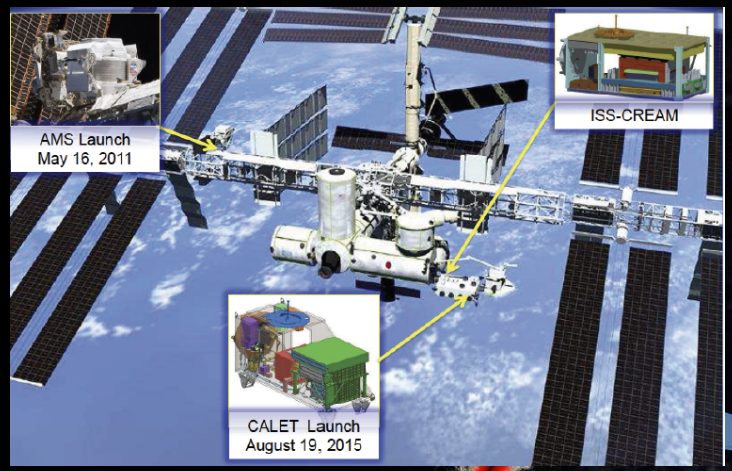
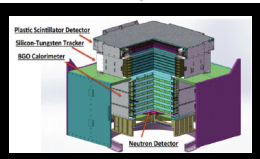
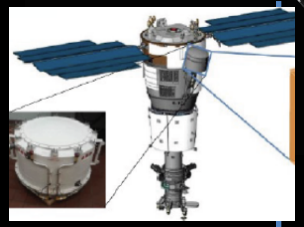
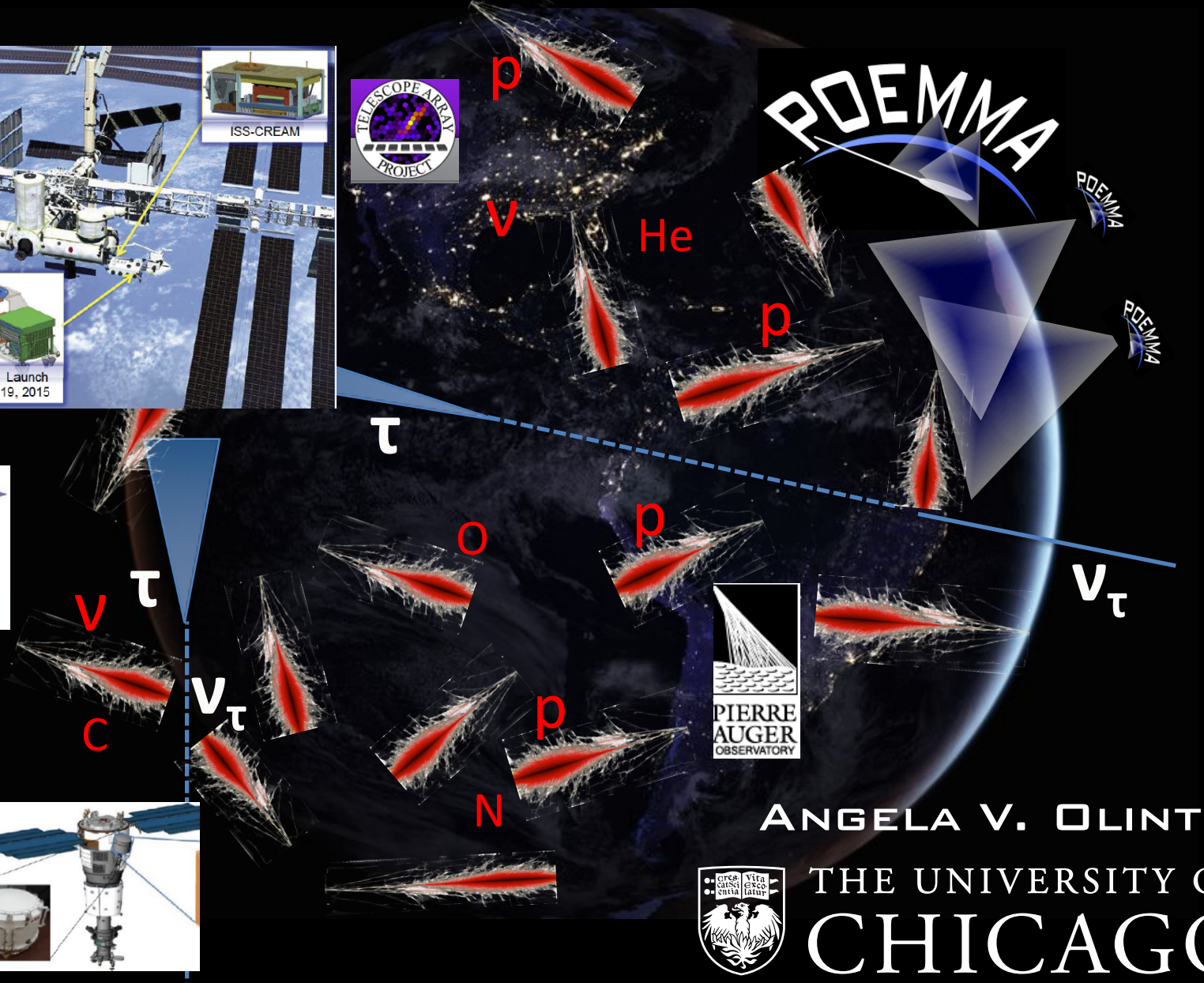
Cosmic Rays and Cosmology





EUSO-SPB

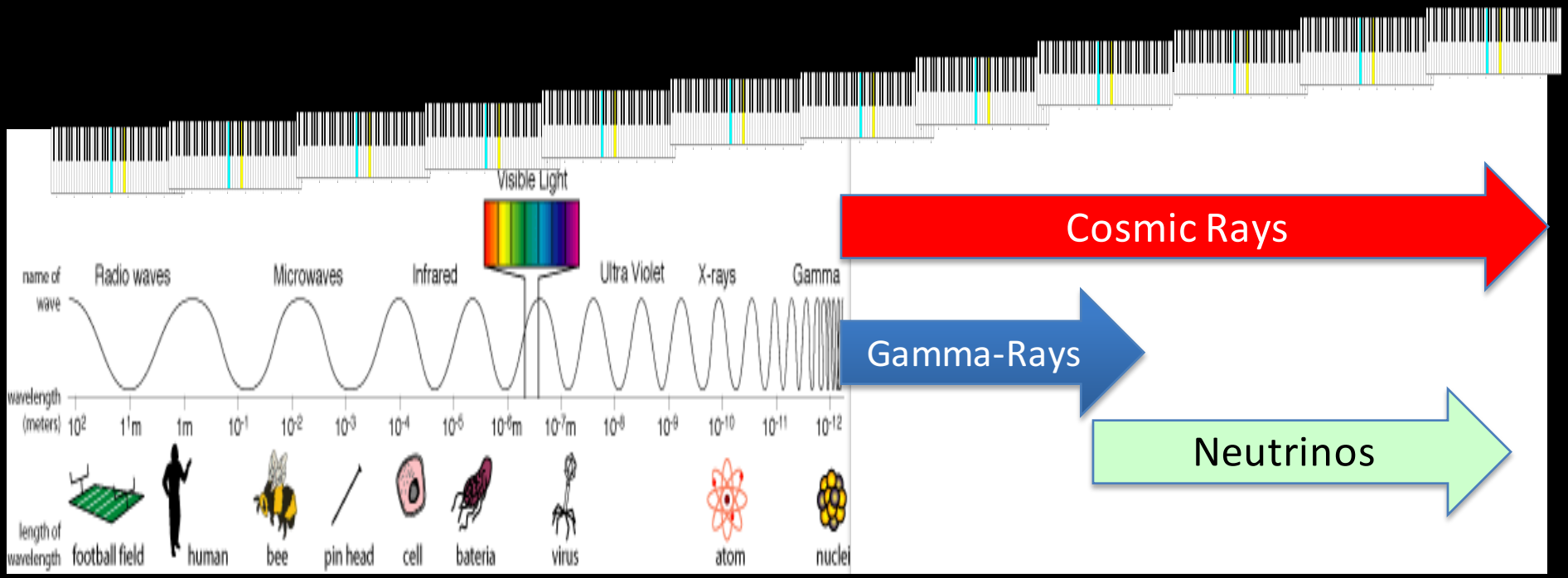




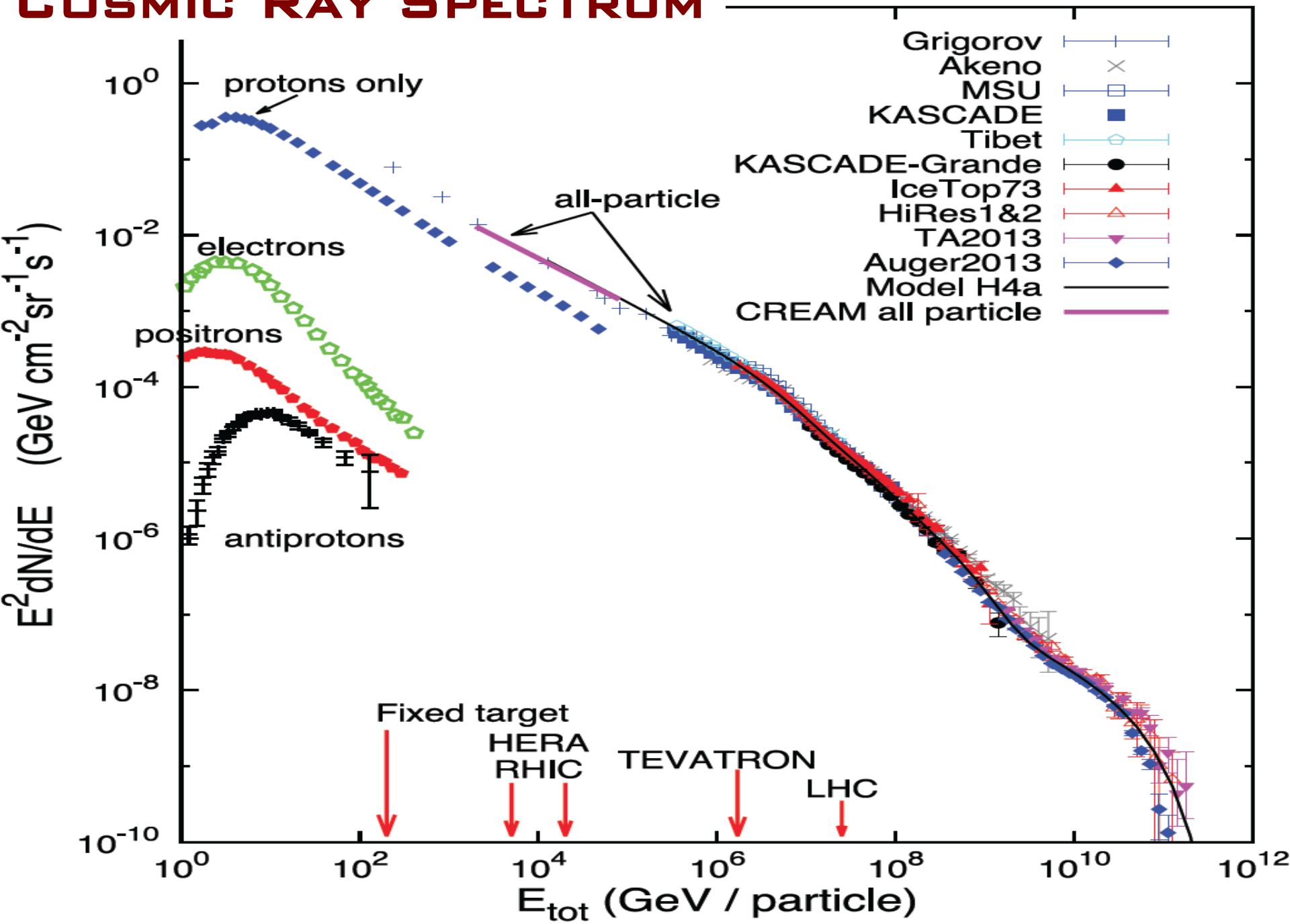
Angela V. Olinto
The University of Chicago

Cosmic Particles

~ double the energy range for Astrophysics

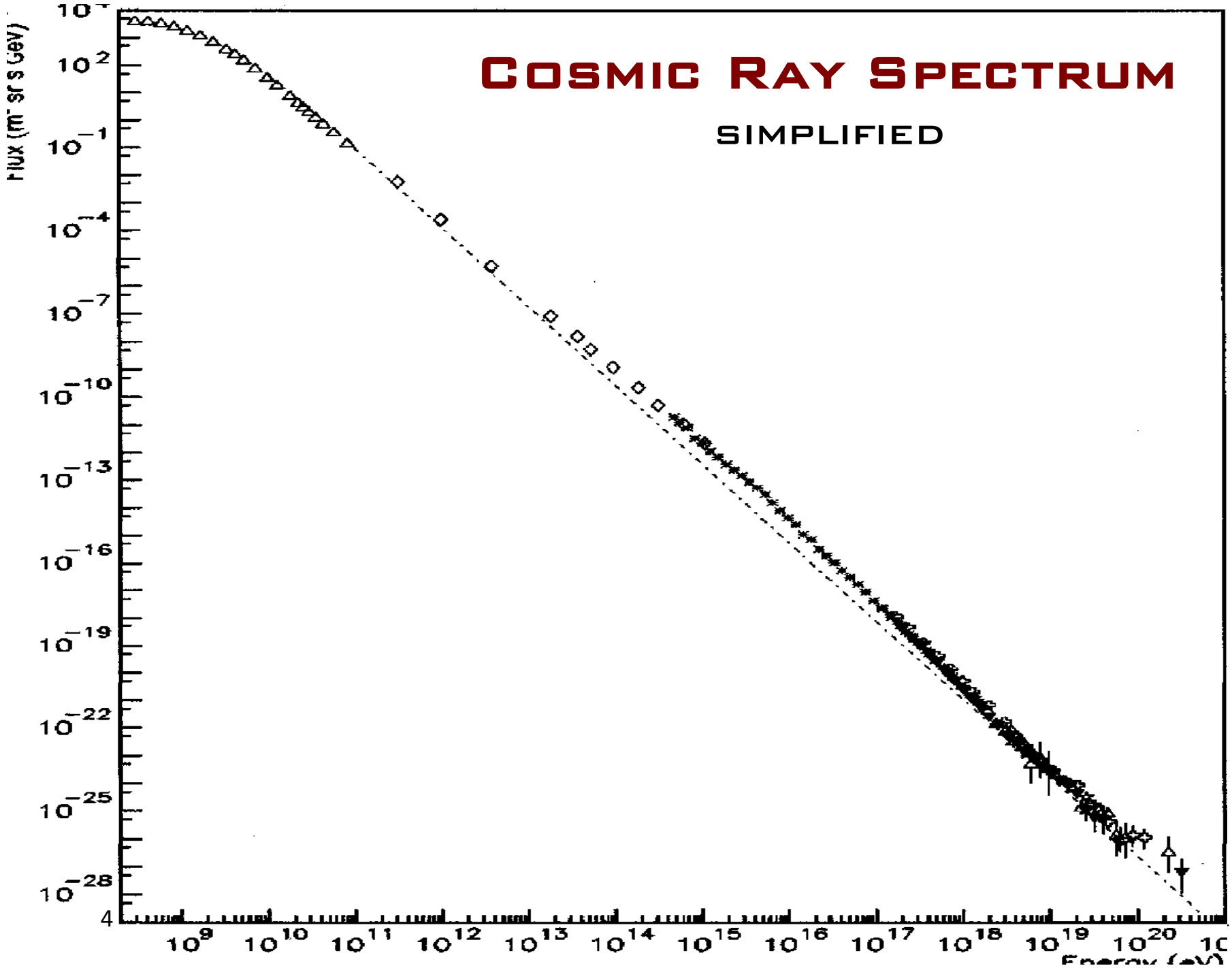


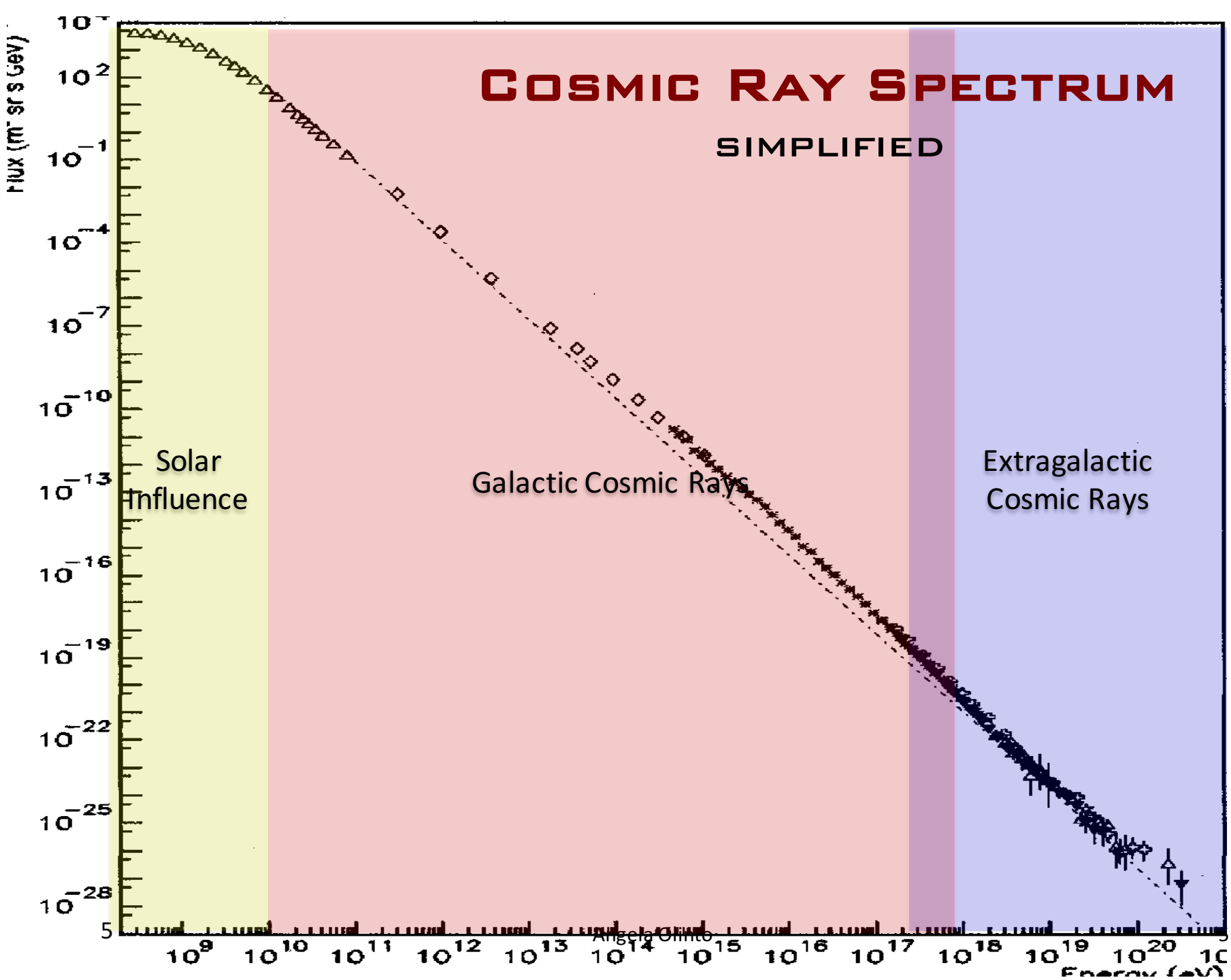
Cosmic Ray Spectrum



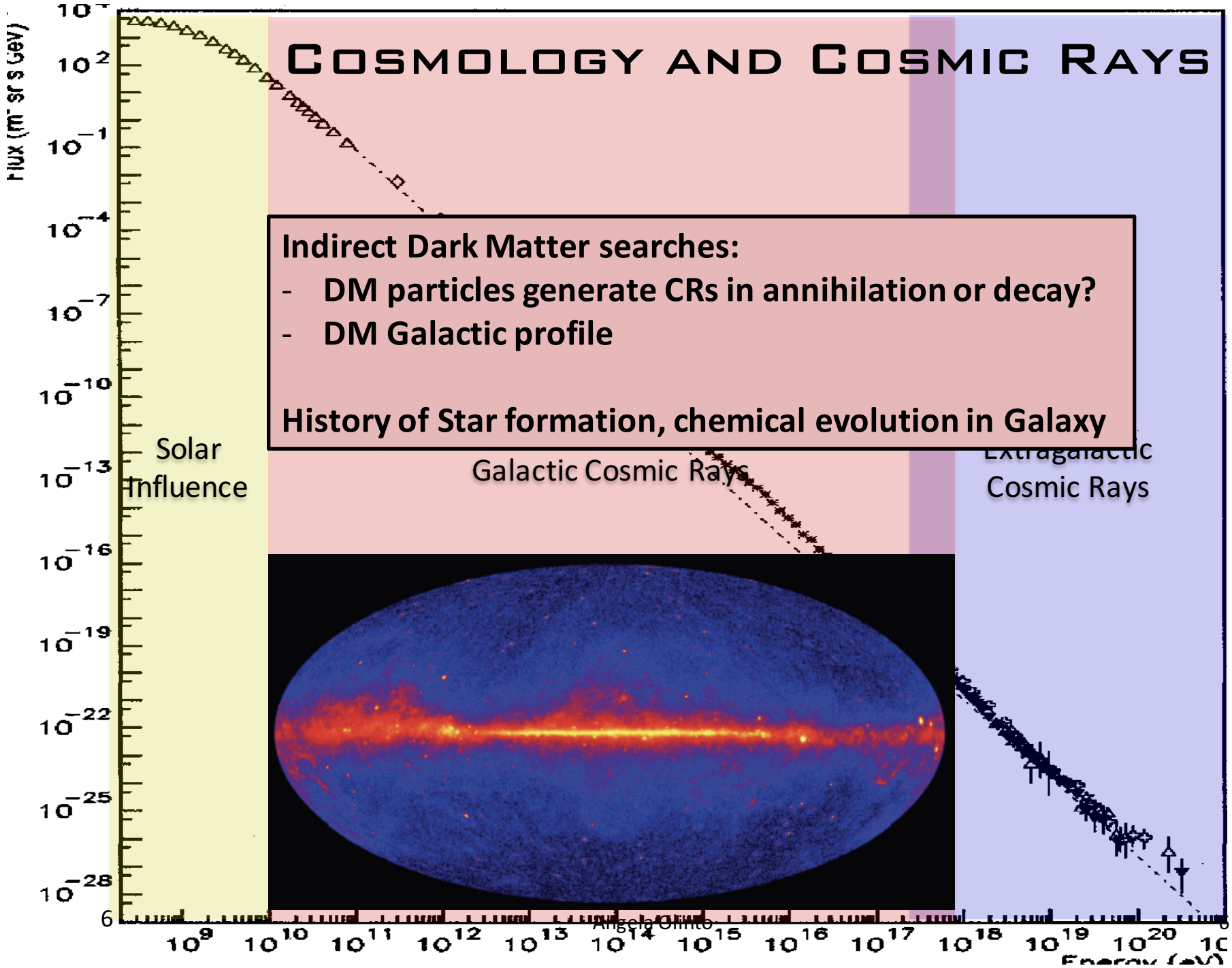
Cosmic Ray Spectrum

SIMPLIFIED




Cosmic Ray Spectrum
simplified
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays
Flux (m⁻ sr s GeV)
Energy (eV)

Cosmology and Cosmic Rays

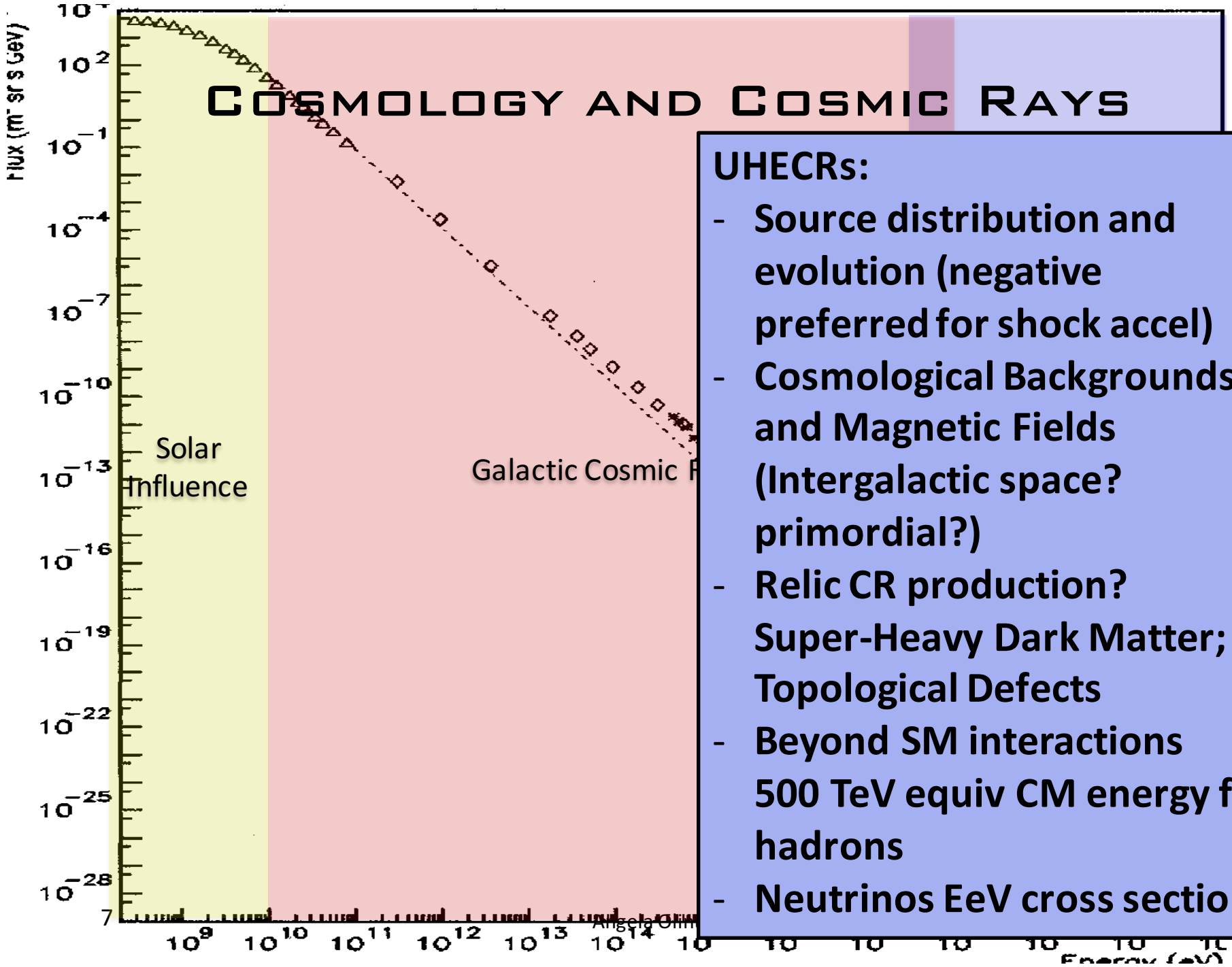


Indirect Dark Matter searches:

- **DM particles generate CRs in annihilation or decay?**
- **DM Galactic profile**

History of Star formation, chemical evolution in Galaxy

Cosmology and Cosmic Rays



UHECRs:

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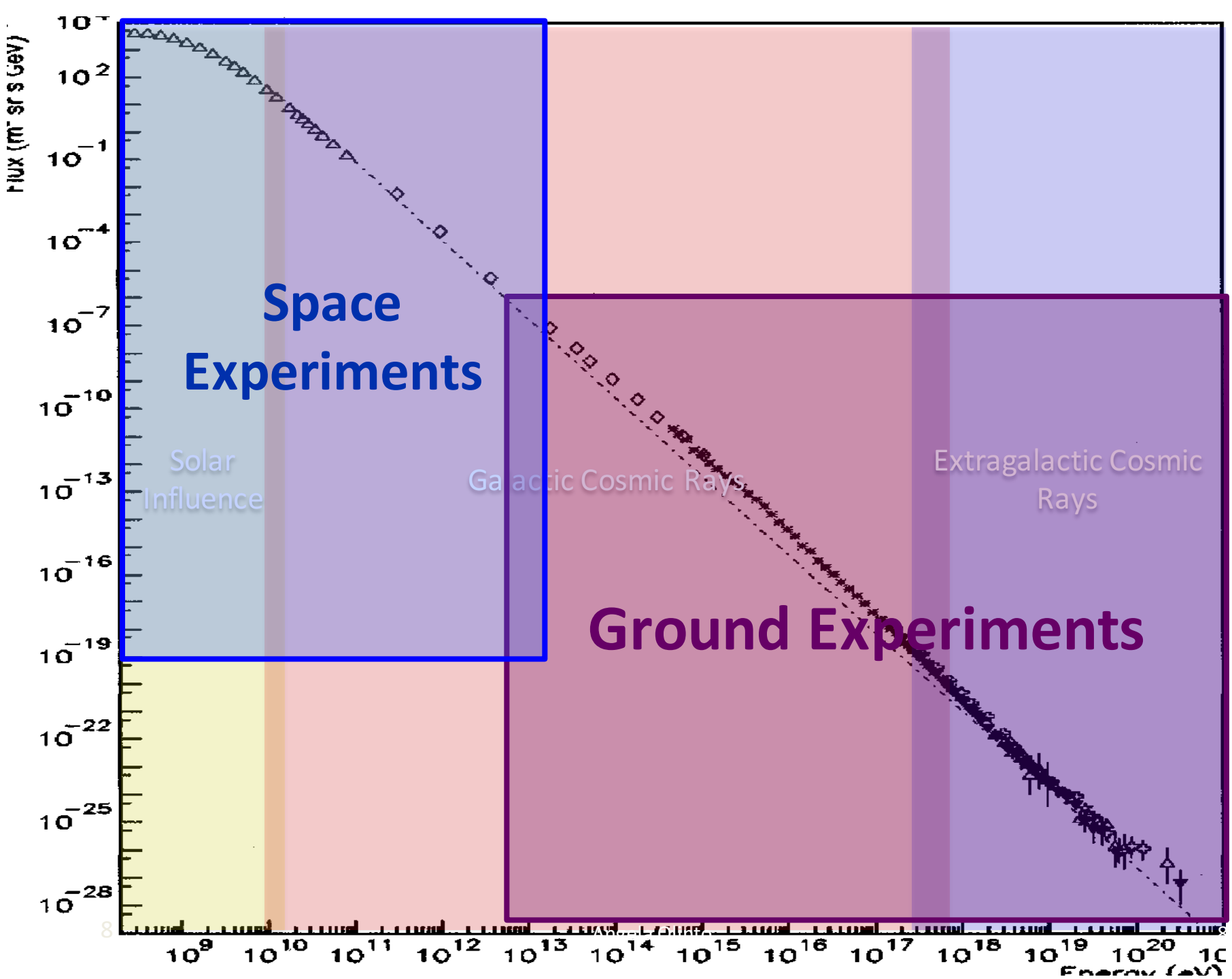
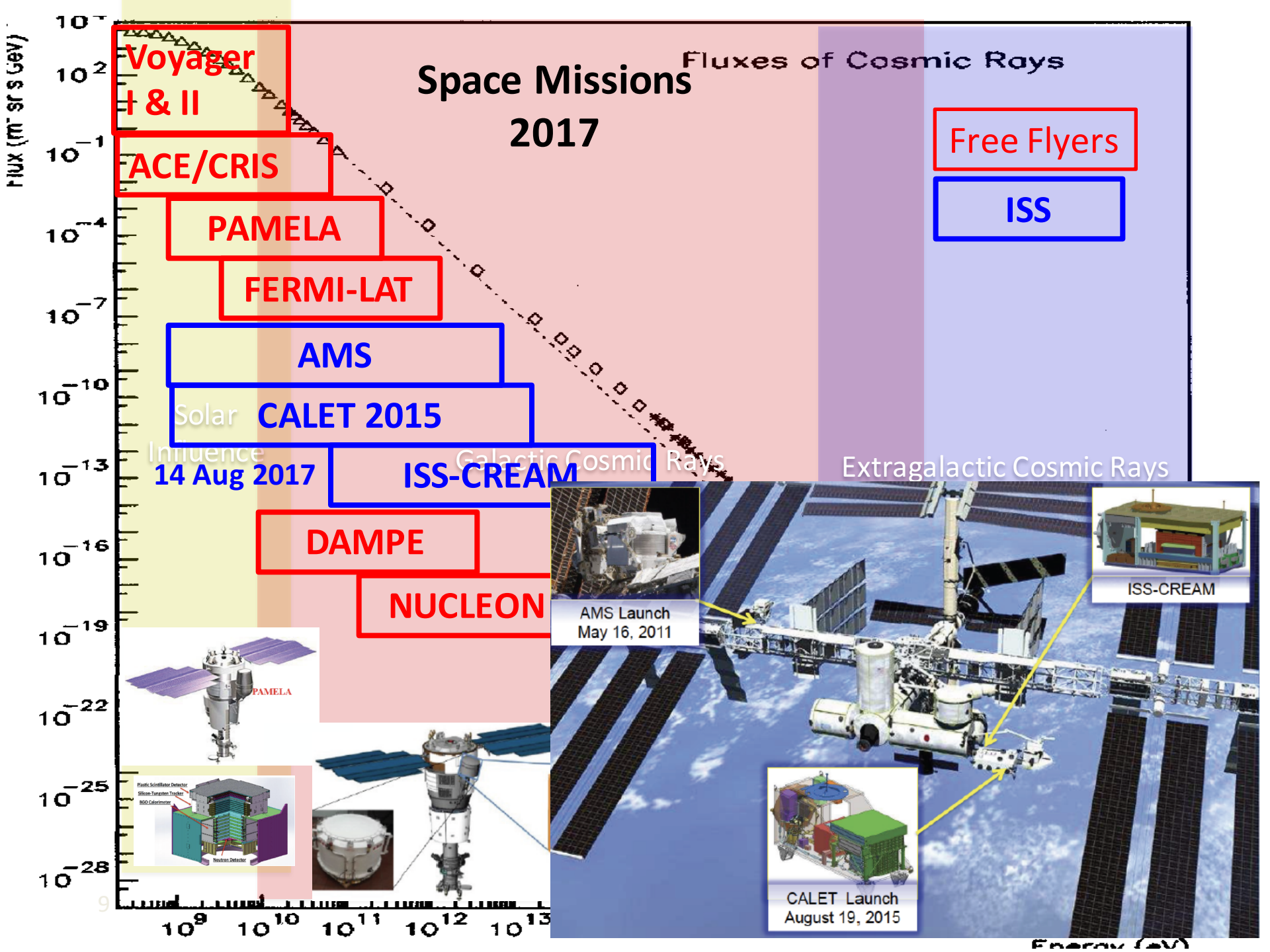
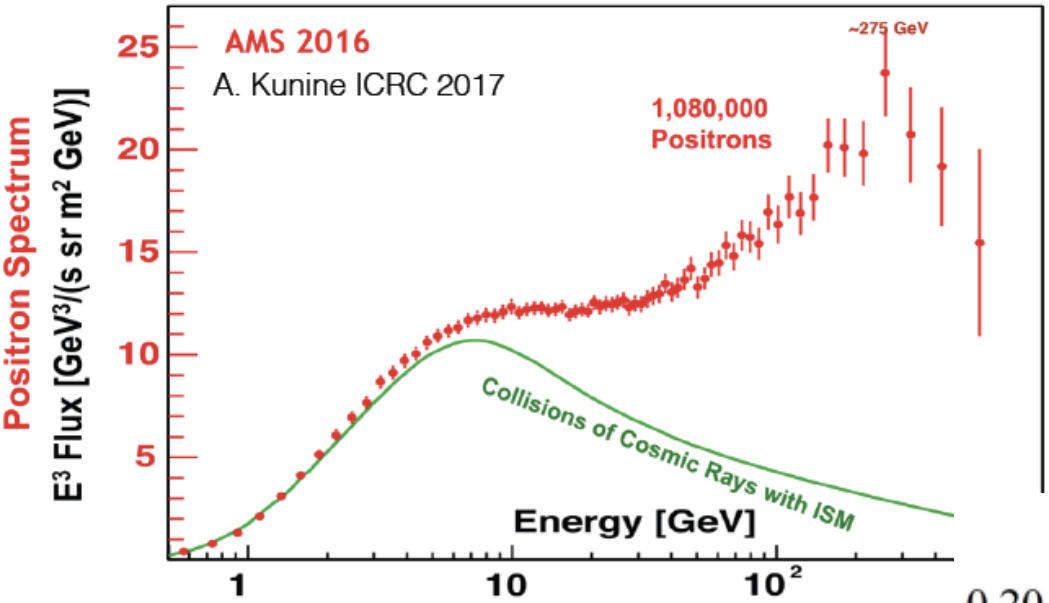

