Cosmic-ray shock acceleration and transport of electron spectra

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in collaboration with

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Outline

Magneto-hydrodynamics (MHD) with cosmic rays

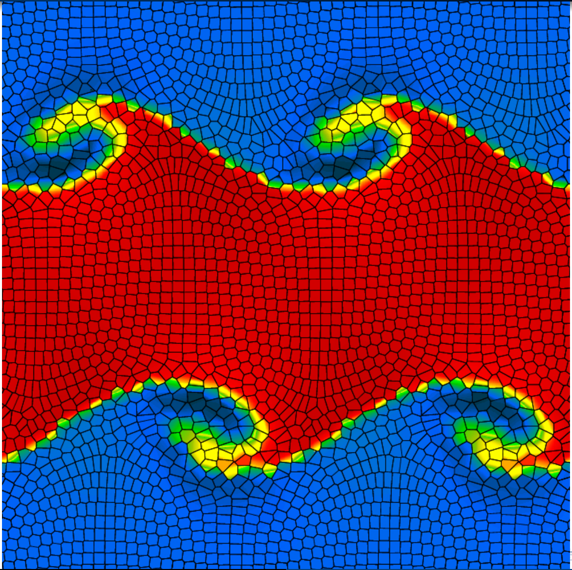
MHD – hyperbolic partial differential equations: $\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \mathbf{F} = \boldsymbol{S}$,

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \varepsilon \\ \varepsilon_{\mathrm{cr}} \\ \boldsymbol{B} \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v}^{\mathrm{T}} + P\mathbf{1} - \boldsymbol{B}\boldsymbol{B}^{\mathrm{T}} \\ (\varepsilon + P)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{v} \cdot \boldsymbol{B}) \\ \varepsilon_{\mathrm{cr}} \boldsymbol{v} + (\varepsilon_{\mathrm{cr}} + P_{\mathrm{cr}})\boldsymbol{v}_{\mathrm{st}} - \kappa_\varepsilon \boldsymbol{b}(\boldsymbol{b} \cdot \boldsymbol{\nabla} \varepsilon_{\mathrm{cr}}) \\ \boldsymbol{B}\boldsymbol{v}^{\mathrm{T}} - \boldsymbol{v}\boldsymbol{B}^{\mathrm{T}} \end{pmatrix},$$

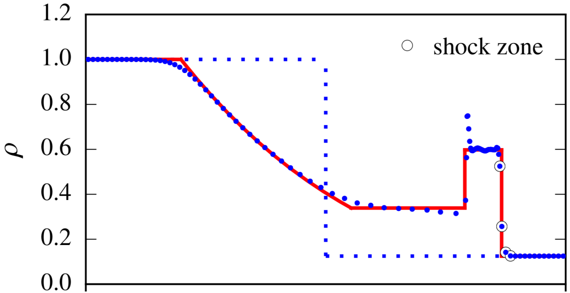
$$\boldsymbol{S} = \begin{pmatrix} 0 \\ \mathbf{0} \\ P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot \boldsymbol{v} - \boldsymbol{v}_{\mathrm{st}} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}} + \Lambda_{\mathrm{th}} + \Gamma_{\mathrm{th}} \\ -P_{\mathrm{cr}} \boldsymbol{\nabla} \cdot \boldsymbol{v} + \boldsymbol{v}_{\mathrm{st}} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}} + \Lambda_{\mathrm{cr}} + \Gamma_{\mathrm{cr}} \\ \mathbf{0} \end{pmatrix},$$

and $P = P_{\mathrm{th}} + P_{\mathrm{cr}} + \boldsymbol{B}^2/2$, $\quad \varepsilon = \varepsilon_{\mathrm{th}} + \rho \boldsymbol{v}^2/2 + \boldsymbol{B}^2/2$, $\quad \boldsymbol{v}_{\mathrm{st}} = -\boldsymbol{v}_{\mathrm{A}}\,\mathrm{sgn}(\boldsymbol{B} \cdot \boldsymbol{\nabla} P_{\mathrm{cr}})$

Cosmological moving-mesh code AREPO (Springel 2010)

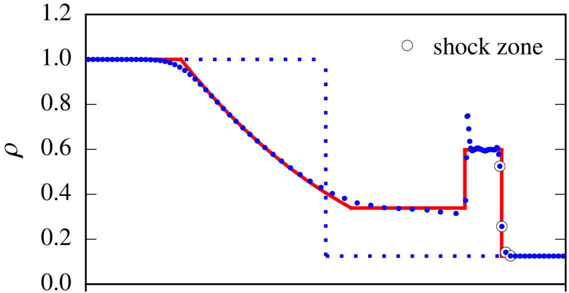


Shock finder



CP, Pakmor, Schaal, Simpson, Springel (2017)

