Extending the spectral cosmic-ray model in OpenGadget3 by including supernova remnants

OpenGadget3 User Meeting, 30 July 2024, Ljubljana

Daniel Karner

Klaus Dolag, Ildar Khabibullin, Ludwig M. Böss

Universitäts-Sternwarte München, Ludwig-Maximilians-Universität München

Contents in a nutshell

Supernova remnants are efficient cosmic-ray accelerators. When stars explode, cosmic rays are seeded, so we want to include a physically-motivated subresolution description for this in OpenGadget3.

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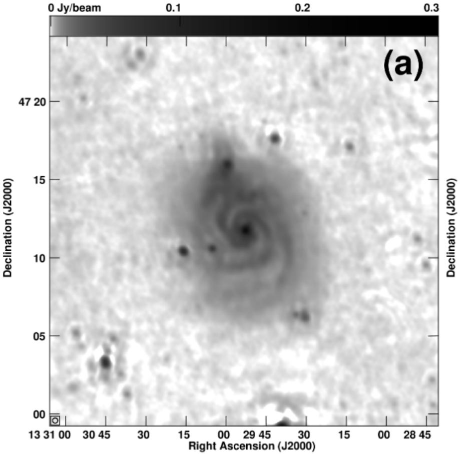
What are cosmic rays? Why do we care?



Radio continuum emission of NGC 5194 at 151 MHz from LOFAR HBA observations (Heesen et al., 2019)

- High-energy, charged particles (not rays!) (0.1 MeV $< E_{\mathrm{kin}} < 10^{20}$ eV)
- Composition:
  - 1% electrons
  - 99% nuclei: 90% protons, 9% alpha particles, 1% heavier nuclei (up to uranium)

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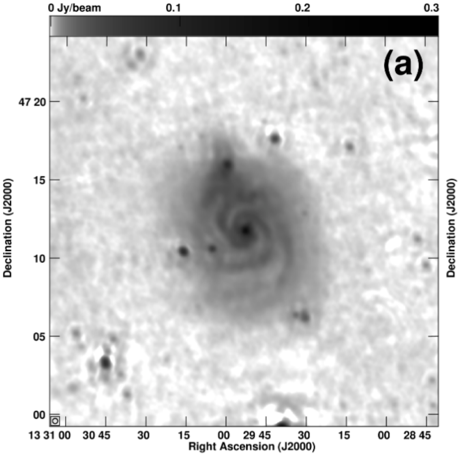

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- Composition:
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- Non-thermal radiation (in X-ray and radio band) as diagnostic tool
- Dynamical impact on galaxy evolution (ISM heating, additional pressure, galactic winds)

Cosmic rays in OpenGadget3

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

Canonical CR propagation equation:

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

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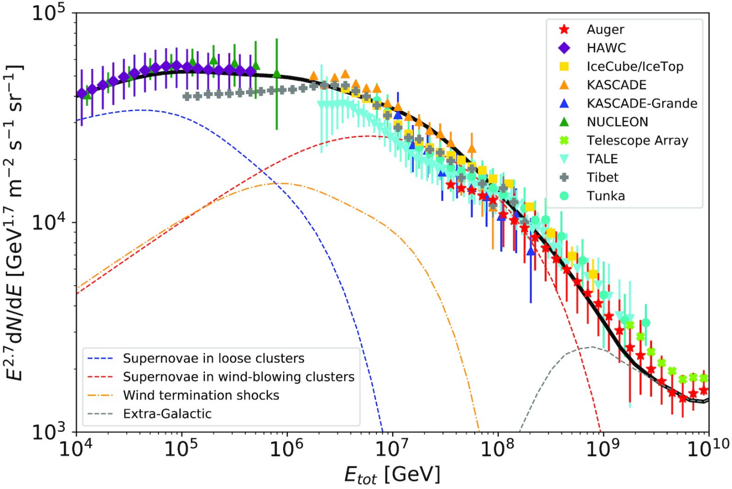
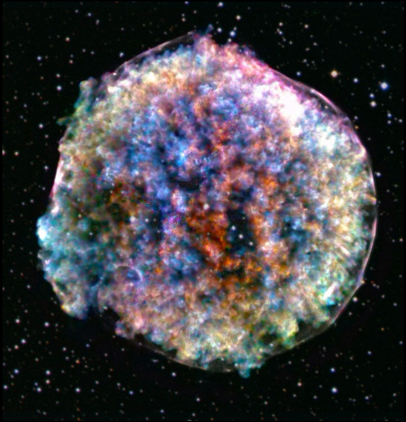
Different contributions to overall cosmic-ray energy spectrum



