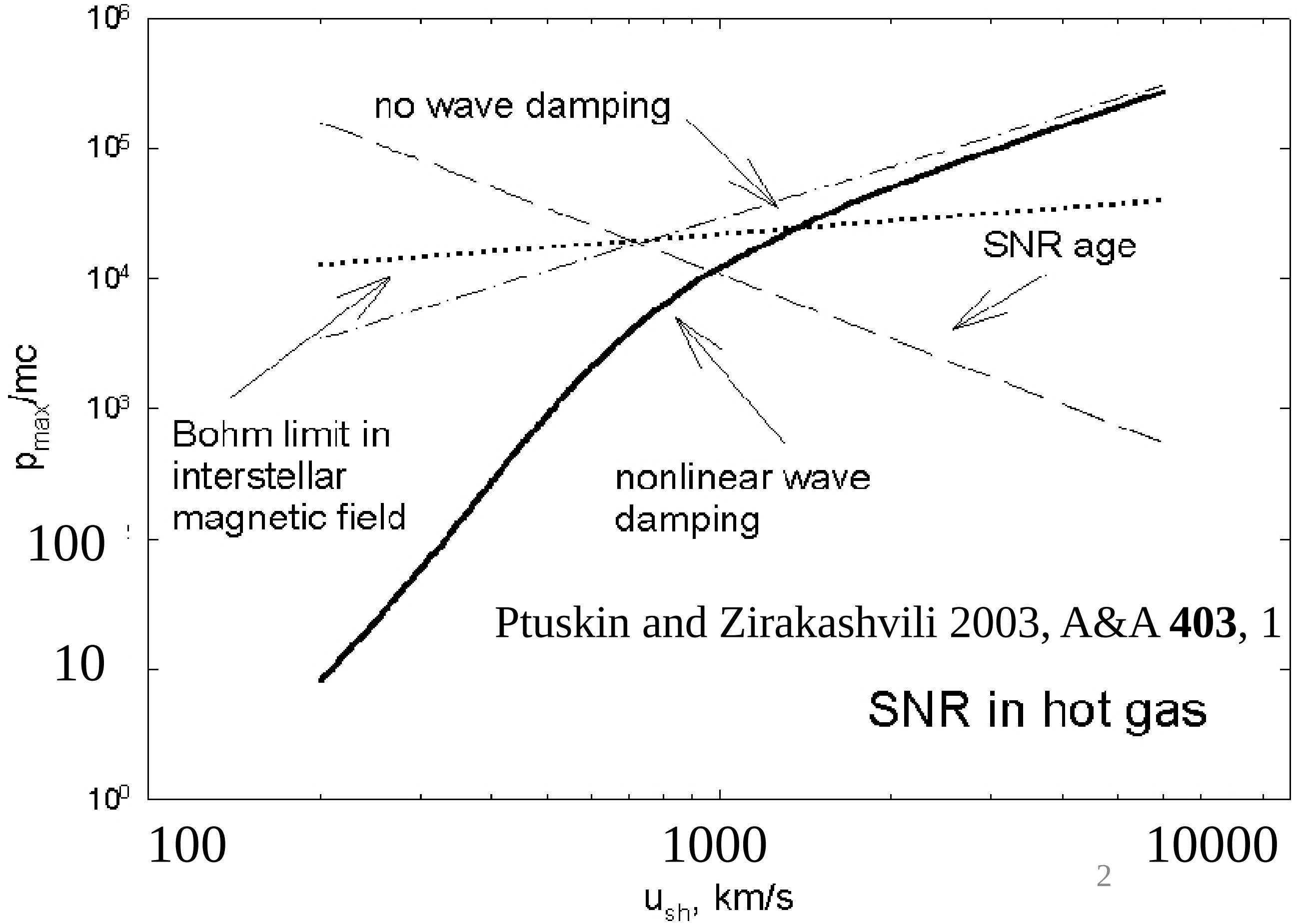
CR acceleration in old supernova remnants

- ❑ γ-ray spectra of old large nearby SNRs
- ❑ Emission from new CRs in the SNR
- ❑ Illumination of clouds by escaping cosmic rays
- ❑ Reacceleration of ambient cosmic rays

Observation based (Fermi)

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**



CR acceleration in old SNRs

- Maximum energy reached by Diffusive Shock Acceleration increases fast with shock velocity (Parizot et al 2006, A&A 453, 387)

$$p_{\mathrm{max}} = \frac{330}{\eta}\left(\frac{v_{\mathrm{sh}}}{100\ \mathrm{km/s}}\right)^2 \frac{t}{10\ kyr}\frac{B_0}{10\mu\mathrm{G}}\ \mathrm{GeV/c}$$

