

Supernova remnants as laboratories for studying cosmic ray acceleration

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in collaboration with

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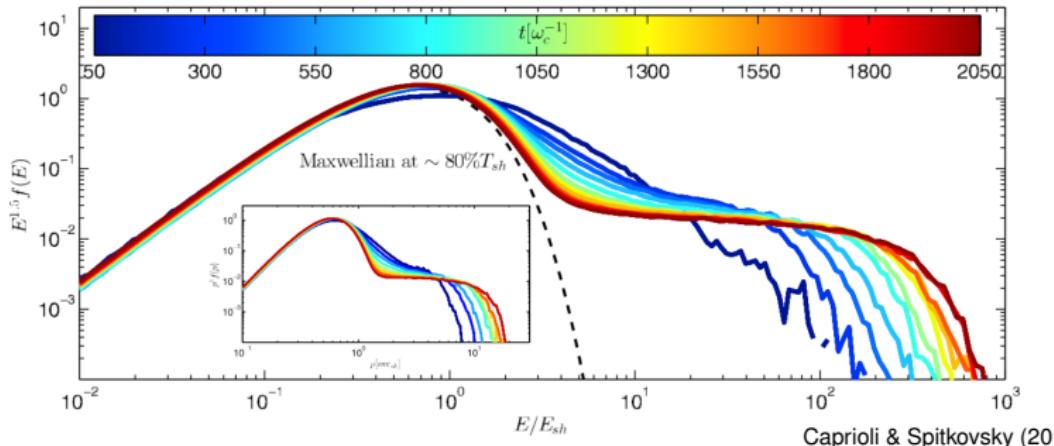
Annual meeting of the German Astronomical Society, Berlin, 2023



SNR Cassiopeia A (NASA/Chandra X-ray)

Ion spectrum

Non-relativistic parallel shock in long-term hybrid simulation

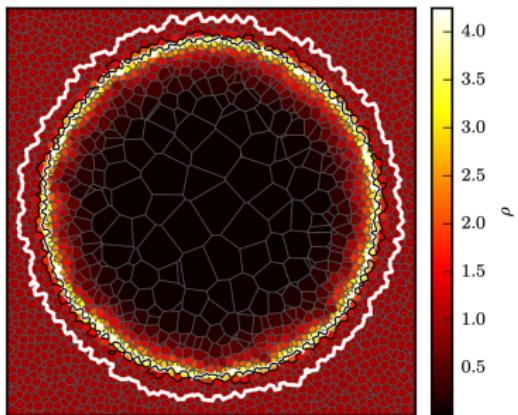


Caprioli & Spitkovsky (2014)

- quasi-parallel shocks accelerate ions
- particles gain energy in each crossing and have probability of leaving the Fermi cycle by being swept downstream → power-law spectrum
- maximum energy increases with time



Global MHD simulations of SNRs with CR physics



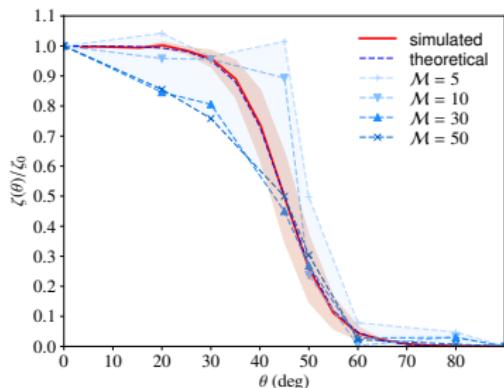
- detect and characterize shocks and jump conditions on the fly

Mach number finder

CP+ (2017) based on Schaal & Springel (2015)



Global MHD simulations of SNRs with CR physics



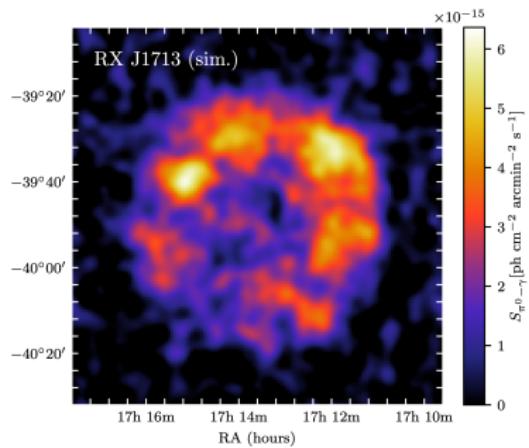
- detect and characterize shocks and jump conditions on the fly
- measure Mach number M and magnetic obliquity θ_B

obliquity-dep. acceleration efficiency

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



Global MHD simulations of SNRs with CR physics

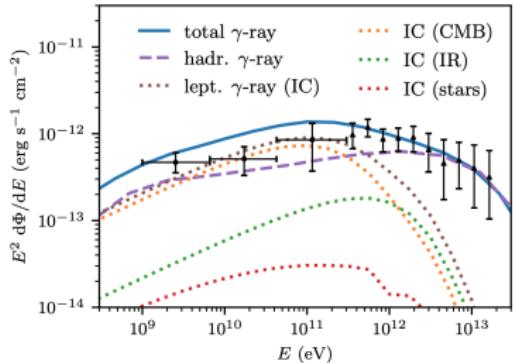


simulated TeV gamma-ray map

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
⇒ dynamical back reaction on gas flow, hadronic emission

