Evidence for Cosmic Ray Acceleration in Cas A

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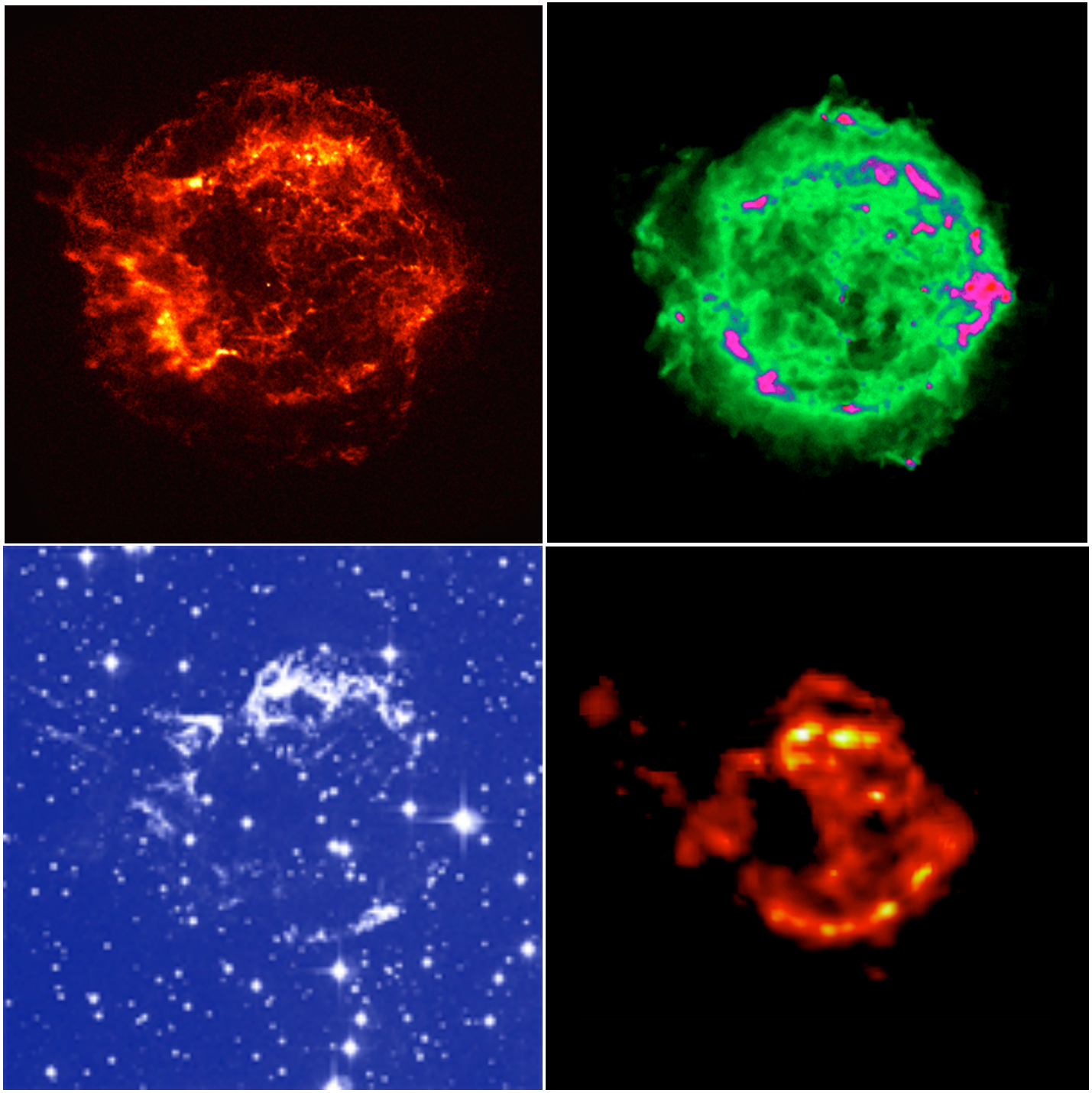
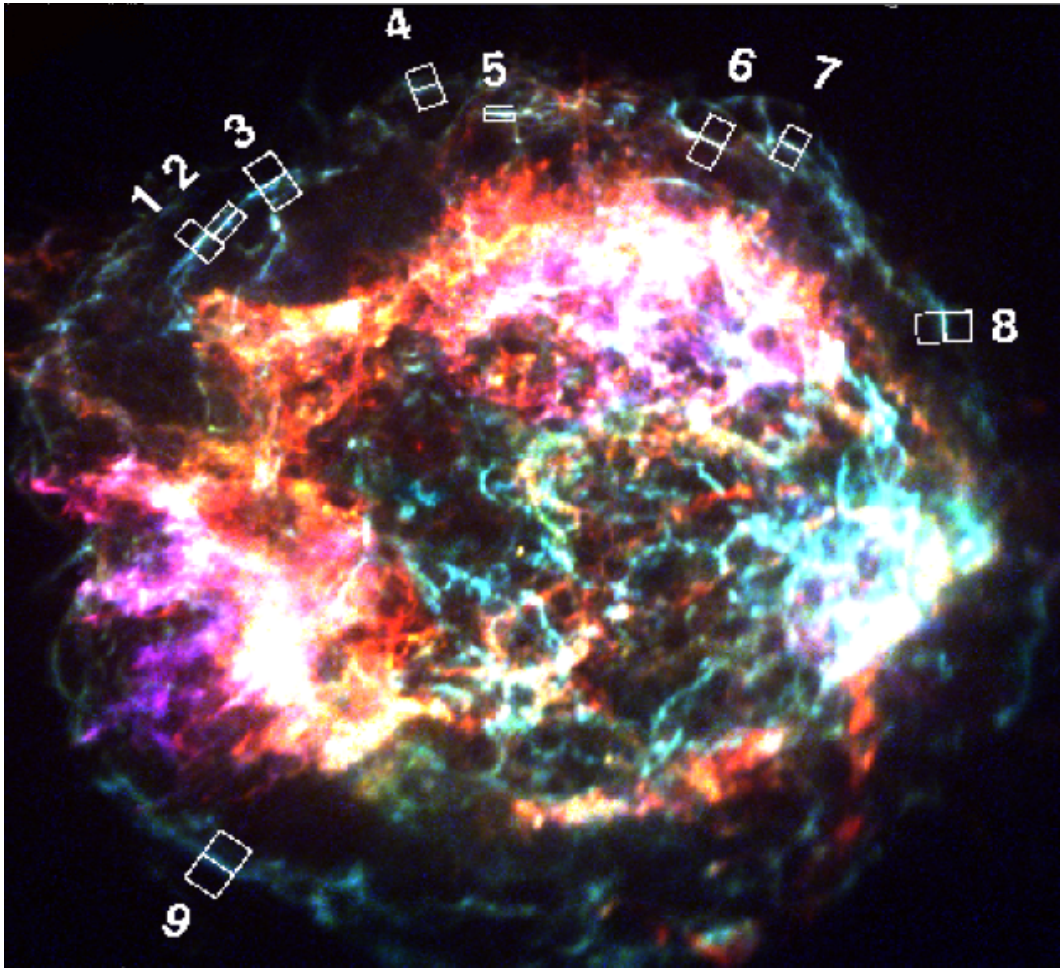
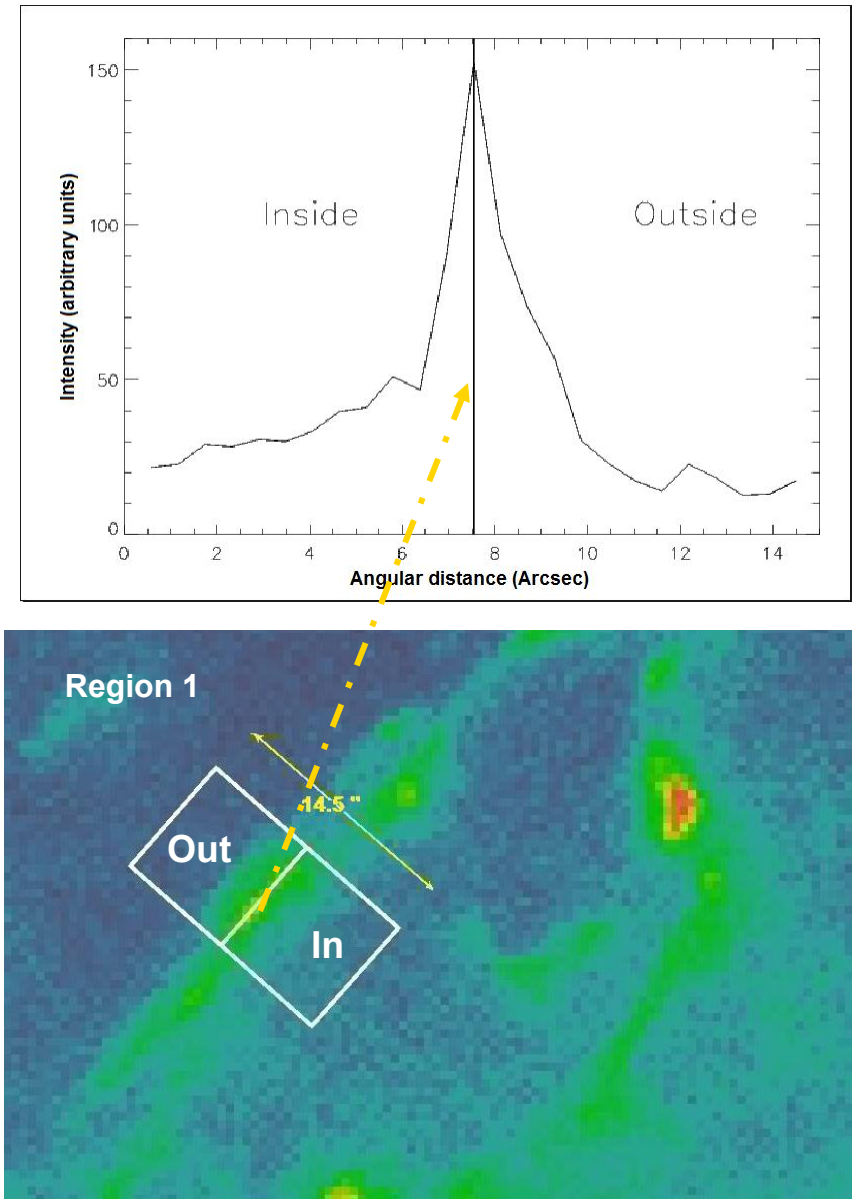