Shock finder

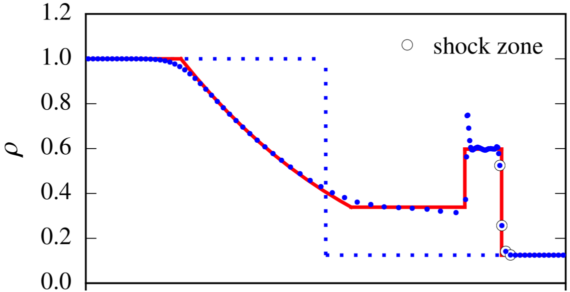


CP, Pakmor, Schaal, Simpson, Springel (2017)

Voronoi cells belong to **shock zone** if

- $\nabla \cdot \boldsymbol{v} < 0$ (converging flow)
- $\nabla T \cdot \nabla \rho > 0$ (filtering out tangential discontinuities)
- $\mathcal{M}_1 > \mathcal{M}_{\mathrm{min}}$ (safeguard against numerical noise)

Shock finder and CR acceleration

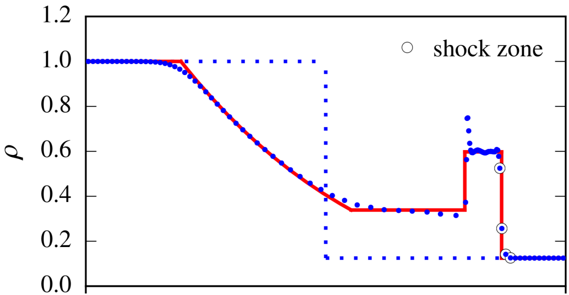


CP, Pakmor, Schaal, Simpson, Springel (2017)

CR acceleration:

- **shock surface:** cell with most converging flow

Shock finder and CR acceleration

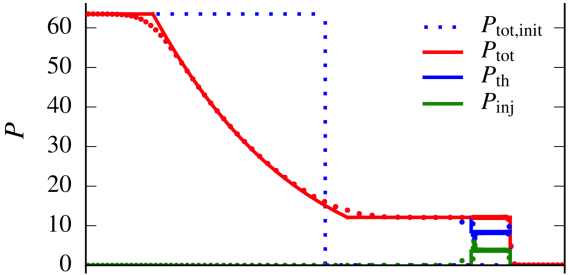


CP, Pakmor, Schaal, Simpson, Springel (2017)

CR acceleration:

- **shock surface:** cell with most converging flow
- collect pre- and post-shock energy at shock surface $\Rightarrow E_{\mathrm{diss}}$
- inject $\Delta E_{\mathrm{cr}} = \zeta(\mathcal{M}_1, \theta)\, E_{\mathrm{diss}}$ to shock and 1$^{\mathrm{st}}$ post-shock cell

Shock finder and CR acceleration



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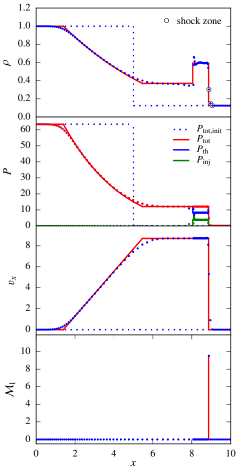
Shock finder and CR acceleration

Comparing simulations to novel exact solutions that include CR acceleration



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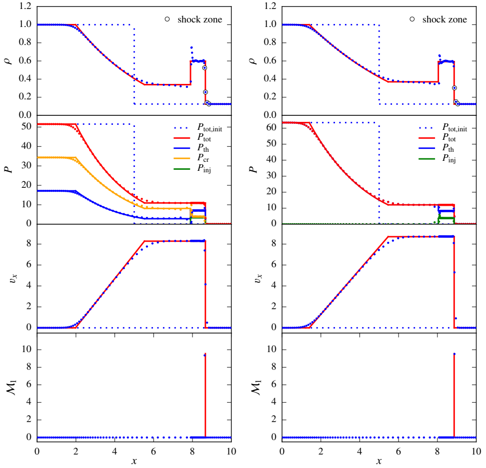

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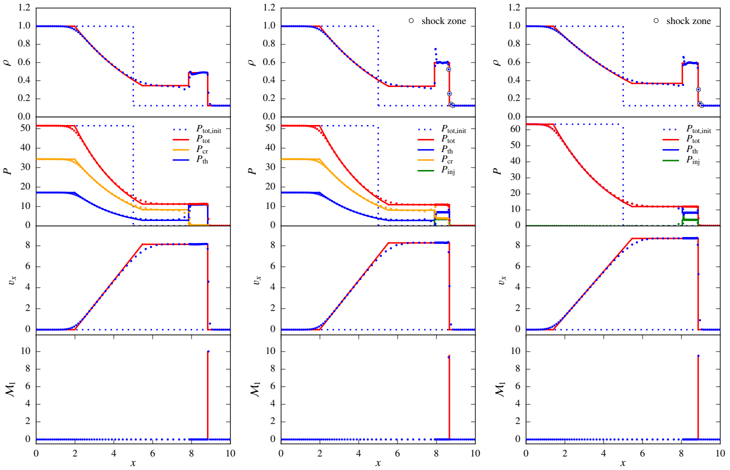

