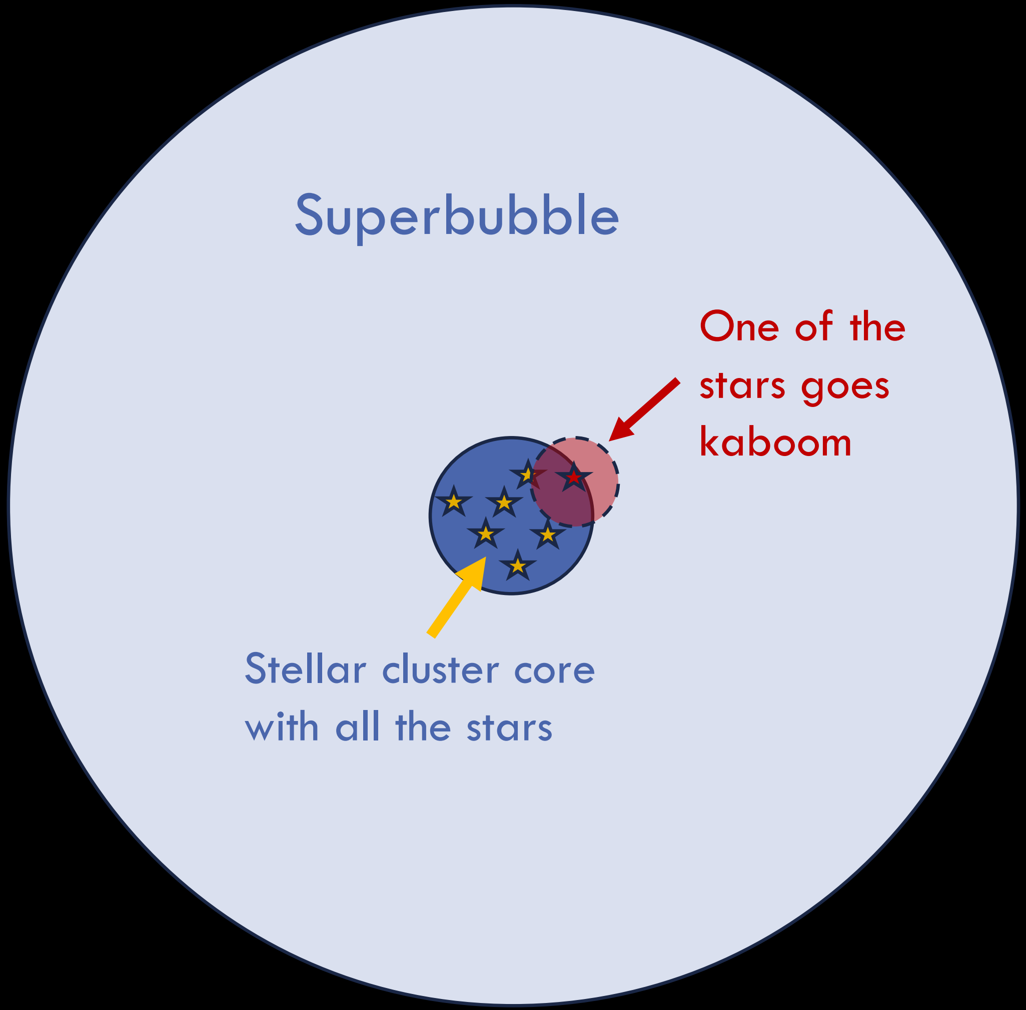


Superbubble

One of the stars goes kaboom

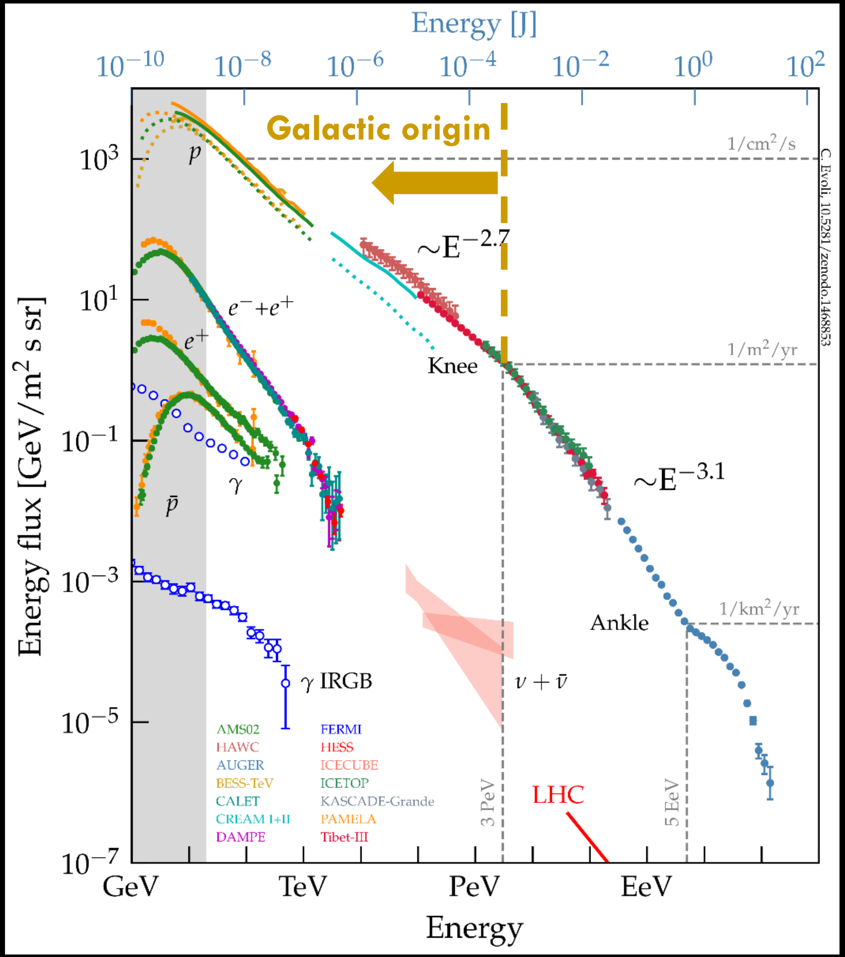
Stellar cluster core with all the stars

SNRs in stellar clusters: particle acceleration

Iurii Sushch

Pasquale Blasi, Robert Brose

Galactic cosmic rays



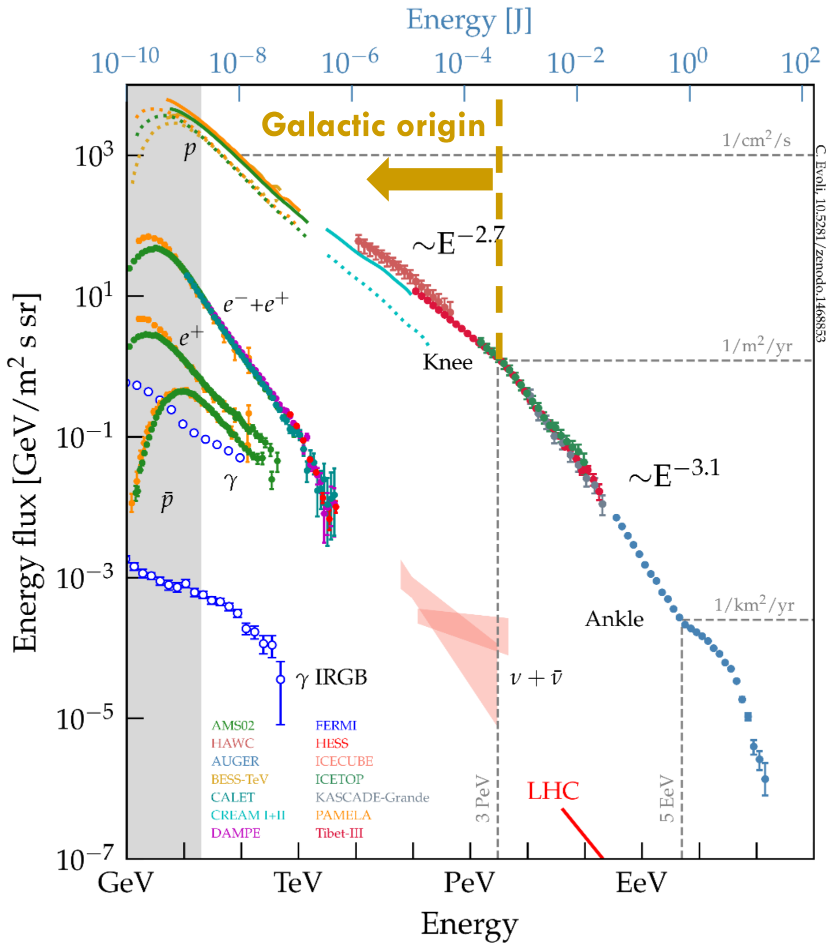
- Featureless $\sim E^{-2.7}$ spectrum up to the ‘knee’ at 3 PeV

- CRs with energies below the ‘knee’ are of Galactic origin

- $\sim 90\%$ protons

Evoli, 2018

SNRs are sources of Galactic CRs - or are they?



