TeVPA Conference | Tendo, Japan | Sep. 1, 2026

SN 1006: A Cosmic Laboratory for Investigating Shock Acceleration Physics

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Credit: https://chandra.si.edu/photo/2008/sn1006c

Standard SNR paradigm

- SNRs are the source of Galactic CRs

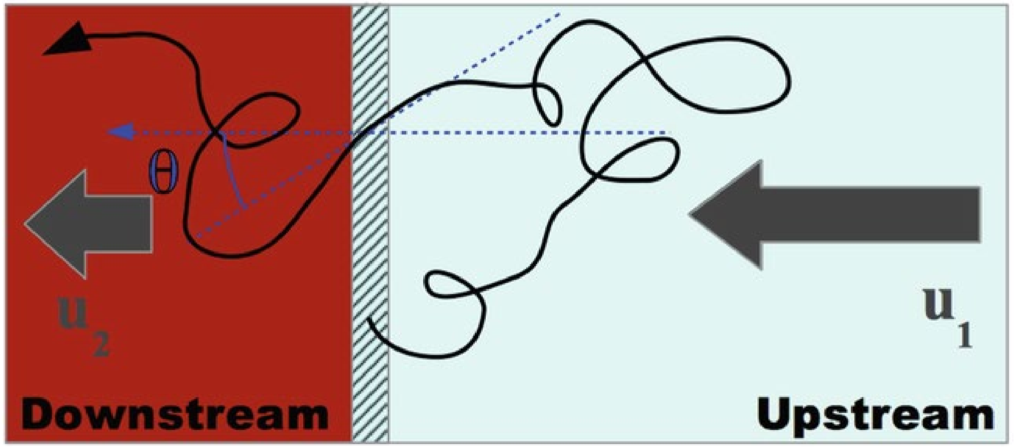
  (e.g., Hillas 2005; Berezhko & Voïlk 2007; Ptuskin et al. 2010; Caprioli et al. 2010)

- SNRs accelerate particles via diffusive shock acceleration (DSA), producing power-law energy distributions:

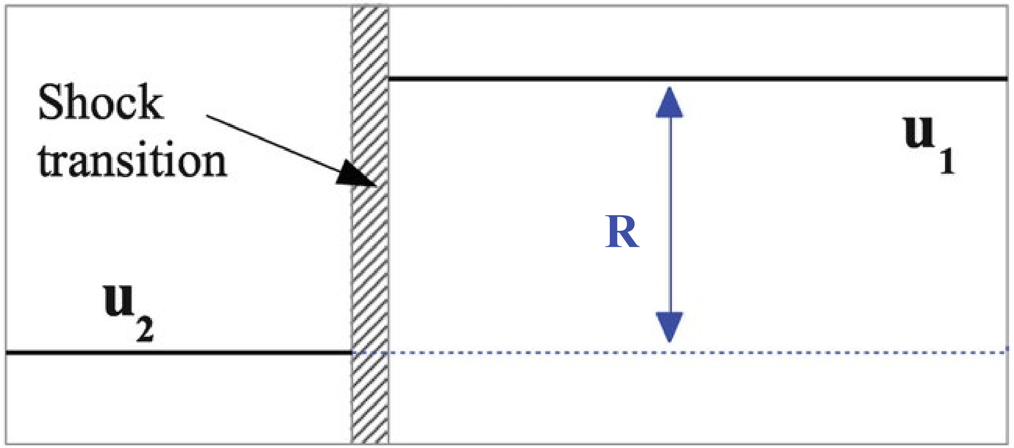
$$\frac{dN}{dE} \propto E^{-q} \qquad q = \frac{R+2}{R-1} \qquad R = \frac{u_1}{u_2}$$

$$R = 4,\ q = 2 \text{ for strong shocks}$$

(Krymskii 1977; Bell 1978; Blandford & Ostriker 1978)



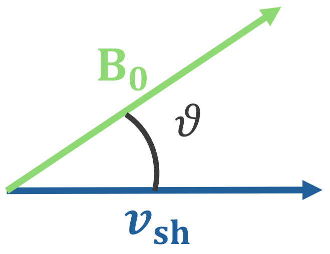
Velocity Profile

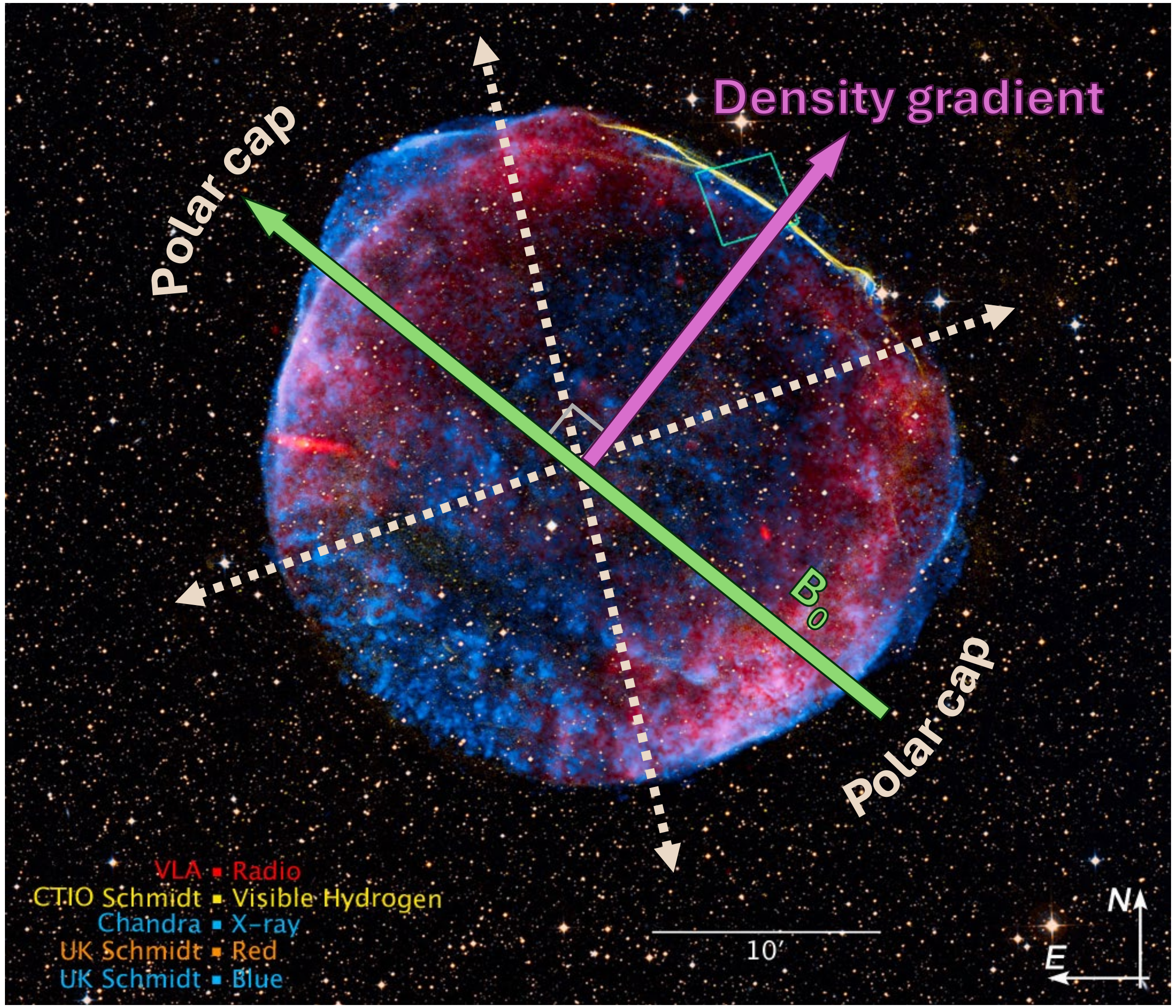


Credit: Morlino, G. (2017). High-Energy Cosmic Rays from Supernovae. In: Alsabti, A., Murdin, P. (eds) Handbook of Supernovae. Springer, Cham. https://doi.org/10.1007/978-3-319-21846-5_11

