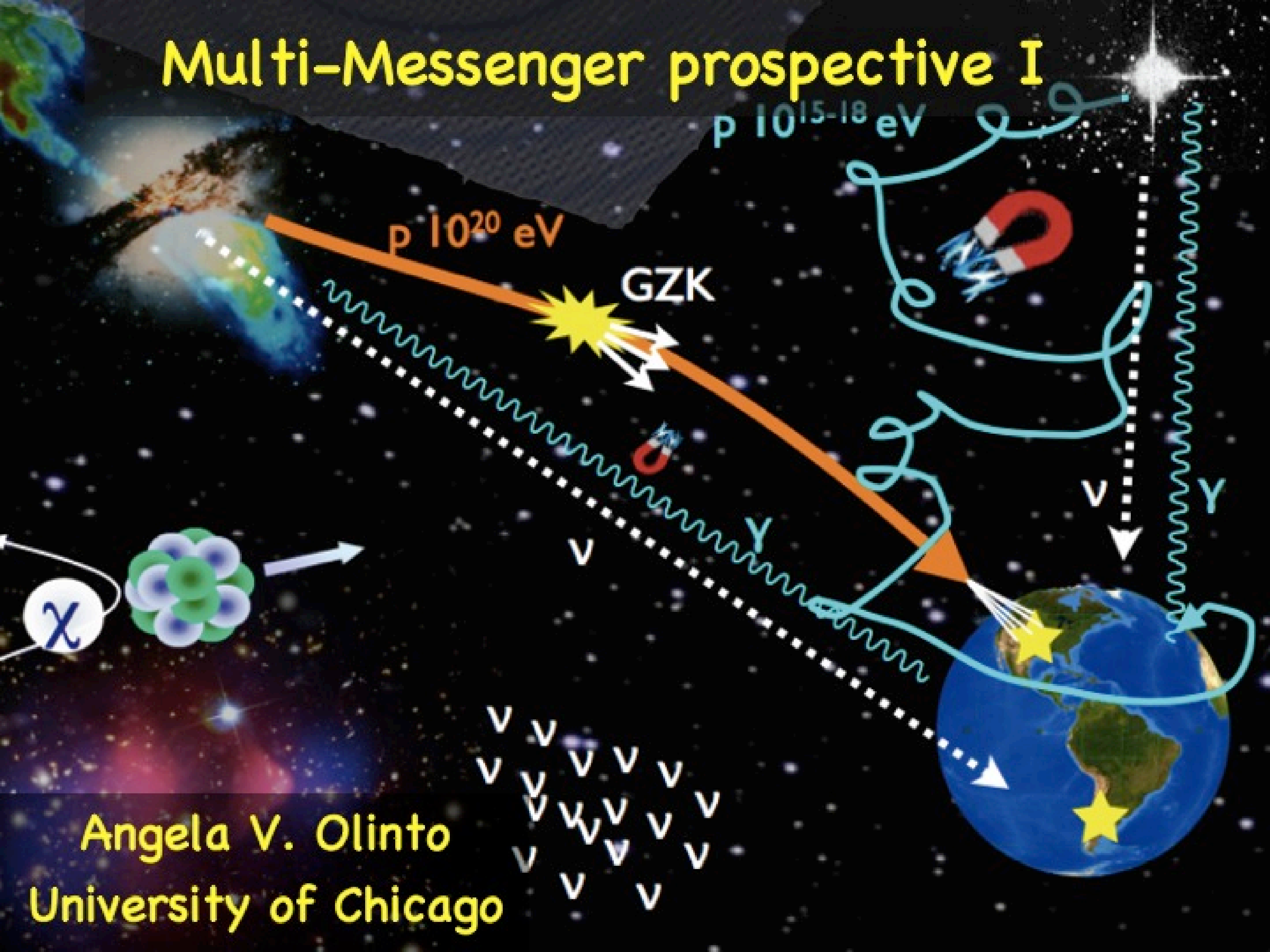
Multi-Messenger prospective I



Angela V. Olinto
University of Chicago

Goals of the Field

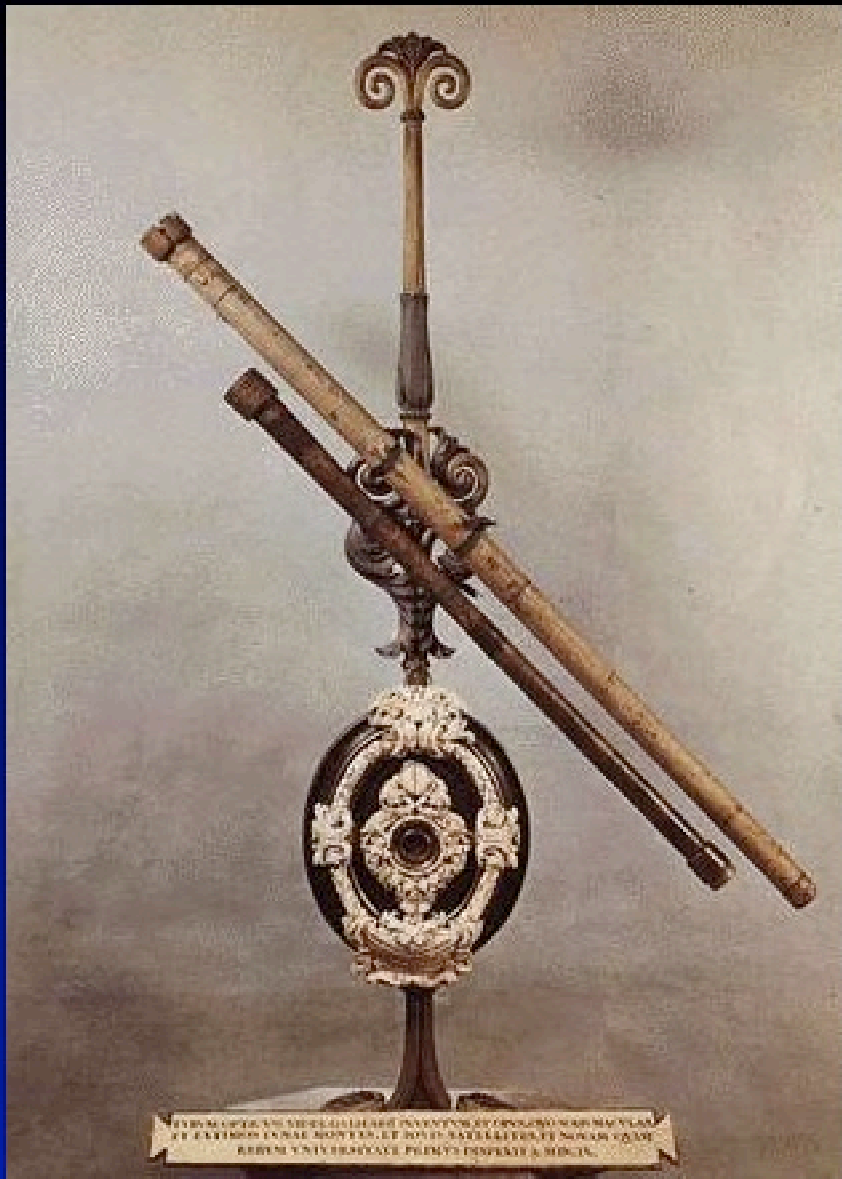
To understand Nature's High Energy Accelerators

To use Cosmic Particles to study HE interactions

What is the easiest Astroparticle to detect?

What is the easiest Astroparticle to detect?

Photon!



What is the easiest Astroparticle to detect?

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In what Energy range do we observe them?

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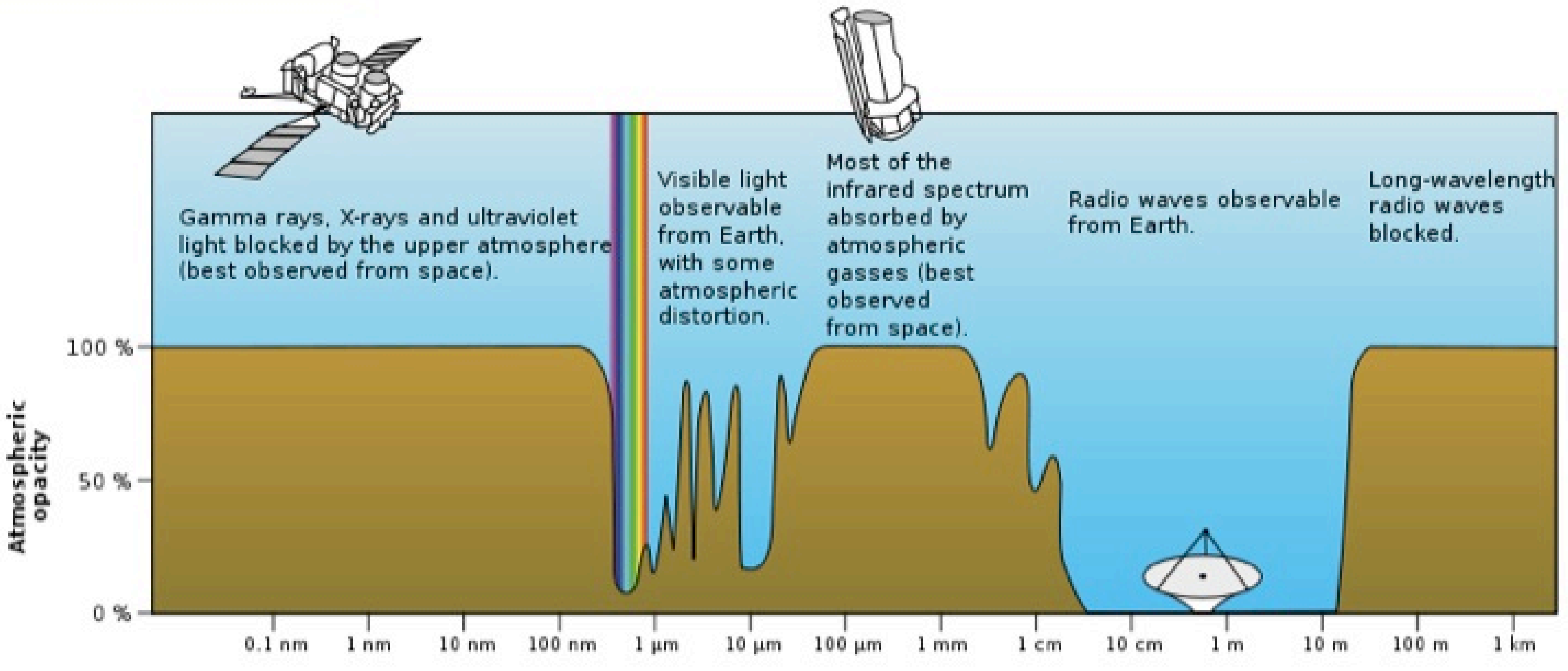
10^{-9} eV to 10^{14} eV   (1 eV = 2.4 10^{14} Hz)



Photon-Photon Opacity

The table shows some important examples of combinations of ε_1 and ε_2. Photons with energies greater than those in the last column are expected to suffer some degree of absorption when they traverse regions with high energy densities of photons with energies listed in the first column.

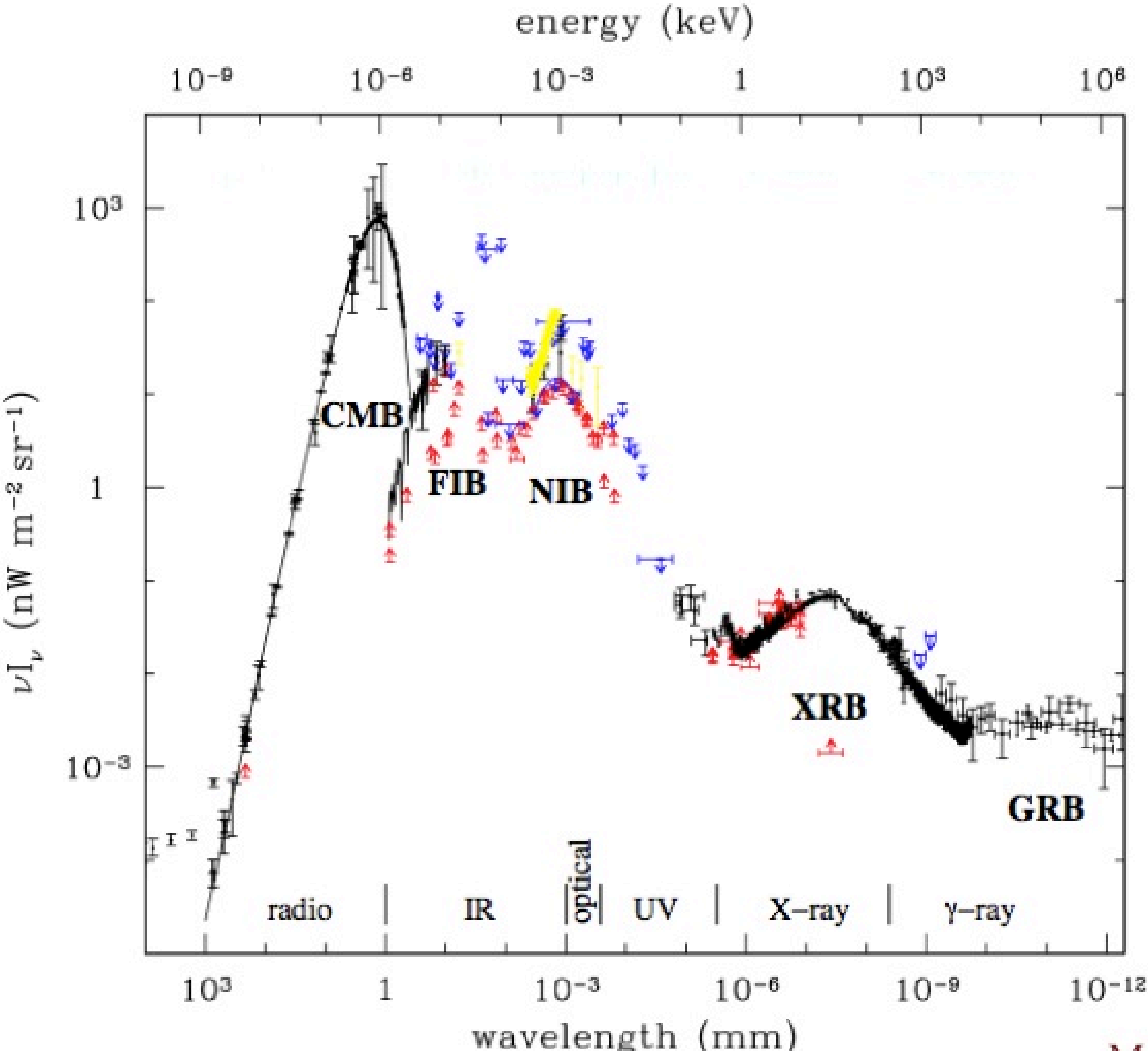
2

	ε_1(eV)	ε_1(eV)
Microwave Background Radiation	6×10^{-4}	4×10^{14}
Starlight	2	10^{11}
X-ray	10^{3}	3×10^{8}

The cross-section for this process for head-on colisions in the ultrarelativistic limit is

$$\sigma = \pi r_{\mathrm{e}}^2 \frac{m_{\mathrm{e}}^2 c^4}{\varepsilon_1 \varepsilon_2} \left[2 \ln \left(\frac{2\omega}{m_{\mathrm{e}} c^2} \right) - 1 \right] \qquad (43$$

where $\omega = (\varepsilon_1 \varepsilon_2)^{1/2}$ and r_{e} is the classical electron radius.



energy (keV)
10^-9
10^-6
10^-3
1
10^3
10^6
10^3
1
10^-3
νI_ν (nW m^-2 sr^-1)
CMB
FIB
NIB
XRB
GRB
optical
radio
IR
UV
X-ray
γ-ray
10^3
1
10^-3
10^-6
10^-9
10^-12
wavelength (mm)

Mo et al' 10

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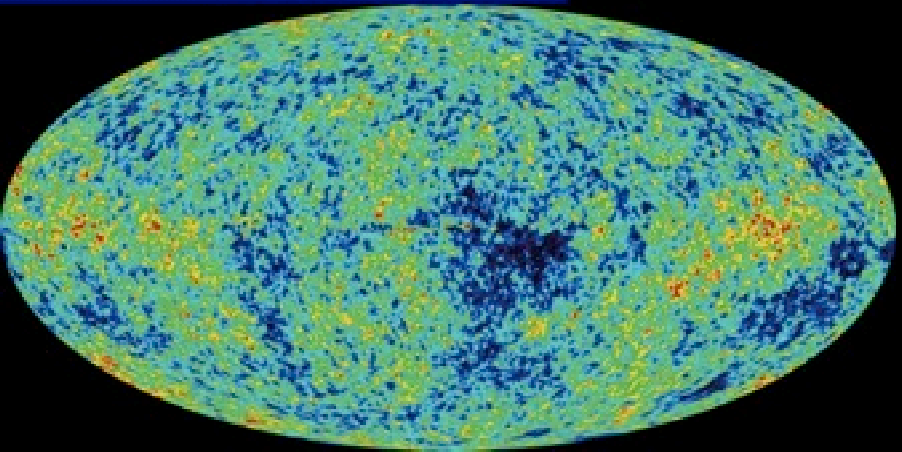
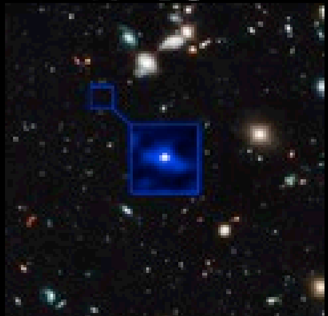
z=1100 (E_{cmb}~ 10^{-3} eV); HEs: z=7 QSOs, z=9.4 GRBs

Galactic Sources (E ~ 100 TeV)

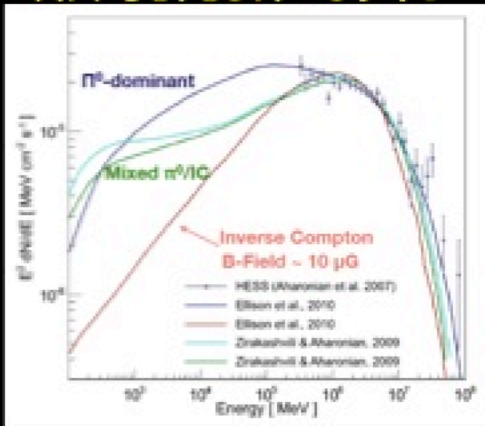


z=10

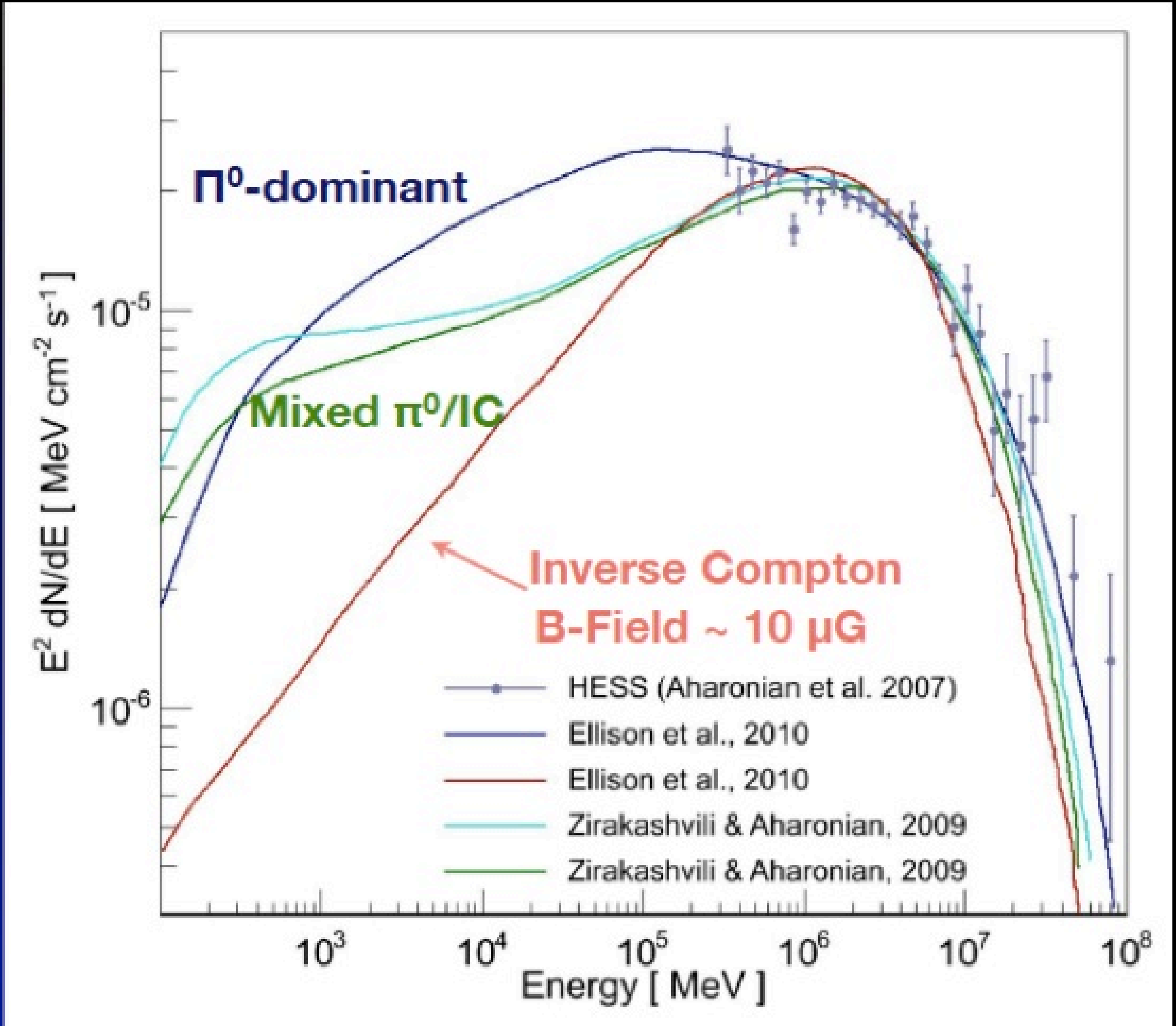


UDFj-39546284

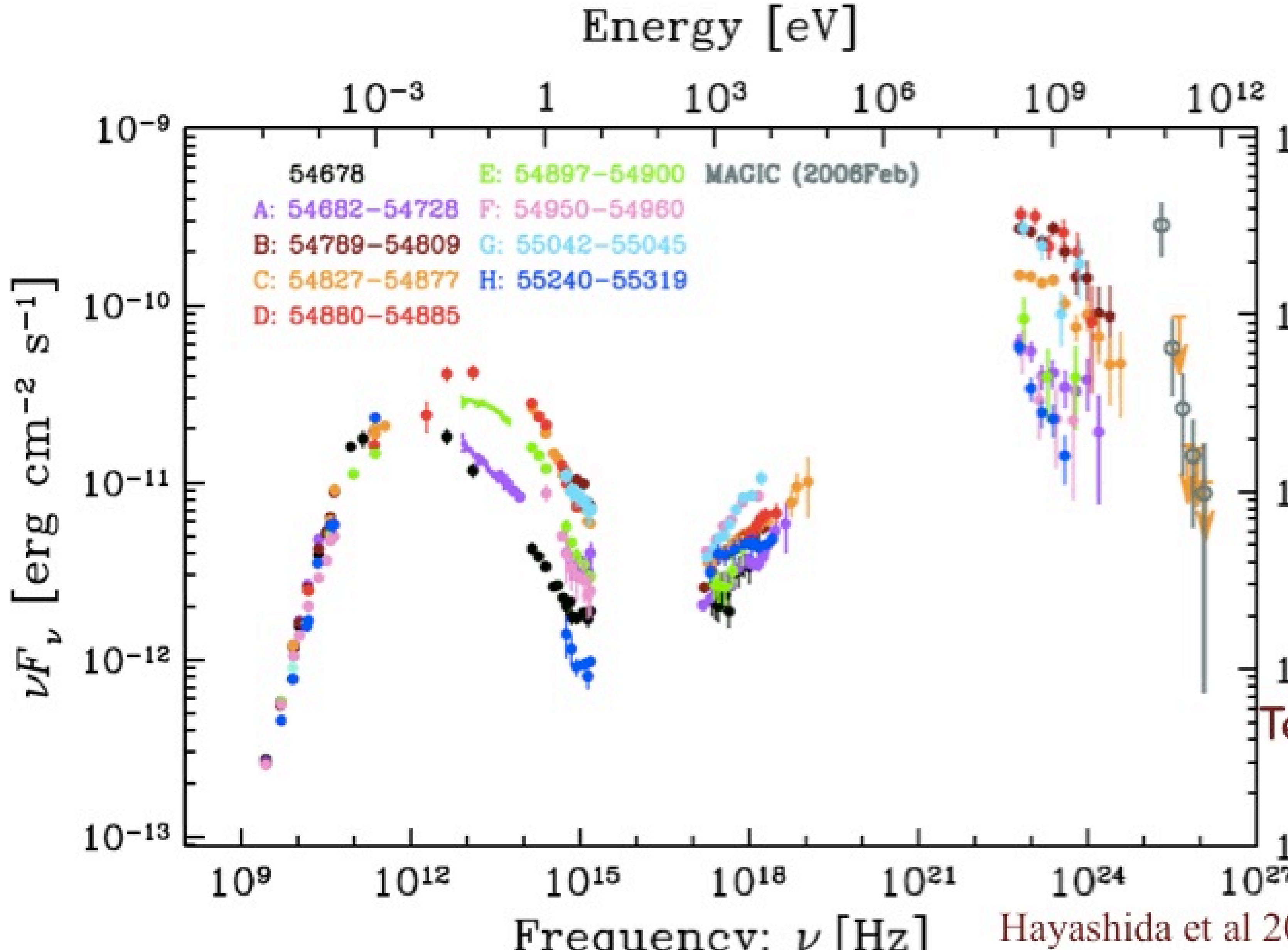
RX J1713.7-3946



RX J1713.7-3946



3C 279



Hayashida et al 2012

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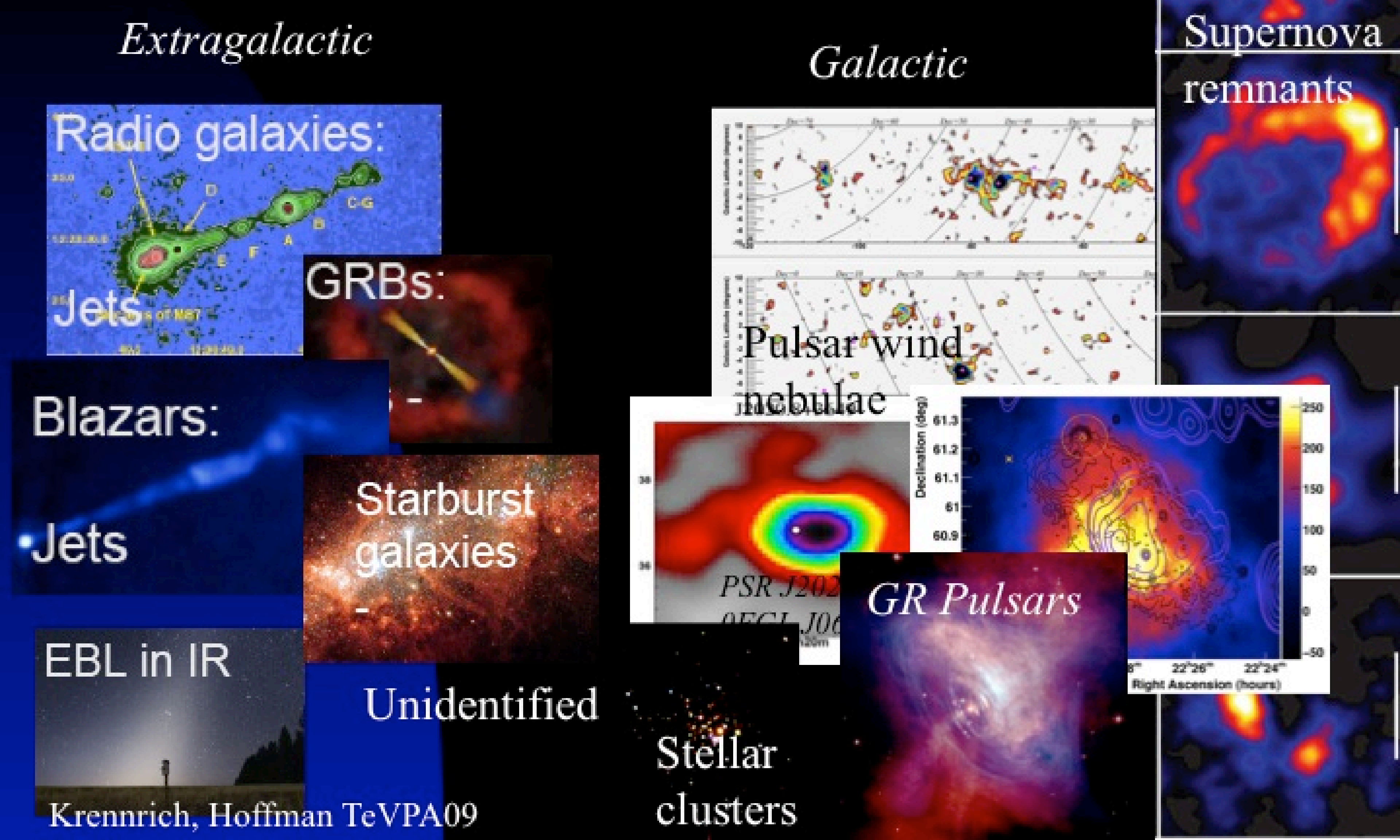
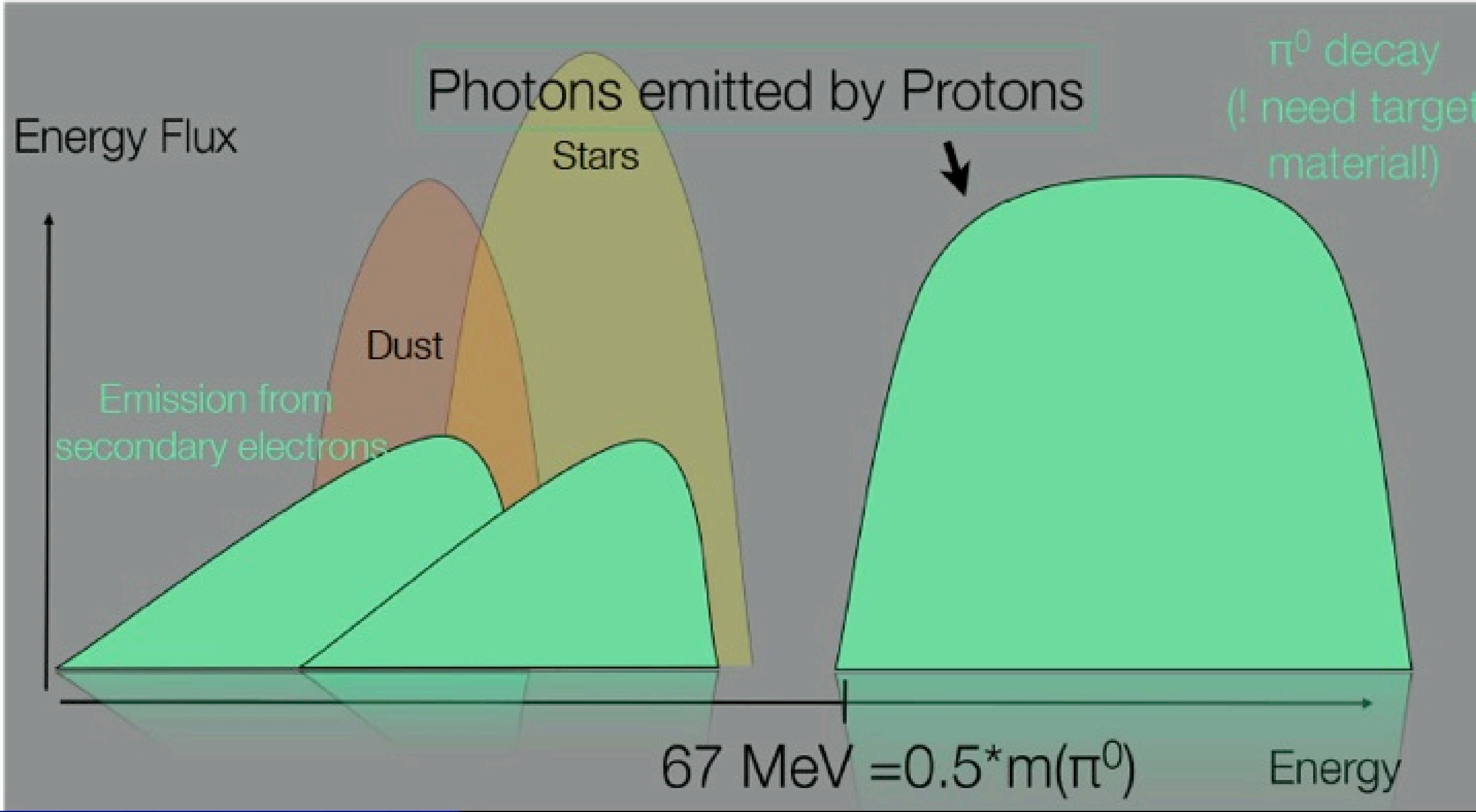
Electromagnetic & Hadronic (π prod) processes

