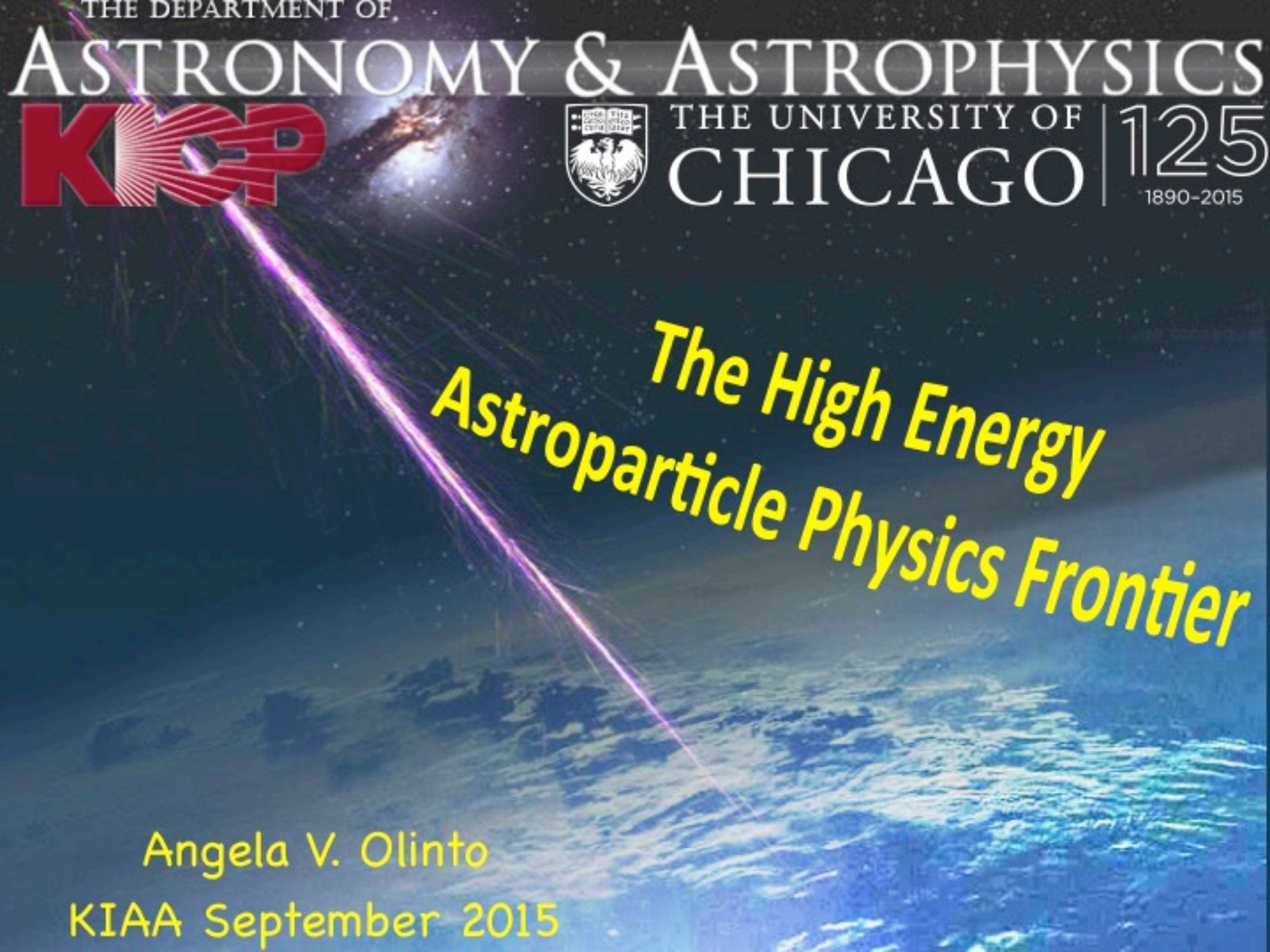

THE DEPARTMENT OF
ASTRONOMY & ASTROPHYSICS
KICP
THE UNIVERSITY OF CHICAGO
125
1890-2015
The High Energy Astroparticle Physics Frontier
Angela V. Olinto
KIAA September 2015

KIAA Workshop on *Astroparticle* Physics

KIAA@Peking University; Sept. 28-29, 2015 — http://kiaa.pku.edu.cn/aph2015/

TOPICS

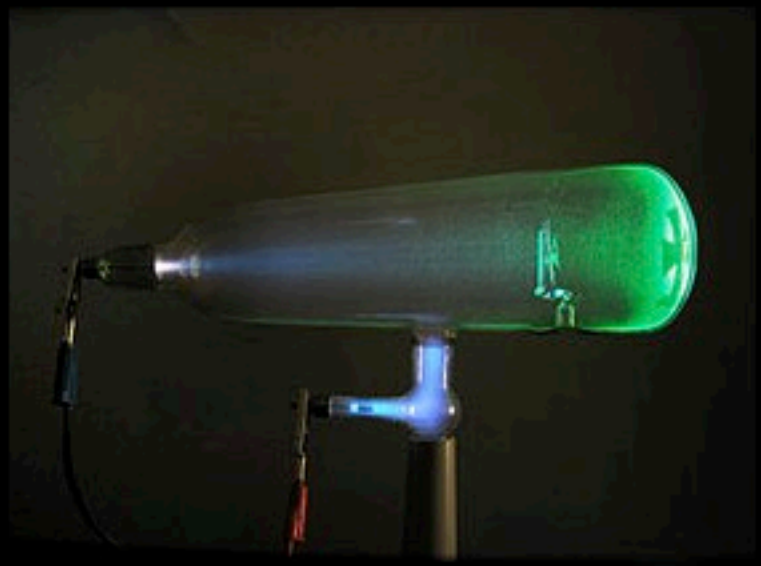
COSMIC RAYS
DARK MATTER DETECTION
PARTICLE COSMOLOGY
PARTICLE PHYSICS IN STARS

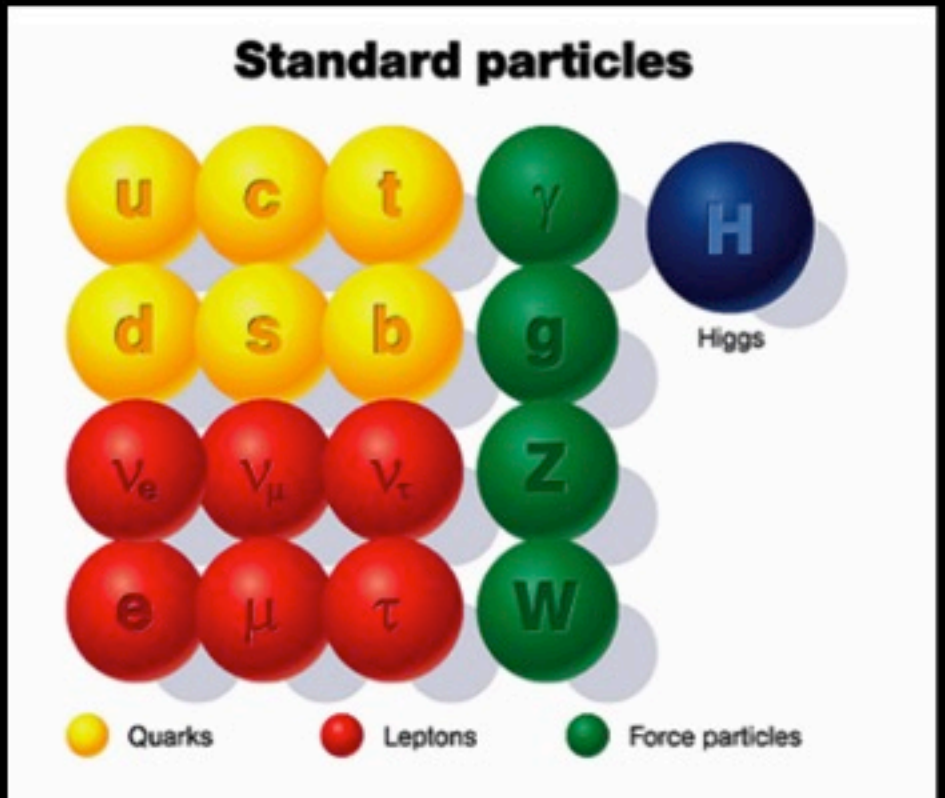
The long-standing quest for understanding the fundamental laws of Nature has motivated the new field of **Astroparticle Physics** where observations of the Universe are used to probe particle interactions. This small workshop will bring together AstroParticle Physics experts to provoke discussion and foster collaboration especially between members of Kavli Institutes.

Organizers
Ke Fang (U Chicago)
Zhaosheng Li (PKU)
Angela V. Olinto (U Chicago)
Meng Su (MIT)
Renxin Xu (PKU)

Particle Physics

Begins with
1897 Discovery of the electron
J. J. Thompson et al.,
Crookes' cathode ray tube

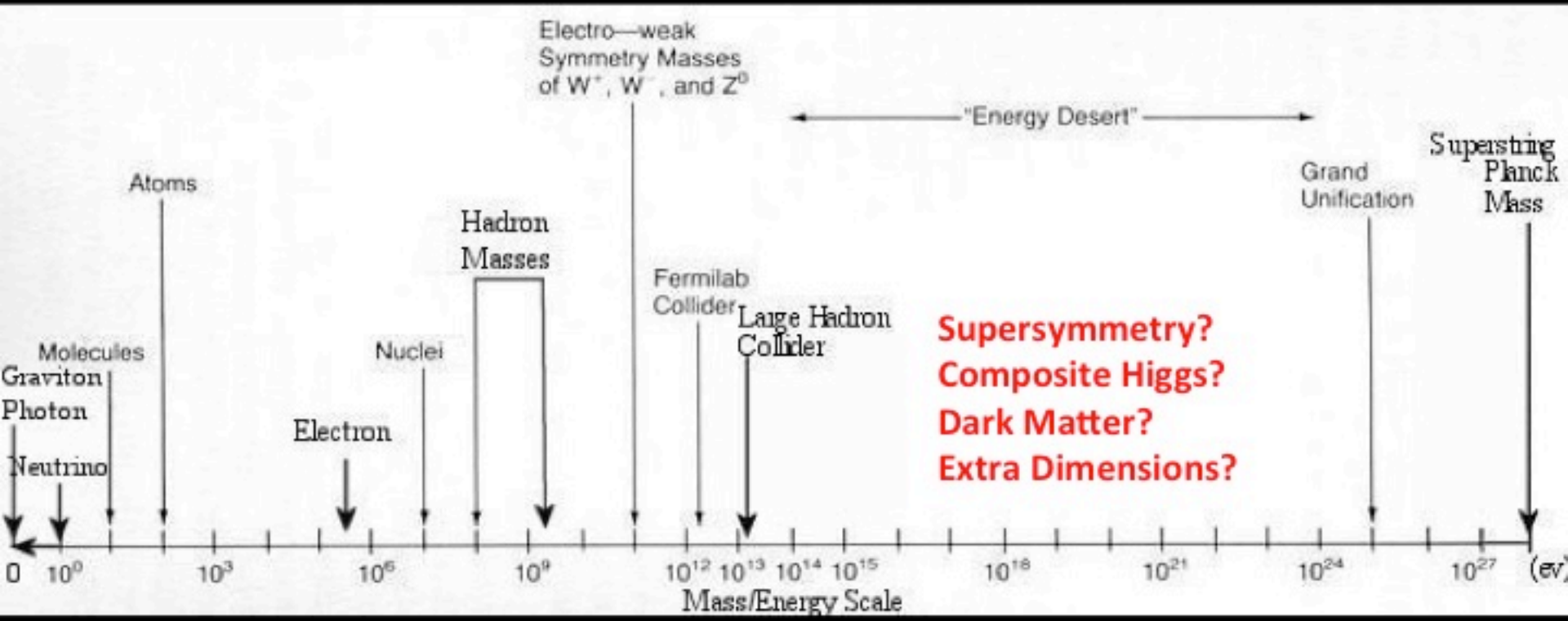




In 2013,
The Standard Model
is complete!!

Precise description of nature up to ~10 TeV

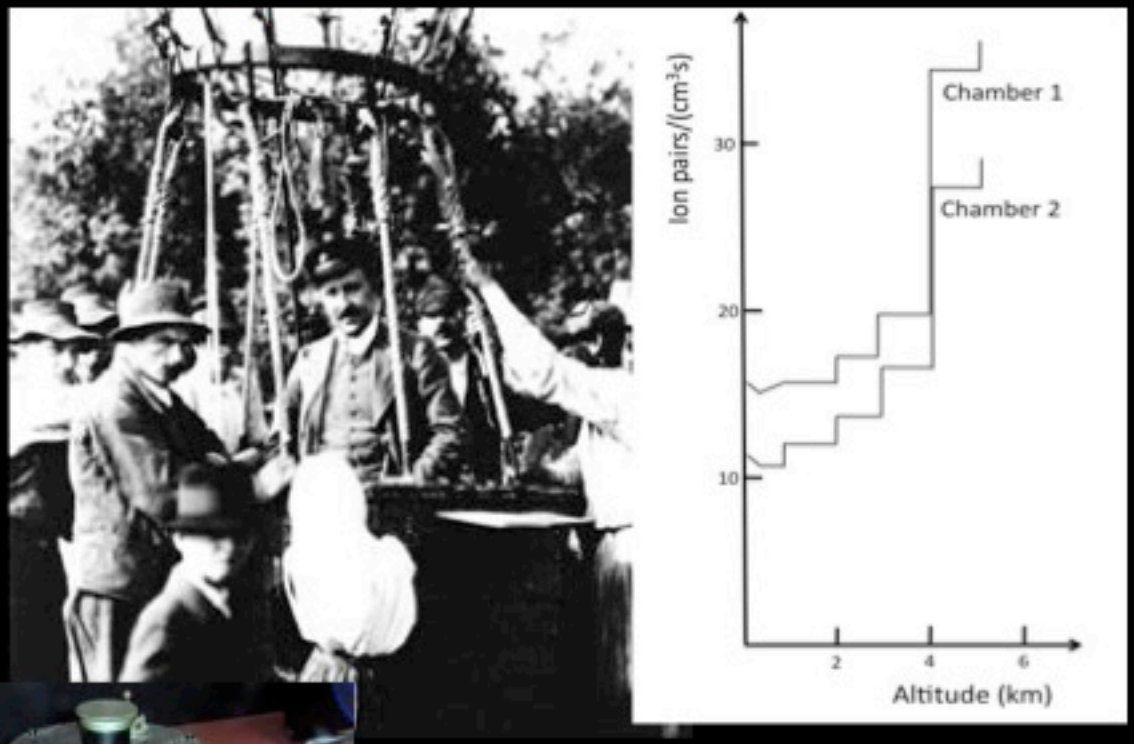
Journey toward Planck



10^{13} eV ⟷ 14 o.o.m. ⟷ 10^{27} eV

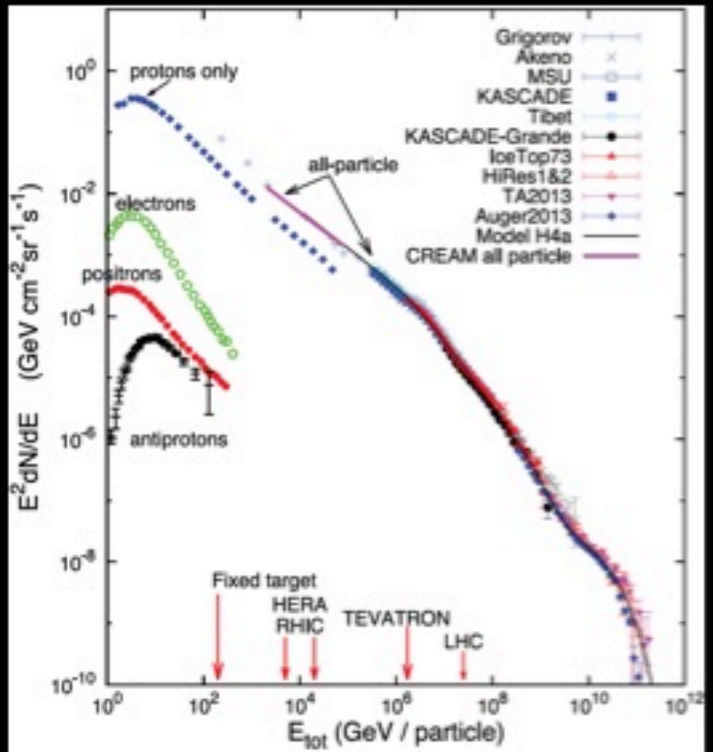
Particle Astrophysics or Astroparticle Physics

Begins in 1912



Victor Hess establishes the cosmic nature of ionizing radiation

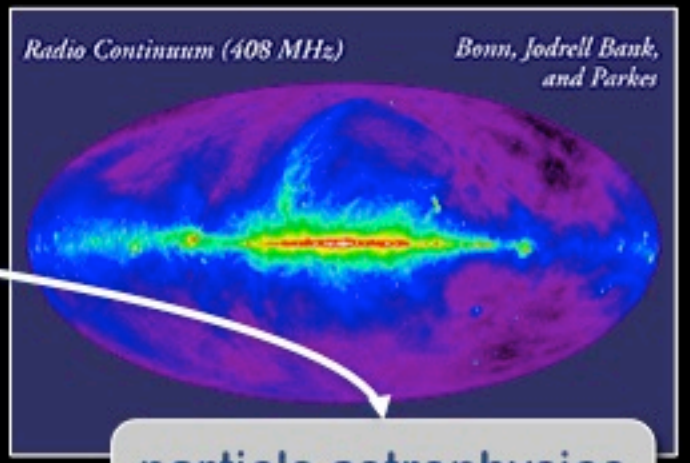
Great progress,
but many open questions
no standard model yet



Joint Development of Particle Physics & Particle Astrophysics

Study of cosmic rays

1953



particle astrophysics

1932 Positron

1936 Muon

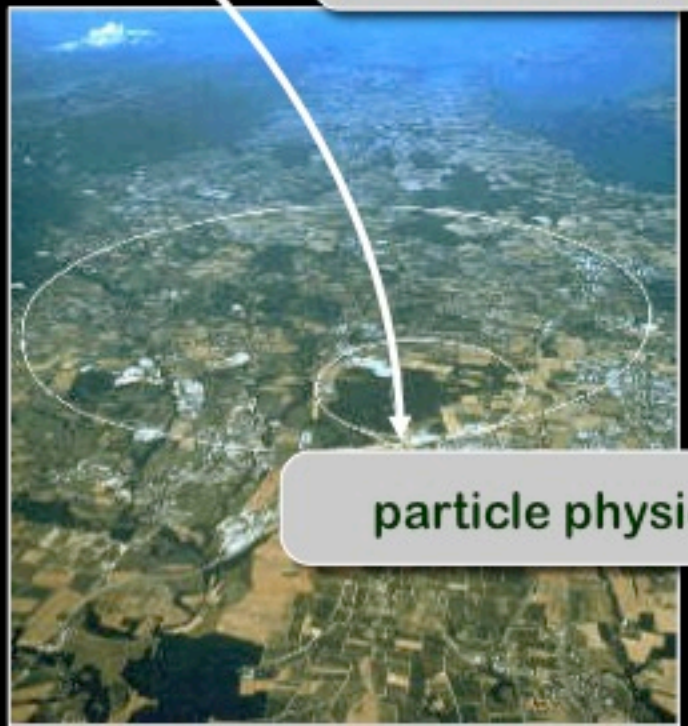
1947 Pions : π^0, π^+, π^-

1949 Kaons (K)

1949 Lambda (Λ)

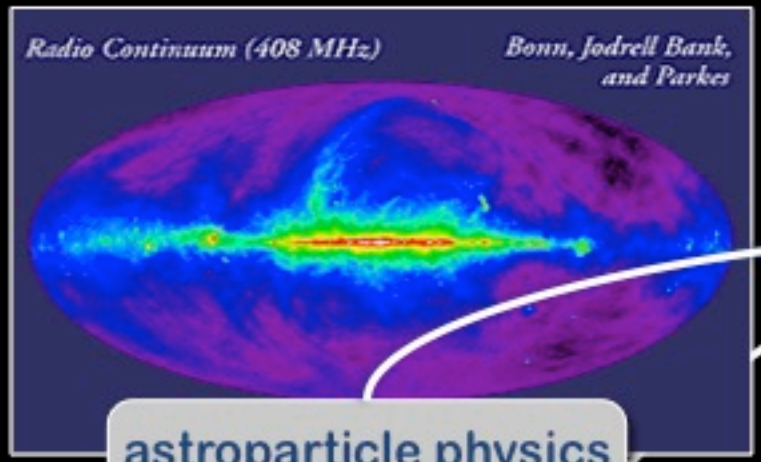
1952 Xi (Ξ)

1953 Sigma (Σ)

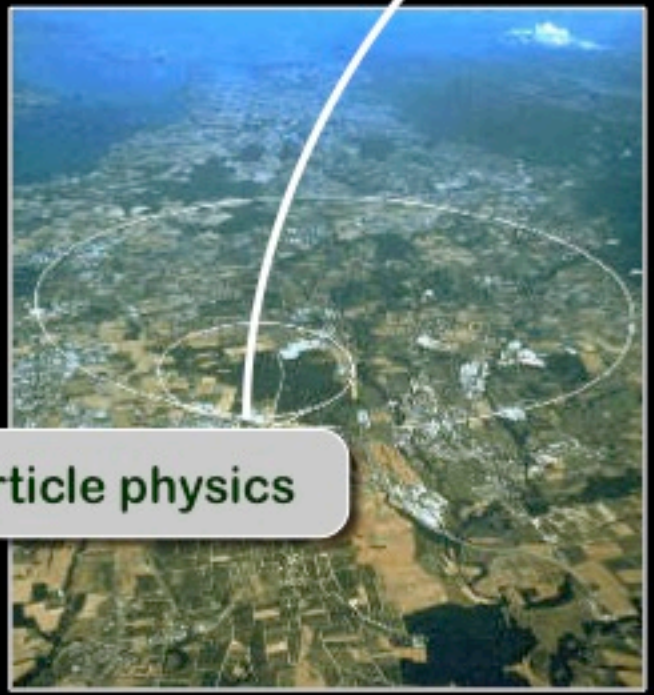


particle physics

Joining forces again
Particle Physics & AstroParticle Physics



astroparticle physics



particle physics

Cosmic particles (CRs, ν's, γ's) with E > LHC

Neutrino Properties: masses, symmetries,..., (e.g. Cosmic Microwave Background, CMB)

Dark Matter: WIMPS, axions, SHDM,...

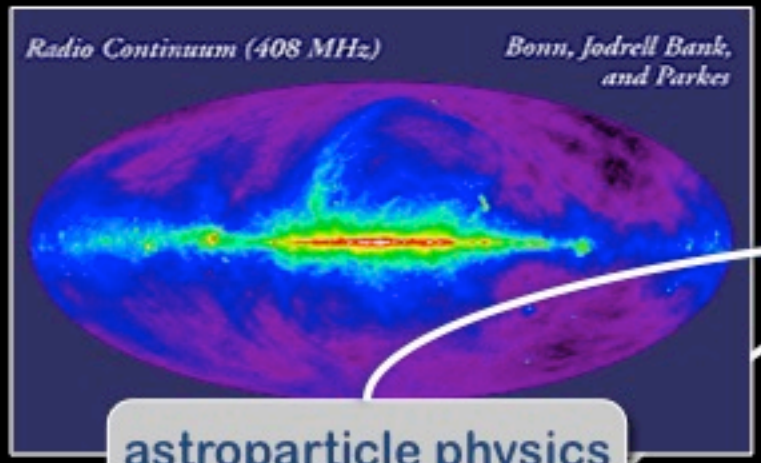
Dark Energy: ????

Inflation and GUT scale physics (e.g., CMB polarization)

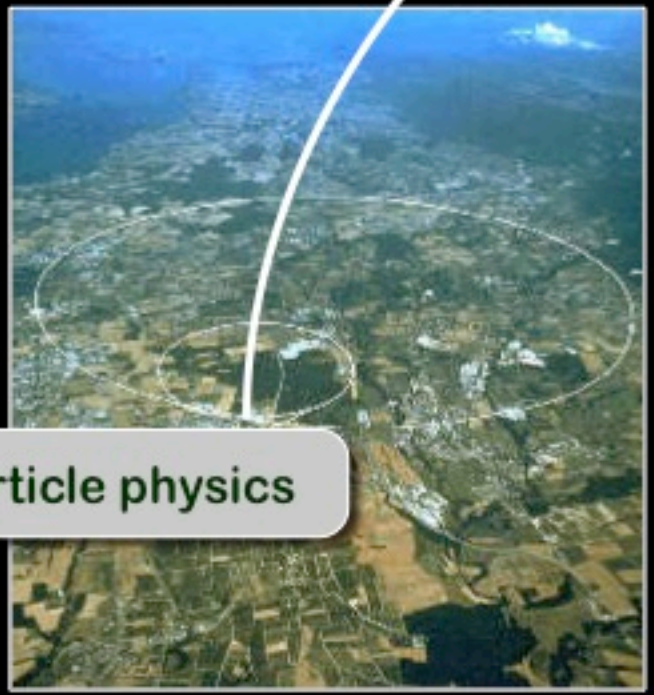
Gravitational Waves

Other Early Universe Relics...

Joining forces again
Particle Physics & AstroParticle Physics



astroparticle physics



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Other Early Universe Relics...

Extensive Air Showers

1937: Pierre Auger

~ 10^{15} eV

CERN

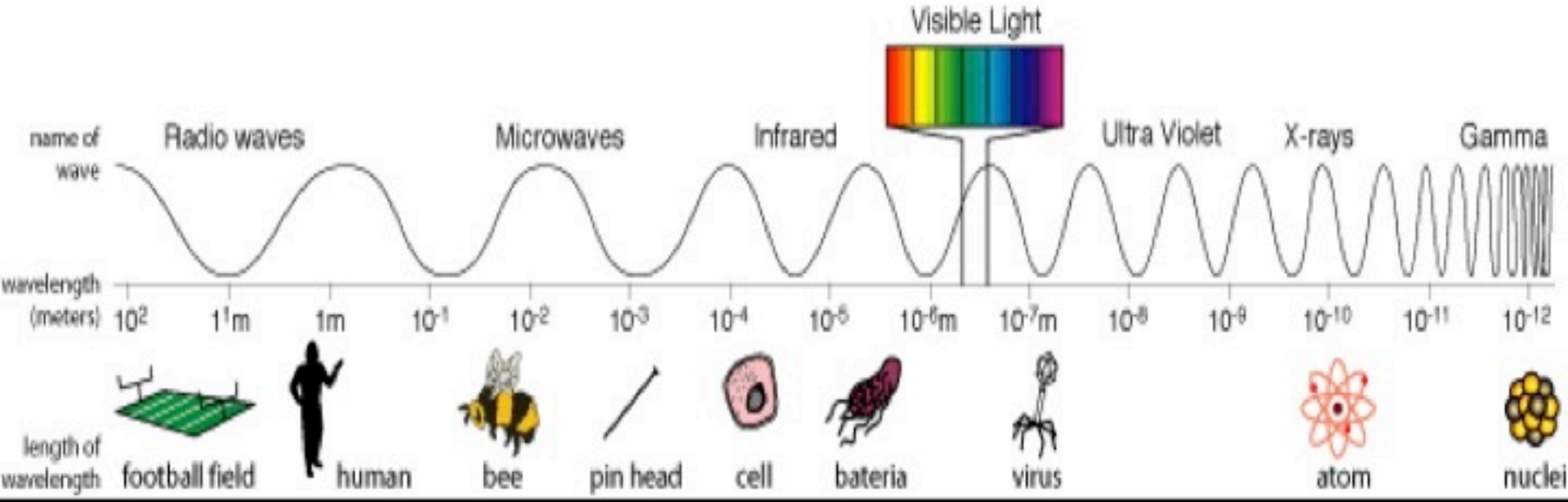
Ultra High Energy Cosmic Rays

1962 John Linsley

~10^{20} eV event

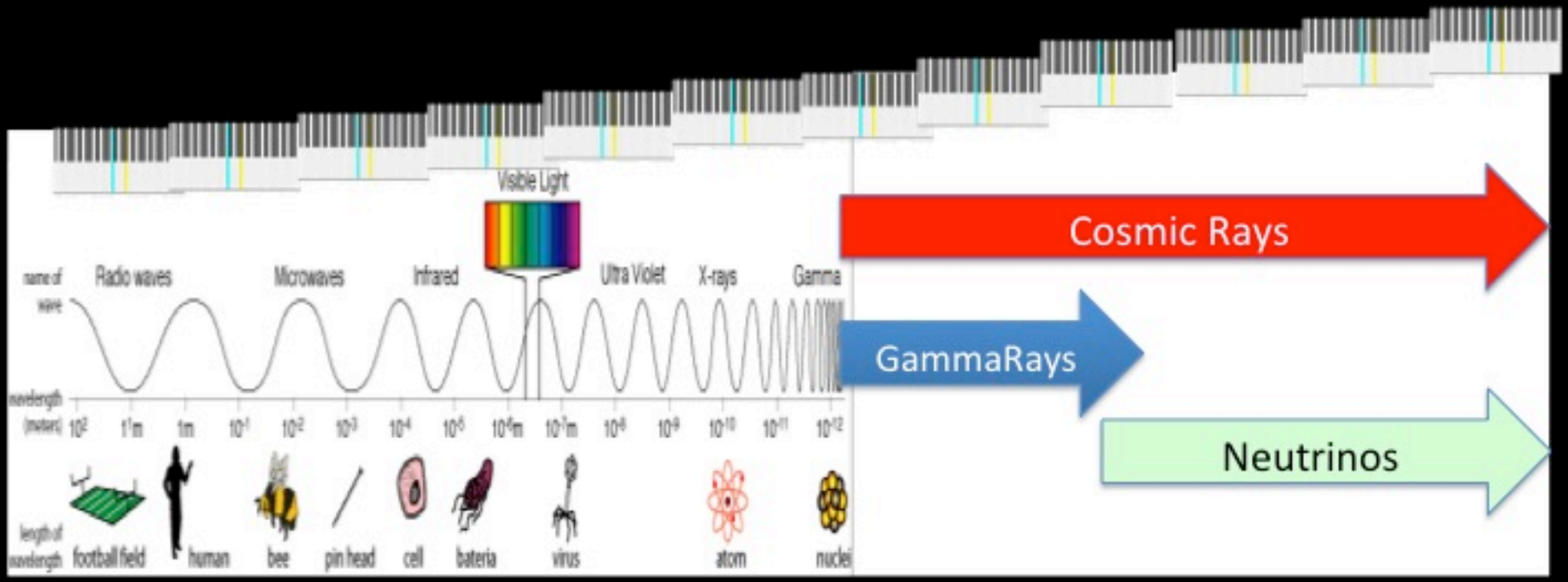
Astronomer's view of energy scales

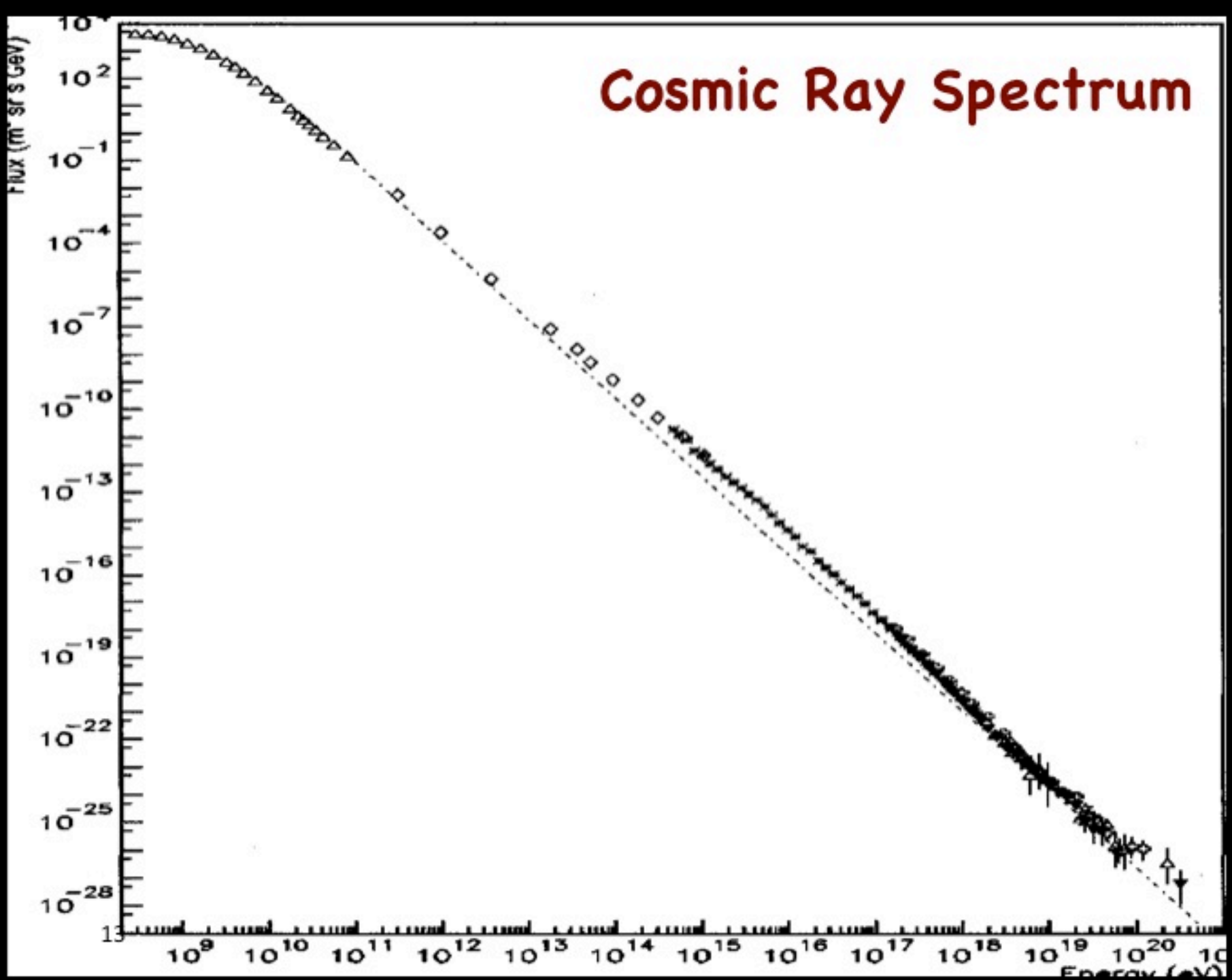
Photon "energy range"

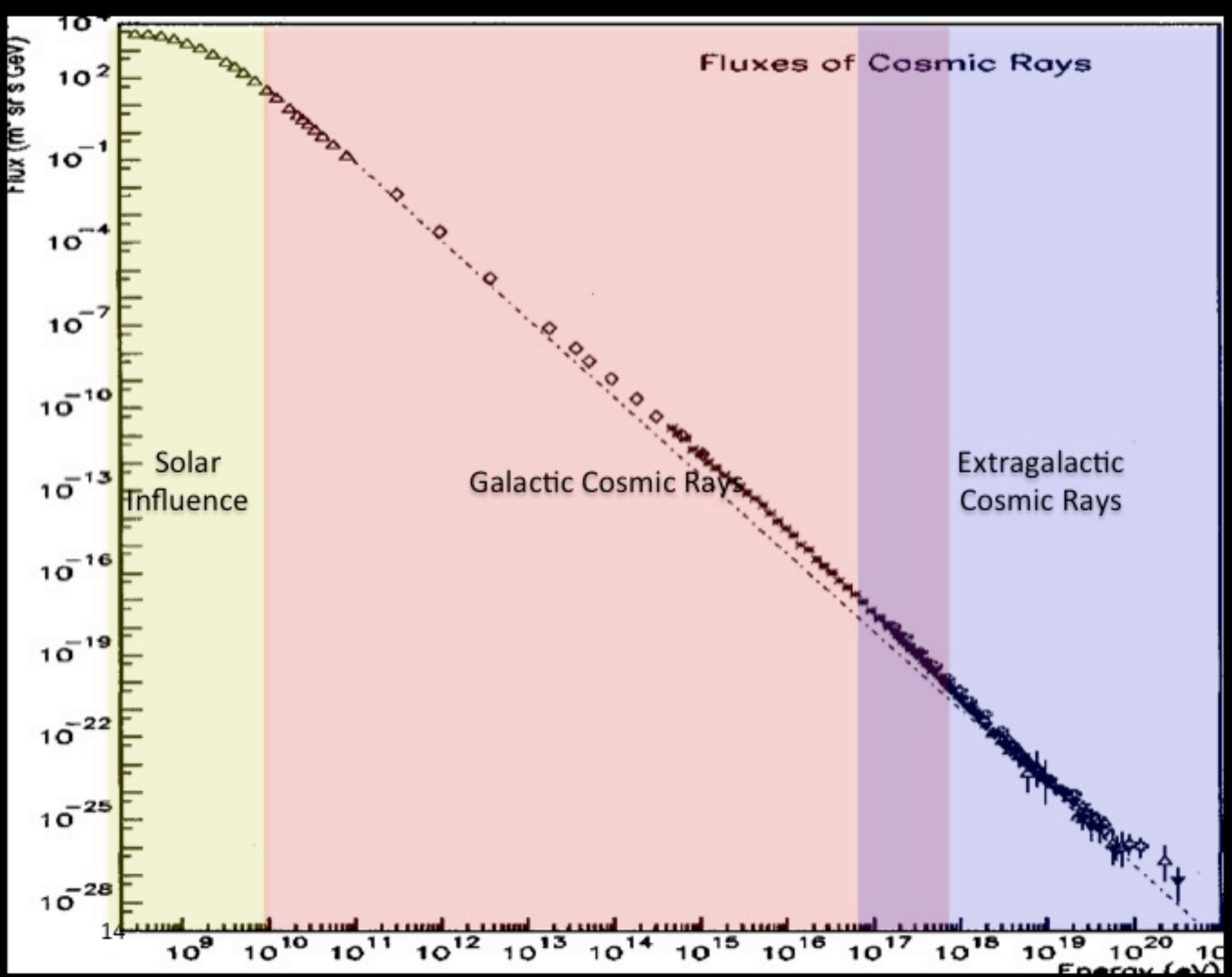


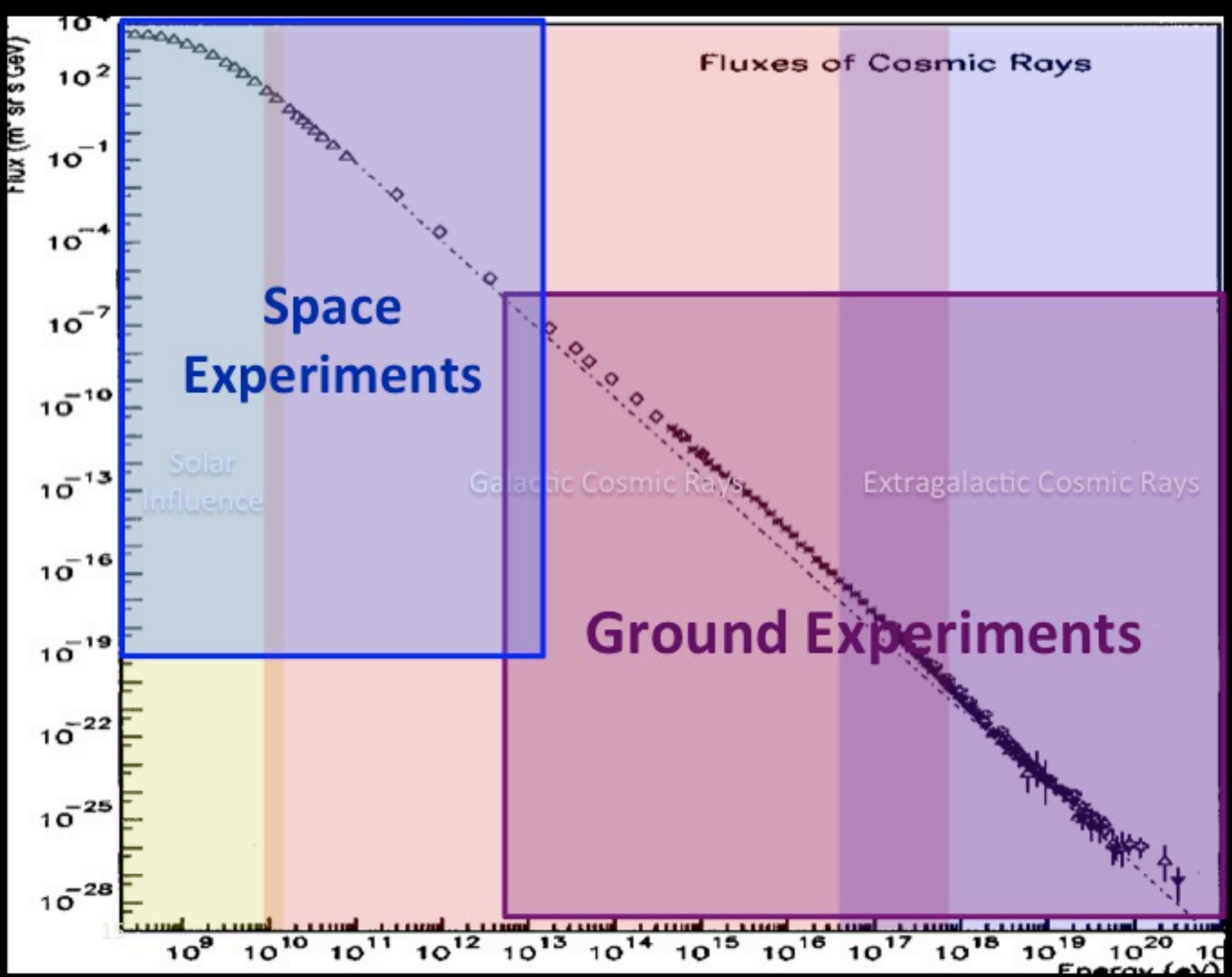
High Energy Particles

~ double the energy range for Astrophysics




Cosmic Ray Spectrum
Flux (m² sr s GeV)
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy (eV)

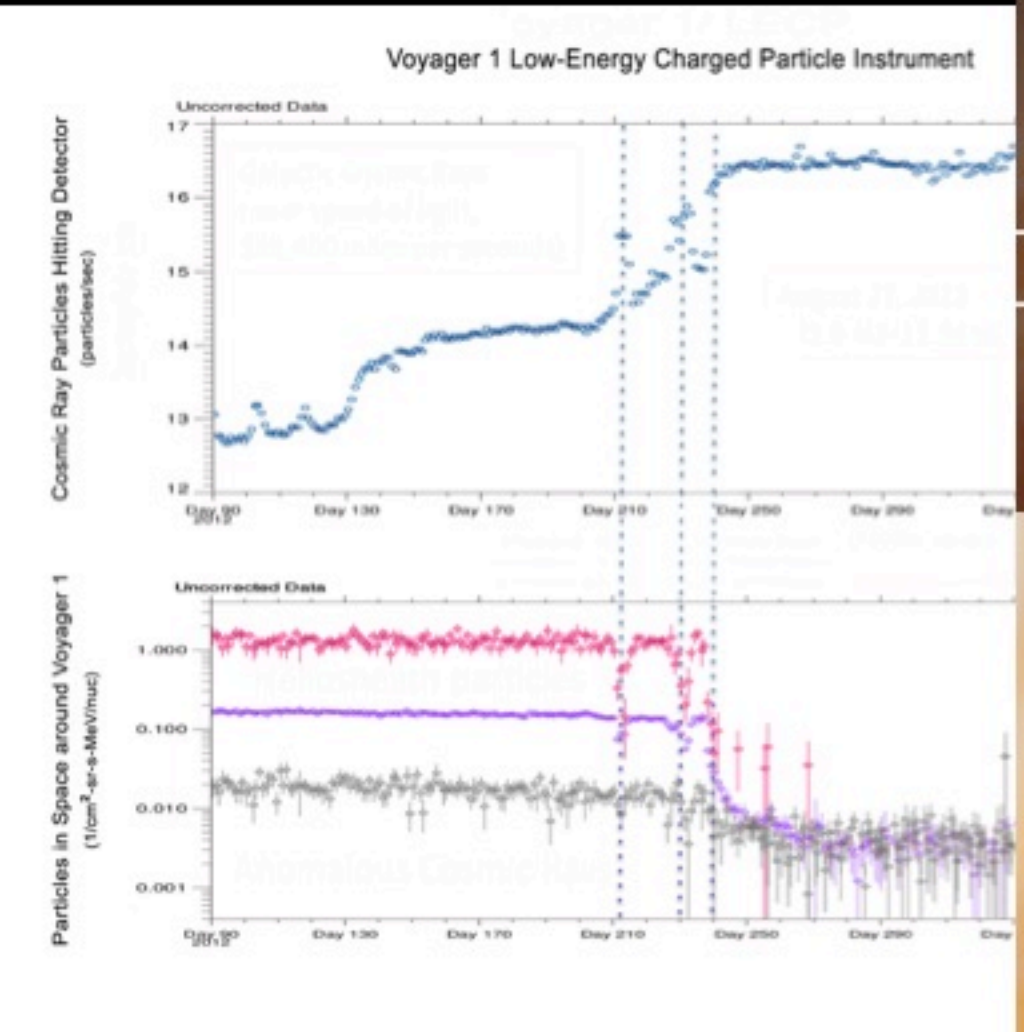

Fluxes of Cosmic Rays
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays

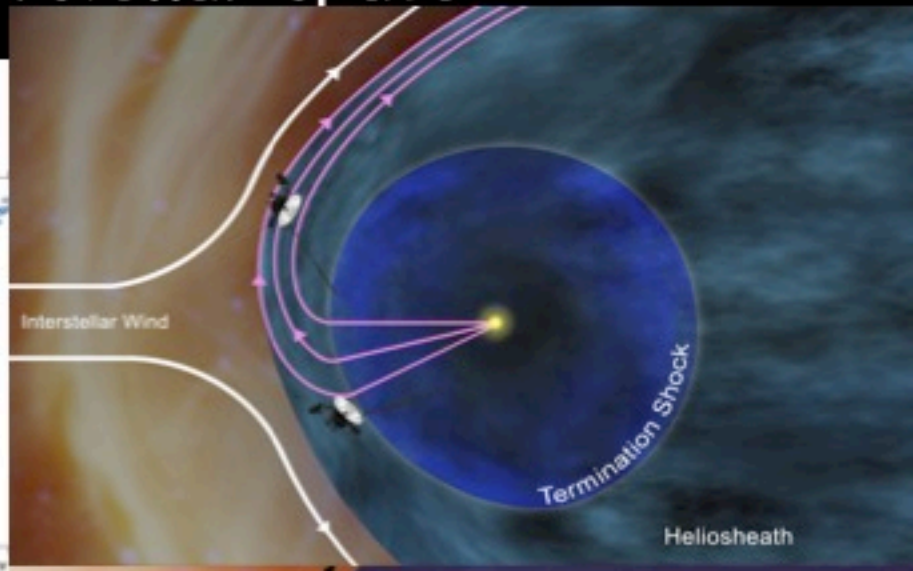

Fluxes of Cosmic Rays
Space Experiments
Ground Experiments
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays

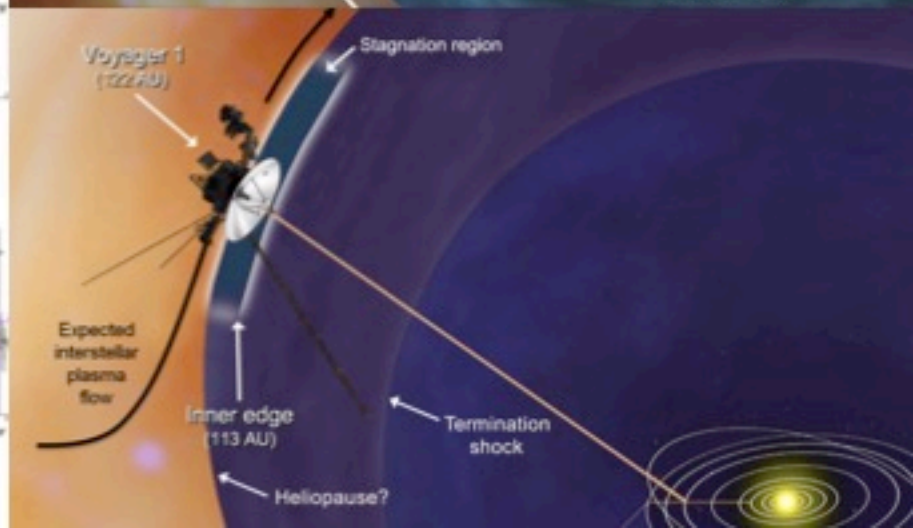
Voyager 1

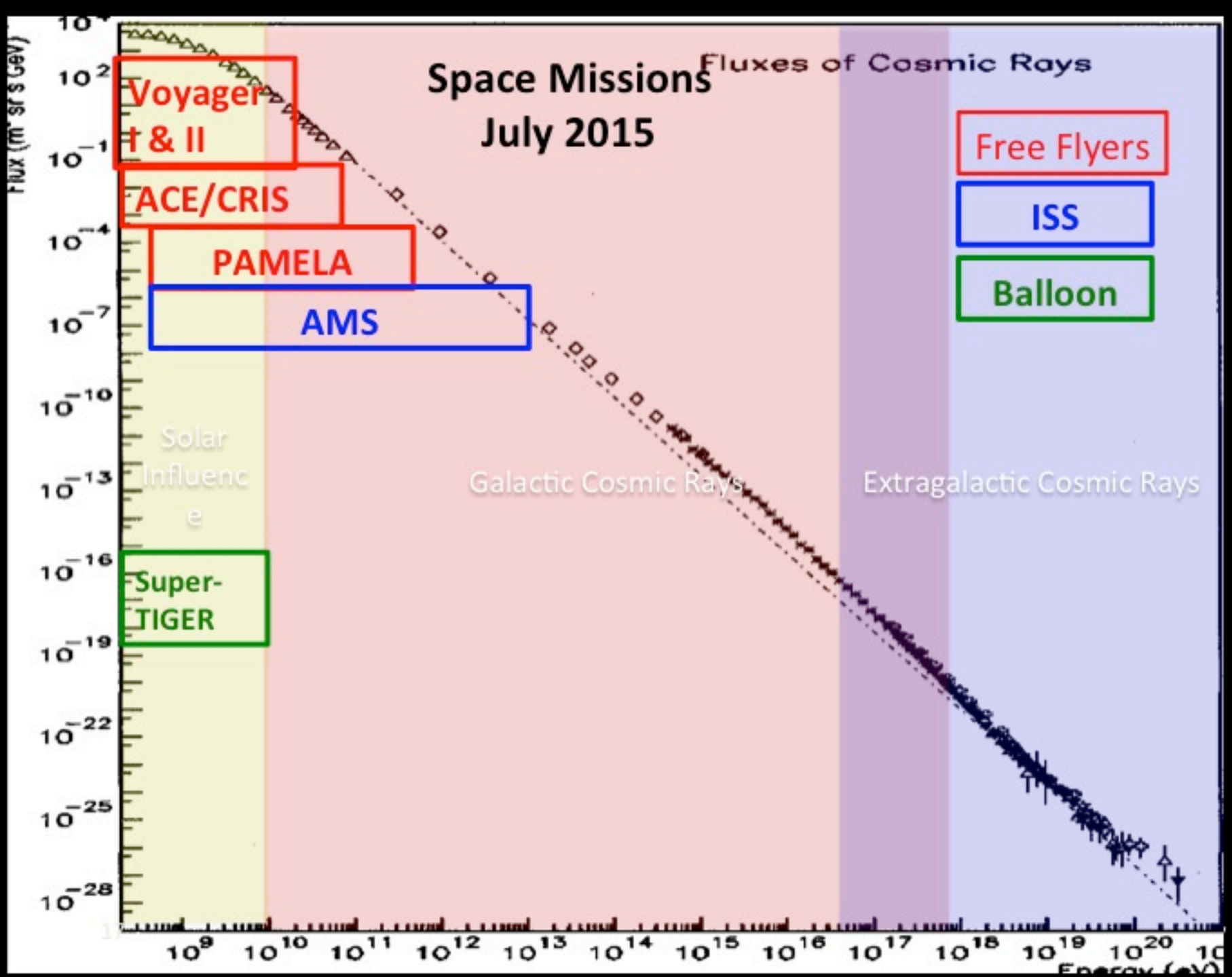
reached 'the magnetic highway' in 2012

on its way to interstellar space

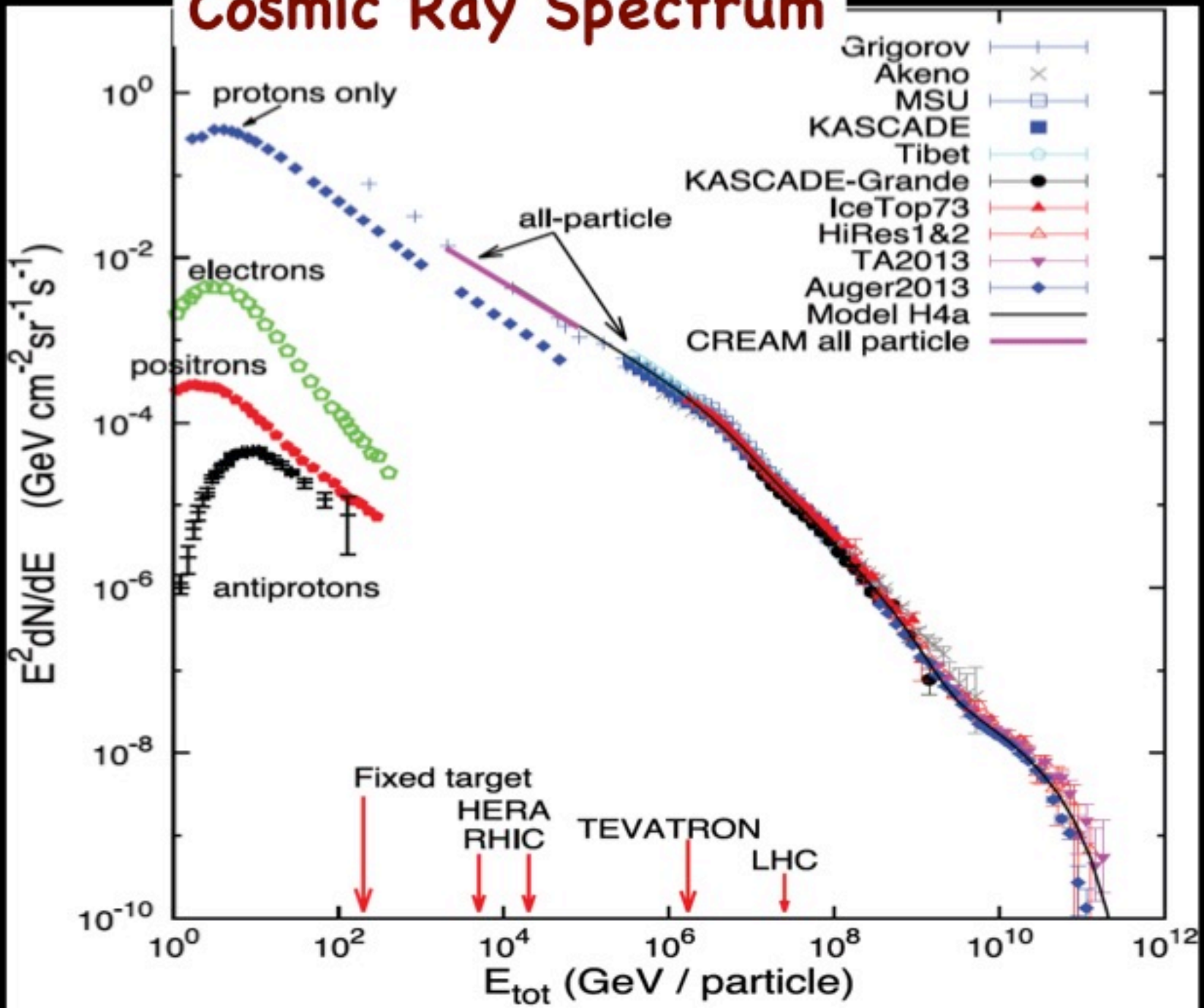




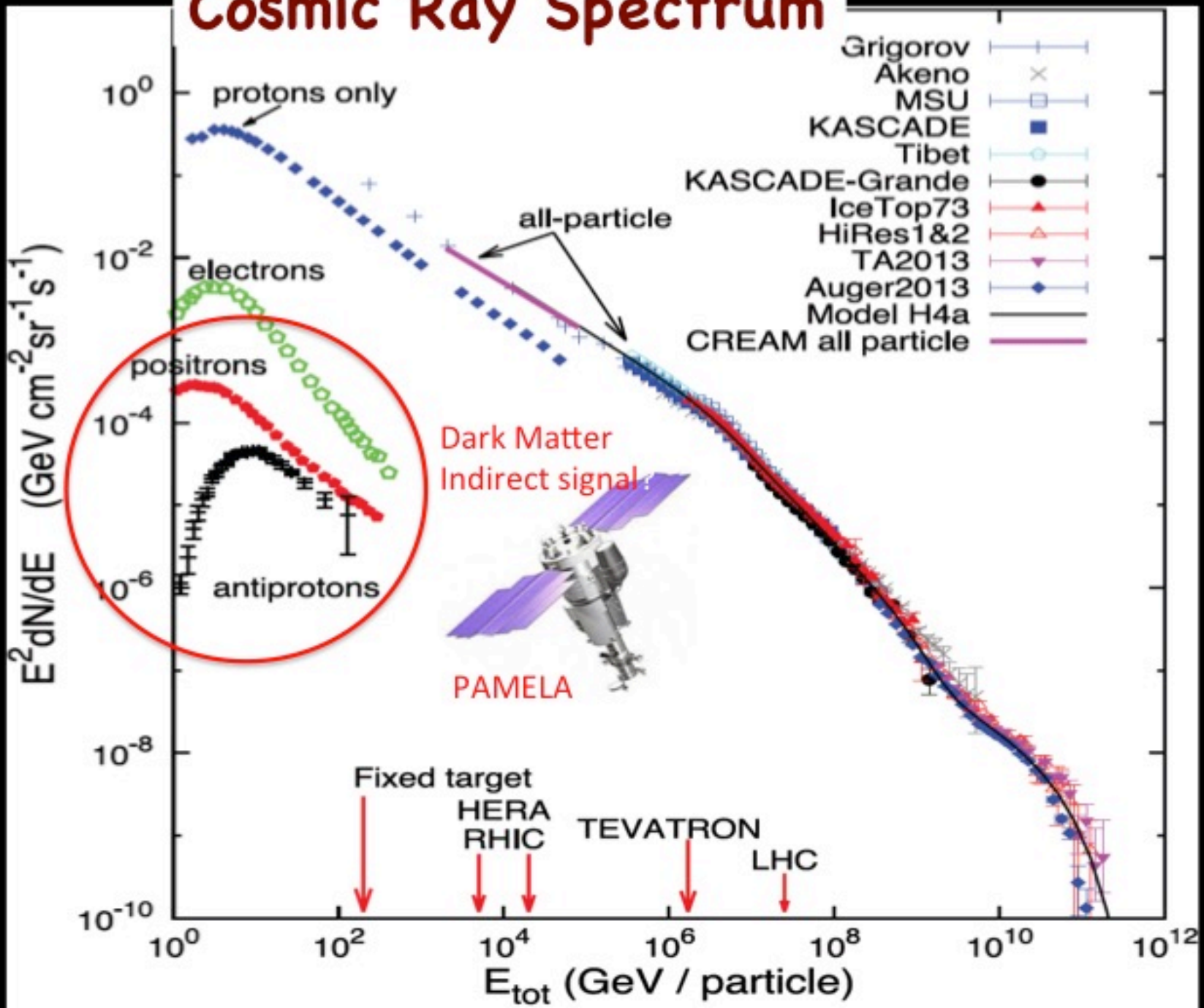



Space Missions
July 2015
Fluxes of Cosmic Rays
Voyager I & II
ACE/CRIS
PAMELA
AMS
Super-TIGER
Free Flyers
ISS
Balloon
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays
Flux (m² sr s GeV)
Energy (eV)