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/2019/tycho/)

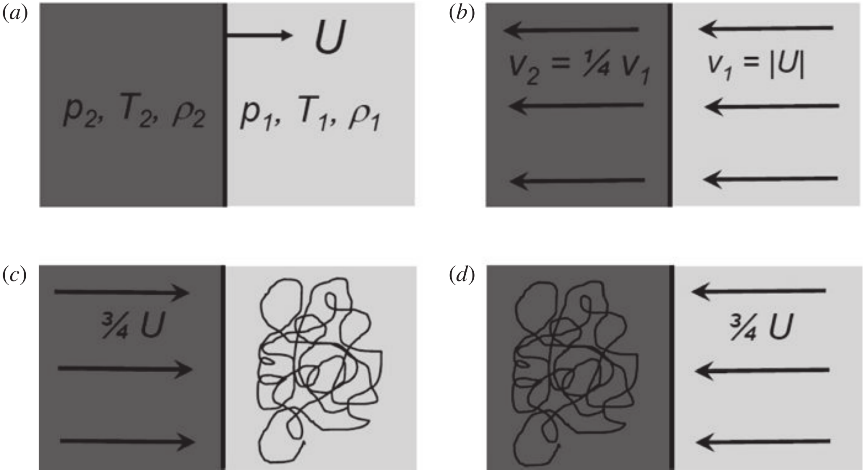
$$u_{\mathrm{CR}} \approx 0.5\,\mathrm{MeV\,m^{-3}}$$

$$\Longrightarrow \quad L_{\mathrm{CR}} = \frac{u_{\mathrm{CR}}\,V_{\mathrm{disk}}}{\tau_{\mathrm{esc}}} \approx 10^{33}\,\mathrm{W}$$

$$L_{\mathrm{SN}} \approx 10^{34}\,\mathrm{W}$$

$$\Longrightarrow \quad L_{\mathrm{CR}} = 0.1 \cdot L_{\mathrm{SN}}$$

Diffusive shock acceleration (DSA)



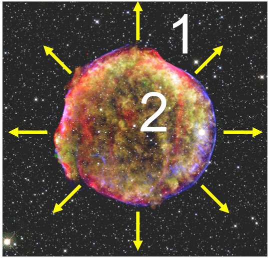
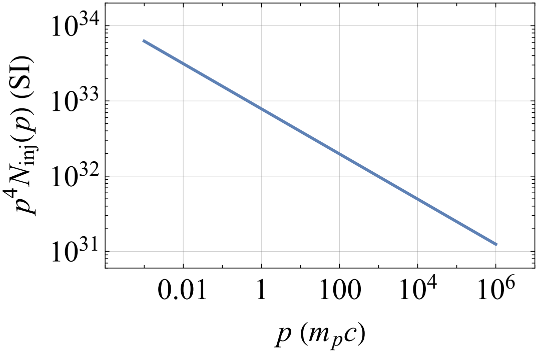


Figure from Longair (2011)

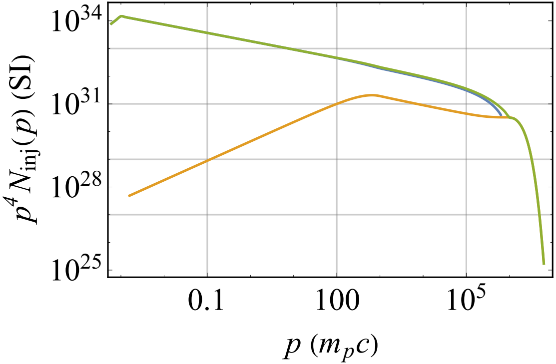
Sub-resolution injection of cosmic-ray spectra

