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SCHOOL OF ADVANCED STUDIES
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INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

SUPERNOVA REMNANTS AS COSMIC RAY ACCELERATORS

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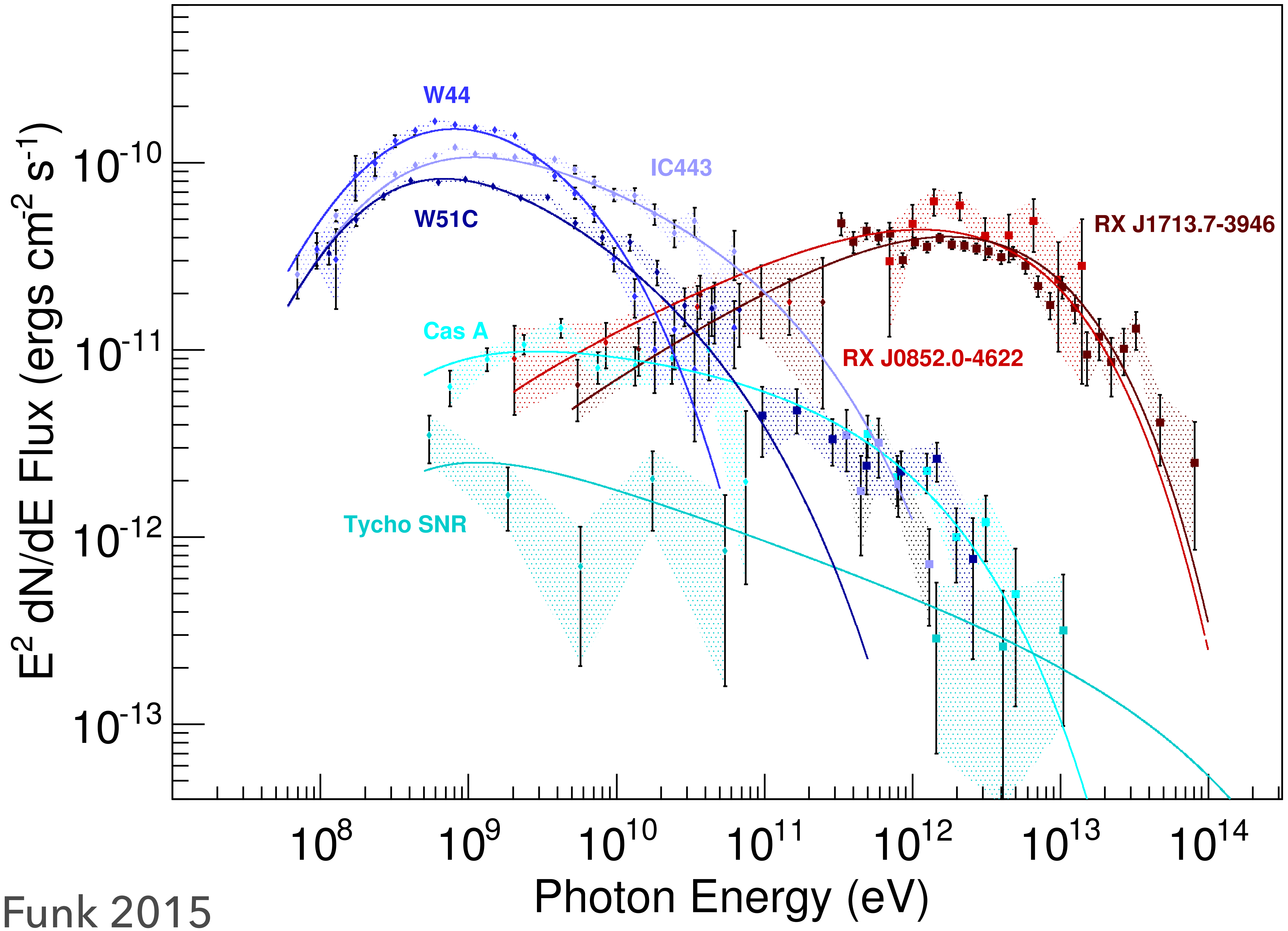
Why Supernova Remnants and why not?

- 1 SN/30 years –> an efficiency of conversion from ram pressure to CR of 3% is sufficient to account for the bulk of CRs observed at the Earth
- Non-thermal emission (in radio, X-ray and gamma rays) has now been observed for quite some time - we know that particle acceleration occurs there
- X-rays provide clear evidence of magnetic field amplification at the shock fronts of virtually all young SNRs – this has been a long awaited for evidence for CR acceleration
- The Obvious implications would be that SNRs may account for CR not only at GeV energies but up to the knee…
- …yet none of the young SNRs has been observed to be a PeVatron
- …no evidence of PeV CR from around these SNRs as well…

So, what is the situation?

We know SNRs accelerate CRs



Funk 2015

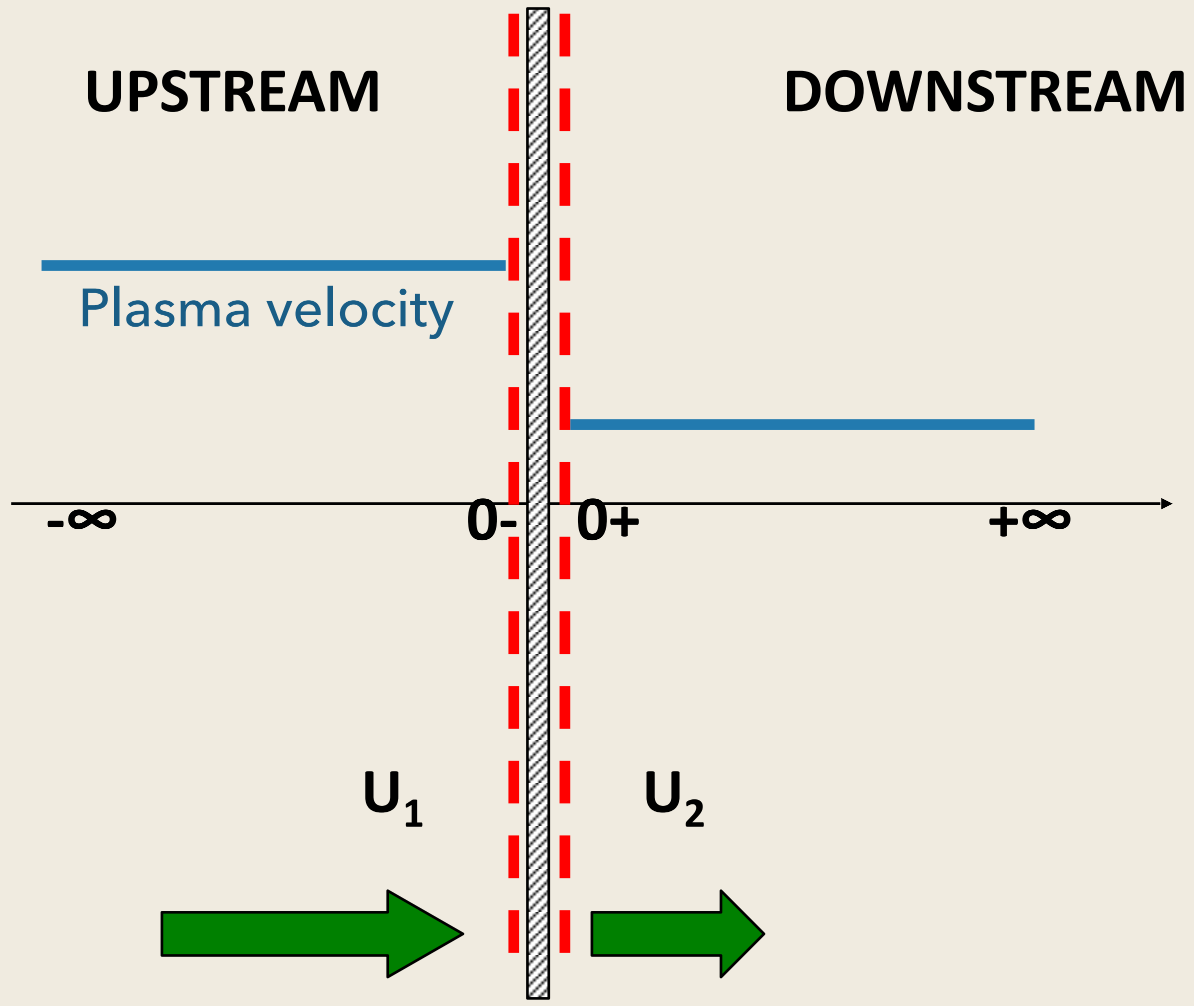
- *Gamma rays with Energy up to ~10 TeV have been observed from virtually all young and several middle aged SNRs*
- *Interestingly, the brightest have a hard spectrum, typically to be attributed to ICS of VHE electrons*
- *Steeper spectra and lower fluxes observed from Cas A and Tycho, extending to <10 TeV gamma rays*
- *Notice that Cas A is a core collapse SN while Tycho is a SN type Ia*

Question is...

Do we not see evidence of PeV acceleration in SNR because they cannot accelerate to such energies? [This is a well posed, yet difficult, theoretical question]

...of we do not see evidence of PeV acceleration because we are not supposed to? [This is both a theory and observation well posed question]

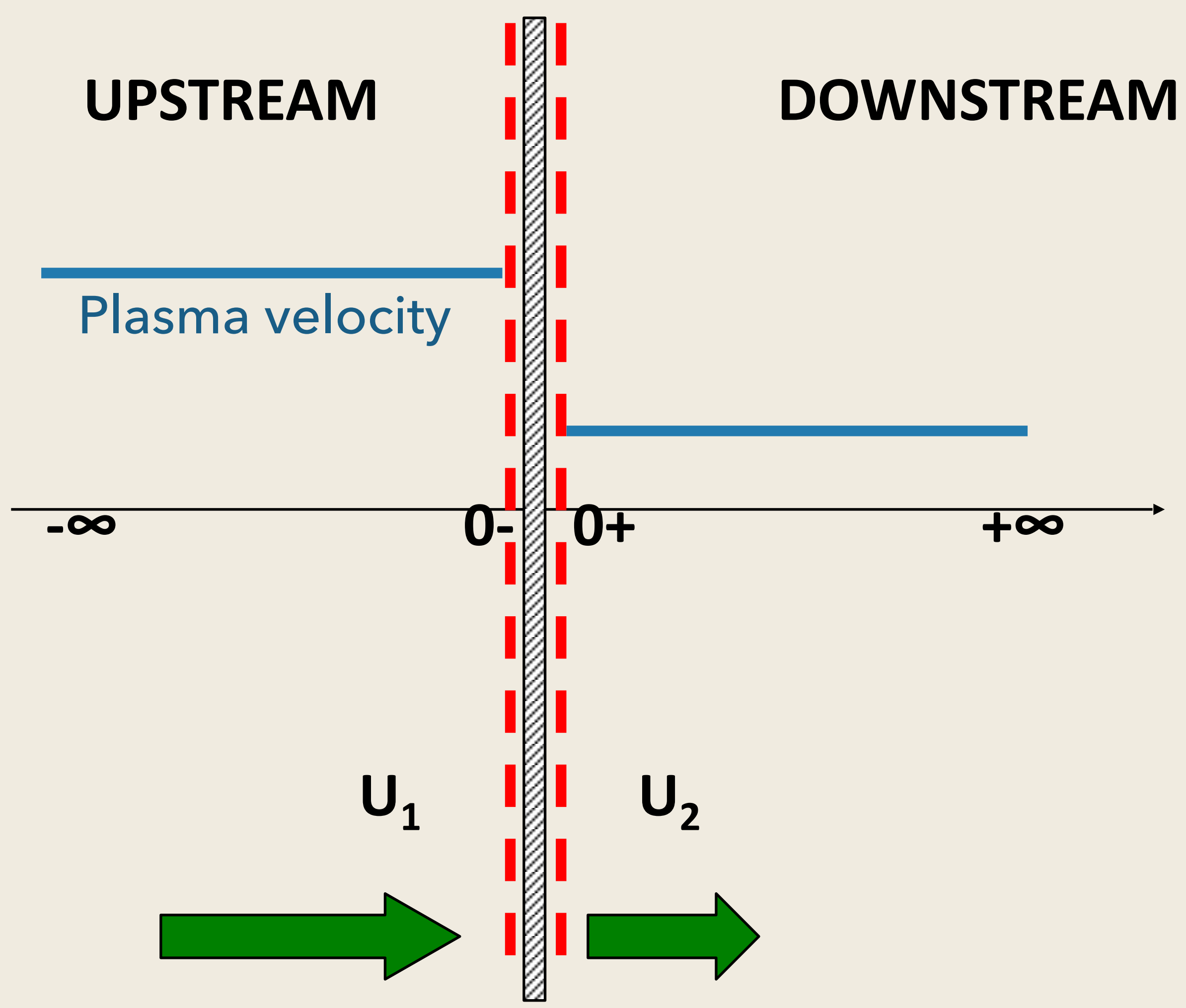
Basics of the theory of DSA in SNRs



$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} + \frac{1}{3}\frac{du}{dx}\,p\frac{\partial f}{\partial p} + Q(x,p,t)$$

DIFFUSION ADVECTION COMPRESSION INJECTION

Basics of the theory of DSA in SNRs



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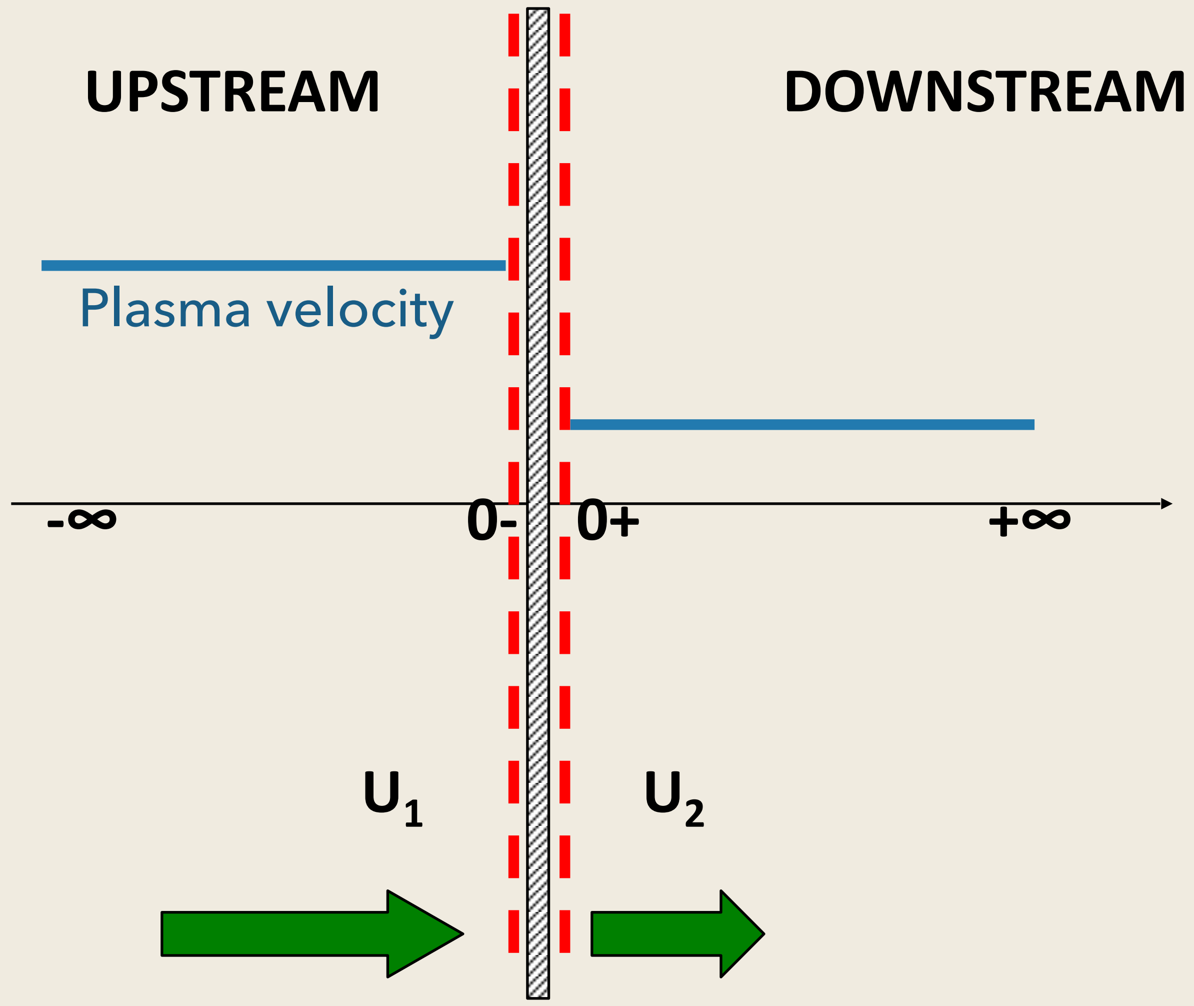

