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The Tough Road to PeV

Acceleration of the highest rigidity Galactic cosmic rays

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Gran Sasso Science Institute

TeVPA 2021 - Chengdu, Oct. 25-29 2021

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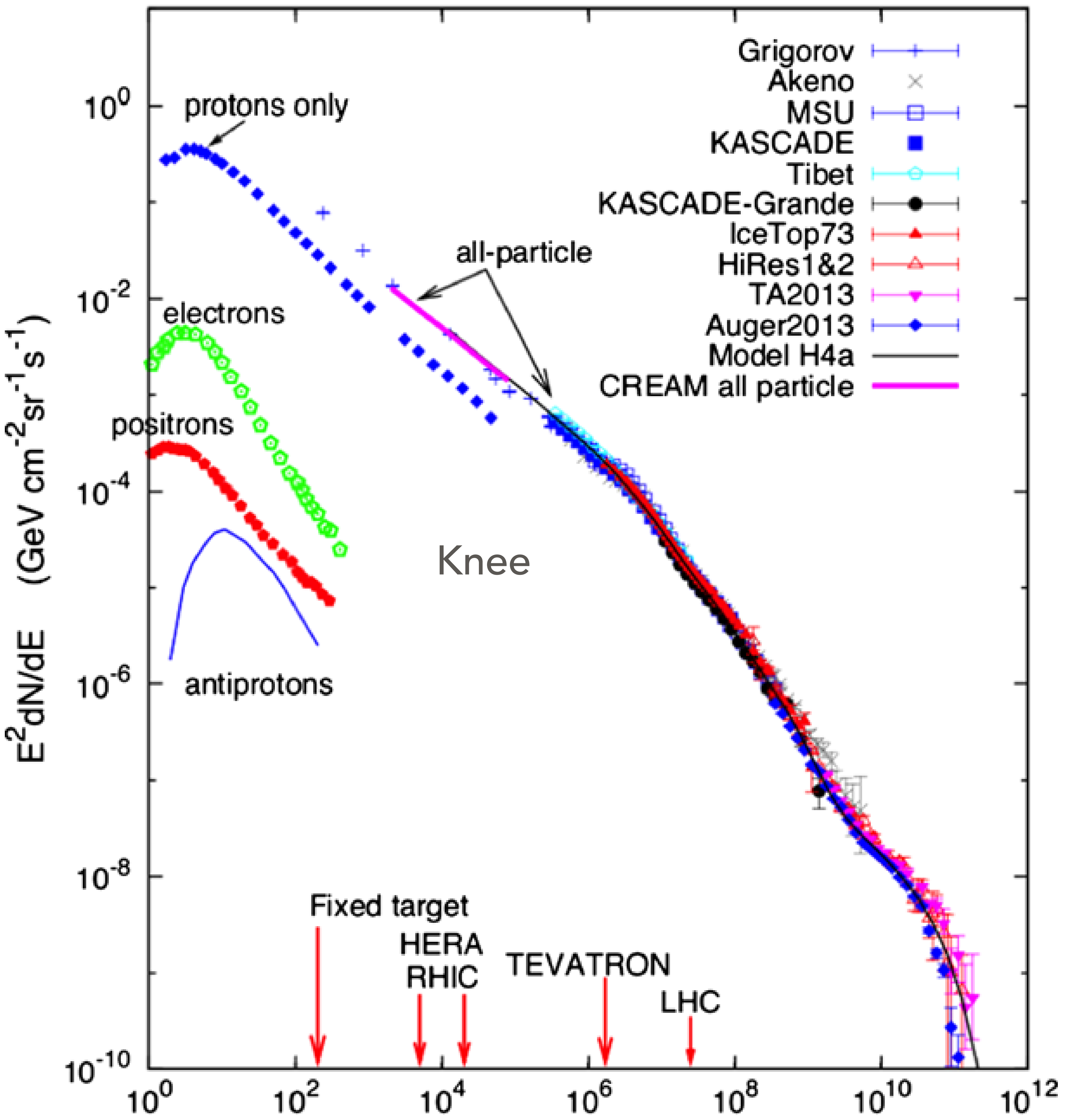
Outline

- General concepts
- Acceleration in SNRs
- Acceleration in Stellar Wind Clusters
- Escape of HE particles around the sources

AN INTRINSICALLY MULTI-MESSENGER AND MULTIFREQUENCY FIELD

- From afar the spectrum looks like a power law
- Broken power laws more interesting (scale->physics)
- After knee and ankle, first evidence of scales also in the spectra of individual elements
- Substantial change in mass composition at the knee —> most likely it is the energy where Galactic CR end (in rigidity)
- Big surprises from secondaries and antimatter



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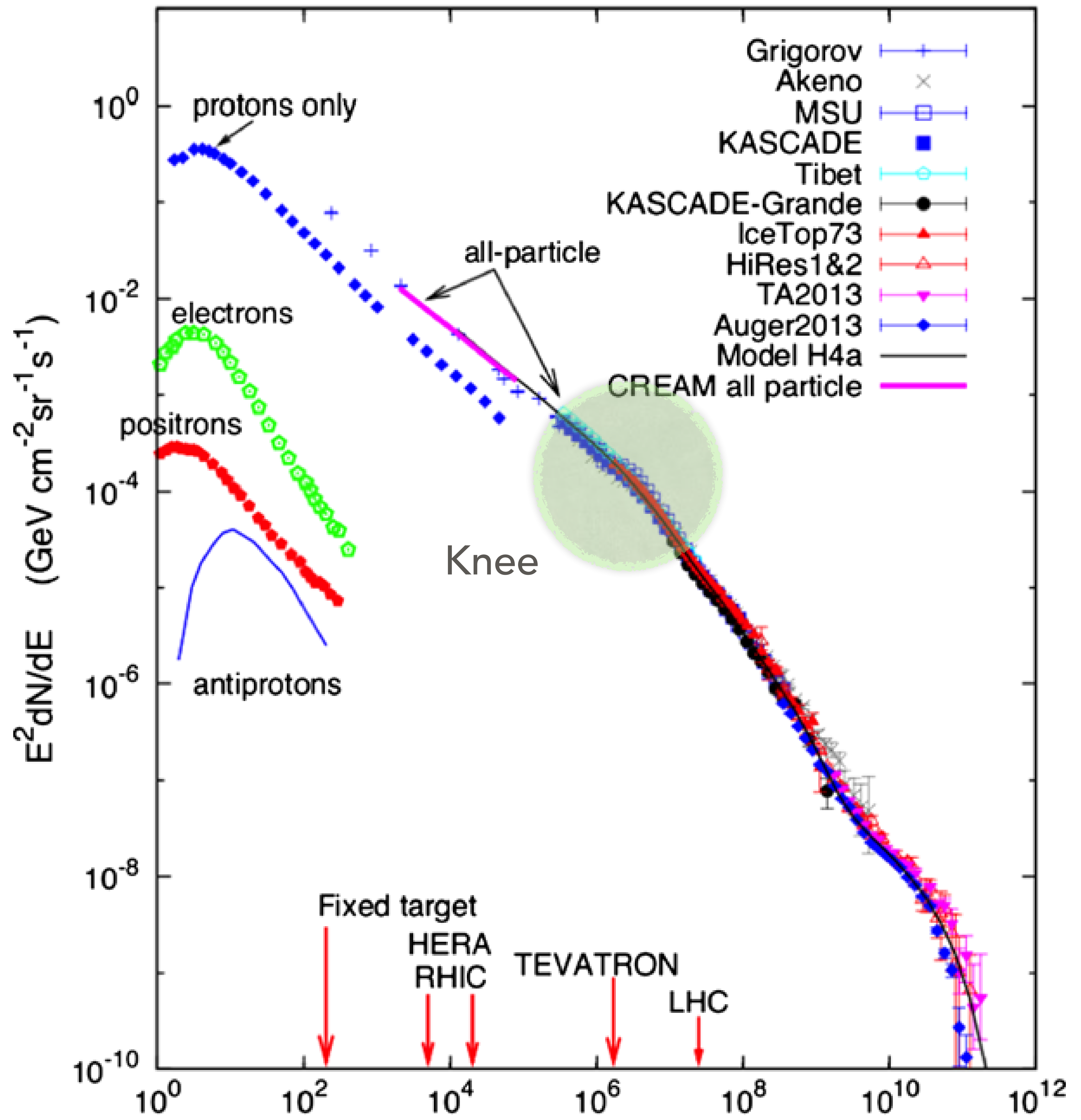

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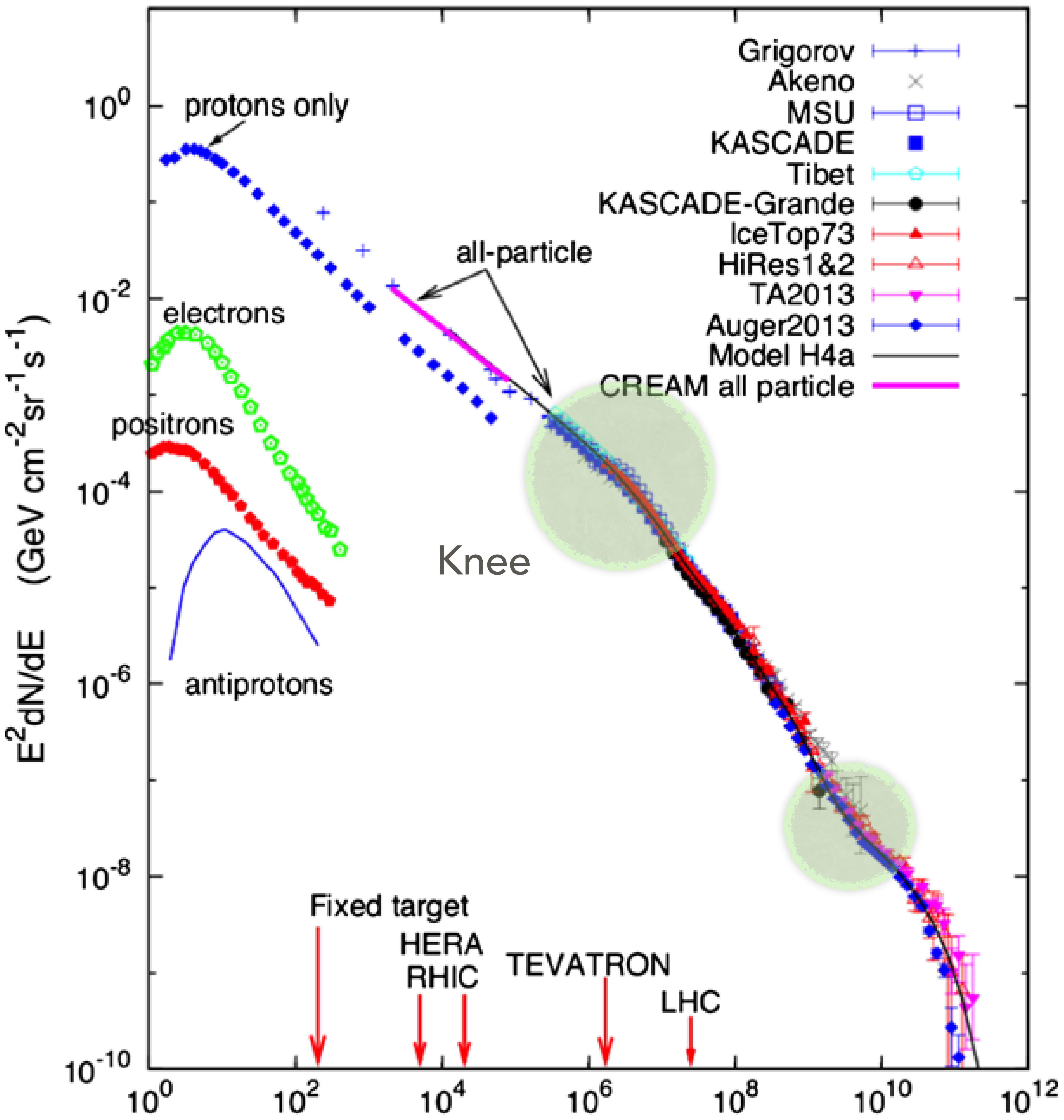

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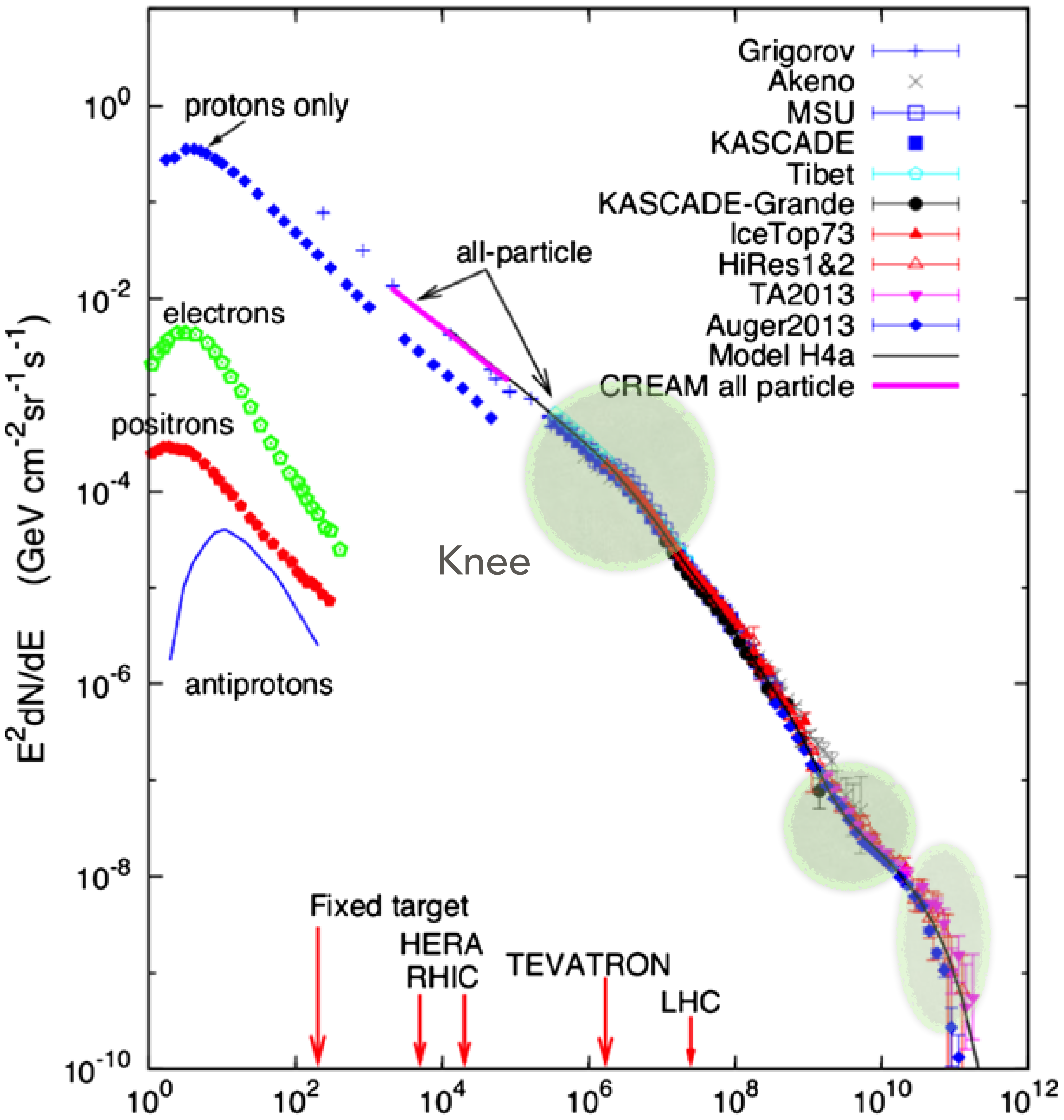

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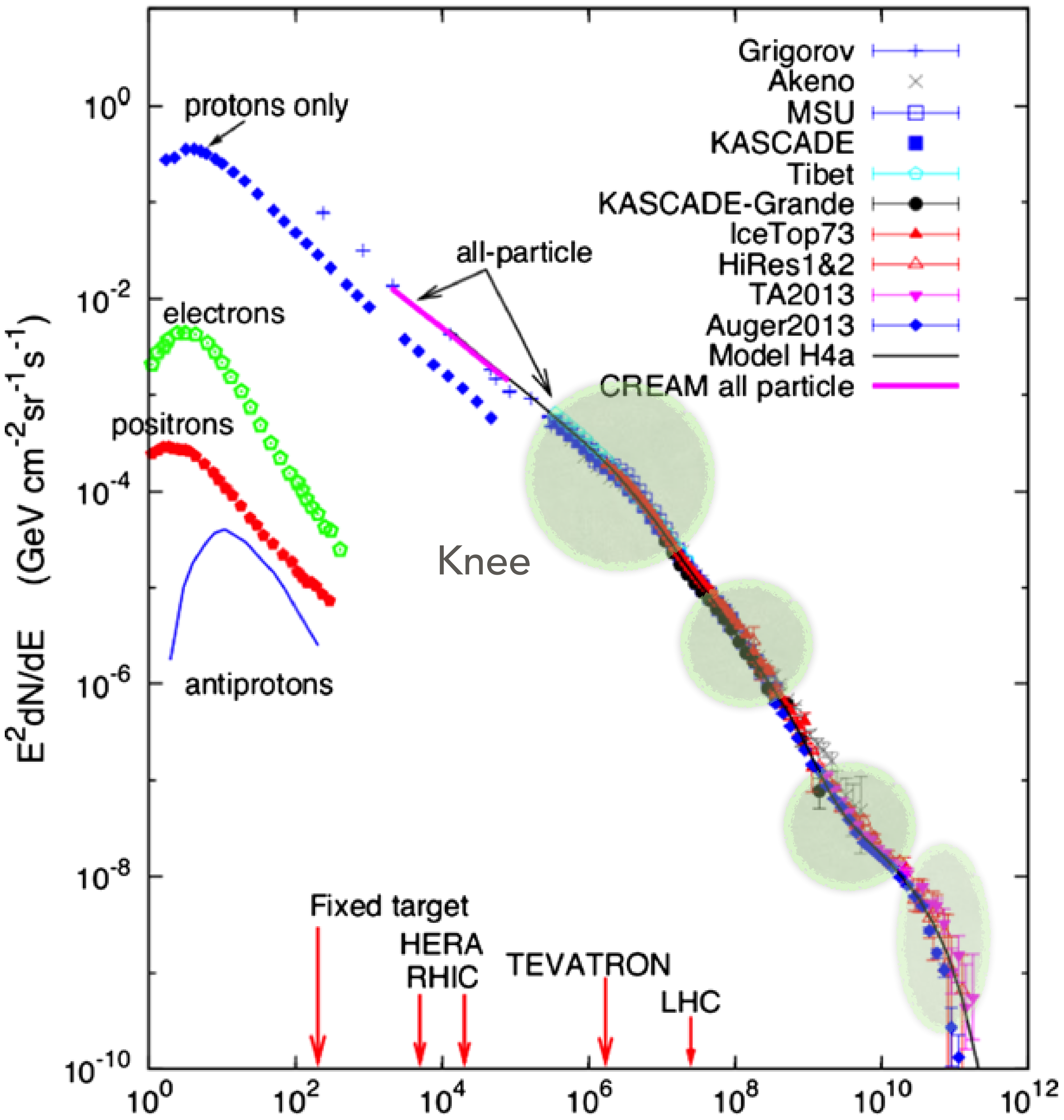

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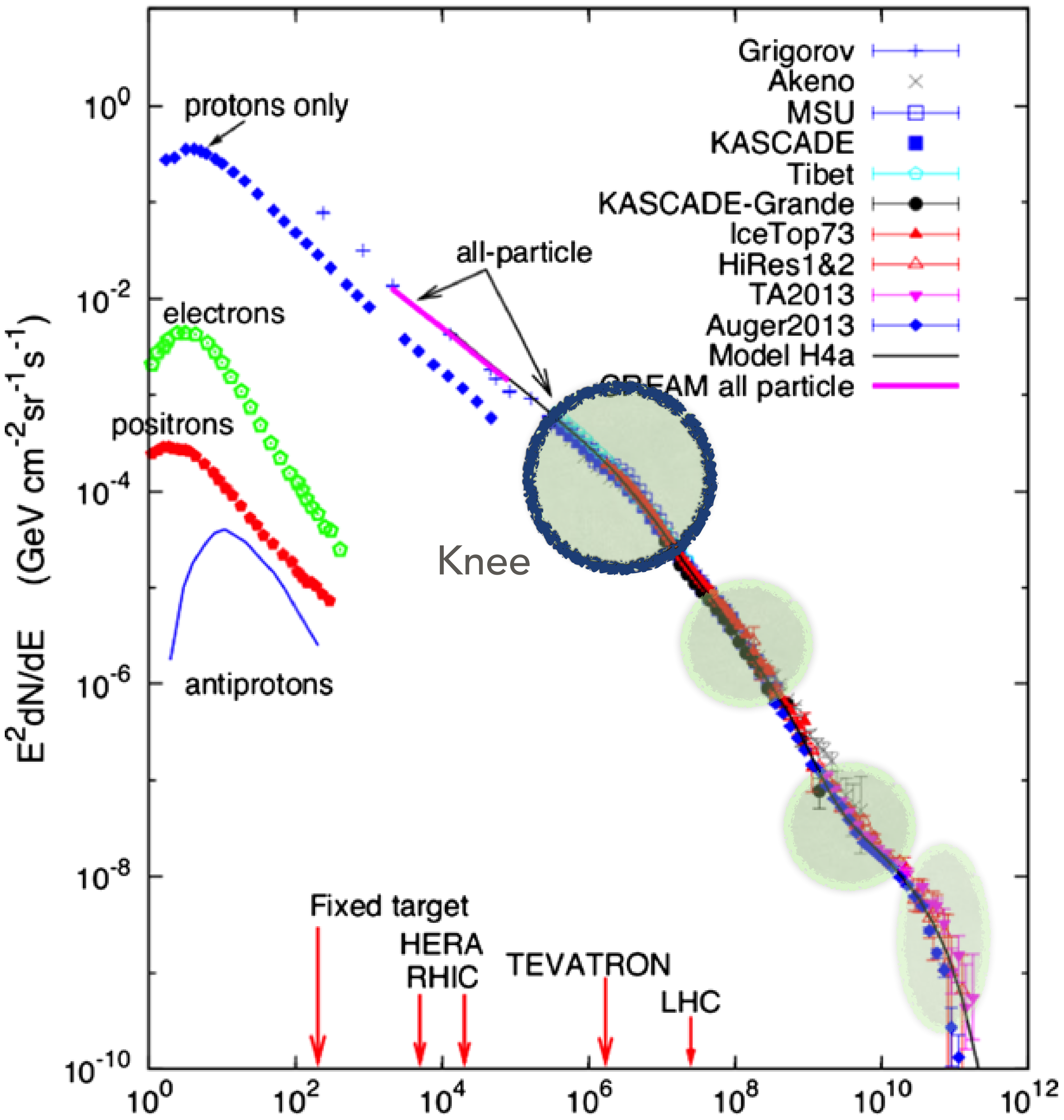
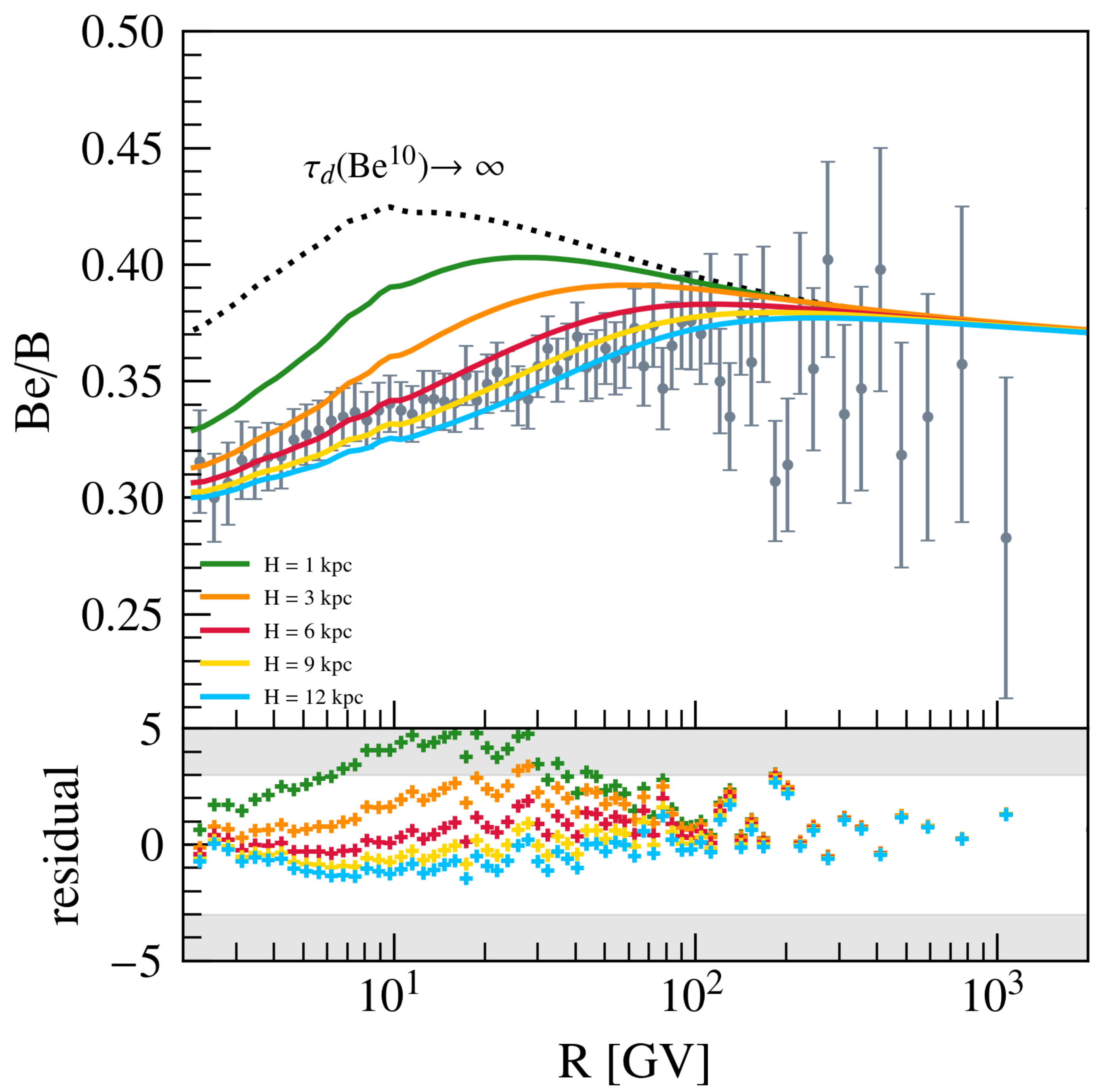