Global MHD simulations of SNRs with CR physics

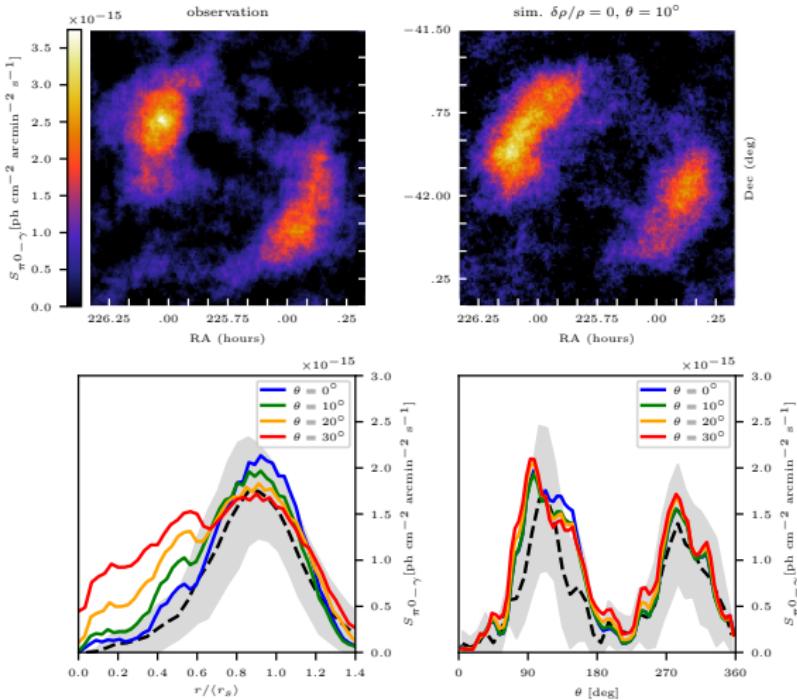


simulated gamma-ray spectrum

Winner, CP+ (2020)

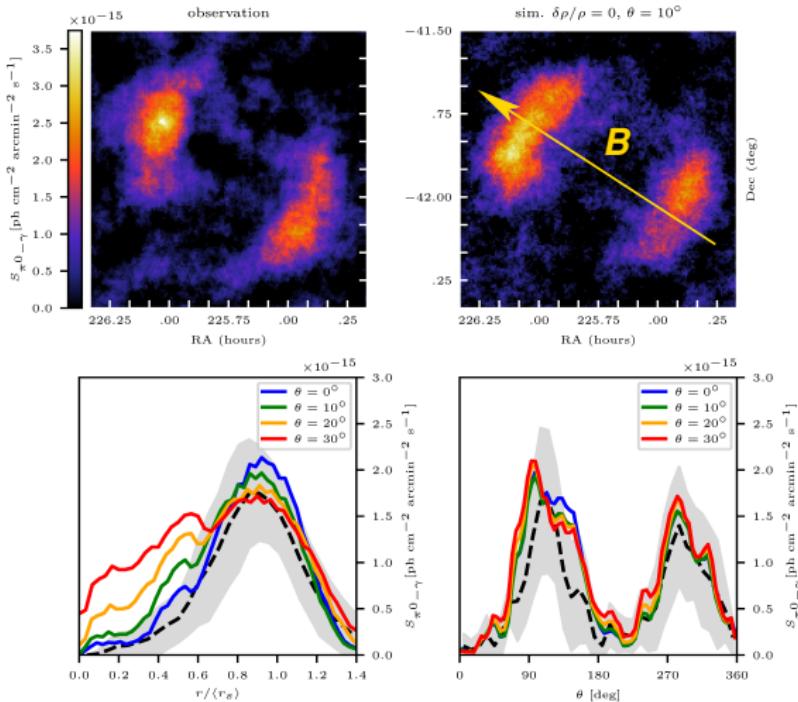
- detect and characterize shocks and jump conditions on the fly
- measure Mach number \mathcal{M} and magnetic obliquity θ_B
- inject and transport CR protons
⇒ dynamical back reaction on gas flow, hadronic emission
- inject and transport CR electrons
- calculate non-thermal radio, X-ray, γ -ray emission

Hadronic TeV γ rays: SN 1006



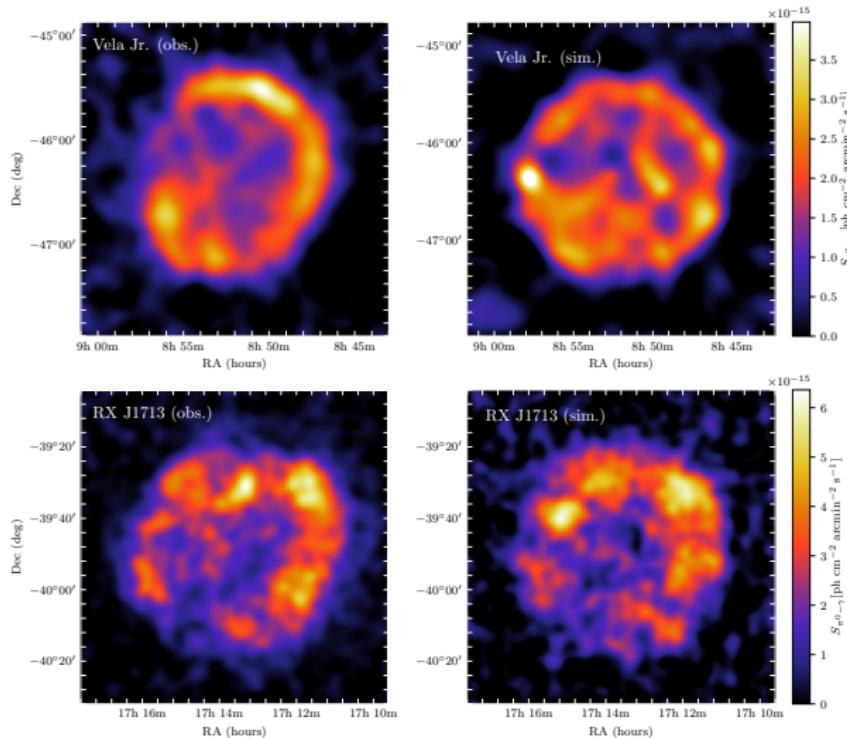
Pais & CP (2020)