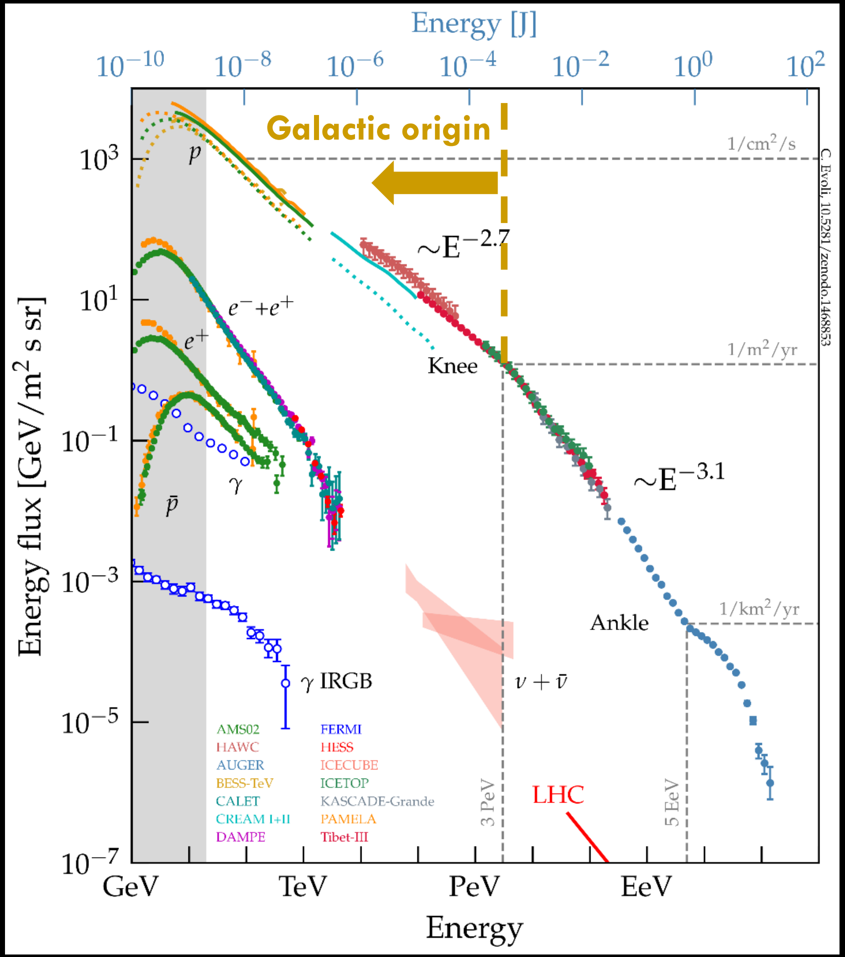
Evoli, 2018

SNR paradigm: SNRs are the primary sites of CR acceleration in our Galaxy

Main argument:

- Enough energy to explain the CR energy density

SNRs are sources of Galactic CRs - or are they?



Evoli, 2018

SNR paradigm: SNRs are the primary sites of CR acceleration in our Galaxy

Main argument:

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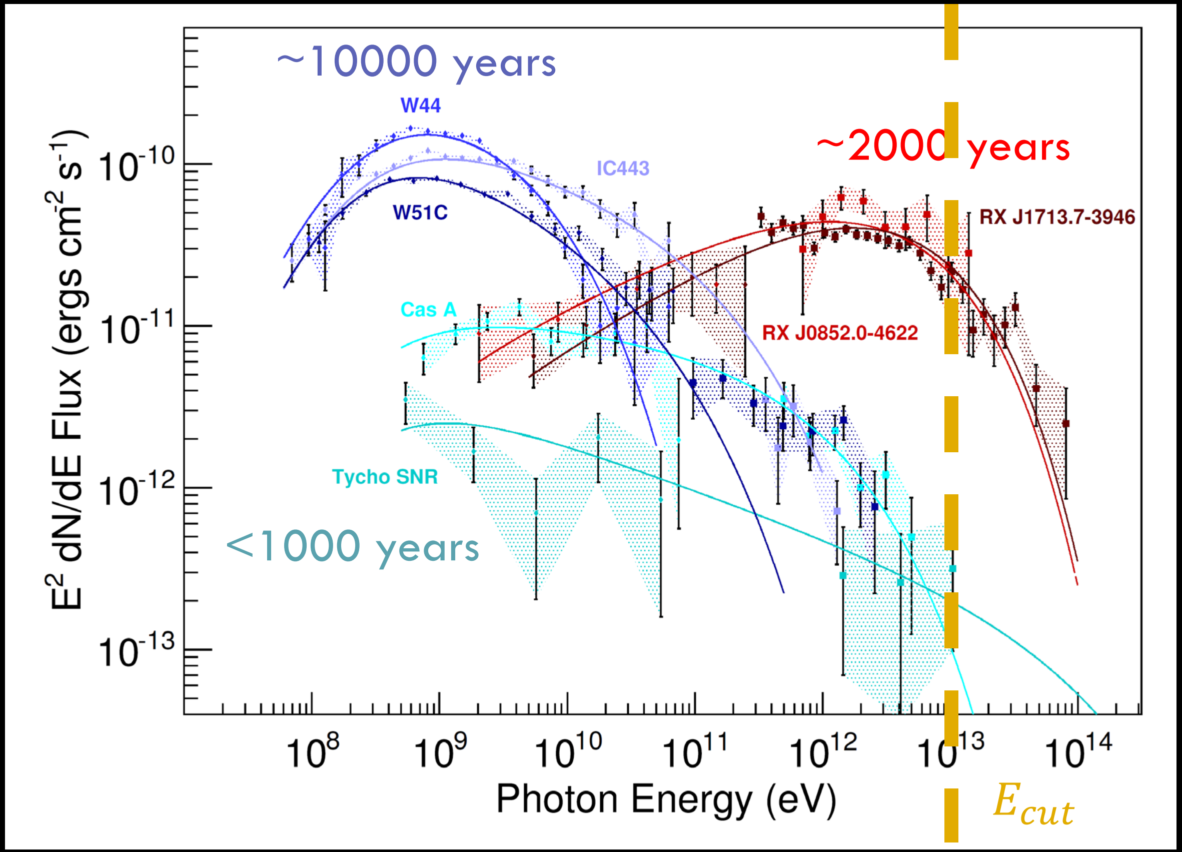
BUT:

Can they accelerate protons to PeV energies?

Evolution of the gamma-ray spectrum



Funk 2015

- Very young SNRs seem to be hadronic with relatively hard spectrum
- Middle-aged SNRs seem to be leptonic
- Old SNRs are hadronic with soft spectrum and usually interacting with molecular clouds

At most reaching ~10 TeV for the cut-off in the gamma-ray spectrum that corresponds to ~100 TeV in maximum energy of protons.

Maximum energy

Hillas criterion or geometrical limit – particles must be contained within the acceleration site, i.e. gyroradius should be smaller than the size of the site

$$E_{max} \sim \frac{B}{1\ mG} \frac{v_{sh}}{1000\ km/s} \frac{r_{sh}}{1\ pc}\ PeV$$

We need at least $100\ \mu G$ for typical values of shock velocities and sizes, while the intergalactic magnetic field is of order of $\sim 1\ \mu G$

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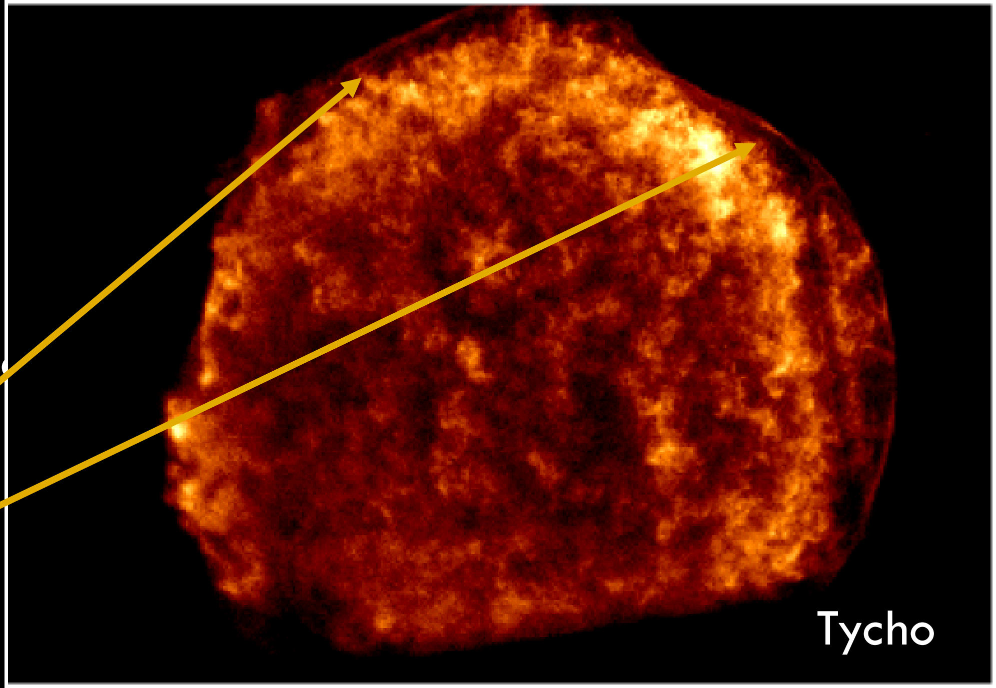
intergalactic magnetic field is of order of $\sim 1\ \mu G$

And observations confirm strong amplification in a number of SNRs through e.g. thin X-ray filamets



Self-generated magnetic turbulence

Resonant Alfven instability (e.g. Bell 1978):

- $k_{res} = \frac{1}{r_g} = \frac{qB}{pc}$
- $\delta B \sim B$

Non-resonant streaming instability (e.g. Bell 2004, Bell et al. 2013):

- Perturbations grow initially on scales much smaller than r_g
- At saturation $\delta B \gg B$
- Requires sufficiently low background field to be excited, i.e. CR pressure should be larger than magnetic pressure

