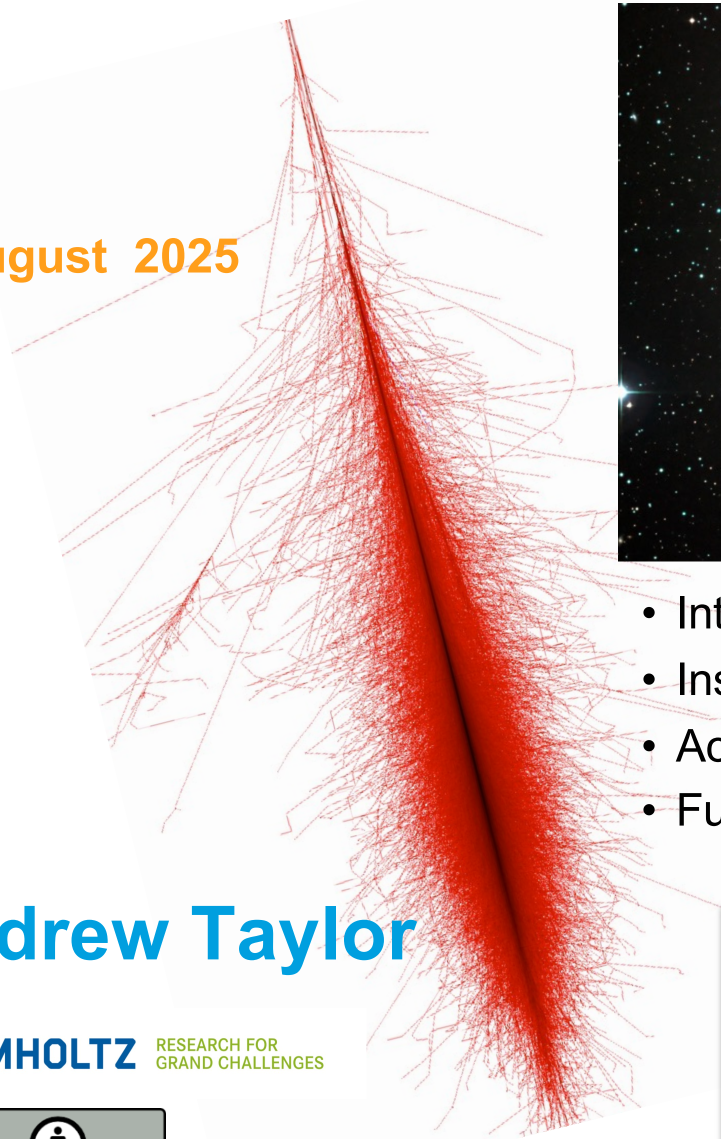
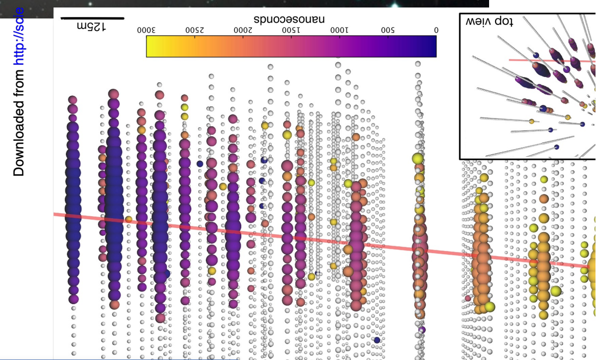
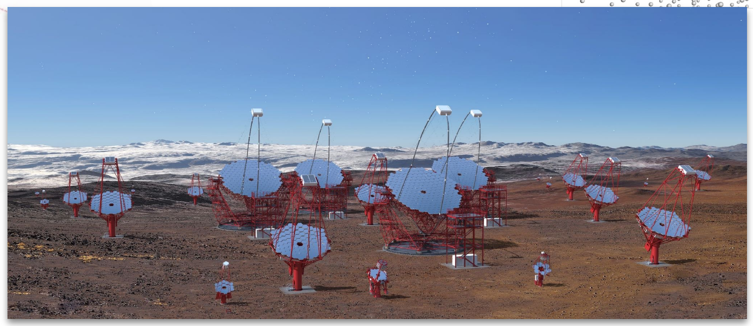
Astroparticle Physics

29 August 2025



- Introduction
- Instrumental Techniques
- Acceleration and Sources
- Fundamental Physics





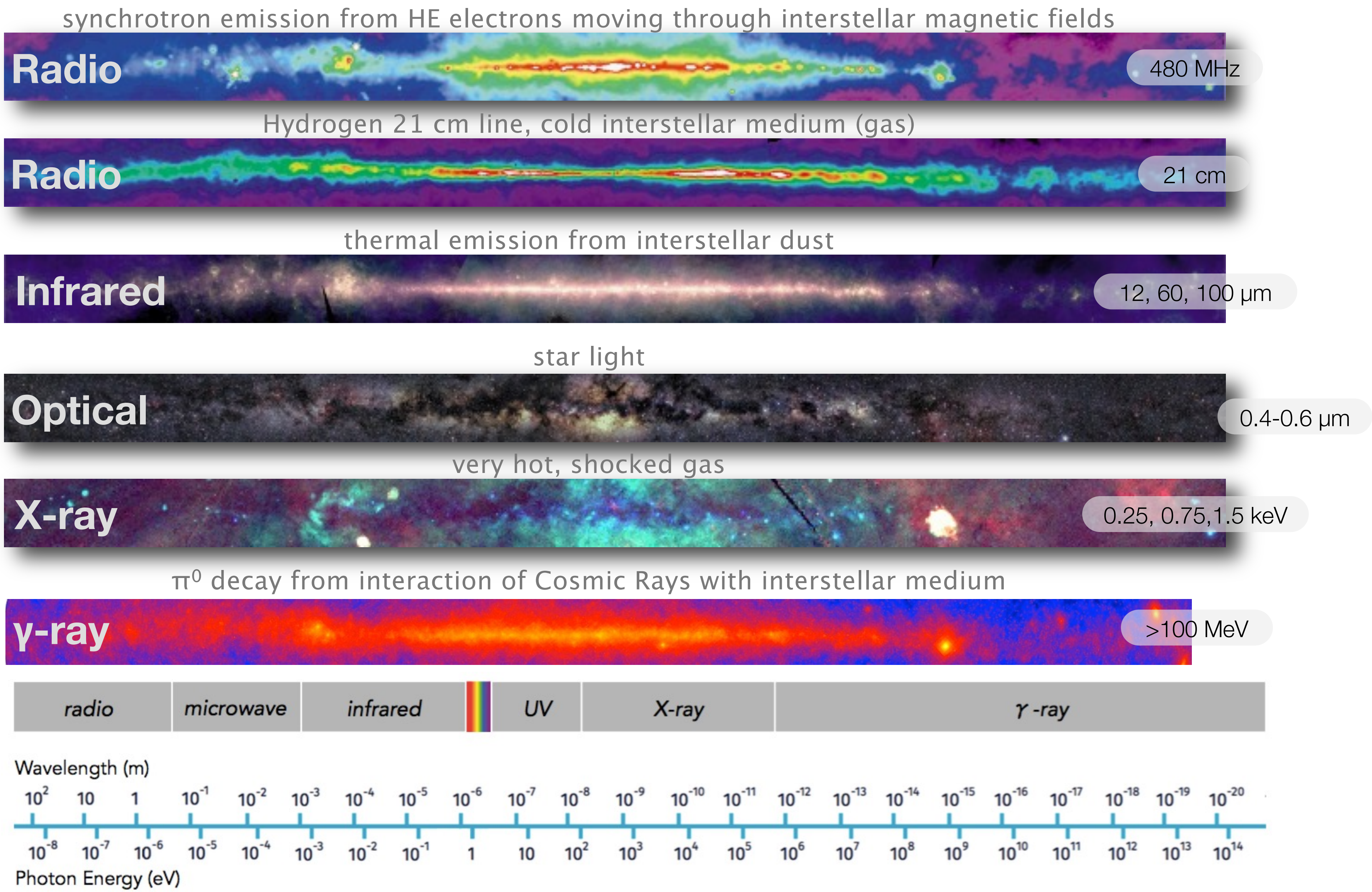
Andrew Taylor

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

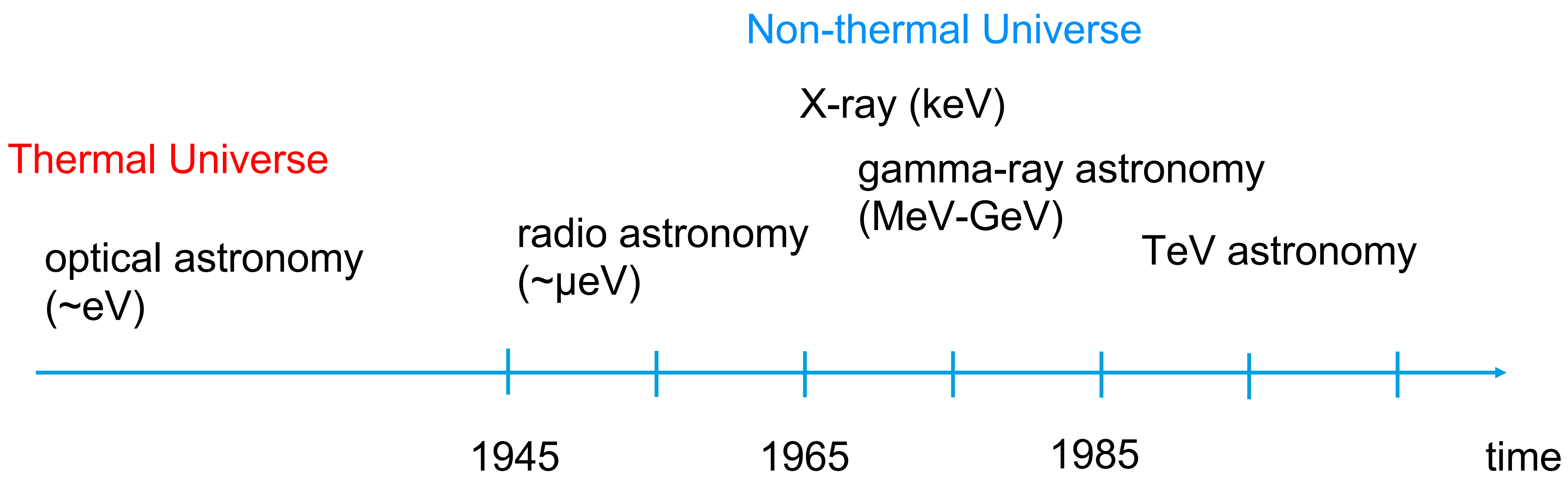
DESY.

Multi-wavelength astronomy

+ high-energetic particles, neutrinos, gravitational waves



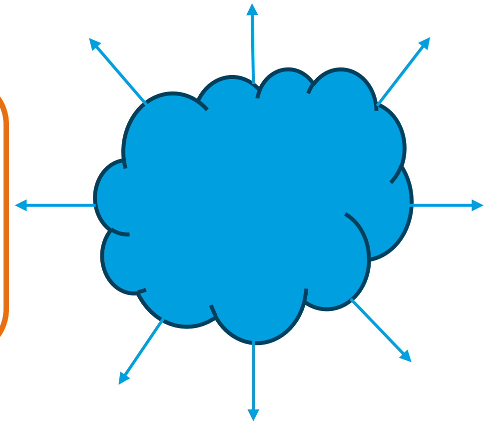
A Brief History of Non-Thermal Astronomy

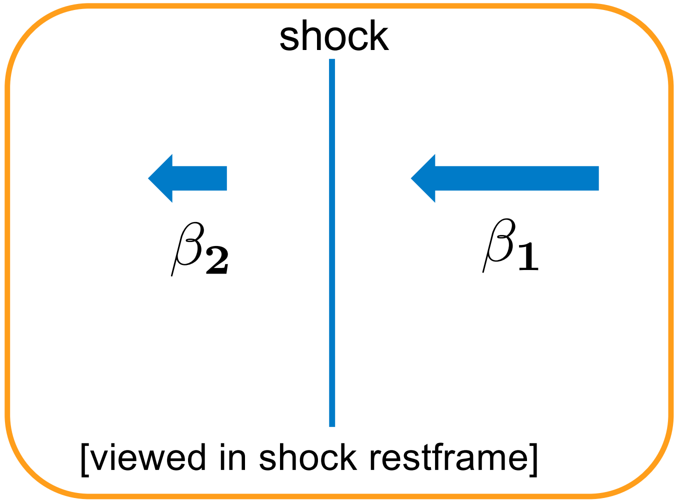


Science Questions

- By what process do particles gain their energy?
- What fraction of the blastwave energy is passed into non-thermal particles and magnetic fields?
- What multi-messenger observational signatures are produced by accelerated particles in the source?
- What role do cosmic rays play in shaping their environment?

Theory/Observation research groups focus on explosive events giving rise to particle acceleration



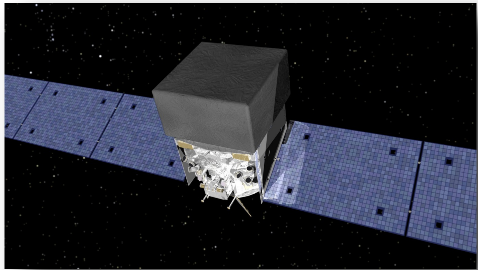


What are the sources of the highest energy Galactic and Extragalactic Cosmic Rays?

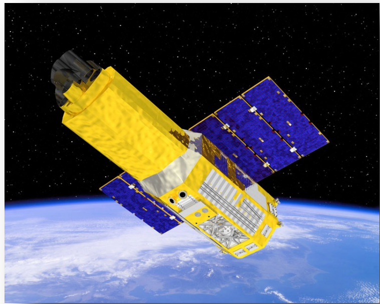
Observatories

SKA

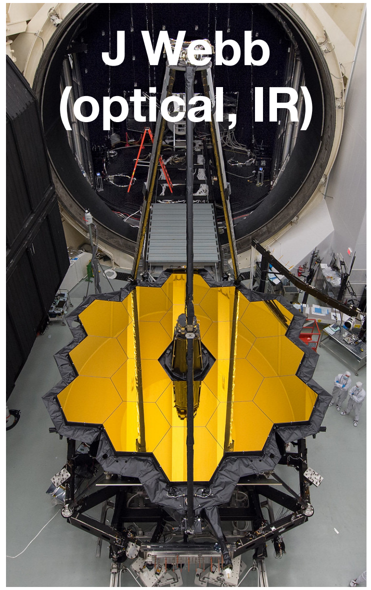
Fermi (Gamma-rays)



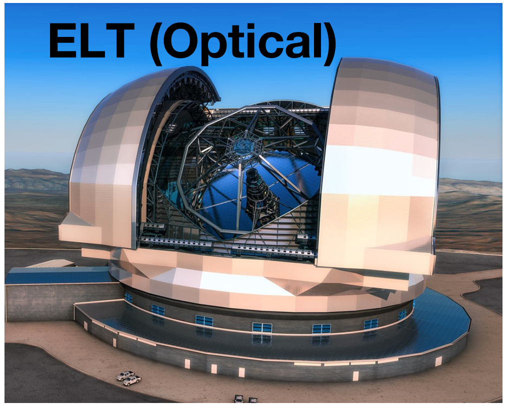
Suzaku (X-rays)



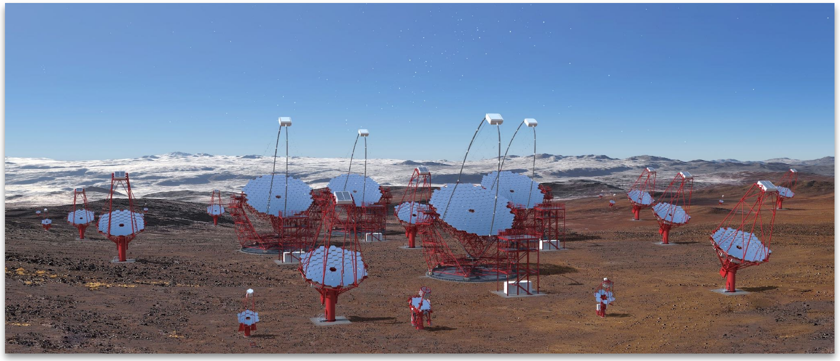
J Webb (optical, IR)



ELT (Optical)



CTA (Gamma-rays)

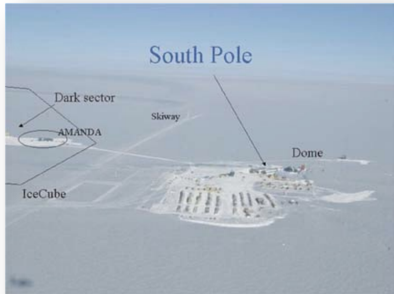


AMS (Cosmic Rays)

Auger (Cosmic Rays)

LIGO (Gravitational waves)

IceCube (Neutrinos)



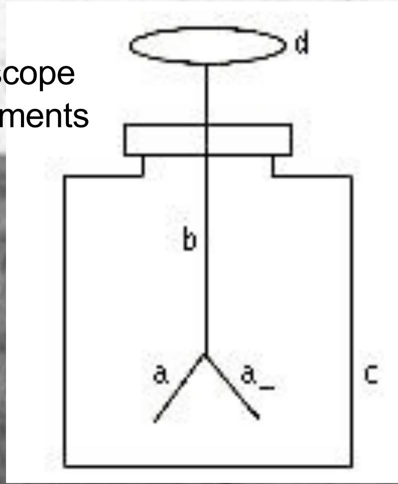
Cosmic Rays

“Cosmic rays are high-energy protons and atomic nuclei which move through space at nearly the speed of light. They originate from the sun, from outside of the solar system, and from distant galaxies.” (Wikipedia)

Viktor Hess

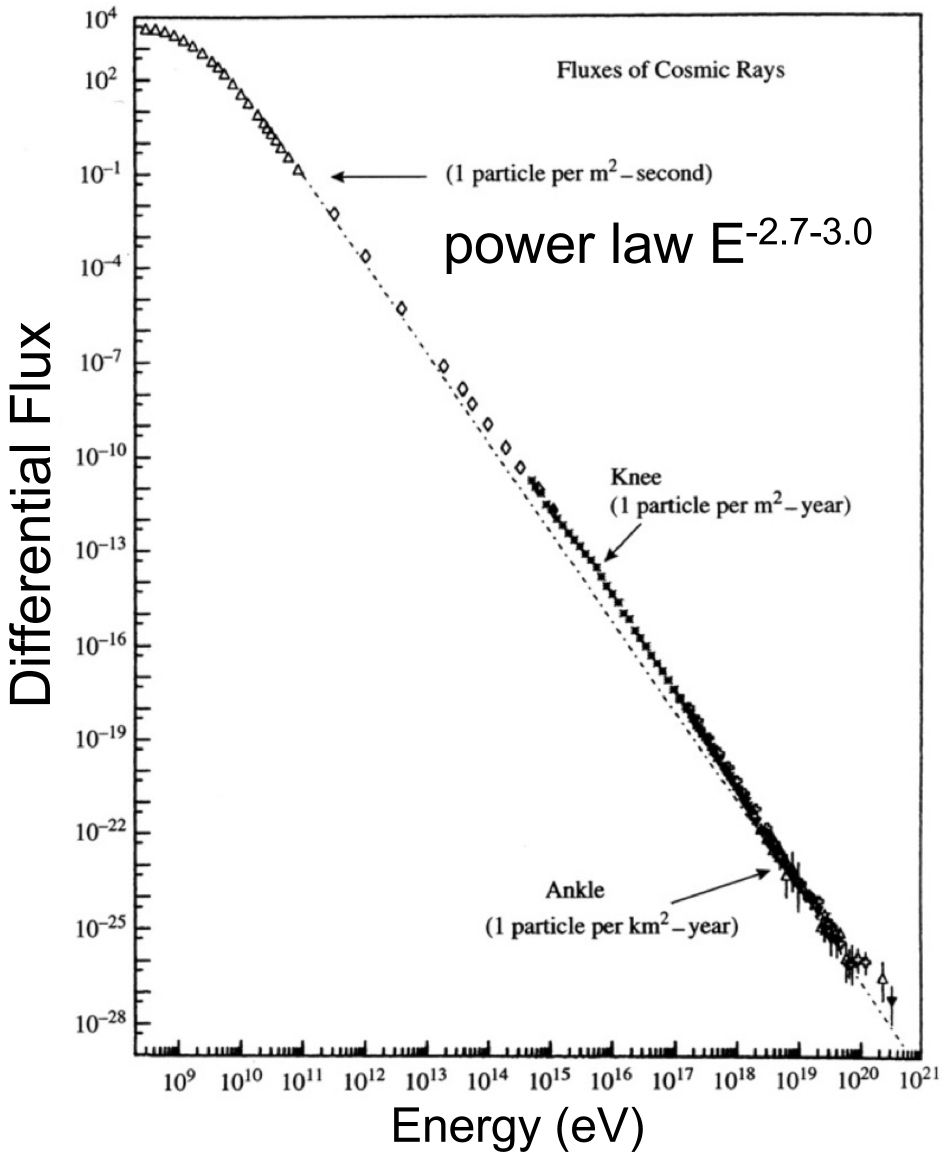
1912: Several ascents up to 5000 m
1936: Nobel prize