Hadronic TeV γ rays: SN 1006



Pais & CP (2020)

Hadronic TeV γ rays: Vela Jr. and RXJ 1713



Pais & CP (2020)

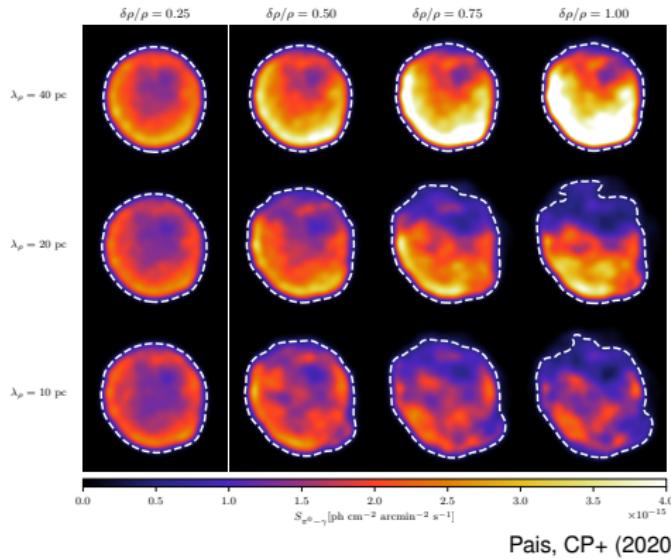
Christoph Pfleiderer

Cosmic ray acceleration at supernova remnants



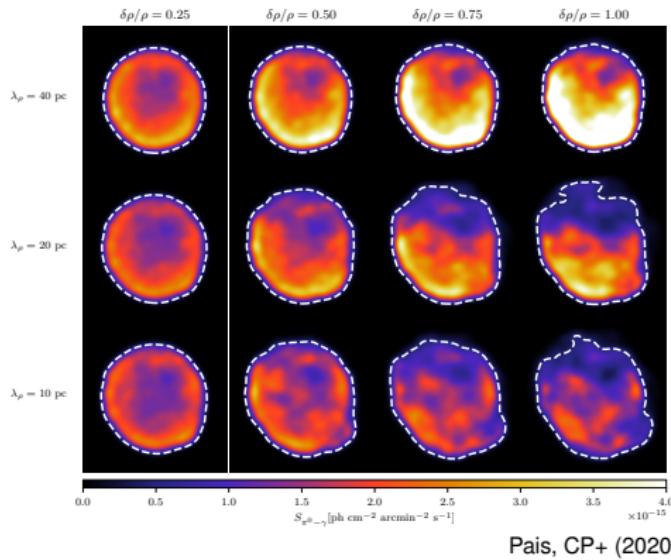
Straw-man's model: isotropic acceleration and $\delta\rho$

Density inhomogeneities $\delta\rho$ cause patchy TeV maps but a corrugated shock surface



Straw-man's model: isotropic acceleration and $\delta\rho$

Density inhomogeneities $\delta\rho$ cause patchy TeV maps but a corrugated shock surface

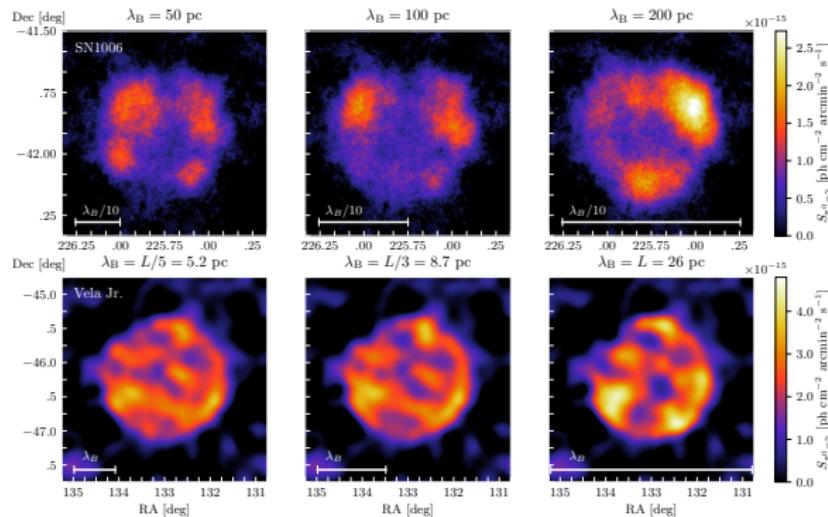


Pais, CP+ (2020)

- ⇒ **anisotropy of corrugated shock surfaces** limits (large-scale) density fluctuations $\delta\rho/\rho \lesssim 0.75$
- ⇒ **only obliquity-dep. acceleration explains patchy TeV γ -ray emission**