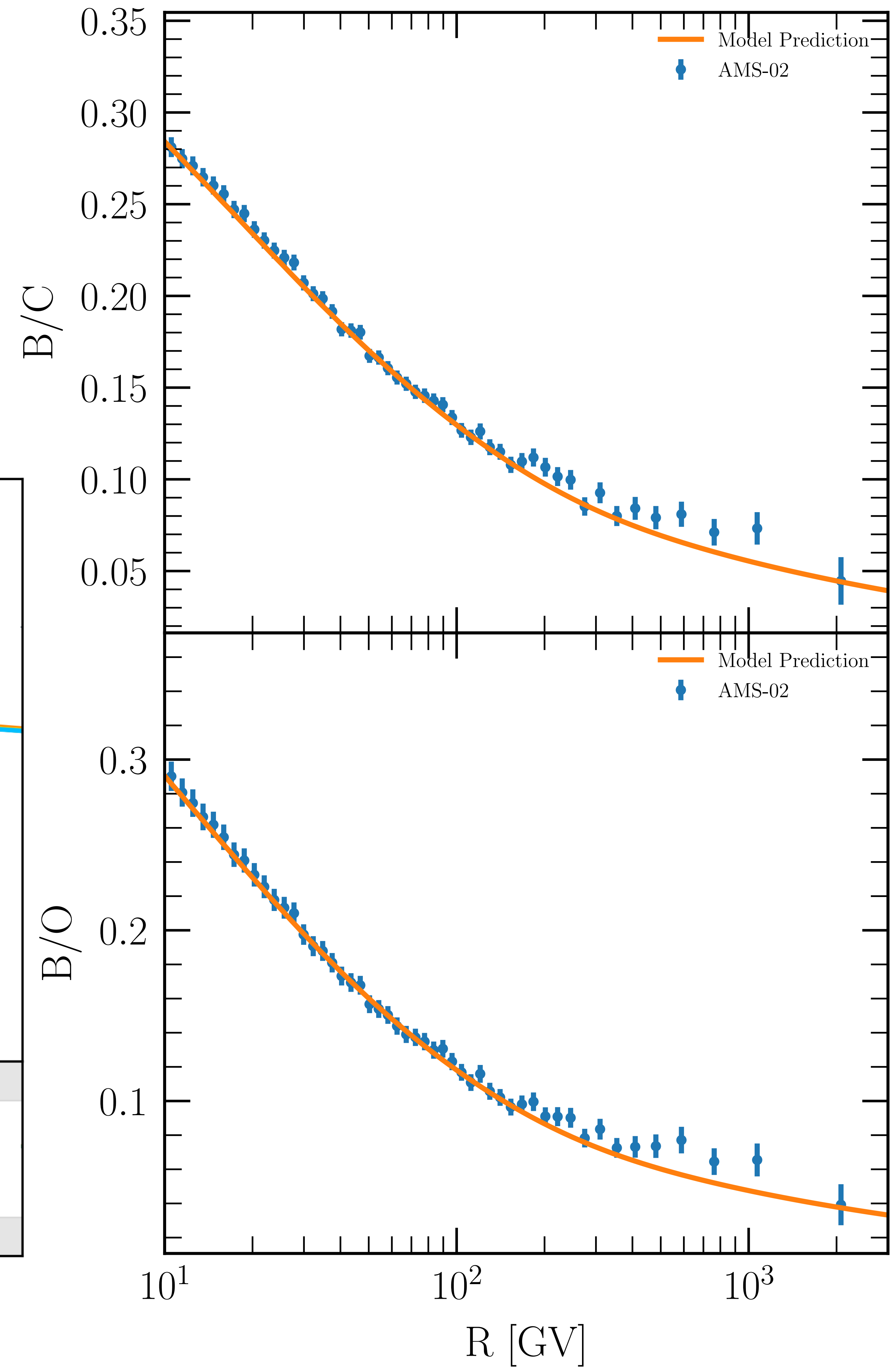
Confinement in the Galaxy

Measurement of secondary/Primary ratios and Secondary/Secondary ratios led to a powerful measurement of the size of the halo and diffusion properties of the ISM

Halo H~5 kpc

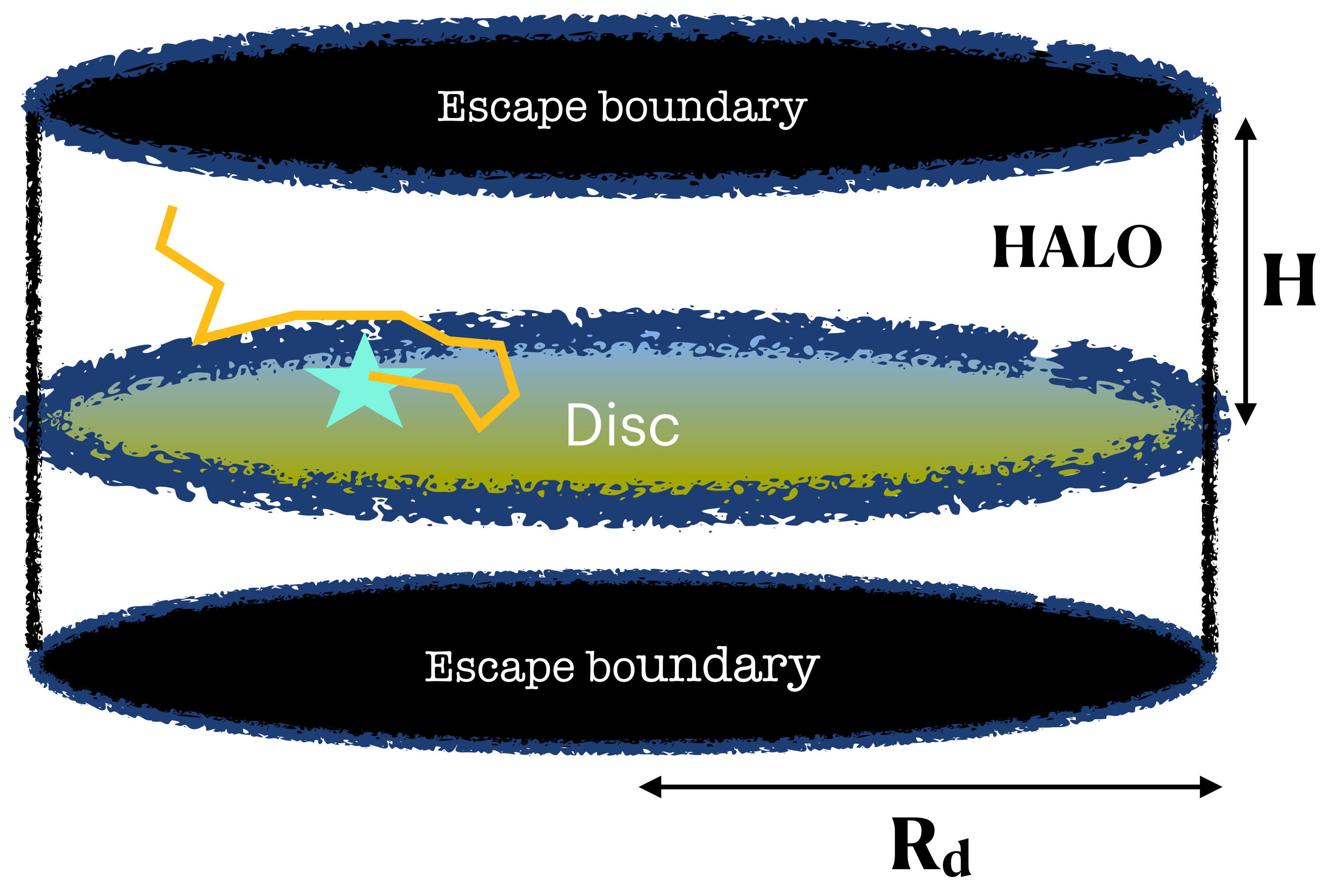
Fixed ratio H/D @ given E





Potential Sources of Galactic CR

The energy density of Cosmic Rays at the position of the Earth is about 0.2 eV/cm3 at E>few GeV - how do we refill it?



$$\epsilon_{CR} = \frac{\dot{E}_{CR}}{2\pi R_d^2}\frac{H}{D(E)}$$

KNOWN FROM B/C

$$\dot{E}_{CR} \approx 2\times 10^{40}\left(\frac{R_d}{15kpc}\right)^2 \text{ erg/s}$$

SN Type IA: Energetics 10^{51} erg Rate 1/100 years — **Required Efficiency ~6%**

SN Type II: Energetics 10^{51} erg Rate 1/30 years — **Required Efficiency ~2%**

SN Type II* (very luminous core collapse): Energetics 10^{52} erg Rate 1/10000 years — **Required Efficiency ~50%**

Stellar Clusters: Typical luminosity 10^{37}-10^{38} erg/s - **if efficiency 10% about few thousand clusters required in the Galaxy**

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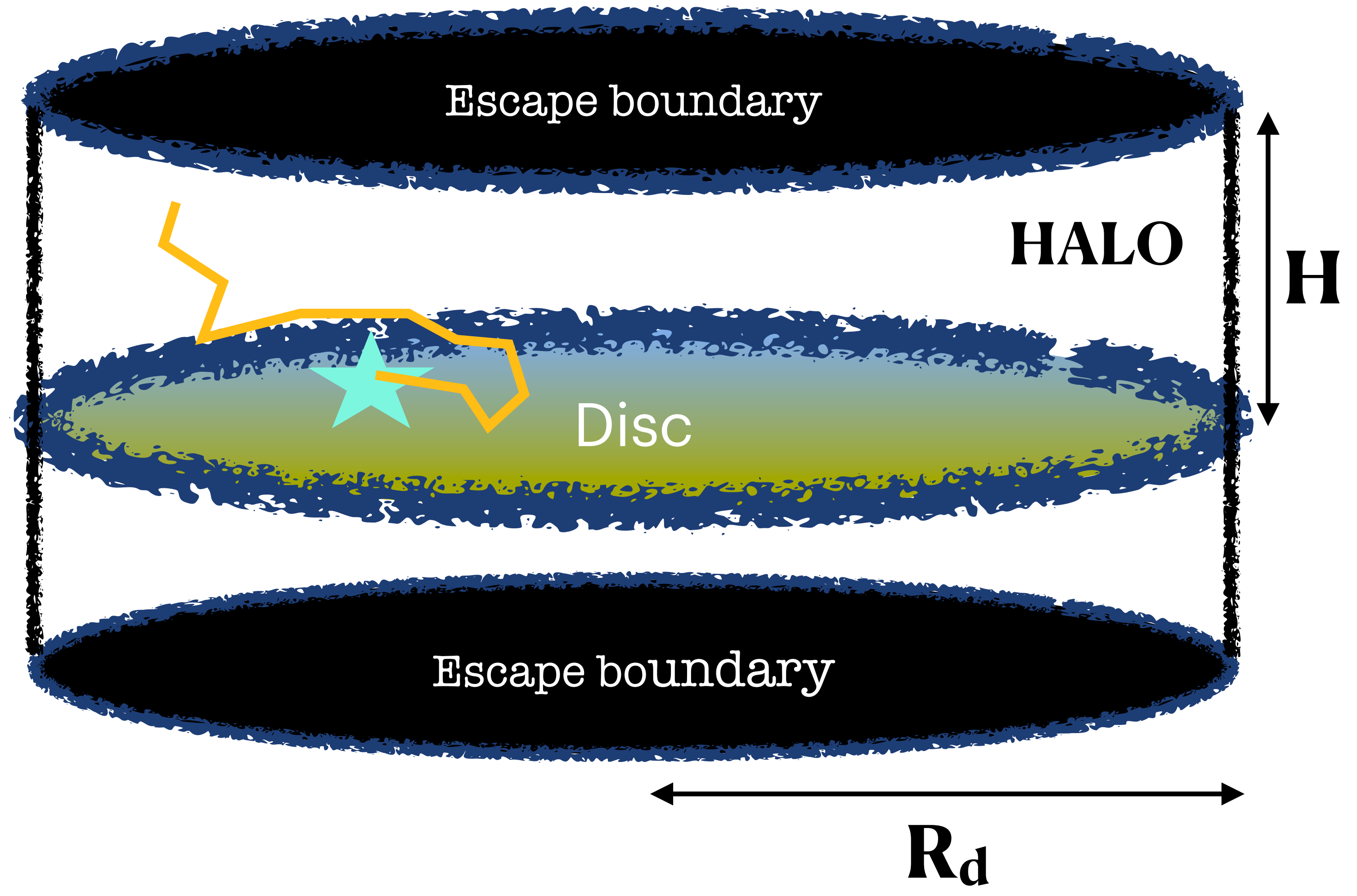

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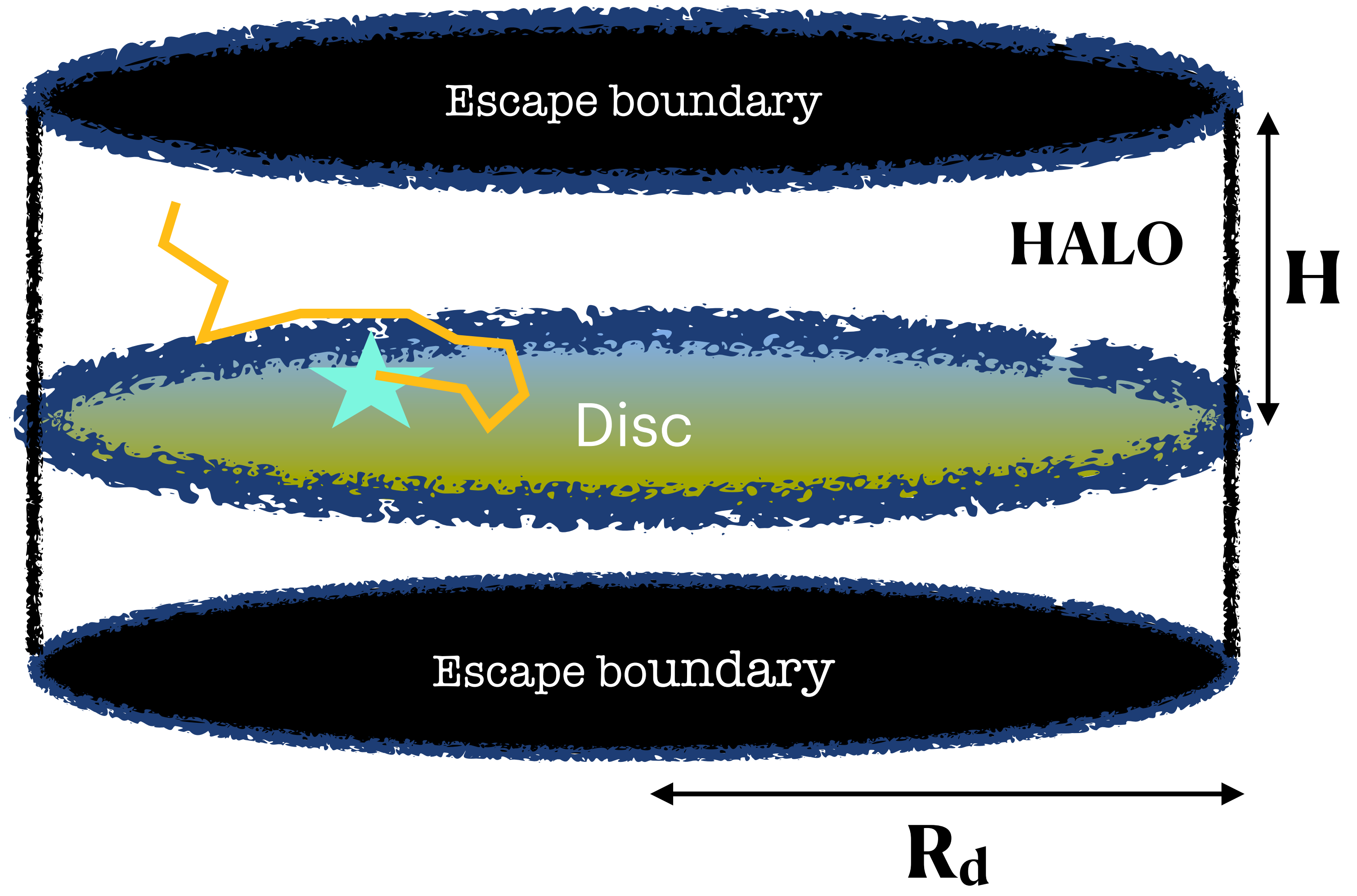

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Supernova Remnants as PeVatrons?

