EXCELENCIA
SEVERO
OCHOA

Astroparticles

the cosmic high energy frontier:

Extreme Universe,

Extreme Detectors

TAE 2016 14-16 Sept.2016 Benasque

Manel Martinez IFAE-BIST

Outline:

Session 1:
- Introduction: The Cosmic High Energy Frontier
- Targets, messengers and goals
- Charged Cosmic rays

Session 2:
- Neutrino Telescopes
- Neutrino properties with Neutrino Telescopes
- Gravitational Waves

Session 3:
- VHE Gamma Rays
- Multi-messengers
- Outlook

Focus:

On the future rather than on the past.

No detailed description of current experiments/situation (search in Wikipedia),

but rather my views on what can we expect in the next decade,

in which **you** may become the main contributors…!

SESSION I

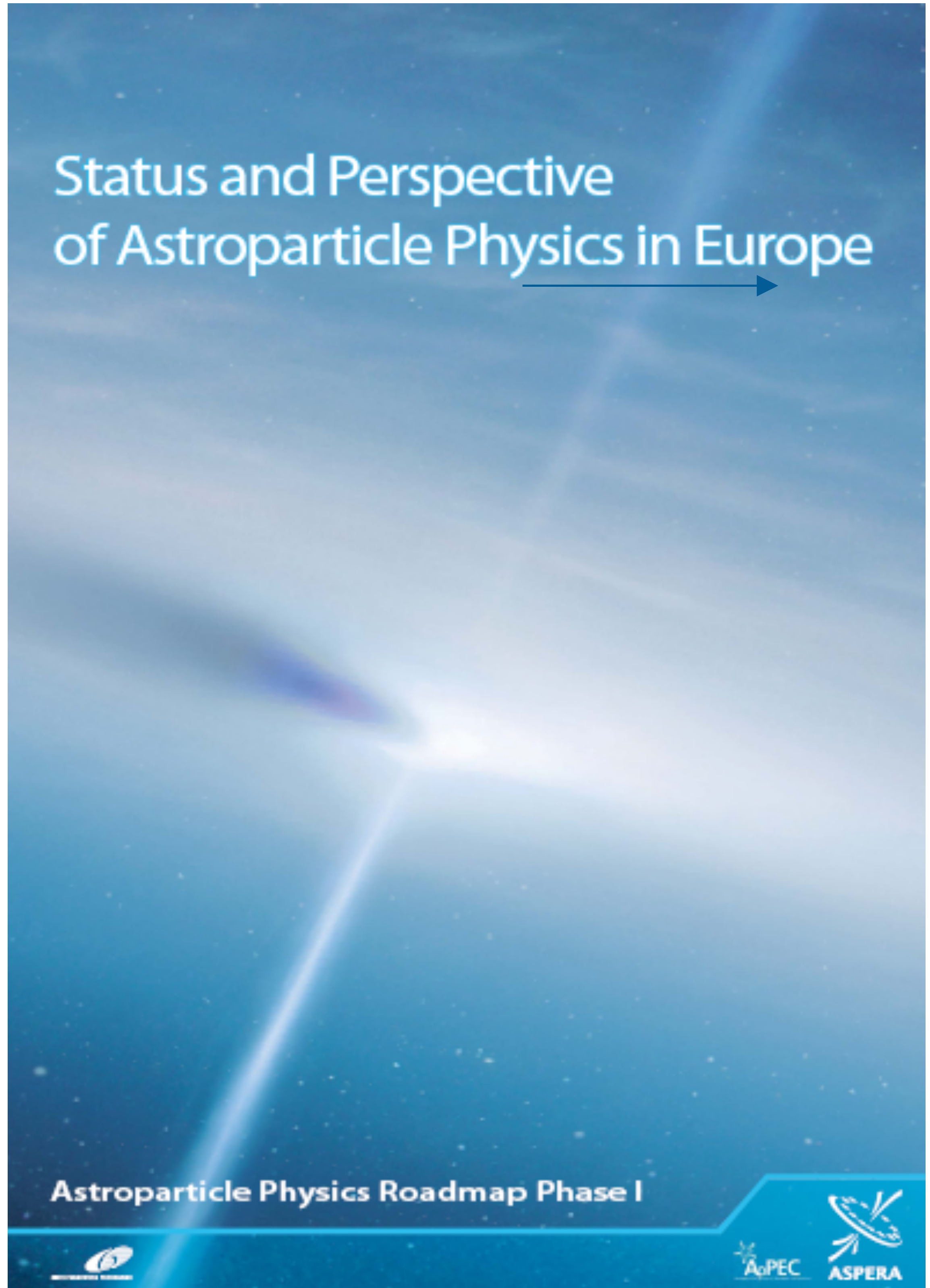
INTRODUCTION

Astroparticle Physics

is that branch of particle physics that studies elementary particles of astronomical origin, and their relation to astrophysics and cosmology.

It is a relatively new field of research emerging at the intersection of particle physics, astronomy, and cosmology.

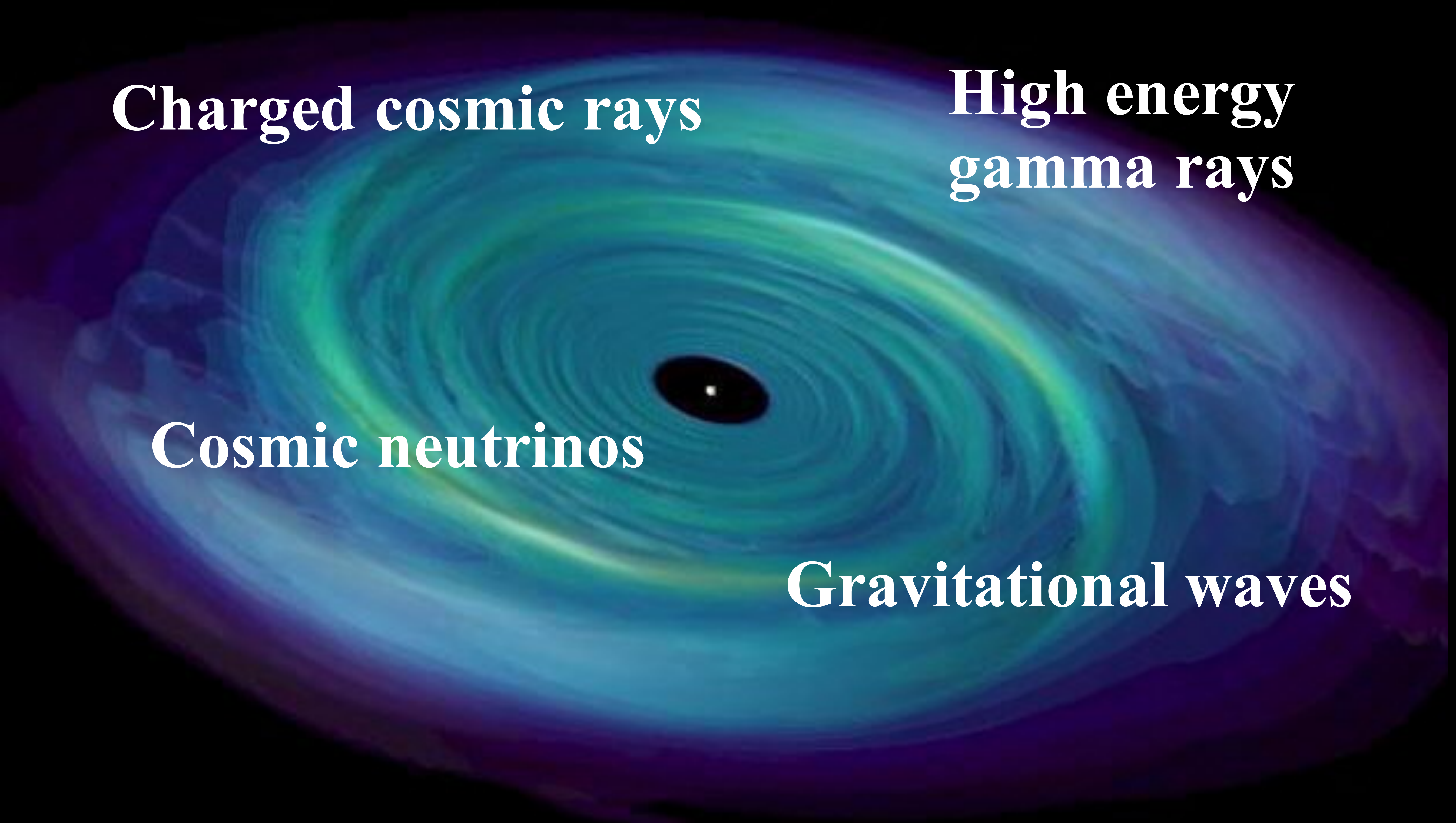
Partly motivated by the historic discovery of neutrino oscillations, the field is undergoing remarkable development, both theoretically and experimentally, over the last decade.


Status and Perspective
of Astroparticle Physics in Europe
Astroparticle Physics Roadmap Phase I
ApPEC
ASPERA

Questions

1) What is the Universe made of?
   In particular: What are **dark matter and energy** ?
2) Do **protons** have a **finite life time**?
3) What are the **properties of neutrinos**?
   What is their role in cosmic evolution?
4) What do **neutrinos** tell us about the interior of the **Sun** and the **Earth**, and about **Supernova** explosions?
5) What is the **origin of cosmic rays**?
   What is the view of the sky at extreme energies?
6) Can we detect **gravitational waves**?
   What will they tell us about violent cosmic processes and about the nature of gravity?

The four pillars of HE Astroparticles



The Cosmic High Energy Frontier

1) Most extreme and violent phenomena in the universe:

- birth and death of stars,
- formation and evolution of galaxies,
- origin and destiny of the universe =>

Very high energies -> Cosmic Accelerators

Interplay between

gravitation and the rest of fundamental interactions

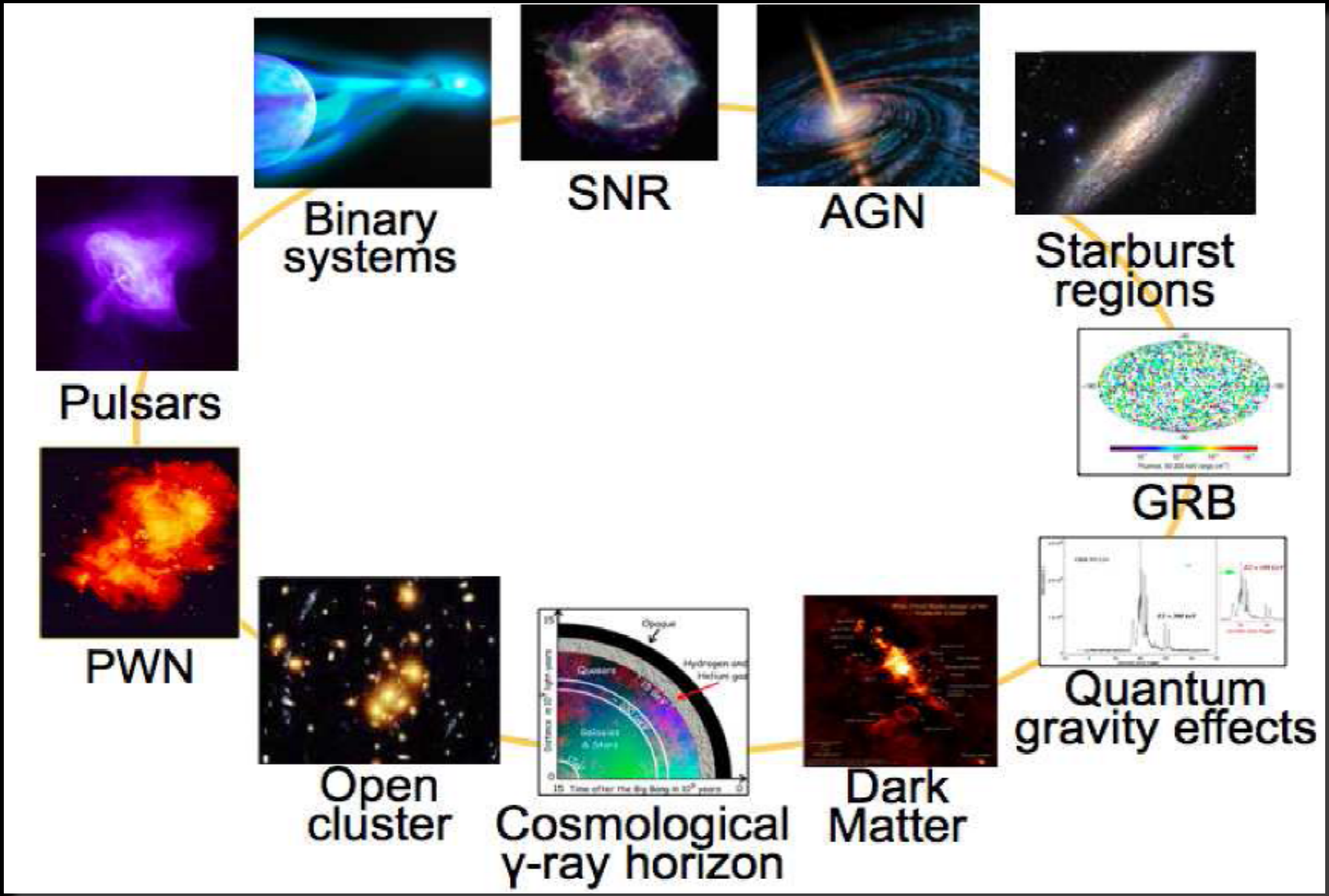
2) The highest energies =>

- Dark matter nature
- Spacetime at short distances -> quantum gravity ?
- …

TARGETS, MESSENGERS & GOALS

TARGETS

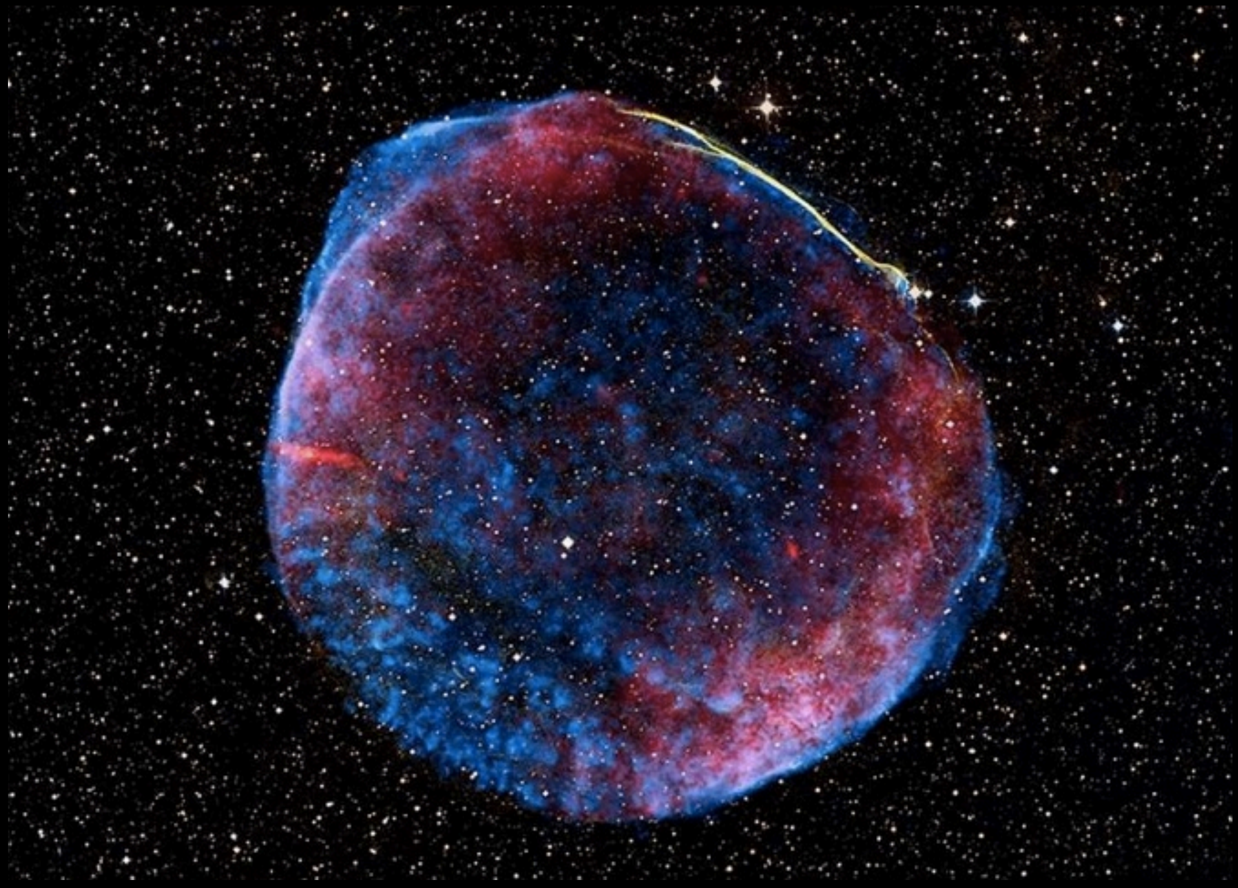
The Cosmic High Energy Targets



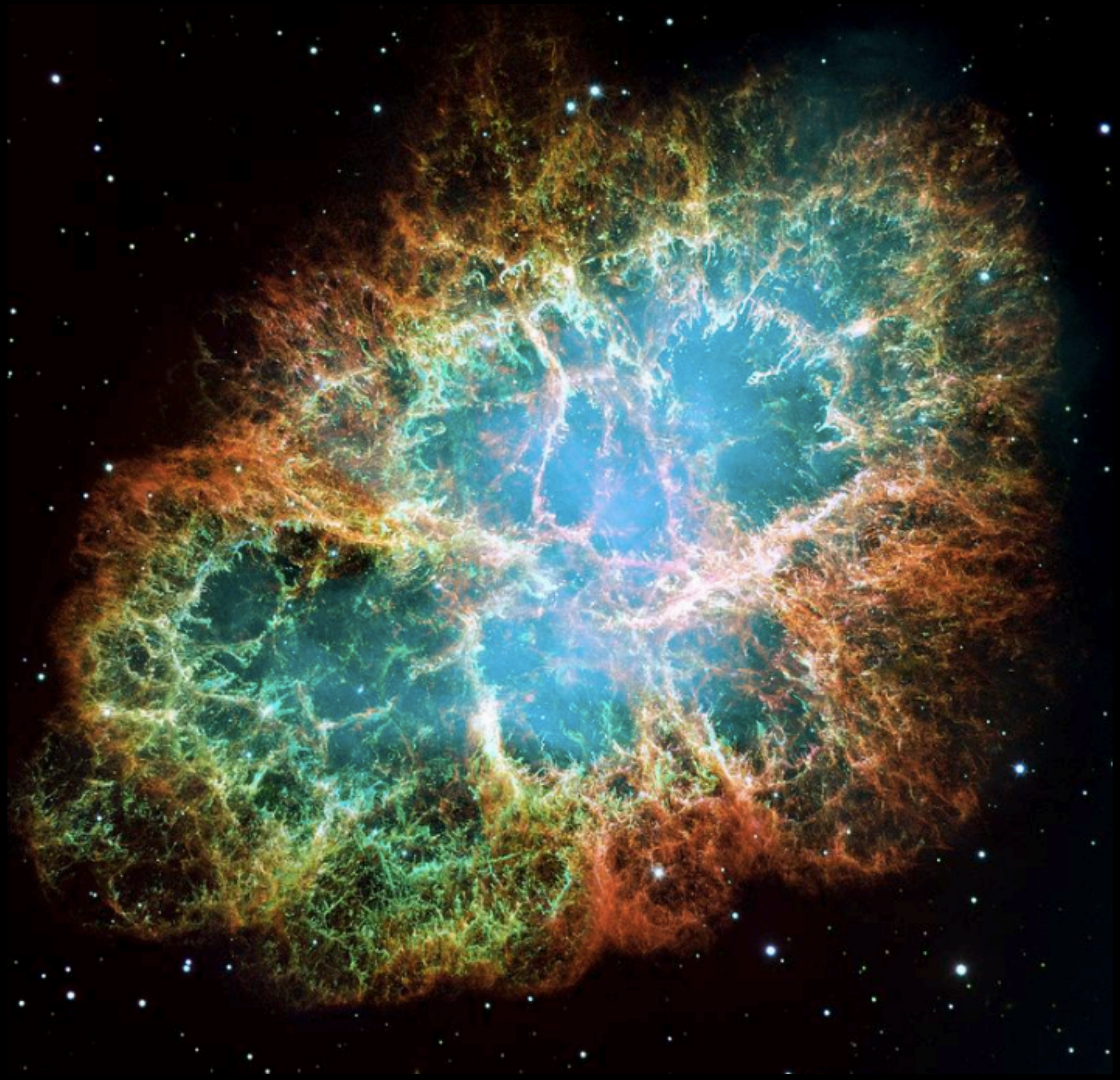
Supernova explosions

Supernova Remnants (SNR):
Shell Supernova, Pulsar wind Supernova (Plerion)

SN 1006, a Type Ia shell supernova in Lupus.

