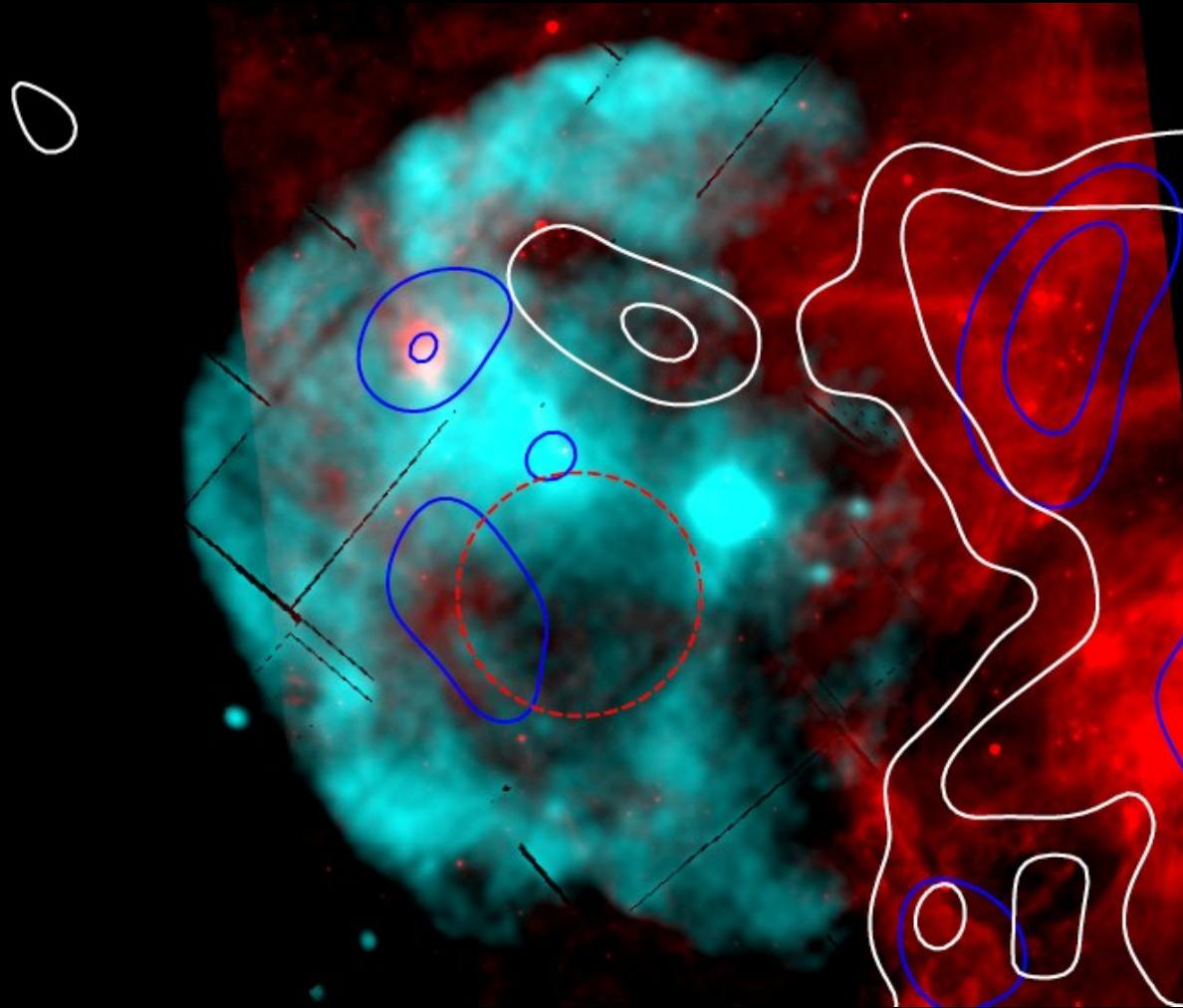
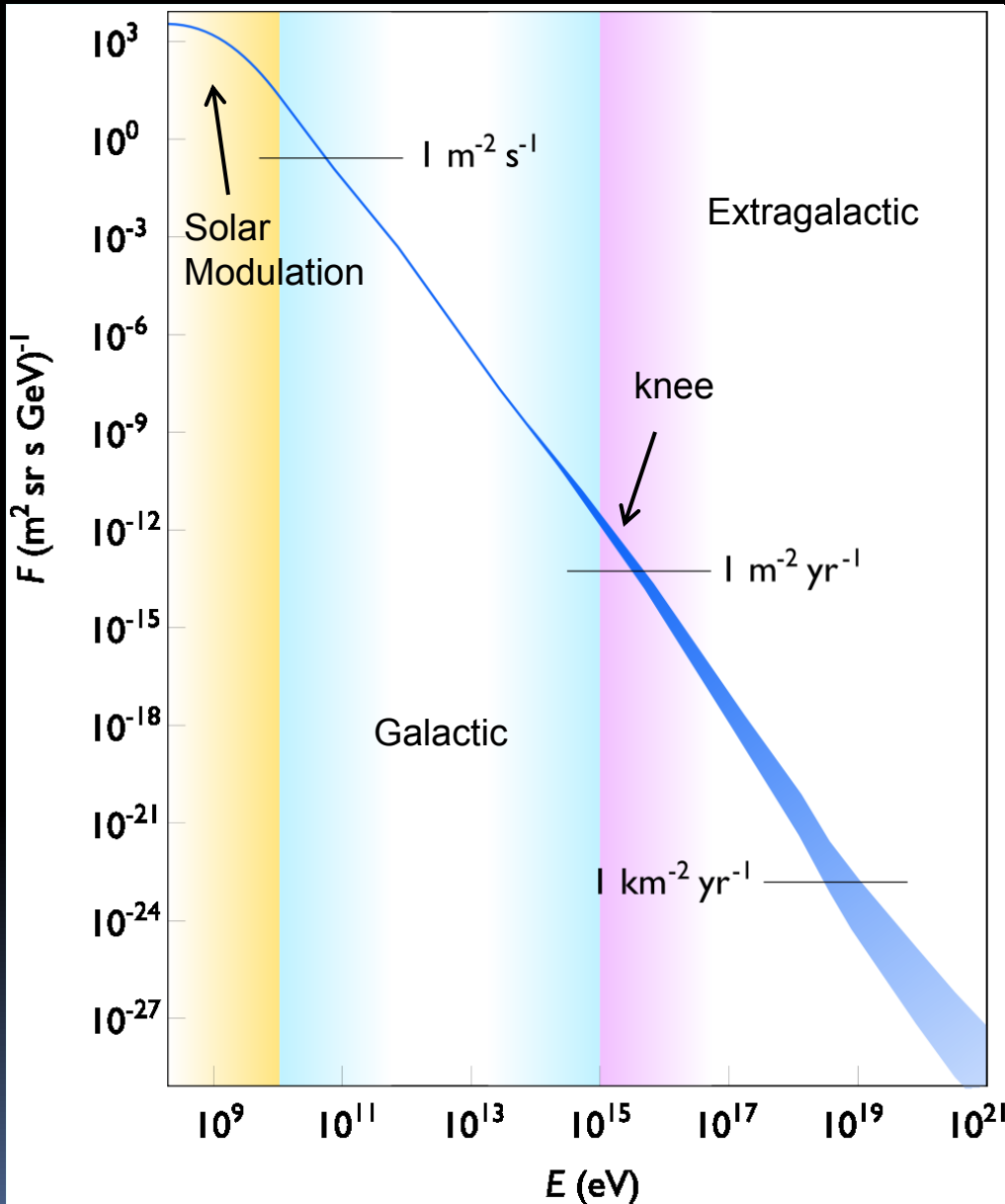


# Multiwavelength Studies of



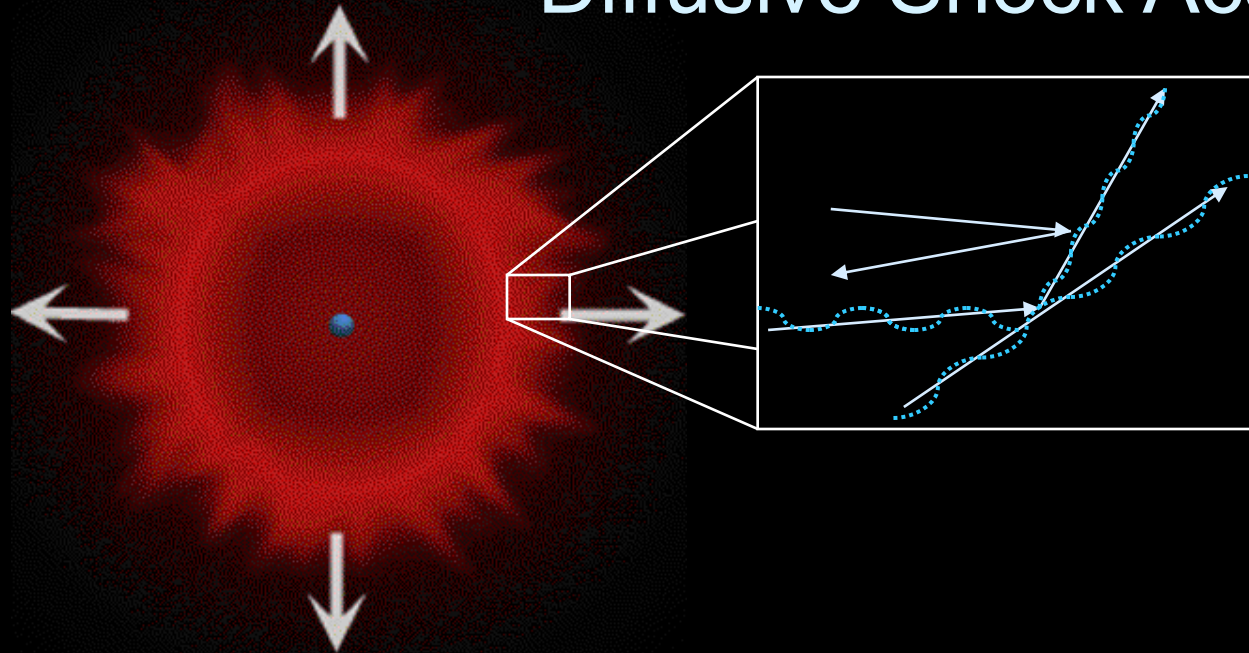
# Galactic Cosmic Ray Sources

# Cosmic Rays and SNRs



- CR spectrum is a power law covering more than 10 decades in energy.
  - “knee” in spectrum at  $\sim 10^{15-16}$  eV
  - CRs below knee thought to be Galactic in origin
- Composition of Galactic CRs similar to well-mixed ISM
  - energy density  $\sim 1 \text{ eV cm}^{-3}$
- Direct evidence of CR acceleration provides opportunity to constrain acceleration physics and address source of CRs
  - multi- $\lambda$  observations are crucial for source/counterpart identification, constraining emission geometry, probing source environment, and breaking modeling degeneracies

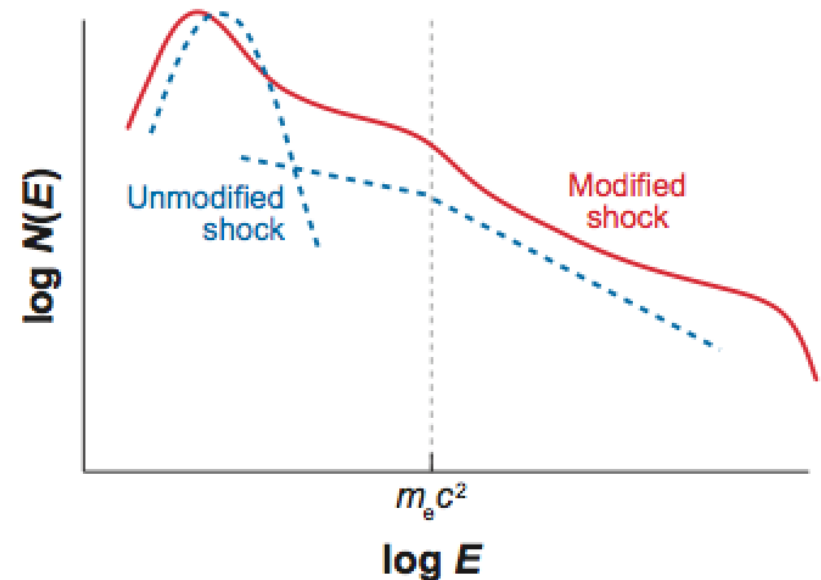
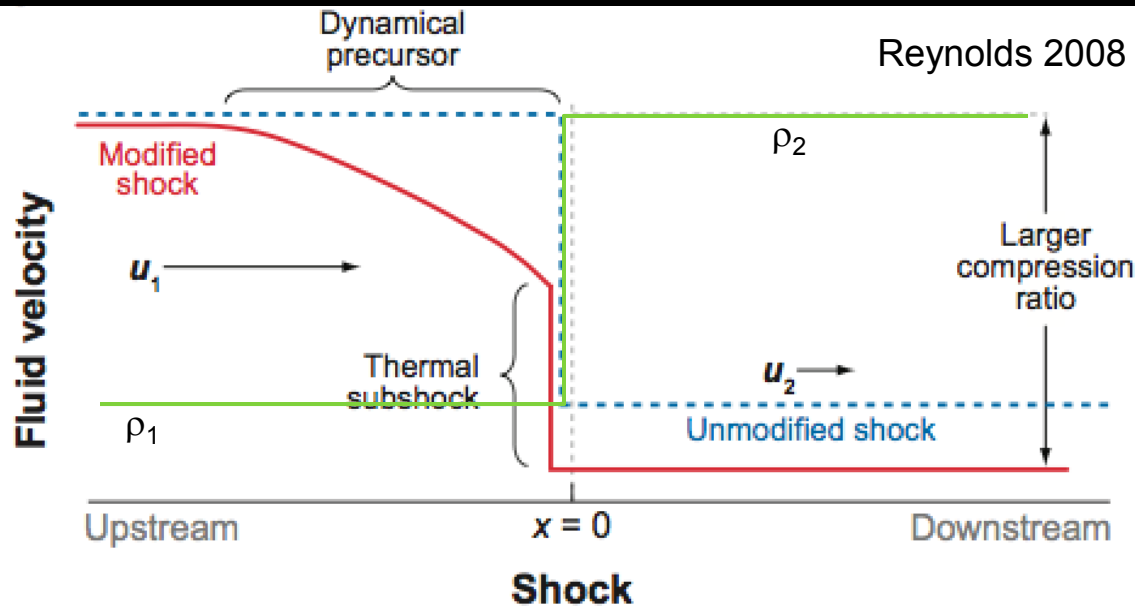
# Diffusive Shock Acceleration



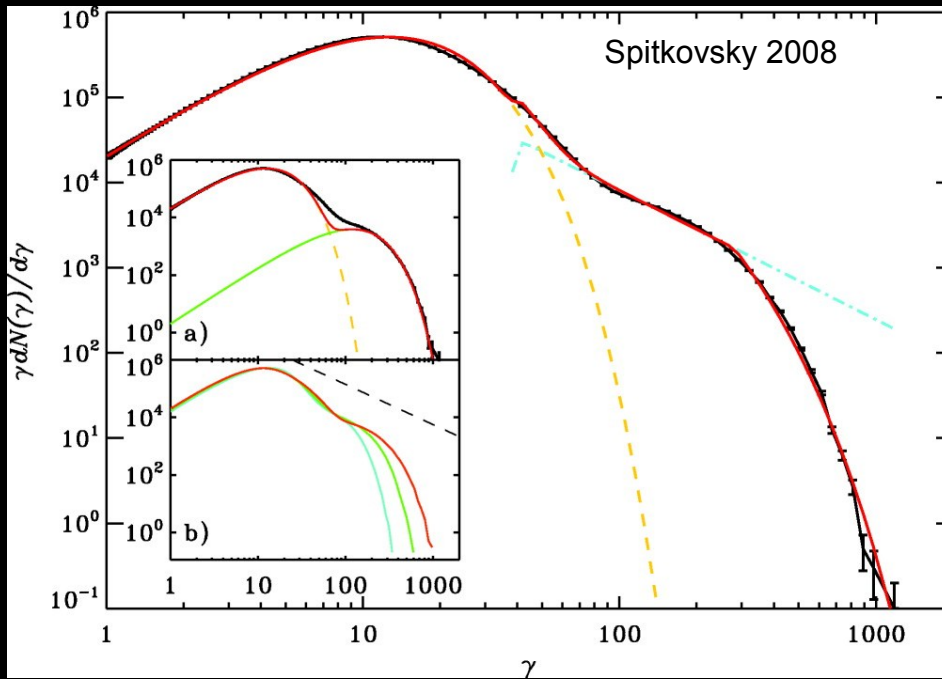
- Particles scatter from MHD waves in background plasma
  - pre-existing, or generated by streaming ions themselves
  - scattering mean-free-path

$$\lambda \propto r_g = E / eB$$

(i.e., most energetic particles have very large  $\lambda$  and escape)



# Pulsar Wind Nebulae



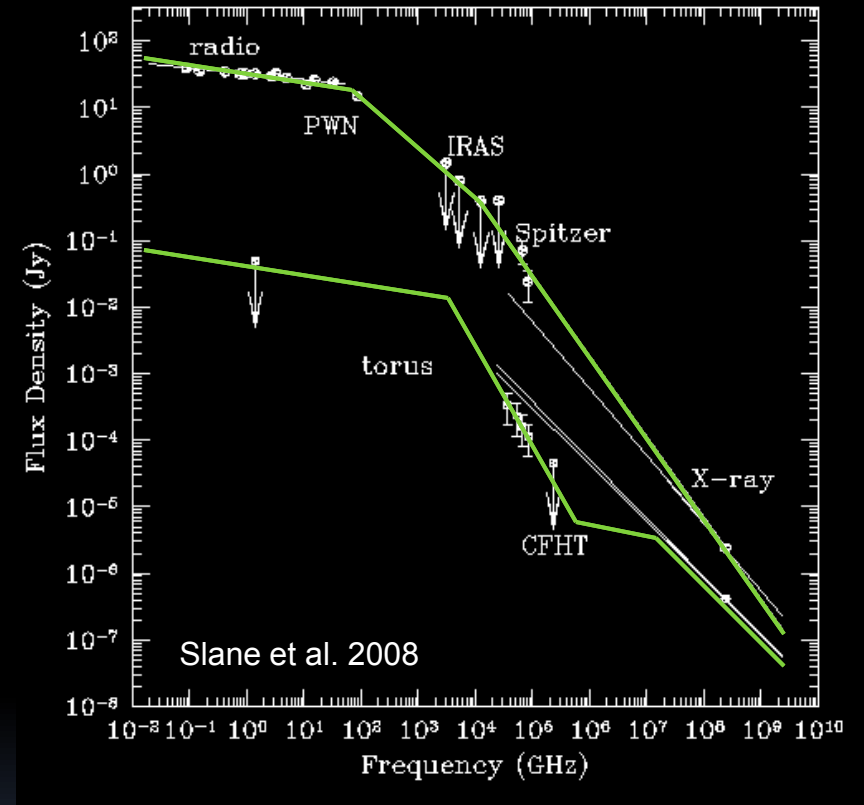
- PIC simulations of particle acceleration in relativistic shocks show build-up of energetic particles (Spitkovsky 2008)
- Input spectrum: Maxwellian + power law
  - and possibly more complex if conditions differ at different acceleration sites