Nature's HE γ Accelerators



Photon emission by accelerated charged particles



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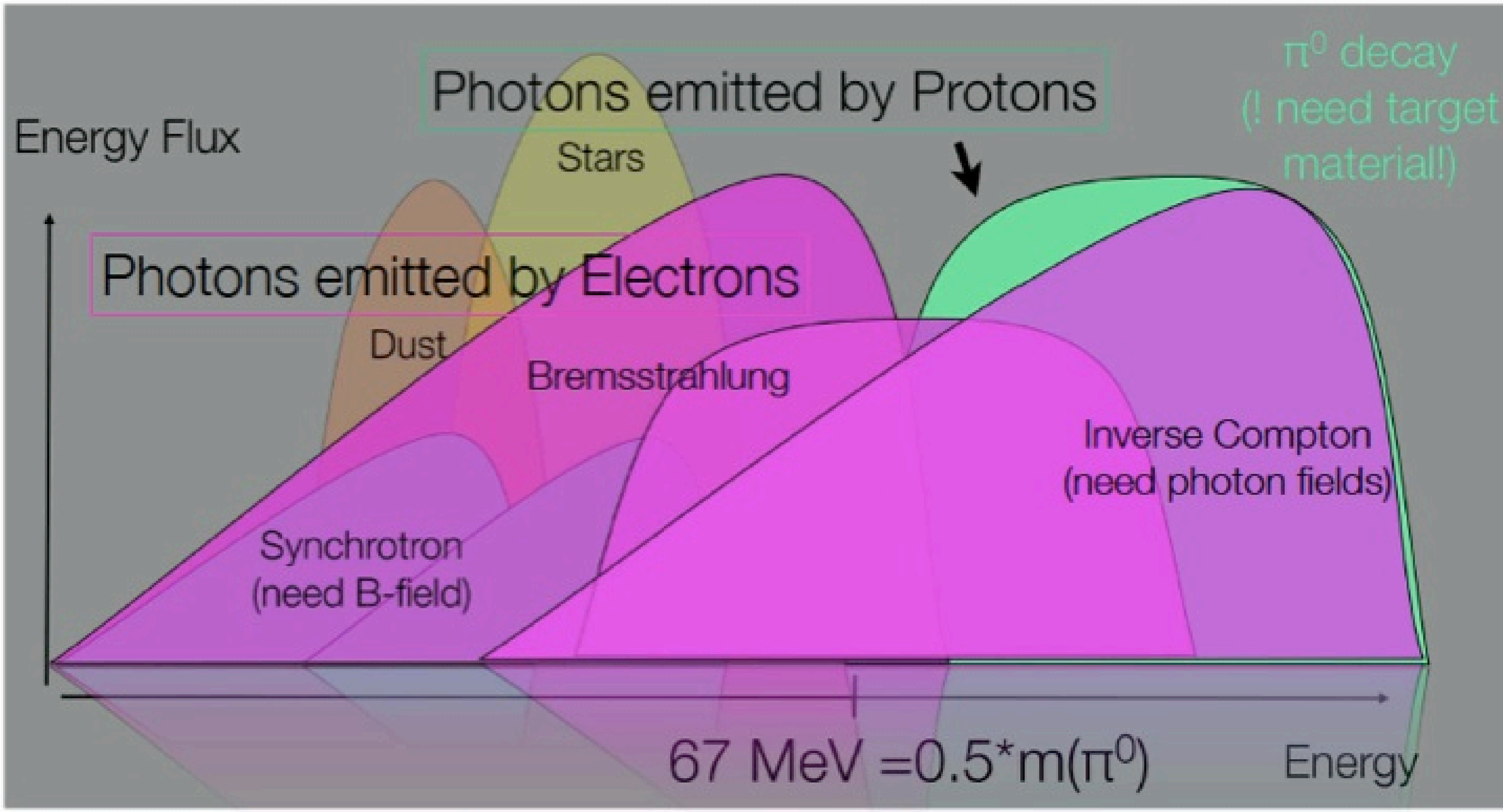

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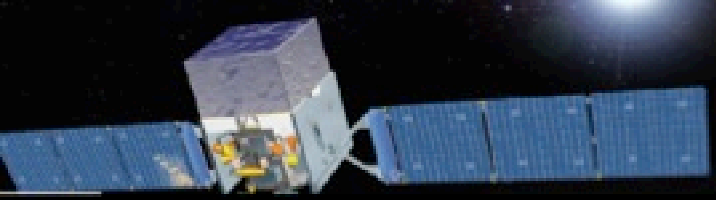
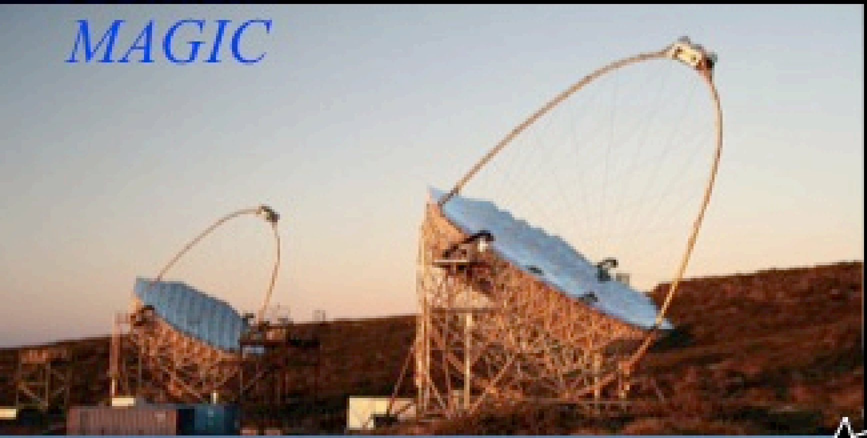
Fermi Satellite & IACTs

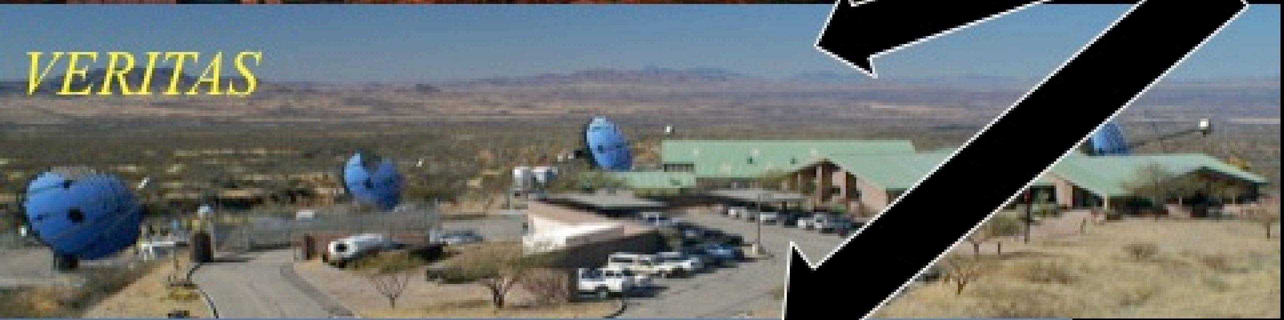
New Eyes
Gamma-Rays

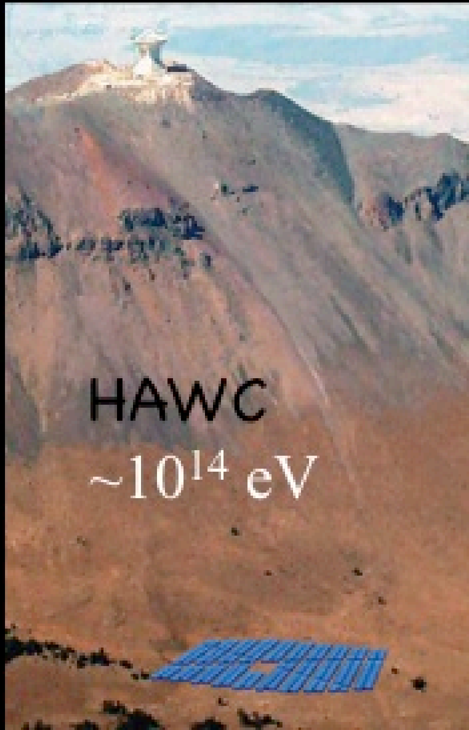


Fermi

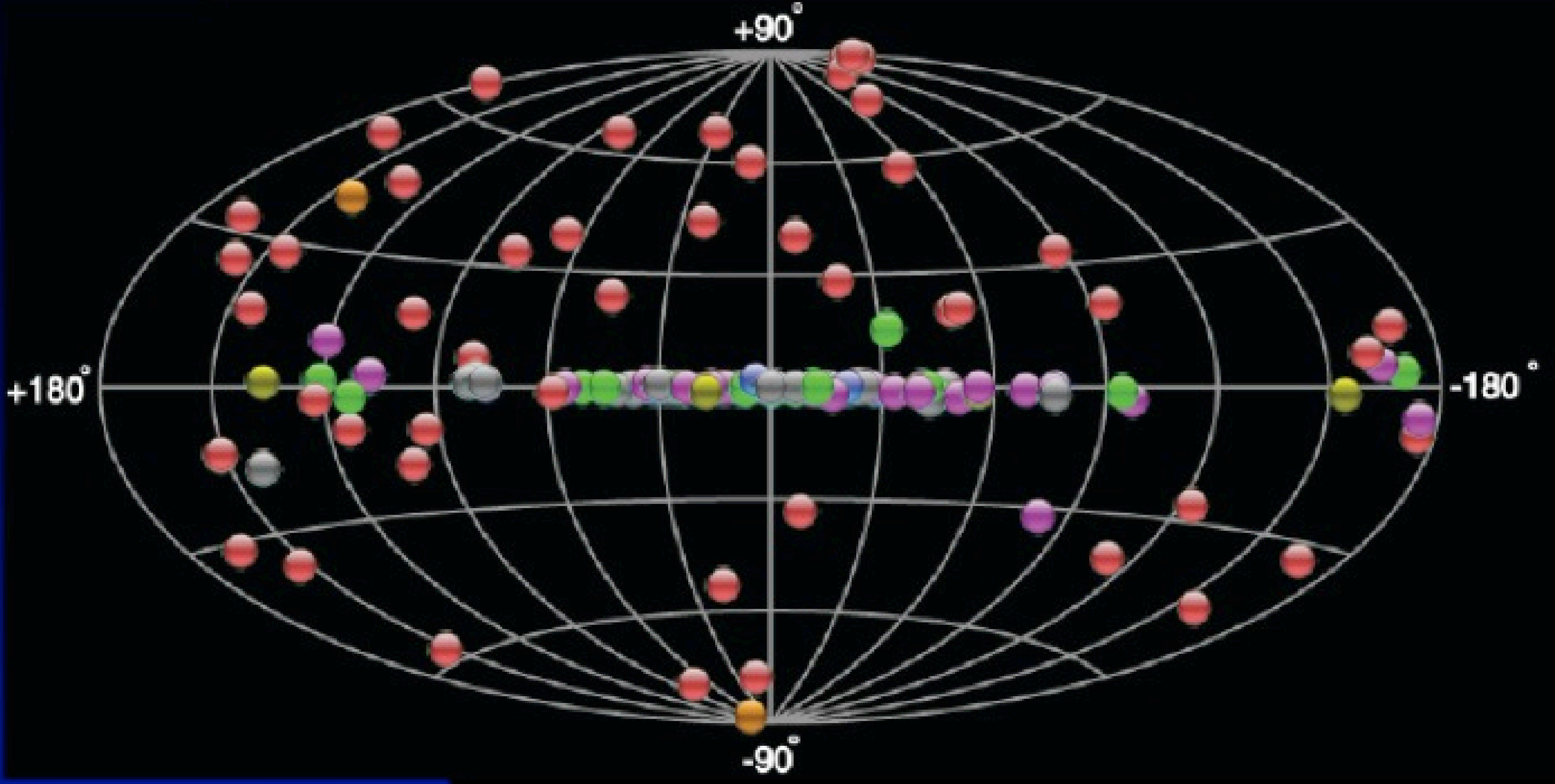


IACT –
Imaging Atmospheric
Cherenkov Telescopes
~10^{10} to <10^{14} eV

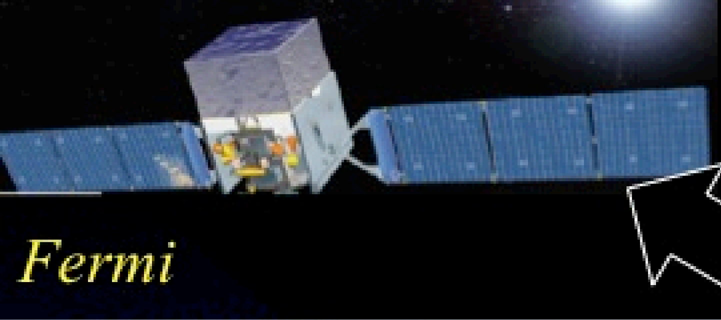




TeV γ Catalog (IACT sky)
> 100 sources

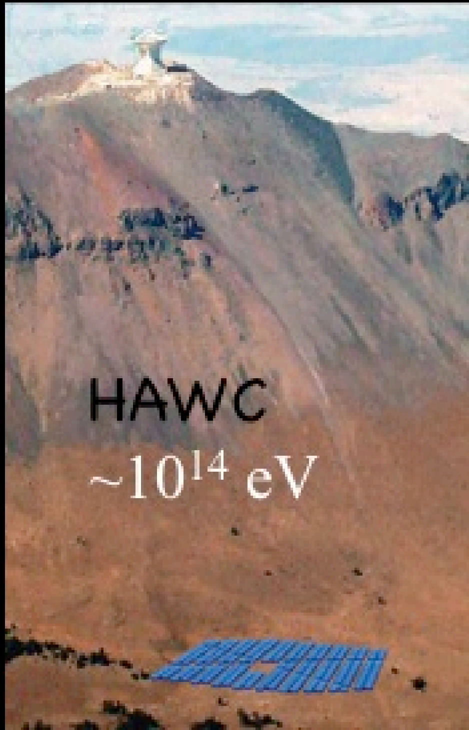


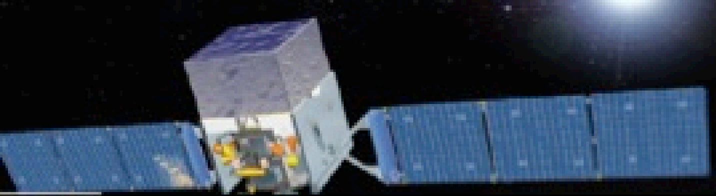
Hoffman TeVPA09



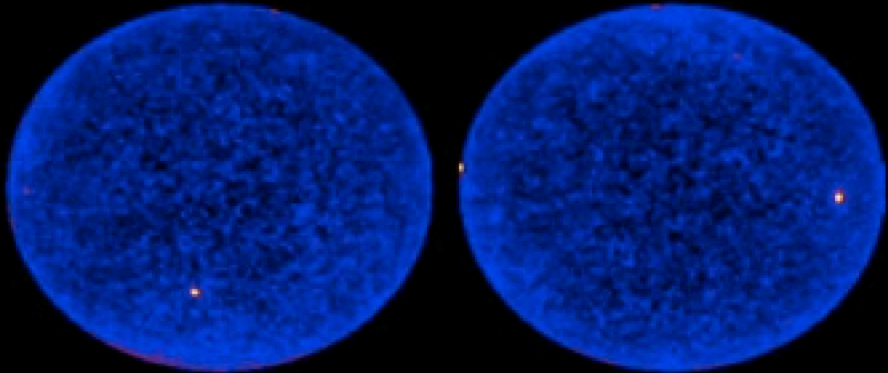
New Eyes Gamma-Rays

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

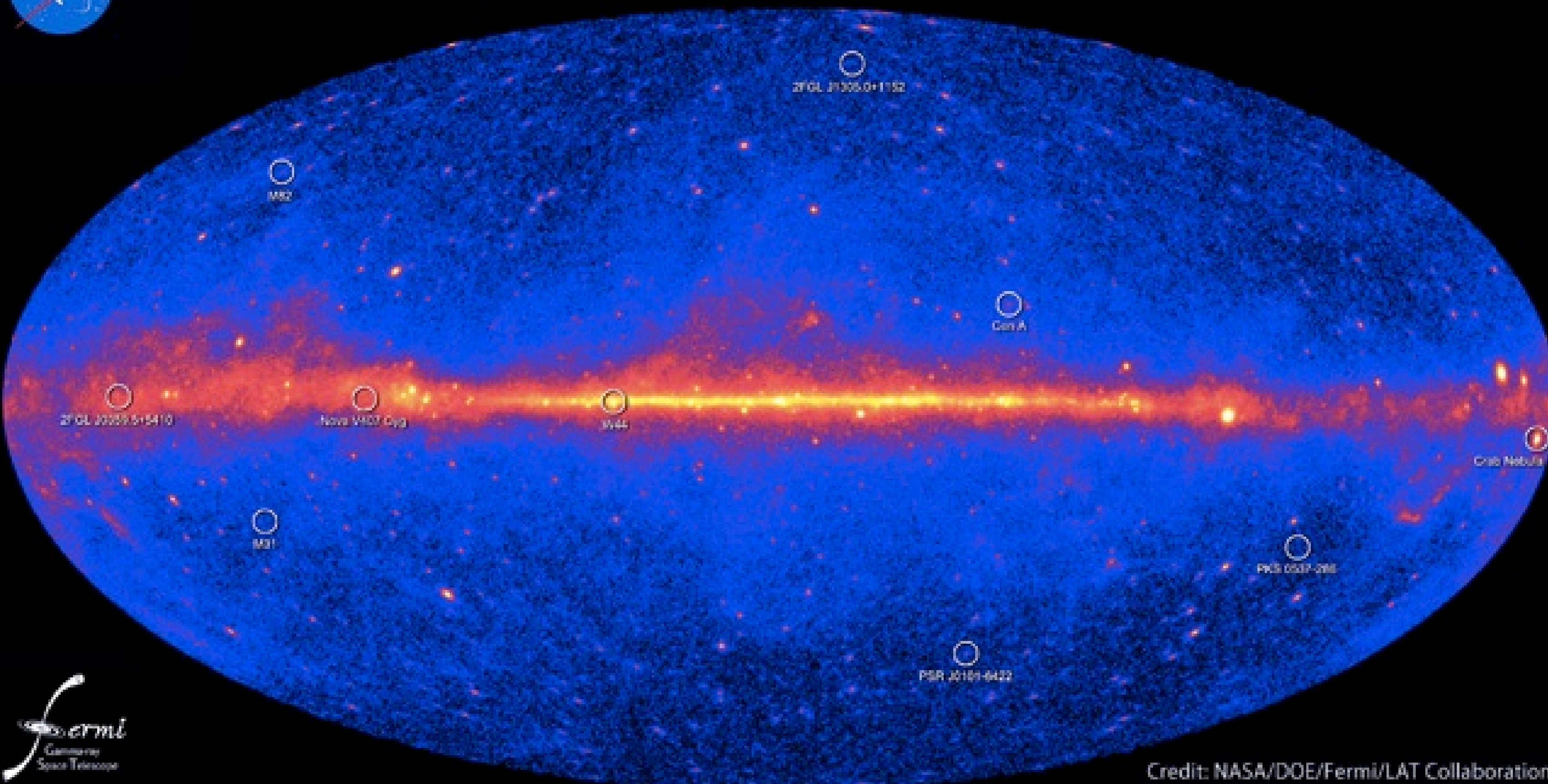




Fermi

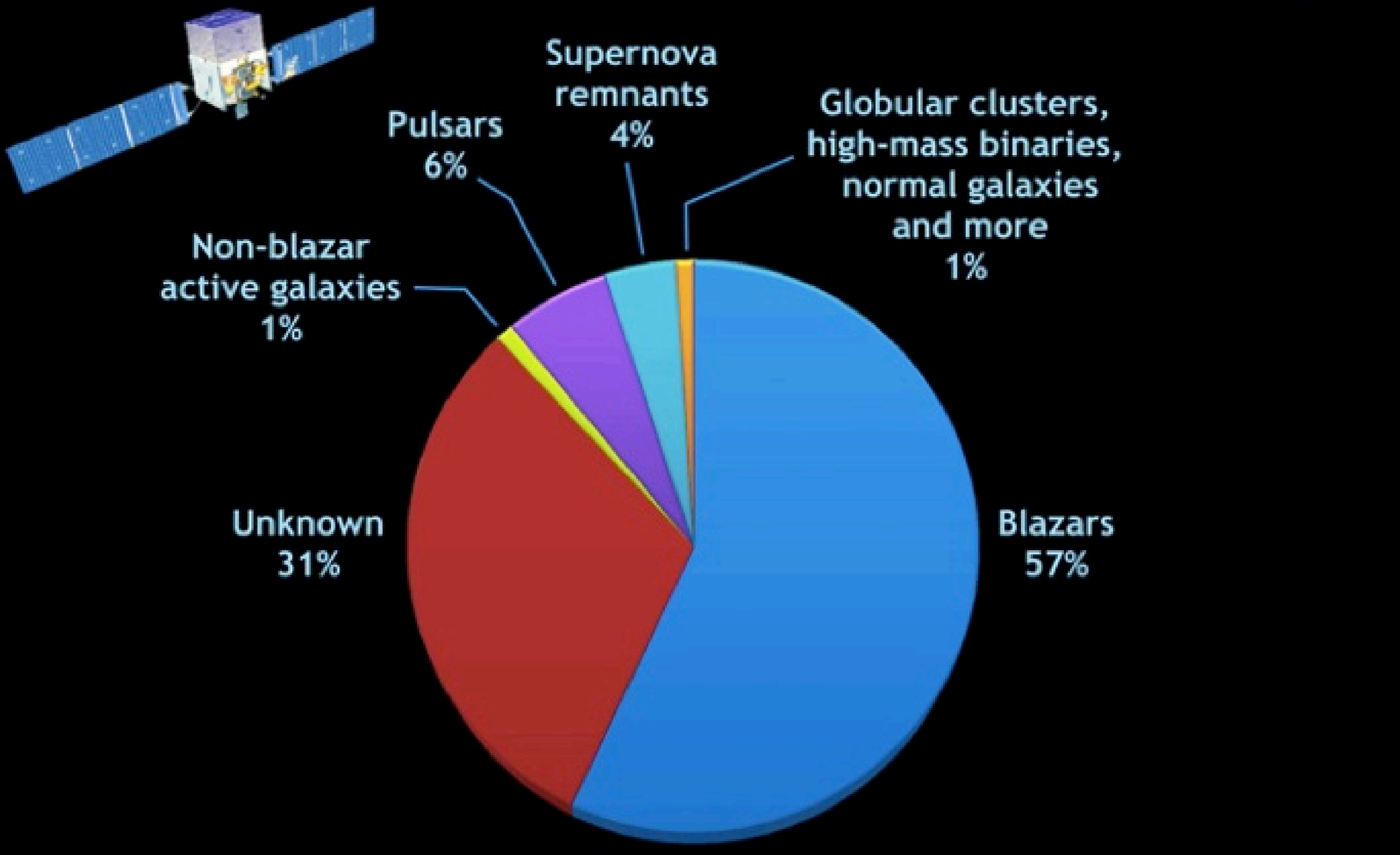


Fermi two-year all-sky map

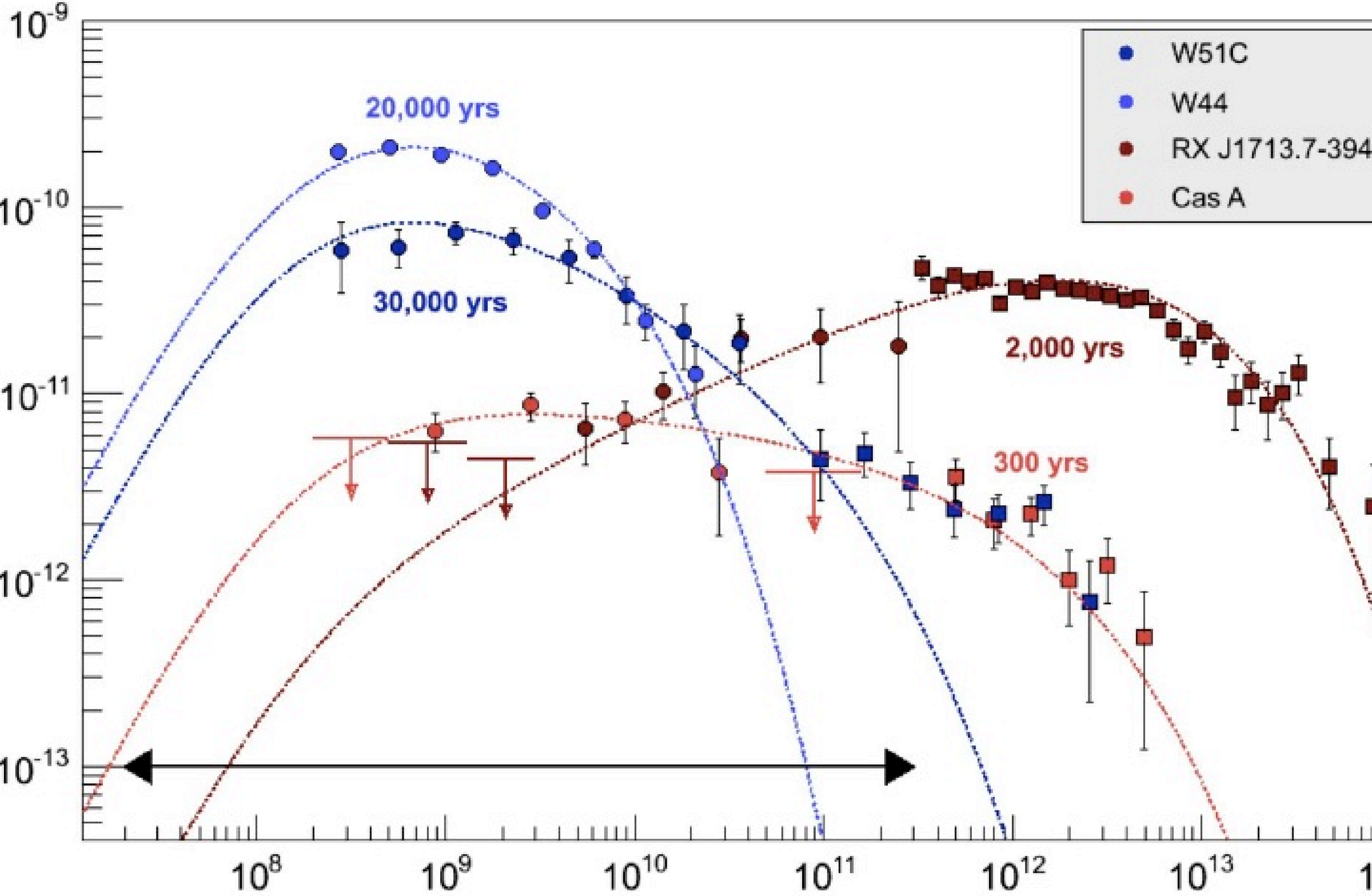


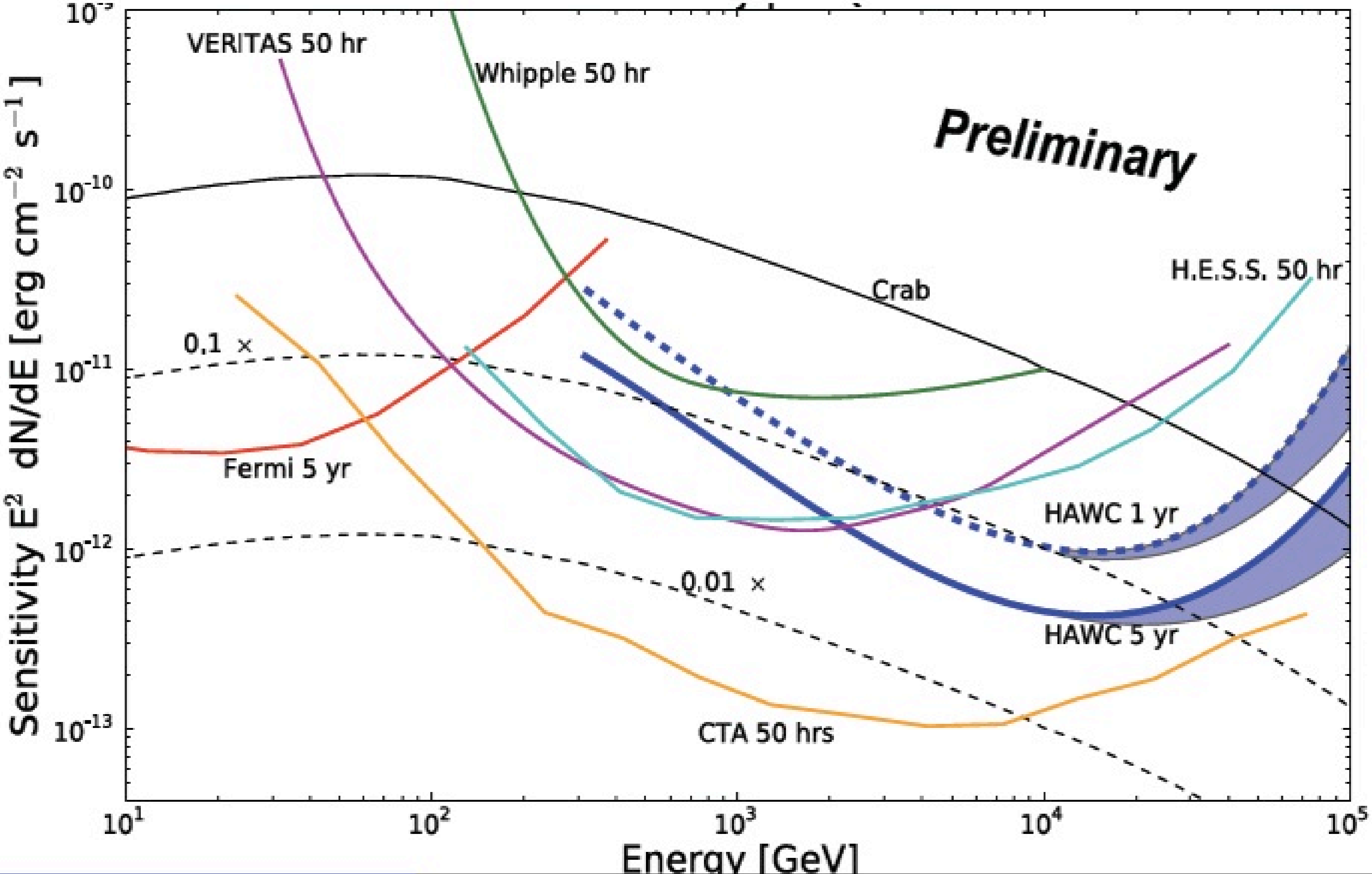
Credit: NASA/DOE/Fermi/LAT Collaboration

What has Fermi found: The LAT two-year catalog



The origin of Cosmic rays - individual SNRs

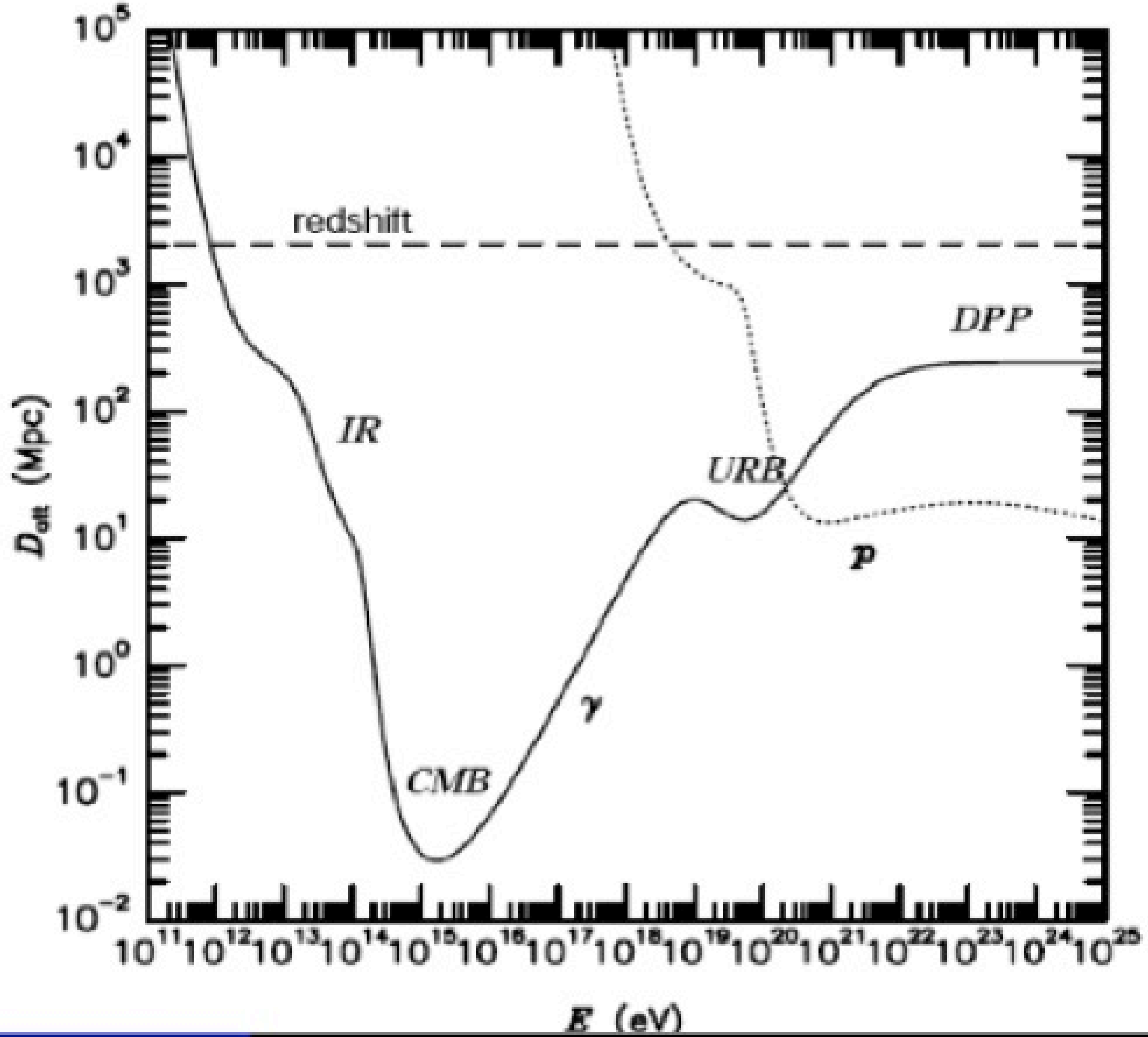




VERITAS 50 hr
Whipple 50 hr
Preliminary
Crab
H.E.S.S. 50 hr
0.1 ×
Fermi 5 yr
HAWC 1 yr
0.01 ×
HAWC 5 yr
CTA 50 hrs
Sensitivity E^2 dN/dE [erg cm^{-2} s^{-1}]
Energy [GeV]
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^1
10^2
10^3
10^4
10^5

Can they be observed at UHEs?