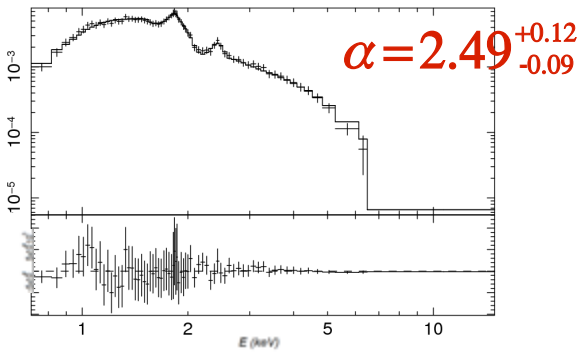
Zoom onto non-thermal X-ray filaments



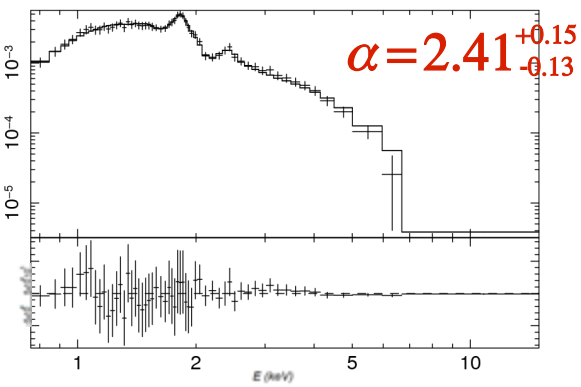


Spectral evolution across filaments

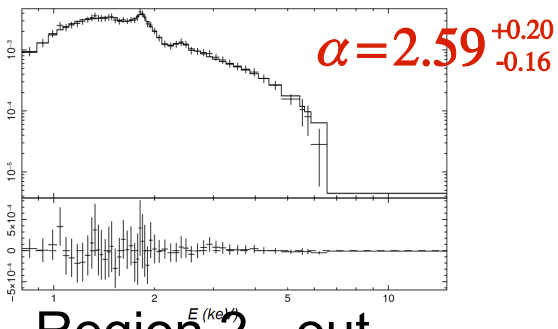
Region 1 - in



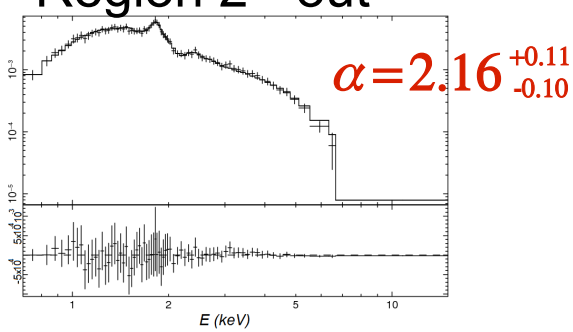
Region 1 - out



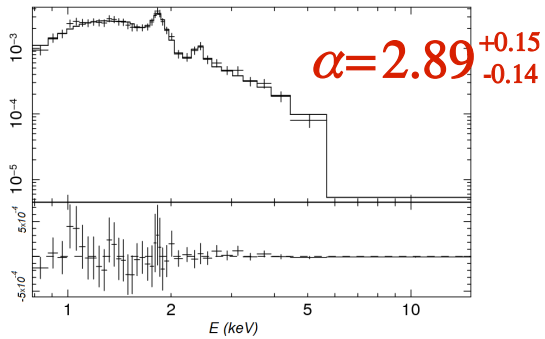
Region 2 - in



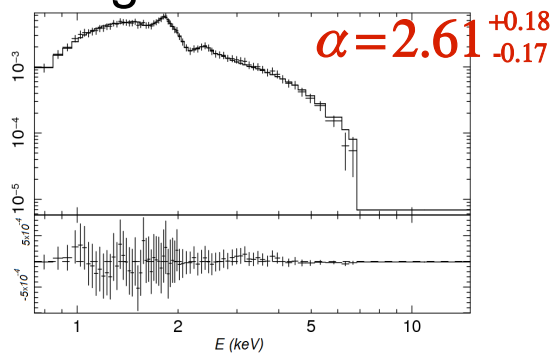
Region 2 - out



Region 8 - in

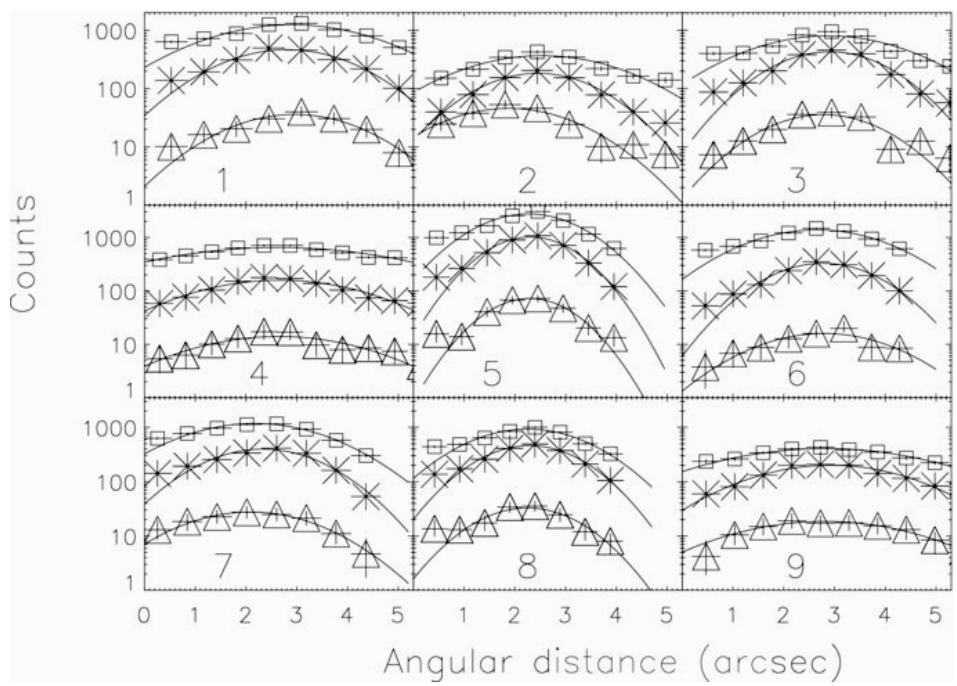


Region 8 - out



Particle cooling

Synchotron cooling?



very weak energy dependence of the width of filaments

Region	1	2	3	4	5	6	7	8