Space Experiments
Ground Experiments
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays

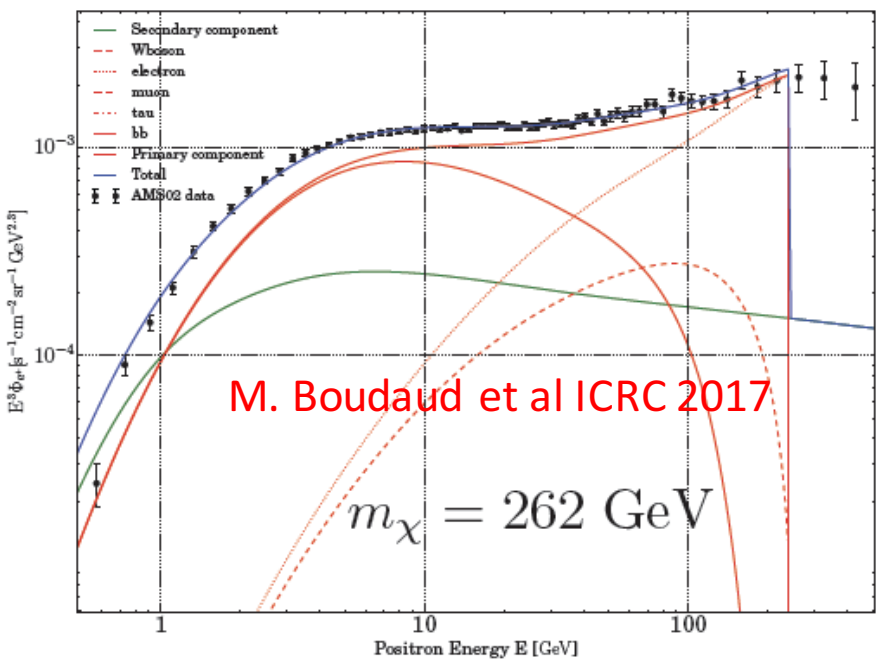

Space Missions
2017
Fluxes of Cosmic Rays
Voyager I & II
ACE/CRIS
PAMELA
FERMI-LAT
AMS
CALET 2015
ISS-CREAM
DAMPE
NUCLEON
Free Flyers
ISS
Solar Influence
14 Aug 2017
Galactic Cosmic Rays
Extragalactic Cosmic Rays
AMS Launch
May 16, 2011
ISS-CREAM
CALET Launch
August 19, 2015
PAMELA
Flux (m² sr s GeV)
Energy (eV)

Experiment	e^+ | e^- (present data)	$e^+ + e^-$ (Energy range)	CR nuclei (Energy range)	charge	Gamma-ray	Type	Launch
PAMELA	$e^+ < 300$ GeV $e^- < 625$ GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	$e^+ < 500$ GeV $e^- < 700$ GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014 Dec 26
CALET	-	1 GeV-20 TeV	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	2017

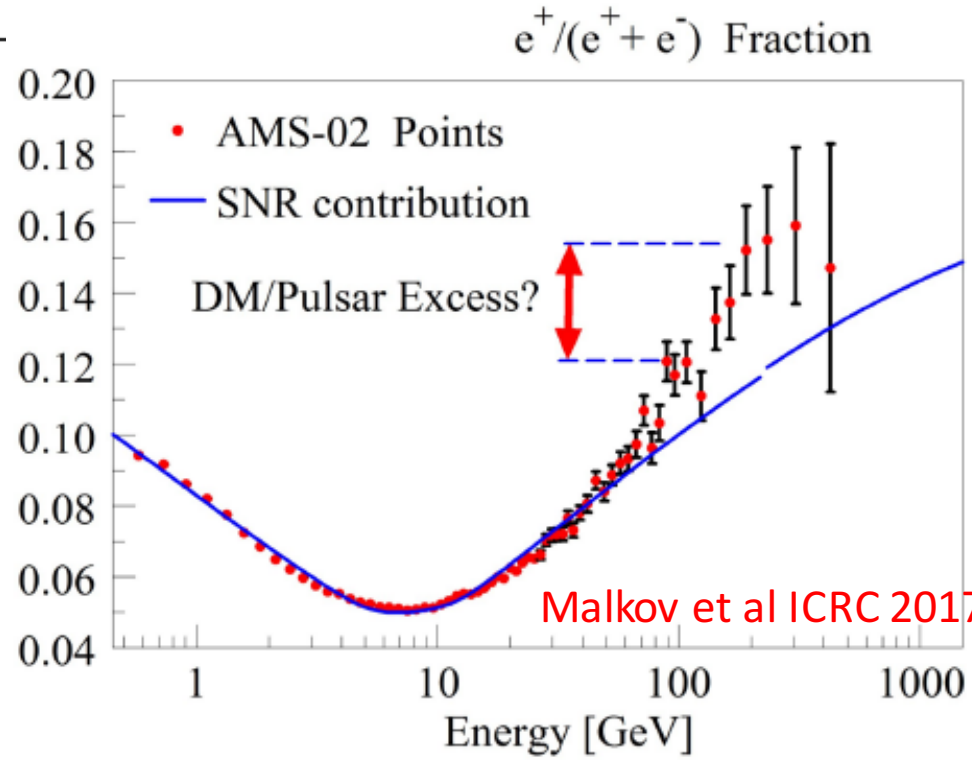
Positron Fraction



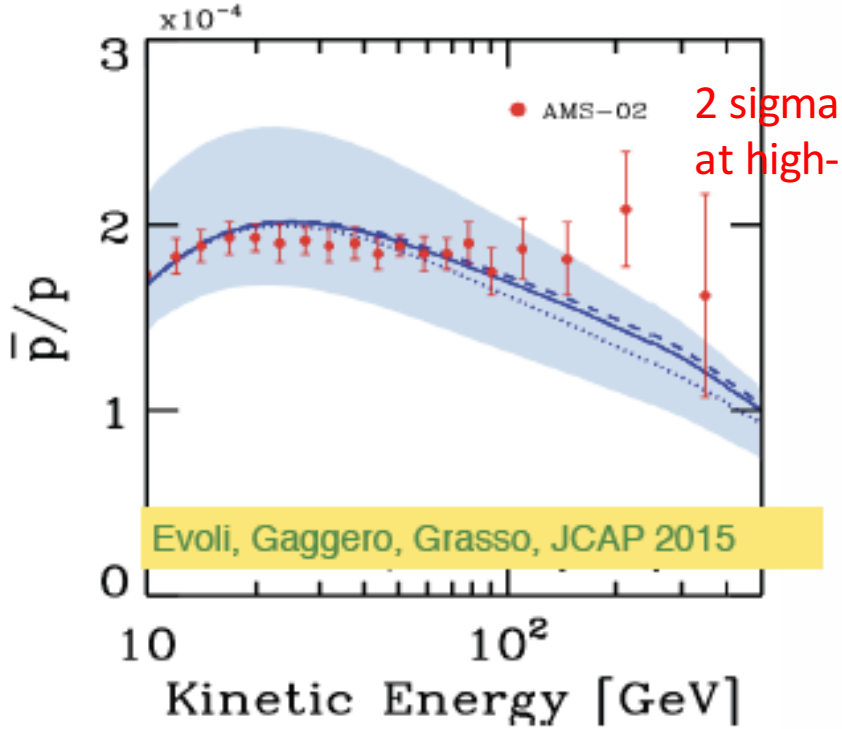
Poor fit disfavors DM as explanation for positron excess – SN + Pulsar Wind Nebulae



M. Boudaud et al ICRC 2017

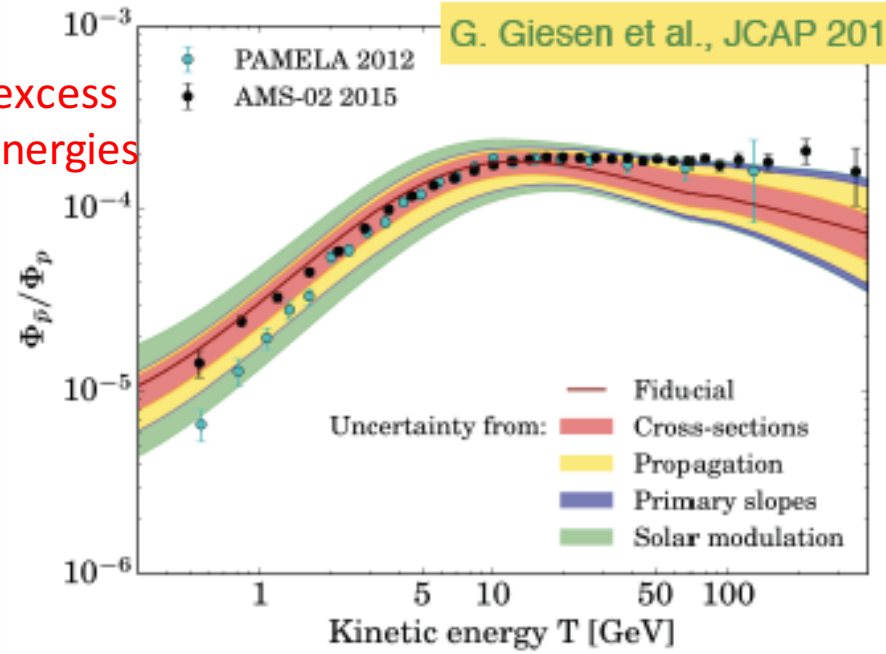


Malkov et al ICRC 2017



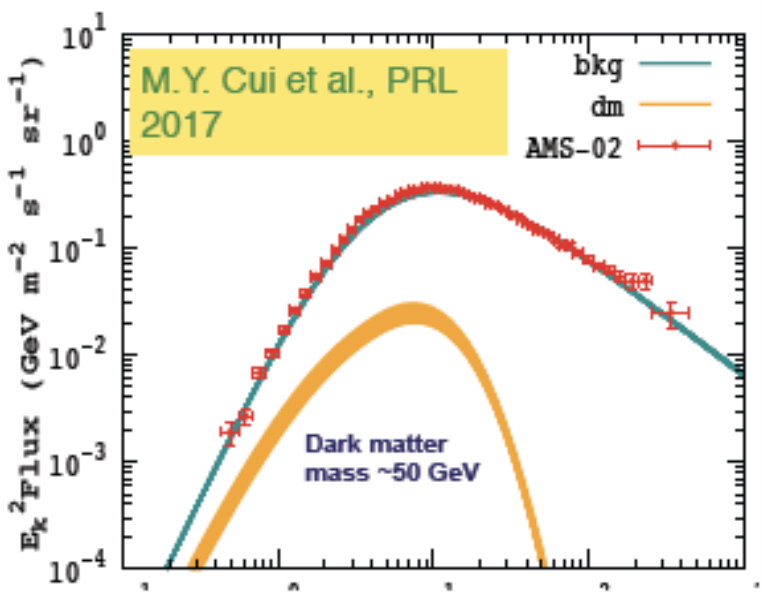
Evoli, Gaggero, Grasso, JCAP 2015

2 sigma excess at high-energies

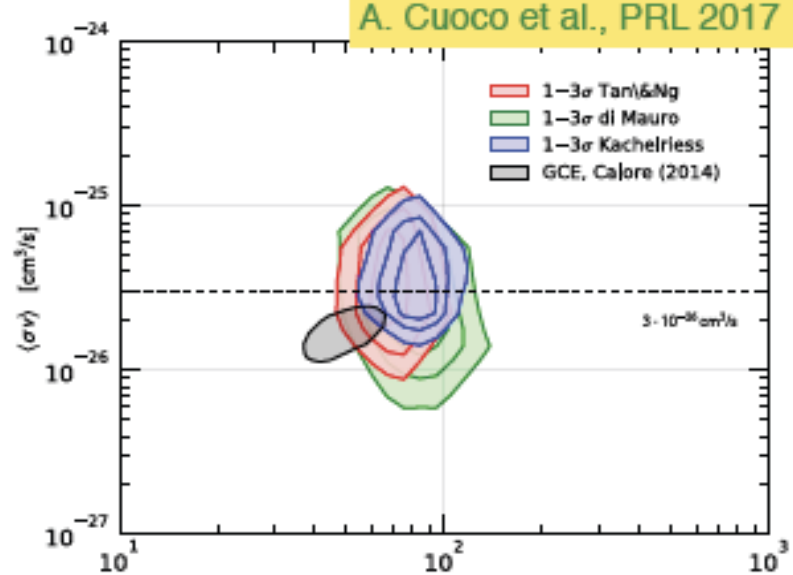


G. Giesen et al., JCAP 2015

Anti-Protons

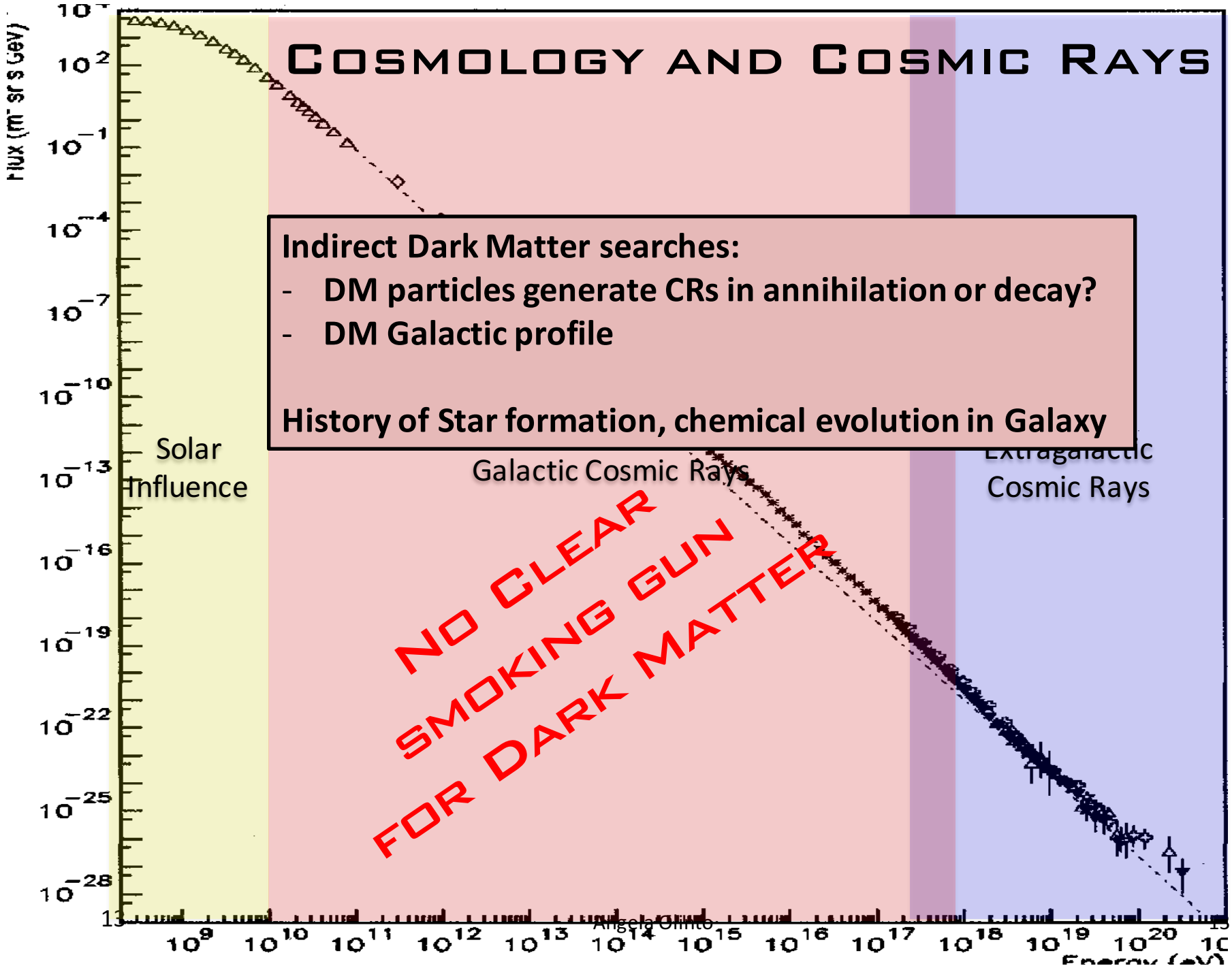


M.Y. Cui et al., PRL 2017



A. Cuoco et al., PRL 2017

Cosmology and Cosmic Rays



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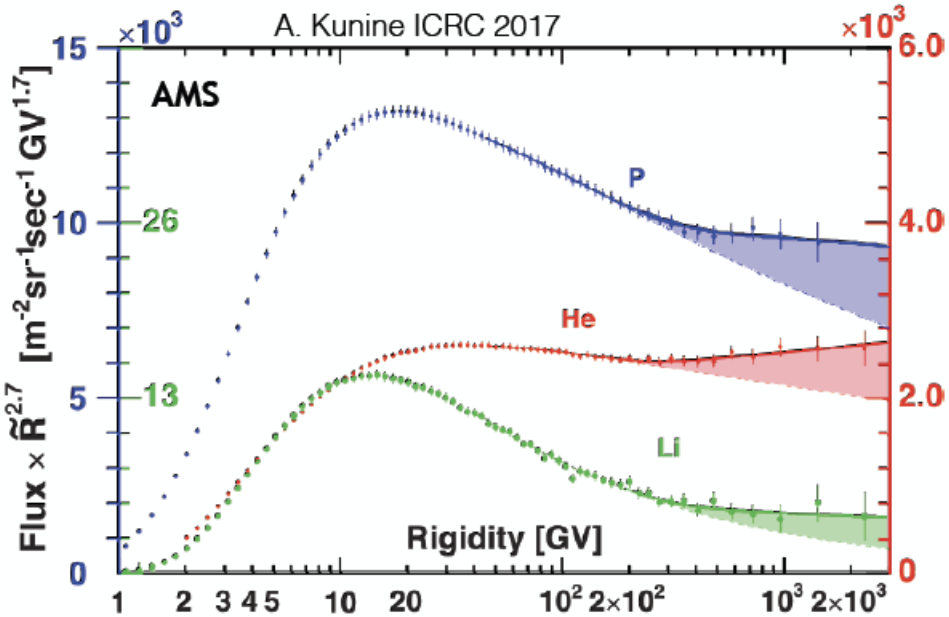
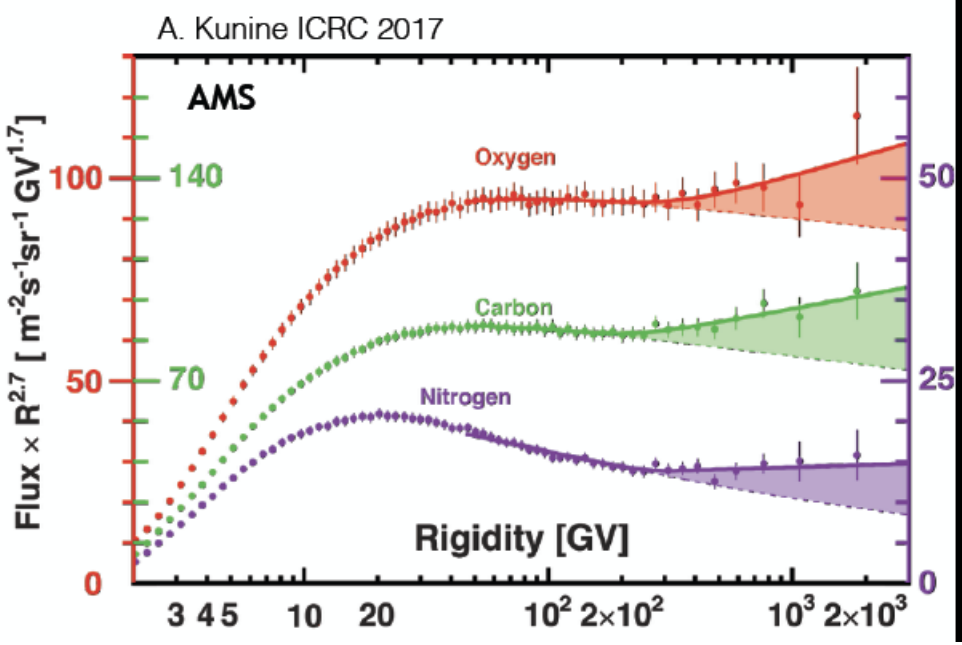
Cosmic Ray Spectra: new features



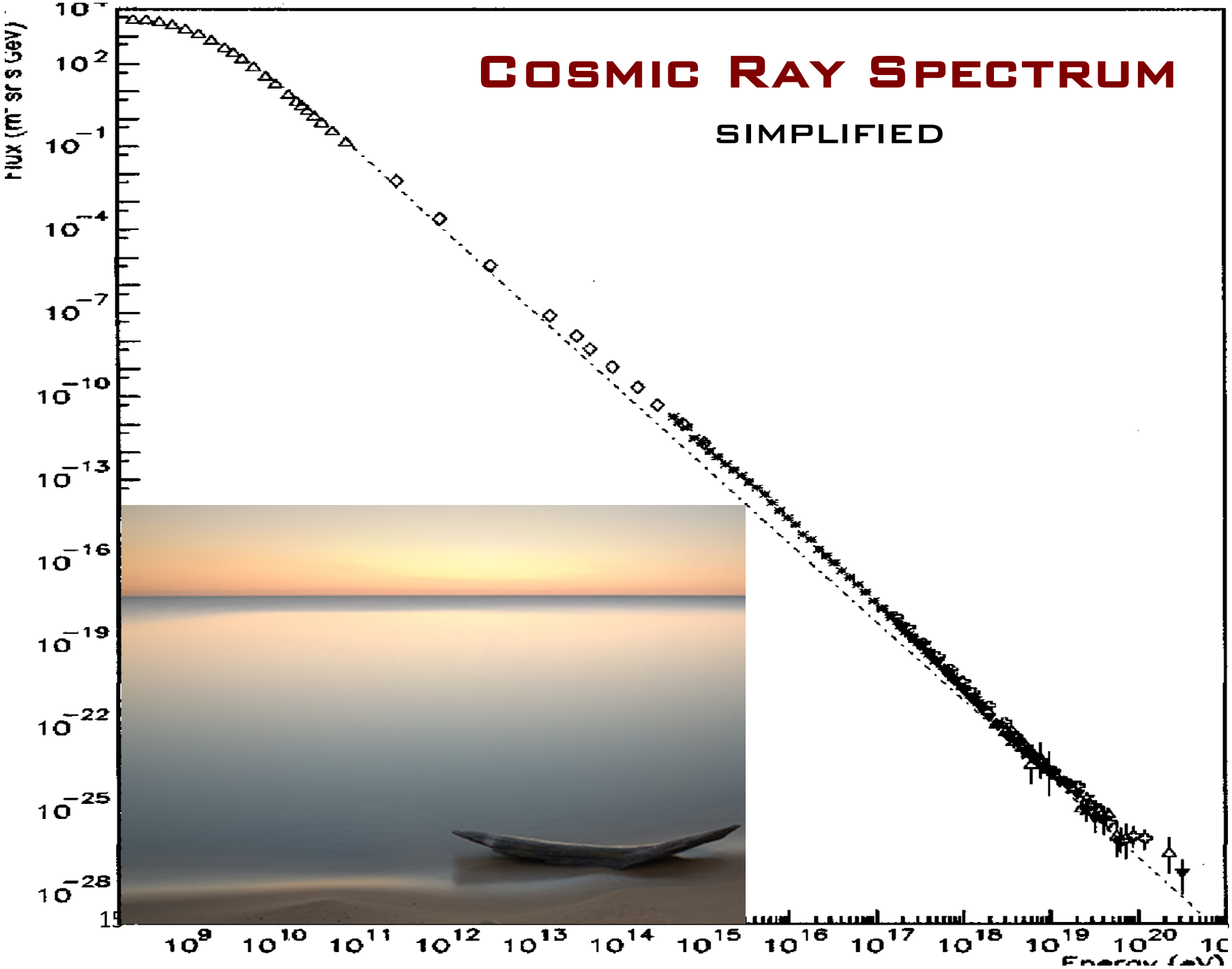


AMS measured a smooth hardening above 230 GV for heavier elements at the same rigidity.
Why the hardening? re-acceleration at the source? propagation? nearby source?

V. Bindi TeVPA17

Cosmic Ray Spectrum

SIMPLIFIED



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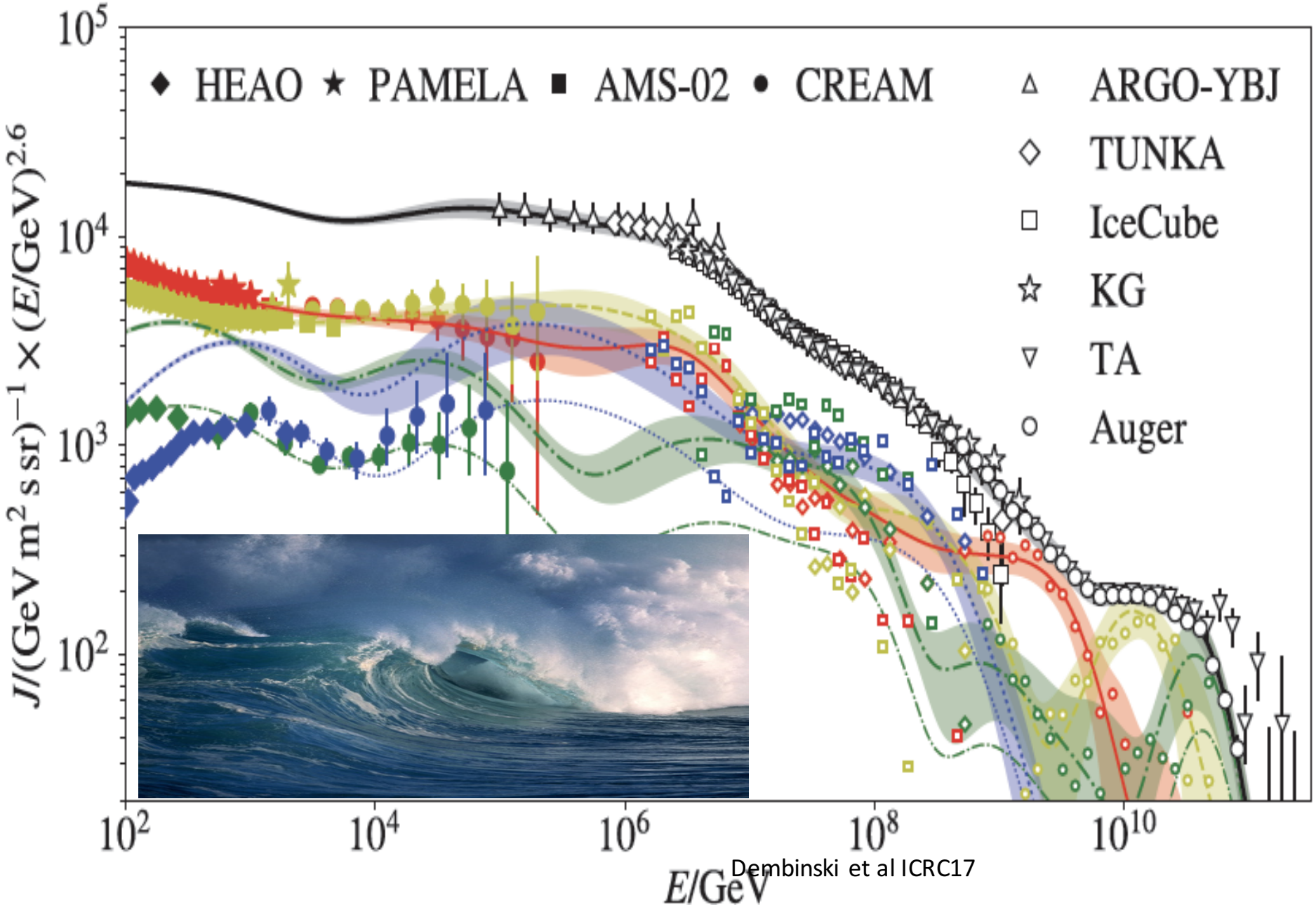
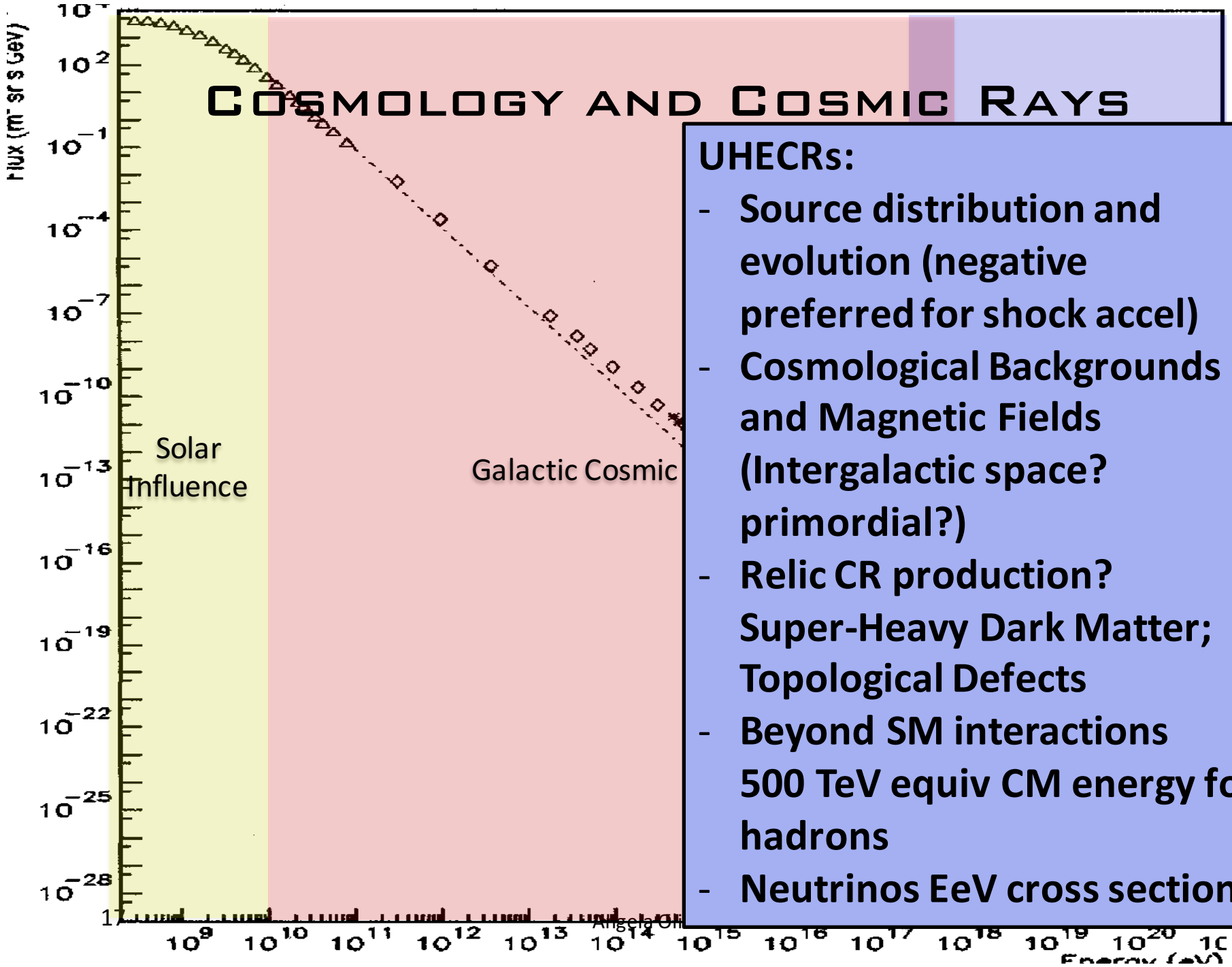


