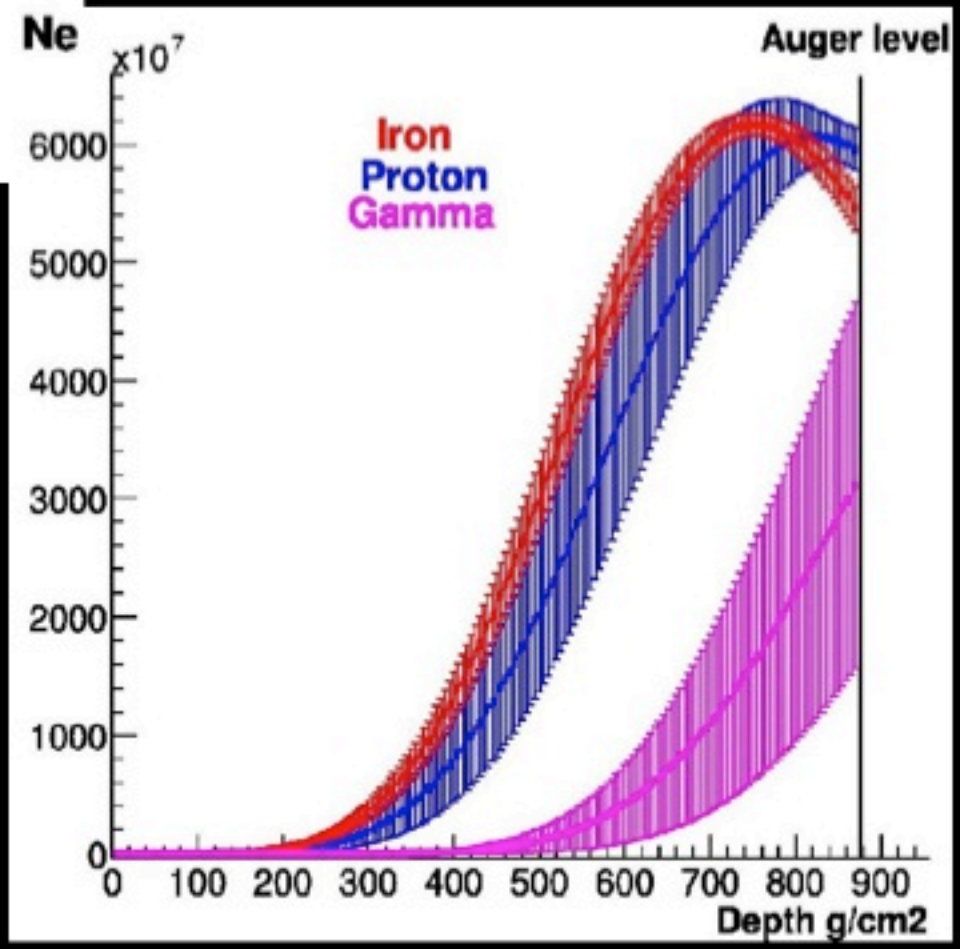


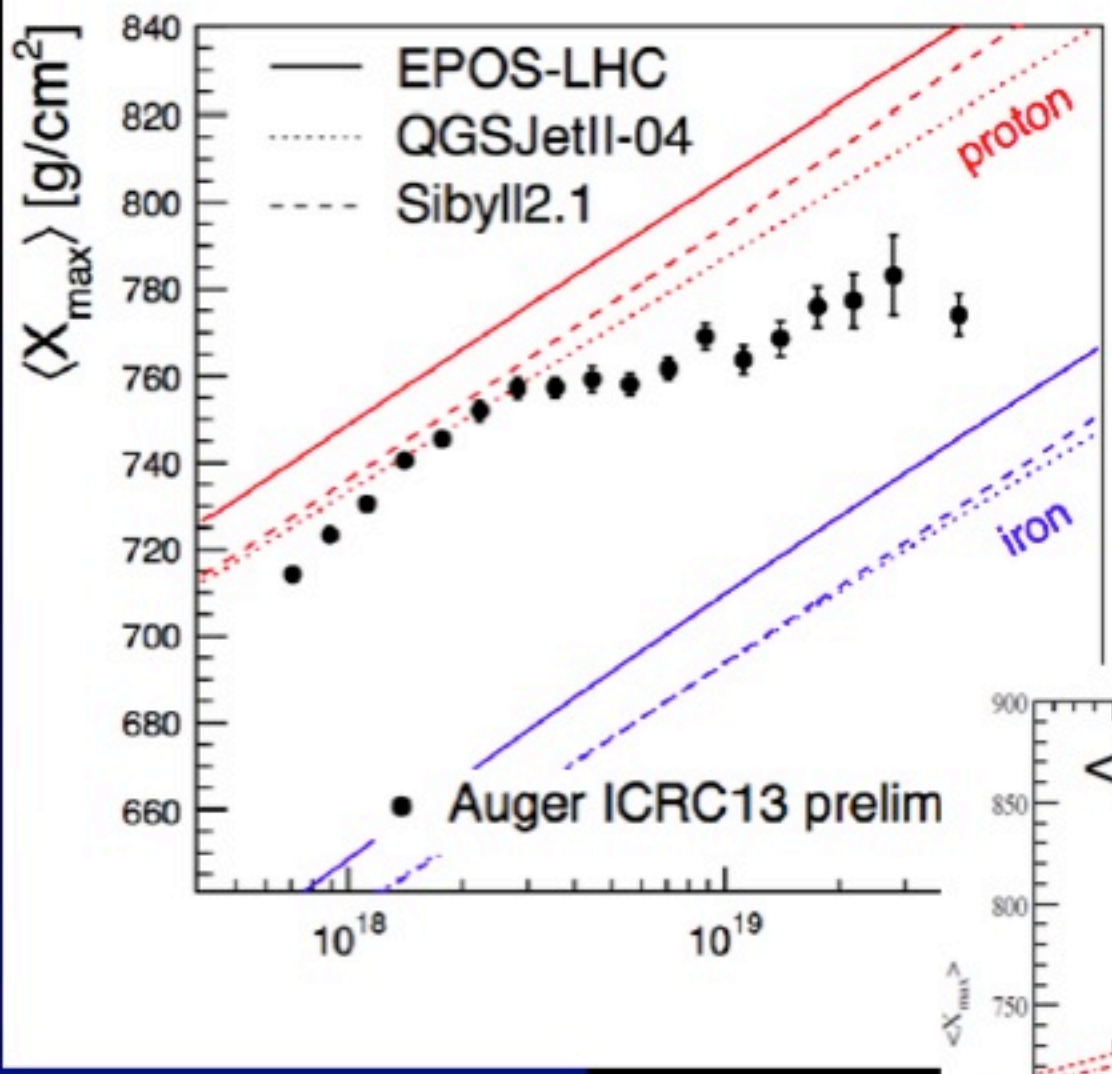
Multi-messengers





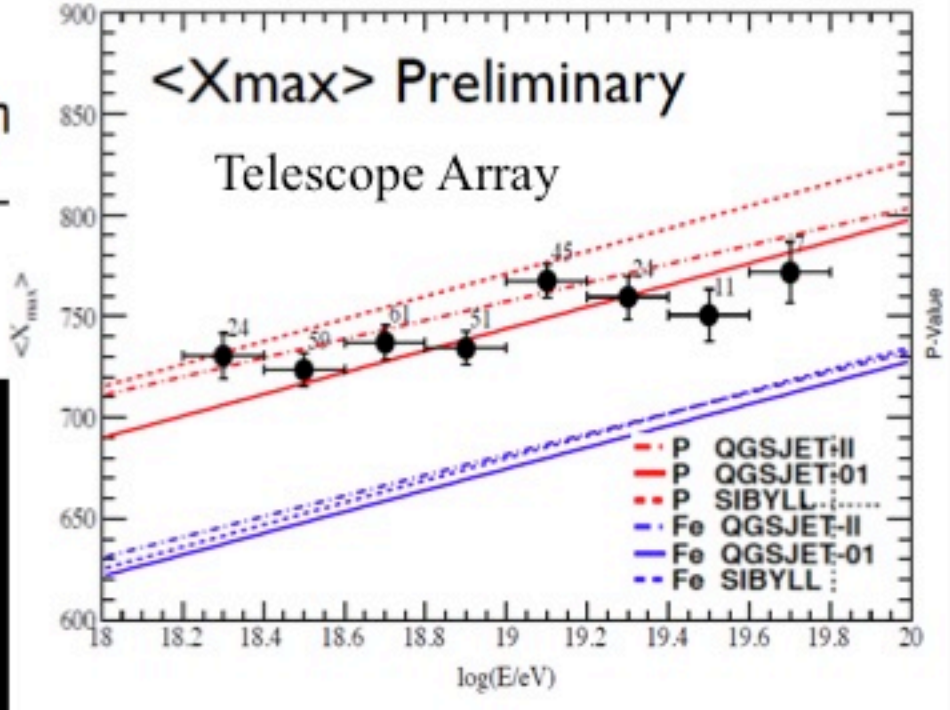
Composition observable: shower maximum

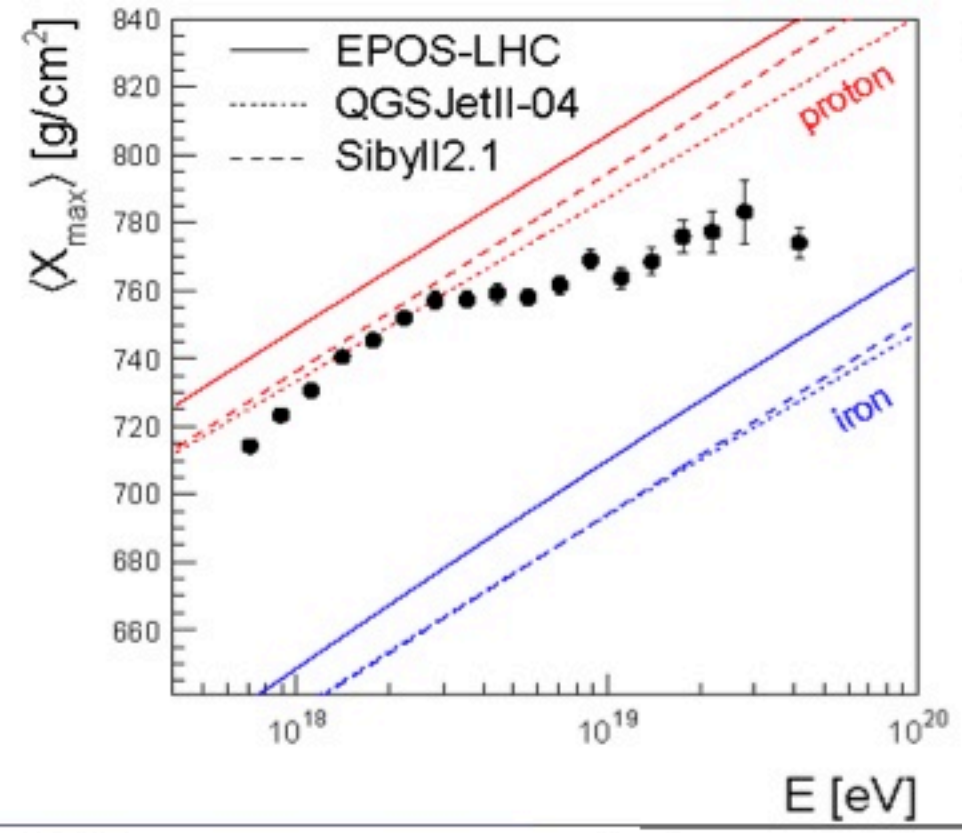


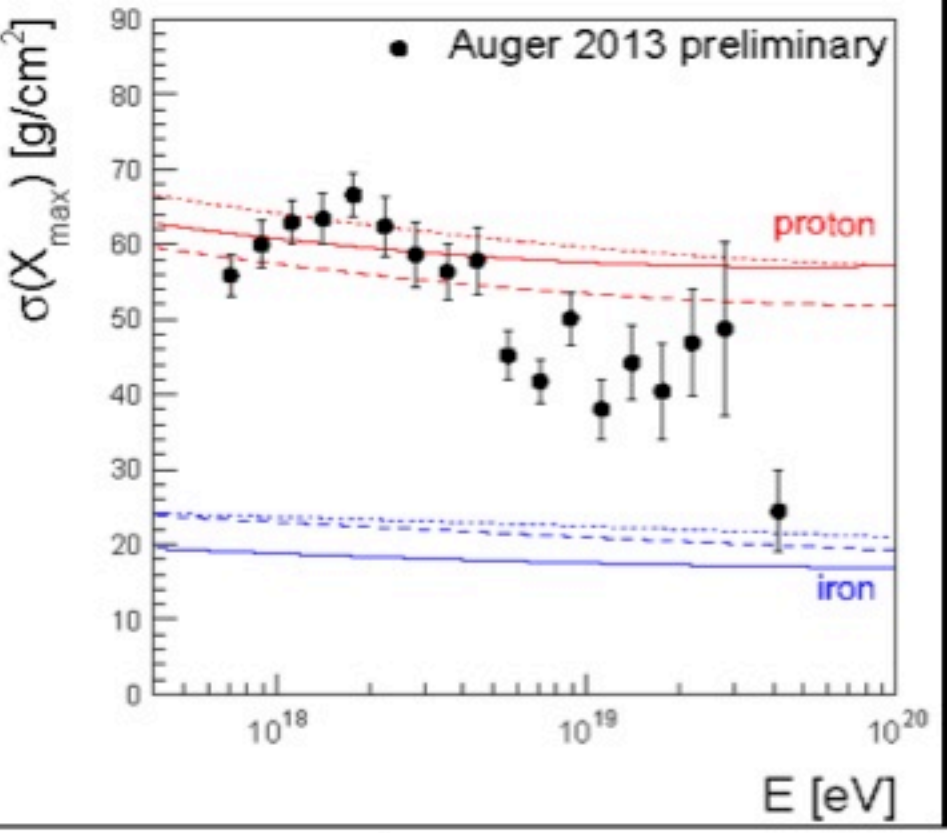


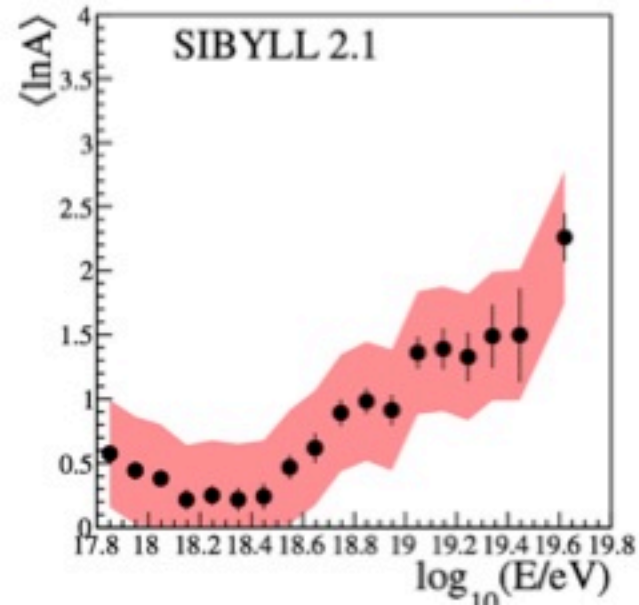
Auger sees change slope: Change in Composition or interactions

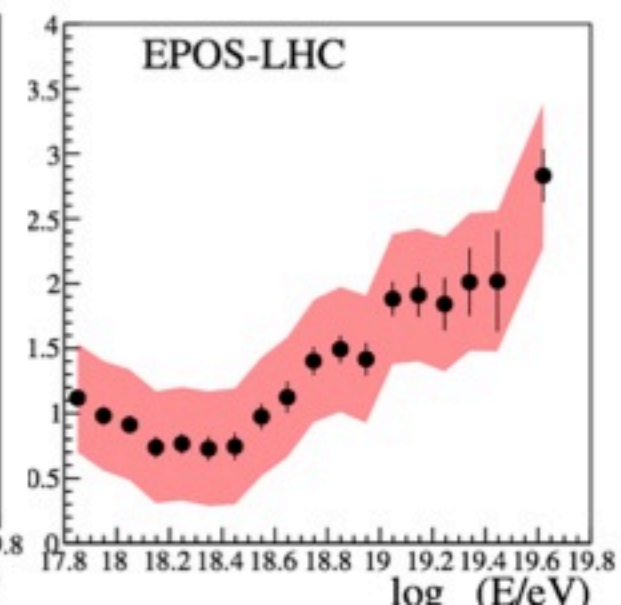
TA: not confirmed yet

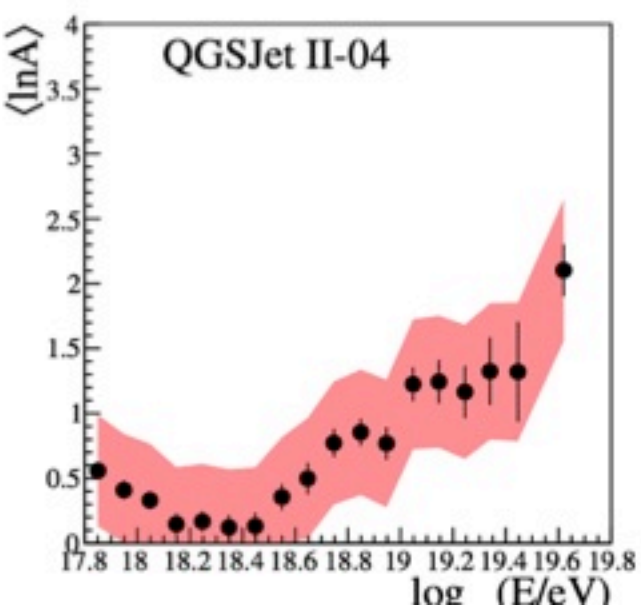



EPOS-LHC
QGSJetII-04
Sibyll2.1
proton
iron
⟨X_max⟩ [g/cm²]
E [eV]

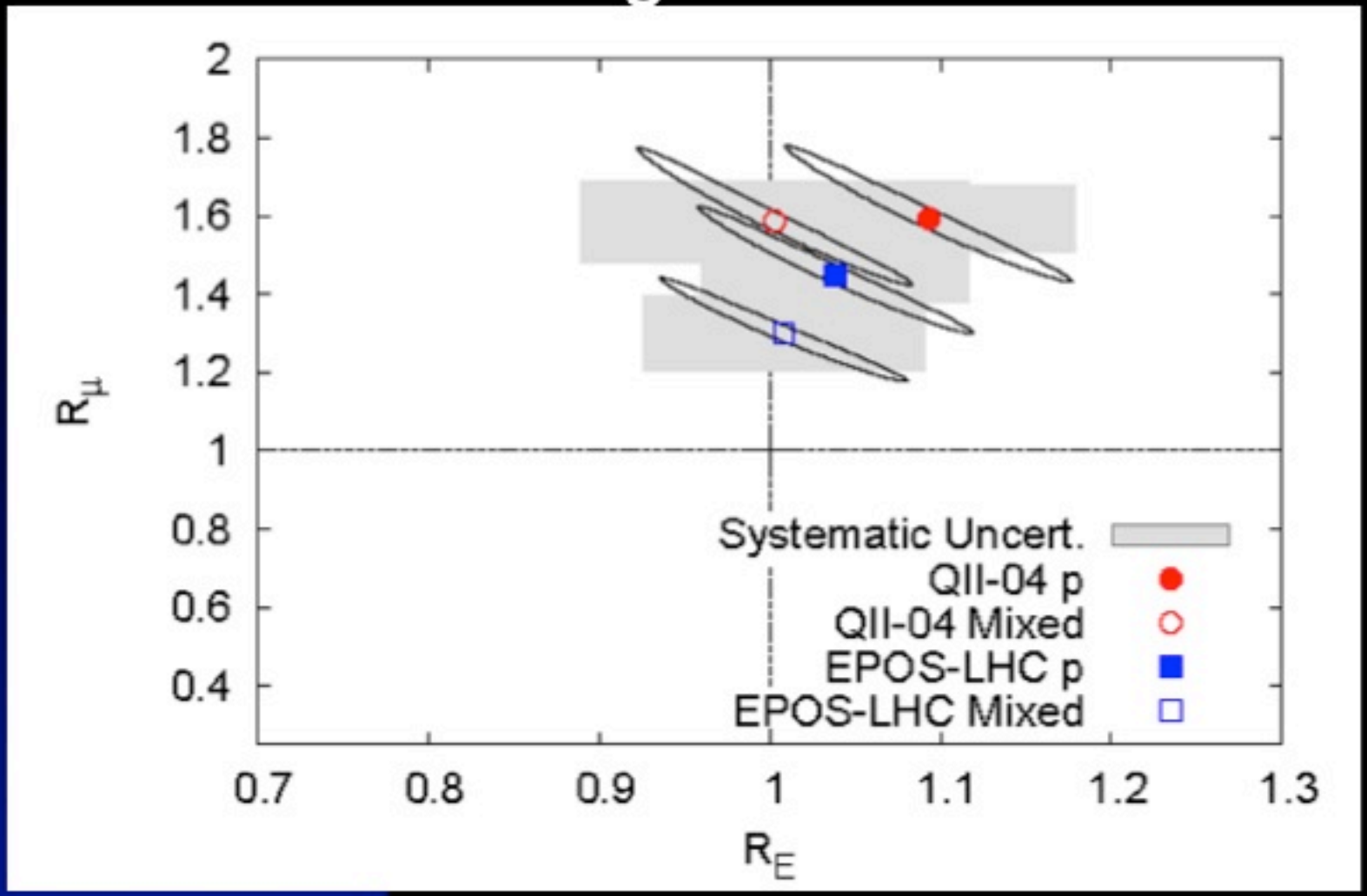

Auger 2013 preliminary
proton
iron
σ(X_max) [g/cm²]
E [eV]


SIBYLL 2.1
⟨lnA⟩
log10(E/eV)


EPOS-LHC
log (E/eV)

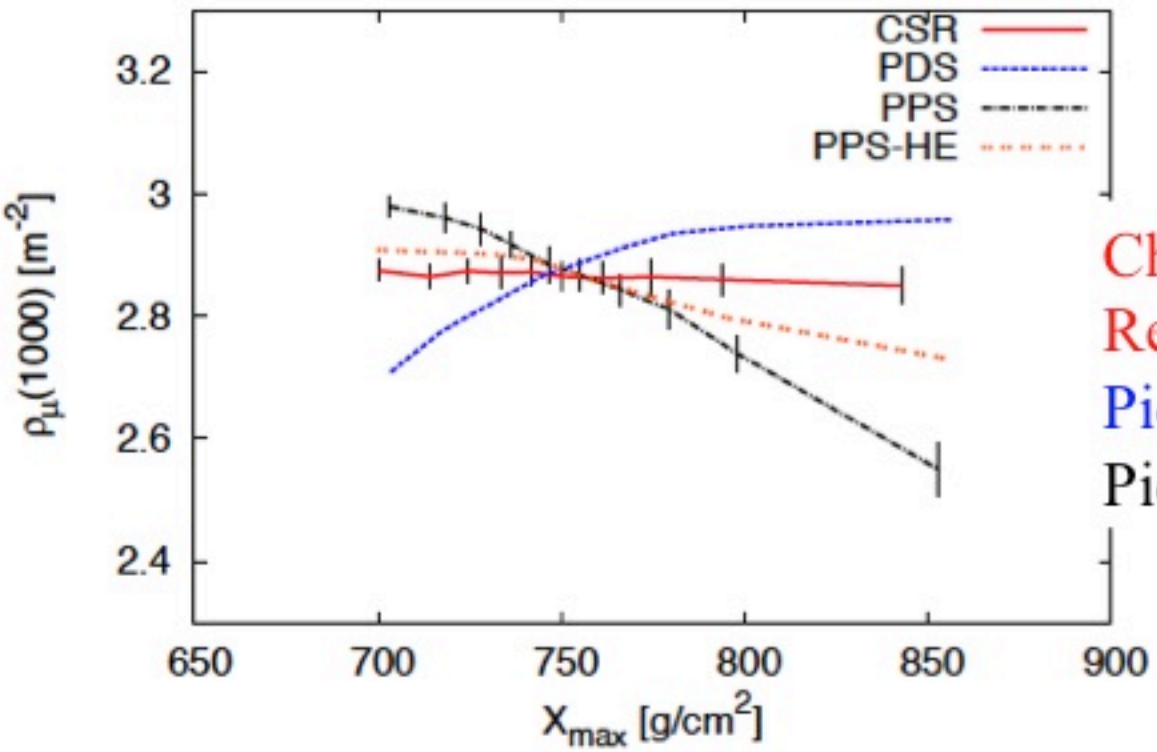

QGSJet II-04
⟨lnA⟩
log (E/eV)

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

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	–

Farrar & Allen ICRC 2013
arXiv:1307.5059,

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?

