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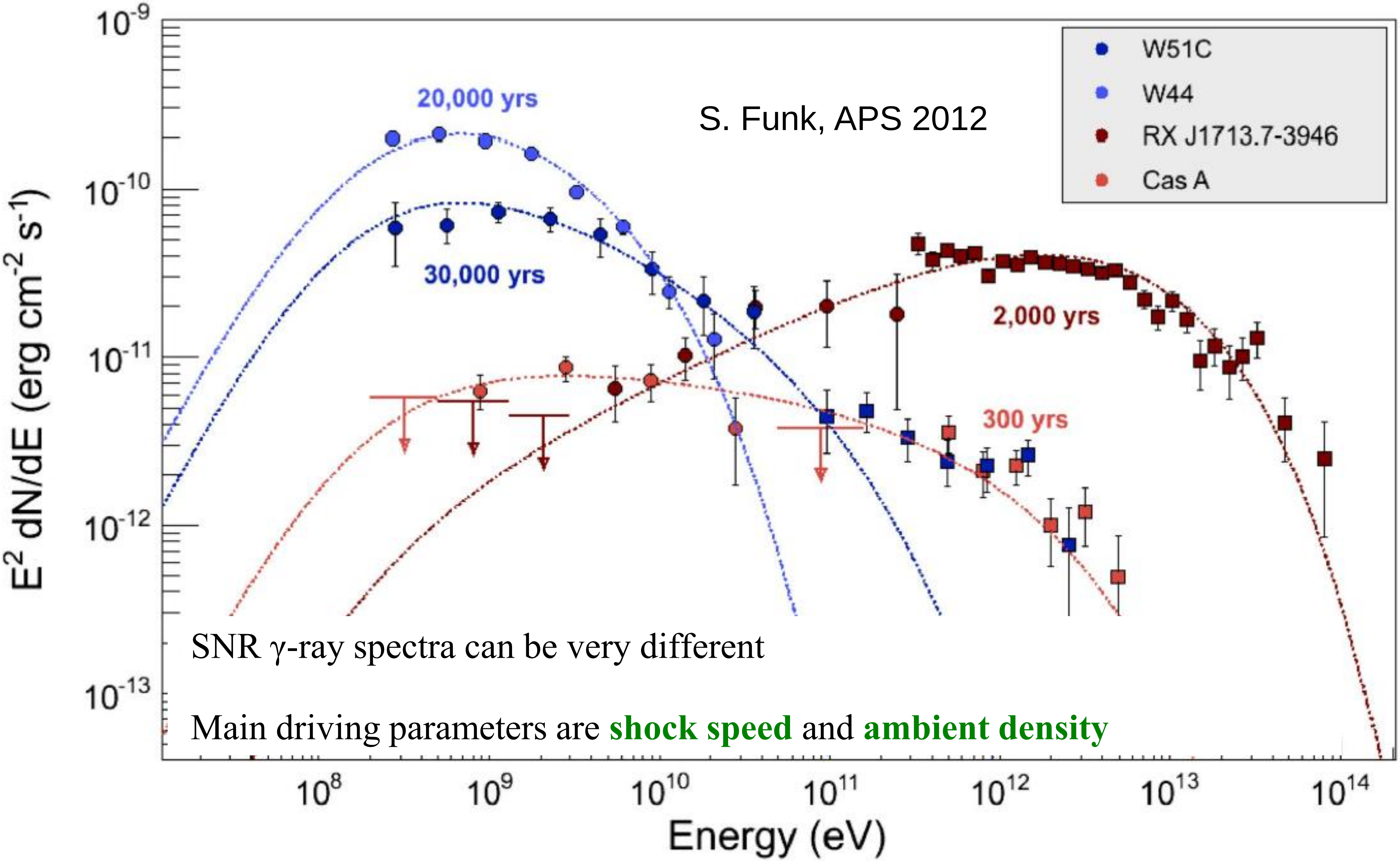
Supernova remnants interacting with interstellar clouds

- Old large nearby SNRs
- Interaction with clouds
- Soft γ-ray spectra
- Illumination by escaping cosmic rays
- Reacceleration of ambient cosmic rays

γ-ray emission

- ❑ Unique domain where the emission can be dominated by the hadrons which are the dominant component of CRs (via π^0 decay)
- ❑ Inverse Compton (leptonic) dominates when the ambient density is small, can be ignored in interstellar clouds
- ❑ Spatial resolution is no better than 0.1°. Cannot extract the spectrum of the shock itself, always mixed up with downstream
- ❑ Many old SNRs observed by *Fermi*

