

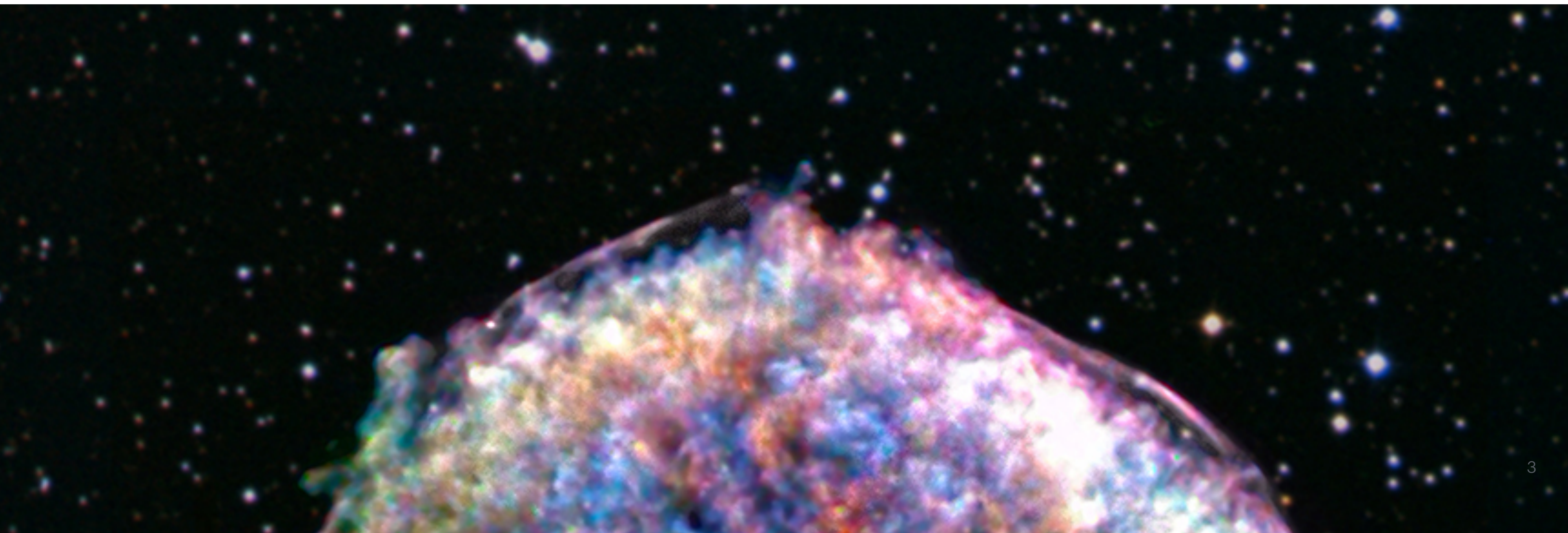
ESCAPE OF COSMIC RAYS FROM SOURCES

Pasquale Blasi
Gran Sasso Science Institute

WHY IS ESCAPE FROM AN ACCELERATOR IMPORTANT?

- 📌 The spectrum of accelerated particles that escape a source (“source term”) — **Generally different from the spectrum at the acceleration site**
- 📌 The CR energy density around the source is bound to be $\gg$ ISM, — **dynamical effects on the environment should be expected**
- 📌 Large gradients of density of charged particles, to be expected near sources, correspond to **electric currents, which can produce instabilities**, which in turn change the way particles move around
- 📌 Escape is what defines the **“boundary conditions”** of an acceleration or transport problem, which are usually imposed by hand
- 📌 I will discuss here three instances:
 - ❖ **supernova remnants**
 - ❖ **pulsar wind nebulae**
 - ❖ **the entire Galaxy (or an entire galaxy) as a source of non thermal particles**

SUPERNOVA REMNANTS



A QUICK LOOK AT INSIDE THE ACCELERATOR FIRST

One of the best studied processes of particle acceleration, at work in a variety of astrophysical sources, is **DIFFUSIVE SHOCK ACCELERATION (DSA)**

Each shock crossing guarantees that particles gain energy

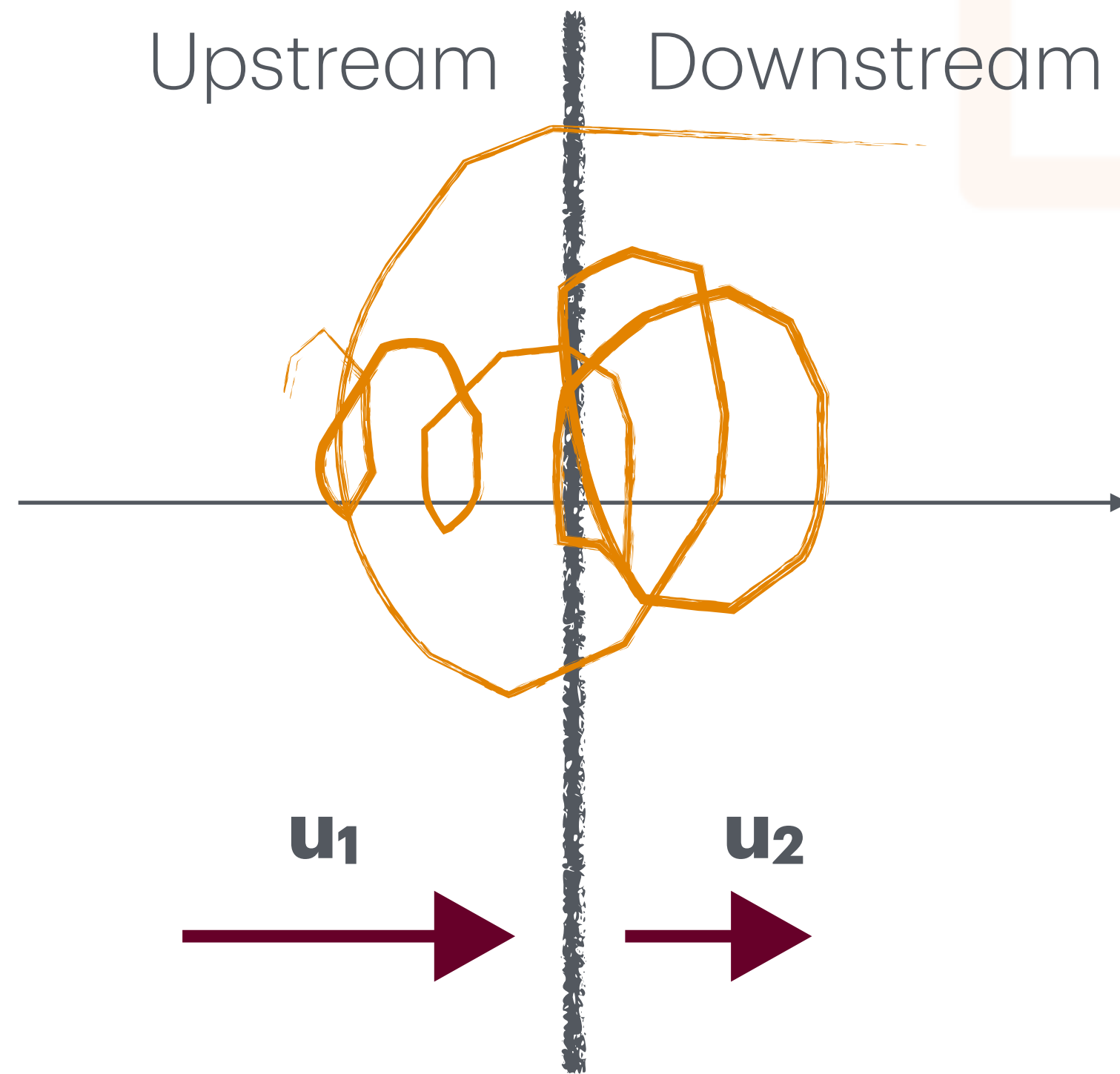
$$\frac{\Delta E}{E} = \frac{4}{3} \frac{u_1 - u_2}{c}$$

The spectrum of accelerated particles is a power law only dependent upon the compression factor at the shock

The process of diffusion provides near isotropization of the distribution of accelerated particles around the shock

...but it also determines how many times the particles can cross the shock front → **$E_{\max}$**

From the microphysics point of view diffusion reflects resonant interactions between charged particles and plasma waves



MAXIMUM ENERGY

- 📌 The maximum energy reached at a shock, for instance in supernova explosions, becomes interesting only if instabilities are excited that increase the level of turbulence **UPSTREAM** of the shock

$$\tau_{acc}(E) = \frac{3}{u_1 - u_2} \left[\frac{D_{up}}{u_1} + \frac{D_{down}}{u_2} \right]$$

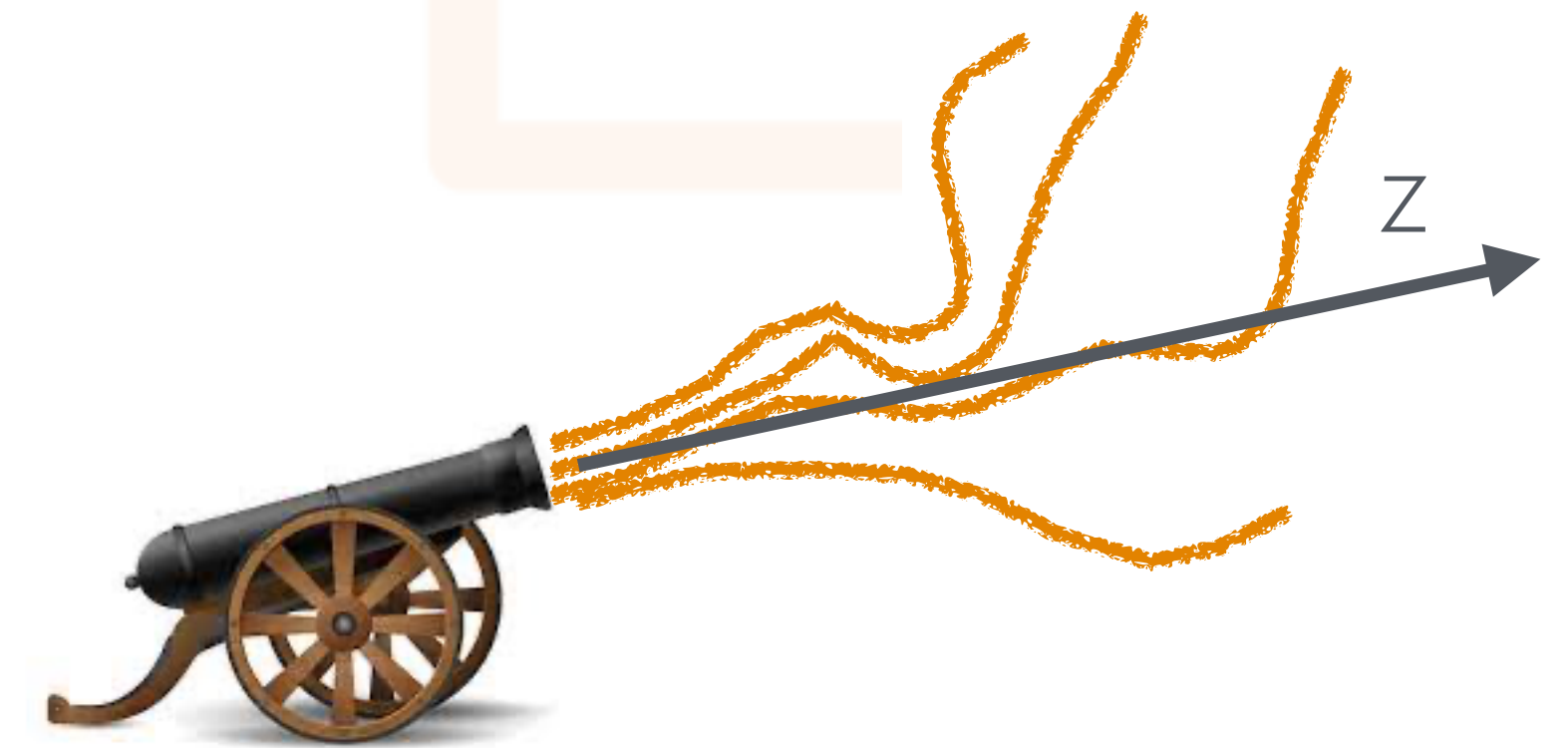
- 📌 The accelerated particles are the only agents able to reach the upstream region of a shock, hence they must excite such instabilities
- 📌 The relevant instability is due to the streaming of accelerated particles and comes in two flavours, **RESONANT** and **NON-RESONANT**

Resonant self-generation of Alfvén waves...the easy way

The net effect of spatial diffusion is to reduce the momentum of the particles in the z direction... forcing them, eventually, to move at the same speed as the waves v_w

$$n_{CR} m v_{dr} \rightarrow n_{CR} m v_w \rightarrow \frac{dp_{CR}}{dt} = \frac{n_{CR}(v_{dr} - v_w)}{\tau_{90}}$$

$$\frac{dp_w}{dt} = \Gamma_{CR} \frac{b^2}{8\pi v_w}$$



And requiring some balance between the two:

$$\Gamma_{CR} \approx \frac{n_{CR}}{n_i} \frac{v_{dr} - v_w}{v_w} \Omega_{cyc}$$

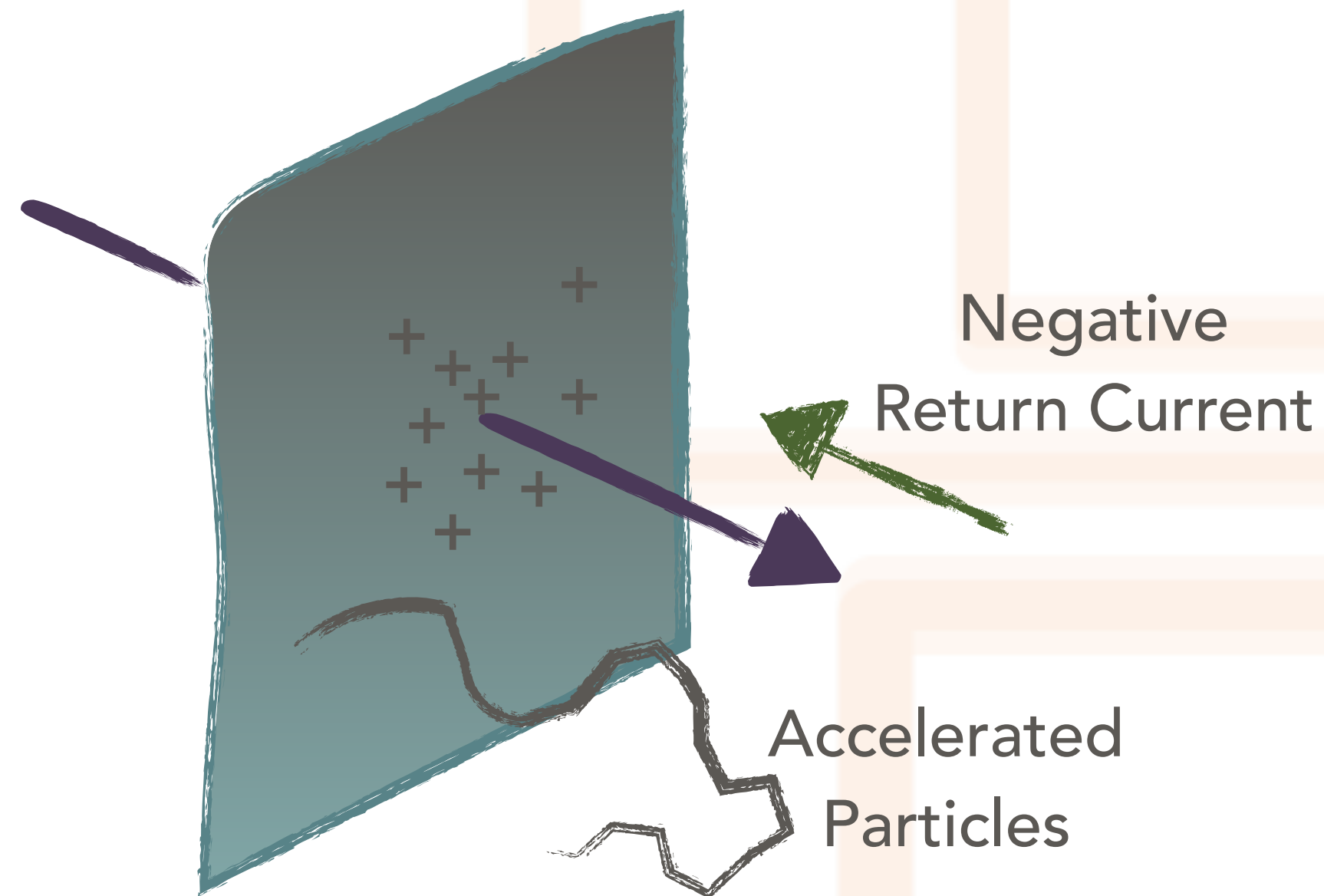
Time for deflection
by 90 degree

If CR stream faster than the waves, the net effect of diffusion is to make waves grow and make CR diffusive motion slow down... this process is known as self-generation of waves (Kulsrud&Pearce 1969)

NON-RESONANT STREAMING INSTABILITY

Bell 2004 - MHD

Amato&PB 2009 - Kinetic



THE ACCELERATING PARTICLES MAKE A POSITIVE CURRENT MOVING IN THE UPSTREAM

IT IS COMPENSATED BY A NEGATIVE CURRENT MADE OF PLASMA ELECTRONS MOVING WITH RESPECT TO IONS

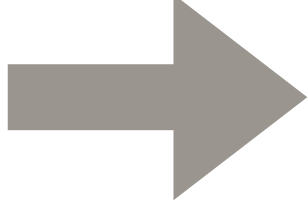
THE SYSTEM OF THESE TWO CURRENTS IS UNSTABLE ON SPATIAL SCALES SMALLER THAN THE LARMOR RADIUS

THE INSTABILITY ONLY GROWS IF

$$n_{CR}(> E) E \frac{v_s}{c} > \frac{B_0^2}{4\pi} = U_{mag}$$

AND ITS GROWTH RATE IS:

$$\gamma_{max} = k_{max} v_A \quad k_{max} B_0 = \frac{4\pi}{c} J_{CR}^{esc}$$

IT CAN BE EASILY SHOWN THAT $k_{max} \gg 1/\text{Larmor}$  NO SCATTERING

THE GROWTH OF THE PERTURBATIONS OCCURS ON SCALES $\ll$ THAN THE LARMOR RADIUS OF THE PARTICLES (NO SCATTERING) $\rightarrow$ **THE CURRENT PROCEEDS UNABATED.**

THIS PROCEEDS WAY INTO THE NON LINEAR PHASE UNTIL THE TRANSVERSE PLASMA DISPLACEMENT DUE TO THE **$\mathbf{J} \times \mathbf{B}$** FORCE BECOMES COMPARABLE WITH THE LARMOR RADIUS IN THE AMPLIFIED FIELD

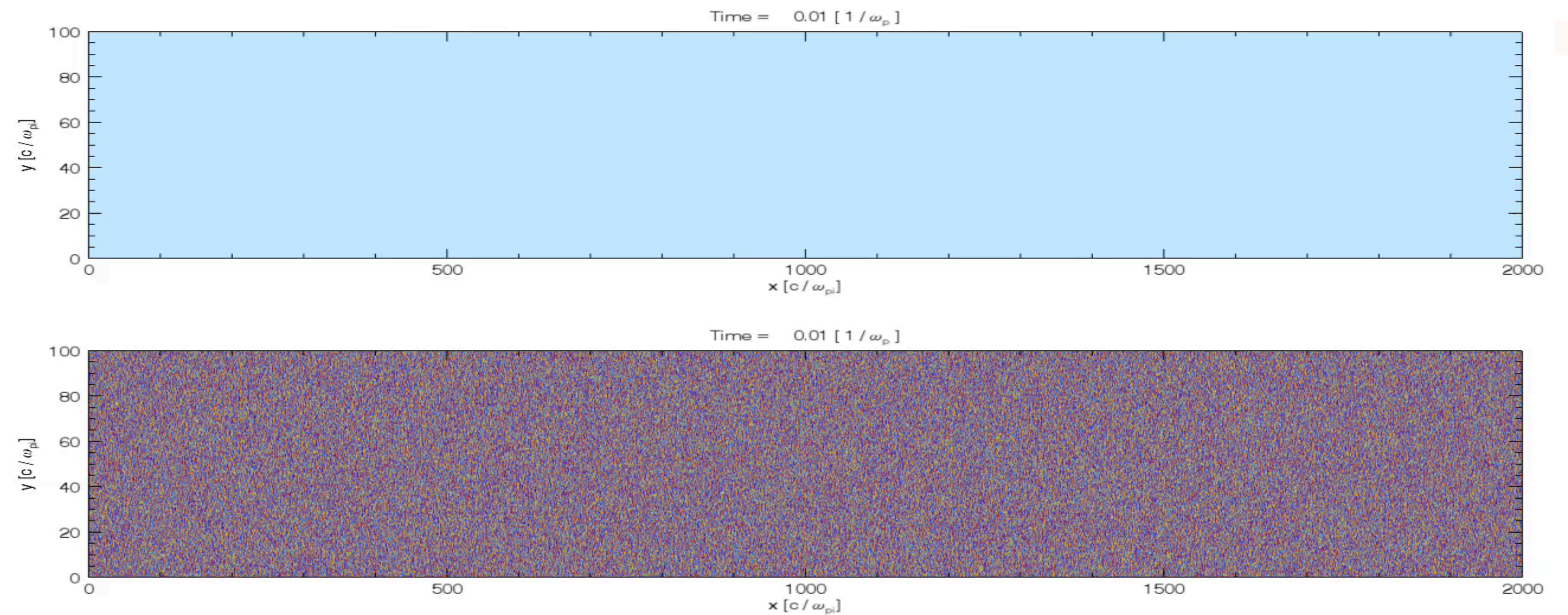
IN THE UPSTREAM REGION OF A STRONG SHOCK THIS CRITERION LEADS TO

$$\frac{\delta B^2}{4\pi} = \frac{\xi_{CR}}{\Lambda} \rho v_s^2 \frac{v_s}{c} \quad \Lambda = \ln(E_{max}/E_{min})$$

