Cosmic ray acceleration at supernova remnants

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in collaboration with

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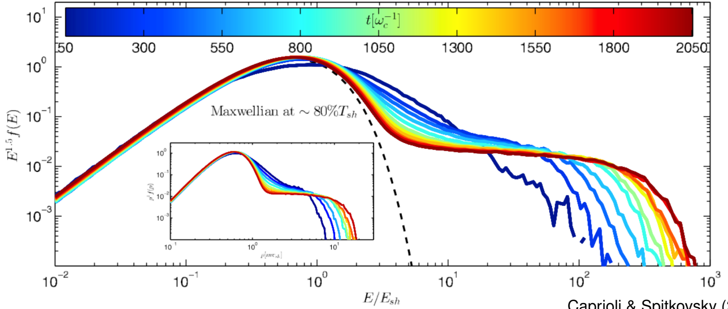
Ion spectrum

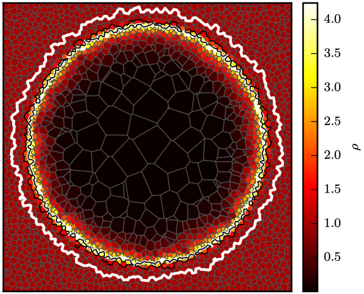
Non-relativistic parallel shock in long-term hybrid simulation



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 $\rightarrow$ power-law spectrum
- maximum energy increases with time

Global MHD simulations of SNRs with CR physics

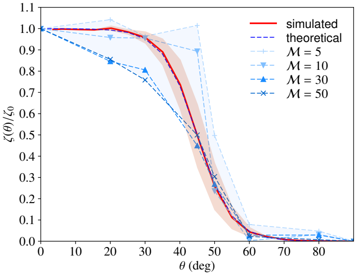


Mach number finder

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

- detect and characterize shocks and jump conditions on the fly

Global MHD simulations of SNRs with CR physics

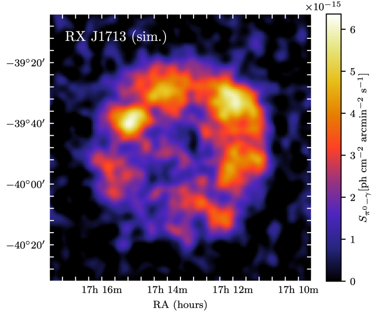


obliquity-dep. acceleration efficiency

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



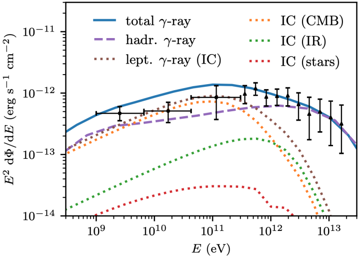
simulated TeV gamma-ray map

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

AIP

Global MHD simulations of SNRs with CR physics

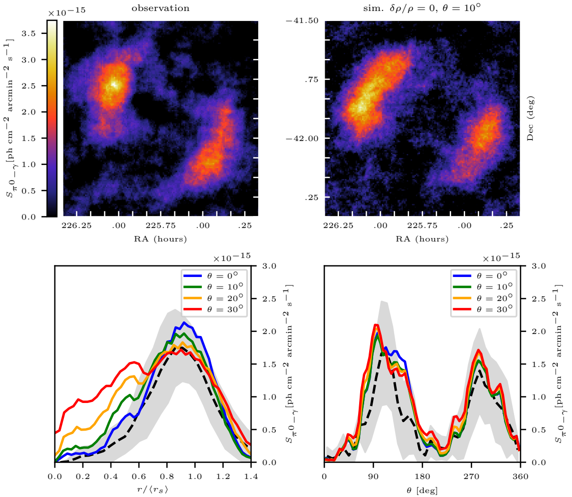


simulated gamma-ray spectrum

Winner, CP+ (2020)