SN 1006

- X-ray and TeV emission confined within polar caps aligned with B_0
  (e.g., Koyama et al.1995; Allen et al. 2001; Acero et al. 2010; Reynoso et al. 2013; Cotton et al. 2024)
- Suggests relationship between efficient CR acceleration and shock obliquity
- Thin X-ray rims imply amplified magnetic fields
- Origin of γ-ray emission is ambiguous

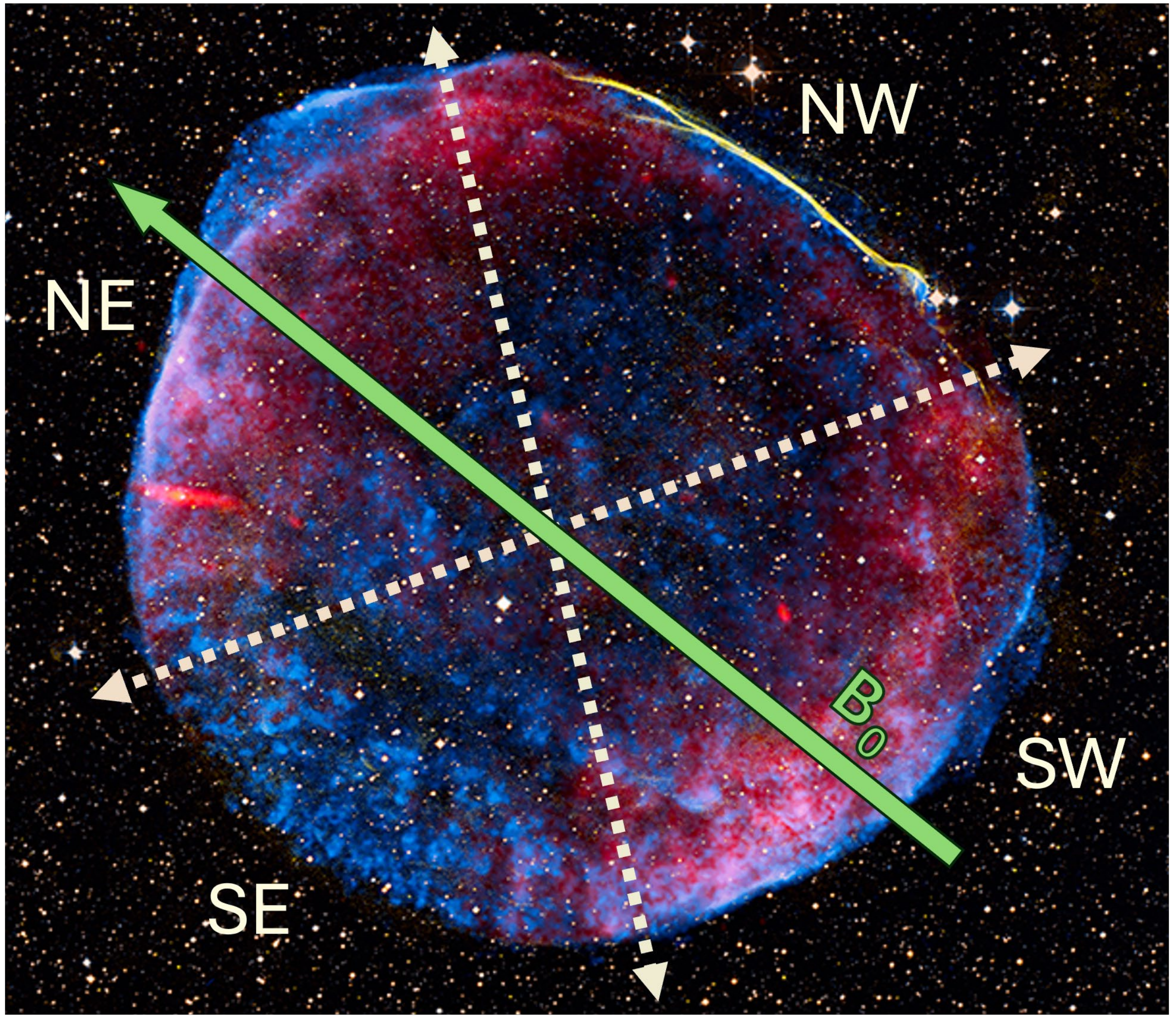




Credit: X-ray: NASA/CXC/Rutgers/G.Cassam-Chenai, J.Hughes et al.; Radio: NRAO/AUI/NSF/GBT/VLA/Dyer, Maddalena & Cornwell; Optical: Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS.

Perform Spatially Resolved Analysis

- Use multi-wavelength spectral and spatial information concurrently to determine if:
  1. quasi-parallel shocks are more efficient than oblique ones
  2. ambient density impacts γ-ray origin



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Model Particle Acceleration

- Use a semi-analytic multi-zone kinetic model of non-linear DSA

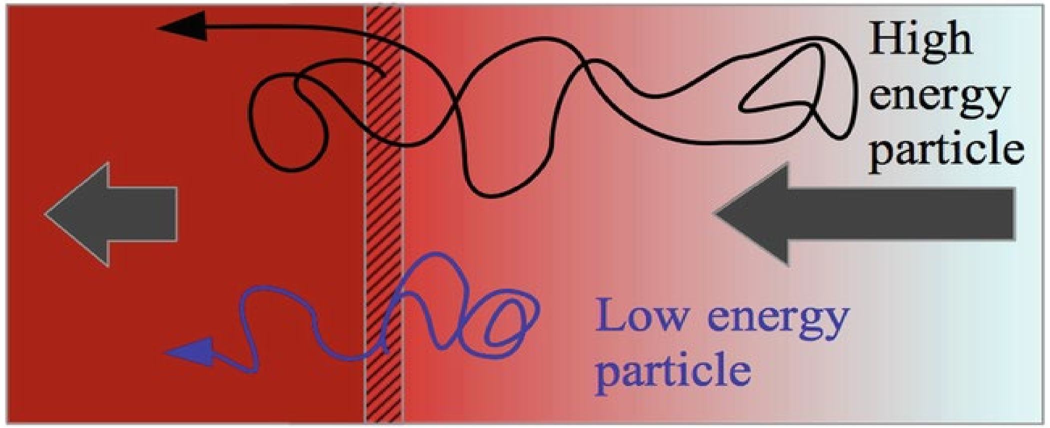
  (Caprioli 2012; Diesing & Caprioli 2019, 2021)

- Self-consistently captures shock modifications due to CRs and turbulent fields

- CR pressure modifies shock by creating a sub-shock region with $\mathrm{R_{sub}} < 4$, allowing $\mathrm{R_{tot}} > 4$, and flattening spectra $\mathrm{q} < 2$

  (e.g., Kang & Jones 2006; Amato & Blasi 2006; Caprioli et al. 2009)

- Includes modifications from escaping CRs and magnetic field amplification (MFA)



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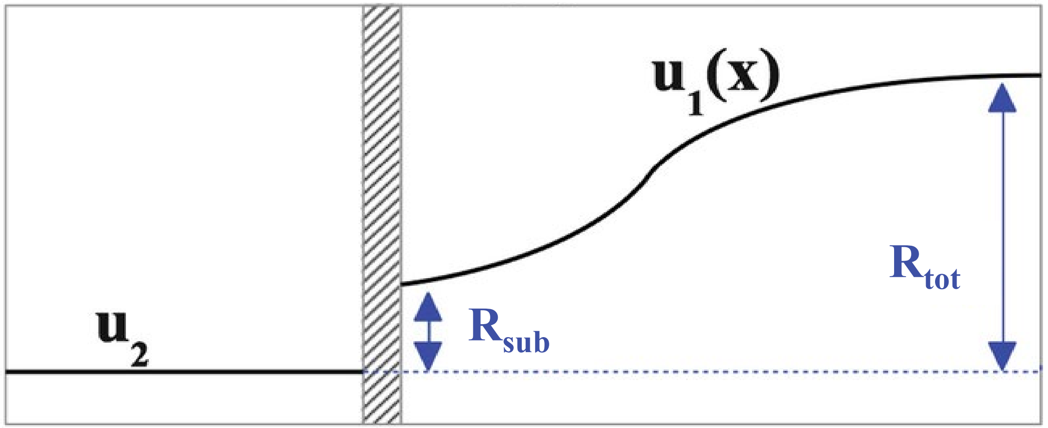

