High Energy Cosmic Ray and Multi-Messenger Astrophysics

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MICRO

SFB1491

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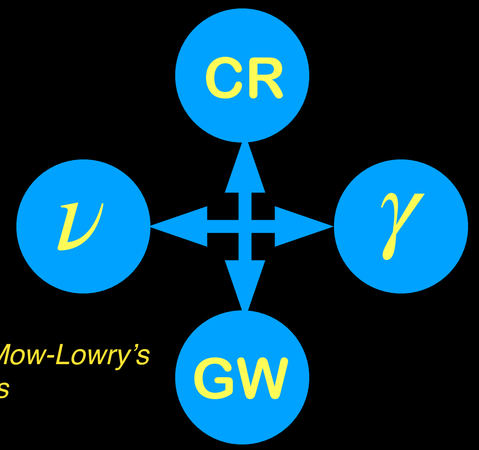
PIERRE AUGER OBSERVATORY

BND Graduate School
Wuppertal, 7.8 - 18.8. 2023

Multi-Messenger Astrophysics

Overarching goal:
learn about the most powerful accelerators in the Universe



Conor Mow-Lowry's Lectures

Adapted from Kumiko Kotera

Underlying physics connects the messengers

→ Measuring all of them is more than the sum of the individuals !

Note, also particle physics experiments do not just measure pions only, or kaons, or protons….

Menu…

1) The Big Picture: A quick overview
2) Astrophysics and Detection of $E<10^{14}$ eV Galactic CRs (very brief)
3) Detection of $E>10^{14}$ eV: Basic air shower phenomenology
4) Basic concepts and technologies of EAS experiments
5) Little bit of particle physics (hands on exercise)
6) Transition from galactic to extragalactic CRs
7) The end of the CR-spectrum: E_{max} of extragalactic accelerators?
8) Anisotropies: Hunting the UHECR sources
9) Multi-Messenger: Lessons and Prospects
10) Related non-CR opportunities
11) UHECR future: challenges and prospects

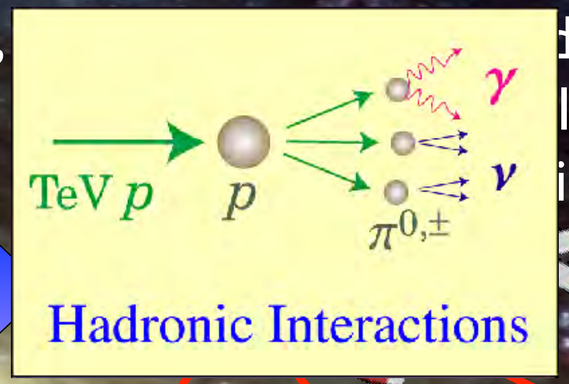
today

The simple world of galactic CRs

Source:
Stellar atmosphere,
Nucleosynthesis…

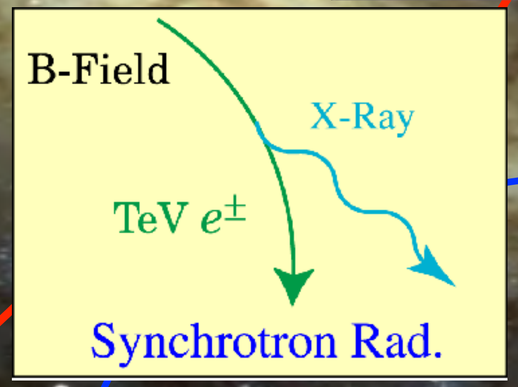
Accelerator:
Supernovae?,
Pulsars? ...

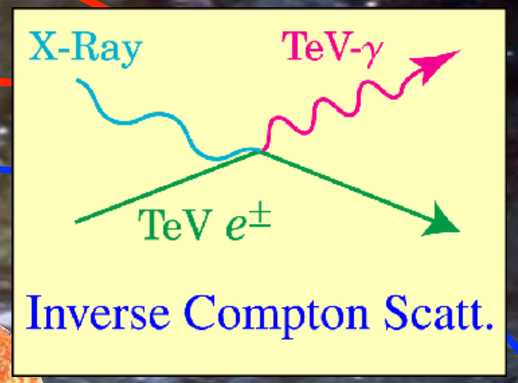
Propagation:
dronic interactions: e.g.
llation, anti-particles, …
ioactive decays, …



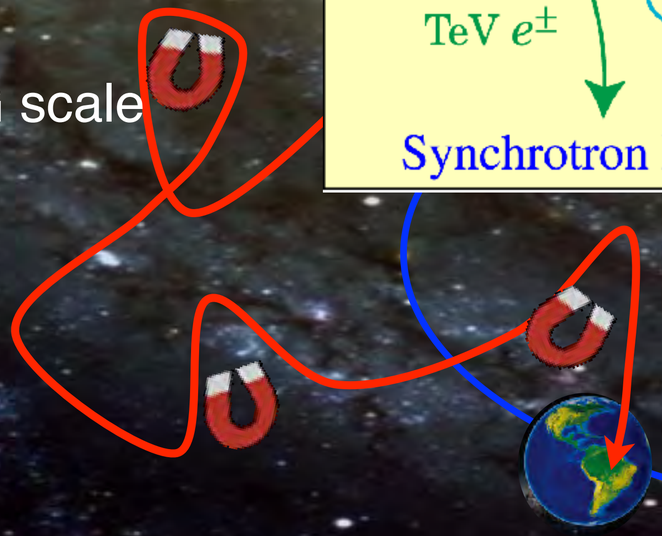
$$D = \frac{\langle x^2 \rangle}{2t}$$

μG scale





solar
modulation



Detection at E<100 TeV:
Ballon & Space born exp.
EAS experiments

The simple world of extragalactic CRs

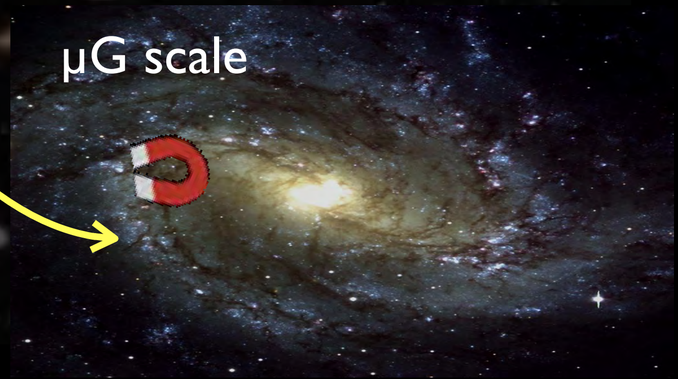
Powerful extragalactic Source

no diffusion, but ballistic propagation
CR interaction with
background photons fields
on 10-100 Mpc scale

still expect CR hadronic
interactions at the source

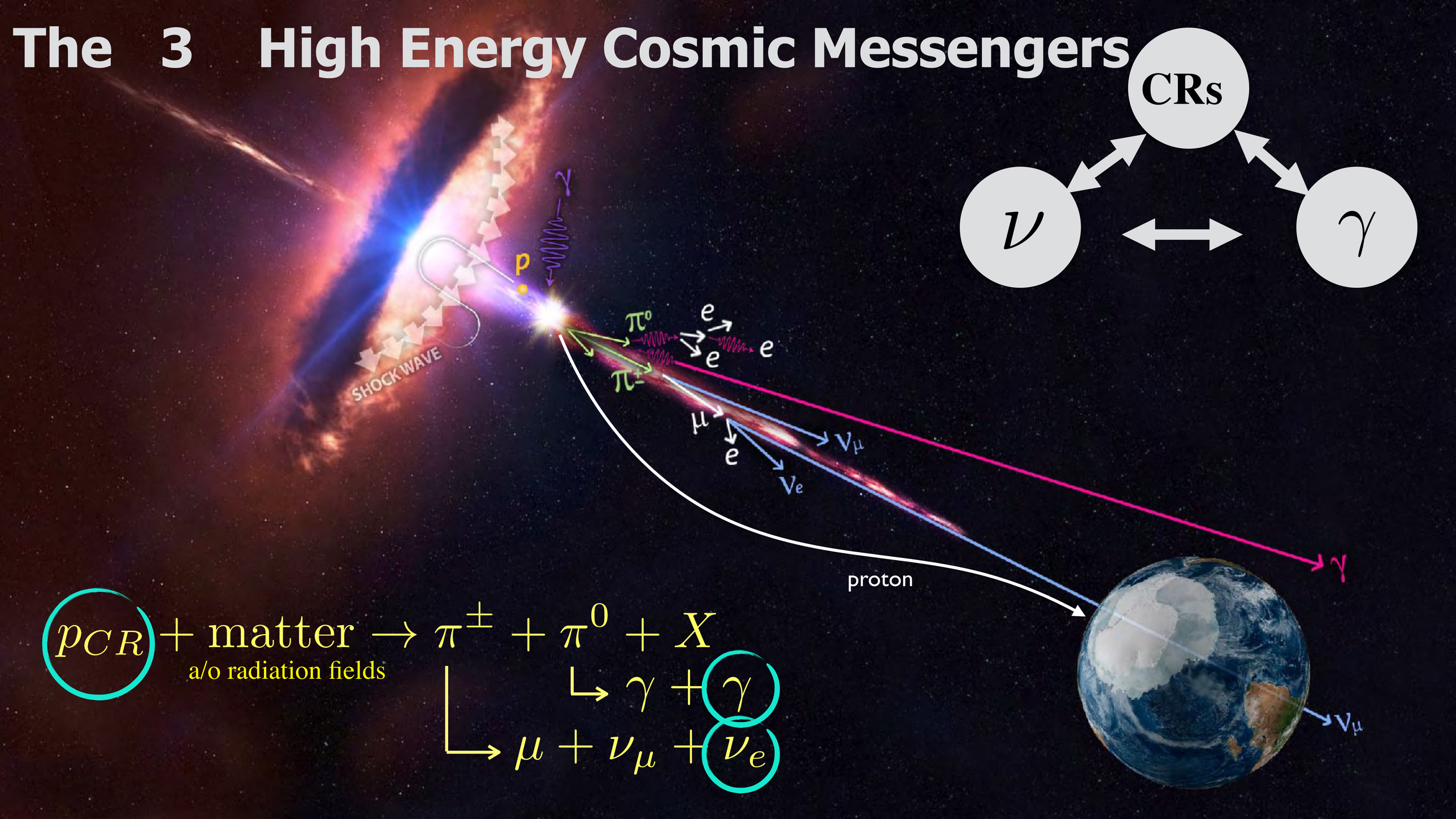
nG scale

Milky Way



μG scale

The 3 High Energy Cosmic Messengers



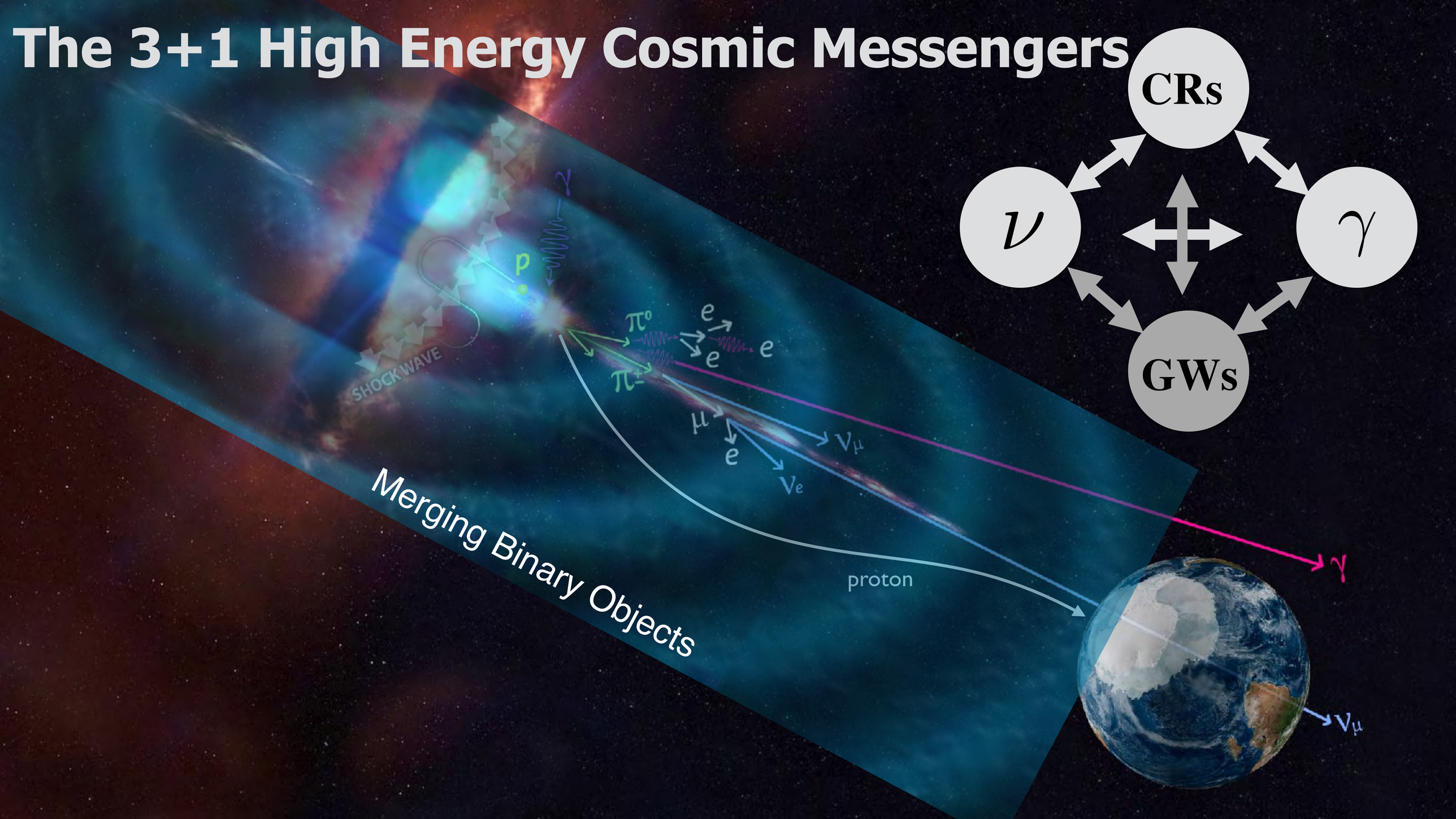
$$p_{CR} + \text{matter} \rightarrow \pi^\pm + \pi^0 + X$$

a/o radiation fields

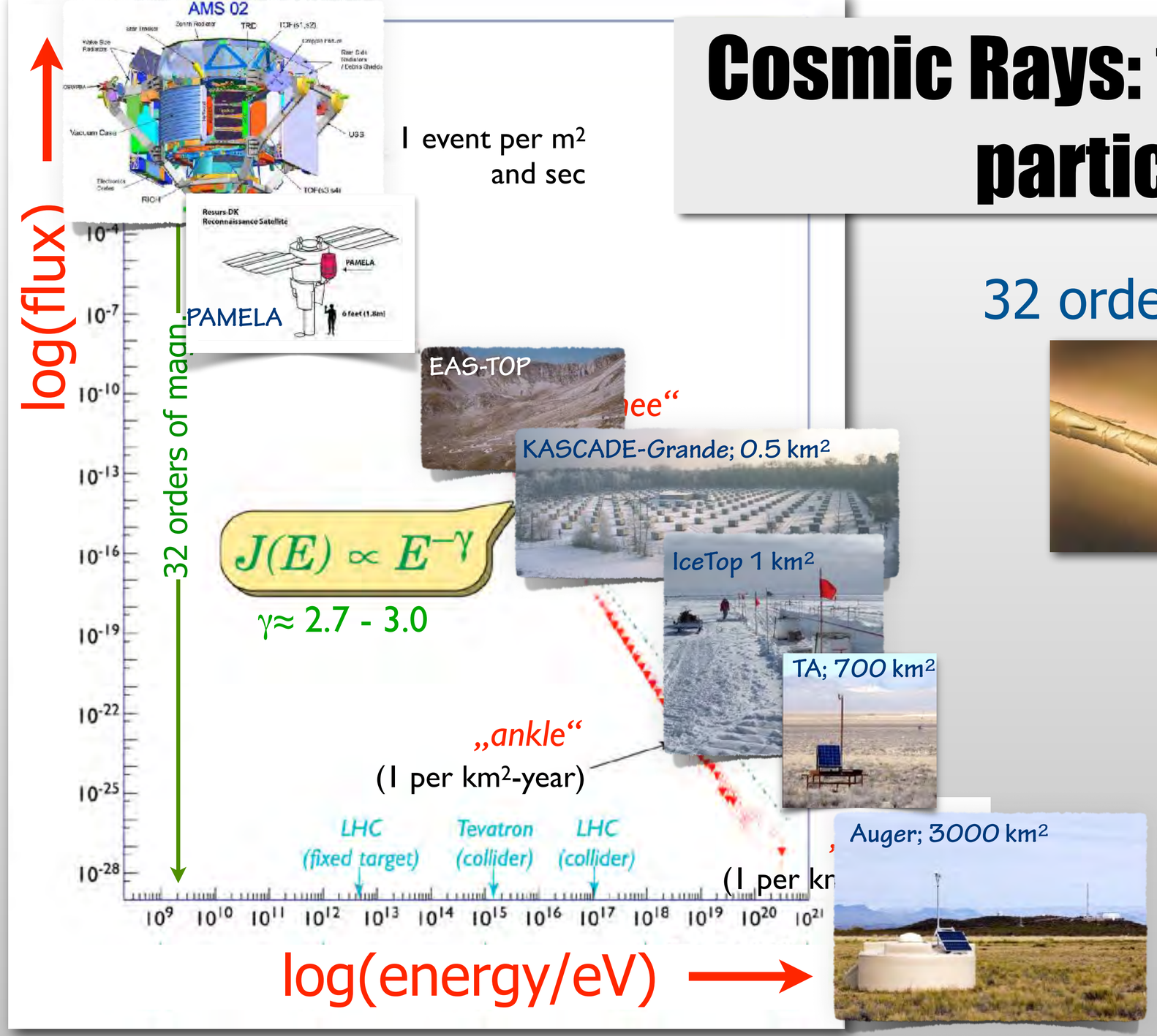
$$\hookrightarrow \gamma + \gamma$$

$$\hookrightarrow \mu + \nu_\mu + \nu_e$$

The 3+1 High Energy Cosmic Messengers



Cosmic Rays: the most energetic particles in the Universe



32 orders of magnitude:

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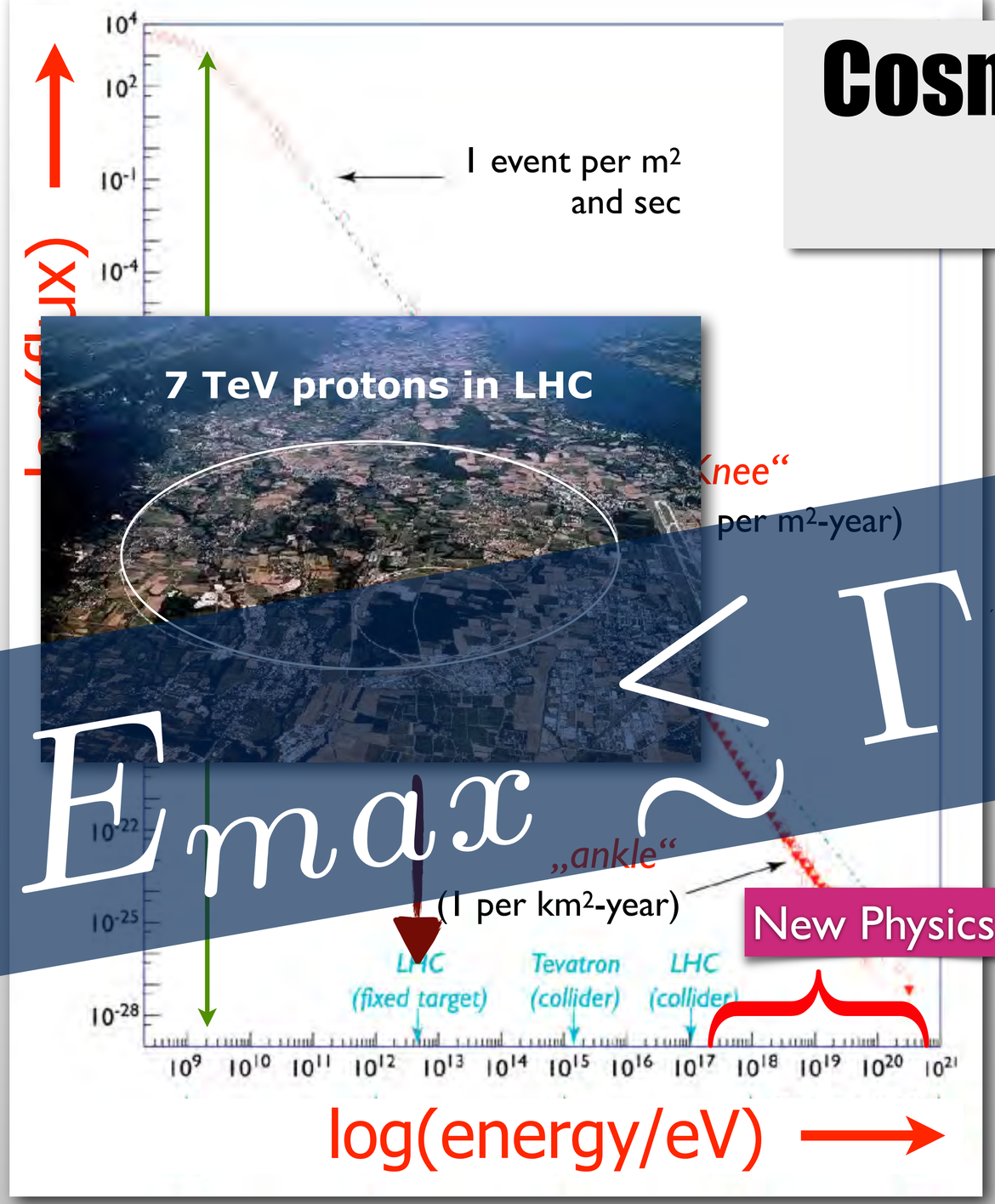
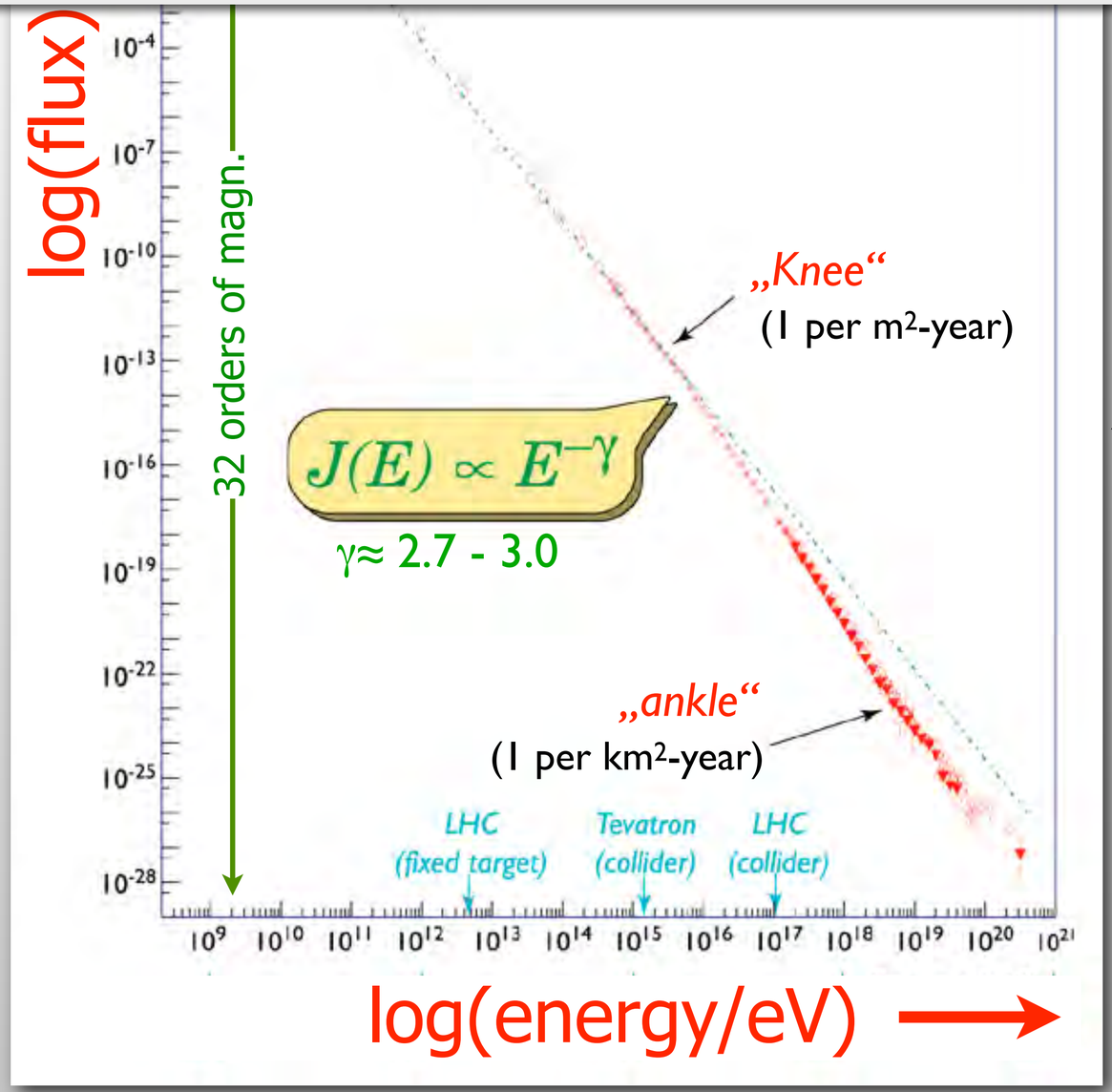
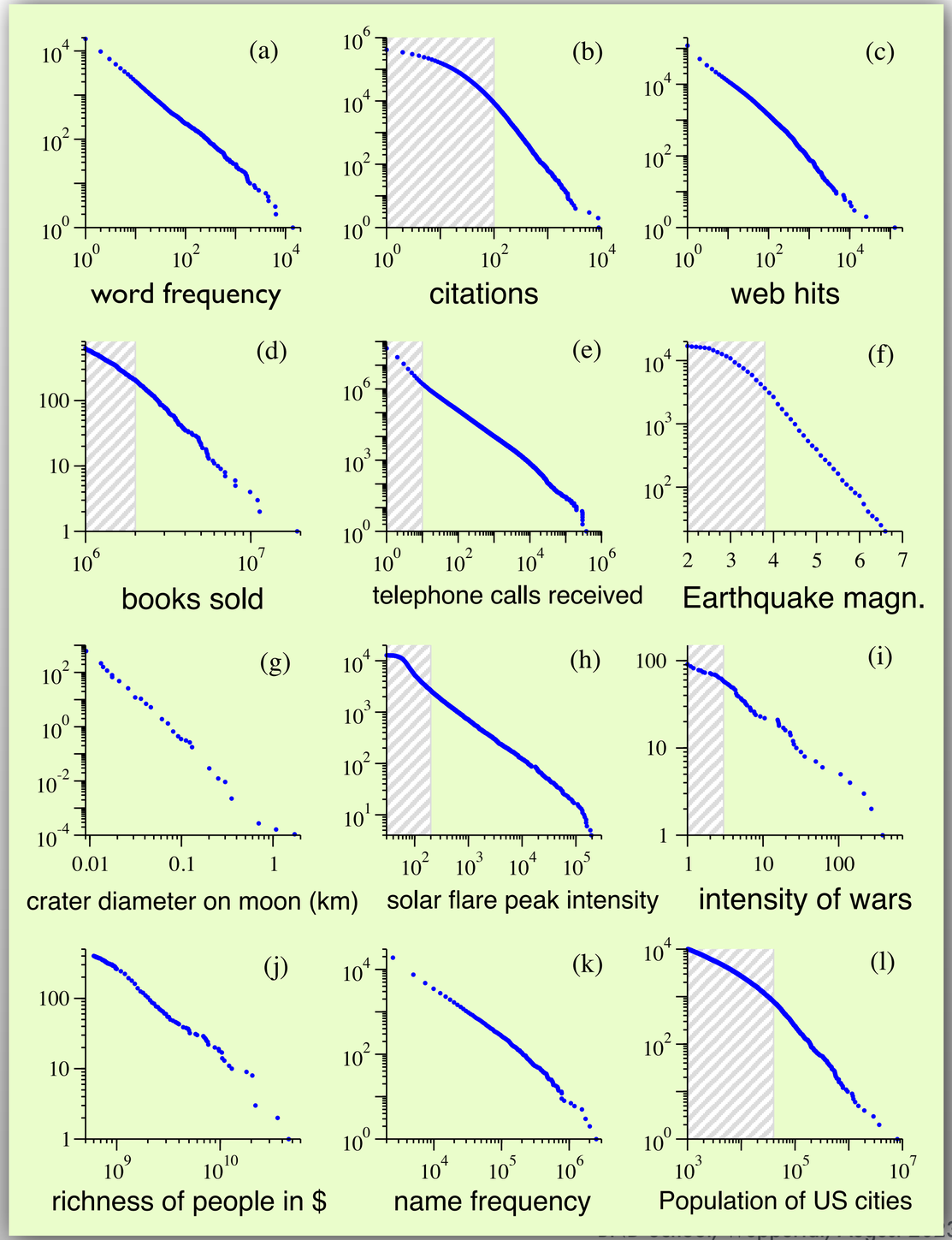


3 · 10^{20} eV protons in LHC would require size of Earth's orbit around the Sun

$$E_{max} \approx \Gamma \cdot Z \cdot R \cdot B$$

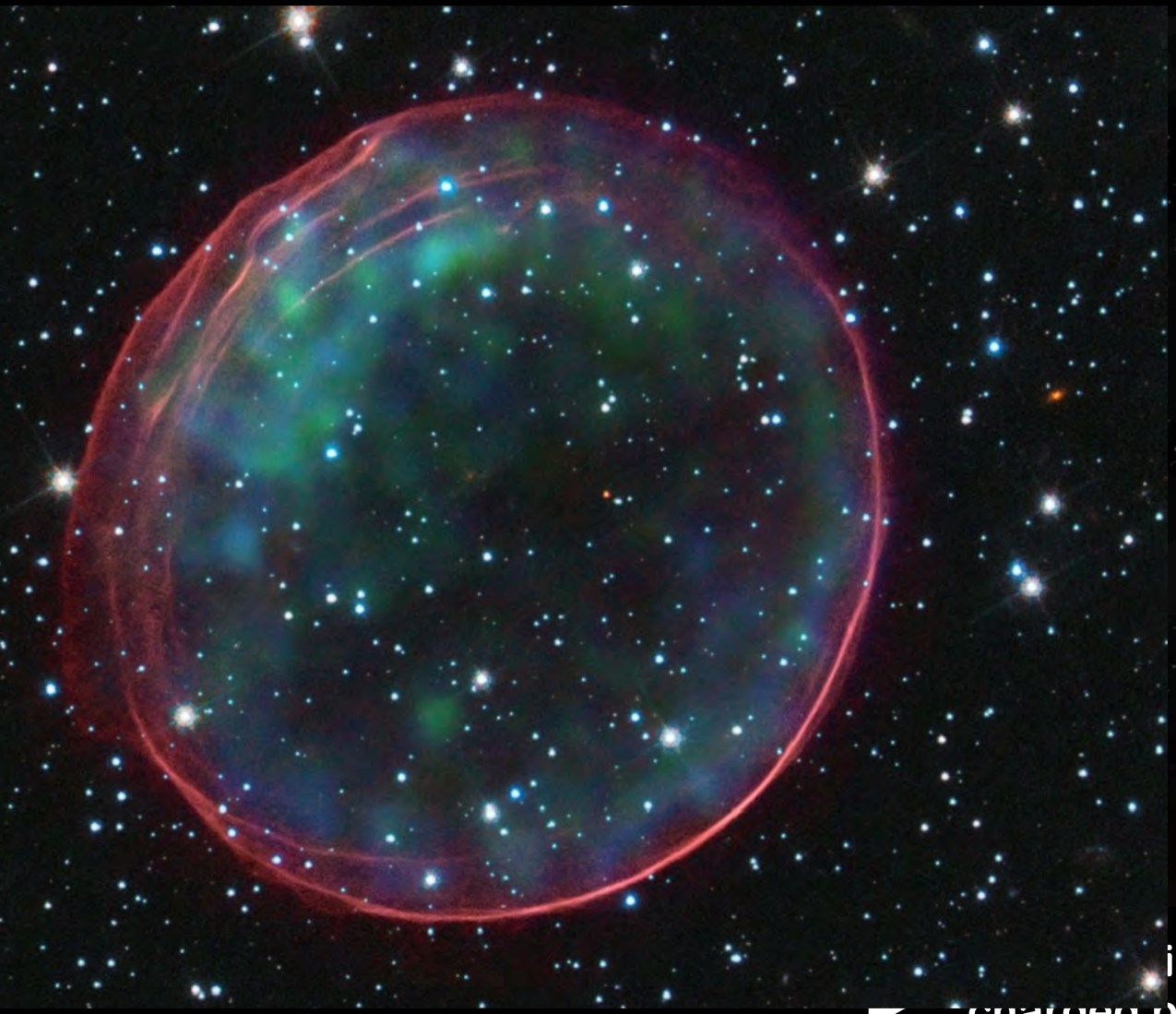
Power laws quite common in nature





MEJ Newman, Contemp. Phys. 46 (2005) 323

Fermi Acceleration of Cosmic Rays at Astrophysical Shocks



This is called
1st order Fermi Acceleration

and it results in a
power-law energy spectrum

$$\frac{dN}{dE} \propto E^{-2+\varepsilon}$$

power-law index $\gamma = -2$
for monoatomic gases

Note the interplay of particles with cosmic magnetic fields: charged particles reflected by B-fields and B-fields get amplified by interactions with charged particles

ic propagation of the shock front into thin medium
charged particles are confined near shock front and gain energy