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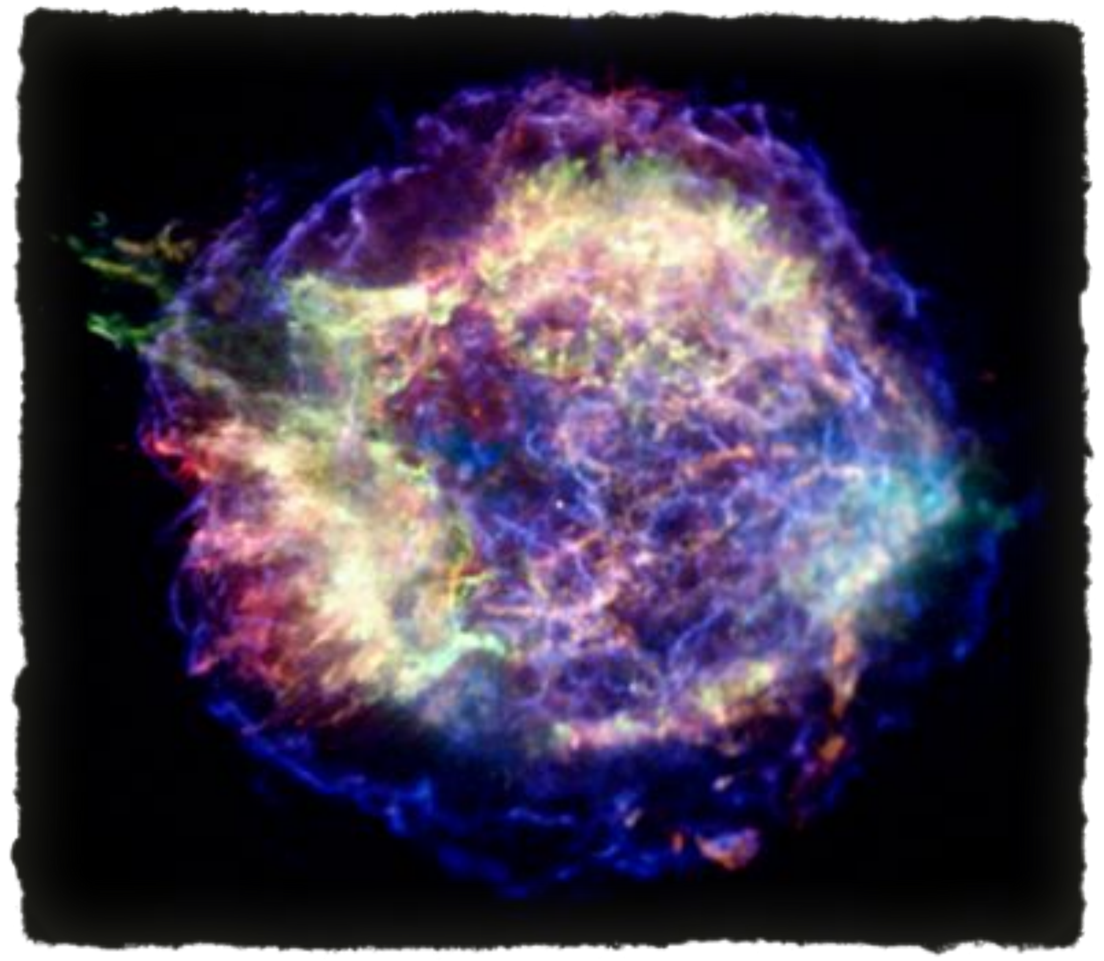
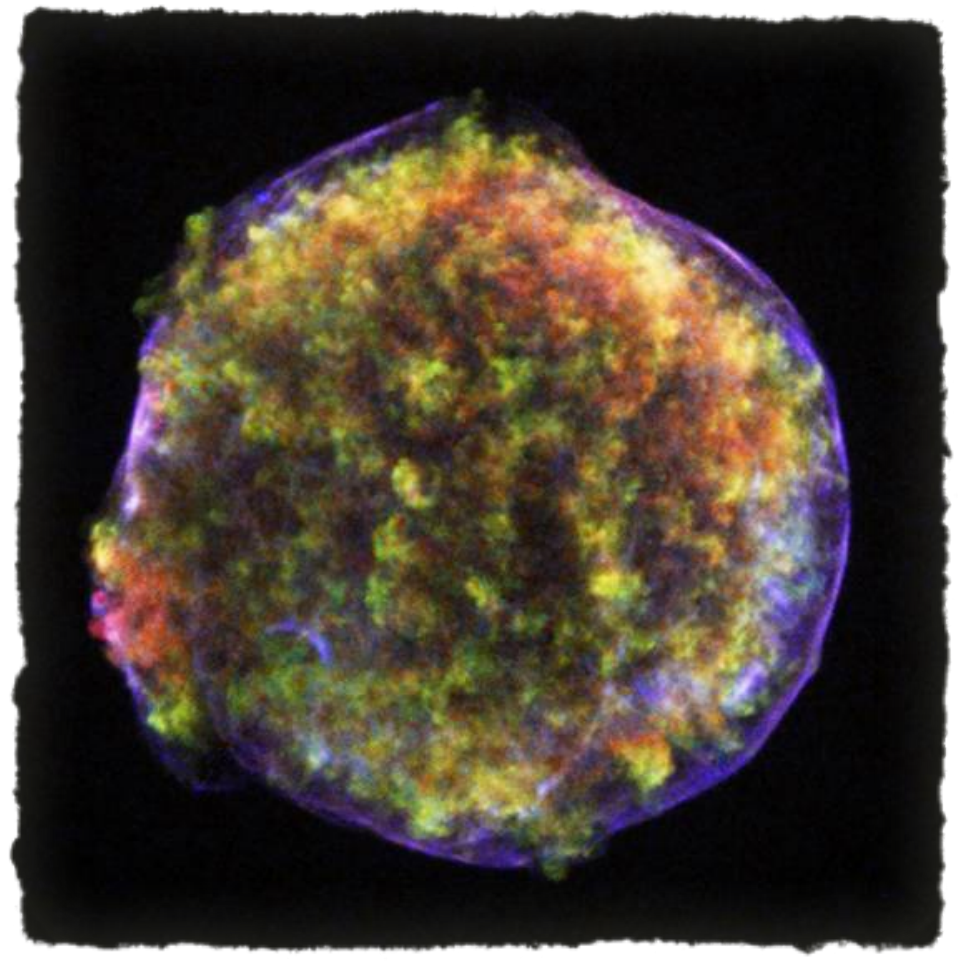
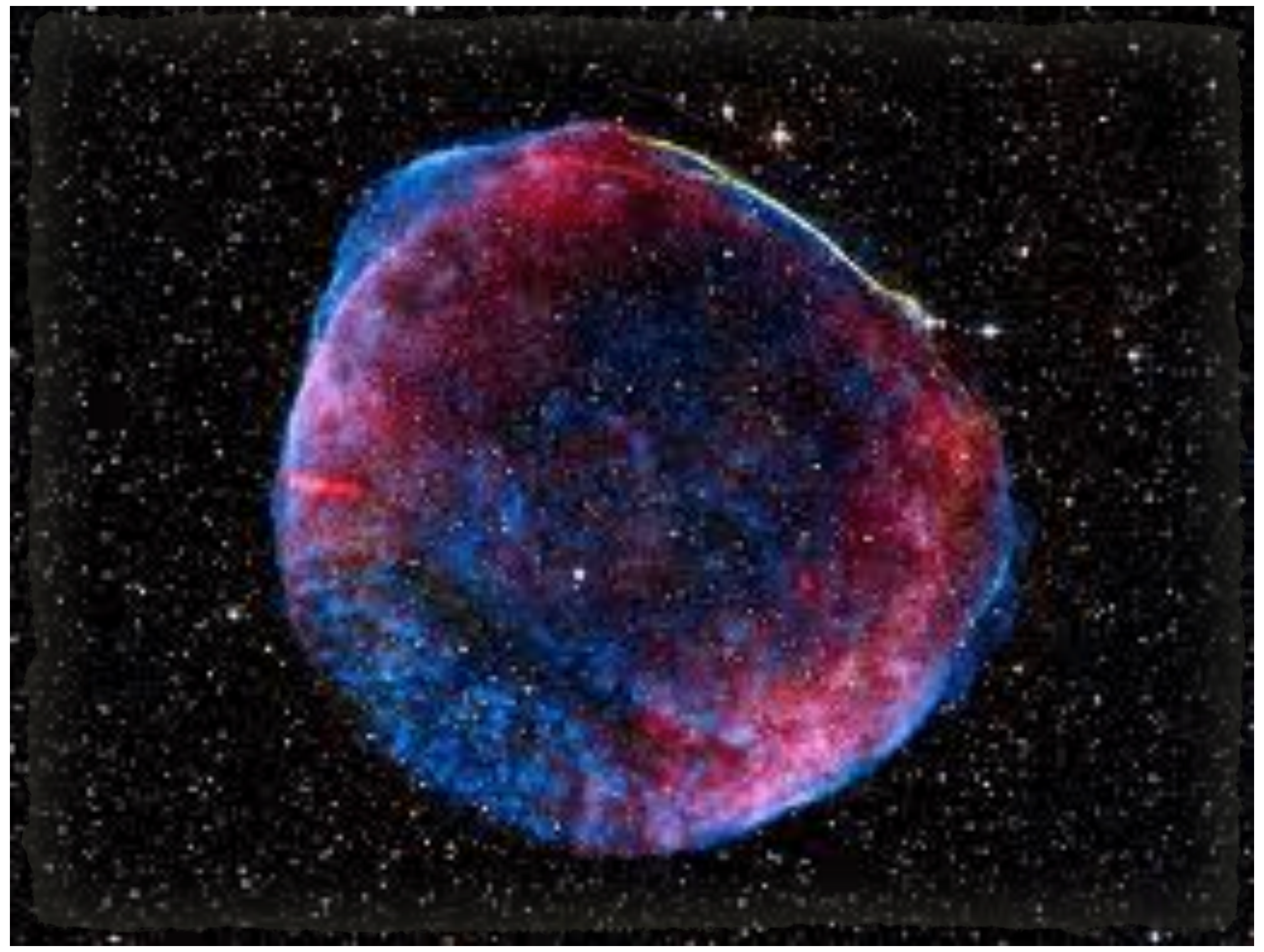
PARTICLE ACCELERATION IN SNRs

FREE EXPANSION VELOCITY: $V_s = \sqrt{\frac{2E_{ej}}{M_{ej}}} = 10^9\ E_{51}^{1/2}\ M_{ej,\Theta}^{-1/2}$ cm/s

THE EXPANSION SPEED DROPS DURING THE SEDOV-TAYLOR PHASE BUT THE MACH NUMBER STAYS >10-100

A STRONG COLLISIONLESS **SHOCK WAVE** IS GENERATED

DIFFUSIVE SHOCK ACCELERATION

Test Particle Approach

- Diffusion of charged particles back and forth across the shock leads to:

$$\frac{\Delta E}{E} = \frac{4}{3}(U_1 - U_2)$$

- POWER LAW SPECTRUM (only depends on compression factor)
- FOR STRONG SHOCKS (Mach>>1): p^{-4} (E^{-2} at relativistic E)
- INDEPENDENT OF MICRO-PHYSICS (e.g. THE DIFFUSION COEFFICIENT)

THE EFFICIENCY REQUIRED PER SNR ~1-10%: TEST PARTICLES?

MORE THAN JUST TEST PARTICLES

- The spectrum E^{-2} is energy divergent —> need to account for particle pressure
- The maximum energy for test particles is ridiculously low

IF TO ASSUME THAT AT THE SHOCK PARTICLES DIFFUSE AS IN THE ISM (see B/C ratio) THEN:

$$D(E) \approx 3 \times 10^{28} (E/10GeV)^{1/2} \; cm^2/s \;\Rightarrow\; \tau_{acc}(E) \approx \frac{8D(E)}{v_s^2} = \tau_{Sedov} \;\Rightarrow\; E_{max} \lesssim 100 \text{ GeV}$$

THE DIFFUSION COEFFICIENT IN THE ACCELERATION REGION MUST BE MUCH SMALLER THAN THE ONE IN THE INTERSTELLAR MEDIUM - CAN THIS PHENOMENON BE DUE TO THE ACCELERATED PARTICLES THEMSELVES?

MORE THAN JUST TEST PARTICLES

EVEN ASSUMING THE BEST POSSIBLE CONDITIONS FOR PARTICLE SCATTERING (BOHM DIFFUSION) ONE CAN SEE THAT

$$\frac{1}{3}\frac{Ec}{eB_{shock}}\frac{1}{v_s^2} \approx \tau_{Sedov}$$

IF ONE WANTS TO USE THESE SHOCK TO ACCELERATE TO PeV ENERGIES THE REQUIREMENT IS:

$$B_{shock} \approx 100 B_{Galaxy}$$

THE MAGNETIC FIELD AT THE SHOCK MUST BE AMPLIFIED BY ABOUT A FACTOR 100

NOTICE THAT IN ORDER TO AFFECT THE ACCELERATION TIME THIS AMPLIFICATION MUST TAKE PLACE UPSTREAM OF THE SHOCK, WHERE ONLY COSMIC RAYS CAN REACH

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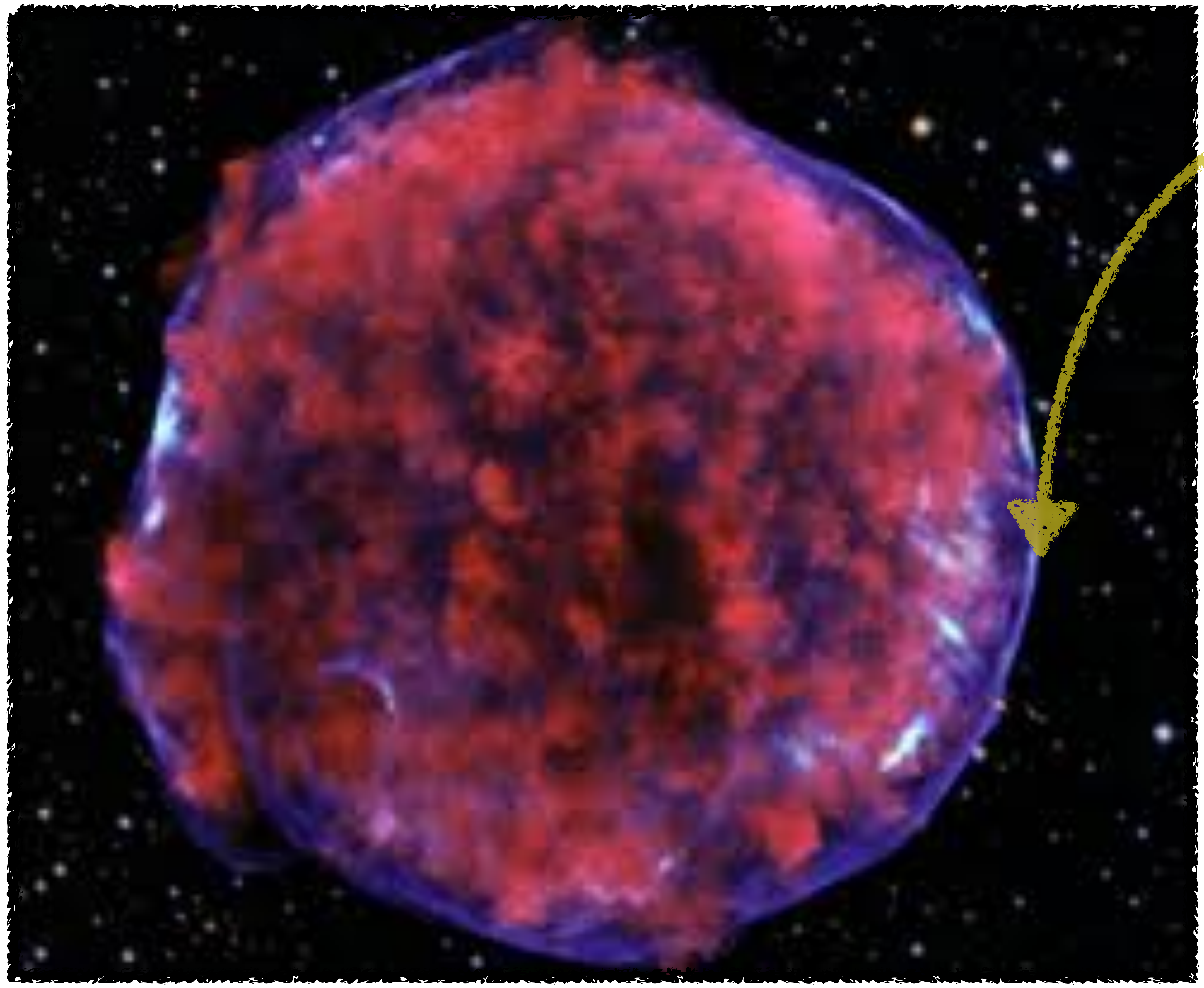
COSMIC RAY INDUCED B FIELDS



X-RAY FILAMENTS

Virtually all young SNRs have thin X-ray filaments

Non-thermal synchrotron emission of high energy electrons accelerated at the shock

$$\Delta x \approx \sqrt{D(E_{max})\tau_{loss}(E_{max})} \approx 0.04\ B_{100}^{-3/2}\ \text{pc}$$

$B \sim 100\ B_{galaxy}$

A HISTORY OF CR INDUCED B AMPLIFICATION

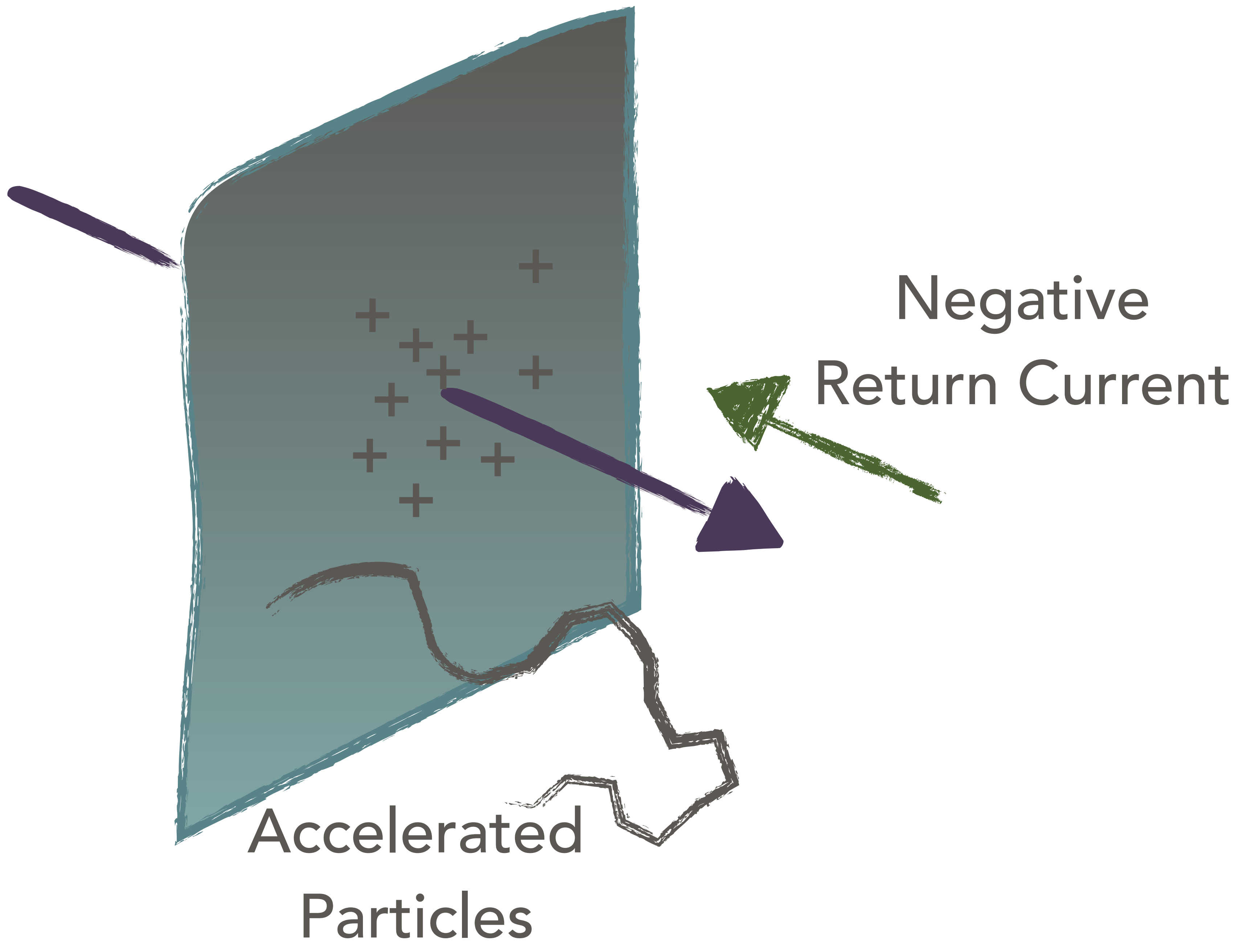
- ALREADY IN THE ORIGINAL BELL (1978) PAPERS IT WAS RECOGNIZED THAT MAGNETIC FIELD AMPLIFICATION IS NEEDED FOR DSA TO WORK TO INTERESTING ENERGIES

- LAGAGE AND CESARSKY (1983) DISCUSSED THE EFFECT OF THE RESONANT STREAMING INSTABILITY —> E_{MAX}~10-100 TEV AT MOST

- A NON-RESONANT BRANCH OF THE STREAMING INSTABILITY WAS DISCOVERED BY BELL (2004,2005) WITH AN MHD APPROACH AND CONFIRMED IN KINETIC APPROACHES (AMATO & PB 2009)

- SEVERAL AUTHORS INVESTIGATED THE EFFECT OF THIS INSTABILITY ON THE MAXIMUM ENERGY (SCHURE AND BELL 2013, 2014, BELL+ 2013, CARDILLO+ 2015, CRISTOFARI+ 2020,2021)

CURRENT DRIVEN INSTABILITY (Bell 2004)



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 VERY SMALL SPATIAL SCALES

THE INSTABILITY GROWS IF

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

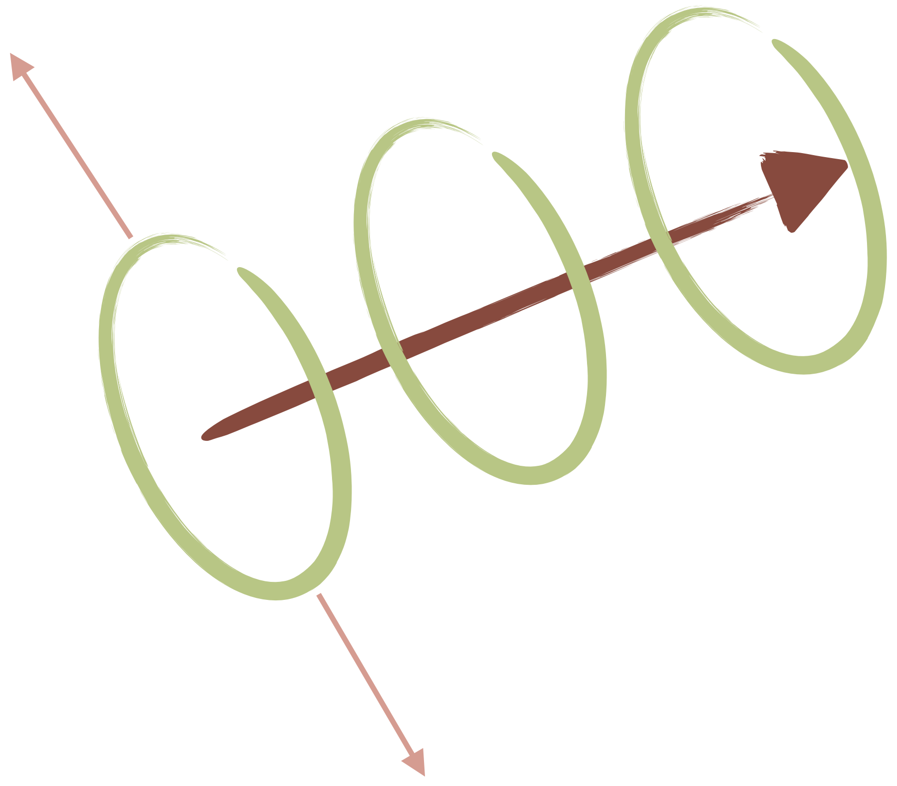
AND ITS GROWTH RATE IS:

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

IT CAN BE EASILY SHOWN THAT k_{max}>>1/Larmor → LITTLE SCATTERING

EASY WAY TO SATURATION OF GROWTH

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 **δ**B … imposing this condition leads to:

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

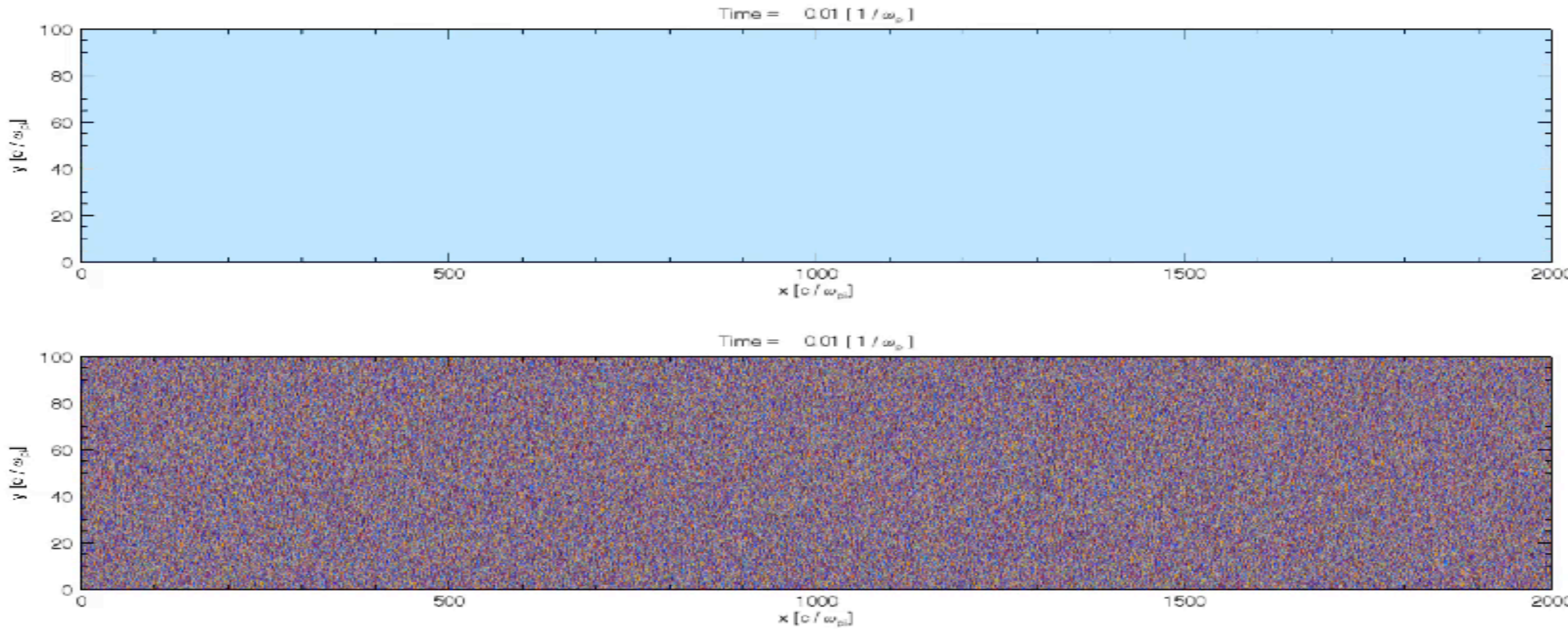
specialized to a strong shock and a spectrum E^{-2}