# Pulsar Wind Nebulae

3C 58  
Chandra

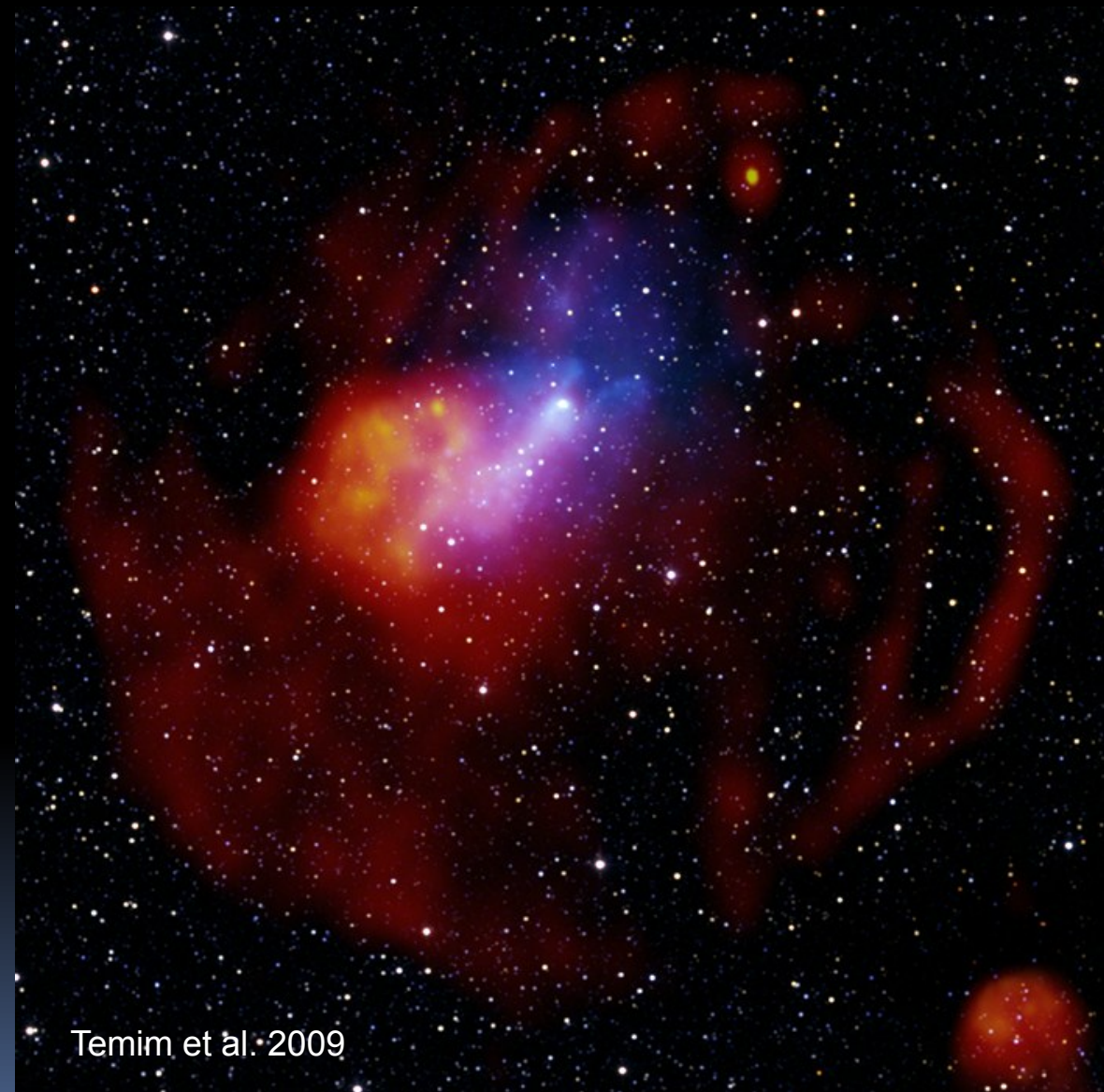


- PIC simulations of particle acceleration in relativistic shocks show build-up of energetic particles (Spitkovsky 2008)
- Input spectrum: Maxwellian + power law
  - and possibly more complex if conditions differ at different acceleration sites



- Broadband studies of 3C 58 show multiple spectral breaks
  - torus spectrum indicates complex injection spectrum

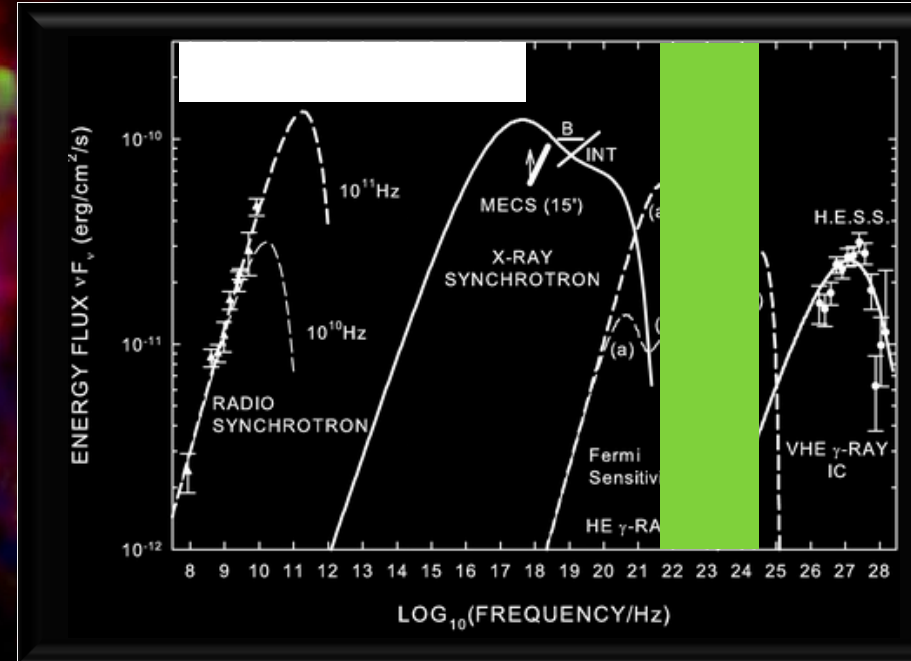
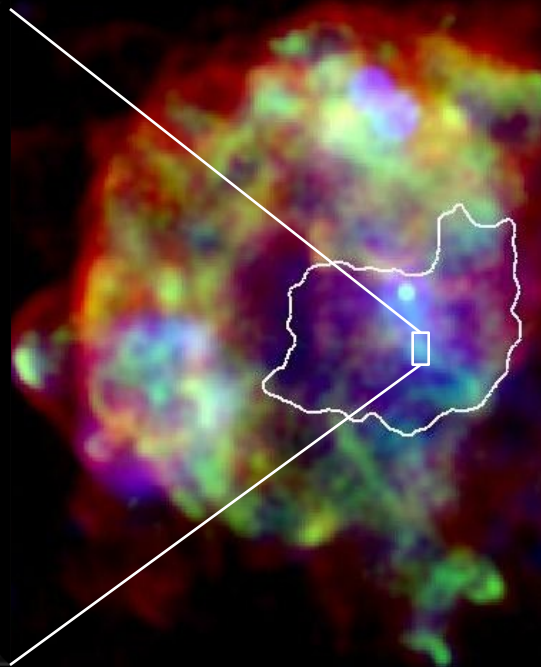
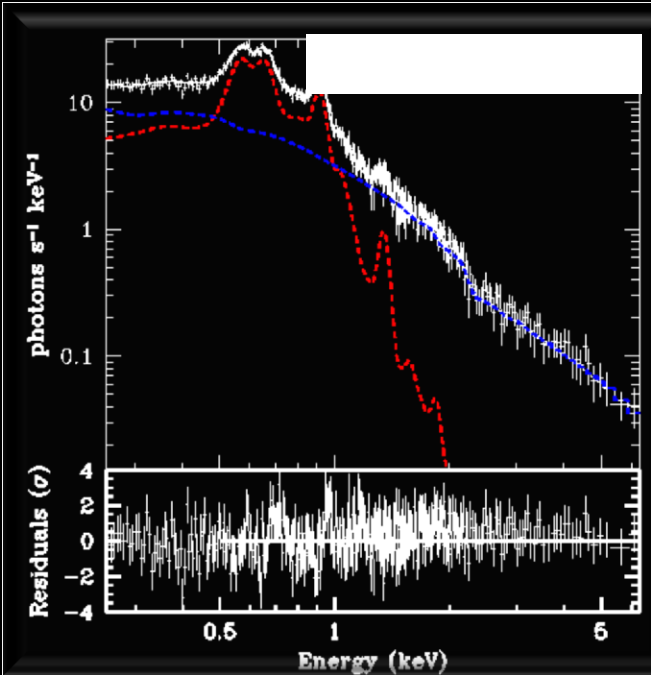
# Pulsar Wind Nebulae



Temim et al. 2009

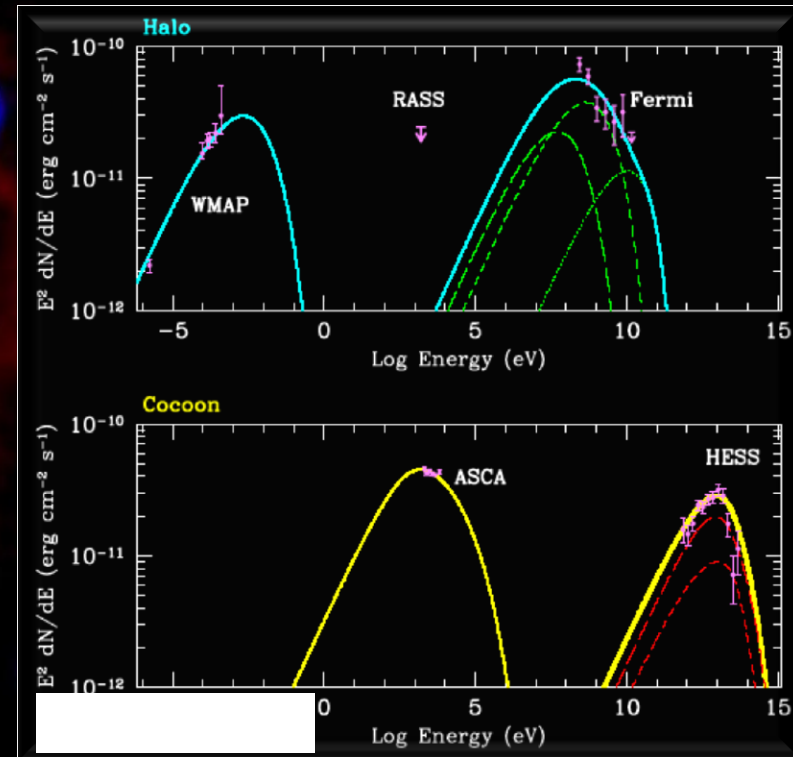
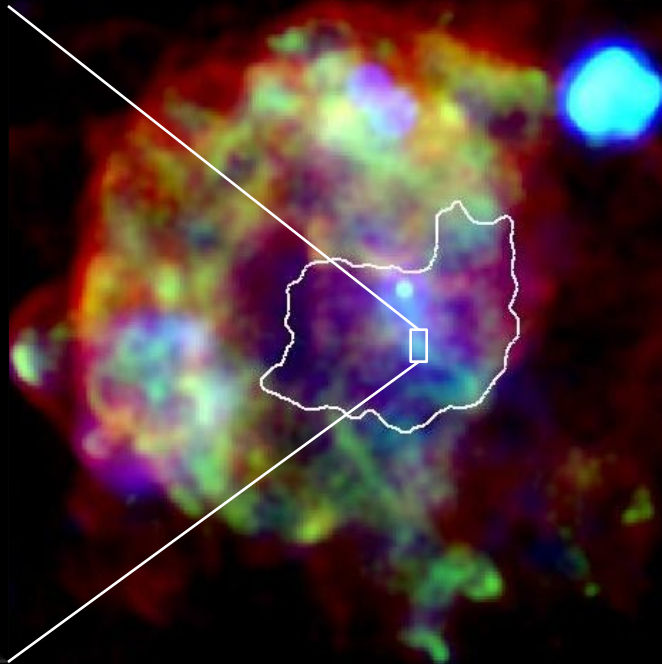
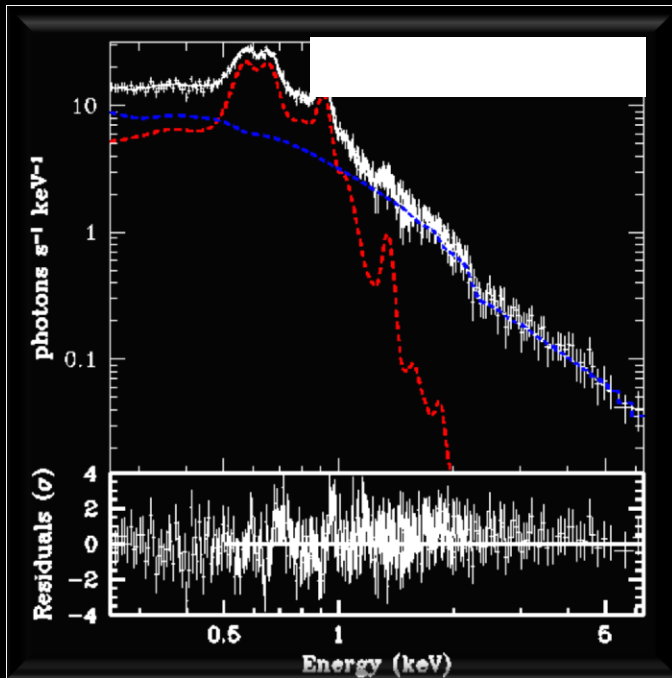
- Evolution of particles injected in shocks is complicated
  - adiabatic losses; reverse shock interactions; diffusion; time-varying magnetic fields; ambient photon fields, all for complex injection spectra
- E.g., simple calculations attributing local enhancements of energetic particles from such sources are, well, too simple...
  - multi- $\lambda$  studies needed to constrain evolution and escape of particles
  - evolved systems may be dominated by  $\gamma$ -ray emission

# Vela X: An Evolved PWN



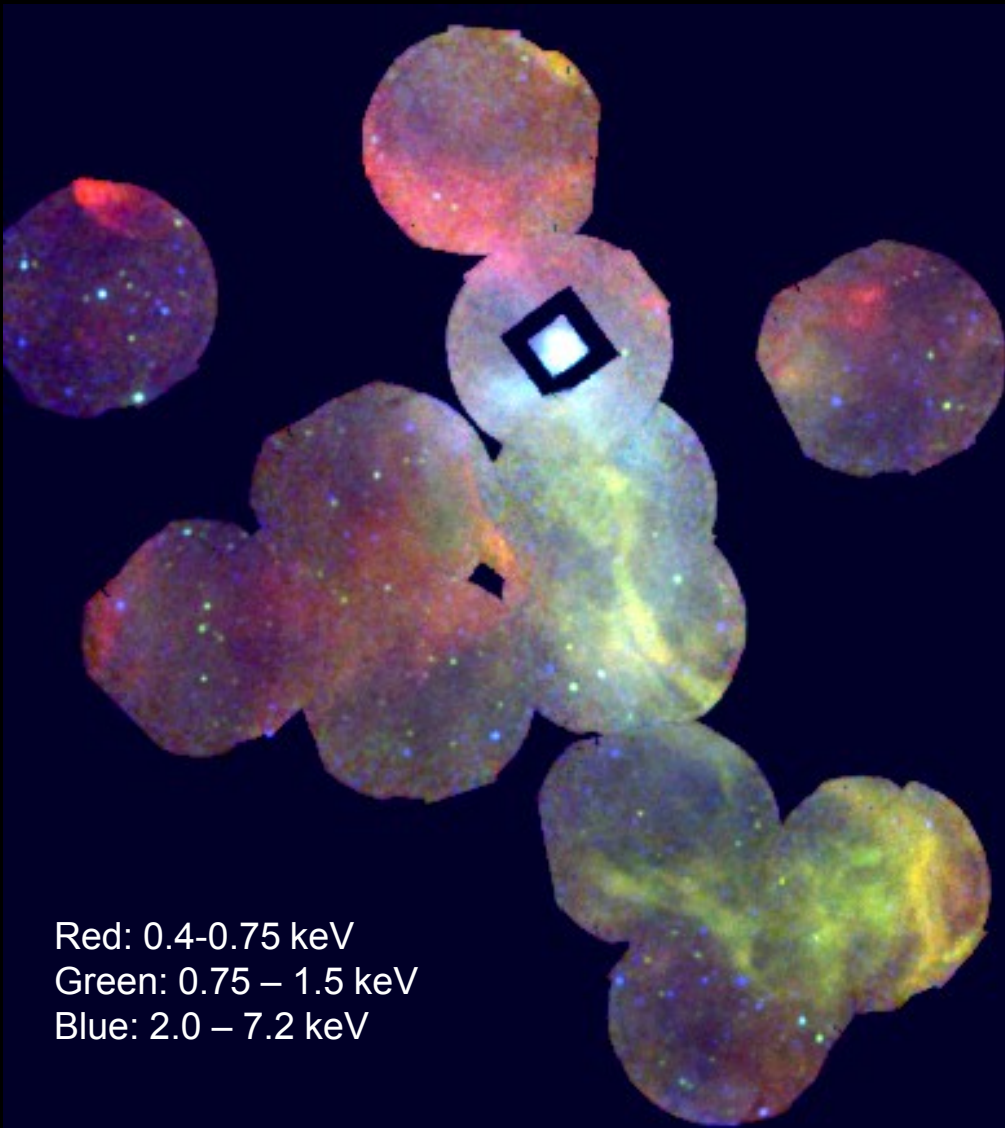
- XMM spectrum shows nonthermal and ejecta-rich thermal emission from cocoon
  - reverse-shock crushed PWN and mixed in ejecta?
- Broadband measurements consistent with synchrotron and I-C emission from PL electron spectrum w/ two breaks, or two populations
  - density too low for pion-production to provide observed  $\gamma$ -ray flux
  - magnetic field very low ( $5 \mu\text{G}$ )