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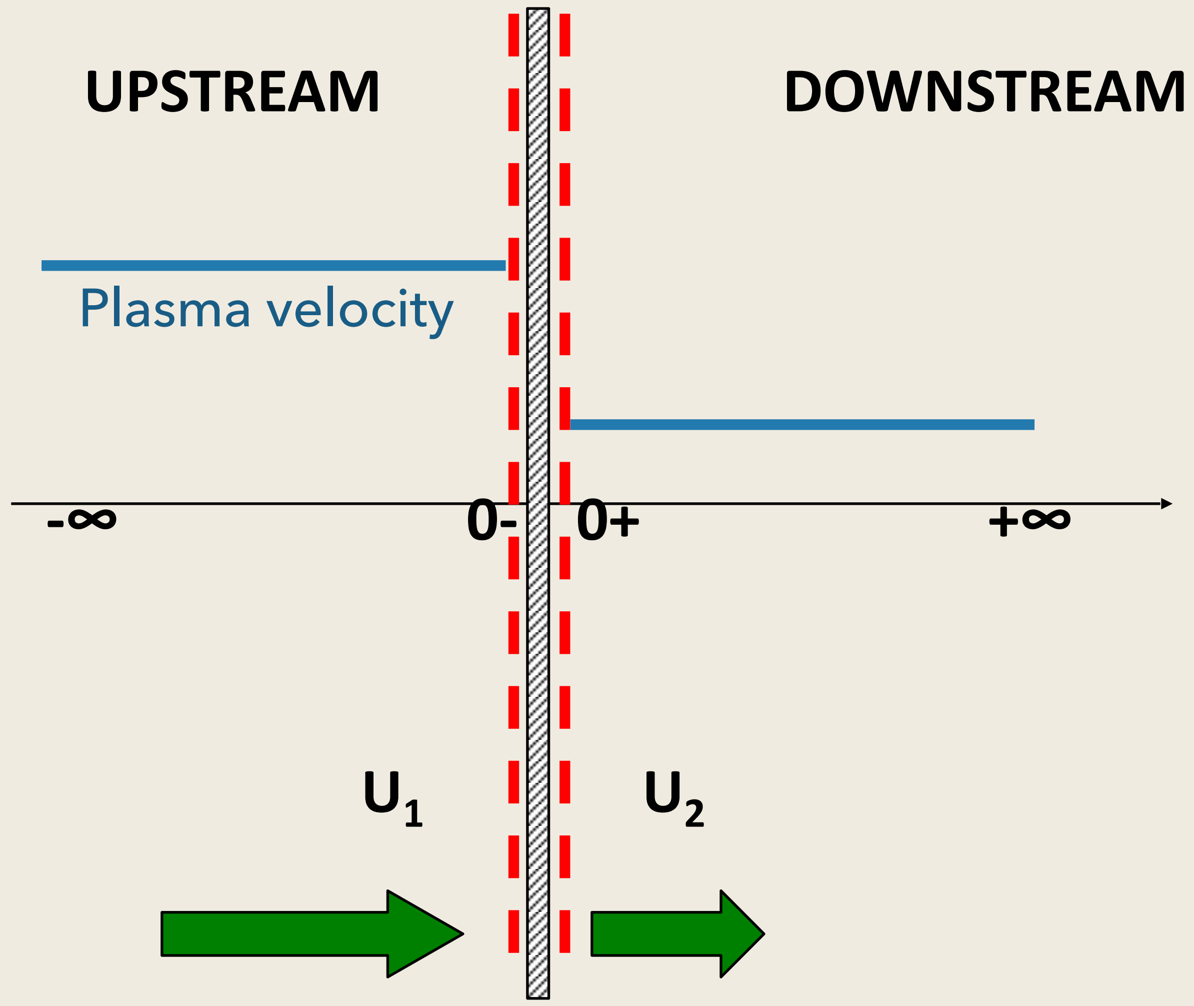
DIFFUSION ADVECTION COMPRESSION INJECTION

UPSTREAM *Solution*

$$\frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} = 0 \quad \rightarrow \quad \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x} - uf\right] = 0$$

$$f(x,p) = f_0 \exp\left[\frac{u_1 x}{D}\right] \quad \rightarrow \quad D\frac{\partial f}{\partial x}|_{x\rightarrow 0^-} = u_1 f_0(p)$$

Basics of the theory of DSA in SNRs



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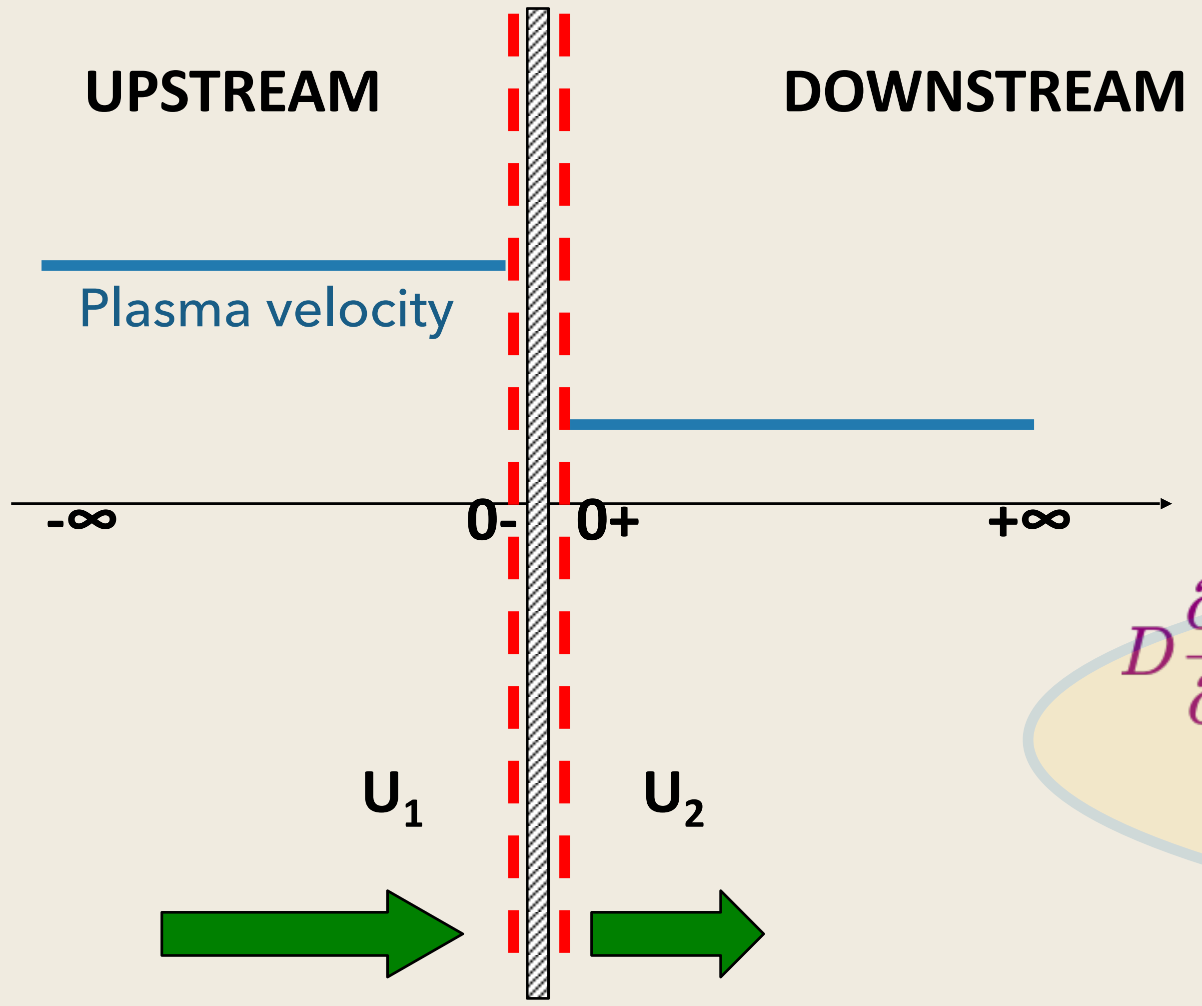

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DIFFUSION ADVECTION COMPRESSION INJECTION

$$D\frac{\partial f}{\partial x}|_{x\to 0^+} - D\frac{\partial f}{\partial x}|_{x\to 0^-} + \frac{1}{3}(u_2-u_1)p\frac{df_0}{dp} + \frac{\eta n_1 u_1}{4\pi p_{inj}^2}\delta(p-p_{inj}) \longrightarrow -u_1 f_0(p) + \frac{1}{3}(u_2-u_1)p\frac{df_0}{dp} = 0 \qquad p > p_{inj}$$

$$\boxed{f_0(p) = Kp^{-\alpha} \qquad \alpha = \frac{3u_1}{u_1-u_2} = \frac{3r}{r-1}}$$

UPSTREAM *Solution*

$$\frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x}\right] - u\frac{\partial f}{\partial x} = 0 \quad \to \quad \frac{\partial}{\partial x}\left[D\frac{\partial f}{\partial x} - uf\right] = 0$$

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Basics of the theory of DSA in SNRs

- The spectrum of accelerated particles is a power law in momentum with slope only depending on the compression factor… **for $M>>1$, $r\rightarrow 4$ and $f(p) \propto p^{-4}$**.

- Actually what really matters is the velocity of the waves scattering the particles, if they are fast enough they can make the spectrum steeper or harder than the canonical one

- The maximum energy of the accelerated particles is infinite in this simple approach due to the assumption of stationarity

- Since the spectrum, in the high energy limit, is $\sim E^{-2}$, this leads to an energetic divergence, incompatible with the basic theory

- In a time dependent approach to DSA you can estimate the maximum energy…

Failure of the basic theory of DSA: E_{max}

In the simple case of a SN exploding in the standard ISM, the Sedov phase starts at time:

$$t_{ST} \approx 430 \text{ yrs} \left(\frac{\mathrm{M_{ej}}}{\mathrm{M_\odot}}\right)^{5/6} \left(\frac{\mathrm{E_{SN}}}{10^{51}\mathrm{erg}}\right)^{-1/2} \left(\frac{\mathrm{n_H}}{0.1\mathrm{cm^{-3}}}\right)^{-1/3}$$

Requiring that the acceleration time, assuming Galactic $D(E)=3\times10^{28}\ E(\mathrm{GeV})^{1/2}$, equals the Sedov time:

$$\frac{D(E)}{v^2} = t_{ST} \rightarrow E_{max} \approx 0.2 \text{ GeV} \left(\frac{\mathrm{M_{ej}}}{\mathrm{M_\odot}}\right)^{-1/3} \left(\frac{\mathrm{E_{SN}}}{10^{51}\mathrm{erg}}\right) \left(\frac{\mathrm{n_H}}{0.1\mathrm{cm^{-3}}}\right)^{-2/3}$$

In the absence of any action making the magnetic field UPSTREAM of the shock larger and more disordered on the scale of the Larmor radius, SNR can accelerate at uselessly low energies

Modern Theory of DSA in SNRs

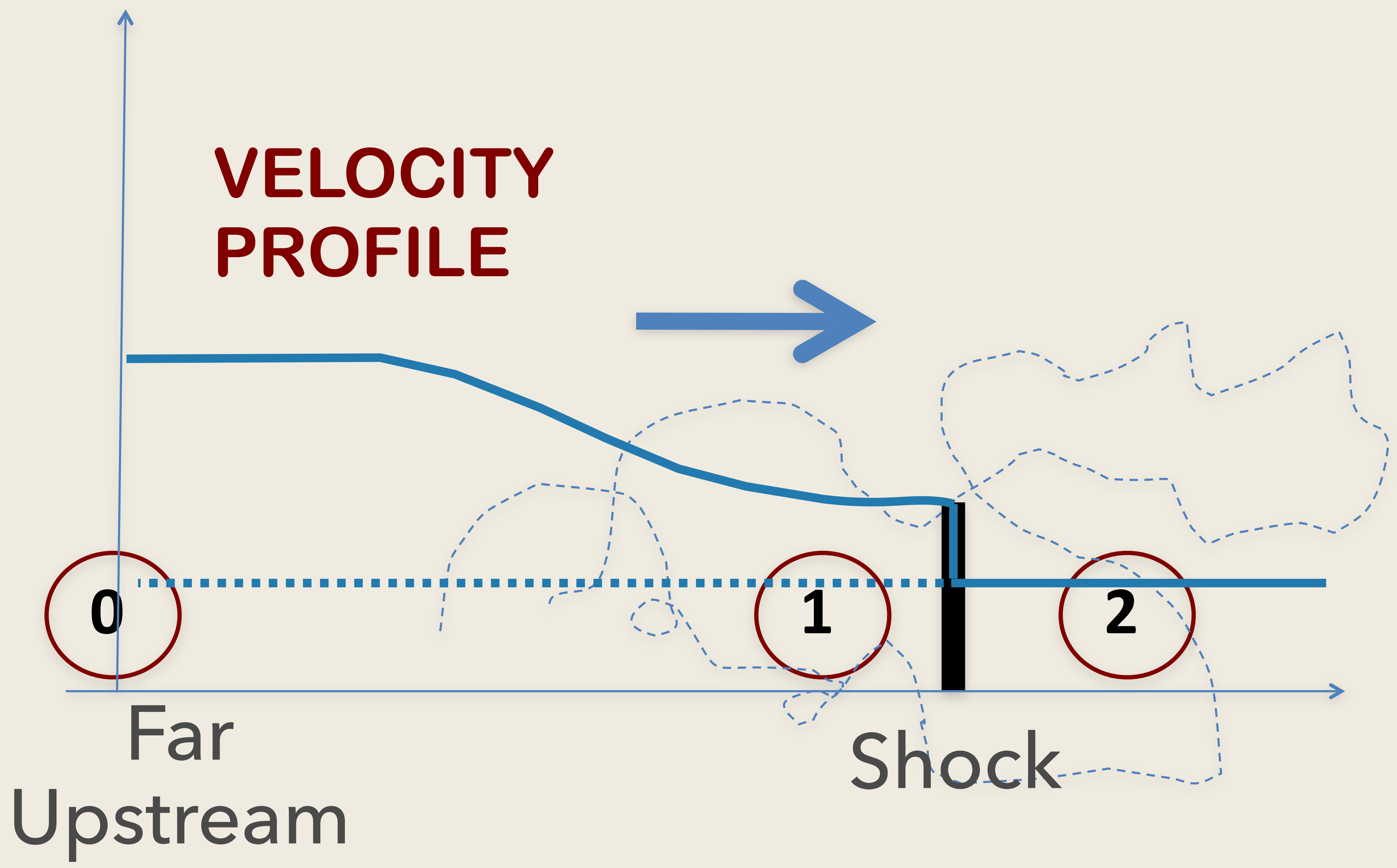
These theories aim at a description of the interplay between accelerated particles and the accelerator itself – the theory becomes non-linear and often untreatable analytically, but Physics is clear

Dynamical Reaction of the Accelerated Particles on the Accelerator

Production of magnetic field perturbations by excitation of plasma instabilities mediated by cosmic rays

Spectrum of Accelerated Particles and Maximum energy

Dynamical Reaction of Cosmic Rays



$$P_g(x) + \rho u^2 + P_{CR} = P_{g,0} + \rho_0 u_0^2$$

$$\frac{P_g}{\rho_0 u_0^2} + \frac{u}{u_0} + \frac{P_{CR}}{\rho_0 u_0^2} = \frac{P_{g,0}}{\rho_0 u_0^2} + 1$$

$$\frac{u}{u_0} \approx 1 - \xi_{CR}(x)$$

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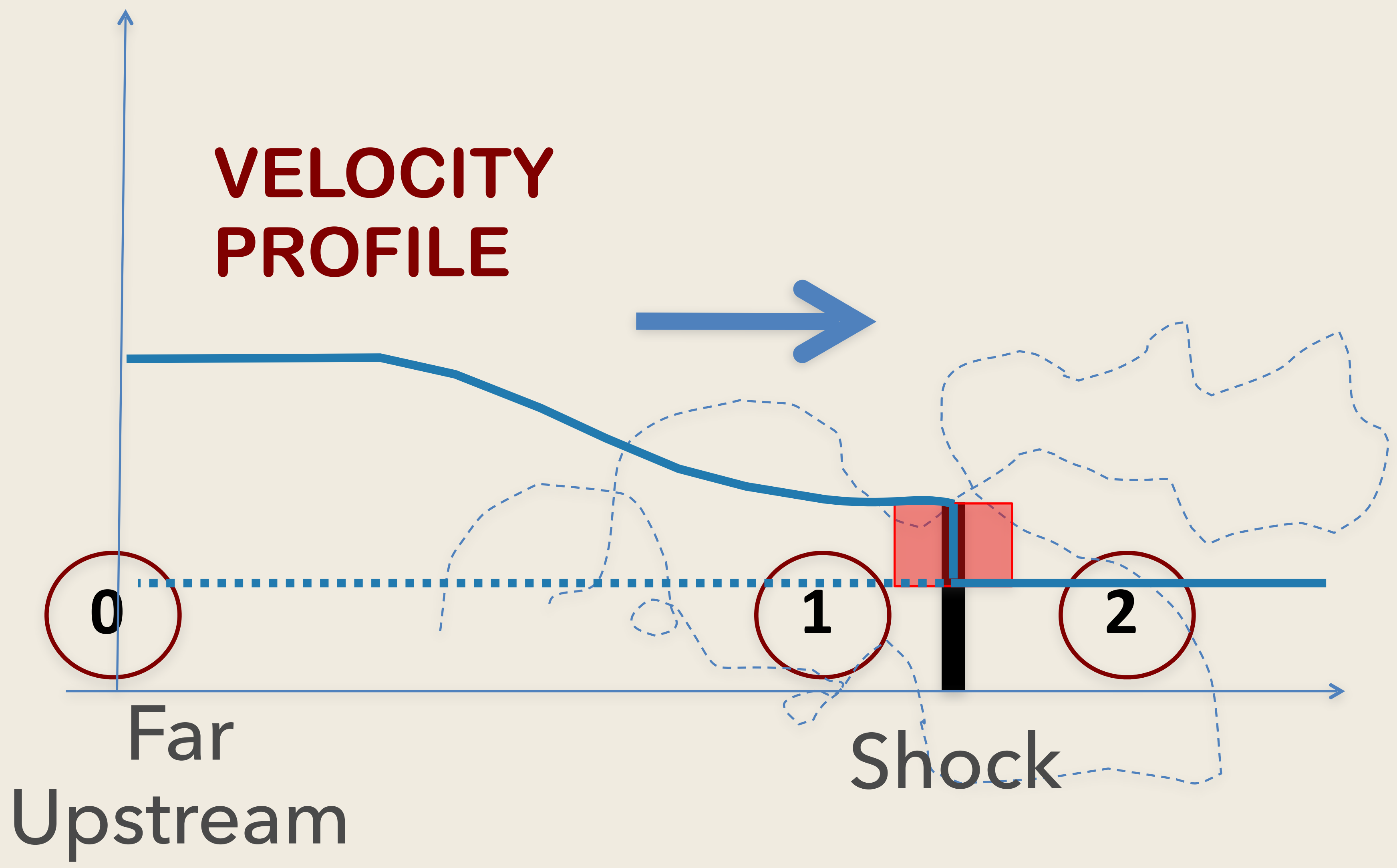