CP, Pakmor, Schaal, Simpson, Springel (2017)

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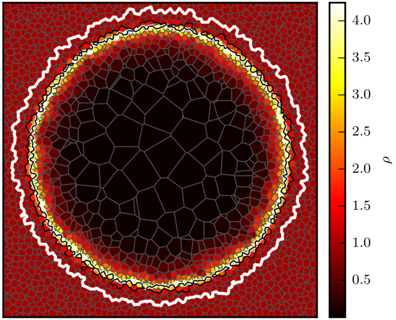

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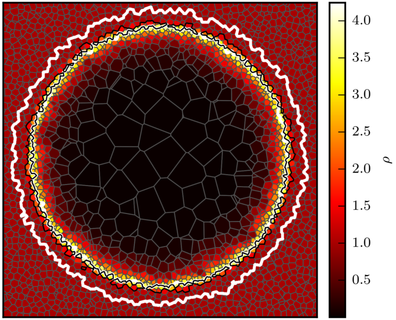
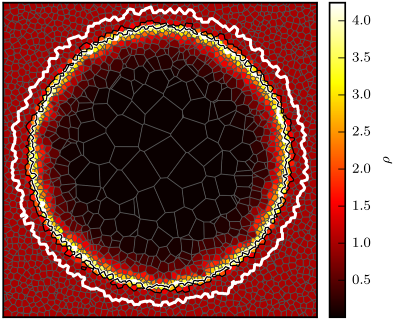


CP, Pakmor, Schaal, Simpson, Springel (2017)

CR acceleration:

- **shock surface:** cell with most converging flow along ∇T

Shock finder and CR acceleration



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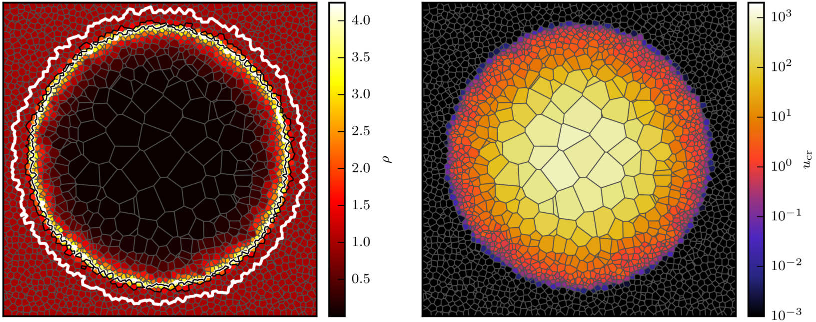

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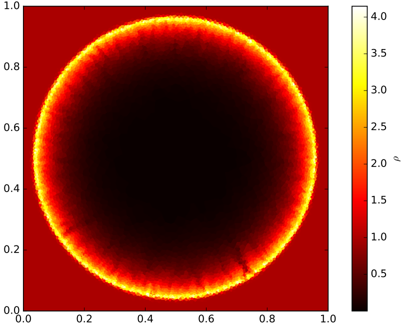
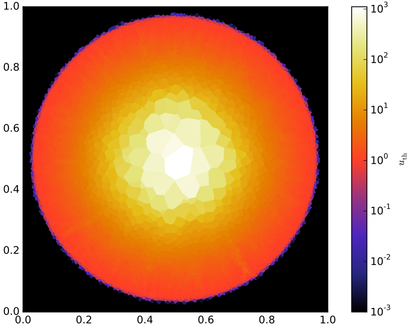
Sedov explosion

density



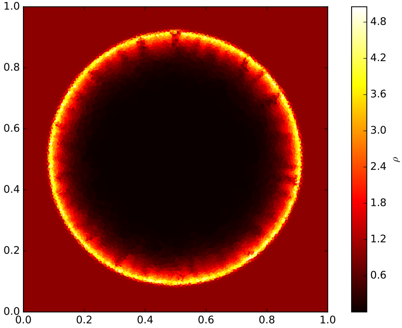
specific thermal energy



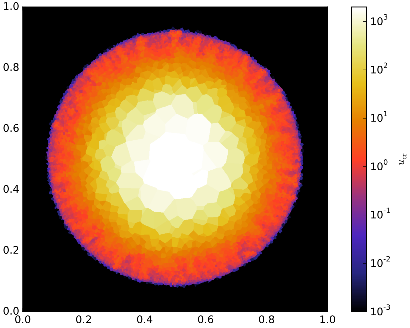
CP, Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

density



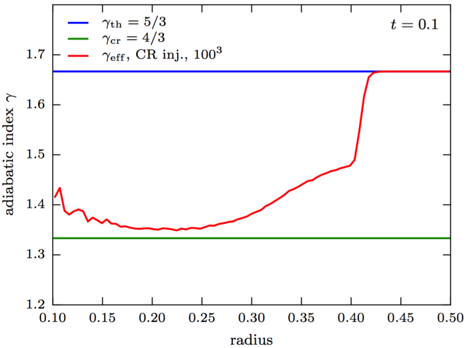
specific cosmic ray energy



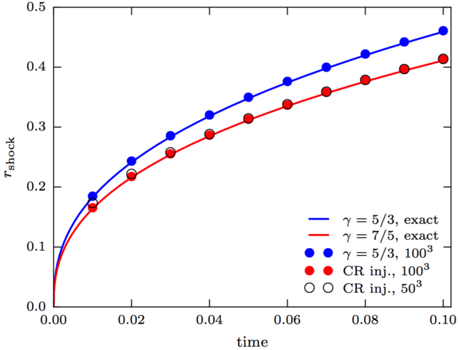
CP, Pakmor, Schaal, Simpson, Springel (2017)