Electroscope measurements



Altitude (km)	Change in Ionization (10^6 m^{-3})
0	0
1	1.2
3	8.8
4	28.7
5	61.3

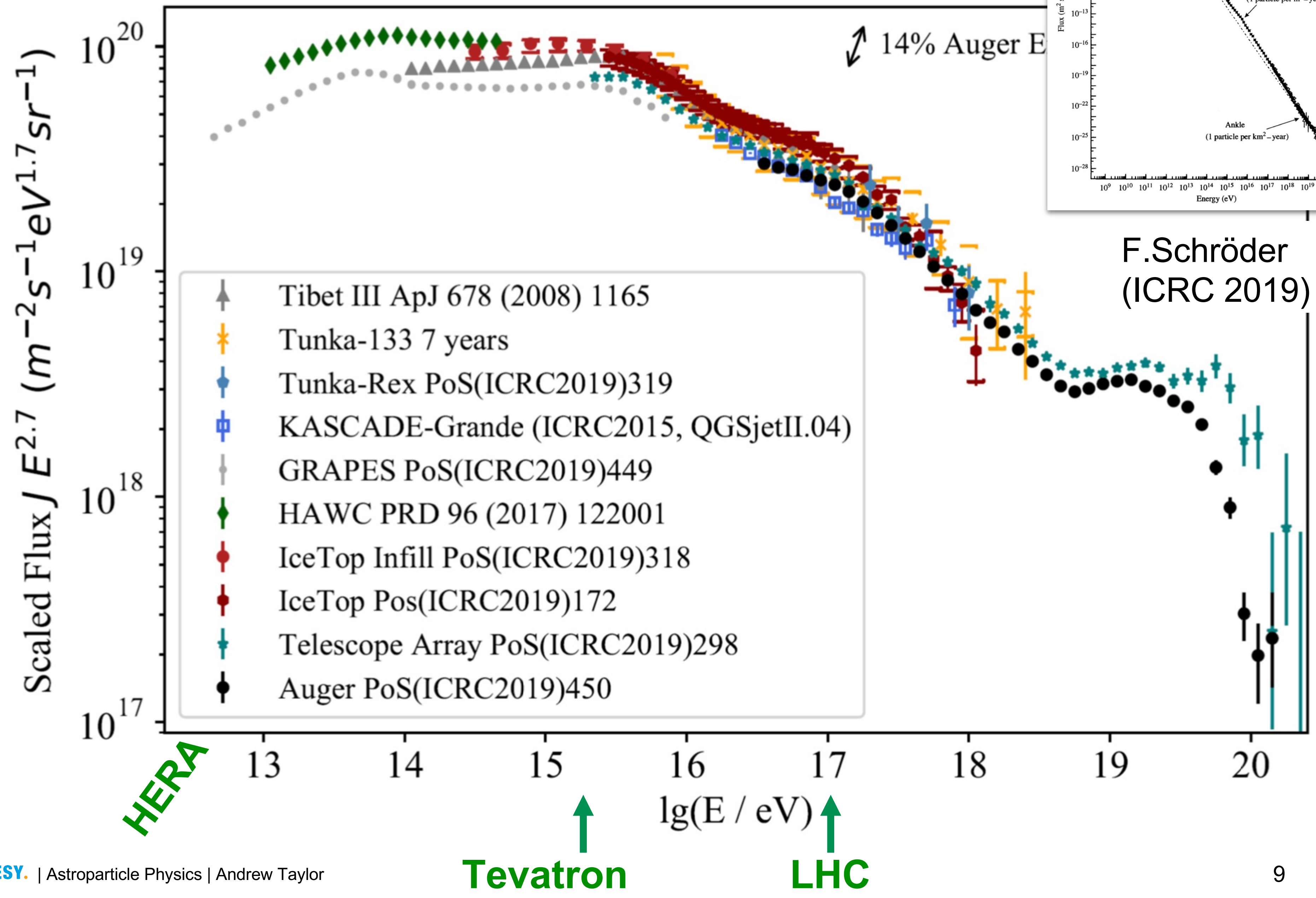
Cosmic Ray Energy Spectrum

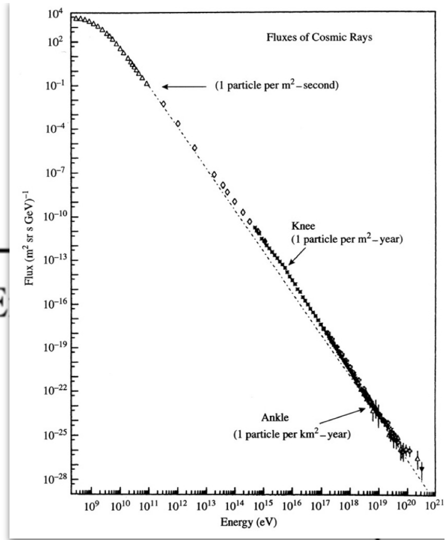


98% nuclei, mostly p, He,
but also heavier nuclei
2% electrons
(at a few GeV;
strongly energy dependent)

cosmic rays energies
up to 10^{20} eV
energy density similar
to star light or magnetic fields

The Cosmic Ray Energy Spectrum





F.Schröder
(ICRC 2019)

Natures Acceleration Spectrum

- Where are Nature's Particle Accelerators?

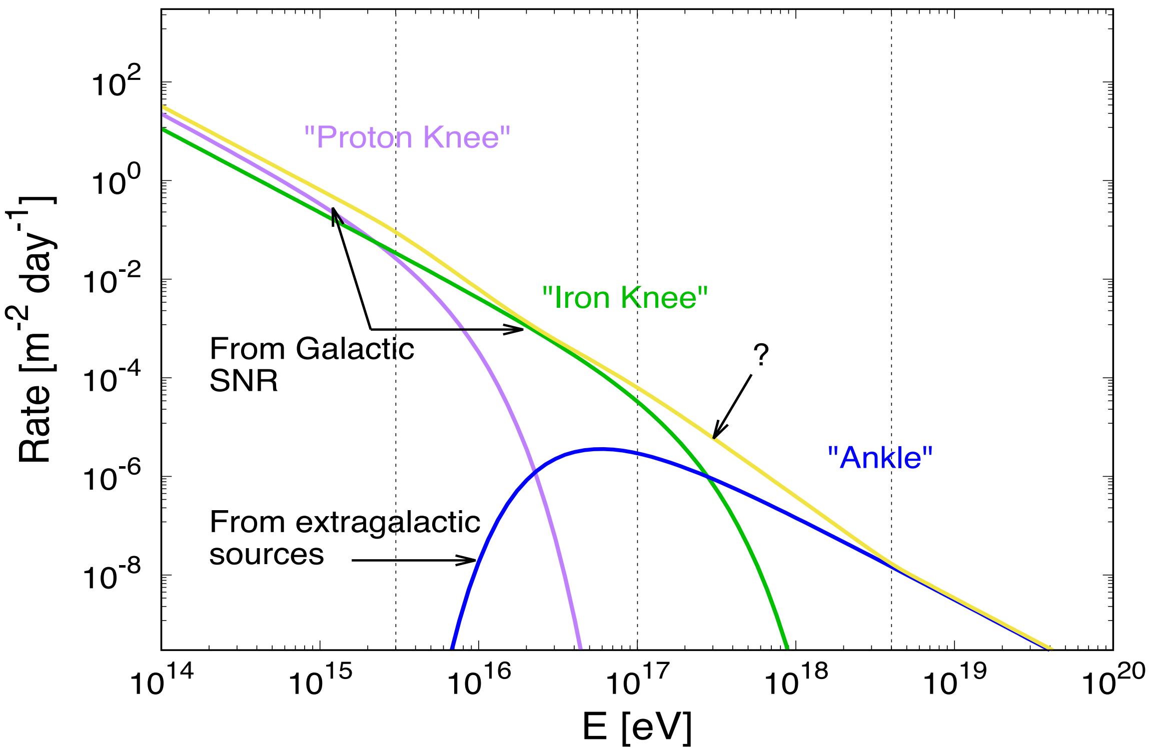
- These particles arrive approximately isotropically

- A broad range of high energy particles are detected arriving to Earth

- The lower energy particles (<PeV) are Galactic in origin

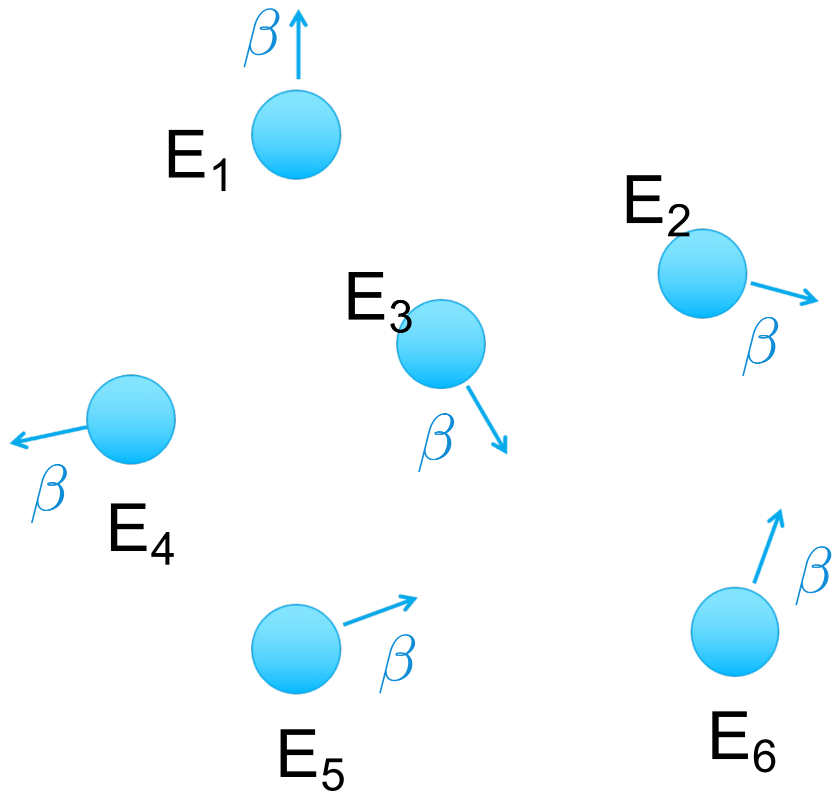
- The higher energy particles (EeV) are extragalactic in origin

Nature, 531 (2016), A M Taylor et al.



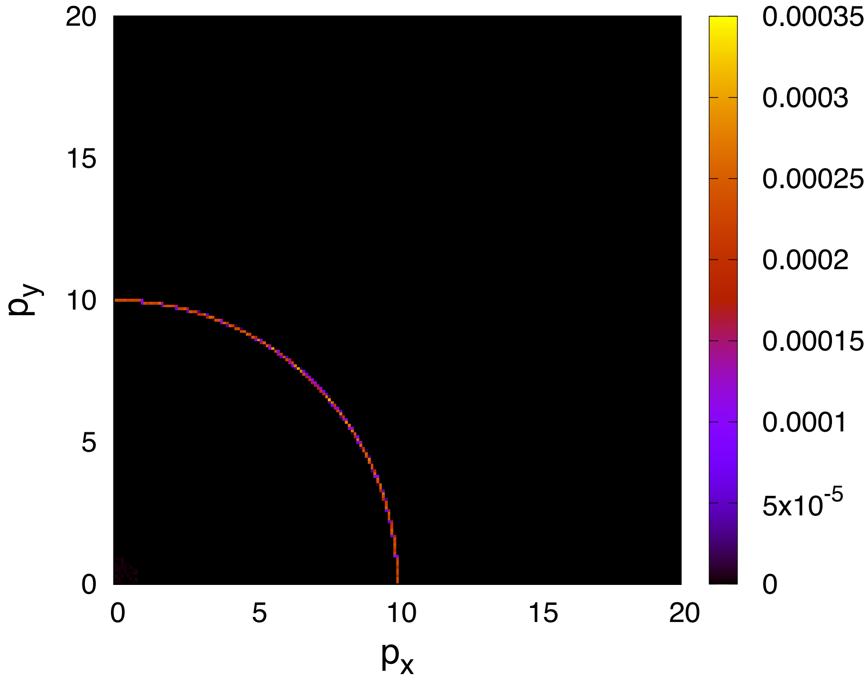
Thermal Particles

Thought experiment- imagine an ensemble of particles all with the same energy bouncing around in a box…..



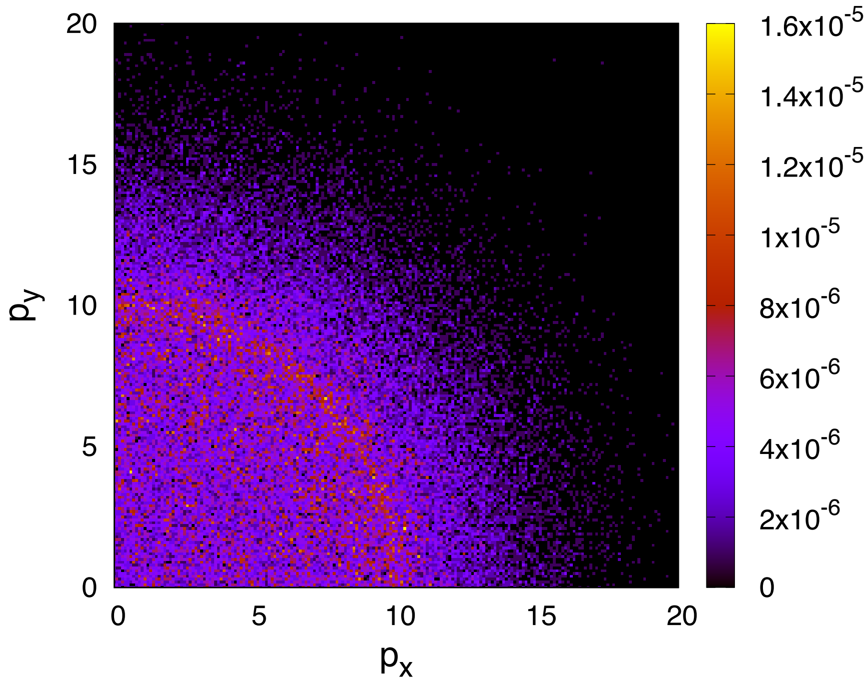
Elastic Collisions

p_x and p_y of each particle start off correlated, and through scattering become decorrelated, appreciated by looking at phase space distribution



each scattering p_x and p_y are individually randomised

$$\mathbf{dp^2 = dp_x^2 + dp_y^2}$$



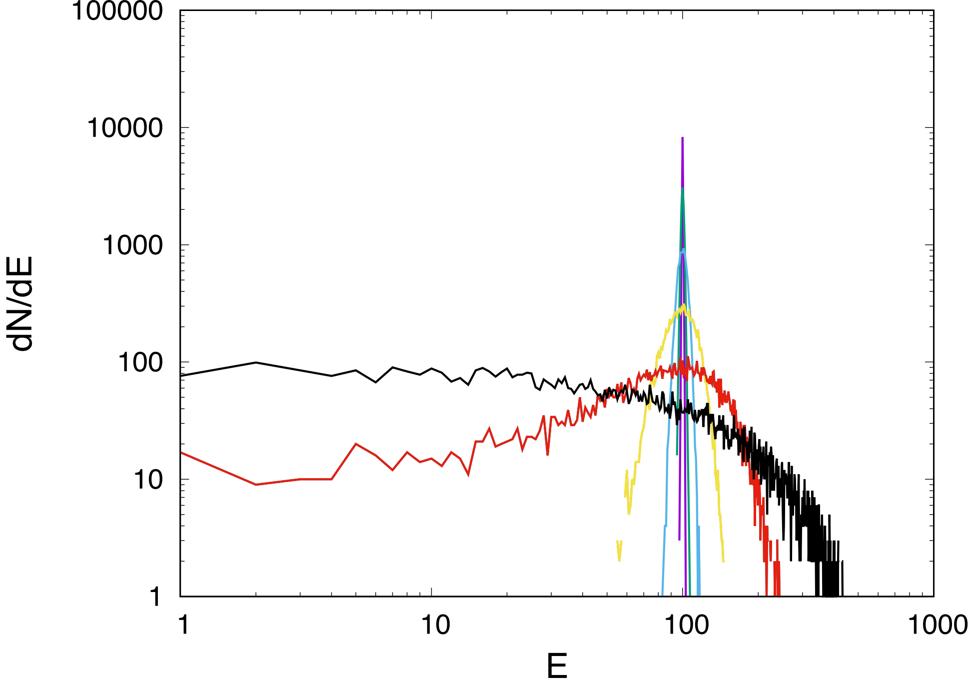
Origin of Thermalised Particle Distribution Function

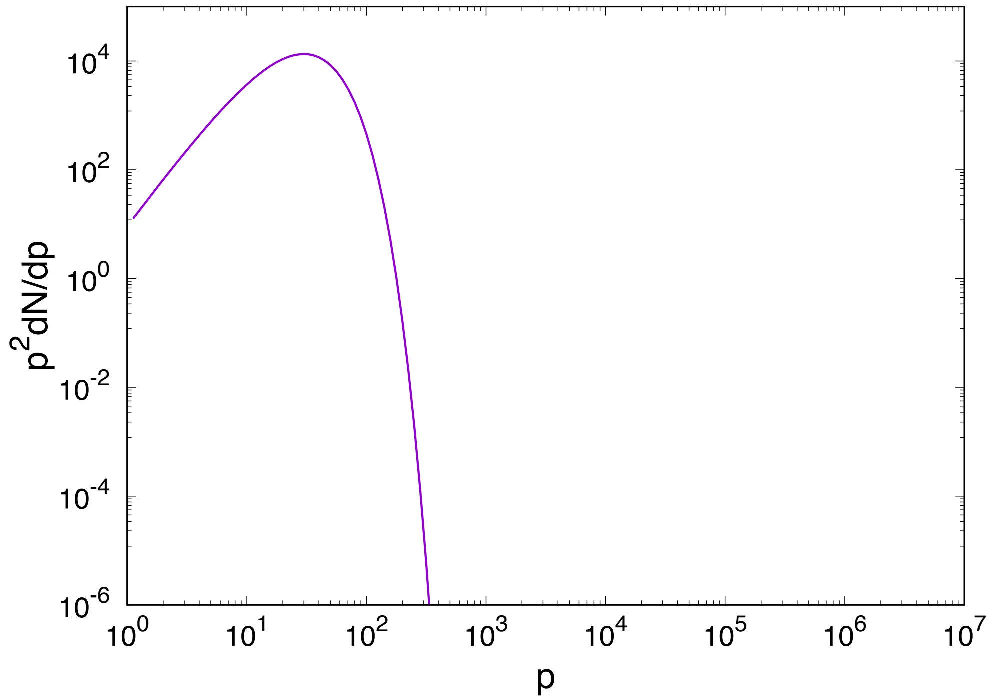
Ensemble of particles exchanging energies:

E_1	E_2	E_3	E_4	E_5	E_6
100	100	100	100	100	100
101	99	100	100	100	100
101	99	100	100	99	101
100	99	101	100	99	101
100	98	101	100	99	102
99	99	101	100	99	102

Relaxing to a Thermal Distribution

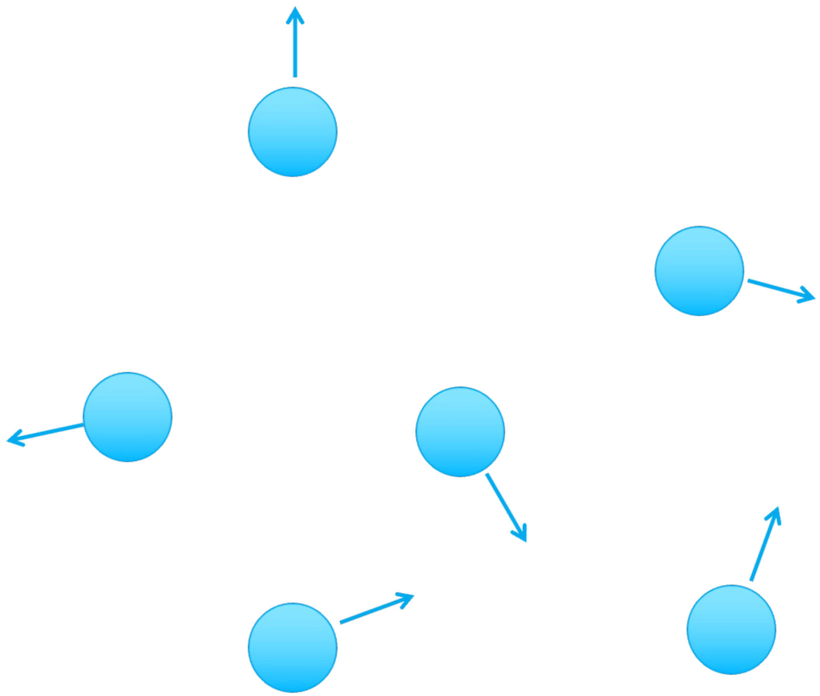
Ensemble of particles exchanging energies:



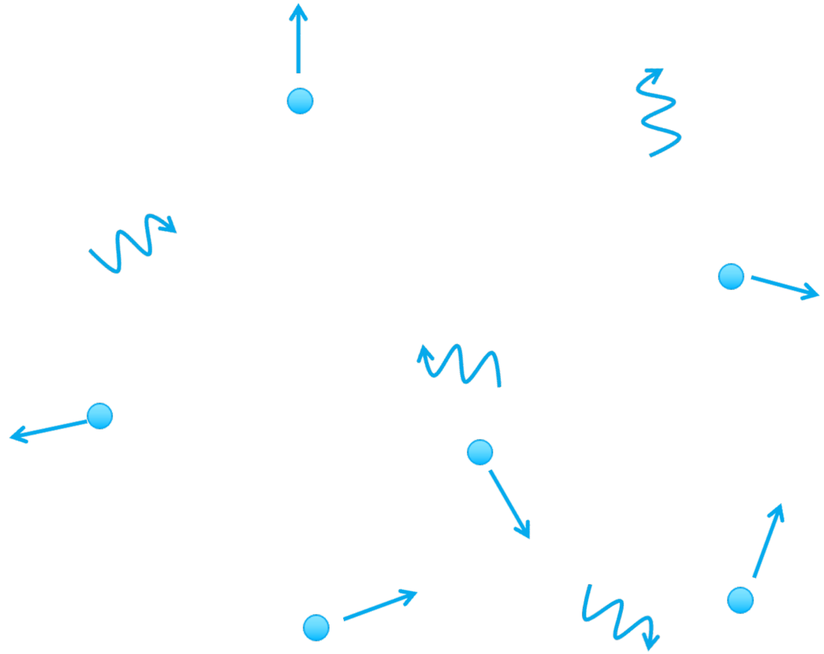


Non-Collisional Gas

<u>Collisional Gas</u>

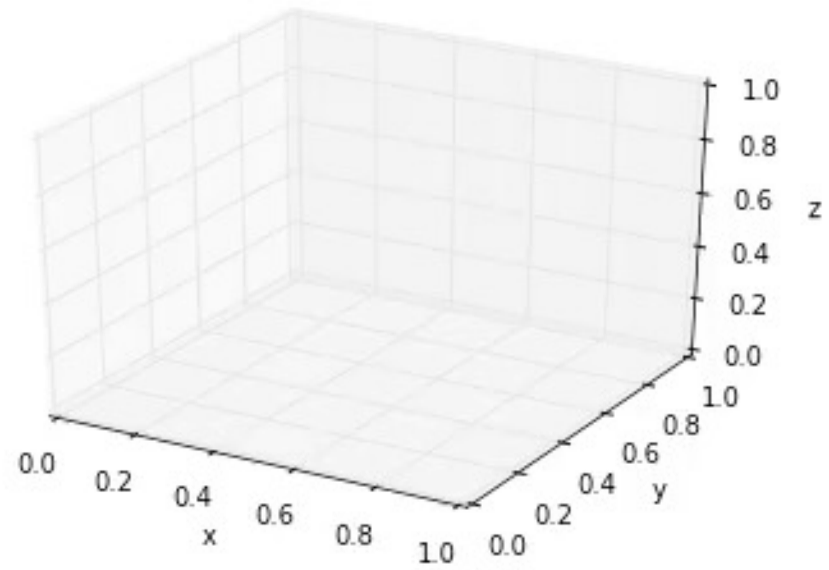


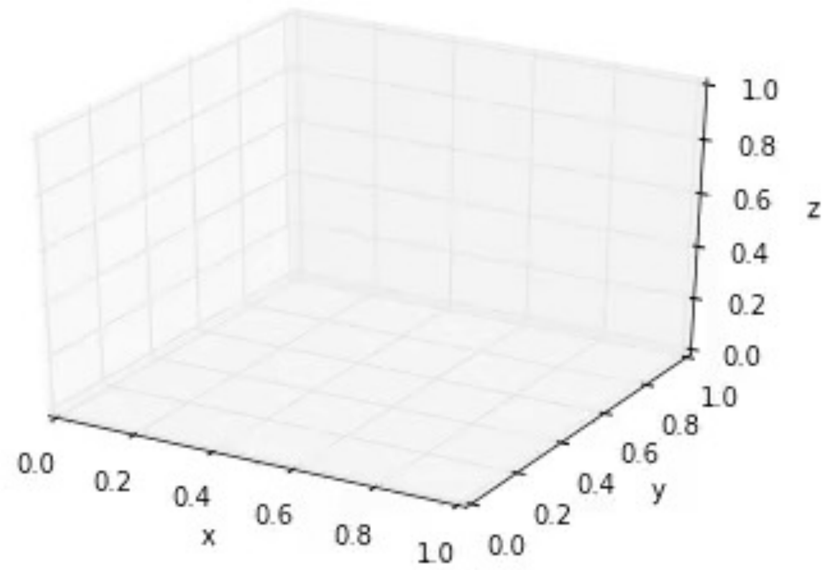
<u>Collisionless Gas</u>



Charged Particles in Magnetic Fields

Note- a lot of what you **may have** studied about charged particle propagation in magnetic fields **likely** assumed magnetic field variation was on much longer length scales than particle Larmor radius.





Cosmic Ray Transport

Cosmic ray propagation in turbulent magnetic fields is chaotic, and can be described by diffusive transport equation

Spatial Transport Equation (Continuity Equation)

$$\frac{\partial \mathbf{f}}{\partial \mathbf{t}} = -\nabla_{\mathbf{x}} \cdot \left[-(\mathbf{D_{xx}} \nabla_{\mathbf{x}} \mathbf{f}) + \mathbf{v f}\right] + \mathbf{Q}$$

Diffusion

Advection

Source term

Collision Time

$$\mathbf{t = \frac{1}{n_e \sigma_T c}}$$

$$\mathbf{\approx \left(\frac{1\ cm^{-3}}{n_e}\right)\ Myr}$$

So objects which live on short timescales (eg. Supernova explosions) don’t have time to thermalize through collisions

Shocks…….a Surprise!

Explosive transient events are therefore a natural place to consider as particle acceleration sites. These sources possess shocks

Collisional Shock- Conservation Conditions

viewed in shock frame

downstream

$(\mathbf{p_2}, \rho_2)$

$\leftarrow \mathbf{v_2}$

upstream

$(\mathbf{p_1}, \rho_1)$

$\leftarrow \mathbf{v_1}$

Number Flux: $\rho_1 \mathbf{v_1} = \rho_2 \mathbf{v_2}$

Momentum Flux: $\mathbf{p_1} + \rho_1 \mathbf{v_1^2} = \mathbf{p_2} + \rho_2 \mathbf{v_2^2}$

Energy Flux: $$\frac{\gamma}{\gamma - 1}\mathbf{p_1}\mathbf{v_1} + \frac{1}{2}\rho_1 \mathbf{v_1^3} = \frac{\gamma}{\gamma - 1}\mathbf{p_2}\mathbf{v_2} + \frac{1}{2}\rho_2 \mathbf{v_2^3}$$

Collisional Shock- Cold Shock Case

Momentum Flux:

$$\rho_1 \mathbf{v_1^2} = \mathbf{p_2} + \rho_2 \mathbf{v_2^2}$$

$$\frac{\mathbf{p_2}}{\rho_1 \mathbf{v_1^2}} = \left(1 - \frac{\mathbf{v_2}}{\mathbf{v_1}}\right)$$

Energy Flux:

$$\frac{1}{2}\rho_1 \mathbf{v_1^3} = \left(\frac{\gamma}{\gamma - 1}\right) \mathbf{p_2 v_2} + \frac{1}{2}\rho_2 \mathbf{v_2^3}$$

$$\frac{2\gamma}{\gamma - 1} \frac{\mathbf{p_2 v_2}}{\rho_1 \mathbf{v_1^3}} = \left(1 - \left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^2\right) = \left(1 - \frac{\mathbf{v_2}}{\mathbf{v_1}}\right)\left(1 + \frac{\mathbf{v_2}}{\mathbf{v_1}}\right)$$

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(\mathbf{1}-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-\mathbf{1}}{\mathbf{2}\gamma}\right)\left(\mathbf{1}-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^{\mathbf{2}}\right)$$

Why not have a go at solving this

Collisional Shock- Cold Shock Case

$$\frac{\mathbf{v_2}}{\mathbf{v_1}}\left(\mathbf{1}-\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)=\left(\frac{\gamma-\mathbf{1}}{\mathbf{2}\gamma}\right)\left(\mathbf{1}-\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}\right)^{\mathbf{2}}\right)$$

$$\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\mathbf{1}\right)\left(\frac{\mathbf{v_2}}{\mathbf{v_1}}-\left(\frac{\gamma-\mathbf{1}}{\gamma+\mathbf{1}}\right)\right)=\mathbf{0}$$

So what are collisional shocks good for?
Stimulating the unstimulated degrees of freedom in the system where energy can be stored

Collisional Shock- Partition of Momentum and Energy

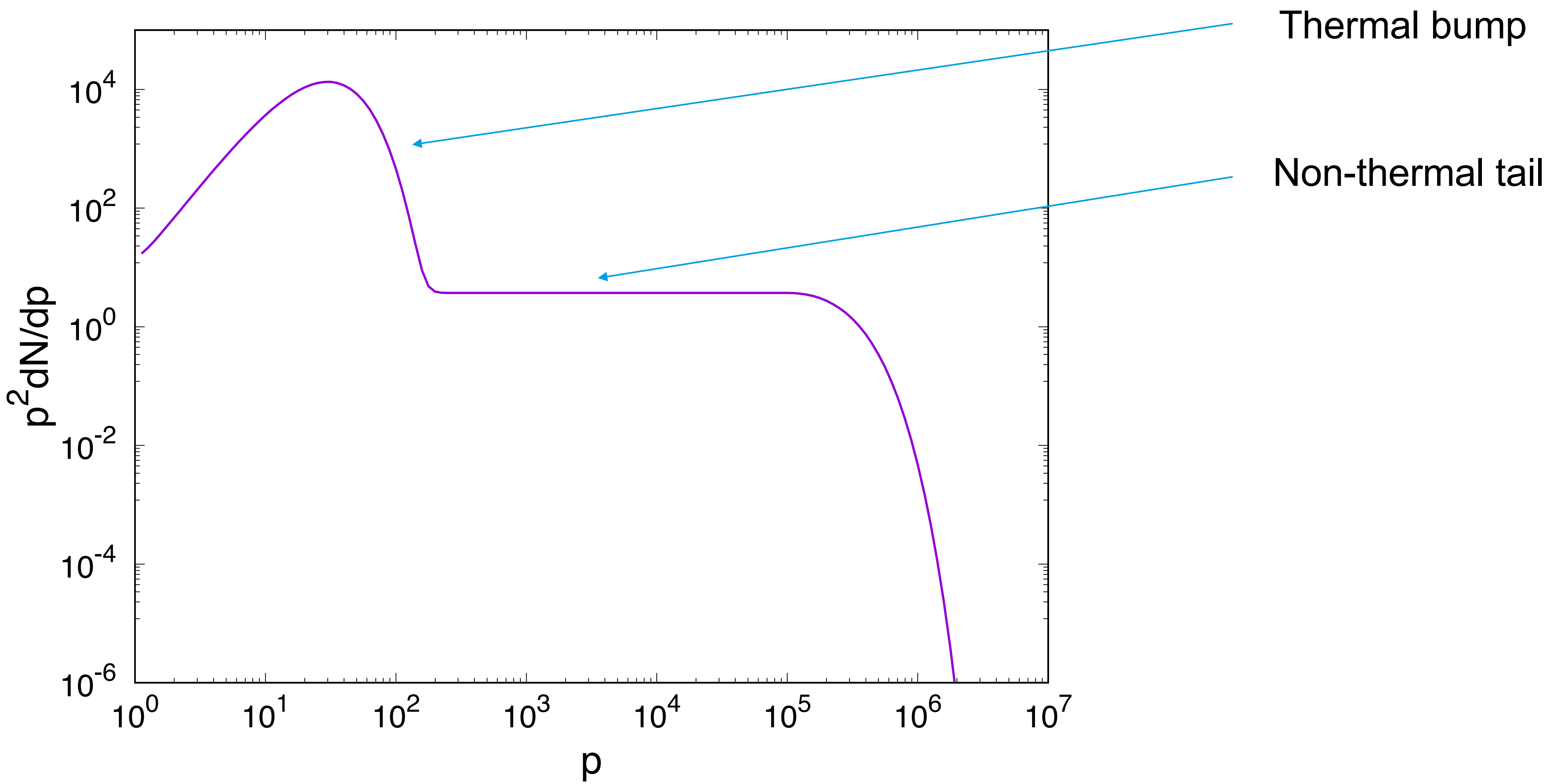
Downstream Momentum Partition:

$$\mathbf{p_2} = \frac{\mathbf{3}}{\mathbf{4}}\rho_{\mathbf{1}}\mathbf{v_1^2}$$

Downstream Energy Partition:

$$\frac{\gamma}{\gamma - \mathbf{1}}\mathbf{p_2 v_2} = \frac{\mathbf{15}}{\mathbf{16}}\left[\frac{\mathbf{1}}{\mathbf{2}}\rho_{\mathbf{1}}\mathbf{v_1^3}\right]$$

Collisionless Shock Can Give Rise to Non-Thermal Tail



Sources of Cosmic Rays

What are they?

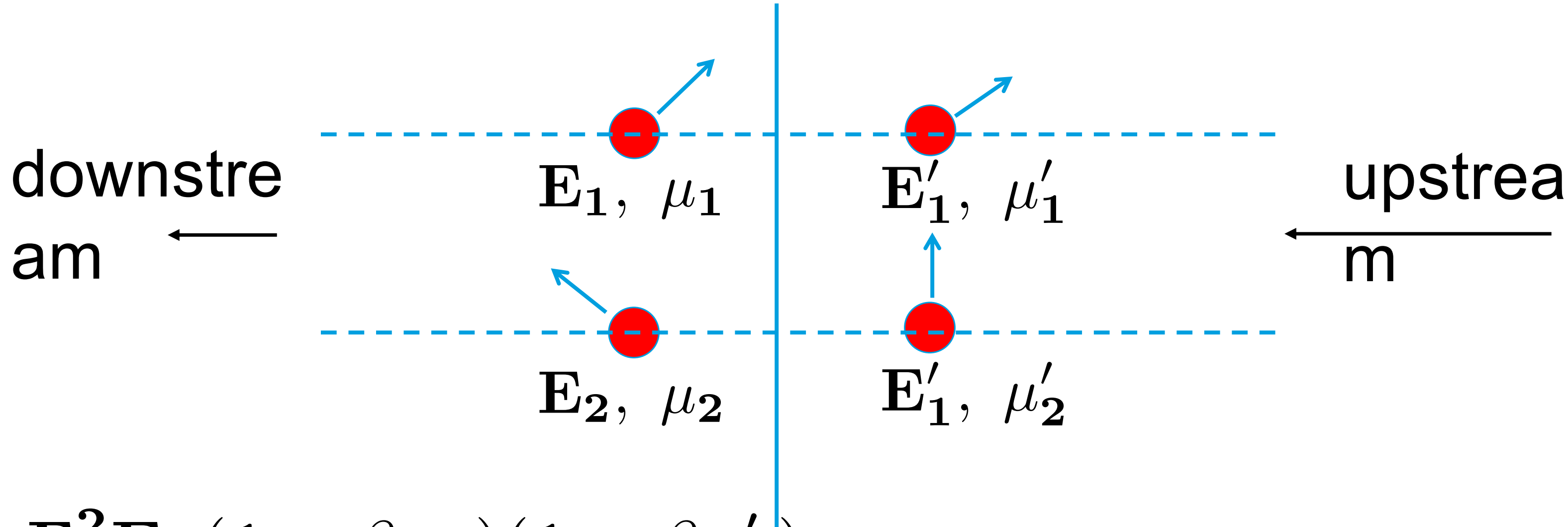
Is it a single source? A single source class?

Where are they? Galactic / extragalactic?

How?

acceleration mechanism, feedback on environment, …

Particle Acceleration at Collisionless Shocks



$$\mathbf{E_2} = \mathbf{\Gamma^2 E_1}(\mathbf{1} - \beta\mu_\mathbf{1})(\mathbf{1} + \beta\mu'_\mathbf{2})$$

$$\mu' = \frac{\mu - \beta}{\mathbf{1} - \beta\mu}$$

$$\mathbf{E_2} = \mathbf{\Gamma^2 E_1}(\mathbf{1} - \beta\mu_\mathbf{1})\left(\mathbf{1} + \beta\left(\frac{\mu_\mathbf{2} - \beta}{\mathbf{1} - \beta\mu_\mathbf{2}}\right)\right)$$

$$\mathbf{E_2} = \mathbf{E_1}\left(\frac{\mathbf{1} + \beta\mu_\mathbf{1}}{\mathbf{1} + \beta\mu_\mathbf{2}}\right)$$

Fermi Shock Acceleration

Energy

$$\frac{\Delta E}{E} = \frac{4v}{3c} = \frac{4}{3}\beta \text{ (energy gain)}$$

$$E_1 = \left(1 + \frac{4}{3}\beta\right) E_0$$

$$E_n = \left(1 + \frac{4}{3}\beta\right)^n E_0$$

Number

$$\frac{\Delta N}{N} = -\frac{4v}{3c} = -\frac{4}{3}\beta \text{ (advection downstream)}$$

$$N_1 = \left(1 - \frac{4}{3}\beta\right) N_0$$

$$N_n = \left(1 - \frac{4}{3}\beta\right)^n N_0$$

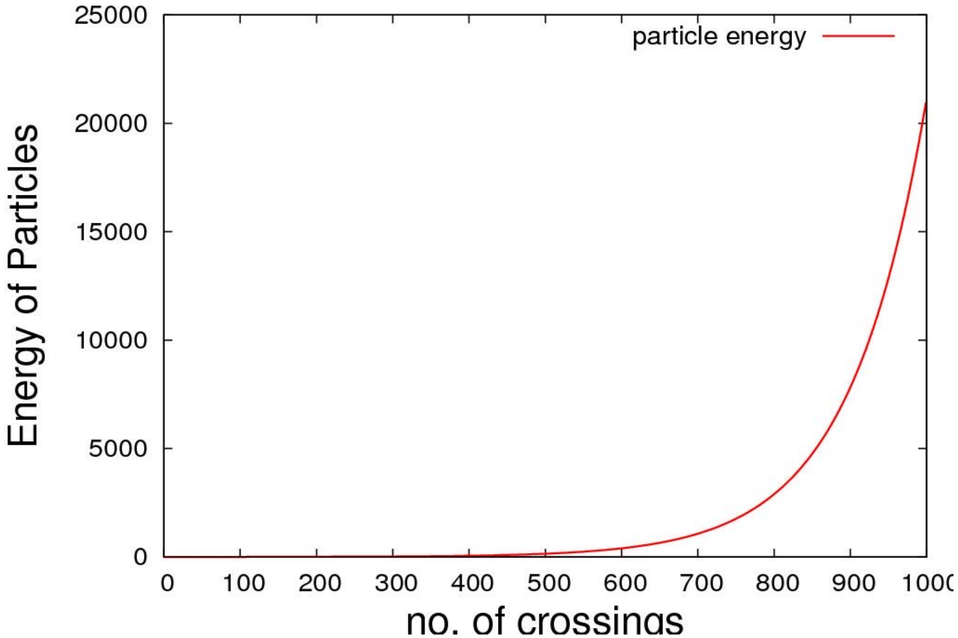
So $n \sim 1/\beta$ crossings are needed before the particle population is significantly altered → SNRs have $v_{sh} \sim 10^3$ km s^{-1} so $\beta \sim 10^{-2}$

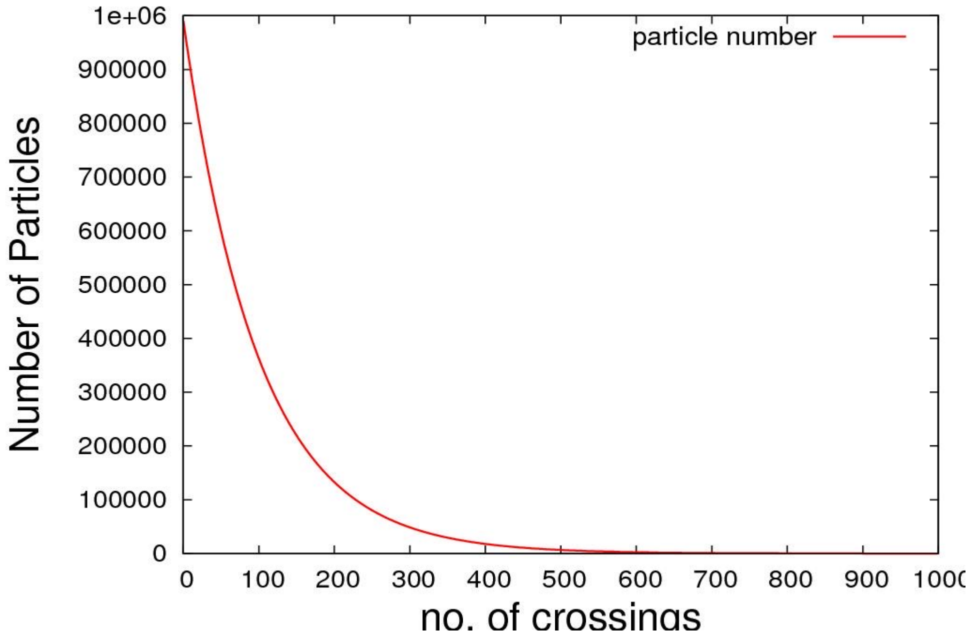
Fermi Shock Acceleration

Energy

Number

$\beta \sim 10^{-2}$





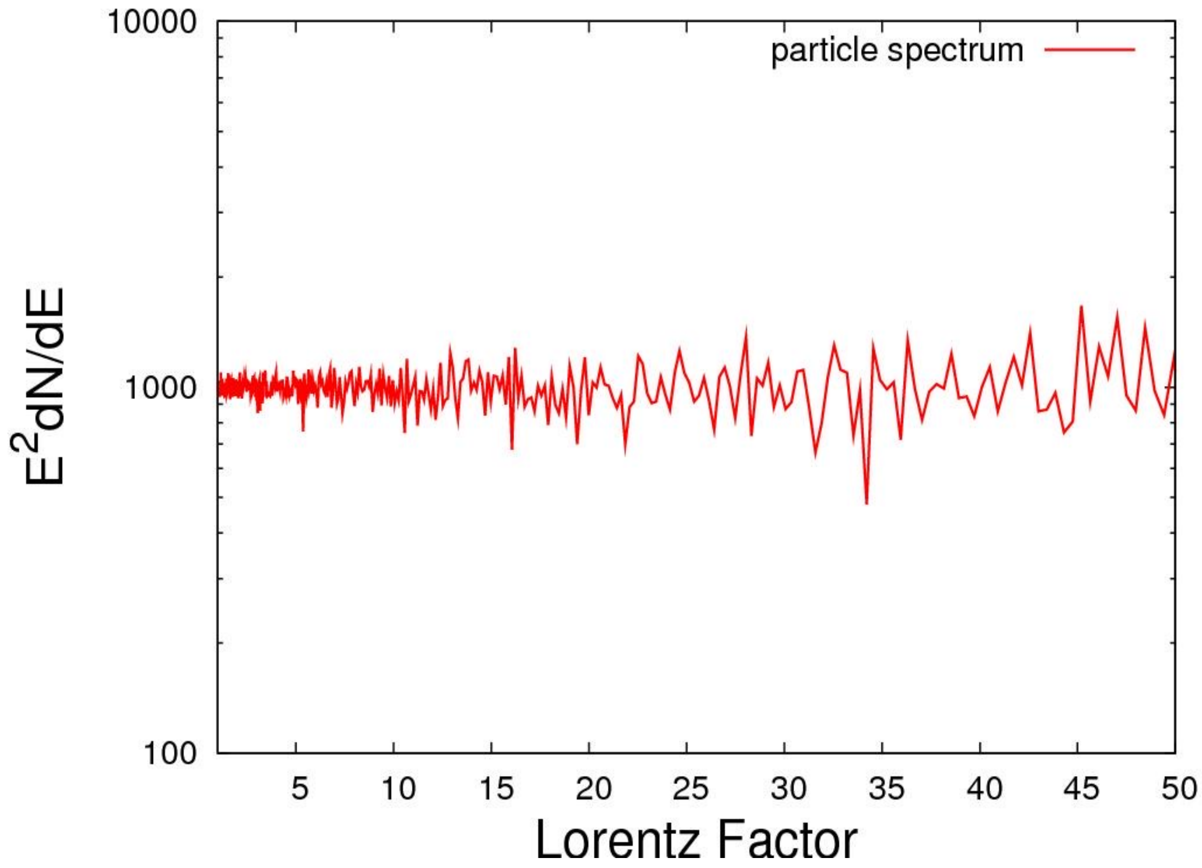
Fermi Shock Acceleration

So,

$$\frac{\Delta N}{\Delta E} = \frac{N_0}{E_0}\left(\frac{1-4\beta/3}{1+4\beta/3}\right)^{n}$$

$$\approx \frac{N_0}{E_0}\left(1+4\beta/3\right)^{-2n}$$

$$\approx N_0 E_0 E^{-2}$$



The flat spectrum, with $dN/dE \sim E^{-2}$, is produced when the acceleration time and the escape time are equal (and have the same energy dependence)