MAGNETIC BOOTSTRAP: YOU NEED ESCAPE TO AVOID ESCAPE

DOWNSTREAM UPSTREAM

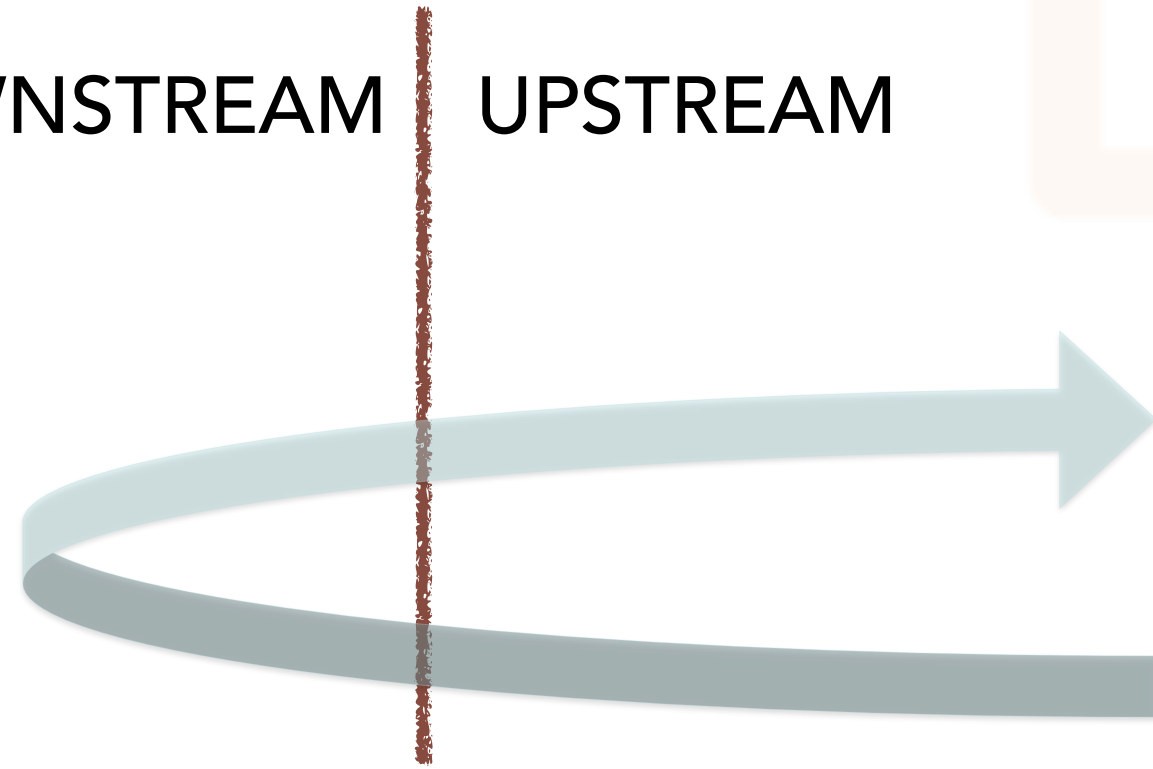
Bell & Schure 2013
Cardillo, Amato & PB 2015



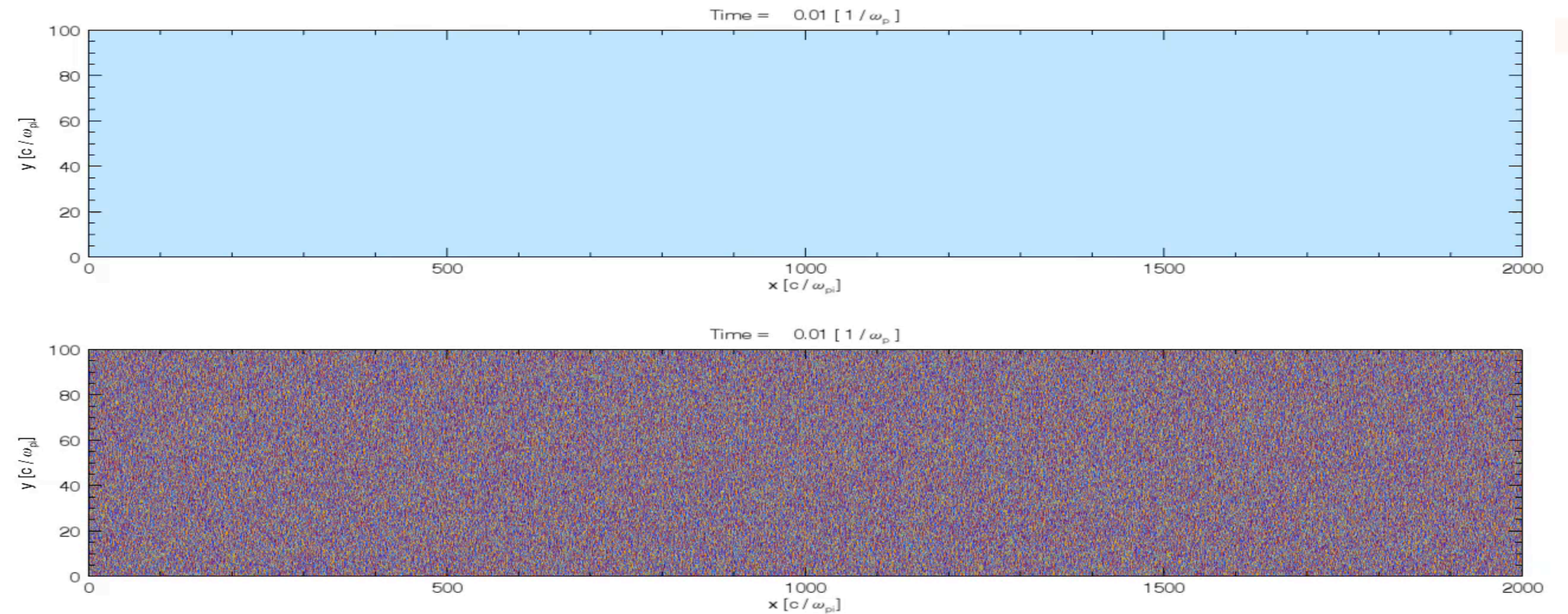
Caprioli & Spitkovsky 2014

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DOWNSTREAM UPSTREAM

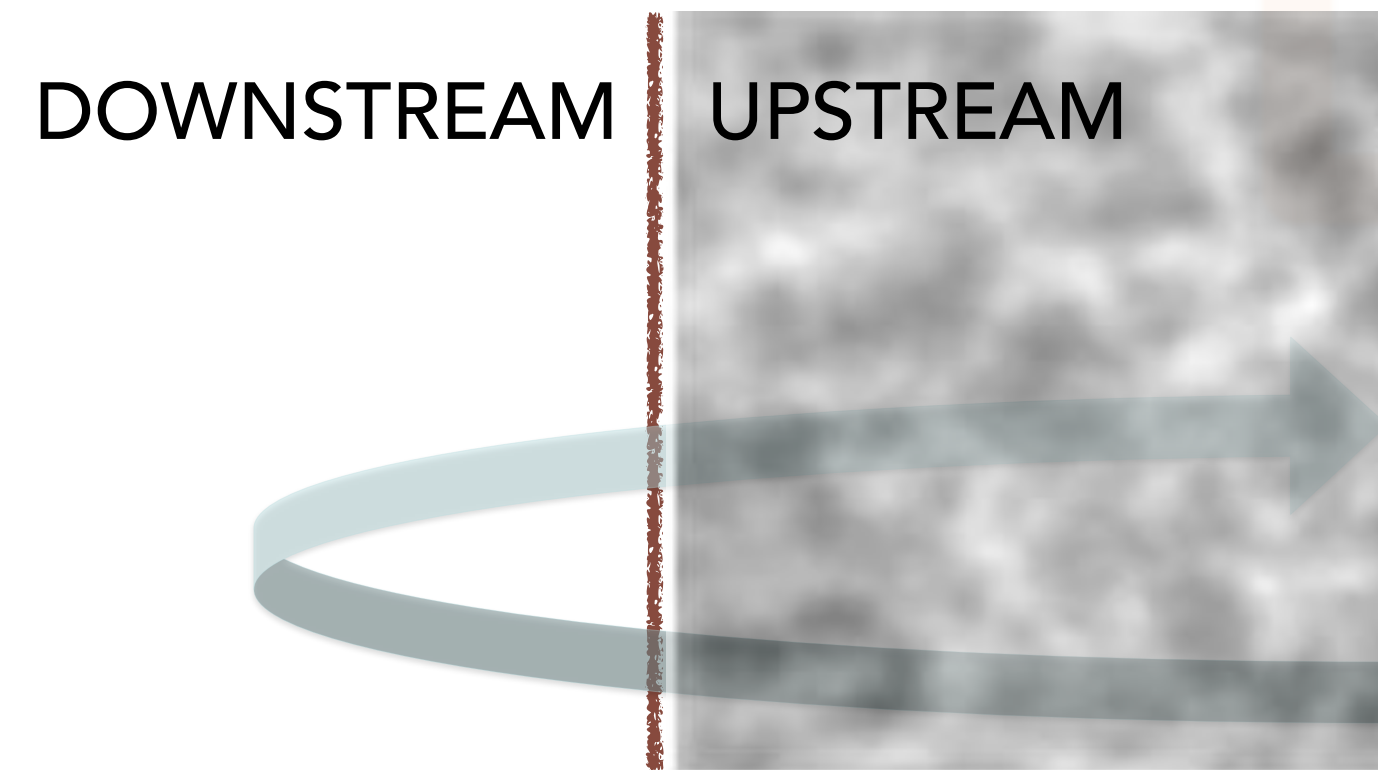


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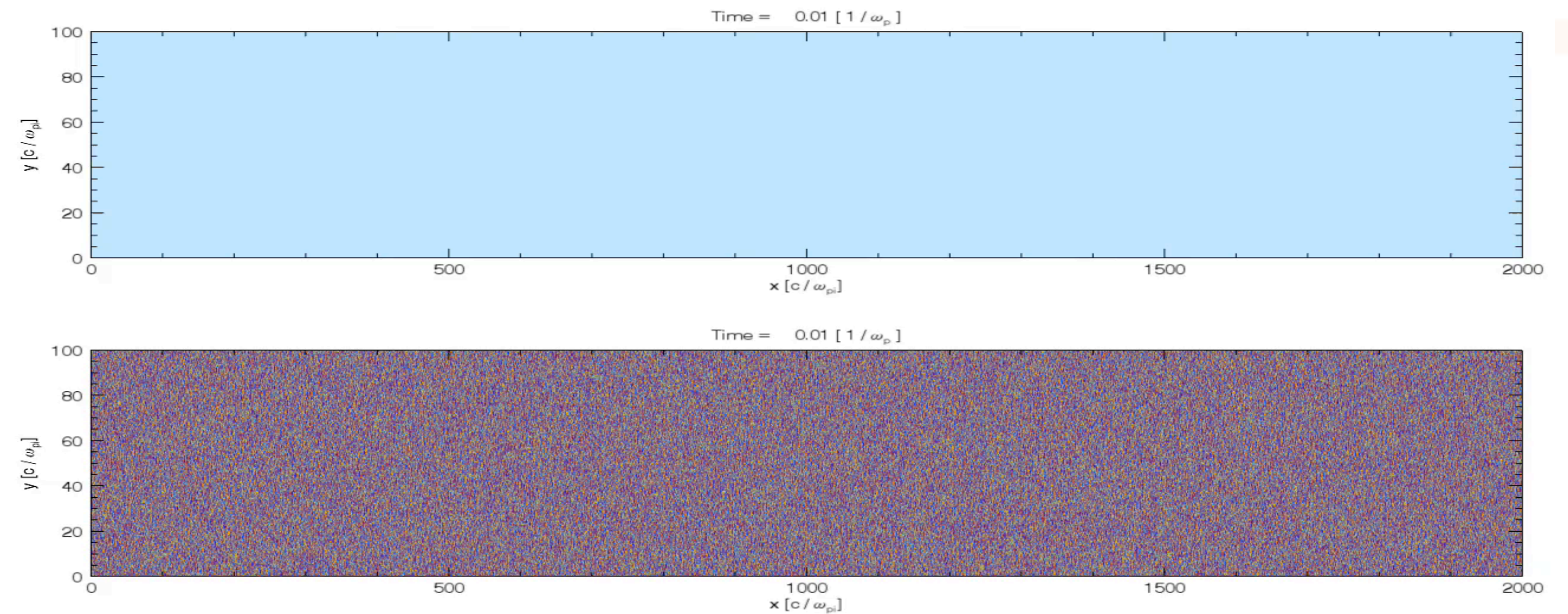


Caprioli & Spitkovsky 2014

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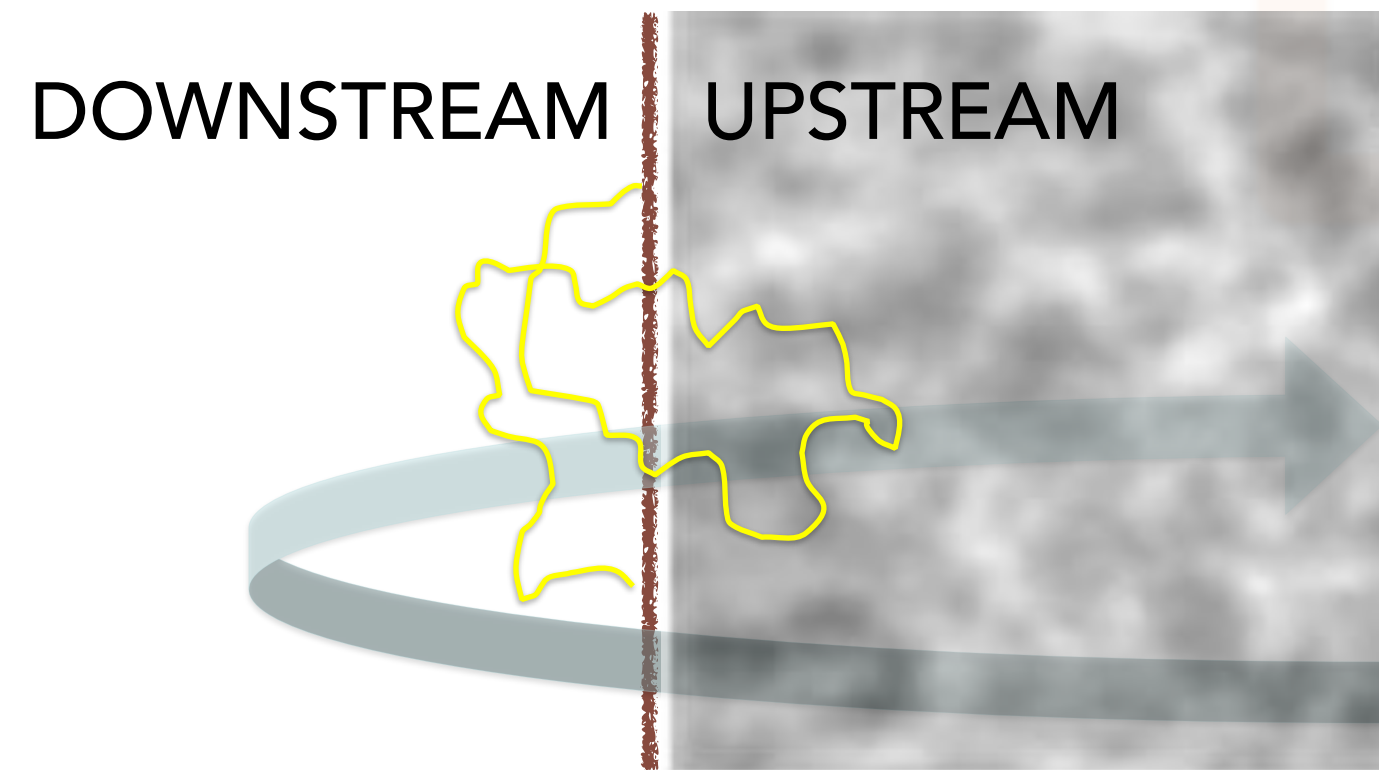


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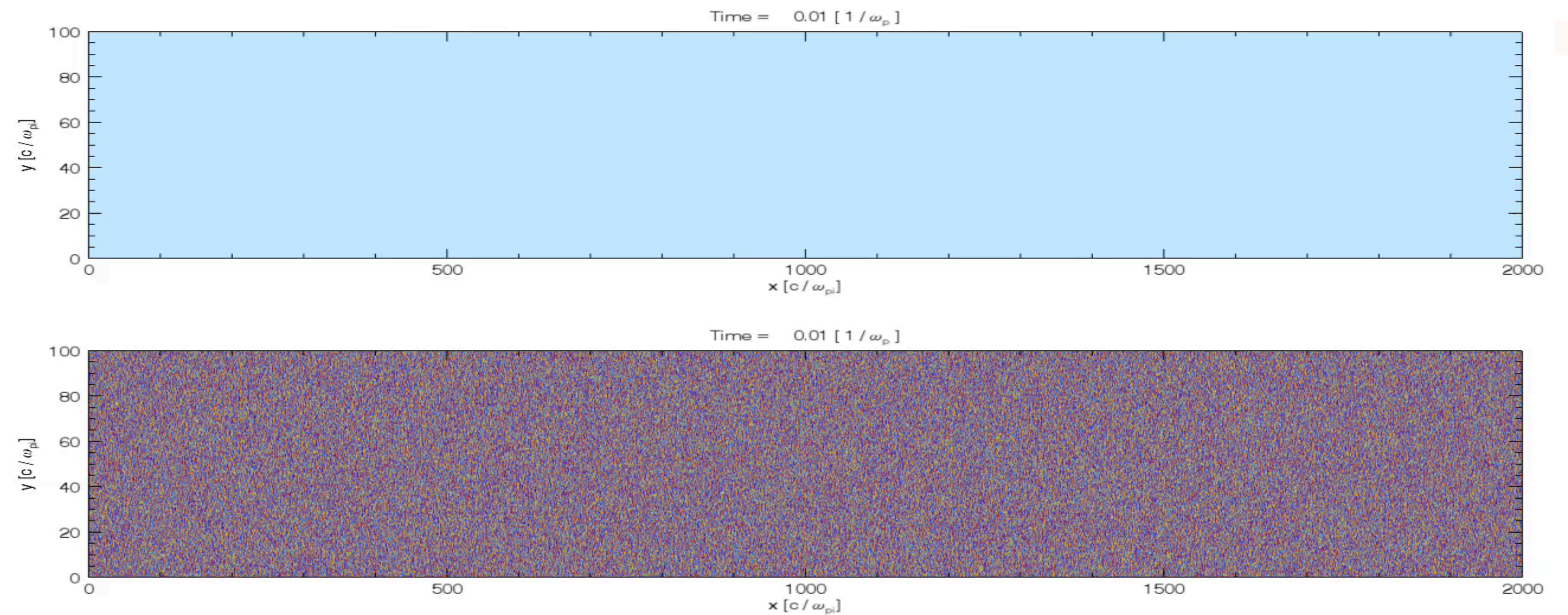


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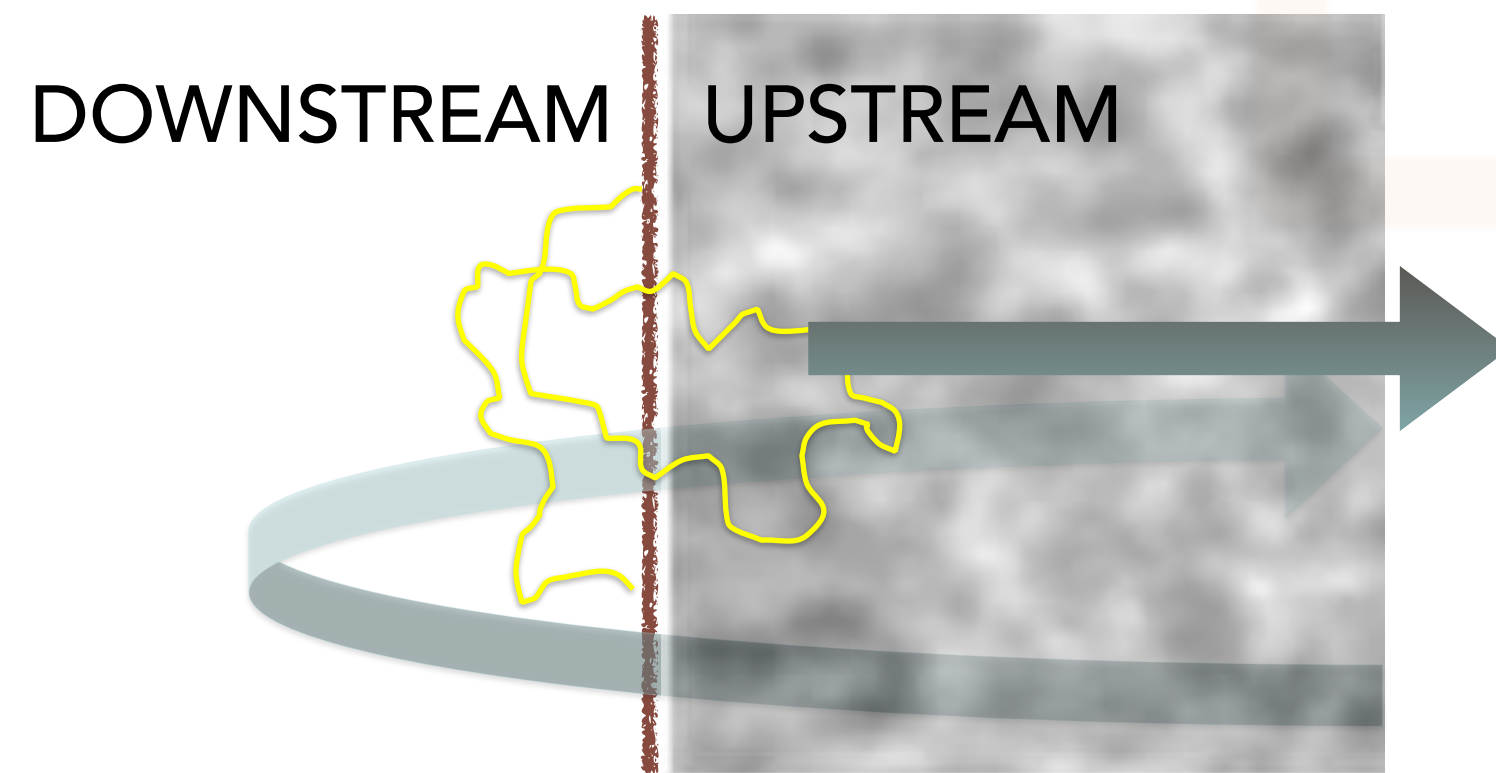


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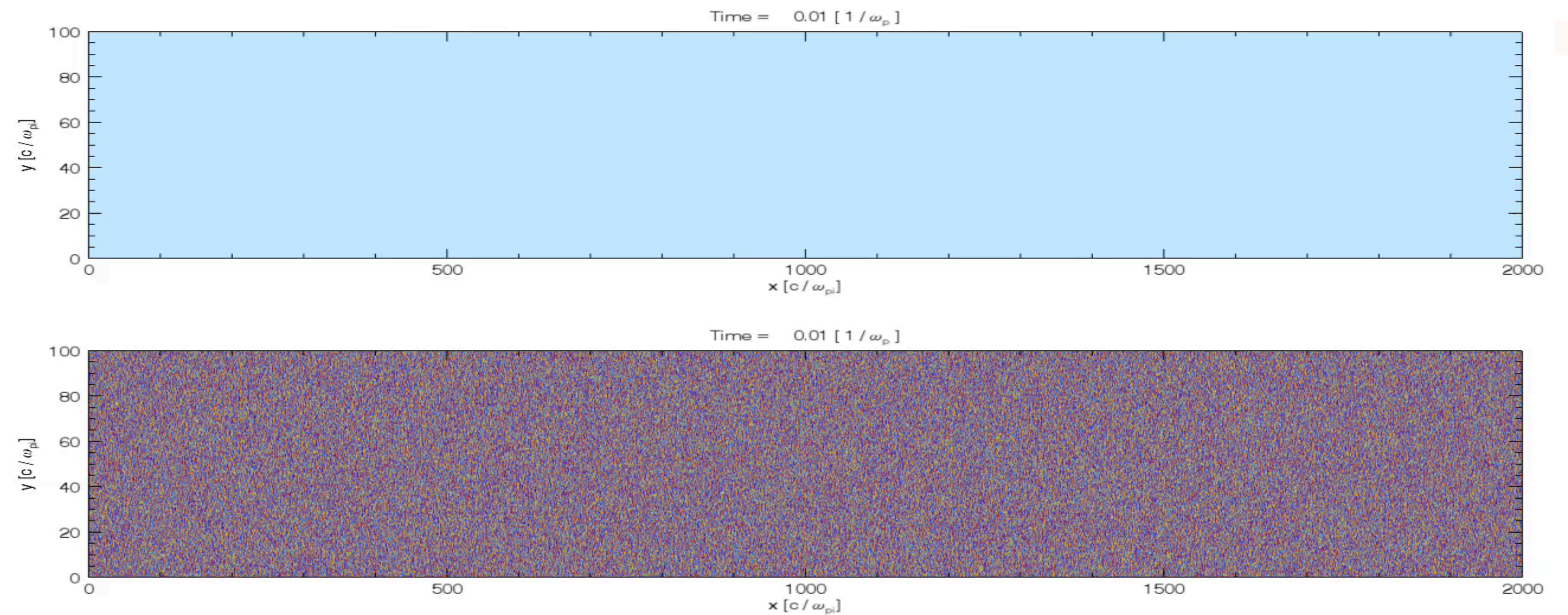