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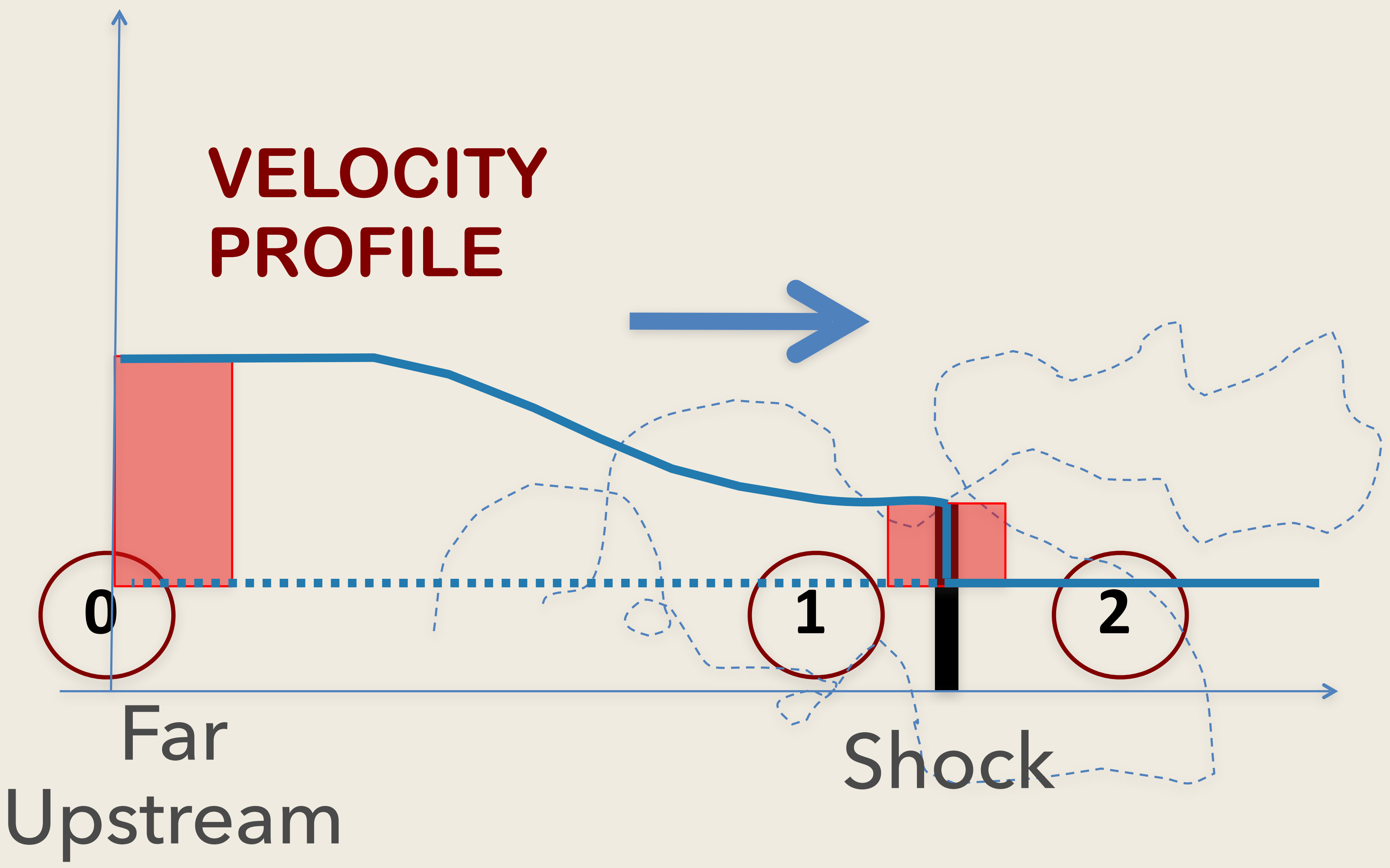

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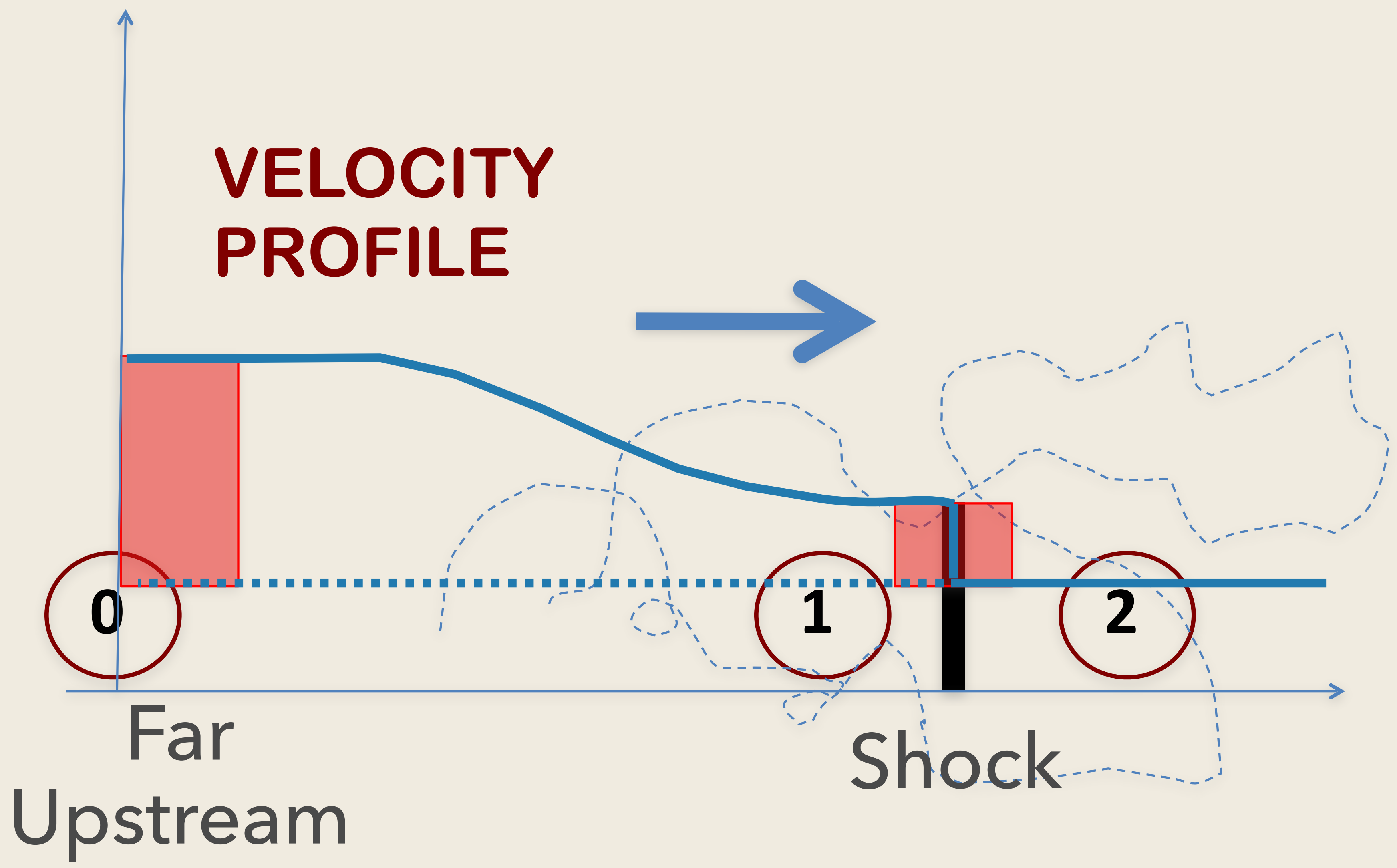

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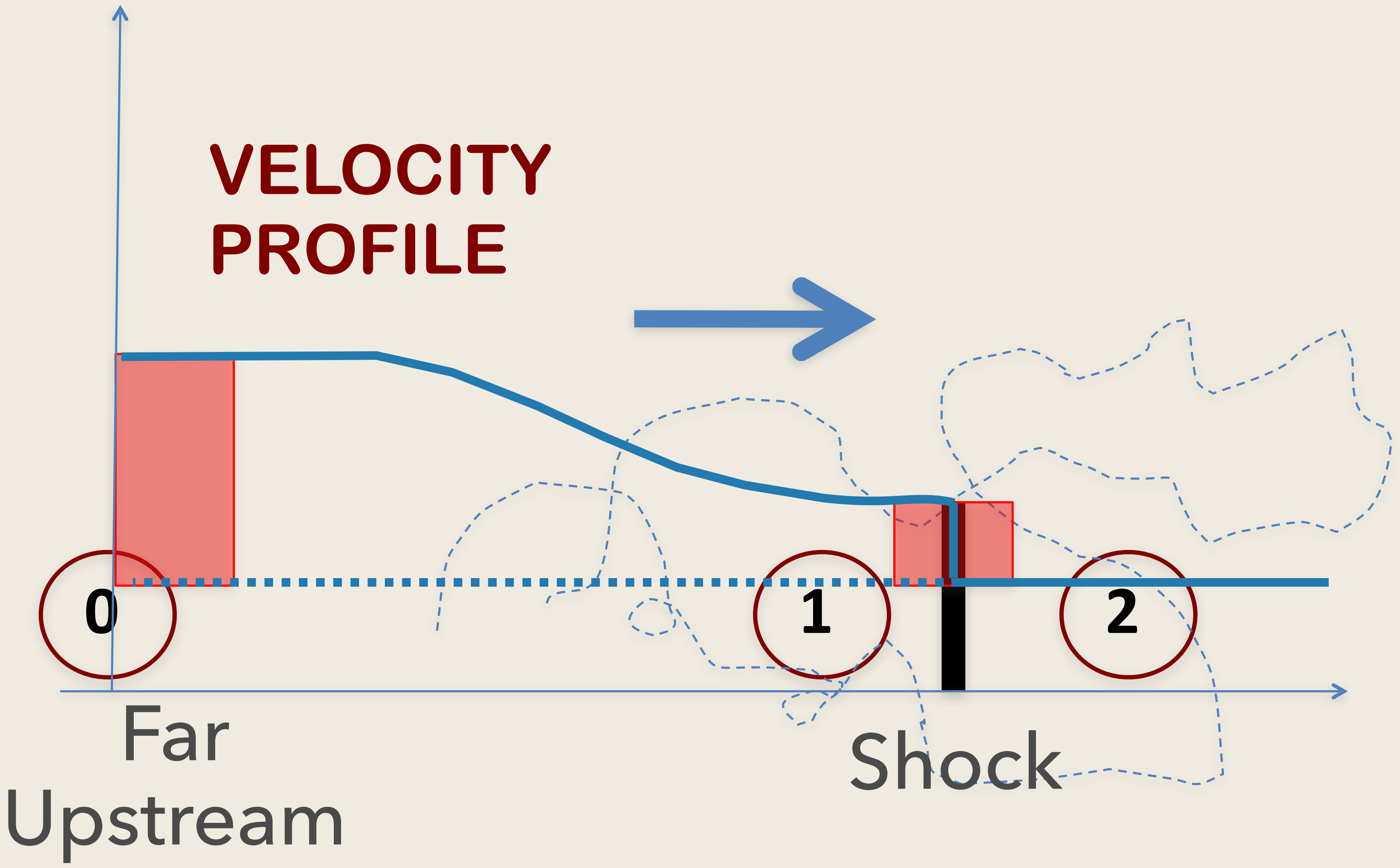
- Spectra are not perfect power laws (concavity)
- Gas behind the shock is cooler because part of the energy has been used to energise CR

Dynamical Reaction of Cosmic Rays



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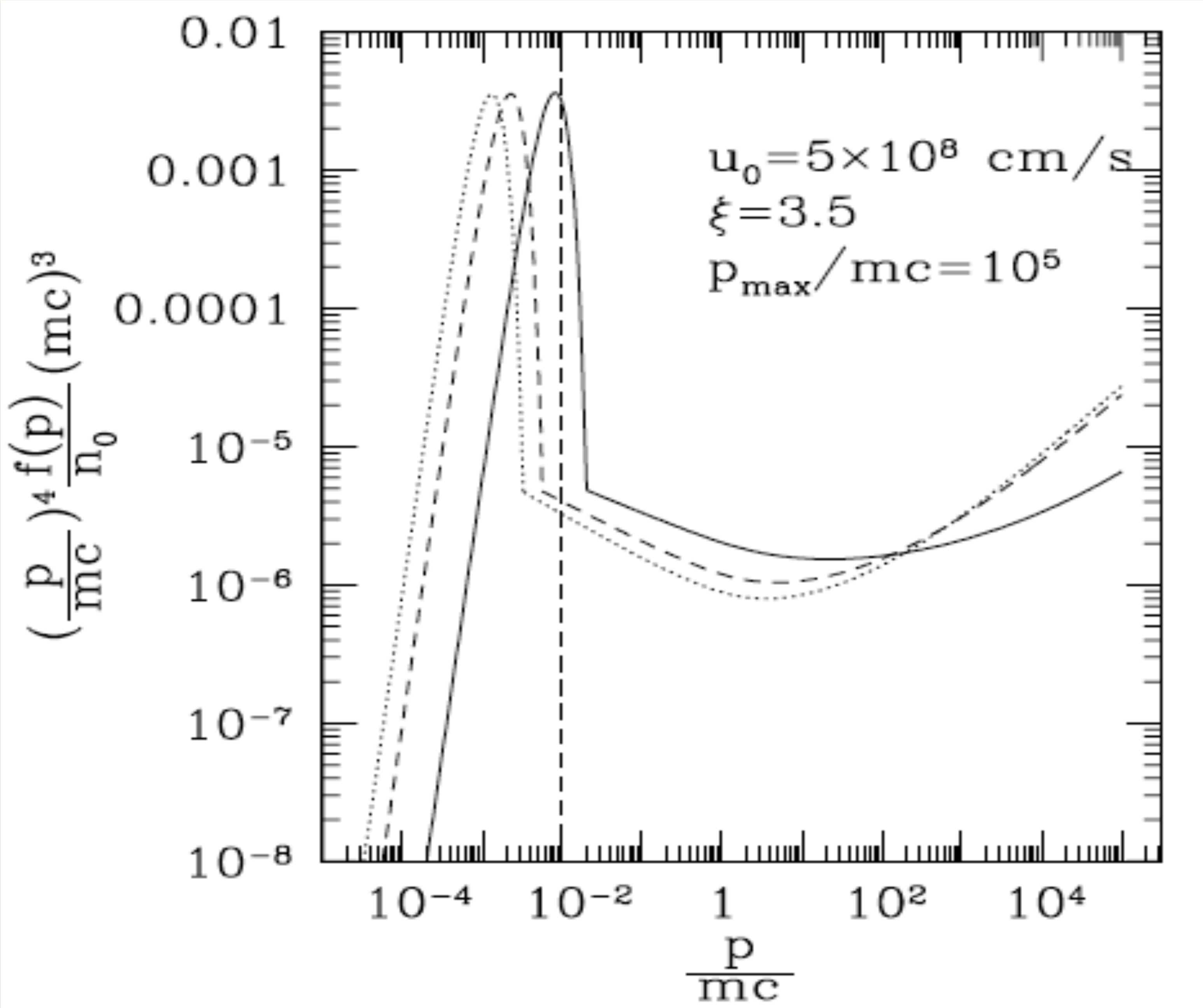

