Particle acceleration in Galactic sources

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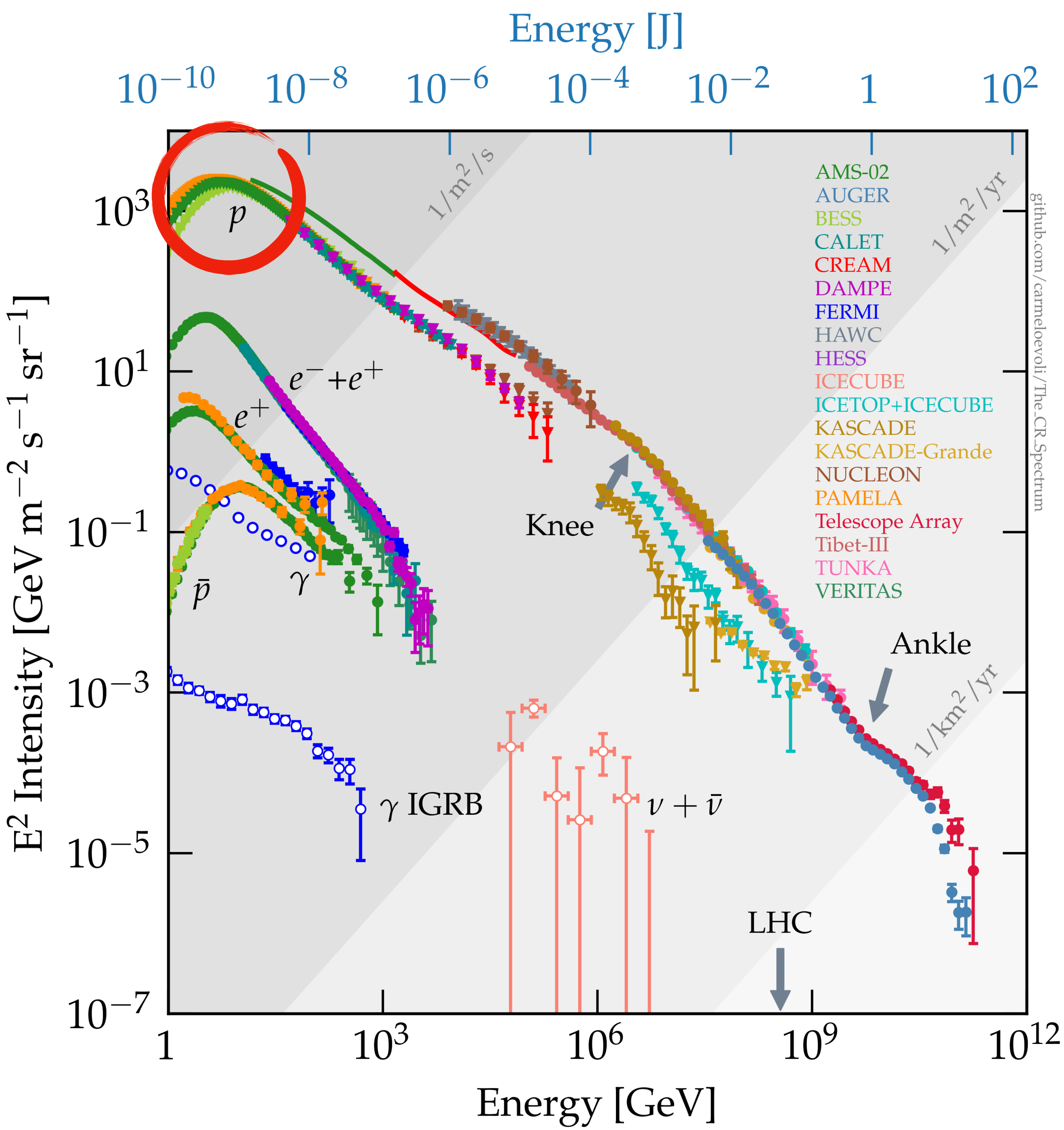
Summary

- Phenomenology of cosmic rays
  - The CR spectrum
  - Transition from Galactic to extra-galactic CRs
  - Chemical composition
  - Anisotropy
- Acceleration mechanisms
  - The Hillas' criterion
  - Fermi II
  - Fermi I
  - Collision-less shocks
- Sources
  - Supernova remnants
  - Stellar clusters
  - Micro-quasars

A quick view of the CR spectrum

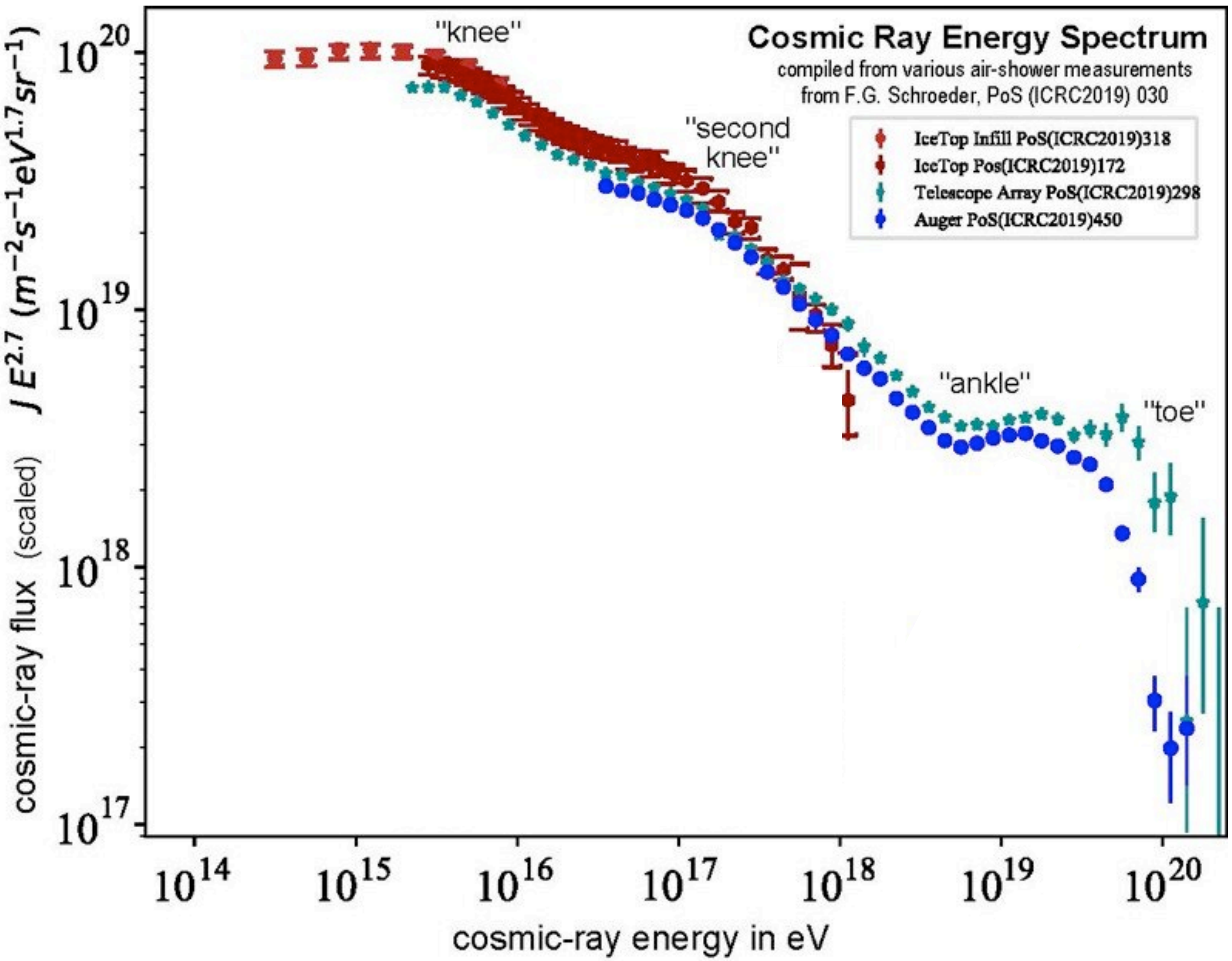


The CR energy is mainly due to 1-10 GeV particles

Component	Energy density in the Galaxy (eV/cm³)
Gas motion	~0.5
Magnetic field	~0.5
Starlight	~0.5
CMB	~0.5
CRs	~0.5

A quick view of the CR spectrum

Flux $\times E^{2.7}$



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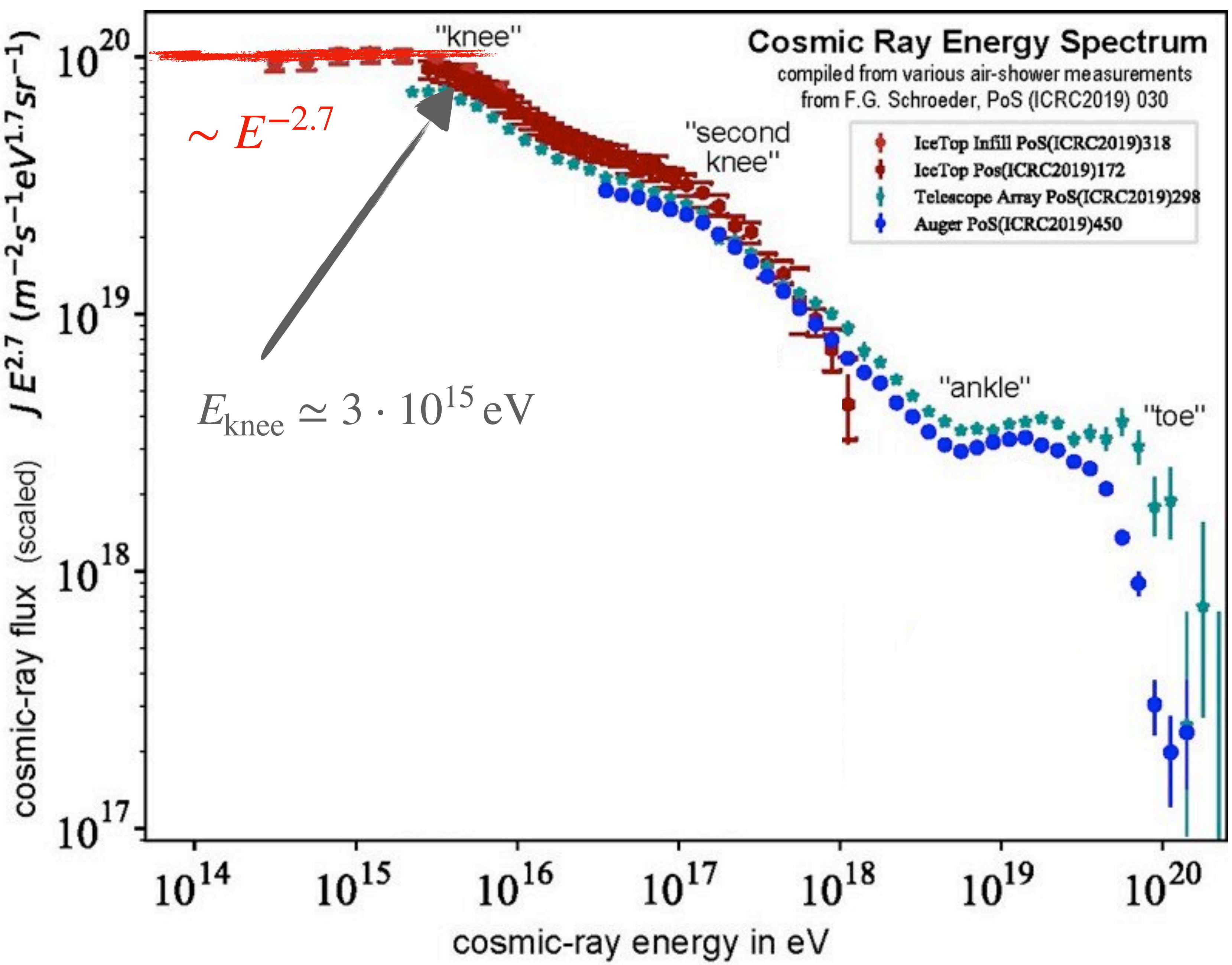

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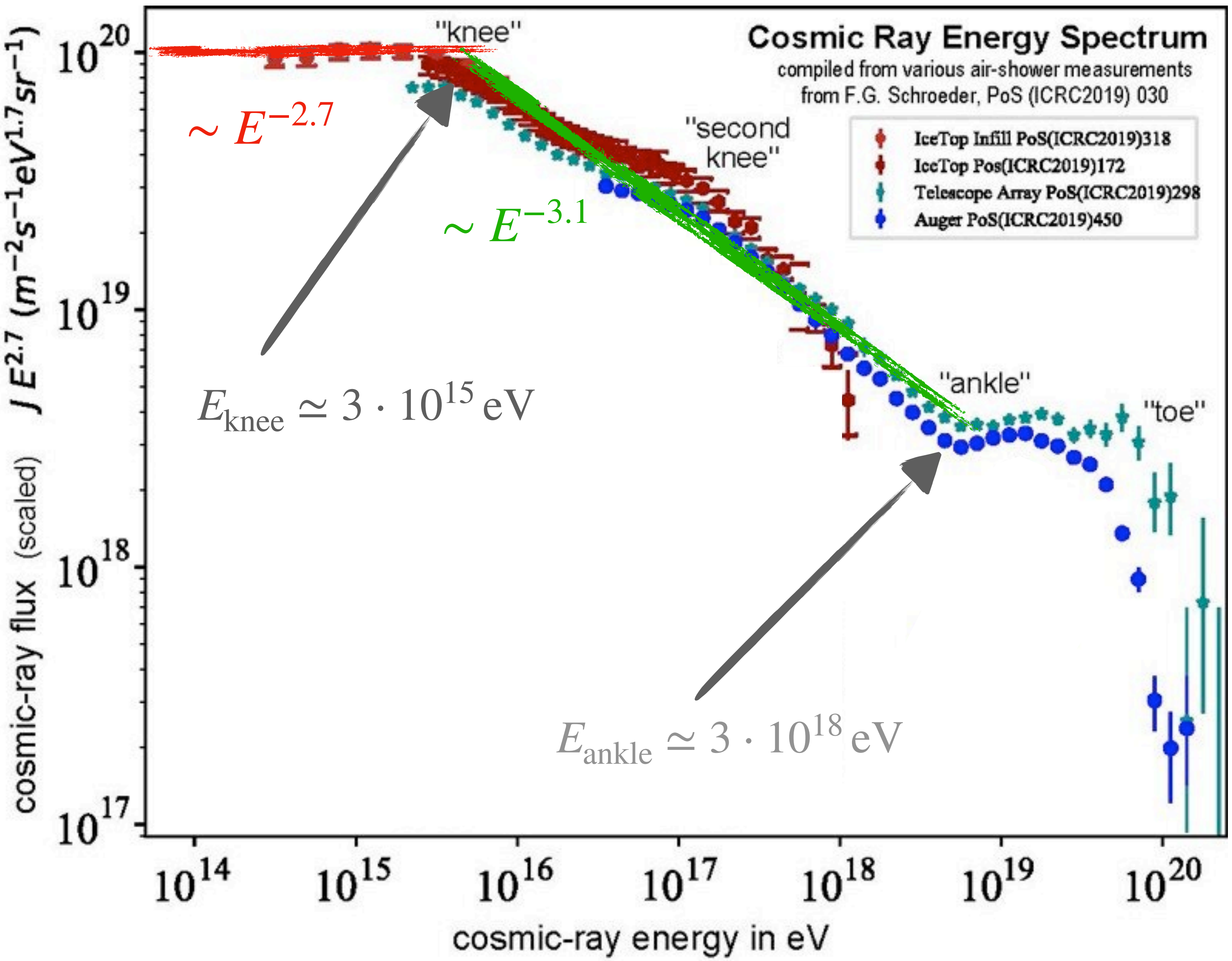

A quick view of the CR spectrum

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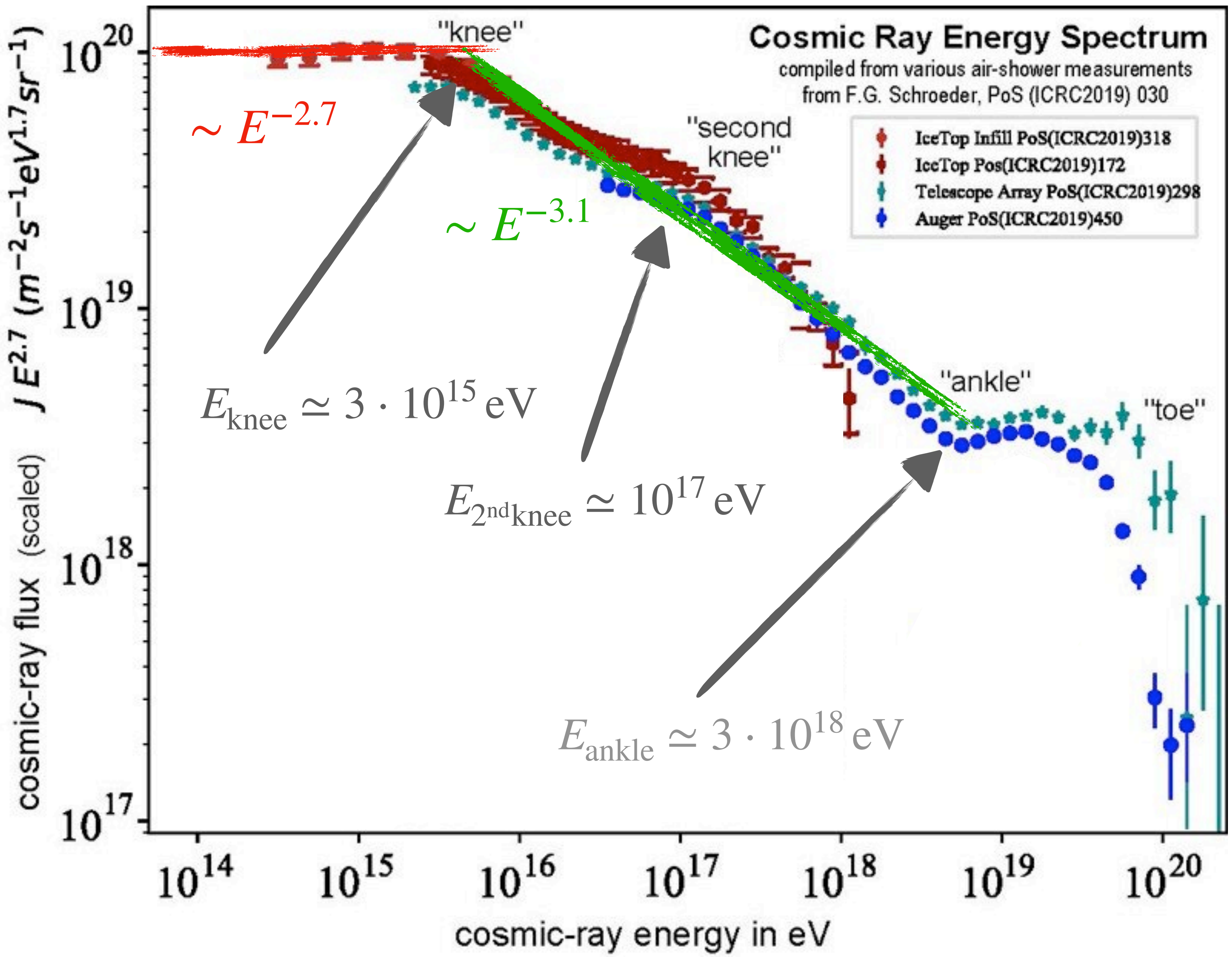

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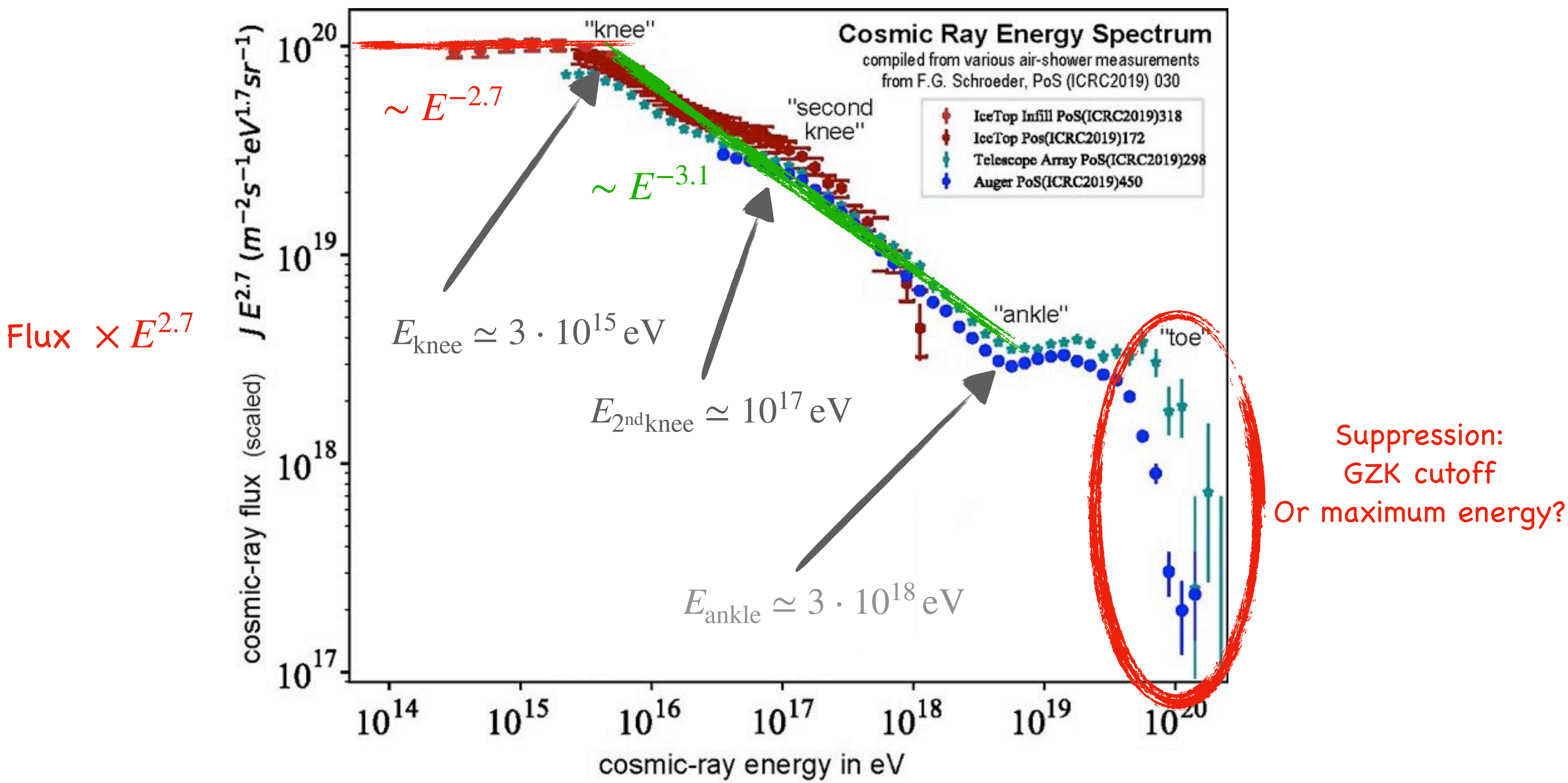
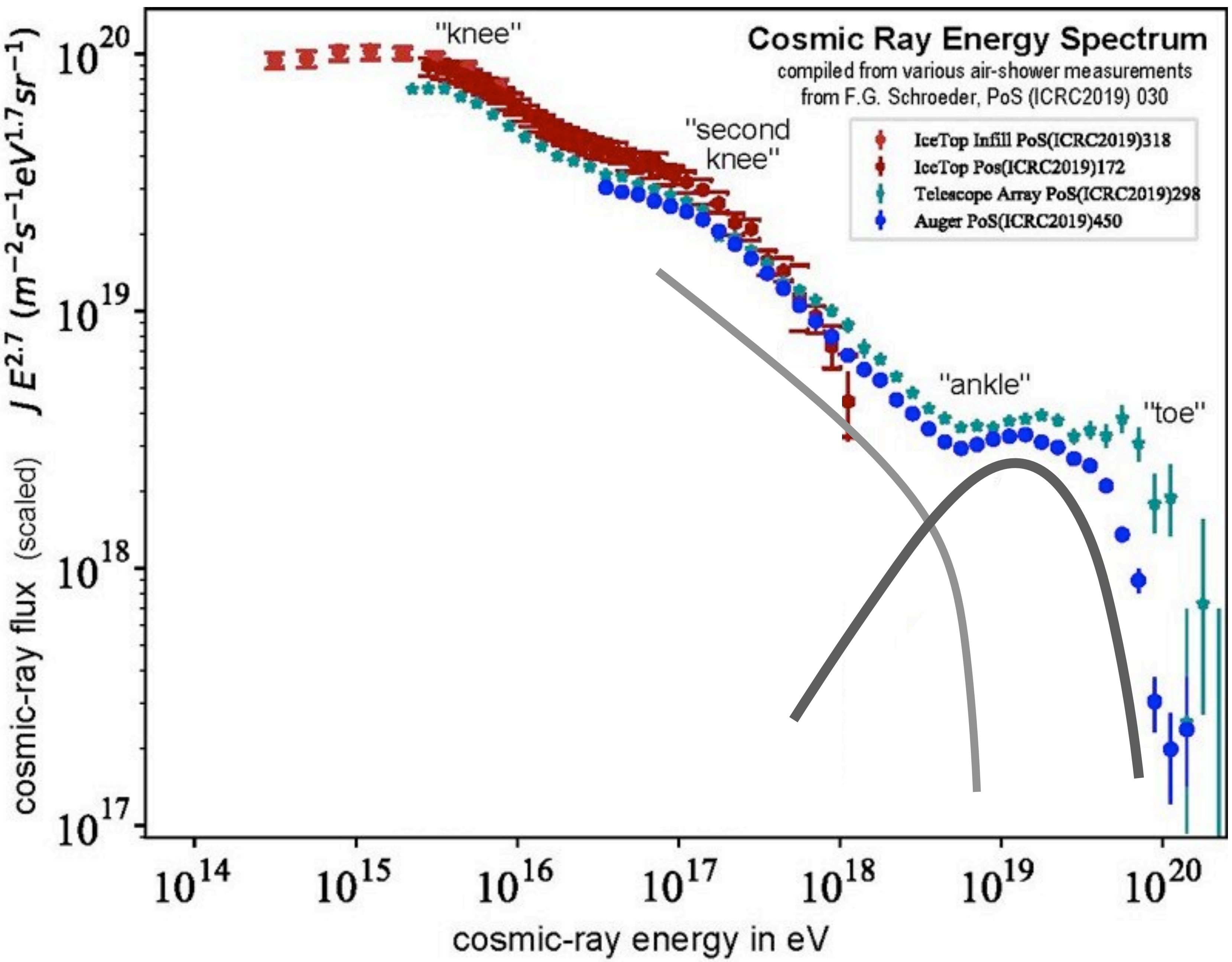


Transition from Galactic to extragalactic component

Flux $\times E^{2.7}$



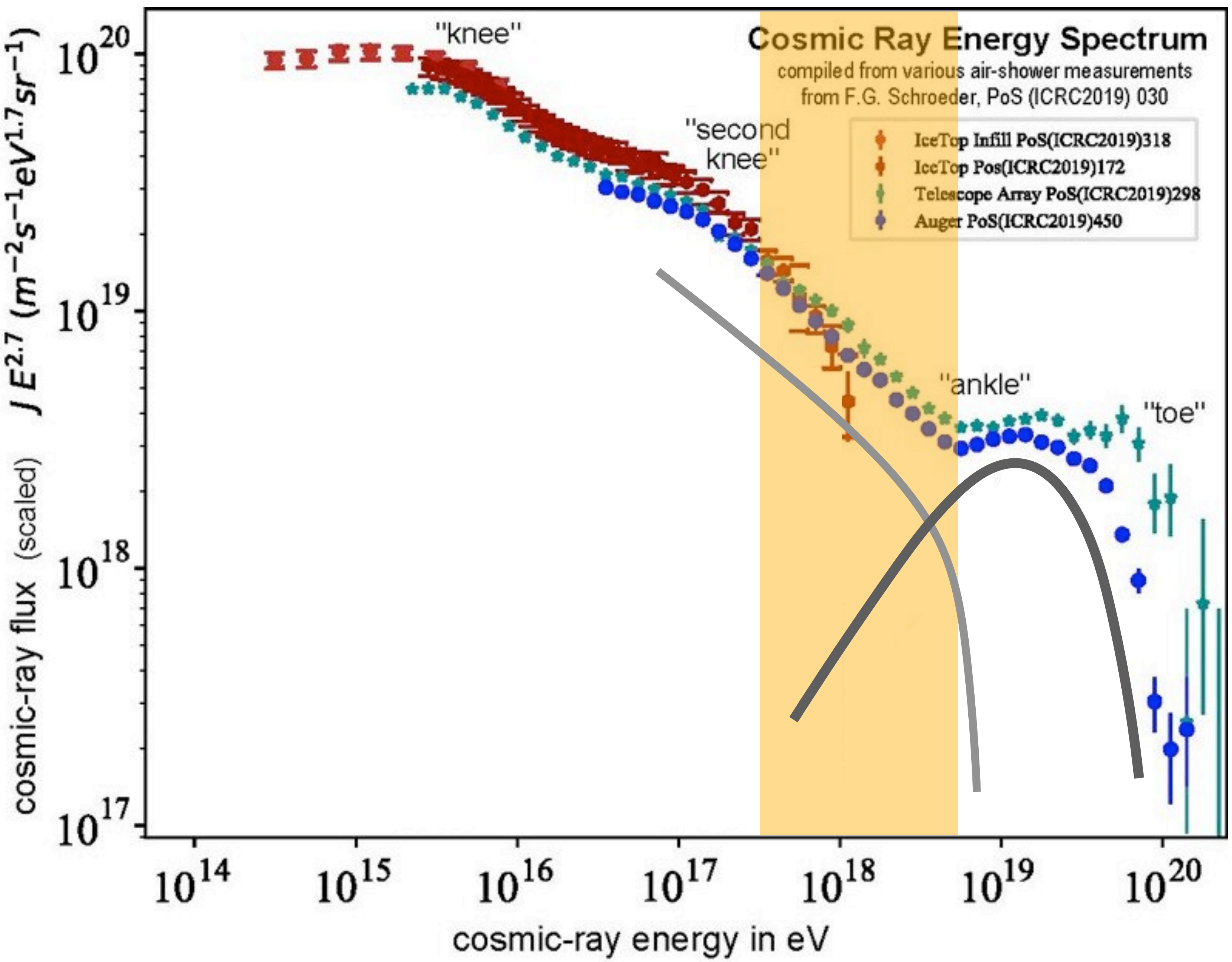
Ankle: the most natural location for the transition

Transition from Galactic to extragalactic component

2 caveats:

1) Larmor radius $r_L = \frac{Ec}{eB} = 100 \left(\frac{E}{10^{17}\,\mathrm{eV}}\right)\left(\frac{B}{1\mu G}\right)^{-1}$ pc → Large level of anisotropy

