Spectrally resolved injection of cosmic rays from supernovae in cosmological simulations

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The simulation code

- OpenGadget3 is a Tree-PM + SPH code (non-public derivative of Gadget2 by Springel (2005))
- CRESCENDO is an on-the-fly Fokker–Planck solver to evolve the distribution functions of CR protons and electrons within every resolution element using the two-moment approach (cf. Böss et al., 2023)

Cosmic rays in OpenGadget3

see Böss et al. (2023, MNRAS, 519, 548)

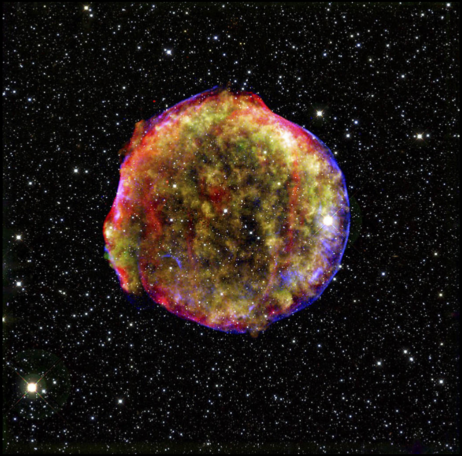
Canonical CR propagation equation:

$$
\begin{aligned}
\frac{\partial f(\mathbf{x}, p, t)}{\partial t} + \mathbf{u} \cdot \boldsymbol{\nabla} f(\mathbf{x}, p, t) = {} & \boldsymbol{\nabla} \cdot \left(\mathbf{D}(p) \boldsymbol{\nabla} f(\mathbf{x}, p, t)\right) \\
& + \left(\frac{1}{3} \boldsymbol{\nabla} \cdot \mathbf{u}\right) p \frac{\partial f(\mathbf{x}, p, t)}{\partial p} \\
& + \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 \sum_l b_l(p) f(\mathbf{x}, p, t) + D_{pp}(p) \frac{\partial f(\mathbf{x}, p, t)}{\partial p} \right) \\
& + \color{red}{Q(\mathbf{x}, p, t)}
\end{aligned}
$$

I will focus on the source term

Supernova remnants as cosmic-ray factories

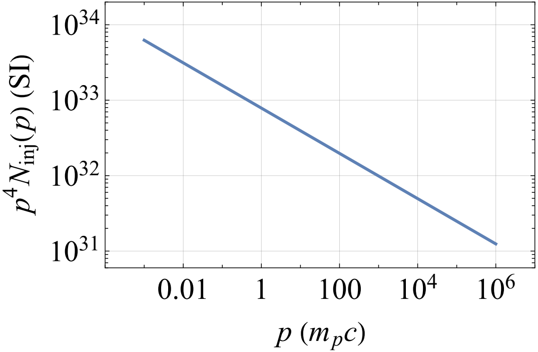
Non-thermal emission + enough energy to maintain energy density of Galactic CRs



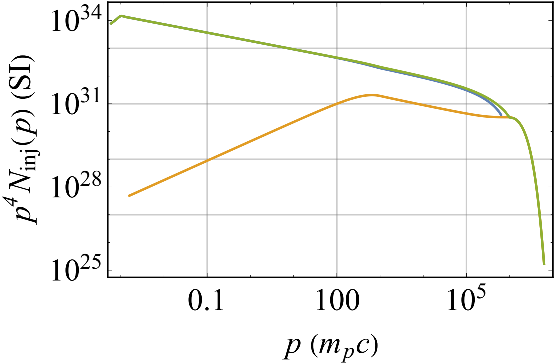
Tycho's supernova remnant (SN 1572). X-ray (Chandra X-ray Observatory): Yellow, Green, Blue; Infrared (Spitzer Space Telescope): Red; Optical (Calar Alto observatory): White background stars (source: https://chandra.harvard.edu/photo/2009/tycho/)

Sub-resolution injection of cosmic-ray spectra

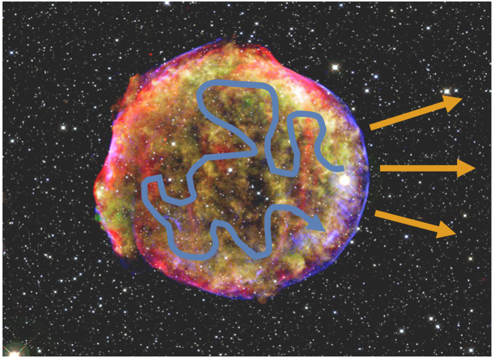
usual approach: $N_{\mathrm{inj}}(p) \propto p^{-\alpha}\,, \;\alpha = 4.3$



more realistic:



Sub-resolution injection of cosmic-ray spectra



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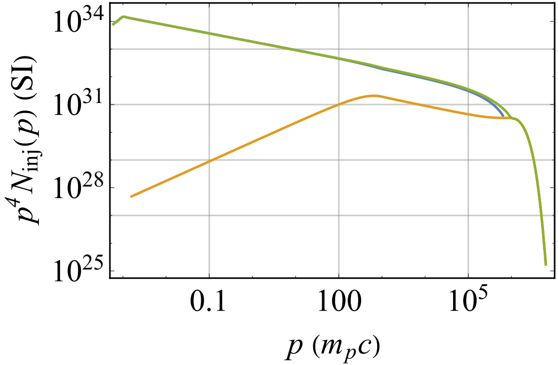


Disclaimer

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)

Modelling cosmic rays from SNRs

Combination of recent proposals

Cristofari et al. (2020, 2021)

- 3 types of supernovae: Ia, II and II*
- Shock evolution from thin-shell approximation for inhomogeneous gas density
- Maximum particle momentum derived from Bell instability

Morlino & Celli (2021)

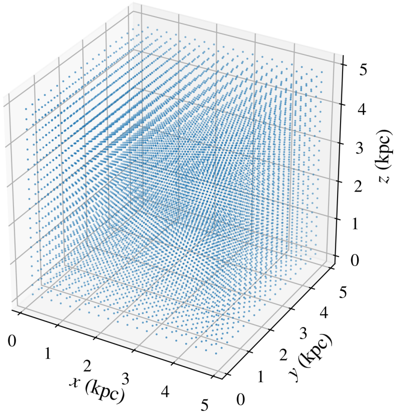
- Only type Ia supernovae (ambient gas with constant density)
- Advanced treatment of time-dependent escape and energy loss processes
- Different descriptions for magnetic field amplification

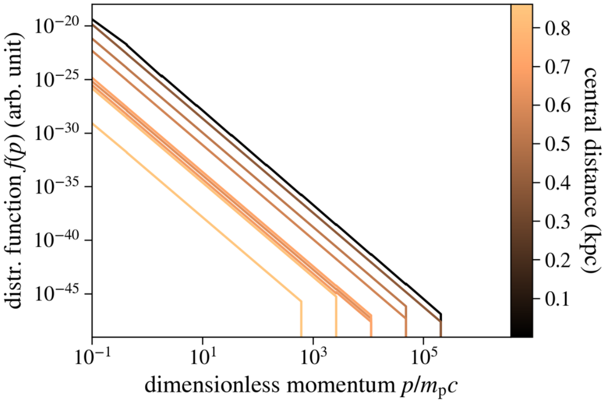
GOALS:

1) Compute a set of **tabulated spectra for various model parameters**, like SN energy, ejecta mass, density profile of ambient gas, background magnetic field
2) Couple these spectra to **star formation model**
3) Analyse effect on **properties** and **non-thermal emission** of galaxies