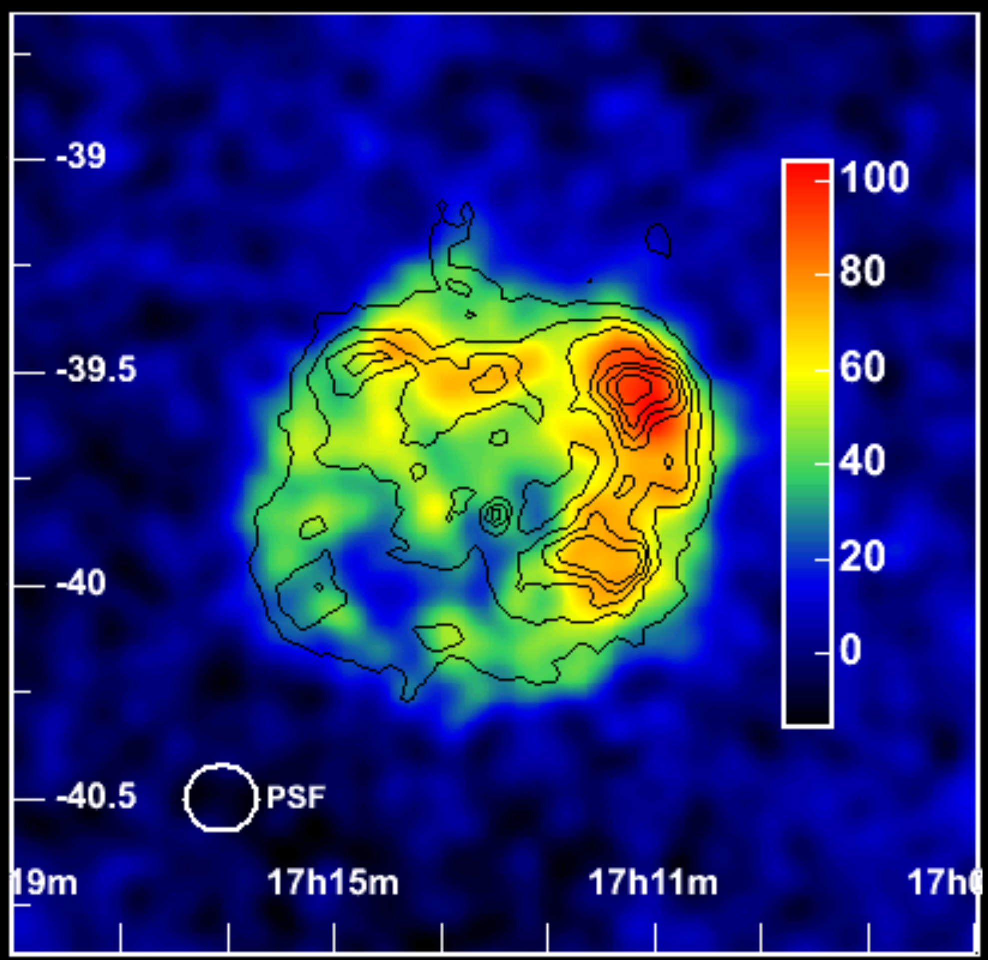


Crab Plerion

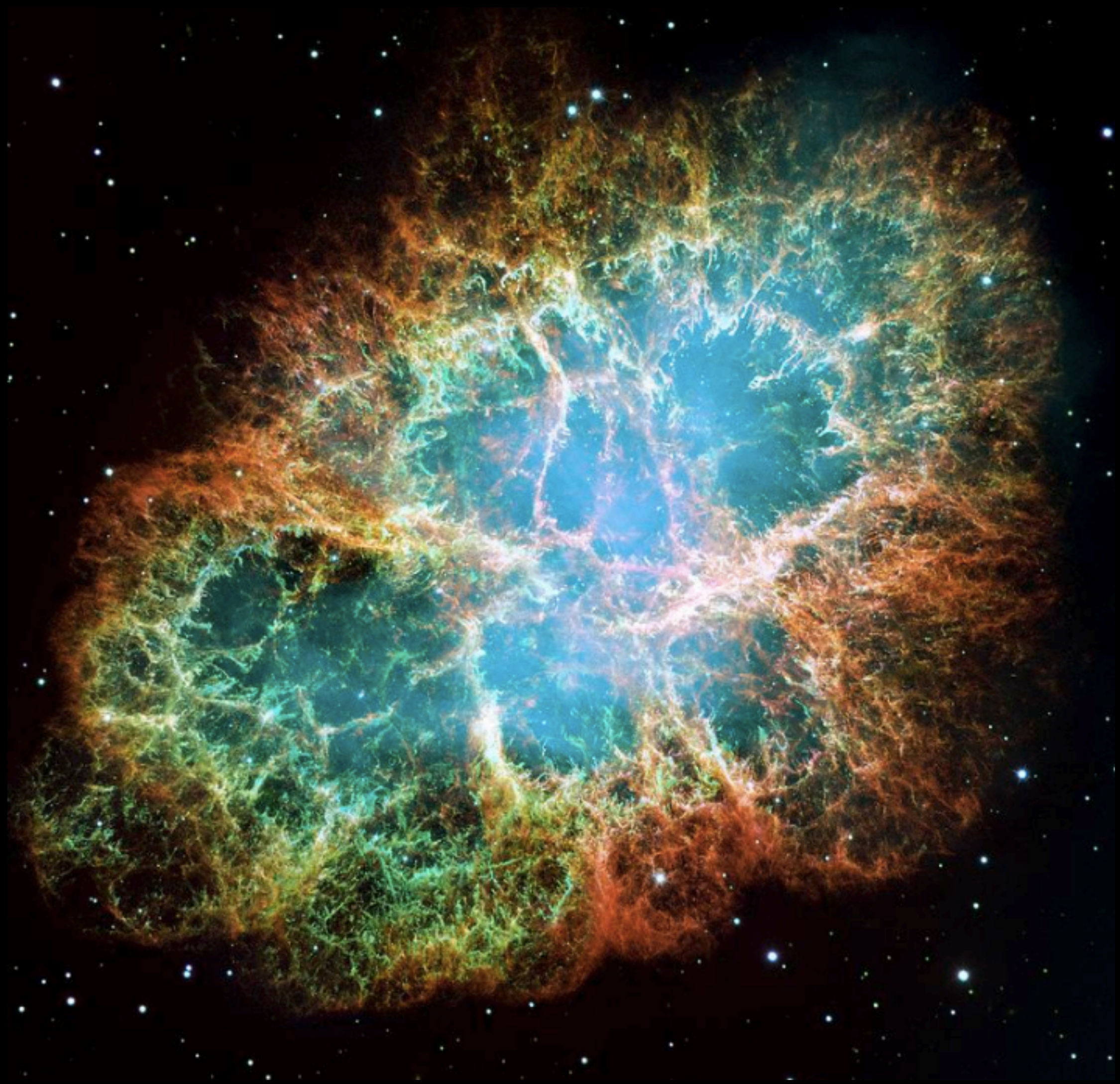


Supernova Remnants (SNR):
Shell Supernova, Pulsar wind Supernova (Plerion)

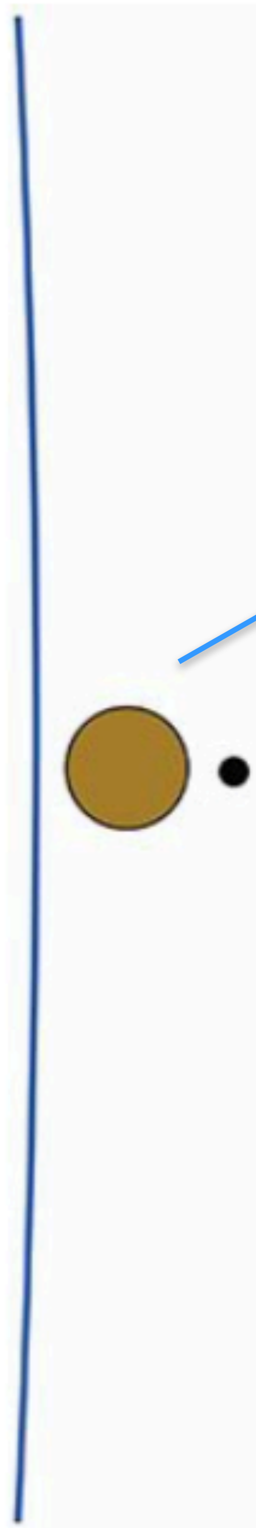
Shell Supernova RX J1713-3946



Crab Plerion



Compact objects



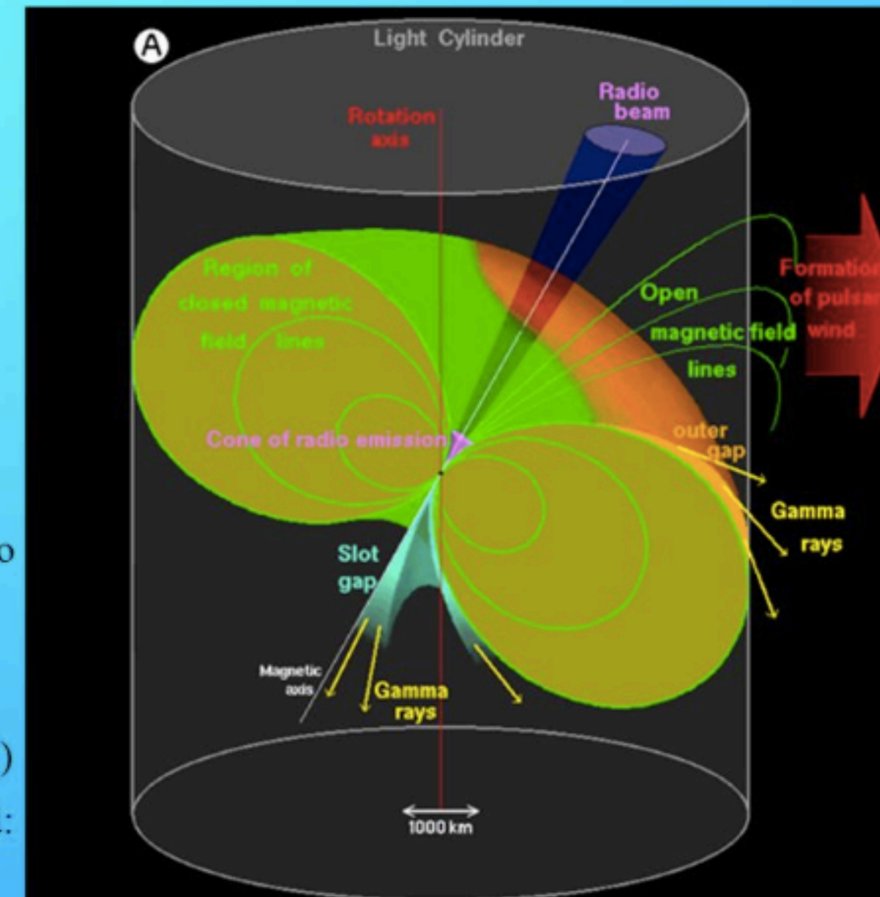
Pulsars

Black Holes

Fig. 2.5. A white dwarf (*left*), neutron star (*middle*), and black hole (*right*) that all weigh as much as 1.2 Suns. For the white dwarf I show only a tiny segment of its surface.

Pulsar Model

- Rotating neutron star
- Light cylinder $R_{LC} = c/\Omega = 5 \times 10^4 P(s)$ km
- Charge flow along open field lines
- Radio beam from magnetic pole (in most cases)
- High-energy emission from outer magnetosphere
- Rotation braked by reaction to magnetic-dipole radiation and/or charge acceleration: $\dot{\Omega} = -K\,\Omega^{-3}$
- Characteristic age: $\tau_c = P/(2\dot{P})$
- Surface dipole magnetic field: $B_s \sim (P\dot{P})^{1/2}$



(Bennet Link)

Schwarzschild Radius and Event Horizon

For an object of mass *M*, the Schwarzschild Radius is:

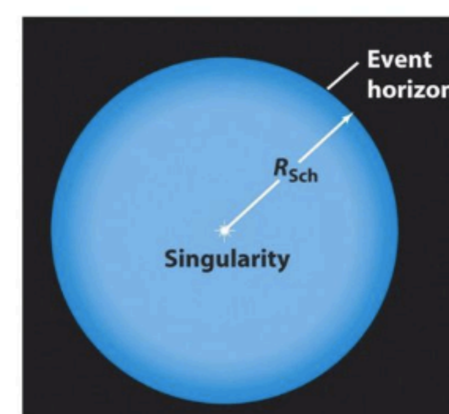
$$R_S = 2GM/c^2$$

at which $v_{esc}=c$, infinite gravitational redshift and time dilation occur.

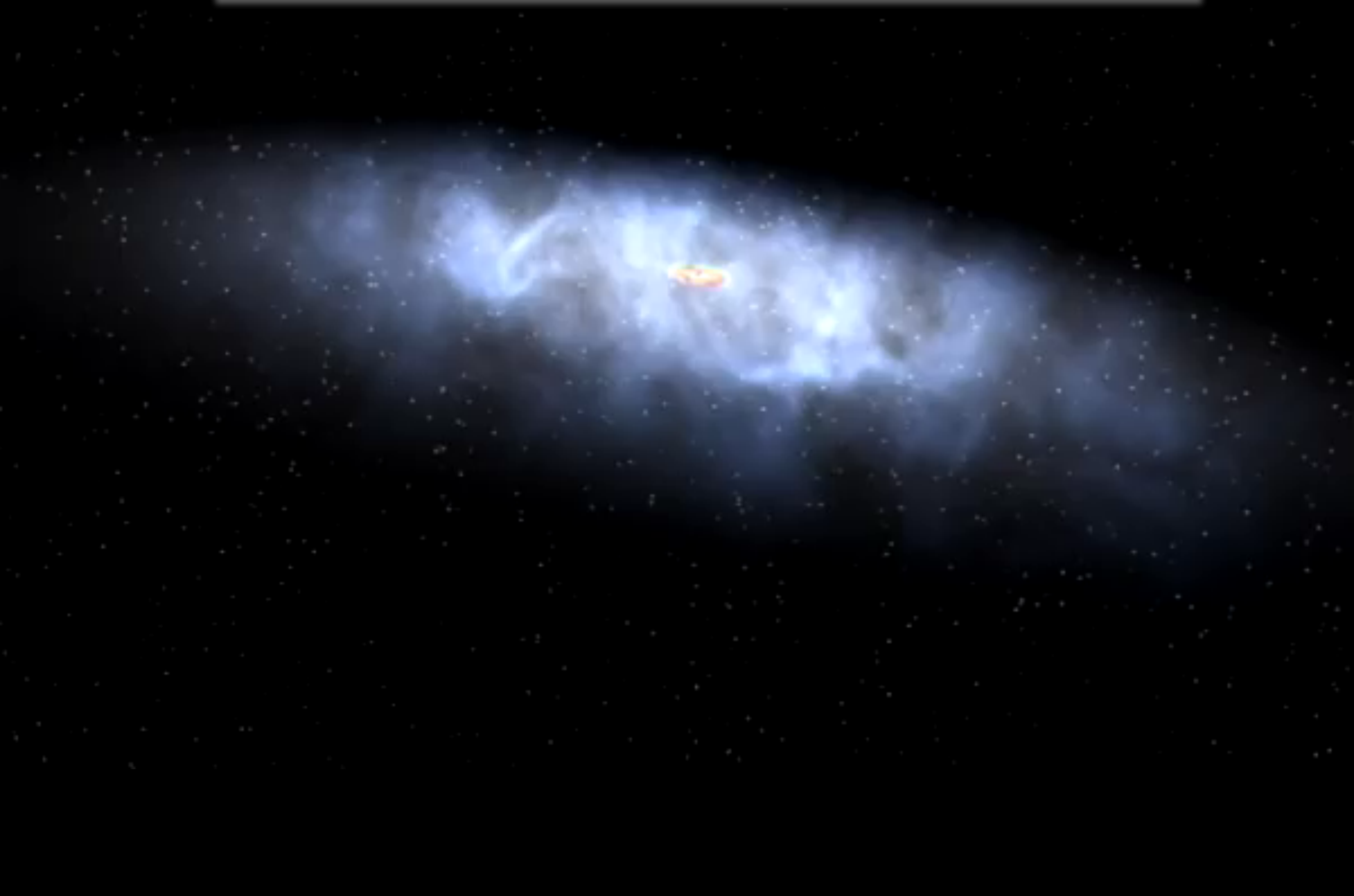
$$R_S \text{ (km)} = 3\,M\,(M_\odot)$$

For Earth, R_S = 1 cm. If you could crush Earth to this size, it would be a black hole.

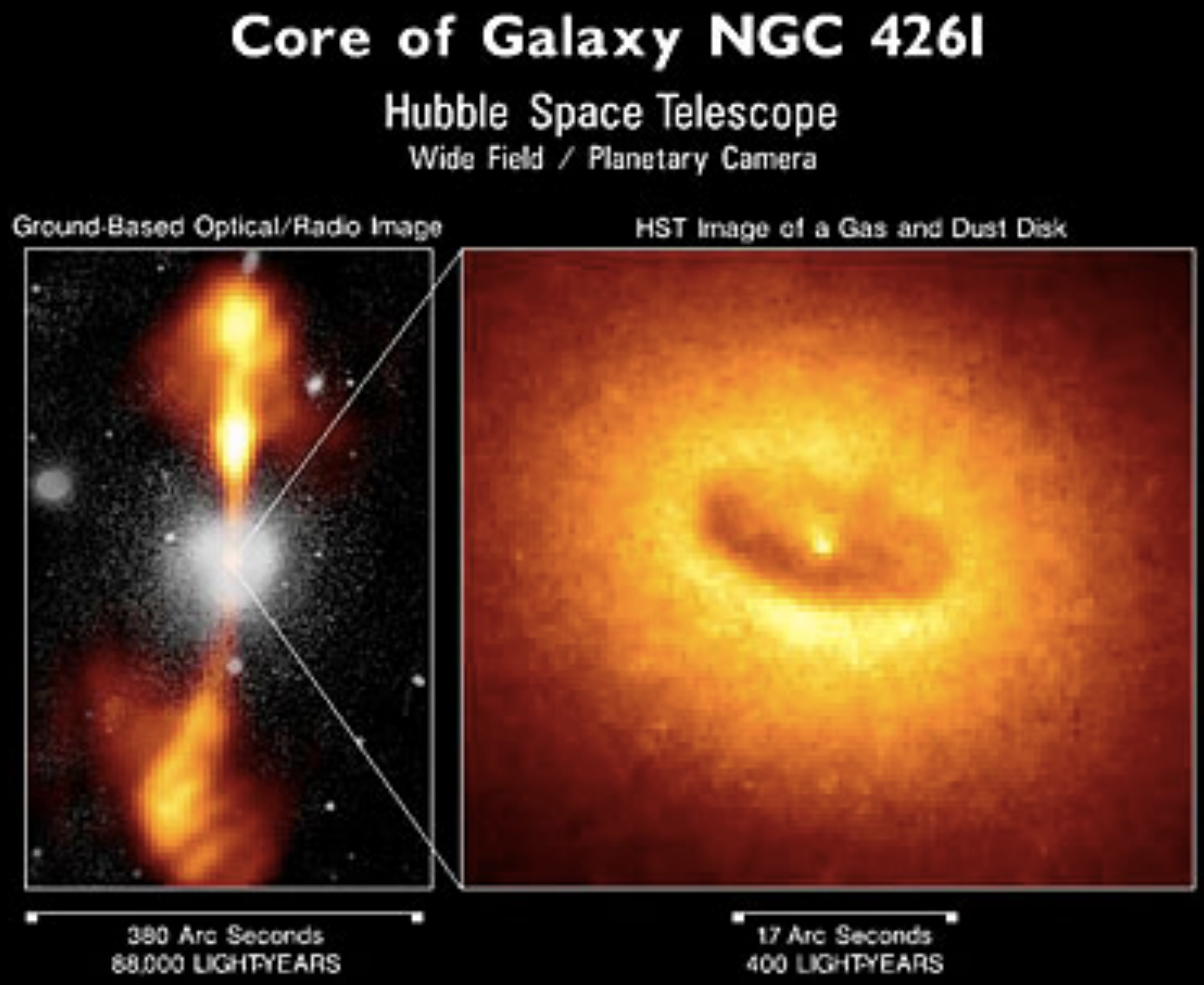
Event Horizon is imaginary sphere with radius R_S.