MAGNETIC BOOTSTRAP

Particles must escape for the Maximum Energy to increase

DOWNSTREAM UPSTREAM

Bell & Schure 2013
Cardillo, Amato & PB 2015



Caprioli & Spitkovsky 2013

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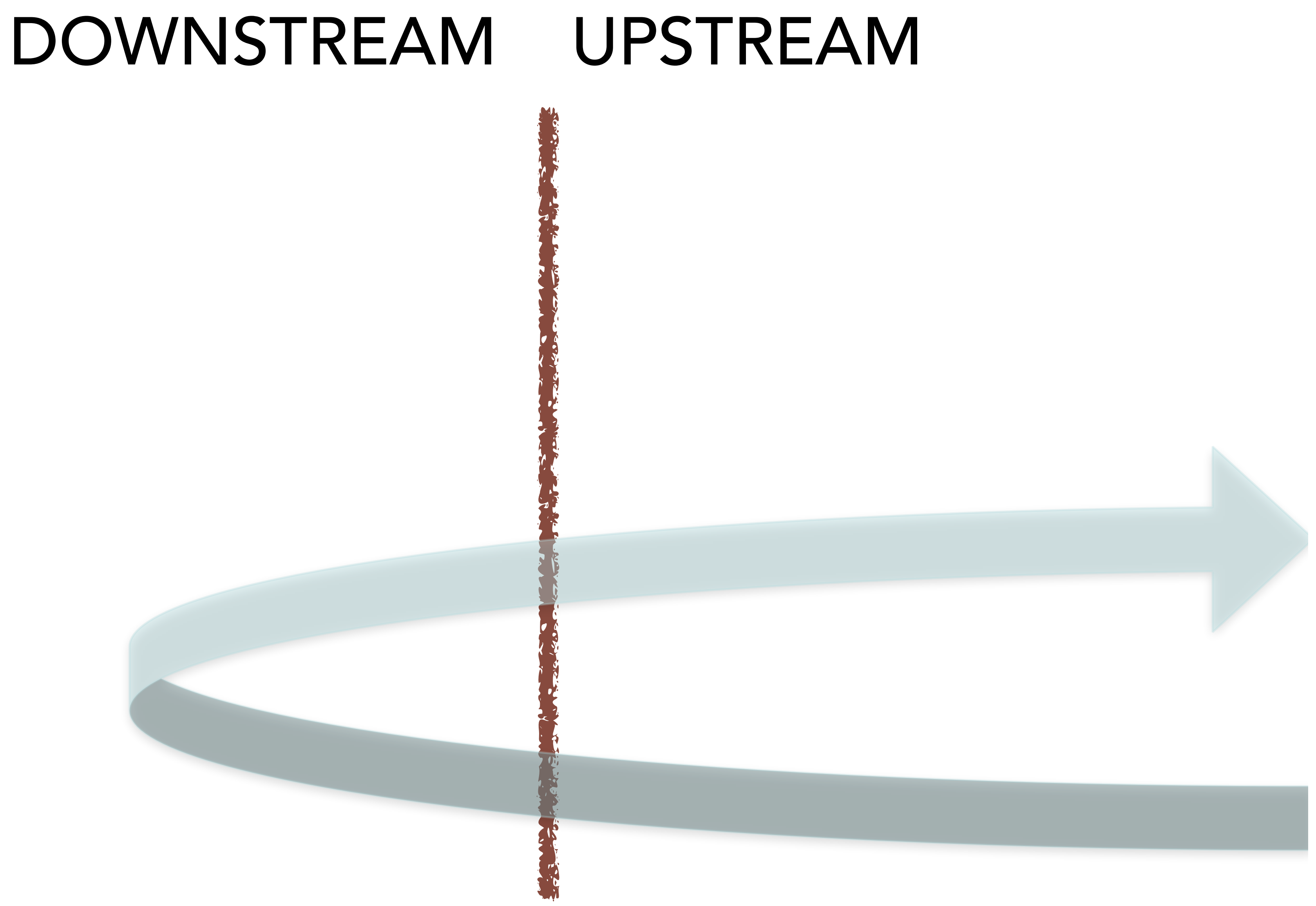

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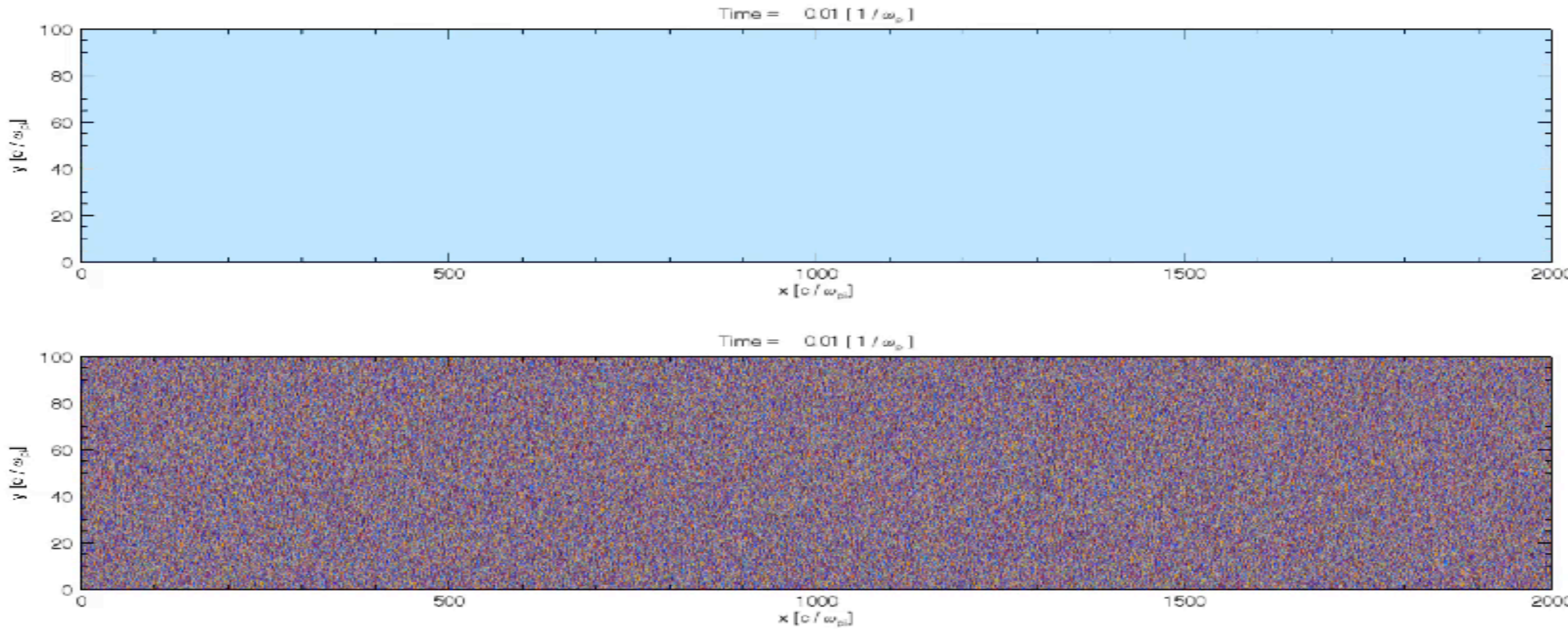

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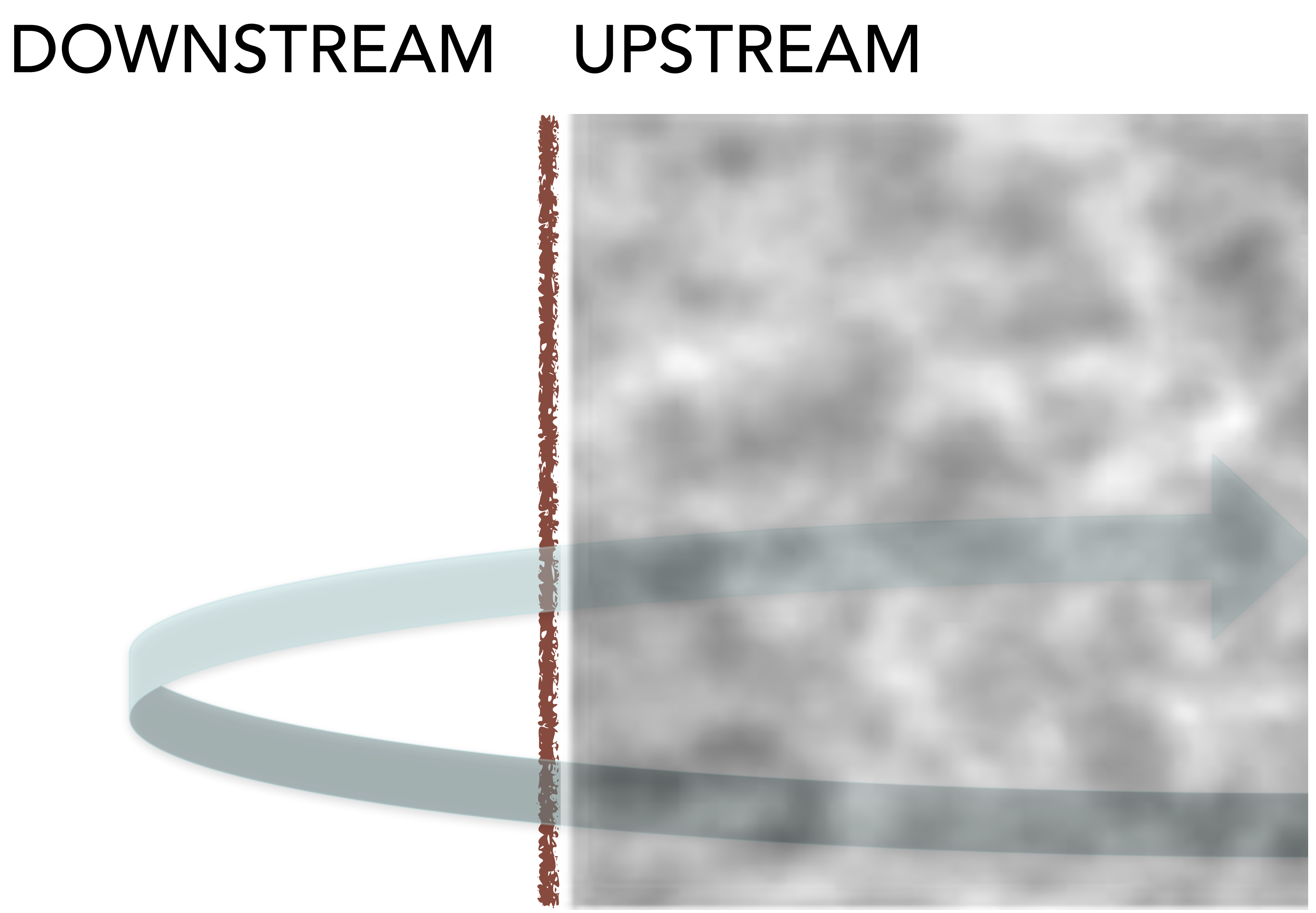

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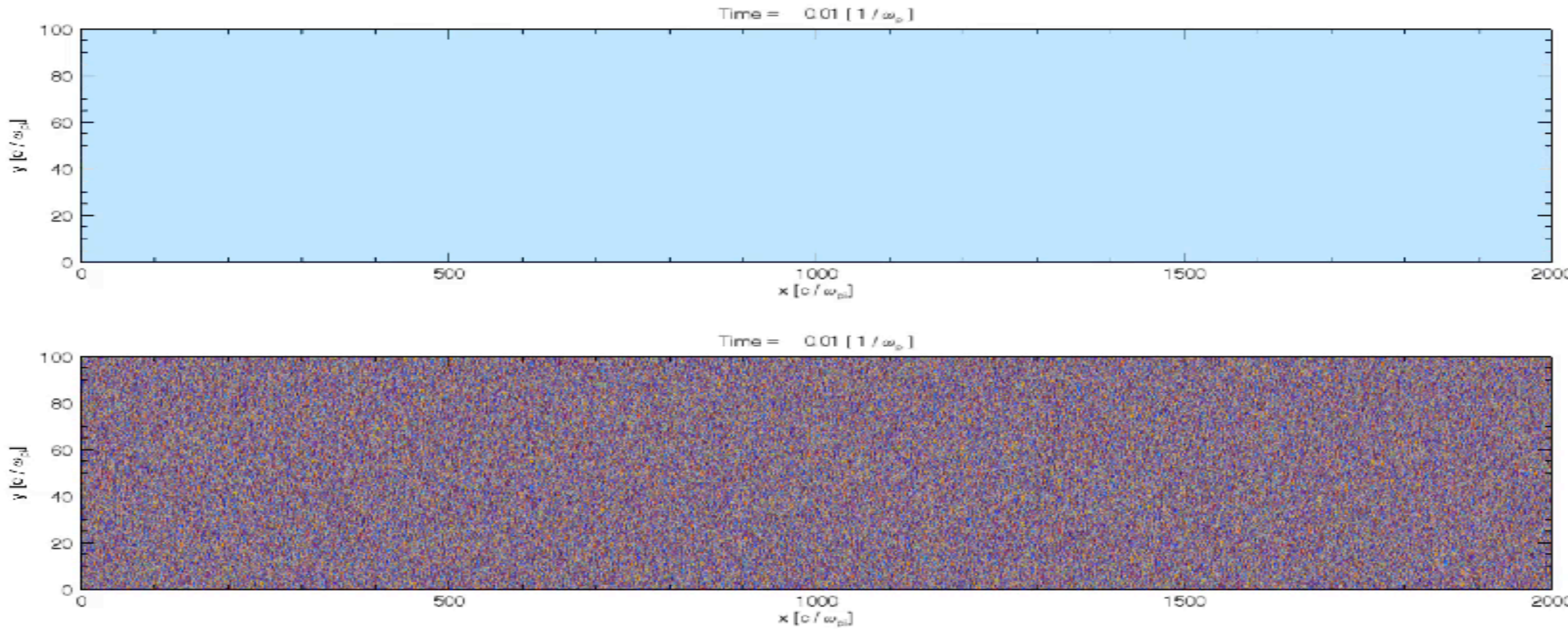

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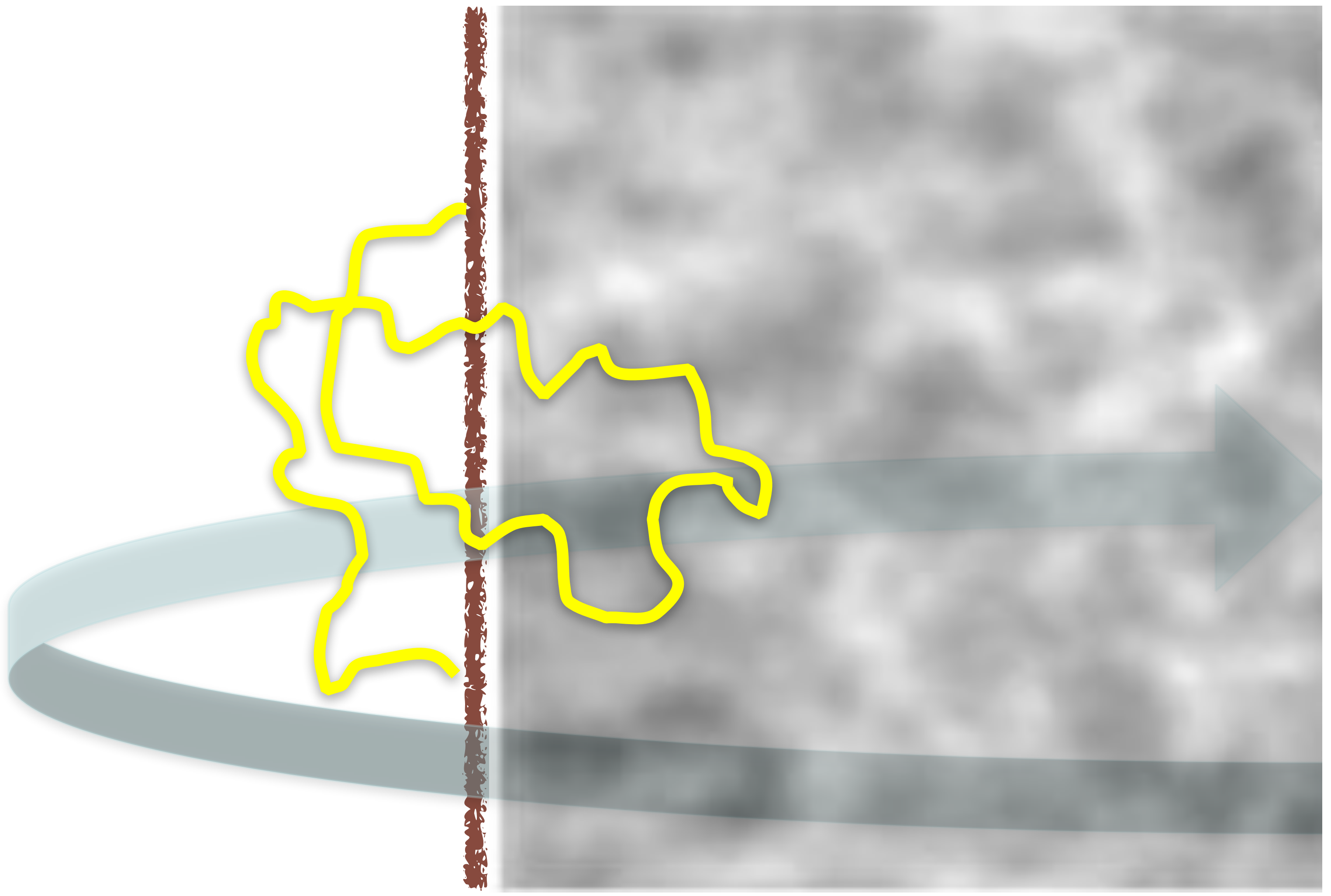

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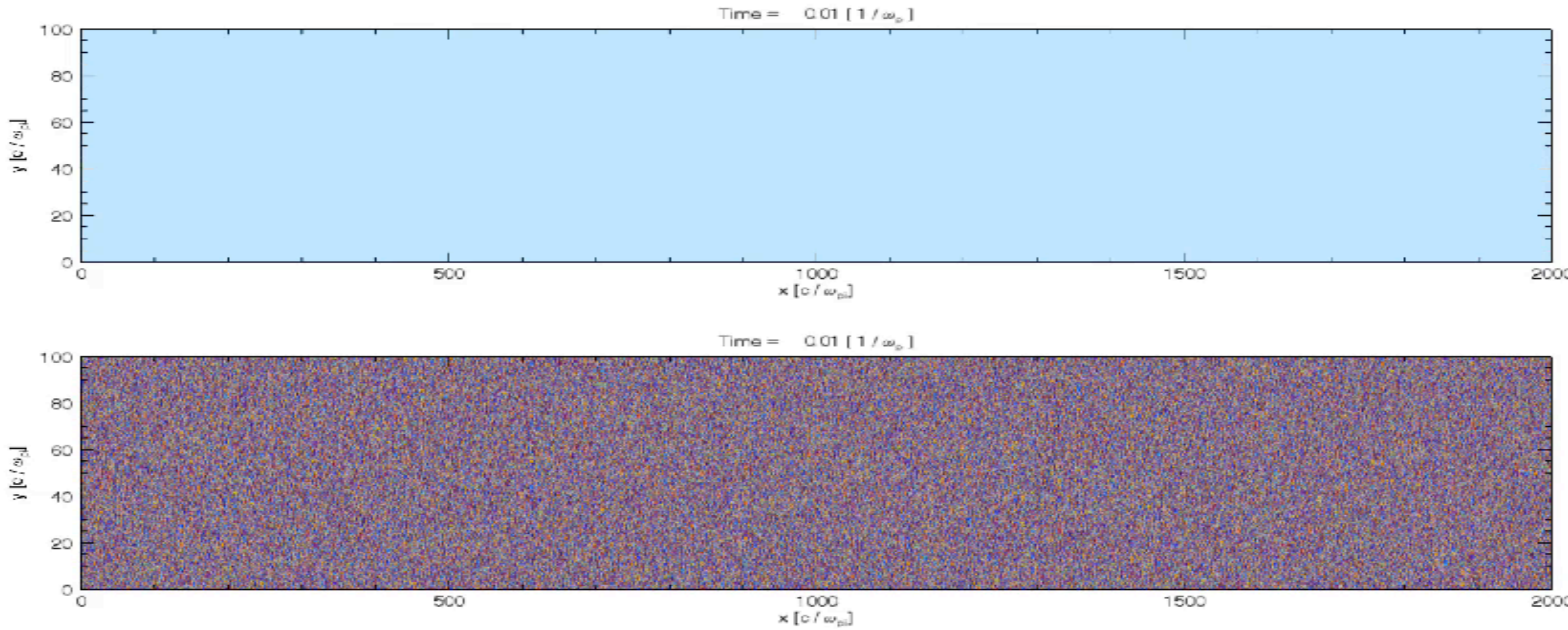

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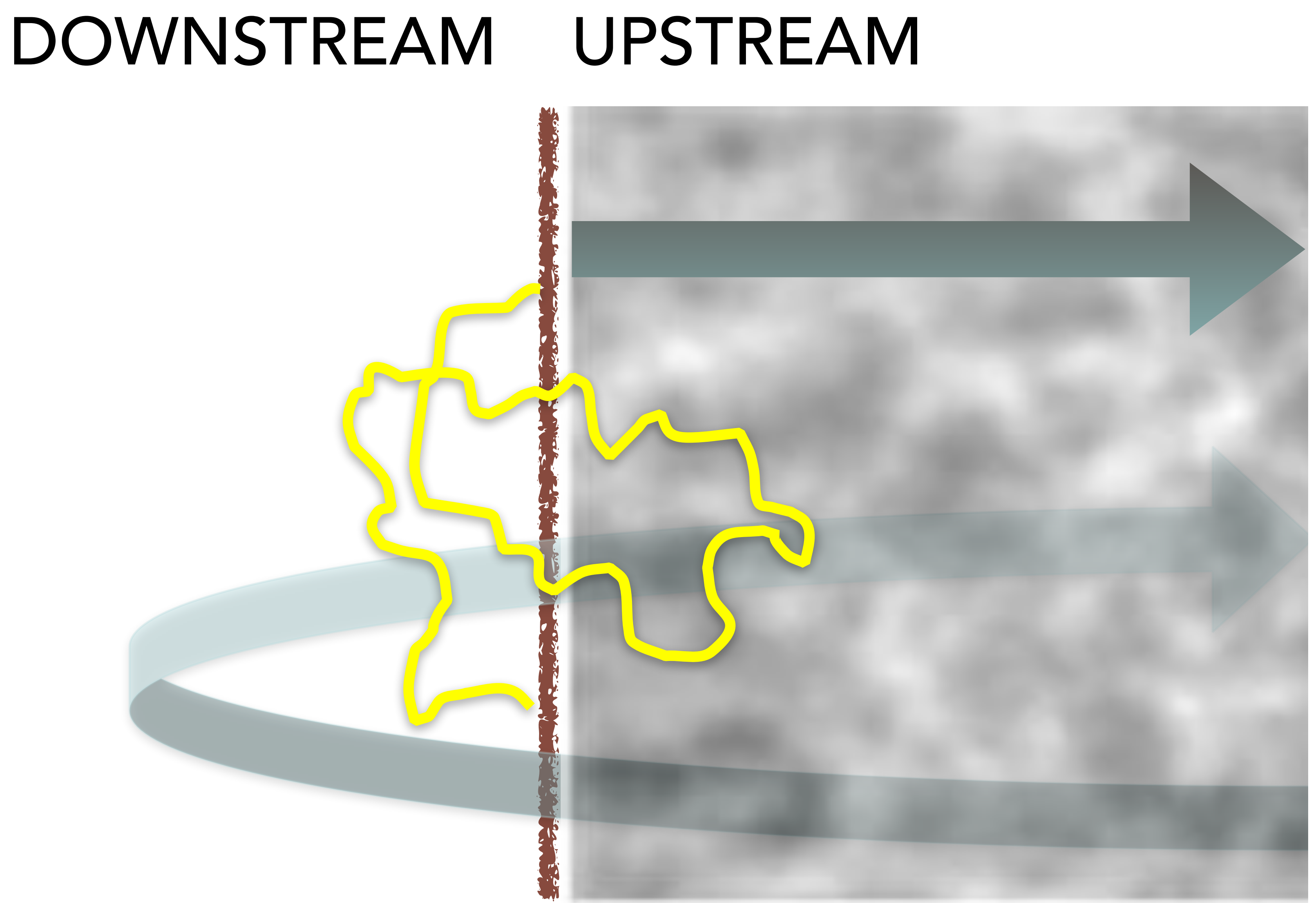