COSMIC RAYS

- **… are very abundant in flux…**
  ~ 300 particles/s/m^2; ~20% of natural radioact. dose
- **… and energy density**
  $\varepsilon_{CR} \approx 1$ eV/cm^3 $\approx \varepsilon_{\text{star light}} \approx \varepsilon_{\text{B-field}}$ (galactic ecosystem)

- … are evidence of **most powerful astrophysical accelerators**

- … give information on **properties of cosmic environment**
  in which there are produced and through which they propagate
- … can be used to study the validity of **physical laws in extreme condition**

- … can be messengers of «**new physics** or yet unknown particles

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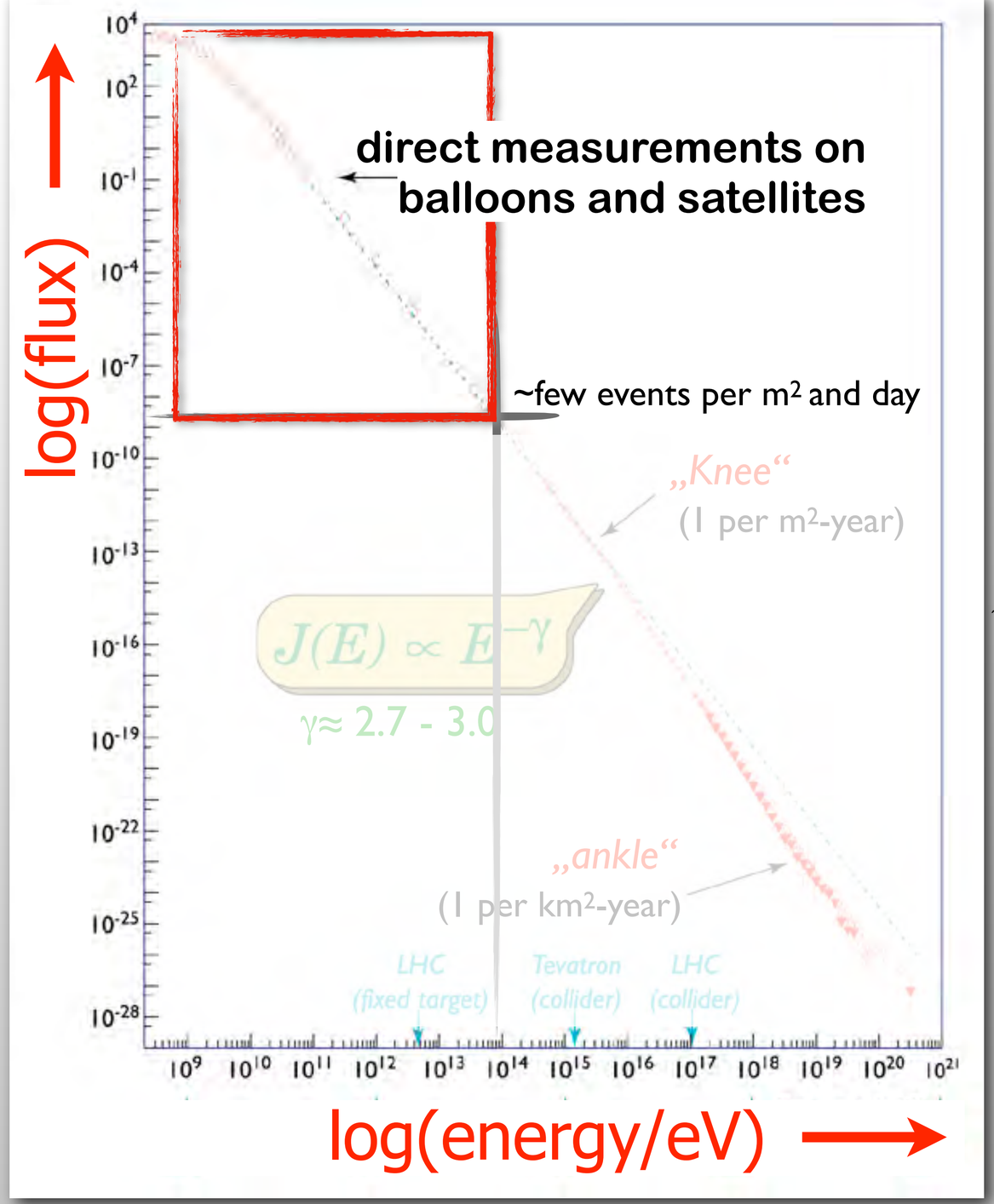
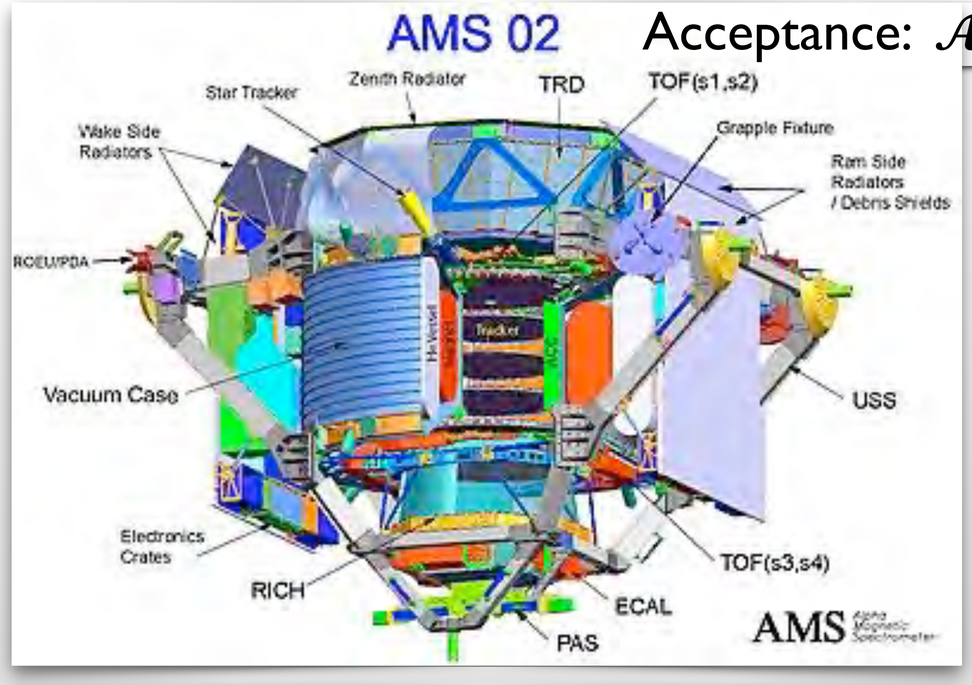
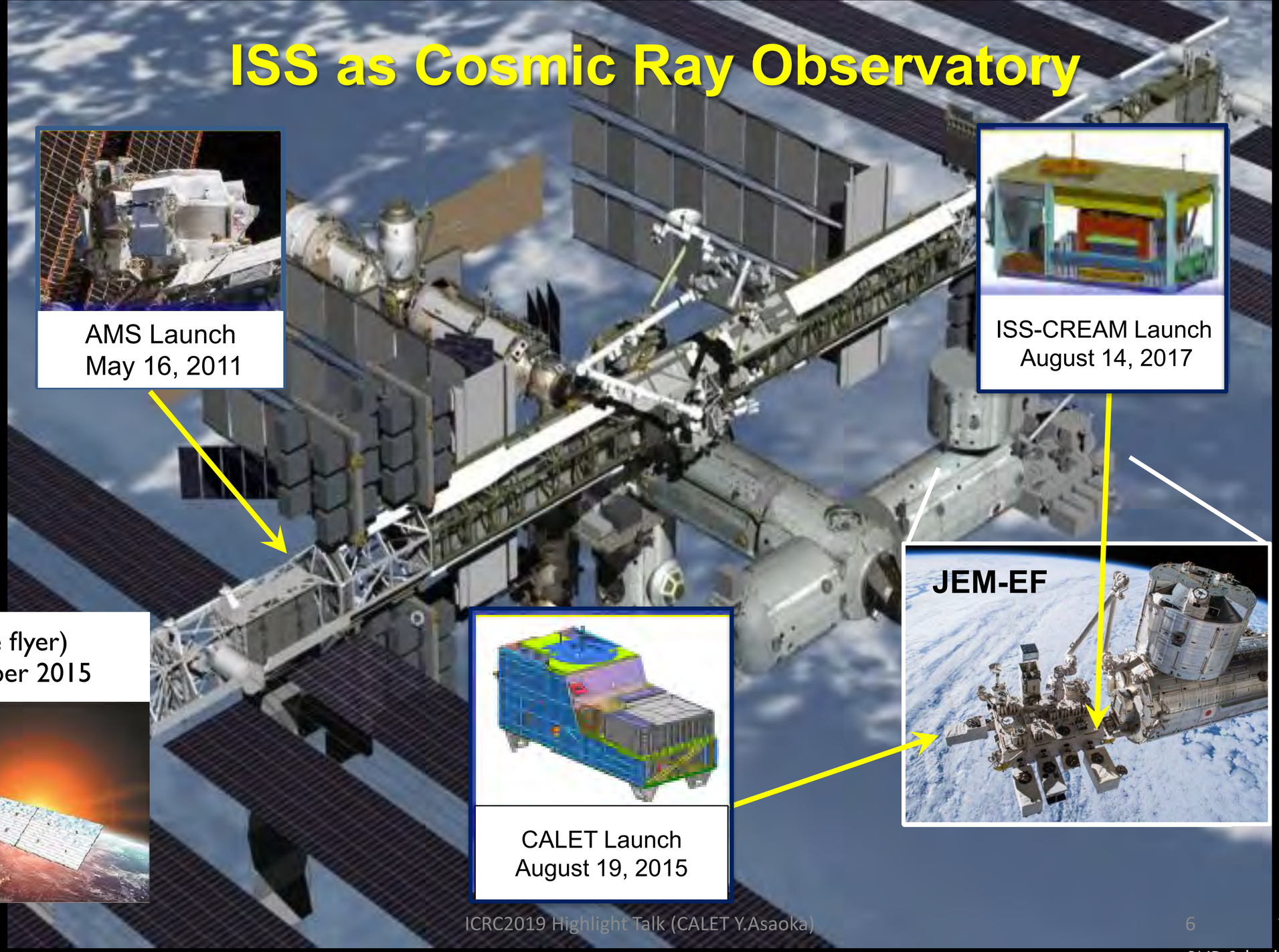