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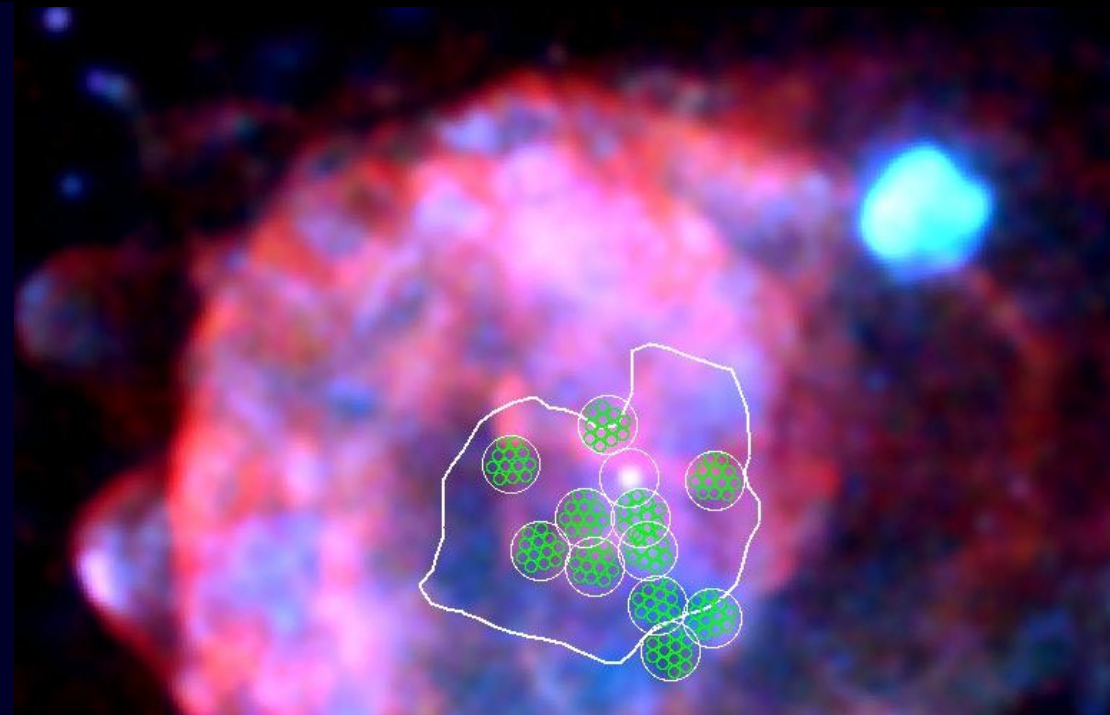


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# Vela X: XMM Large Project



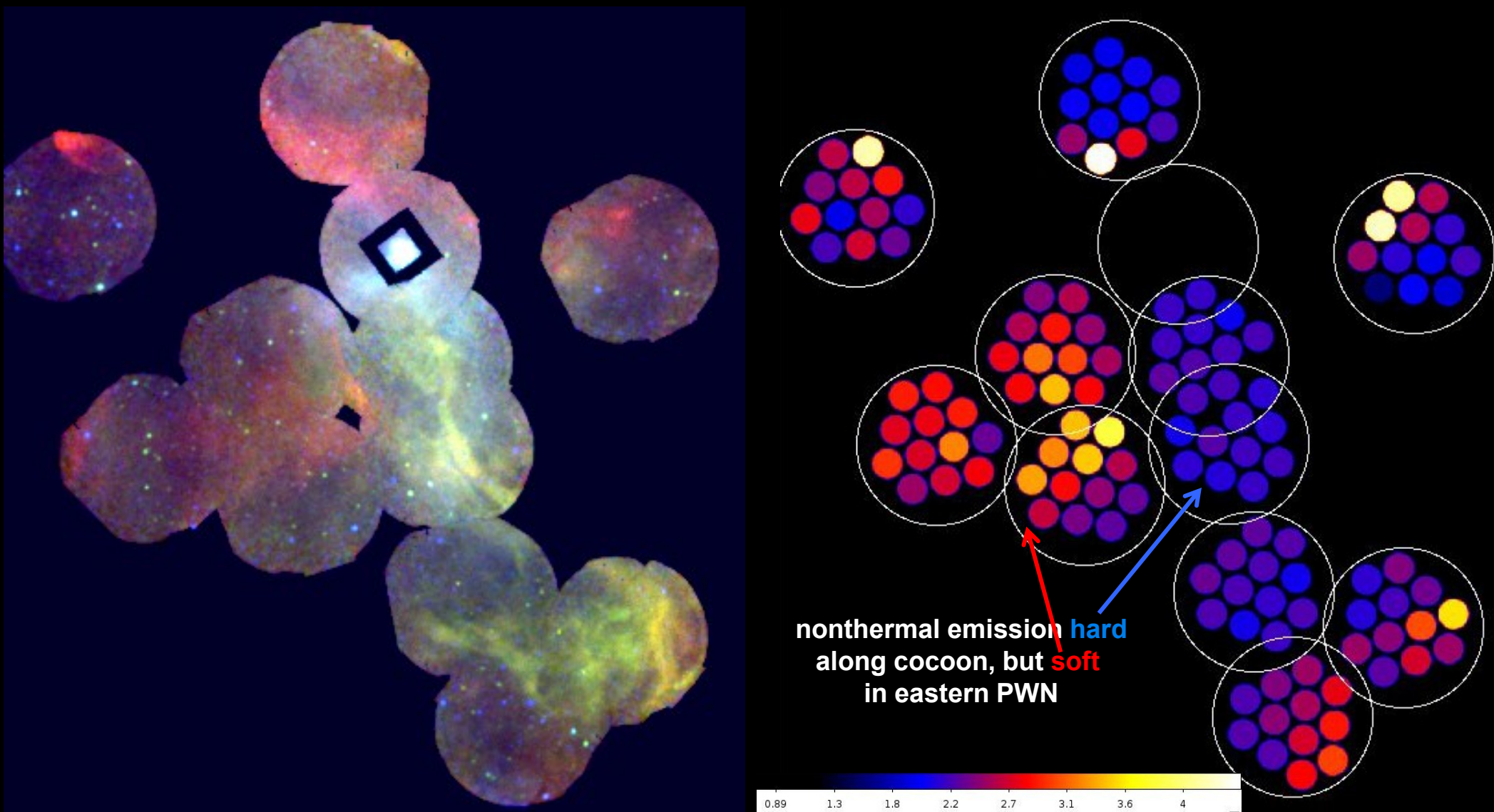
Red: 0.4-0.75 keV  
Green: 0.75 – 1.5 keV  
Blue: 2.0 – 7.2 keV



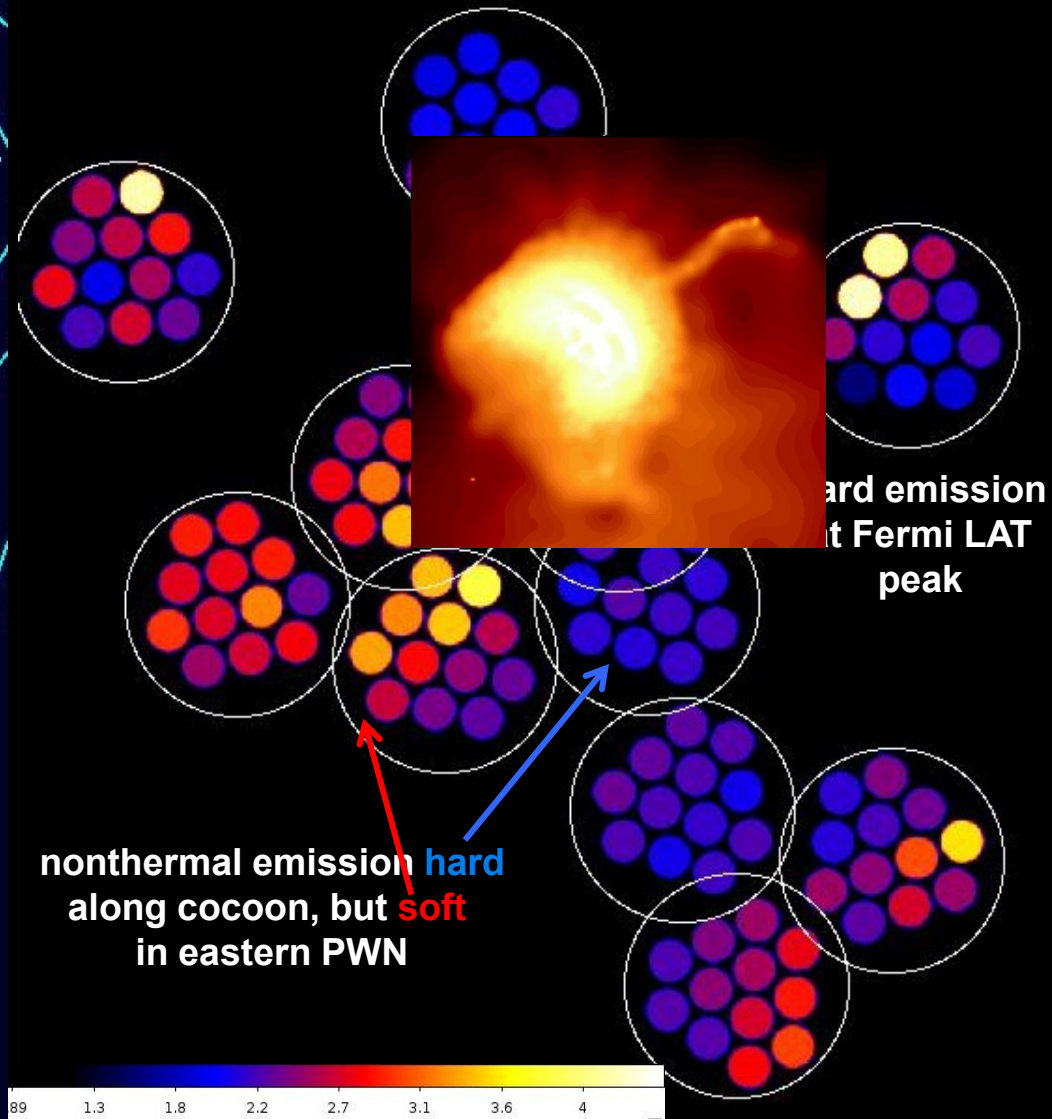
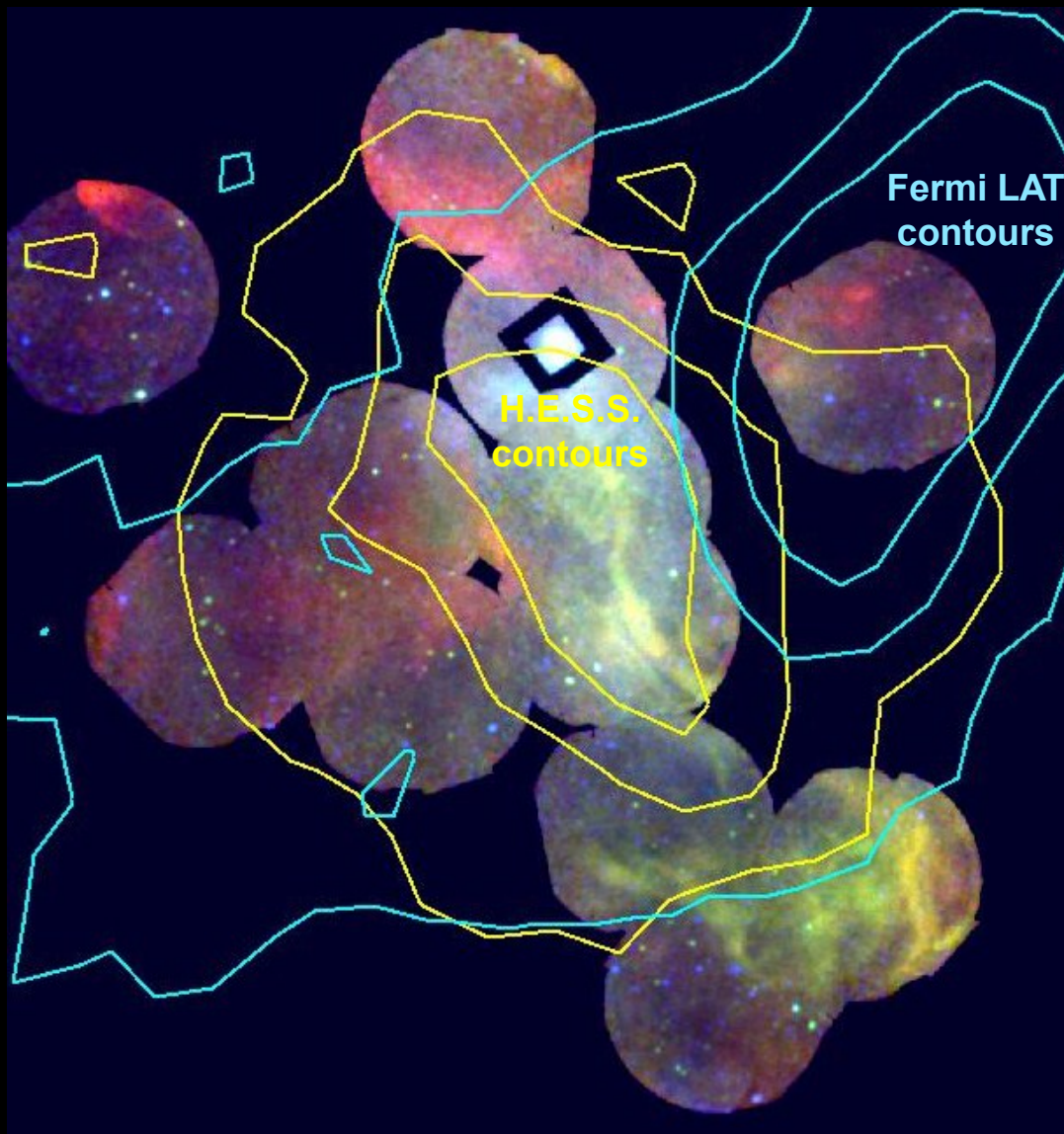
- Spectral fits in 12 regions for 11 pointings
  - model internal lines, extragalactic bkd, local ISM, particle bkd
  - use absorbed PL + VNEI for Vela X
- Thermal emission enriched w/ ejecta
- Observe variations in  $kT$ ,  $\Gamma$