$\frac{W_{0.3-2.0keV}}{W_{6.0-10.0keV}}$	$1.27^{+0.38}_{-0.35}$	$1.19^{+0.46}_{-0.34}$	$1.34^{+0.59}_{-0.41}$	$1.42^{+1.18}_{-1.02}$	$1.23^{+0.27}_{-0.23}$	$1.02^{+0.63}_{-0.86}$	$1.07^{+0.48}_{-0.49}$	$1.19^{+0.57}_{-0.37}$

Synchrotron+Advection: $\frac{W_{0.3-2.0keV}}{W_{6.0-10.0keV}} > 4$ → Diffusion

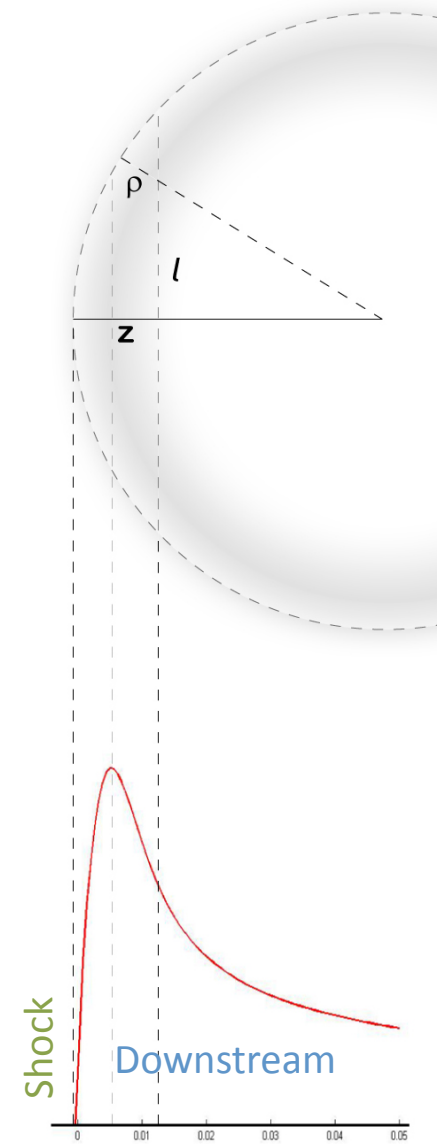
Model

- Non-thermal filaments modeled as thin spherical regions associated with the forward shock
- Power-law spectral distribution of particles injected at the shock
- Down-stream advection of particles
  - Advection velocity from proper motion measurements
- Diffusion of particles
  - Bohm type assumed $D = \kappa D_B$
- Synchrotron cooling