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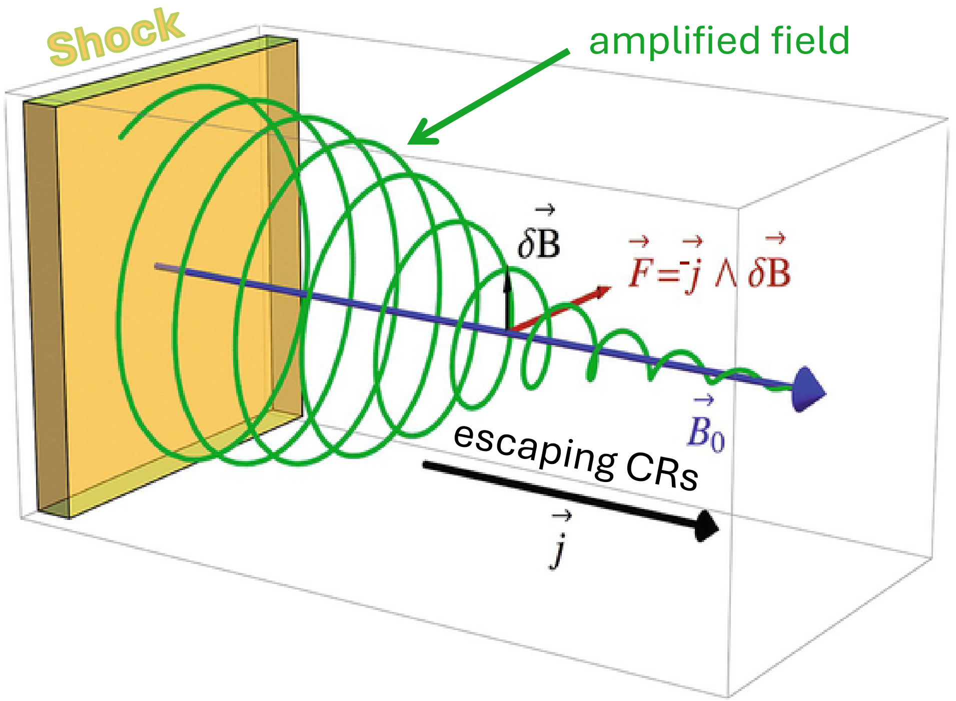
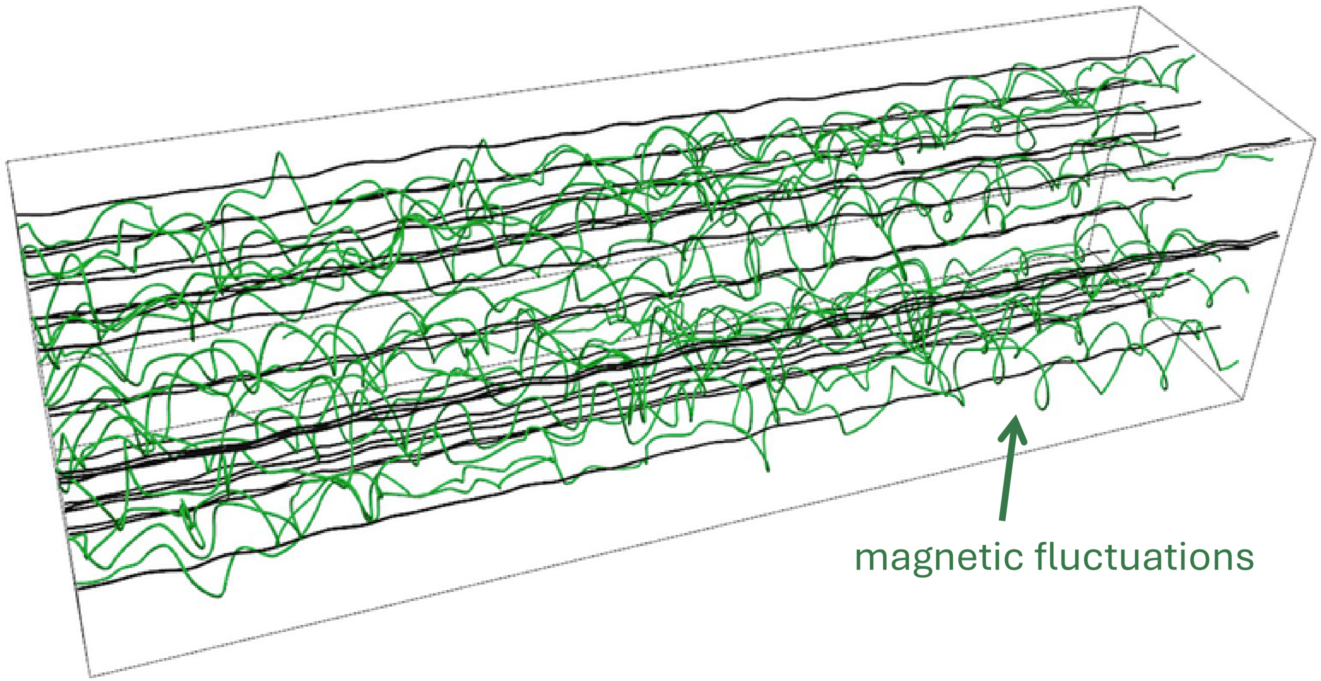
Magnetic Field Amplification

- CRs drive plasma instabilities that amplify magnetic fields and drive turbulence
  (e.g., Skilling 1975; Bell 1978; Bell 2004; Zacharegkas et al. 2024)

- MFA dominated by non-resonant streaming instabilities driven by escaping CRs upstream
  (e.g., Bell et al. 2013; Blasi et al. 2015; Cristofari et al. 2020)





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Drifting Magnetic Fluctuations

- CRs scatter off magnetic fluctuations advected downstream

- Fluctuations retain their upstream inertia, drifting at about local v_A

  (Haggerty & Caprioli 2020; Caprioli et al. 2020)

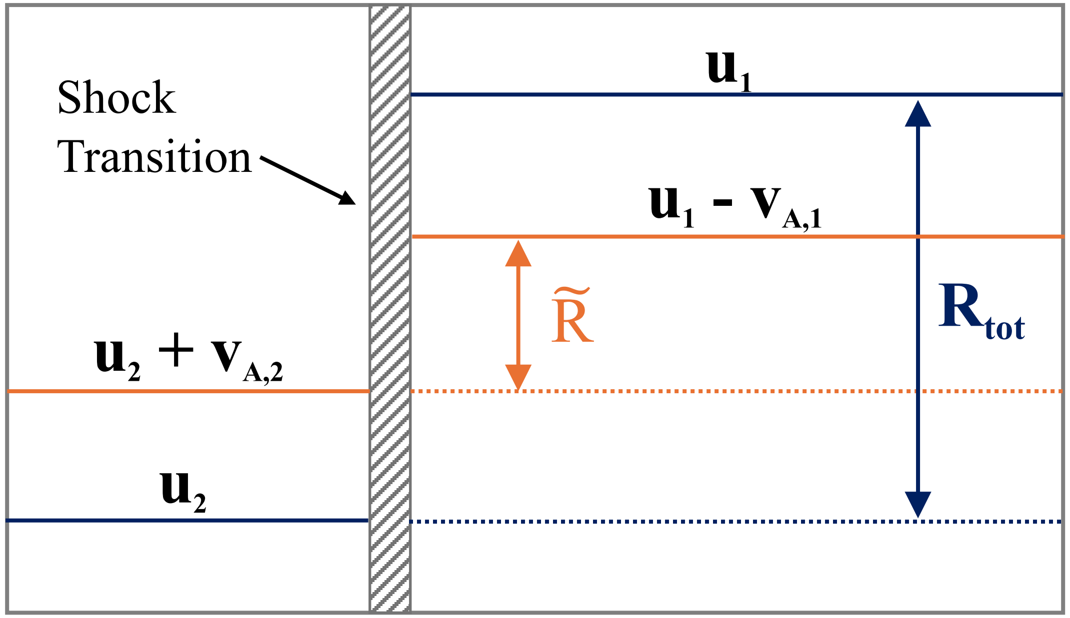
- Creates effective compression ratio smaller than R_{tot}:

$$\tilde{R} = \frac{u_1 - v_{A,1}}{u_2 + v_{A,2}} < \frac{u_1}{u_2}$$

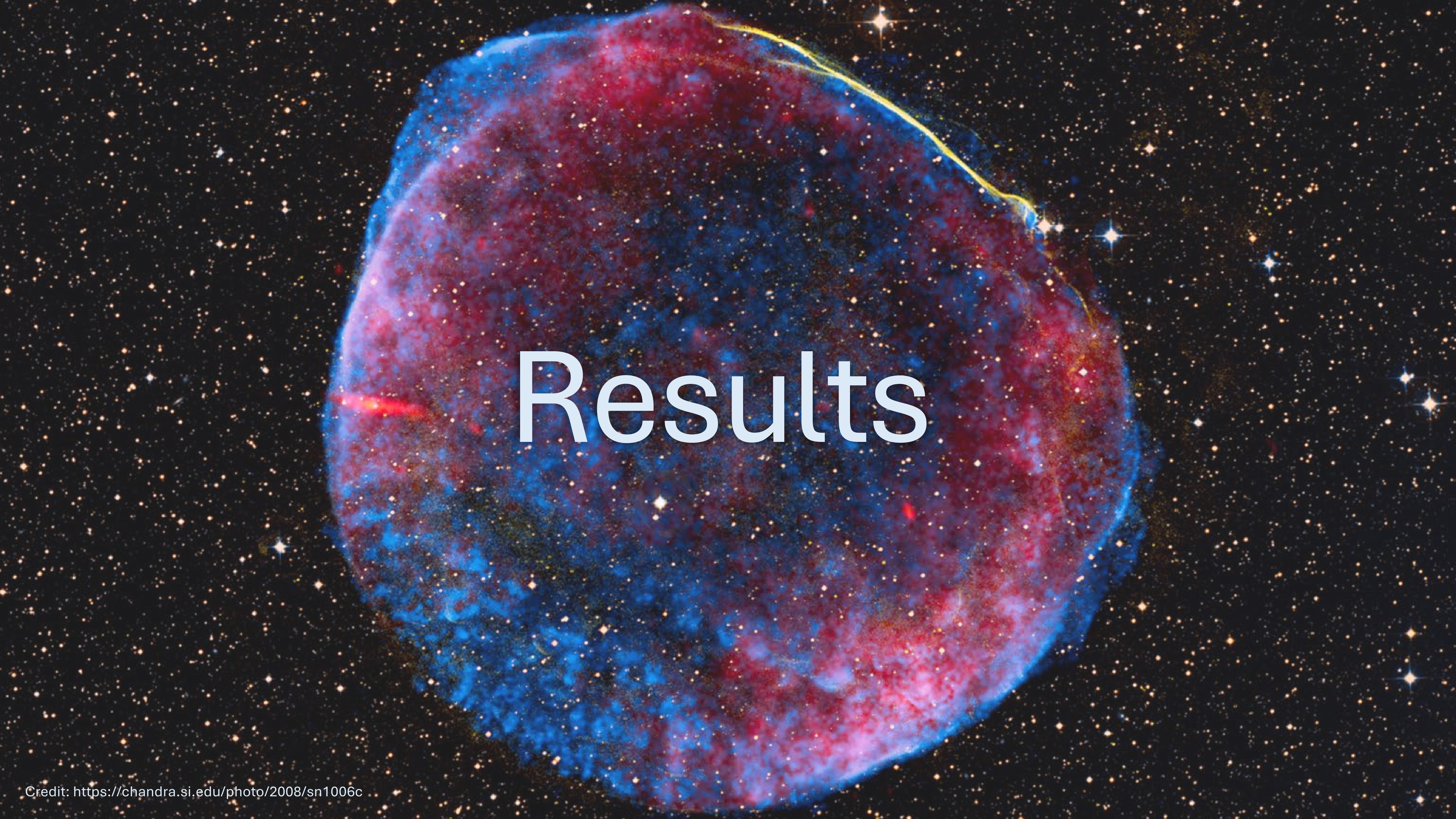
- Enhances CR escape, increases R_{tot}, and steepens spectra $q > 2$

  (Haggerty & Caprioli 2020; Caprioli et al. 2020)

