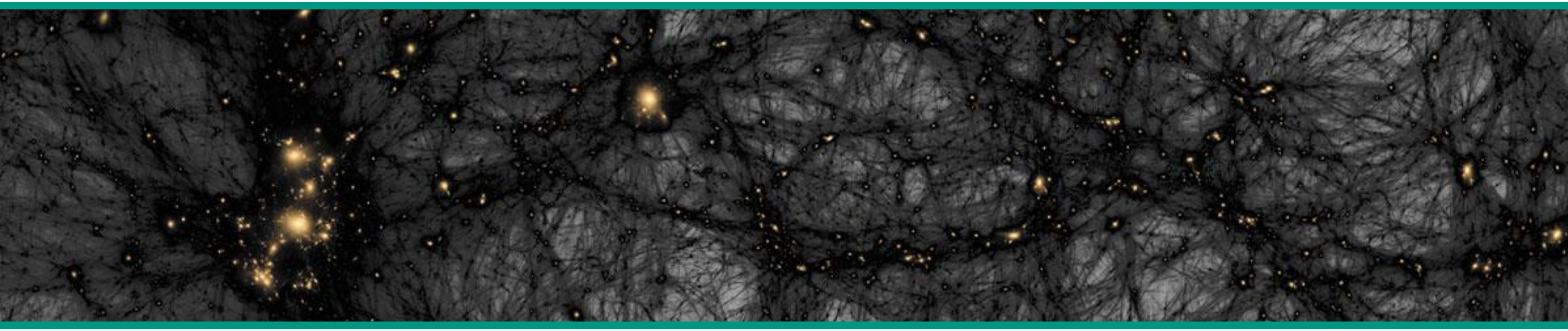
Astroparticle physics I – Dark Matter

WS22/23 Lecture 5 Nov. 10, 2022



Recap of Lecture 4

- **Extensive air showers: lateral & longitudinal distributions**

  - primary CR **energy E_0**:
    use integration over lateral distributions of $N_e + N_\mu$ (´**foot print**´) as good indicator for E_0 (compare Greisen-fit to CORSIKA simulations)

  - primary CR **mass M**:
    use observed longitudinal distribution to determine shower maximum X_{max}
    - heavy CR (^{56}Fe): small X_{max} ⇨ **small ratio N_e/N_μ**
    - light CR (p): large X_{max} ⇨ **large ratio N_e/N_μ**

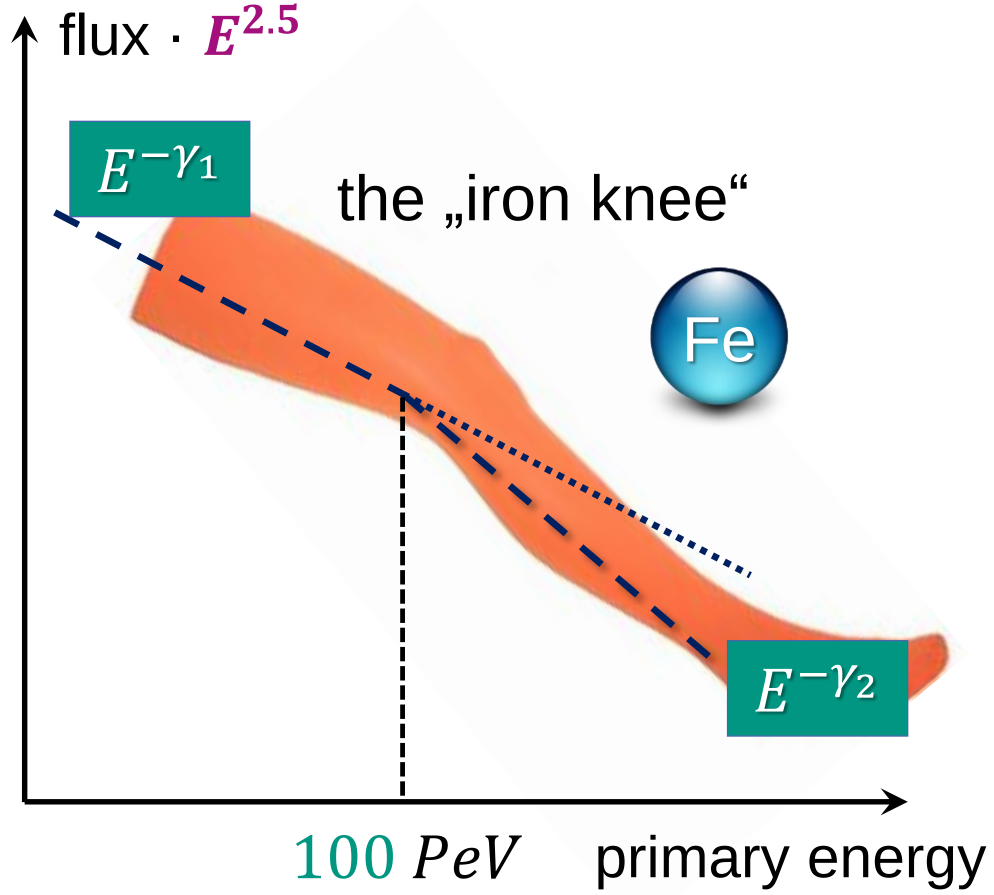
- **Pioneering air shower experiment KASCADE at KIT Campus North**

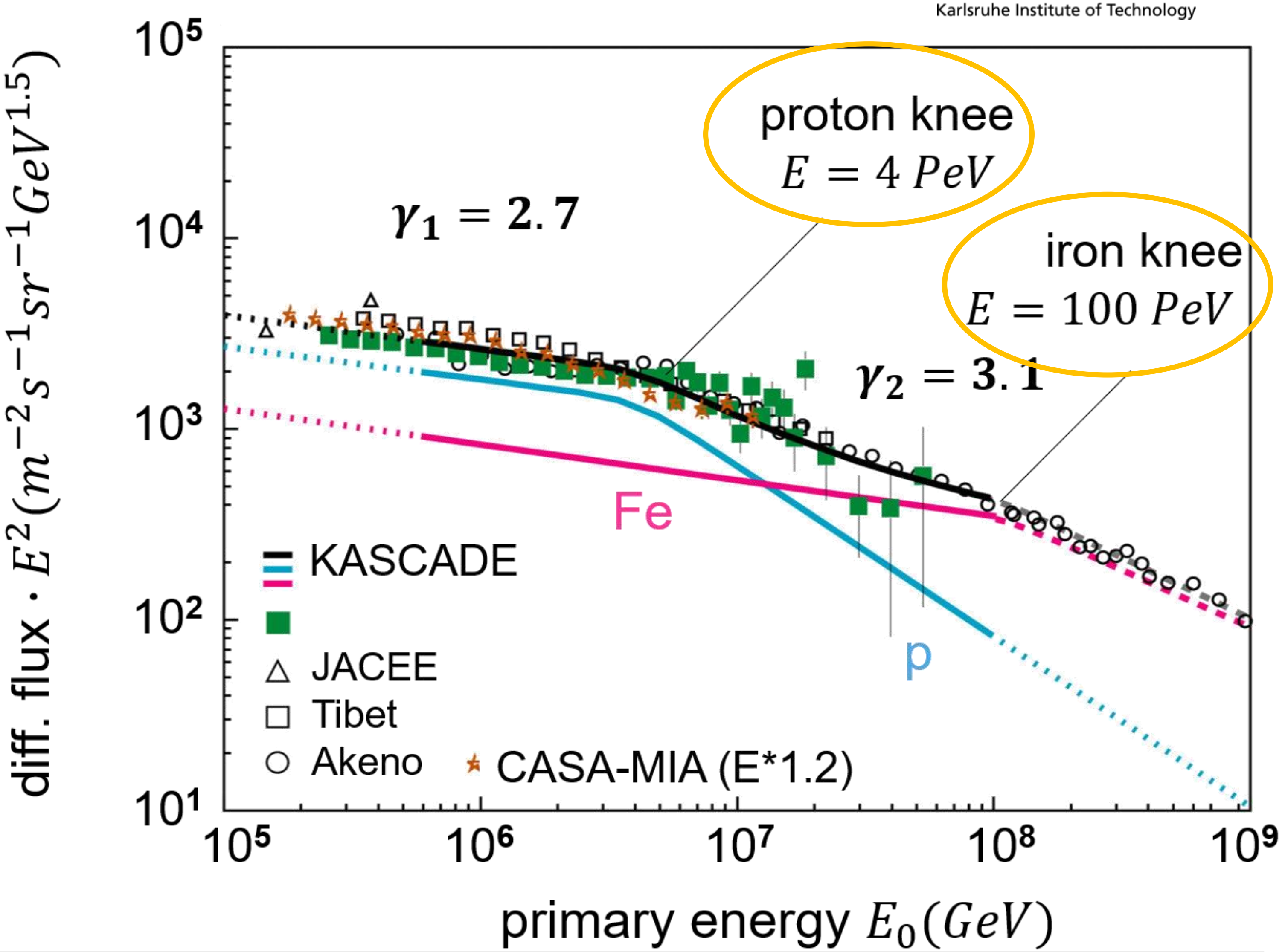
  - components: large scintillator array, muon tunnel, central hadron calorimeter

  - extension to KASCADE-Grande: at the knee - change of mass composition

Power-Law Feature: element-specific ´knees´

- **Iron knee at $E = 100\ PeV$**

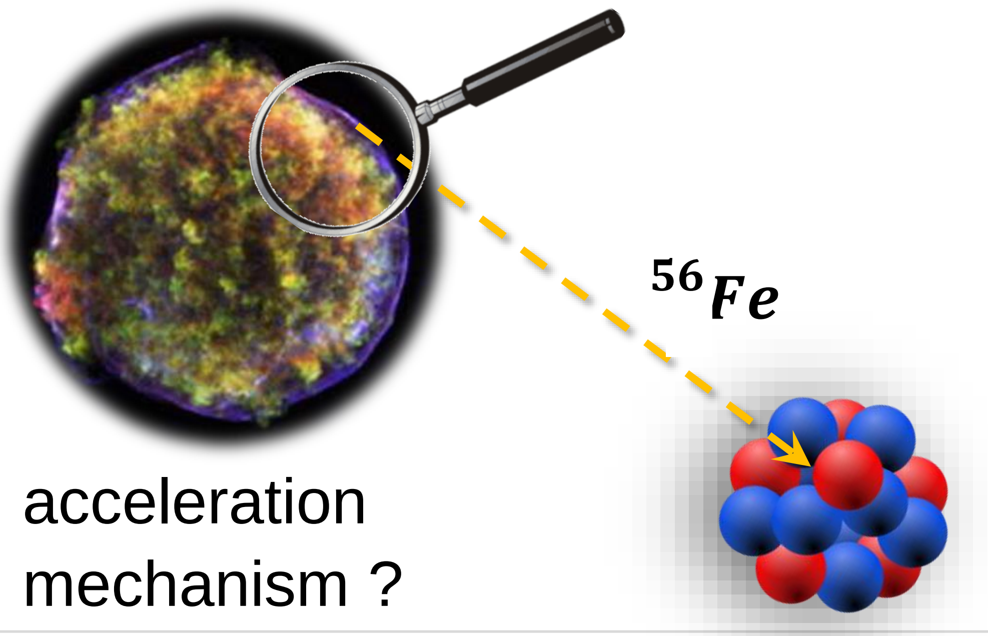




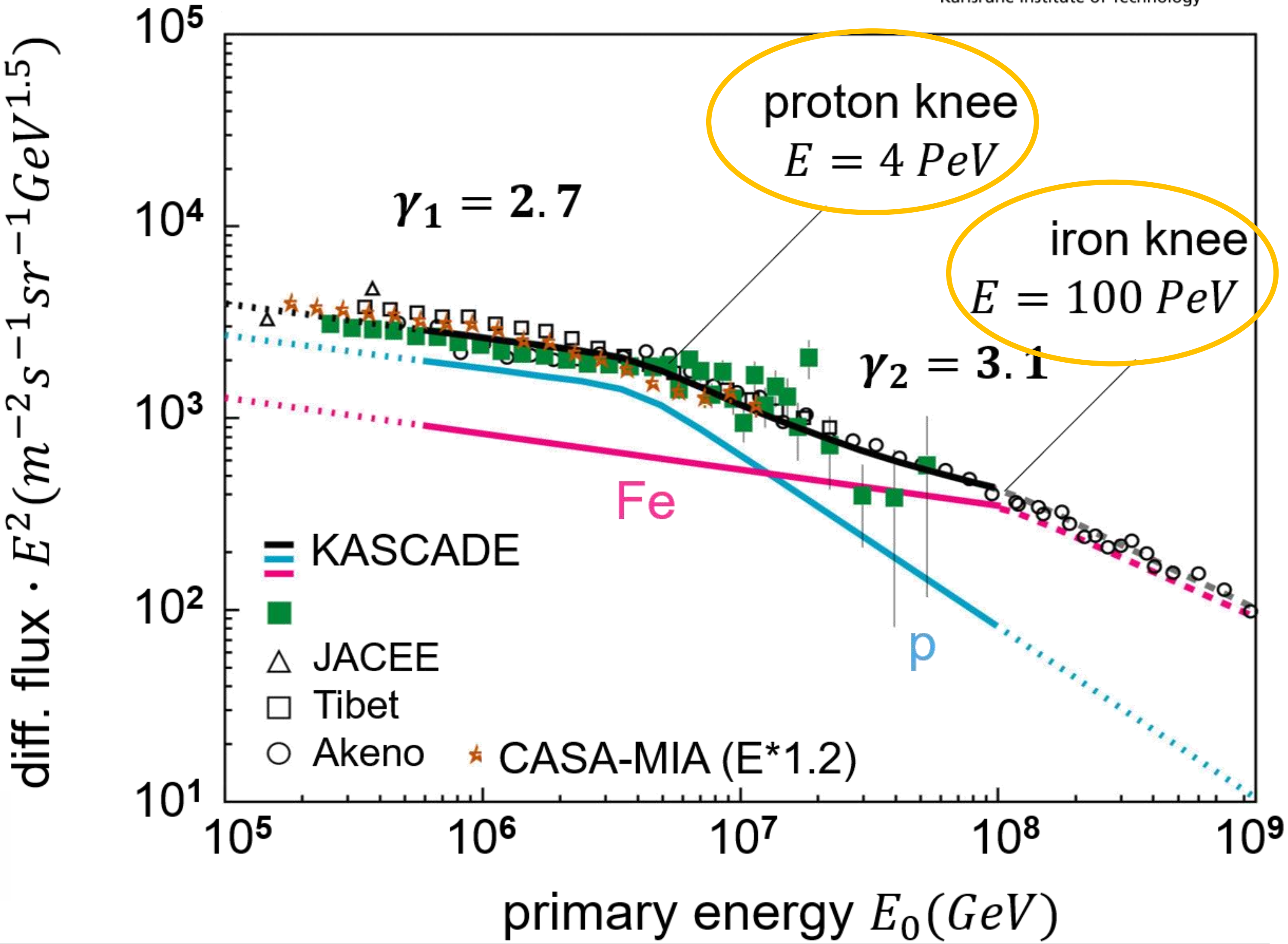
Power-Law Feature: p-knee & Fe-knee

■ **Observations at 100 PeV**

- KASCADE-Grande: first ever observation of Fe-knee



acceleration mechanism ?



Knee due to particle losses during propagation?

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- **Propagation of CRs with energy E & mass A**

- **GALPROP-MC-Code**
  transport of galactic CRs from the source to Earth (Diffusion): diffusion of particles in ´**leaky box**´

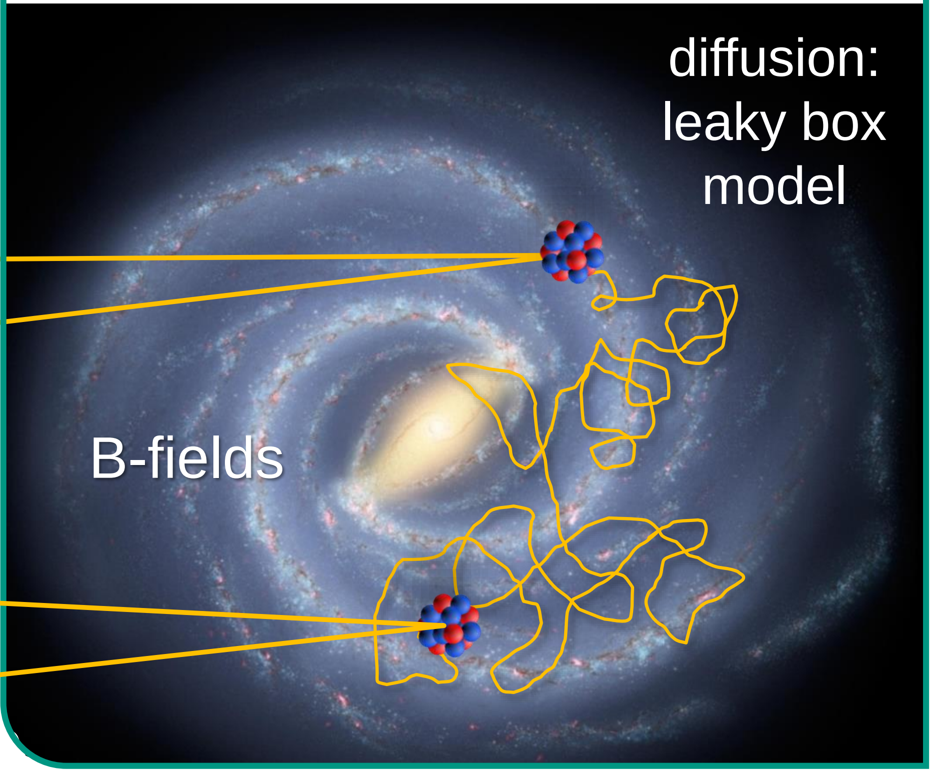
- detailled modelling of effects due to CR propagation:

  a) orientation of galactic B-fields

  b) energy losses (light particles):
  - inverse Compton effect
  - emission of synchrotron radiation

CR propagation in galaxis

- charged CRs (fully ionised nuclei): diffusion in $B_{galactic}$



Propagation of cosmic rays in our galaxy

- **Charged CRs: guided by galactic magnetic fields with $B \sim \text{few}\ \mu G$**