Preliminary results

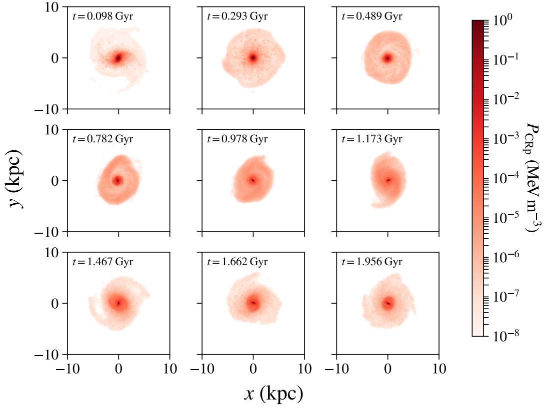
Testcase for refined seeding



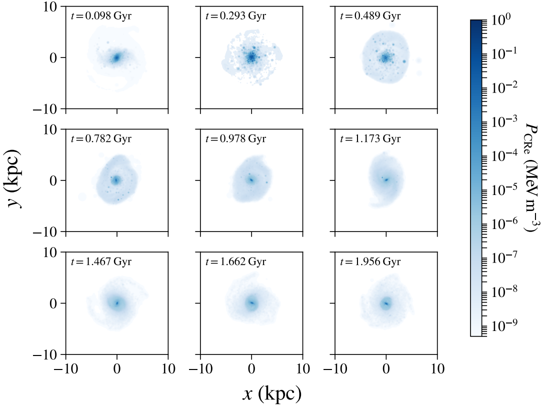


Preliminary results

Test simulation of small galaxy with simplified power-law seeding



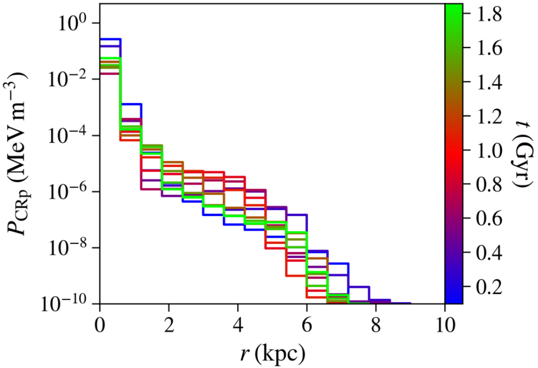
protons



electrons

Preliminary results

Test simulation of small galaxy with simplified power-law seeding



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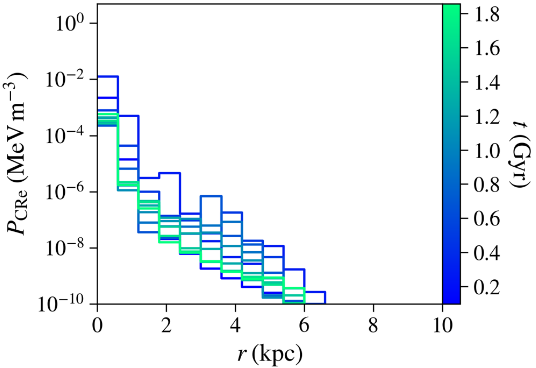


electrons

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

References

Böss L. M., Steinwandel U. P., Dolag K., Lesch H., 2023, MNRAS, 519, 548

Cristofari P., Blasi P., Amato E., 2020, Astropart. Phys., 123, 102492

Cristofari P., Blasi P., Caprioli D., 2021, A&A, 650, A62

Morlino G., Celli S., 2021, MNRAS, 508, 6142

Murante G., Monaco P., Borgani S., Tornatore L., Dolag K., Goz D., 2015, MNRAS, 447, 178

Springel V., 2005, MNRAS, 364, 1105

Springel V., Hernquist L., 2003, MNRAS, 339, 289

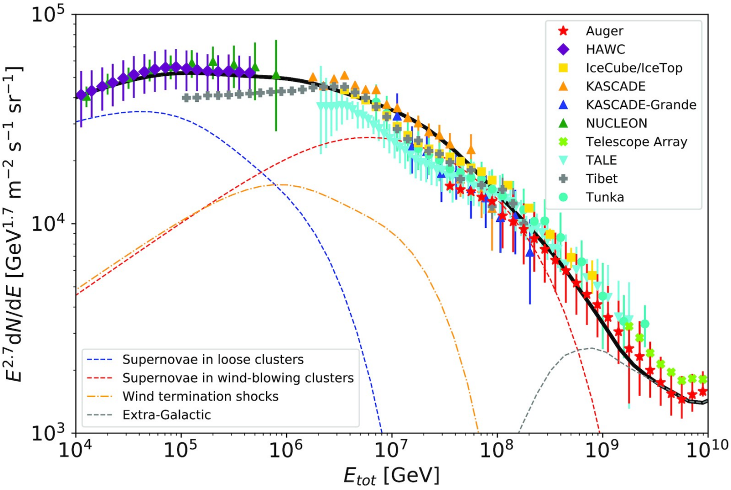
Tornatore L., Borgani S., Matteucci F., Recchi S., Tozzi P., 2004, MNRAS, 349, L19

Tornatore L., Borgani S., Dolag K., Matteucci F., 2007, MNRAS, 382, 1050

Valentini M., et al., 2020, MNRAS, 491, 2779

Vieu T., Reville B., 2023, MNRAS, 519, 136

Motivation: different contributions to overall cosmic-ray energy spectrum



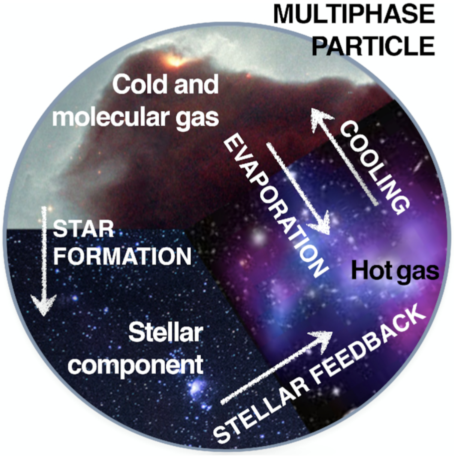
All-particle cosmic-ray spectrum from Vieu & Reville (2023)

