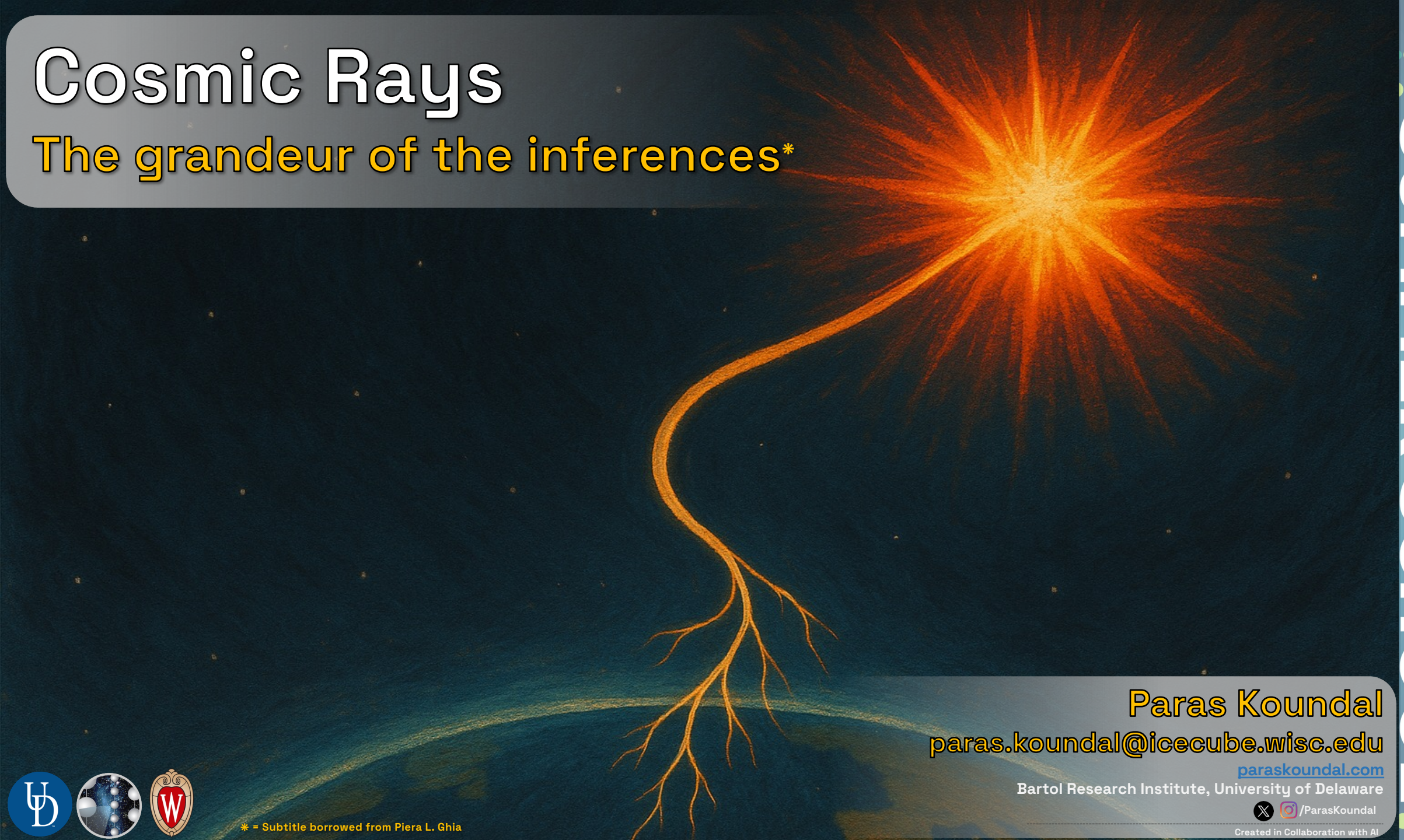
Cosmic Rays

The grandeur of the inferences*



ICECUBE SUMMER SCHOOL

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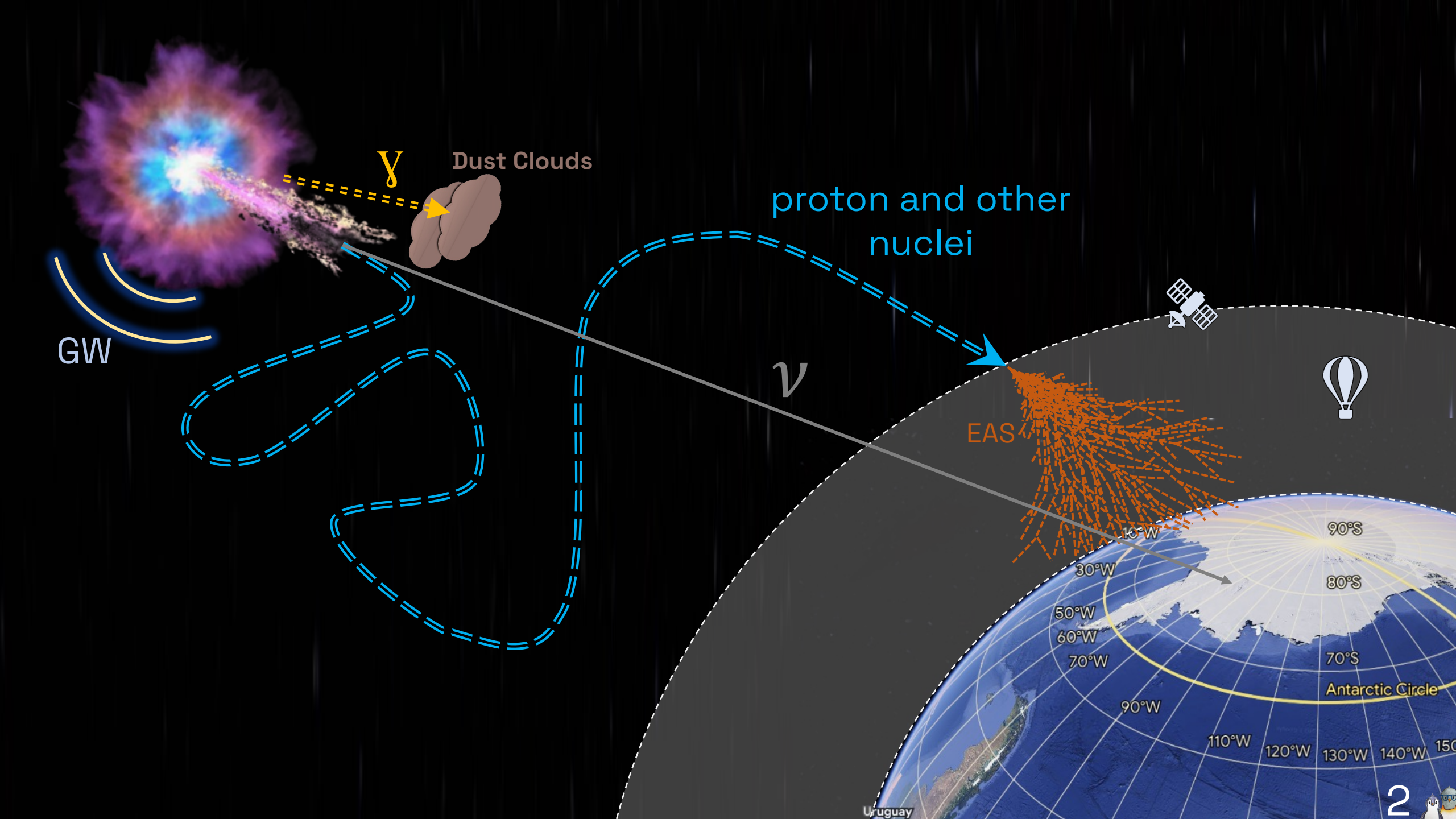
paraskoundal.com

Bartol Research Institute, University of Delaware

/ParasKoundal

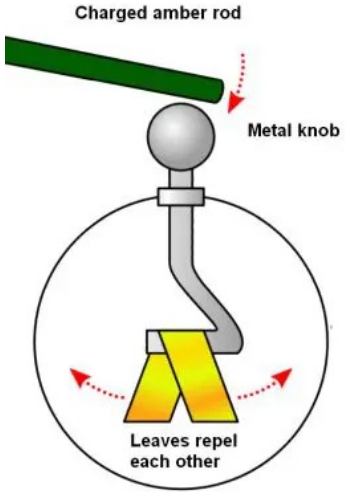
Created in Collaboration with AI

* = Subtitle borrowed from Piera L. Ghia


γ
Dust Clouds
proton and other
nuclei
GW
ν
EAS
90°S
80°S
70°S
Antarctic Circle
30°W
50°W
60°W
70°W
90°W
110°W
120°W
130°W
140°W
Uruguay

A century of Cosmic Rays

Explaining Electrical Discharge @ Gold-Foil



Charles-Augustin de Coulomb

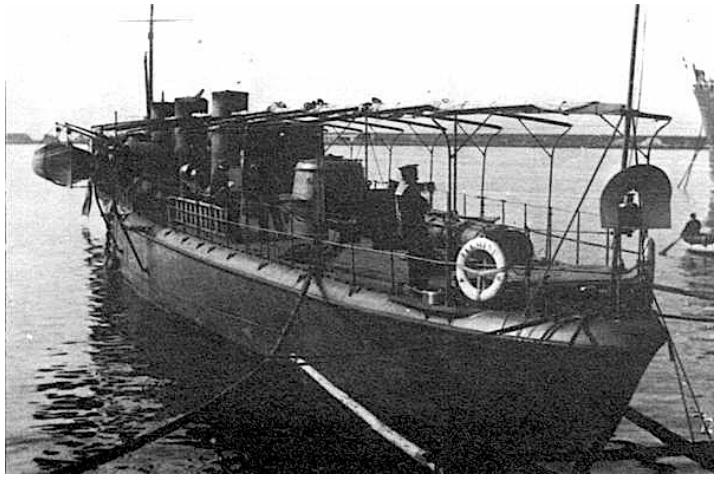
Sir William Crookes

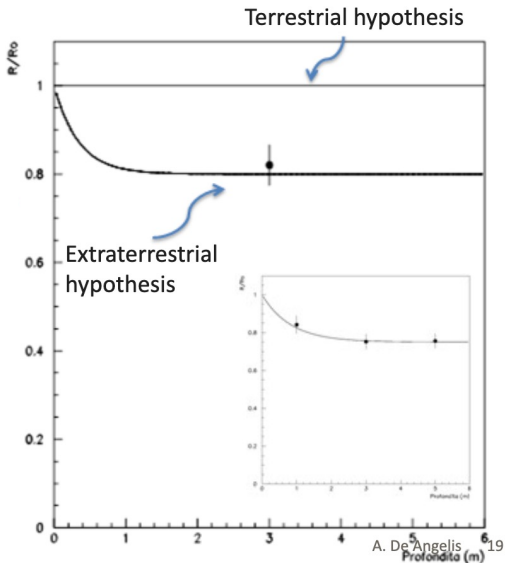
Joseph John Thomson

Julius Elster (left) and Hans Geitel

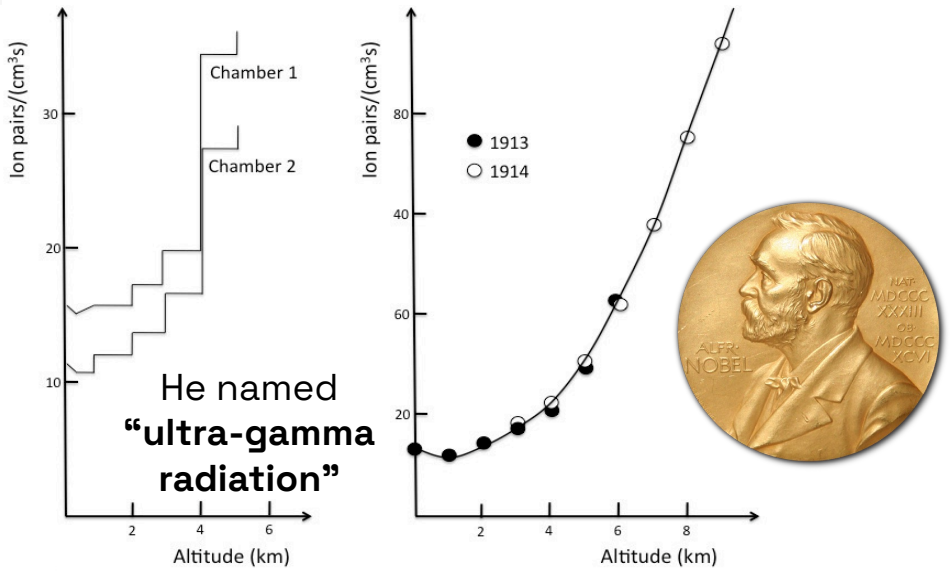
Testing Expectations – Pacini : The Explorer

Domenico Pacini

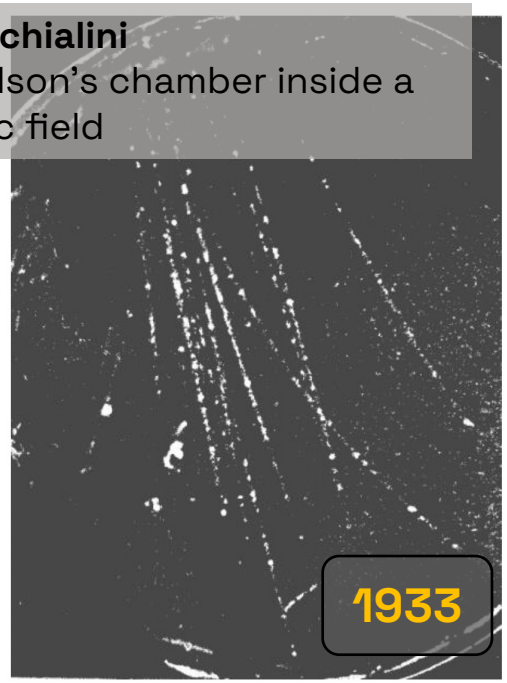


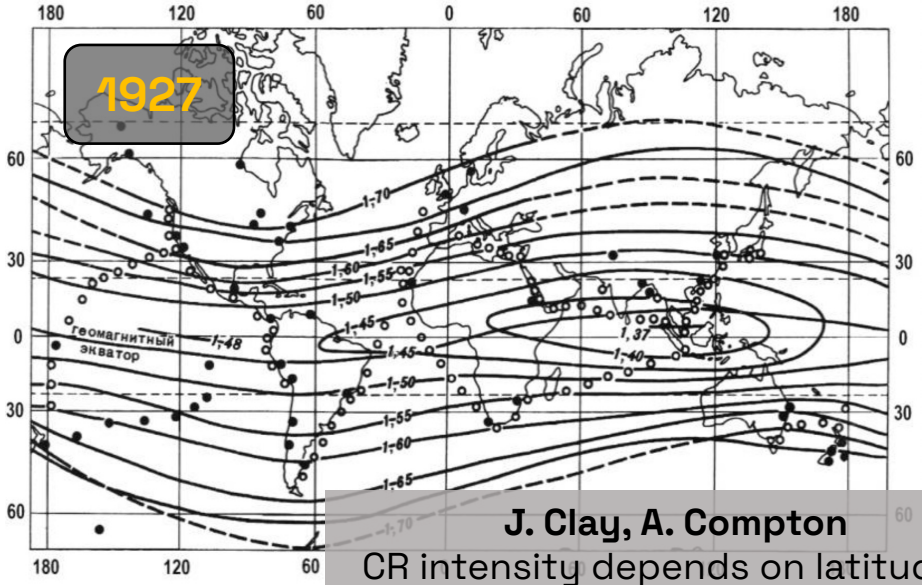


Around the World

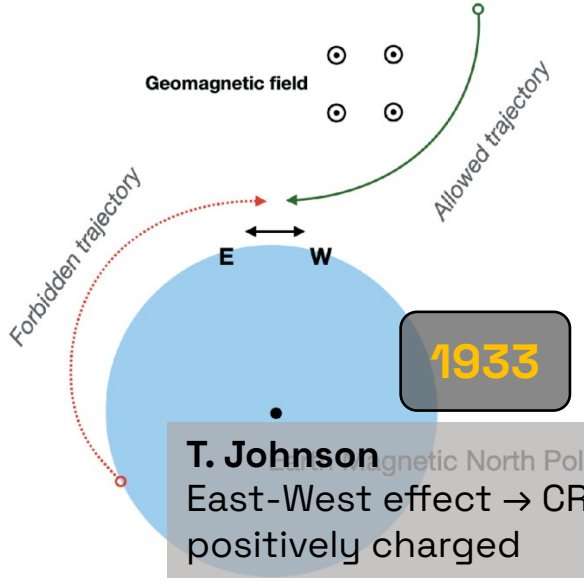


Blackett and Occhialini
CR shower in Wilson’s chamber inside a strong magnetic field

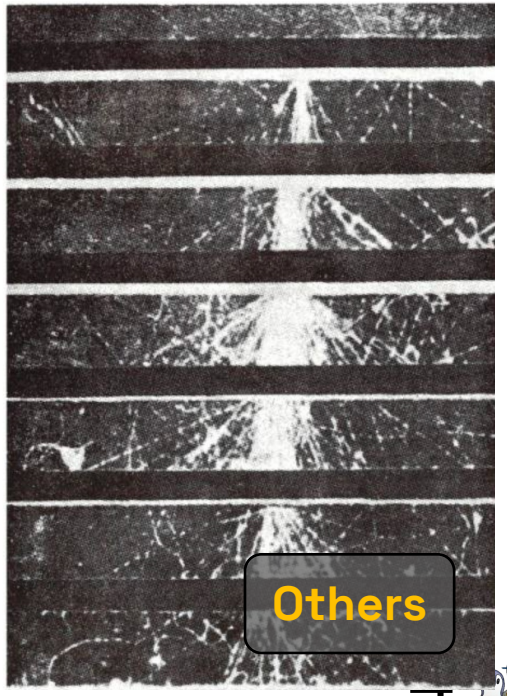




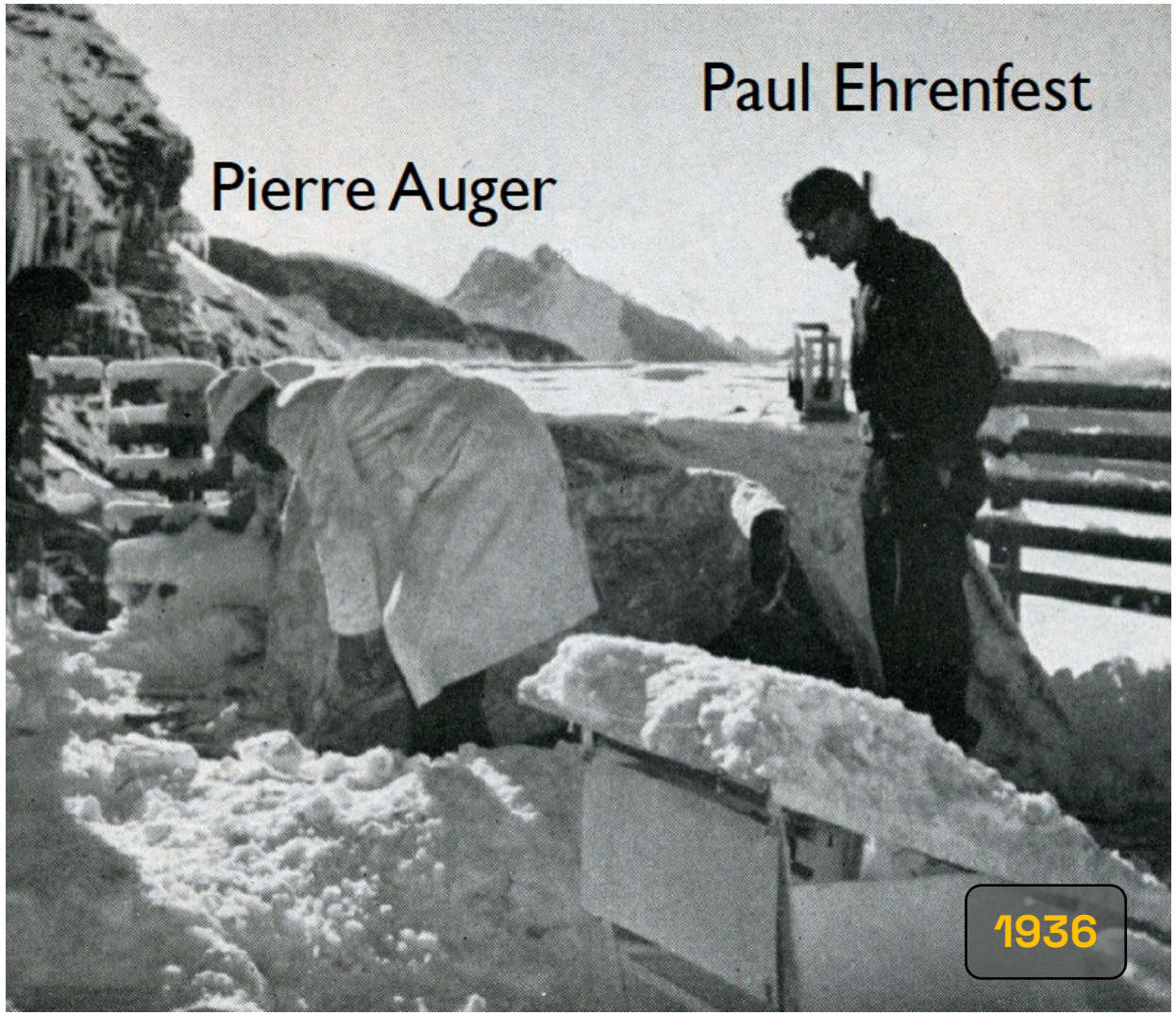
J. Clay, A. Compton
CR intensity depends on latitude & follows geomagnetic field lines



T. Johnson
East-West effect → CRs are positively charged



Air Showers



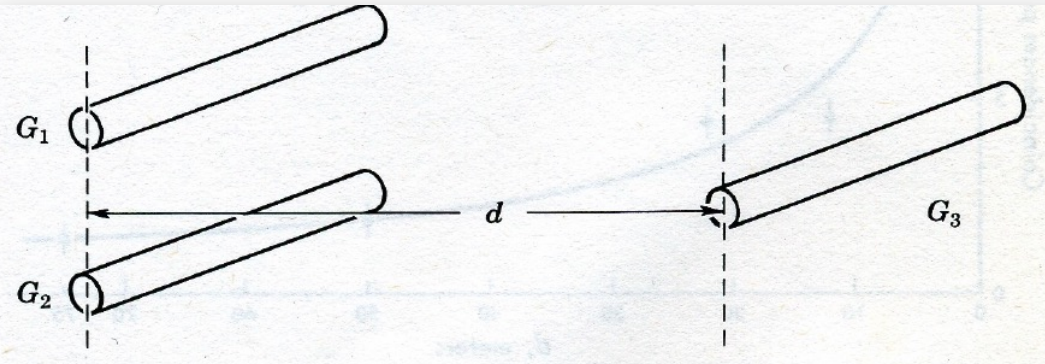


Fig. 12-1 Air-shower experiments by Auger and his collaborators in 1938 were made with the counter arrangement shown here. Counters G_1 and G_2 were placed one above the other, with their axes 22 cm apart. The third counter G_3 was moved horizontally to various distances d ranging from 15 centimeters to 75 meters.