Dembinski et al ICRC17

Cosmology and Cosmic Rays



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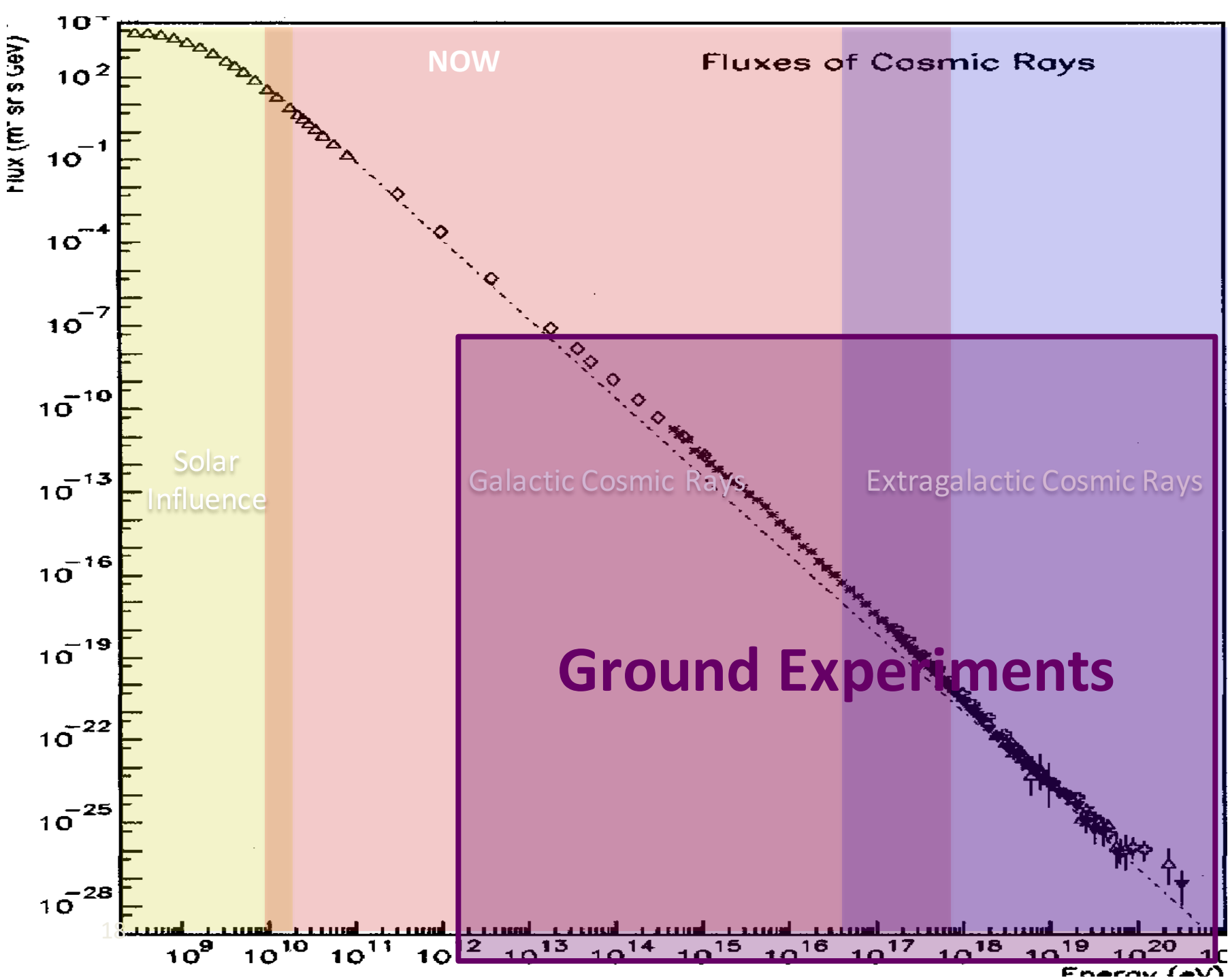
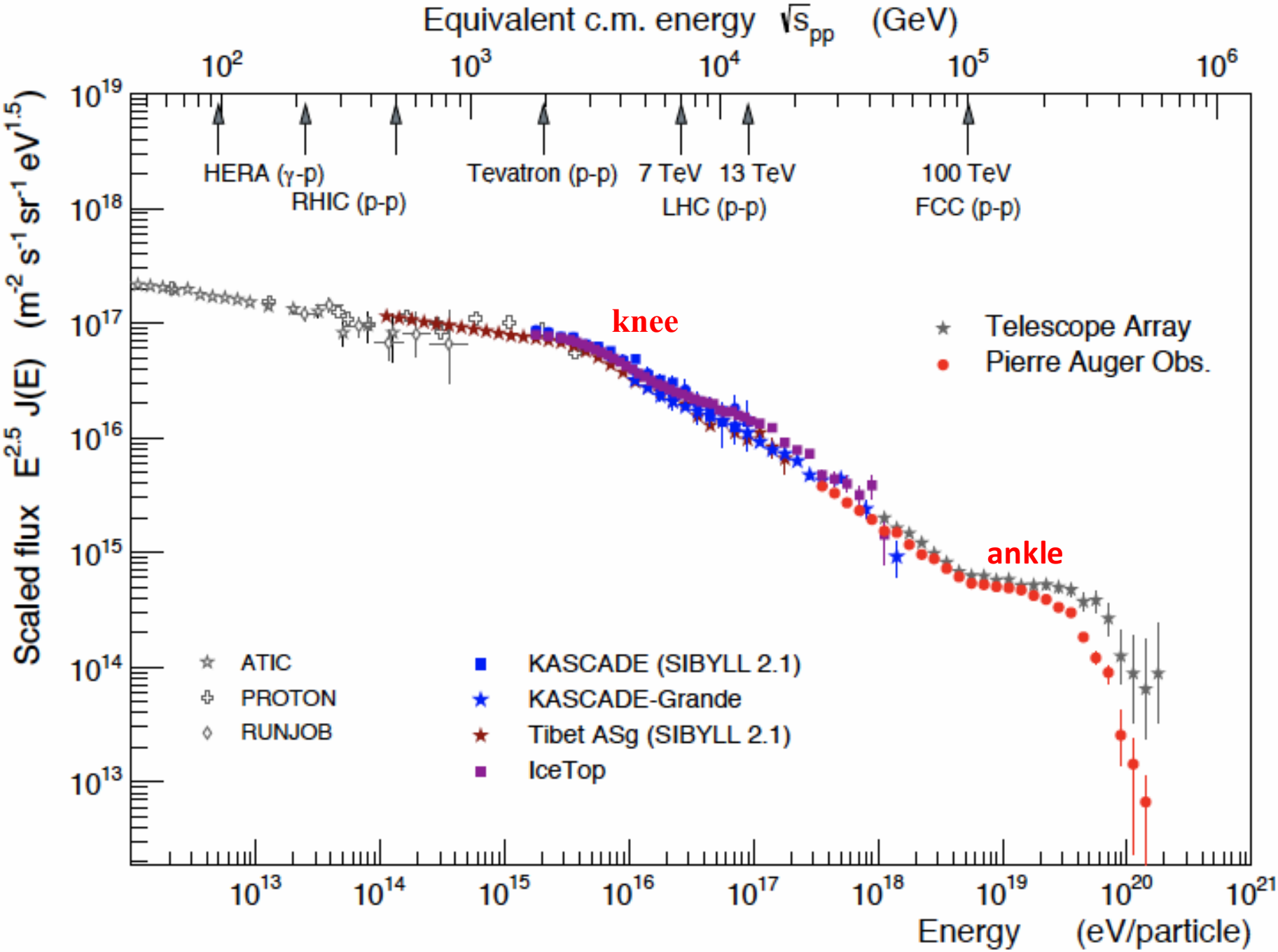
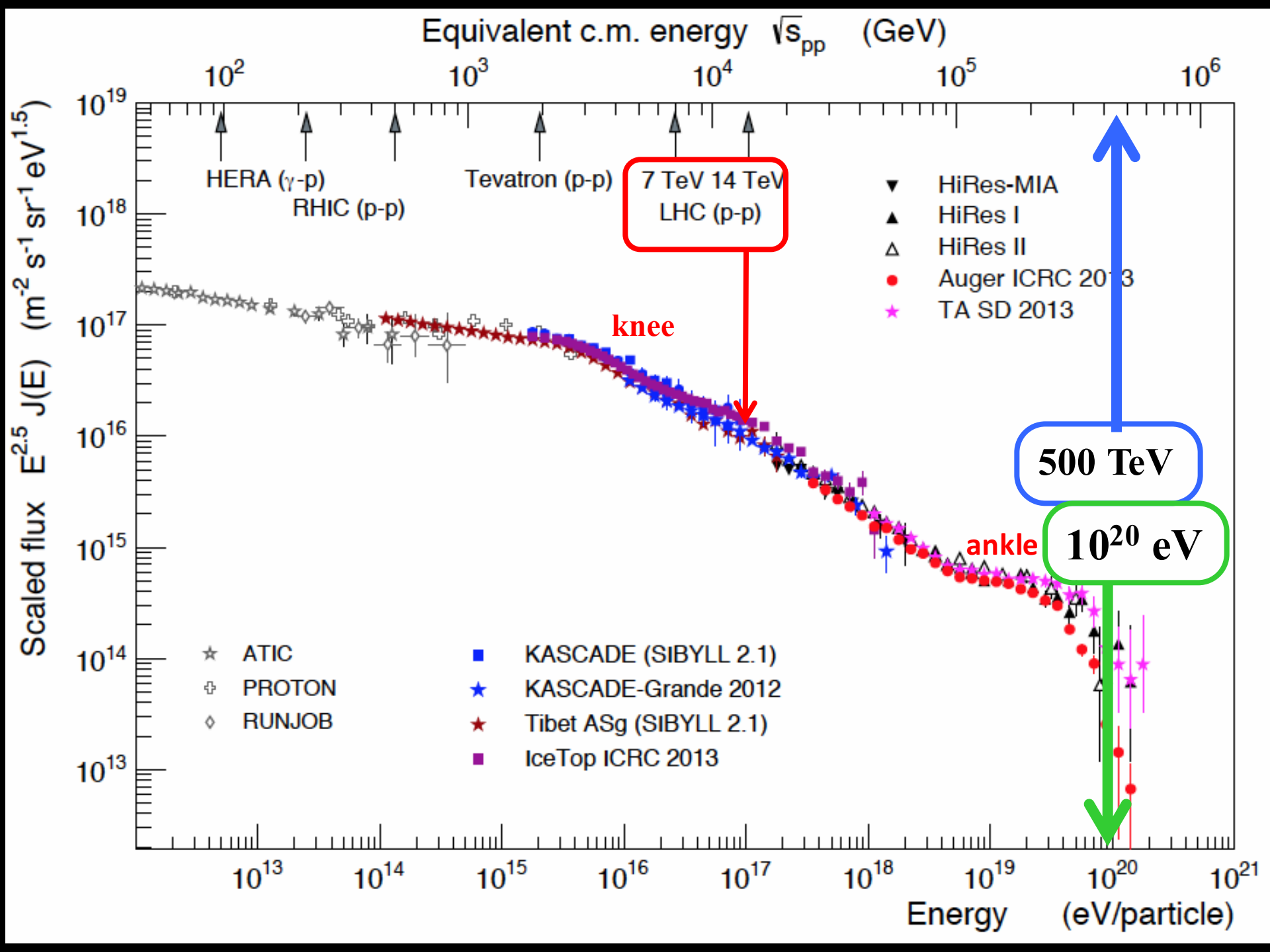
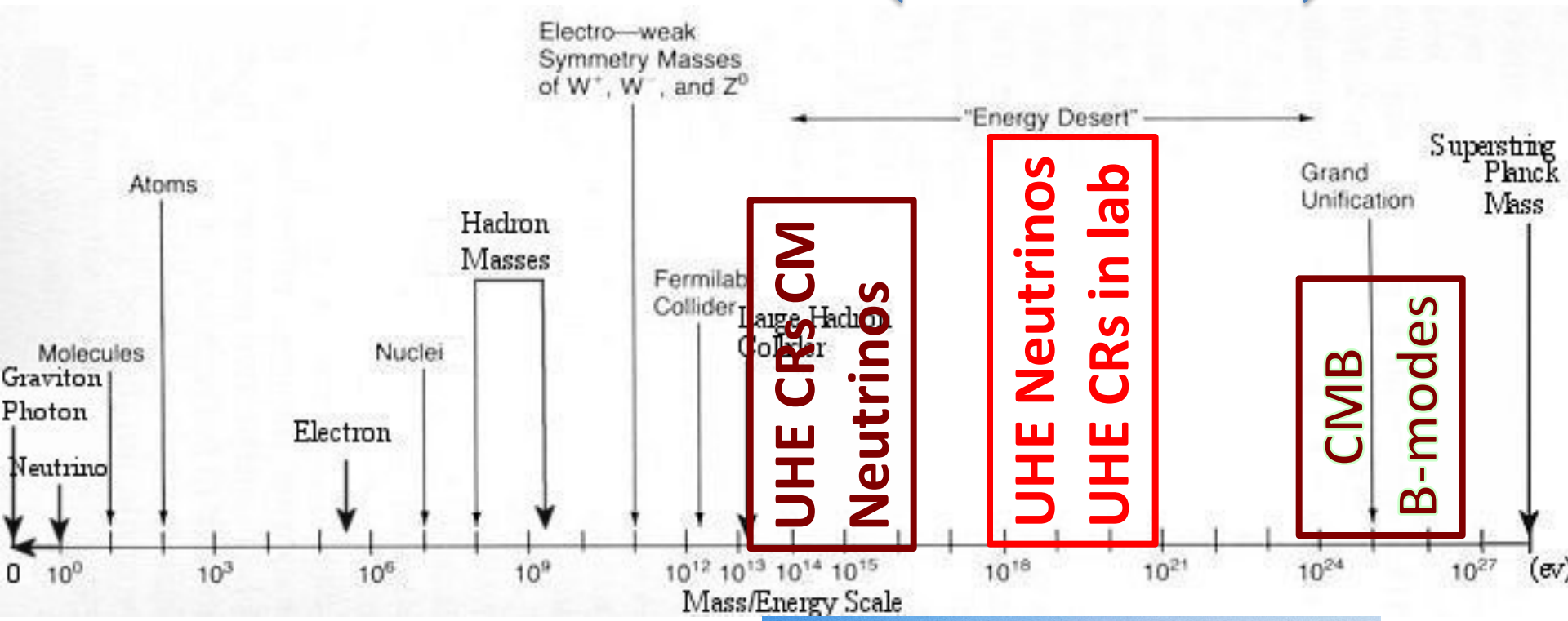

Fluxes of Cosmic Rays
NOW
Solar Influence
Galactic Cosmic Rays
Extragalactic Cosmic Rays
Ground Experiments
Flux (m⁻ sr s GeV)
Energy (eV)

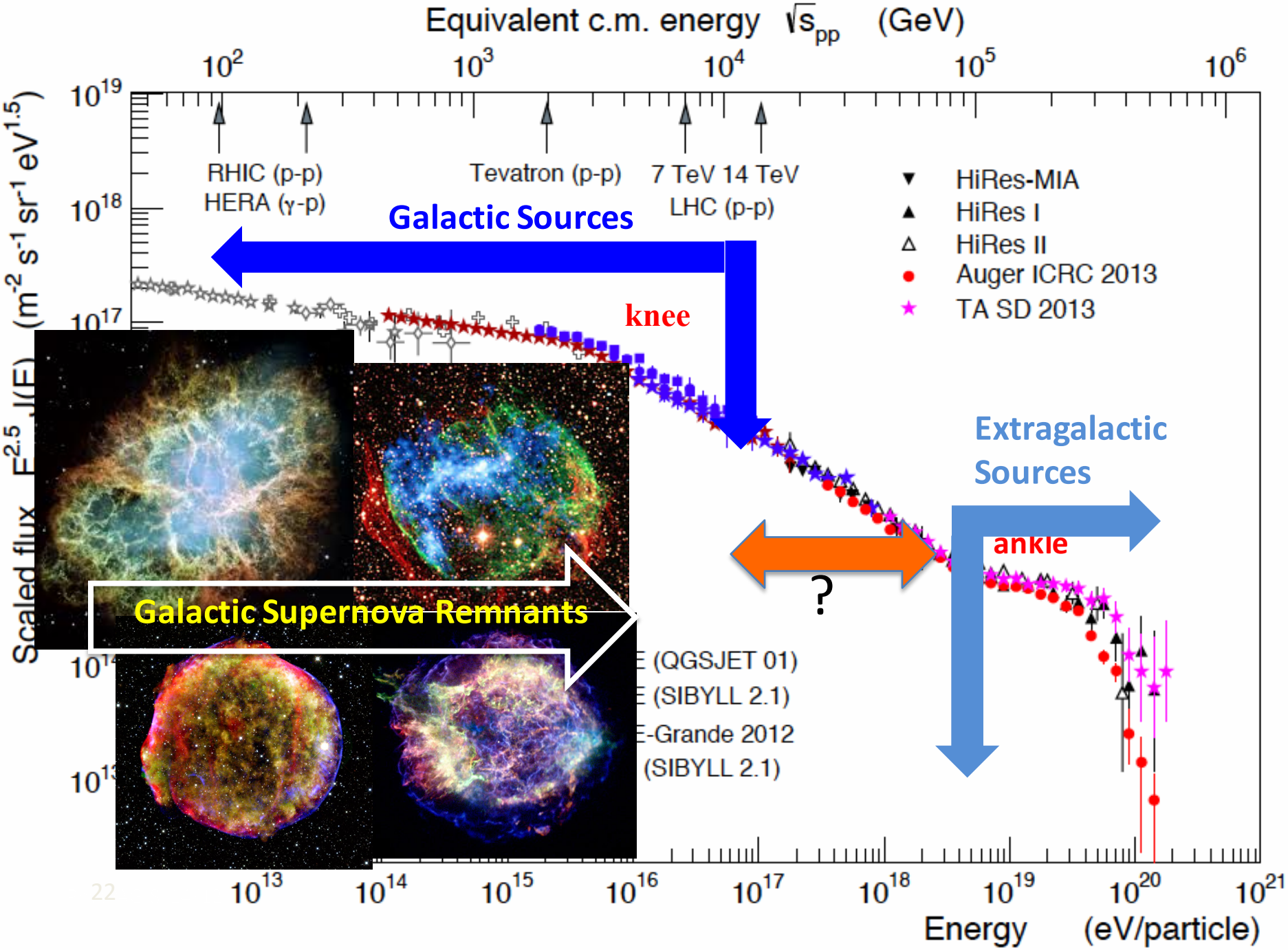

Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
7 TeV
13 TeV
LHC (p-p)
100 TeV
FCC (p-p)
knee
ankle
Telescope Array
Pierre Auger Obs.
ATIC
PROTON
RUNJOB
KASCADE (SIBYLL 2.1)
KASCADE-Grande
Tibet ASg (SIBYLL 2.1)
IceTop
Scaled flux E^2.5 J(E) (m^-2 s^-1 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)

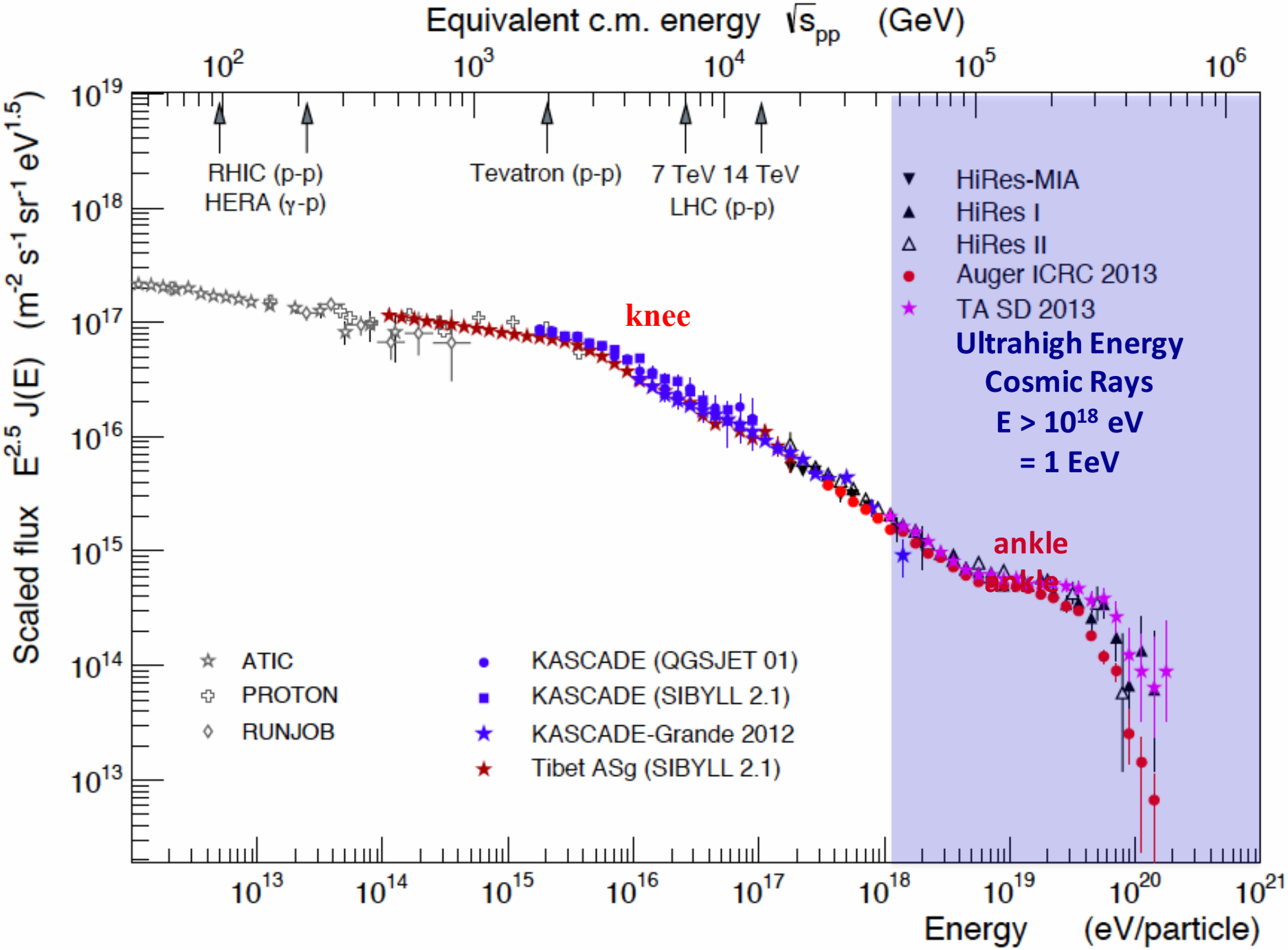

Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
HERA (γ-p)
RHIC (p-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
ankle
500 TeV
10^20 eV
ATIC
PROTON
RUNJOB
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
IceTop ICRC 2013
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)

Journey toward Planck

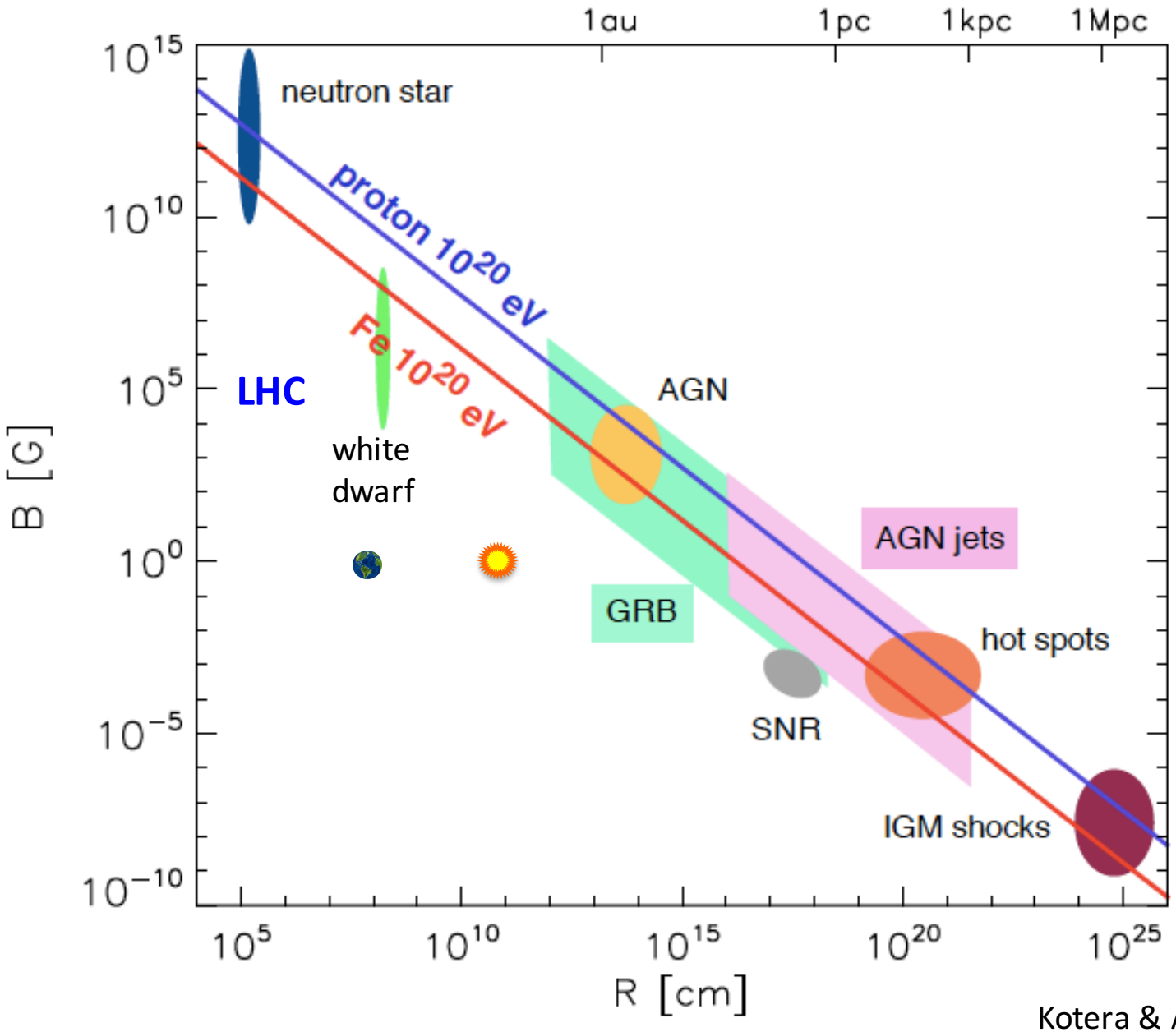
10^{13} eV ← 14 o.o.m. → 10^{27} eV



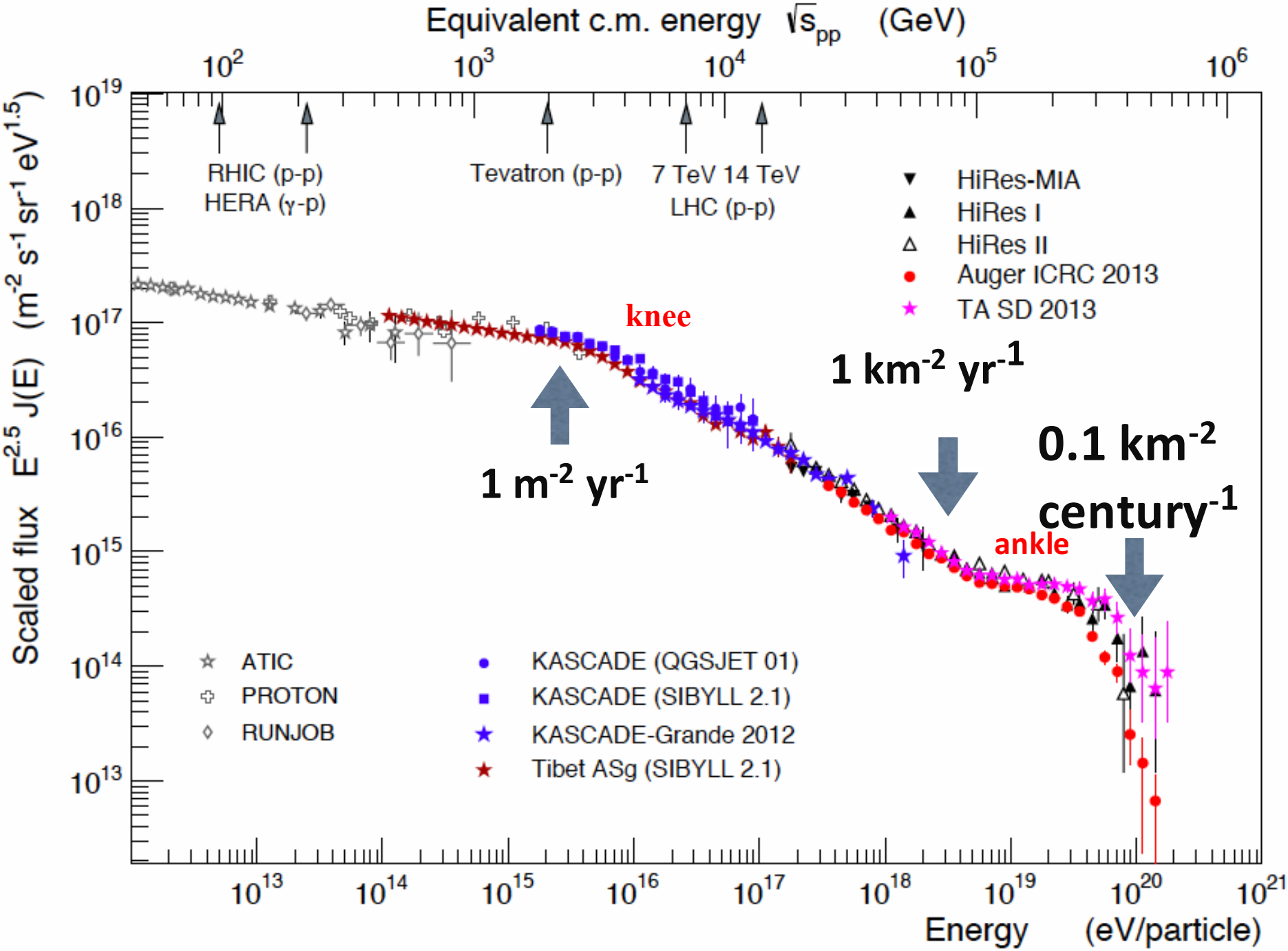

Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
Galactic Sources
knee
Extragalactic Sources
ankle
?
Galactic Supernova Remnants
(QGSJET 01)
(SIBYLL 2.1)
-Grande 2012
(SIBYLL 2.1)
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
10^19
10^18
10^17
10^13
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
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
ankle
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)

Hillas Plot: E_{max} required



Kotera & AO'11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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
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10^19
10^18
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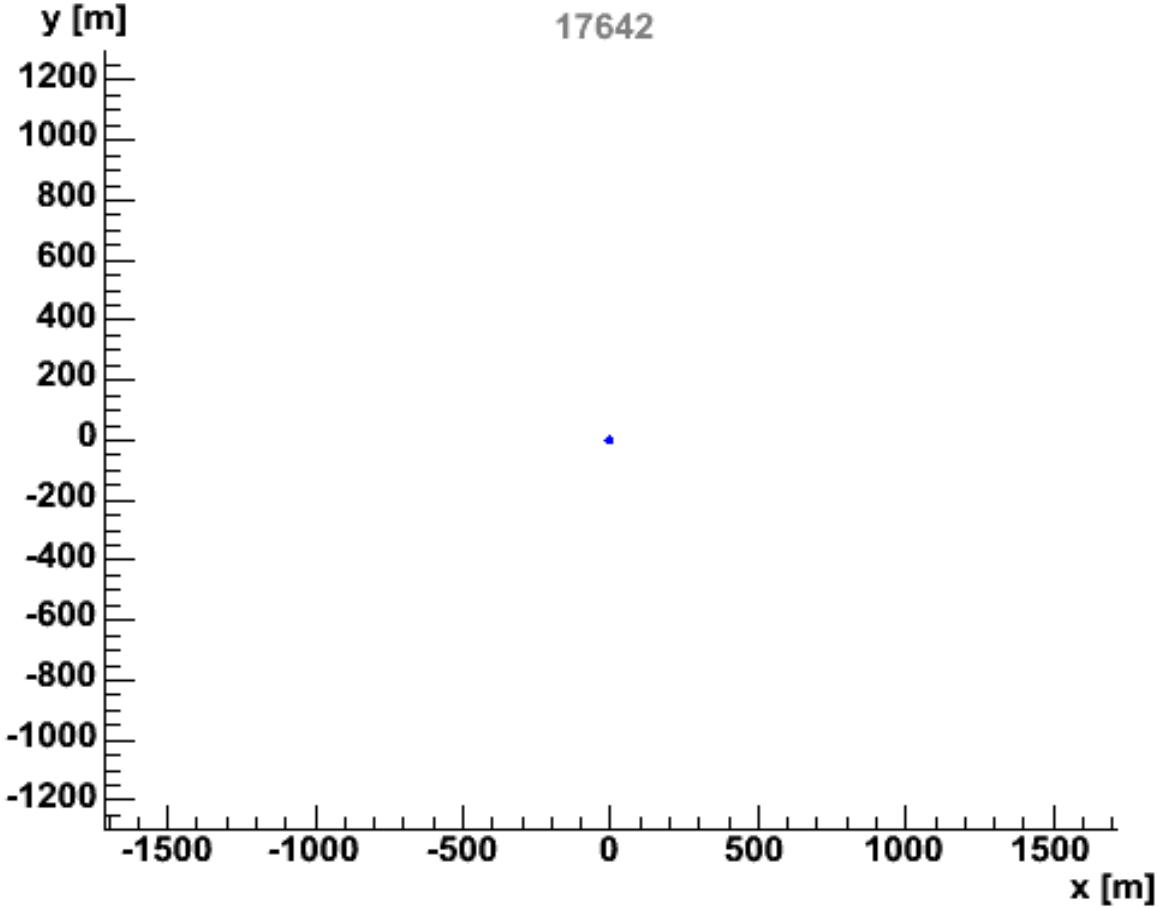
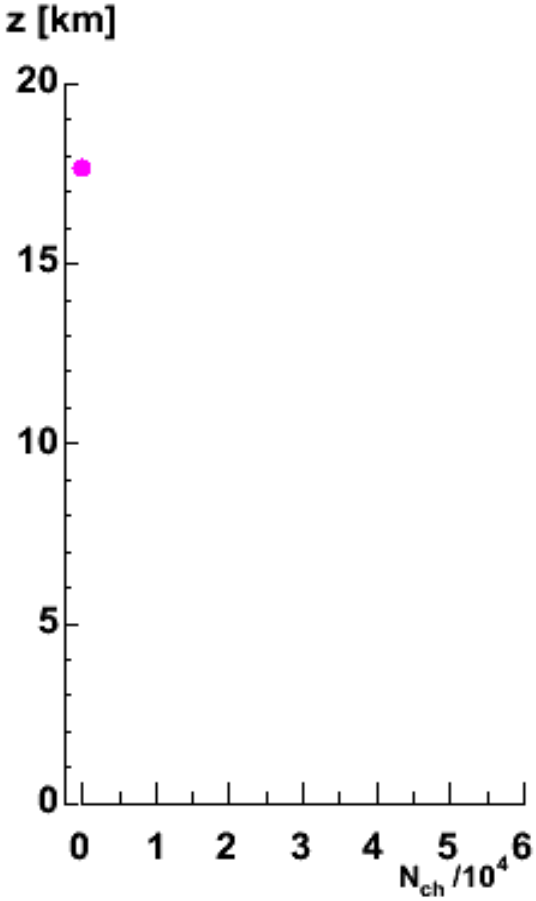
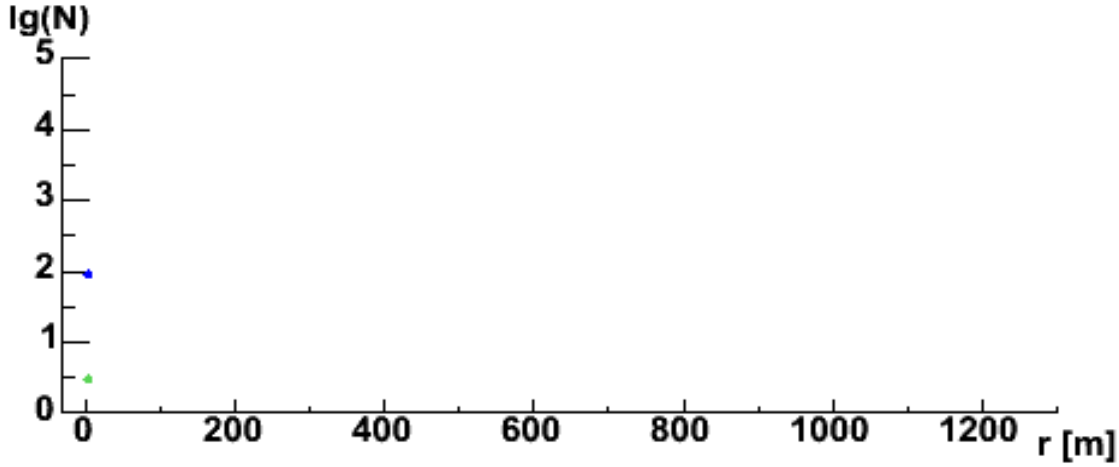
10^14
10^13
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)