Modern high-pressure balloons allow up to ~60 days of flight time

ISS as Cosmic Ray Observatory



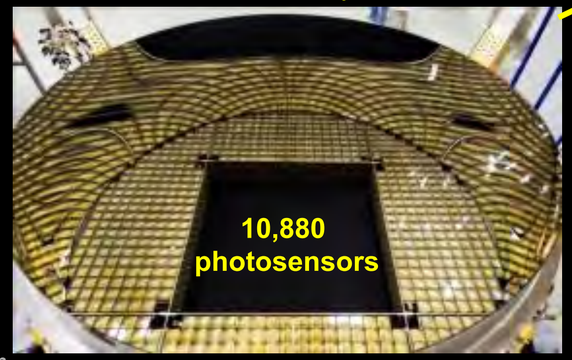
based on
Y.Asaoka, ICRC2019

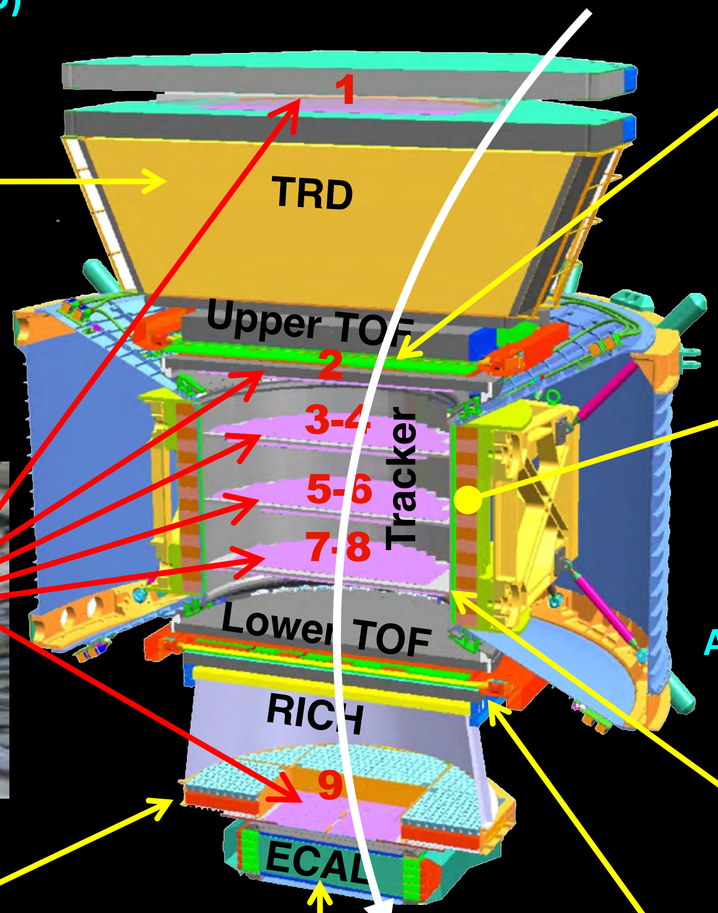
AMS 02: HEP Experiment in Space

Transition Radiation Detector (TRD)
identify e^+, e^-

Silicon Tracker
measure Z, P

Ring Imaging Cerenkov (RICH)
measure Z, E





Electromagnetic Calorimeter (ECAL)
measure E of e^+, e^-

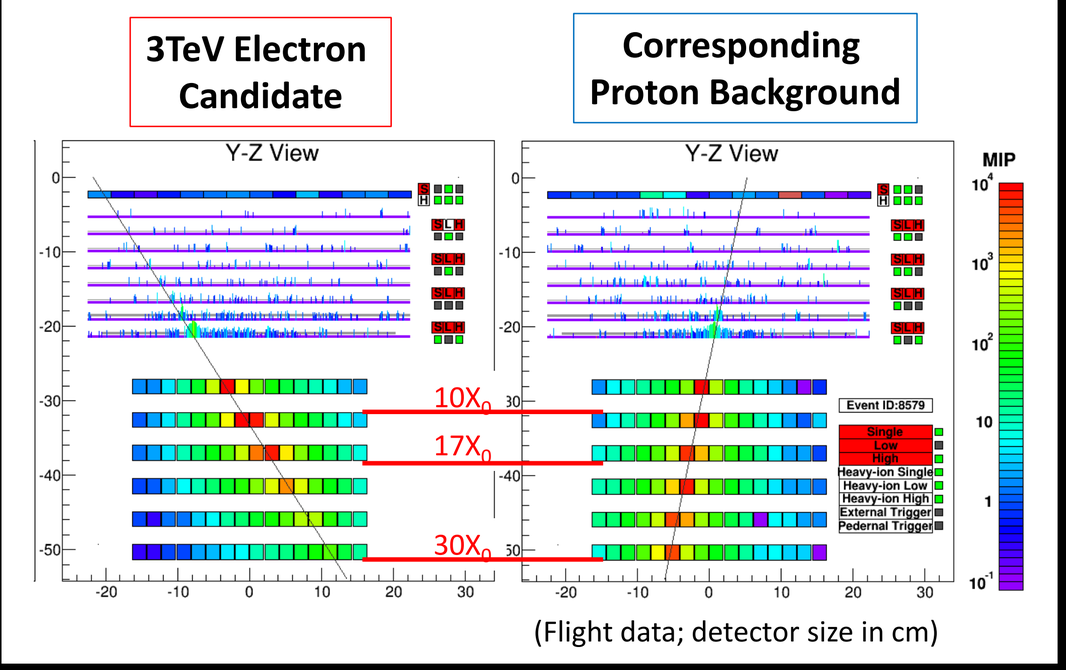
Upper TOF measure Z, E

Magnet identify ±Z, P

Anticoincidence Counters (ACC)
reject particles from the side

Lower TOF measure Z, E

Z-measurements & PID

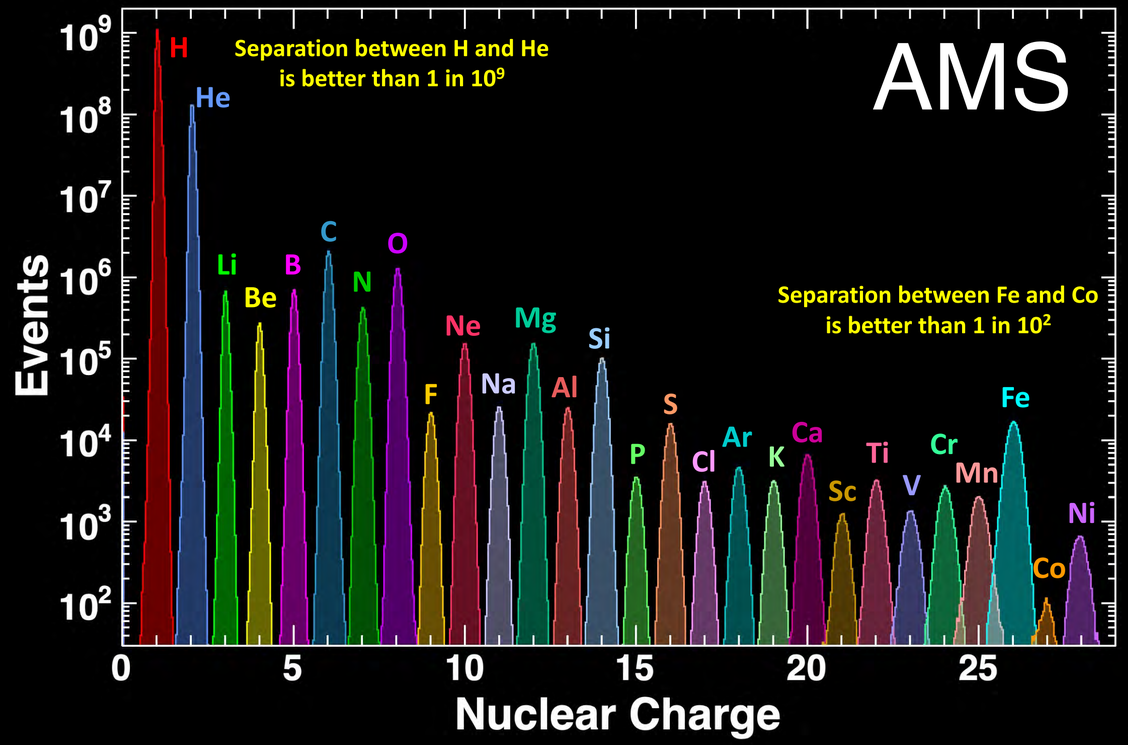


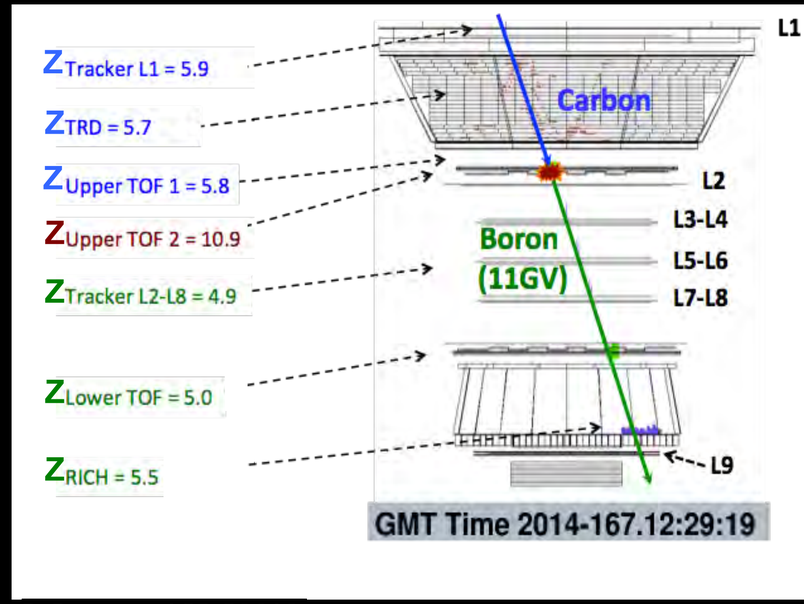
(Flight data; detector size in cm)

General principle:

- dE/dx (Bethe Bloch) ∝ Z^2/A
- magnetic spectrometer ∝ p
- calorimeter ∝ E
- Time of Flight a/o Cherenkov a/o TRD → v
- tracking → direction

CALET





B. Bertucci, ICRC2019
Weiwei Xu, ICRC2023

Element-selected CR energy spectra (200 MeV - 1 PeV)

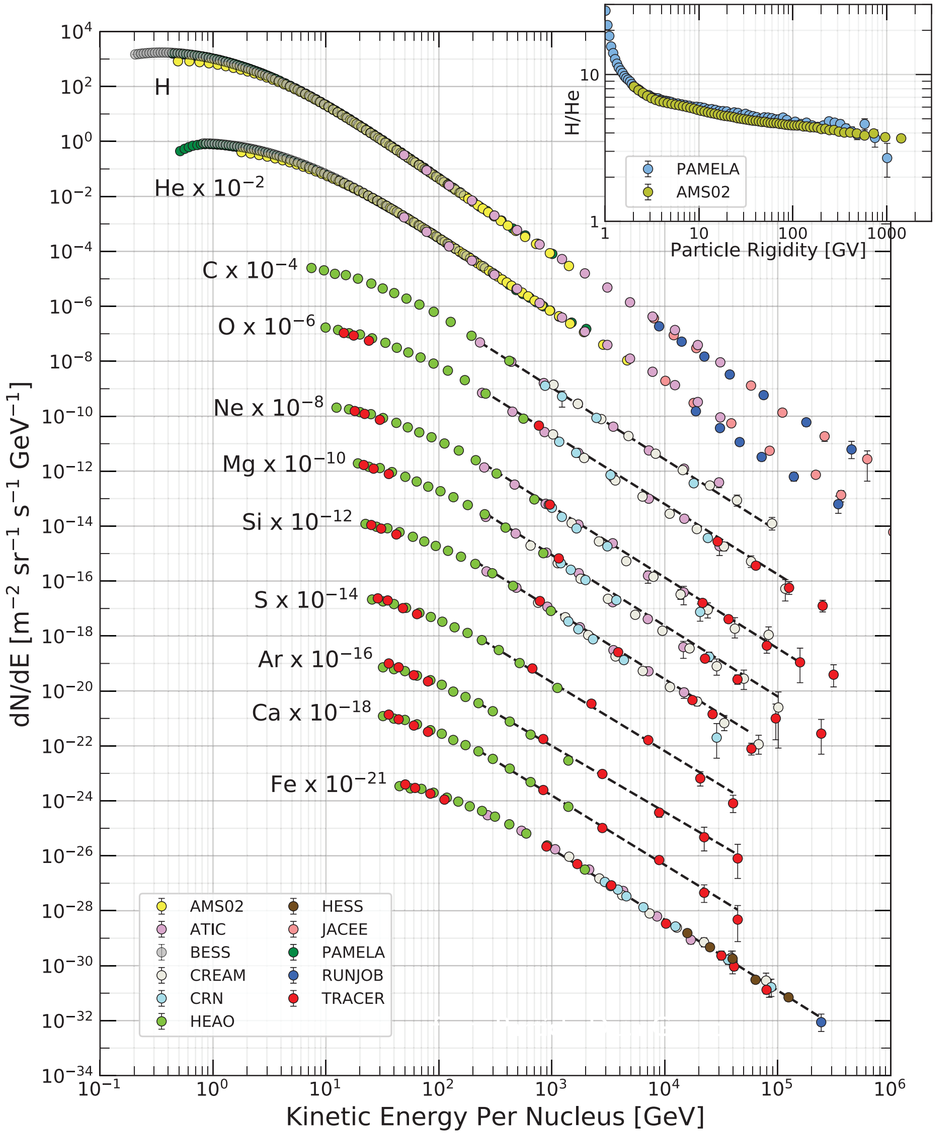
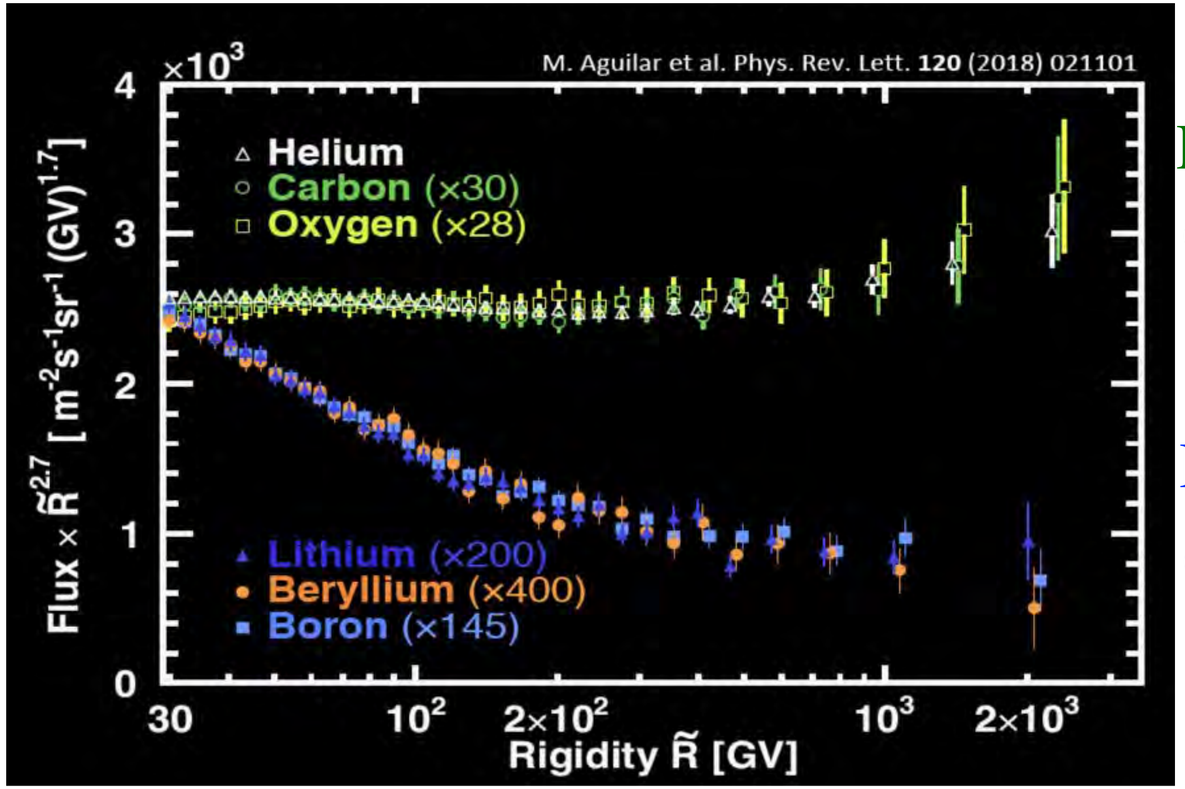


Figure 29.1: Fluxes of nuclei of the primary cosmic radiation in particles pe energy-per-nucleus are plotted vs energy-per-nucleus using data from Refs. [2–1 The inset shows the H/He ratio at constant rigidity [2,4].

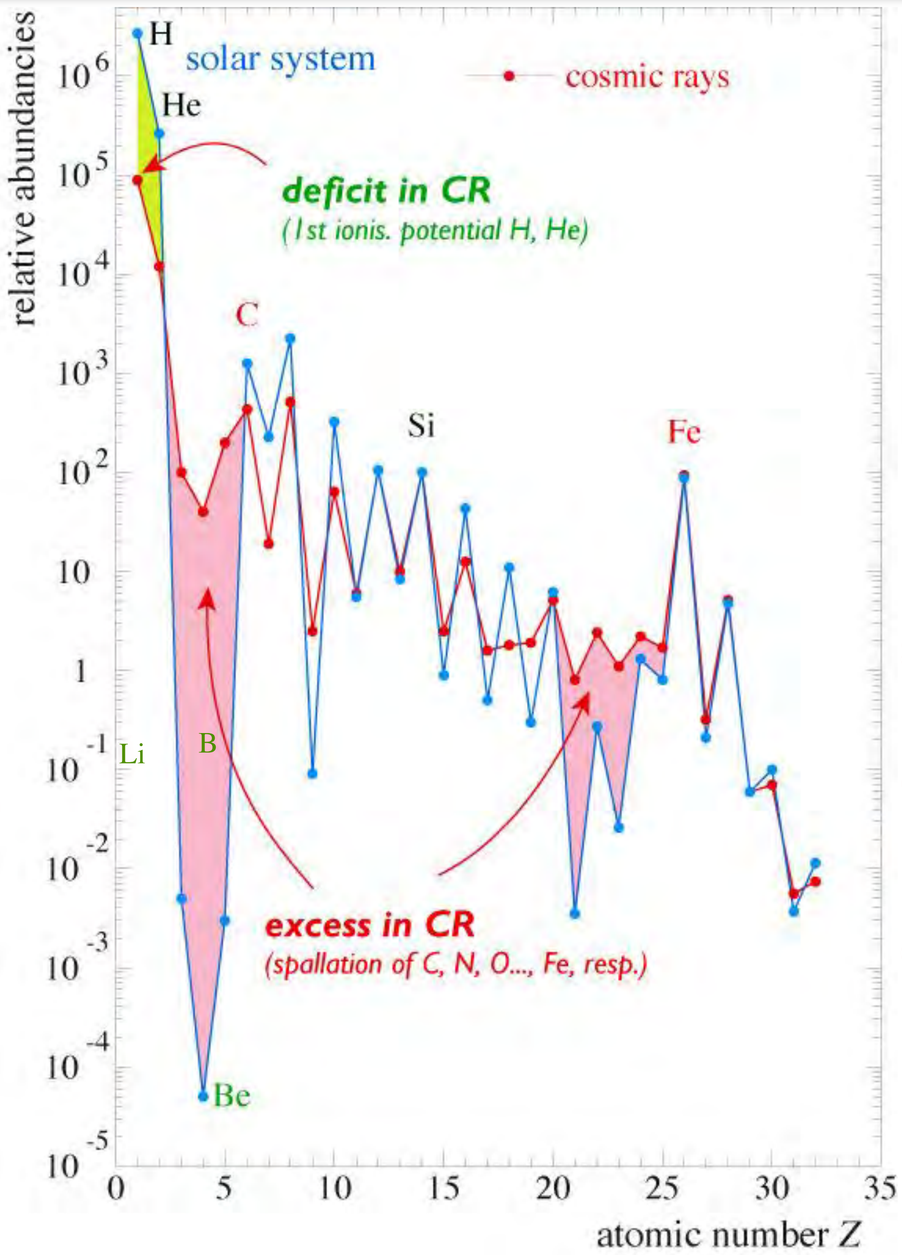
A closer look...