$\frac{v_s}{c}\frac{\eta}{\Lambda}\, v_s^2 \rho > \frac{B^2}{4\pi}, \quad \Lambda = \ln\left(\frac{p_{max}}{m_p c}\right) \sim 10, \eta$ – fraction of the ram pressure in CRs

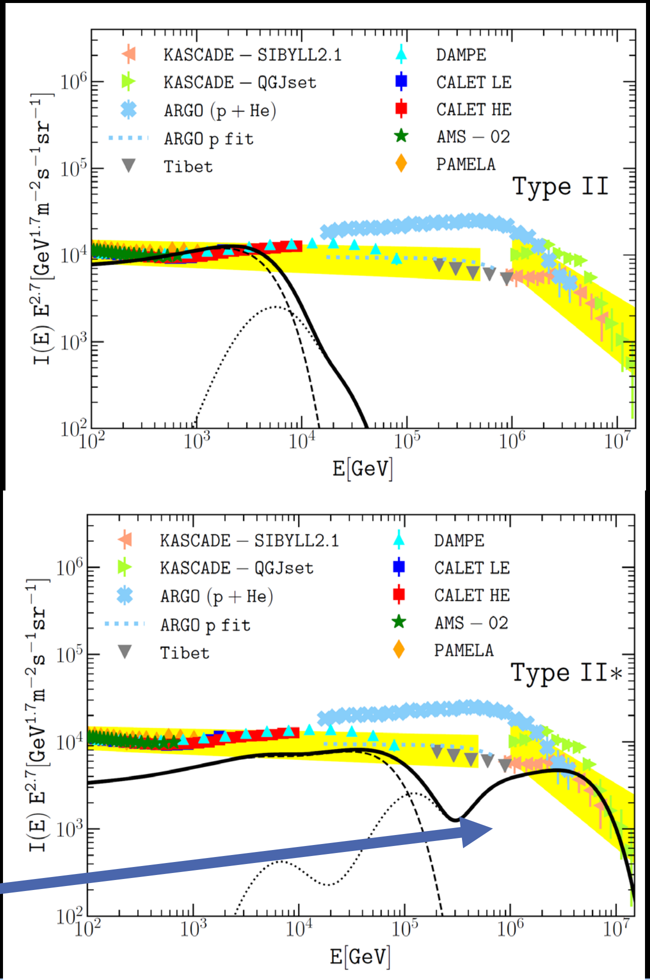
- Grows exponentially with time but needs 5-10 e-foldings – CRs need to escape freely ahead of the shock at first

Best case – very young core collapse SNRs

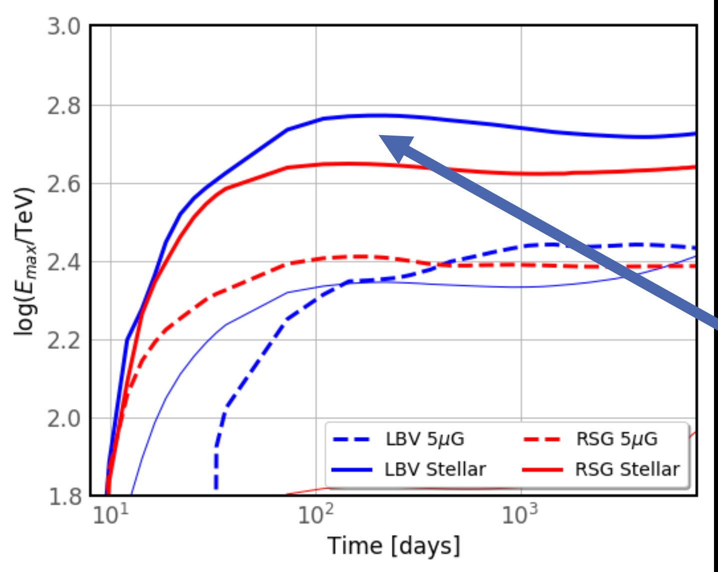
Necessary conditions can be met:

- Initial expansion velocities can reach 30,000 km/s
- High density in the wind of the progenitor star
- However, the magnetic field in the wind is also high, which could be a problem for excitation of the non-resonant Bell instability

Cristofari, Blasi, Amato 2020



Recent active research indicates that only in some special and rare cases PeV energies can be achieved



saturates at ~600 TeV for progenitor stars with high mass loss rates

Brose, IS, Mackey, 2022

very energetic SNRs (10^{52} ergs)

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Cristofari, Blasi, Amato 2020

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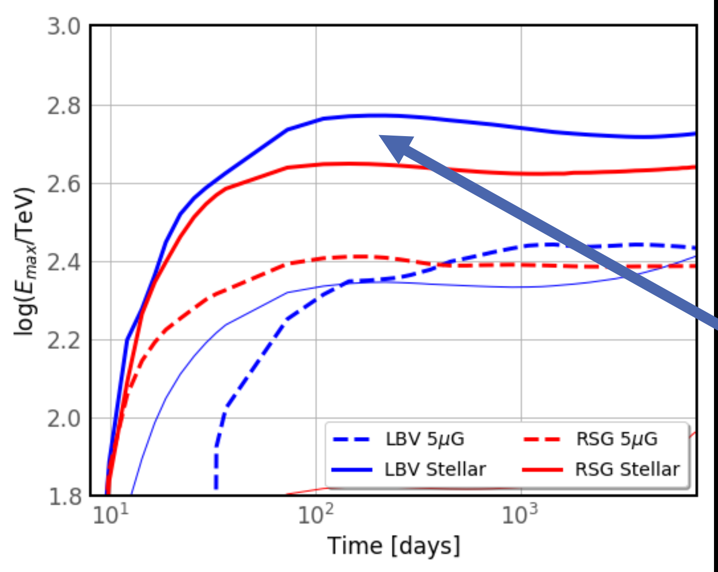
Check also Robert's poster on FBOTs: S8.1



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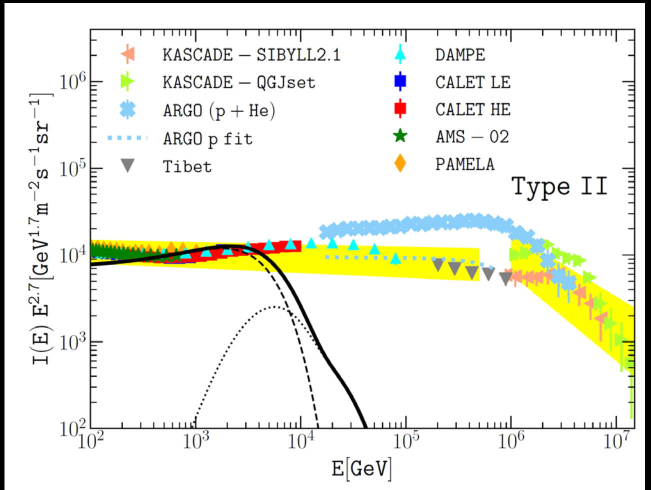