Proton 10^{14} eV

h^{1st} = 17642 m

hadrons muons

neutrons **electrs**

J.Oehlschlaeger,R.Engel,FZKarlsruhe

Leading Observatories of Ultrahigh Energy Cosmic Rays

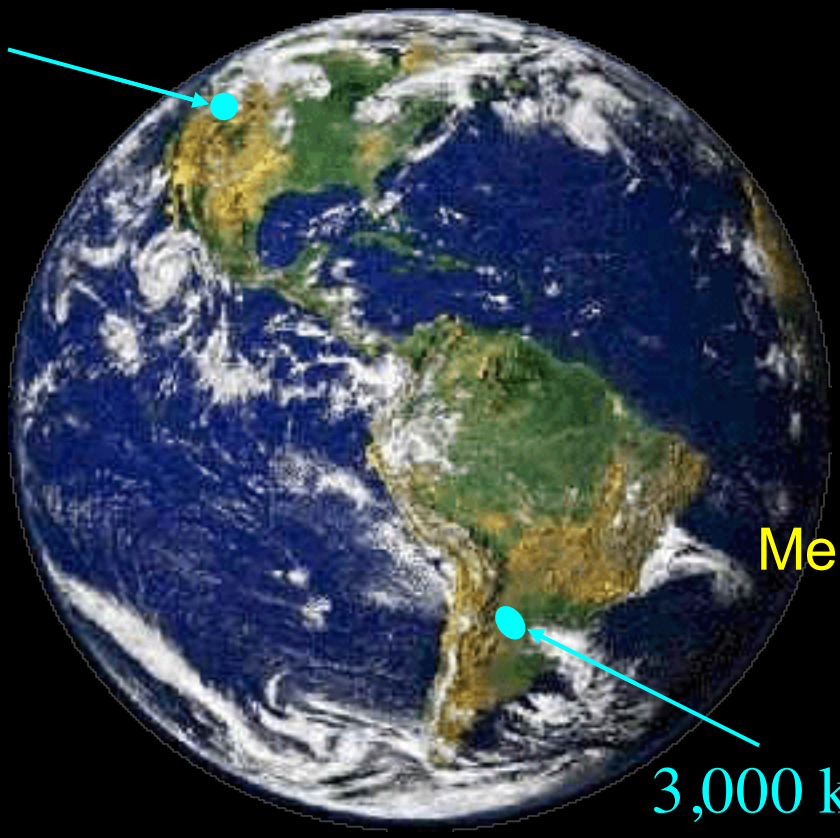
Telescope Array

Utah, USA

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



Pierre Auger Observatory

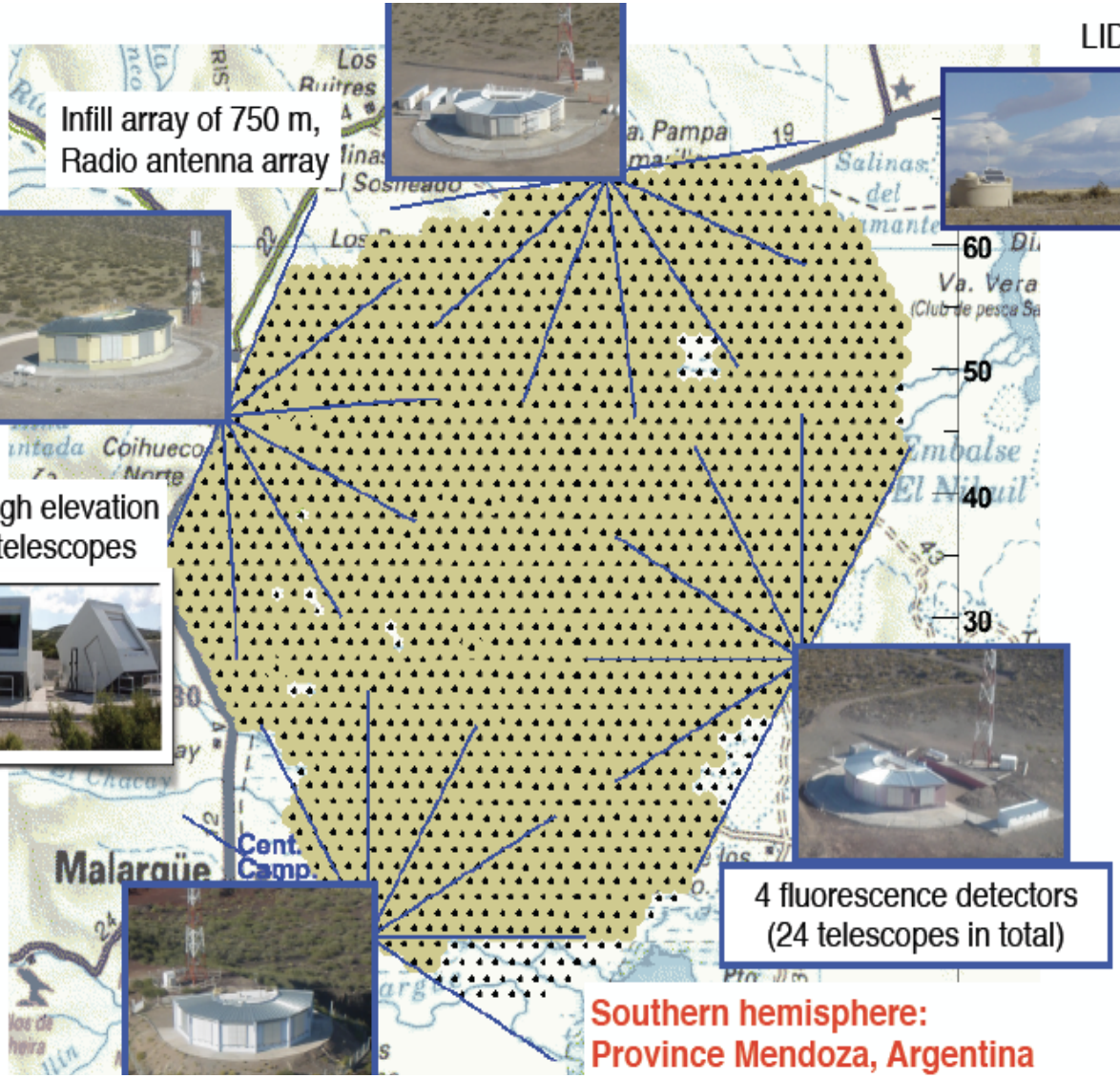
Mendoza, Argentina

(19 country collaboration)

3,000 km^2 array

4 fluorescence telescopes

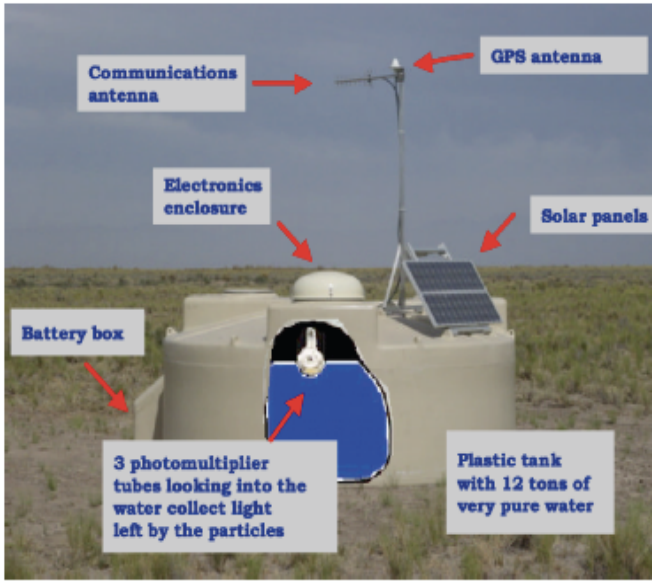
The Pierre Auger Observatory



LIDARs and laser facilities

PIERRE AUGER OBSERVATORY

1665 surface detectors:
water-Cherenkov tanks
(grid of 1.5 km, 3000 km²)

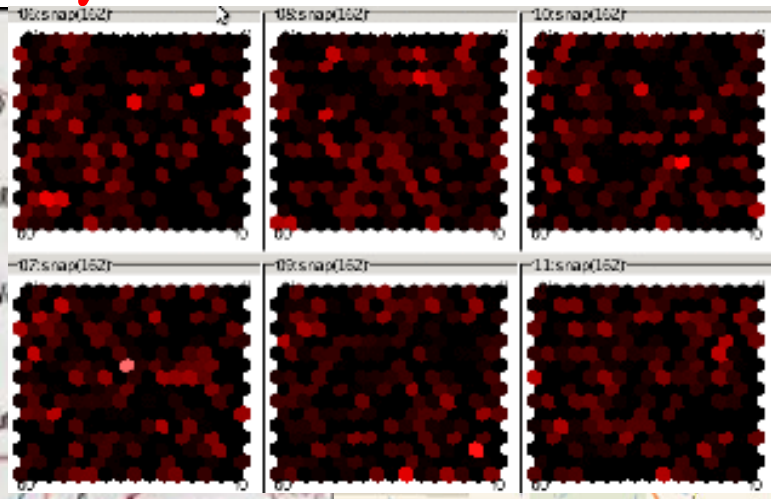


Southern hemisphere:
Province Mendoza, Argentina

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

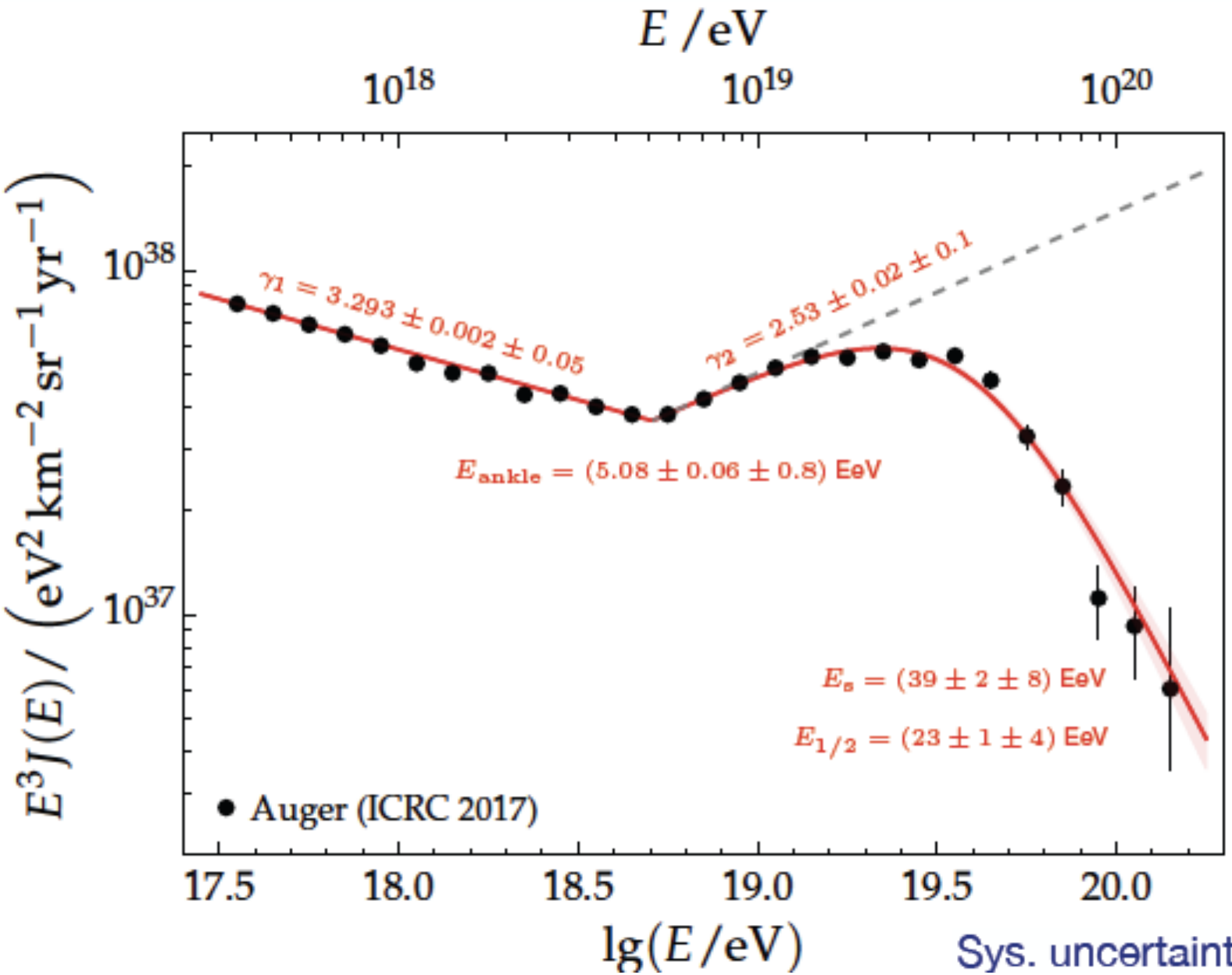
Telescope Array

Belgium
Japan
Korea
Russia
USA



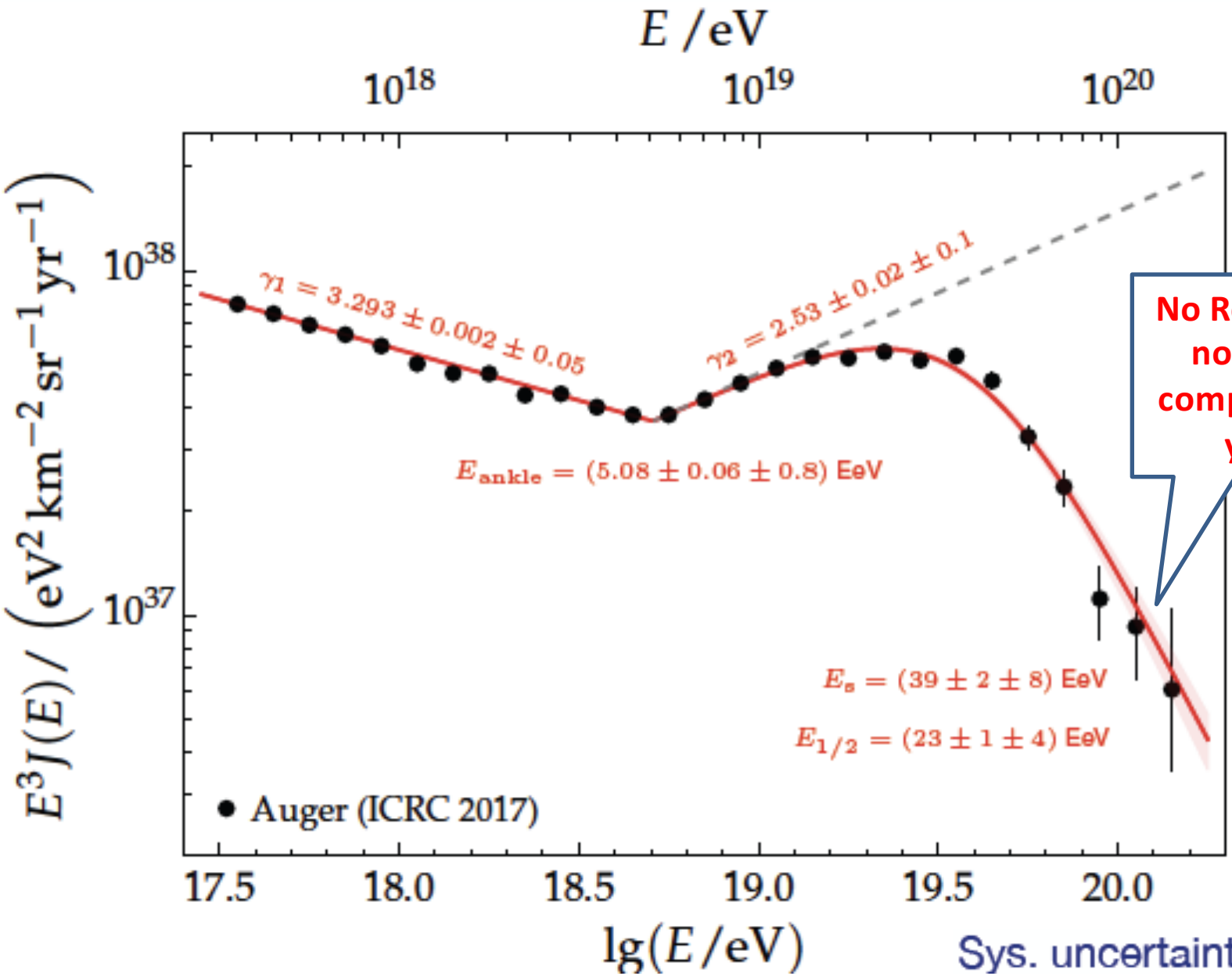
Area: 700 km^2

3 FD stations overlooking an array of 507 scintillator surface detectors (SD)



Sys. uncertainty

Auger $\Delta E/E = 14\%$

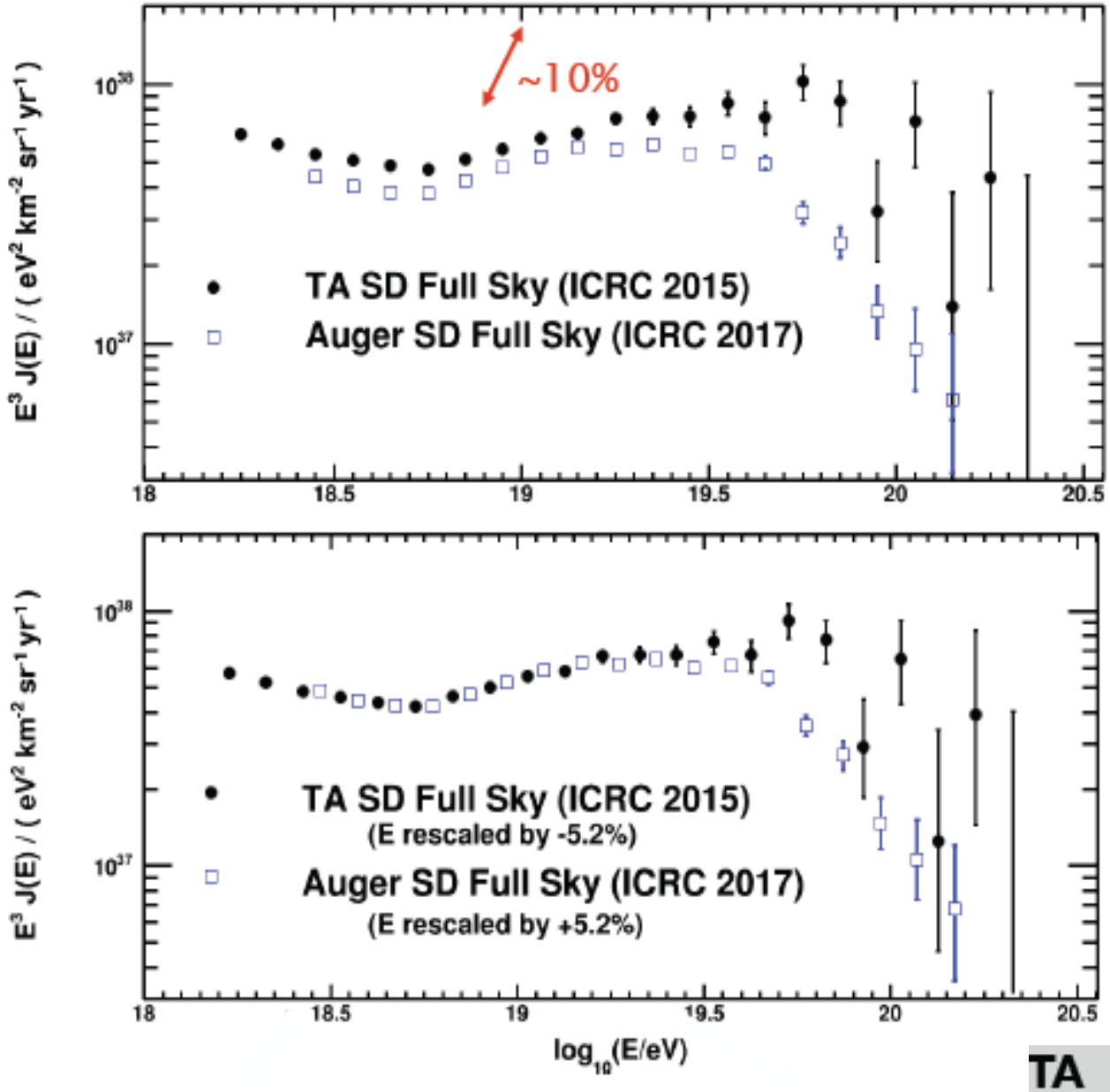


No Recovery nor new components yet!

Sys. uncertainty

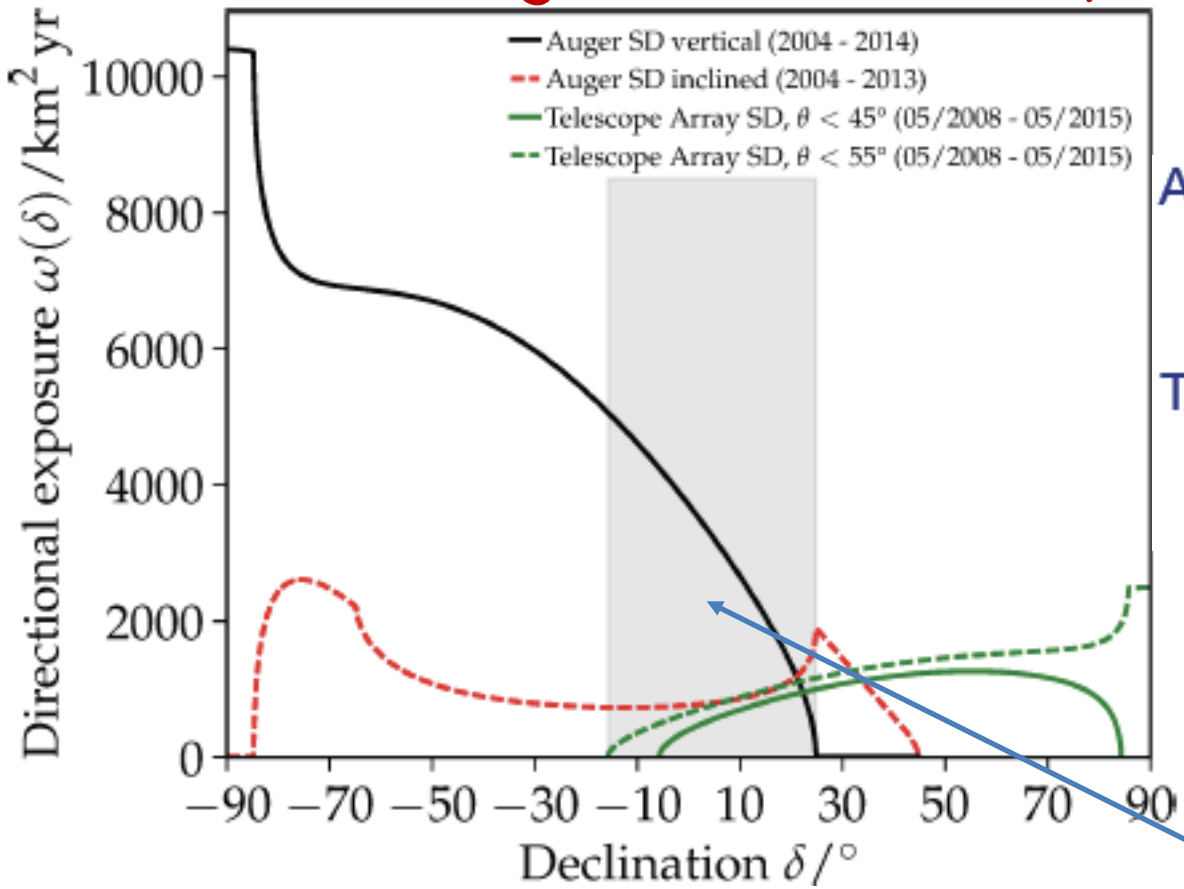
Auger $\Delta E/E = 14\%$

(Auger-TA Spectrum Working Group)



TA $\Delta E/E = 21\%$

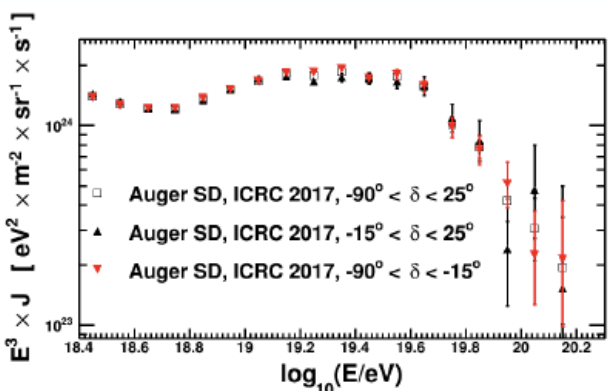
Auger + TA: Full Sky Coverage

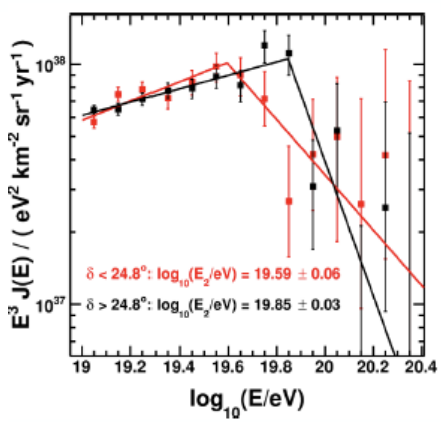


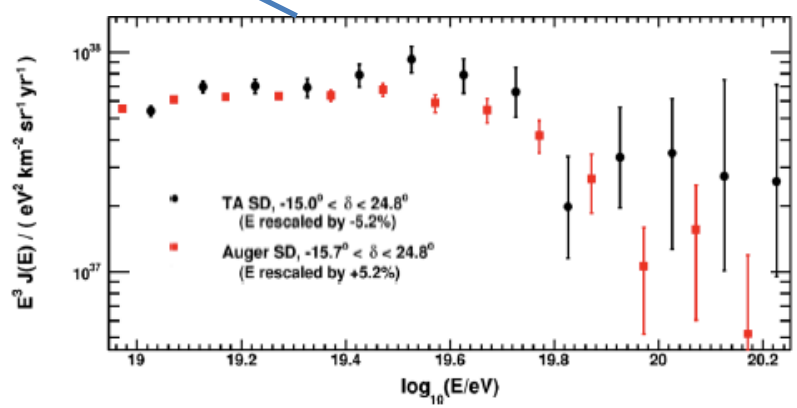
Auger:
- 6.7 x 10^4 km^2 sr yr (spectrum)
- 9 x 10^4 km^2 sr yr (anisotropy)

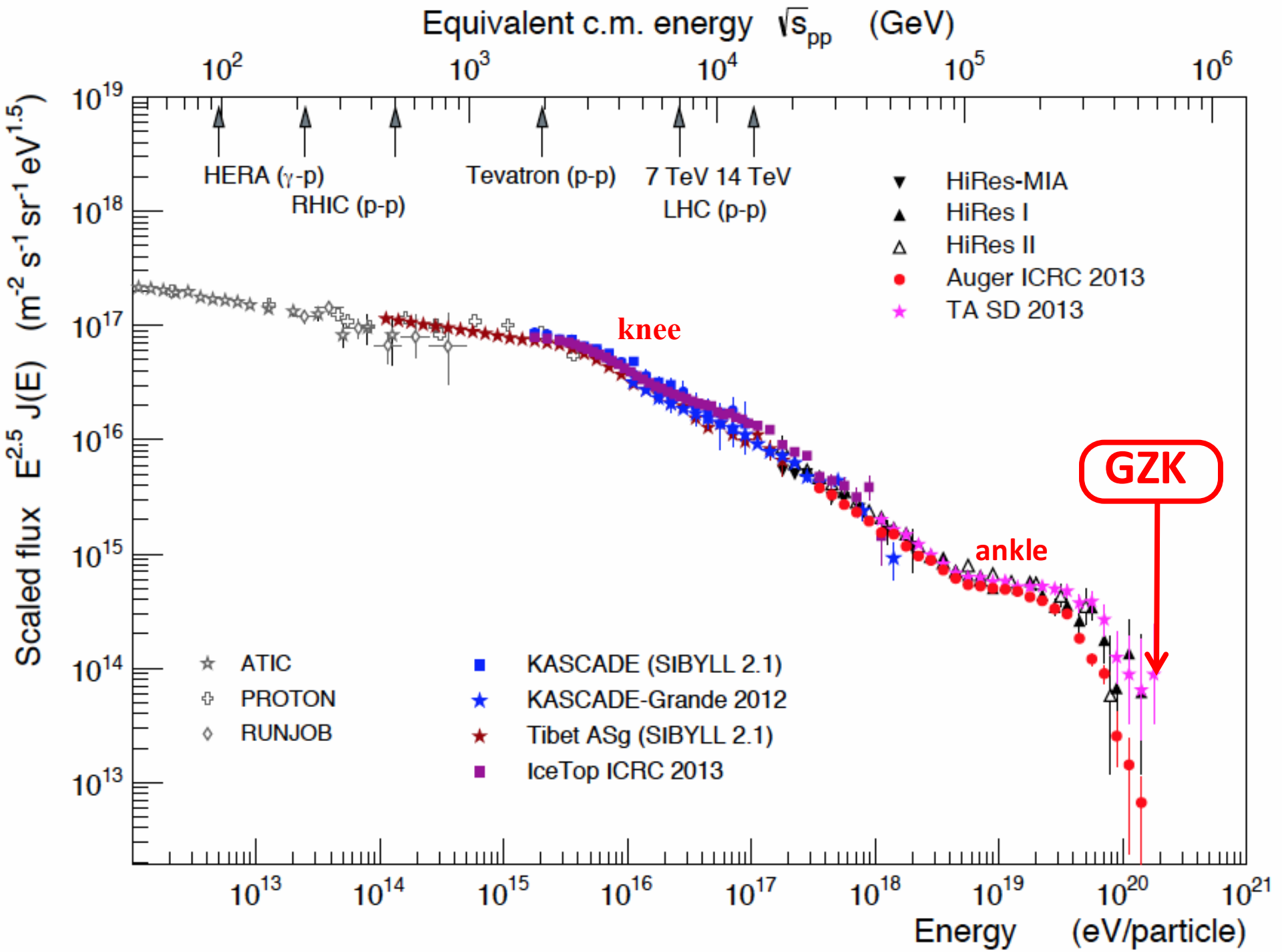
TA:
- 8.1 x 10^3 km^2 sr yr (spectrum)
- 8.6 x 10^3 km^2 sr yr (anisotropy

Common declination band








Equivalent c.m. energy $\sqrt{s_{pp}}$ (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
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)

"Cosmologically Meaningful Termination"