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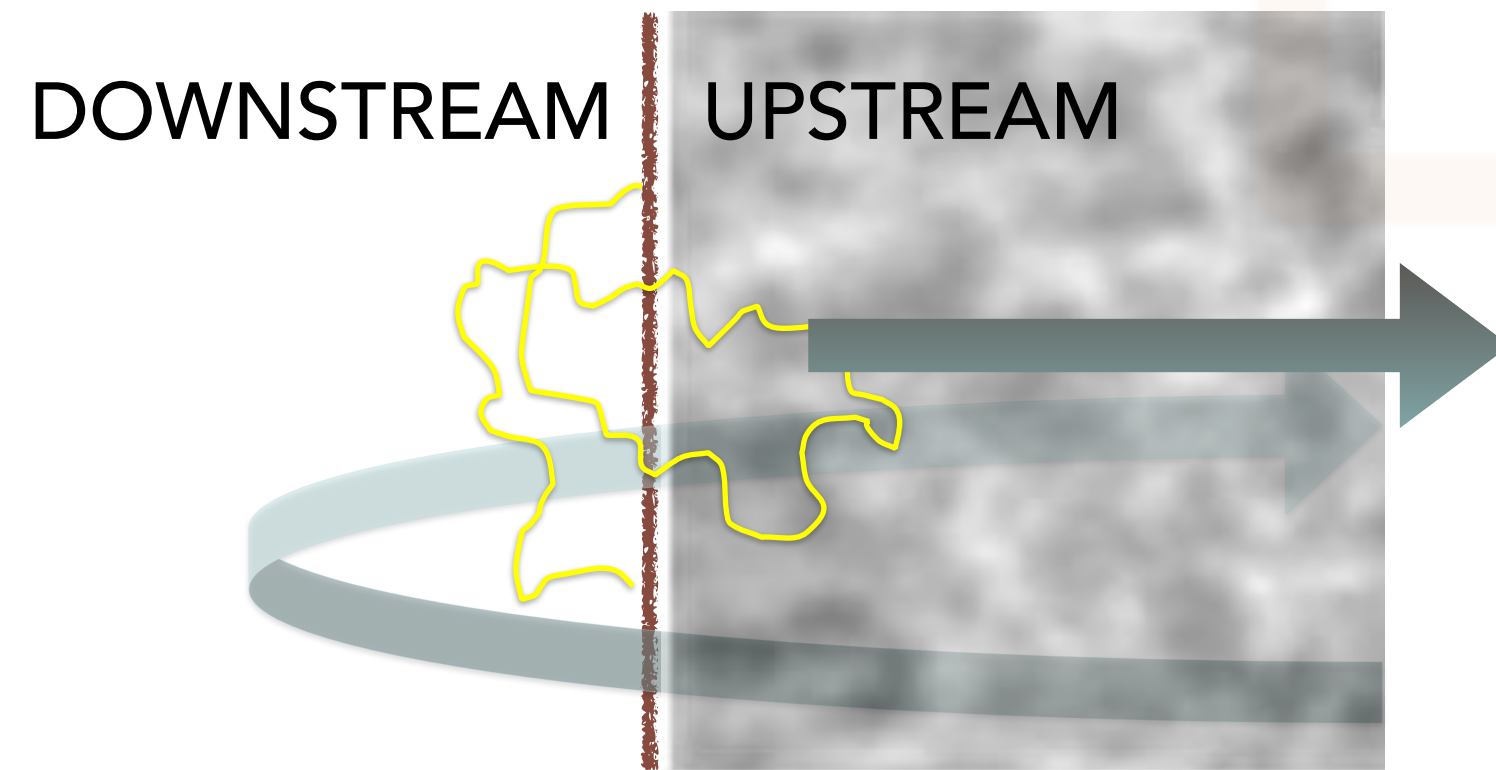


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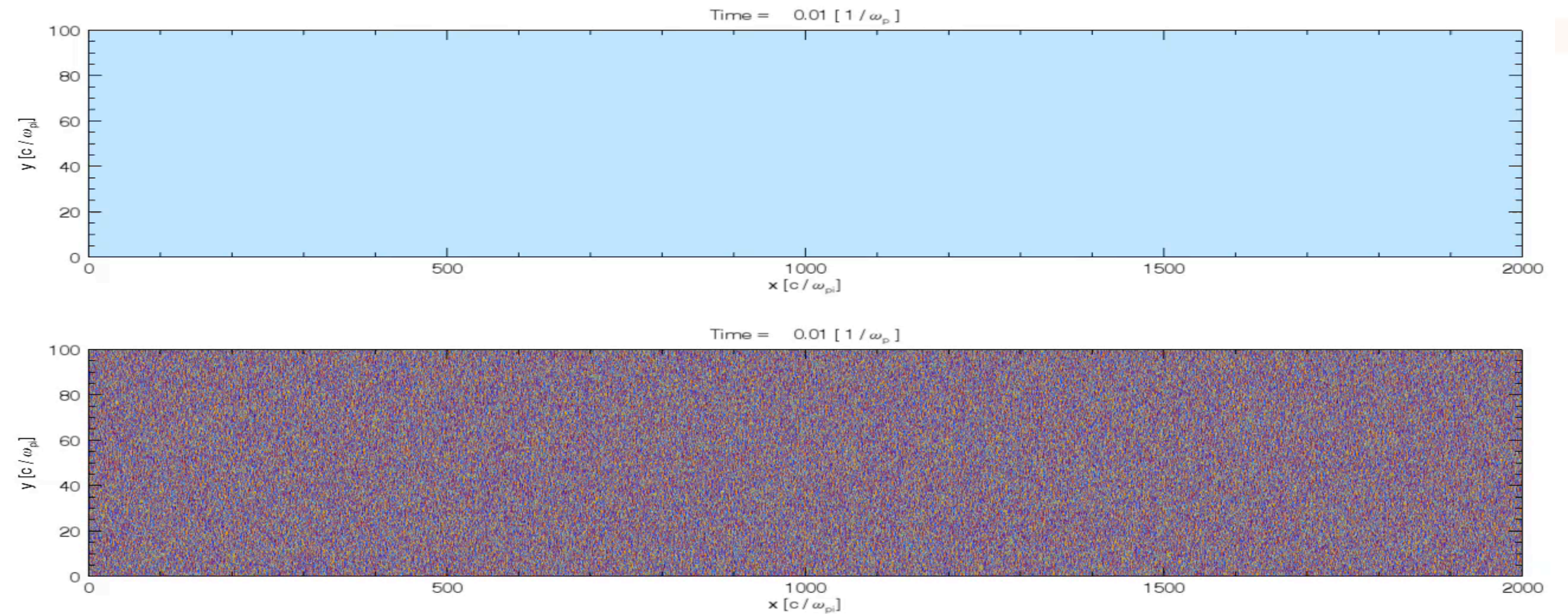


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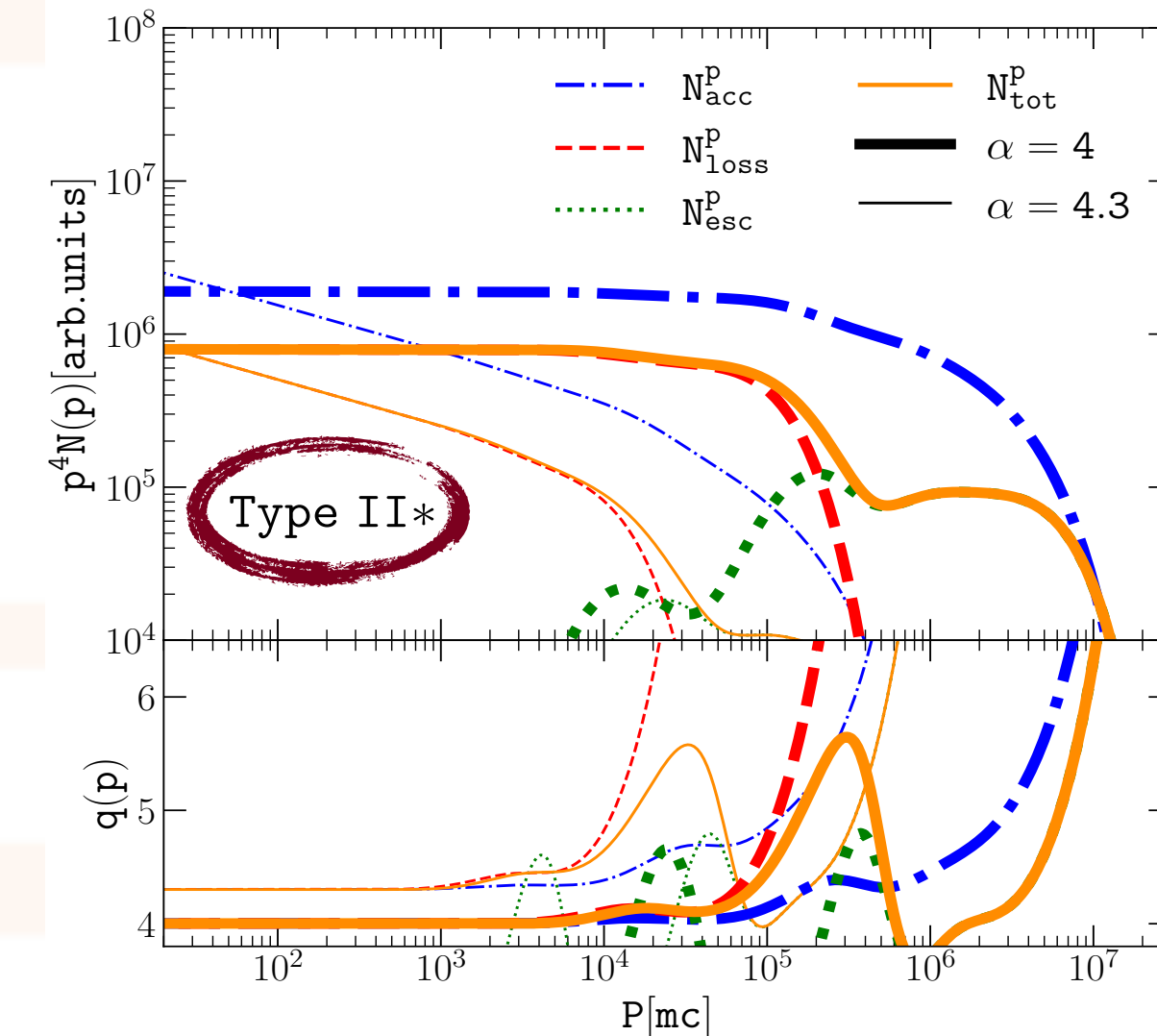
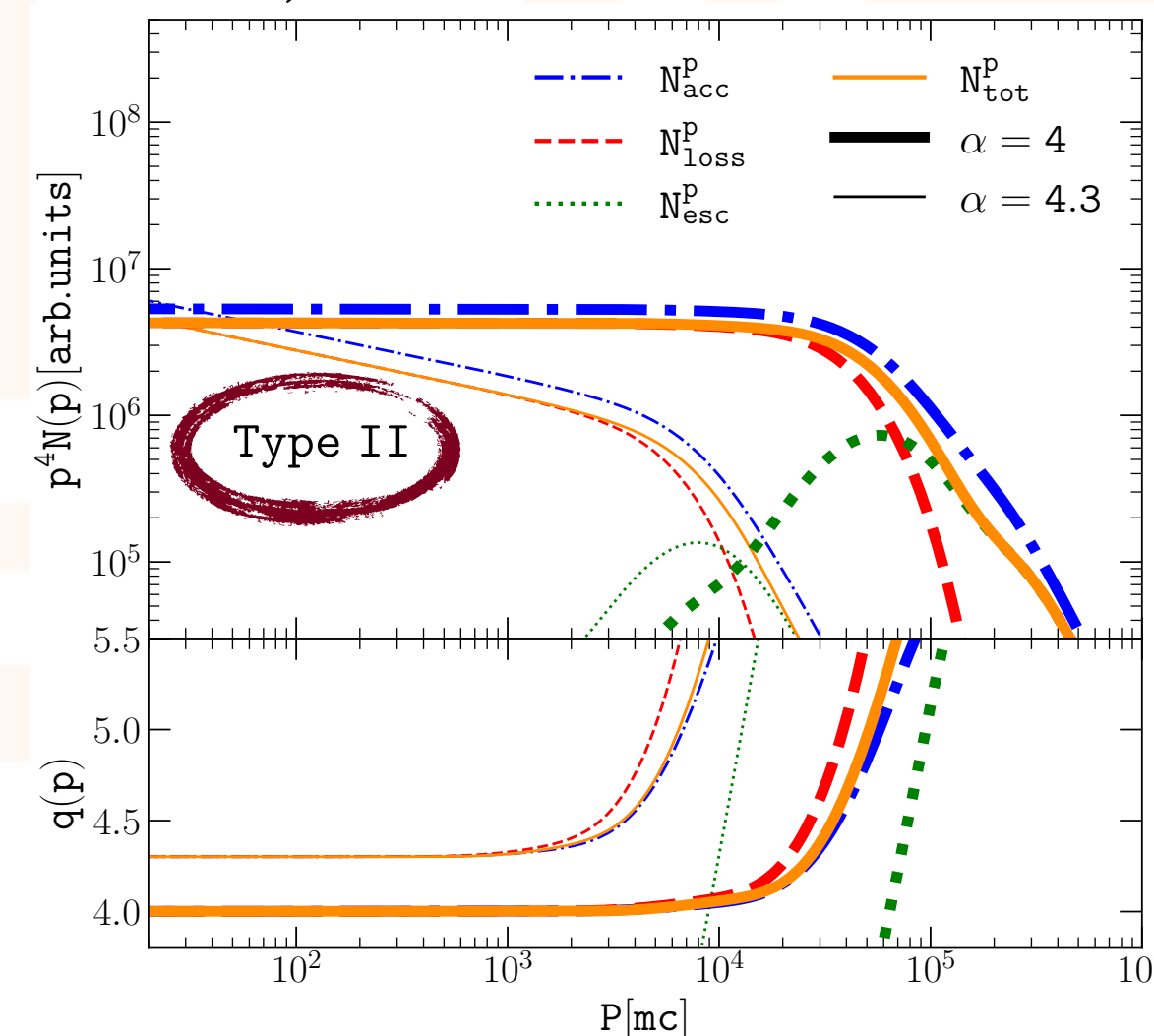
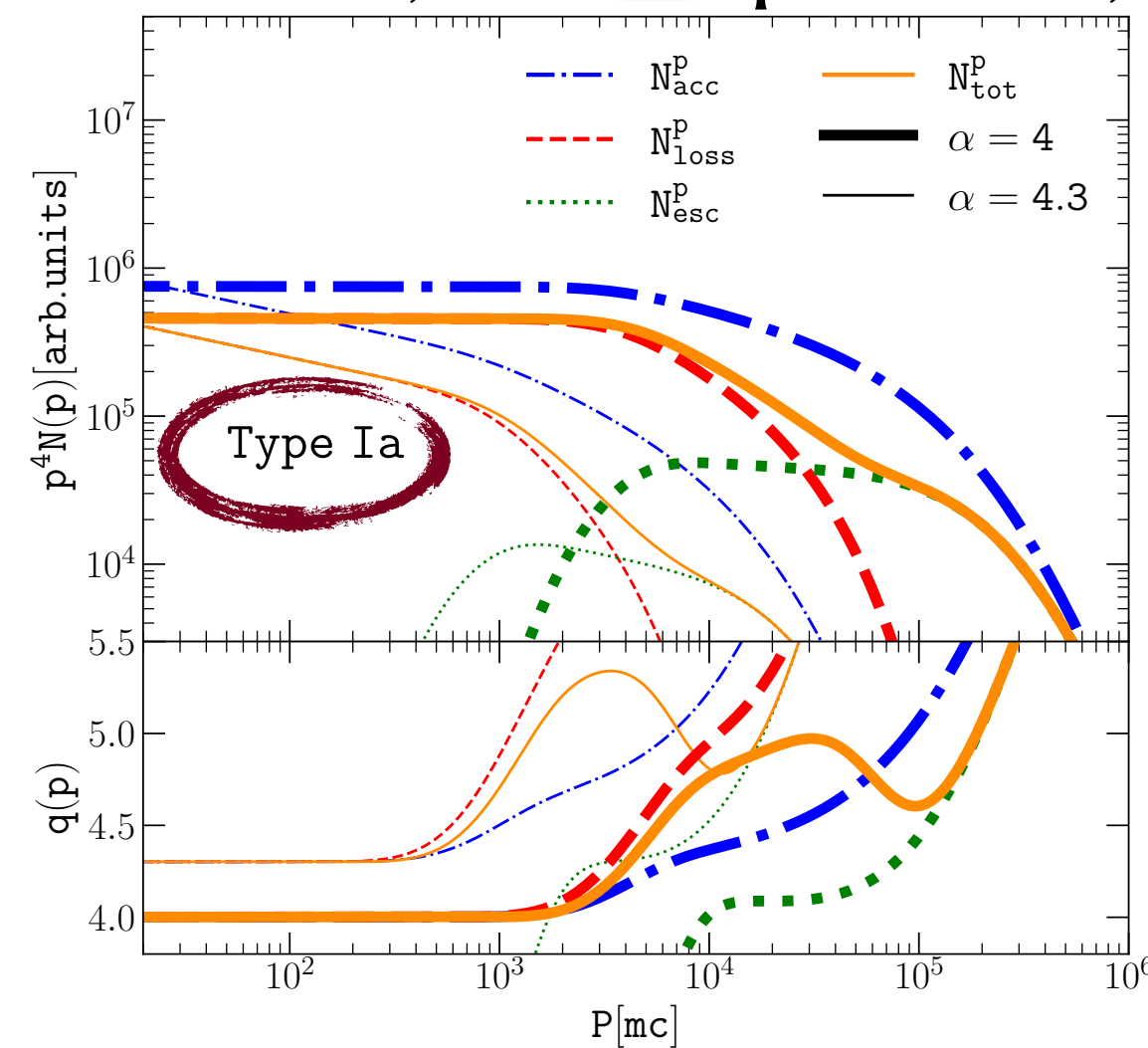
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Caprioli & Spitkovsky 2014

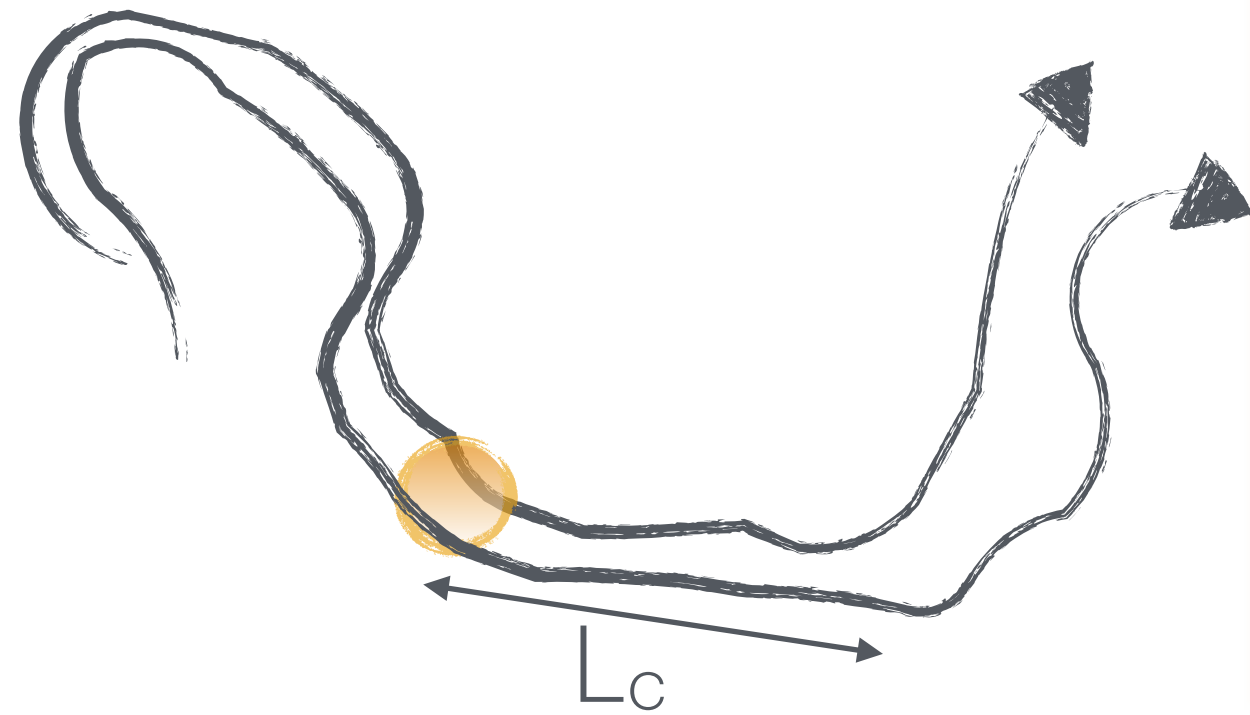
THE SPECTRUM OF CR ESCAPING A SNR

Cristofari, PB & Caprioli 2021, Cristofari, PB & Amato 2020



- ☑ THE SPECTRUM RELEASED INTO THE ISM IS THE SUM OF CR ESCAPING FROM UPSTREAM AND THE ONES TRAPPED DOWNSTREAM (COMPLEX SPECTRAL SHAPES)
- ☑ THE EFFECTIVE MAX ENERGY FOR IA AND II IS <100 TeV
- ☑ PEVATRONS ONLY FROM EXTREMELY POWERFUL AND RARE SUPERNOVA REMNANTS

...AND ESCAPE THEY DO...