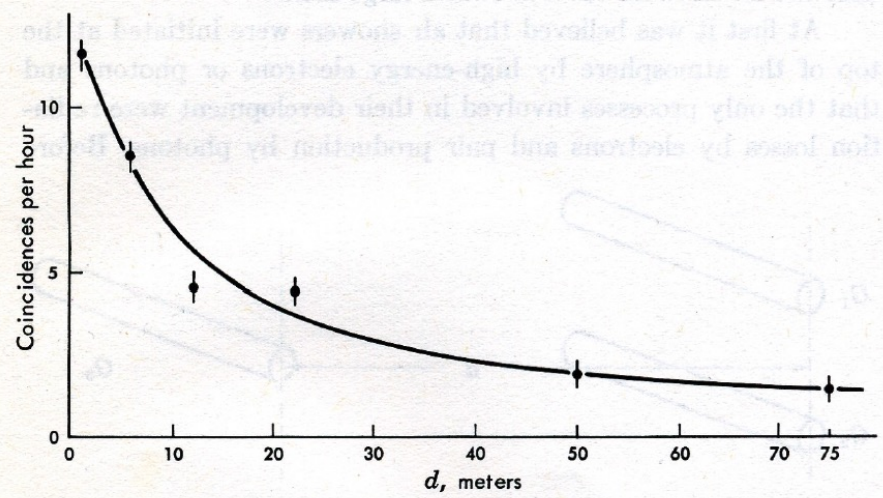
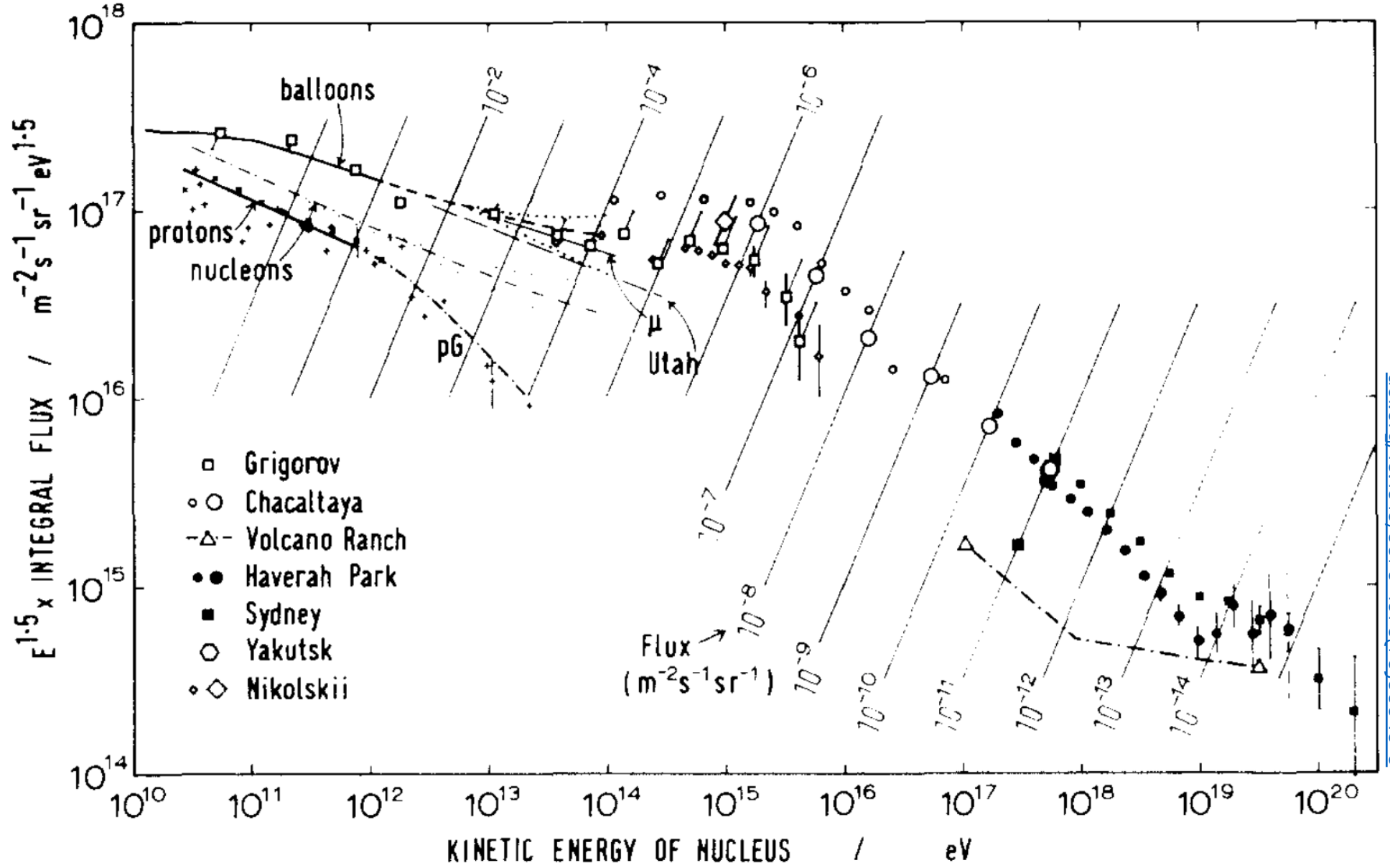


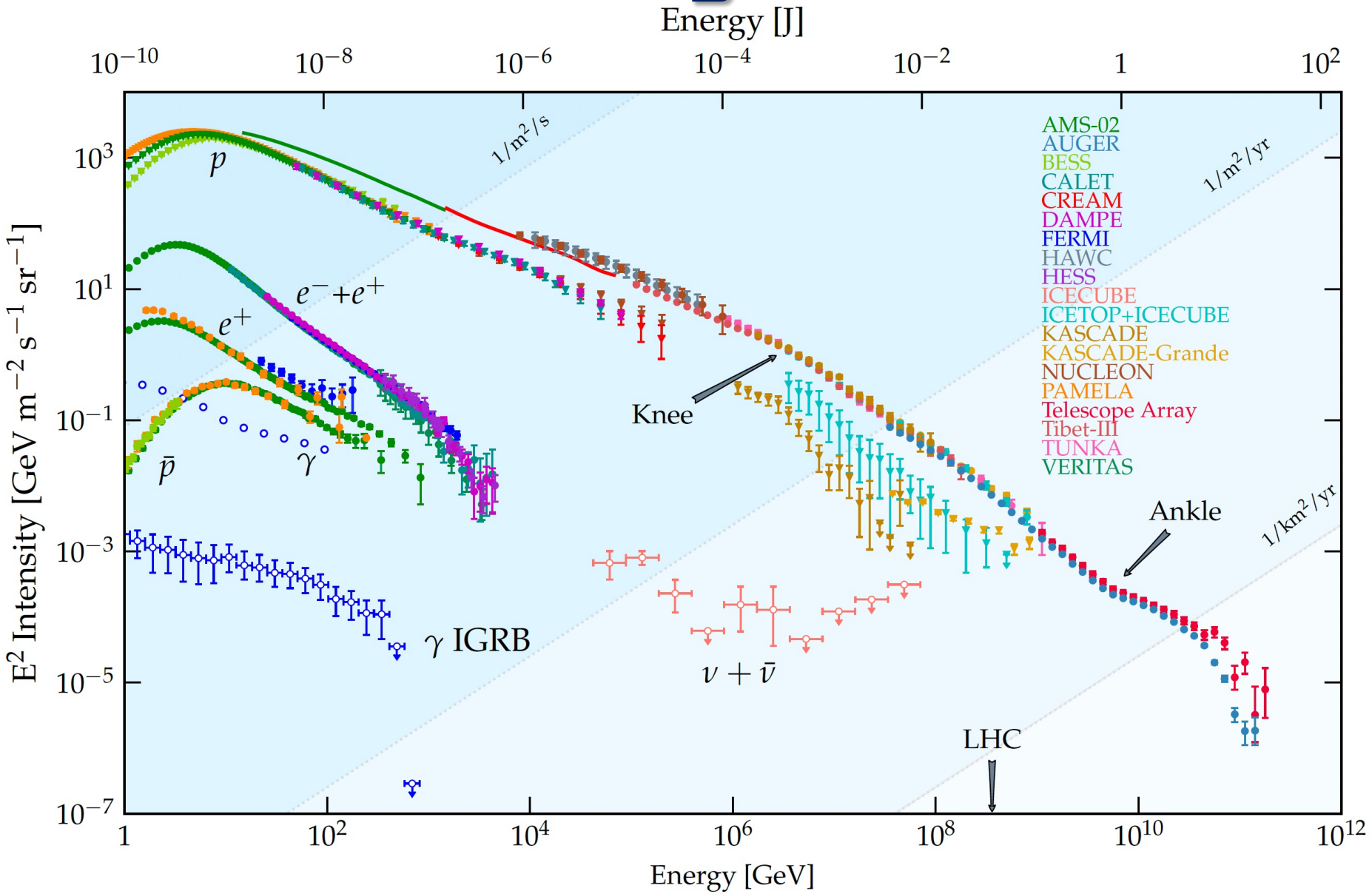
Fig. 12-2 Air-shower data obtained by Auger with the counter arrangement shown in Fig. 12–1. The horizontal scale gives the horizontal distance d between counter G_3 and the pair of counters G_1 and G_2; the vertical scale, the number of coincidences per hour. (From a paper in *Le Journal de Physique et Le Radium*, vol. 10, p. 39, 1939.)

Understanding till 1970s

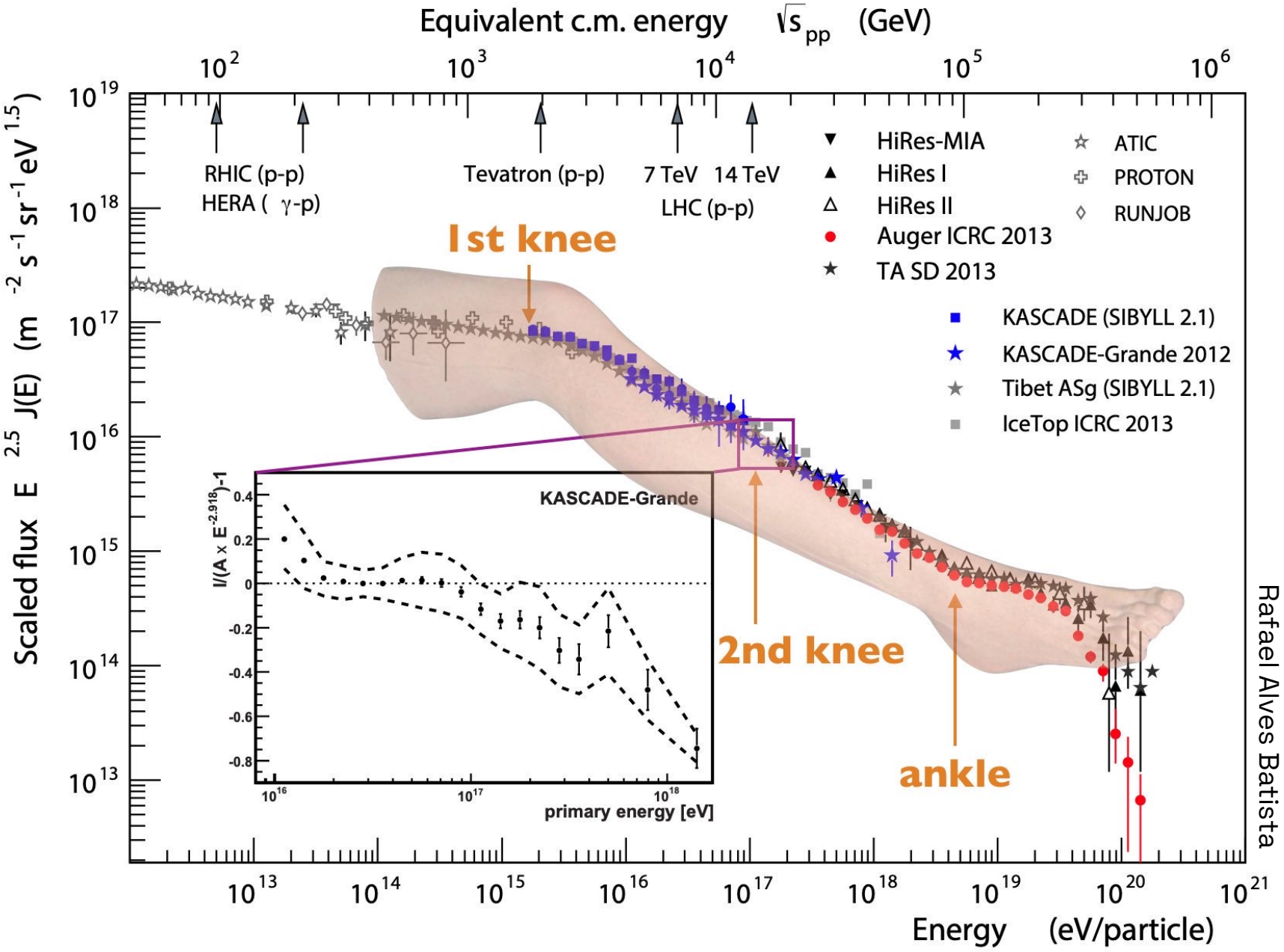


doi.org/10.1016/0370-1573(75)90045-9

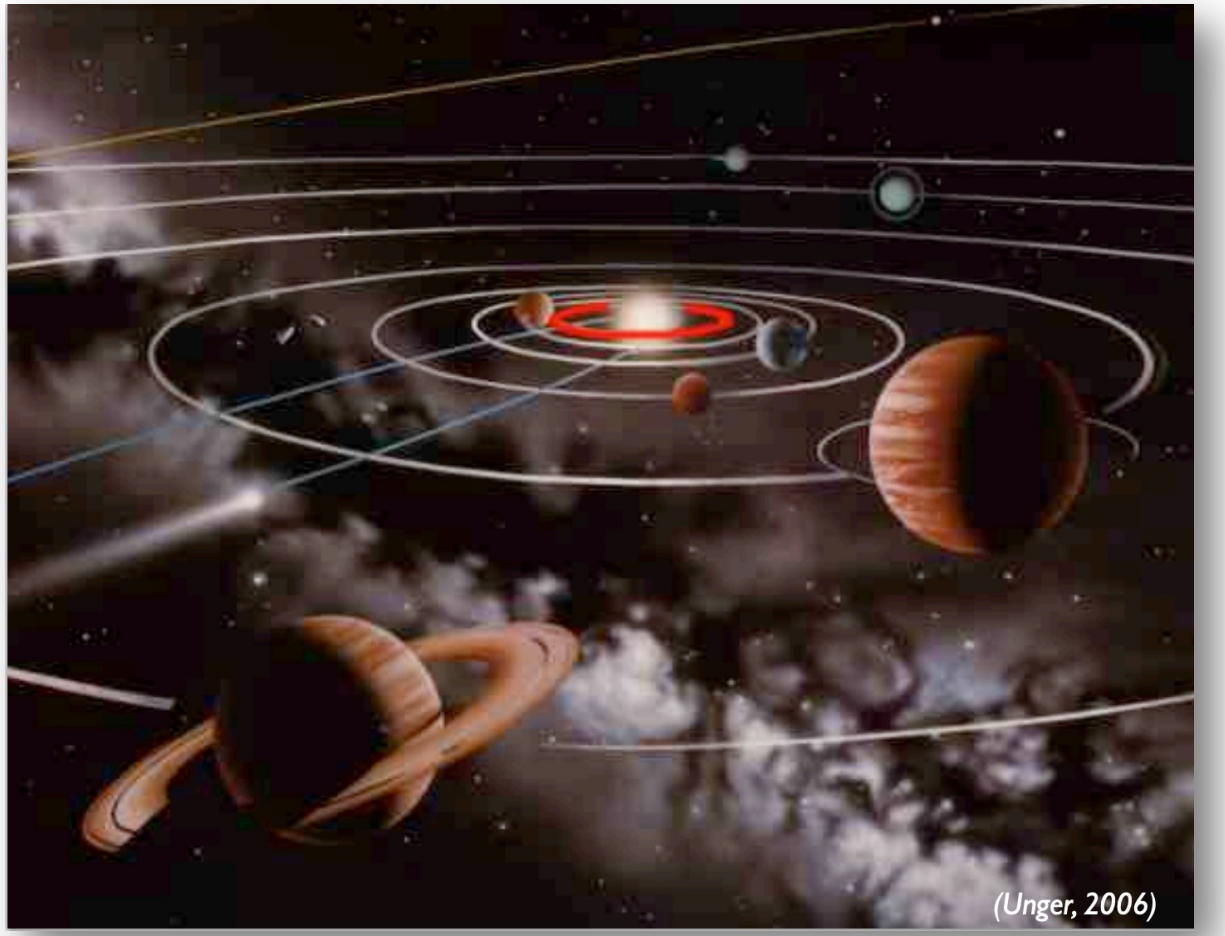
Current Understanding



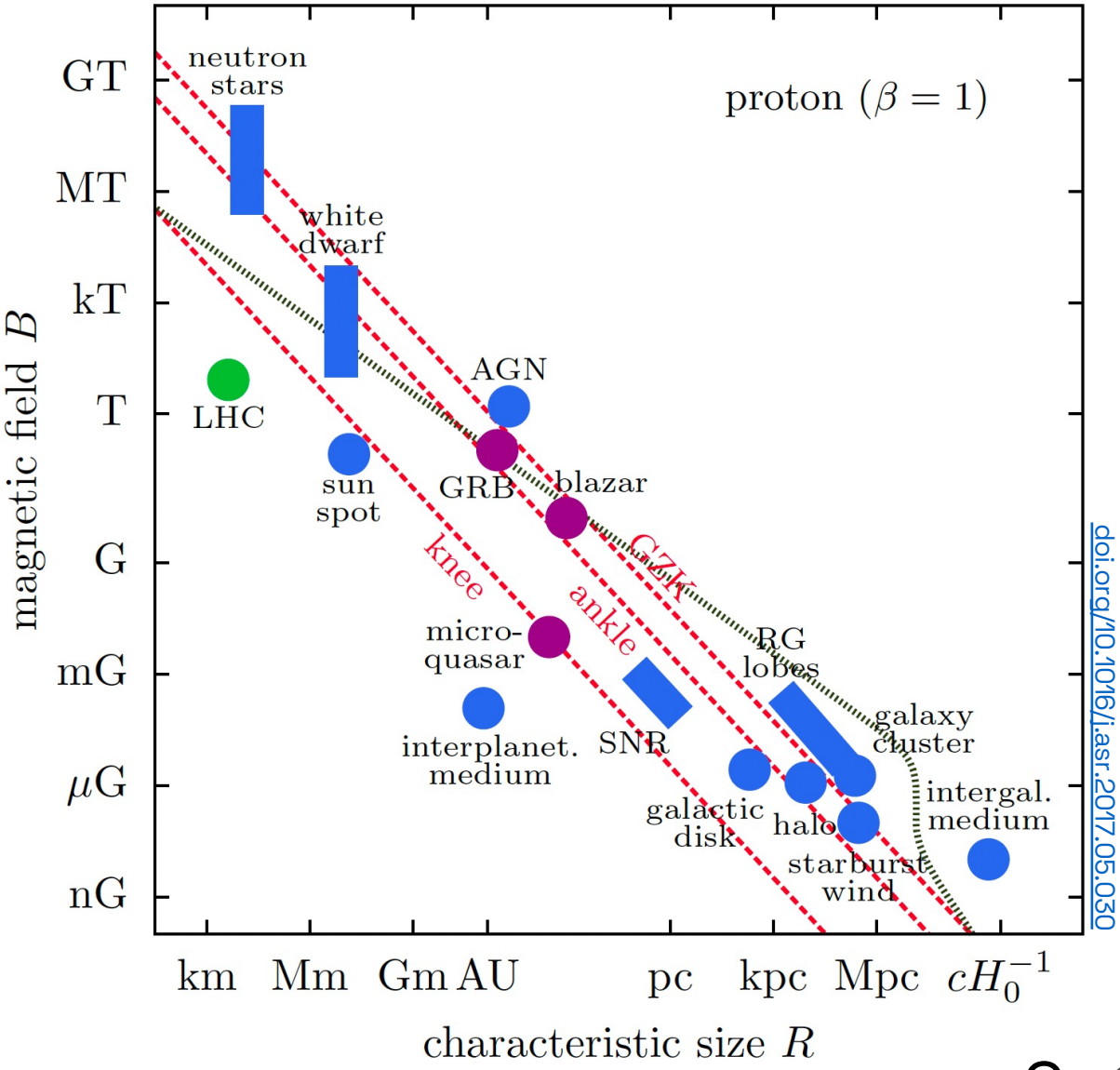
Current Understanding



Energy Budget

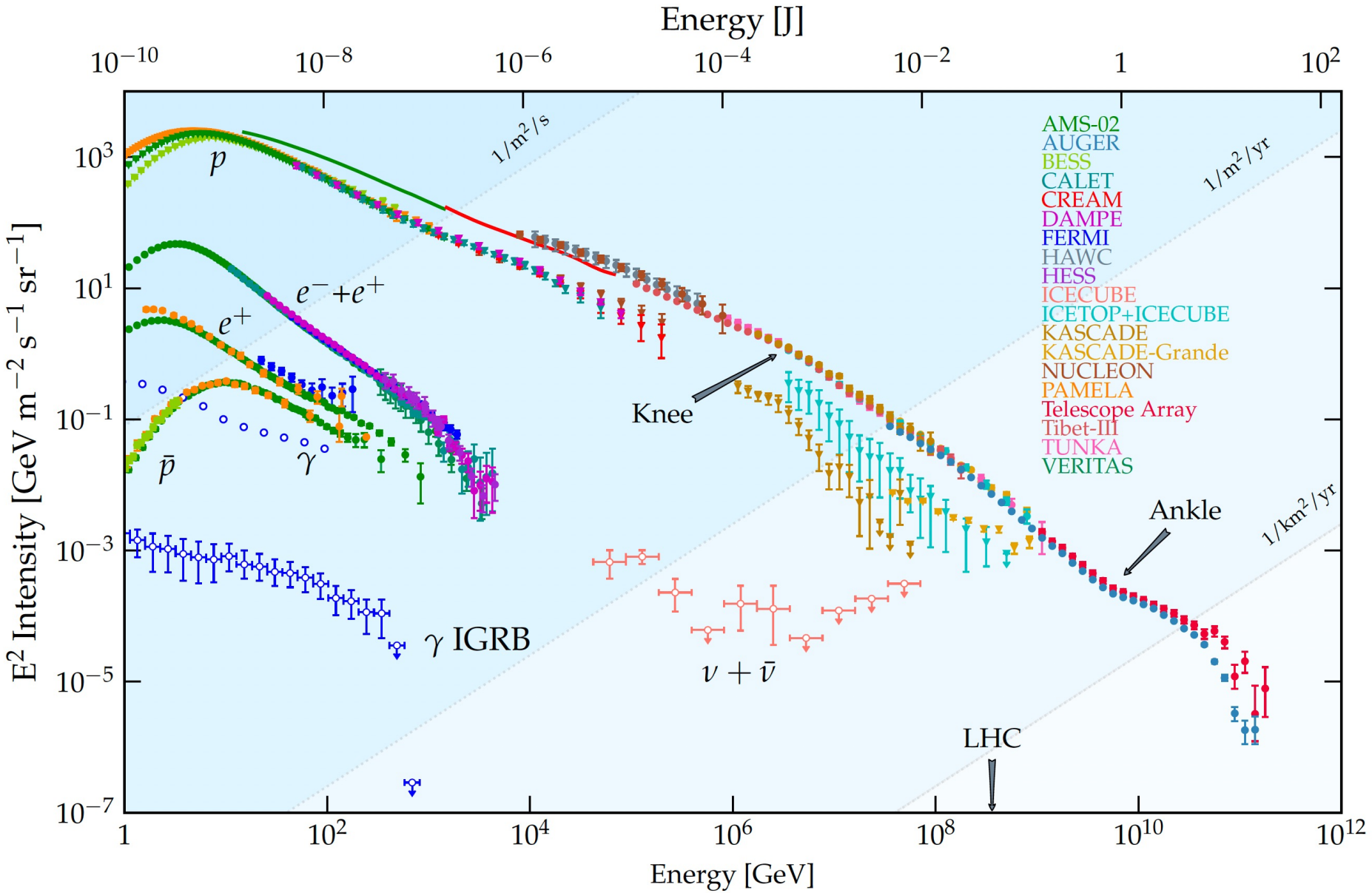


Need Mercury-orbit-sized accelerator to reach 10^{20} eV using LHC tech.



doi.org/10.1016/j.asr.2017.05.030

CR Spectrum


Energy [J]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
E^2 Intensity [GeV m^{-2} s^{-1} sr^{-1}]
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
p
$e^- + e^+$
e^+
$\bar{p}$
γ
γ IGRB
$\nu + \bar{\nu}$
Knee
Ankle
LHC
$1/m^2/s$
$1/m^2/yr$
$1/km^2/yr$
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
Energy [GeV]