Active Galactic Nuclei (AGN), Quasars, Blazars



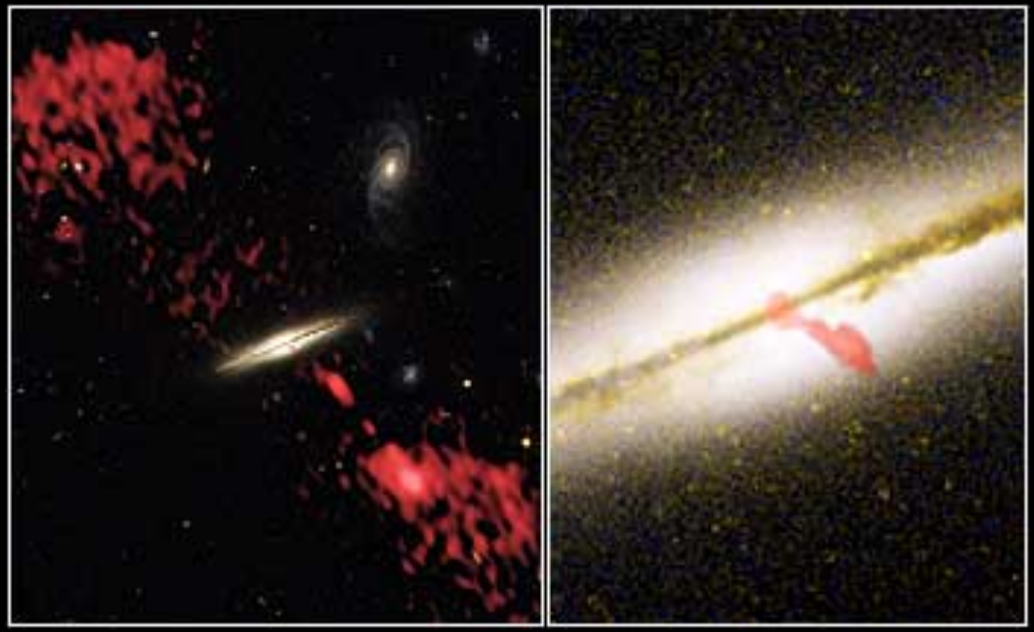
AGN



Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

AGN

QUASAR: Galaxy 0313-192



- Compact regions at the center of some (most) galaxies, where there is a supermassive black hole (~ 10^9 solar masses) that ejects material in the form of jets of thousands of light-years extension.

- They exhibit very high brightness in most of the spectrum. The radiation comes from the accretion disk surrounding the black hole, forming jets along the axis of rotation.

- Most intense e.m. radiation sources in the universe. High variability.

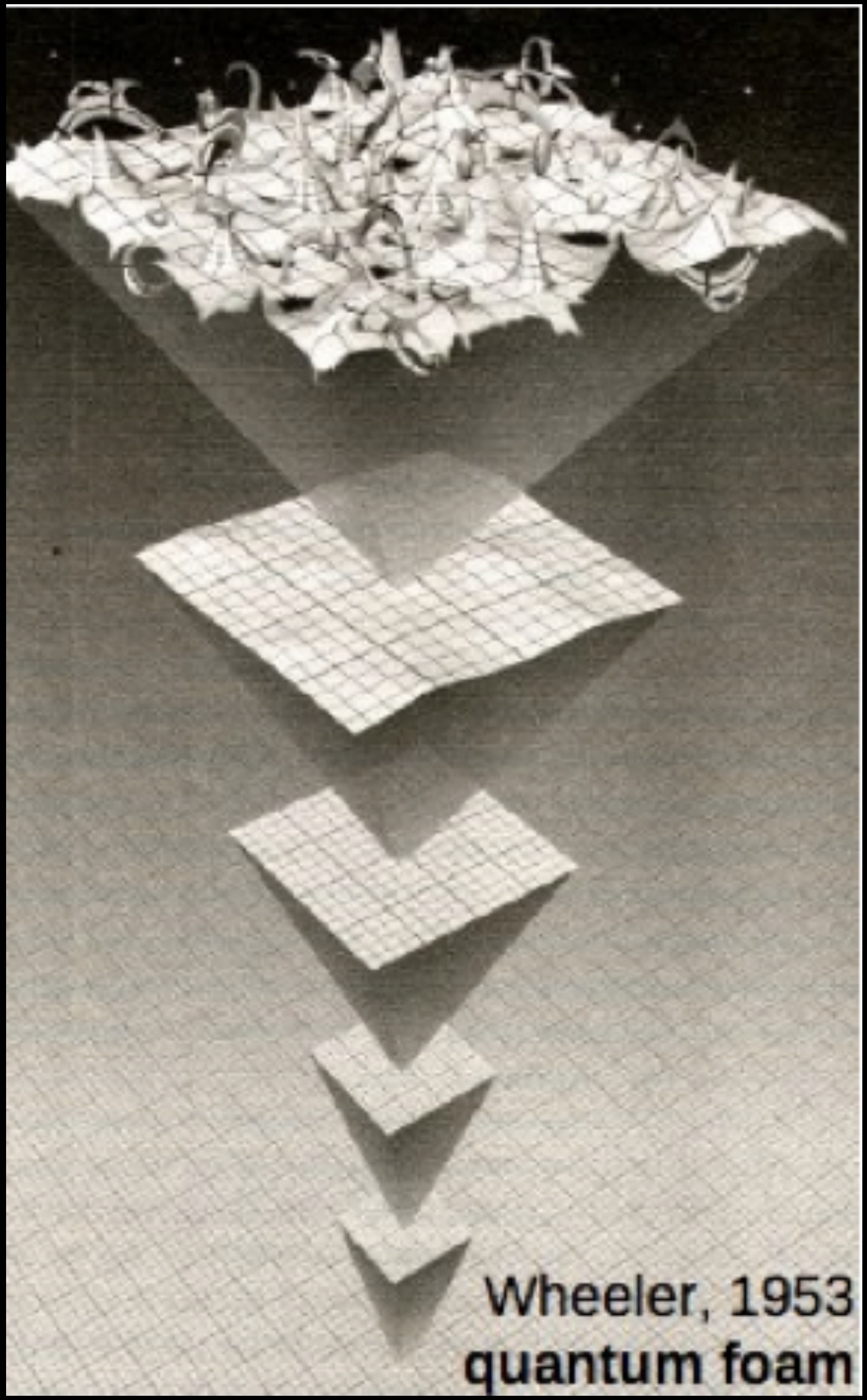
- Blazars (jet points us ->large boost factor) observable at great distances (cosmology).

Dark Matter indirect search

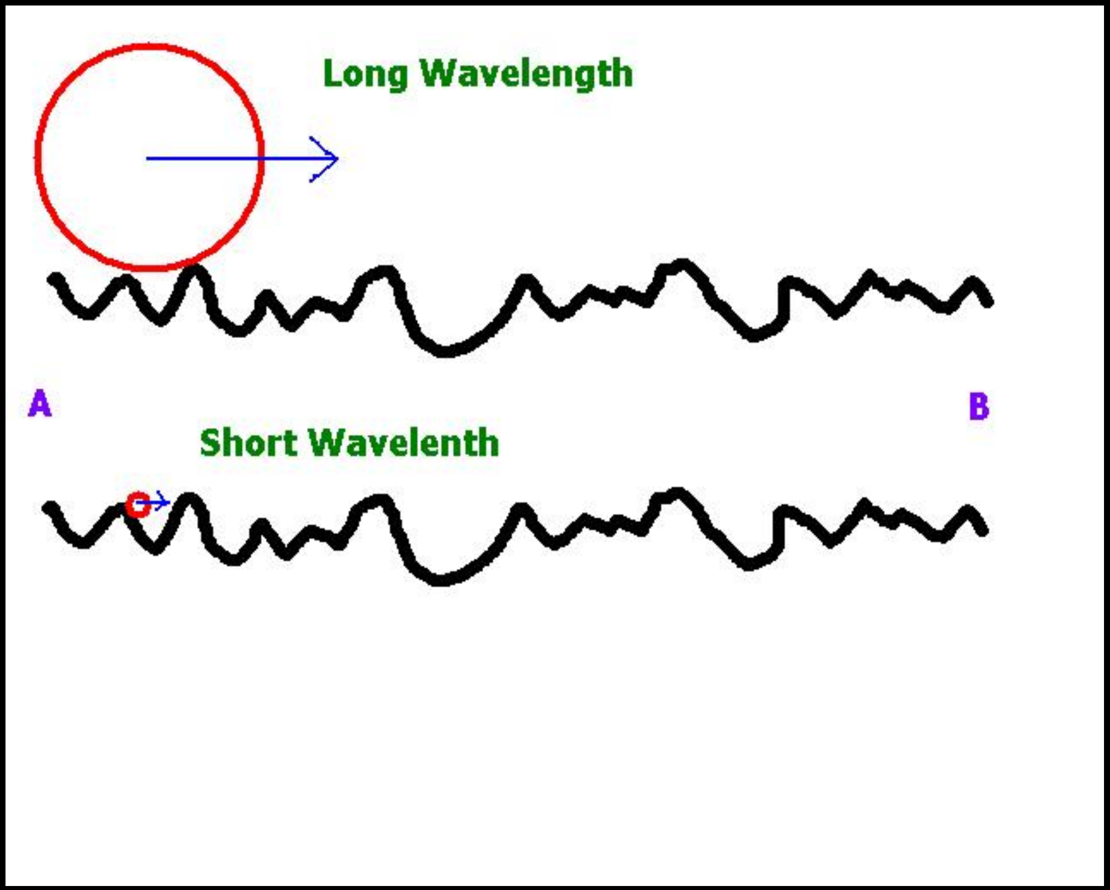
- If Dark Matter are WIMPs their annihilation or decay shall produce high cosmic rays (e, , gamma).

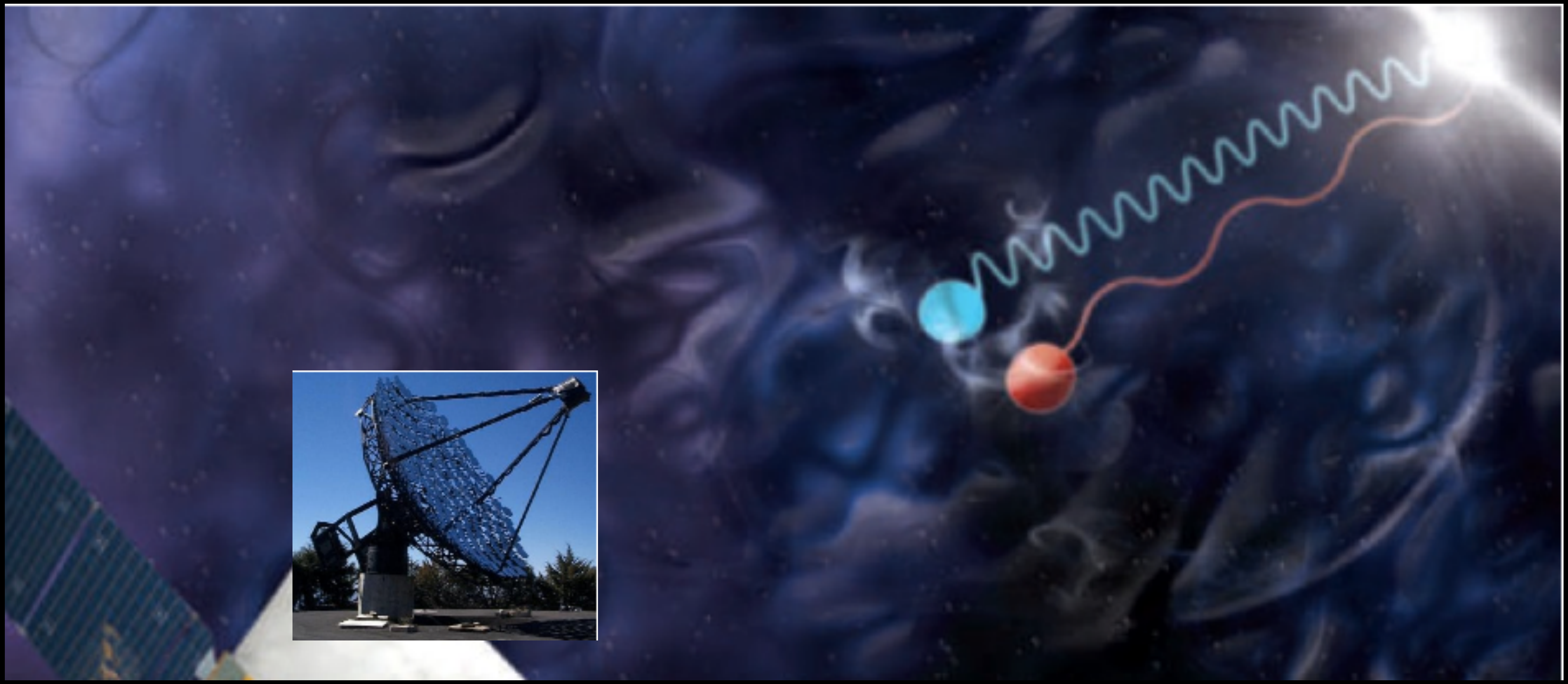
- If Dark Matter are ALPs the conversion of cosmic gamma rays should change the opacity of the universe.

Quantum Gravity effects



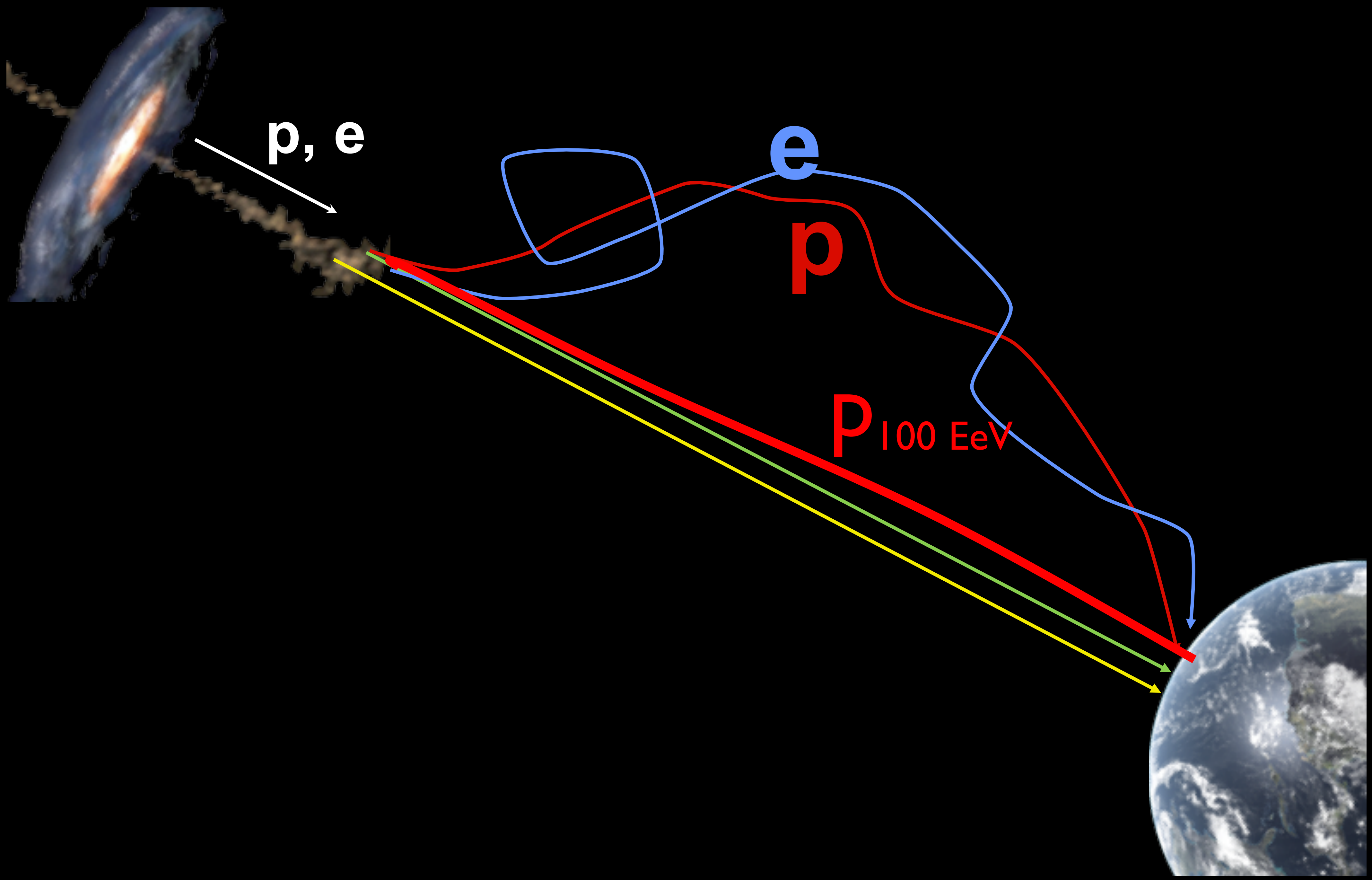
- If gravity behaves like a quantum theory, spacetime at very short distances (very high energies) has a very complex structure (”foamy").
- The speed of light in vacuum can be wavelength (energy) dependent.