The UHE Gamma Ray Astronomical Window



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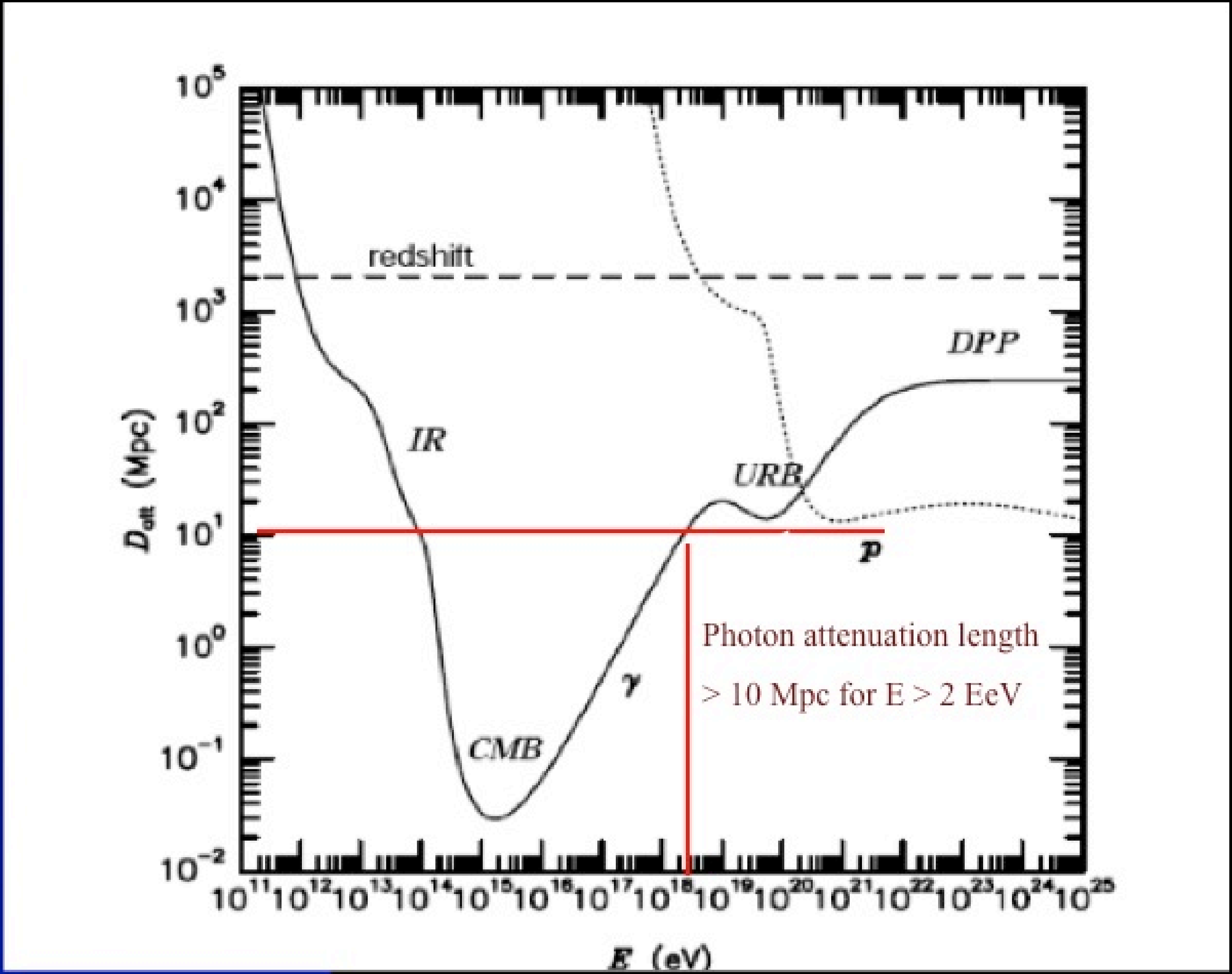
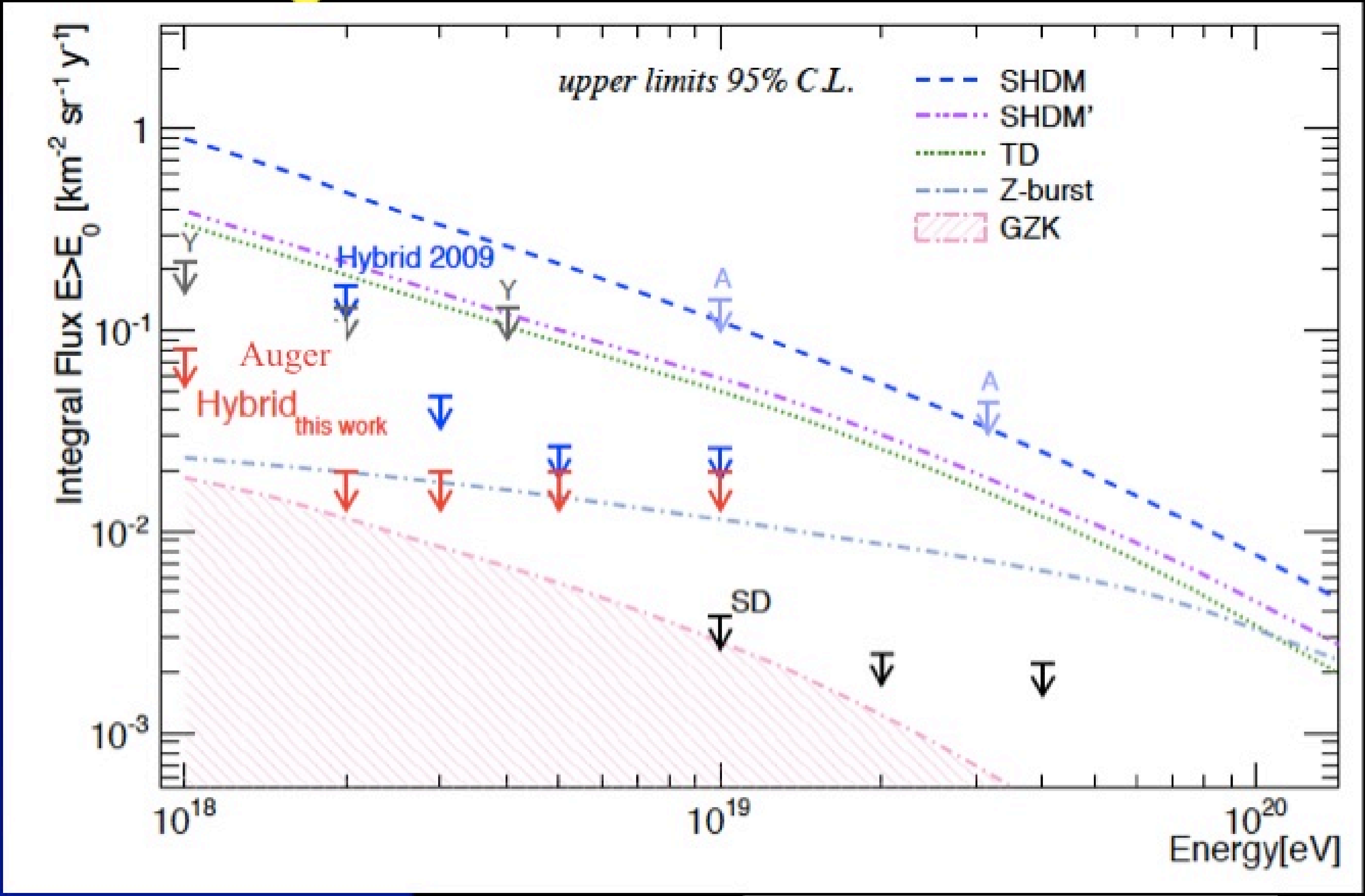


Auger Photon Limits

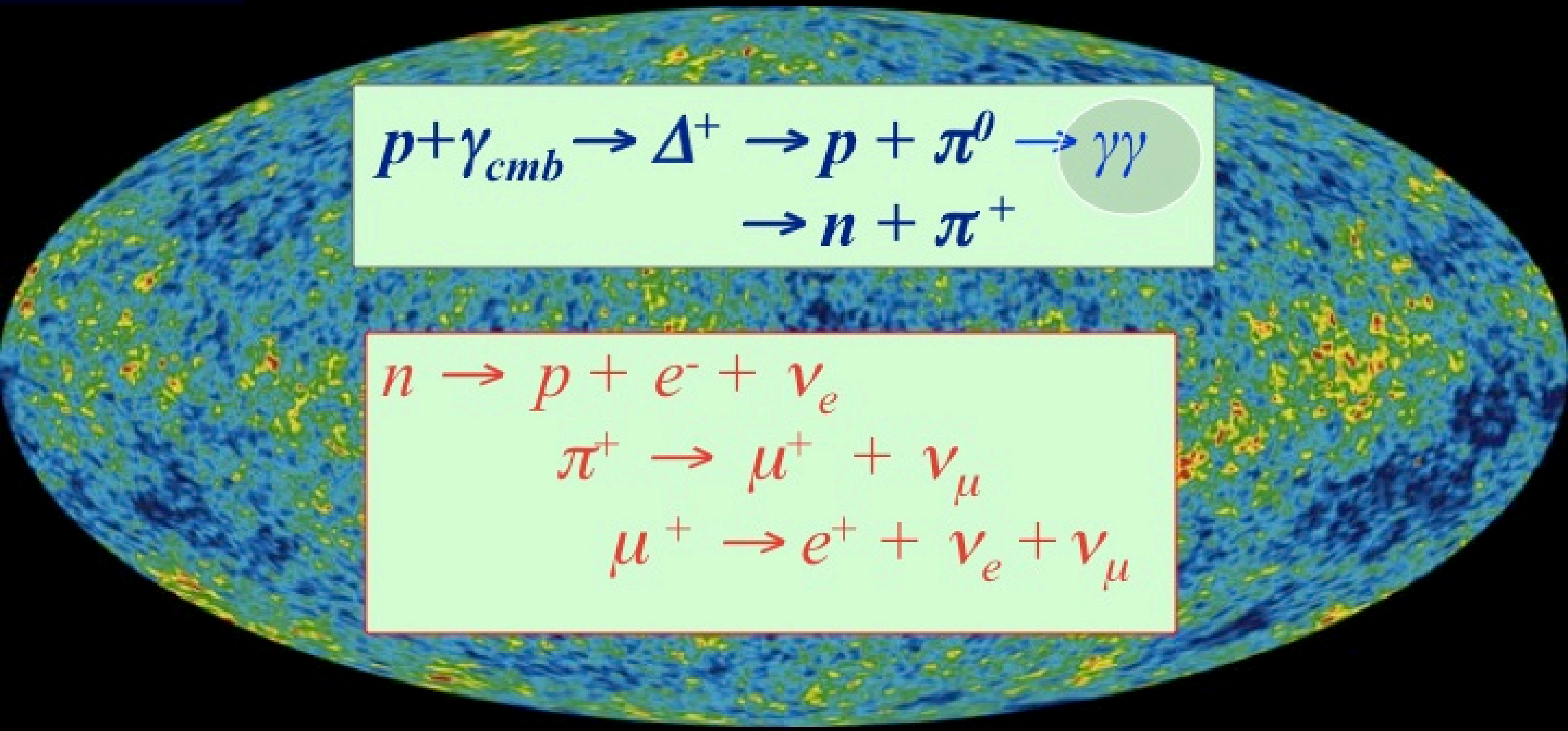
ICRC11



TA consistent (ICRC11)

Cosmogenic (GZK) Neutrinos & Photons

and UHECR composition



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

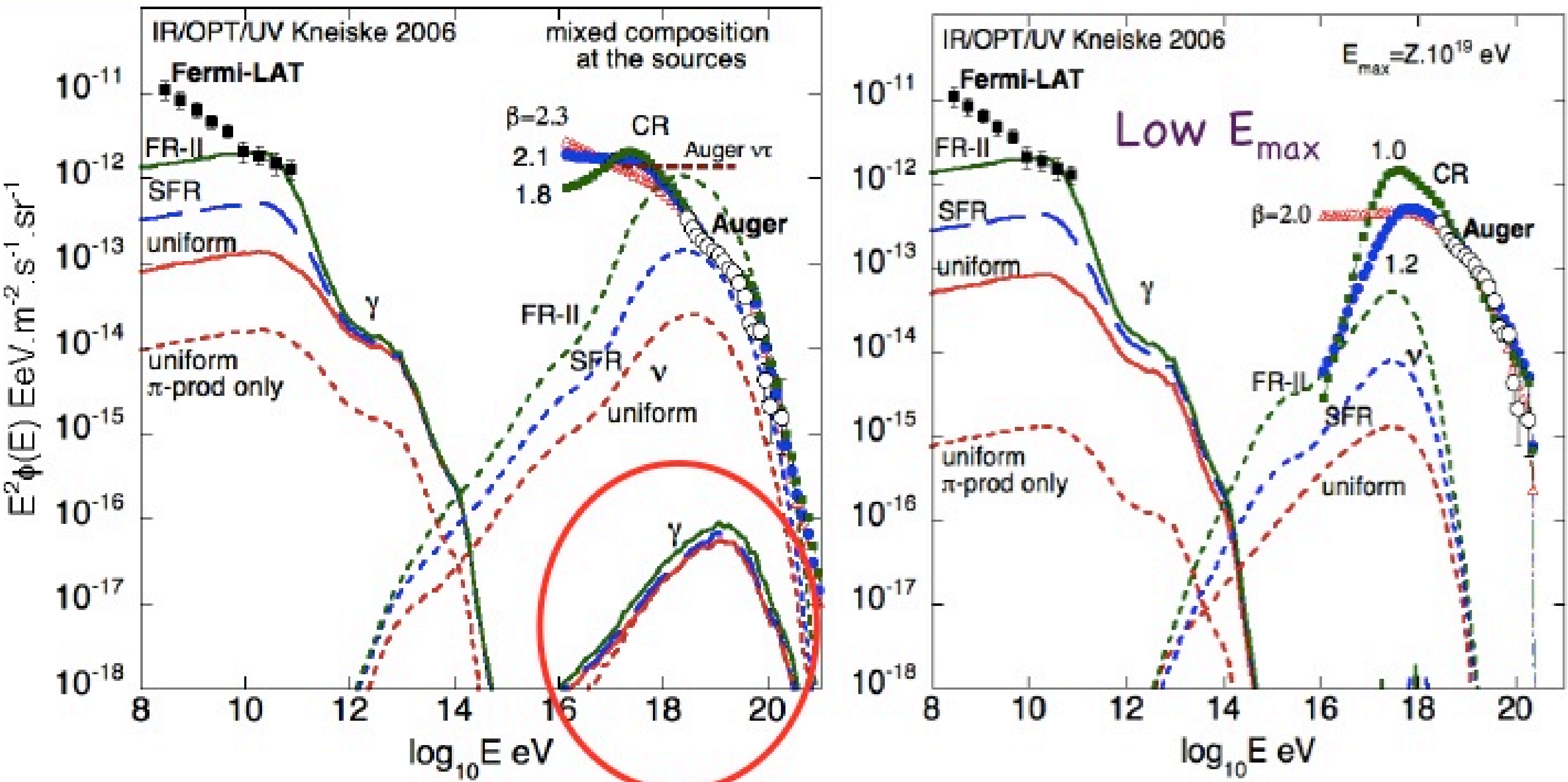
$$\rightarrow n + \pi^{+}$$

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

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \nu_{\mu}$$

GZK/Cosmogenic Photons



Decerprit & Allard 11

What are the most energetic Astroparticles?

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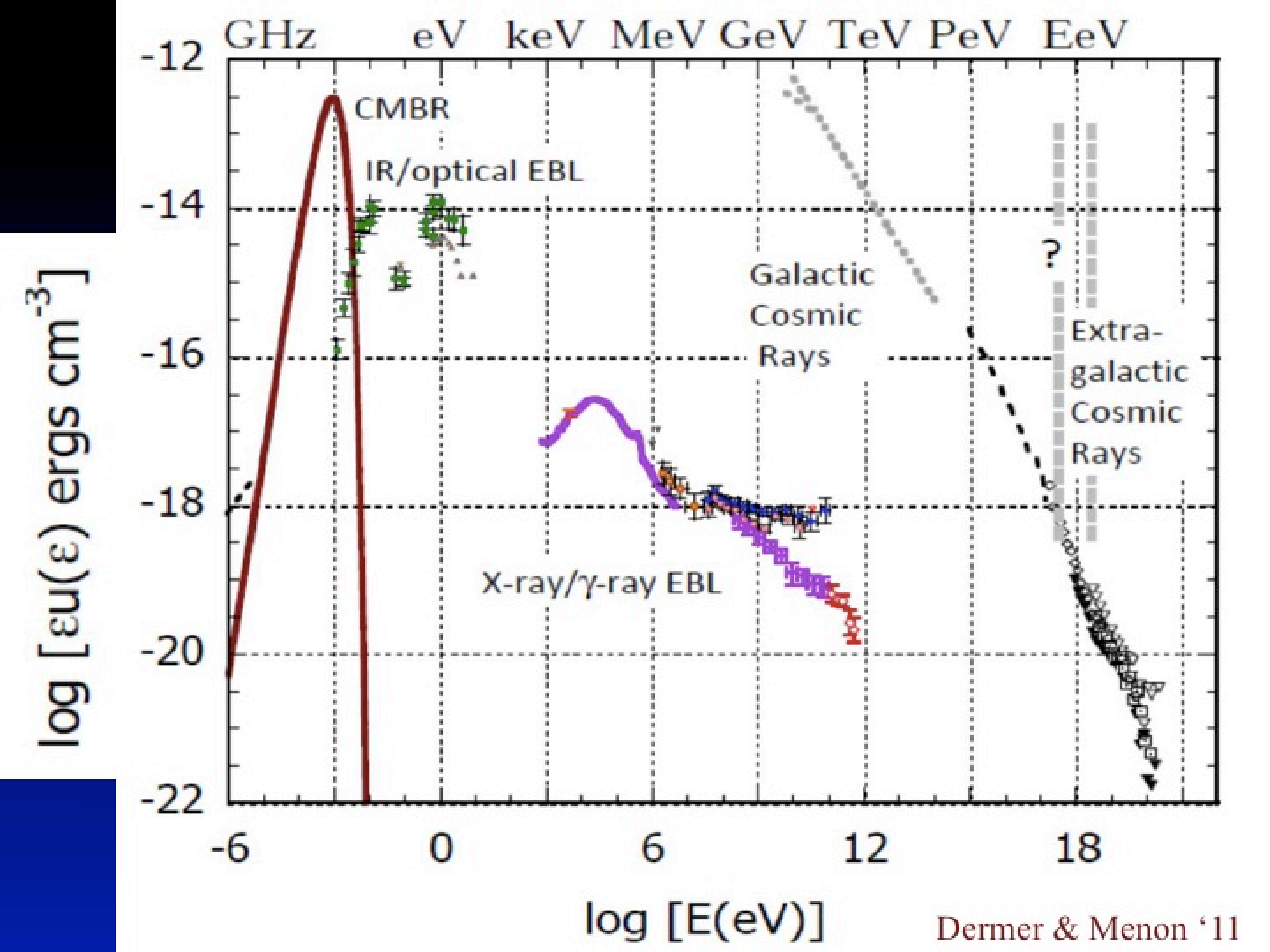
Ultra High Energy Cosmic Rays (UHECRs)


GHz
eV
keV
MeV
GeV
TeV
PeV
EeV
CMBR
IR/optical EBL
Galactic
Cosmic
Rays
?
Extra-
galactic
Cosmic
Rays
X-ray/γ-ray EBL
-12
-14
-16
-18
-20
-22
-6
0
6
12
18
log [εu(ε) ergs cm^-3]
log [E(eV)]
Dermer & Menon '11

What are the most energetic Astroparticles?

Ultra High Energy Cosmic Rays (UHECRs)

In what Energy range do we observe them?

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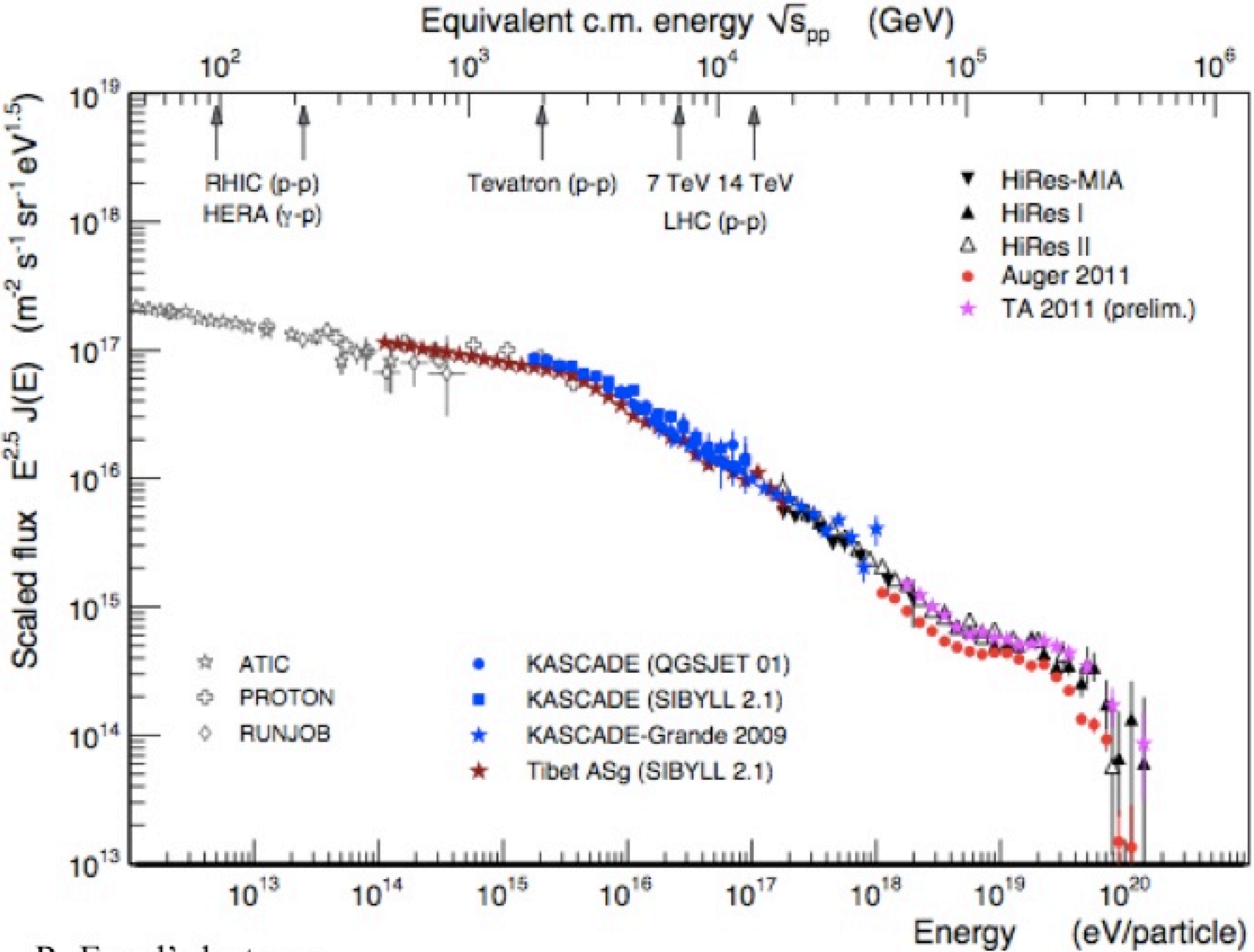
from ~ GeV to 0.3 ZeV - 10^9 to 10^{20} eV



R. Engel's lectures

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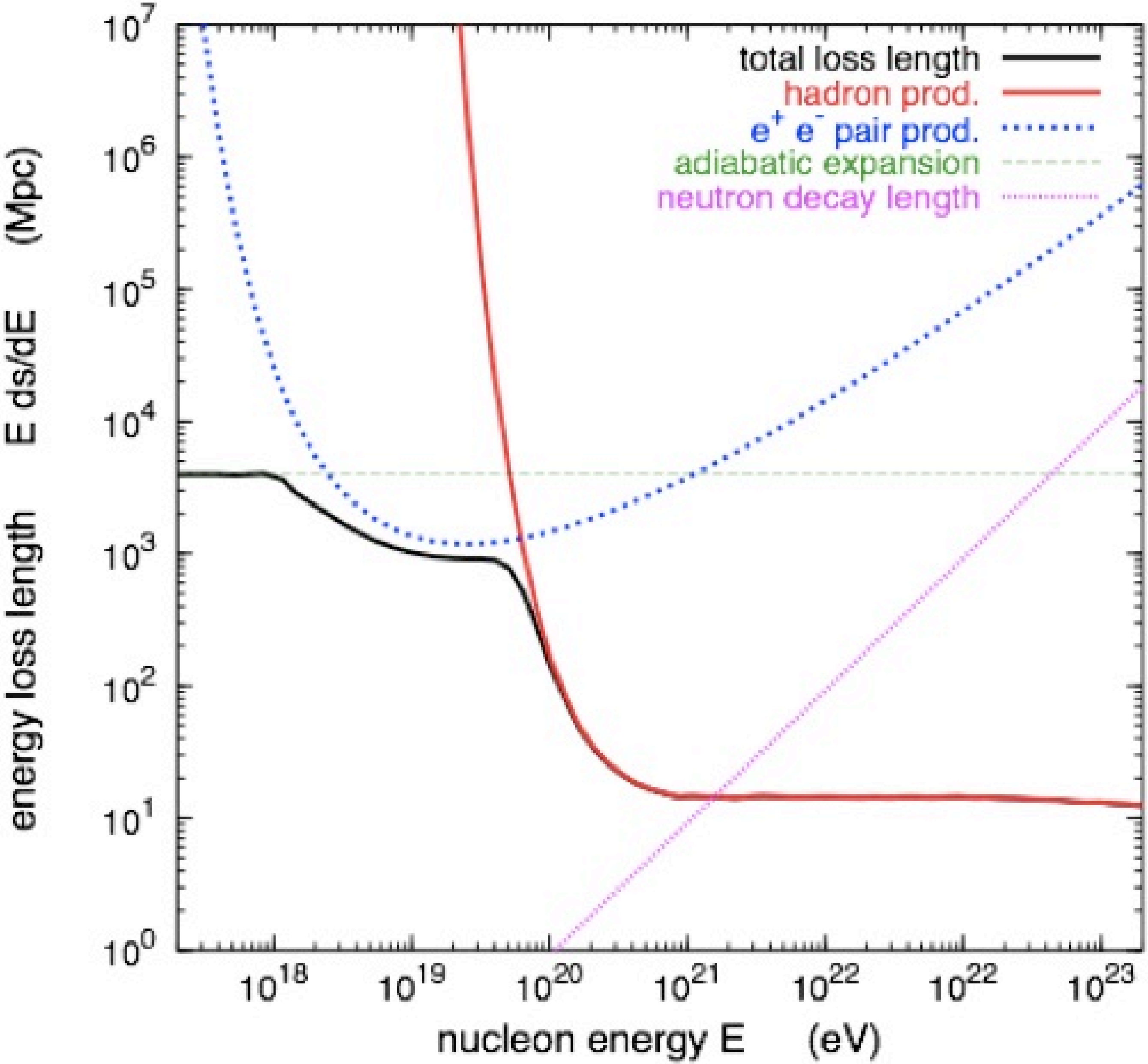
z=3 (E ~ EeV =10^{18} eV)

< 100 Mpc (E ~ 100 EeV)



R. Engel's lectures

(Stanev et al., Phys. Rev. D62 (2000) 09300

Propagation of UHECRs

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

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

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END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York
(Received 1 April 1966)

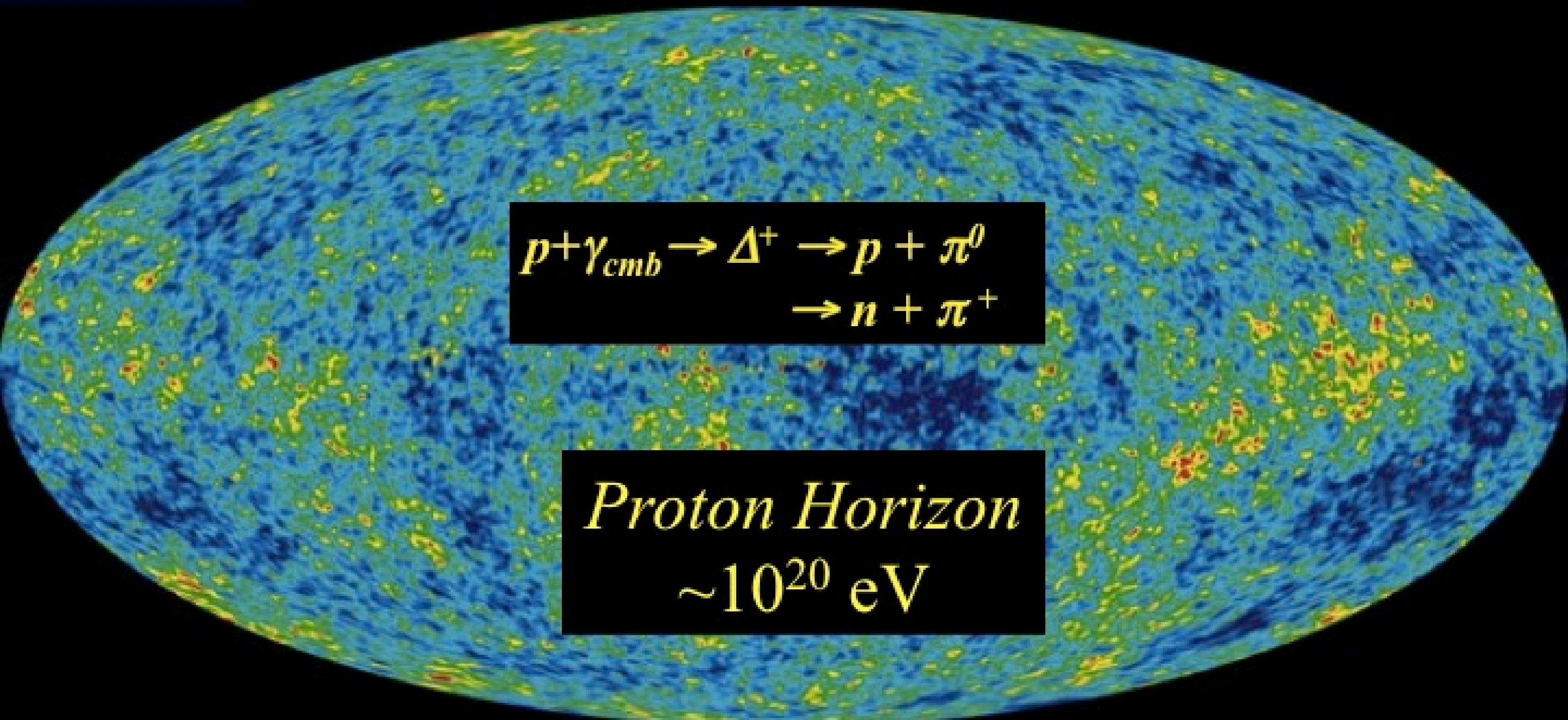
One cannot save the day for superhigh-energy cosmic rays by calling on heavy nuclei. The threshold for photodisintegration against photons of 7×10^{-4} eV is only 5×10^{18} eV/nucleon, and at 10^{19} eV/nucleon most of the photons can excite the giant dipole resonance, for which the cross section is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

protons & nuclei

G. T. Zatsepin and V. A. Kuz'min
P. N. Lebedev Physics Institute, USSR Academy of Sciences
Submitted 26 May 1966
ZhETF Pis'ma 4, No. 3, 114-117, 1 August 1966