Solar Modulation

Heliopause

Galactic
Cosmic Rays

Voyager 1

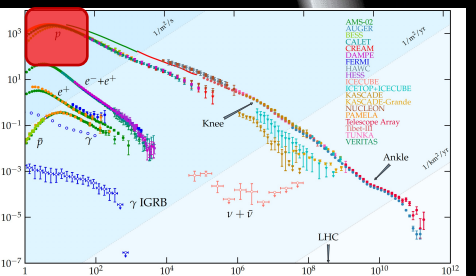
Solar Wind

Pioneer 11

Pioneer 10

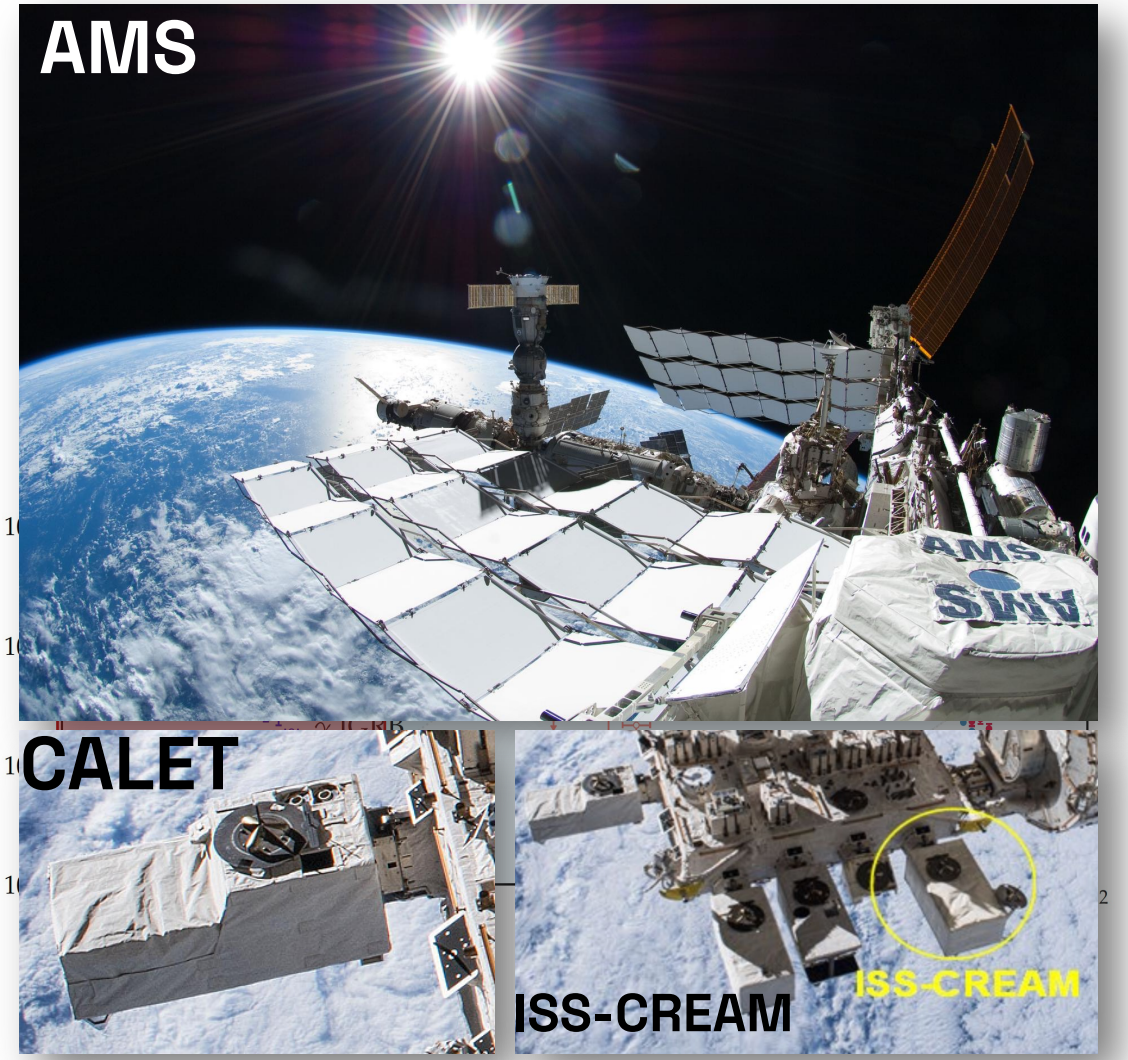
Voyager 2

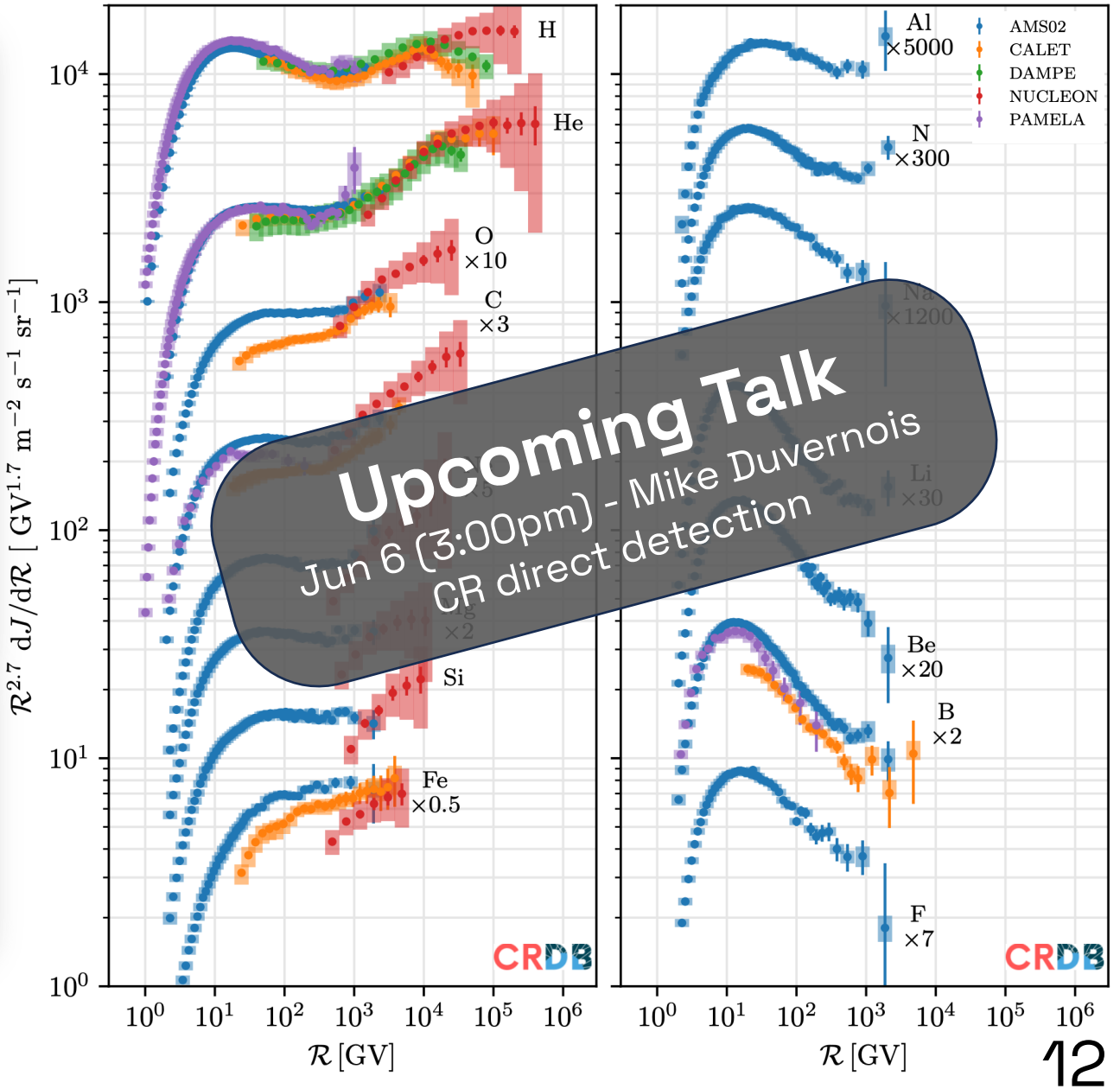
Termination
Shock



Credit: NASA

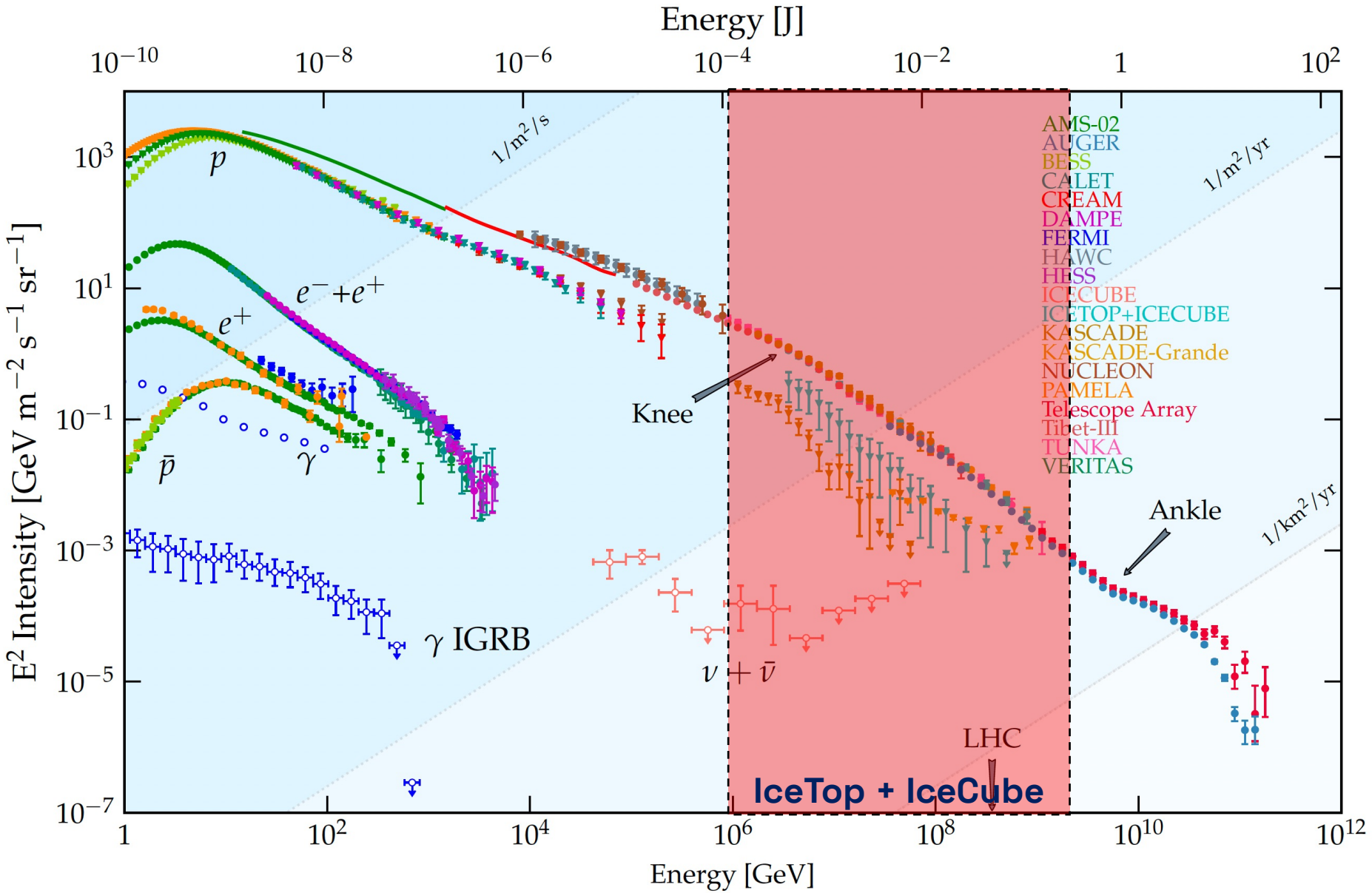
Direct Detection @ Edge of Atmosphere



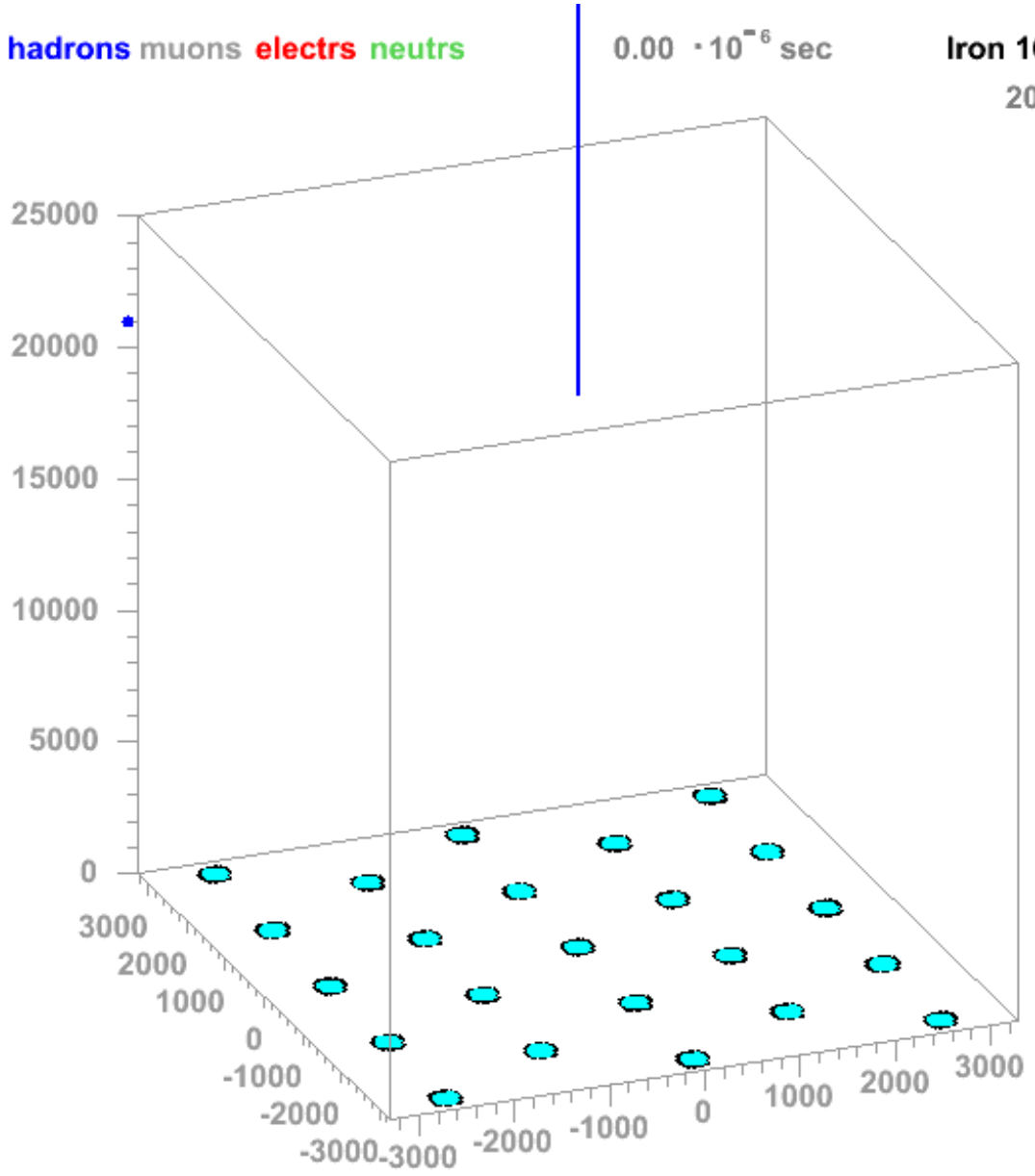


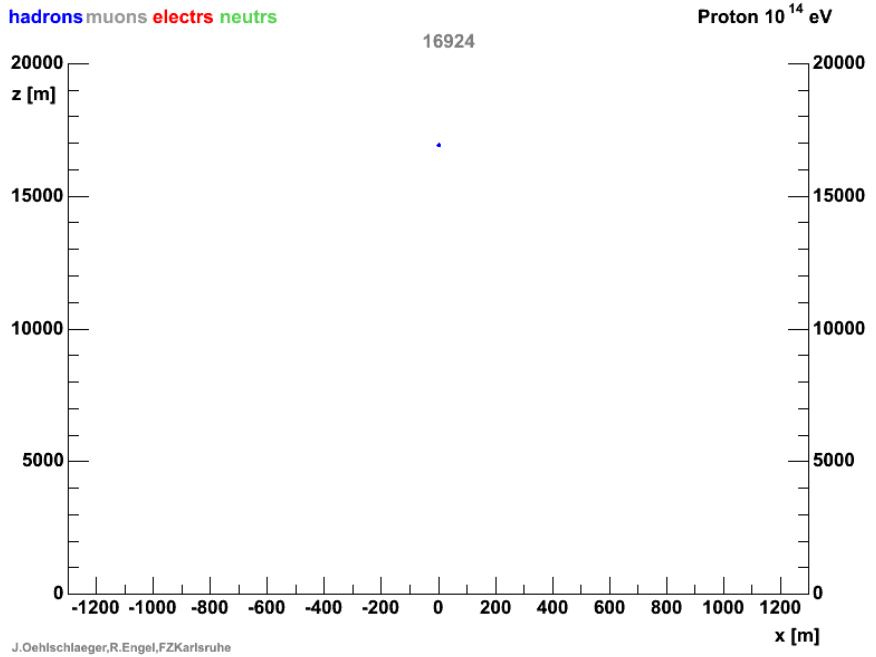
Upcoming Talk
Jun 6 (3:00pm) - Mike Duvernois
CR direct detection

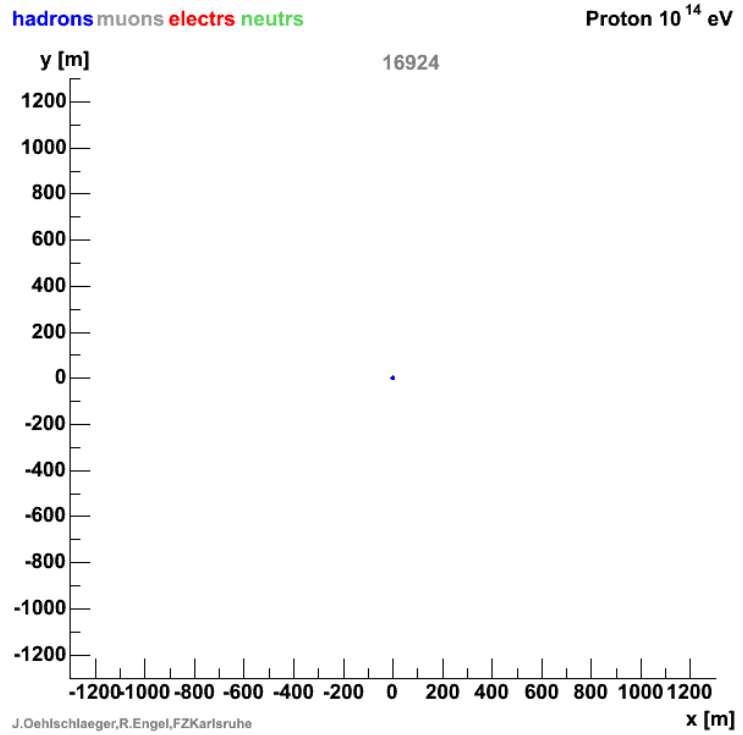
CR Spectrum


Energy [J]
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
E^2 Intensity [GeV m^{-2} s^{-1} sr^{-1}]
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$1/m^2/s$
$1/m^2/yr$
$1/km^2/yr$
p
$e^- + e^+$
e^+
$\bar{p}$
γ
γ IGRB
$\nu + \bar{\nu}$
Knee
Ankle
LHC
IceTop + IceCube
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS
1
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
10^{12}
Energy [GeV]

EAS : The Movie



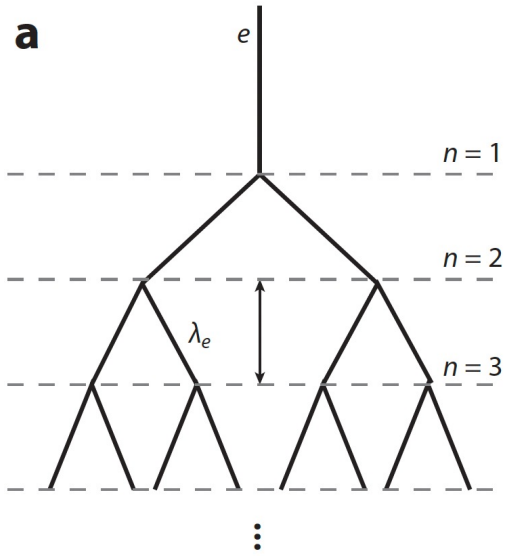




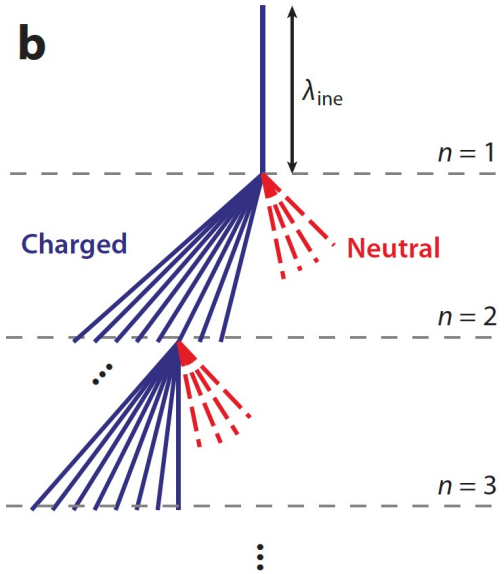
Indirect Detection using Extensive Air Shower

Heitler-Matthews Model

EM Shower

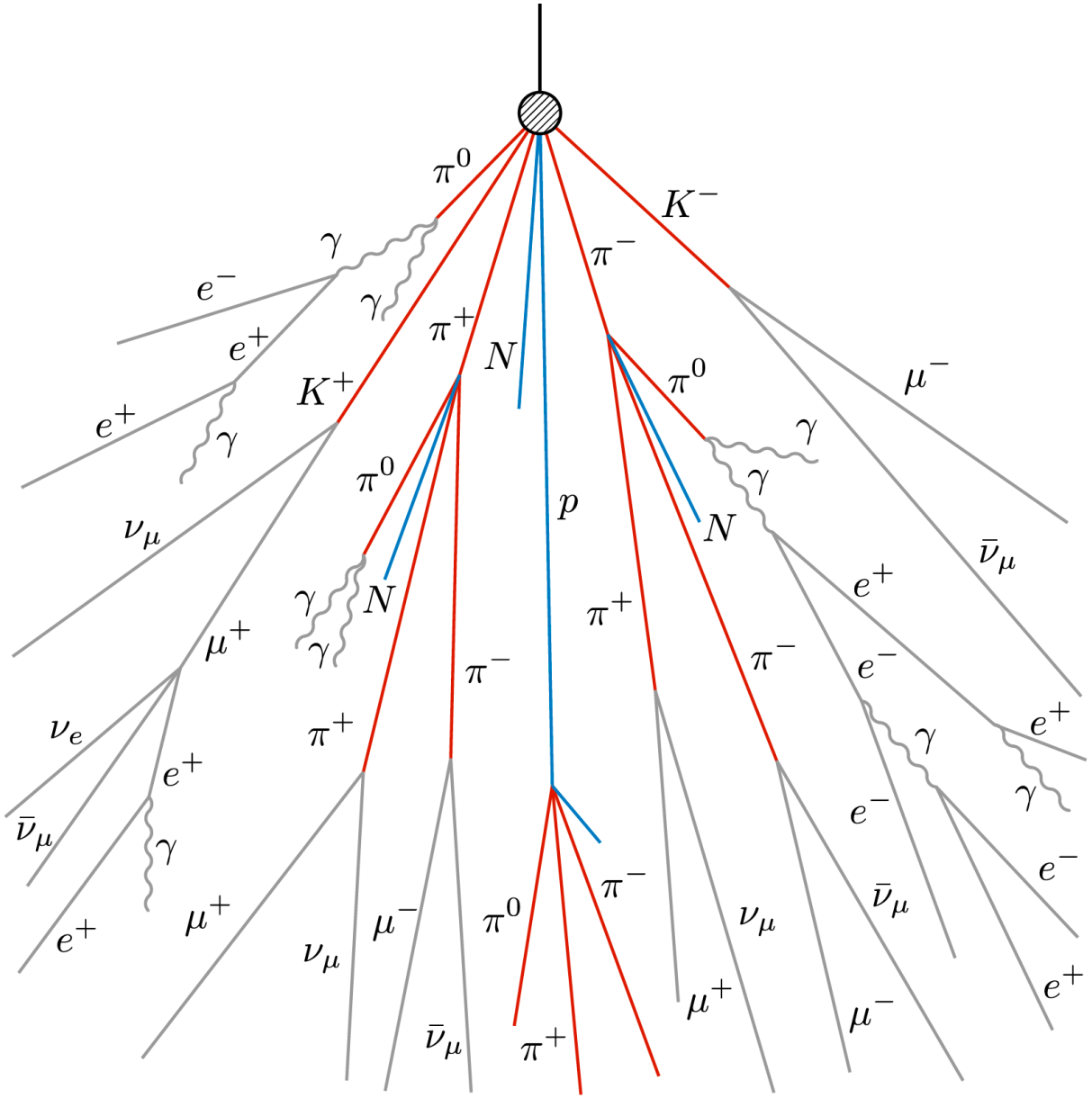


Hadronic Shower

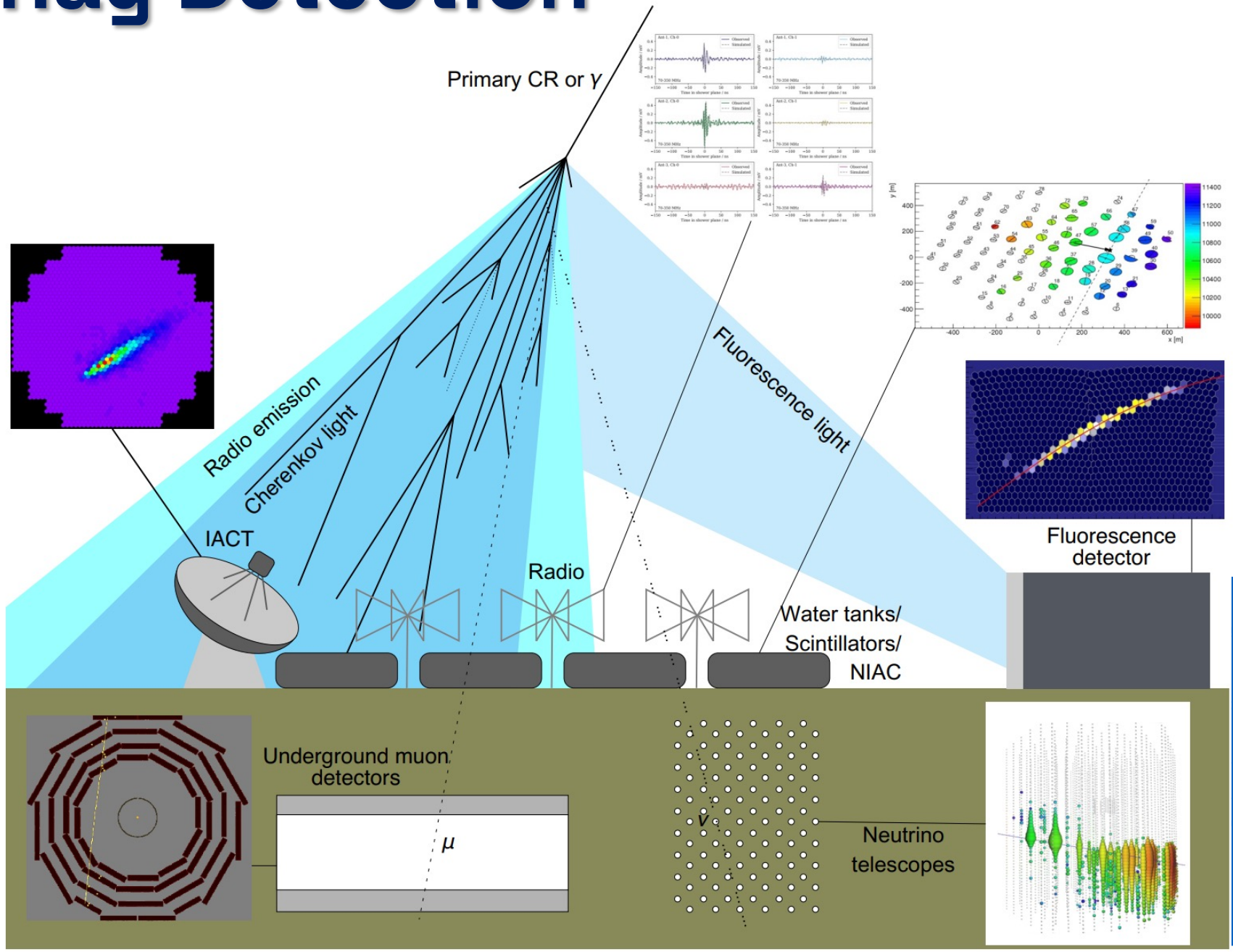


Simplified model to explain particle cascade production in atmosphere

Good enough to understand correlation between various observables → Details upcoming in the talk @ the CR School