Flux $\times E^{2.7}$



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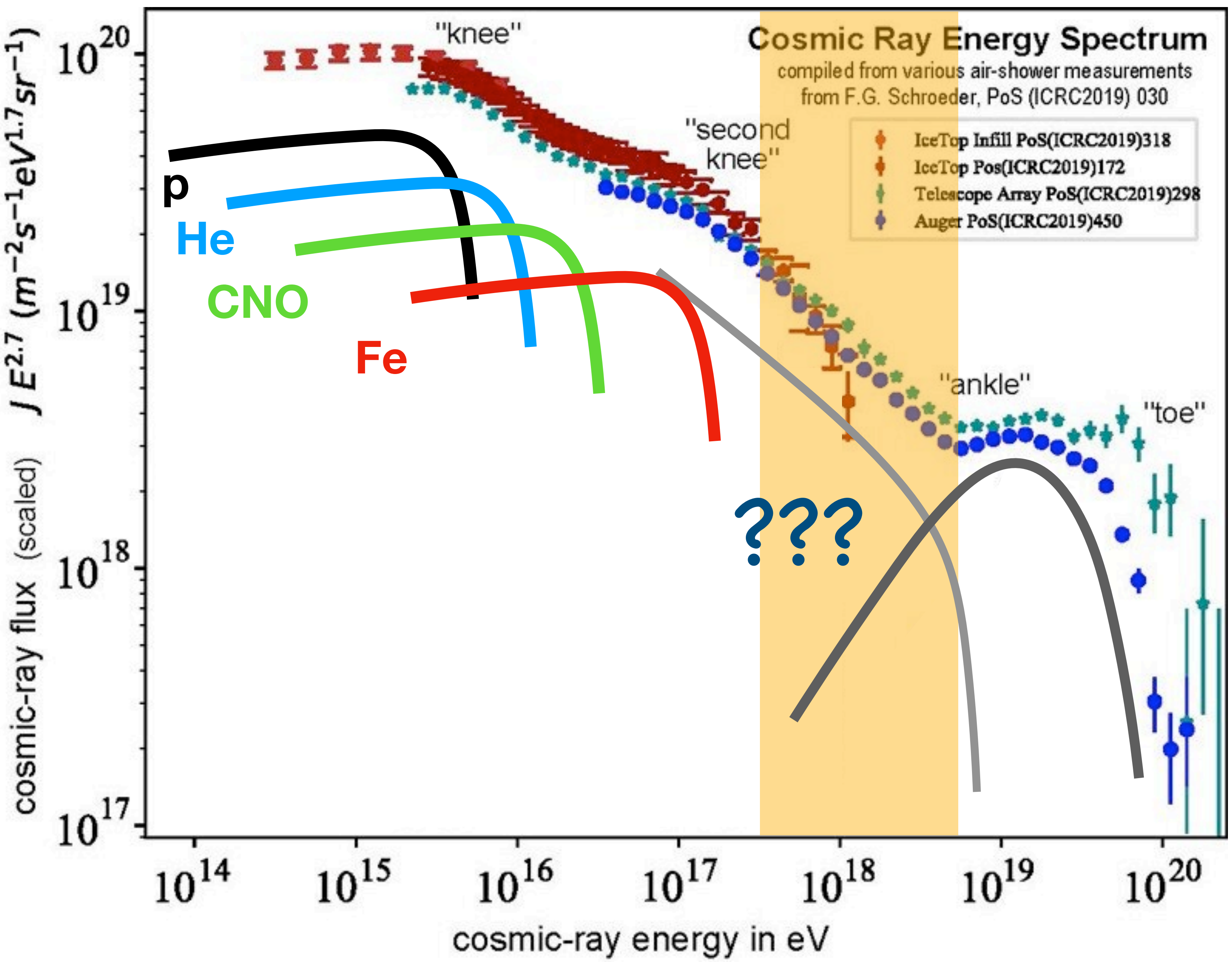
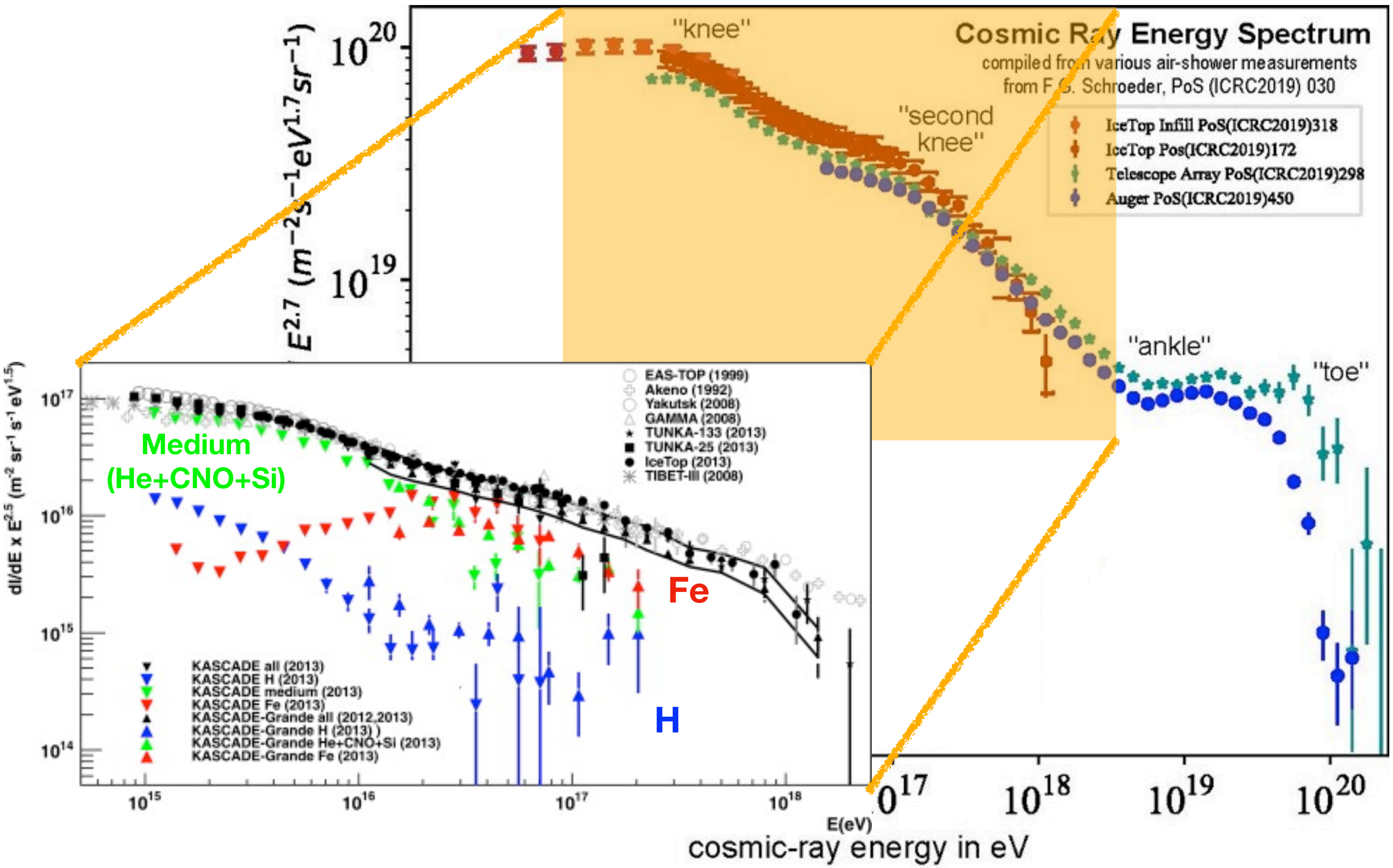
2) What beyond the 2nd knee?

Flux $\times E^{2.7}$



Ankle: the most natural location for the transition

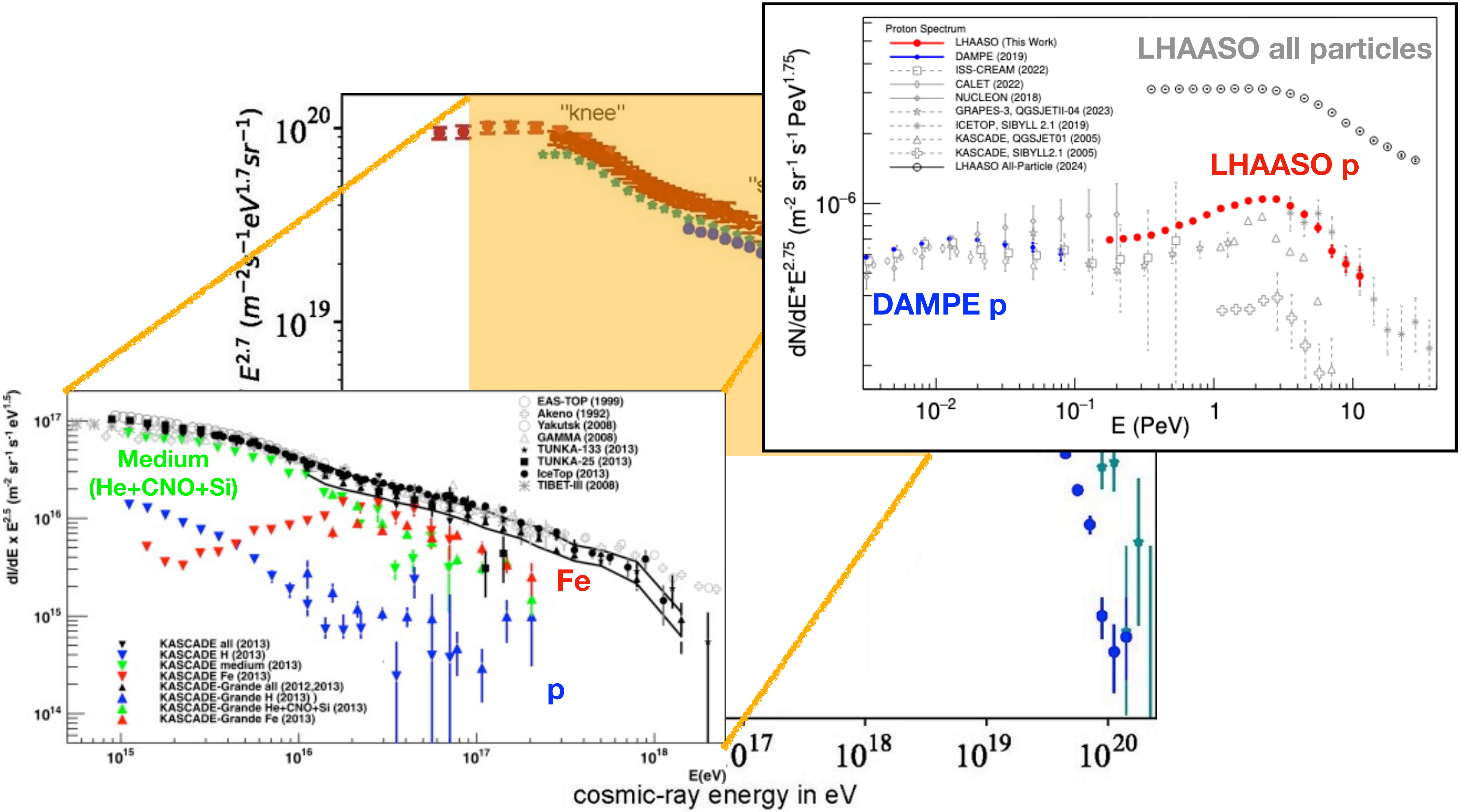
Chemical composition at the knee



A light component seems to appear much below 10^{18} eV

Chemical composition at the knee

Latest results for the proton spectrum
[LHAASO coll. arXiv:2505.1444]



The full proton spectrum

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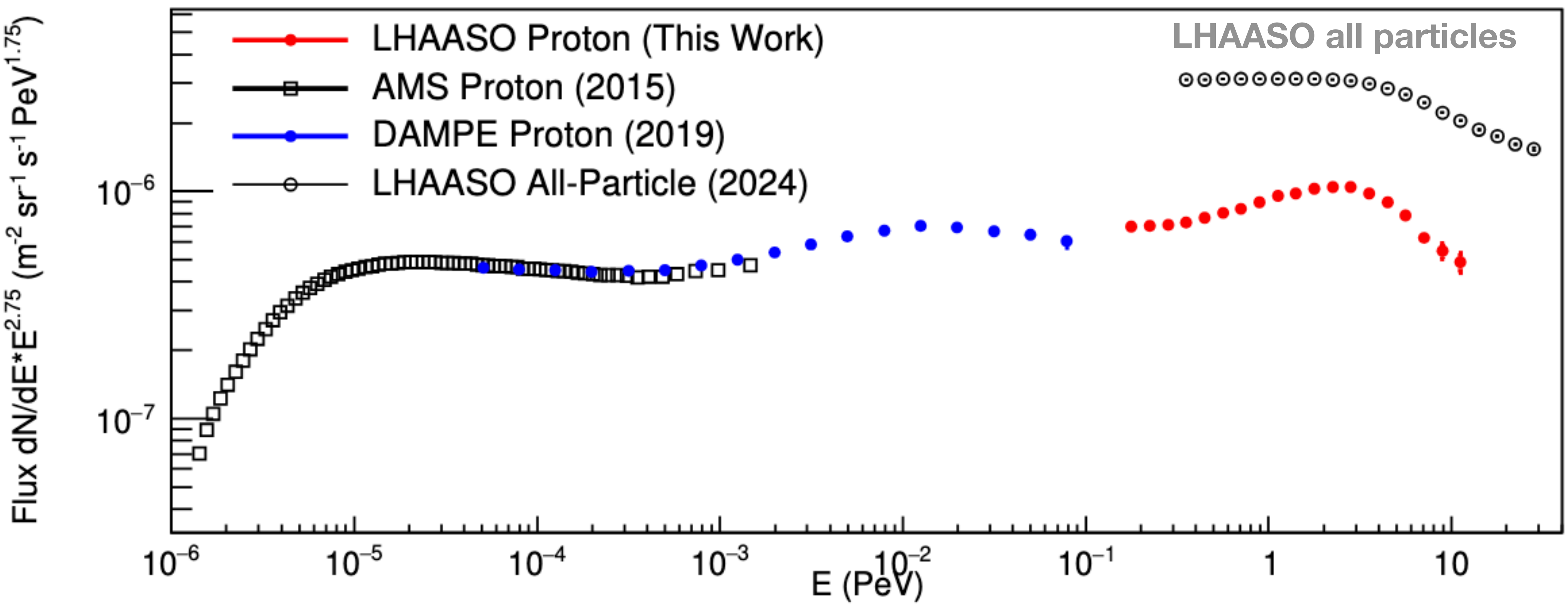
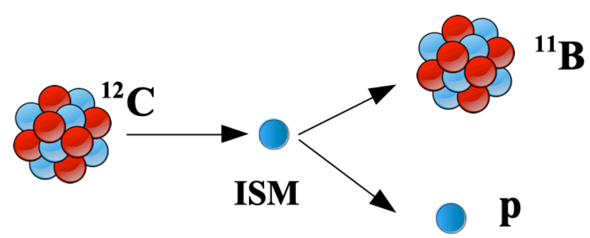


Chemical composition

- The relative abundance of some elements is larger than in the Solar system
- Those "secondary" CRs are produced in spallation reaction of primary CRs



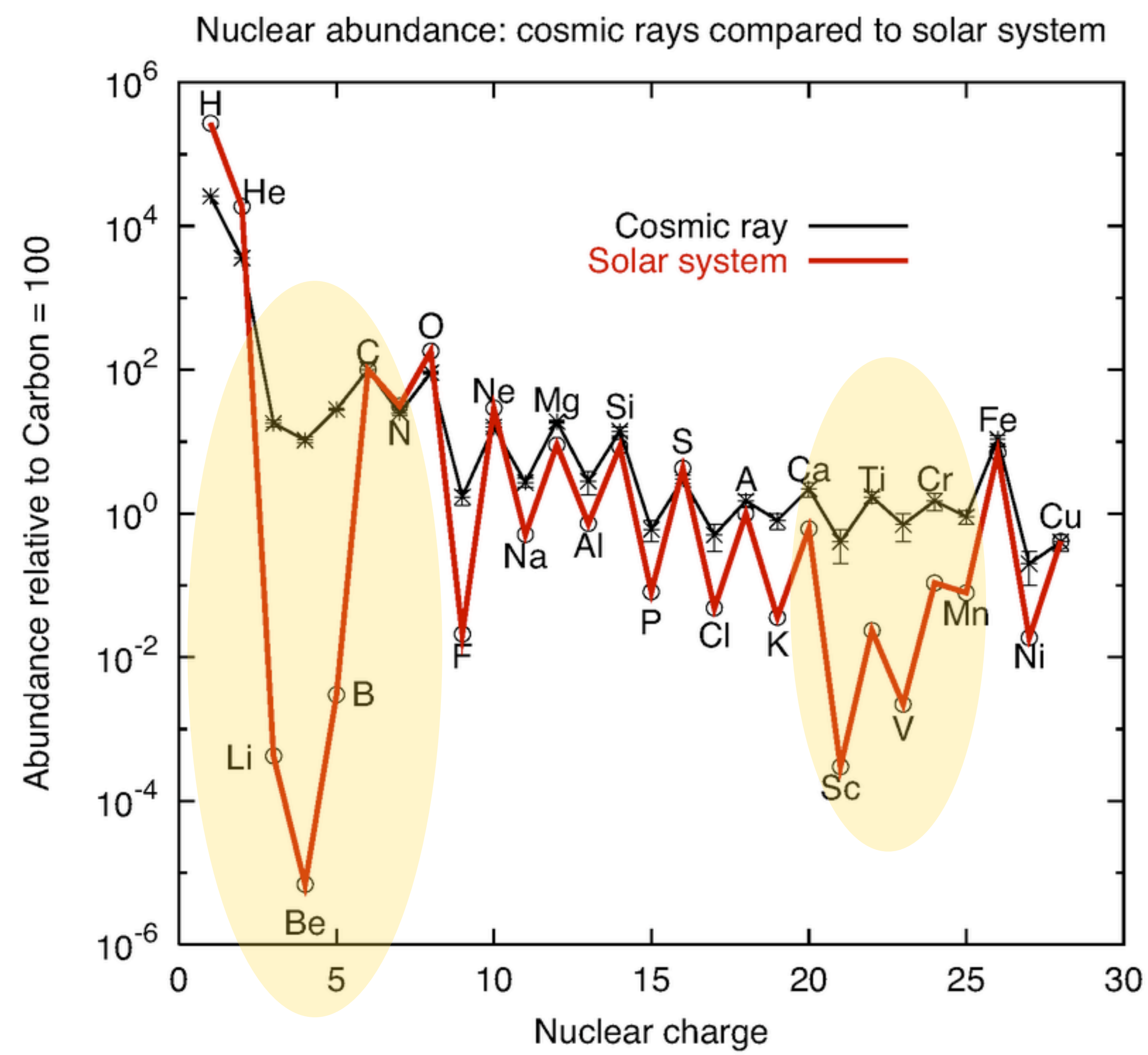
- Primary CRs should propagate in the Galaxy for a time comparable with the interaction time

$$\tau_{\rm int} = \frac{1}{n_{\rm gas} c \sigma_{\rm spall}} \approx 10 - 100 \ {\rm Myr}$$

Maximum propagation time in the Galaxy:

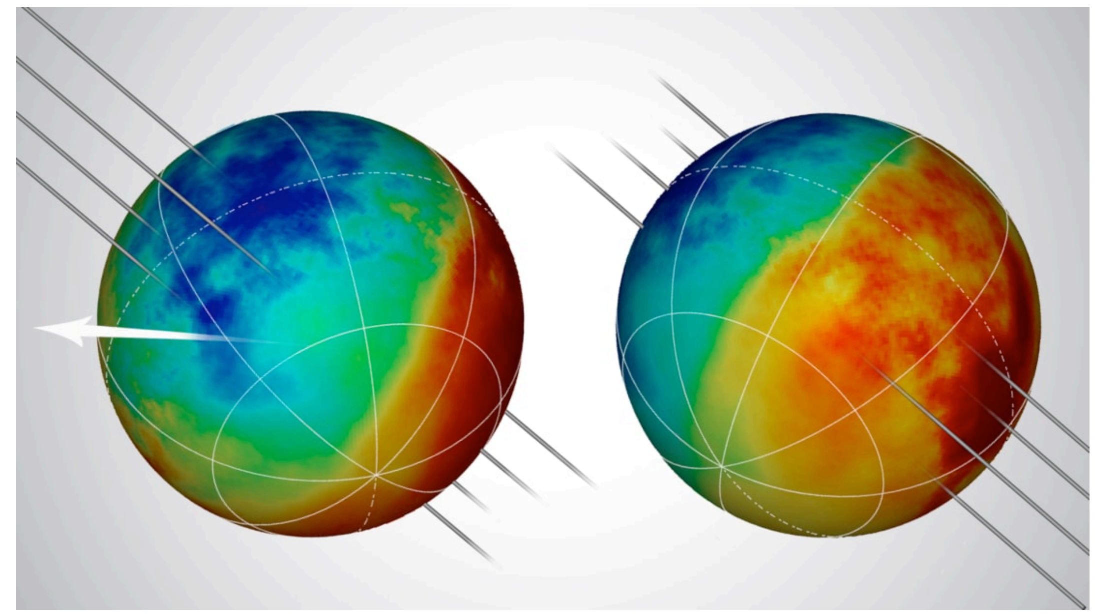
$$\tau_{\rm gal} = \frac{15\,{\rm kpc}}{c/3} \approx 1.5 \times 10^5 \ {\rm Myr}$$

$\Rightarrow$ CR have to diffuse in the Galaxy

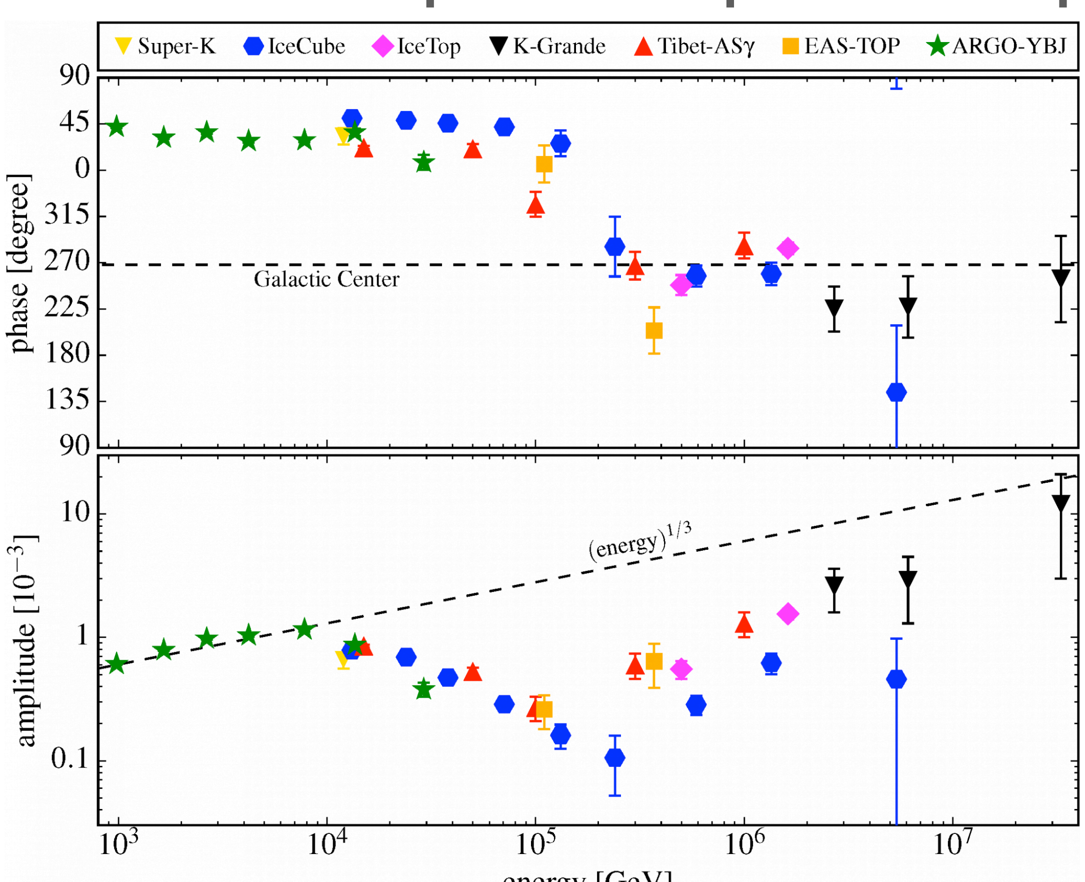


Anisotropy

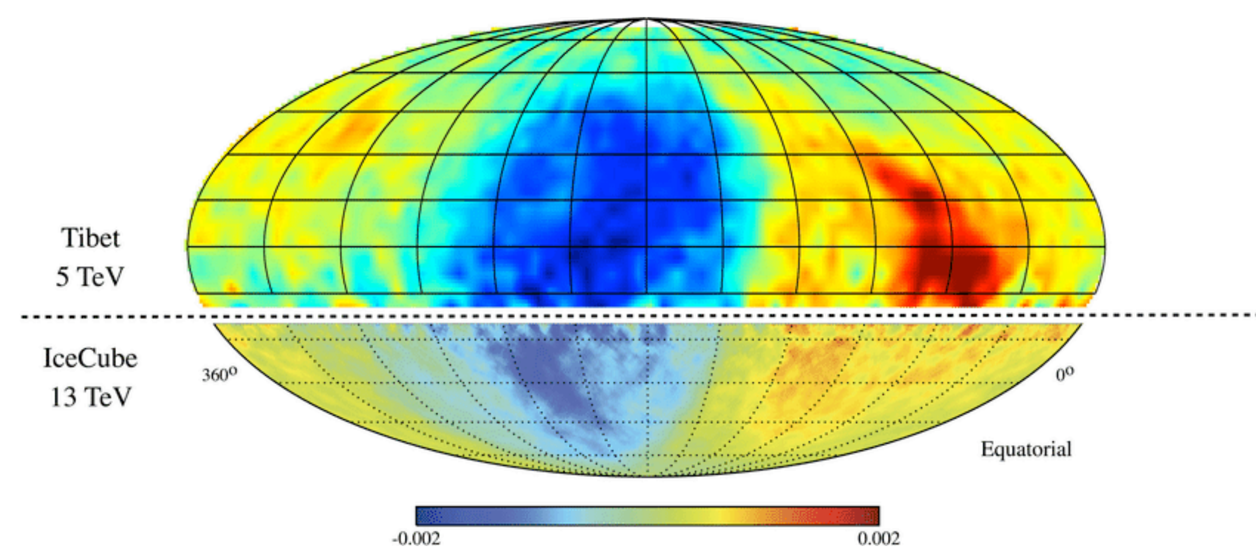
- The level of anisotropy is very low ~10^{-3}
- A dipole anisotropy is present even when the Compton-Getting effect is removed
- Some small scale anisotropy are also present



Phase and amplitude of dipole anisotropy



Combined cosmic ray anisotropy of the Tibet-AS and IceCube experiments in the equatorial coordinate system.



Anisotropy

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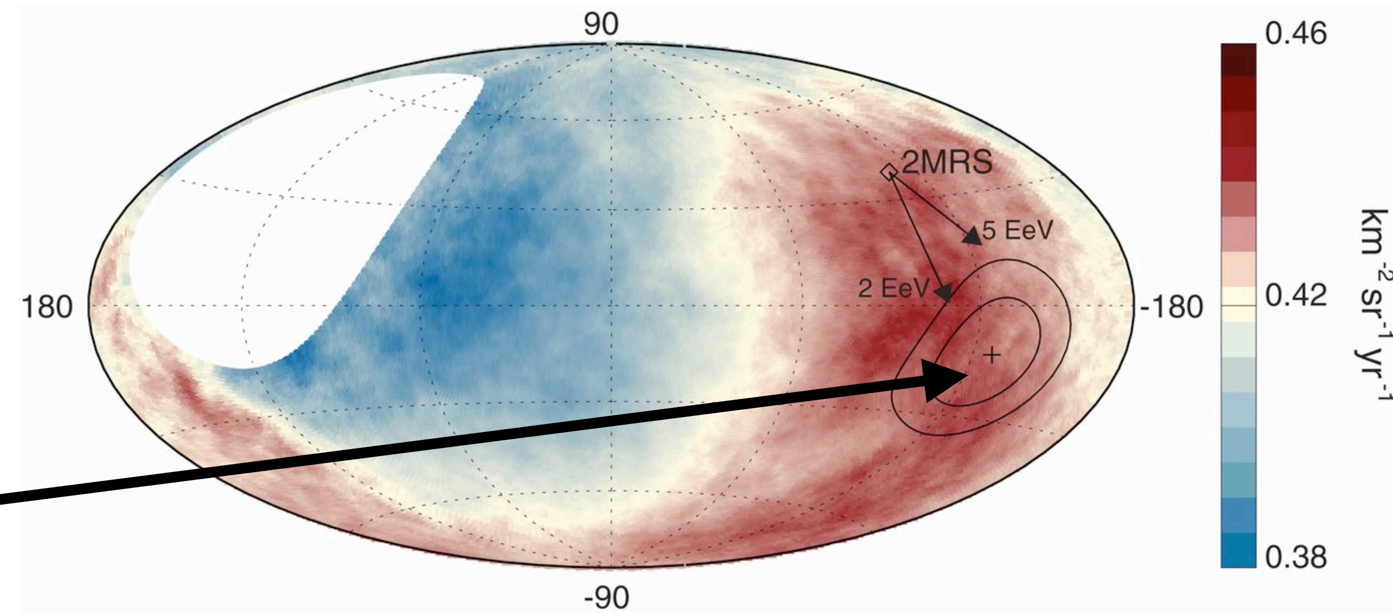
- A dipole anisotropy is present even when the Compton-Getting effect is removed
- Some small scale anisotropy are also present
- At E> 8×10^{18} eV the dipole points toward extragalactic direction



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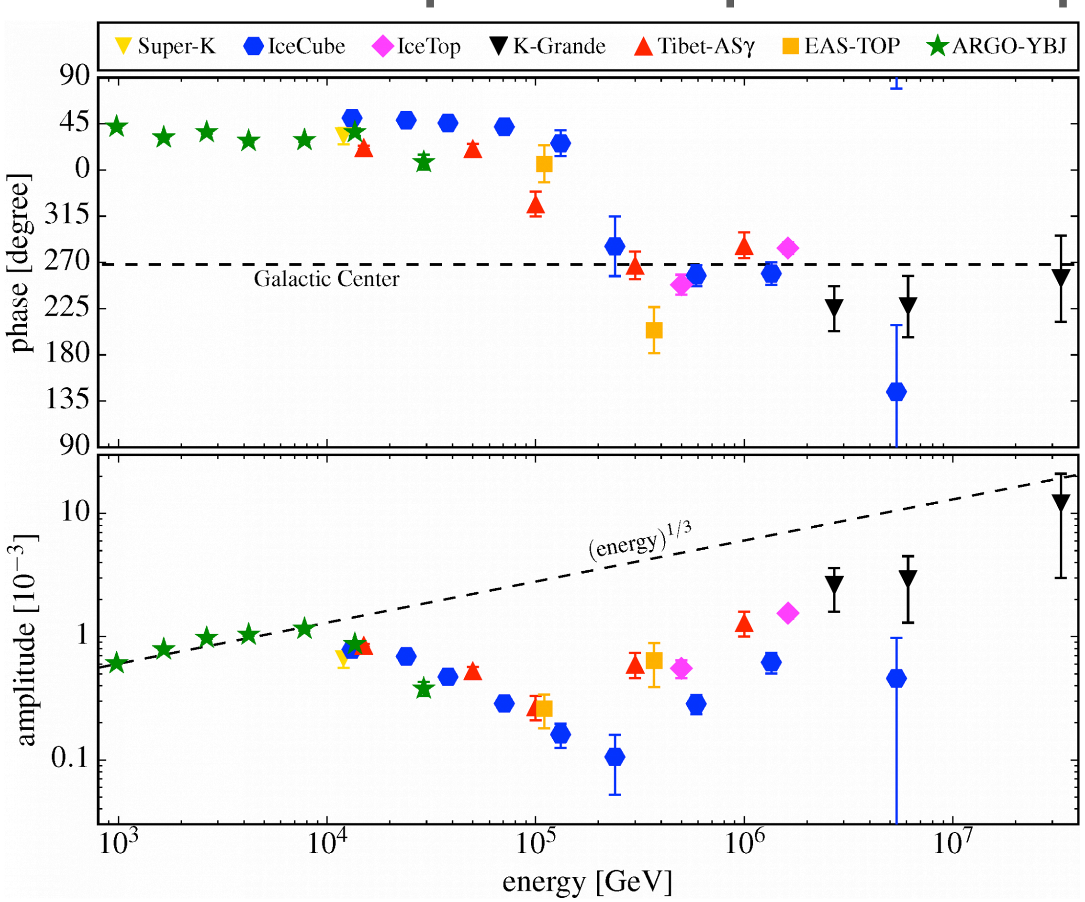

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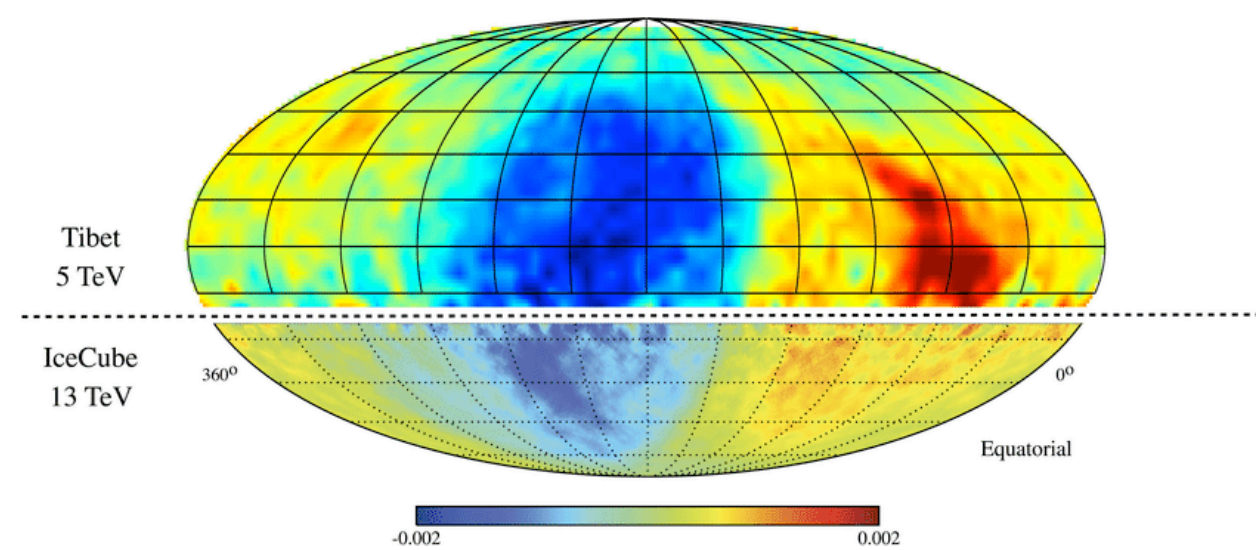


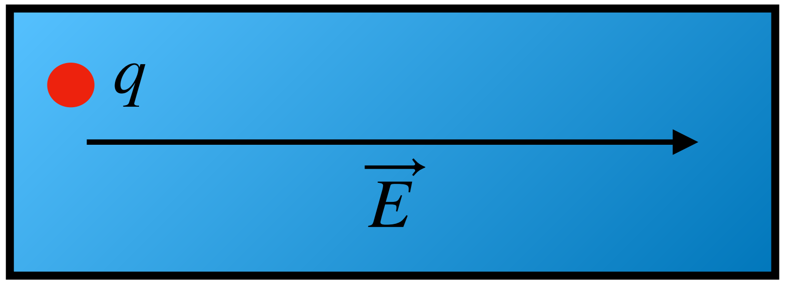
A short summary

- CRs diffuse in the Galaxy:
    - Chemical composition ("secondary" CRs are produced in spallation reaction)
    - Low level of anisotropy
- Galactic sources should accelerate CRs protons at least up to PeV
- The transition between Galactic and extra-galactic CRs is unclear:
    - If the transition is the "Ankle" -> need of Galactic component at $E > 10^{17}$eV
    - If below the ankle -> need of multiple extragalactic spectra

Acceleration mechanisms

The Hillas' criterion

The best possible accelerator



- Absolute maximum energy

$$E_{\rm max} = q\,|\,\vec{E}\,|\,L$$

- Current:

$$\vec{j} = \sigma \vec{E}_{\rm lab} = \sigma \left(\vec{E} + \frac{1}{c}\vec{v} \times \vec{B} \right)_{\rm rest\ frame}$$

- Astrophysical plasmas has a very large conductivity (electrons can move almost freely)

$$\sigma \simeq 7 \times 10^7 \frac{T^{3/2}}{\ln \Lambda}\, {\rm s}^{-1}$$

$$\Rightarrow \;\; \vec{E}_{\rm lab} \simeq 0; \;\; \vec{E}_{\rm RF} \simeq -\frac{1}{c}\vec{v} \times \vec{B}$$

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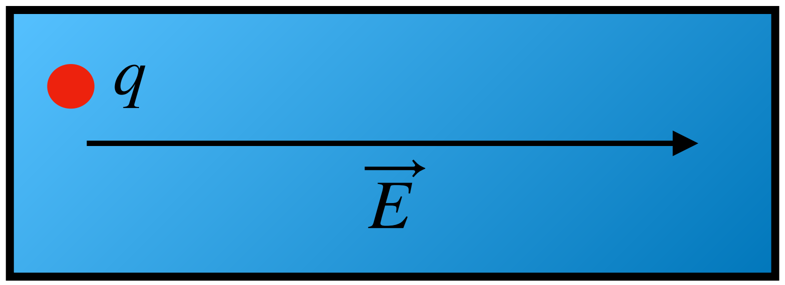

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Where does the electric field come from?