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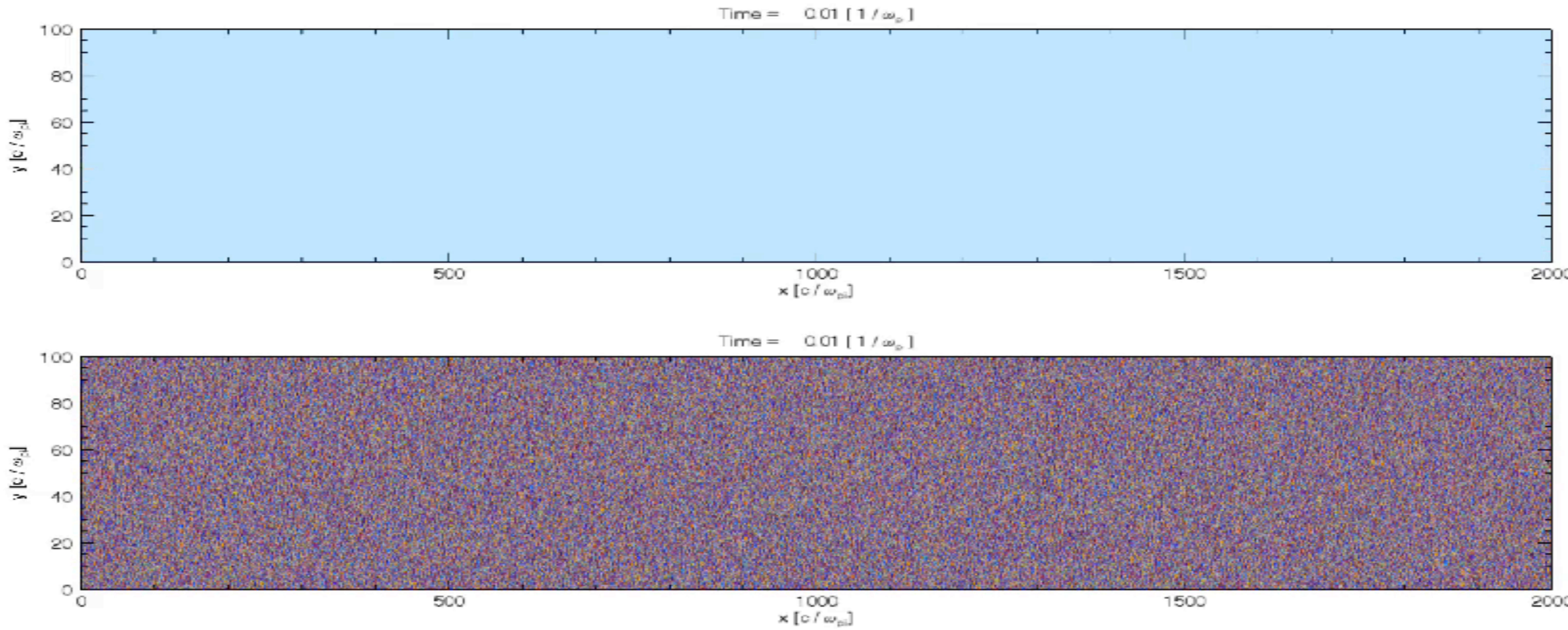

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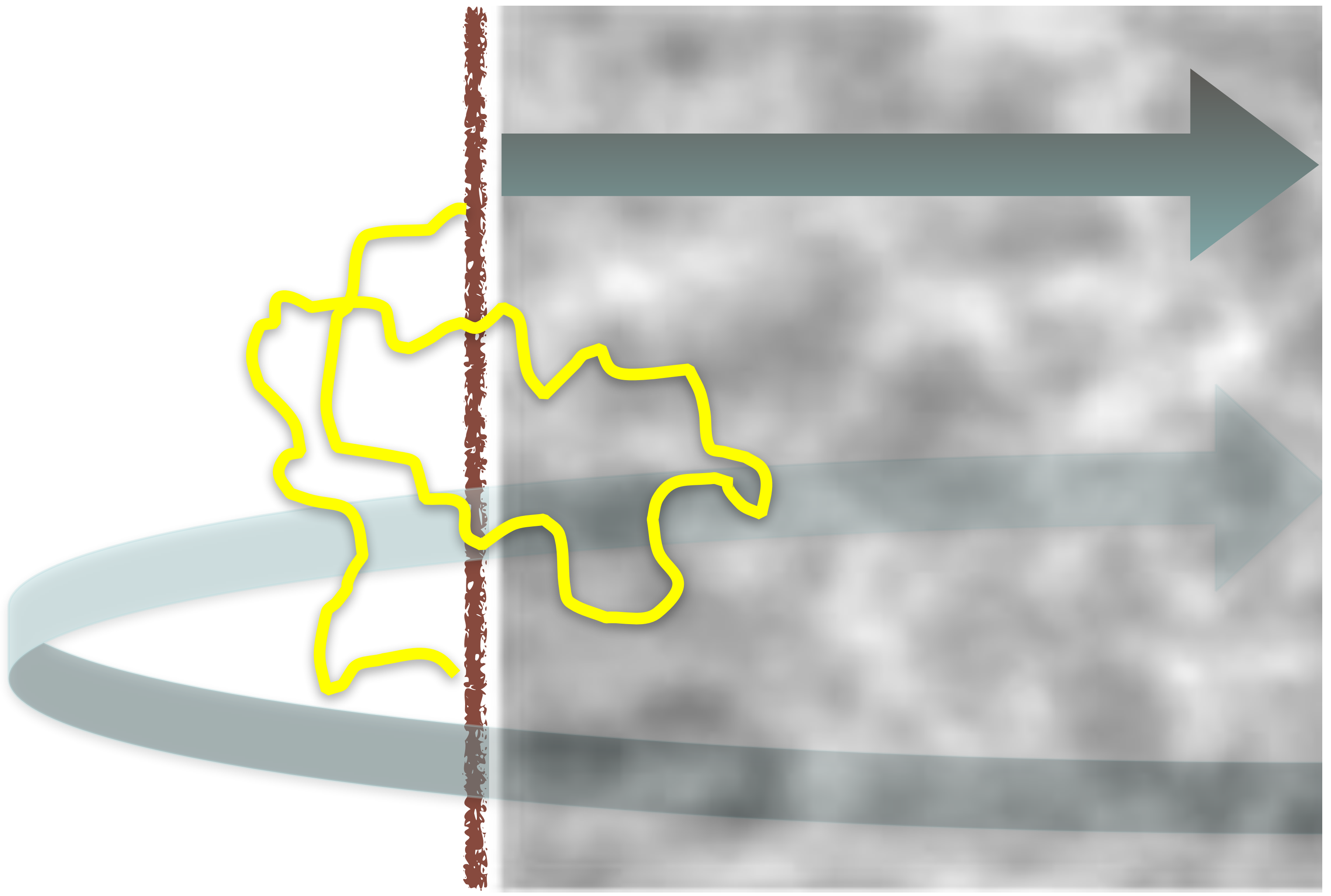

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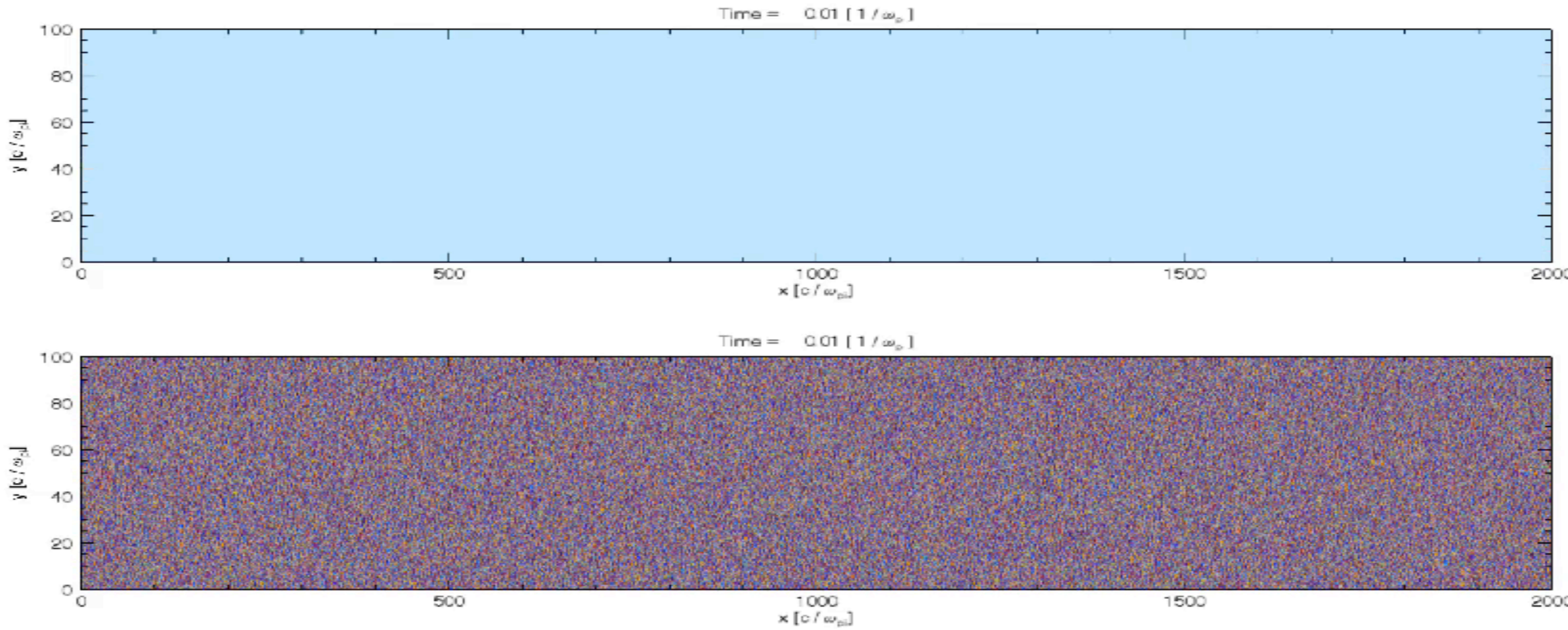
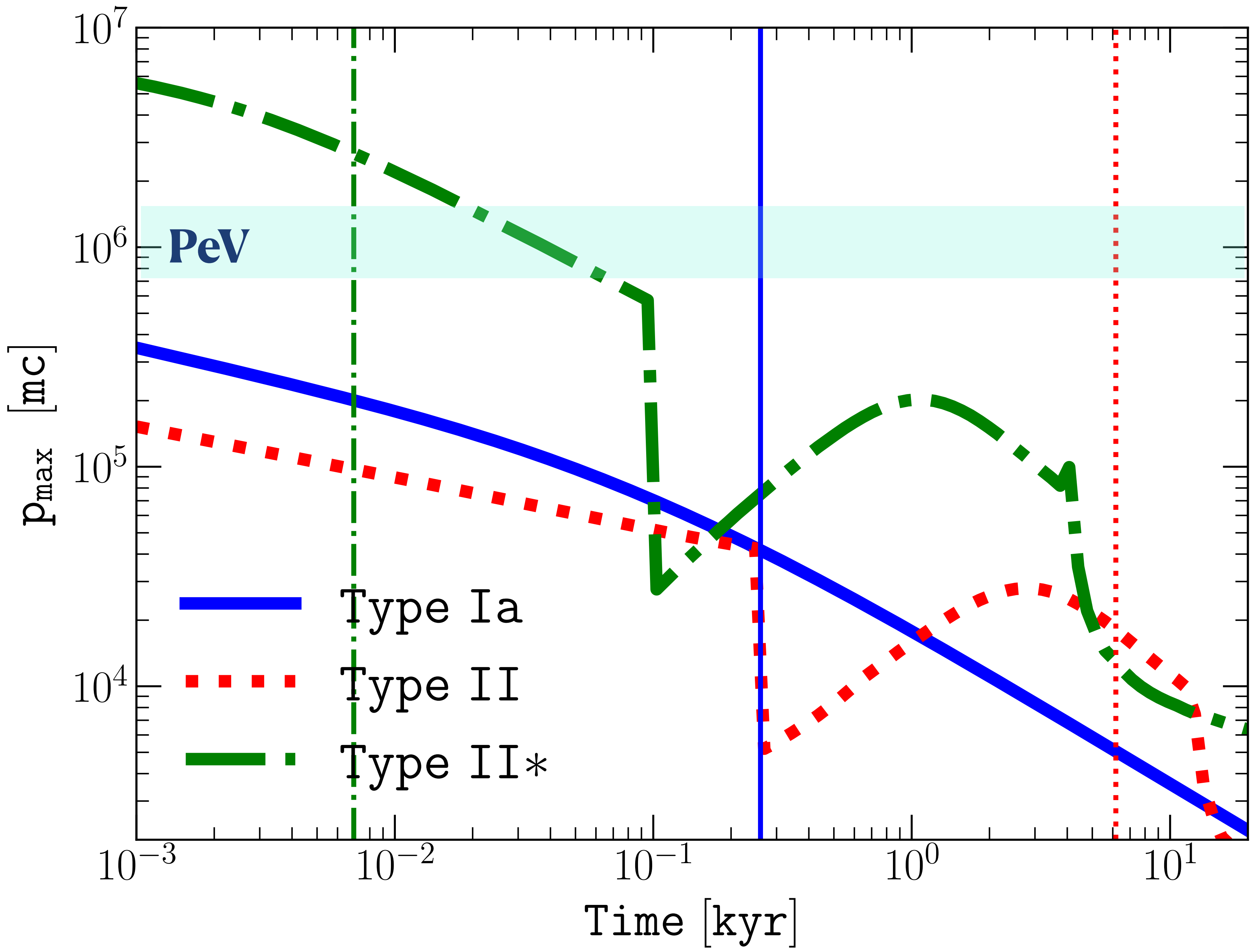
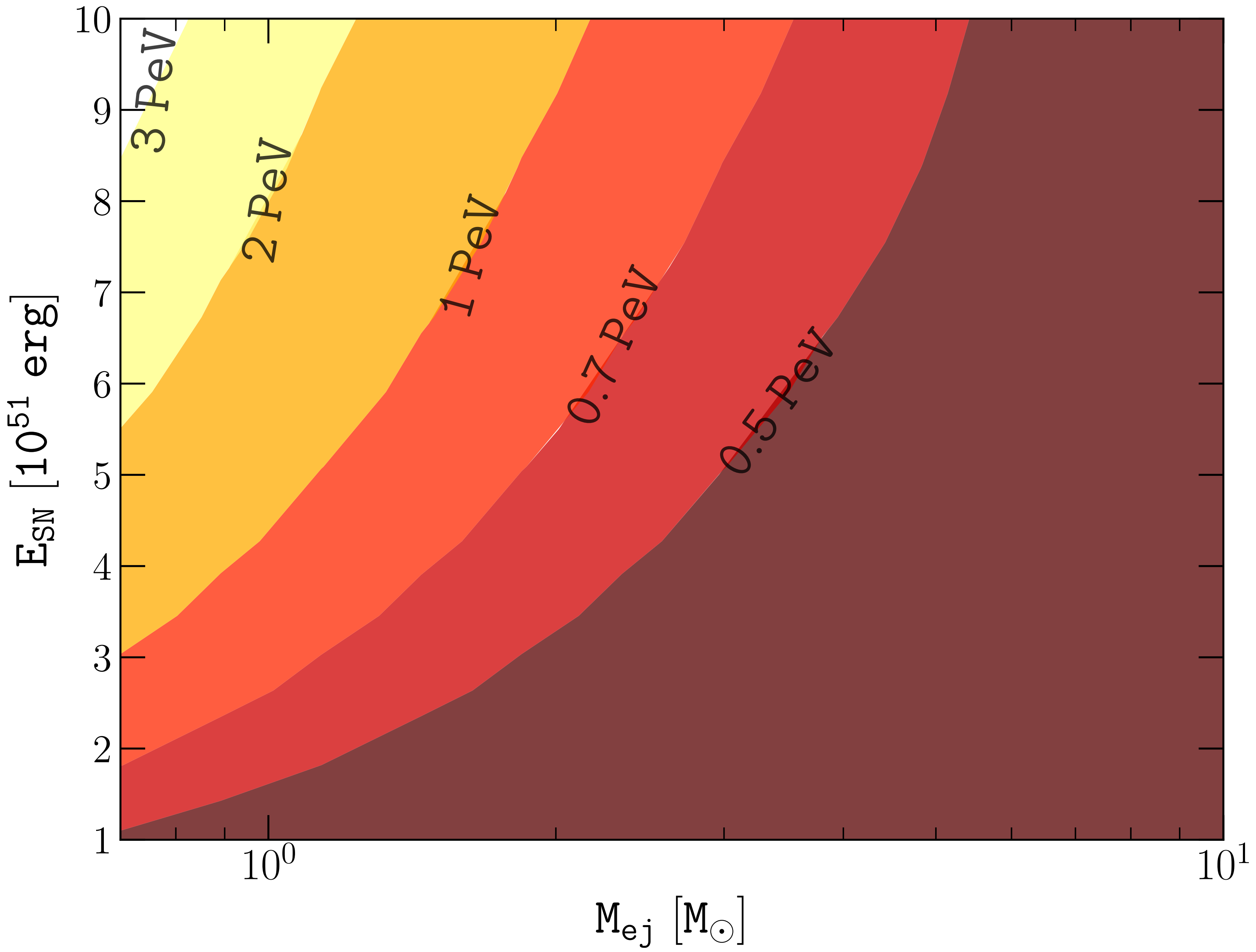


Caprioli & Spitkovsky 2013

SNRs as PeVATRONS?

Cristofari, PB & Amato 2020





- ☑ THE HIGHEST ENERGIES ARE REACHED AT VERY EARLY EVOLUTIONARY STAGES! (Implications for gamma ray observations!)
- ☑ ...BUT THE FLUX CONTRIBUTED IN THOSE STAGES IS LOW, AND IN FACT THIS CORRESPONDS TO THE VERY STEEP PART OF THE SPECTRA RELEASED INTO THE ISM
- ☑ FOR CORE COLLAPSE SNR THE TEMPORAL EVOLUTION OF THE MAXIMUM ENERGY IS IN GENERAL RATHER COMPLEX
- ☑ THE EFFECTIVE E_{MAX} IS THE ONE CORRESPONDING TO THE BEGINNING OF THE SEDOV-TAYLOR PHASE (vertical lines)

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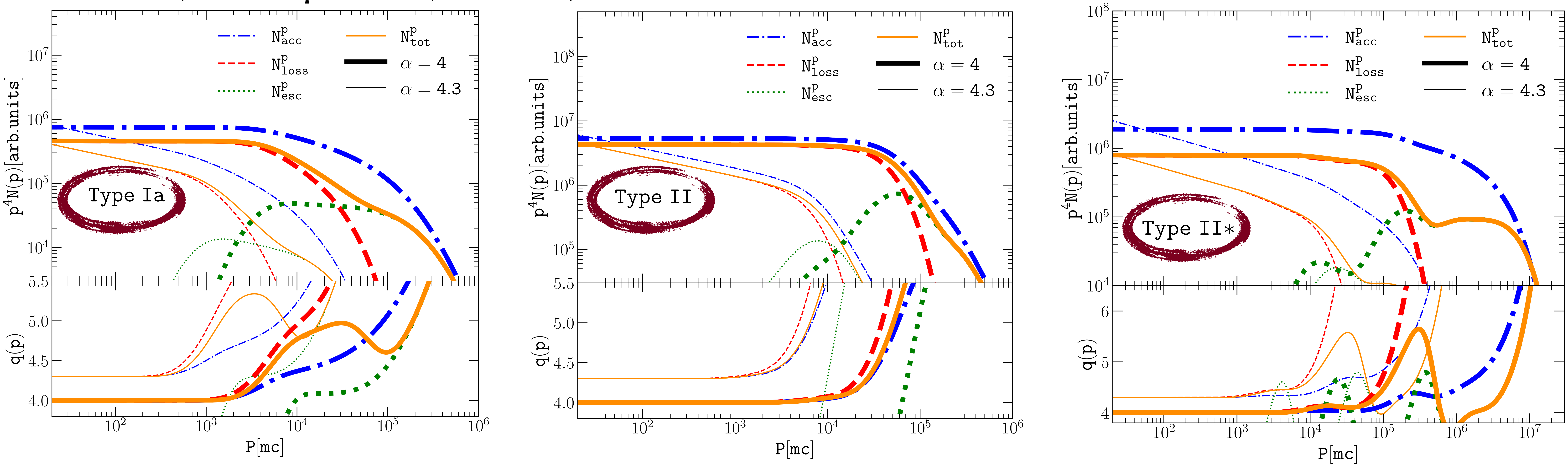
SNRs as PeVATRONS?

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



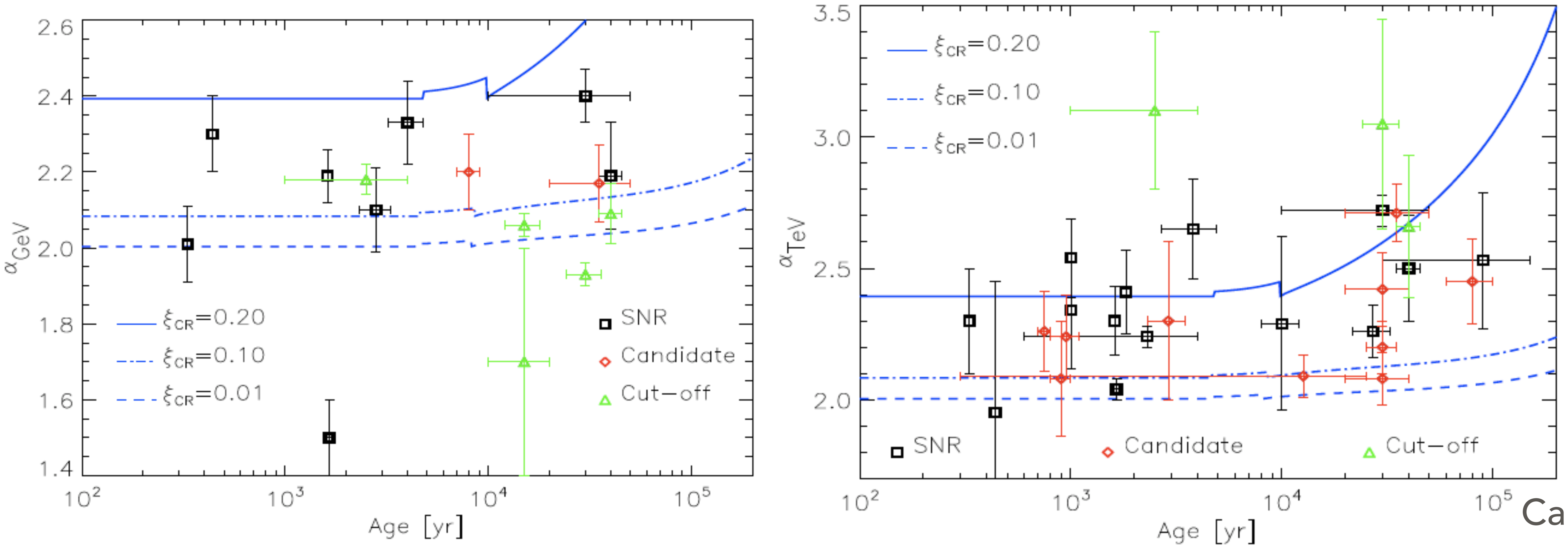
☑ THE SPECTRUM RELEASED INTO THE ISM IS THE SUM OF CR ESCAPING FROM UPSTREAM AND THE ONES TRAPPED DOWNSTREAM (COMPLEX SPECTRAL SHAPES)

☑ THE EFFECTIVE MAX ENERGY FOR IA AND II IS <100 TEV

☑ PEVATRONS ONLY FROM EXTREMELY POWERFUL AND RARE SUPERNOVA REMNANTS

☑ EITHER WAY, THE SUPPRESSION IS NOT EXPONENTIAL!!!

