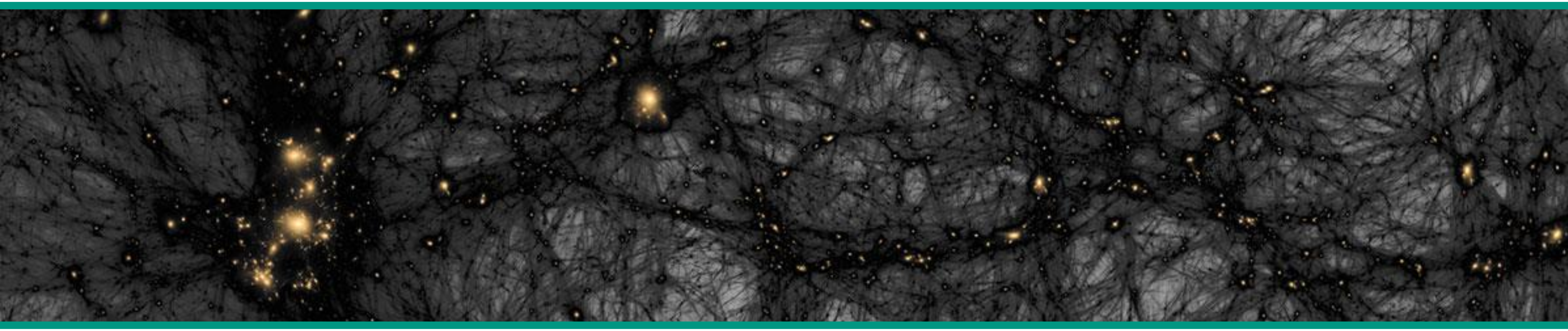
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 5 Nov. 9, 2023



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 (Greisen–fits to be matched 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**

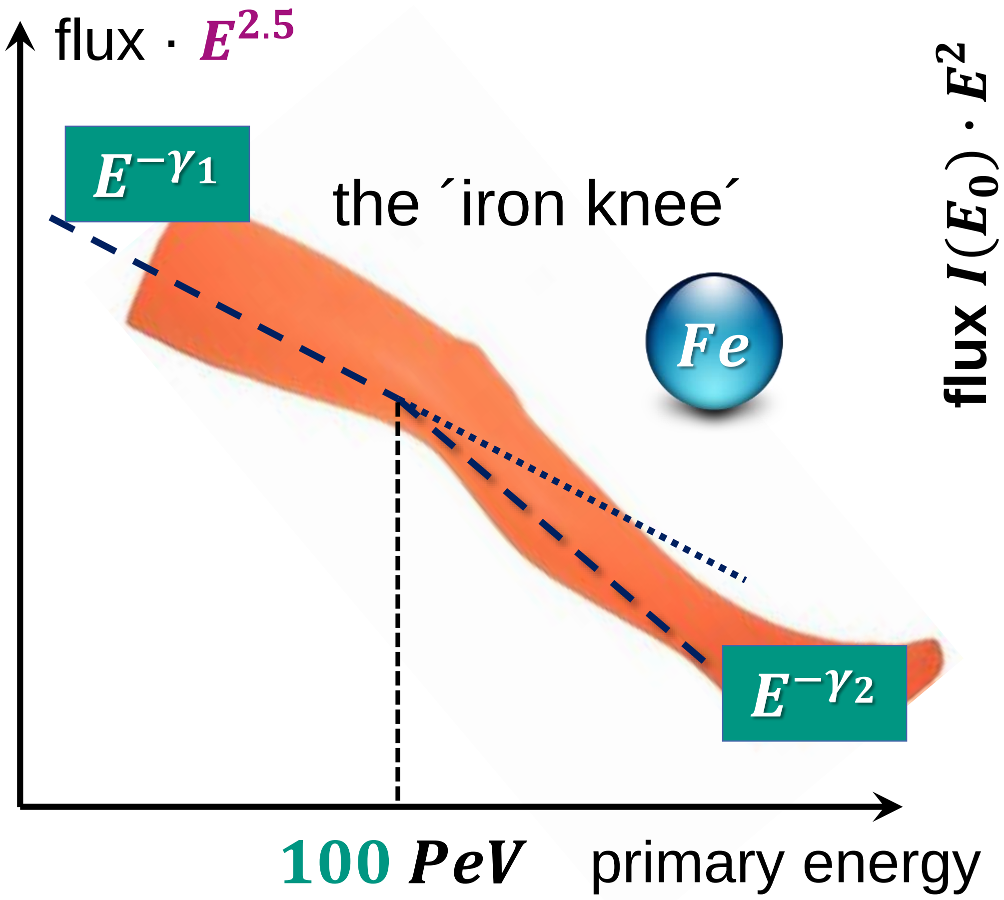
- **Pioneering air shower experiment $KASCADE$ at KIT Campus North**

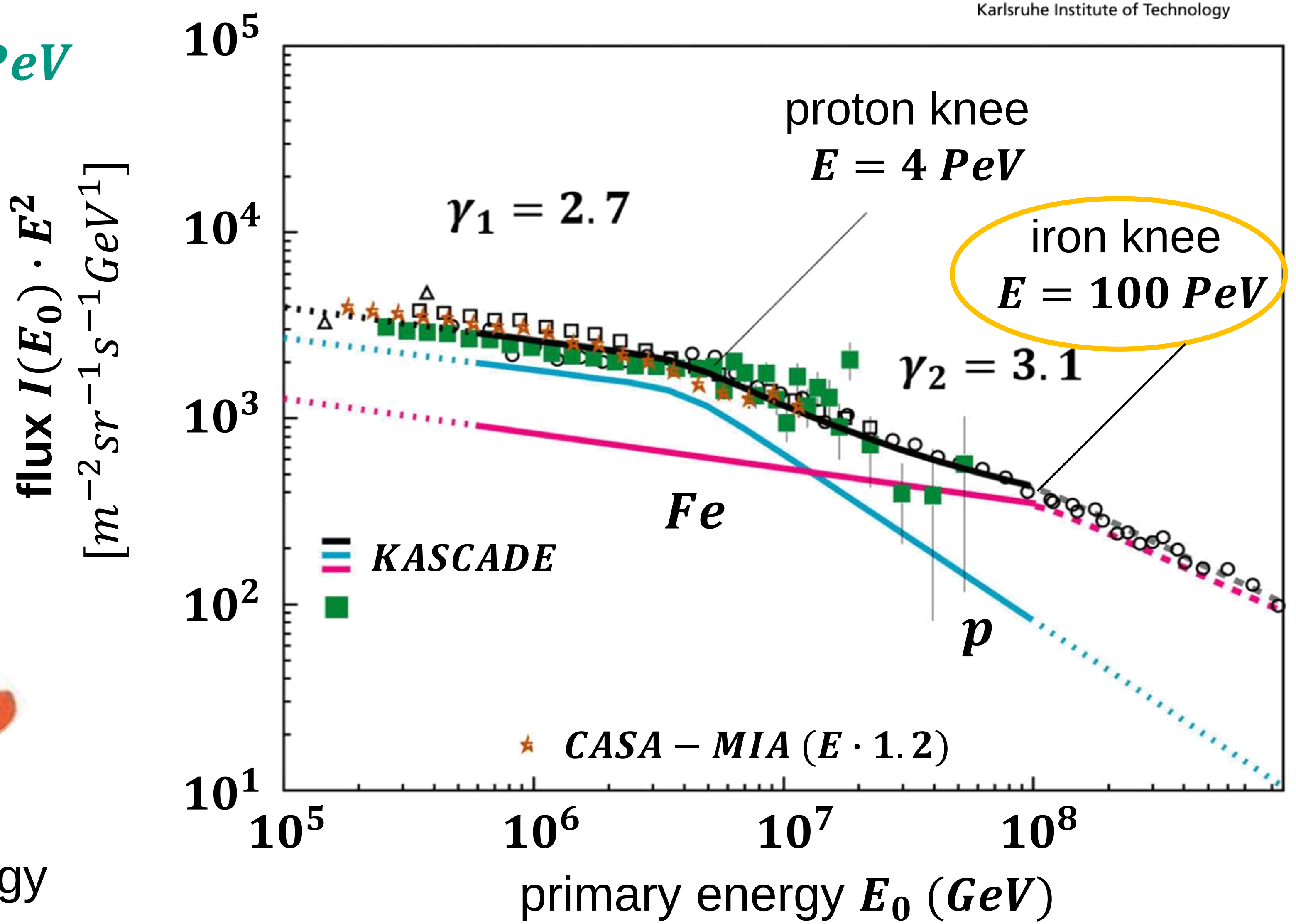
  - components: large scintillator array, muon tunnel, central hadron calorimeter

  - extension to $KASCADE - Grande$: at knee – **change of mass composition**

Power–Law feature: element–specific ´knees´

- observations at $E = 100\ PeV$

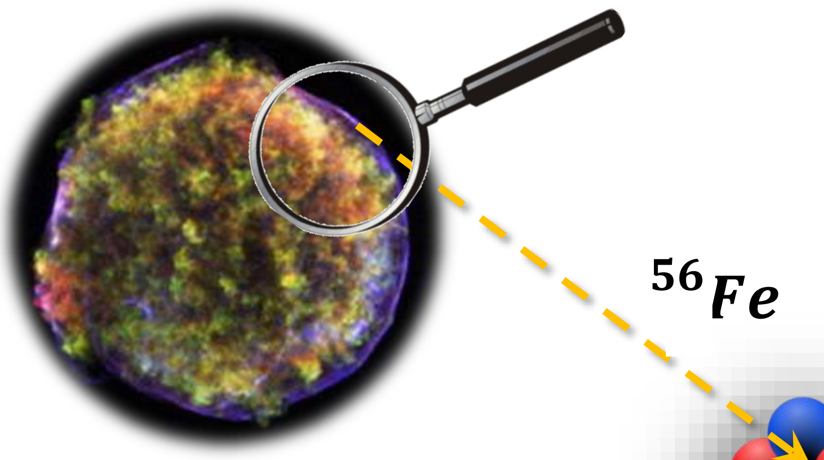


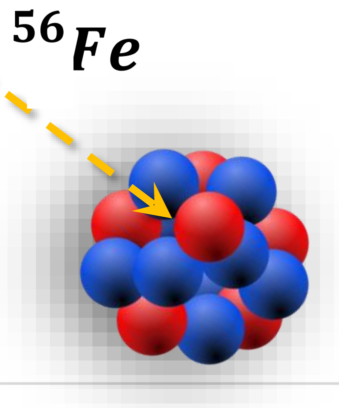


Power–Law feature: element–specific ´knees´

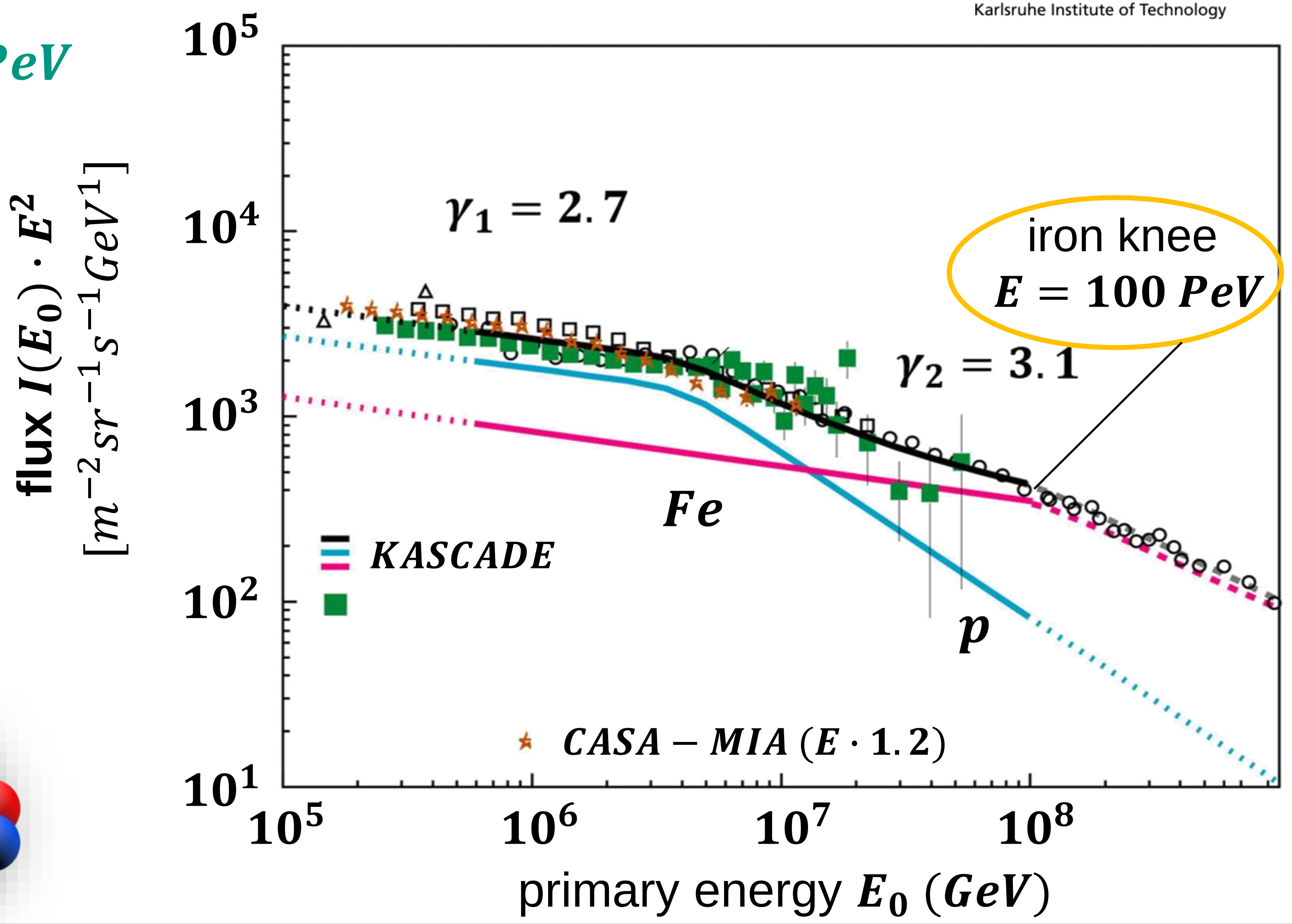
- **observations at $E = 100\ PeV$**

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





open: acceleration
mechanism ?



Knee due to particle losses during propagation?

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

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

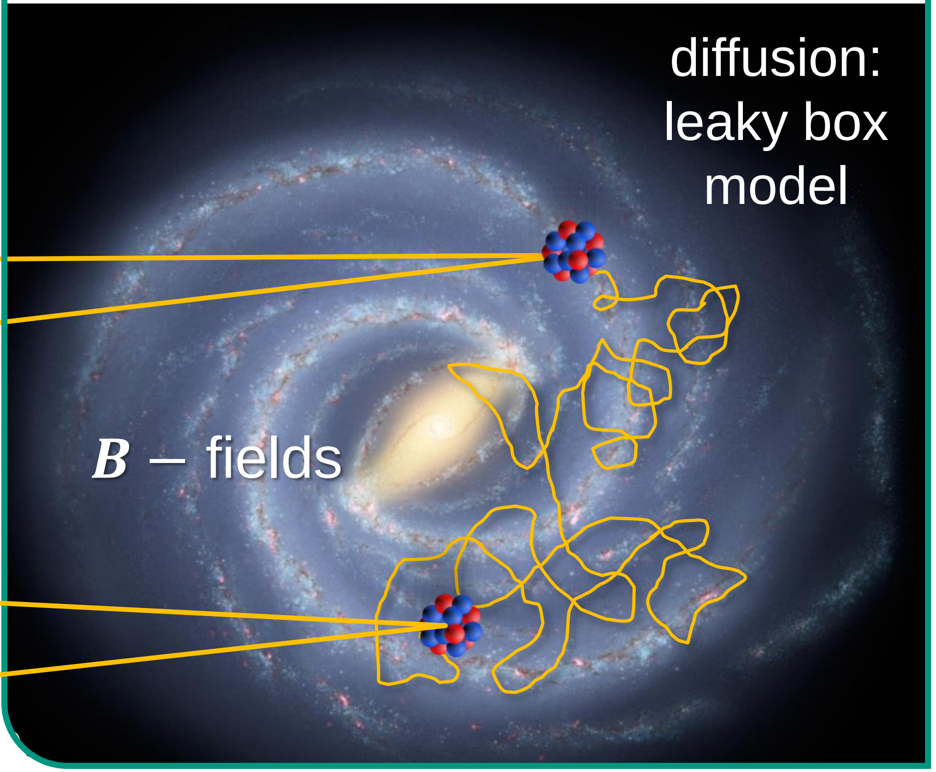
  - **detailed modelling** of effects due to CR propagation:

    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 $B \sim$ few μG**

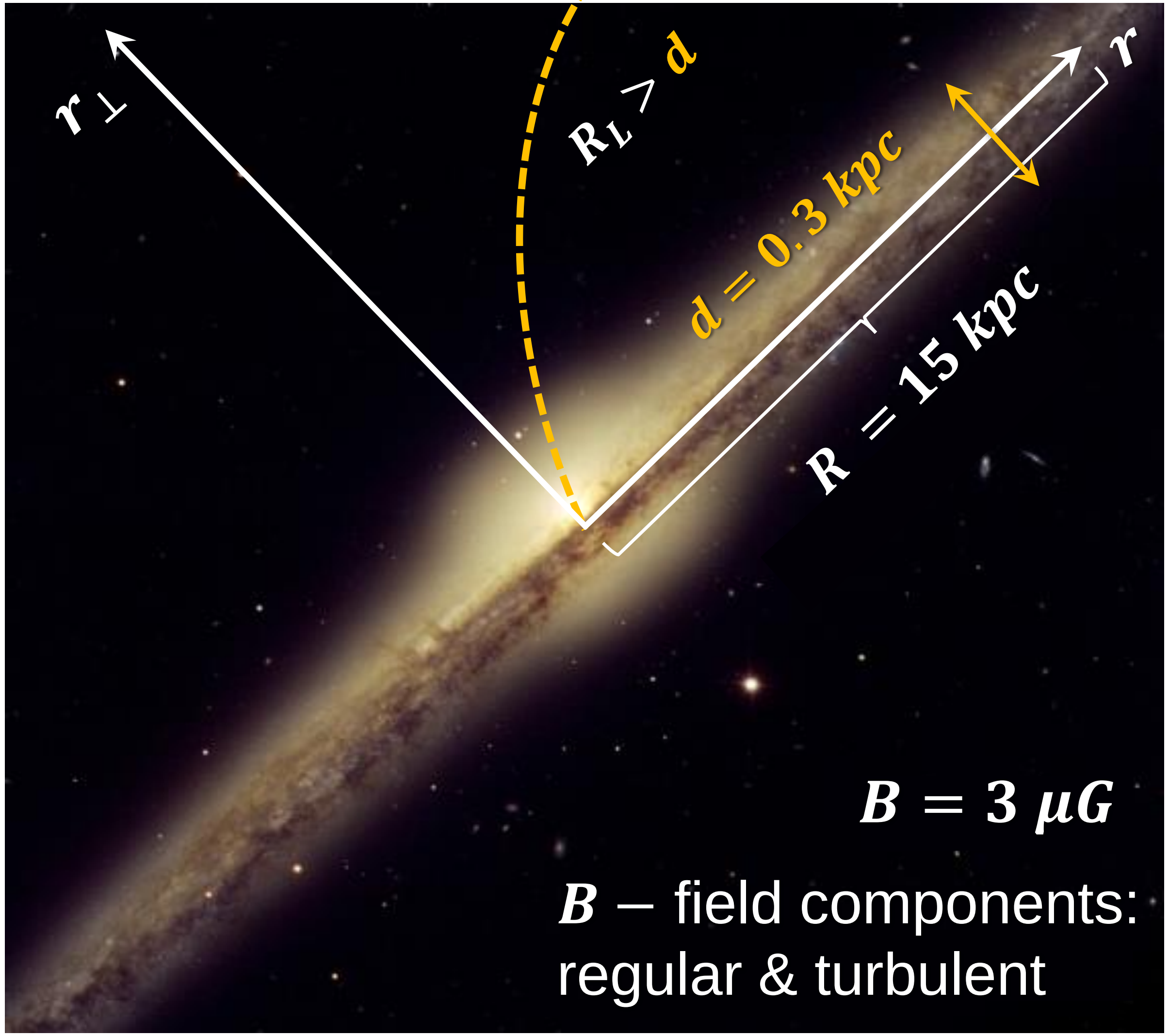
  - important parameter:
    Larmor radius R_L

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

  - for CRs at **high** energies:

$$R_L > d = 0.3\,kpc$$

⇨ these CR nuclei will **leave** the galaxis



Propagation of cosmic rays in our galaxy

- **Charged CRs: guided by galactic magnetic fields with $B \sim$ few μG**

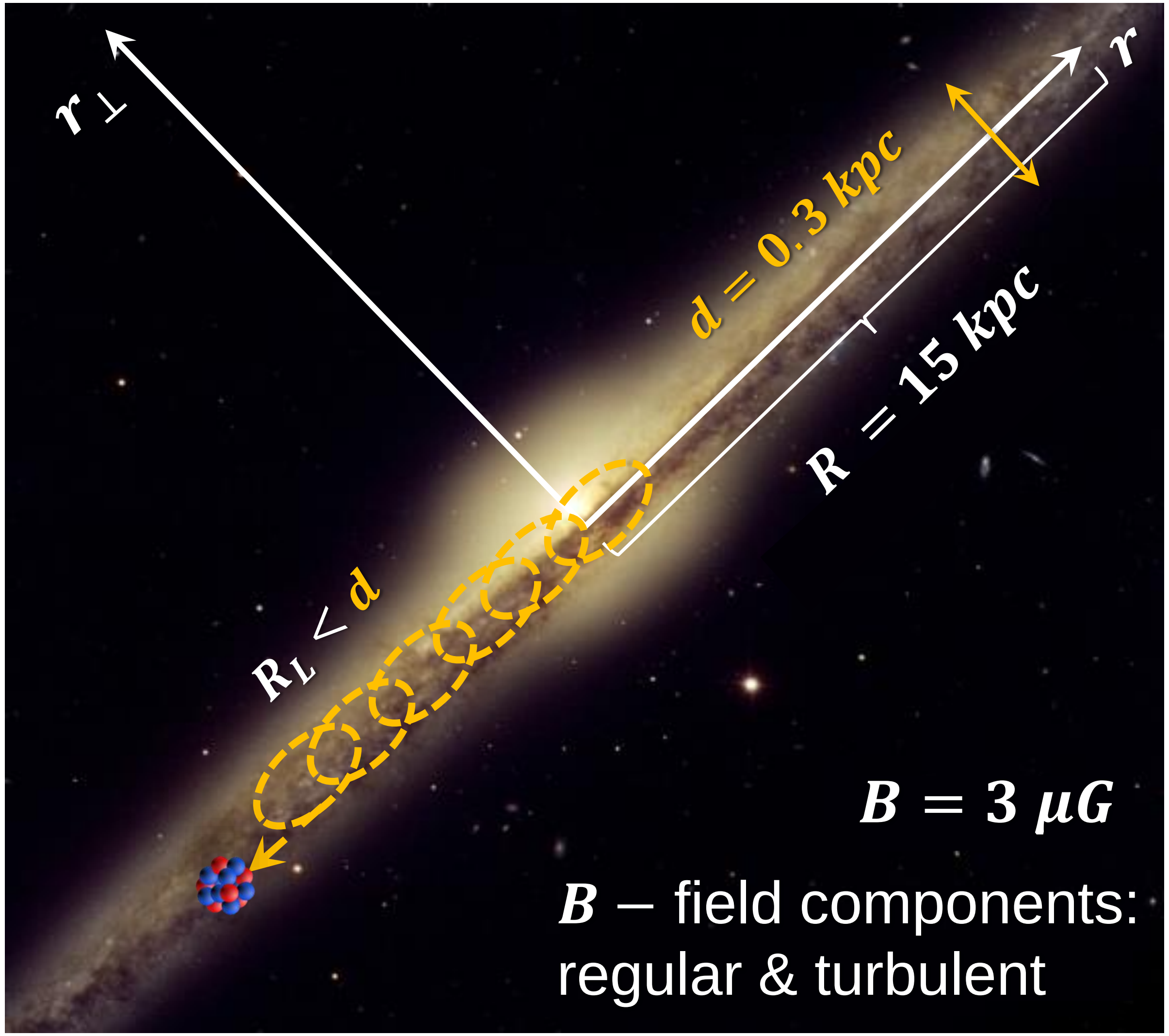
  - important parameter:
    Larmor radius R_L

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

  - for CRs at **low** energies:

$$R_L < d = 0.3\,kpc$$

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



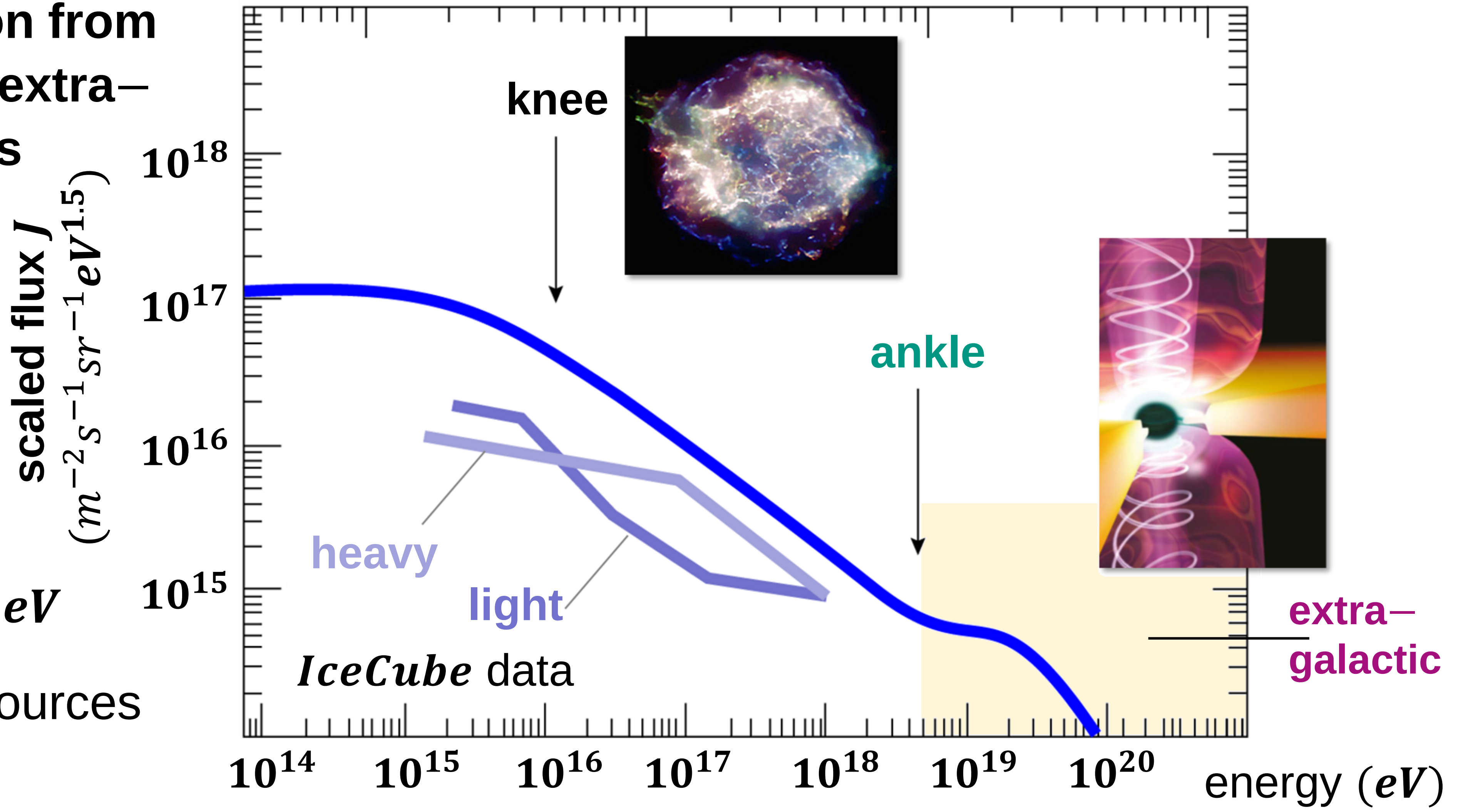
CR spectrum feature: the ankle

- **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

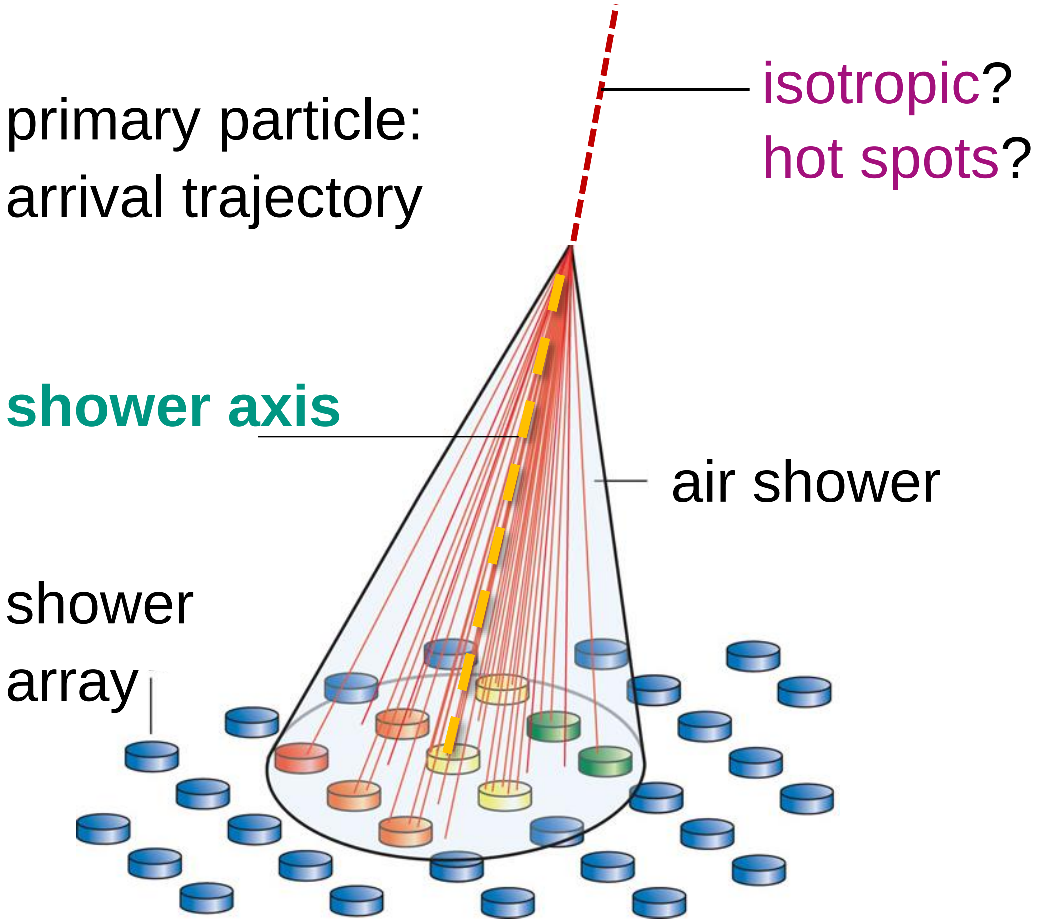
What is the degree of isotropy of cosmic rays?

- **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 $E \sim 10^{15}\,eV$

Karlsruhe Institute of Technology

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

$KASCADE$ results (> 10 years):

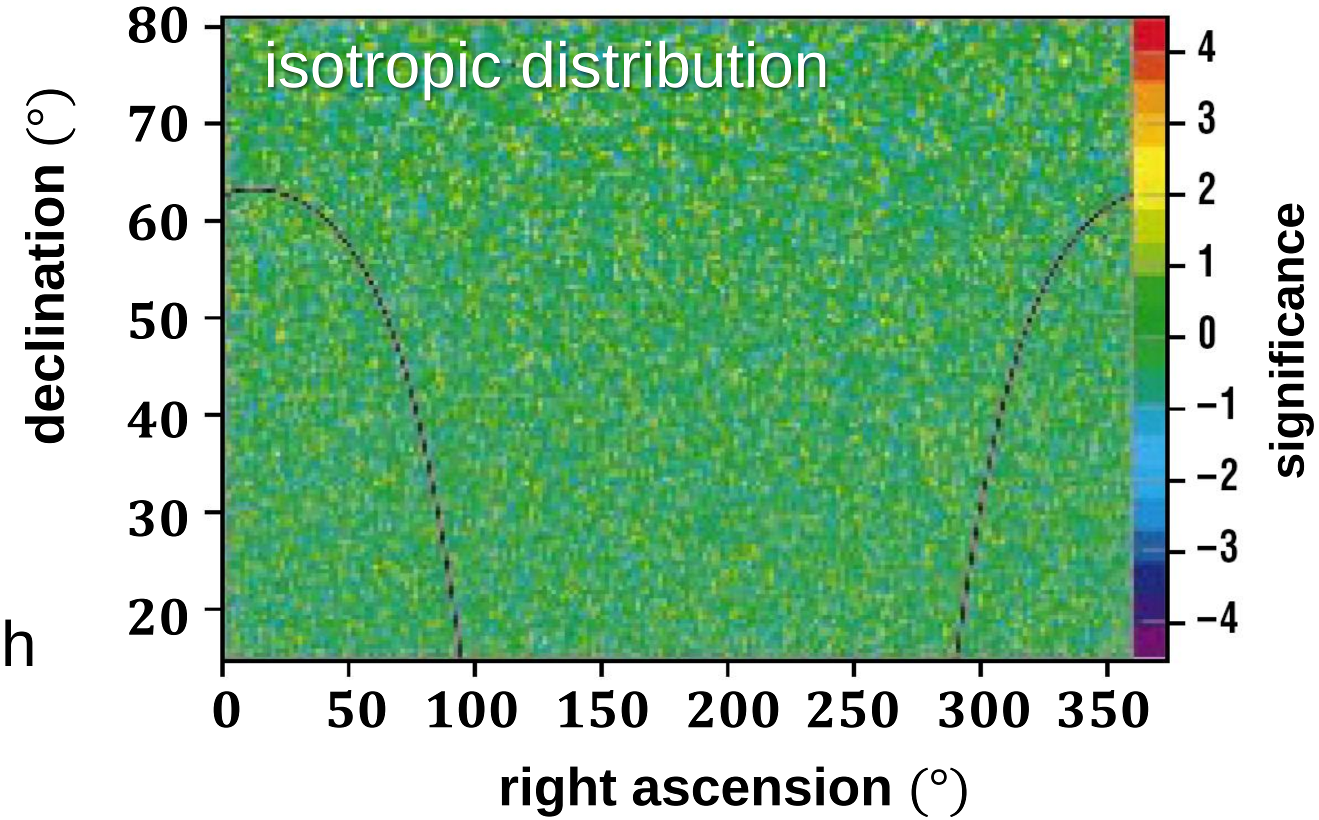
- to first order ($\sim\mathbf{10^{-3}}$): data show an **isotropic arrival distribution**

- conclusions: there are

↳ **no nearby** sources of CRs

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

$KASCADE$: arrival distribution of CRs



Looking very precisely: a vey small anisotropy!