Faraday's law: $\nabla \times \vec{E} = -\dfrac{1}{c}\dfrac{\partial \vec{B}}{\partial t}$

$\nabla \times \longrightarrow \dfrac{1}{L}$ characteristic length

$\dfrac{\partial}{\partial t} \longrightarrow \dfrac{1}{T}$ characteristic time

$$\Rightarrow \quad E \approx \frac{L}{T}\frac{B}{c} \approx \frac{U}{c}B$$

velocity

Charge

$$\boxed{\Rightarrow \quad E_{\rm max} \approx \frac{U}{c}\, q\, B\, L}$$

Size

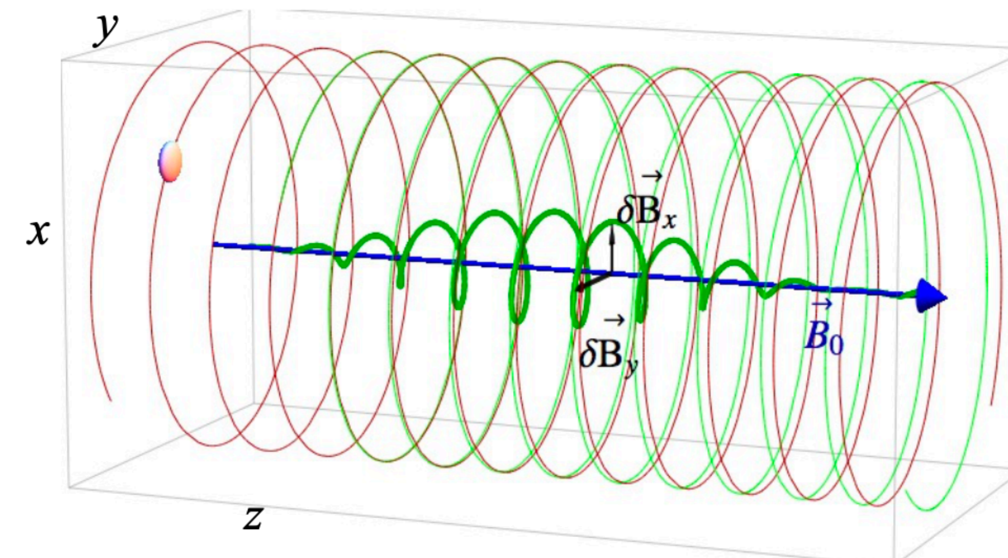
B-field

This result should be considered an upper limit

Alfvén waves

Alfvén (1942)

- Ideal MHD equations predicts three different kind of waves (combination of electromagnetic-hydromagnetic waves):
  - Fast magneto-sonic
  - Slow magneto-sonic
  - Alfvén waves



- Alfvén waves propagate along the large scale magnetic field with velocity

$$v_A = \frac{B}{\sqrt{4\pi\rho_i}}$$

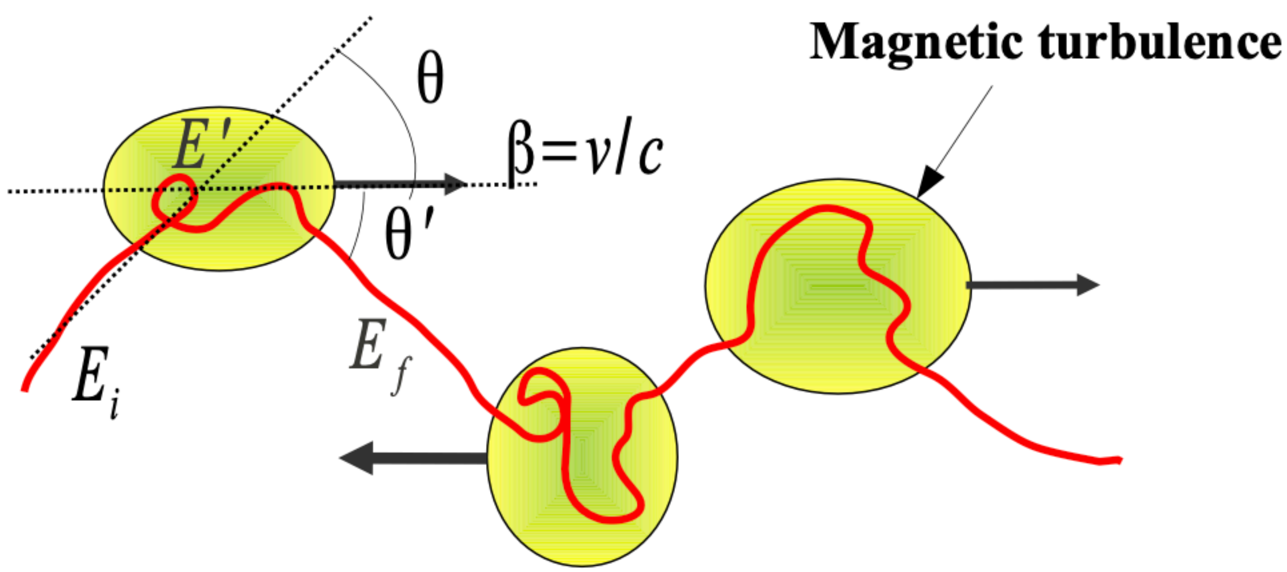
- Analogy with a wave on a string: $v = \sqrt{T/\mu}; \;\; T \to B^2/4\pi, \;\; \mu \to \rho$

- Magneto-sonic waves speed: $\left[v_A^2 + c_s^2 \pm \sqrt{(v_A^2 + c_s^2)^2 - 4 v_A^2 c_s^2 \cos\theta} \right]^{1/2}$ ← Combination of magnetic and fluid pressure

- The damping of Alfvén waves is less efficient than the magneto sonic waves

- Interaction of particles with Alfvén waver can produce scattering if $\boxed{r_L = \lambda = 1/k}$ Resonant condition

II order Fermi acceleration



Applying Lorentz transformation for a single encounter:

$$E' = \gamma E_1 (1 - \beta\mu)$$

$$E'_f = E'_i = E'$$

$$E_f = \gamma E' (1 + \beta\mu')$$

$$\Rightarrow \quad E_f = \gamma^2 E_i (1 - \beta\mu)(1 + \beta\mu')$$

Many encounters:

$$\langle \frac{\Delta E}{E} \rangle_{\mu'} = \int_{-1}^{1} \frac{E_f - E_i}{E_i} d\mu' = 2 \left[\gamma^2 (1 - \beta\mu) - 1\right]$$

Assuming isotropy in the cloud's reference frame

$$\langle \frac{\Delta E}{E} \rangle_{\mu'\mu} = \int_{-1}^{1} \underbrace{\frac{1}{2}(1 - \beta\mu)}\, 2 \left[\gamma^2 (1 - \beta\mu) - 1\right] d\mu = \frac{4}{3}\beta^2$$

Losses and gains are both presents but do not compensate exactly

Particle's incident flux $\beta_{\rm rel} = (c - v\mu)/c$

II order Fermi acceleration

Take away messages:

- Particles are energised by induced electric field

$$\nabla \times \delta \vec{E} = -\frac{1}{c}\frac{\partial \delta \vec{B}}{\partial t}$$

- The energy gain is only proportional to $(v/c)^2$

$$\langle \frac{\Delta E}{E} \rangle = \frac{4}{3}\left(\frac{v_{\rm cloud}}{c}\right)^2$$

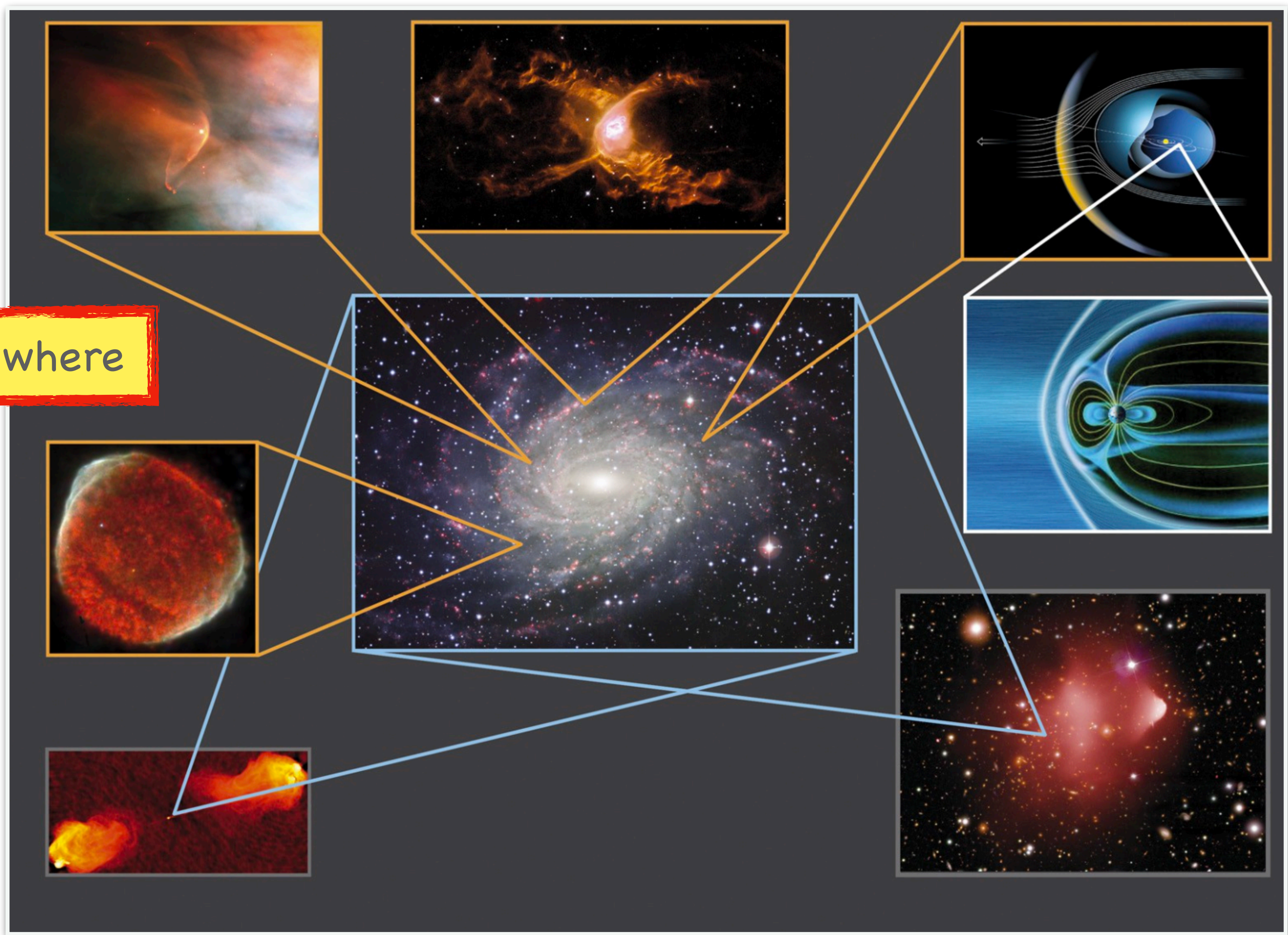
- In general $v_{\rm cloud} \simeq v_A \simeq 10\,{\rm km/s} \Rightarrow$ the maximum energy is at most ~10 GeV
- The predicted spectrum strongly depends on details (clouds distribution, volume filling factor) ⇒ is difficult to obtain $\sim E^{-2.7}$

⇒ **II order Fermi mechanism cannot explain the CR flux**

From II to I order Fermi acceleration

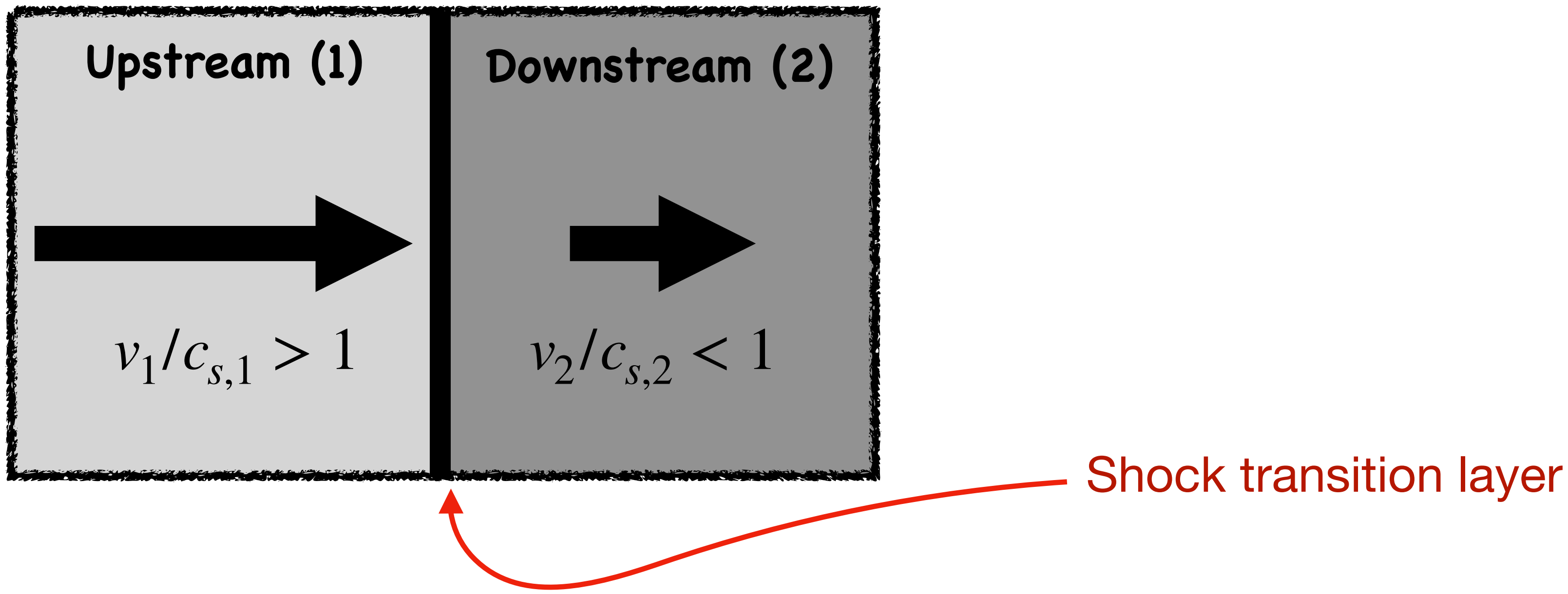
In the '70s several researchers independently realised that applying the Fermi's idea to a different geometry, i.e. plane shocks, results in a much more efficient mechanisms [Skilling, 1975; Axford et al., 1977; Krymskii, 1977; Bell, 1978; Blandford and Ostriker, 1978]

Shocks are everywhere



What is a shocks?

A shock is formally a discontinuity solution of the fluid equations where a supersonic flow becomes subsonic



Conservation laws

$$\begin{cases} [\rho u]_1 = [\rho u]_2 \\ [\rho u^2 + P]_1 = [\rho u^2 + P]_2 \\ \left[\frac{1}{2}\rho u^3 + \frac{\gamma}{\gamma - 1} P u\right]_1 = \left[\frac{1}{2}\rho u^3 + \frac{\gamma}{\gamma - 1} P u\right]_2 \end{cases}$$

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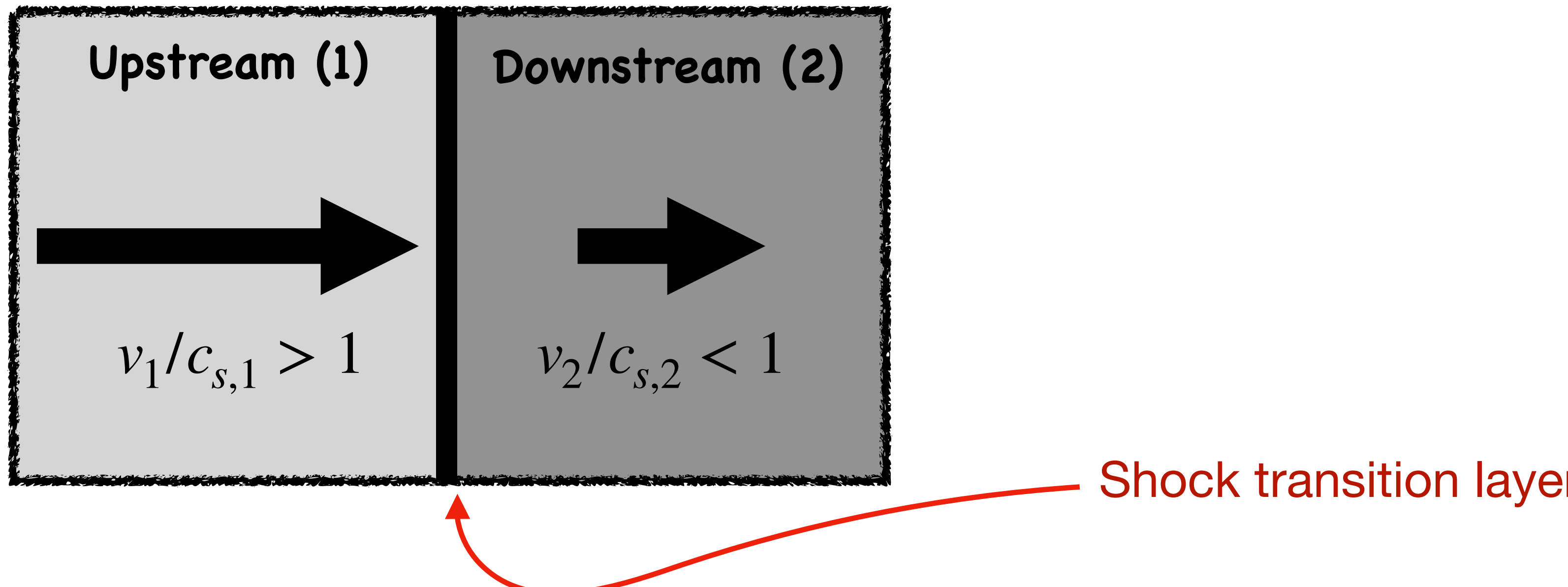

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$$

$$
\begin{cases}
\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}(M_1^2 - 1) \\
\frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2 + 2} \\
\frac{T_2}{T_1} = \frac{P_2}{P_1}\frac{\rho_1}{\rho_2} \propto M_1^2
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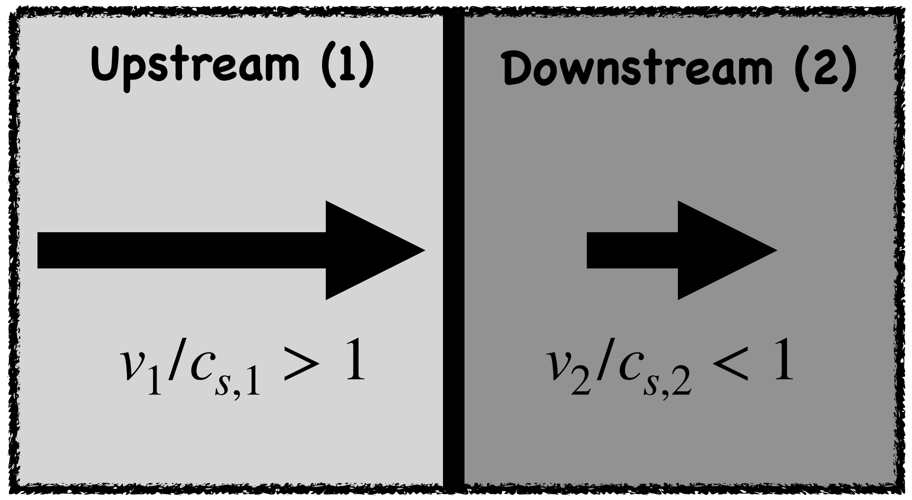

Shock transition layer

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Strong shocks
$M_1 \gg 1$

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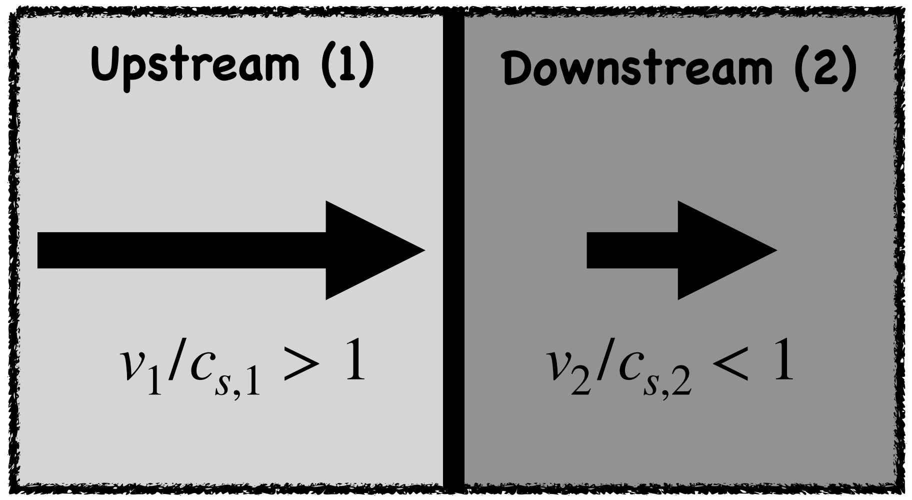

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Strong shocks
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Caveats:
- What produces the shock transition?
- Does fluid equations describe correctly astrophysical plasmas?

Collision-less shocks

What produces the shock transition?

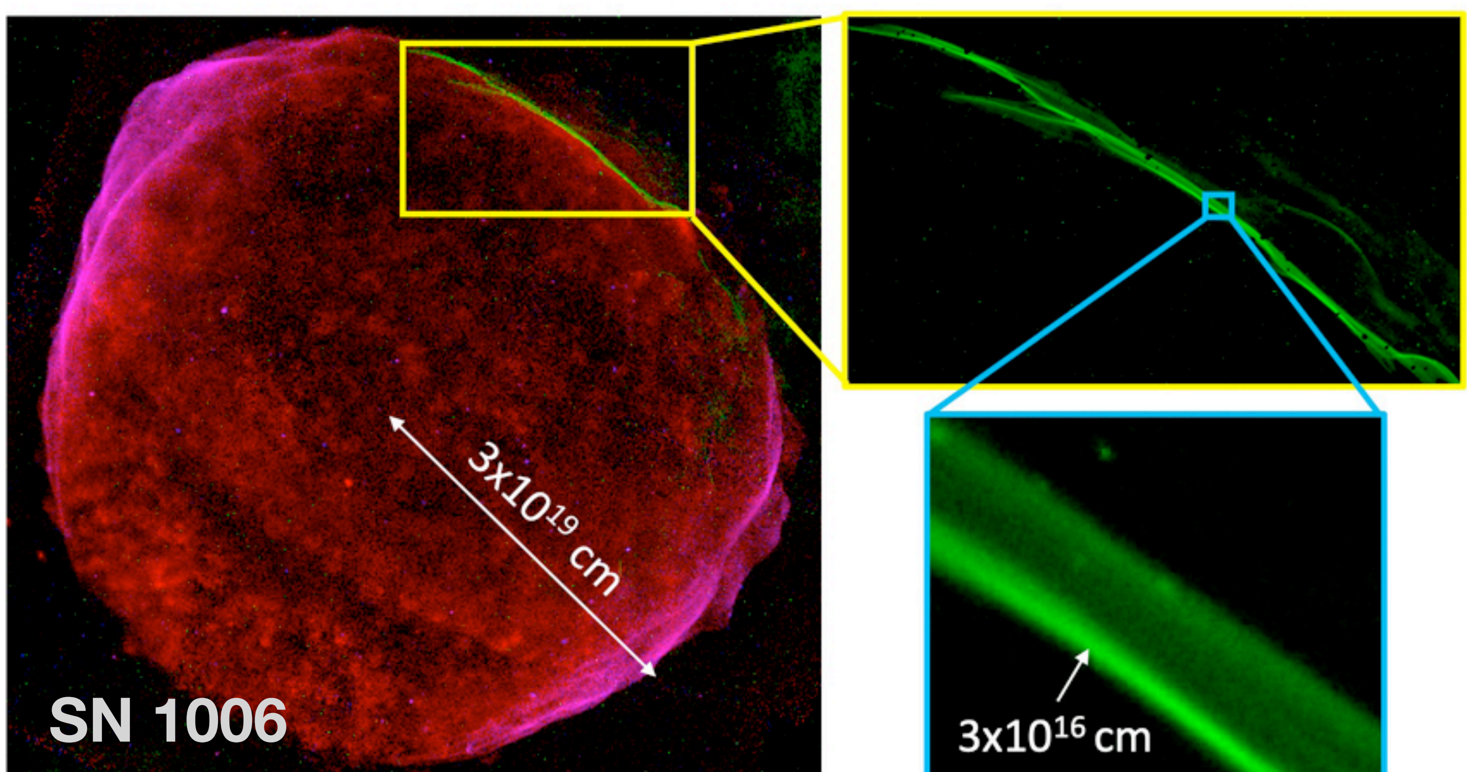
$$\lambda_{\rm mfp} = \begin{cases} \dfrac{1}{N_A \rho_{\rm air} (2\pi a_0)} \sim 10^{-7}\,{\rm cm} & \text{Earth atmosphere} \\ \dfrac{1}{n_{\rm ISM}\,\sigma_{\rm Coul}} > \;{\rm pc} & \text{Interstellar medium} \end{cases}$$

$$\sigma_{\rm Coul} = \frac{4\pi Z_1^2 Z_2^2 e^4}{m^2 v^4} \simeq \frac{10^{-13}}{E_{\rm eV}^2}\,{\rm cm}^2$$

$$v_{\rm sh} \sim 10^3\,{\rm km/s} \;\Rightarrow\; E \simeq {\rm keV}$$

However observations of some astrophysical shocks reveal thickness << pc

Balmer emission from the SNR SN 1006



What can produce the transition?

Collision-less shocks

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Length-scales for electromagnetic processes

Electron skin depth $\dfrac{c}{\omega_{pe}} = \left(\dfrac{m_e c^2}{4\pi n_e e^2}\right)^{1/2} = 5.3\times10^5\, n_e^{-1/2}\, cm$

ω_{pe} = elctron plasma frequency
ω_{pi} = ion plasma frequency

Ion skin depth $\dfrac{c}{\omega_{pi}} = \left(\dfrac{m_i c^2}{4\pi n_i e^2}\right)^{1/2} = 2.3\times10^7\, n_i^{-1/2}\, cm$

p's Larmor radius $r_L(v_{sh}) = \dfrac{m_p v_{sh} c}{eB} = 10^{10}\left(\dfrac{v_{sh}}{3000\, km/s}\right)\left(\dfrac{B}{3\mu G}\right)^{-1} cm$

Shock thickness between these two length-scales

Electro-magnetic instabilities

- The shock transition is mediated by electromagnetic interactions.
  Collisions have no role $\to$ the Mach number does not properly describe the shock properties
- Alfvénic Mach number is more appropriate:

$$M_A = \frac{v_{\rm sh}}{v_A}; \; v_A = \frac{B_0}{\sqrt{4\pi\rho}} \approx 2 \left(\frac{B}{\mu \rm G}\right) \left(\frac{n}{\mu \rm cm^{-3}}\right)^{-1/2} \; \rm km/s$$

- Collisionless shocks require Alfvénic Mach number $M_A > 1$
- If magnetic and thermal energy are in equipartition: $v_A \simeq c_s$ (sonic and Alfvénic Mach number are almost equal)

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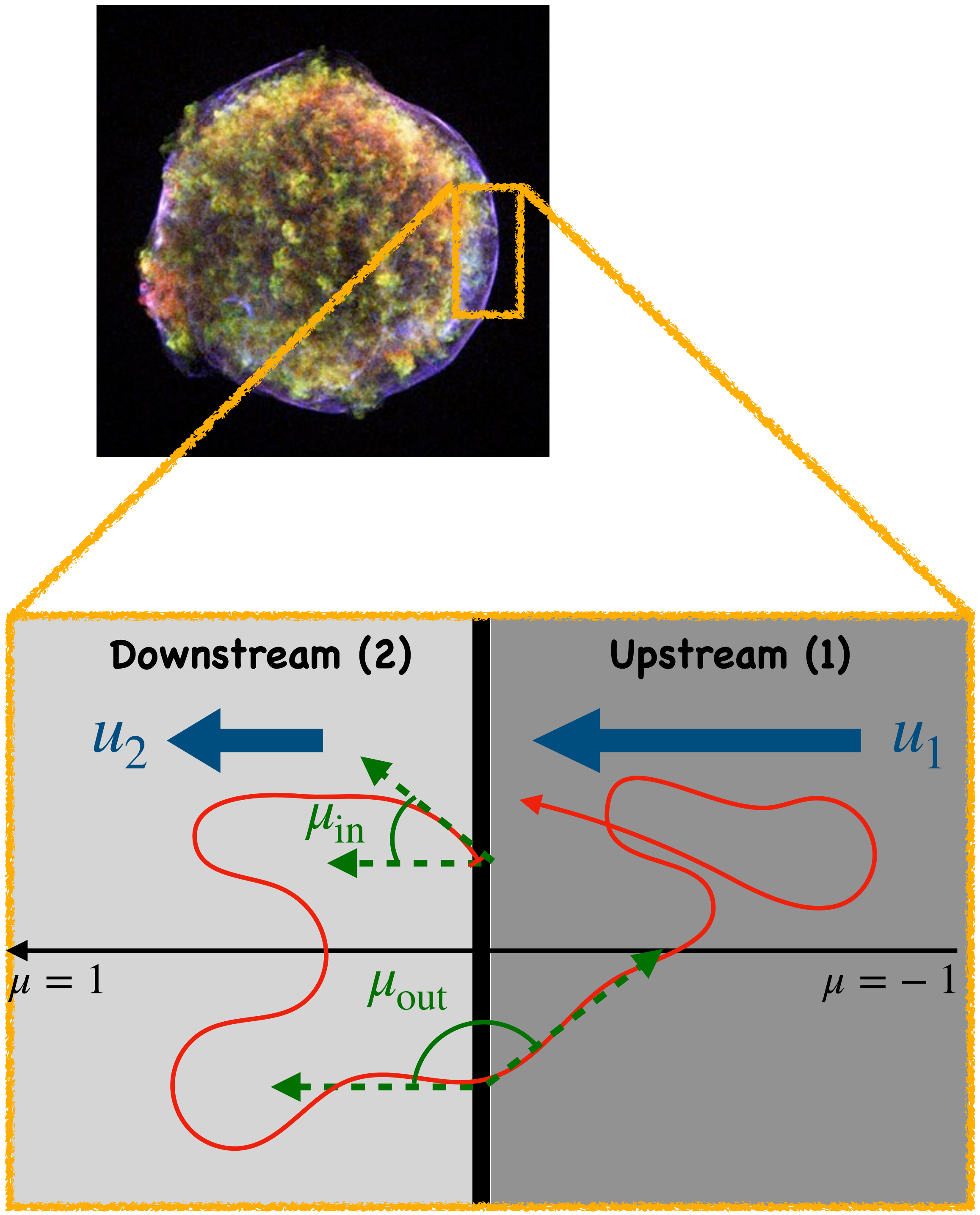
Which instability is responsible for the shock transition?

- Two stream instability
- Weibel instability
- Oblique instability
- Filamentation
- ...