ISSUES WITH SPECTRA INSIDE SNR



Caprioli 2011

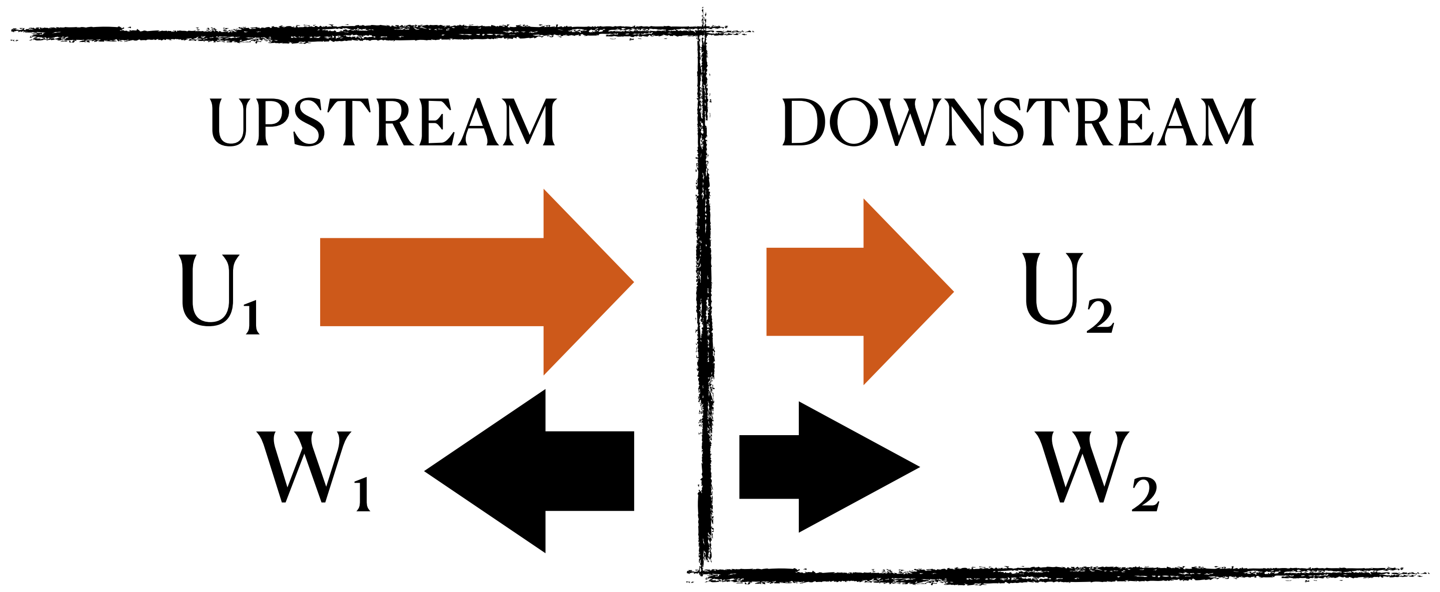
BOTH GAMMA RAY OBSERVATIONS AND CR TRANSPORT SUGGEST THAT THE SPECTRUM CONTRIBUTED BY SNR IS STEEPER THAN E^{-2} BUT THIS SEEMS INCOMPATIBLE WITH THEORETICAL EXPECTATIONS!

THESE SUBTLE FEATURES ARE SENSITIVE TO THE MICROPHYSICS...

POSTCURSORS

- 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 THE MAGNETIC FIELD MAKES ANOTHER EFFECT APPEAR:



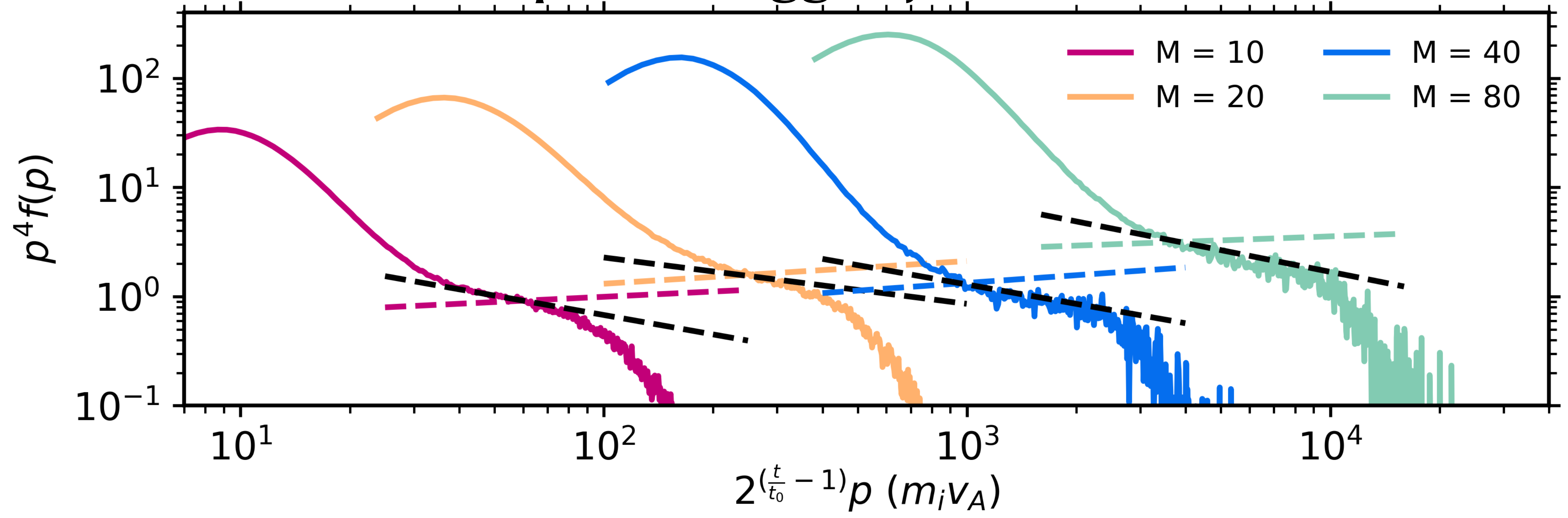
THE VELOCITY OF THE WAVES UPSTREAM IS $U_1 - W_1 \approx U_1$

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

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

THE SPECTRUM BECOMES STEEPER

Caprioli, Haggerty & PB 2020



Star Cluster Winds

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MANY ACCELERATION PROCESSES MAY BE AT WORK

YOUNG STELLAR CLUSTERS (no SNRs)

- *Collision of winds* [Reimer, Pohl, Reimer (2006); Bykov, Gladilin & Osipov (2013); Vieu, Gabici & Tatischeff (2020)]
- *Termination shock of individual stars in the cluster*
- ***DSA at the termination shock of the collective wind*** [Morlino, PB, Peretti & Cristofari 2021]

SUPERBUBBLES WITH WINDS AND SNR EXPLOSIONS

- *DSA at shocks of individual SNR (large turbulence in the cluster) [Parizot et al. 2004]*
- *Acceleration at multiple shocks*
- *Acceleration by turbulence and multiple shocks [Bykov & Toptygin 1993,Parizot et al. 2004; Ferrand & Markowith 2010; Vieu, Gabici & Tatischeff ICRC 2021]*

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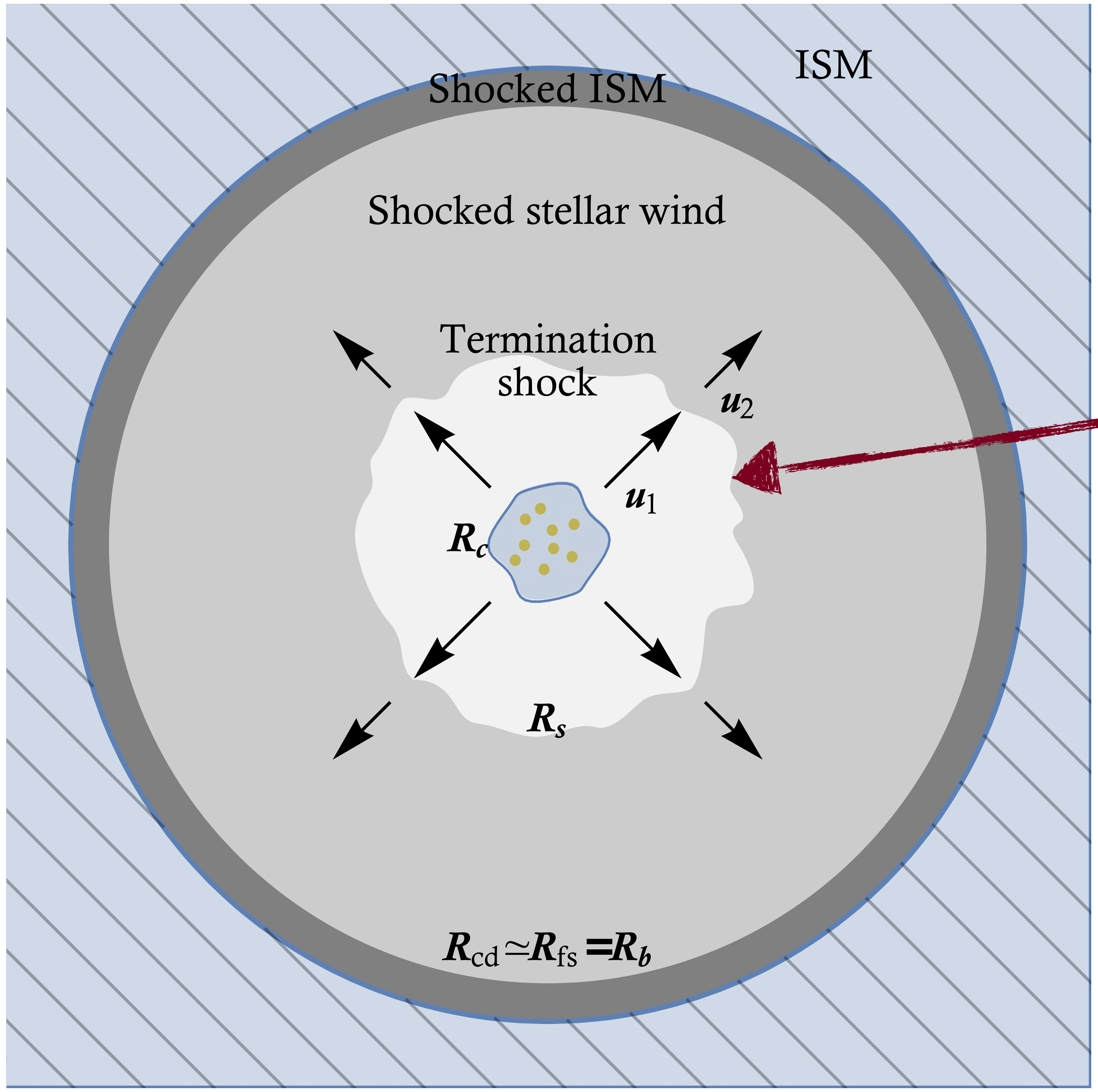
Why Star Cluster Winds?

- The typical luminosity of a SC is $L_W=(1/2)\dot{M}V_W^2\approx 10^{38}$ erg/s
- In CRs the abundance of ^{22}Ne is about 5 times solar and the winds of massive stars are rich in ^{22}Ne
- Collisions of stellar winds in the compact core (~1000 stars) injects turbulence in the system, useful for CR acceleration
- Several Star Clusters are being detected in gamma rays up to hundreds of TeV
- The expected topology of the acceleration region seems to be ideal for CR acceleration

DYNAMICS OF A STAR CLUSTER CAVITY



Morlino, PB, Peretti & Cristofari, 2021

THE COLLECTIVE WIND OF THE STAR CLUSTER EXCAVATES A CAVITY IN THE ISM, WITH A SIZE OF ~ $R_b(t) = 174\, \rho_1^{-1/5} L_{37}^{1/5} t_{10}^{3/5}$ pc AND A TERMINATION SHOCK DEVELOPS AT

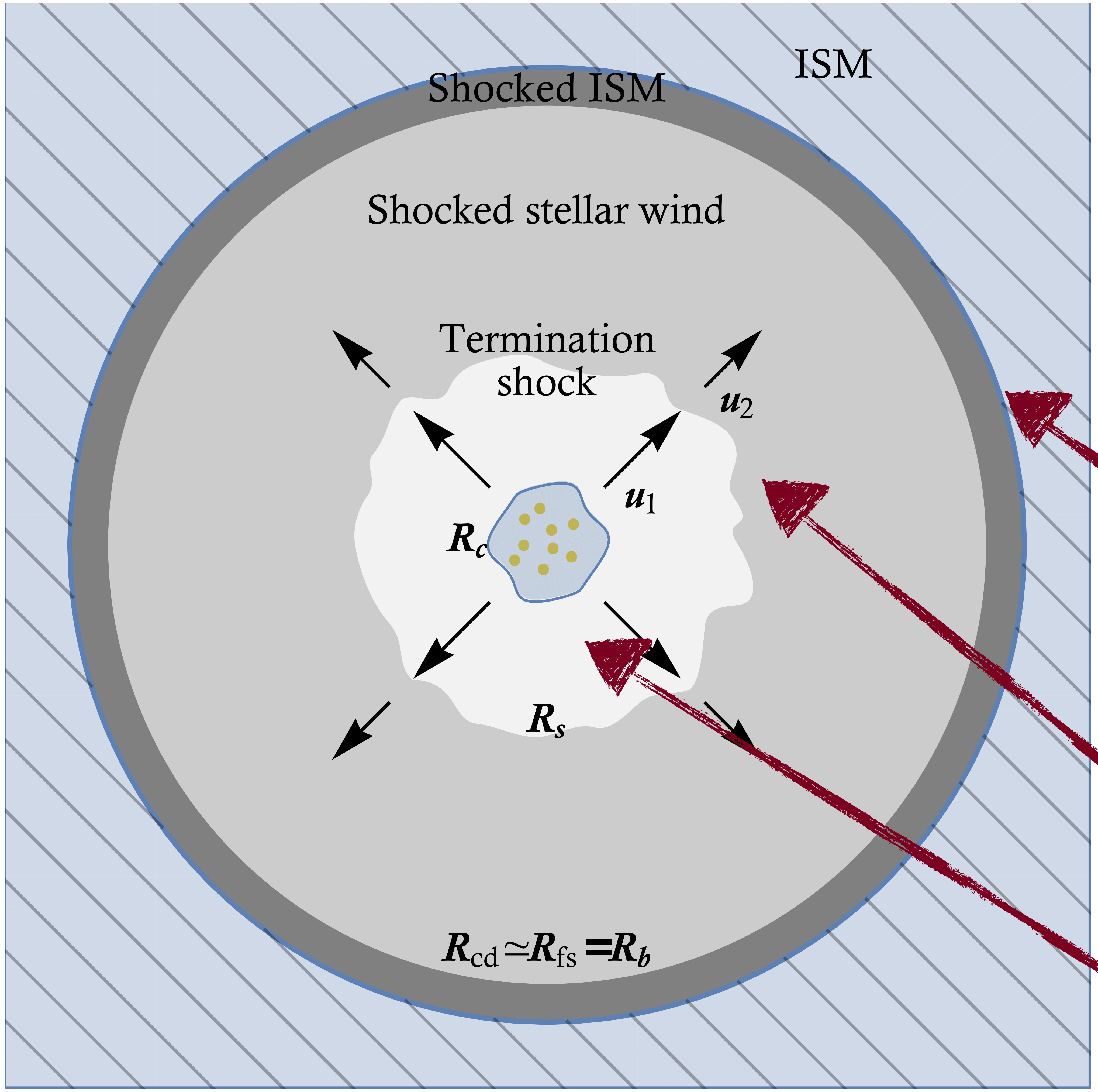
$$R_s = 48.6\, \dot{M}_{-4}^{3/10} v_8^{1/10} \rho_1^{-3/10} t_{10}^{2/5} \text{ pc}$$

THE STRUCTURE IS QUASI-STATIONARY WITH THE FORWARD SHOCK VERY SLOWLY MOVING OUTWARD.

AT THE TERMINATION SHOCK, THE WIND OF THE STAR GETS SLOWED DOWN AND HEATED UP.

AT THE TERMINATION SHOCK DIFFUSIVE PARTICLE ACCELERATION TAKES PLACE, BUT IN A CONFIGURATION THAT IS PRETTY DIFFERENT FROM THAT OF SNR

DSA AT THE TERMINATION SHOCK



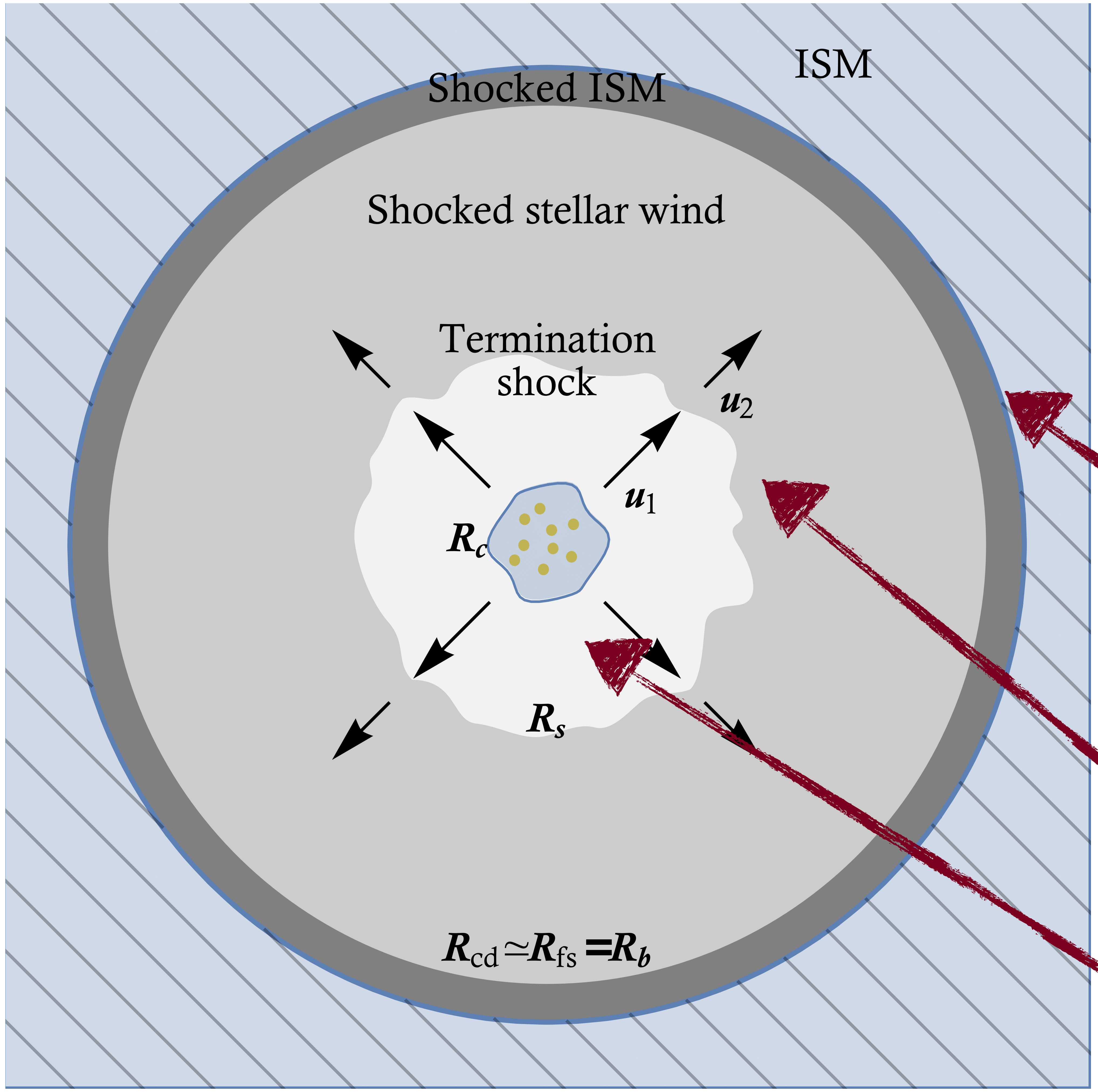
Morlino, PB, Peretti & Cristofari, 2021

ESCAPE OCCURS AT THE OUTER BOUNDARY

DOWNSTREAM IS IN THE CAVITY

UPSTREAM IS IN THE WIND

DSA AT THE TERMINATION SHOCK



Morlino, PB, Peretti & Cristofari, 2021

PARTICLES ARE TRAPPED IN THE UPSTREAM REGION AND THEY CAN ONLY LEAVE THE SYSTEM WHEN THEY REACH THE OUTER BOUNDARY (THROUGH ADVECTION AND DIFFUSION) - VERY DIFFERENT CASE FROM THAT OF SNRs

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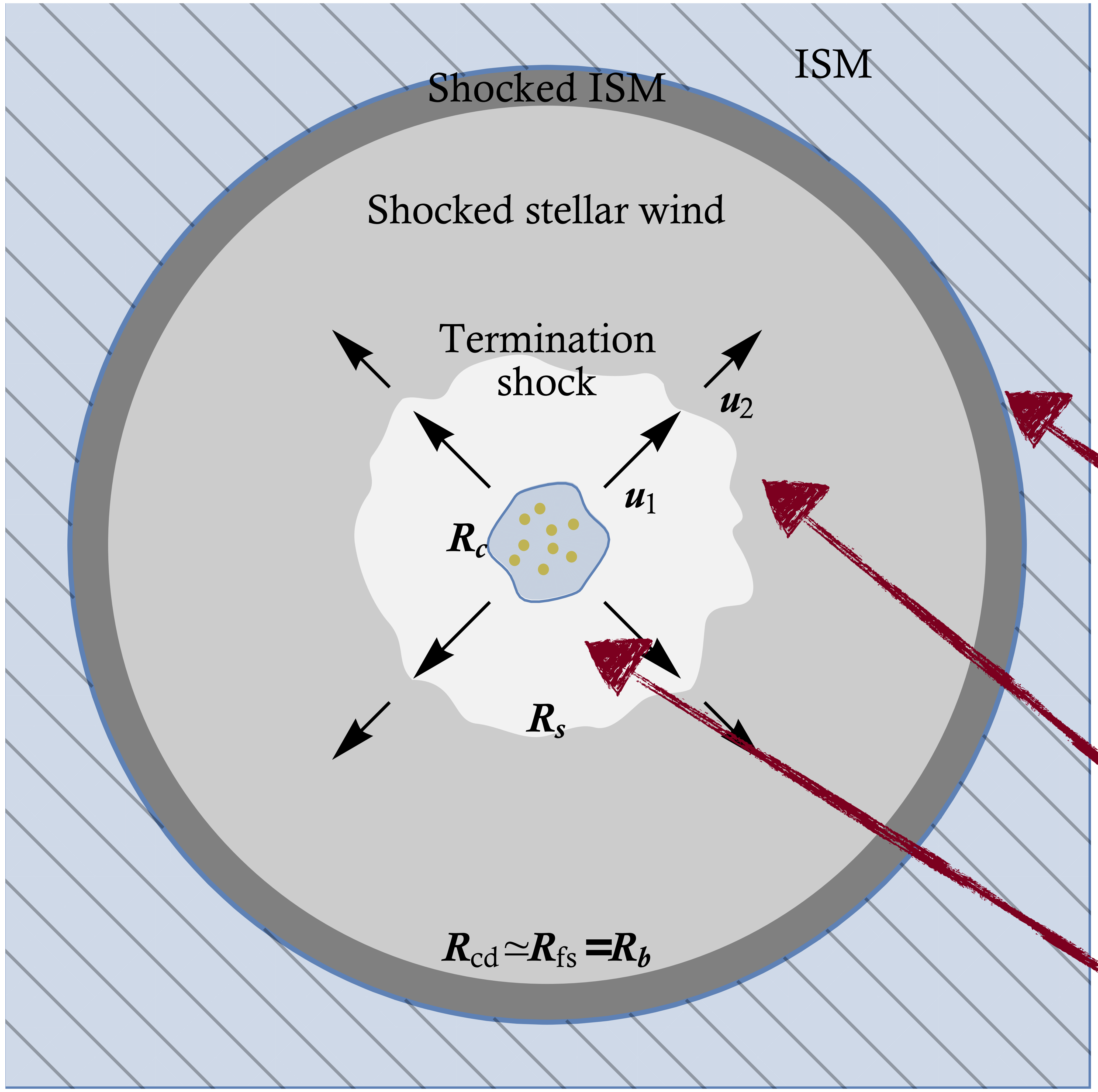