Sedov explosion with CR acceleration

adiabatic index



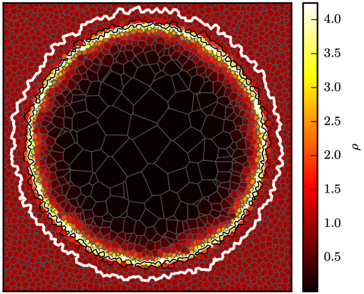
shock evolution



CP, Pakmor, Schaal, Simpson, Springel (2017)

Outline

Global MHD simulations of SNRs with CR physics

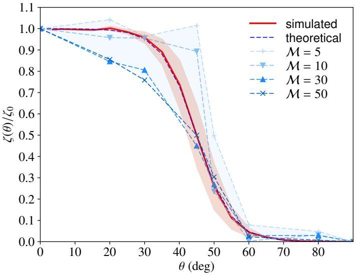


Mach number finder with CRs

CP+ (2017)

- detect and characterize shocks and jump conditions on the fly

Global MHD simulations of SNRs with CR physics

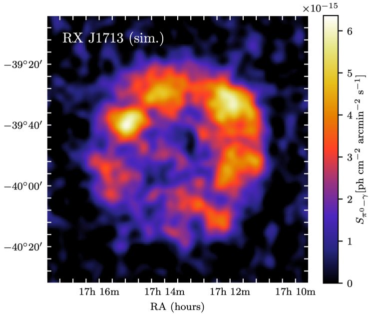


obliquity-dep. acceleration efficiency

Pais, CP+ (2018) based on
hybrid PIC sim.'s by Caprioli & Spitkovsky (2015)

- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B

Global MHD simulations of SNRs with CR physics

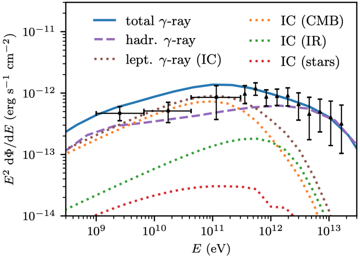


simulated TeV gamma-ray map

Pais & CP (2020)

- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission

Global MHD simulations of SNRs with CR physics



simulated gamma-ray spectrum

Winner, CP+ (2019, 2020)

- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission
- inject and transport CR electrons
- calculate non-thermal radio, X-ray, γ-ray emission

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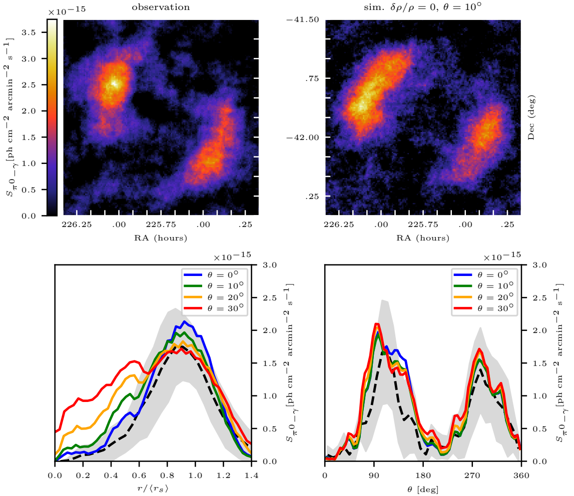
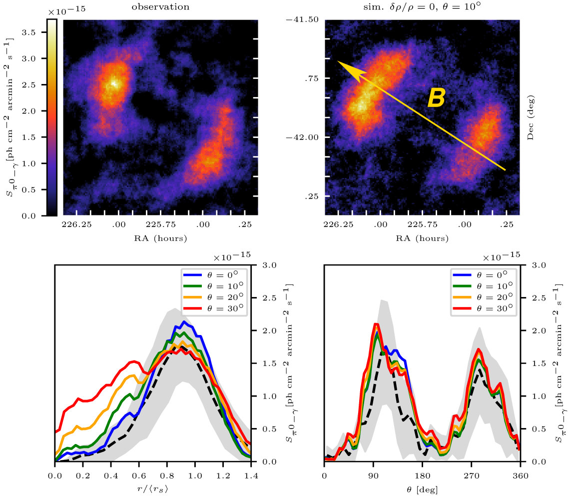
Hadronic TeV γ rays: SN 1006