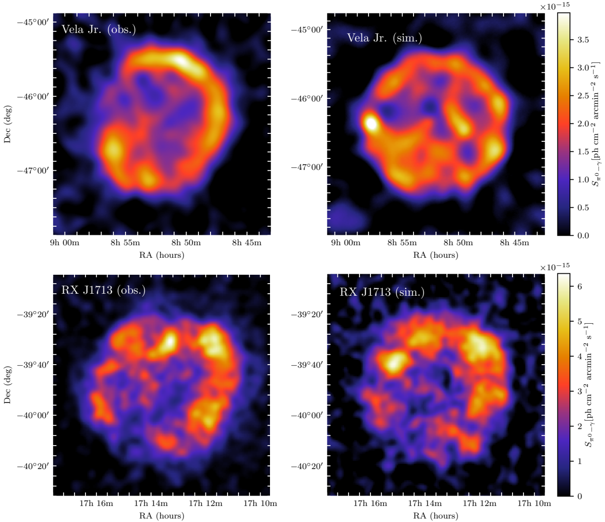
- detect and characterize shocks and jump conditions on the fly
- measure Mach number $\mathcal{M}$ and magnetic obliquity θ_B
- inject and transport CR protons $\Rightarrow$ dynamical back reaction on gas flow, hadronic emission
- inject and transport CR electrons
- calculate non-thermal radio, X-ray,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

Hadronic TeV γ rays: SN 1006



Pais & CP (2020)

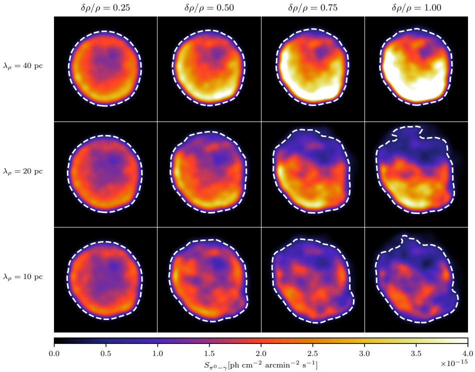
Hadronic TeV γ rays: Vela Jr. and RXJ 1713



Pais & CP (2020)

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)

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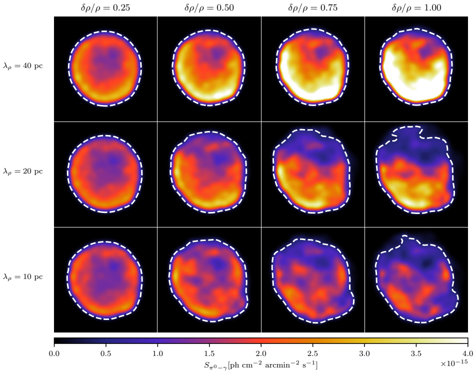


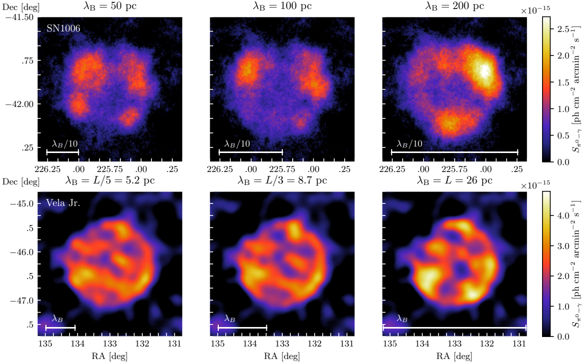
Pais, CP+ (2020)

$\Rightarrow$ anisotropy of corrugated shock surfaces limits (large-scale) density fluctuations $\delta\rho/\rho \lesssim 0.75$

$\Rightarrow$ 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

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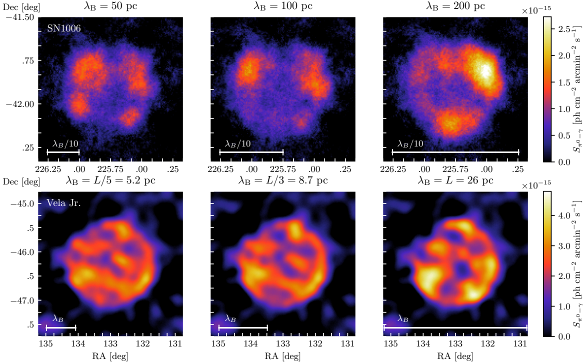
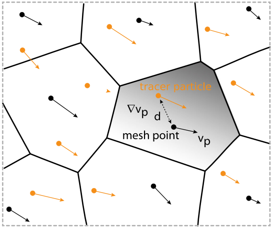


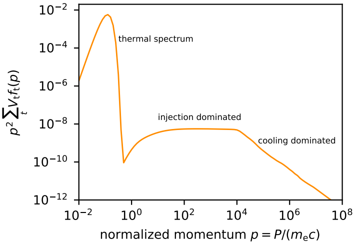
Pais, CP+ (2020)