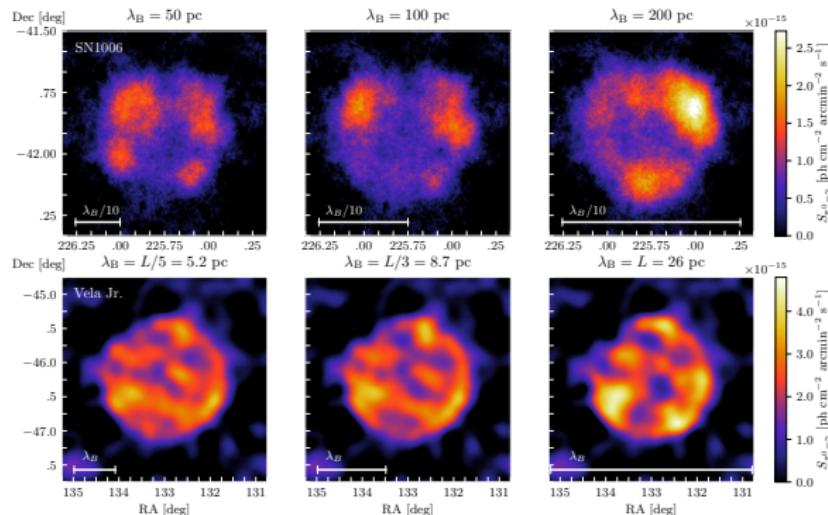
TeV γ rays from shell-type supernova remnants

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



TeV γ rays from shell-type supernova remnants

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



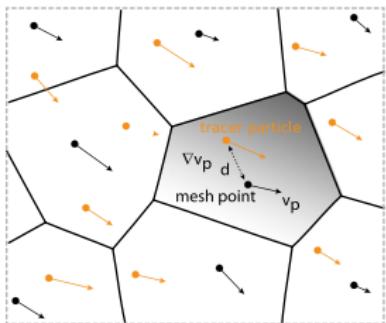
Pais, CP+ (2020)

⇒ Correlation structure of patchy TeV γ -rays constrains magnetic coherence scale in ISM:

SN 1006: $\lambda_B > 200^{+80}_{-10}$ pc

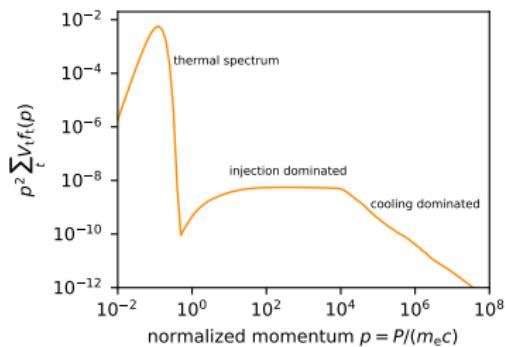
Vela Junior: $\lambda_B = 13^{+13}_{-4.3}$ pc

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

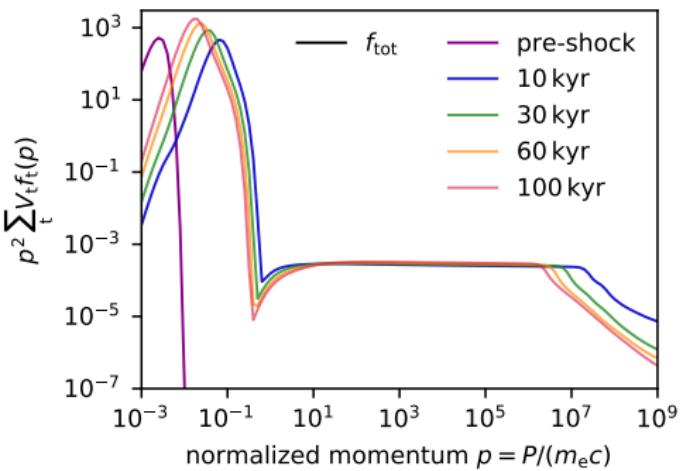
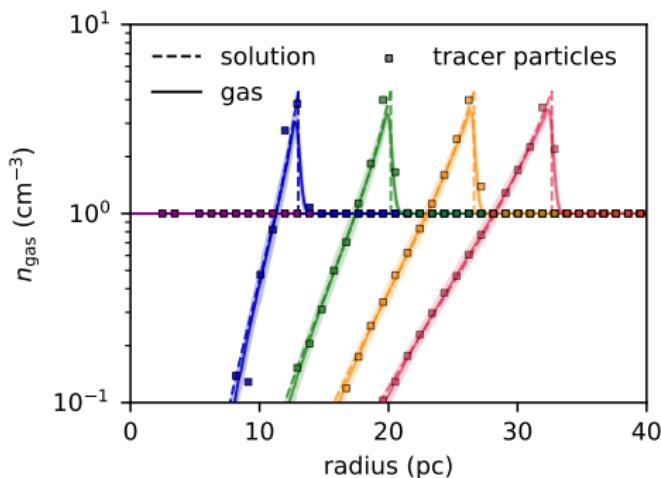


Link to observations

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



Sedov–Taylor blast wave: spectral evolution

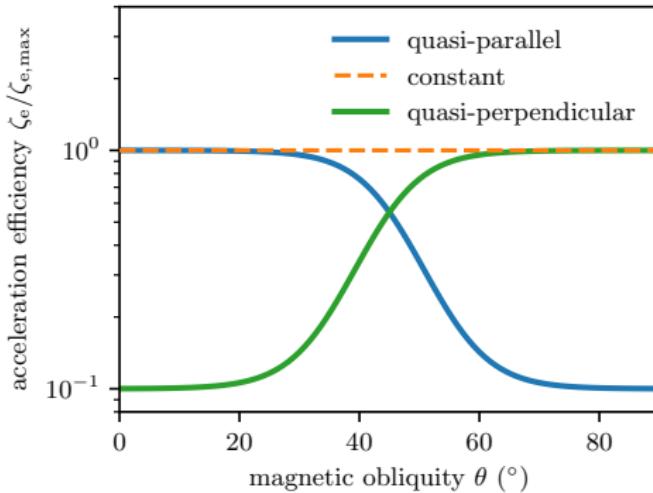


$$E_0 = 10^{51} \text{ erg}, \quad n_{\text{gas}} = 1 \text{ cm}^{-3}, \quad T_0 = 10^4 \text{ K}, \quad B = 1 \mu\text{G}$$