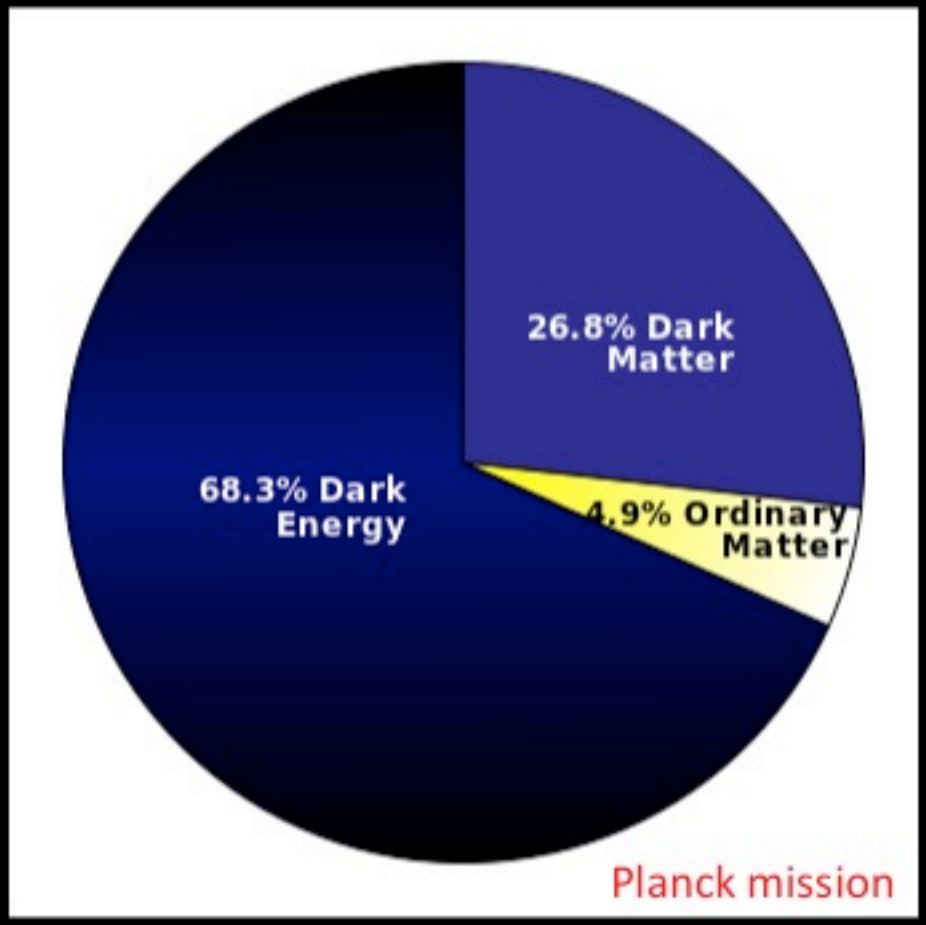
Cosmic Ray Spectrum



Cosmic Ray Spectrum



Cosmological Surprises:



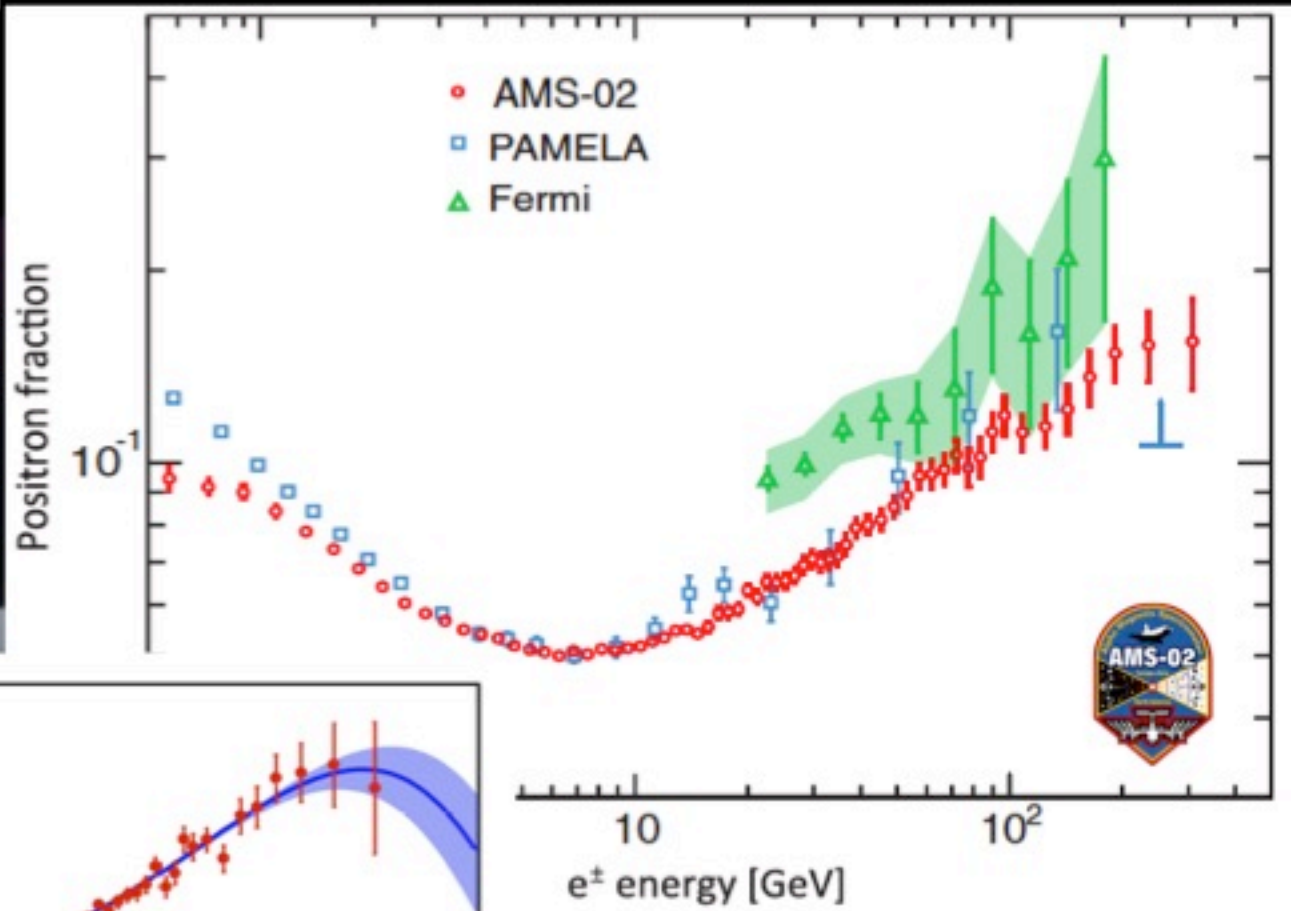
Standard Model explains ~5% of the universe, 27% Dark Matter, & 68% named Dark Energy!

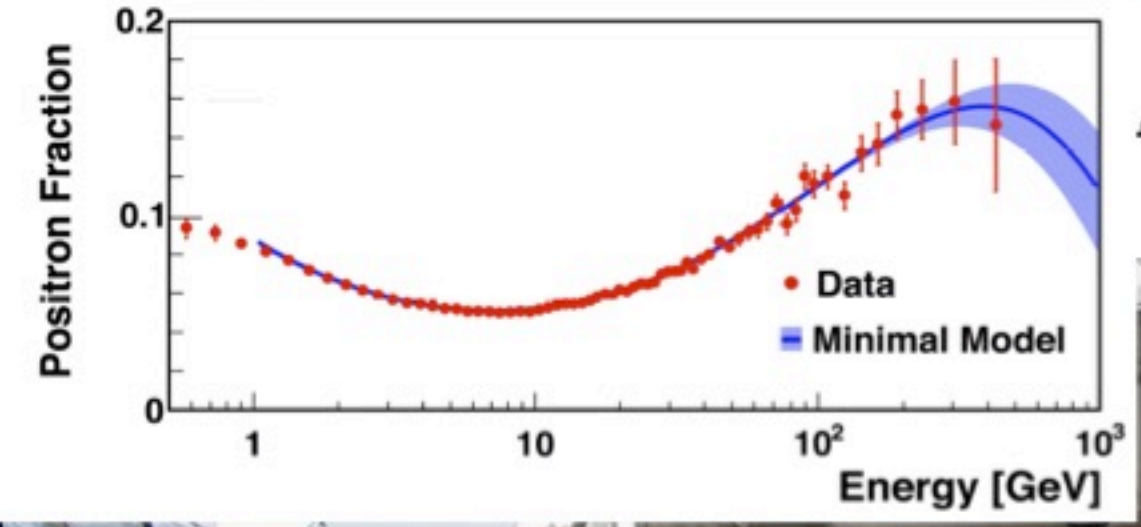
Alpha Magnetic Spectrometer

AMS on the ISS

Alpha Magnetic Spectrometer

Positron Fraction

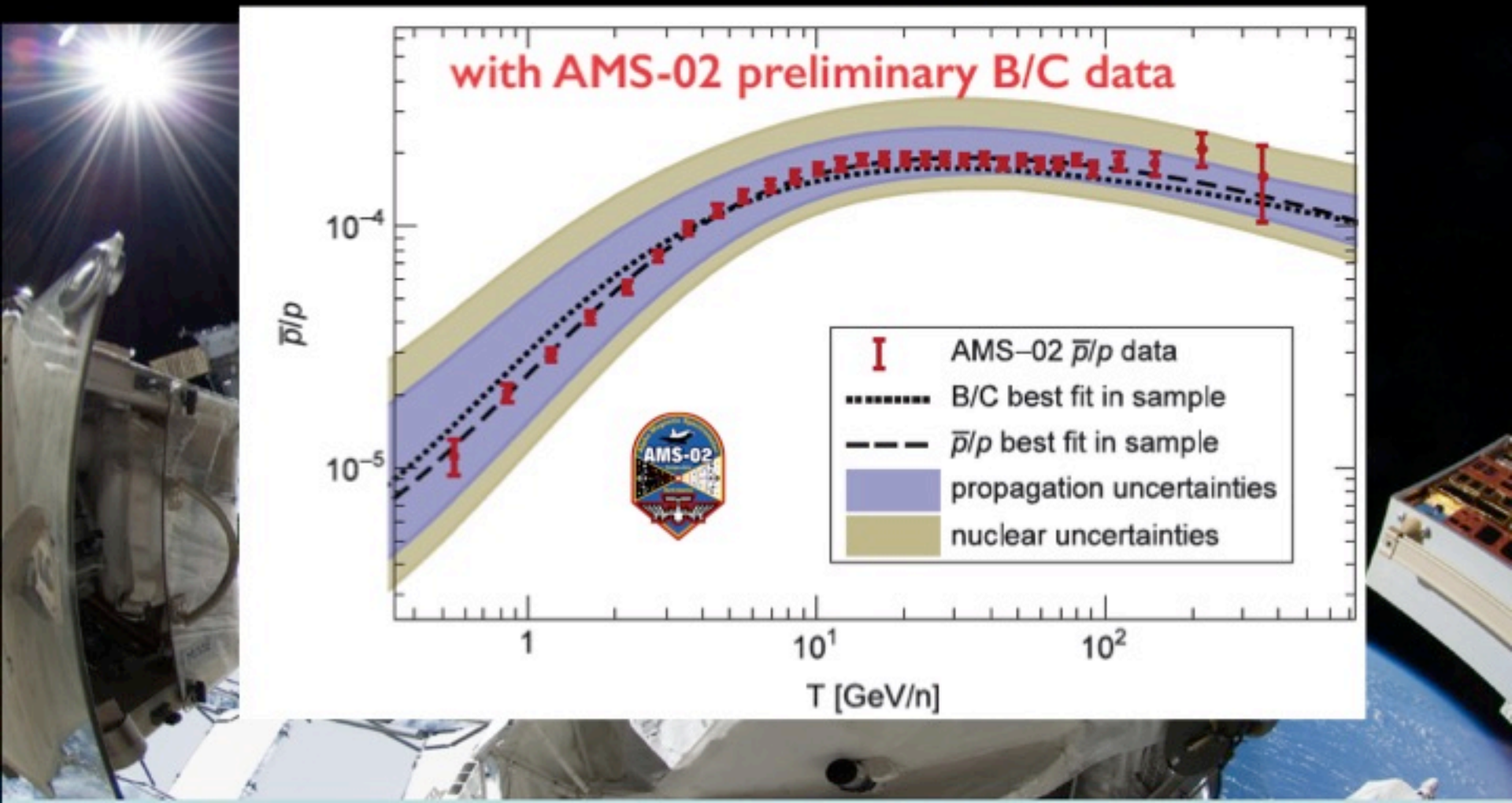


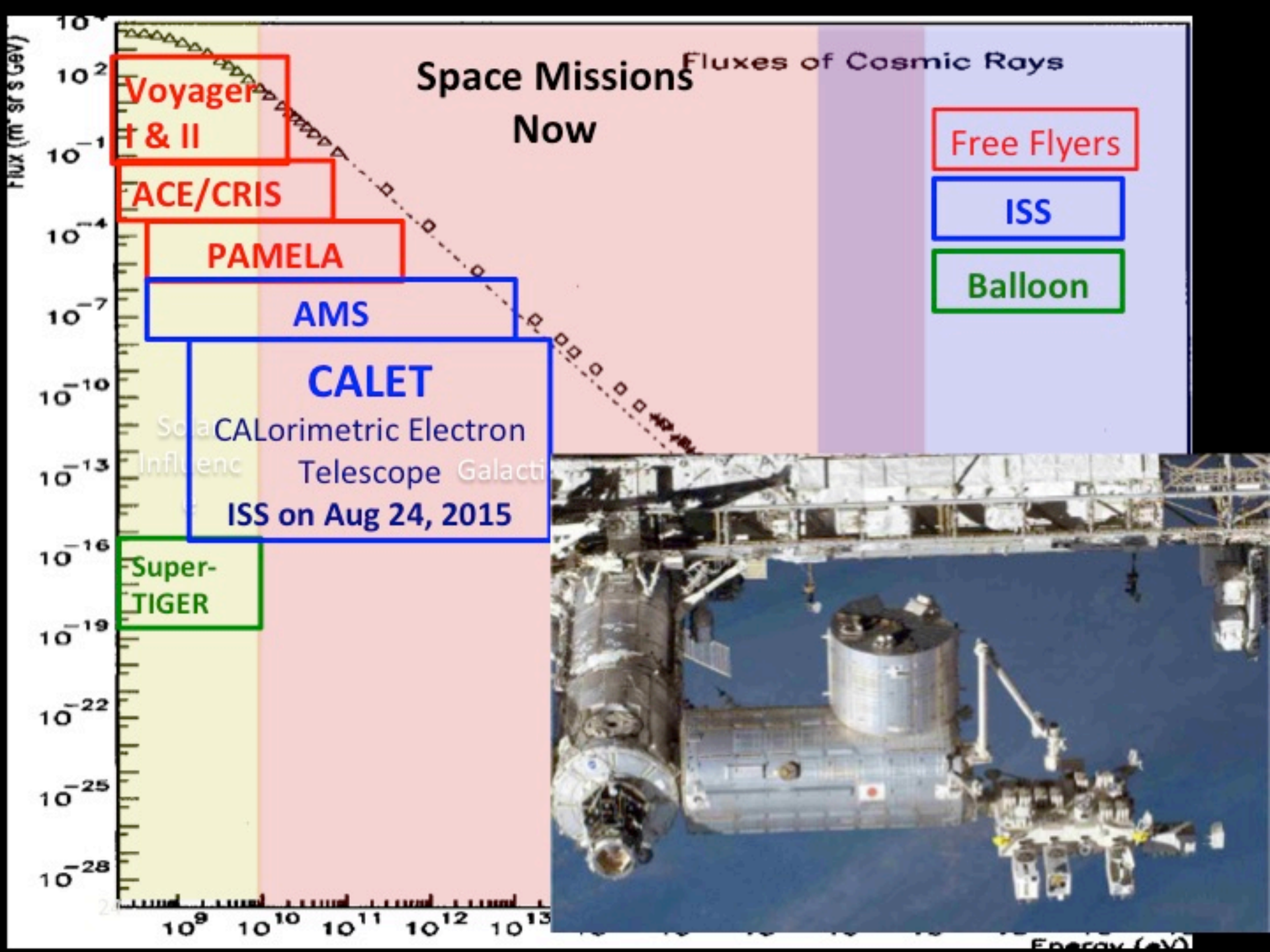


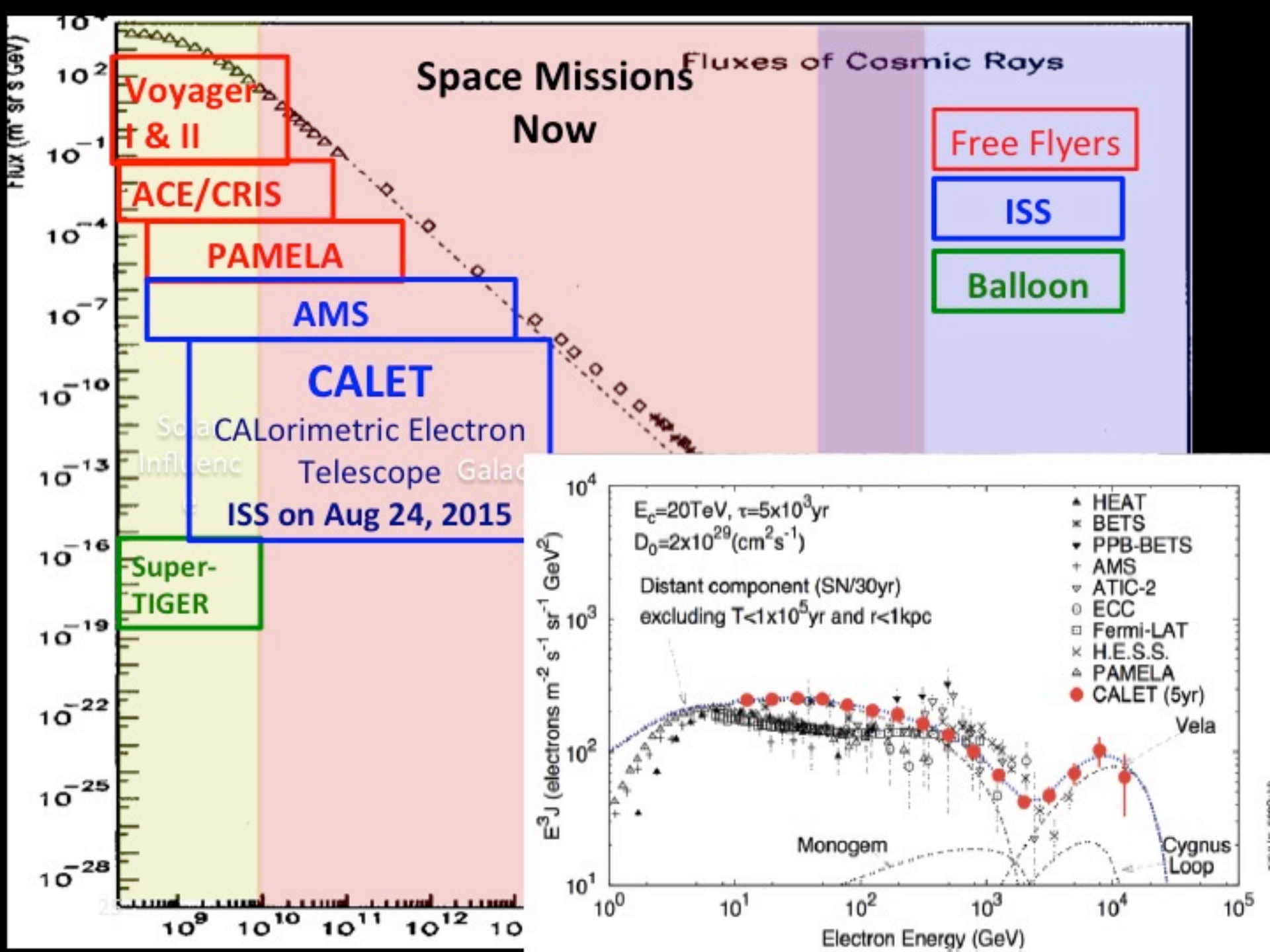
Alpha Magnetic Spectrometer

Anti-Proton Fraction

No clear Dark Matter smoking gun yet




Space Missions
Now
Fluxes of Cosmic Rays
Voyager I & II
ACE/CRIS
PAMELA
AMS
CALET
CALorimetric Electron Telescope
ISS on Aug 24, 2015
Super-TIGER
Free Flyers
ISS
Balloon
Flux (m² sr s GeV)
Energy (eV)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Super-TIGER
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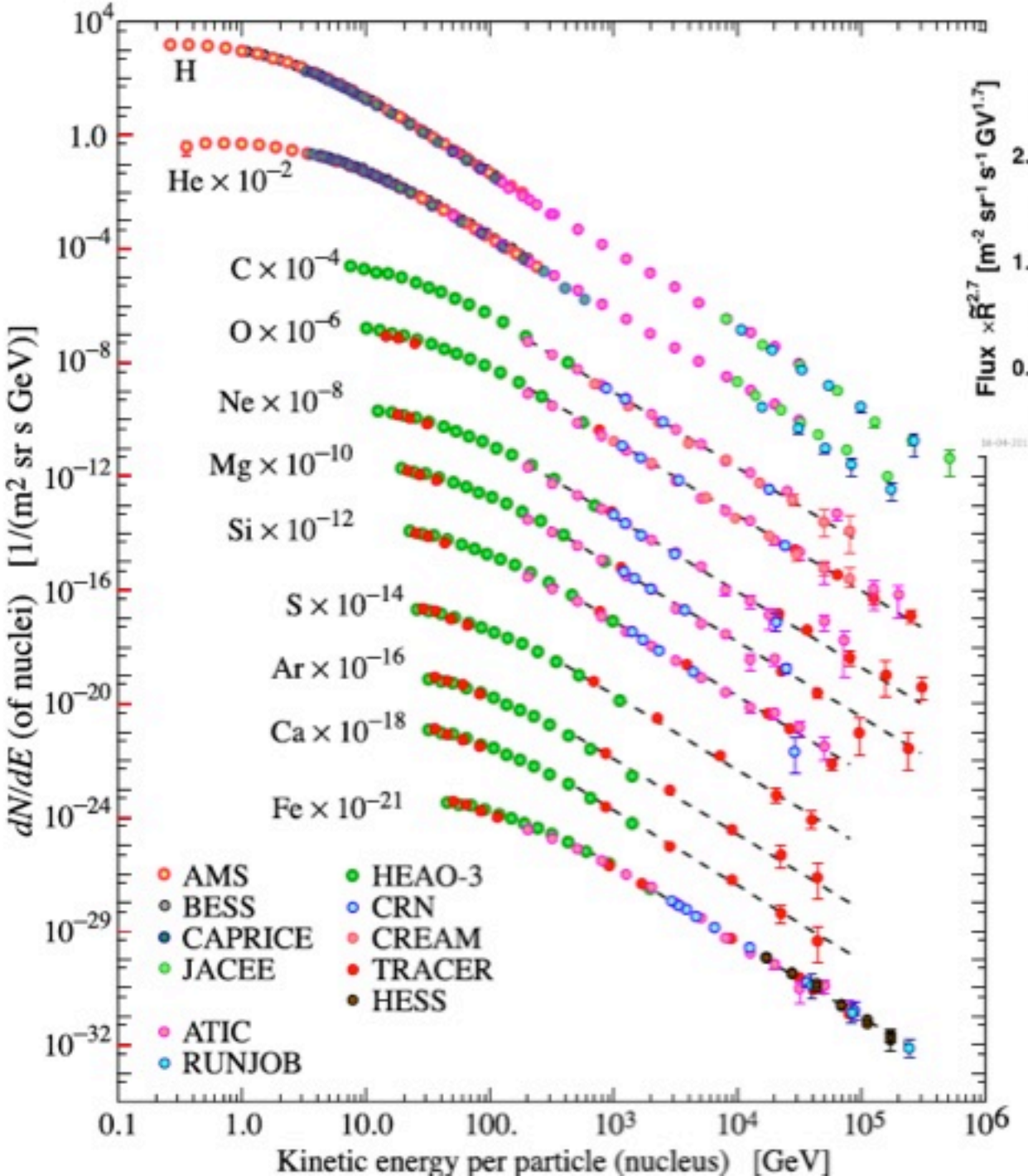
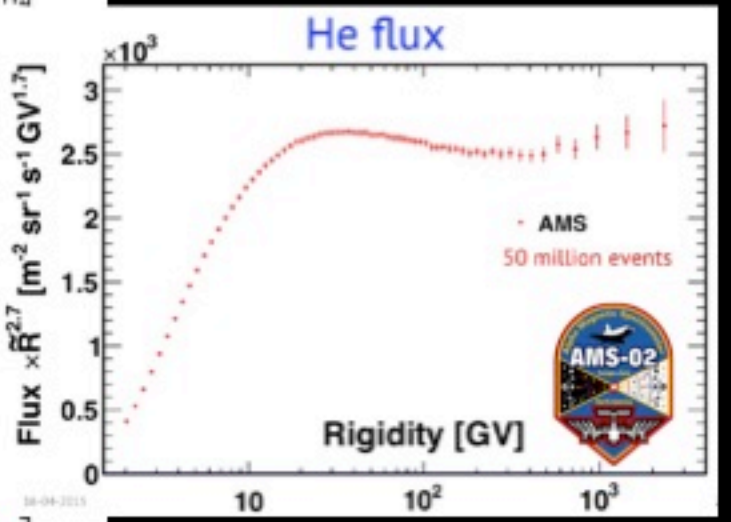
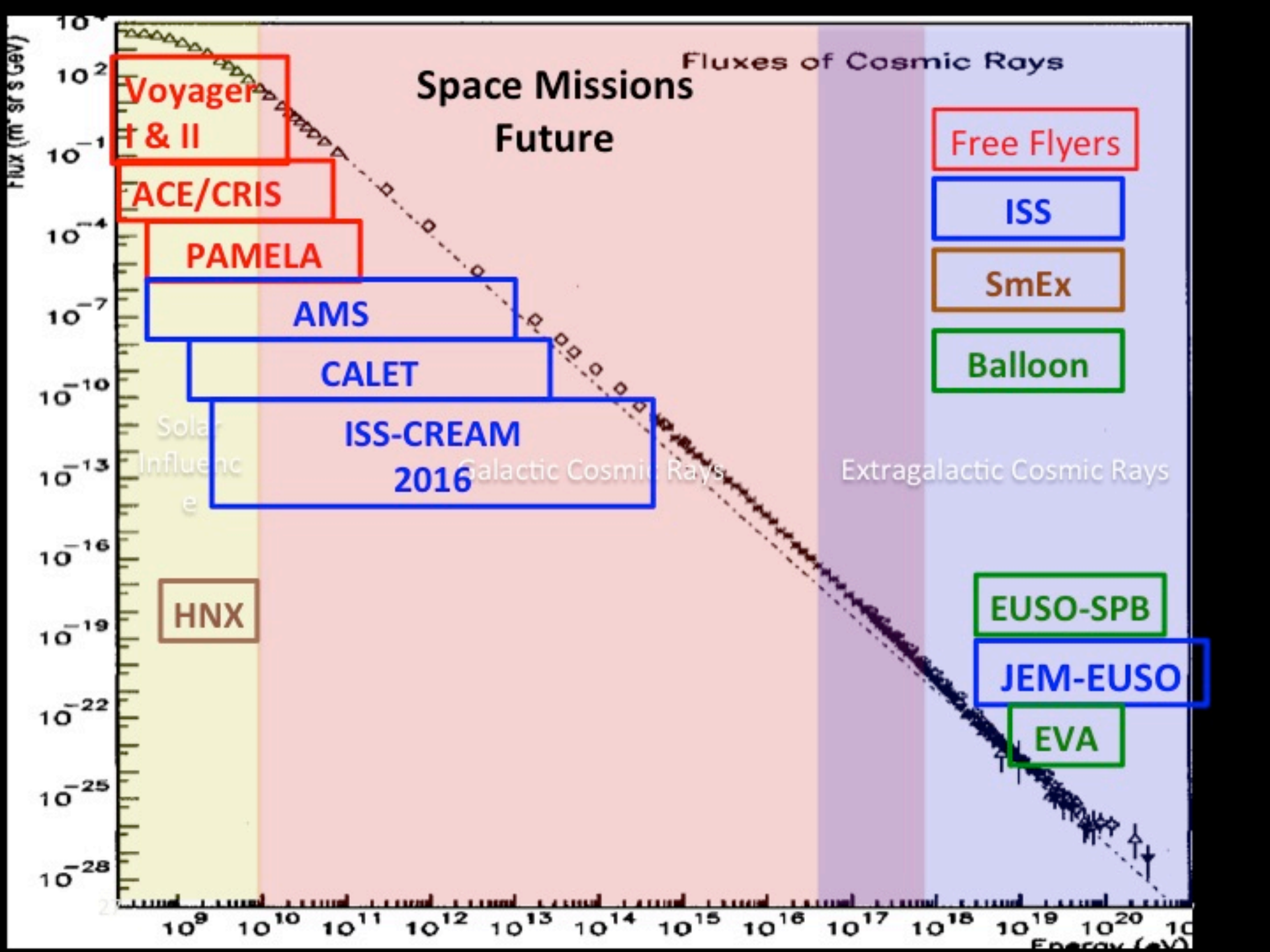
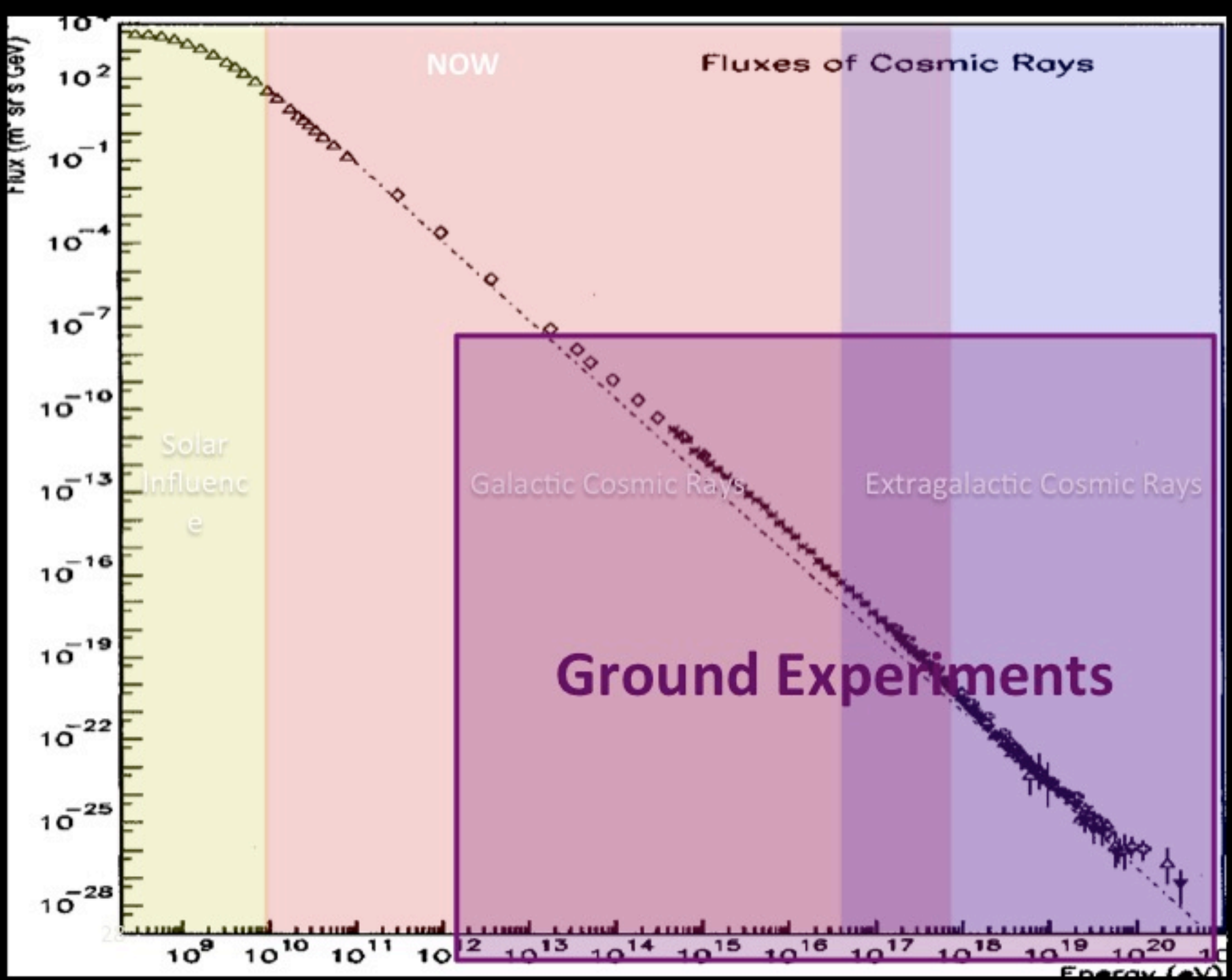
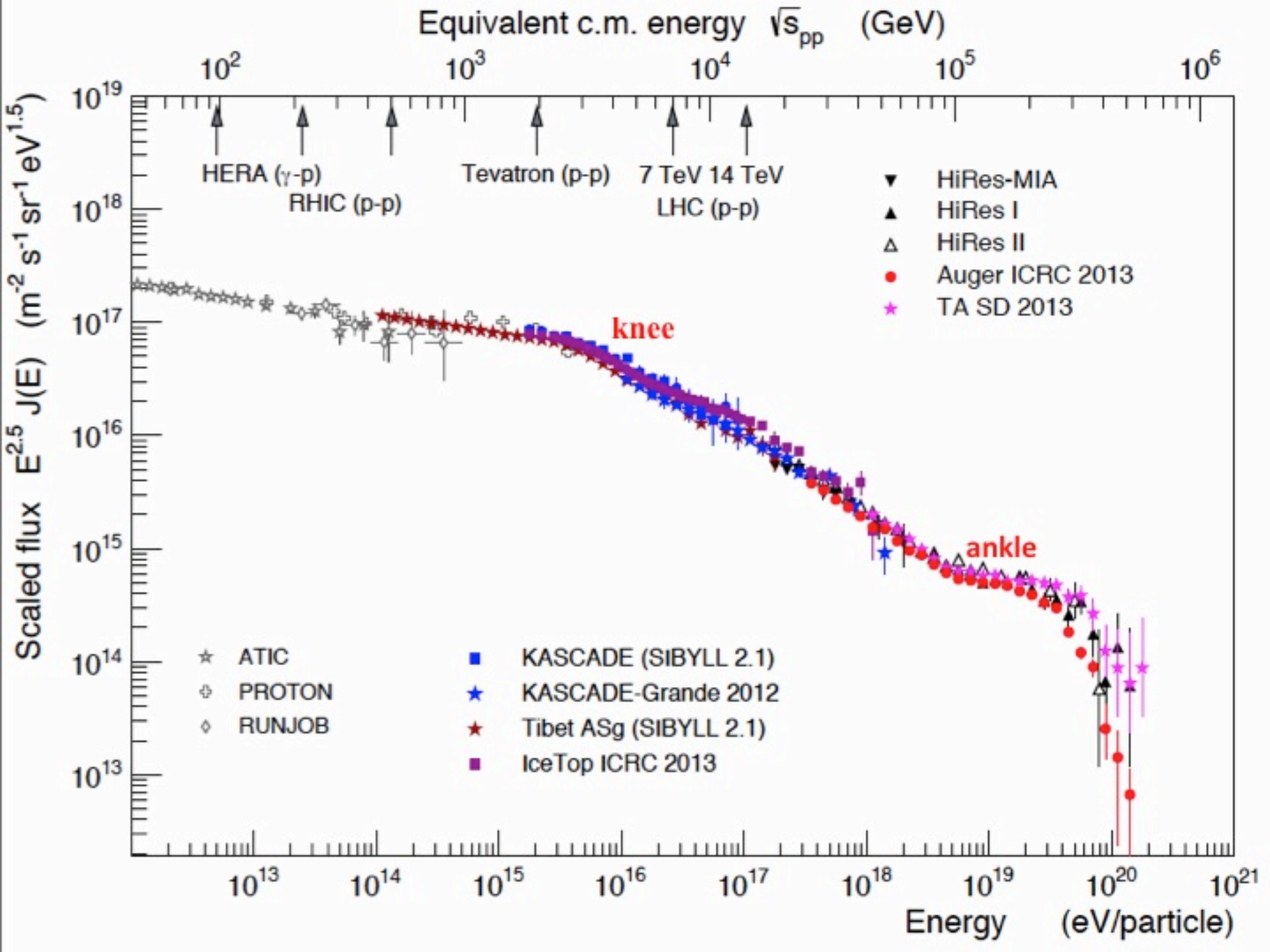
ISS
Balloon
Flux (m² sr s GeV)
Solar Influenc
Galac
10^{9} 10^{10} 10^{11} 10^{12}
E_c=20TeV, τ=5x10³yr
D_0=2x10²⁹(cm²s⁻¹)
Distant component (SN/30yr)
excluding T<1x10⁵yr and r<1kpc
HEAT
BETS
PPB-BETS
AMS
ATIC-2
ECC
Fermi-LAT
H.E.S.S.
PAMELA
CALET (5yr)
Vela
Monogem
Cygnus Loop
E^3J (electrons m^{-2} s^{-1} sr^{-1} GeV^2)
Electron Energy (GeV)

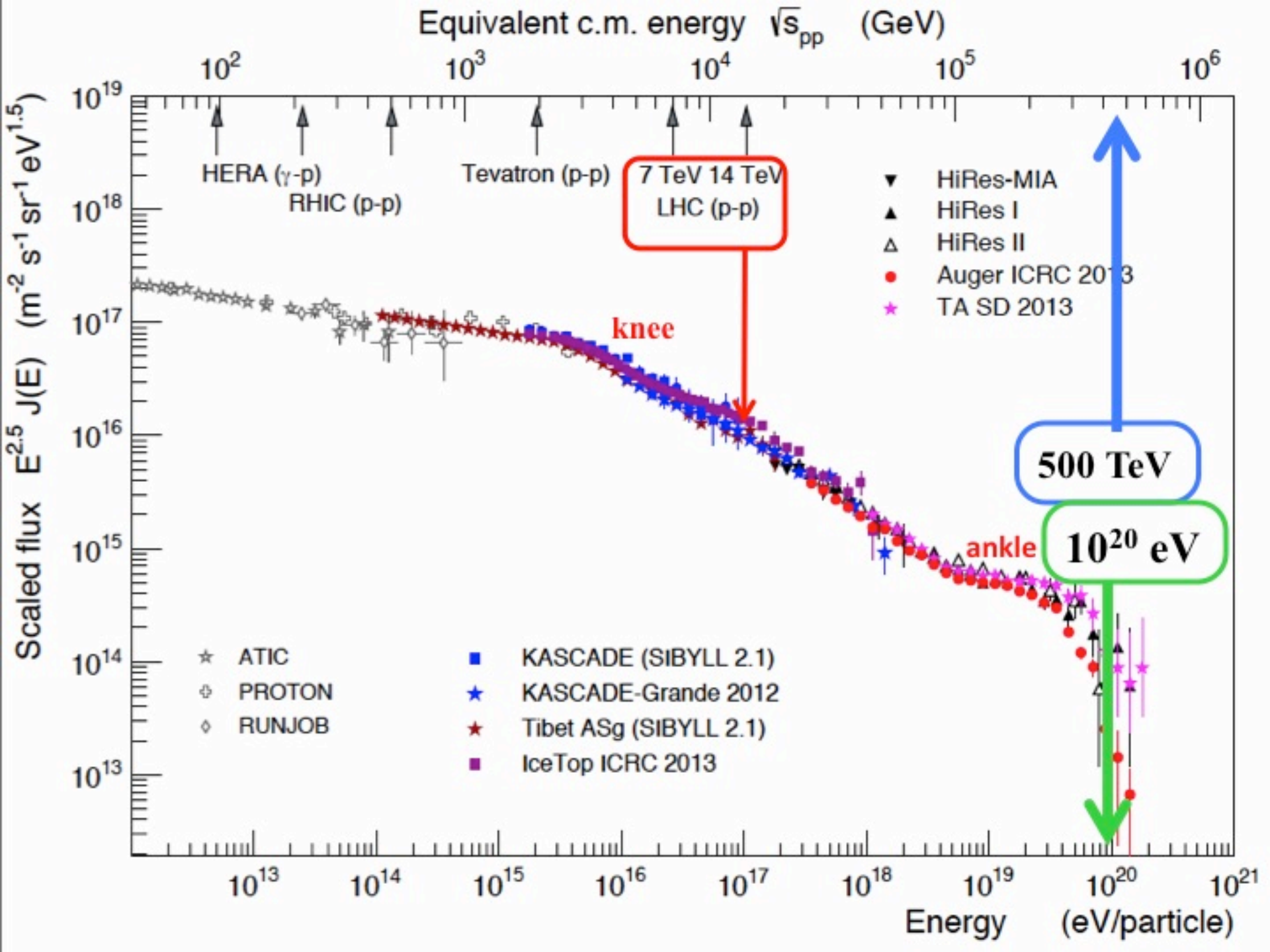

H
He × 10^−2
C × 10^−4
O × 10^−6
Ne × 10^−8
Mg × 10^−10
Si × 10^−12
S × 10^−14
Ar × 10^−16
Ca × 10^−18
Fe × 10^−21
AMS
BESS
CAPRICE
JACEE
ATIC
RUNJOB
HEAO-3
CRN
CREAM
TRACER
HESS
dN/dE (of nuclei) [1/(m² sr s GeV)]
Kinetic energy per particle (nucleus) [GeV]


He flux
Flux ×R^2.7 [m^-2 sr^-1 s^-1 GV^1.7]
AMS
50 million events
AMS-02
Rigidity [GV]


Fluxes of Cosmic Rays
Space Missions
Future
Voyager I & II
ACE/CRIS
PAMELA
AMS
CALET
ISS-CREAM 2016
HNX
Free Flyers
ISS
SmEx
Balloon
EUSO-SPB
JEM-EUSO
EVA
Galactic Cosmic Rays
Extragalactic Cosmic Rays


Fluxes of Cosmic Rays
NOW
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays
Ground Experiments
Flux (m² sr s GeV)
Energy (eV)


Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
ankle
ATIC
PROTON
RUNJOB
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
IceTop ICRC 2013
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
10^21
Energy (eV/particle)


Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)
10^2
10^3
10^4
10^5
10^6
HERA (γ-p)
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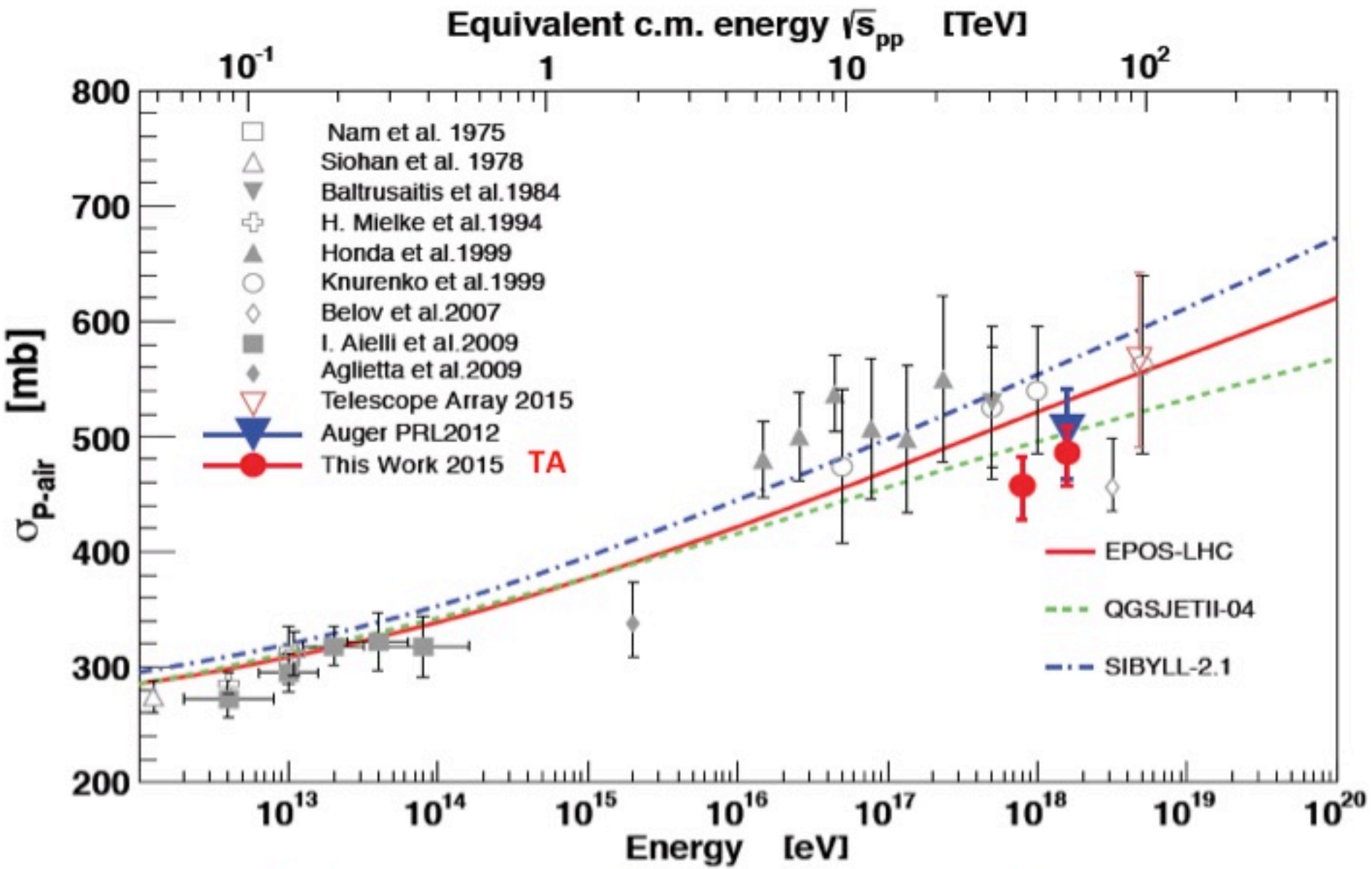
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
ankle
500 TeV
10^{20} eV
ATIC
PROTON
RUNJOB
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
IceTop ICRC 2013
Scaled flux $E^{2.5}$ J(E) (m^{-2} s^{-1} sr^{-1} $eV^{1.5}$)
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
Energy (eV/particle)

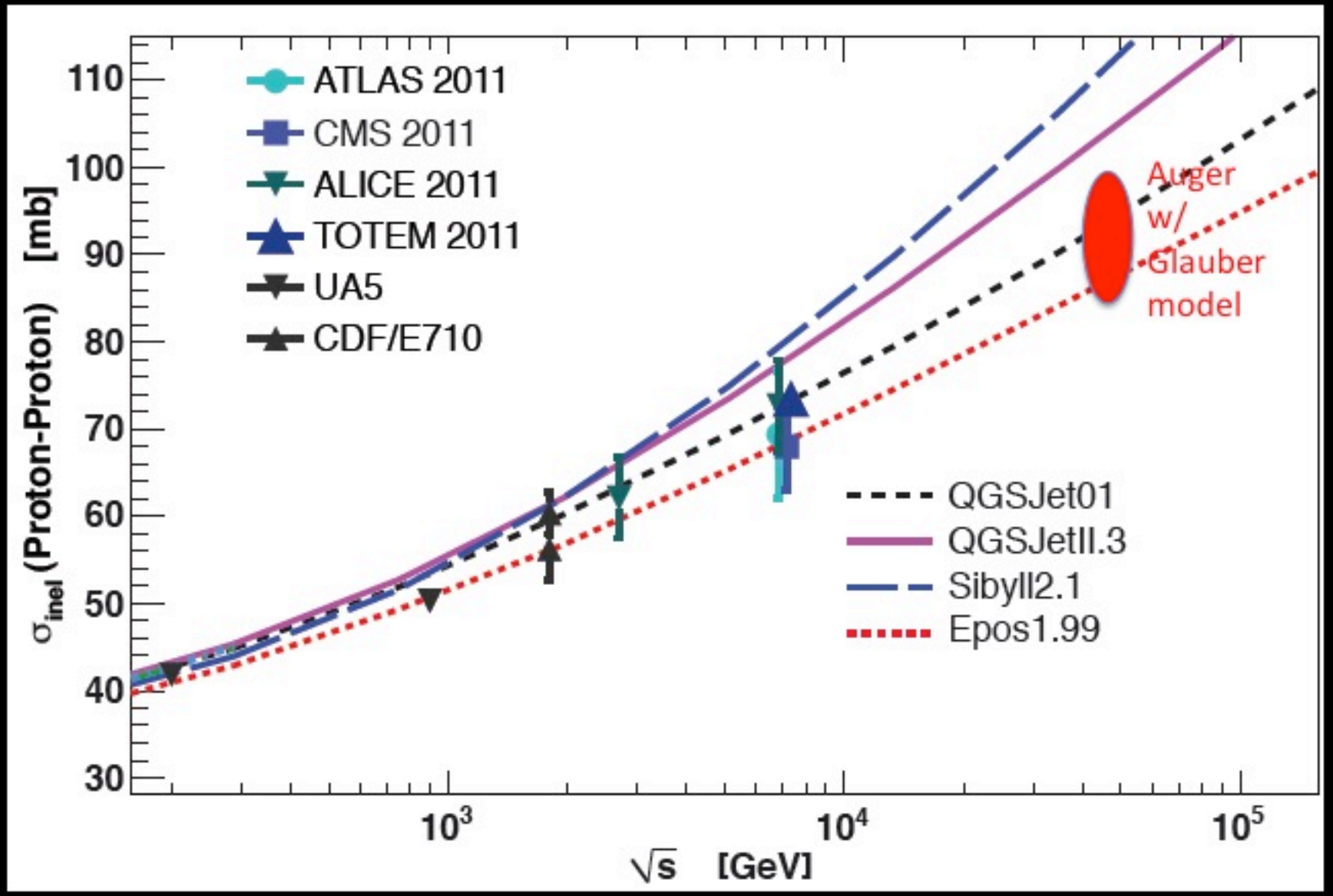


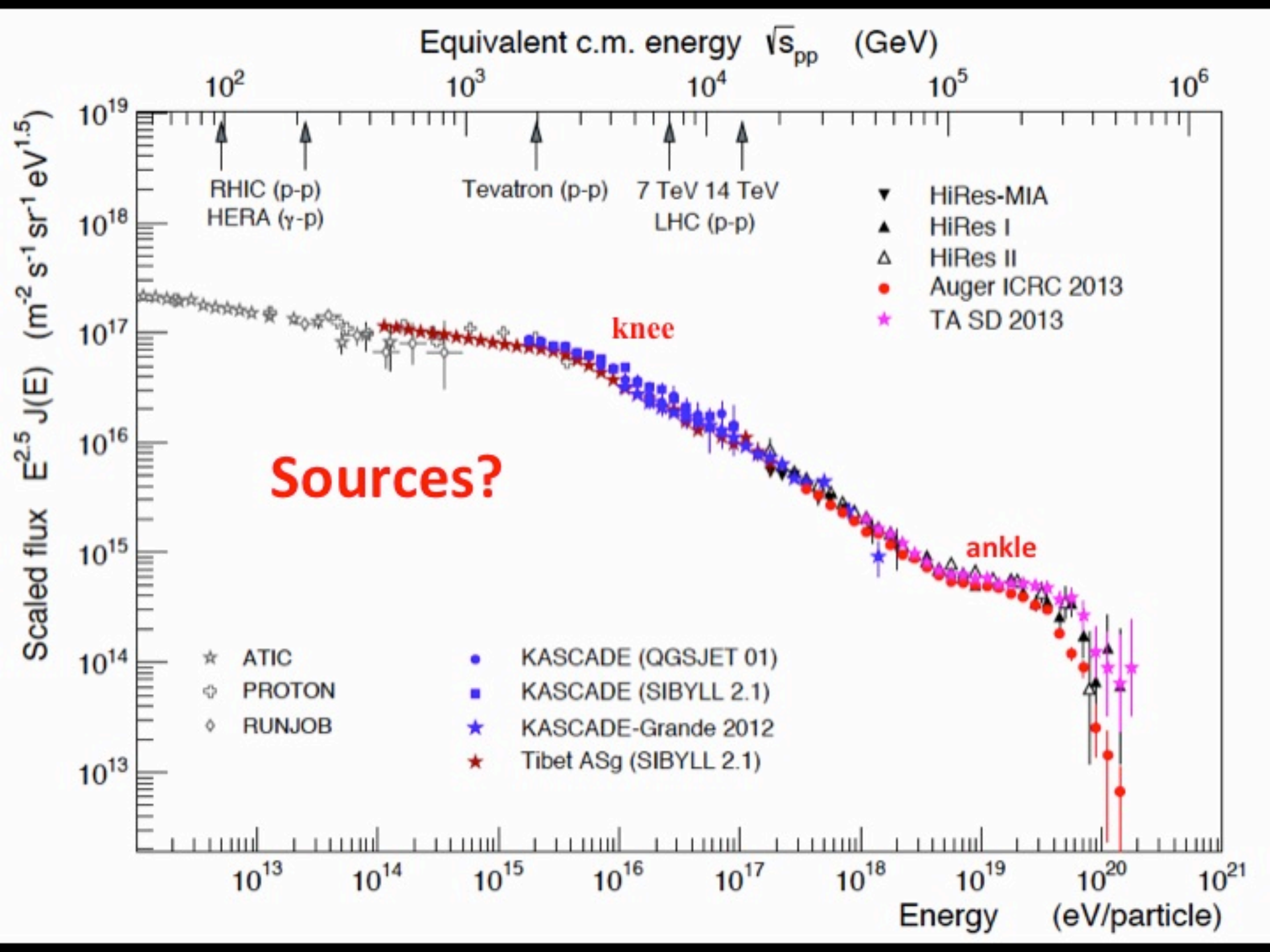
Auger

$$\sigma_{pp}^{\text{inel}} = [92 \pm 7(\text{stat})^{+9}_{-11}(\text{syst}) \pm 7(\text{Glauber})] \text{ mb},$$

$$\sigma_{pp}^{\text{tot}} = [133 \pm 13(\text{stat})^{+17}_{-20}(\text{syst}) \pm 16(\text{Glauber})] \text{ mb}.$$