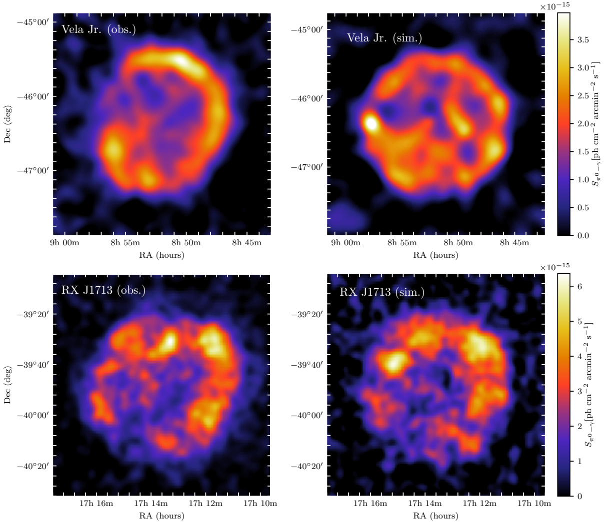
Pais & CP (2020)

Hadronic TeV γ rays: SN 1006



Pais & CP (2020)

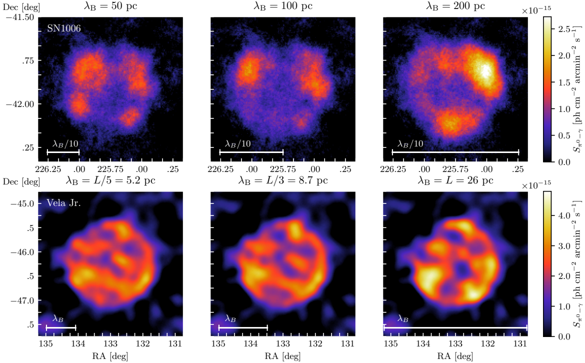
Hadronic TeV γ rays: Vela Jr. and RXJ 1713



Pais & CP (2020)

TeV γ rays from shell-type supernova remnants

Varying magnetic coherence scale in simulations of SN 1006 and Vela Junior



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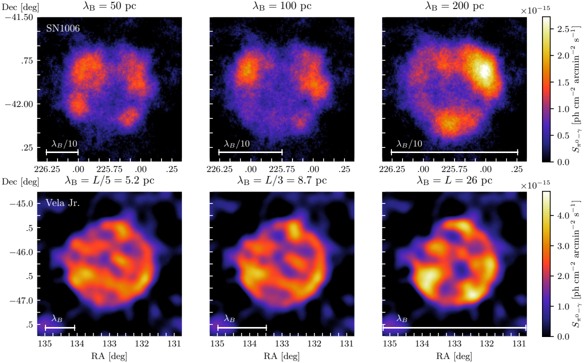
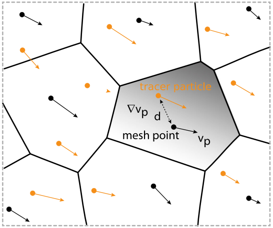


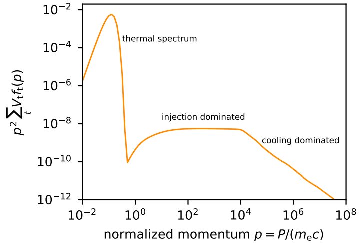
Pais, CP+ (2020)

$\Rightarrow$ Correlation structure of patchy TeV γ-rays constrains magnetic coherence scale in ISM:

SN 1006: $\lambda_B > 200^{+80}_{-10}$ pc   Vela Junior: $\lambda_B = 13^{+13}_{-4.3}$ pc

CREST - Cosmic Ray Electron Spectra evolved in Time





CREST code (Winner, CP+ 2019)

- post-processing MHD simulations
- on Lagrangian particles
  - adiabatic processes
  - Coulomb and radiative losses
  - Fermi-I (re-)acceleration
  - Fermi-II reacceleration
  - secondary electrons

Link to observations

- radio synchrotron
- inverse Compton (IC) γ-ray

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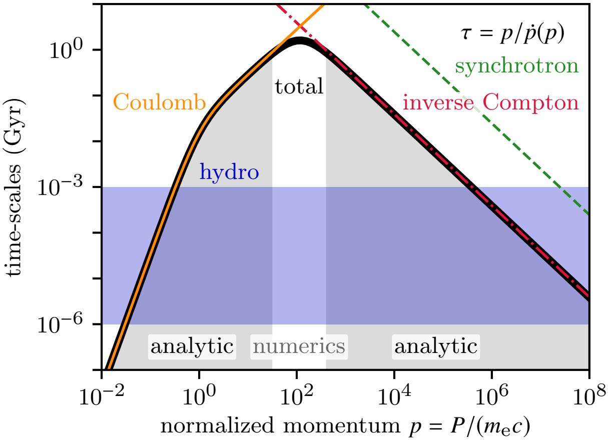
Electron cooling time scales