Four key parameters:

$$l_{dif} = \left(\frac{6\pi m^2 c^4}{\sigma_T q B^3} \right)^{1/2} \qquad \Gamma$$

$$l_{adv}(\gamma) = \frac{6\pi m c V_{adv}}{\sigma_T B^2 \gamma} \qquad \kappa$$



Things learned

M. Araya et al. 2010, ApJ, 714, 396

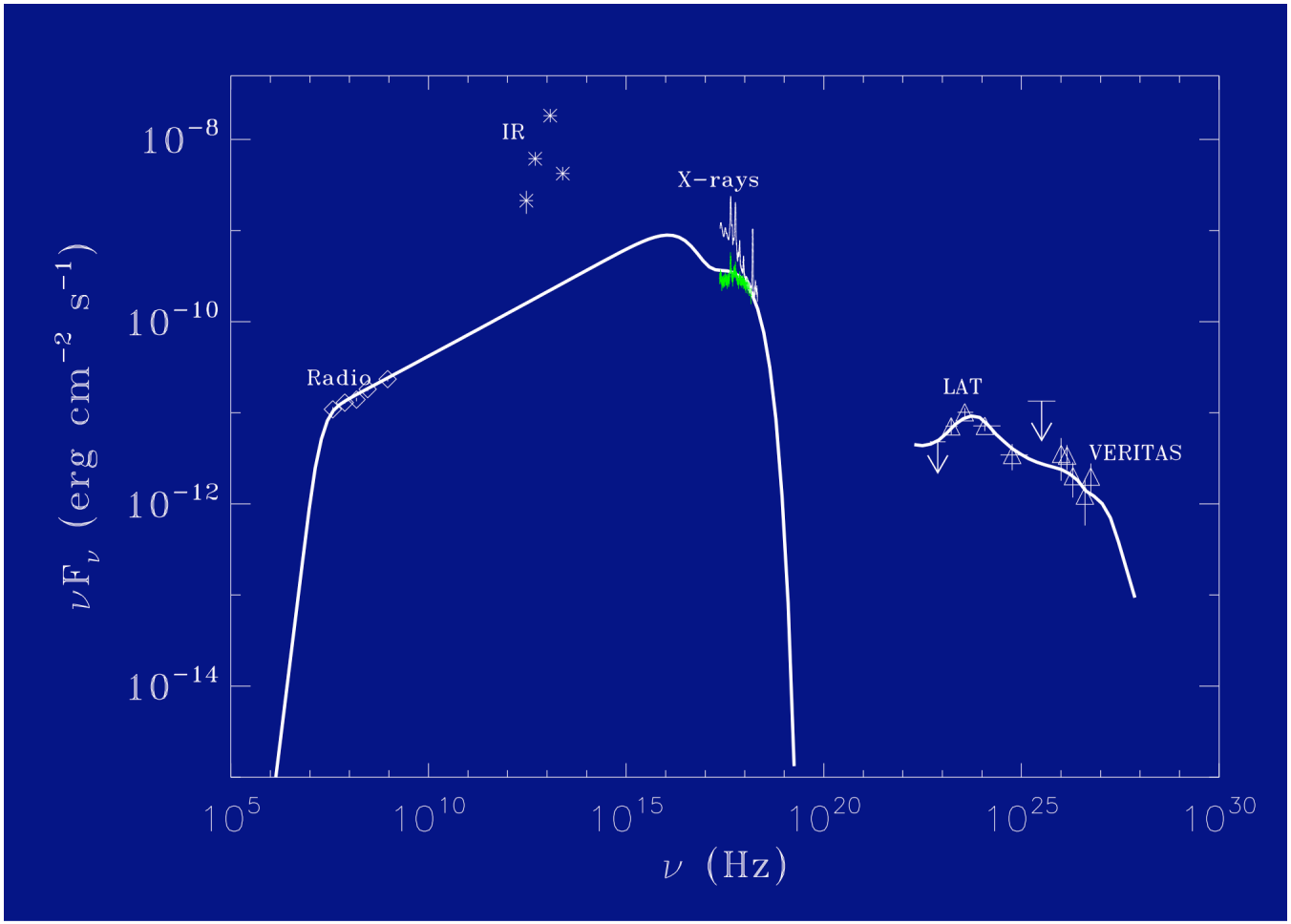
- The effects of diffusion are significant.
  - Spectral evolution across filaments
  - Weak energy dependence of filament widths
- Diffusion coefficient: $\kappa \sim 0.02$
- Turbulence: $\delta B/B \sim 0.2$
- Quasi-perpendicular shock
- The magnetic field is nearly perpendicular to the shock front.
- Magnetic field in filaments: $B \sim 50\ \mu G$
- Electron spectral index: $\Gamma \sim 2.6\text{-}3.0$