LHC measurements

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7 TeV 14 TeV
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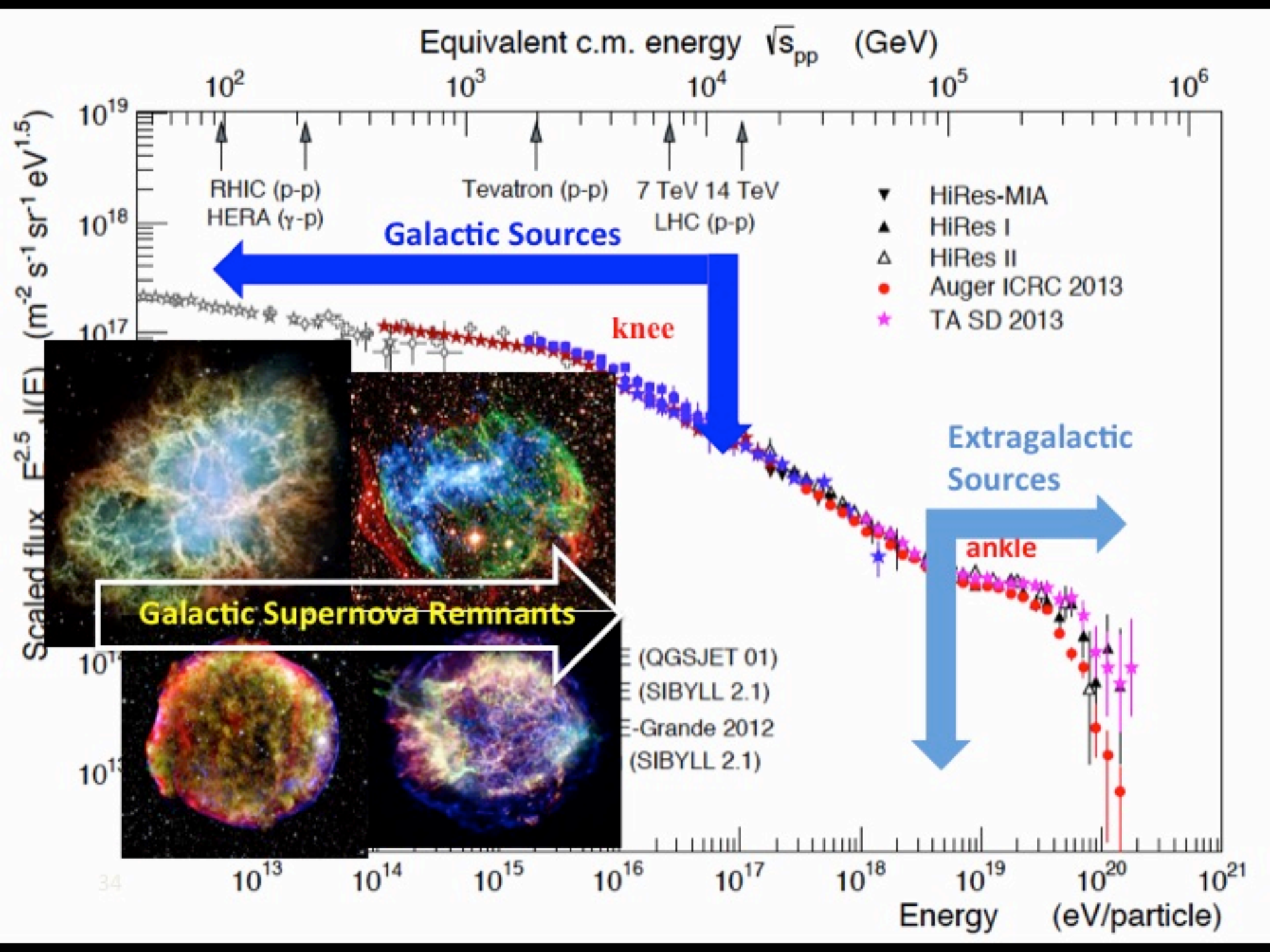
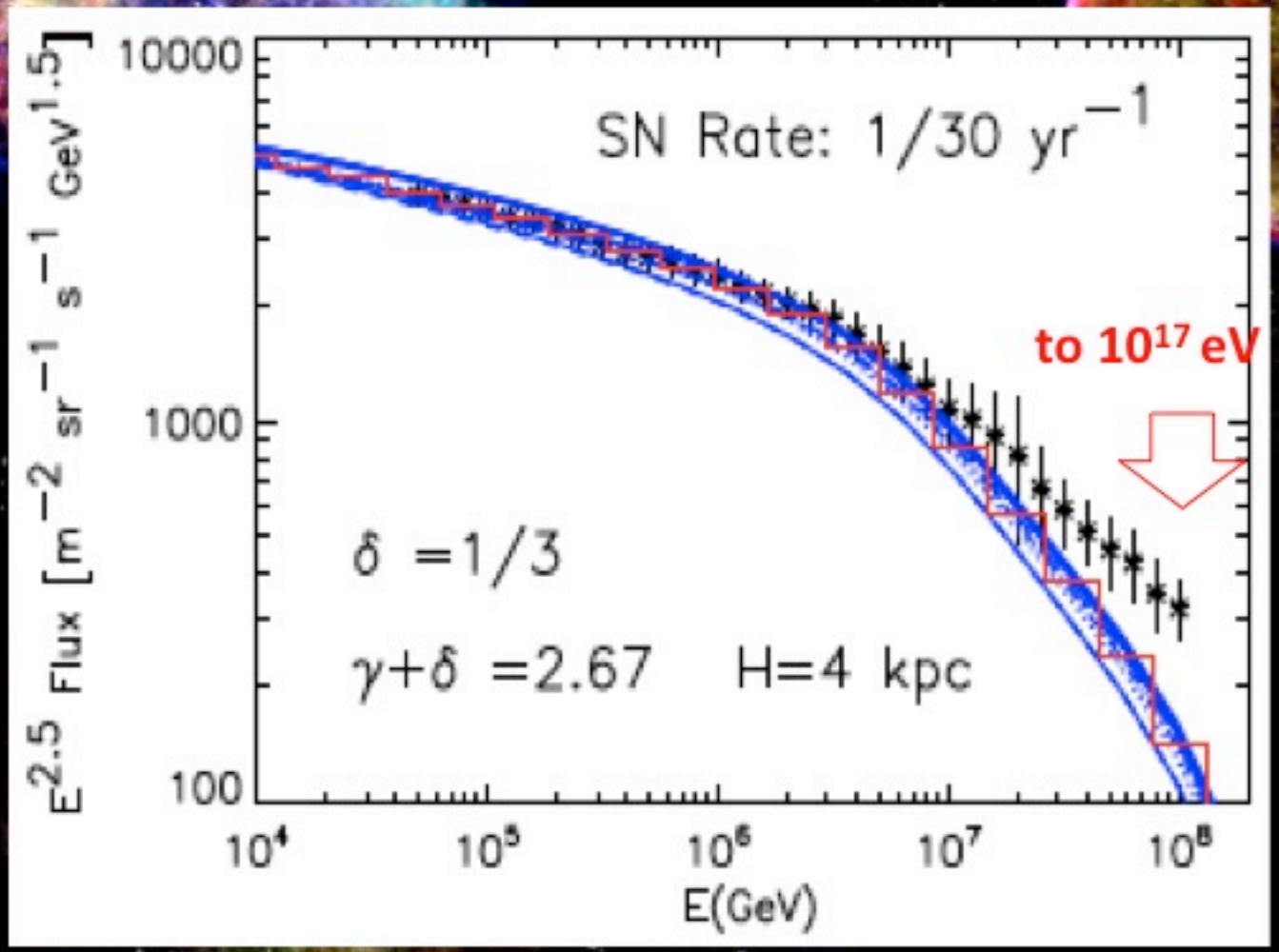
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
ankle
Sources?
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
10^19
10^18
10^17
10^16
10^15
10^14
10^13
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)


Equivalent c.m. energy √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 ICRC 2013
TA SD 2013
Galactic Sources
knee
Extragalactic
Sources
ankle
Galactic Supernova Remnants
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
10^19
10^18
10^17
(QGSJET 01)
(SIBYLL 2.1)
-Grande 2012
(SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

Supernova Remnants

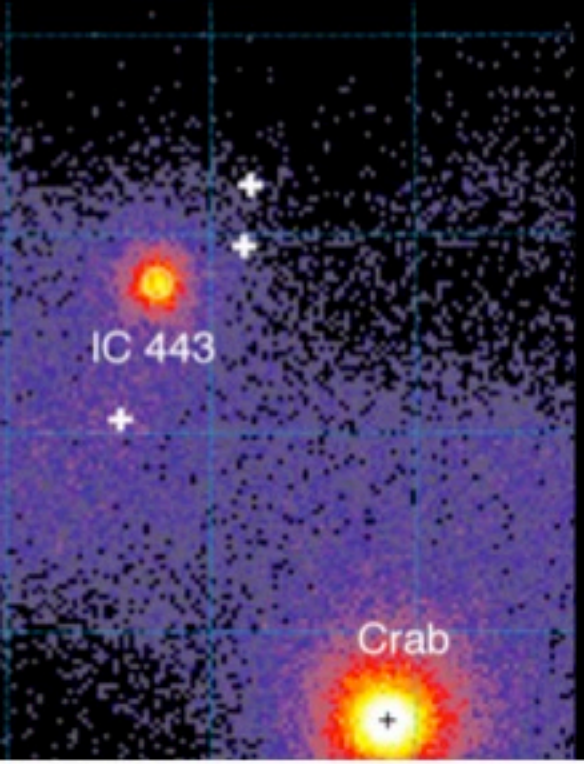


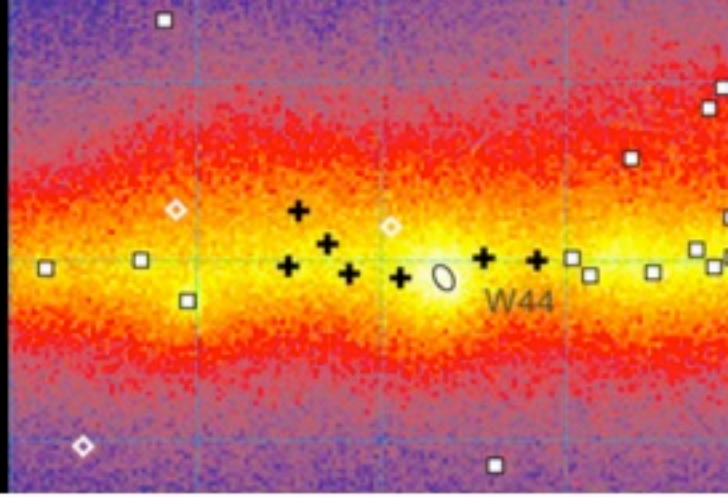
Blasi & Amato 2012

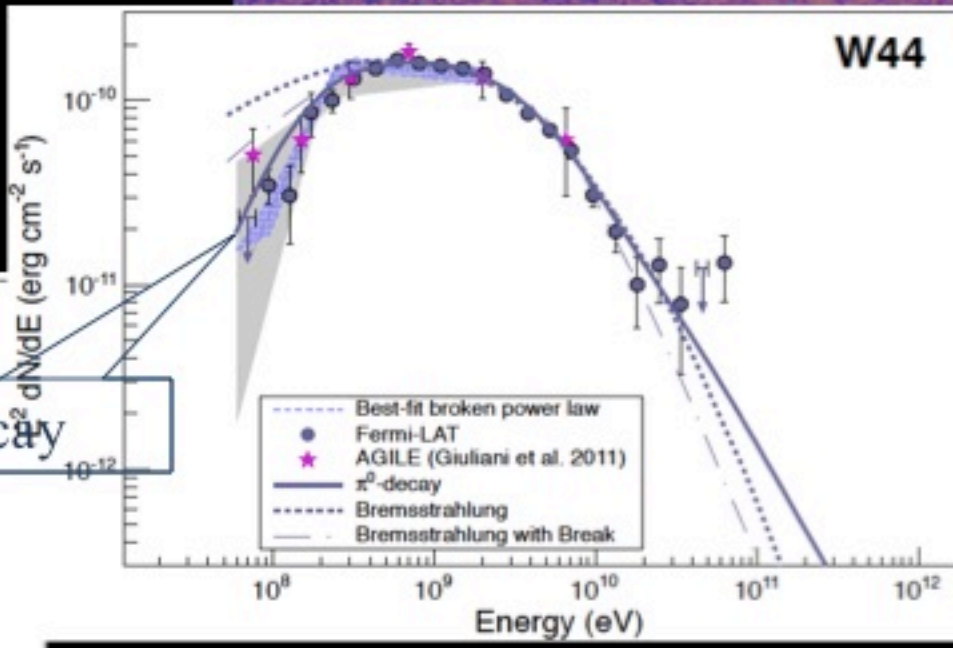
π^0 decay!

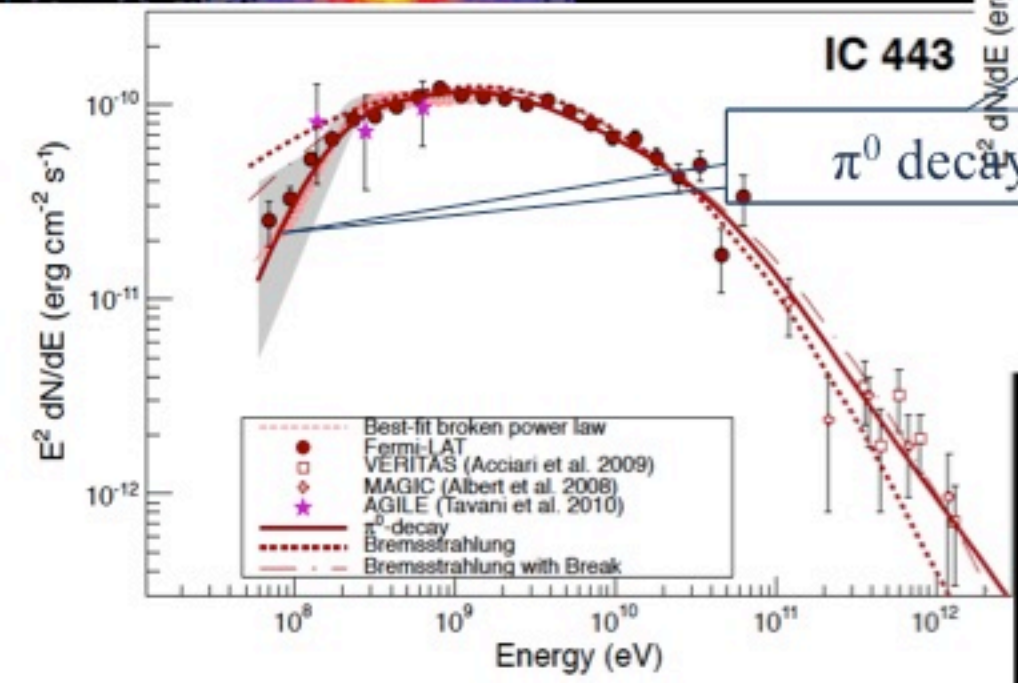
IC 443 & W44

Fermi & AGILE

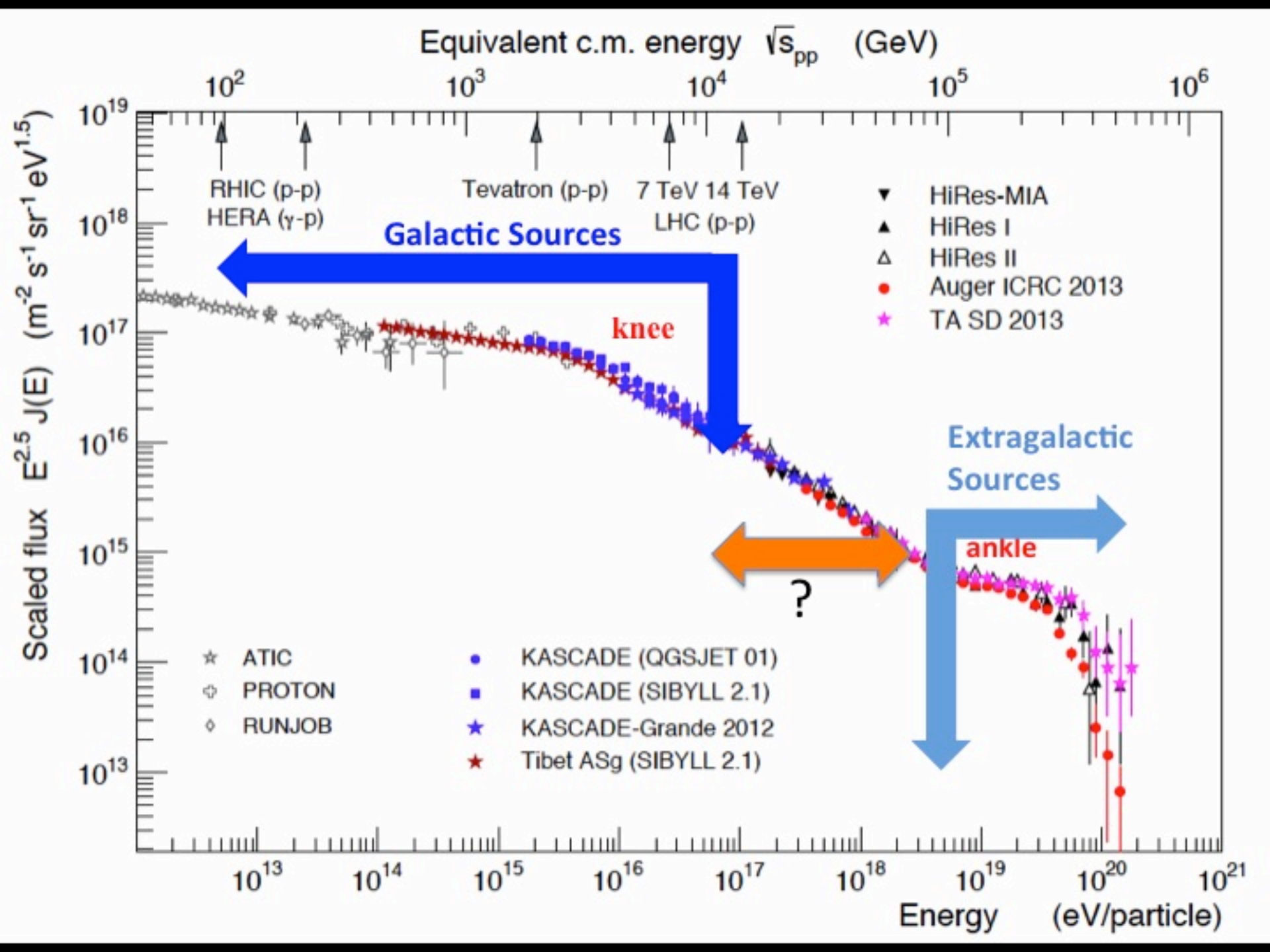


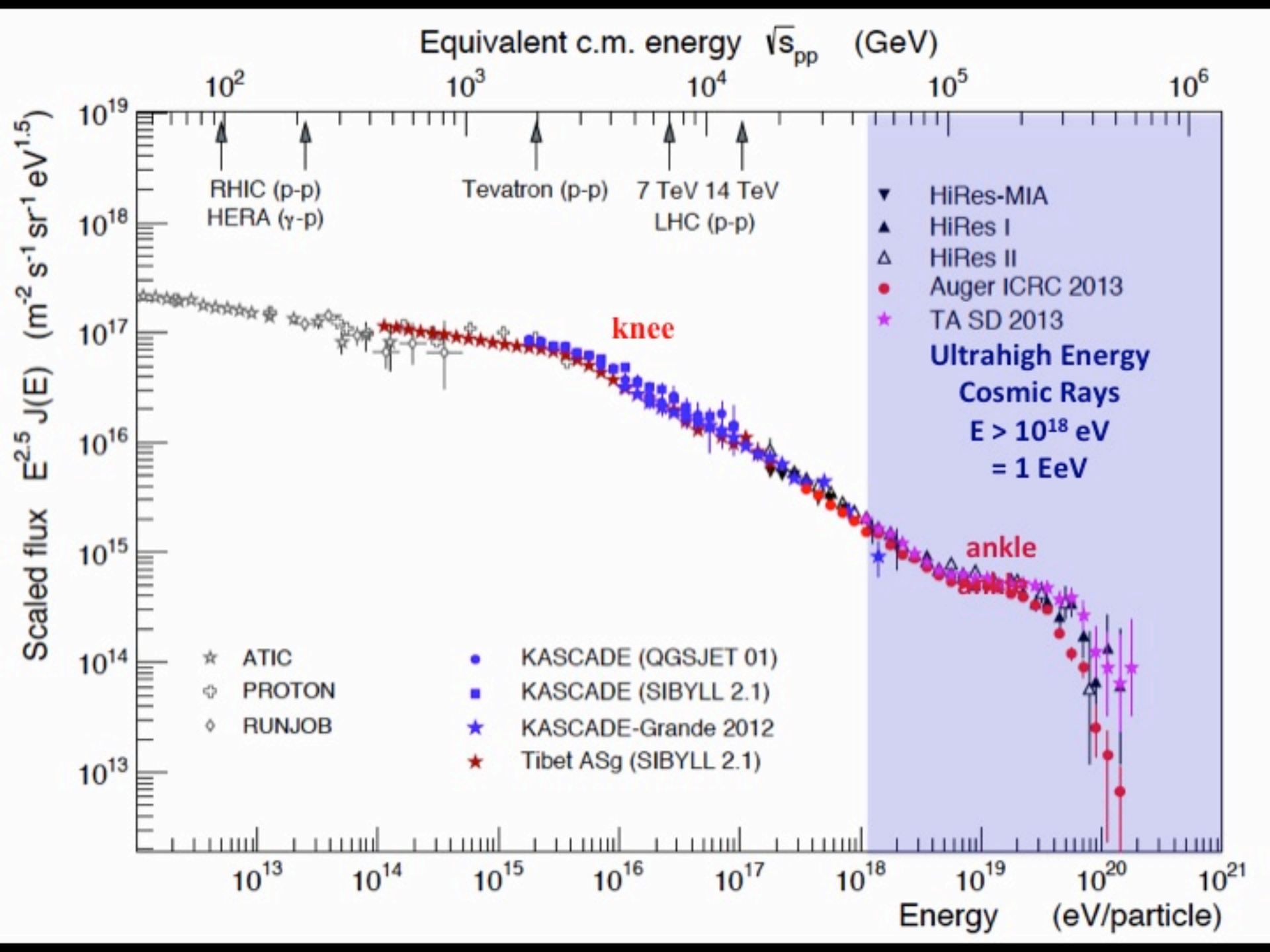






Ackermann et al (Fermi Collab) ’13
arXiv:1302.3307

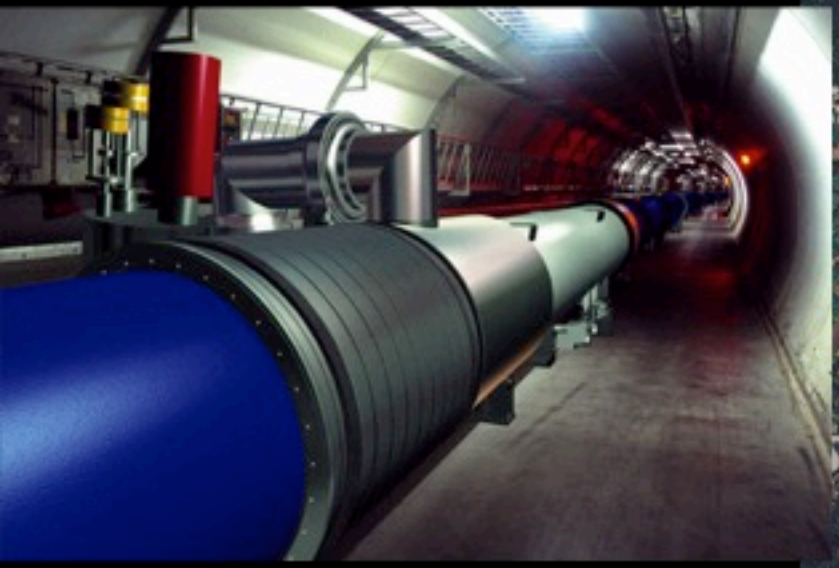

Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
Galactic Sources
knee
Extragalactic
Sources
ankle
?
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
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
10^21
Energy (eV/particle)


Equivalent c.m. energy √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 ICRC 2013
TA SD 2013
Ultrahigh Energy
Cosmic Rays
E > 10^18 eV
= 1 EeV
knee
ankle
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 2012
Tibet ASg (SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

Large Hadron Collider

reaches 14 TeV
1.4 10^{13} eV

8.36 Tesla magnets



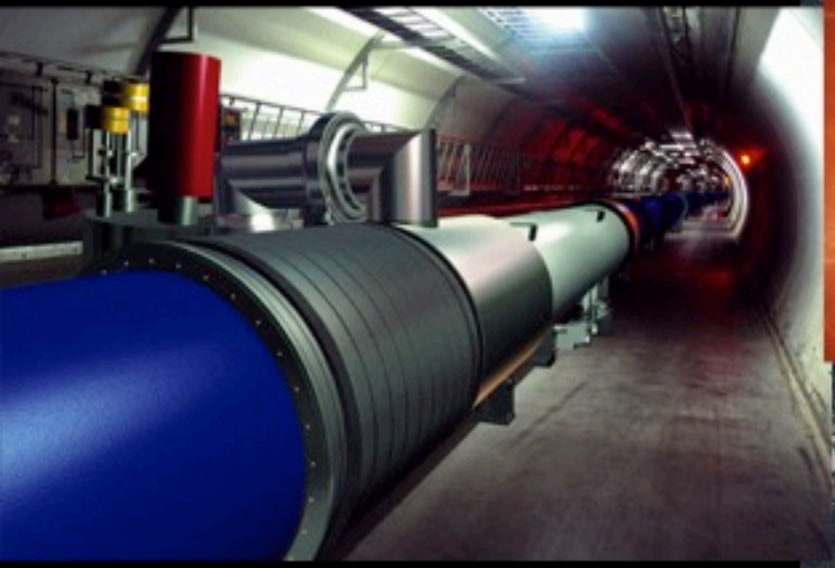
8.4 Tesla

Challenging Accelerators

to reach 10^{20} eV

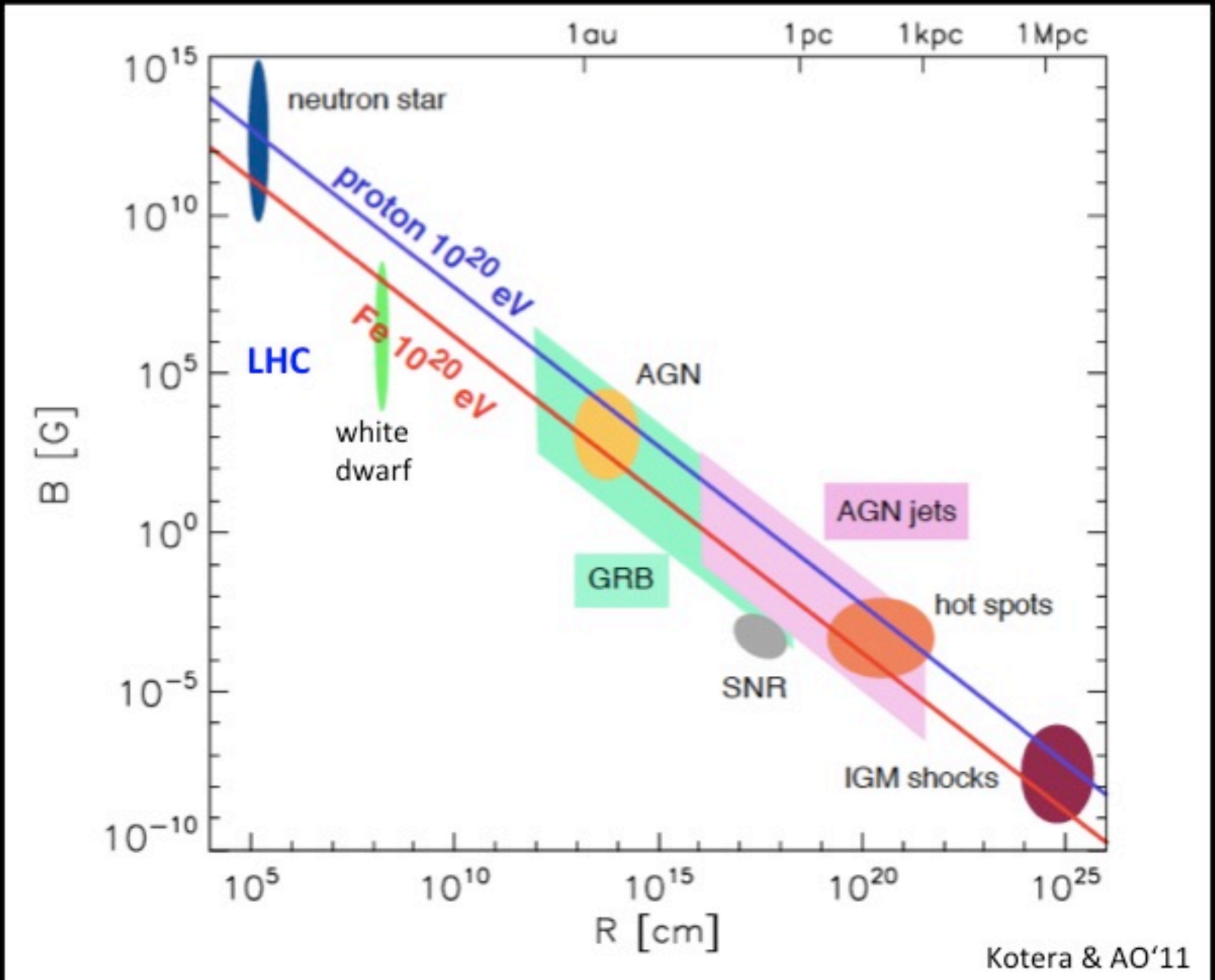
with LHC magnetic field,
radius ~ 10^7 km (Sun - Mercury)

or **10 GT** magnets!



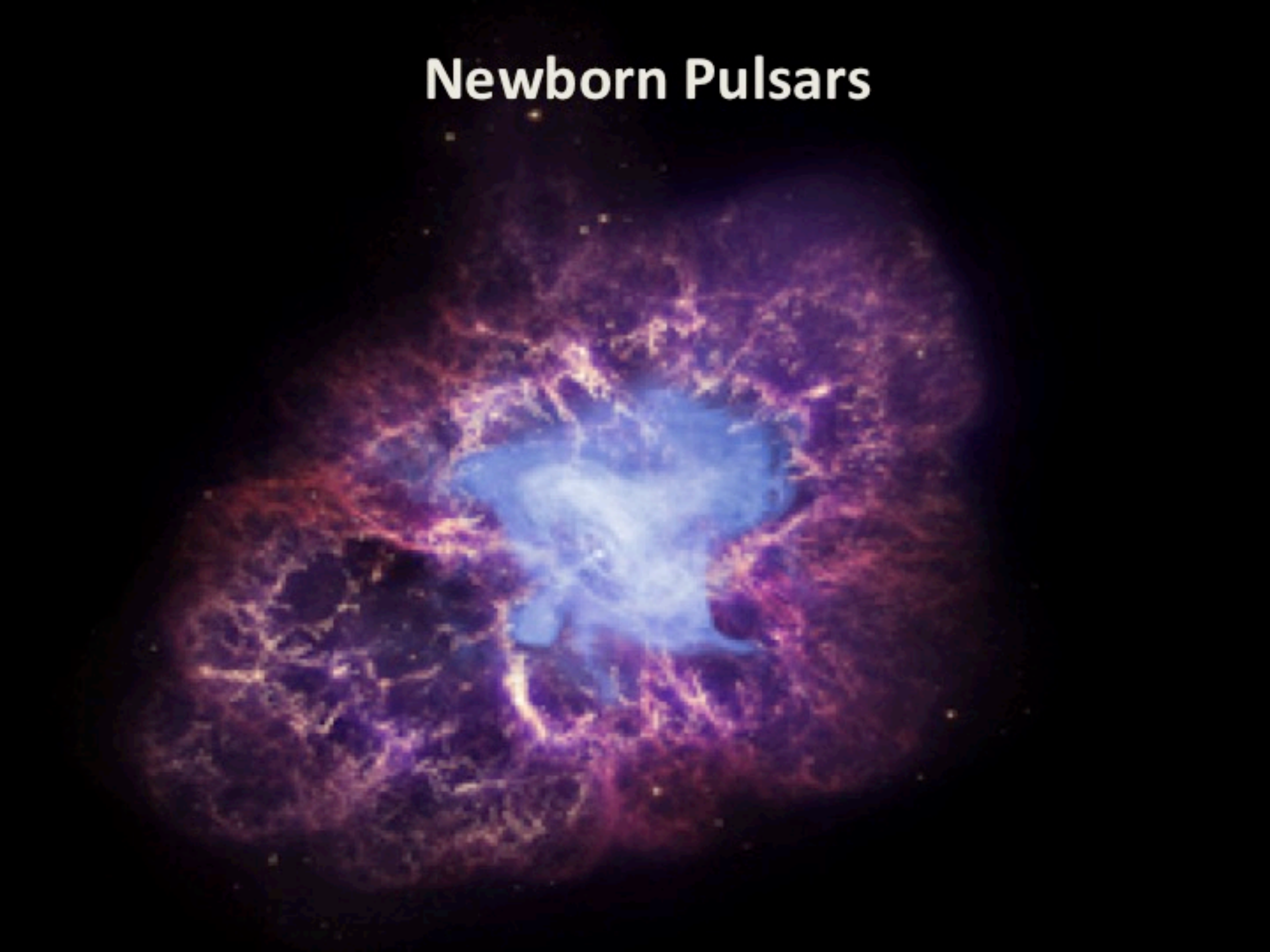
8.4 Tesla

Hillas Plot: E_{max} required

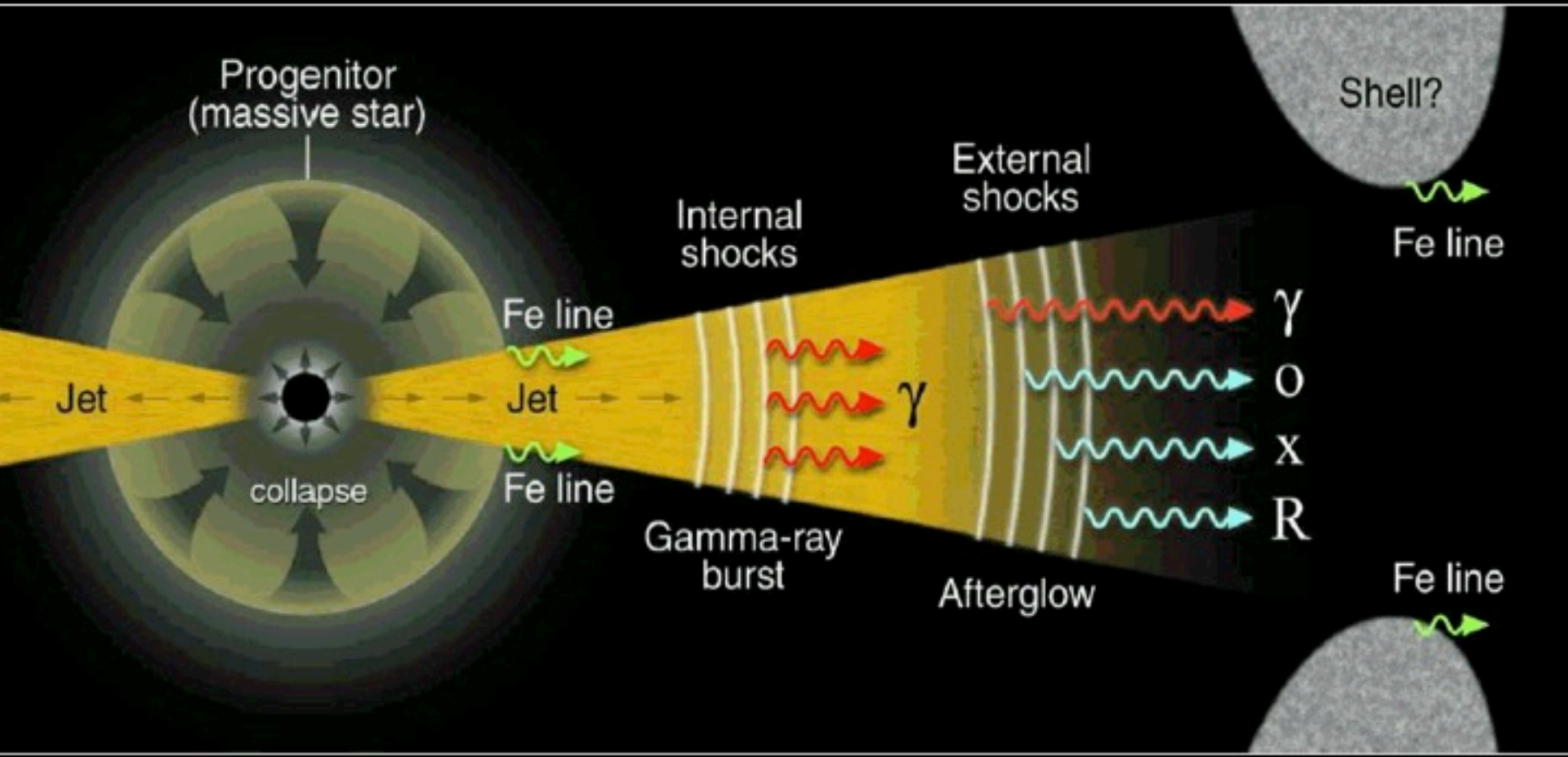


Kotera & AO'11

Newborn Pulsars

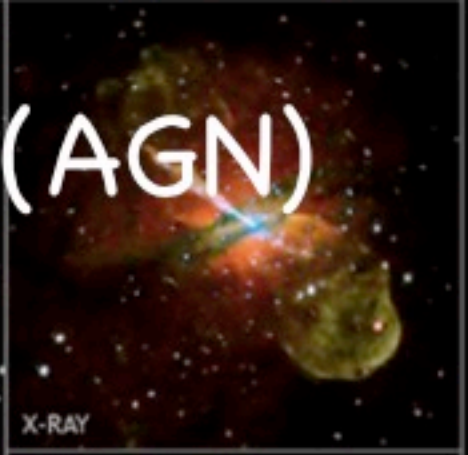


Gamma-ray Bursts

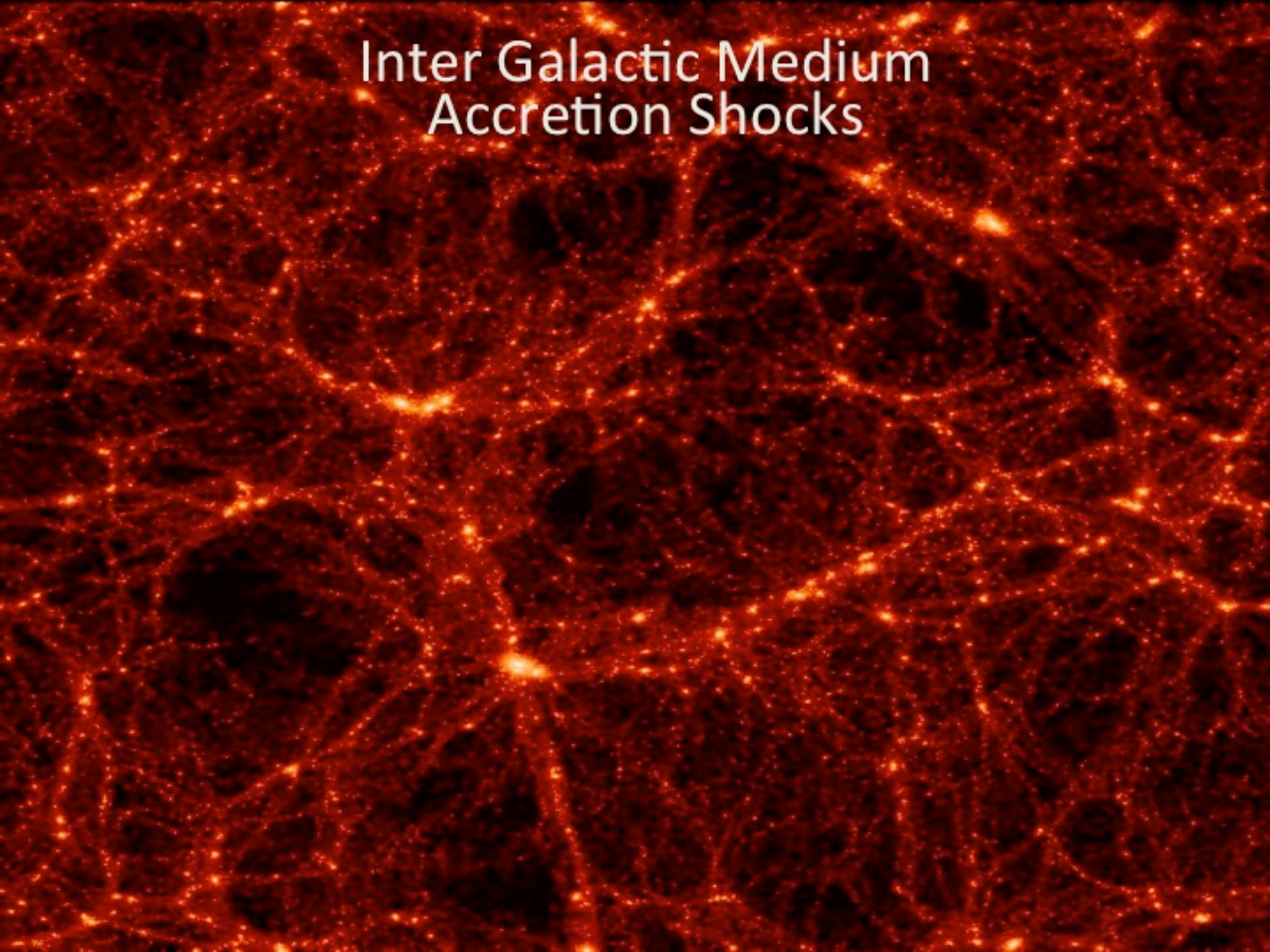


Meszaros '01

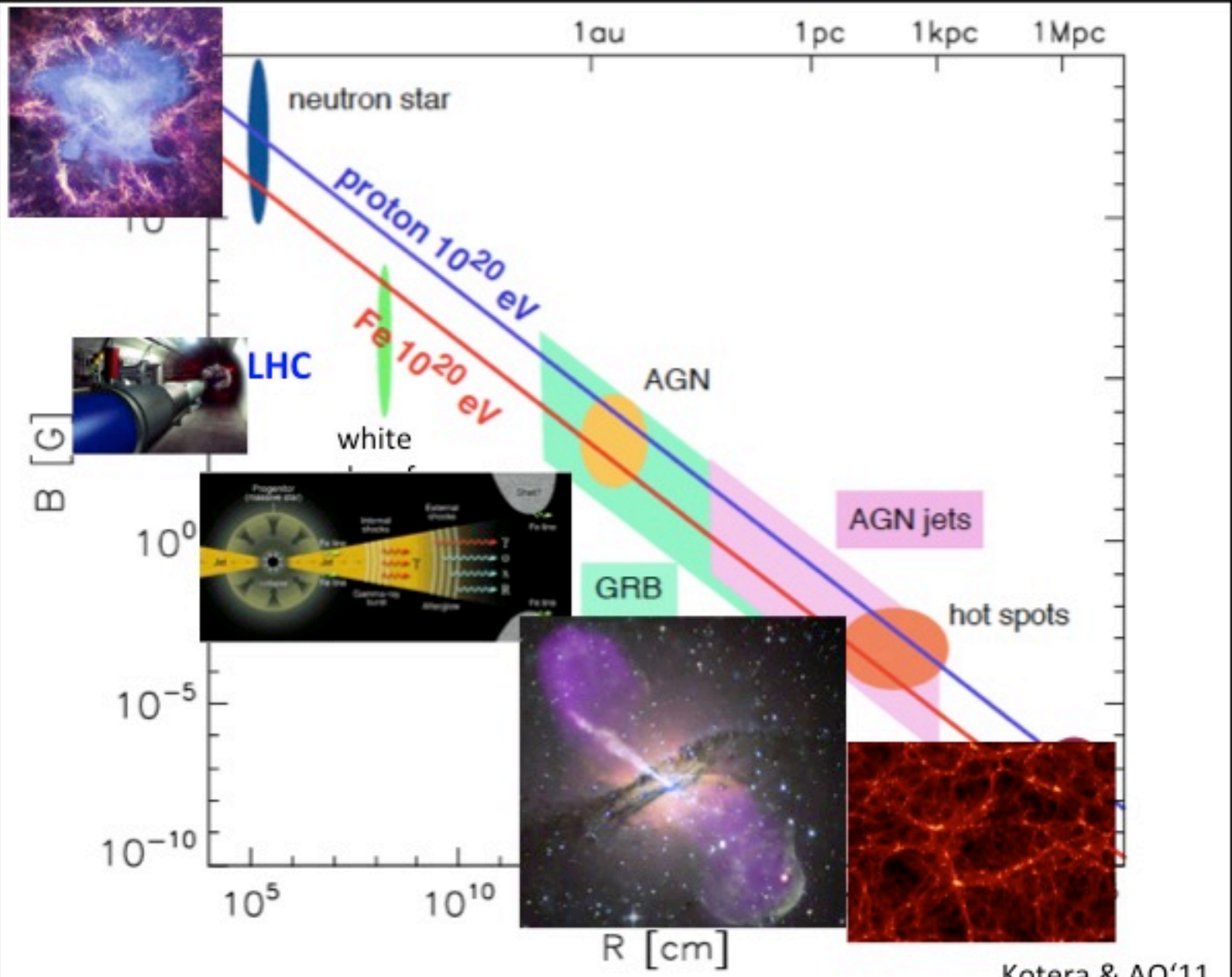
Active Galactic Nuclei (AGN)



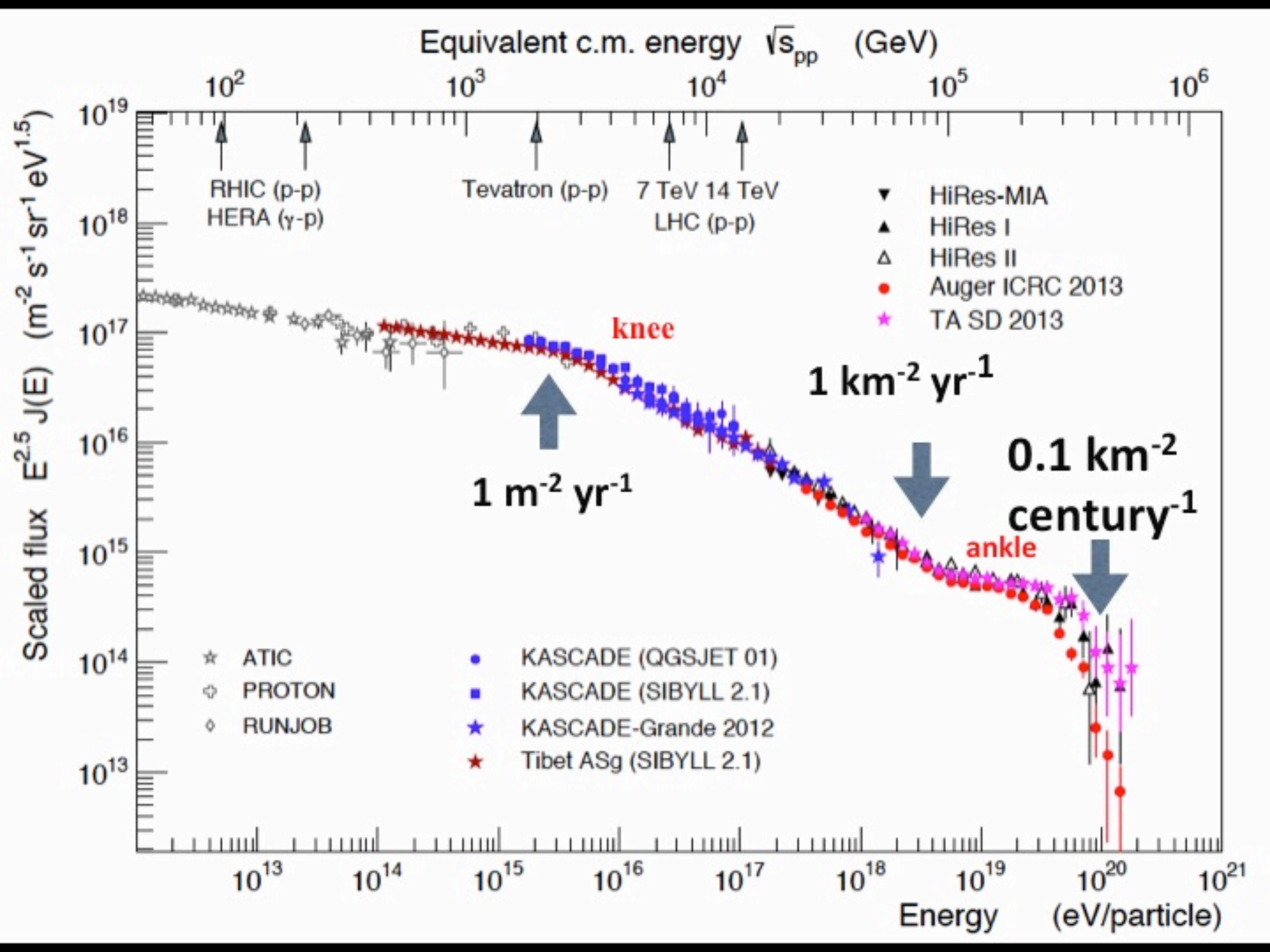
$L_{\rm bol} = 10^{43}$ erg/s $\quad d = 3.4\,{\rm Mpc}$ $\quad L_{\gamma>100{\rm MeV}} \approx 10^{41}$ erg/


Inter Galactic Medium
Accretion Shocks

Hillas Plot: E_{max} required



Kotera & AO'11


Equivalent c.m. energy √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 ICRC 2013
TA SD 2013
knee
1 km^-2 yr^-1
1 m^-2 yr^-1
0.1 km^-2 century^-1
ankle
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 2012
Tibet ASg (SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

Leading Observatories of Ultrahigh Energy Cosmic Rays

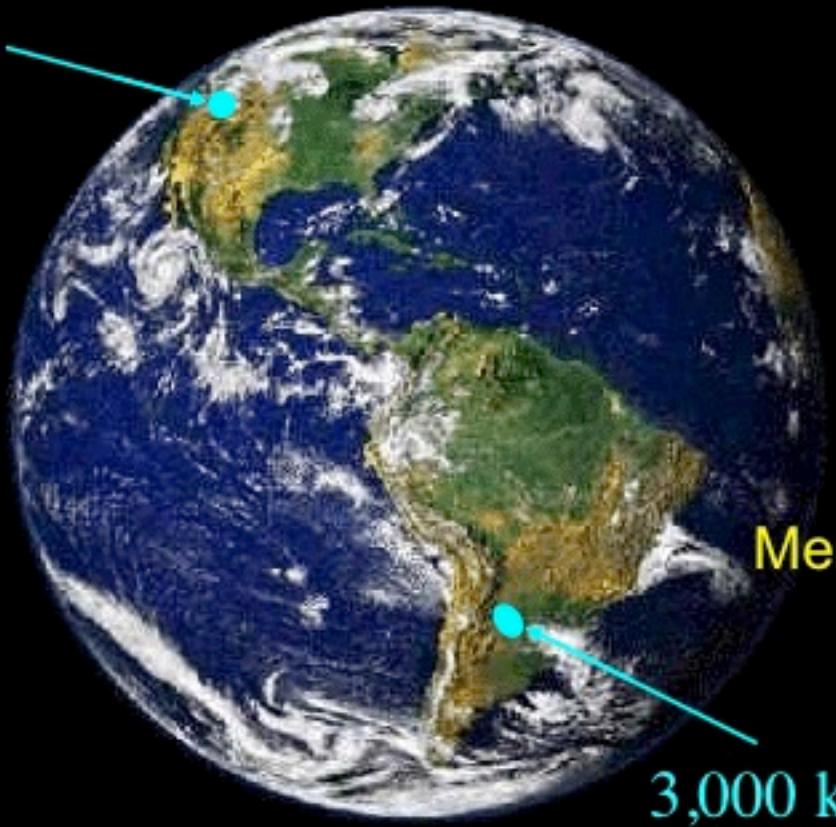
Telescope Array

Utah, USA

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



Pierre Auger Observatory

Mendoza, Argentina

(19 country collaboration)