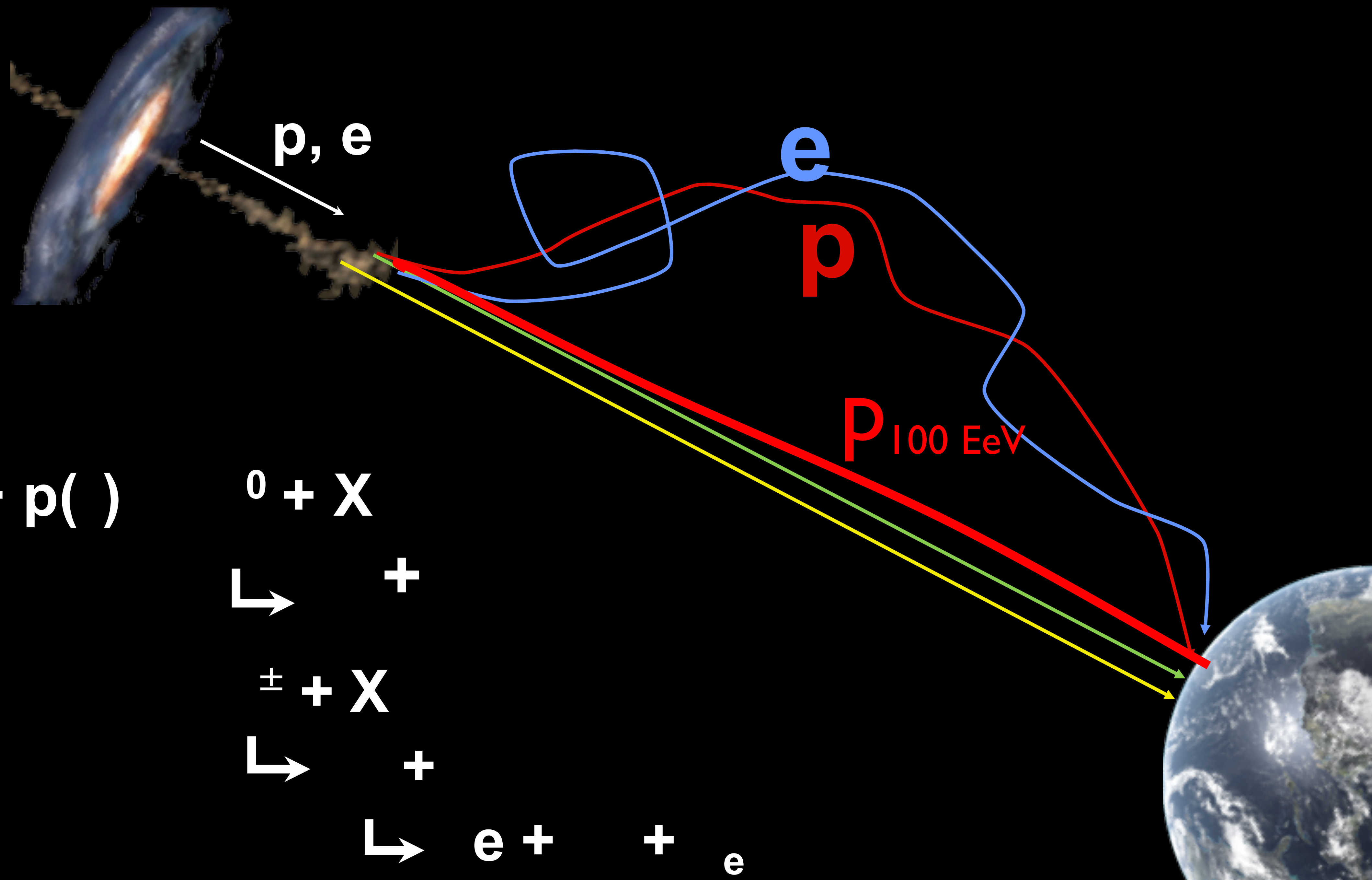

Long Wavelength
A
B
Short Wavelenth



MESSENGERS

The Cosmic High Energy Messengers





p + p( ) ^{0} + X

↳   +

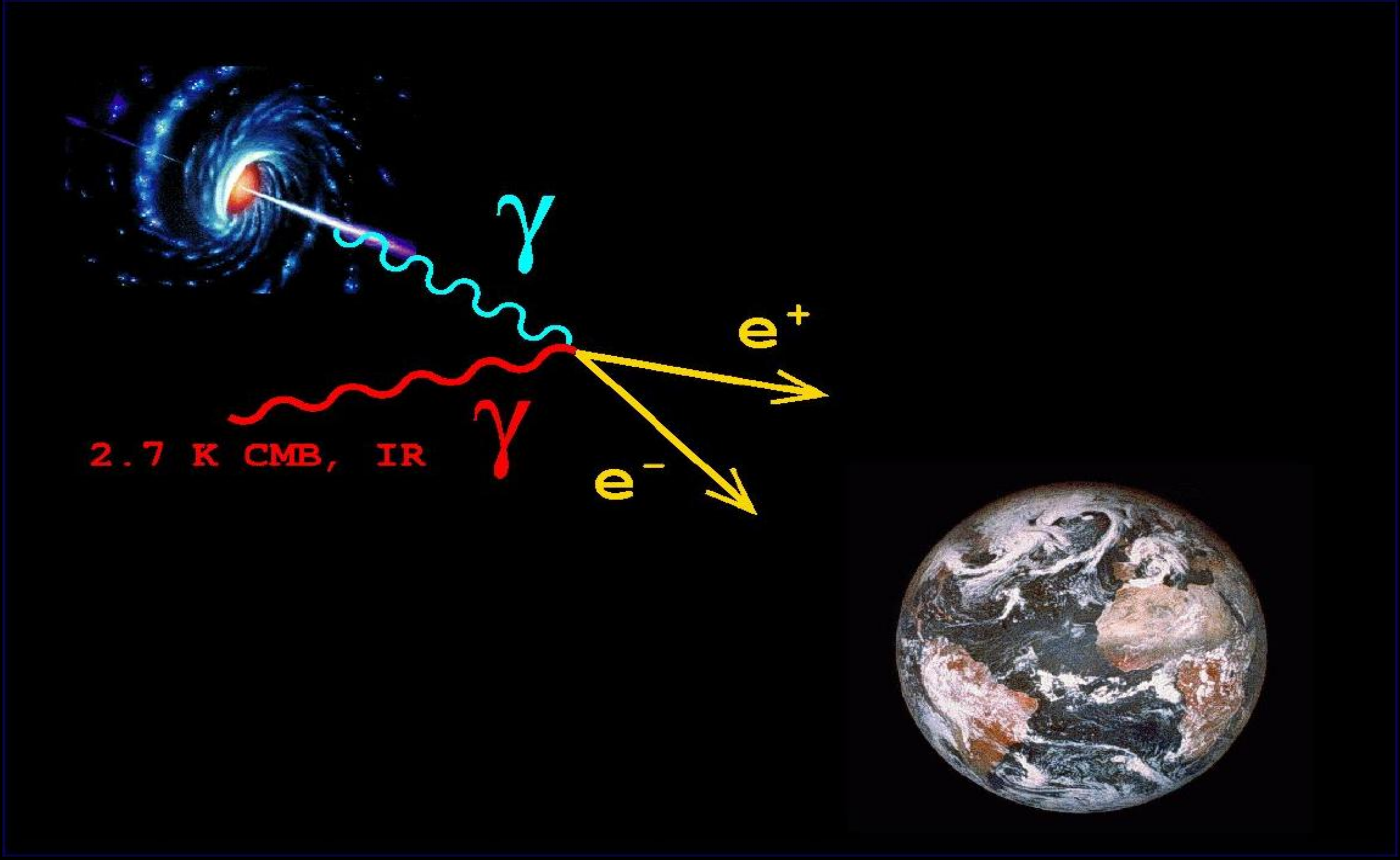
$^{\pm}$ + X

↳   +

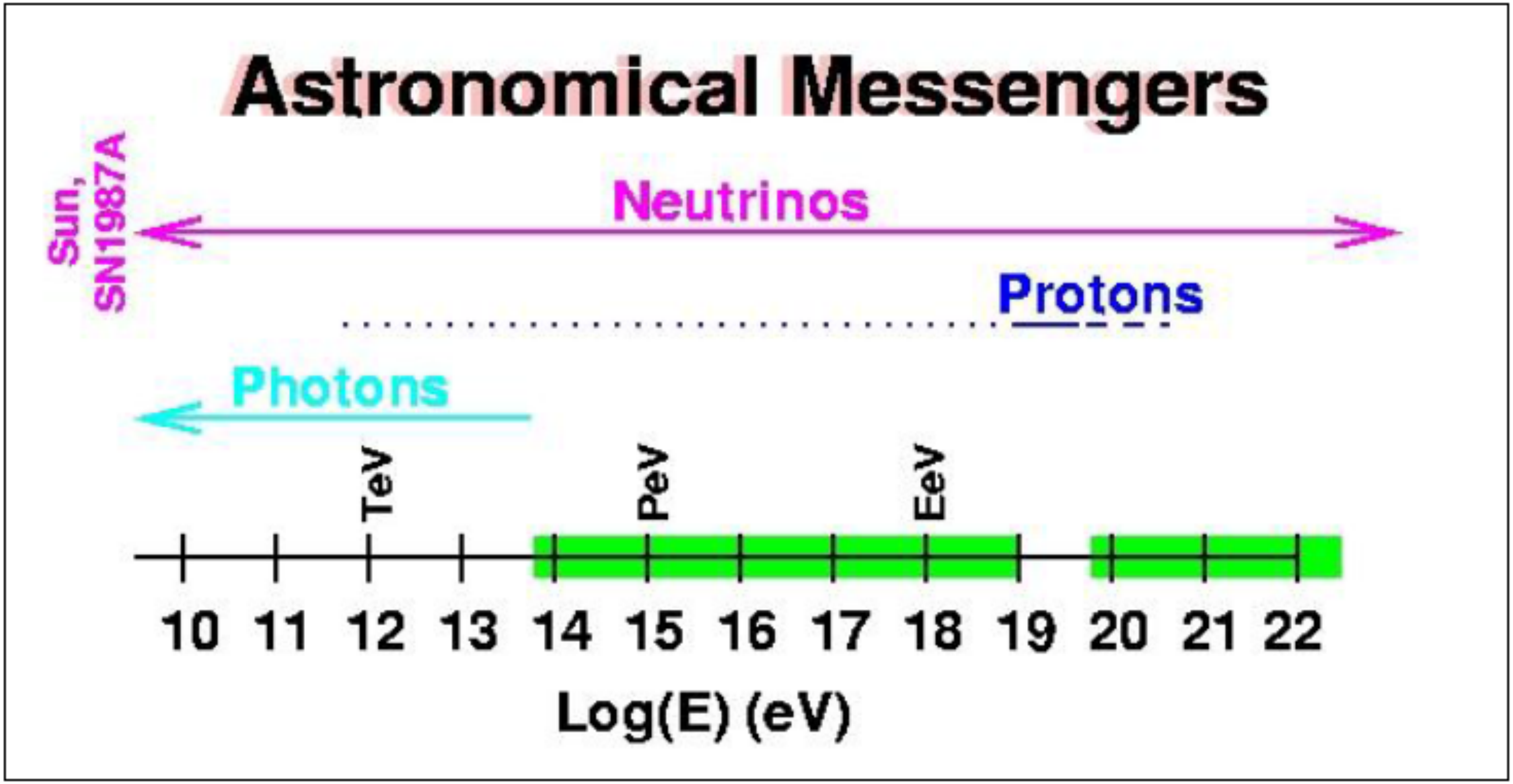
↳ e +   + $_{e}$

e +   (Inverse Compton) ⟶ e +

Cosmological Gamma Ray Horizon



Accessible energy regions



GOALS

The questions: Astrophysics & Cosmology

- ## Cosmic particle acceleration and propagation
  - How and where are cosmic particles accelerated?
  - How do they propagate – within and outside the Galaxy?
  - What is their impact on the environment (Galaxy formation, Earth system, biology, …)?

- ## Probing extreme environments
  - Processes close to black holes and neutron stars
  - How do supernovae explode, role of neutrinos?
  - Processes in relativistic jets, winds and radio lobes
  - Understanding cosmic magnetic fields

- ## Cosmic Evolution

The questions: Particle Physics & Basic Laws

- **Standard Model**
  - Understanding forward physics at LHC
  - pp and cross sections at highest energies
  - Charm production at highest energies
  - Neutrino oscillations , mass hierarchy (ORCA & PINGU)
  - …

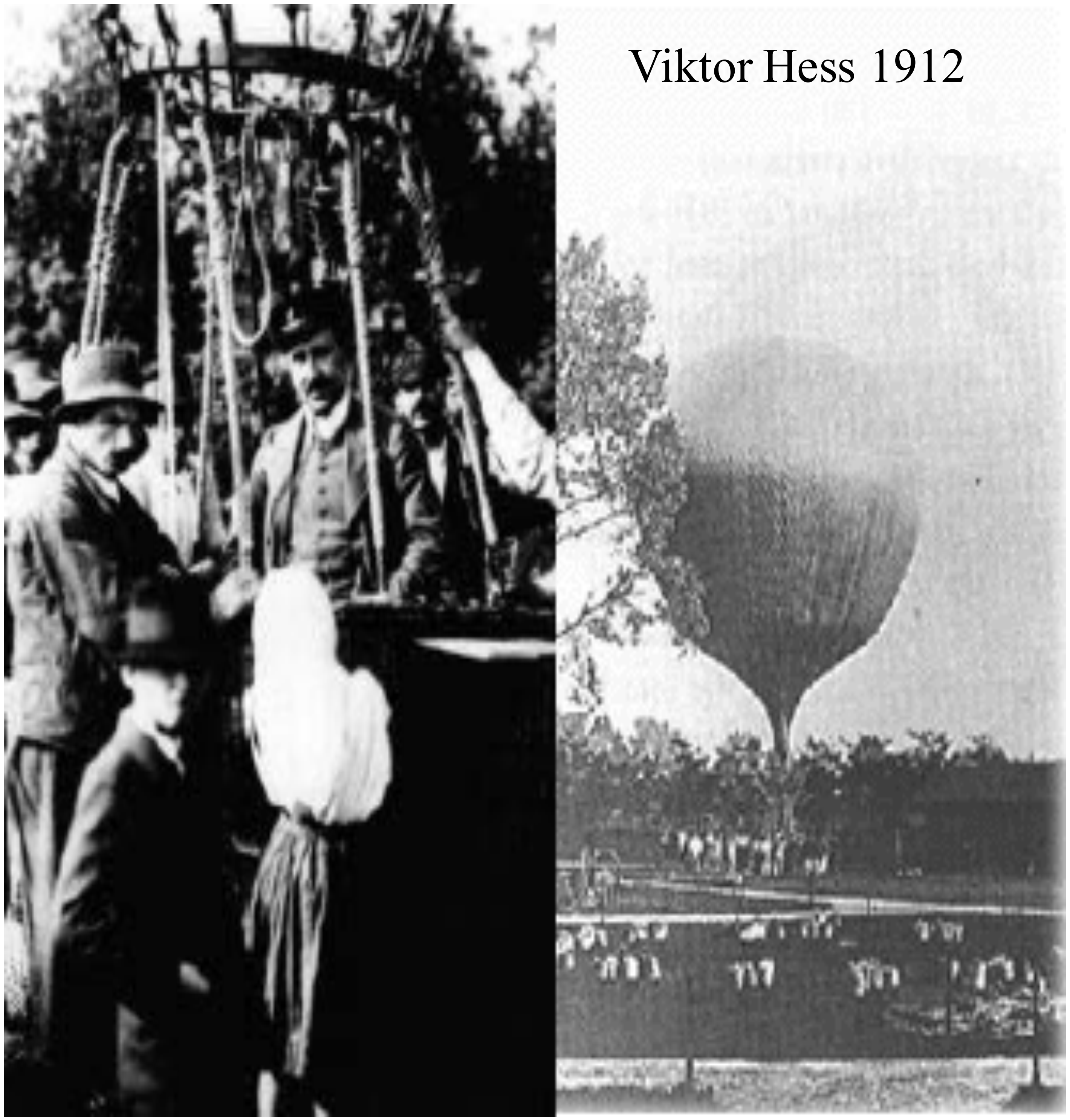
- **Beyond the Standard Model & Basic Laws**
  - Dark matter: SUSY WIMPs, Q-balls, magnetic monopoles …
  - Violation of Lorentz invariance
  - New particle physics at extreme energies
  - Sterile neutrinos
  - …

EeV COSMIC RAYS

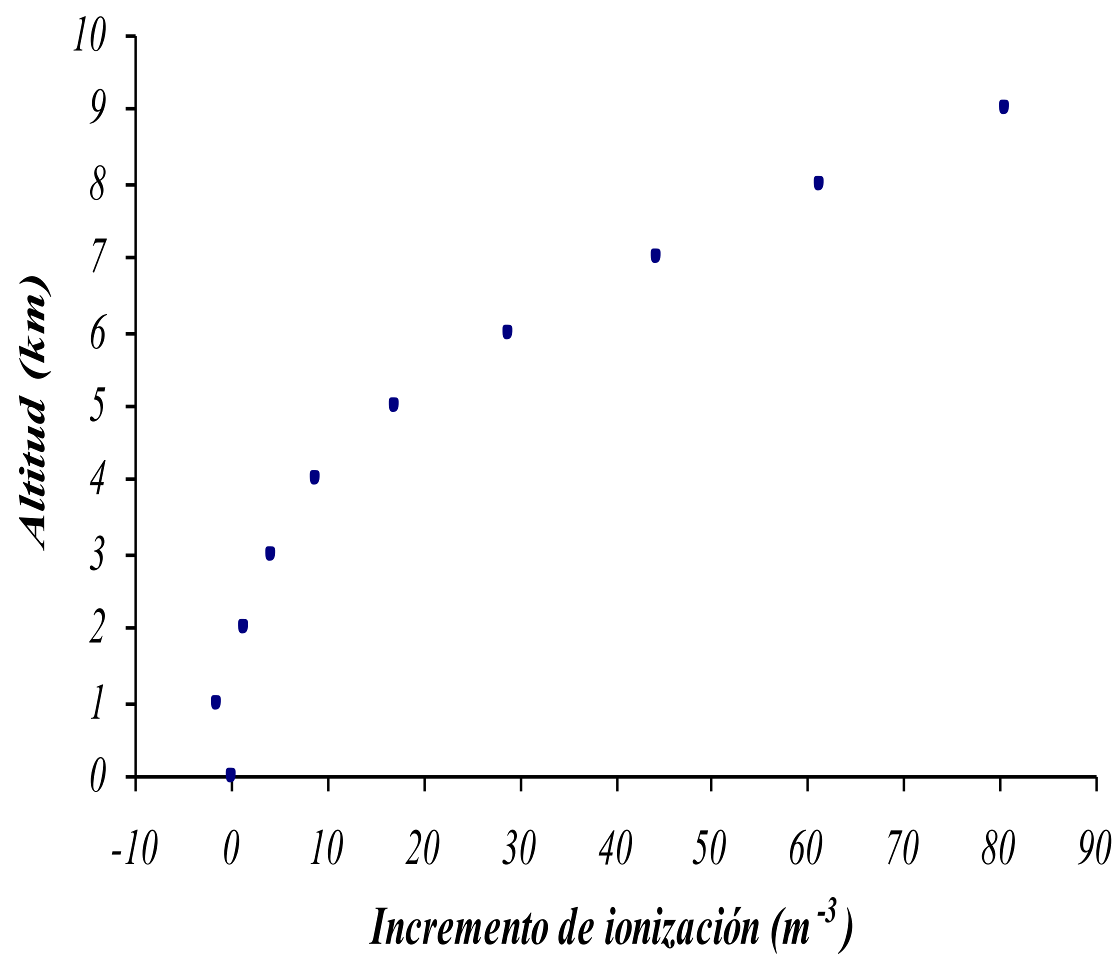
APPROACHING A TURNING POINT ?

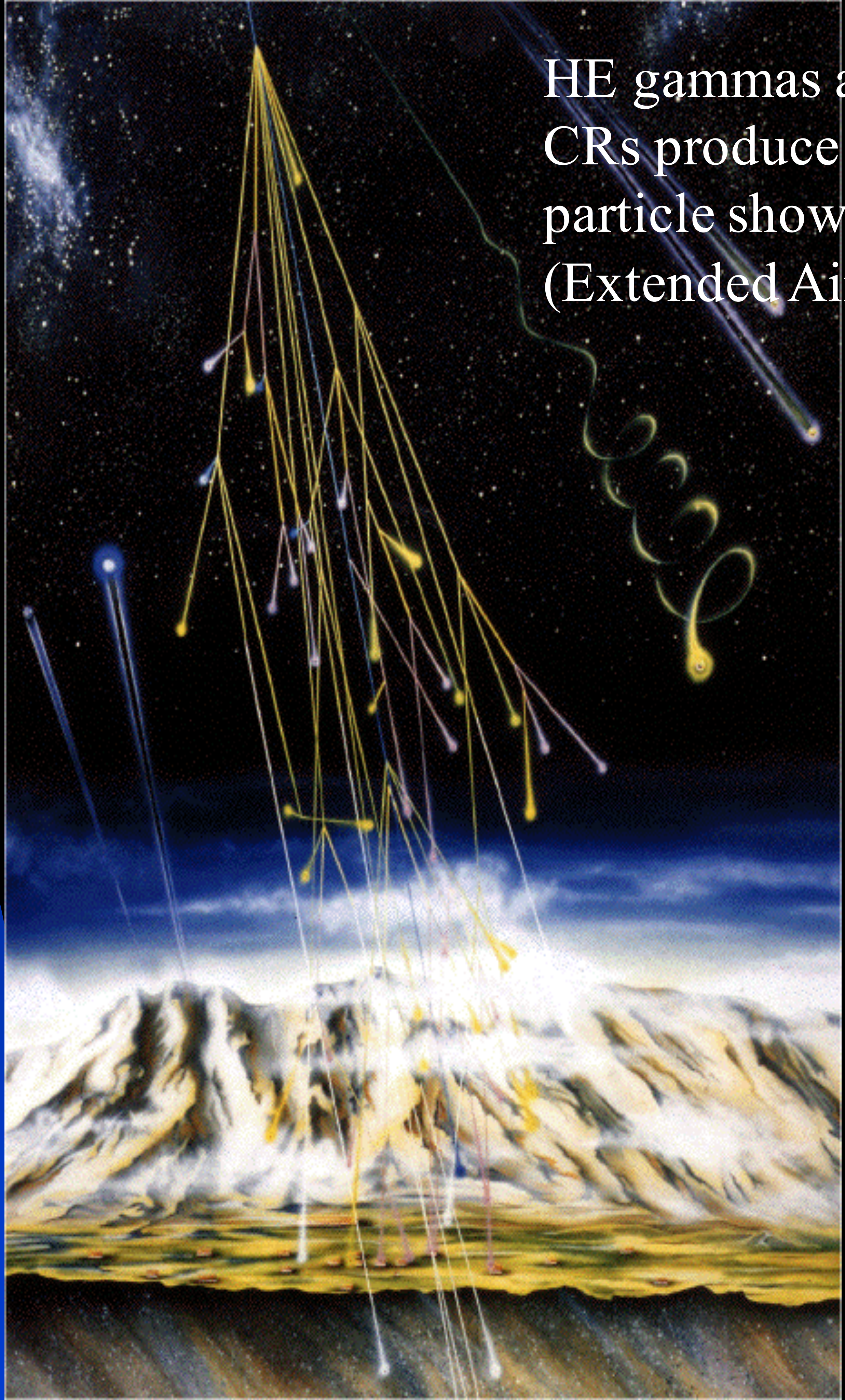
Viktor Hess

1912


Viktor Hess 1912


EXTRATERRESTRIALS !!!