The relative importance depends on the initial condition of the plasma

I order Fermi acceleration



Energy gain

$$E_2 = \frac{(1-\beta_{rel}\mu_{in})(1+\beta_{rel}\mu_{out})}{(1+\beta_{rel^2})} E_1$$

Averaging over $0 < \mu_{in} < 1$ and $-1 < \mu_{out} < 0$

$$\langle \frac{\Delta E}{E} \rangle = \int_0^1 d\mu \int_{-1}^0 d\mu' \, \frac{E_2 - E_1}{E_1} d\mu_{in} d\mu'_{out} =$$

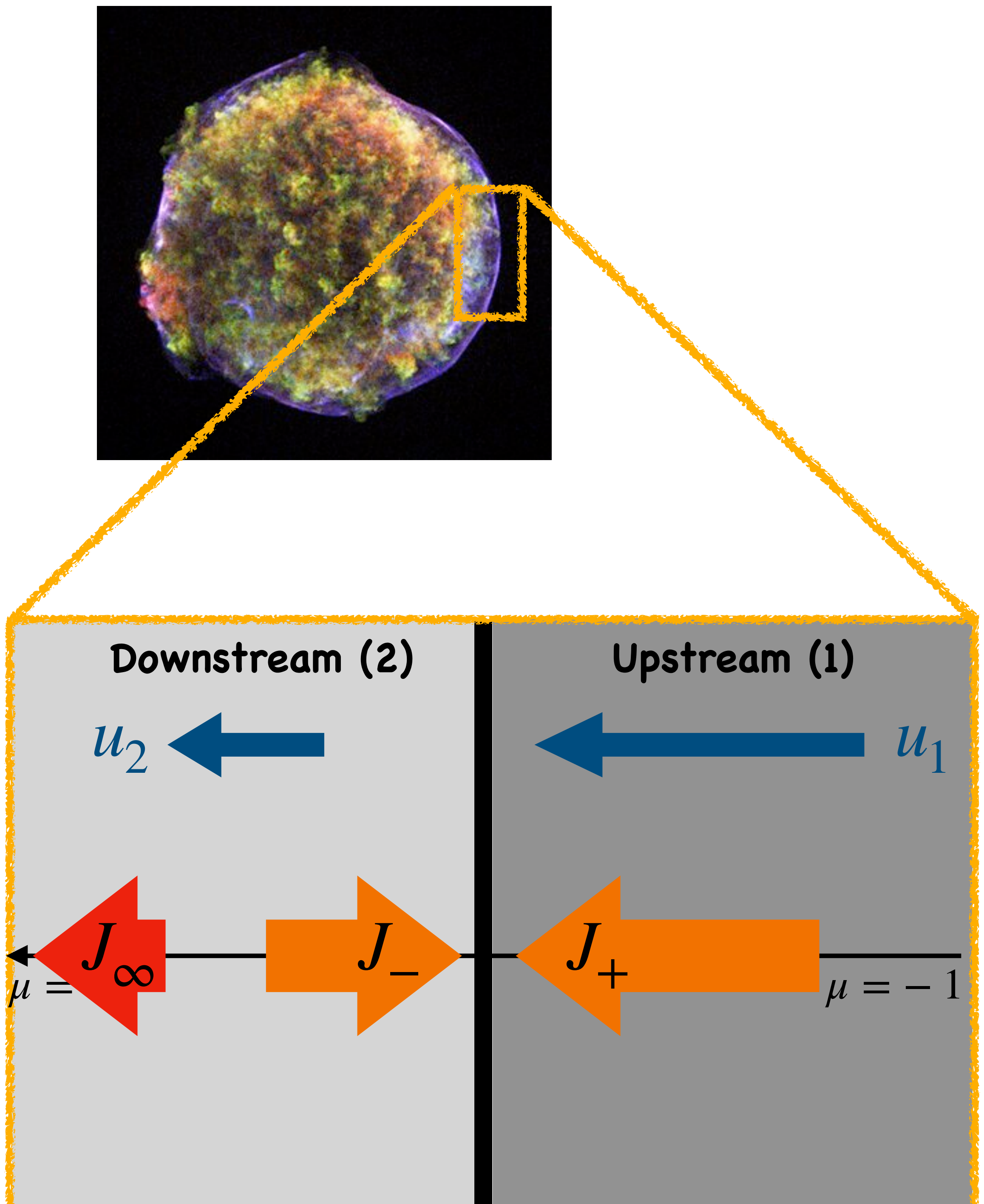
$$= \frac{1 + \frac{4}{3}\beta_{rel} + \frac{4}{9}\beta_{rel}^2}{1-\beta_{rel}^2} \simeq \frac{4}{3}\beta_{rel}$$

The energy gain is now 1st order in v/c because for each cycle

upstream -> downstream upstream

the particle can only gain energy

I order Fermi acceleration: particle spectrum



Assuming isotropic distribution

$$J_\infty = n u_2$$ Escaping flux

$$J_- = \int \frac{d\Omega}{4\pi} nc\cos(\theta) = \frac{nc}{4}$$ Returning flux

$$P_{\rm esc} = \frac{J_\infty}{J_+} = \frac{J_\infty}{J_\infty + J_-} \simeq 4\frac{u_2}{c}$$ Escaping probability

Energy after k interaction

$$E_k = E_0(1+\xi)^k \;\Rightarrow\; k = \frac{\ln(E/E_0)}{\ln(1+\xi)}$$

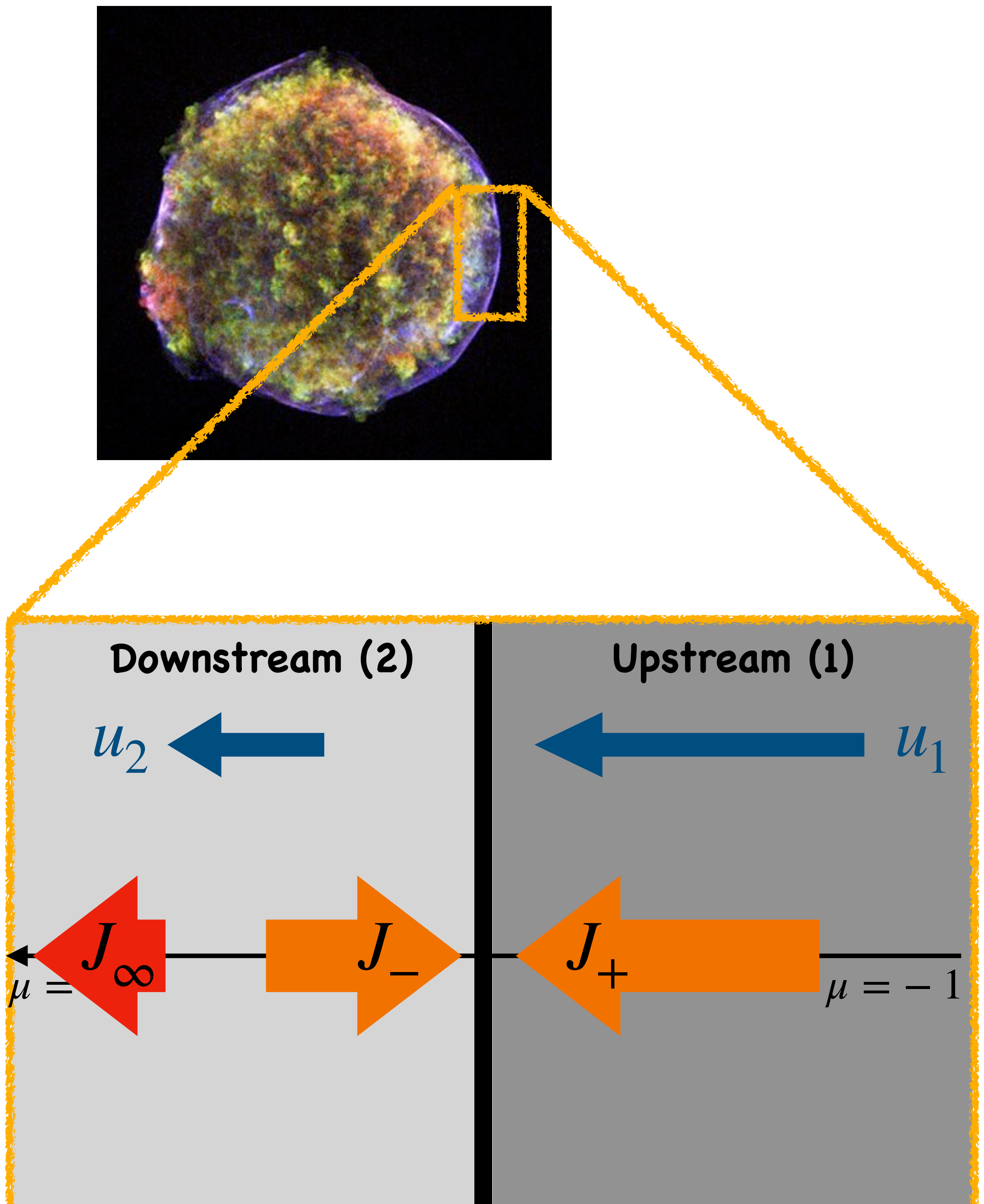
The number of particles with energy > E is:

$$N(>E) = \Sigma_{i=k}^{\infty}(1-P_{\rm esc})^i = \frac{(1-P_{\rm esc})^k}{P_{\rm esc}} = \frac{1}{P_{\rm esc}}\left(\frac{E}{E_0}\right)^{\delta}$$

With $\delta = -\dfrac{\ln(1-P_{\rm esc})}{\ln(1+\xi)} \simeq \dfrac{P_{\rm esc}}{\xi}$

Both independent on energy

I order Fermi acceleration: particle spectrum



Differential energy spectrum

$$f(E) = \frac{dN(>E)}{dE} \propto E^{-(\delta+1)}$$

Slope:

$$\begin{cases} \alpha \equiv \delta + 1 \simeq 1 + \dfrac{P_{\rm esc}}{\xi} \\ = 1 + \dfrac{4u_2/c}{4(u_1-u_2)/(3c)} = \dfrac{r+2}{r-1} \longrightarrow 2 \end{cases}$$

For strong shocks and
monoatomic gas
$r \equiv u_1/u_2 \to 4$

Spectrum in momentum:

$$4\pi p^2 dp\, f_p(p) = f(E)dE$$

$$\boxed{\Rightarrow f(E) \propto E^{-2} \to f_p(p) \propto p^{-4}}$$

I order Fermi acceleration

Take away messages:

1) The particle spectrum obtained from the 1st order Fermi acceleration is independent from the scattering properties

2) A power low spectrum is the consequence of P_{esc} and $\Delta E/E$ being independent on the initial energy

3) The slope E^{-2} is valid for strong shocks (i.e. $r \to 4$)

4) What depends on the scattering properties is the maximum achievable energy

But we are neglecting feedback effects…

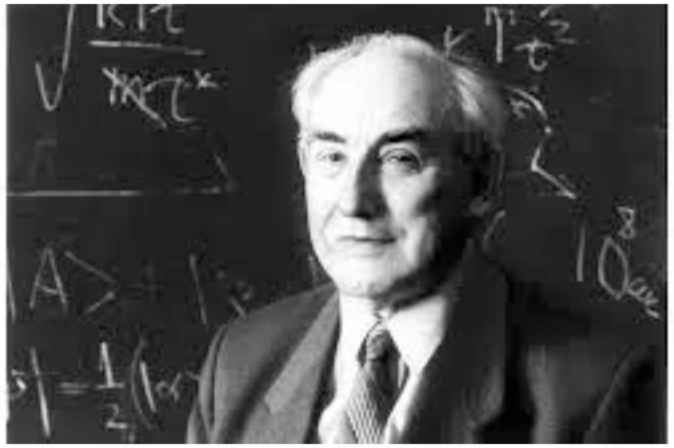
Galactic sources of high energie particles:

supernova remnants

Supernova remnants

- Zwicky & Baade were the first to postulate that SNR could be plausible sources of CRs (1934). However their conclusion was negative because at that time CRs were supposed to be of extragalactic origin

- Vitali Lazarevich Ginzburg made the argument for SNRs as sources of galactic CR in the 60's in a more quantitative form.

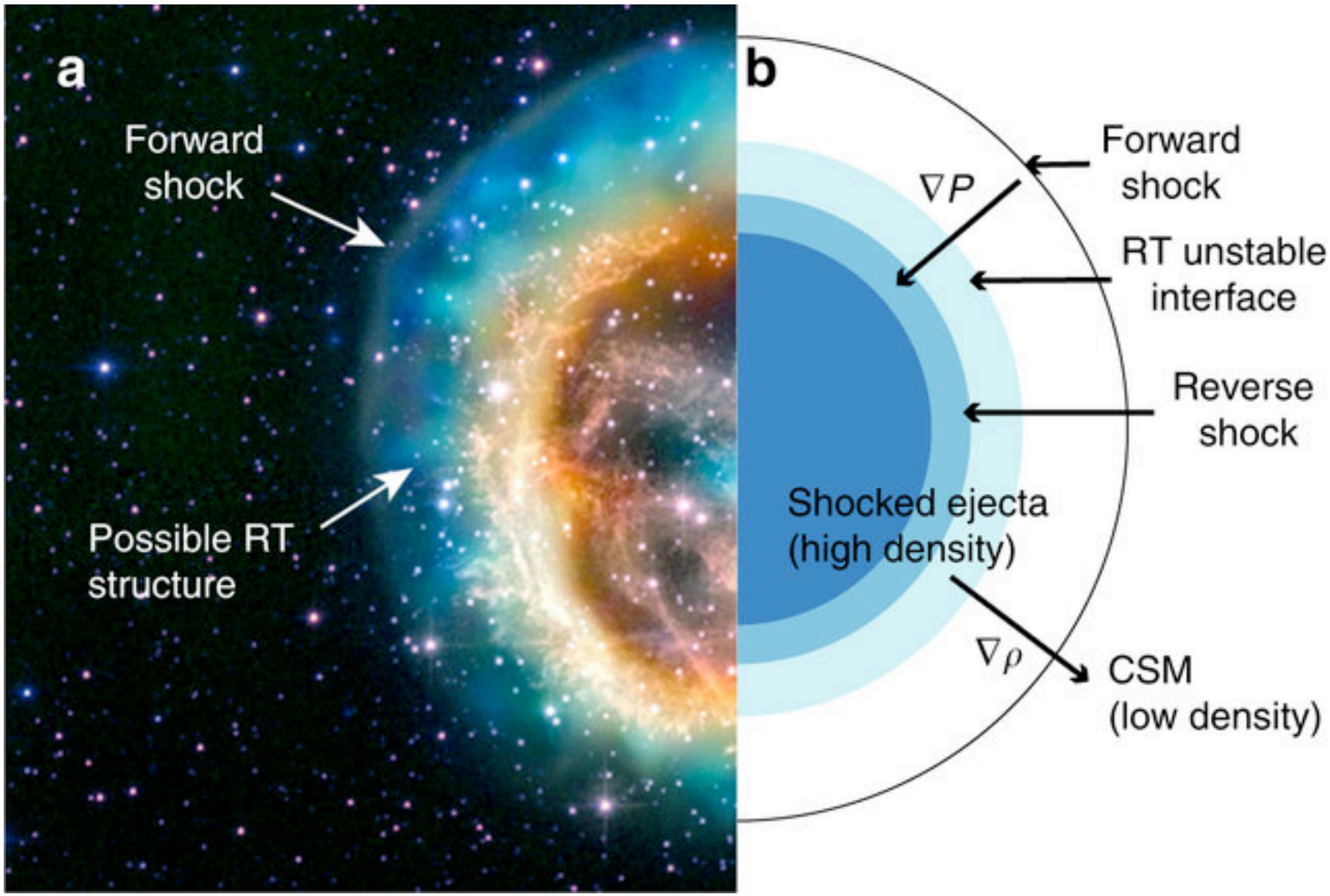


$$\begin{cases} W_{\rm CR} = \dfrac{U_{\rm CR}\, \pi R_g^2 2H}{\tau_{\rm res}} = 3 \cdot 10^{40} \dfrac{U_{\rm CR}}{0.5 {\rm eV/cm^3}} \dfrac{R_g}{15{\rm kpc}} \dfrac{H}{3{\rm kpc}} \left(\dfrac{\tau_{\rm res}}{100{\rm Myr}}\right)^{-1} {\rm erg/s} \\ W_{\rm SN} = \mathscr{R}_{\rm SN} E_{\rm SN} \approx \dfrac{1}{100 yr} \times 10^{51}\, {\rm erg} \approx 3 \cdot 10^{41}\, {\rm erg/s} \end{cases}$$

$$\Rightarrow \frac{W_{\rm CR}}{W_{\rm SN}} \simeq 0.1$$

It is enough to have ~10% of the SNR energy converted into non thermal particles to explain the CR flux

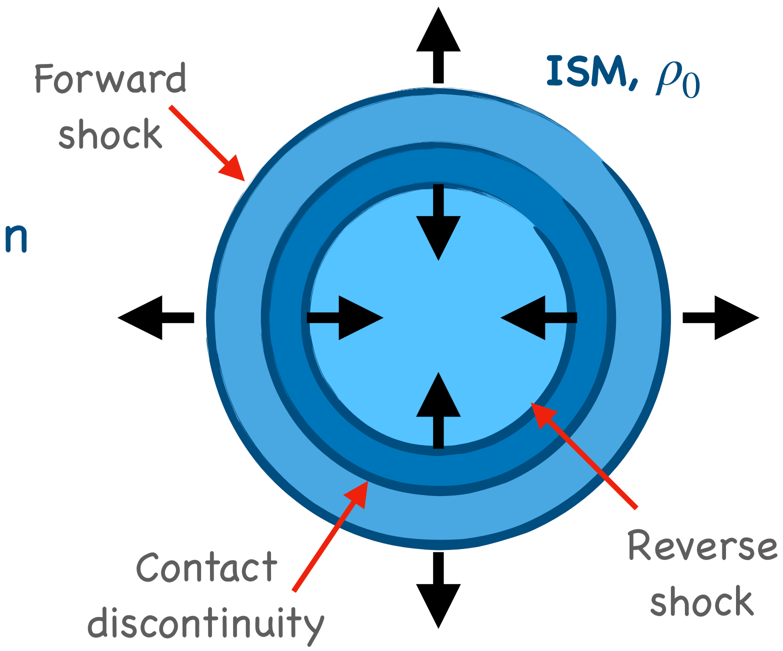
The structure of a Supernova remnants



Supernova remnants dynamics

We can distinguish 3 different phases:

1. "Ejecta dominated": $M_{ejecta} > M_{swept\text{-}up}$ -> almost stationary motion



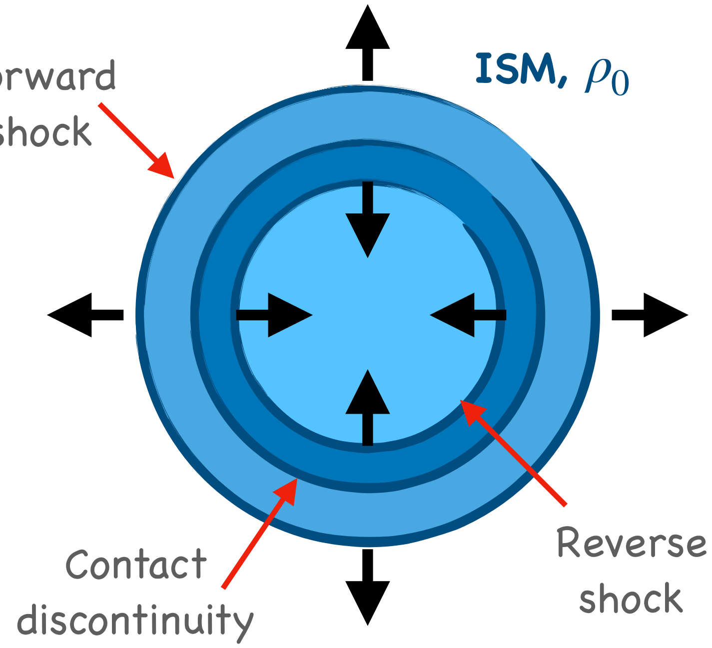
1

$$M_{\rm sw} = \frac{4\pi}{3} R_{\rm ST}^3 \rho_0$$

$$E_{\rm SN} = \frac{1}{2} M_{\rm ej} v_{\rm sh}^2$$

$$T_{\rm ST} = \frac{R_{\rm ST}}{v_{\rm sh}}$$

Supernova remnants dynamics



We can distinguish 3 different phases:

1. "Ejecta dominated": $M_{ejecta} > M_{swept\text{-}up}$ -> almost stationary motion
2. Adiabatic expansion: $M_{ejecta} < M_{swept\text{-}up}$ -> Energy conservation

1

$$M_{sw} = \frac{4\pi}{3} R_{ST}^3 \rho_0$$

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2$$

$$T_{ST} = \frac{R_{ST}}{v_{sh}}$$

2

Relevant quantities

E_{SN}, ρ_0, t

Velocity:

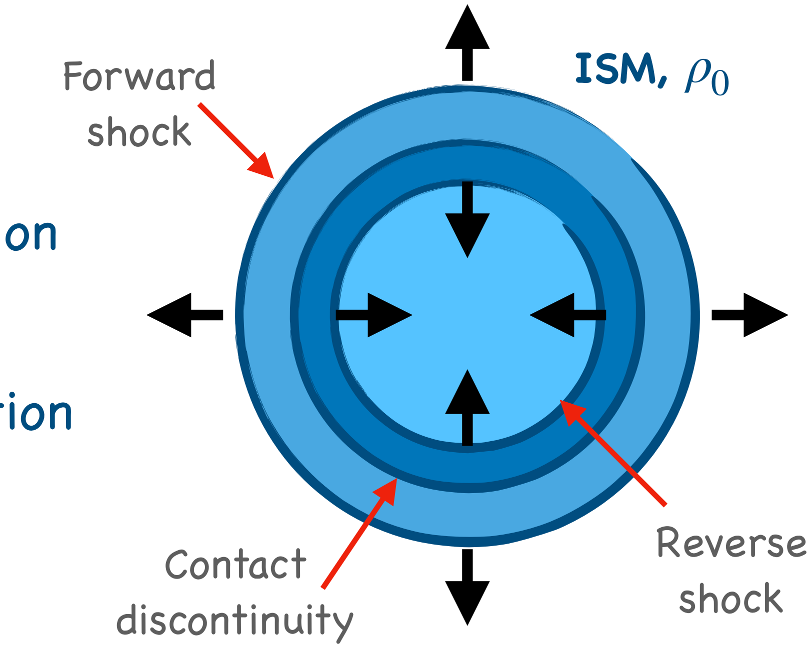
$$v_{sh} \propto \left(\frac{E_{SN}}{\rho_0} \right)^{1/5} t^{-3/5}$$

Exercise: try to get this equation

Supernova remnants dynamics

We can distinguish 3 different phases:

1. "Ejecta dominated": $M_{ejecta} > M_{swept\text{-}up}$ -> almost stationary motion
2. Adiabatic expansion: $M_{ejecta} < M_{swept\text{-}up}$ -> Energy conservation
3. "Snow-plough" phase: age >> $t_{radiation}$ -> Momentum conservation



1

$$M_{\rm sw} = \frac{4\pi}{3} R_{\rm ST}^3 \rho_0$$

$$E_{\rm SN} = \frac{1}{2} M_{\rm ej} v_{\rm sh}^2$$

$$T_{\rm ST} = \frac{R_{\rm ST}}{v_{\rm sh}}$$

2

Relevant quantities

$E_{\rm SN}, \rho_0, t$

Velocity:

$$v_{\rm sh} \propto \left(\frac{E_{\rm SN}}{\rho_0}\right)^{1/5} t^{-3/5}$$

3

Relevant quantities

$P_{\rm SN}, \rho_0, t$

Velocity:

$$v_{\rm sh} \propto \left(\frac{P_{\rm SN}}{\rho_0}\right)^{1/4} t^{-3/4}$$

Exercise: try to get this equation

Maximum energy

It is possible to accelerate up to the knee?

- E_{max} is obtained comparing the acceleration time with the age of the system and losses

$$t_{\rm acc} = \min[t_{\rm age}, t_{\rm loss}]$$

Losses are generally negligible for protons but important for electrons

- Acceleration time $t_{\rm acc} = \dfrac{t_{\rm cycle}}{\Delta E/E}$
- For one cycle (upstream -> downstream -> upstream): $t_{\rm cycle} = \tau_{\rm diff,1} + \tau_{\rm diff,2}$
- Diffusion time upstream: equating the flux of incoming particles during a diffusion time with the number of particles upstream in one advection length D/u:

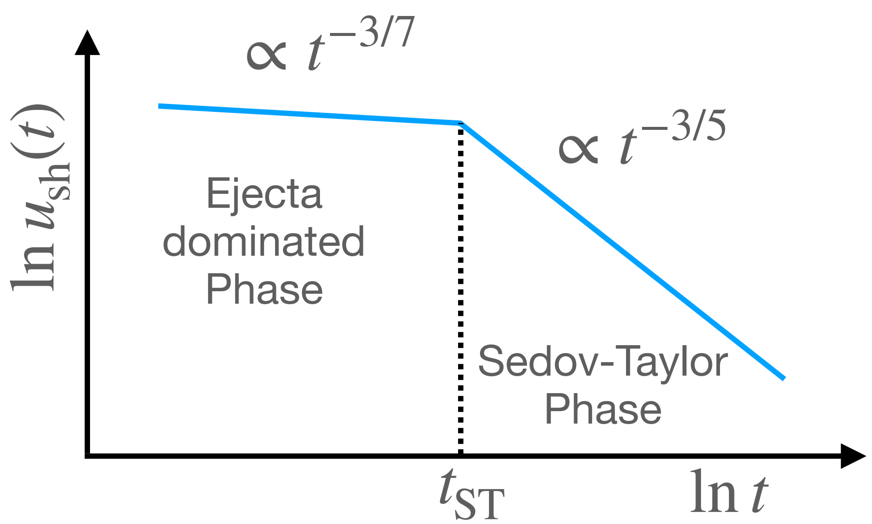
$$\frac{nc}{4} \Sigma \tau_{diff,1} = n\,\Sigma\, D_1/u_1 \;\Rightarrow\; \tau_{diff,1} = \frac{4D_1}{cu_1}$$

- Energy gain $\dfrac{\Delta E}{E} = \dfrac{4(u_1 - u_2)}{3c}$

$$\boxed{t_{\rm acc} = \frac{3}{u_1 - u_2}\left(\frac{D_1}{u_1} + \frac{D_2}{u_2}\right) \simeq 8\frac{D_1}{u_1^2}}$$

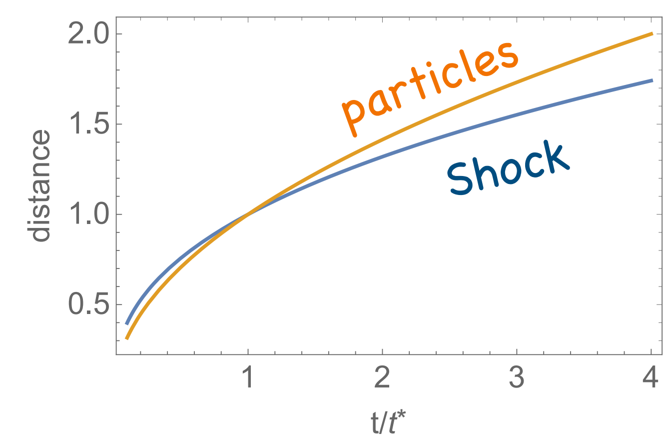
Maximum energy

Maximum energy can only increases during the ejecta dominated phase



Radius: $\begin{cases} R_{\rm sh} \propto t^{4/7} & \text{Ejecta-dominated} \\ R_{\rm sh} \propto t^{2/5} & \text{Sedov-Taylor} \end{cases}$

However, particles ahead of the shock diffuse: $\langle d \rangle \propto \sqrt{Dt}$



$\Rightarrow$ during the ST phase the highest energy particles cannot be caught by the shock and escape towards upstream

Beginning of the ST phase:

$$\begin{cases} M_{\rm sw} = \dfrac{4\pi}{3} R_{\rm ST}^3 \rho_{\rm CSM} \\ E_{\rm SN} = \dfrac{1}{2} M_{\rm ej} v_{\rm sh}^2 \\ t_{\rm ST} = \dfrac{R_{\rm ST}}{v_{\rm sh}} \end{cases} \Rightarrow \boxed{t_{\rm ST} \approx 50 \left(\frac{M_{\rm ej}}{M_\odot}\right)^{5/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-1/2} \left(\frac{n_{\rm CSM}}{cm^{-3}}\right)^{-1/3} {\rm yr}}$$

Maximum energy

Equating t_{ST} with the acceleration time

$$t_{\rm acc} \approx 8\frac{D}{u_{\rm sh}} \quad = \quad t_{\rm ST} \approx 50 \left(\frac{M_{\rm ej}}{M_\odot}\right)^{5/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-1/2} \left(\frac{n_{\rm ISM}}{cm^{-3}}\right)^{-1/3} {\rm yr}$$

Using the diffusion coefficient from linear theory: $D = \frac{1}{3}\frac{r_L(p)c}{k_{\rm res}P(k_{\rm res})}$

$P(k) = \frac{\delta B(k)^2}{B_0^2}$ is the power in magnetic turbulence at the resonant scale

$$E_{\rm max} = 50\; k_{\rm res}P(k_{\rm res}) \left(\frac{B}{\mu{\rm G}}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-1/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{1/2} \left(\frac{n_{\rm ism}}{{\rm cm}^{-3}}\right)^{-1/3} {\rm TeV}$$

E_{max} is weakly dependent on ambient parameters

High energies can be achieved only for large B and large turbulence

Where the turbulence is coming from?