Winner, CP+ (2019)



SN 1006: CR electron acceleration models

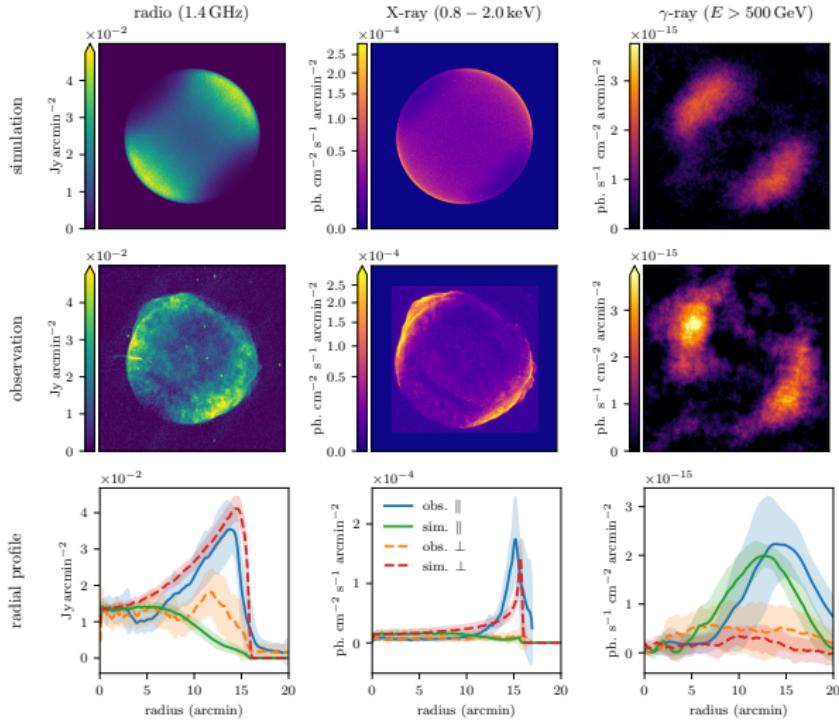


Winner, CP+ (2020)

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

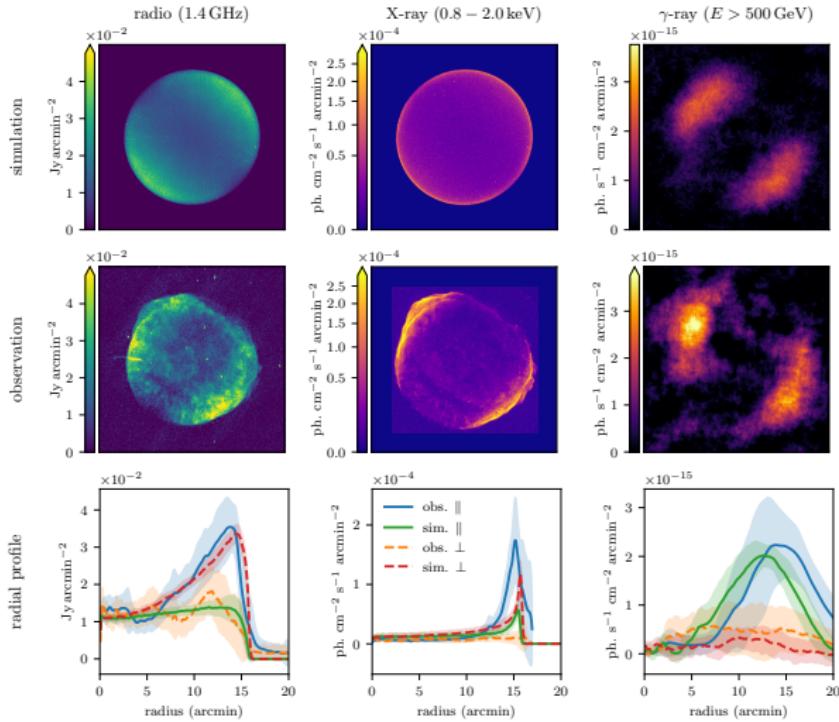


CR electron acceleration: quasi-perpendicular shocks



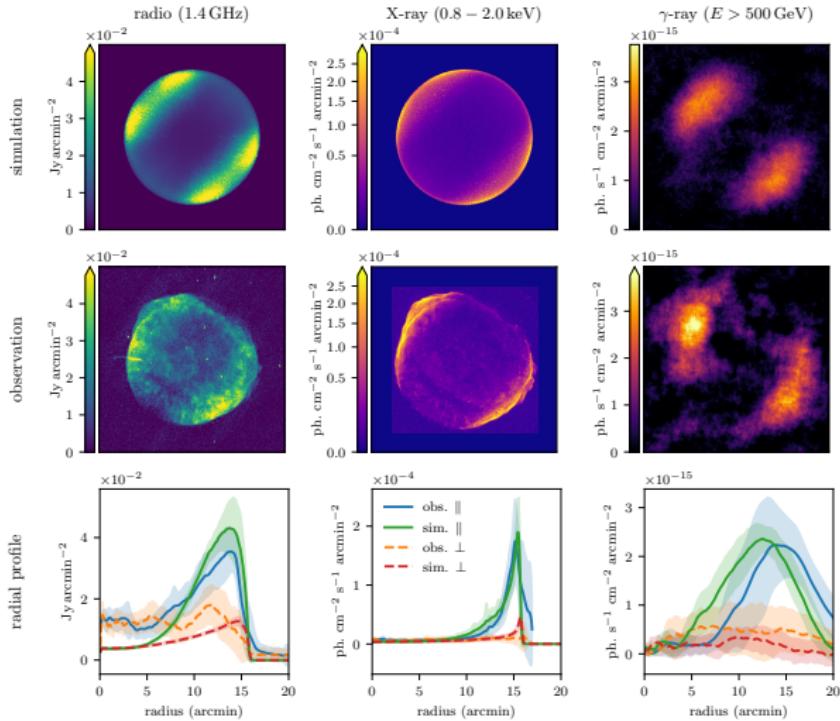
Winner, CP+ (2020)