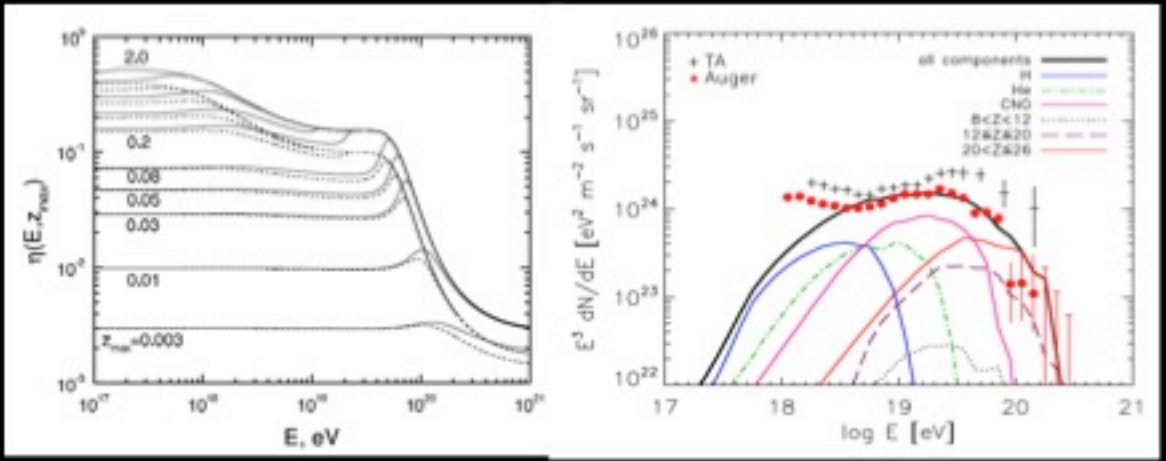
Muon Numbers & X_{max}

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

Auger Upgrade

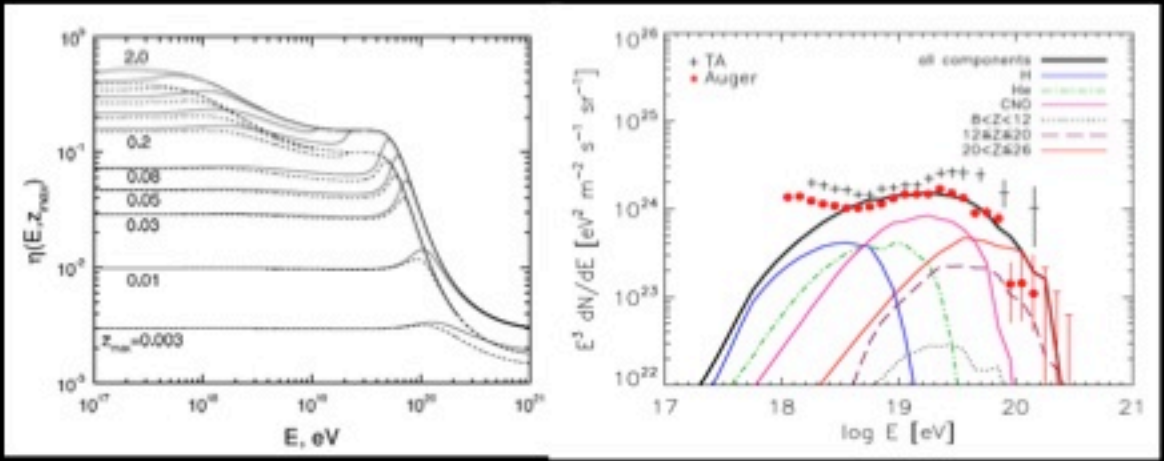
How can we tell New Physics from Astrophysics?

Look for Spectral Recovery – indicate PROTONS



How can we tell New Physics from Astrophysics?

Look for Spectral Recovery – indicate PROTONS



FIND THE SOURCES!!!

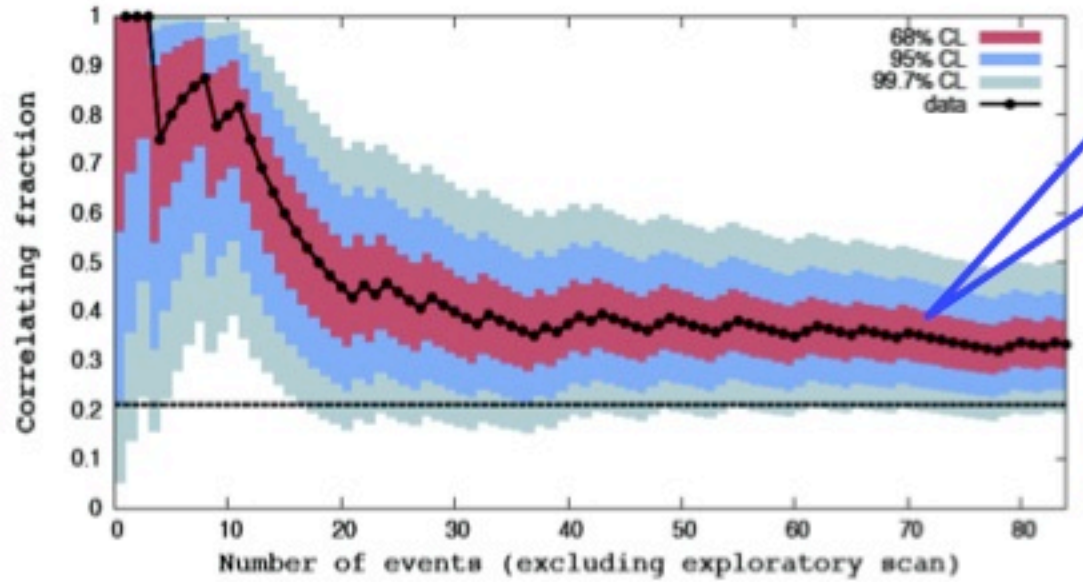
Where are they coming from?

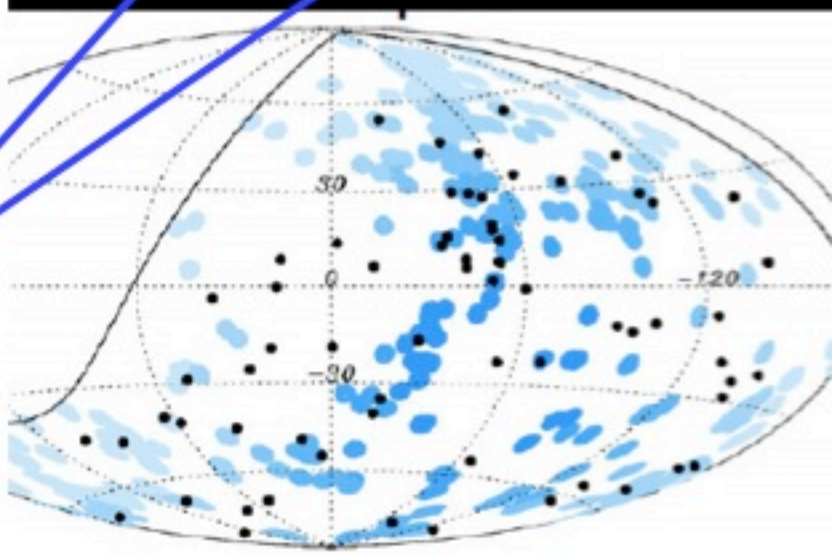
Don't know!

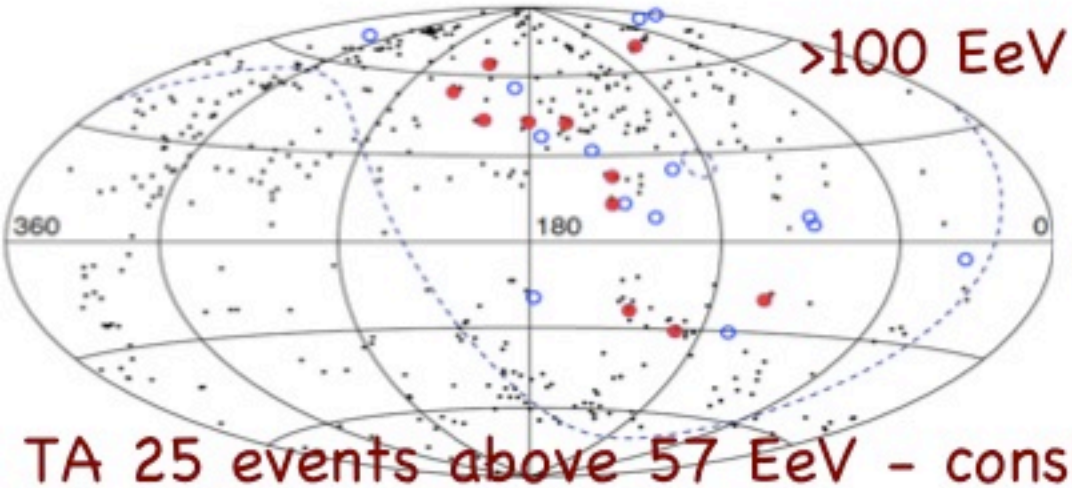
EECR Anisotropy Hints

E > 60 EeV

Mild anisotropy - still dominated by isotropic background at 55 EeV

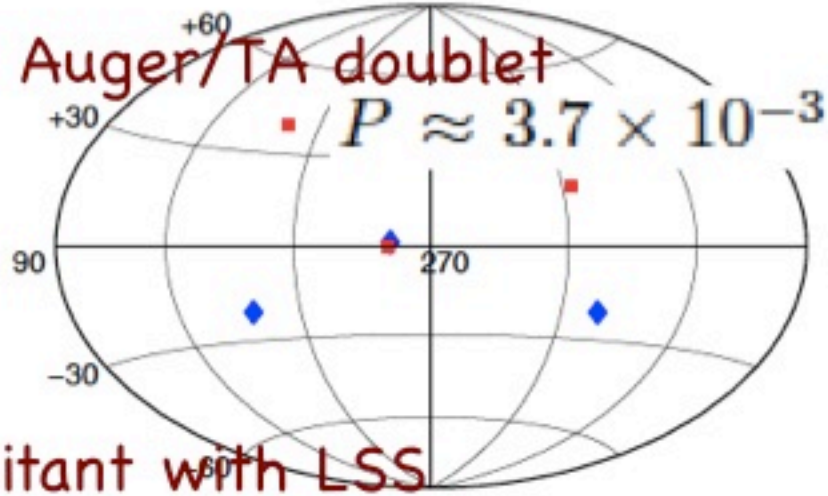




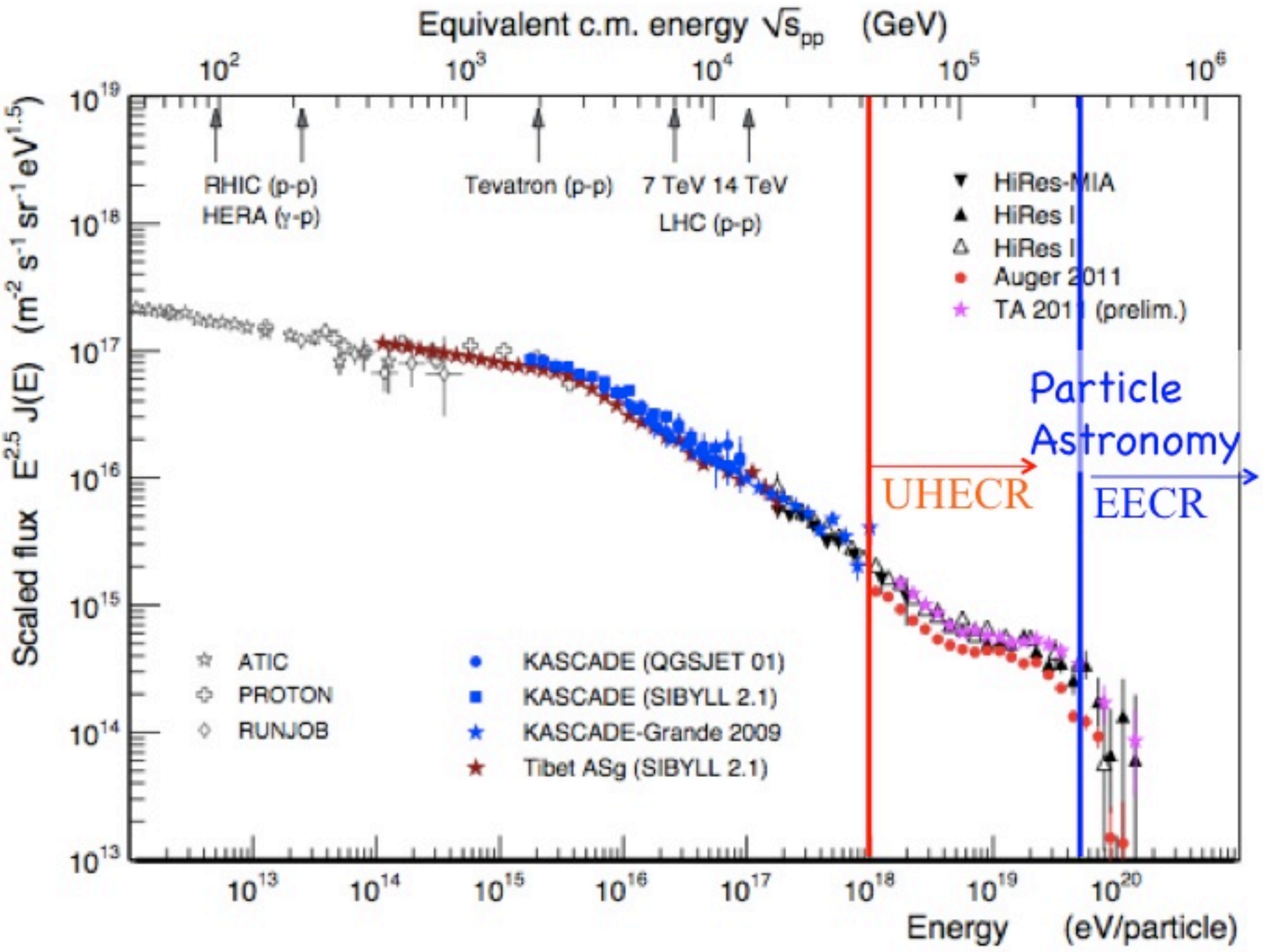


>100 EeV Auger/TA doublet

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



TA 25 events above 57 EeV - consitant with LSS


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 I
Auger 2011
TA 201 (prelim.)
Particle
Astronomy
UHECR
EECR
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}
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy (eV/particle)

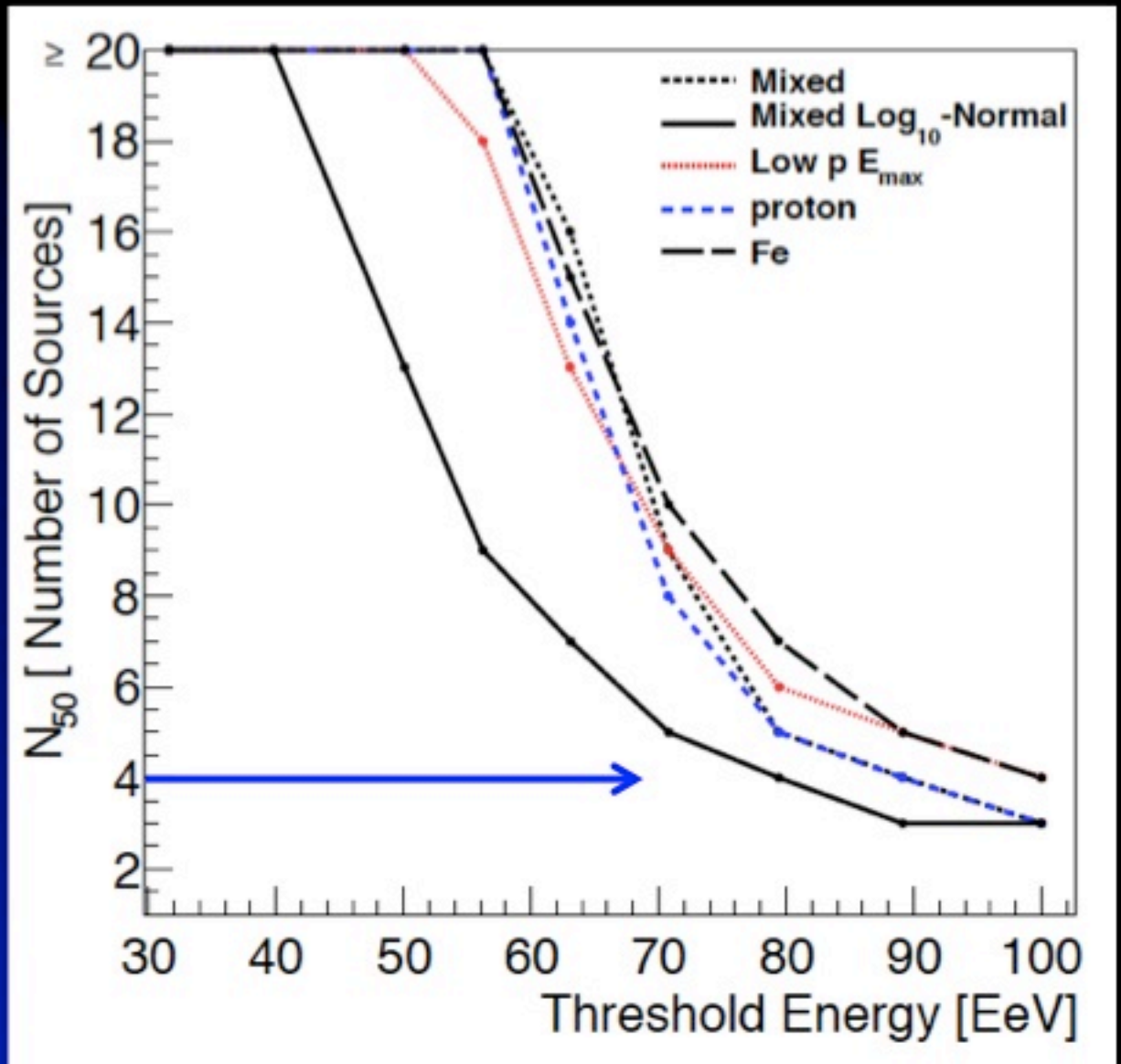
How can we tell New Physics from Astrophysics?

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

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

To detect sources

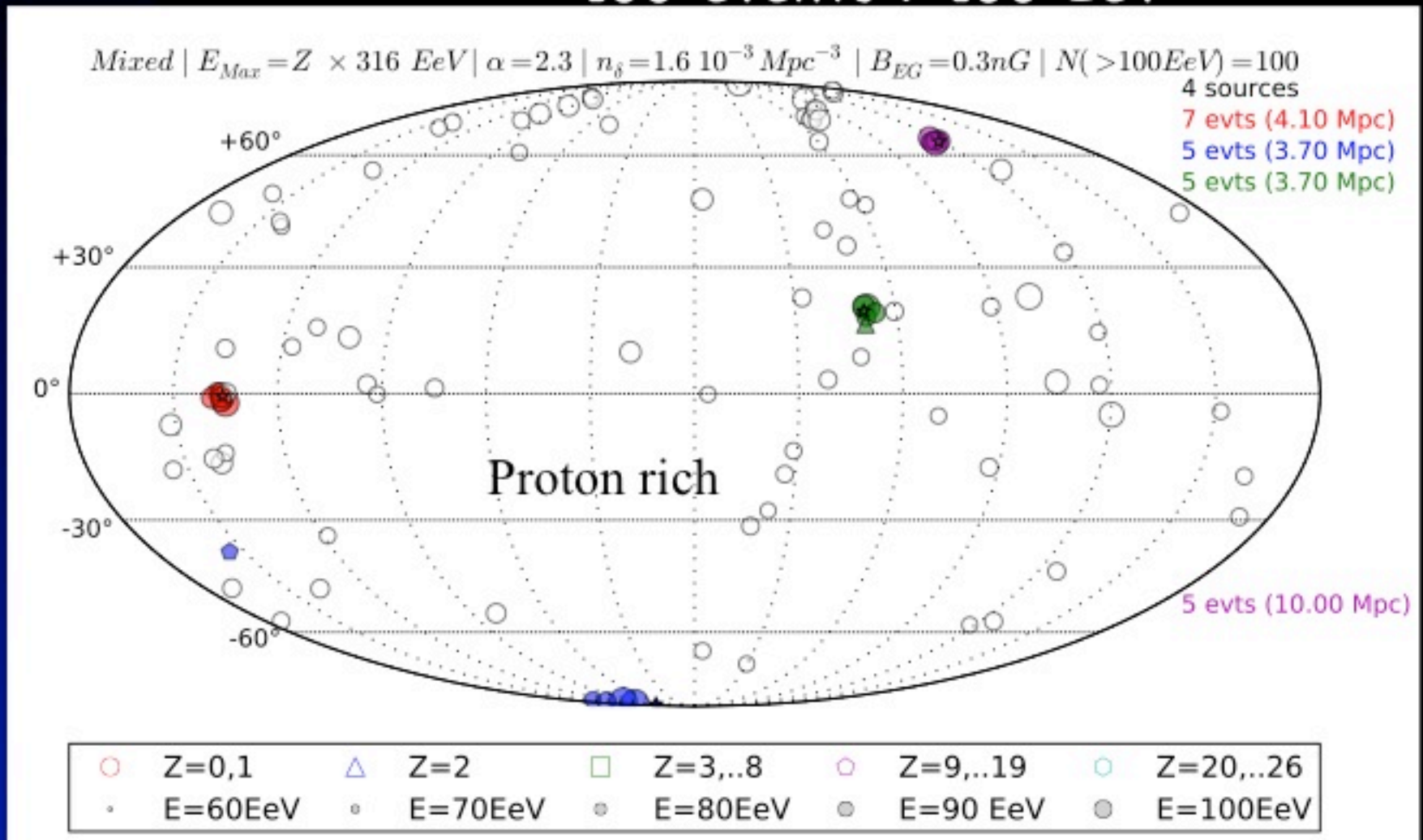
Observe at higher energies – fewer sources



To detect sources

Increase statistics: ~1,000 events > 60 EeV

~100 events > 100 EeV



To detect sources

Increase statistics: ~1,000 events > 60 EeV

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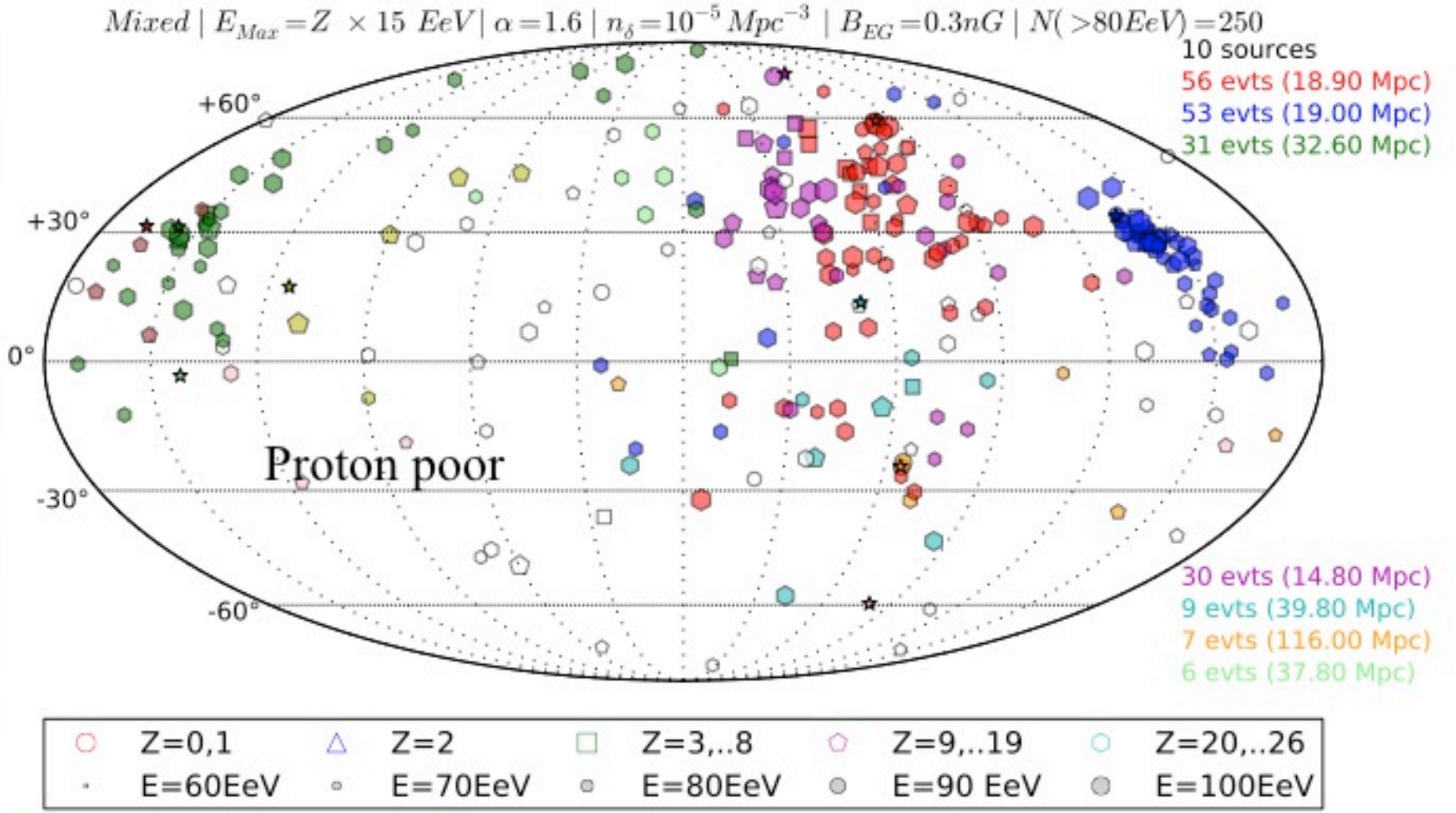

How many EECRs > 60 EeV?