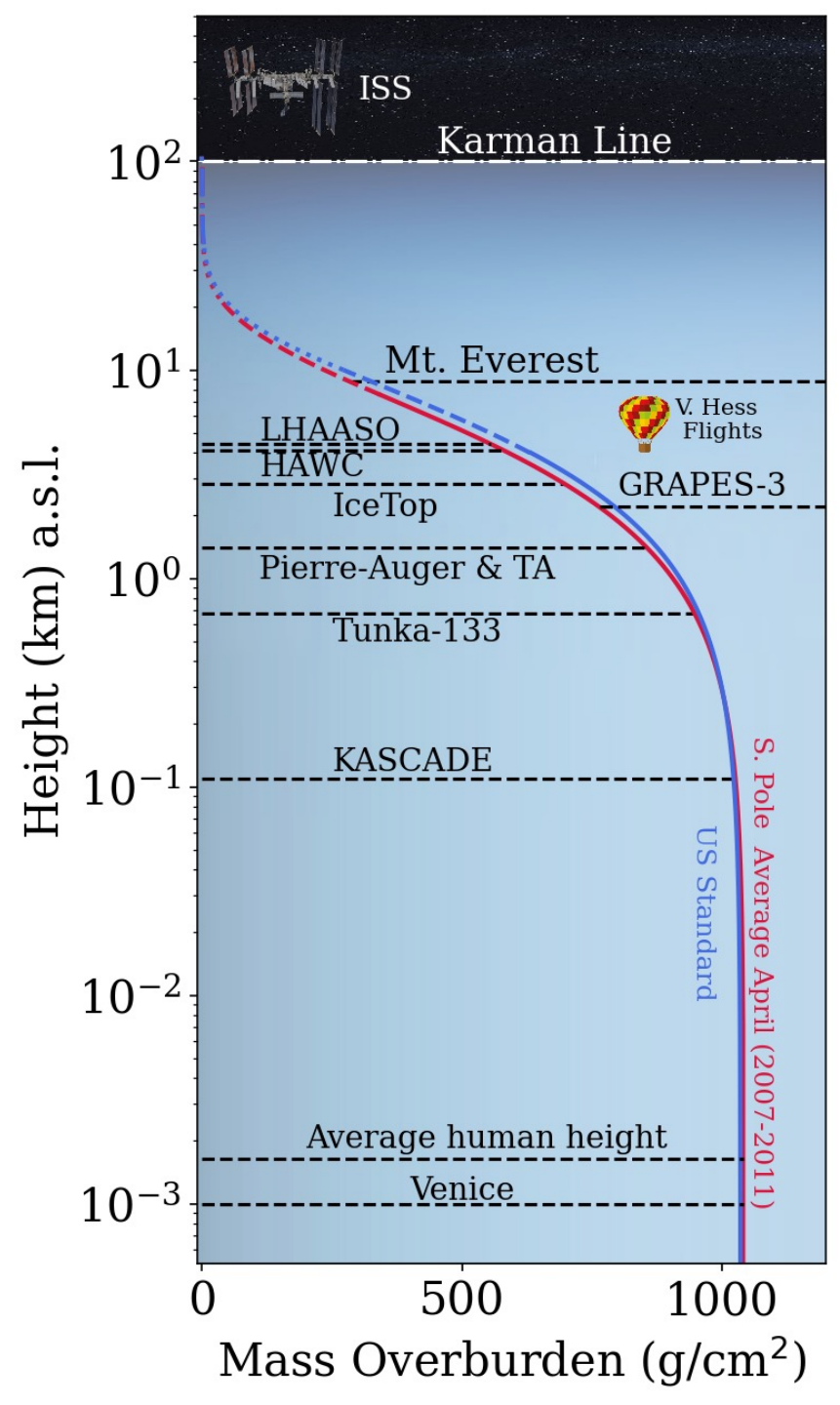


Cosmic Ray Detection

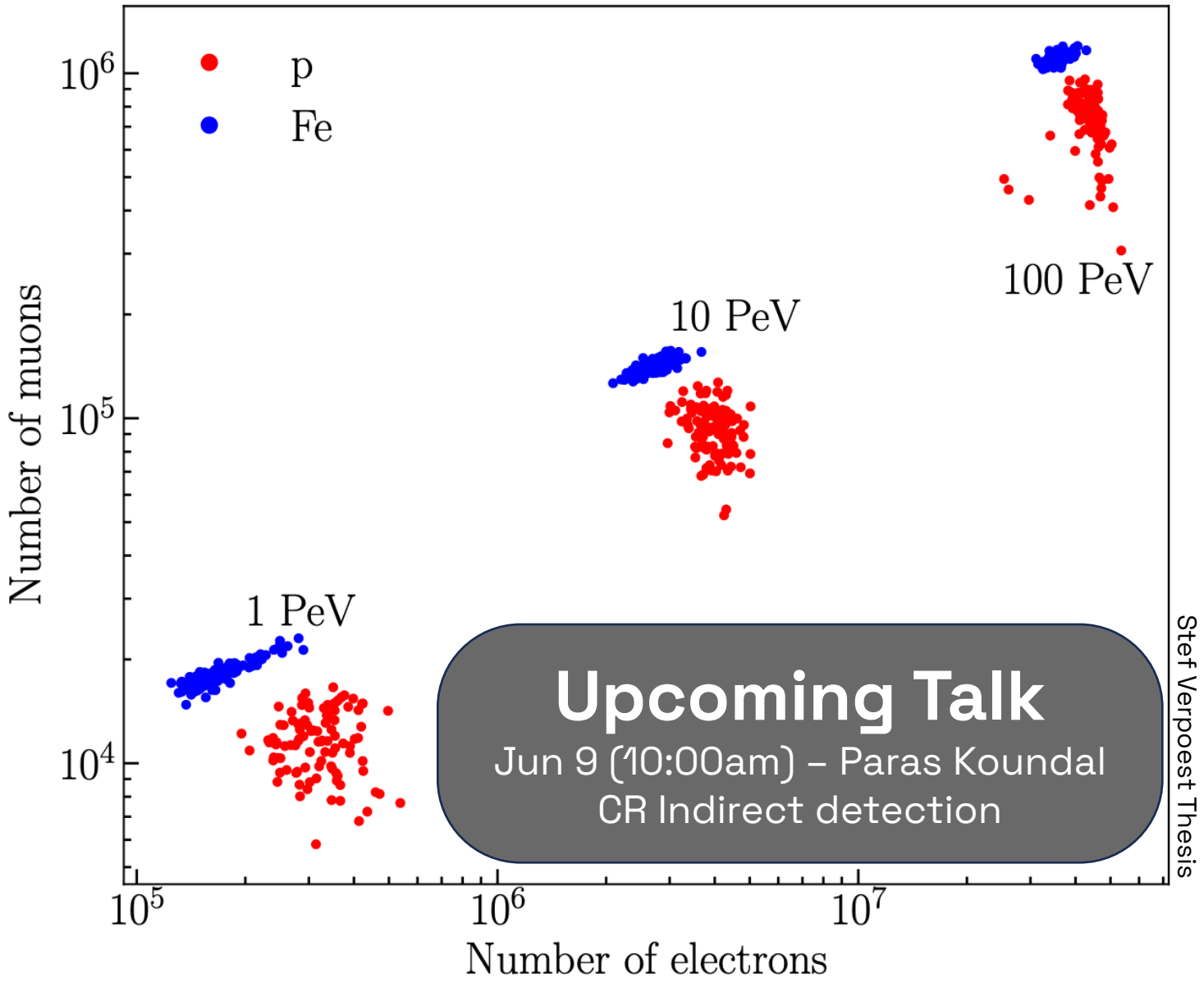


doi.org/10.1016/j.astropartphys.2023.102819


LHAASO : ≈ 4.41 km


ISS
Karman Line
Mt. Everest
V. Hess
Flights
LHAASO
HAWC
GRAPES-3
IceTop
Pierre-Auger & TA
Tunka-133
KASCADE
US Standard
S. Pole Average April (2007-2011)
Average human height
Venice
Height (km) a.s.l.
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
0
500
1000
Mass Overburden (g/cm^2)

EAS : Particle Numbers

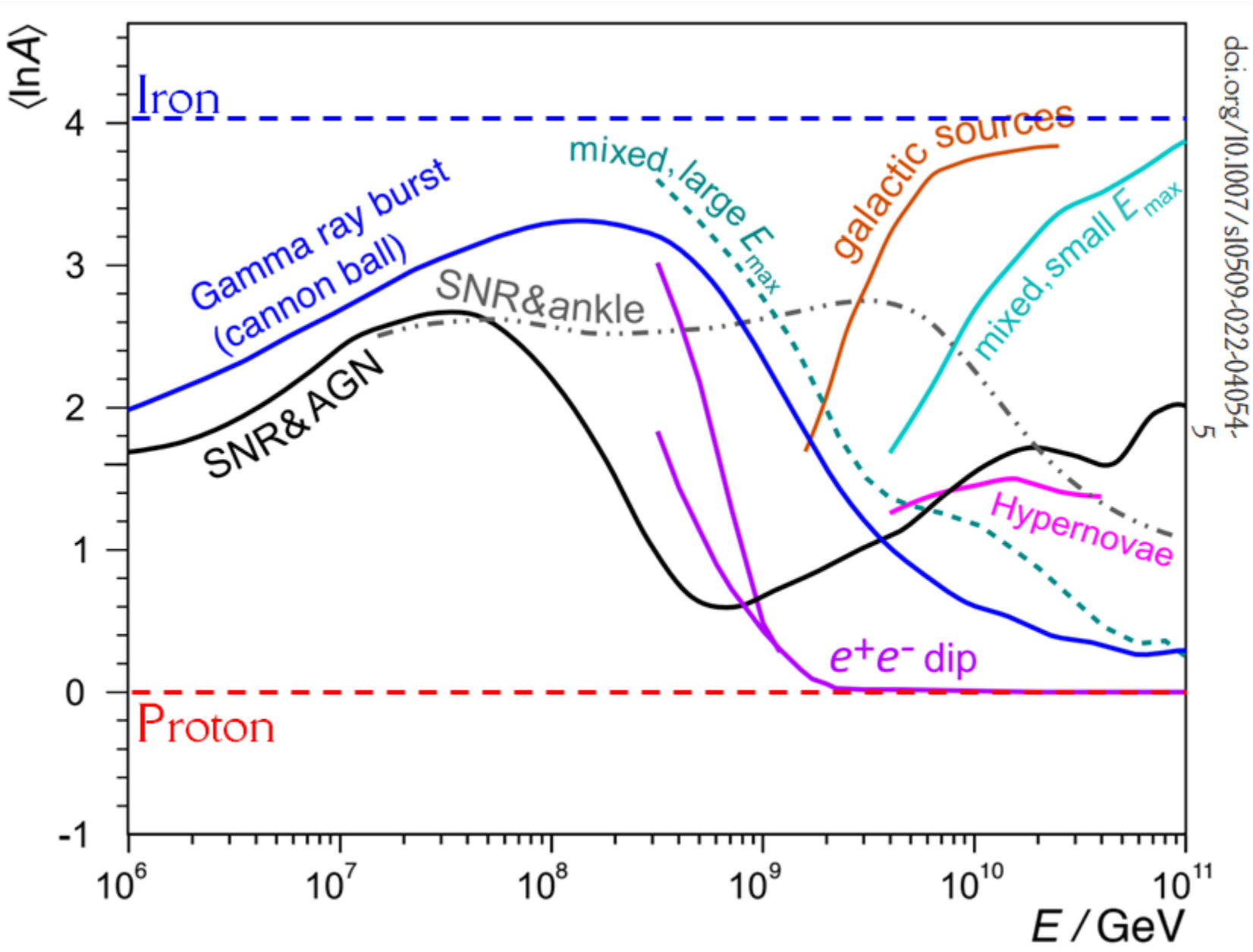


Upcoming Talk

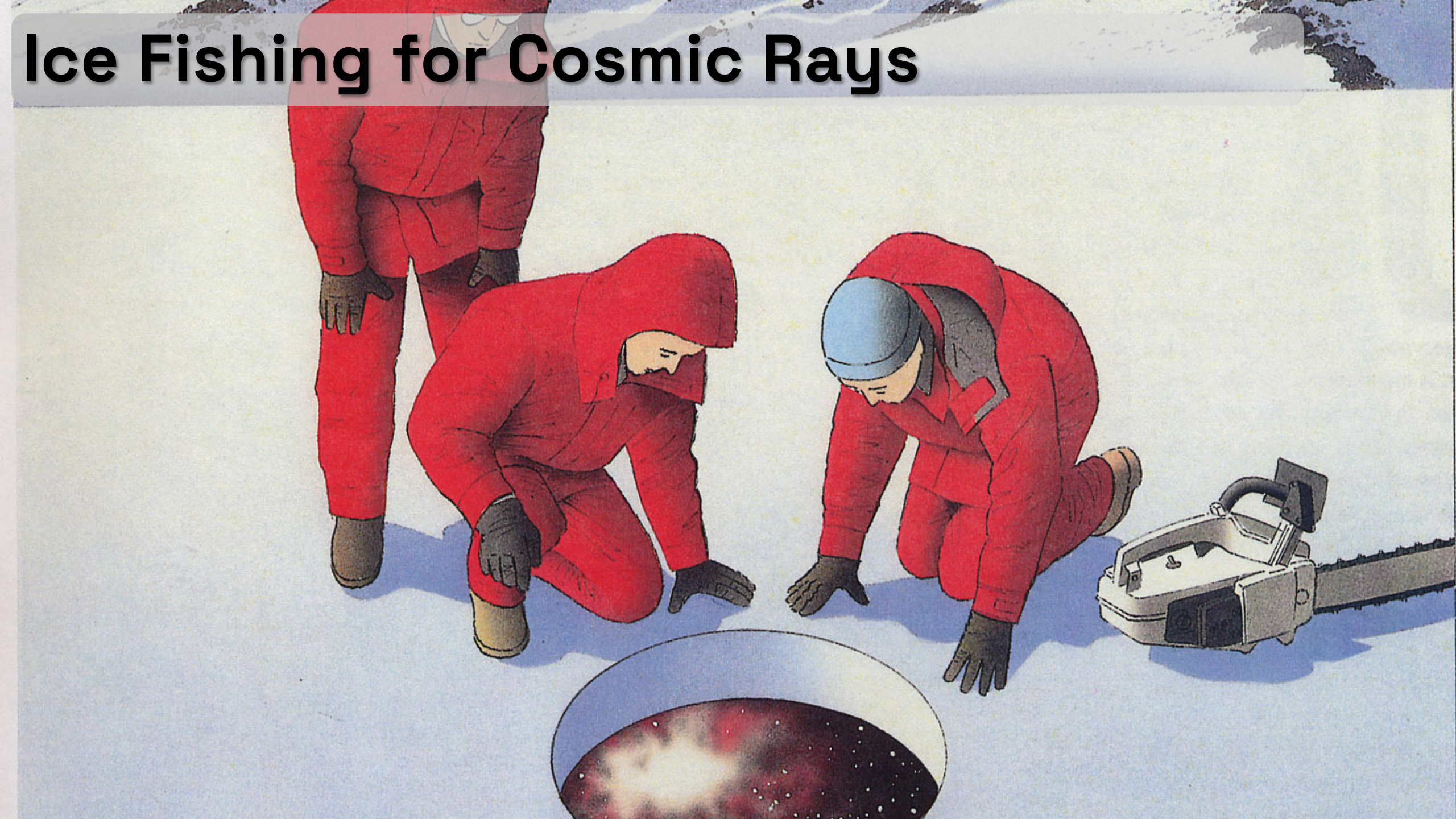
Jun 9 (10:00am) – Paras Koundal

CR Indirect detection

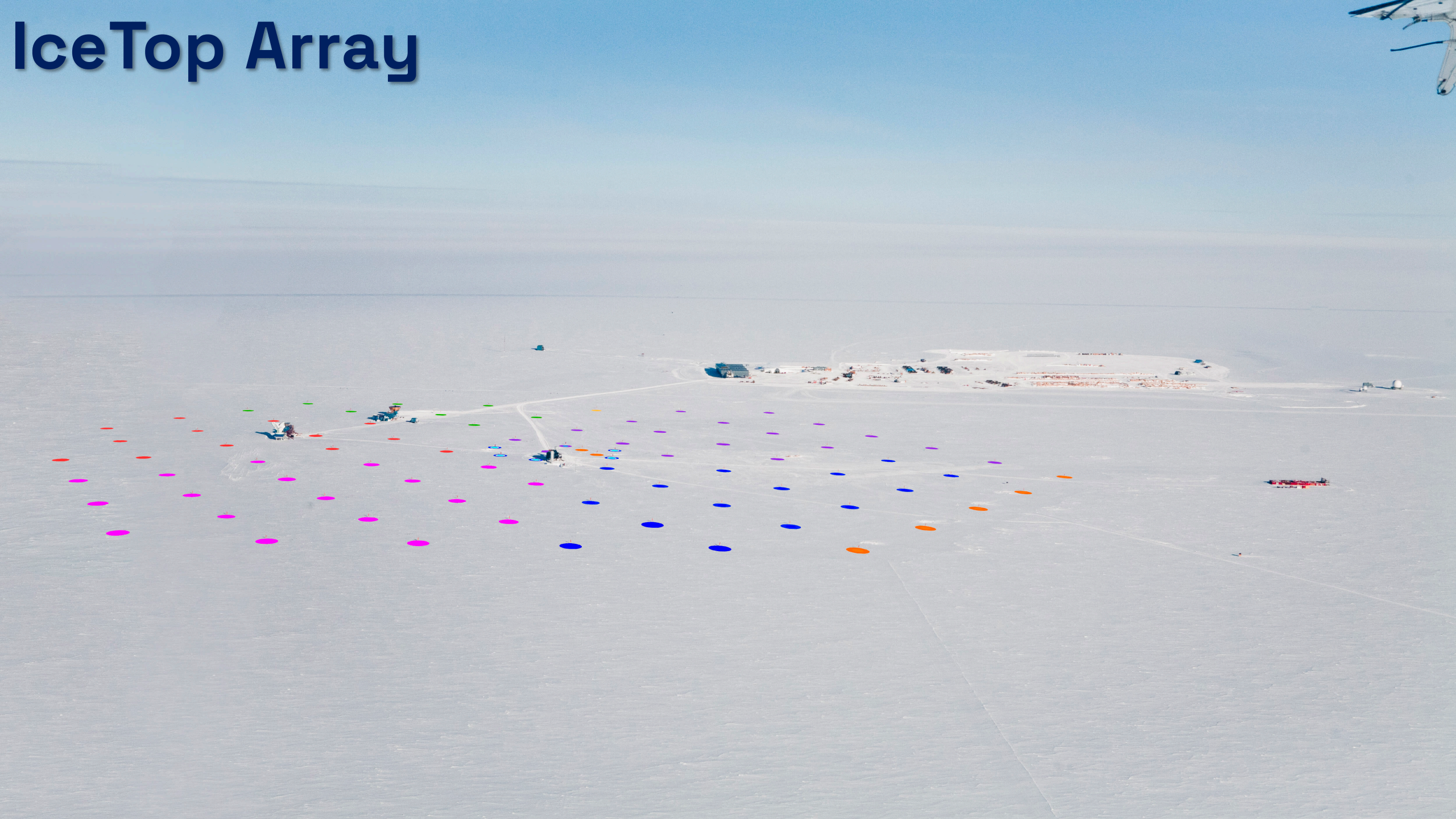
Why Energy & Composition?



Ice Fishing for Cosmic Rays

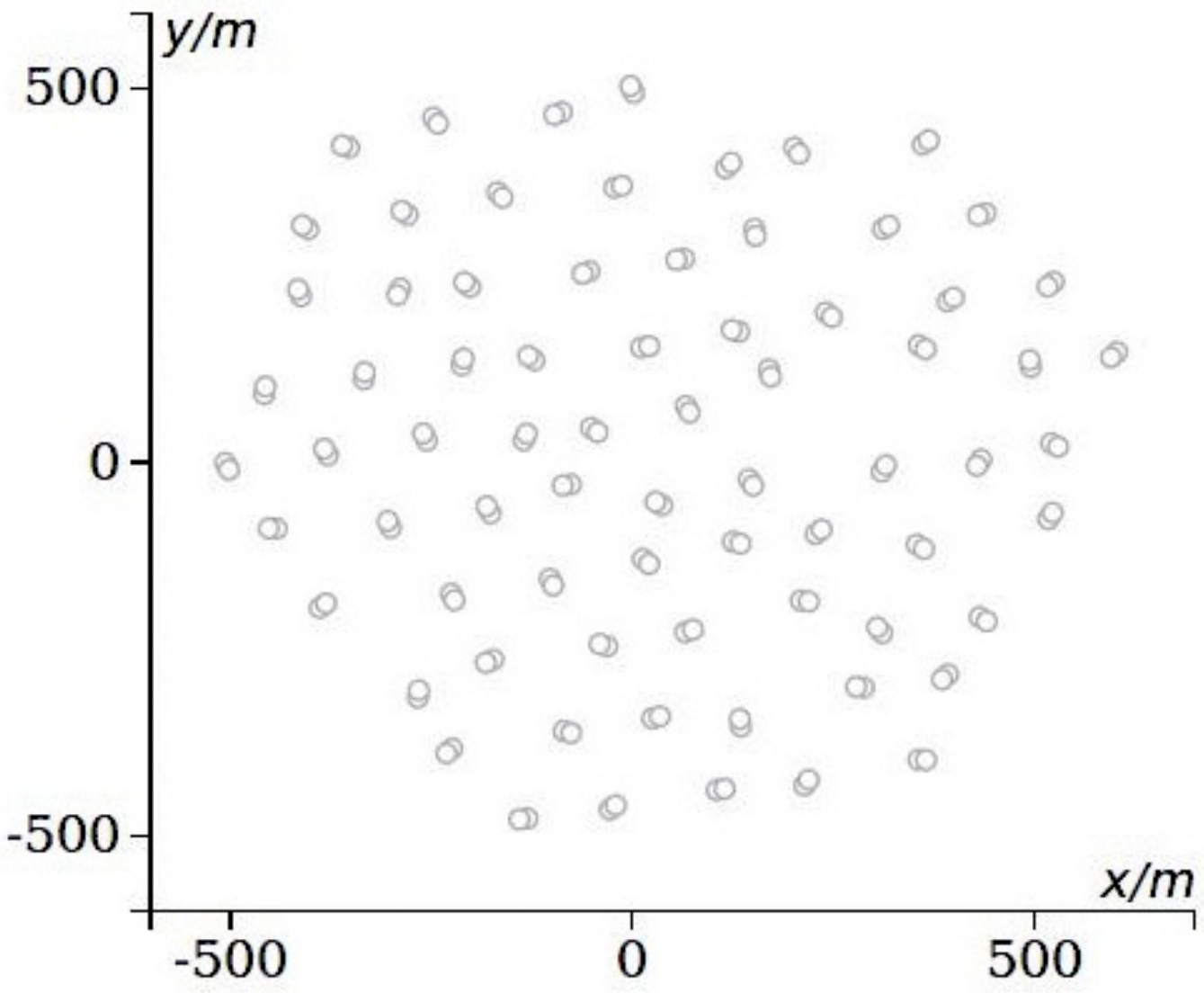


IceTop Array



IceTop Station

Core & Direction

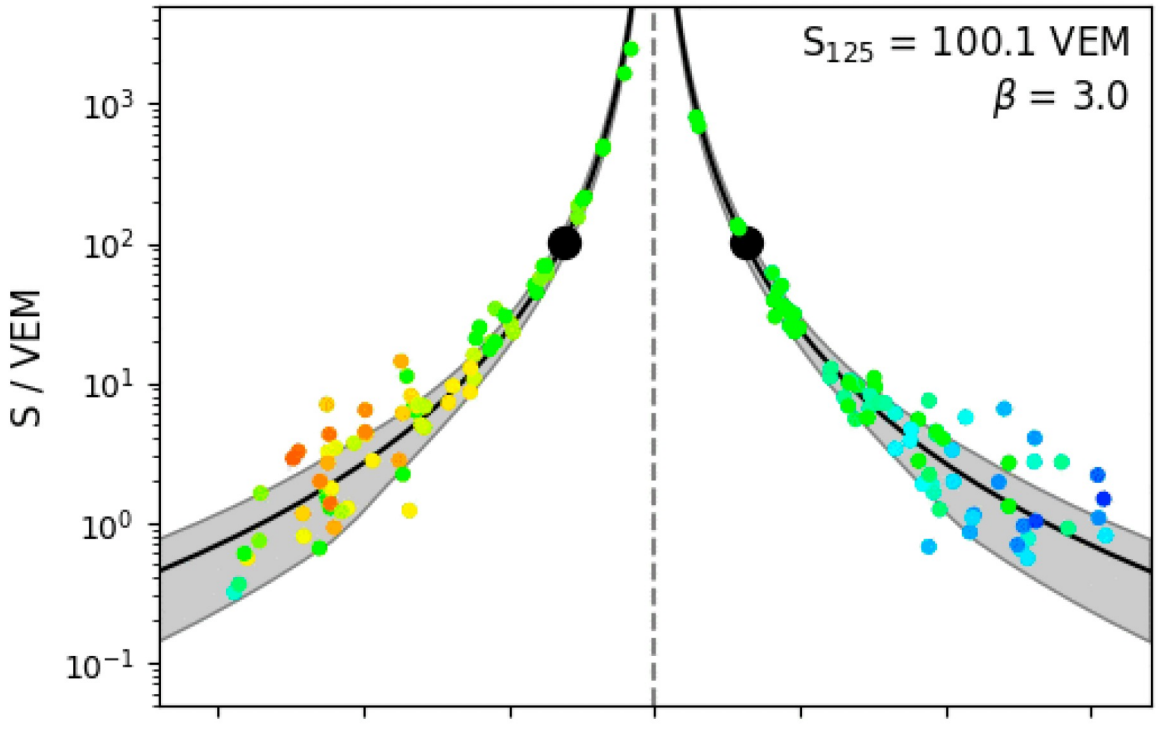


Practice Yourself

In reality

Complex likelihoods considering spatiotemporal, charge, saturation etc. information are built and minimized