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

"Cosmologically Meaningful Termination"

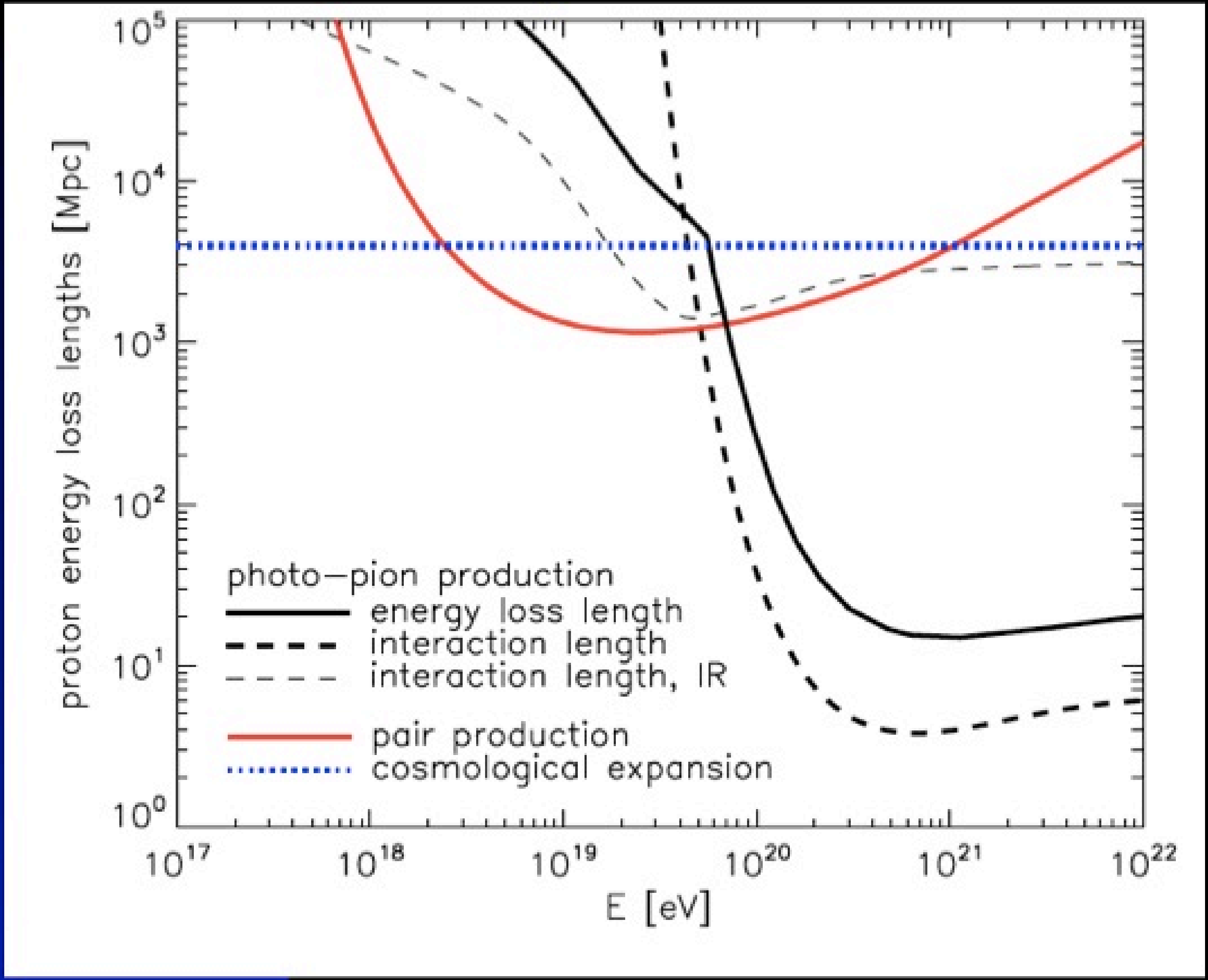


GZK Cutoff

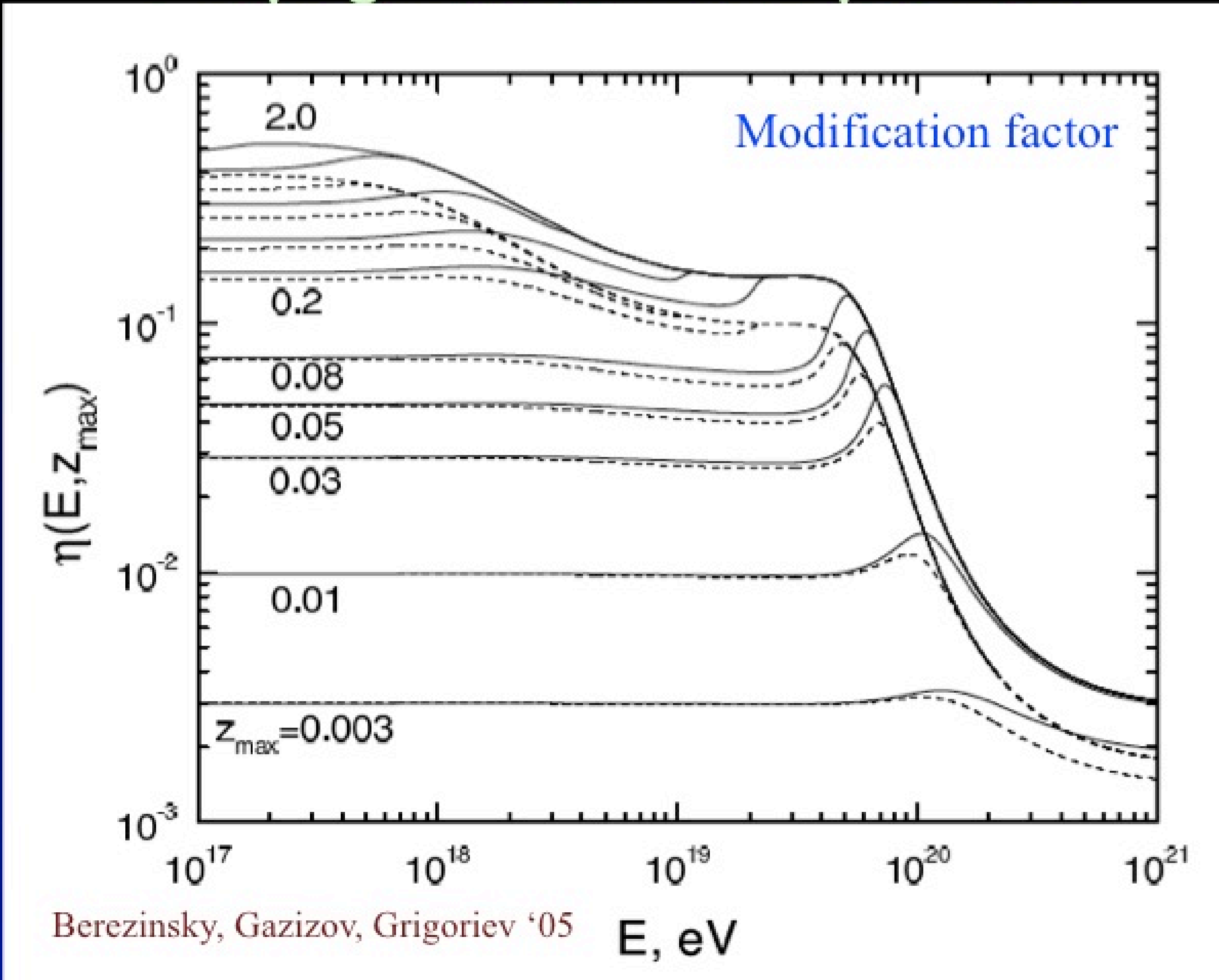
Greisen, Zatsepin, Kuzmin

1966

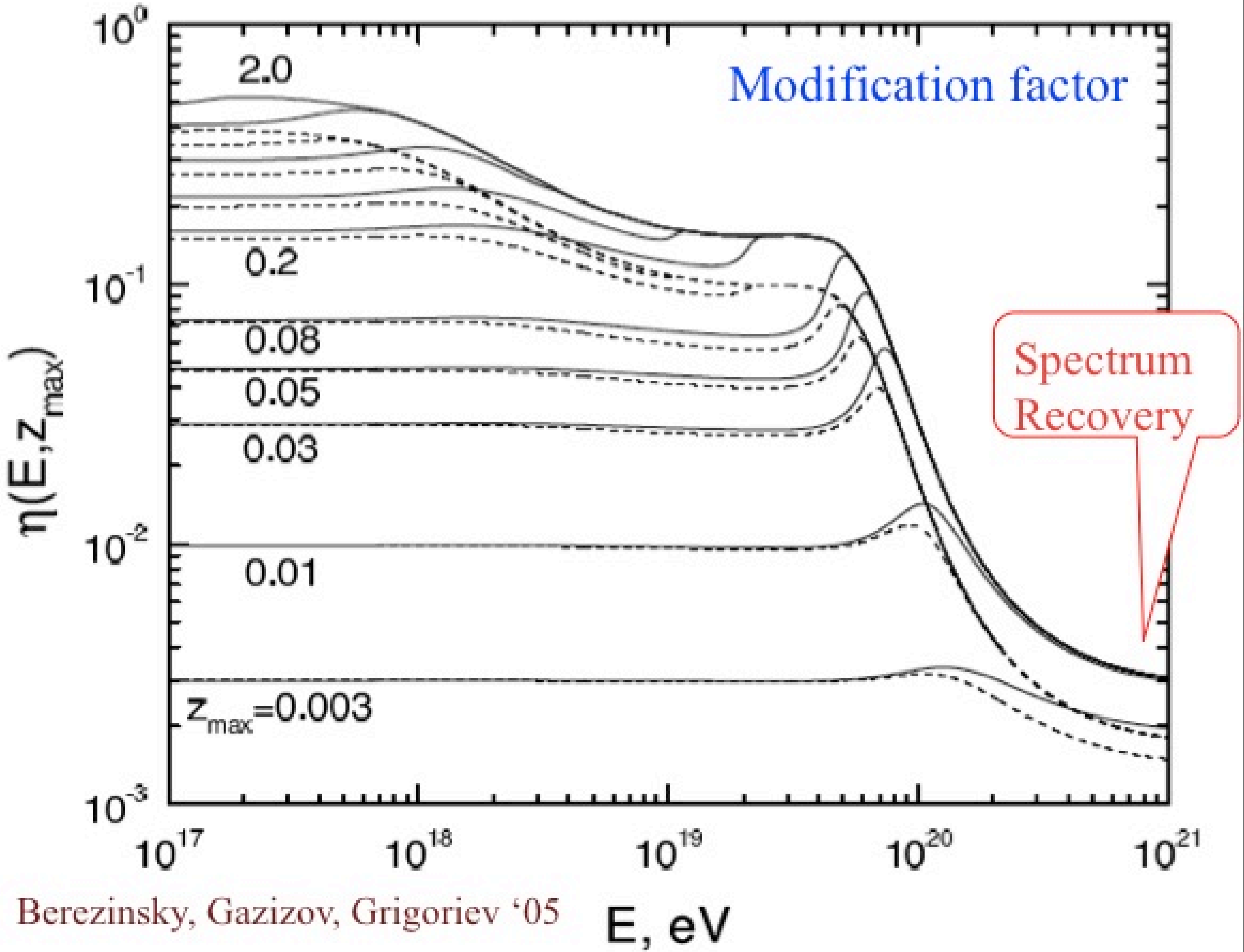
GZK effect for protons



Propagation of UHE protons

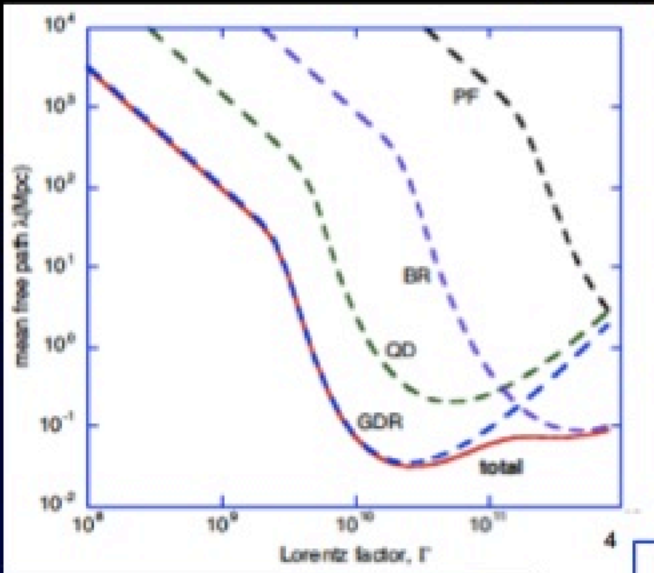


Propagation of UHE protons



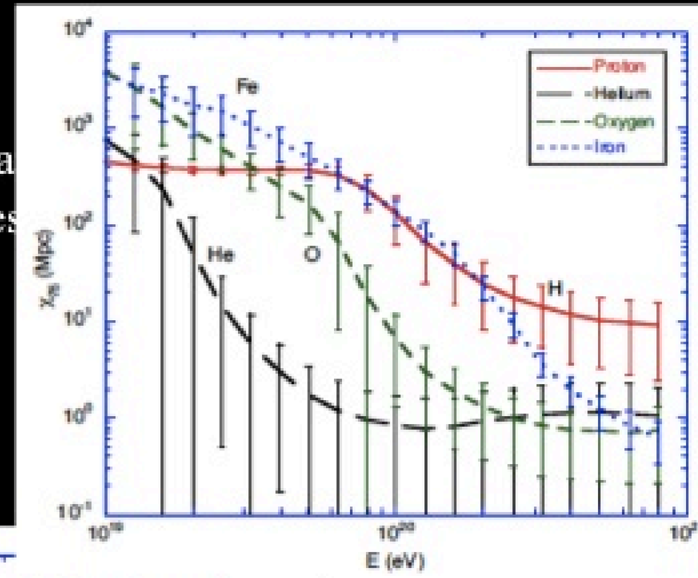
Berezinsky, Gazizov, Grigoriev '05

Propagation of UHE nuclei

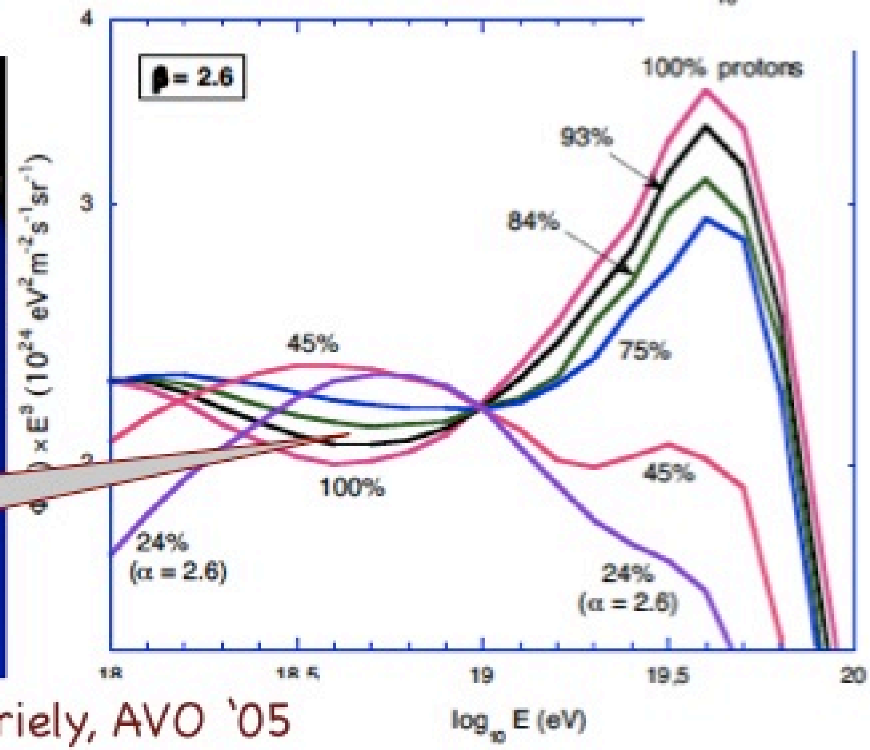


^{56}Fe mean-free-path
CMB IRB interaction

GDR: giant dipolar resona
QD: quasi-deuteron proces
BR: baryonic resonances
PF: photo-fragmentation



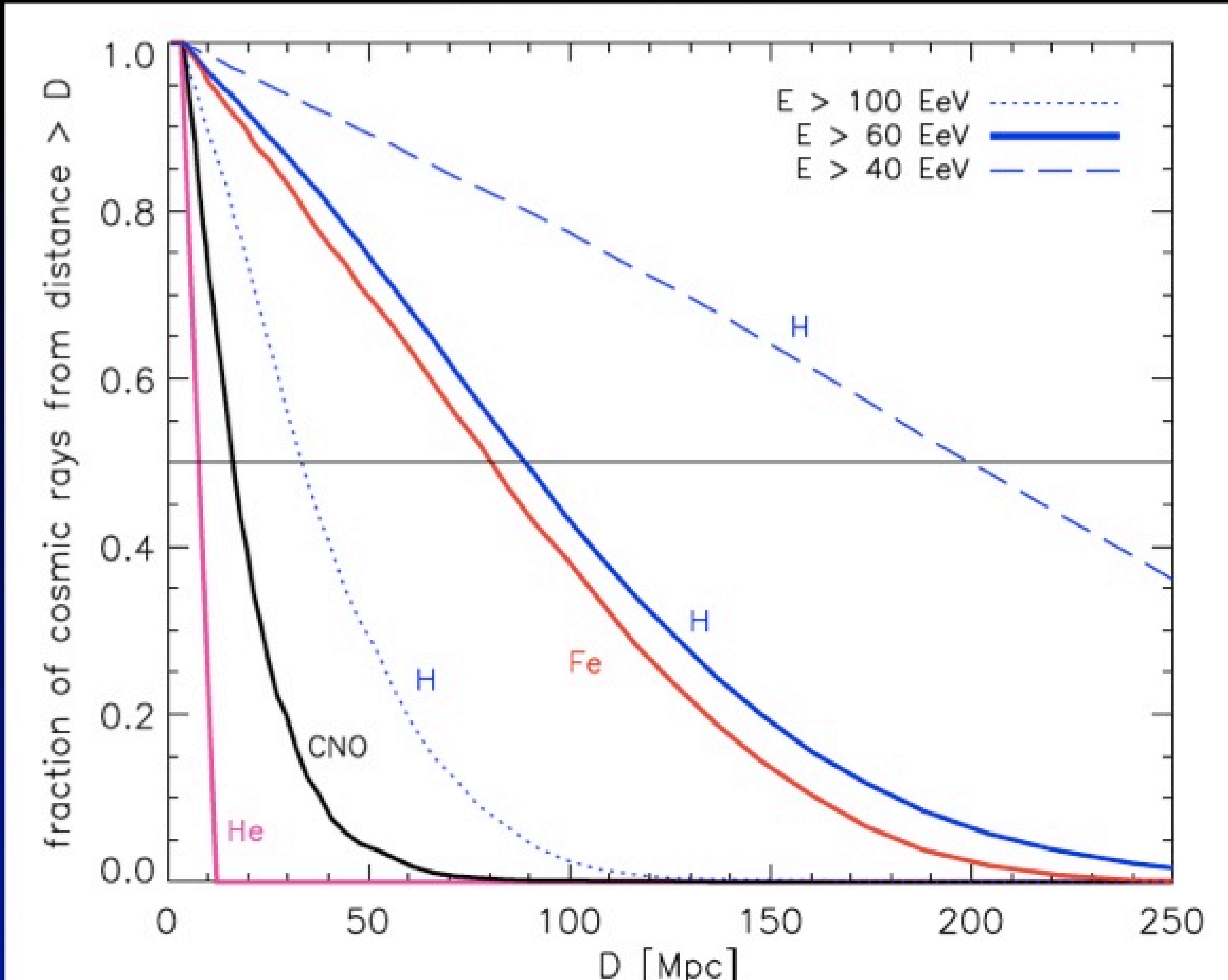
Energy Loss
Length



dip only for
protons

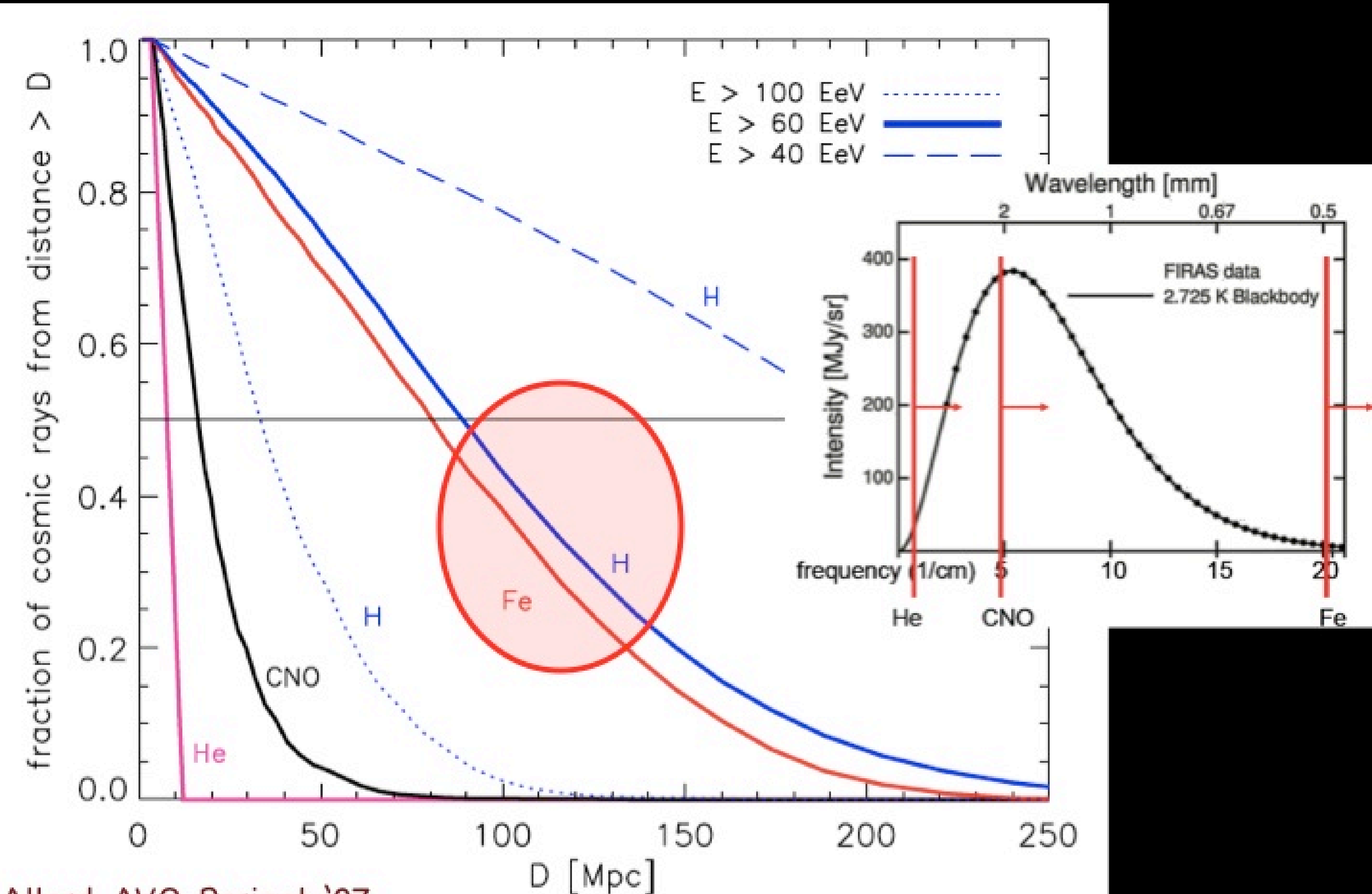
Allard, Parizot, Khan, Goriely, AVO '05

GZK Horizon



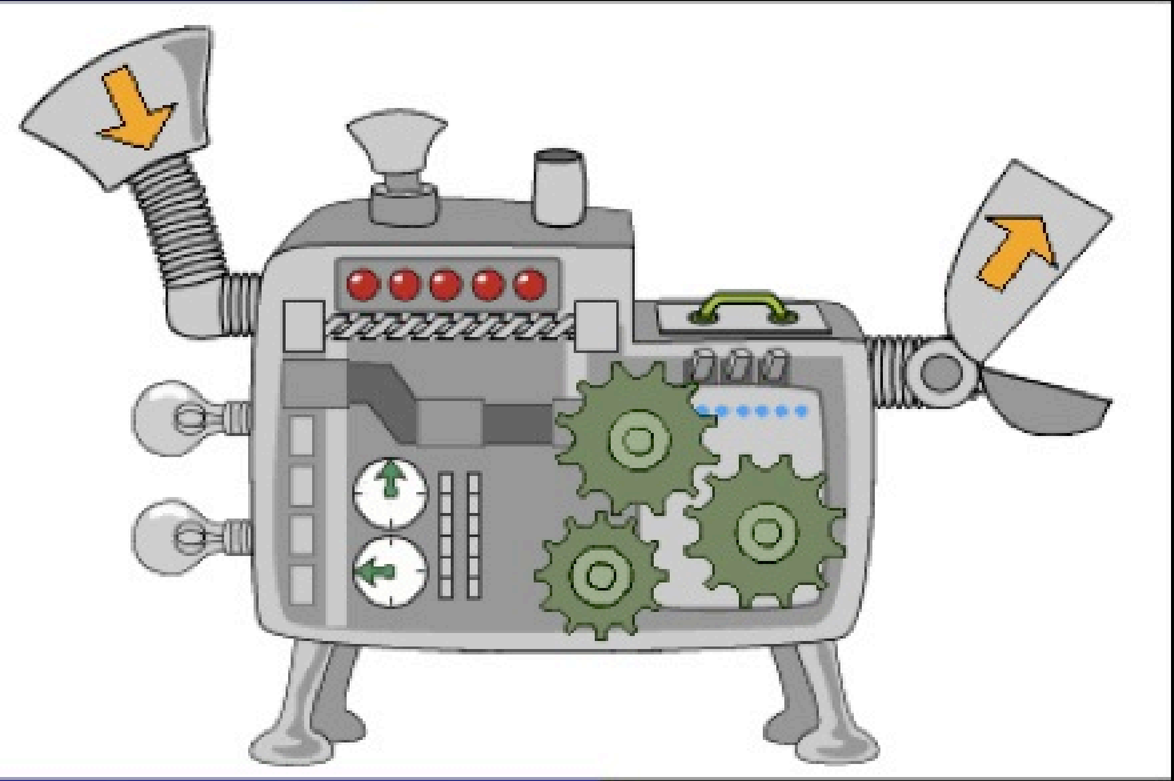
Allard, AVO, Parizot '07

GZK Horizon



Allard, AVO, Parizot '07

Modern Propagation Codes



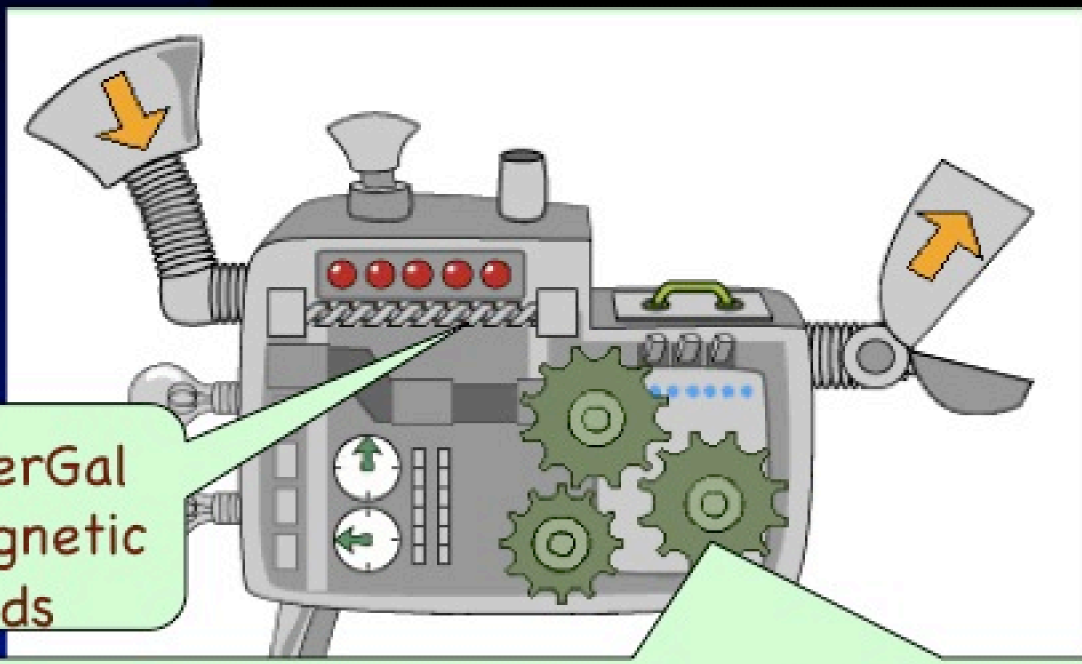
Public:

CRPropa
1.0 Armengaud et al '06
2.0 Kampert et al. '12
SimProp
Aloisio et al '12

Private:

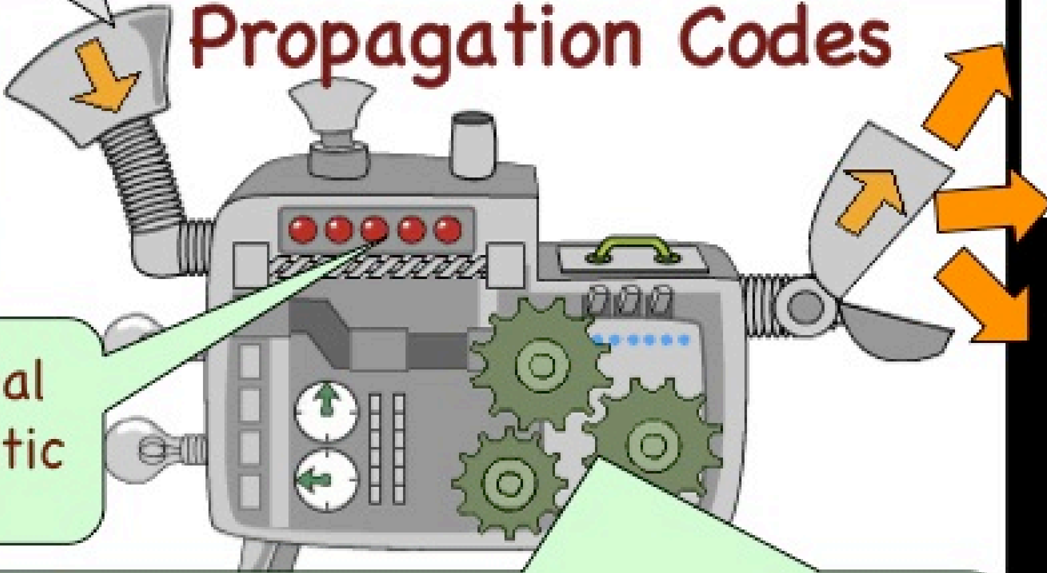
Allard et al '04
Taylor '07
Ahlers '10
others...

Modern Propagation Codes



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

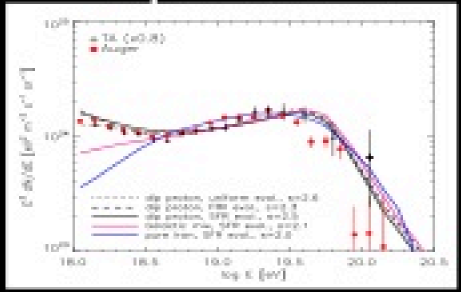
Propagation Codes



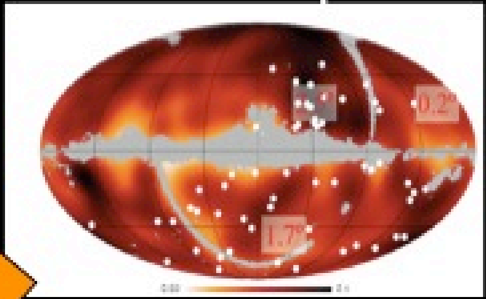
InterGal Magnetic Fields

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

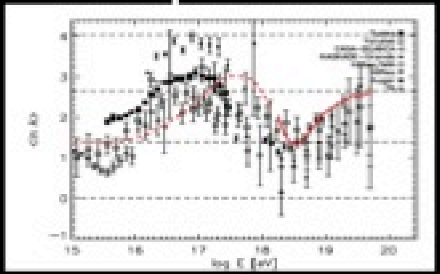
Spectrum



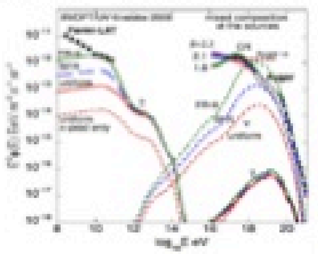
Anisotropies



Composition



Multi-messengers



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z=3 (E ~ EeV =10^{18} eV)

< 100 Mpc (E ~ 100 EeV)

At UHEs, how are they Observed?