Fermi (First Order) Acceleration Time

$$\mathbf{t_{acc} = E\frac{\Delta t_{cycle}}{\Delta E_{cycle}}}$$

Transport of particles in each region is dictated by competition between diffusion and advection

downstream

upstream

$$\mathbf{t_{diff} = \frac{R^2}{D_{xx}}}$$

$$\mathbf{t_{adv} = \frac{R}{v_{adv}}}$$

Balancing these timescales

$$\mathbf{t_{resid} = \frac{D_{xx}}{(c\beta_{sh})^2}}$$

Fermi (First Order) Acceleration Time

$$\mathbf{t_{acc} = E\frac{\Delta t_{cycle}}{\Delta E_{cycle}}}$$

$$\mathbf{t_{resid} = \frac{D_{xx}}{(c\beta_{sh})^2}}$$

However, during the time it takes advection to dominate over diffusion, the particle will have crossed the shock $1/\beta$ times

$$\mathbf{\Delta t_{cycle} = \frac{D_{xx}}{(c^2\beta_{sh})}}$$

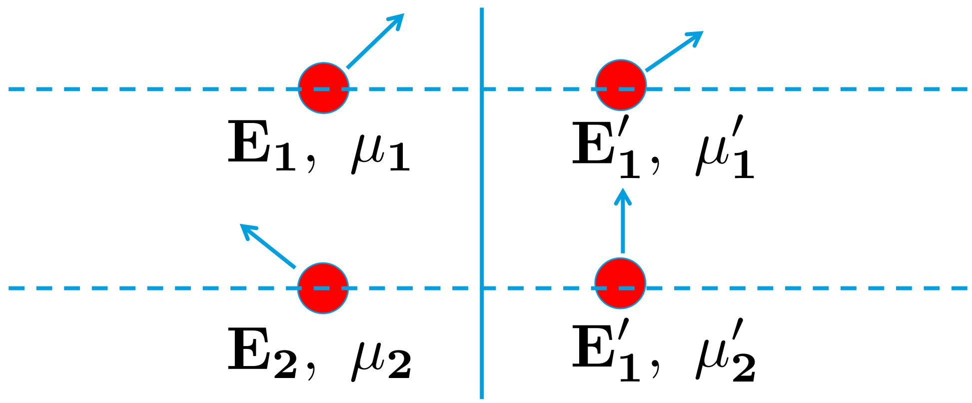
Fermi (First Order) Acceleration Time

$$\mathbf{t_{acc} = E\frac{\Delta t_{cycle}}{\Delta E_{cycle}}}$$

$$\mathbf{\Delta t_{cycle} = \frac{D_{xx}}{(c^2\beta_{sh})}}$$

$$\mathbf{\Delta E_{cycle} = E\beta_{sh}}$$

$$\mathbf{t_{acc} = \frac{D_{xx}}{(c\beta_{sh})^2} = \frac{t_{scat}}{\beta_{sh}^2}}$$



$$\mathbf{E_2 = E_1\left(\frac{1+\beta\mu_1}{1+\beta\mu_2}\right)}$$

Particle Acceleration Limit

$$\mathbf{t_{acc}} = \frac{\mathbf{R_{lar}}}{\mathbf{c}\beta^{\mathbf{2}}}$$

$$\mathbf{t_{esc.}} = \frac{\mathbf{R^2}}{\mathbf{cR_{lar}}}$$

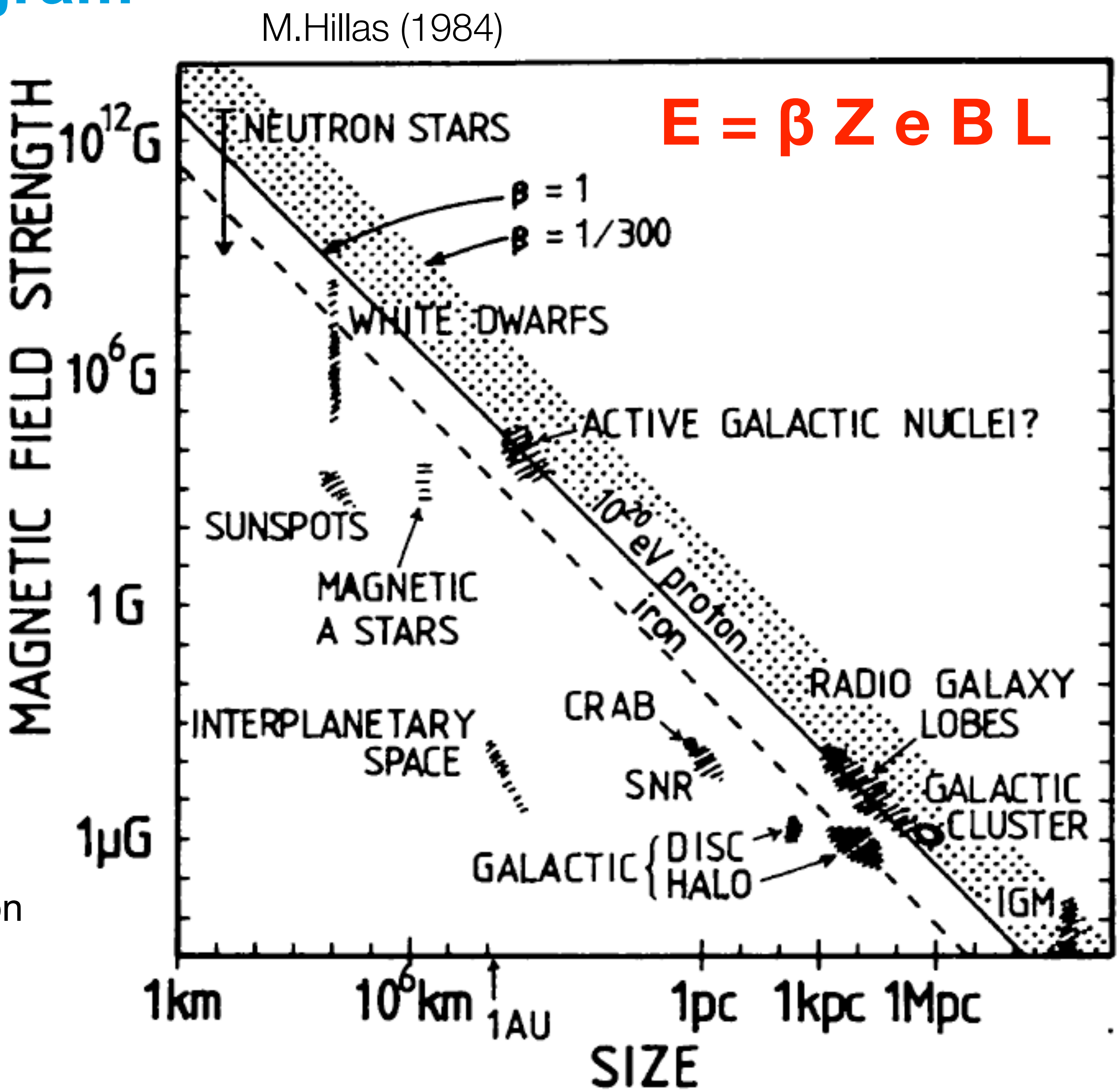
Maximum energy
(Hillas criterion)

$$\mathbf{R_{lar}} = \beta\mathbf{R}$$

AM Hillas (1984)

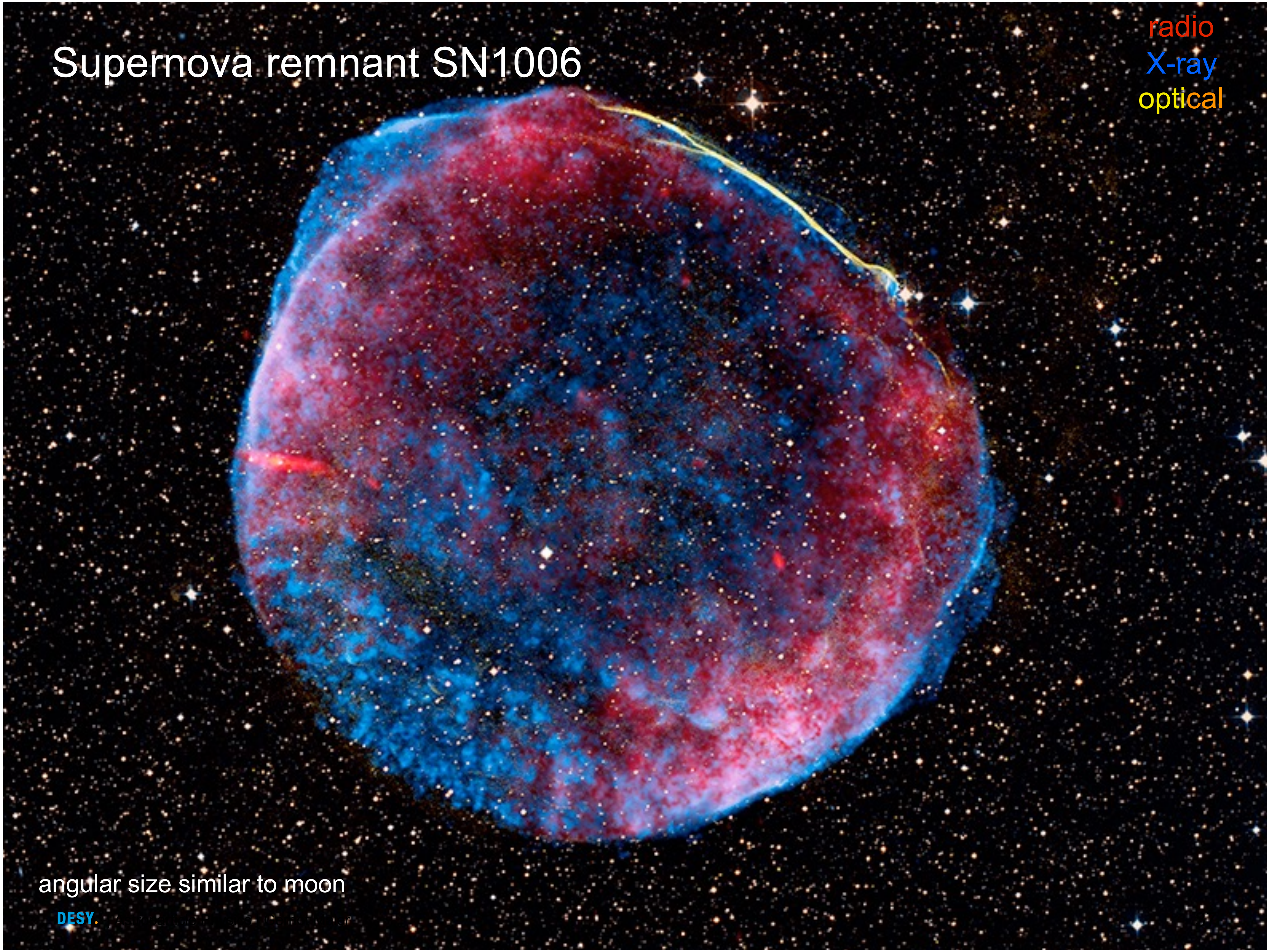
Maximum energy of an accelerator

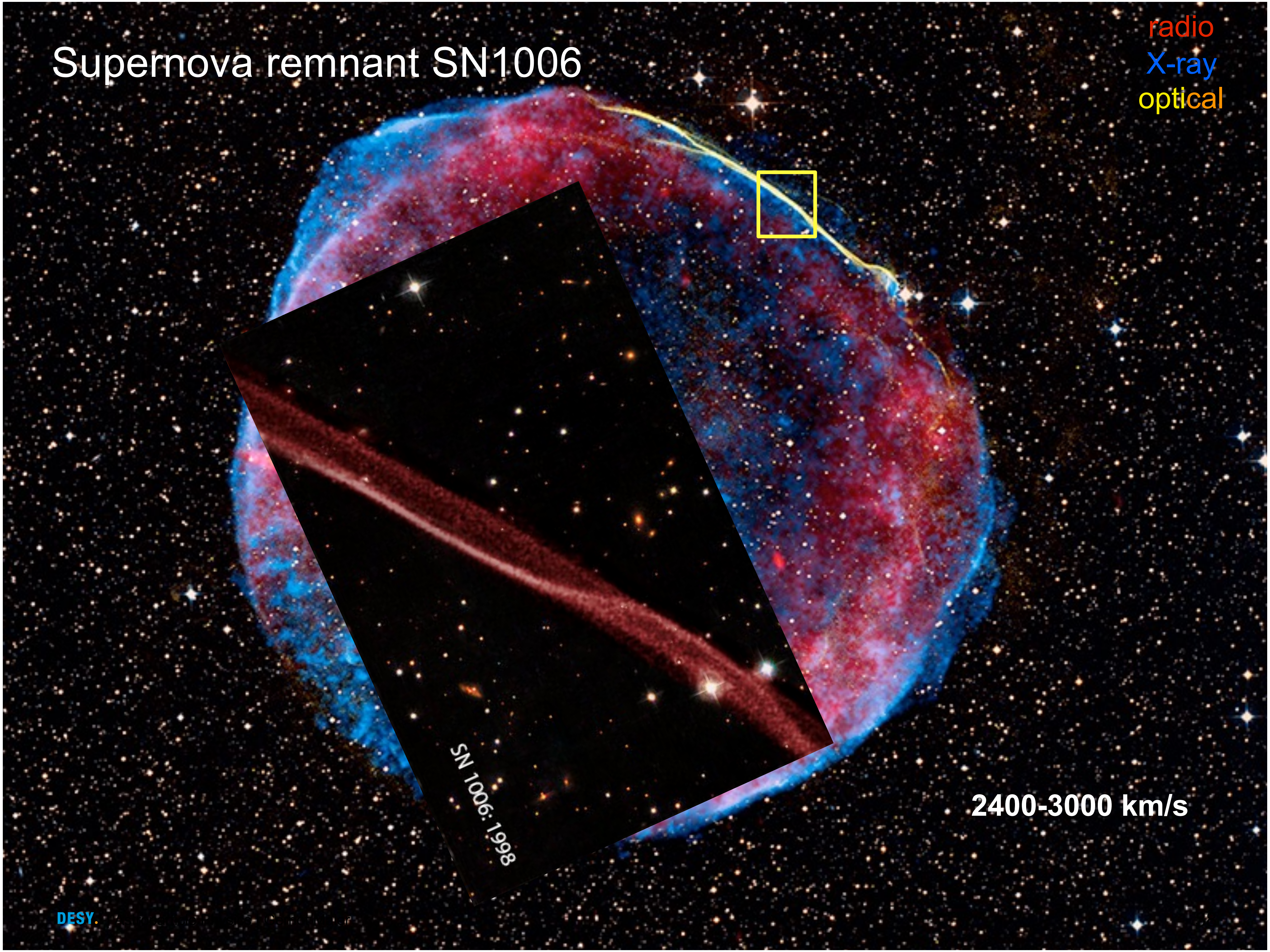
Hillas Diagram



Energy limited by:

- B-field
- time for acceleration
- energy losses


Supernova remnant SN1006
radio
X-ray
optical
angular size similar to moon


Supernova remnant SN1006
radio
X-ray
optical
SN 1006: 1998
2400-3000 km/s
DESY.

Supernovae Explosions & Energy Budget

assume Milky Way is filled uniformly with Cosmic Rays (CR), diffuse out diffuse out of this volume in typically $t_{GD} \approx 10^7$y

CR energy density: $\rho_E \approx 0.5$ eV/cm^3 (similar to starlight)

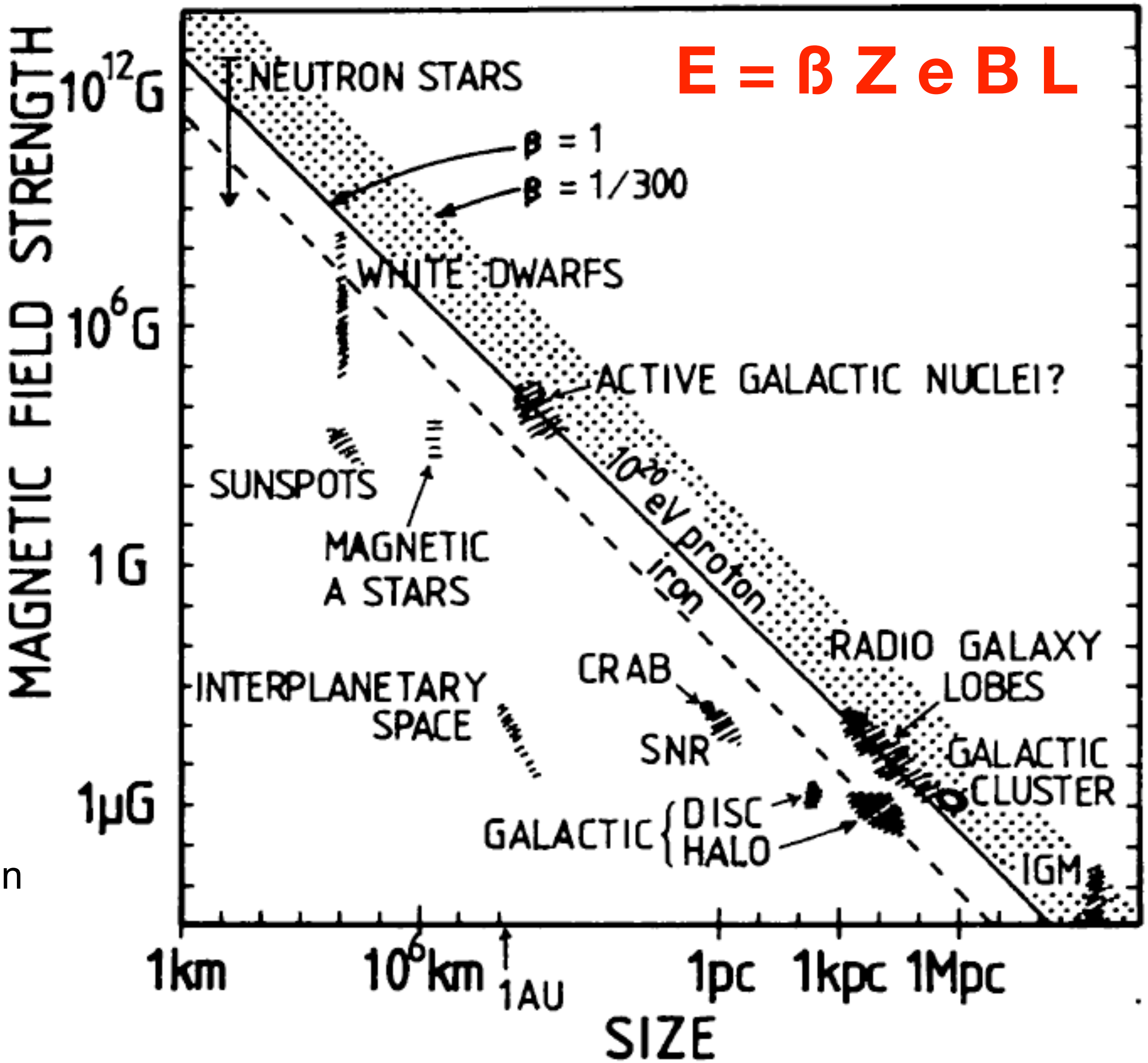
$$L_{CR} = \frac{V_{GD} \cdot \rho_E}{t_G D} \simeq 3 \times 10^{40} \mathrm{erg/s}$$

typical 2-3 Supernovae per 100 y in our Galaxy are enough to sustain this luminosity assuming a 10% conversion rate from mechanical to cosmic-ray energy