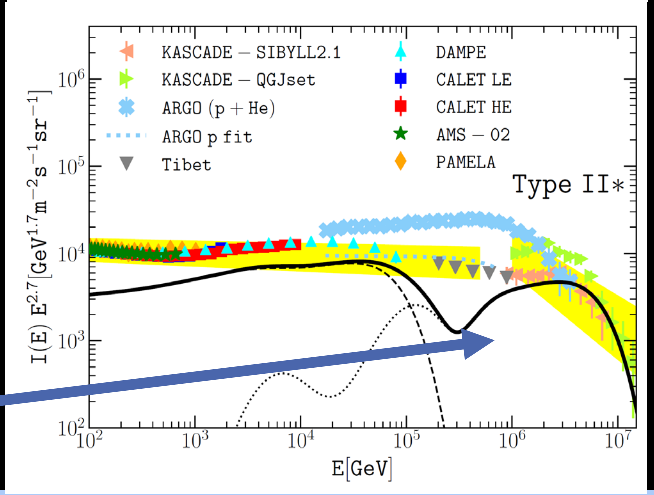

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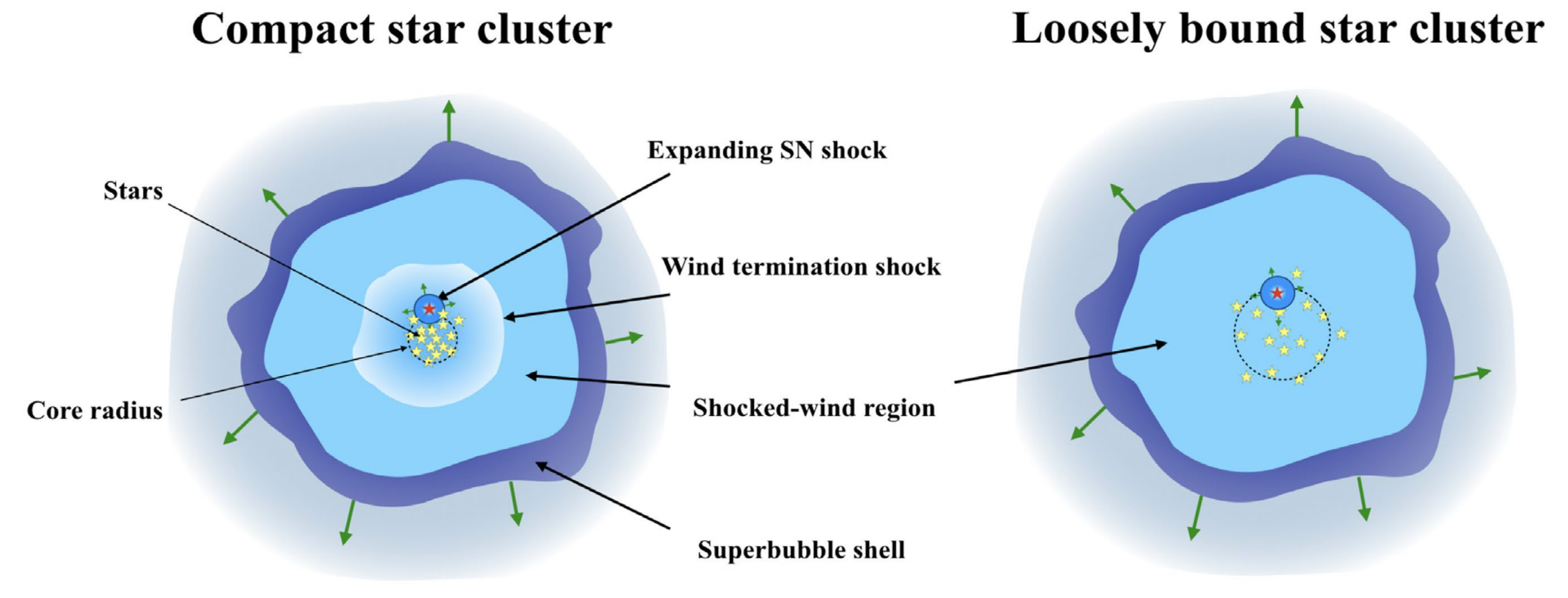
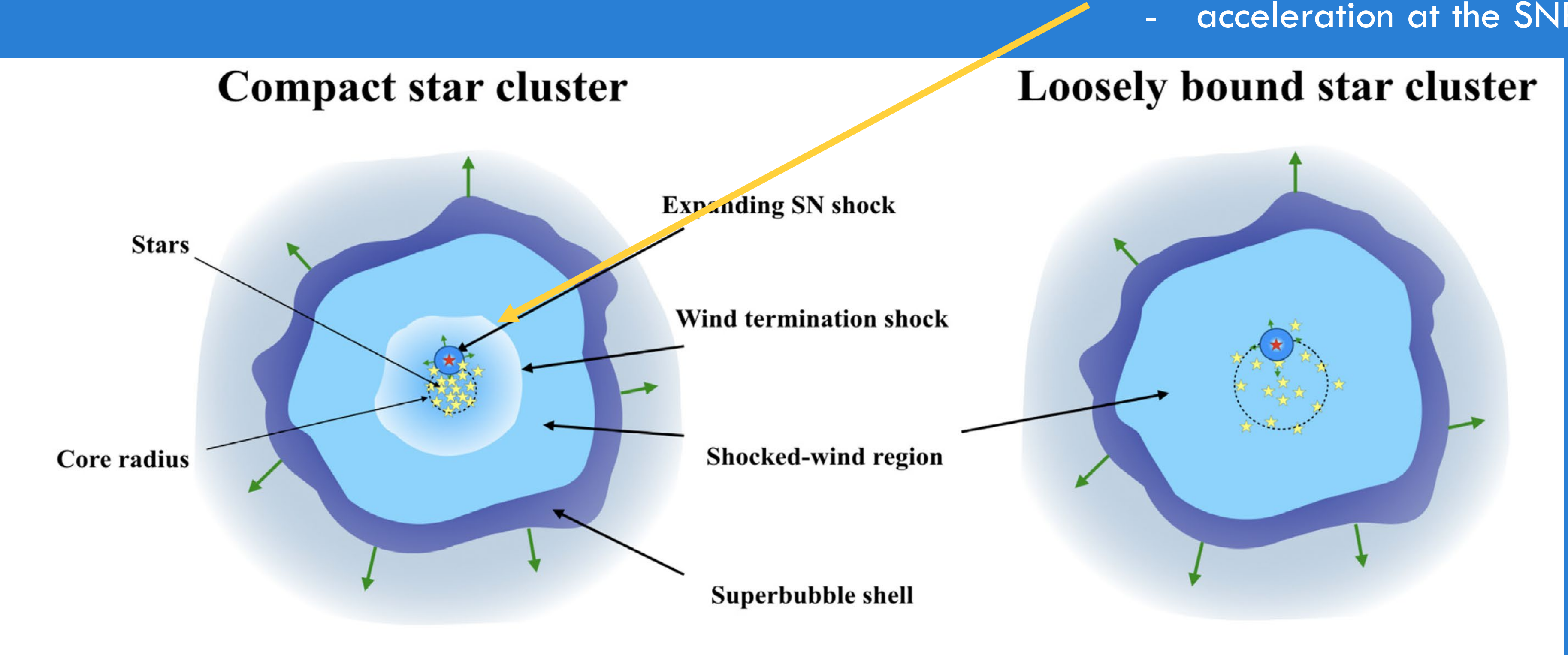


Gupta et al. 2020

SNRs in bubbles of stellar clusters

Potentially promising conditions for particle acceleration:

- acceleration at the termination shock
- acceleration at the SNR shock



Gupta et al. 2020

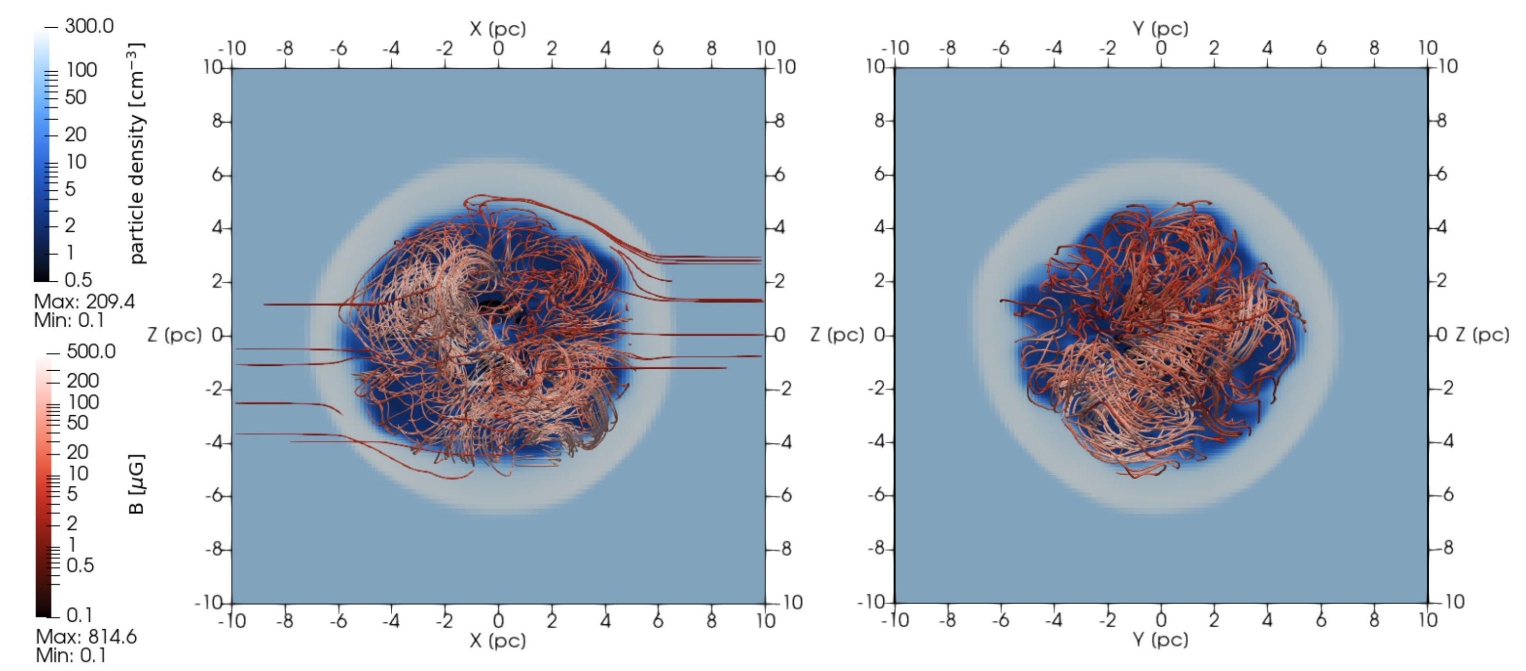
SNRs in bubbles of stellar clusters

What's so special for an SNR?

- Dense collective wind
- Pre-existing turbulence generated by wind-wind collisions

Up to 500 μG field found in MHD simulations in the core of the cluster (Härer et al. ICRC2023)

Good enough to get to PeV energies for an SNR exploding at the edge of the core?