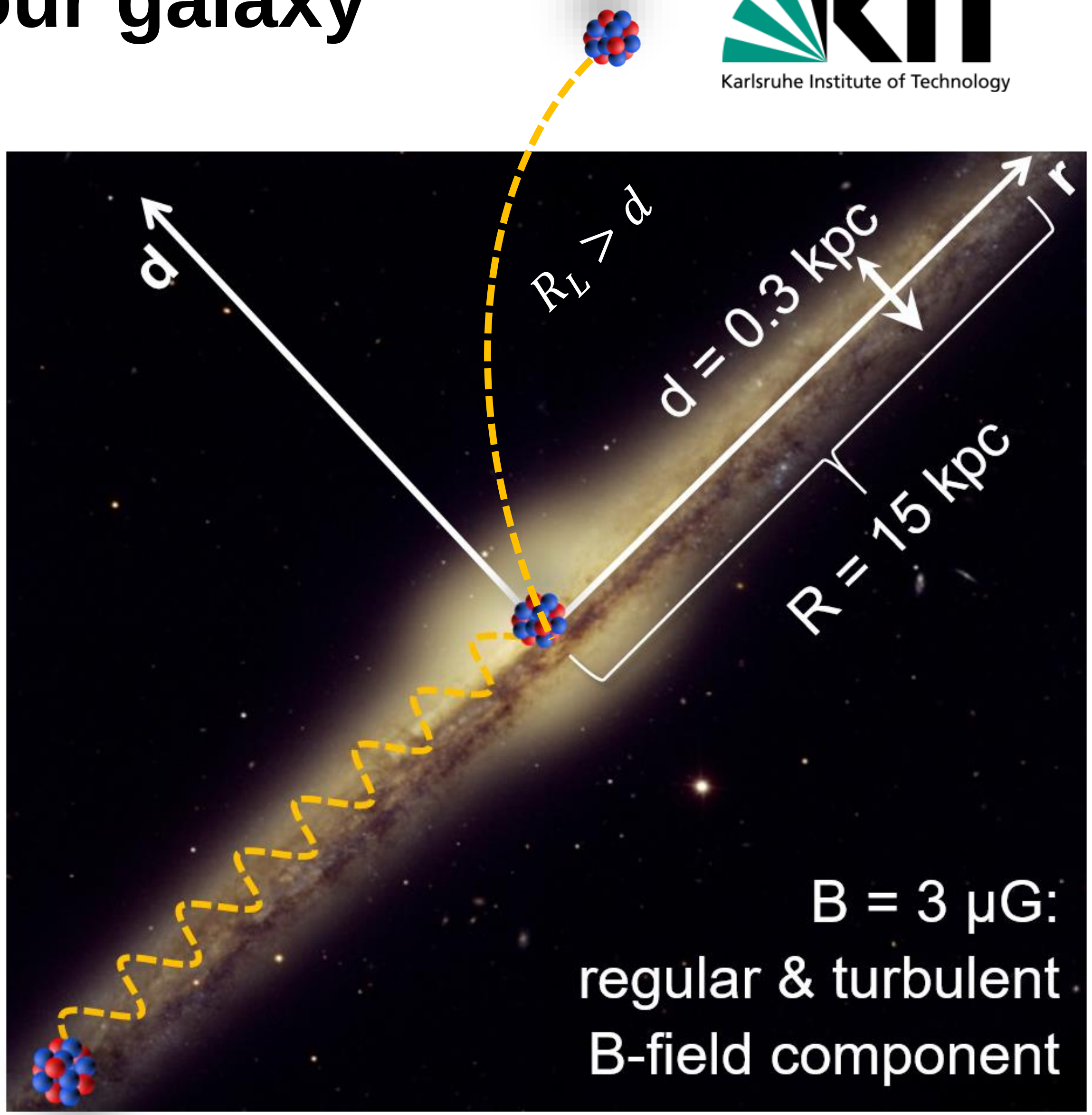
  - important parameter:
  Larmor radius R_L

$$R_L \cong 1pc \cdot \left(\frac{E}{10^{15}eV}\right) \cdot \left(\frac{\mu G}{Z \cdot B}\right)$$

  - high energies:

$$R_L > d = 0.3\ kpc$$

⇨ these CR nuclei will leave the galaxis



Propagation of cosmic rays in our galaxy

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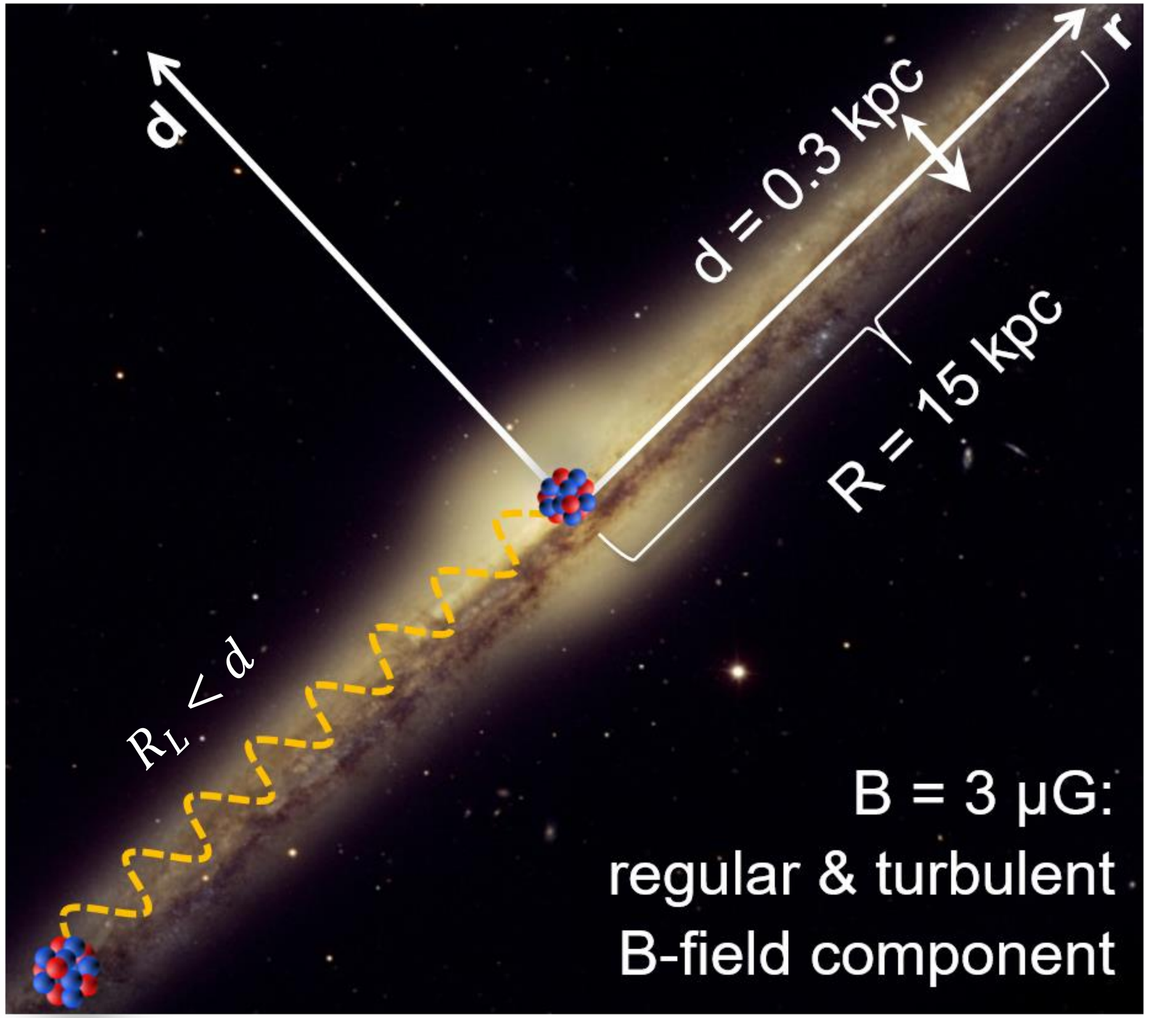
  - important parameter:
  Larmor radius R_L

$$R_L \cong 1pc \cdot \left(\frac{E}{10^{15}eV}\right) \cdot \left(\frac{\mu G}{Z \cdot B}\right)$$

  - low energies:

$$R_L < d = 0.3\ kpc$$

⇨ these CR nuclei are trapped in galaxis on time scales $\tau \sim 3 \ldots 10 \cdot 10^6\ y$



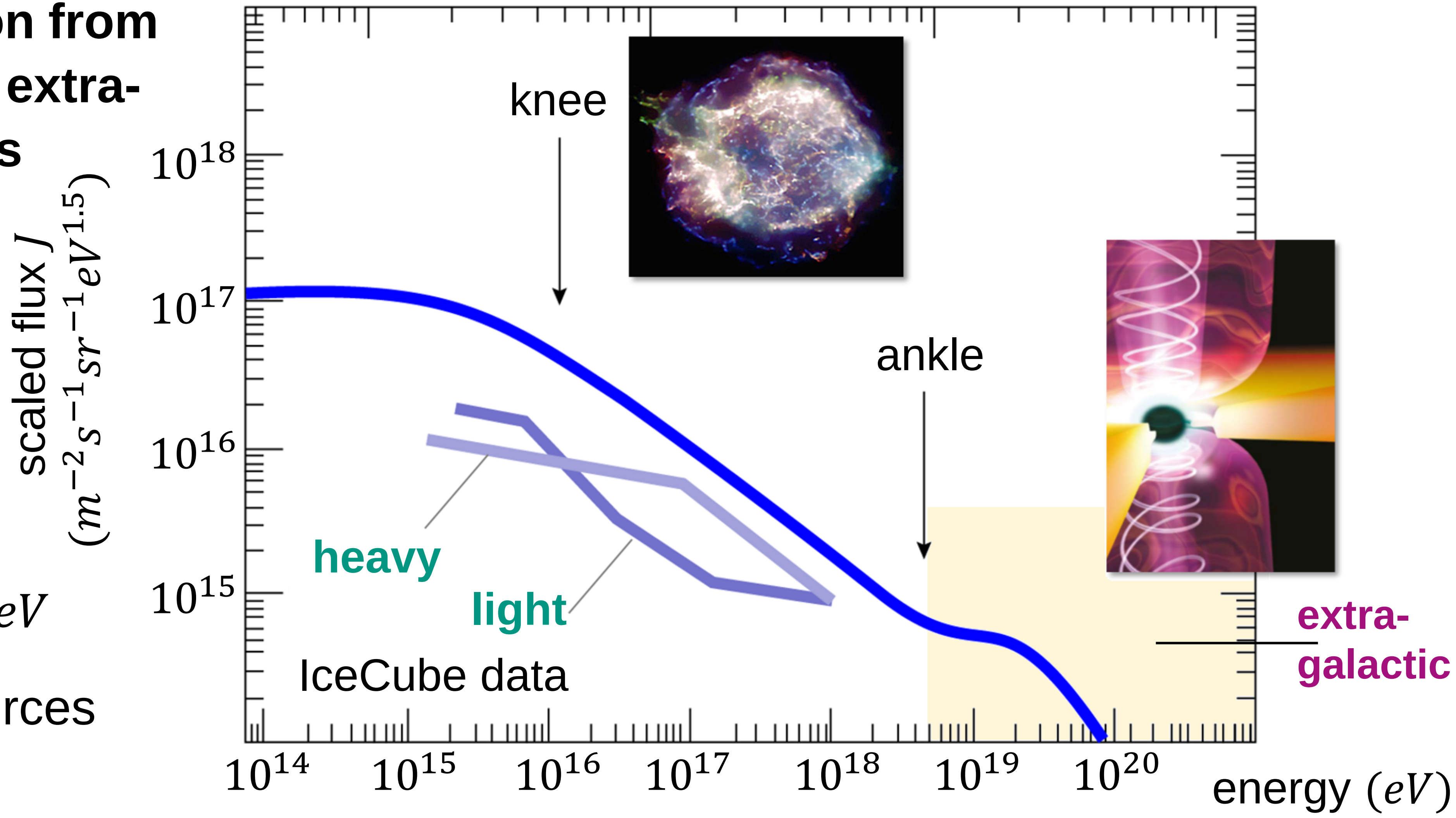
CR spectrum feature: the ankle

- **Ankle: transition from galactic CRs to extra-galactic sources**

- IceCube*: **light** + **heavy** **CRs** (galaxis)

⇨ all galactic accelerators only up to ~ 10^{18} eV

⇨ extra-galactic sources must be different



*surface array at Southpole

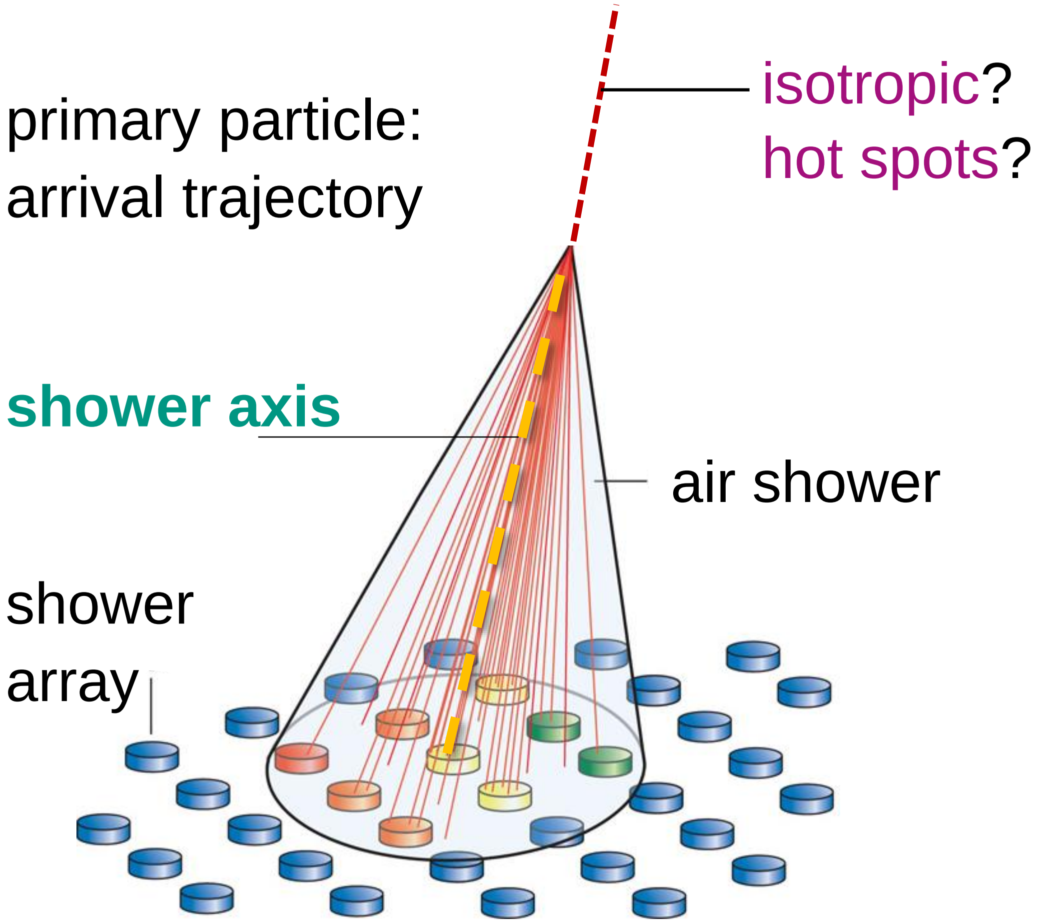
What is the degree of isotropy of cosmic rays?

- **Reconstructing the arrival direction of CRs from the shower axis**

  - **galactic CRs**:
    many sources, energies $\sim 10^{15}\ eV$,
    galactic B –fields result in deflection
    ⇨ expect a high degree of isotropy

  - **extra-galactic CRs**:
    fewer sources at scales of UHECRs
    ⇨ nearby sources could be identified

  - the **axis of a large air shower**
    allows to reconstruct the arrival
    direction of the primary particle



Results for galactic cosmic rays at $E \sim 10^{15} eV$

■ **The observed distribution of galactic CRs is indeed isotropic to first order**

KASCADE results (>10 years):

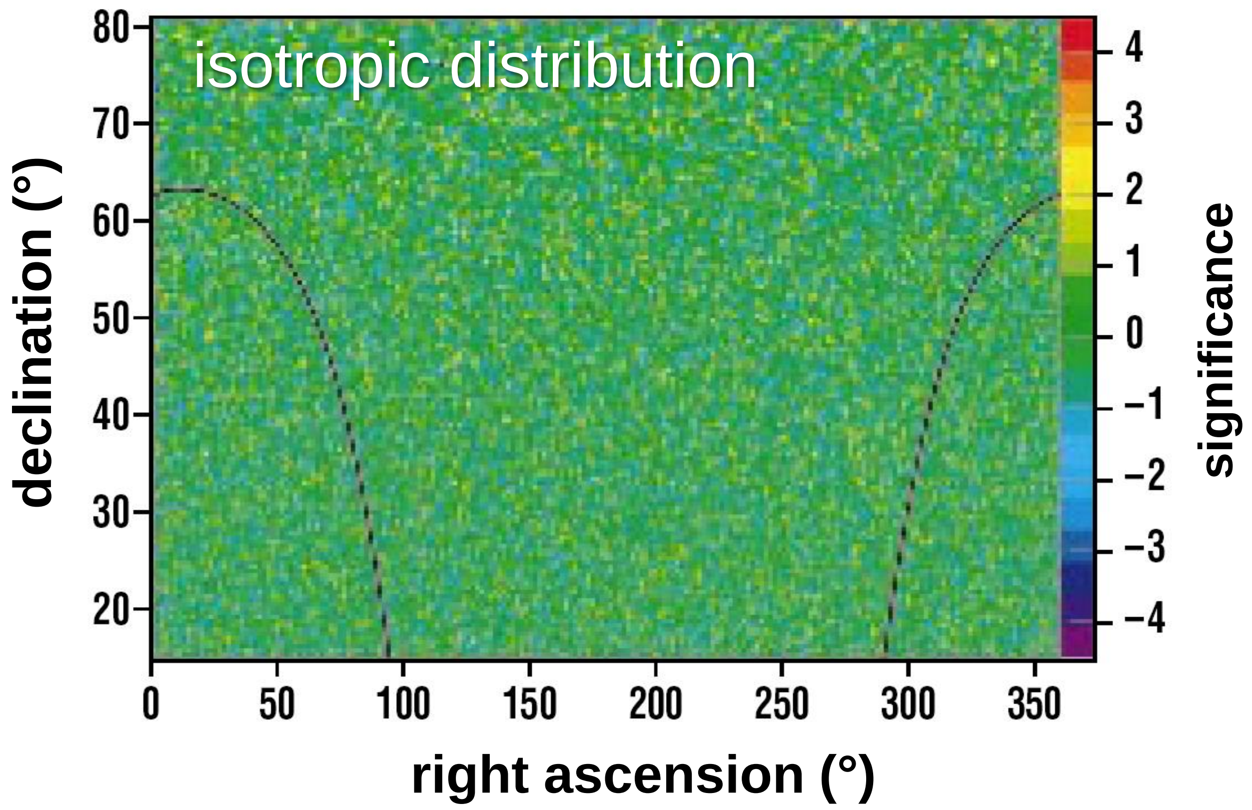
- to first order ($\sim 10^{-3}$) one sees an **isotropic arrival distribution**

- conclusions: there are

  ↳ no nearby sources of CRs

  ↳ no neutral primaries (gammas) which initiate showers and which would point back to sources of CRs

KASCADE: arrival distribution of CR



Looking very precisely: a vey small anisotropy!