3,000 km^2 array

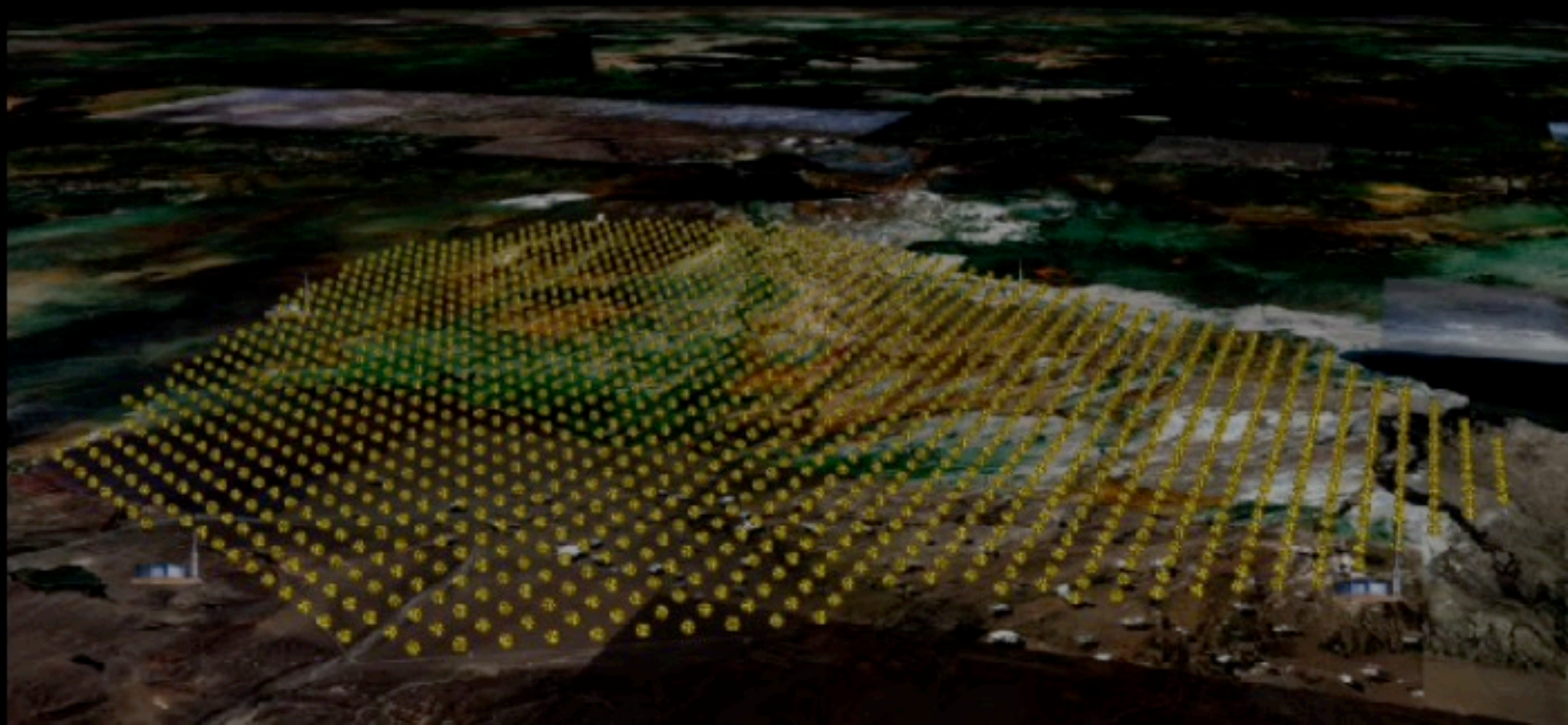
4 fluorescence telescopes

Pierre Auger Observatory

3,000 km² water cherenkov detectors array

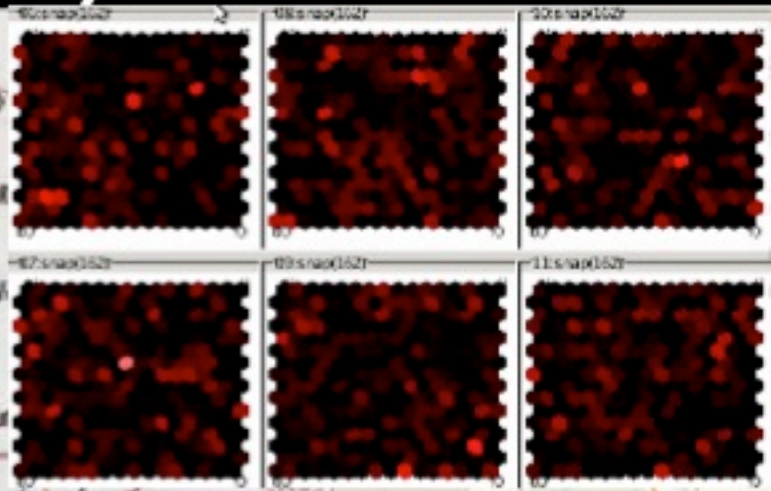
4 fluorescence Telescopes, Malargue, Argentina

~ 500 Scientists, 19 Countries



Telescope Array

Belgium
Japan
Korea
Russia
USA

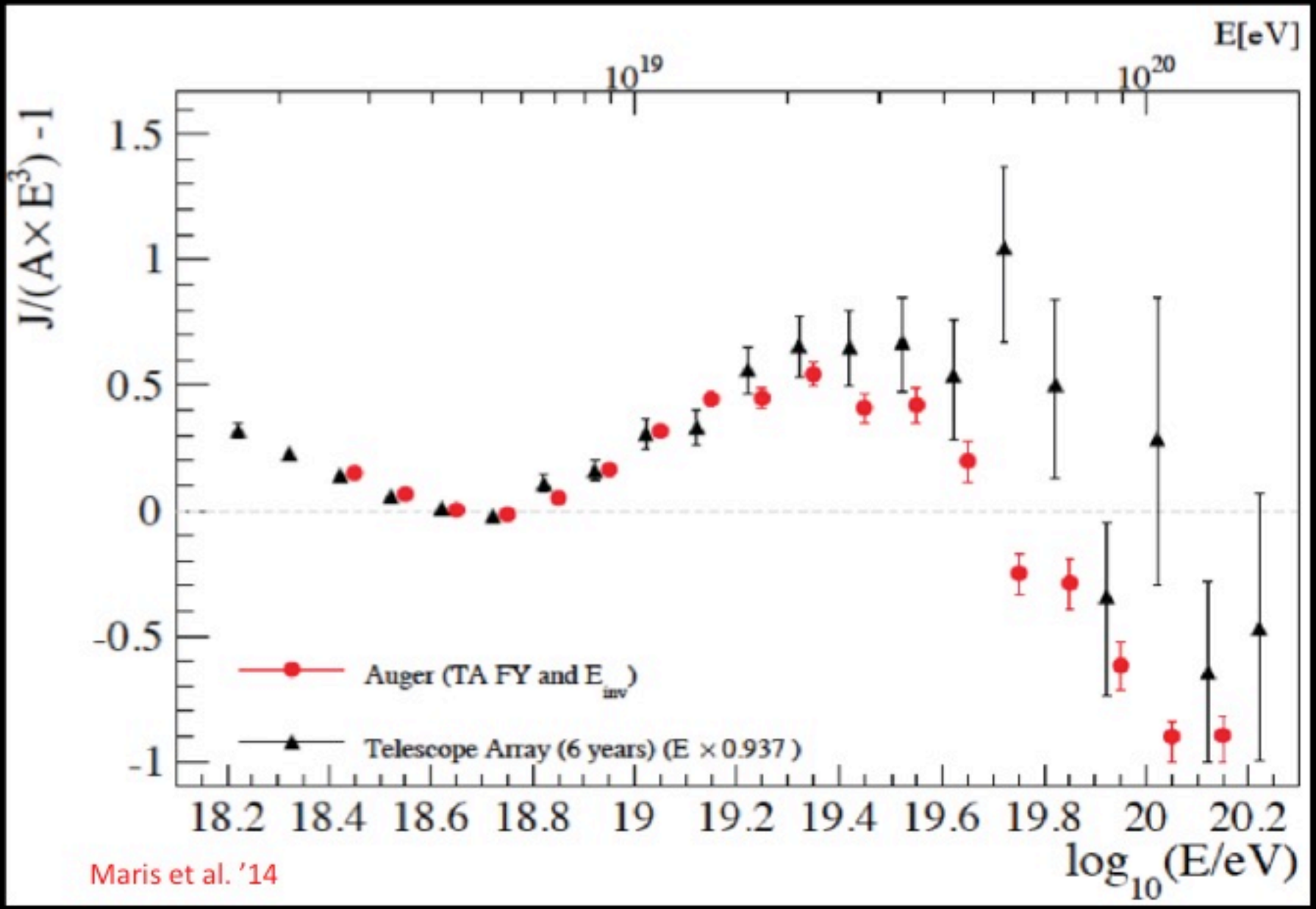


Area: 700 km^2

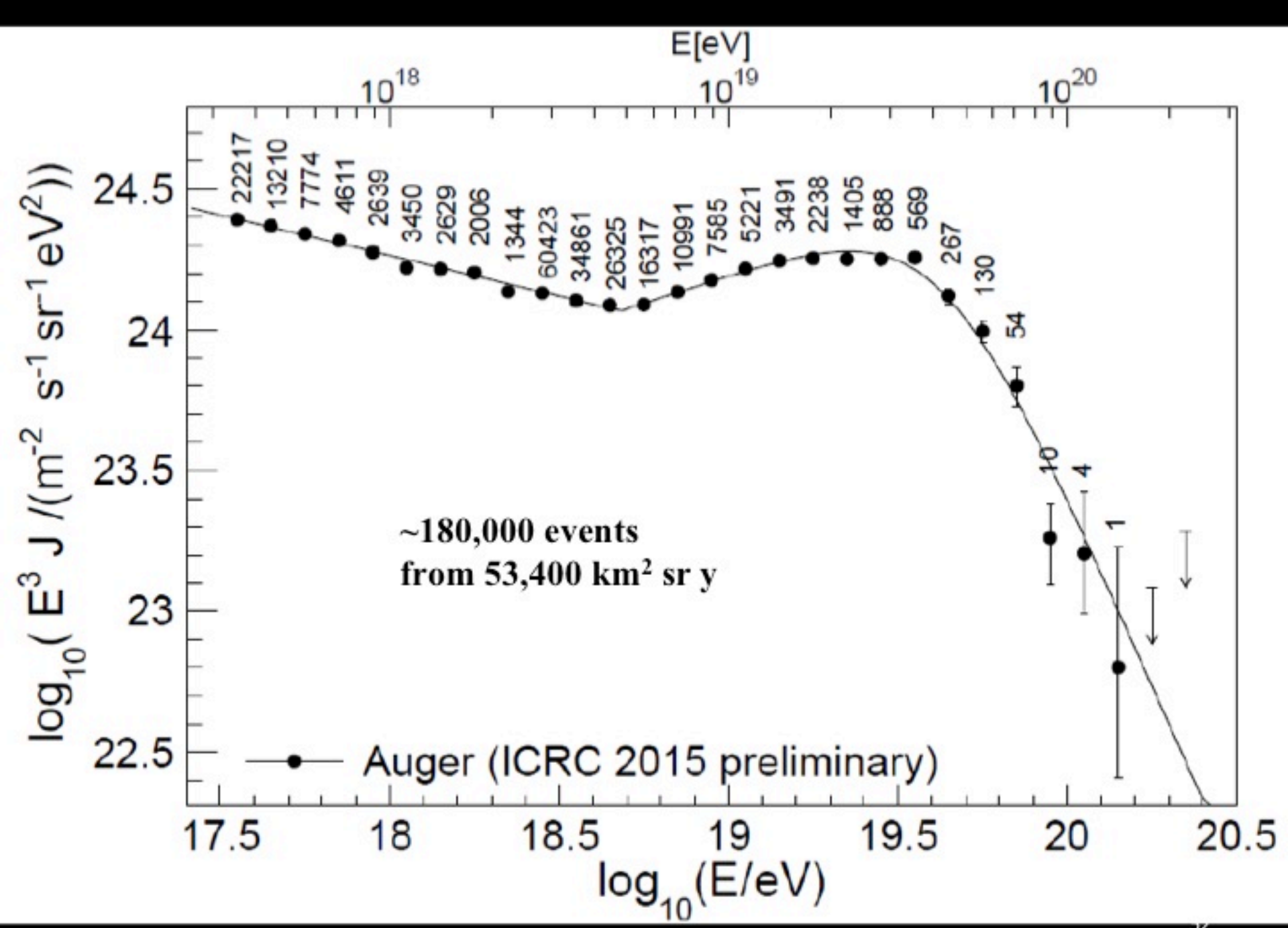
3 FD stations overlooking an array of

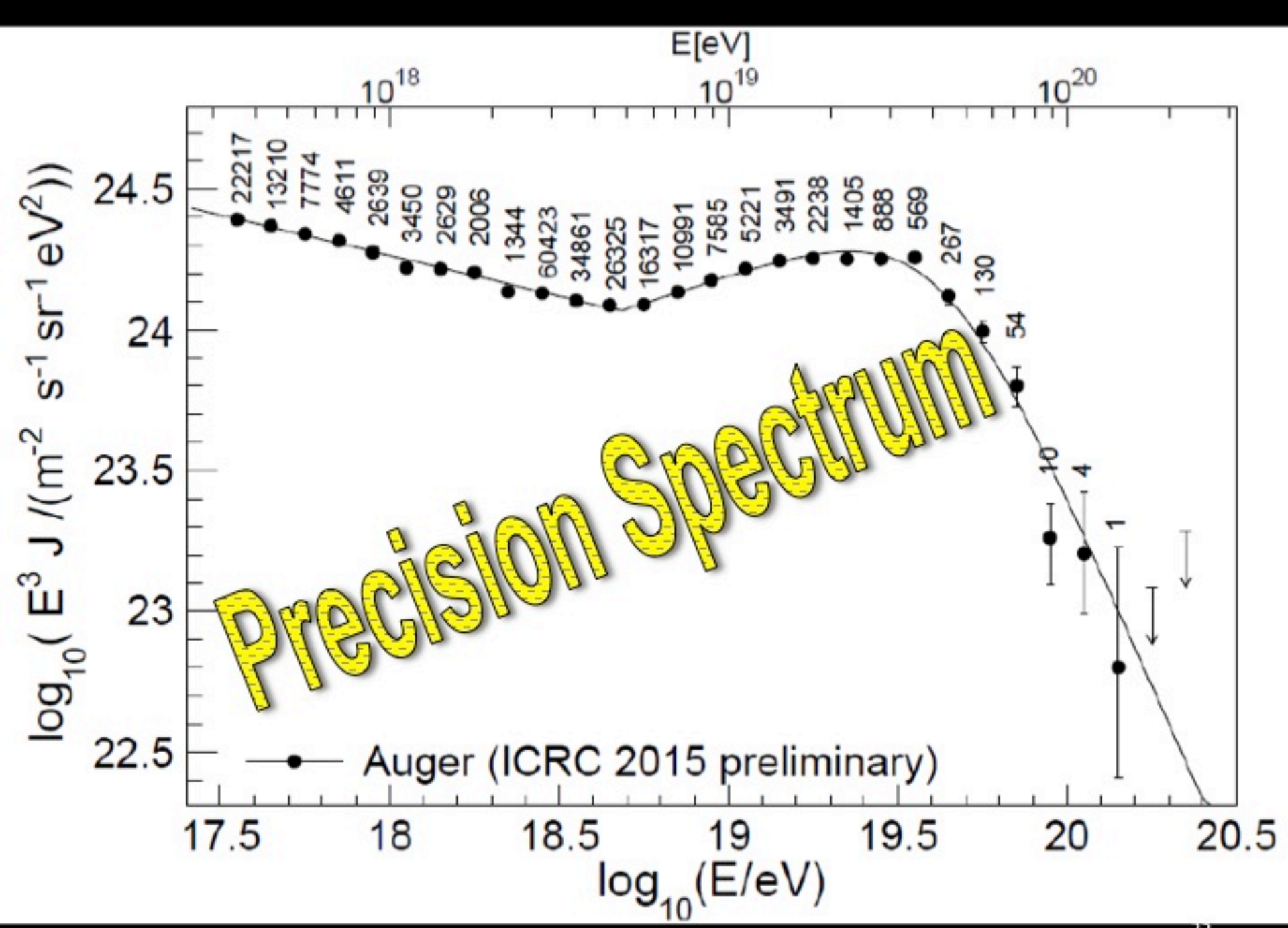
507 scintillator surface detectors (SD)

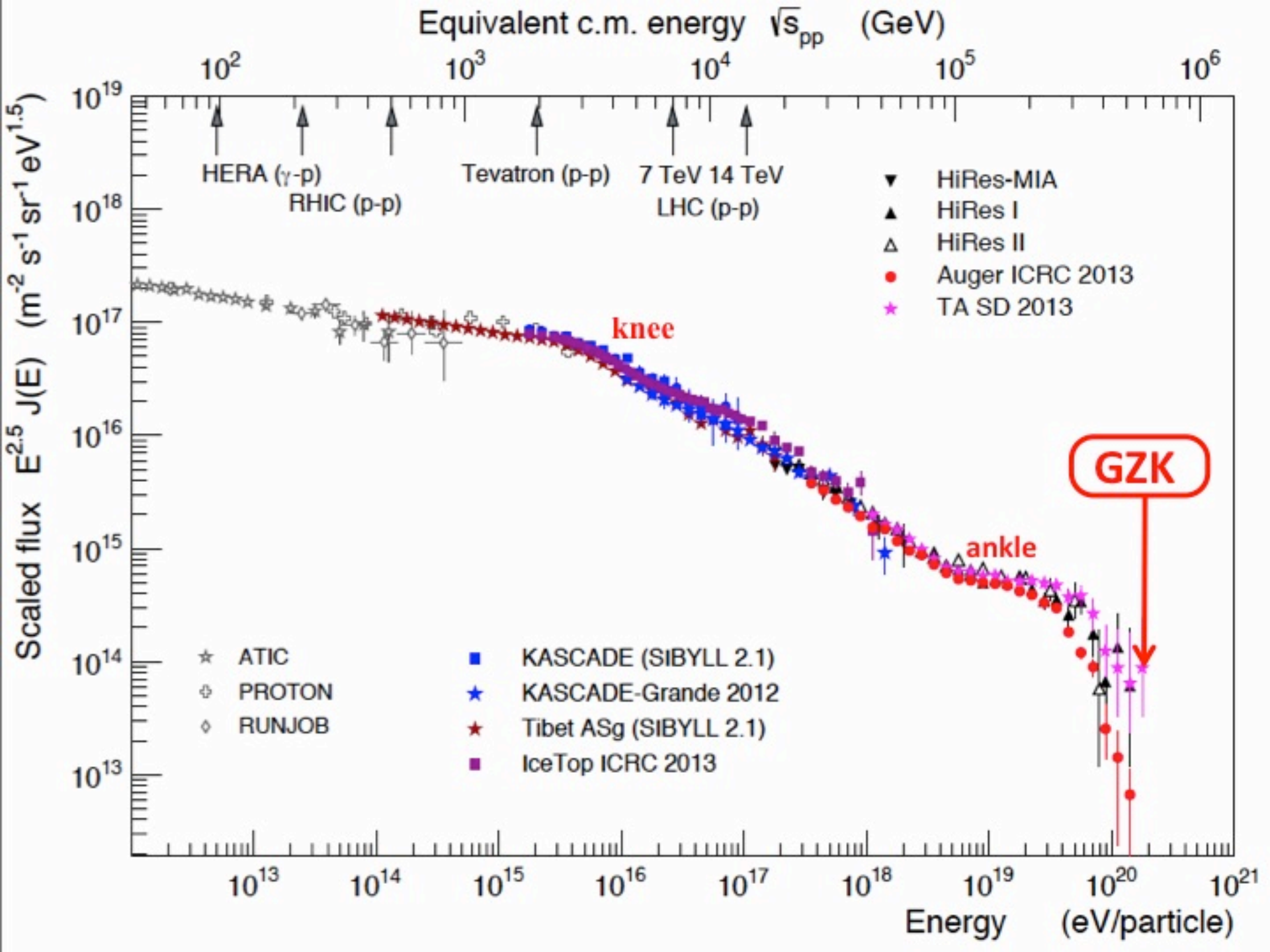
UHECR 2014 Working Group – Joint Spectrum



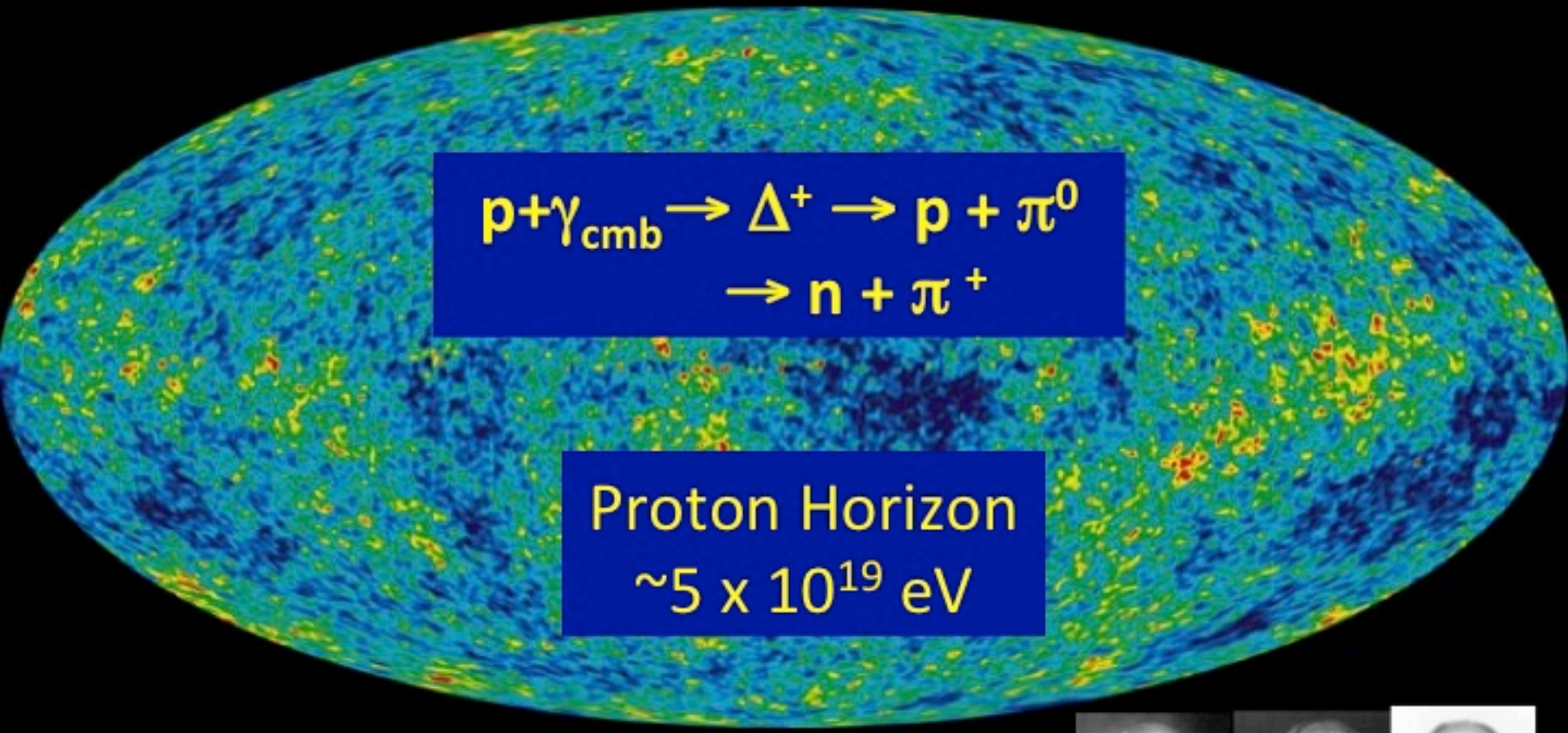
Maris et al. '14


E[eV]
10^18
10^19
10^20
22217
13210
7774
4611
2639
3450
2629
2006
1344
60423
34861
26325
16317
10991
7585
5221
3491
2238
1405
888
569
267
130
54
10
4
1
~180,000 events
from 53,400 km² sr y
Auger (ICRC 2015 preliminary)
log10(E³ J /(m⁻² s⁻¹ sr⁻¹ eV²))
log10(E/eV)
24.5
24
23.5
23
22.5
17.5
18
18.5
19
19.5
20
20.5


E[eV]
10^{18}
10^{19}
10^{20}
22217
13210
7774
4611
2639
3450
2629
2006
1344
60423
34861
26325
16317
10991
7585
5221
3491
2238
1405
888
569
267
130
54
10
4
1
24.5
24
23.5
23
22.5
$\log_{10}(E^3 J /(m^{-2} s^{-1} sr^{-1} eV^2))$
Precision Spectrum
Auger (ICRC 2015 preliminary)
17.5
18
18.5
19
19.5
20
20.5
$\log_{10}(E/eV)$


Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
ankle
GZK
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 (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
IceTop ICRC 2013
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

"Cosmologically Meaningful Termination"



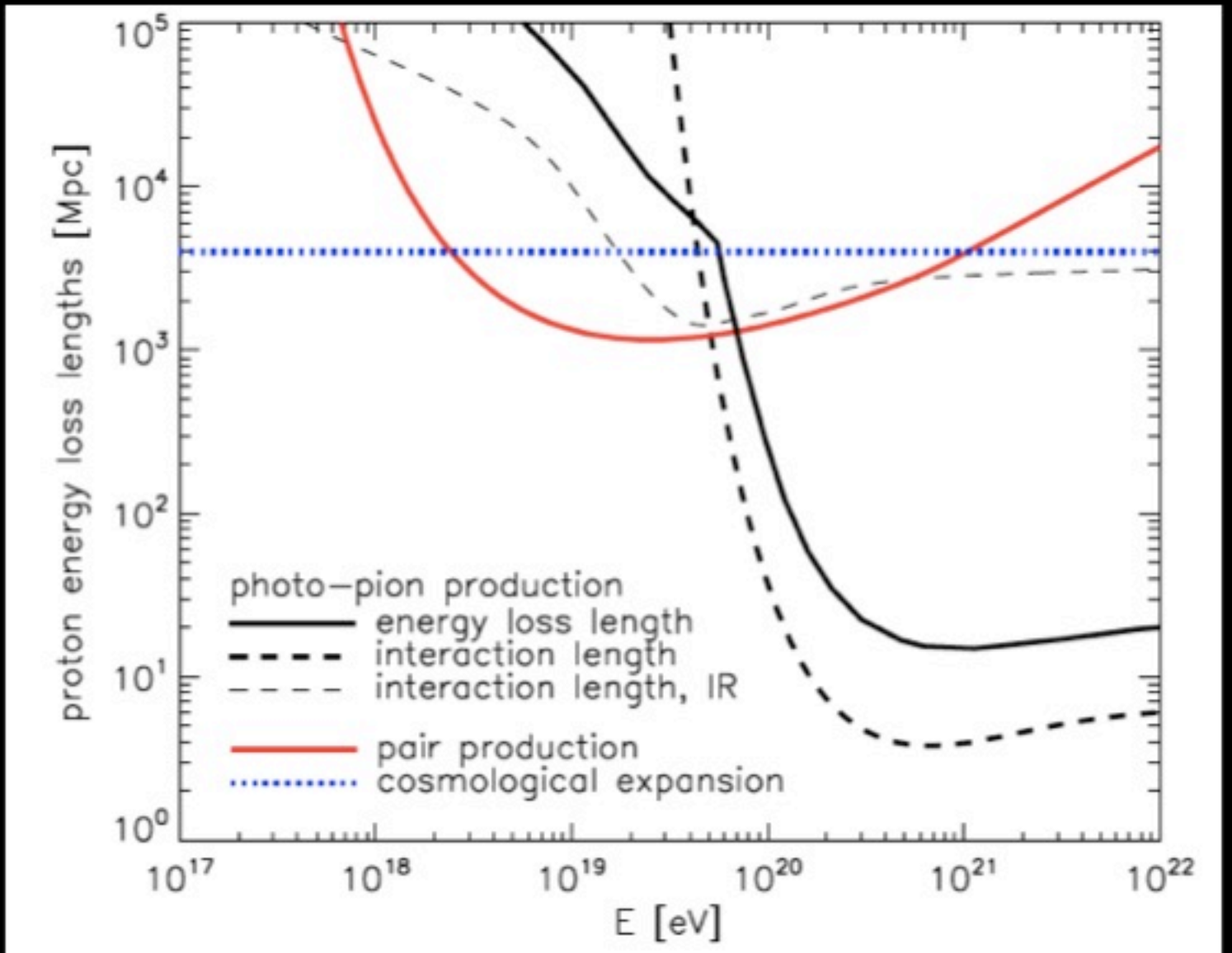
$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Proton Horizon
~5 x 10^{19} eV

GZK Cutoff

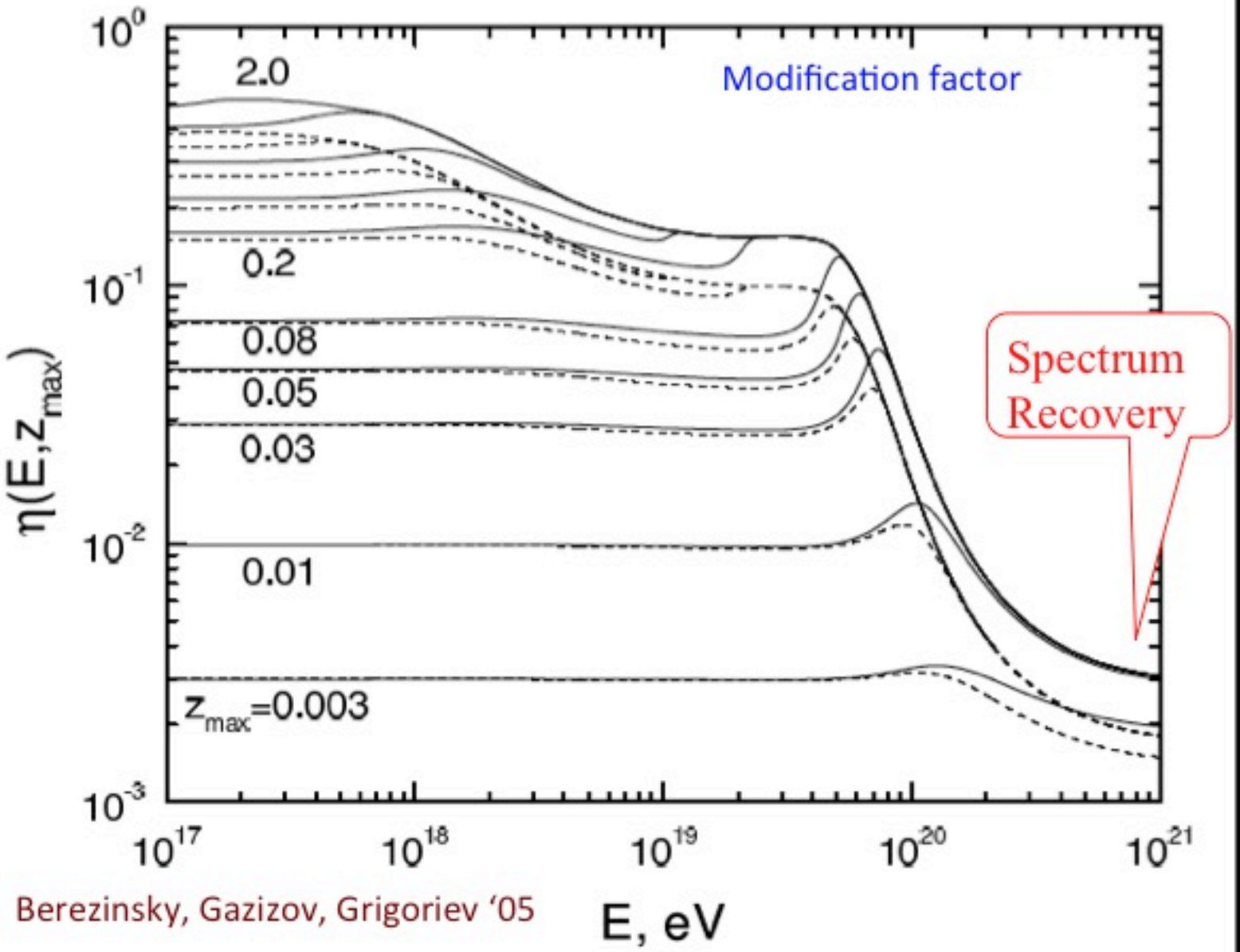
Greisen, Zatsepin, Kuzmin 1966

Greisen-Zatsepin-Kuzmin effect

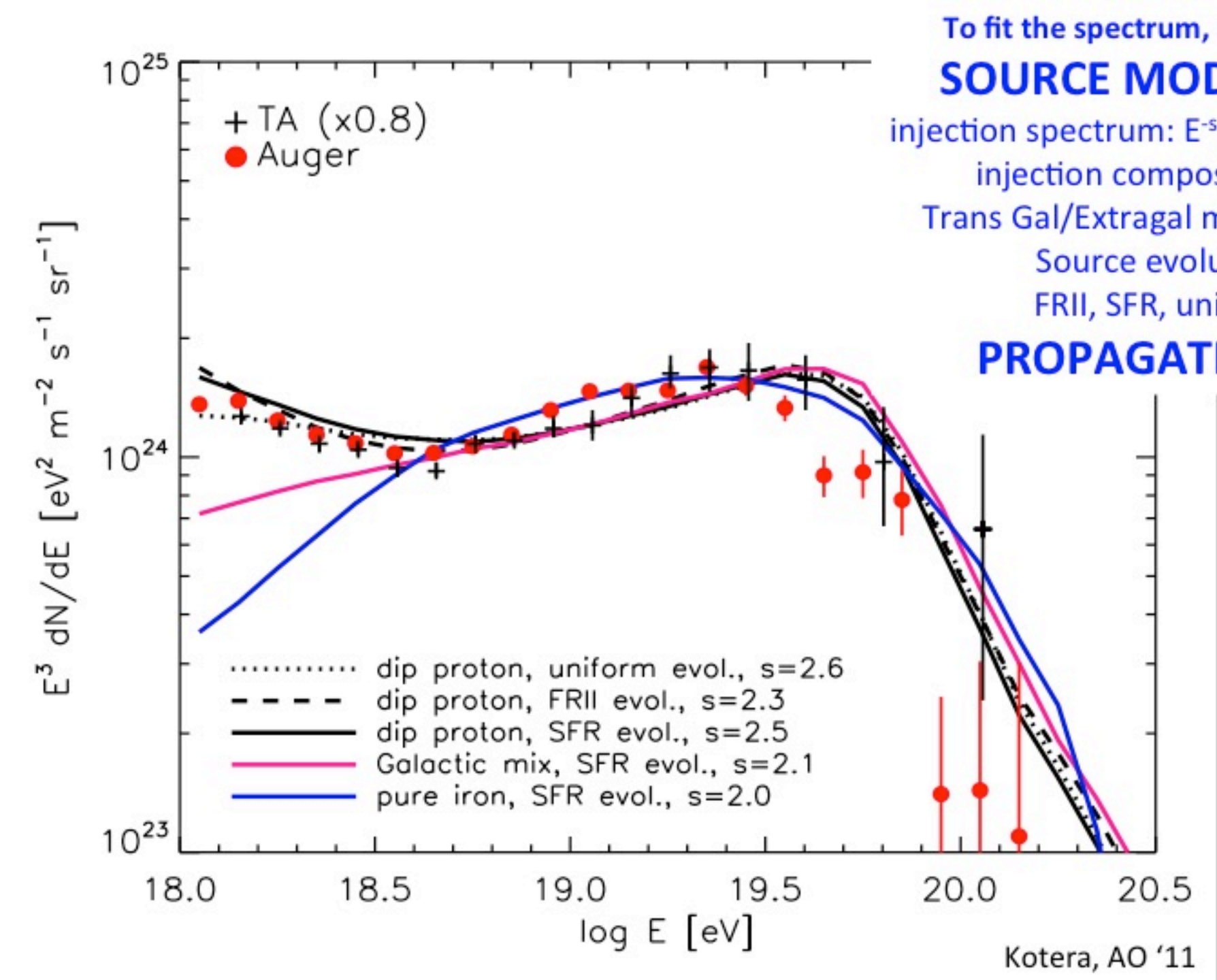


Kotera & AO 11

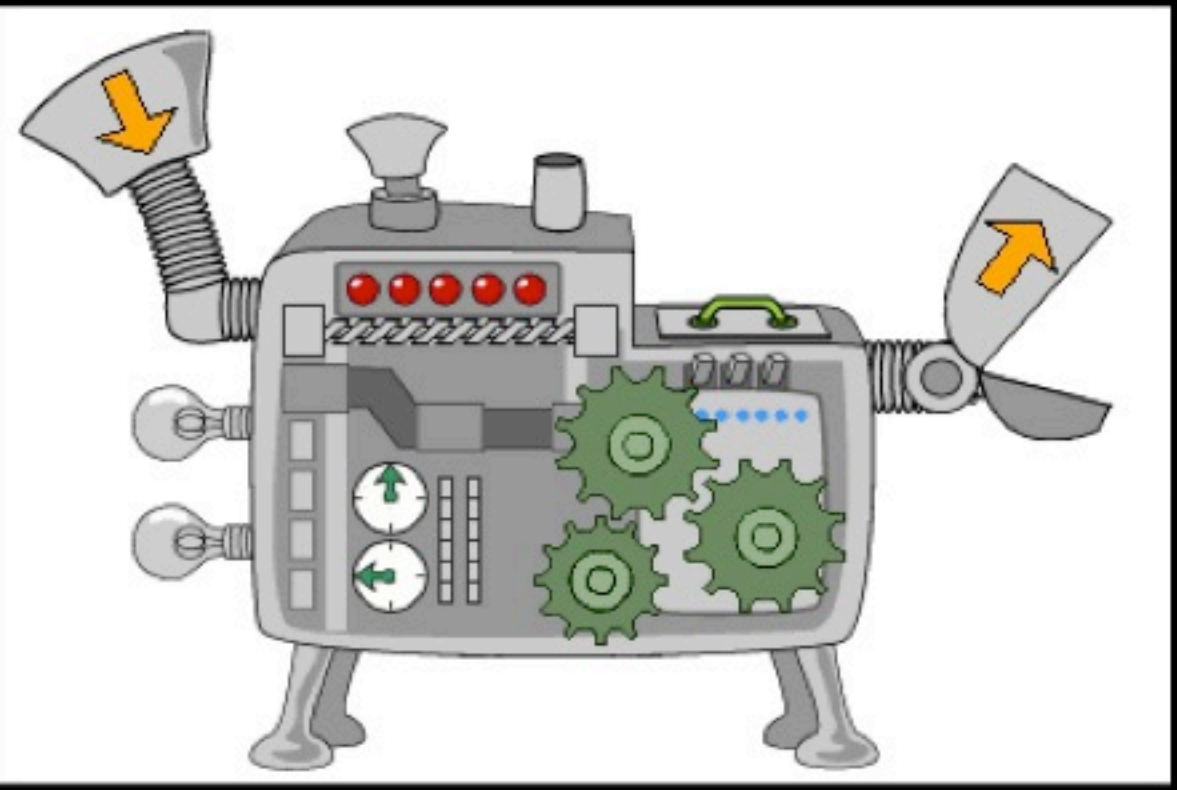
Propagation of UHE protons



Berezinsky, Gazizov, Grigoriev '05


To fit the spectrum, need:
SOURCE MODEL:
injection spectrum: E^{-s}, E_{max}
injection composition
Trans Gal/Extragal model
Source evolution:
FRII, SFR, uniform
PROPAGATION
+ TA (x0.8)
● Auger
10^{25}
10^{24}
10^{23}
E^3 dN/dE [eV^2 m^{-2} s^{-1} sr^{-1}]
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]
Kotera, AO '11

Modern Propagation Codes



Public:

CRPropa
1.0 Armengaud et al ‘06
2.0 Kampert et al. ’12
3.0 Alvez Batista et al ’14
SimProp
Aloisio et al ’12
v2r2: Aloisio et al ’15

Private:

Allard et al ’04
Taylor ’07
Ahlers ‘10
others…

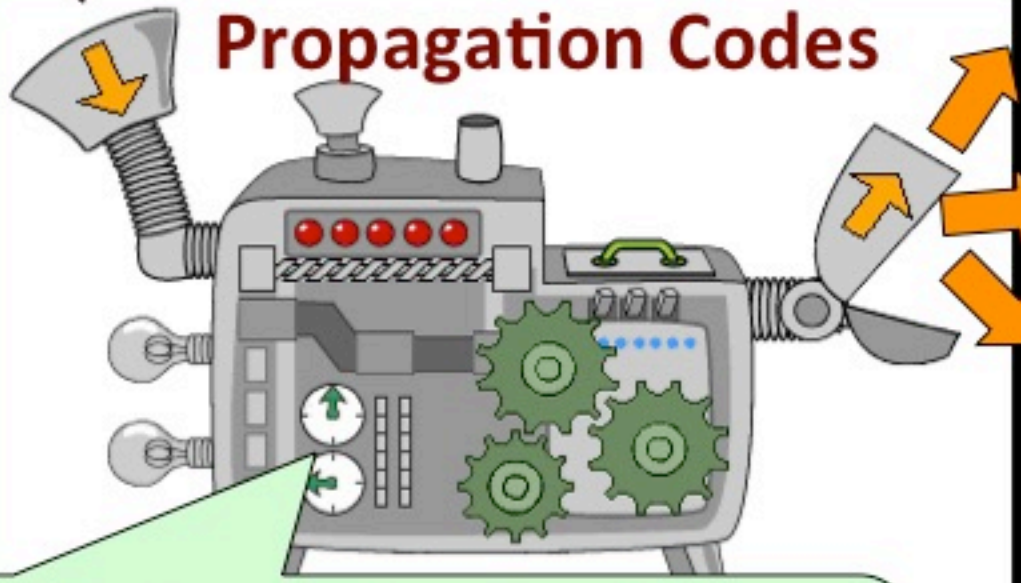
Source Model:

injection spectrum: E^{-s}

injected composition

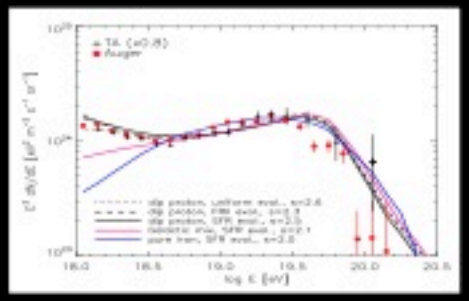
redshift distribution

Propagation Codes

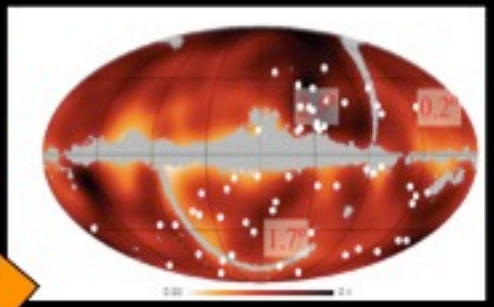


Interaction Cross Sections, z evolution, Intergal B fields, CMB, UV/Opt/IR background, Primary, Secondary nuclei, nucleons, e+e-, gamma-rays, neutrinos,...

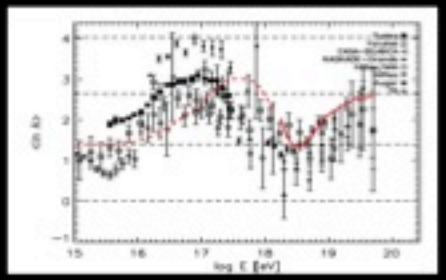
Spectrum



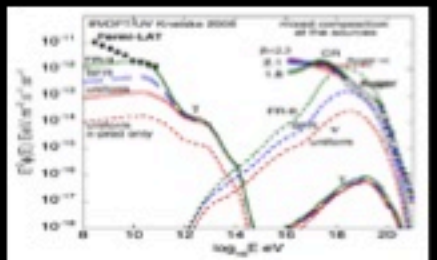
Anisotropies

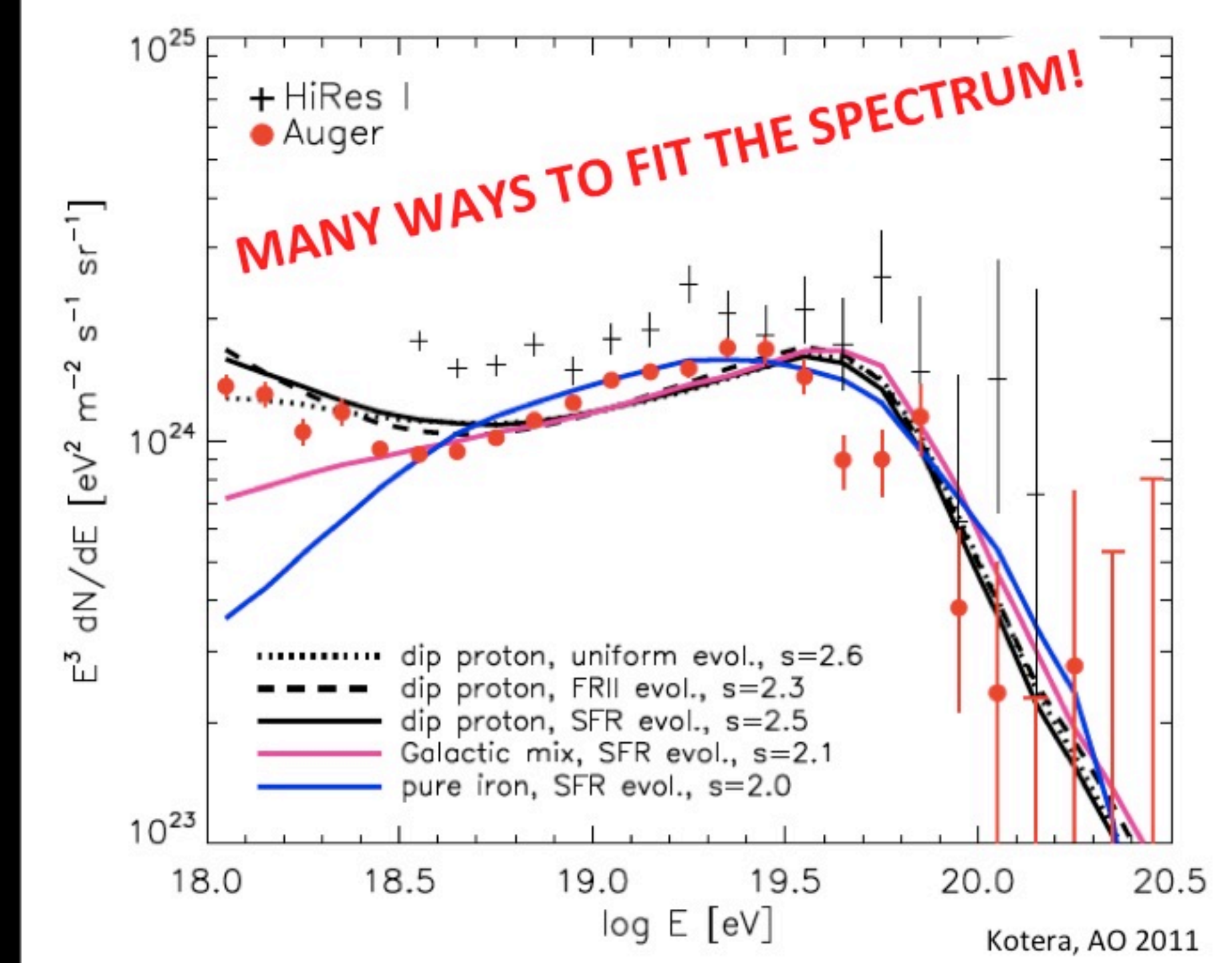


Composition



Multi-messengers




MANY WAYS TO FIT THE SPECTRUM!
HiRes I
Auger
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
E^3 dN/dE [eV^2 m^{-2} s^{-1} sr^{-1}]
10^{25}
10^{24}
10^{23}
18.0
18.5
19.0
19.5
20.0
20.5
log E [eV]
Kotera, AO 2011

UHECRs Current Status

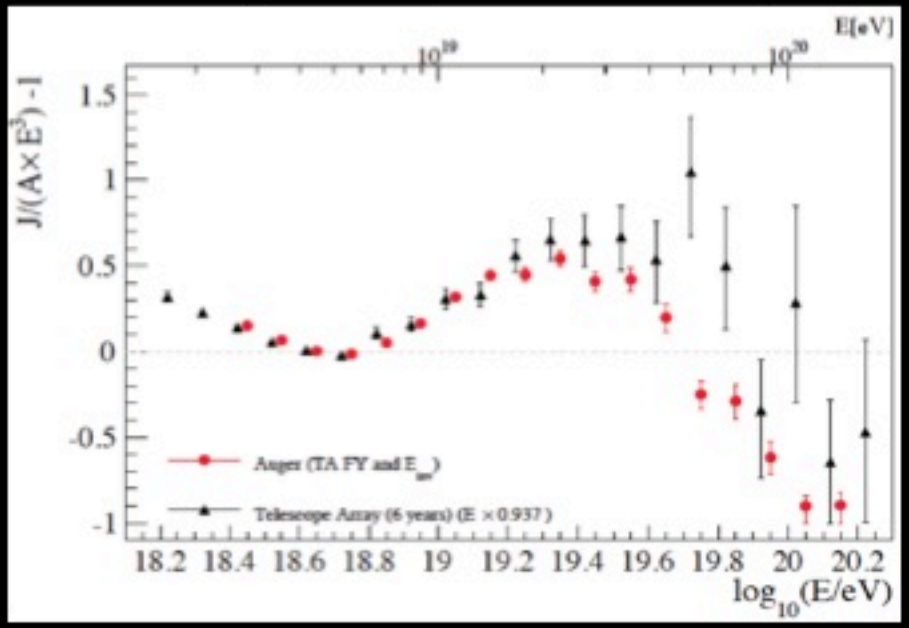
Leading Observatories: Auger & Telescope Array agree on the shape of the spectrum

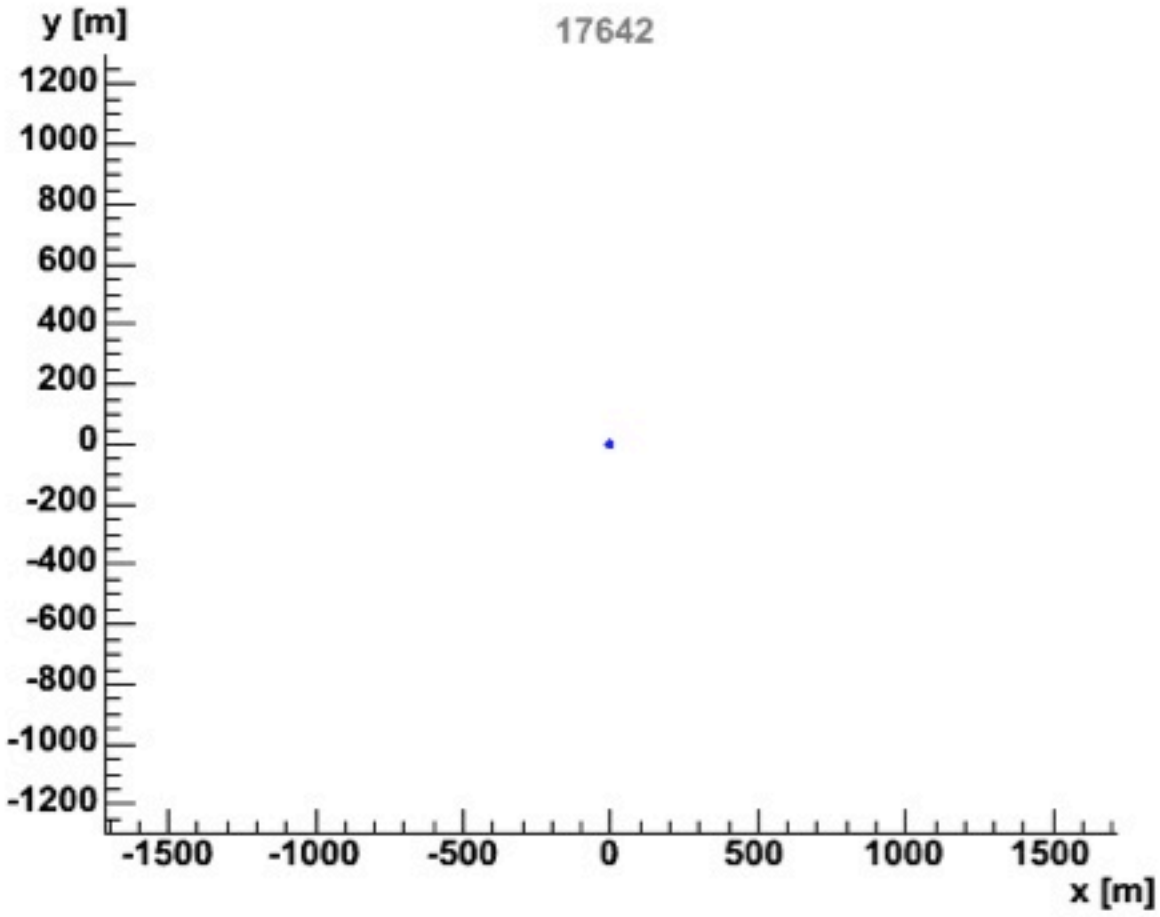
Energy scale: ~10% difference; TA enhanced at Extreme Energies (>60 EeV)

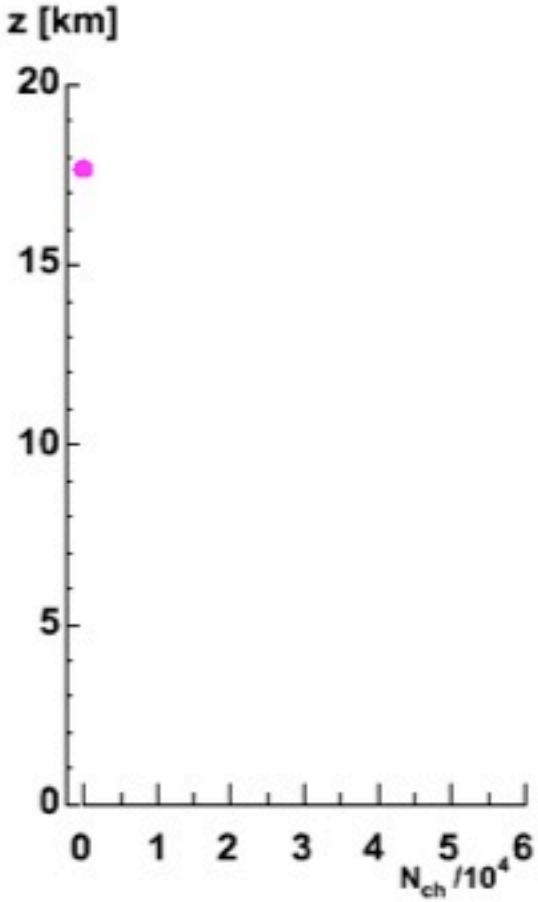
Composition?

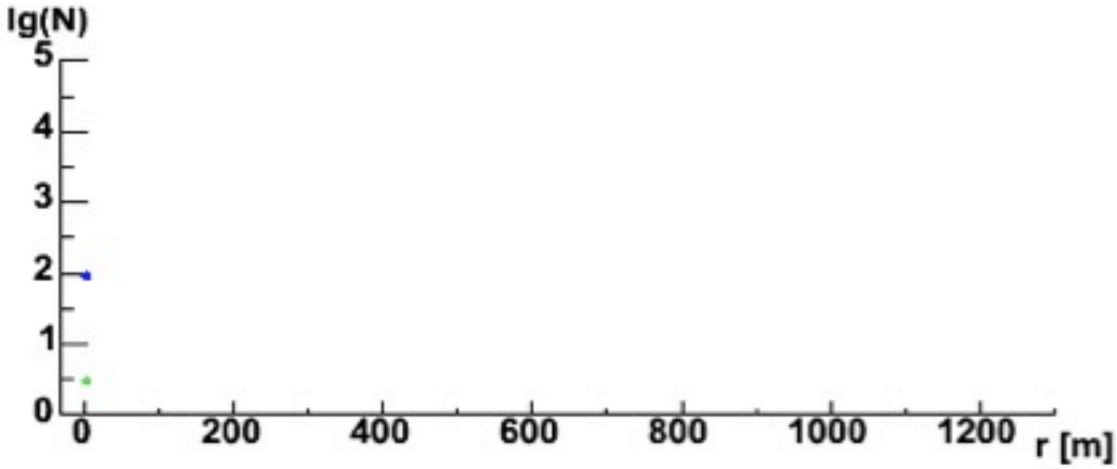
Anisotropies?

Multi-messengers?