Malkov 2001, PB 2002, PB, Gabici & Vannoni 2005,…

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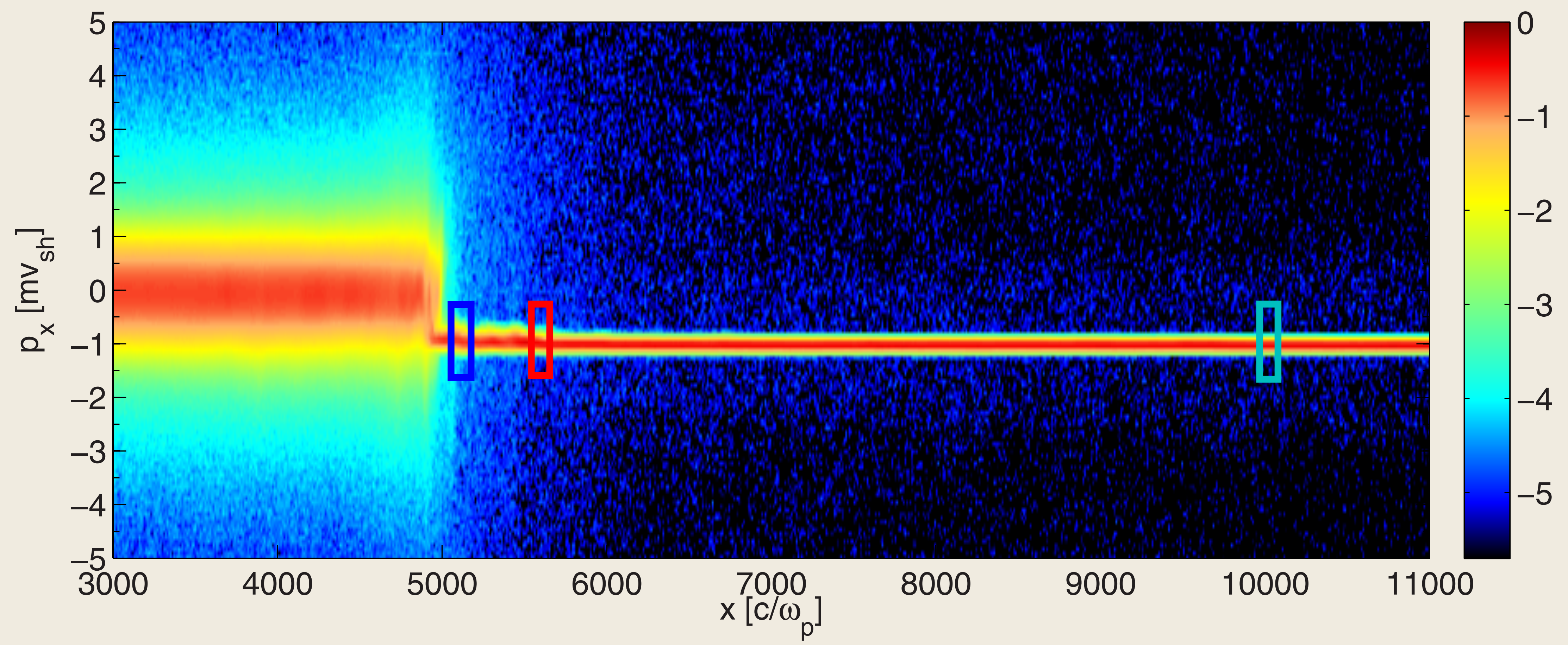
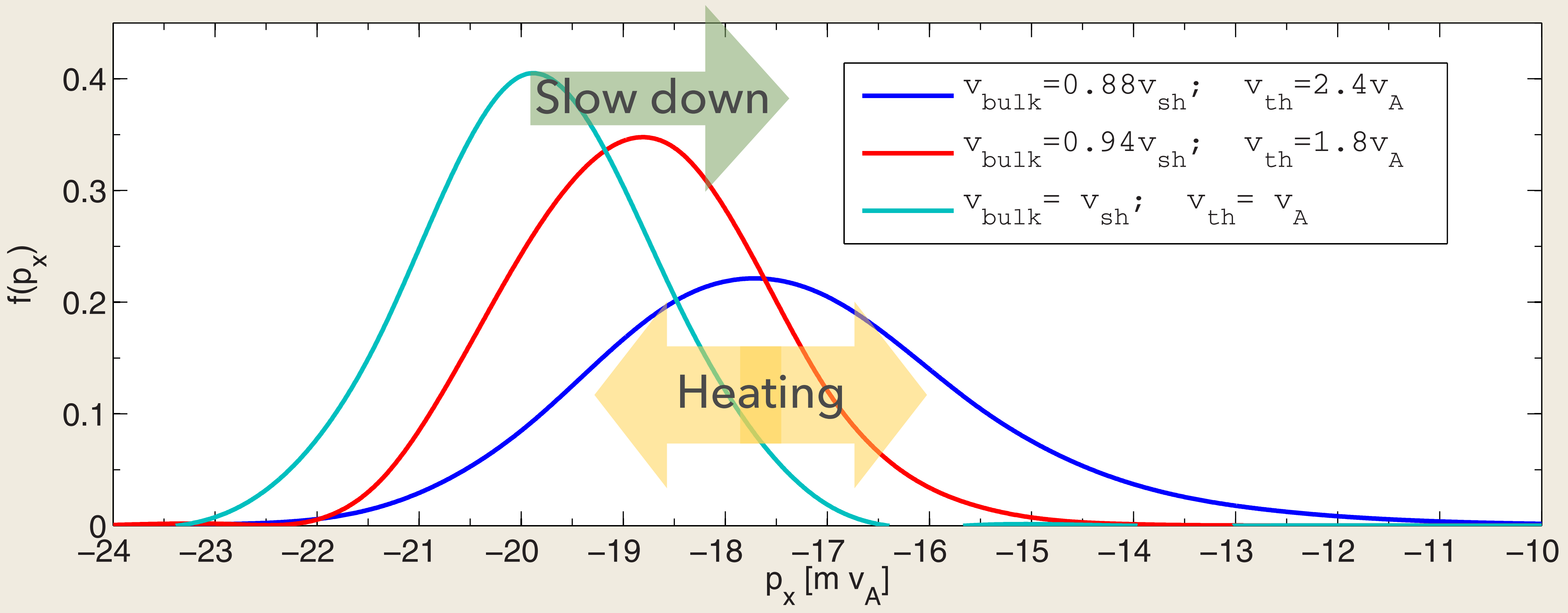


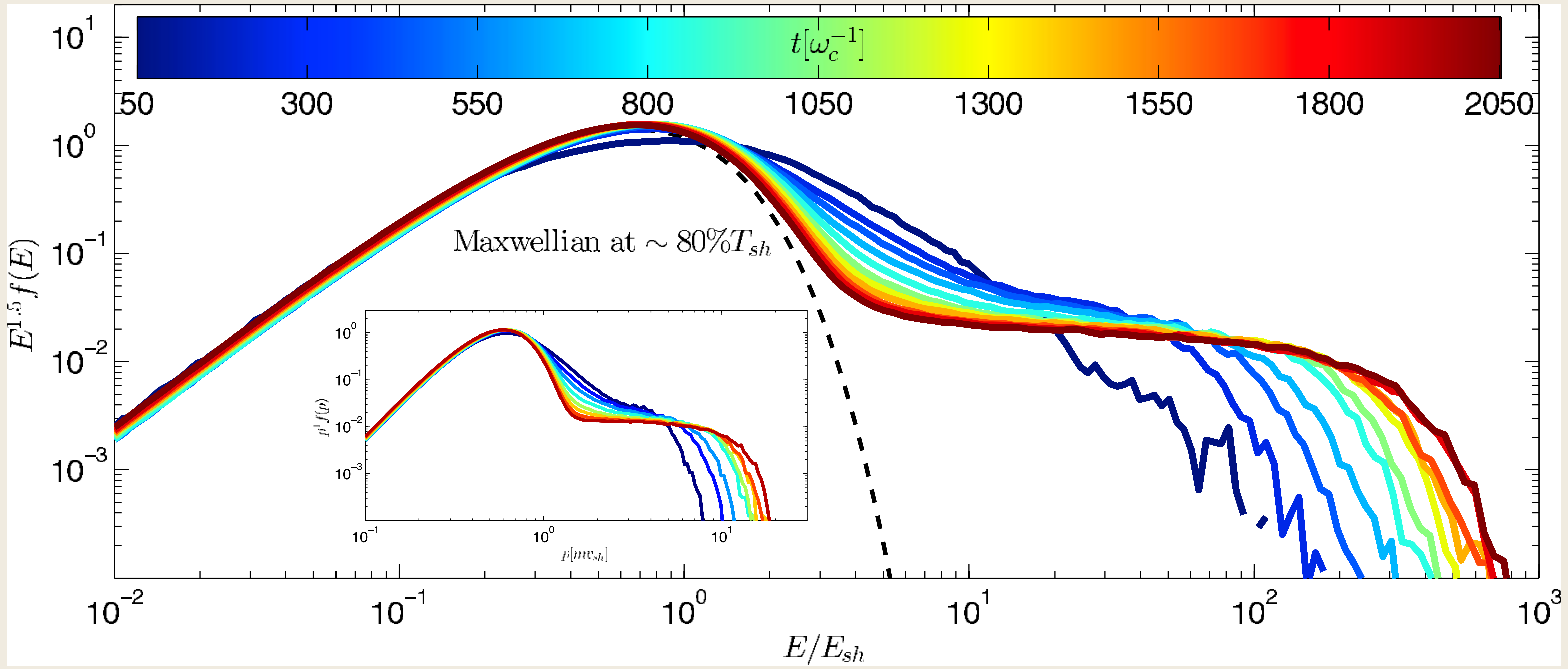


Caprioli & Spitkovsky 2014

Hybrid simulations now confirm that the shock is modified by the accelerated particles…

They also confirm that some level of heating occurs also upstream, resulting in lower Mach number and a reduced curvature

As a result: spectra close to power laws and efficiency of order 10%



Magnetic Field Amplification (MFA)

The single most important non linear effect that makes DSA interesting if the turbulent amplification of magnetic fields induced by the accelerated particles

The necessary condition for the process to be important for acceleration is that enough power is created in magnetic fields on the scale of the gyration radius of the particles you want to accelerate

The main channels that have been investigated, both analytically and numerically, are:

RESONANT STREAMING INSTABILITY
Kulsrud & Pearce 1969, Bell 1978, Lagage & Cesarsky 1982

NON RESONANT HYBRID STREAMING INSTABILITY
Bell 2004, Amato & PB 2009

ACOUSTIC INSTABILITY AND TURBULENT AMPLIFICATION
Drury & Falle 1986, Berezniak, Jones & Lazarian 2012

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MFA through Resonant Streaming Instability

This is a phenomenon of the utmost importance for both Galactic CR transport and particle acceleration at shocks…

It requires that you have particles drifting at $v_D > v_A$ – **in the case of DSA $v_D \sim v_{shock} >> v_A$**

A small perturbation δB grows exponentially with a growth rate that can be easily estimated as:

$$\Gamma_{res}(k) = \frac{n_{CR}(>E)}{n_i}\frac{v_{shock}}{v_A}\Omega_{cyc} = \frac{\xi_{CR}}{\Lambda} M_A \left(\frac{v_{shock}}{c}\right)^2 \frac{c}{r_L(E)}$$

Assuming a spectrum E^{-2}

$$M_A = \frac{v_{shock}}{v_A}$$

Alfvenic Mach number of the Shock

$$\Lambda = \ln(E_{max}/m_p c^2) \sim 10$$

…and the instability grows on scales $k \sim 1/r_L(E)$ —— *Once δB becomes of order B_0 (pre-existing field) the process stops!*

Imposing that the acceleration time equals the beginning of Sedov-Taylor:

$$\boxed{E_{max} \approx 20\ TeV \left(\frac{v_{shock}}{10^9\ \mathrm{cm/s}}\right)^2 \left(\frac{B_0}{3\mu G}\right)\left(\frac{T_{Sedov}}{150\ \mathrm{yrs}}\right)}$$

Lagage & Cesarsky 1982

Some useful considerations

Adopting Quasi-Linear Theory as a benchmark, one can write the diffusion coefficient as:

$$D(E) = \frac{1}{3} v \frac{r_L(E)}{F(k)} |_{k=1/r_L} \qquad F(k) = \left(\frac{\delta B(k)}{B_0}\right)^2$$

In the presence of resonant streaming instability, F(k)= constant if the spectrum of accelerated particles is ~E^{-2}, so that diffusion is linear in E (Bohm diffusion)

If one requires that E_{max}=1 PeV it is easy to infer that:

$$F(k)|_{k=1/r_L(1PeV)} \approx 140 \left(\frac{v_{shock}}{10^9 \text{ cm/s}}\right)^{-2} \left(\frac{B_0}{3\mu G}\right)^{-1} \left(\frac{T_{Sedov}}{150 \text{ yrs}}\right)^{-1} >> 1$$

...namely for a SNR to be a PeVatron, one cannot be in the regime of resonant streaming instability!

The Bell Instability
[a.k.a. Non resonant Hybrid Instability]

This instability was discovered in 2004 by T. Bell and attracted immediately much attention, for several reasons:

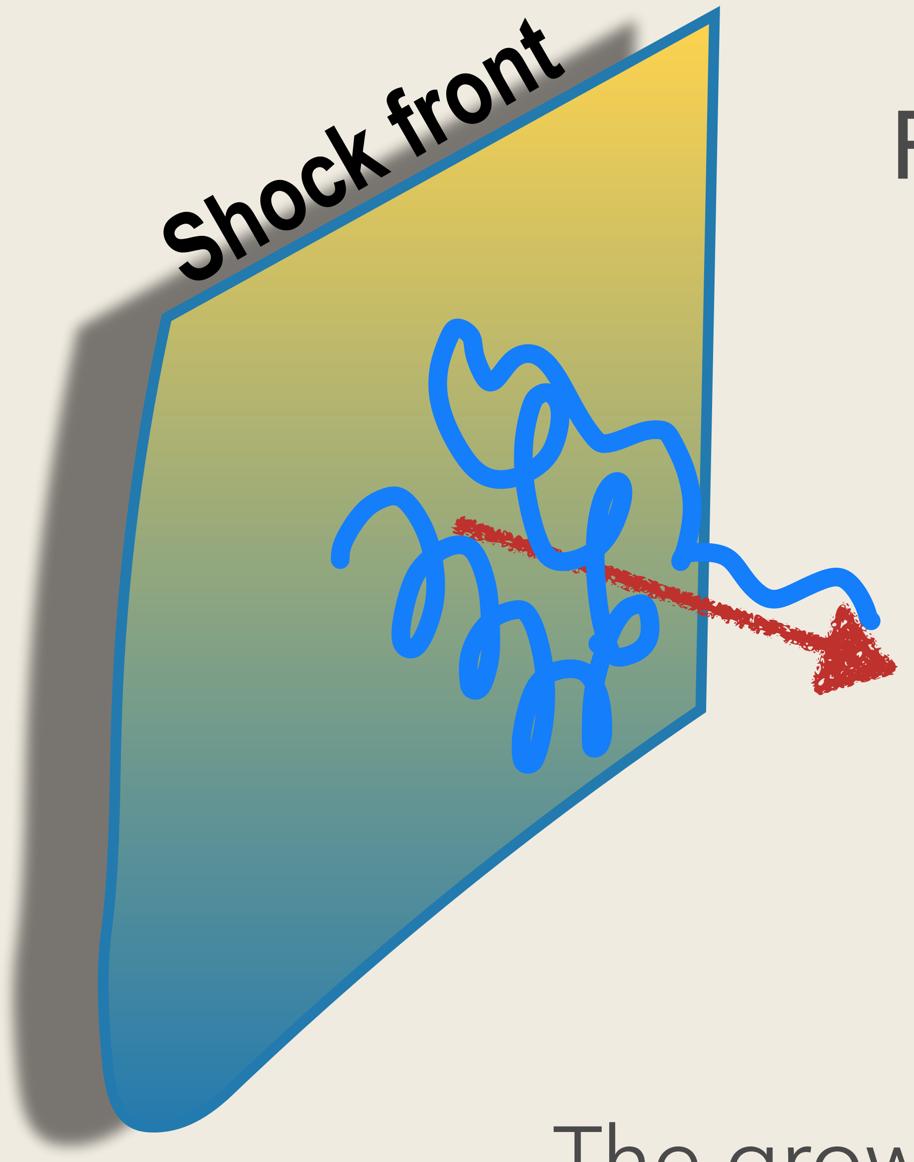
1) *Under certain conditions (see below) it grows much faster than the RSI discussed earlier*
2) *The level of δB reached seems to compare well with those inferred from X-ray morphology*
3) *It is potentially capable to allow acceleration to much larger energies*

Reasons of concern…

a) *it develops on very small scales compared with the Larmor radius – in the beginning no scattering*
b) *it grows the "wrong" polarisation in the linear regime… again, in the beginning no scattering*

The Bell Instability

[a.k.a. Non resonant Hybrid Instability]



Protons of given energy upstream of the shock represent a current $J_{CR}=n_{CR}(>E)\ e\ v_{shock}$

The background plasma cancels the CR positive current with a return current created by a slight relative motion between thermal electrons and protons, thereby creating a two stream instability that grows the fastest on scales $l \sim 1/k_{max}$ where

$$k_{max} B_0 = \frac{4\pi}{c} J_{CR}$$

The growth occurs at a rate that can be approximated as: $\Gamma_{max} = k_{max} v_A$

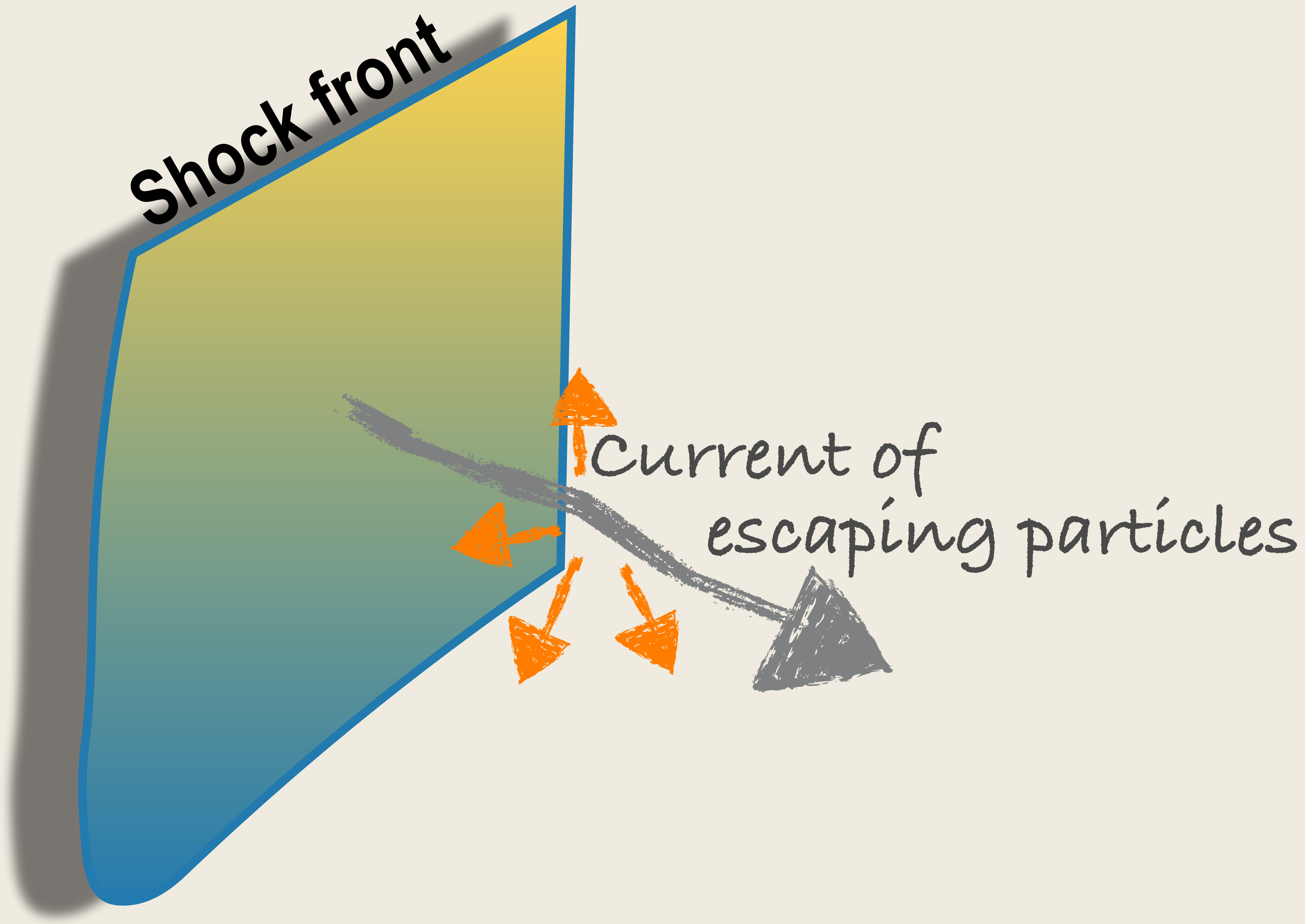
The condition for this instability to develop is that $k_{max}>1/r_L(E)$, which is equivalent to requiring that:

$$n_{CR}(>E) E \frac{v_{shock}}{c} > \frac{B_0^2}{4\pi} \quad \Rightarrow \quad M_A > \left(\frac{\Lambda}{\xi_{CR}} \frac{c}{v_{shock}}\right)^{1/2} \approx 500 \left(\frac{\xi_{CR}}{0.1}\right)^{-1/2} \left(\frac{v_{shock}}{10^9\ \mathrm{cm/s}}\right)^{-1/2}$$

for E^{-2} spectrum

Only works in very young SNR with large Alfvenic Mach number

Saturation and Maximum Energy in SNR



The current of escaping particles acts as a force on the background plasma in the direction perpendicular to both the current and the amplified field:

$$\rho \frac{dv}{dt} \sim \frac{1}{c} J_{CR} \delta B \longrightarrow \Delta x \sim \frac{J_{CR}}{c\rho} \frac{\delta B(0)}{\gamma_{max}^2} exp(\gamma_{max} t)$$