$\Rightarrow$ 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





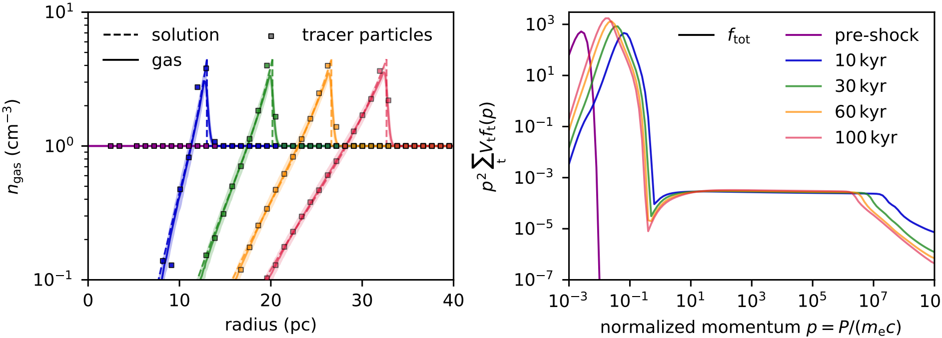
CREST code (Winner, CP+ 2019)

- 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

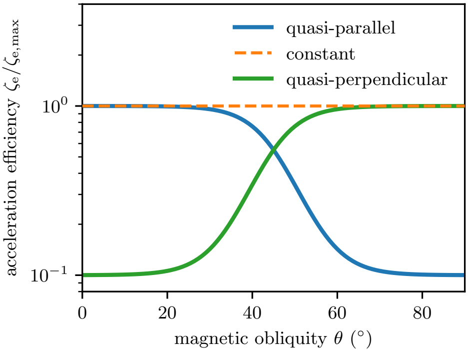
Sedov–Taylor blast wave: spectral evolution



Winner, CP+ (2019)

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

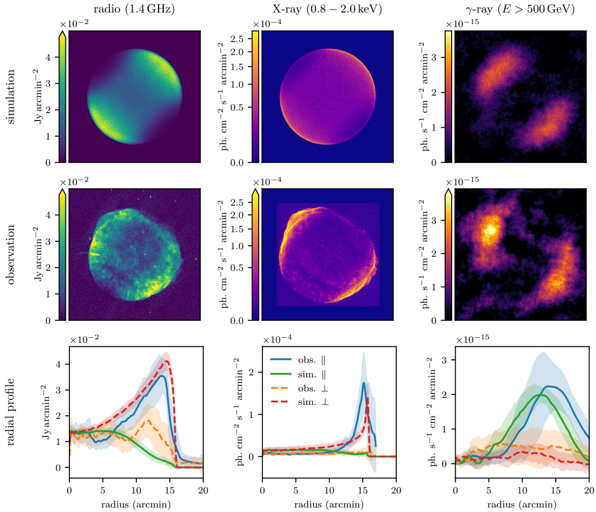
SN 1006: CR electron acceleration models



Winner, CP+ (2020)

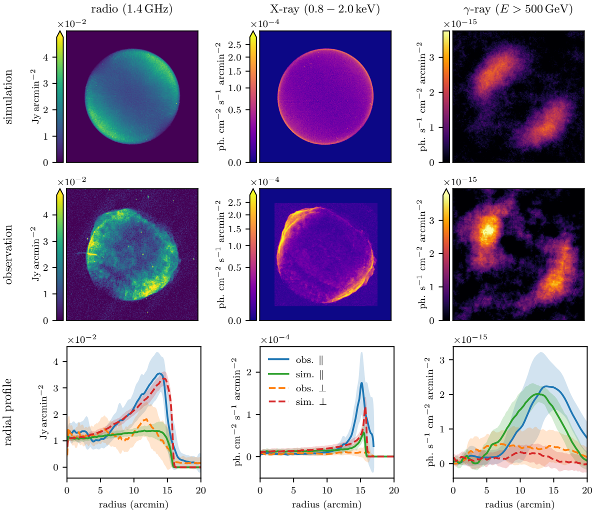
- different obliquity dependent electron acceleration efficiencies:
  1. preferred quasi-perpendicular acceleration (PIC simulations)
  2. constant acceleration efficiency (a straw man's model)
  3. preferred quasi-parallel acceleration (like CR protons)