Model setup

$$L = \frac{1}{2}\dot{M} v_w^2 \sim 6 \times 10^{38} \text{ erg/s}$$

Collective wind:

- $\dot{M} = 2 \times 10^{-4}\ M_\odot/year$

– equivalent to 100 typical WR stars

- $v_w = 3 \times 10^8$ cm/s – typical for WR

Termination shock (Weaver bubble):

$$R_{TS} \sim 20\ pc$$
$$\times \left(\frac{n_{ISM}}{10\ cm^{-3}}\right)^{3/10} \left(\frac{\dot{M}}{10^{-4}\ M_\odot/y}\right)^{3/10} \left(\frac{v_w}{10^8 cm/s}\right)^{1/10} \left(\frac{t}{10^6 y}\right)^{2/5}$$

Magnetic field:

- Turbulent magnetic field of $10\ \mu G$ at the termination shock (set at 20 pc)
- About $200\ \mu G$ at the location of SN explosion (scales as 1/r in the wind)
- Compressed by a factor of $\sqrt{11}$ at the termination shock and constant farther out

Pre-generated turbulence

The coherence scale of pre-generated turbulence is assumed to be L = 1 pc:

- Kolmogorov spectrum: $D = \frac{1}{3} r_L v \left(\frac{r_L}{L}\right)^{-2/3}$

$$E_{max} = 23\, j^3 \left(\frac{t}{t_{TS}}\right)^{5j-3} \left(\frac{L}{1\, pc}\right)^{-2} \left(\frac{R_{TS}}{20\, pc}\right)^{3} \left(\frac{v_{sh,TS}}{10^9\, cm/s}\right)^{3} \left(\frac{B_{TS}}{10\, \mu G}\right)\ TeV$$

- Kraichnan spectrum: $D = \frac{1}{3} r_L v \left(\frac{r_L}{L}\right)^{-1/2}$

$$E_{max} = 227\, j^2 \left(\frac{t}{t_{TS}}\right)^{3j-2} \left(\frac{L}{1\, pc}\right)^{-1} \left(\frac{R_{TS}}{20\, pc}\right)^{2} \left(\frac{v_{sh,TS}}{10^9\, cm/s}\right)^{2} \left(\frac{B_{TS}}{10\, \mu G}\right)\ TeV$$

By equating the acceleration time with the age and referencing to the time when the SNR shock reaches the termination shock

$$r \propto t^j, j < 1$$

Self-generated turbulence

Resonant instability:

- Assume that the growth is efficient and instantaneous
- Diffusion coefficient can be expressed as Bohm-like: $D = \frac{1}{3}\eta_B r_L v$
- Assuming saturation of instability: $\eta_B = 0.5\frac{Br}{v_s}\left(\frac{v_w}{\dot{M}}\right)^{1/2}\frac{\Lambda}{\eta}$, where η is the ratio of CR pressure to ram pressure and $\Lambda = \ln\left(p_{max}/m_p c\right) \sim 10$
- $\eta_B \approx 5$ at the termination shock for adopted parameters and $\eta = 0.1$, very slow dependence on time
- E_{max} reaches ~200 TeV. $E_{max} = \frac{3}{10} j \left(\frac{\dot{M}}{v_w}\right)^{1/2}\frac{\eta}{\Lambda}\frac{q}{\mathrm{c}} v_{sh}^2$

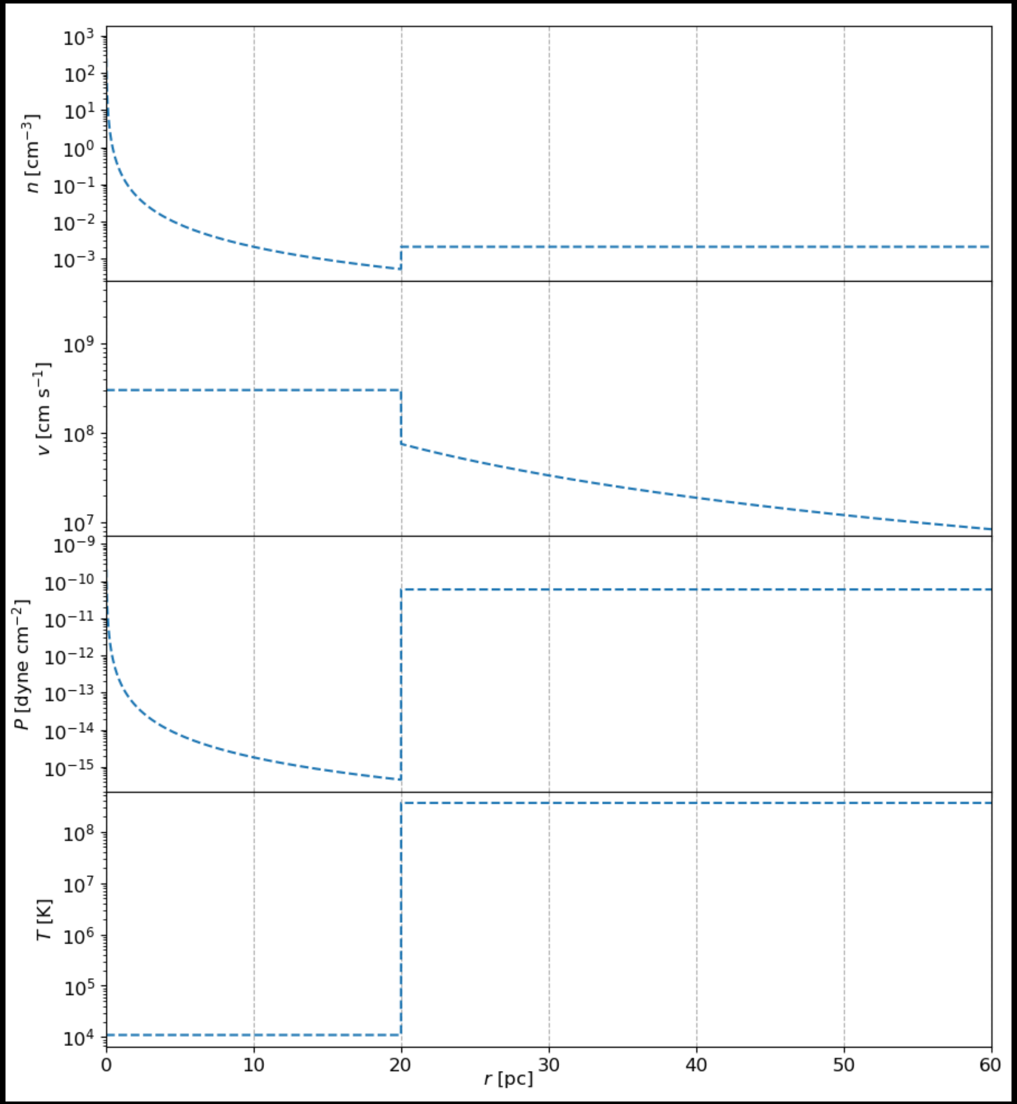
Non-resonant instability:

- $\frac{v_s}{c}\frac{\eta}{\Lambda}\, v_s^2 \rho > \frac{B^2}{4\pi}$
  condition for excitation gives $B < 2\ \mu G$ at the termination shock for adopted parameters. We have $10\ \mu G$ there
- Can possibly be excited only at very early stages for a short period of time (~ year or less)

Numeric simulations

Explored for three modes of turbulence:

- Pre-generated with the Kolmogorov spectrum (KOLM)
- Pre-generated with the Kraichnan spectrum (KRAI)
- Bohm diffusion in the precursor of the shock on top of the pre-generated KOLM turbulence



Medium in the bubble
shaped by the stellar cluster

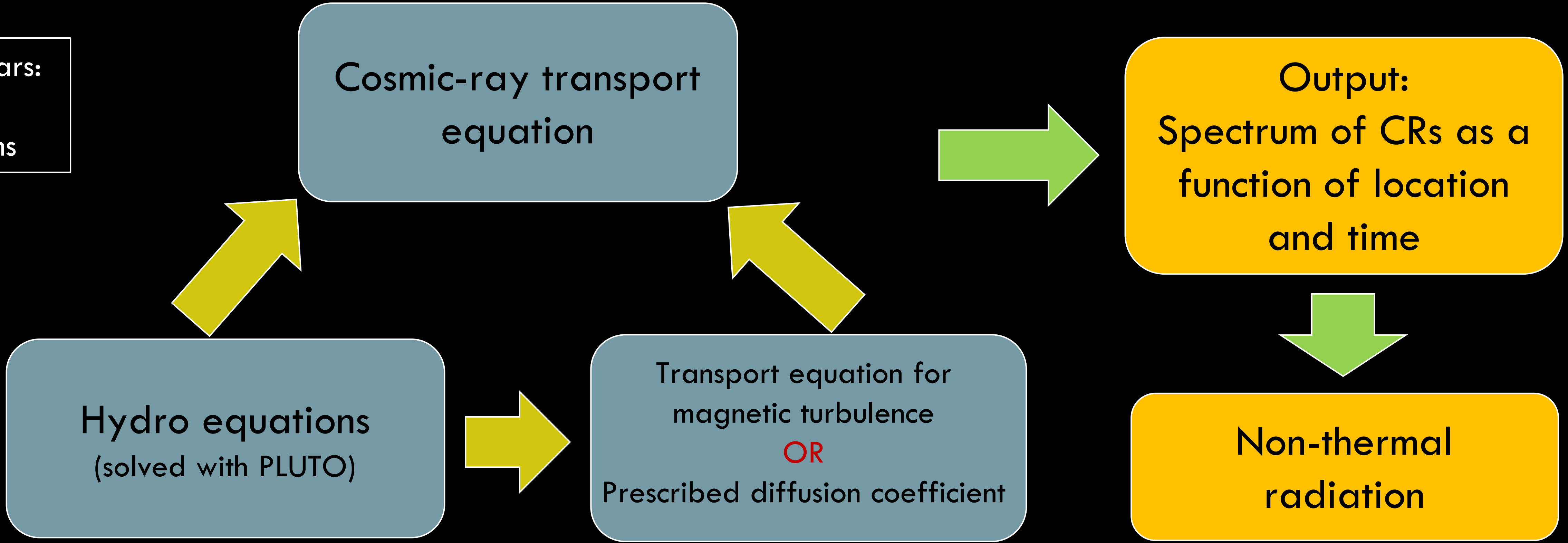
Collaborators: Robert Brose (DCU/DIAS, Ireland), Martin Pohl (DESY, Germany), Samata DAS (DESY, Germany) and others

RATPaC

Radiation Acceleration Transport Parallel Code

Powered by RATPaC

In last 6 years:
10 papers
120 citations



Cosmic-ray transport equation

Hydro equations
(solved with PLUTO)