γ-ray spectra of SNRs

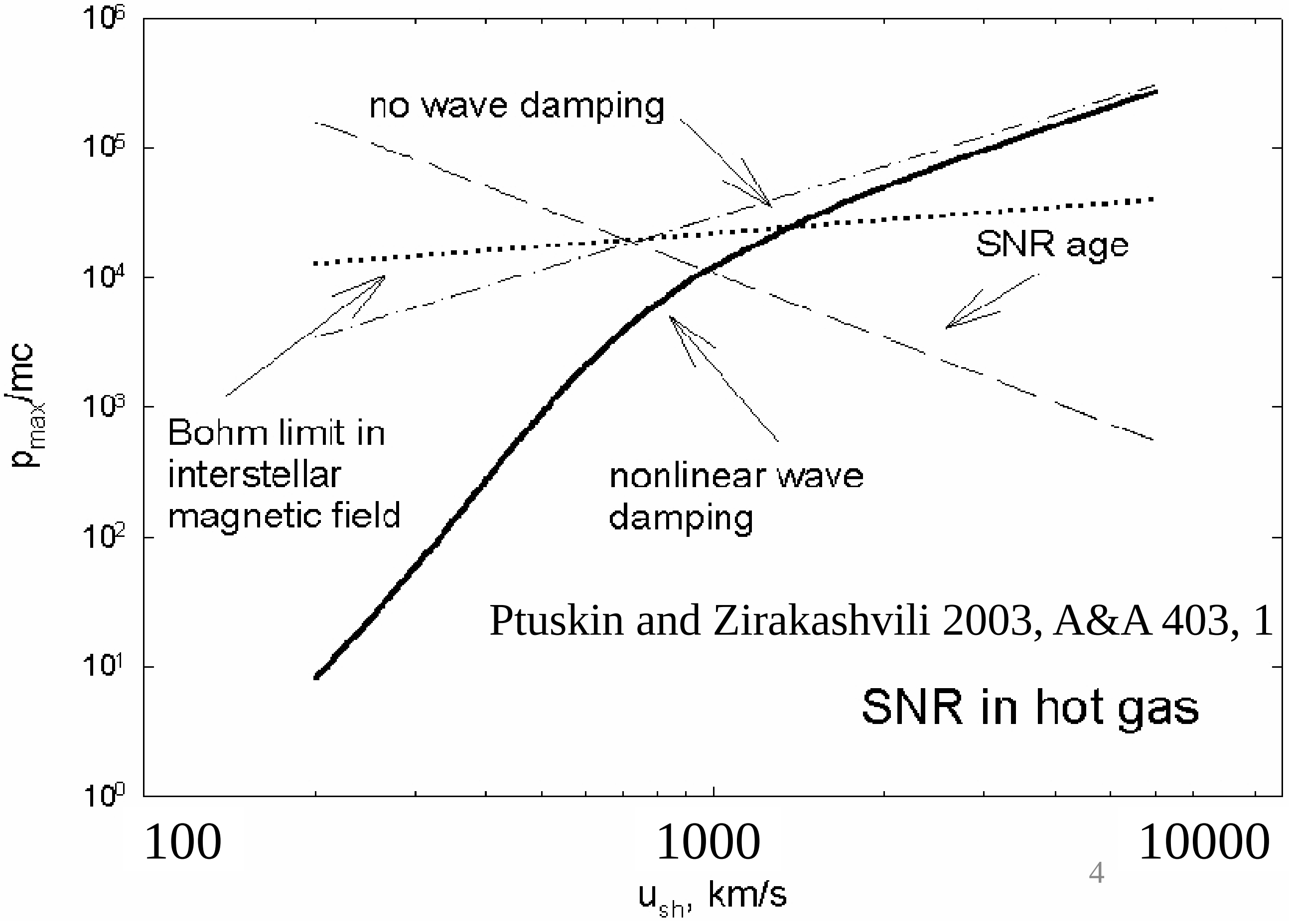


SNR γ-ray spectra can be very different

Main driving parameters are **shock speed** and **ambient density**

Time evolution of magnetic turbulence

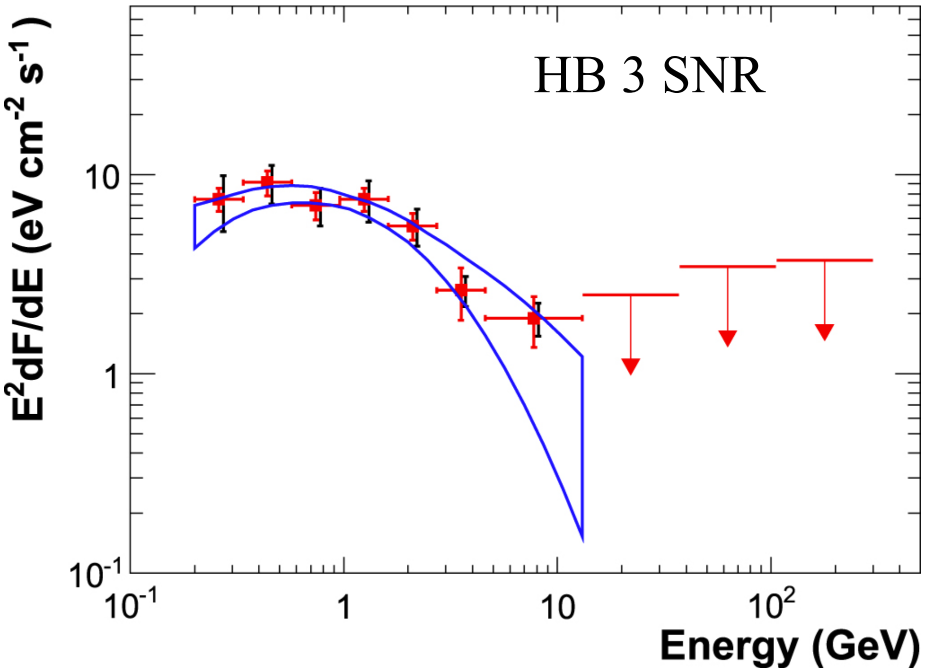
- ✓ Excitation of the turbulence decreases with shock velocity, while damping (by non-linear wave interactions and ion-neutral collisions) does not
- ✓ Reduces maximum energy of particles
- ✓ Can allow already accelerated particles to **escape**

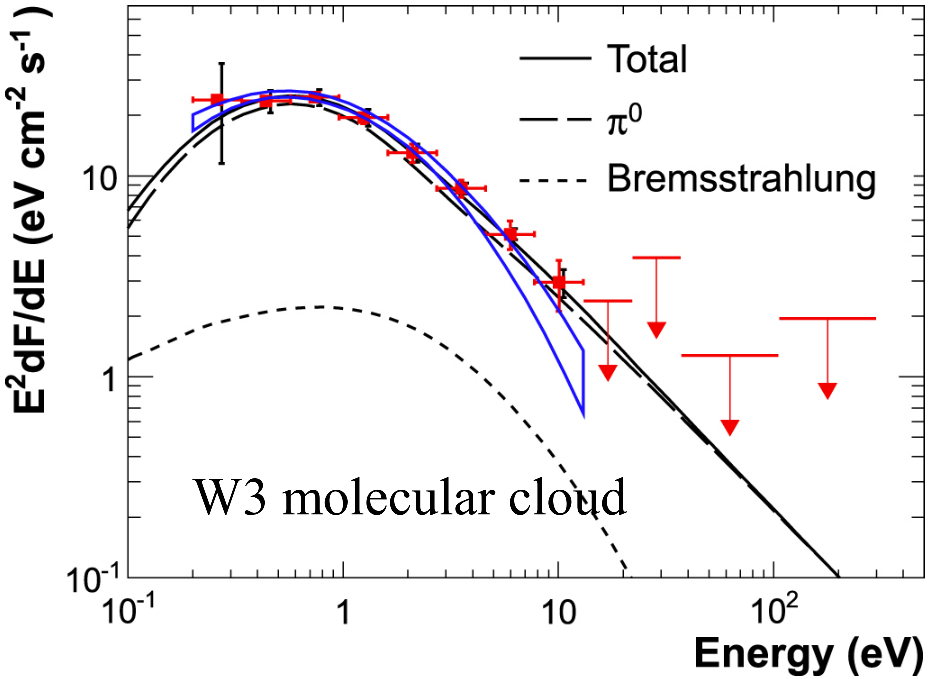


Ptuskin and Zirakashvili 2003, A&A 403, 1

Interacting SNRs: HB 3 + W3

Katagiri et al. 2016, ApJ 818, 114





Hadronic γ-ray emission from both the supernova remnant HB 3 (0.65° radius) and the nearby W3 molecular cloud. Circumstantial evidence of interaction.