CR electron acceleration: constant efficiency



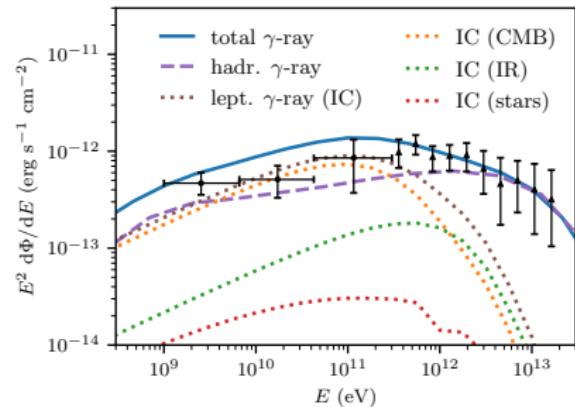
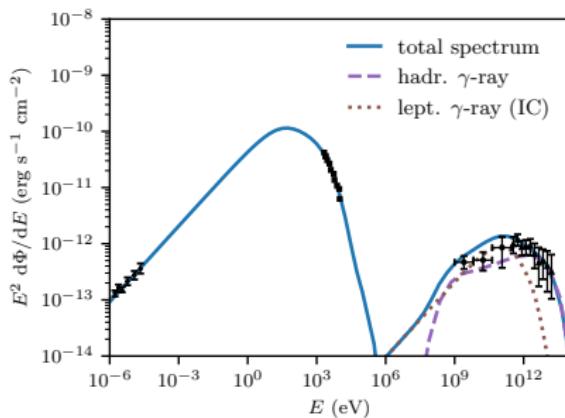
Winner, CP+ (2020)

CR electron acceleration: quasi-parallel shocks



Winner, CP+ (2020)

SN 1006: multi-frequency spectrum

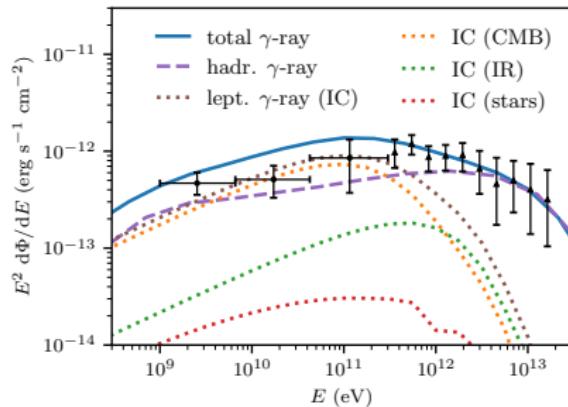
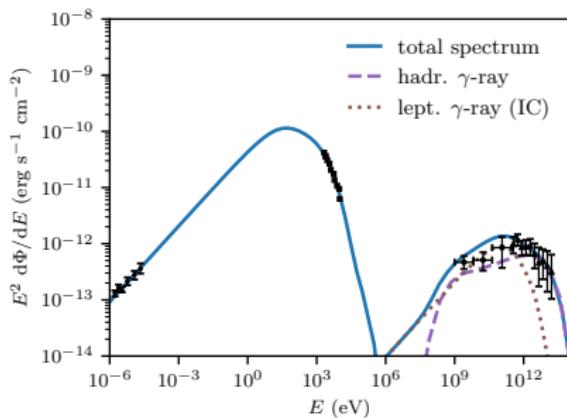


Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum



SN 1006: multi-frequency spectrum



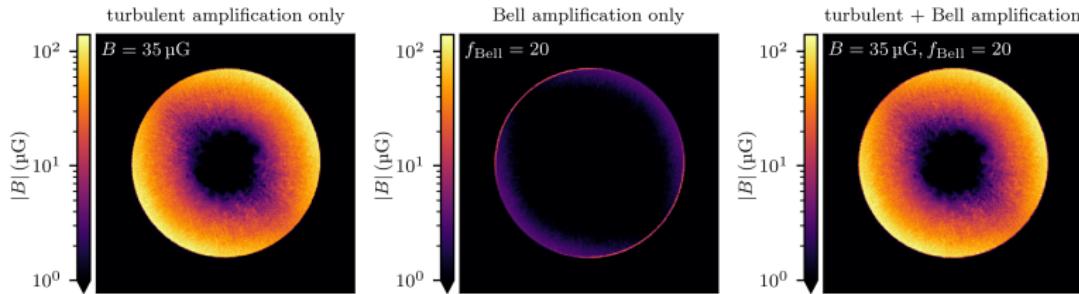
Winner, CP+ (2020)

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



SN 1006: magnetic field amplification models

Magnetic amplification due to a turbulent dynamo and Bell's instability



Winner, CP+ (2020)