Energy

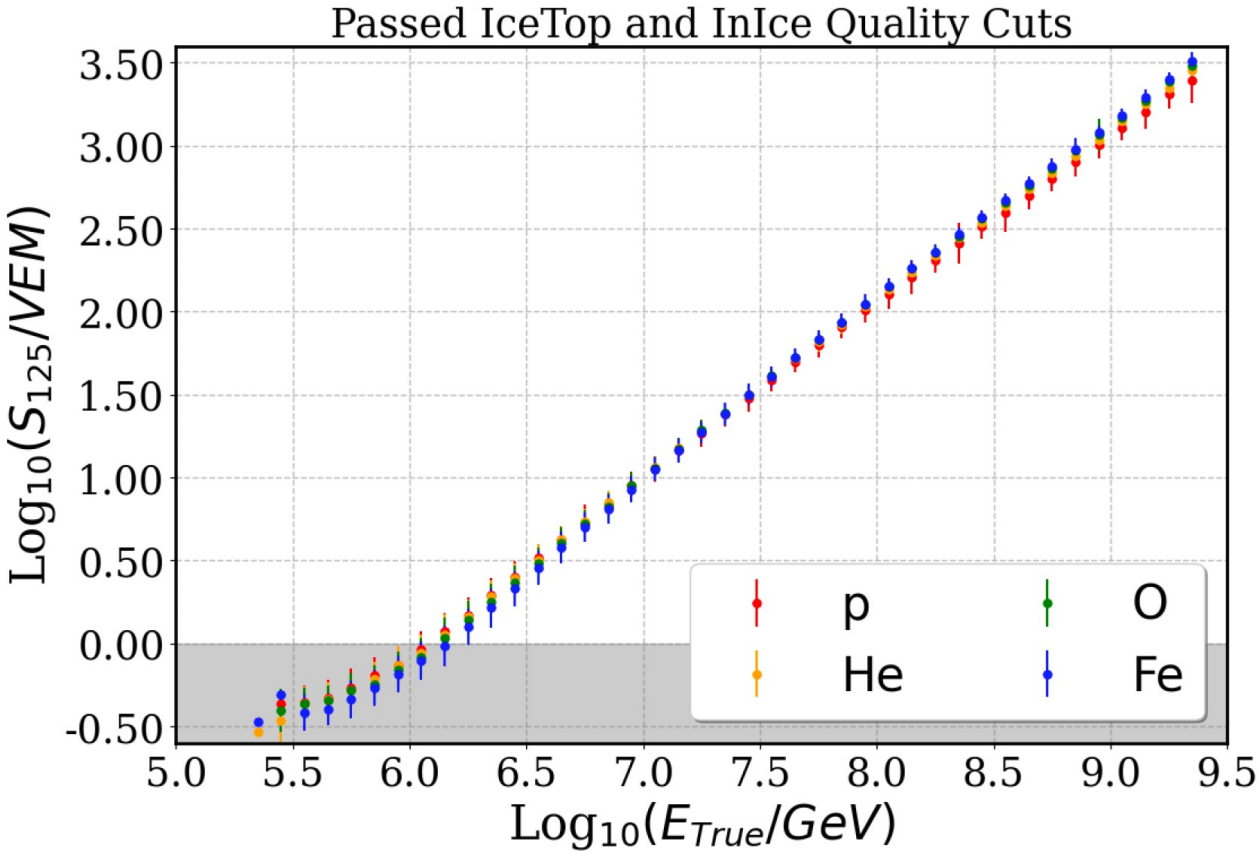


Measure of the steepness of the LDF

$$S = S_{125} \cdot \left(\frac{r}{125\ \mathrm{m}}\right)^{-\beta-\kappa\log_{10}\left(\frac{r}{125\,\mathrm{m}}\right)}$$

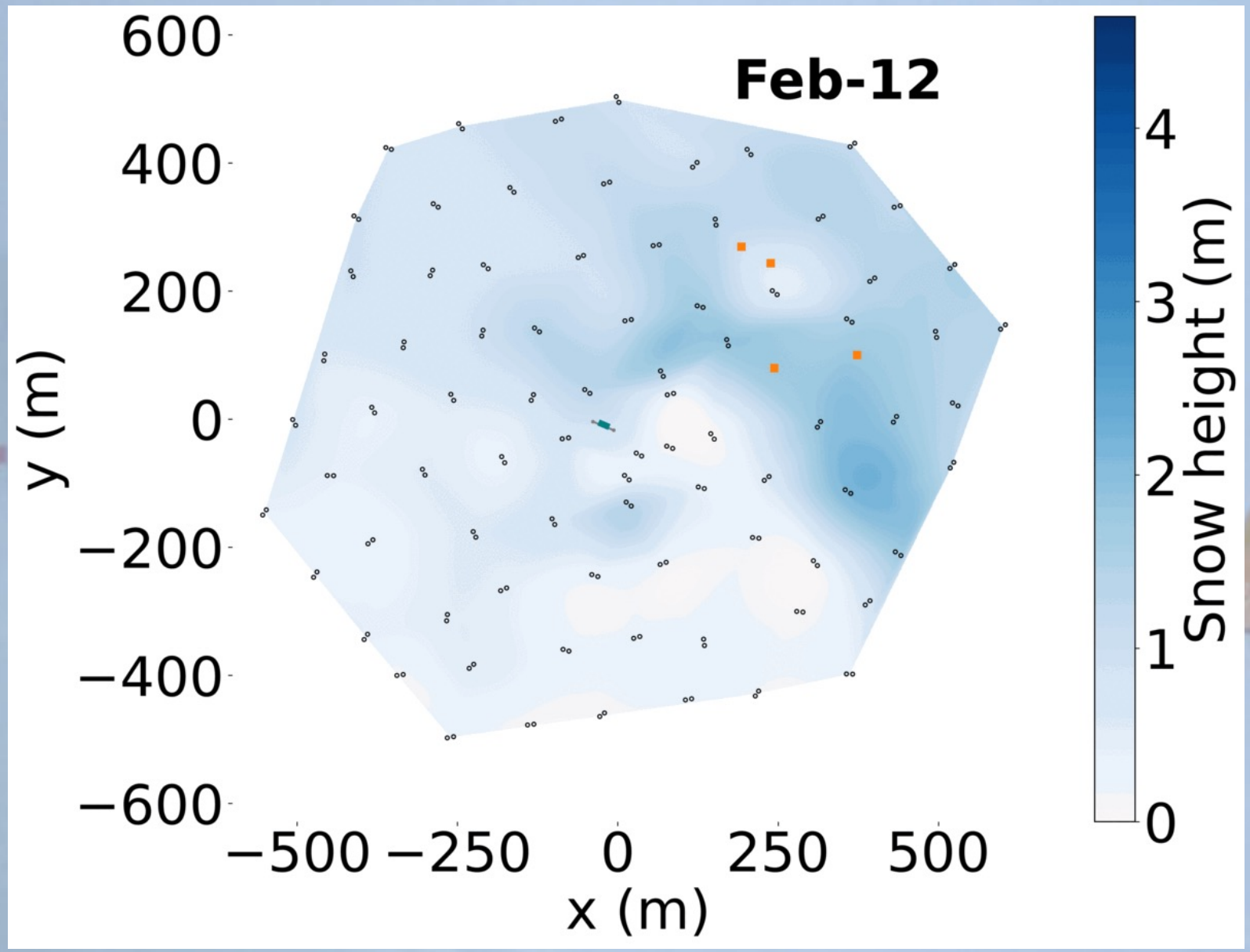
$\kappa \approx 0.303$

Signal expectation at 125 m from shower axis



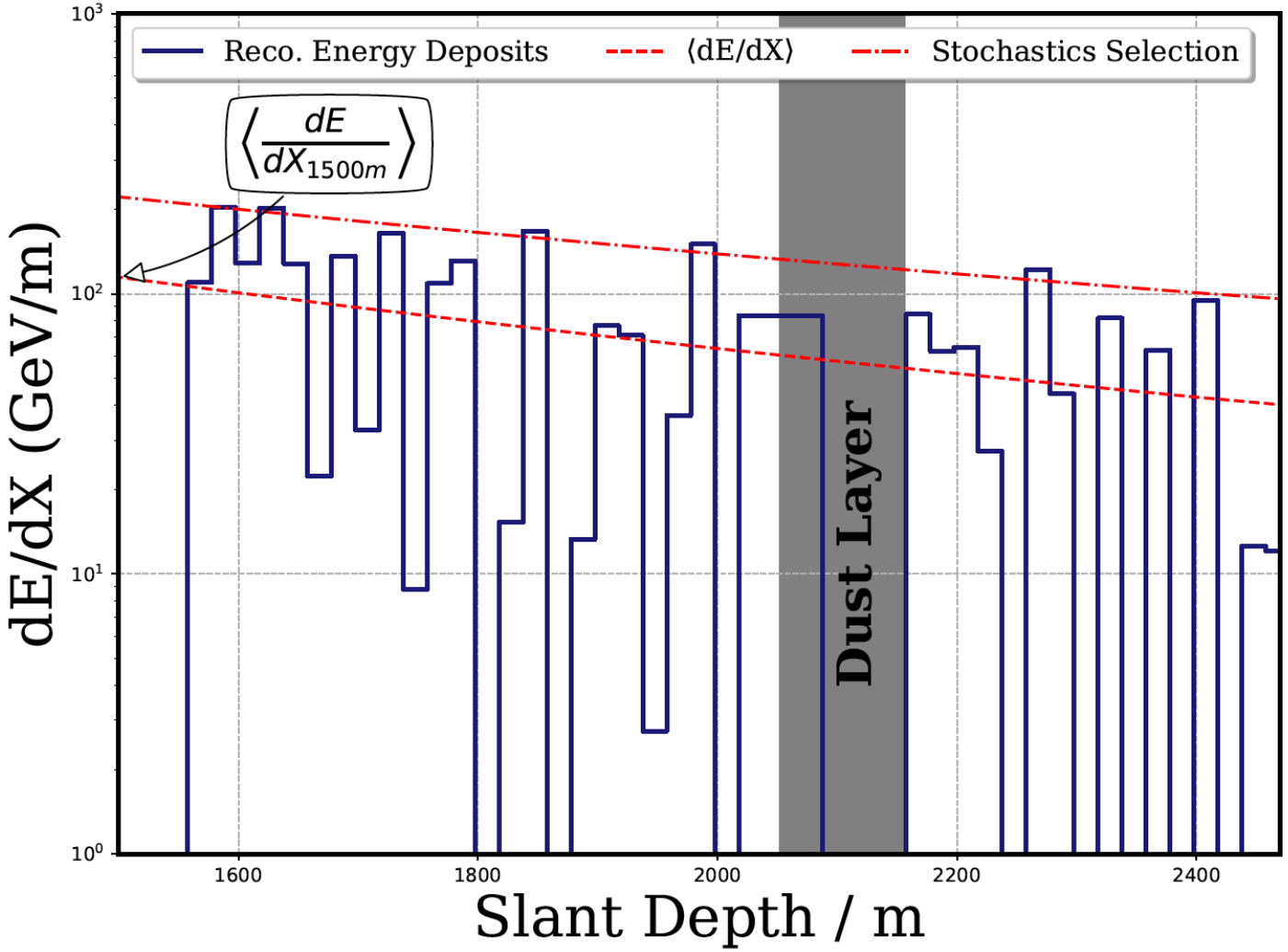
S_{125} is a good energy proxy

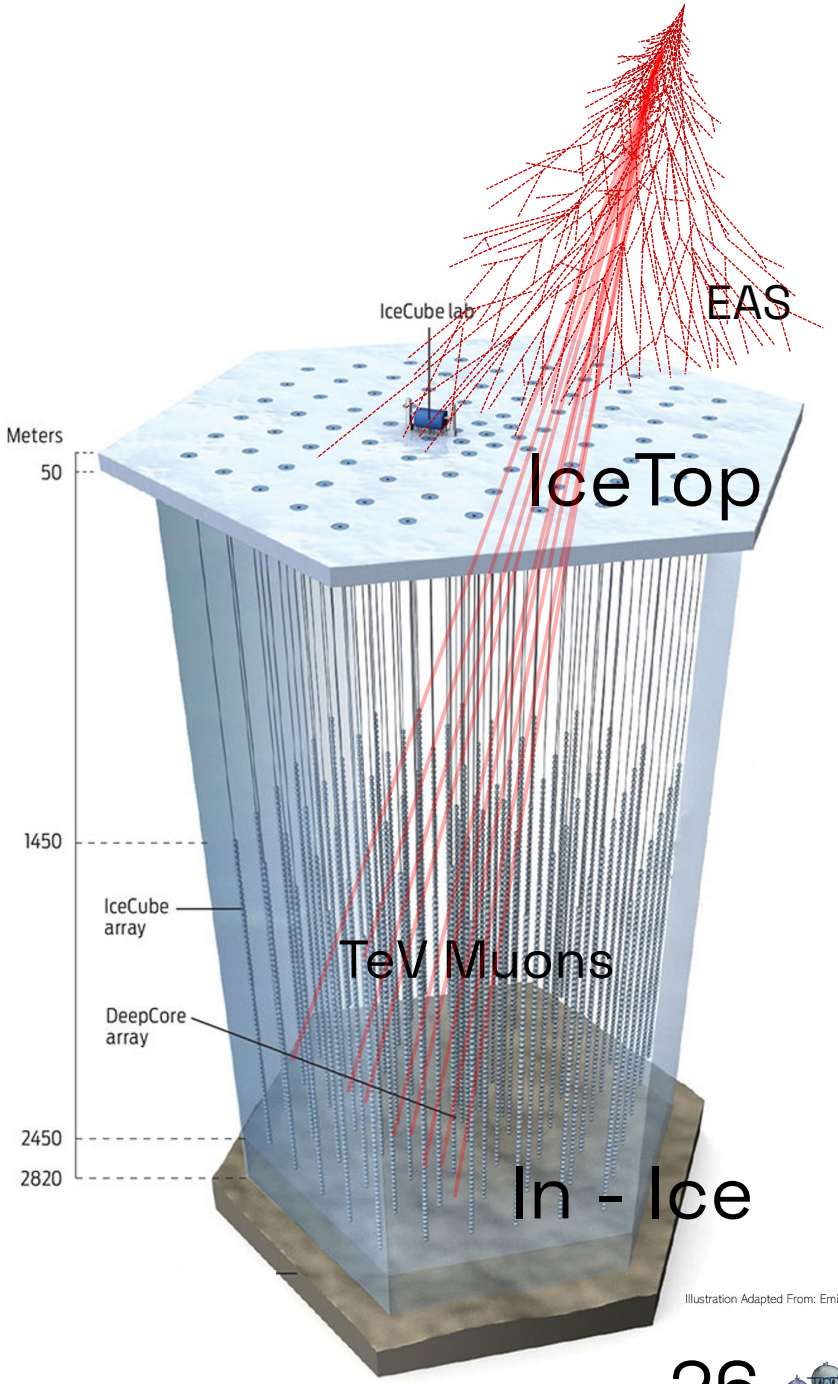
Energy Correction



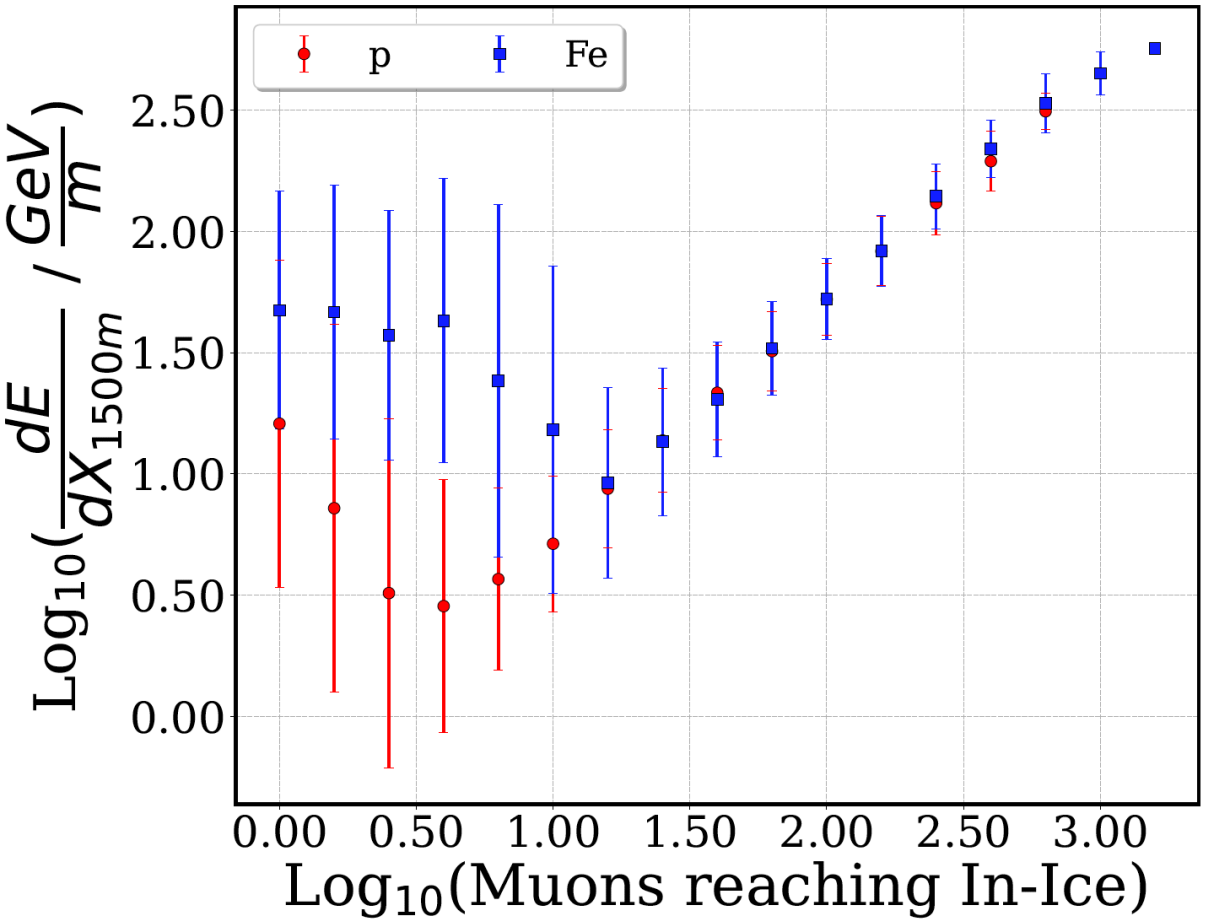
Composition

Direct muon counting is not possible





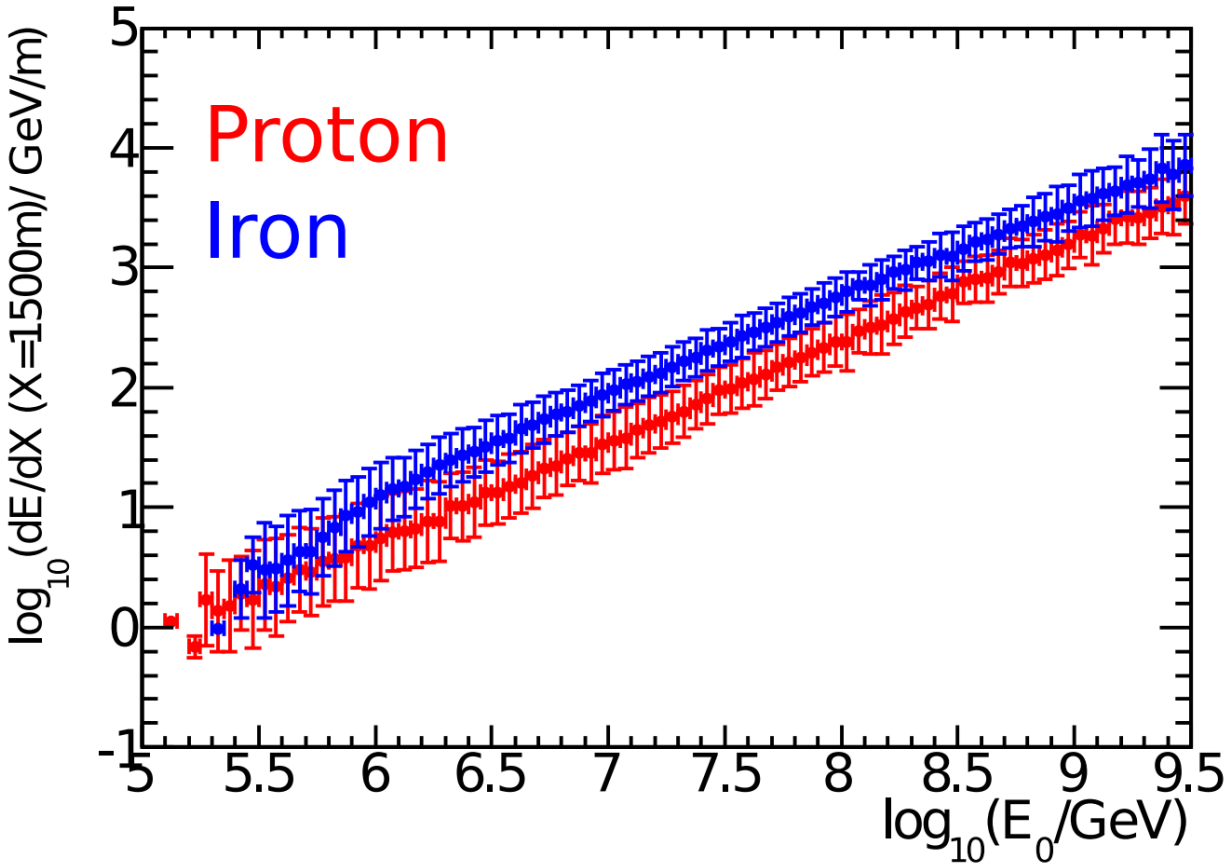
Composition



In-Ice Muon Energy deposit is a good proxy for muon-number

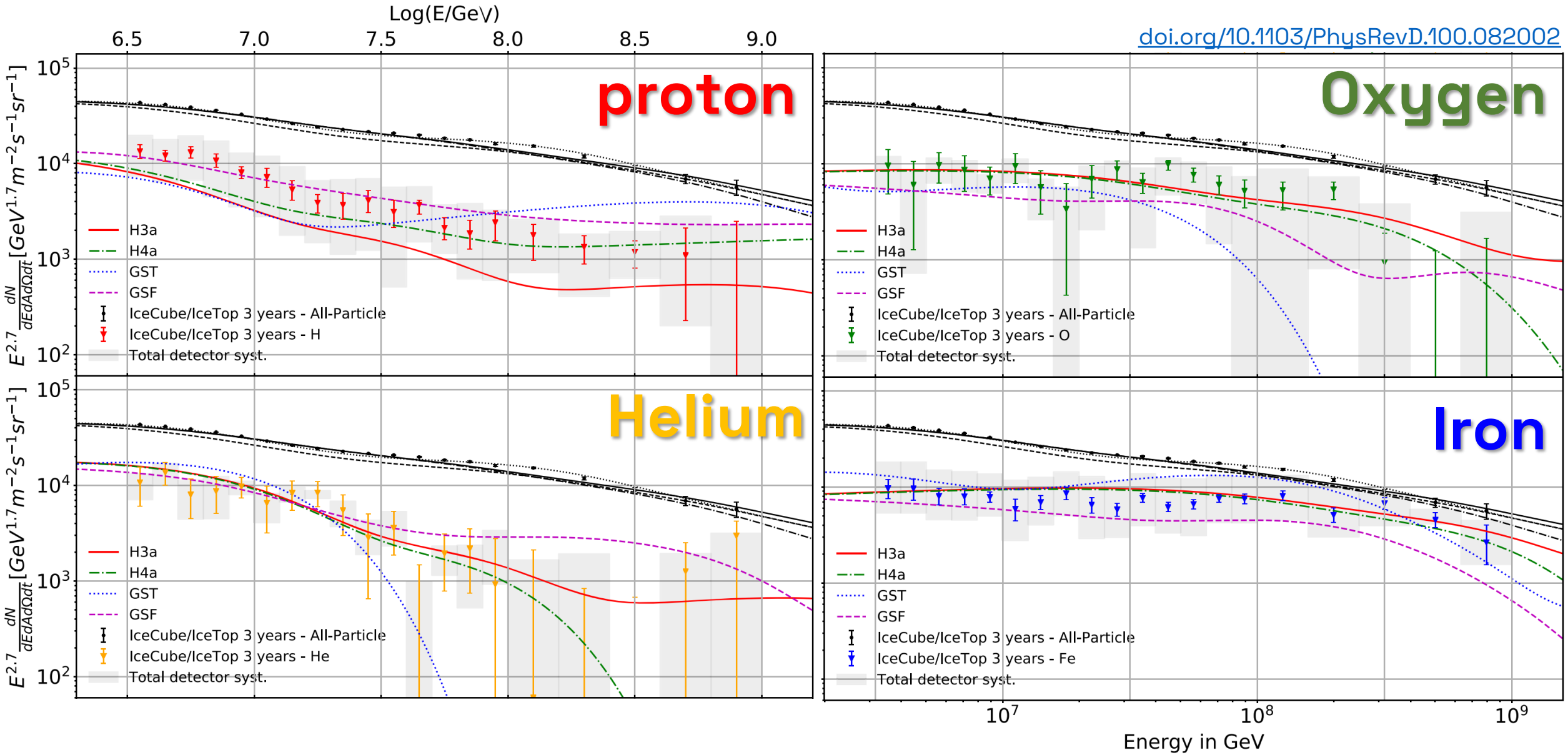
Elbert Formula

$$\langle N_\mu(>E_\mu, E_0, A, \theta)\rangle \approx \frac{14.5\mathrm{GeV}\cdot A}{E_\mu \cos(\theta)}\left(\frac{E_0}{A\cdot E_\mu}\right)^{0.757}\left(1-\frac{A\cdot E_\mu}{E_0}\right)^{5.25}$$