Conclusion: supernovae provide sufficient energy budget to power the cosmic ray population we see in the Milky Way Galaxy

Hillas Diagram

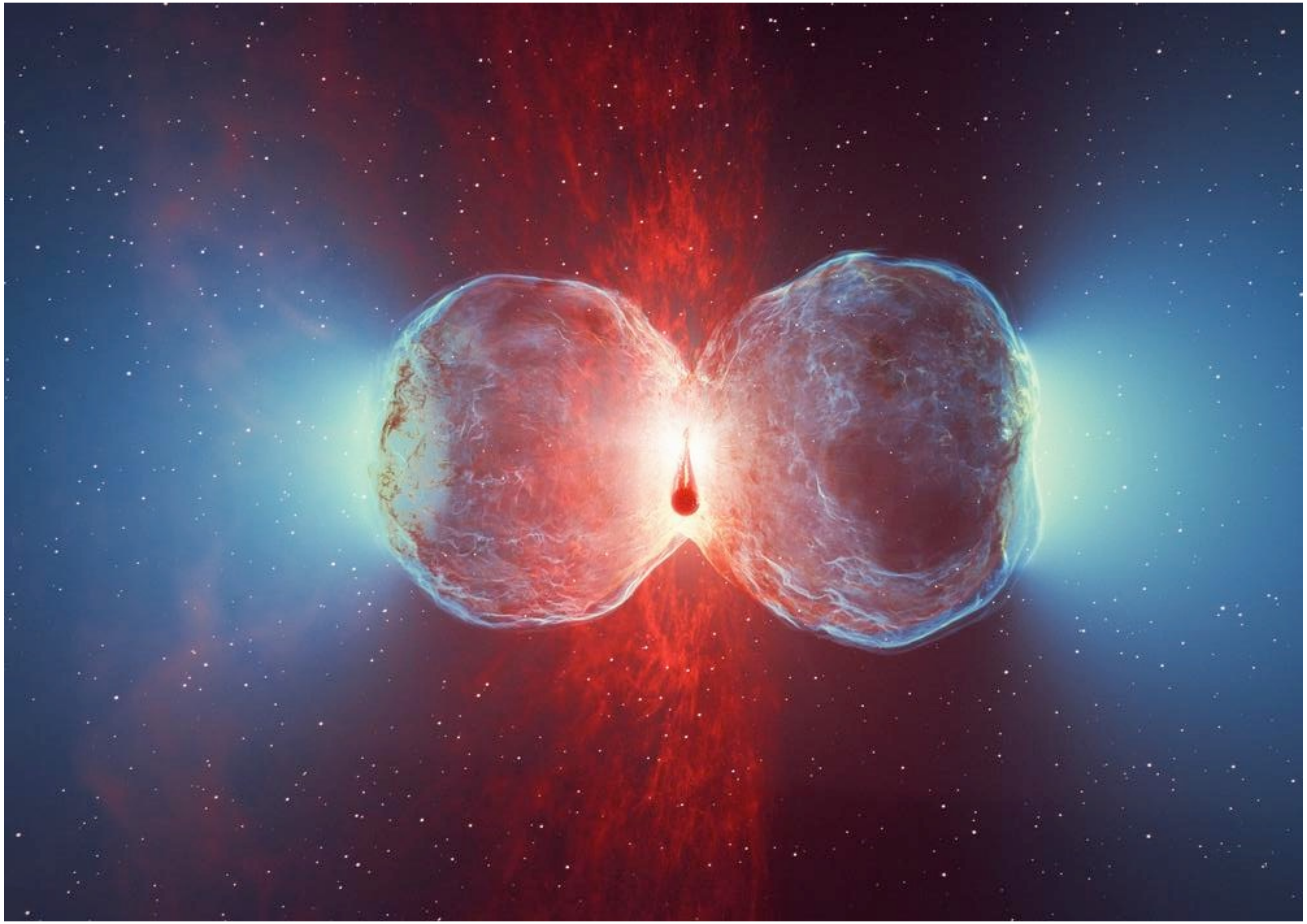
M.Hillas (1984)



Energy limited by:

- B-field
- time for acceleration
- energy losses

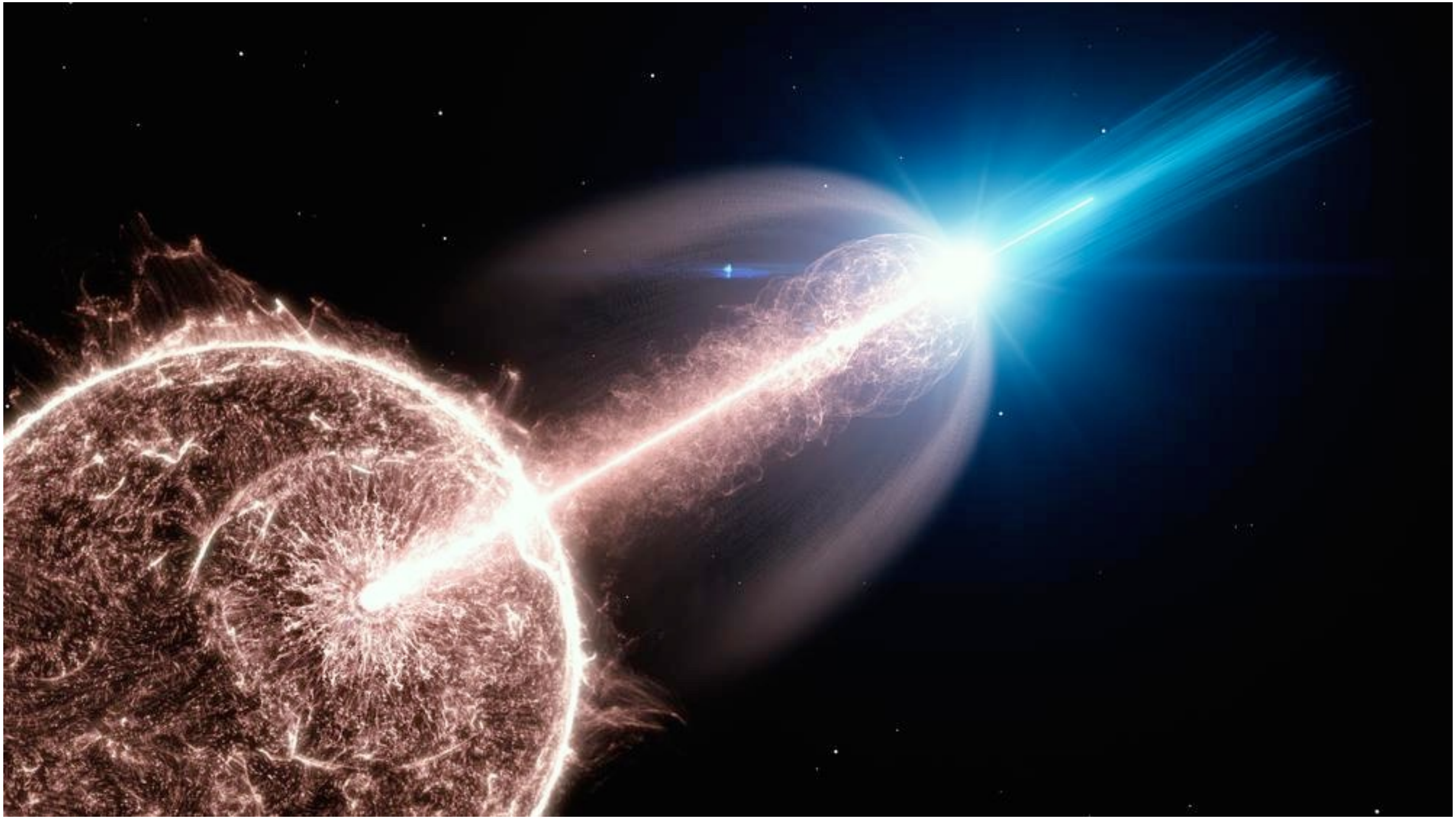
Nova



DESY, Science Communication Lab

Microquasars

Gamma-ray bursts



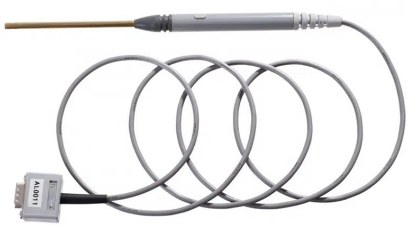
DESY, Science Communication Lab

Tidal Disruption Events

DESY, Science Communication Lab

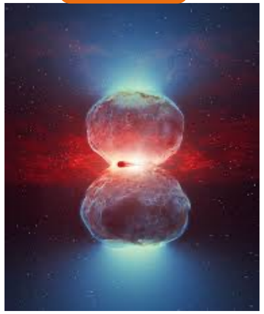
Probing the Accelerator Environment

Hall Probe



$$E_{max} < 2\,\mathrm{PeV}\left(\frac{L}{10^{38}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{\beta}{0.1}\frac{\eta_B}{0.1}\right)^{1/2}$$

Nova



Microquasar

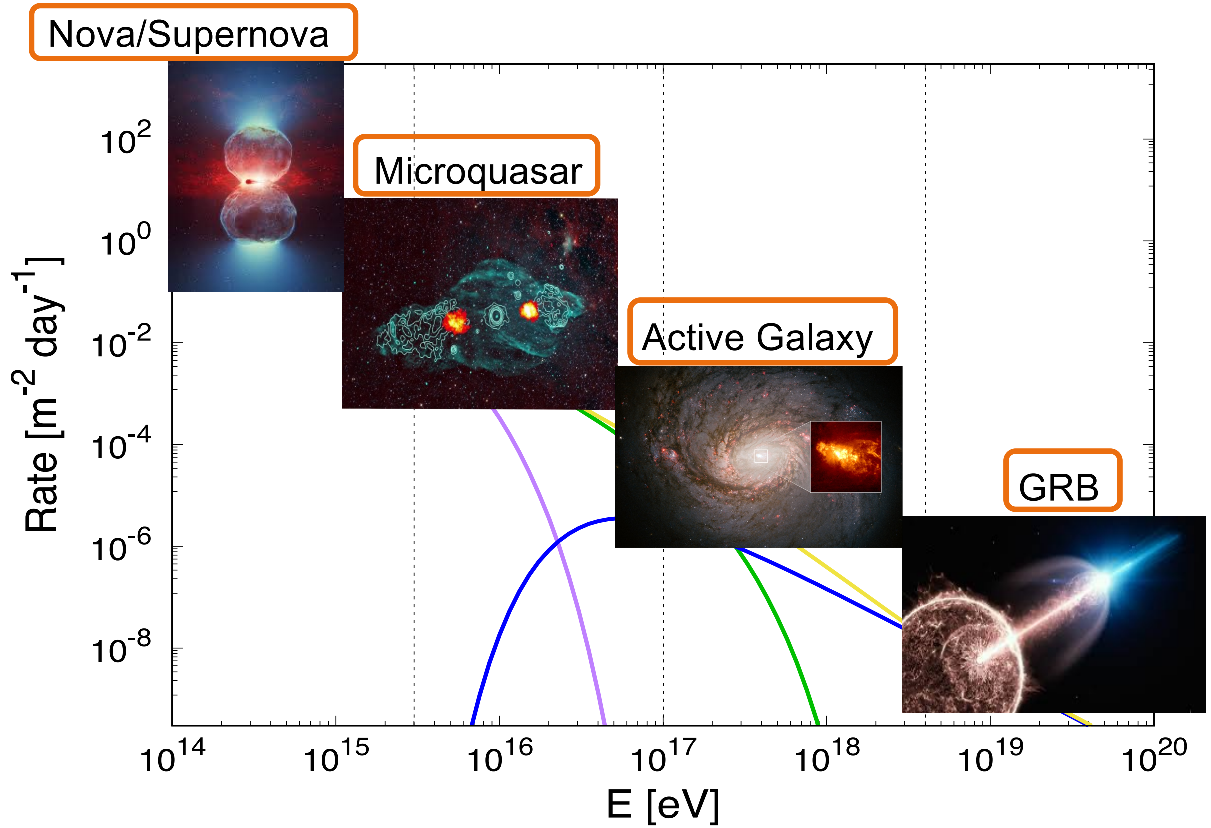
Active Galaxy

GRB

Maximum Energy

The Impact of these Results

- How the gamma and neutrino results are transforming the field

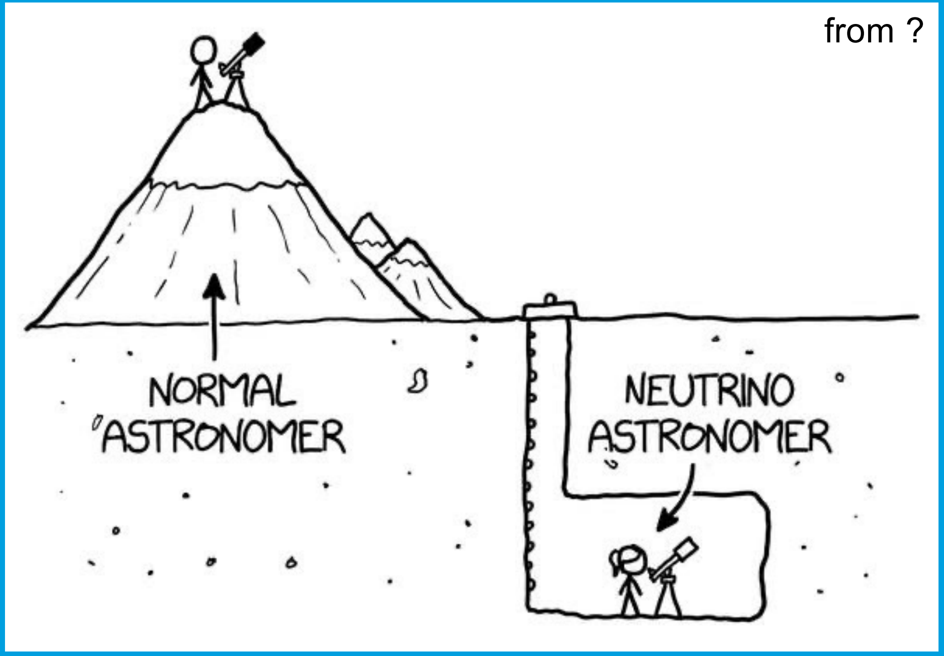


*The **tapestry** of candidate sources, at different cosmic ray energies, **is now richer***

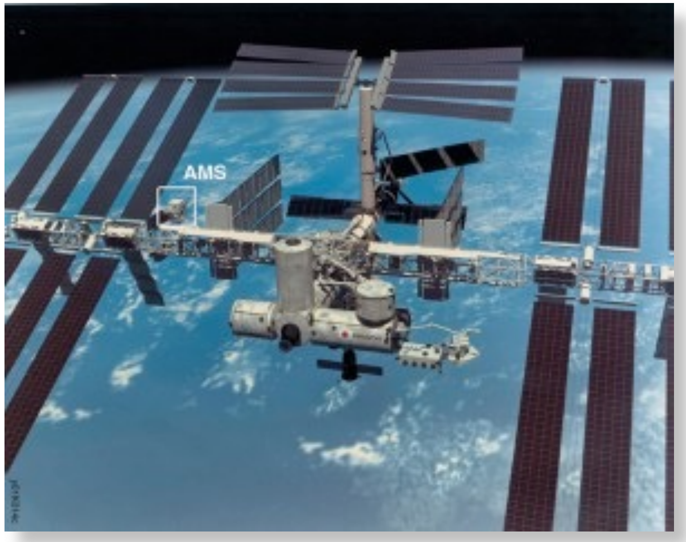
Instruments

How to detect cosmic rays,

gamma rays, neutrinos, …



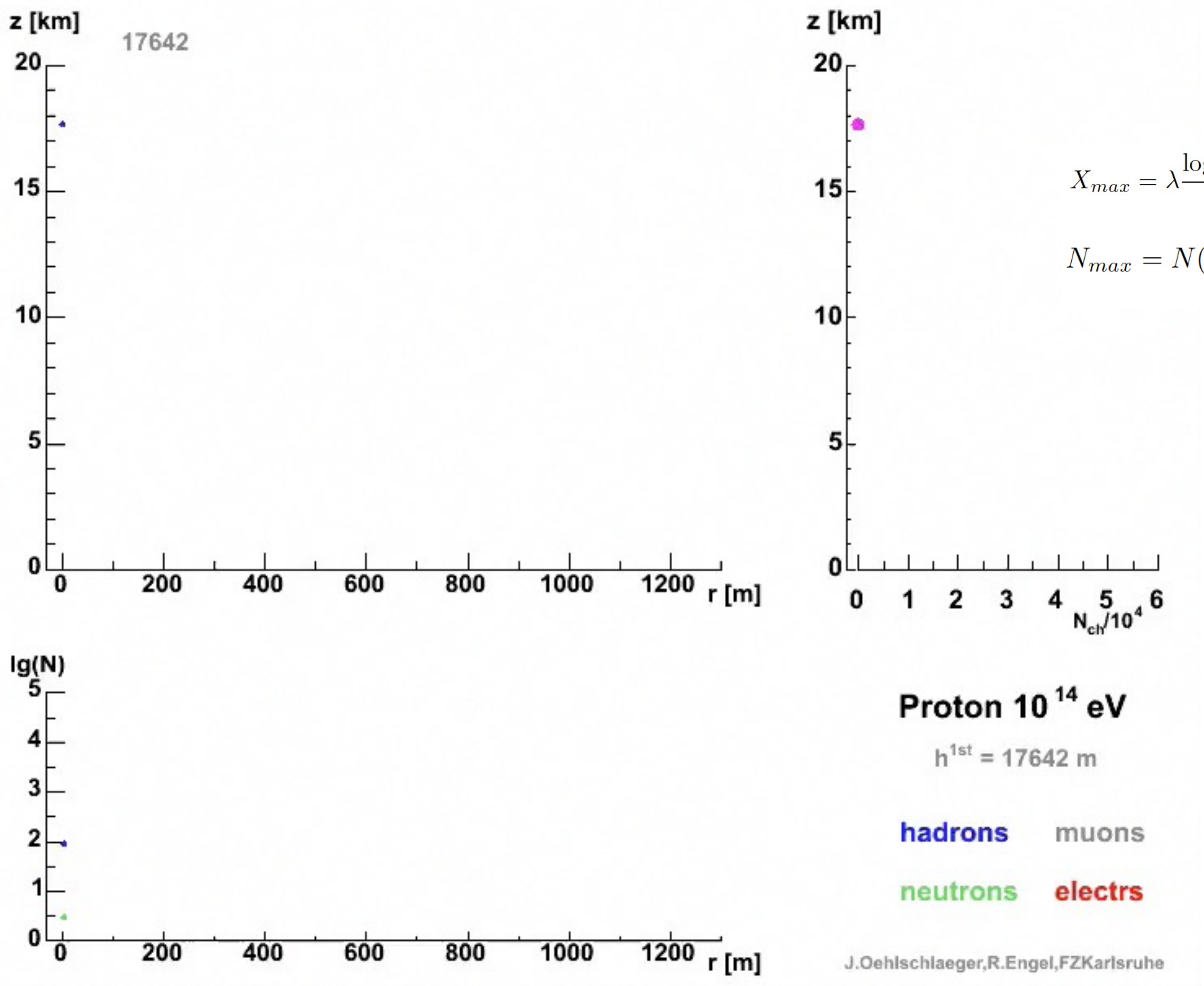
Effective Area of Instrument



AMS on the ISS has a 1 m^2 effective area…..so a large flux is needed for a reasonable detection rate to be achieved. Possible for low energy cosmic rays, but the high energy cosmic ray flux is too small

Instead, the Earth's atmosphere itself can be used as part of the particle detector (providing a transparent target material). For ground-based gamma-ray telescopes, this allows an effective area of 10^5 m^2 to be achieved!