**Note: very much a work in progress!**

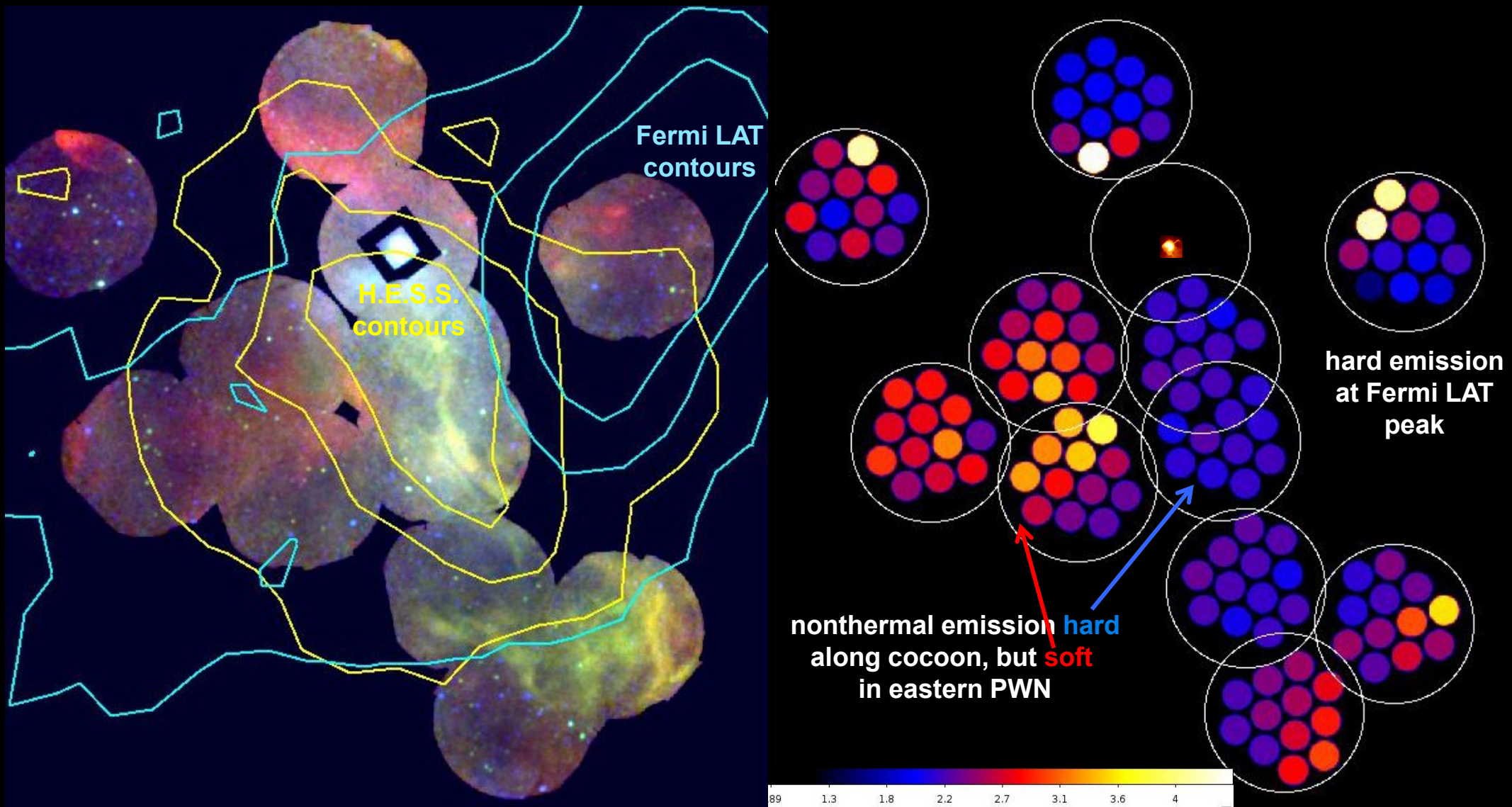
# Vela X: Spectral Index Map



# Vela X: XMM Large Project

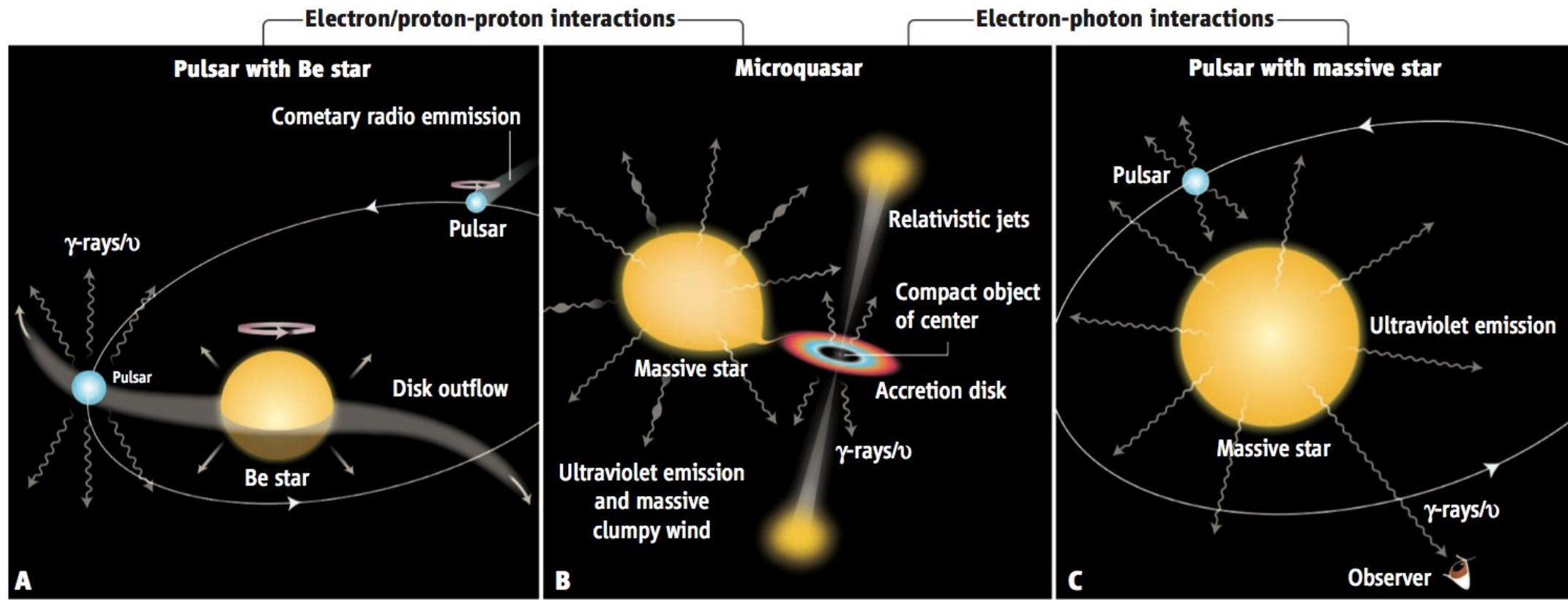


# Vela X: XMM Large Project



CTA studies should identify many more evolved PWNe. Resolution will allow us to measure distribution of emission, compare with radio/X-ray, and look for energy-dependent morphology.

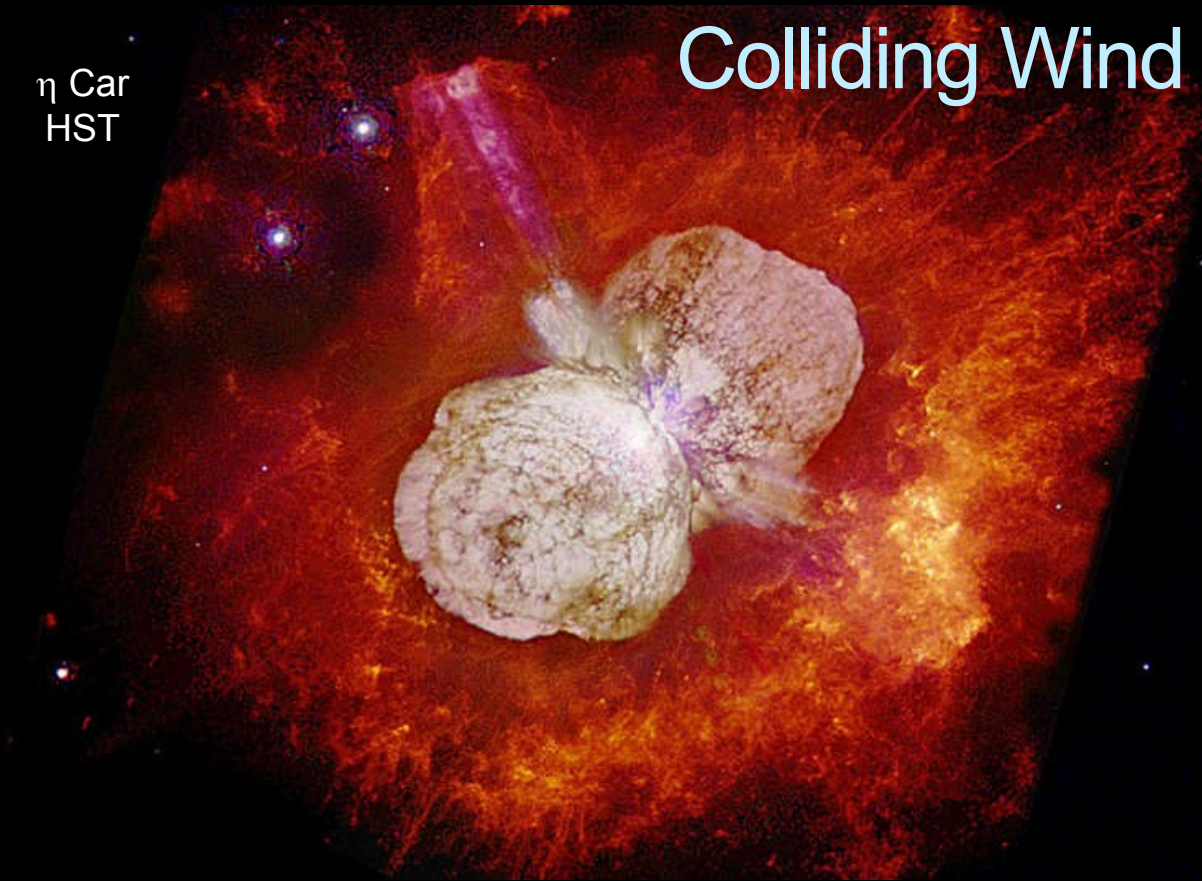
# Gamma-Ray Binaries



See talk by Felix Mirabel

# Colliding Wind Systems

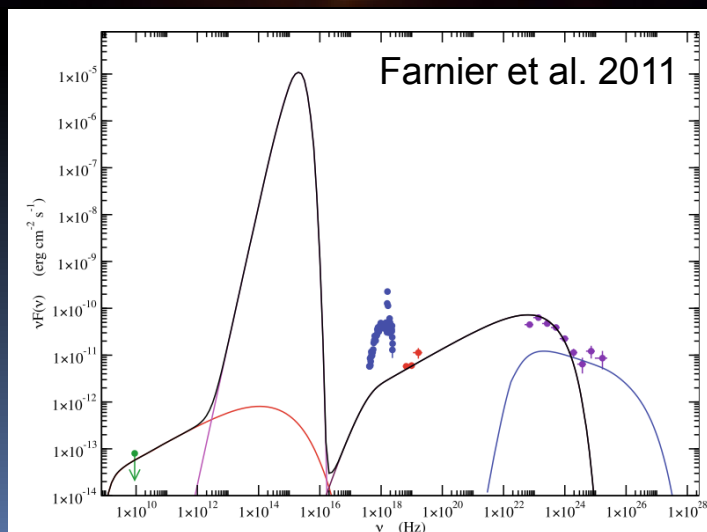
$\eta$  Car  
HST



- Fast winds in massive stellar binaries may result in particle acceleration

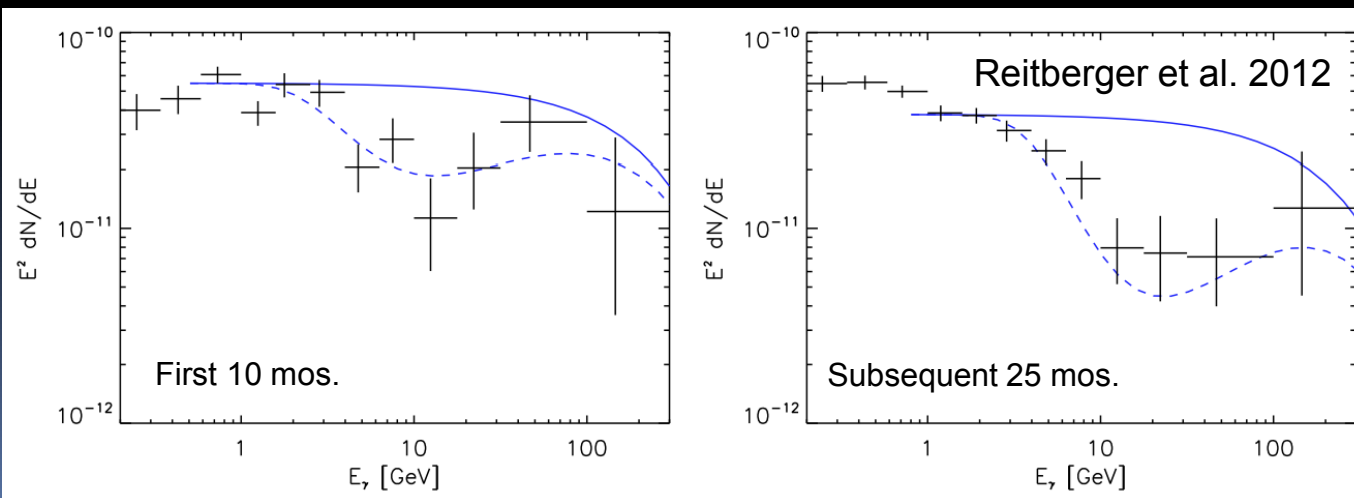
# Colliding Wind Systems

- Fast winds in massive stellar binaries may result in particle acceleration
- Chandra observations of  $\eta$  Car show both point-like and extended emission
  - the latter is hard and may result from the colliding winds
- BeppoSAX and INTEGRAL observation show hard emission extending to  $E > 70$  keV
- Fermi observations suggest hadronic emission
  - may show evidence for  $\gamma$ - $\gamma$  attenuation from gas within or surrounding binary system



# Colliding Wind Systems

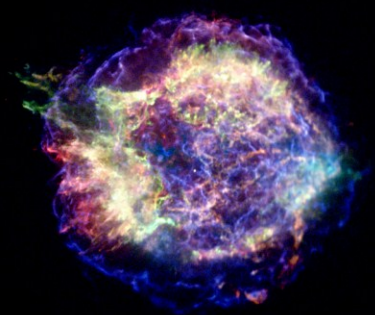
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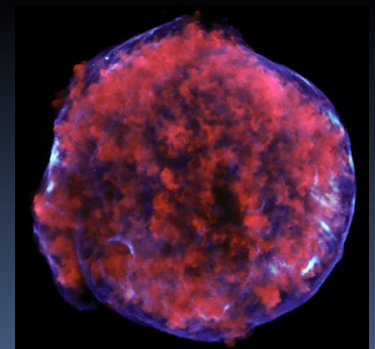
# Multi- $\lambda$ Studies of CR Acceleration in SNRs



- 1E 0102.2-7219: Expansion measurements show  $v_{\text{sh}} \approx 6000 \text{ km s}^{-1}$ 
  - X-ray studies give  $kT = 0.4 - 1.0 \text{ keV}$ ; much too low unless considerable energy has gone into something other than heating of plasma (Hughes et al. 2000)

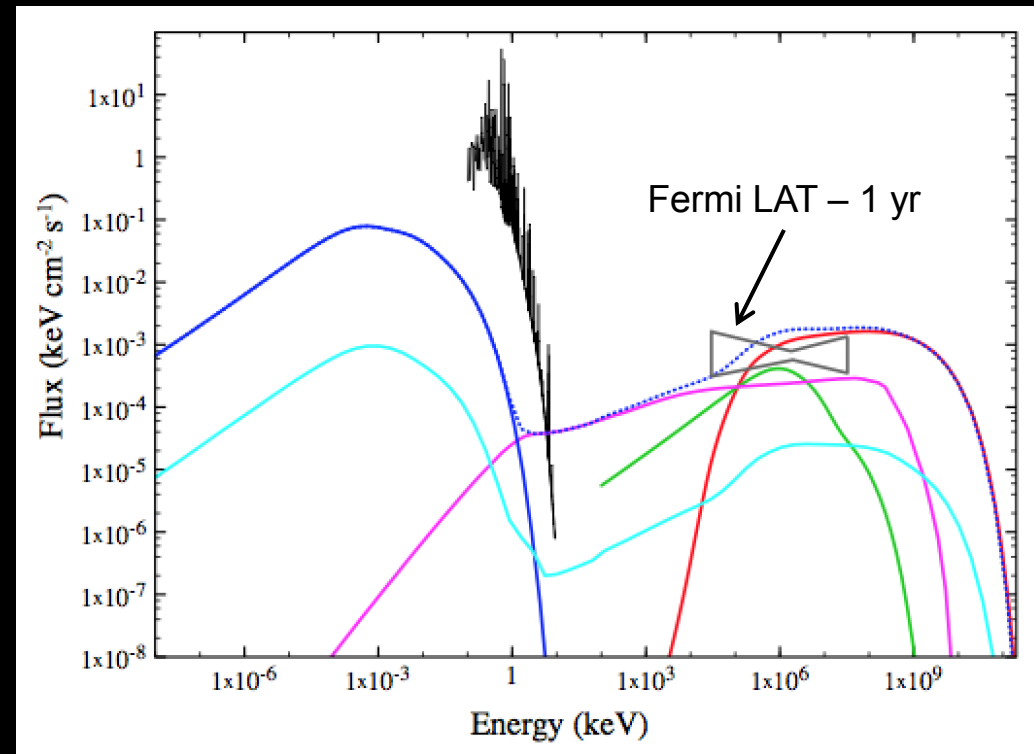
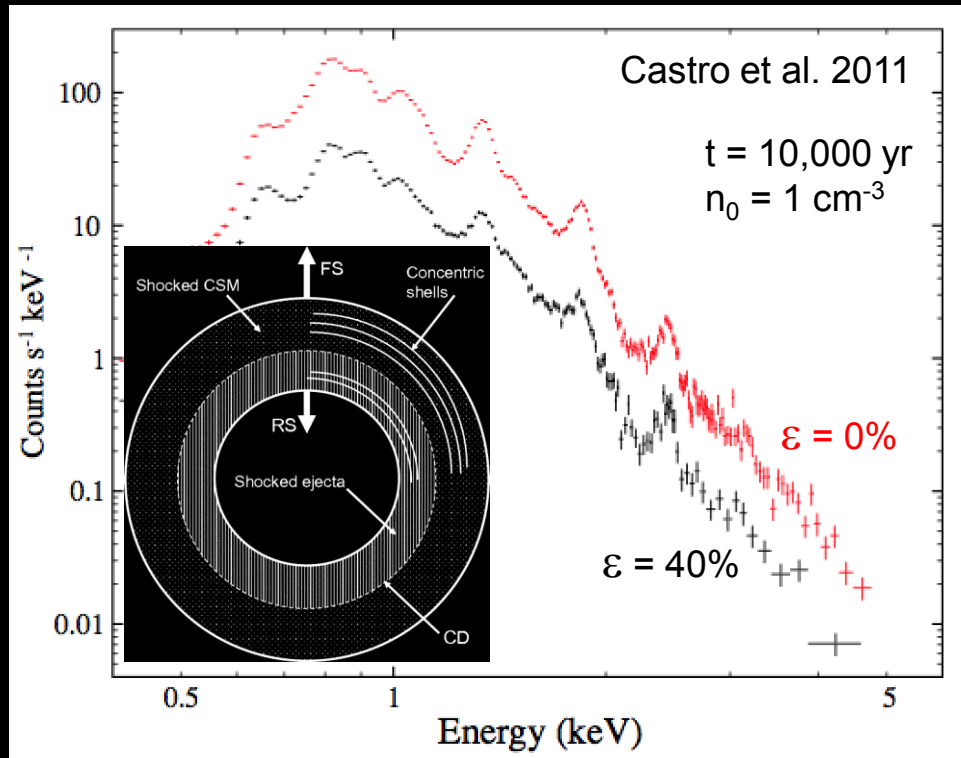


- Cas A: Nonthermal X-rays give  $E_e > 100 \text{ TeV}$ 
  - variability of nonthermal X-rays implies magnetic field amplification – byproduct of particle acceleration
  - broadband modeling, including GeV/TeV emission, also requires efficient acceleration of CRs



- Tycho: Dynamical measurements of shock positions and temperature, along with known age, require efficient CR acceleration (Warren et al. 2005)
  - modeling of radio, X-ray synchrotron, + GeV/TeV emission confirms scenario