Velocity Profile



Results



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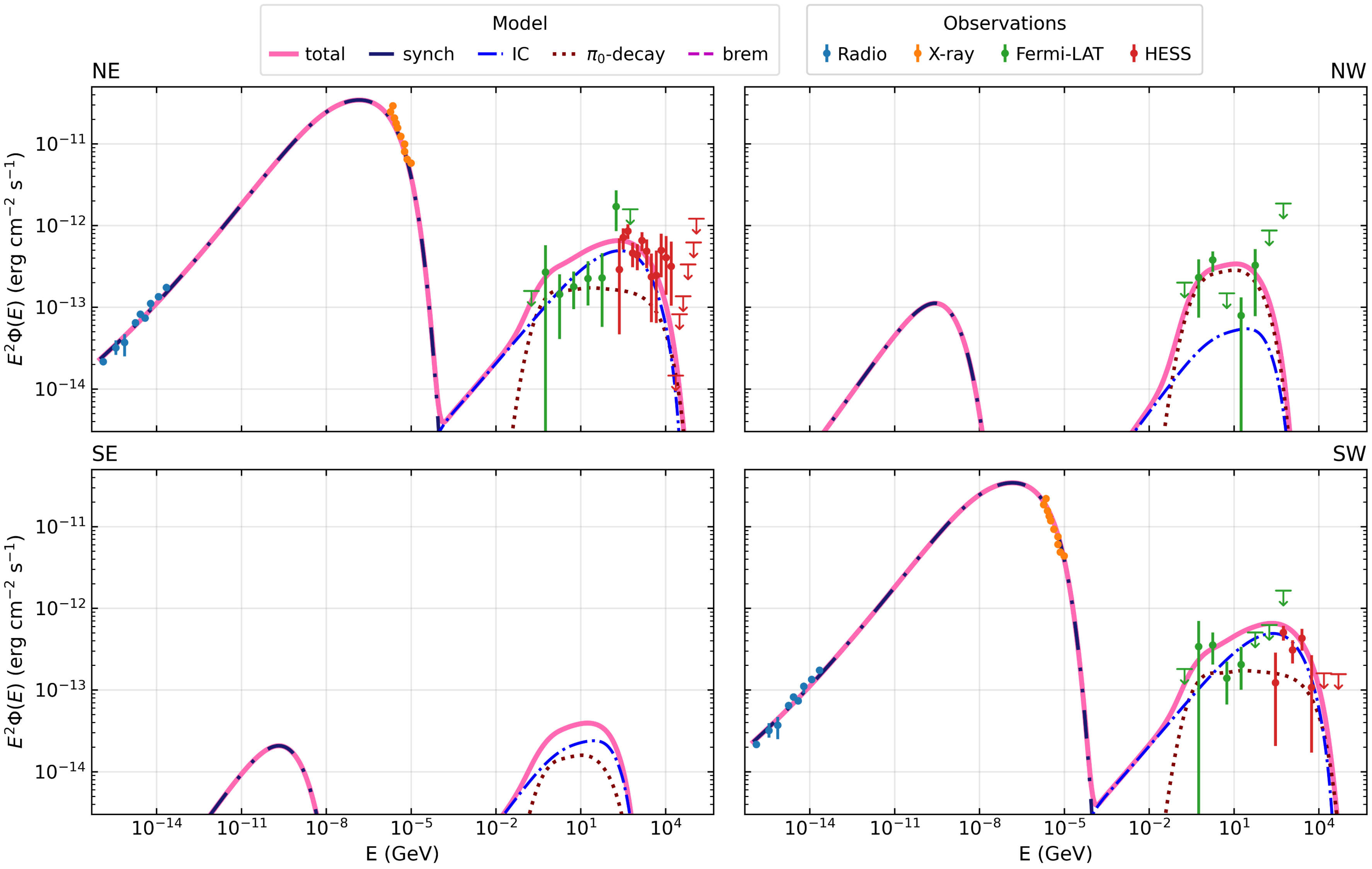
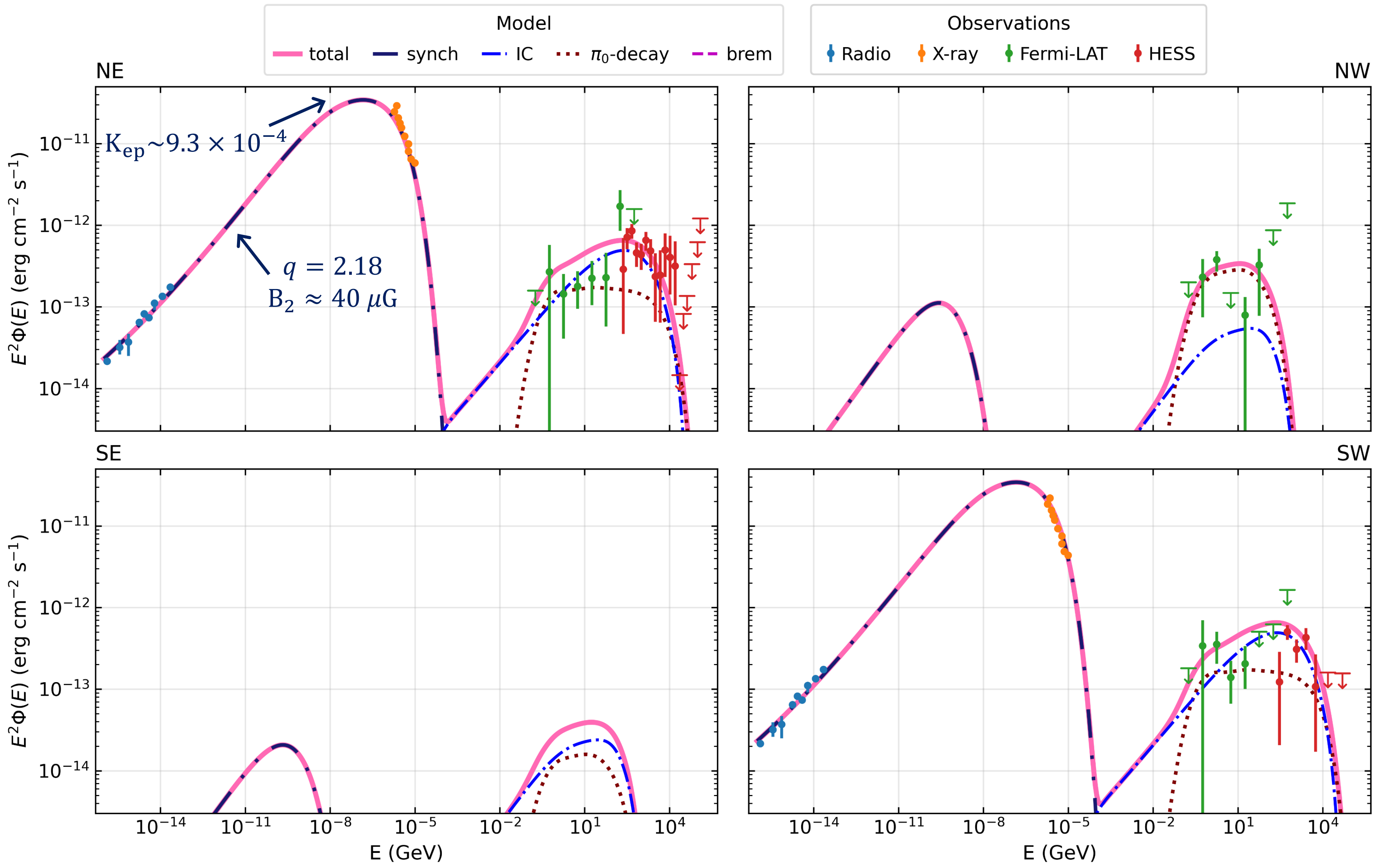
Photon Spectra



Credit: McGinness et al. 2026

- Closely reproduce observations

Photon Spectra



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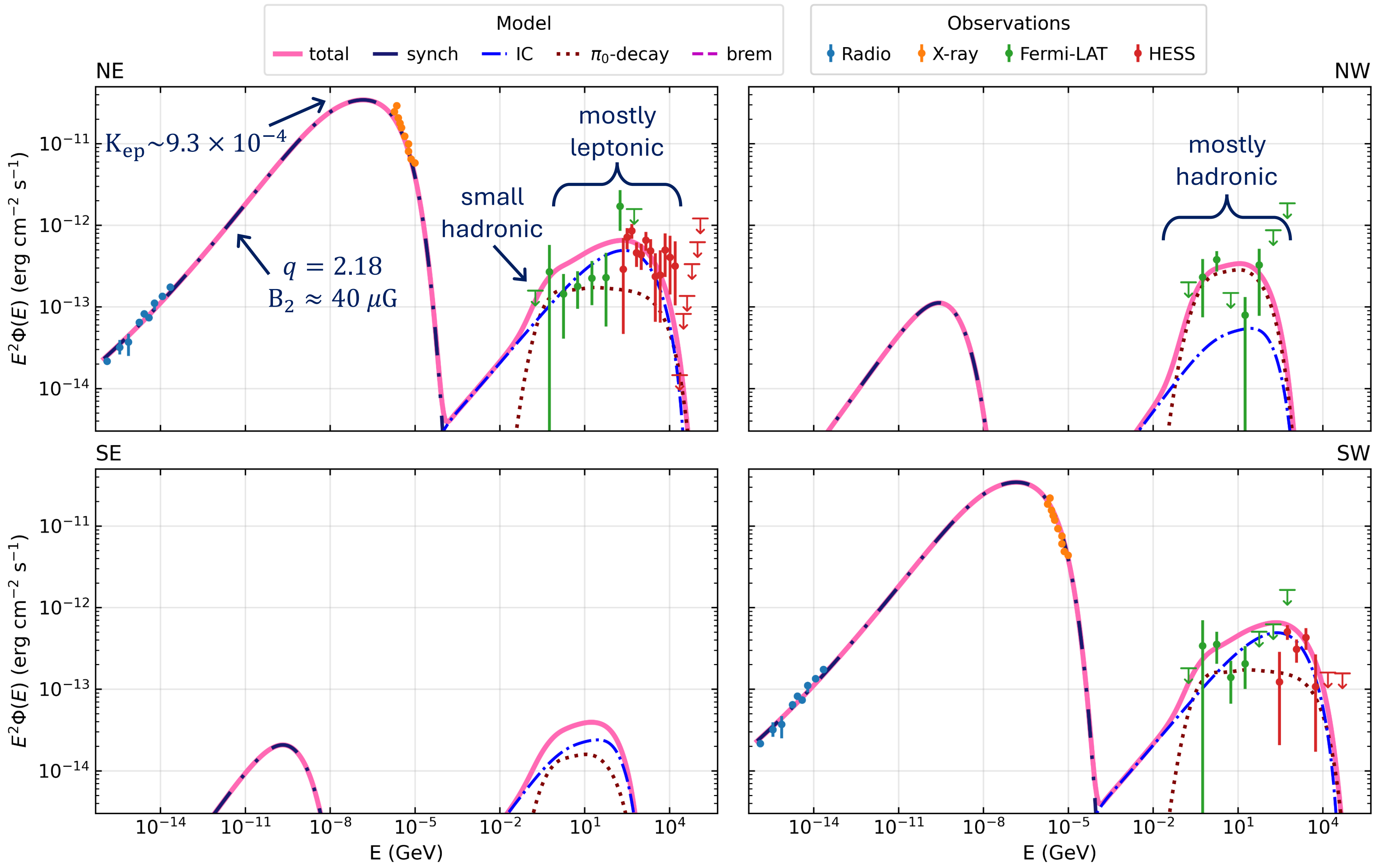