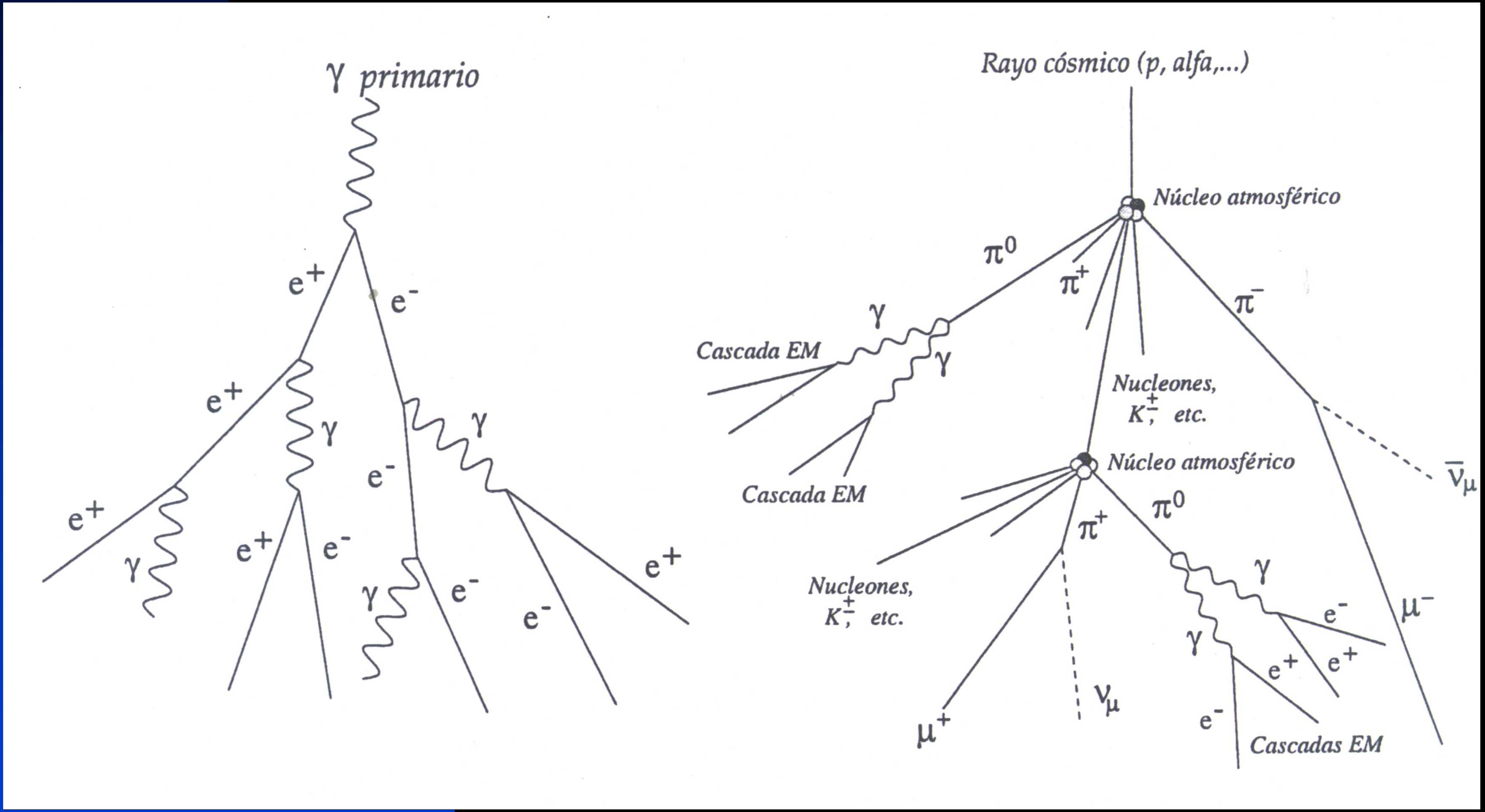

Altitud (km)
0
1
2
3
4
5
6
7
8
9
10
-10
0
10
20
30
40
50
60
70
80
90
Incremento de ionización (m^{-3})



HE gammas and charged CRs produce in the atmosphere particle showers (Extended Air Showers)

Particle showers:

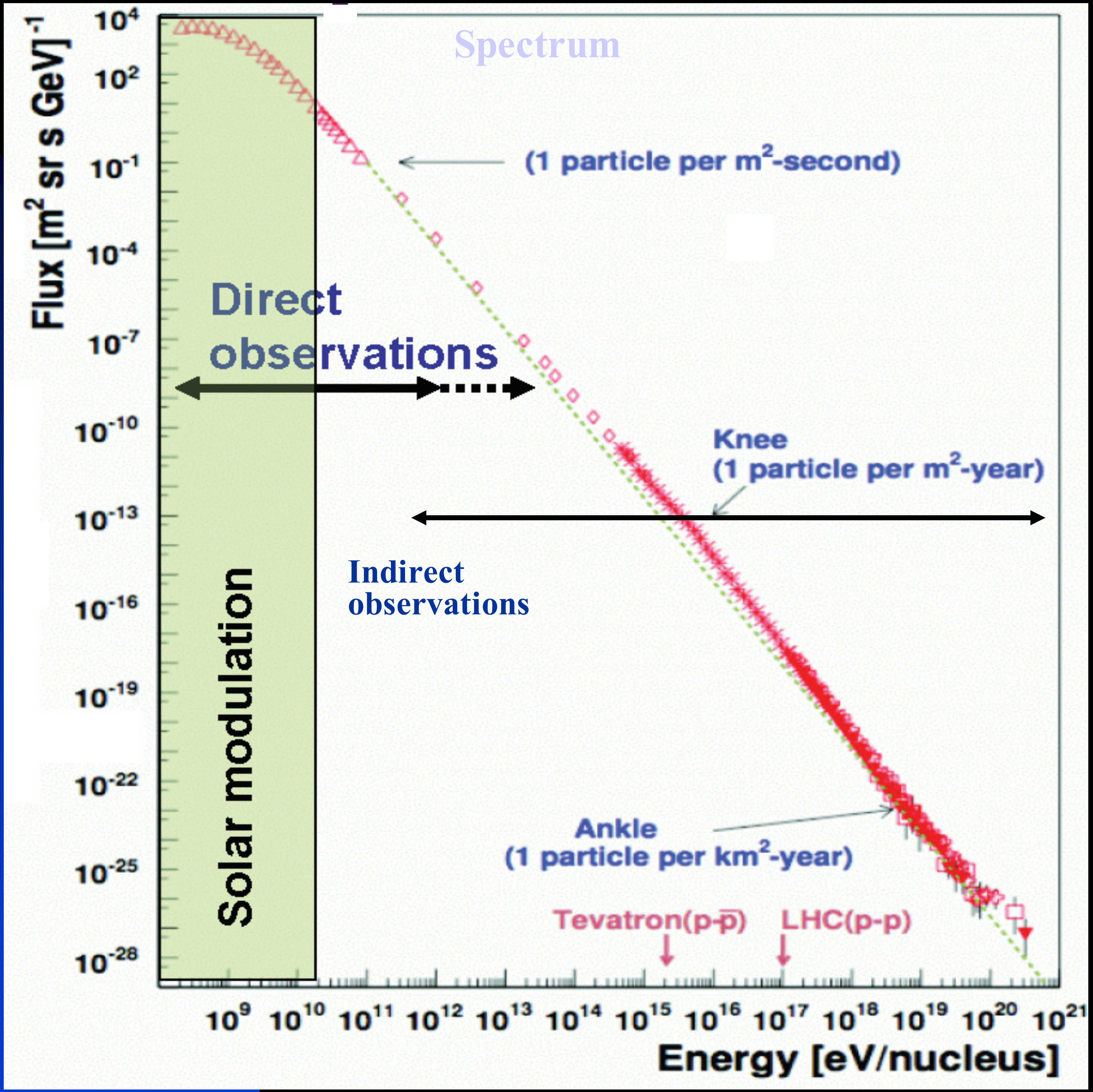
Electromagnetic / Hadronic



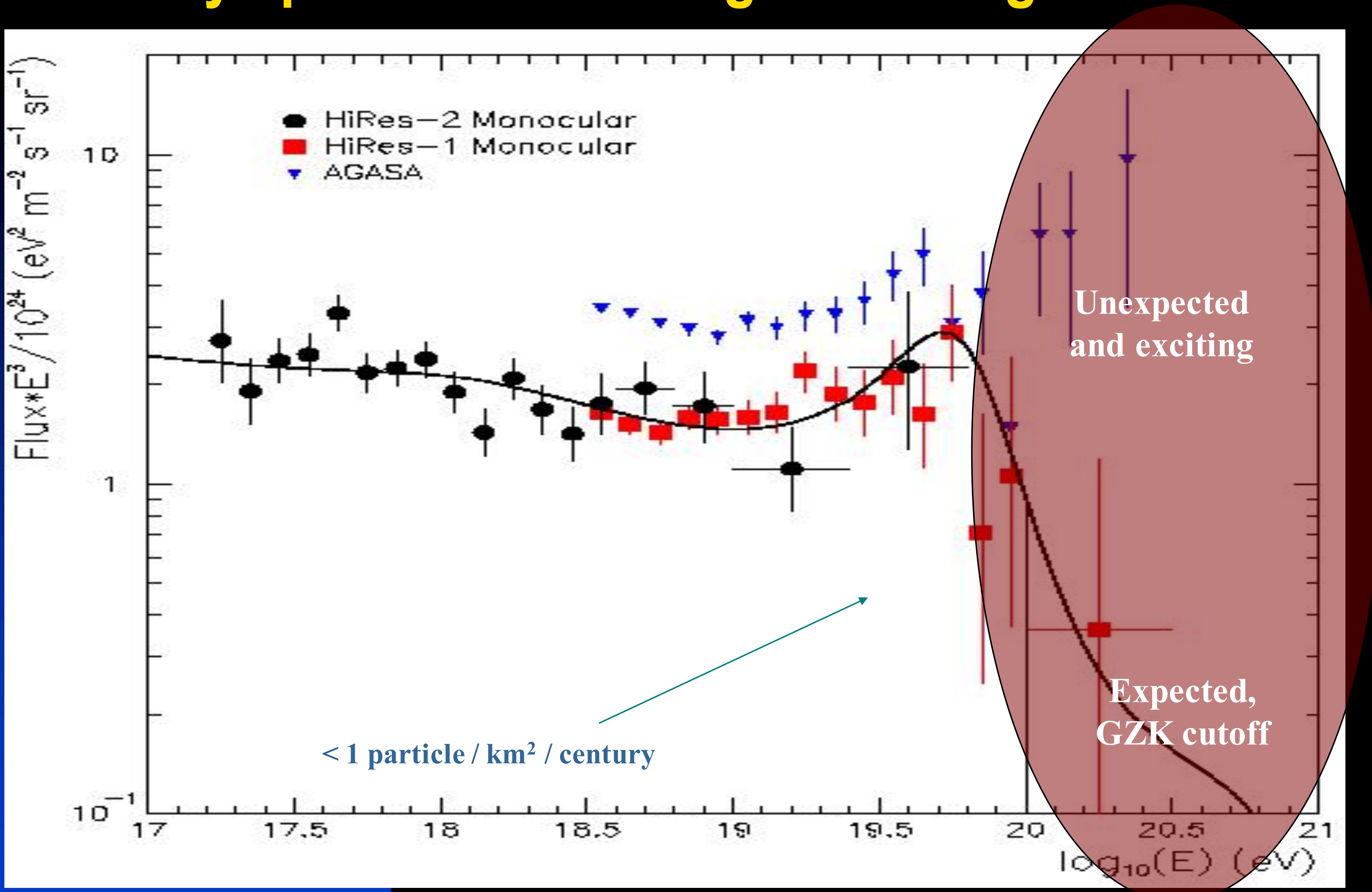
Pierre Auger

1939

Charged cosmic rays



Cosmic ray spectrum at the highest energies



GZK (Greisen-Zatsepin-Kuzmin) cutoff:

$$\gamma_{\rm CMB} + p \to \Delta^+ \to p + \pi^0,$$

or

$$\gamma_{\rm CMB} + p \to \Delta^+ \to n + \pi^+.$$

Pierre Auger Observatory

Province Mendoza, Argentina

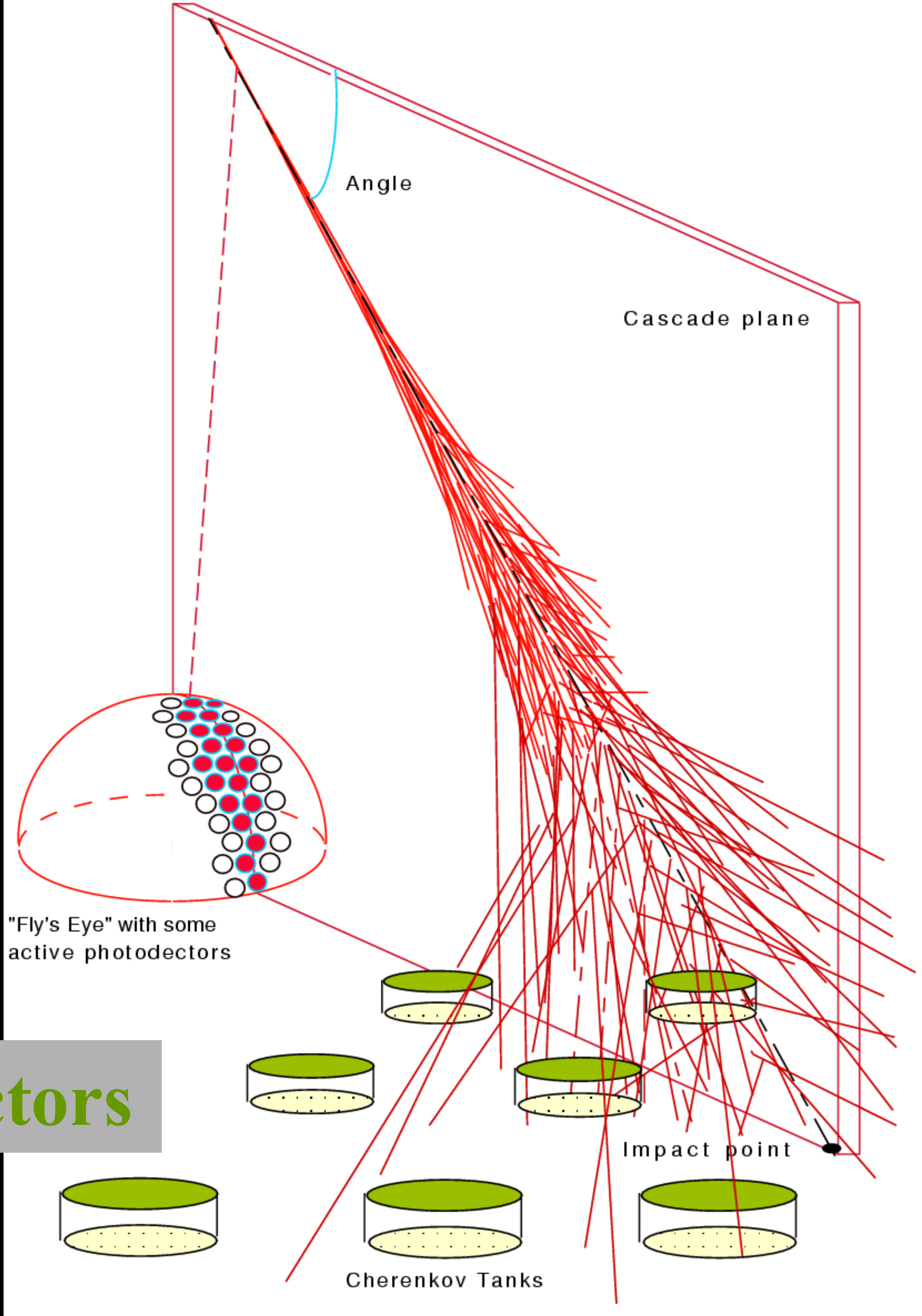
1660 detector stations on 1.5 km grid

27 fluores. telescopes at periphery

130 radio antennas

Jim Cronin, Alan Watson

Two succesful techniques

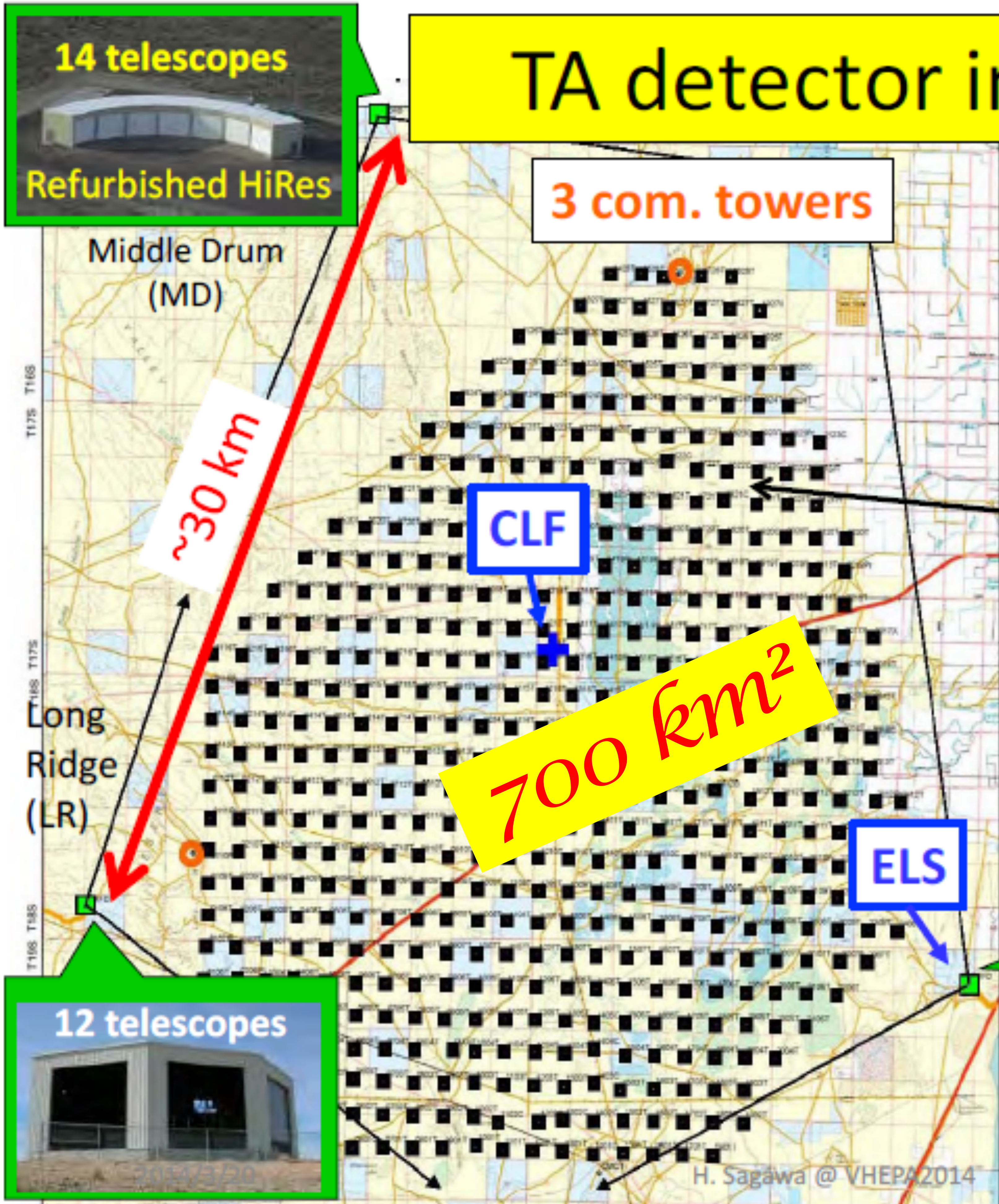


Fluorescence

Array of particle detectors

TA detector in Utah

39.3°N, 112.9°W
~1400 m a.s.l.