Density of local CR: $n_s^{1D}(E) = \frac{N(E)}{\pi R_s^2 (4\pi D(E)t)^{1/2}} \exp \left[\frac{z^2}{4D(E)t} \right]$

Density of Galactic CR: $n_{Gal}(E) = \frac{N(E)rH}{2\pi R_d^2 D(E)}$

r =rate of source occurrence

R_d =radius of Galactic disc

H =Size of the Galactic halo

L_c =coherence length GMF

The solution remains 1D for as long as the particles do not reach L_c

$$4D(E)t < L_c^2 \rightarrow t \lesssim t_1 = 10^4 \text{ yr } E_{\text{GeV}}^{-1/2}$$

On the other hand the local density dominates upon the sea of CR for as long as:

$$t \lesssim \left(\frac{R_d}{R_s} \right)^4 \frac{D(E)}{r^2 H^2} = t_2 \sim 10^7 \text{ yr } E_{\text{GeV}}^{1/2} \gg t_1 \quad \text{for the energies we are interested in}$$

DYNAMICAL EFFECTS OF CR NEAR A SOURCE

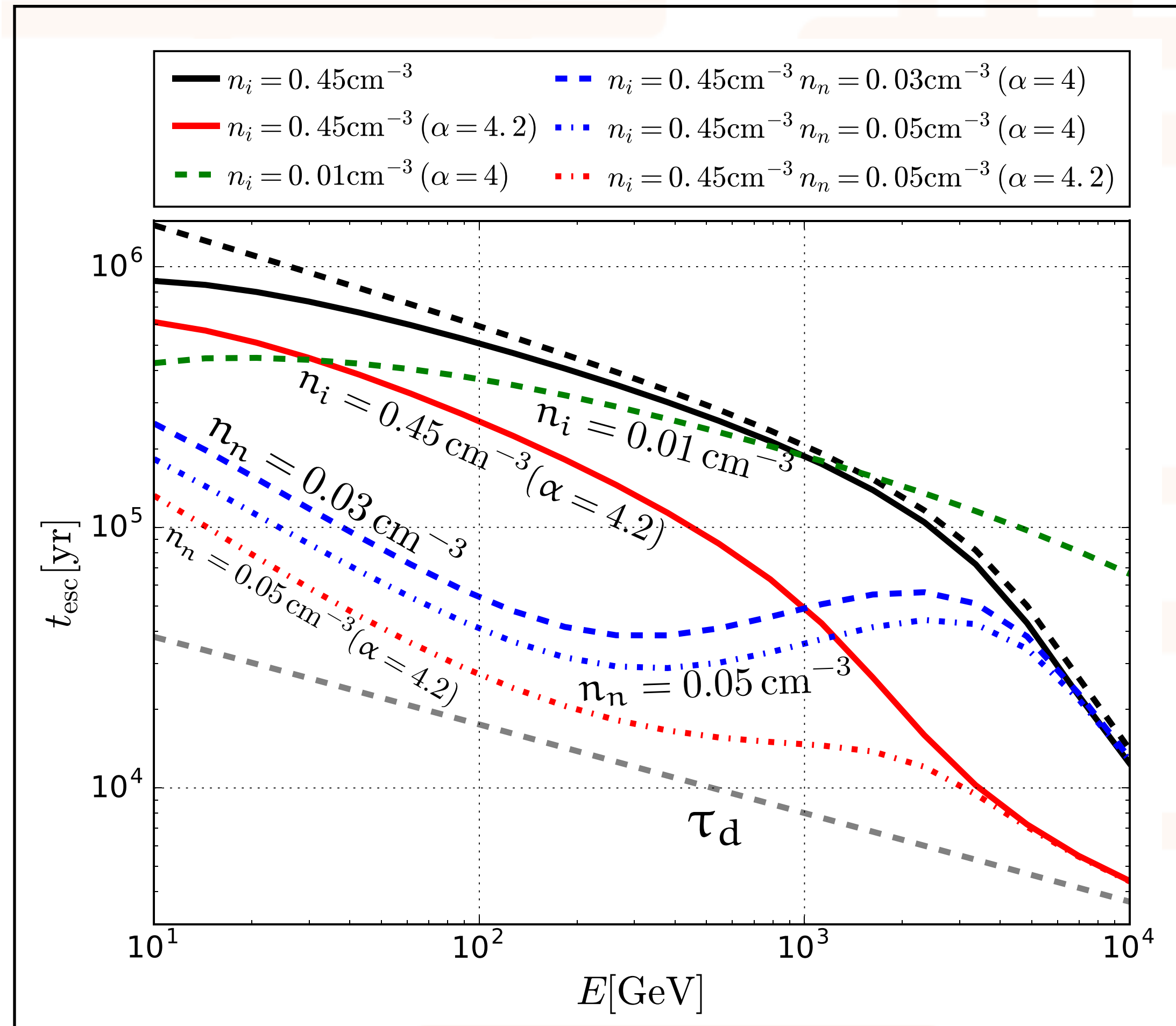
Since in the ordinary ISM $E_{CR} \approx E_B \approx E_{th}$, it is clear that near a source the escaping CR must produce

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



MOST REALISTIC SITUATION IS
THAT OF EITHER LOW DENSITY
MAINLY IONIZED GAS

OR

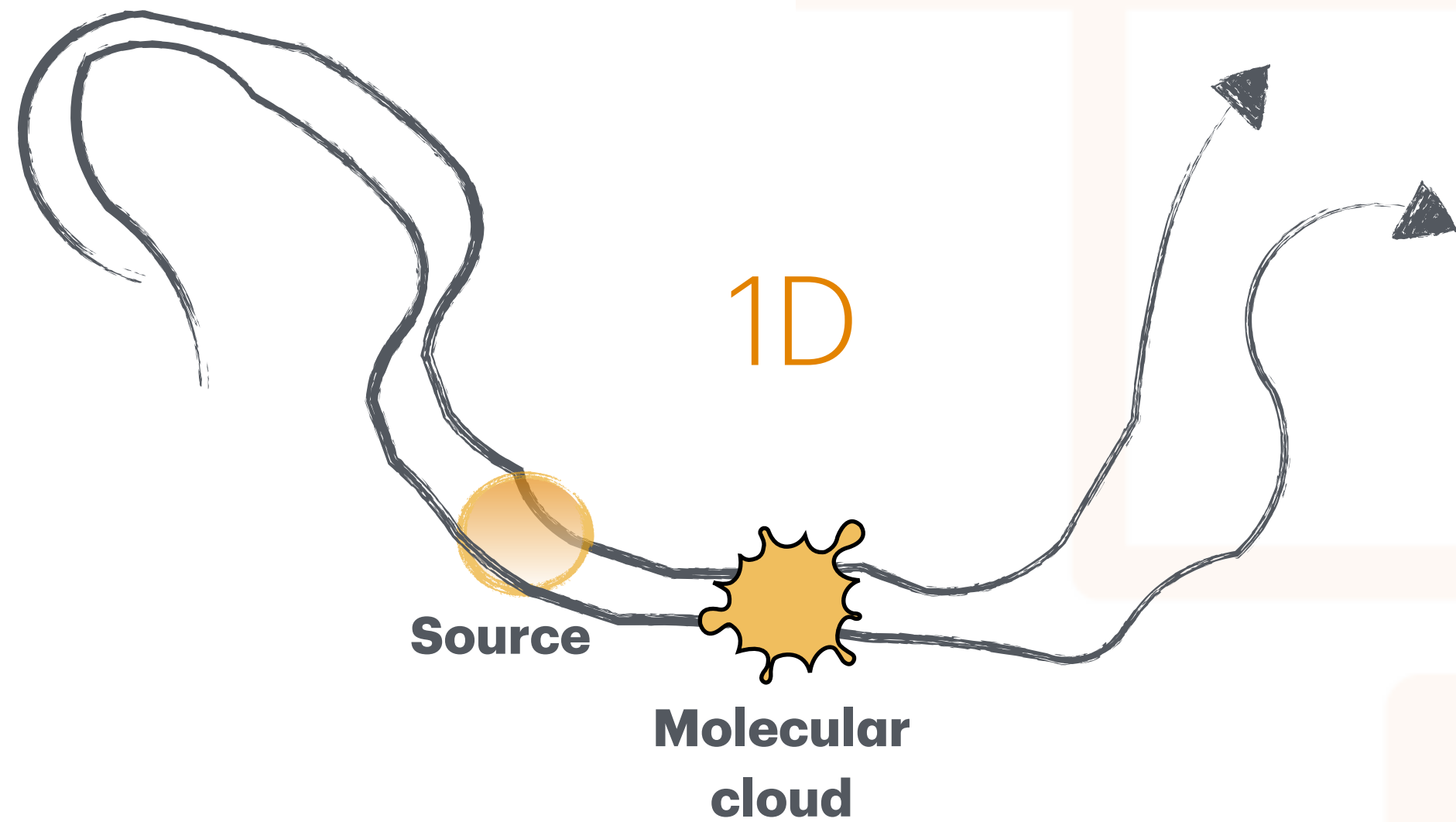
HIGHER DENSITY MOSTLY
NEUTRAL H-GAS

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



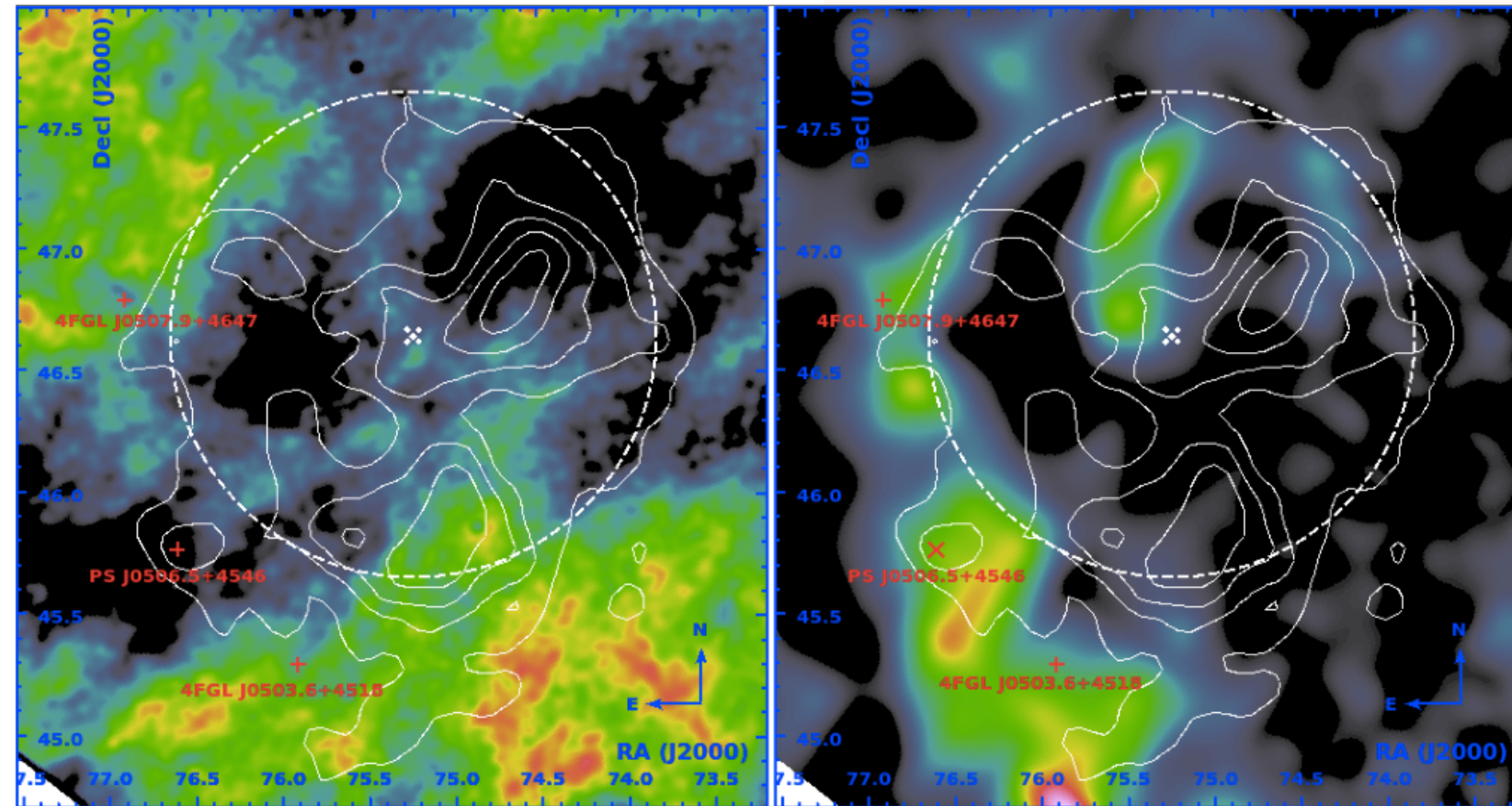
While confinement is easier if the surrounding medium is almost completely ionized, interactions of CR are easier in denser (hence partially ionized) plasma

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

The instance of HB9

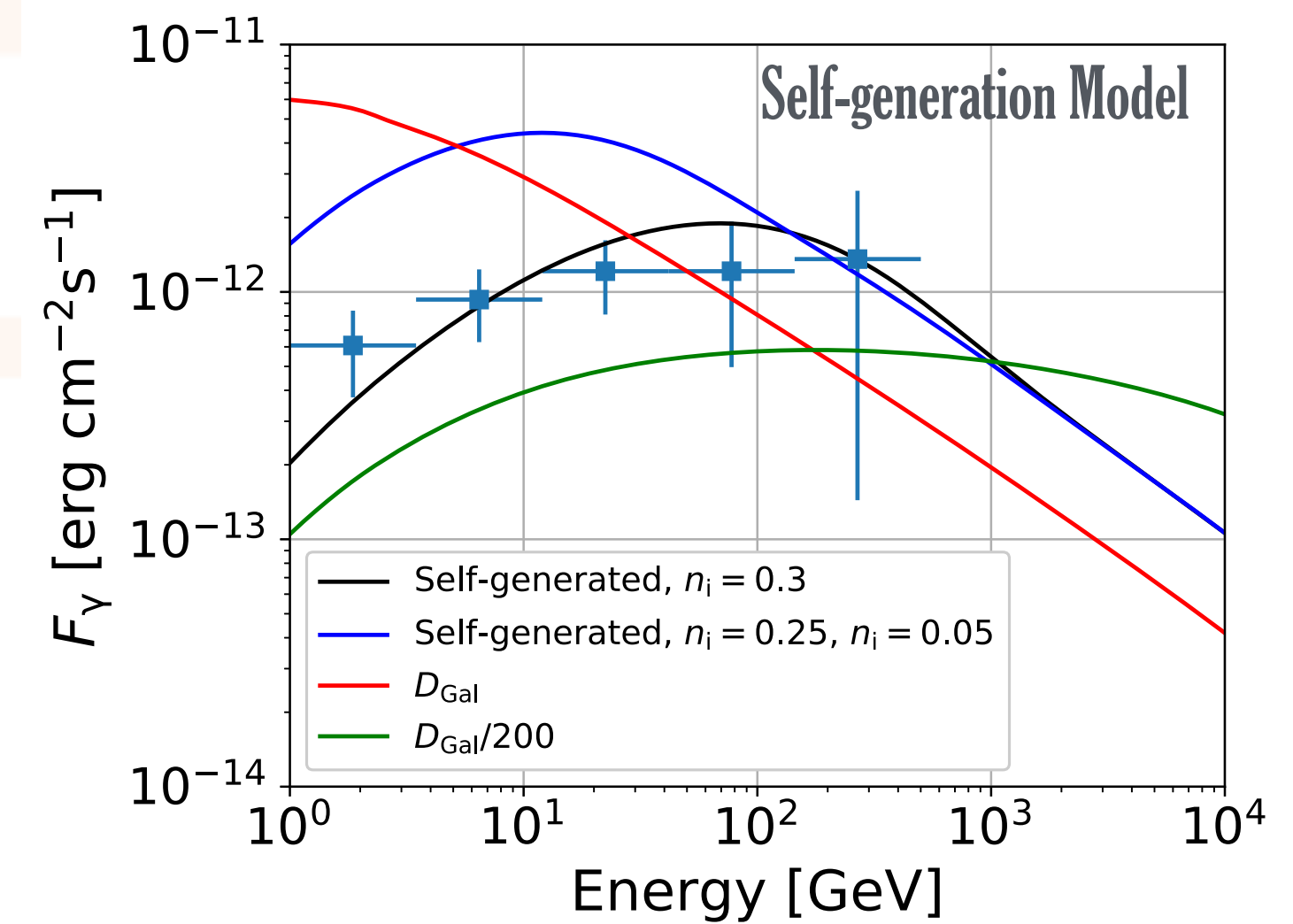
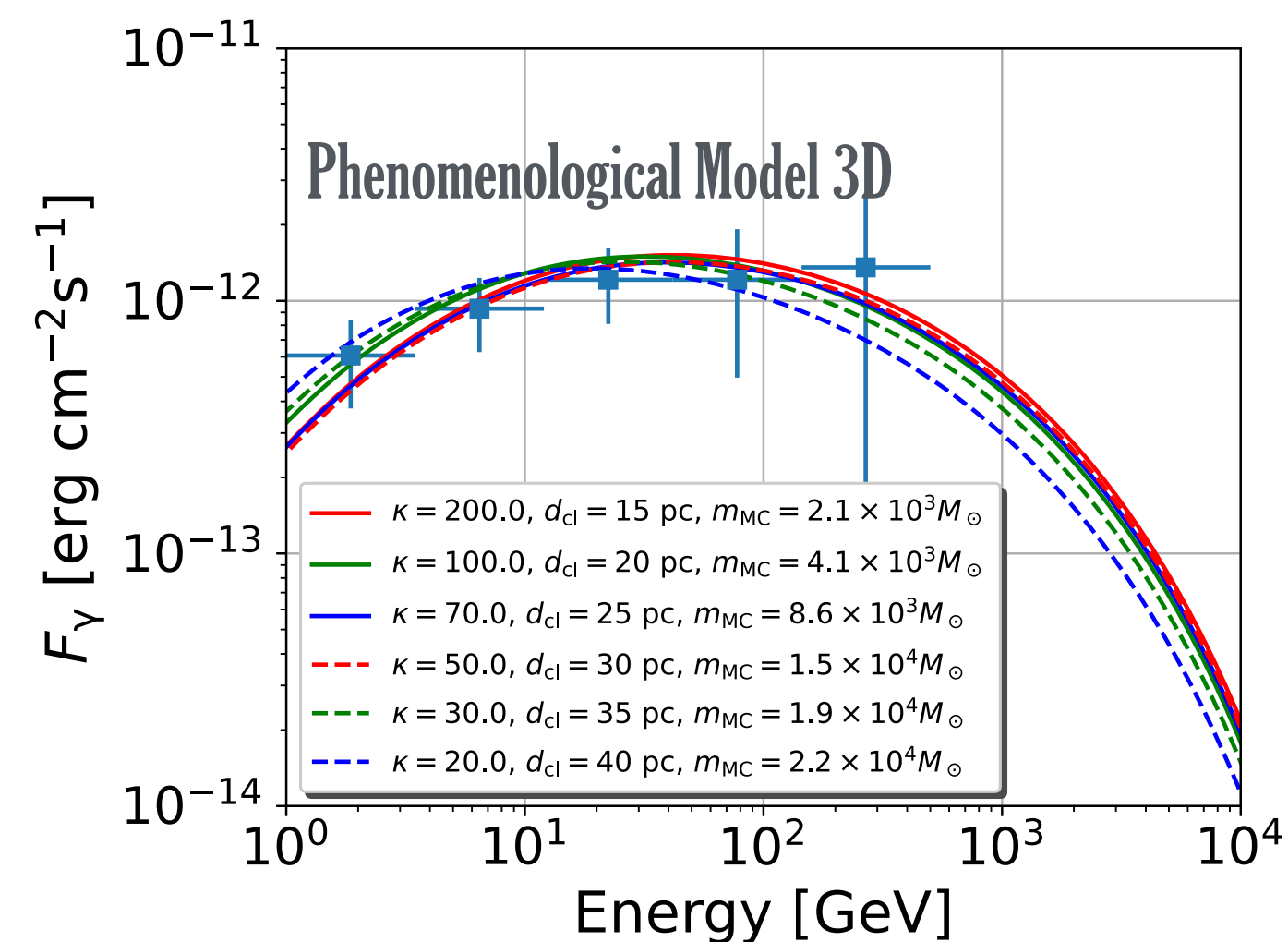
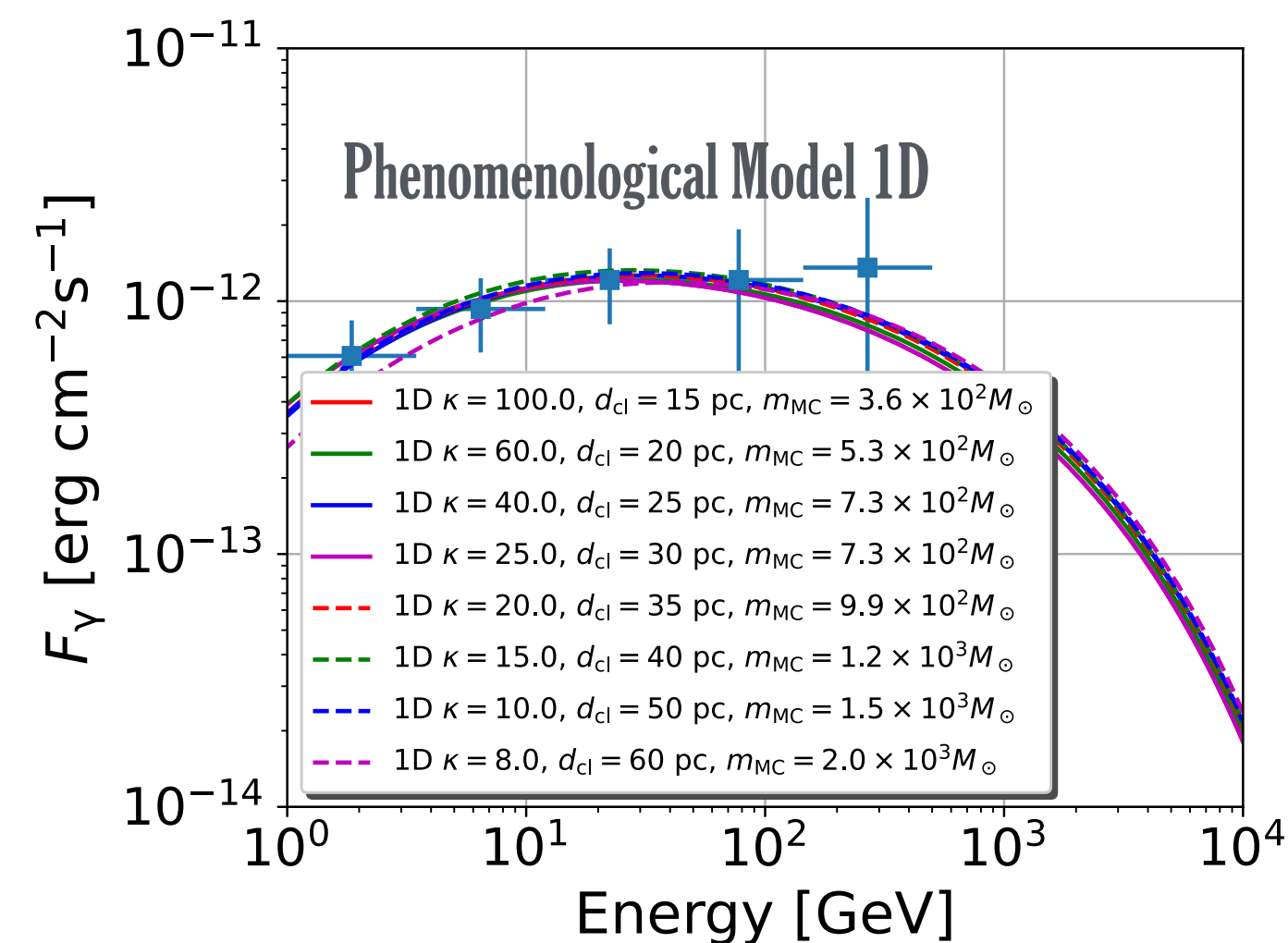