Transport equation for magnetic turbulence
OR
Prescribed diffusion coefficient

Output:
Spectrum of CRs as a function of location and time

Non-thermal radiation

Collaborators: Robert Brose (DCU/DIAS, Ireland), Martin Pohl (DESY, Germany), Samata DAS (DESY, Germany) and others

RATPaC

Radiation Acceleration Transport Parallel Code

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RATPaC related posters at “Supernova remnants III”:

S2.23 “Role of reflected shocks in particle acceleration in supernova remnants” by Iurii Sushch

S5.14 “The production of unstable cosmic-ray isotopes in supernovae clusters” by Xin-Yue Shi

S8.1 “Fast Blue Optical Transients as cosmic-ray sources” by Robert Brose

Shock evolution

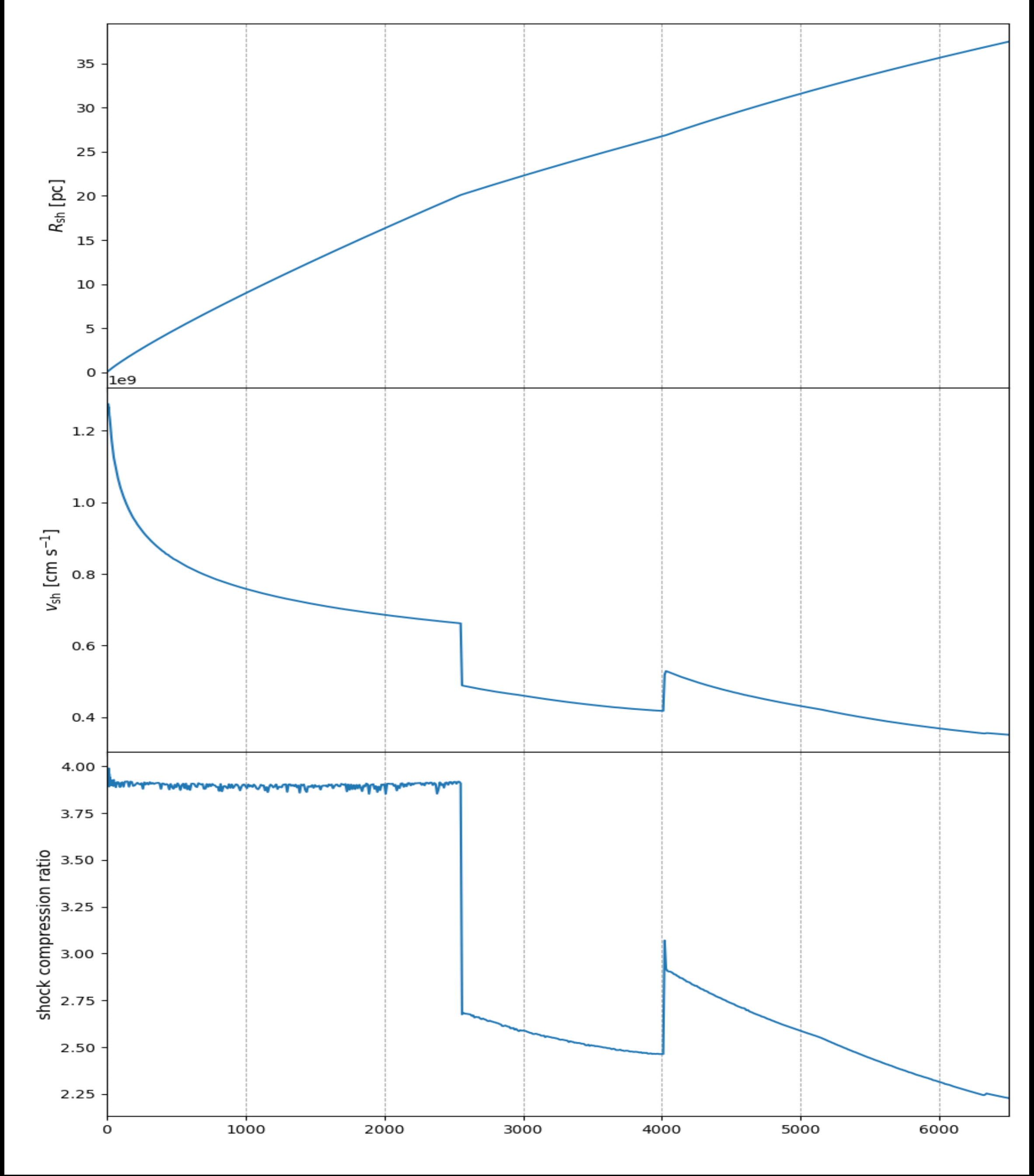
At later stages shock becomes very week due to propagation in the hot medium

↓

Accelerates to a very soft spectrum

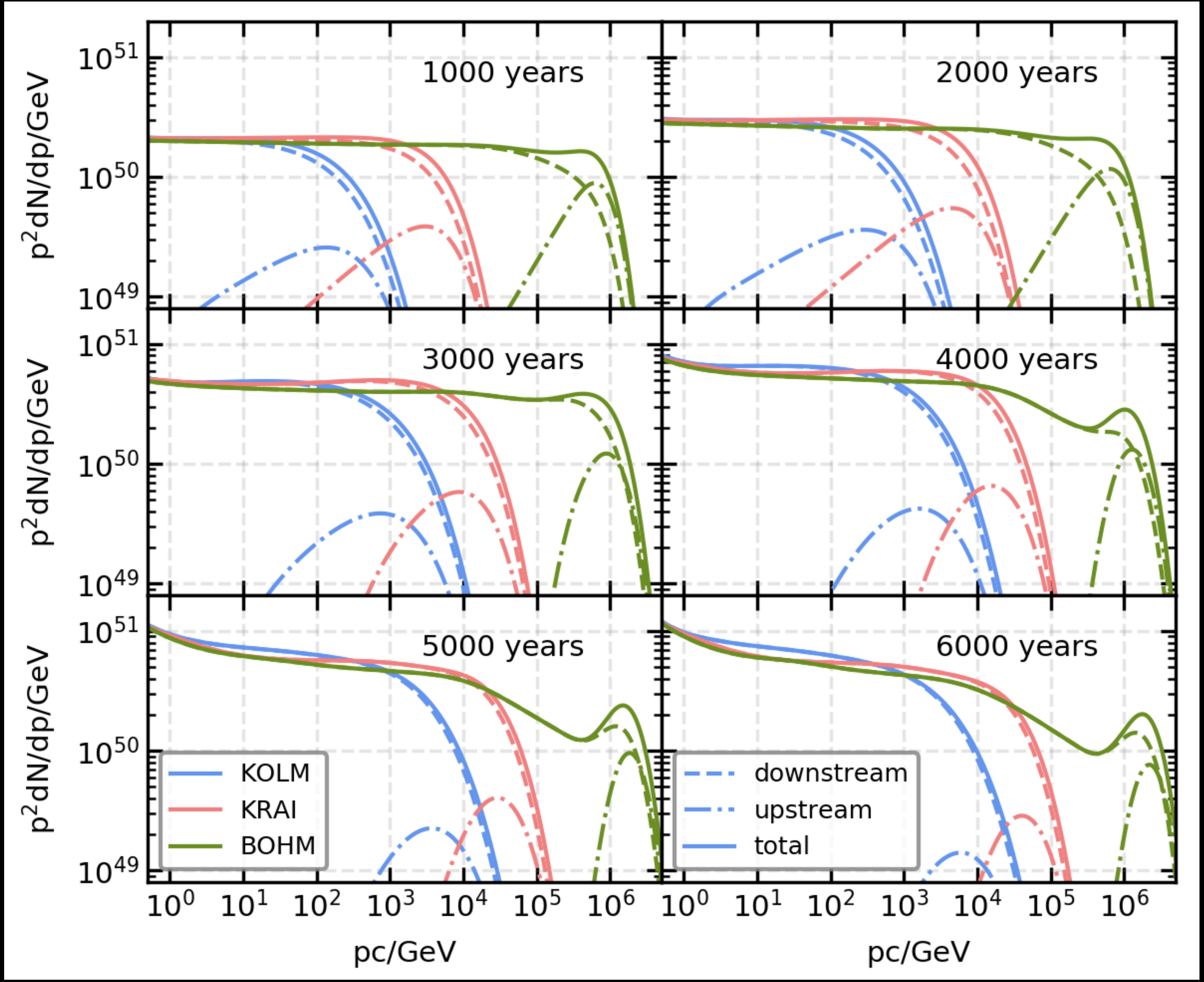
↓

E_{max} becomes irrelevant



Proton spectrum

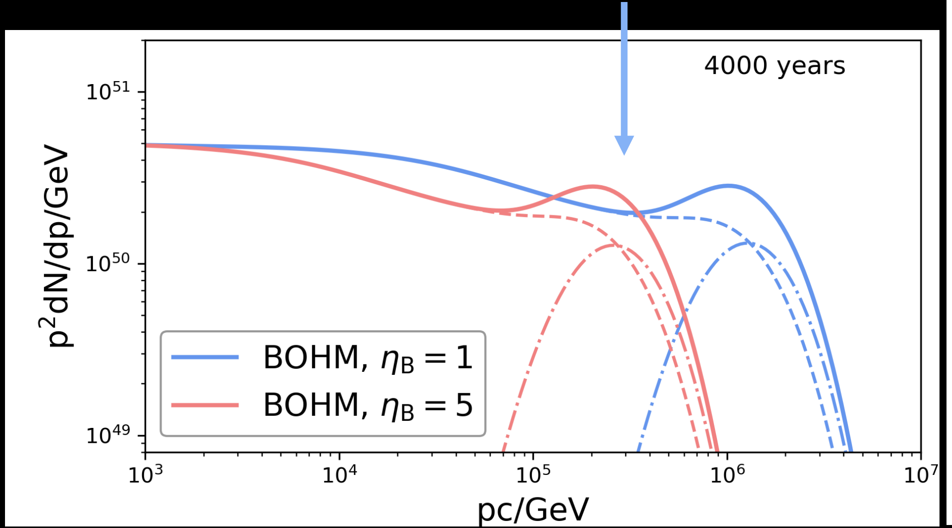
PeV energies achievable for Bohm diffusion, but it's not clear how to get the Bohm diffusion