Surface Detector (SD)

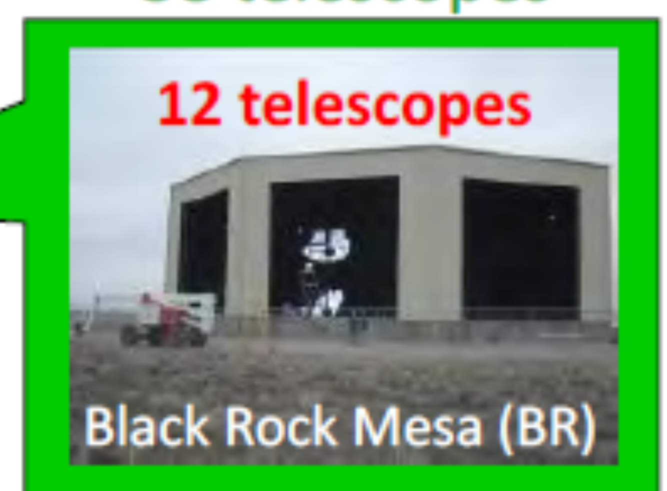
507 plastic scintillator SDs

1.2 km spacing

Fluorescence Detector(FD)

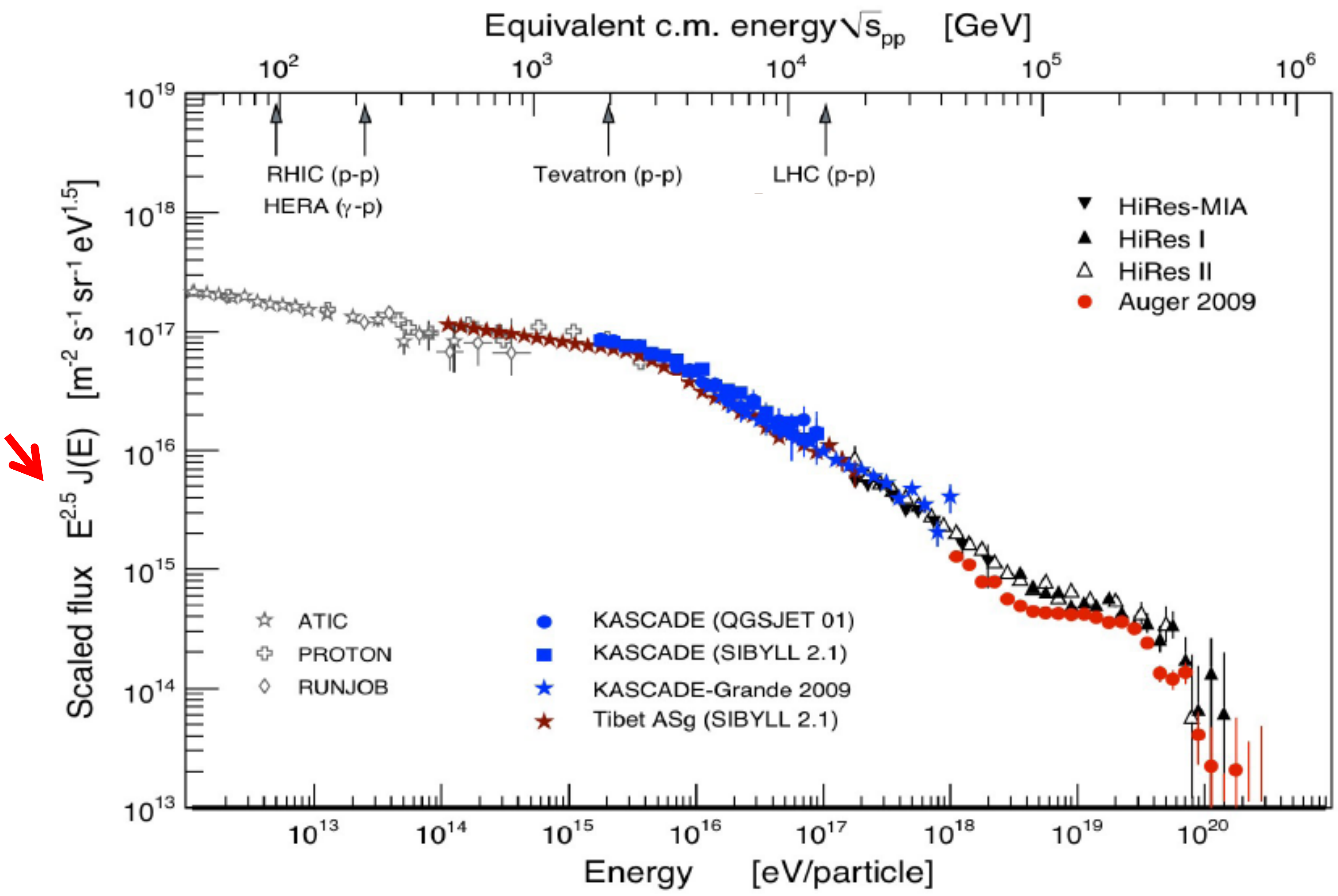
3 stations

38 telescopes



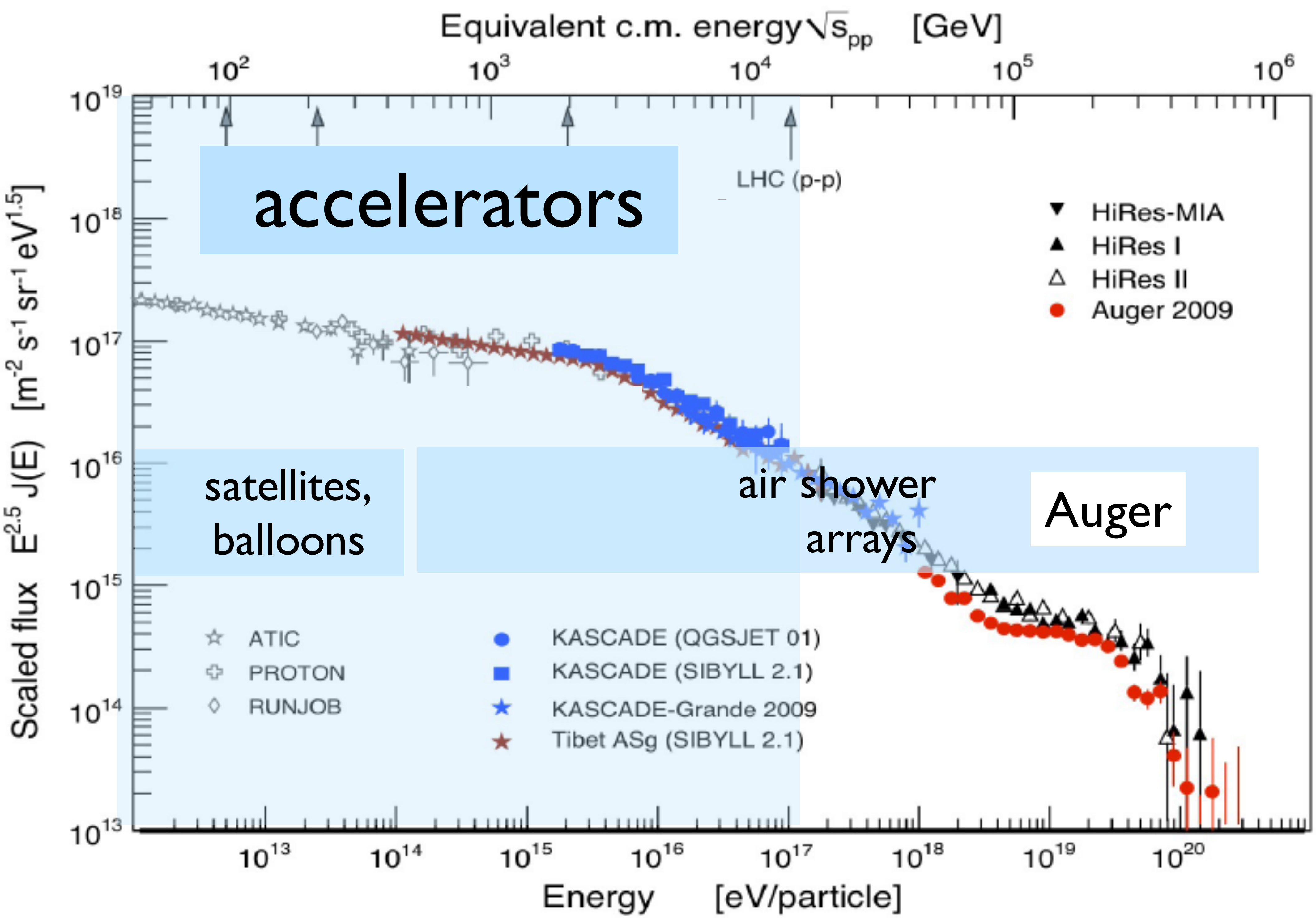
FD and SD: fully operational since 2008/May 4

Spectrum of Cosmic Rays



R. Engel (KIT)

Spectrum of Cosmic Rays



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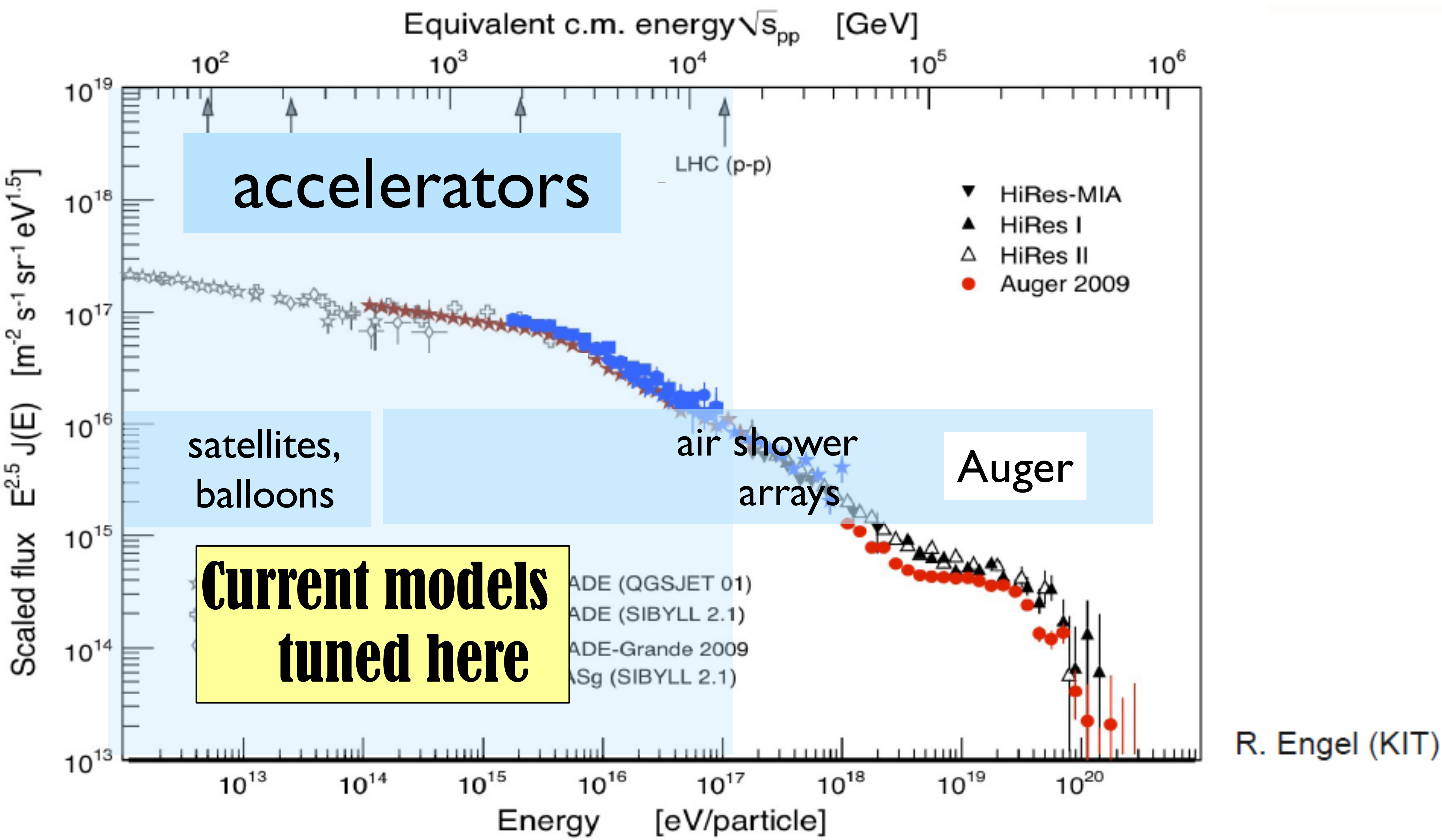
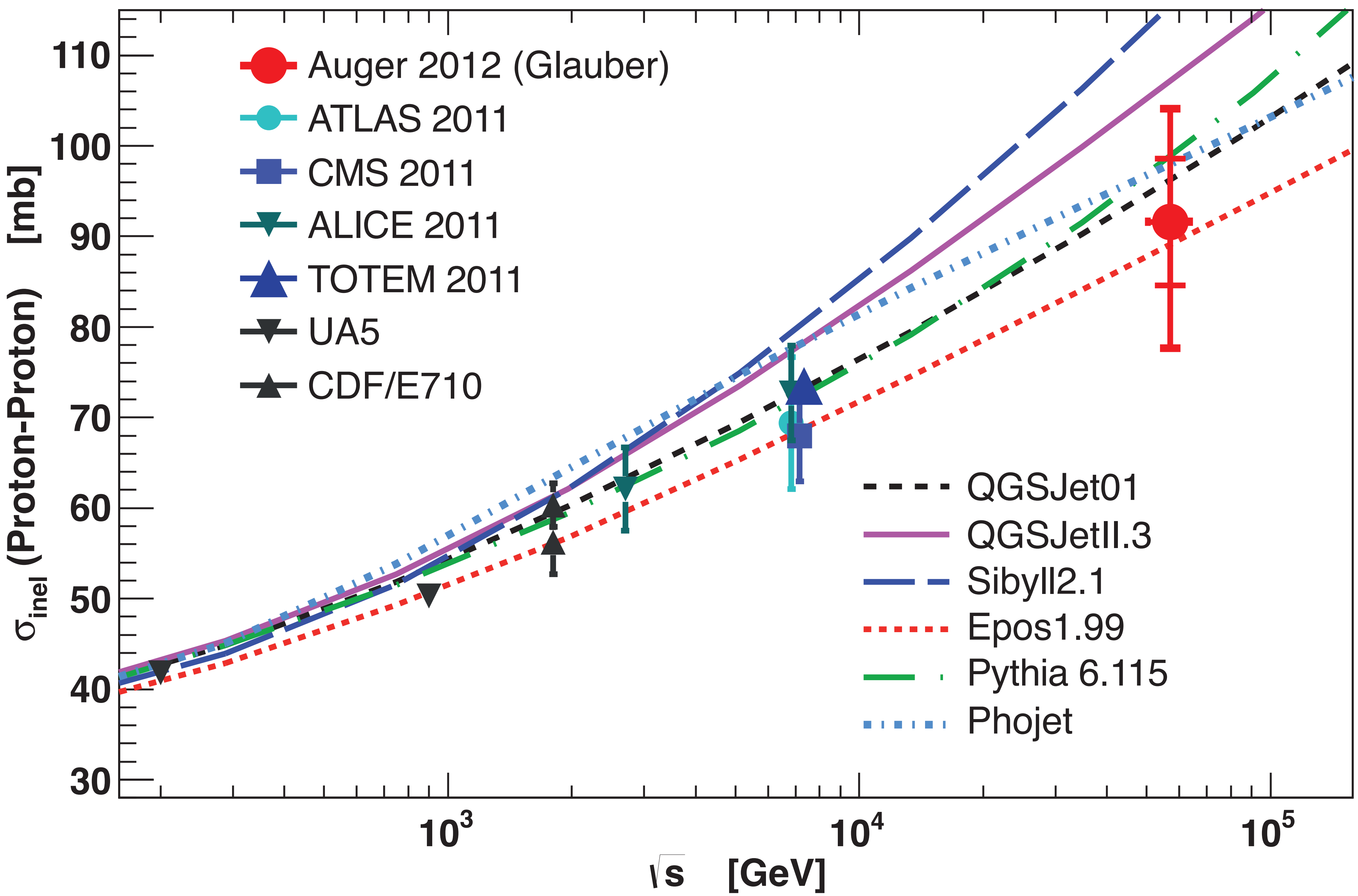
Spectrum of Cosmic Rays



Cosmic Rays and LHC

pp inel. cross section at sqrt(s)=57 TeV



- Compare to QCD and Glauber model, tuning EAS simulations

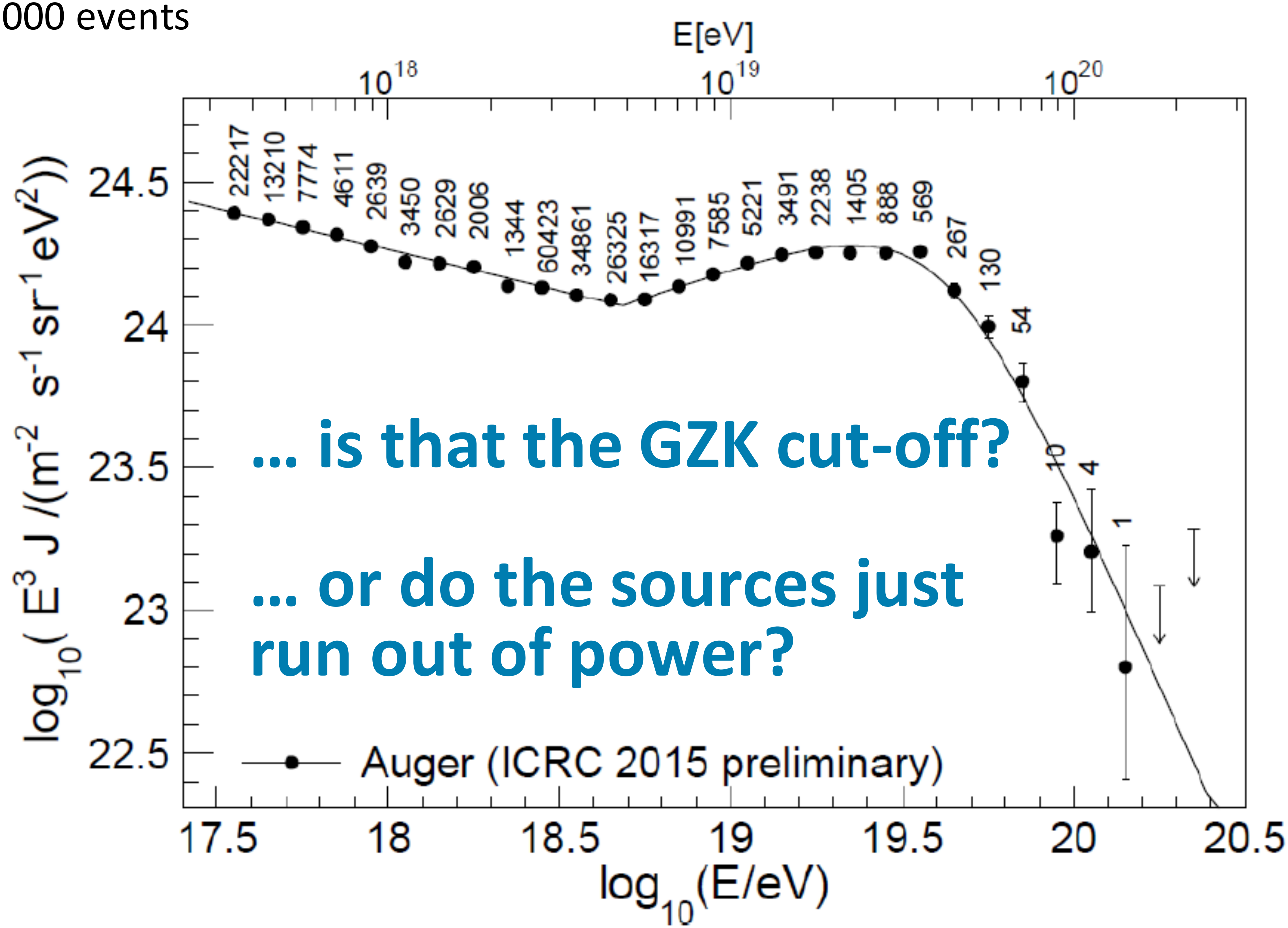
Cosmic Rays and LHC

- **Cooperation of particle- and CR-physicists has been intensified over the last years.**
- **Extremely useful for understanding CR nature**
- **Accelerator data helped improving shower models. Tools of CR community will also help better understanding HE particle interactions: models sometimes better than HEP models**
- **Need common approach to understand muons in CR**

- **NA61/SHINE (SPS Heavy Ion and Neutrino Experiment):**
  important input data for cosmic ray and neutrino experiments.