- Mass swept-up by SNR per unit ln(t) in the Sedov phase goes as $\rho v_{\mathrm{sh}} R^2 t \propto \rho R^3 \propto \rho t^{1.2} \propto \rho v_{\mathrm{sh}}^{-2}$

- **Most of the CR acceleration in SNRs takes place at low shock velocities**, a few 100 km/s

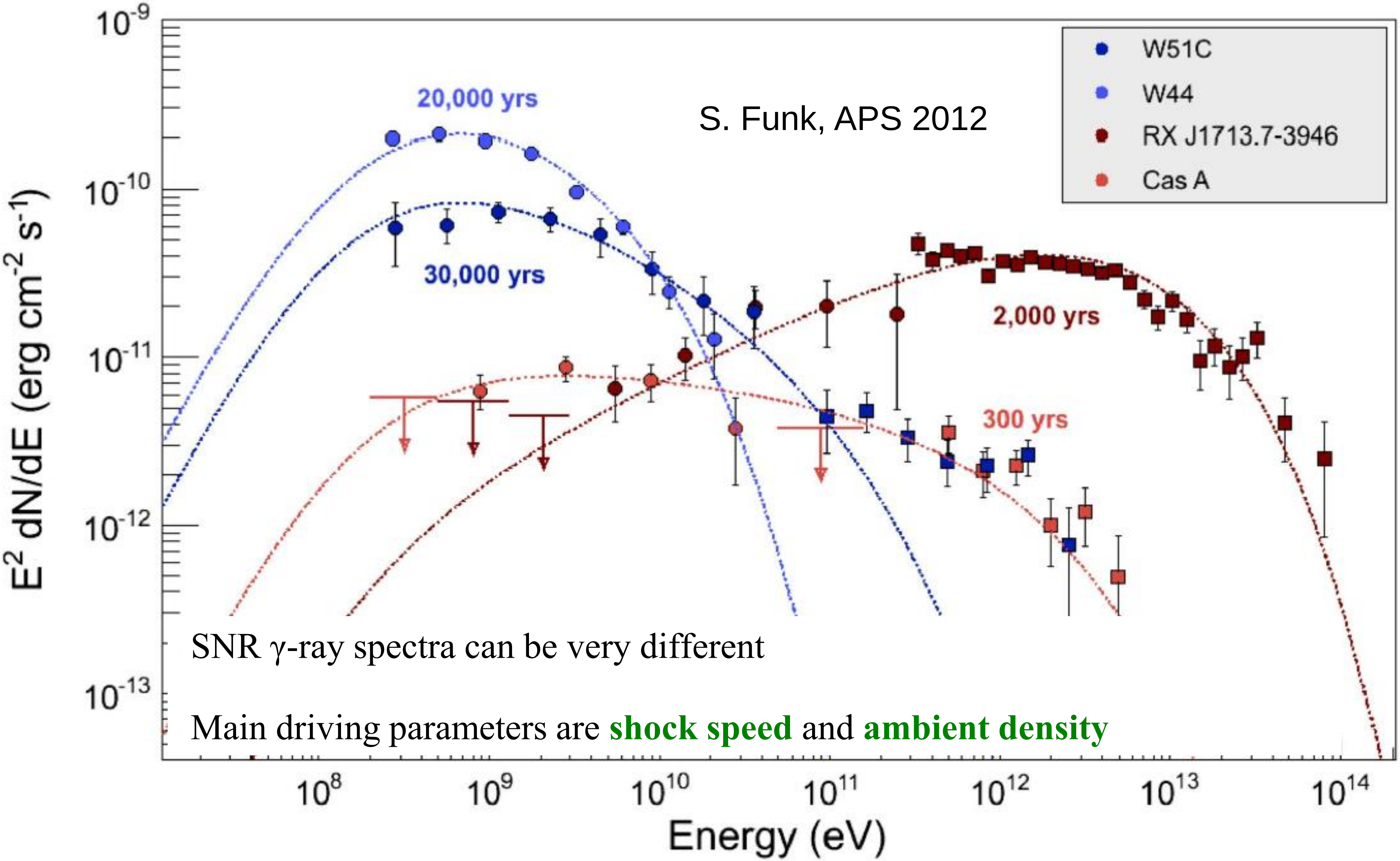
- We expect the bulk of CRs to be accelerated in that phase (**GeVatrons**!)