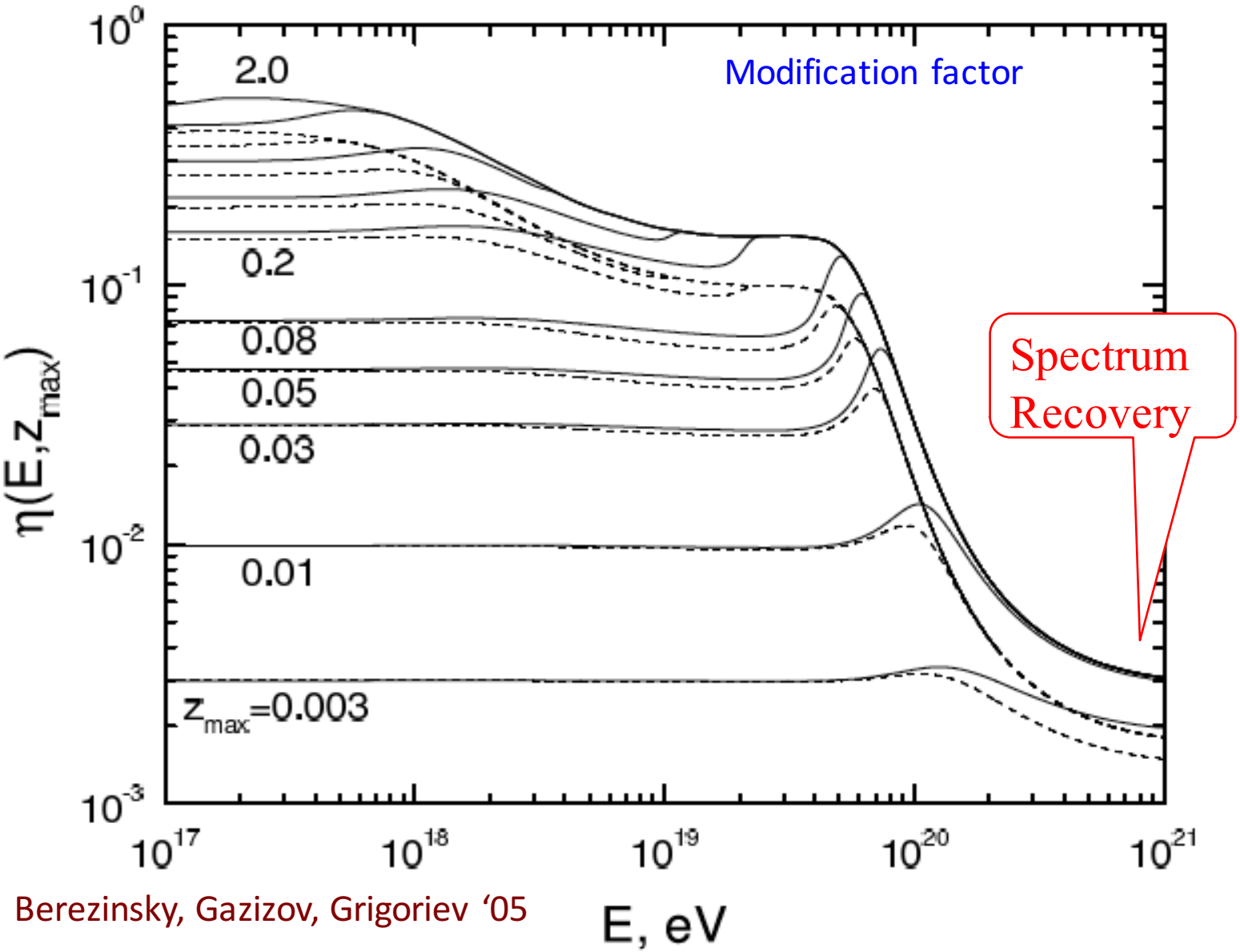
$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Proton Horizon
~5 x 10^{19} eV

GZK Cutoff

Greisen, Zatsepin, Kuzmin 1966

Propagation of UHE protons



Berezinsky, Gazizov, Grigoriev '05

Super Heavy Dark Matter

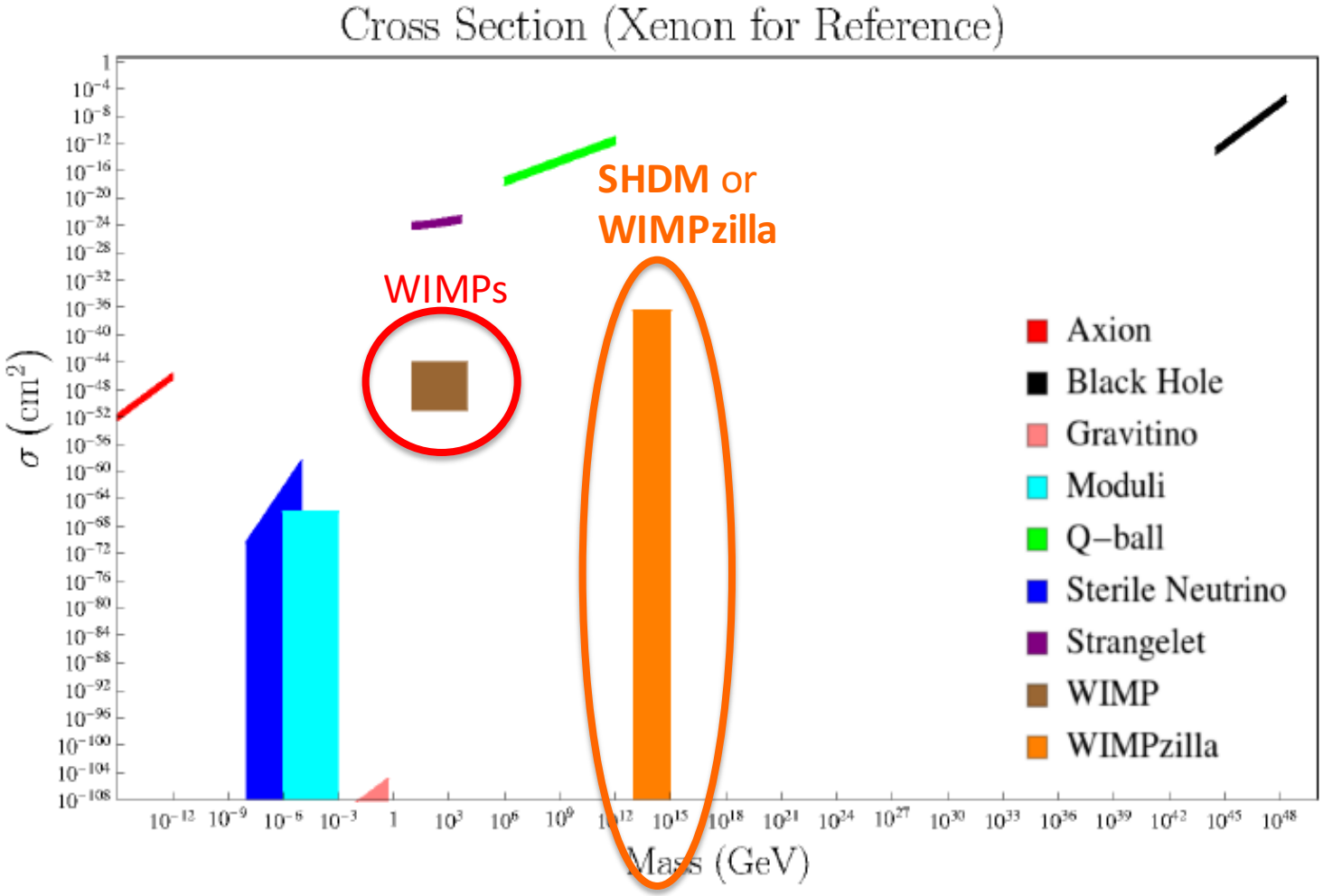
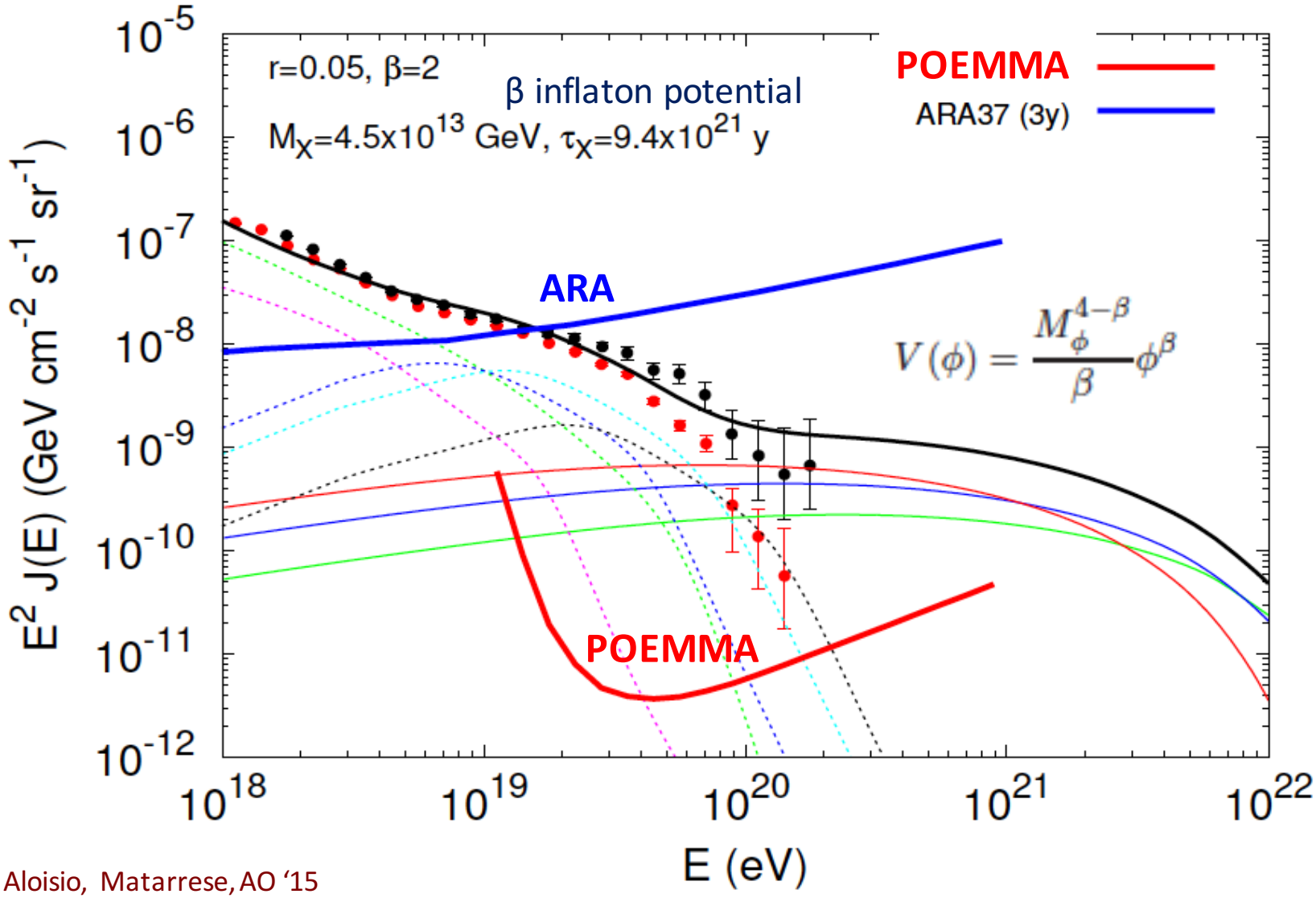


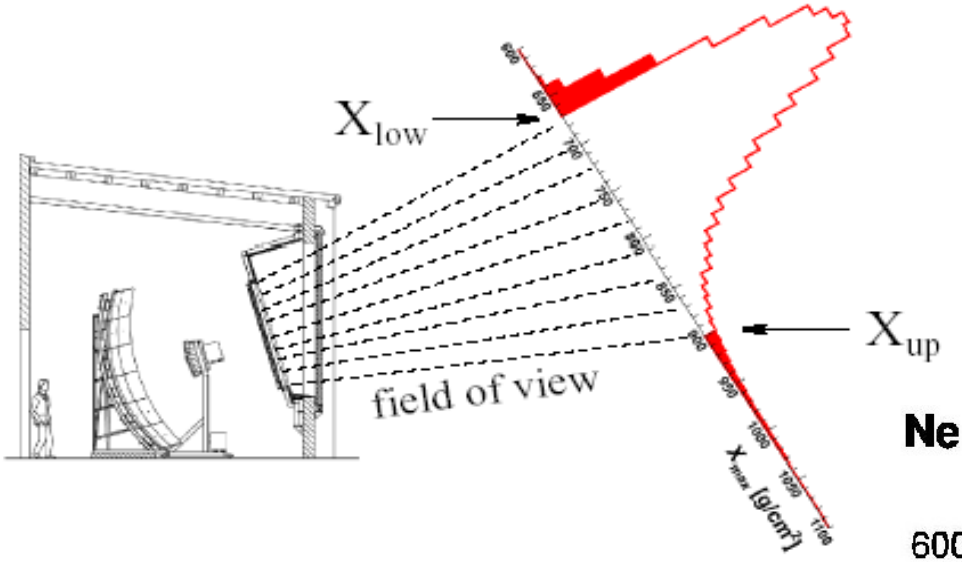
Figure 4-8. *The range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates have an enormous range of possible masses and interaction cross sections.*

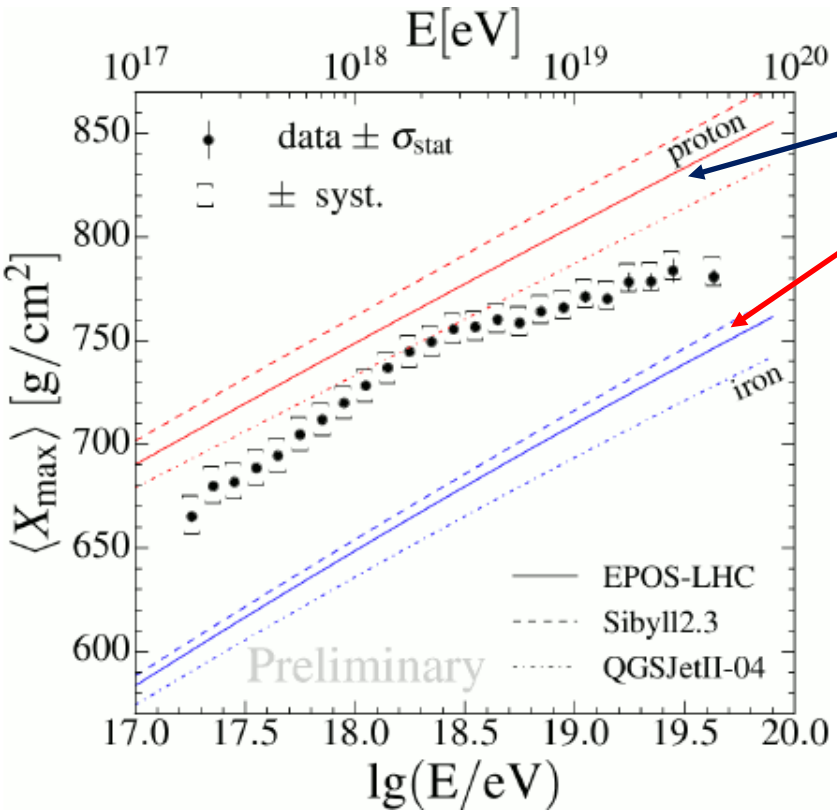
Super Heavy Dark Matter

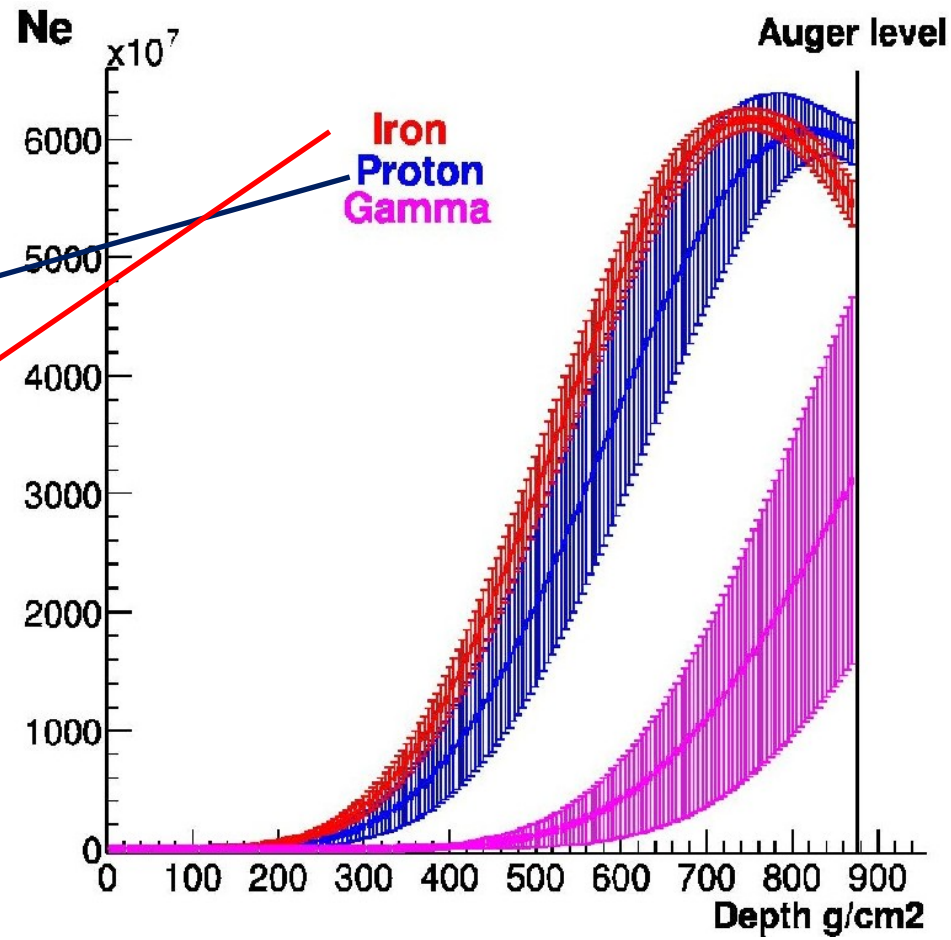


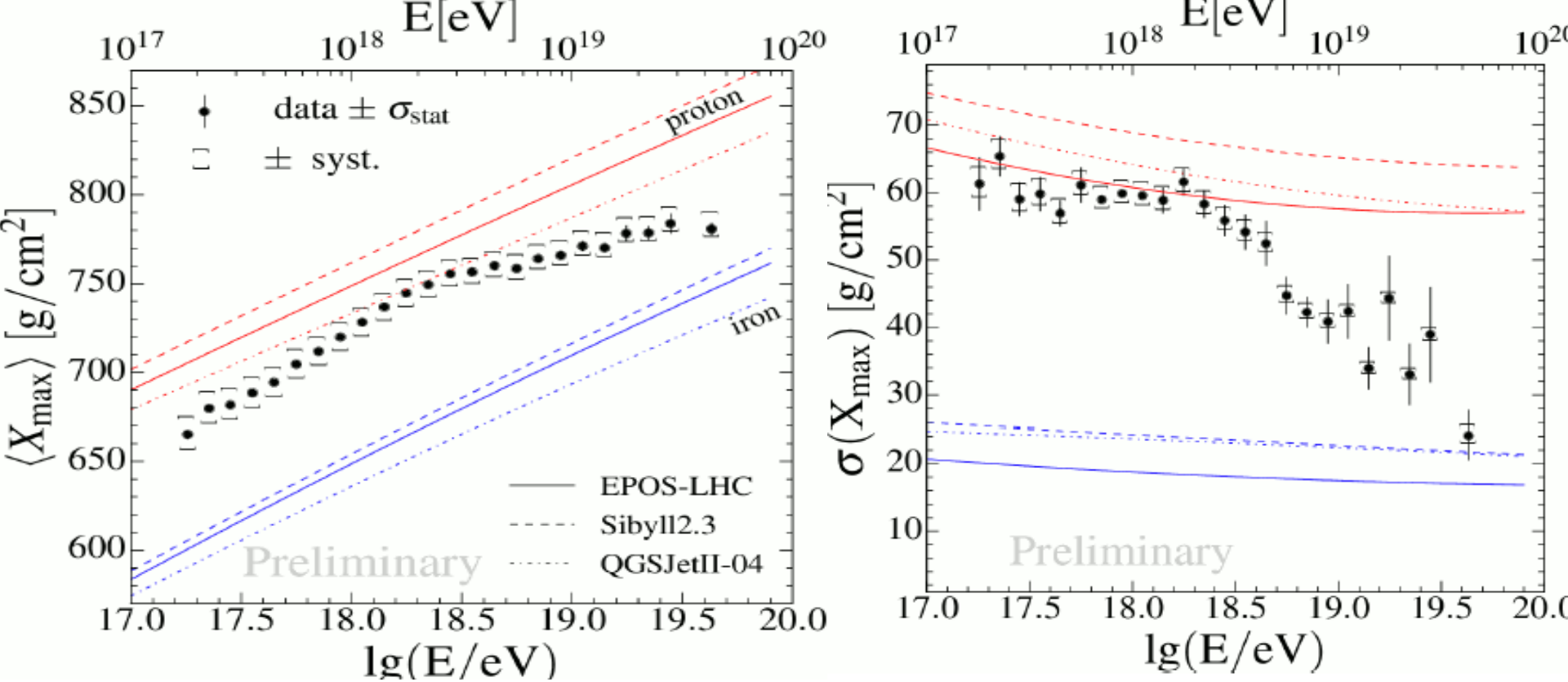
Aloisio, Matarrese, AO '15

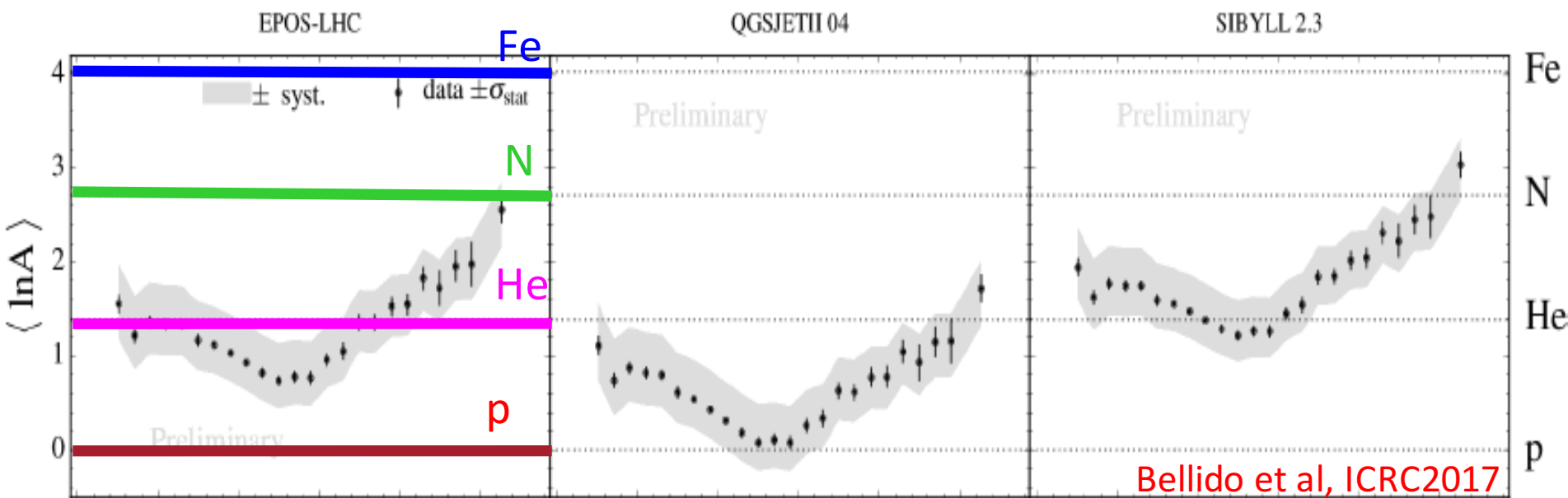
Composition observable: shower maximum average and fluctuations



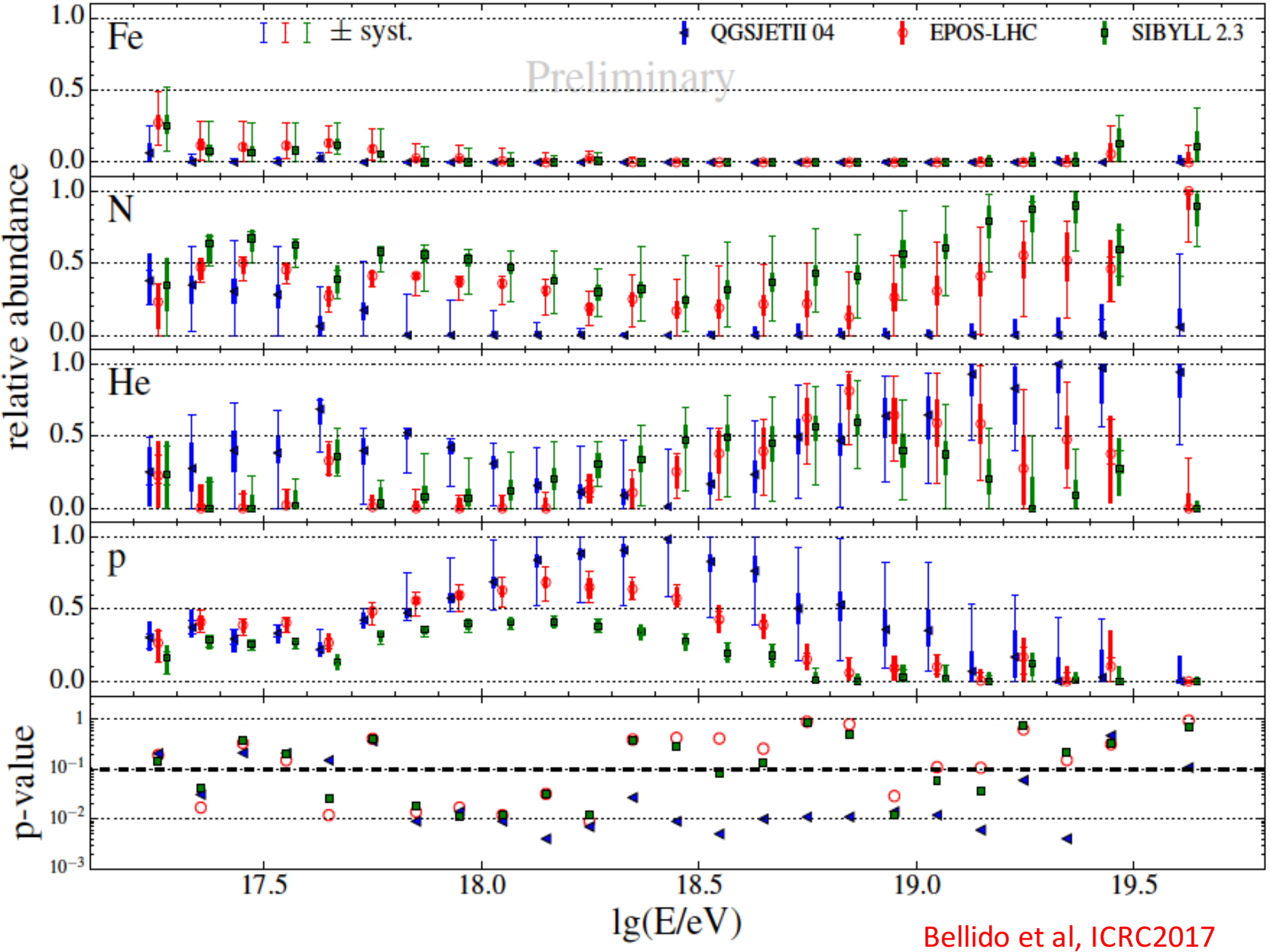








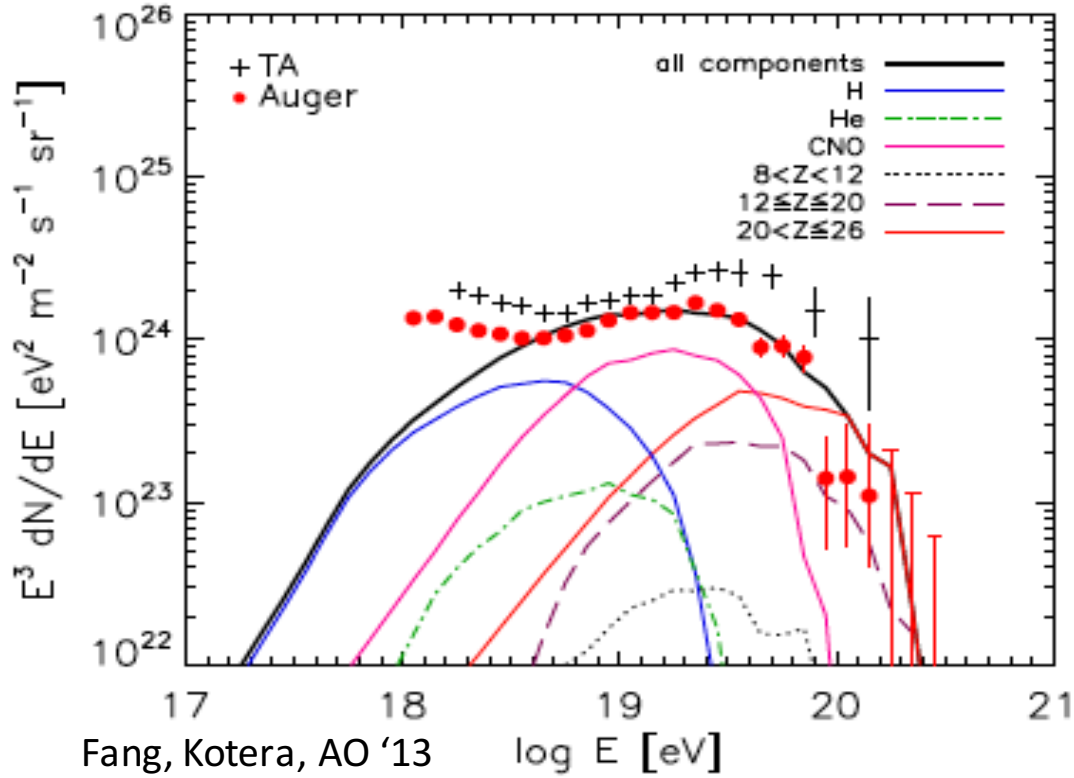
Bellido et al, ICRC2017



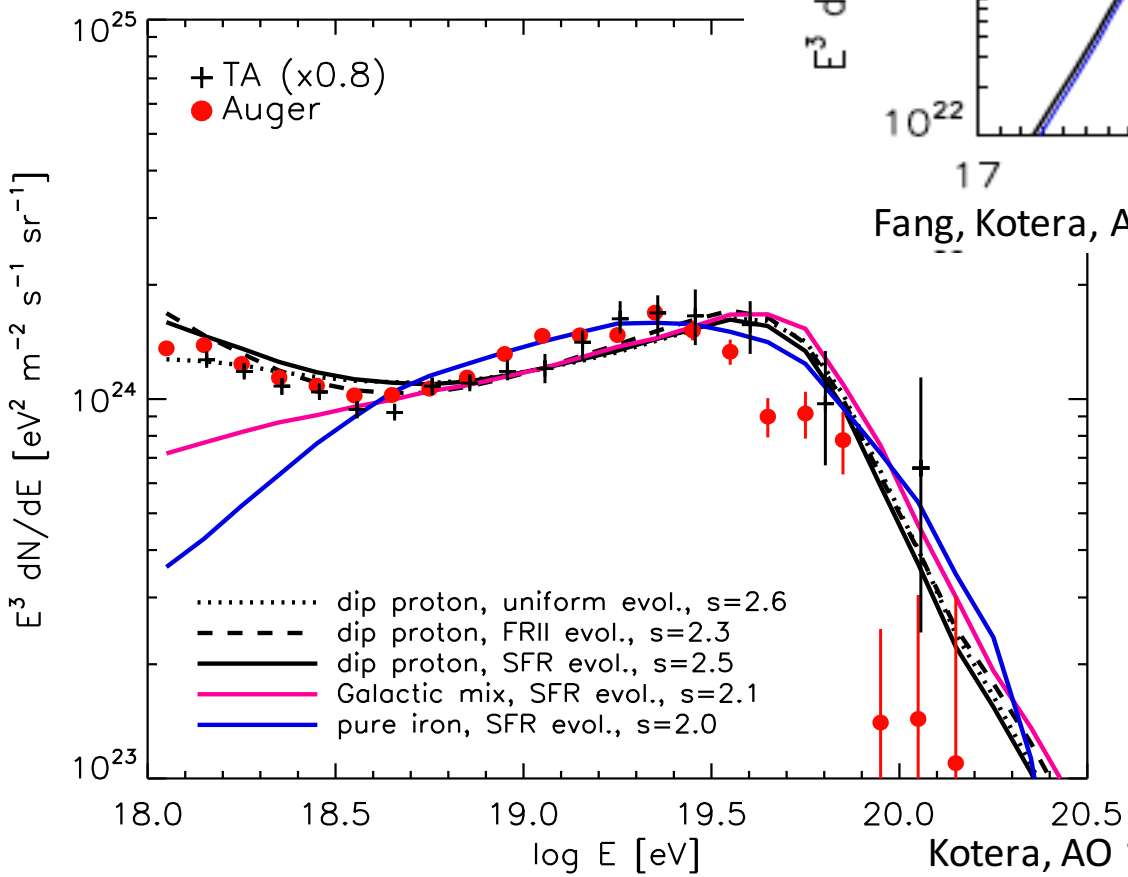
Bellido et al, ICRC2017

GZK or E_{max}?