Cut-off at highest energies confirmed, but …

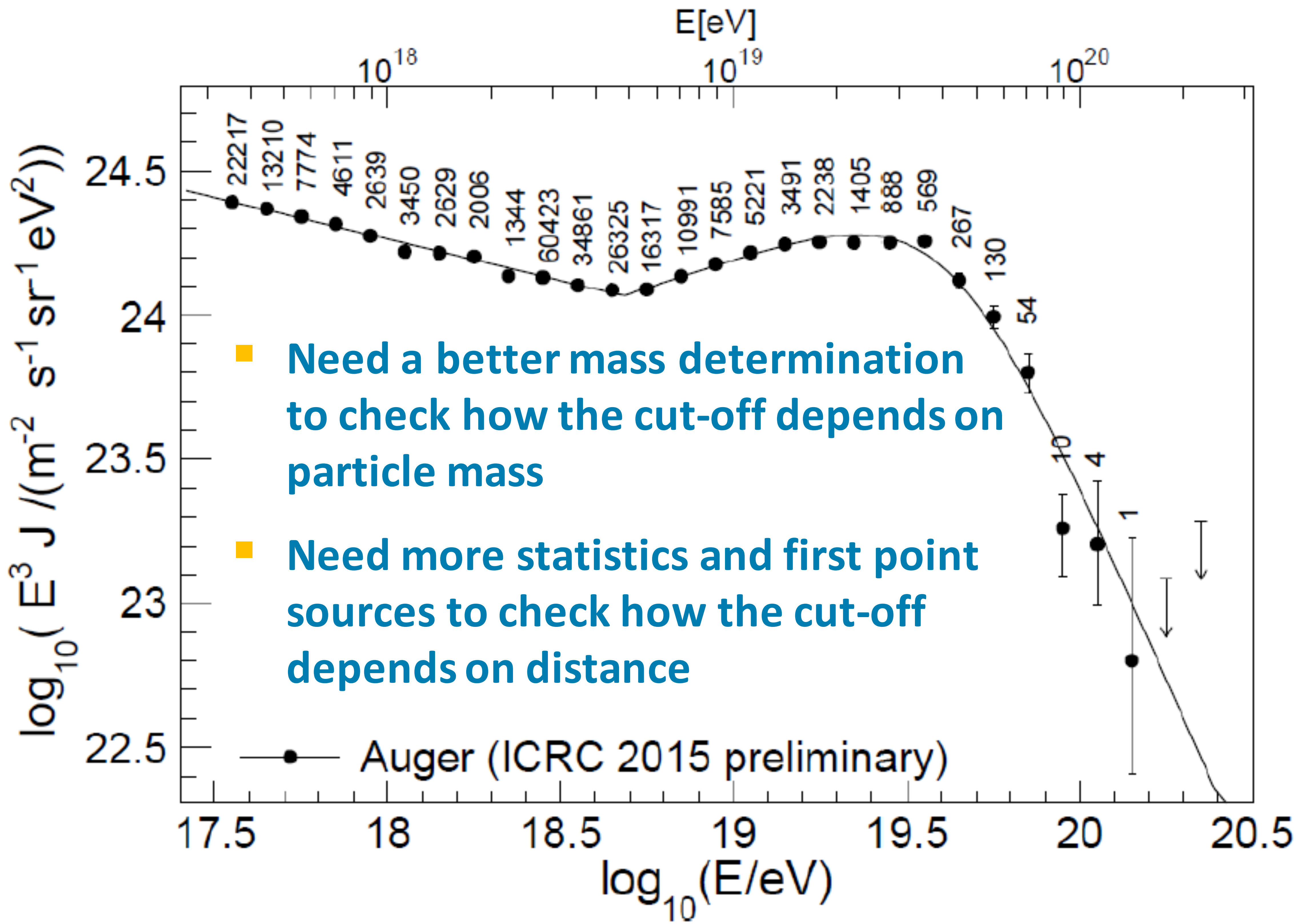
190 000 events



… is that the GZK cut-off?

… or do the sources just run out of power?

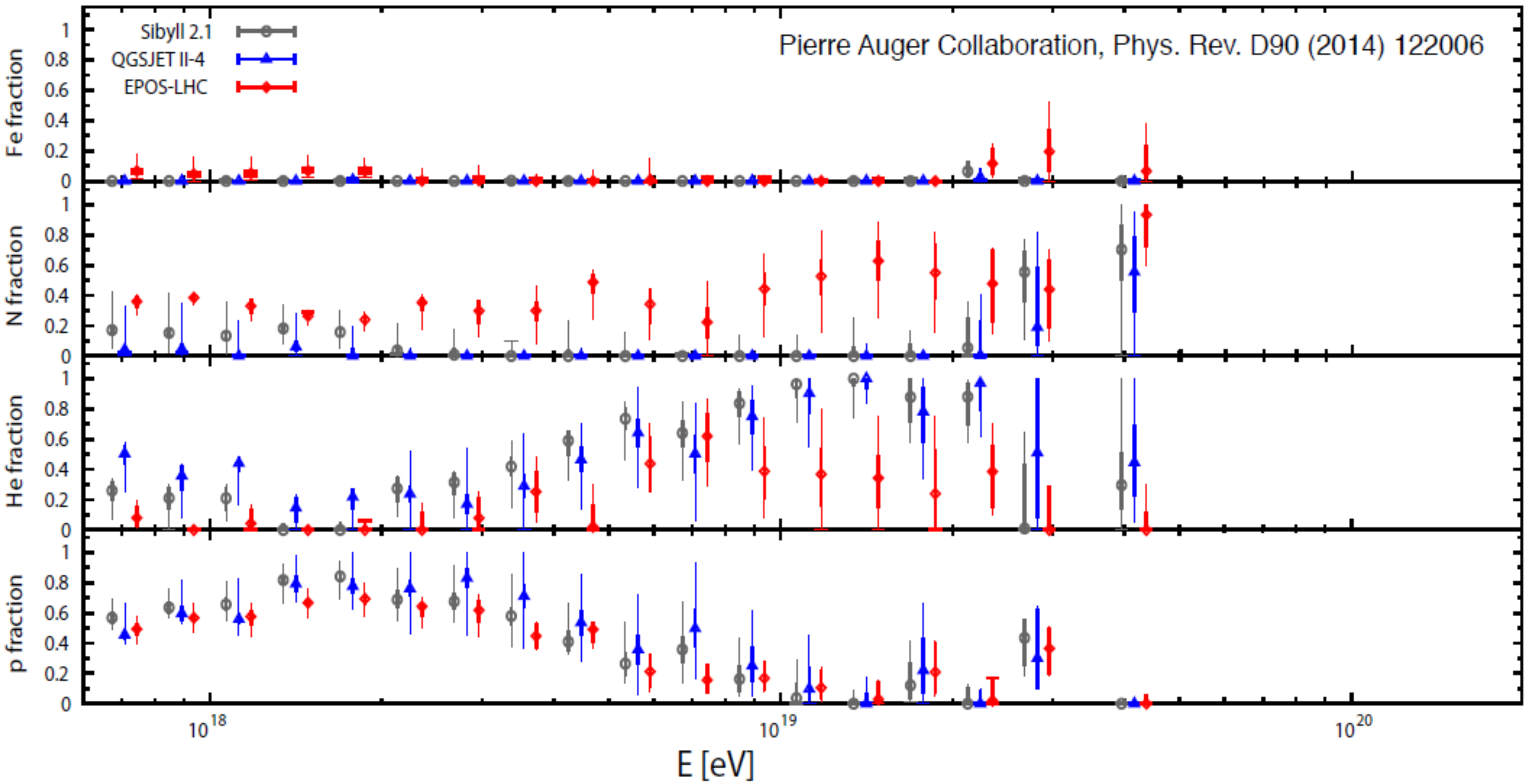
Cut-off: how to understand its nature



- **Need a better mass determination to check how the cut-off depends on particle mass**
- **Need more statistics and first point sources to check how the cut-off depends on distance**

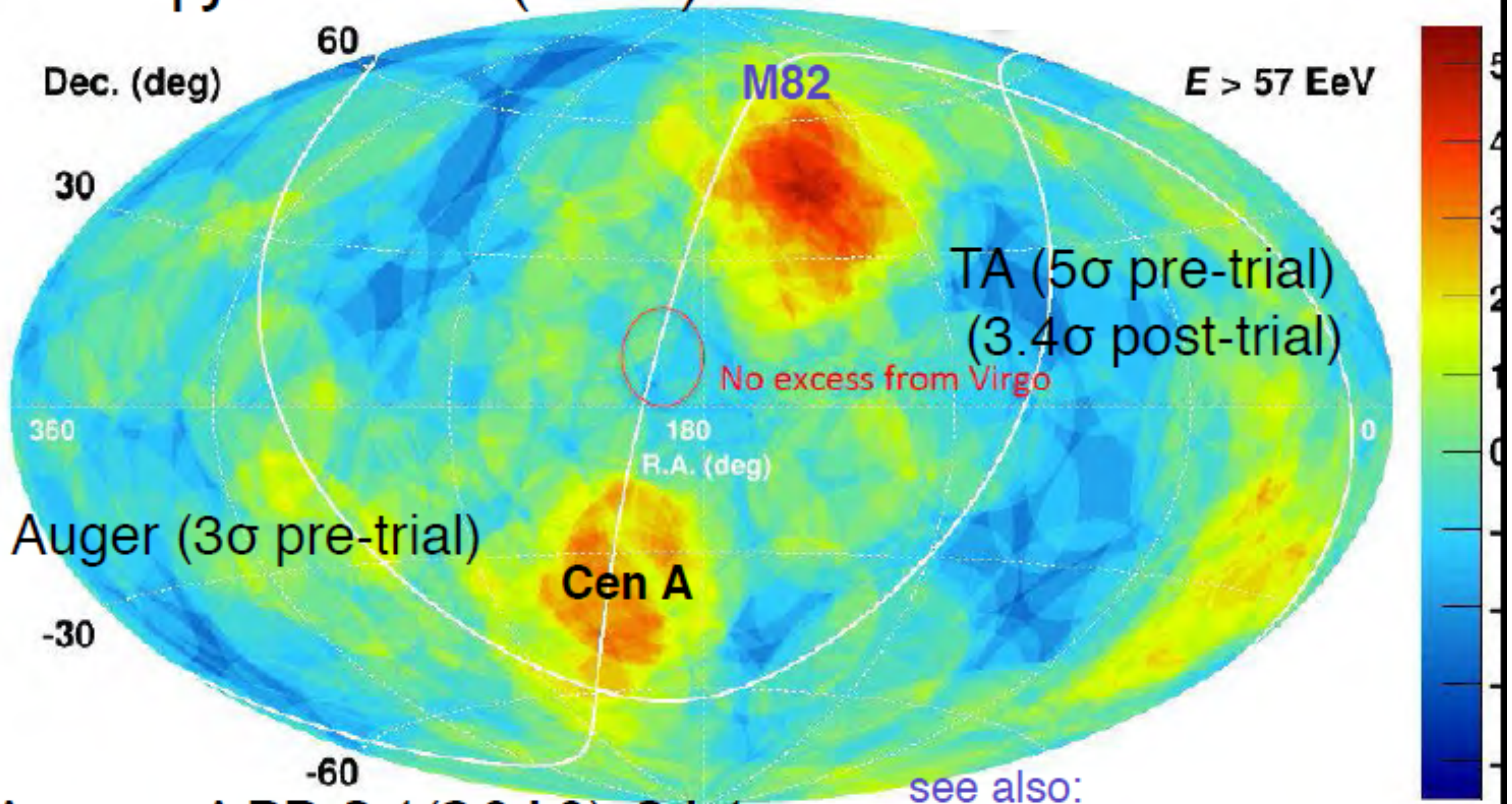
Can we do astronomy ?

- **Need protons -- heavy nuclei too strongly deflected.**
- **Presently derived proton contribution seems disappointingly small (~10%)**
- **Is that the final word? Could well be 30% !!**
- **Need better mass determination and more statistics above 3 10^{19} eV!**



Point Sources: Tantalizing hot spot at TA

TA: ApJ 790:L21 (2014)



Auger: APP 34(2010) 314

see also:
D. Fargion; arXiv:1412.1573

Auger and TA upgrades

AugerPrime

- improve measurement of mass composition !!
- no area extension
- upgrading water tanks with scintillators on top + new electronics

    better event-to-event composition measurement, into cut-off region

    in-depth study of muon excess, CR models, …
- raising Fluorescence Detector duty cycle by 10-15%   more hybrid events

Telescope Array upgrade

- more statistics for hot spot !!
- increasing array from 700 km^2 to 2800 km^2 (approved in Japan April 2014)
- 2 new Fluorescence detectors (proposal submitted in USA)

What after results with upgraded arrays ?

- Ultrahigh-energy cosmic ray physics is at a turning point
  - High-energy cut-off has been clearly confirmed, but nature unclear
  - No point sources, but hot spot TA + “warm” spot Auger
  - Detection and study of point sources was one of the two primary goals of Auger/TA. Would also be the primary motivation for any future EeV CR experiment – ground based arrays of the 30 000 – 90 000 km^2 class or the space based JEM-EUSO.
  - Key to move ahead in both directions: more precise mass assignment of individual events and the separation of a proton event sample which is minimally polluted by heavier nuclei.

What after results with upgraded arrays ?

- **If proton component < 5-10%:** Next-generation detectors would fail *by definition* to identify point sources.
  That would very likely herald the end of the race towards *astronomy* with charged cosmic rays.
- **If the proton component would be much higher than the presently estimated 10%, or if even point sources could be identified, the path towards cosmic ray astronomy would be open**.
- **AugerPrime extremely important for the future of the full field**:
  For small cost guidance, whether CR physics at highest energies should be continued or whether it will have reached its natural end.
- **In the most positive case, AugerPrime or TA would detect first point sources and break through a long-standing wall.**
- A larger detector could later study these sources in more detail.

The Auger Collaboration

Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania
Slovenia
Spain
USA

*associated

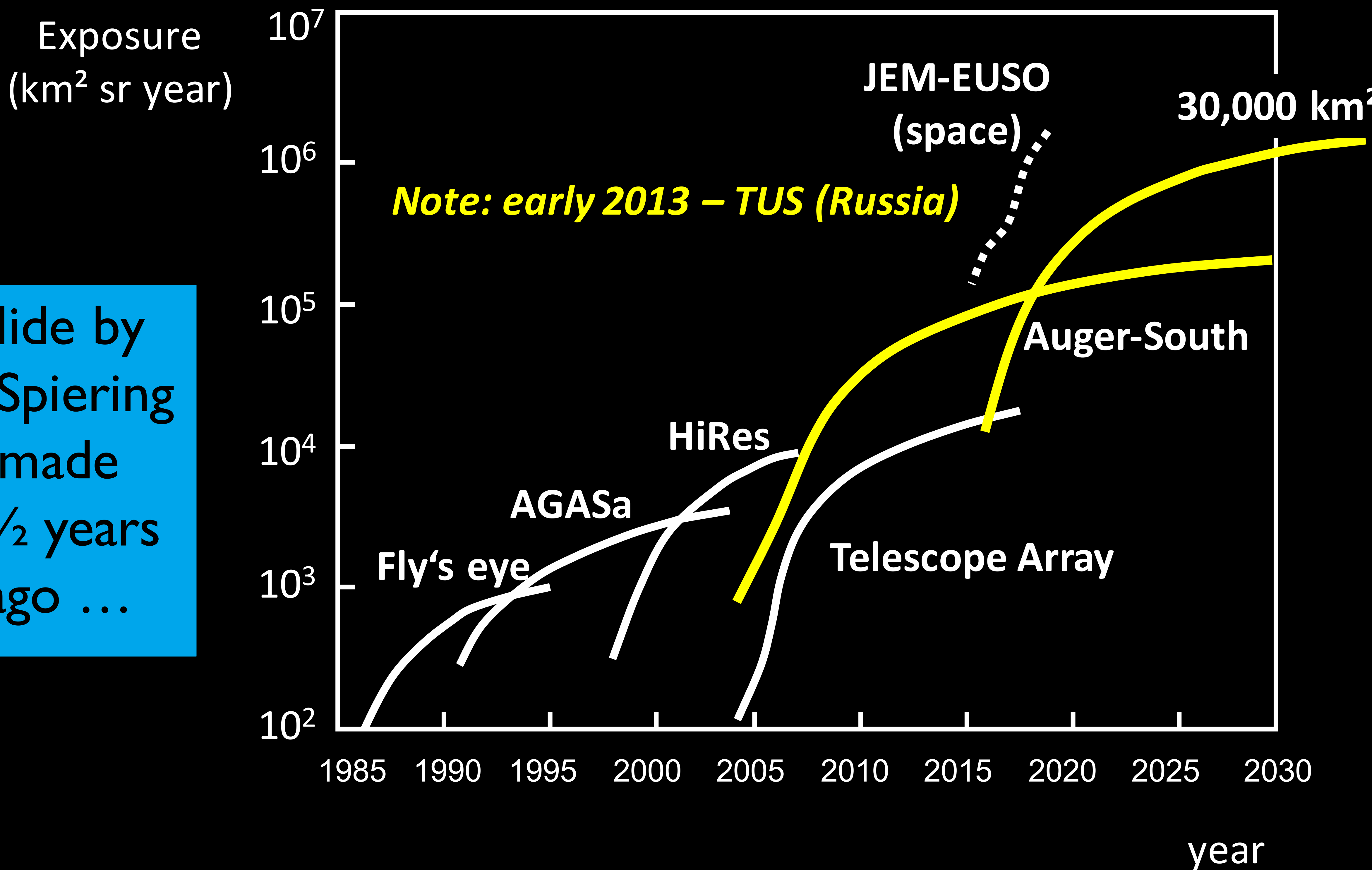
The Auger Collaboration and AugerPrime

- **Funding for AugerPrime approved (by now > 50%)**

Argentina
Australia
Brasil
Colombia*
Czech Republic
France
Germany ■
Italy ■
Mexico
Netherlands ■
Poland
Portugal
Romania
Slovenia ■
Spain
USA