Distributions of H I (left panel) and $^{12}\text{CO}(J=1-0)$ (right panel) in the gamma-ray analysis region are shown in Equator

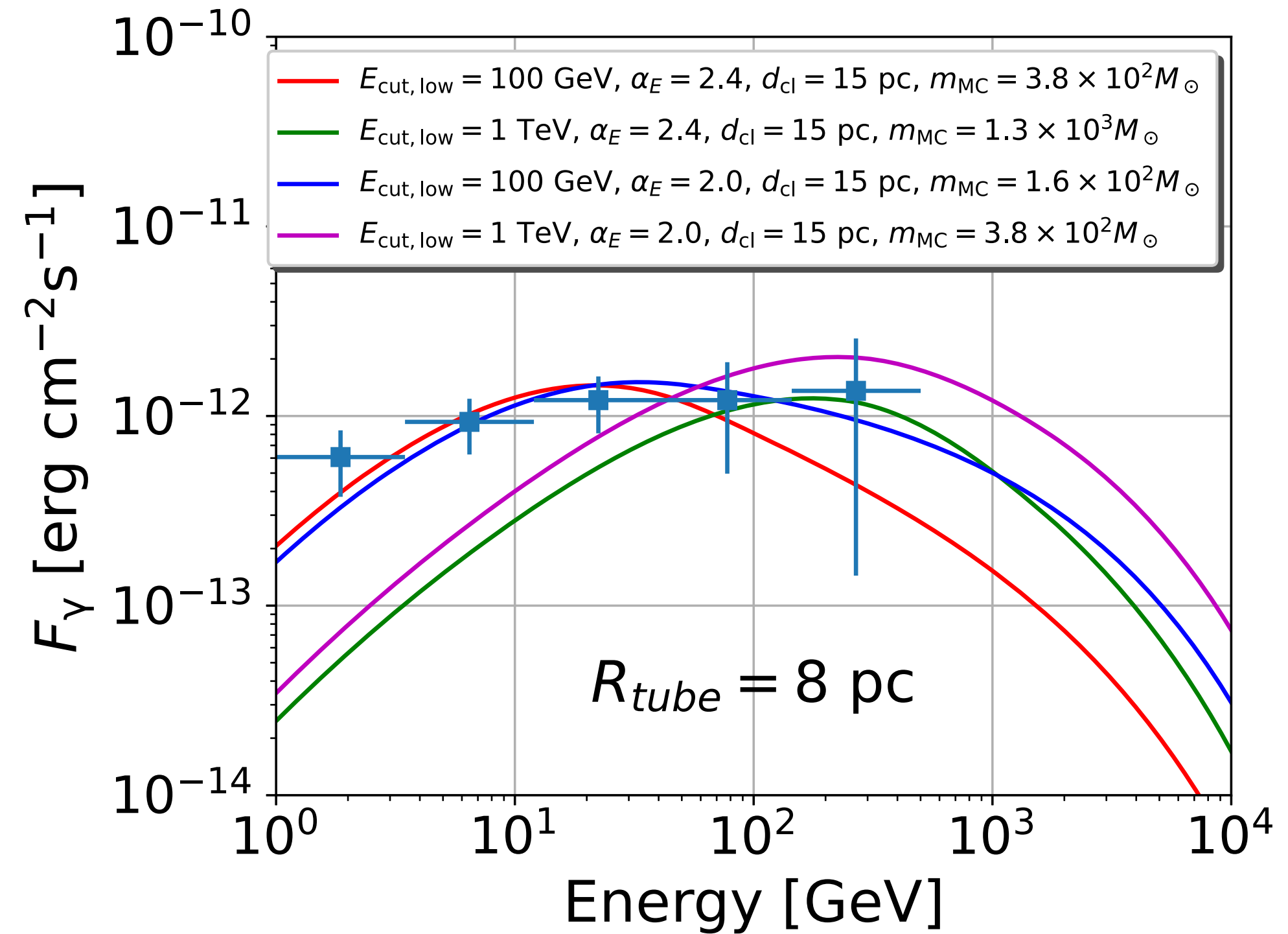
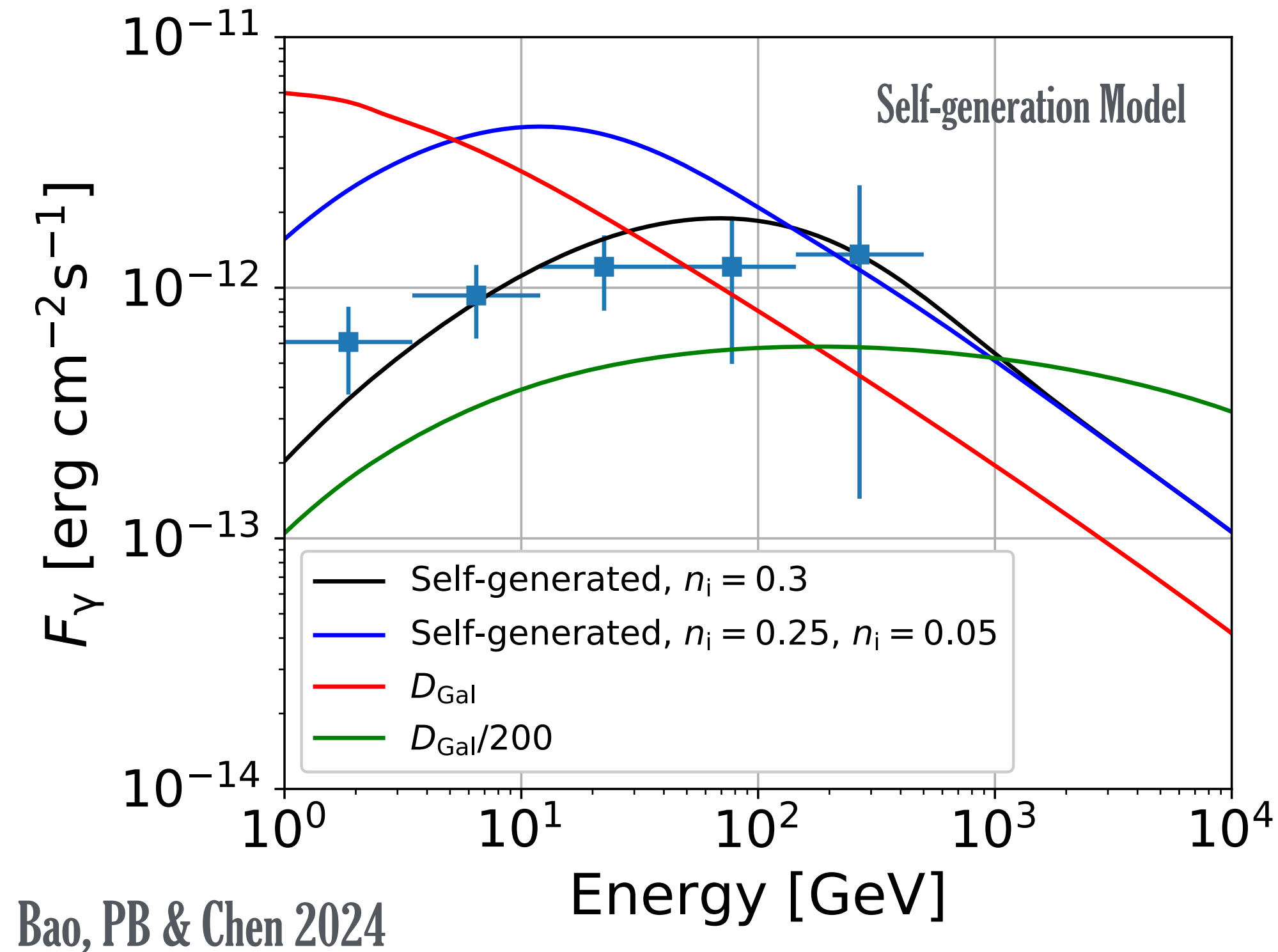
HB9 is a composite SNR with age ~ 7 kya and has two MC around, R1 and R2

R1 shows 1720 MHz maser emission, flagging shock-MC interaction, R2 seems cleaner

The estimated shock velocity at present is 640 km/s, certainly not a record breaker, but common in mature SNR



The instance of HB9: yet another ambiguous case



IF IT HAPPENS THAT THE MAX ENERGY AT THE AGE OF HB9 IS AS LOW AS 100 GeV, THEN THE LOW ENERGY SUPPRESSION MAY BE PRESENT EVEN WITHOUT SELF-GENERATION

THE EXPECTED MAX ENERGY IN THE PRESENCE OF ION-NEUTRAL DAMPING IS EXPECTED TO BE A FEW TeV, BUT HARD TO RULE OUT A LOWER VALUE

GRAMMAGE NEAR THE SOURCE

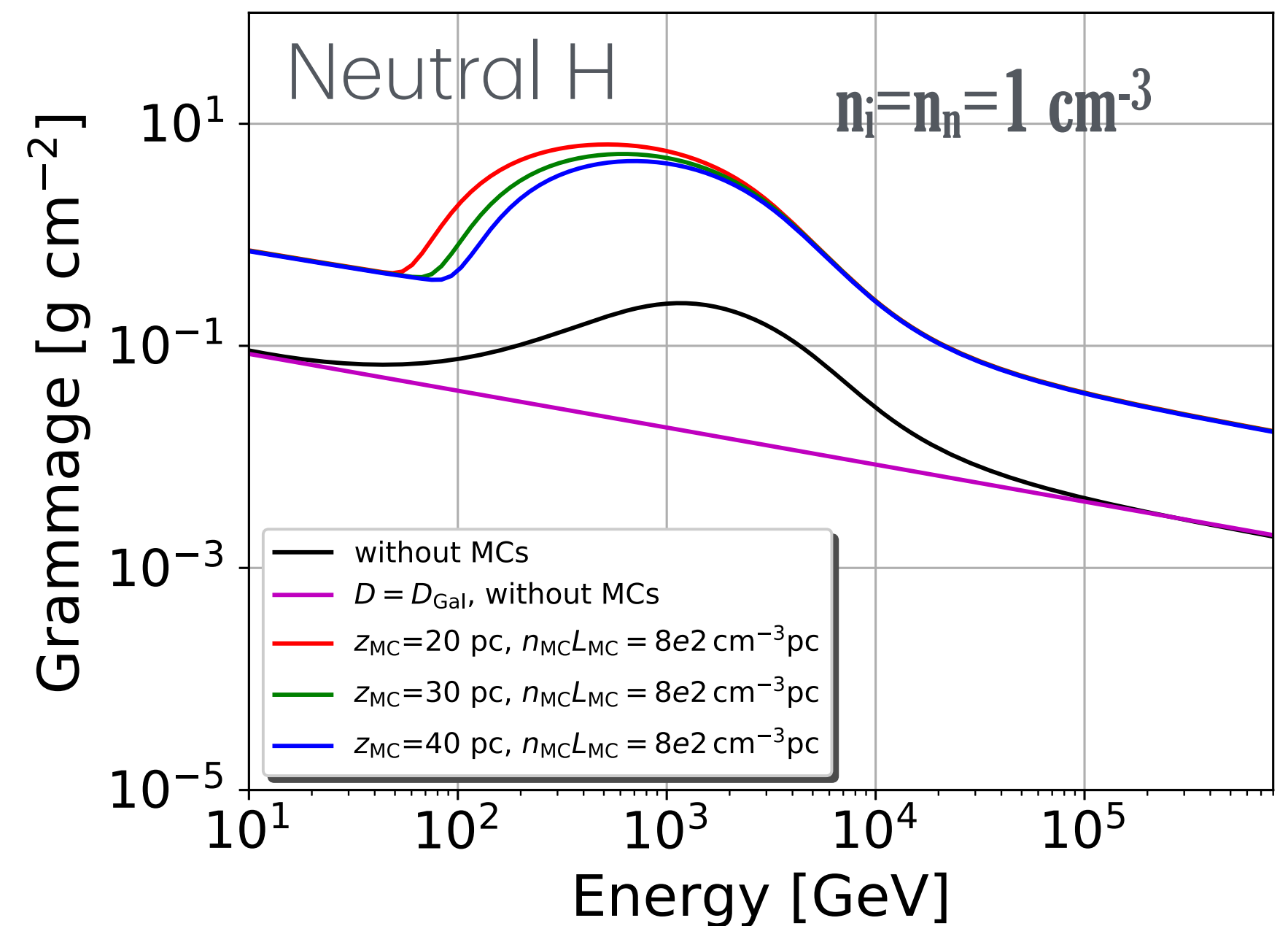
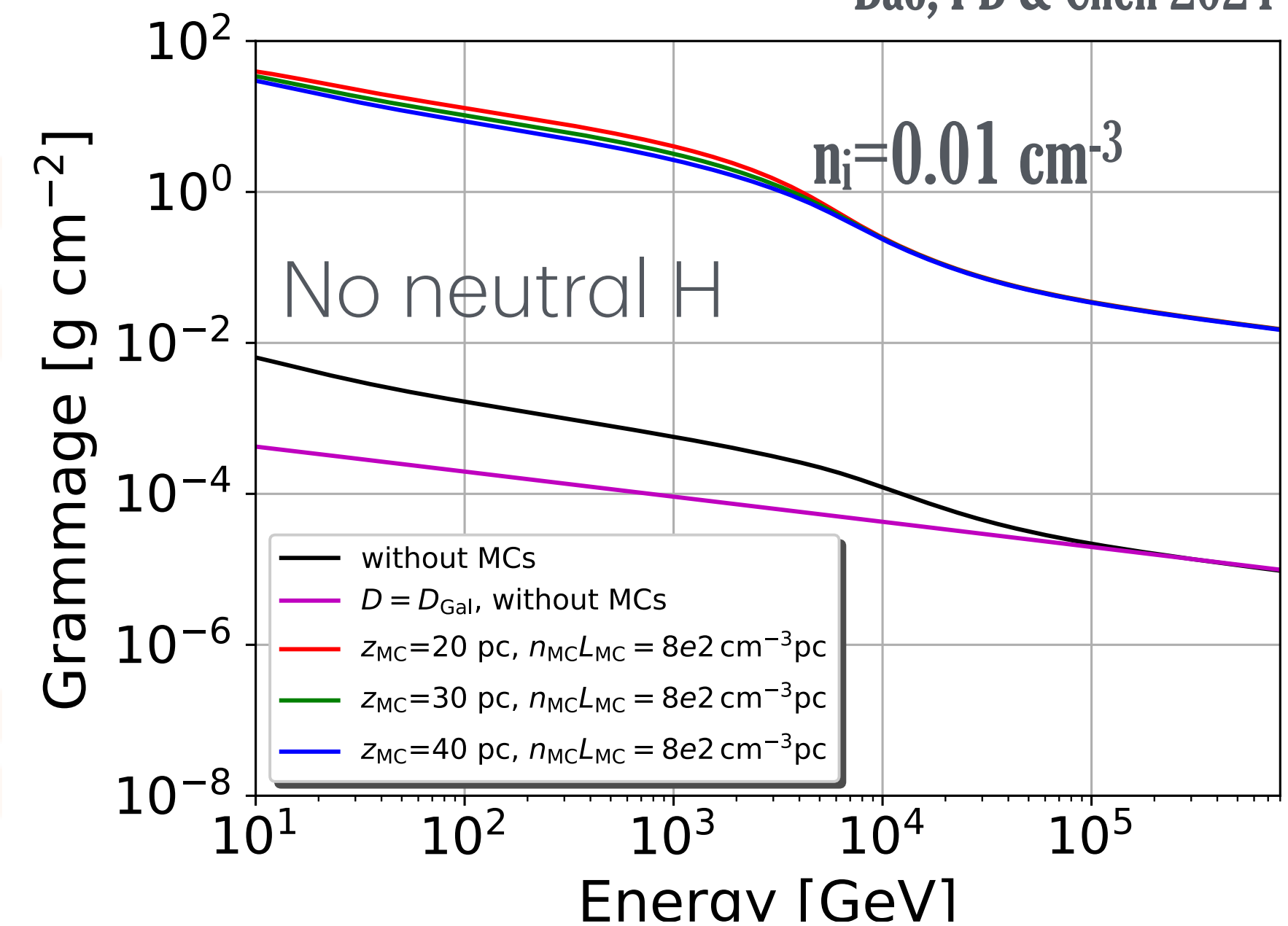
The grammage accumulated by CR near a source due to self-confinement depends on conditions (level of ionisation, coherence length)

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

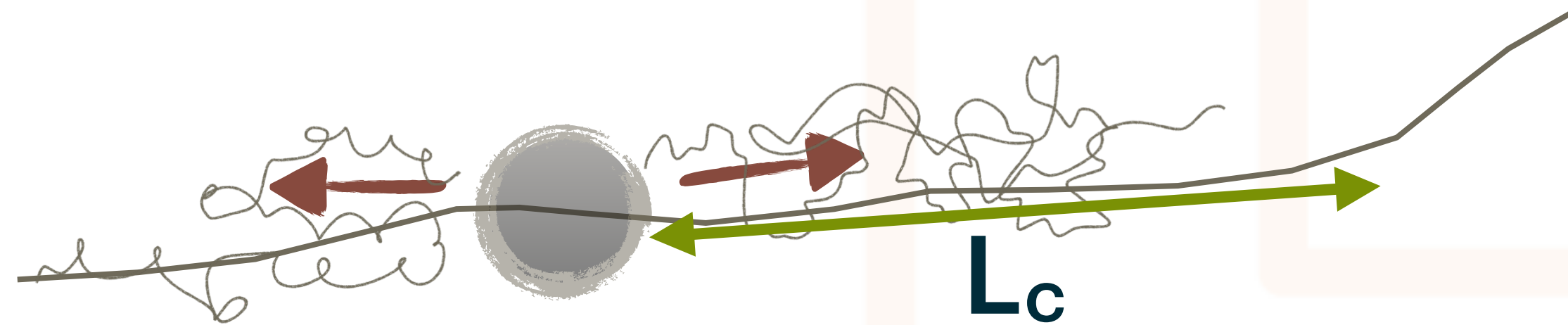
...but it is clear that it is not a phenomenon that we can ignore at a time in which measurements are made at percent level

... and at a time in which the diffuse fluxes of gamma rays and neutrinos hint at some possible anomalous behaviour

Bao, PB & Chen 2024



A CLOSER LOOK AT CR ESCAPING A YOUNG SNR



It is easy to show that the diffusive path length in the Galaxy is expected to be $\lambda(E) \approx 30 \text{ pc } E_{\text{TeV}}^{1/2}$

so that a $>\text{TeV}$ particle should travel almost undisturbed on scales $\sim L_c$ thereby contributing to a CR electric current

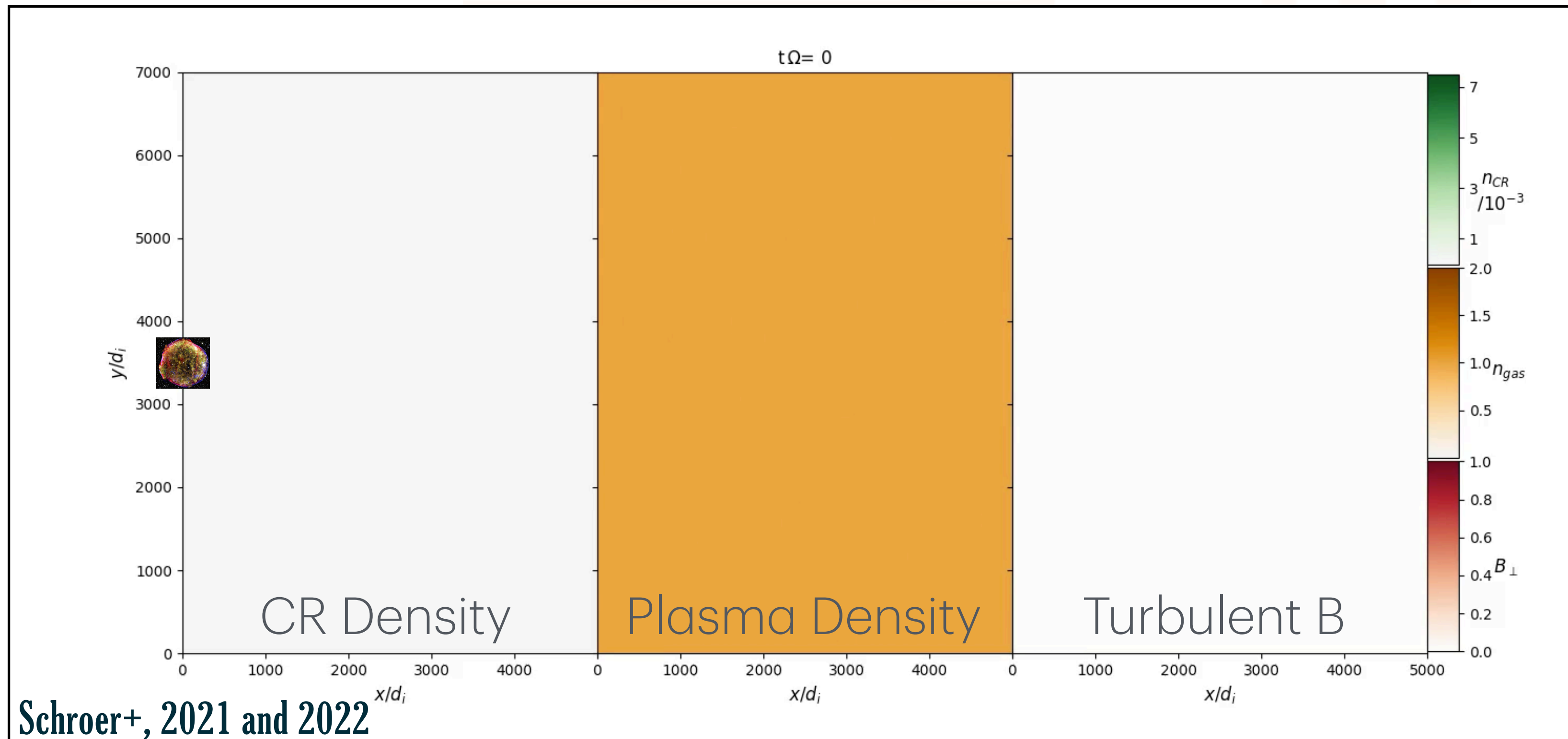
If the SNR is relatively young, the cross section of the flux tube is small, hence the energy density of the particles can be large and possibly satisfy the conditions for the growth of the non resonant streaming instability

$$n_{CR}(> E) E \frac{v_D}{c} \geq \frac{B_0^2}{4\pi}$$

where the drift velocity for streaming particles is close to c

Notice that the energy density carried by these high energy particles may by itself be $>\text{ISM}$ energy density!