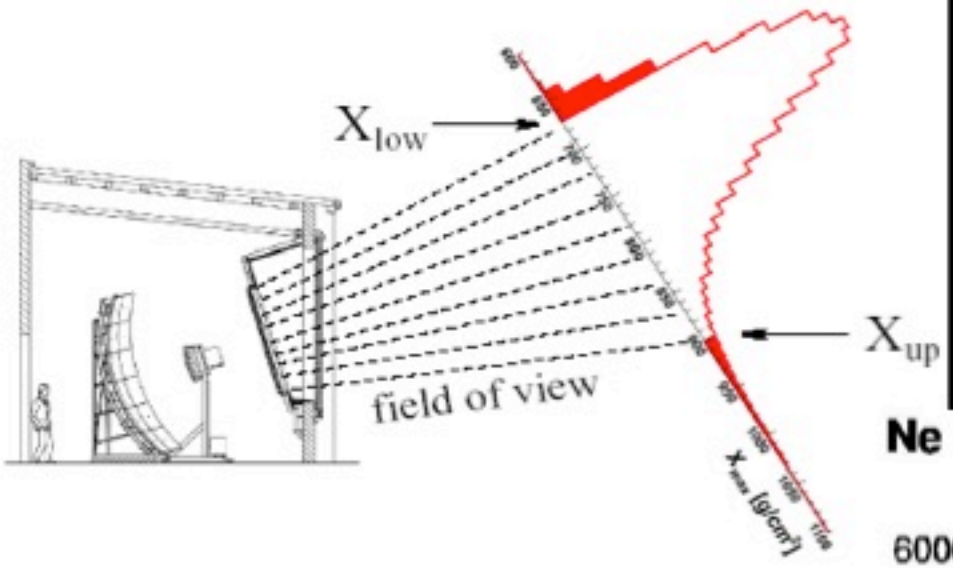
Proton 10^{14} eV

h^{1st} = 17642 m

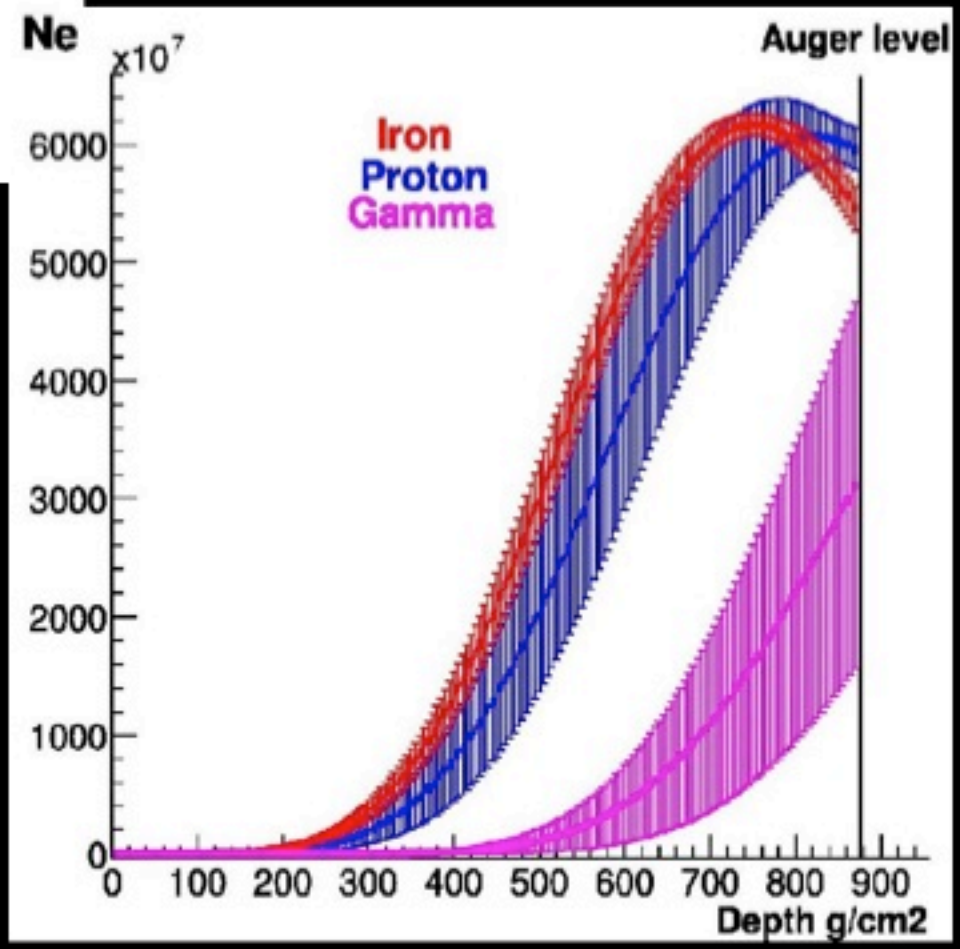
hadrons muons

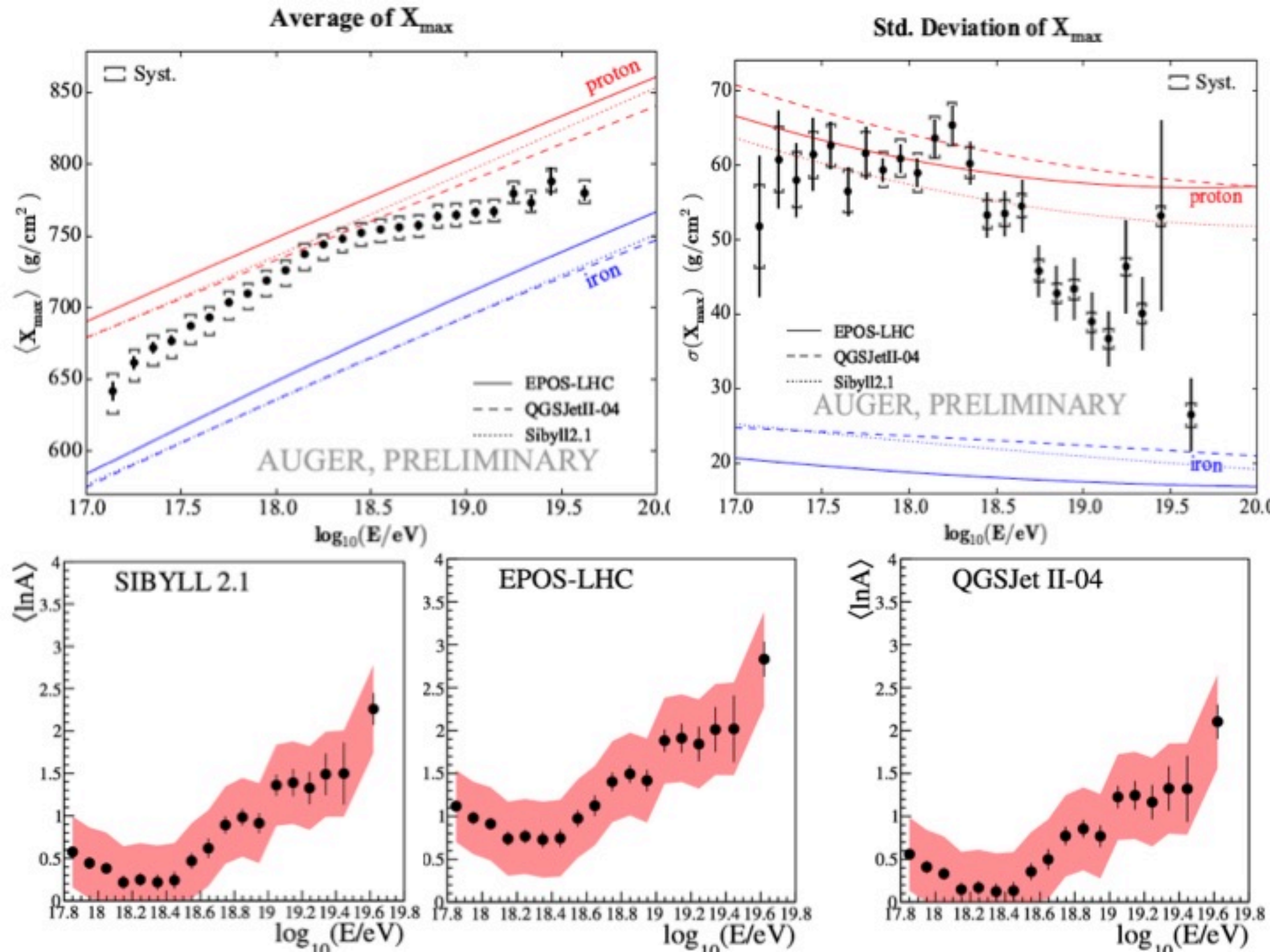
neutrons **electrs**

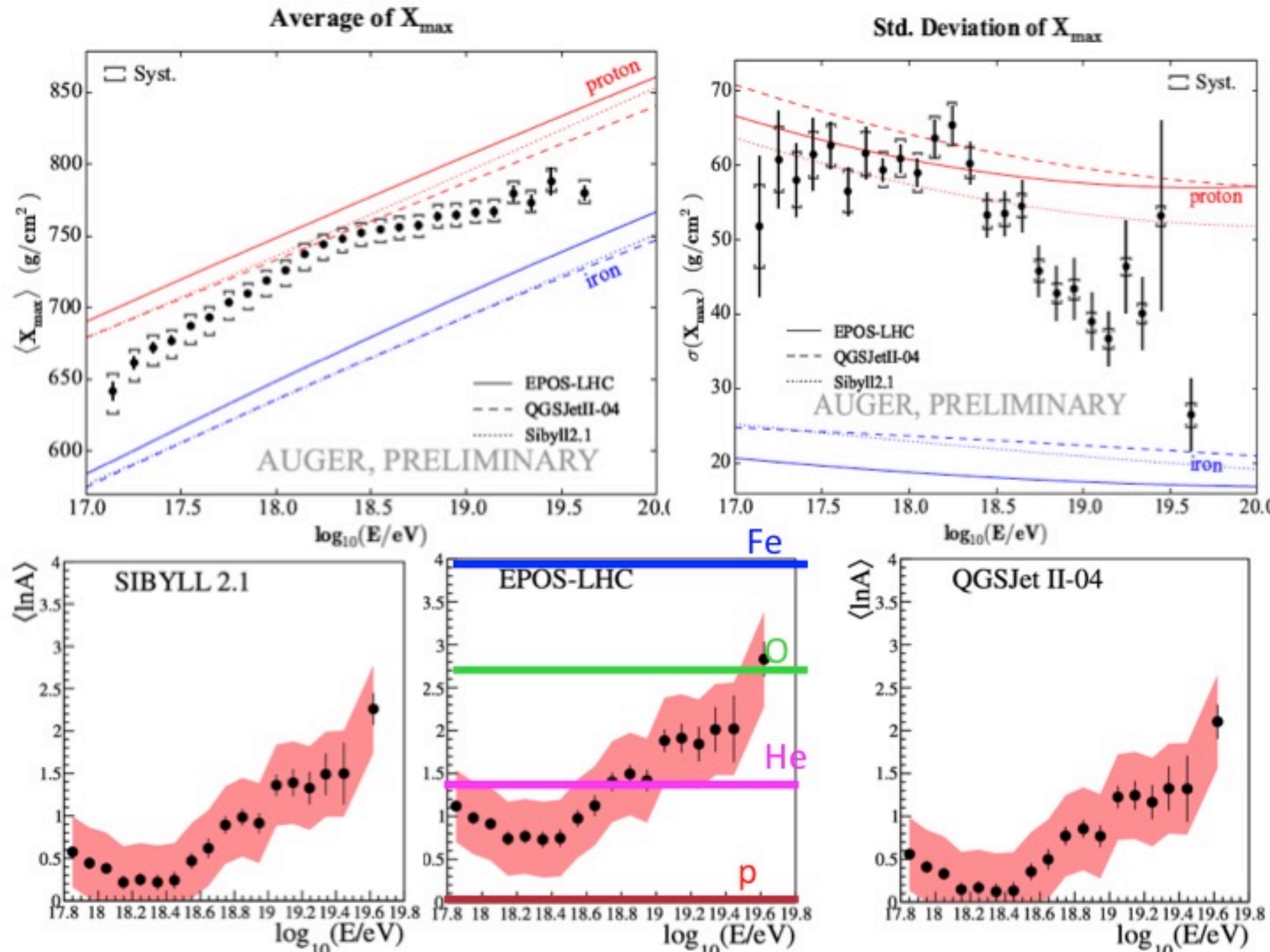
J.Oehlschlaeger,R.Engel,FZKarlsruhe

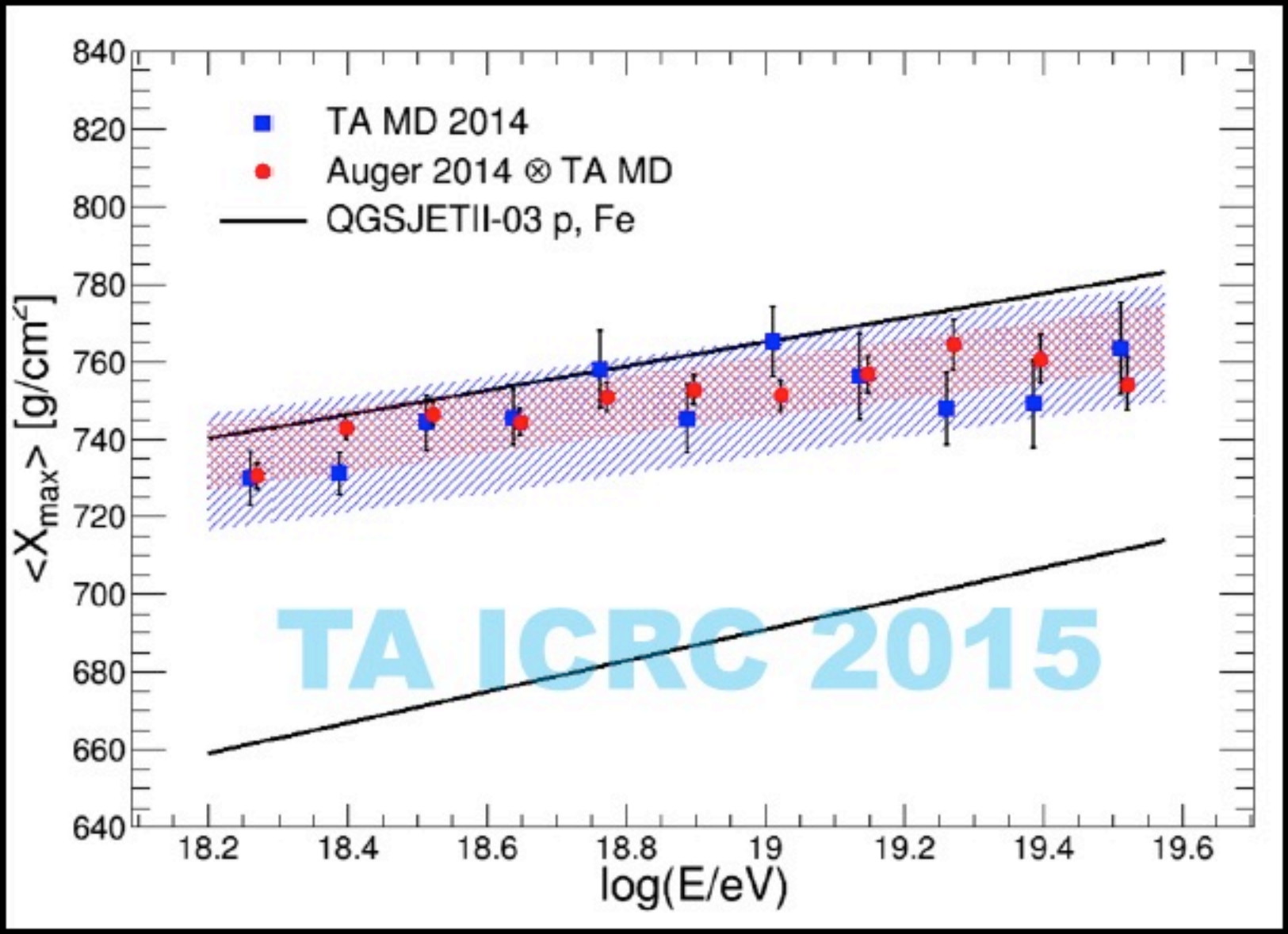


Composition observable: shower maximum average and fluctuations




Average of X_{max}
Syst.
proton
iron
EPOS-LHC
QGSJetII-04
Sibyll2.1
AUGER, PRELIMINARY
$\langle X_{max} \rangle$ (g/cm^2)
$\log_{10}$(E/eV)
Std. Deviation of X_{max}
$\sigma(X_{max})$ (g/cm^2)
SIBYLL 2.1
EPOS-LHC
QGSJet II-04
$\langle \ln A \rangle$
$\log_{10}$(E/eV)


Average of X_{max}
Syst.
proton
iron
EPOS-LHC
QGSJetII-04
Sibyll2.1
AUGER, PRELIMINARY
$\langle X_{max} \rangle$ (g/cm^2)
$\log_{10}$(E/eV)
Std. Deviation of X_{max}
$\sigma(X_{max})$ (g/cm^2)
SIBYLL 2.1
EPOS-LHC
QGSJet II-04
Fe
O
He
p
$\langle$lnA$\rangle$
$\log_{10}$(E/eV)

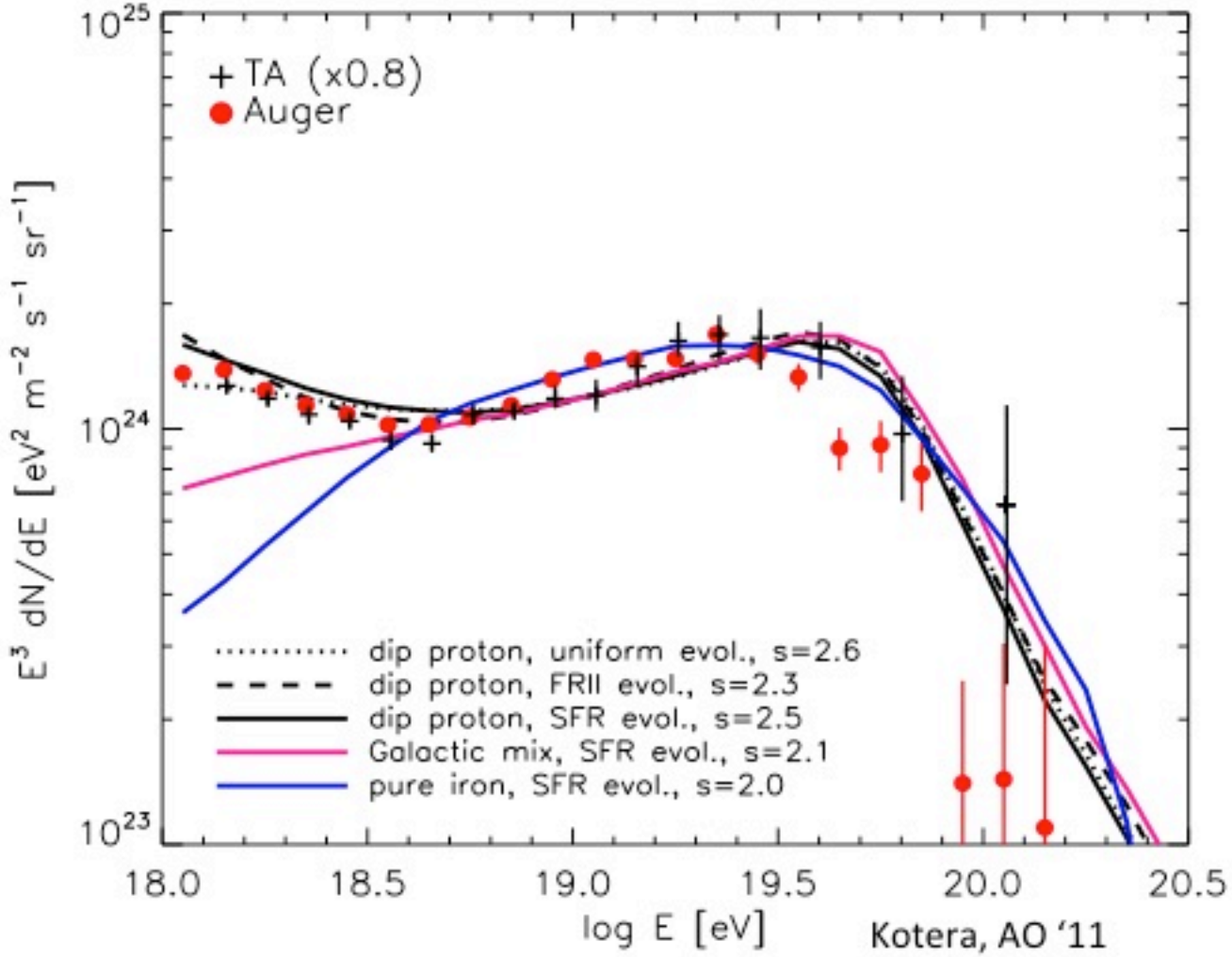

TA MD 2014
Auger 2014 ⊗ TA MD
QGSJETII-03 p, Fe
<X_max> [g/cm²]
log(E/eV)
840
820
800
780
760
740
720
700
680
660
640
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
TA ICRC 2015

UHECRs Current Status

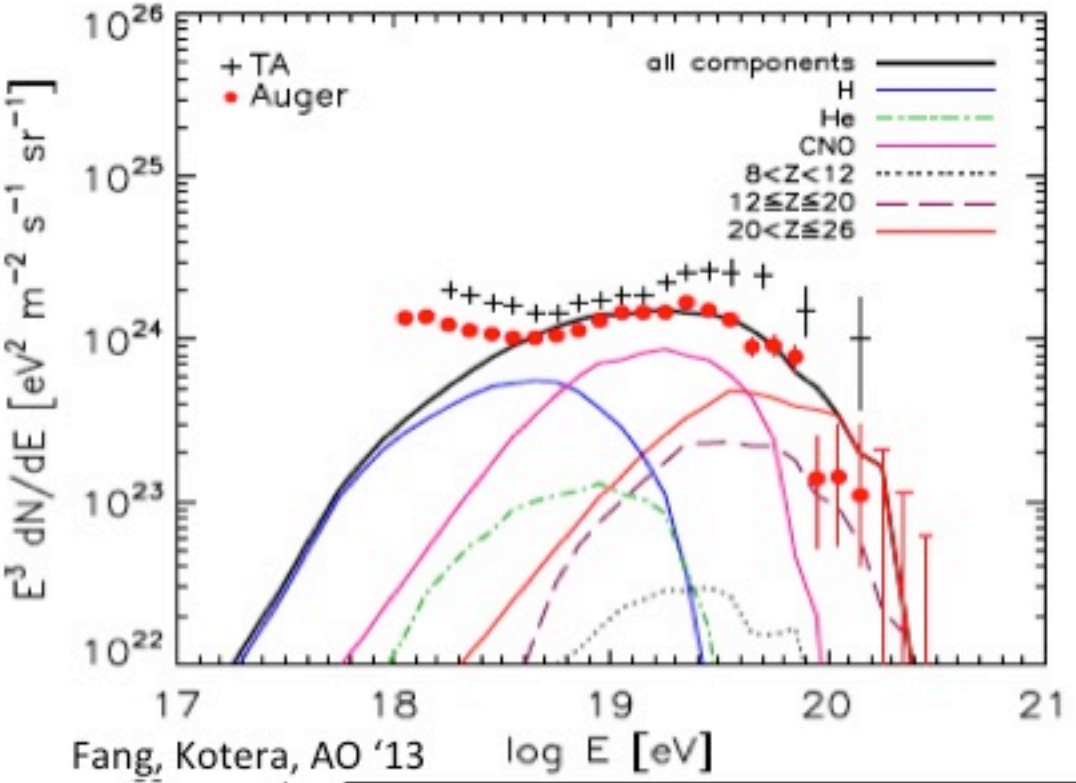
Leading Observatories: Auger & Telescope Array agree on the shape of the spectrum

Composition: transition to mixed (heavier) at highest energies (TA still unclear)

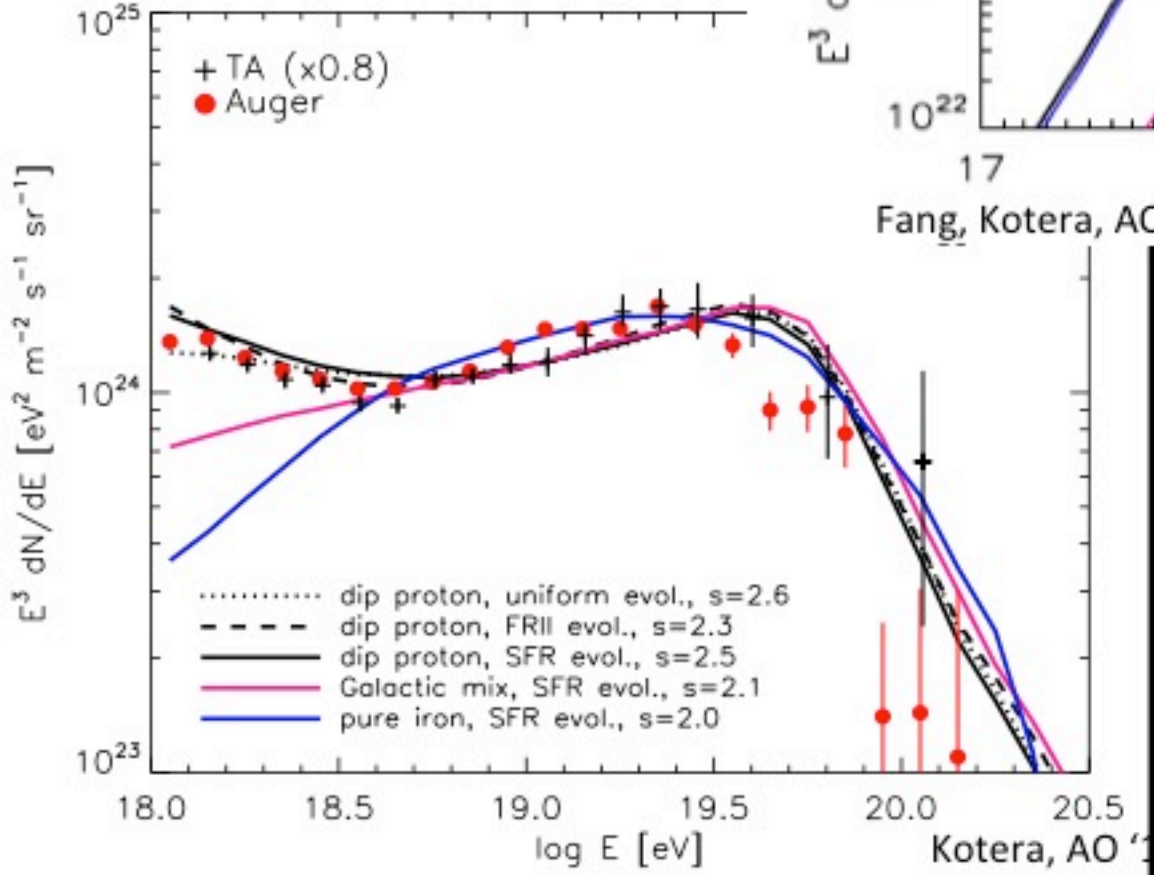
GZK ?


+ TA (x0.8)
● Auger
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
10^{25}
10^{24}
10^{23}
18.0
18.5
19.0
19.5
20.0
20.5
log E [eV]
E^3 dN/dE [eV^2 m^{-2} s^{-1} sr^{-1}]
Kotera, AO '11

GZK or E_{max}?

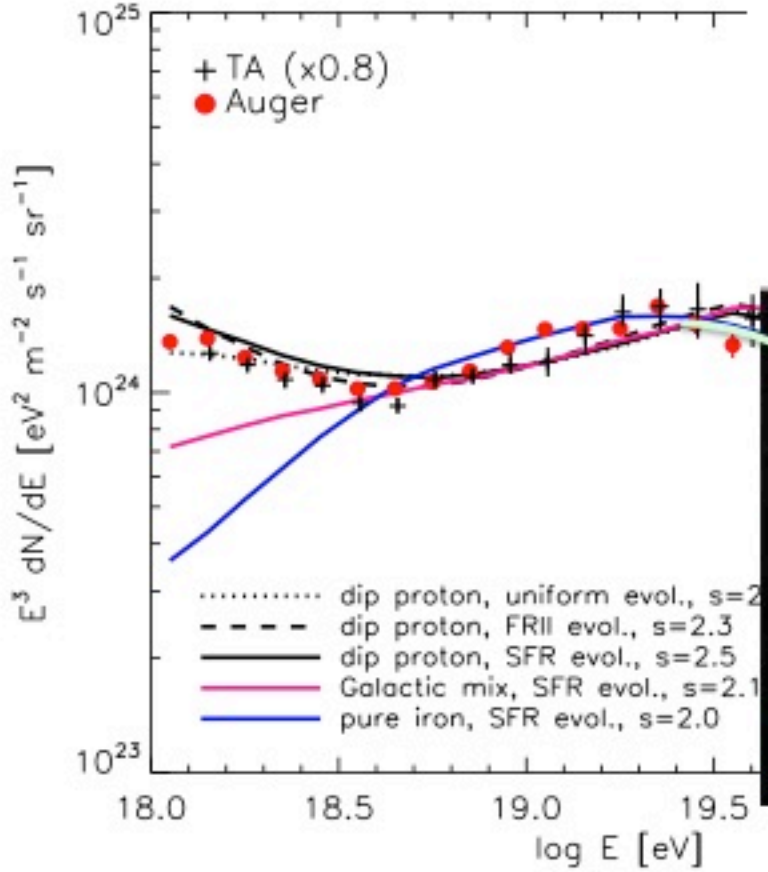


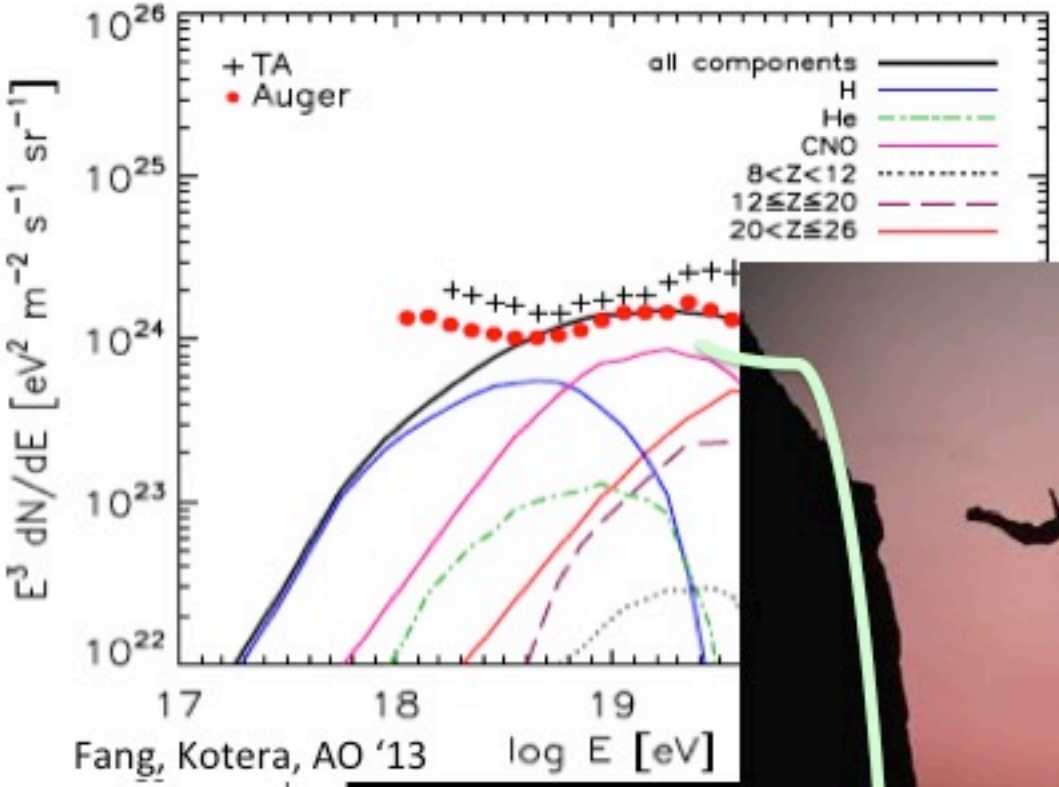
Fang, Kotera, AO '13



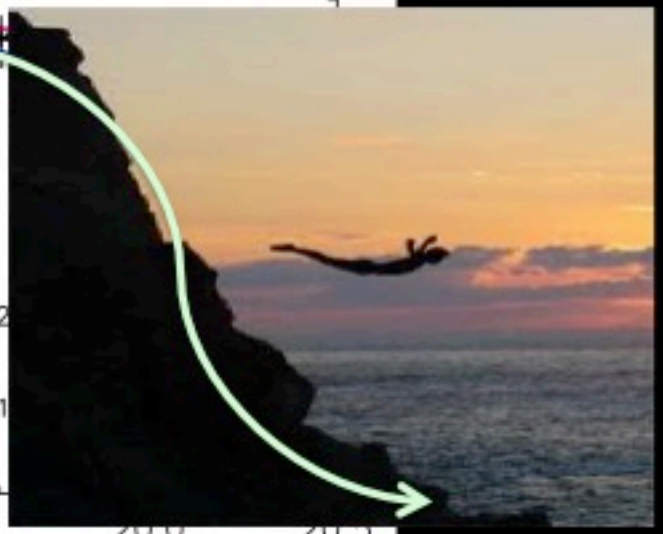
Kotera, AO '1

GZK vs E_{max}



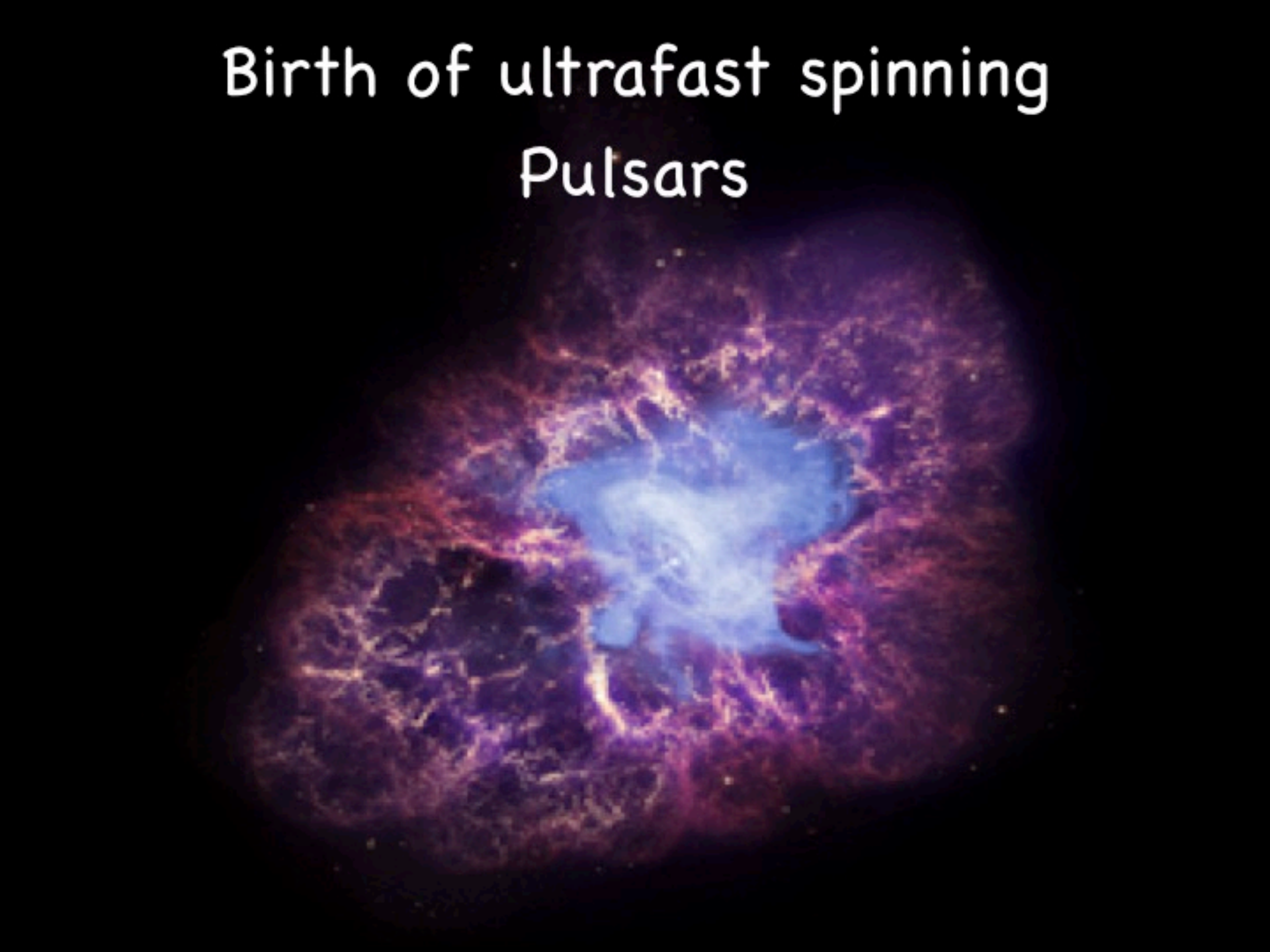


Fang, Kotera, AO '13

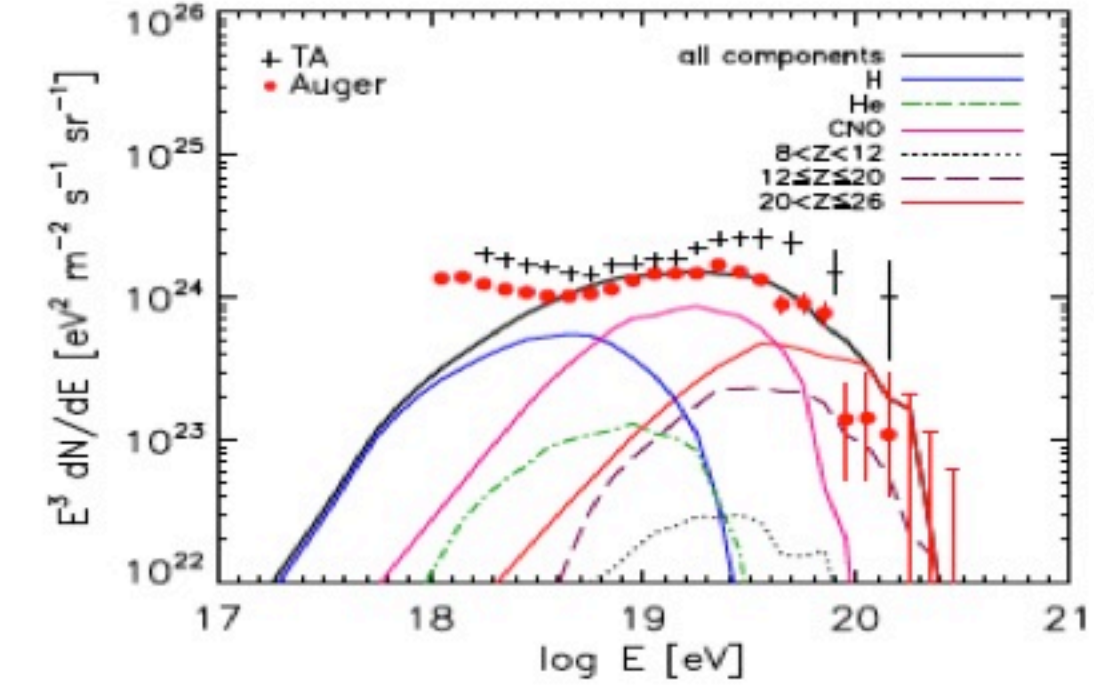


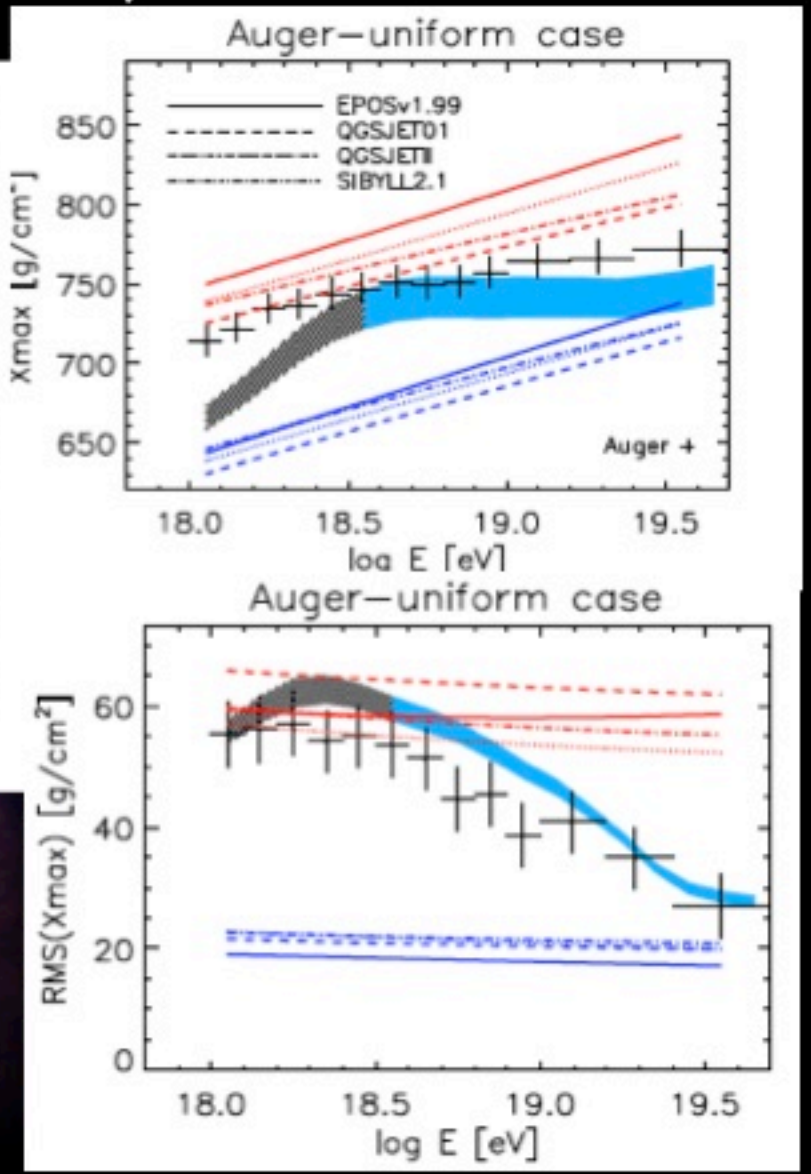
Kotera, AO '11

Birth of ultrafast spinning Pulsars



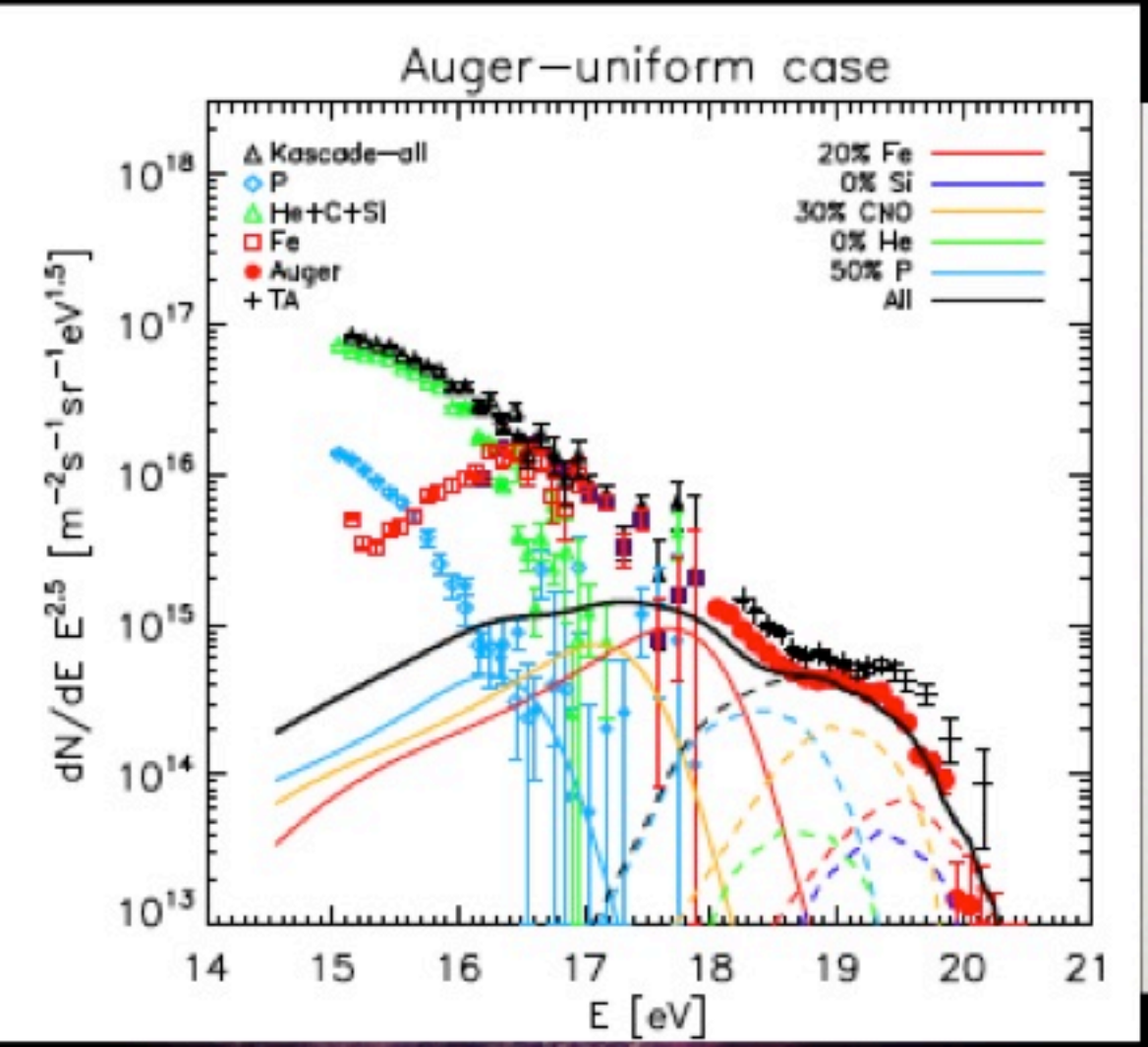
Fast Spinning Newborn Pulsars fit Spectrum & Auger Composition !

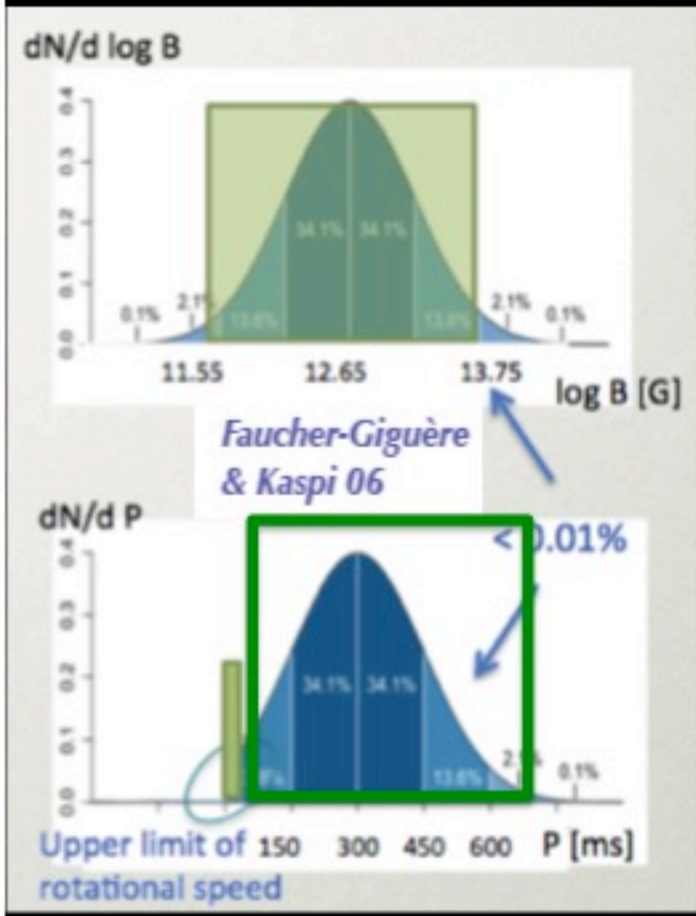




Fang, Kotera, AVO '13

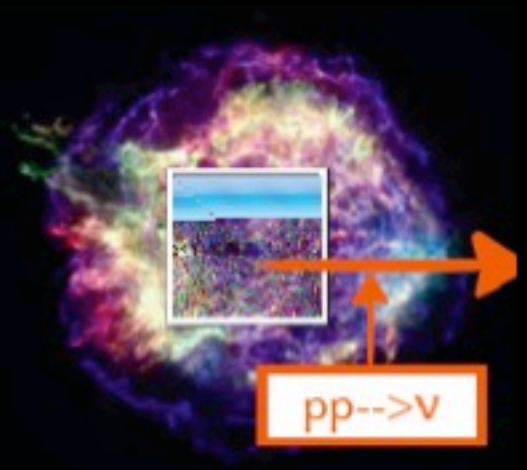
Galactic Newborn Pulsars

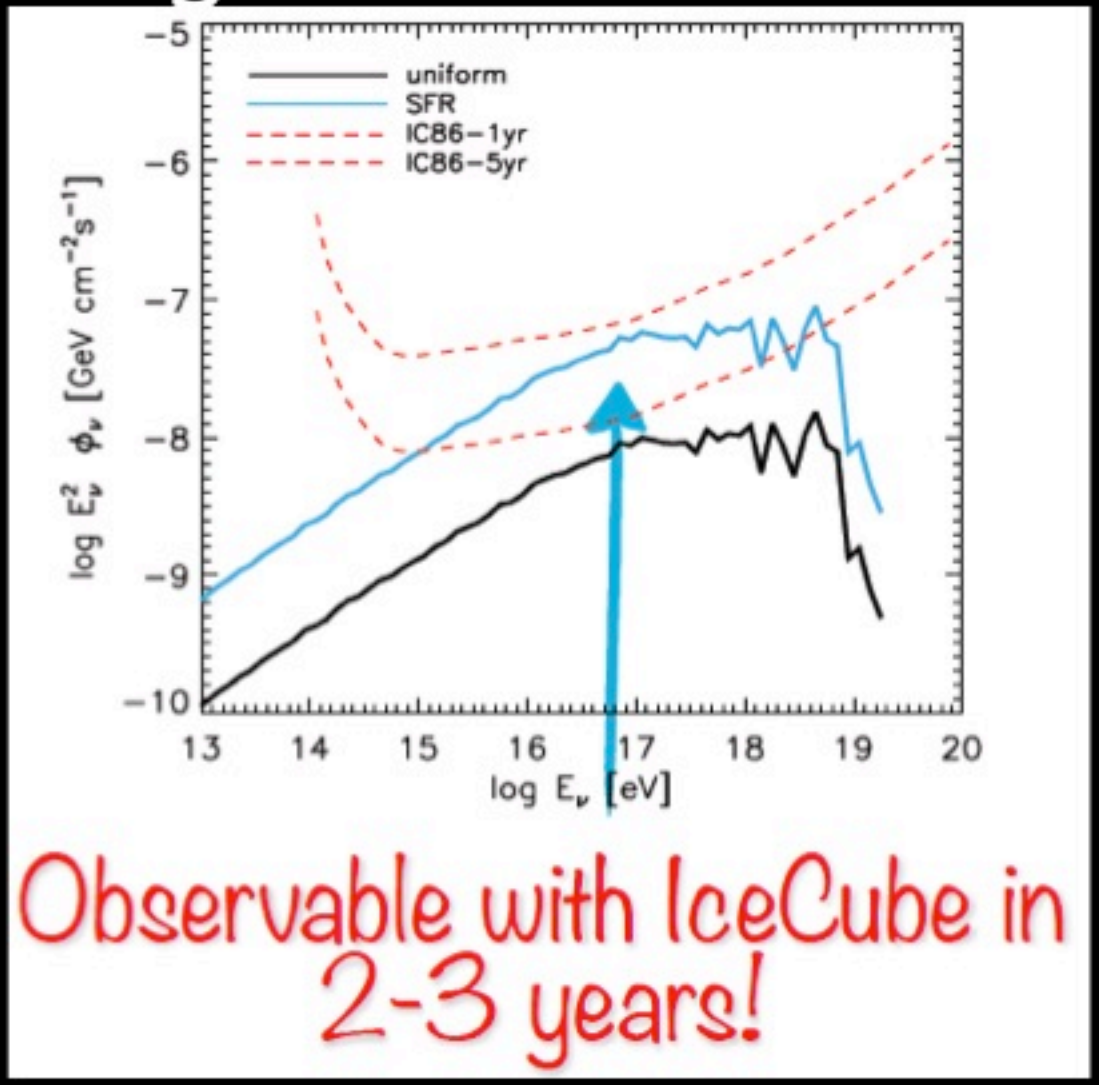




Fang, Kotera, AVO '13

Multimessenger Predictions





Fang, Kotera, Murase, AVO '13

UHECRs Current Status

Leading Observatories: Auger & Telescope Array agree on the shape of the spectrum

Composition: transition to mixed at highest energies

Anisotropies?