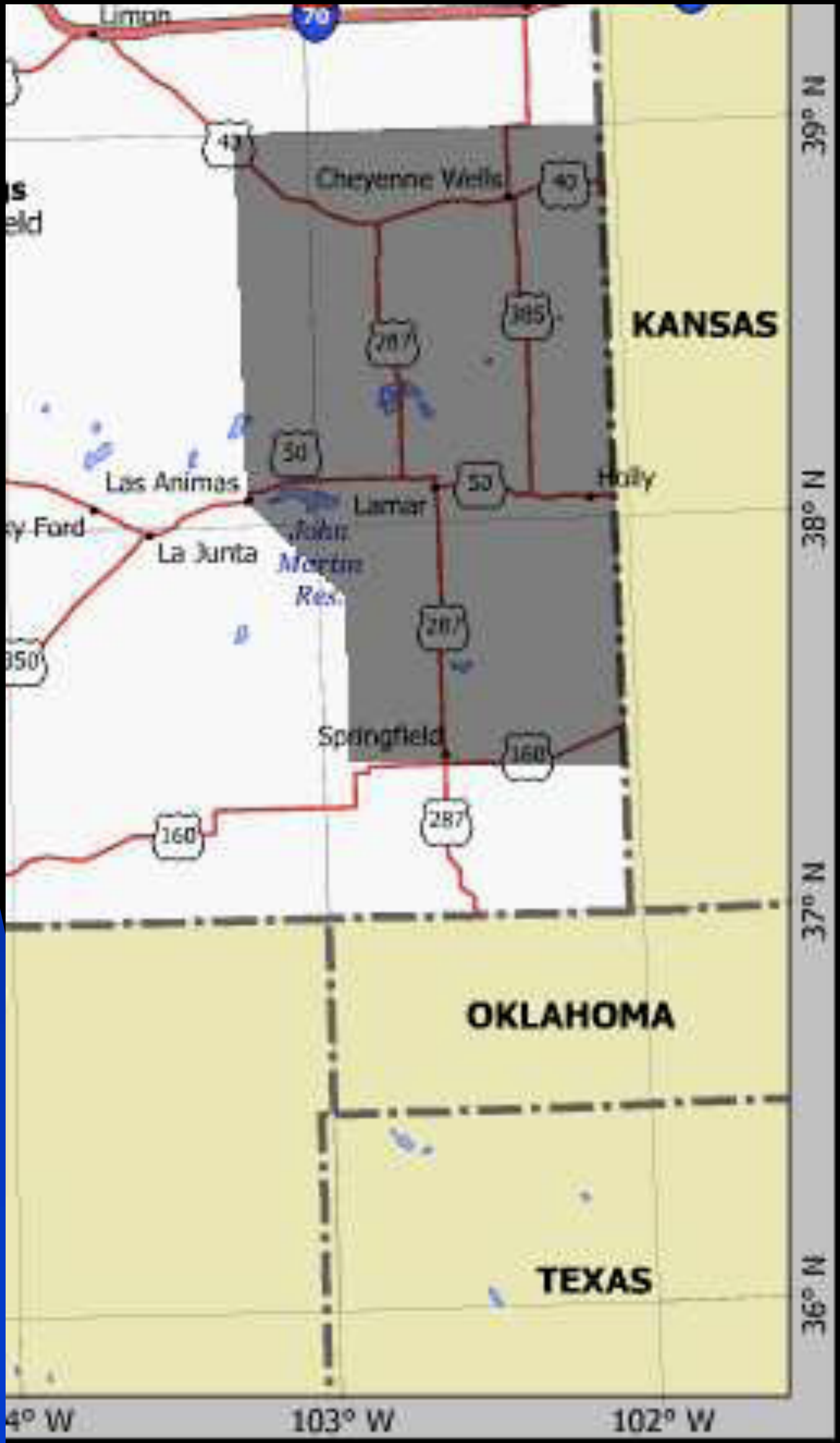
*associated

Perspective for cosmic rays at highest energies

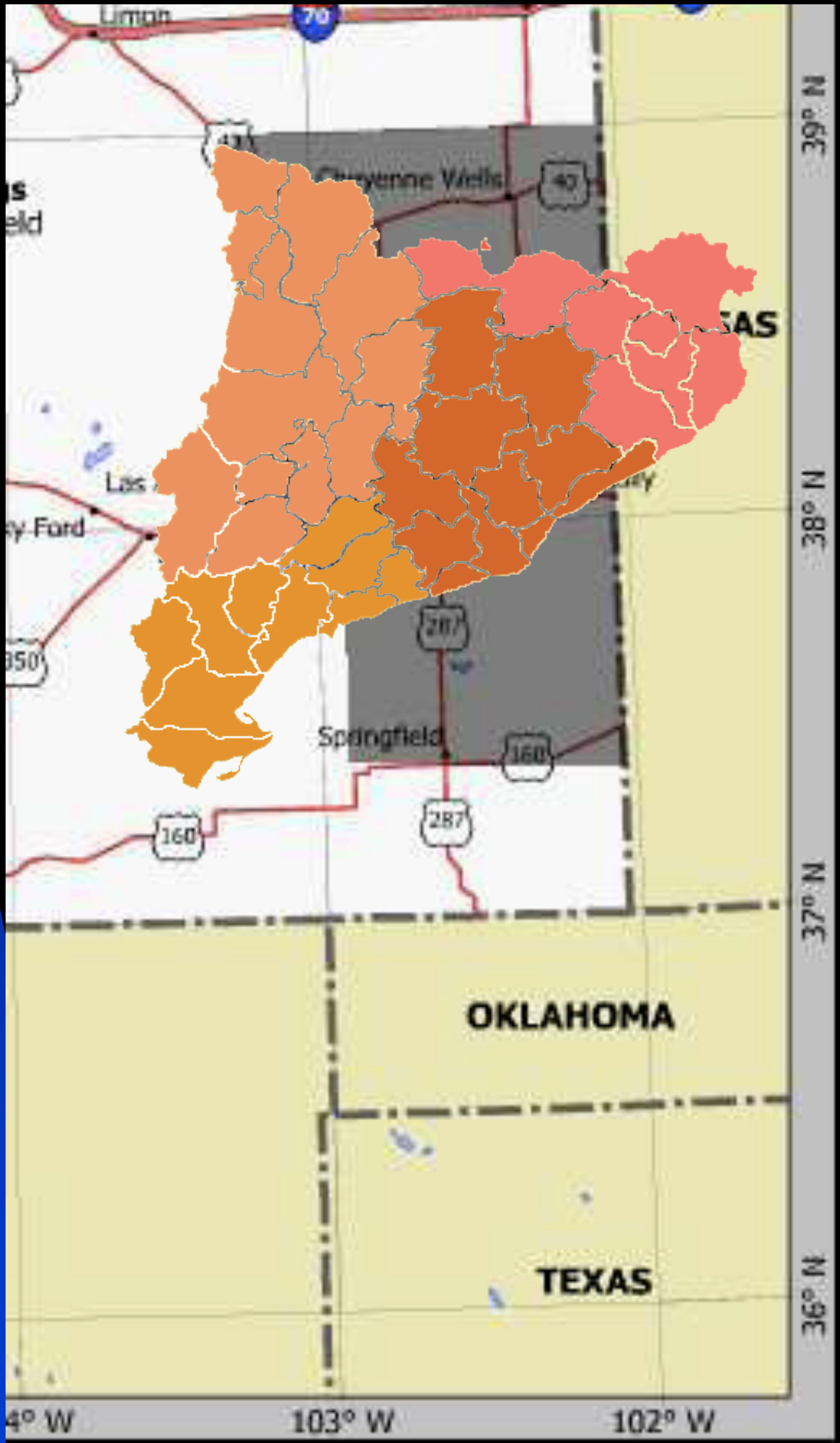


Slide by C.Spiering made 4½ years ago …

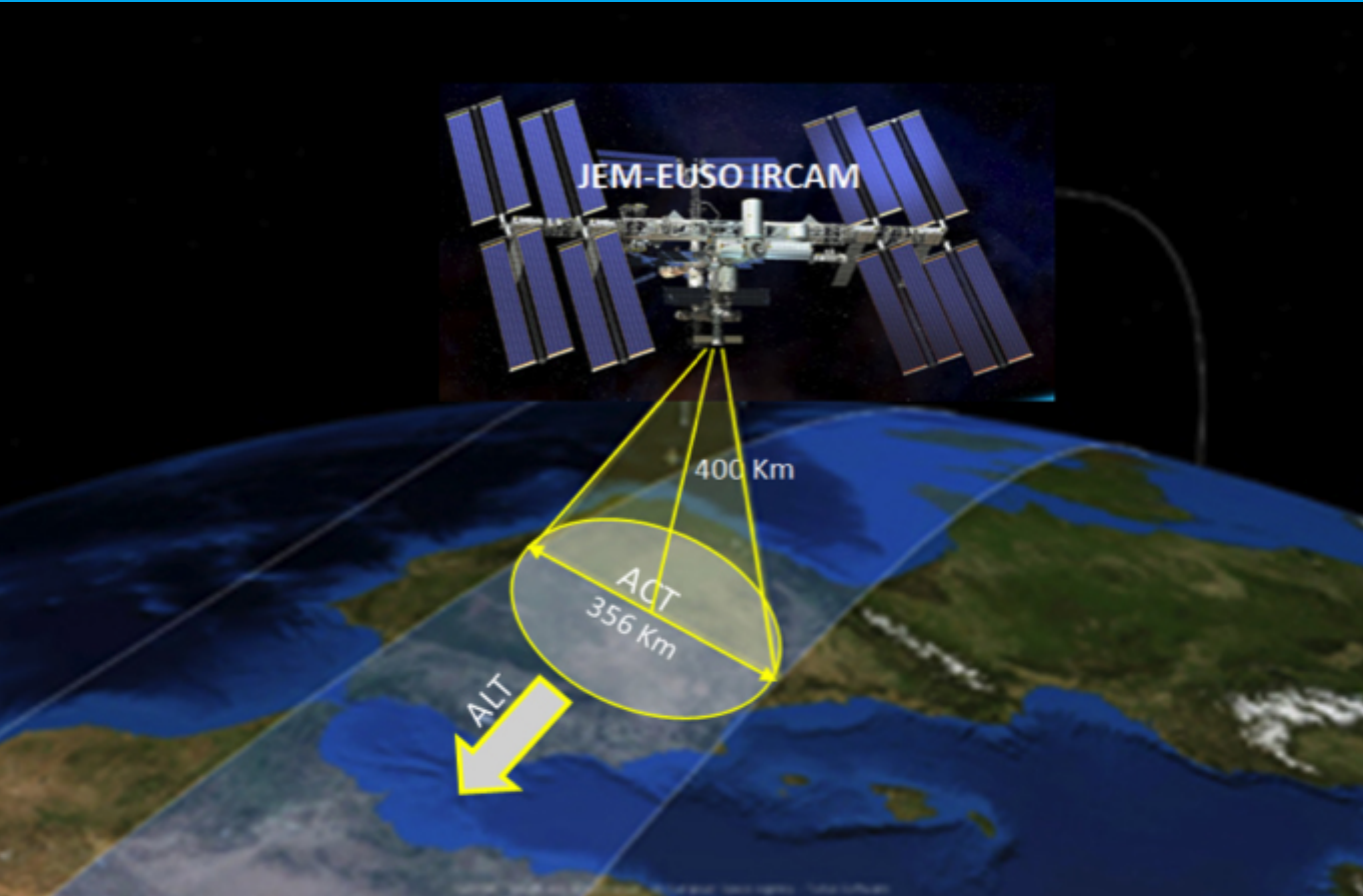
AUGER North (discarded)



AUGER North (discarded)

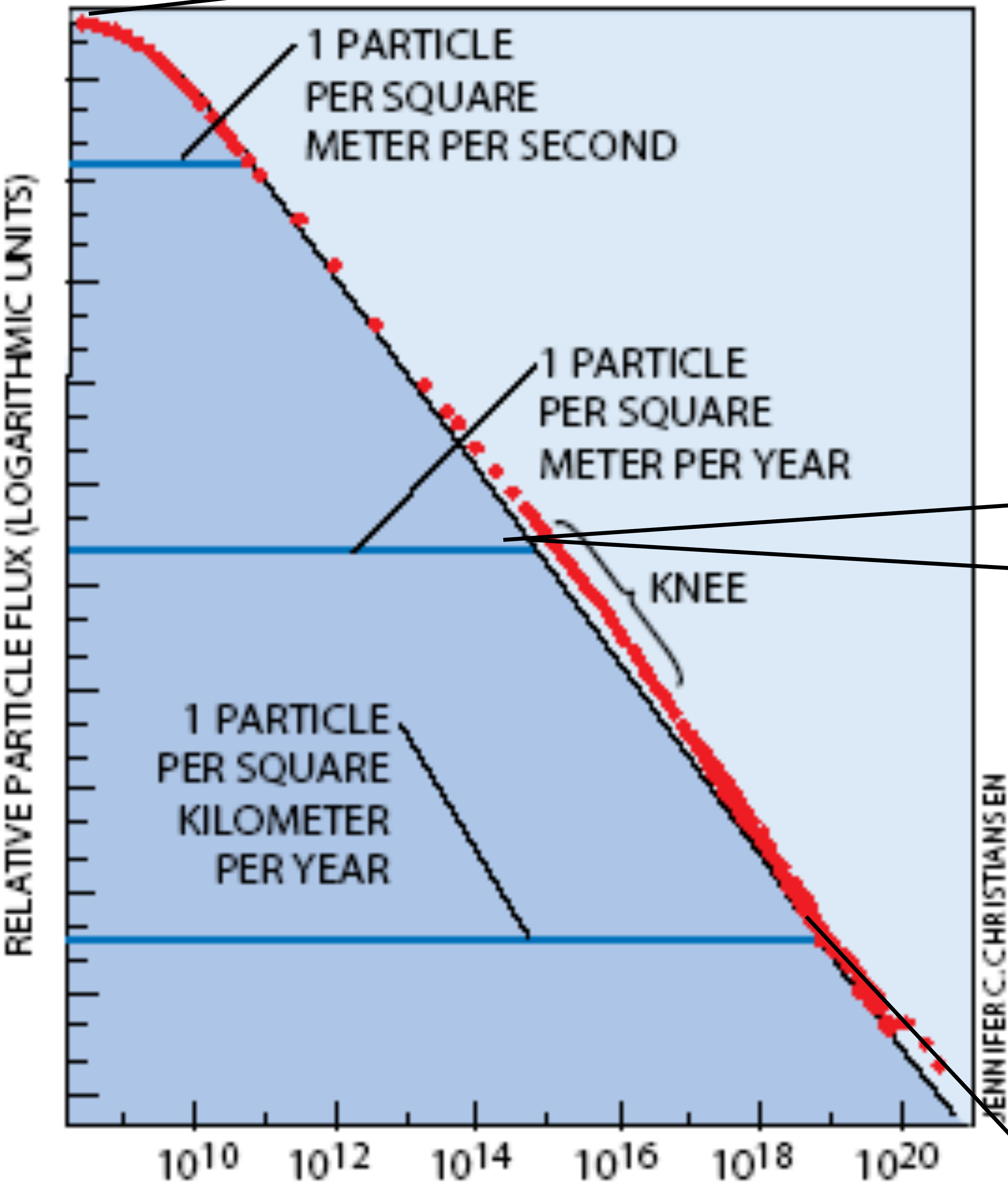


JEM-EUSO



COSMIC RAY SCIENCE BELOW 10^{18} eV

Satellites and balloons

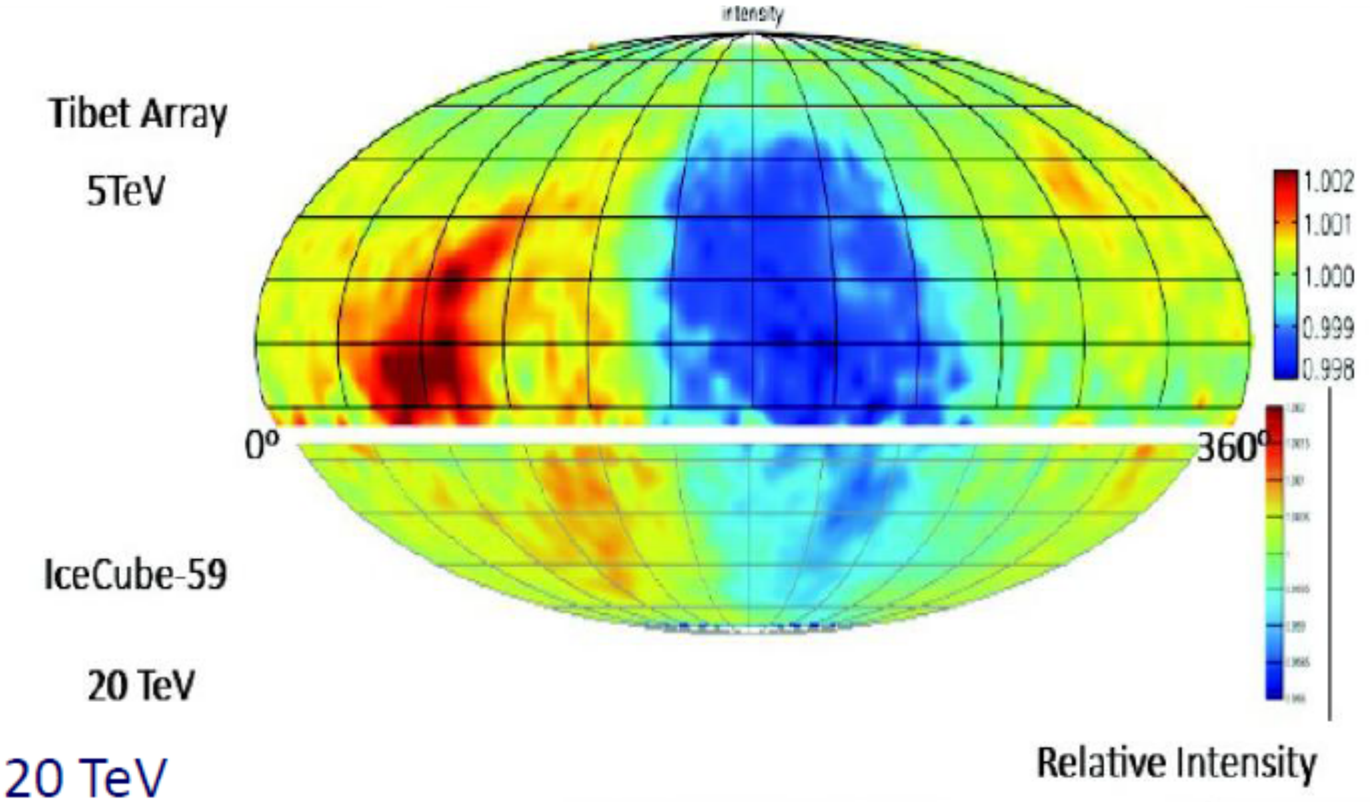


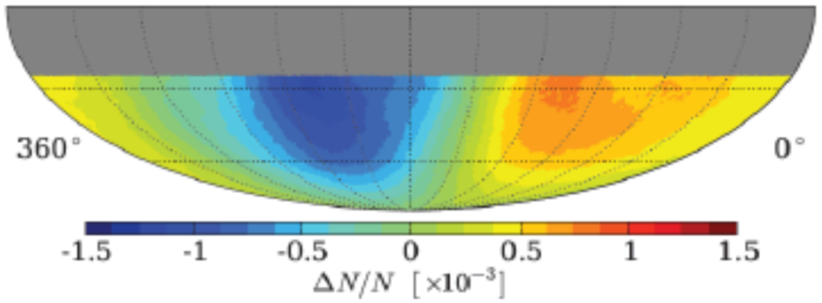
- **Satellites (and balloons)**
  - indirect dark matter search
  - cosmic spectrum and mass composition (direct measurement)
  - Heavy (anti-) nuclei
- **Detectors:**
  - Pamela, AMS, 2015: CALET, DAMPE

- **1-10 km² air shower arrays**
  - Galactic CR, transition extragal. CR
  - understand EAS models LHC
- **Detectors:**
  - (ARGO/YBJ, KASCADE-Grande), AMIGA
  - TAIGA (Siberia)
  - LHHASO (Tibet)

Example: CR anisotropies at 5 – 5000 TeV

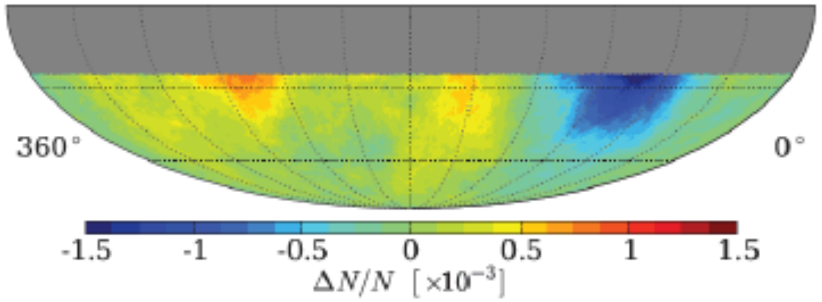
- On scales down to 3°-5°
- Origin unclear





- IceCube-59: 20 TeV

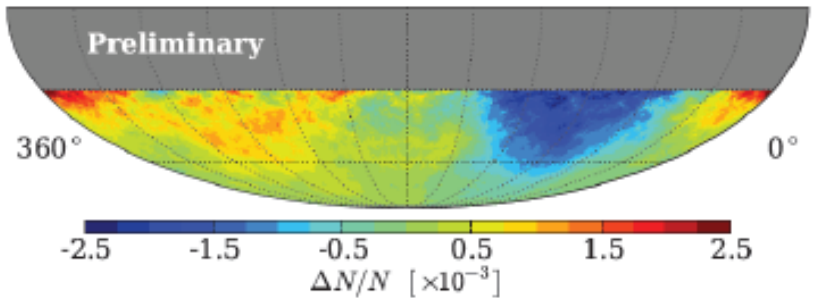
Change
of polarity



- IceCube-59: 400 TeV

Still much to do!

HAWC, LHHASO, TAIGA



- IceTop-59: PeV-range