The current is weakly disturbed until the transverse displacement becomes of order the Larmor radius in the amplified field…this condition leads to the following saturation condition:

$$\frac{\delta B^2}{4\pi} = n_{CR}(> E) E \frac{v_{shock}}{c} \approx \frac{\xi_{CR}}{\Lambda} \rho v_{shock}^2 \frac{v_{shock}}{c}$$ independent on scale (Bohm Diff)

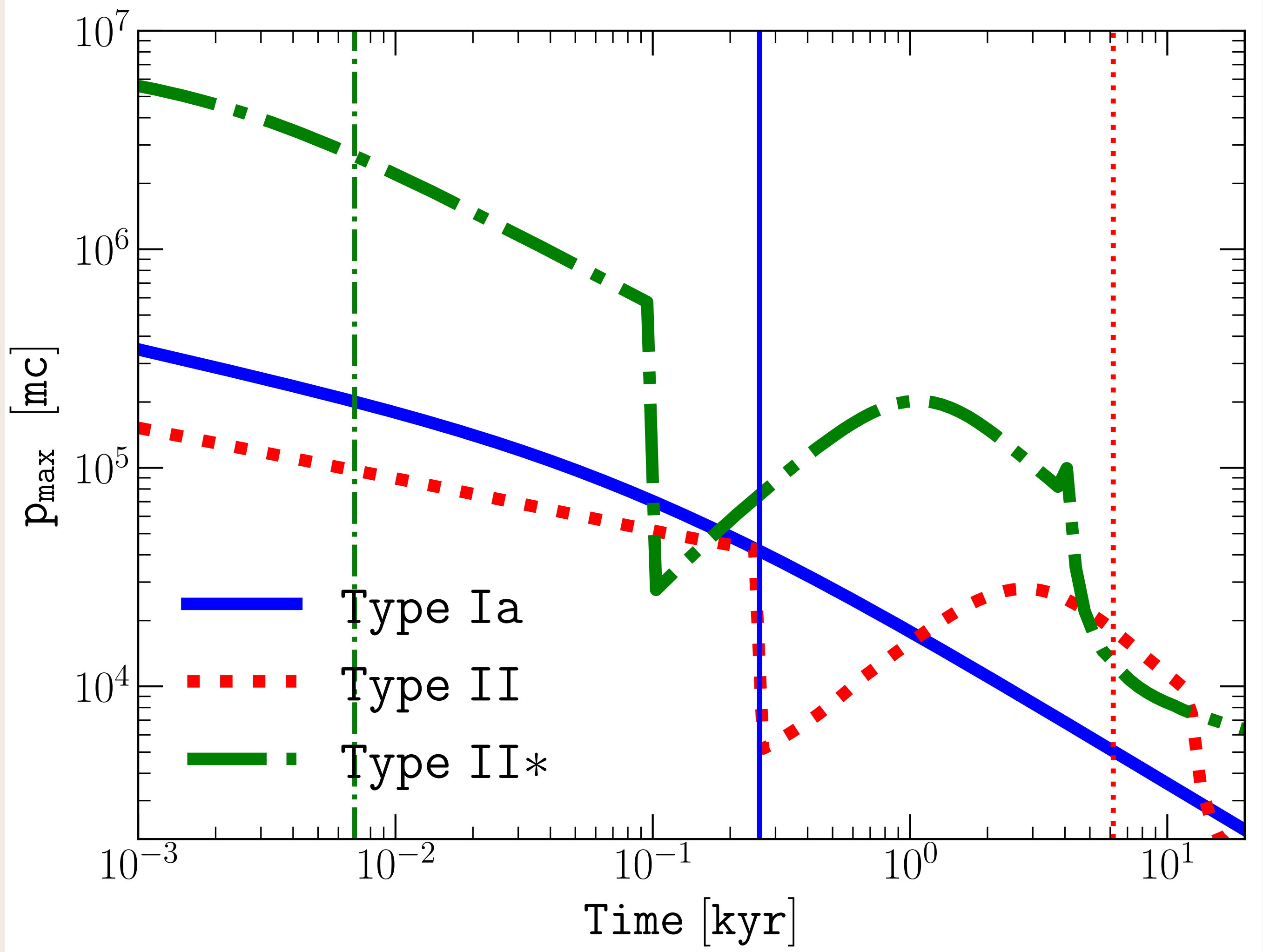
The maximum energy at time T is estimated by requiring that the growth time of the instability equals ~T/5:

$$E_{max} \approx \frac{\xi_{CR}}{10\Lambda} \frac{\sqrt{4\pi\rho}}{c} e R_{shock}(T) v_{shock}^2(T)$$

The time dependence of R_{shock} and v_{shock} is different depending on the type of SNR

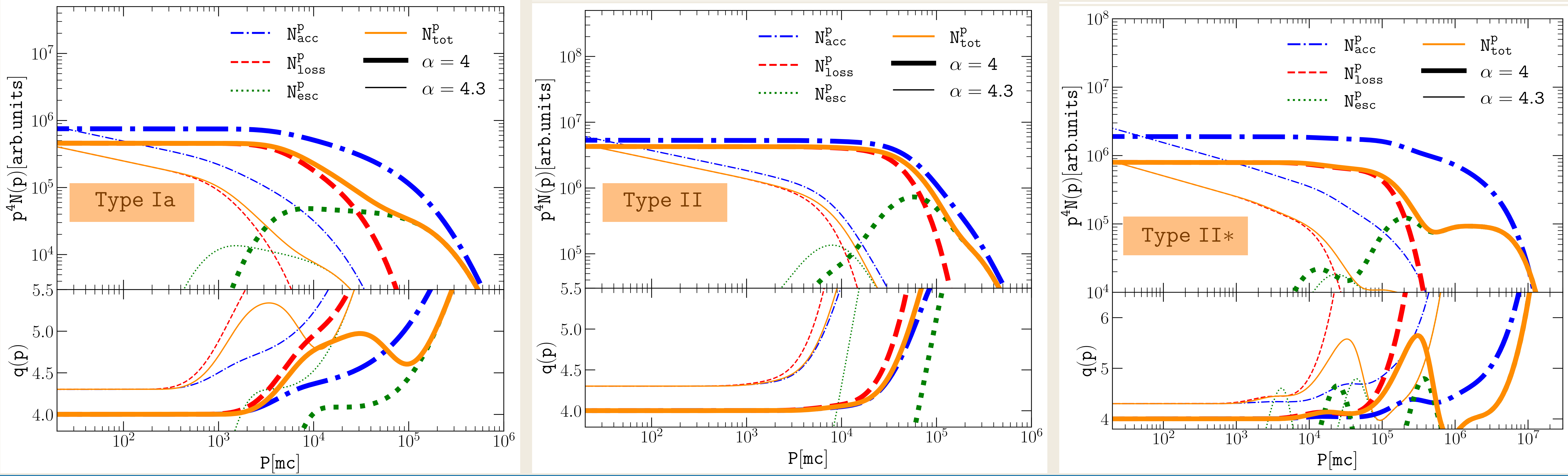
Maximum Energy of CR in SNR

Cristofari, PB & Amato 2020



CR accelerated at SNR are liberated in two stages:

1) particles leave the remnant at each time t with energy $E_{max}(t)$
2) the particles trapped downstream (lower E) lose energy adiabatically and escape at the end of the SNR life
3) The time integrated spectrum drops at an **effective E_{max} that is the maximum energy reached at the beginning of Sedov**
4) The cut is NOT exponential, it's a power law reflecting time dependence in the ejecta dominated phase



Cristofari, PB & Caprioli 2022

CR in SNR: the role of escaping particles

The escaping particles play a crucial role in all aspects of both acceleration and observability of SNR:

1) Escaping particles are the ones that guarantee the excitation of the Bell instability far upstream so that high energies can be achieved
2) At each given time t the only particles that may have escaped the acceleration region are the ones with $E>E_{max}(t)$
3) …But the spectrum of the particles that escaped before the Sedov phase is insignificant, **typically $\sim E^{-5}$**.
4) **THIS IS THE REASON WHY, NO MATTER HOW HIGH IS E_{max} AT EARLY TIMES, THE SPECTRUM HAS A SUPPRESSION AT THE E_{max} AT THE BEGINNING OF SEDOV PHASE – *This is what we call the Maximum Energy*.**
5) The spectrum of escaping particles has also a LOW ENERGY cutoff, at the maximum energy at the end of the Sedov phase

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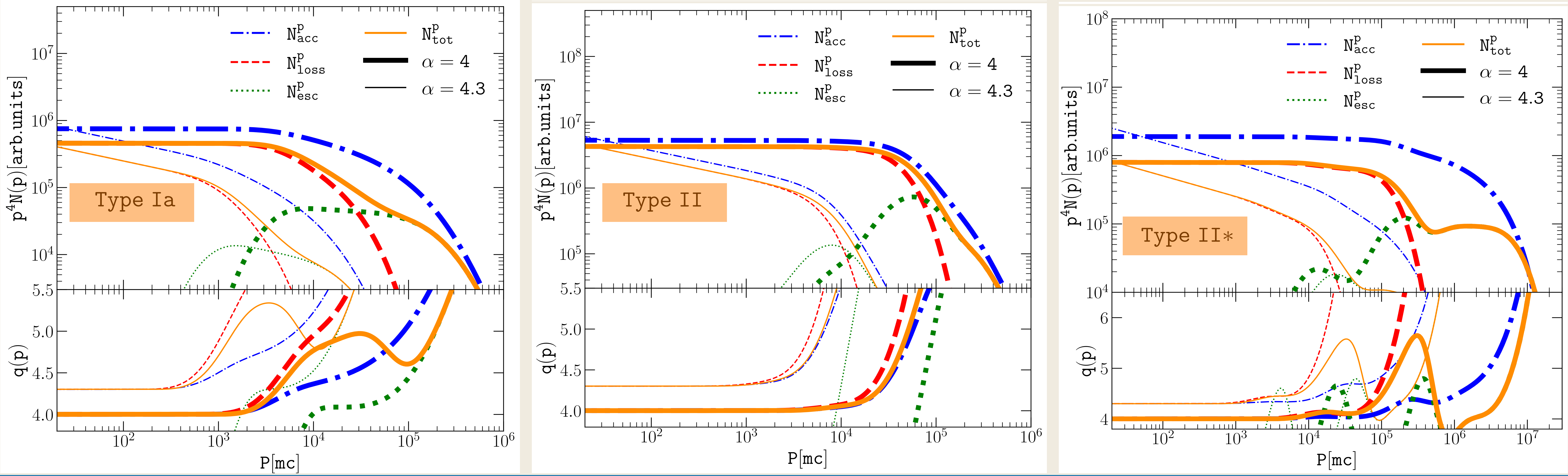
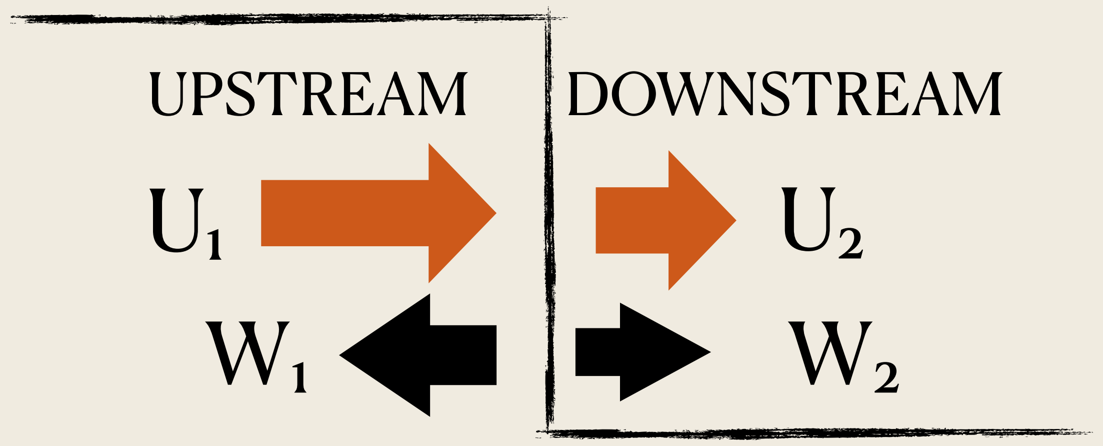


Cristofari, PB & Caprioli 2022

Effect of MFA on the Spectrum of accelerated particles

- THE ACTION OF COSMIC RAYS IS IN GENERAL OF INCREASING THE COMPRESSION FACTOR AT THE SHOCK DUE TO THE CHANGE OF ADIABATIC INDEX (AND OTHER EFFECTS, **PRECURSOR**) —> SPECTRUM SHOULD BECOME HARDER THAN STANDARD DSA

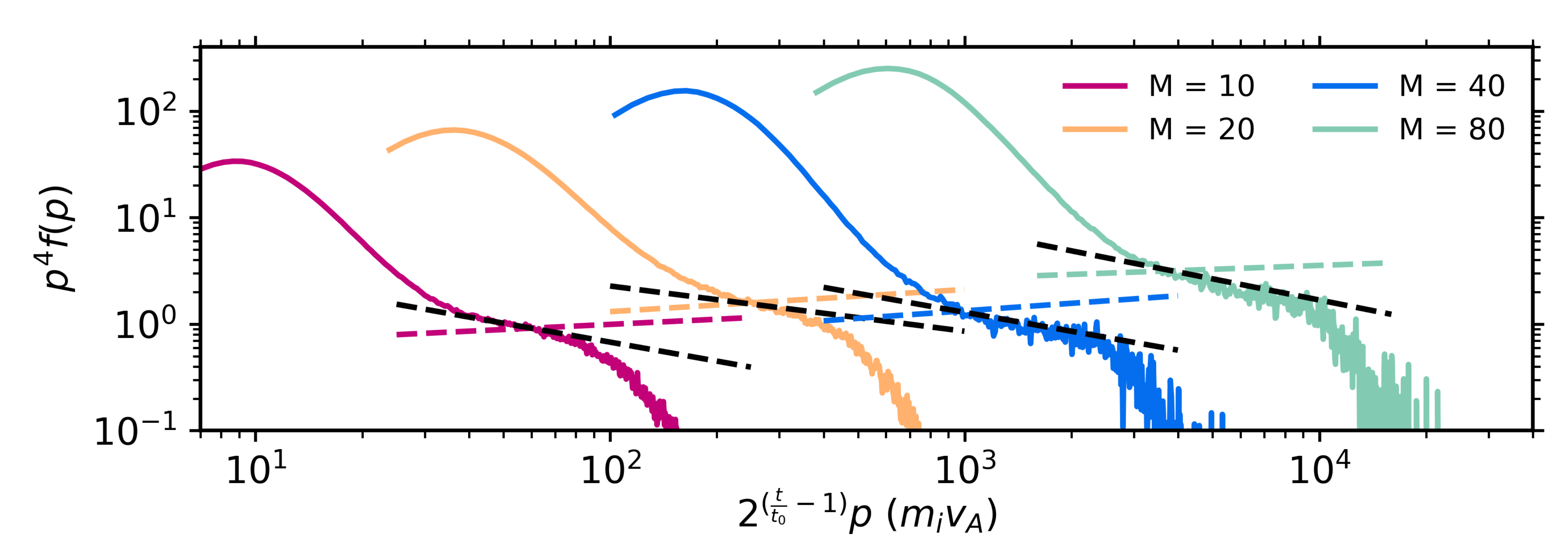
- HOWEVER, THE AMPLIFICATION OF MAGNETIC FIELD MAKES ANOTHER EFFECT APPEAR:



THE VELOCITY OF THE WAVES UPSTREAM IS $U_1 - W_1 \approx U_1$

IN HYBRID SIMULATIONS THE DOWNSTREAM WAVES ARE SEEN TO MOVE IN THE SAME DIRECTION AS THE PLASMA, WITH APPROXIMATELY THE ALFVEN SPEED IN THE AMPLIFIED FIELD (POSTCURSOR)