Spectral cosmic-ray model for supernova remnants

Assumptions and simplifications

- Spherically symmetric geometry
- Ambient gas is either homogeneous or has simple piece-wise density profile (no ambient clouds or local ISM over-densities)
- Cosmic rays do not affect time evolution of shock
- No detailed hydrodynamical treatment of shock (like conduction or fluid instabilities)
- Ultra-relativistic limit for various energy-loss processes
- Particles are immediately released after the Sedov-Taylor phase
- Effects of collective stellar winds in super-bubbles not considered yet

Star formation models in OpenGadget3



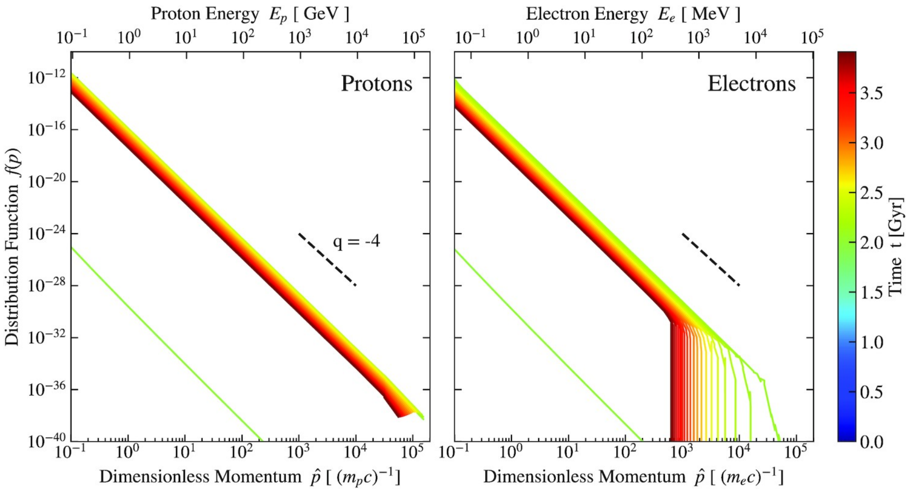
Valentini et al. (2020)

Three variants for star formation and stellar evolution:

- **Springel & Hernquist (2003)**:
  simple sub-resolution model for SF in multiphase ISM
- **Springel & Hernquist (2003) + Tornatore et al. (2004, 2007)**:
  star formation + stellar evolution + metal enrichment from stars and SNe + thermal feedback from SNII and SNIa (with time delay) + different IMFs
- **MUPPI model (Murante et al., 2015; Valentini et al., 2020) + Tornatore et al. (2004, 2007)**:
  more refined sub-resolution description for star formation + stellar evolution + cooling + chemical enrichment + AGN feedback

Cosmic rays in OpenGadget3

see Böss et al. (2023, MNRAS, 519, 548)



Evolution of the proton (left) and electron (right) distribution function of an arbitrarily chosen tracer particle (from Böss et al. 2023)

CR propagation equation

- Initalize CR spectra
- At the shock front the CR pressure is 10% of the ram pressure
- Calculate CR energy and number from distribution function (piecewise power-law in momentum)
- Calculate CR number fluxes and energy losses per bin
- Update CR energies and numbers
- Update slopes (solve implicit equation)
- Update norms (value of distribution function)
- Update spectral cut-off (upper momentum boundary is closed)

- Shock waves (different injection recipes)
- Supernova remnants (simple power-law with selectable slope and cut-offs; normalization corresponds to $E_{\mathrm{CR}} = 0.1 E_{\mathrm{SN}}$)

CRESCENDO module

Non-thermal radiation

- Compute synchrotron emissivity j_ν from distribution function of CR electrons; from this also follows intensity, luminosity and flux
- Hadronic γ-ray source function q_ν is obtained from pion-production cross section (parametrized with Geant4 toolkit (Agostinelli et al., 2003; Allison et al., 2006)) and CR proton distribution function

CRESCENDO module

Assumptions and simplifications

- Distribution function is 1) isotropic in momentum, $F(\mathbf{x}, \mathbf{p}, t) = f(\mathbf{x}, p, t)$, and (2) a piecewise power-law: $f(p) = \sum_{j=0}^{N_{\mathrm{bins}}} f_j \left(\frac{p}{p_j}\right)^{-\alpha_j}$
- Ultra-relativistic limit for kinetic particle energy: $E_{\mathrm{kin}}(p) = pc$
- Simplified and incomplete treatment of spatial diffusion (e.g. no coupling to turbulent magnetic field)
- Works only in SPH framework of OpenGadget3 so far