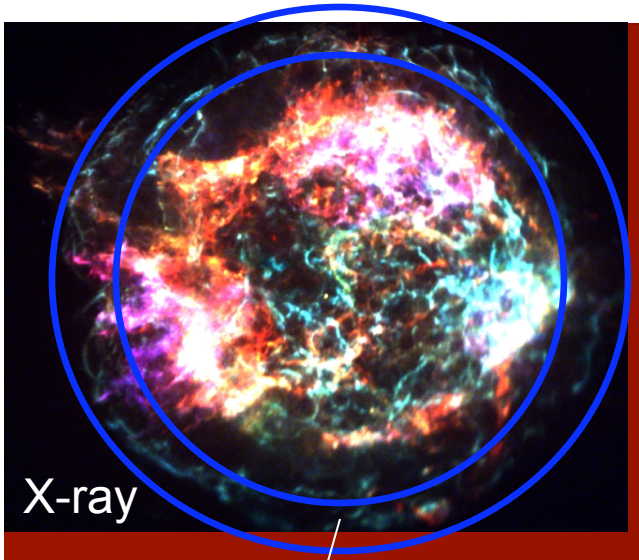
Multi-wavelength observations of Cas A

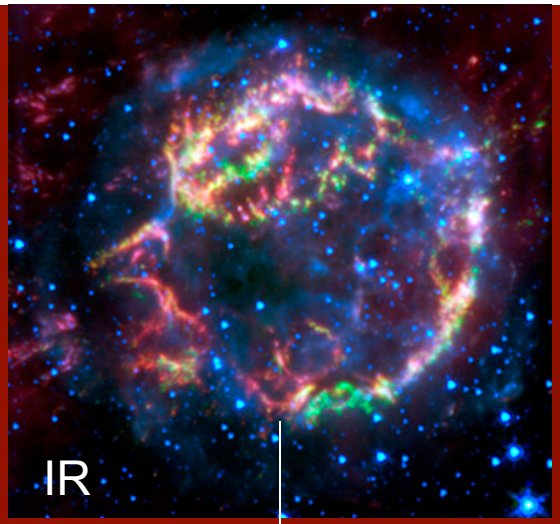
DATA

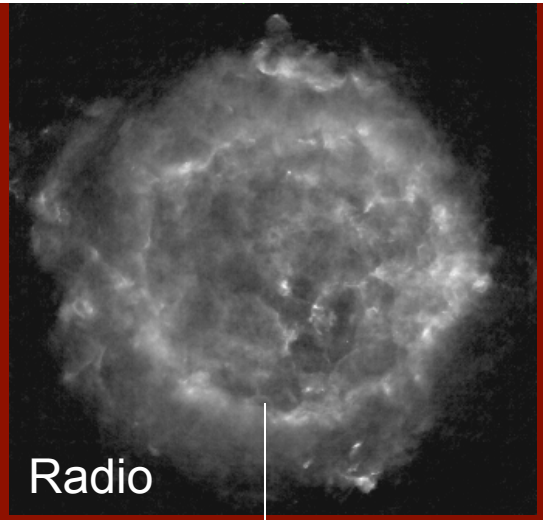
- Radio: many instruments
- Infrared (12-100 μm): IRAS (Dwek et al. 1987, ApJ, 315, 571)
- X-ray (0.3-10 keV): 1 Ms exposure with Chandra (Hwang et al. 2004, ApJ, 615, L117
- GeV Gamma ray (0.2-50 GeV): Fermi (from 2008 August 4 to 2010 March 10)
- TeV Gamma ray (0.15-10 TeV): VERITAS (Acciari et al. 2010, ApJ, 714, 163)

Spectral Energy Distribution









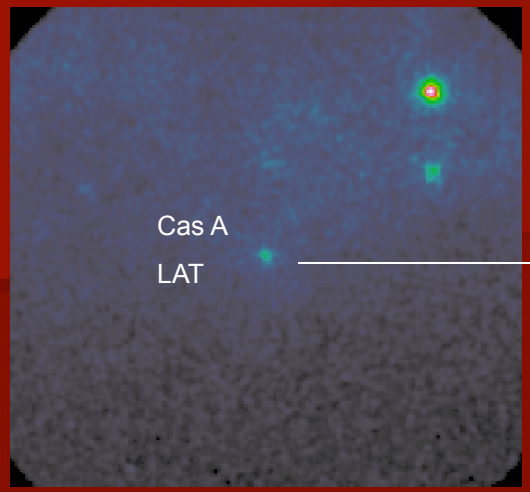
Zone 1: X-ray-emitting electrons

- Clumped in spherical blobs
- Ambient proton density: 0.5 cm^{-3}
- $dN/dE_{e-} \propto E^{-2.6}$
- B = 50 μG
- vol ~ $V_{SNR}/10$
- $E_{e-} \sim 10^{50}$ erg