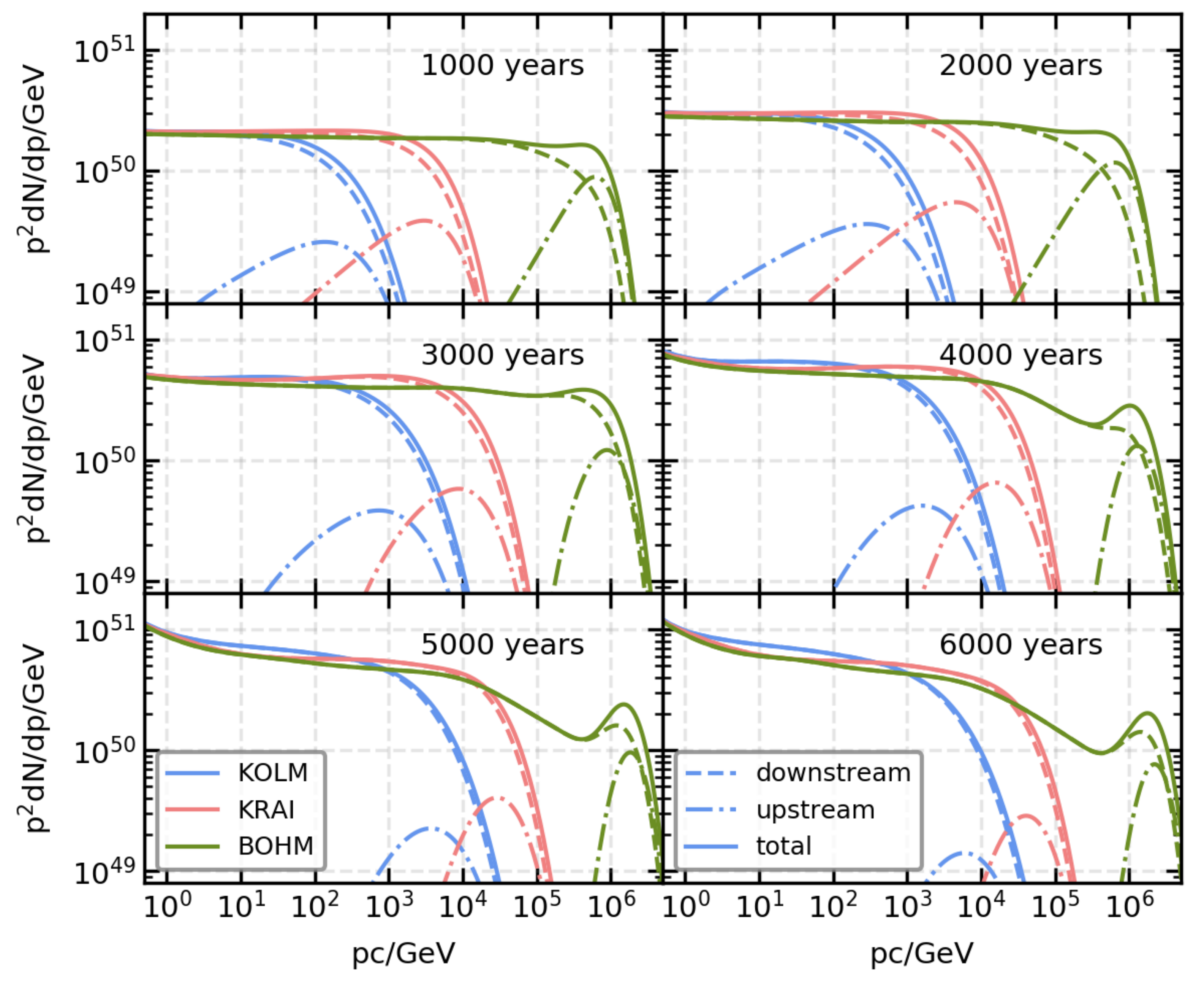


Proton spectrum

PeV energies achievable for Bohm diffusion, but it's not clear how to get the Bohm diffusion

$\eta_B = 5$ motivated by resonant instability moves E_{max} to ~100 TeV

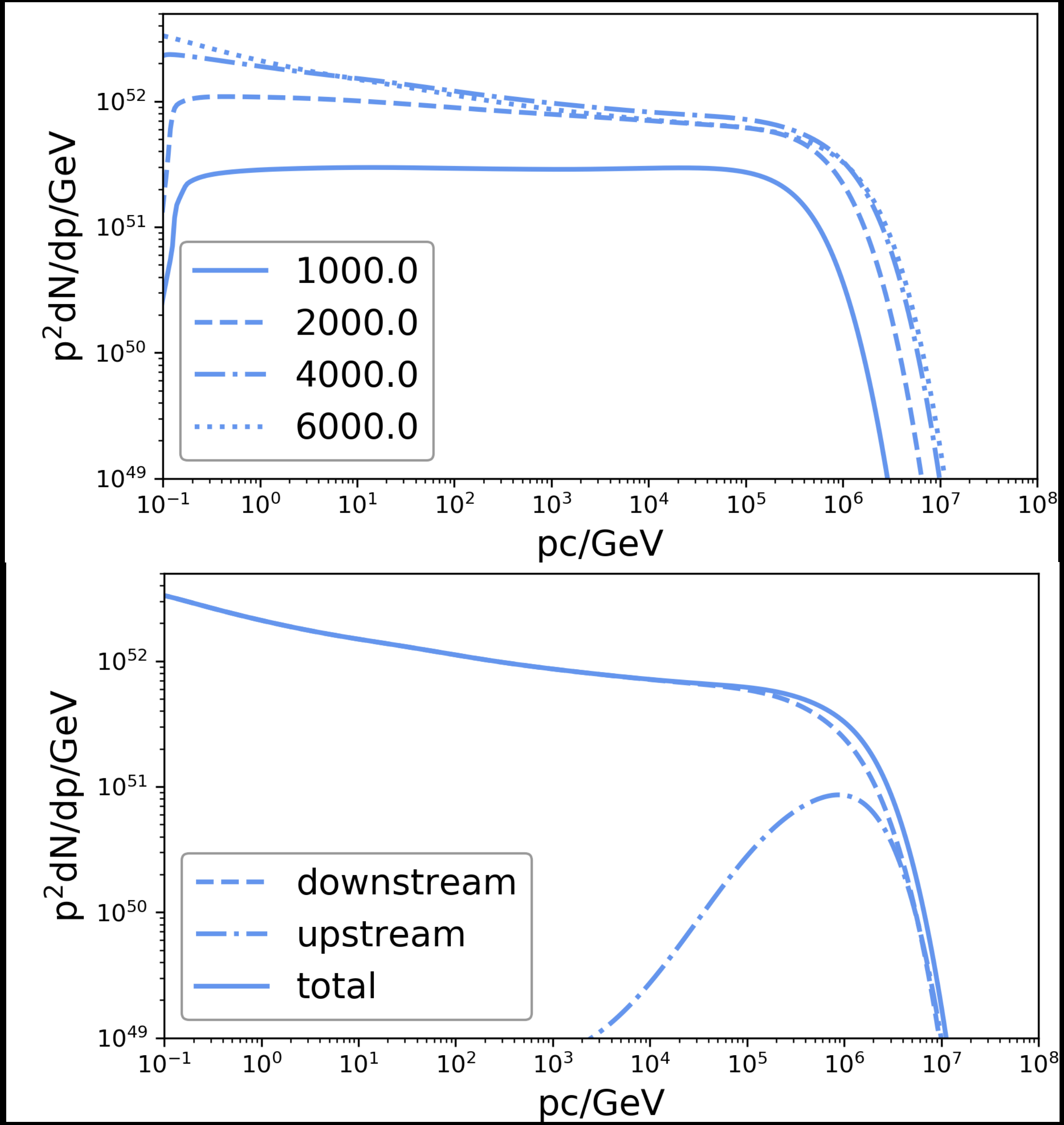




Energetic case

Explosion energy 10^{52} erg
Kraichnan turbulence
Other parameters are the same

We can marginally reach PeV in this case, but these are rare events



Summary

Similarly to isolated SNRs, SNRs exploding in stellar clusters seem to be able to accelerate to PeV energies only under special and rare conditions.

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So, let’s keep looking for PeVatrons

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Similarly to isolated SNRs, SNRs exploding in stellar clusters seem to be able to accelerate to PeV energies only under special and rare conditions.

So, let’s keep looking for PeVatrons

And let’s stop genocide!