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- Closely reproduce observations
- Mostly leptonic emission
- Evidence for relationship between γ-ray origins and density

(Corso et al. 2023)

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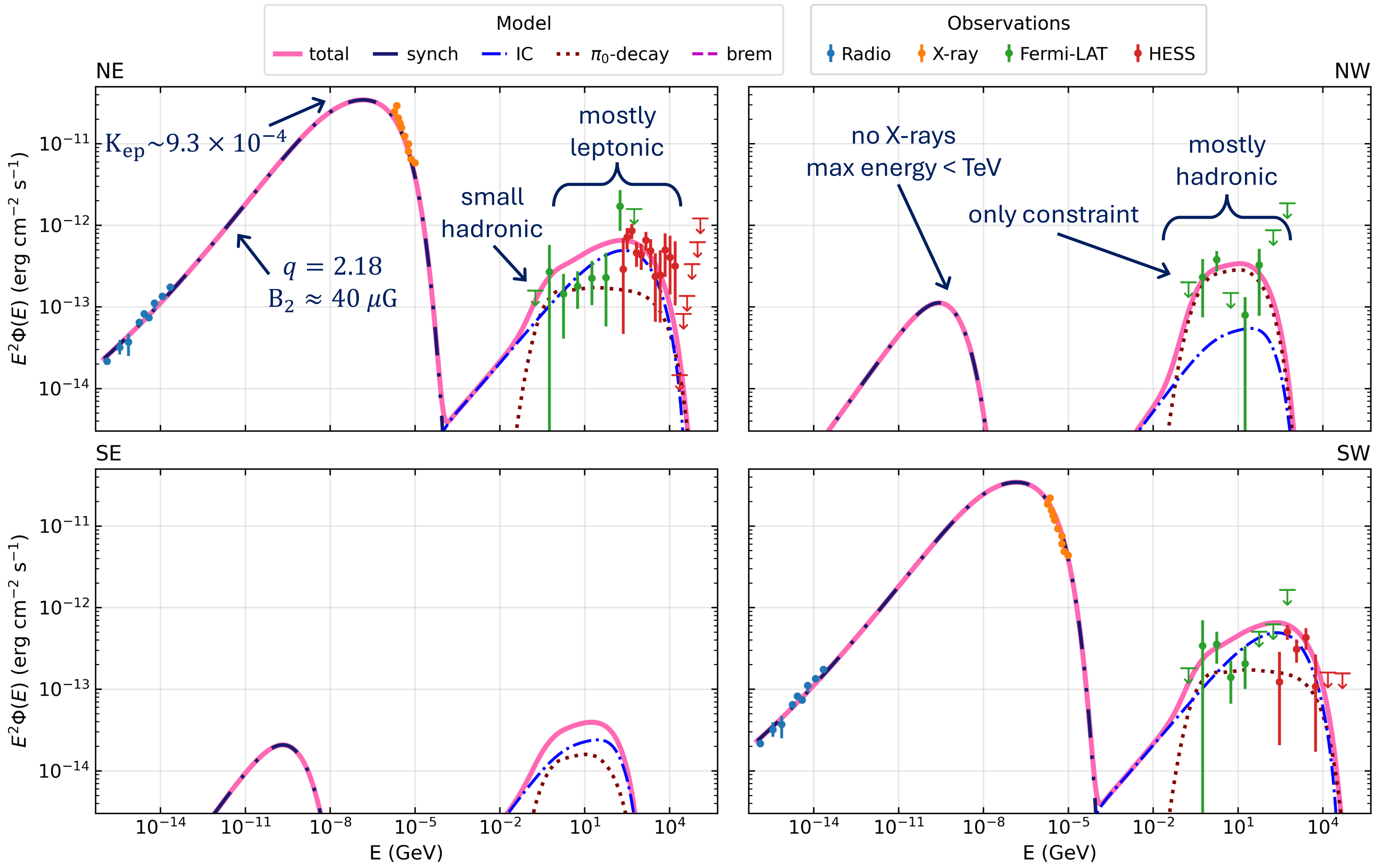