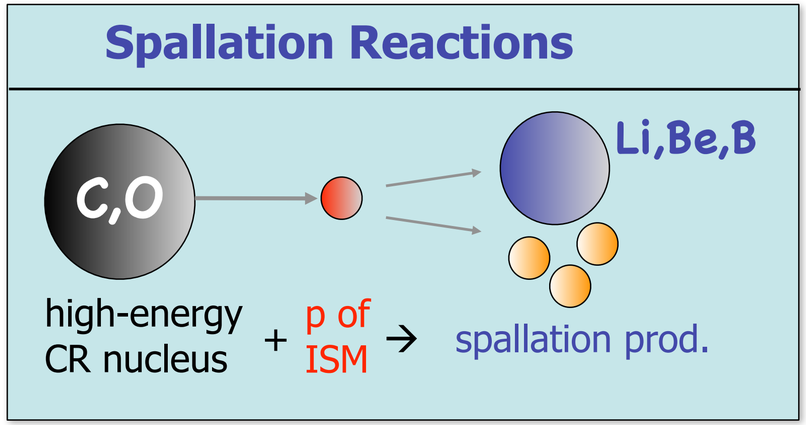


He, CNO $\propto E^{-2.7}$

Li, Be, B $\propto E^{-3.1}$

CR composition as a tracer of propagation history



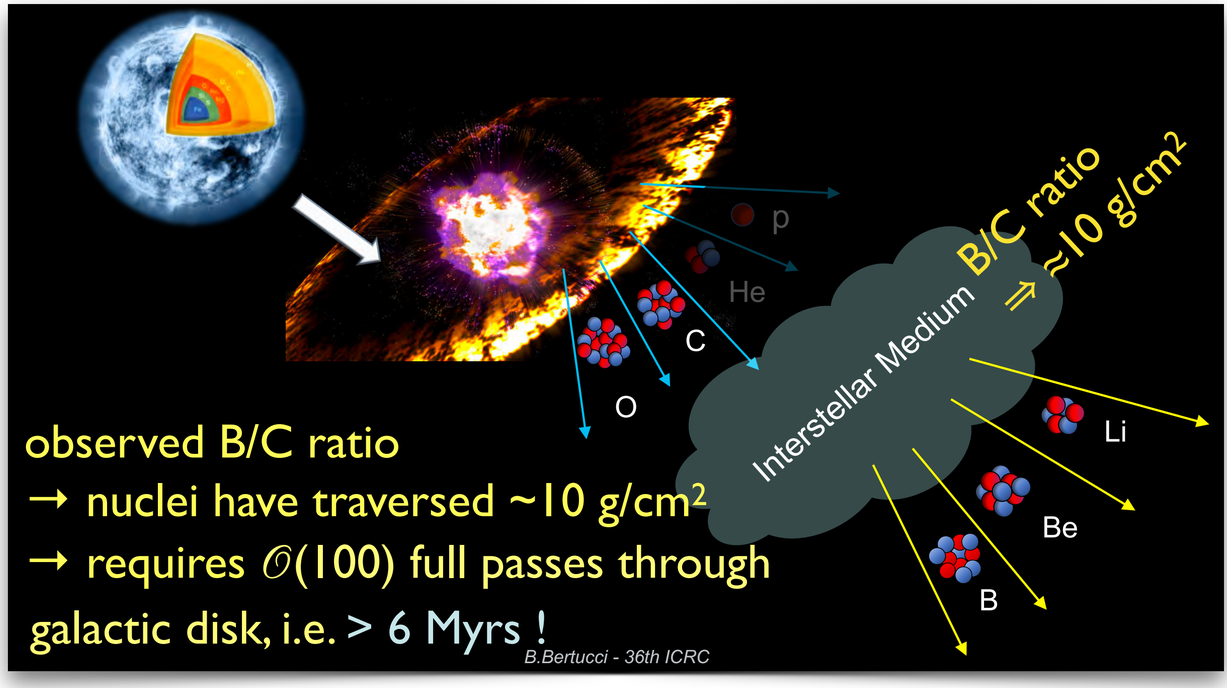


Essentially all Li, Be, B and Sc, Ti, V, Cr, Mn nuclei are produced by spallation reactions of CRs in the ISM !
we call them „secondary" CRs

The more reactions, the higher their abundances…
➽ history of propagation

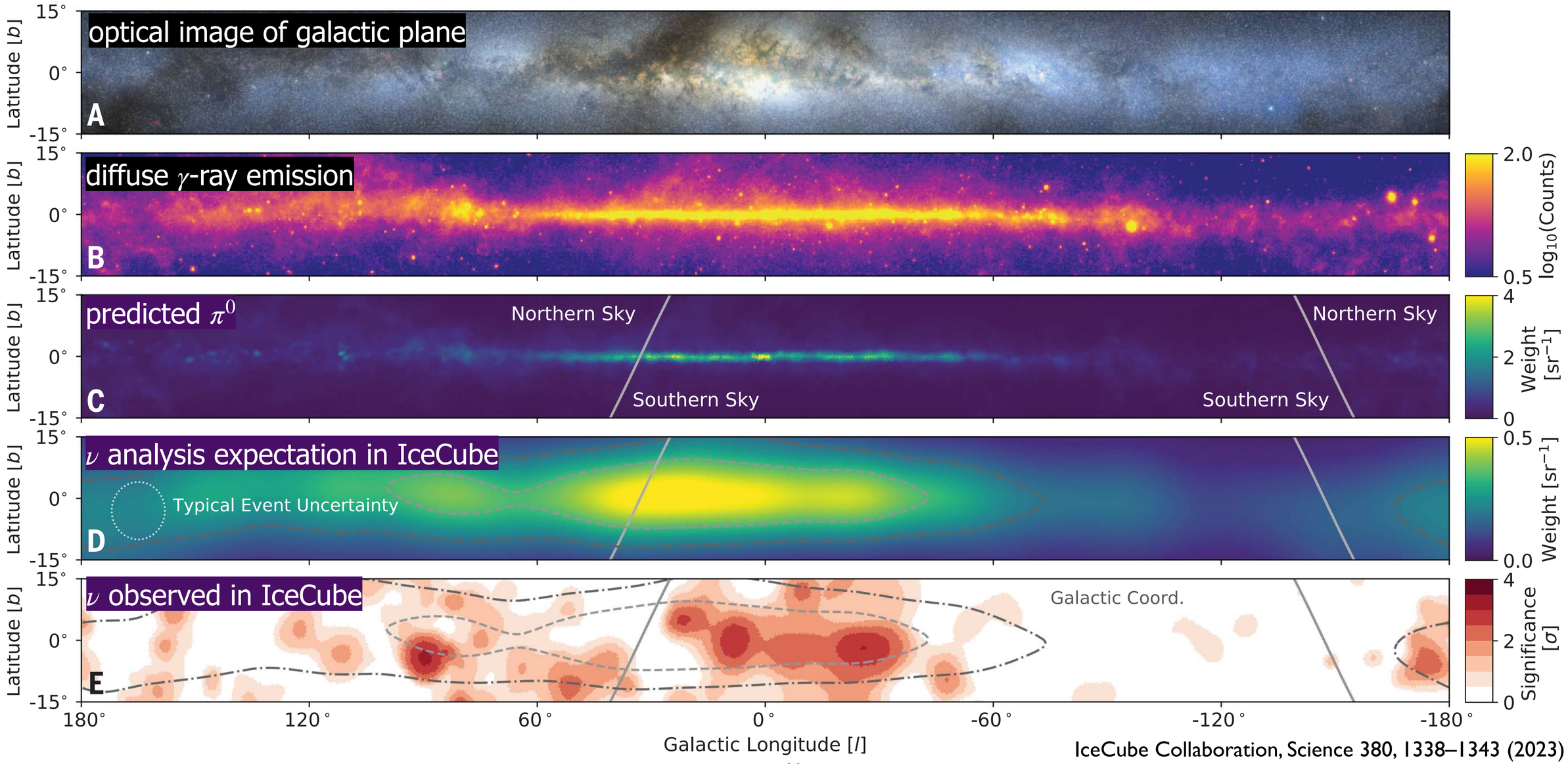
85% H (p)
12% He (α)
3% heavier nuclei
10^{-5}-10^{-4} antiprotons

$e^{\pm}$: 2% of H
(~90% are e^-)



ν and γ as a tracer of galactic CR interactions

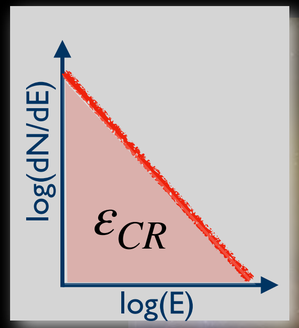
$$X_{CR} + p \rightarrow Y_{CR} + p + n + \pi^0 + \pi^{\pm} \ldots \rightarrow \gamma, \nu$$



IceCube Collaboration, Science 380, 1338–1343 (2023)

The Supernova Paradigm

Integrating the cosmic ray energy spectrum
→ CR energy density $\varepsilon_{CR} \approx 1\,\mathrm{eV/cm^3}$



$$\Rightarrow\ E_{tot}^{CR} \approx \varepsilon_{CR} \times V_{gal}$$
$$\approx 1\,\mathrm{eV/cm^3} \times \pi \times 15\,\mathrm{kpc^2} \times 1\,\mathrm{kpc}$$
$$\approx 2 \cdot 10^{67}\,\mathrm{eV}$$

Flux constant in time → E_{tot}^{CR} needs to be renewed every $\tau_{CR} \simeq 10$ Mio years

$$\Rightarrow\ L^{CR} \simeq \frac{E_{tot}^{CR}}{\ln 2 \cdot \tau_{CR}} \simeq \frac{2 \cdot 10^{67}\,\mathrm{eV}}{10^7\,\mathrm{yrs}} \simeq 10^{53}\,\mathrm{eV/s} \simeq 1.6 \cdot 10^{41}\,\mathrm{erg/s}$$

$L_{solar} \simeq 3.86 \cdot 10^{33}\,\mathrm{erg/s}$ and only radiation, almost no particles

Supernovae: $L_{SN} \simeq 10^{53}\,\mathrm{erg}$ total, (kinetic+optical)
1 SN per 30 years → $10^{42}\,\mathrm{erg/s}$

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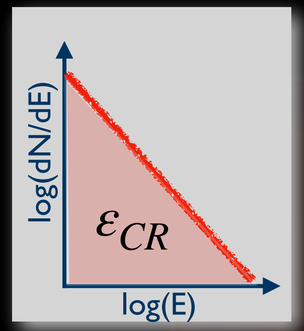

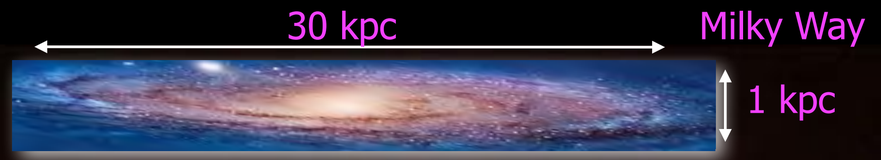

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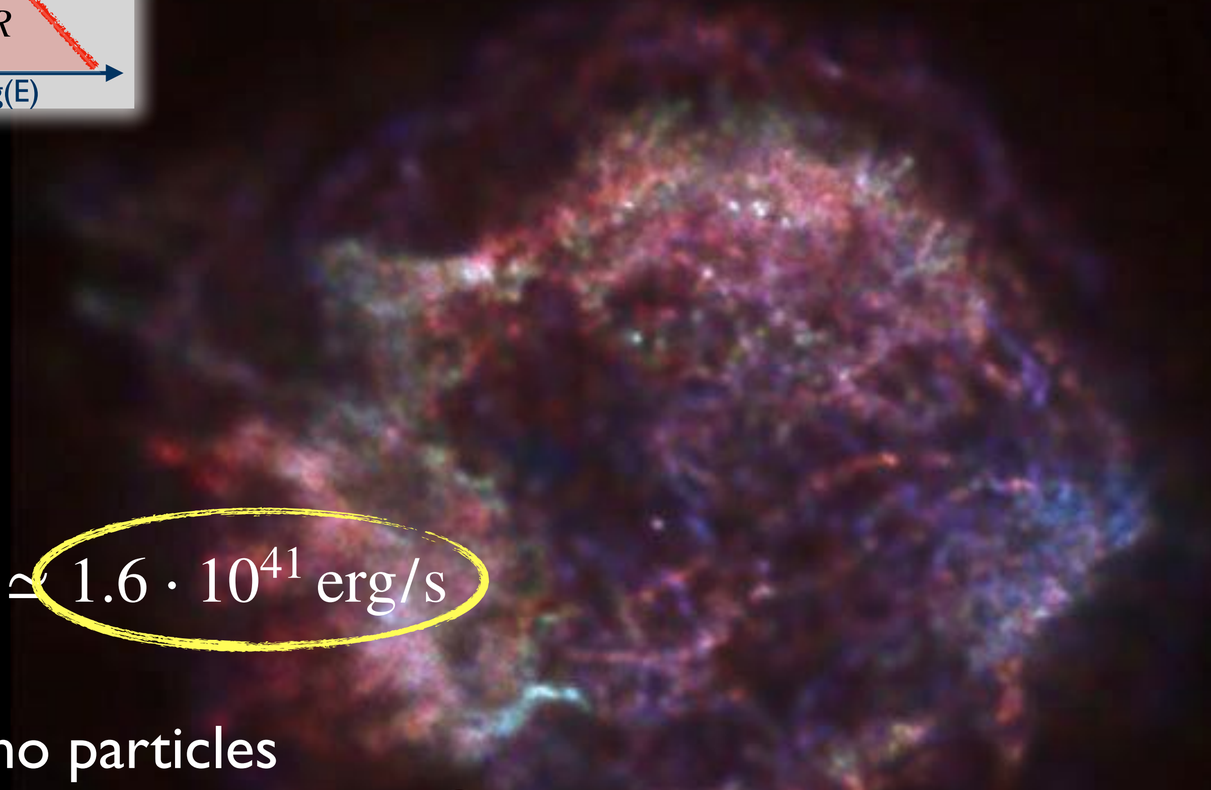


Cassiopeia A
SN at 2.8 kpc observed 1658
dynamics → $5 \cdot 10^{51}$ erg/s kinetic energy in filaments

January 19, 1934

Los Angeles Times

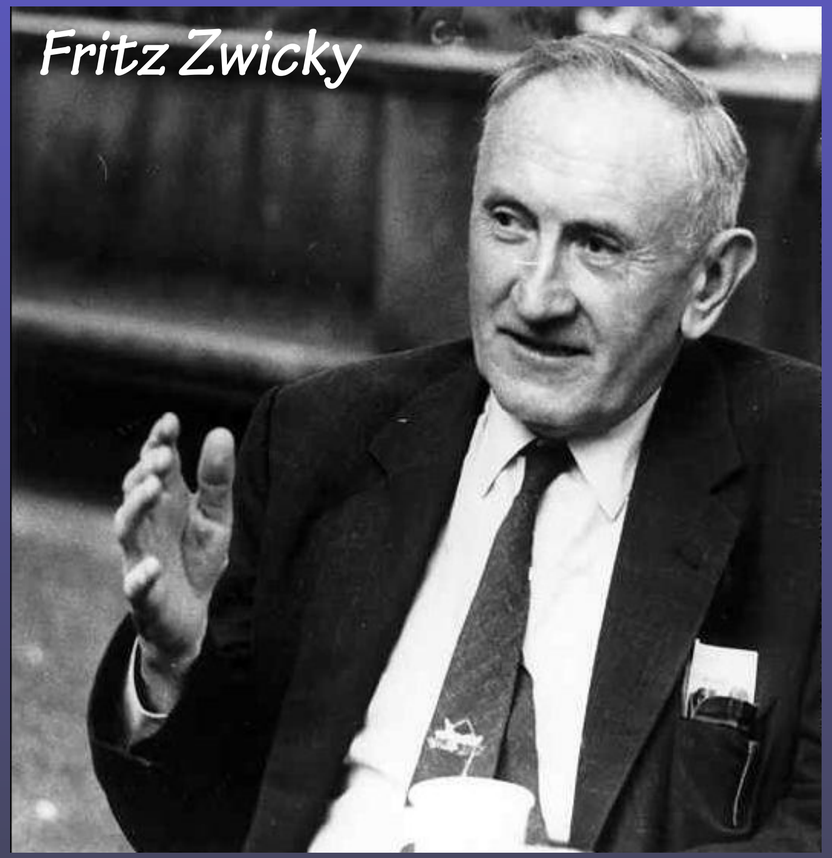

Los Angeles Times

One of the most concise **triple predictions** ever made in science:

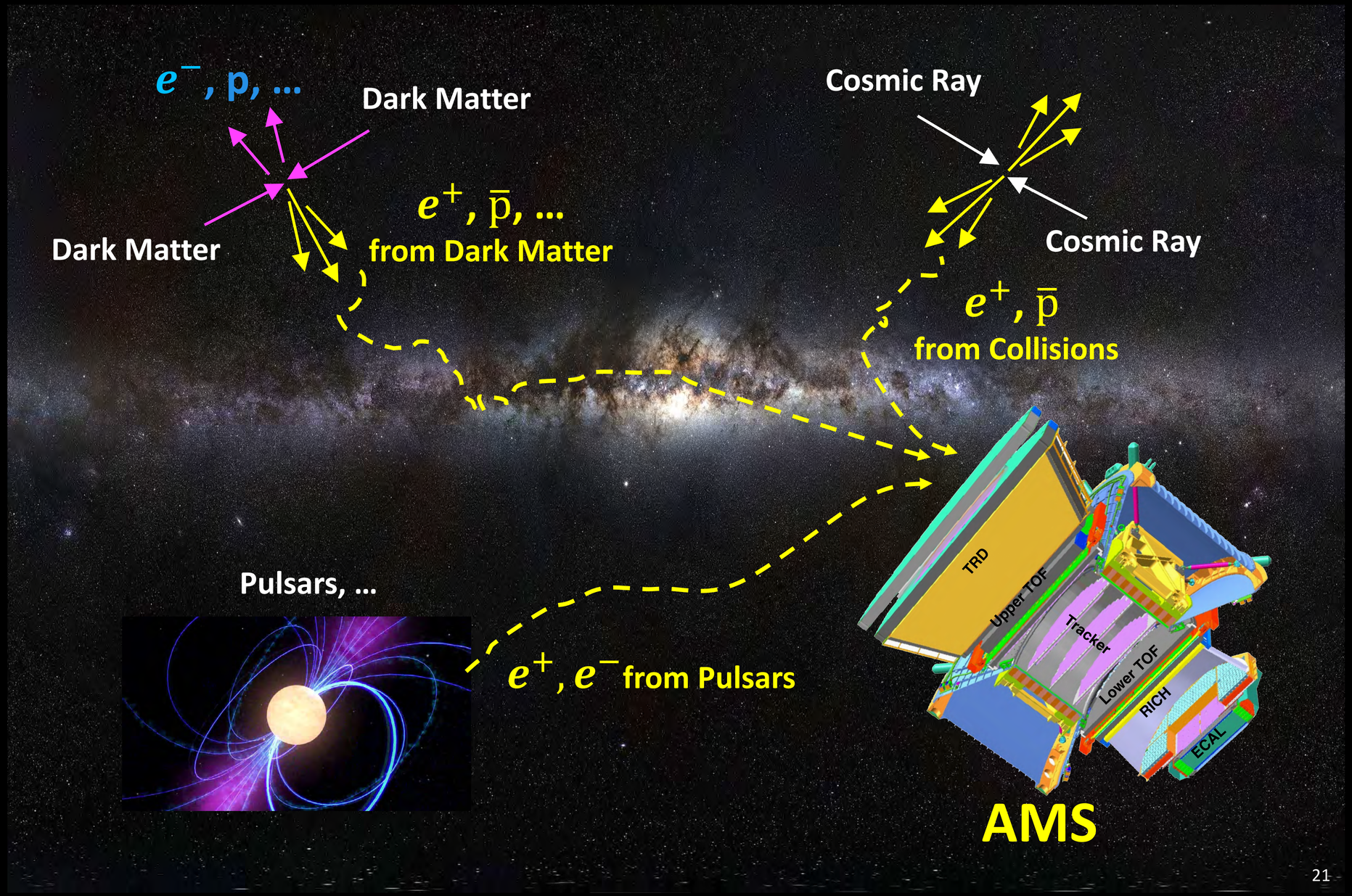
insert in one of the cosmic trips, entitled "Be Scientific with Ol'Doc Dabble" stated

'Cosmic Rays are caused by exploding stars which burn with a fire equal to 100 million suns and then shrivel from 1/2 million miles diameter to little spheres 14 miles thick'

... says Prof. Fritz Zwicky, Swiss Physicist



Anti-Particles in CRs: Signal of Dark Matter?