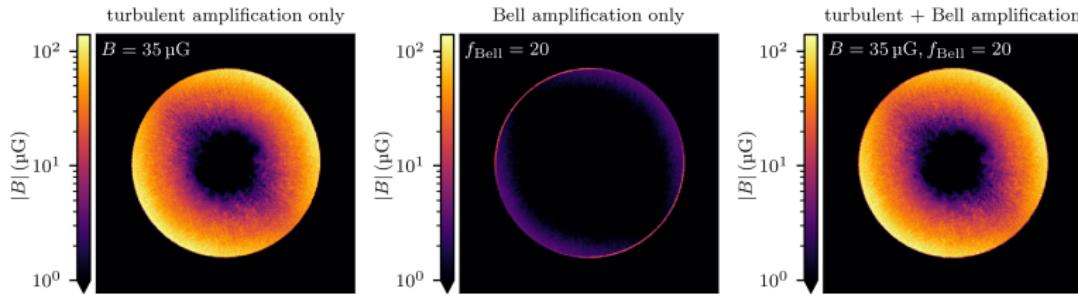
- magnetic field strength in a slice through the simulated SNRs



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SN 1006: magnetic field amplification models

Magnetic amplification due to a turbulent dynamo and Bell's instability

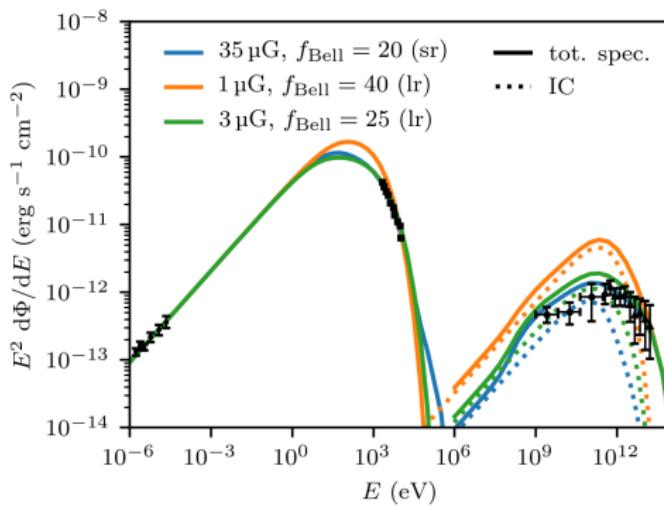


Winner, CP+ (2020)

- magnetic field strength in a slice through the simulated SNRs
- **left: effect of turbulent amplification only**, maximum realized at quasi-perpendicular shock, adiabatic cooling inside the SNR
- **middle: effect of Bell amplification only**, f_{Bell} follows obliquity dependence of CR proton efficiency
- **right: sum of both, turbulent and Bell amplification**



Constraining the volume-filling, turbulent \mathbf{B} field

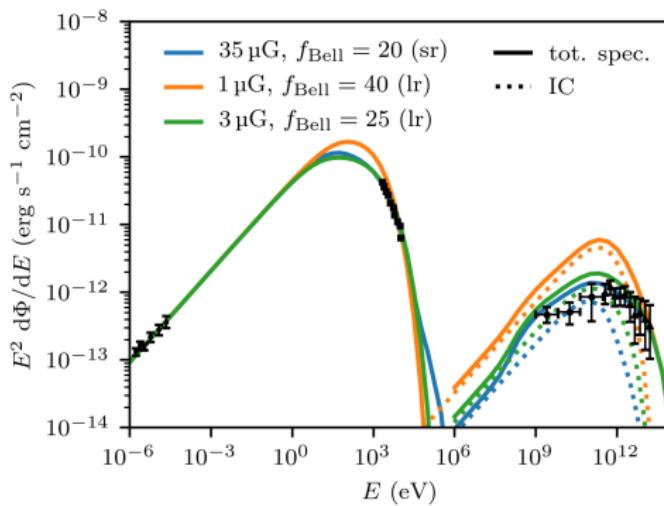


Winner, CP+ (2020)

- multi-frequency spectra: synchrotron (radio + X-rays) and IC and hadronic γ -ray emission



Constraining the volume-filling, turbulent \mathbf{B} field

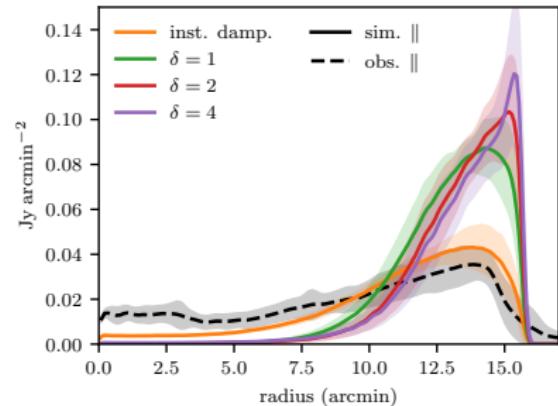
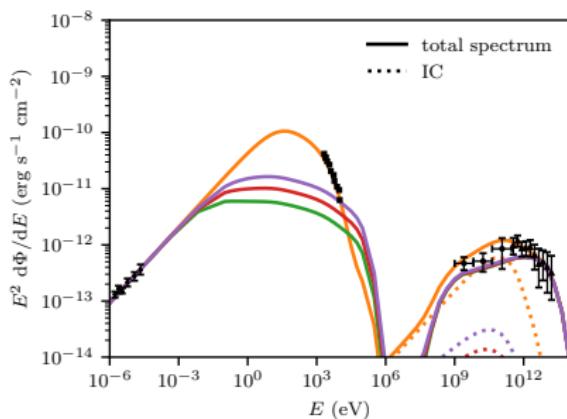


Winner, CP+ (2020)

- multi-frequency spectra: synchrotron (radio + X-rays) and IC and hadronic γ -ray emission
- strong, volume-filling \mathbf{B} field ($\approx 35 \mu\text{G}$) required to suppress IC γ -ray component and to match steep X-ray spectrum