- Main seed photon contribution to IC
- $F^{IR}_{\lambda=25\,\mu m}$ = 150 Jy

Zone 2: Radio-emitting electrons

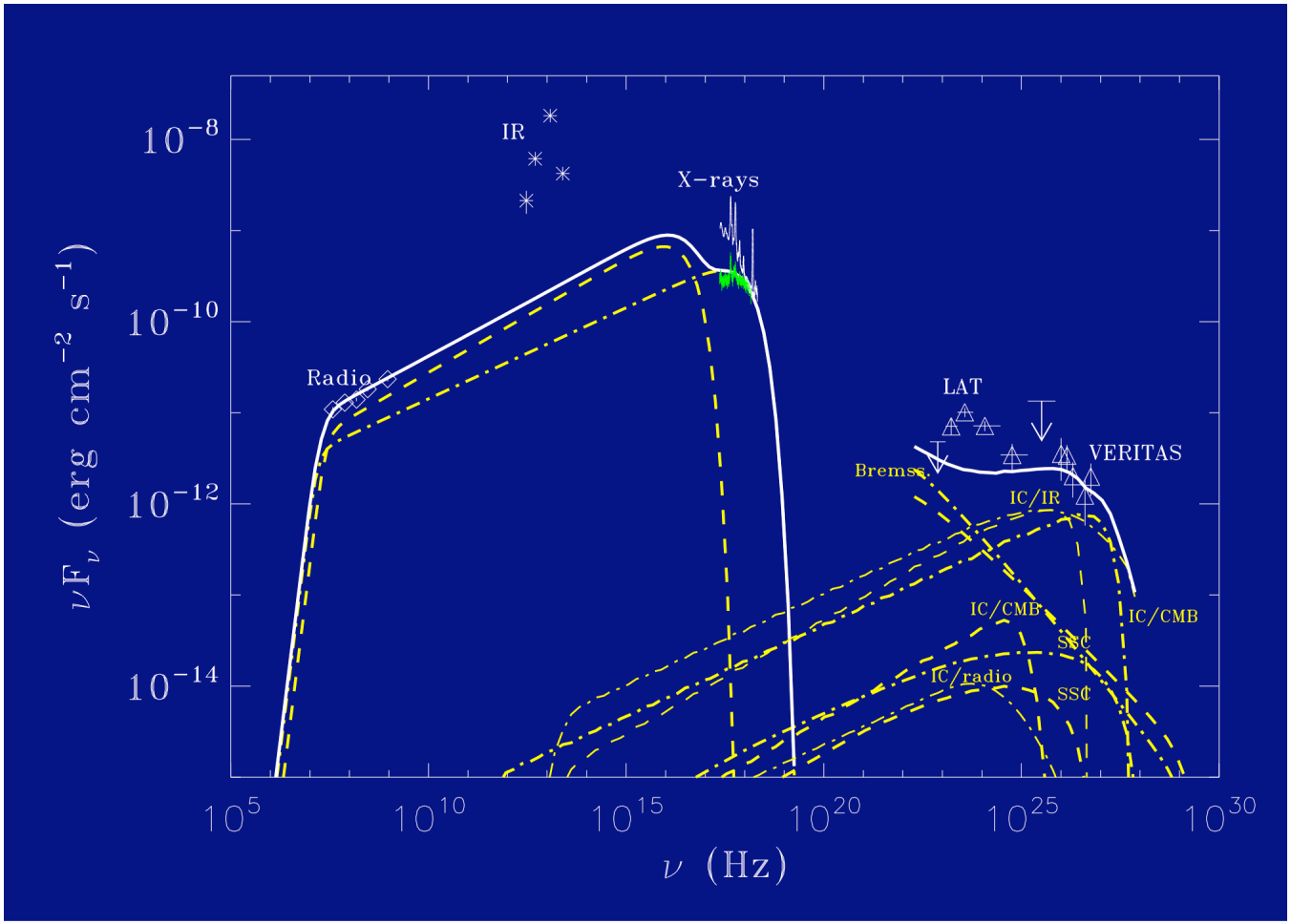
- Uniformly distributed
- Ambient proton density: 4.4 cm^{-3}
- $dN/dE_{e-} \propto E^{-2.54}$
- B = 300 μG
- vol = V_{SNR}



