Cosmic rays from supernova remnants in cosmological simulations

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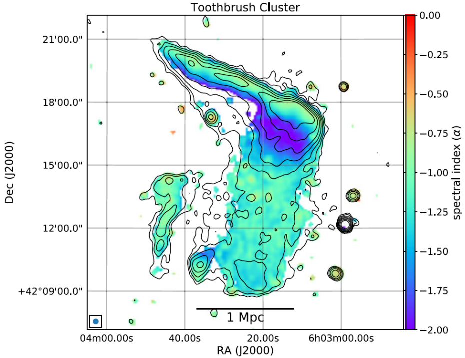
What are cosmic rays?



Spectral index map of the radio halo in the **Toothbrush Cluster** between 150 MHz and 1.5 GHz using LOFAR and the VLA. North of the radio halo, a luminous 2 Mpc radio shock is also present (van Weeren et al., 2019)

- High-energy, charged particles (in Milky Way about every billionth gas particle is a cosmic ray)
- Composition:
  - 1% electrons
  - 99% nuclei: 90% protons, 9% alpha particles, 1% heavier nuclei (up to uranium)

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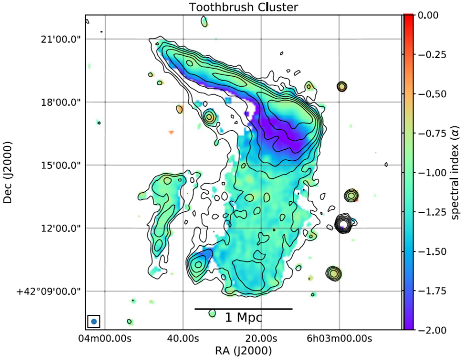

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- Composition:
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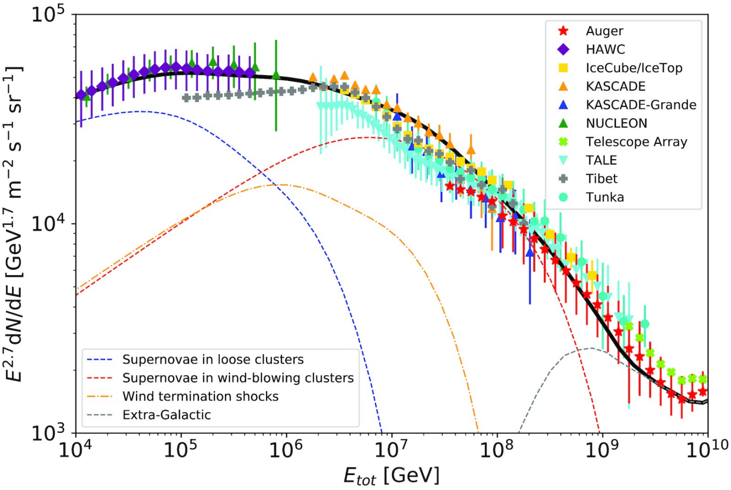
- Highly energetic cosmic rays (above ~ 10 GeV) produce non-thermal radiation (in X-ray and radio band)
- In disk galaxies cosmic rays have an energy density comparable to magnetic fields, thermal gas, turbulent motion and radiation field $\rightarrow$ dynamical impact on galaxy evolution

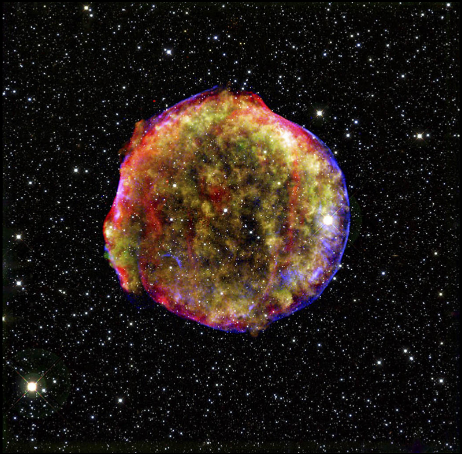
Different sources contribute to overall cosmic-ray energy spectrum



All-particle cosmic-ray spectrum from Vieu & Reville (2023)

Supernova remnants as cosmic-ray factories

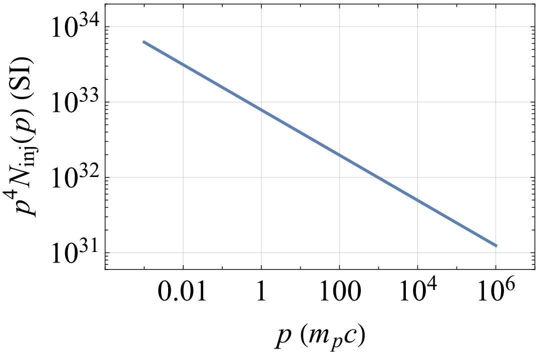
Non-thermal emission + enough energy to maintain energy density of Galactic CRs



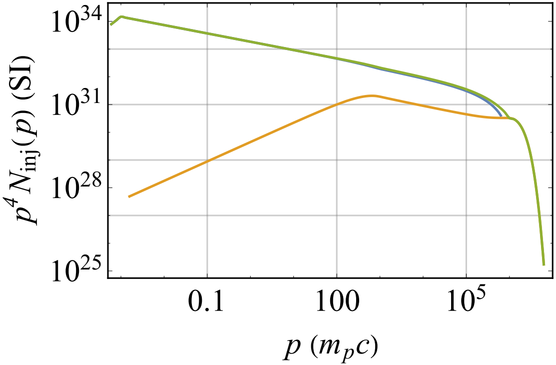
Tycho's supernova remnant (SN 1572). X-ray (Chandra X-ray Observatory): Yellow, Green, Blue; Infrared (Spitzer Space Telescope): Red; Optical (Calar Alto observatory): White background stars (source: https://chandra.harvard.edu/photo/2009/tycho/)