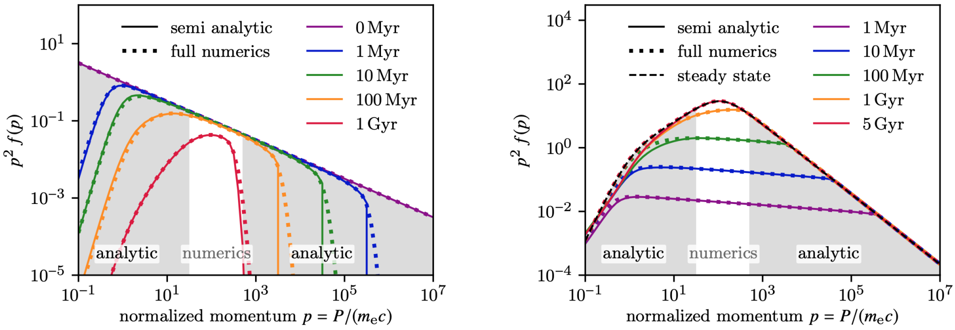
Complementing the numerics with analytical solutions in the limiting regimes



Winner, CP+ (2019)

Cooling electron spectra

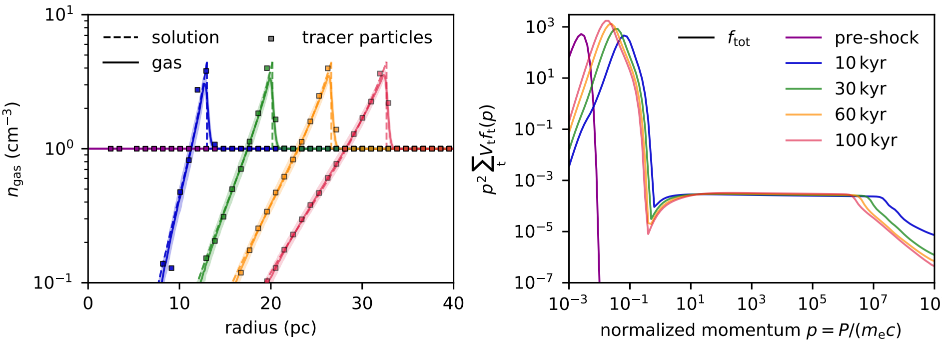
Freely cooling spectra vs. steady state solution



Winner, CP+ (2019)

- freely cooling solution develops cutoffs: numerical solution more diffusive in extreme energy regimes
- steady state spectrum approaches analytical solution

Sedov–Taylor blast wave: spectral evolution



Winner, CP+ (2019)

$E_0 = 10^{51}$ erg, $n_{\rm gas} = 1\,{\rm cm}^{-3}$, $T_0 = 10^4$ K, $B = 1\,\mu$G

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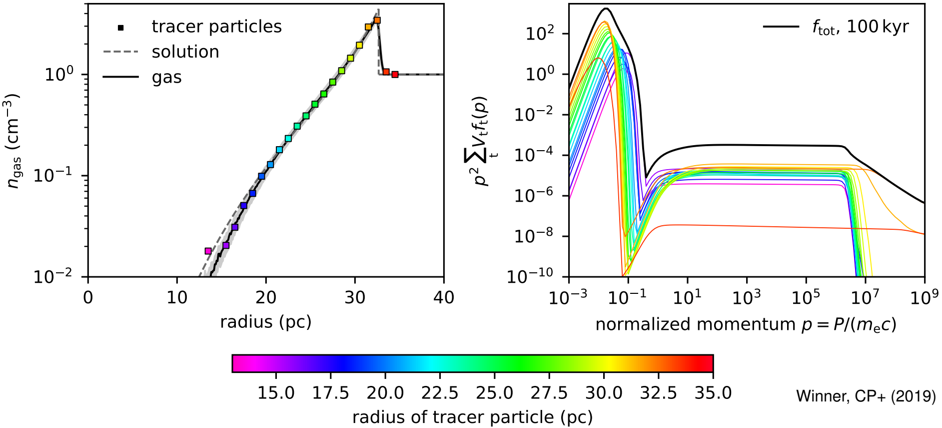
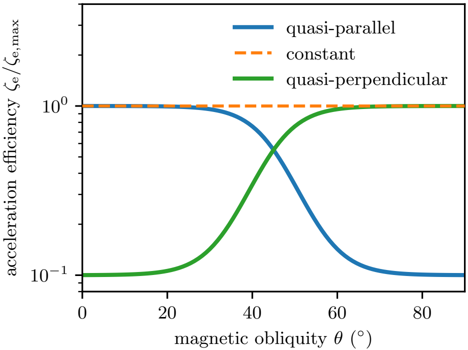
Sedov–Taylor blast wave: radial contribution



Winner, CP+ (2019)