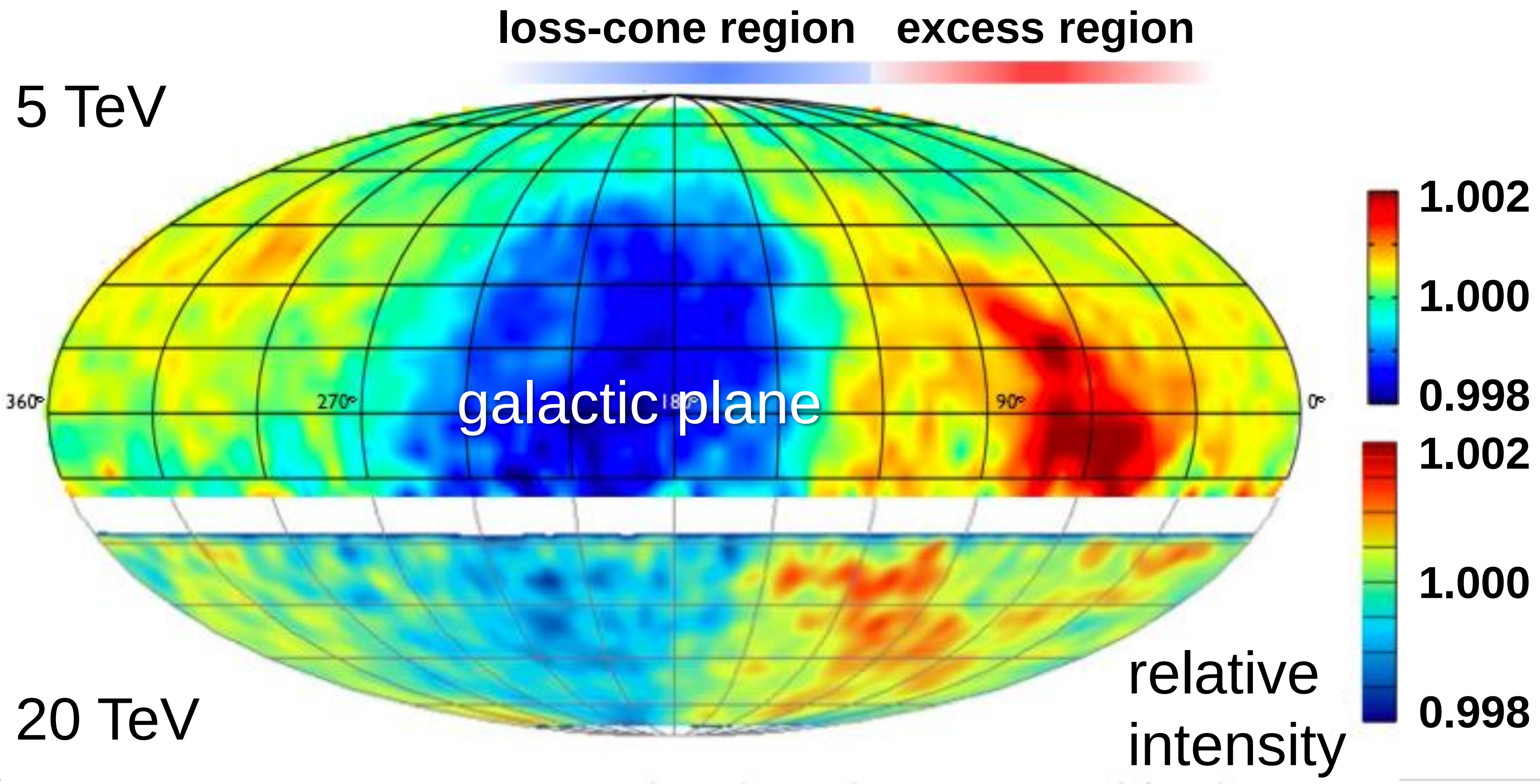
- new results of arrival distributions reveal a tiny anisotropy of galactic CRs

  - anisotropic arrival distribution with small dipole amplitude $A \sim 6 \cdot 10^{-4}$

TIBET-III

consistent data from northern & southern hemispheres!

IceCube-22 (south pole)



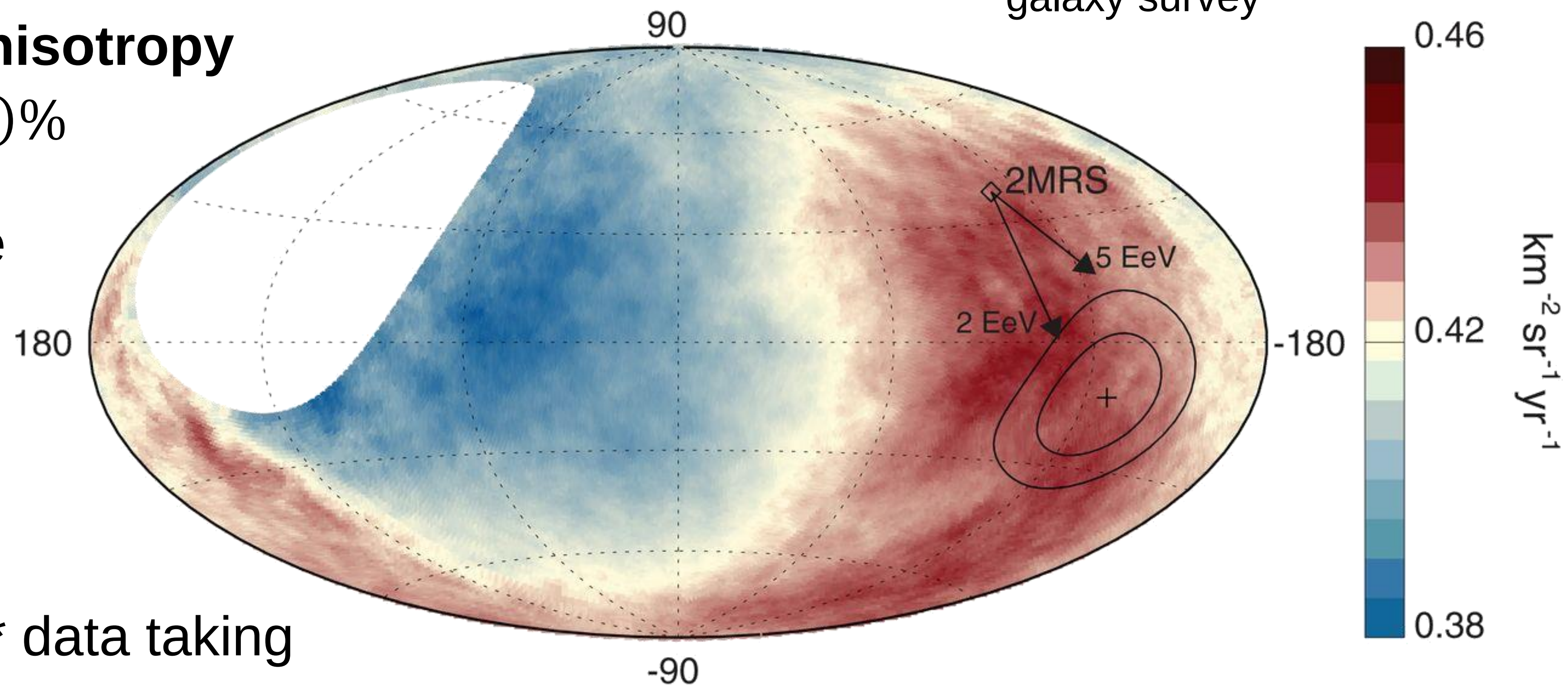
Anisotropy at ultra-high energies: southern view

- **Pierre Auger Observatory* reveals spatial anisotropy at energies $E > 8\ EeV$**

- at the highest EeV-scales: UHECRs with nuclear chage $Z = 1.7 - 5$ show a **small dipole anisotropy** with $A = (6.5\ \pm 1)\%$

2MRS = galaxy survey

- UHECRs must be nearby, hot spot despite extended intergalactic B – fields



~ 13 years of PAO* data taking

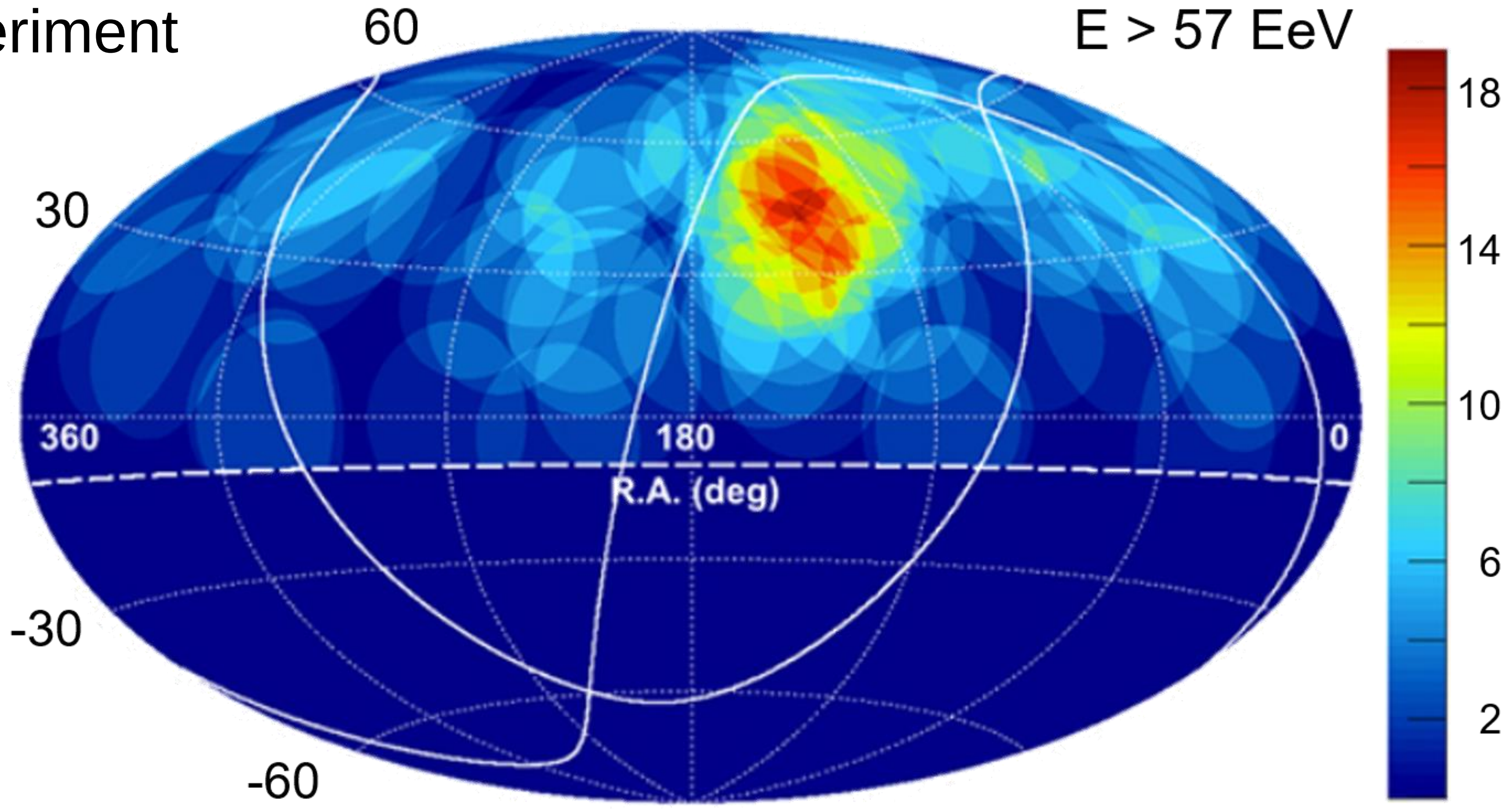
*PAO

Anisotropy at ultra-high energies: northern view

- **The Telescope Array reveals a localised ´hot spot´ above $E = 5.7 \cdot 10^{19} eV$**

Telescope Array (TA) experiment in Utah (USA) observes UHECRs in nothern hemisphere

- data taking since 2008: 27 events from only 6% of the area being surveyed: a **hot spot of UHECR**



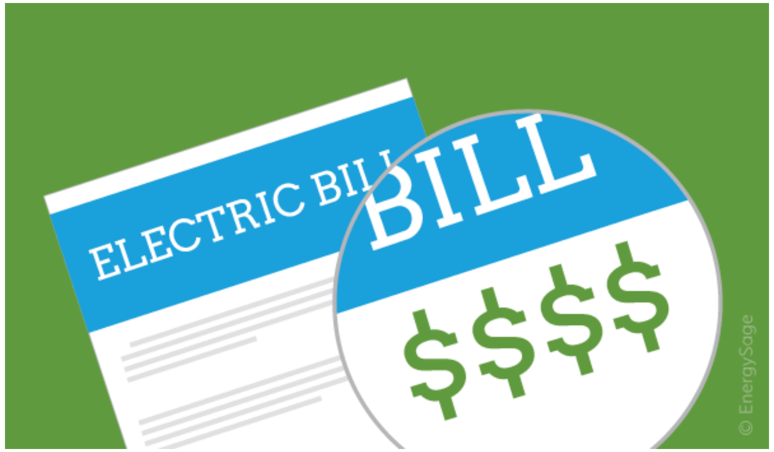
Cosmic accelerators: principles

- **galactic/extra-galactic accelerators: who powers them & how do they do it?**

- where does the energy for CRs come from?

- what is the efficiency of cosmic accelerators?

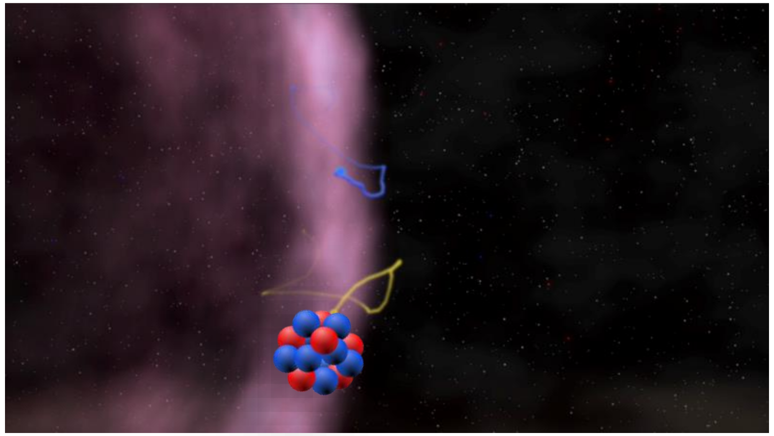
- can cosmic accelerators work over long time scales?



- how do cosmic acclerators work up to $10^{15} \ldots 10^{20} eV$?

- what limits the energy of galactic acclerators?

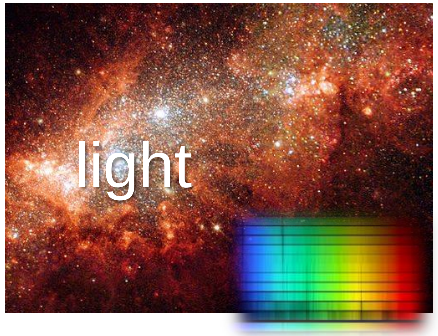
- why do extra-galactic accelerators go beyond?



Local (galactic) energy densities: an overview

- **CR energy density: galactic sources must be able to provide this value**

local energy densities in the Milky Way	
electromagnetic radiation (star light)	$\sim 0.6\ eV/cm^3$
galactic magnetic field ~ $B^2 / 2\mu_0$ (3µG)	$\sim 0.25\ eV/cm^3$
cosmic microwave background (CMB)	$\sim 0.26\ eV/cm^3$
cosmic rays	$\sim \mathbf{1\ eV/cm^3}$
local matter density (WIMPs)	$\sim 0.3\ GeV/cm^3$



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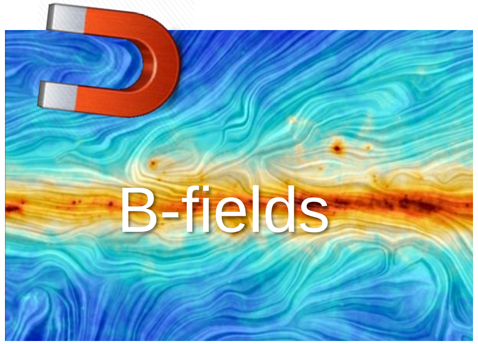

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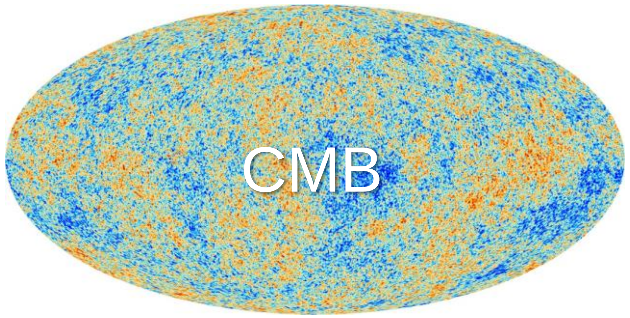

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comparison of W_{SN} & W_{CR} in galaxis

- **Do galactic supernovae provide enough power W to account for CRs?**

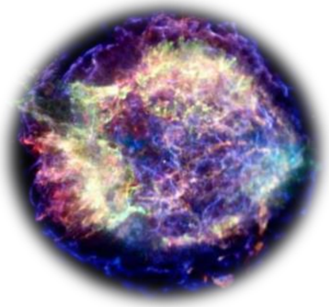
- Total energy/year W_{CR} going into galactic cosmic rays

$$W_{CR} = \rho_{CR} \cdot \pi \cdot R^2 \cdot d \cdot \tau^{-1} \qquad = 2 \cdot 10^{41} J/year$$

CR

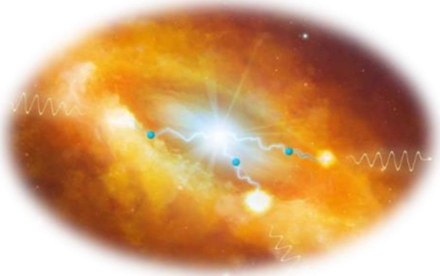
- Total energy/year W_{SN} produced by supernovae in galaxis

$$W_{SN} \sim 3 \text{ SN-explosions/century} = 5 \cdot 10^{42} J/year$$



SNR

- **Supernovae** = ideal candidate sites* for galactic CR
  required efficiency for $W_{CR} \rightarrow W_{SN}$: $< 5\%$