Based on models of Cristofari et al. (2020, 2021); Morlino & Celli (2021)

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



more realistic:



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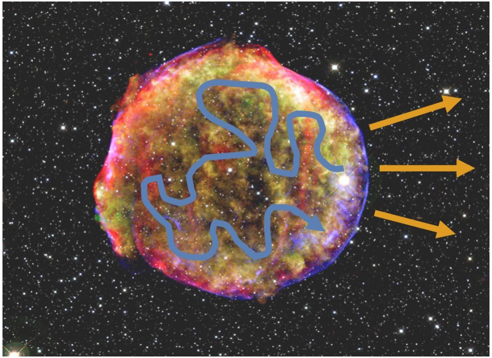

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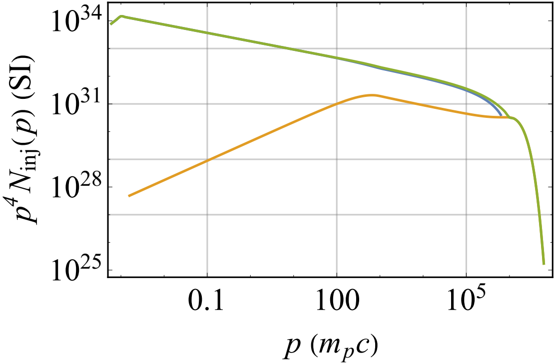

Modelling cosmic rays from SNRs

INGREDIENTS:

- Time evolution of forward shock
- CR distribution function at shock front
- Magnetic field amplification/evolution (from CRs and turbulence)
- Evolution of maximum momentum of accelerated particles
- Energy loss mechanisms for confined particles

Four phases of supernova remnant evolution

① Ejecta-dominated phase (free expansion, ~ 200 yr)
② Sedov-Taylor phase (adiabatic expansion, $\sim 20\,000$ yr)
③ Pressure-driven phase (snow-plough phase, radiative losses, up to $500\,000$ yr)
④ Merging phase (dispersion in ISM)

Assumption: CR acceleration stops at beginning of snow-plough phase

Evolution of the remnant’s radius and velocity

cf. Tang & Chevalier (2017)

Analytical description after several simplifications:

$$R_{\mathrm{sh}}(t) = R_{\mathrm{ch}} \left(\left(\tilde{\zeta} \frac{t}{t_{\mathrm{ch}}} \right)^{-a\lambda_{\mathrm{ED}}} + \left(\tilde{\xi} \frac{t}{t_{\mathrm{ch}}} \right)^{-a\lambda_{\mathrm{ST}}} \right)^{-1/a},$$

$$v_{\mathrm{sh}}(t) = \frac{\mathrm{d}R_{\mathrm{sh}}(t)}{\mathrm{d}t}$$

Tabulated parameters: $a, \tilde{\zeta}, \tilde{\xi}, \lambda_{\mathrm{ED}} > \lambda_{\mathrm{ST}}$