Spectra consistent with the same accelerated protons (density, spectrum)

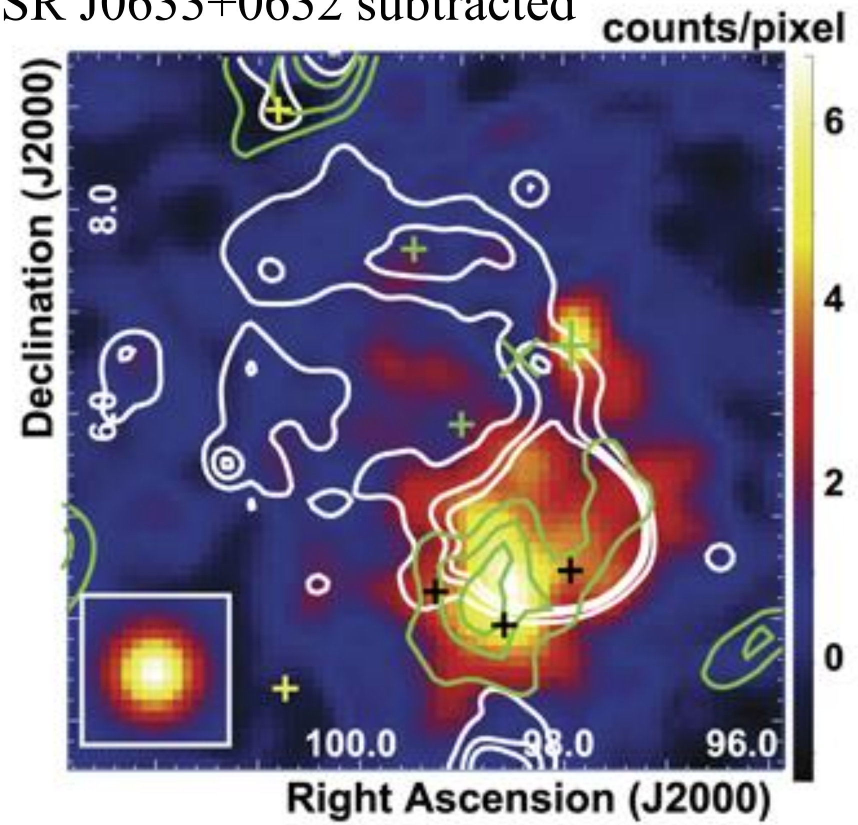
Break/cutoff around 10 GeV/c (particle momentum)

Target gas density is 100 cm^{-3} in W3 and 2 cm^{-3} in HB 3; Solid angle of W3 is about 5%

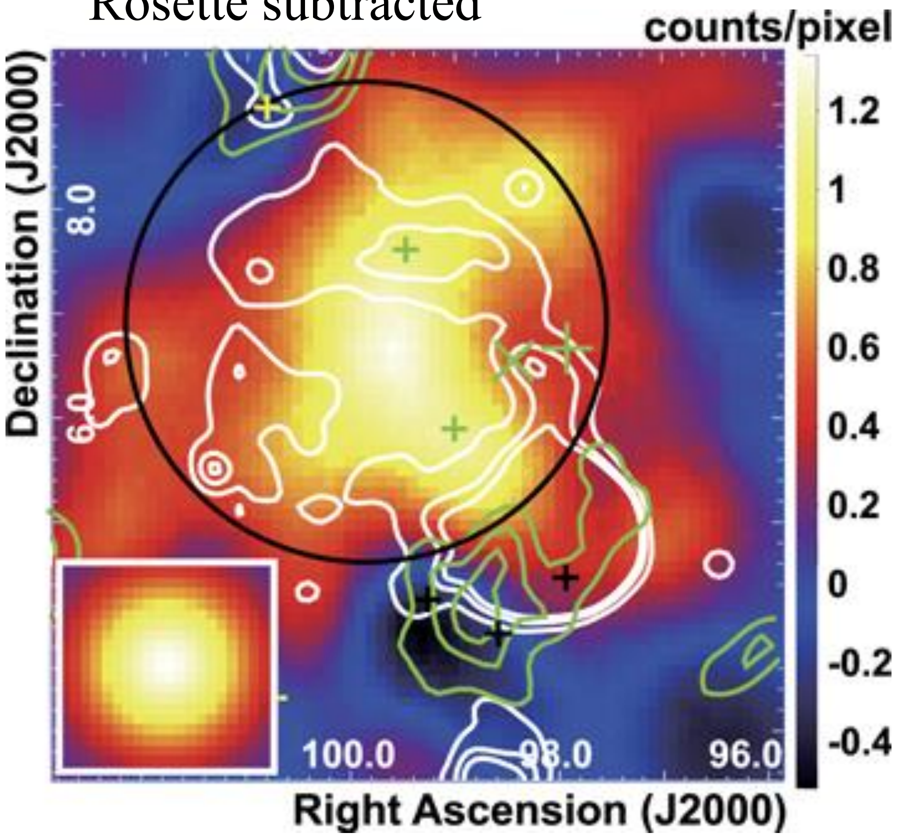
Interacting SNRs: Monoceros + Rosette

Katagiri et al. 2016, ApJ 831, 106

PSR J0633+0632 subtracted



Rosette subtracted



Hadronic γ-ray emission from both the Monoceros SNR and the nearby Rosette nebula. Circumstantial evidence of interaction.

Larger SNR (1.9° radius). Spectra similar to W3 / HB3

Reacceleration in radiative shocks

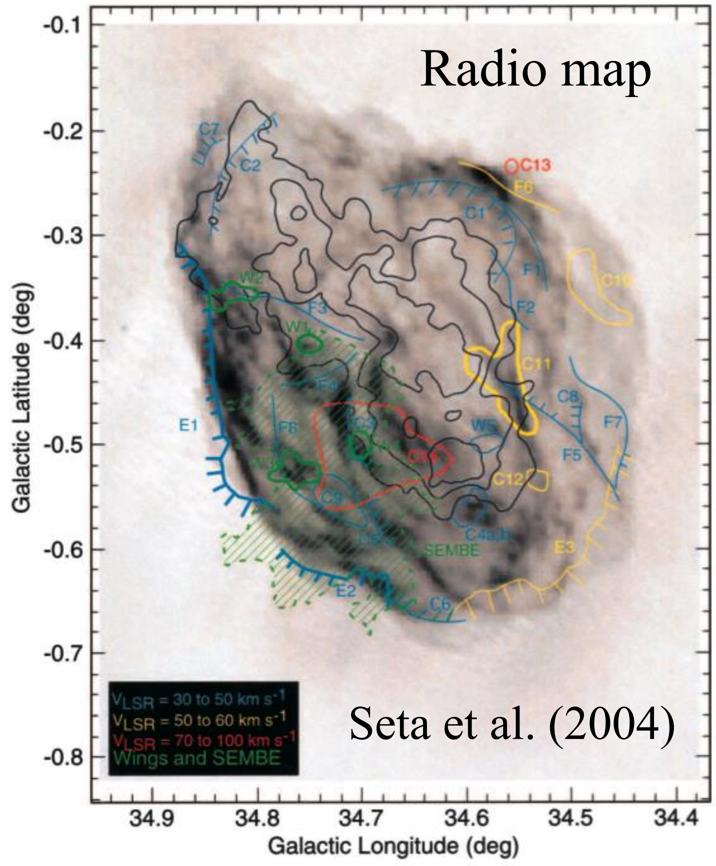
- ✓ Many bright GeV and radio SNRs are interacting with molecular clouds
- ✓ Chevalier 1999, ApJ 511, 798; Uchiyama et al. 2010, ApJ 723, L122
- ✓ Slow shocks (< 100 km/s); Fermi mechanism cannot reach TeV energies
- ✓ Complications due to neutral gas
- ✓ Injection from thermal gas difficult, but can work on existing Galactic CRs
- ✓ Radiative shocks ➔ strong compression downstream
- ✓ Compresses together the accelerated particles, the magnetic field (synchrotron) and the gas (π^0-decay)
- ✓ Very large emissivity over very small volume