Kolmogorov theory of turbulence

Turbulence in isotropic uniform 3D fluid

- Relevant quantities

Viscosity $[\nu] = \mathrm{L}^2\mathrm{T}^{-1}$

Dissipation rate $[\epsilon] = L^2 T^{-3}$

Dissipation scale

$$\lambda_{\rm diss} \propto \left(\frac{\nu^3}{\epsilon}\right)^{1/3}$$

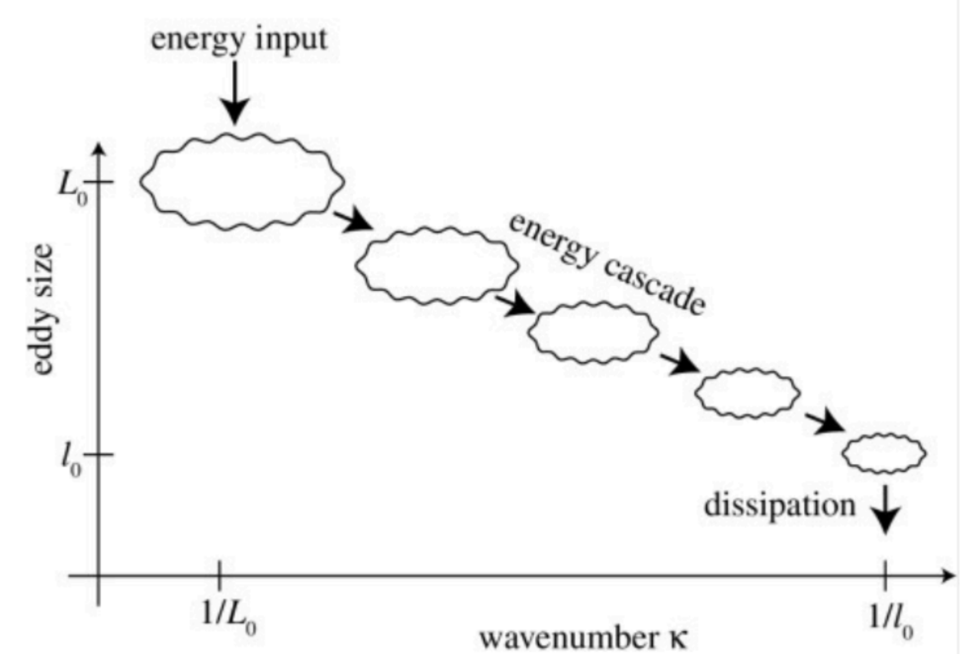
- Power spectrum: $P(k)dk = \dfrac{dU}{\rho} \;\Rightarrow\; [P] = \mathrm{L}^3\mathrm{T}^{-2}$

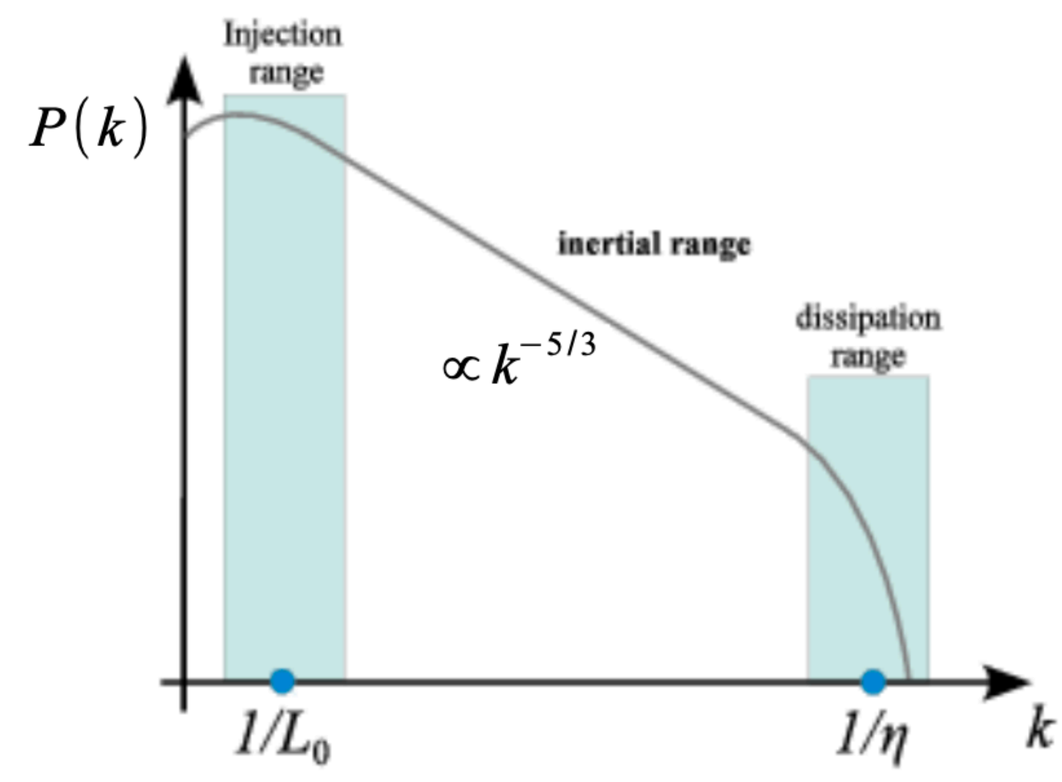
- In the inertial range, P should not depend on viscosity

$$P(k) = P(\epsilon, k)$$

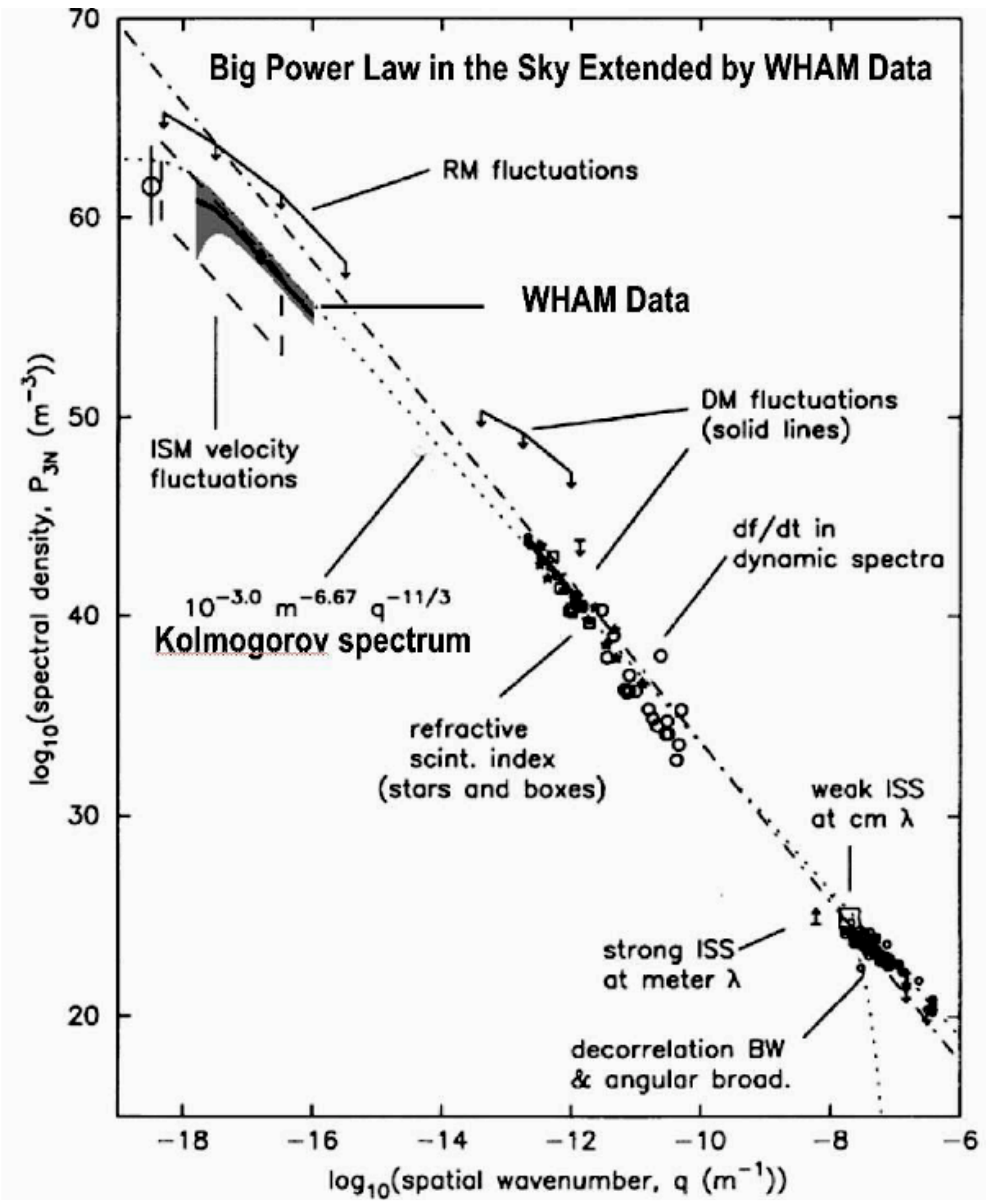
- From dimensional analysis:

$$P(k) \propto \epsilon^{2/3}\, k^{-5/3}$$





A simplified model for the interstellar turbulence



Electron density fluctuation in the ISM
[Armstrong et al. 1995, ApJ 443, 209

- From observations electron density fluctuation follow Kolmogorov spectrum:

$$n_e \propto k^{-5/3}$$

- Magnetic fluctuations follow density fluctuations (i.e. magnetic field is a passive tracer so it has the same spectrum: $\delta B^2 \propto \delta n$):

$$P(k) = \frac{\langle \delta B \rangle^2}{B_0^2} \propto k^{-5/3}$$

- Turbulence is stirred by SNRs at a typical scale

$$L_0 = 1/k_0 \approx 10 - 100\,\mathrm{pc}$$

- Fluctuation of velocity and magnetic field are assumed to be Alfvénic

Using the interstellar turbulence

We can use the interstellar turbulence to estimate the maximum energy

- Injection scale: $k_0 = 1/L_0 \approx (10\,\mathrm{pc})^{-1}$
- Turbulence total power: $\eta_B = \int \frac{\langle \delta B(k) \rangle^2}{B_0^2} dk \approx 0.1$
- Resonant frequency: $k_{\rm res} = r_L(E)^{-1}$

$$\Rightarrow k_{\rm res} P(k_{\rm res}) = \frac{2}{3}\eta_B \left(\frac{k_{\rm res}}{k_0}\right)^{-2/3} \simeq 10^{-6} \left(\frac{\eta_B}{0.1}\right) \left(\frac{E}{\mathrm{GeV}}\right)^{2/3} \left(\frac{B}{\mu\mathrm{G}}\right)^{-2/3} \left(\frac{L_0}{10\,\mathrm{pc}}\right)^{-2/3}$$

$$\left(\frac{k_{\rm res}}{k_0}\right) = \left(r_L(E)/L_0\right)^{2/3}$$

- Maximum energy

$$\boxed{E_{\max} \simeq 0.5\, \eta_{0.1}^3\, B_{\mu g}^{-2}\, L_{10}^{-5}\, M_{\rm ej,\odot}^{-1/2}\, E_{\rm SN,51}^{3/2}\, n_{\rm ISM,1}^{-1}\, \mathrm{MeV}}$$

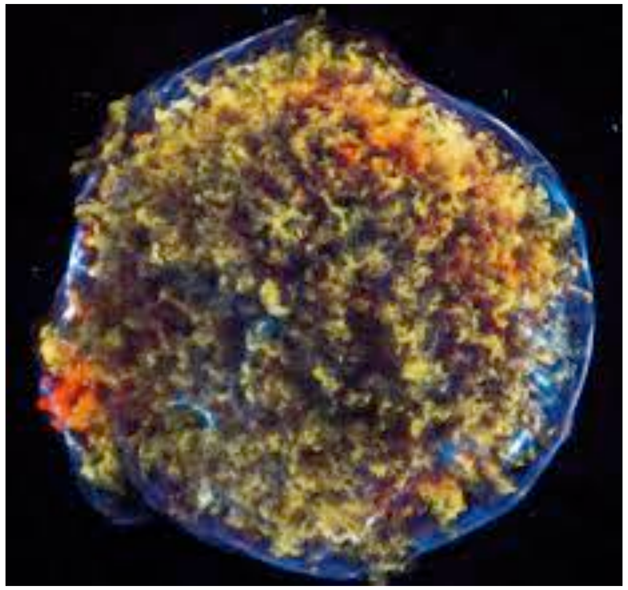
We miss ~9 orders of magnitudes

➡ **Magnetic field needs to be amplified**

Evidence for magnetic field amplification

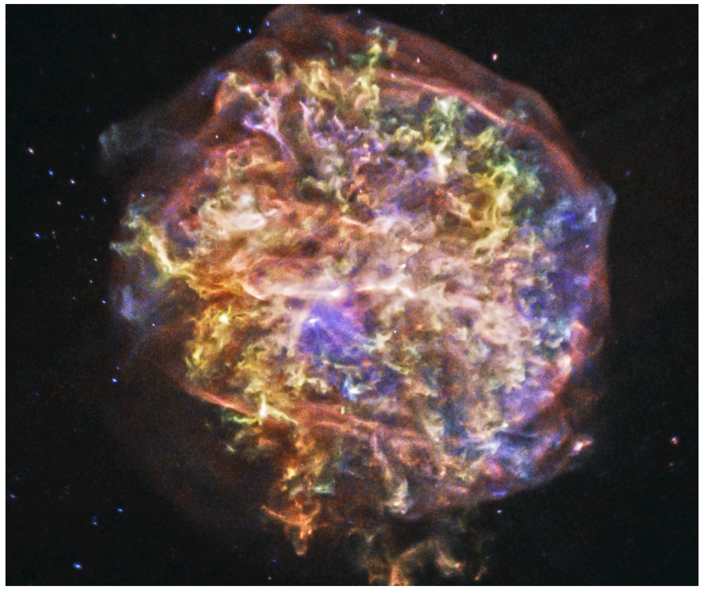
X-ray images of some SNR as observed by the Chandra satellite

Tycho

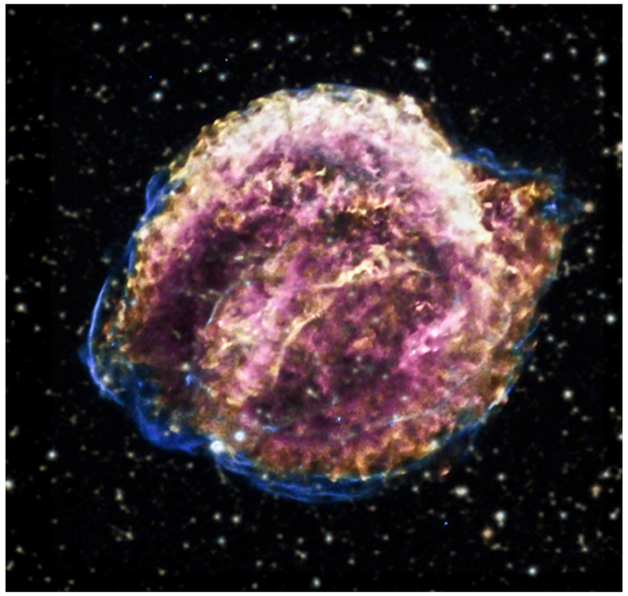


G299.-2.92

G292.0+1.8

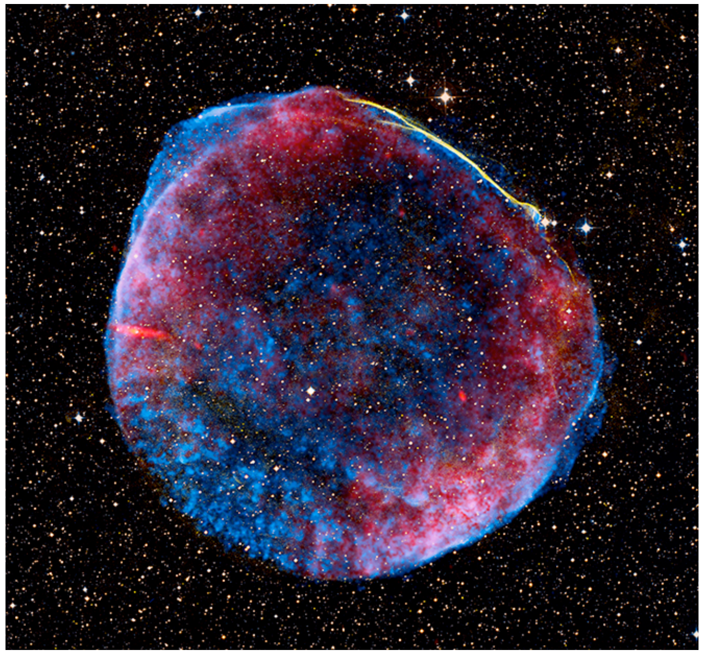


Kepler



Cassiopea A

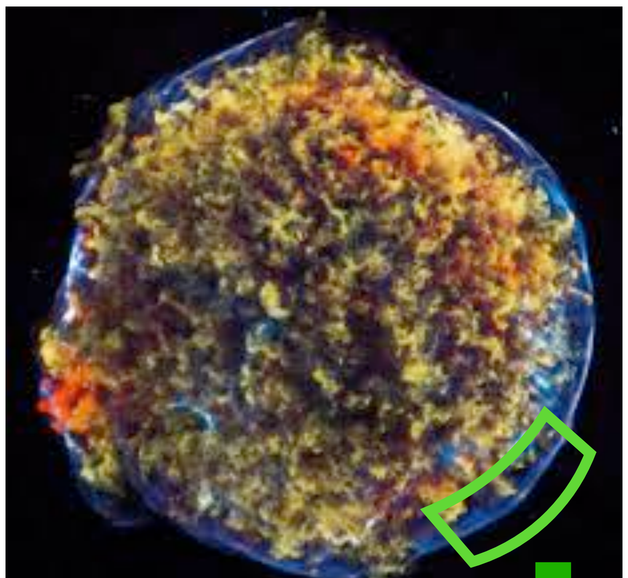
SN 1006

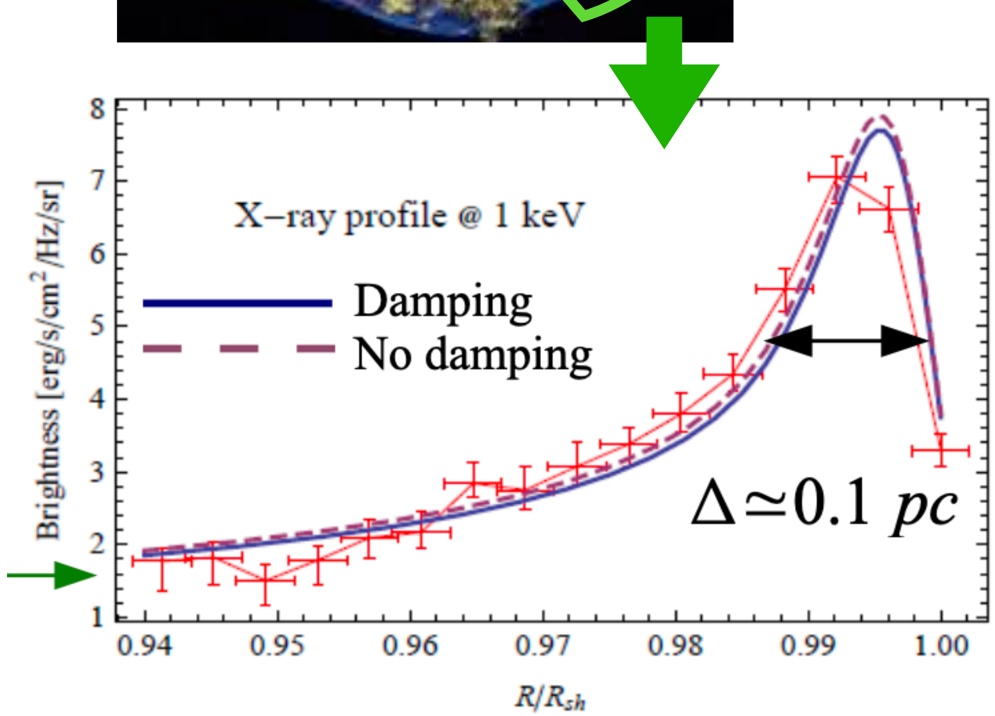


Evidence for magnetic field amplification

Thin non-thermal X-ray filaments provide evidence for magnetic field amplification

Tycho





Chandra X-ray map.
Data for the green sector are from
Cassam-Chenaï et al (2007)

Filaments' thickness could be determined by synchrotron losses

Bohm diffusion

$$D = \frac{1}{3} r_L c \propto \frac{E}{B}$$

Synchrotron losses

$$\tau_{\rm syn} = \frac{3 m_e c^2}{4 \sigma c \gamma \beta^2 U_B} \propto \frac{E}{B^2}$$

$$\Delta = \sqrt{D \tau_{\rm loss}} \propto B^{-3/2}$$

$$\boxed{\Delta \simeq 0.1\,{\rm pc} \ \Rightarrow \ B \approx 100 - 300\,\mu{\rm G}}$$

Magnetic field amplification: theory

Possible CR-driven instabilities:

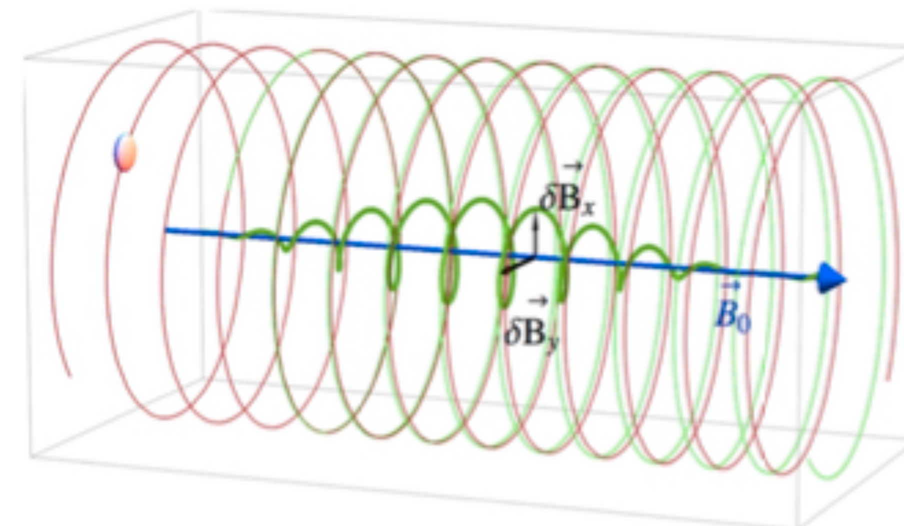
- **Resonant streaming instability**
  Skilling 1975; Bell & Lucek 2001; Amato & Blasi 2006; Blasi 2014

- **Non-resonant (Bell) instability**
  Bell 2004; Bell et al. 2013, 2014; Amato & Blasi 2009

- **Turbulent amplification**
  Drury & Downes 2012; Xu & Lazarian 2017

Magnetic field amplification: theory

Resonant streaming instability



- Amplification is due to resonant interaction between CR with Larmor radius r_L and waves with wave-number $k=1/r_L$.
- Fast growth rate

$$\Gamma_{CR}(k) = \frac{v_A}{B_0^2/8\pi}\frac{1}{kW(k)}\frac{\partial P_{CR}(>p)}{\partial x}$$

(~10 yr for typical SNR shocks)

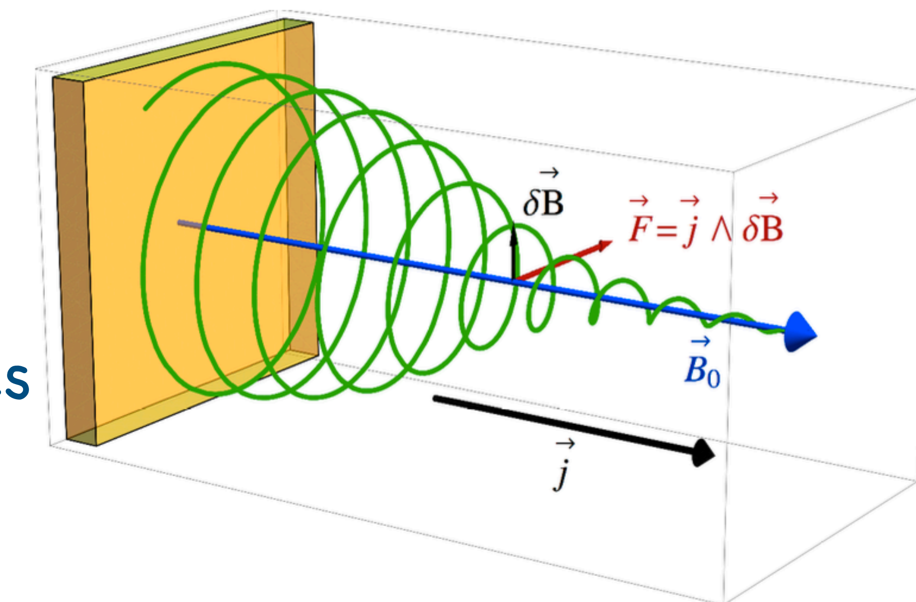
- But saturation level at $\boxed{\delta B/B_0 \lesssim 1}$ ⇒ $\boxed{E_{max} \approx 50 \text{ TeV}}$

A factor ~50 below the *knee*

Magnetic field amplification: theory

Non-resonant streaming instability

- Amplification due to force of escaping CR current with magnetic field perturbations
- Fast growth rate but excites small wavelength waves
- -> need of inverse cascade?
- high level of amplification only in dense environments (Type II SNe exploding into dense progenitor stellar winds)



$$E_{\max} \simeq \frac{e\,\xi_{cr}}{10\,c}\frac{\sqrt{4\pi\rho}}{\Lambda}v_{sh}^2 R_{sh} \simeq 30\,\mathrm{TeV}\left(\frac{\xi_{cr}}{0.1}\right)\left(\frac{\rho/m_p}{\mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{v_{sh}}{5000\,\mathrm{km/s}}\right)^2\left(\frac{R_{sh}}{\mathrm{pc}}\right)$$

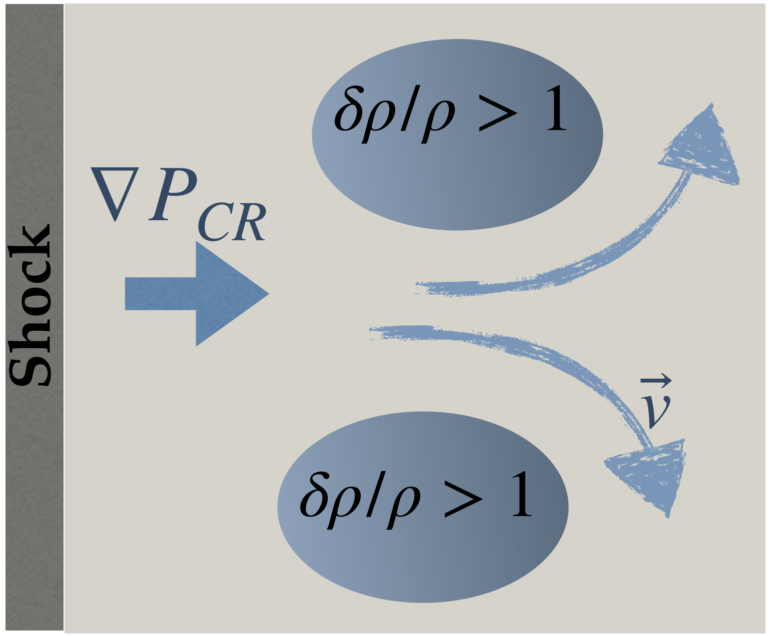
PeV can be achieves by strong shocks in dense environments

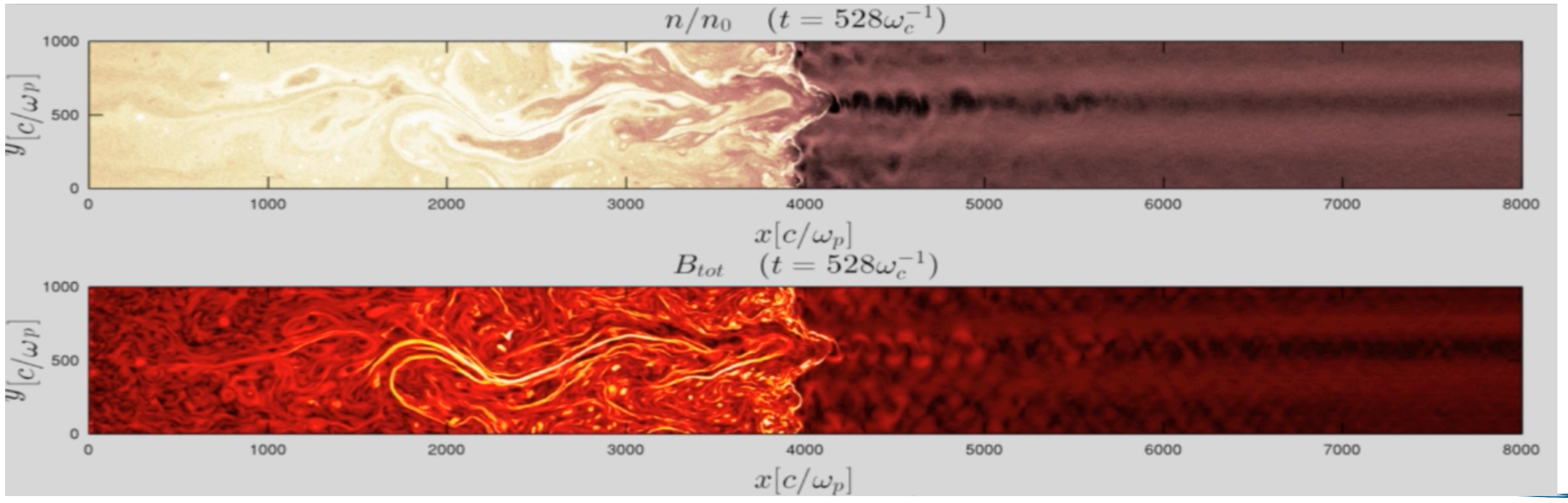
Magnetic field amplification: theory

Turbulent amplification

- In presence of density inhomogeneities, the different CR force acting onto plasma can generate vorticity
- This mechanism is effective only in large precursors (hence E_{max} already large enough and flat spectrum $\sim E^{-2}$)
- The density discontinuities can be generated even through the non-resonant instability

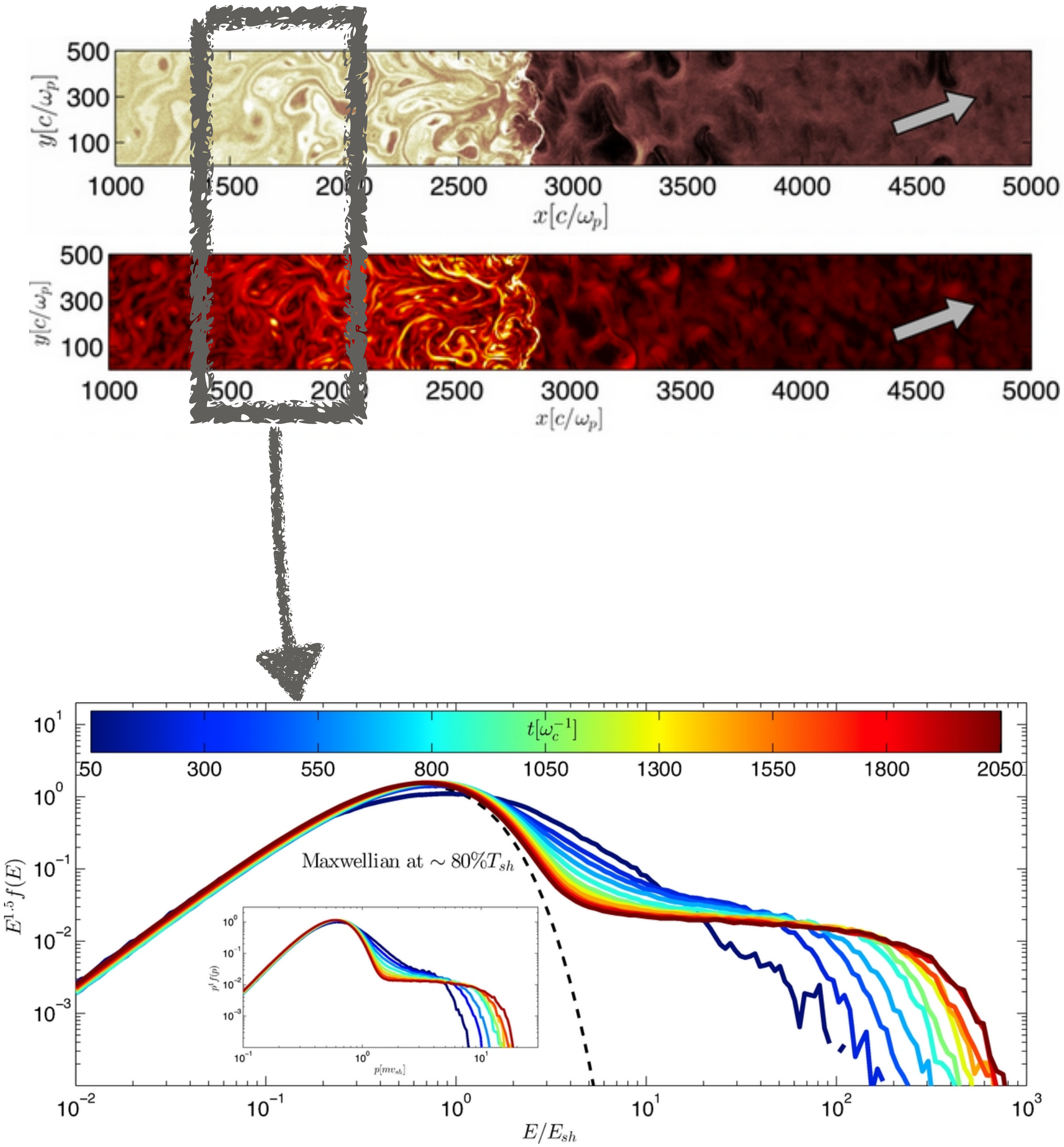
→ filamentation





Filamentation instability observed in 2D hybrid simulations [Caprioli & Spitkovsky, 2013]

PIC simulations of I order Fermi acceleration



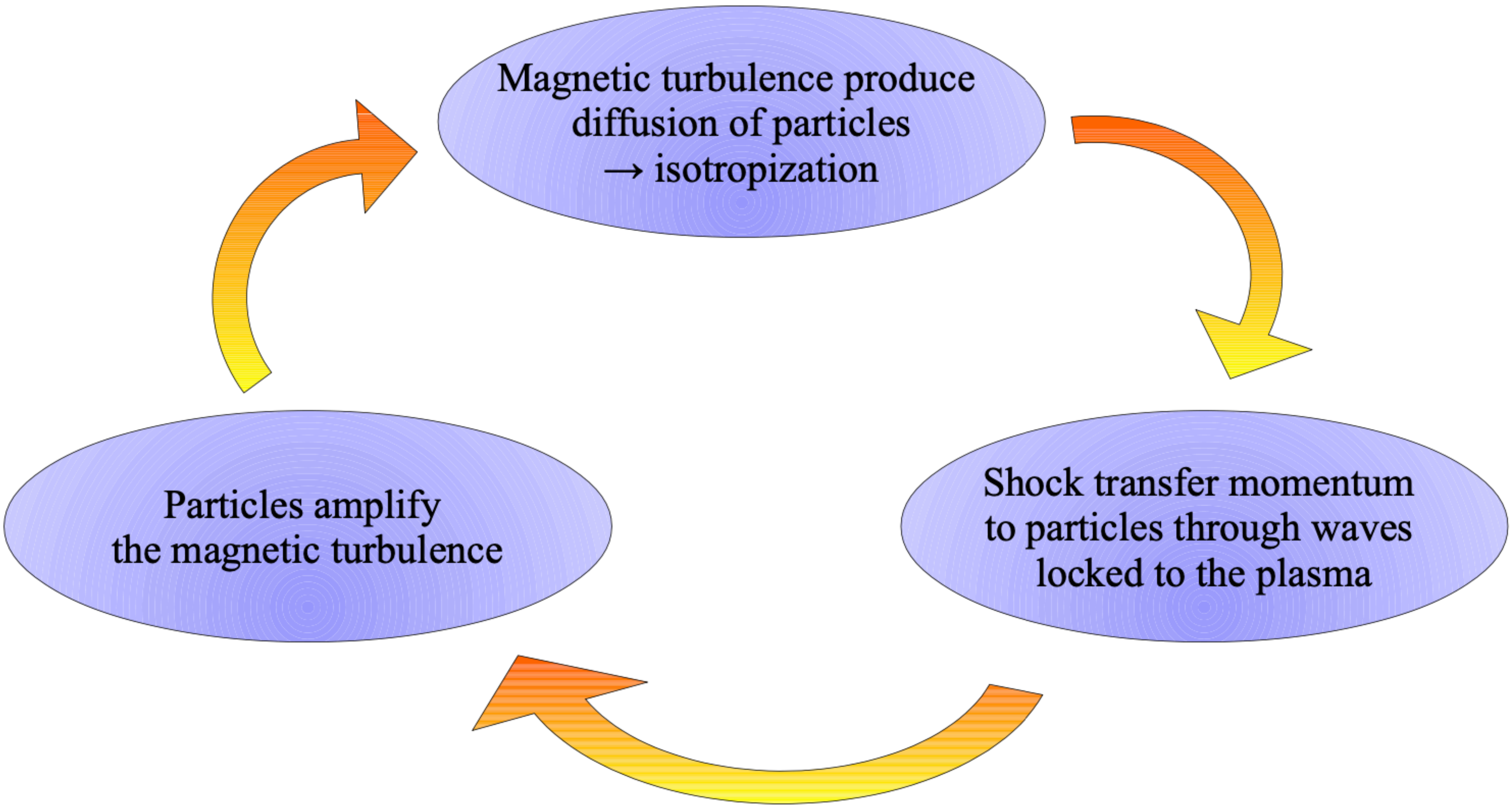
A nice confirmation of DSA predictions comes from particle in cell (PIC) simulations:

- Large efficiency ~ 10-20%
- Spectrum ~ p^{-4} (~ $E^{-1.5}$ at non-relativistic energies)
- self-generated magnetic turbulence

However, PICs can only simulate the beginning of the acceleration process (small dynamical range: $E_{max} << 1$ GeV)

$\Rightarrow$ No conclusion on E_{max}

The essence of non-linearity



Only very young SNR can accelerate up to PeV

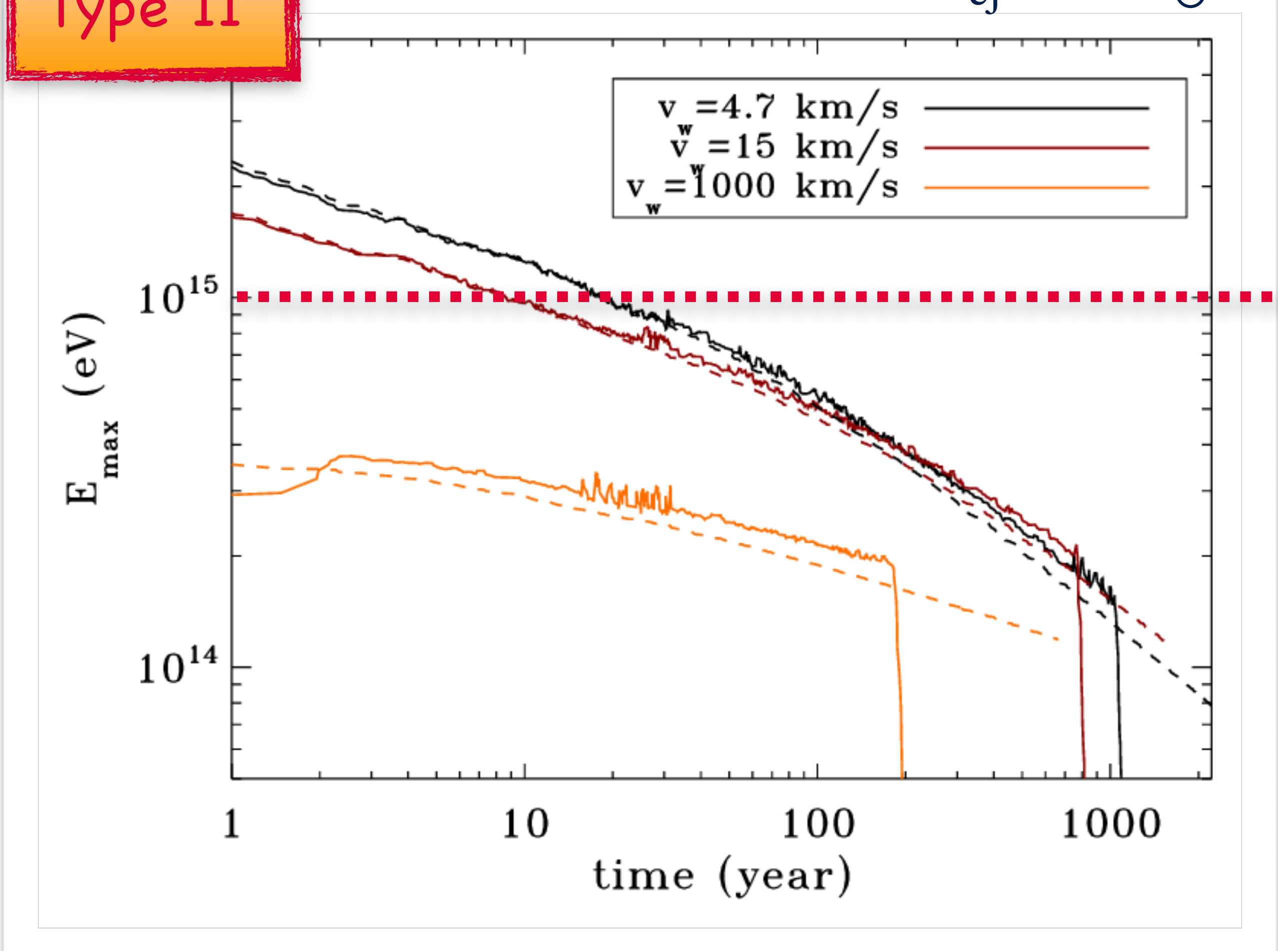
Using non-resonant instability:

$$\frac{B_{\rm sat}^2}{B_0^2} \sim \frac{U_{\rm CR}}{U_{B_0}} \frac{v_d}{c} \propto n_0 v_{sh}$$

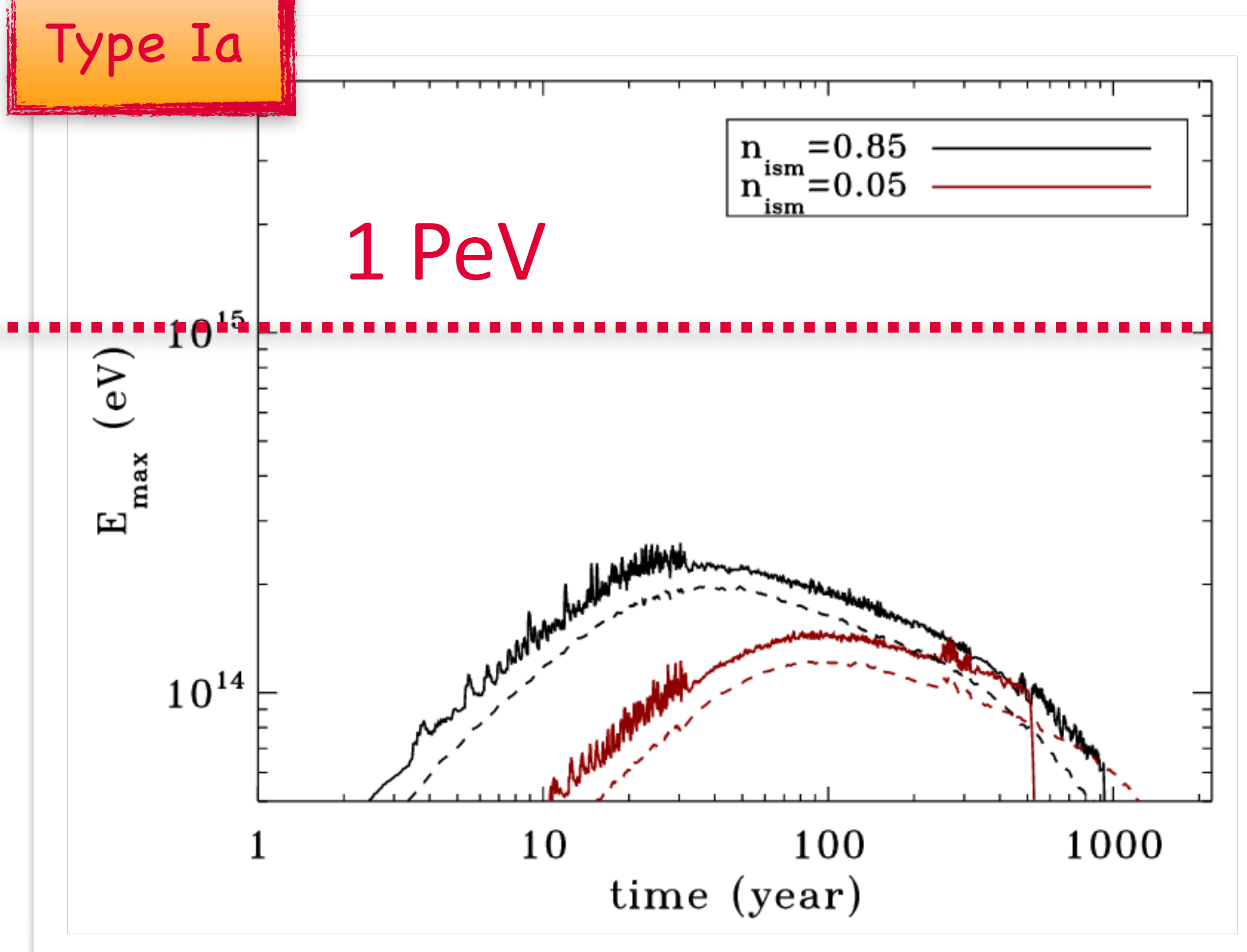
Efficient amplification requires:
- large densities
- large shock speed

Type II

Assumed ejecta mass: $M_{\rm ej} \simeq 1\, M_\odot$



Type Ia



Application of Bell's instability to different type of SNR

Comparison with the CR spectrum

Assumed acceleration efficiency $\xi_{cr} \approx 0.10$

	Type Ia	Type II	Type II*
$E_{\rm SN}$ [10^{51} erg]	1	1	$5 \div 10$
$\dot{M}_{\rm wind}$ [$M_\odot/yr$]	$--$	10^{-5}	10^{-4}
$M_{\rm ej}$ [$M_\odot$]	1.4	10	1.0
$\nu_{\rm SN}$ [yr^{-1}]	10^{-2}	2×10^{-2}	3×10^{-4}

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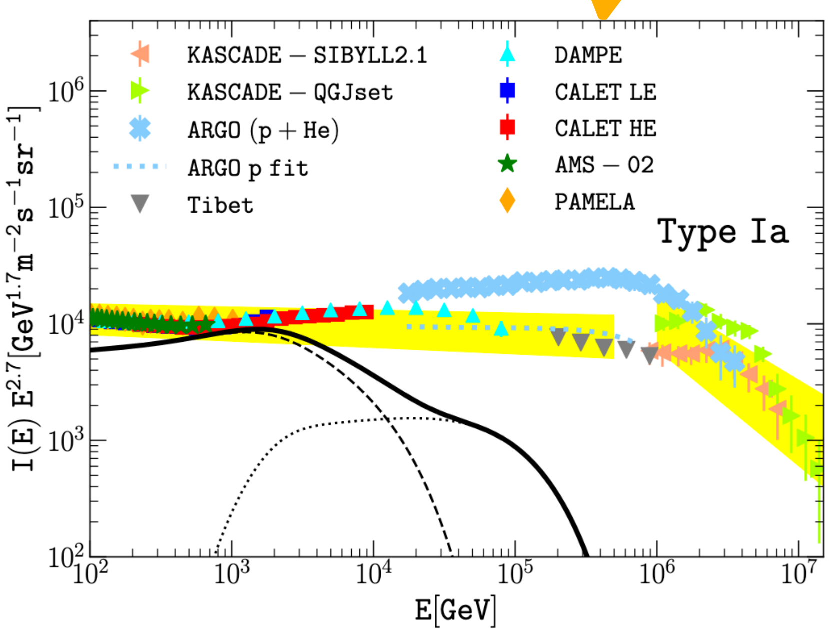

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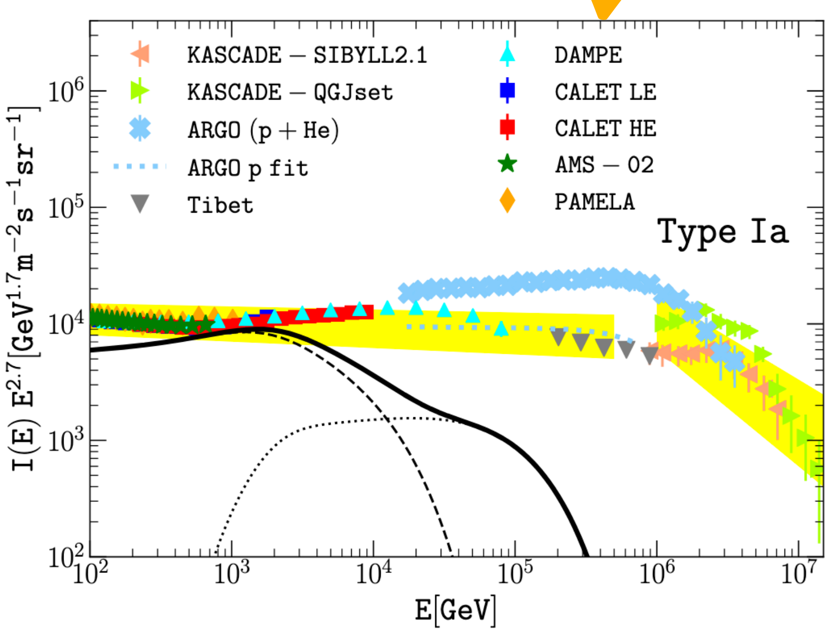

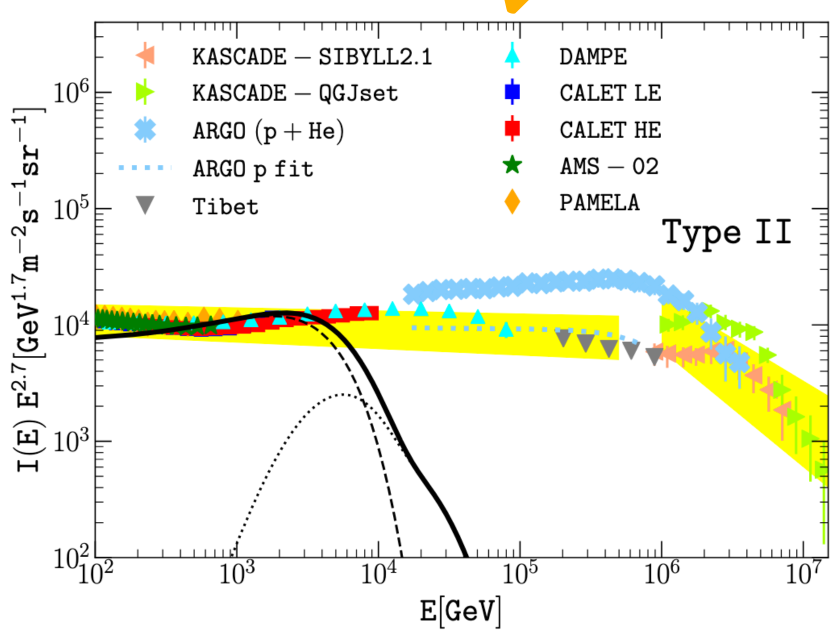

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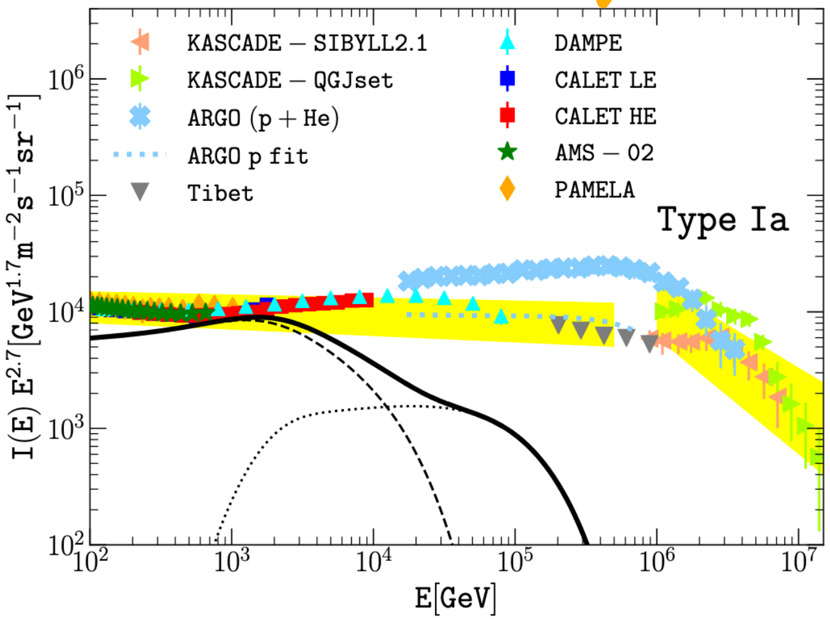
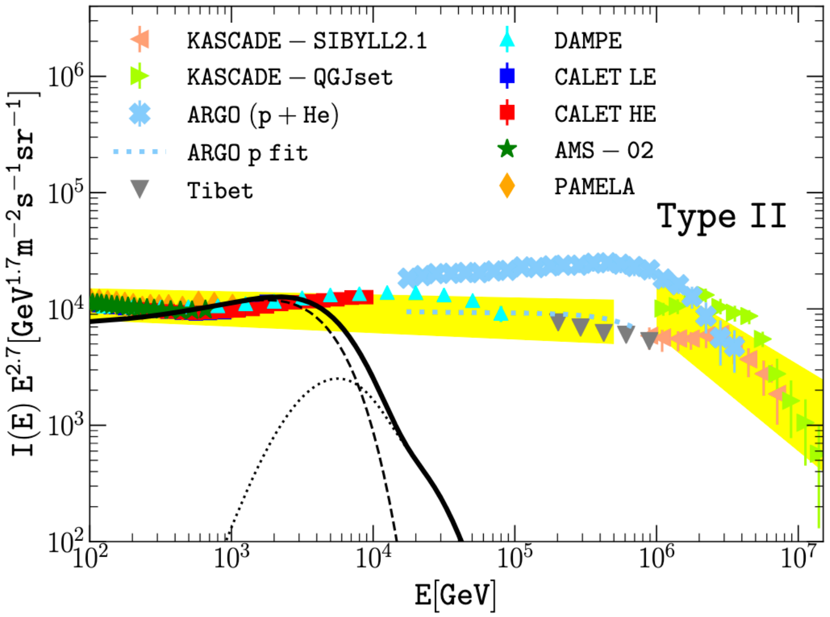
Comparison with the CR spectrum

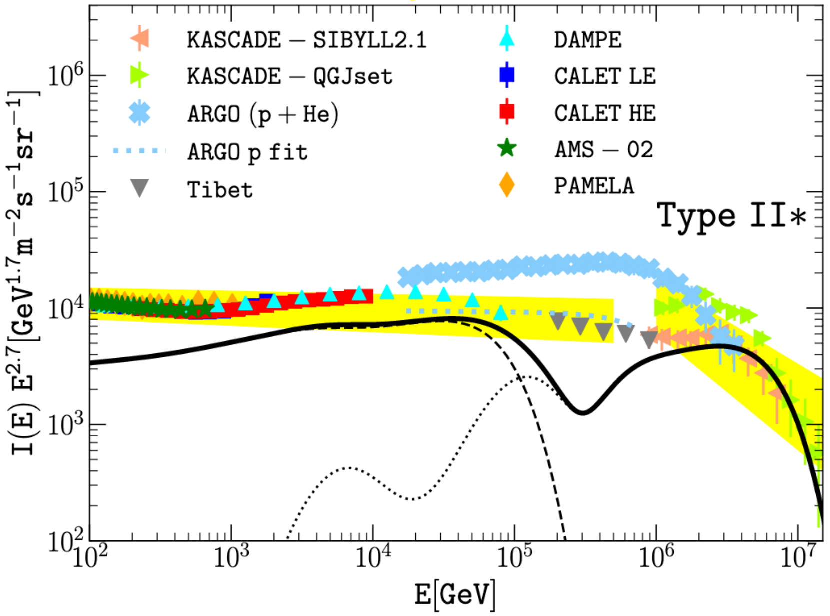
Assumed acceleration efficiency $\xi_{cr} \approx 0.10$

	Type Ia	Type II	Type II*
E_{SN} [10^{51} erg]	1	1	$5 \div 10$
$\dot{M}_{wind}$ [$M_\odot/yr$]	$--$	10^{-5}	10^{-4}
M_{ej} [$M_\odot$]	1.4	10	1.0
ν_{SN} [yr^{-1}]	10^{-2}	2×10^{-2}	3×10^{-4}

Only very rare and powerful events can account for PeV particles







EM radiation from accelerated particles

Radiative processes relevant for CR physics

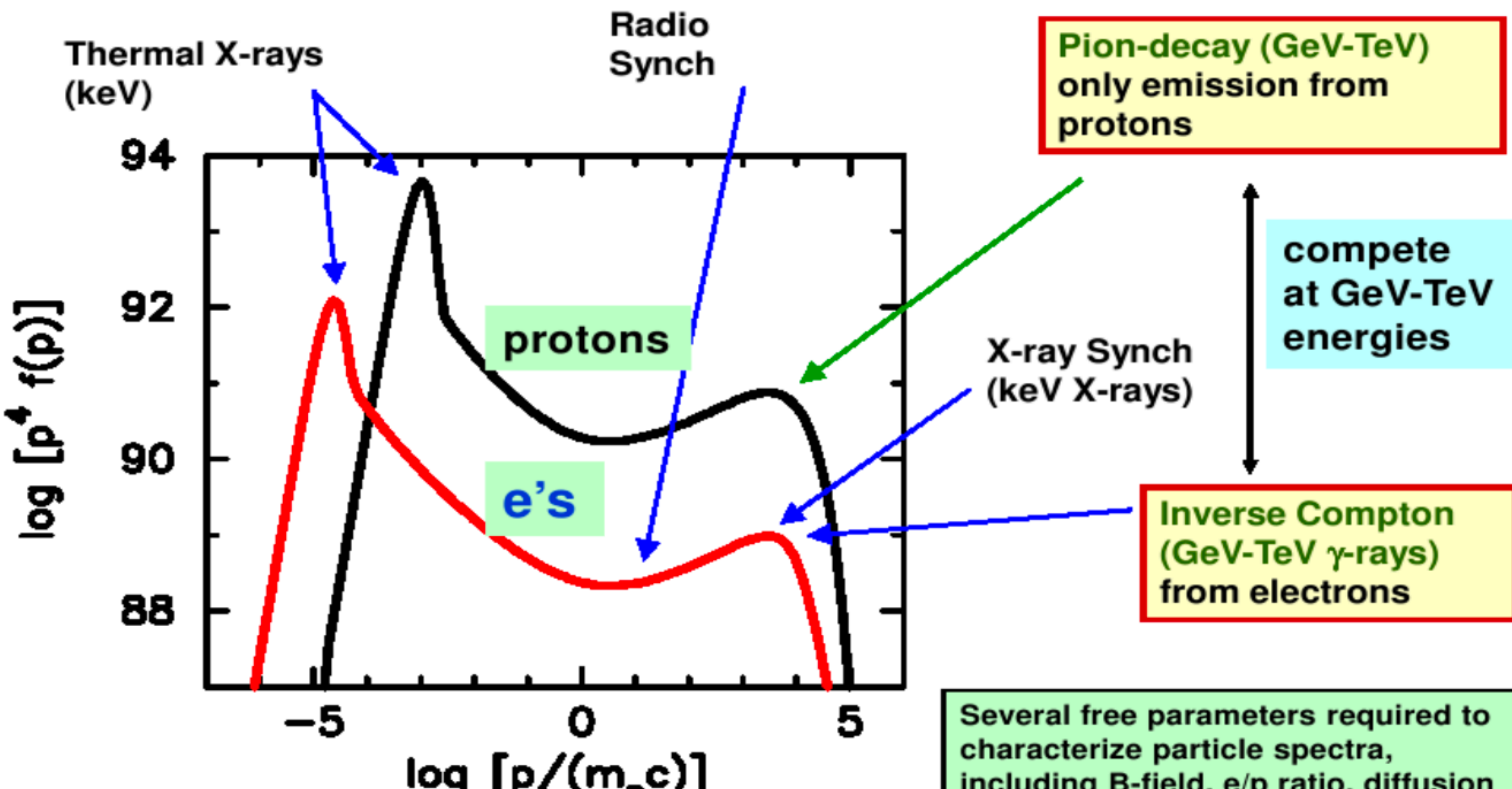
- Leptons
  - Synchrotron emission $e^{\pm} + B \longrightarrow e^{\pm} + \gamma$
  - Bremsstrahlung $e^{\pm} + \mathrm{Nucl.} \longrightarrow e^{\pm} + \gamma$
  - Inverse Compton $e^{\pm} + \gamma_{\mathrm{bk}} \longrightarrow e^{\pm} + \gamma$

- Hadrons
  - Pion production: $p_{\mathrm{CR}} + p_{\mathrm{gas}} \longrightarrow p_{\mathrm{CR}} + p_{\mathrm{gas}} + \begin{cases} \pi^0 \to \gamma\gamma \\ \pi^{\pm} \to \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu}) \end{cases}$

$$\hookrightarrow e^{\pm}\nu_e(\bar{\nu}_e)$$

EM radiation from accelerated particles

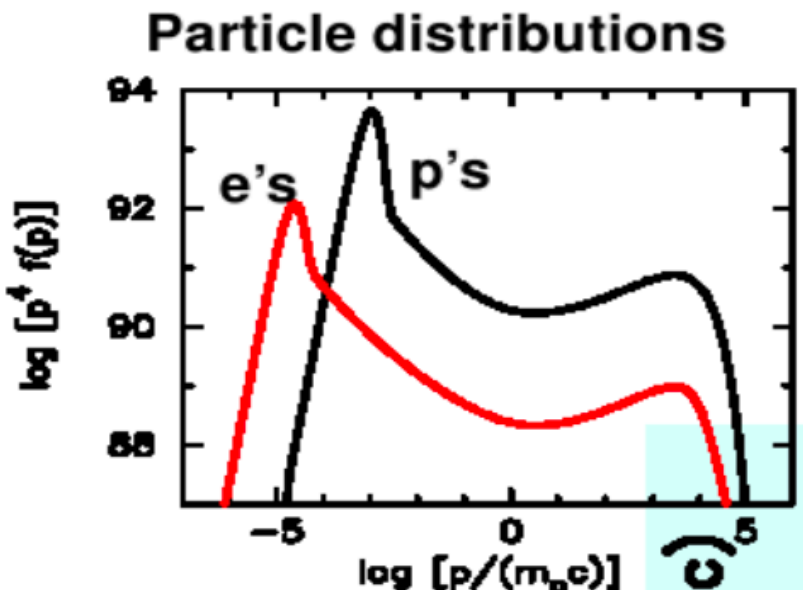
Electron and proton distribution from efficient (non-linear) shock acceleration



Several free parameters required to characterize particle spectra, including B-field, e/p ratio, diffusion coefficient

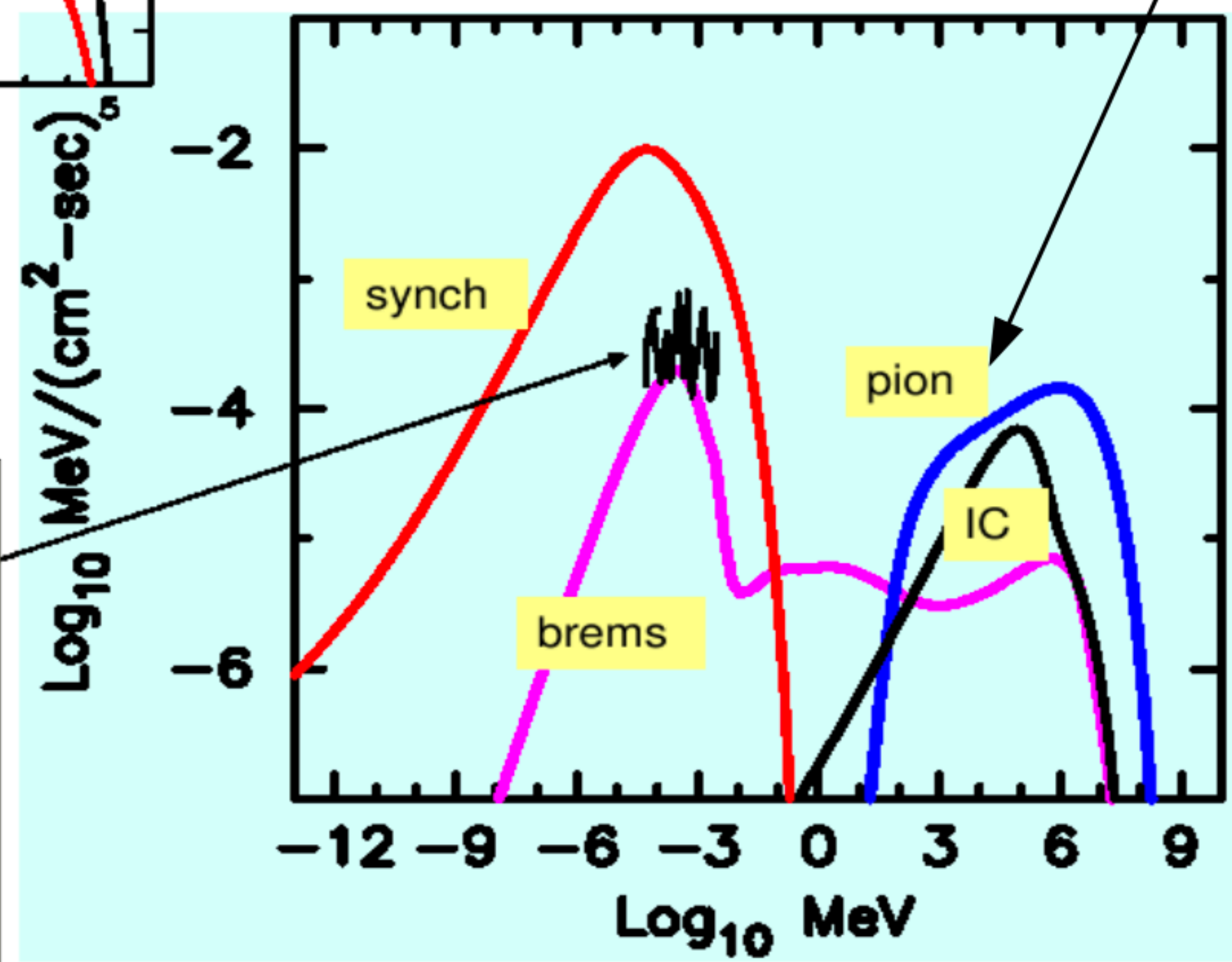
Spectra calculated with semi-analytic model of Blasi, Gabici & Vannoni 2005

EM radiation from accelerated particles



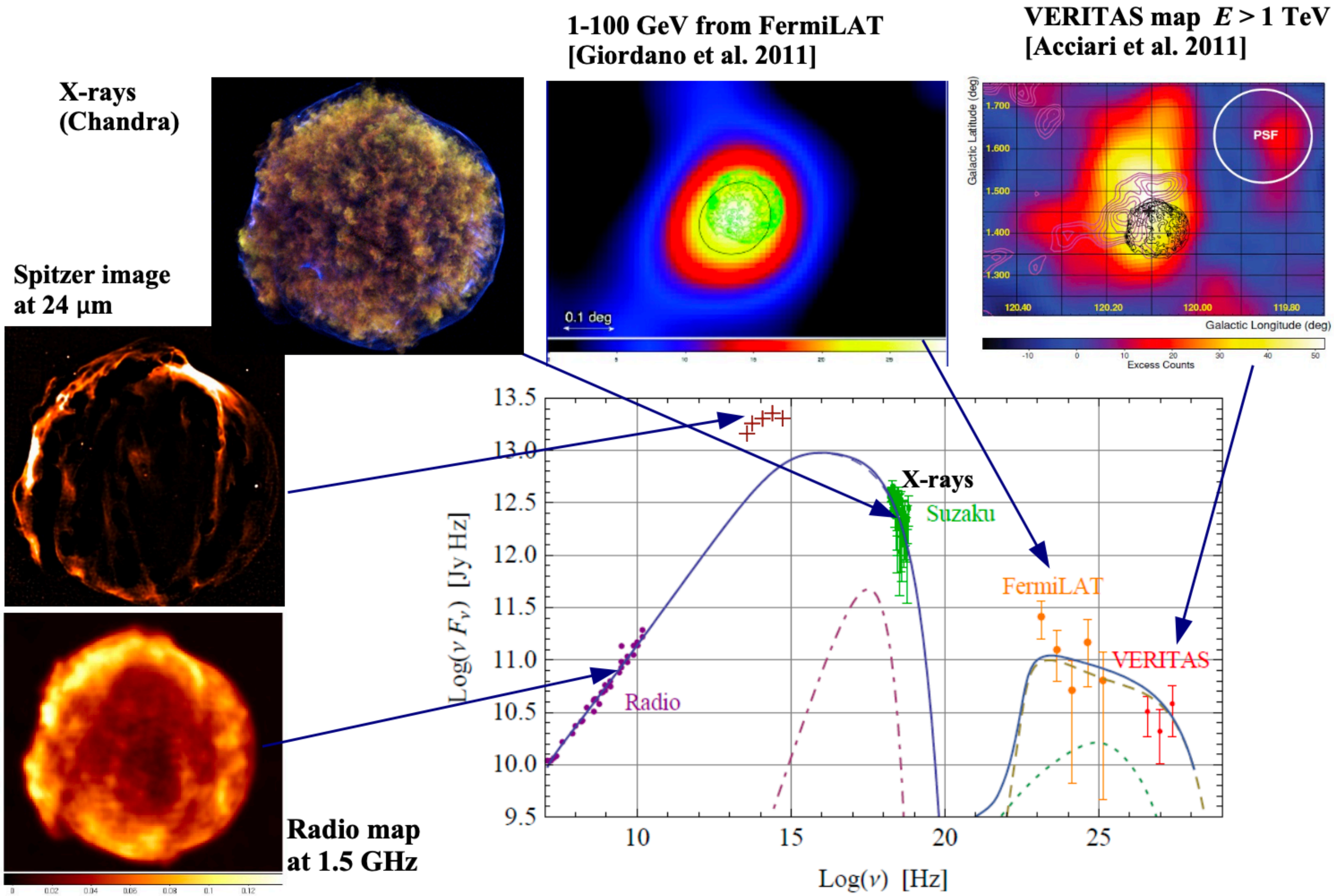
continuum emission

Pion decay and IC are competitive mechanisms



Hadronic models	Leptonic models
↓	↓
Large B >~ 100 μG	Low B ~ 10 μG

The case of Tycho's SNR



Spectral slope

1) Maximum energy is always < 100 TeV

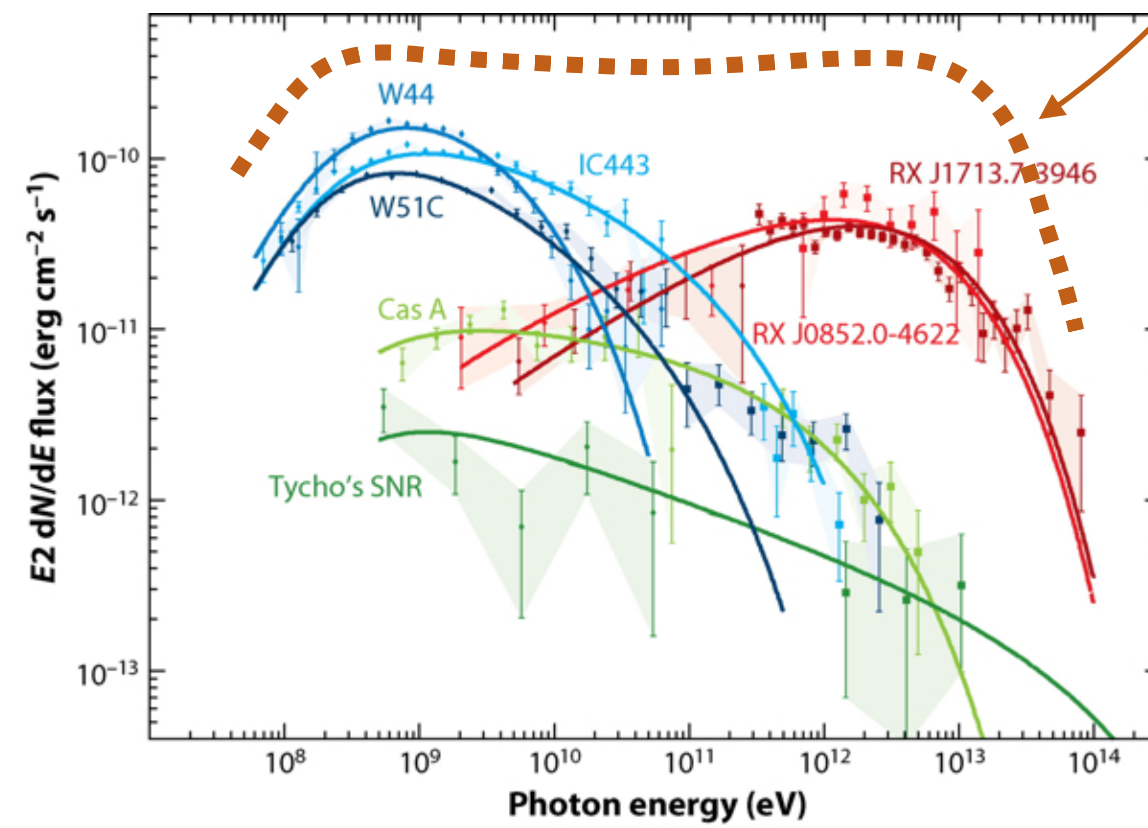
2) The gamma-ray spectrum does not agree with the basic prediction of Fermi acceleration.