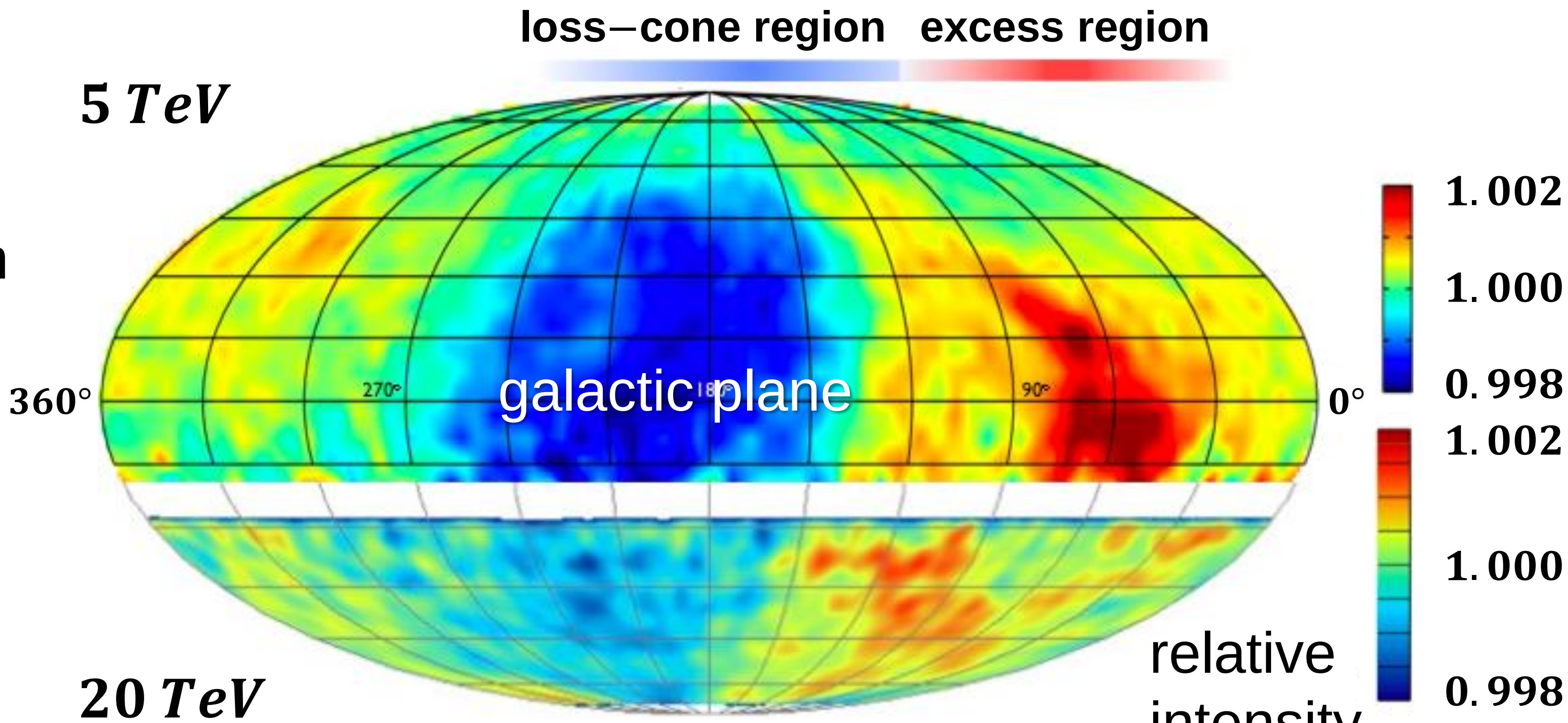
- **new results of arrival distributions reveal a tiny anisotropy of galactic CRs**

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

$TIBET - III$

$5\ TeV$

consistent data from Northern & Southern hemispheres!



$IceCube - 22$

(South Pole)

$20\ TeV$

Anisotropy at ultra–high energies: Southern view

Karlsruhe Institute of Technology

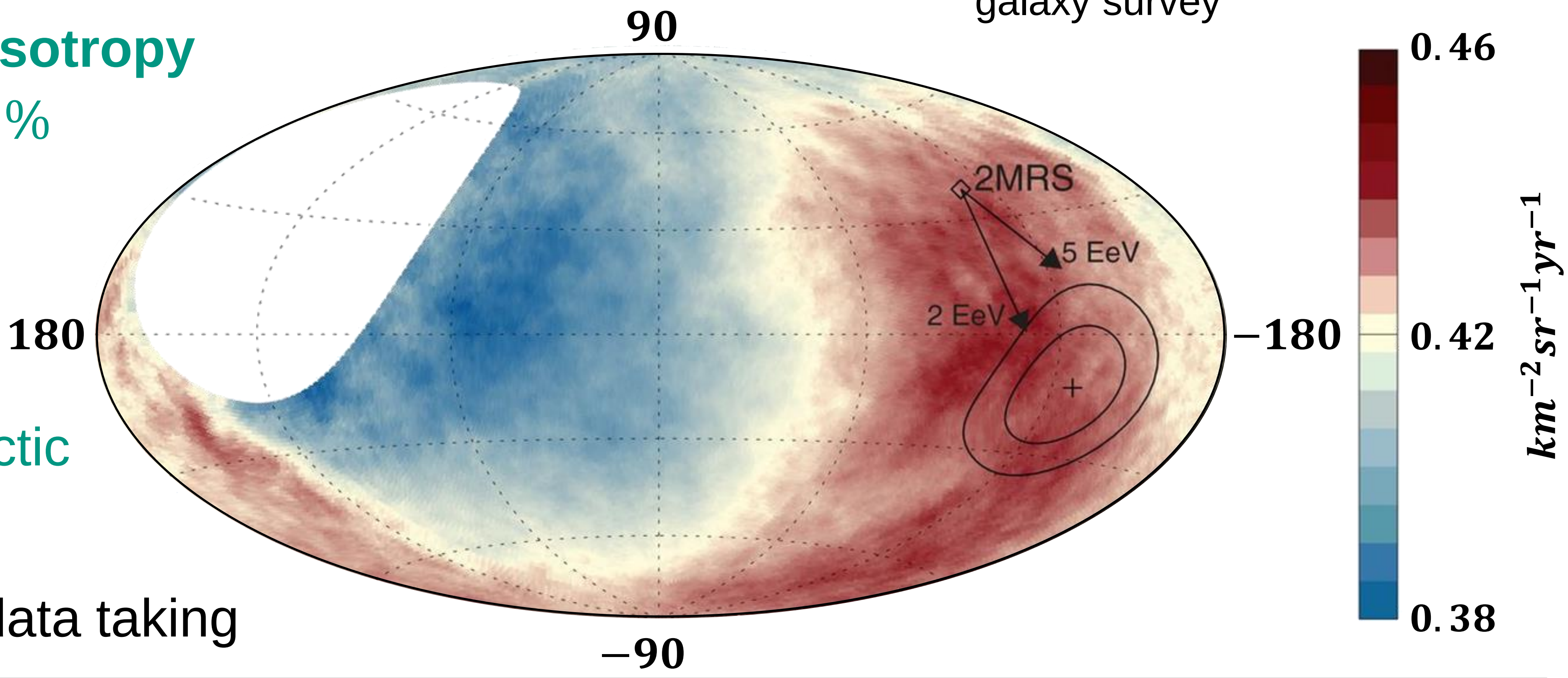
- ***P**ierre **A**uger **O**bservatory* reveals spatial anisotropy at energies $E > 8\ EeV$*

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

- $\boldsymbol{UHECRs}$ must be nearby, as hot spot despite extended intergalactic $\boldsymbol{B}$ – fields

~ $\mathbf{13}$ years of $\boldsymbol{PAO}$ data taking

$\mathbf{2}\boldsymbol{MRS}$ = galaxy survey



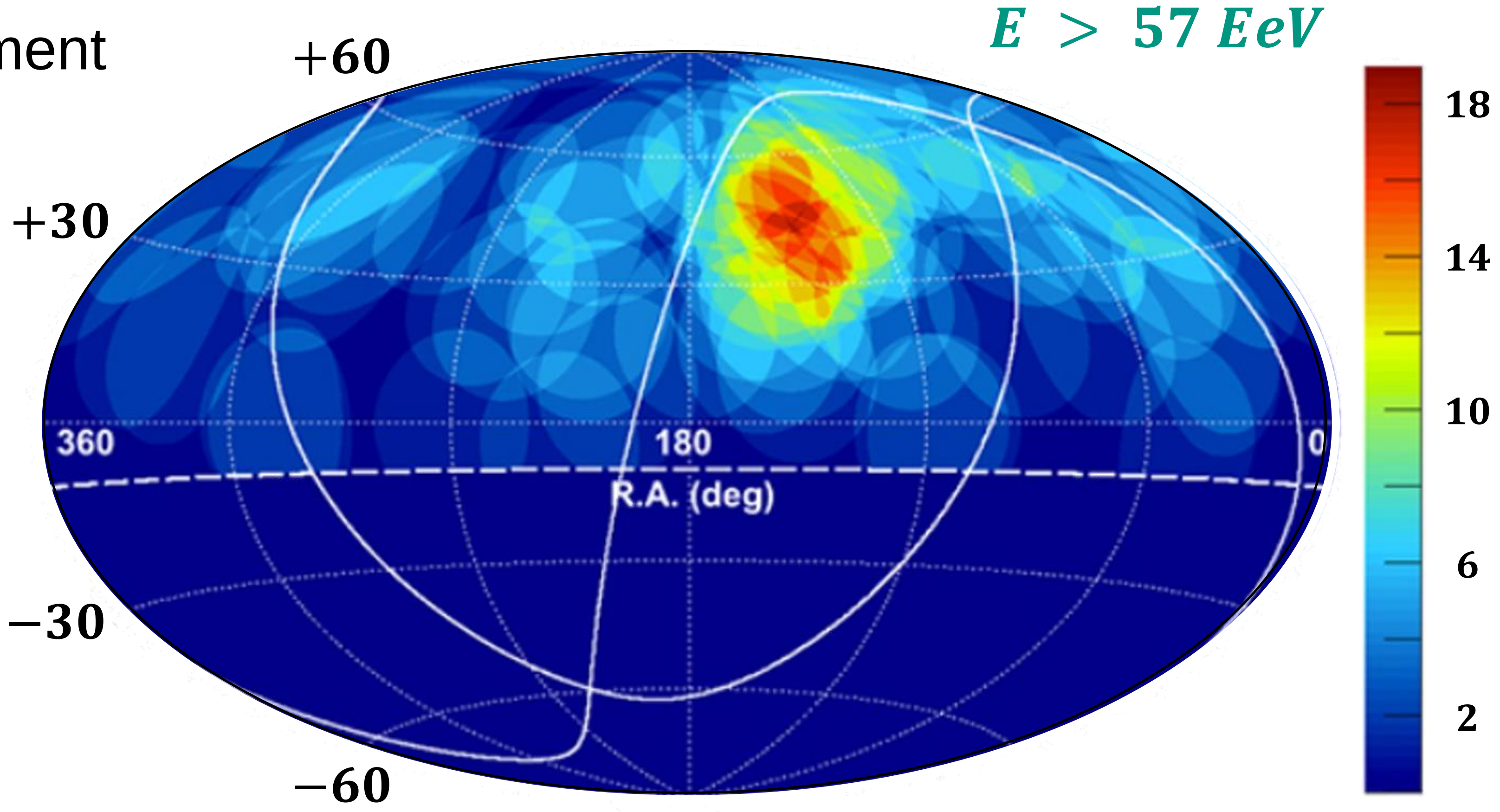
*$\boldsymbol{PAO}$

Anisotropy at ultra–high energies: northern view

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

*T*elescope *A*rray (*TA*) experiment in Utah (*US*) observes ***UHECRs*** in nothern hemisphere

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



Cosmic accelerators: principles

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

- where does the **energy** for $\boldsymbol{CRs}$ come from ?

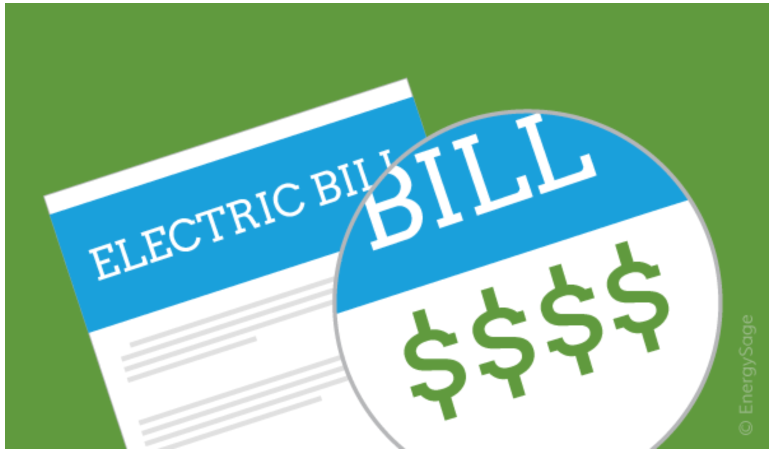
- what is the **efficiency** of cosmic accelerators ?

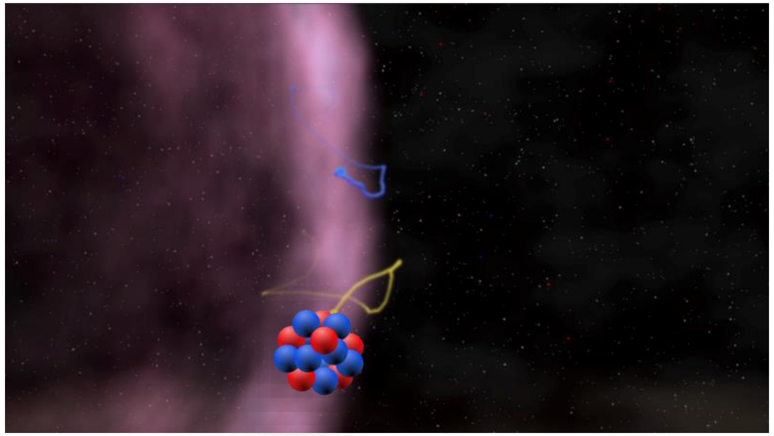
- can cosmic accelerators work over long **time scales** ?

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

- what **limits** the energy of galactic acclerators ?

- why do **extra–galactic** accelerators go beyond ?

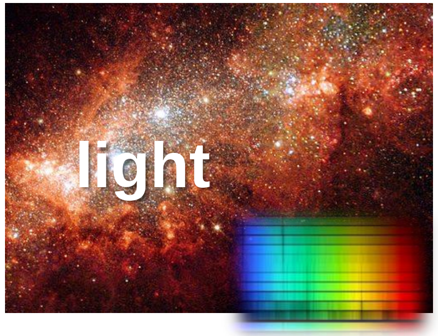




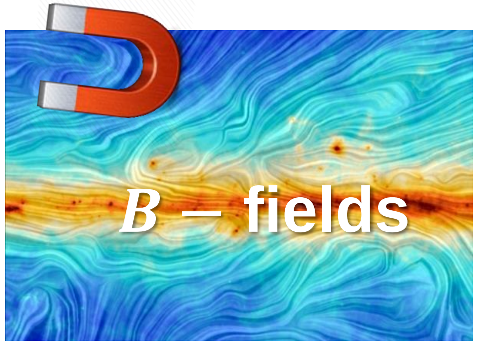
Local (galactic) energy densities: an overview

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

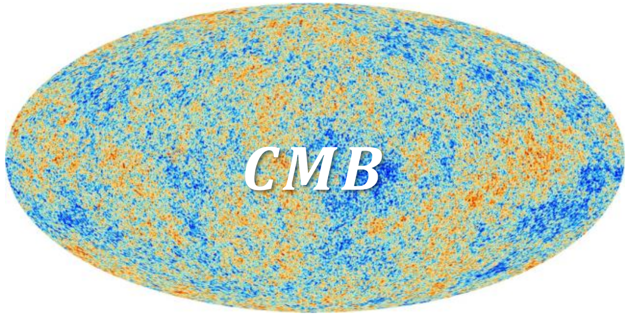
local energy densities in the Milky Way	
electromagnetic radiation (star light)	$\sim 0.6\ eV/cm^3$
galactic magnetic field $\sim B^2/2\,\mu_0$ $(3\ \mu G)$	$\sim 0.25\ eV/cm^3$
cosmic microwave background (CMB)	$\sim 0.26\ eV/cm^3$
cosmic rays	$\sim 1\ eV/cm^3$
local matter density $(WIMPs)$	$\sim 0.3\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



≈



≈



≈

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

Karlsruhe Institute of Technology

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

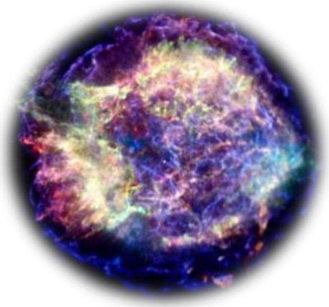
- total energy/year W_{CR} going into **galactic cosmic rays**

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

CR

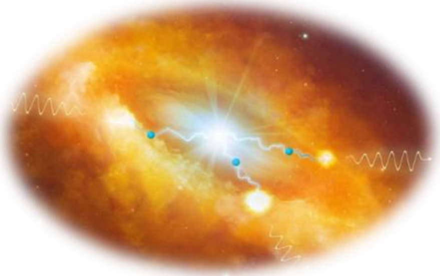
- total energy/year W_{SN} produced by **supernovae** in galaxis