Stefano Gabici
ICRC 2023

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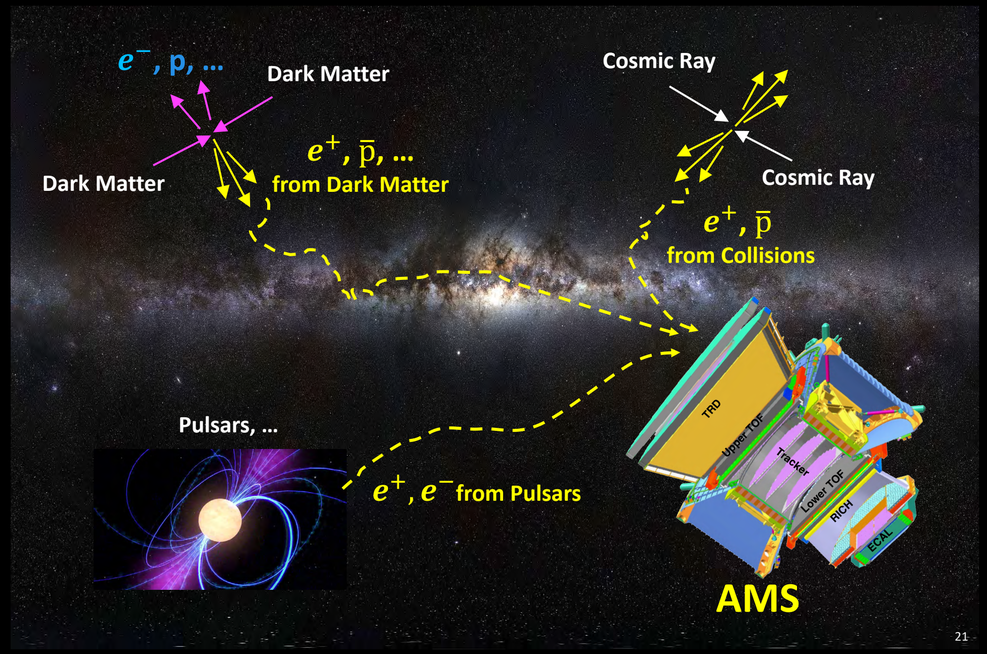
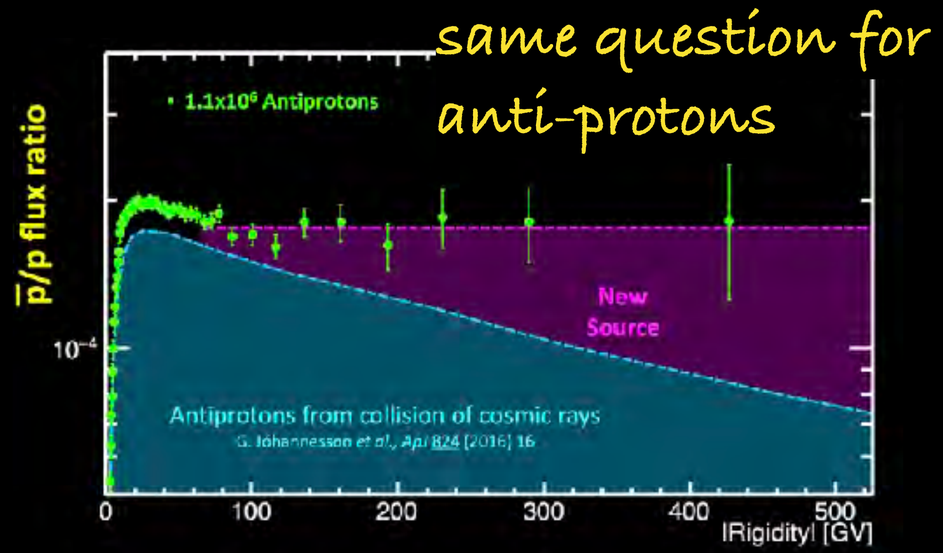


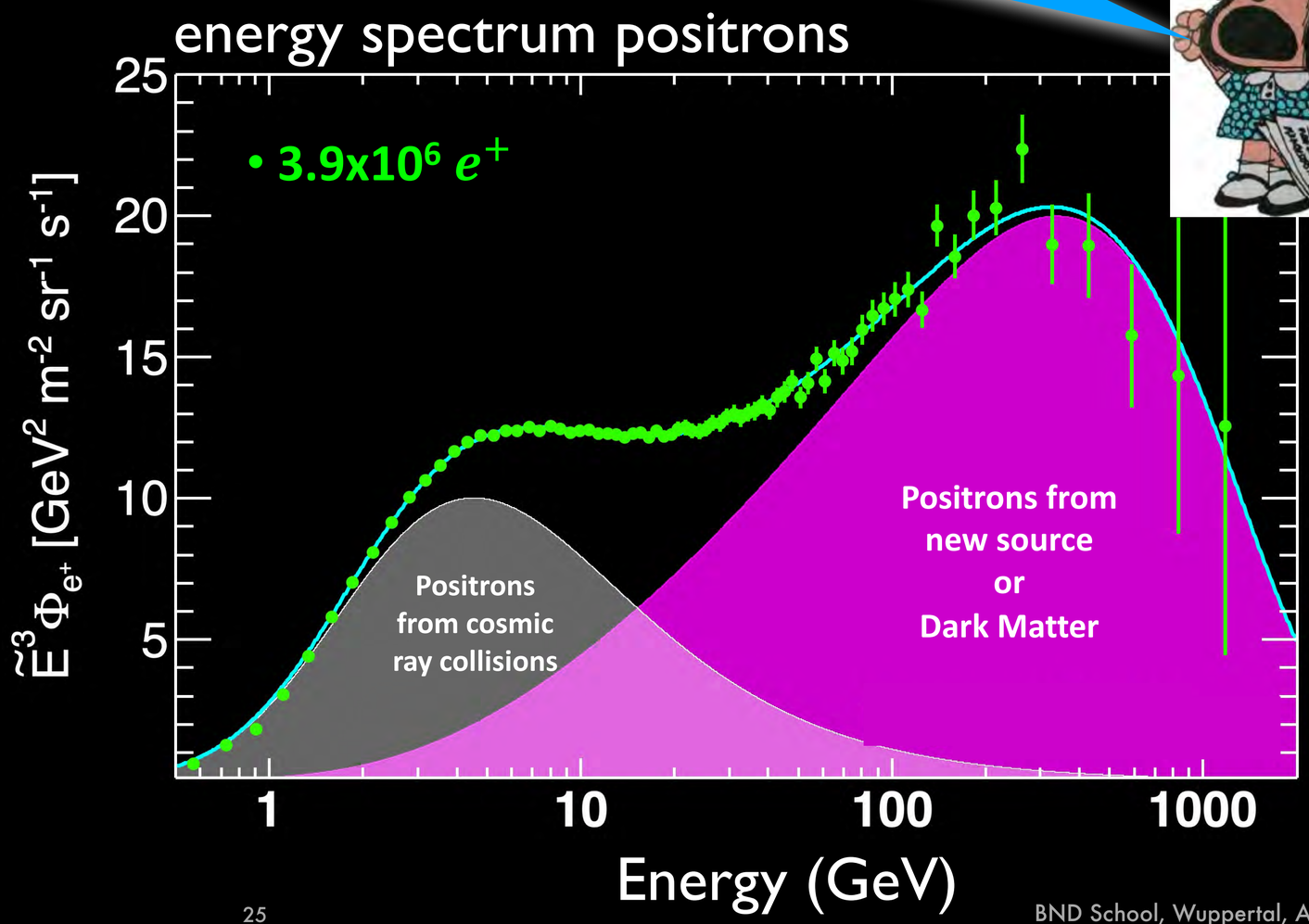
hot debate two weeks ago in Nagoya

is it a break or a cut-off ?

pulsars

DM





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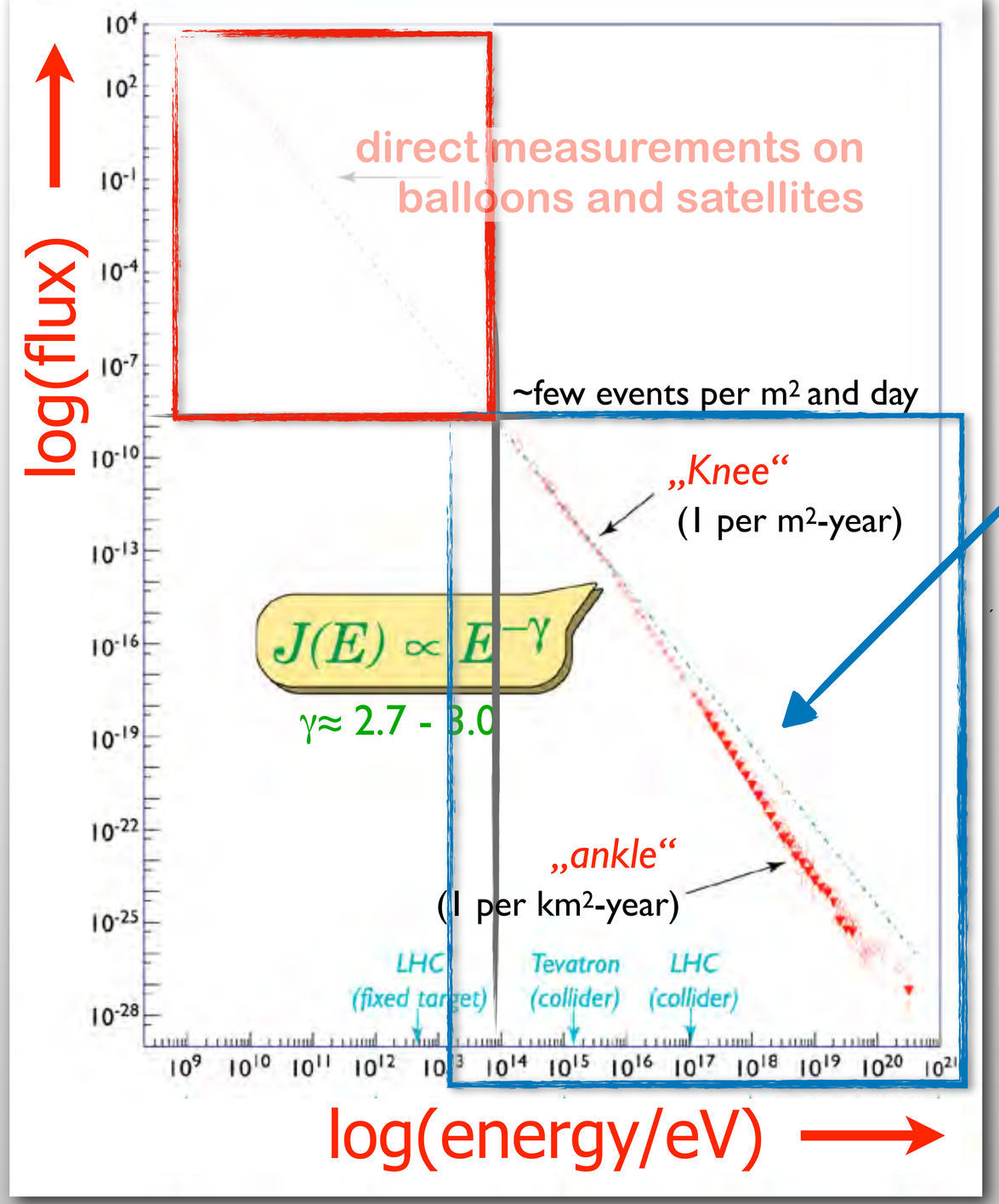
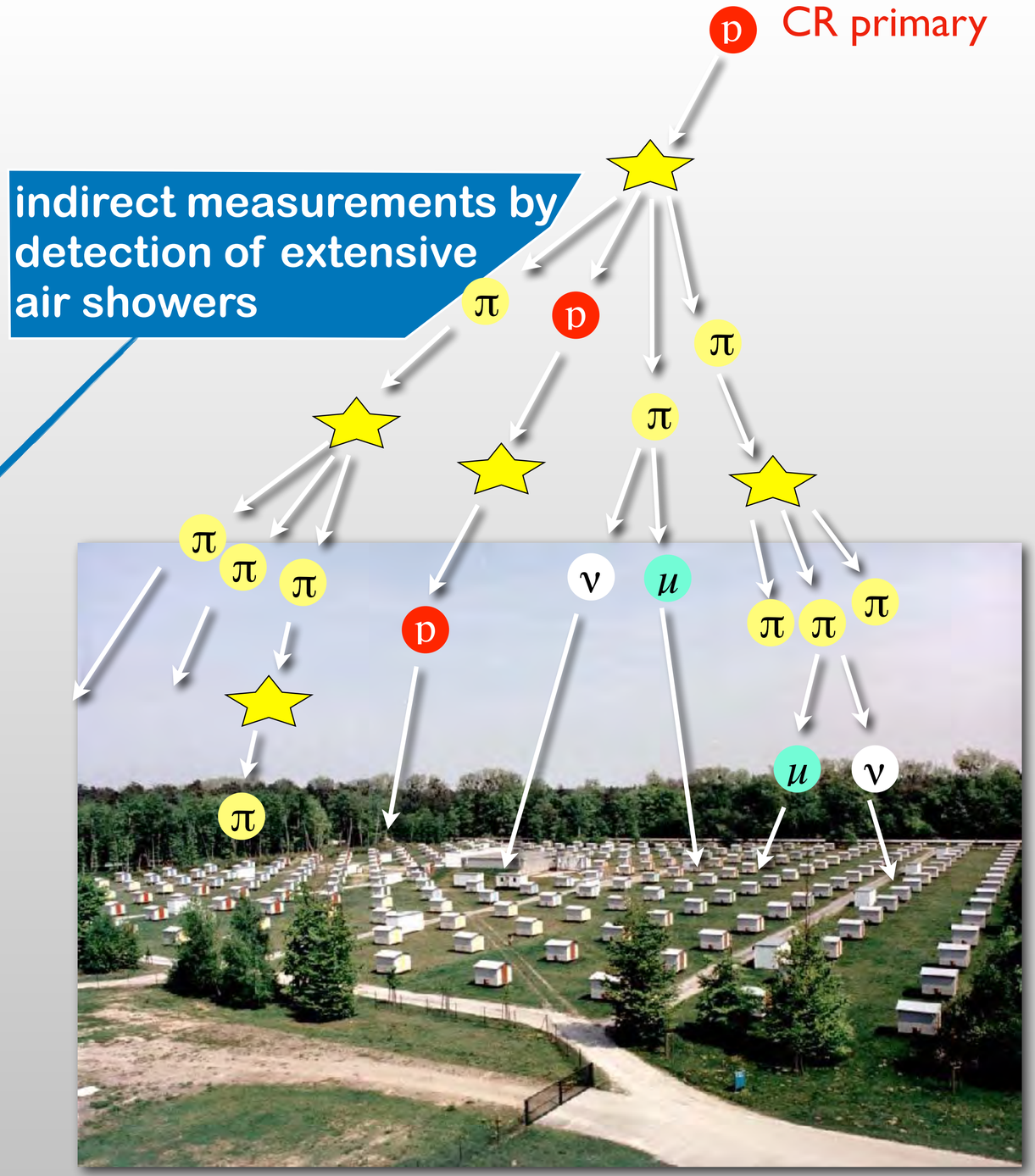
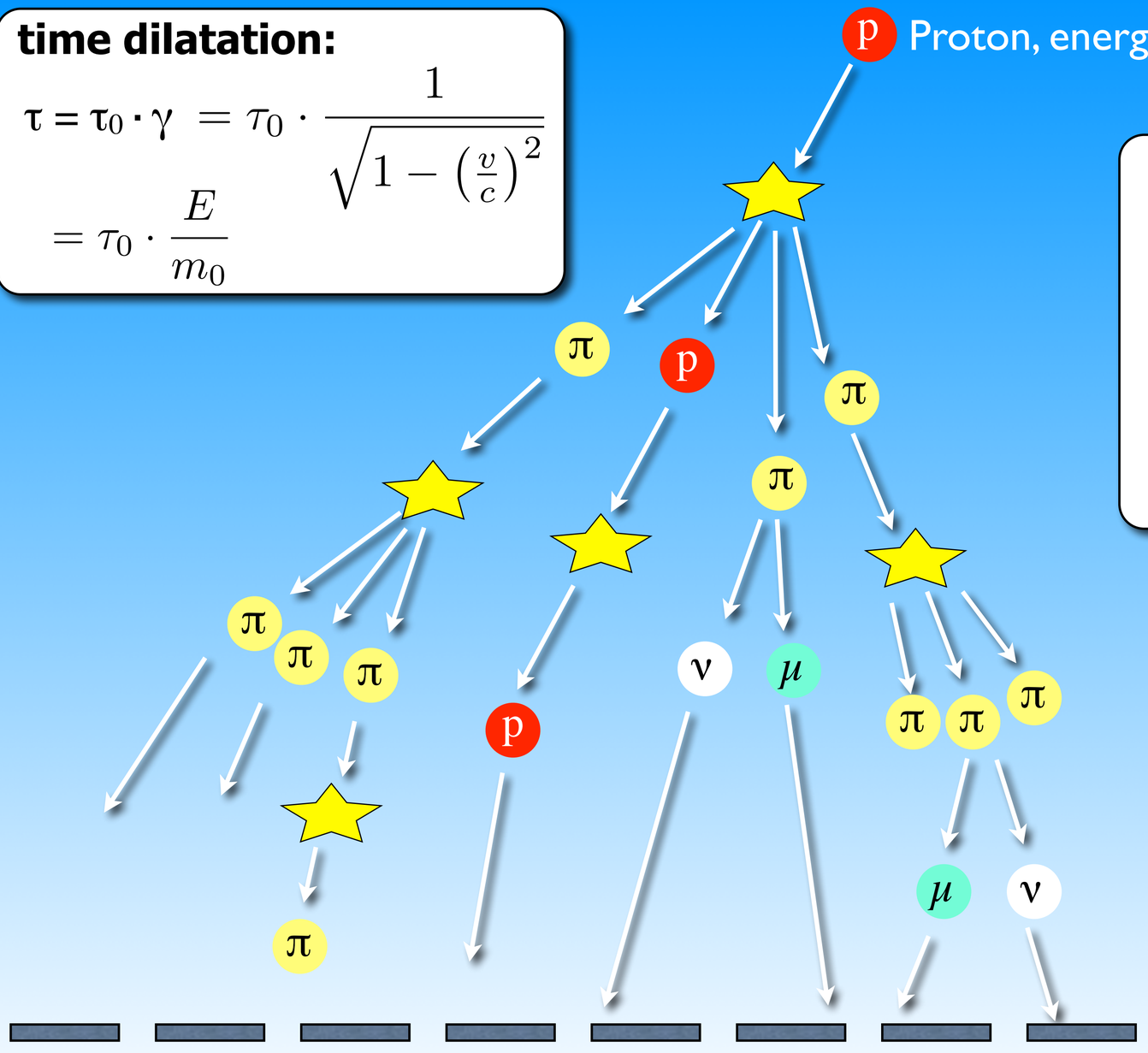