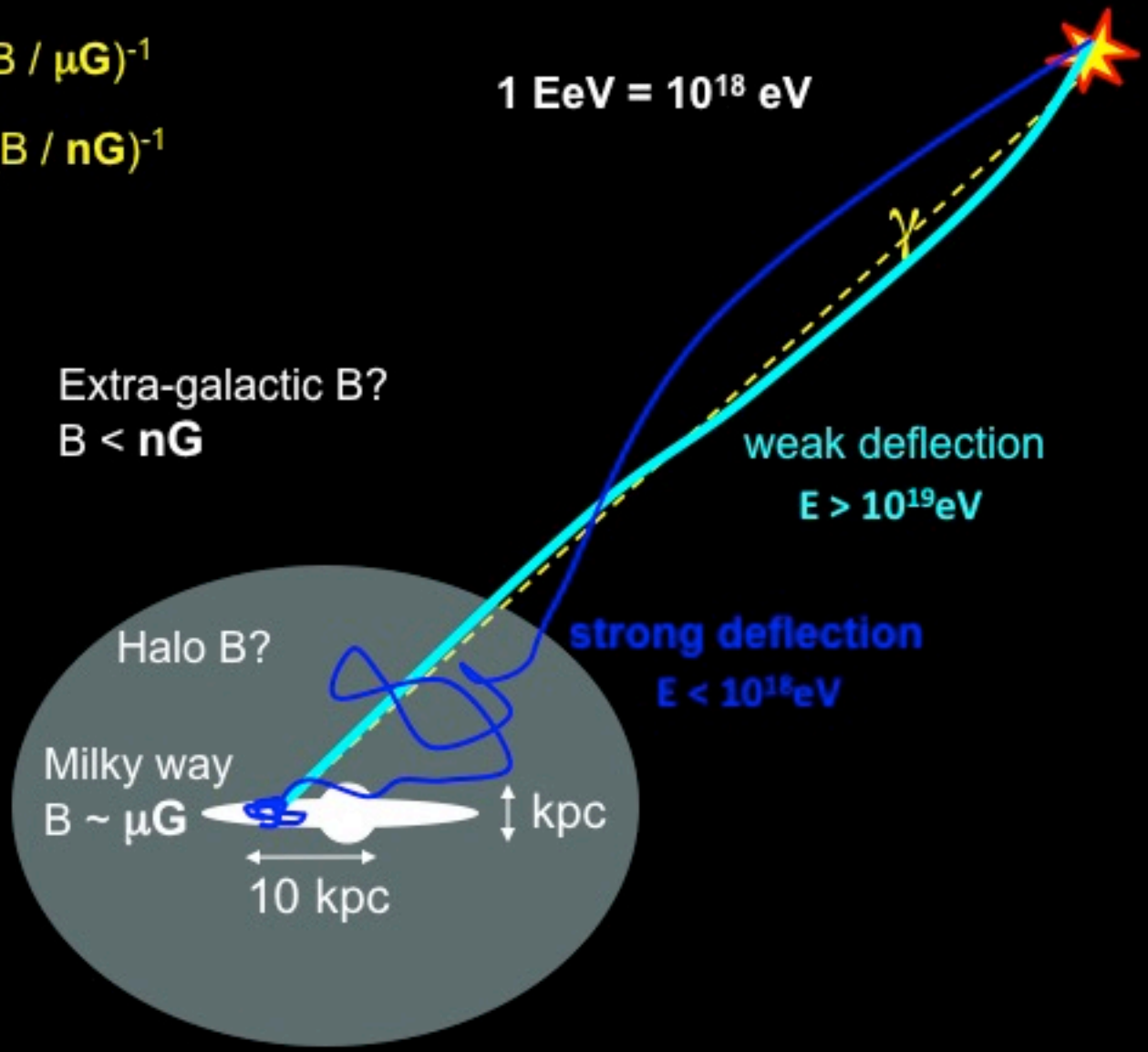
"Known unknown"

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

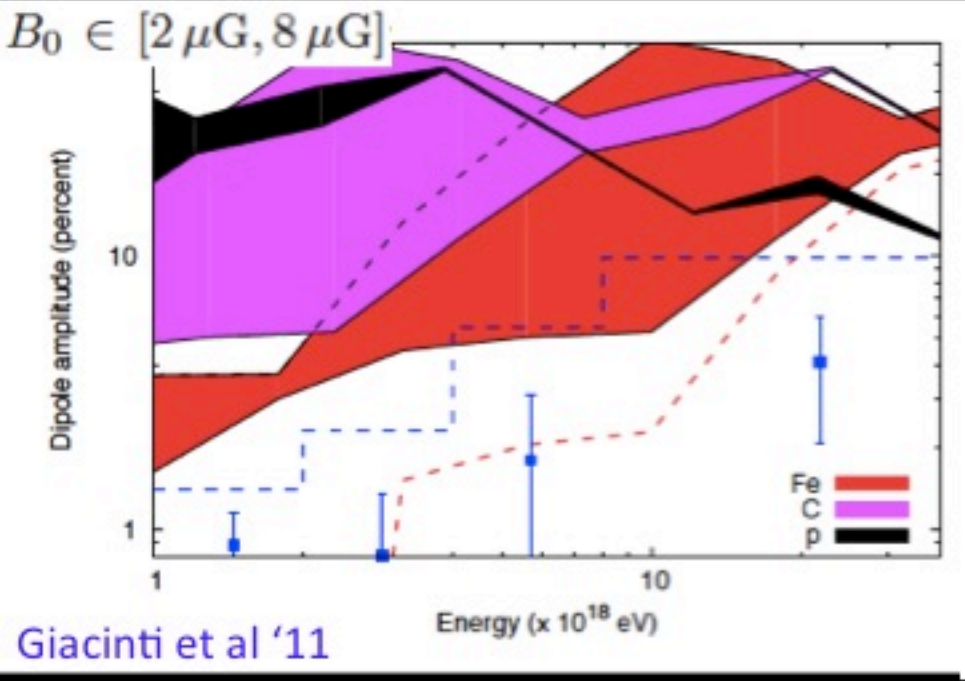


Galactic B deflection
<< 10^o Z (40 EeV/E)
anisotropic in sky

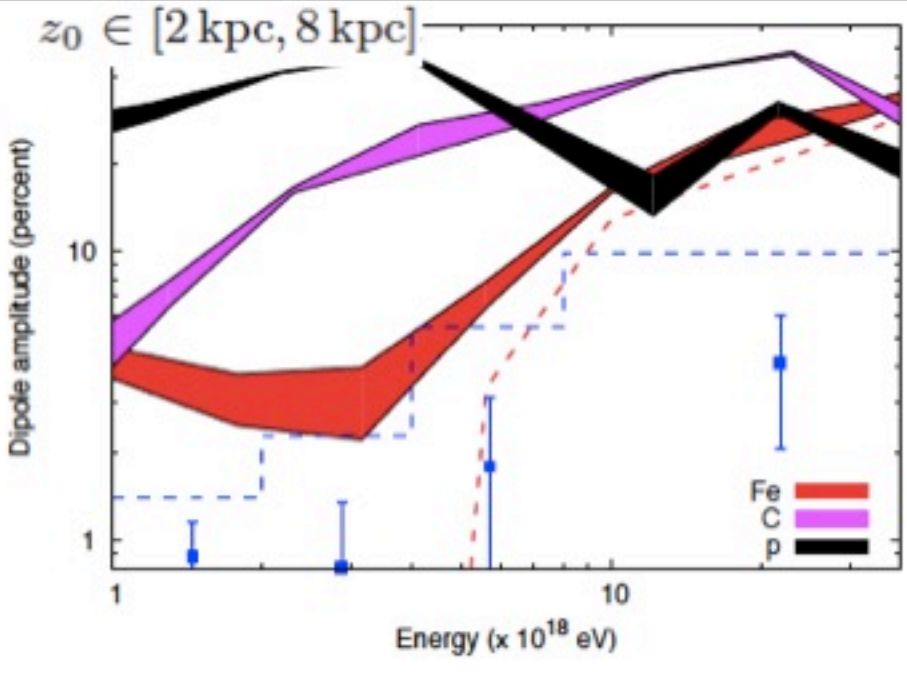
E>20 EeV Cosmic Rays are EXTRAGALACTIC

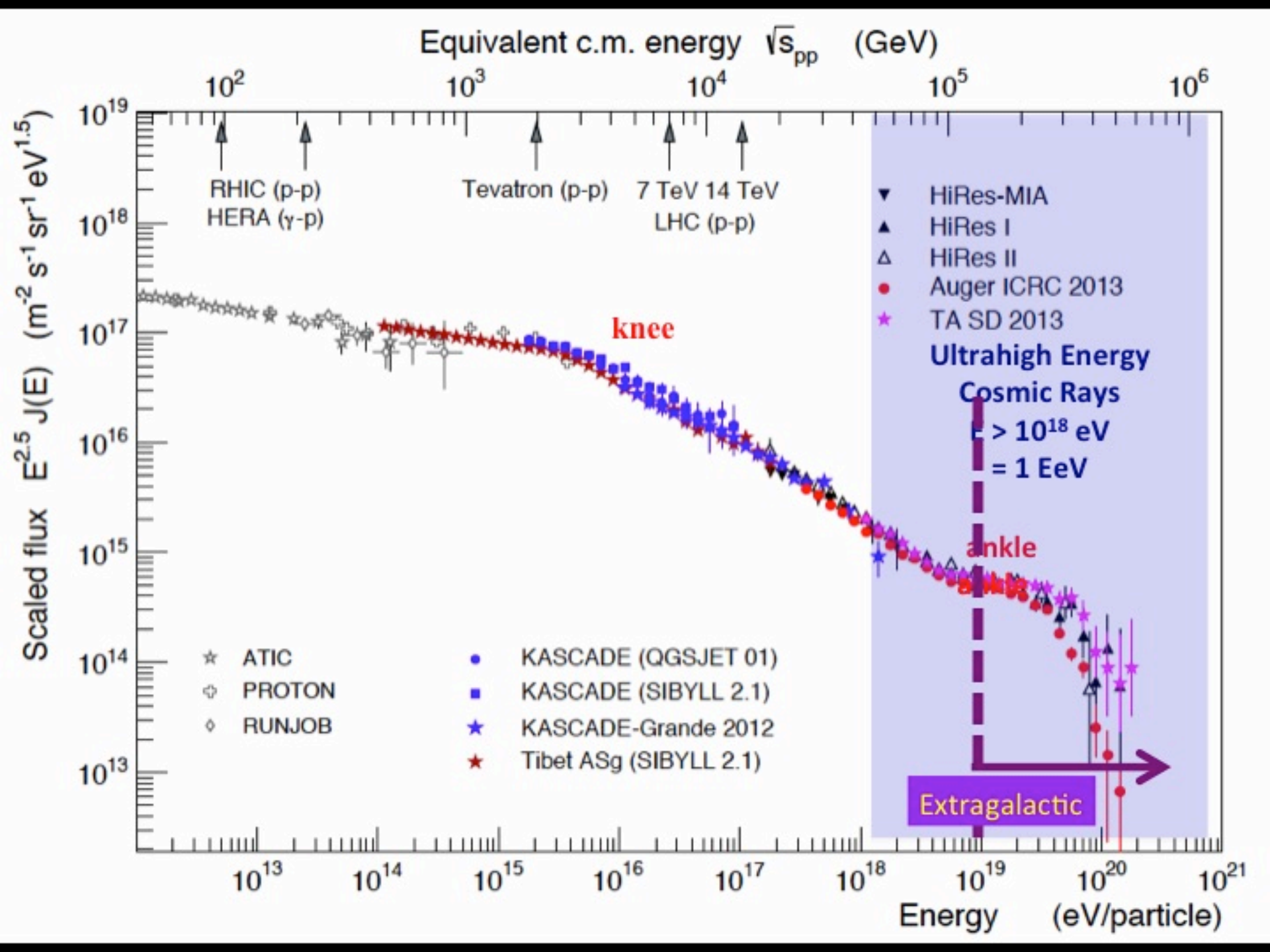
No Galactic Plane Anisotropy

Auger Anisotropy limits: rule out Galactic protons to CNO as dominant CR component **E > 1 EeV** and Fe above 20 EeV

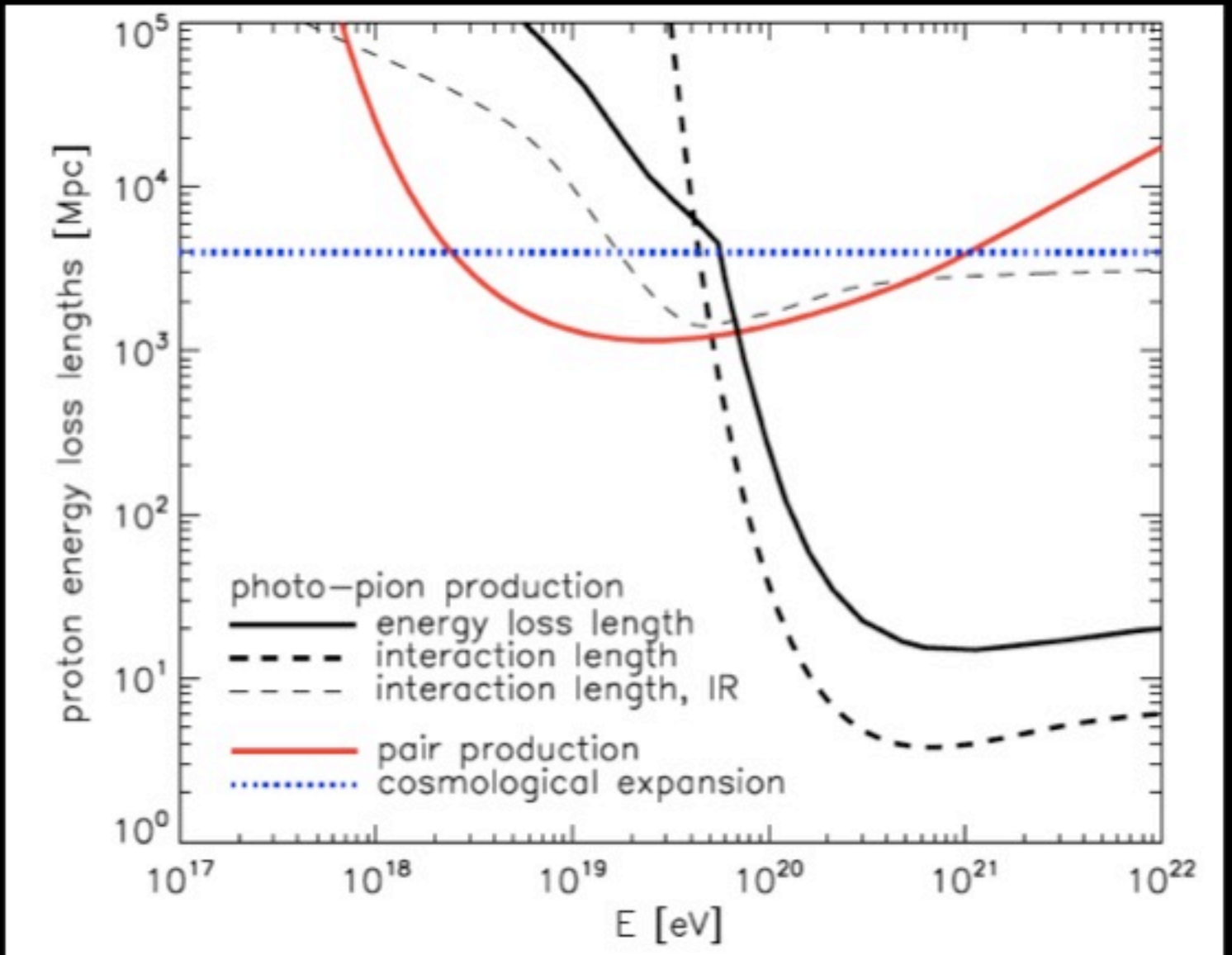


Giacinti et al '11



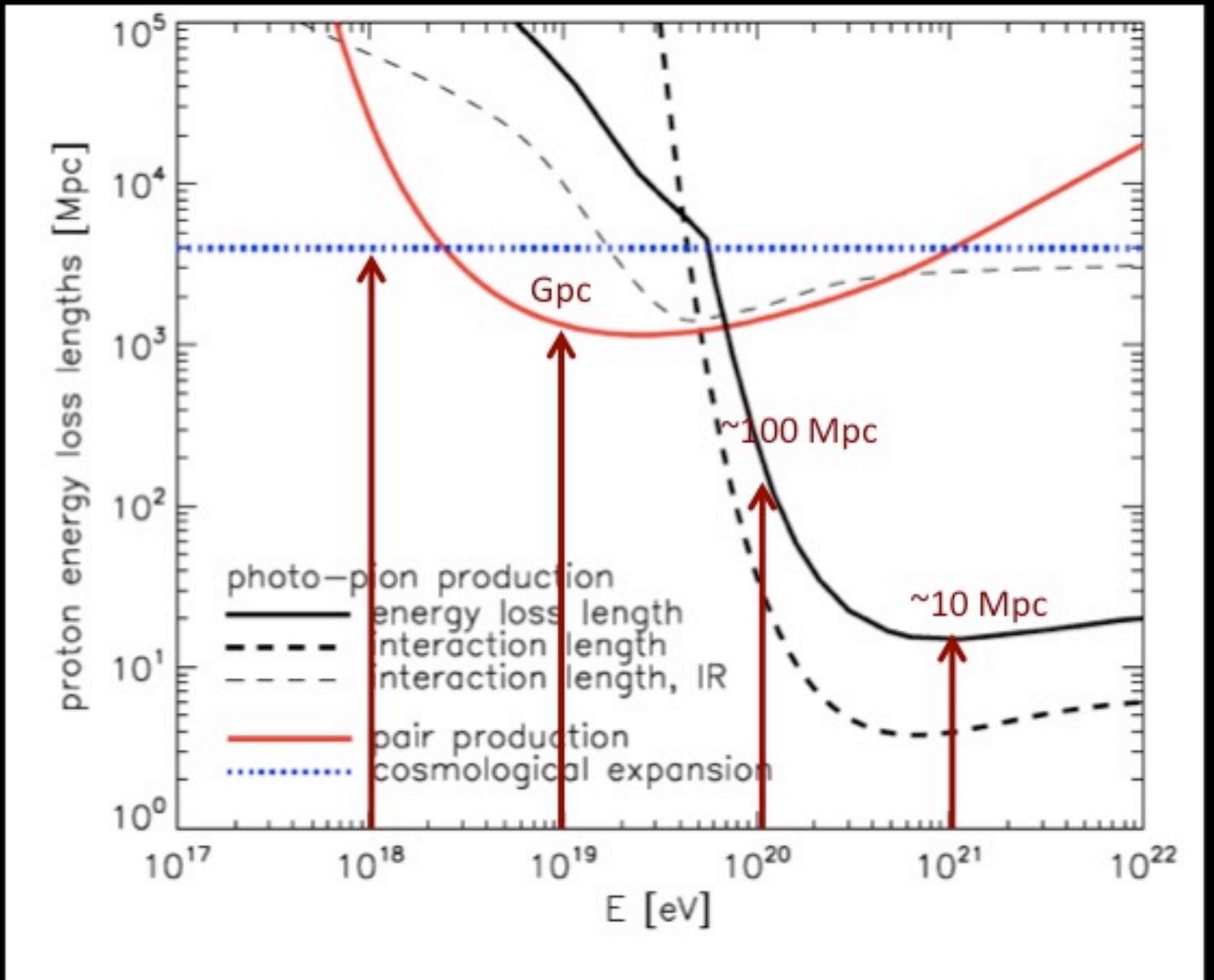

Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
Ultrahigh Energy
Cosmic Rays
E > 10^18 eV
= 1 EeV
ankle
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
10^19
10^18
10^17
10^16
10^15
10^14
10^13
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
Extragalactic
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

Greisen-Zatsepin-Kuzmin effect

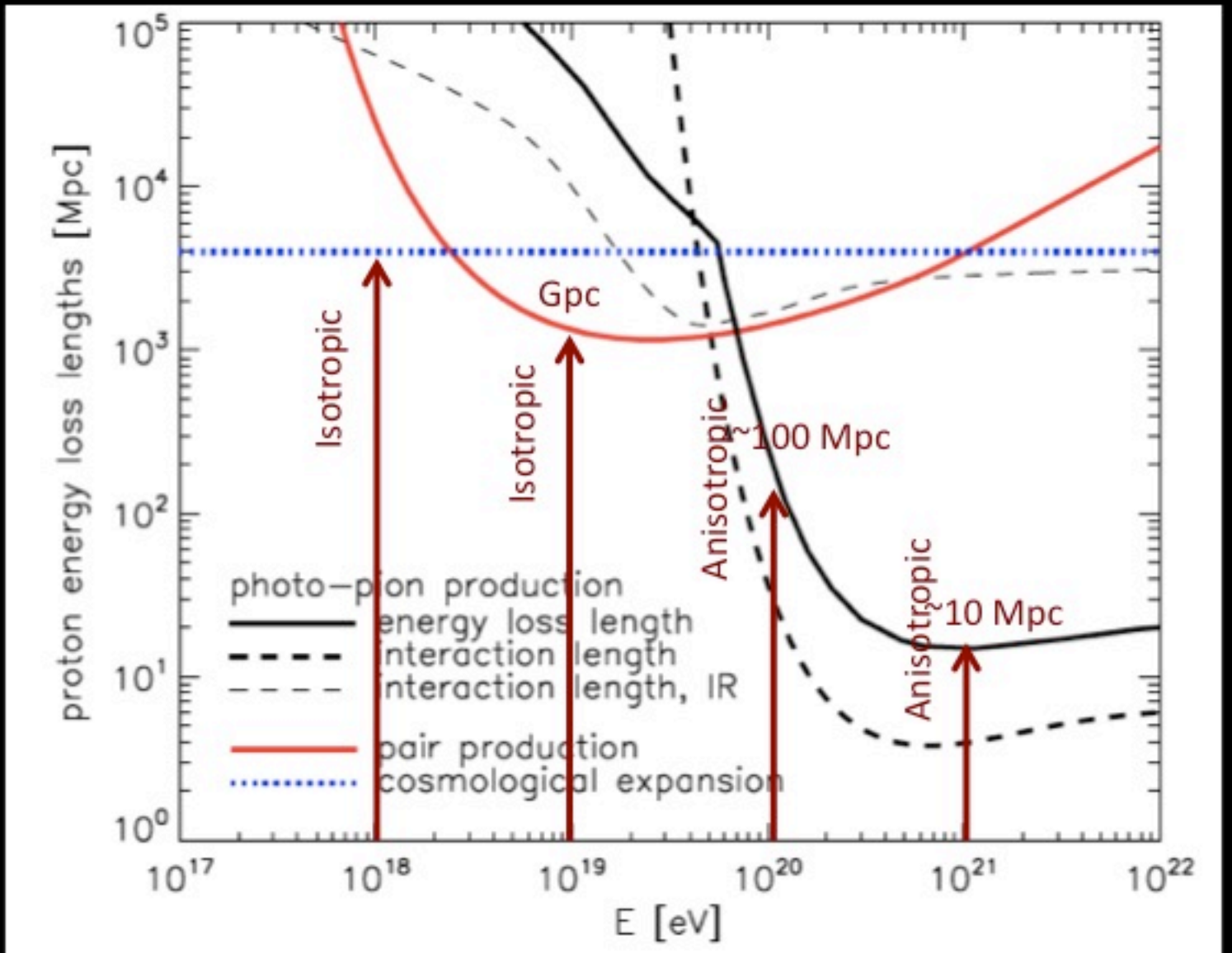


Kotera & AO 11

Greisen-Zatsepin-Kuzmin effect



Greisen-Zatsepin-Kuzmin effect

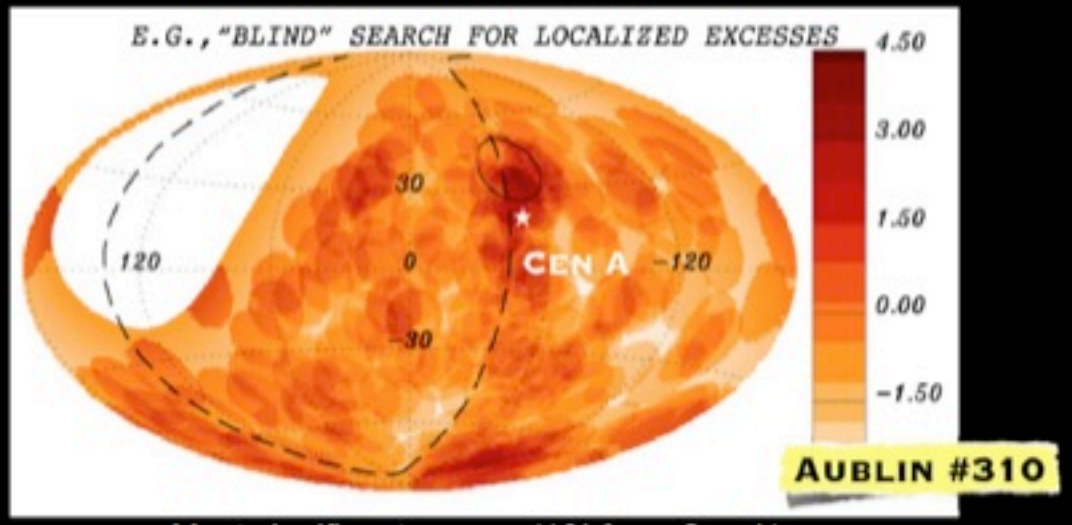


Recent Auger Results

At small/intermediate scales: no evidence of anisotropy

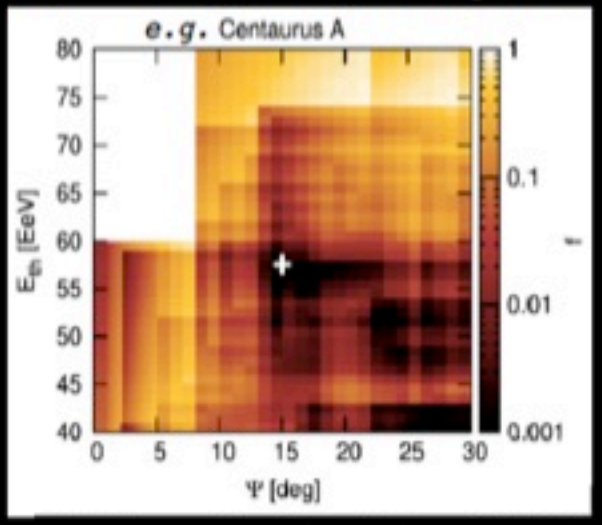
Data set: 602 events with E > 40 EeV, $\vartheta < 80^\circ$ (66450 km^2 sr y) Covered FOV in declination: -90° - +45°
Anisotropy tests over a wide range of angles: 1° - 30°; at different energy thresholds: 40 - 80 EeV

"INTRINSIC" ANISOTROPY TESTS
Cross-correlation, blind search for excesses



Most significant excess (18° from Cen A):
Post-trial probability: 69%

ASTROPHYSICAL CATALOGS TESTS
2MRS galaxies, Swift-BAT AGNs, radio galaxies, Cen A



Minimum at = 15° and E_{th} = 58 EeV
Post-trial probability: 1.4%

NO STATISTICALLY SIGNIFICANT DEVIATION FROM ISOTROPY IN NONE OF THE TESTS
The most significant deviations from isotropy are at intermediate scales

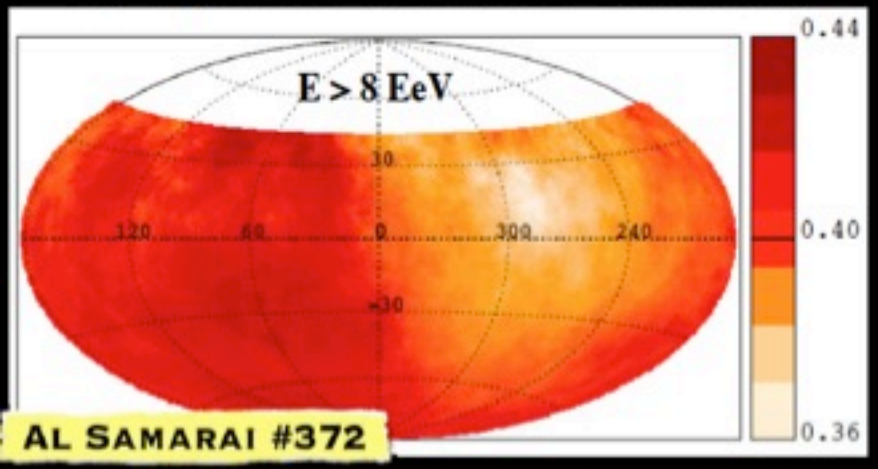
Ghia for Auger at ICRC15

Recent Auger Results

At large scales: indication of a dipole at E>8 EeV

AUGER: Harmonic analysis in right ascension and azimuth (declination-sensitive)
≈ 70000 events with E>4 EeV and $\vartheta < 80°$
85% sky coverage. Two energy bins: 4-8 EeV and > 8 EeV

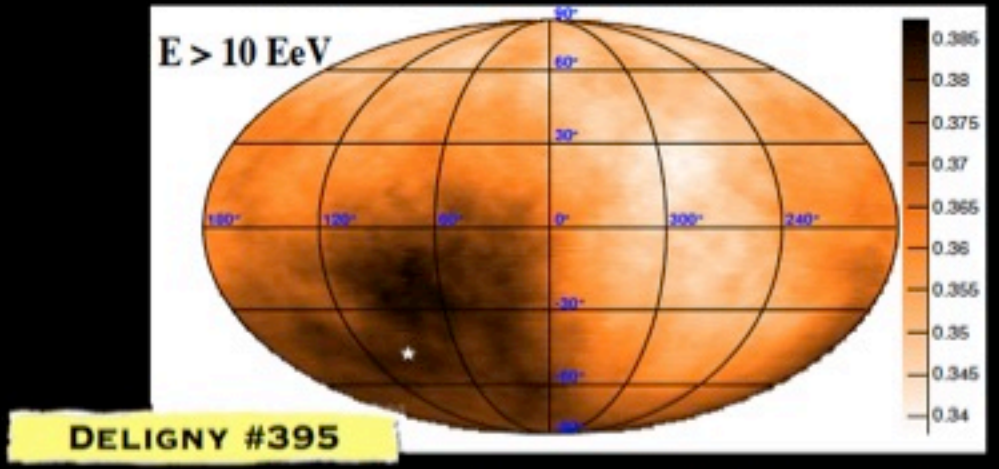
Sky map of the CR flux (45° smoothing)



Dipole Amplitude: 7.3 ± 1.5% (p=6.4x10^{-5})
Pointing to (a, d) = (95°±13°, -39°±13°)

AUGER and TA: Spherical harmonic analysis
≈ 17000 Auger events and ≈ 2500 TA events with E>10 EeV
Full sky coverage

Sky map of the CR flux (60° smoothing)



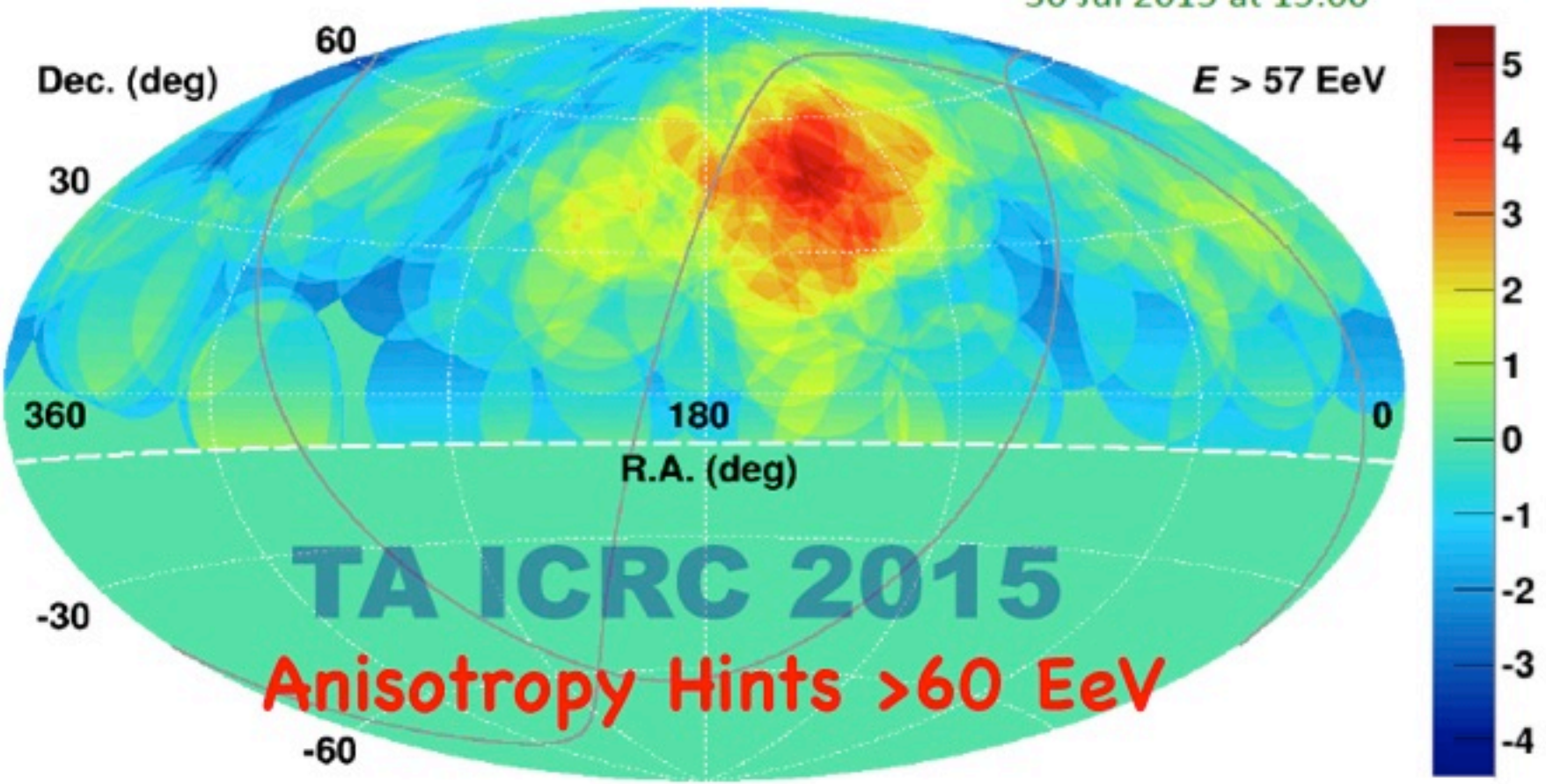
Dipole Amplitude: 6.5 ± 1.9% (p=5x10^{-3})
Pointing to (a, d) = (93°±24°, -46°±18°)

Indications of large-scale anisotropies of CRs at E > 8-10 EeV challenging the original expectations of isotropy at these energies

TA Results

7 Year Excess Map

[414 - PoS 276] Parallel CR03
Aniso Track: CREX Presented
by Kazumasa KAWATA on
30 Jul 2015 at 15:00



Max significance **5.1**σ (N_{SIG} = 24, N_{BG}=6.88) for 7 years
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)
Global Excess Chance Probability: 3.7×10^{-4} : 3.4σ (~ same as first 5 years)

UHECRs Current Status

Leading Observatories: Auger & Telescope Array agree on the shape of the spectrum

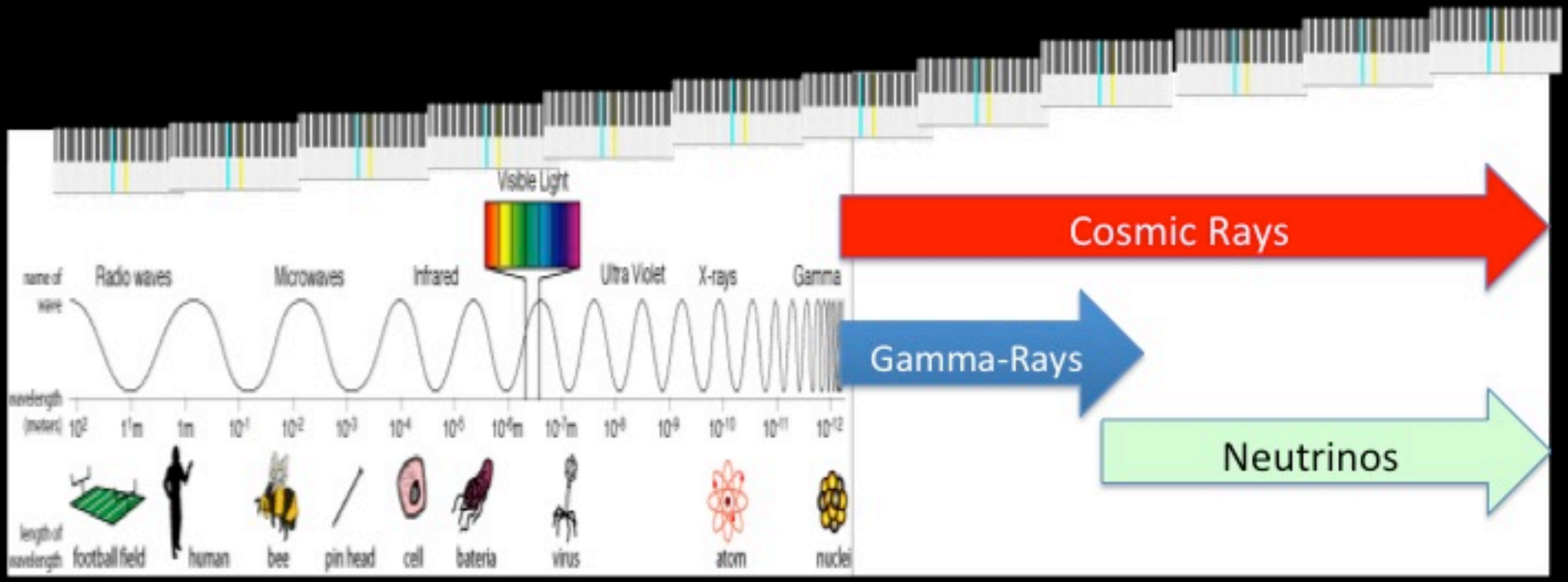
Composition: transition to mixed at highest energies

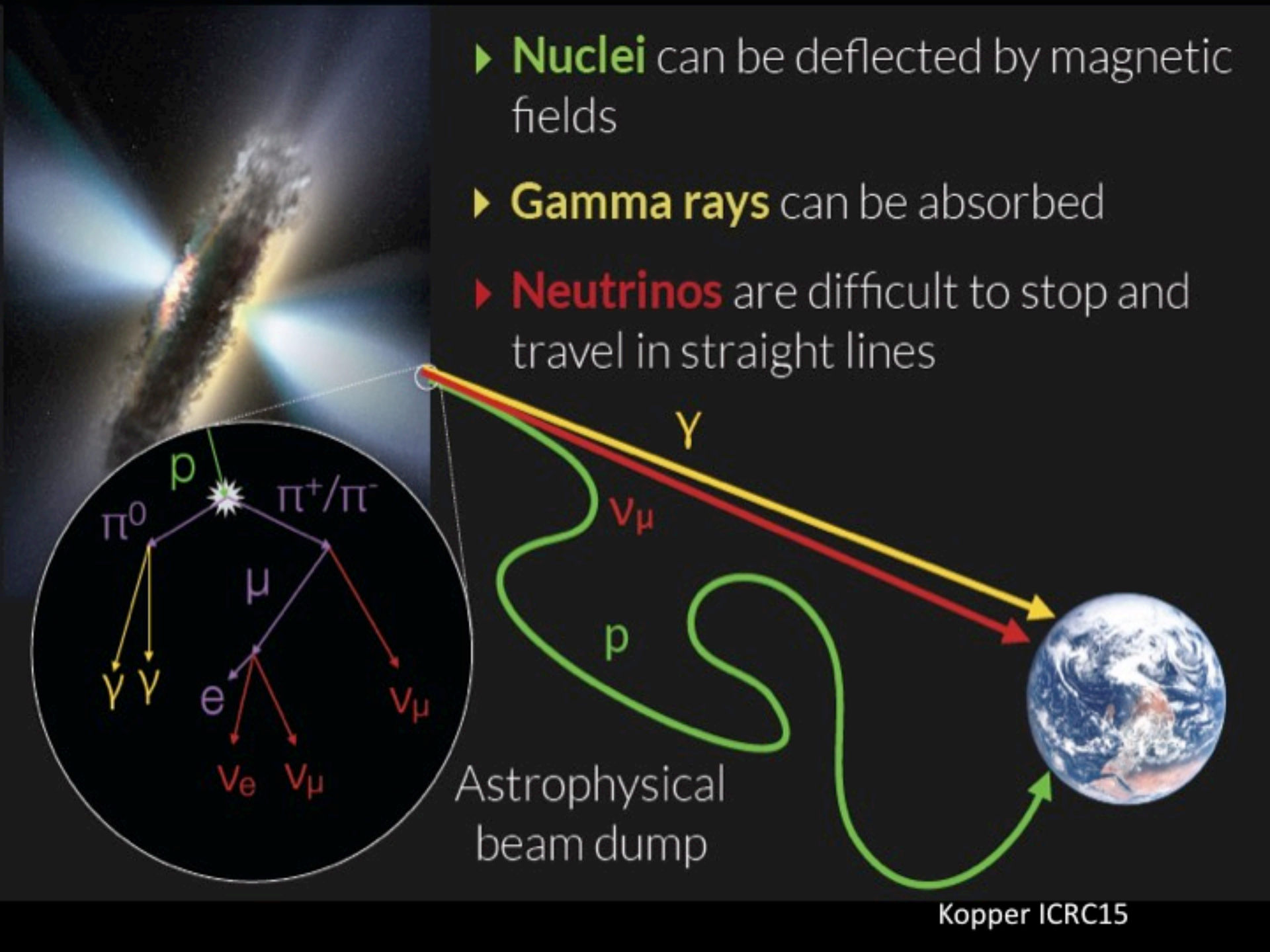
Anisotropies: large scale change at 10 EeV, hints of (TA) hotspot above 60 EeV

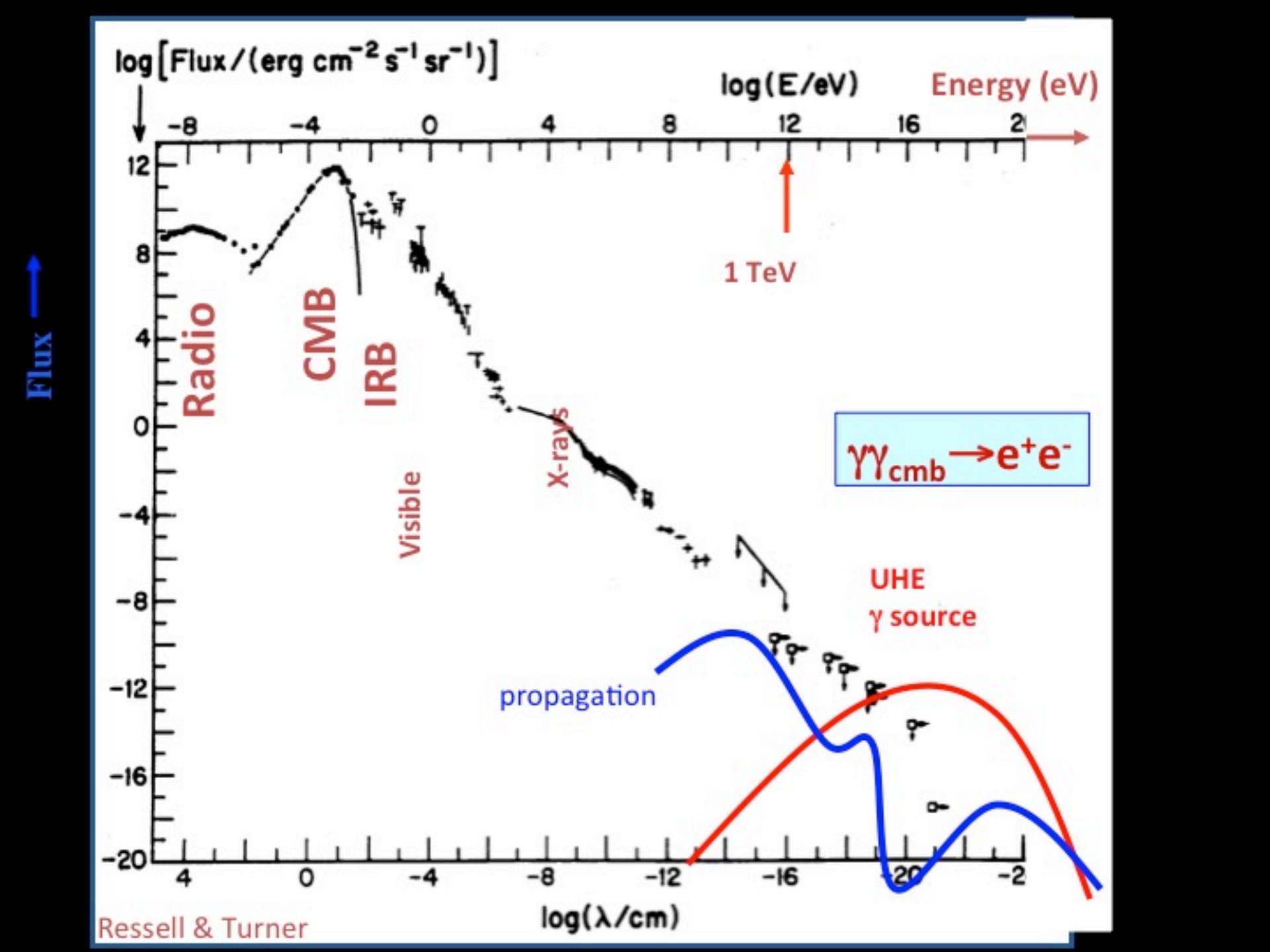
Multi-messenger clues?

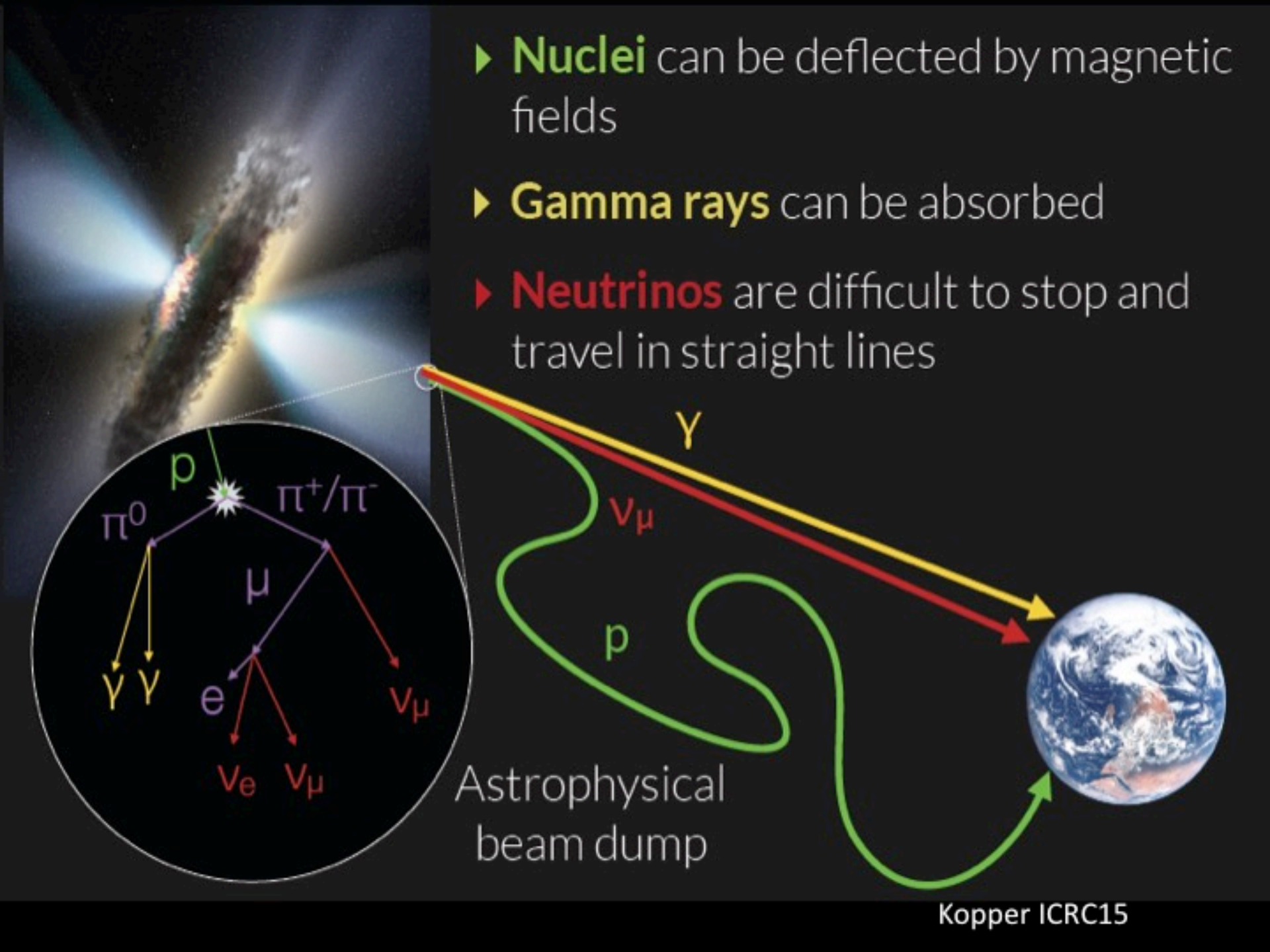
High Energy Particles

neutrinos & gamma-rays



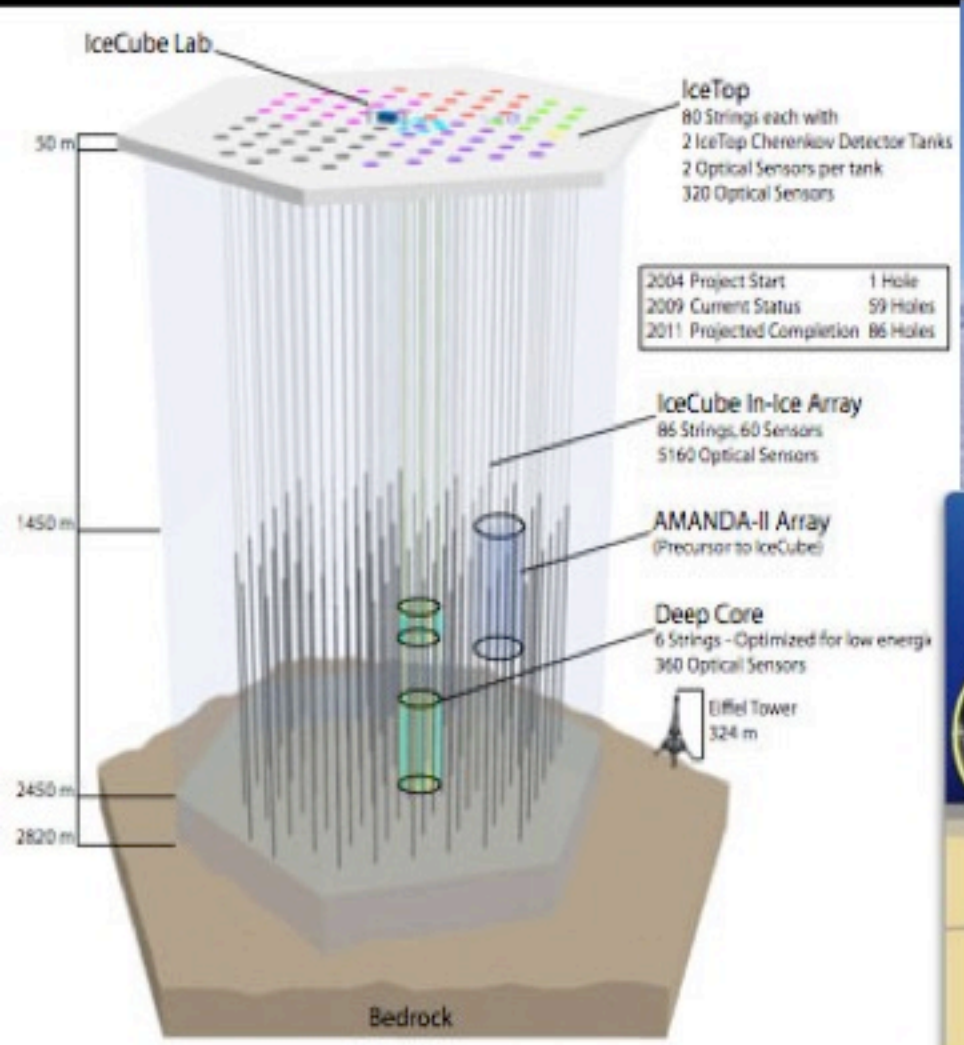

Nuclei can be deflected by magnetic fields
Gamma rays can be absorbed
Neutrinos are difficult to stop and travel in straight lines
γ
νμ
p
p
π+/π-
π0
μ
γ γ
e
νμ
νe νμ
Astrophysical beam dump
Kopper ICRC15


log[Flux/(erg cm^{-2} s^{-1} sr^{-1})]
log(E/eV)
Energy (eV)
-8
-4
0
4
8
12
16
2
12
8
4
0
-4
-8
-12
-16
-20
1 TeV
Radio
CMB
IRB
Visible
X-rays
$\gamma\gamma_{cmb} \rightarrow e^+e^-$
UHE
γ source
propagation
Flux
4
0
-4
-8
-12
-16
-20
-2
log(λ/cm)
Ressell & Turner

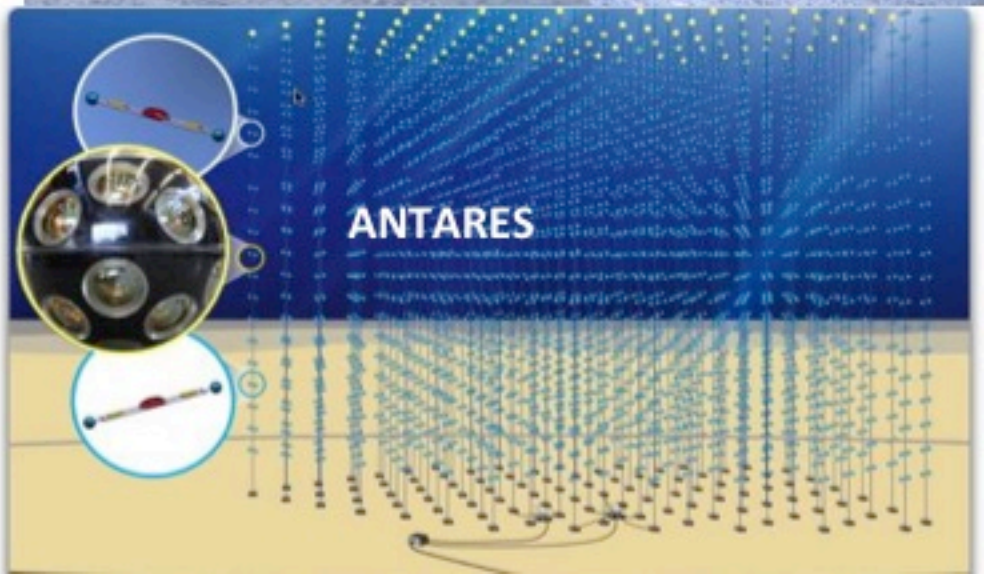

Nuclei can be deflected by magnetic fields
Gamma rays can be absorbed
Neutrinos are difficult to stop and travel in straight lines
γ
νμ
p
p
π+/π-
π0
μ
γ γ
e
νμ
νe νμ
Astrophysical beam dump
Kopper ICRC15