Evolution of the remnant's radius and velocity

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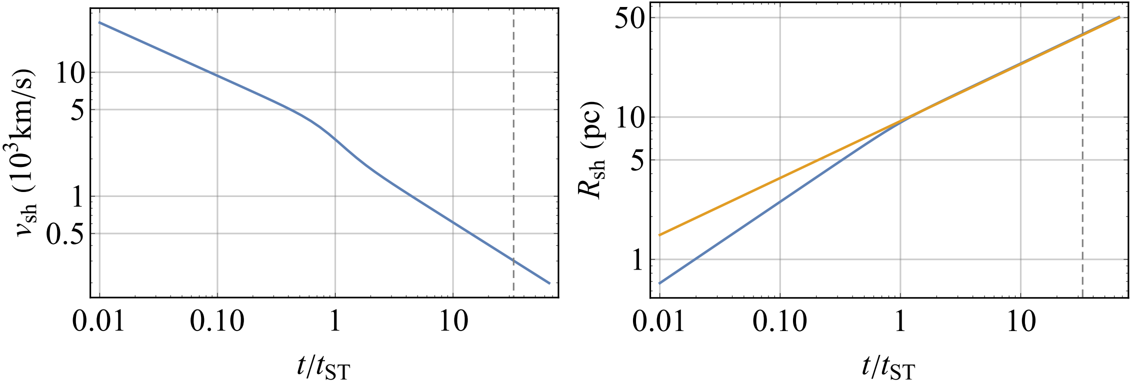
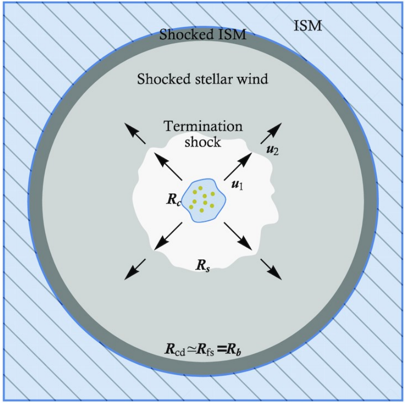
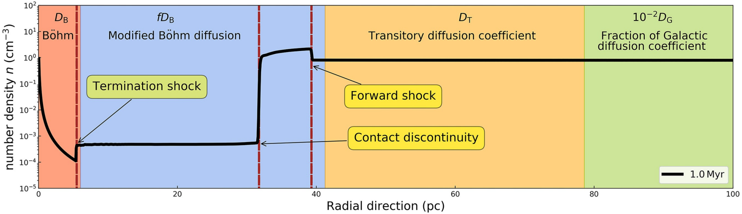


Evolution of the shock front of a **type Ia** supernova remnant. Left: shock velocity $v_{\rm sh}(t)$. Right: shock radius $R_{\rm sh}(t)$ (blue line); after $t = t_{\rm ST}$ the function converges to the Sedov-Taylor solution $R_{\rm sh} \propto t^{2/(5-s)}$ (orange line). The grey dashed line marks the beginning of the snowplough phase at $t_{\rm SP} \approx 50$ kyr.

Stellar winds of supernova progenitors make things more complicated



Morlino et al. (2021)



Meyer (2024)

Cosmic ray distribution function at the shock

- Fundamental quantity: distribution function $f(\mathbf{x}, \mathbf{p}, t)$ defined via

$$N(t) = \iint f(\mathbf{x}, \mathbf{p}, t)\, \mathrm{d}^3 x\, \mathrm{d}^3 p \quad \Longrightarrow \quad n(\mathbf{x}, t) = \int\limits_0^\infty f(\mathbf{x}, \mathbf{p}, t)\, \mathrm{d}^3 p$$

- Simplification $f(\mathbf{x}, \mathbf{p}, t) \longrightarrow f(r, p, t)$

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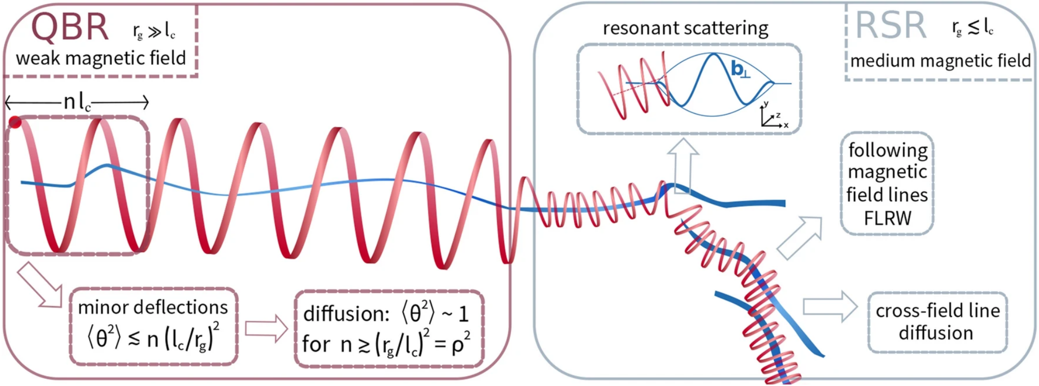
- Simplification $f(\mathbf{x}, \mathbf{p}, t) \longrightarrow f(r, p, t)$
- At the shock front we have:
  $f_{\mathrm{sh}}(p, t) \coloneqq f(R_{\mathrm{sh}}(t), p, t) = A(t) (p/m_{\mathrm{p}}\, c)^{-\alpha}\, \Theta(p - p_{\mathrm{inj}}(t))\, \exp(-p/p_{\mathrm{max}}(t))$