Sub-resolution injection of cosmic-ray spectra

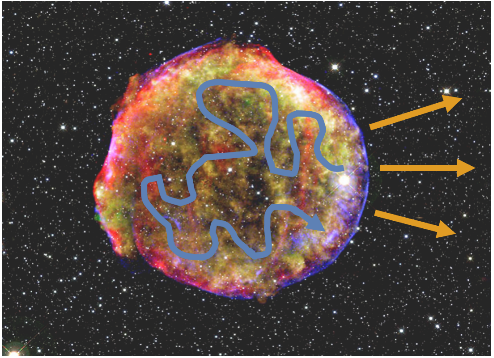
usual approach: $N_{\mathrm{inj}}(p) \propto p^{-\alpha}\,,\ \alpha = 4.3$



more realistic:



Sub-resolution injection of cosmic-ray spectra



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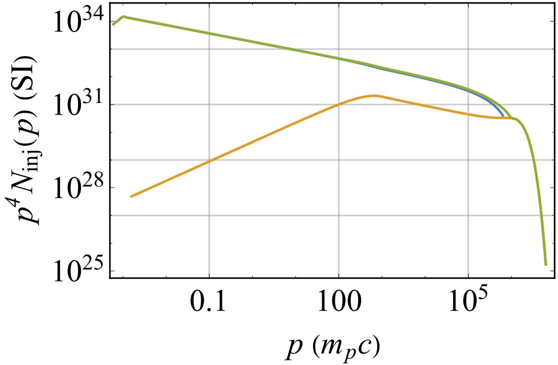


Disclaimer

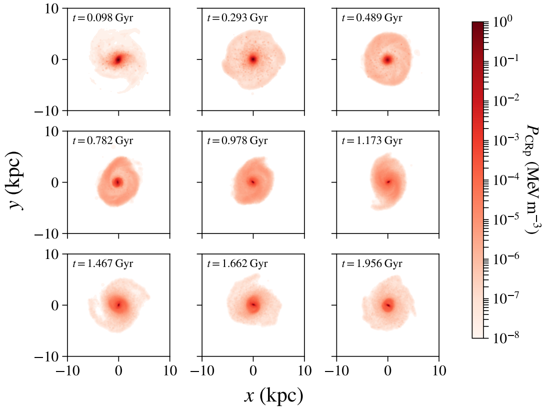
Parameters are **physically motivated** by observations and PIC-MHD simulations – but the models are still **analytical** and rather simple!

Ingredients for building a spectral CR model for SNRs

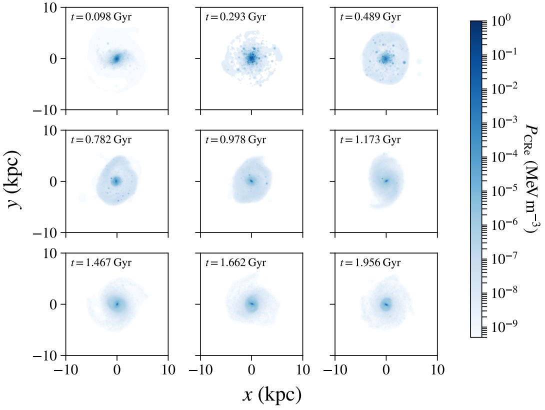
- Time evolution of forward shock
- Magnetic field amplification/evolution (from CRs and turbulence)
- Instantaneous spectrum at shock related to acceleration process (slope, cut-off, normalization)
- Evolution of maximum momentum of accelerated particles
- Energy loss mechanisms for confined particles (inverse Compton scattering, synchrotron radiation, adiabatic losses)

Preliminary results

Test simulation of small galaxy with simplified power-law seeding



protons



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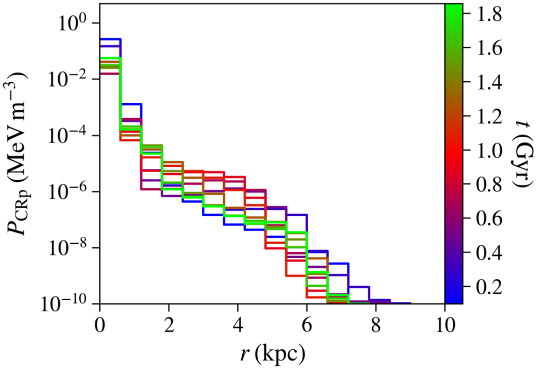

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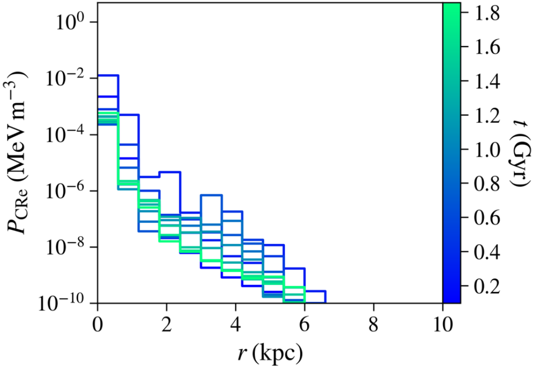

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Summary

Work in progress...

We currently develop a refined subresultion description for
cosmic-ray injection by supernova remnants in cosmological simulations.

- First test runs with new model have been successful
- Flexible implementation: only an update of tabulated spectra required
- Investigate the significance in simulations of isolated and clustered galaxies
- Other sub-galactic CR sources might be included in the future

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