log(flux)
direct measurements on balloons and satellites
~few events per m² and day
„Knee“
(1 per m²-year)
$J(E) \propto E^{-\gamma}$
γ≈ 2.7 - 3.0
„ankle“
(1 per km²-year)
LHC (fixed target)
Tevatron (collider)
LHC (collider)
log(energy/eV)


p CR primary
indirect measurements by detection of extensive air showers
π
p
ν
μ

Extensive Air Showers (schematic)

time dilatation:

$$\tau = \tau_0 \cdot \gamma = \tau_0 \cdot \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}} = \tau_0 \cdot \frac{E}{m_0}$$



Pions:

$\pi^{\pm}$: $\tau_0 = 2.6 \cdot 10^{-8}$ s

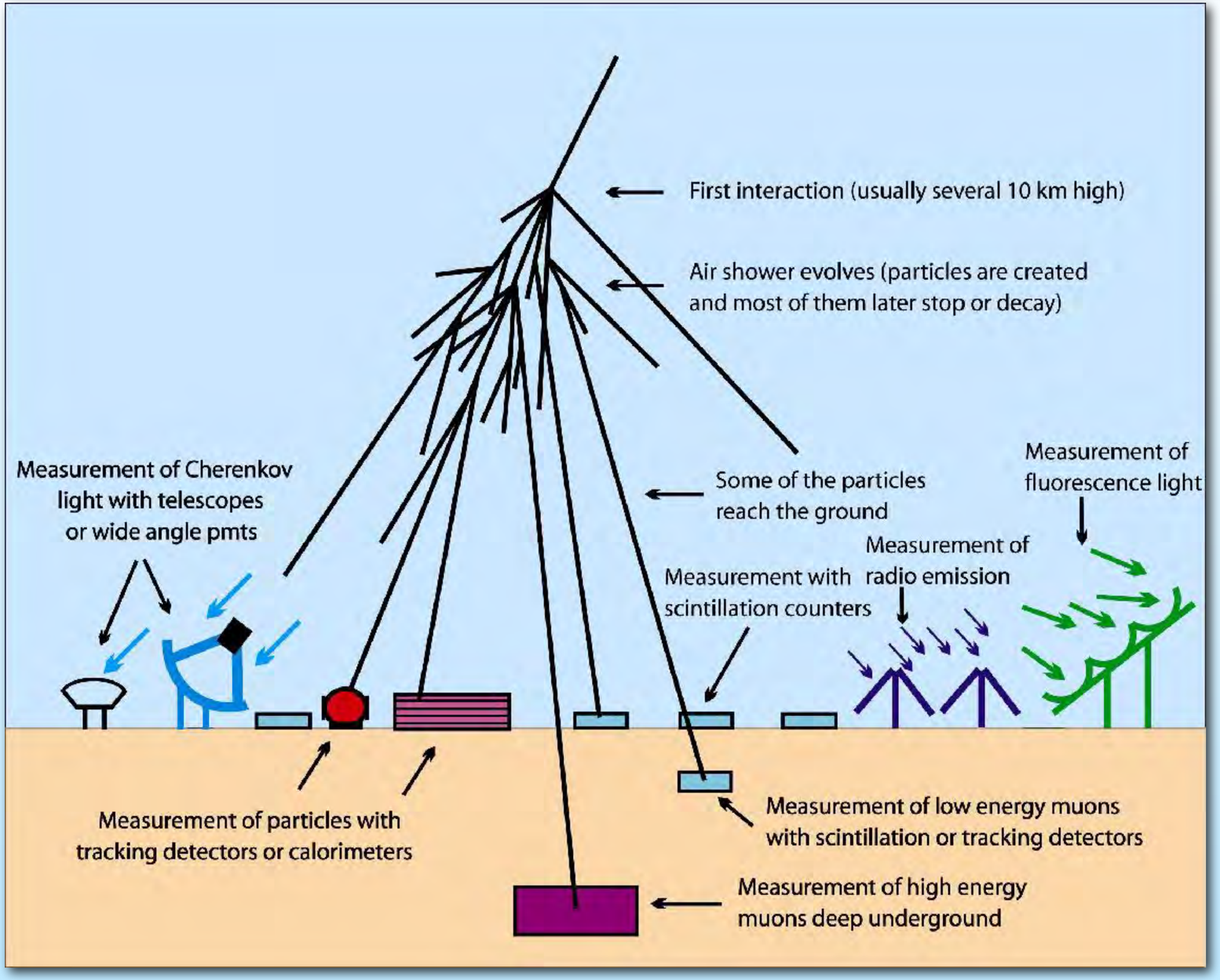
$\pi^+ \rightarrow \mu^+ + \nu_\mu$

Myons:

$\mu^{\pm}$: $\tau_0 = 2.2 \cdot 10^{-6}$ s

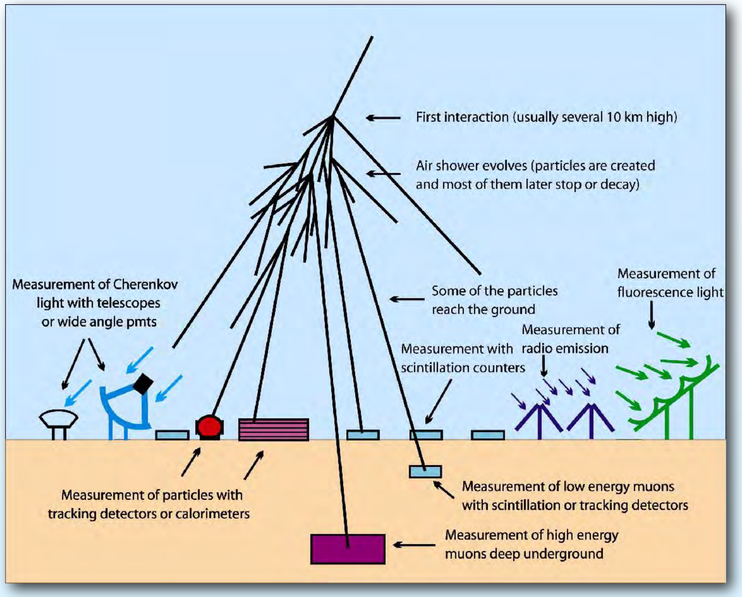
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$

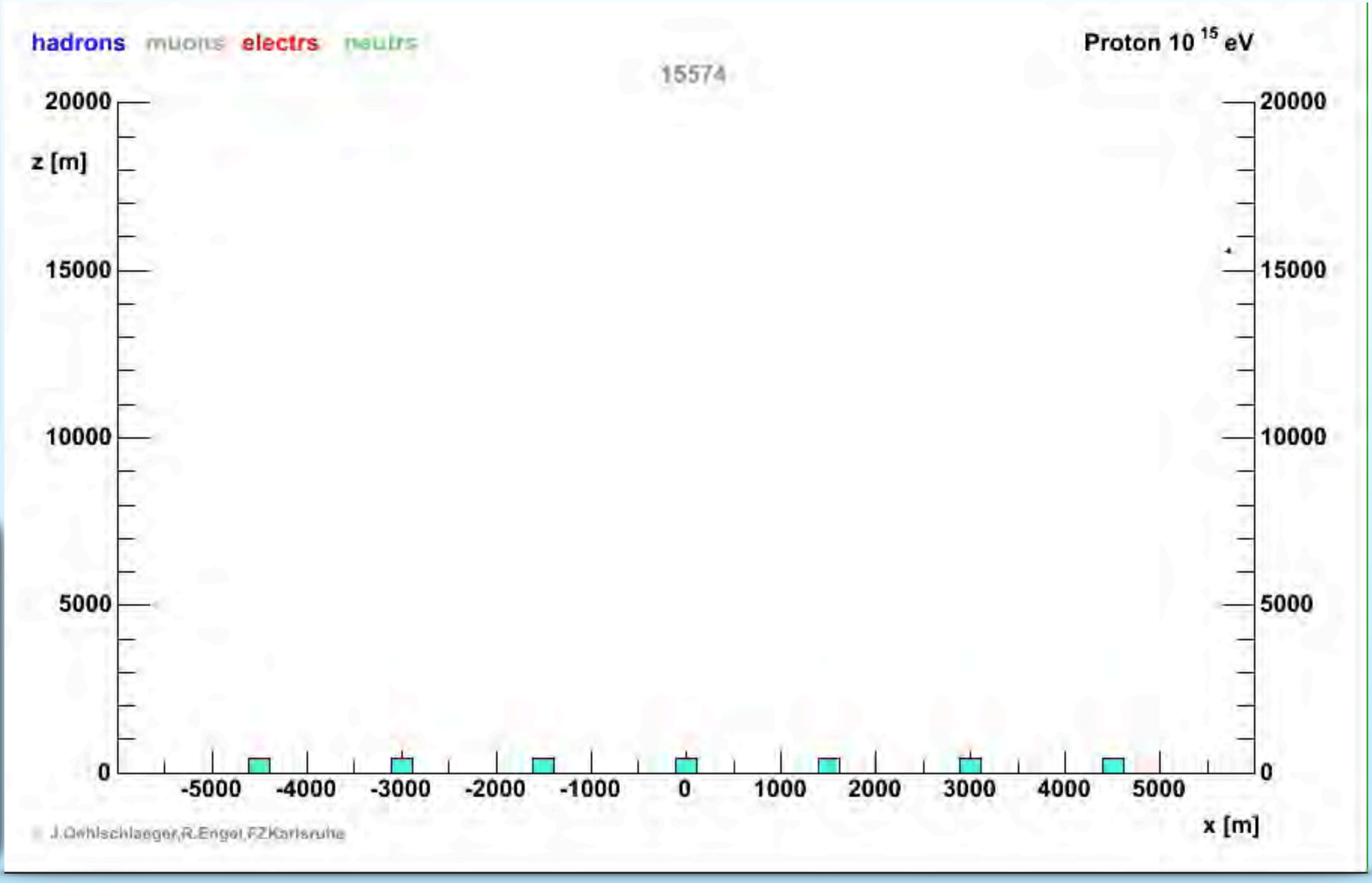
Measurement Techniques of Air Showers



George Zatsepin at work…
1946 at Pamir

Measurement Techniques of Air Showers





Particle composition at ground @ E= 10^{15} eV

≈ 80% photons
≈ 18% electrons/positrons
≈ 1.5% muons
≈ 0.3 % hadrons

for a total of ≈ **10^6 secondaries**

Extensive Air Showers (I): interaction lengths

Atmospheric Thickness:

1035 g/cm²

≈ 11 λ_I (hadr. interact. lengths)

≈ 27 X_0 (radiation lengths)

Some basics...

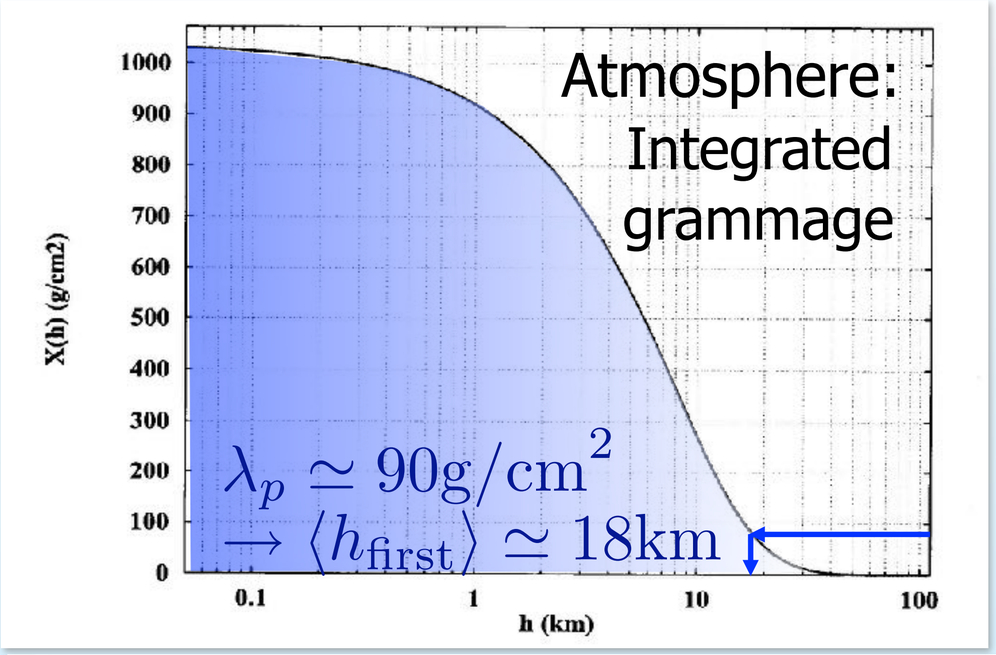
$$\lambda_I = \frac{\rho}{n \cdot \sigma} \cong 90 \text{ g/cm}^2 \text{ (p-Air)}$$