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



SNR

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



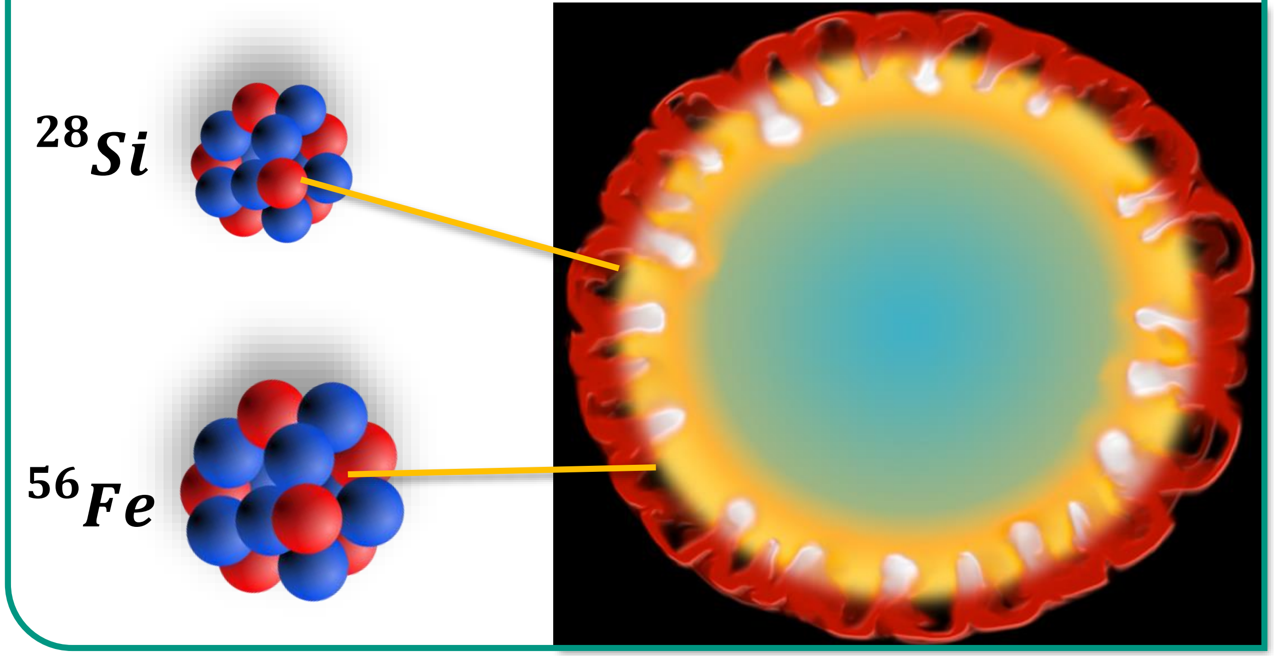
*CR acceleration in SN – shock fronts

Sources of Cosmic Rays in our galaxy

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

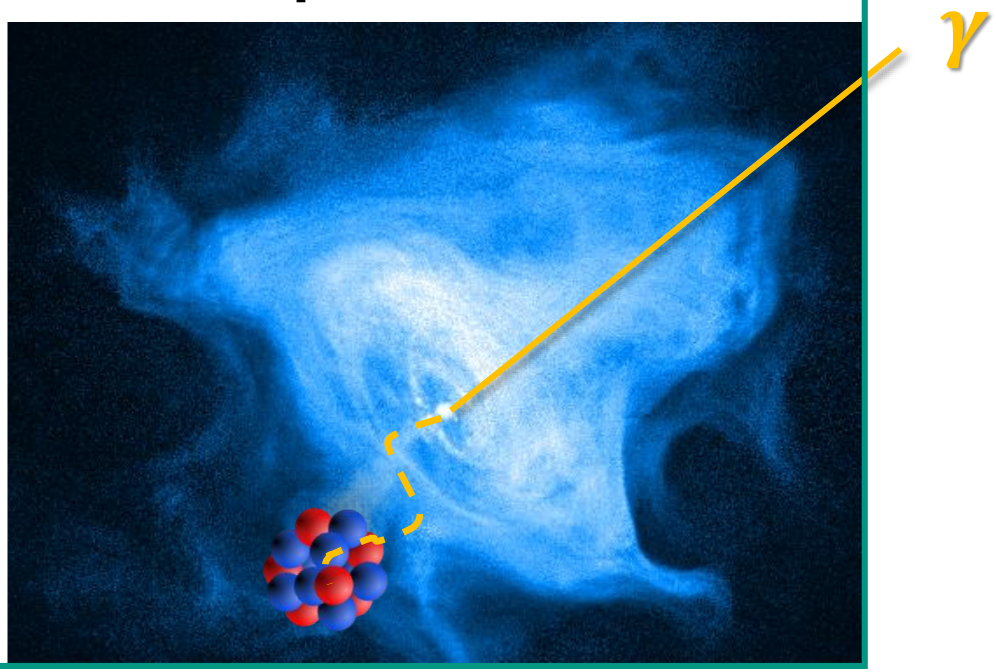
supernovae: shock fronts

- 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**

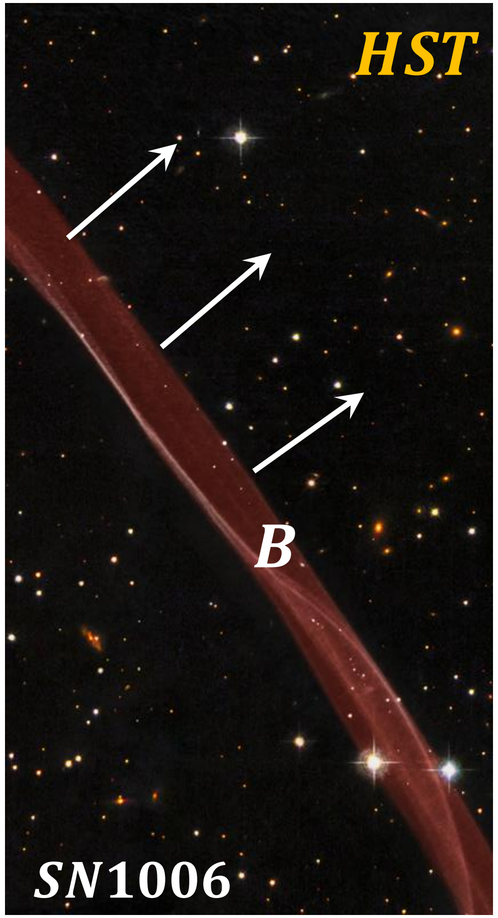
  time–variable

  E, B – fields

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

with

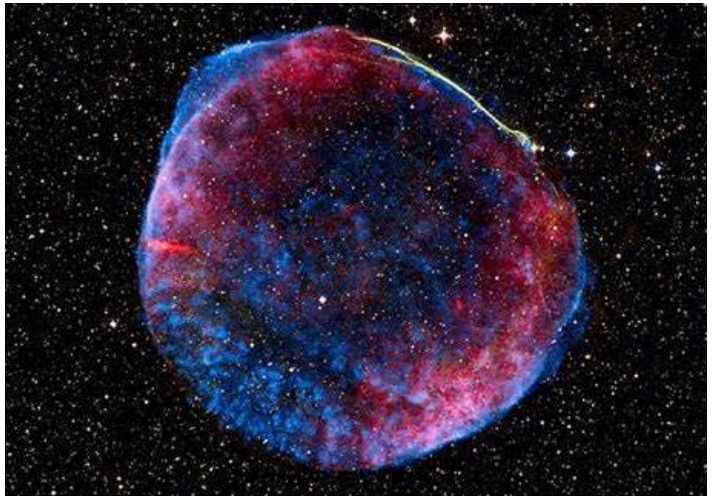
$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

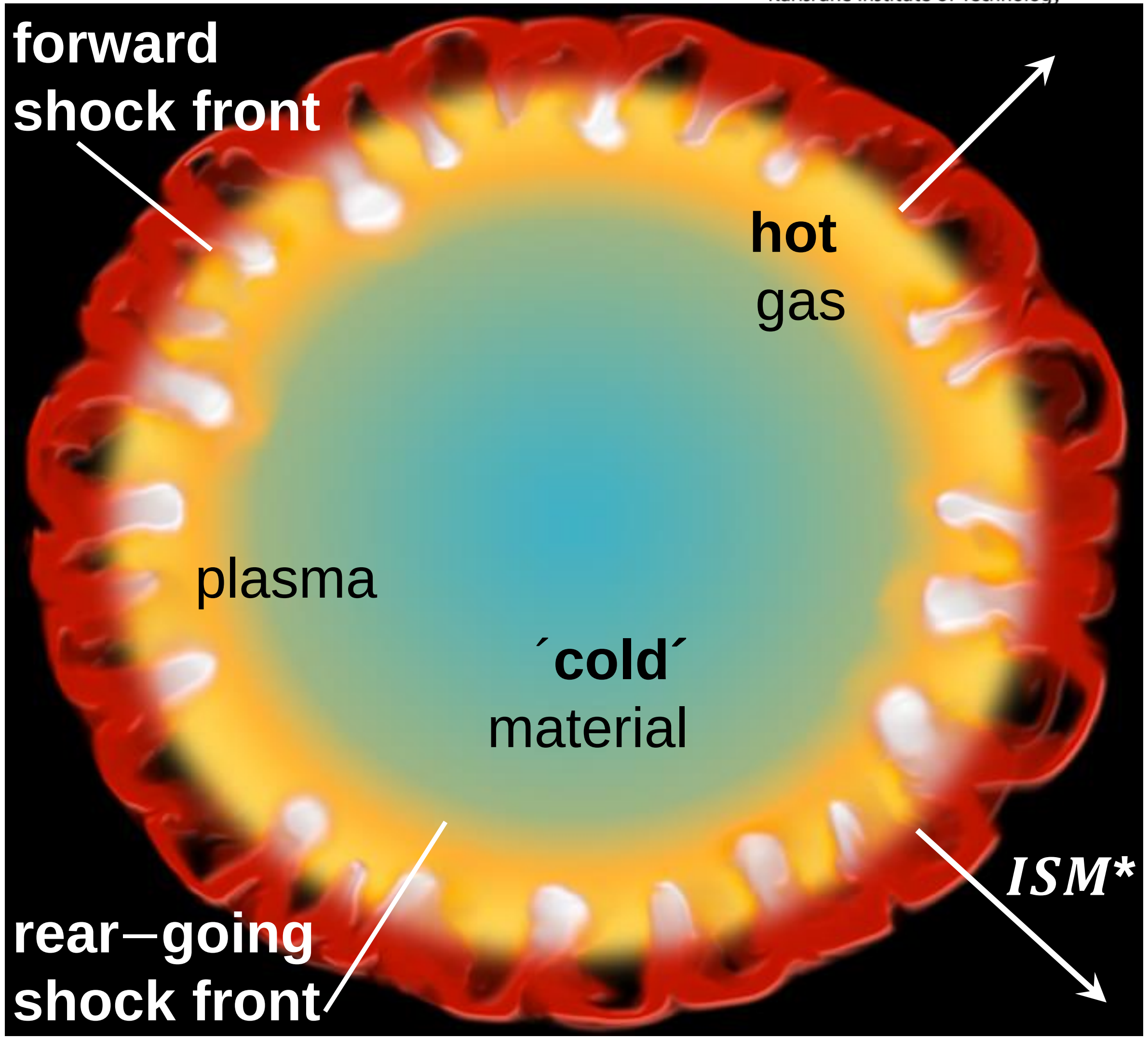


Fermi accleration in shock fronts of SN remnants

- **Simplified $1D$ – scenario**

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



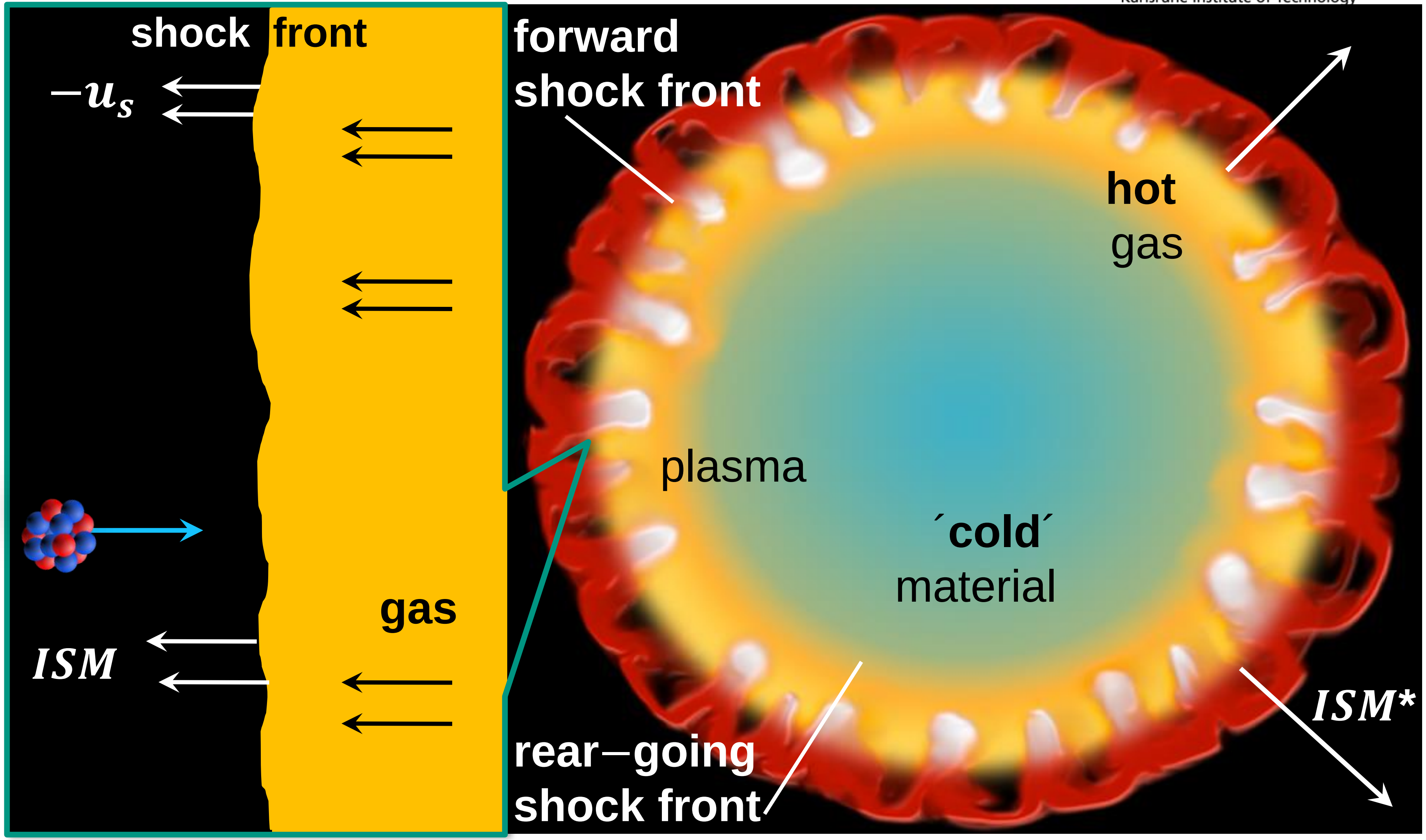


*Inter–Stellar Medium

Fermi accleration in shock fronts of SN remnants

- **Simplified $1D$ – scenario**

- **SN – shockfront** propagates with $u_s \cong 10^4\ km/s$ or $\beta_s = 0.03$
- **β_s** will decrease over time

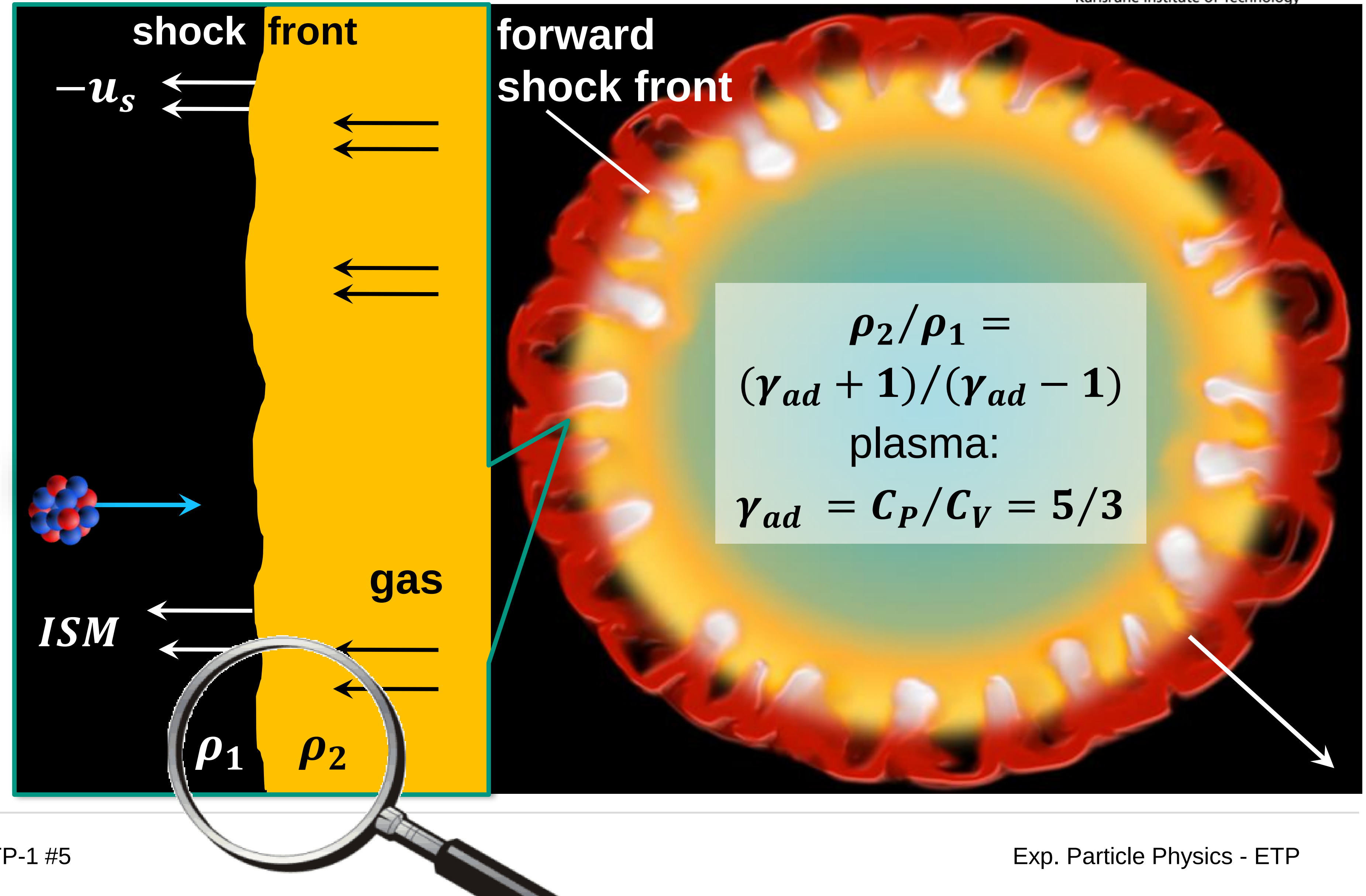


Fermi accleration in shock fronts of SN remnants

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

- ISM: density ρ_1,
  shock: density ρ_2

- plasma physics:
  ratio ρ_2/ρ_1 depends on the **adiabatic coefficient γ_{ad}**