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!!!

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Auger w/ 3,000 km^2

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Telescope Array w/ 700 km^2

~5 events > 60 EeV/ yr

Auger + TA ~ 25 events/yr

40 years to reach 1,000

500 to go!

Earth surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

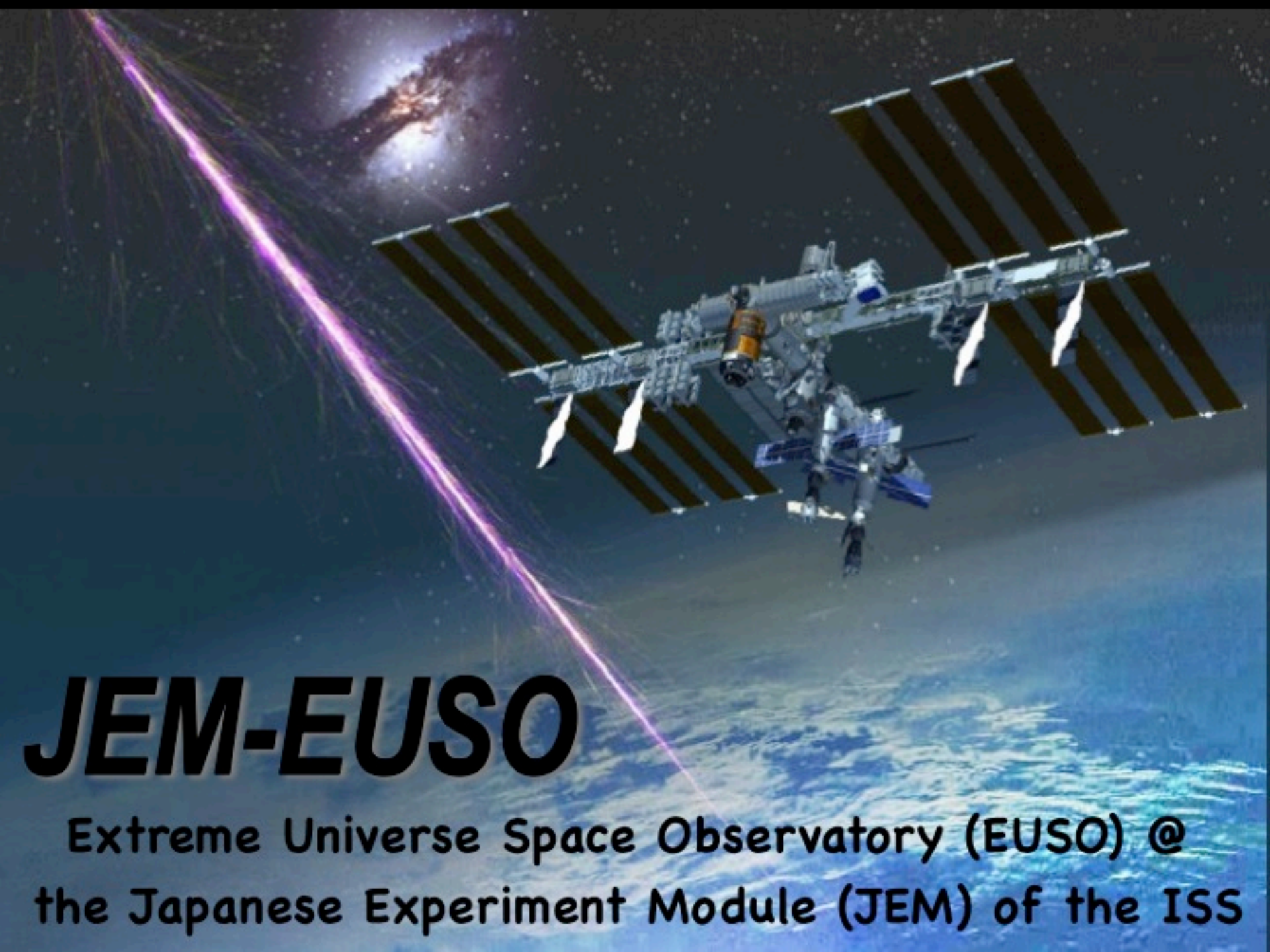
How can we tell New Physics from Astrophysics?

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


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

How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO

~200 events > 60 EeV/ yr

How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO

~200 events > 60 EeV/ yr

400 km to go!

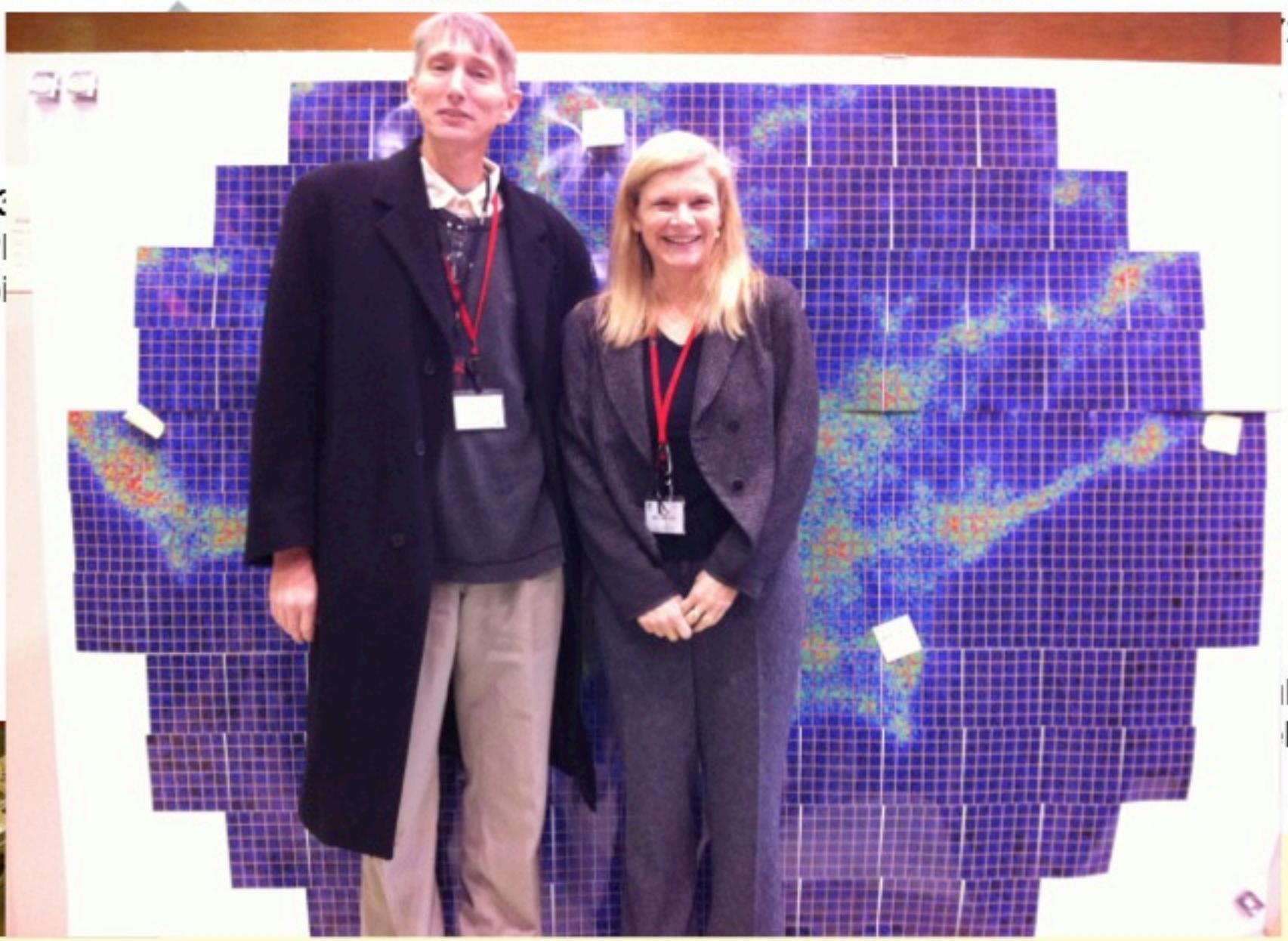
Earth surface ~ $5\ 10^8$ km^2

~$3.4\ 10^6$ events/yr

JEM-EUSO Mission

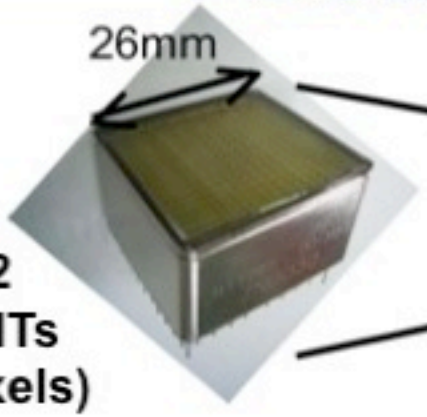
UV telescope 60° FOV
4.5 m^2 Focal Surface

Focal Surface Detector

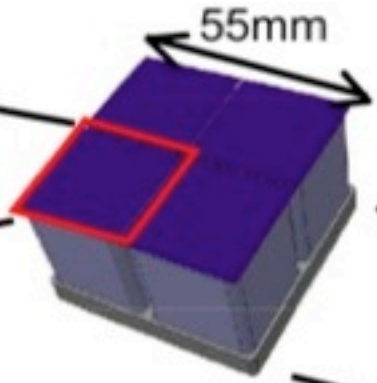


Focal Surface Detector

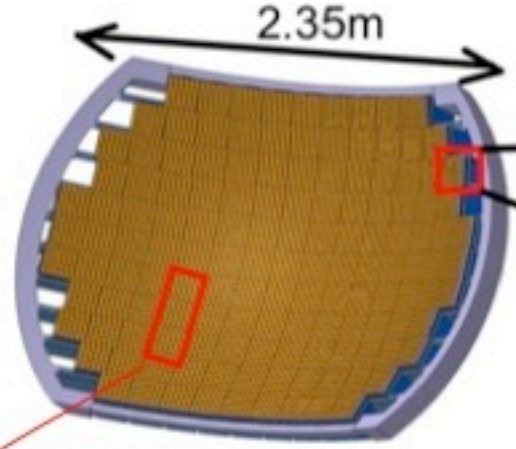
Y. Kawasaki, ID 0472
M. Ricci, ID 0335

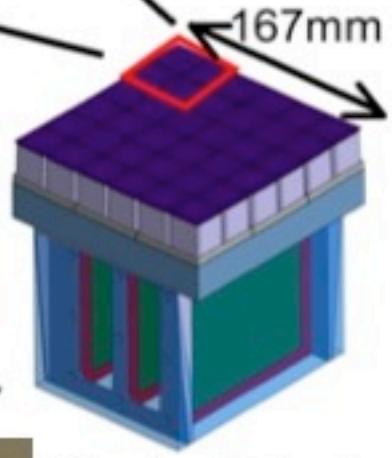


4932
MAPMTs
(8x8 pixels)



Elementary Cell
(2x2 PMTs = 256 pixels)





Focal Surface detector
137 PDMs
= 0.3M Pixels

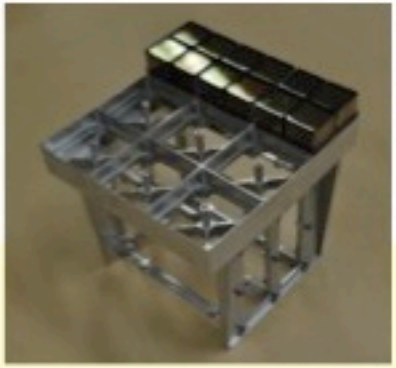


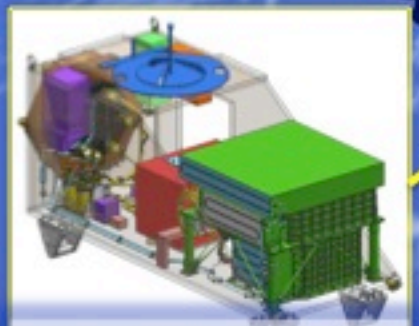
Photo-Detector Module
(3x3 ECs = 2,304 pixels

1 High Voltage / PDM

"Cosmic Ray Observatory on the ISS"

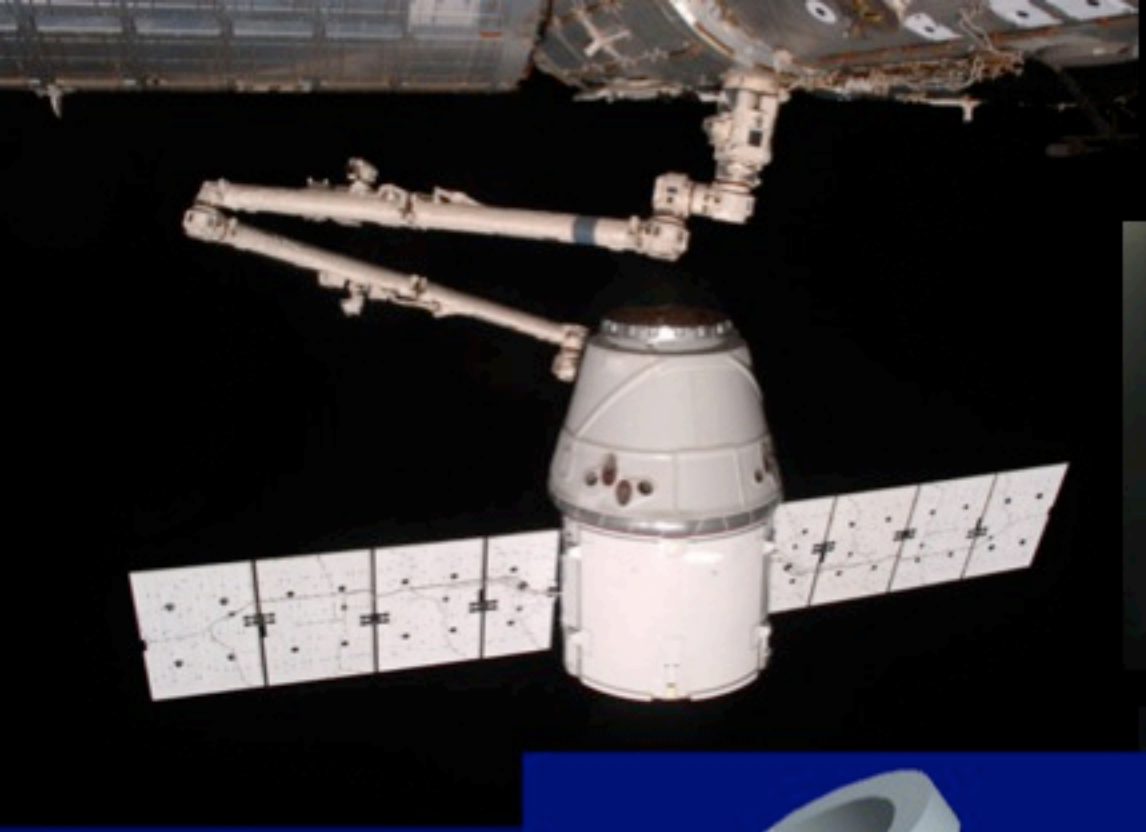
AMS Launch
May 16, 2011

ISS-CREAM
Sp-X Launch 2014



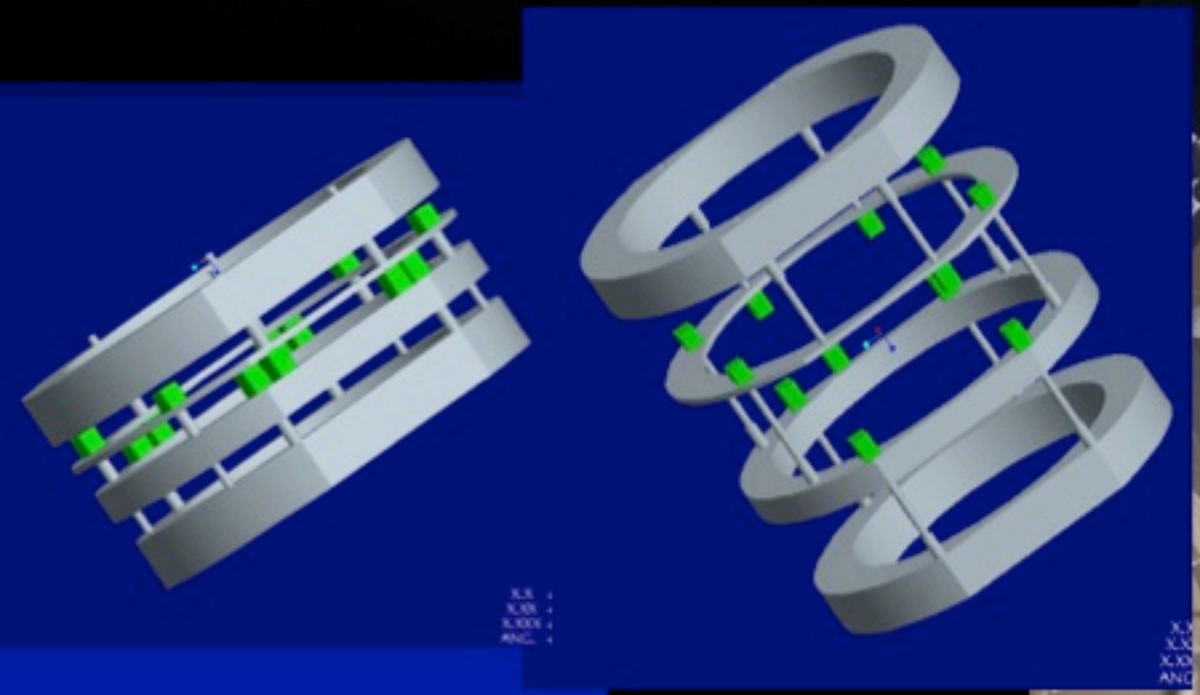
CALET on JEM
HTV Launch 2014

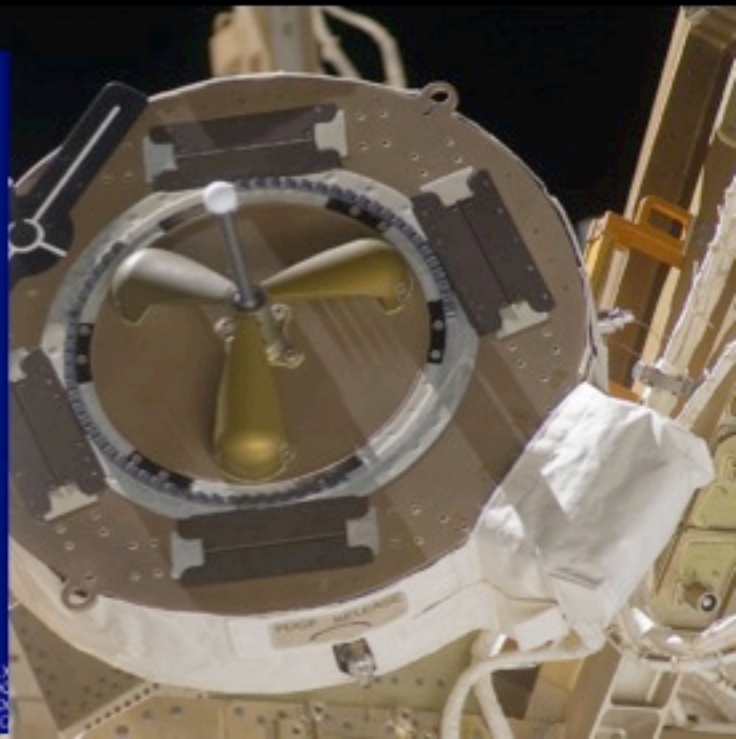
JEM-EUSO
Launch Tentatively
planned for 2017