- Old SNRs are more numerous and can be found closer than young ones ➔ more detailed observations and population studies

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 cold or warm interstellar medium
- ❑ **Spatial resolution is no better than 0.1°** (actually worse below 10 GeV). Cannot extract the spectrum of the shock itself, always mixed up with downstream
- ❑ Many old SNRs observed by *Fermi*

γ-ray spectra of SNRs



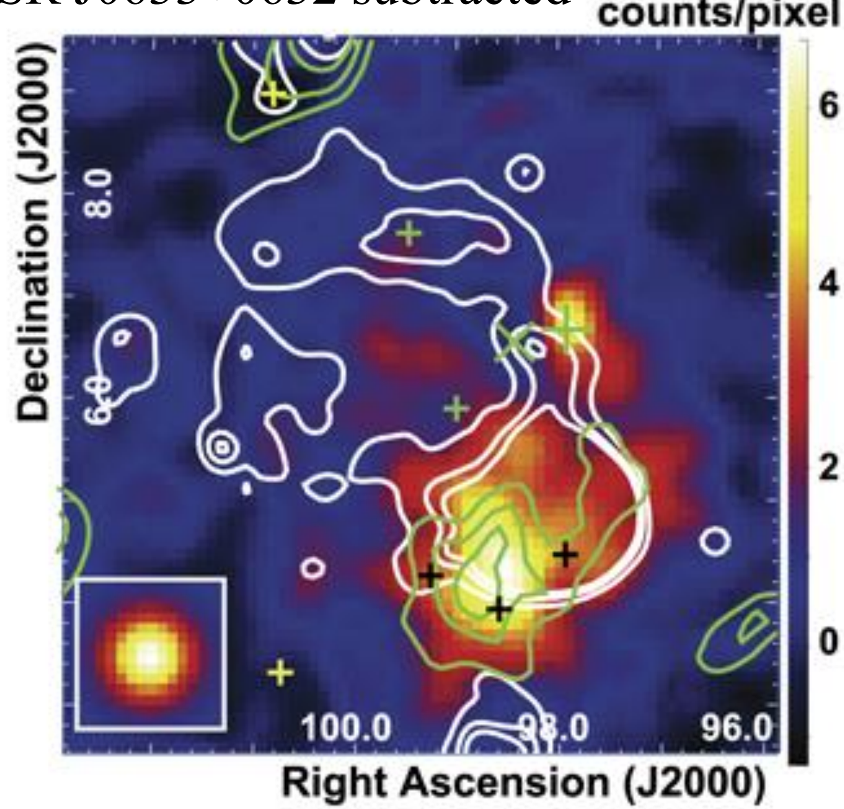
SNR γ-ray spectra can be very different

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