What are the most energetic Astroparticles?

Ultra High Energy Cosmic Rays (UHECRs)

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At UHEs, how are they Observed?

Large detector Arrays (Auger and TA)

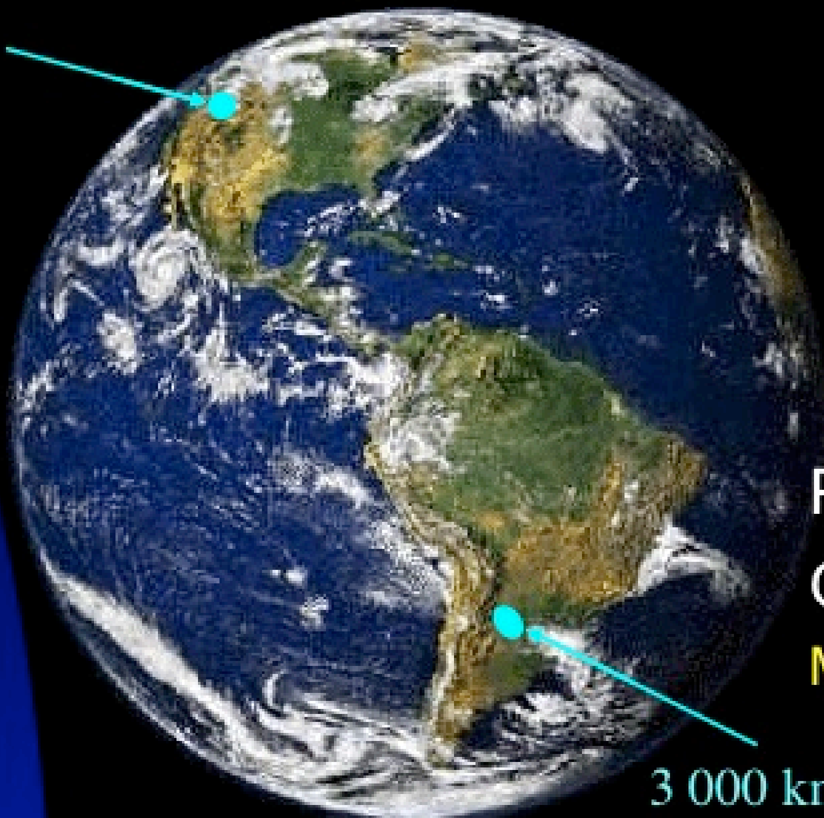
Ultrahigh Energy Cosmic Rays
Leading Observatories

Telescope Array

Utah, USA

680 km^2 array

3 fluorescence sites



Pierre Auger Observatory

Mendoza, Argentina

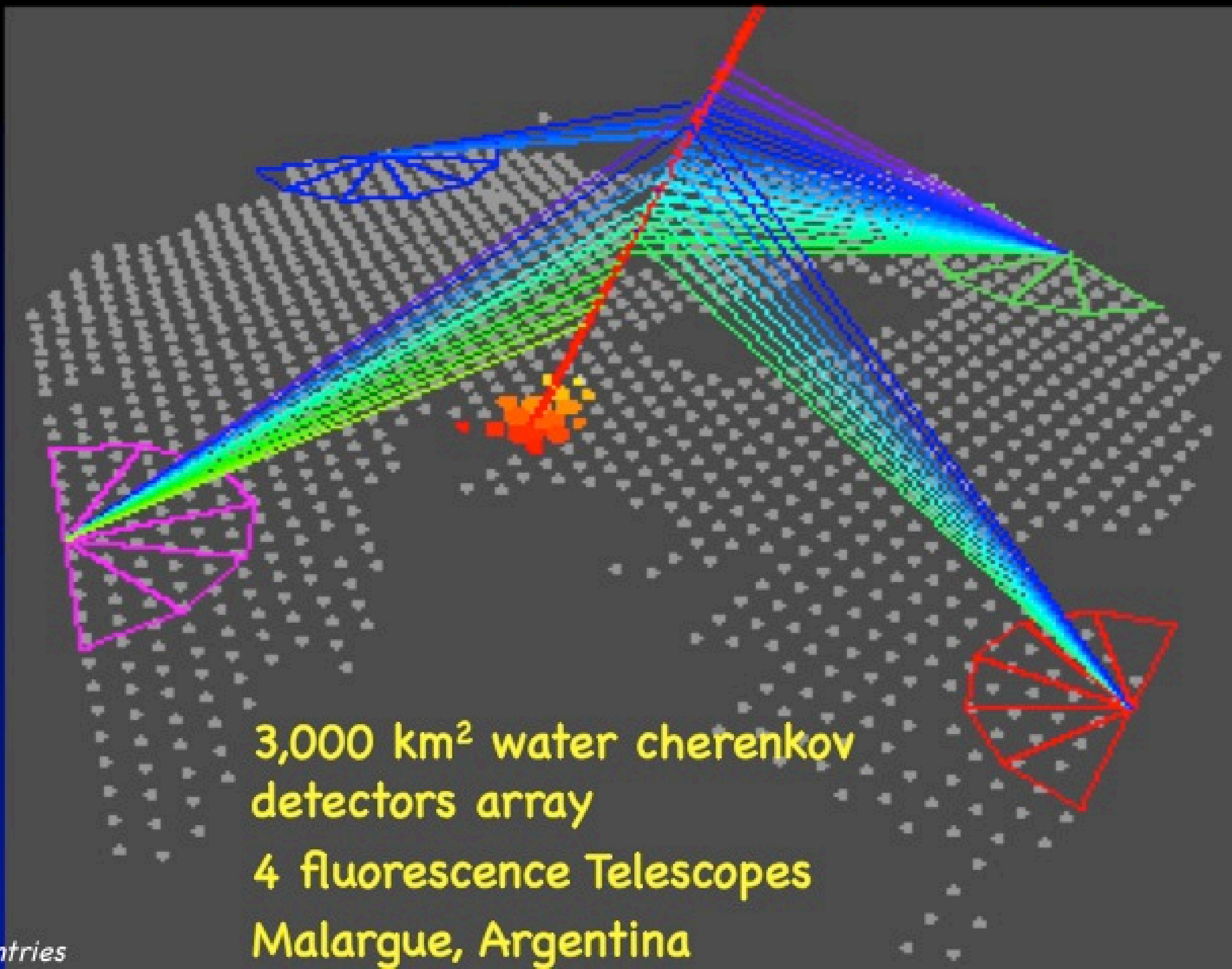
3 000 km^2 array

4 fluorescence sites

The Pierre Auger Observatory

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

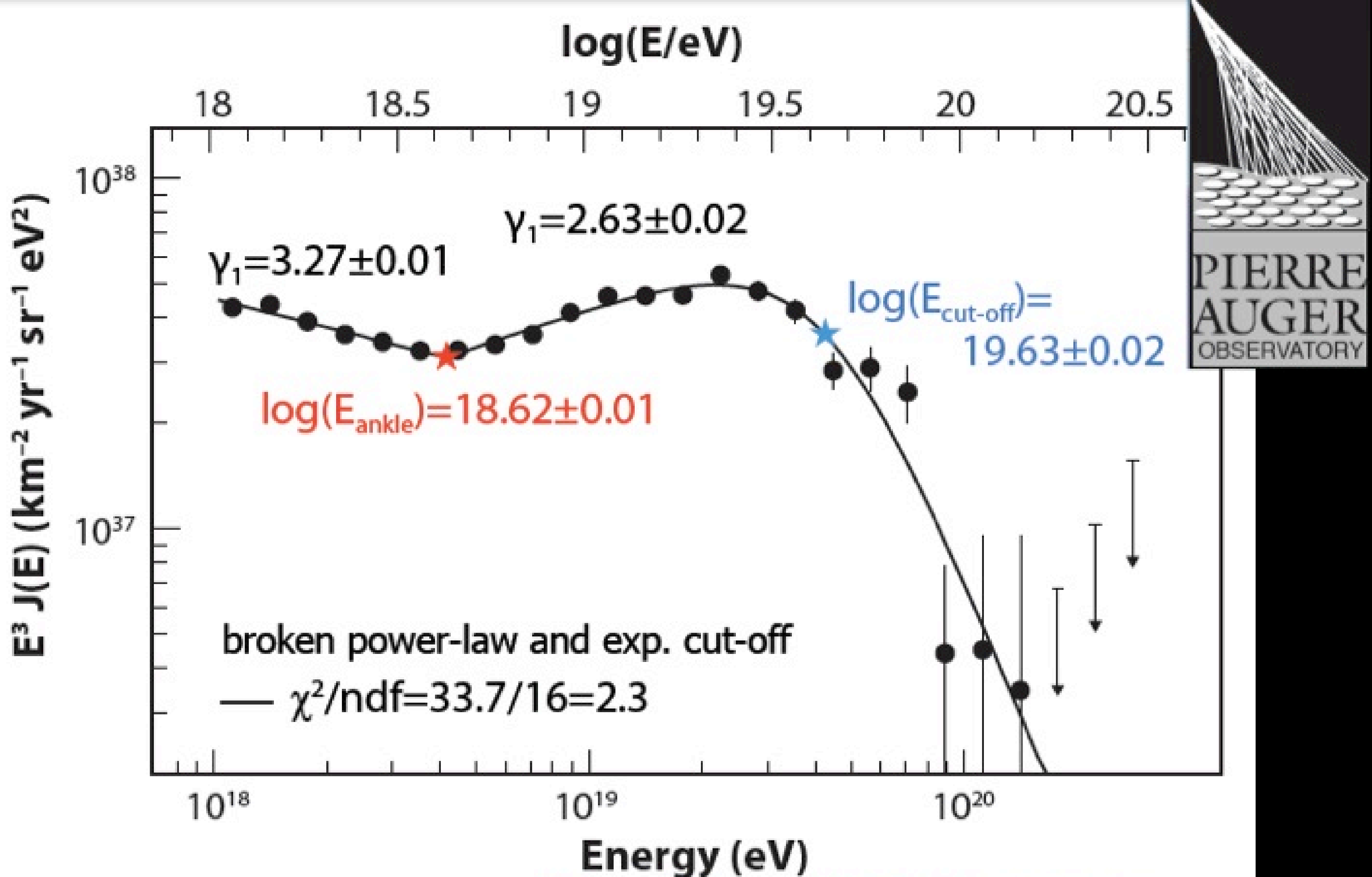
*Associate Countries



surface detector


array of tanks

4 times 6 telescopes overlooking the site



Systematic uncertainty 7% (15%) at 10 EeV (100 EeV)

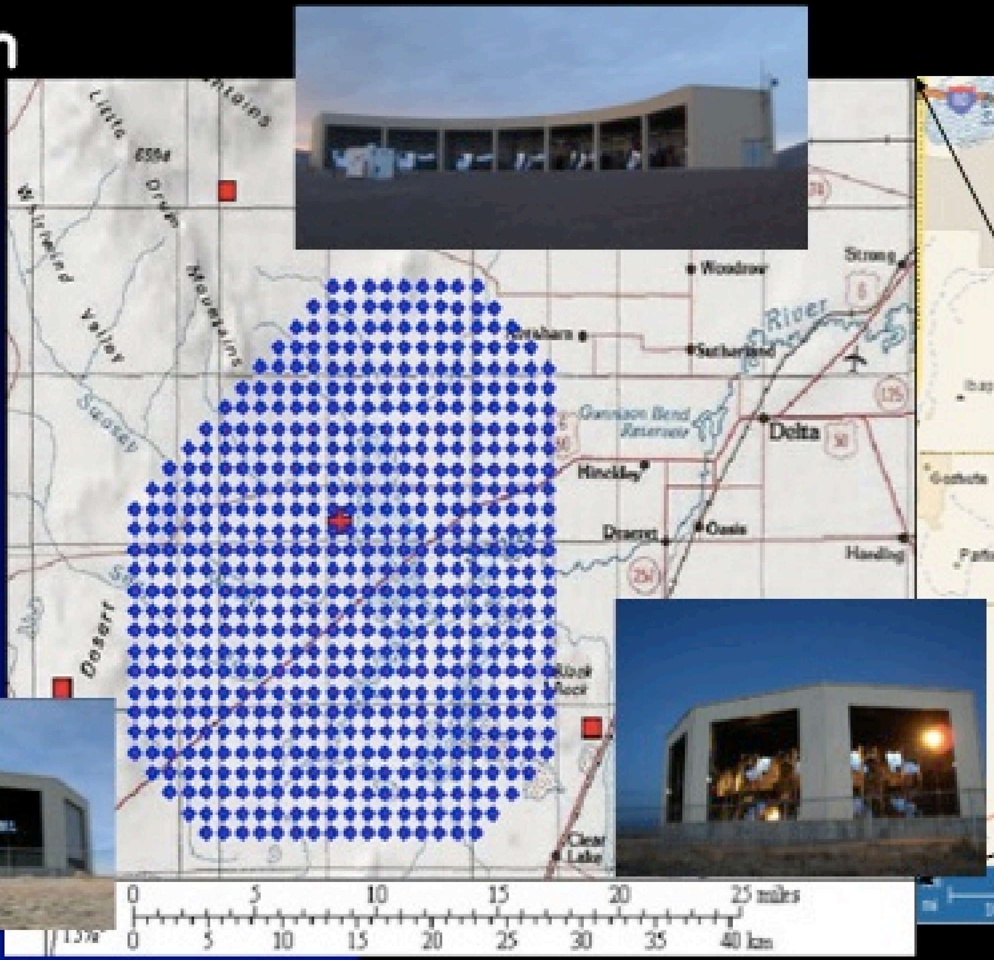
Total uncertainty of E-scale: 22% (dominated by Fl.-yield. 14%)

Exposure = 20905 km² sr yr

Telescope Array

Area: 680 km^2

Belgium
Japan
Korea
Russia
USA

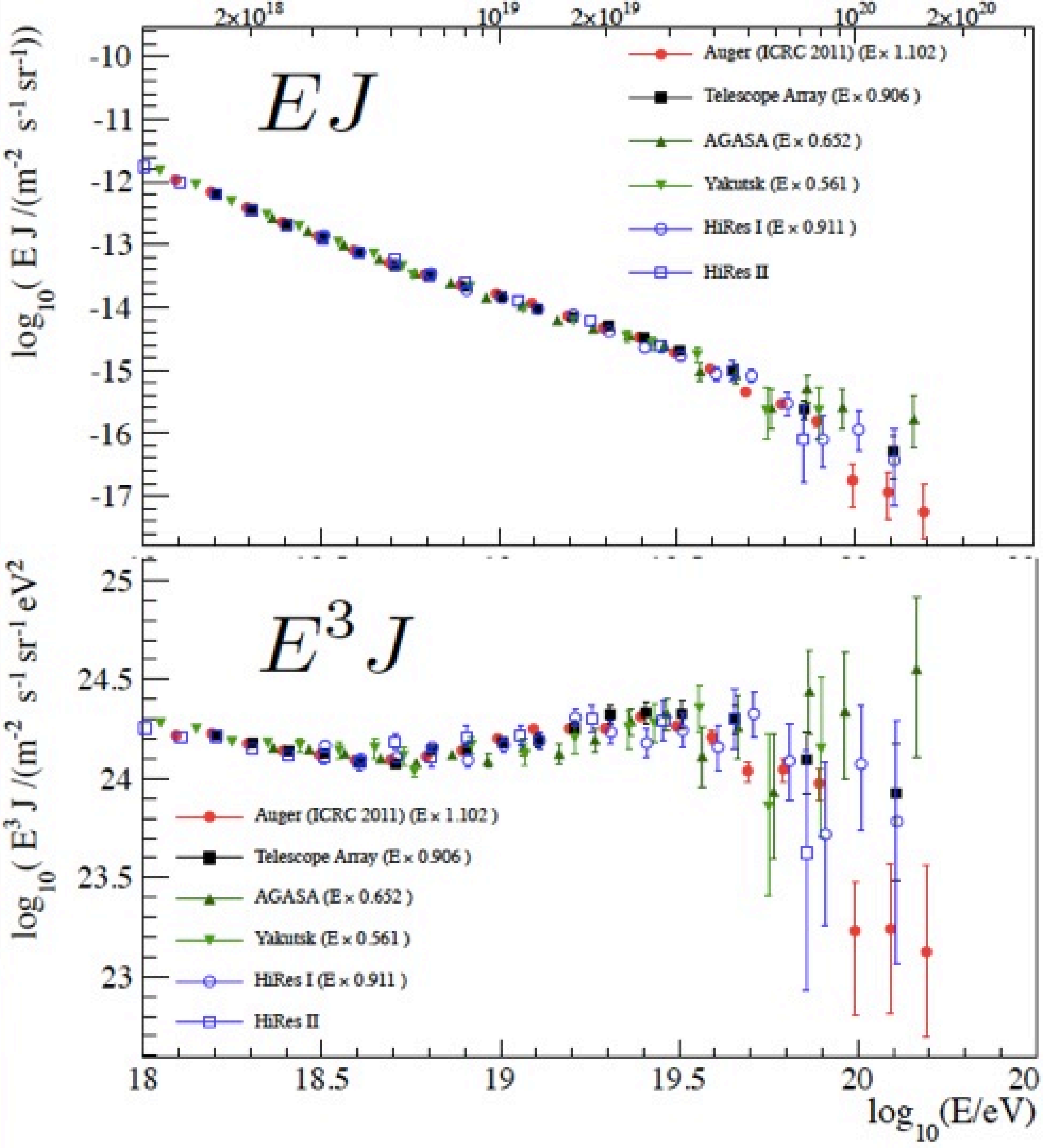


3 FD stations overlooking an array of
507 scintillator surface detectors (SD)
complete and operational as of ~1/2008.

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

2012 CERN Working Group

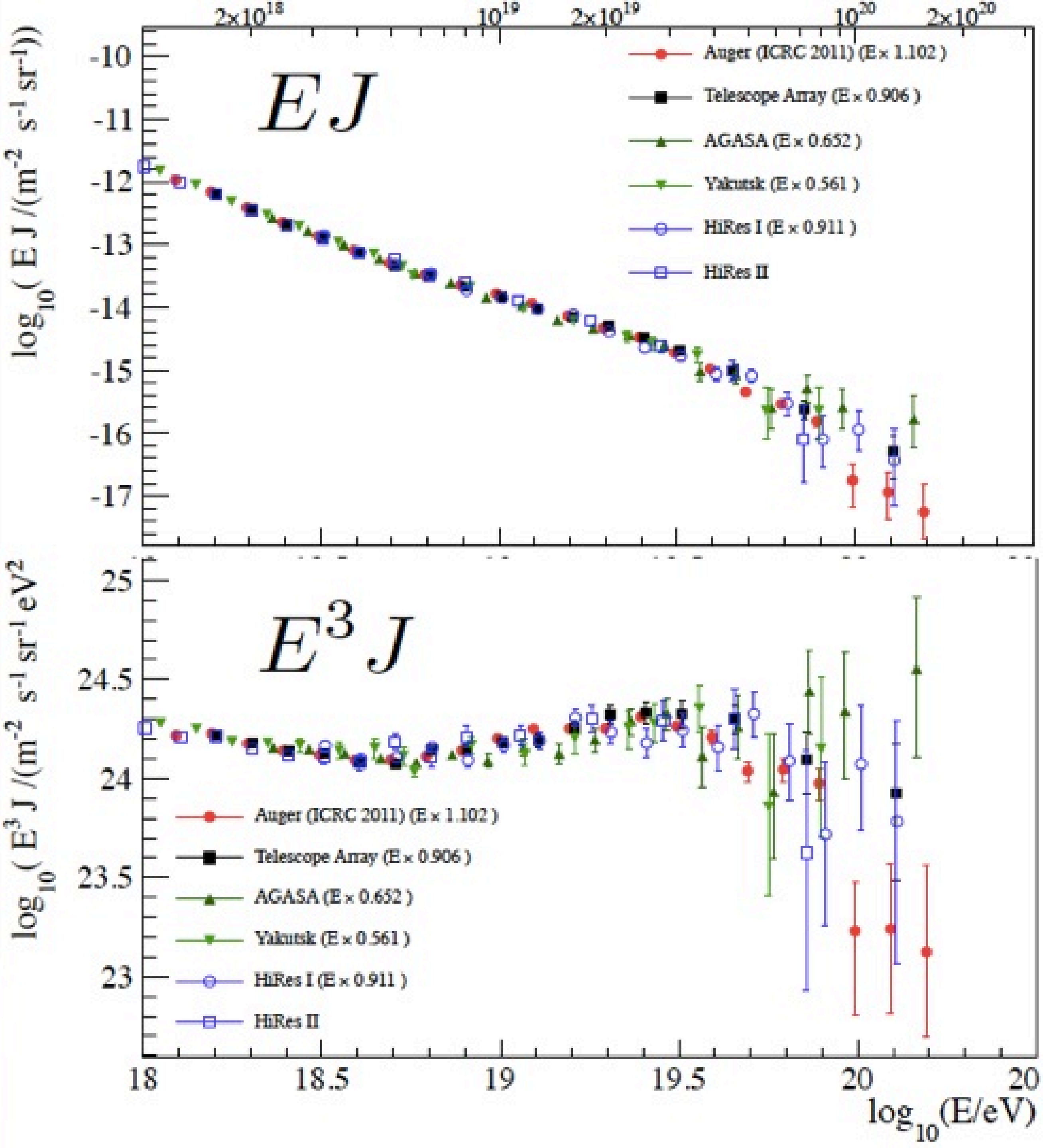
Unified Spectrum



2012 CERN Working Group

Unified Spectrum

20% energy shifts, but **absolute energy scale MATTERS!**



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< 100 Mpc ($E \sim 100$ EeV)

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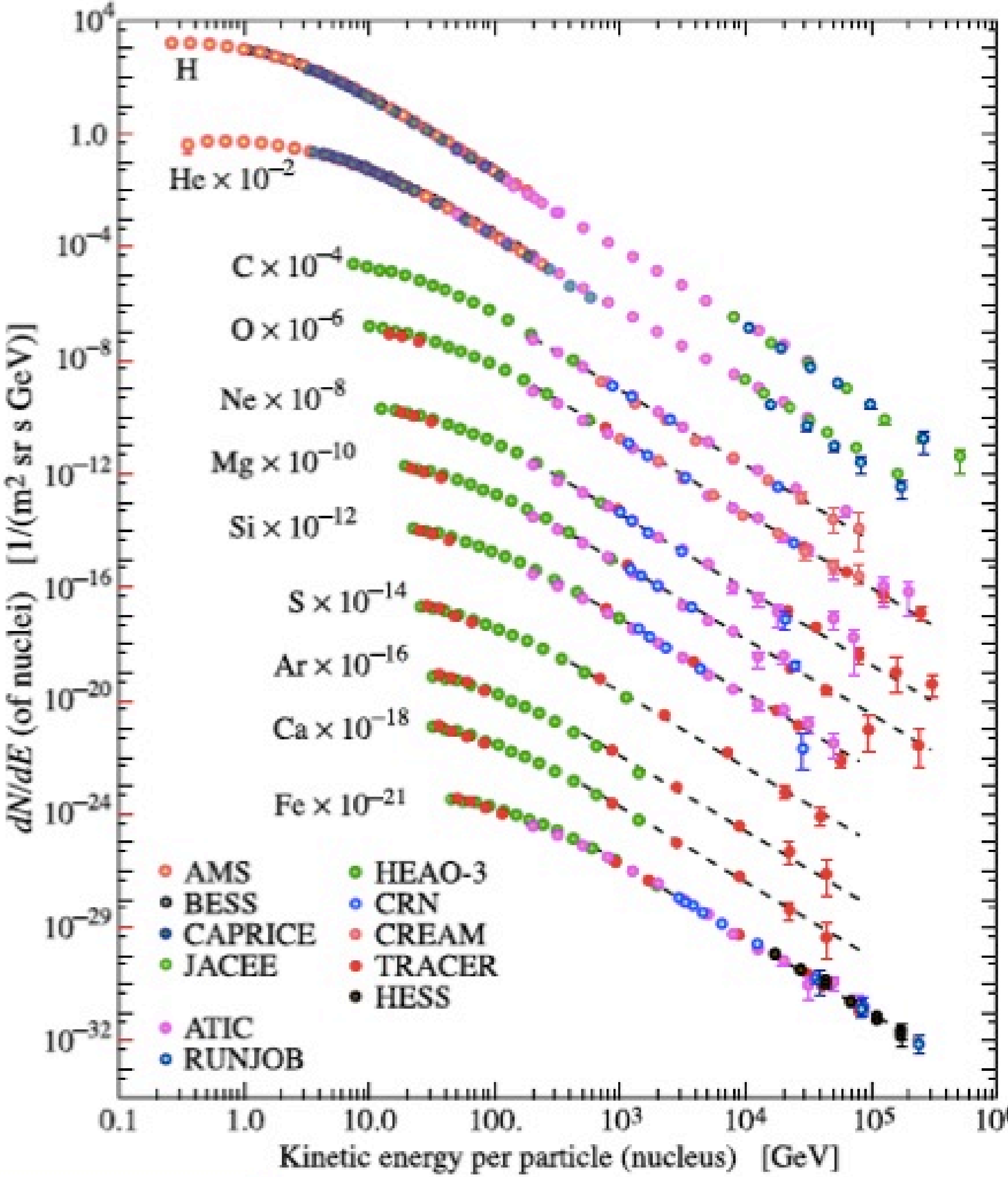
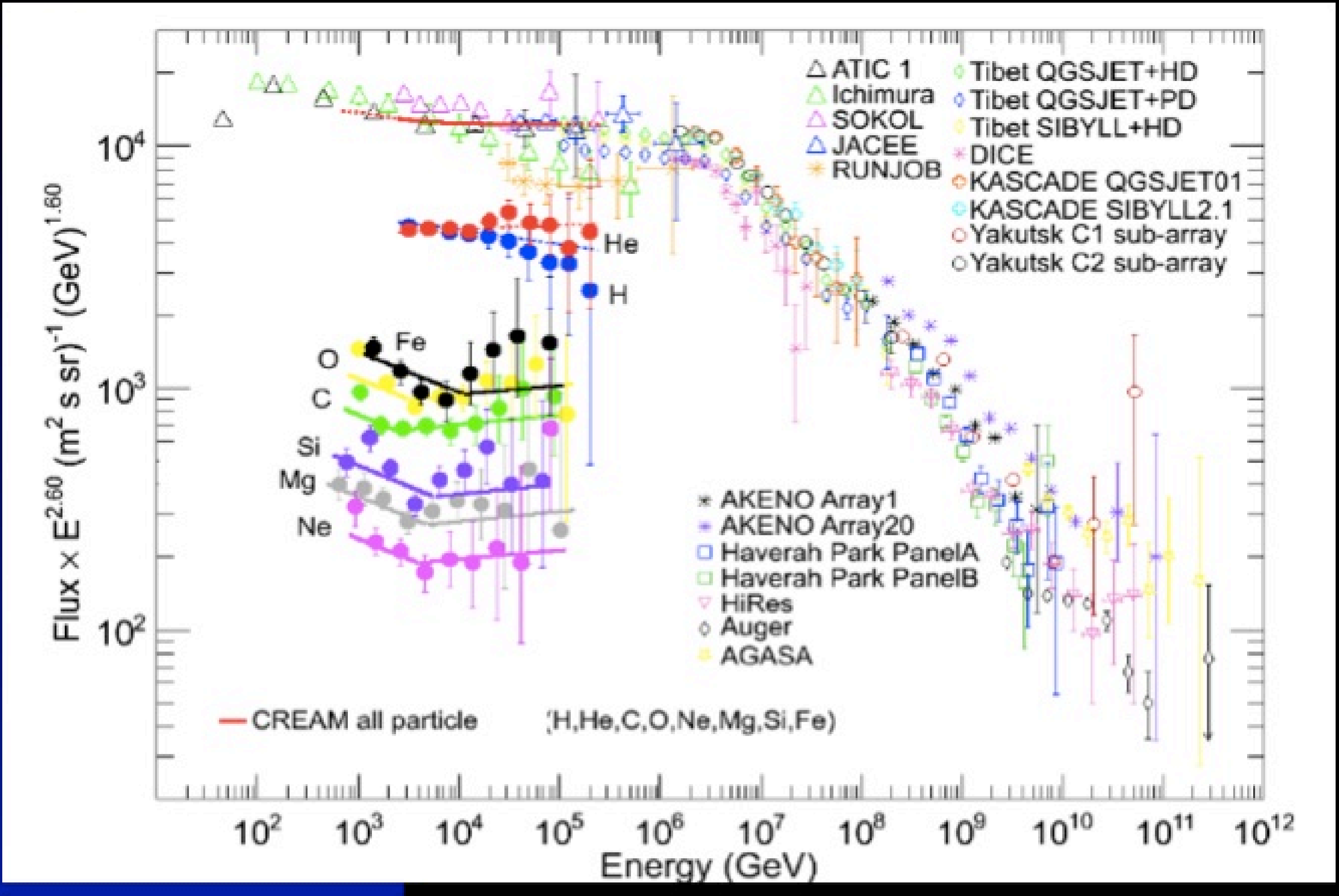
Large detector Arrays (Auger and TA)

What are UHECRs? protons or nuclei or both.