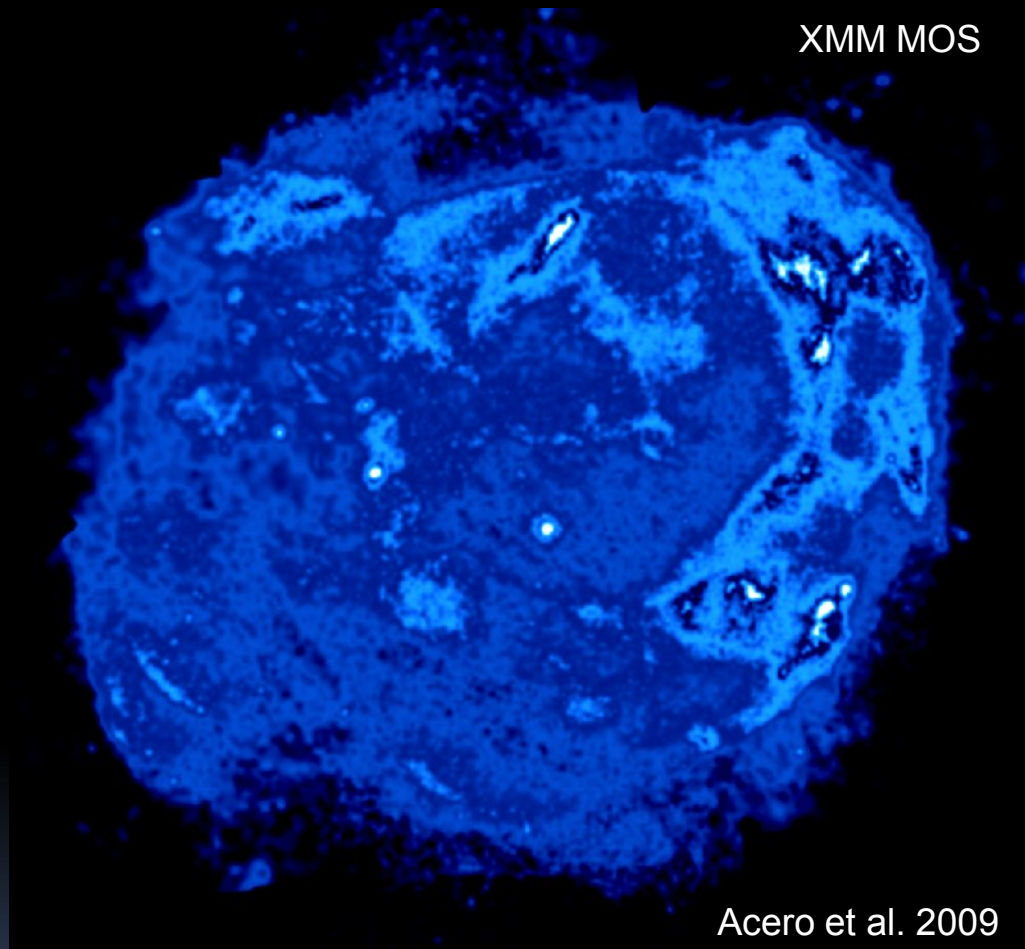
# Multi- $\lambda$ Studies of CR Acceleration in SNRs



- Middle-aged SNRs have swept up so much mass that thermal emission can hide nonthermal X-rays; are there still signatures of CR acceleration?
  - YES: application of standard Sedov models (i.e., ignoring acceleration) will yield low explosion energies
  - But these remnants may still be detectable by GeV/TeV telescopes

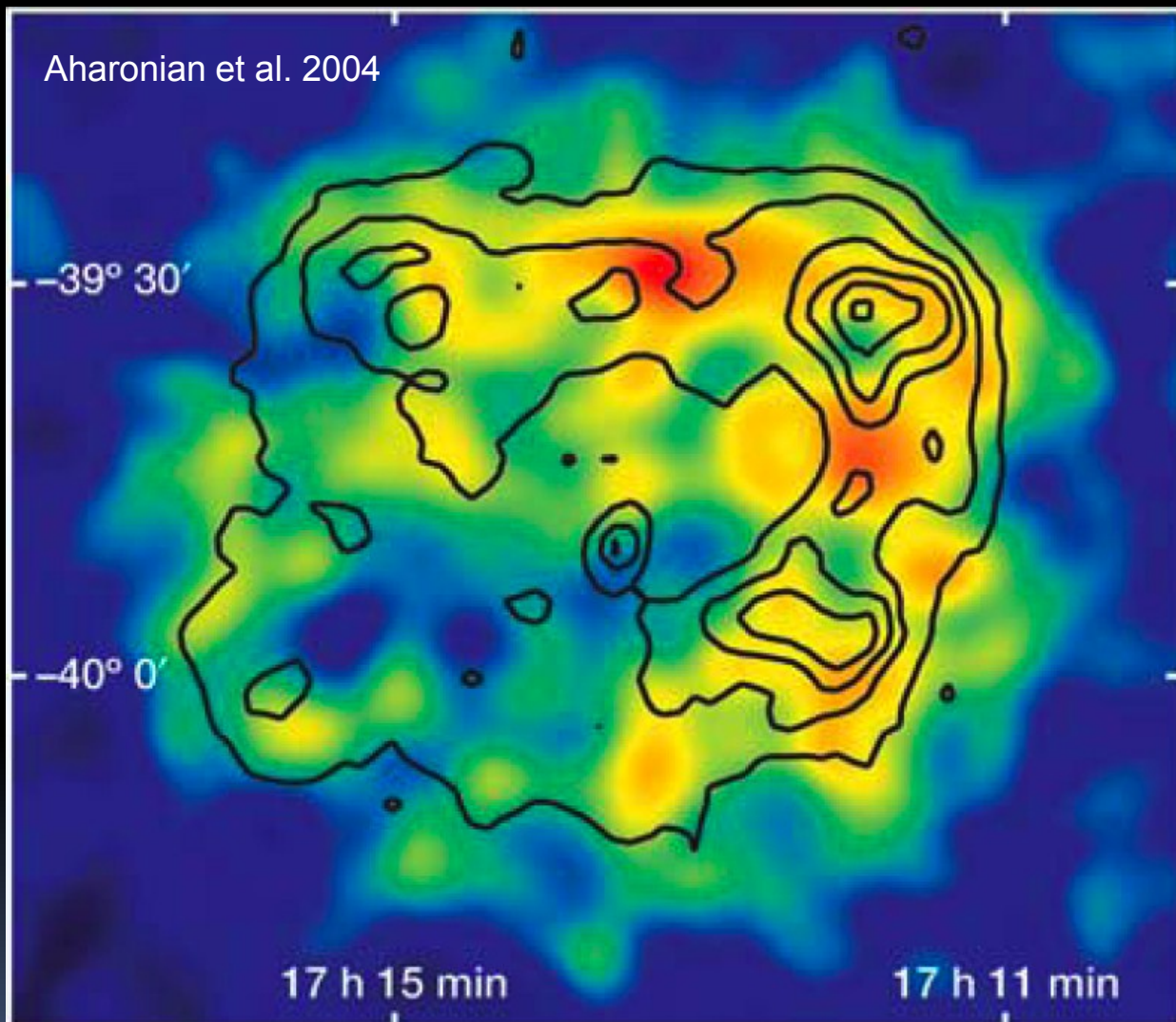
As discussed below, we may be seeing these now. Better sensitivity (particularly angular resolution) at gamma-ray energies is crucial here.

# G347.3-0.5/RX J1713.7-3946



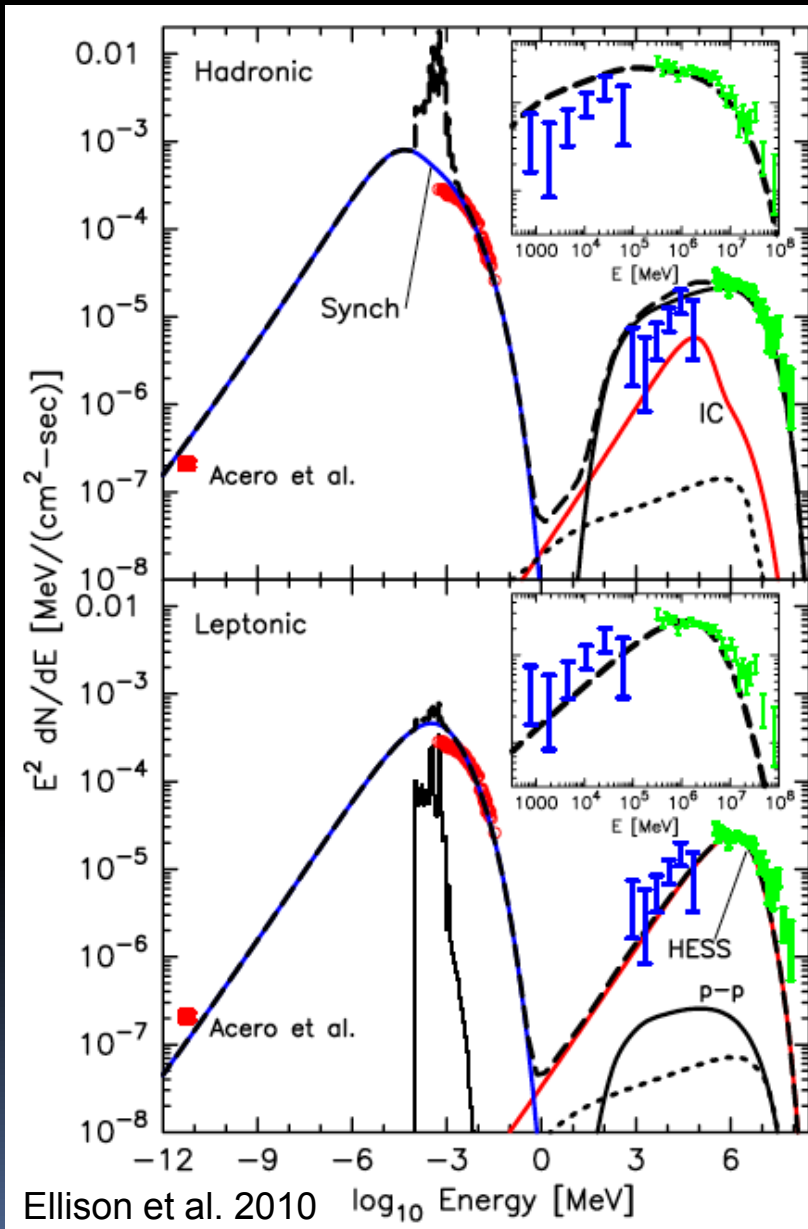
- X-ray observations reveal nonthermal spectrum
  - no hint of thermal emission
- SNR detected directly in TeV  $\gamma$ -rays
  - $\gamma$ -ray morphology very similar to X-rays; I-C?

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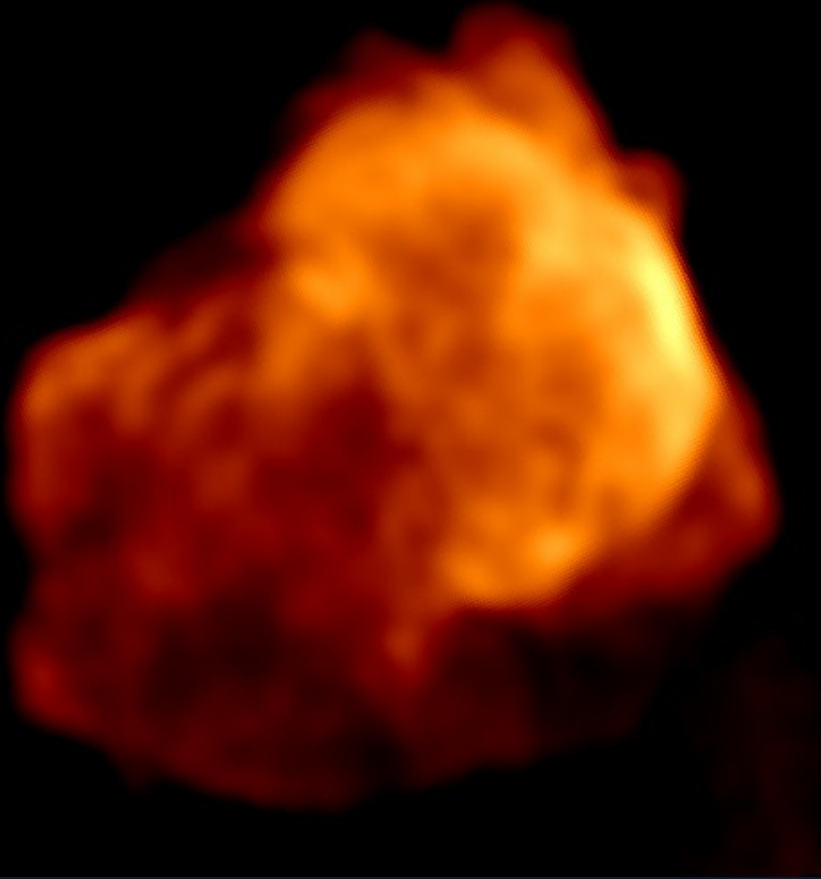


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- SNR detected directly in TeV  $\gamma$ -rays  
-  $\gamma$ -ray morphology very similar to X-rays; I-C?
- Broadband modeling shows  $\gamma$ -rays are dominated by leptons

NOTE: Hadrons are accelerated; they dominate the energy.

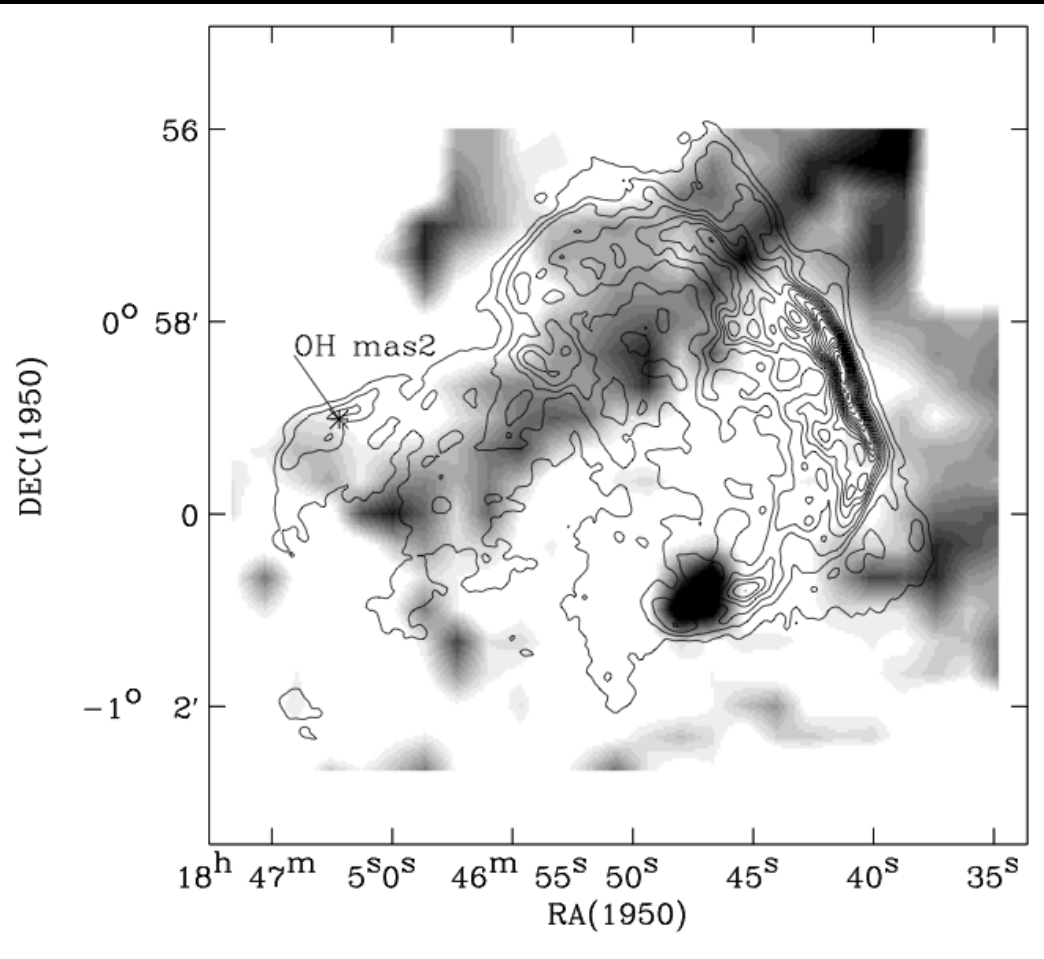
Also: Spectral curvature is included, and  $E_{\text{max}} > 10^{14}$  eV

# SNRs in Dense Environments: 3C 391



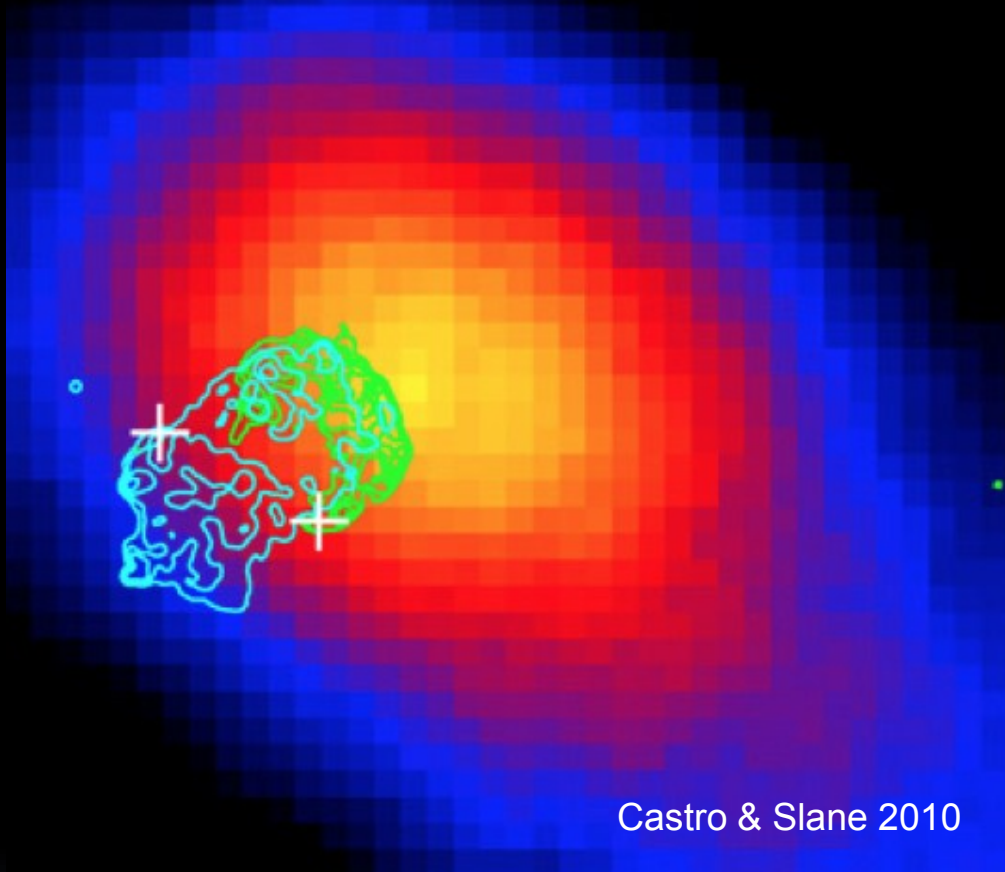
- SNRs interacting with molecular clouds are likely sources of hadronic emission
  - high density supports  $\pi^0 \rightarrow \gamma\gamma$  from p-p collisions
- 3C 391 shows distinct evidence of MC interaction
  - bright, flattened radio morphology
  - adjacent CO cloud
  - OH masers