Middled-aged SNRs: W 44

Definite interaction with **molecular cloud** over large fraction of the surface

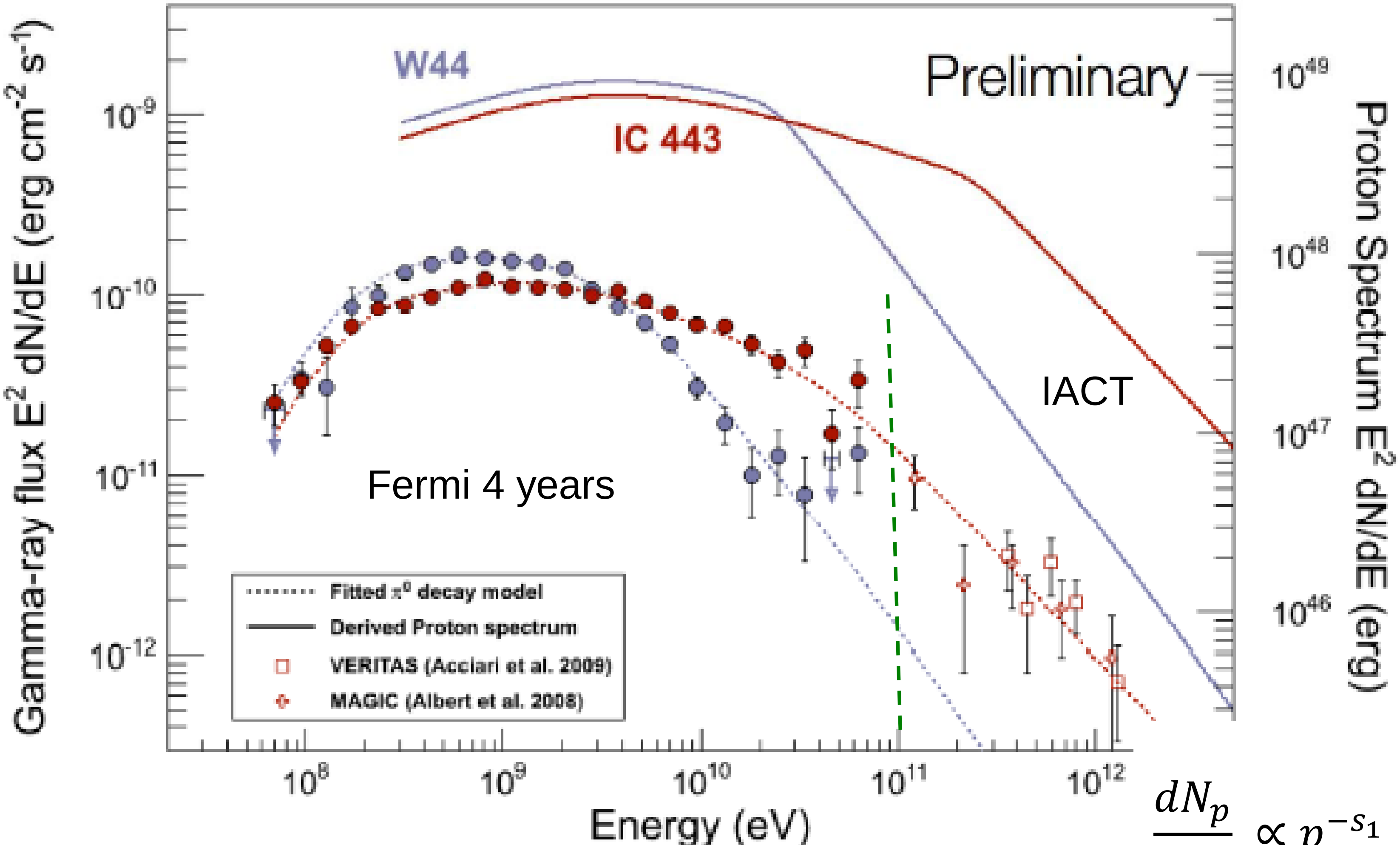
Consistent with CRs reaccelerated and compressed in **radiative shock**

Other such SNRs: IC 443, W 51C, W 49B, W 28, 3C 391, G349.7+0.2



π^0-decay bump

Ackermann et al 2013, Science 339, 807



$$\frac{dN_p}{dp} \propto p^{-s_1}\left[1+\left(\frac{p}{p_{br}}\right)^{\frac{s_2-s_1}{\beta}}\right]^{-\beta}$$

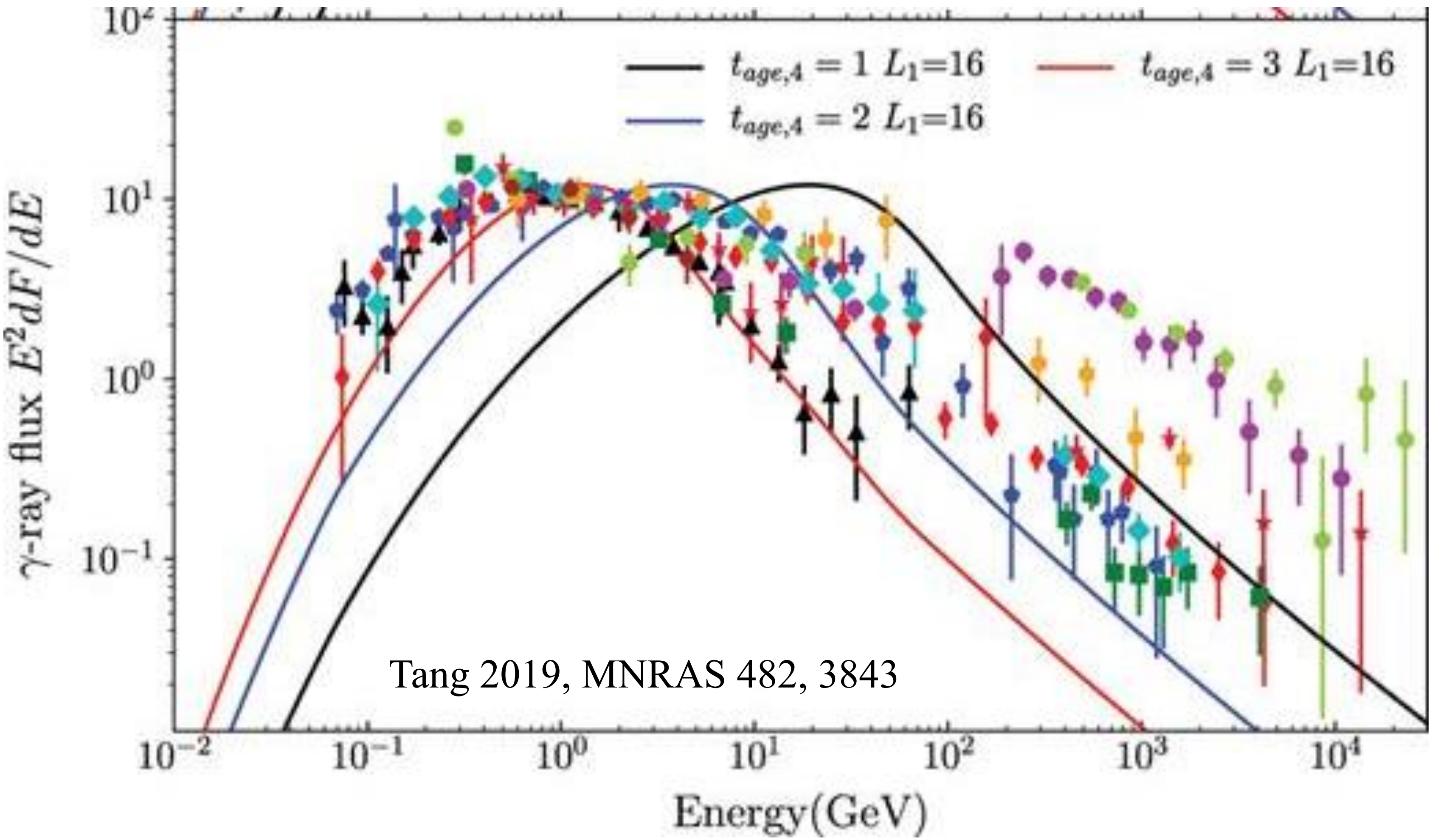
Full γ-ray spectrum: broken power-law in **momentum**