(TA

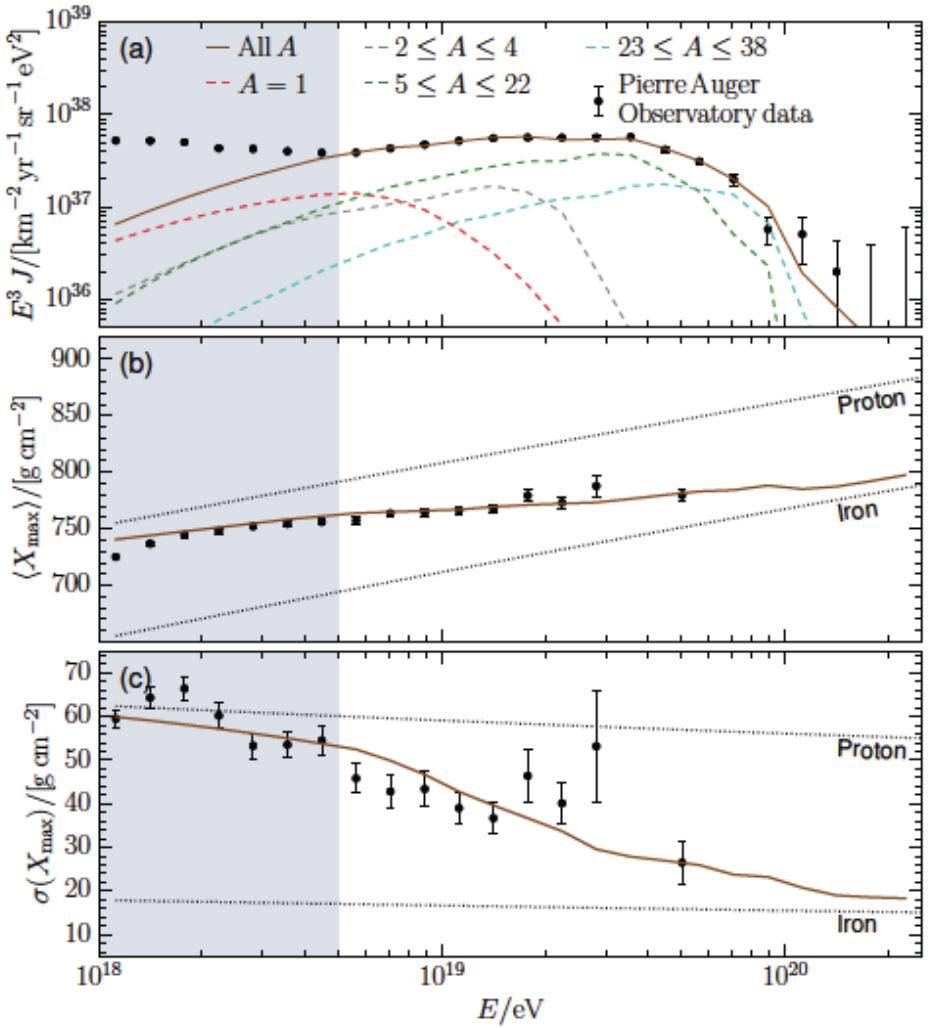


Fang, Kotera, AO '13



Kotera, AO '11

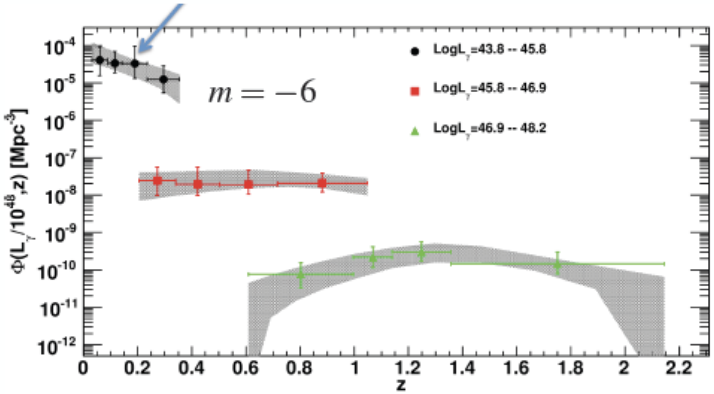
Negative Source Evolution
to agree with shock acceleration injection



(Wittkowski ICRC 2017)

Source evolution parameter	γ
$m = 3$	1.20
$m = 0$	1.61
$m = -3$	1.78
$m = -6$	1.95
$m = -9$	2.05

Fermi: low-luminosity, high-synchrotron peaked (HSP) BL Lacs

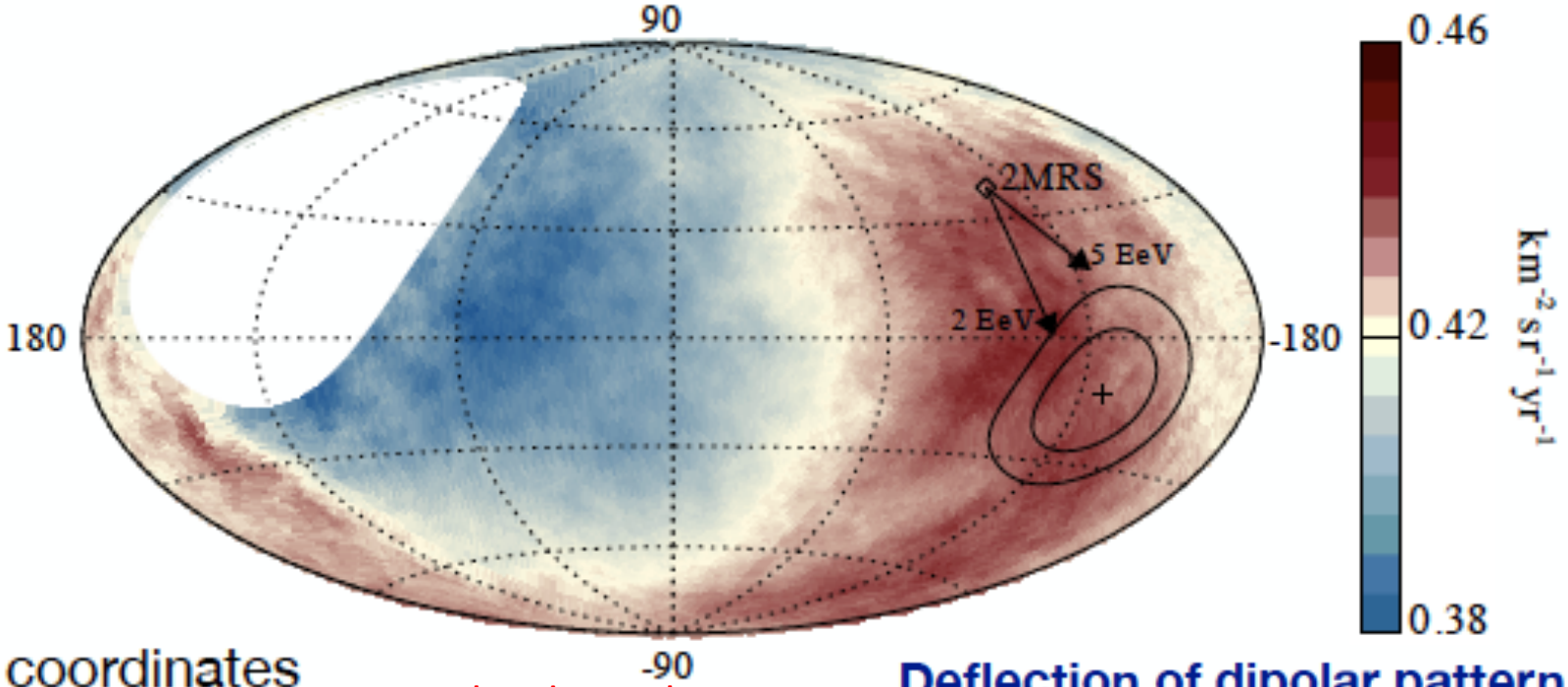


(Taylor, ICRC 2017)

Ajello et al. (2014), 1310.0006

3-d dipole above 8 EeV: **Auger Dipole !!!**

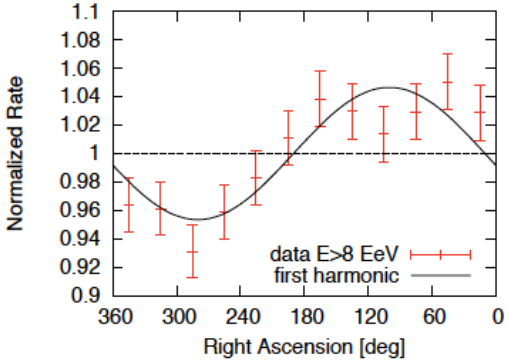
$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100°, -24°)$ $\quad (l, b) = (233°, -13°)$



gal. coordinates

Taborda et al ICRC17

Deflection of dipolar pattern due to Galactic magnetic field

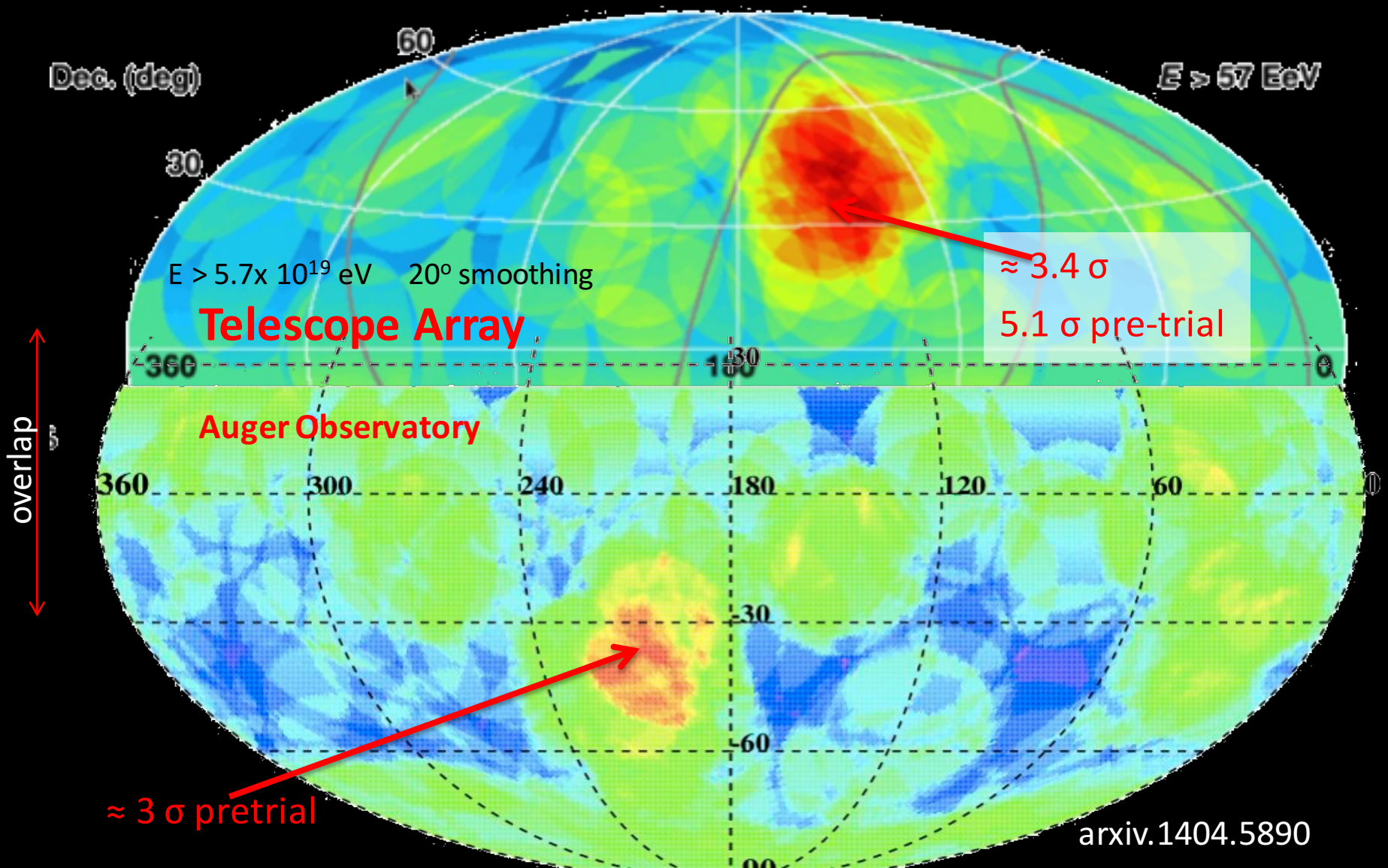


Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

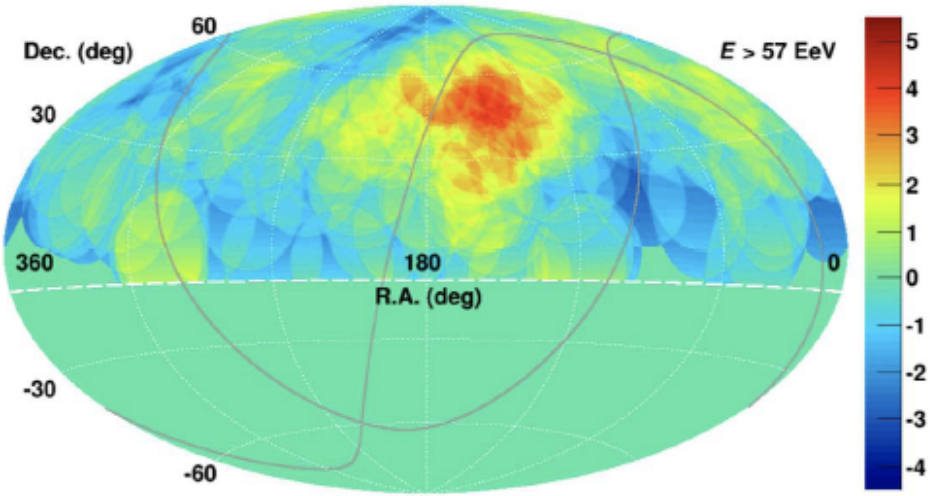
significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)

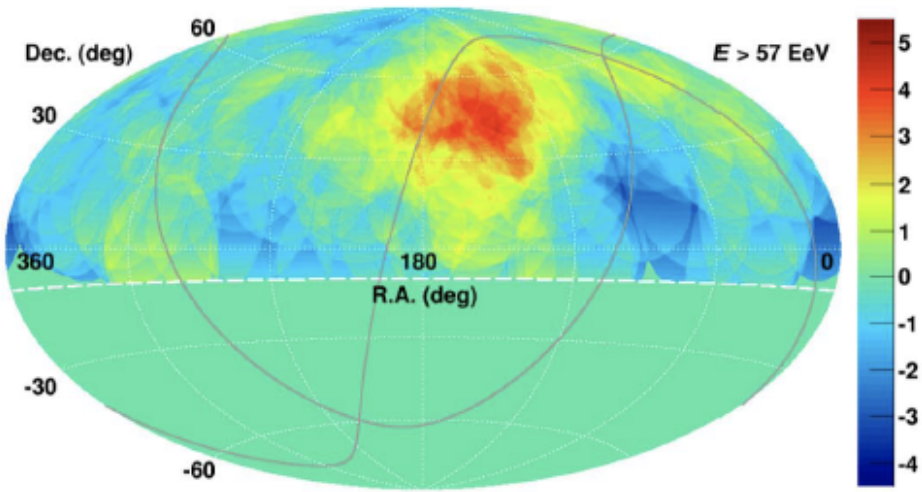
Anisotropy Hints > 60 EeV



arxiv.1404.5890

Intermediate-scale anisotropy – Hot spot (TA data)





With original 20° oversampling, spot looks larger…. Thus, scan over 15°, 20°, 25°, 30°, & 35°

With 25° oversampling, significance maximum 3σ

Binsize	15		20		25		30		35	
	Local	Global	Local	Global	Local	Global	Local	Global	Local	Global
Year 5	5.12	3.14	5.43	3.55	5.16	3.19	4.82	2.73	4.33	2.05
Year 7	4.92	2.84	5.37	3.44	5.65	3.80	5.37	3.44	5.03	2.99
Year 9	4.42	2.06	4.72	2.50	5.06	2.96	5.01	2.91	4.66	2.41

2017)

(Matthews, ICRC 2017)

Active Galactic Nuclei

- Selected from 2FHL Catalog (*Fermi*-LAT, 360 sources):
  Φ(> 50 GeV) ---> proxy for UHECR flux
- Selection of the 17 objects within 250 Mpc
- Majority blazars of BL-Lac type and radio-galaxies of FR-I type

Giaccari et al ICRC17

Star-forming or Starburst Galaxies

Use of *Fermi*-LAT search list for star-formation objects (Ackermann+ 2012)

- 63 objects within 250 Mpc, only 4 detected in gamma rays:
  correlated Φ(> 1.4 GHz) ---> proxy for UHECR flux
- Selection of brightest objects (flux completeness) with Φ(> 1.4 GHz) > 0.3 Jy
- 23 objects, size similar to the gamma-ray AGN sample

Assumption UHECRs flux proportional to non thermal photon flux

γ-ray detected AGNs

f_{ani} = 7%, Ψ = 7°

TS = 15.2 ⟶ *p-value* 5.1×10^{-4}

Post-trial probability

3×10^{-3} (~ 2.7 σ)

Starburst Galaxies

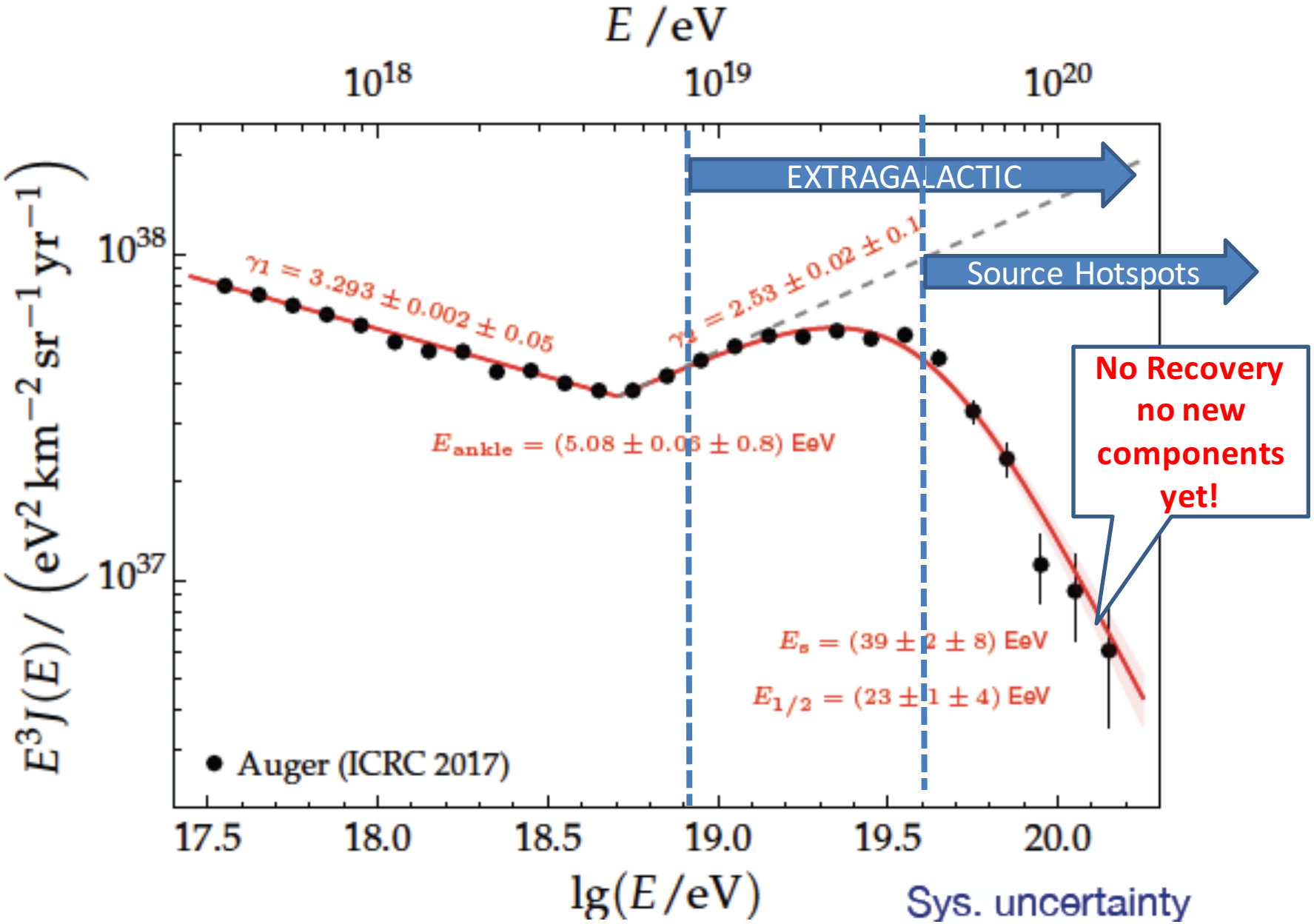
f_{ani} = 10%, Ψ = 13°

TS = 24.9 ⟶ *p-value* 3.8×10^{-6}

Post-trial probability

4×10^{-5} (~ 3.9 σ)

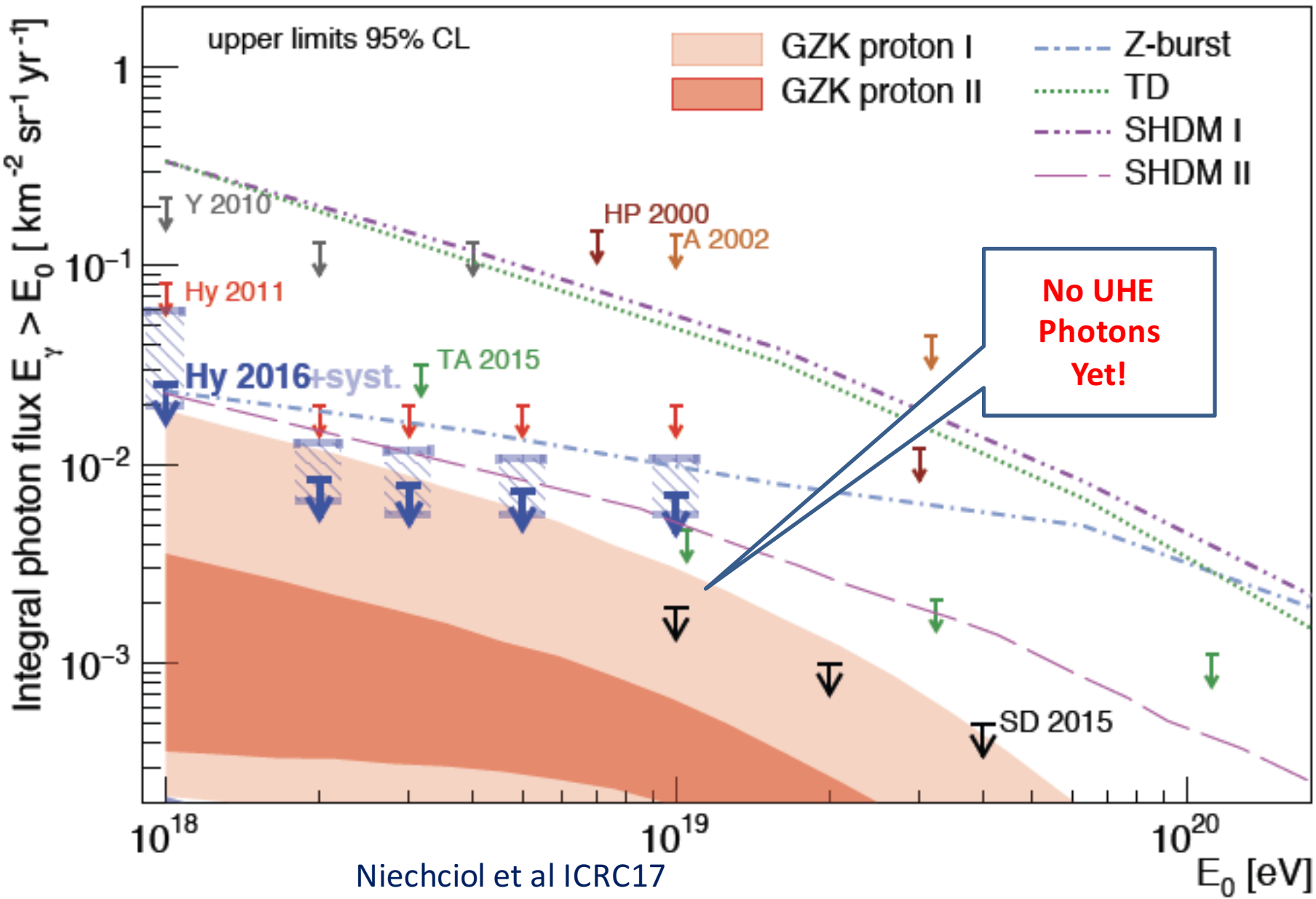
E> 39 EeV at 13°



Sys. uncertainty

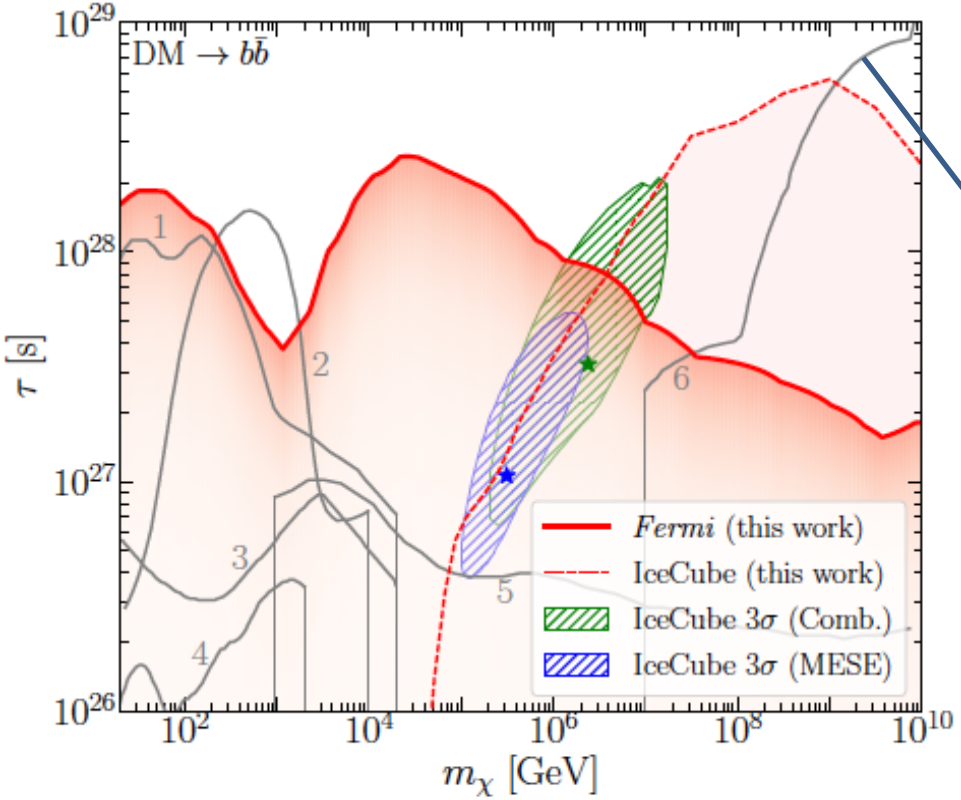
Auger $\Delta E/E = 14\%$

Auger Photon Limits



Niechciol et al ICRC17

Gamma-ray Constraints on Decaying Dark Matter

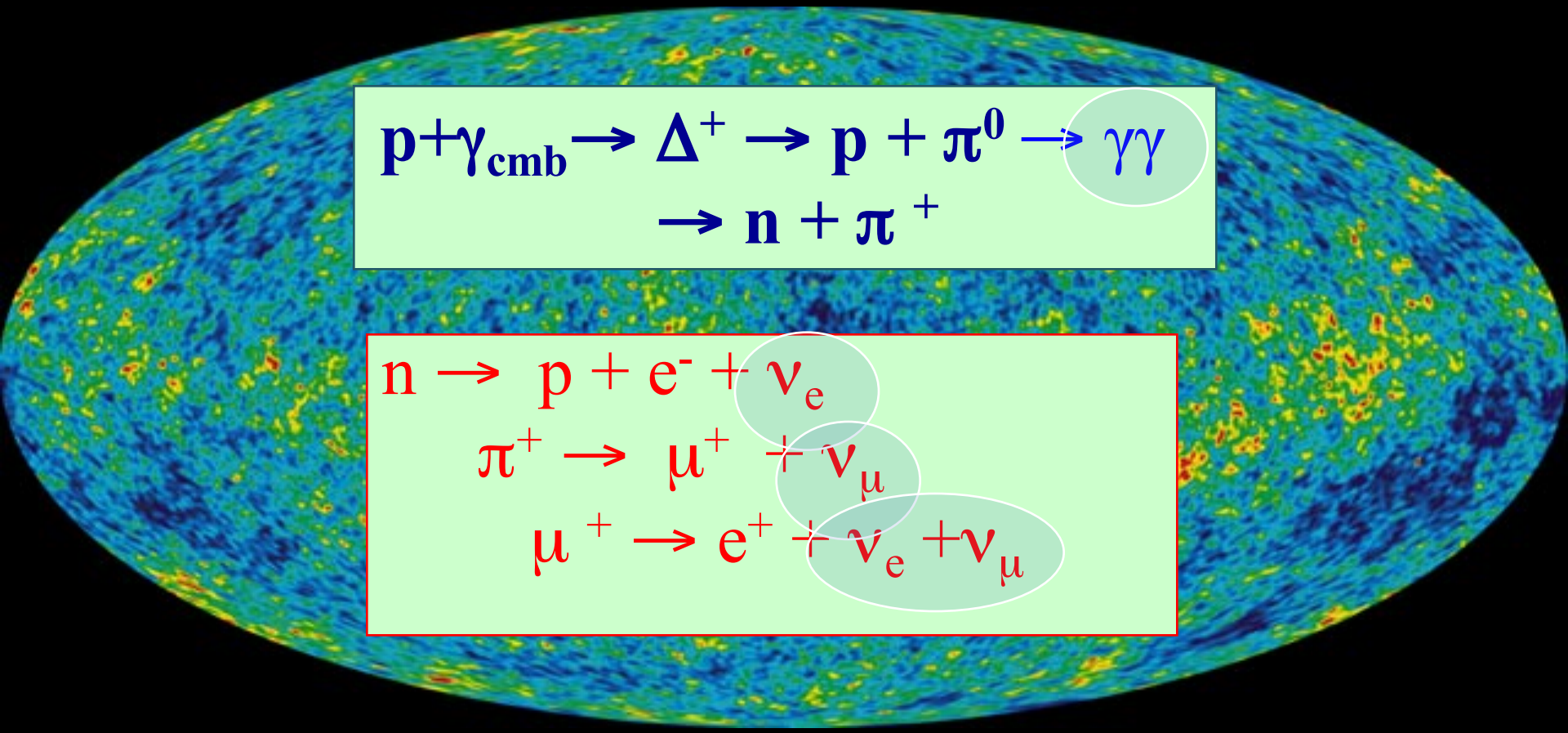


Pierre Auger Limit

FIG. 1: Limits derived in this work on DM decays to $b\bar{b}$, as compared to previously computed limits using data from *Fermi* (2,3,5), AMS-02 (1,4), and PAO/KASCADE/CASA-MIA (6). The hashed green (blue) region suggests parameter space where DM decay may provide a $\sim 3\sigma$ improvement to the description of the combined maximum likelihood (MESE) IceCube neutrino flux. The best-fit points, marked as stars, are in strong tension with our gamma-ray results. The red dotted line provides a limit if we assume a combination of DM decay and astrophysical sources are responsible for the spectrum.