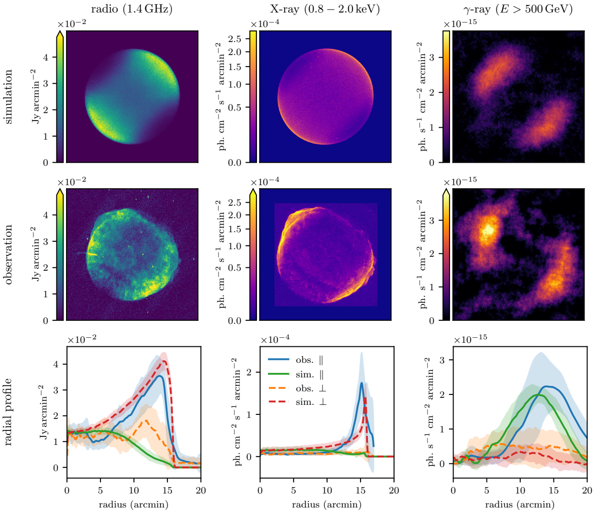
SN 1006: CR electron acceleration models



Winner, CP+ (2020)

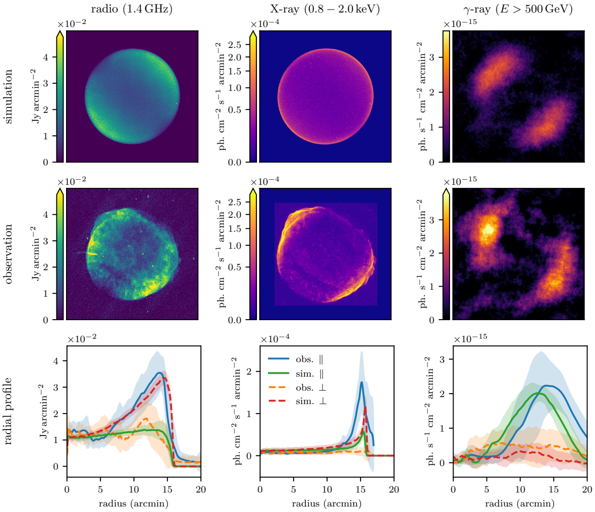
- different obliquity dependent electron acceleration efficiencies:
  1. preferred quasi-perpendicular acceleration (PIC simulations)
  2. constant acceleration efficiency (a straw man's model)
  3. preferred quasi-parallel acceleration (like CR protons)

CR electron acceleration: quasi-perpendicular shocks



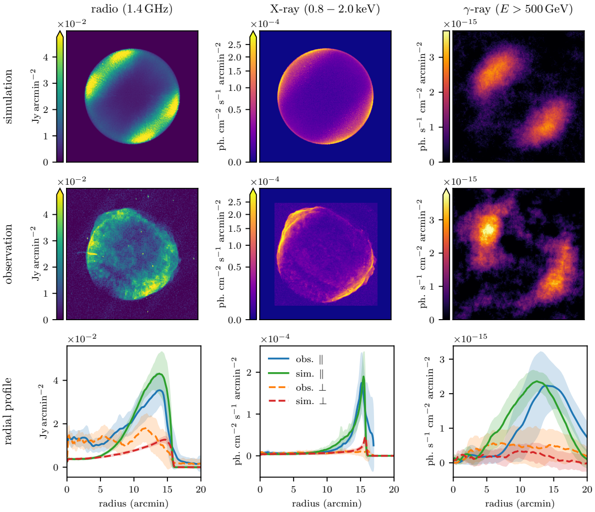
Winner, CP+ (2020)

CR electron acceleration: constant efficiency



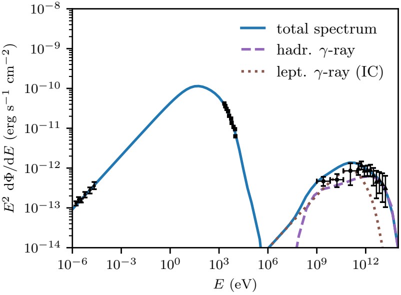
Winner, CP+ (2020)

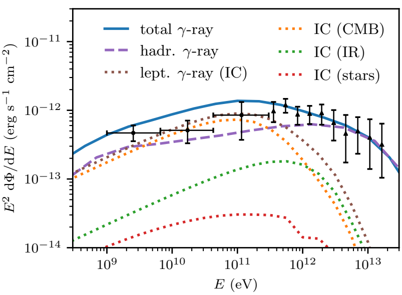
CR electron acceleration: quasi-parallel shocks



Winner, CP+ (2020)