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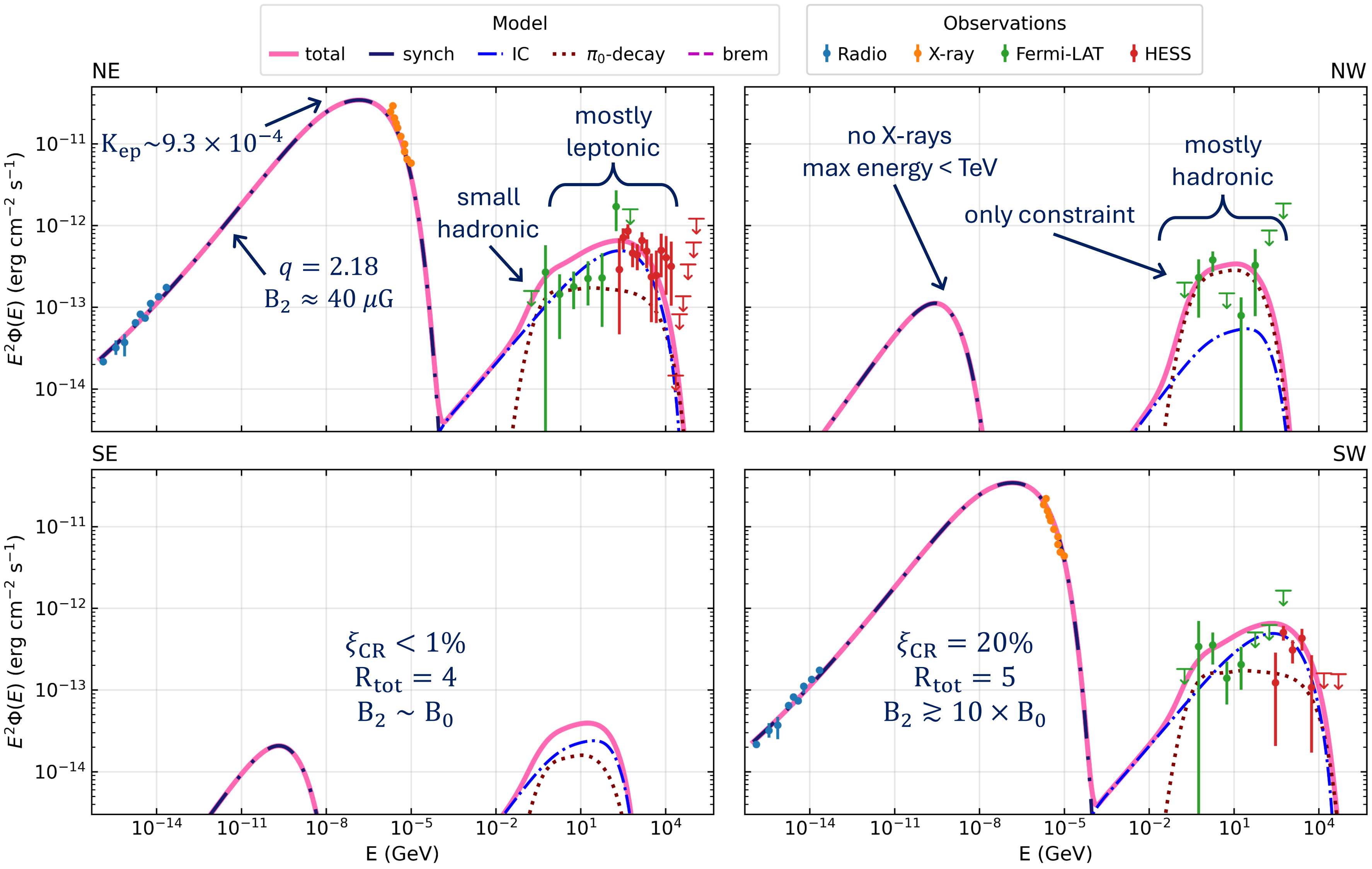
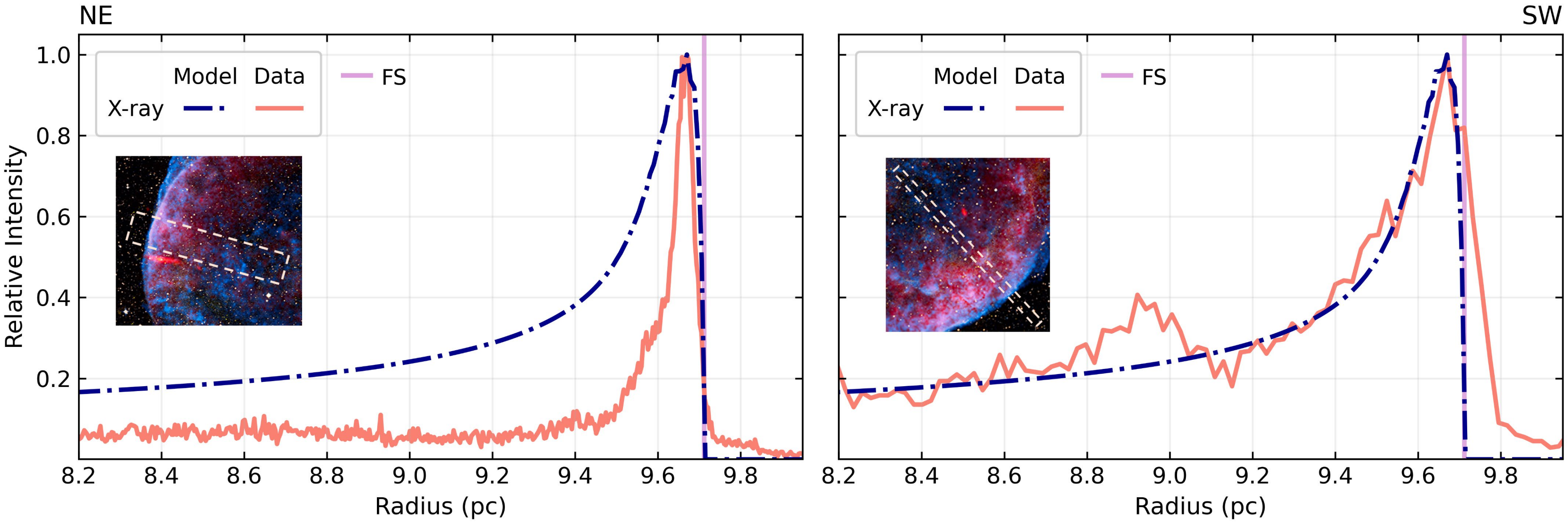


Credit: McGinness et al. 2026

- Closely reproduce observations
- Mostly leptonic emission
- Evidence for relationship between γ-ray origins and density
  (Corso et al. 2023)
- Supports dependence of CR efficiency on shock obliquity
  (e.g., Caprioli & Spitkovsky 2014; Caprioli et al. 2015)

X-Ray Profiles

- Post-shock field is sufficiently large to reproduce X-ray rims
- Changing amplified field affects rim width → rims determined by synchrotron losses



Credit: McGinness et al. 2026

Downstream field
B~40μG

- Particle slope $q{\sim}2.2$
- Compression ratio $R_{tot}{\sim}5$
- X-ray rim widths
- Synchrotron Normalization

Summary

- Reproduced multi-wavelength spectral and X-ray spatial properties of SN 1006 using a self-consistent model of particle acceleration that includes MFA via instability driven by escaping CRs and drifting magnetic fluctuations

- Downstream field simultaneously accounts for the steep CR spectral slope, modified shock hydrodynamics, X-ray rim widths, and synchrotron normalization

- The non-thermal emission echoes the relationship between CR efficiency and shock obliquity predicted, with efficient CR acceleration and MFA in the polar caps

- Majority of SN 1006 γ-ray emission is leptonic except in the NW quadrant where density is enhanced, suggesting the significance of the environment in γ-ray origins

Paper QR Code:

Scan Me

Thank you! Questions?

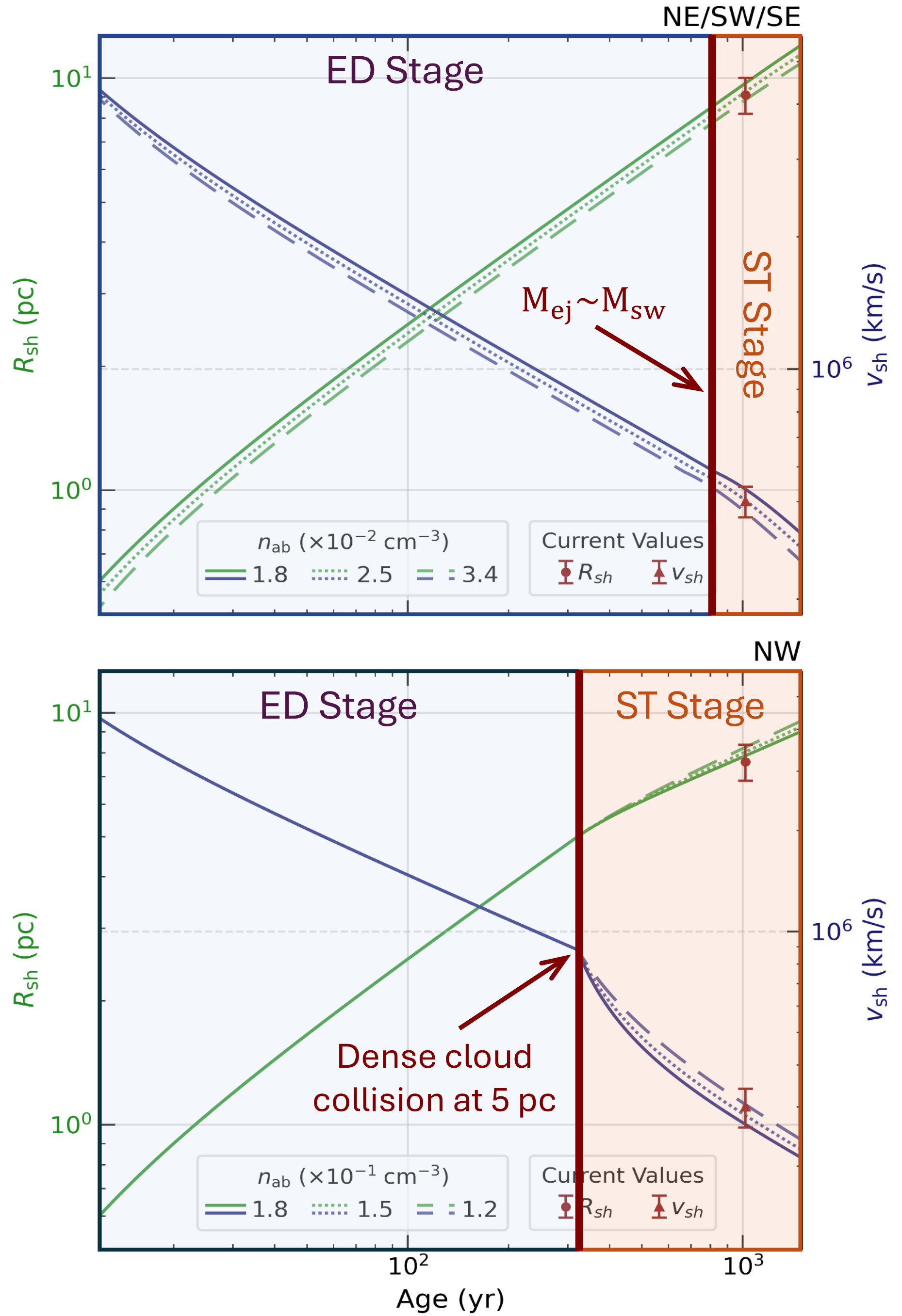
Credit: https://chandra.si.edu/photo/2008/sn1006c