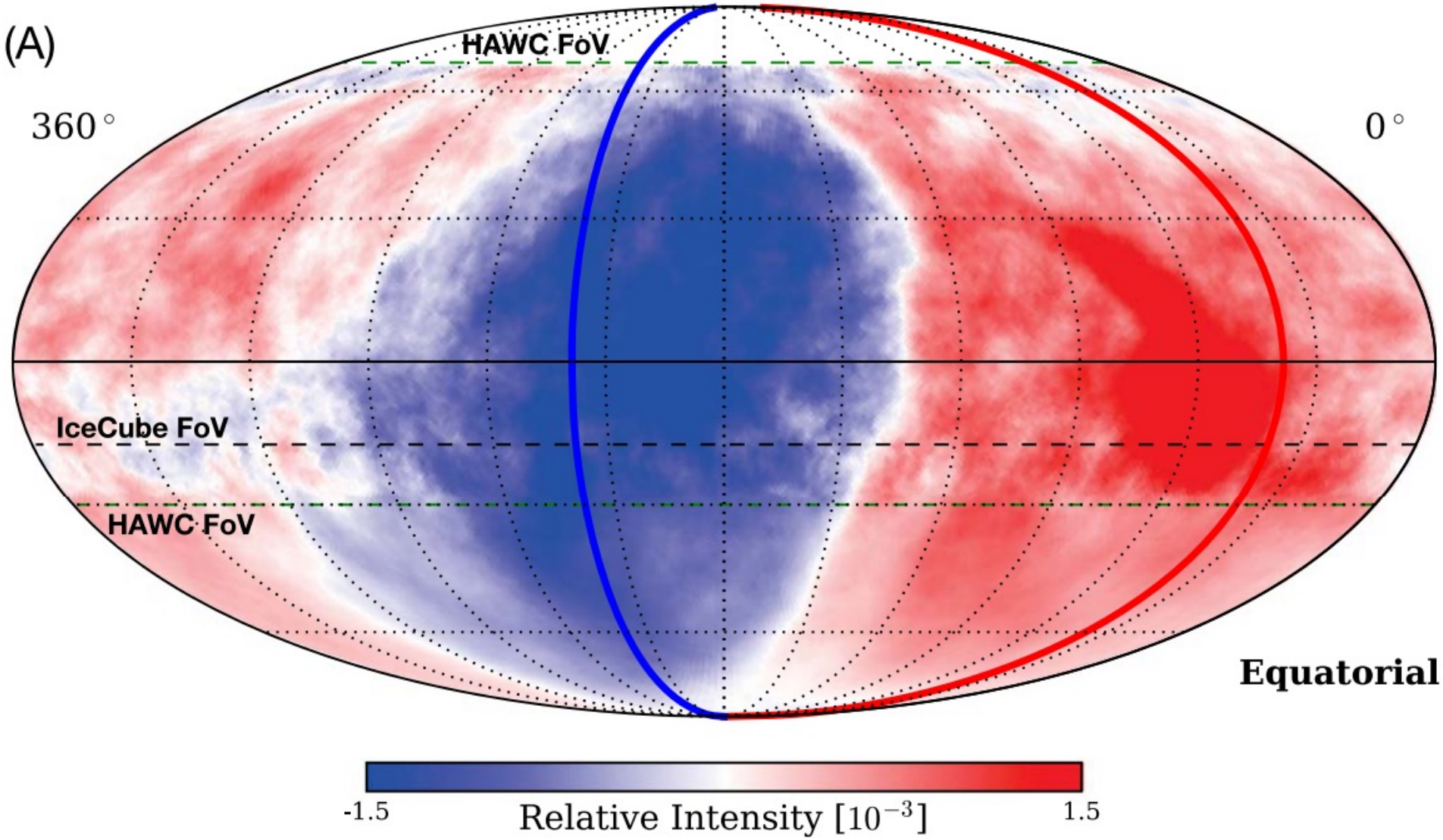


Spectrum

doi.org/10.1103/PhysRevD.100.082002

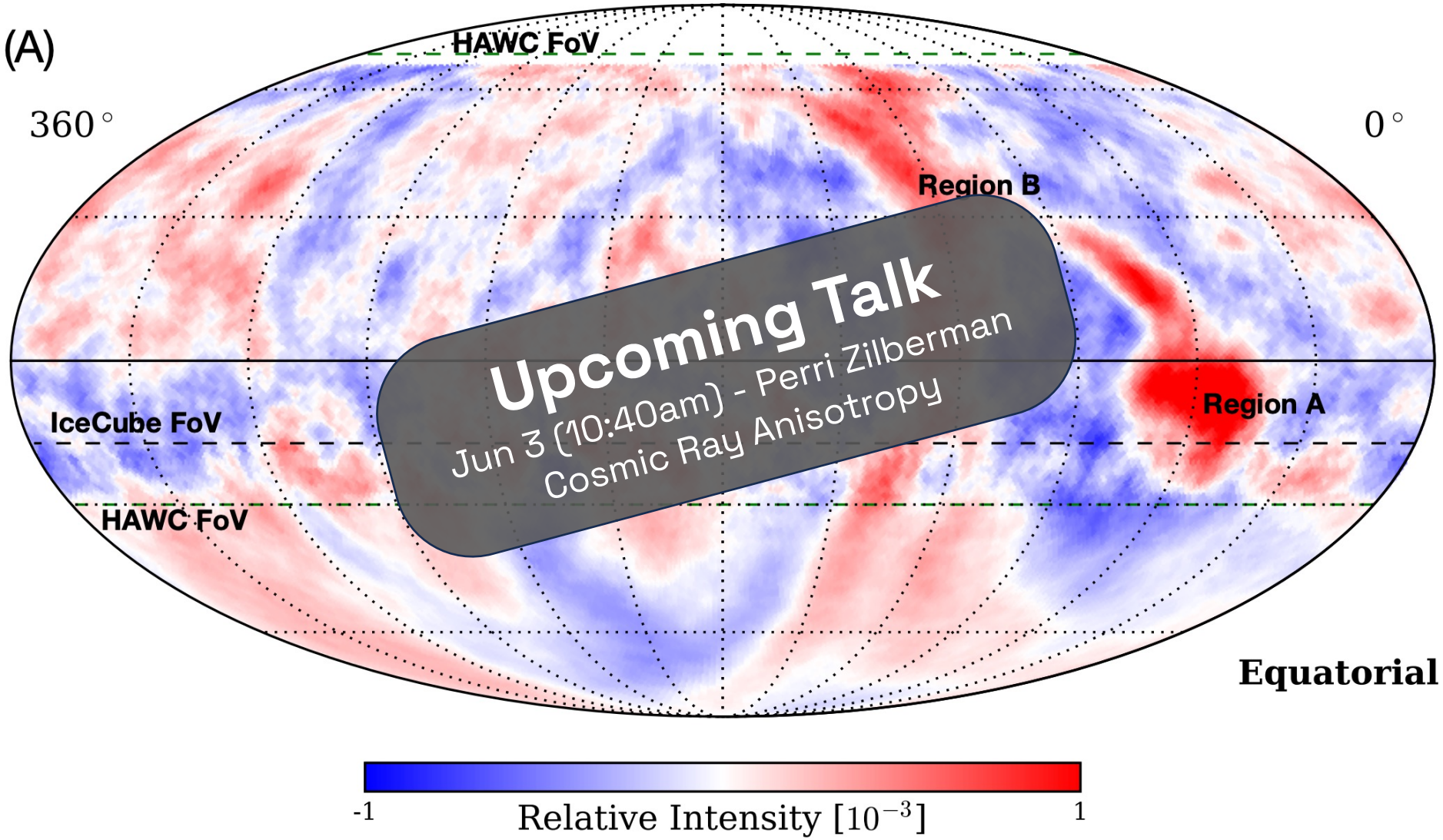


Anisotropy



doi.org/10.3847/1538-4357/aaf5cc

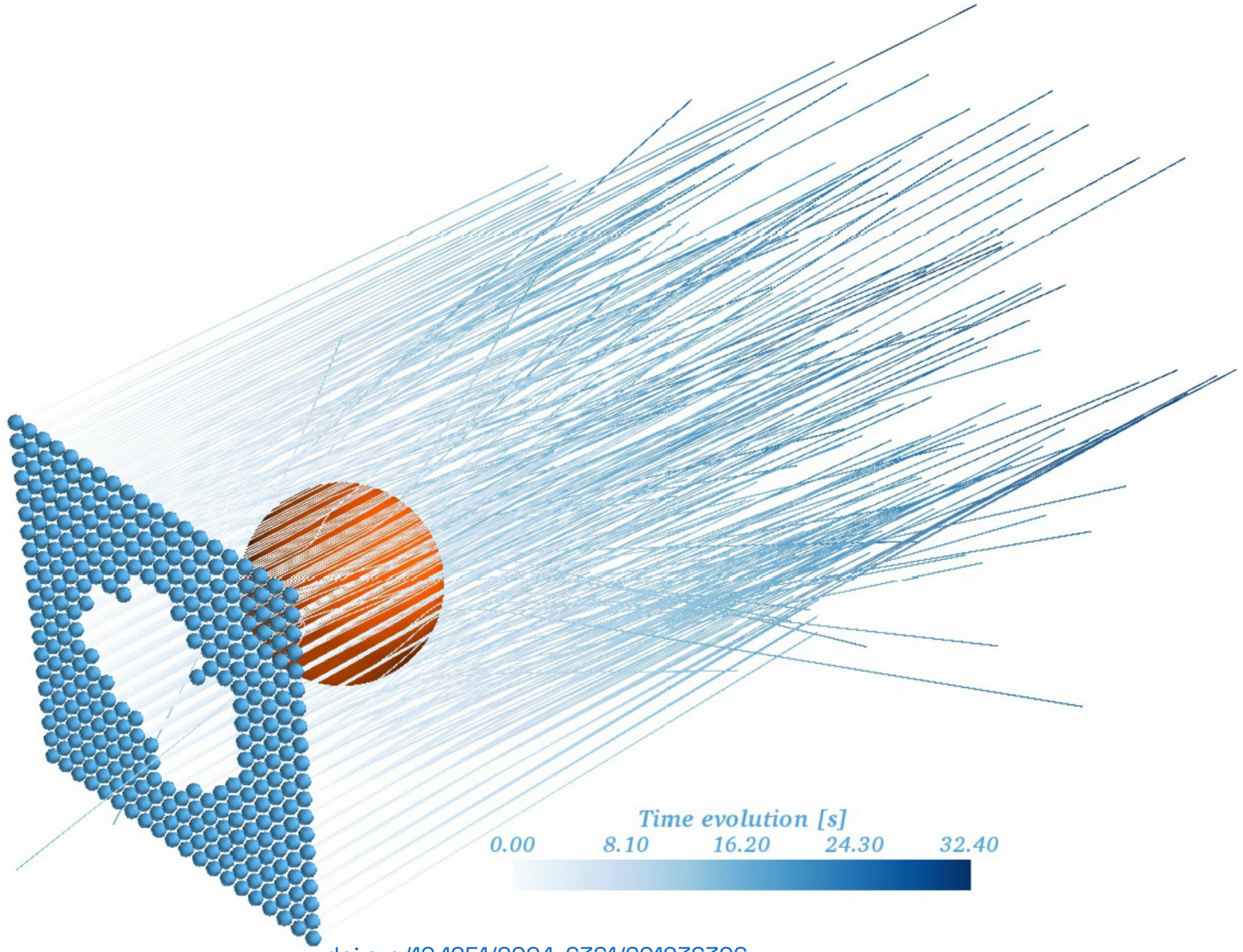
Anisotropy



Upcoming Talk
Jun 3 (10:40am) - Perri Zilberman
Cosmic Ray Anisotropy

doi.org/10.3847/1538-4357/aaf5cc

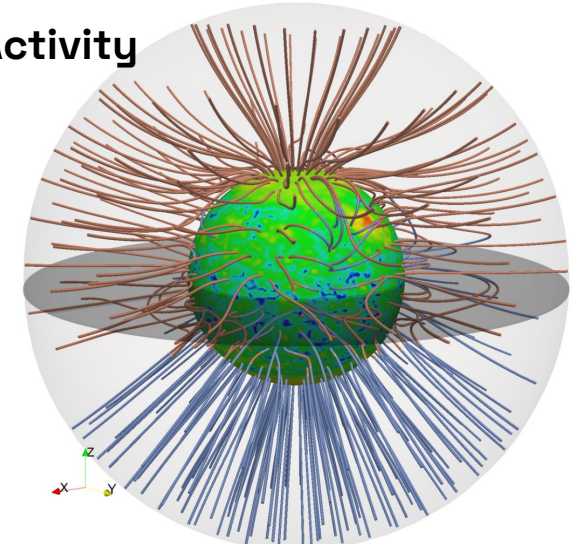
Sun & Moon Shadow



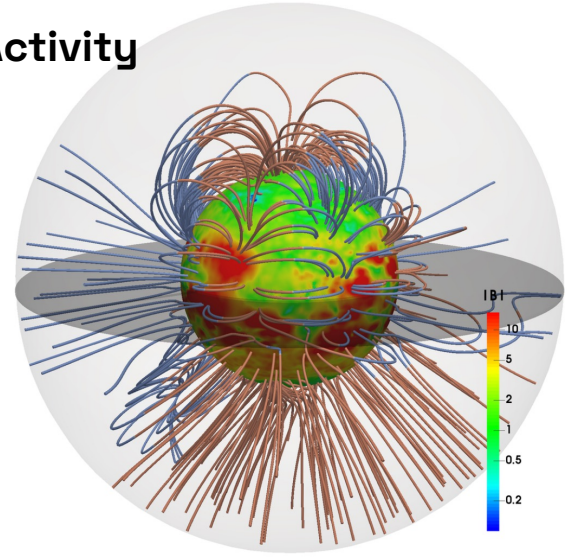
doi.org/10.1051/0004-6361/201936306

Solar Magnetic Field

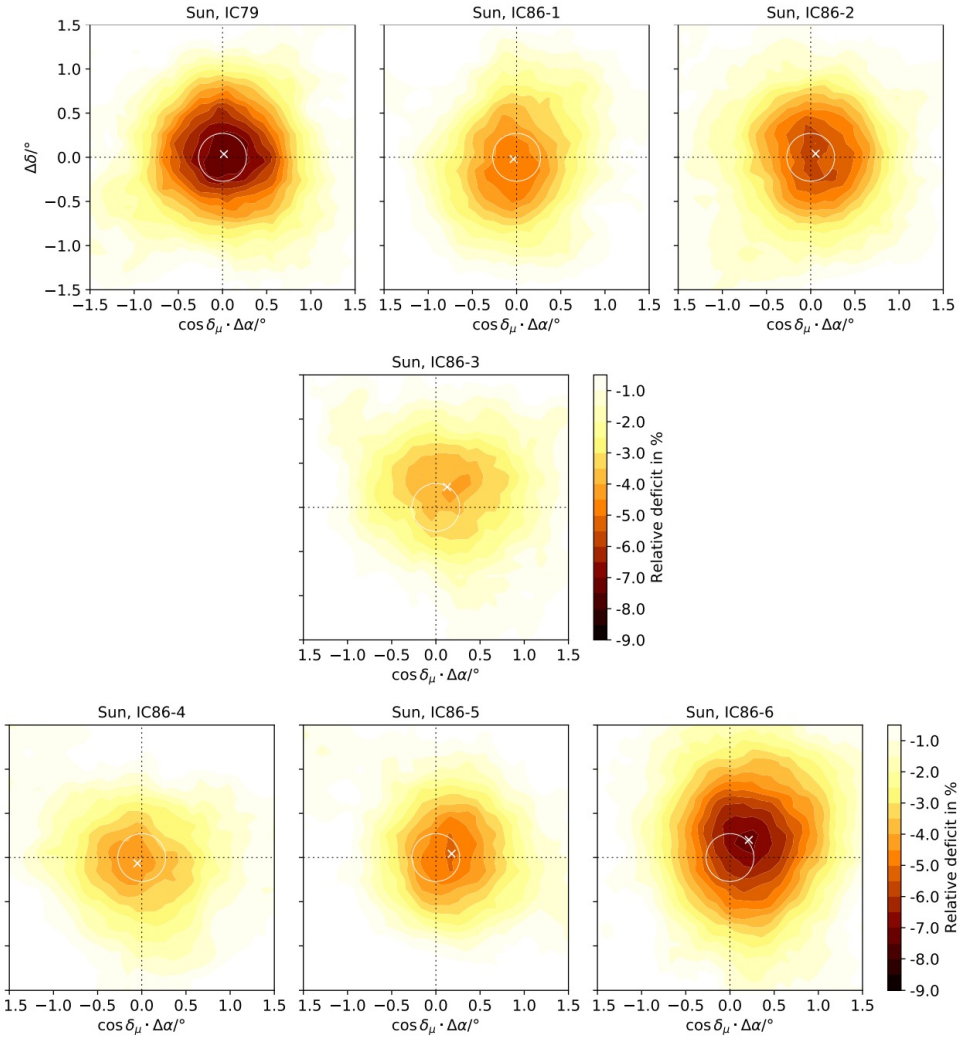
Low Activity

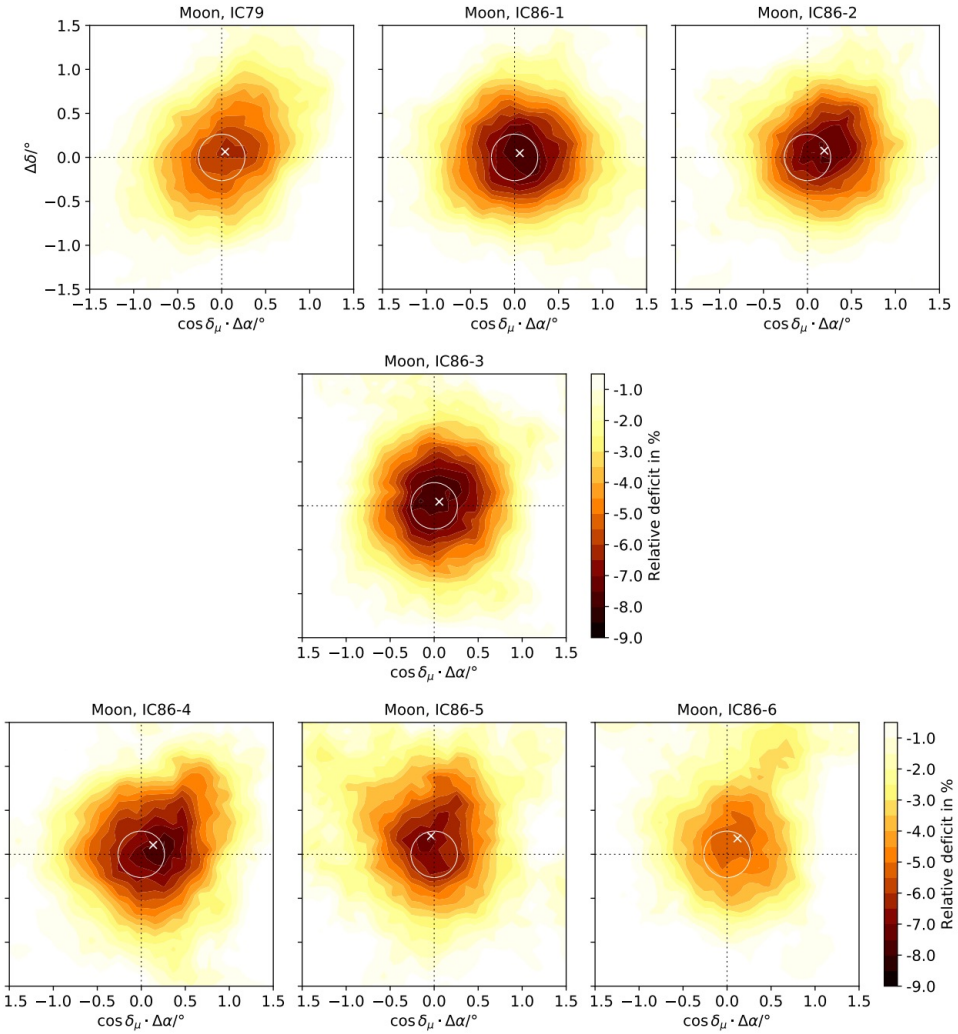


High Activity



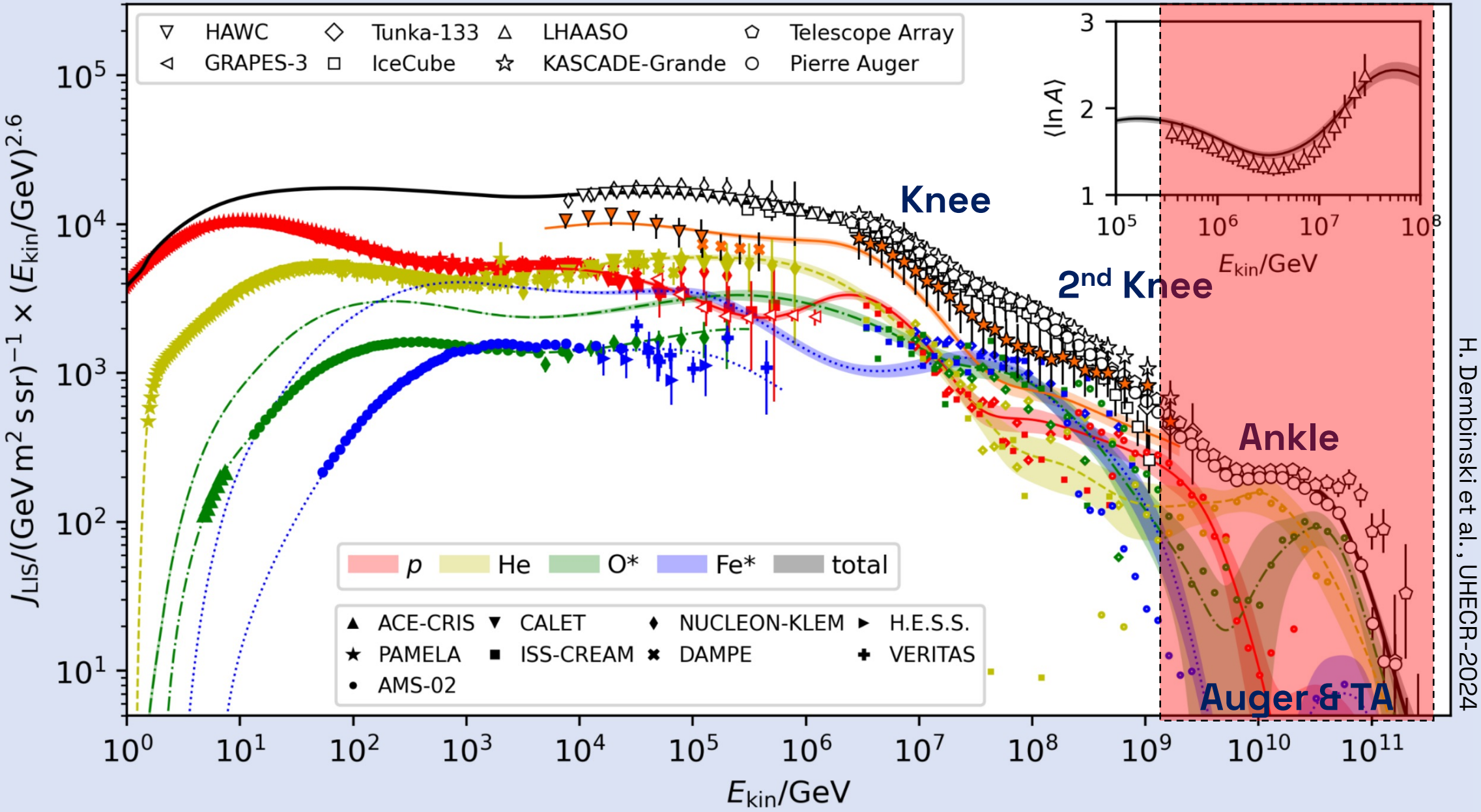
Sun & Moon Shadow



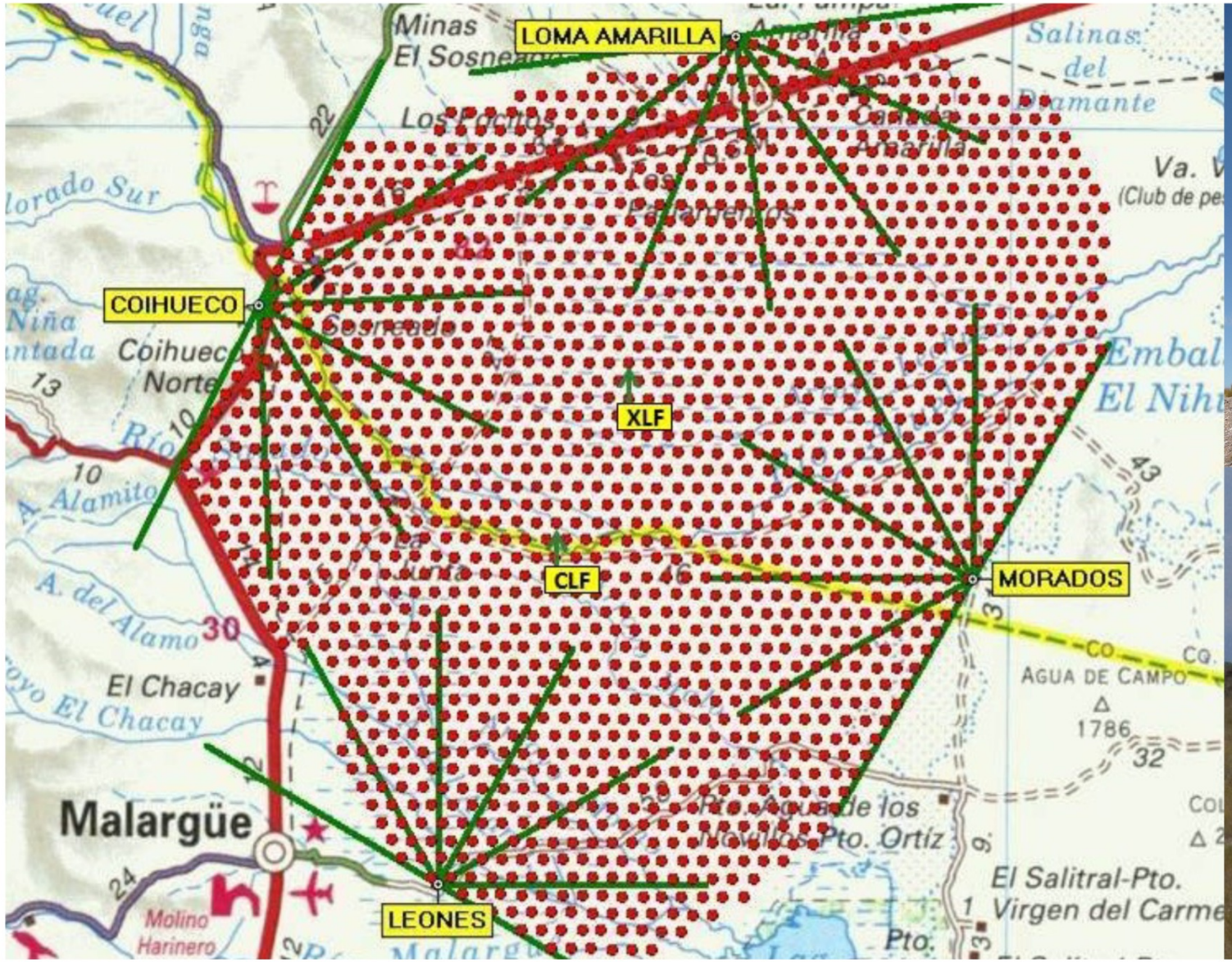


doi.org/10.1103/PhysRevD.103.042005

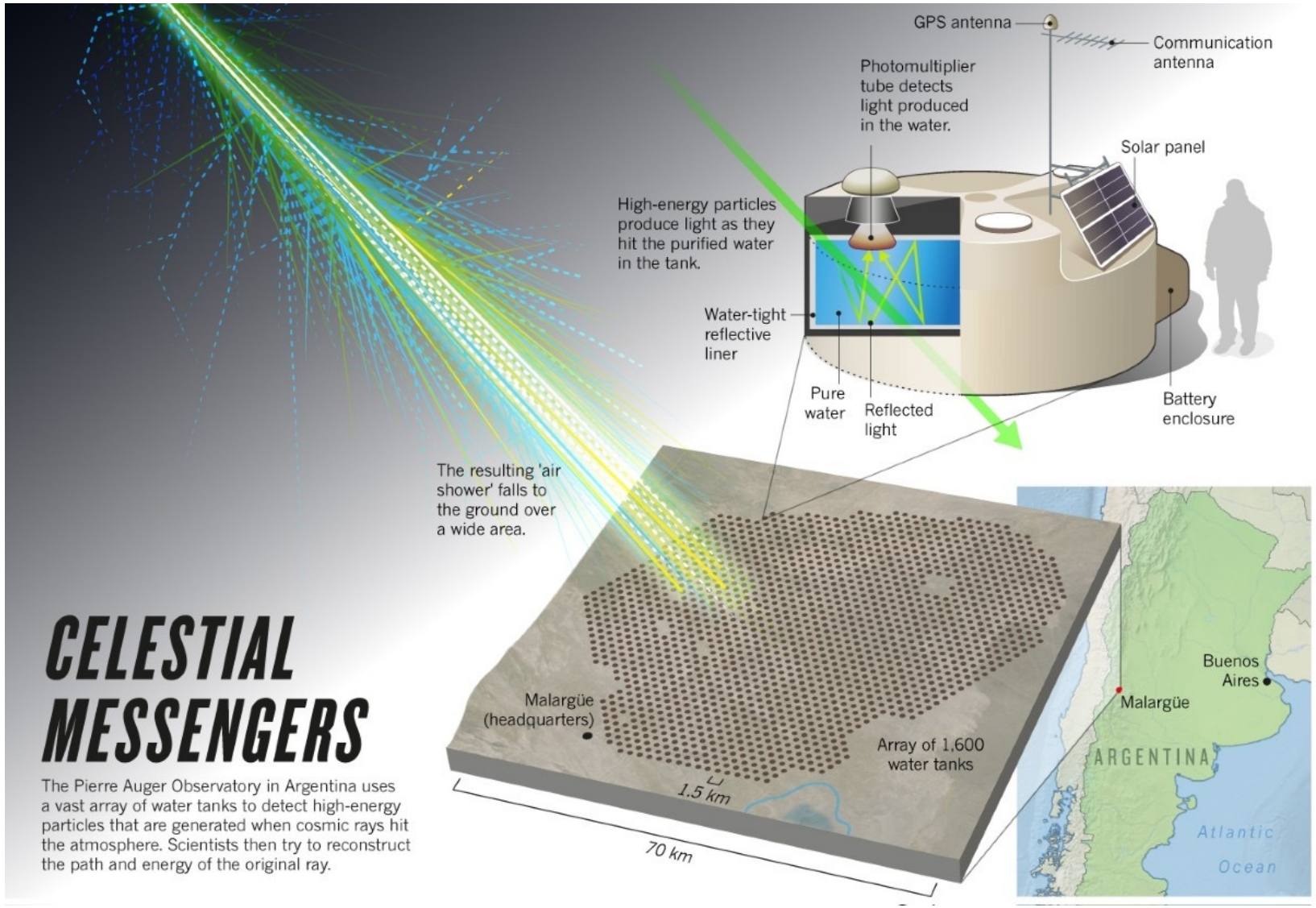
CR Landscape

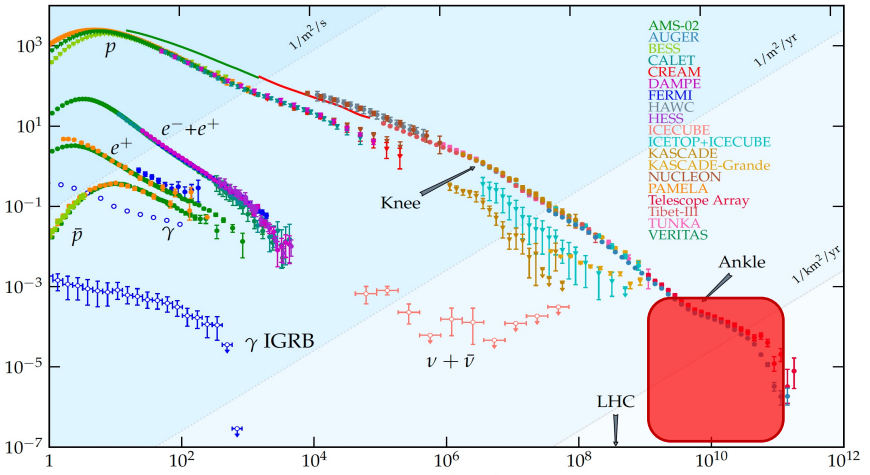


Pierre Auger Observatory