CR electron acceleration: quasi-perpendicular shocks



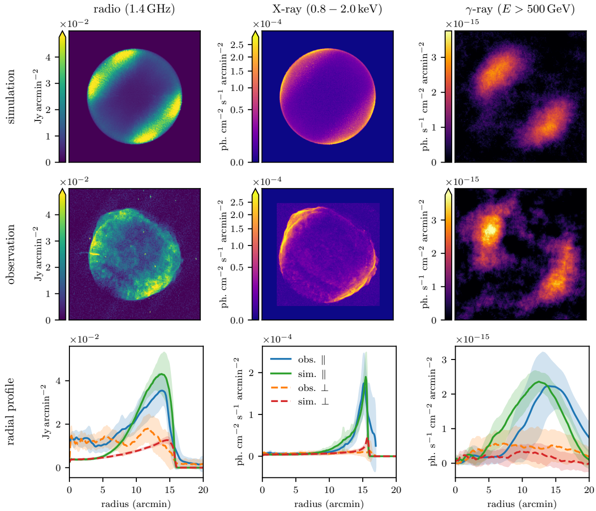
Winner, CP+ (2020)

CR electron acceleration: constant efficiency



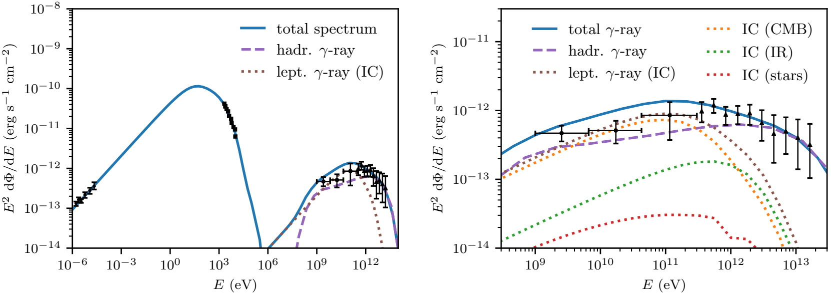
Winner, CP+ (2020)

CR electron acceleration: quasi-parallel shocks



Winner, CP+ (2020)

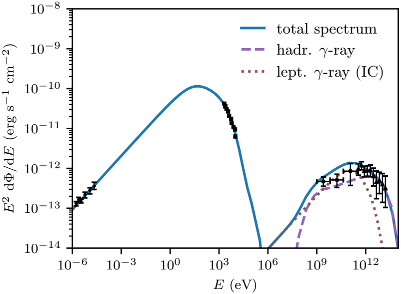
SN 1006: multi-frequency spectrum

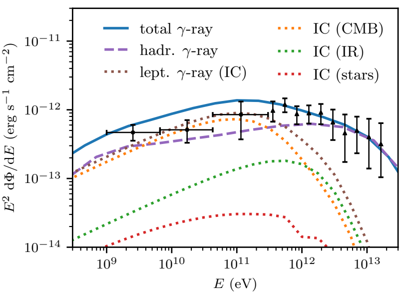


Winner, CP+ (2020)

- quasi-parallel acceleration model fits multi-frequency spectrum

SN 1006: multi-frequency spectrum



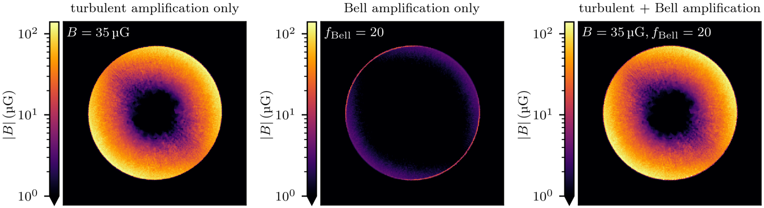


Winner, CP+ (2020)

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

SN 1006: magnetic field amplification models

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

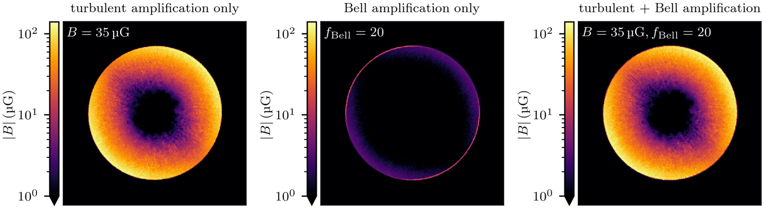


Winner, CP+ (2020)