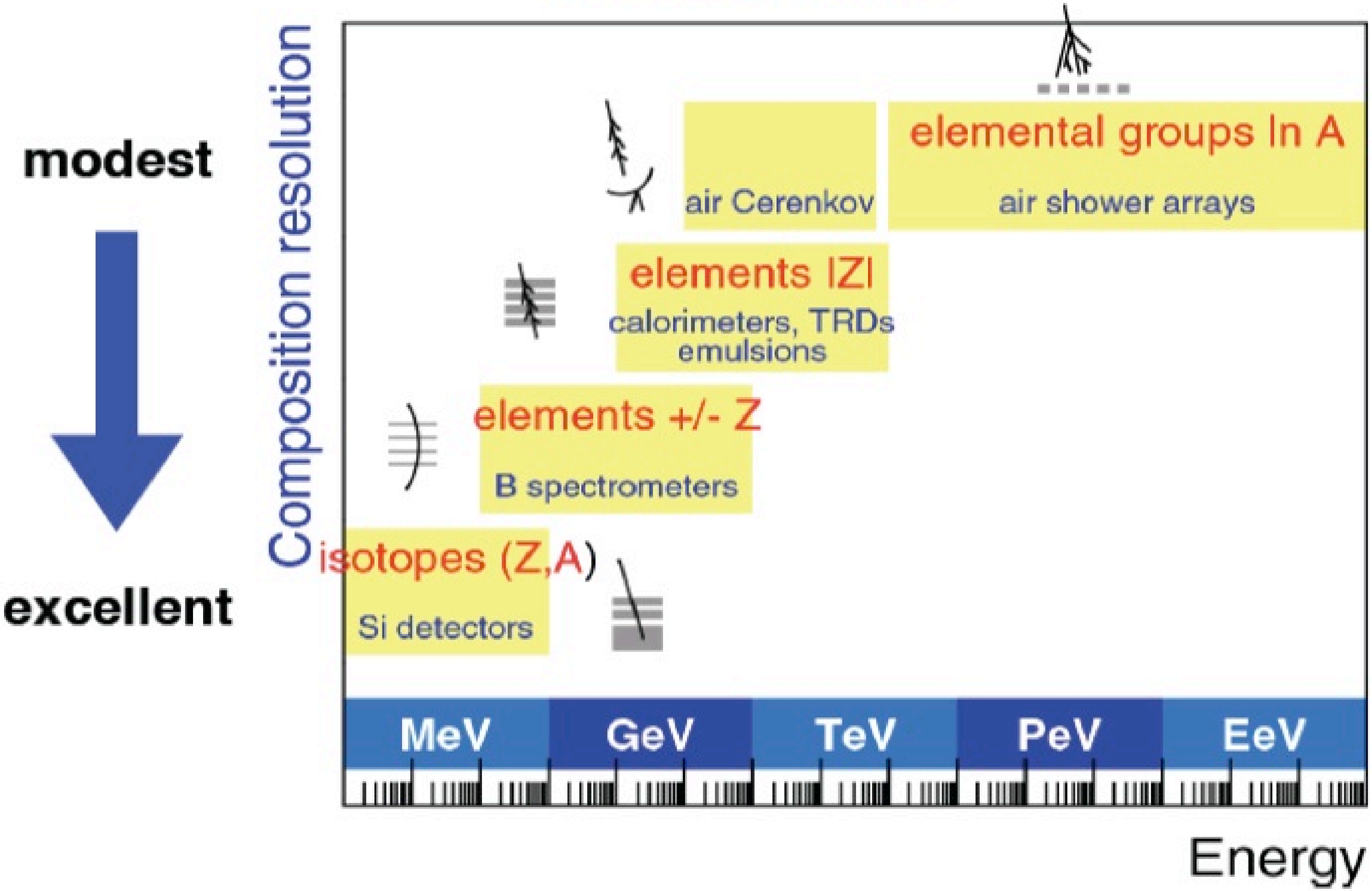


H
He × 10^−2
C × 10^−4
O × 10^−6
Ne × 10^−8
Mg × 10^−10
Si × 10^−12
S × 10^−14
Ar × 10^−16
Ca × 10^−18
Fe × 10^−21
AMS
BESS
CAPRICE
JACEE
HEAO-3
CRN
CREAM
TRACER
HESS
ATIC
RUNJOB
dN/dE (of nuclei) [1/(m² sr s GeV)]
Kinetic energy per particle (nucleus) [GeV]
10^4
1.0
10^−4
10^−8
10^−12
10^−16
10^−20
10^−24
10^−29
10^−32
0.1
1.0
10.0
100.
10^3
10^4
10^5
10^6

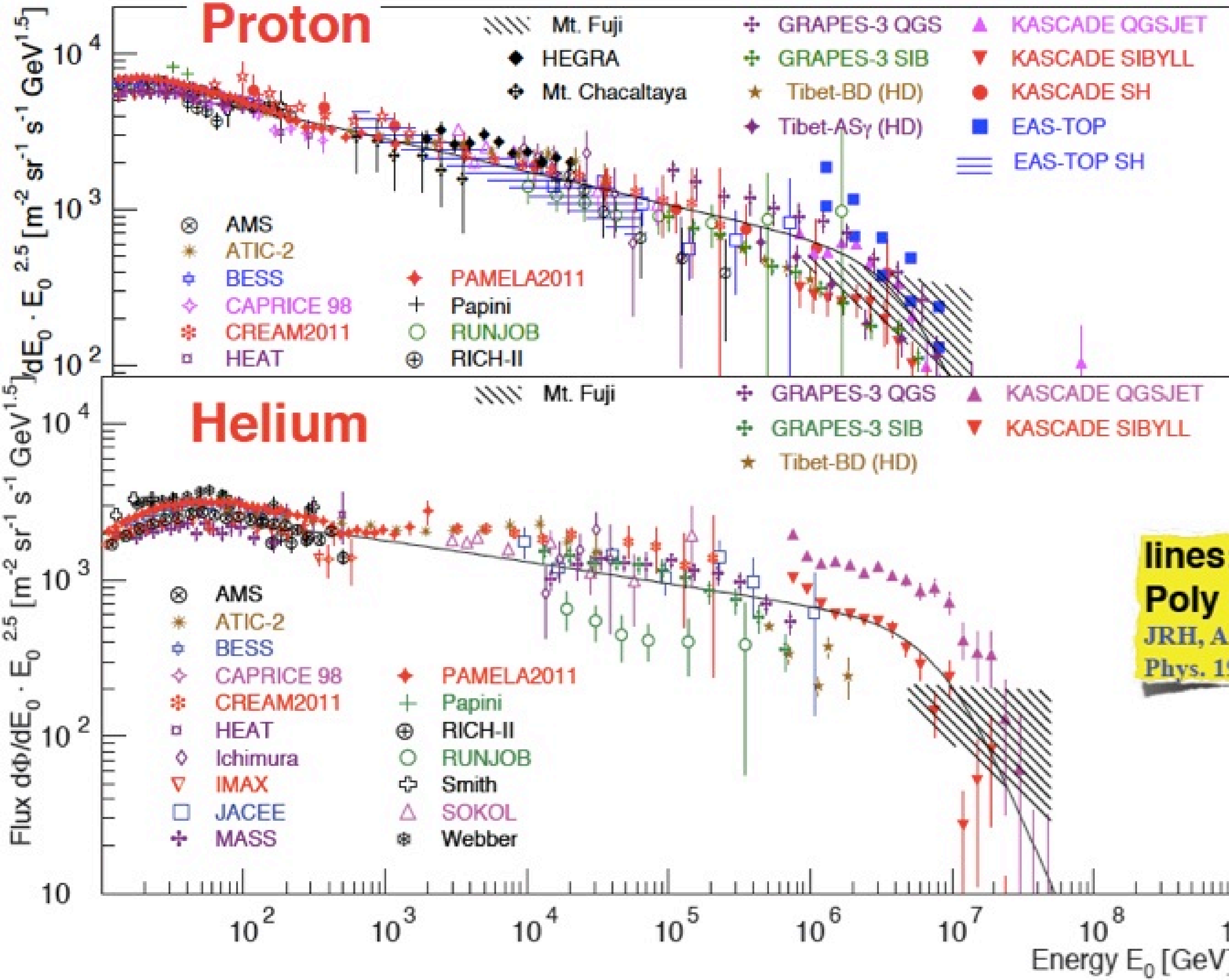
Just Below the Knee...



Resolution for composition measurements

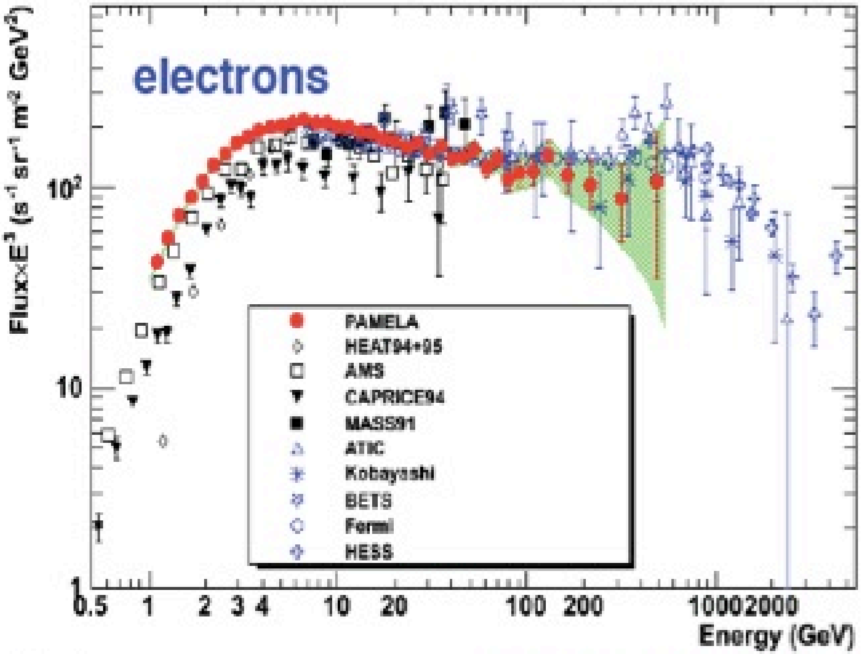


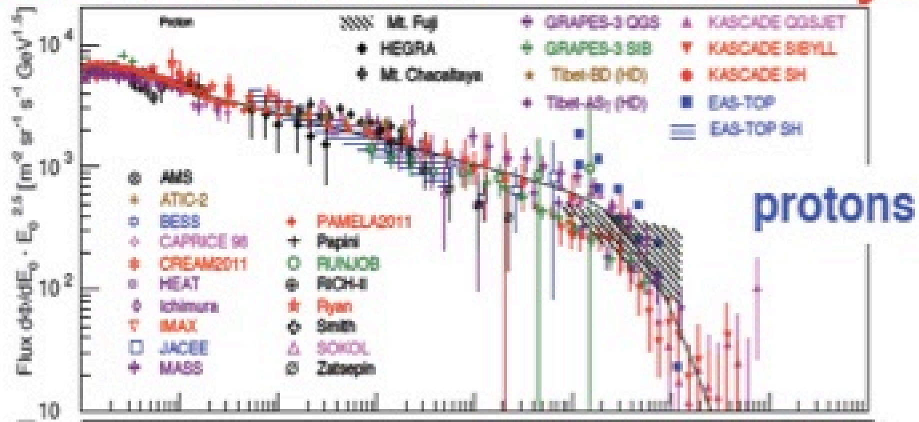
JRH, Adv. Space Res. 41 (2008) 442

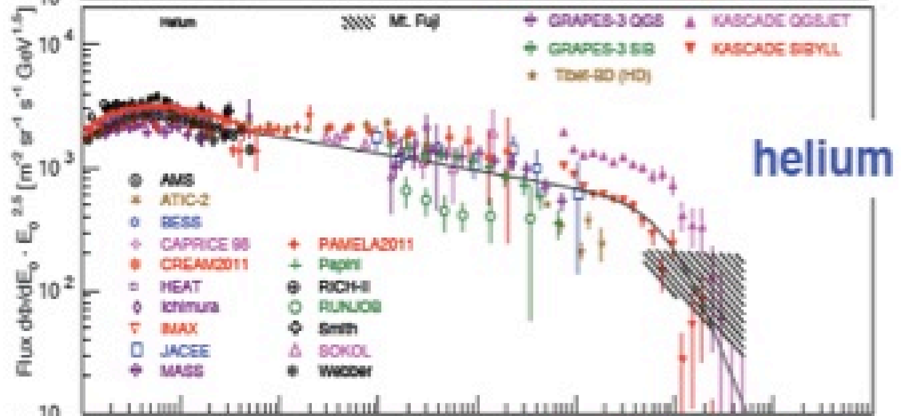


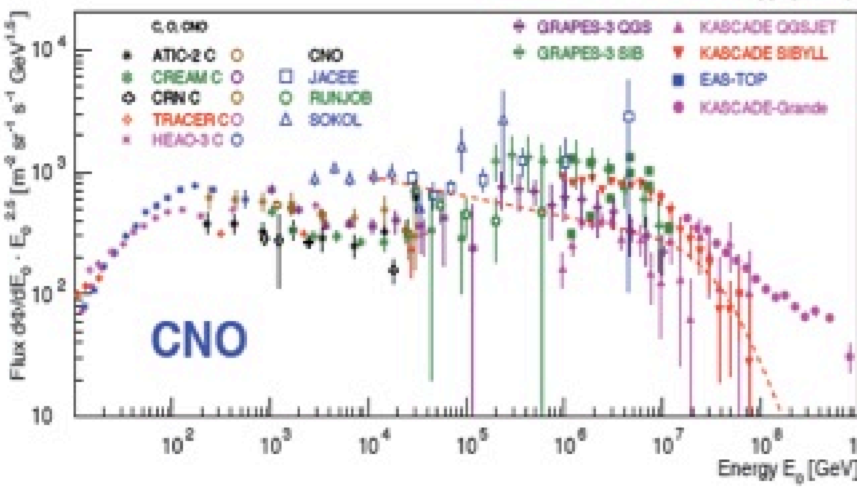
lines:
Poly Gona
JRH, Astropart
Phys. 19 (2003)

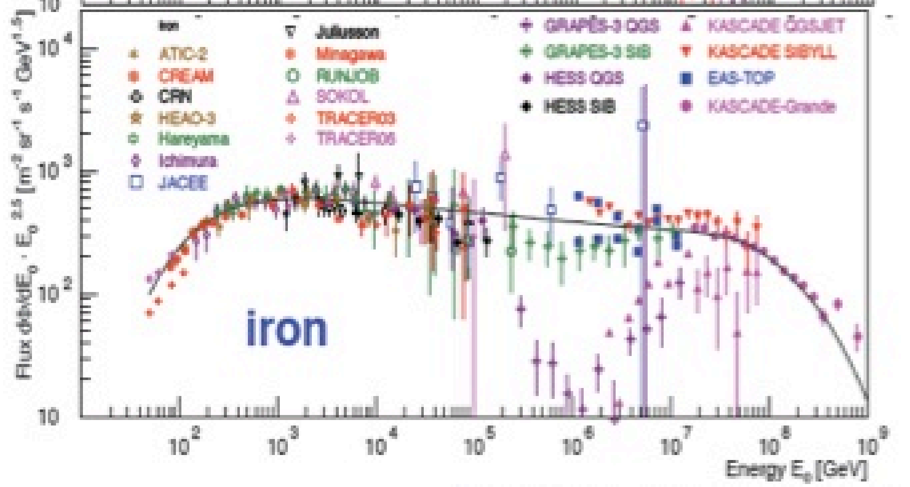
The Elemental Composition of Galactic Cosmic Rays



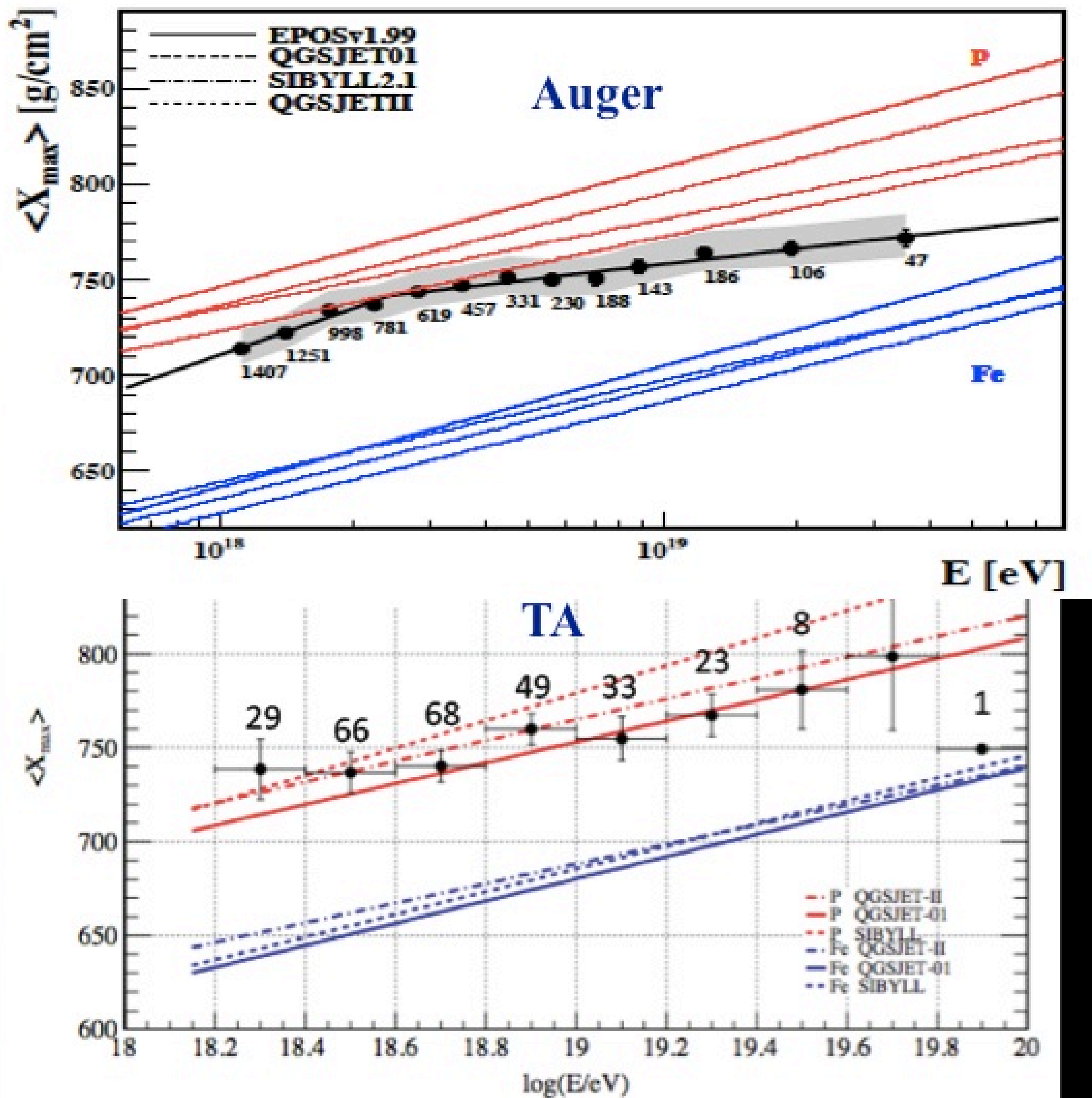






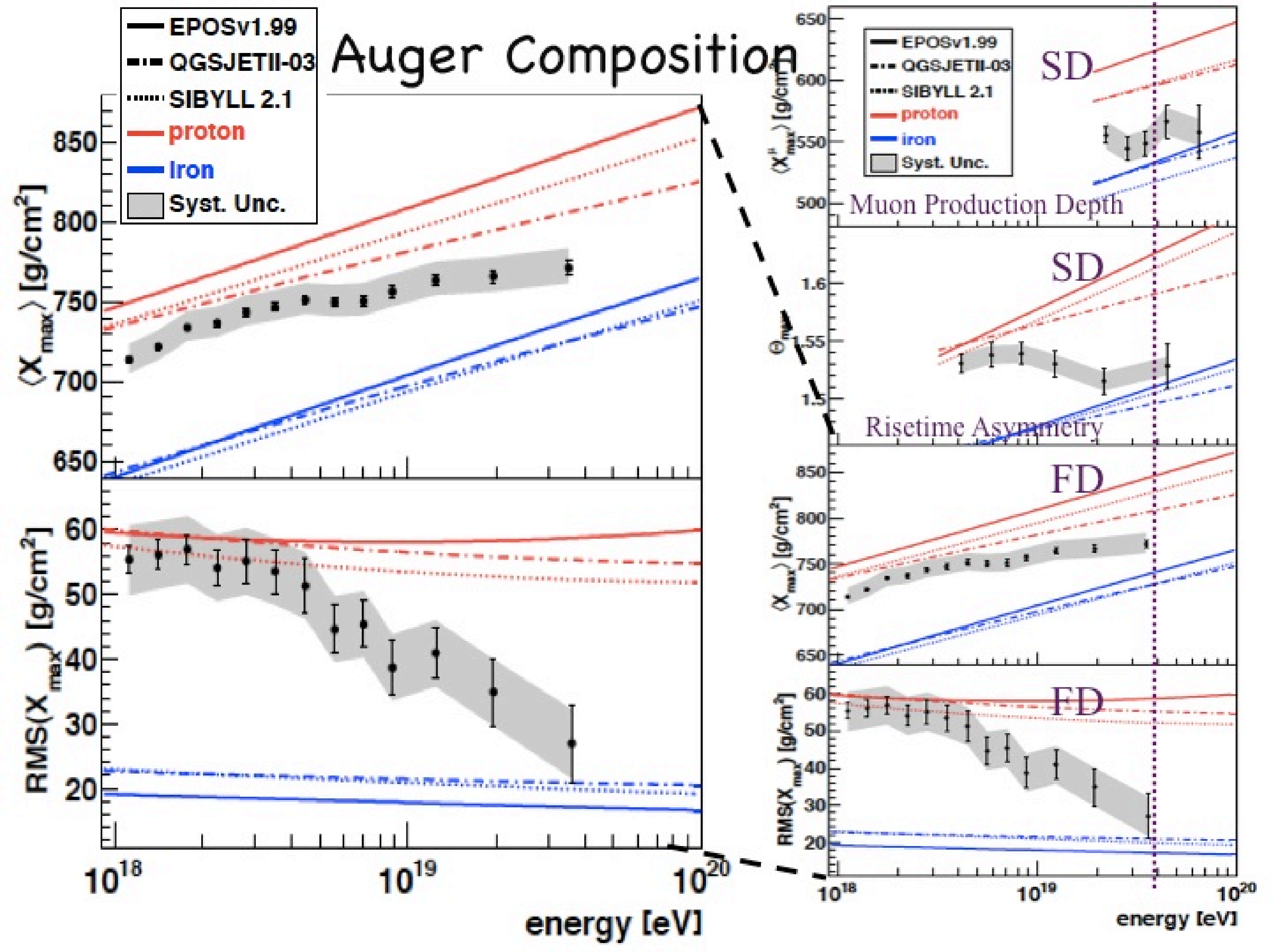


Jörg R. Hörandel
Radboud University Nijmegen



Auger
EPOSv1.99
QGSJET01
SIBYLL2.1
QGSJETII
p
Fe
1407
1251
998
781
619
457
331
230
188
143
186
106
47
E [eV]
TA
29
66
68
49
33
23
8
1
P QGSJET-II
P QGSJET-01
P SIBYLL
Fe QGSJET-II
Fe QGSJET-01
Fe SIBYLL
log(E/eV)

Auger Composition



What is the hardest Astroparticle to detect?

What is the hardest Astroparticle to detect?

Dark Matter?

What is the hardest Astroparticle to detect?

Dark Matter?

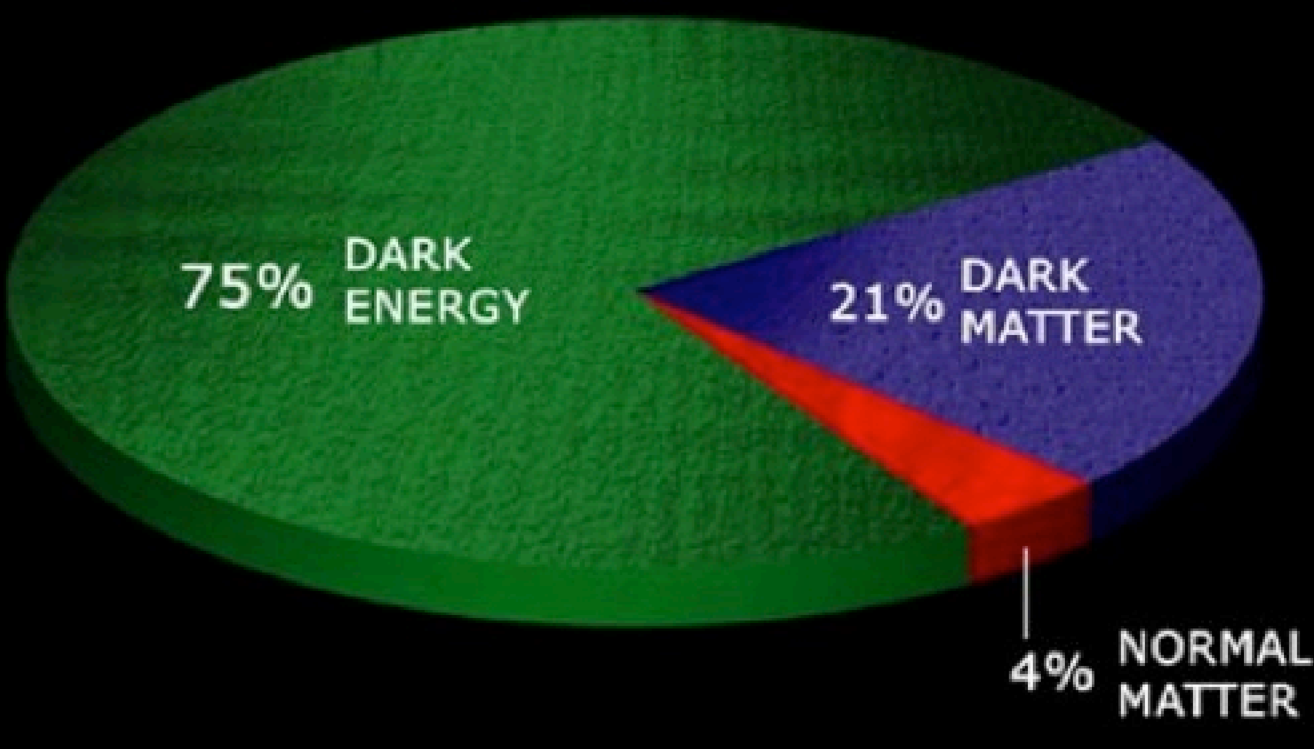
How abundant is it?

What is the hardest Astroparticle to detect?

Dark Matter?

How abundant is it?

23% of the contents of the Universe



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How are we trying to observe it?

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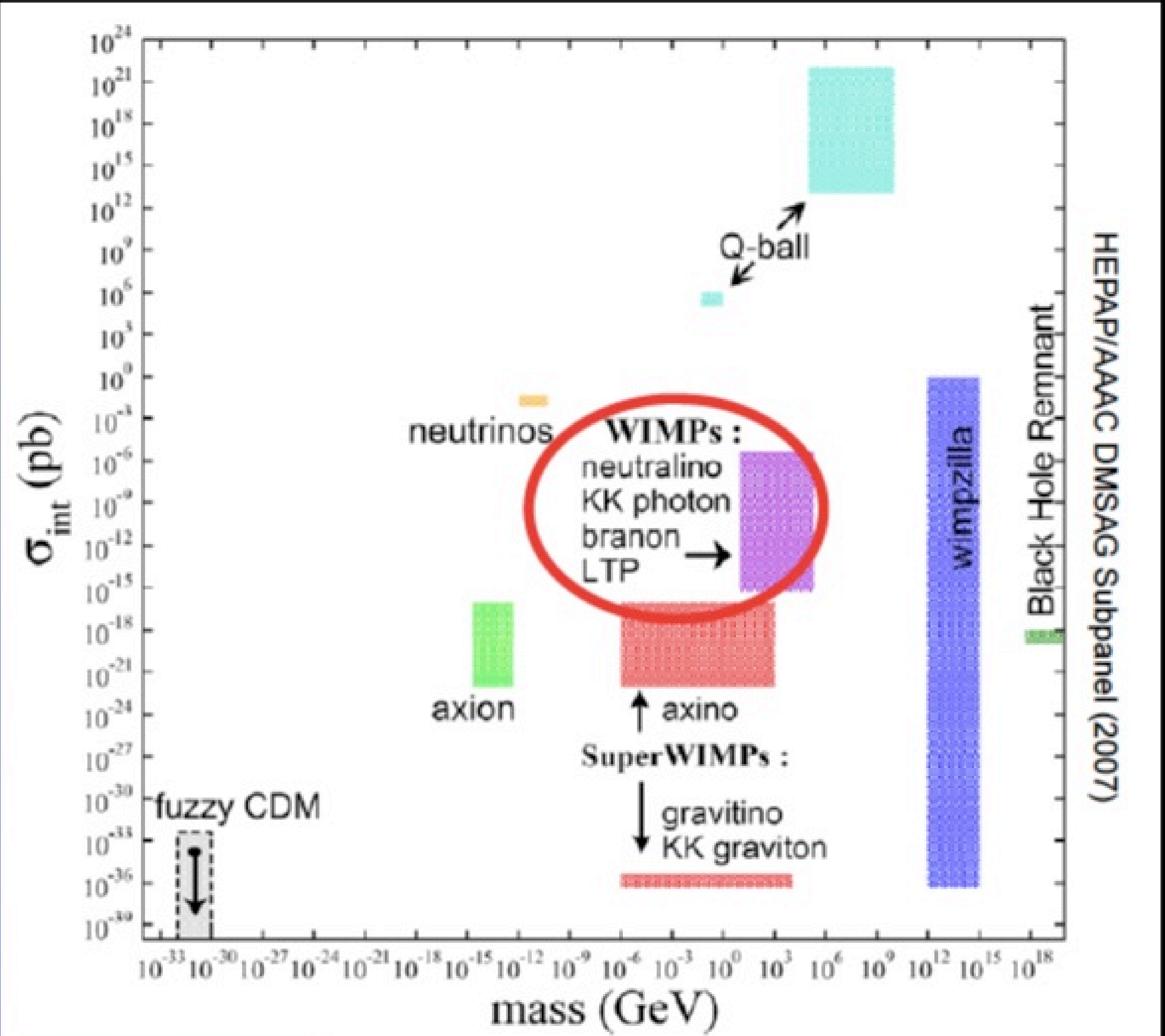
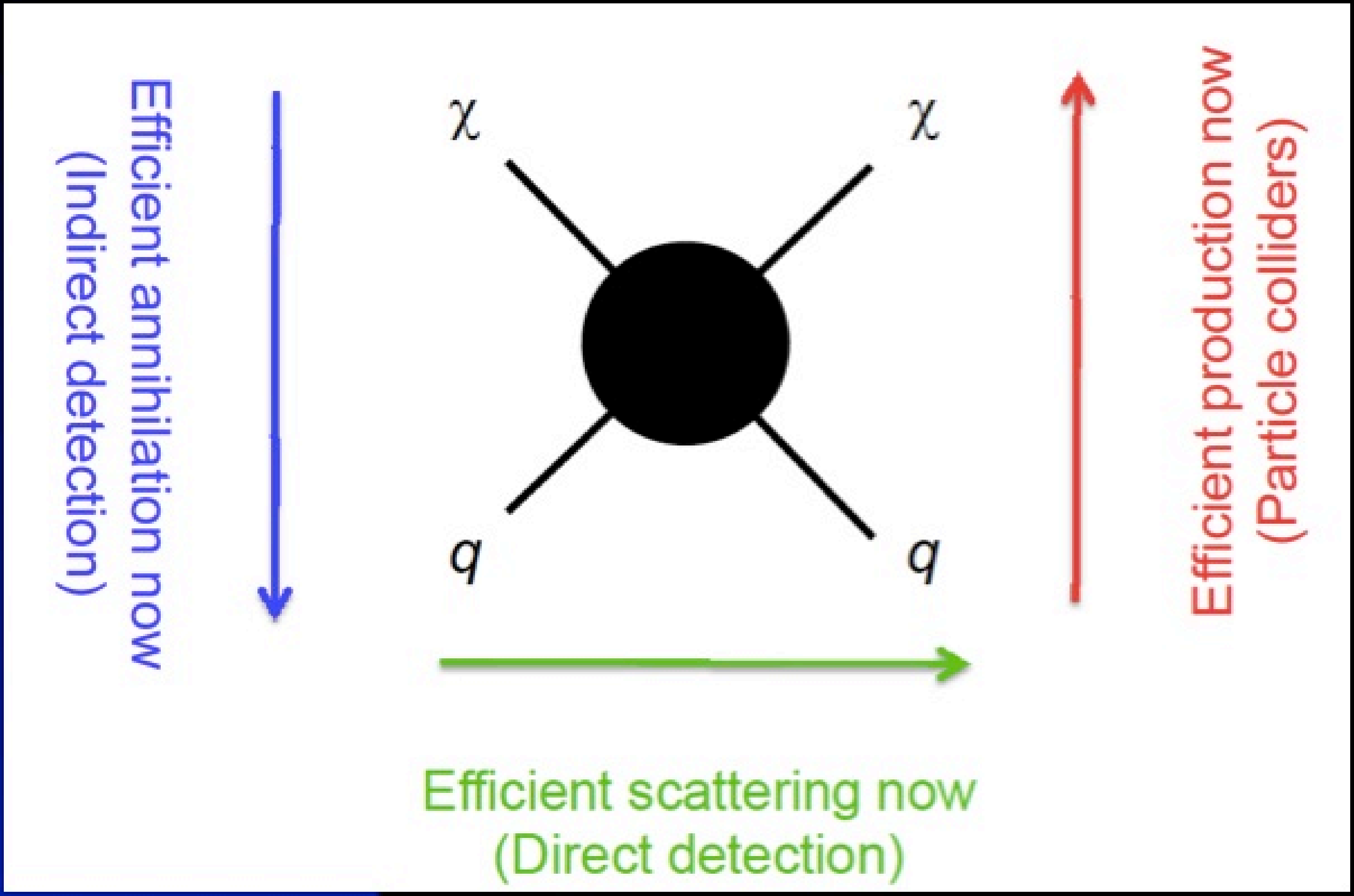
Direct Detection - underground detectors

Indirect Detection

Accelerator Searches



Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
wimpzilla
Black Hole Remnant
HEPAP/AAAC DMSAG Subpanel (2007)
σ_int (pb)
mass (GeV)


Efficient annihilation now
(Indirect detection)
χ
χ
q
q
Efficient production now
(Particle colliders)
Efficient scattering now
(Direct detection)

What is the hardest Astroparticle to detect?

Dark Matter?

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How are we trying to observe it?

Direct Detection - underground detectors

Indirect Detection

Accelerator Searches

What is used in Indirect Searches?

What is the hardest Astroparticle to detect?

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How abundant is it?

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How are we trying to observe them?