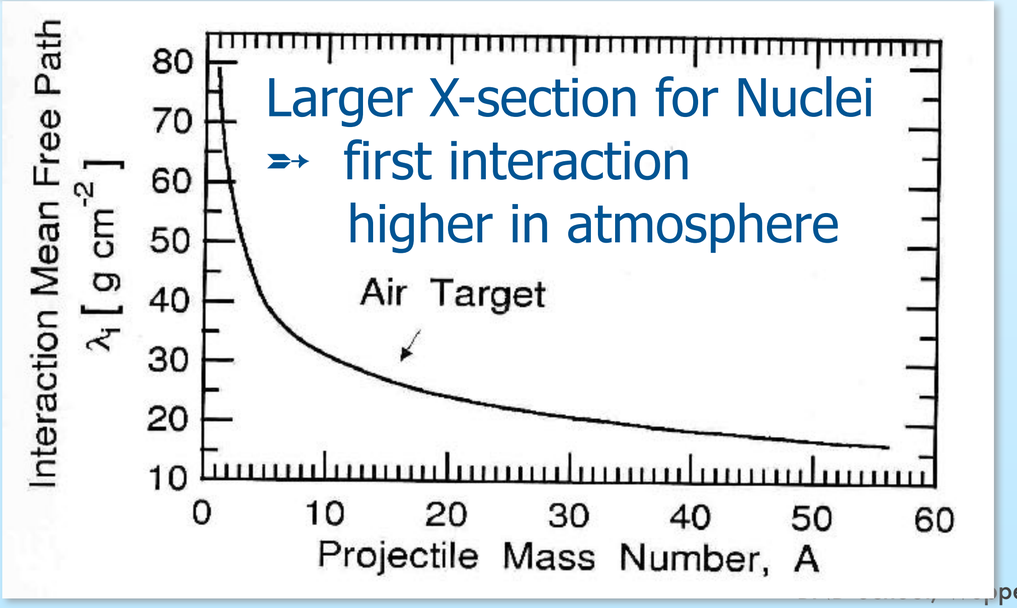
ρ: specific density of absorber (g/cm^{-3})
n: density of absorber nuclei (cm^{-3})
σ: total inelastic X-section (cm²)

X_0 defined by energy loss of high-energy electrons in media:

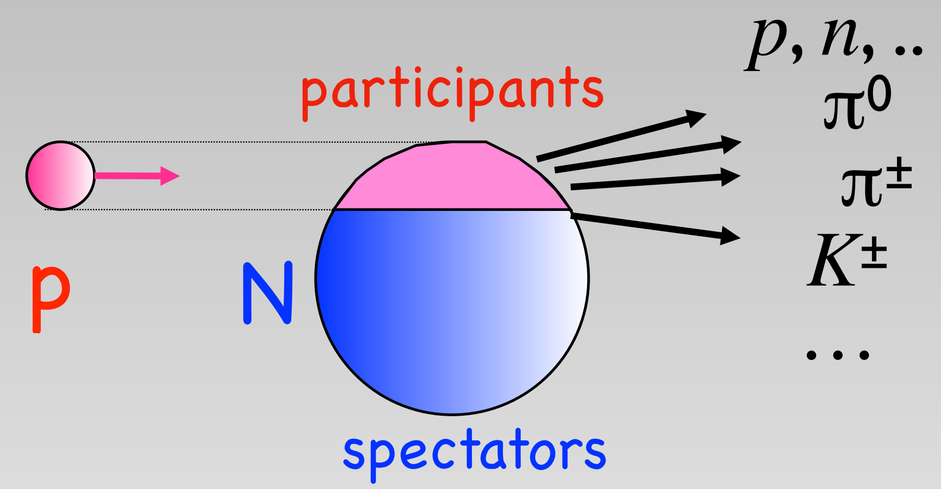
$$-\left(\frac{dE}{dX}\right)_{brems} = \frac{E}{X_0} \; ; \; \langle E_e \rangle \propto e^{-X/X_0}$$

In air: X_0 = 36.66 g/cm²





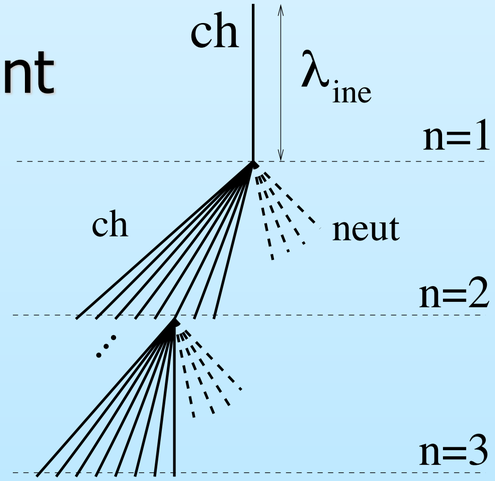
Extensive Air Showers (II): hadronic and muonic component



after ~ 1 λ_I

projectile looses ~ 40-60% of its initial energy (inelasticity)

pions are the most abundant hadrons in showers;
μ's are integrative;
their decay into e± is of no relevance



$\pi^0 \rightarrow \gamma\gamma$ ($\tau_0 = 0.8 \cdot 10^{-16}$ s)

$\pi^\pm \rightarrow \mu^\pm + \nu_\mu$ ($\tau_0 = 26$ ns)

Decay length of $\pi^\pm$:

$$R_\pi = \gamma \cdot v \cdot \tau_0 \cong \frac{E_\pi^{tot}}{m_0 c^2} \cdot c \cdot \tau_0$$

≈7.8 m

e.g.: E_π=140 GeV ⇨ R_π =7.8 km

λ_i at 5 km height ≈ 1 km

consequence:
in early shower, the hadronic interaction of $\pi^\pm$ is much more probable than decay into muons and vice versa in late showers

Extensive Air Showers (III): electromagnetic component

$\gamma \rightarrow e^+ + e^-$ pair production

γ either directly from space
or from $\pi^0 \rightarrow \gamma\gamma$ decay

$e^+ \rightarrow e^+ + \gamma$ Bremsstrahlung

$\rightarrow e^+ + e^-$

$\rightarrow e^+ + \gamma$

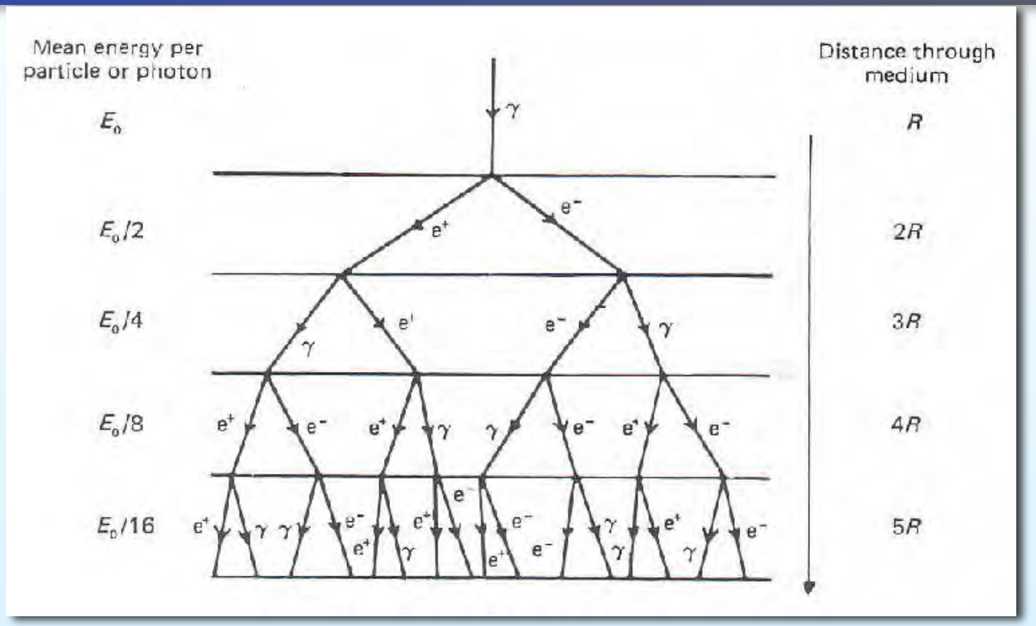
processes repeat every $\sim X_0$
➪ particle number increases like

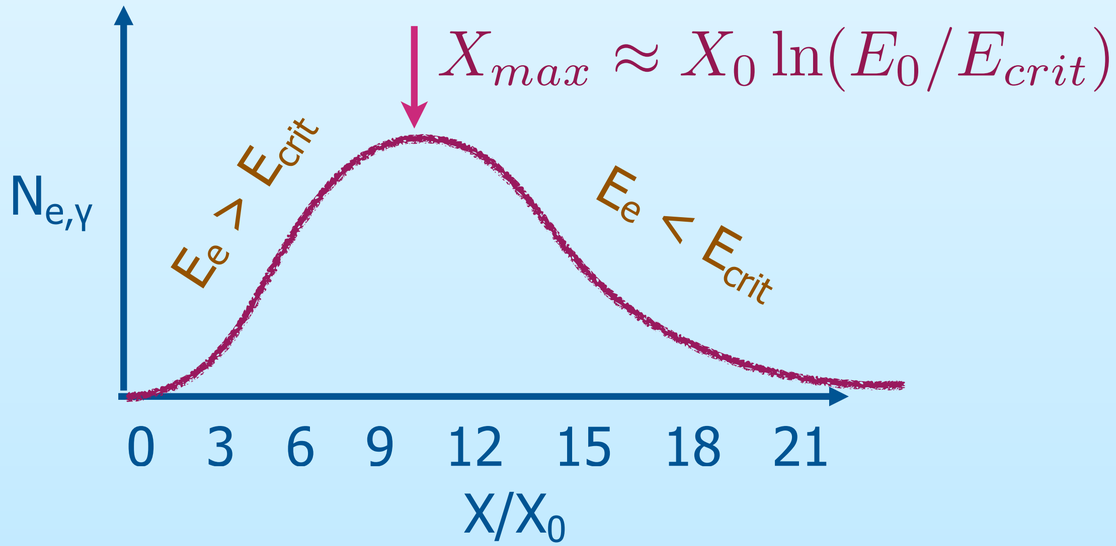
$$N_e \approx 2^n \approx 2^{X/X_0} \; ; \; \langle E_e \rangle \approx E_0/2^{X/X_0}$$

stops when

$$\left(\frac{dE}{dx}\right)_{ions} > \left(\frac{dE}{dx}\right)_{brems}$$

i.e. at $E < E_{crit}$
(critical energy ≈ 84 MeV in air)

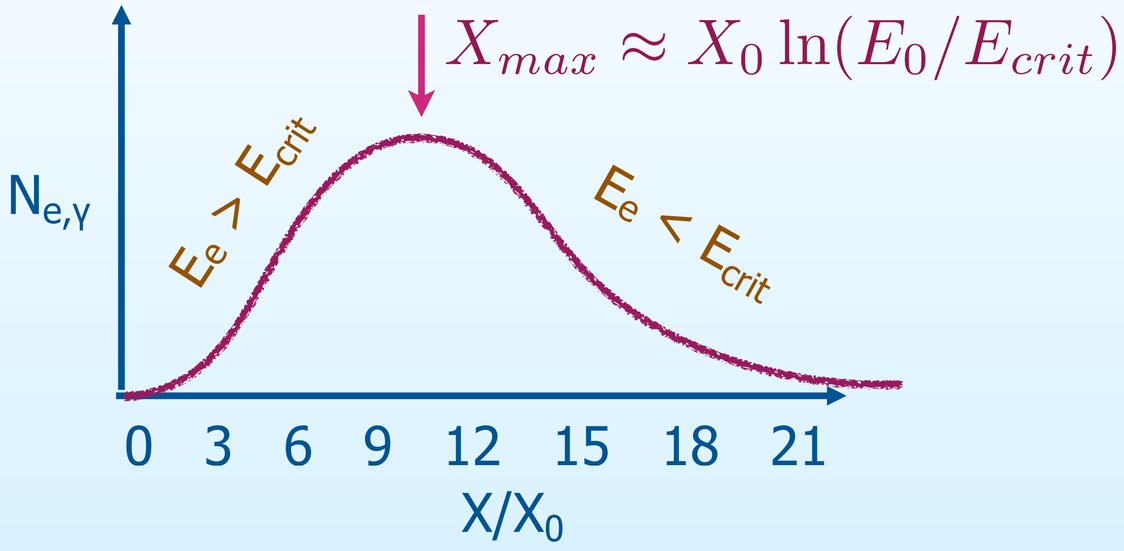




Strictly, this Bethe-Heitler consideration applies only to pure em-showers !

Extensive Air Showers (IV): em → general case

Pure electromagnetic case



empiric parametrisation, accounting also for fluctuations, by **Gaisser-Hillas** (1977)

modifications for hadron induced EAS

- 1st interaction after hadronic interaction length λ_p
- Mean multiplicity *N* of hadrons O(10-100) → average hadron energy ≈ E_0/N
- Only fraction κ_{ela} (elasticity) is used for secondary particle production

$$\rightarrow X_{max} \approx \lambda_p + X_0 \ln\left(\frac{\kappa_{ela} E_0}{2 N E_{crit}}\right)$$

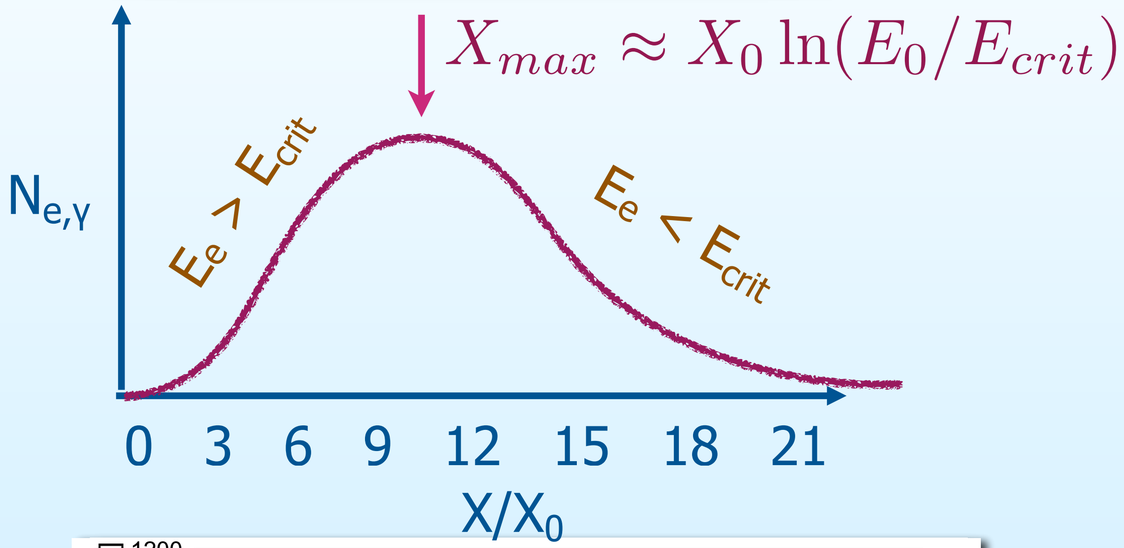
KHK & Unger, APP35 (2012) 660

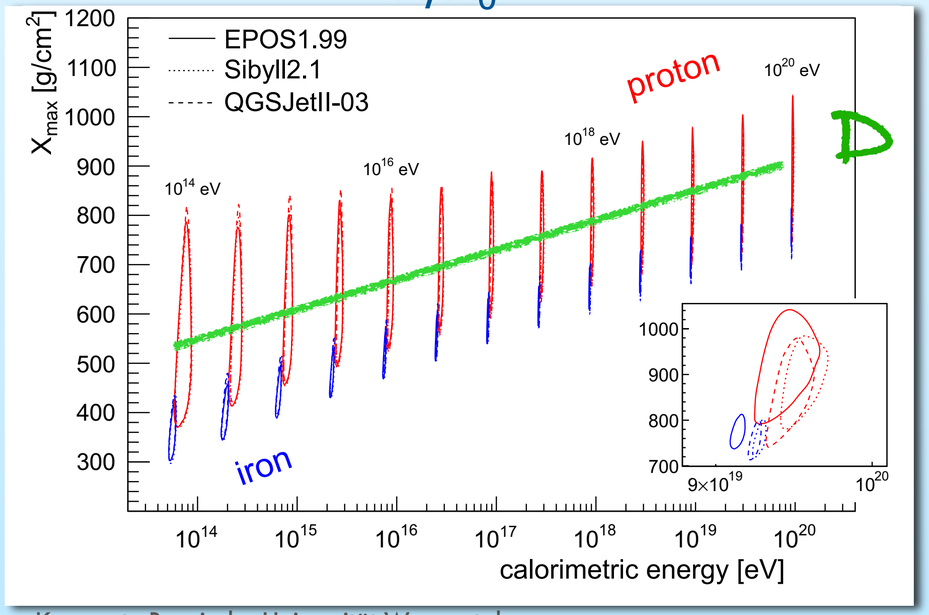
$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{(X_{max}-X_0)/\lambda} \cdot e^{(X_{max}-X)/\lambda}$$

N_{max}: No. of particles at shower maximum; X_0: point of 1st interaction; λ: width of distribution

Extensive Air Showers (IV): em → general case

Pure electromagnetic case





KHK & Unger, APP35 (2012) 660

modifications for hadron induced EAS

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KHK & Unger, APP35 (2012) 660

Change of X_{max} with primary energy is called:

elongation rate

$$D = \frac{d\langle X_{max}\rangle}{d \ln E_0}$$