W 44: s_1 = 2.36 +/- 0.05, s_2 = 3.5 +/- 0.3, p_{br} = 22 +/- 8 GeV/c

Excellent overall fit with a **single break**, GeV curve due to **transrelativistic** protons

Low-energy electron spectrum (from radio) is harder (1.74)

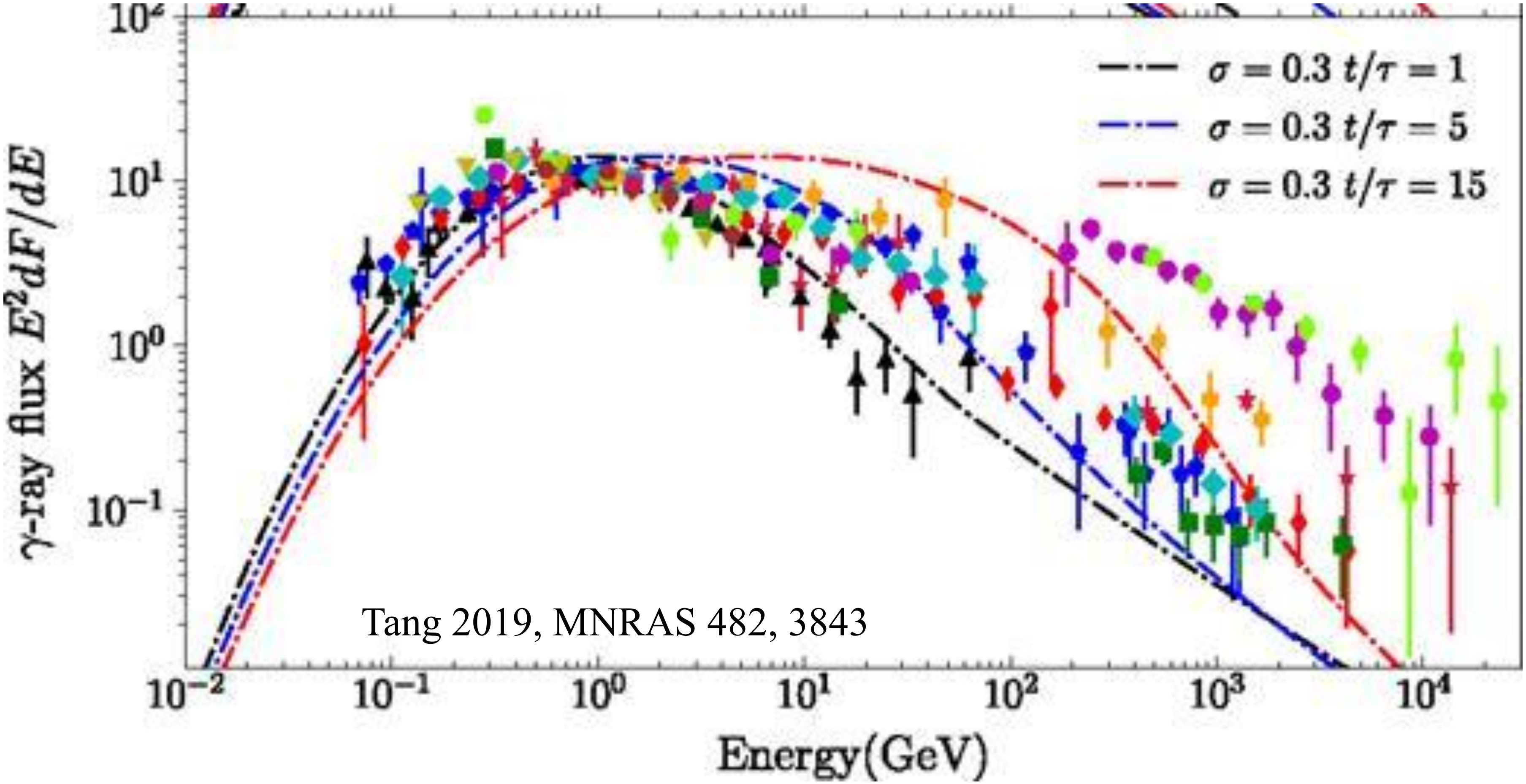
Interacting SNRs: Modeling



Escape model at different ages (in units of 10,000 yrs), assuming a target cloud at 16 pc, always outside the SNR

Peak emission goes down as shock velocity, but cannot account for observed spectra unless SNR touches the cloud

Interacting SNRs: Modeling



Radiative shock model with reacceleration (leads to low-energy bump)