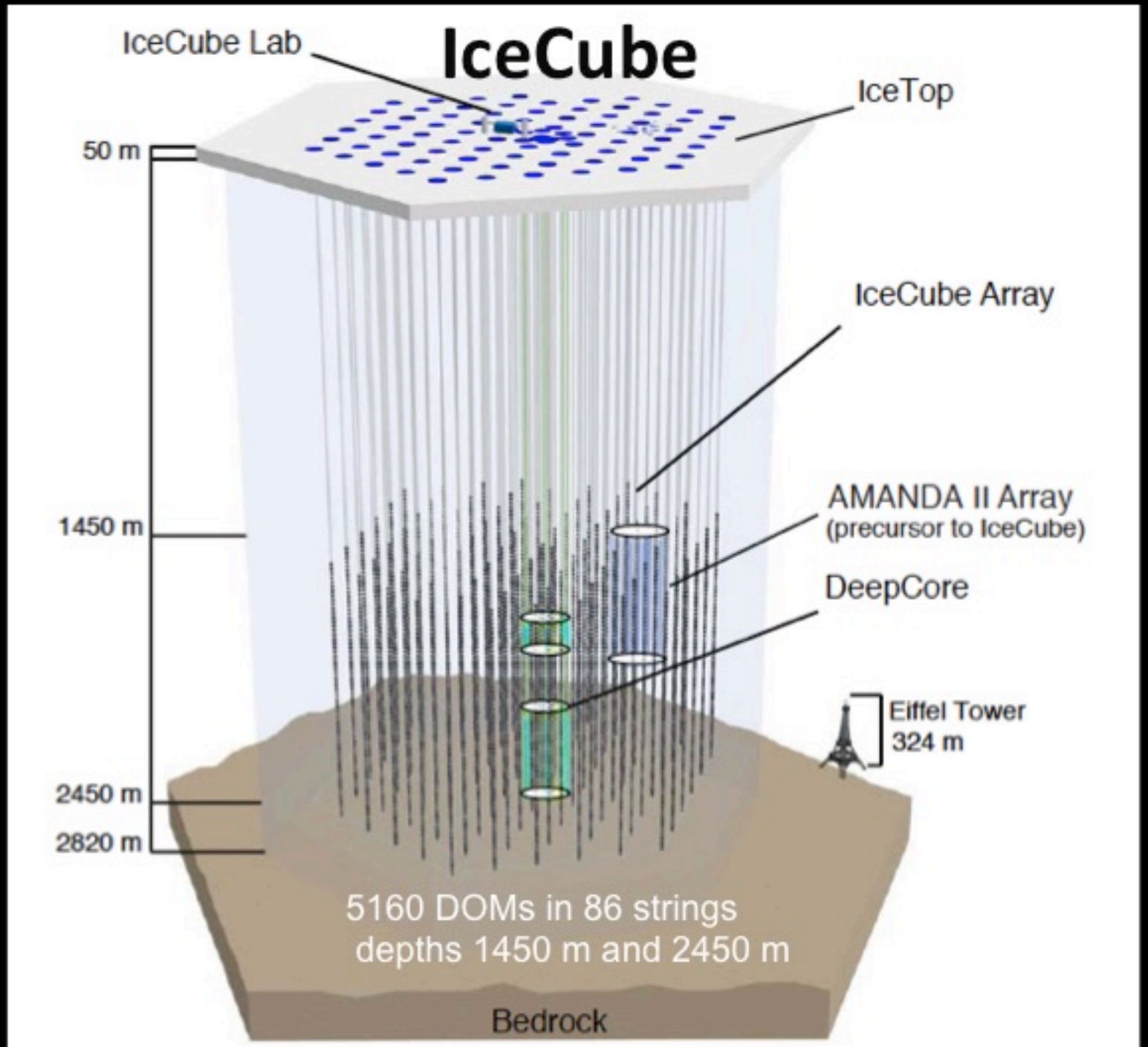
Highest Energy Neutrino Observatories

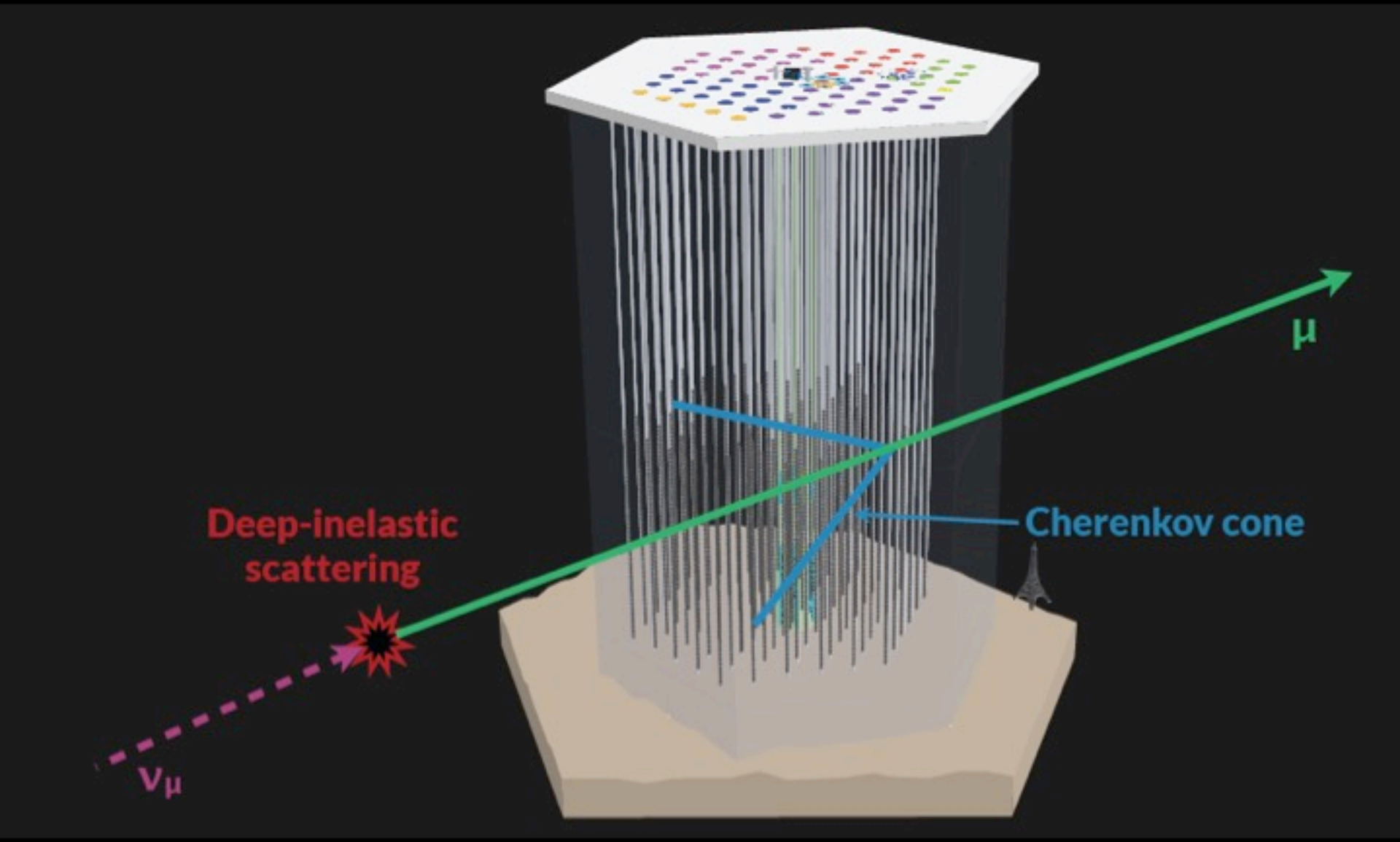
IceCube



ANITA




IceCube
IceCube Lab
IceTop
50 m
IceCube Array
AMANDA II Array
(precursor to IceCube)
1450 m
DeepCore
Eiffel Tower
324 m
2450 m
2820 m
5160 DOMs in 86 strings
depths 1450 m and 2450 m
Bedrock



Kopper ICRC15

time

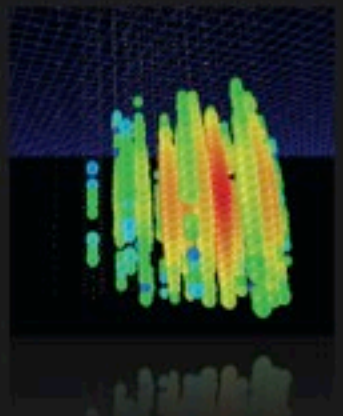
CC Muon Neutrino

$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



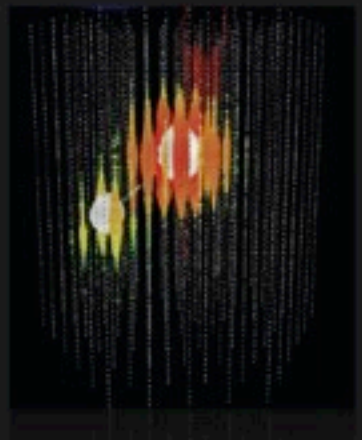
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

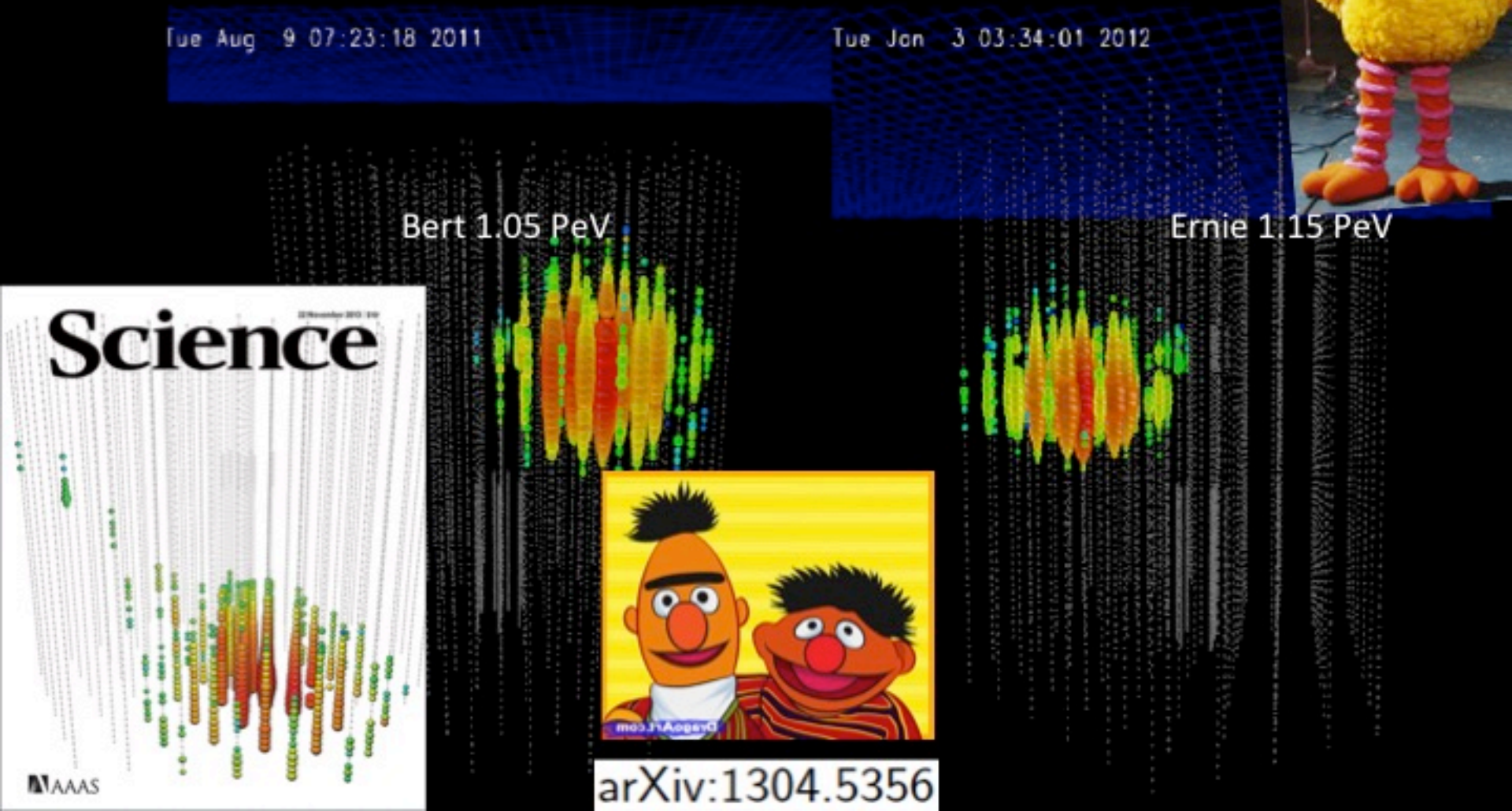
"double-bang" (≳10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

Kopper ICRC15

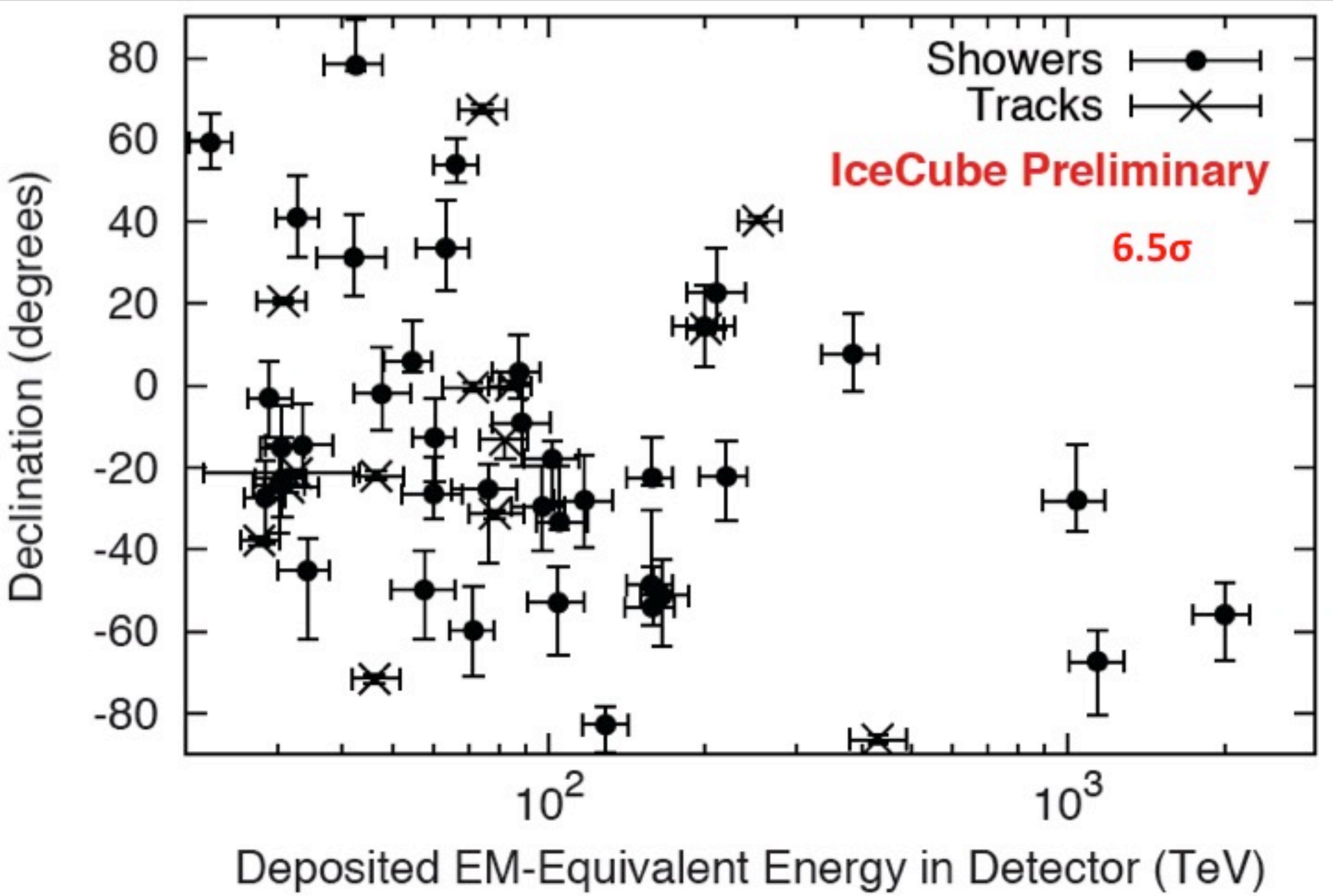
Neutrino Astronomy Begin

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

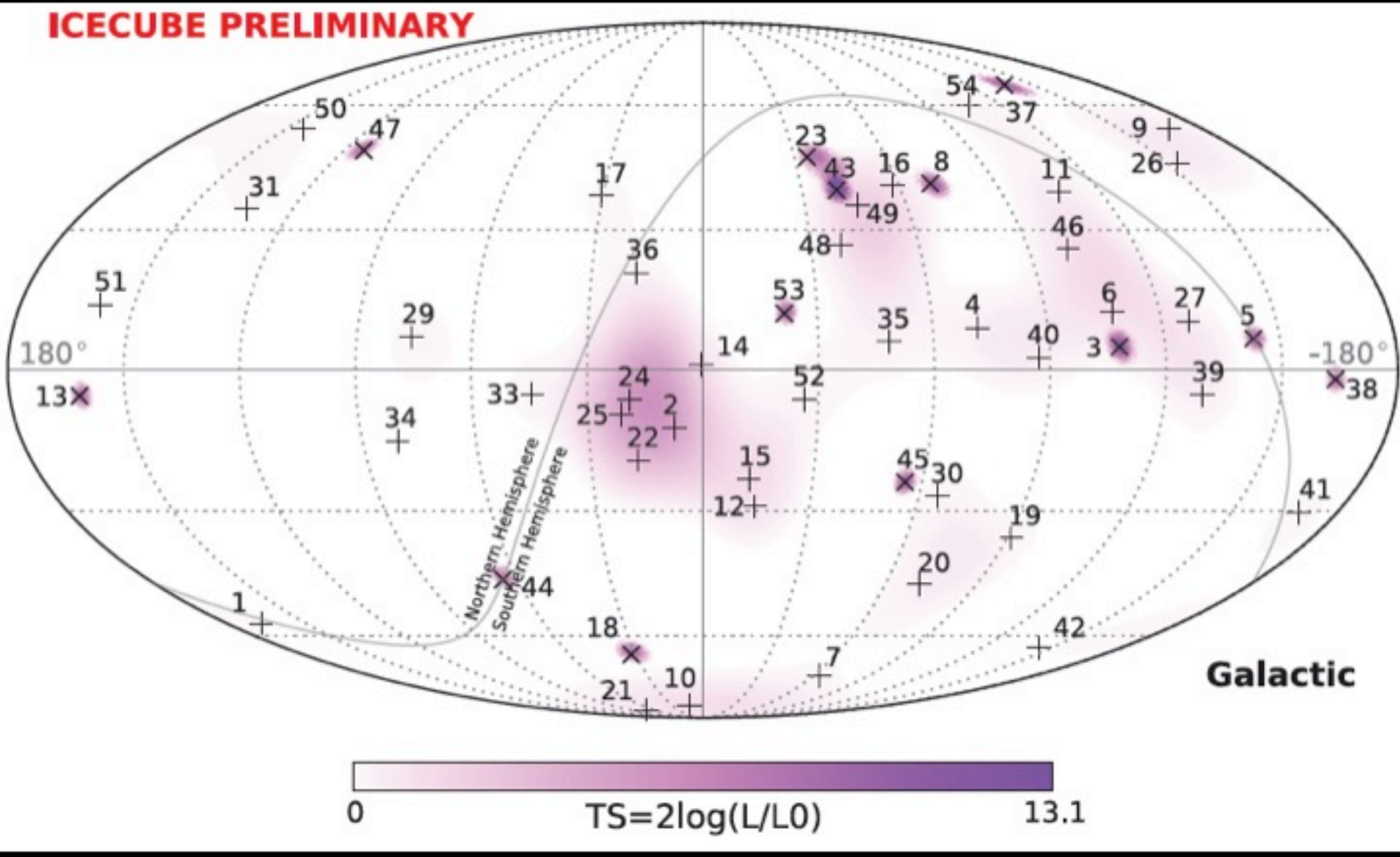


arXiv:1304.5356

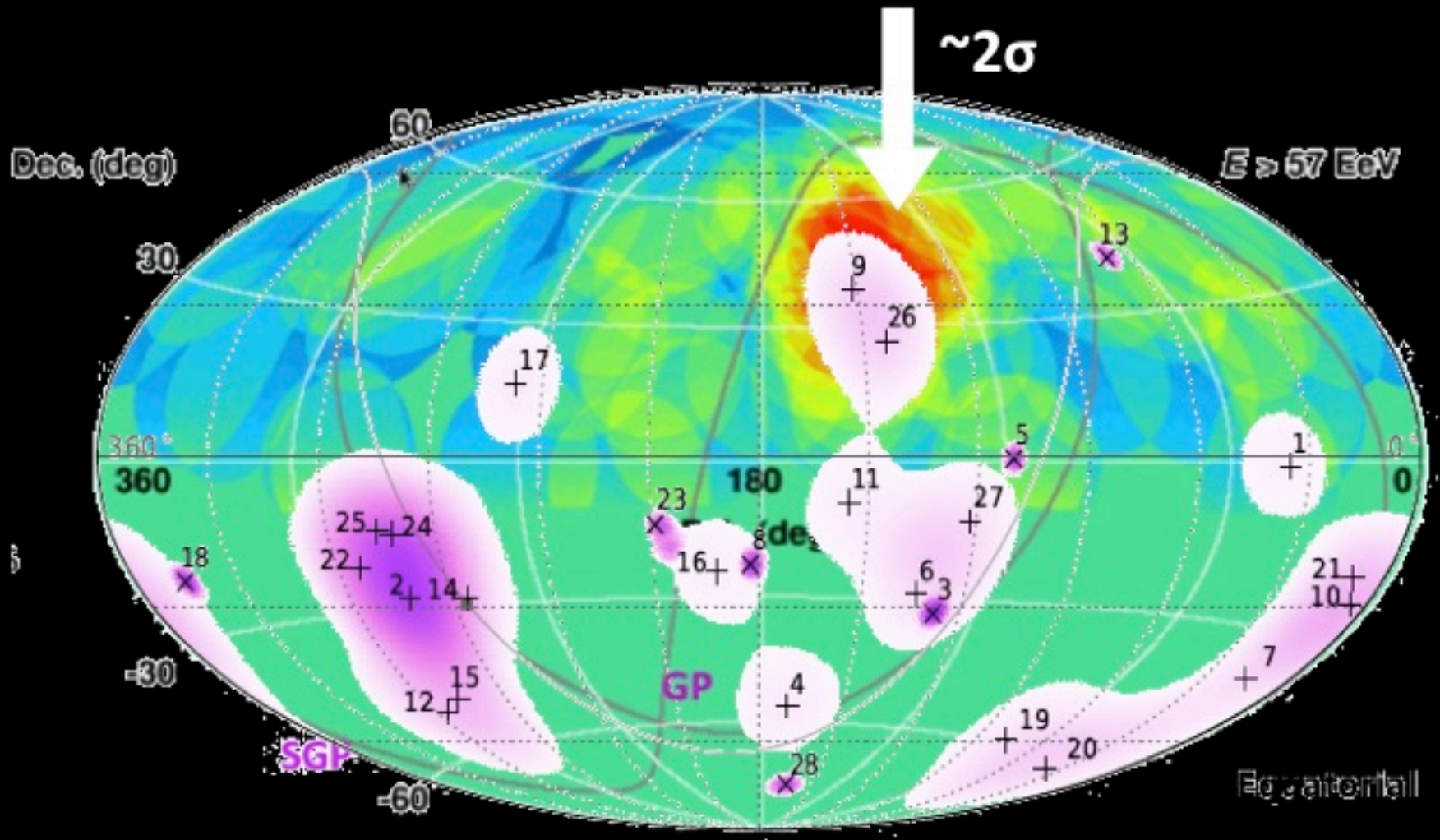
54 Events


Showers
Tracks
IceCube Preliminary
6.5σ
Declination (degrees)
80
60
40
20
0
-20
-40
-60
-80
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

54 Events

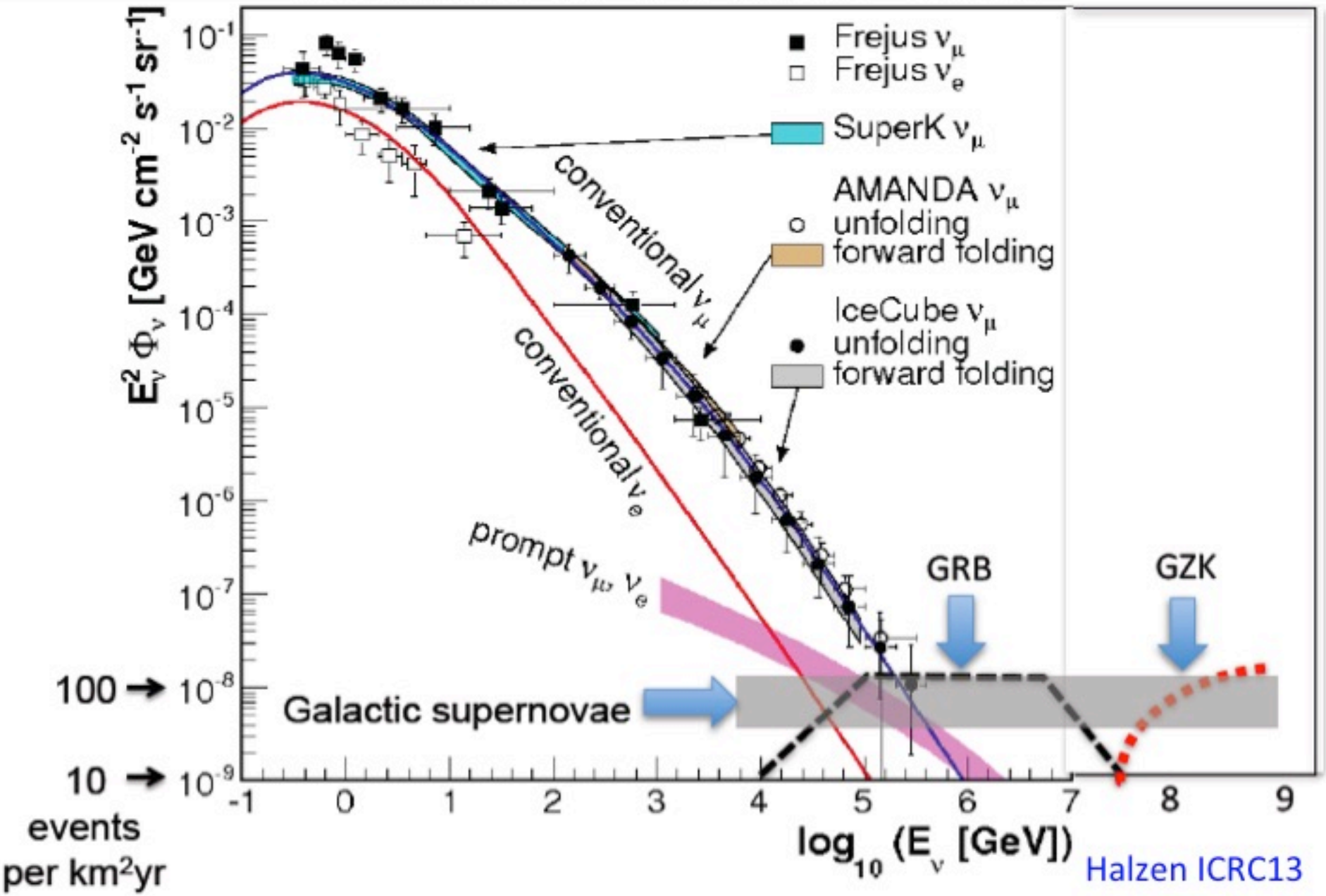

ICECUBE PRELIMINARY
180°
-180°
Northern Hemisphere
Southern Hemisphere
Galactic
0
TS=2log(L/L0)
13.1

Neutrino & UHECR Coincidence



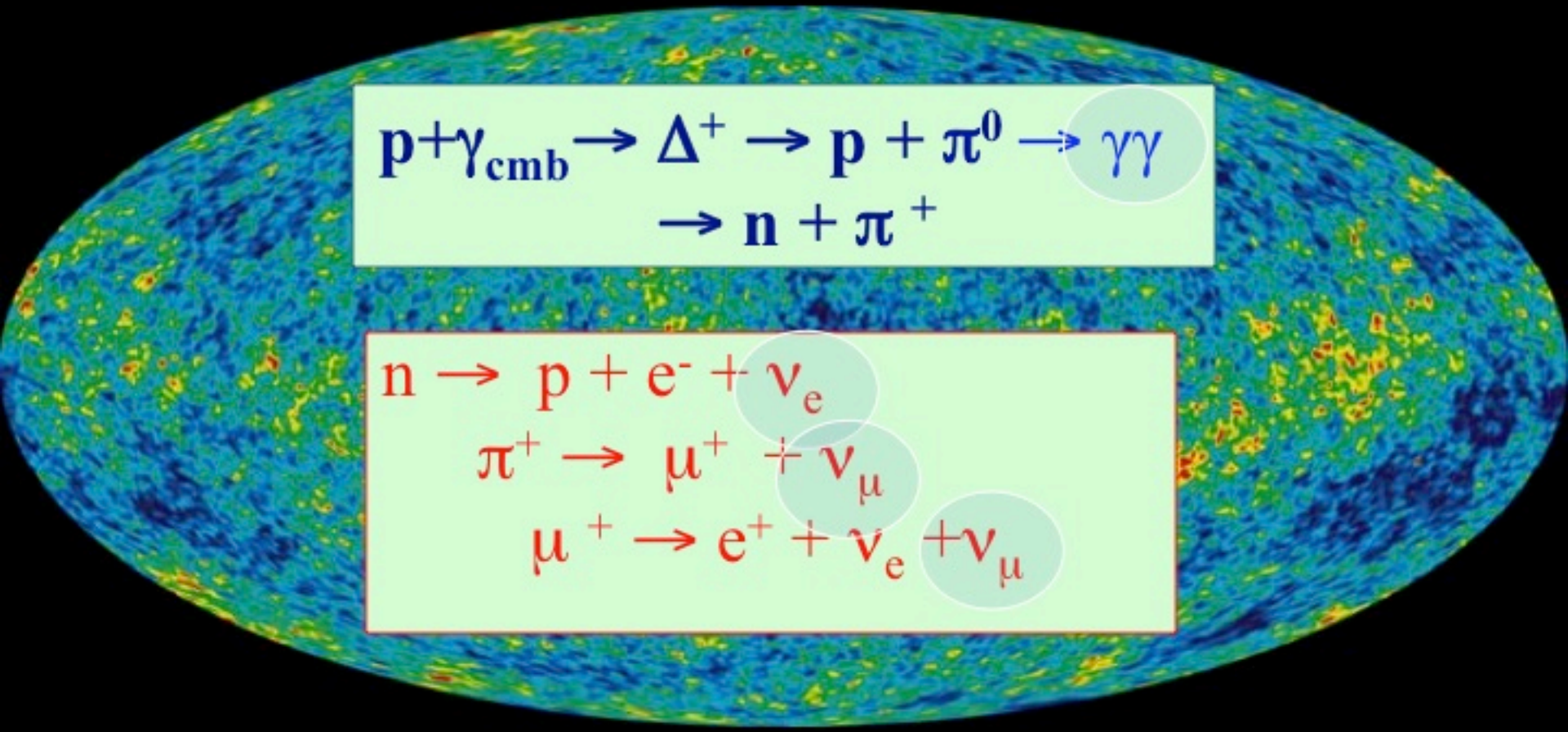
Fang, Fujii, Linden, AO '14

Galactic or XtraGal CRs?



Halzen ICRC13

Cosmogenic (GZK, BZ*) Neutrinos & Photons



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

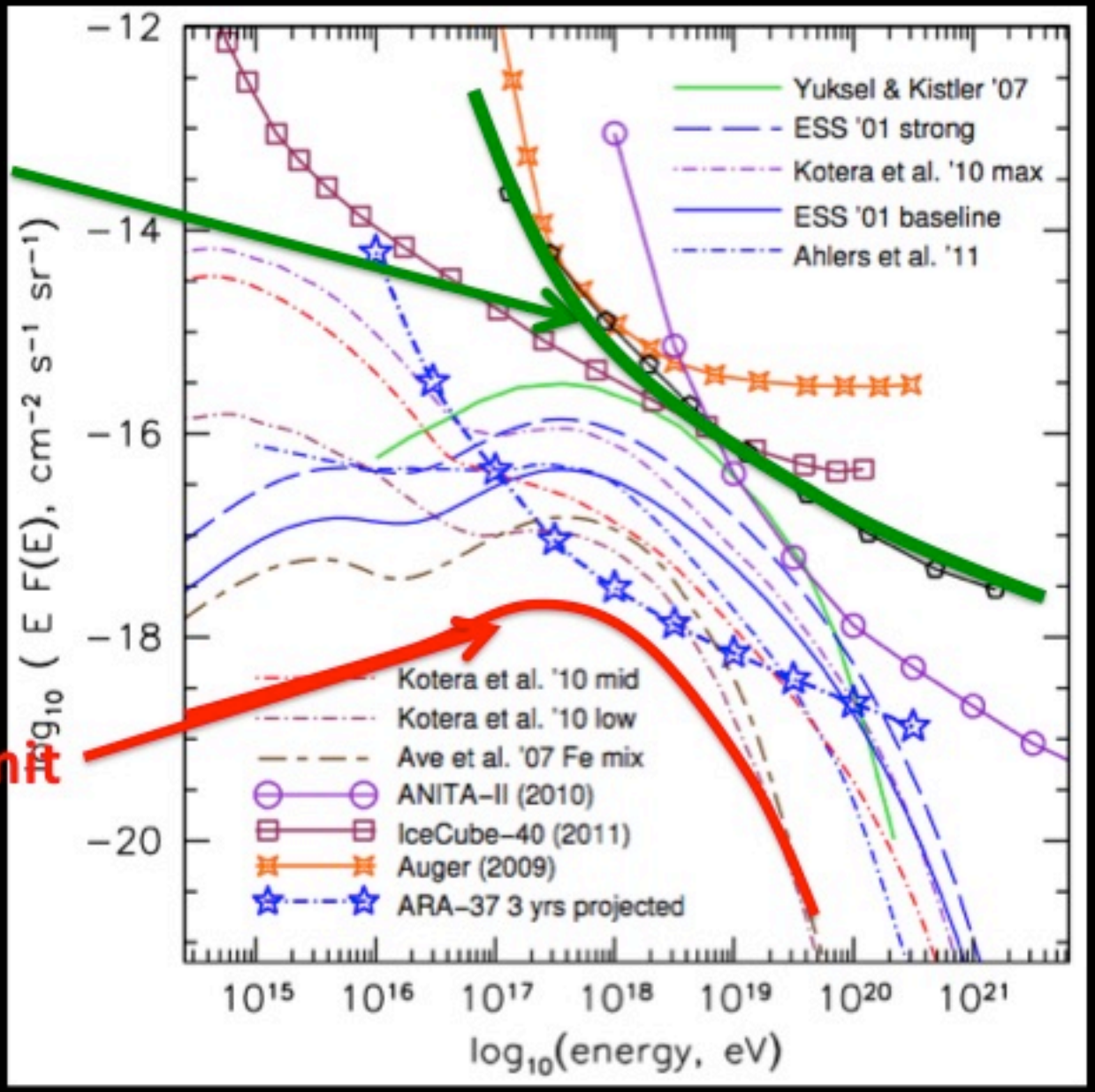
$$n \rightarrow p + e^{-} + \nu_{e}$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu}$$

*Berezinsky & Zatsepin '69

Neutrino Detectors

Current Limits

Flux Lower Limit

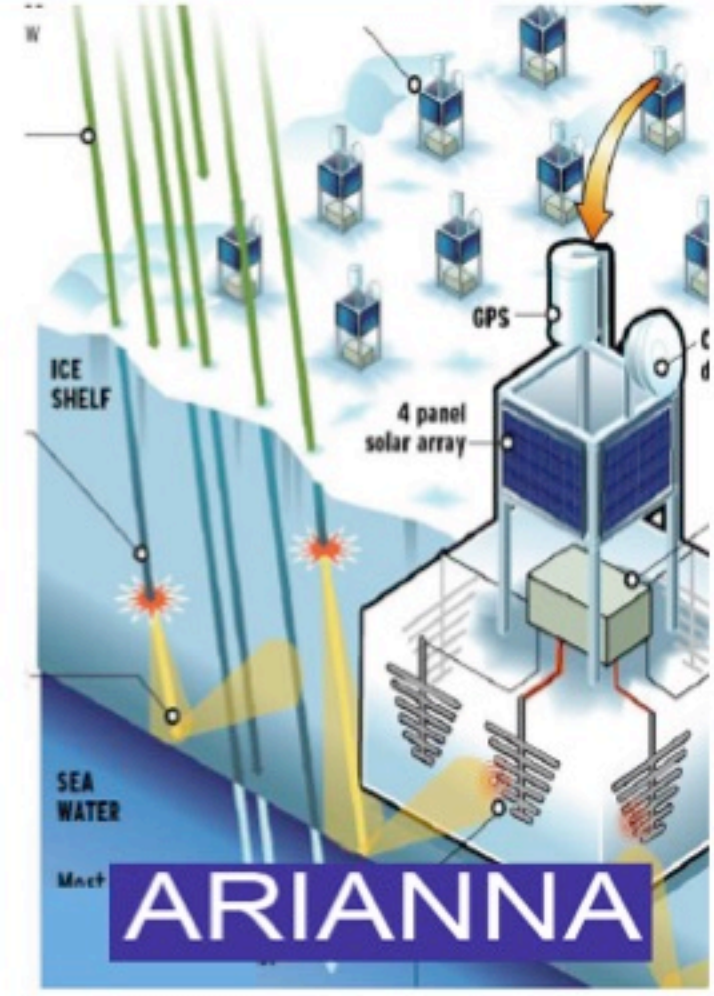


Next Generation UHE neutrinos

ExaVolt antenna (EVA)

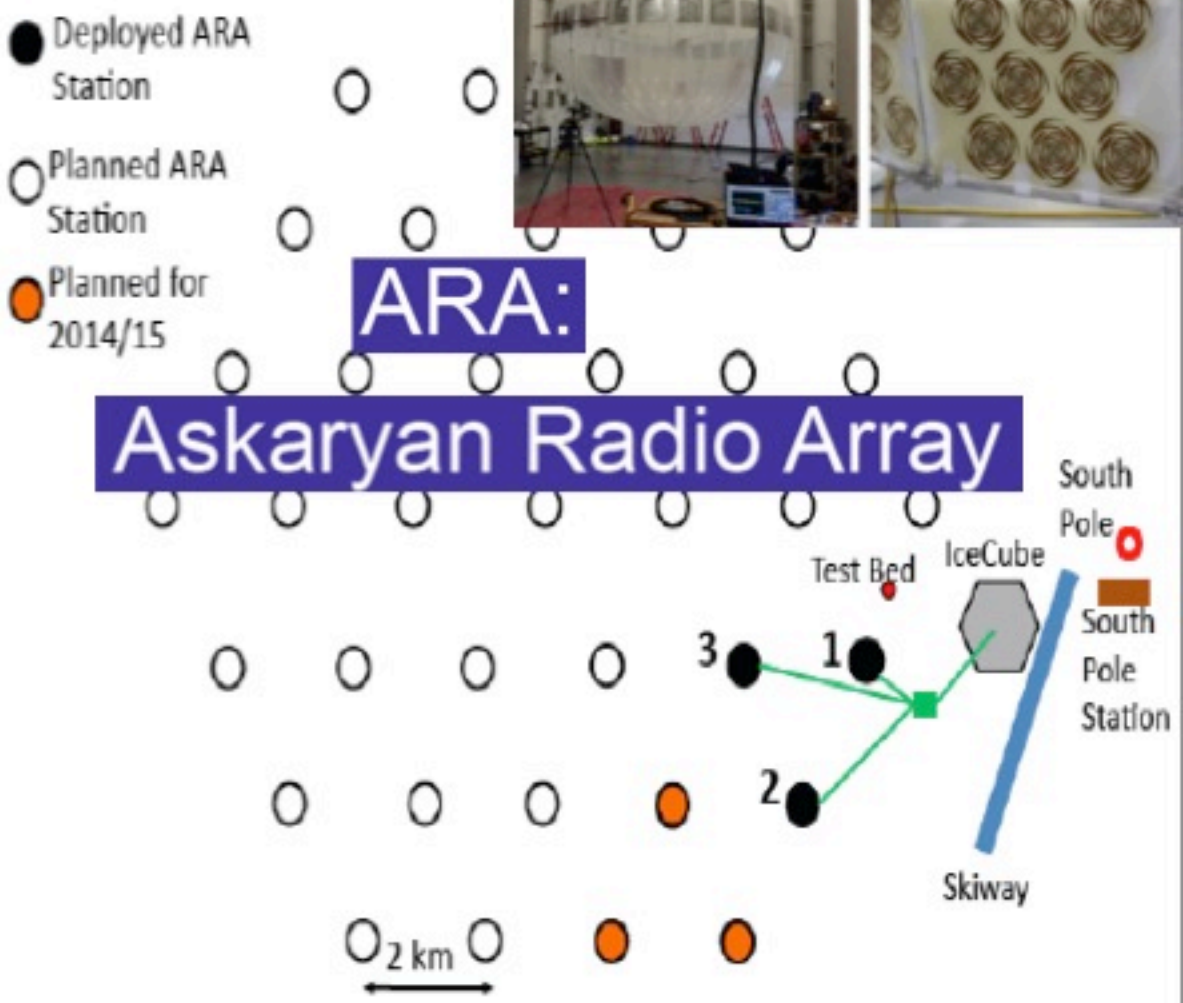
P. Gorham

Wallops: successful 1/20th scale model test,



ARIANNA

ARIANNA Coll. See arXiv:1207.3

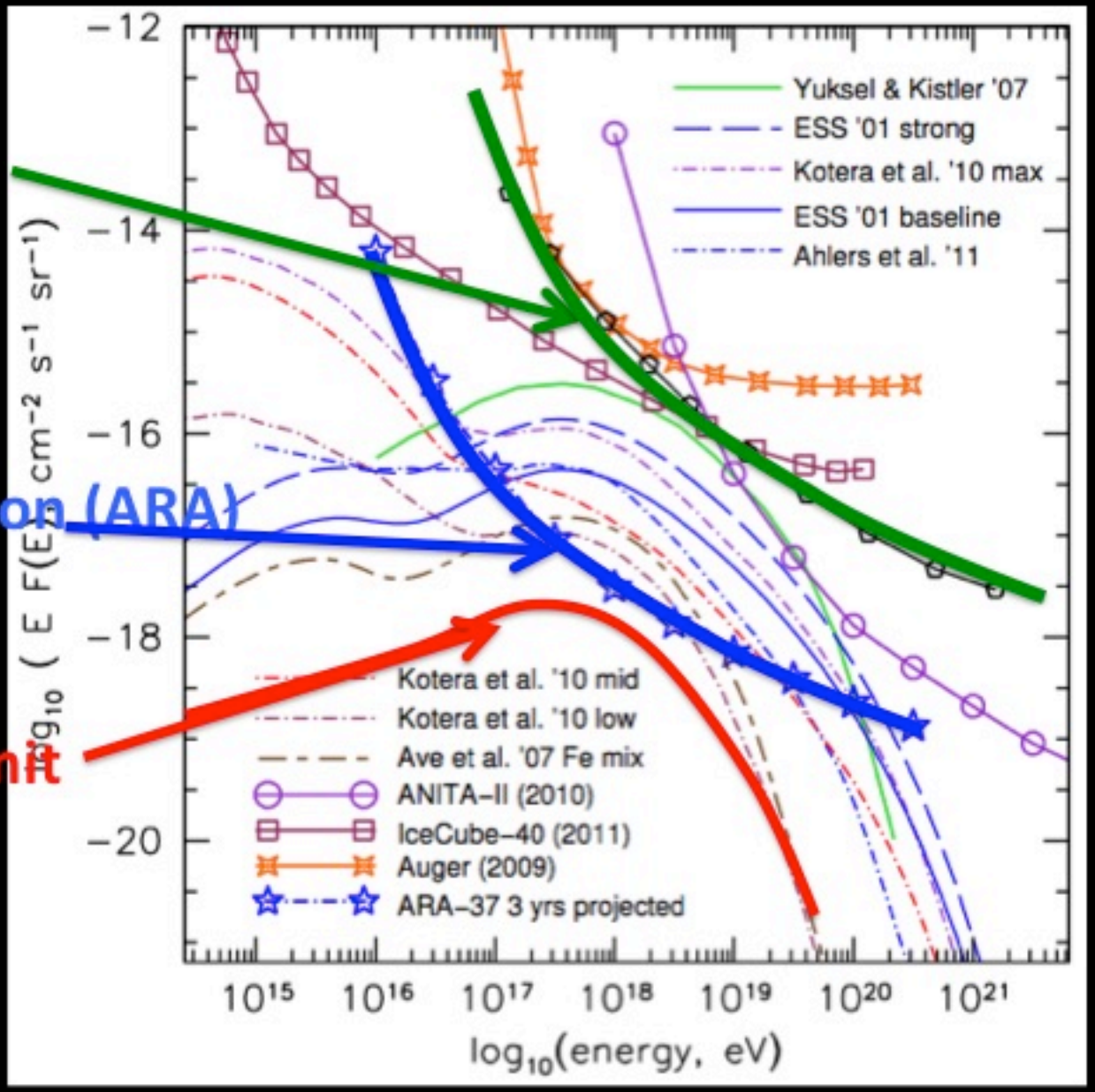


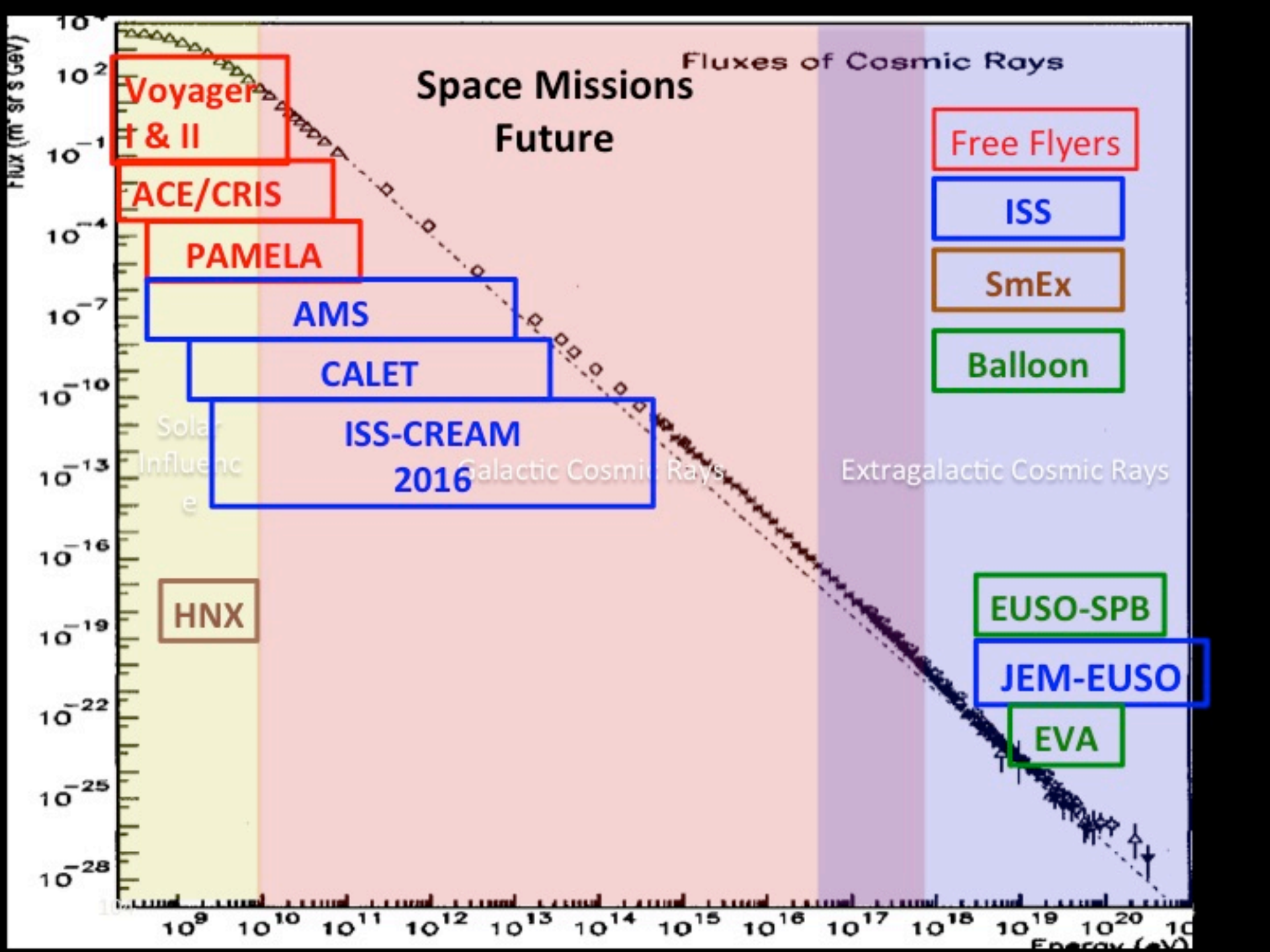
Neutrino Detectors

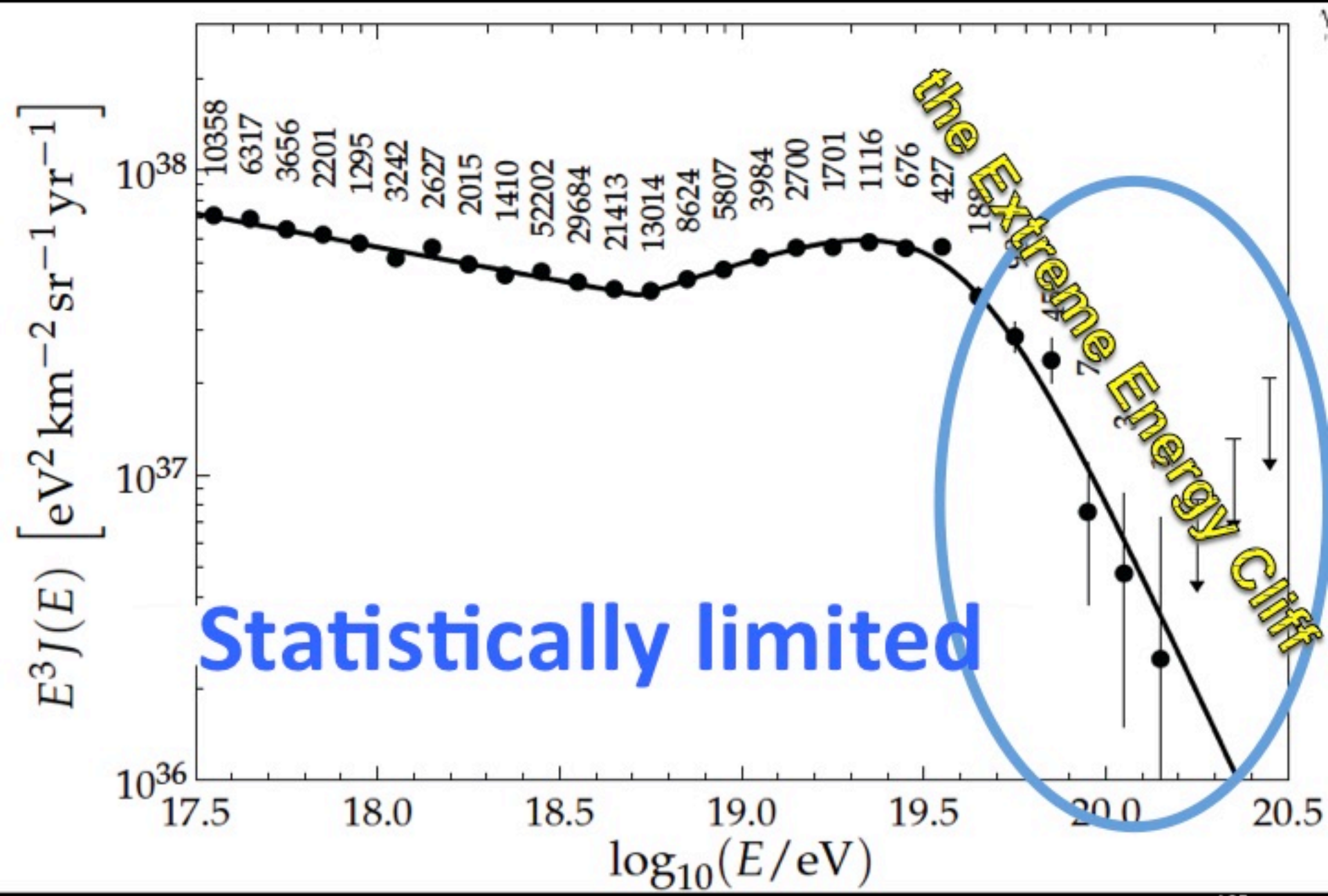
Current Limits

Next Generation (ARA)

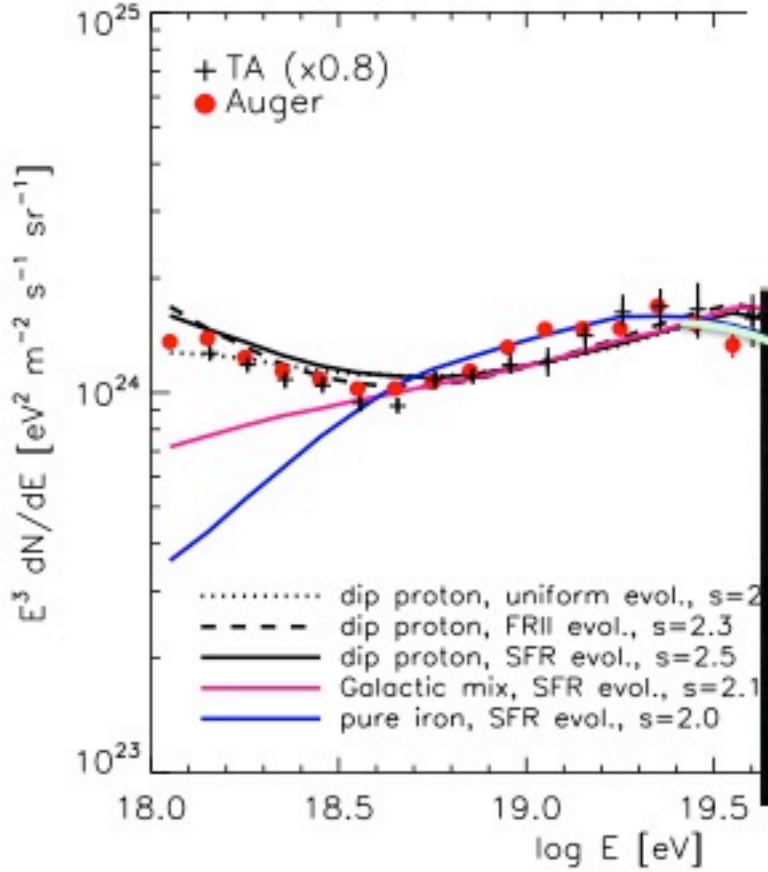
Flux Lower Limit

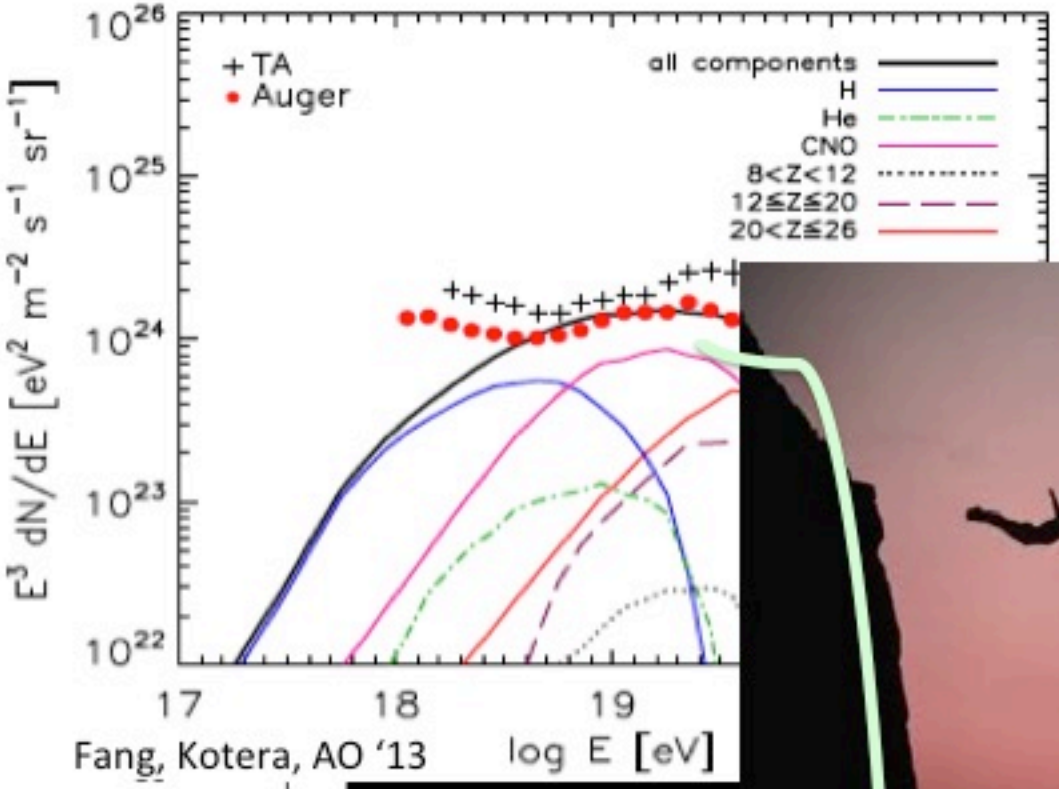


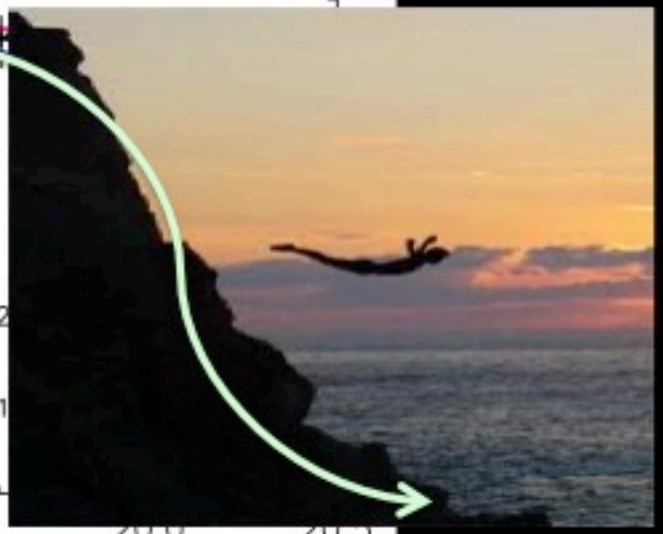

Fluxes of Cosmic Rays
Space Missions
Future
Voyager I & II
ACE/CRIS
PAMELA
AMS
CALET
ISS-CREAM 2016
HNX
Free Flyers
ISS
SmEx
Balloon
EUSO-SPB
JEM-EUSO
EVA
Galactic Cosmic Rays
Extragalactic Cosmic Rays