- Normalization factor $A(t)$: $P_{\mathrm{CR}}(R_{\mathrm{sh}}) \overset{!}{=} \xi_{\mathrm{CR}}\, P_{\mathrm{ram}} = \xi_{\mathrm{CR}}\, \rho_{\mathrm{amb}}\, v_{\mathrm{sh}}^2$

Confinement of cosmic rays

Intuitive picture



Motion of a charged particle in magnetic fields with different scales (Reichherzer et al., 2022)

Confinement of cosmic rays

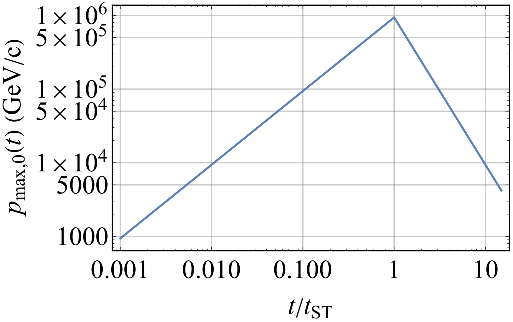
- Propagation of CRs strongly affected by pitch-angle scattering at (self-generated) Alfvén waves.
- CRs streaming faster than local Alfvén speed $v_{\mathrm{A}} = \frac{B}{\sqrt{\mu_0 \rho}}$ excite gyroresonant streaming instability (Alfvén waves grow in amplitude)

Confinement of cosmic rays

- Propagation of CRs strongly affected by pitch-angle scattering at (self-generated) Alfvén waves.
- CRs streaming faster than local Alfvén speed $v_\mathrm{A} = \frac{B}{\sqrt{\mu_0 \rho}}$ excite gyroresonant streaming instability (Alfvén waves grow in amplitude)
- **Problem:** This instability saturates when $\delta B \approx B_0$
- Non-resonant streaming instability (Bell, 2004) allows $\delta B \gg B_0$

Particle escape from accelerator

Morlino & Celli (2021)



Maximum proton momentum $p_{\mathrm{max},0}(t)$ at shock.

Simple parametrization for maximum proton momentum at shock:

$$p_{\mathrm{max},0}(t) = \begin{cases} p_{\mathrm{M}}\left(t/t_{\mathrm{ST}}\right) & \text{if } t \leq t_{\mathrm{ST}}\,, \\ p_{\mathrm{M}}\left(t/t_{\mathrm{ST}}\right)^{-\delta} & \text{if } t > t_{\mathrm{ST}}\,. \end{cases}$$

Escape time:

$$t_{\mathrm{esc}}(p) = \begin{cases} t_{\mathrm{SP}} & \text{if } p \leq p_{\mathrm{max},0}(t_{\mathrm{SP}})\,, \\ t_{\mathrm{ST}}\left(p/p_{\mathrm{M}}\right)^{-1/\delta} & \text{if } p > p_{\mathrm{max},0}(t_{\mathrm{SP}})\,. \end{cases}$$

Energy loss mechanisms for particles trapped inside the remnant

- Cosmic rays are trapped inside remnant until escape time when shock has become weak enough
- Loss mechanisms:
  - Adiabatic losses (for both p and e^-)
  - Synchrotron radiation and inverse Compton scattering (only e^-):