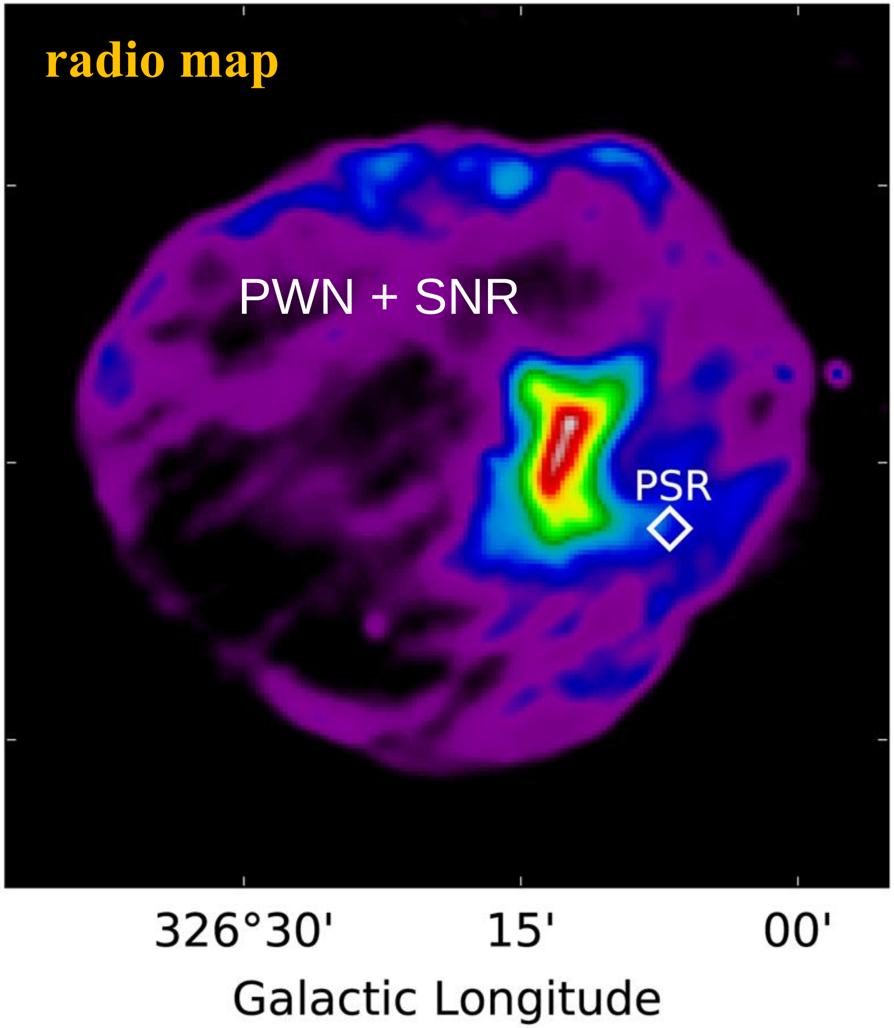
t/τ is the time since the shock hit the cloud in units of t_{acc} at 1 GeV

σ is the turbulence index (0.3 is Kolmogorov)

Data do not show clearly low-energy bump on top of power law

Interacting SNRs: MSH 15-56

Devin et al. 2018, A&A 617, A5



Composite SNR

Large enough (0.5°) to be resolved in γ rays

Concentrate on SNR here

Pressure from X-rays (ambient density 0.1 cm^{-3} and blast wave velocity 500 km/s)

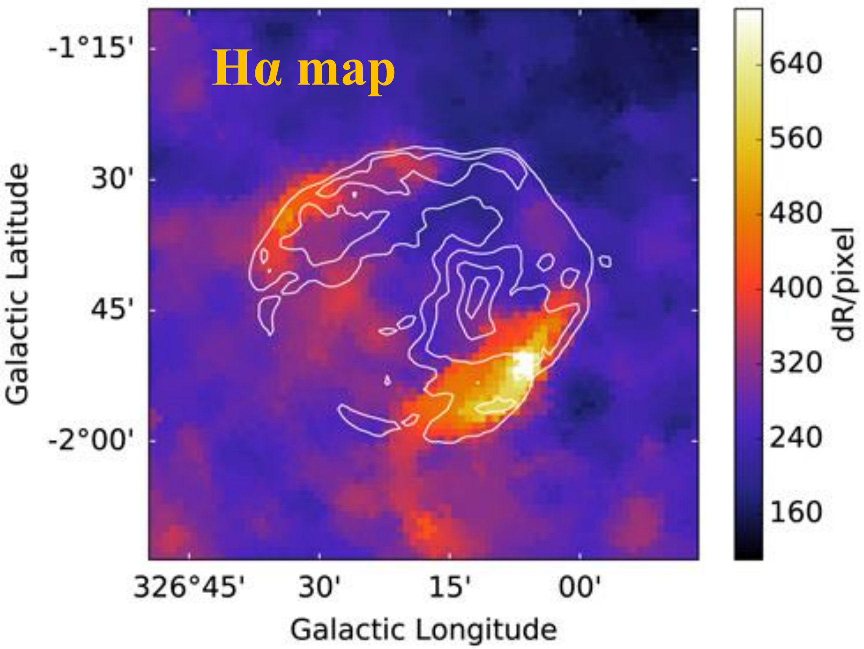
Explosion energy and age from distance, size and velocity (temperature): $5\ 10^{50}$ erg

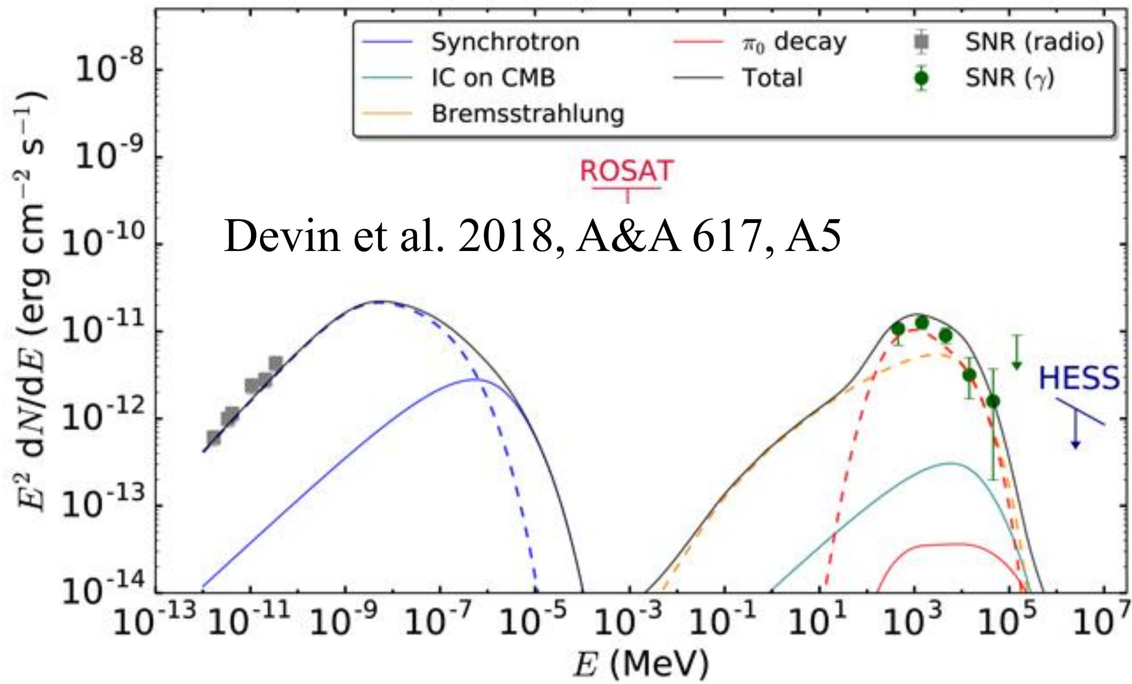
Deduce B-field in radiative shocks (magnetically supported): 160 μG

Consider relation $B_0 \approx \sqrt{n_0}$ in ISM

No molecular clouds, but radiative shocks in HI clouds (estimated density about 2 cm^{-3})

Interacting SNRs: MSH 15-56





Consistent model with the same E^{-2} spectrum for electrons and protons (except synchrotron cooling)