Possible explanations:

- Spectra harder than E^{-2}:
  - Leptonic origin
  - Hadronic origin for shock expanding in clumpy media
- Spectra steeper than E^{-2}:
  - Modified velocity of scattering centres
  - Energy losses during acceleration
  - Break of isotropy (only for $v_{sh} > 10^4$ km/s)
  - Shock structure modified by neutral Hydrogen (only for $v_{sh} < 3000$ km/s)
  - Particle escaping (only for middle-aged SNRs)

Slope predicted by standard Fermi acceleration $f(E) \sim E^{-2}$ from hadronic emission

Gamma-ray emission from shell-type SNRs



Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

But we are looking at the instantaneous accelerated spectrum.
What about the escaping spectrum?

STELLAR CLUSTERS

Young stellar clusters

- Young stellar clusters (age $\lesssim$ few Myr) can reach mass up to $\sim 6 \times 10^4 M_\odot$
- May contains thousand of stars and several tens of OB stars
- They strongly affect the circumstellar environment due to powerful stellar winds
- They can host an high density of supernovae
  - SNe
    - ~20% Type Ia
    - ~80% core-collapse -> ~50% explode in clusters and OB association
- **Recently several massive star clusters have been associated with gamma-ray sources**

30 Doradus

Cygnus OB2

Westerlund 1

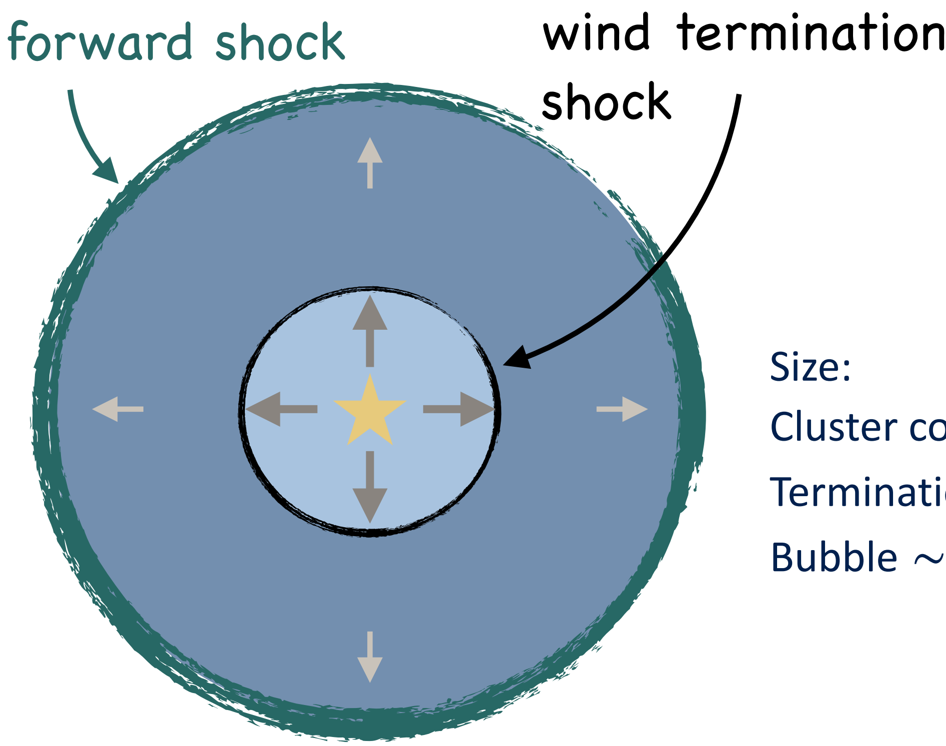
What power star clusters?

Different sources of power

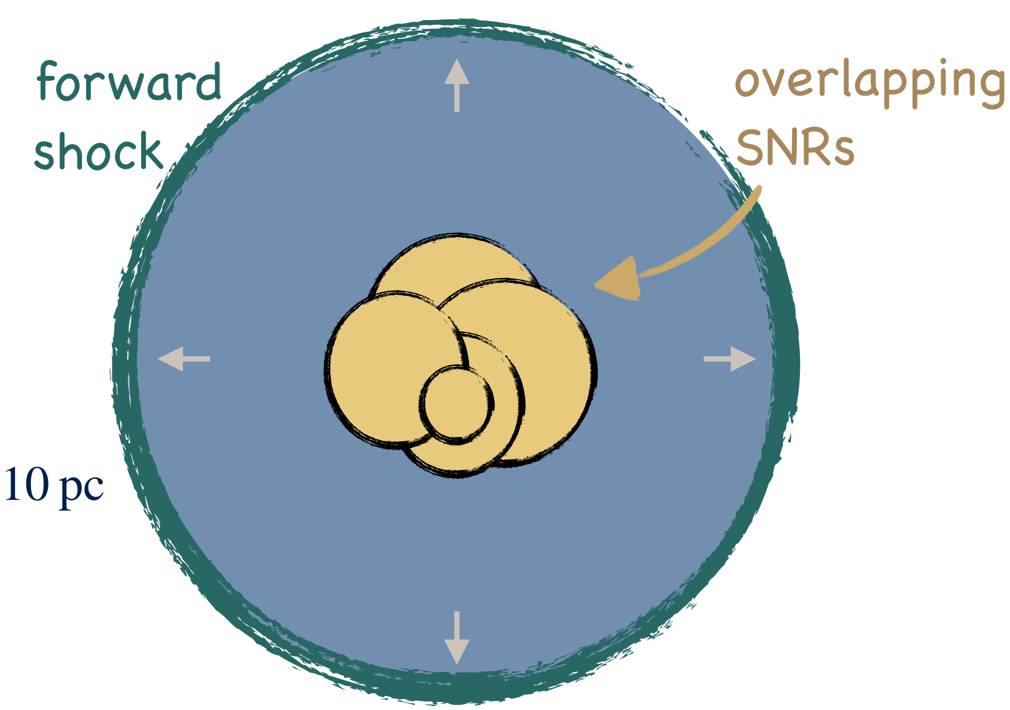
Phase	Source	Duration
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim$ Myr
$3\,\mathrm{Myr} \lesssim t \lesssim 7\,\mathrm{Myr}$	WR stellar winds	$t \sim 10^5\,\mathrm{yr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim 10^3 - 10^4\,\mathrm{yr}$

$t \lesssim 3\,\mathrm{Myr}$: only stellar winds

$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$: stellar winds + SNe



Size:
Cluster core $\sim 1\,\mathrm{pc}$
Termination shock $\sim 5 - 10\,\mathrm{pc}$
Bubble $\sim 50 - 100\,\mathrm{pc}$



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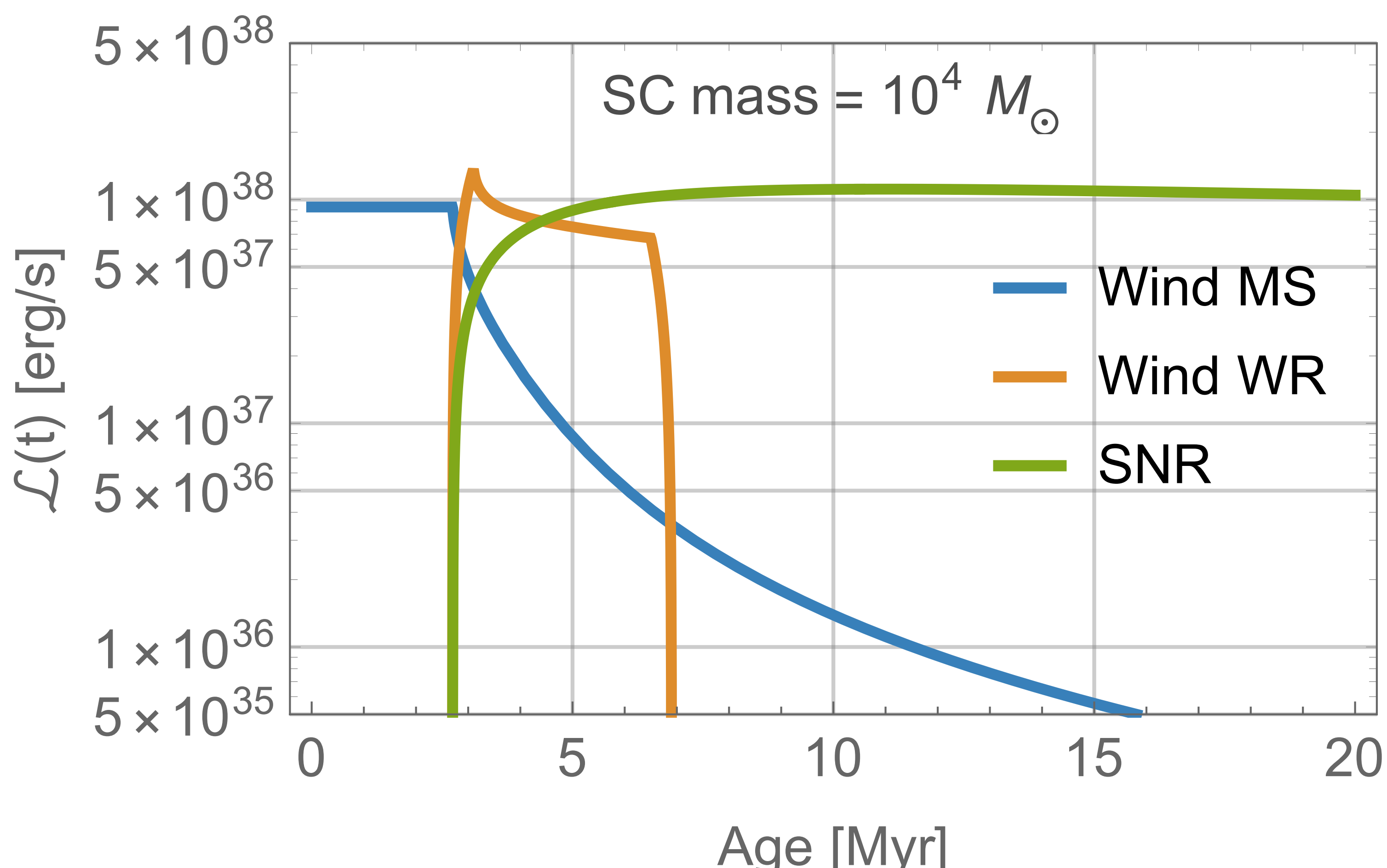
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim 10^3 - 10^4\,\mathrm{yr}$

Stellar cluster luminosity



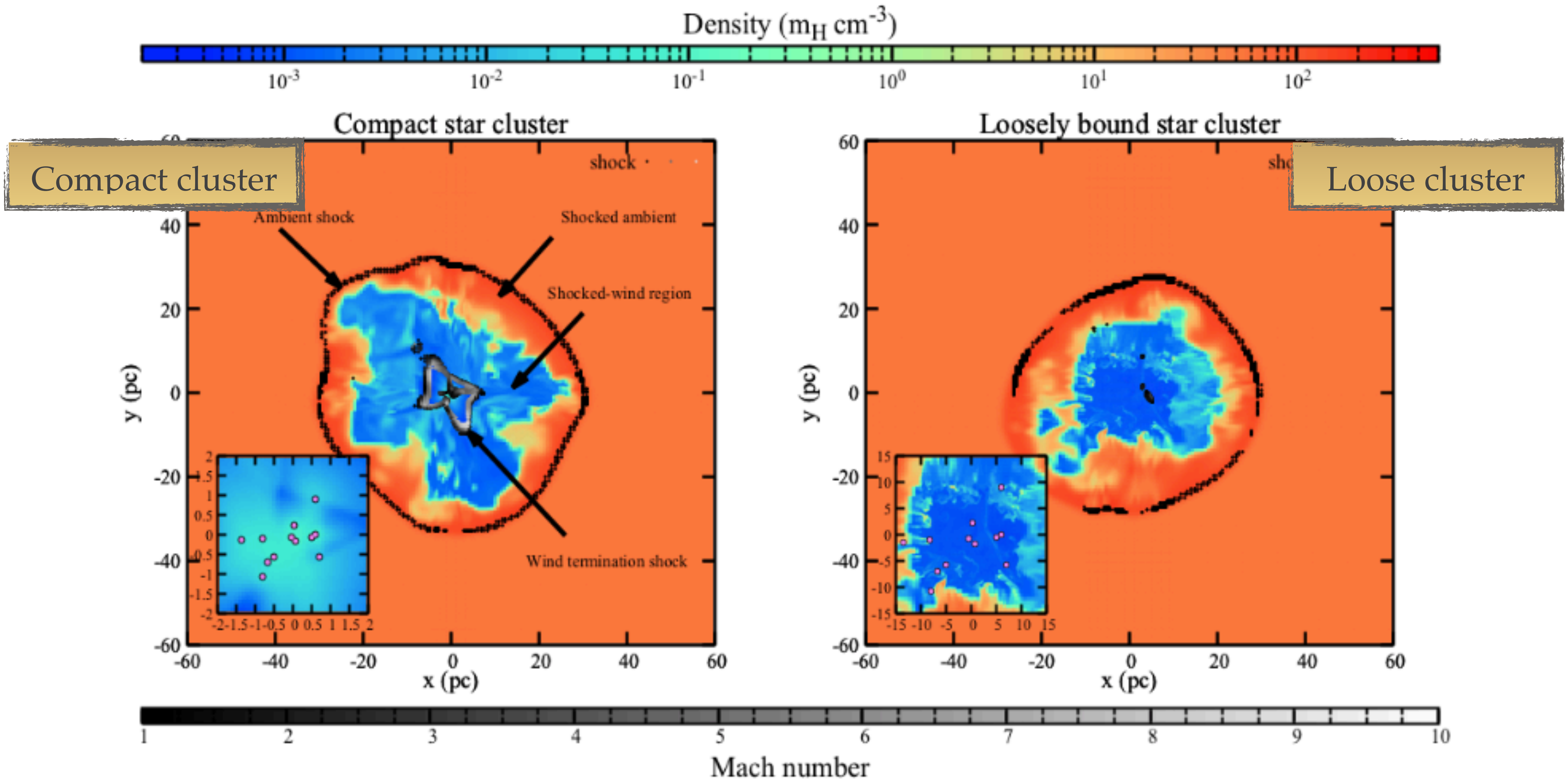
Possible acceleration mechanisms

- Shock acceleration at the wind termination shock [GM et al. (2021)]
- Shock acceleration at the SNR forward shock propagating inside the bubble. [Vieu et al. (2022); Vieu & Reville (2023); A. Mitchell, GM et al. (2024)]
- II order Fermi acceleration by strong magnetic turbulence [Vieu & Gabici (2023); J. Vink (2024)]
- Wind-wind collisions from massive stars in the cluster center [Bylkov, Gadilin, Osipov (2013)]

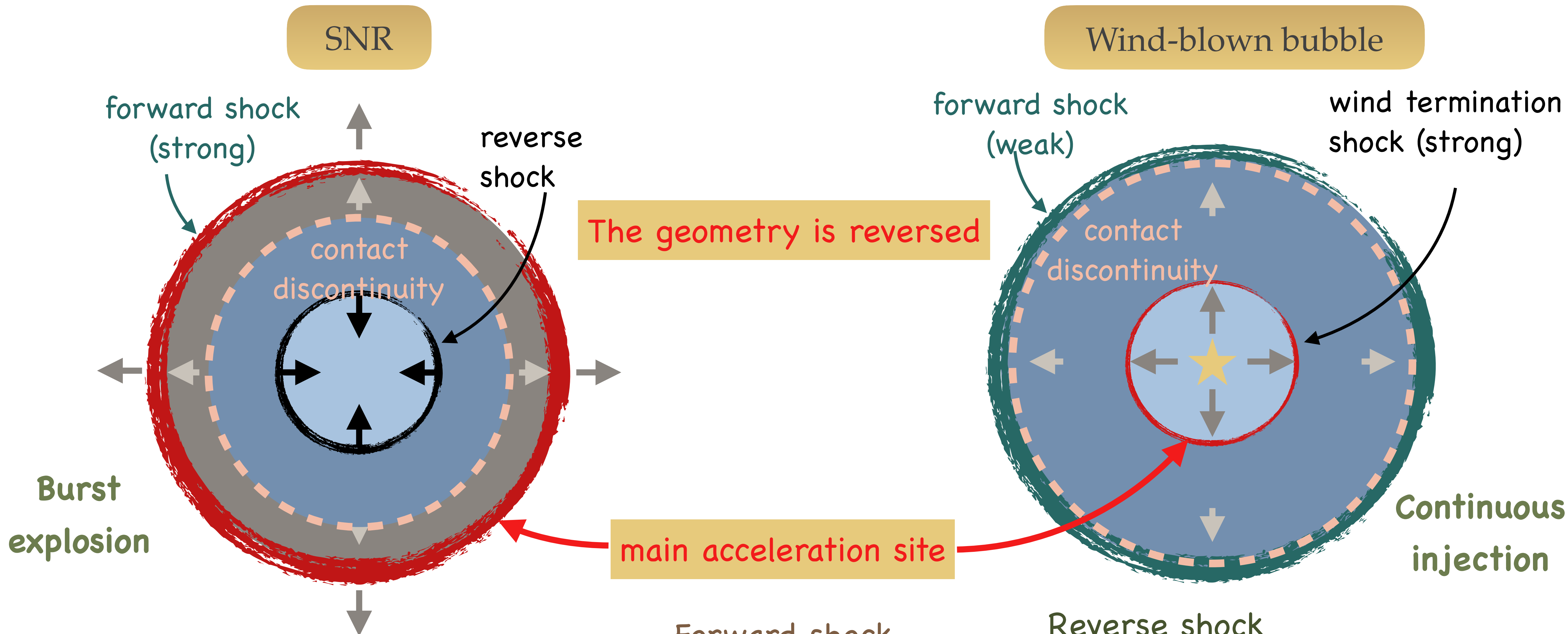
Wind termination shock

The WTS develops only if the cluster is compact enough: $R_{cluster} \ll R_{TS}$

[Gupta, Nath, Sharma & Eichler, MNRAS 2020]



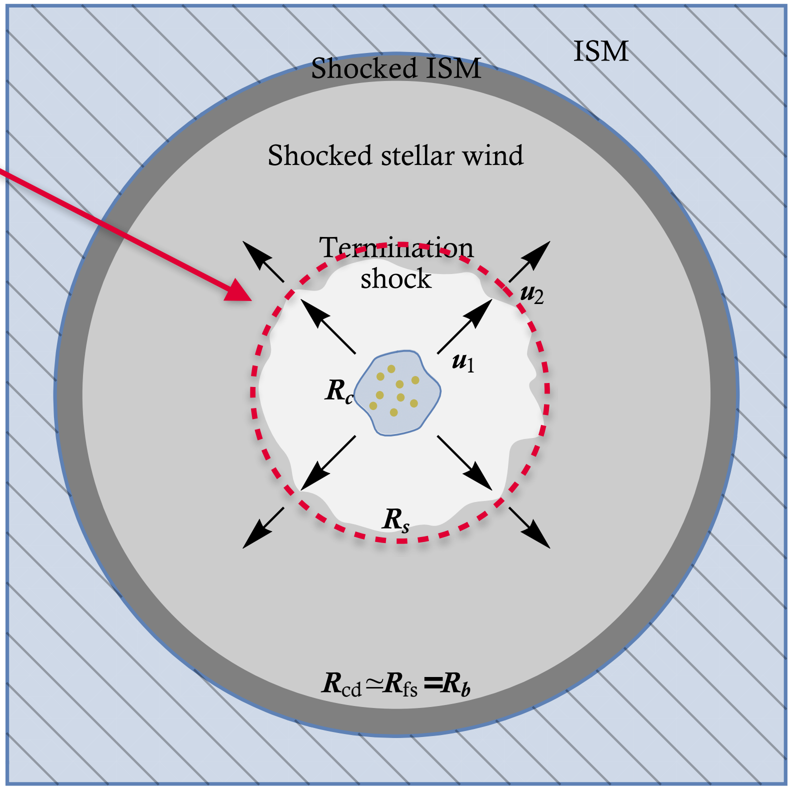
Stellar winds vs. SNRs



		Forward shock		Reverse shock	
	age	V_{FS} [km/s]	R_{FS} [pc]	V_{RS} [km/s]	R_{RS} [pc]
SNR	kyr	> 5000	< 1	< 3000	< 1
Wind bubble	Myr	10 - 20	50-100	< 3000	1-10

Acceleration at the wind termination shock

Acceleration at the collective **wind termination shock** [GM et al.(2019)]



Assumptions:

- CR Acceleration efficiency ~few % of the wind kinetic luminosity
- Magnetic turbulence produced by wind non-stationarity and inhomogeneities
  - Few % of wind kinetic energy converted in magnetic energy
- Diffusion coefficient depends on the type of energy cascade

$$\begin{cases} D_{\rm Kol}(E) = \frac{v}{3} r_L (\delta B)^{1/3} L_c^{2/3} \\ D_{\rm Kra}(E) = \frac{v}{3} r_L (\delta B)^{1/2} L_c^{1/2} \\ D_{\rm Bohm}(E) = \frac{v}{3} r_L (\delta B) \end{cases}$$

L_c is the injection scale of turbulence, assumed of the order of the cluster size (~pc)

Parameters tuned on gamma ray emission from Cygnus OB2 cluster.

Particle spectrum from a single cluster

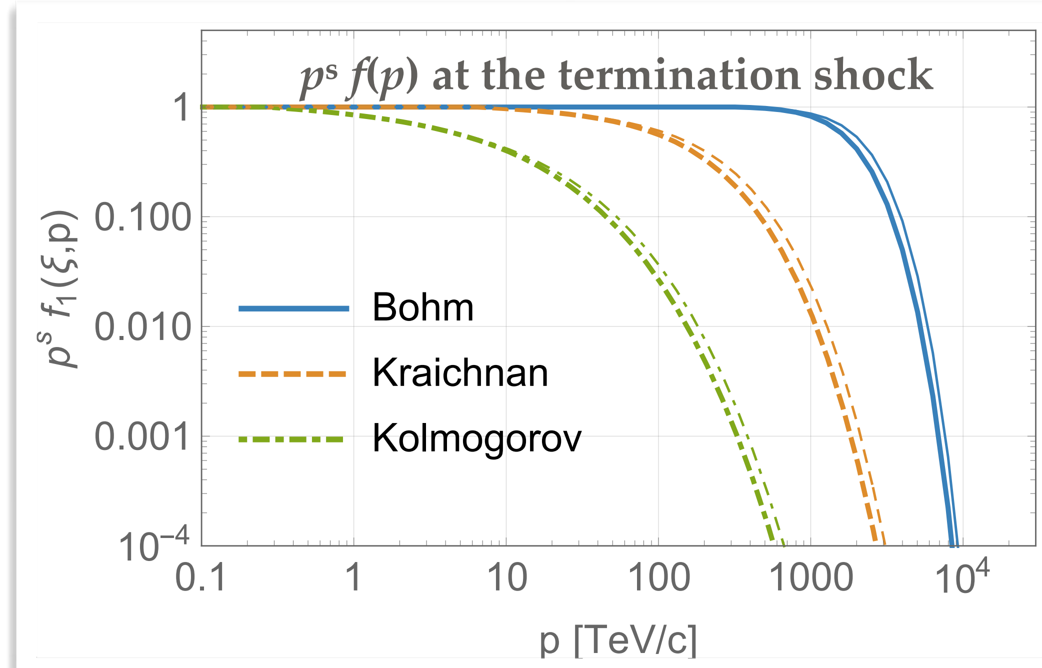
$$f_s(p) = s\frac{\eta_{\rm inj}\, n_1}{4\pi\, p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} e^{-\Gamma_1(p)}\ e^{-\Gamma_2(p)}$$

$$s = \frac{3\sigma}{\sigma - 1}$$

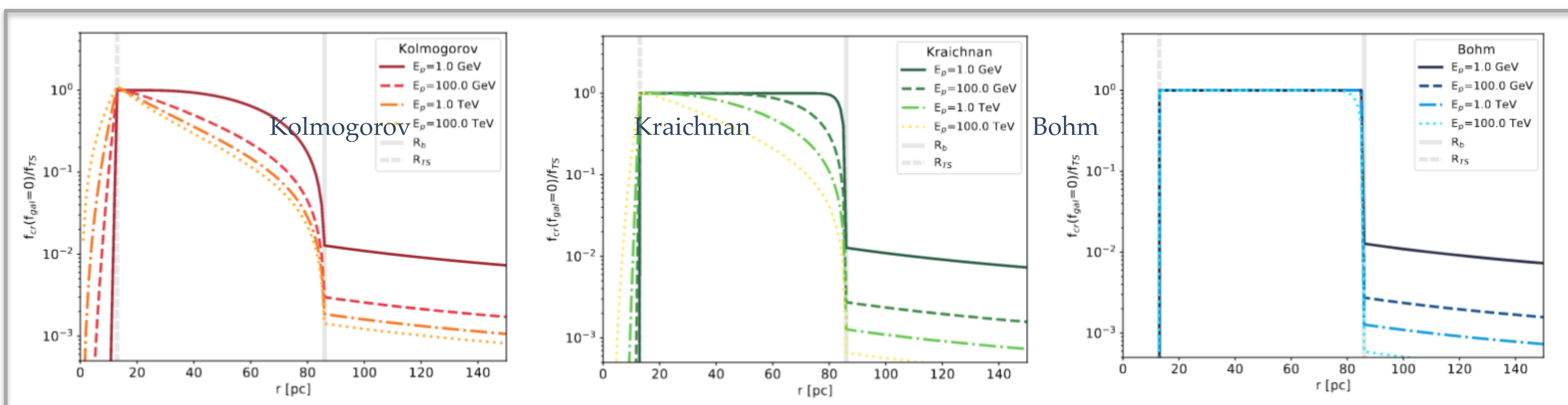
Standard power-law for plane shocks

Cutoff due to particle confinement upstream in a spherical geometry

Cutoff due to particle escaping from the bubble

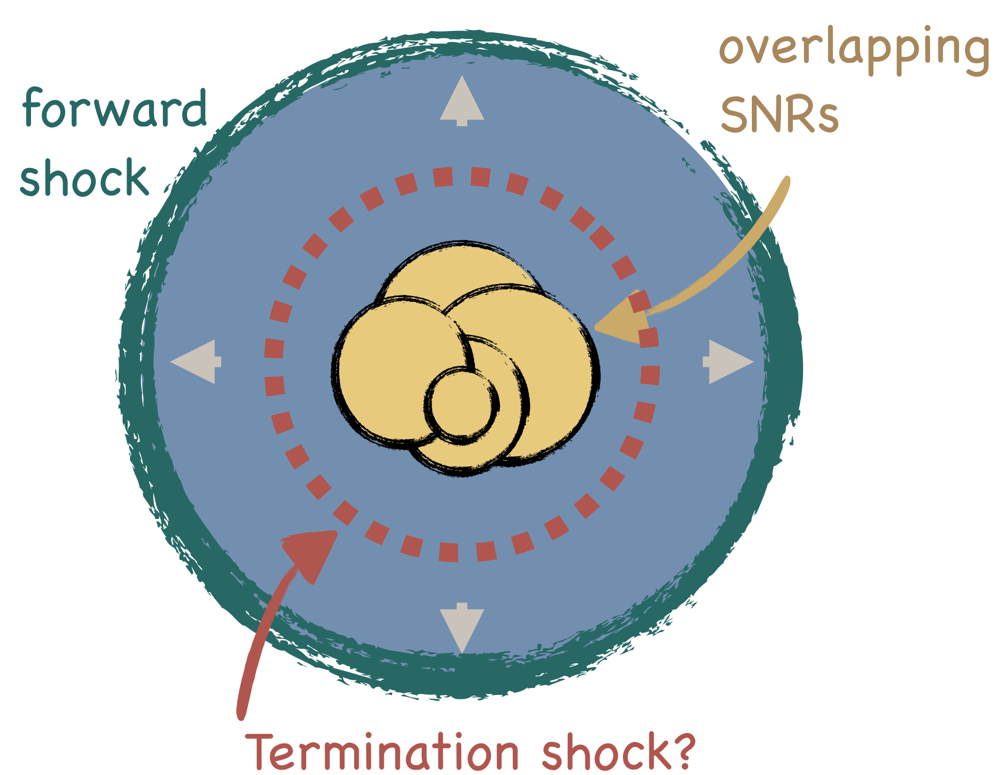


Spatial profile: the harder is the diffusion coefficient the flatter is the CR distribution