T. Cohen et al 2017

Cosmogenic (GZK, BZ*) Neutrinos & Photons

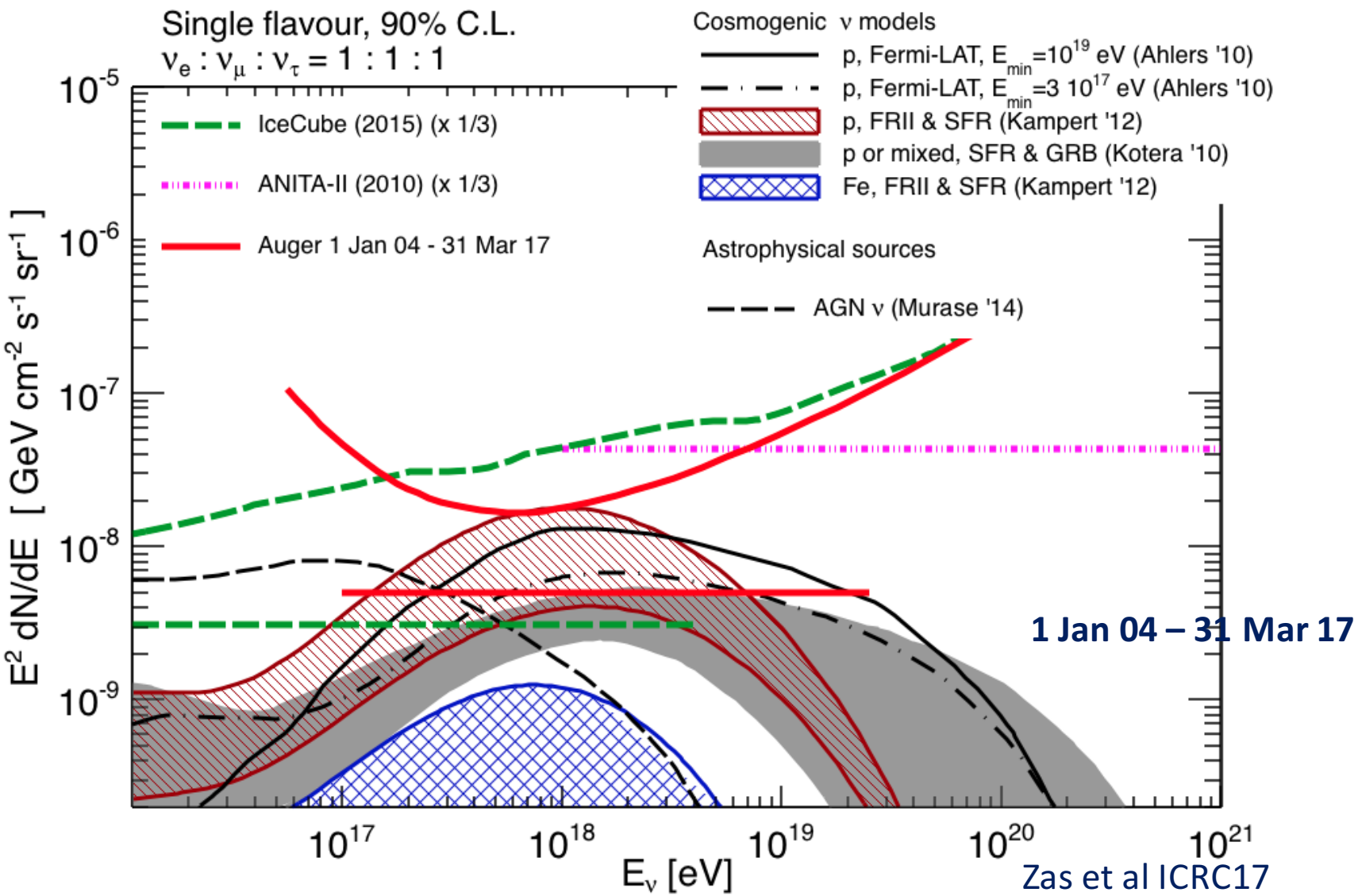


$$p + \gamma_{cmb} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

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

*Berezinsky & Zatsepin '69

Limit on diffuse Neutrino flux

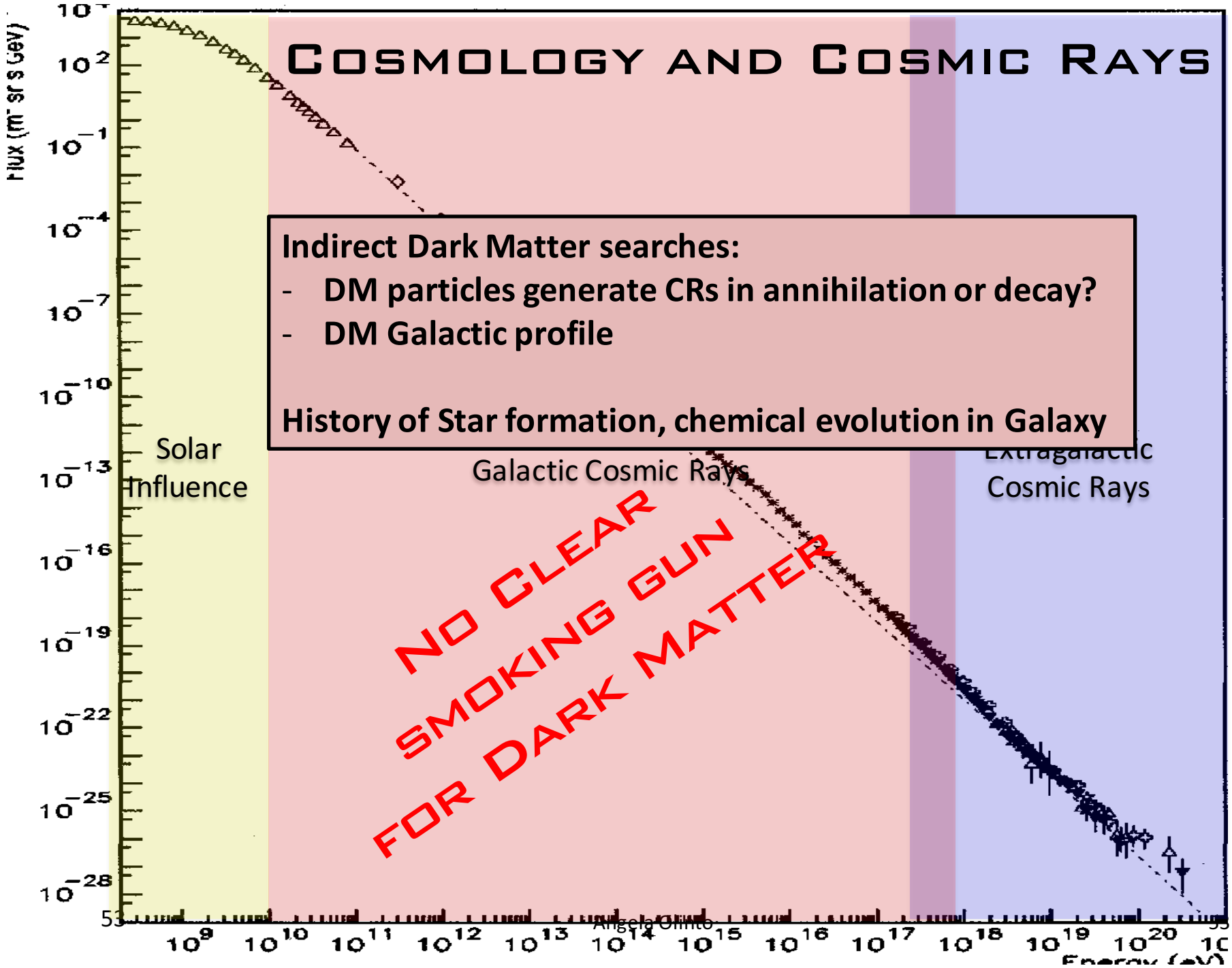


Zas et al ICRC17

Assumed flavor ratio (1:1:1)

Auger LIMIT to normalization of $dN/dE = k\ E^{-2}$
1 Jan 04 – 31 Mar 17 => $k \leq 5.0 \times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

Cosmology and Cosmic Rays



Indirect Dark Matter searches:

- **DM particles generate CRs in annihilation or decay?**
- **DM Galactic profile**

History of Star formation, chemical evolution in Galaxy

Experiment	e^+ | e^- (present data)	$e^+ + e^-$ (Energy range)	CR nuclei (Energy range)	charge	Gamma-ray	Type	Launch
PAMELA	e^+ < 300 GeV e^- < 625 GeV	1-700 GeV (3 TeV with cal)	1 GeV-1.2 TeV (extendable -> 2TeV)	1-8	-	SAT	2006 Jun 15
FERMI	-	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008 Nov 11
AMS-02	e^+ < 500 GeV e^- < 700 GeV	1 GV-1 TV (extendable)	1 GV-1.9 TV (extendable)	1-26 ++	1 GeV-1 TeV (calorimeter)	ISS	2011 May 16
NUCLEON	-	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014 Dec 26
CALET	-	1 GeV-20 TeV	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015 Aug 19
DAMPE	-	10 GeV-10 TeV	50 GeV-500 TeV	1-20	5 GeV-10 TeV	SAT	2015 Dec 17
ISS-CREAM	-	100 GeV-10 TeV	1 TeV-1 PeV	1-28 ++	-	ISS	2017
CSES	-	3-200 MeV	30-300 MeV	1	-	SAT	2017
GAMMA-400	-	1 GeV-20 TeV	1 TeV-3 PeV	1-26	20 MeV-1 TeV	SAT	~2023-25
HERD	-	10(s) –10^4 GeV	up to PeV	TBD	10(s) –10^4 GeV	CSS	~2022-25
HELIX	-	-	< 10 GeV/n	light isotopes	-	LDB	proposal
HNX	-	-	~ GeV/n	6-96	-	SAT	proposal
GAPS	-	-	< 1GeV/n	Anti-p, D	-	LDB	

Cosmology and Cosmic Rays

UHECRs:

- **Source distribution and evolution (negative preferred for shock accel) – cosmology input to CRs**
- **Cosmological Backgrounds and Magnetic Fields (Intergalactic space? primordial?) – CRs give B once sources are id'ed**
- **Relic CR production?**
- **Super-Heavy Dark Matter; Topological Defects: CR limits**
- **Beyond SM interactions**
- **500 TeV equiv CM energy for hadrons**
- **Neutrinos EeV cross section – Once BZ/cosmogenic Neutrinos**

TAx4 Project

TA SD (~3000 km²): Quadruple area

- Approved in Japan 2015
- 500 scintillator SDs
- 2.08 km spacing
- 3 yrs construction, first 173 SDs have arrived in Utah for final assembly, next 77 SD to be prepared at Akeno Obs. (U.Tokyo) 2017-08 and shipped to Utah

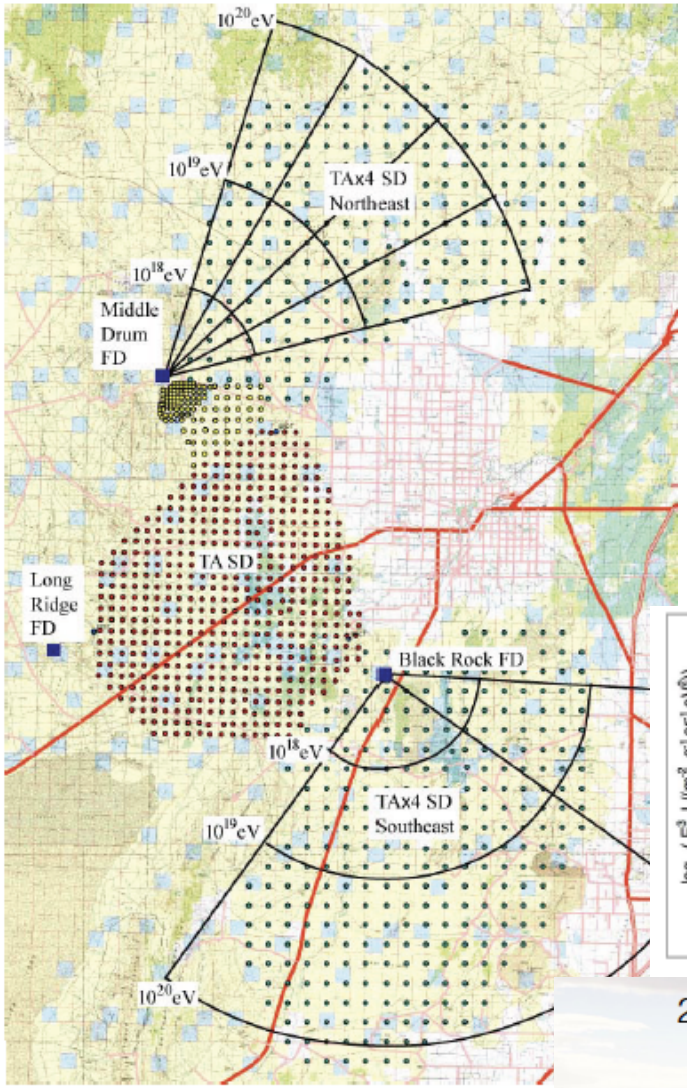
2 FD stations (12 HiRes Telescopes)

- Approved US NSF 2016
- Telescopes/electronics being prepared at Univ. Utah
- Site construction underway at the northern station.

Get 19 TA-equiv years of SD data by 2020

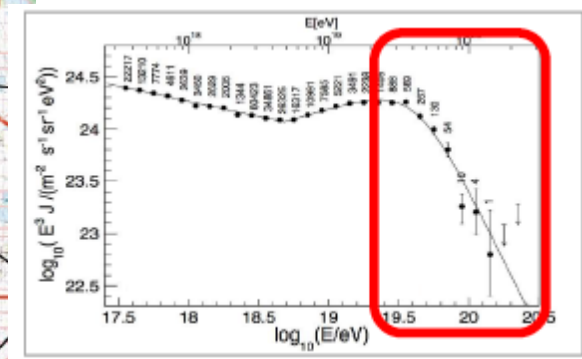
- Get 16.3 (current) TA years of hybrid data

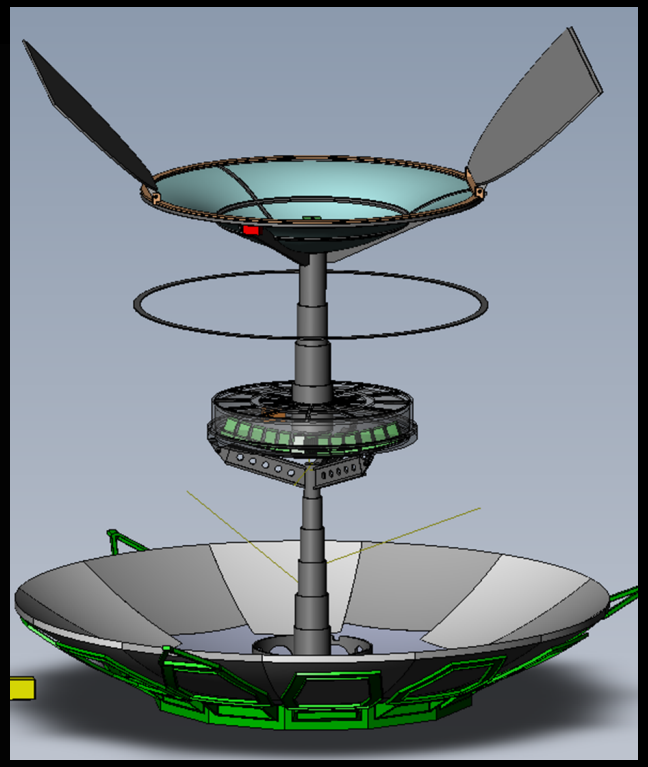
(Kido, Matthews ICRC 2017)



AugerPrime

Muon excess and composition with surface detector

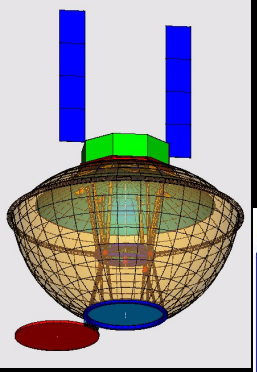




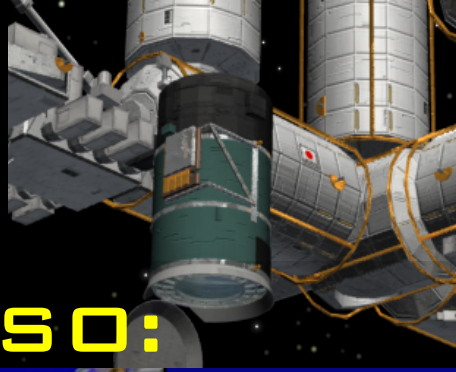
POEMMA:

Probe of Extreme Multi-Messenger Astrophysics

UHECRs and Neutrinos



Extensive Air-shower Fluorescence from SPACE



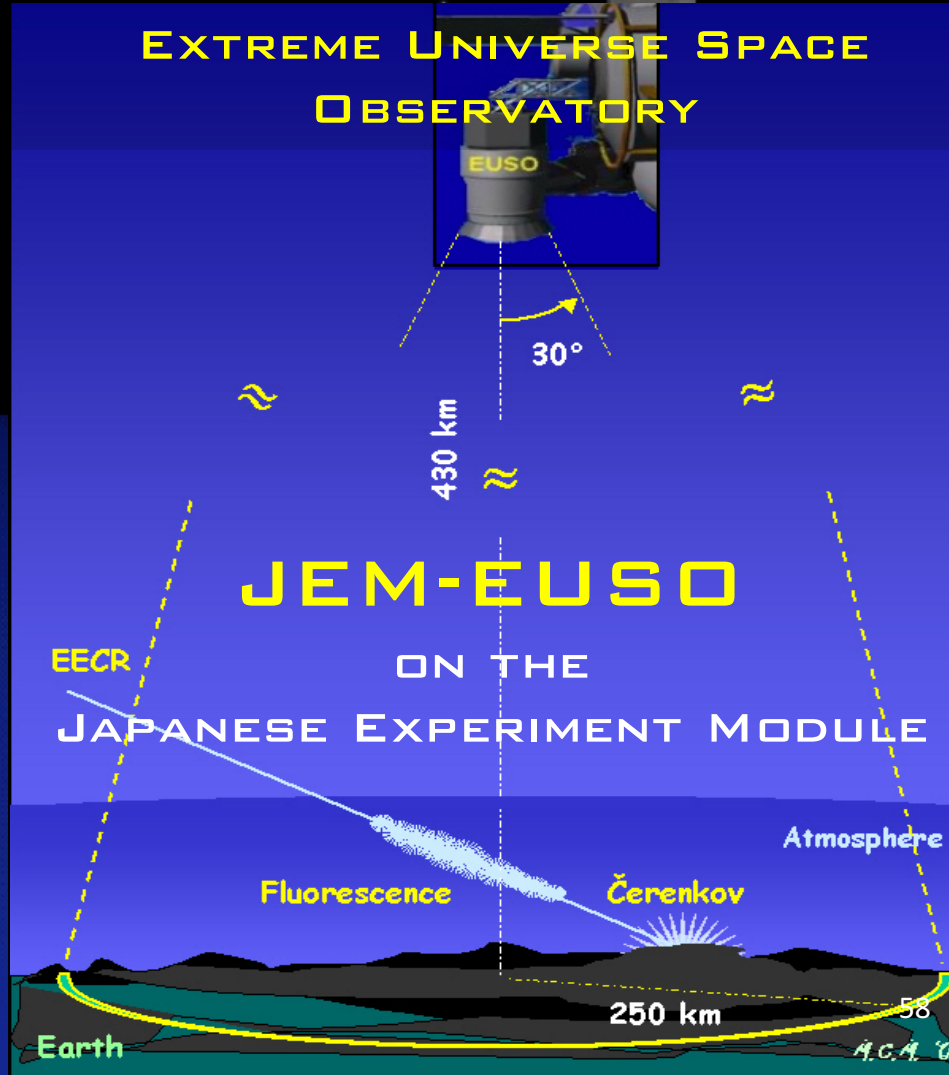
Orbiting Wide-angle Light-collectors

OWL

2002 design

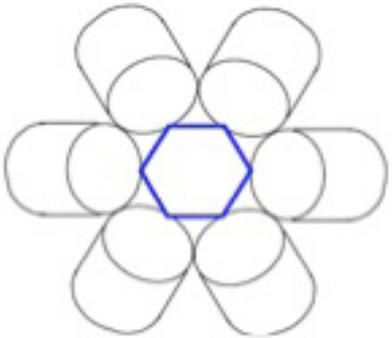
EUSO:

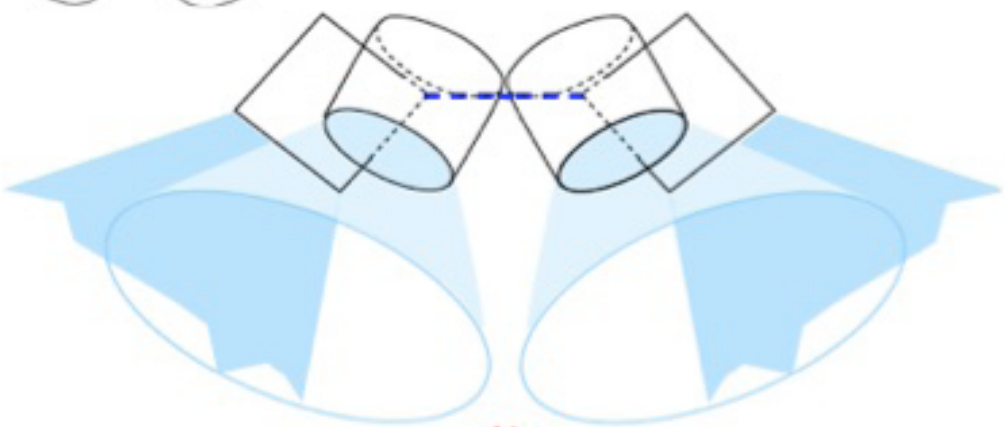
Extreme Universe Space Observatory

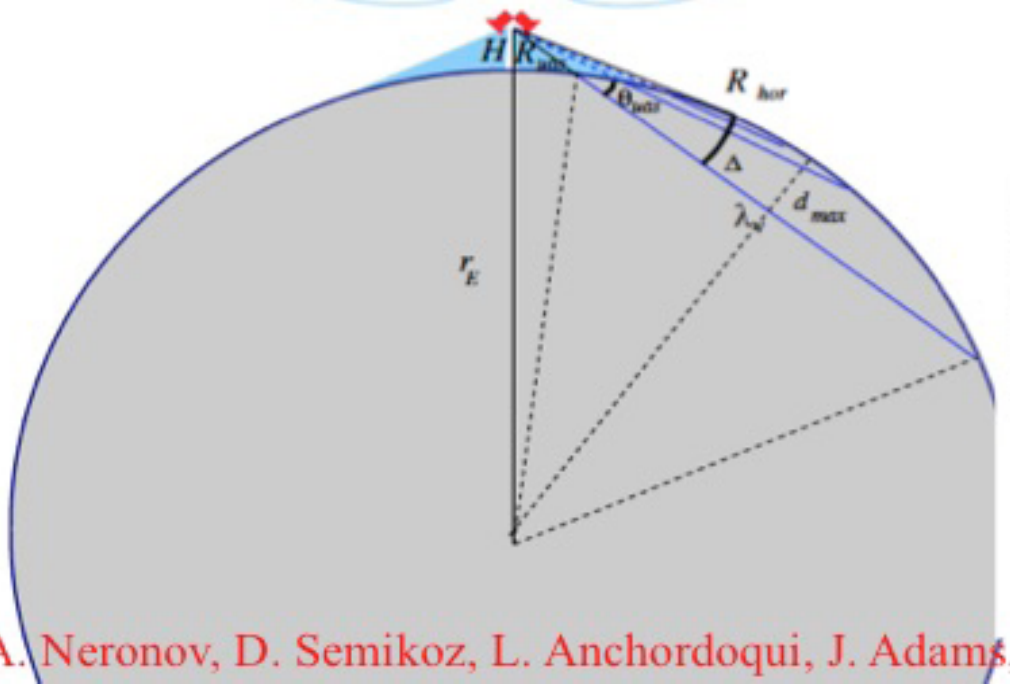


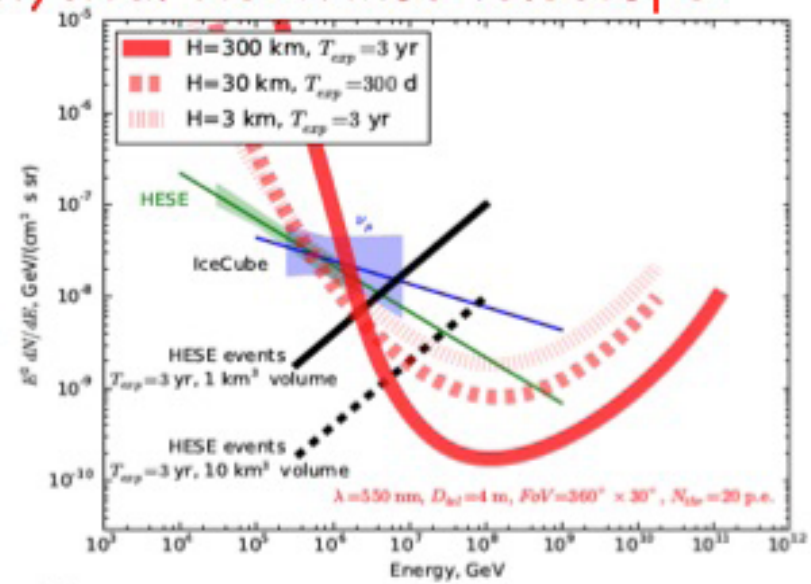
CHANT

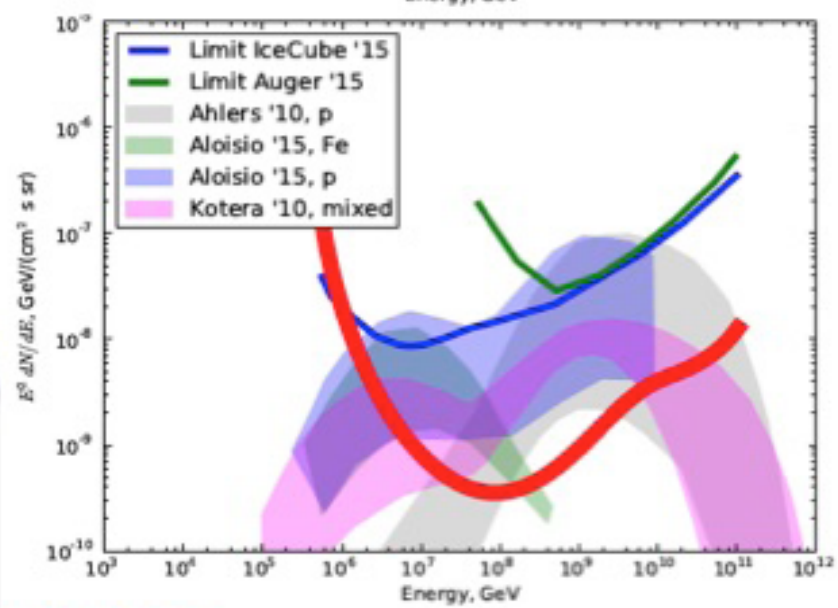
Cherenkov from Astrophysical Neutrinos Telescope







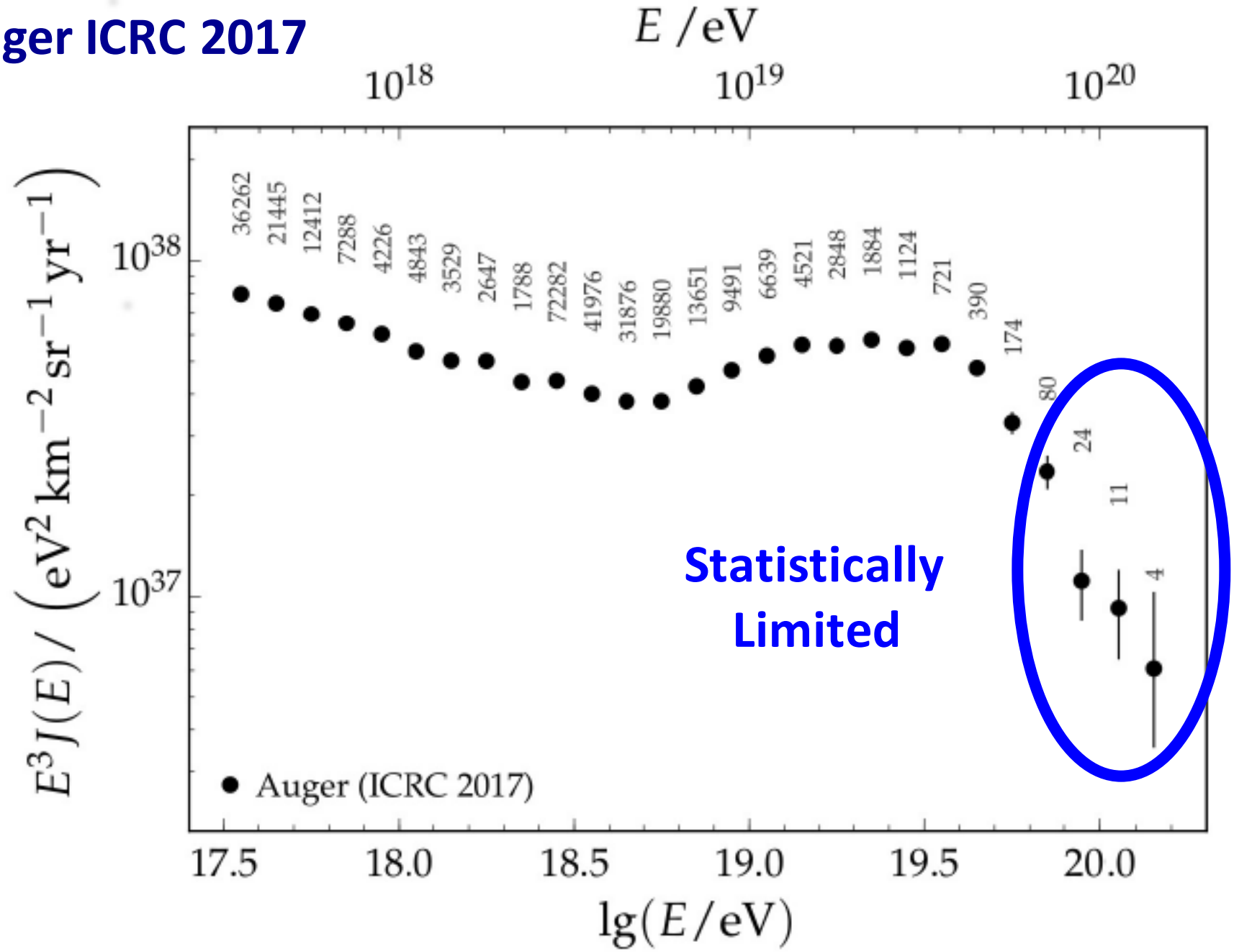




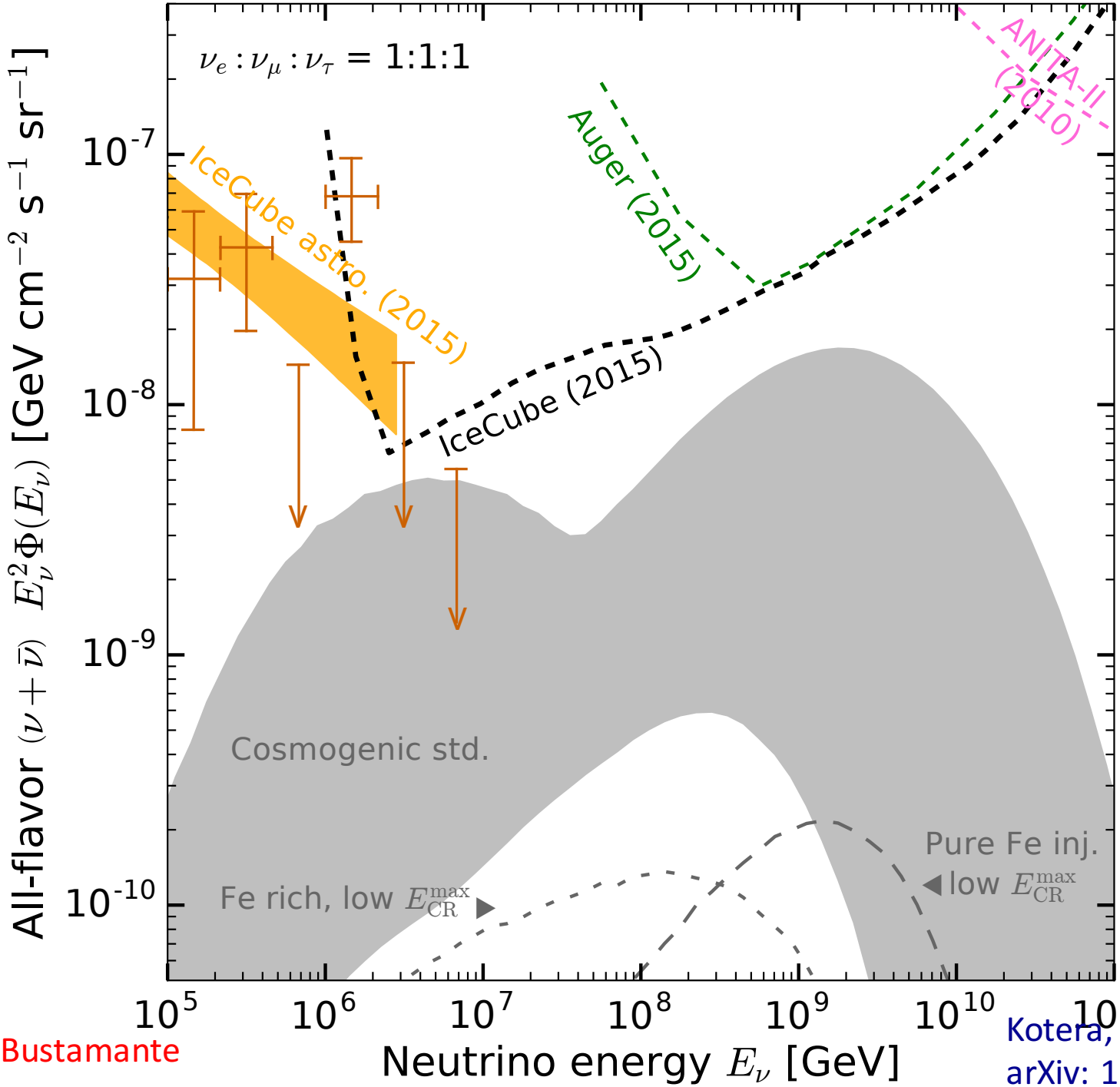
A. Neronov, D. Semikoz, L. Anchordoqui, J. Adams, AVO'16