SIMULATING THE STREAMING OF CR NEAR A SOURCE



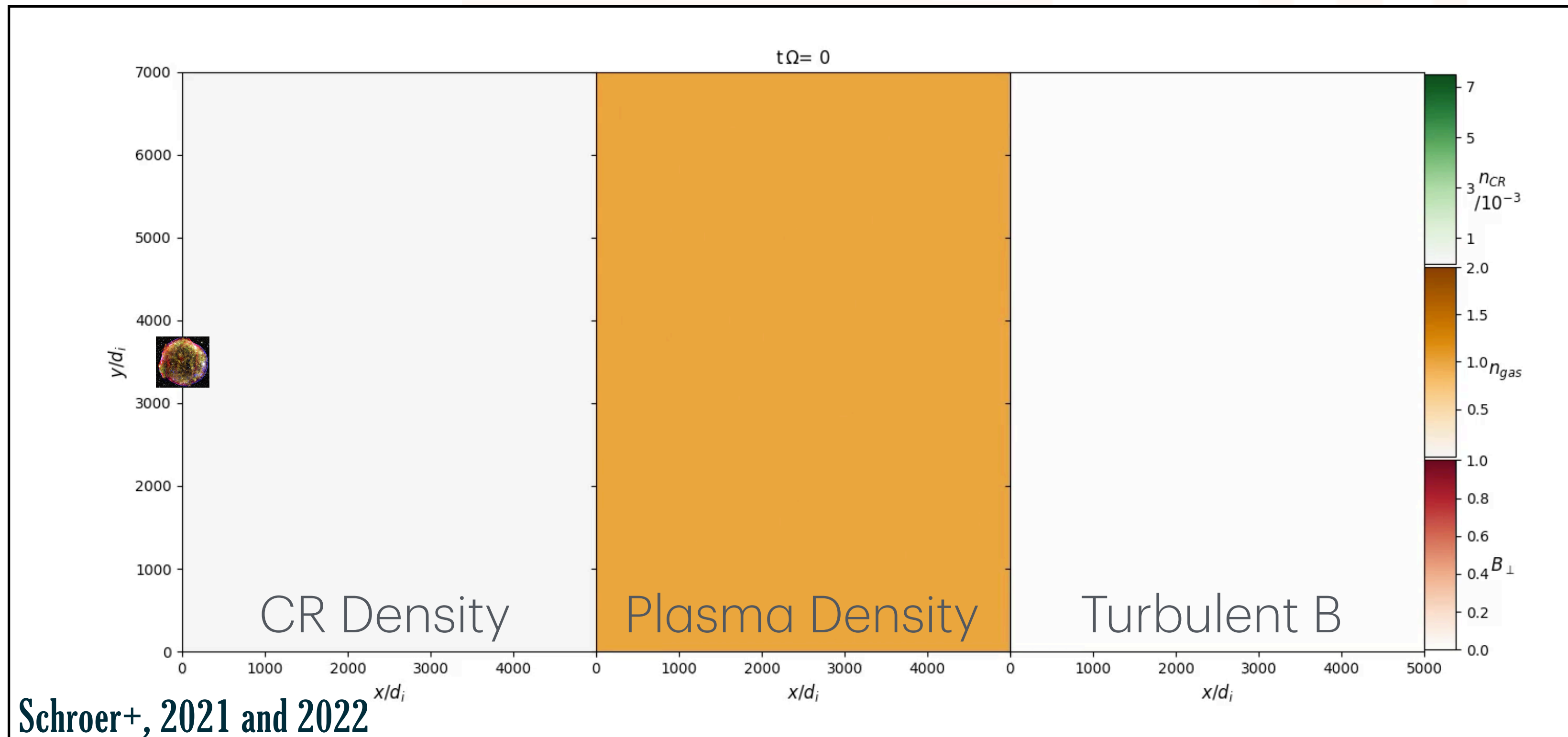
We used 2D and 3D PIC Hybrid numerical simulations to mimic the streaming of particles in the ISM near a source

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)

SIMULATING THE STREAMING OF CR NEAR A SOURCE



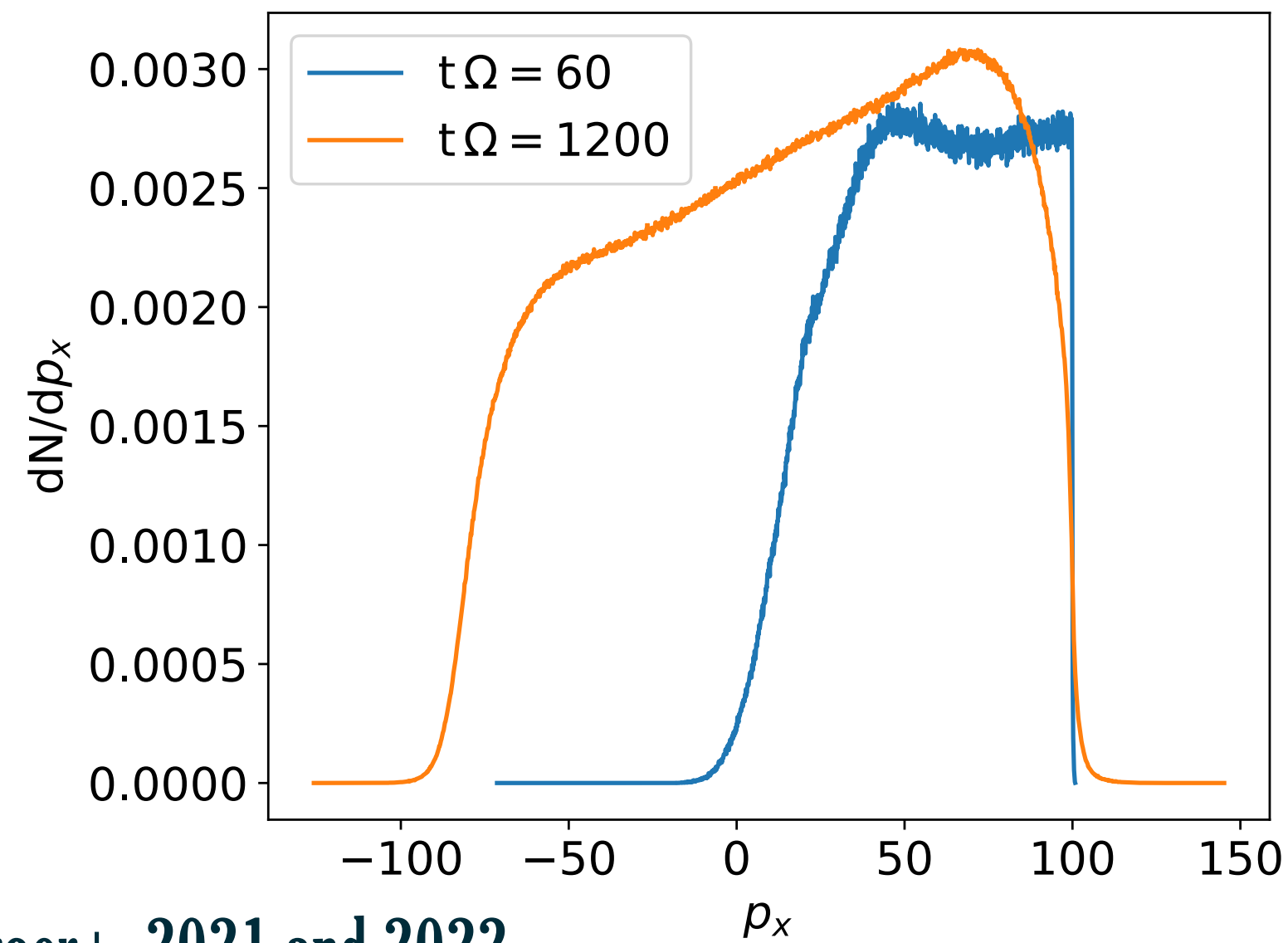
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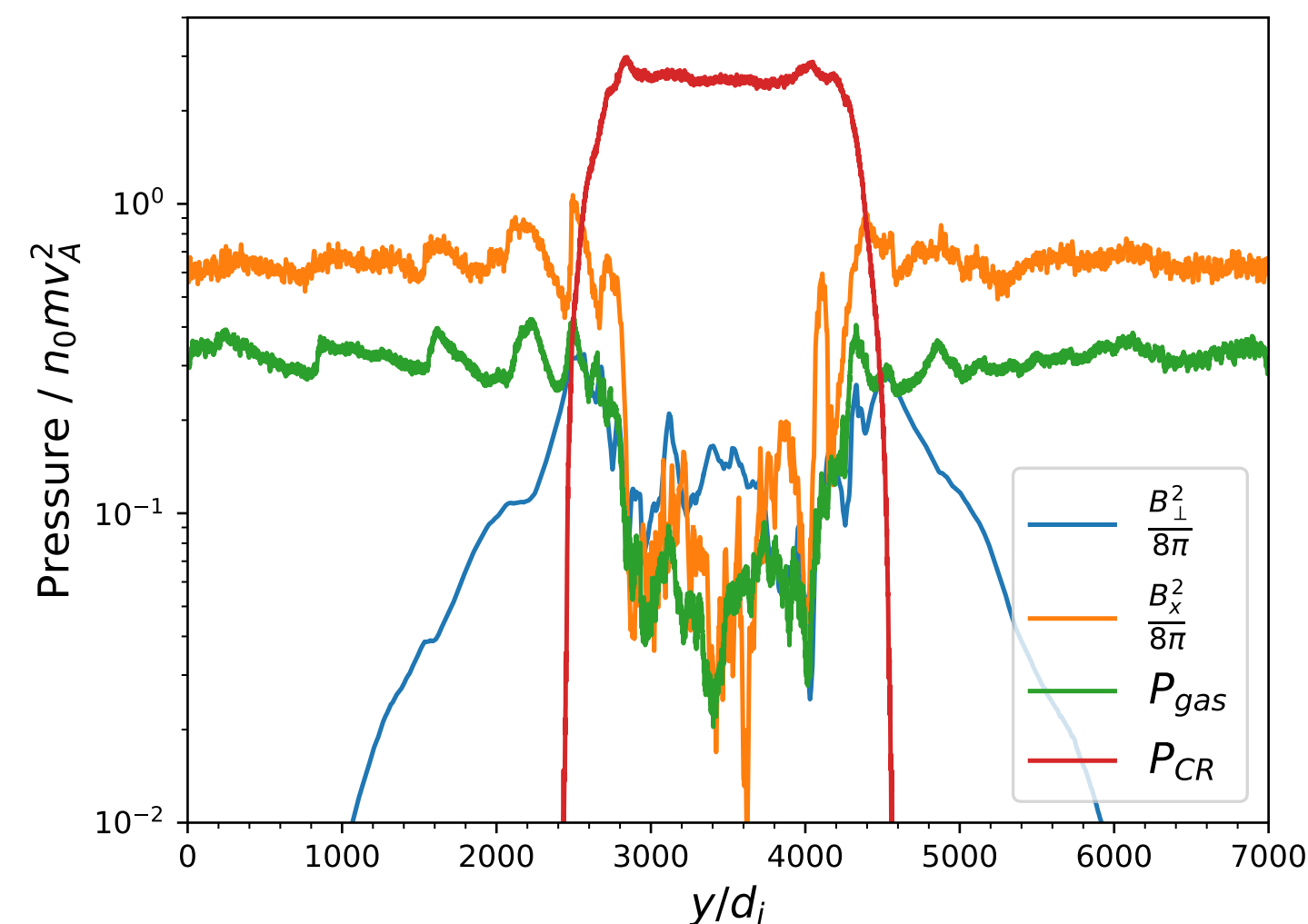
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Onset of diffusion and creation of the bubble



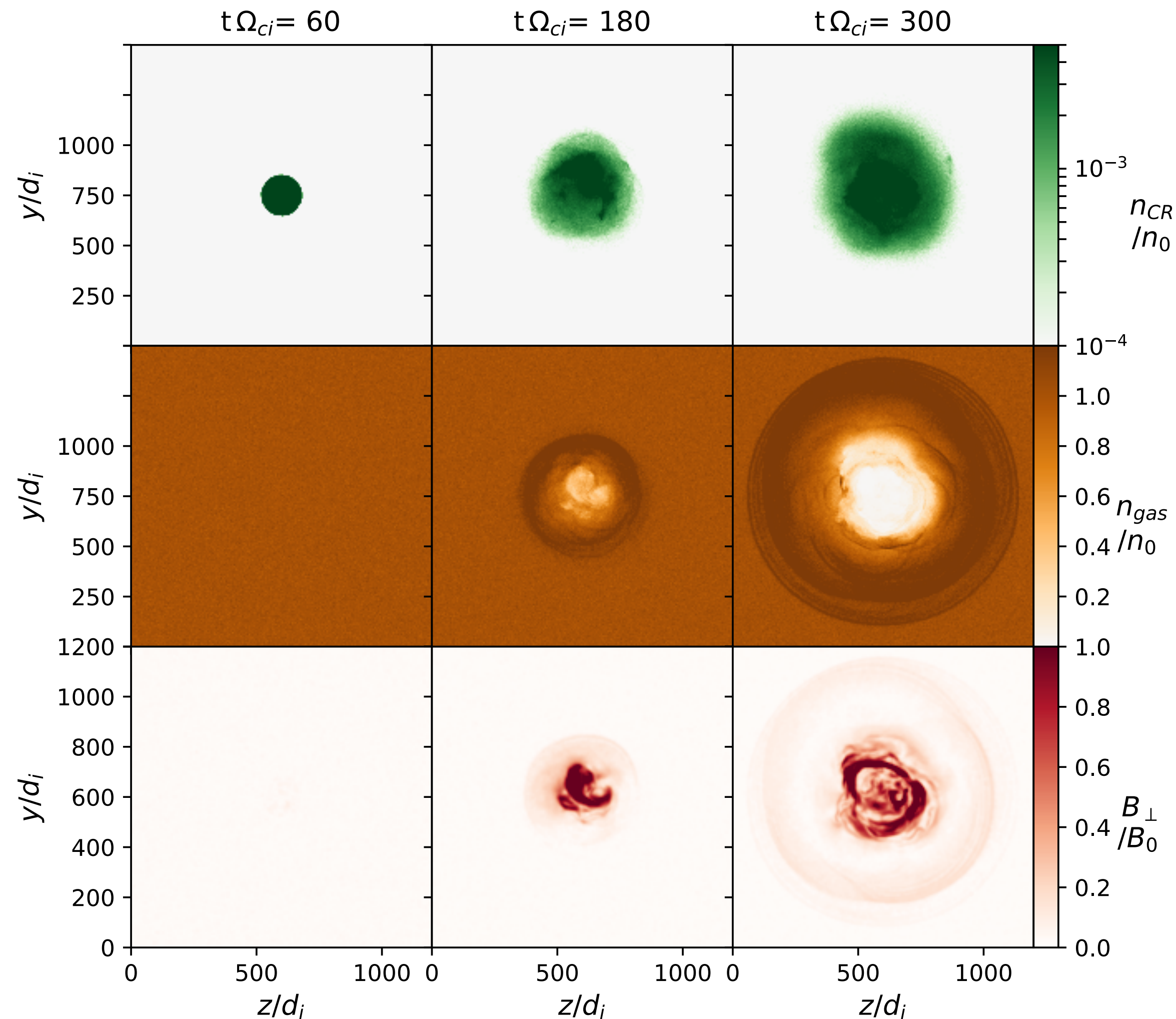
Schroer+, 2021 and 2022



- 📌 In the beginning most particles move forward, $\mu > 0$
- 📌 When B is created particles scatter and populate $\mu < 0$
- 📌 Eventually the particles get isotropized

- ◆ After production of the perturbations, the regular field is plowed away outward
- ◆ The turbulent field grows and eventually saturates
- ◆ The gas is evacuated from the bubble, n_{gas} drops
- ◆ The CR density increases considerably

3D PIC Hybrid



- The global picture seems unaltered, though numerical limitations force us to stop at earlier times

- The bubble is still evacuated of the gas due to the CR pressure gradient, but more mixing with outside ISM

- Similar growth of the magnetic field in the bubble

Assuming that a fair amount of the CR energy is injected in the bubble before the Sedov phase (small region) and neglecting damping, the bubble should expand until pressure balance with ISM $\longrightarrow R_{\text{bubble}} \sim 50\text{-}100 \text{ pc}$

The evacuation ensures that the grammage remains small despite the long confinement time in the near source region (unless clouds...)

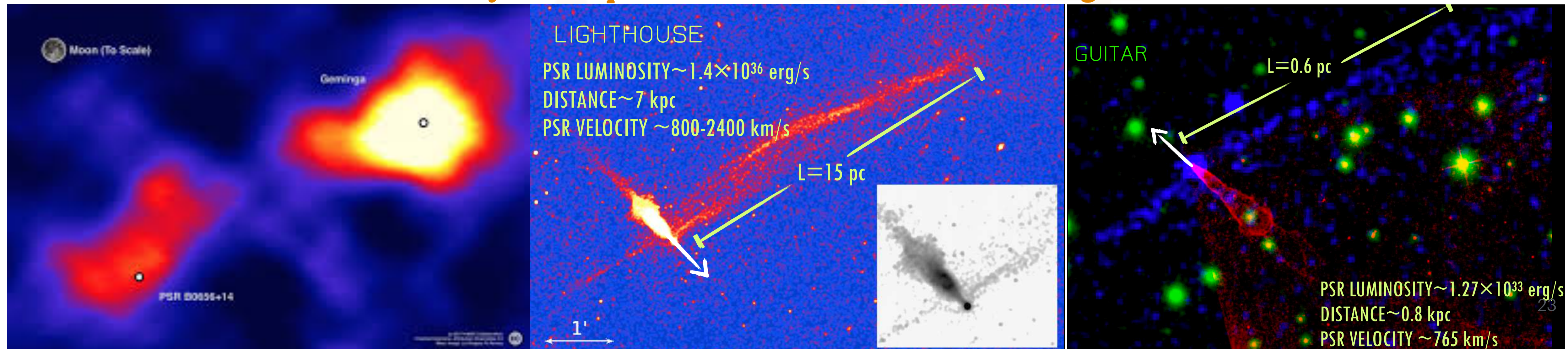
A vibrant pink and purple nebula streaks diagonally across the upper half of the image. The background is a deep blue-black space filled with numerous bright, out-of-focus stars of varying sizes and colors, primarily white and blue. The nebula has a soft, ethereal glow with some darker, more defined structures within it.

ESCAPE FROM A PULSAR WIND NEBULA

TeV HALOS AND FILAMENTS

- Several PWN have now been observed to be at the center of TeV halos
- The diffusion coefficient in these regions is inferred to be ~ 100 - 1000 times smaller than in the ISM
- These regions are the first firm proof of the production of pairs by PWN (important for positron excess)
- In addition to the halos, long filaments of X-ray emission protruding from PWN have been observed, with inferred strength of the magnetic field of a few tens μG

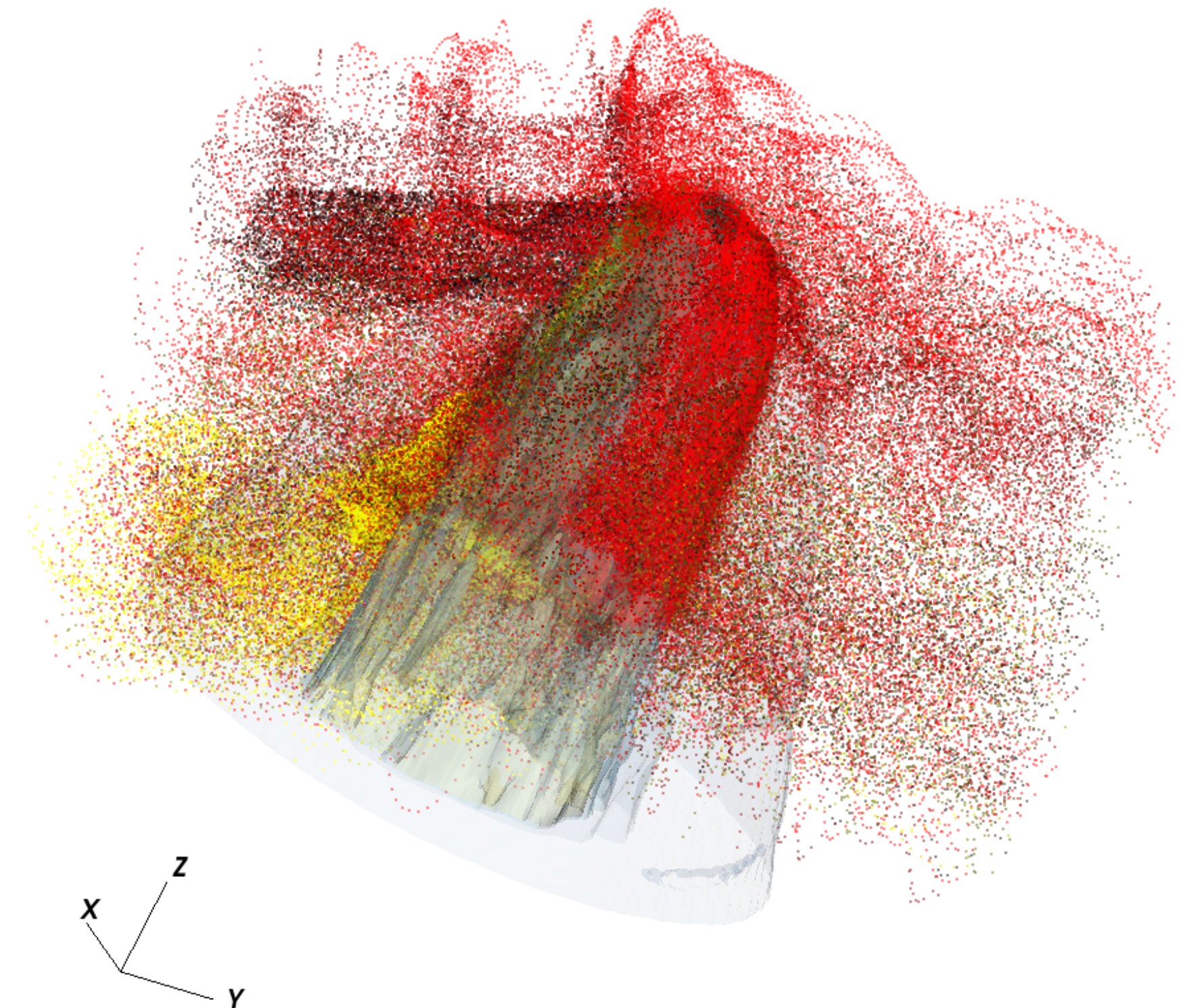
May these phenomena have a common origin?