Morlino, PB, Peretti & Cristofari, 2021

Particles are trapped in the upstream region and they can only leave the system when they reach the outer boundary (through advection and diffusion) - **very different case from that of SNRs**

Escape occurs at the outer boundary

Downstream is in the cavity

Upstream is in the wind

Diffusion in the upstream very sensitive to the turbulence transported by the wind and cascading to smaller scales

much less sensitive to self-generation

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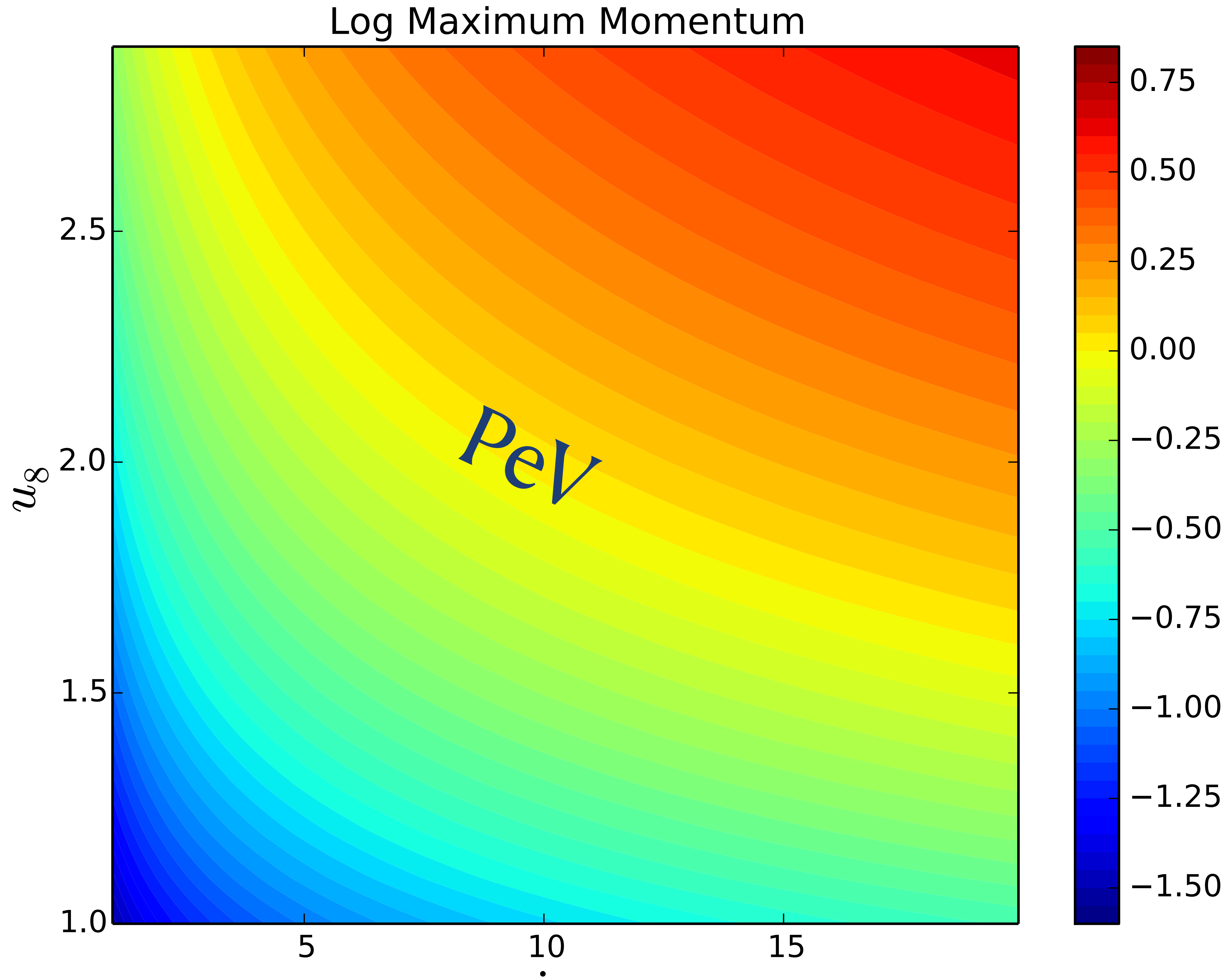
The maximum Energy

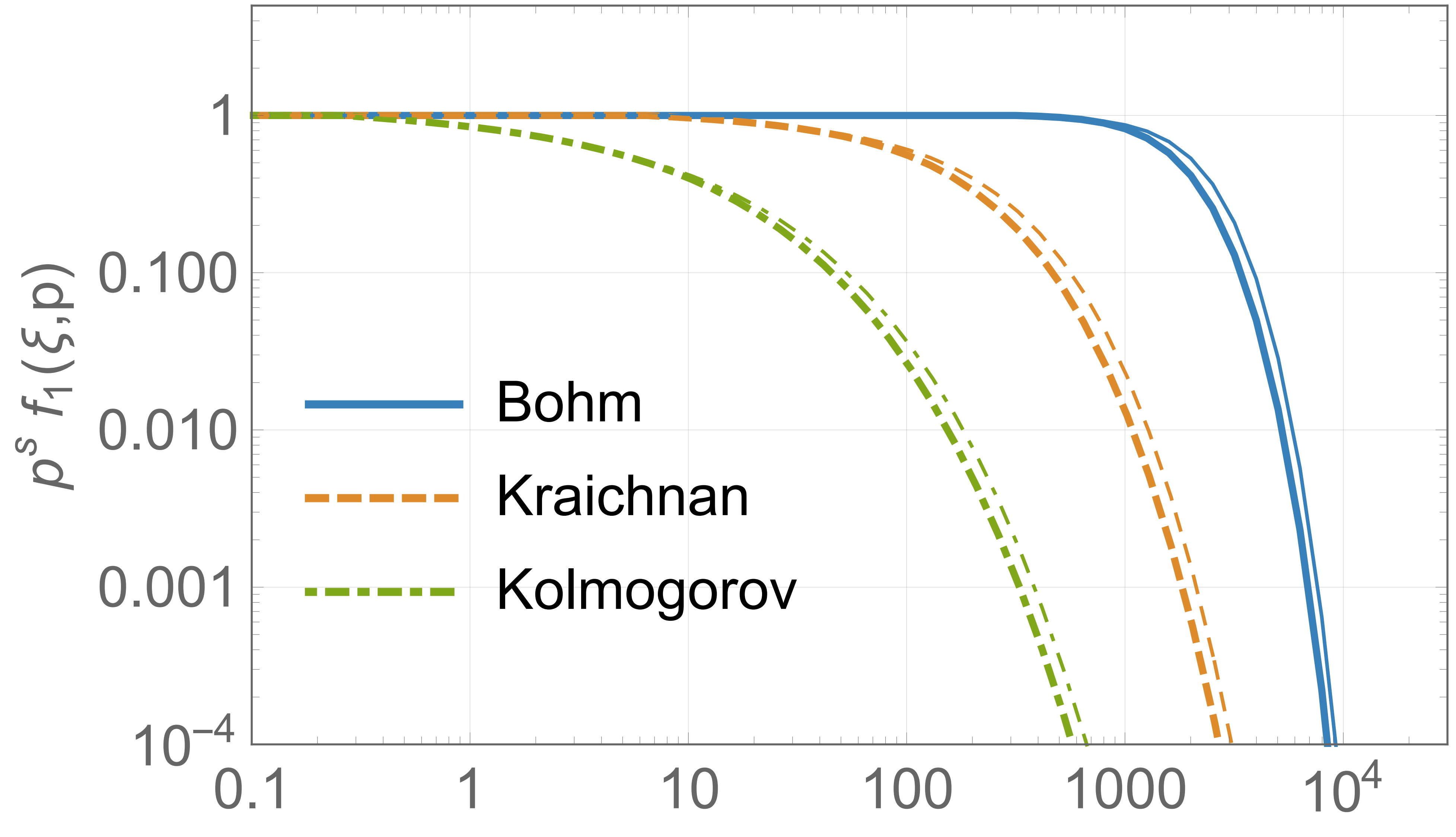


PB & Morlino, in preparation

$$E_{\max} \approx 4\times 10^{14}\, \eta_B^{1/2} \dot{M}_{-4}^{4/5} v_8^{13/5} \rho_1^{-3/10} t_{10}^{2/5} \left(\frac{L_c}{2\mathrm{pc}}\right)^{-1} \mathrm{eV}$$

Acceleration to PeV for luminous star clusters (large wind speed, large mass loss rate)

But shape of the cutoff strongly dependent upon the diffusion coefficient



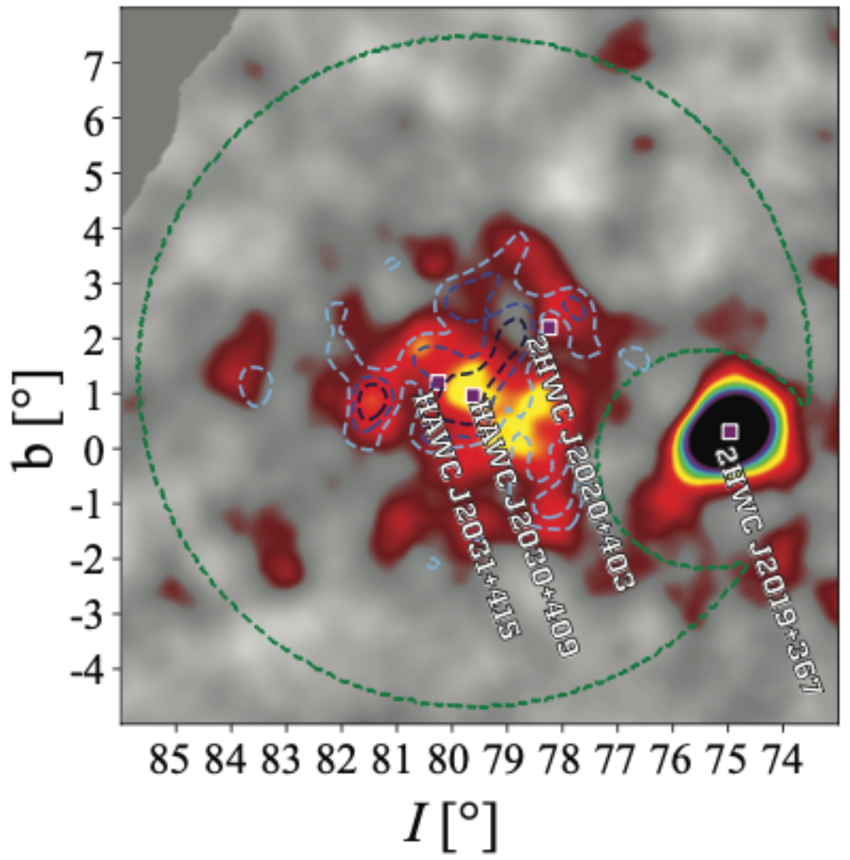
Morlino, PB, Peretti & Cristofari, 2021 p [TeV/c]

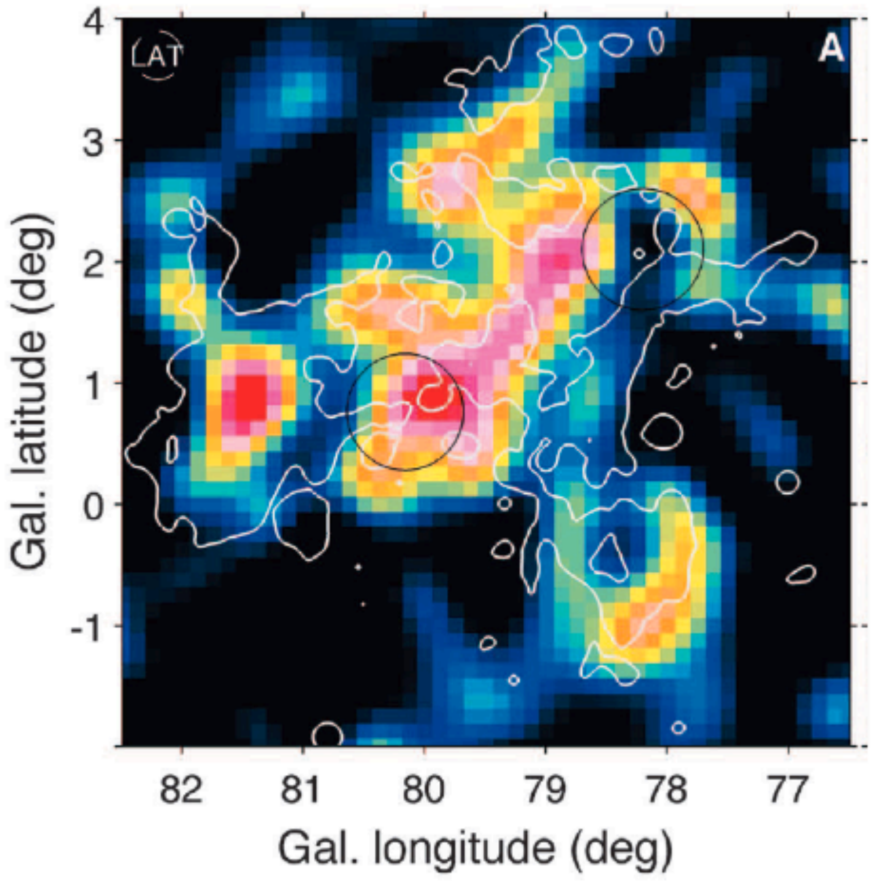
GAMMA RAYS FROM STAR CLUSTERS

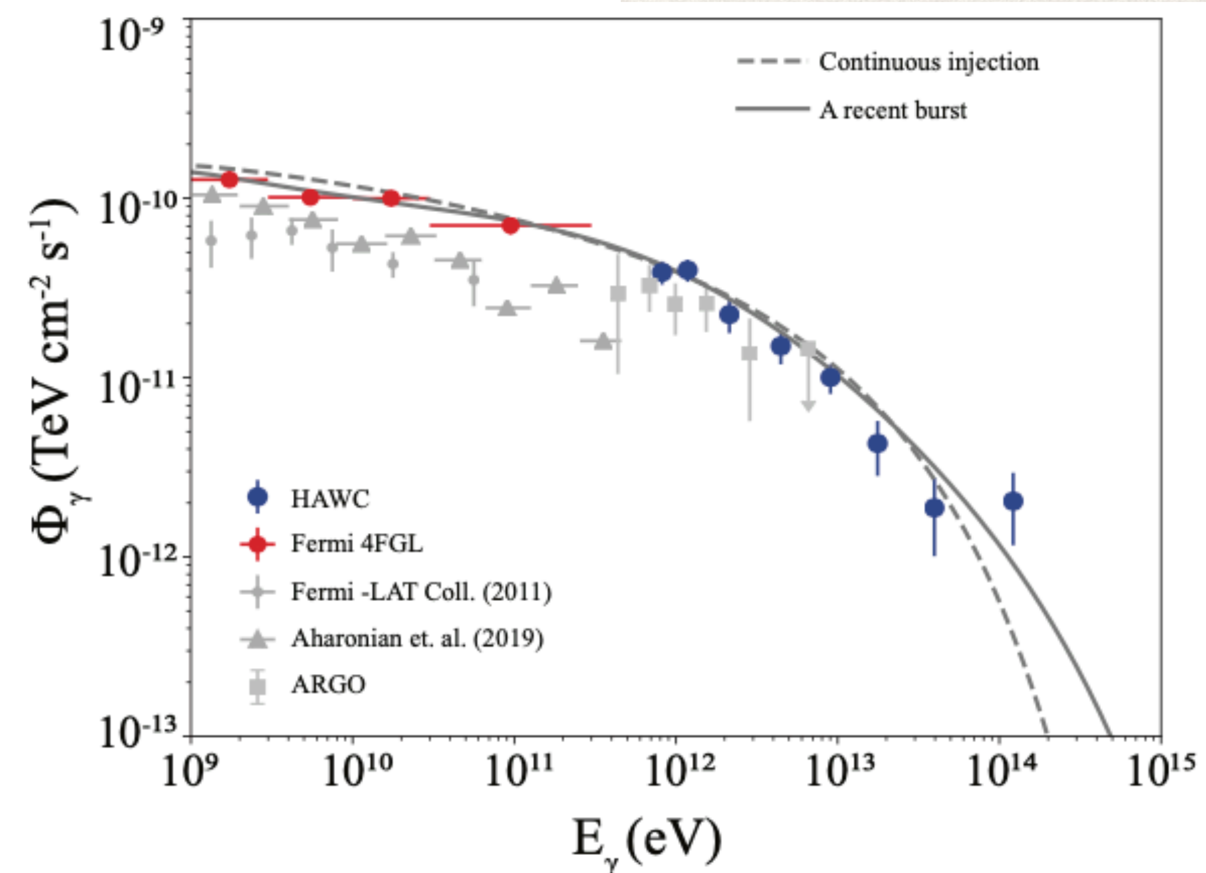
Cygnus-OB2

Abeysakara et al. (2021) Nat. Astron. **HAWC**

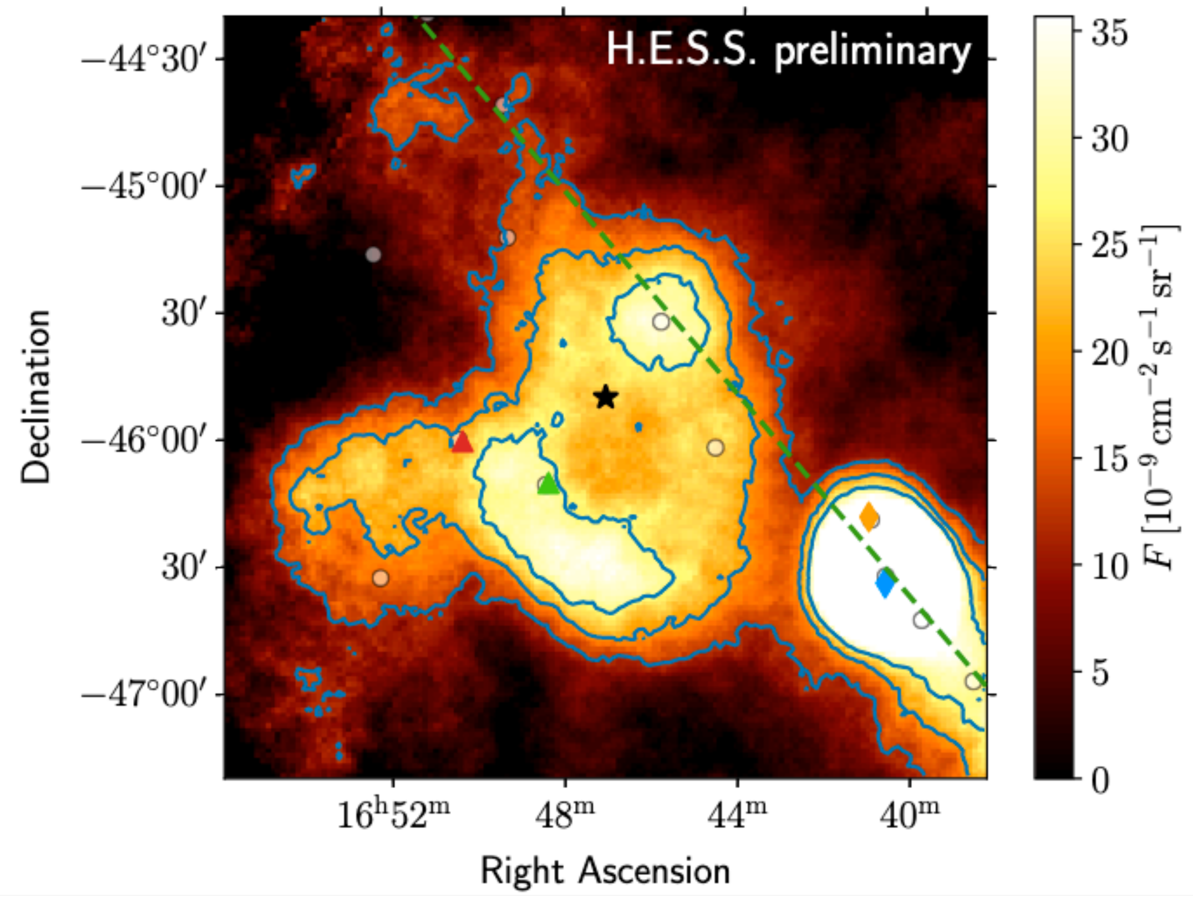
Ackermann et al. (2011) Science 334 **Fermi-LAT**