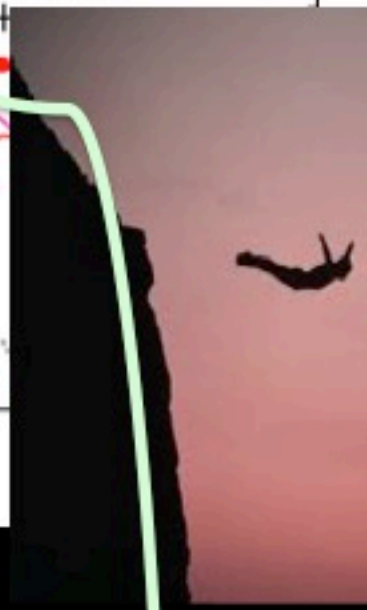

10358
6317
3656
2201
1295
3242
2627
2015
1410
52202
29684
21413
13014
8624
5807
3984
2700
1701
1116
676
427
182
45
7
3
the Extreme Energy Cliff
Statistically limited
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
10^{38}
10^{37}
10^{36}
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$

GZK vs E_{max}







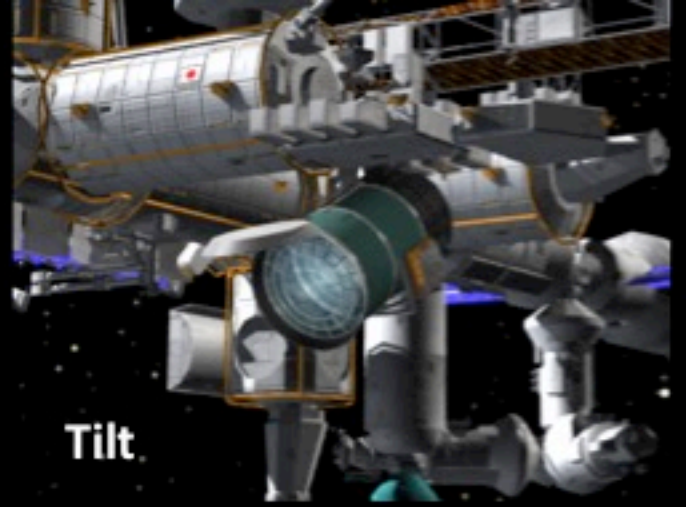


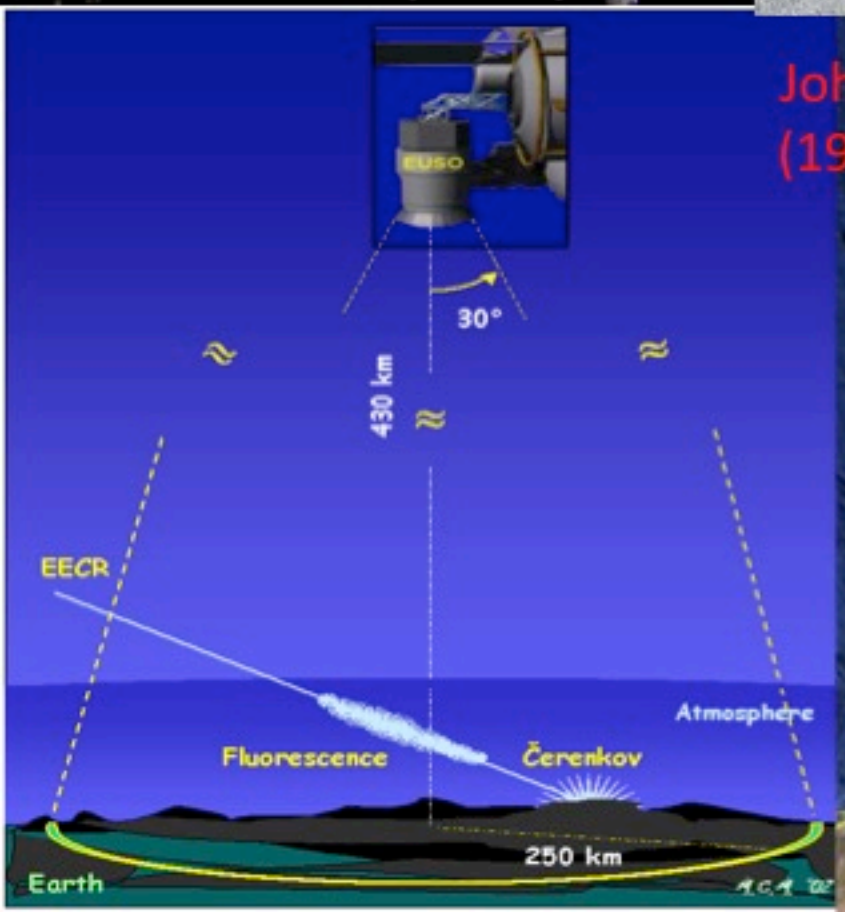
Kotera, AO '11

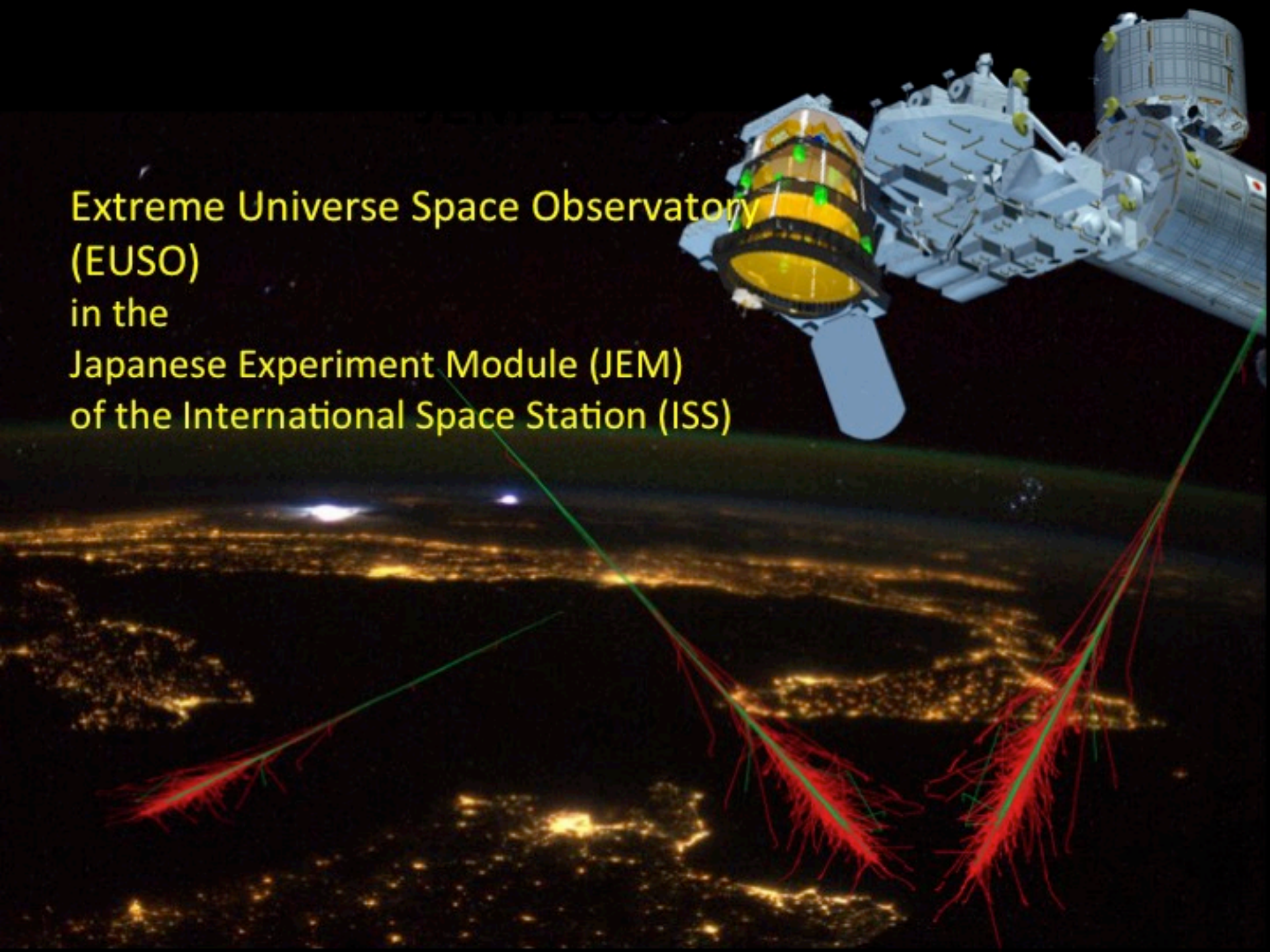
Off the Extreme Energy Cliff

Fluorescence from SPACE

John Linsley
(1925-2002)



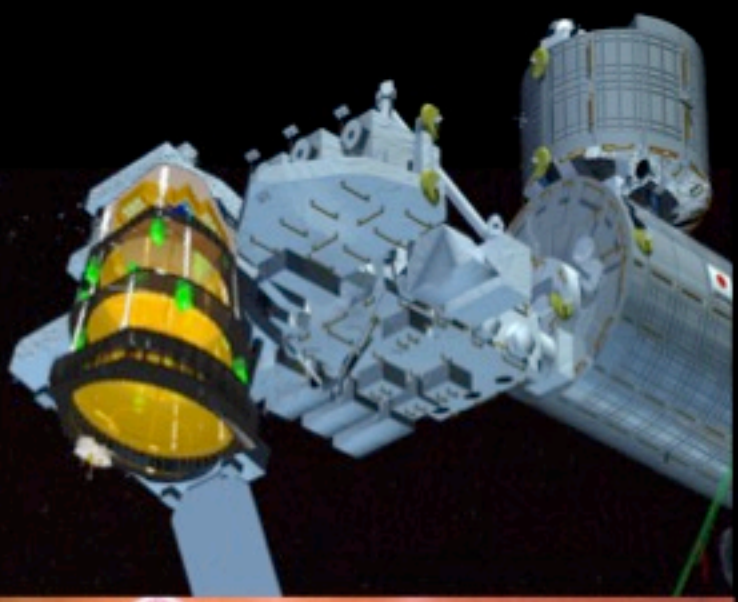


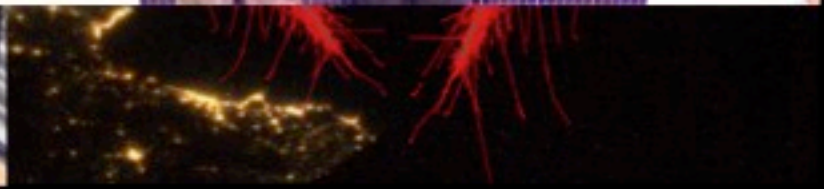

Extreme Universe Space Observatory
(EUSO)
in the
Japanese Experiment Module (JEM)
of the International Space Station (ISS)

JEM-EUSO Collaboration

Scientists from 16 countries

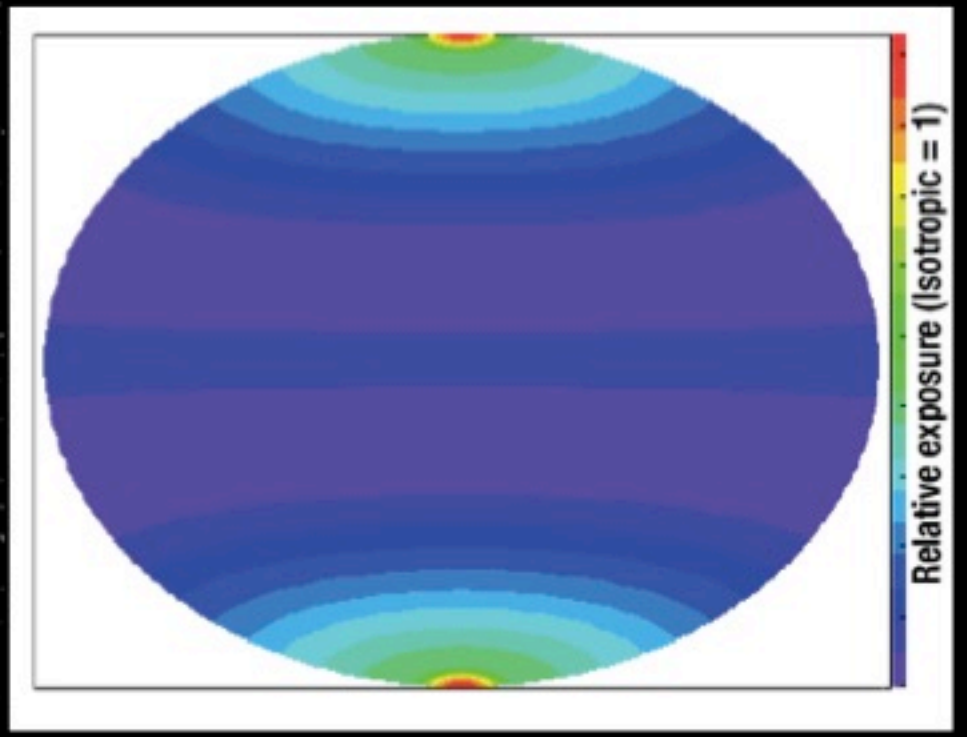
JEM-EUSO Telescope





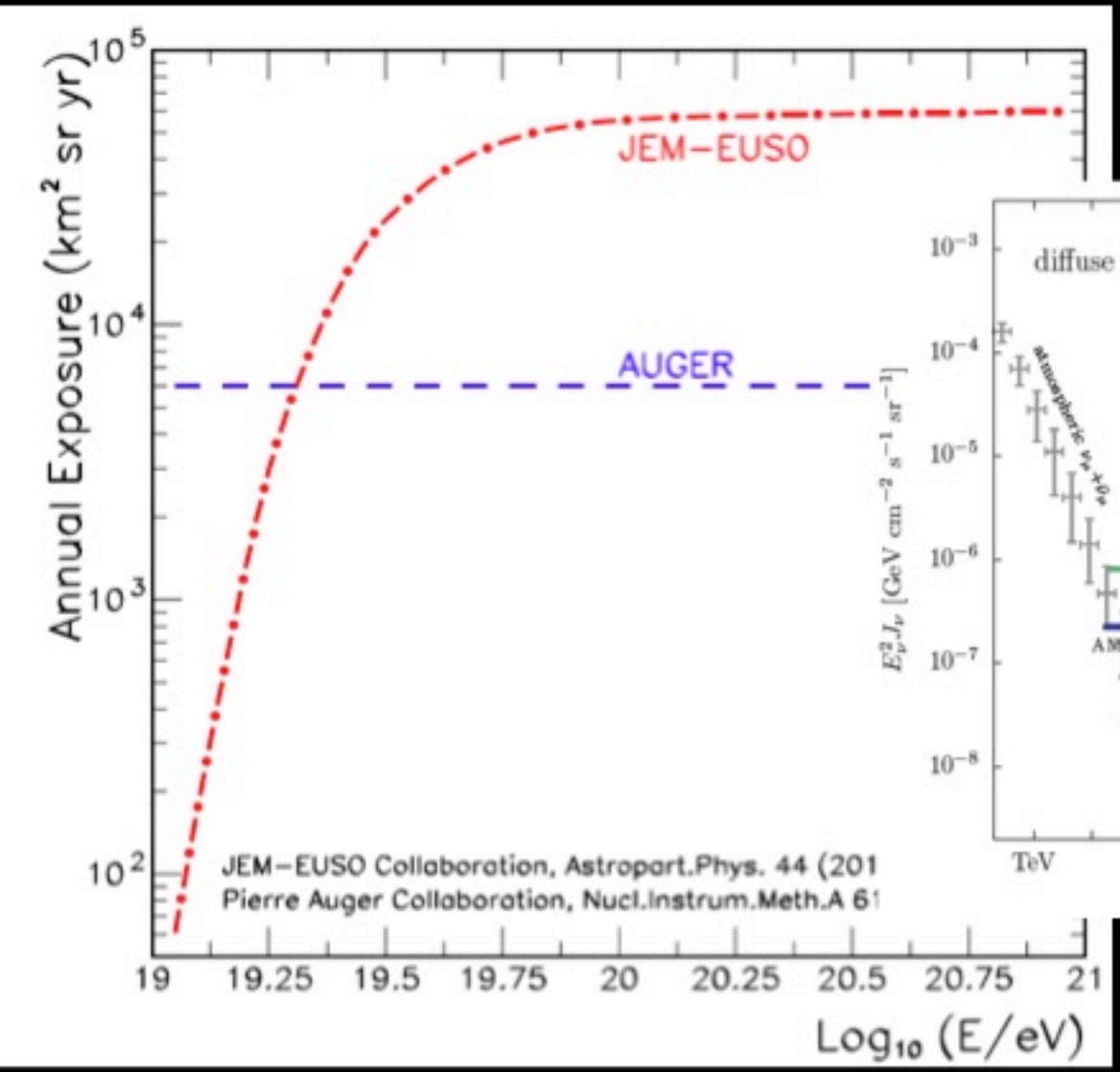
Full Sky Coverage

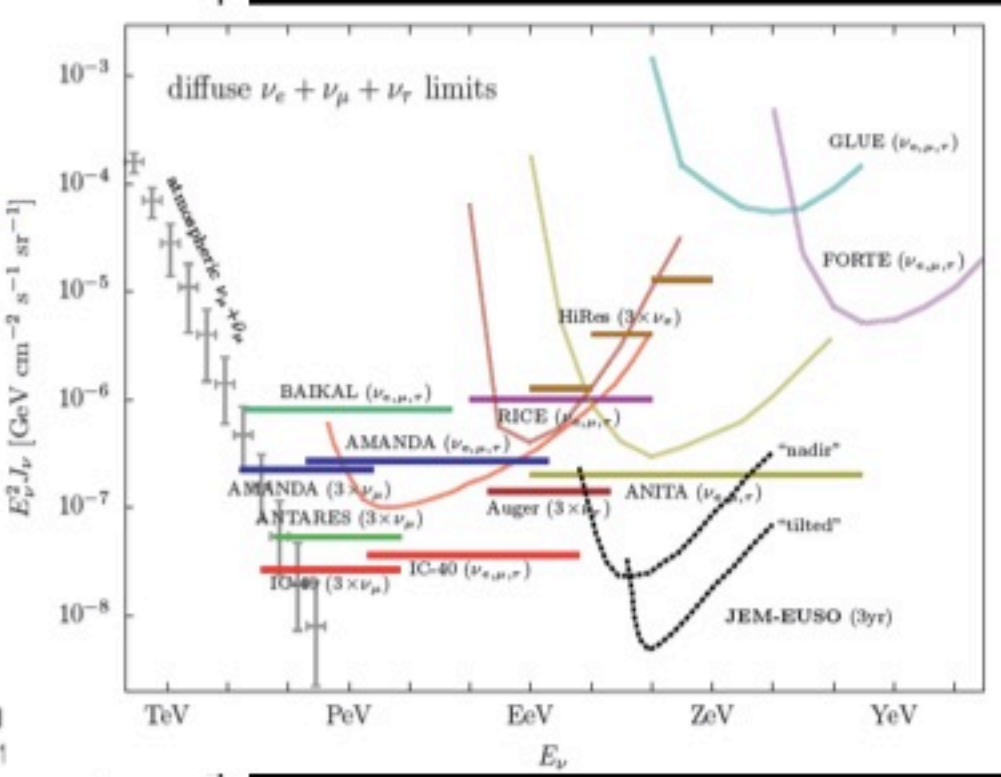
with nearly uniform exposure



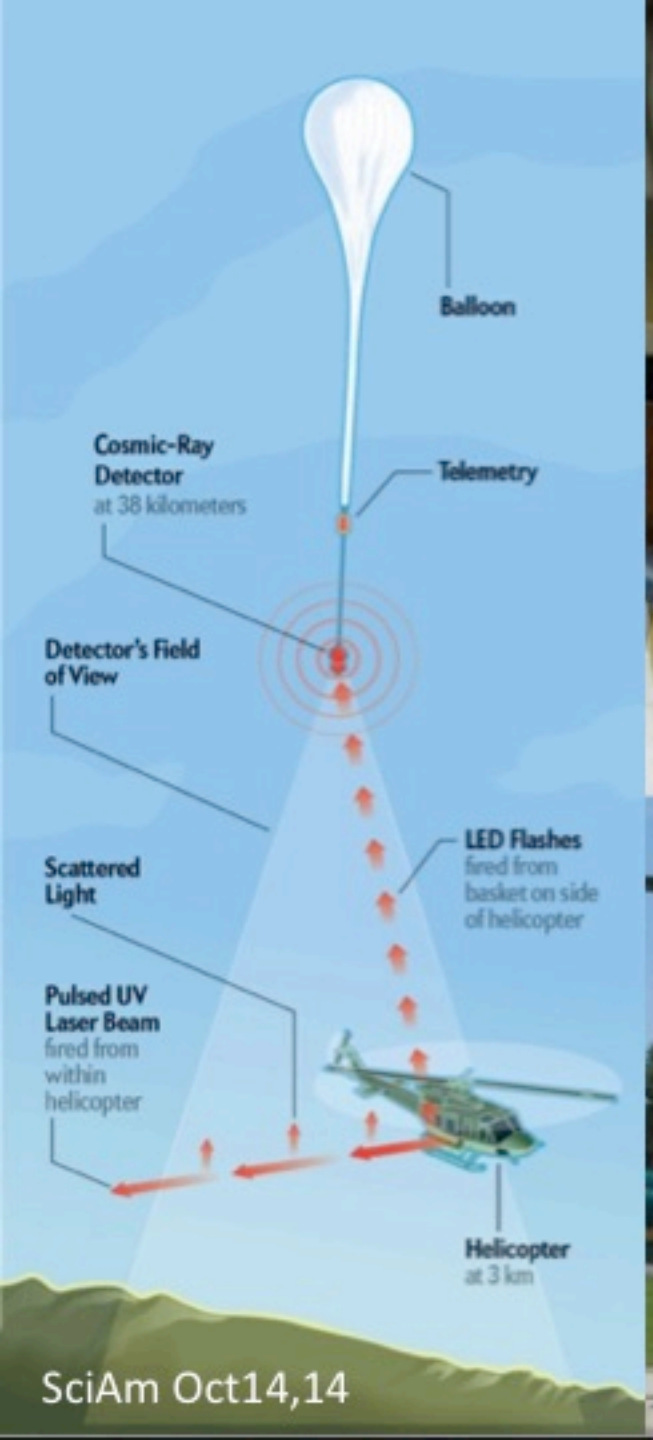
Inclination: 51.6°
Height: ~400km

JEM-EUSO


Annual Exposure (km² sr yr)
JEM−EUSO
AUGER
JEM−EUSO Collaboration, Astropart.Phys. 44 (201
Pierre Auger Collaboration, Nucl.Instrum.Meth.A 61
Log₁₀ (E/eV)


diffuse $\nu_e + \nu_\mu + \nu_\tau$ limits
$E_\nu^2 J_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
atmospheric ν_μ+$\bar{\nu}_\mu$
GLUE ($\nu_{e,\mu,\tau}$)
FORTE ($\nu_{e,\mu,\tau}$)
HiRes ($3\times\nu_e$)
BAIKAL ($\nu_{e,\mu,\tau}$)
RICE ($\nu_{e,\mu,\tau}$)
AMANDA ($\nu_{e,\mu,\tau}$)
AMANDA ($3\times\nu_\mu$)
ANTARES ($3\times\nu_\mu$)
Auger ($3\times\nu_\tau$)
ANITA ($\nu_{e,\mu,\tau}$)
"nadir"
"tilted"
IC-40 ($\nu_{e,\mu,\tau}$)
IC40 ($3\times\nu_\mu$)
JEM-EUSO (3yr)
TeV
PeV
EeV
ZeV
YeV
E_ν

EUSO Balloon:
1st flight and first light on 24-25.8.2014

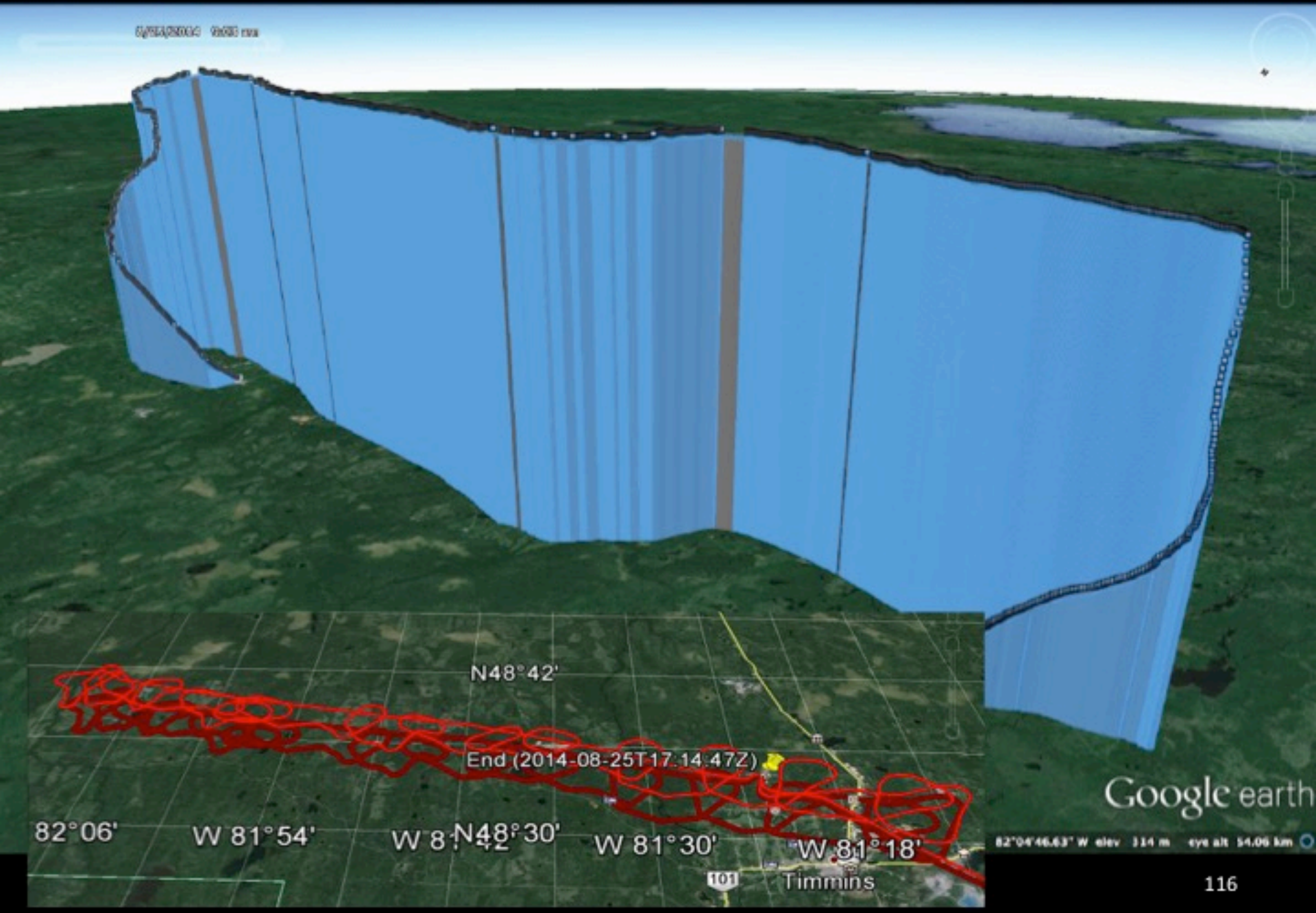


SciAm Oct14,14

Xenon Flasher

Laser System

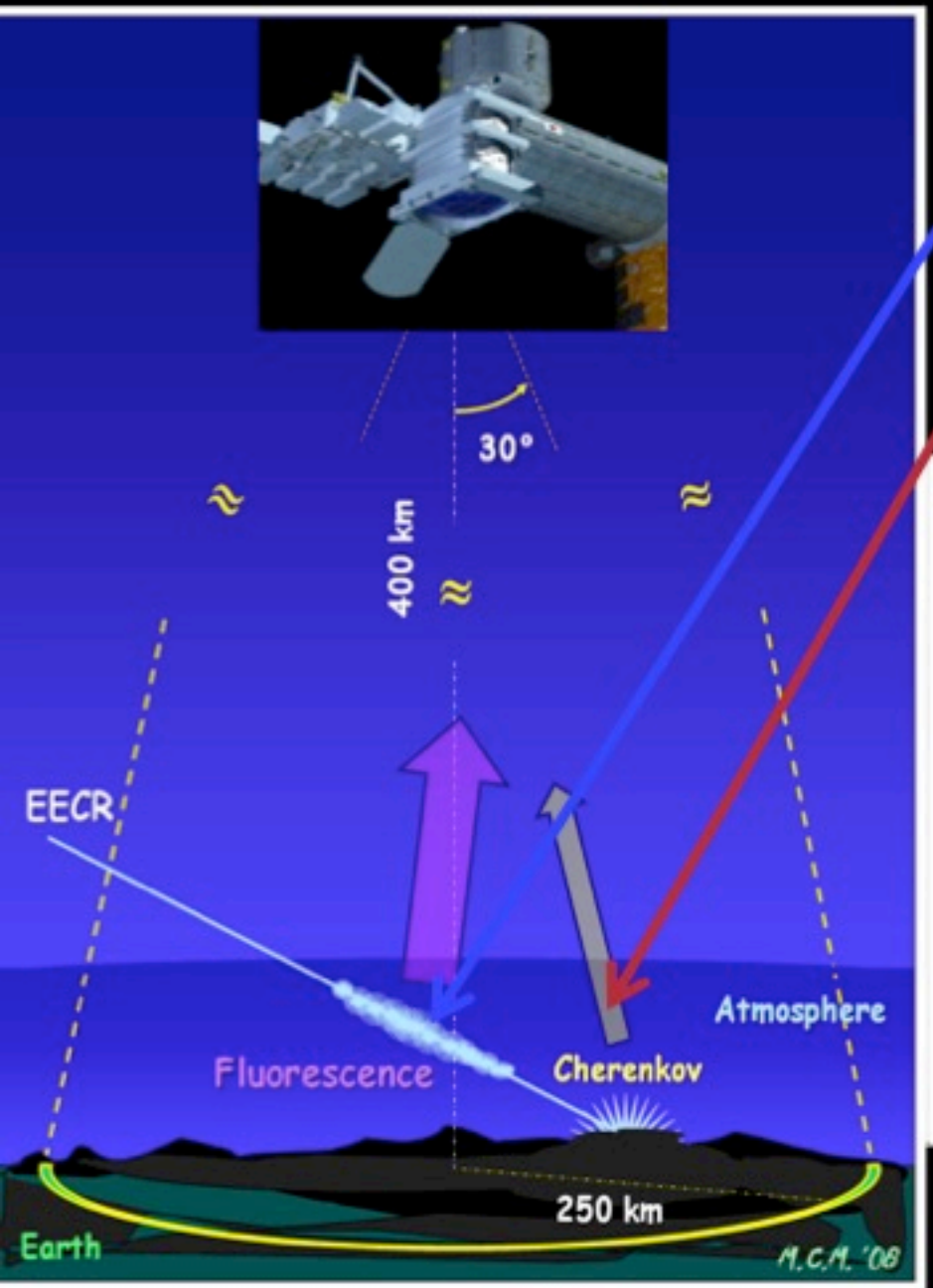
UV LED Flasher


N48°42'
End (2014-08-25T17:14:47Z)
82°06'
W 81°54'
W 81°42'
N48°30'
W 81°30'
W 81°18'
101
Timmins
Google earth

EUSO-SPB mission

Super Pressure Balloon = SPB

Fluorescence from SPACE

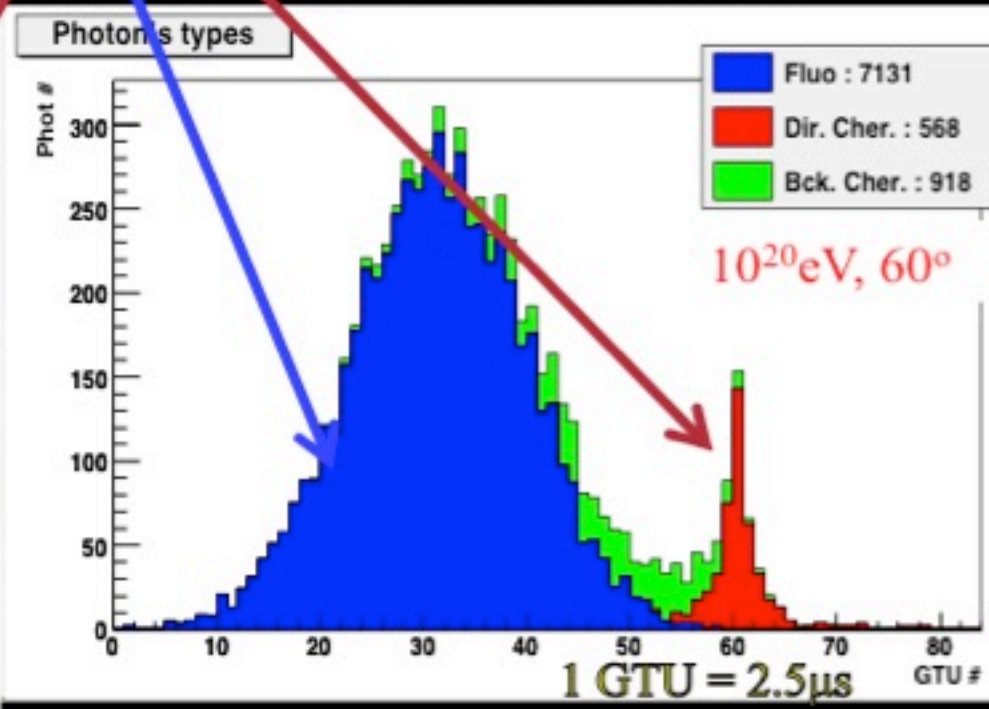


Fast Signal: 50 -150 μs

a) Fluorescence

b) Scattered Cherenkov

c) Direct (reflected Cherenkov)



Background: 500 /m^2 sr ns

How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO

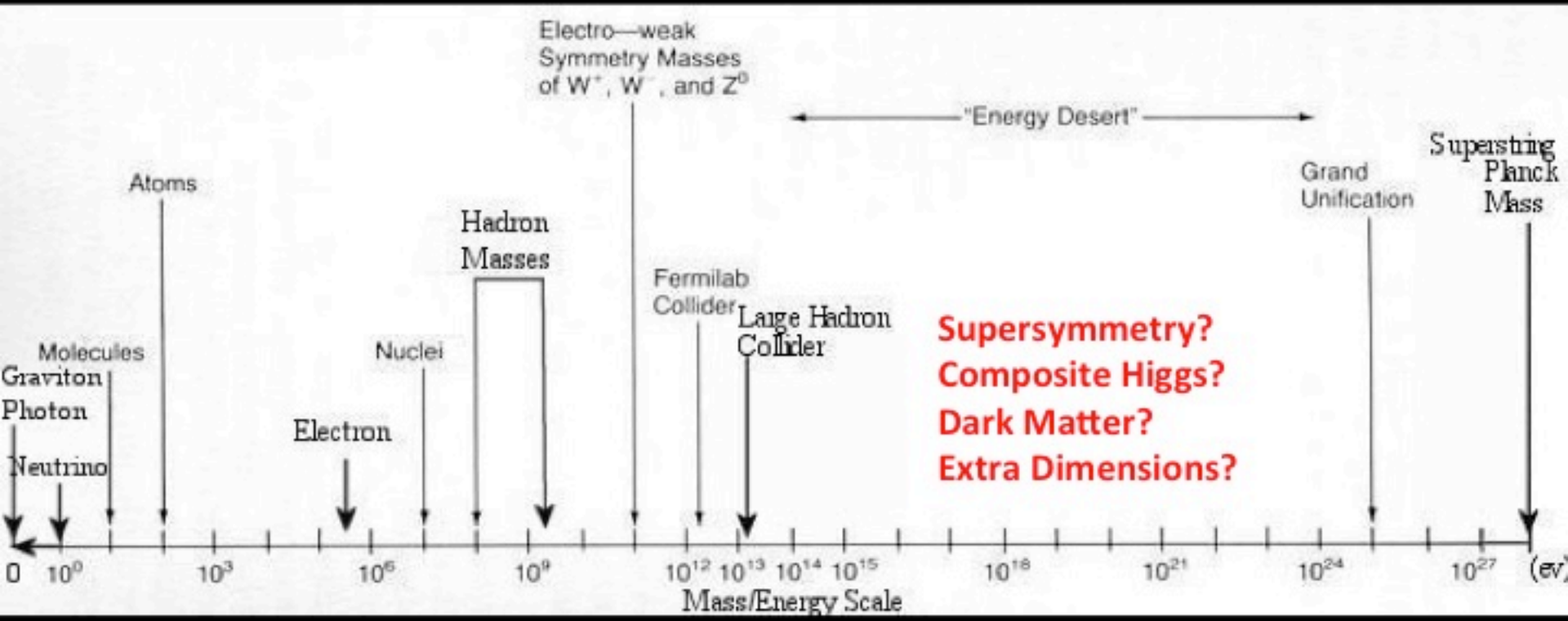
~200 events > 60 EeV/y

400 to go!

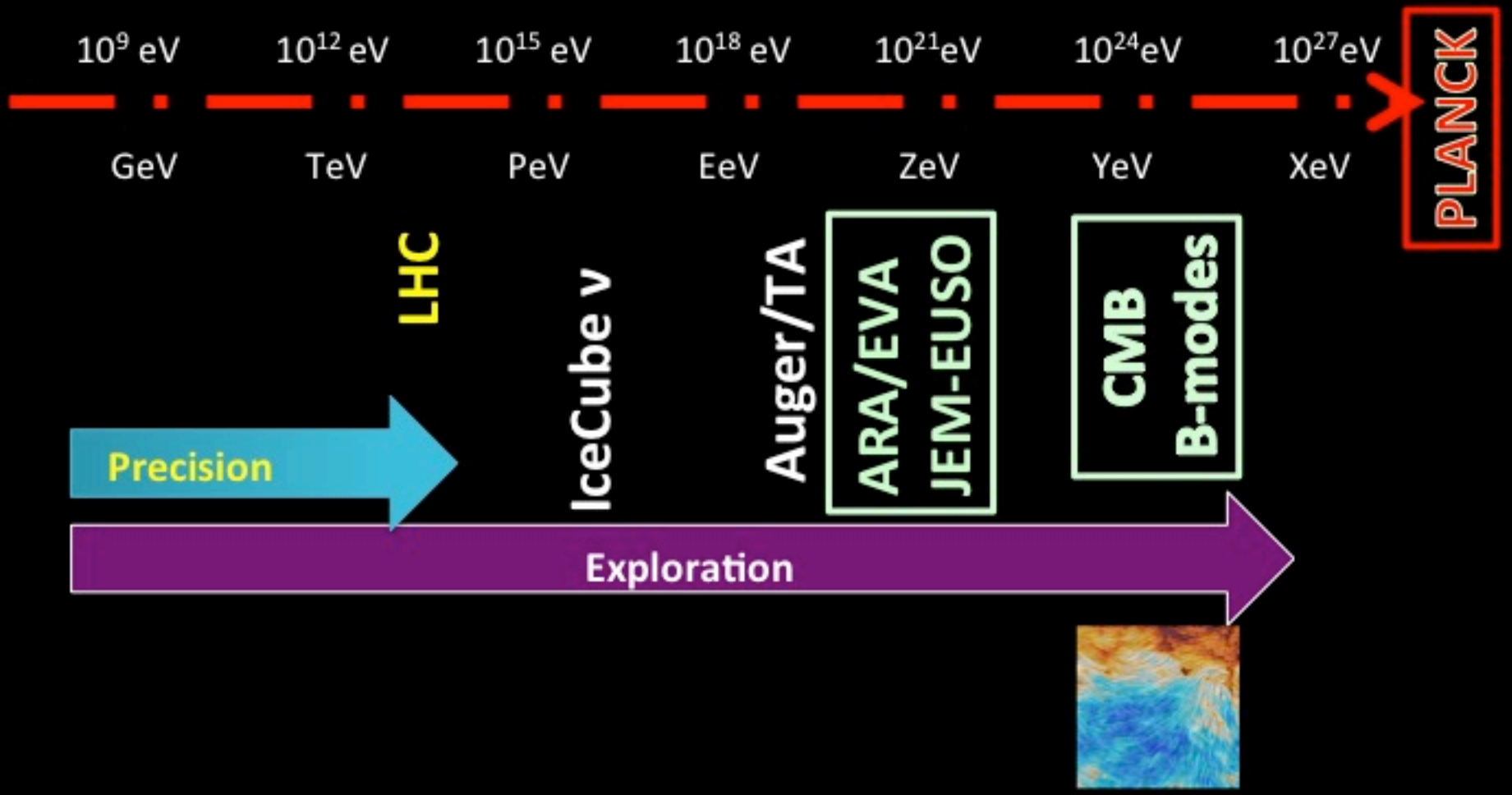
Earth surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

Journey toward Planck



10^{13} eV ⟷ 14 o.o.m. ⟷ 10^{27} eV


10^9 eV
10^{12} eV
10^{15} eV
10^{18} eV
10^{21}eV
10^{24}eV
10^{27}eV
PLANCK
GeV
TeV
PeV
EeV
ZeV
YeV
XeV
LHC
IceCube ν
Auger/TA
ARA/EVA
JEM-EUSO
CMB
B-modes
Precision
Exploration

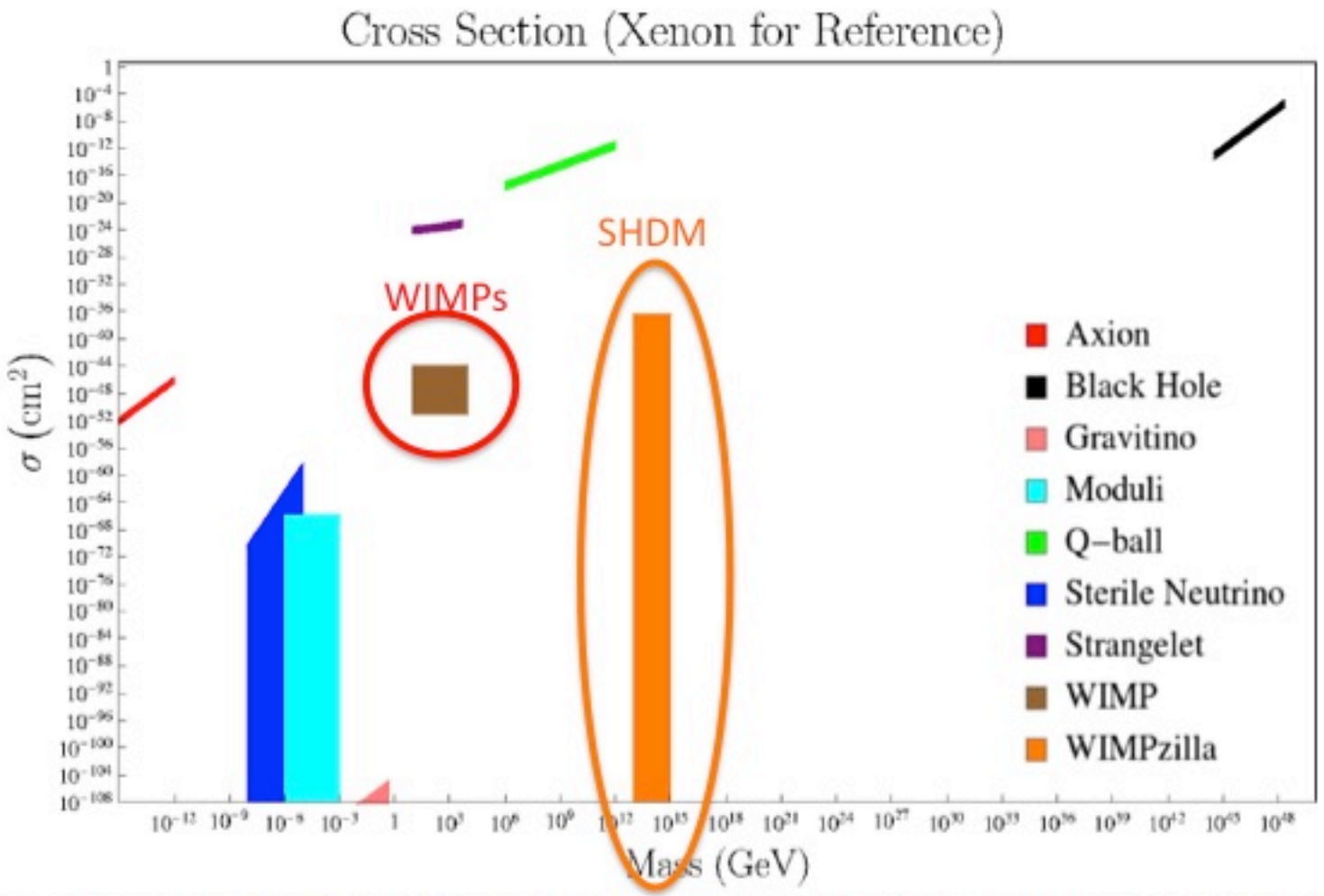
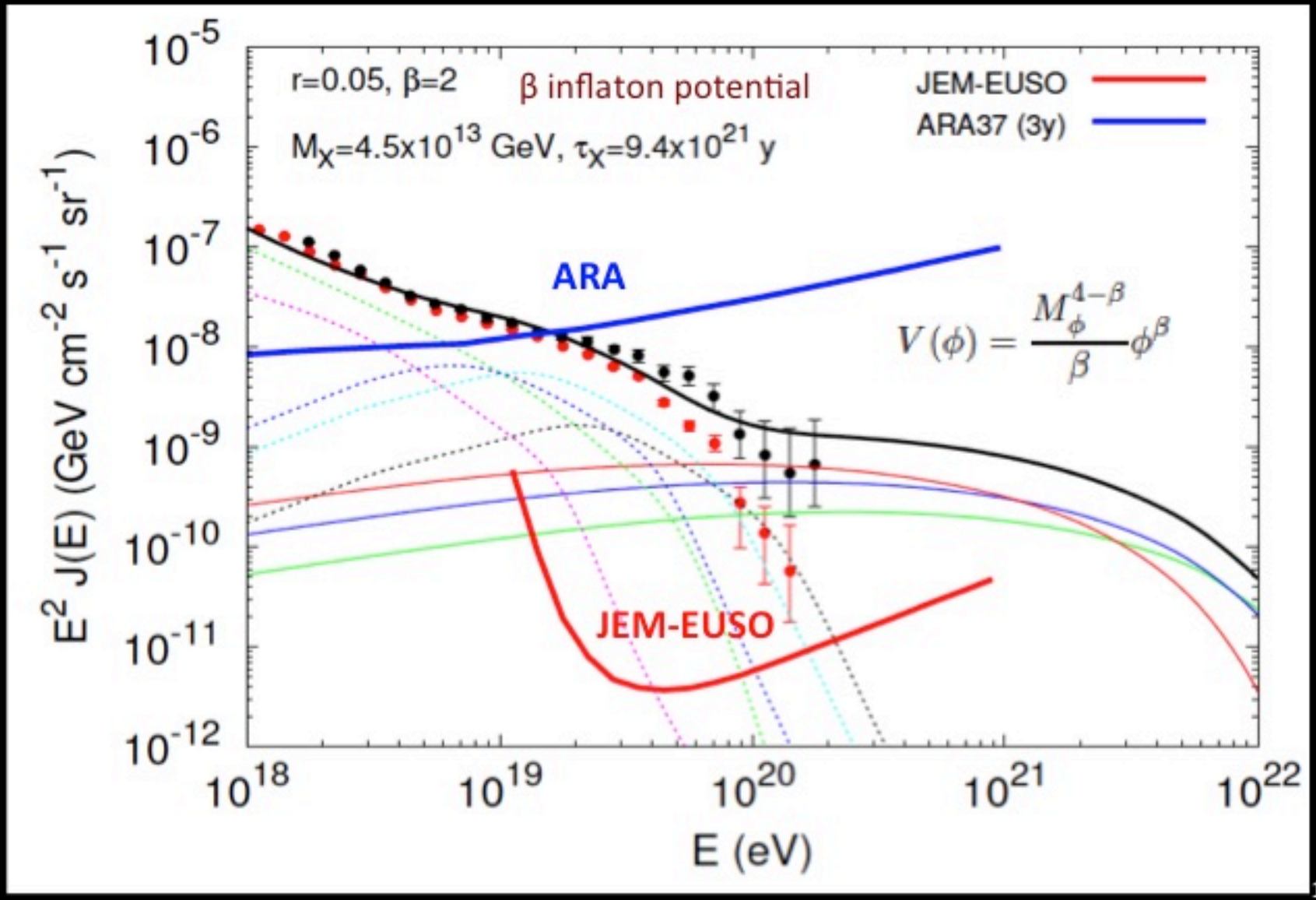


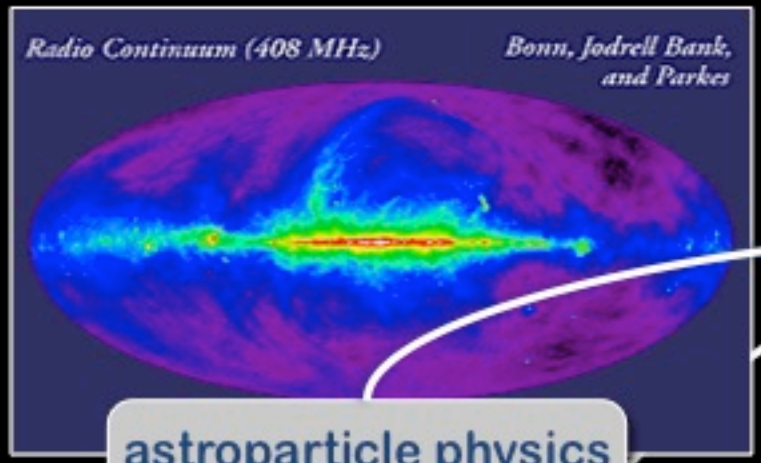
Figure 4-8. *The range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of possible masses and interaction cross sections.*

Super Heavy Dark Matter

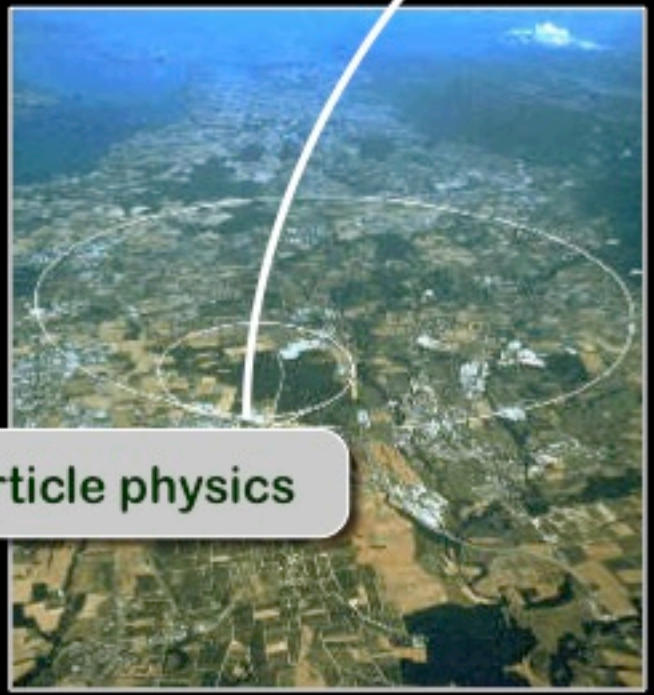
Aloisio, Matarrese, AO '15



Joining forces again
Particle Physics & AstroParticle Physics



astroparticle physics



particle physics

Cosmic particles (CRs, ν's, γ's) with E > LHC

Neutrino Properties: masses, symmetries,..., (e.g. Cosmic Microwave Background, CMB)

Dark Matter: WIMPS, axions, SHDM,...

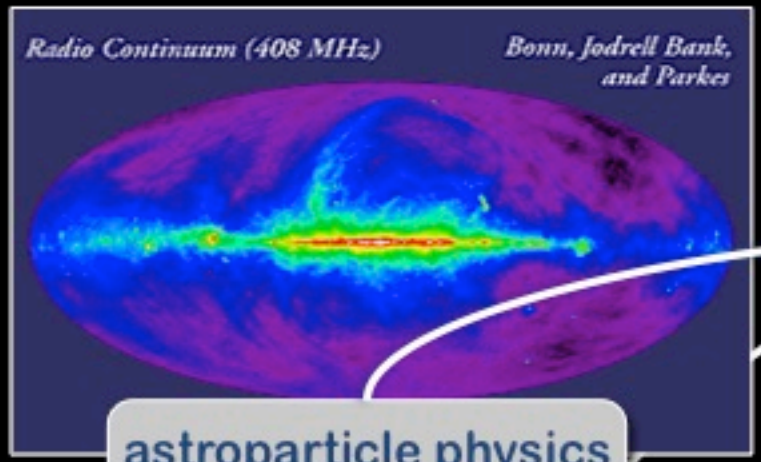
Dark Energy: ????

Inflation and GUT scale physics (e.g., CMB polarization)

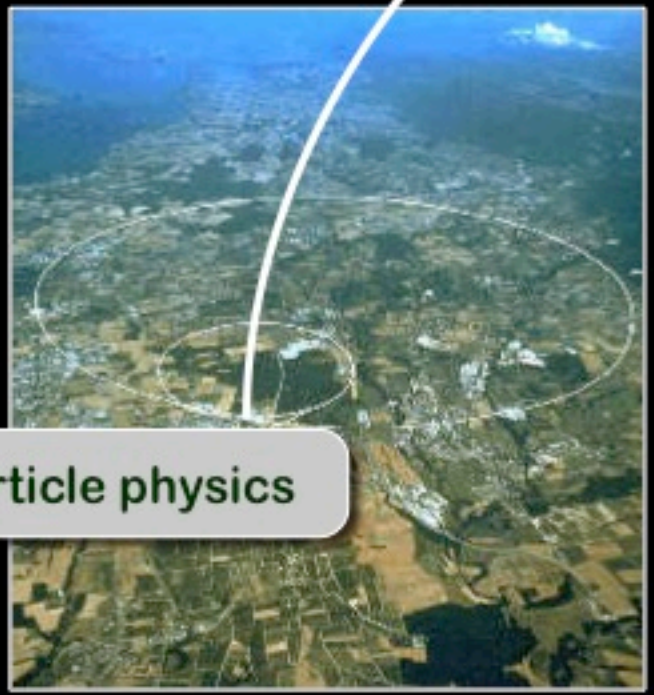
Gravitational Waves

Other Early Universe Relics...

Joining forces again
Particle Physics & AstroParticle Physics



astroparticle physics



particle physics

Cosmic particles (CRs, ν's, γ's) with E > LHC

Neutrino Properties: masses, symmetries,..., (e.g. Cosmic Microwave Background, CMB)

Dark Matter: WIMPS, axions, SHDM,...

Dark Energy: ????

Inflation and GUT scale physics (e.g., CMB polarization)

Gravitational Waves

Other Early Universe Relics...

KIAA Workshop on *Astroparticle* Physics

KIAA@Peking University; Sept. 28-29, 2015 — http://kiaa.pku.edu.cn/aph2015/

TOPICS

COSMIC RAYS
DARK MATTER DETECTION
PARTICLE COSMOLOGY
PARTICLE PHYSICS IN STARS

The long-standing quest for understanding the fundamental laws of Nature has motivated the new field of **Astroparticle Physics** where observations of the Universe are used to probe particle interactions. This small workshop will bring together AstroParticle Physics experts to provoke discussion and foster collaboration especially between members of Kavli Institutes.

Organizers
Ke Fang (U Chicago)
Zhaosheng Li (PKU)
Angela V. Olinto (U Chicago)
Meng Su (MIT)
Renxin Xu (PKU)


Reach out to the Cosmos to study the Highest Energies!
謝謝
Xièxiè