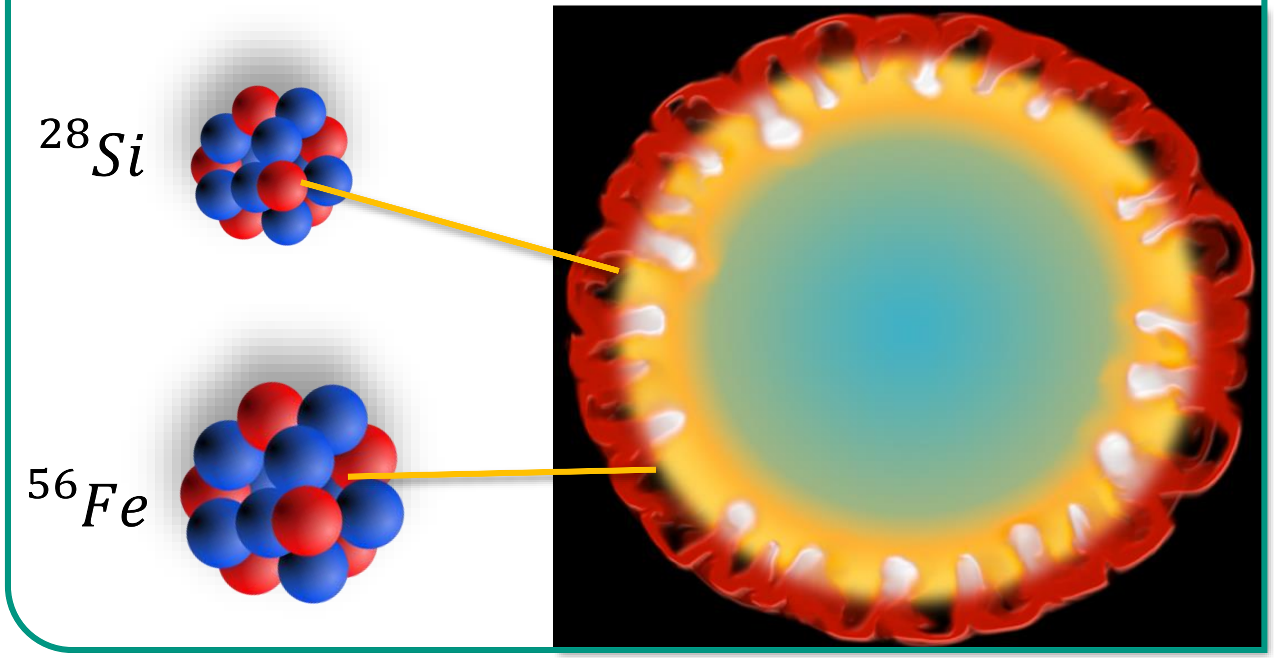
*CR acceleration in SN-shock fronts

Sources of Cosmic Rays in our galaxy

- **Most likely Cosmic Ray sources in our galaxy at $E \sim 10^{15} eV$**

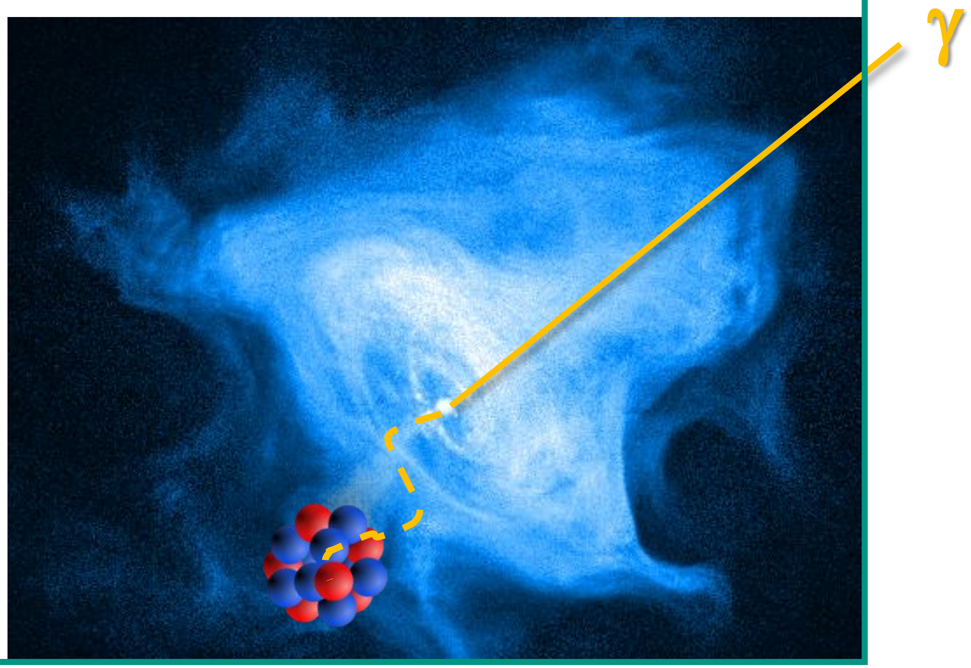
Supernova shock fronts

- shock fronts in SNR: energy distribution ? maximum energy E_0 ? what nuclei ${}^{A}Z$?



Pulsars, pulsar wind nebulae

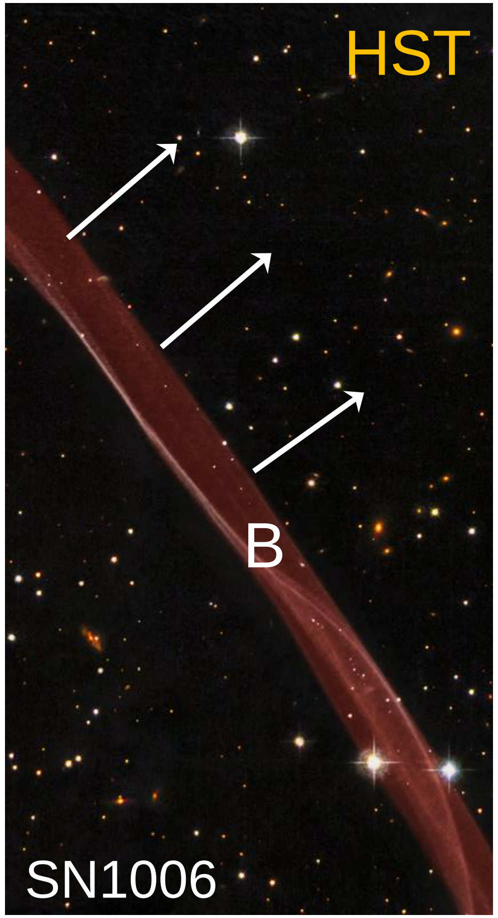
- acceleration mechanism: hadronic / leptonic schemes ?



Accleration mechanism for CRs

■ **Fundamental physics principles to accelerate particles**

- **dynamical**
  scattering (reflection) of particles in magnetic clouds (Fermi-acceleration)



- **hydrodynamic**
  accleration in plasma sheets

- **electromagnetic**
  time-variable $E, B-$ fields

$$\frac{d}{dt}(\gamma \cdot m \cdot \vec{v}) = e \cdot (\vec{E} + \vec{v} \times \vec{B})$$

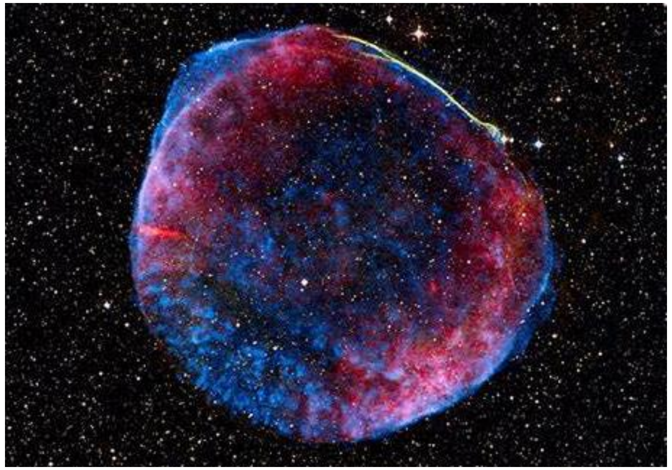
with

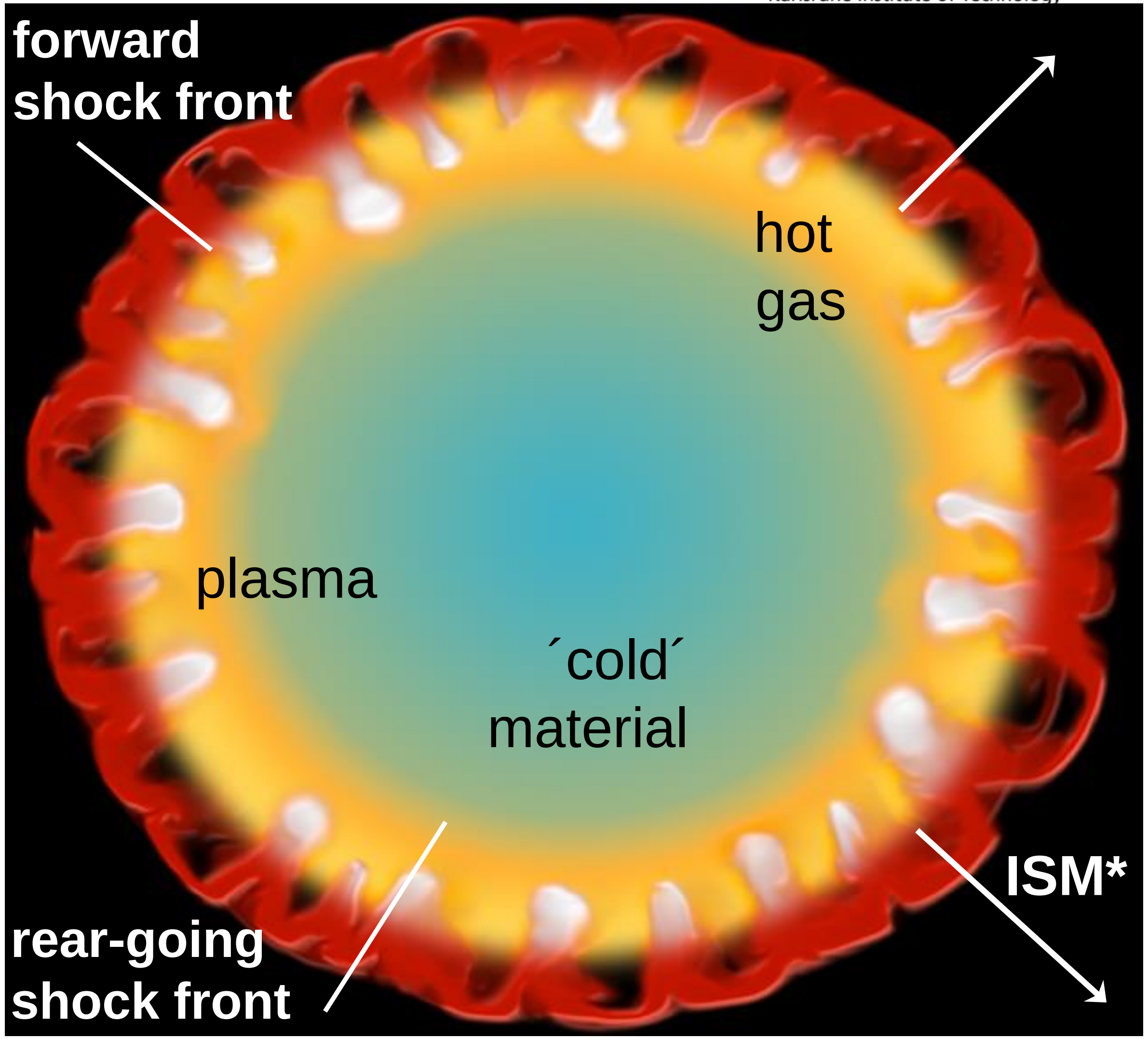
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Fermi accleration in shock fronts of SN remnants

- **Simplified 1D-scenario**

- **SN-shock front:**
  spreads out into the very thin ISM* over extended time scales of $t = 10^4 \dots 10^5 y$.





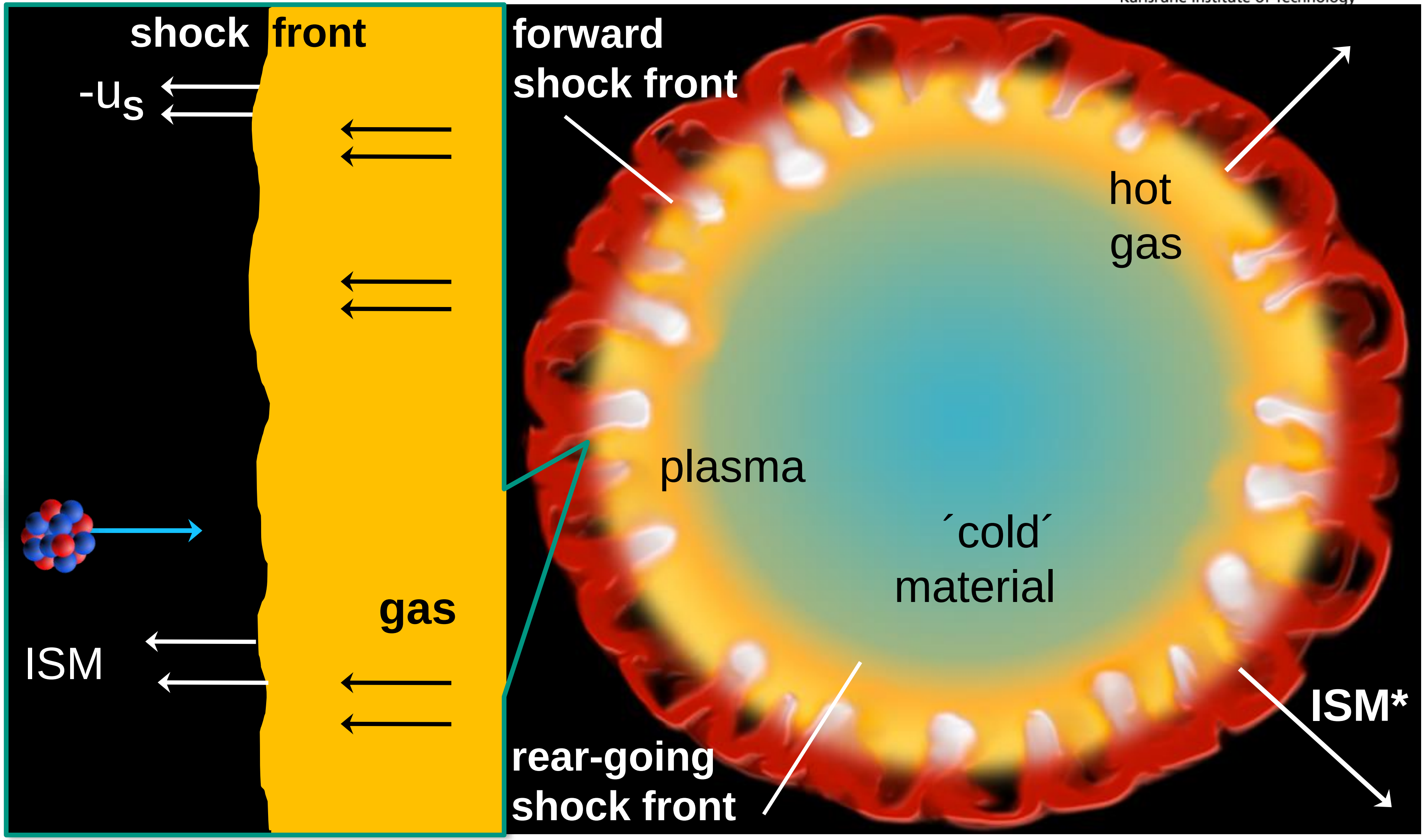
*ISM = interstellar medium

Fermi accleration in shock fronts of SN remnants

- **Simplified 1D-scenario**

- SN-shockfront propagates with $u_s \cong 10^4 \ km/s$ or $\boldsymbol{\beta_s = 0.03}$

- β_s decreases over time

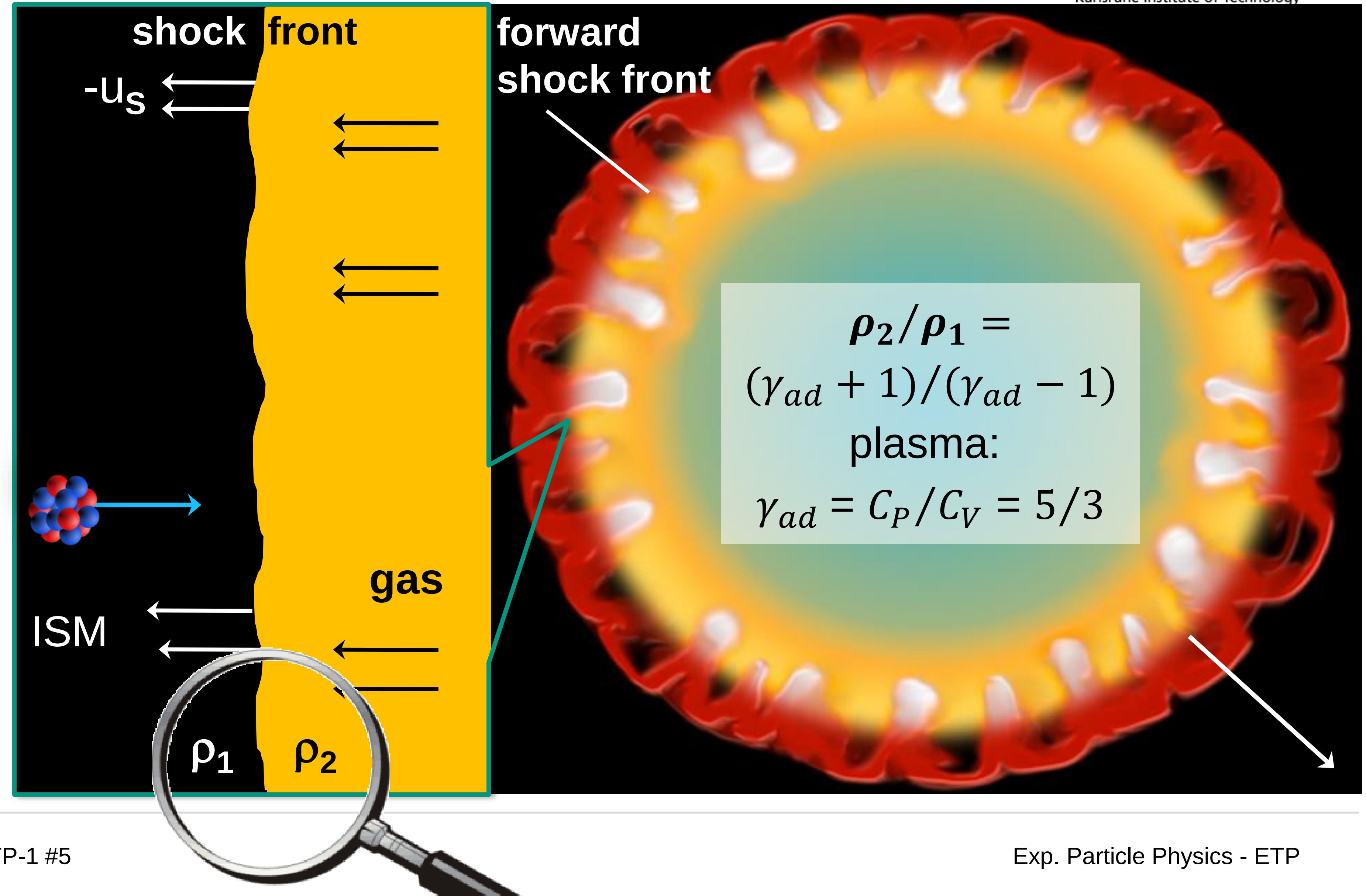


Fermi accleration in shock fronts of SN remnants

- **important: there is a density gradient at the transition to ISM**

- ISM: density $\boldsymbol{\rho_1}$, shock: density $\boldsymbol{\rho_2}$

- plasma physics: ratio $\boldsymbol{\rho_2/\rho_1}$ depends on the adiabatic coefficient γ_{ad}