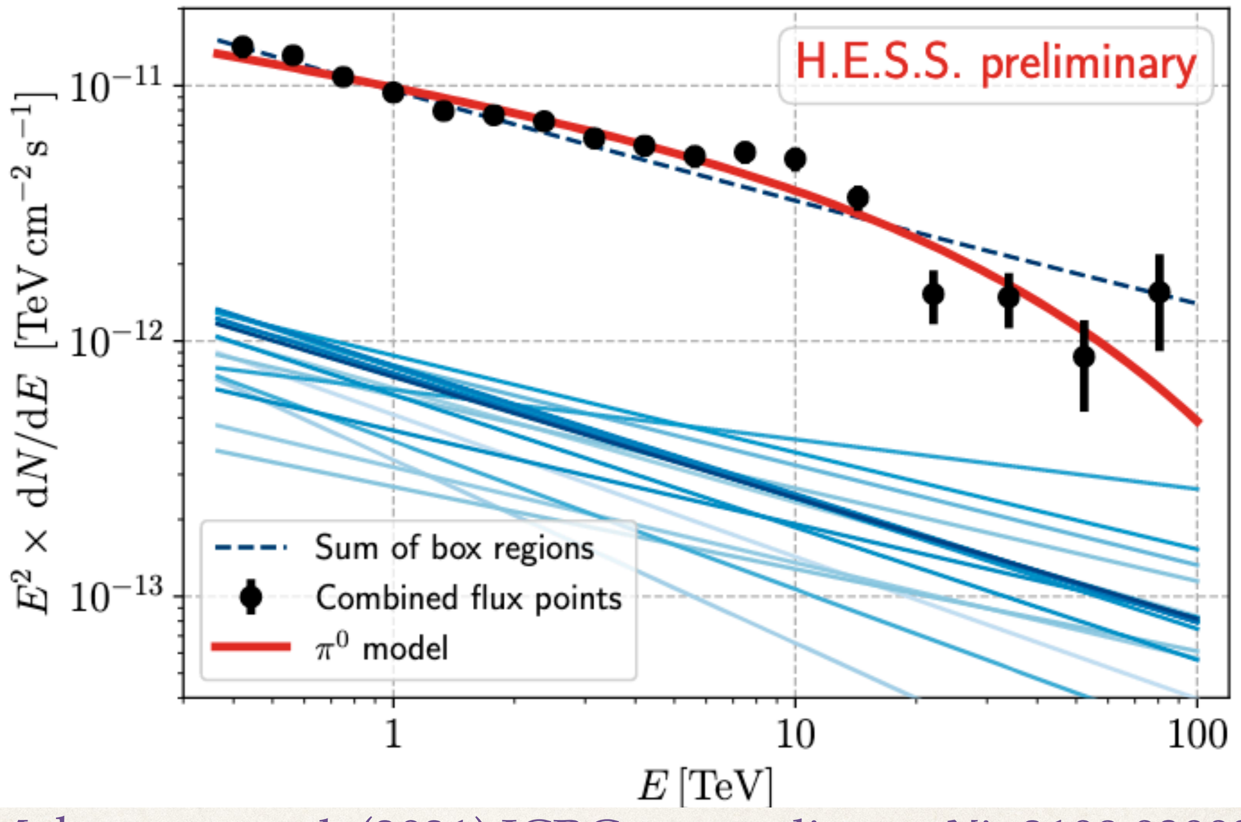






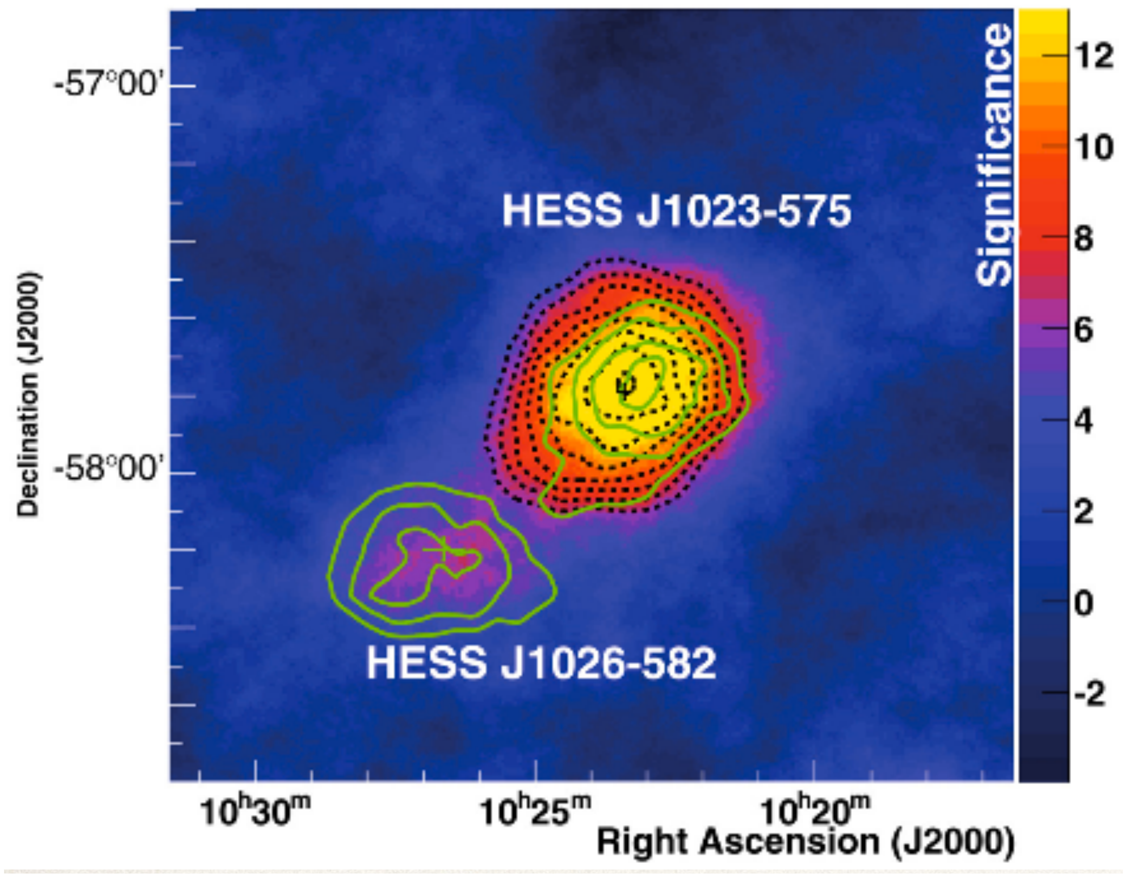
Westerlund 1

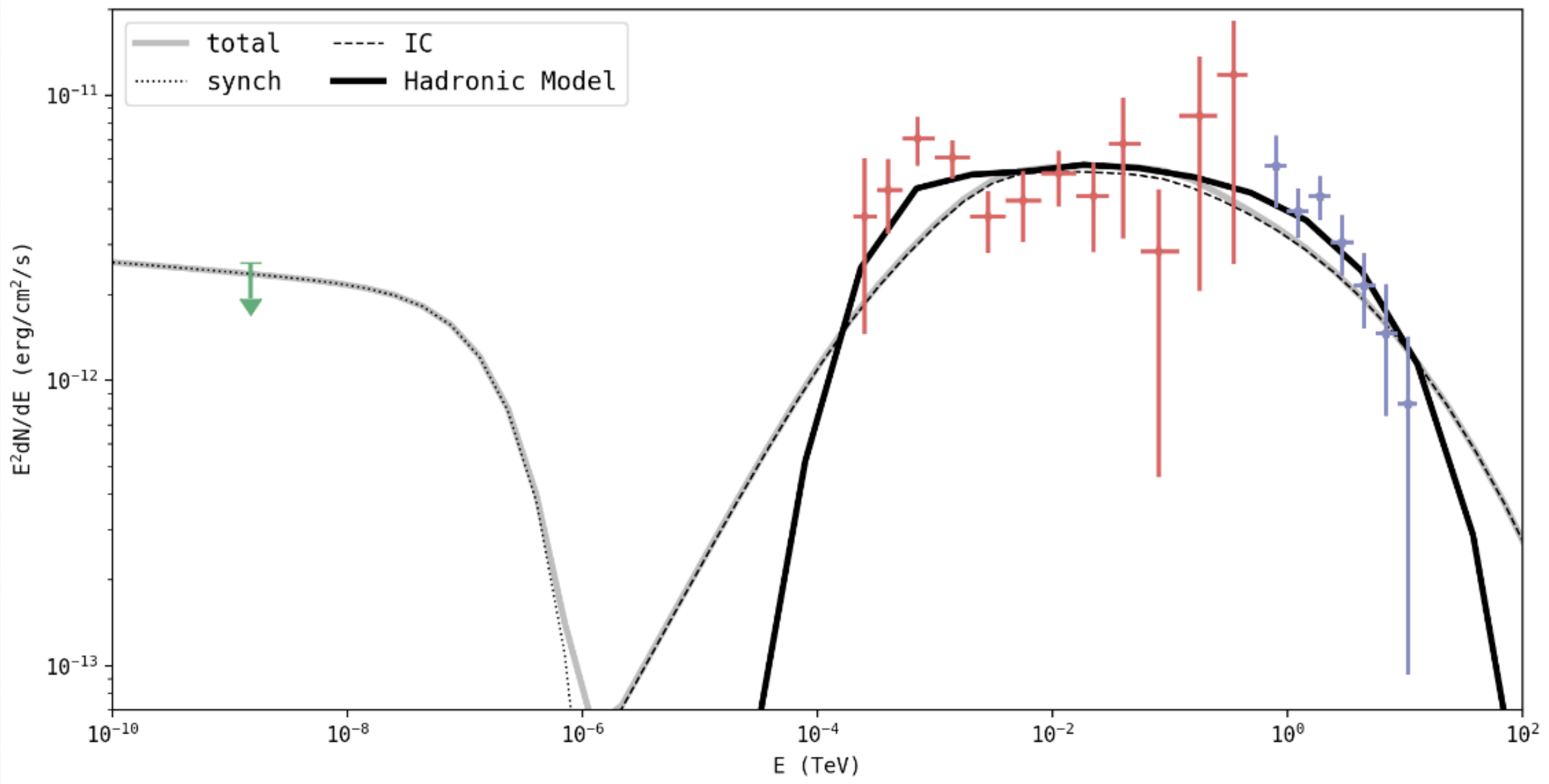




Mohrmann et al. (2021) ICRC proceeding, arXiv2108.03003

Westerlund 2





Mestre et al. (2021) MNRAS, 502, 2

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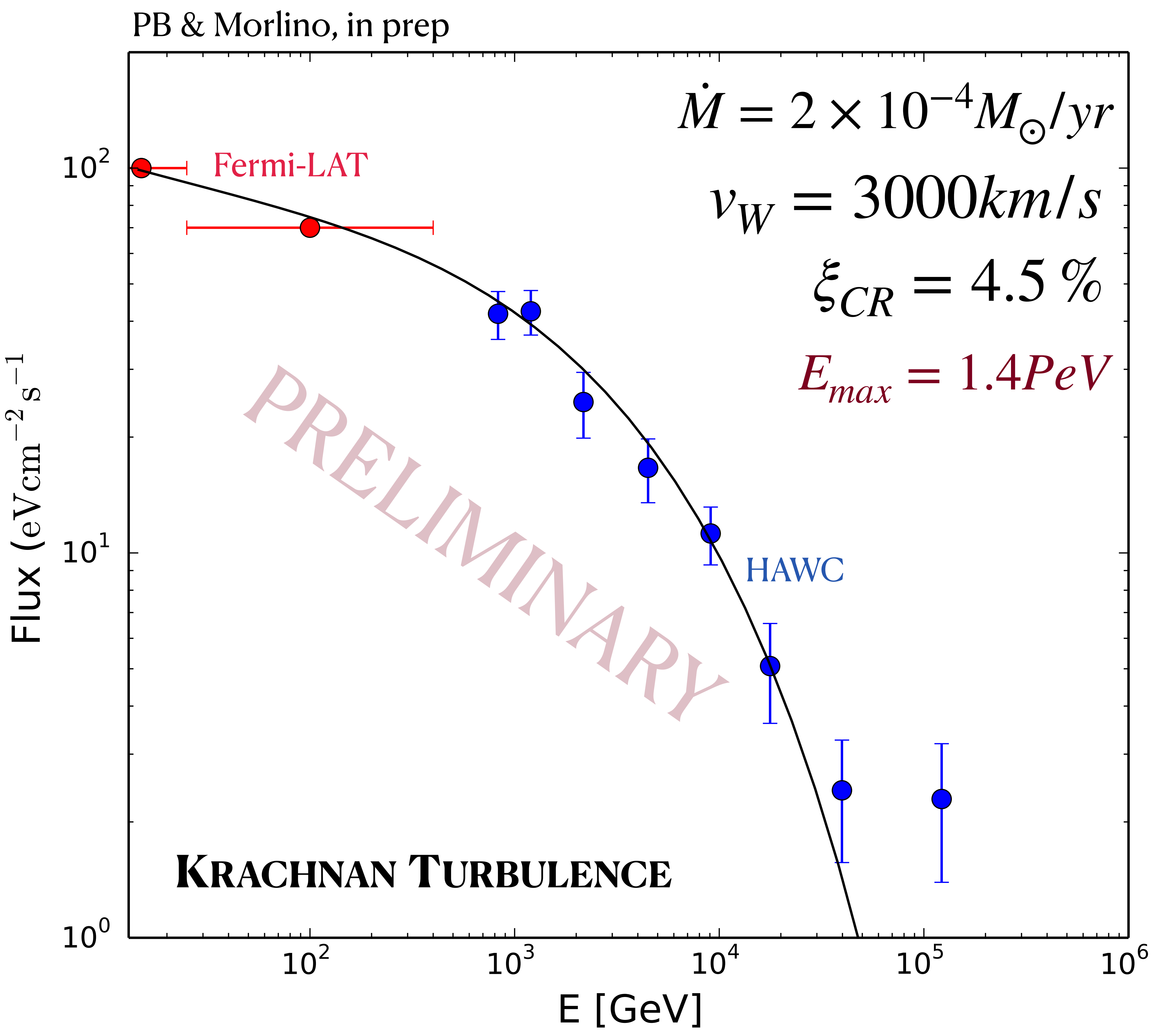
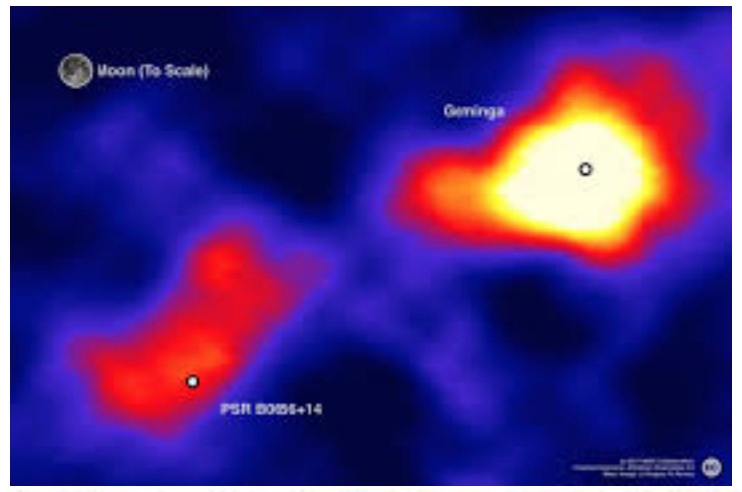
Gygnus Cocoon Gamma Rays



- Particle acceleration in Cygnus can lead to VHE but at least for Krachnan turbulence this requires high luminosity
- The data of HAWC are all in the cutoff region - beware to claim the existence of a slope and a PeVatron
- The morphology adds information to the origin of the turbulence and the gas distribution
- Upcoming LHAASO data will shed light on the high energy behaviour and help discriminating the type of turbulence or the presence of accelerators inside Cygnus cocoon

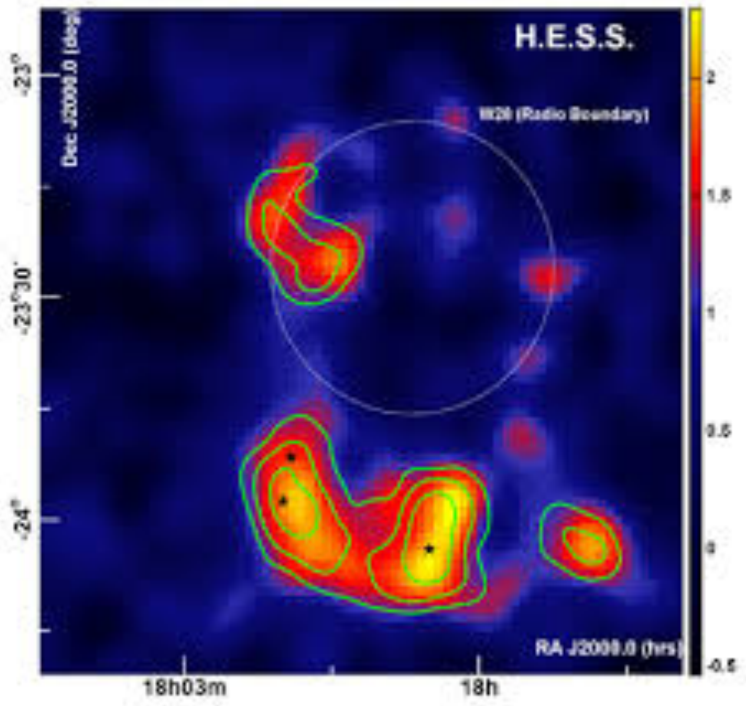
The fate of VHE particles leaving their sources

REDUCED DIFFUSIVITY AROUND SOURCES



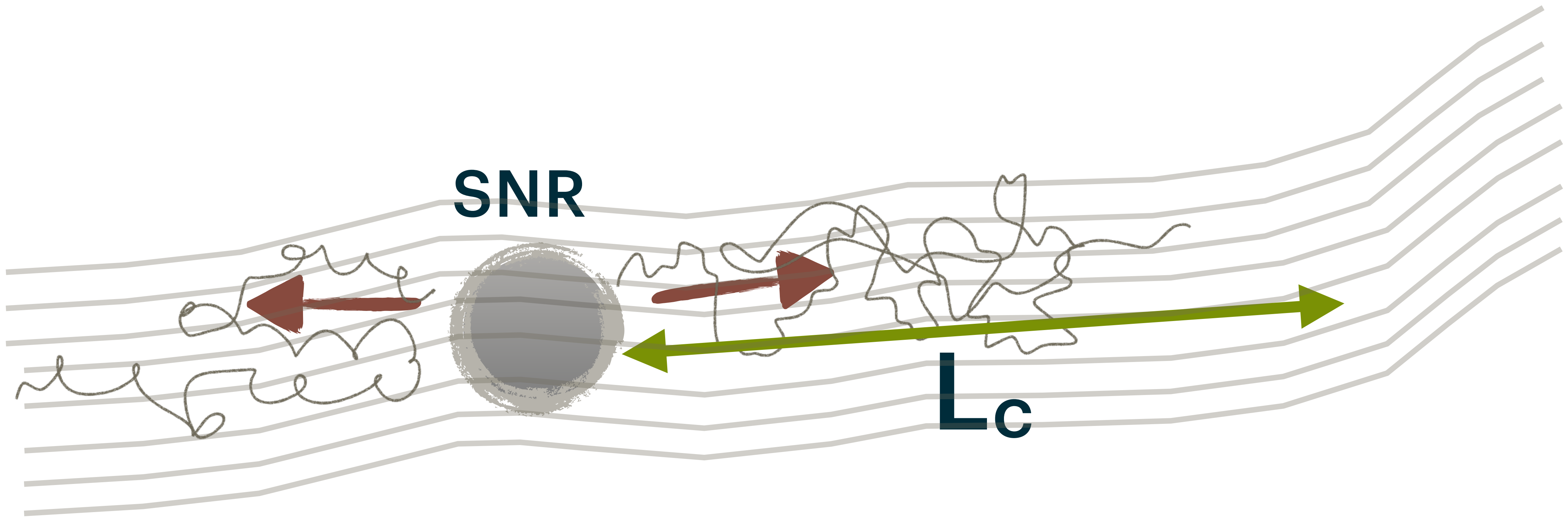
HAWC has recently detected regions of extended gamma ray emission around selected PWNe, in the >TeV energy region, suggesting that the diffusion coefficient in these regions is ~1/100 of the Galactic one [Abeysekara+ 2017]

HESS observations of several star clusters have also shown extended regions (~100 pc) with TeV gamma ray emission, with inferred D(E)<< than the Galactic one [Aharonian+ 2018]



Evidence from gamma ray observations of gamma ray emission from molecular clouds positioned at different distances from SNRs (for instance W28) that the diffusion coefficient is ~1/40 of the Galactic one [Gabici+ 2010]

HIGH ENERGY PARTICLES LEAVING A SNR



ADOPTING THE GALACTIC DIFFUSION COEFFICIENT AS A BENCHMARK

$$D(E) = \frac{1}{3} v\lambda \rightarrow \lambda \approx 1pc \left(\frac{E}{GeV}\right)^{1/2} \approx L_c \left(\frac{E}{2.5TeV}\right)^{1/2}$$

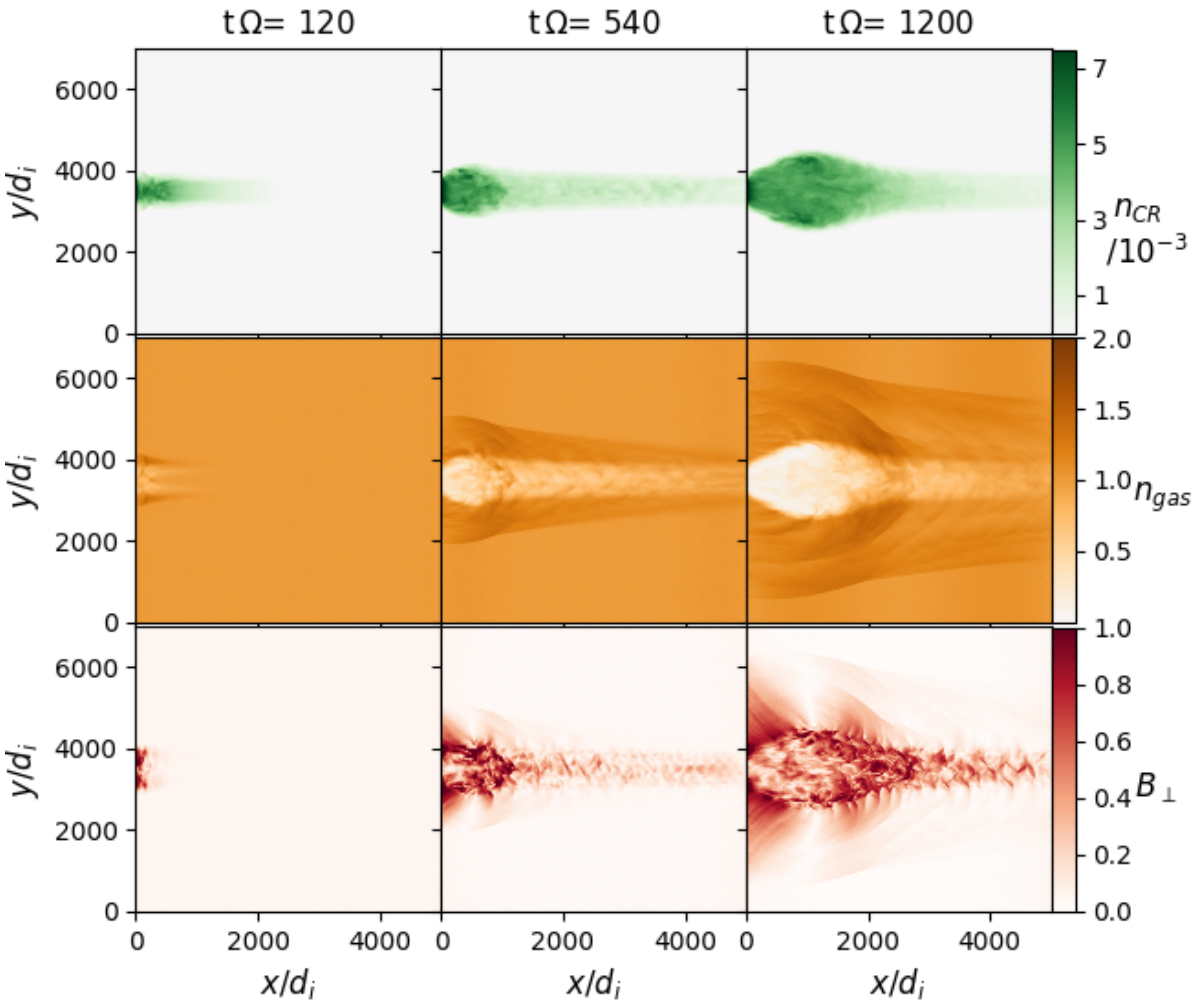
EVEN ASSUMING BALLISTIC MOTION IN SUCH REGION, FOR THE PARAMETERS OF A SNR:

$$n_{CR}(>E) \approx 5.4 \times 10^{-8} E_{GeV}^{-1}\ \mathrm{cm}^{-3} \rightarrow n_{CR}(>E)E > \frac{B_0^2}{4\pi}$$

THE NON RESONANT MODES 'a la Bell' ARE ALLOWED TO GROW ON A TYPICAL TIME SCALE:

$$\gamma_{max}^{-1} \approx 1.1(\mathrm{E}/2.5\mathrm{TeV})^{-1}\ \text{years}$$

HYBRID SIMULATIONS



- 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)

Schroer+, 2021, *Dynamical effects of cosmic rays leaving their sources*

Grammage in the near source region

If the diffusion coefficient in the region surrounding the source gets suppressed enough and for long enough time, then CR can accumulate some grammage in the region

This near-source grammage depends on the D(E) suppression (ξ) and on the gas evacuation (η)

This grammage can be compared with that in the Galaxy. The near-source remains small if

$$\frac{\xi}{\eta} \lesssim \frac{L^2}{Hh} \approx 3\times 10^{-3}\left(\frac{L}{50pc}\right)^2\left(\frac{H}{5kpc}\right)^{-1}\left(\frac{h}{150pc}\right)^{-1}$$

Nevertheless the near-source grammage can significantly affect our modelling of the data as well as antiproton/proton and positron fraction

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Summary and Perspectives

SUMMARY AND PERSPECTIVES

- ACCELERATION OF COSMIC RAYS TO PEV REMAINS CHALLENGING

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Summary and Perspectives

- Acceleration of cosmic rays to PeV remains challenging
- In typical SNRs PeV energies are reached at early times, hard to detect in gamma rays. Effect on the overall spectrum minimal (steep part)

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- For instance one may hope of detecting High E particles escaped at earlier times, only if D is substantially reduced