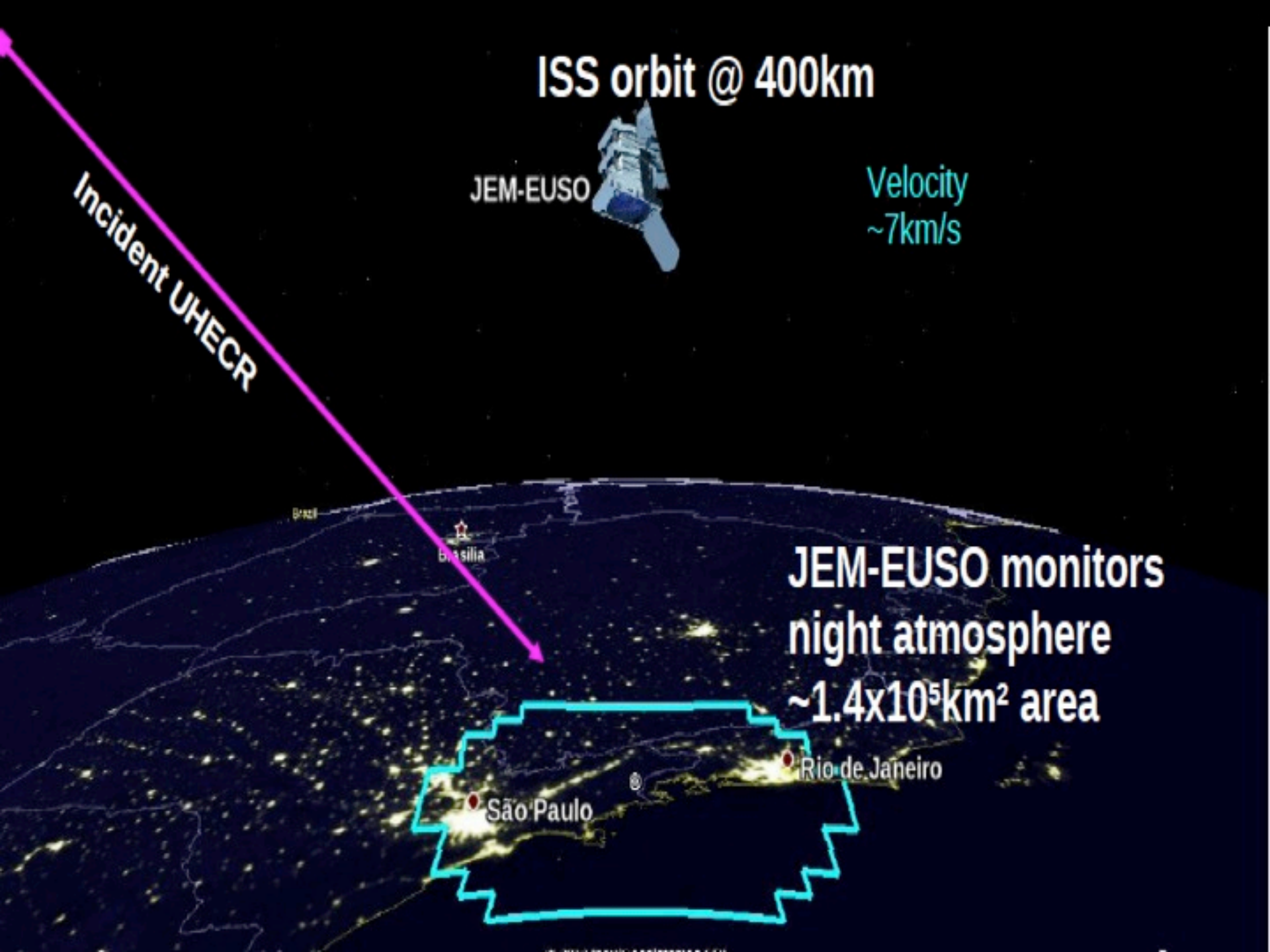


SPACEX

DRAGON

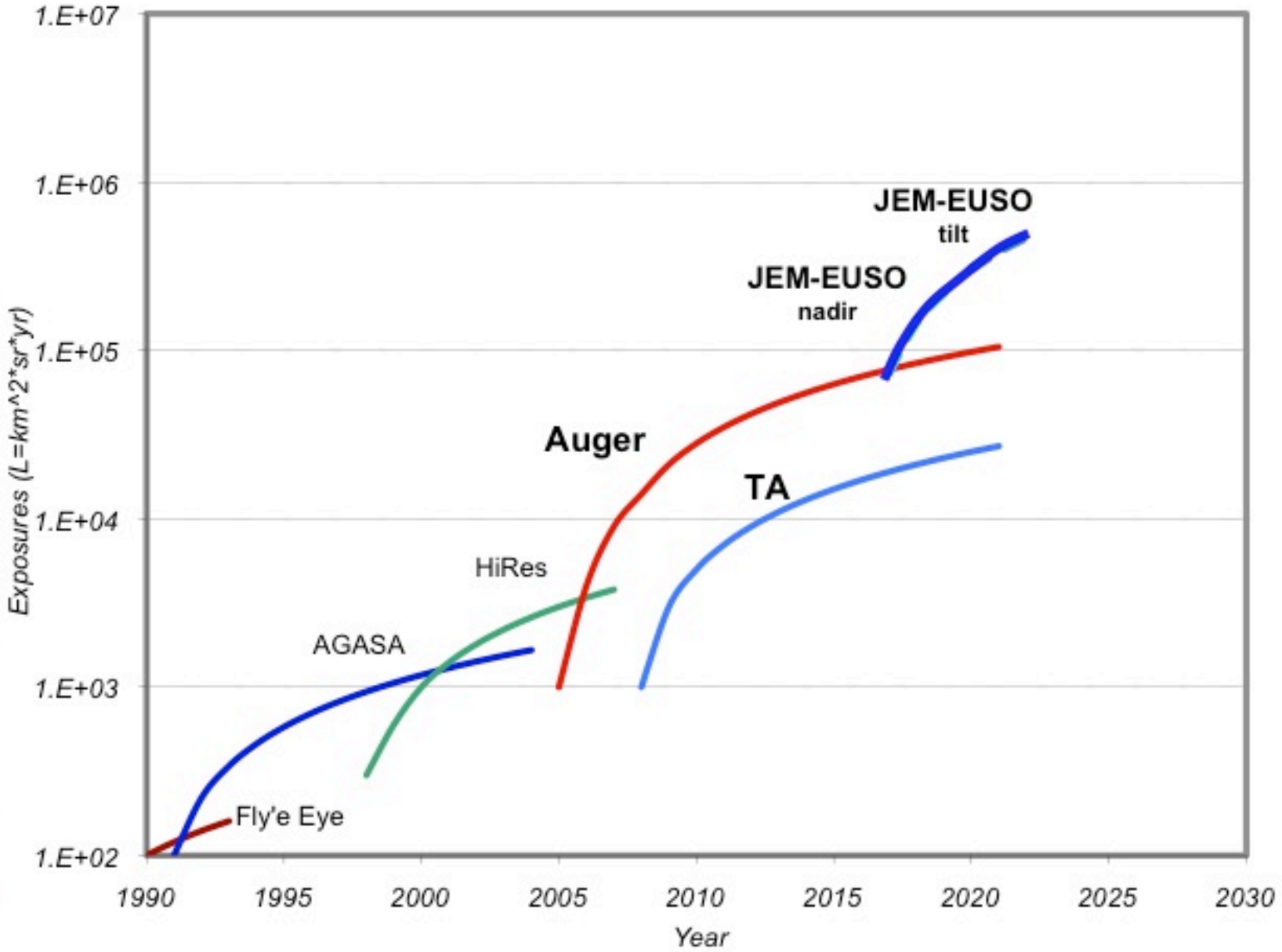





ISS orbit @ 400km
JEM-EUSO
Velocity
~7km/s
Incident UHECR
Brasilia
JEM-EUSO monitors
night atmosphere
~1.4x10⁵km² area
Rio de Janeiro
São Paulo


NADIR
TILT
A
B
Sierra Nevada Mountains
California
Nevada
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image Landsat
© 2013 Google
© 2013 INEGI

Exposure History




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

CF-6 Summary

Origin of highest energy particles in the universe (multi-messenger campaign)

Fundamental physics accessible with next generation instruments

Control of astrophysical systematics with precision VHE gamma-rays (**CTA**)

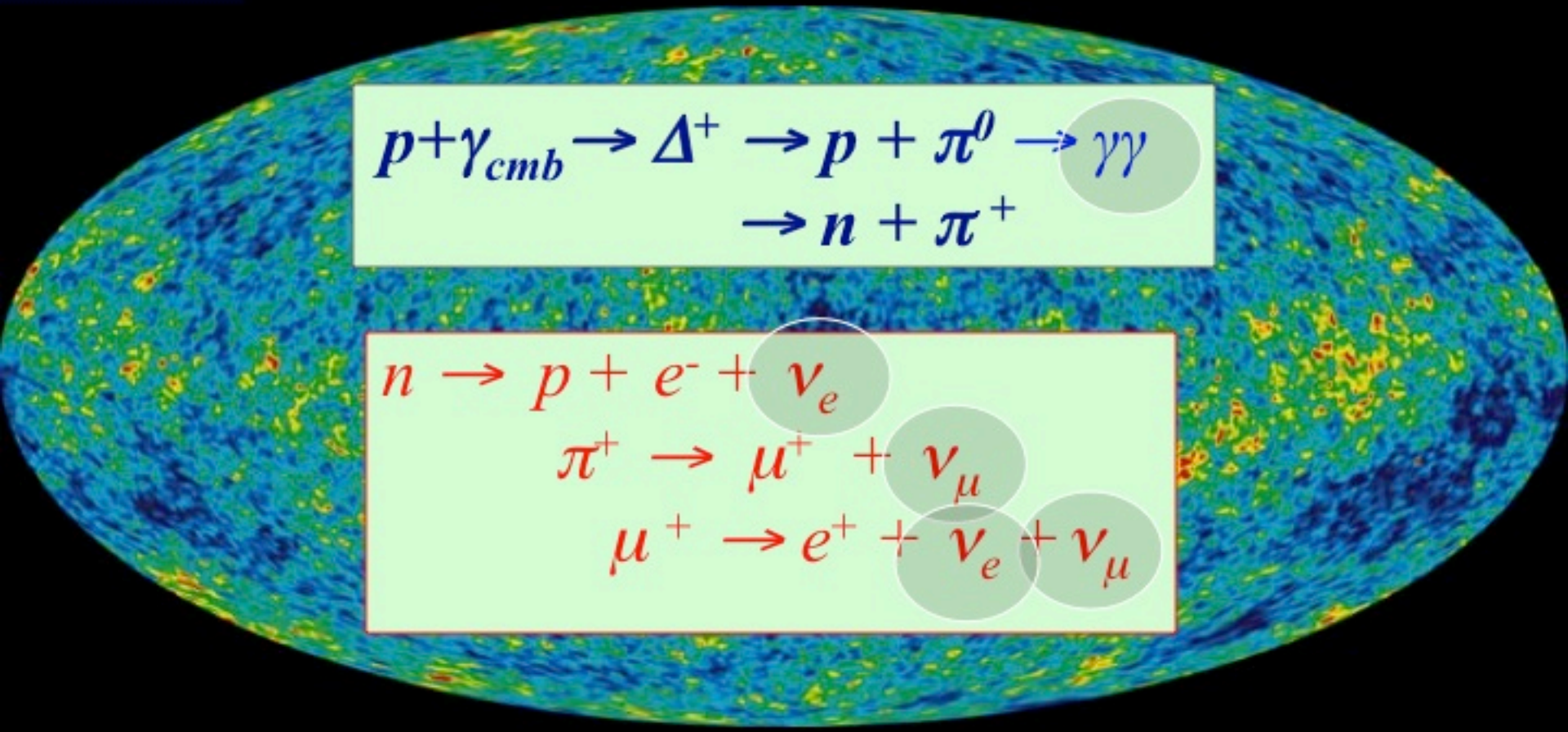
Neutrino interactions at high energies to be measured with GZK neutrinos (**ARIANNA, ARA,** ...)

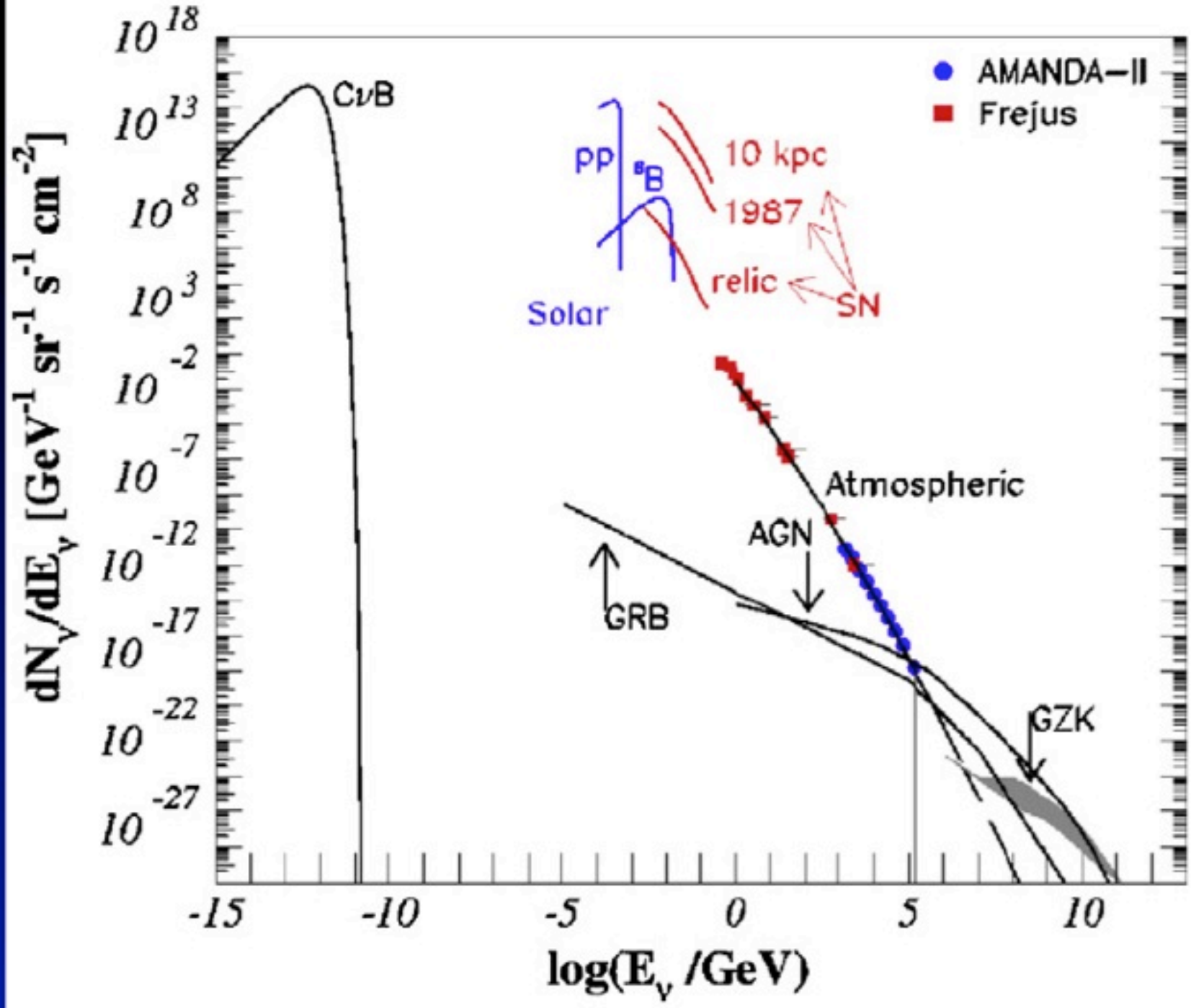
300 TeV C-M interactions to be measured with UHECRs (**JEM-EUSO**)

Probing Planck scale physics is now possible

Cosmogenic (GZK) Neutrinos & Photons

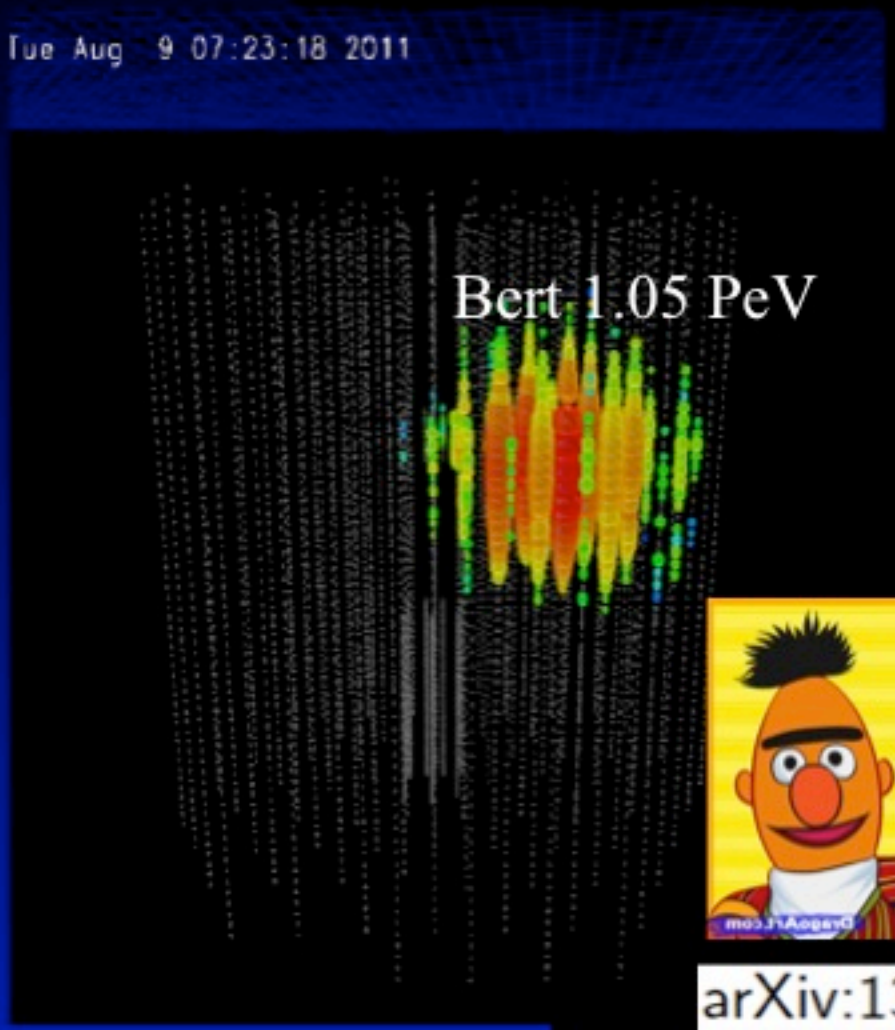
and UHECR composition



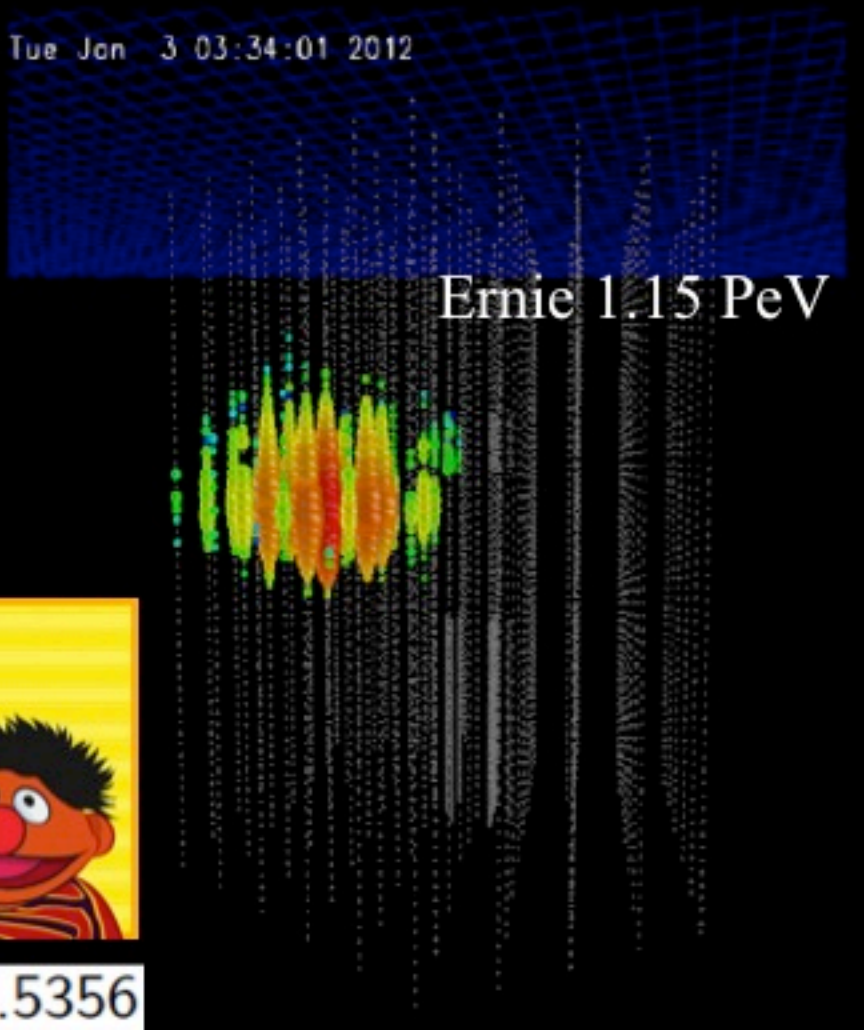

AMANDA–II
Frejus
CνB
pp
⁸B
10 kpc
1987
relic
SN
Solar
Atmospheric
AGN
GRB
GZK
dN_ν/dE_ν [GeV^{-1} sr^{-1} s^{-1} cm^{-2}]
log(E_ν /GeV)
10^{18}
10^{13}
10^{8}
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
10^{-22}
10^{-27}
-15
-10
-5
0
5
10

Neutrino Astronomy Begins

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

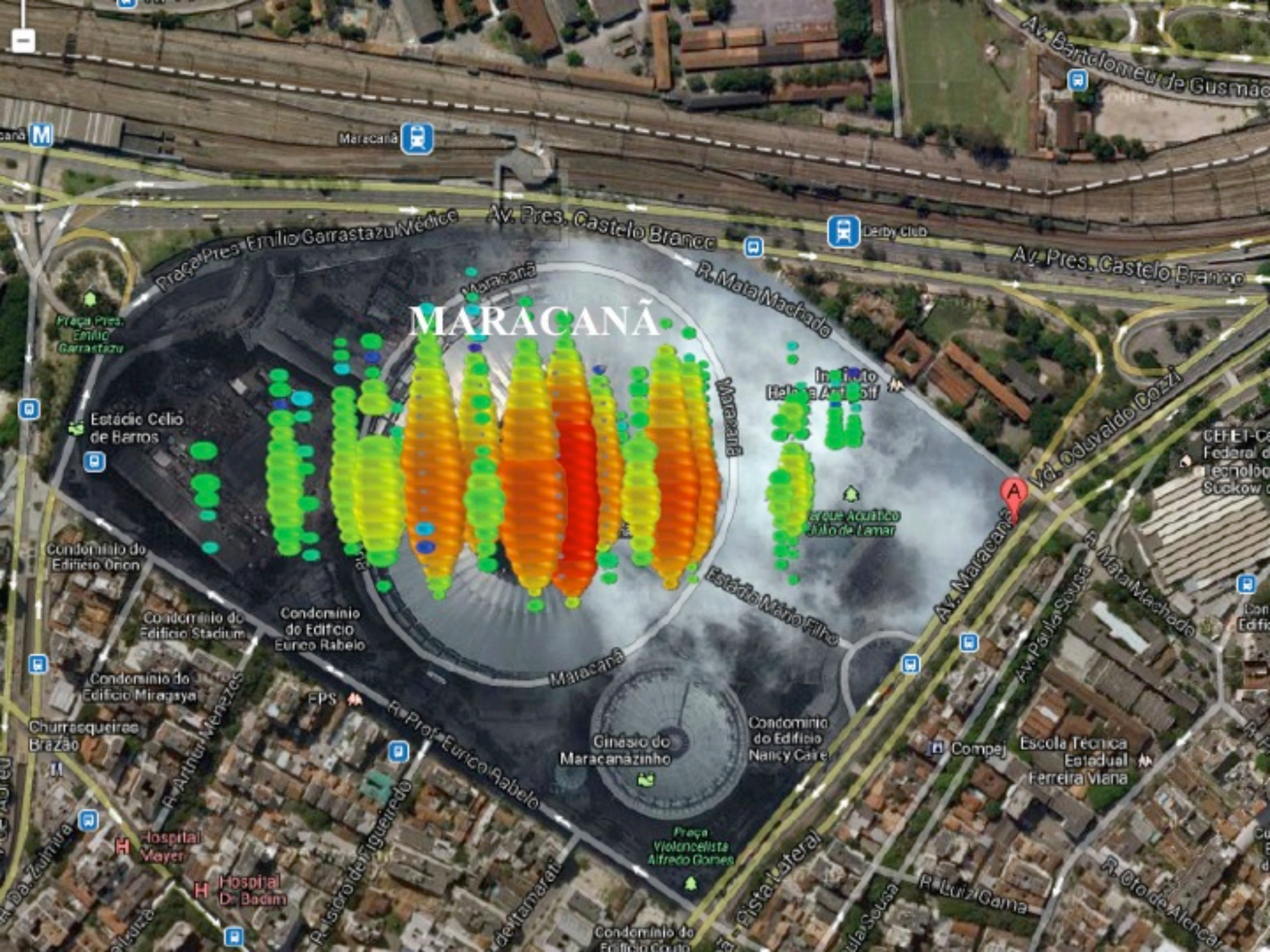


Bert 1.05 PeV



Ernie 1.15 PeV

arXiv:1304.5356


MARACANÃ
Maracanã
Av. Pres. Castelo Branco
Praça Pres. Emílio Garrastazu Médici
R. Maia Machado
Derby Club
Estádio Célio de Barros
Condomínio do Edifício Orion
Condomínio do Edifício Stadium
Condomínio do Edifício Eurico Rabelo
Condomínio do Edifício Mirapaya
Churrasqueiras Brazão
EPS
R. Prof. Eurico Rabelo
Ginásio do Maracanãzinho
Condomínio do Edifício Nancy Cairé
Compej
Escola Técnica Estadual Ferreira Viana
Hospital Mayer
Hospital D. Badim
Praça Violoncelista Alfredo Gomes
Vista Lateral
R. Luiz Gama
Av. Maracanã
Vd. Odyvaldo Cozzi
Av. Paula Sousa
Estádio Mário Filho