Fermi accleration in shock fronts of SN remnants

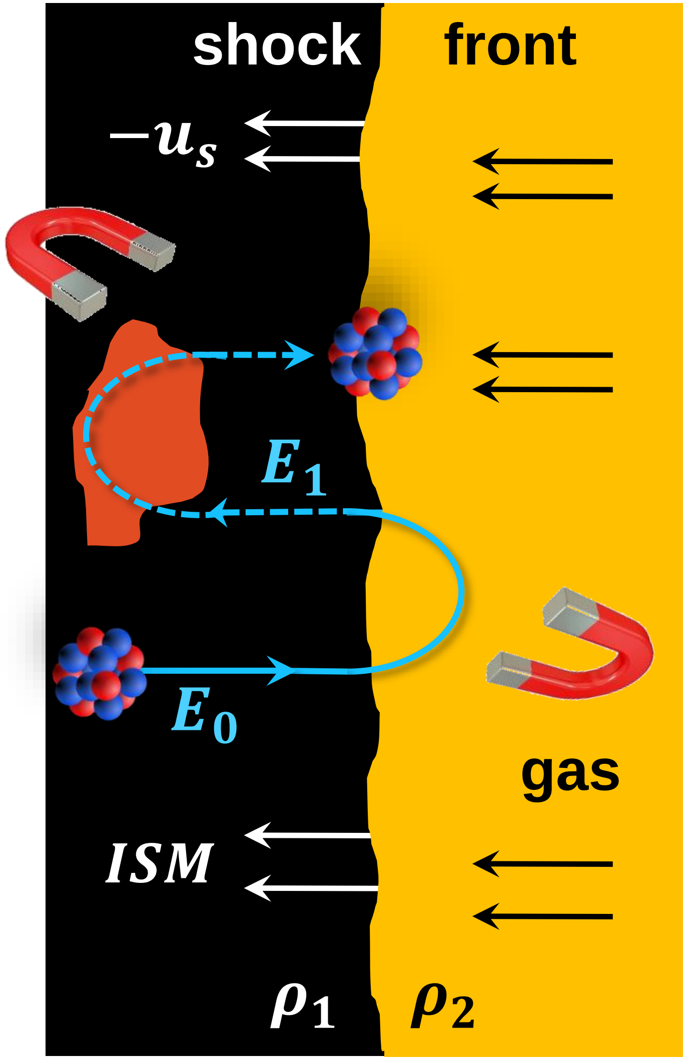
- **The process of Fermi acceleration of CRs comprises several key steps:**

  - 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 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



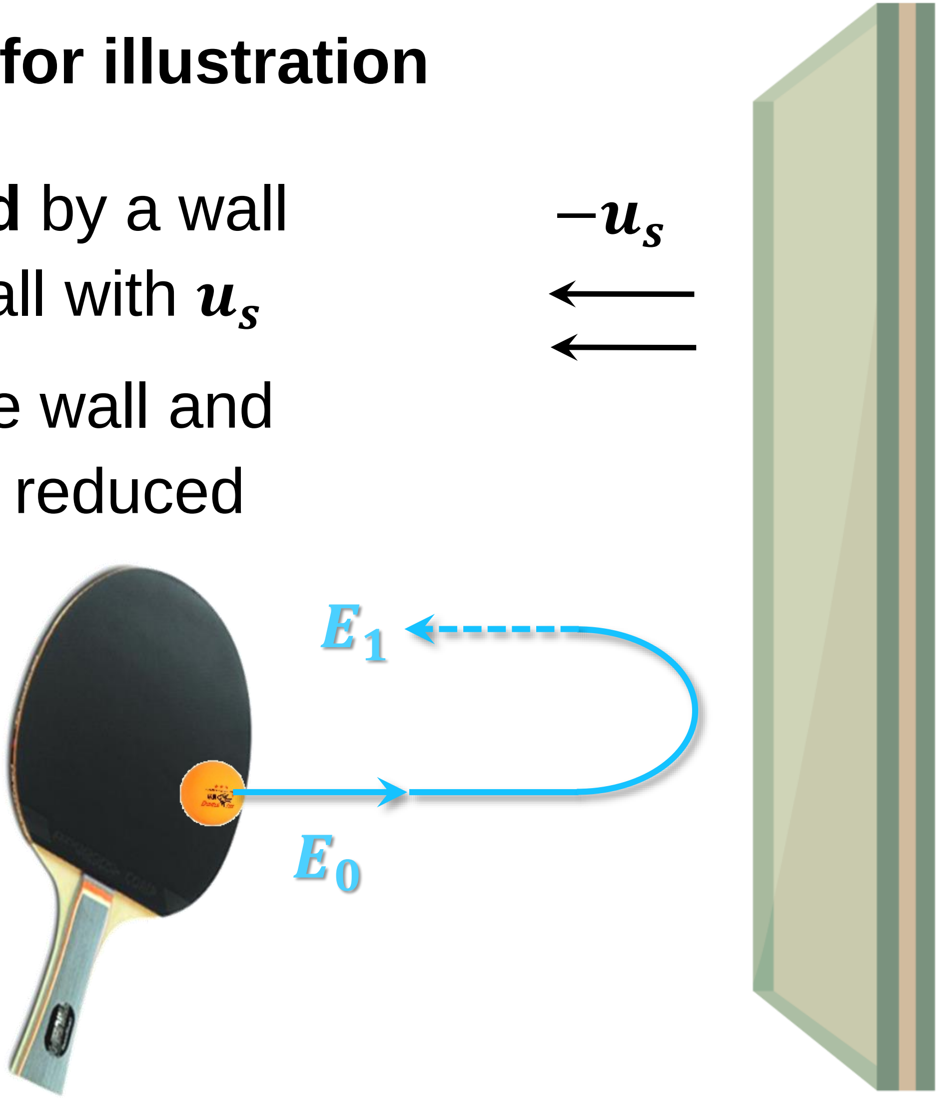
Fermi accleration in shock fronts: an analogon

- a **mechanic analogon** for illustration

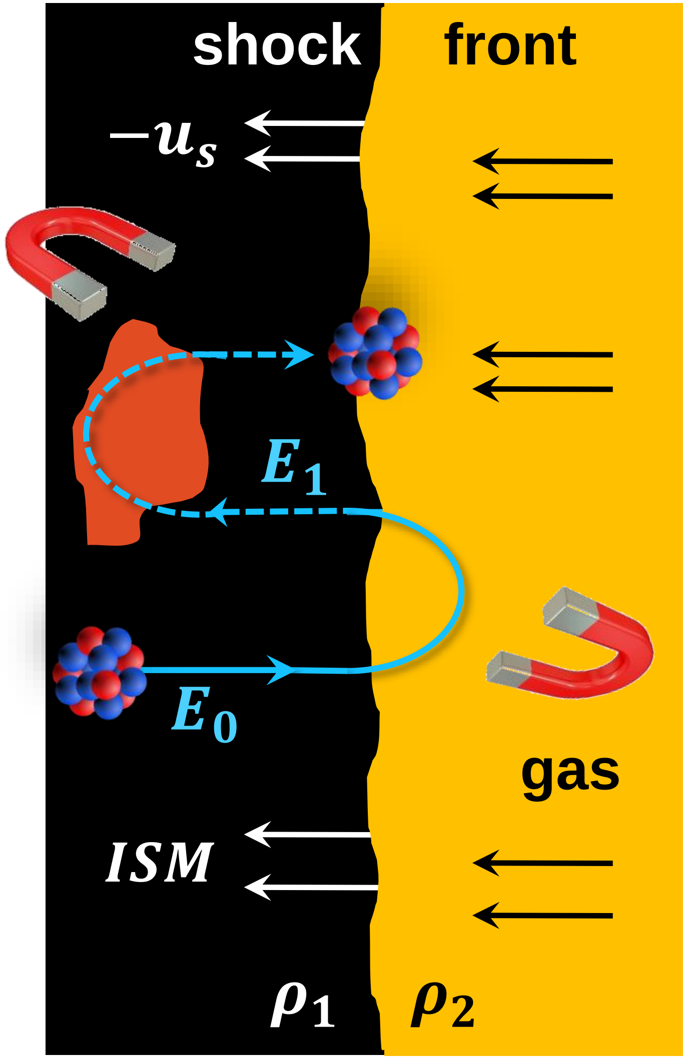
  - ping pong ball **reflected** by a wall which moves against ball with $\boldsymbol{u_s}$

    ⇨ 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**

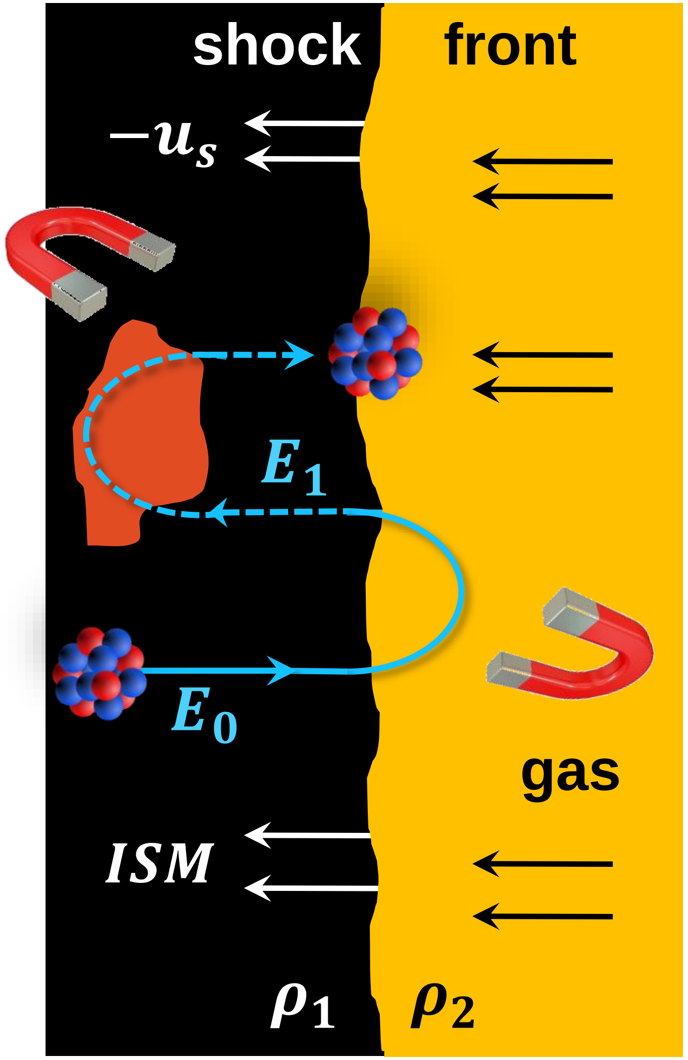
  - by **Fermi acceleration**, which is …

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

  … a collision–free 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**

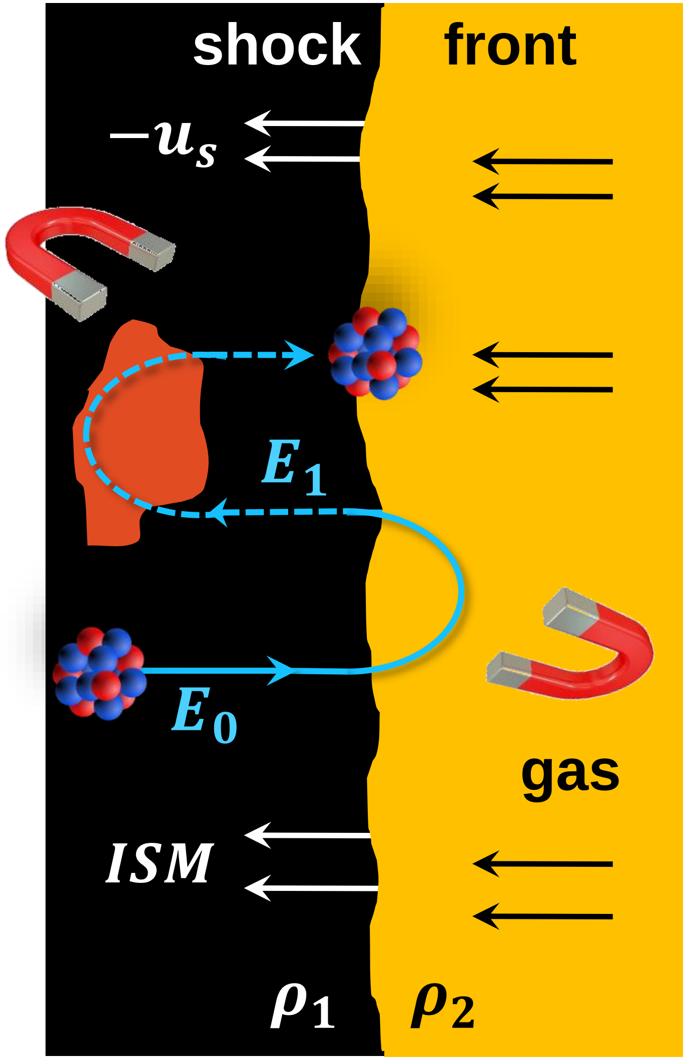
$$\Delta E = \alpha \cdot E$$

  - ***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 **maximum energy E**:

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



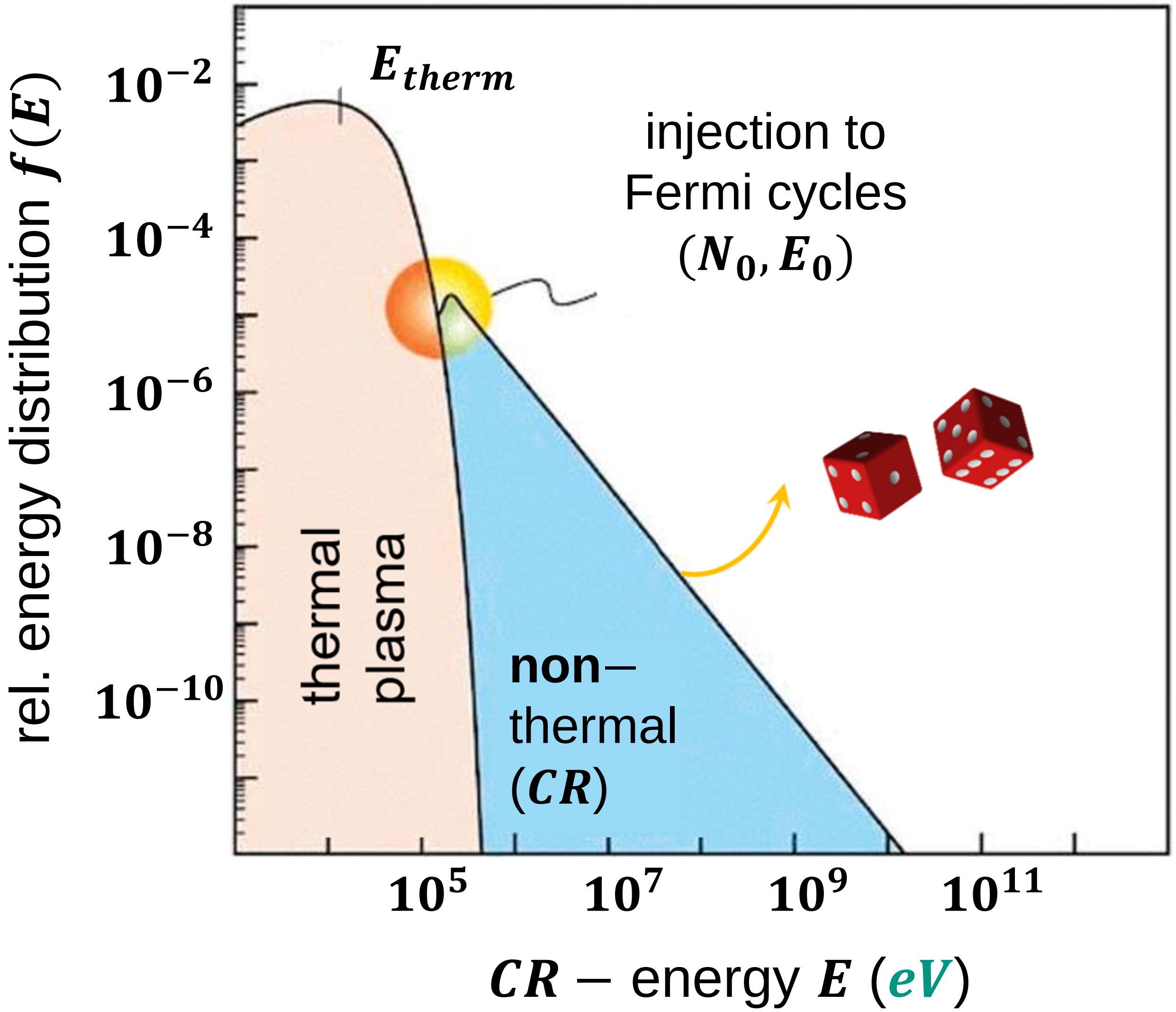
Origin of the CR power–law distribution

- **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 characteristic **power–law distribution**