Fermi accleration in shock fronts of SN remnants

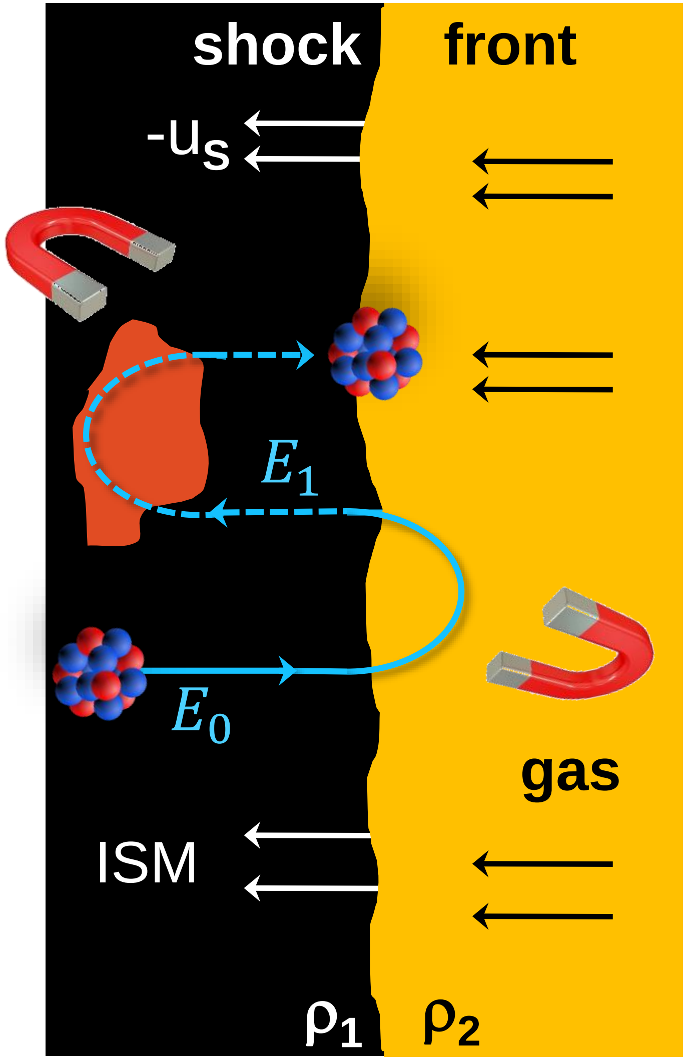
- **The process of Fermi acceleration of CRs comprises several key steps:**

- charged nucleus from ISM with **primary energy E_0** passes the SN-shock front: **energy gain ΔE**

- B-fields within the gas of the shock front back-reflect the nucleus: **adiabatic process** without energy loss!

- nucleus again passes passes pressure gradient (in opposite direction): again **energy gain ΔE**

- further adiabatic backscattering of nucleus due to electro-magnetic fields in the ISM



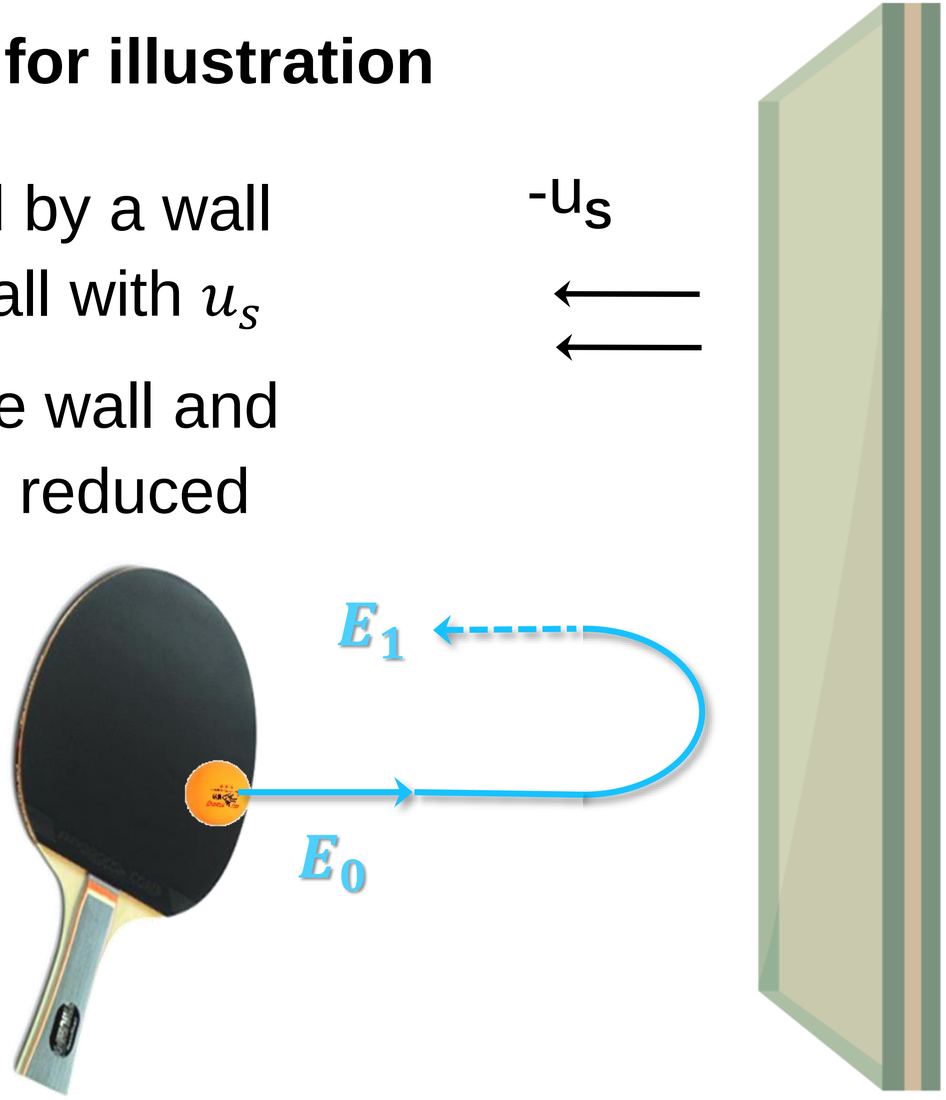
Fermi accleration in shock fronts: an analogon

- **a mechanic analogon for illustration**

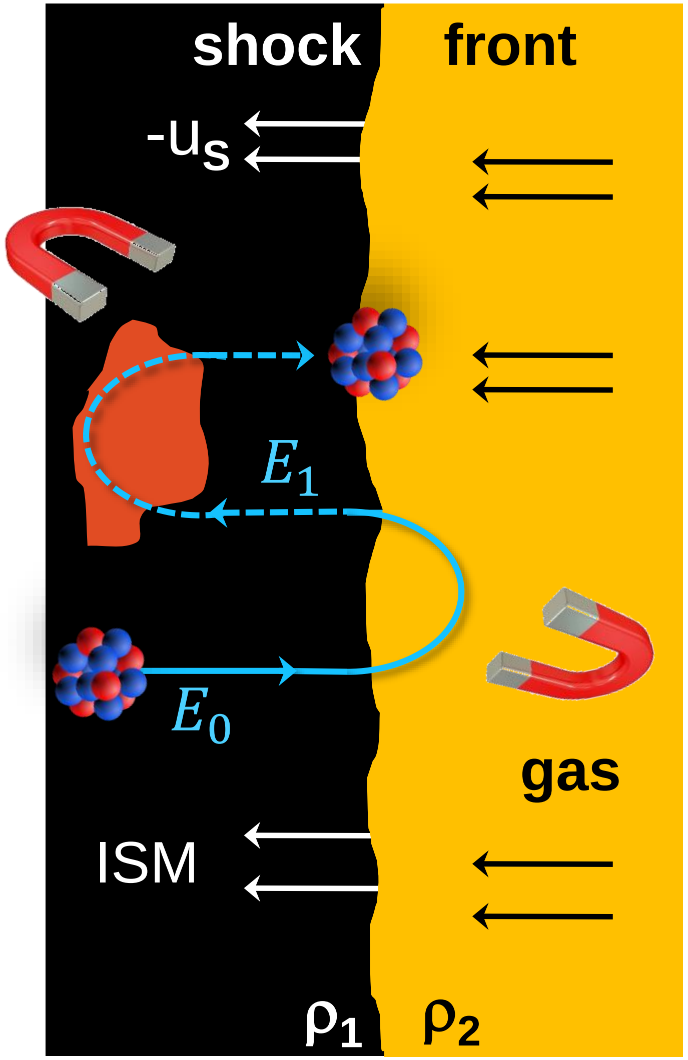
  - ping pong ball reflected by a wall which moves against ball with u_s

    ⇨ distance between the wall and table tennis racket is reduced

    ⇨ ball is accelerated, and (if this can be repeated) it will be ever faster



n = 1



Fermi accleration in shock fronts: a net gain

- **Summing up: the CR nucleus gains energy**

  - by Fermi acceleration, which is …

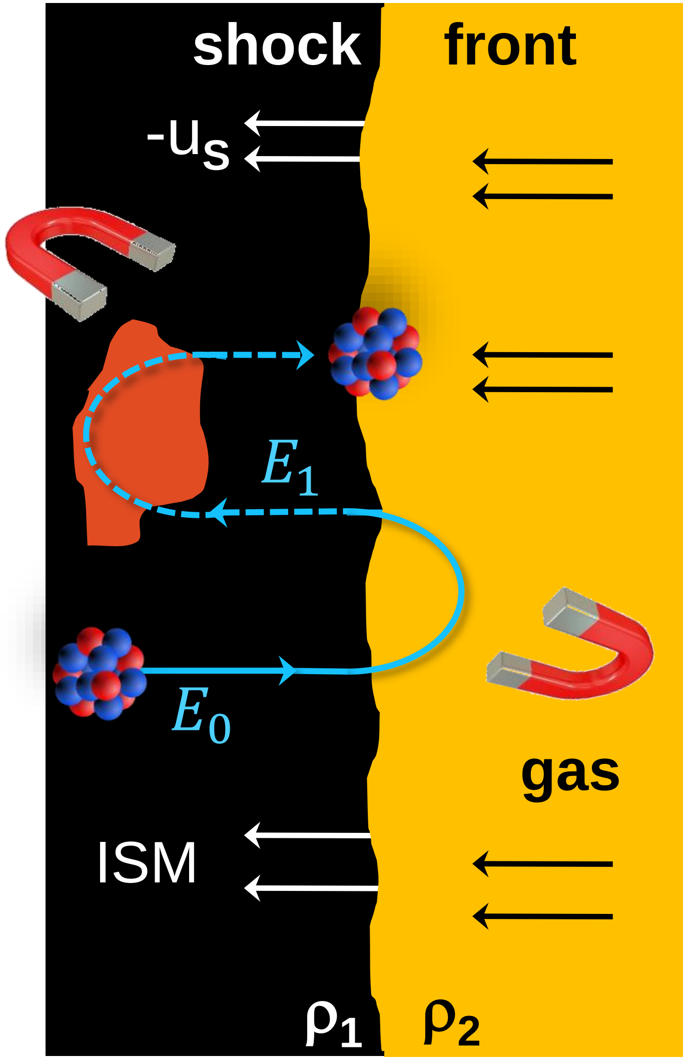
  … based on the **multiple passing** of a SN-shockfront

  … a collission-less process, i.e. **no energy losses** due to inelastic scattering in the gas of the shock front

- **Energy gain ΔE**

  for a single acceleration cycle (& independent of the direction of the nucleus) one obtains a net energy gain

$$\frac{\Delta E}{E} = \frac{u_S}{c} = \beta_S$$



Fermi accleration in shock fronts: many cycles

Summing up: single cycle vs. multiple cycles

- net energy gain ΔE per single accleration cycle

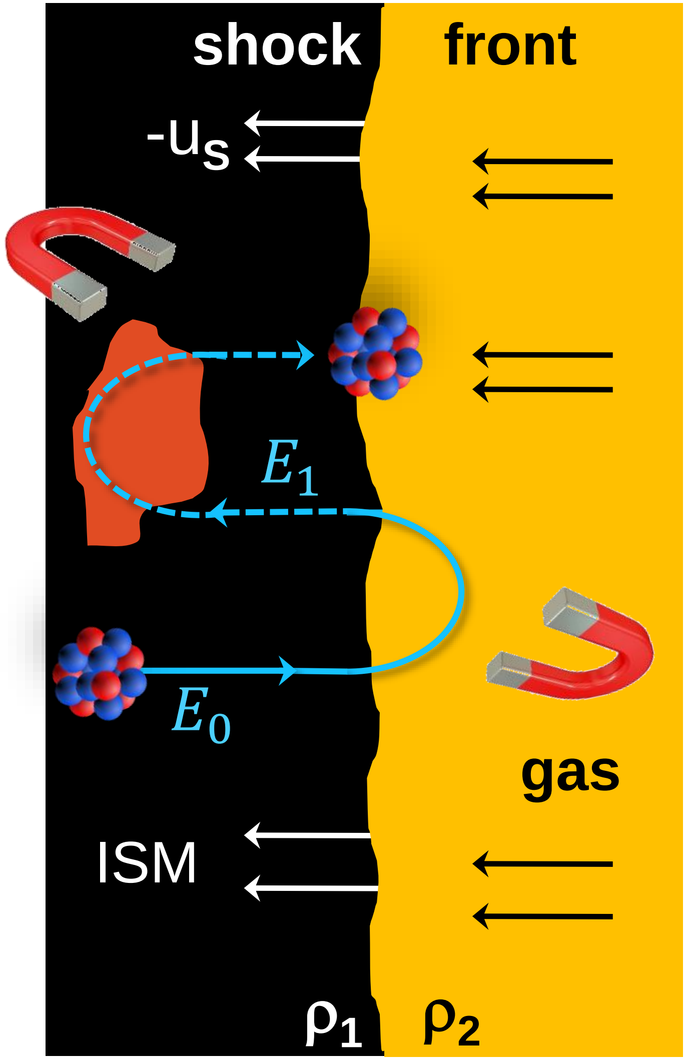
$$\Delta E = \alpha \cdot E$$

- CR **energy E** after **n accleration cycles** (for starting energy E_0)

$$E = E_0 \cdot (1+\alpha)^n$$

- number n of acceleration cycles to reach max. energy E:

$$n = \frac{\ln(E / E_0)}{\ln(1+\alpha)}$$



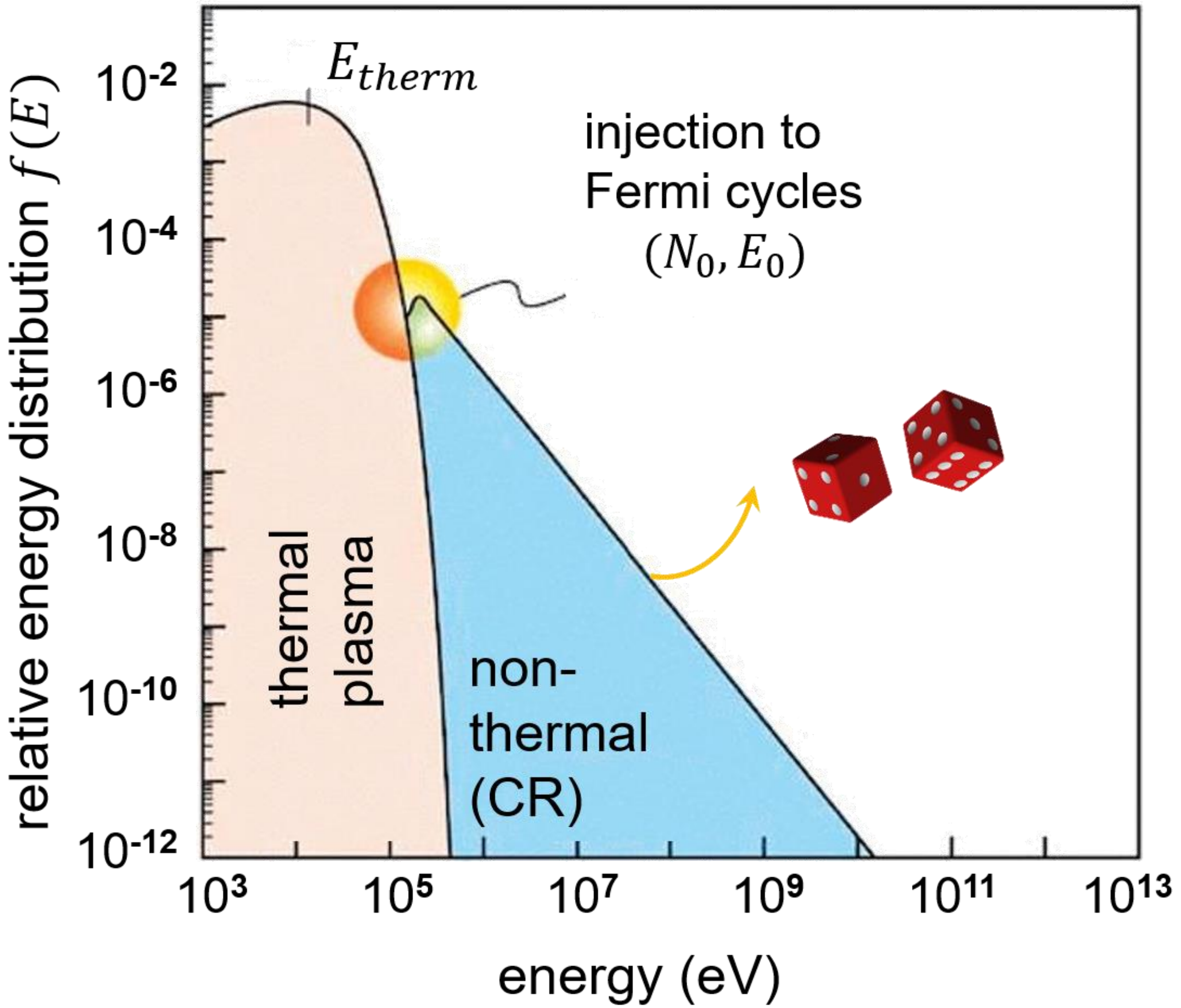
Origin of the CR power law distribution

- **power law distribution due to Fermi acceleration**

- taking into account an energy-dependent probability P for particle losses during the acceleration cycle, we obtain a power-law distribution