Formation of the spectrum

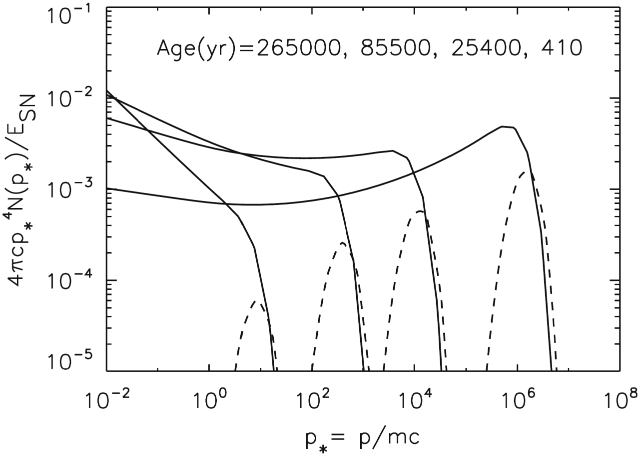
Two contributions: upstream precursor and trapped particles

Accumulated CR spectrum is given by “momentum-space density” $F(p)$:

$$F(p) = F_{\mathrm{conf}}(p) + F_{\mathrm{prec}}(p) = \int\limits_0^{R_{\mathrm{sh}}(t_{\mathrm{esc}}(p))} \left(f_{\mathrm{conf}}(r, p, t_{\mathrm{esc}}(p)) + f_{\mathrm{prec}}(r, p, t_{\mathrm{esc}}(p))\right) 4\pi r^2 \,\mathrm{d}r$$

Formation of the spectrum

Two contributions: upstream precursor and trapped particles



Dashed lines: upstream escape flux; solid lines: advected spectra at four different times (see Caprioli et al., 2010)

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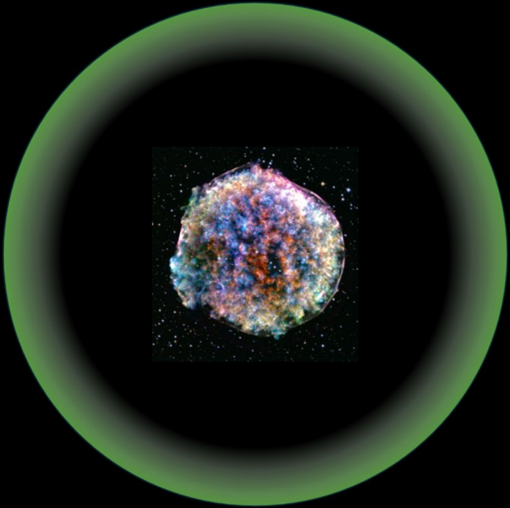
Workflow

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 spectra to effective **star formation model** by Springel & Hernquist (2003)
3. Run **simple test cases** and then go to larger scales

The momentum-space density F(p) alias “spectrum”



The momentum-space density F(p) alias “spectrum”

A look into `CRp_SNIa_input_spectrum.dat`:

```
// discretised CR proton spectrum for a supernova of type Ia
// particle momentum lg[p/(m_p*c)], momentum space density lg[F(p)/(m_p*c)^-3]
-2.     60.1648
-1.98   60.0788
-1.96   59.9928
-1.94   59.9068
-1.92   59.8208
-1.9    59.7348
```

Modifications visible for the user

- path: OpenGadget3/CosmicRays/SNTables
- config.sh: DK_SPECTRAL_SN_SEEDING
- parameter file: CR_SNTables_Path