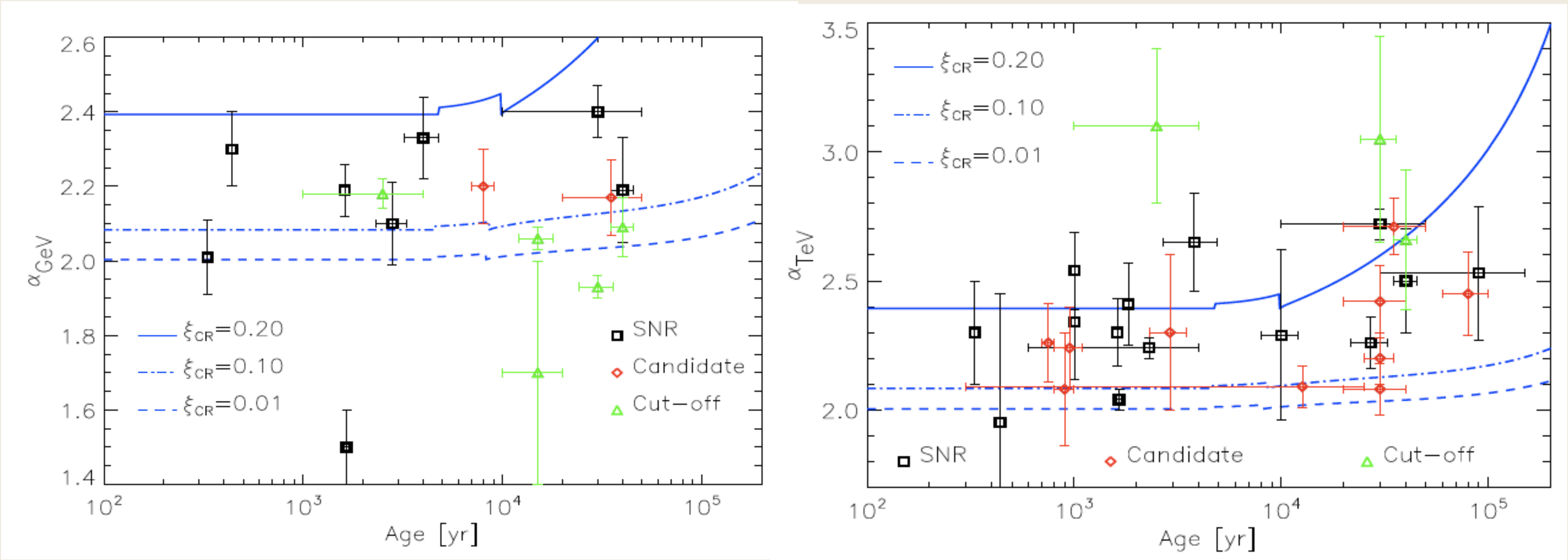
Haggerty & Caprioli 2020; Caprioli, Haggerty & PB 2020



$$W_2 \approx \frac{\delta B}{\sqrt{4\pi\rho}} = \alpha U_2 \quad \Rightarrow \quad q \approx \frac{3R}{R-1-\alpha}$$

THE SPECTRUM BECOMES STEEPER

ISSUES WITH SPECTRA INSIDE SNR



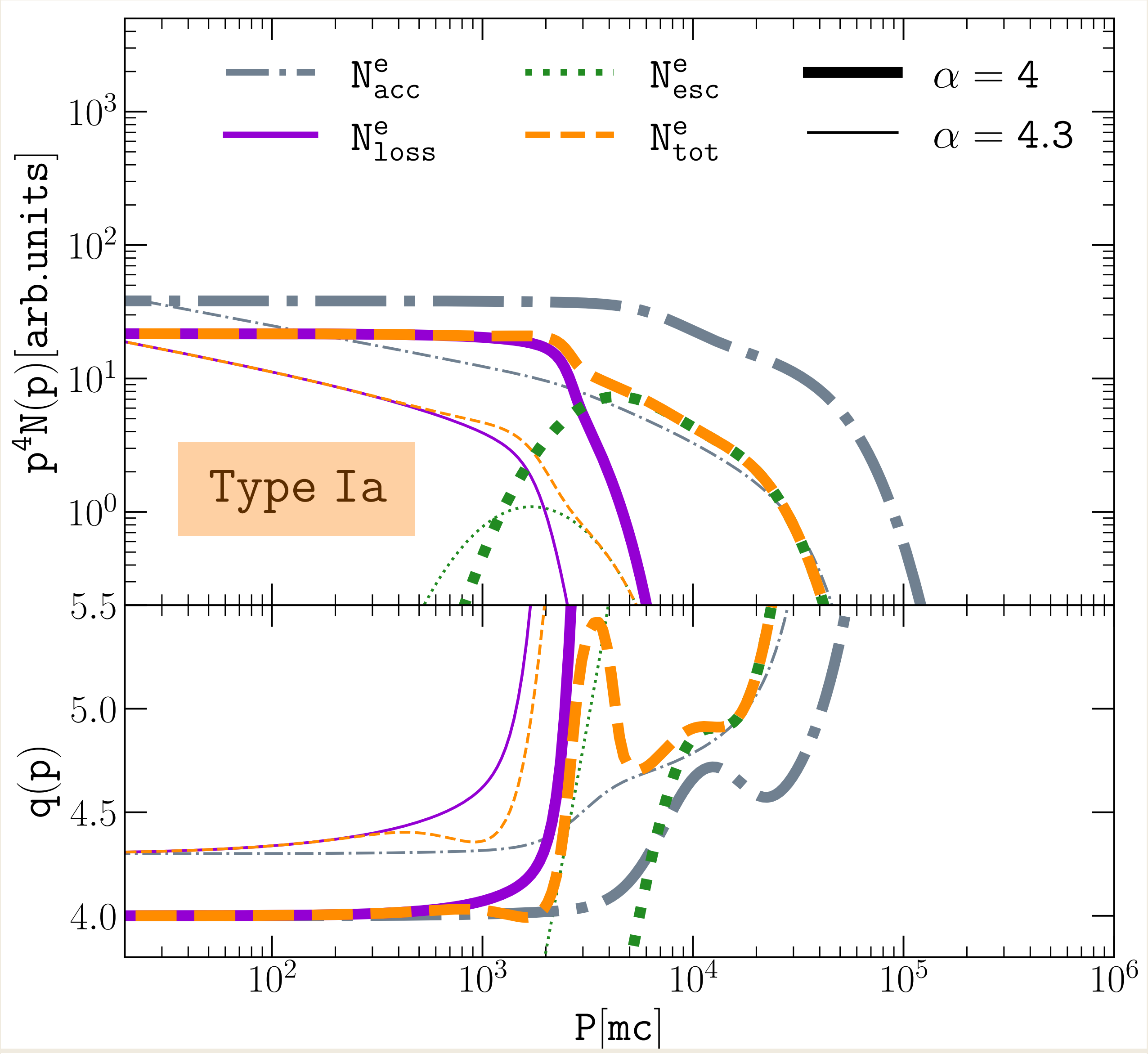
Caprioli 2011

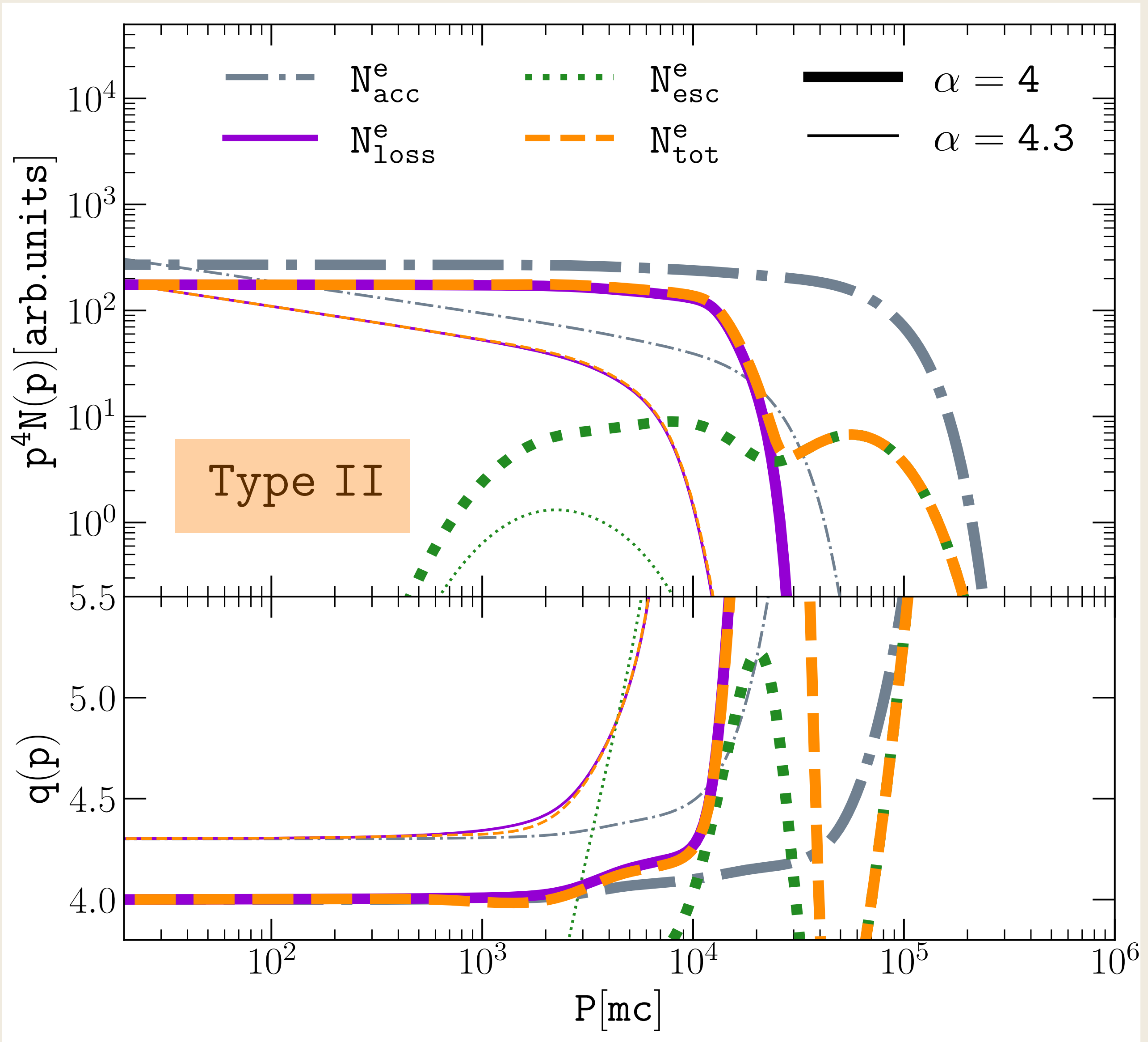
BOTH GAMMA RAY OBSERVATIONS AND GALACTIC CR TRANSPORT SUGGEST THAT THE SPECTRUM CONTRIBUTED BY SNR IS STEEPER THAN E^{-2} BUT THIS SEEMS INCOMPATIBLE WITH THEORETICAL EXPECTATIONS!

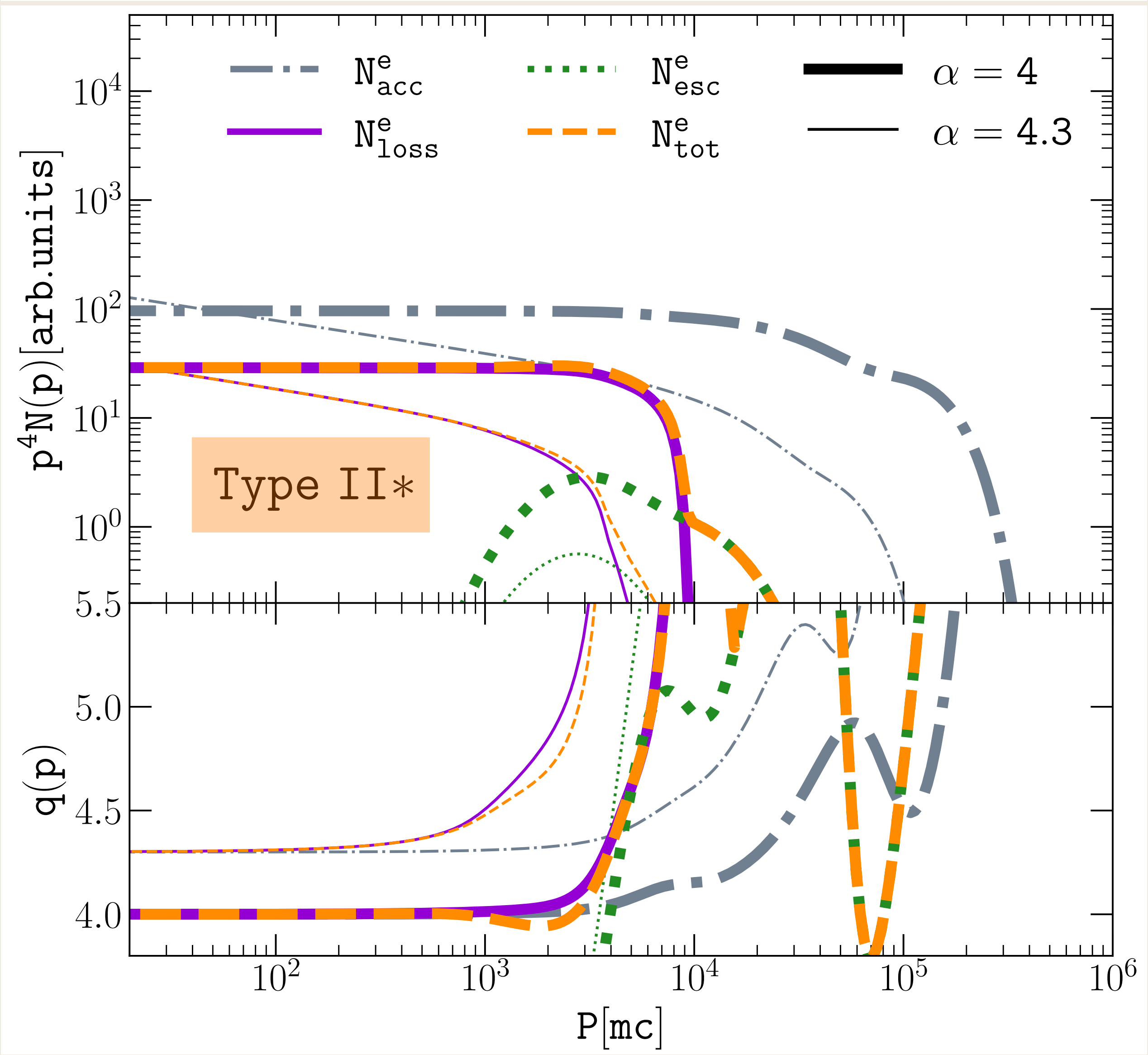
THESE SUBTLE FEATURES ARE SENSITIVE TO THE MICROPHYSICS...

Spectrum of electrons from SNR

- It is well known that Galactic CR require the spectrum of electrons and protons at source to be different (steeper electrons)
- The efficient acceleration of protons implies that CR must excite large magnetic fields at the shock and in such fields electrons lose a small fraction of energy

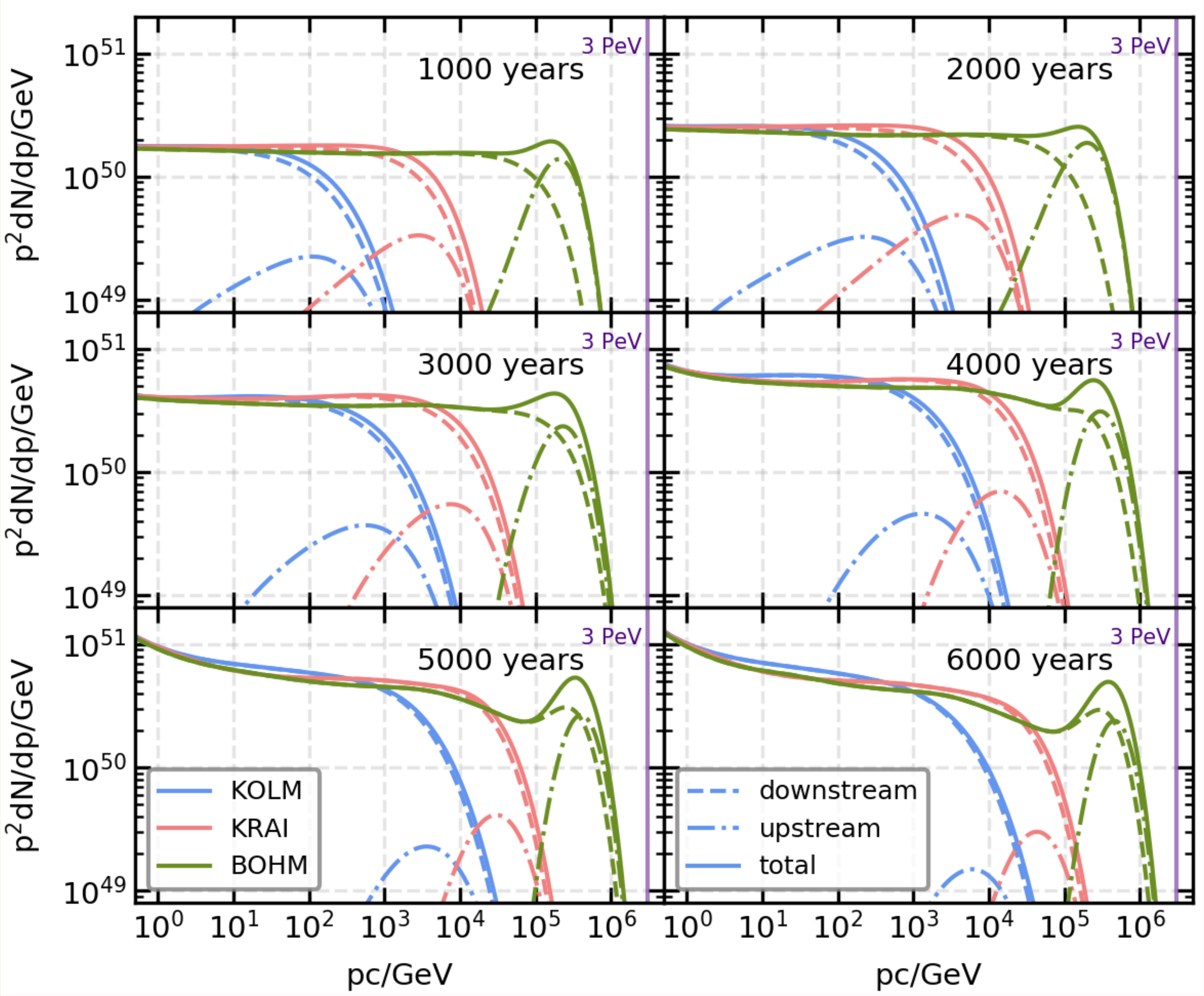






Cristofari, PB & Caprioli 2022

The case of a SNR in a star cluster



- A SNR that explodes in a star cluster is different mainly because of the environment where it occurs
- The shock propagates in a medium that is the collective wind of the cluster and its turbulence
- No large self-generation expected with the possible exception of kinematic dynamo
- The highest energy remains somewhat below PeV even with Bohm diffusion
- The only exception is a very energetic SNR

Schush, PB & Brose 2025

The case of *Cas-A*

This is the remnant of a SN explosion occurred 340 years ago. It is a core collapse that exploded in the wind of its red giant progenitor.