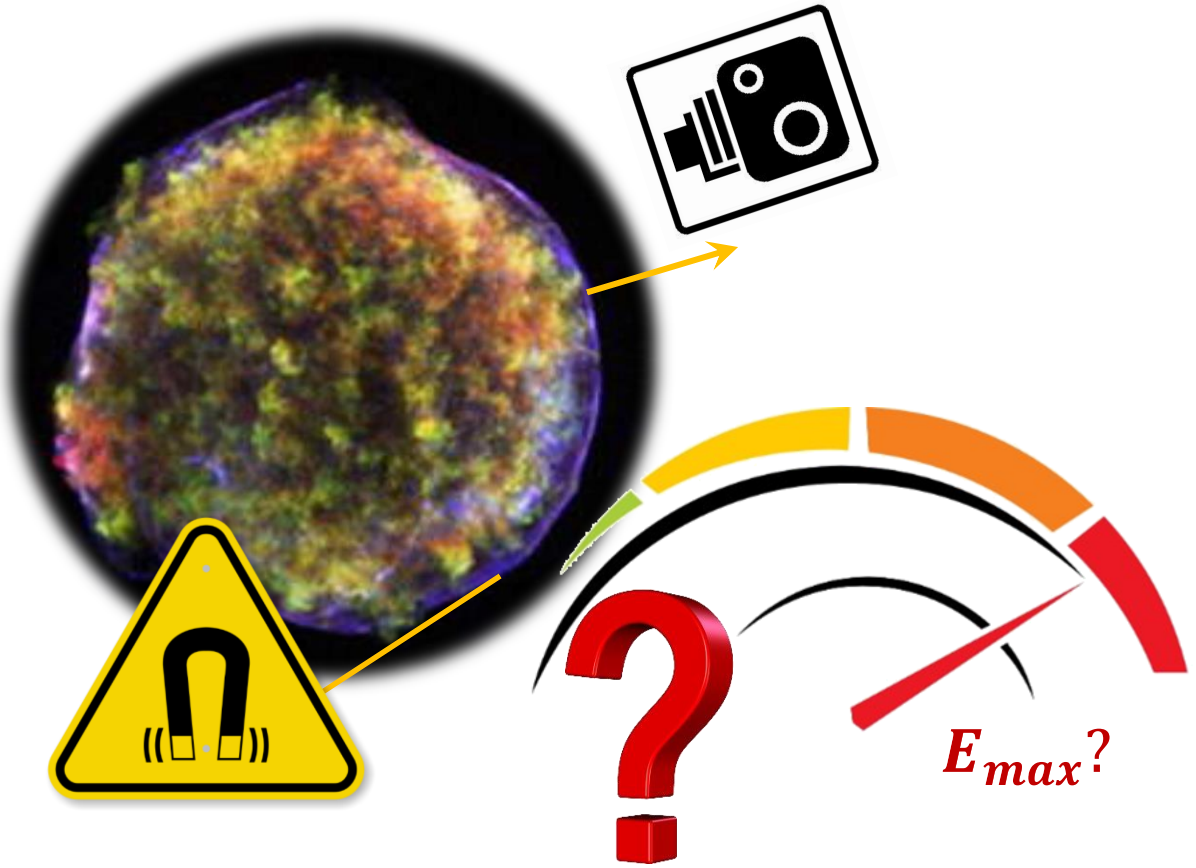
$$\frac{dN(E)}{dE} \sim E^{-2.7}$$

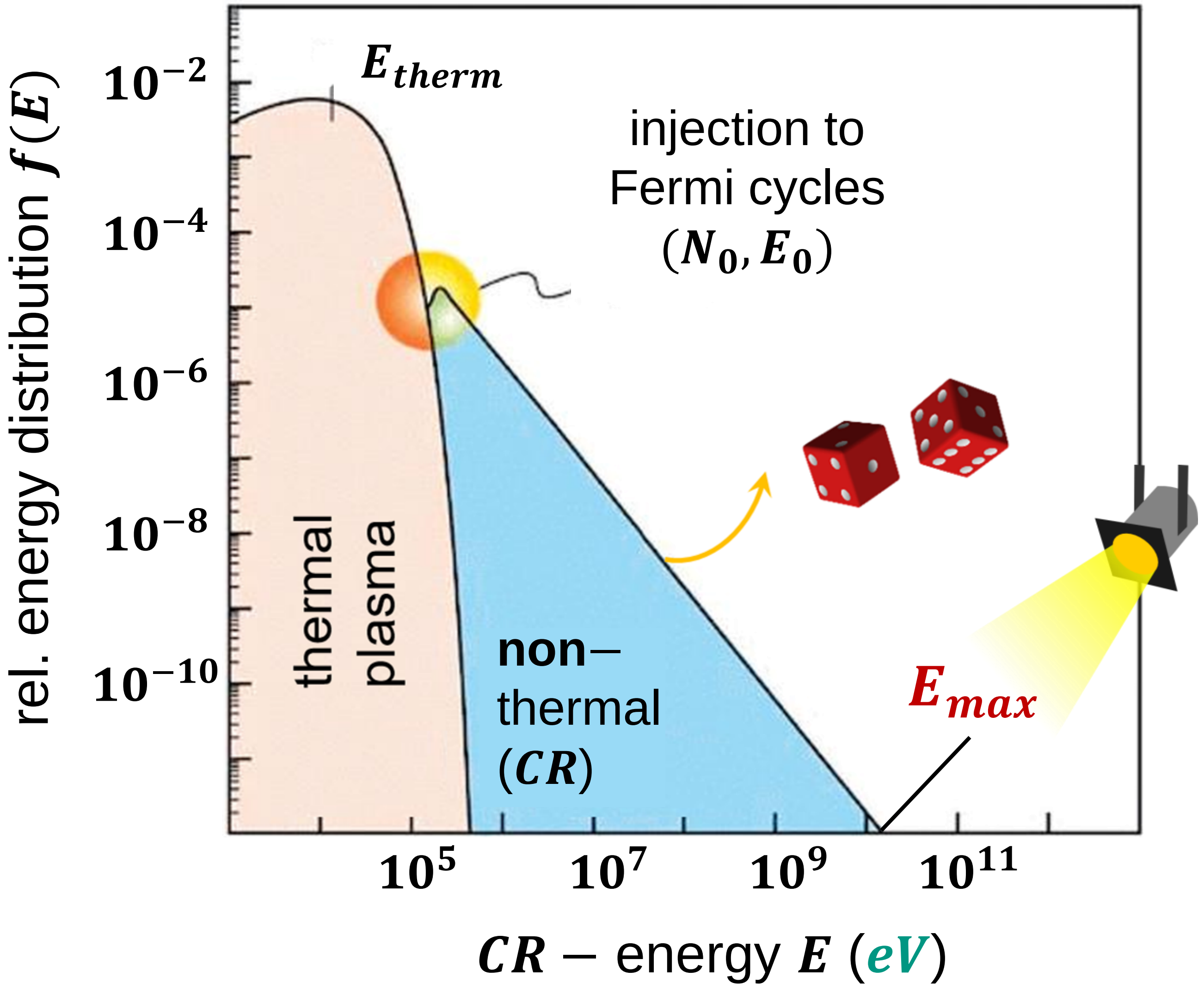
power–law spectrum



Maximum energy of CRs due to SN shocks?

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

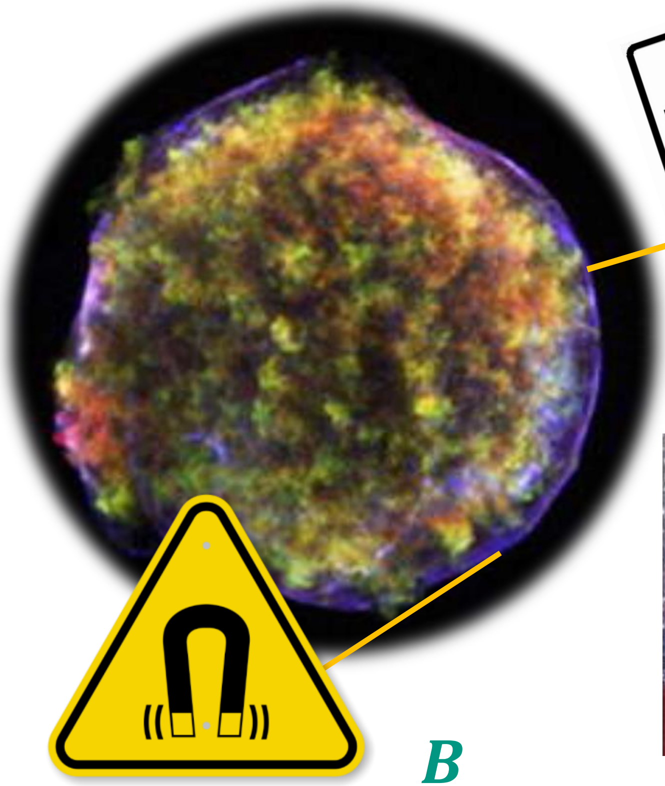




Maximum energy of CR via famous Hillas formula

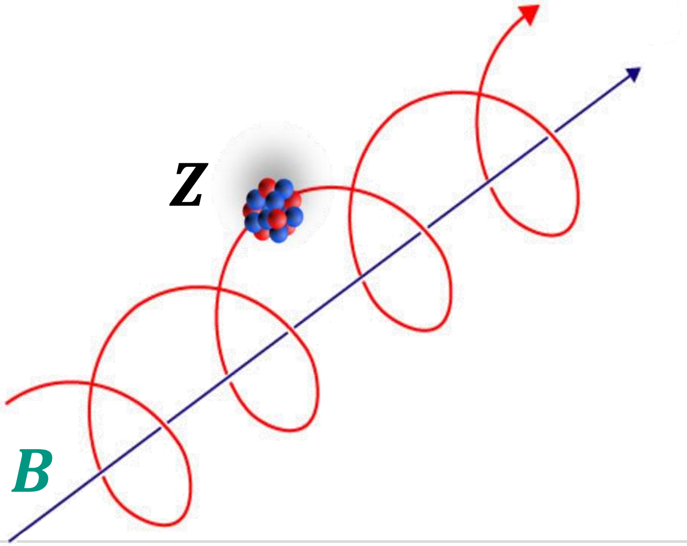
- *A.M. Hillas*: cosmic acclerators use a B – field of size L to guide particles

- **maximum energy** E_{max} of a particle of **charge** Z in a SN shock front (based on dimensional arguments !)




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

A. M. Hillas



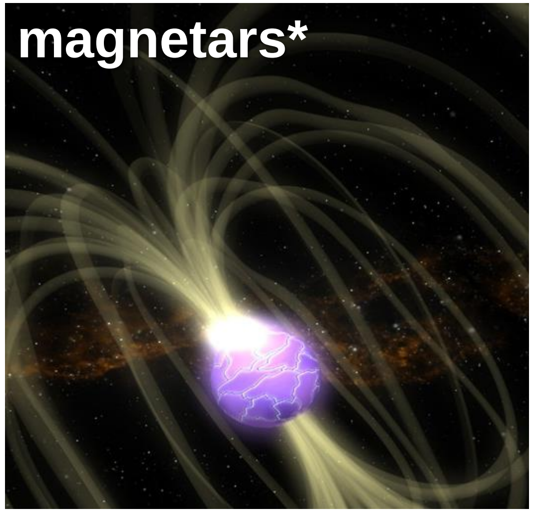
particle:
- nuclear charge Z

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

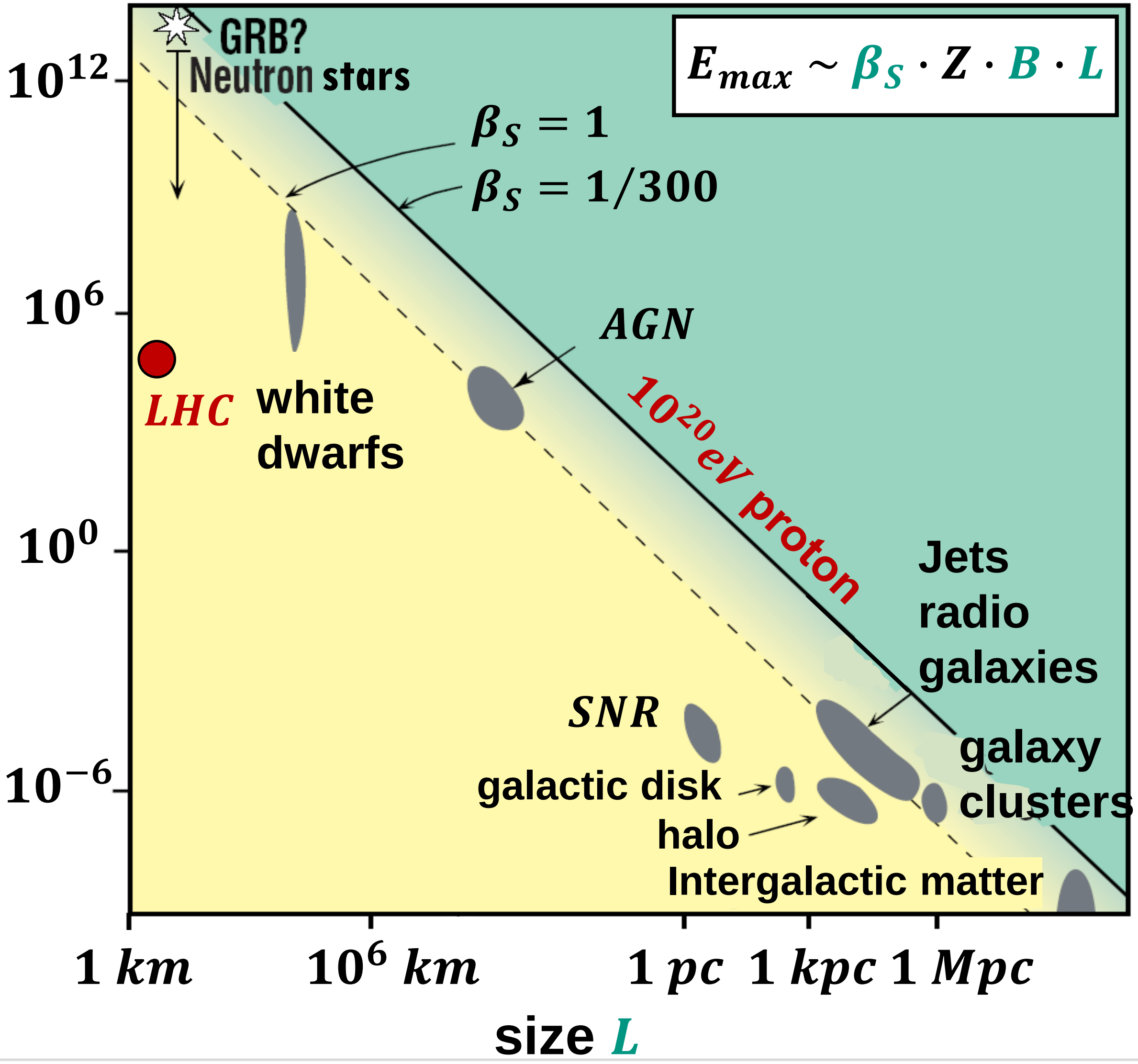
Hillas plot for $UHECRs$ up to $E_{max} = 10^{20}\ eV$

- candidate sites

small L / large B



B – field
… $10^9\ T$
dimension
$10\ km$ …



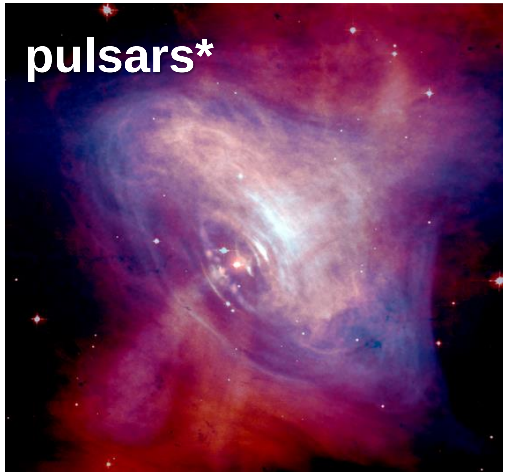
large L / small B

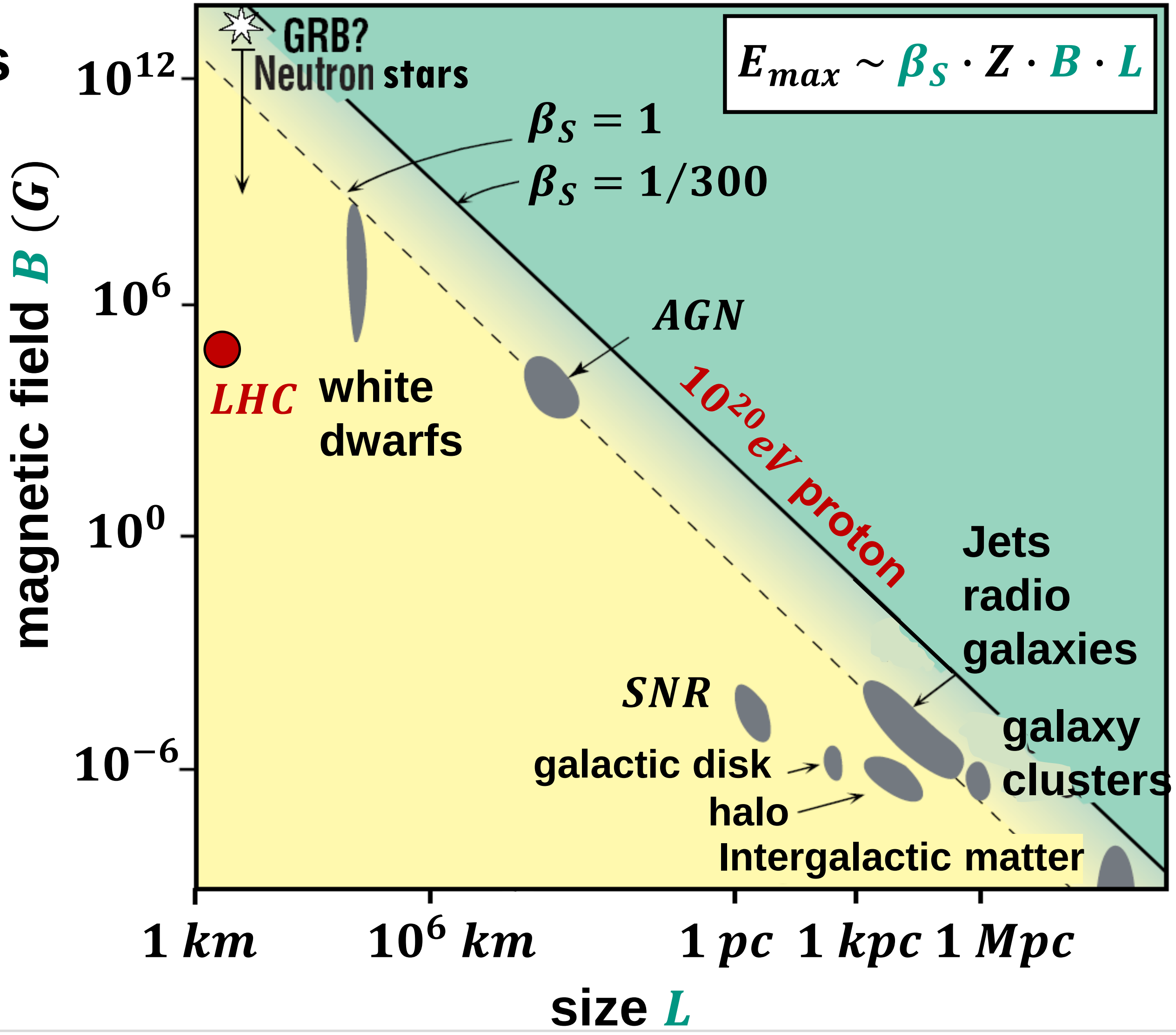
B – field
… $10^{-9}\ T$
dimension
$1\ Mpc$ …