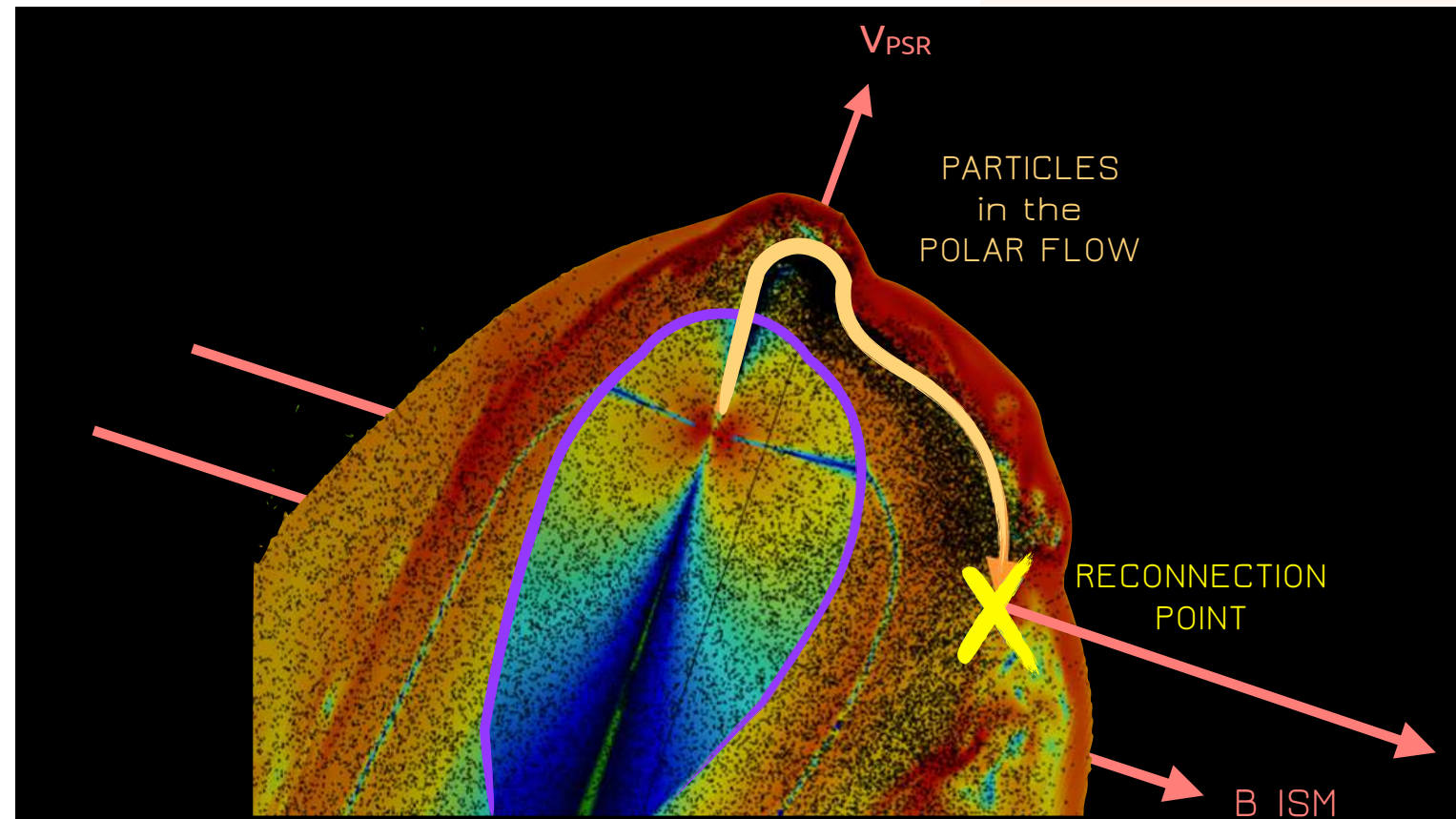
DIFFERENCES BETWEEN PWN AND SNR

- 📌 The energetic in the form of non-thermal particles of a SNR is usually larger than that of PWN
- 📌 The vast majority of the non-thermal energy of a SNR is emitted in the form of electric charges of one sign (protons)
- 📌 In general, PWN produce an equal number of electrons and positrons, so that the total charge at any given location vanishes (**no net current** → **no non-resonant modes**)
- 📌 *...with the exception of particles near the potential drop, where charge separation between positrons and electrons is possible and in fact expected*

Olmi & Bucciantini 2019



THE MAKING OF AN X-RAY FILAMENT



Courtesy B. Olmi

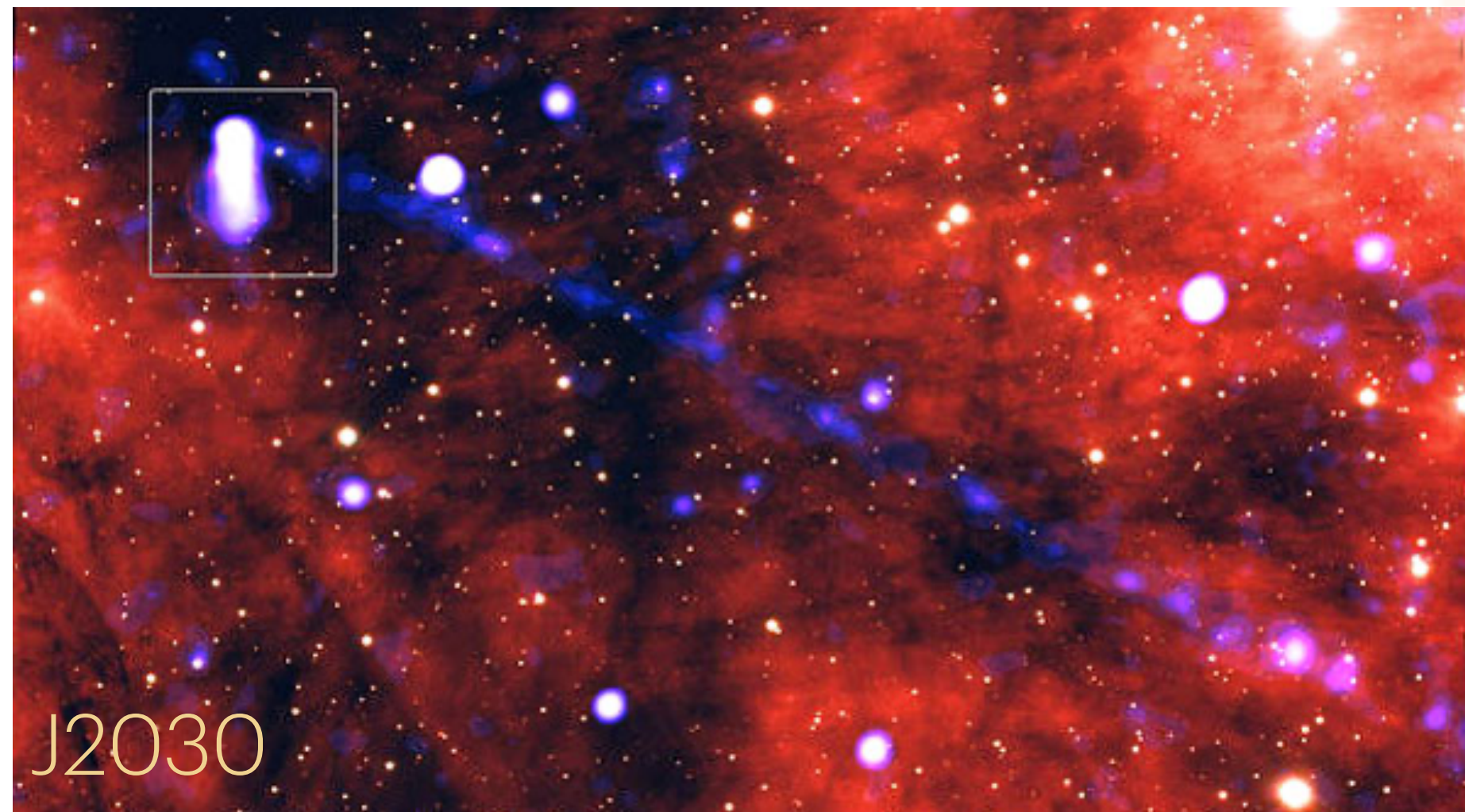
Particles with Lorentz factor below but close to the maximum potential drop may be able to leave the nebula, for instance through a reconnection point:

$$\gamma_{\text{MPD}} = \frac{e}{mc^2} \sqrt{\frac{\dot{E}}{c}}$$

Particles move along the ISM B-field covering a transverse surface A and carrying a current:

$$j_p = \epsilon \frac{m c^3}{e \pi R^2} \frac{\gamma_{\text{MPD}}^2}{\gamma_{\text{esc}}} = e \epsilon \dot{E} / (m c^2 \gamma_{\text{esc}} A)$$

The length and width of the X-ray feature together with the X-ray luminosity of the feature fix the parameters of the problem [Olmi, Amato, Bandiera & PB 2024]



THE MAKING OF AN X-RAY FILAMENT

The non-resonant hybrid instability is excited if the beam of particles is sufficiently collimated, and it grows as

$$\Gamma = \Omega_{cyc} \left(\frac{v_A}{c} \right) \frac{\epsilon}{\epsilon_{lim}} \frac{1}{\gamma_{esc}} \quad \epsilon_{lim} = \frac{\sin^2 \alpha}{4} \left(\frac{\gamma_{esc}}{\gamma_{MPD}} \right)^2$$

Provided $\epsilon > \epsilon_{lim}$ the instability is excited and saturates at a level

$$\left(\frac{\delta B}{B_0} \right)^2 = \frac{\epsilon}{\epsilon_{lim}}$$

Recall that the non resonant hybrid instability initially grows on scales much smaller than the Larmor radius of the particles dominating the current, hence it can grow exponentially way into its non linear stage, until scattering starts, when the scale becomes comparable with the gyration scale

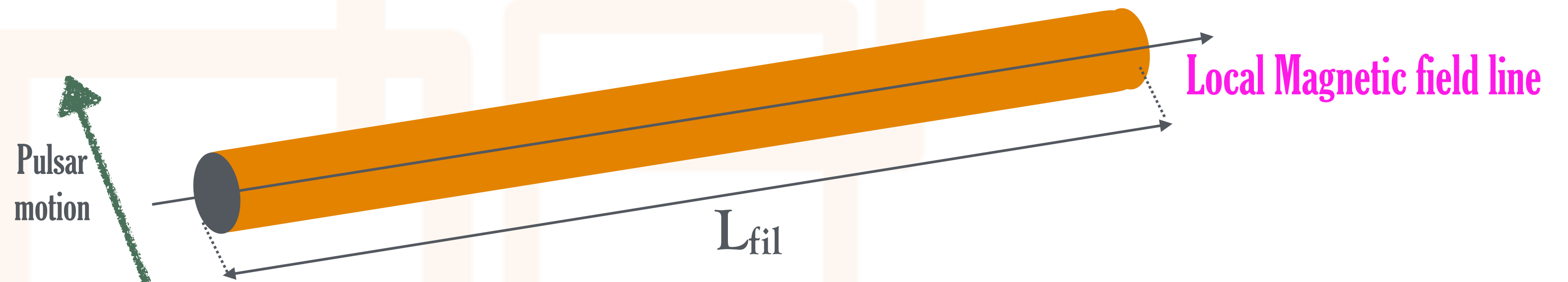
LENGTH OF THE FILAMENTS

Typically the instability requires 5-10 e-folds for saturation, during which the particles move at $\sim c$

After saturation particles start diffusing and the escape time from the filament becomes long

The length of the filament is therefore:

$$L_f \approx 5c \tau_{\text{CR}} = \frac{5c}{\Omega_c} \left(\frac{c}{v_A} \right) \left(\frac{\epsilon}{\epsilon_{\text{lim}}} \right)^{-1} \gamma_{\text{esc}} \\ \simeq 422 \text{ pc} \left(\frac{\epsilon}{\epsilon_{\text{lim}}} \right)^{-1} \gamma_7 n_1^{1/2} B_3^{-2}$$

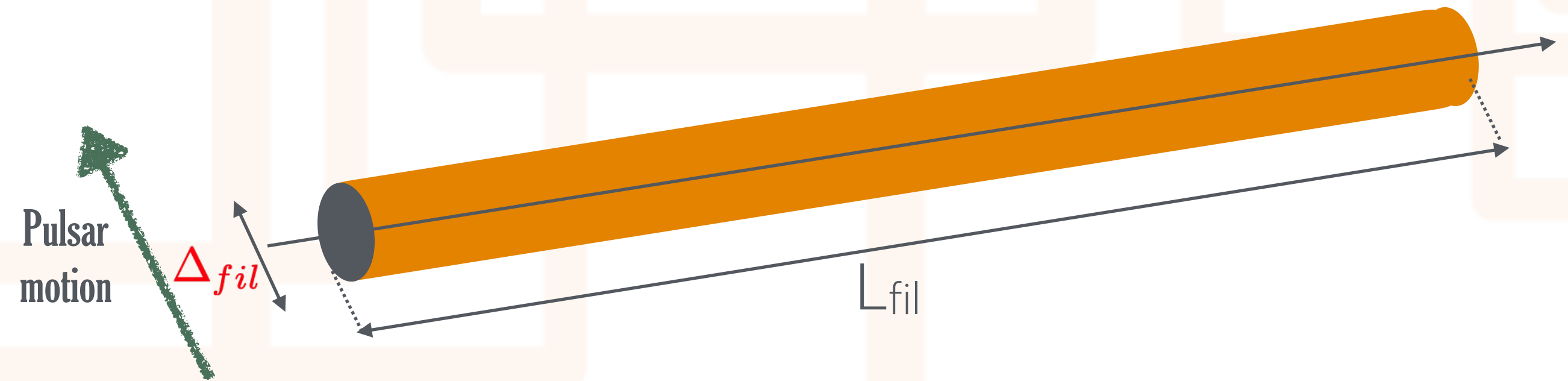


The particles that radiate in X-rays usually have energy a bit larger than the escaping particles...

Their diffusion time was estimated by using the small pitch angle assumption... they get isotropized very quickly after saturation of the instability

THICKNESS OF THE FILAMENTS

Once the magnetic field is amplified, the motion of the pulsar would transform the filament into a stripe, if it were not for synchrotron energy losses that limit the thickness



$$\Delta_{fil} \approx v_{pulsar} \tau_{loss}(E)$$

$$\tau_{loss} \approx 100 \text{ years} \left(\frac{L_{fil}}{0.6 \text{ pc}} \right)^{3/4} \left(\frac{\gamma_{esc}}{10^7} \right)^{-3/4} \left(\frac{E_X}{\text{keV}} \right)^{-1/2}$$

The filament is reformed continuously while the pulsar moves forward, but its thickness remains roughly the same and limited by losses in the self-generated magnetic field

THE CASE OF THE GUITAR NEBULA



$$\dot{E} = 1.27 \times 10^{33} \text{ erg/s}$$

$$v_{\text{pulsar}} = 765 \text{ km/s}$$

$$\gamma_{\text{MPD}} = 1.2 \times 10^8 \quad \text{Maximum Potential Drop}$$

$$E_X = 1 \text{ keV}$$

$$L_{\text{fil}} = 0.6 \text{ pc}$$

$$\Delta_{\text{fil}} = 0.08 \text{ pc}$$

$$\mathcal{L}_X \approx 3.6 \times 10^{30} \text{ erg/s}$$

The calculations require that the focusing occurs on angles $\sin \alpha \approx 5 \times 10^{-2}$

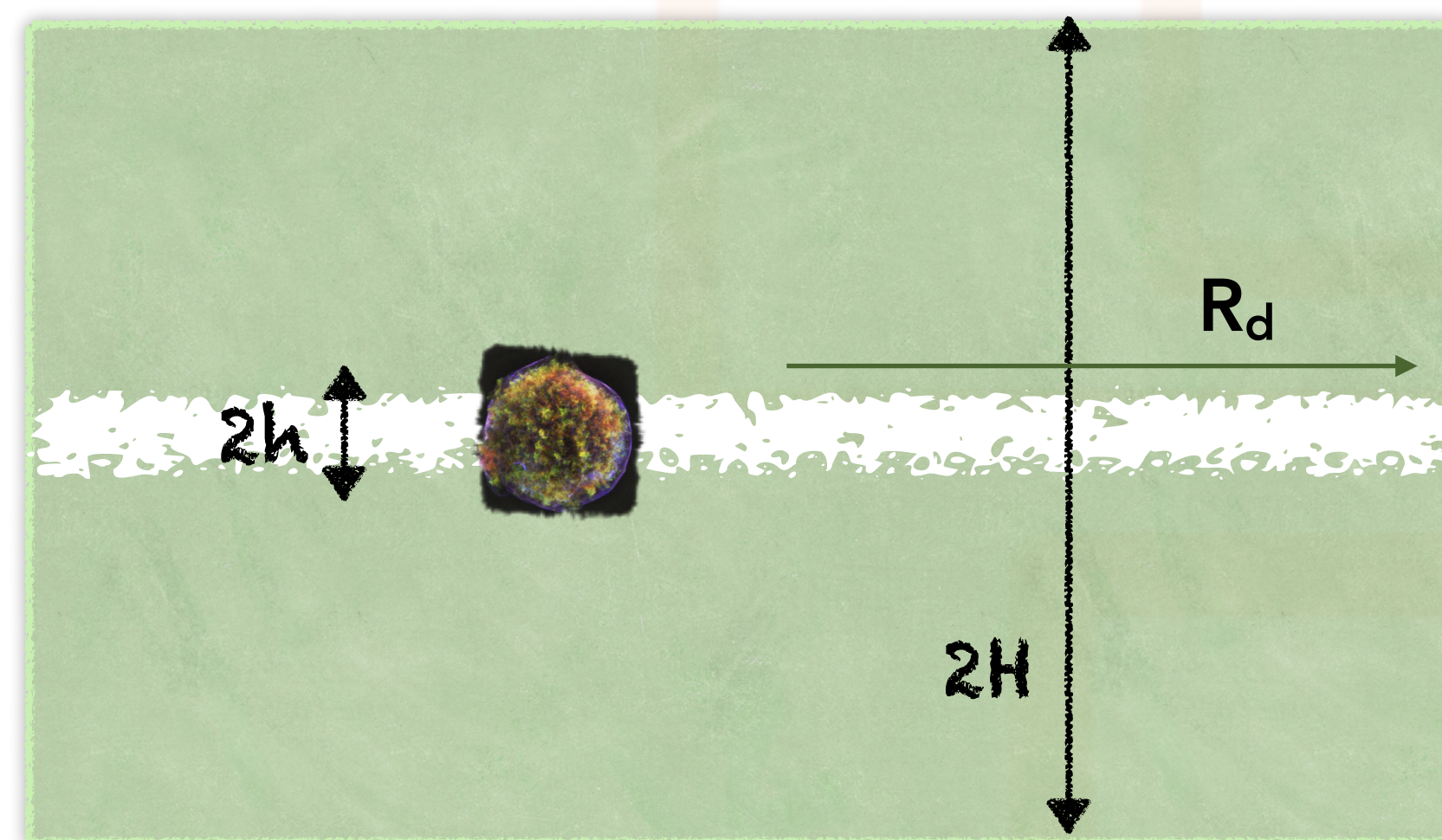
with an efficiency $\epsilon \approx 7 \times 10^{-3}$ and a Lorentz factor of escaping electrons $\gamma_{\text{esc}} = 1.5 \times 10^7$

The magnetic field in the filament after the saturation of the instability is $\delta B \approx 70 \mu\text{G}$
compatible with the thickness of the filament being loss dominated

ESCAPE OF COSMIC RAYS FROM A GALAXY



A TOY MODEL FOR PROTONS in OUR GALAXY



HALO ~ several kpc

DISC ~ 300 pc

Assumptions of the model:

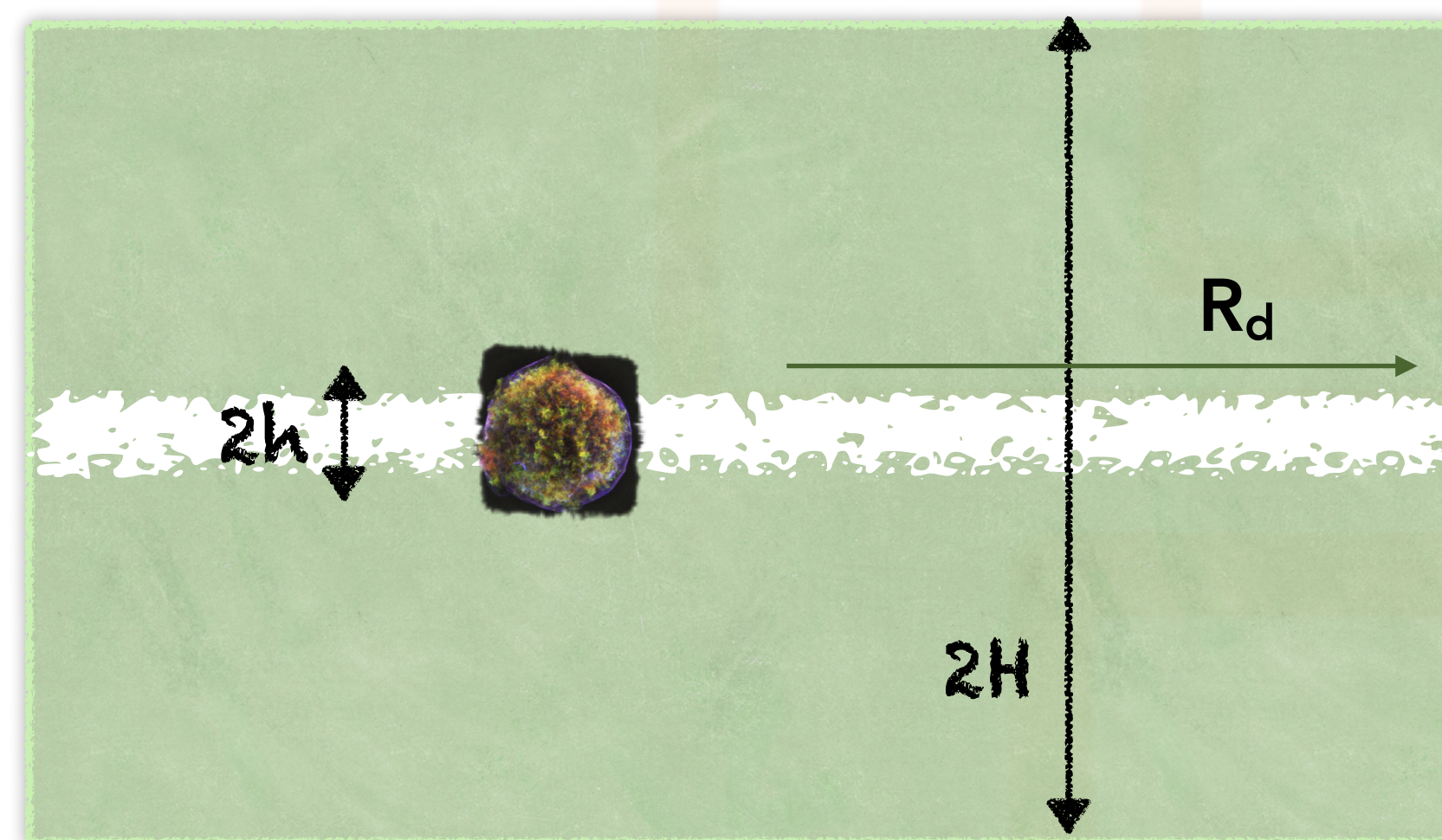
1. CR are injected in an infinitely thin disc
2. CR diffuse in the whole volume
3. CR freely escape from a boundary

1 $Q(p, z) = \frac{Q_0(p)}{\pi R_d^2} \delta(z)$

2 $-\frac{\partial}{\partial z} \left[D \frac{\partial f}{\partial z} \right] = Q(p, z)$