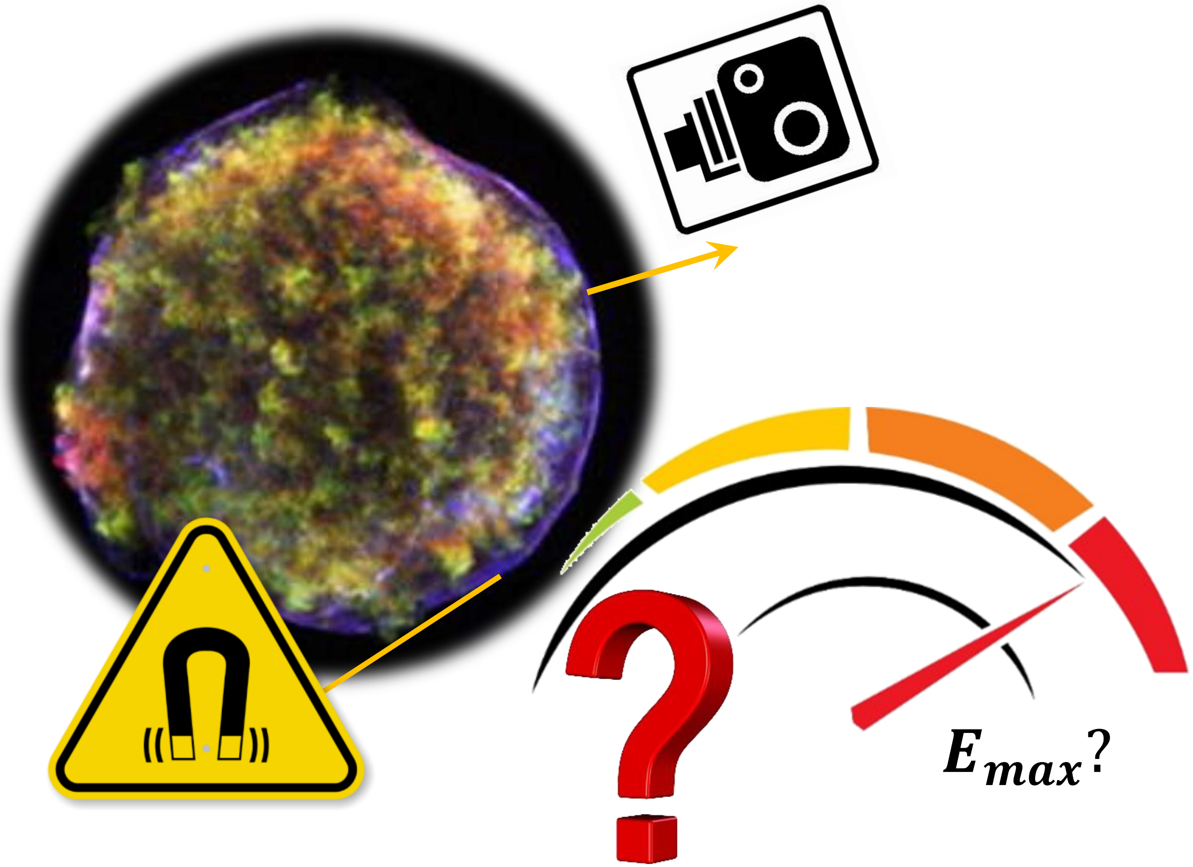
$$\frac{dN(E)}{dE} \sim E^{-2.7}$$

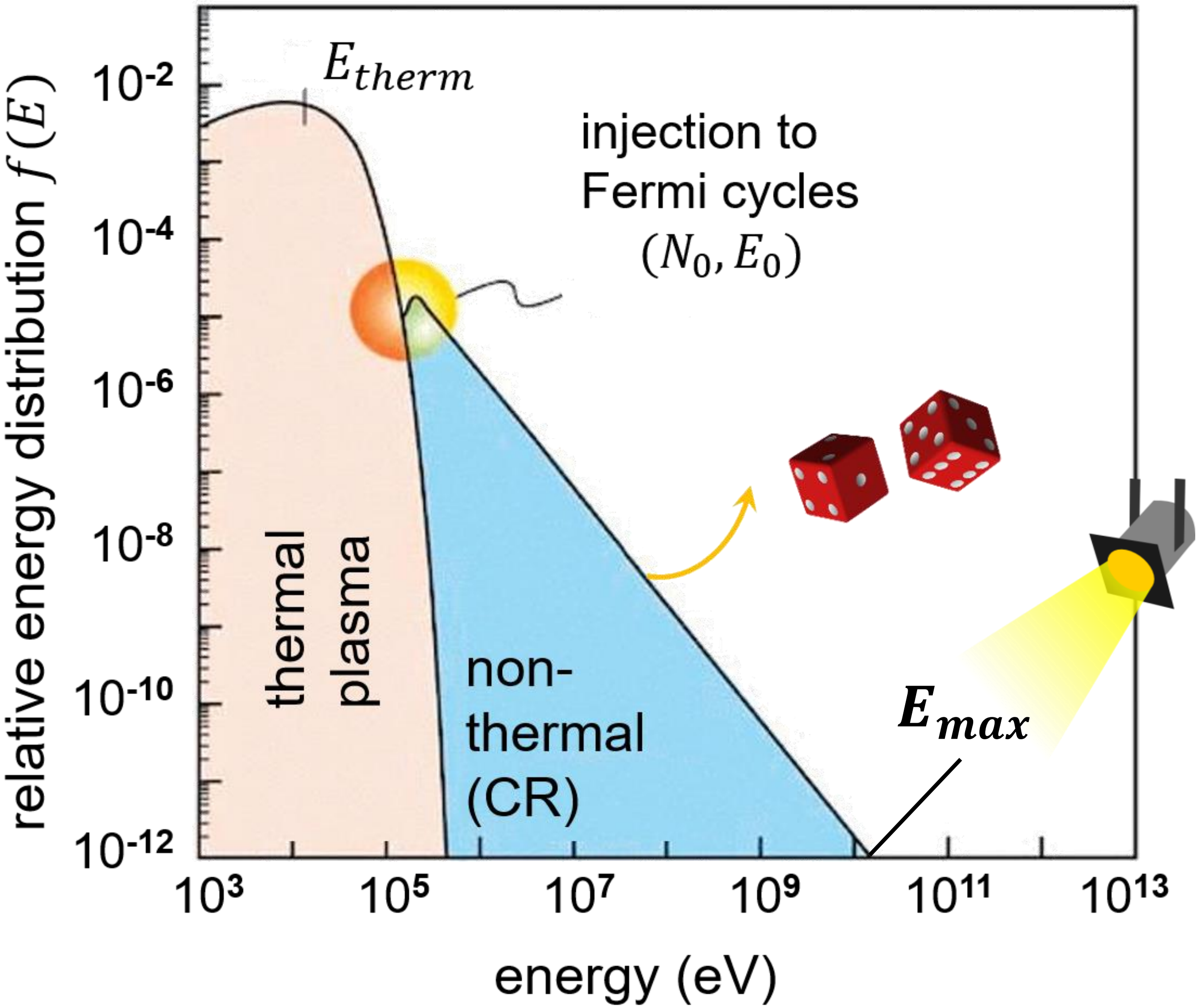
power law spectrum



Maximum energy of CR due to SN shocks?

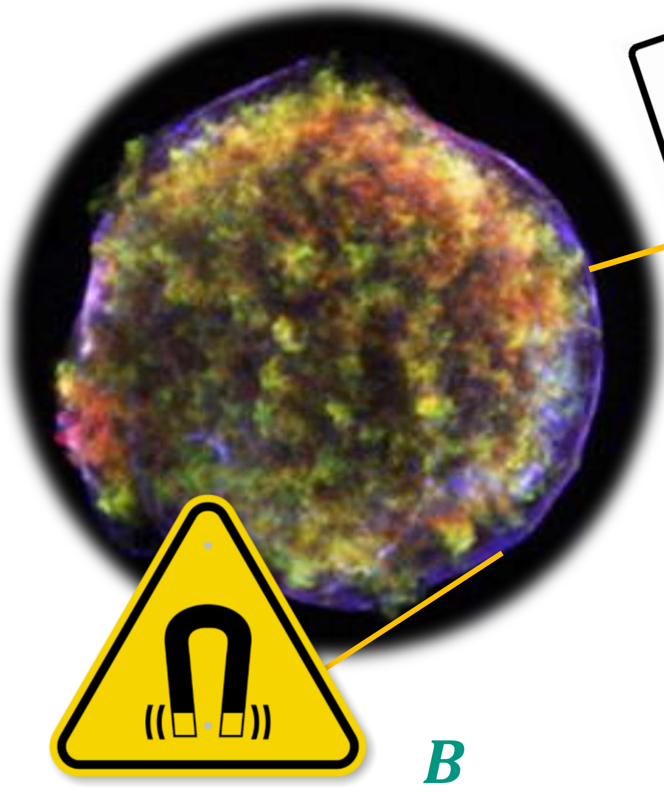
- **What are the parameters defining the maximum CR energy E_{max}?**





Maximum energy of CR via famous Hillas formula

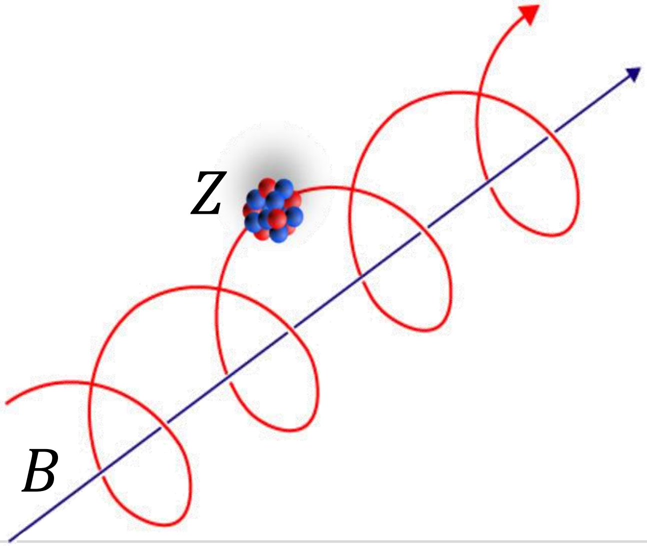
- **A.M. Hillas: cosmic acclerators use a B-field of size L to guide particles**




A. M. Hillas

- **maximum energy E_{max}** of a particle of **charge Z** in a SN shock front (see dimensions!)