Cutoff momentum 80 GeV/c from 150 km/s shock assuming cloud interaction for $t_{SNR}/2$

Negligible emission from SNR outside radiative shocks

No obvious correlation between γ rays, radio and Hα

CTB 37A scaled up version (larger density) of MSH 15-56 (Abdollahi et al, Fermi symp 2018)

Discussion

- ❑ **Why are certain SNRs naturally explained by reacceleration/compression and others by escape?**

With escape, break/cutoff related to current E_{max} in SNR

With reacceleration, break/cutoff related to much slower shock in cloud

My current understanding

- ✓ **Escape dominates at early times in the interaction (SNR barely touches cloud) then reacceleration/compression dominates as radiative shock develops**

Summary

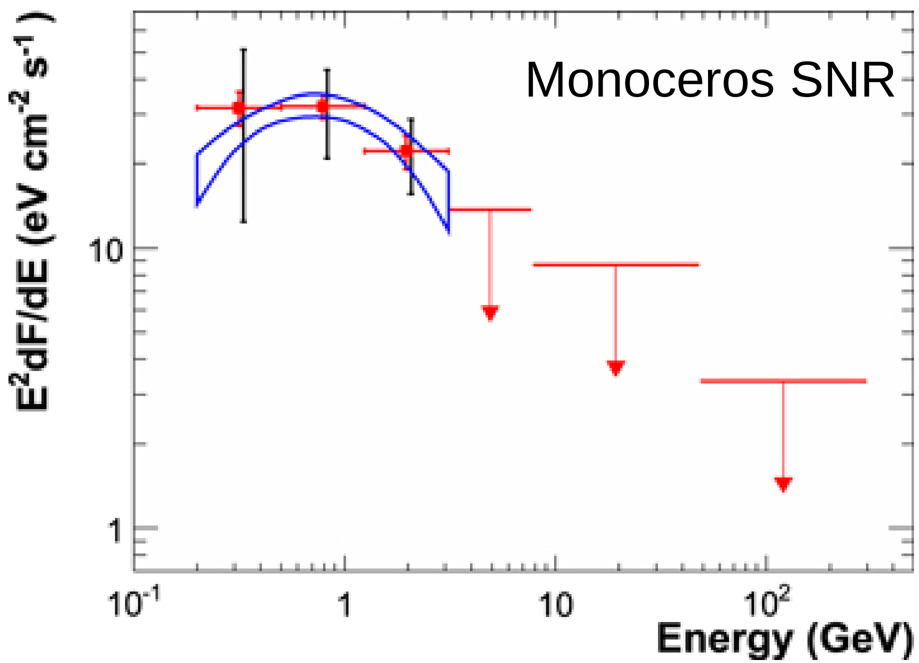
Large body of observations:

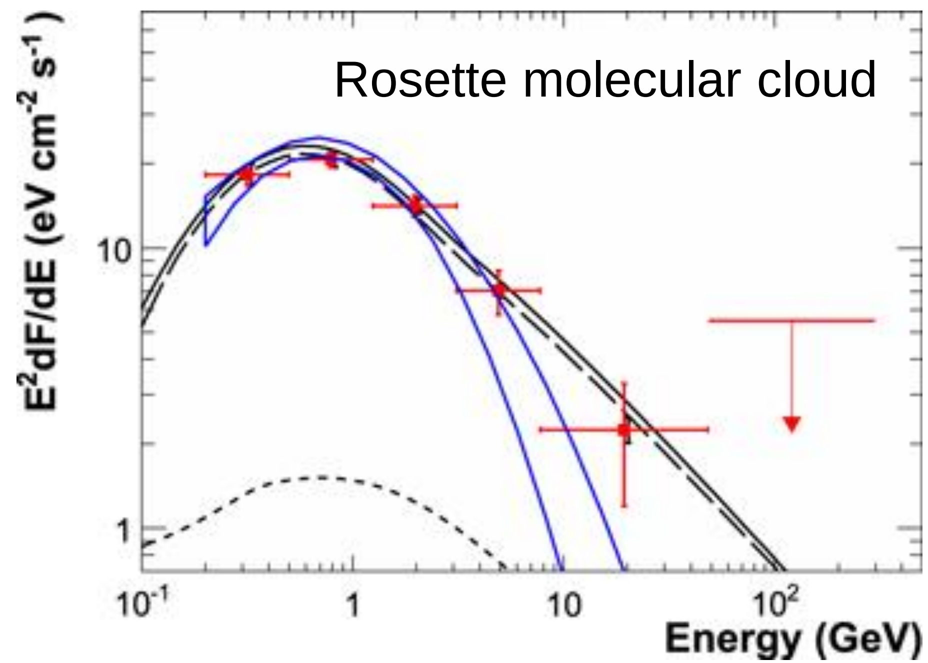
- **Many old interacting SNRs** observed at GeV, bright because of large target density in molecular clouds
- Good knowledge of **local conditions** from interstellar lines (density), X-rays (pressure), radio continuum (electrons), γ-rays (protons)
- **Particles escaping** from blast wave
- **Reacceleration** at radiative shocks (direct interaction)

Backup

Interacting SNRs: Monoceros + Rosette

Katagiri et al. 2016, ApJ 831, 106





Hadronic γ-ray emission from both the Monoceros SNR and the nearby Rosette nebula. Circumstantial evidence of interaction.

Consistent with the same accelerated protons (density, spectrum)

Break/cutoff < 10 GeV/c (particle momentum)