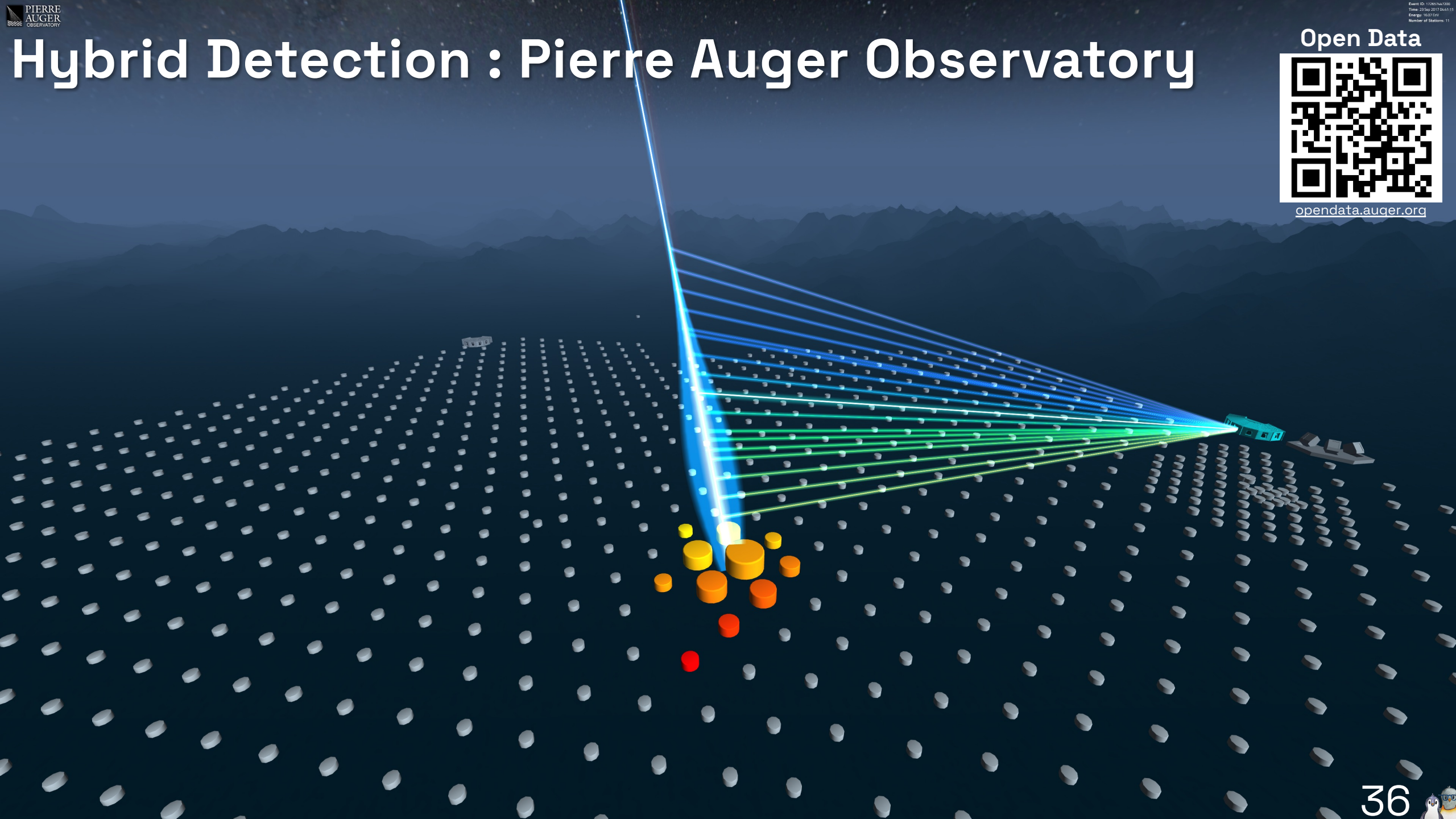
Pierre Auger Observatory





doi.org/10.1038/514020a

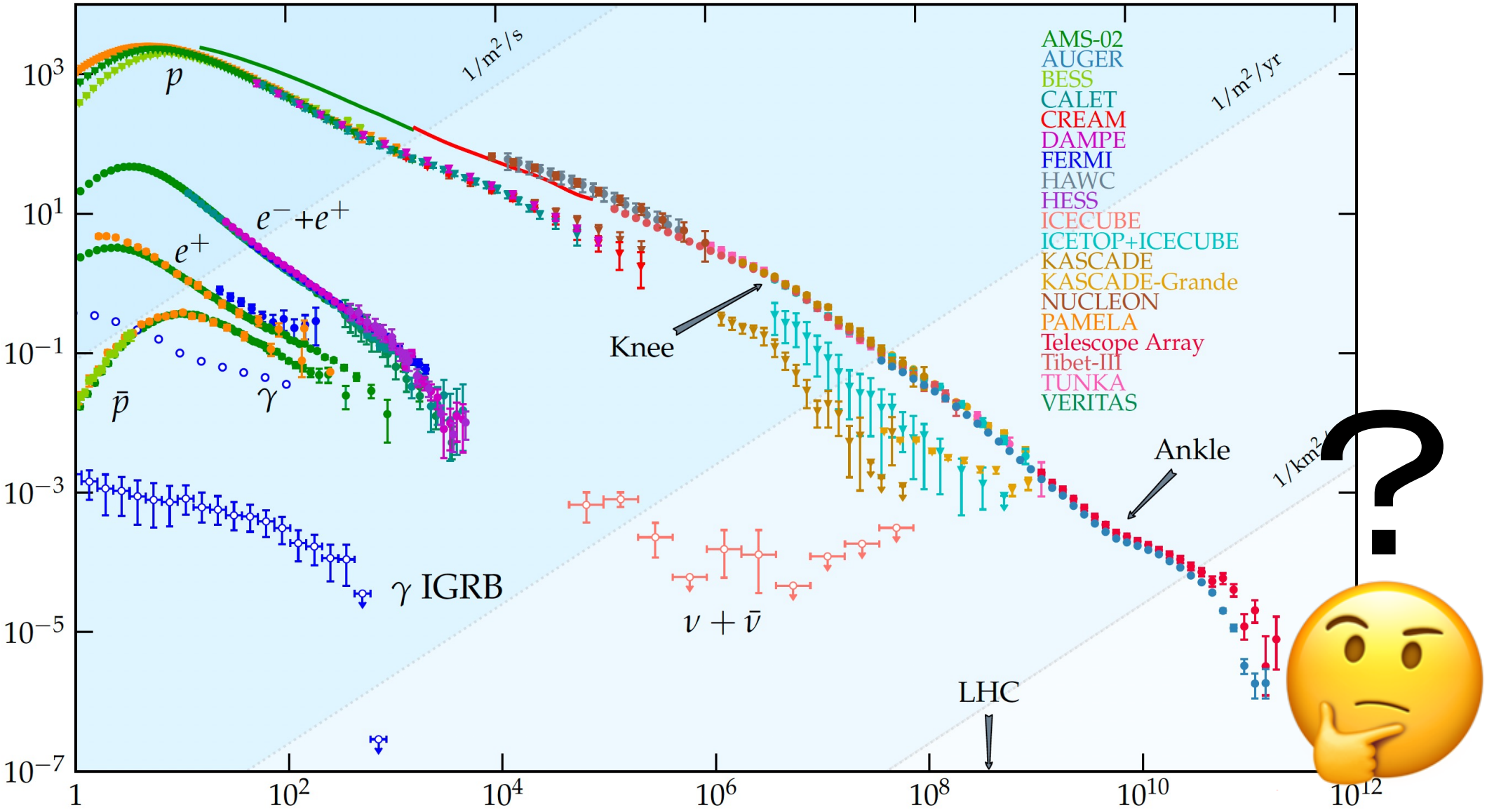
Hybrid Detection : Pierre Auger Observatory



Open Data

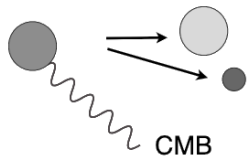
opendata.auger.org

GZK


10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
1
10^2
10^4
10^6
10^8
10^{10}
10^{12}
$1/m^2/s$
$1/m^2/yr$
$1/km^2$
p
$e^- + e^+$
e^+
$\bar{p}$
γ
γ IGRB
$\nu + \bar{\nu}$
Knee
Ankle
LHC
AMS-02
AUGER
BESS
CALET
CREAM
DAMPE
FERMI
HAWC
HESS
ICECUBE
ICETOP+ICECUBE
KASCADE
KASCADE-Grande
NUCLEON
PAMELA
Telescope Array
Tibet-III
TUNKA
VERITAS

GZK (Greisen–Zatsepin–Kuzmin) Limit

Protons →



n p π^+ π^0

Photo-pion production
(mainly Δ resonance)

Nuclei →

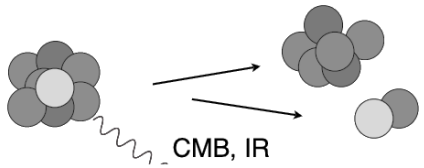
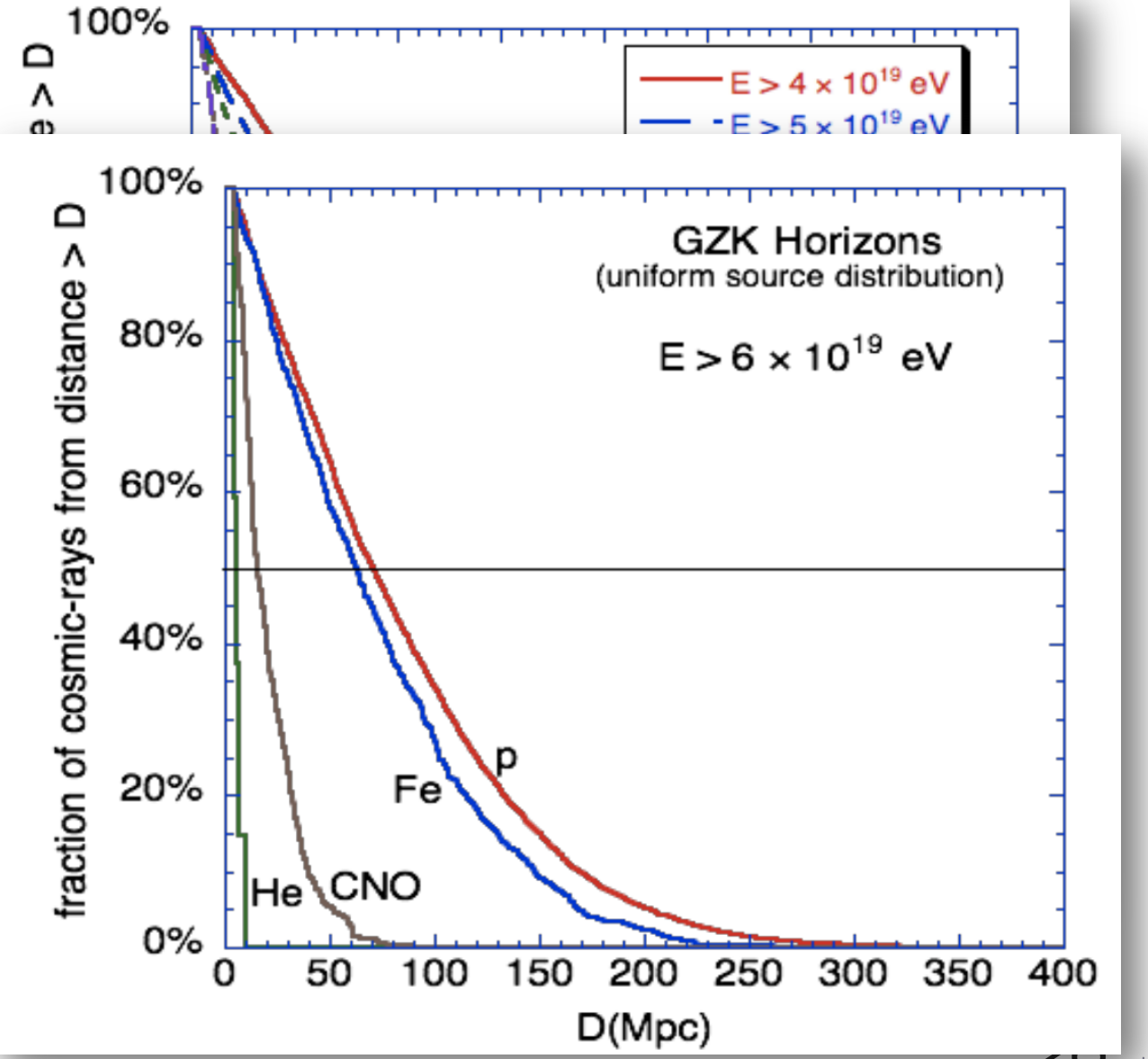
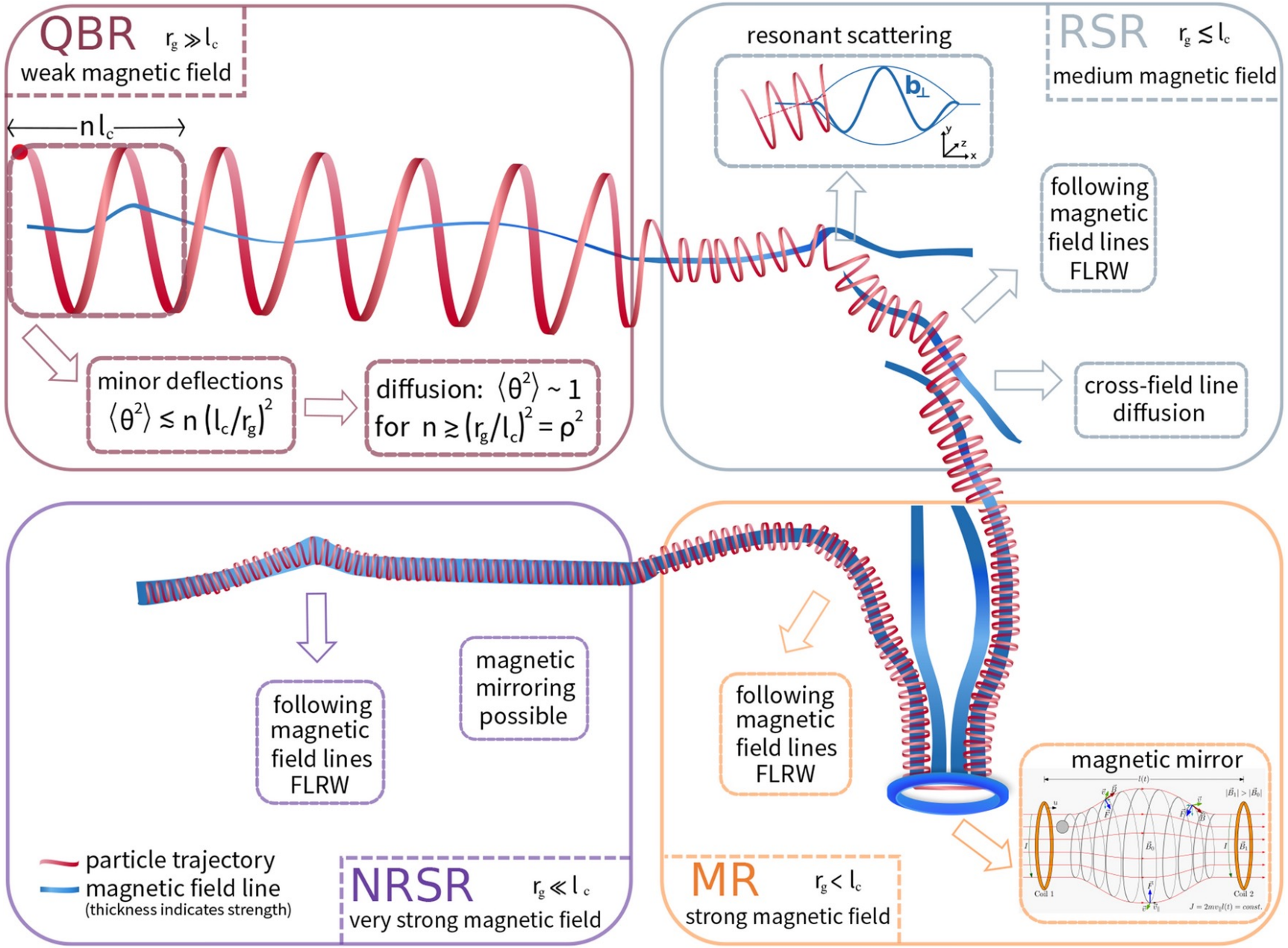


Photo-dissociation
(giant dipole resonance)