Extensive Air Shower



$$X_{max} = \lambda \frac{\log(E_0/E_C)}{\log 2} \propto \log(E_0)$$

$$N_{max} = N(X_{max}) = \frac{E_0}{E_C} \propto E_0$$

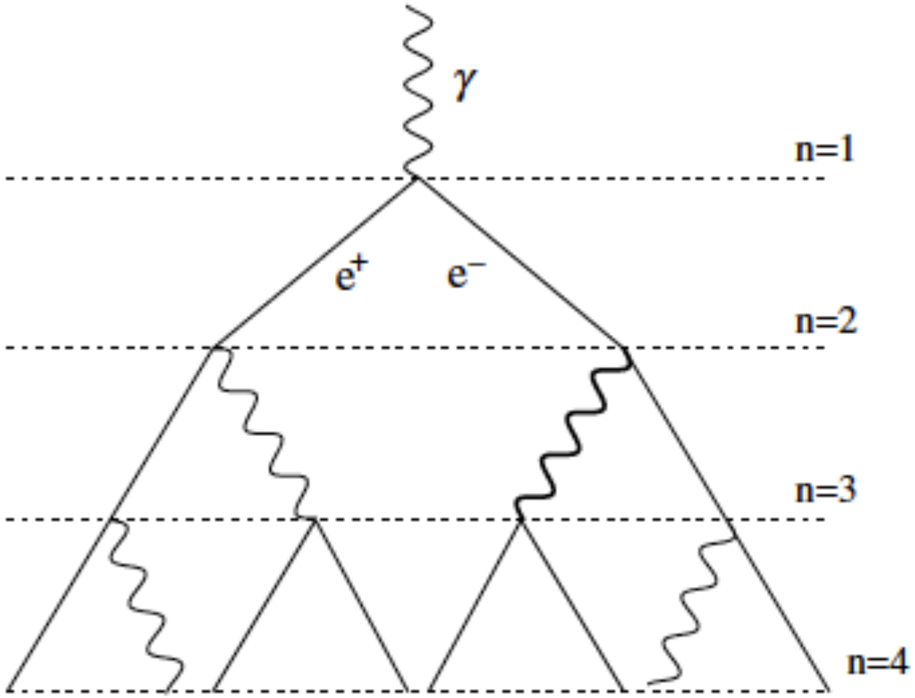
Extensive Air Shower: toy model for particle cascades

$$N(X) = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{N(X)}$$

$$N_{max} = N(X_{max}) = \frac{E_0}{E_C} \propto E_0$$

$$X_{max} = \lambda \frac{\log(E_0/E_C)}{\log 2} \propto \log(E_0)$$

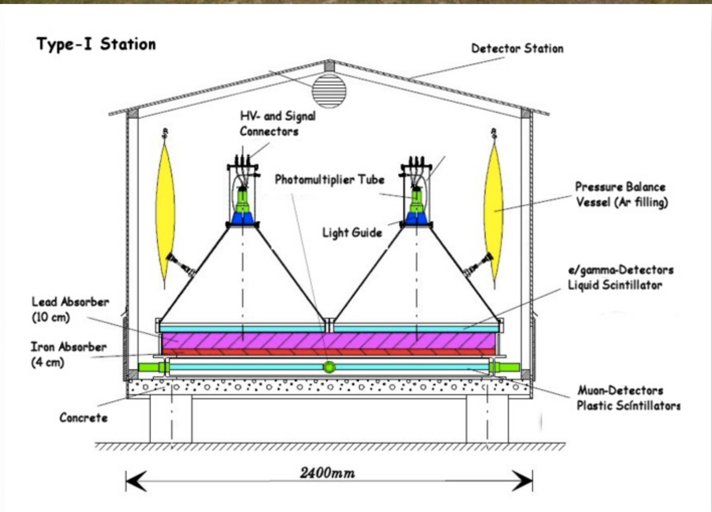


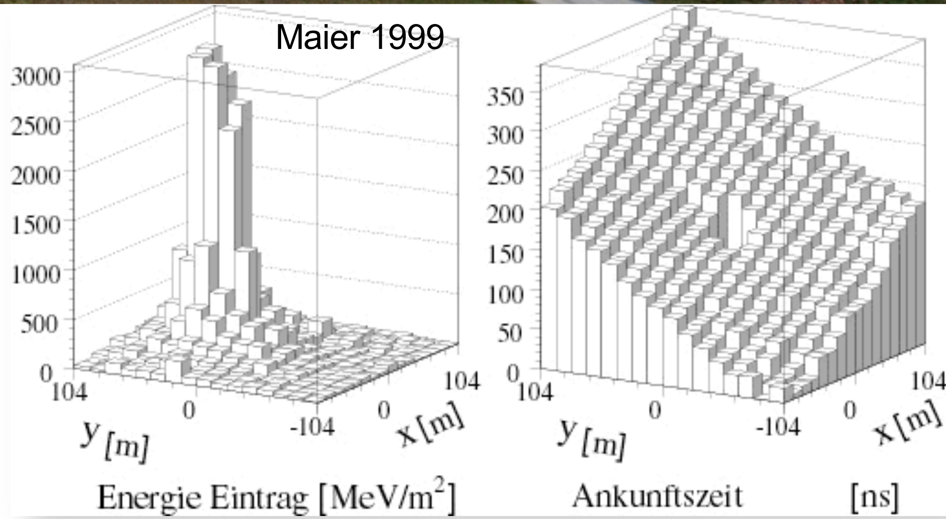
Heitler Model

here: primary particle is a photon
(similar: hadronic showers)

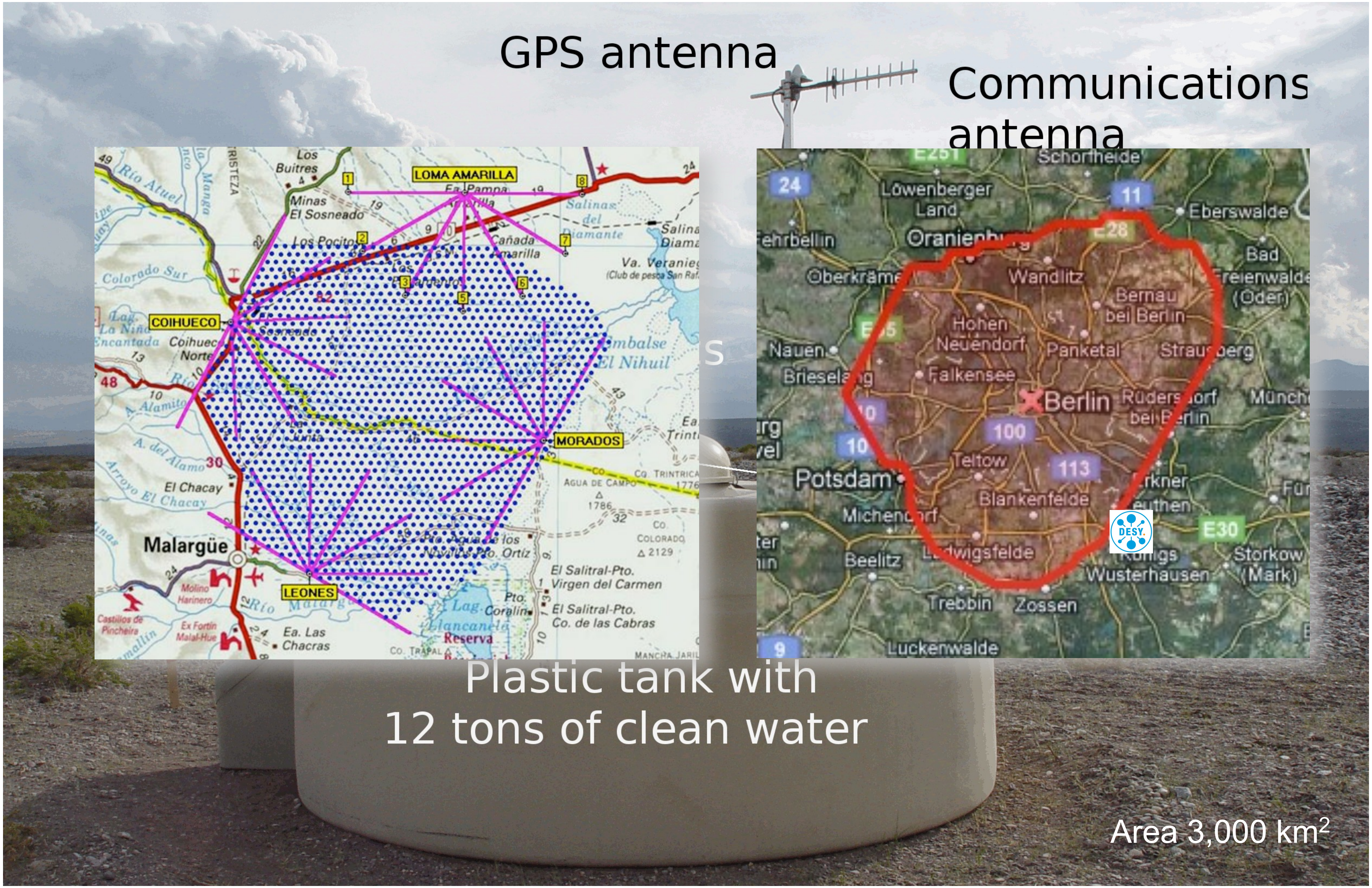
- Measure
  - particles reaching ground
  - superluminal particles create Cherenkov light
  - high-energy electrons excite nitrogen (fluorescence light)

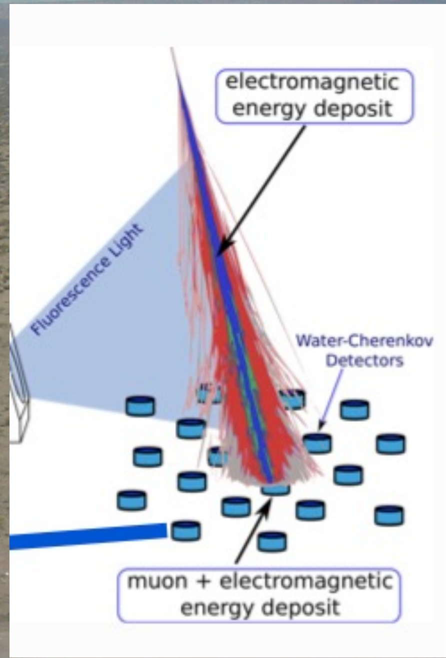
KASCADE
Karlsruhe Shower Core and Array Detector





The Pierre Auger Observatory

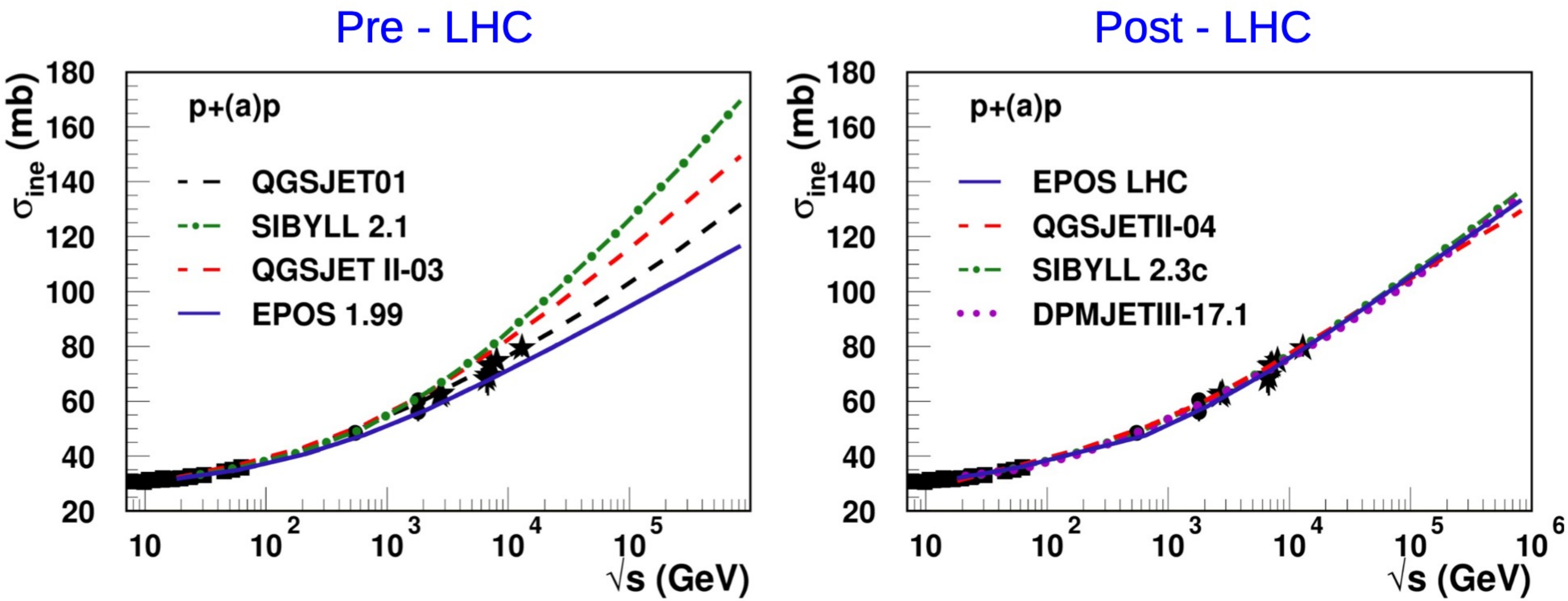




electrons excite N_2
decay to ground state by
isotropically emitting UV photons
~380nm

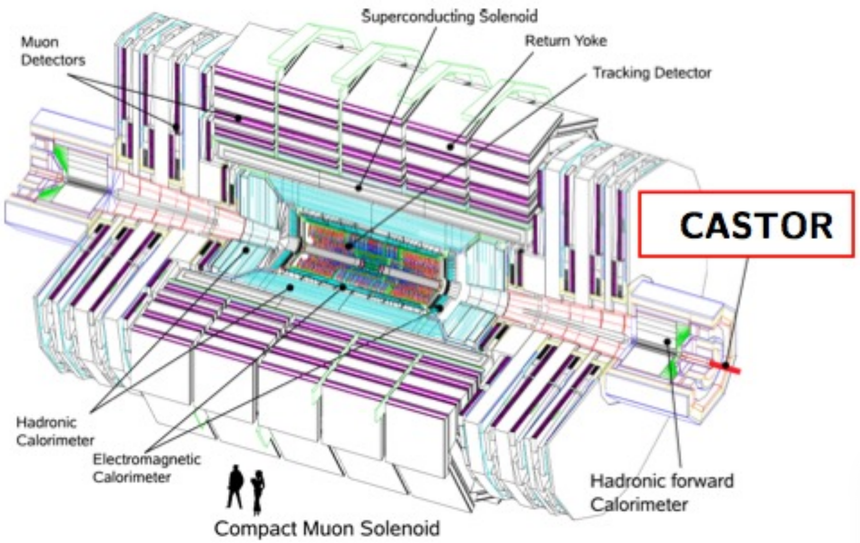
Extensive air shower: hadronic interactions

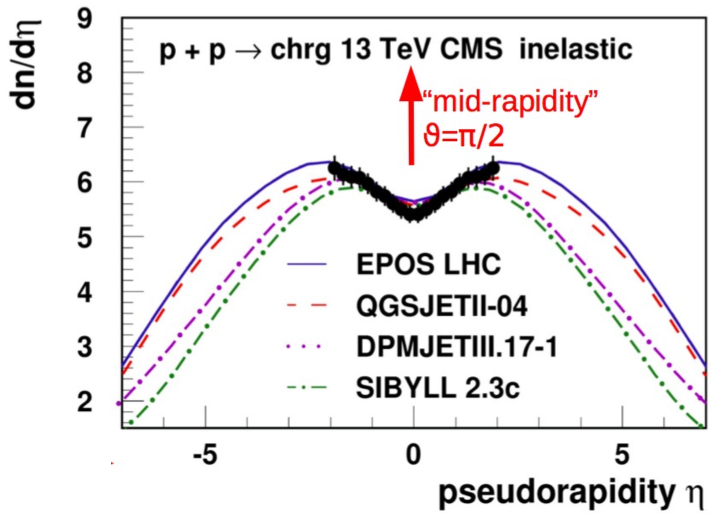
understanding of extensive air showers relies on extrapolations of several orders of magnitude using models of the hadronic interaction