# SNRs in Dense Environments: 3C 391



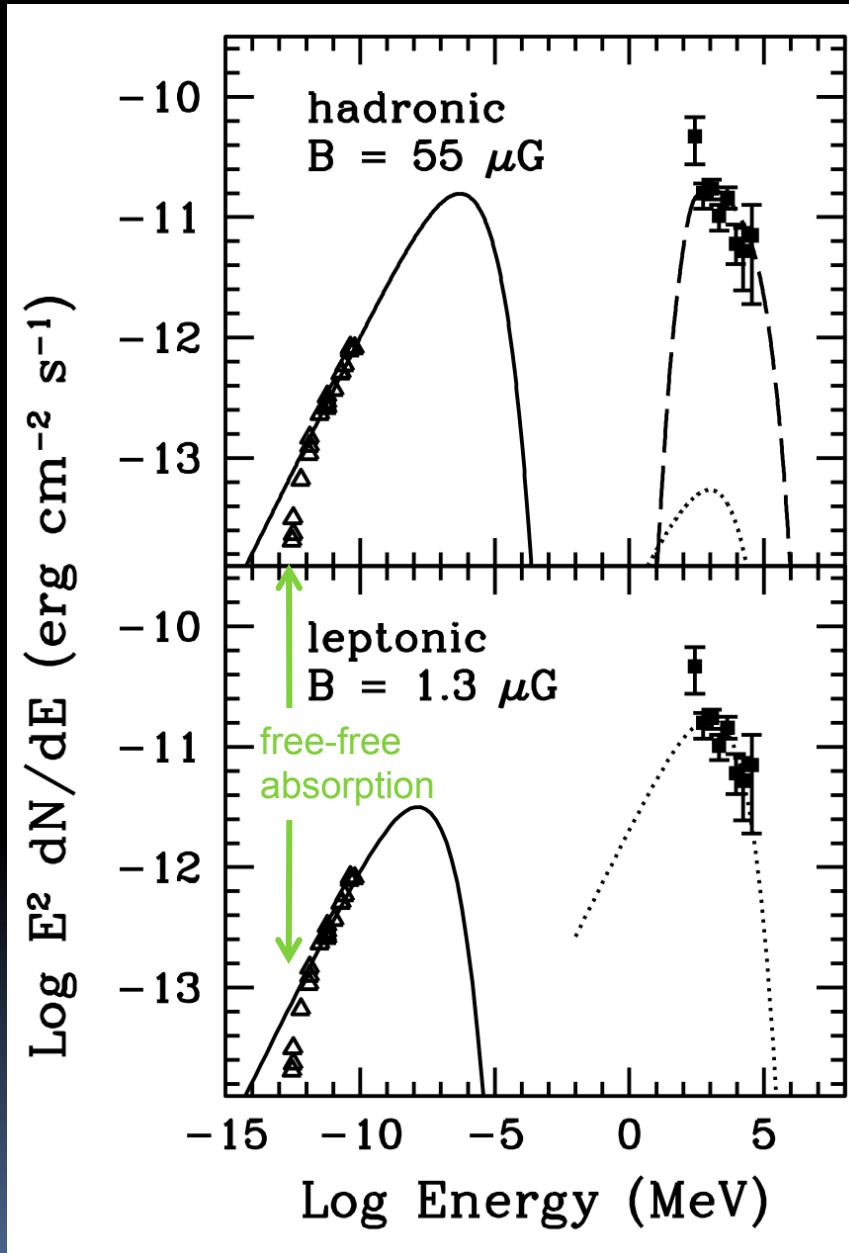
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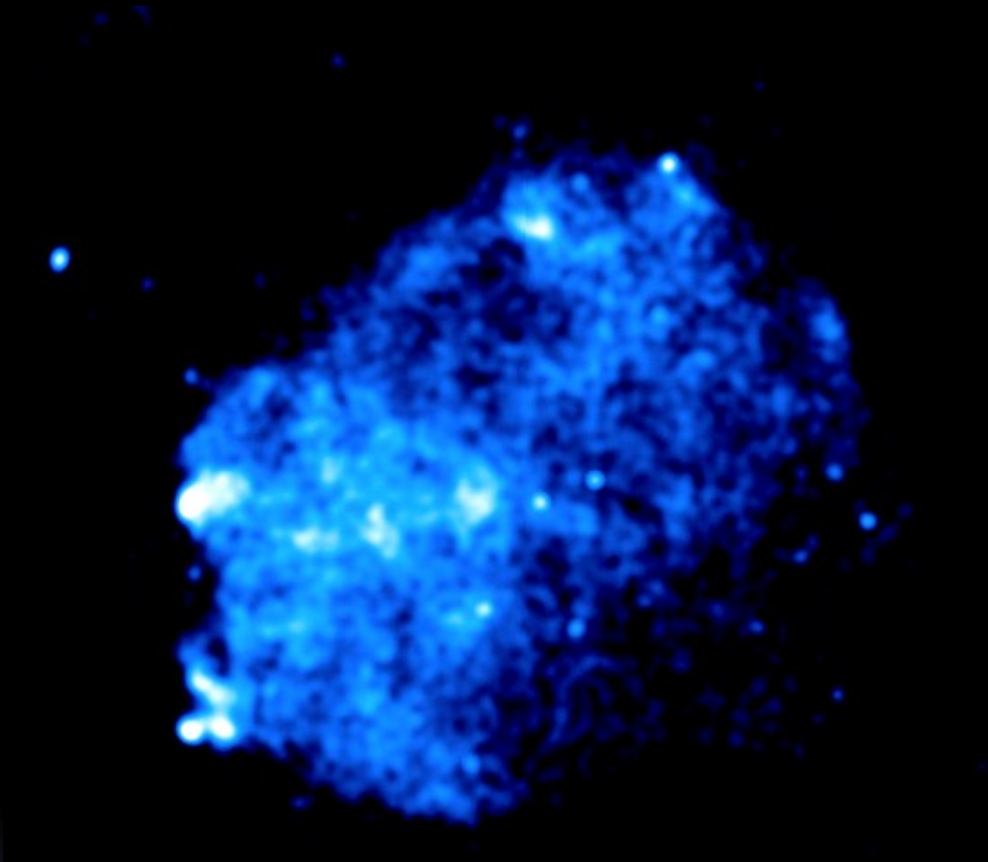
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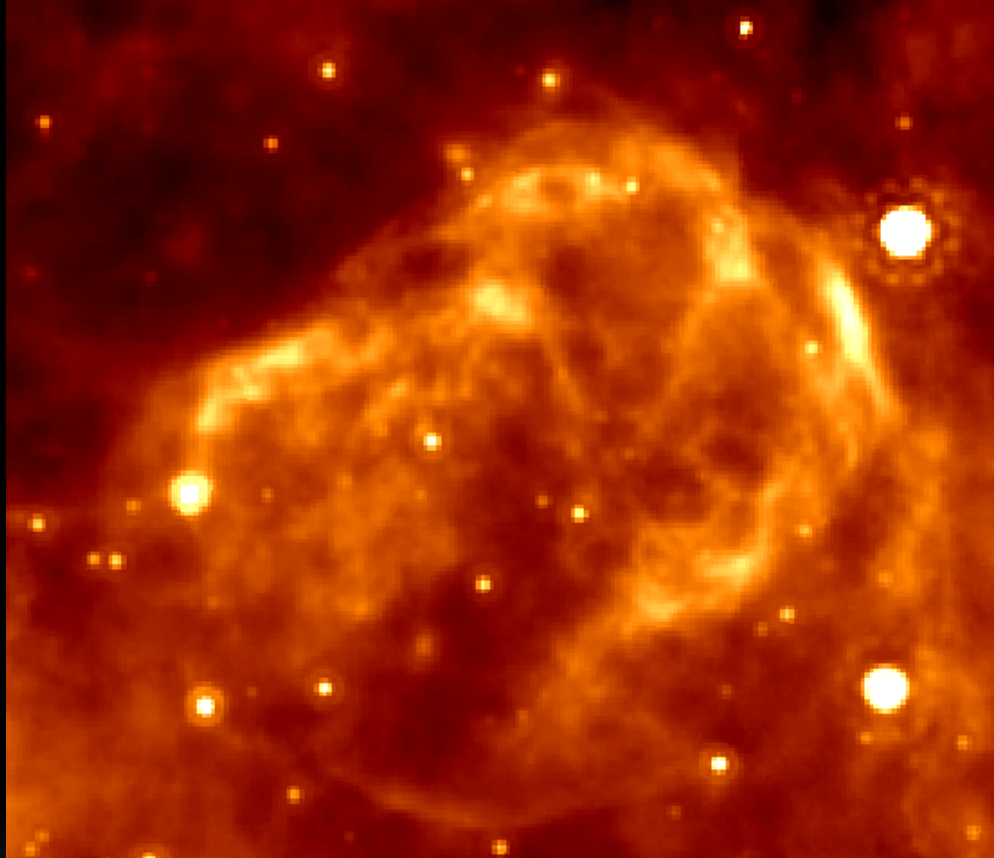
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  - IC model requires  $E_e > 10^{51}$  erg;  $\pi^0$  emission must dominate
  - inferred density much higher than X-rays indicate; suggests clumping, which is supported by X-ray images

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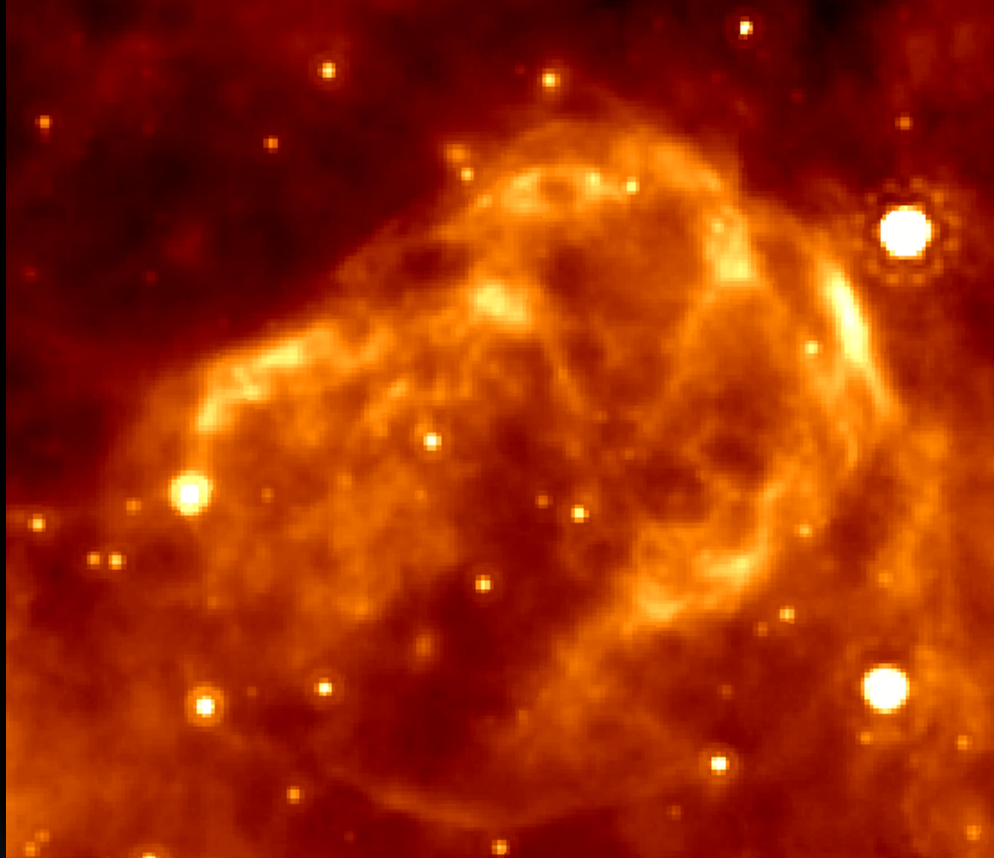
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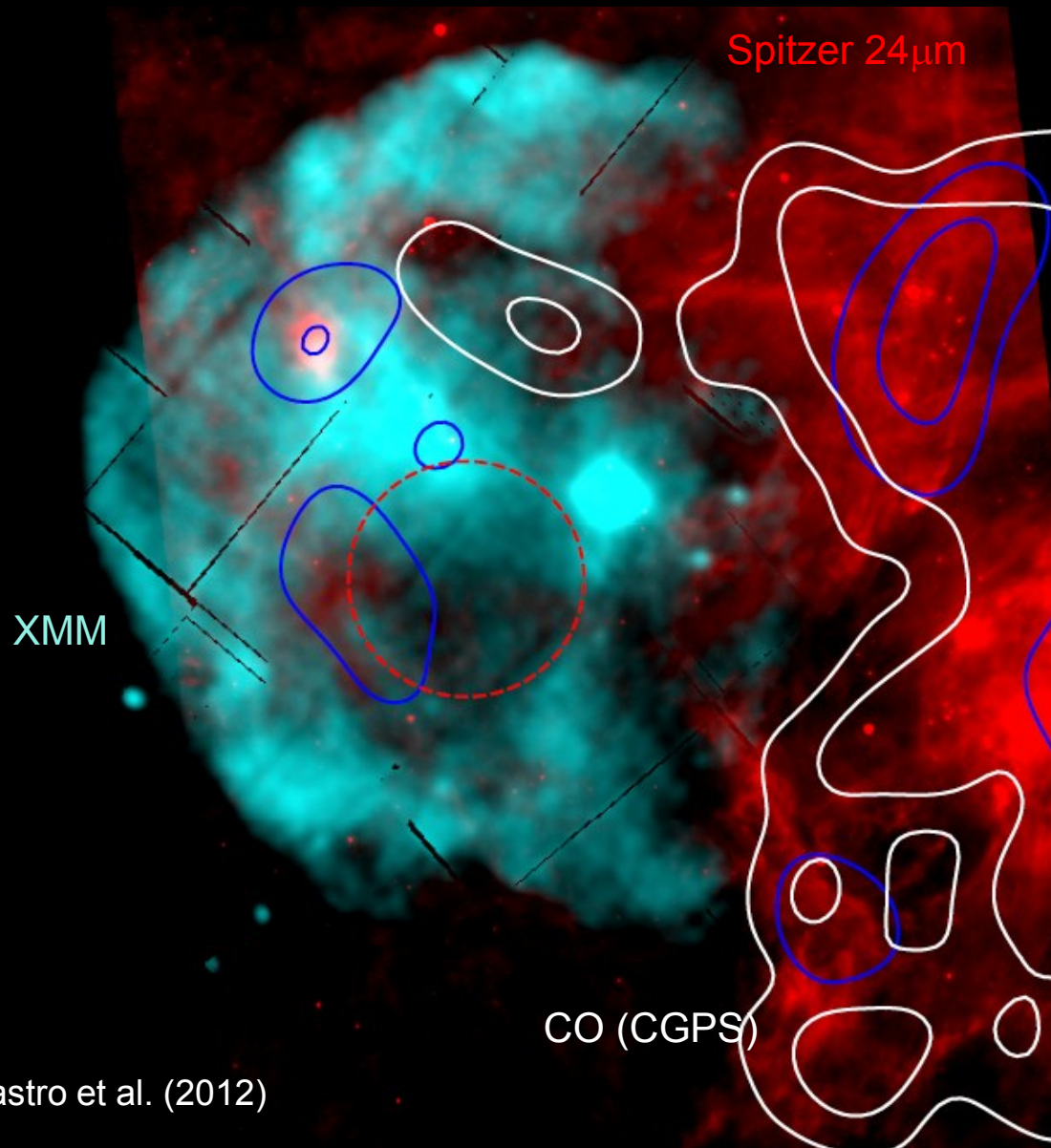
# SNRs in Dense Environments: 3C 391



More sensitive observations, particularly at high energies, and with improved spatial resolution, are needed to confirm the nature of the emission from such SNRs interacting w/ MCs

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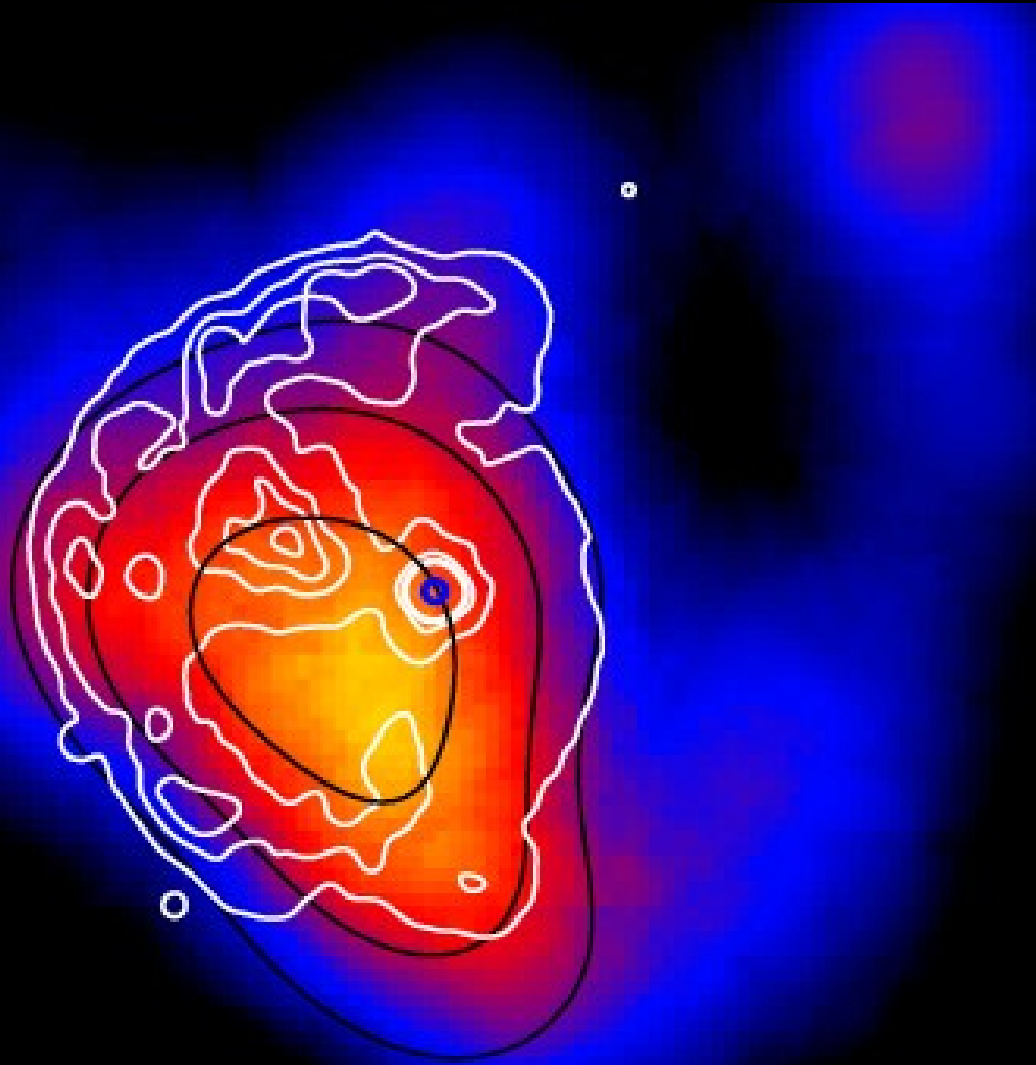
# Particle Acceleration in CTB 109