$$E_{max} \sim \beta_S \cdot Z \cdot B \cdot L$$



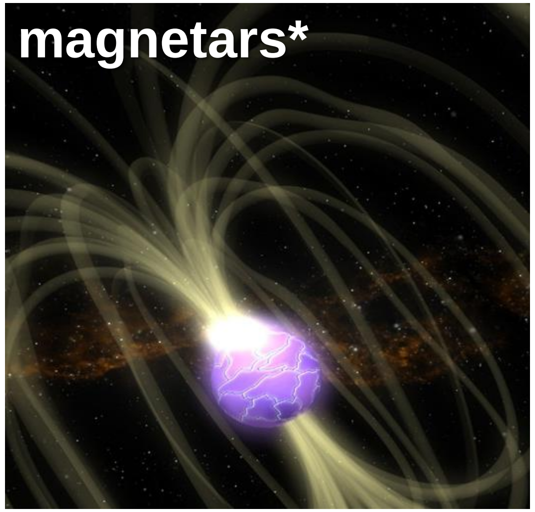
particle:
- nuclear charge Z

source:
- field strength B
- size L
- shock velocity β_S

Hillas plot for UHECRs up to $E_{max} = 10^{20}\ eV$

- candidate sites

small L / large B

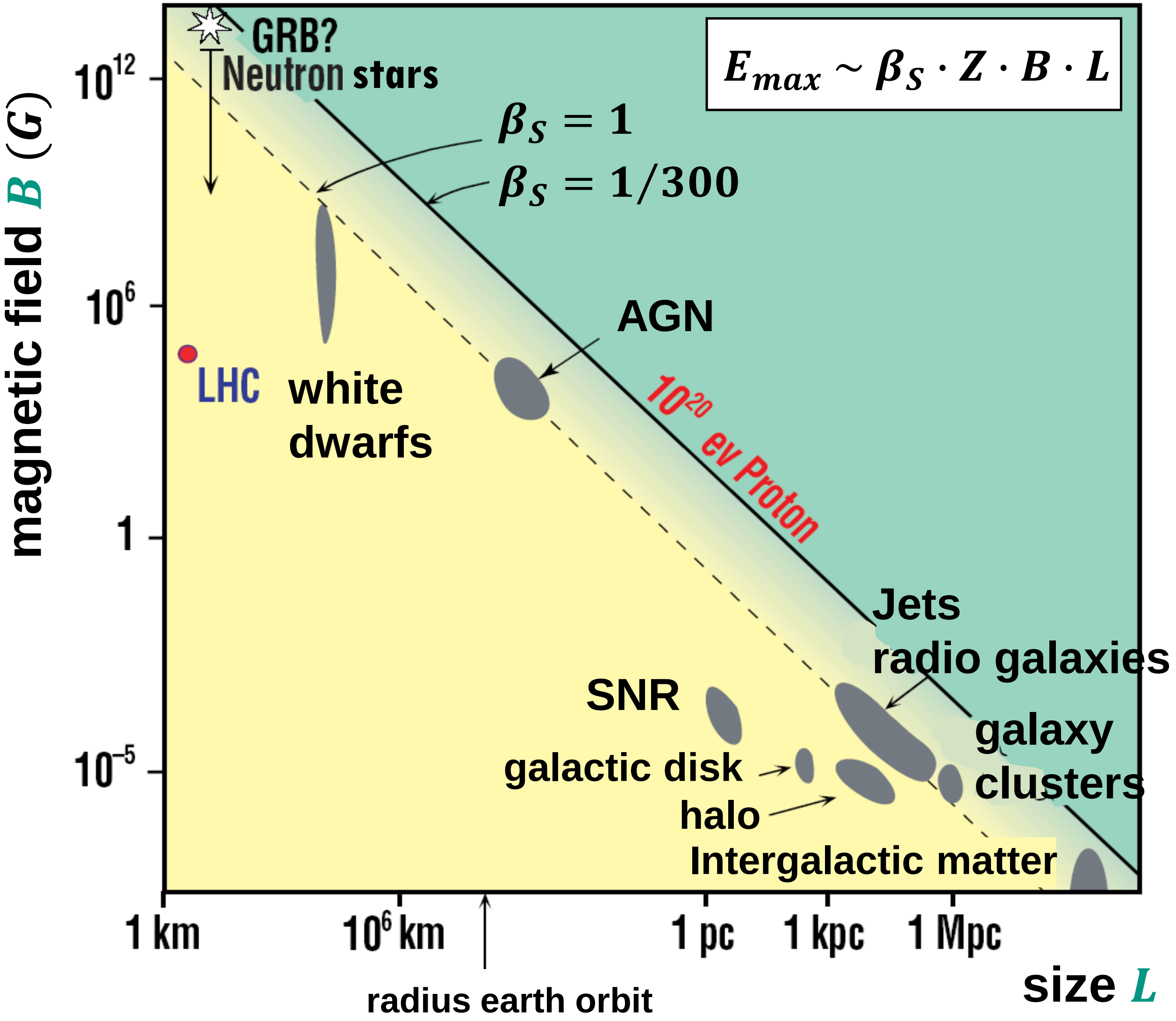


B-field

$\ldots 10^9\ T$

dimension

$10\ km \ldots$



large L / small B

B-field

$\ldots 10^{-9}\ T$

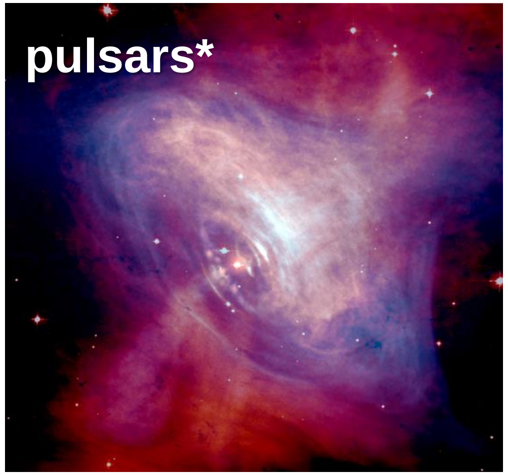
dimension

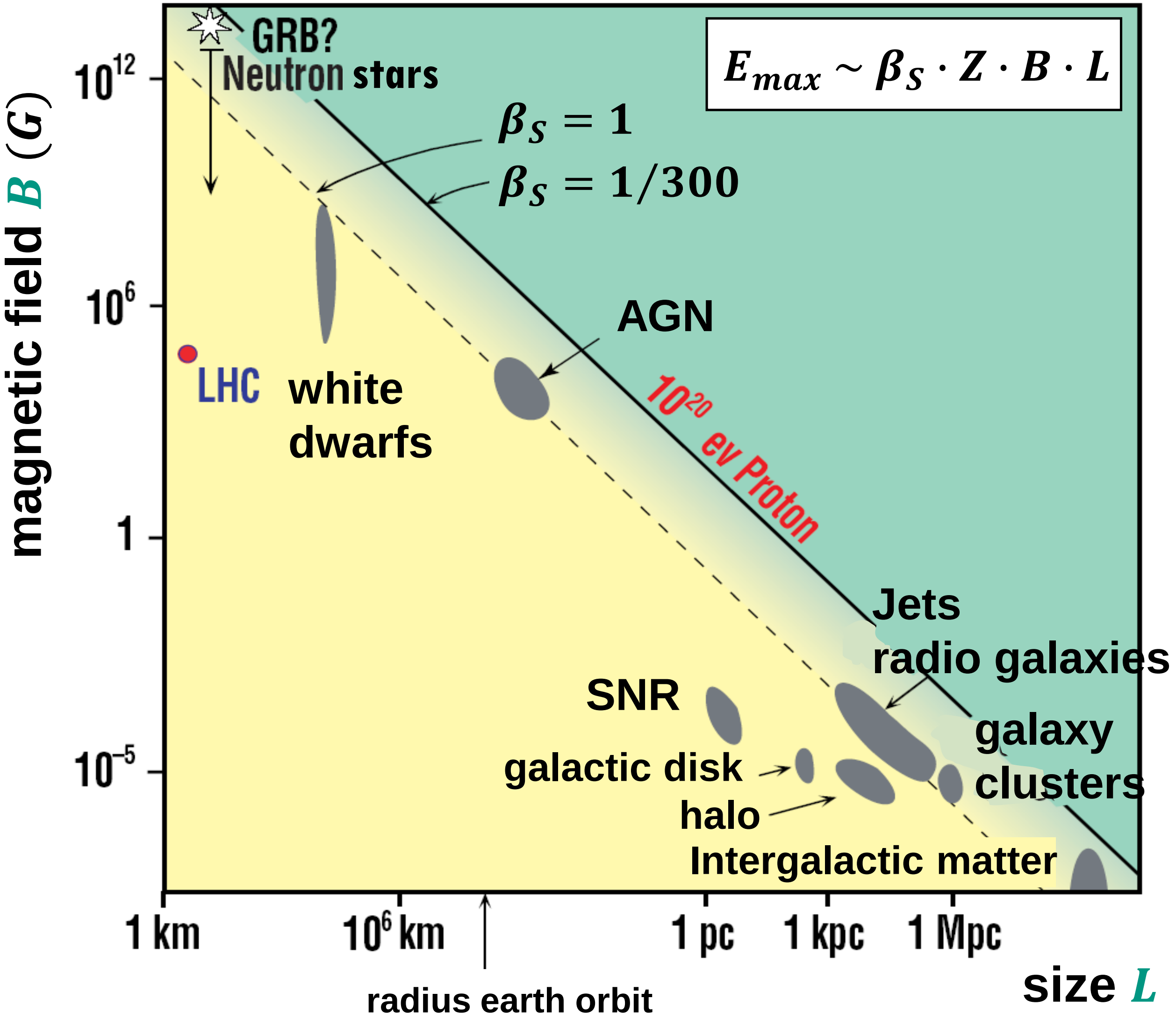
$1\ Mpc \ldots$

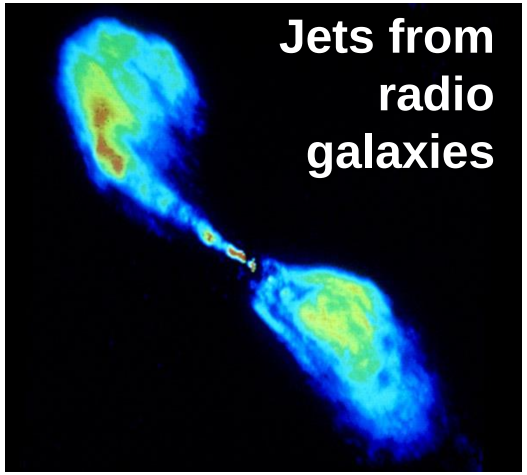
*s. ATP-2 summer term 2023

Sources of UHECRs up to $E_{max} = 10^{20}\ eV$

- candidate sites







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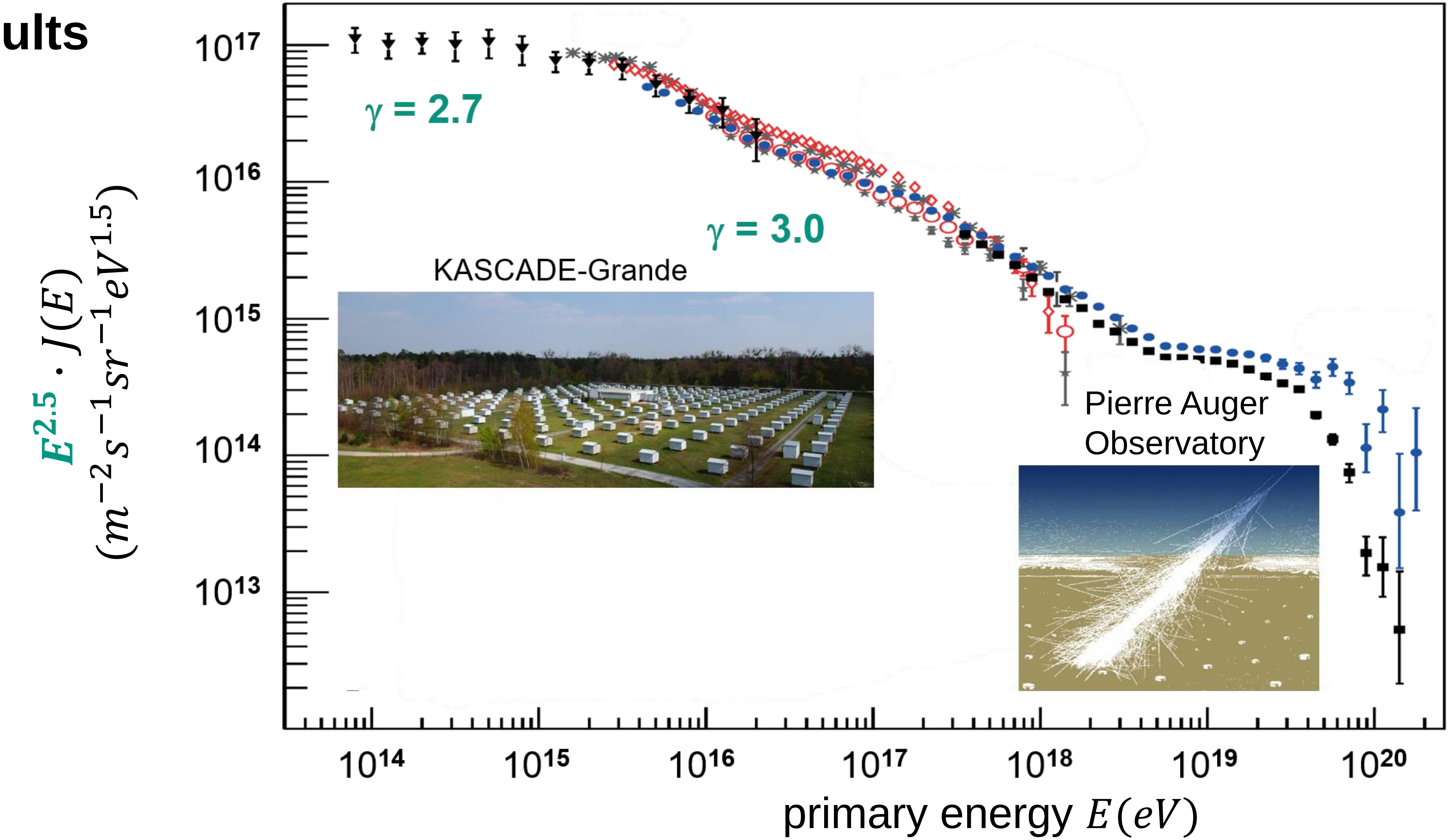
Energy spectrum of UHECR

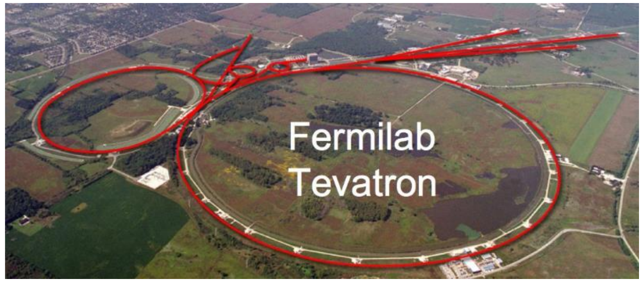
- **Overview of results**

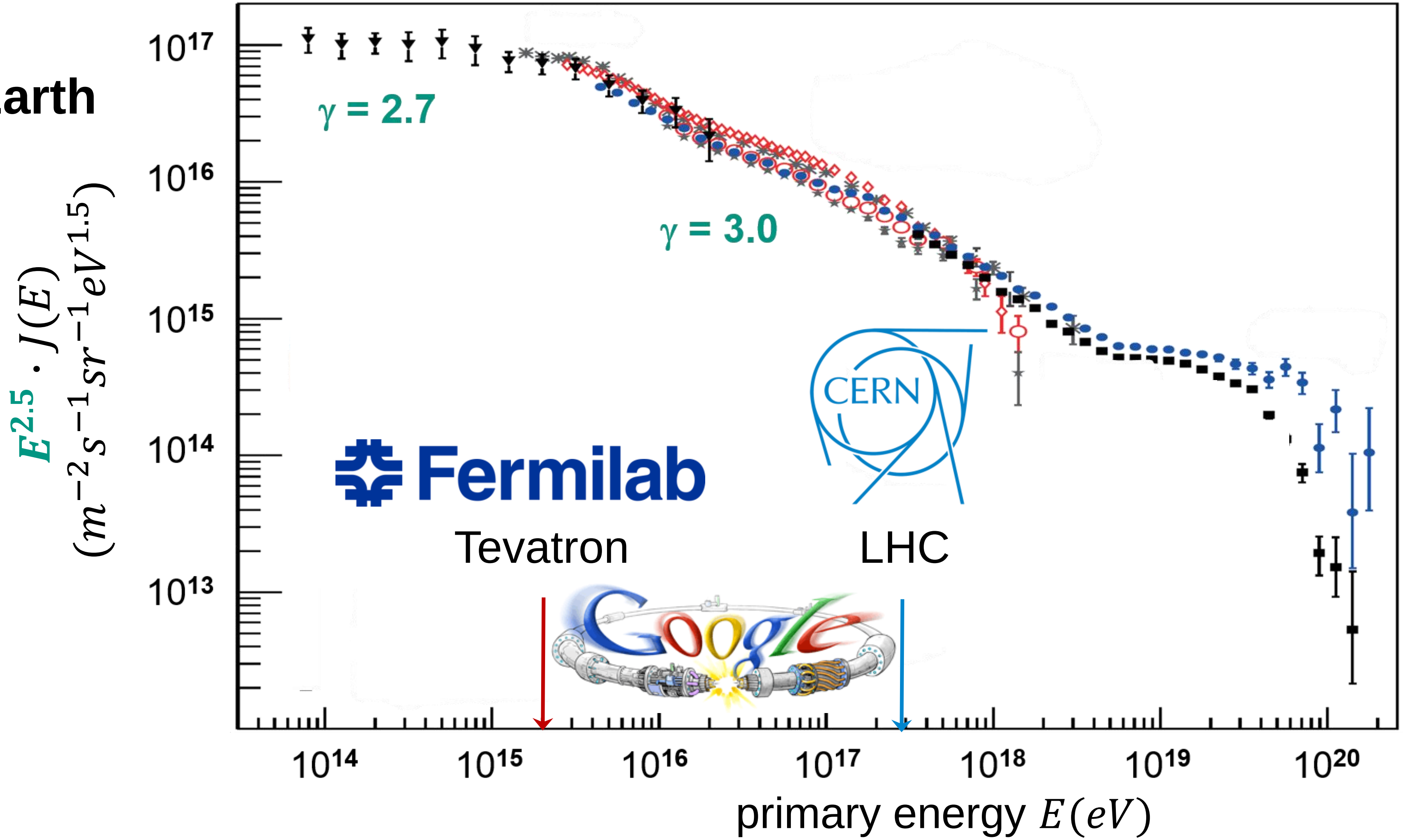
  - measurements of air showers arrays with KIT participation



Energy spectrum of UHECR & acclerators

- **Comparison to accelerators on Earth**





Energy spectrum of high-energy CRs & features

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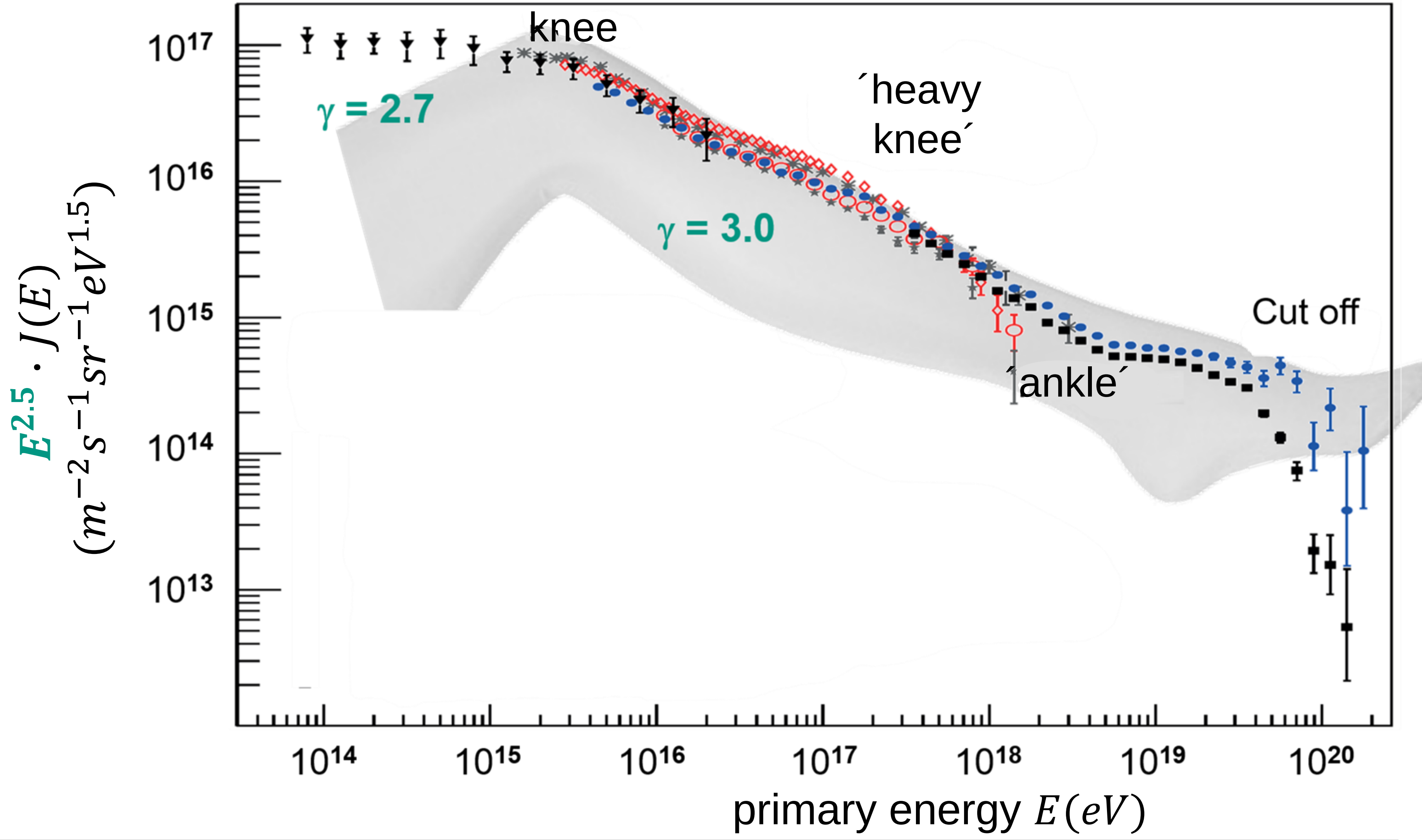
- **Energy spectrum influenced by:**

- change of mass composition (**light → heavy**): Hillas relation

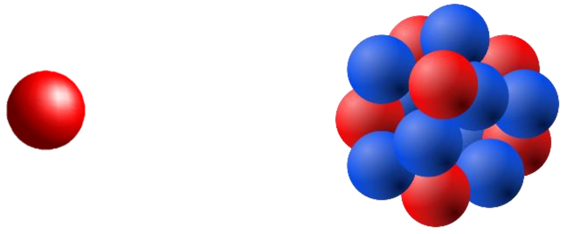
- change of sources & CR acceleration mechanisms (**galactic → extra-galactic**)



Energy spectrum of high-energy CRs & features

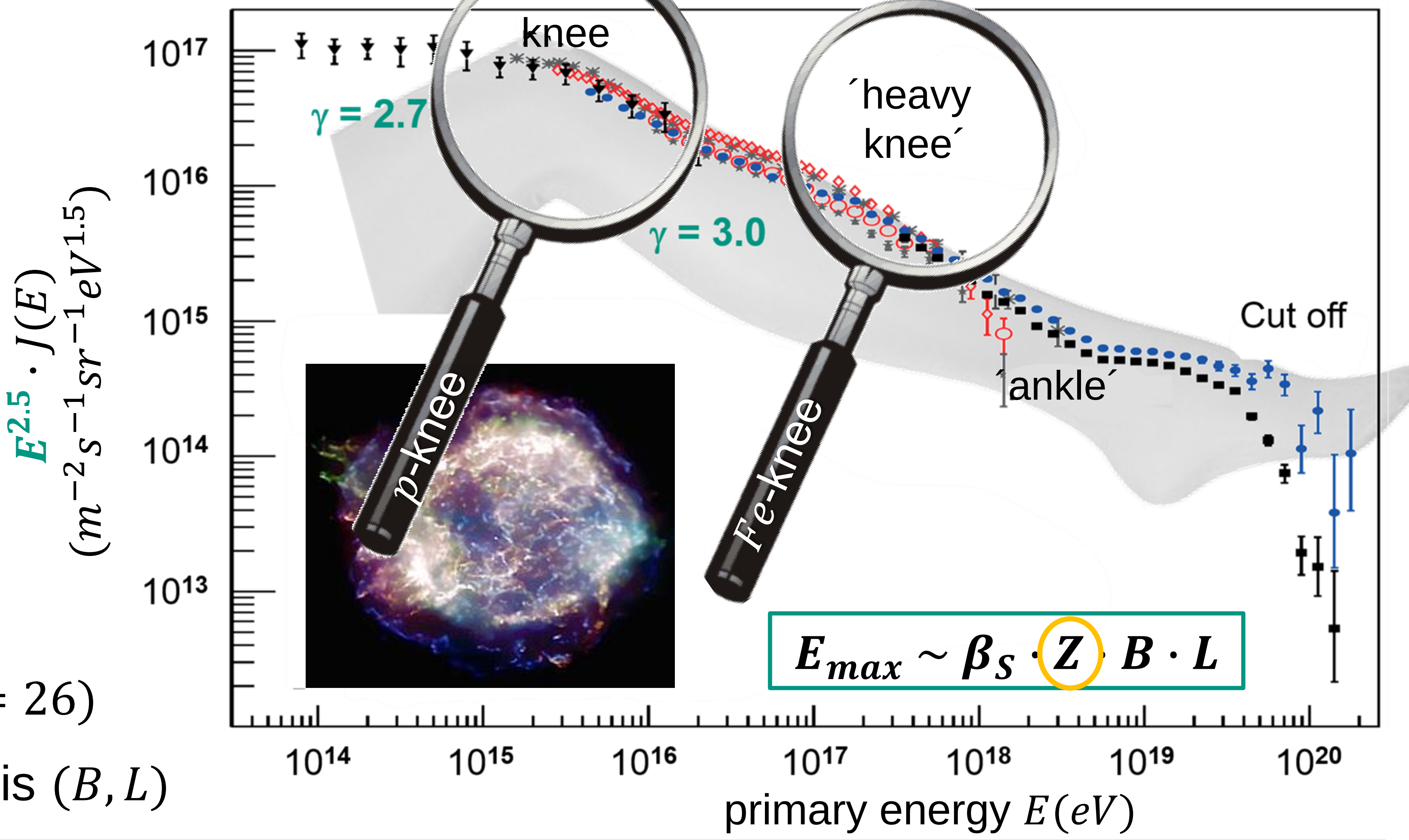
- **Energy spectrum of galactic CRs:**

  - change of mass composition (**light → heavy**): Hillas relation



$p\ (Z = 1)$ $^{56}Fe\ (Z = 26)$

sources: SNR in galaxis (B, L)



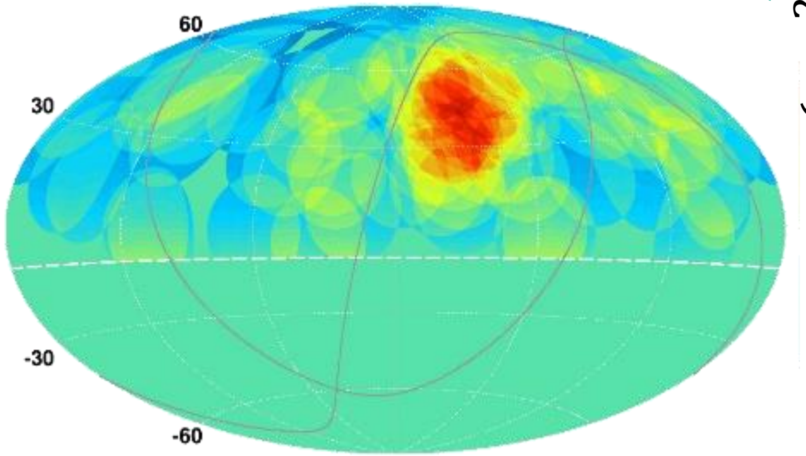
$$E_{max} \sim \beta_S \cdot Z \cdot B \cdot L$$