- magnetic field strength in a slice through the simulated SNRs

SN 1006: magnetic field amplification models

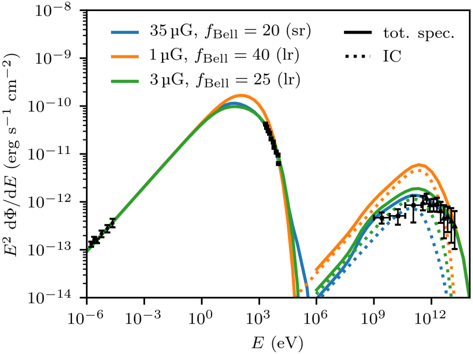
Magnetic amplification due to a turbulent dynamo and Bell's instability



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 *B* field



Winner, CP+ (2020)

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

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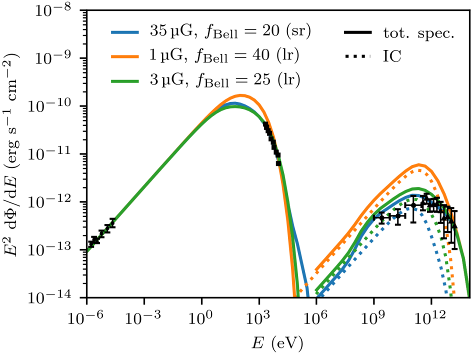
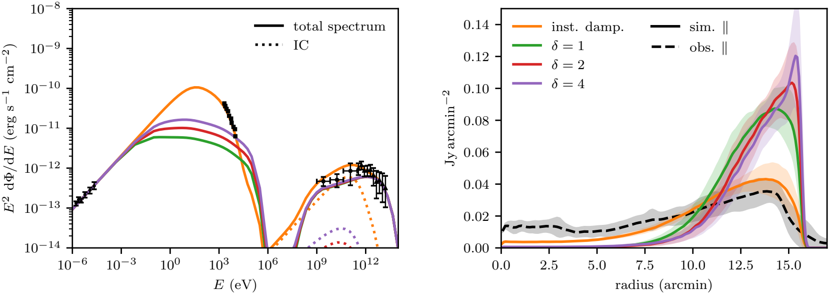


Winner, CP+ (2020)

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

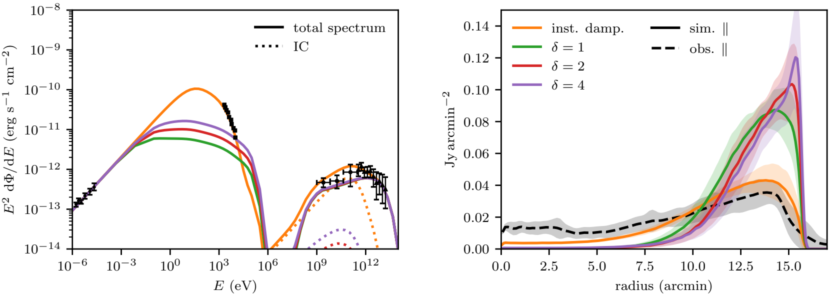
Constraining the damping of Bell-amplified *B* field



Winner, CP+ (2020)

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

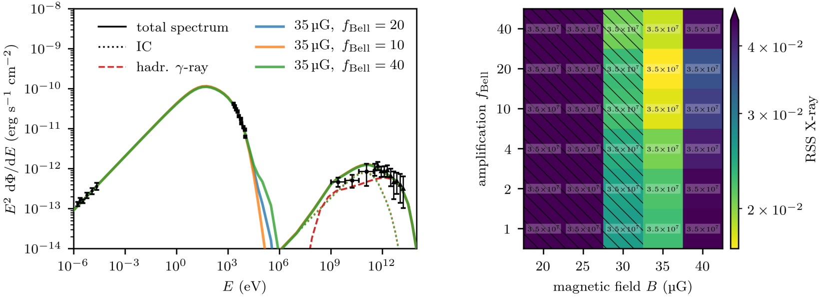
Constraining the damping of Bell-amplified *B* field



Winner, CP+ (2020)

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

SN 1006: best-fit multi-frequency spectrum



Winner, CP+ (2020)

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

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

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, more work needed 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

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

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Literature for the talk

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Cosmic ray electron acceleration:

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- 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, 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.