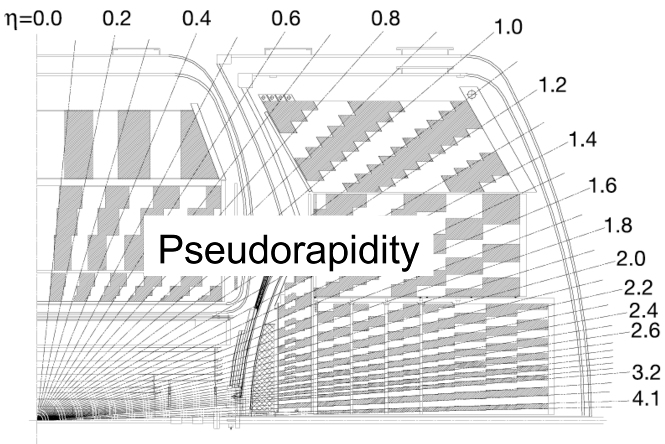


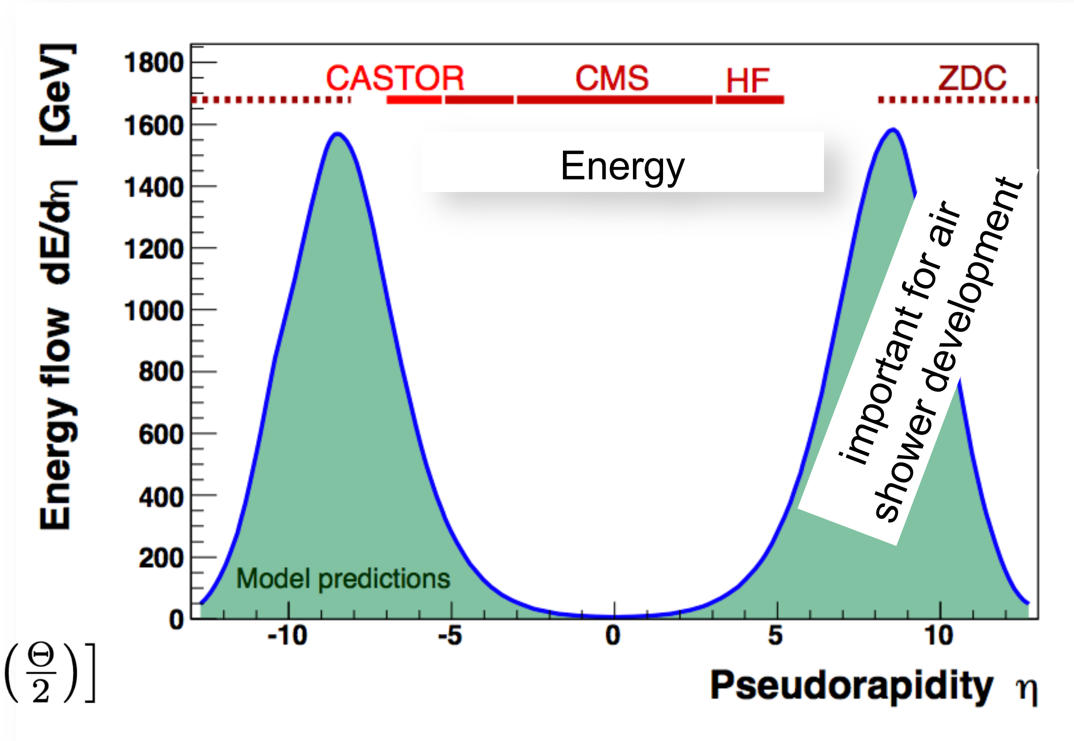
Pierog 2017

Forward Direction



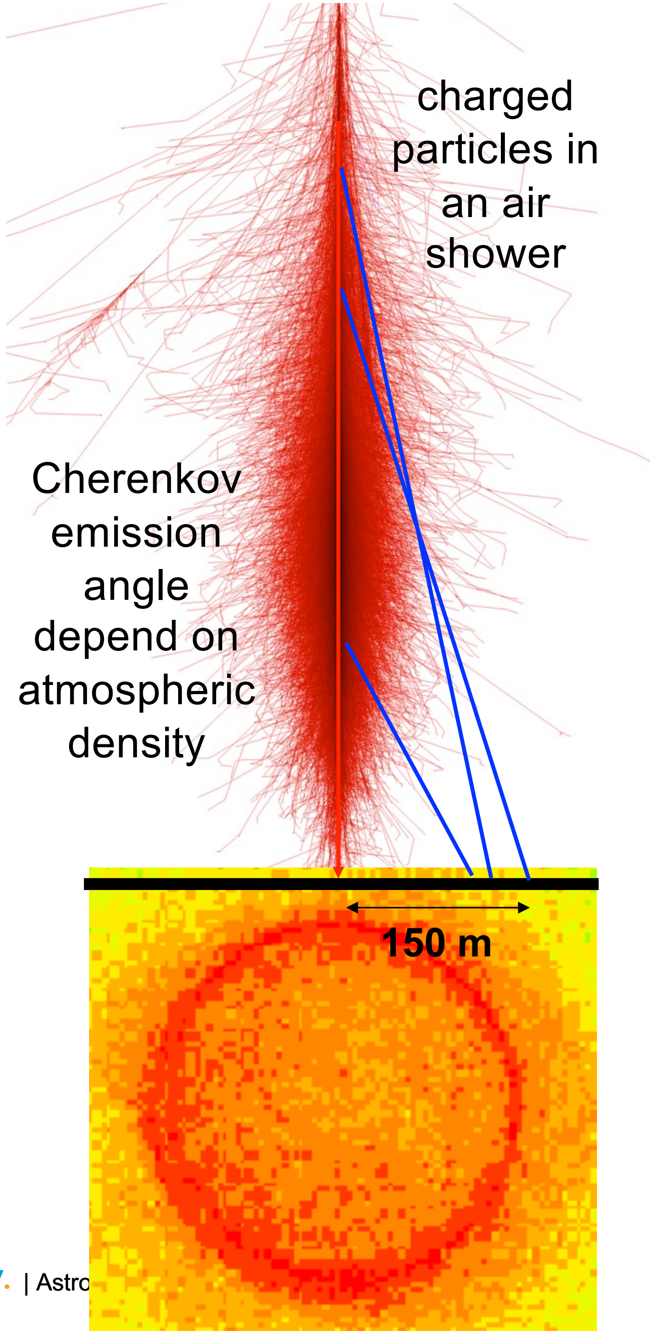


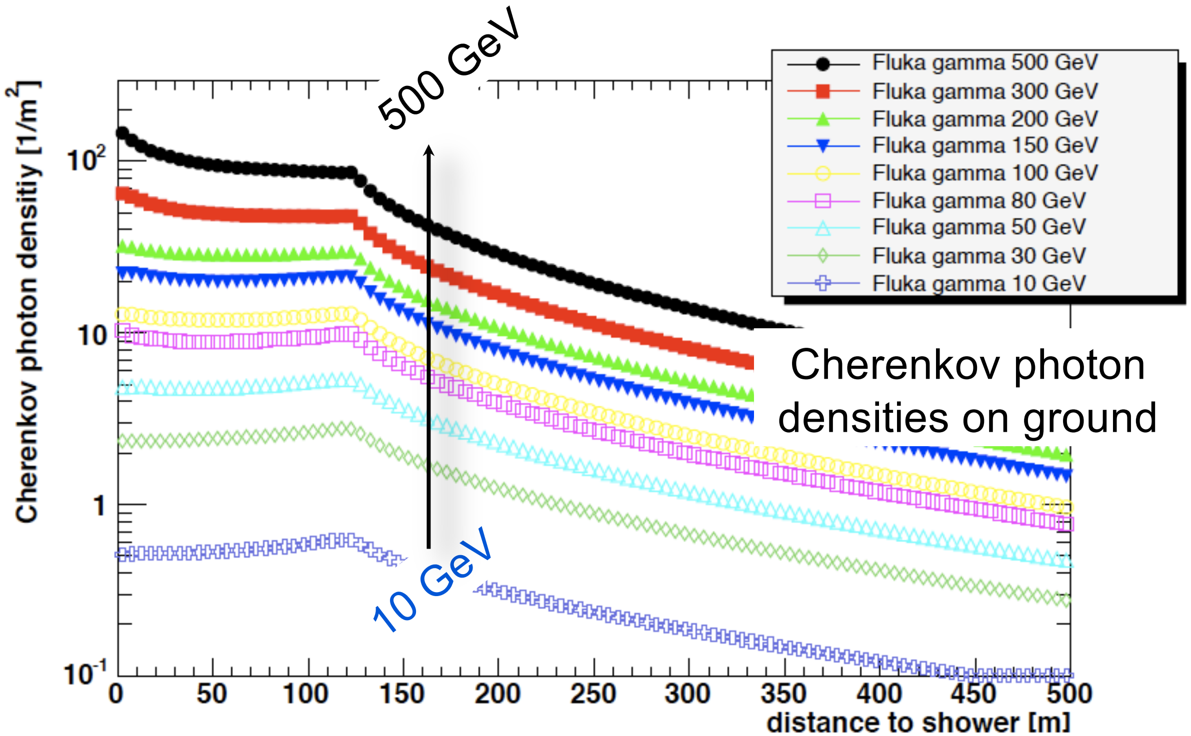




pseudorapidity: $\eta = -\ln\left[\tan\left(\frac{\Theta}{2}\right)\right]$

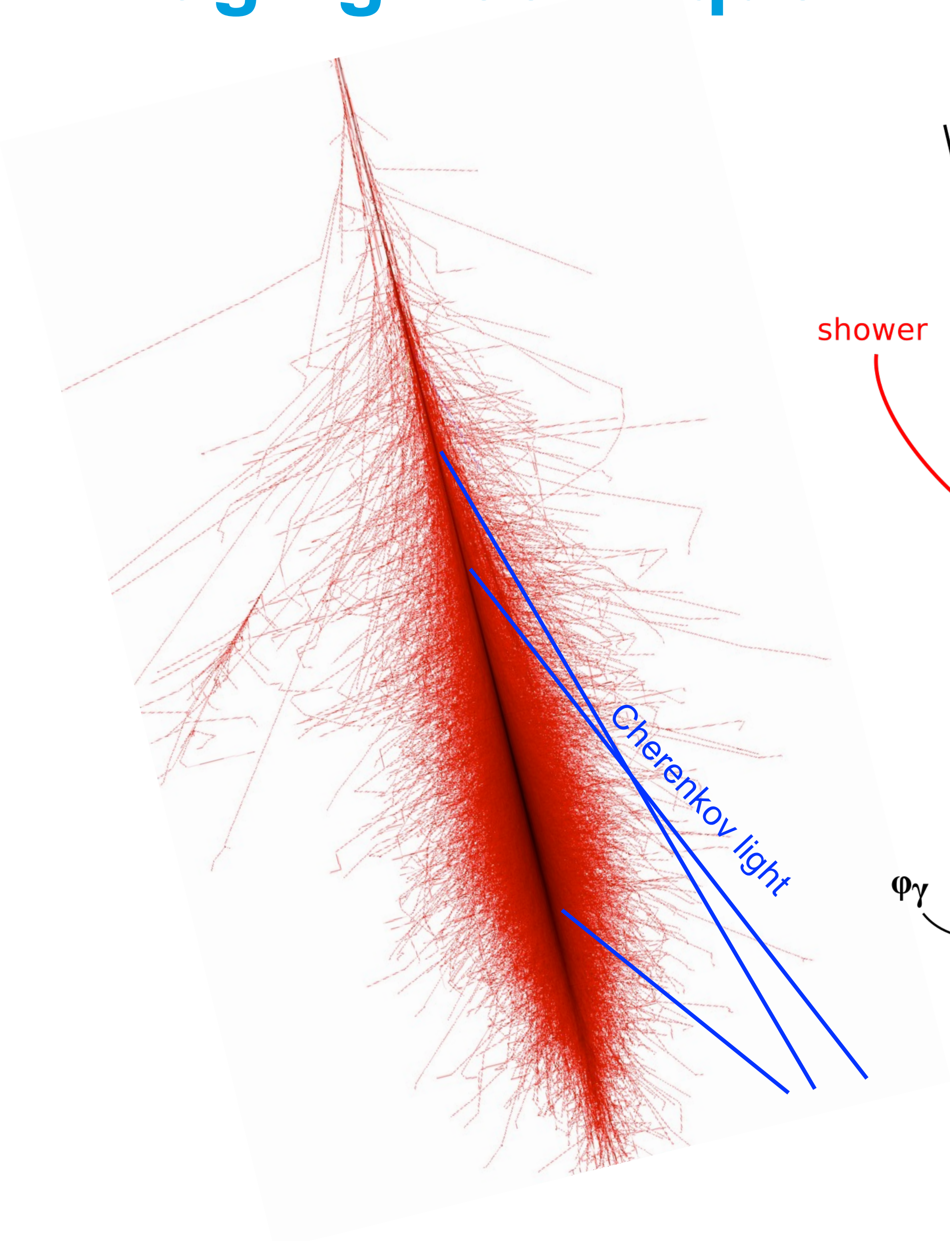
Extensive Air Showers and Cherenkov Emission

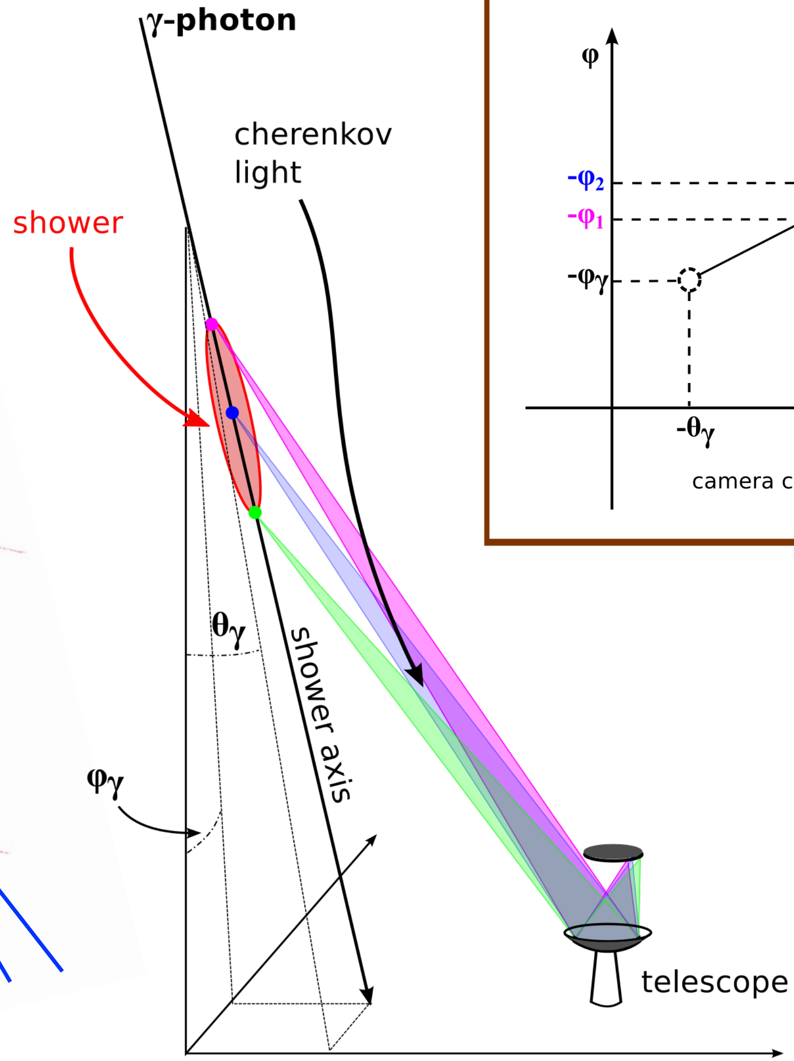


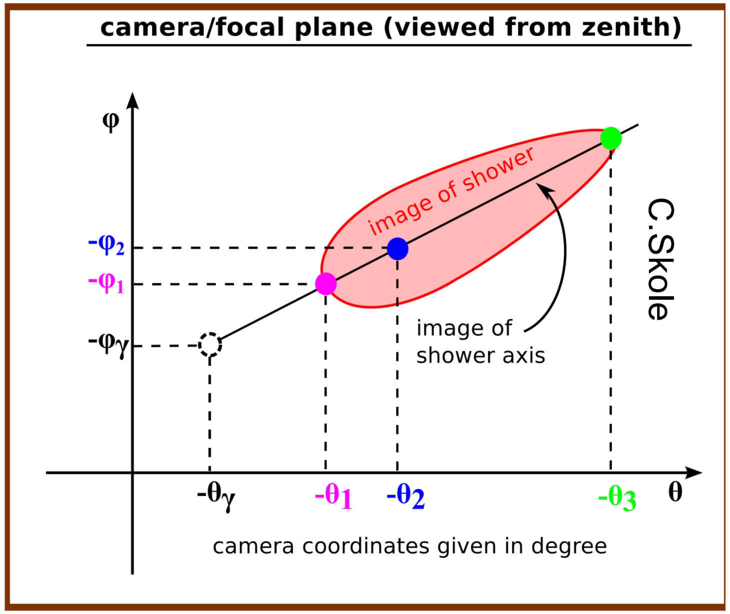


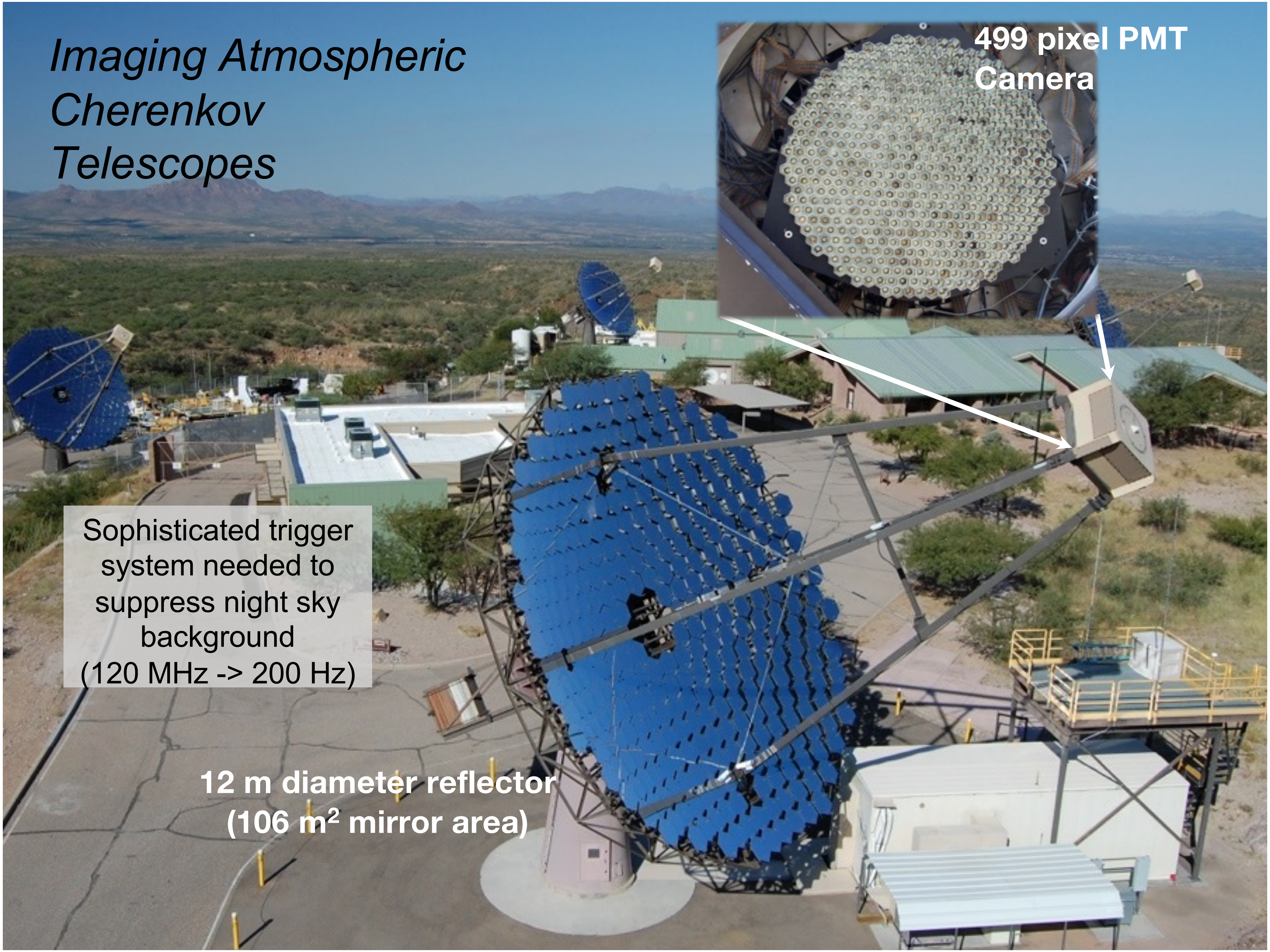
Cherenkov light from air showers: weak (~10 ph/m^2), short (~ns), blue (300-550nm) flash of light

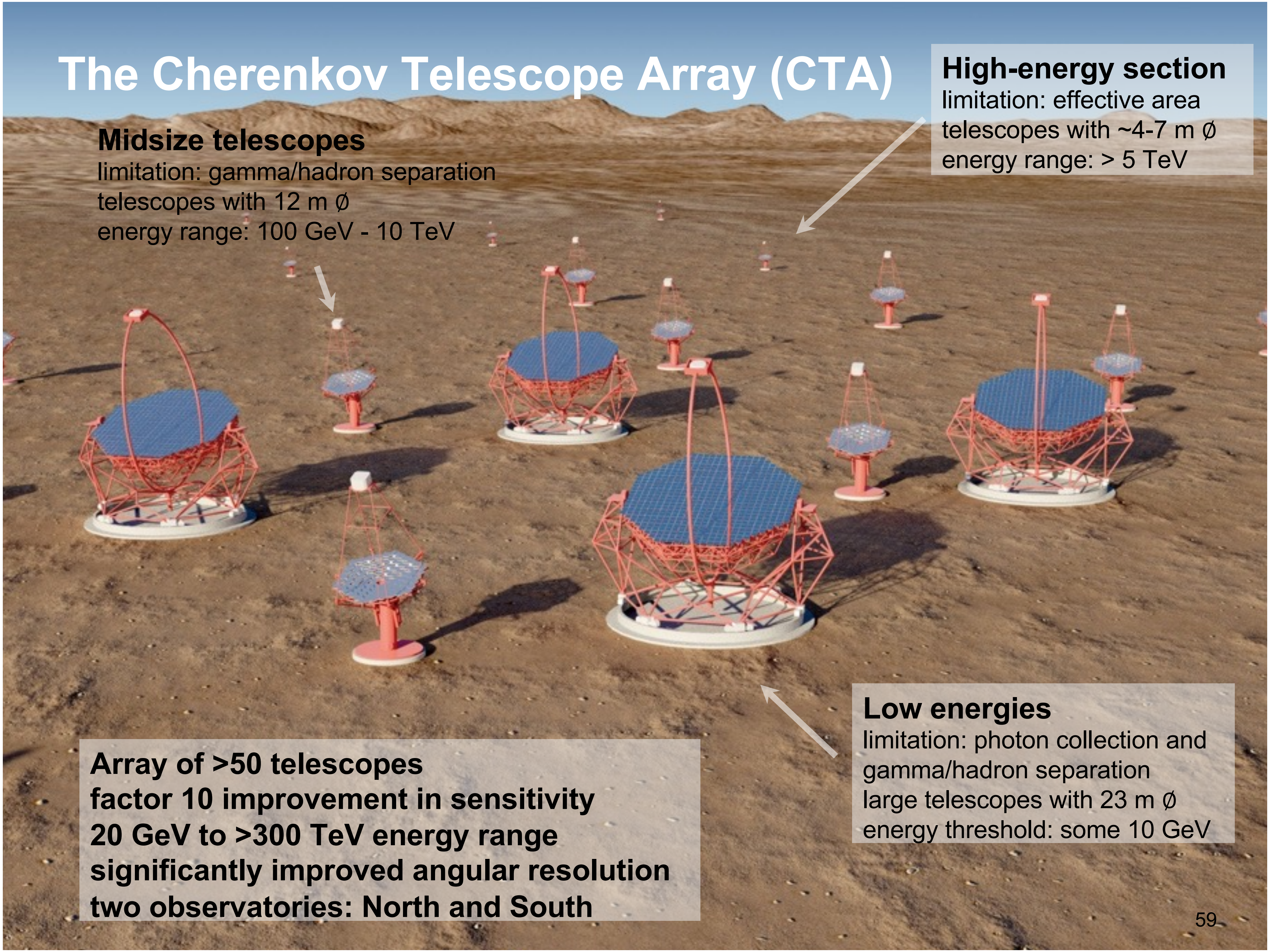
Imaging Technique - Air Showers





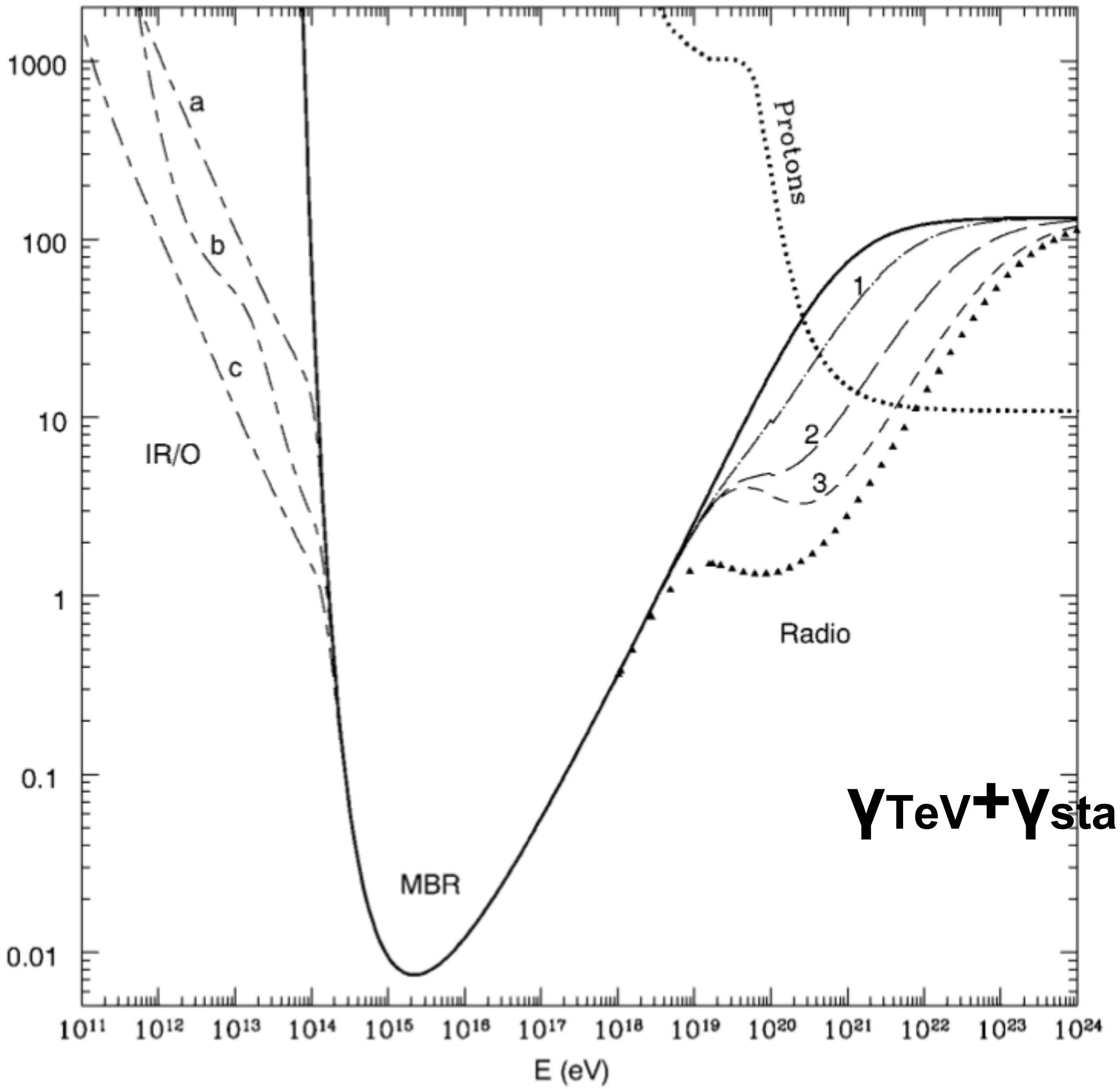



Imaging Atmospheric Cherenkov Telescopes
499 pixel PMT Camera
Sophisticated trigger system needed to suppress night sky background (120 MHz -> 200 Hz)
12 m diameter reflector (106 m² mirror area)