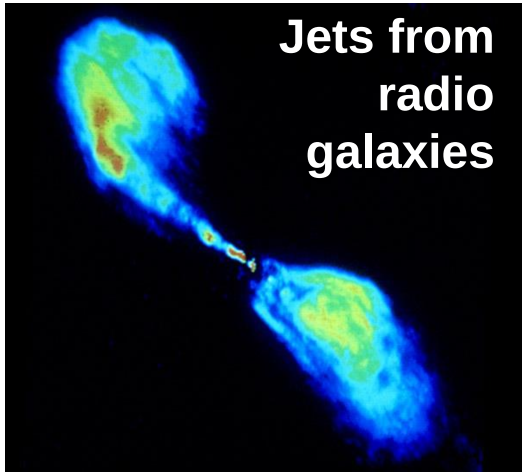
*s. ATP – 2 summer term 2024

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

- candidate sites





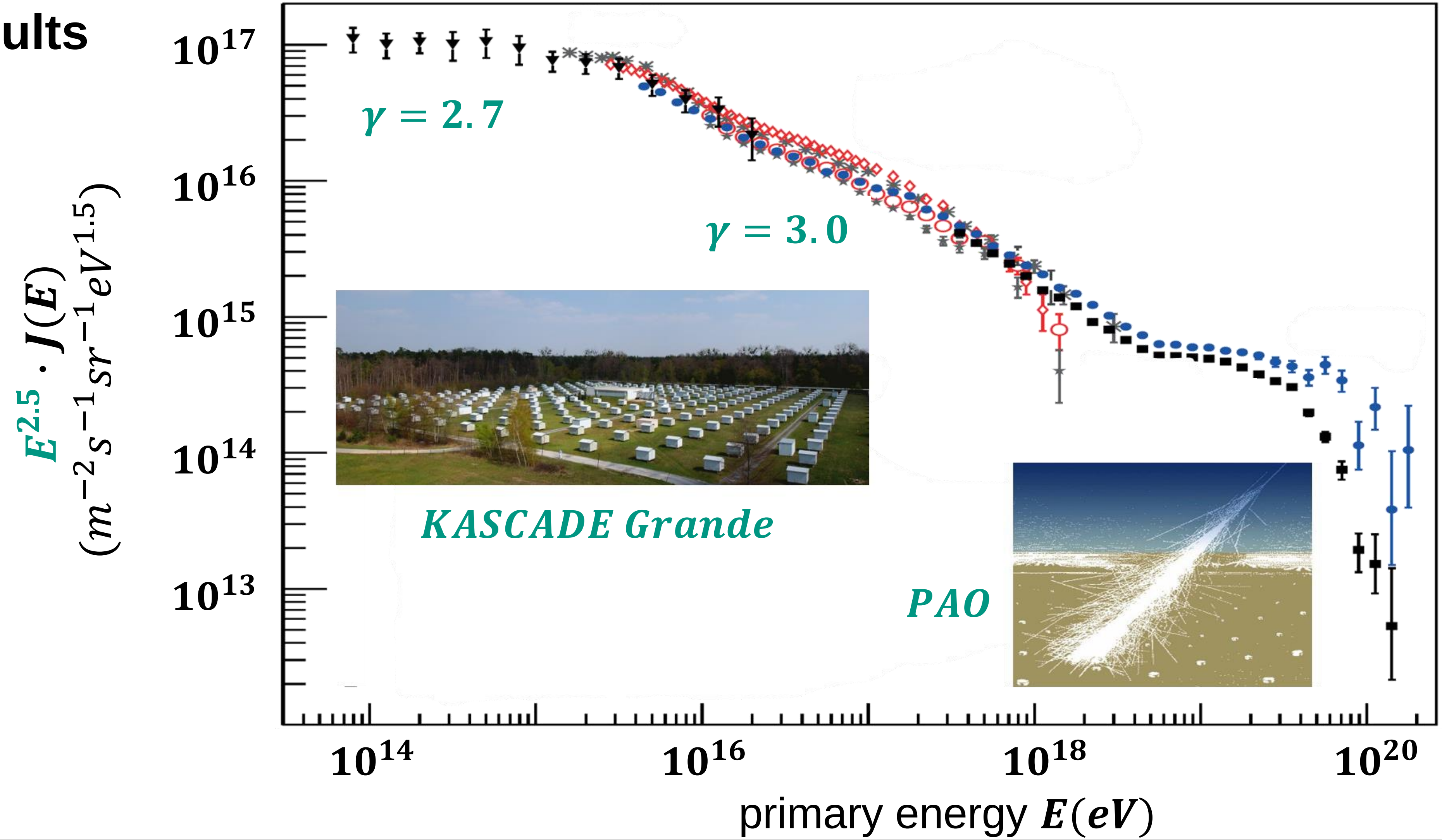


*s. $ATP-2$ summer term 2024

Energy spectrum of *UHECR*

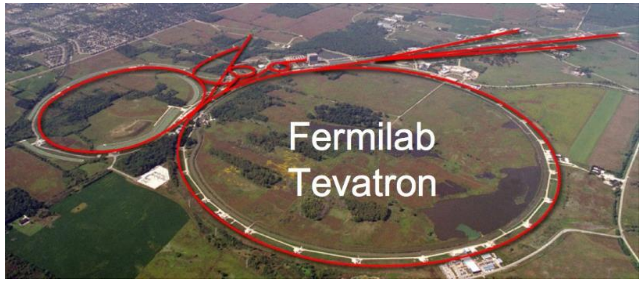
- **Overview of results**

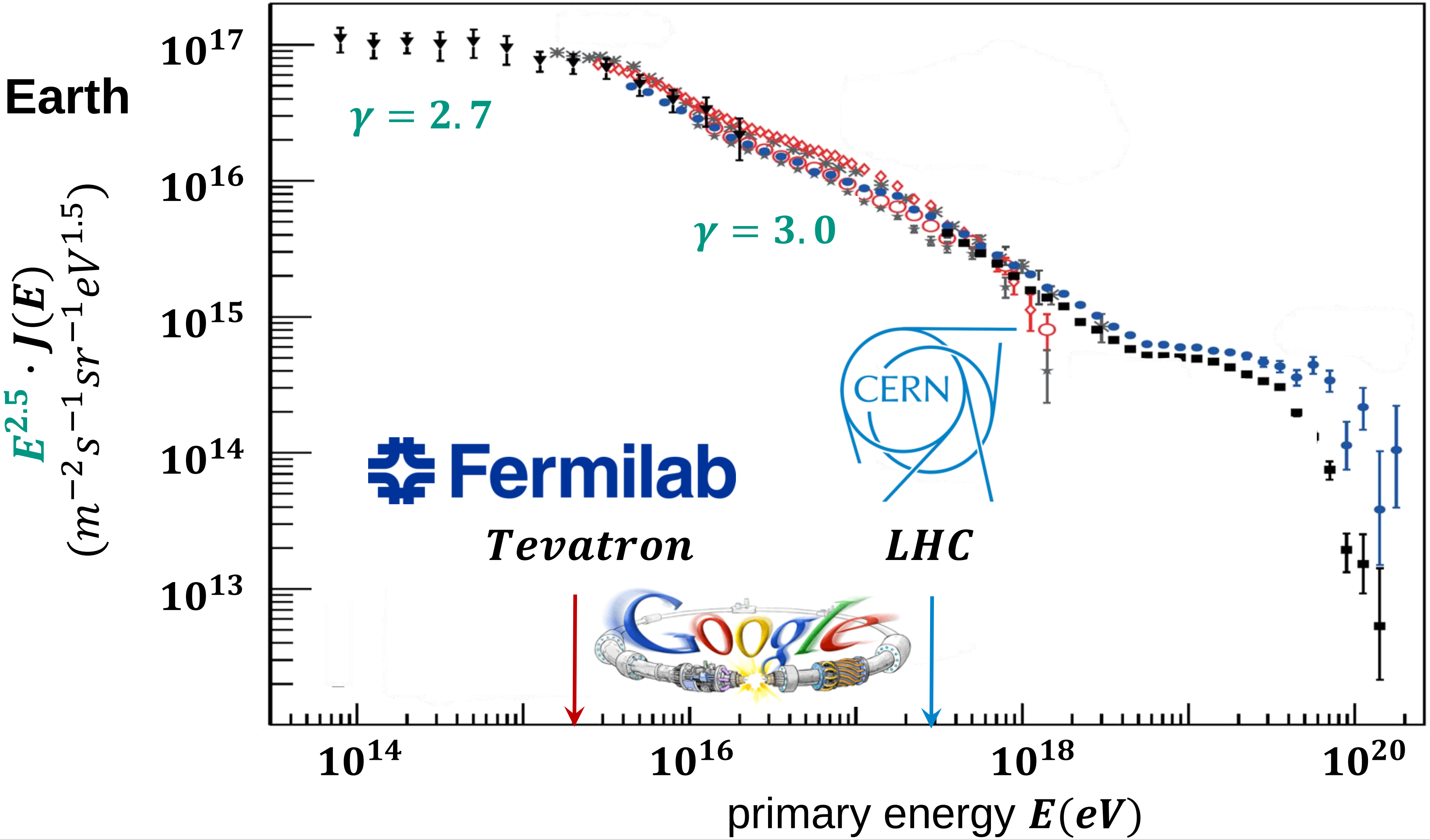
- measurements of air showers arrays with ***KIT*** participation



Energy spectrum of *UHECR* & acclerators

- Comparison to accelerators on Earth



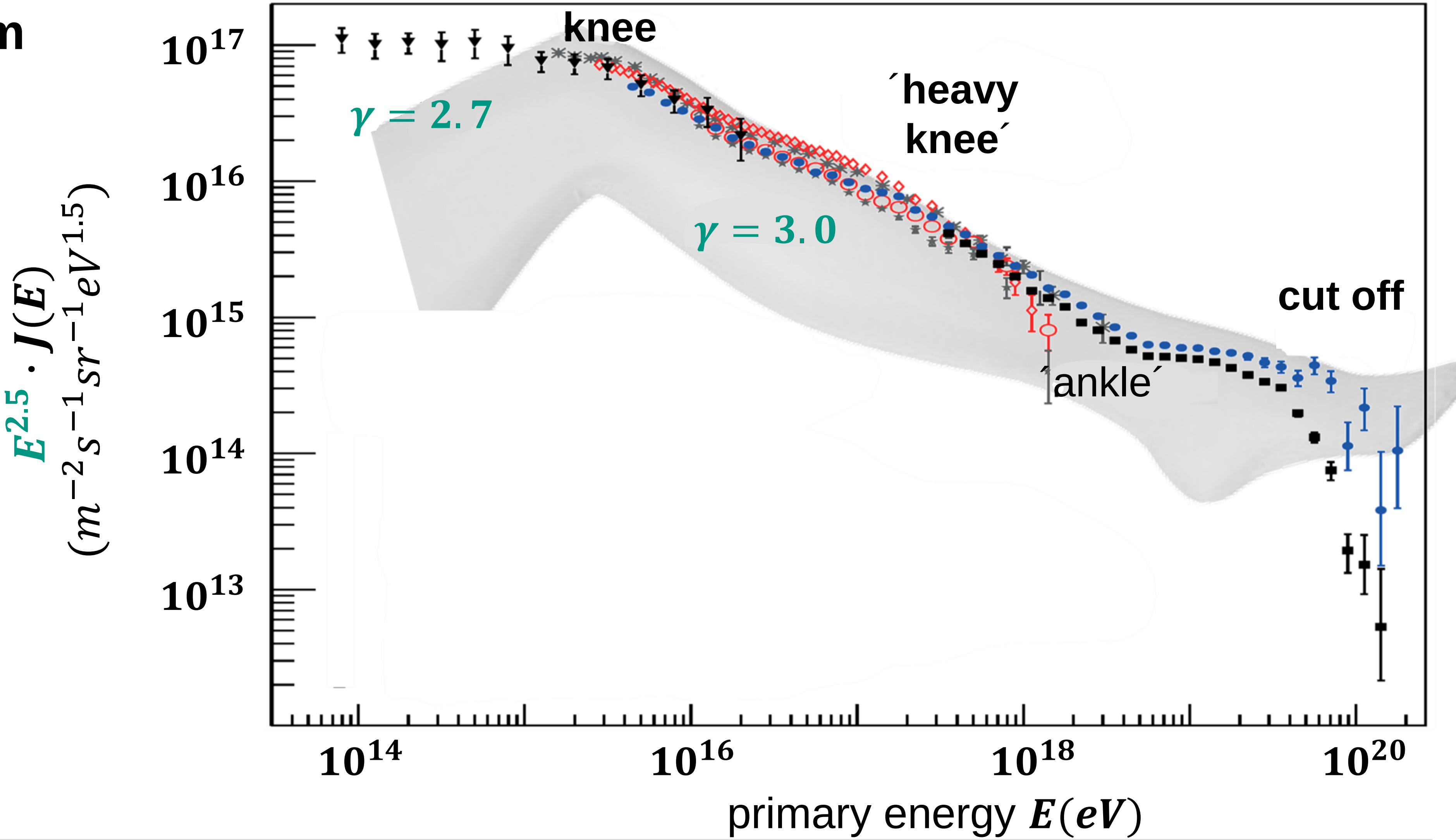


Energy spectrum of high−energy CRs & features

- **Energy spectrum influenced by:**

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

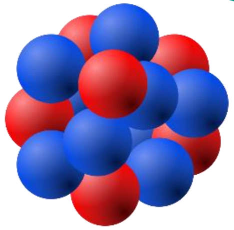
- change of sources & $\boldsymbol{CR}$ acceleration mechanisms (**galactic → extra−galactic**)



Energy spectrum of high−energy CRs & features

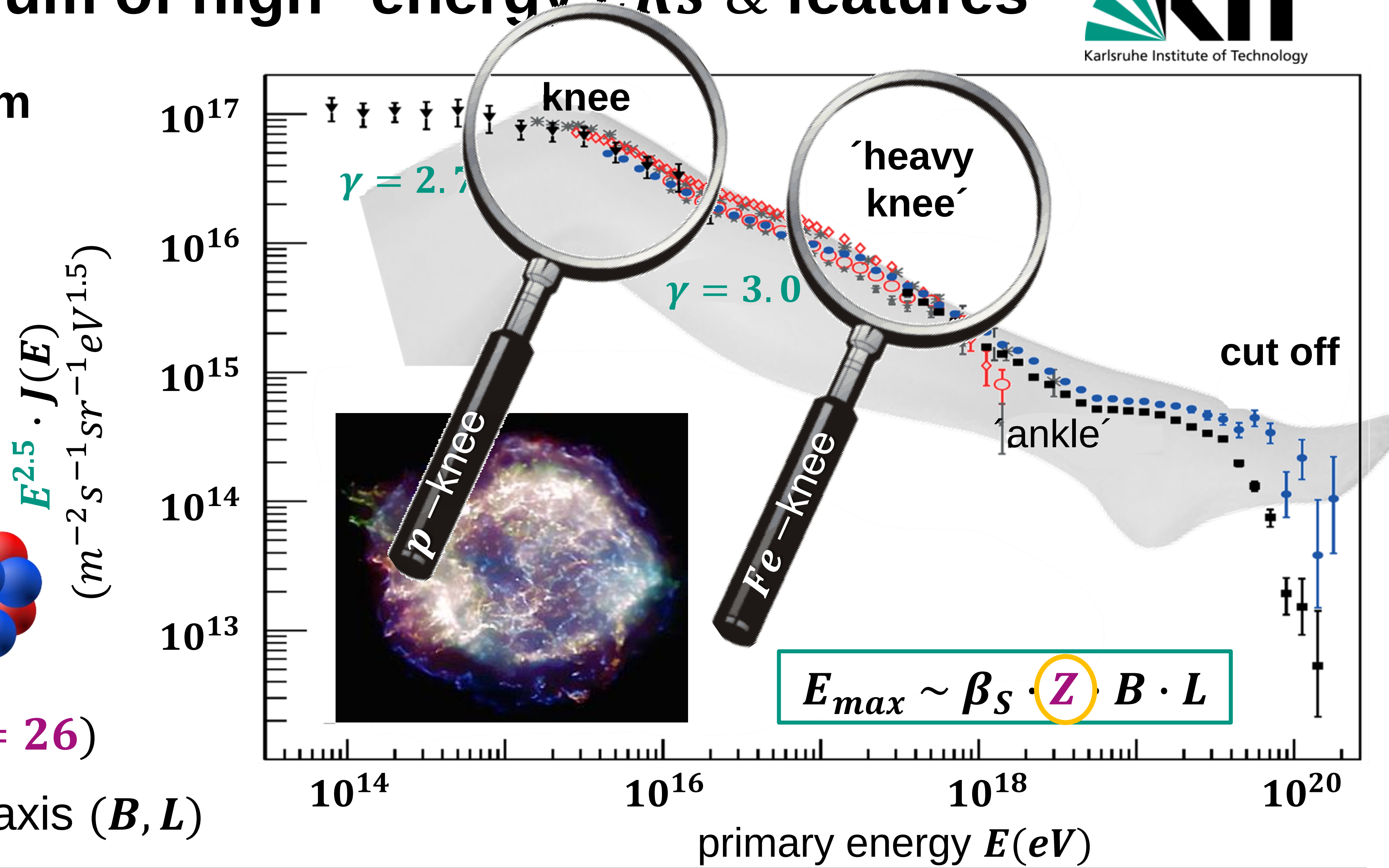
- **Energy spectrum of galactic CRs:**

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



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

sources: SNR in galaxis (B, L)