arXiv:1606.03629

Auger ICRC 2017

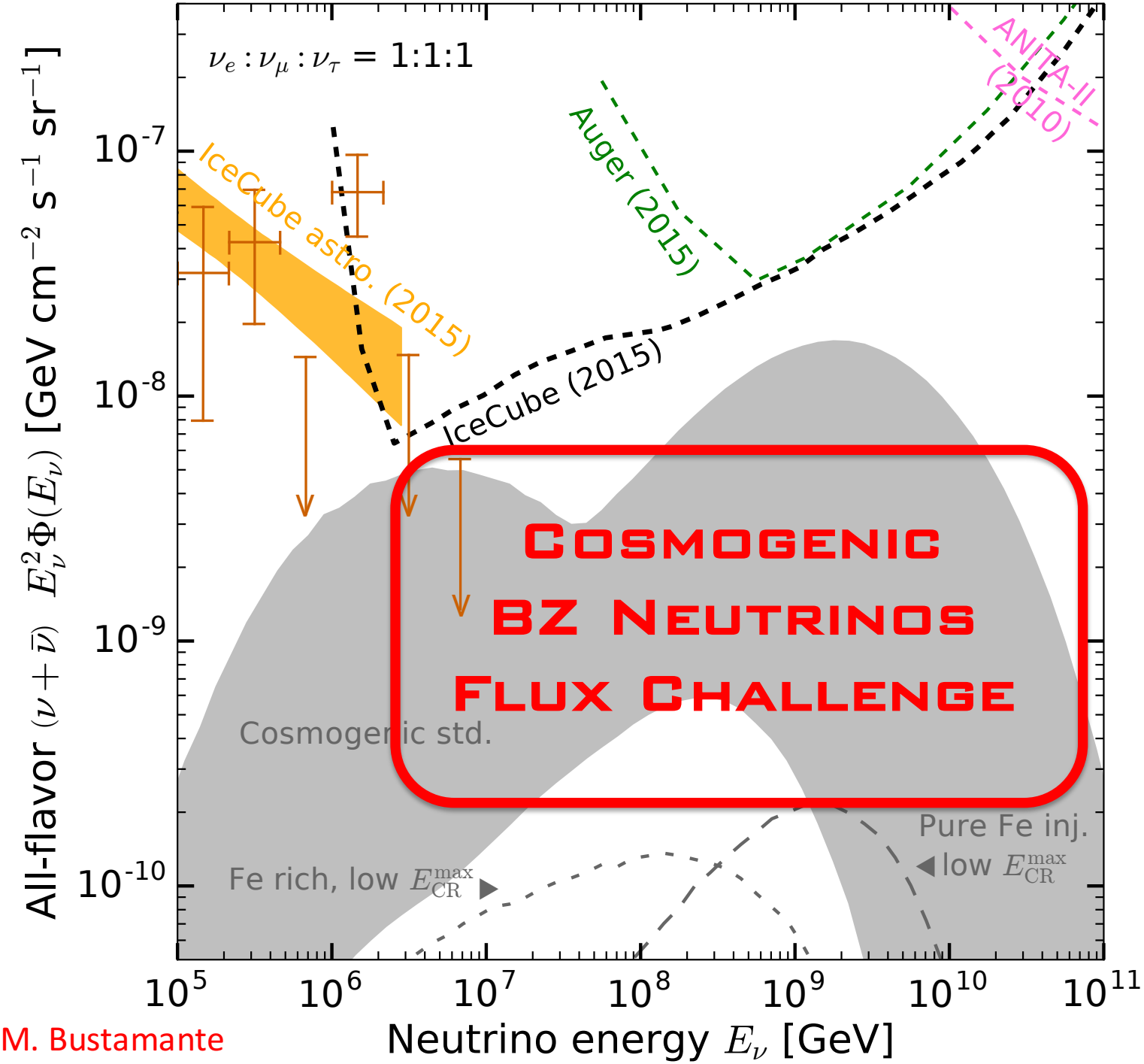


Exposure = 67000 km² sr yr



credit M. Bustamante

Kotera, AVO
arXiv: 1101.4256

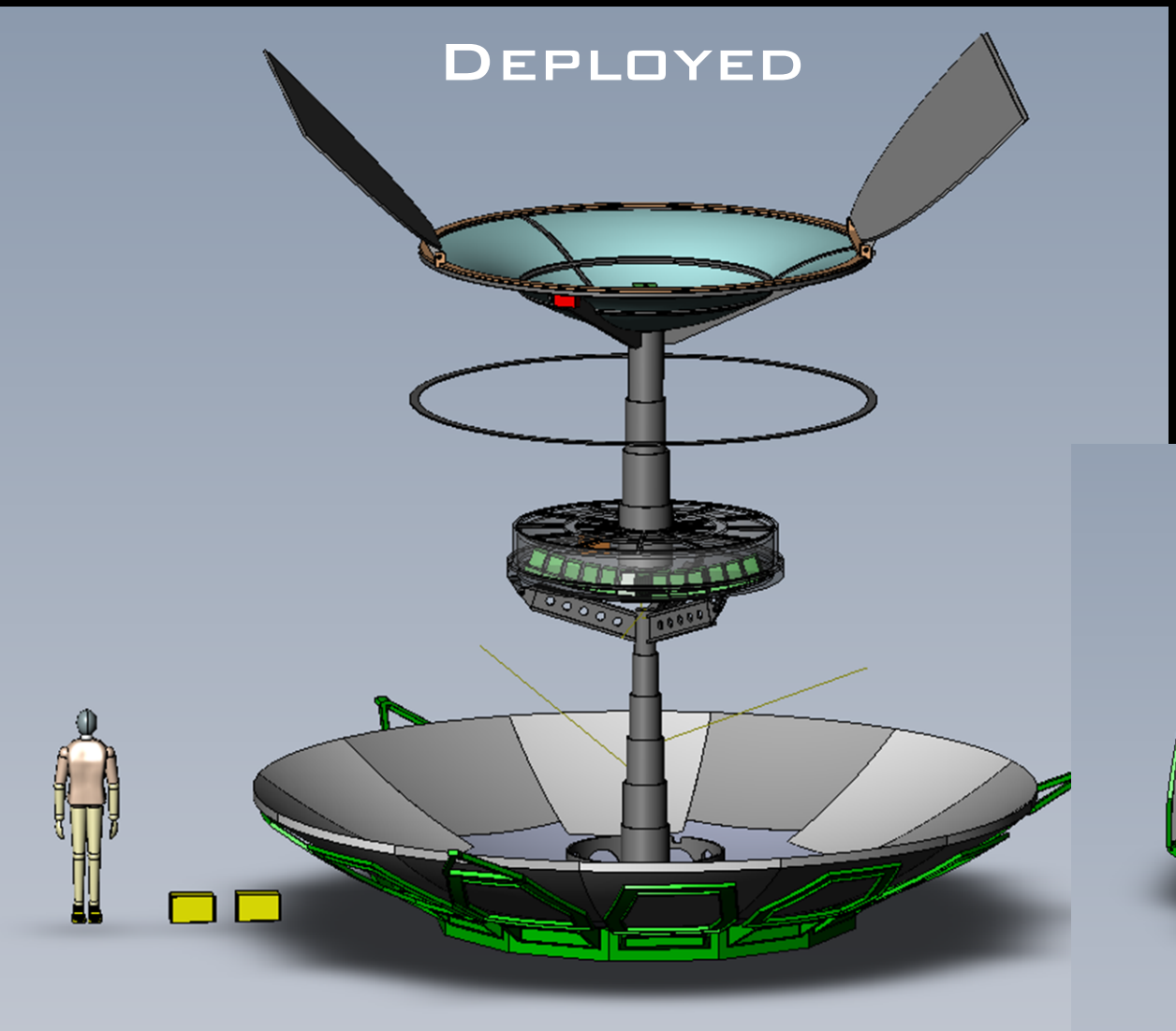


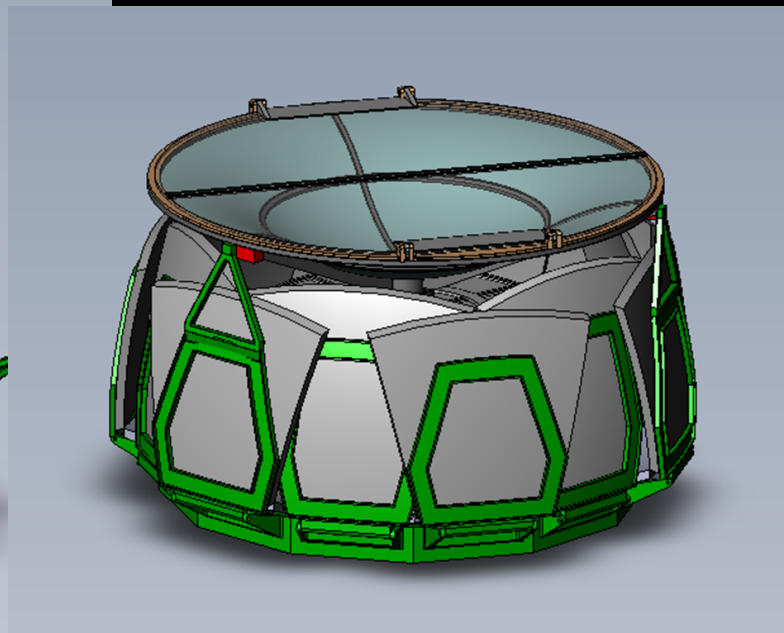
Cosmogenic BZ Neutrinos Flux Challenge

credit M. Bustamante

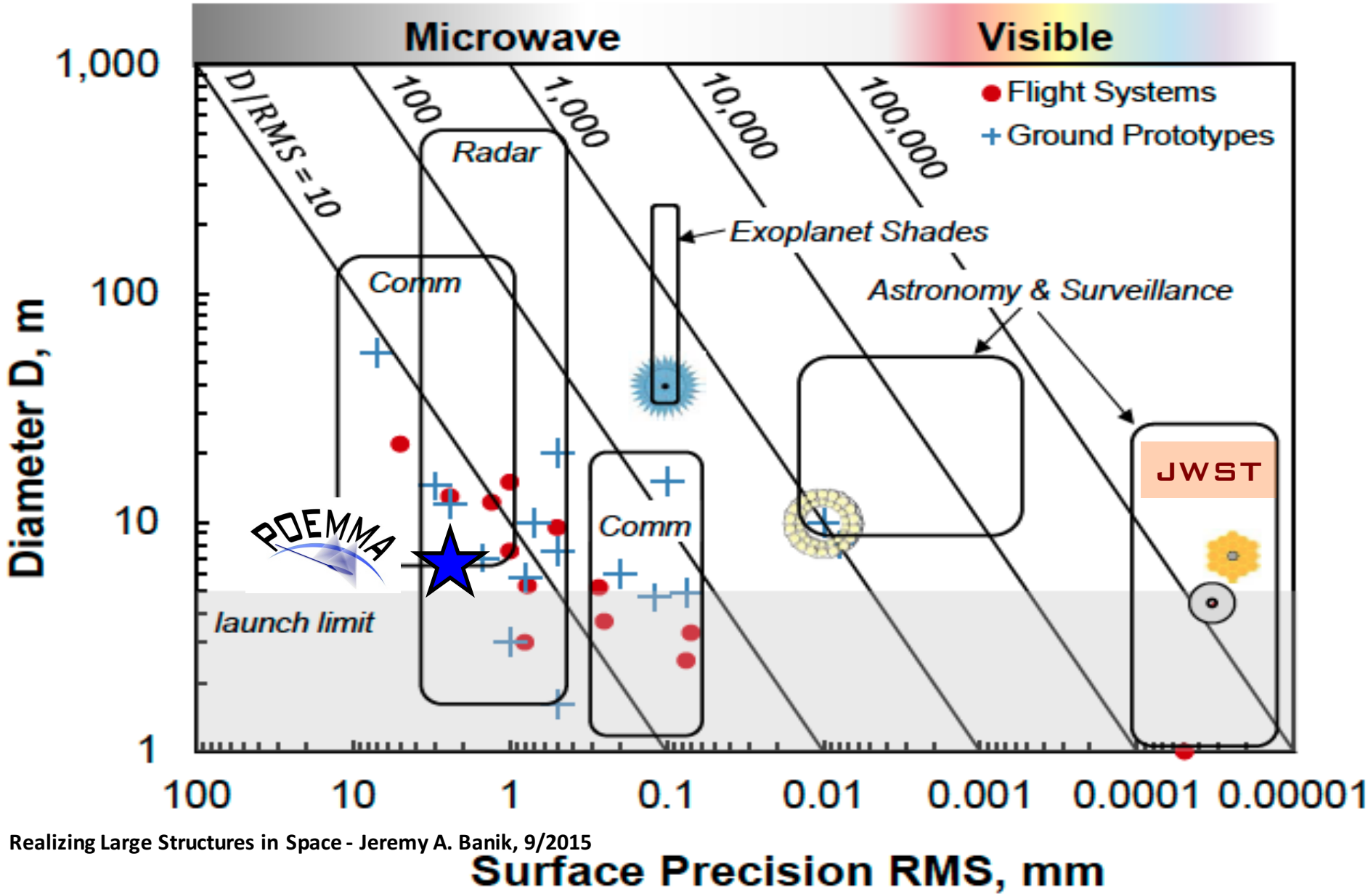
POEMMA

Probe of Extreme Multi-Messenger Astrophysics





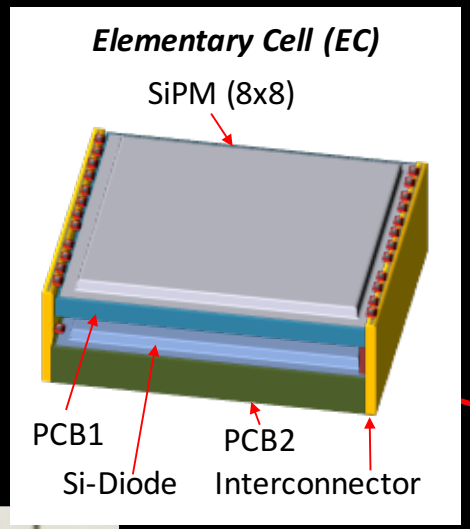
Large Reflectors

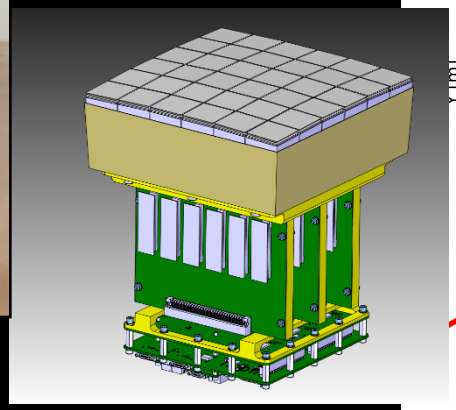


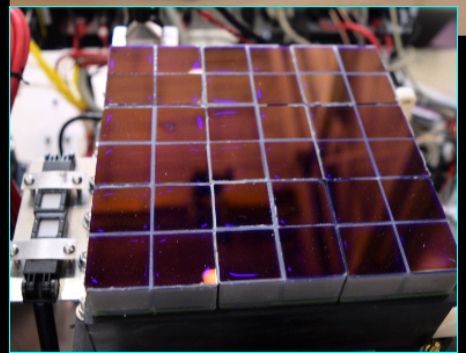
Realizing Large Structures in Space - Jeremy A. Banik, 9/2015

Hybrid Focal Surface

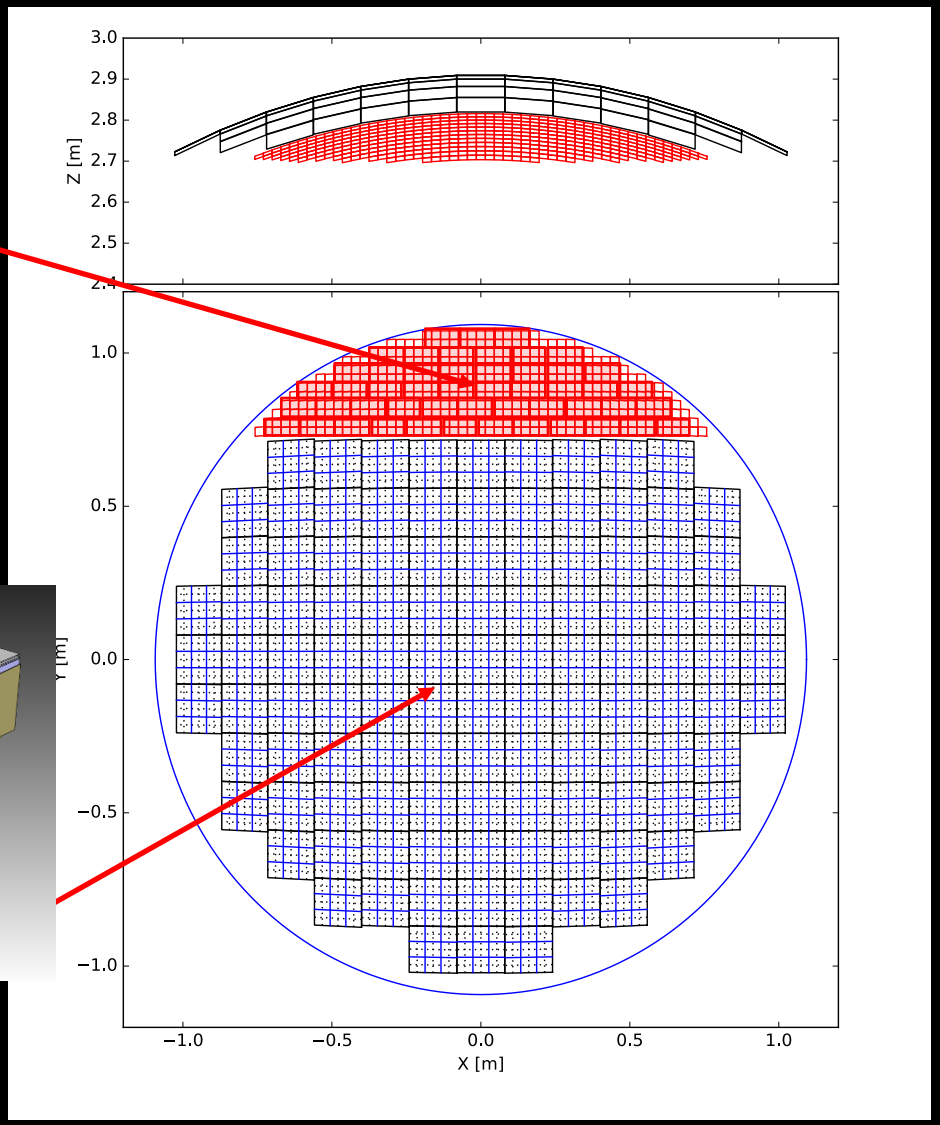
50 FSU focal surface units







111 PDMs



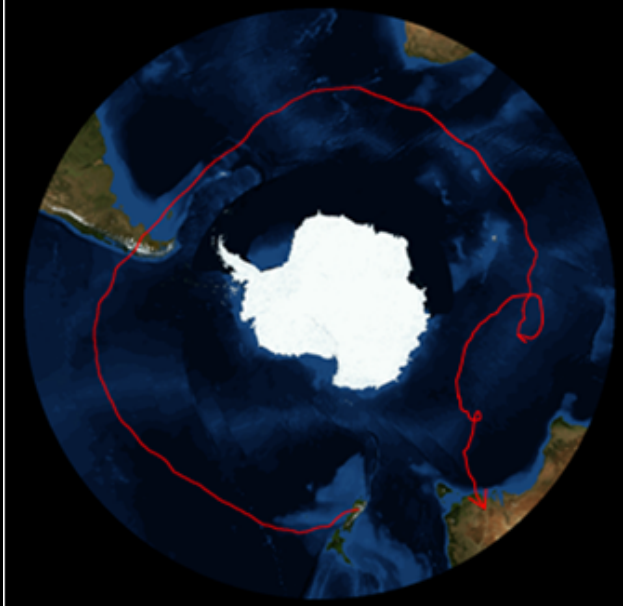

EUSO-SPB
LAUNCH,
APRIL 25,
2017

WANAKA 2017 Campaign

Super Pressure Balloon (SPB) EUSO mission

2015

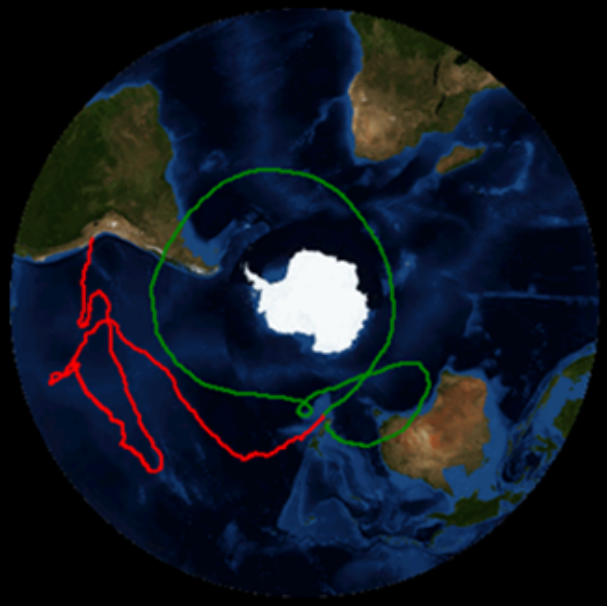
NASA **Engineering** Flight



32 d 5 h

2016

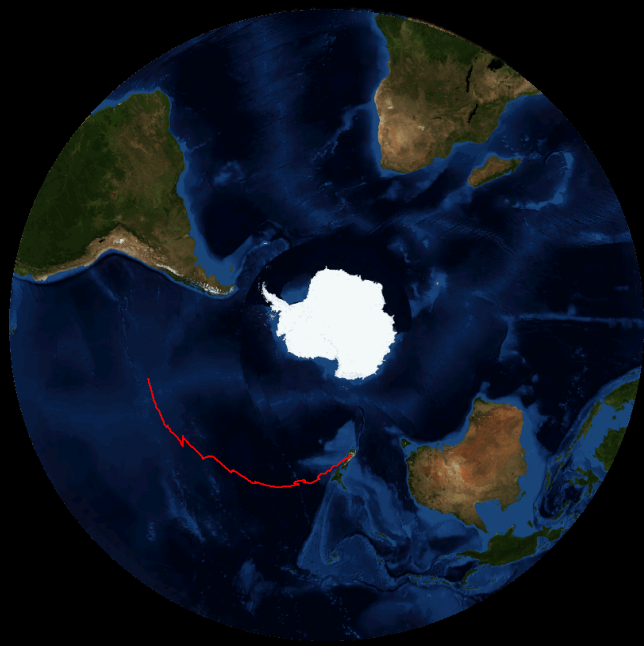
COSI

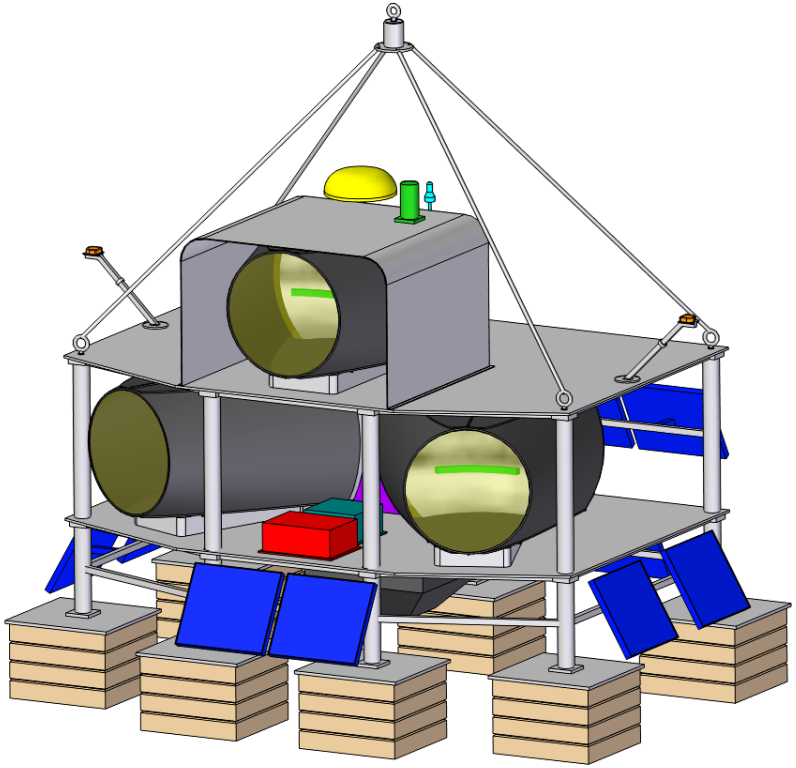


46 d 20 h

2017

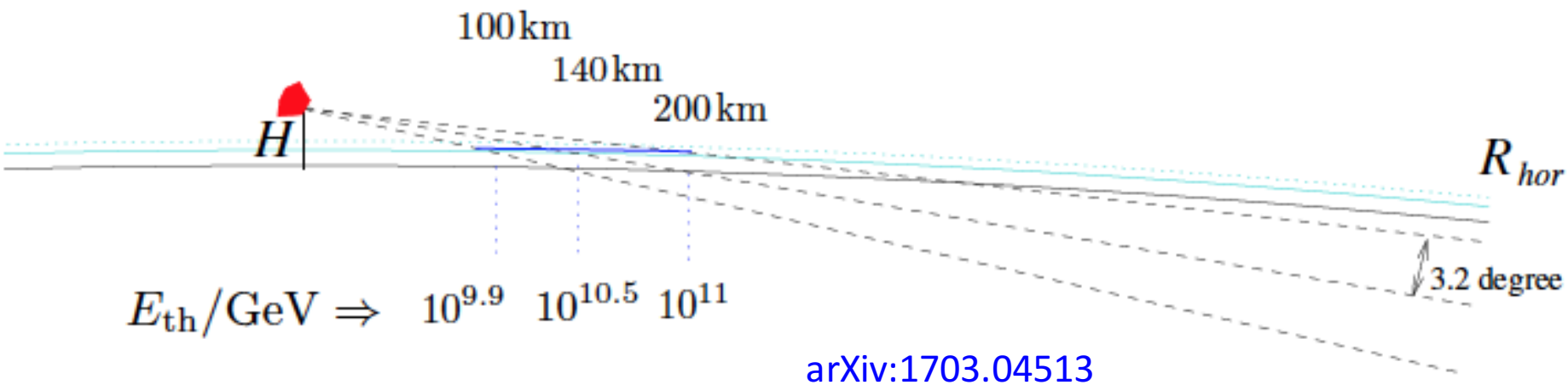
EUSO-SPB





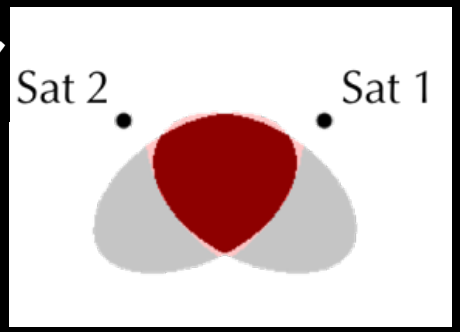
EUSO-SPB2

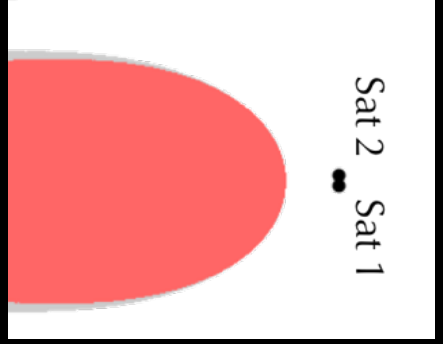
Cherenkov Emission from UHECRs Tau Neutrino background



arXiv:1703.04513

POEMMA



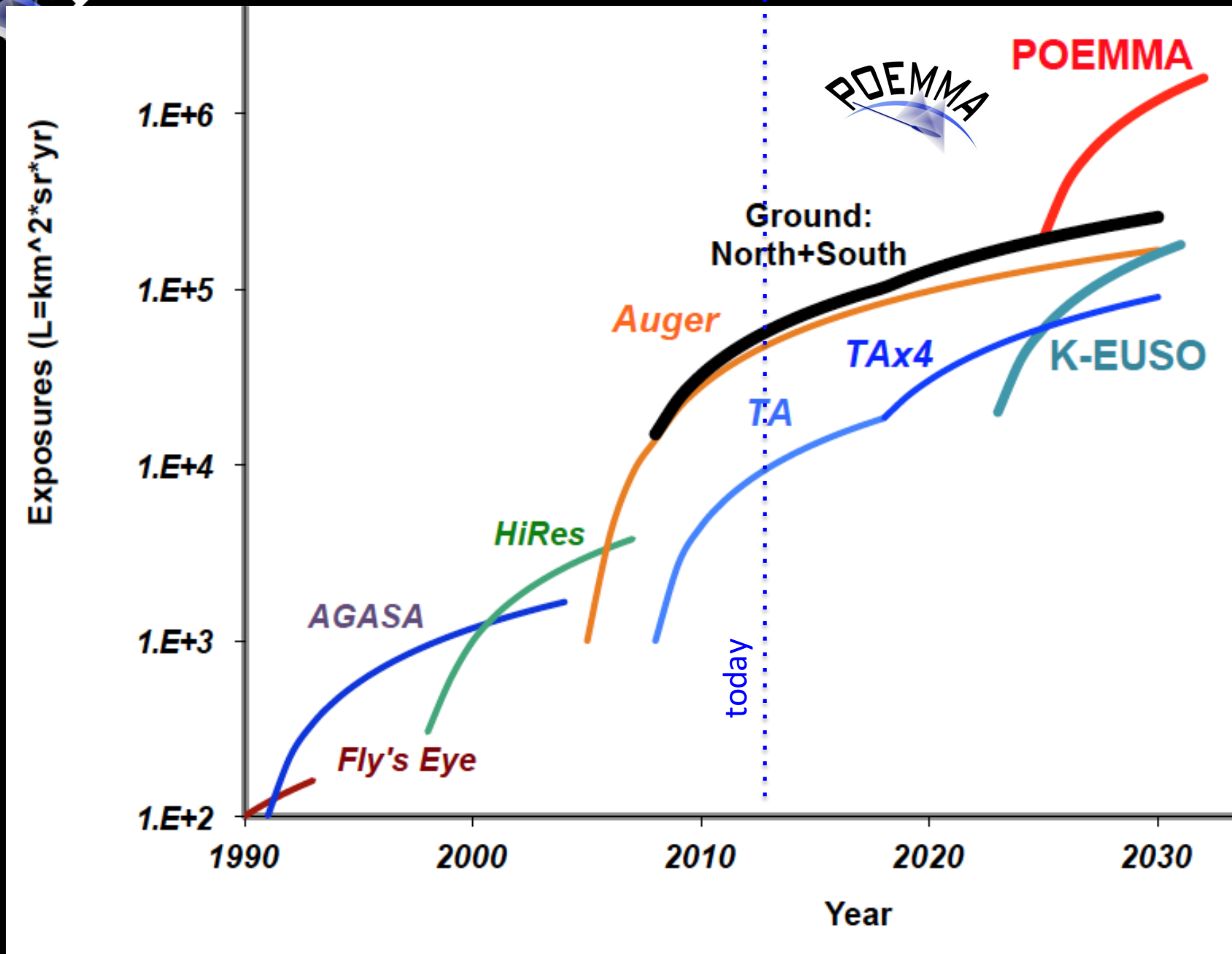


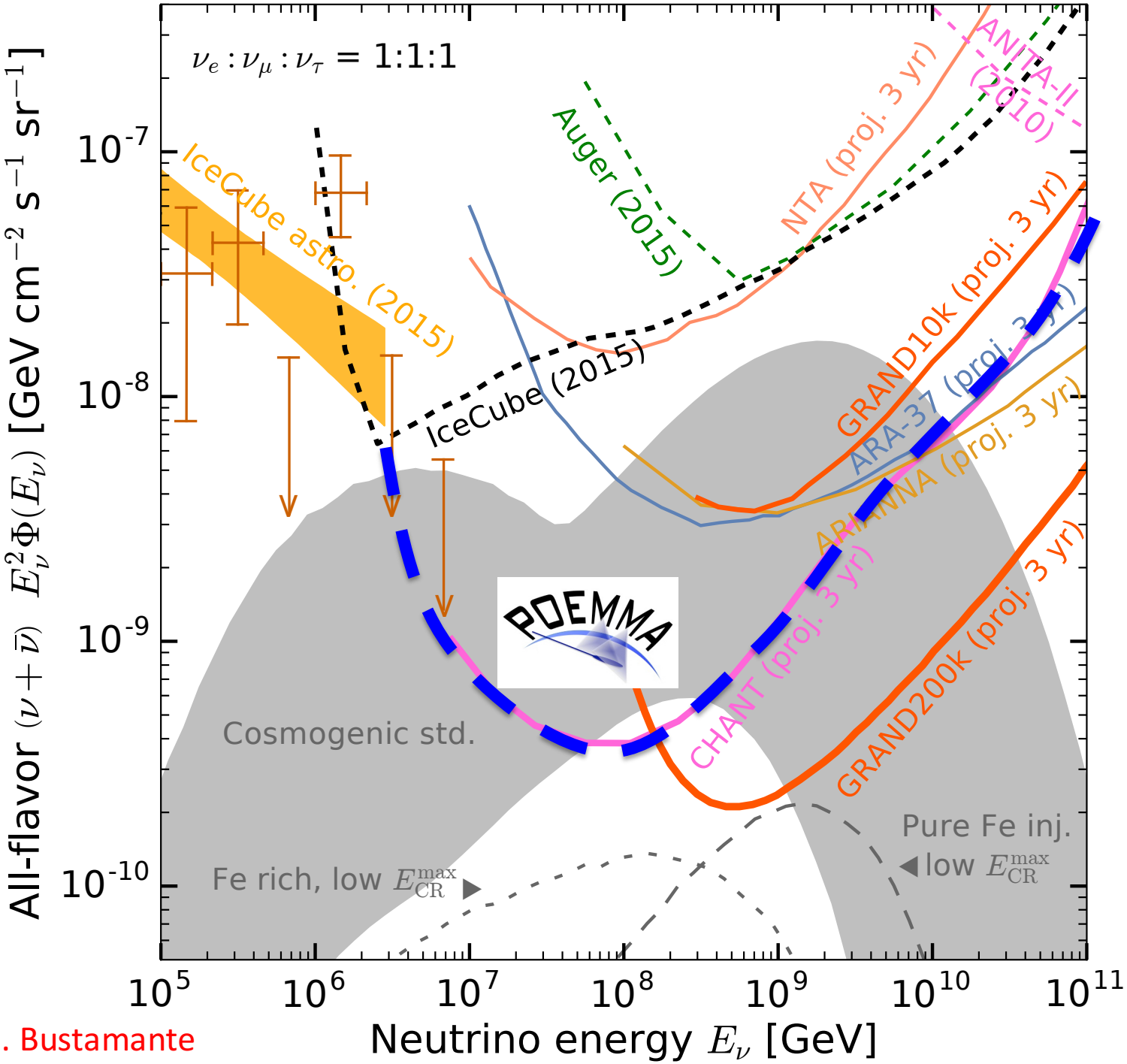
Nadir for UHECR:
Radius 200-400 km

Limb for Neutrinos:
Radius 2.6-3.7 10^3 km

POEMMA to measure UHECR spectrum, composition at the highest energies (to understand the source mechanisms), find significant anisotropies (to identify the sources), and search for cosmogenic neutrinos .

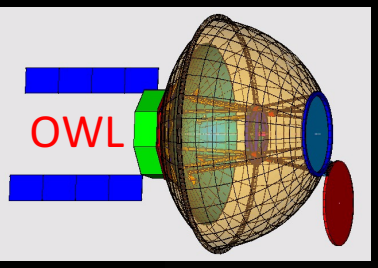
UHECR Exposure History





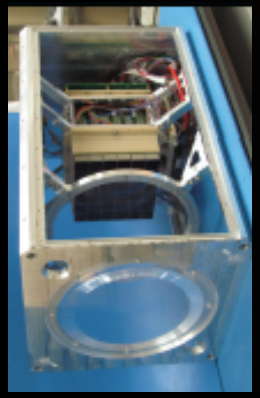
credit M. Bustamante

Towards Space Probes of UHECRs and BZ/Cosmogenic Neutrinos

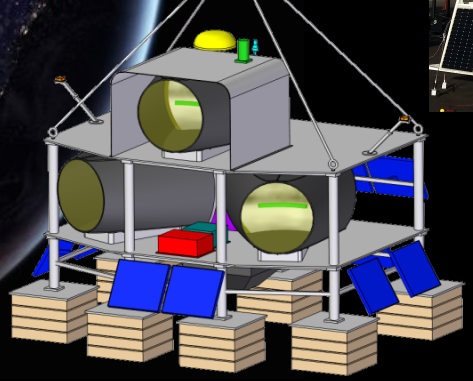


EUSO-Balloon

Mini-EUSO



EUSO-SPB2



EUSO-SPB1