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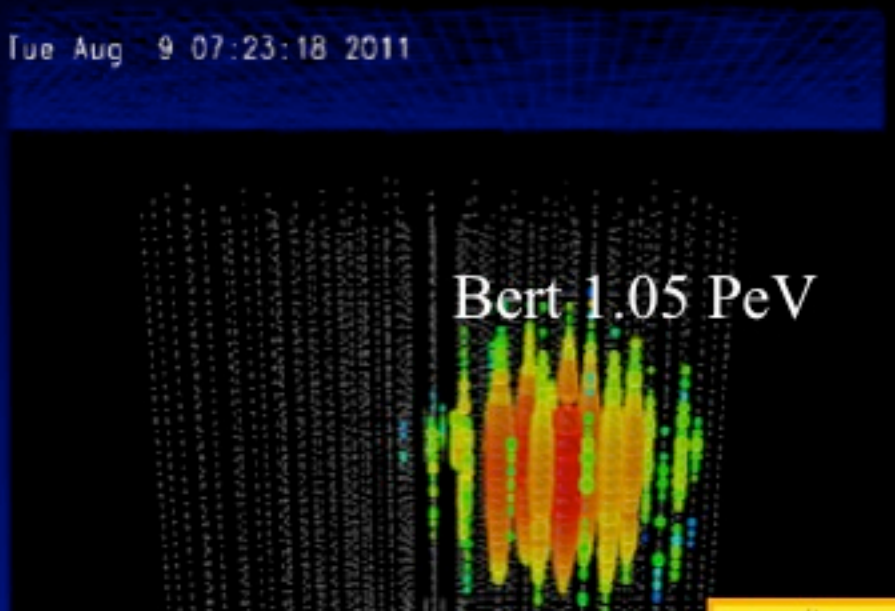
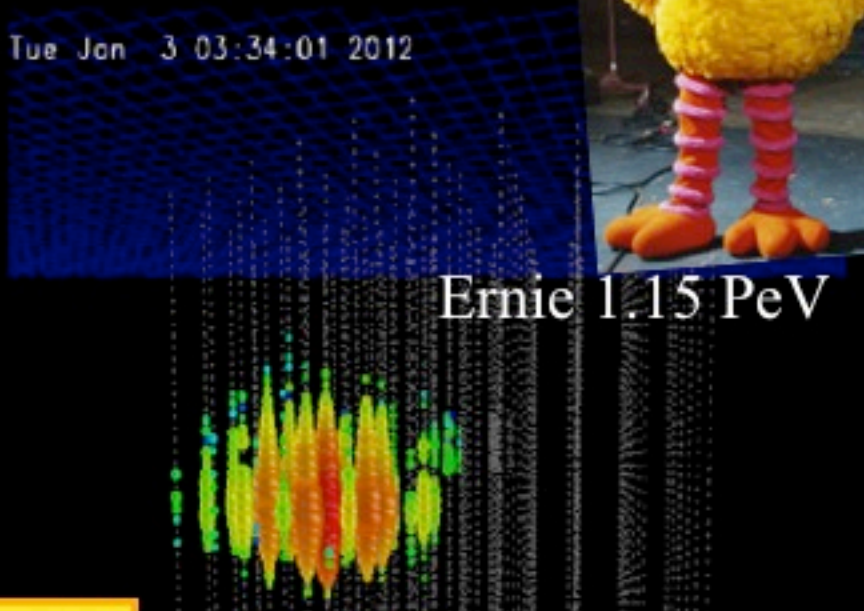


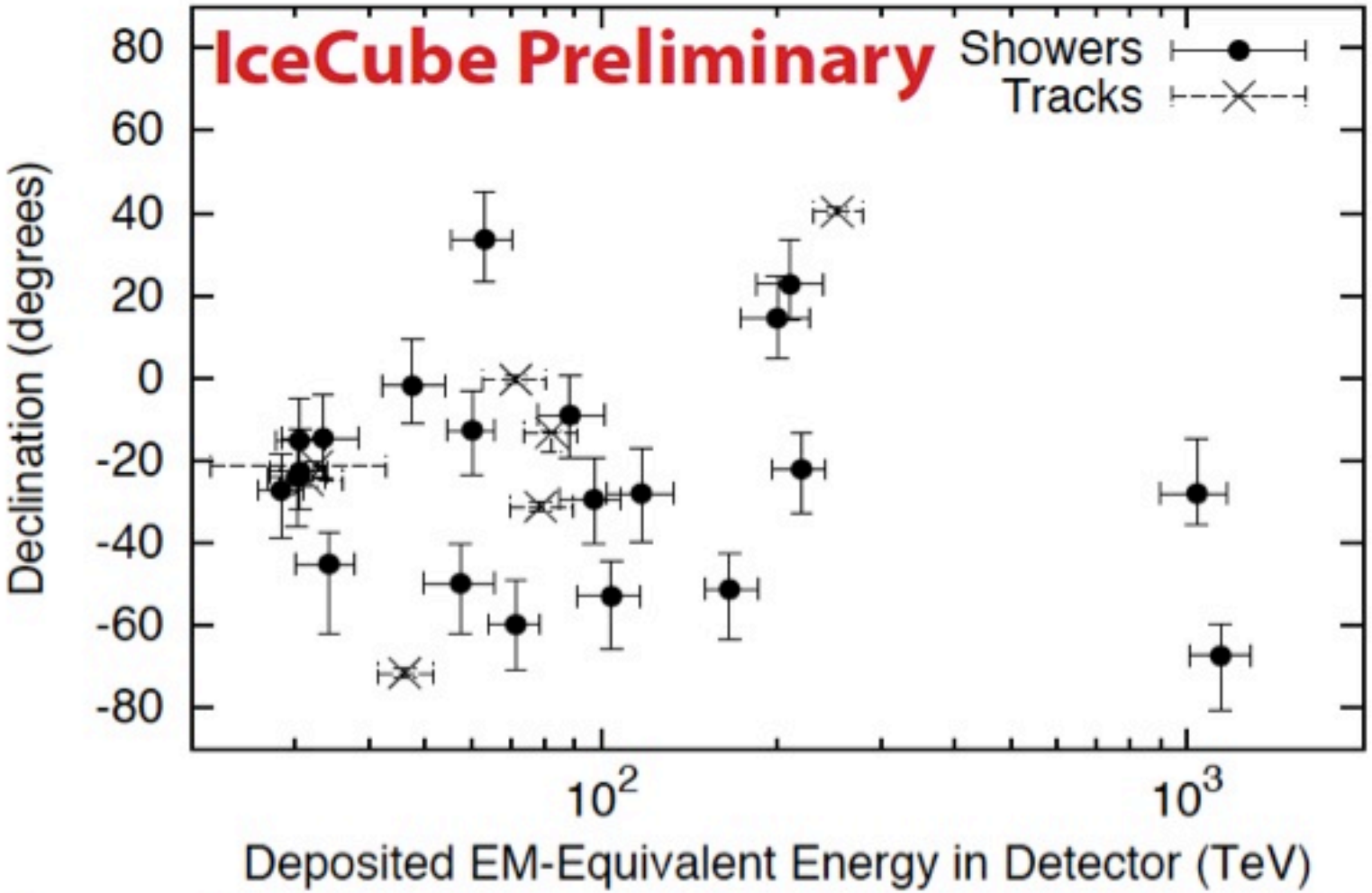
Bert 1.05 PeV



Ernie 1.15 PeV

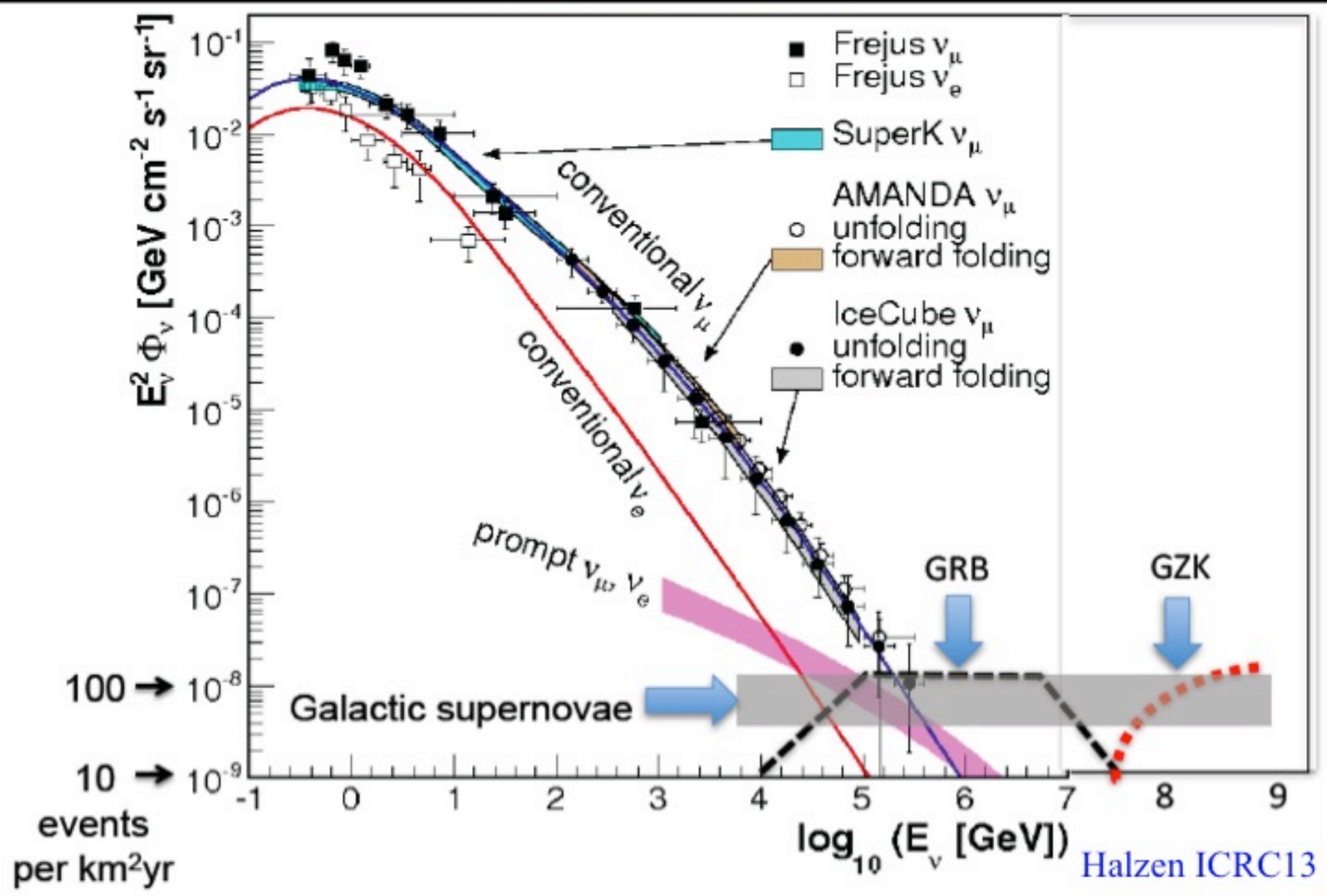
arXiv:1304.5356

Results of Contained Vertex Event Search (4.3σ)

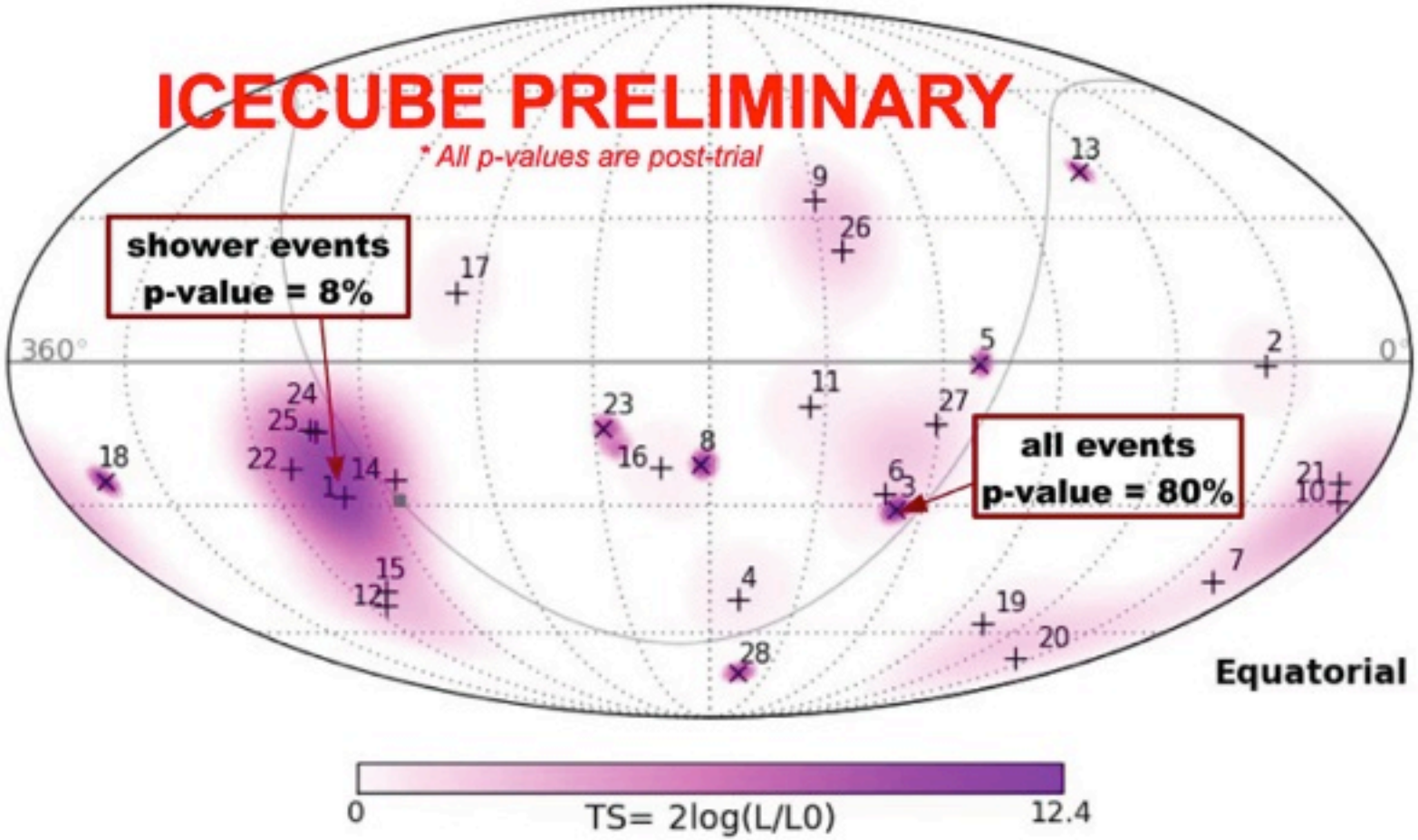


28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

Galactic CRs?