- CTB 109 is interacting with a massive molecular cloud
  - small cloud interactions as well
  - no nonthermal X-ray emission

Castro et al. (2012)

# Particle Acceleration in CTB 109

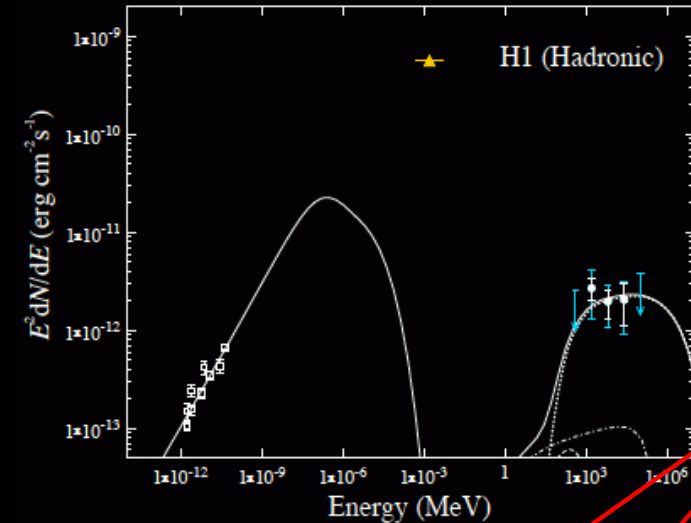


Castro et al. (2012)

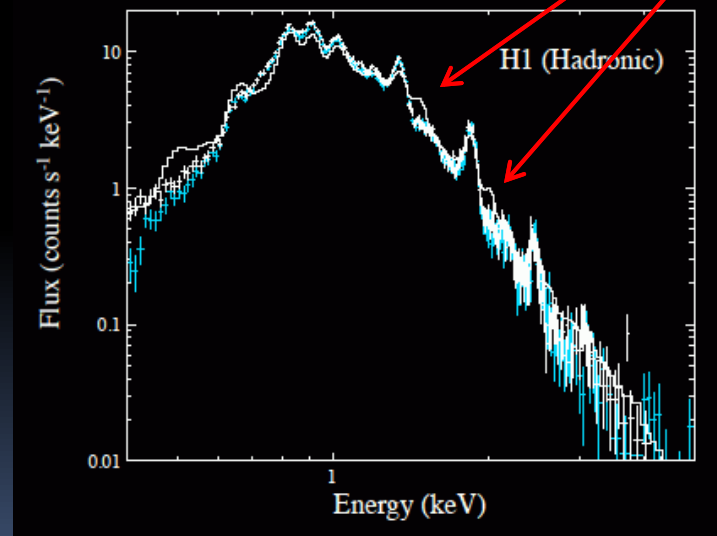
- CTB 109 is interacting with a massive molecular cloud
  - small cloud interactions as well
  - no nonthermal X-ray emission
- SNR is detected in Fermi LAT
  - emission concentrated on SNR, not from western MC region
- GeV emission can be fit by both hadronic and leptonic models
  - self-consistent modeling that includes thermal X-ray emission solves the problem

# Particle Acceleration in CTB 109

Castro et al. (2012)

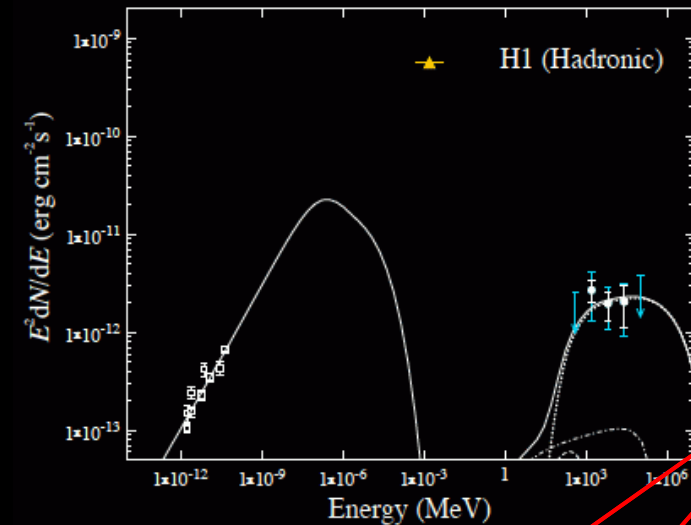


- Hadronic model requires high density and small distance
  - high ionization states overpredicted due to high density

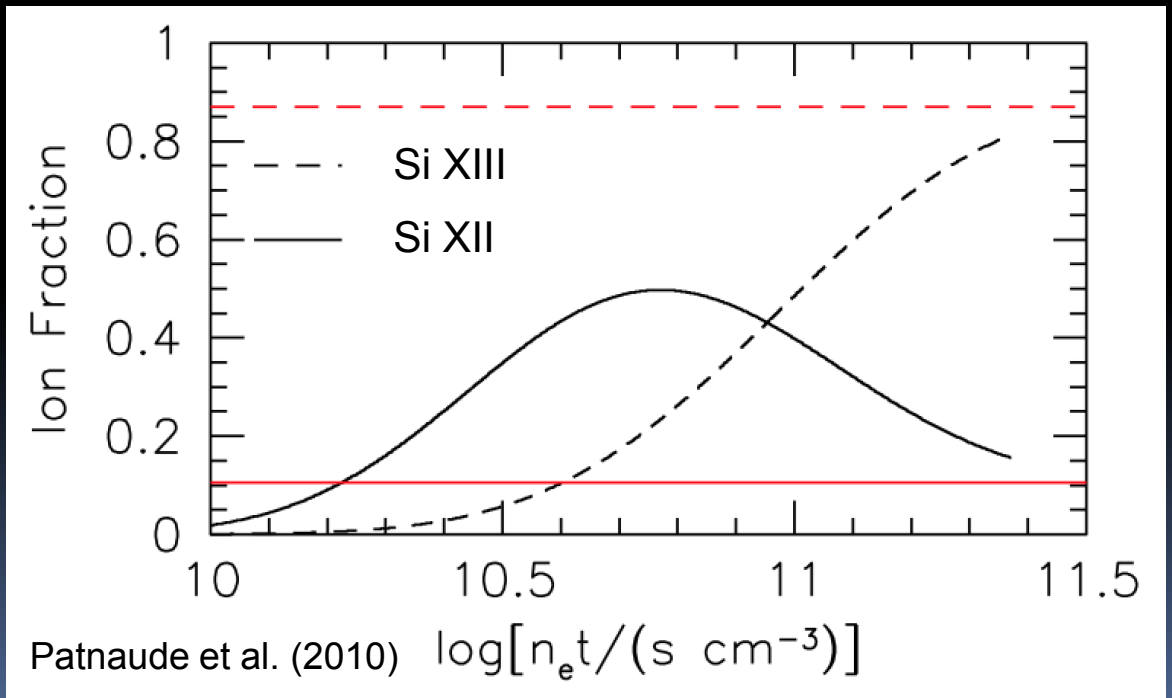
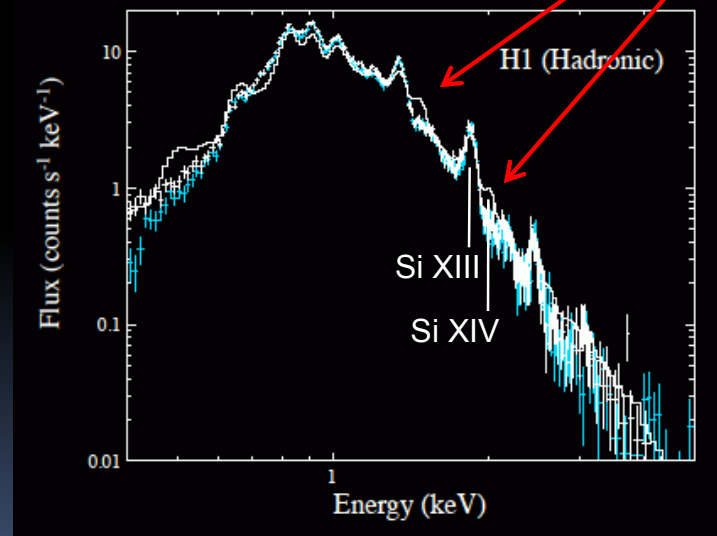


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Castro et al. (2012)

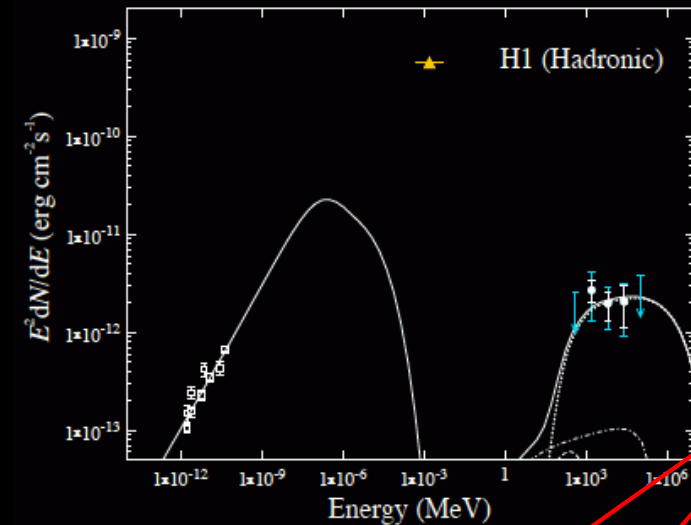


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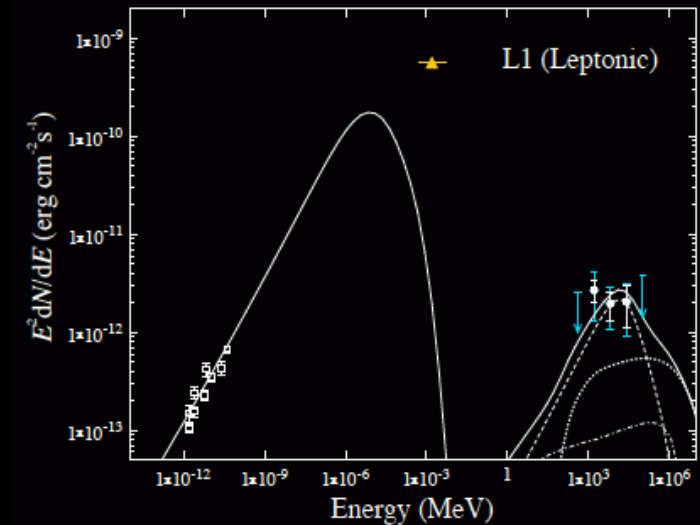


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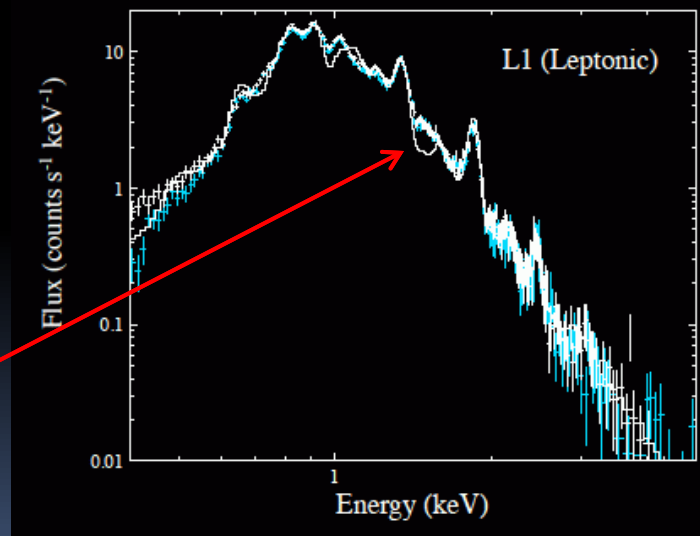
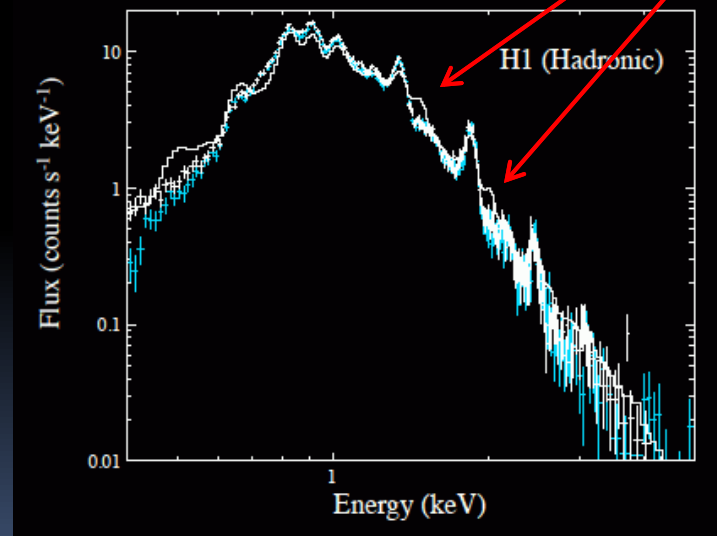
Castro et al. (2012)



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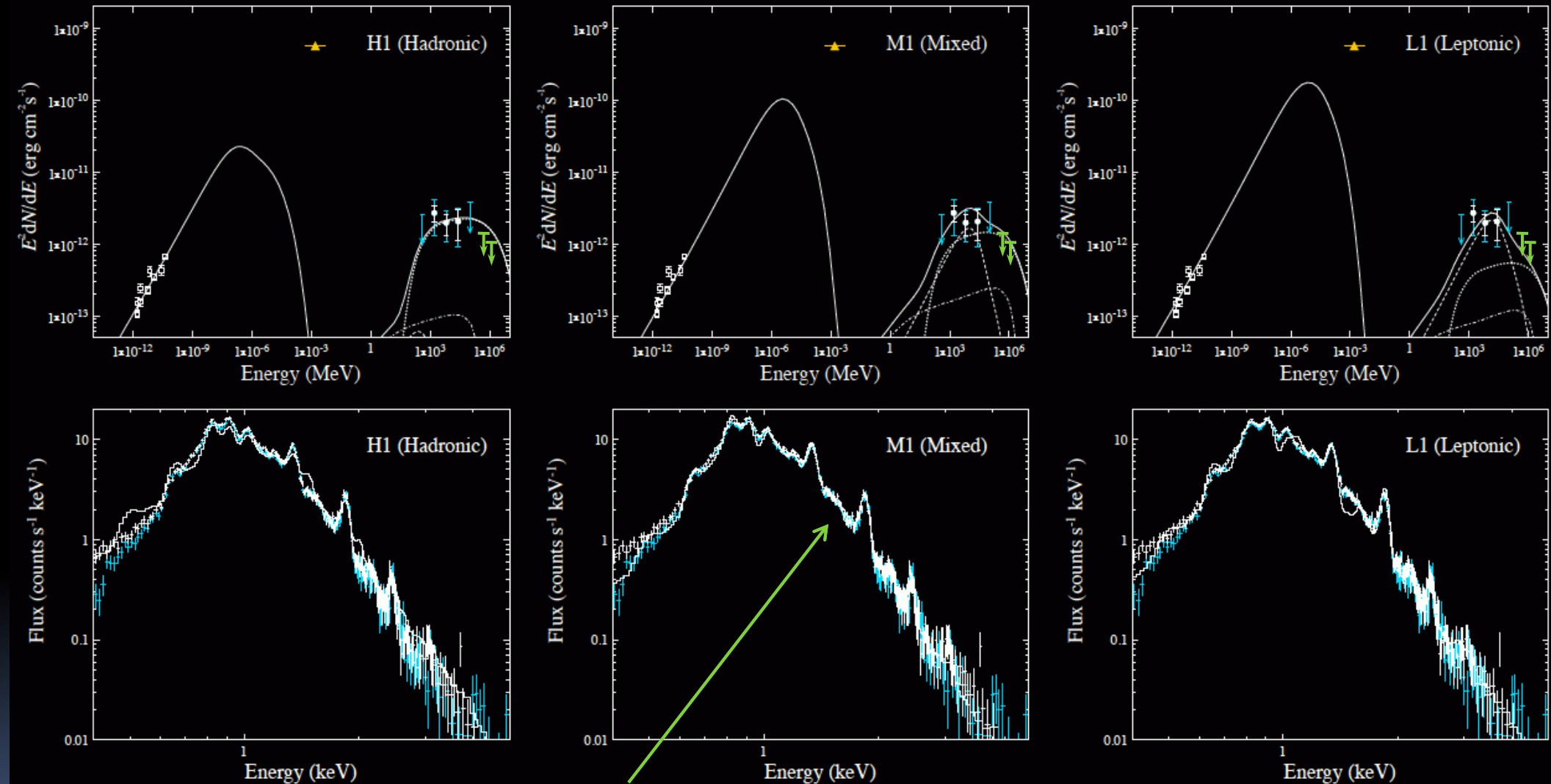


- Leptonic model requires low density and larger distance
  - high ionization states now underpredicted