Direct Detection - underground detectors

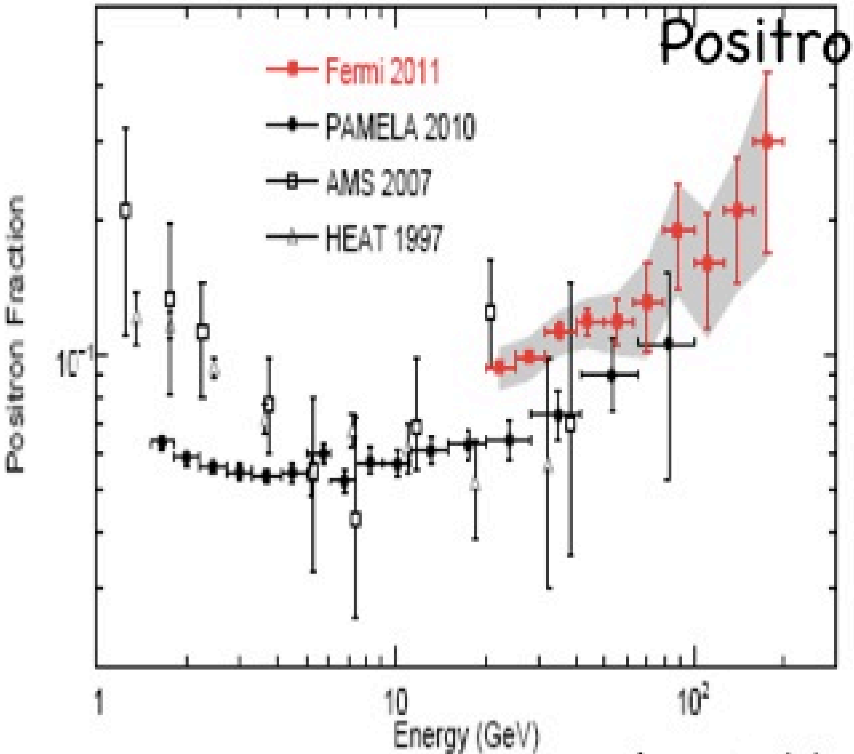
Indirect Detection

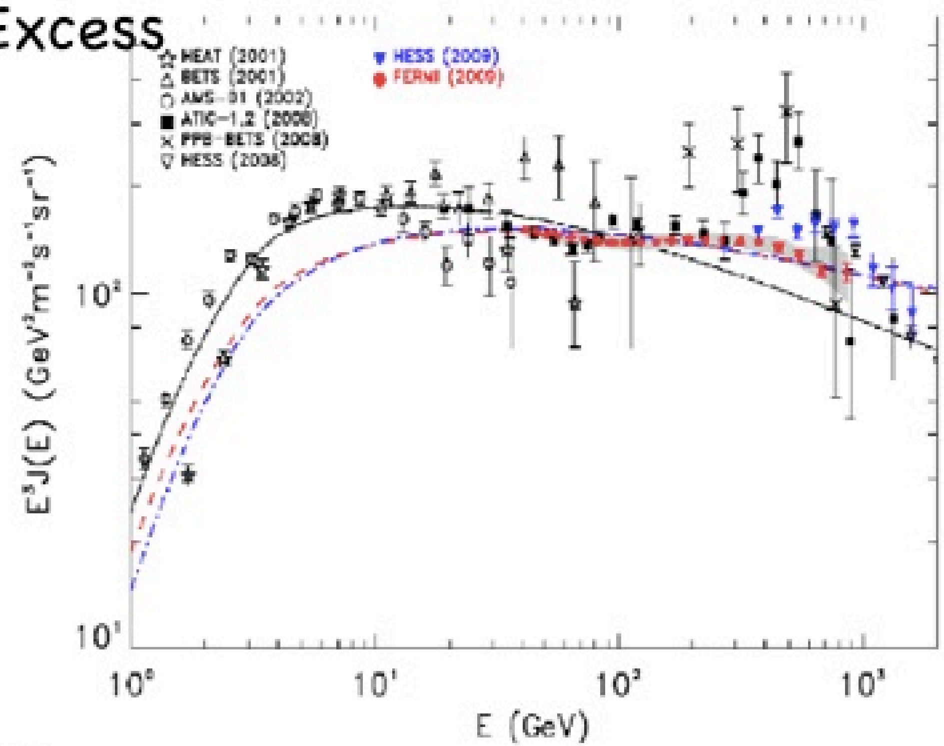
Accelerator Searches

What is used in Indirect Searches?

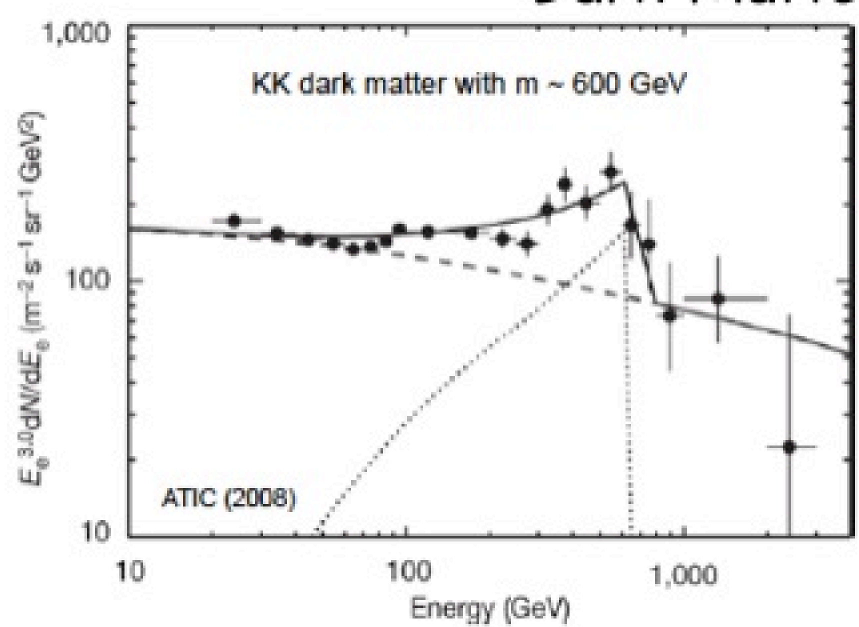
gamma-rays (Fermi Line?), neutrinos, positrons, anti-nuclei (AMS)...

Positron Excess

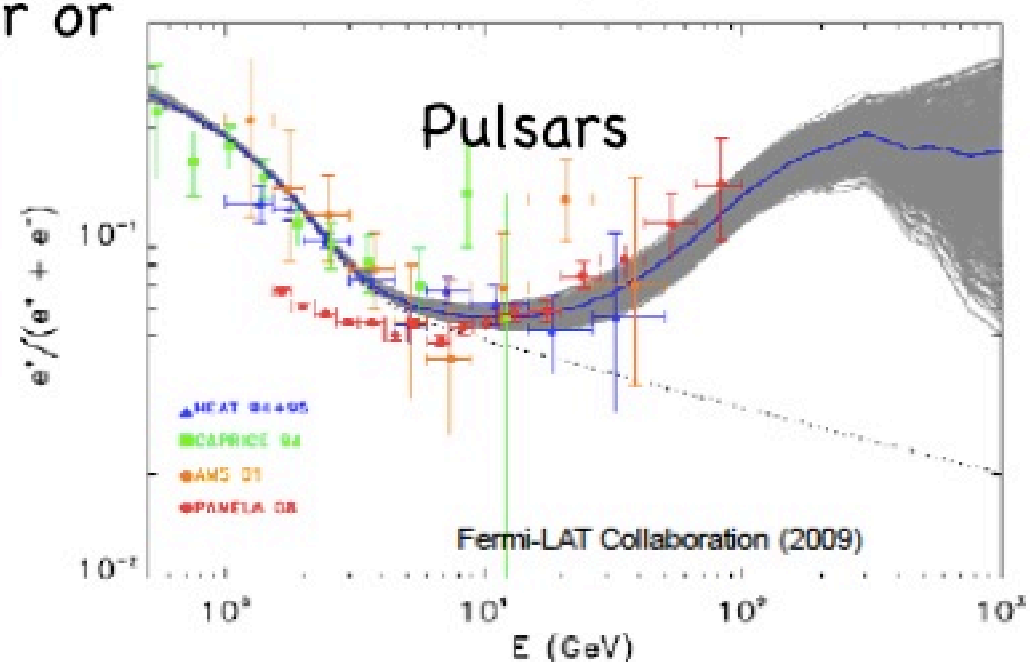


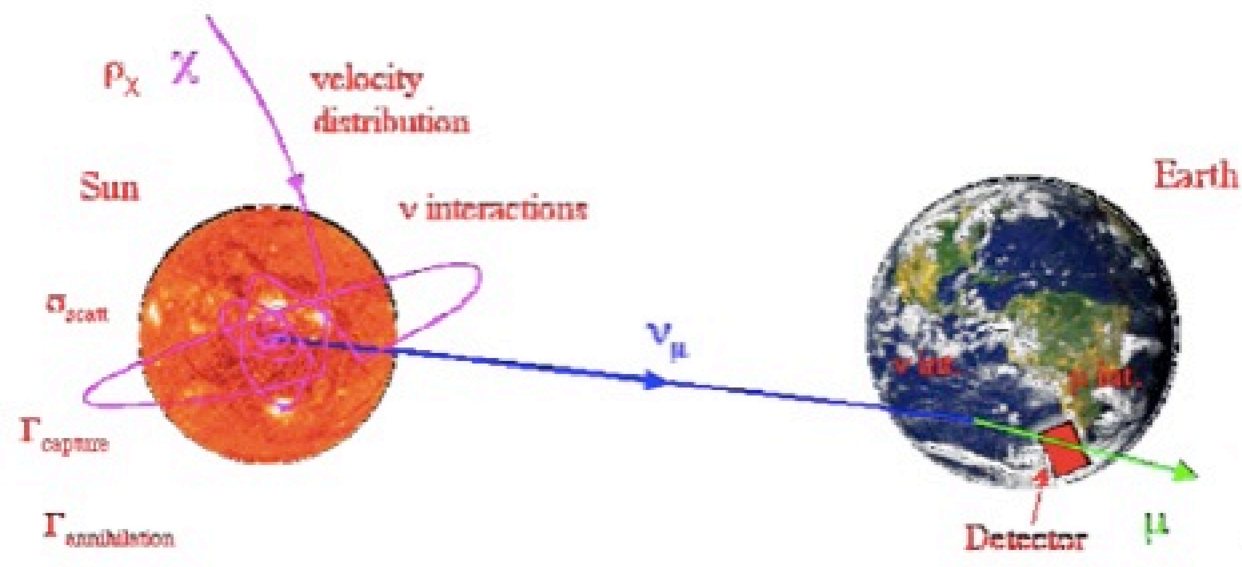


Dark Matter or

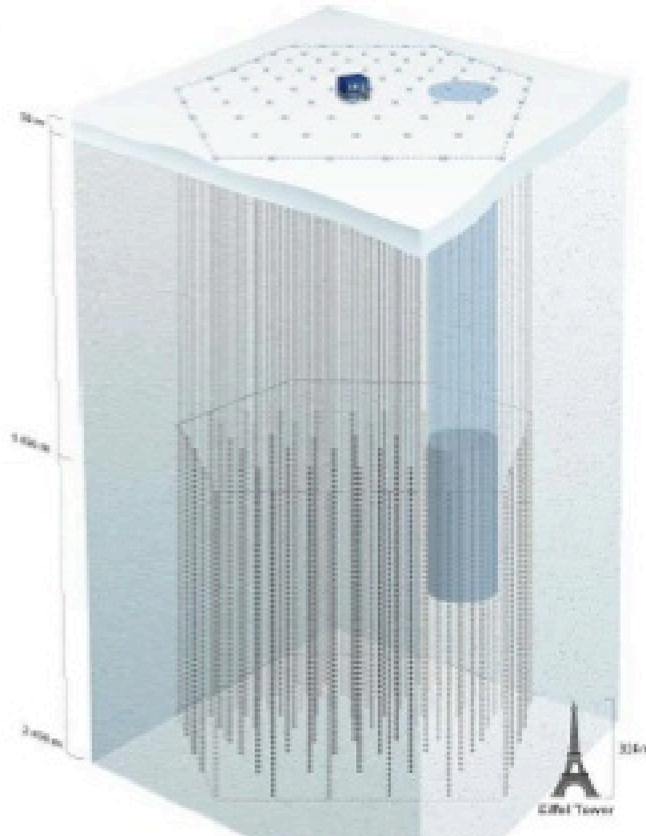


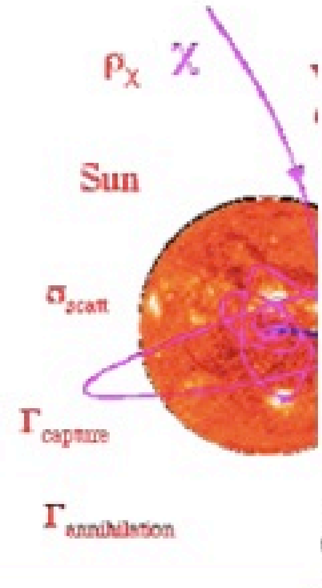
Pulsars

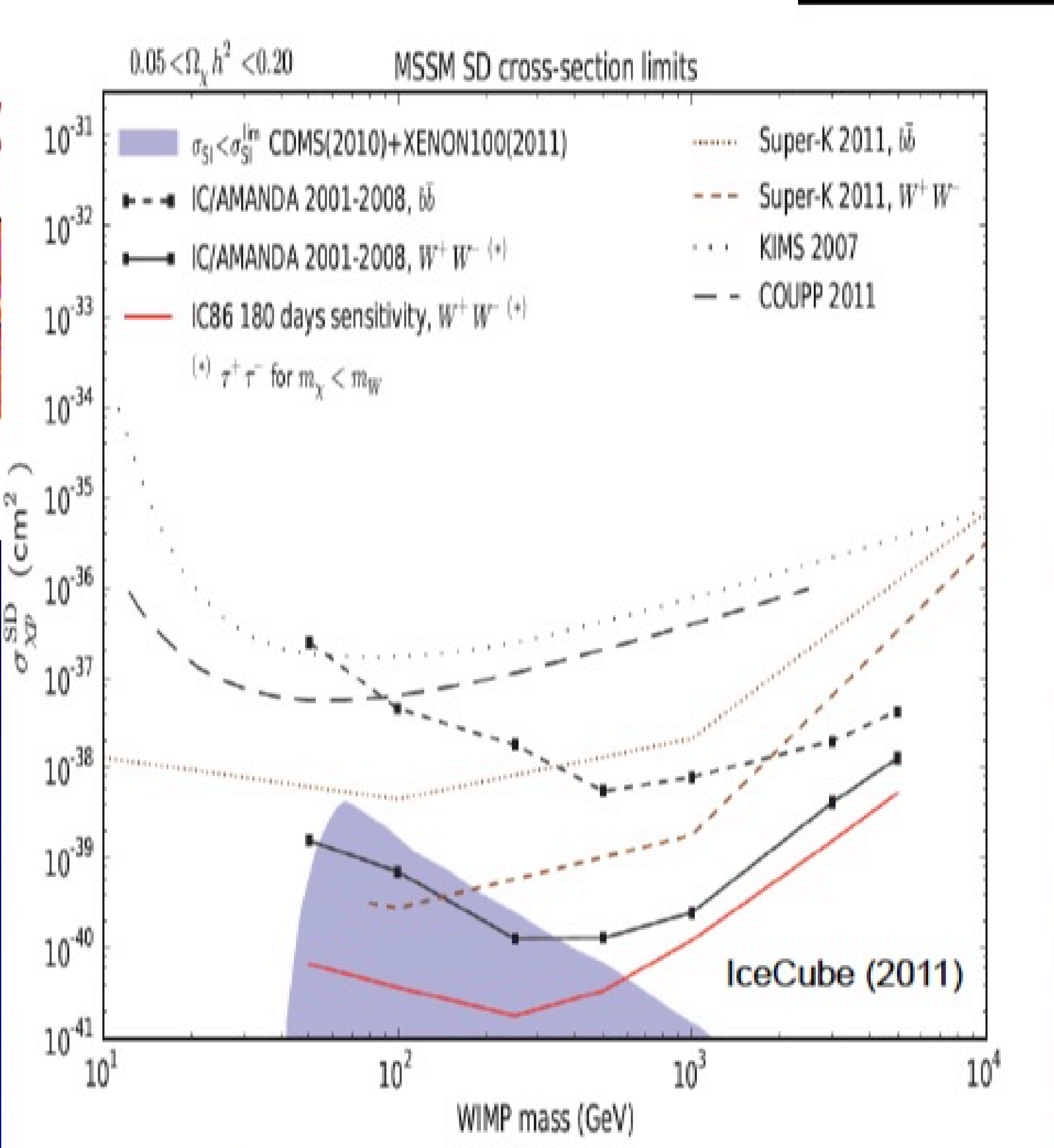


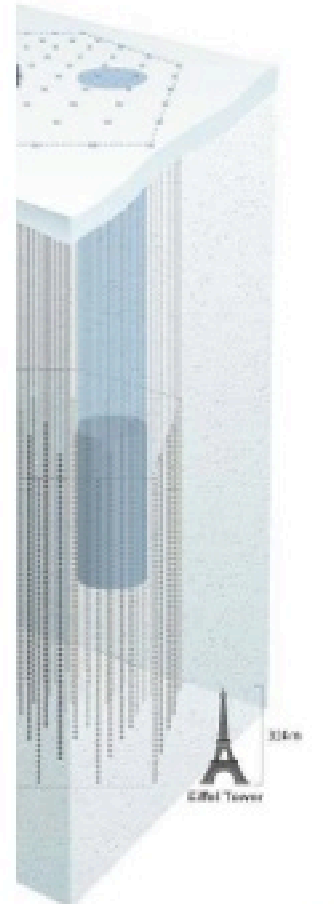


ρ_χ
χ
velocity
distribution
Sun
ν interactions
Earth
σ_{scatt}
ν_μ
$\Gamma_{capture}$
ν int.
μ int.
$\Gamma_{annihilation}$
Detector
μ



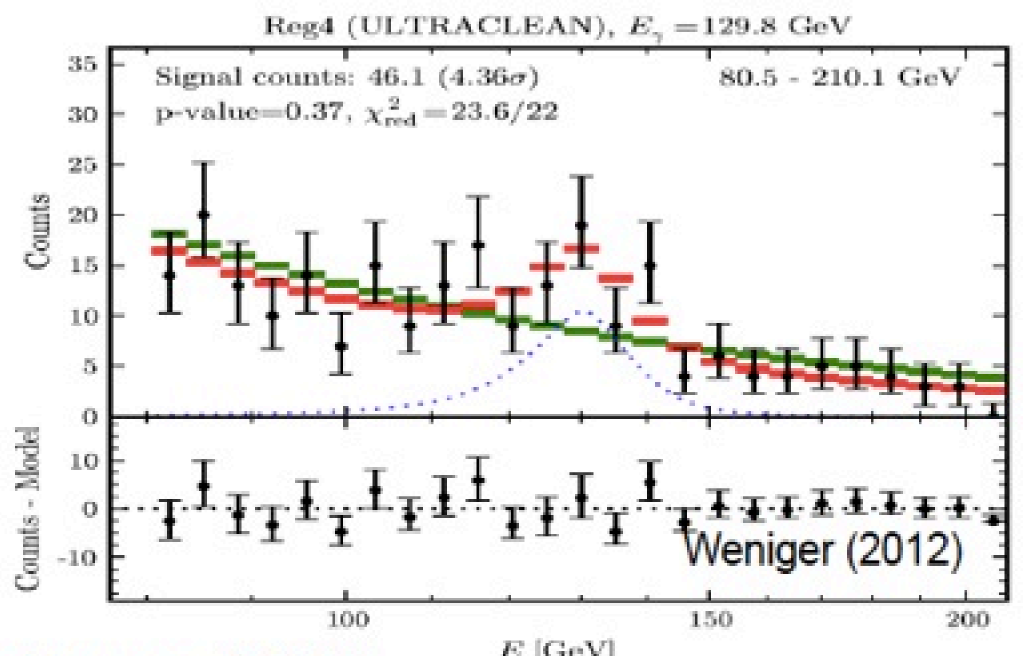

ρχ χ
Sun
σscatt
Γcapture
Γannihilation


0.05 < Ωχ h² < 0.20
MSSM SD cross-section limits
σSI < σSI^lim CDMS(2010)+XENON100(2011)
IC/AMANDA 2001-2008, bb̄
IC/AMANDA 2001-2008, W+ W- (*)
IC86 180 days sensitivity, W+ W- (*)
(*) τ+ τ- for mχ < mW
Super-K 2011, bb̄
Super-K 2011, W+ W-
KIMS 2007
COUPP 2011
IceCube (2011)
σχp^SD (cm²)
WIMP mass (GeV)
10^-31
10^-32
10^-33
10^-34
10^-35
10^-36
10^-37
10^-38
10^-39
10^-40
10^-41
10^1
10^2
10^3
10^4

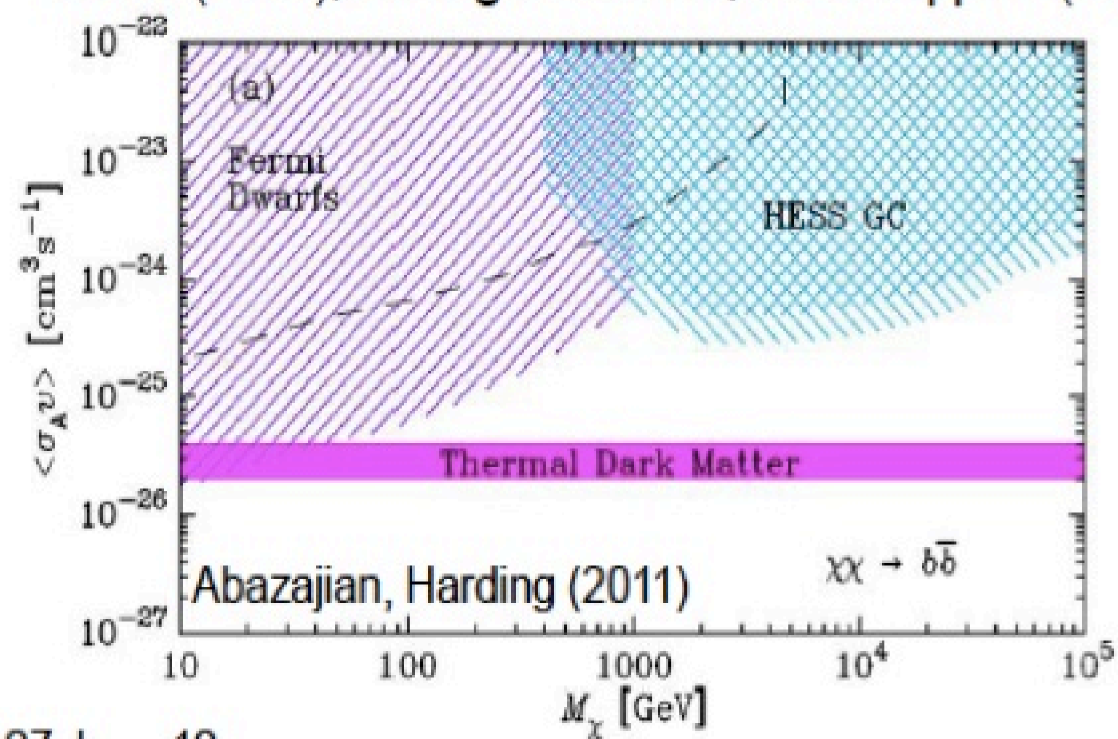


Gamma-rays

For some annihilation channels, bounds exclude light thermal relics



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



Current interest:
3-5σ Eγ =130 GeV, $\langle \sigma v \rangle = 10^{-27} cm3/s$

What is the 2nd hardest Astroparticle to detect?

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Gravitons/ Gravitational Waves

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Gravitons/ Gravitational Waves

How far can they travel from?

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back to the early Universe!

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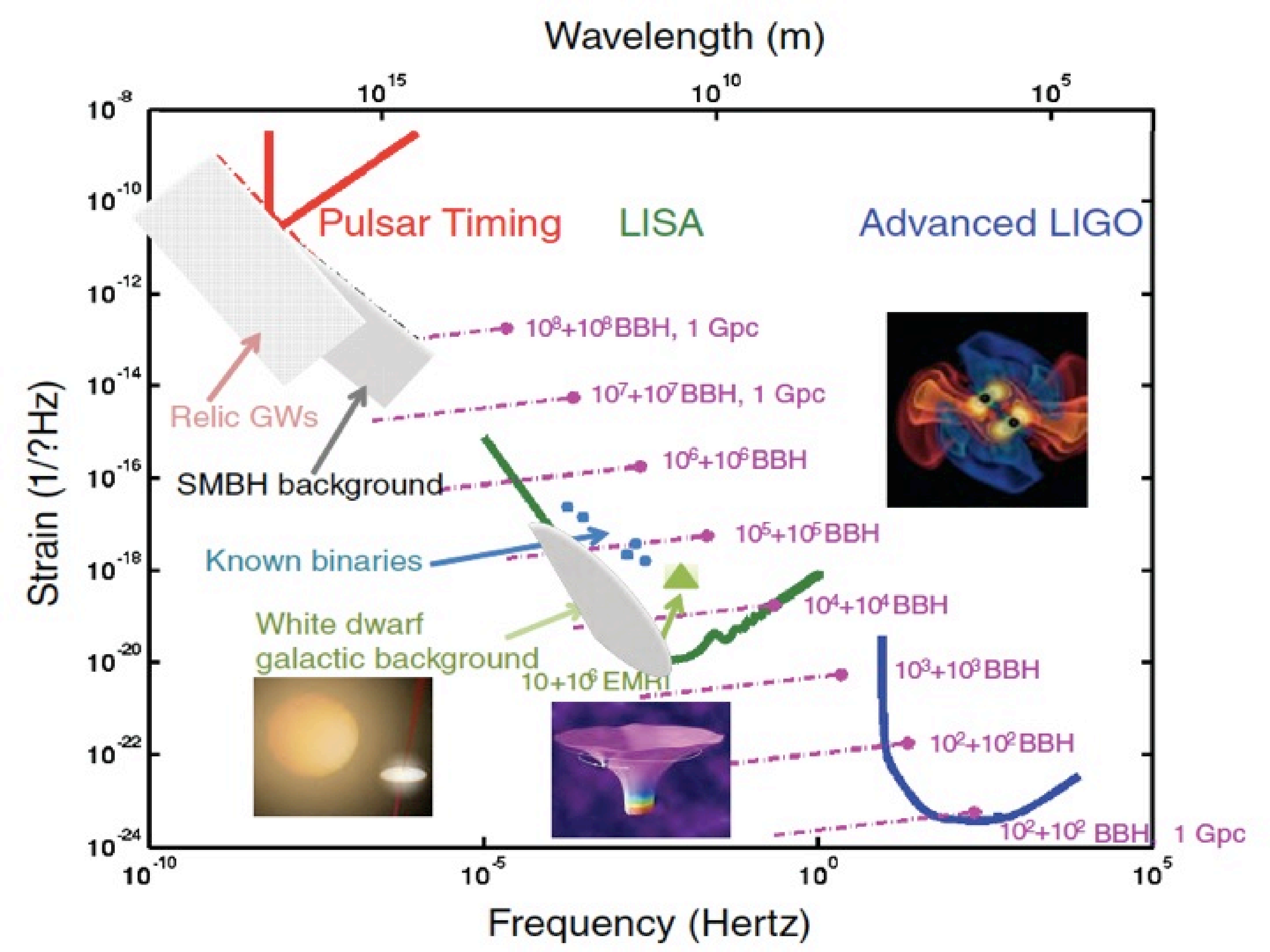

Wavelength (m)
10^15
10^10
10^5
10^-8
10^-10
10^-12
10^-14
10^-16
10^-18
10^-20
10^-22
10^-24
Strain (1/?Hz)
Pulsar Timing
LISA
Advanced LIGO
10^8+10^8 BBH, 1 Gpc
10^7+10^7 BBH, 1 Gpc
10^6+10^6 BBH
10^5+10^5 BBH
10^4+10^4 BBH
10^3+10^3 BBH
10^2+10^2 BBH
10^2+10^2 BBH, 1 Gpc
Relic GWs
SMBH background
Known binaries
White dwarf
galactic background
10+10^6 EMRI
10^-10
10^-5
10^0
10^5
Frequency (Hertz)

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How are we trying to observe GWs?

What is the 2nd hardest Astroparticle to detect?

Gravitons/ Gravitational Waves

How far can they travel from?

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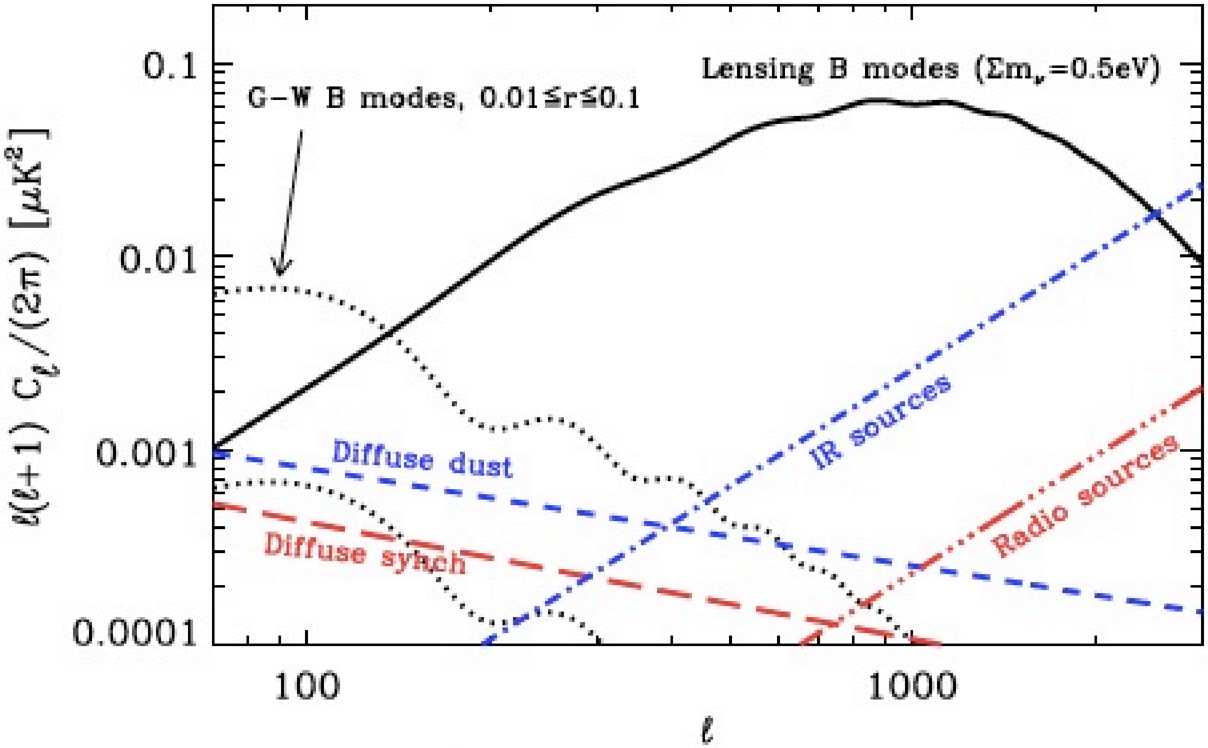
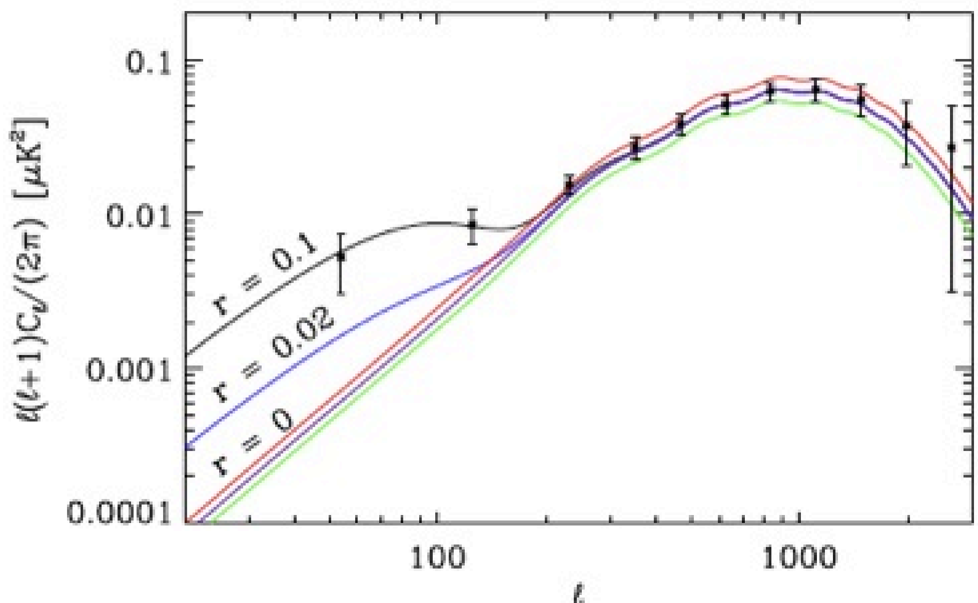
How are we trying to observe GWs?

- Large interferometers on the ground (and hopefully one day in space)
- Pulsar timing Arrays
- CMB polarization



r=scalar to tensor ratio



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Have we observed Gravitational Waves?

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Have we observed Gravitational Waves?

Not yet...

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What is the 3rd hardest Astroparticle to detect? Neutrinos

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How abundant are they?

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0.3% of the contents of the Universe

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How far can can they travel?

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Low Energies: underground detectors, reactors, accelerators, CMB

High Energies: ice and water km3 detectors

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Have we observed cosmic Neutrinos?