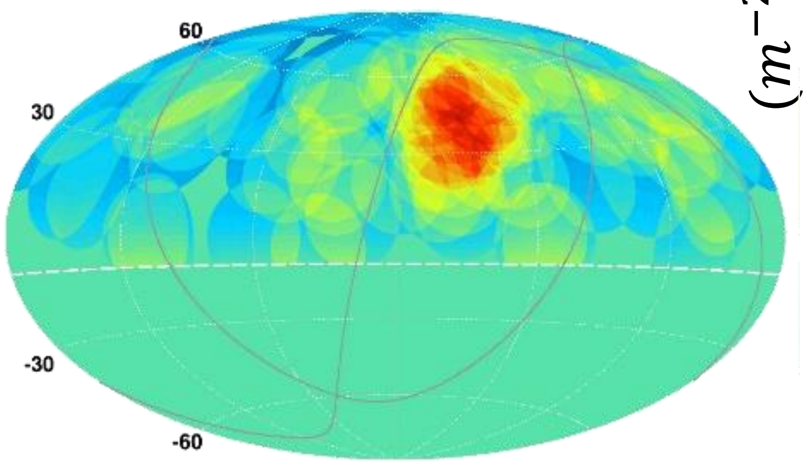


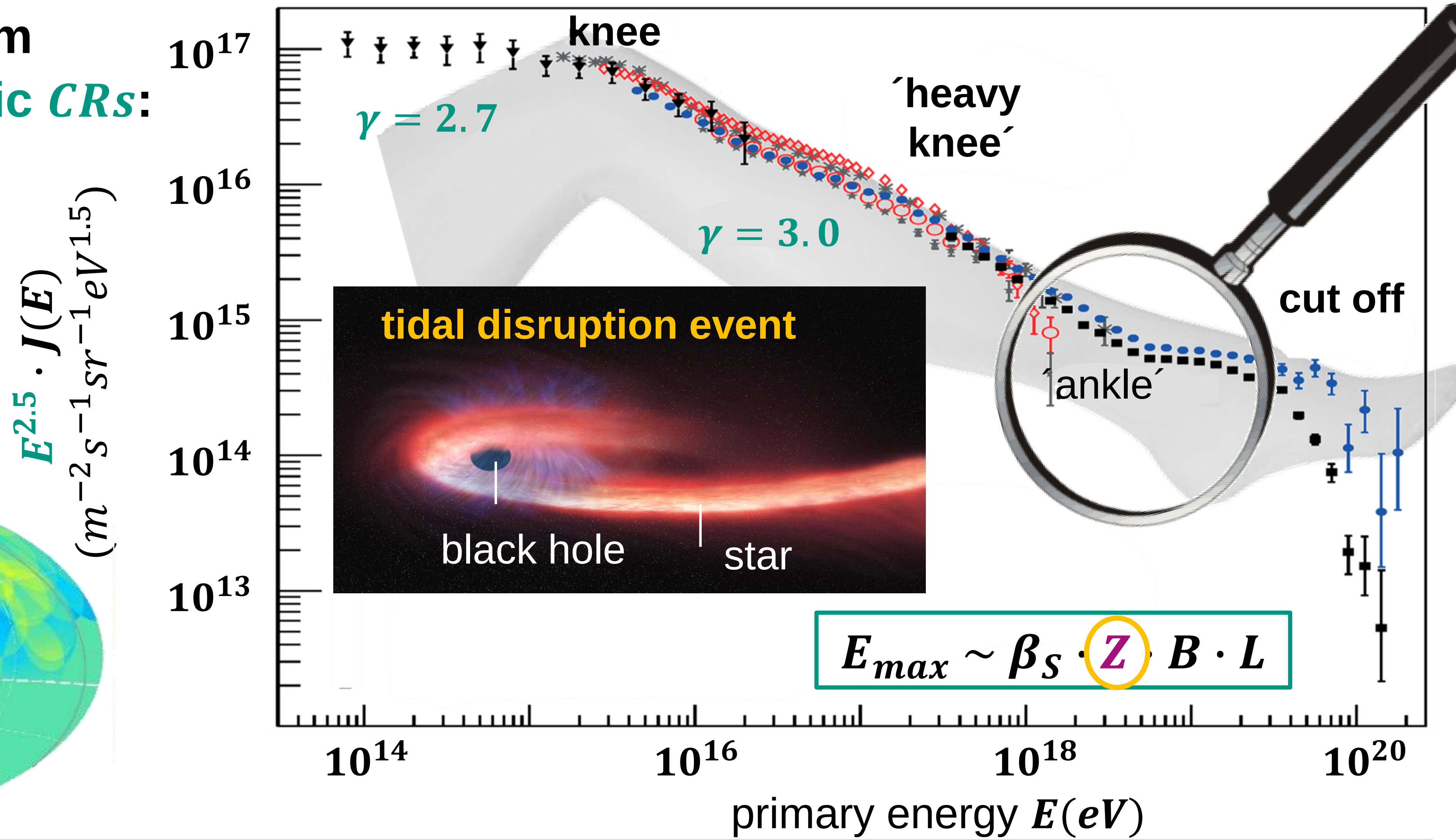
Energy spectrum of high−energy CRs & features

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

- change of acceleration sites

tidal disruptions?





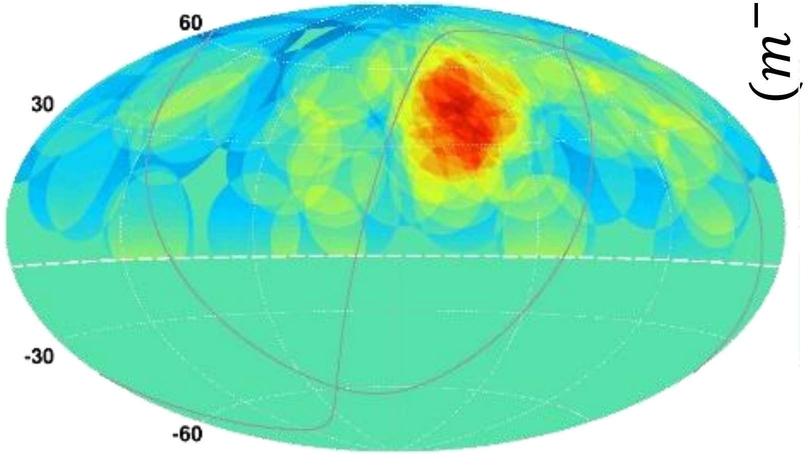
$$E_{max} \sim \beta_S \cdot Z \cdot B \cdot L$$

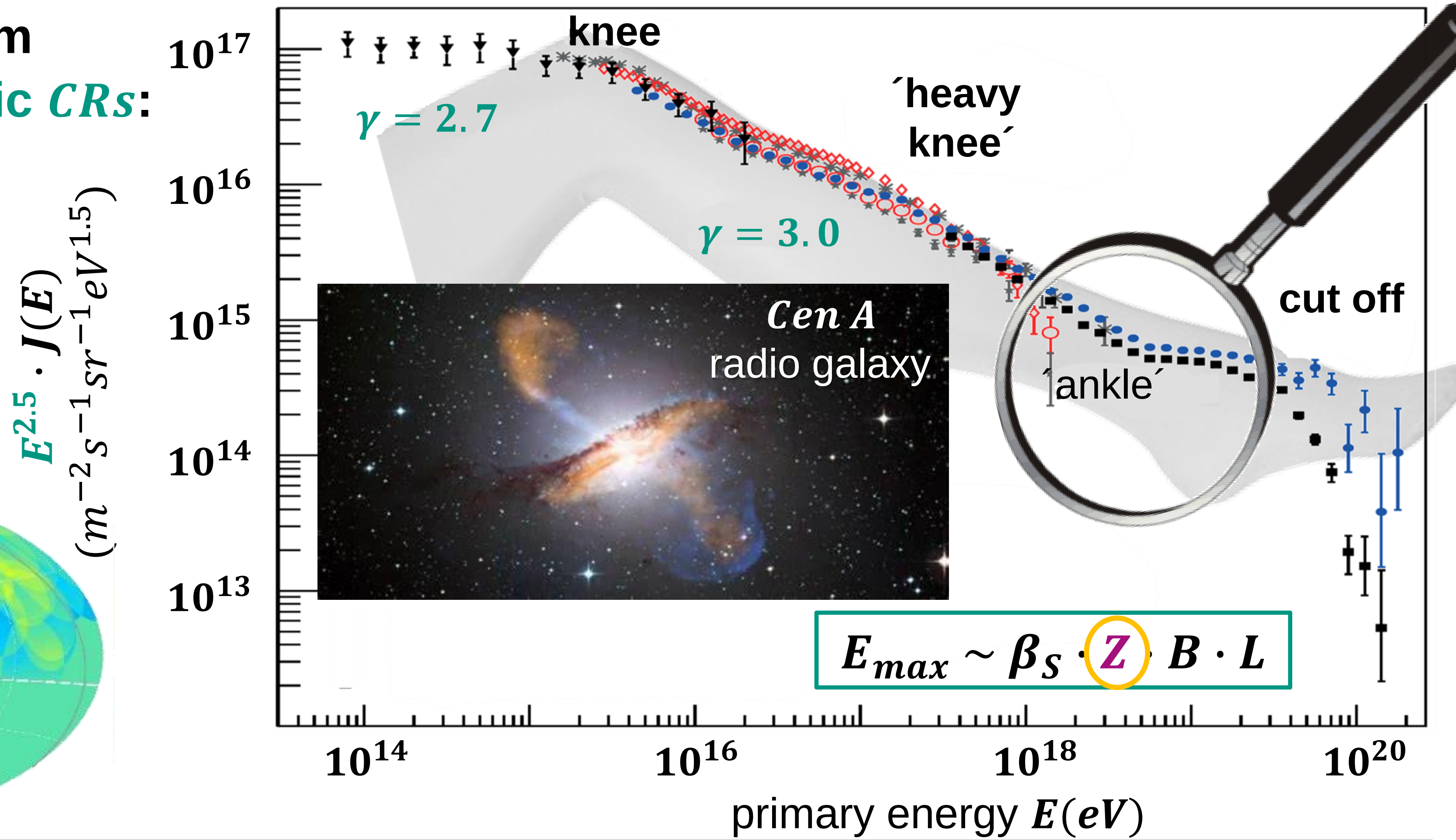
Energy spectrum of high–energy CRs & features

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

- change of acceleration sites

radio galaxies?



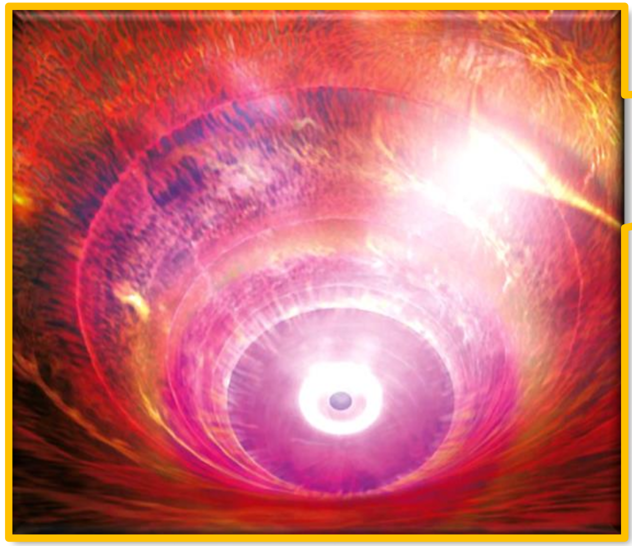


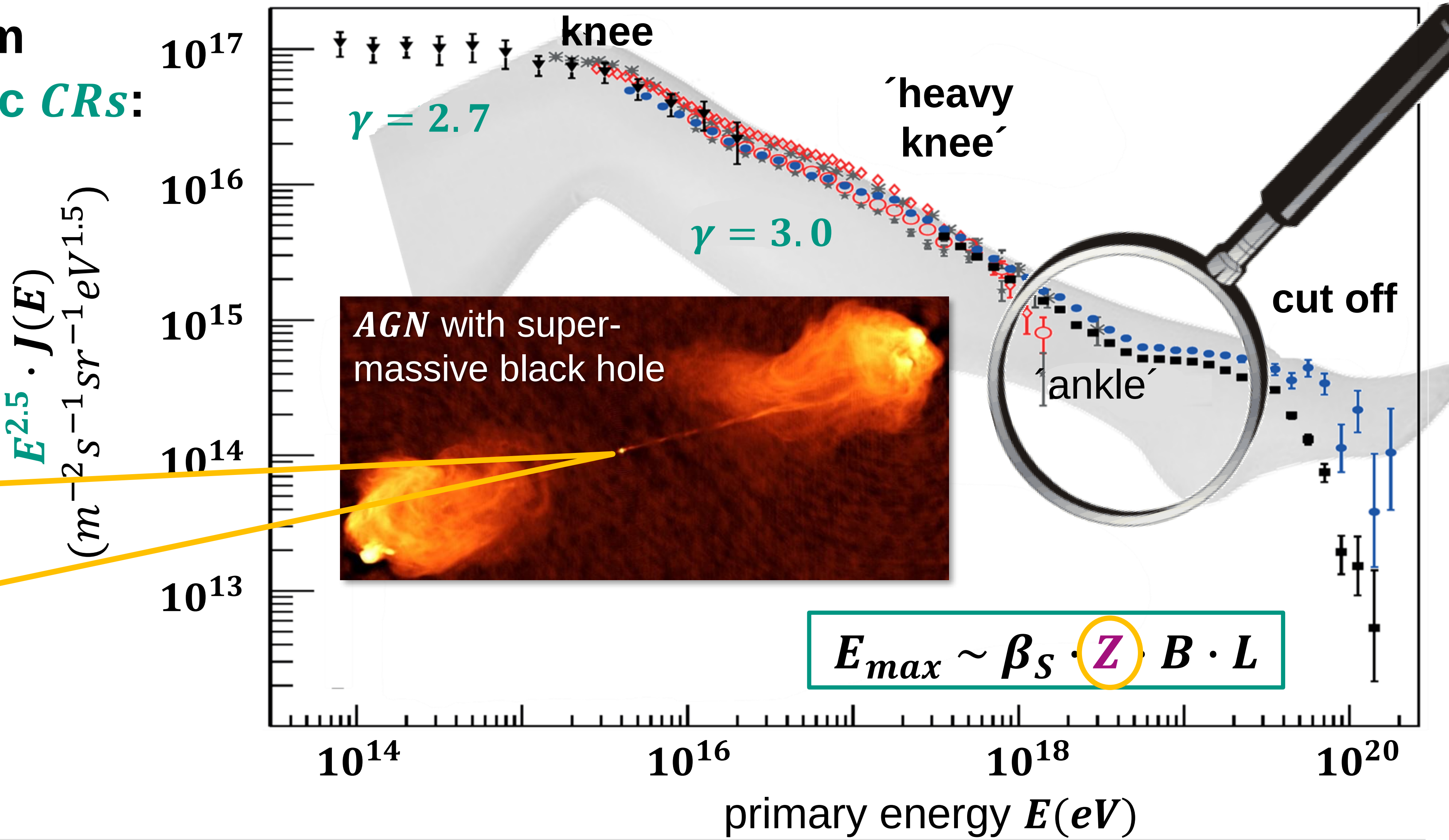
Energy spectrum of high–energy CRs & features

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

  - change of acceleration sites

***AGNs*?**



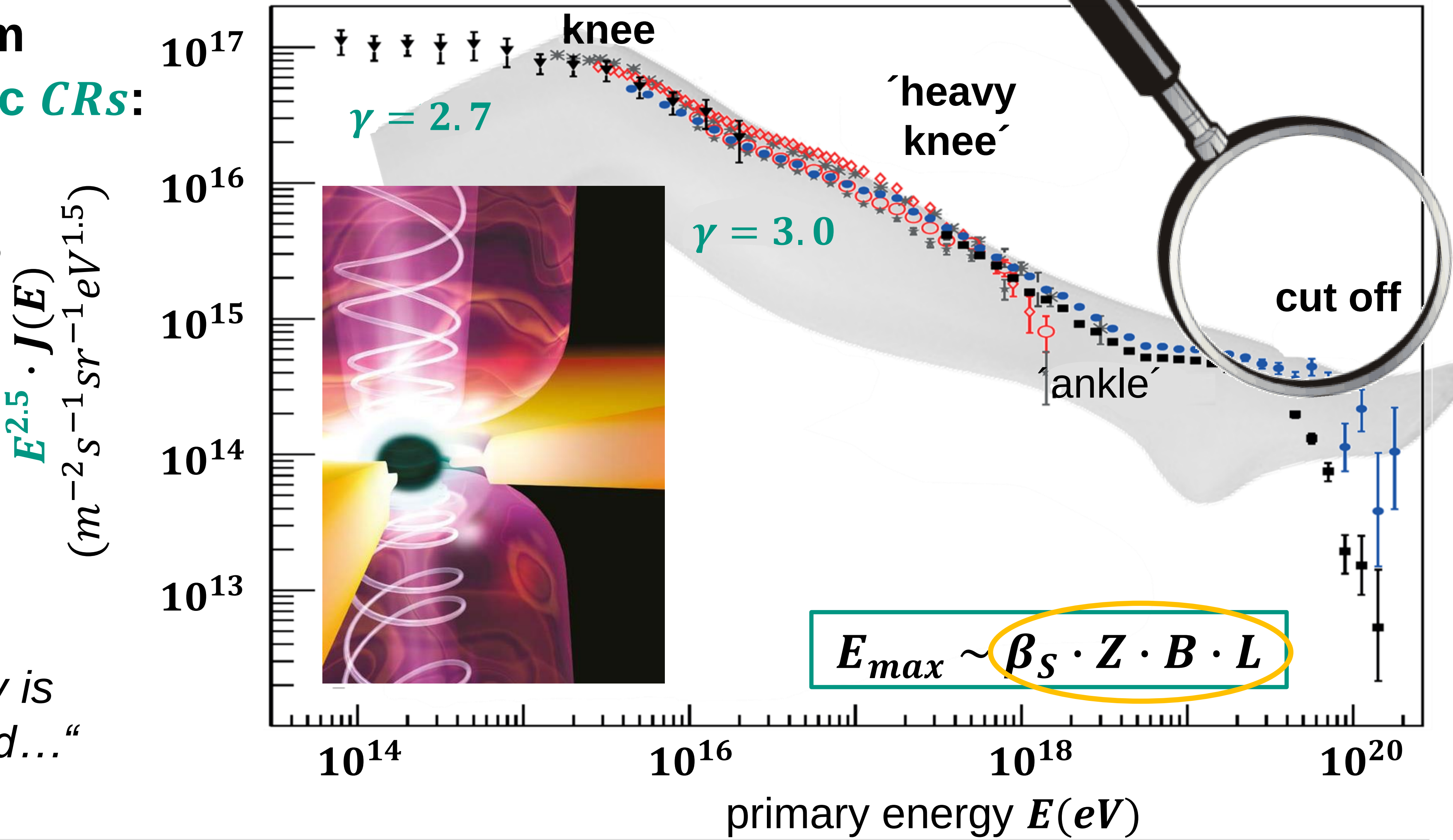


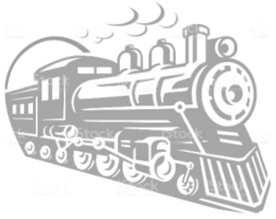
Energy spectrum of $UHECRs$ & cut–off

- **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)