Target gas density is 100 cm^{-3} in Rosette and 3.6 cm^{-3} in Monoceros

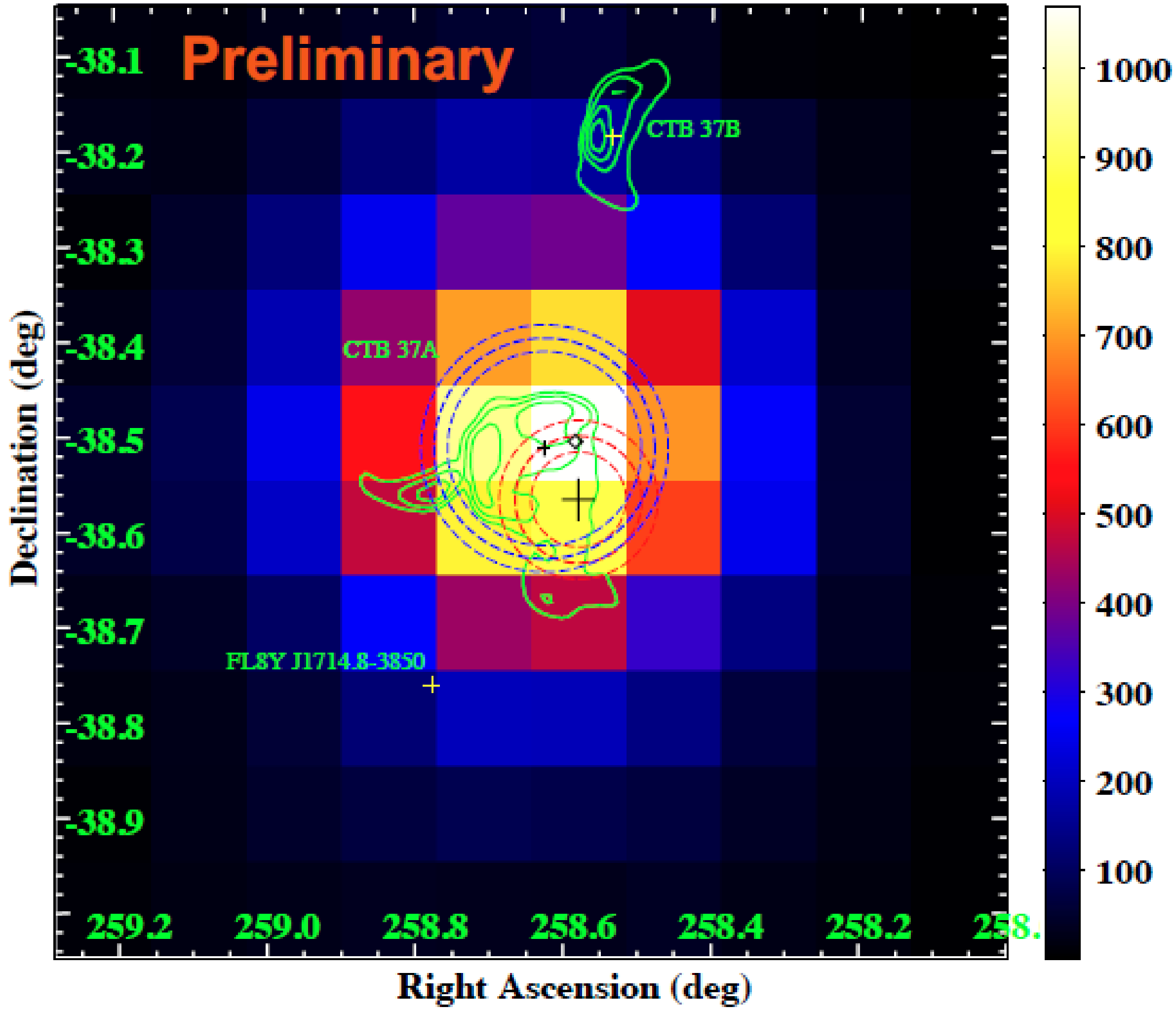
The solid angle of Rosette is about 2%

Interacting SNRs: CTB 37A

Abdollahi et al. 2018
Fermi symposium

Bright γ-ray source but very confused region

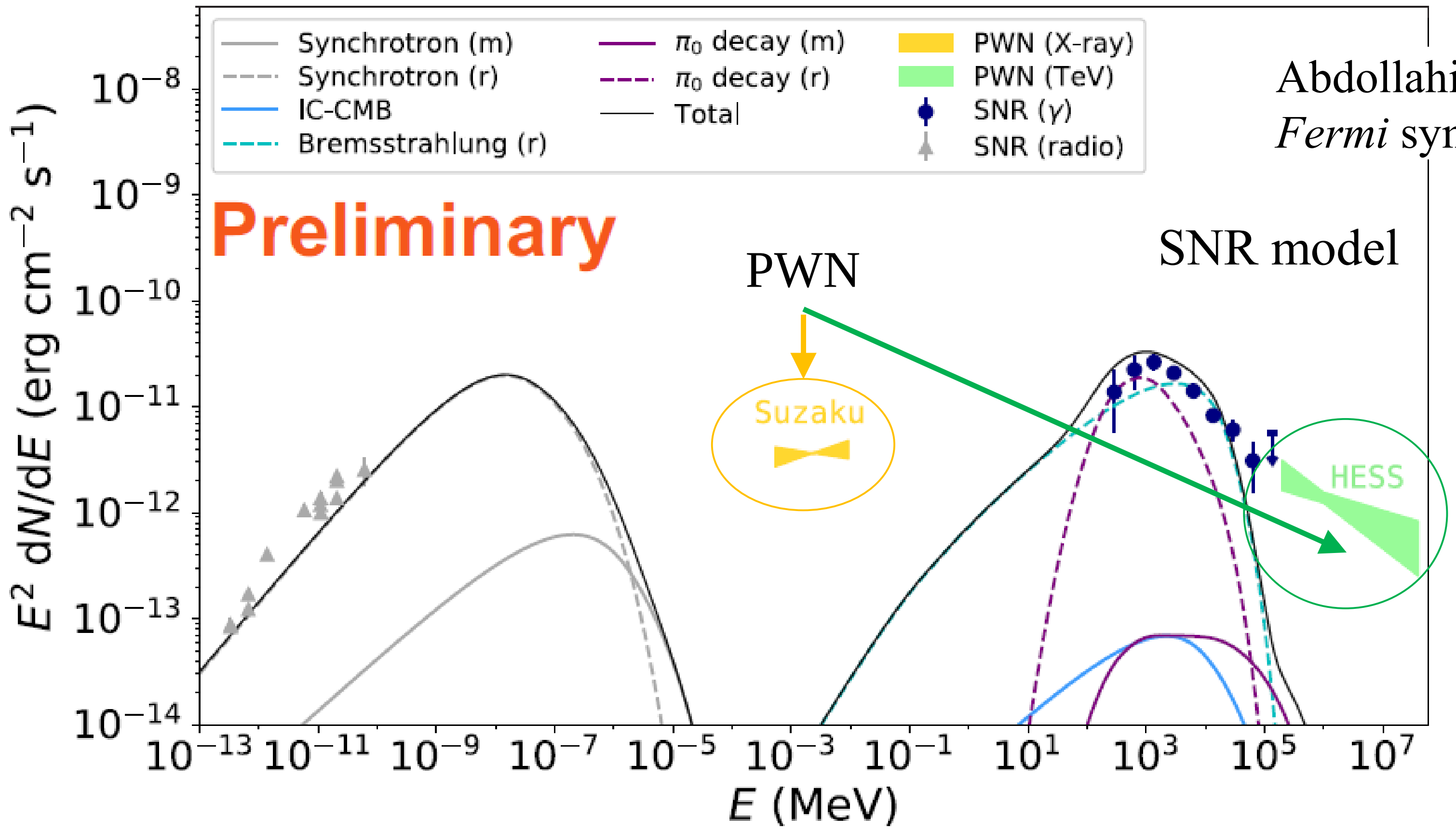
Two other *Fermi* sources within 0.4°, CTB 37A slightly extended



Definite evidence of molecular shocks (H_20 and OH masers)

Radio SNR, X-ray PWN (*Fermi* PSR announced at the same meeting)

Interacting SNRs: CTB 37A



Abdollahi et al. 2018
Fermi symposium

Radiative shock model, pressure from X-rays ➔ B = 500 μG and target gas density 3000 cm^{-3} in radiative shocks

Maximum momentum 30 GeV/c from 100 km/s shock assuming cloud interaction for $t_{SNR}/2$

Very consistent, although electron fraction is a bit large (3%, leading to large Bremsstrahlung contribution)