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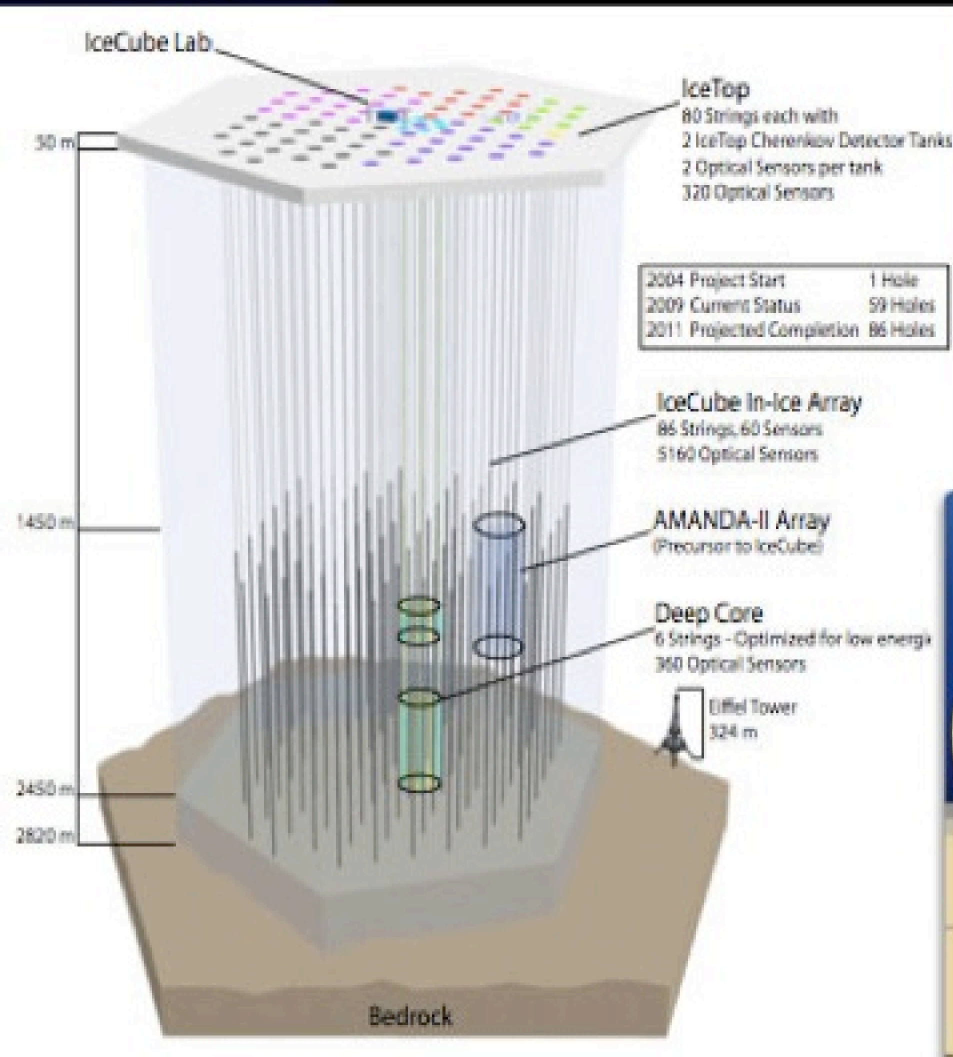
High Energies: ice and water km3 detectors

Have we observed cosmic Neutrinos?

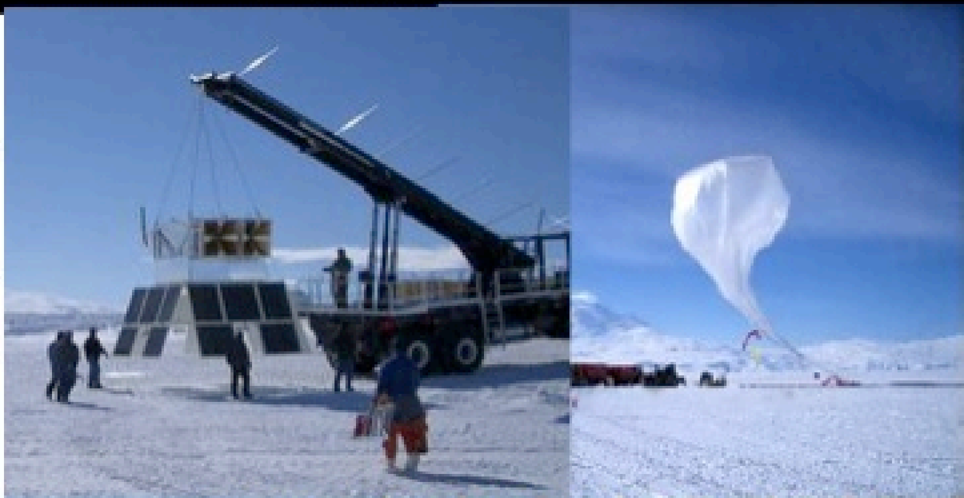
Solar, SN87A, ... and 2 PeV neutrinos??

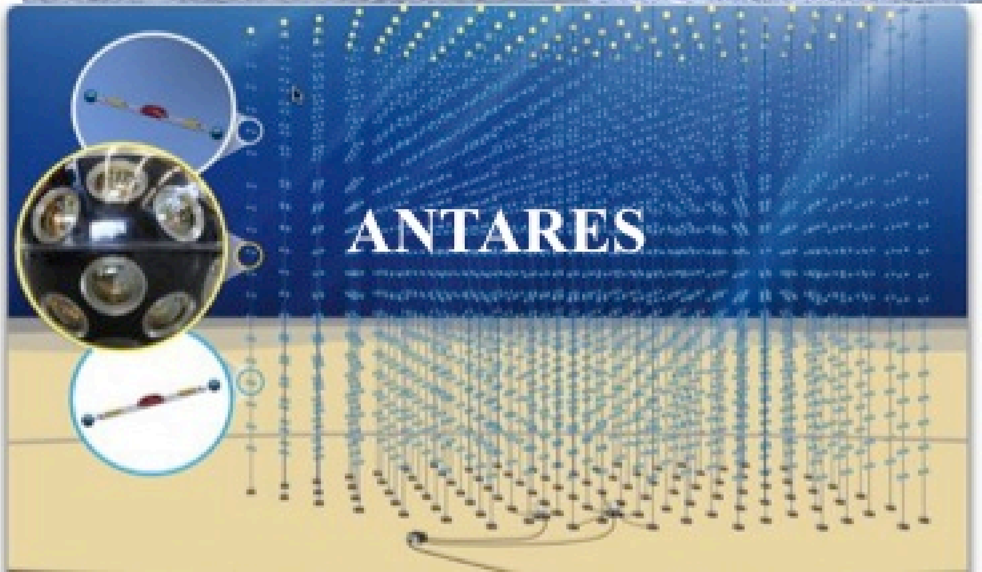
Highest Energy Neutrino Observatories

IceCube



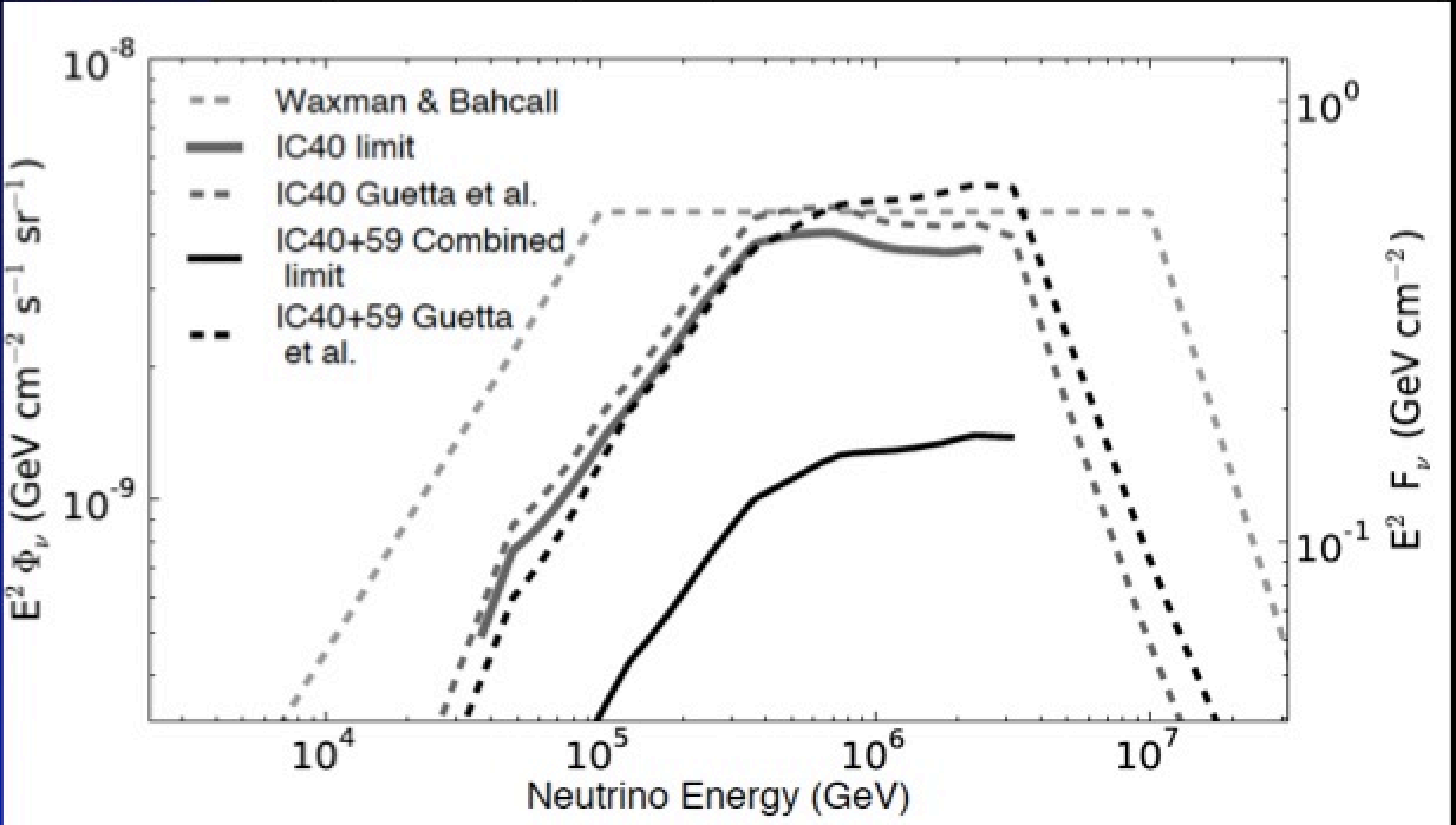
ANITA





HE Neutrino Limits – thus far

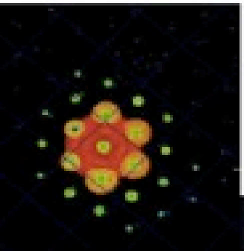
- IceCube Nature '12 – constraints on (some)
- Gamma-ray Bursts (GRB) Fireball Models



Beginning of PeV Neutrino "Astronomy"?

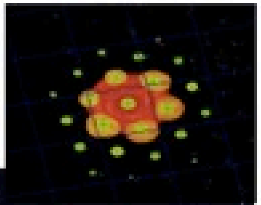
Two events passed the selection criteria

2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events
preliminary p-value: 0.0094 (2.36σ)

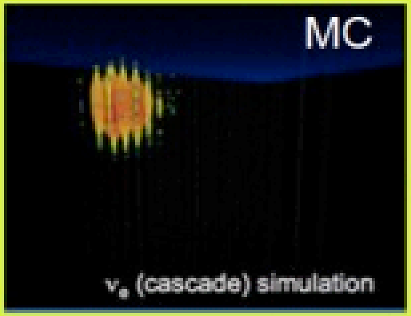


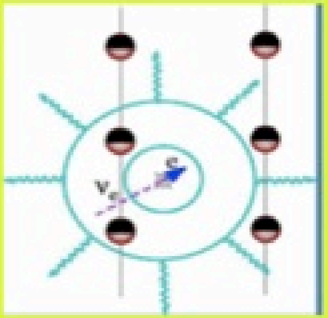
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628x10⁴
Number of Optical Sensors 312

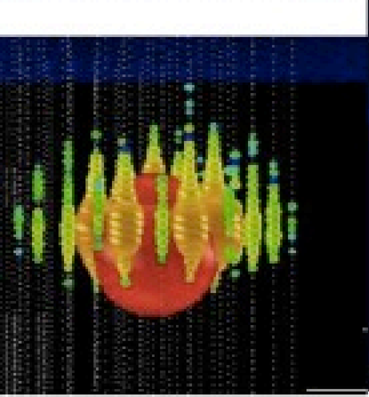
Run118545-Event63733662
August 9th 2011
NPE 6.9928x10⁴
Number of Optical Sensors 354

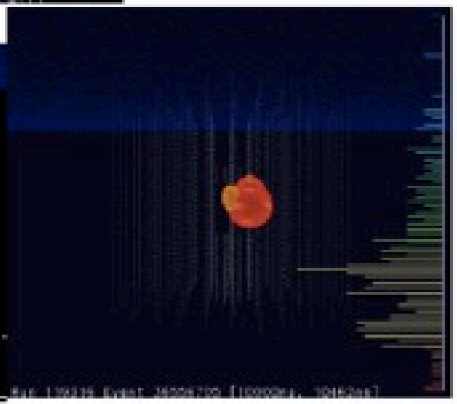


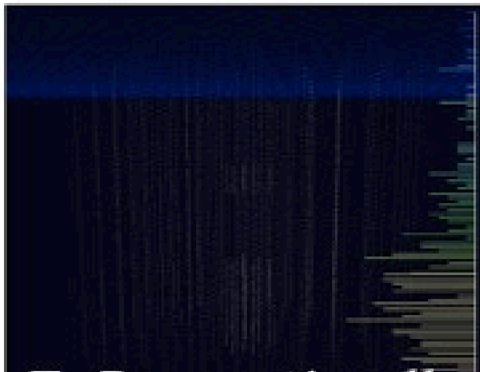
CC/NC interactions in the detector

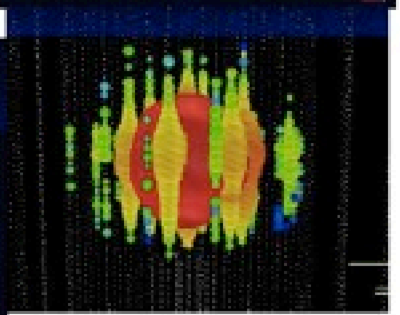












E. Resconi's talks

What other Astroparticles may we use?

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Neutrons? Muons? (Monopoles?)

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How far can we see with muons?

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not far: E > 10^{16} eV to make it from the Sun

$\tau = 2.2 \times 10^{-6}\,\mathrm{s}$ $\frac{1\,\mathrm{AU}}{c} = \gamma\tau$ $\gamma = 2.3 \times 10^{8}$ $E_\mu = 2.4 \times 10^{16}\,\mathrm{eV}$

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How far can we see with neutrons?

with E > EeV they can come from the Galactic Center

$\tau = 881.5\,\mathrm{s}$

$$E_n = \frac{2.57 \times 10^{22}\,\mathrm{cm}}{3 \times 10^{10}\,\mathrm{cm/s} \times 881.5\,\mathrm{s}} \times 938\,\mathrm{MeV} = 9.13 \times 10^{17}\,\mathrm{eV}$$


p 10²⁰ eV
GZK
p 10¹⁵⁻¹⁸ eV
ν
γ
ν
γ
χ
The Best is
Yet to Come!

AMON: Introduction

The Astrophysical Multimessenger Observatory Network (AMON)

- Generalization of the good ideas being used in a number of active follow-up programs (e.g., SNEWS, IceCube-ROTSE):
  - use global multilateral coincidence among (ν, γ, GW, n)
  - use above- *and* sub-threshold data from contributing observatories
  - use unified approach to all datagrams, anonymity, data access, data dissemination, archived data, etc.
  - enable all possible communication channels before the first big multimessenger source "pops"

Definitions

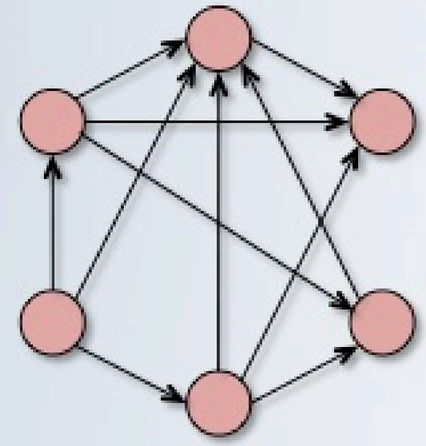
- "Triggering" observatories provide sub- & above-threshold candidate events to AMON archivally, then in real time

- AMON:
  - Actively aggregates events and seeks realtime coincidences in (t,ψ)
    - archival searches also foreseen
  - Generates, broadcasts and archives alerts
    - alerts will not indicate source detector

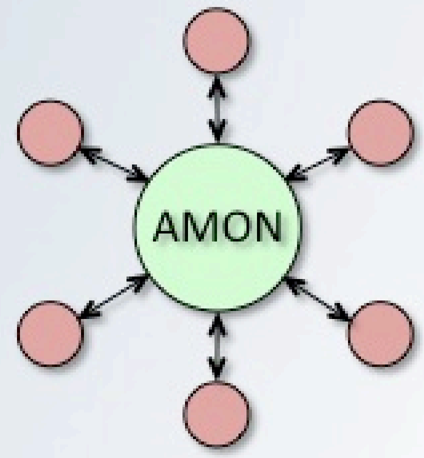
- "Follow-up" observatories:
  - Respond in real time to alerts
  - Will include numerous optical telescopes around the globe
  - (Triggering observatories can also do follow-up)

AMON & Status Quo?

- Status quo:
  - numerous bilateral, uni-directional arrangements
  - N^2 pairings: lots of MoUs, lots of wheel-reinvention, hard to maintain
  - misses many possible correlations



- AMON is a qualitative improvement
  - multilateral
  - omnidirectional
  - minimal latency
  - higher overall uptime fraction
  - unified approach
  - most efficient use of available data; increasing aggregate sensitivity at nominal added cost
  - permits previously ~impossible archival searches
  - reduces anxiety: we're more likely to be ready "in case everything goes *right*"

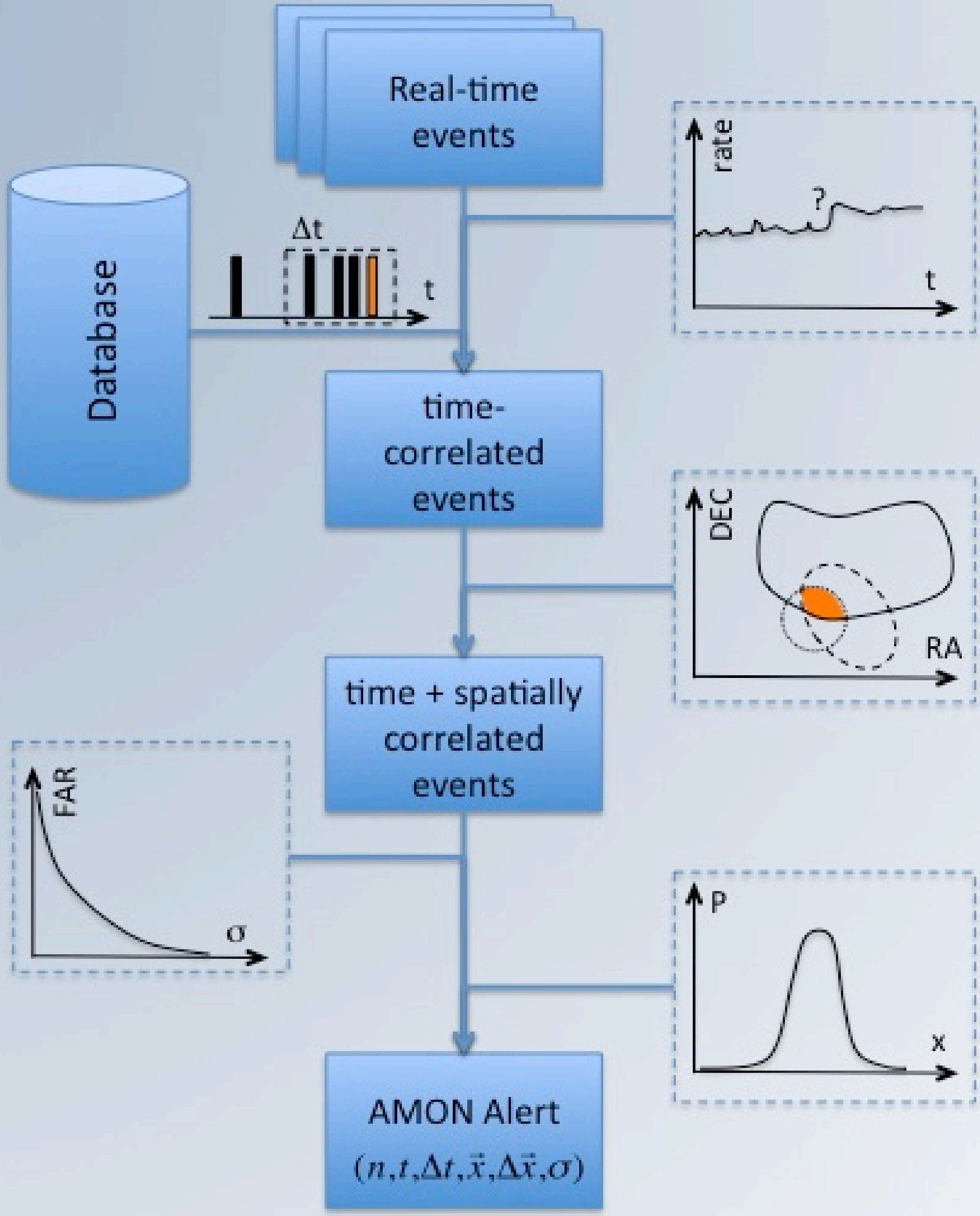


Definition: Sub-Threshold

Example Above and Sub-Threshold Potential Signals

- IceCube
  - neutrino triplet (sub-threshold: single neutrino)
- Swift
  - 0.4 photons/cm^2/s (sub-threshold: 0.1)
- Fermi (an educated guess)
  - 5 photons (sub-threshold: 1)

Coincidence Search

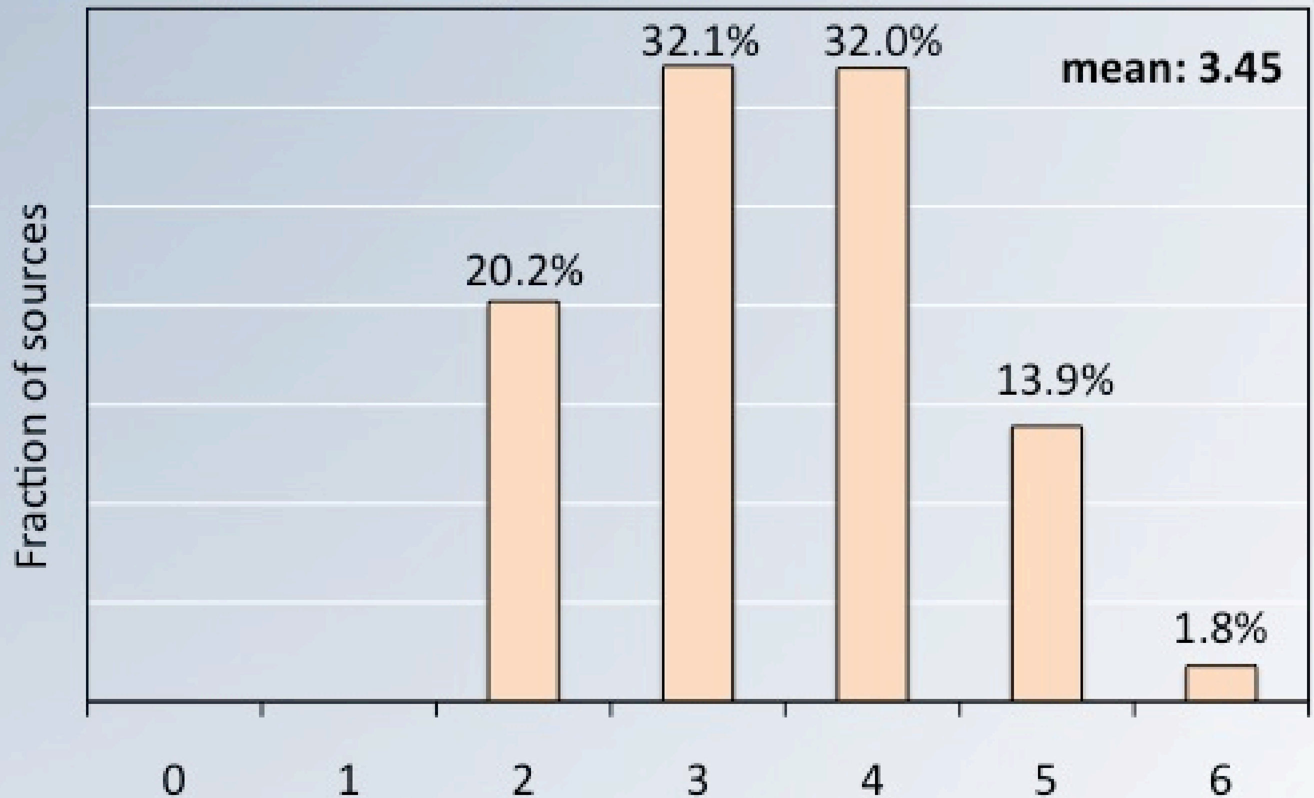


1. Monitor each observatory's status, sub-threshold event rate
2. Time filter: Events occur within Δt window
3. Position filter: Events occur in same part of sky
4. Calculate False Alarm Rate (FAR)
5. Calculate best-fit position, uncertainty
6. Distribute alert based on FAR

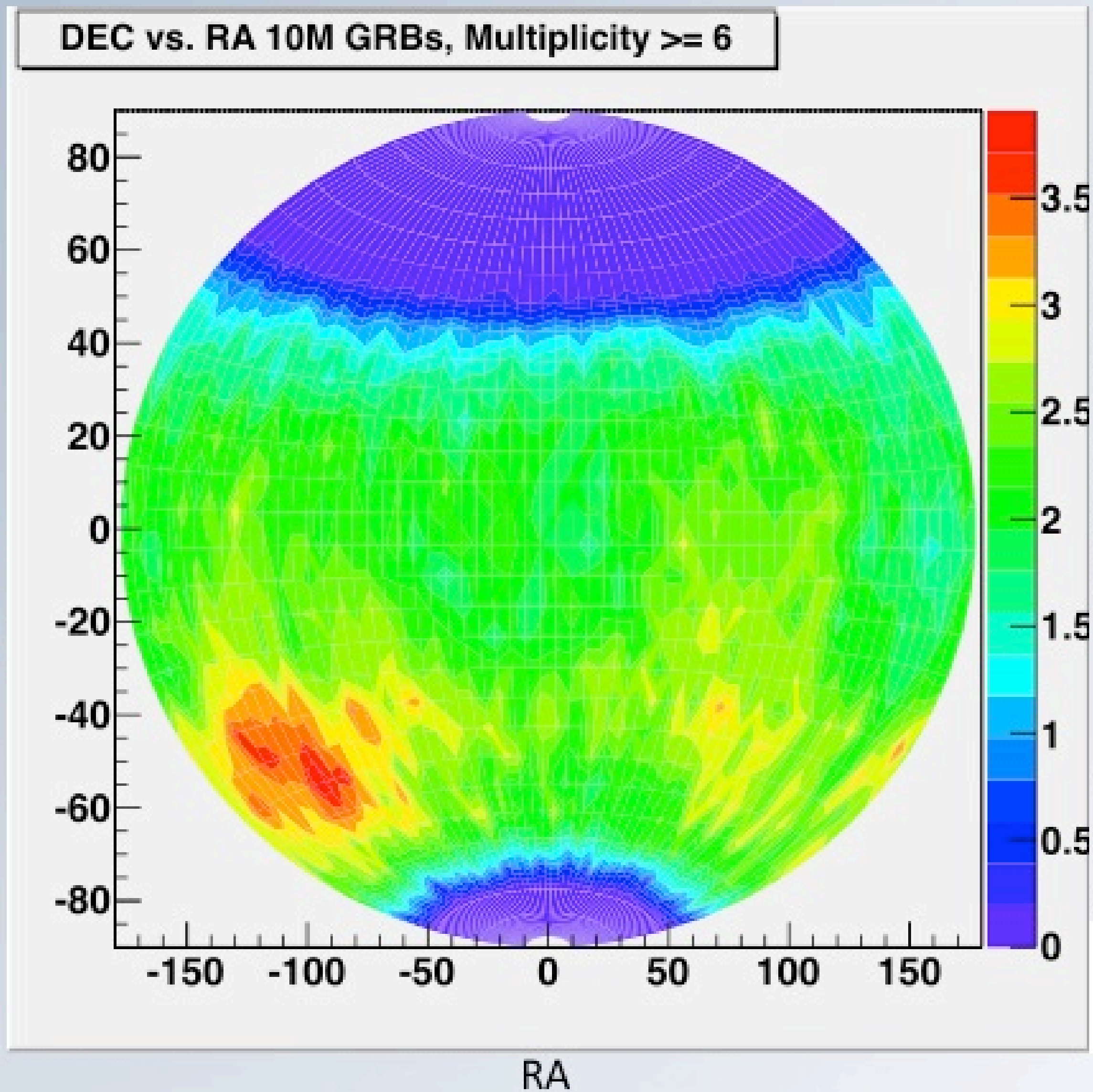
Simulations: pointing

- Simulated 10^7 source locations throughout a year
- 7 event streams: IceCube Northern & Southern hemispheres, Auger, Swift, Fermi, LIGO, HAWC
- Used Fermi and Swift 2010 pointing information
- Did not consider detector downtime

Number of co-pointing observatories for each source



Simulations: pointing



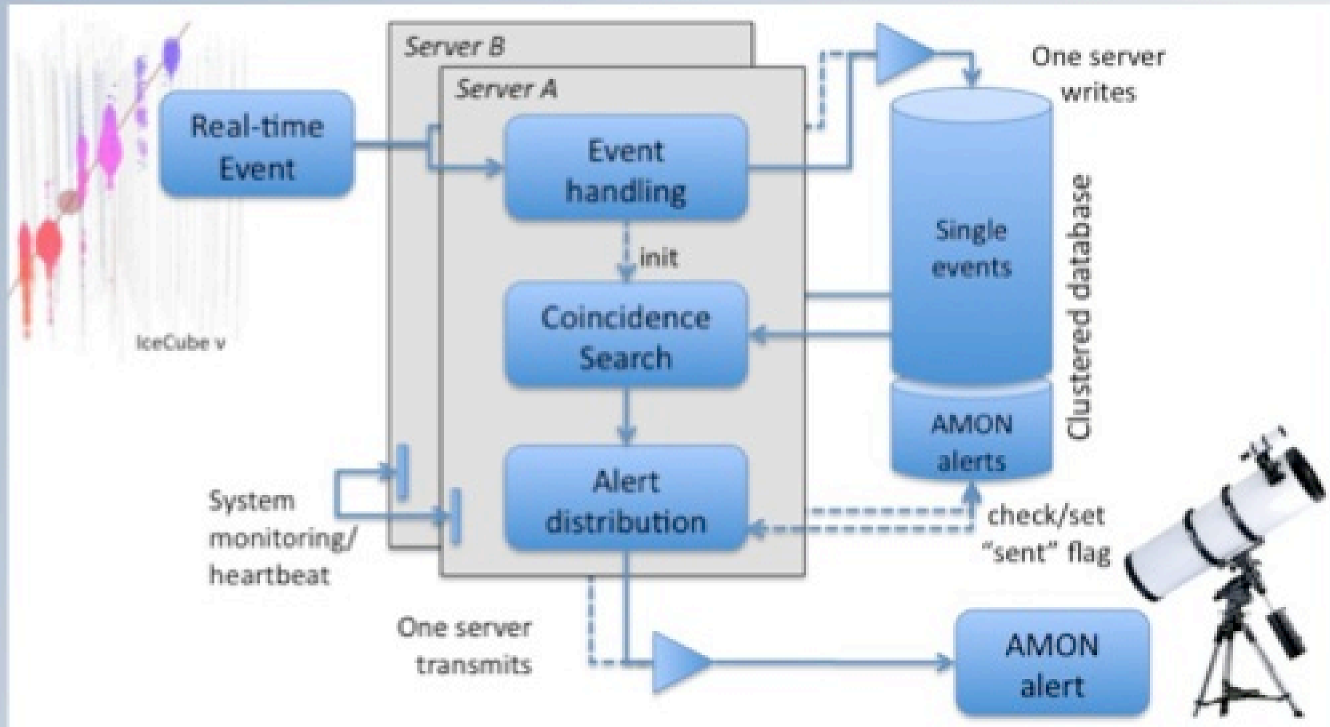
Number of co-pointing observatories

$N \geq 6$

AMON Triggering Observatories: Summary

Observatory	Force	Particle	Status	FoV (sr)	δψ	latency	R(norm) / R(sub-thr)
Auger	strong	n, γ, ν	running	6.28	~1°	TBD	TBD / TBD
Fermi	EM	γ	running	7.91	0.04° (@100GeV)	<= 1 d	10/yr / ~0.1Hz
HAWC	EM	γ	2012/ 2013	~2	<0.5°	<10 s	few/y / ~0.1Hz
IceCube	weak	ν	running	6.28-12.56	<1°	~1m	~0 / 10/h
LIGO	grav.	g	restart: ~2014	12.56	$(250°)^2 \times (12/\rho)^{2.5}$	TBD	~0 / ~0.1Hz
Swift	EM	γ	running	1.4	1arcmin	<90m	100/y / 100/d

Technical Details: Systems



- Dual servers and "clustered" database for redundancy
- Systems physically and cyber-secure
- Very high level of uptime
- Data needs are modest:
  - Traffic: 10 kB/sec (average), 1 MB/sec (peak)
  - Storage: 2 TB (5 years)
  - Processing: < 0.1 CPU