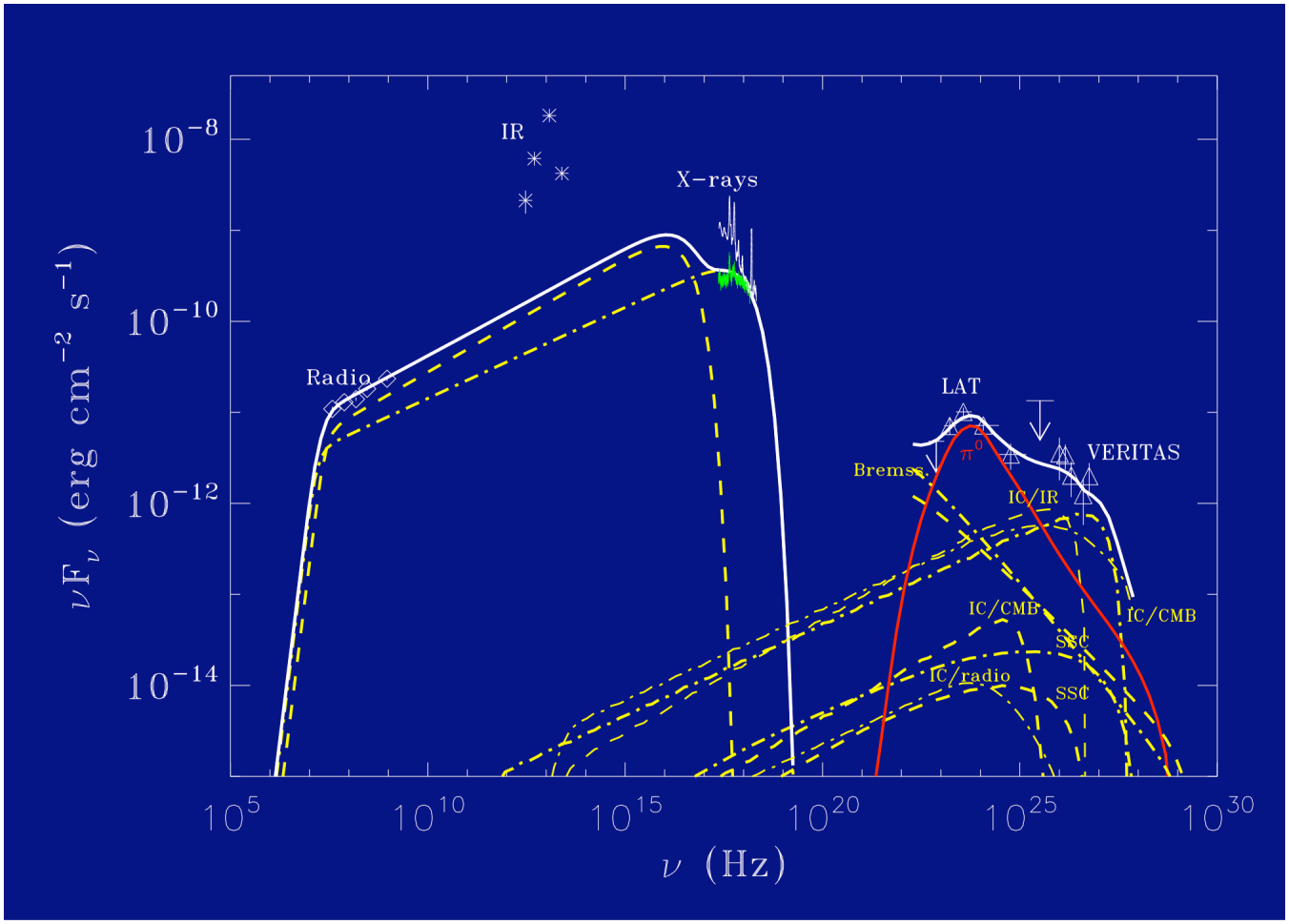
GeV-TeV emission: IC + Bremss + π^0 decay

- $dN/dE_p \propto T_p^{-2.1}$ T_p < 11 GeV
  $T_p^{-2.7}$ T_p > 11 GeV
- Ambient proton density: 4.4 cm^{-3}
- vol ~ V_{SNR}
- $E_{protons} \sim 0.6 \times 10^{50}$ erg
- Hadronic emission dominates at GeV energies

Leptons only



Need for hadronic contribution



Conclusion & Issues

It seems difficult to explain the spectral energy distribution of Cas A without a significant hadronic contribution to the observed gamma-ray emission at GeV energies.

Issues:

- Distribution of "cold" ions
  - more realistic density profile of the SNR
- Distribution of relativistic particles
  - integrating particles of different ages
- Magnetic field structure
  - compression and generation

REF: Araya & Cui 2010, to appear in ApJ