It is thought to have entered the Sedov phase about 150 years after explosion, namely ~200 years ago

The maximum energies can be estimated as follows:

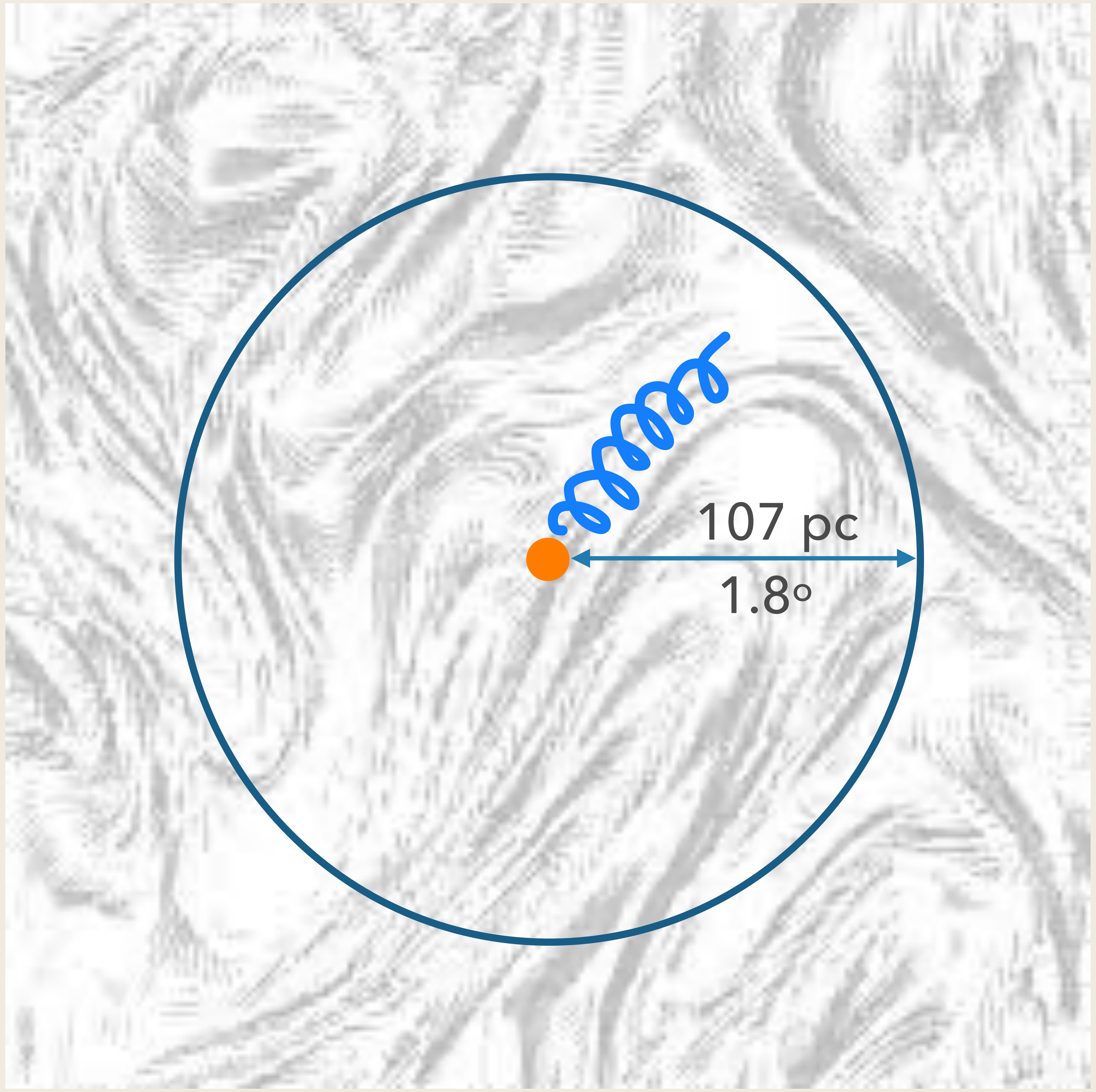
$$E_{max}(t) \approx \frac{e\xi_{CR}}{5c\Lambda}\sqrt{\frac{\dot{M}}{v_w}}v_{shock}^2(T) = \begin{cases} 500TeV\left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{\dot{M}}{10^{-5}\mathrm{M}_\odot/\mathrm{yr}}\right)^{1/2}\left(\frac{v_w}{10km/s}\right)^{-1/2} & \text{At the beginning of ST} \\ 290TeV\left(\frac{\xi_{CR}}{0.1}\right)\left(\frac{\dot{M}}{10^{-5}\mathrm{M}_\odot/\mathrm{yr}}\right)^{1/2}\left(\frac{v_w}{10km/s}\right)^{-1/2} & \text{At the present time} \end{cases}$$

Only particles with energy between ~290 TeV and ~500 TeV can have escaped Cas A at present, and these are the only particles that can produce gamma rays from the region around this remnant –> ***The CR spectrum around Cas A is almost monochromatic***

Waiting longer, the spectrum of the escaped particles would become E^{-2}, almost independent of the spectrum inside the SNR!

The spectrum of CR currently inside the remnant is basically cut off at <290 TeV, which corresponds to a gamma ray cut at <30 TeV

The case of *Cas-A*



If D(E) in the region around CasA is the Galactic one, the path length for diffusion is:

$$\lambda(E) \approx 1kpc \left(\frac{E}{PeV}\right)^{1/2} >> L_c$$

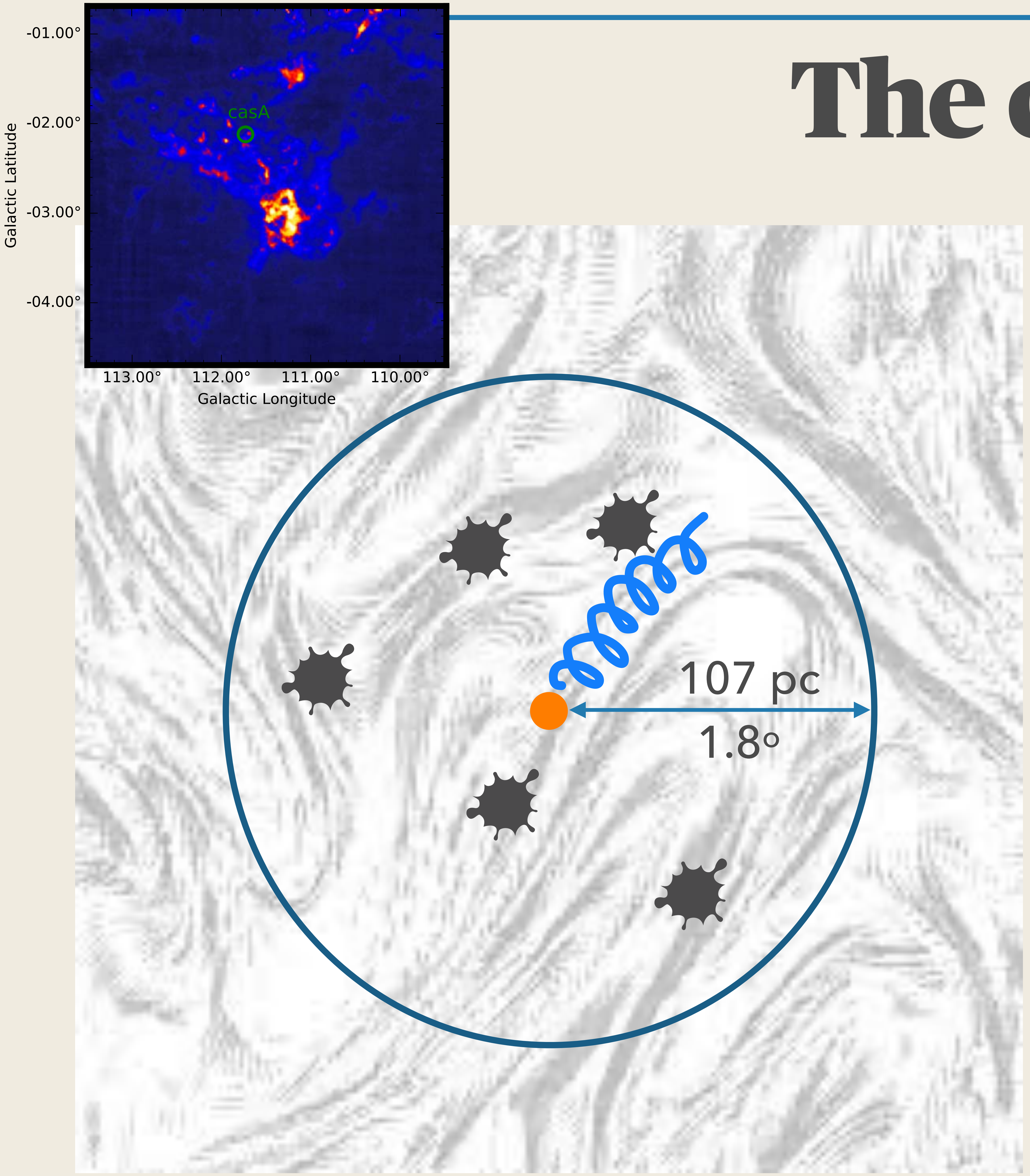
coherence scale of the Galactic B-field

$$r_L(E) \approx 1pc \left(\frac{E}{PeV}\right) << L_c$$

Hence on a scale of ~100 pc, 0.1-1PeV particles free stream parallel to B

The highest energy particles escaped CasA ~200 yrs ago, reaching ~60 pc at the present time, still inside 1.8 degrees from the source

The case of *Cas-A*



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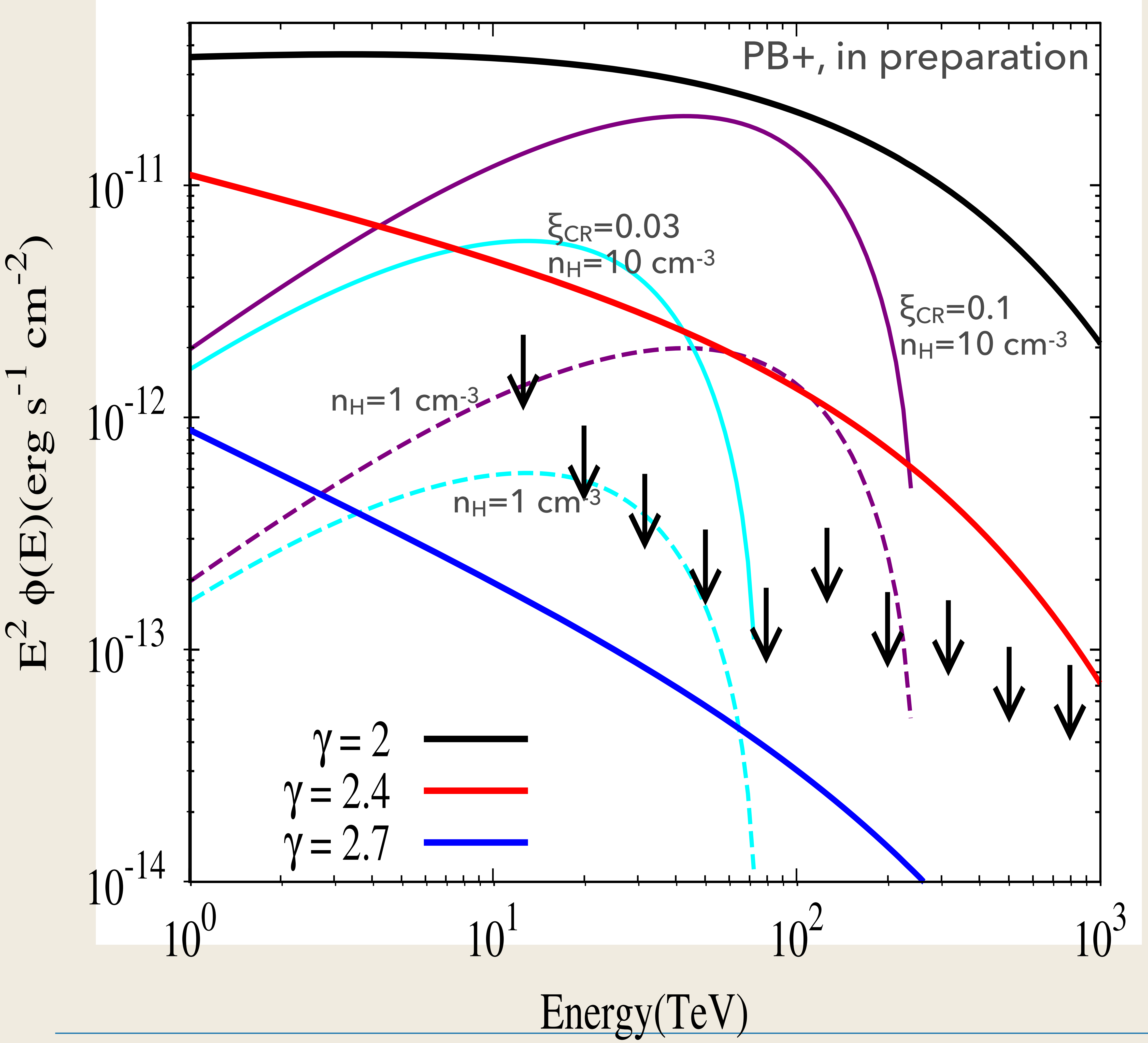
The gamma ray emission from the region reflects

1) the number of CR particles released as a function of energy
2) the structure of the local magnetic field
3) the gas distribution in the region

The case of *Cas-A*

Modified from Cao et al. 2024



- The gamma ray emission from escaping particles has been overlapped to the curves from the LHAASO paper on Cas A
- The purple curves refer to ξ_{CR}=10% and density 10 cm^{-3} (solid) and 1 cm^{-3} (dashed)
- The cyan curves refer to ξ_{CR}=3% and density 10 cm^{-3} (solid) and 1 cm^{-3} (dashed)
- The plot shows that the relative distribution of escaping particles and gas is crucial to assess the issue of the maximum energy reached in Cas A
- In fact it would be desirable to have deeper observations to confirm the picture on the escape during the Sedov phase
- If the intrinsic spectrum is a bit steeper than E^{-2}, these constraints becomes even weaker, although the shape of these curves does not change!

Dynamical Effects of CR near a source

Since in the ordinary ISM $E_{CR} \approx E_B \approx E_{th}$, it is clear that near a source the escaping CR must produce

1. **Local dynamical effects (gas evacuation, heating, vorticity, etc)**

2. **Magnetic field modification (amplification, shears, etc)**

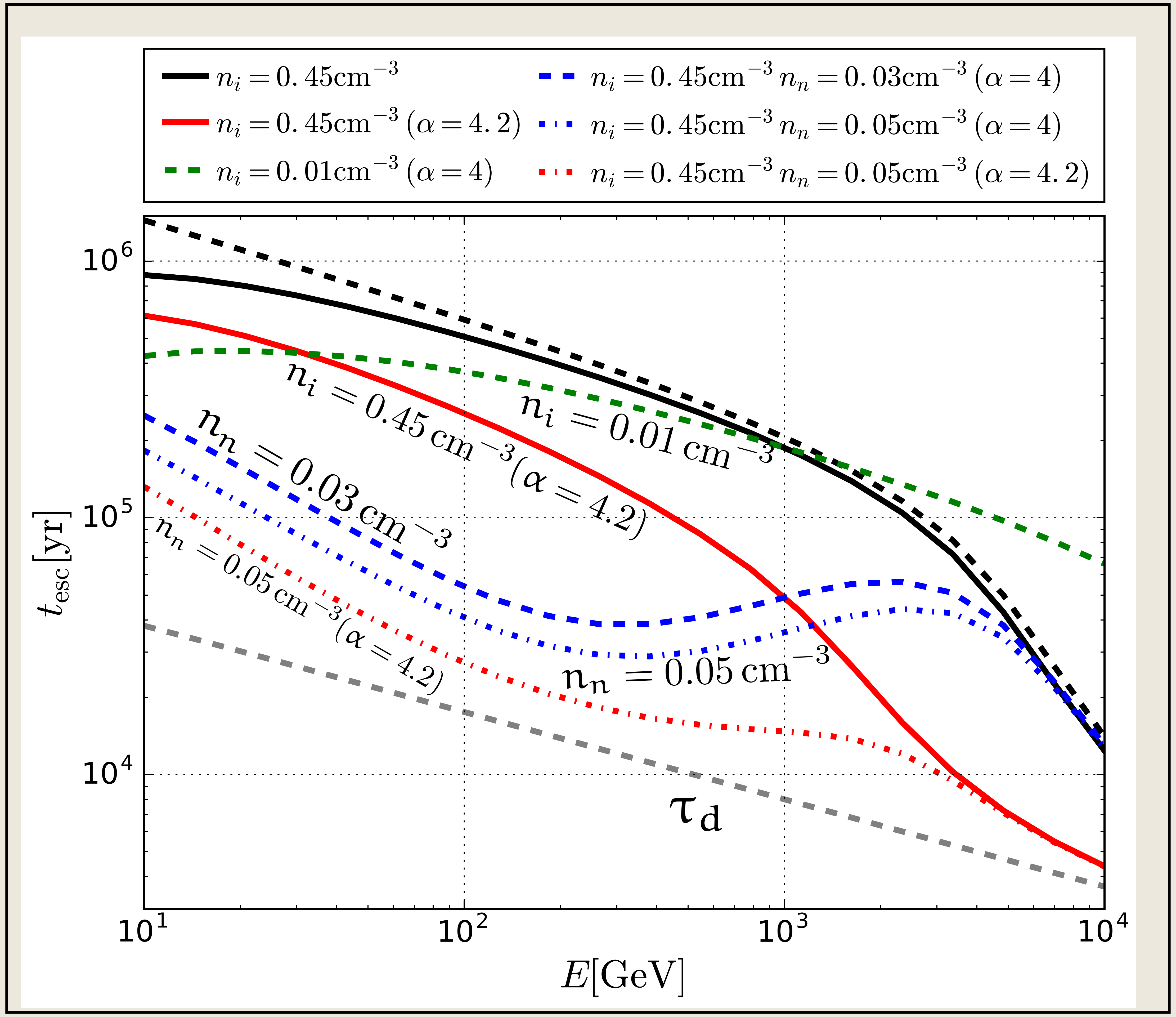
Notice that self-generation has a positive feed-back: larger gradients lead to stronger confinement which in turn lead to larger CR densities