3 $f(z = H, p) = 0$

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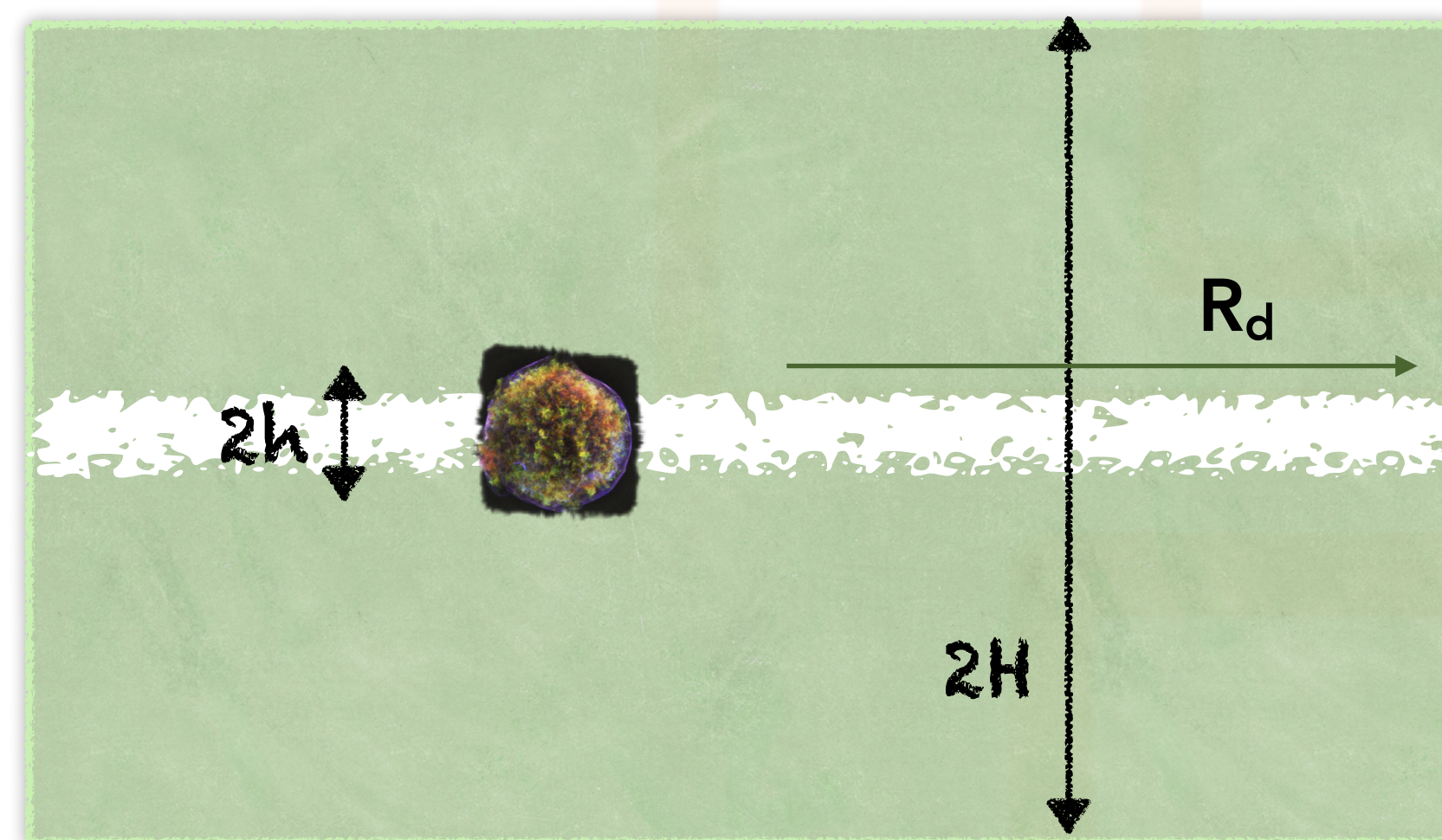
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For $z \neq 0$:

$$D \frac{\partial f}{\partial z} = \text{Constant} \rightarrow f(z) = f_0 \left(1 - \frac{z}{H} \right)$$

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$$D \frac{\partial f}{\partial z} \Big|_{z=0+} = -D \frac{f_0}{H}$$

Let us now integrate the diffusion equation around $z=0$

$$-\frac{\partial}{\partial z} \left[D \frac{\partial f}{\partial z} \right] = \frac{Q_0(p)}{\pi R_d^2} \delta(z) \quad \Rightarrow \quad -2D \frac{\partial f}{\partial z} \Big|_{z=0^+} = \frac{Q_0(p)}{\pi R_d^2}$$

and recalling that

$$D \frac{\partial f}{\partial z} \Big|_{z=0^+} = -D \frac{f_0}{H} \quad \Rightarrow \quad f_0(p) = \frac{Q_0(p)}{2\pi R_d^2} \frac{H}{D} = \frac{Q_0(p)}{2\pi R_d^2 H} \frac{H^2}{D}$$

Diffusion
Time

Rate of
injection per
unit volume

Since $Q_0(p) \sim p^{-\gamma}$ and $D(p) \sim p^{\delta}$
 $f_0(p) \sim p^{-\gamma-\delta}$

WHICH CR FLUX WOULD BE MEASURED BY AN OBSERVER OUTSIDE OUR GALAXY?

WE ALREADY ESTABLISHED THAT

$$D \frac{\partial f}{\partial z} = \text{constant}$$

BUT THIS IS EXACTLY THE FLUX ACROSS A SURFACE IN DIFFUSIVE REGIME:

$$\Phi_{esc}(p) = -D \frac{\partial f}{\partial z} \Big|_{z=H} = -D \frac{\partial f}{\partial z} \Big|_{z=0^+} = \frac{Q_0(p)}{2\pi R_d^2}$$

THE SPECTRUM OF COSMIC RAYS OBSERVED BY AN OBSERVER OUTSIDE OUR GALAXY IS THE SAME AS INJECTED BY SOURCES, NOT THE SAME AS WE MEASURE AT THE EARTH!

MODELS WITH SELF-GENERATED HALO (in passing)

There have been a few attempts to investigate the possibility that the whole CR-confining halo of the Galaxy is self-produced by the CR streaming (Evoli, PB, Morlino & Aloisio 2018; Chernyshov, Dogiel, Ivlev, Erlykin & Kiselev 2022)

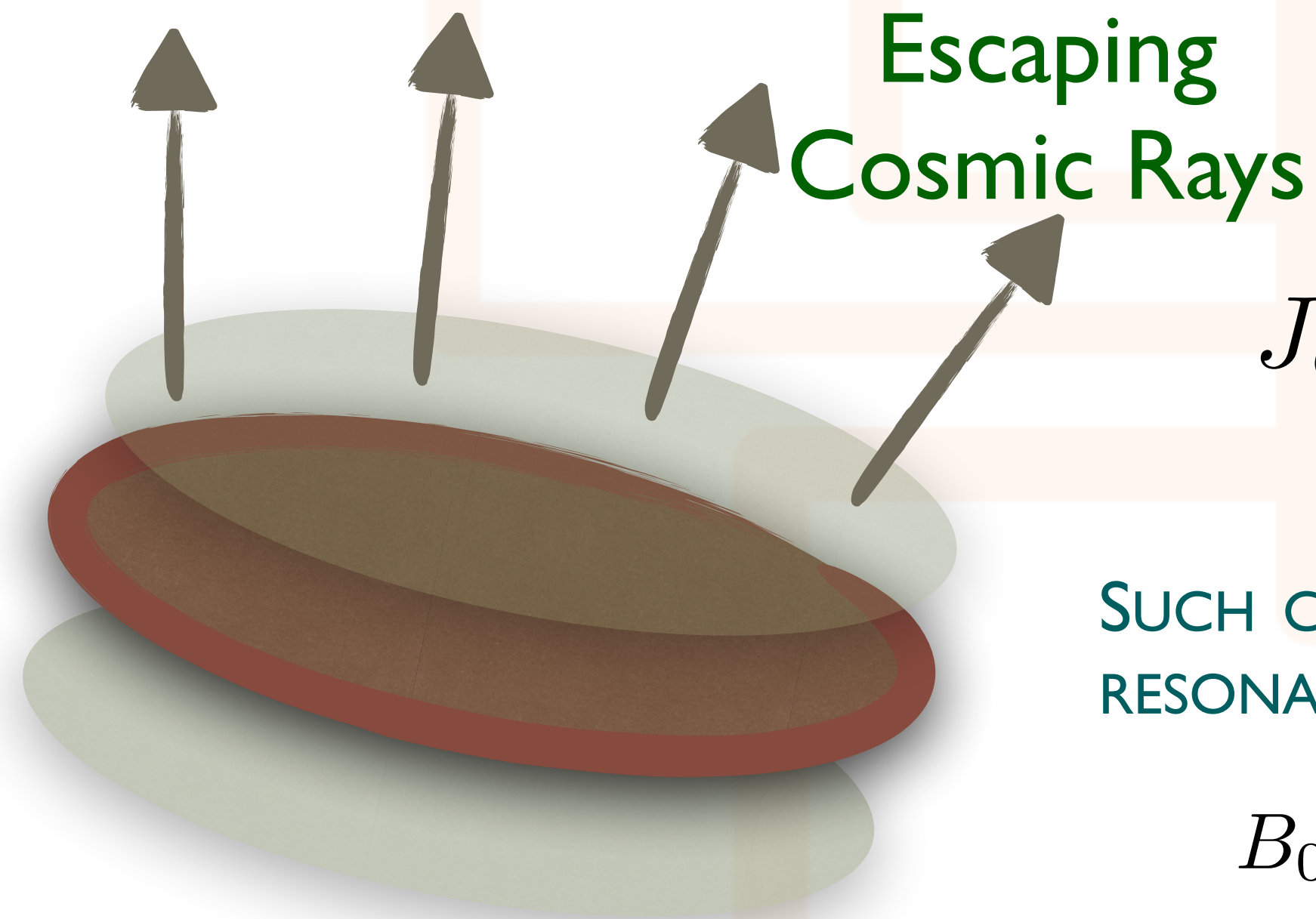
In these models there is no boundary condition at some fixed surface of free escape

The idea is that at some (energy dependent) distance from the disc, self-generation becomes so strong that transport becomes advection dominated at the local Alfven speed

This results in spectra that are in good agreement with the observed ones

ESCAPE OF GALACTIC CR

PB & Amato 2019



THE CURRENT OF ESCAPING CRs IS WELL KNOWN:

$$J_{CR}(p) = eD \frac{\partial f}{\partial z} \Big|_{z=H} = \frac{eQ_0(p)}{2\pi R_d^2}$$

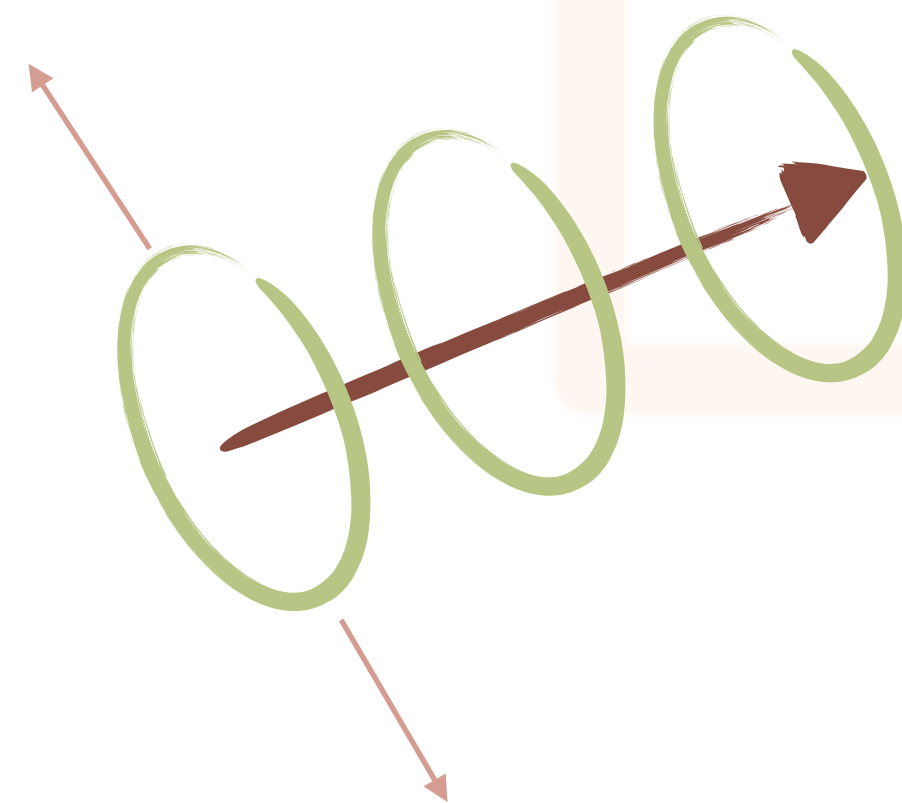
SUCH CURRENT IN THE TYPICAL IGM EXCITES A NON-RESONANT BELL-LIKE INSTABILITY PROVIDED:

$$B_0 \leq B_{sat} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1} \text{ G}$$

At a wavenumber $k_{max} = \frac{4\pi}{cB_0} J_{CR}$

and with a growth rate: $\gamma_{max} = k_{max} v_A \approx 0.5 \text{ yr}^{-1} \delta_G^{-1/2} E_{\text{GeV}}^{-1} L_{41} R_{10}^{-2}$

AN EASY WAY TO SATURATION



CURRENT

The current exerts a force of the background plasma

$$\rho \frac{dv}{dt} \sim \frac{1}{c} J_{CR} \delta B$$

which translates into a plasma displacement:

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

which stretches the magnetic field line by the same amount...

The saturation takes place when the displacement equals the Larmor radius of the particles in the field δB

$$\delta B \approx B_{\text{sat}} \approx \sqrt{\frac{2L_{CR}}{c R_d^2 \Lambda}} \approx 2.4 \times 10^{-8} L_{41}^{1/2} R_{10}^{-1} \text{ G}$$

THE EMERGING PICTURE

When escaping CR reach a region where the field drops below $\sim 10^{-8}$ G, they excite a non-resonant instability that slows down CR diffusion and eventually sets the plasma in motion

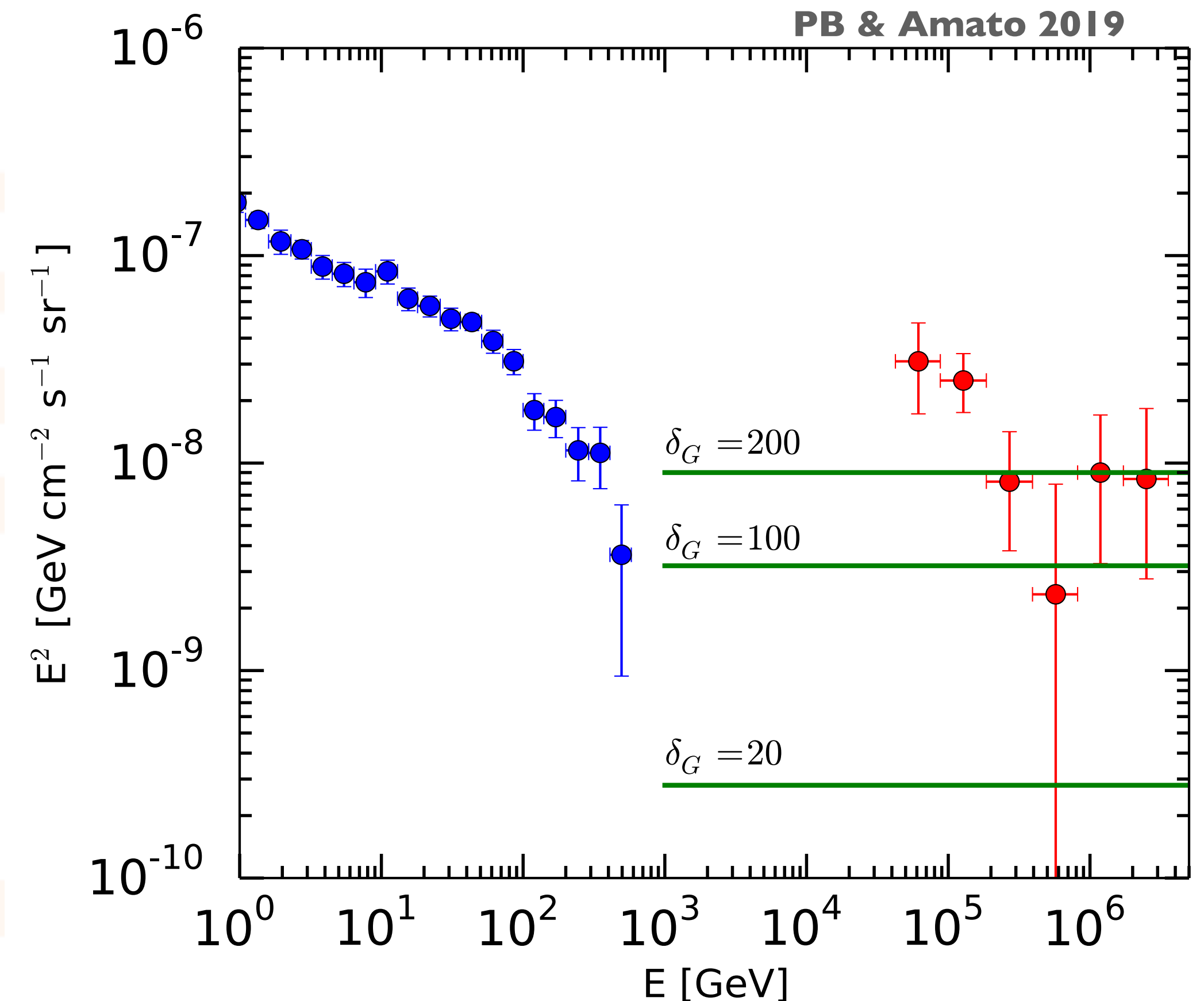
Hence, their density is set by advection

$$n_{CR}(E) = \frac{\phi_{CR}}{\tilde{v}_A}$$

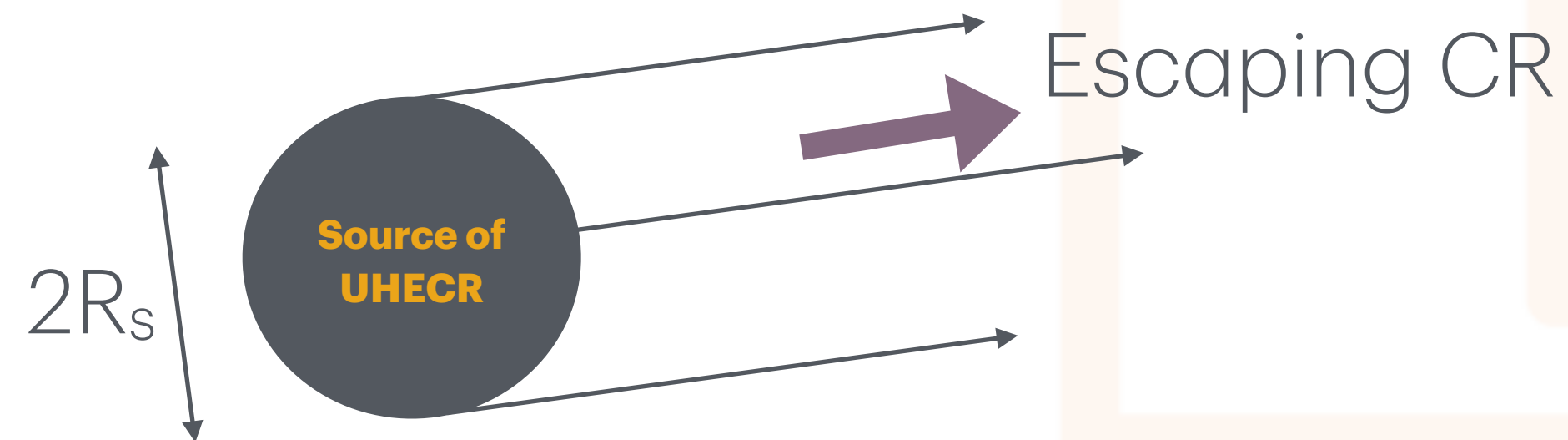
We started this gedankenexperiment by assuming that CR freely escape at a boundary and we reached the conclusion that they instead they almost come to a stop... This probably means that it is not very physical to impose the boundary by hand: **the problem chooses it in a self-regulated manner**

ESCAPE OF GALACTIC CR

- ◆ COSMIC RAYS SHOULD EVENTUALLY SLOW DOWN THEIR FREE ESCAPE AND ACCUMULATE AT LARGE DISTANCES FROM THE GALAXY (~ 30 Kpc)
- ◆ AROUND EVERY GALAXY THERE SHOULD BE A REGION WITH $B \sim L_{\text{CR}}^{1/2}$ DUE TO THE ACTION OF ESCAPING CR
- ◆ THE INTERACTION OF CR WITH THE LOCALLY OVERDENSE INTERGALACTIC MEDIUM LEADS TO PRODUCTION OF A QUASI-ISOTROPIC FLUX OF SECONDARIES (FOR INSTANCE NEUTRINOS)



IMPLICATIONS FOR UHECRs



Cosmic rays escaping the source can excite a non resonant streaming instability provided (**D'Angelo, PB & Amato 2015, Cermenati, Evoli, Aloisio, PB 2024**)

$$B_0 < B_{\text{sat}} = \sqrt{\frac{4\mathcal{L}}{\Lambda R_s^2 c}} \sim 7.8 \text{ nG} \times \frac{\mathcal{L}_{44}^{1/2}}{R_{s,\text{Mpc}}}$$

The instability leads to self-confinement for energies below:

$$E_{\text{sat}}(t) \sim 24 \text{ PeV} \frac{\mathcal{L}_{44} t_{\text{Gyr}}}{\delta^{1/2} R_{s,\text{Mpc}}^2}$$

meaning that CR with $E < E_{\text{sat}}$ take longer than the age of the universe to escape.

For typical luminosities invoked for UHECR sources the instability causes a low energy cutoff in the $\sim 0.1\text{-}1 \text{ EeV}$ range, interesting since the Auger data seem to require a similar trend.

Moreover, every source should be surrounded by a $\sim 10 \text{ Mpc}$ region with $\sim \text{nG}$ magnetic fields

SUMMARY: WHY SHOULD YOU WANT TO UNDERSTAND ESCAPE

- 📌 Escape is regulated by microphysics of plasma-particles interactions and is a missing link between the physics of the accelerator and the physics of transport on large scales
- 📌 In the case of SNR this phenomenon is responsible for E_{max} as well as for the transport in the near source region — **GRAMMAGE AROUND THE SOURCE?**
- 📌 In the regions around PWN we have evidence for extended regions of reduced diffusivity (**TeV halos**) and for long, thin X-ray **filaments** with large magnetic fields... **DO THEY HAVE A COMMON ORIGIN? IMPORTANT IMPLICATIONS FOR CR POSITRONS**
- 📌 The escape of CR from the Milky Way is mimicked by using a free escape boundary condition, but if we impose such a condition we infer that those particles do not freely escape — **DIFFUSE NEUTRINOS? B-FIELDS?**
- 📌 When applied to UHECR from very energetic sources the phenomenon implies a low energy cutoff in the region around 0.1-1 EeV — **REASON FOR STRANGE AUGER SPECTRA?**

SUMMARY: WHY SHOULD YOU WANT TO UNDERSTAND ESCAPE

- 📌 We could have ignored these effects when error bars on measurements were large, but not now that we are able to measure the grammage at a few percent level
- 📌 There are hints, perhaps just hints, that something interesting is happening at high energies:
 - ◆ Diffuse gamma and neutrino flux from the Milky Way
 - ◆ Possible hardening of the B/C at $E/n > \text{TeV}/n$
- 📌 Some anomalies (positron excess) have even stimulated profoundly different ideas on transport that require alternative ways to accumulate grammage (Cowsik 2016, Lipari 2017)
- 📌 Moreover, for the first time we have “good eyes” to look at large diffuse sources → Chance to look at the escape regions around sources