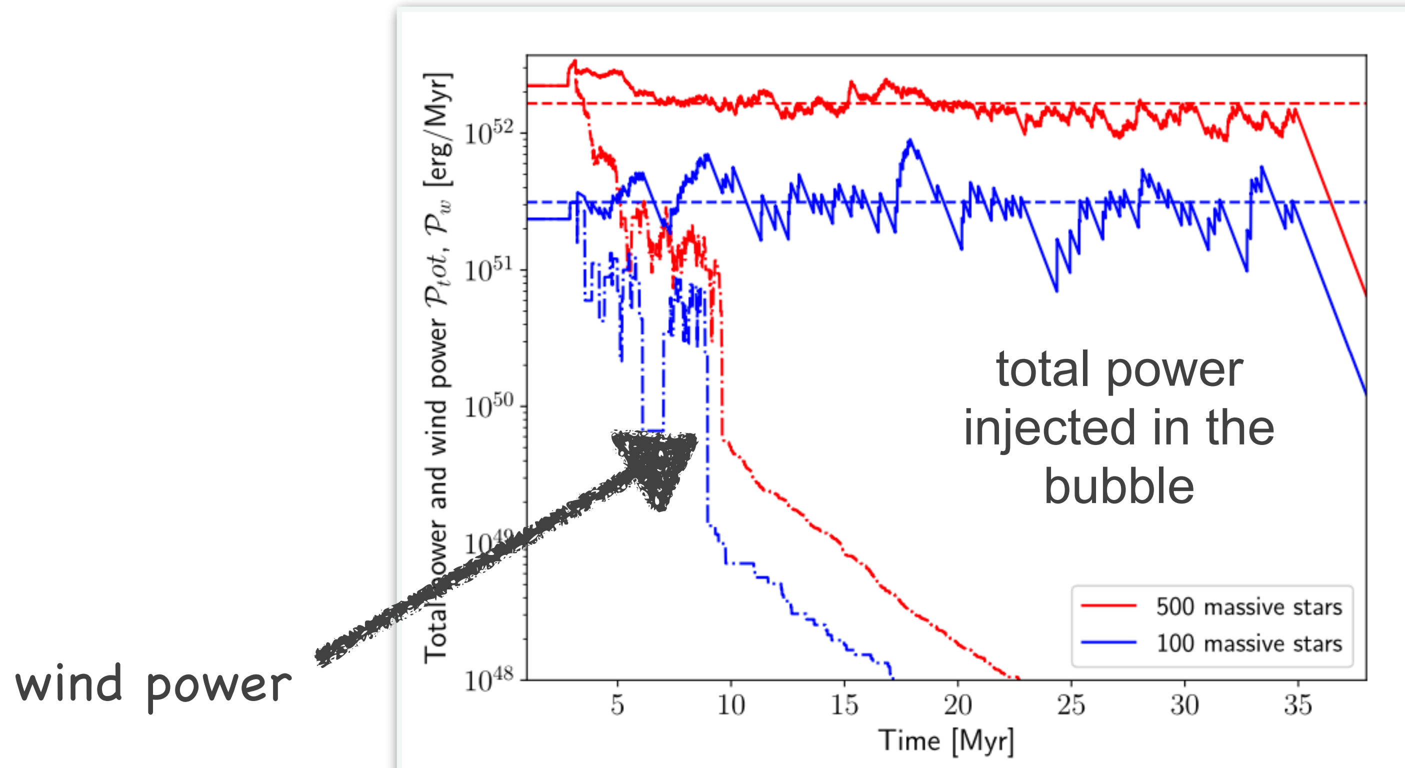


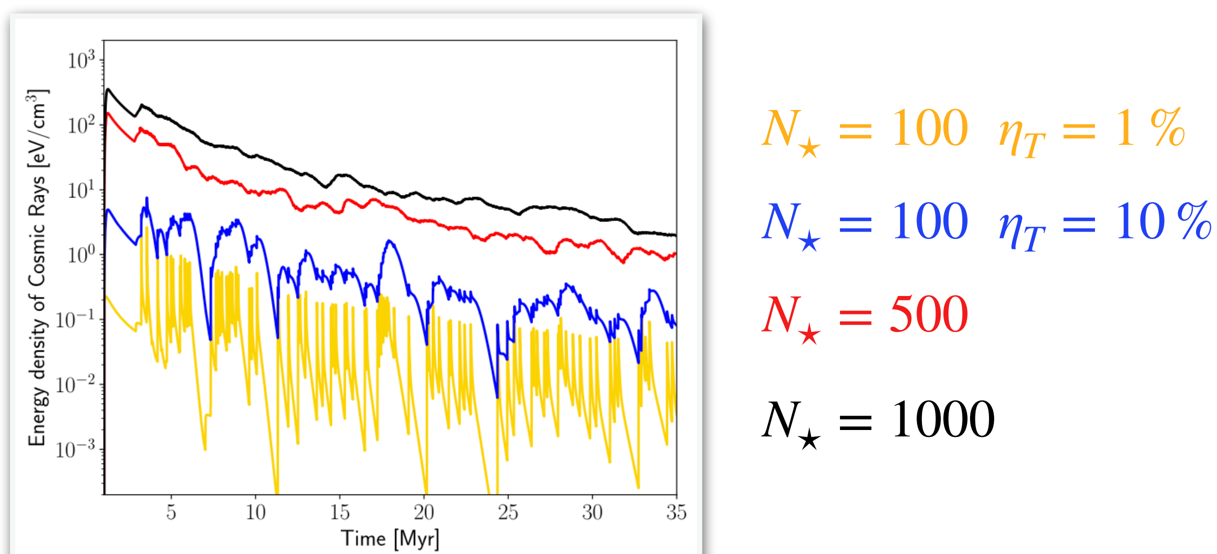
Old cluster -> superbubbles

$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe



Vieu et al. (2022):
consider acceleration at WTS + SNR forward shock + turbulent acceleration



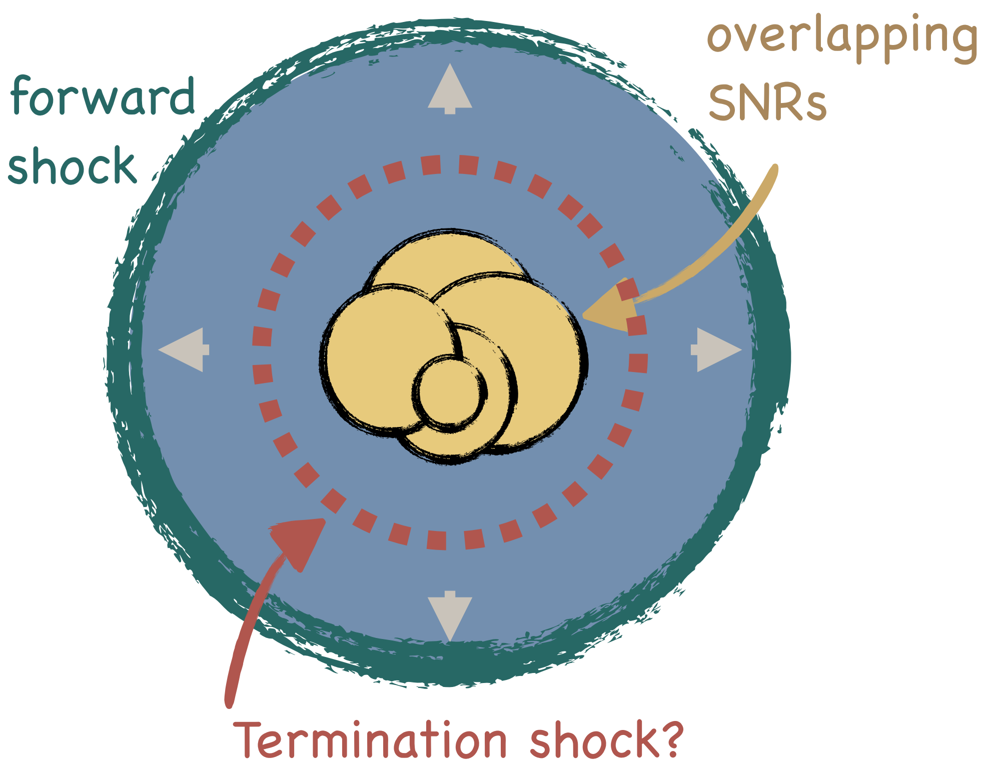


- Does the TS still exist?
- The turbulence in the bubble remains high due to wind and SN explosions

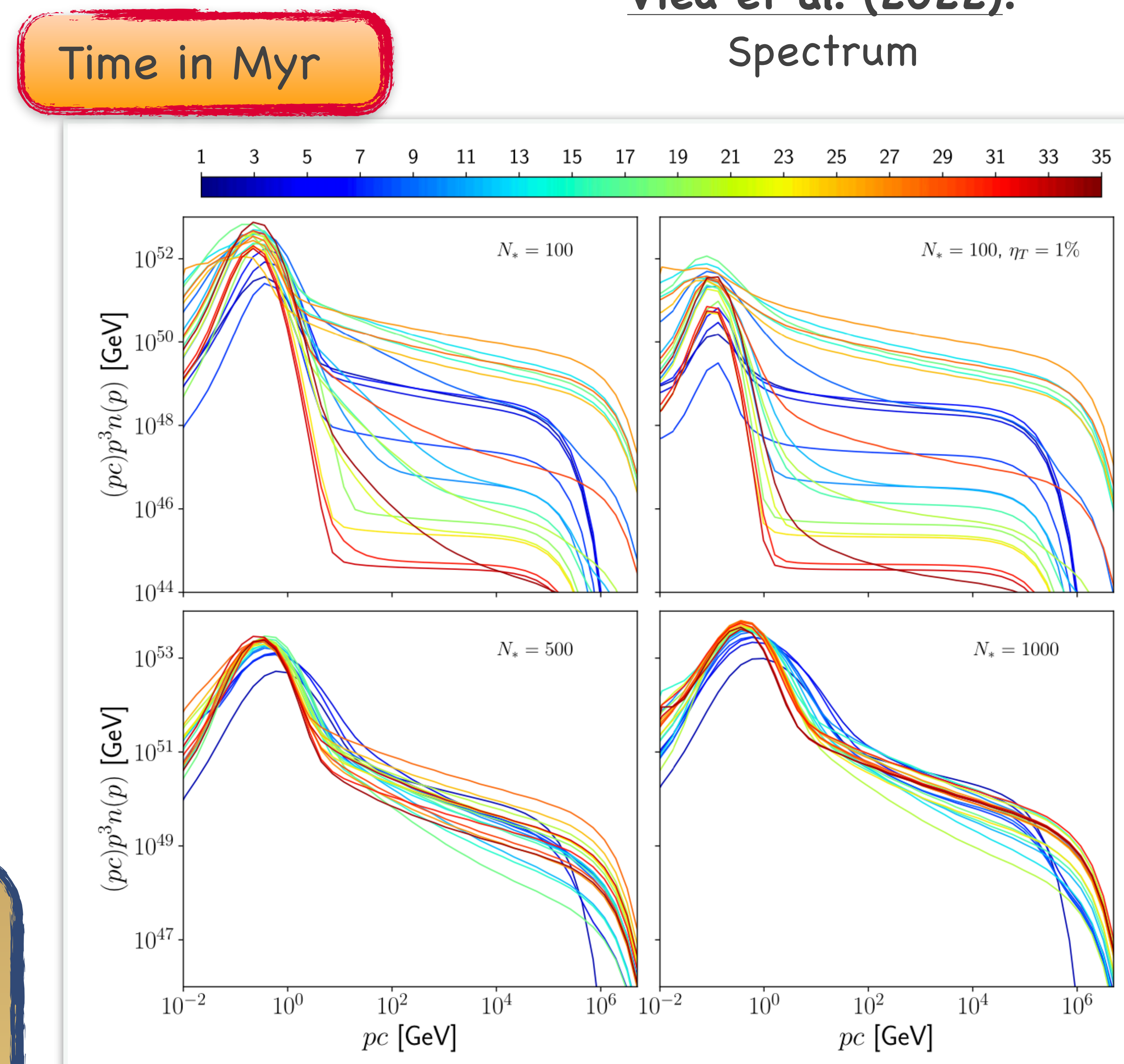
  → Efficient particles confinement in the bubble
- Maximum energy probably similar to the WTS case

Old cluster -> superbubbles

$t \gtrsim 3\,\mathrm{Myr}$ stellar wind + SNe



Vieu et al. (2022):
Spectrum

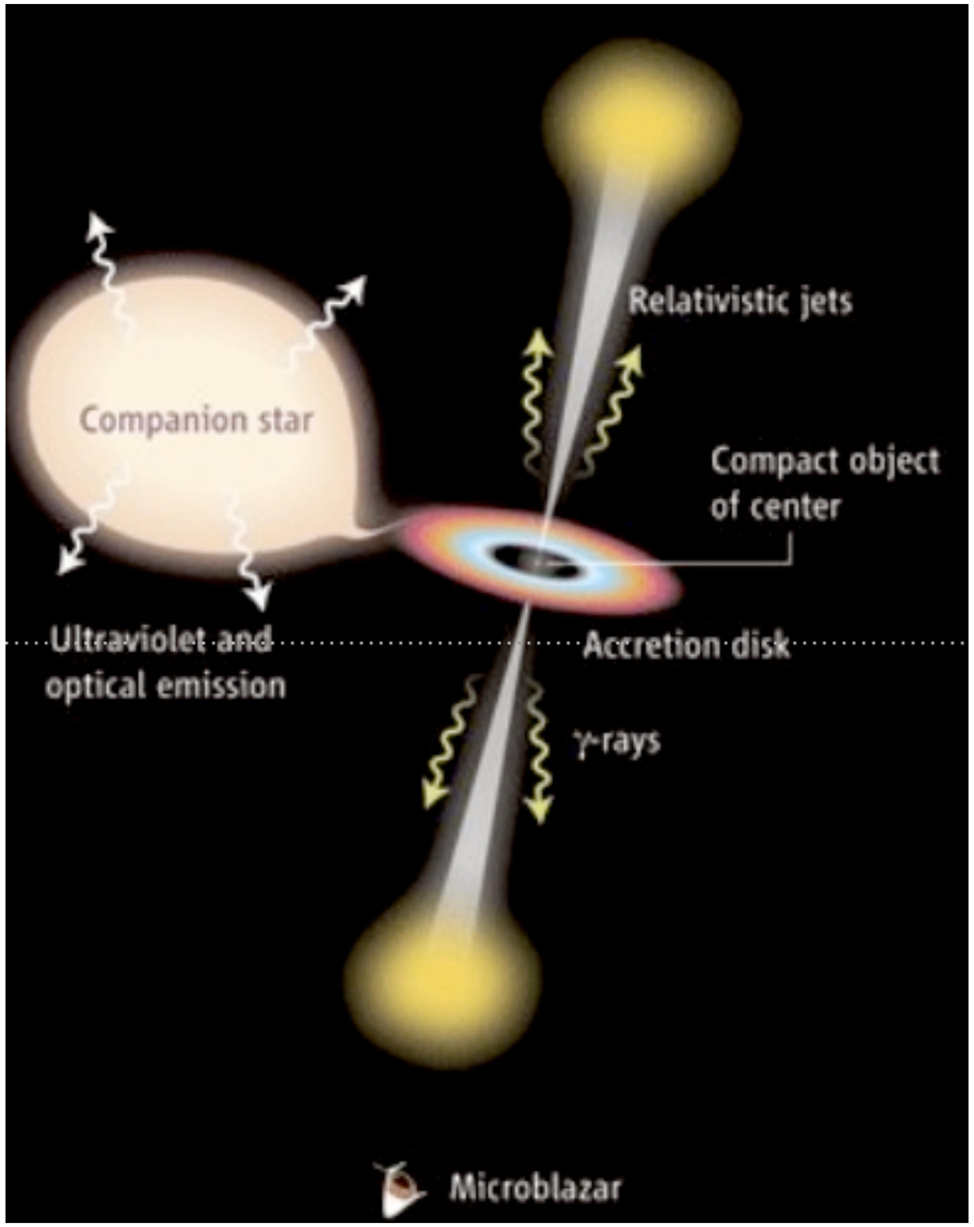


- Energetically Super-bubbles may produce the bulk of CRs
- Maximum energy can reach ~PeV
- The spectrum is not universal -> strong intermittency

MICRO QUASARS

Micro-quasars

- μ-quasars are the stellar version of AGN:
  - A compact object (BH or neutron star) accretes matter from the companion star
  - An accession disk and a jet are formed
- First discovered: SS 433 in 1997 thanks to superluminal motion of the jet
- Number of μ-quasars discovered in the Milky Way ~ 20 (3 detected in gamma-rays)
- Estimated total number of μ-quasars: ~40-100
- Total luminosity of a single object 10^{39}-10^{40} erg/s
- Total population luminosity 10^{40}-10^{42} erg/s
- Efficiency in CR acceleration: unknown



Gamma-loud binaries at VHE: state-of-the-art

Category	System	Star spectral type	Compact object	Porb [days]	HE emission	VHE emission	UHE emission
Gamma-ray binaries (non-accreting pulsars)	PSR B1259-63	O9.5Ve	48ms pulsar	1236.72	yes	yes	-
	LS 5039	O	pulsar?	3.91	yes	yes	yes (> 25 TeV)
	LS I +61 303	Be	pulsar	26.49	yes	yes	yes
	HESS J0632+057	Be	-	315.50	yes	yes	-
	FGL J1018.6-5856	O	-	16.58	yes	yes	-
	LMC P-3	O	-	10.2	yes	yes	-
	HESS J1832-093	O	-	82	yes	yes	-
	PSR J2032+4127	Be	143 ms pulsar	50 years	yes	yes	-
Microquasars	SS 433	A	BH	13.08	yes	yes	yes
	V4641 Sgr	B9III	BH	2.8	no	yes	yes
	Cyg X-1	O9.7Iab	BH	5.6	yes	hint (4.0 σ)	hint (4.0 σ)
CWB	eta Carinae	LBV	O/B star	5.5 years	yes	yes	-
Novae	RS Ophiuchi	red giant	white dwarf	454	yes	yes	-

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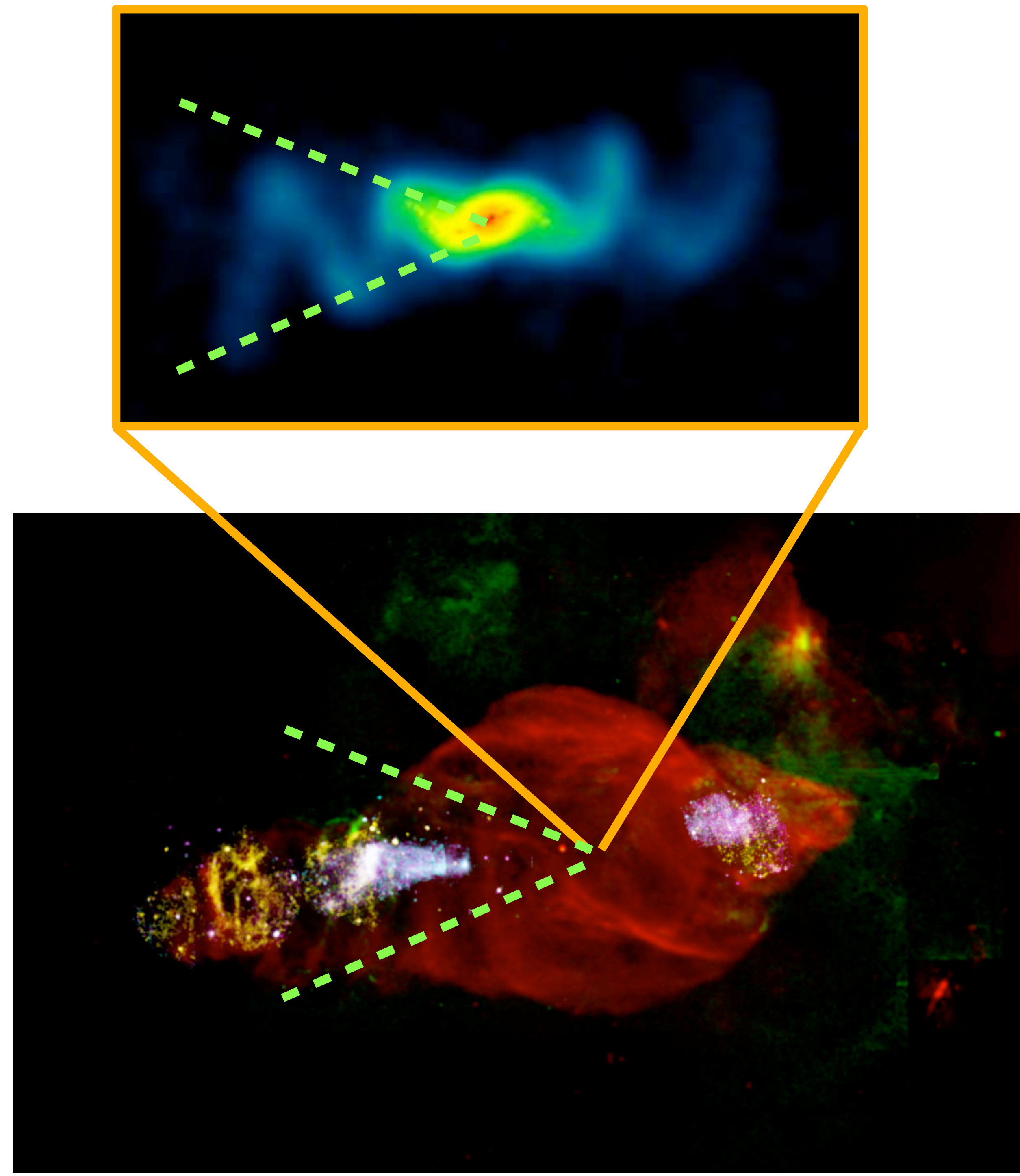
	Cyg X-1	O9.7Iab	BH	5.6	yes	hint (4.0 σ)	hint (4.0 σ)
CWB	eta Carinae	LBV	O/B star	5.5 years	yes	yes	-
Novae	RS Ophiuchi	red giant	white dwarf	454	yes	yes	-

They accrete at super-Eddington regime

SS 433

- Distance ~5 kpc
- Power: ~10^{40} erg/s (super-Eddington)
- Radio: precessing jet in the inner core
- Jet velocity: 0.26 c [Panferov, 2013]
- Recollimated jets reappears at ~30 pc
- Large cocoon/bubble (W50): parent SNR or wind blown bubble?

ALMA observations (radio)



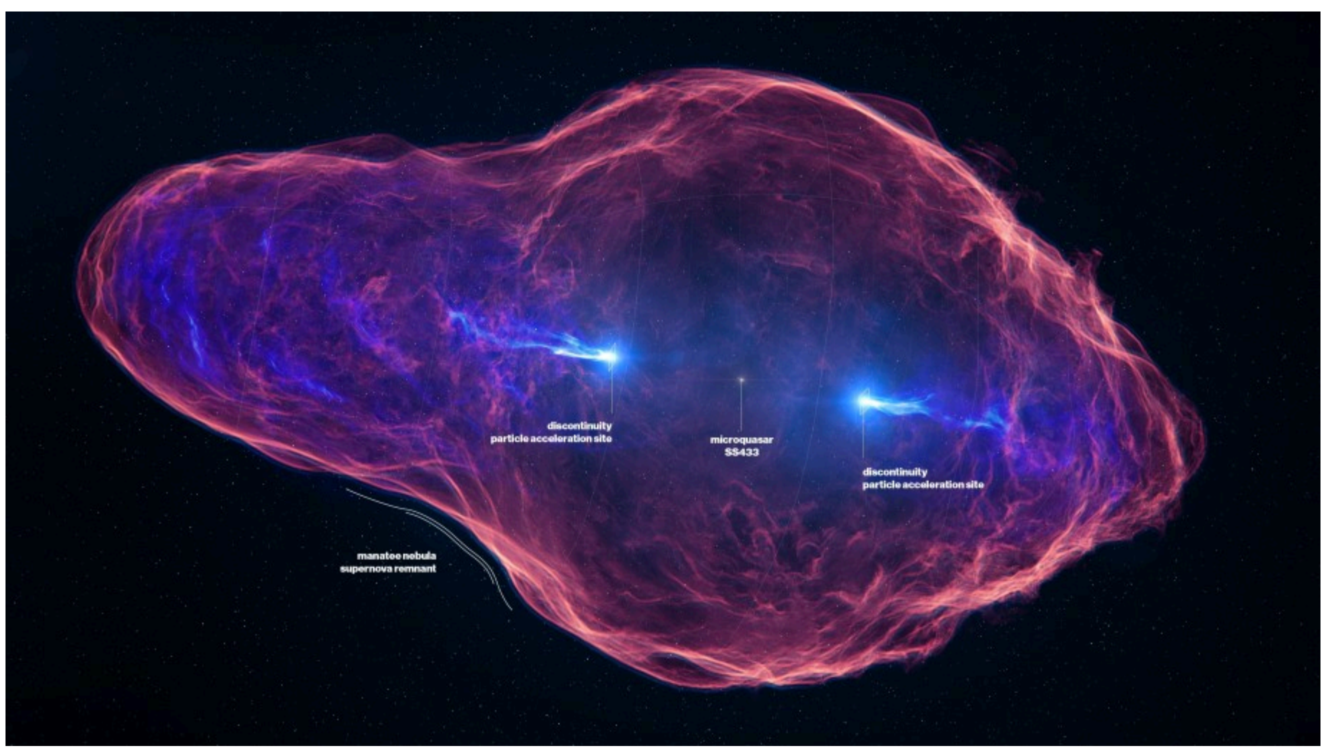
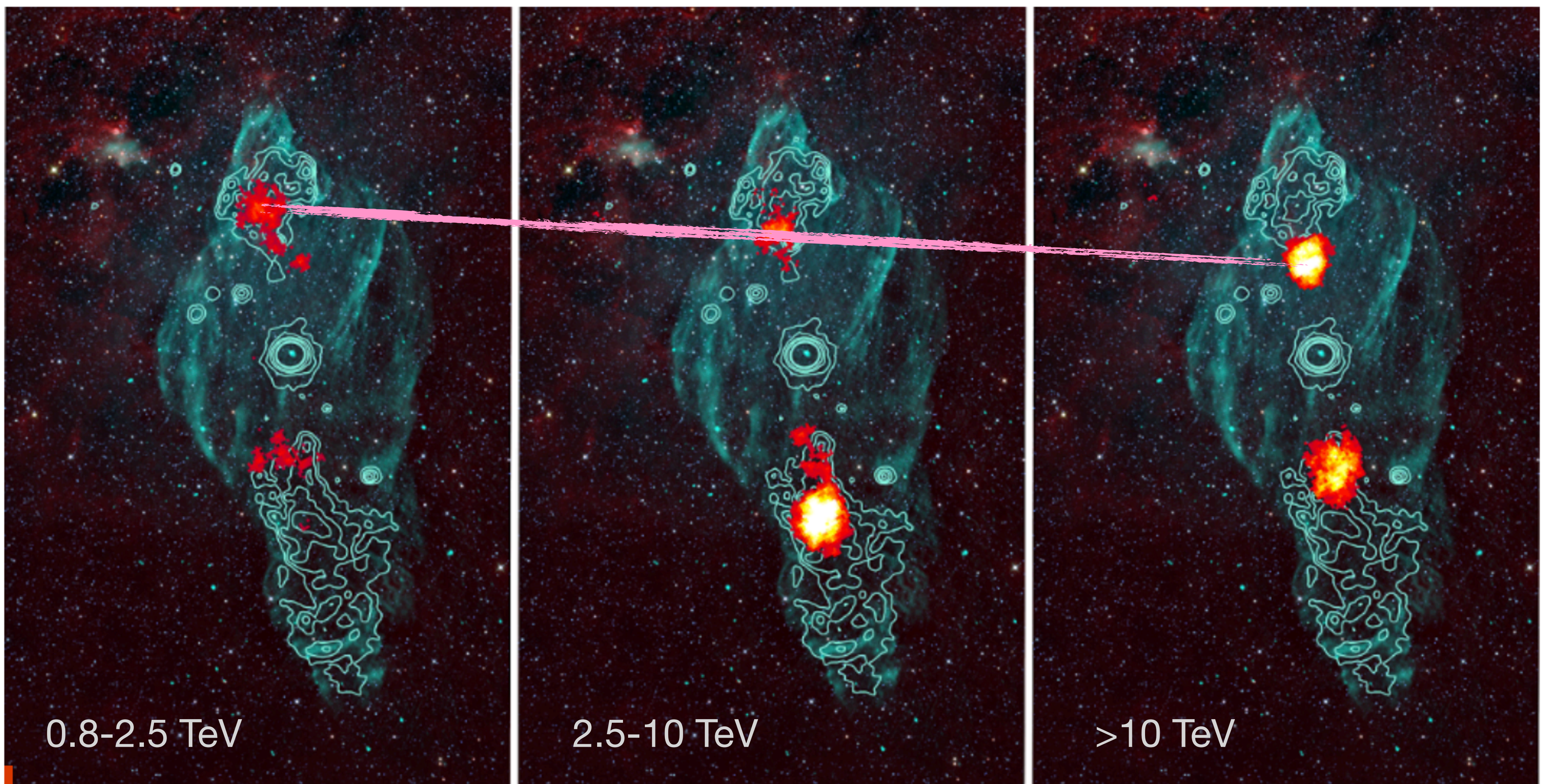


Figure 1: Artist's impression of the SS 433 system, depicting the large-scale jets (blue) and the surrounding Manatee Nebula (red). Credit: Science Communication Lab for MPIK/H.E.S.S.

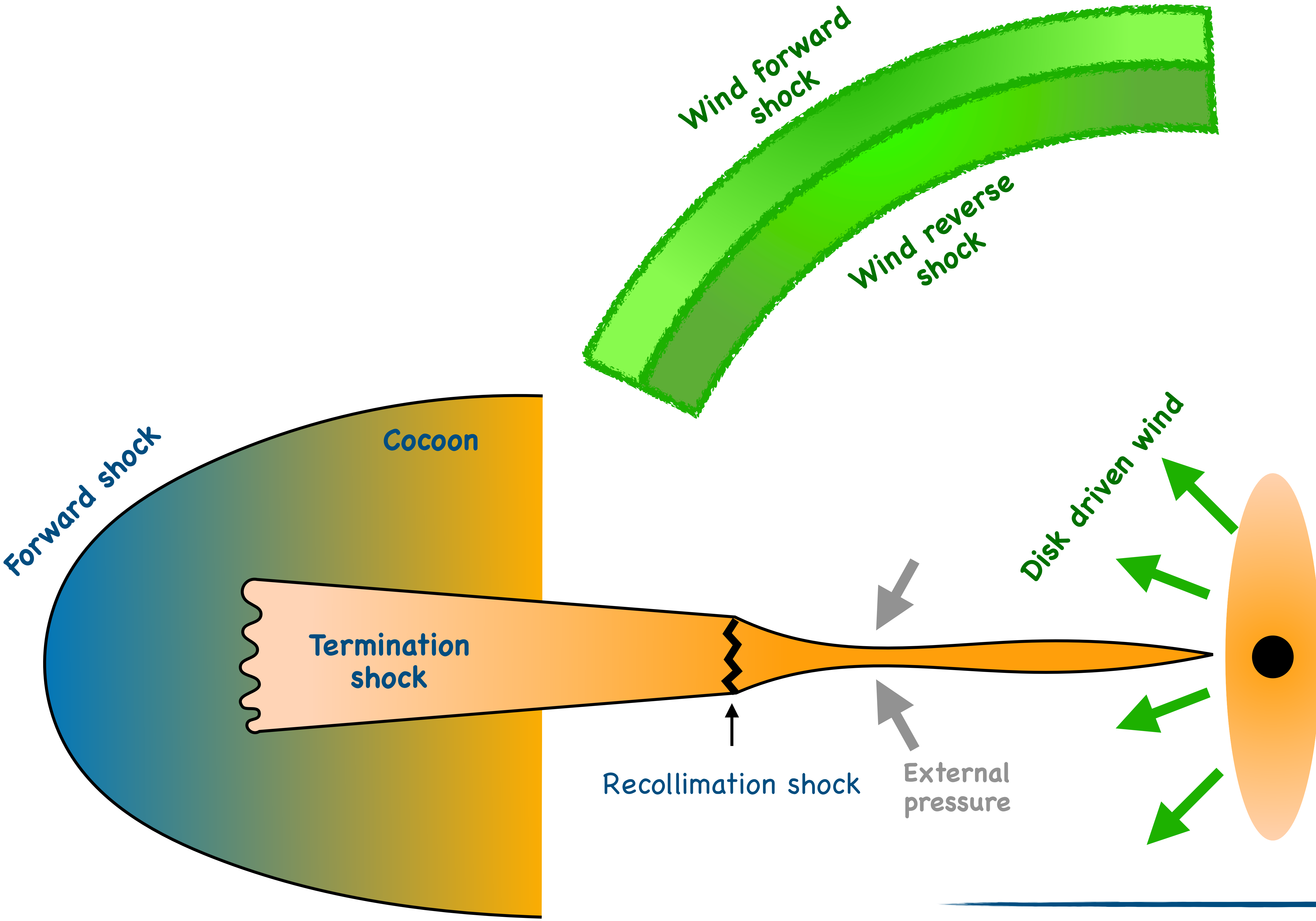
SS 433

- Green diffuse: Radio
- Green contours: X-rays
- Red: gamma-rays (HESS) -> compatible with leptonic emission (fast cooling)



Credit : Background : NRAO/AUI/NSF, K. Golap, M. Goss ; Wide Field Infrared Survey Explorer (WISE) (NASA) ; X-rays (green outline) : ROSAT/W. Brinkmann ; TeV (red colours) : H.E.S.S collaboration

Possible acceleration sites



Summary

GALACTIC CANDIDATE SOURCES FOR HADRONIC CASMIC RAYS

	Power	Spectrum	Maximum energy	Comments
SNR	🙂	🙂	🙁	The most credible sources for the bulk of CRs
Young stellar clusters	😐	🙂	🤨	Powered by stellar winds
Super-bubbles	🙂	?	🧐	Stellar winds + SNe
Micro-quasars	🙁	?	🙂	Probably useful to explain particles at $E > 100$ TeV No clear theoretical model
Core-collapse SNe	🙂	?	?	No detection yet of gamma-rays
Galactic Centre	😐	🙂	🙂	Unclear origin Too distant to explain all local CRs
Pulsars	🙁	🙁	🙂	Not clear if they accelerate hadrons
Giant magnetic islands	?	?	?	Only a theoretical hypothesis

NOT DISCUSSED HERE