This chain of events leads to some self-regulation of the whole process

Self-Confinement Near a SNR

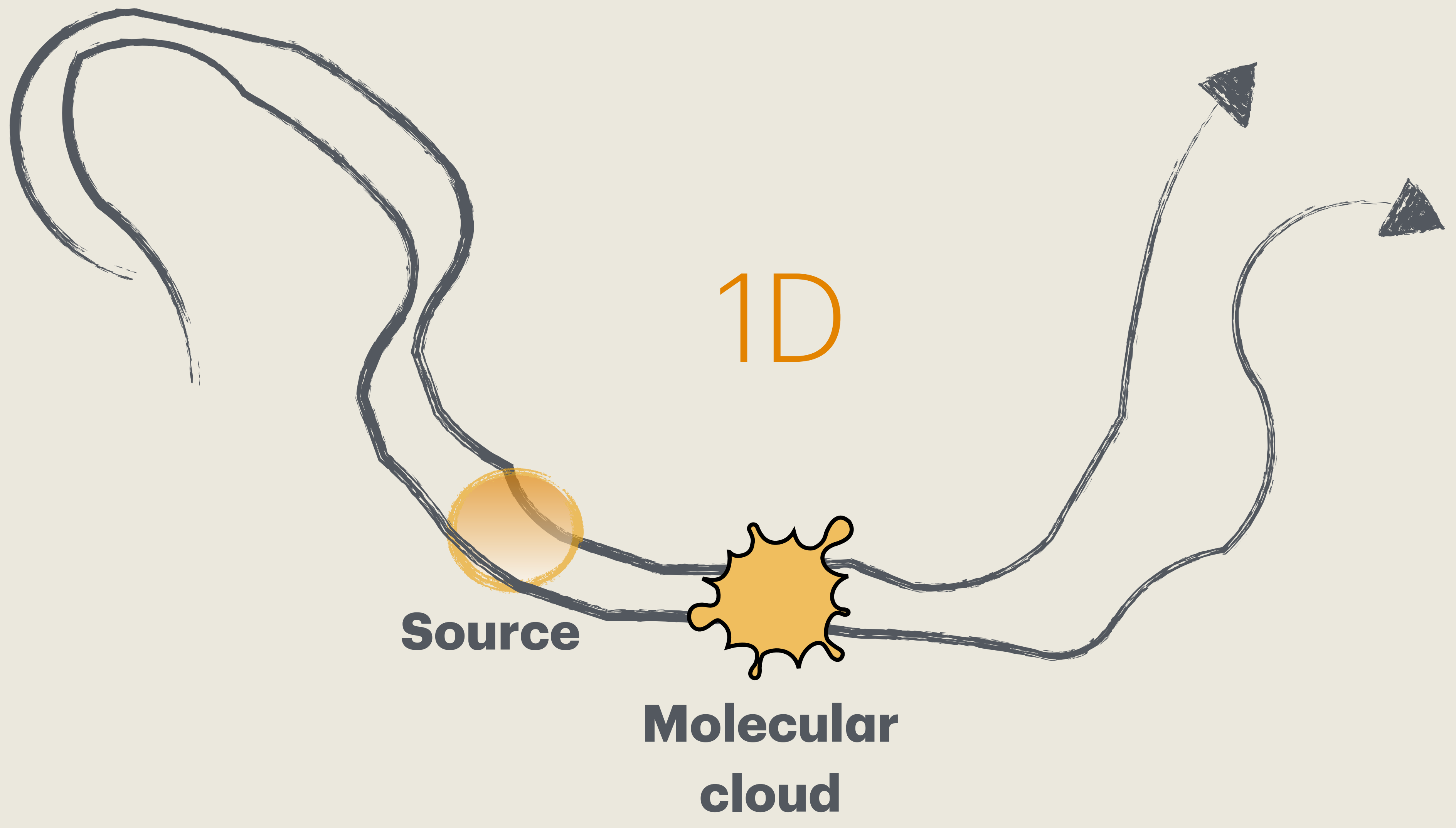
D'Angelo, PB, Amato 2016, 2018

Nava+2016, Recchia+, 2023



Depending on the total and ionized density in the circum-source medium, self-generation increases the confinement time by about one order of magnitude

Gamma rays from occasional nearby molecular clouds



While confinement is easier if the surrounding medium is almost completely ionized, interactions of CR are easier in denser (hence partially ionized) plasma

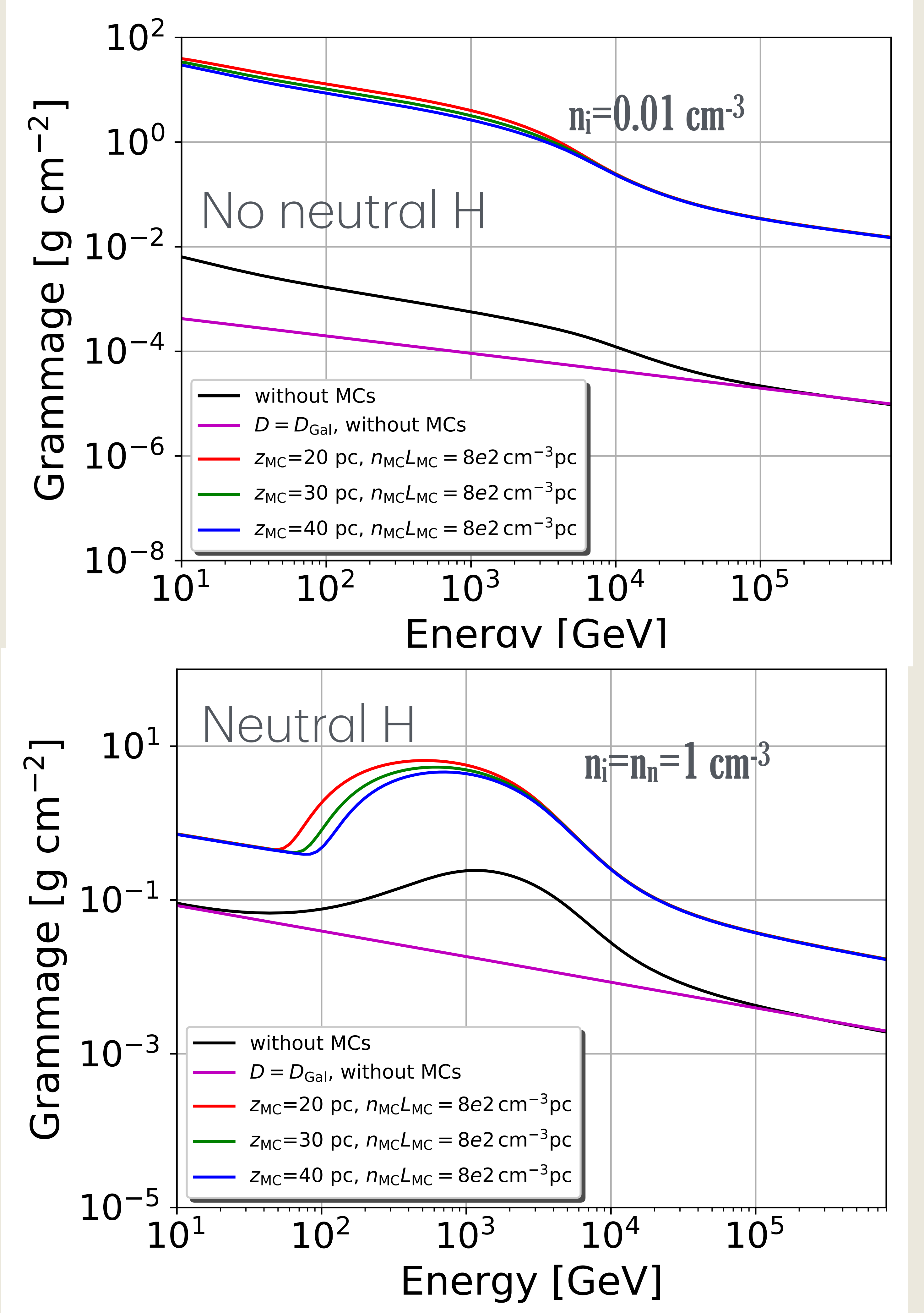
The coexistence of these two conditions may occur when a SNR is located near a molecular cloud, that only acts as target, while confinement is guaranteed by the surrounding ionized medium

Molecular cloud touching the shock is not a good place to test diffusion and self-generation phenomena for many good reasons…

- The shock velocity drops quickly making acceleration inefficient
- Only ionized gas takes part in the shock formation, low number of particles to become CR
- Large density of neutrals implies strong damping of waves —–> weak acceleration

Grammage near the source

Bao, PB & Chen 2023

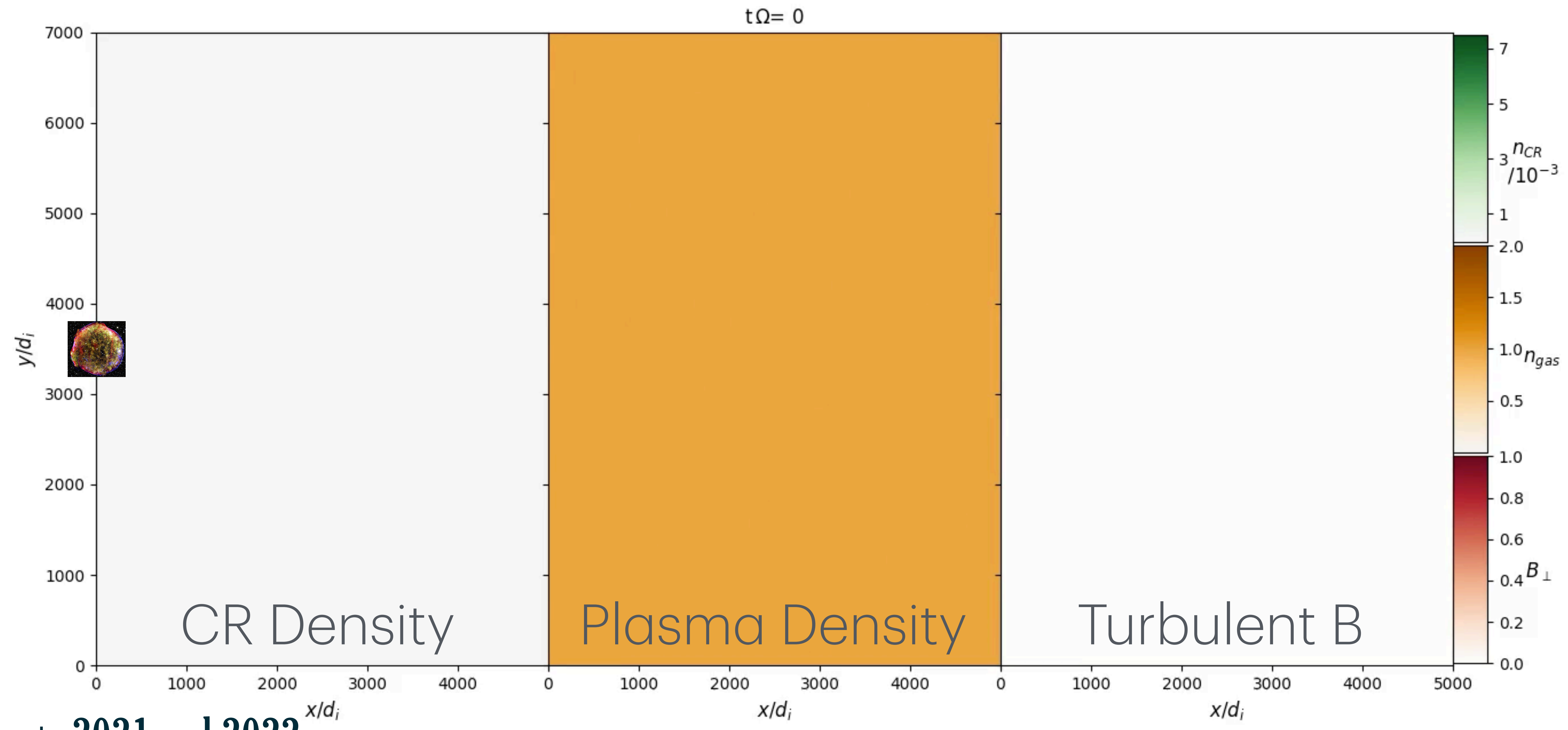


The grammage accumulated by CR near a source due to self-confinement depends on conditions (level of ionisation, coherence length)

Most importantly it depends upon the presence of molecular clouds in the neighbourhood of a source

…but it is clear that it is not a phenomenon that we can ignore at a time in which measurements are made at percent level

SIMULATING THE STREAMING OF CR NEAR A SOURCE



Schroer+, 2021 and 2022

We used 2D and 3D PIC Hybrid numerical simulations to mimic the streaming of particles in the ISM near a source

The simulation is initialised so that the NR streaming instability is excited, but similar to those expected for a young SNR

Due to numerical limitations, v_A is only c/20

- THE EXCITATION OF THE INSTABILITY LEADS TO STRONG PARTICLE SCATTERING, WHICH IN TURN INCREASES CR DENSITY NEAR THE SOURCE
- THE PRESSURE GRADIENT THAT DEVELOPS CREATES A FORCE THAT LEADS TO THE INFLATION OF A BUBBLE AROUND THE SOURCE
- THE SAME FORCE EVACUATES THE BUBBLE OF MOST PLASMA
- THERE IS NO FIELD IN THE PERP DIRECTION TO START WITH, BUT CR CREATE IT AT LATER TIMES (SUPPRESSED DIFFUSION, ABOUT 10 TIMES BOHM)

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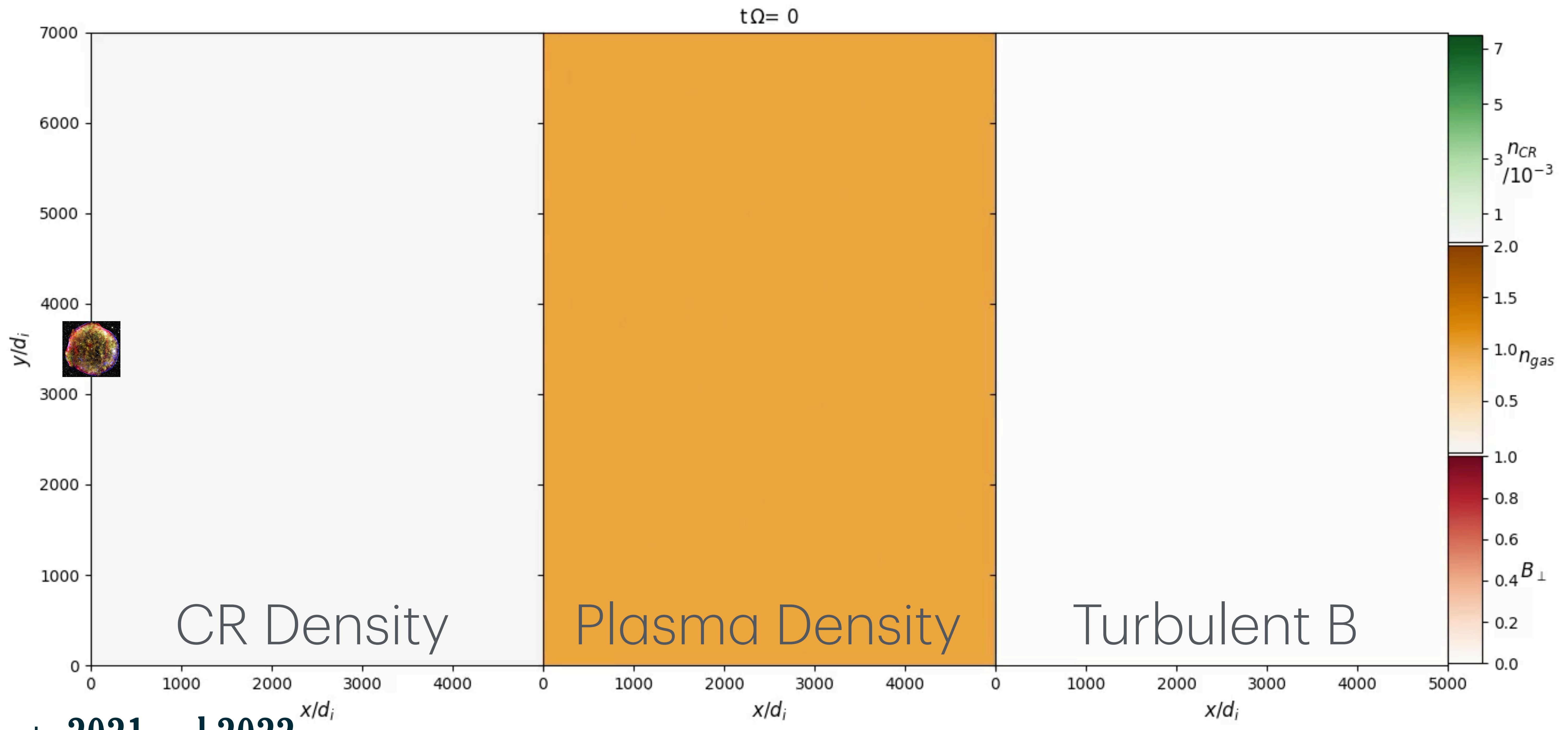

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Conclusions

- SNR are certainly CR accelerators – the question is: up to which energy and which type of SNR accelerate what?
- The theory of non-linear DSA provides a good description of what happens in terms of spectra and acceleration efficiency
- But the issue of maximum energy is tightly connected to that of magnetic field amplification – could we have missed anything?
- Based on non resonant streaming instability, SNR should not be PeVatrons, with the exception of rare, super luminous ones … unless other instabilities kick in …
- The maximum energy of the accelerator is NOT the highest energy reached (this depends on how much mass has been processed) but the highest energy at the beginning of the Sedov Phase (difficult to catch it in gamma rays!)
- Should we see evidence of PeV particles AROUND SNR if a given SNR accelerates them?
- With some care, interesting constraints can be obtained from these observations, especially for very young SNR
- For older ones, non linear effects kick in and things become more complicated to interpret