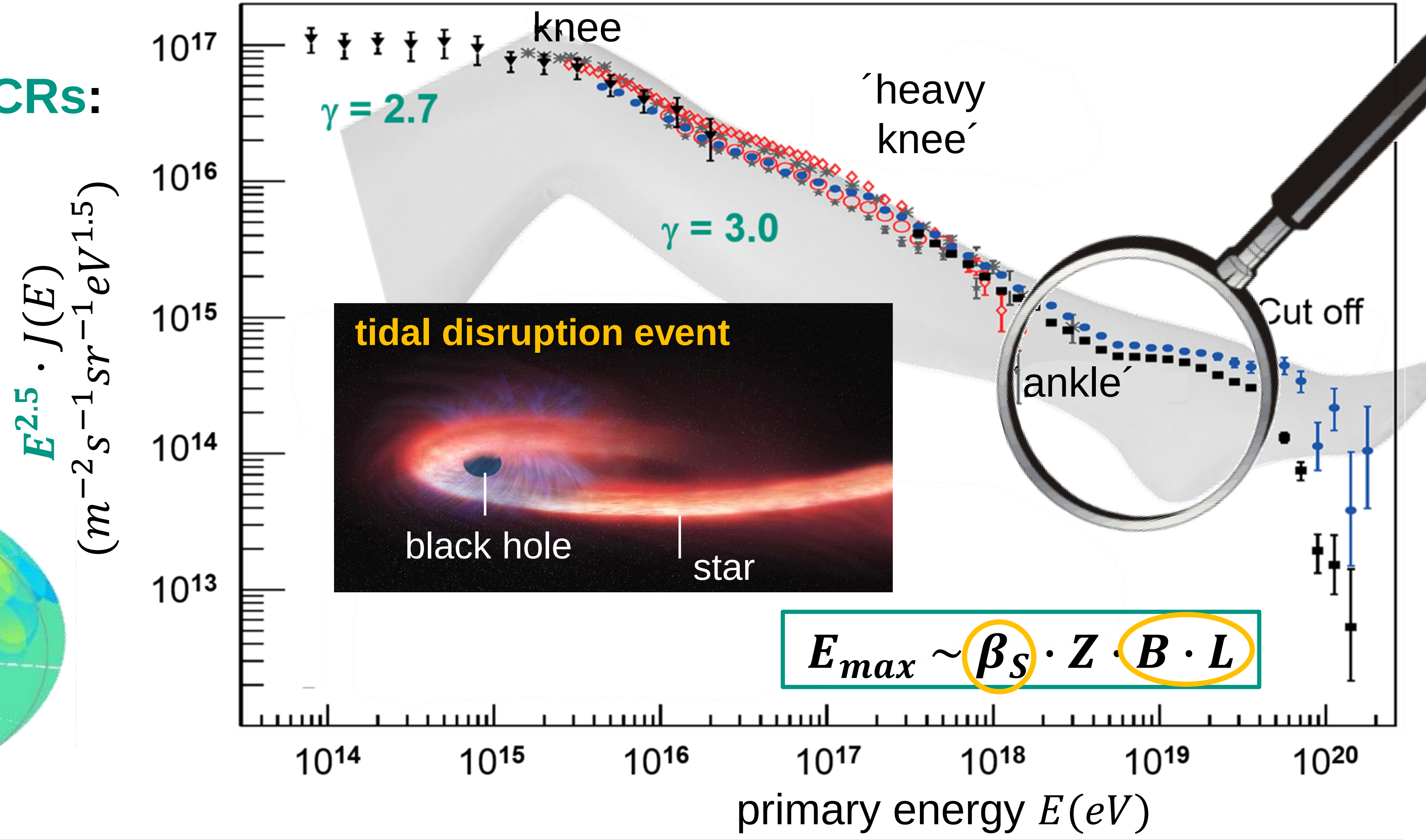
Energy spectrum of high-energy CRs & features

- **Energy spectrum of extra-galactic CRs:**

- change of acceleration sites

tidal disruptions?



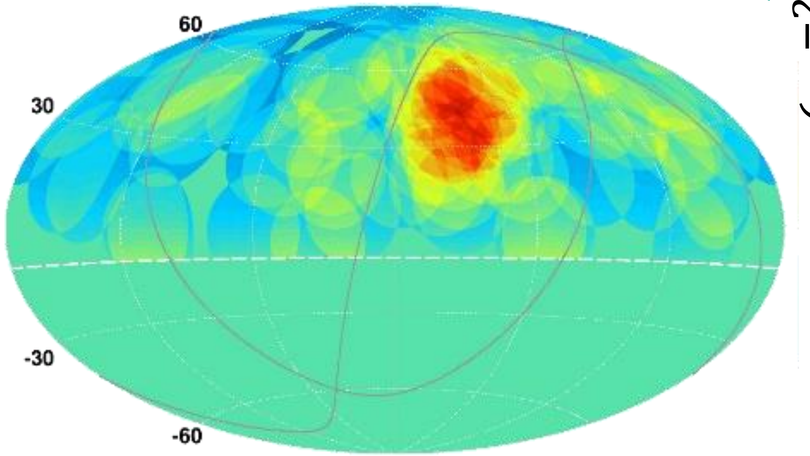


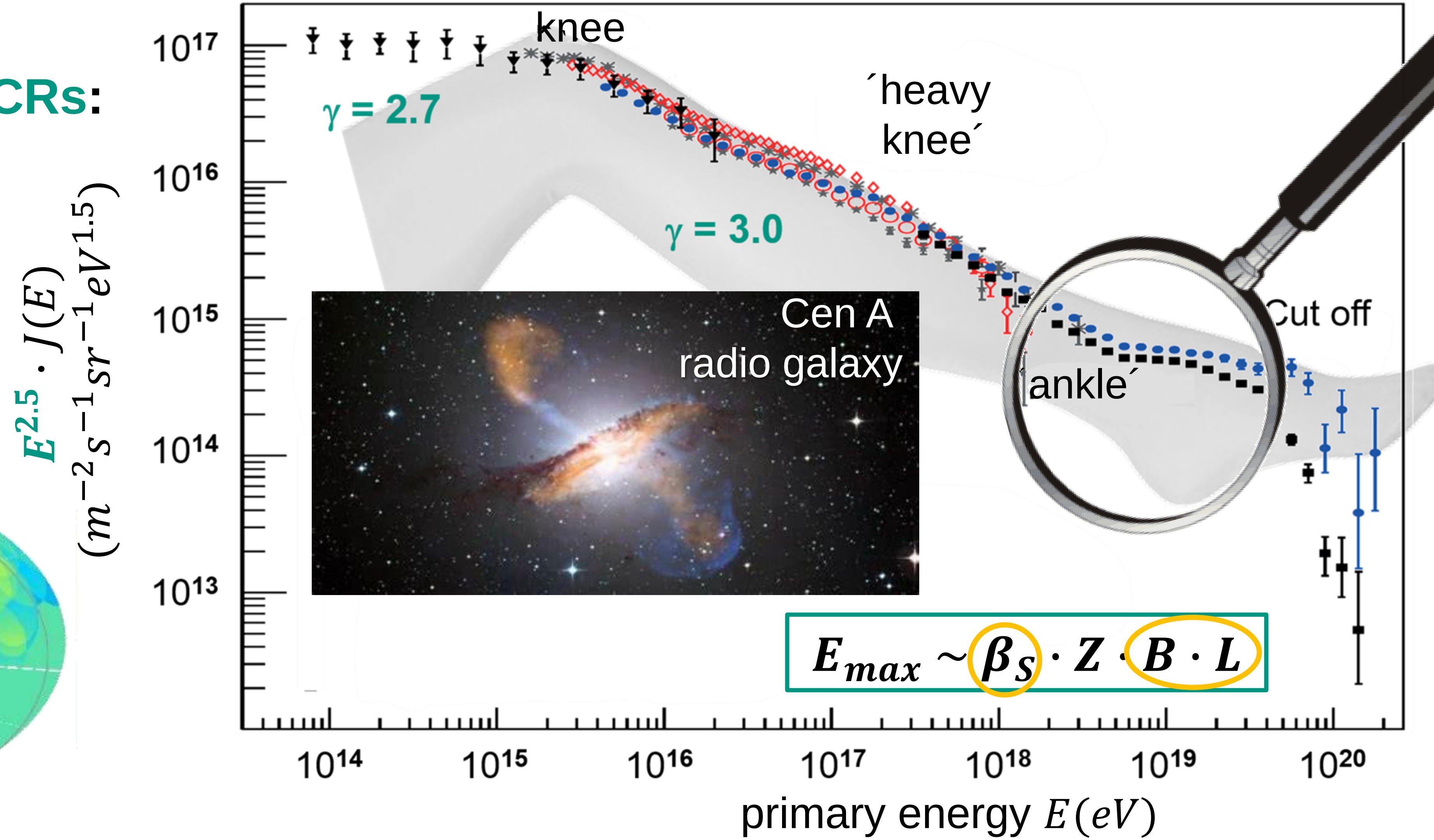
Energy spectrum of high-energy CRs & features

- **Energy spectrum of extra-galactic CRs:**

- change of acceleration sites

radio galaxies?



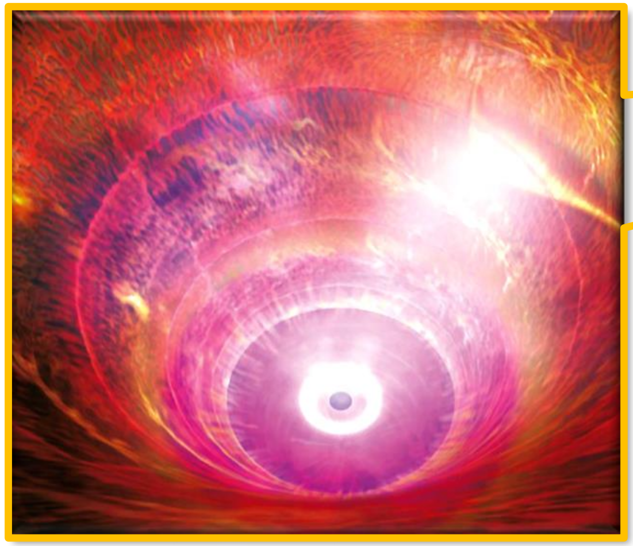


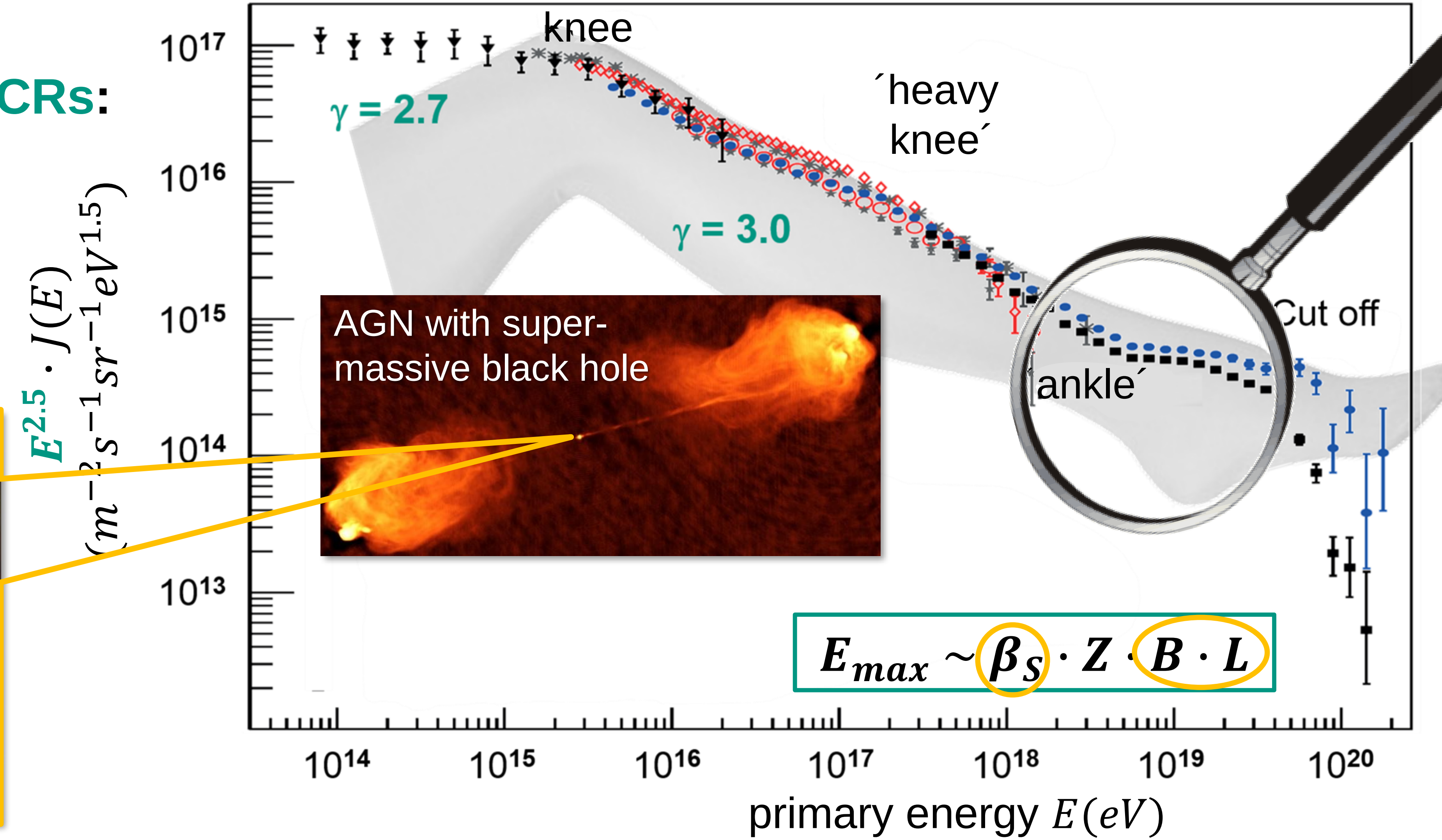
Energy spectrum of high-energy CRs & features

- **Energy spectrum of extra-galactic CRs:**

- change of acceleration sites

AGNs?



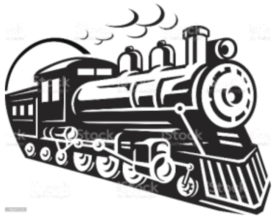


Energy spectrum of UHECRs & cut-off

- **Energy spectrum of extra-galactic CRs:**

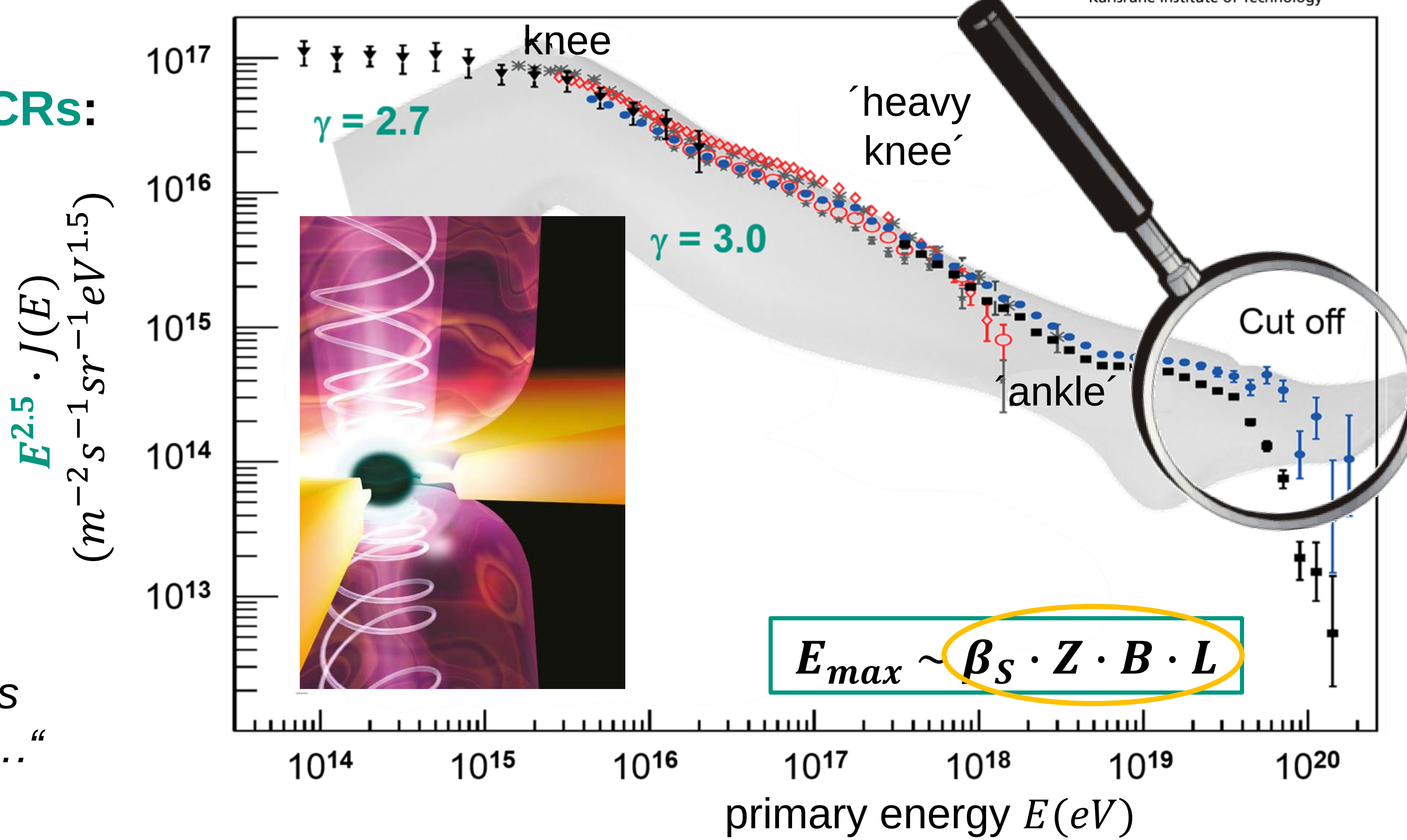
- what causes the cut-off at $\sim 10^{20} eV$?

a) the accelerators ´run out of steam´



„there simply is an upper end…“

A. M. Hillas



Energy spectrum of UHECRs & cut-off

- **Energy spectrum of extra-galactic CRs:**

- what causes the cut-off at $\sim 10^{20} eV$?

b) cosmic back-ground fields (CMB) limit range

Greisen, ***Zatsepin*** & ***Kuzmin (GZK)***