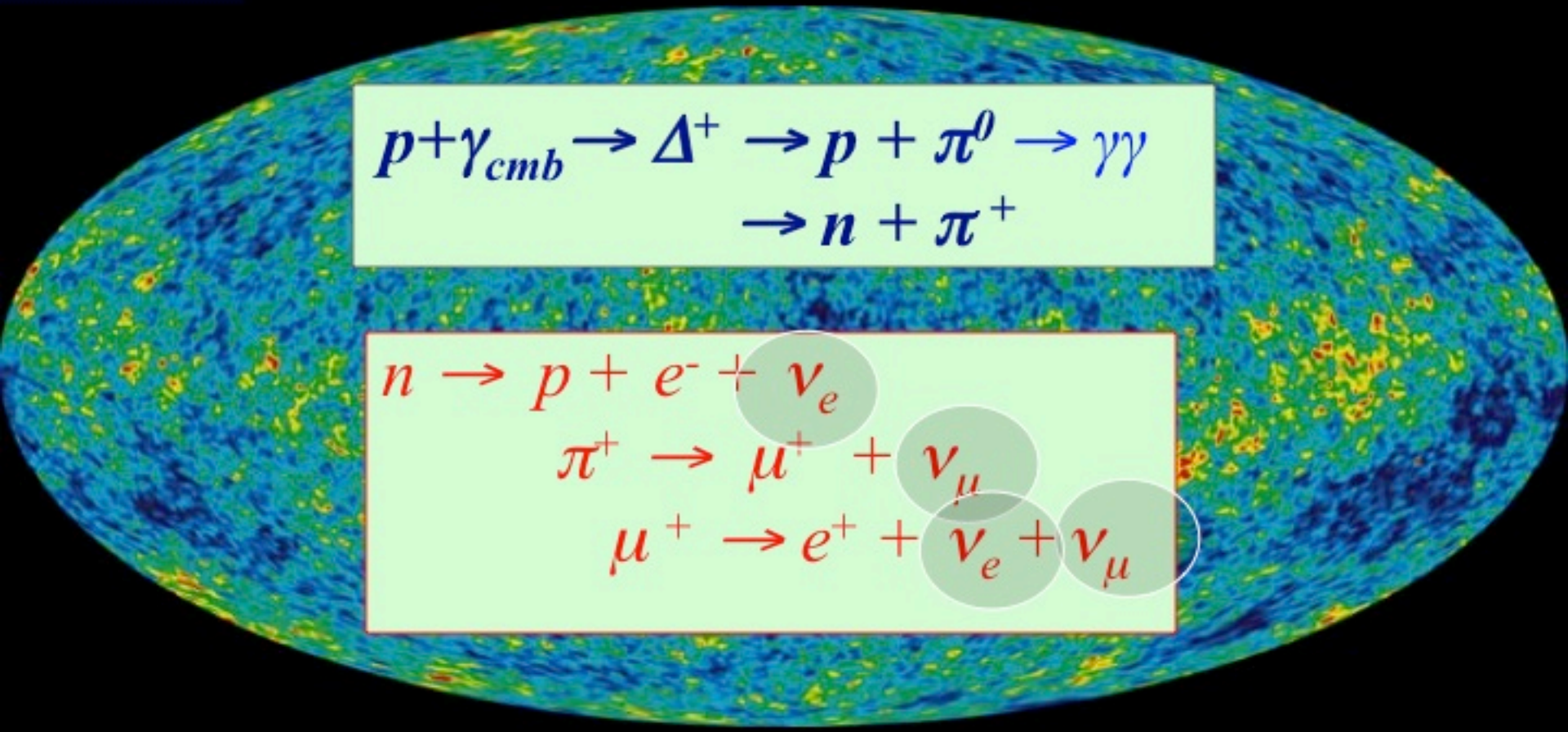
Skymap: No Significant Clustering



See: talk by Naoko Kurahashi Neilson

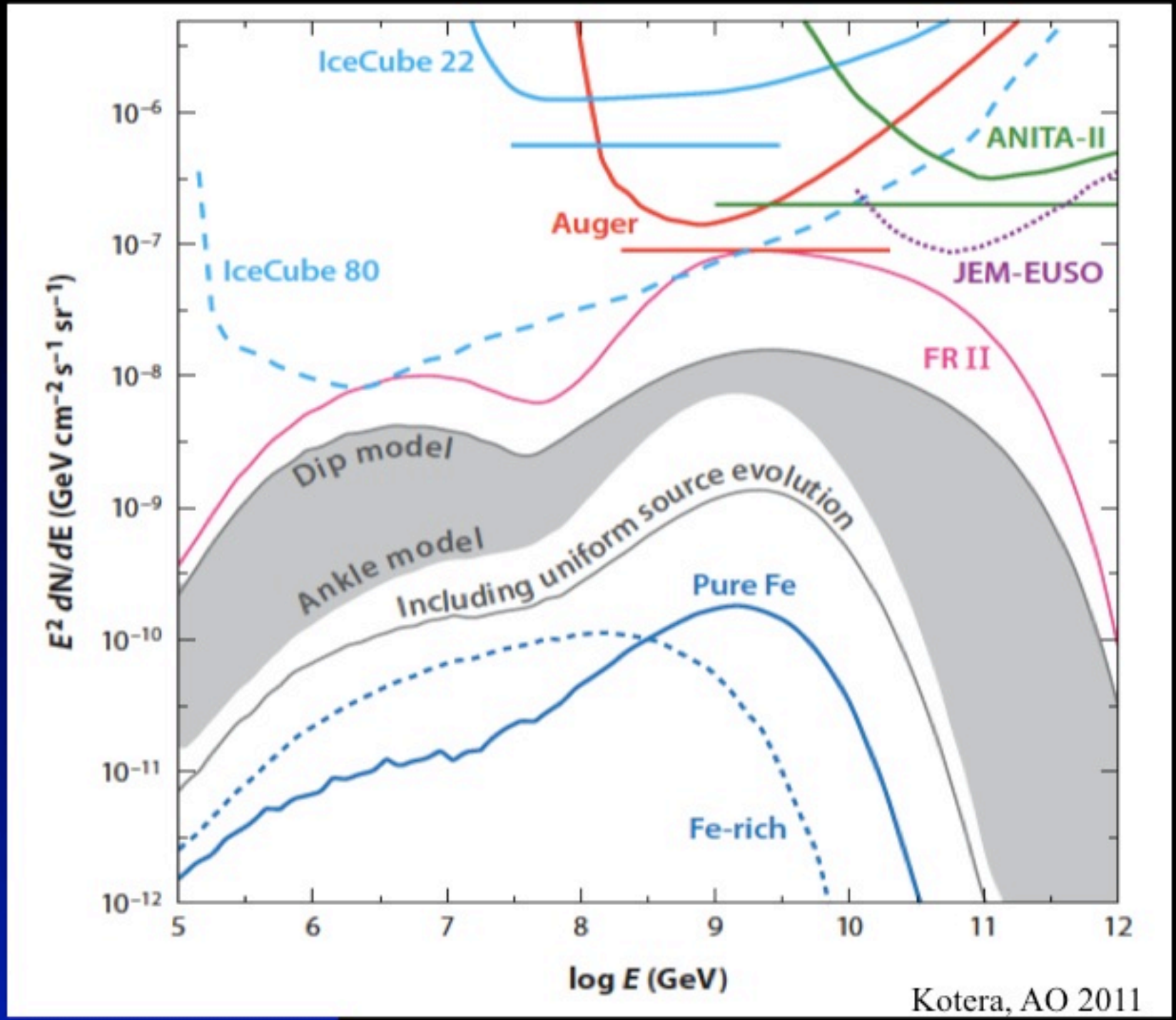
Cosmogenic (GZK) Neutrinos & Photons

and UHECR composition

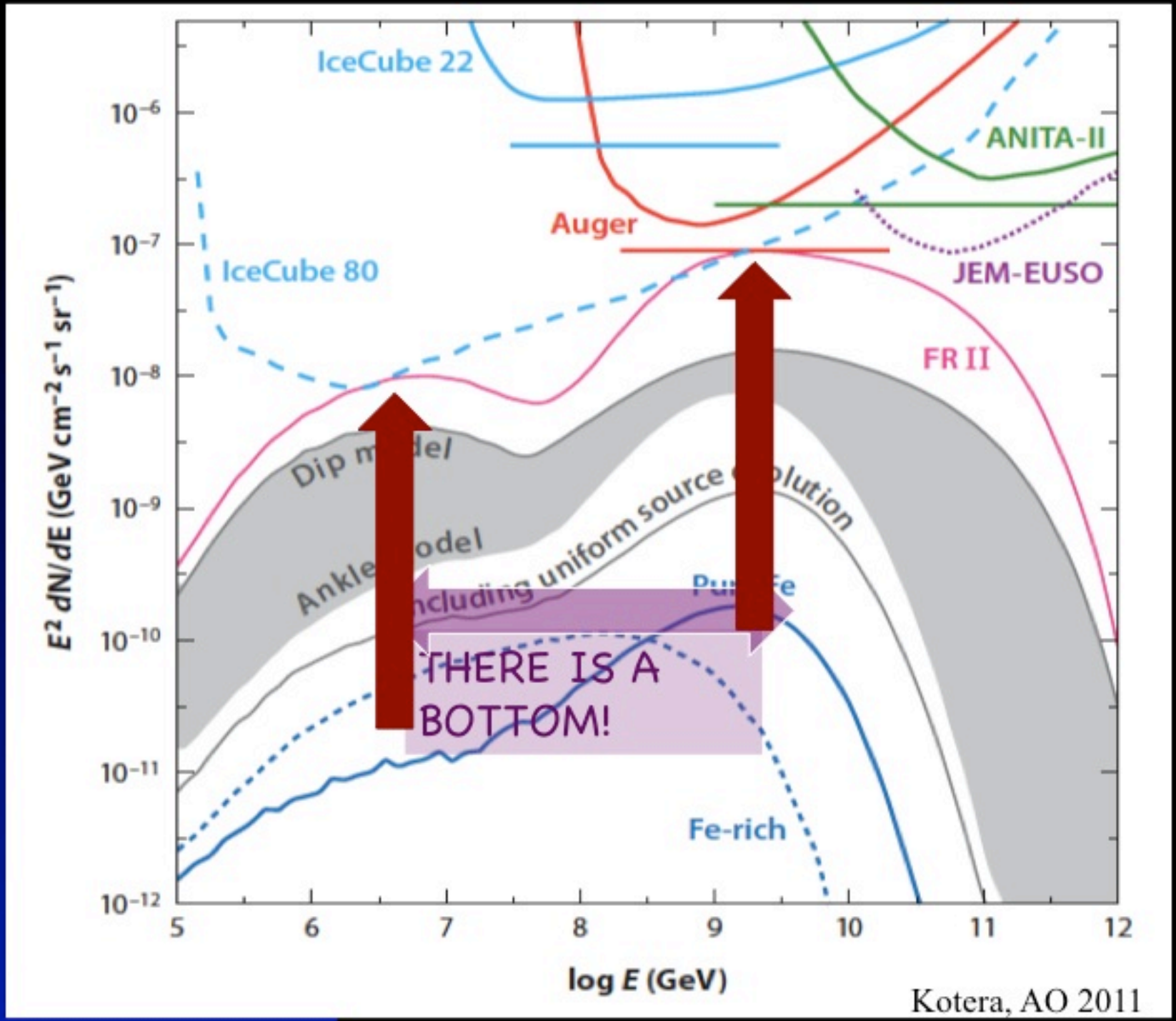


$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

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



Kotera, AO 2011



Kotera, AO 2011

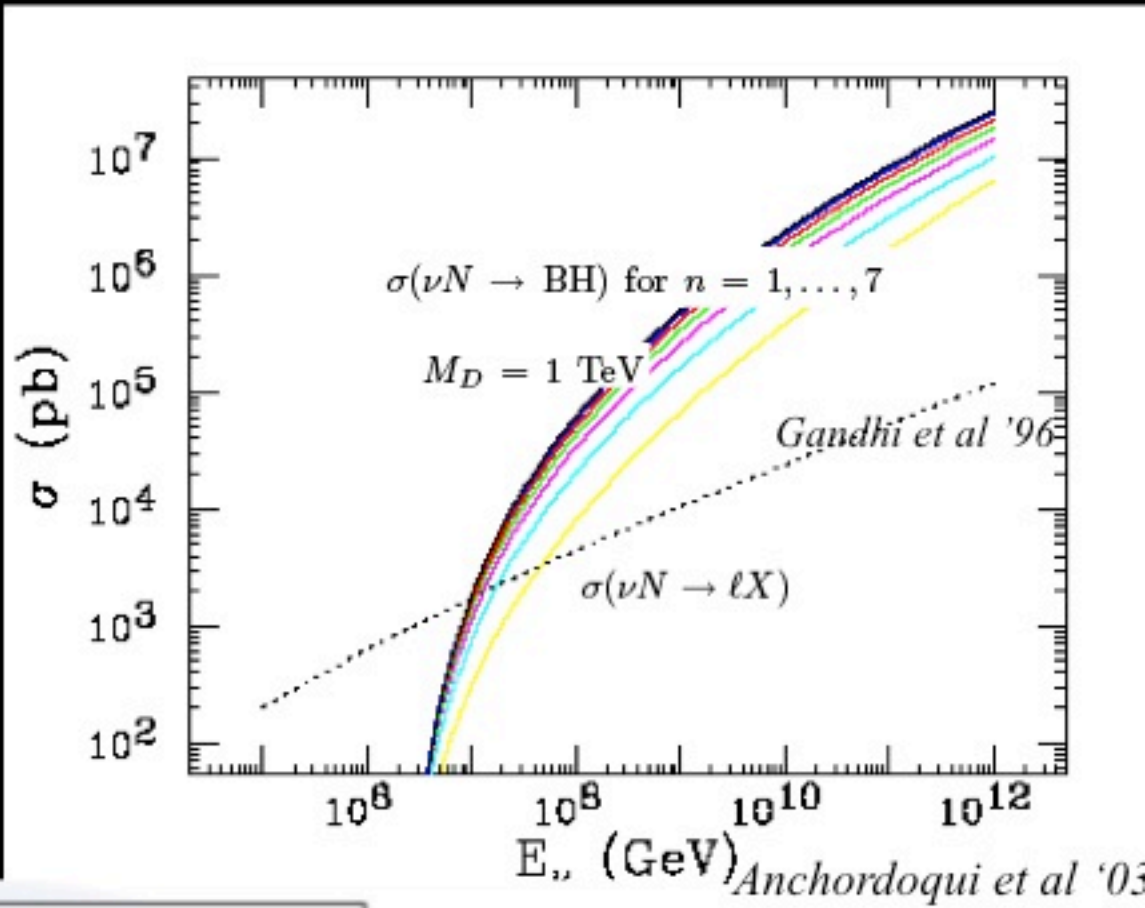
What is so cool about GZK neutrinos?

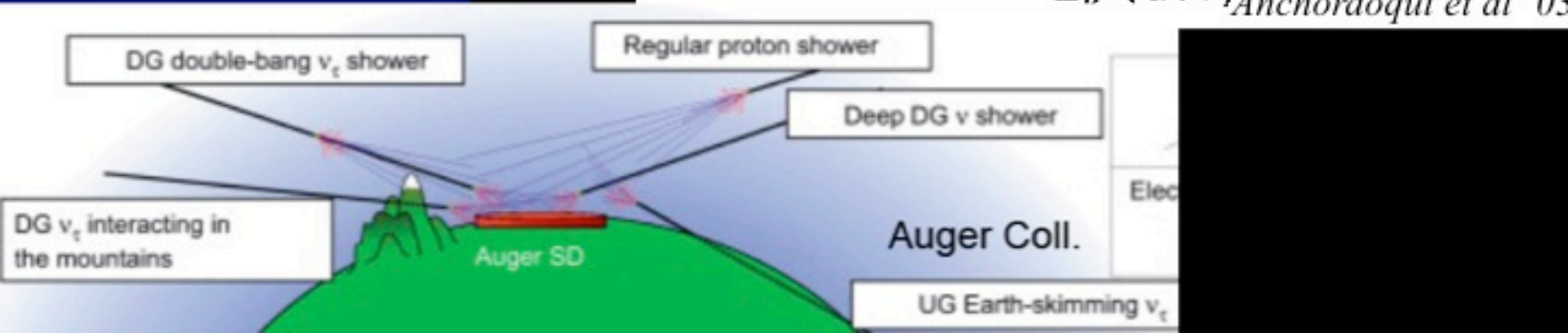
They can answer many questions about the origin of UHECRs

and

Can test BSM physics directly

Tests of UHE Neutrino Interactions





Earth-Skimming & Airshowers ν's

BSM neutrino-nucleon cross section C.M ~245 TeV (E_ν =30 EeV)

Earth Skimming in Earth's crust or ocean $\nu_\tau \pm N \rightarrow \tau^\pm X$

Aishowers produced deep in atmosphere $\nu_\ell \pm N \rightarrow \ell^\pm X$

Ex: leptophobic interaction

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

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

Earth-Skimming & Airshowers ν's

BSM neutrino-nucleon cross section C.M ~245 TeV (E_ν =30 EeV)

Earth Skimming in Earth's crust or ocean $\nu_\tau \pm N \rightarrow \tau^\pm X$

Aishowers produced deep in atmosphere $\nu_\ell \pm N \rightarrow \ell^\pm X$

Ex: leptophobic interaction

Earth-skimming τ showers

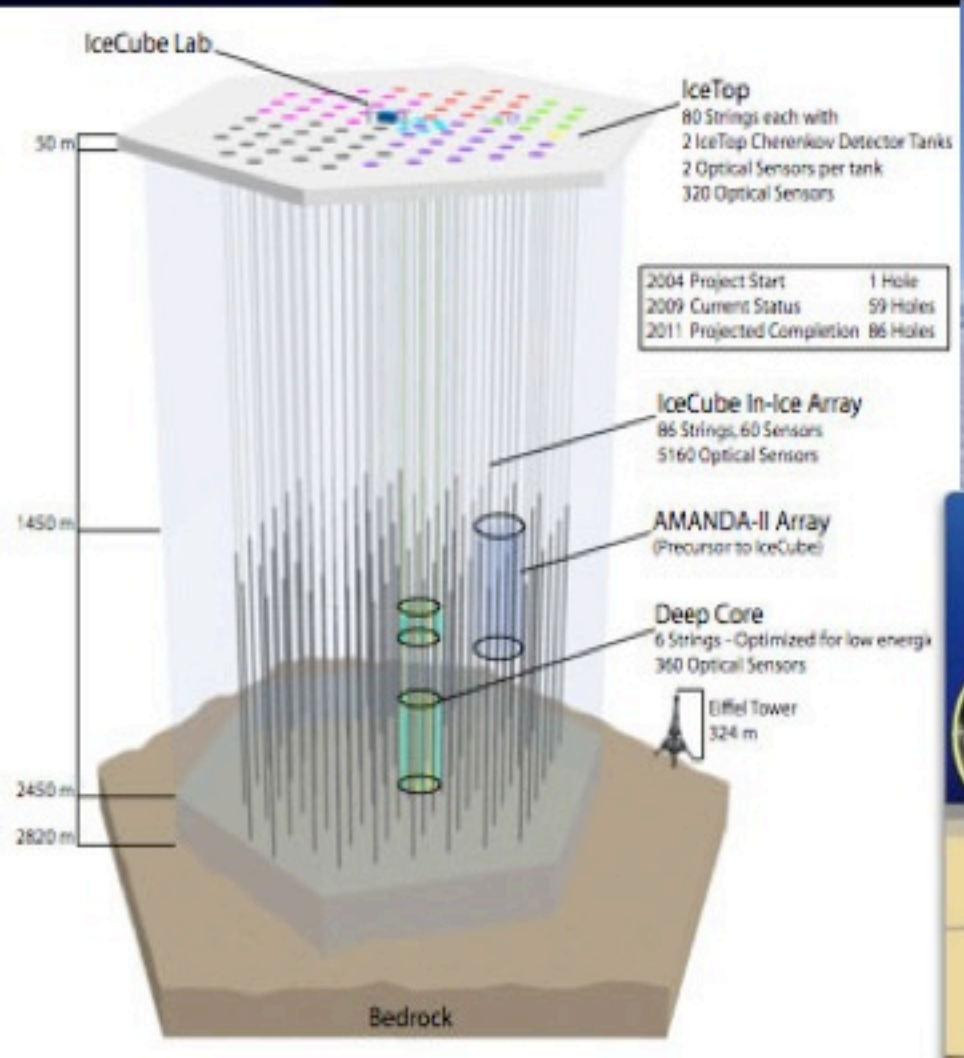
$$N_{ES} \approx C_{ES} \frac{\Phi^\nu}{\Phi_0^\nu} \frac{\sigma_{CC}^{\nu\,2}}{(\sigma_{CC}^\nu + \sigma_{NP}^\nu)^2}$$

Down-going (quasi-horizontal) showers

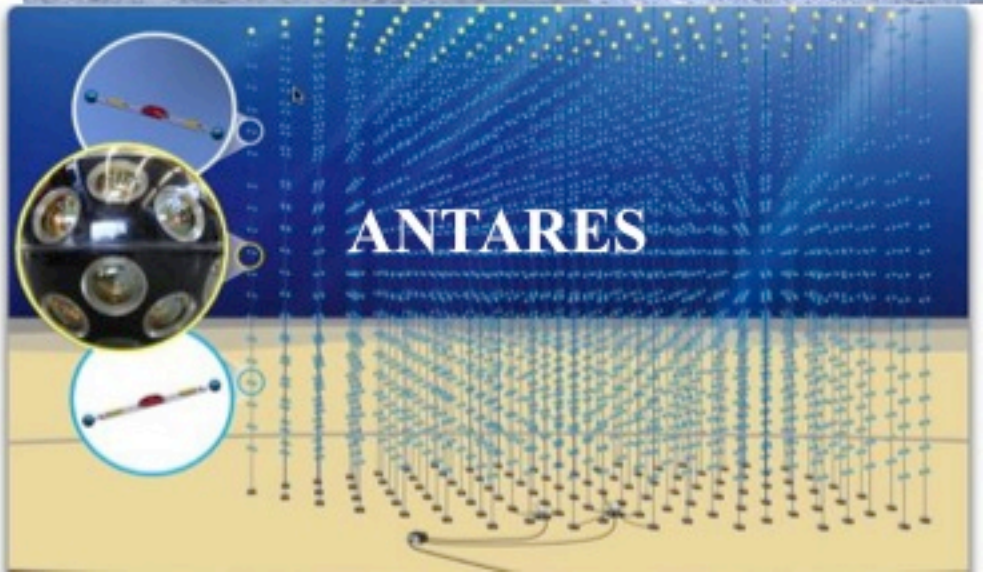
$$N_{QH} = C_{QH} \frac{\Phi^\nu}{\Phi_0^\nu} \frac{\sigma_{CC}^\nu + \sigma_{NP}^\nu}{\sigma_{CC}^\nu}$$