The Cherenkov Telescope Array (CTA)
High-energy section
limitation: effective area
telescopes with ~4-7 m ∅
energy range: > 5 TeV
Midsize telescopes
limitation: gamma/hadron separation
telescopes with 12 m ∅
energy range: 100 GeV - 10 TeV
Low energies
limitation: photon collection and
gamma/hadron separation
large telescopes with 23 m ∅
energy threshold: some 10 GeV
Array of >50 telescopes
factor 10 improvement in sensitivity
20 GeV to >300 TeV energy range
significantly improved angular resolution
two observatories: North and South

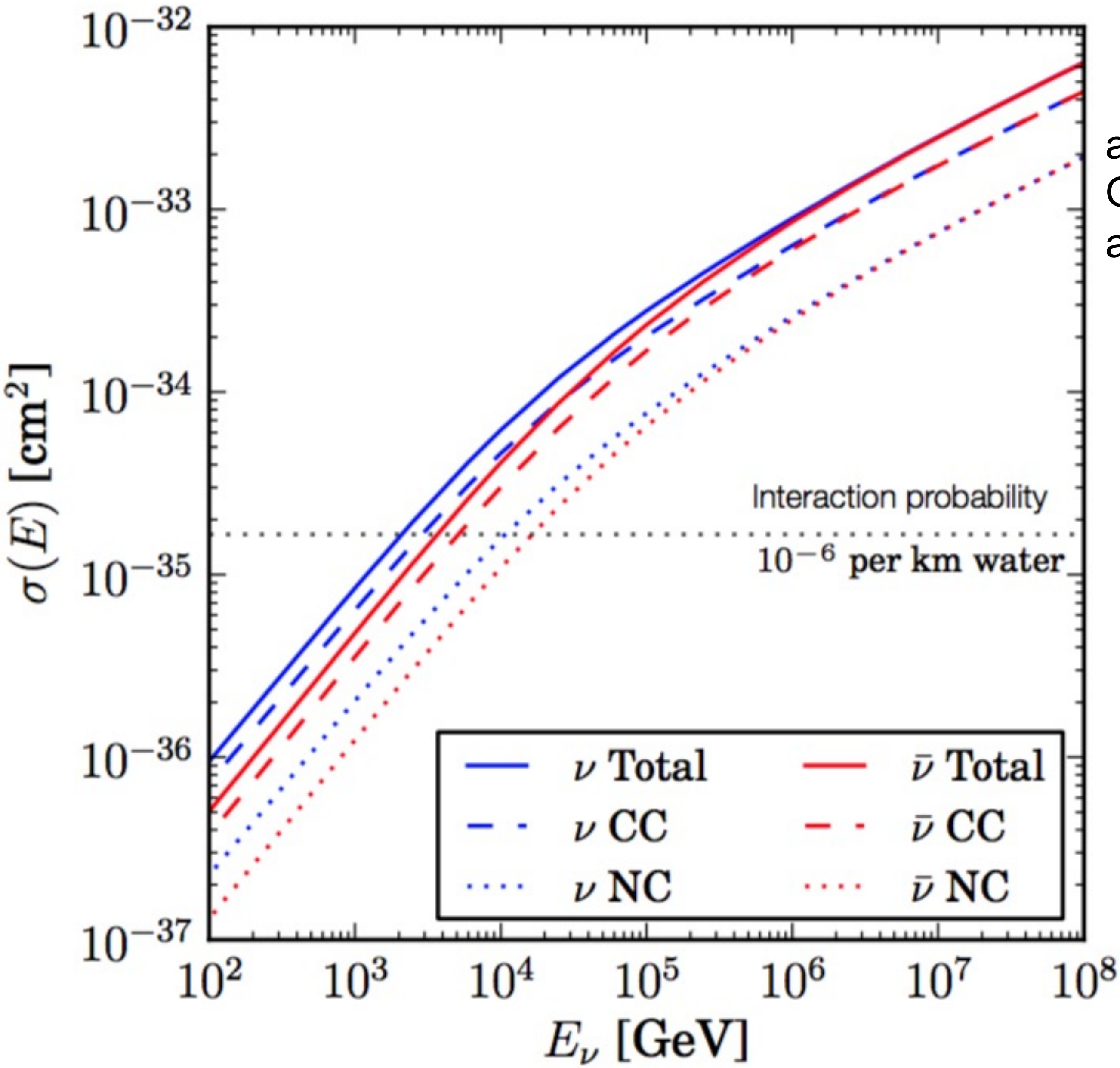
Opacity of the Universe to high-energy photons

Mean free path for photons



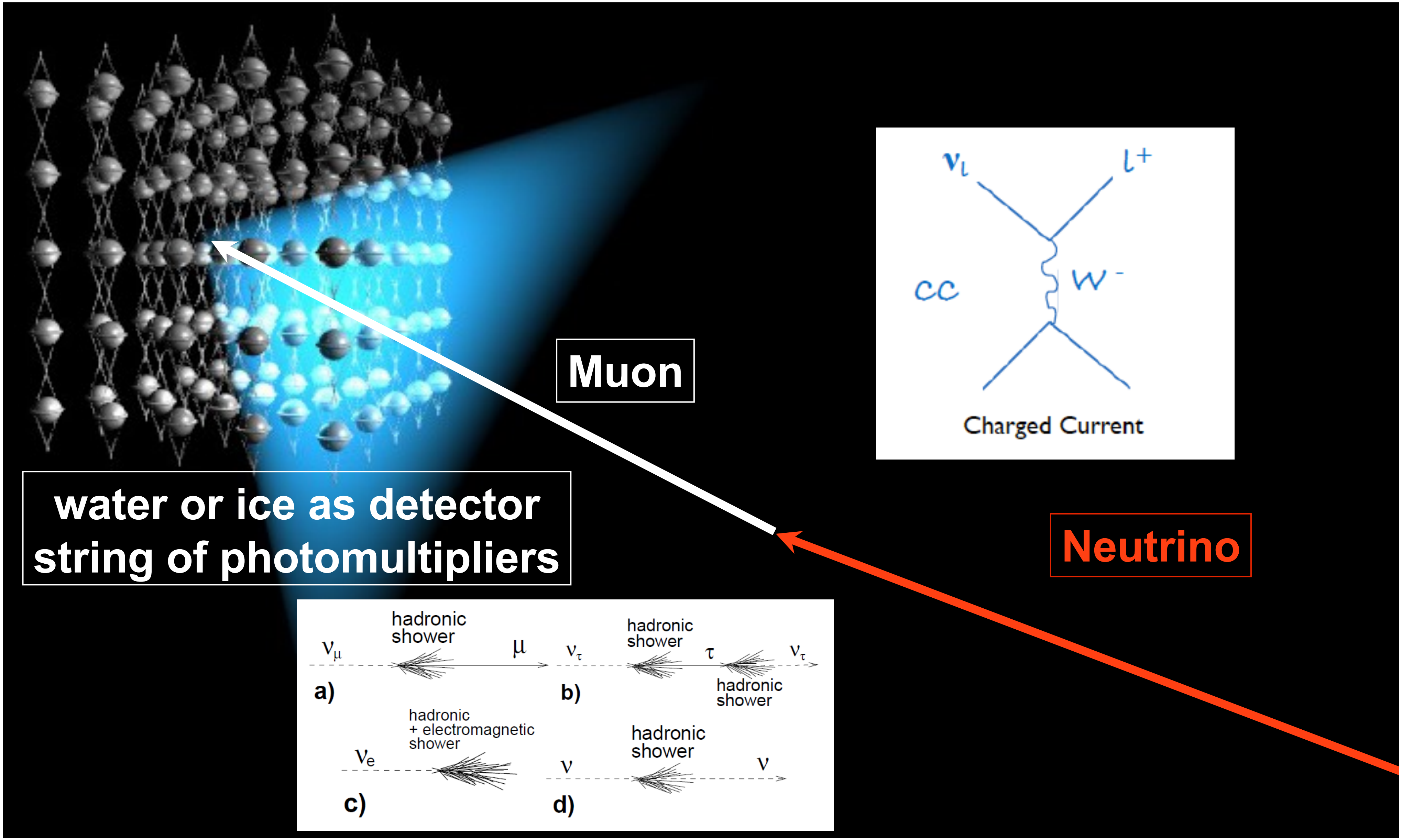
$\gamma_{TeV} + \gamma_{star} \rightarrow e^{+}e^{-}$

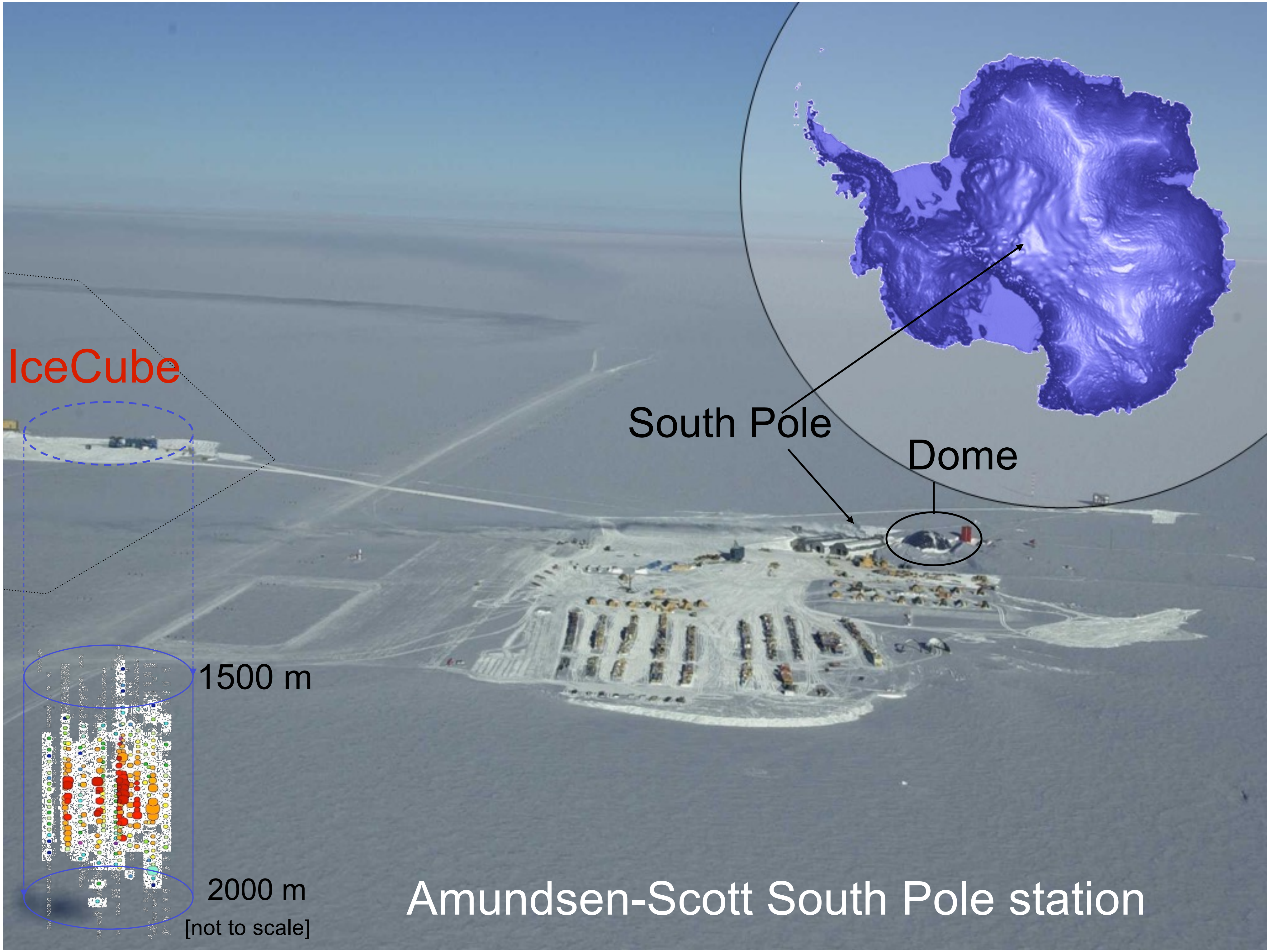
Neutrino detection



astrophysical flux:
$O(10^5)$ per km^2 per year
above 100 TeV

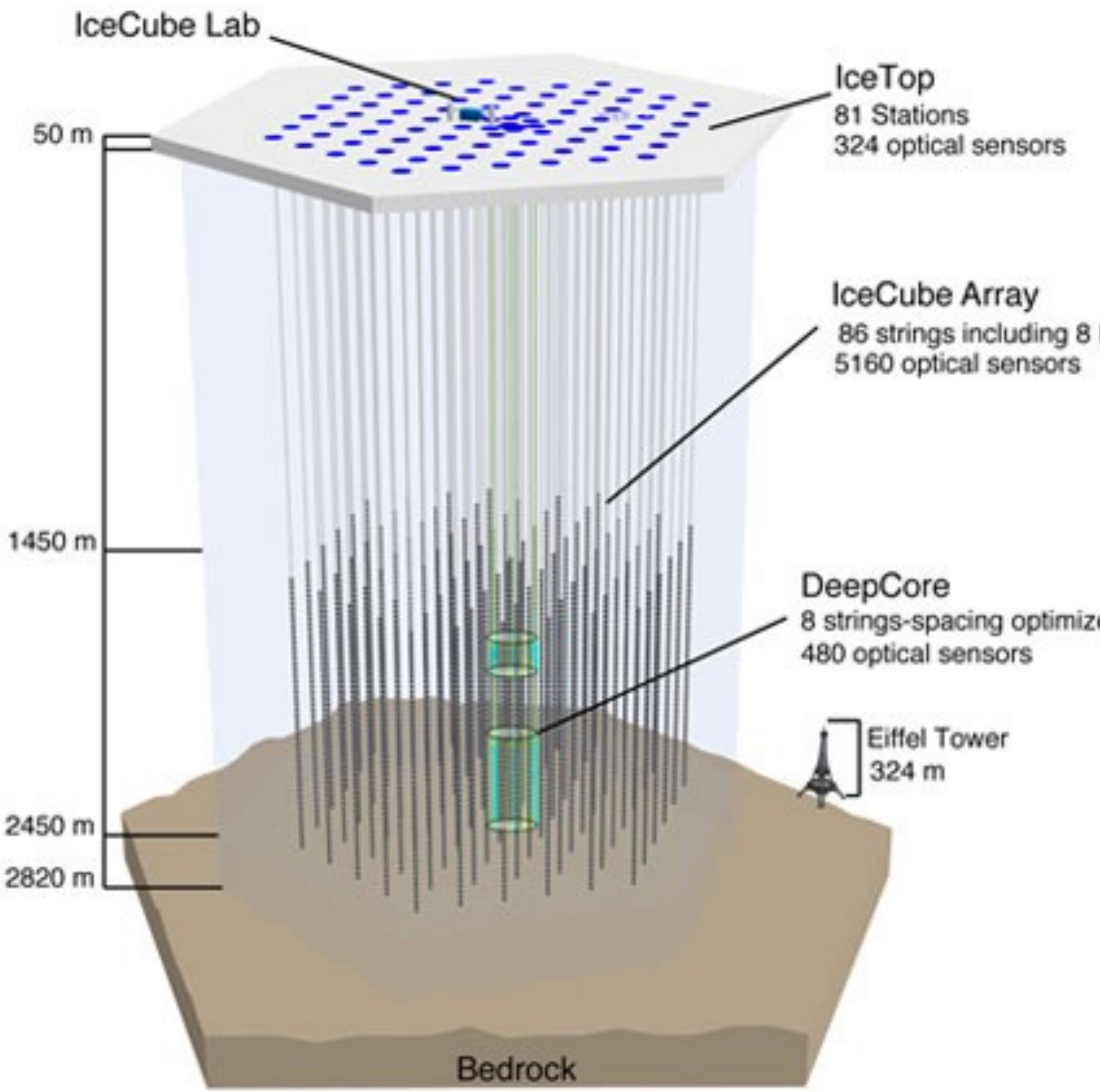
High-energy neutrino detection

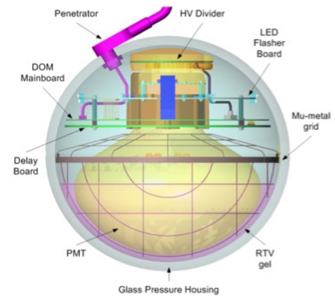




IceCube
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

IceCube



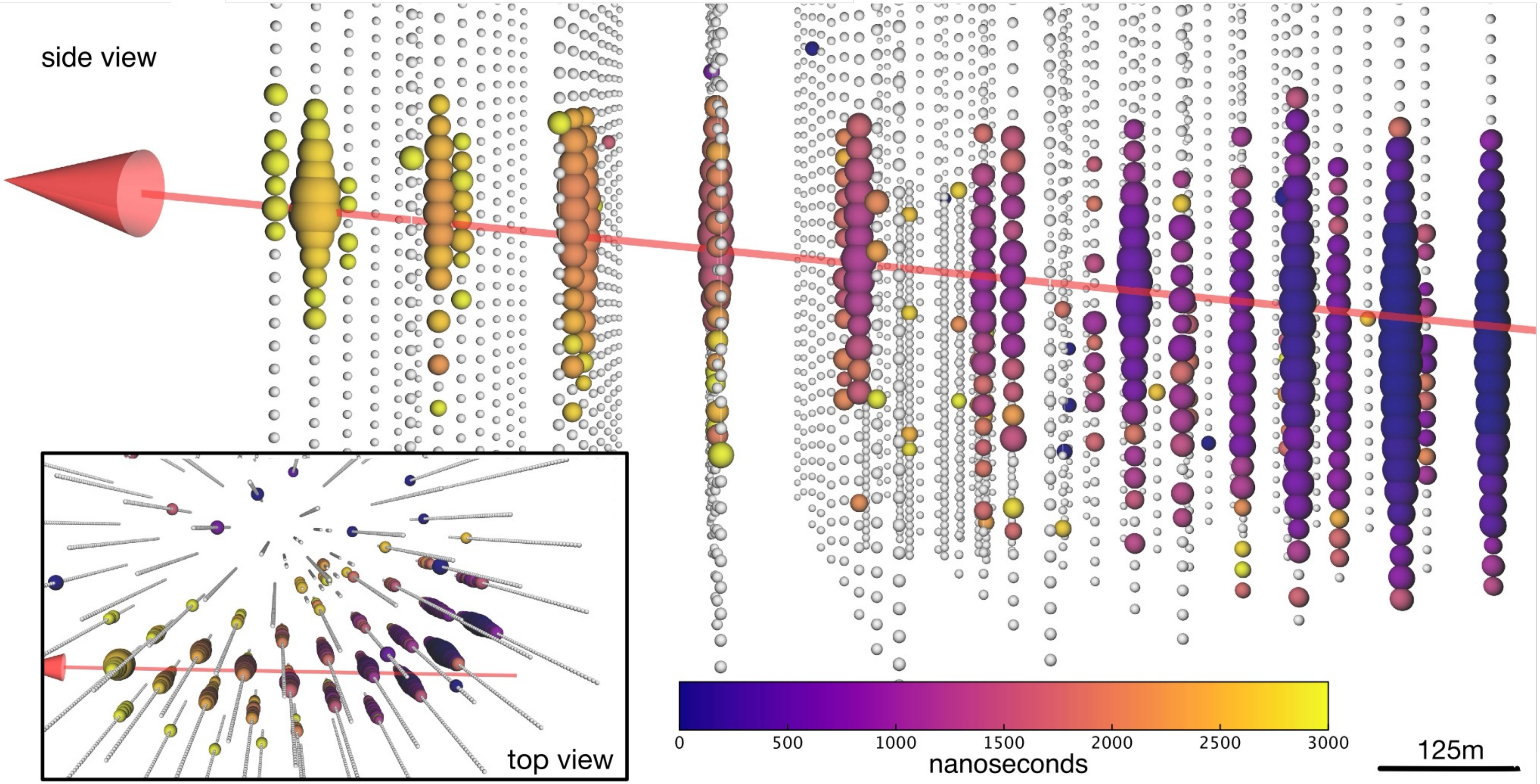


light collection by DOMs

ergy, allowing easily identi- -neutrino as-

IceCube can robustly identify astrophysical neutrinos at PeV energies, for individual neutrinos at several hundred TeV, an atmospheric origin

of neutrinos was found from the direction of TXS 0506+056 near the time of the alert, there are indications at the 3σ level of high-energy neutrino



ectrons. Inset is an overhead perspective view of the event. The best-fitting track direction is shown as an arrow,
.0.50 .0.30 degrees below the horizon.

B

Fri 22 Sep 17 20:55:13 UT

New Physics

Random example!

Lorenz Invariance Violations

- **Standard Model** and **General Relativity**:
  best theories describing the four fundamental forces
  - no conflict between them - but fundamentally different
- —> **Quantum Theory of Gravity**?
  - zoo of theories of Quantum Gravity
  - predict in general new physics at the Planck Energy Scale

$$E_{\mathrm{Pl}} \simeq 1.2 \times 10^{19}\ \mathrm{GeV}$$

—> Lorentz Invariance Violation (LIV)

LIV: arrival time measurements

- new dispersion relation

$$c^2 p^2 = E_\gamma^2 [1 \pm \xi_1 E_\gamma / E_{QG} \pm \xi_2 (E_\gamma^2 / E_{QG}{}^2) \pm \ldots]$$

depending on sign: subluminal or superluminal case

- time delays in arrival times of photons

$$\delta t \simeq \left(\frac{\Delta E}{\xi_\alpha E_{Pl}} \right)^\alpha \frac{L}{c}$$

Summary - astroparticle physics

- **cosmic rays - cosmic environments - fundamental physics**

- **Major new results from multi-messenger observatories**

- **large number of new instruments coming online in the next years:**
  - Cherenkov Telescope Array
  - IceCube Gen2
  - Auger upgrades
  - Gravitational wave observatories + radio (SKA)

Credit: F. Acero & H. Gast

End.

Credit: John Quinn/CfA