Model Shock Hydrodynamics

- Uniform density except in NW, where shock collides with a dense cloud
  (e.g., Acero et al. 2007; Bandiera et al. 2018; Giuffrida et al. 2022)
- Model ED stage $(M_{ej} > M_{sw})$ using an analytic solution, and ST stage $(M_{ej} < M_{sw})$ using the thin-shell approx.
  (Tang & Chevalier (2017); Ptuskin & Zirakashvili 2005)
- Constrain shock evolution using morphology
  (e.g., Katsuda et al. 2009; Winkler et al. 2003)

Parameters:

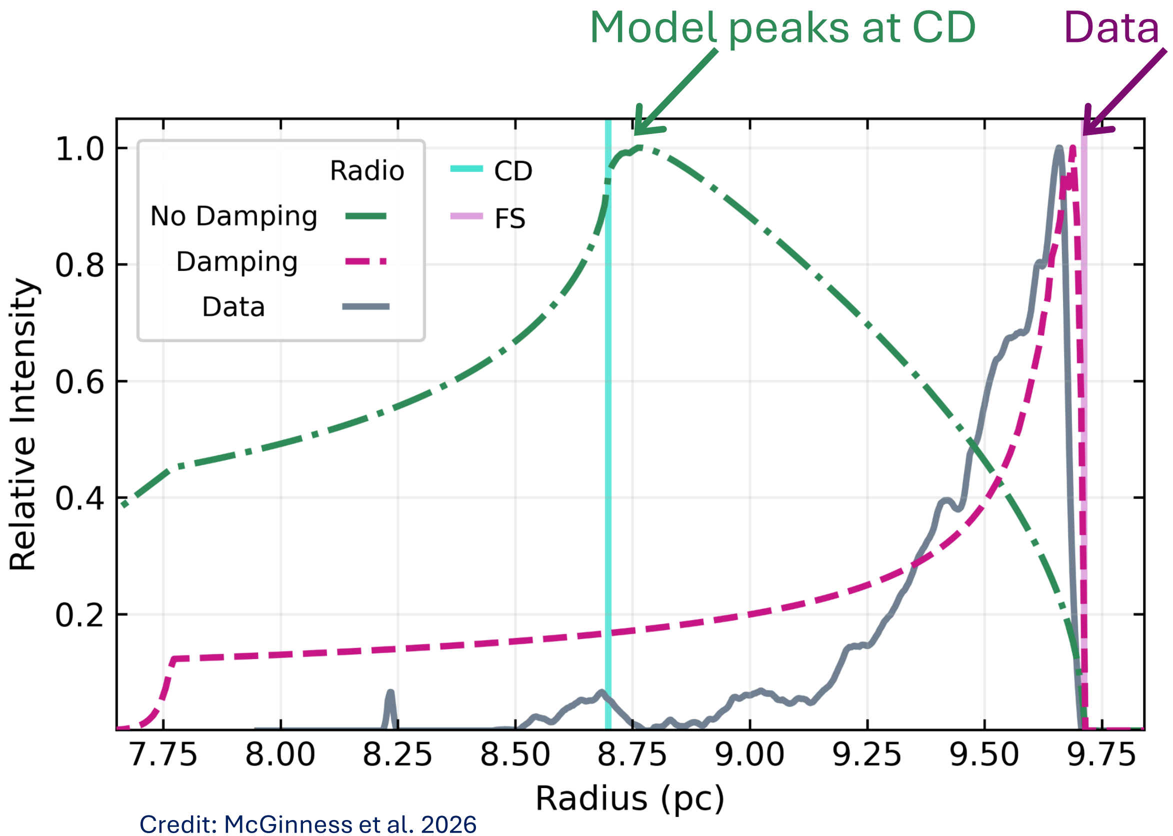
$$E_{SN} = 10^{51} \text{ ergs}$$
$$M_{ej} = 1.2\ M_{\odot}$$
$$T_0 = 10^4 \text{ K}$$
$$B_0 = 3\ \mu G$$

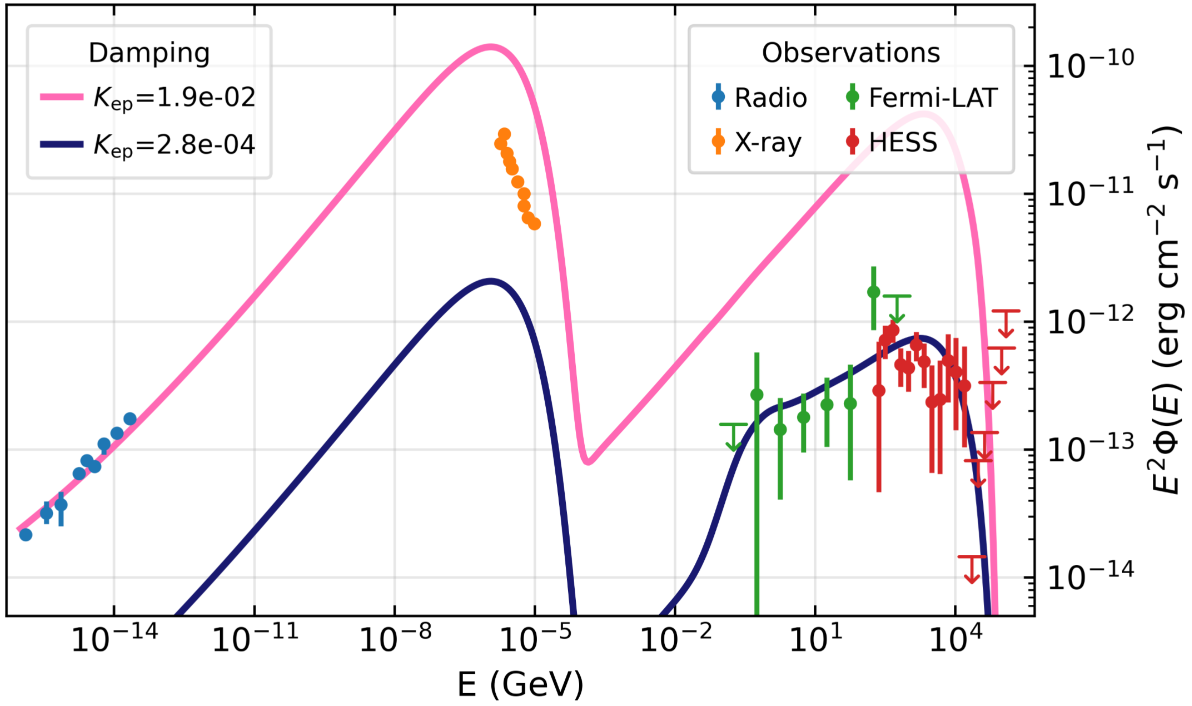


Credit: McGinness et al. 2026

Radio Profile

- Problematic because reflects entire SNR evolution
- Adding damping to the model improves profile at the cost of fitting the multi-wavelength spectrum
- Attribute discrepancy to disregard of the CD's vulnerability to hydrodynamical instabilities





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