Highest Energy Neutrino Observatories

IceCube



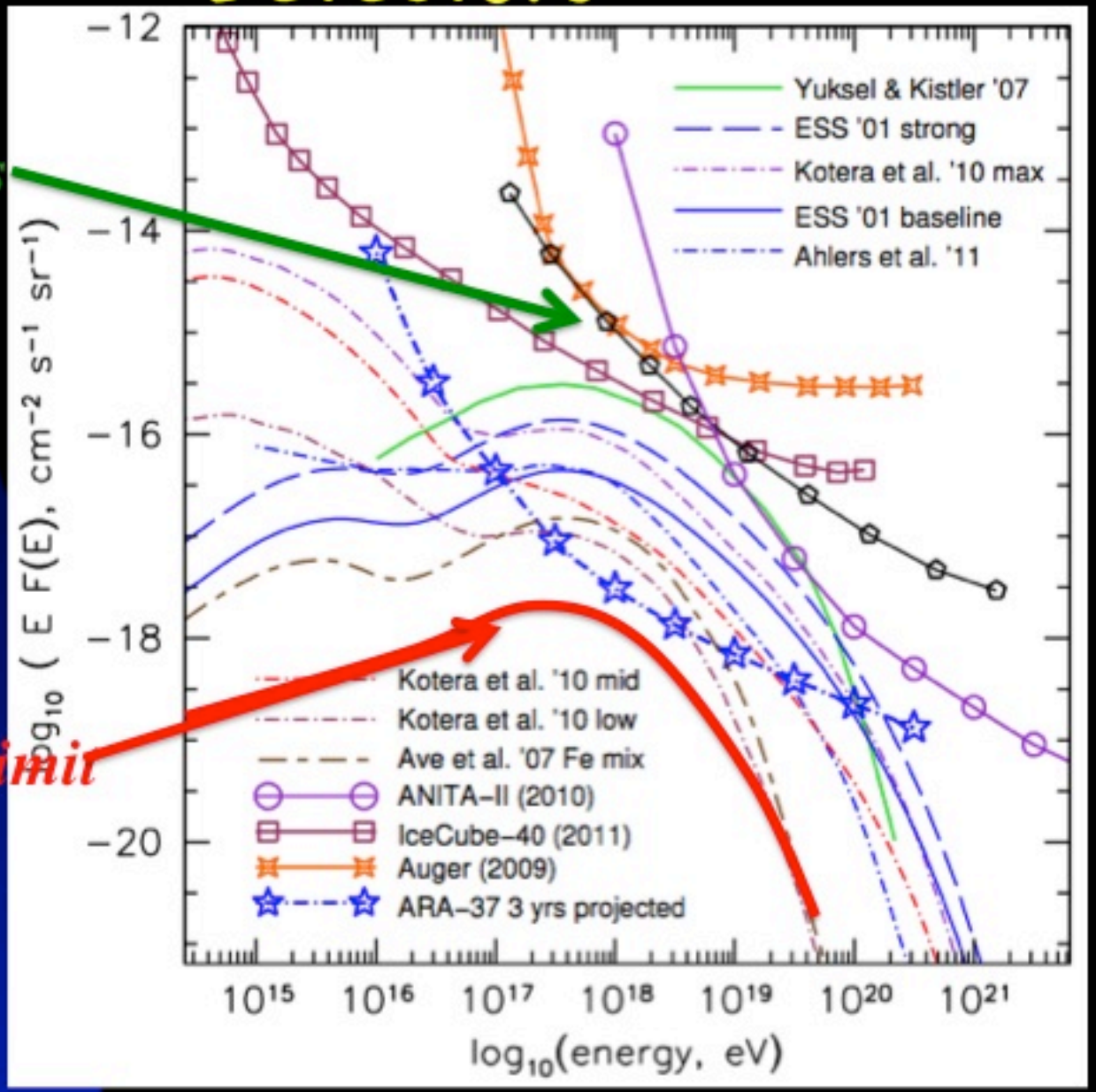
ANITA



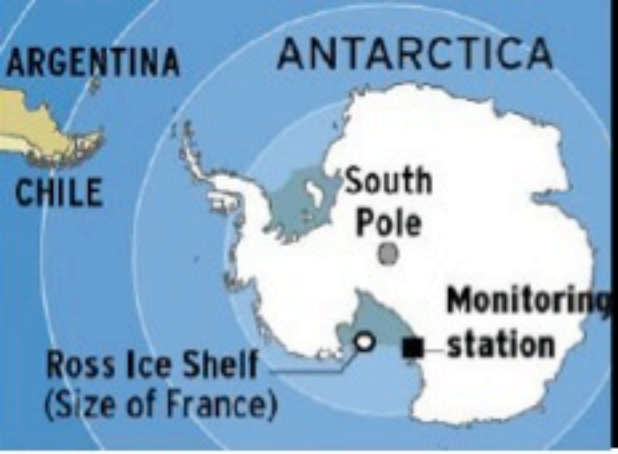
Next Generation GZK Neutrino Detectors

Current Limits

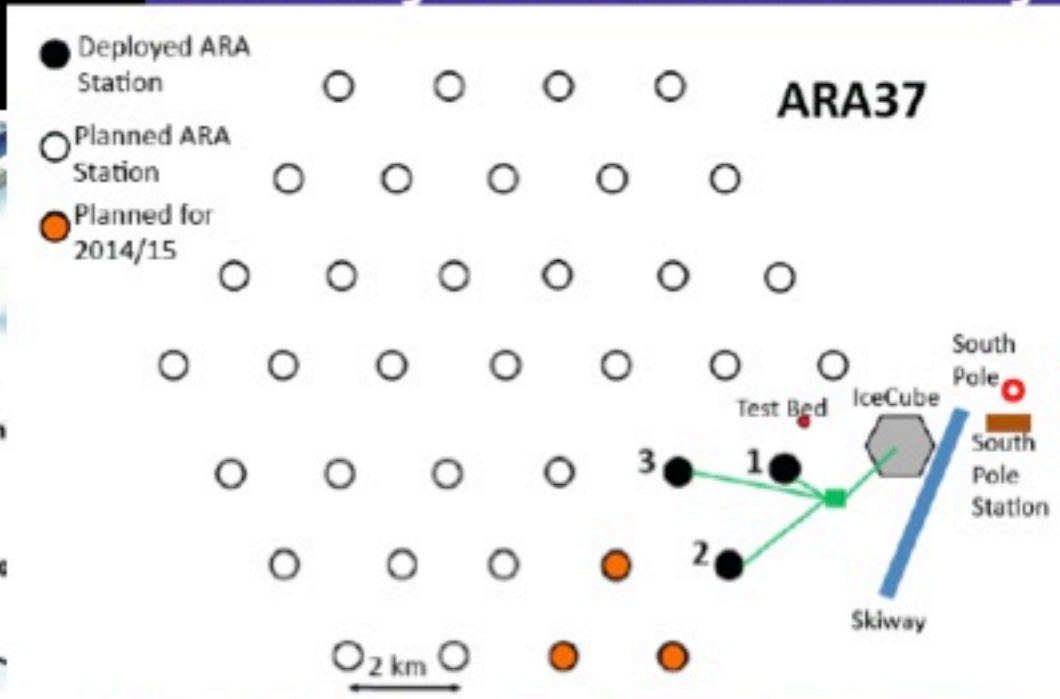
Flux Lower Limit

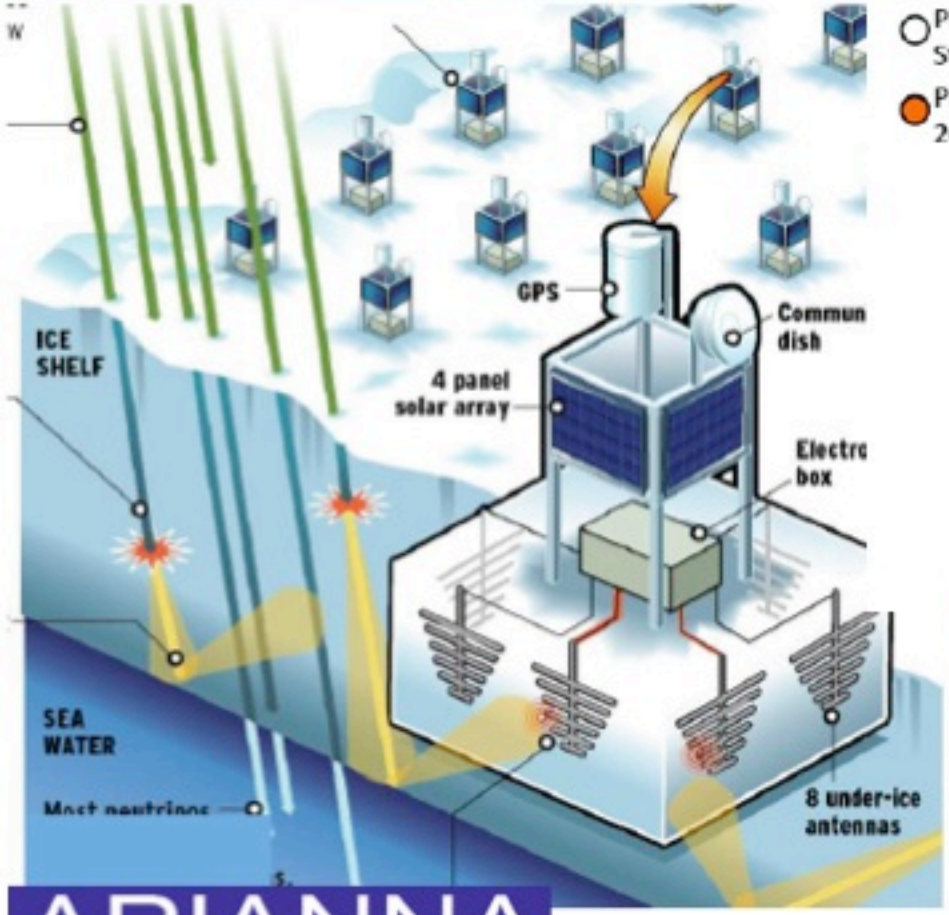


Next Generation



ARA: Askaryan Radio Array





ARIANNA

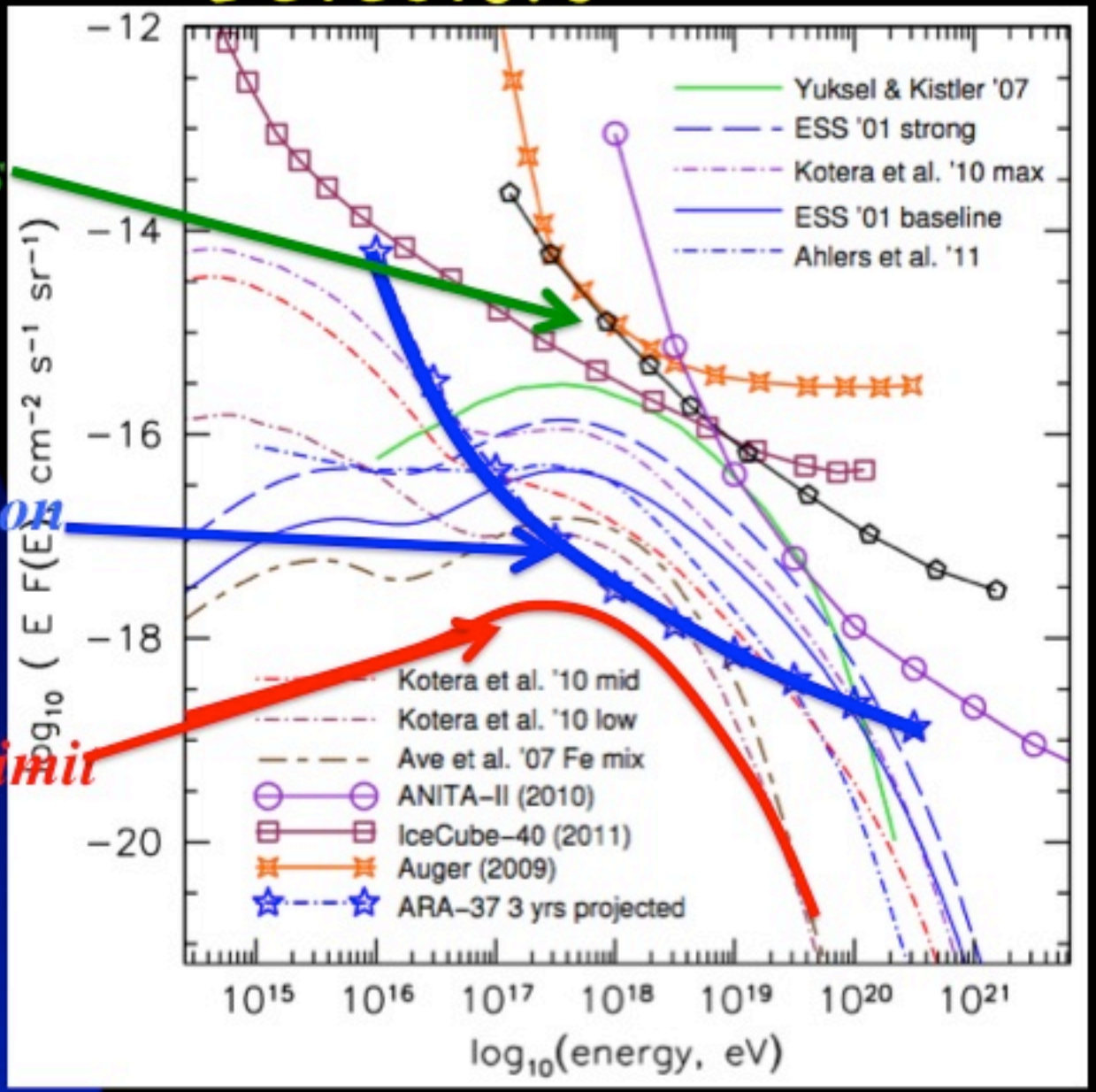
Kiv:1207.3846

Next Generation GZK Neutrino Detectors

Current Limits

Next Generation

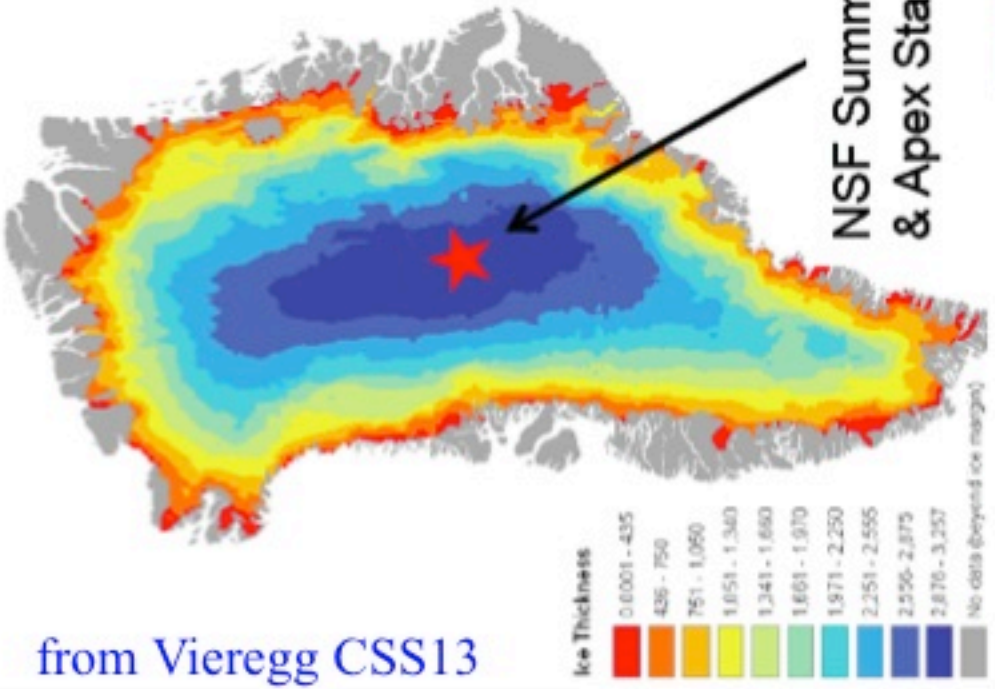
Flux Lower Limit



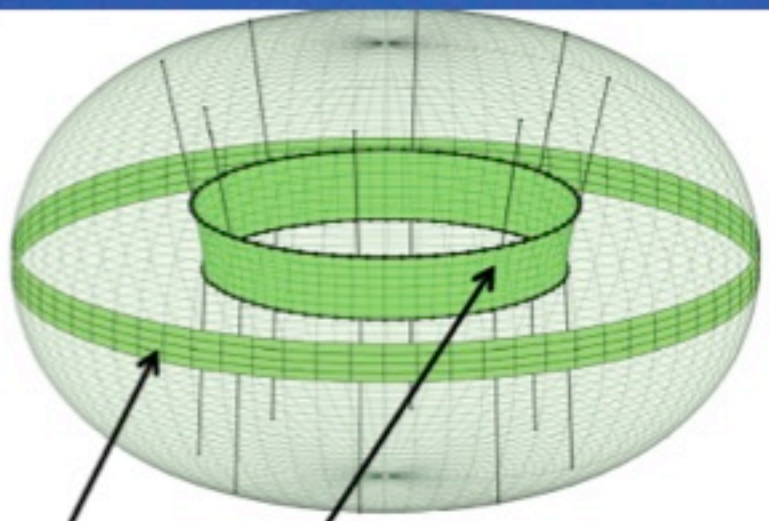
EVA:
ExaVolt Antenna

Greenland Ice Thickness

NSF Summit Station
& Apex Station Site



from Vieregg CSS13



reflector

feed array @ focus

What other Cosmic Particles 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

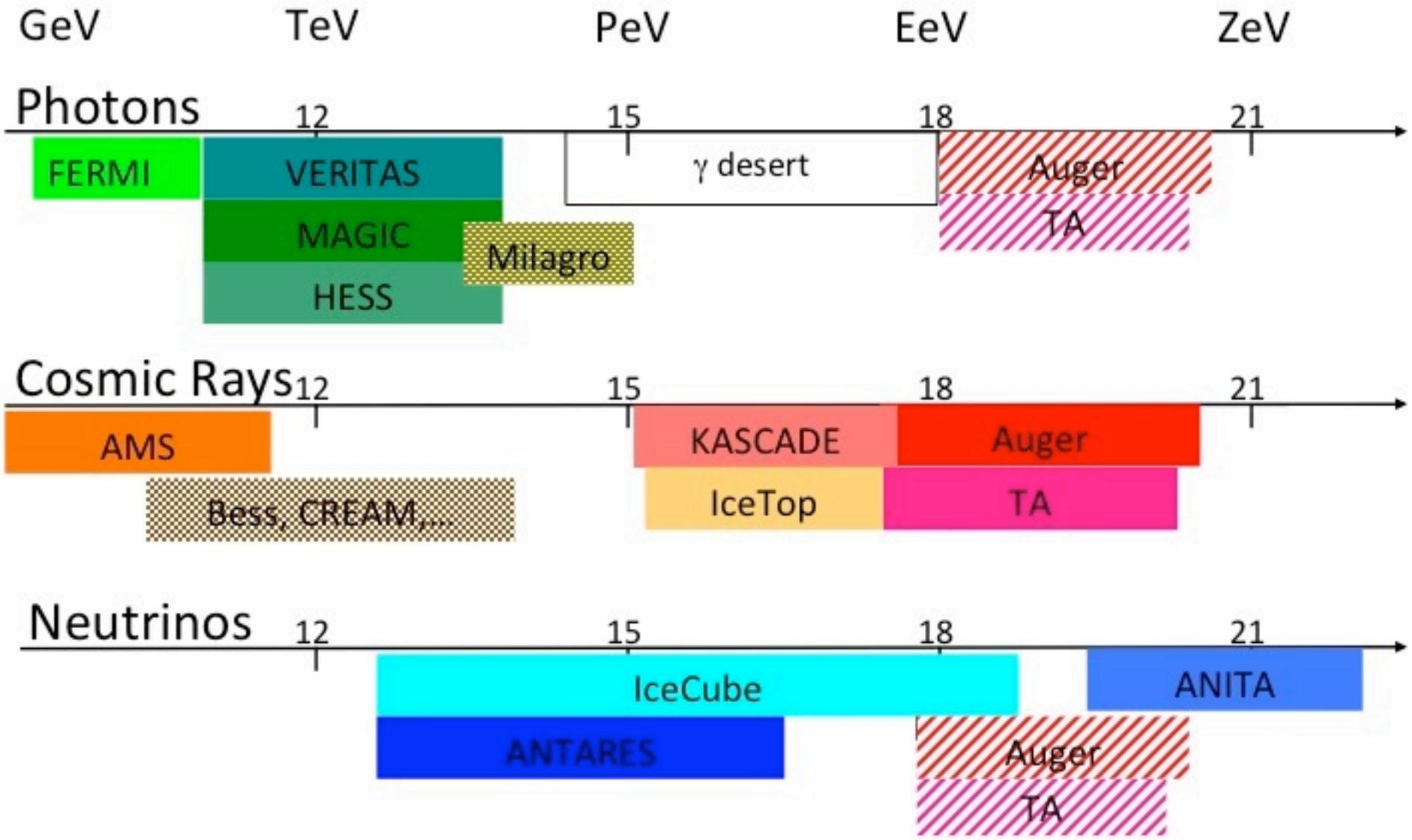
Strangelets

Nucleorites

etc...

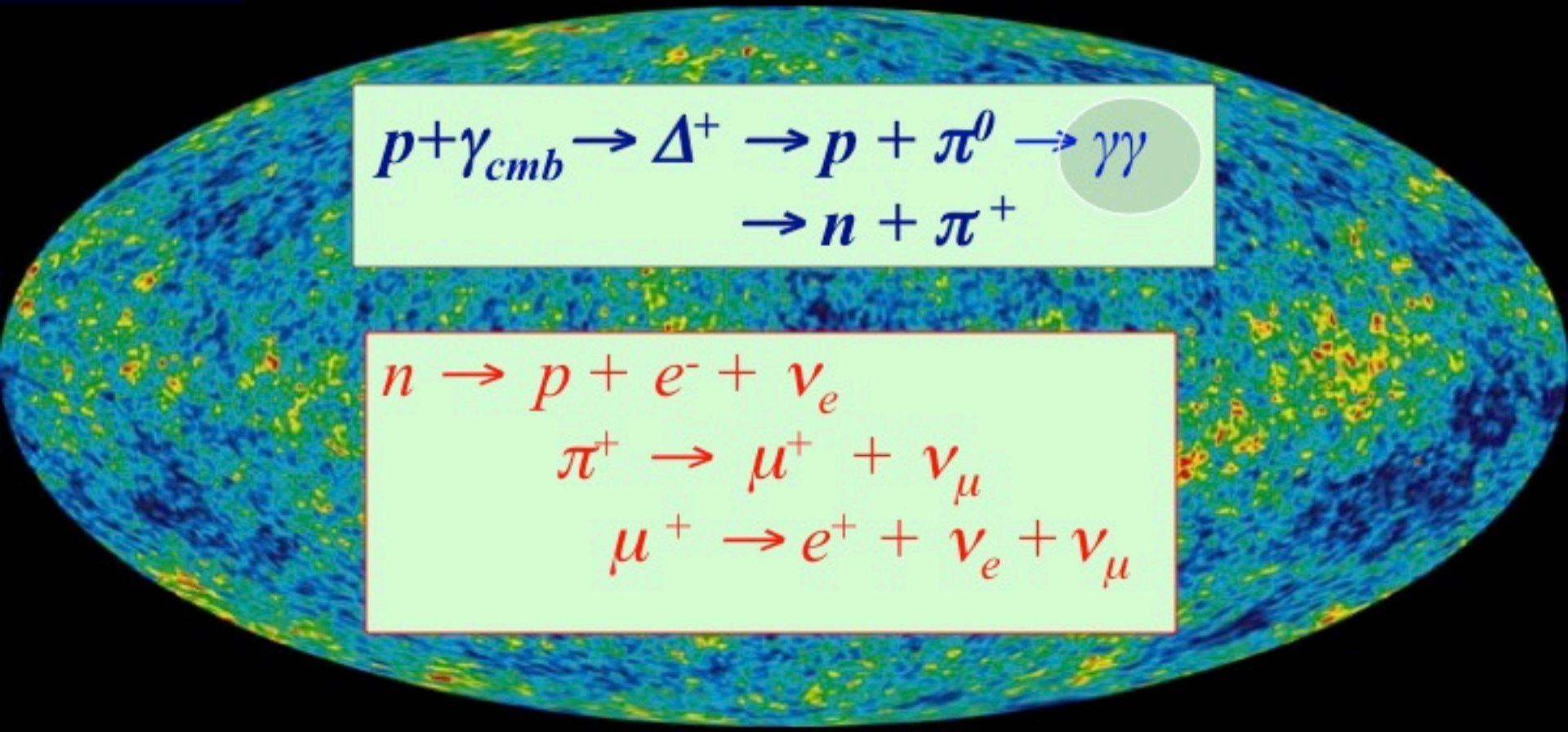
Current Detectors

Cosmic Particles 2013



Cosmogenic (GZK) Neutrinos & Photons

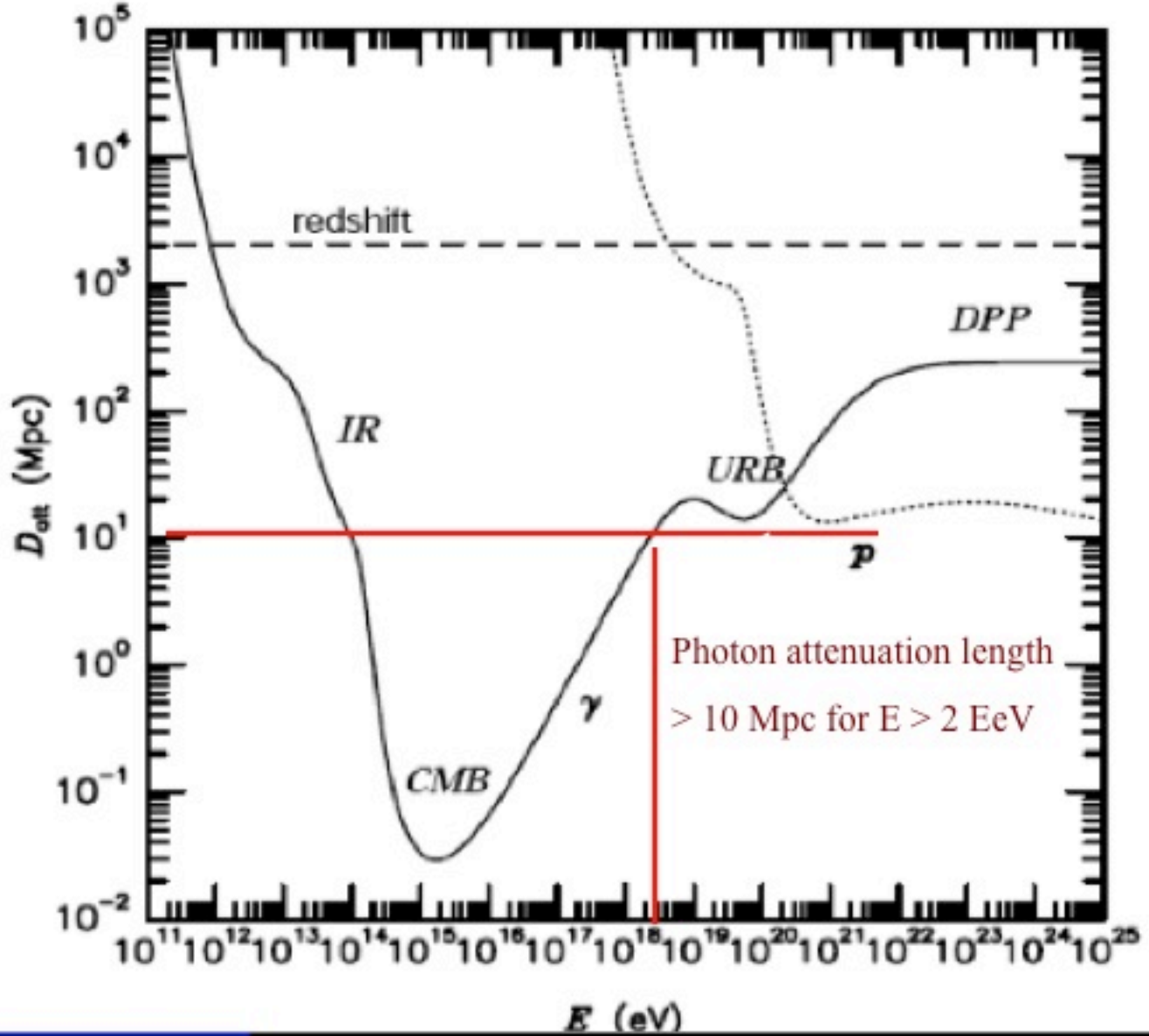
and UHECR composition



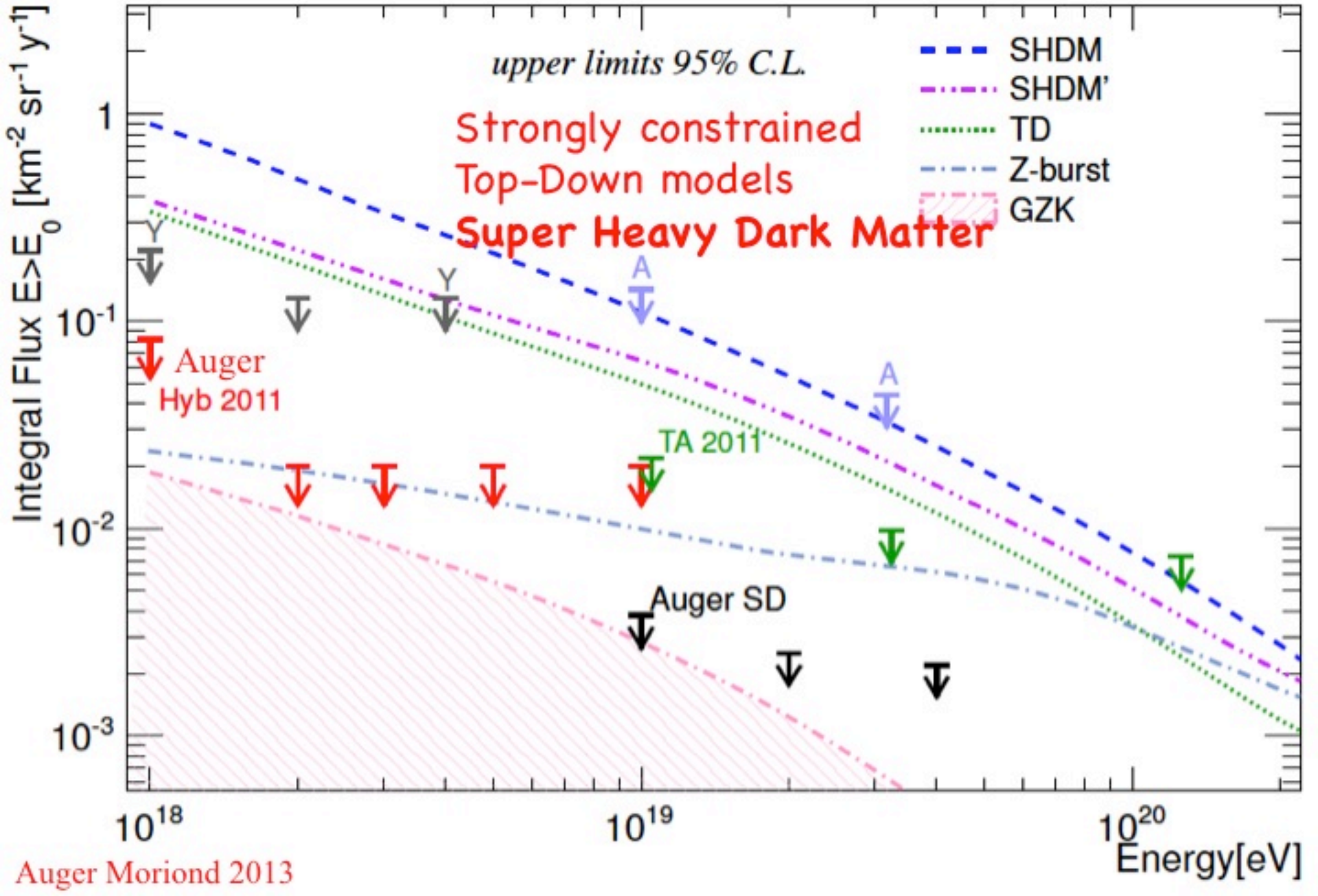
$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