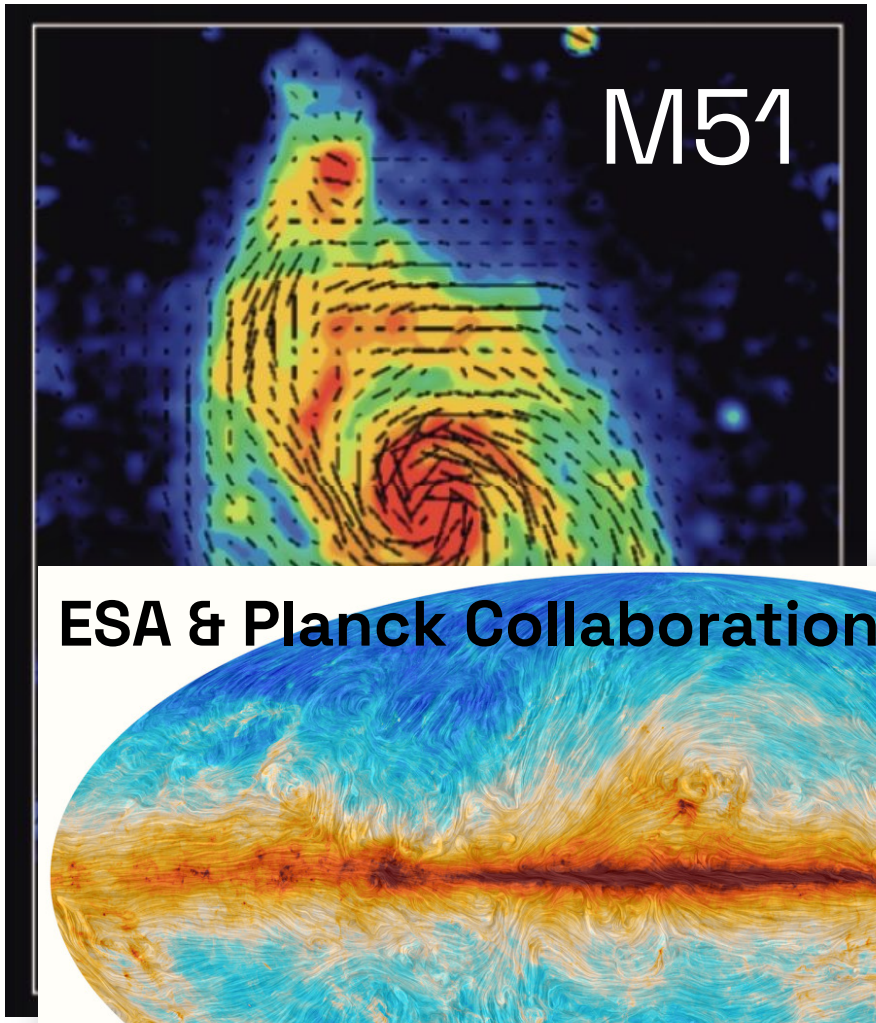


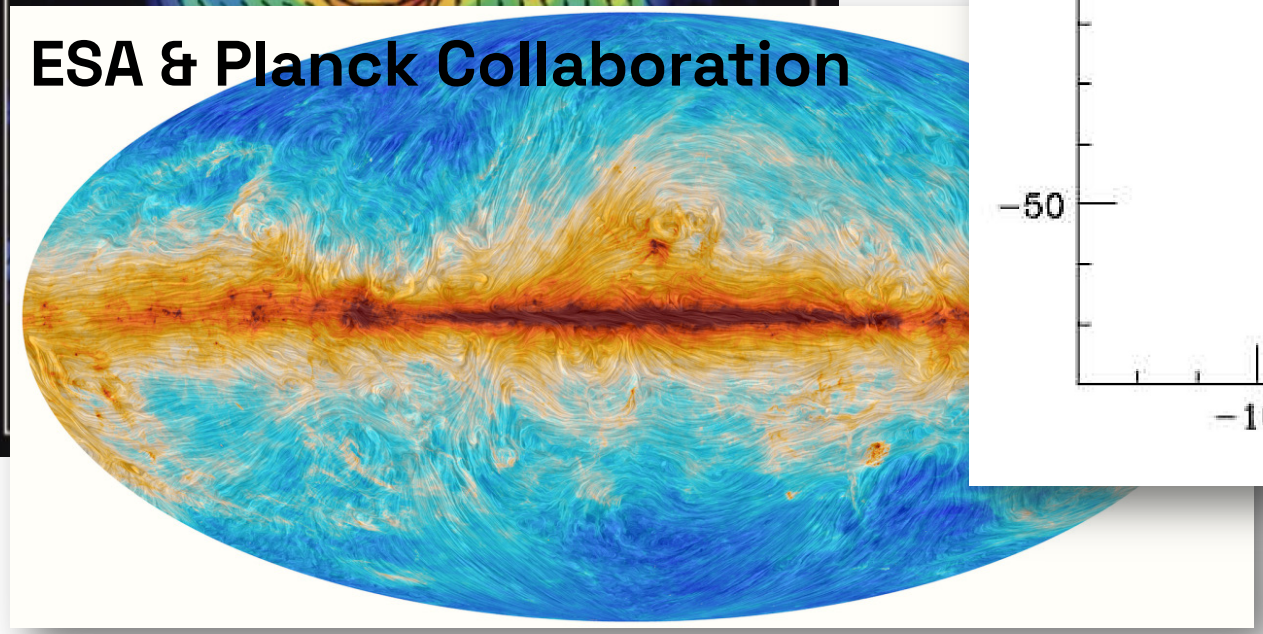
Charged Particle in Magnetic Field

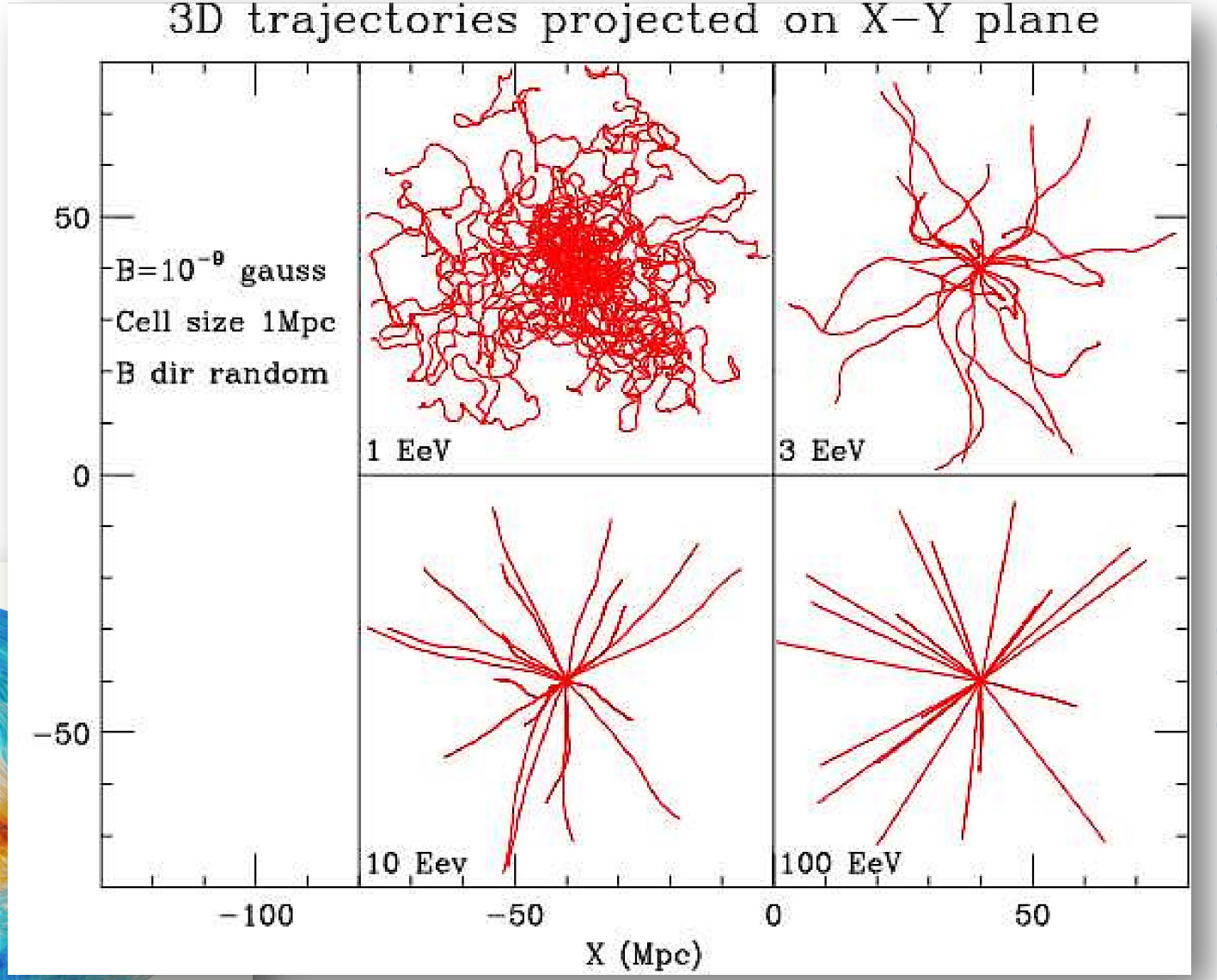


doi.org/10.1007/s42452-021-04891-z

Magnetic Fields

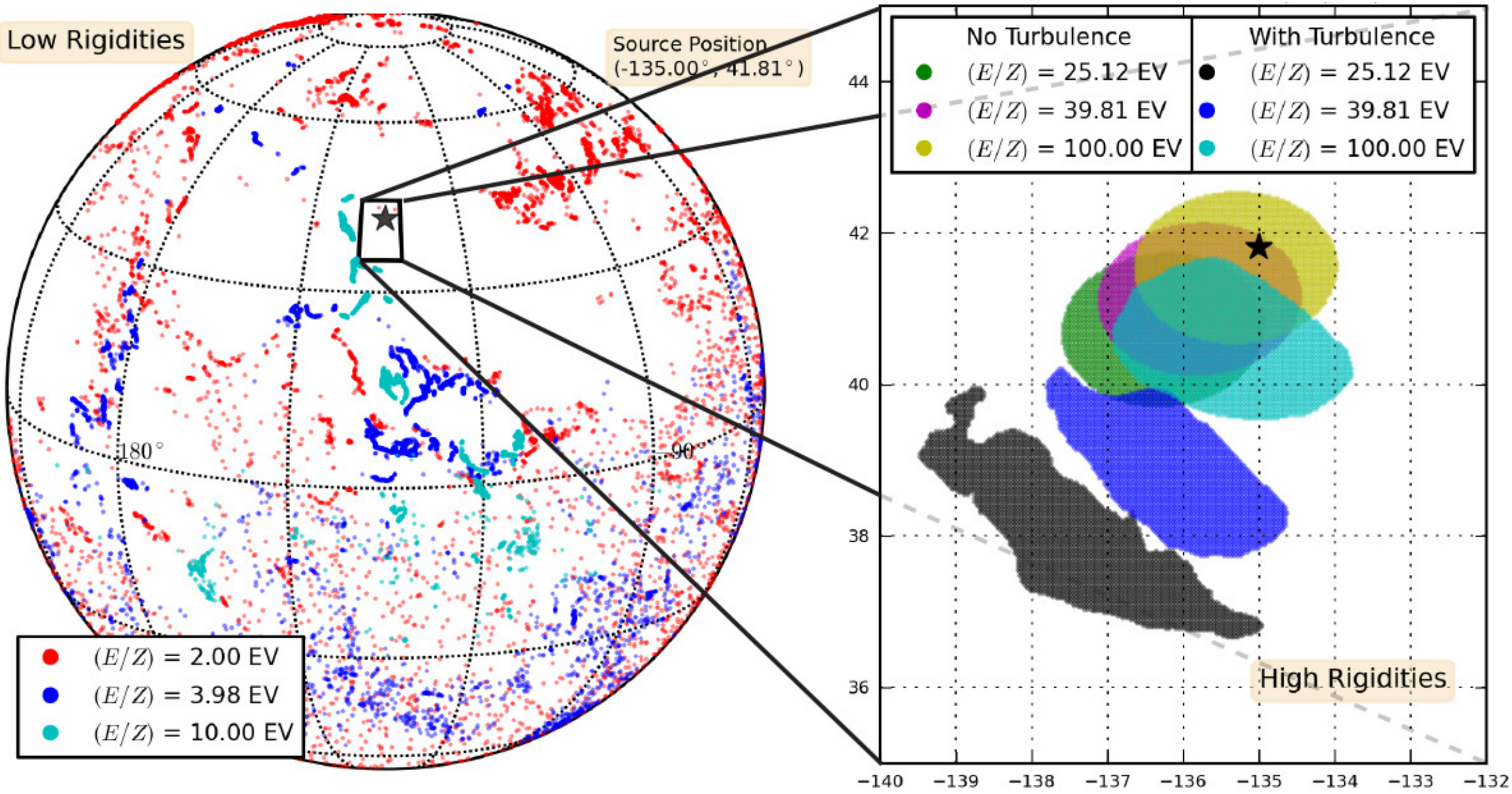






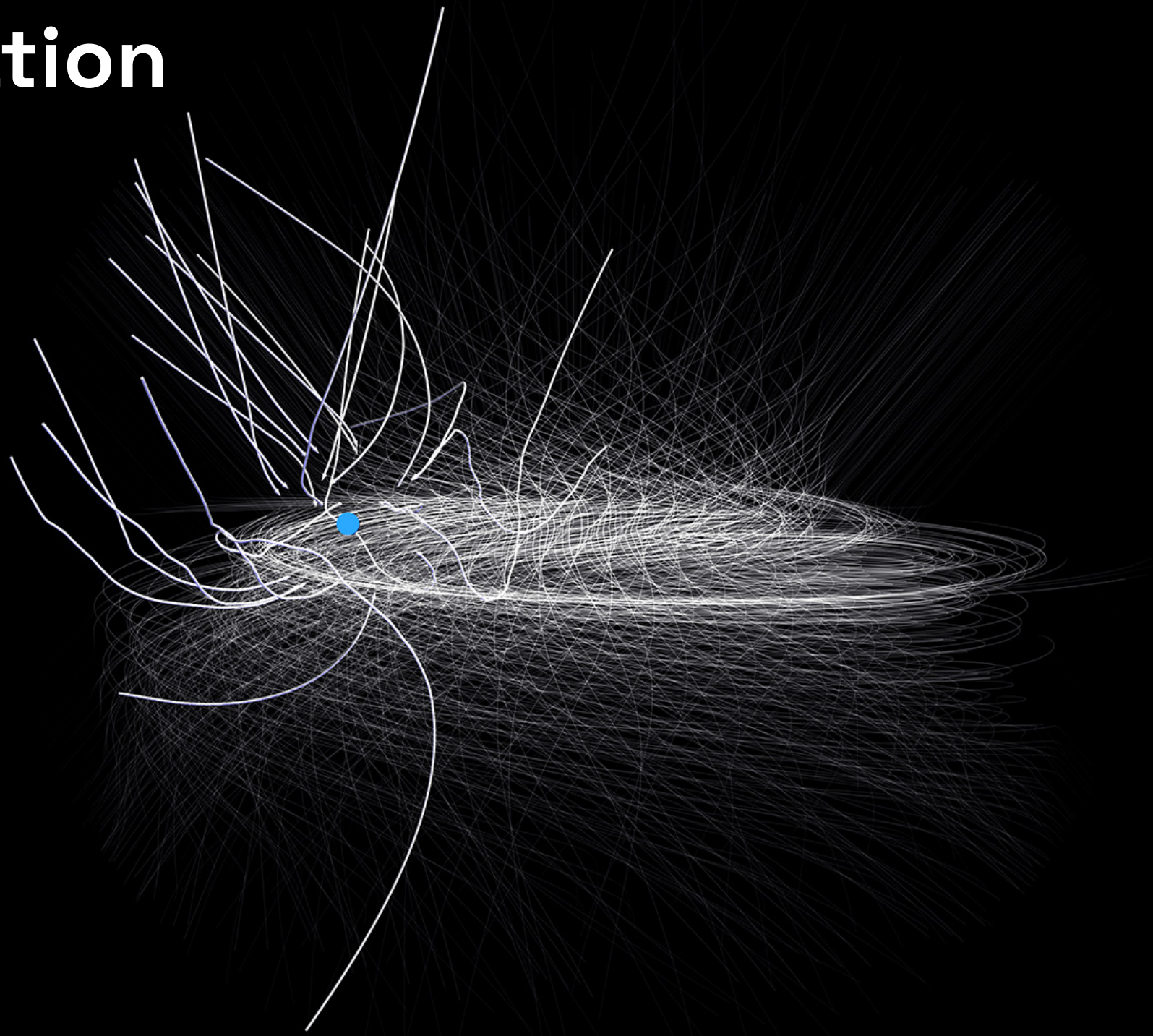
doi.org/10.1016/j.nuclphysbps.2004.11.107

Propagation



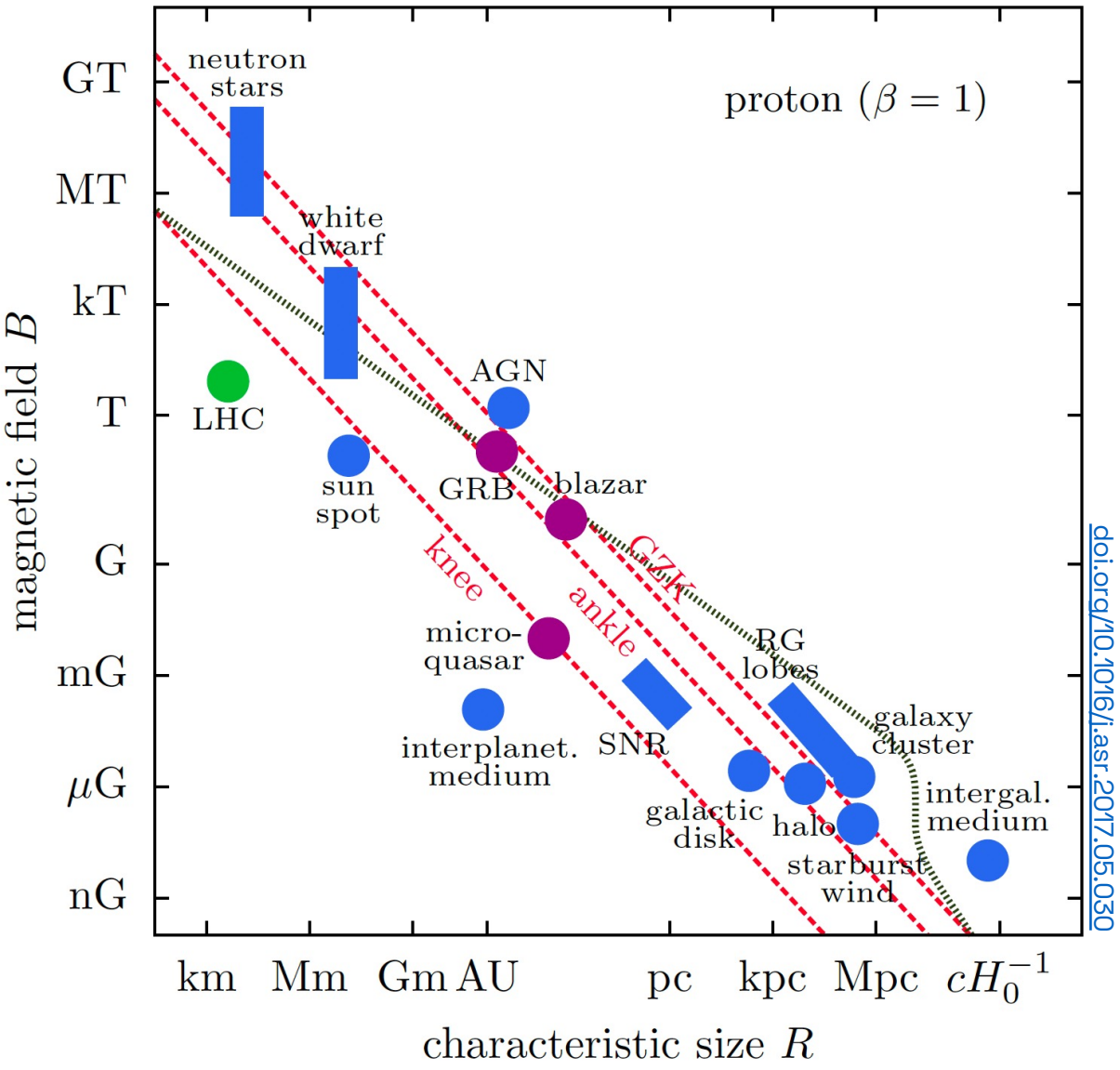
Credits : Michael Sutherland

Propagation

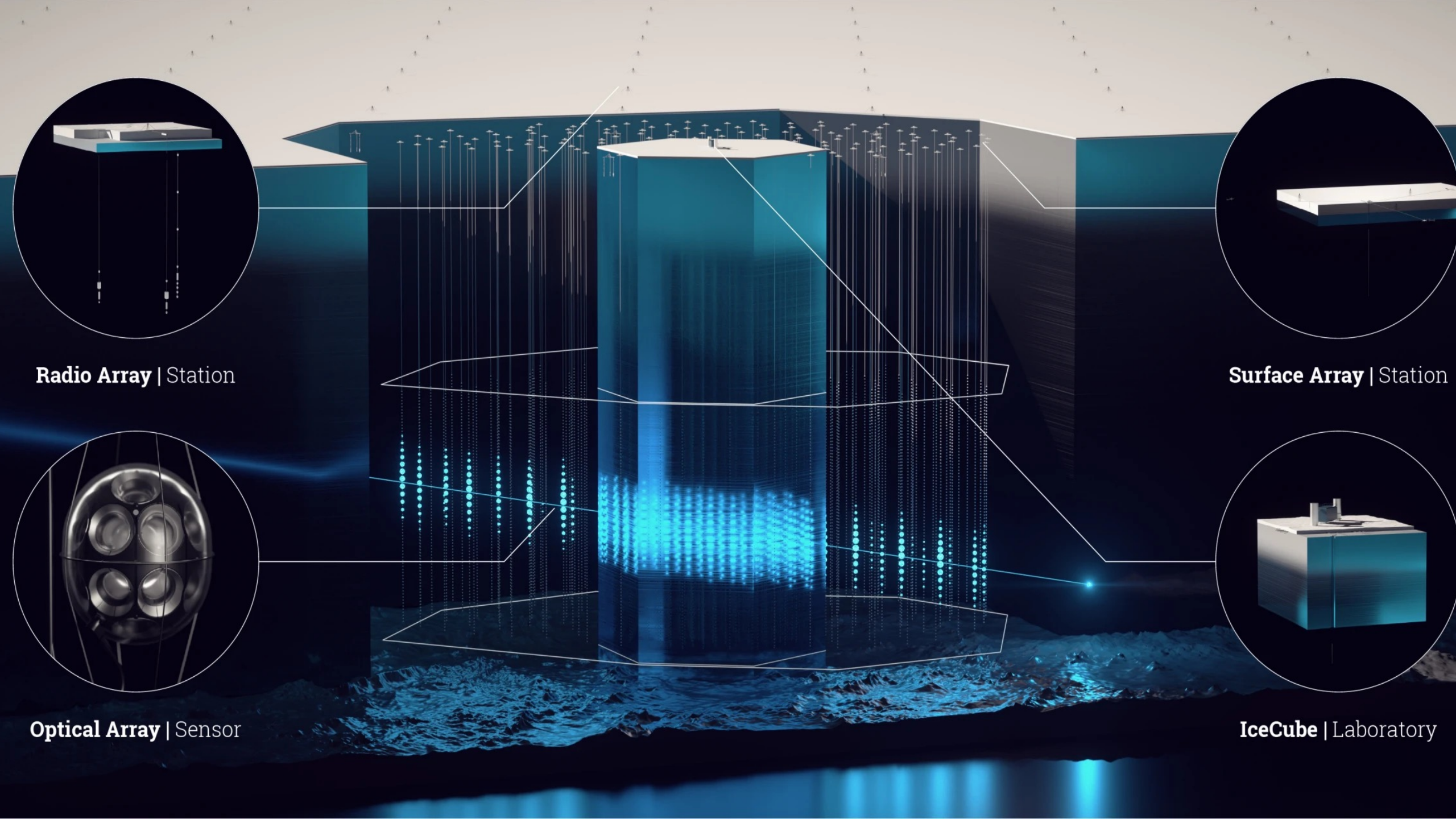


Credits : Michael Sutherland

Sources

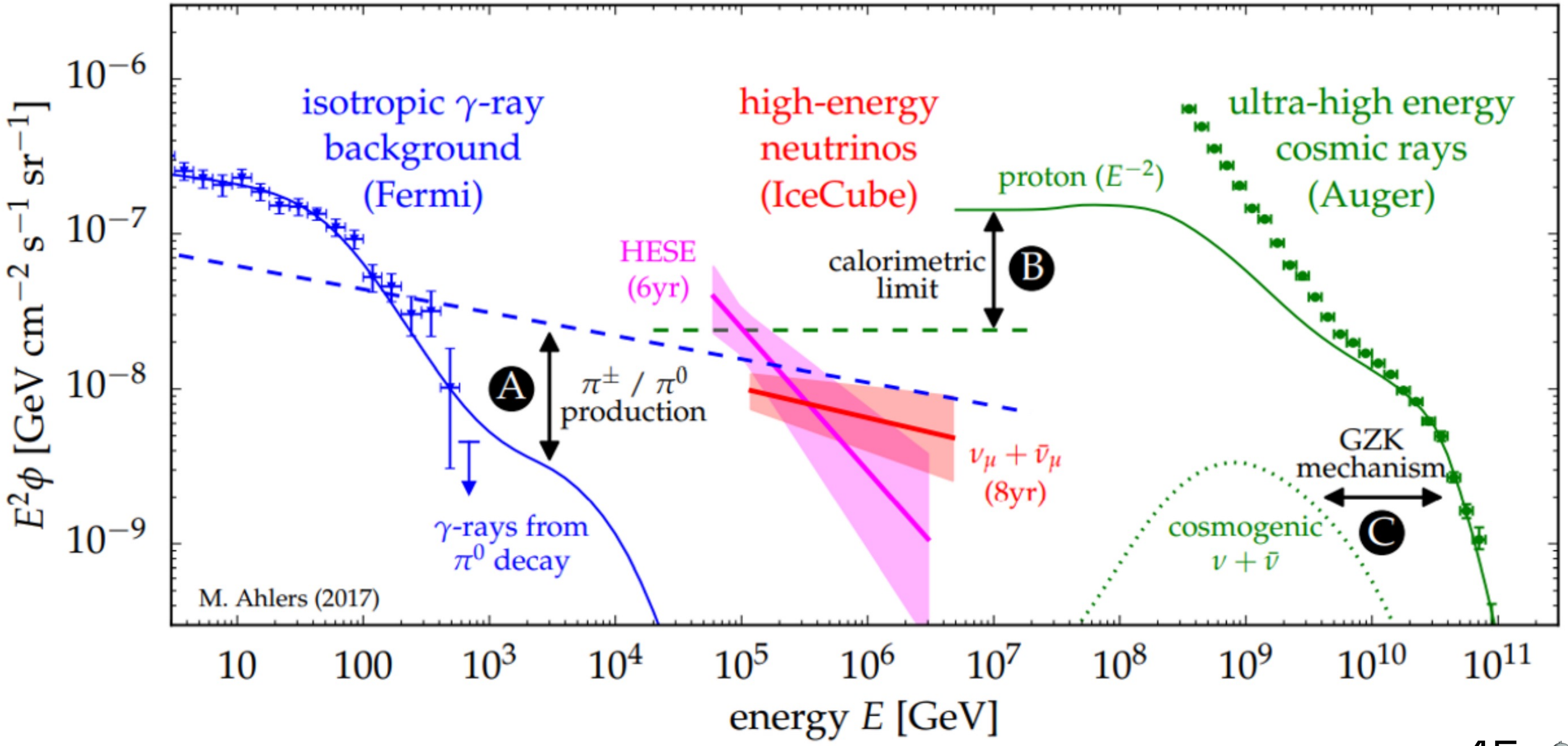


doi.org/10.1016/j.asr.2017.05.030


Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory

The Final Frontier

doi.org/10.22323/1.459.0005



CRWG @ IceCube

WG-Leads

Matthias Plum

Stef Verpoest

Tech-Lead

Katherine Rawlins

Calls : 9:00 am @ Every Friday (CDT)

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