Vovchansk, 2024 (now)


Chasiv Yar, 2024 (now)


Bakhmut, 2023


Beit Lahia, Gaza Srip

BACKUP SLIDES

RATPaC

Radiation Acceleration Transport Parallel Code

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Cosmic-ray transport

$$\frac{\partial N}{\partial t} = \nabla(\underbrace{D_r \nabla N}_{\text{Diffusion}} - \underbrace{vN}_{\text{Advection}}) - \frac{\partial}{\partial p}\left(\underbrace{N\dot{p}}_{\text{Cooling}} - \underbrace{\frac{\nabla v}{3} Np}_{\text{Acceleration}}\right) + \underbrace{Q}_{\text{Injection}}$$

- Time-dependent
- 1D with spherical symmetry
- CR and MT equations solved on co-moving expanding grid
- Particle injected at a certain momentum at the shock

Hydrodynamics

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \boldsymbol{m} \\ E\end{pmatrix} + \nabla\begin{pmatrix}\rho \boldsymbol{v} \\ \boldsymbol{m}\boldsymbol{v} + P\boldsymbol{I} \\ (E+P)\boldsymbol{v}\end{pmatrix}^T = \begin{pmatrix}0 \\ 0 \\ 0\end{pmatrix}$$

$$\frac{\rho v^2}{2} + \frac{P}{\gamma - 1} = E$$

Magnetic turbulence transport

$$\frac{\partial E_w}{\partial t} + \underbrace{\nabla_r(\boldsymbol{u}E_w)}_{\text{Advection}} + \underbrace{k\nabla_k k^2 D_k \nabla_k \frac{E_w}{k^3}}_{\text{Cascading}} = \underbrace{2(\Gamma_g - \Gamma_d)E_w}_{\text{Growth + Damping}}$$

E_w: Energy density in magnetic turbulence per unit logarithmic bandwidth

RATPaC

Radiation Acceleration Transport Parallel Code

Powered by RATPaC

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$$\frac{\rho v^2}{2}+\frac{P}{\gamma-1}=E$$

Magnetic turbulence transport

- Isotropic Alfvenic turbulence
- Resonant streaming instability (e.g. Bell 1978)
- Enhance the growth rate by a scaling factor to mimic more efficient non-resonant mode (Bell 2004, Amato&Blasi 2009)

Magnetic turbulence

$$\frac{\partial E_w}{\partial t} + \underbrace{\nabla_r(\boldsymbol{u}E_w)}_{\text{Advection}} + \underbrace{k\nabla_k k^2 D_k \nabla_k \frac{E_w}{k^3}}_{\text{Cascading}} = \underbrace{2(\Gamma_g - \Gamma_d)E_w}_{\text{Growth + Damping}}$$

The equation is solved:

- Assuming isotropic alfvenic turbulence
- 1D and spherically symmetric
- Same spatial grid as for cosmic rays

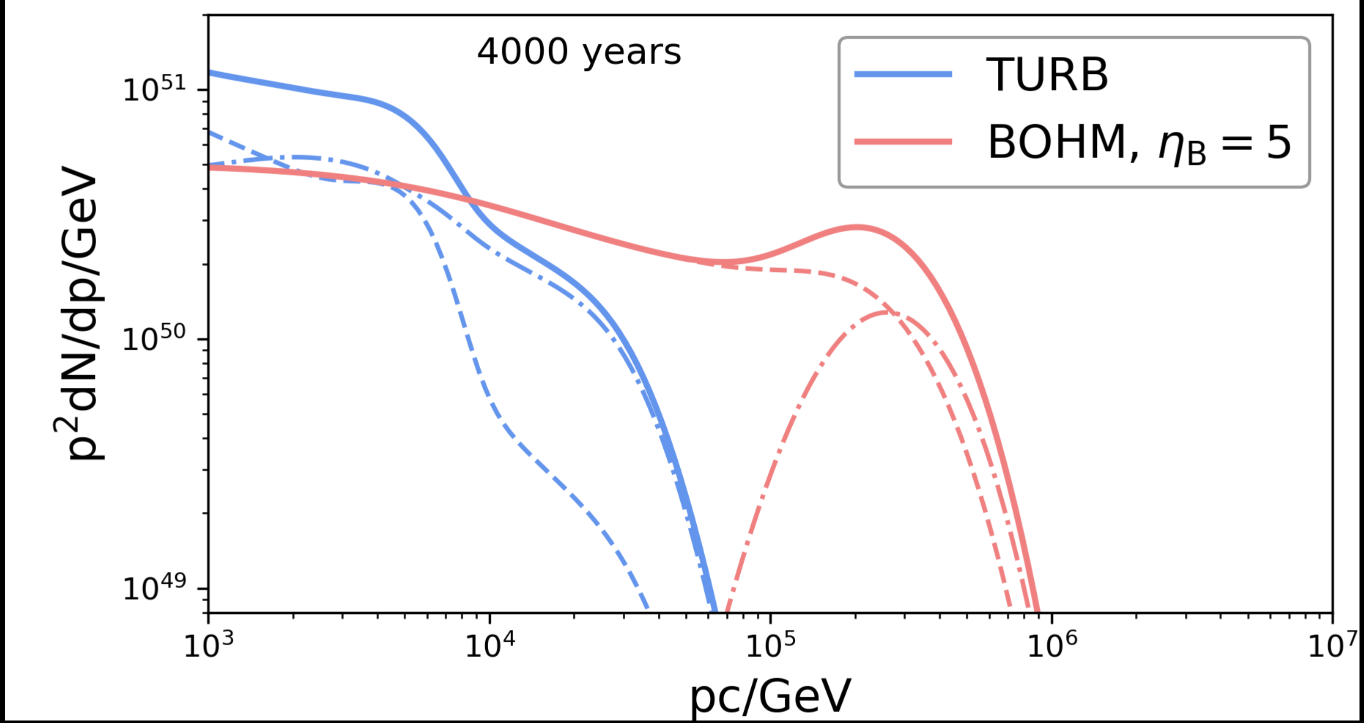
E_w: Energy density in magnetic turbulence per unit logarithmic bandwidth

$$\langle \delta B^2 \rangle = 4\pi \int E_w d \ln k \qquad B_{tot} = \sqrt{B_0^2 + \langle \delta B^2 \rangle} \qquad D_r = \frac{4v}{3\pi} r_g \frac{U_m}{E_w}$$ - diffusion coefficient of CRs

$$\Gamma_g = A \frac{v_A p^2 v}{3E_w} \left| \frac{\partial N}{\partial r} \right|$$ - growth rate based on the resonant streaming instability (e.g. Bell 1978)

A = 10 - linear scaling factor to artificially enhance the amplification mimicking more efficient non-resonant streaming instability (Lucek&Bell 2000, Bell 2004)

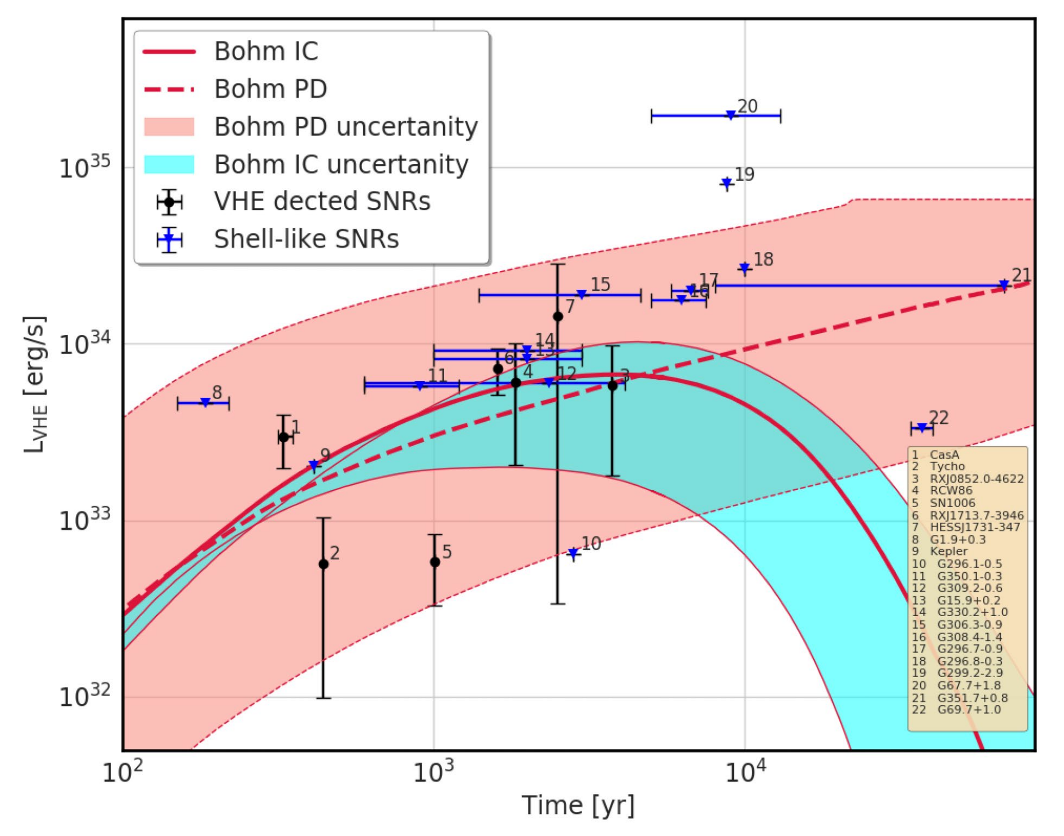
Simulation of turbulence (preliminary)



Solving transport equation for turbulence gives somewhat lower maximum energies

We inject more particles in these simulations to boost turbulence growth, but η is kept at the level of <0.05, so lower maximum energy is expected.

Evolution of the gamma-ray luminosity



Uncertainty bands represent ambient density in the range from 0.04 to 4 cm^{-3}
Electron-to-proton ratio at ~10^{-3}

Leptonic:

- peaks at 2-4 kyrs
- drops at later stages due to synchrotron cooling

Hadronic:

- keeps growing with time for assumed Bohm diffusion

Brose, Pohl, IS, et al. 2020