SN 1006: multi-frequency spectrum

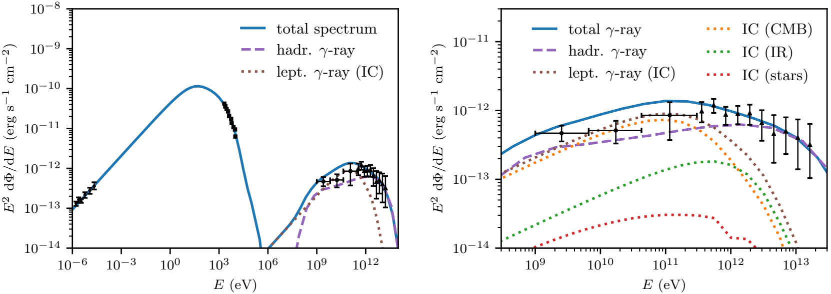




Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum

SN 1006: multi-frequency spectrum

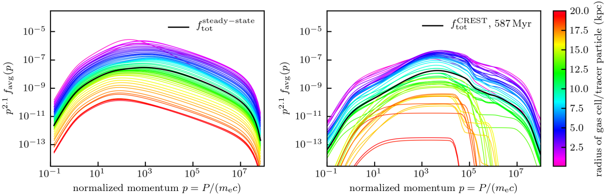


Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum
- GeV regime: leptonic inverse Compton dominates
- TeV regime: hadronic pion decay

Steady-state vs. evolved CR electron spectra

3D MHD-CR simulations of isolated forming galaxies with evolving electron spectra



Werhahn+ (in prep.): PRELIMINARY

Steady-state vs. evolved CR electron spectra

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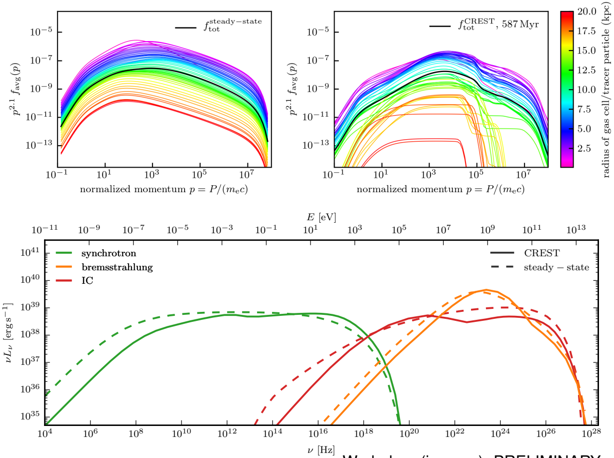
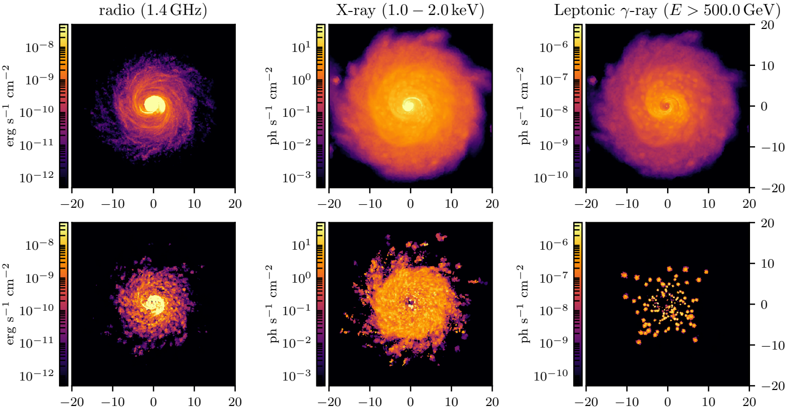


Werhahn+ (in prep.): PRELIMINARY

Steady-state vs. evolved CR electrons: emission maps

3D MHD-CR simulations of isolated forming galaxies with evolving electron spectra



Werhahn+ (in prep.): PRELIMINARY

Conclusions for cosmic ray physics in galaxies

CR physics tools:

- Shock finder enables CR acceleration in MHD simulations
- CR hydrodynamics enables capturing CR dynamics: extensions to 2-moment spectral and spatial CR transport (Timon Thomas)
- CR electron spectral transport (CREST): multi-frequency spectra and emission maps

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- CR electron spectral transport (CREST): multi-frequency spectra and emission maps

CR acceleration:

- TeV shell-type SNRs probe magnetic coherence scale in ISM
- hybrid-PIC simulations of p^+ acceleration agree with global SNR simulations
- global SNR simulations imply preferred quasi-parallel e^- acceleration: new intermediate instability modifies physics of e^- acceleration (Mohamad Shalaby)

CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtioN

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Literature for the talk

Cosmic ray acceleration:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh,* 2017, MNRAS, 465, 4500.
- Pais, Pfrommer, Ehlert, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics,* 2018, MNRAS, 478, 5278.
- Pais, Pfrommer, Ehlert, Werhahn, Winner, *Constraining the coherence scale of the interstellar magnetic field using TeV gamma-ray observations of supernova remnants,* 2020, MNRAS, 496, 2448.
- Pais, Pfrommer, *Simulating TeV gamma-ray morphologies of shell-type supernova remnants,* 2020, MNRAS, 498, 5557.
- Winner, Pfrommer, Girichidis, Pakmor, *Evolution of cosmic ray electron spectra in magnetohydrodynamical simulations,* 2019, MNRAS, 488, 2235.
- Winner, Pfrommer, Girichidis, Werhahn, Pais, *Evolution and observational signatures of the cosmic ray electron spectrum in SN 1006,* 2020, MNRAS, 499, 2785.