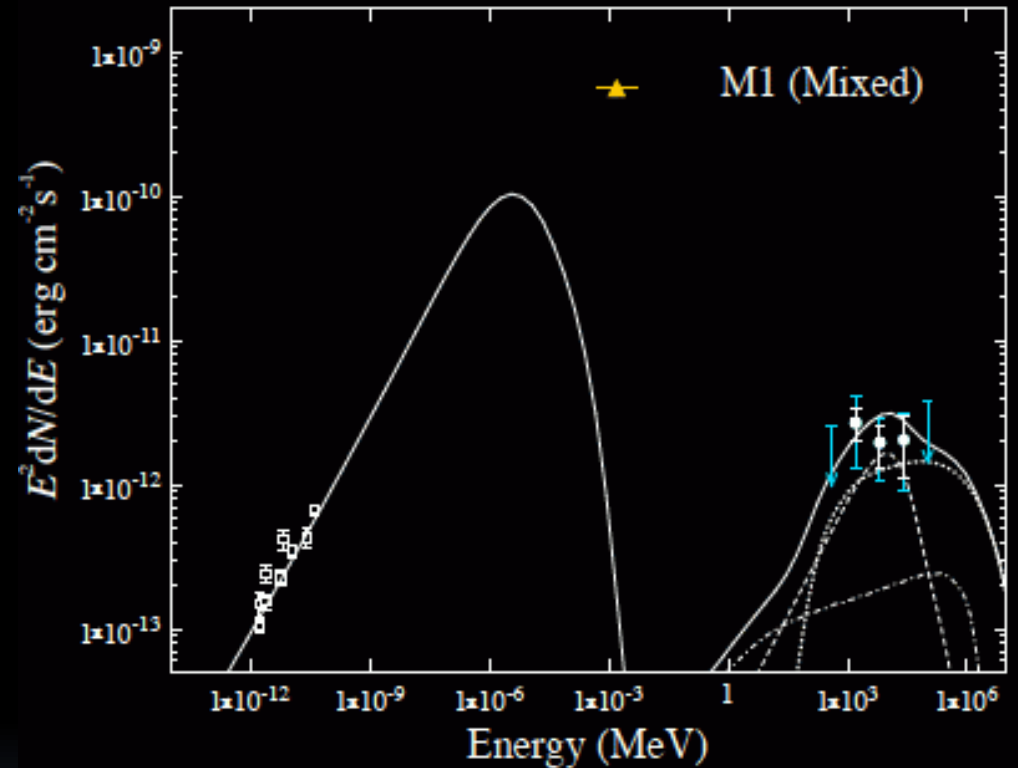
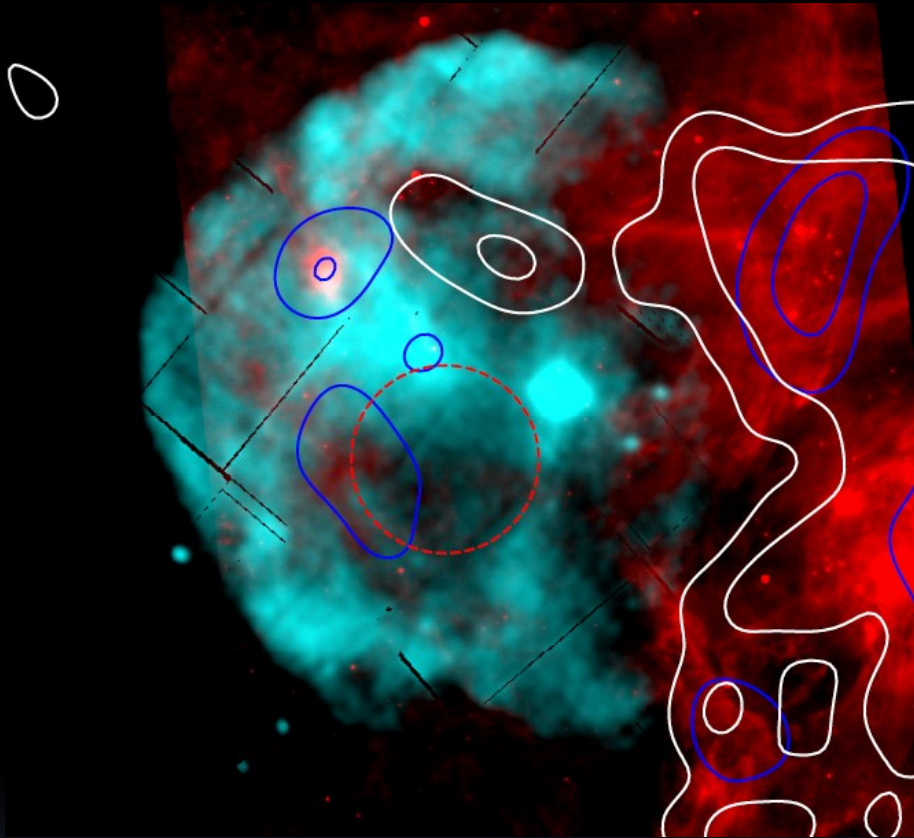
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Castro et al. (2012)



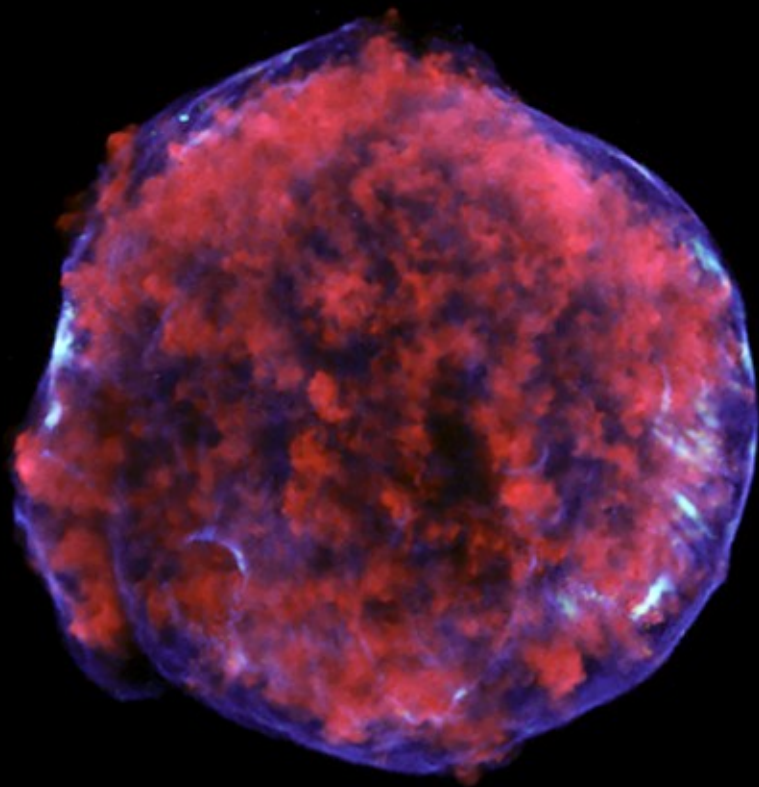
- Mixed leptonic/hadronic scenario provides excellent fit to spectra.

# Particle Acceleration in CTB 109



Improved localization of gamma-ray emission, and sensitive measure of TeV spectrum are required to understand source of interaction and nature of particle acceleration process.

# Gamma-Rays from Tycho's SNR



- Tycho's SNR is shows strong dynamical evidence for CR acceleration

# Gamma-Rays from Tycho's SNR

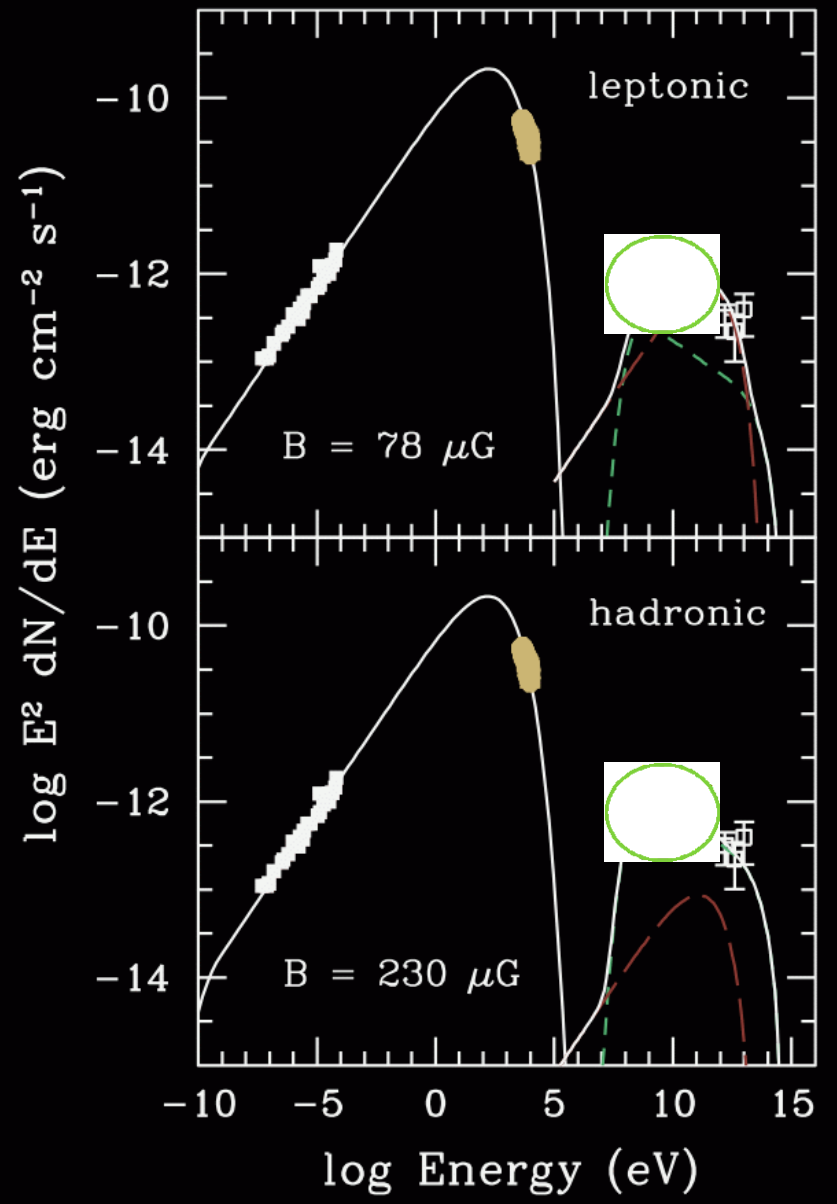
Acciari et al. 2011



- Tycho's SNR is shows strong dynamical evidence for CR acceleration
- Tycho is also detected in  $\gamma$ -rays
  - VERITAS centroid appears shifted slightly toward molecular cloud

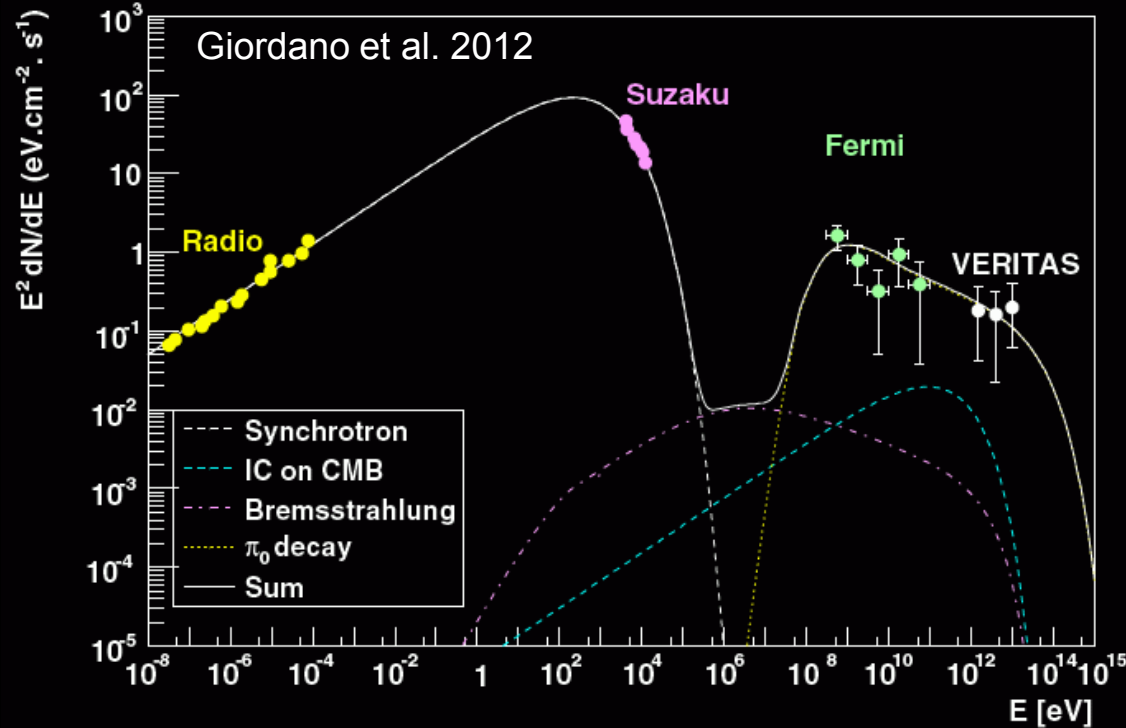
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Acciari et al. 2011



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  - VERITAS centroid appears shifted slightly toward molecular cloud
- Both hadronic and leptonic models can reproduce broadband spectrum

# Gamma-Rays from Tycho's SNR



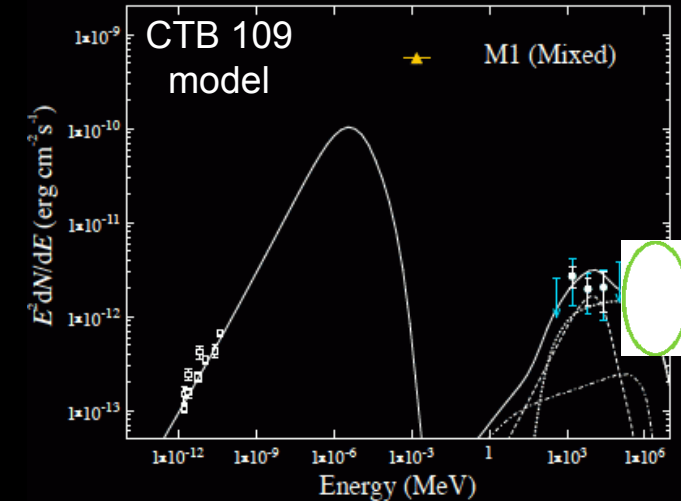
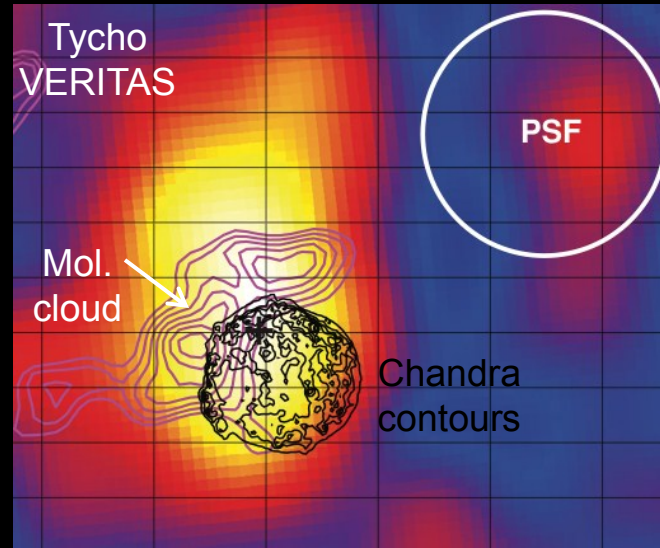
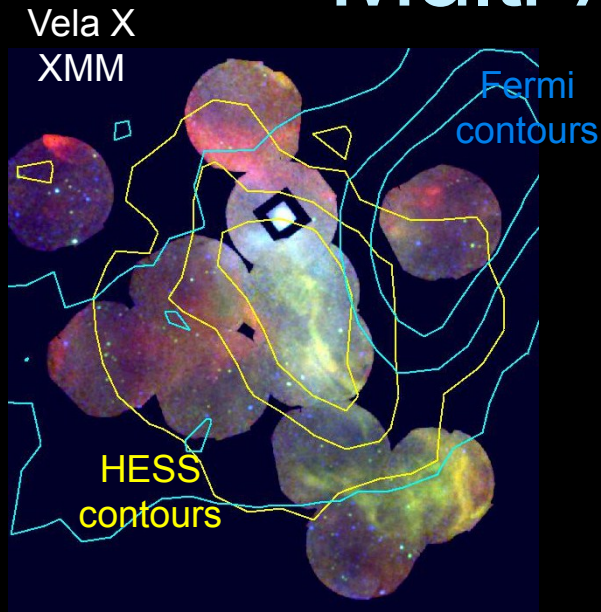
- Tycho's SNR shows strong dynamical evidence for CR acceleration
- Tycho is also detected in  $\gamma$ -rays
  - VERITAS centroid appears shifted slightly toward molecular cloud
- Both hadronic and leptonic models can reproduce broadband spectrum
- Fermi detection strongly favors hadrons as primary source of  $\gamma$ -rays

Better TeV resolution is needed to ascertain potential connection with molecular cloud. Better sensitivity at high energies will constrain the maximum energy available in this particle accelerator.

# Summary

- Cosmic ray particles appear to have Galactic component below  $10^{15}$  eV
  - Shock properties and overall energetics suggest SNRs may produce the bulk of these particles
  - Additional contributions may come from colliding winds, PWNe, binaries
- Multi- $\lambda$  observations provide unique information on energetic particles
  - Synchrotron emission from multi-TeV electrons
  - Dynamical evidence of ion acceleration in SNRs
  - Evidence of magnetic field amplification
  - Identification of dense gas for efficient beam dump target
- Gamma-ray observations are a key part of the multi- $\lambda$  program
  - Modeling of broadband emission, including thermal X-ray emission, is generally required understand gamma-ray emission
  - SNRs interacting with molecular clouds provide important environment for detection of gamma-ray emission from hadronic component
- Large improvements in resolution and sensitivity offered by CTA will play a huge role in improving our understanding of the acceleration process, energy budget, and propagation of Galactic CRs

# Multi- $\lambda$ Studies of Galactic CRs



- Identification and mapping of PWNe constrains particle injection, evolution, and escape of relativistic particles into Galaxy. Good resolution, low energy response, and large field of view important for such studies.
- “High” angular resolution studies of SNRs will isolate emission regions, leading to better understanding of acceleration mechanisms and energy budget for CRs produced in SNRs.
- Higher sensitivity will identify SNRs interacting with molecular clouds, along with subsequent diffusion of cosmic rays.