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

The UHE Gamma Ray Window

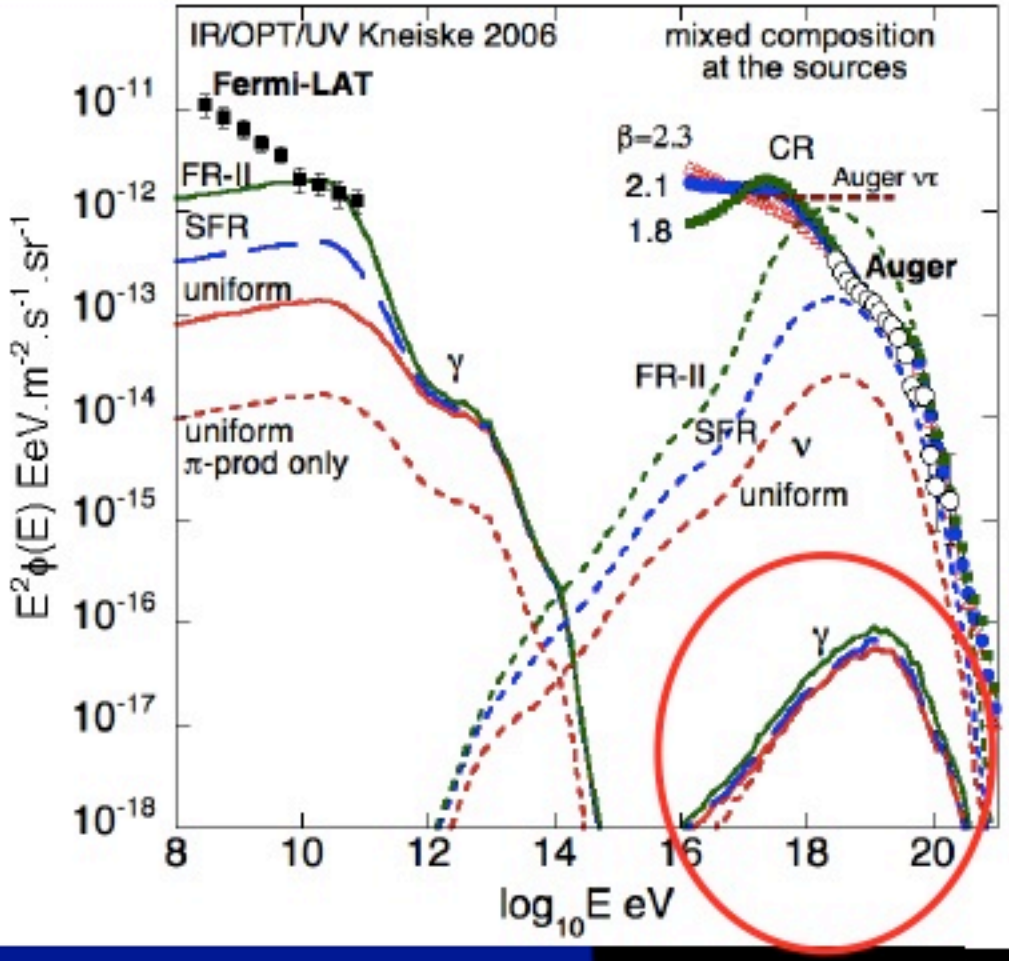


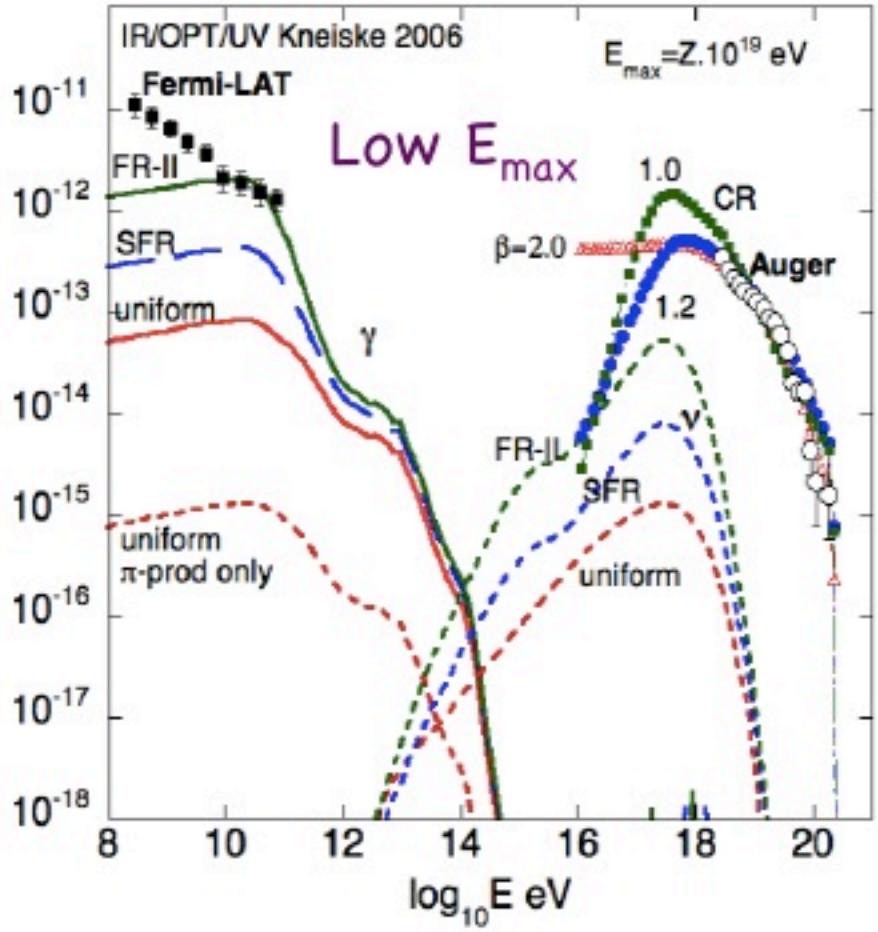
Auger Photon Limits



Auger Moriond 2013

GZK/Cosmogenic Photons E_{max} dependent

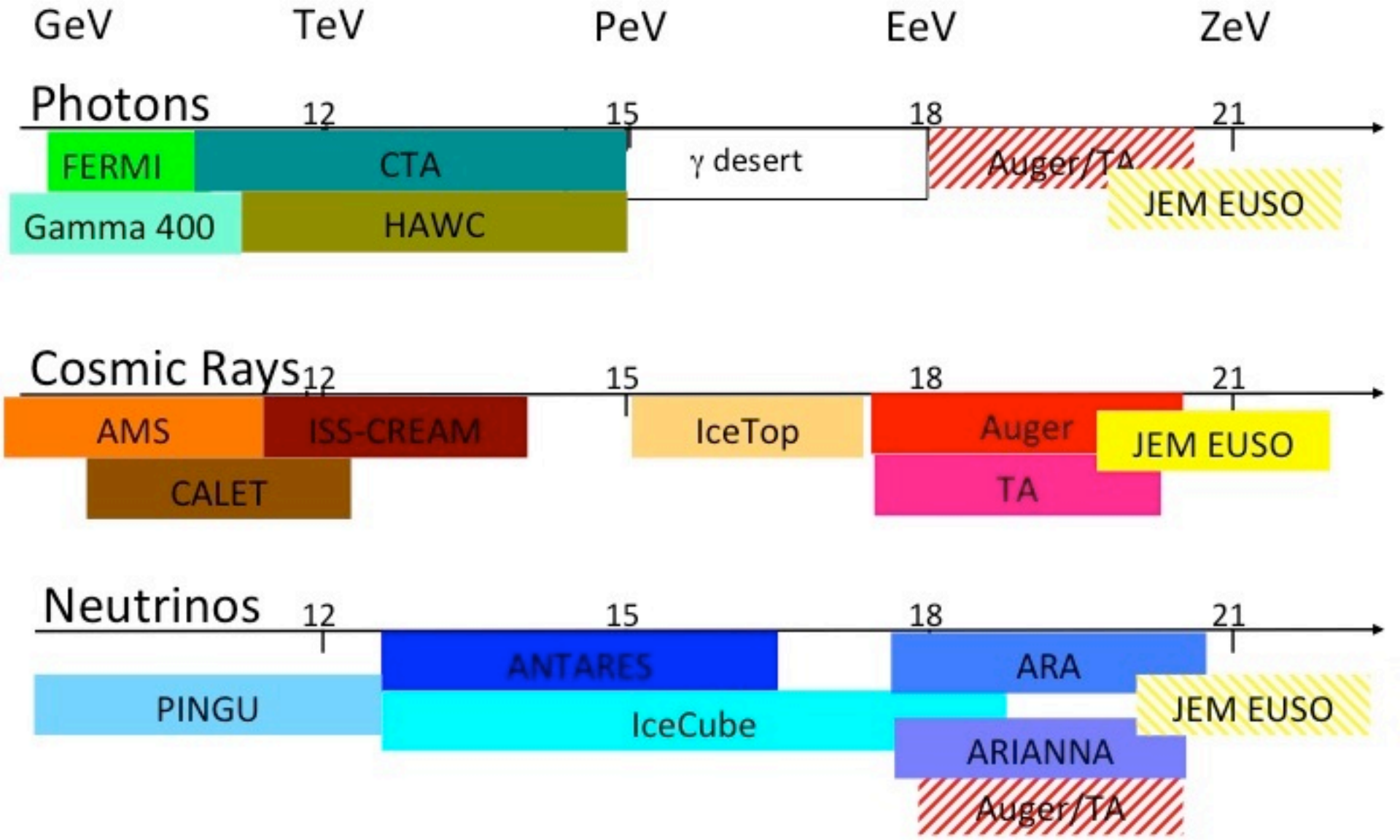




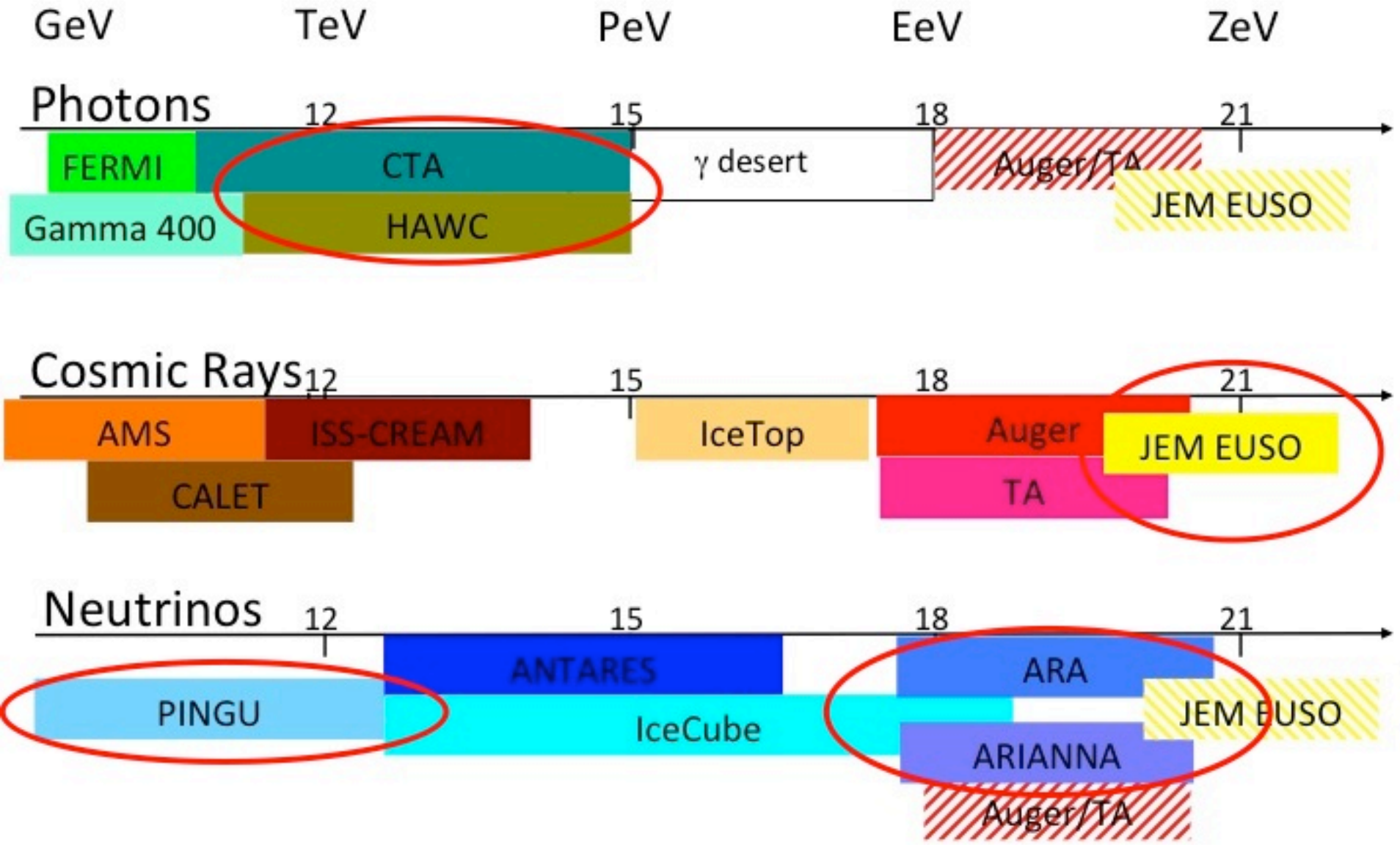
Decerprit & Allard 11

Future Detectors

Cosmic Particles 2020



Cosmic Particles 2020

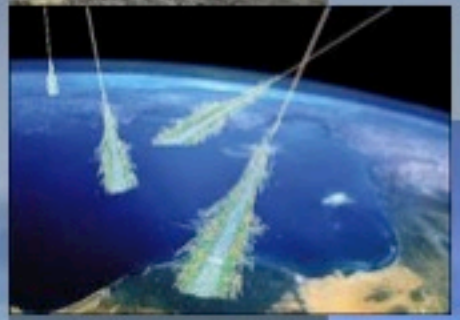


Busy HE Particles!!!!









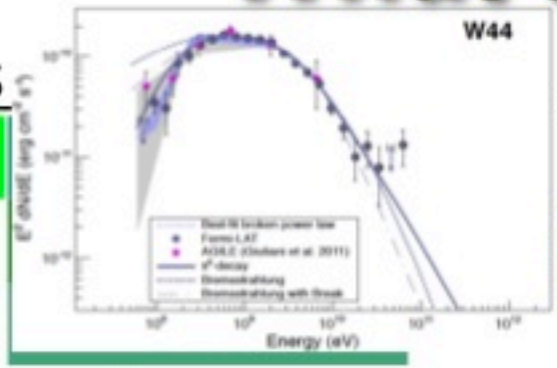

Cosmic Particles 2013

What a great YEAR!

GeV TeV PeV EeV ZeV

Photons

FERMI



.5 18 21

γ desert

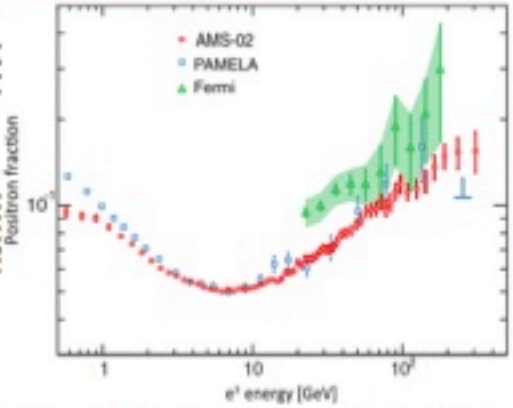
Auger

TA

Cosmic Rays

AMS

Bess



18 21

KASCADE

Auger

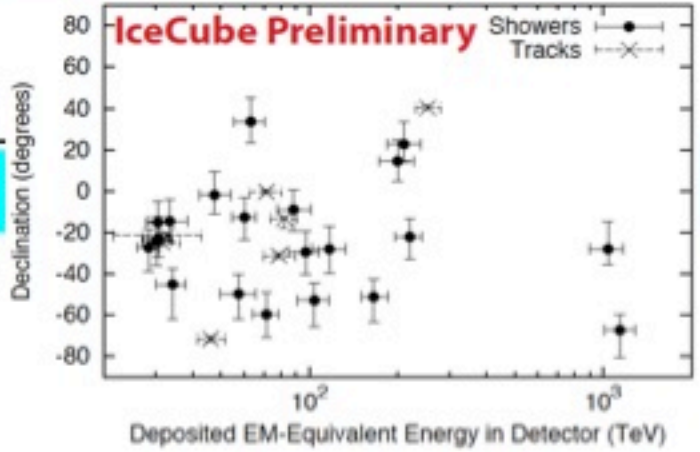
IceTop

TA

Neutrinos

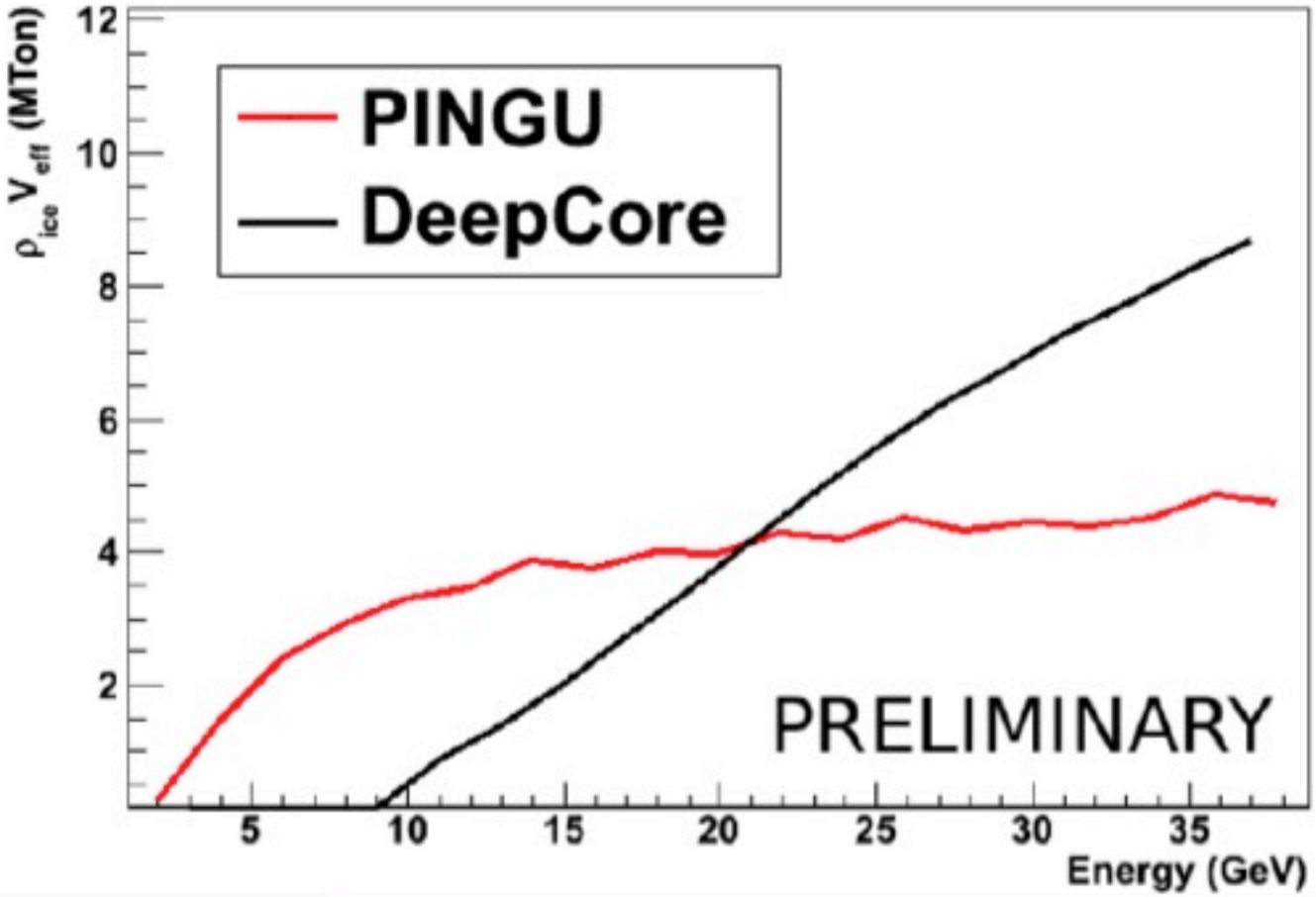
IceCube

ANTARES



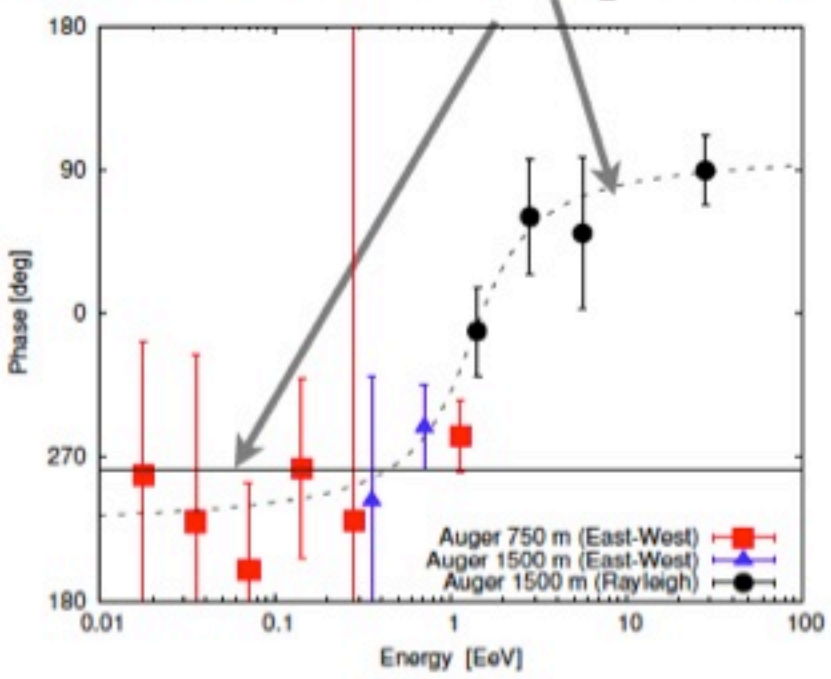

p $10^{15\text{-}18}$ eV
p 10^{20} eV
GZK
ν
γ
χ
The Best is
Yet to Come!

- Below $E_\nu \sim 20$ GeV, PINGU provides gain in fiducial mass relative to the existing low E_ν in-fill, DeepCore

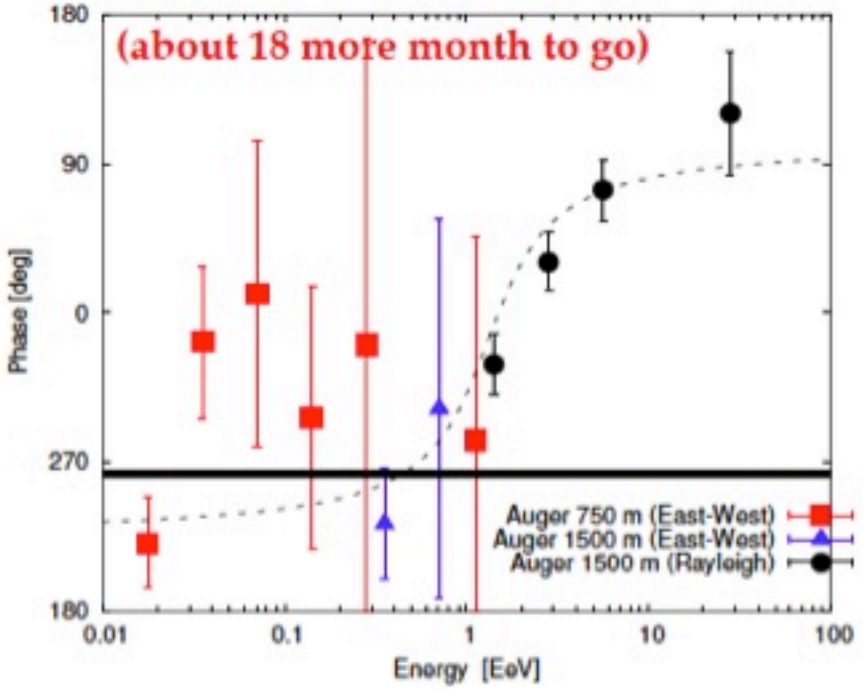


Auger – First Harmonic Analysis

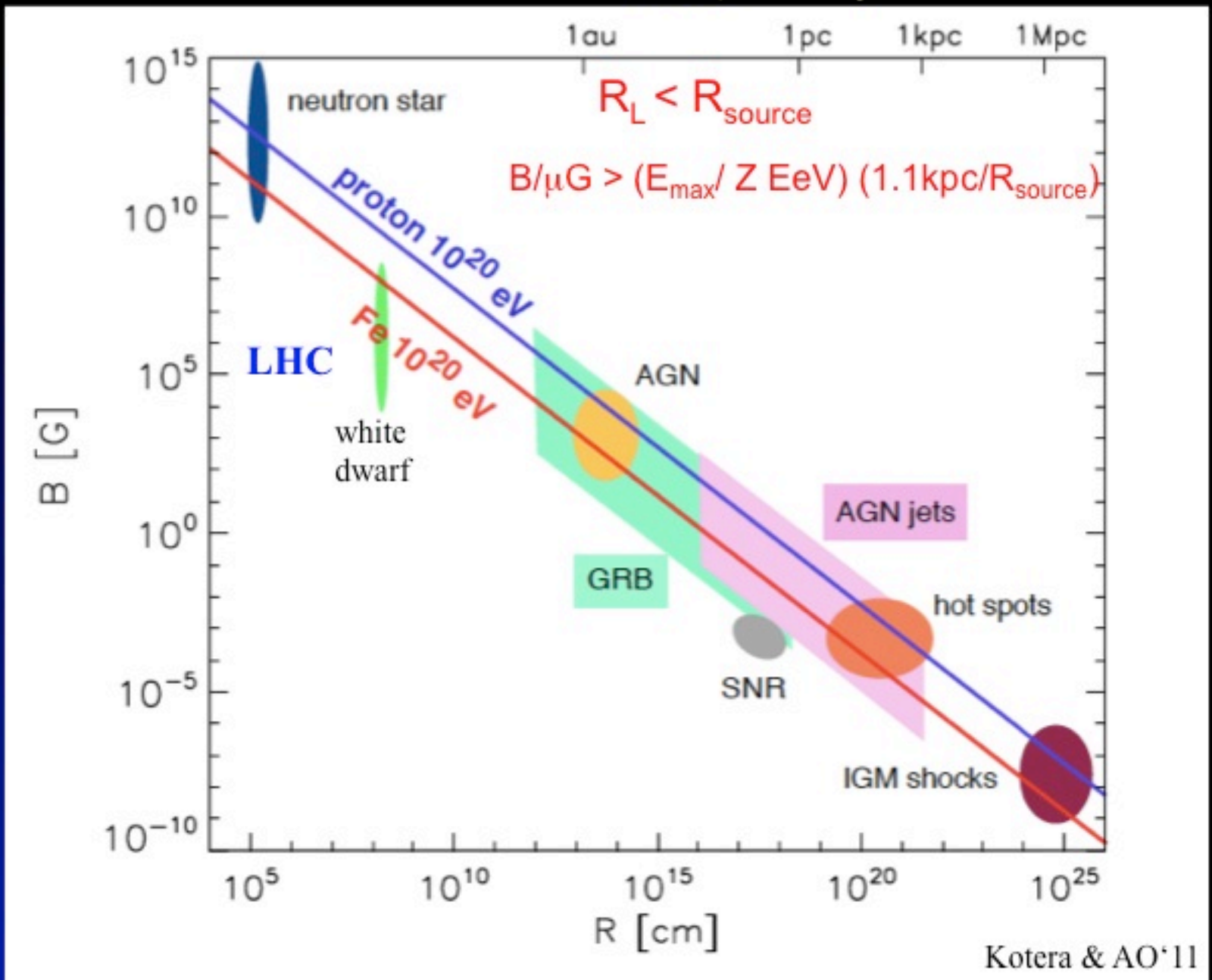
Data up to December 2010
(April 2011) Prescription set



New data Prescription status



Hillas Plot: E_{max} required



Kotera & AO'11