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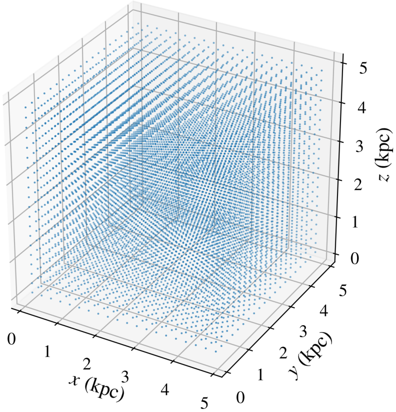
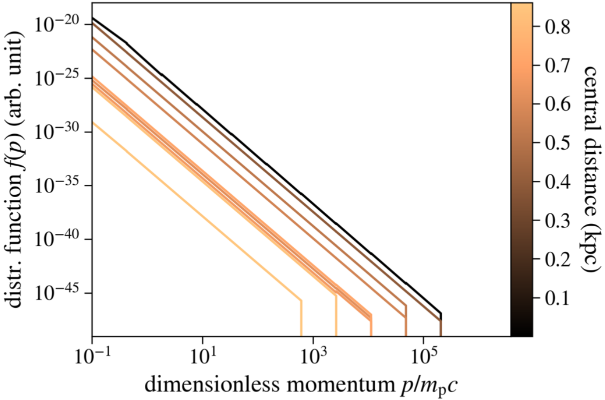
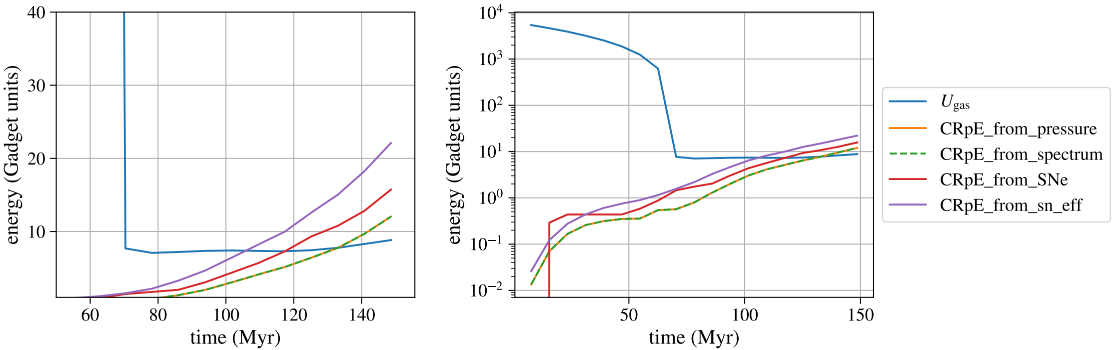
Our standard testcase for refined CR seeding





Same energy, different numerical methods



Same energy, different numerical methods

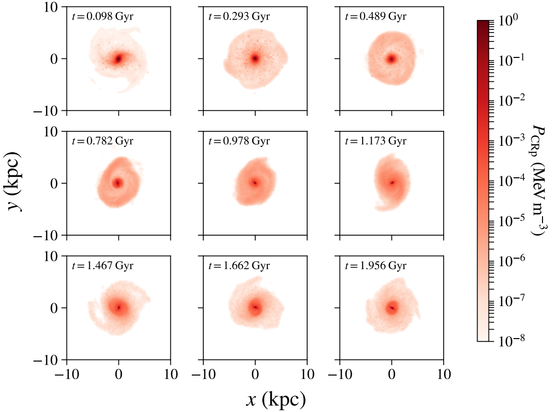
from spectrum: $$E_{\mathrm{CR}} = \sum_{i=1}^{N_{\mathrm{bins}}} \frac{4\pi c f_i p_i^4}{\rho} \frac{\left(\left(\frac{p_{i+1}}{p_i}\right)^{4-q_i} - 1\right)}{4-q_i}$$

from cosmic-ray pressure: $$P = (\gamma - 1) u \rho \quad \Longrightarrow \quad E_{\mathrm{CR}} = um = \frac{Pm}{(\gamma-1)\rho}$$