Constraining the damping of Bell-amplified \mathbf{B} field

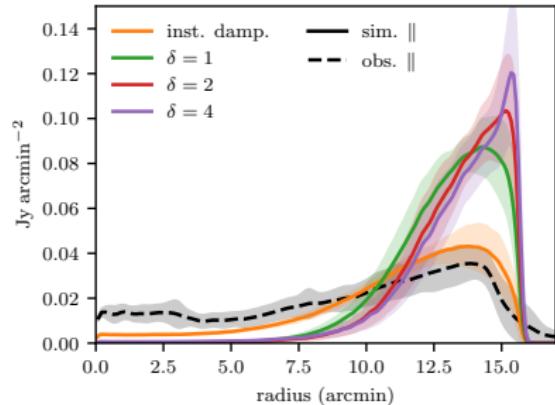
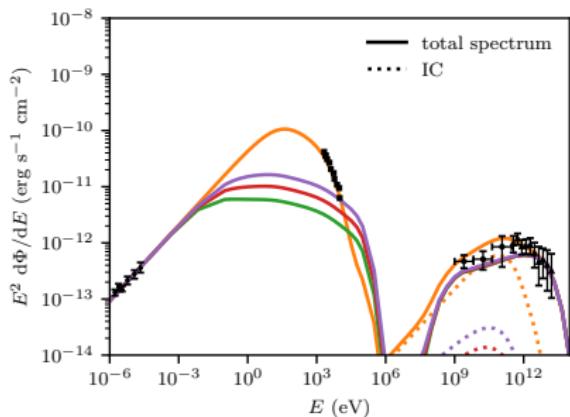


Winner, CP+ (2020)

- multi-frequency spectra (left) and radial radio profiles (right) for different decay models of the Bell-amplified \mathbf{B} field: $B \propto n^\delta B_{\text{amp}}$



Constraining the damping of Bell-amplified \mathbf{B} field

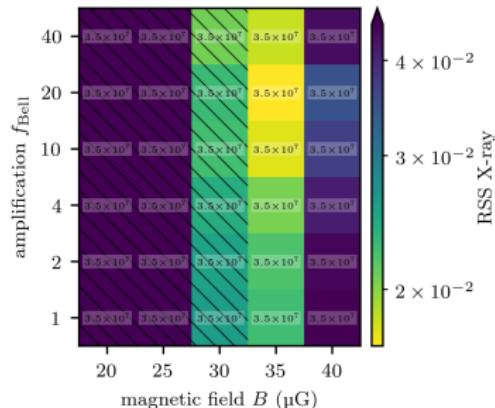
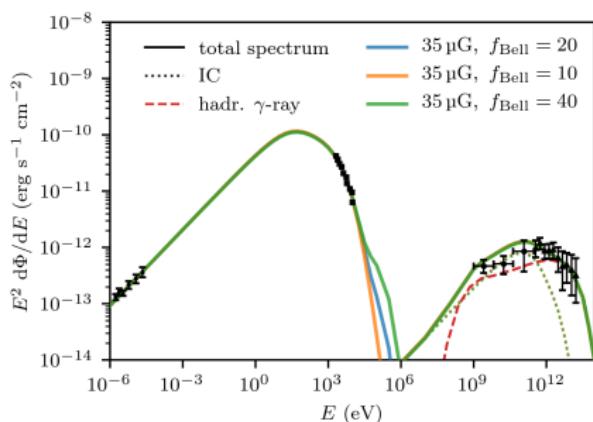


Winner, CP+ (2020)

- multi-frequency spectra (left) and radial radio profiles (right) for different decay models of the Bell-amplified \mathbf{B} field: $B \propto n^\delta B_{\text{amp}}$
- smooth radio profile and steep X-ray spectrum requires slow CRe cooling and fast damping of Bell modes (~ 100 gyroradii for TeV particles)



SN 1006: best-fit multi-frequency spectrum



Winner, CP+ (2020)

- parameter optimization of magnetic amplification processes
- strong ($\approx 35 \mu\text{G}$) volume-filling B field (turbulent dynamo): lower B field excluded by IC component
- Bell-amplification factor f_{Bell} 10 – 20 weakly constrained



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Conclusions

CR proton acceleration:

- TeV shell-type SNRs probe magnetic coherence scale in ISM
- global SNR simulations agree with hybrid-PIC simulations of p^+ acceleration



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Conclusions

CR proton acceleration:

- TeV shell-type SNRs probe magnetic coherence scale in ISM
- global SNR simulations agree with hybrid-PIC simulations of p^+ acceleration

CR electron acceleration (SN 1006):

- global SNR sim's imply preferred quasi-parallel e^- acceleration, see Shalaby+ for PIC sim's of e^- acceleration
- GeV: leptonic IC emission, TeV: hadronic pion decay
- strong, volume-filling B field required to suppress IC gamma rays
- fast damping of Bell modes required by radio/X-rays



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation



European Research Council
Established by the European Commission



This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICOGAL-101019746).

Literature for the talk

Cosmic ray hydrodynamics and shock acceleration:

- Pfrommer, Pakmor, Schaal, Simpson, Springel, *Simulating cosmic ray physics on a moving mesh* 2017, MNRAS, 465, 4500.

Cosmic ray electron acceleration:

- 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.

Cosmic ray proton acceleration:

- Pais, Pfrommer, Ehrt, Pakmor, *The effect of cosmic-ray acceleration on supernova blast wave dynamics*, 2018, MNRAS, 478, 5278.
- Pais, Pfrommer, Ehrt, 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.