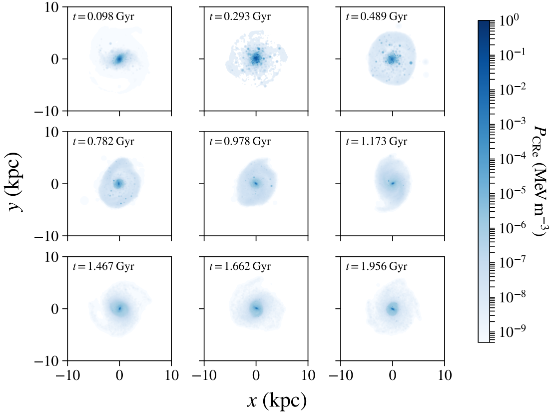
Salpeter IMF: $$\phi(m) \coloneqq \frac{\mathrm{d}N_*}{\mathrm{d}m} \propto m^{-(1+\alpha)}\,; \quad \alpha = 1.35\,; \quad m \in [0.1, 100]\,\mathrm{M}_\odot$$

$\Longrightarrow \quad E_{\mathrm{SN}} = 7.422 \cdot 10^{41}\,\mathrm{J}/\mathrm{M}_\odot \quad \Longrightarrow$ 10% of this energy goes into CR protons

Isolated spiral galaxy with simplified power-law seeding



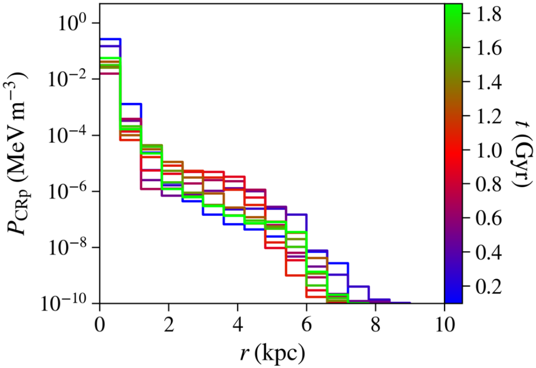
protons



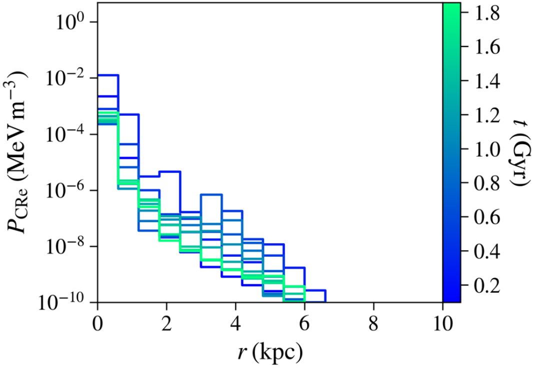
electrons

Preliminary results

Test simulation of small galaxy with simplified power-law seeding



protons



electrons

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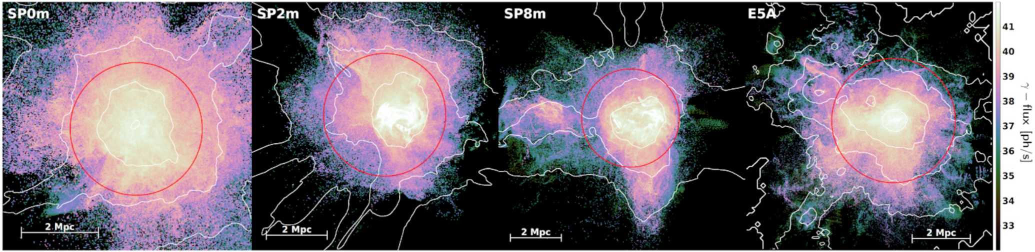
Possible applications in OpenGadget3

- Simulations of (isolated) galaxies (dynamical impact of cosmic rays + non-thermal emission)
- Missing gamma-ray problem in galaxy clusters (now shocks AND supernovae cause trouble):

  $p_{\mathrm{CR}} + p \rightarrow \pi^0 + p + p\,, \quad \pi^0 \rightarrow 2\gamma$ (threshold momentum: 0.78 GeV/c)



Wittor et al. (2020)

Summary

Work in progress...

We extend the spectral cosmic ray model in OpenGadget3 by including a physically-motivated subresolution recipe for supernova remnants.

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

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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

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

Modelling cosmic rays from SNRs

Comparison for type Ia SNe (Morlino & Celli, 2021)