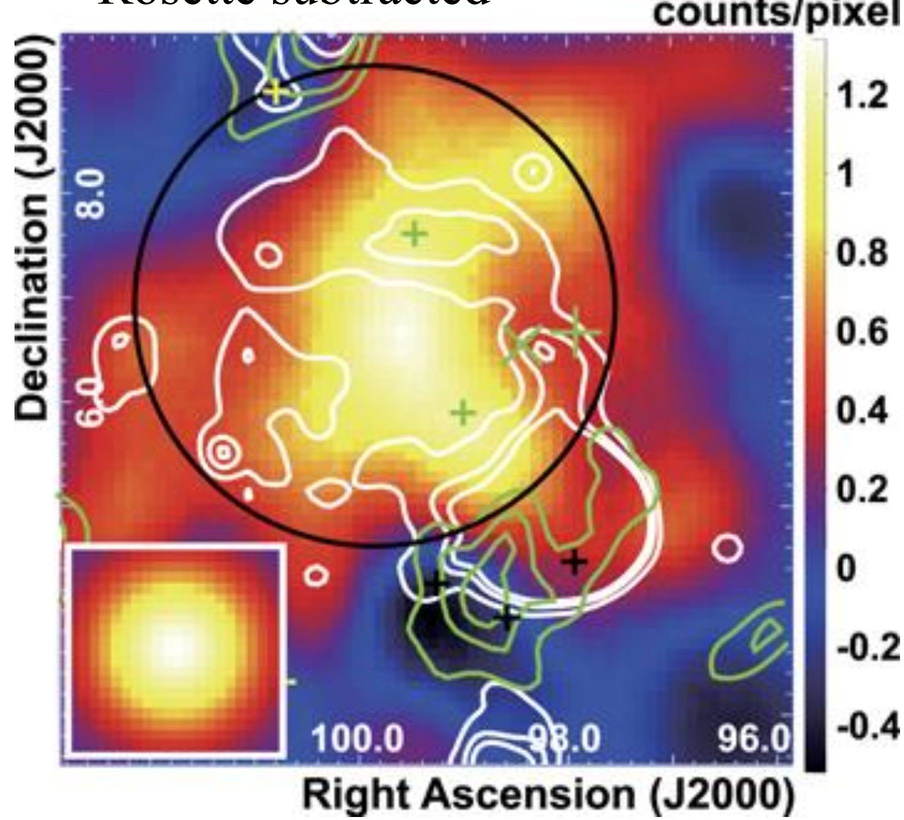
Interacting SNRs: Monoceros + Rosette

Katagiri et al. 2016, ApJ **831**, 106

PSR J0633+0632 subtracted



Rosette subtracted

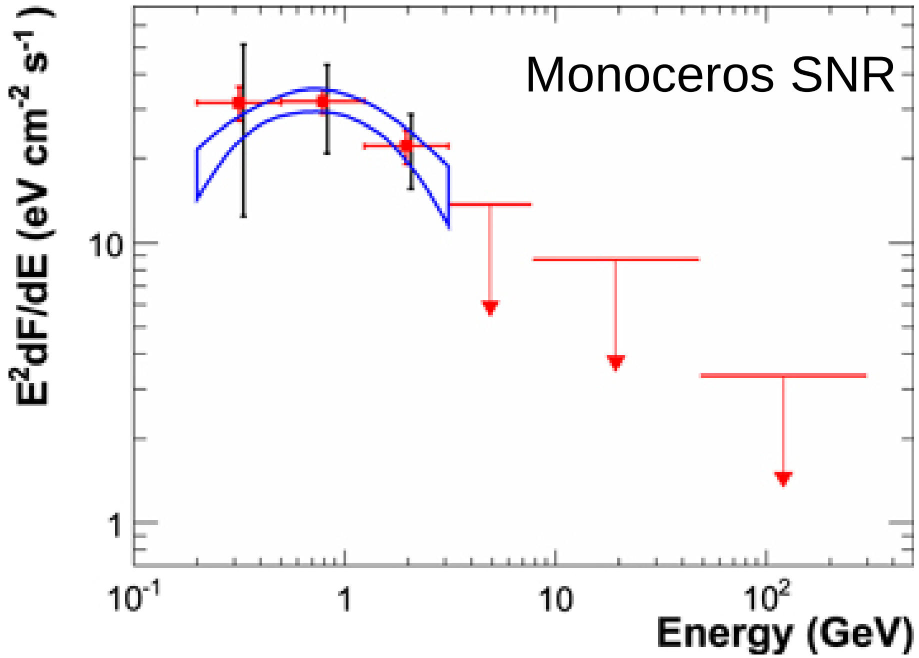


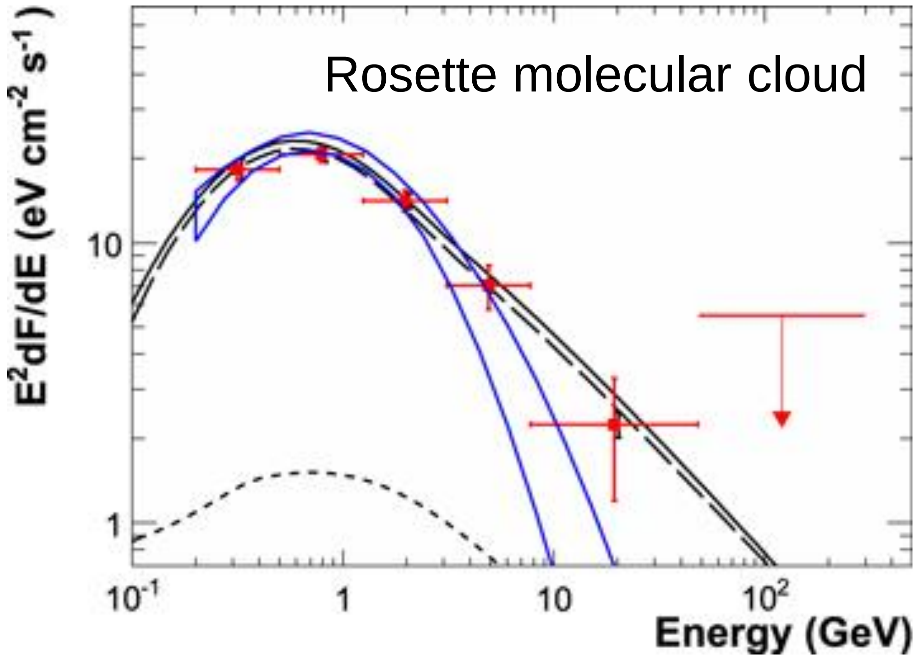
γ-ray emission from both the Monoceros SNR and the nearby Rosette nebula ($\approx$ 1.6 kpc). Circumstantial evidence of interaction.

Large SNR (1.9° radius)

Interacting SNRs: Monoceros + Rosette

Katagiri et al. 2016, ApJ **831**, 106





Consistent with the **same accelerated protons** (density, spectrum)
8% of the supernova explosion energy

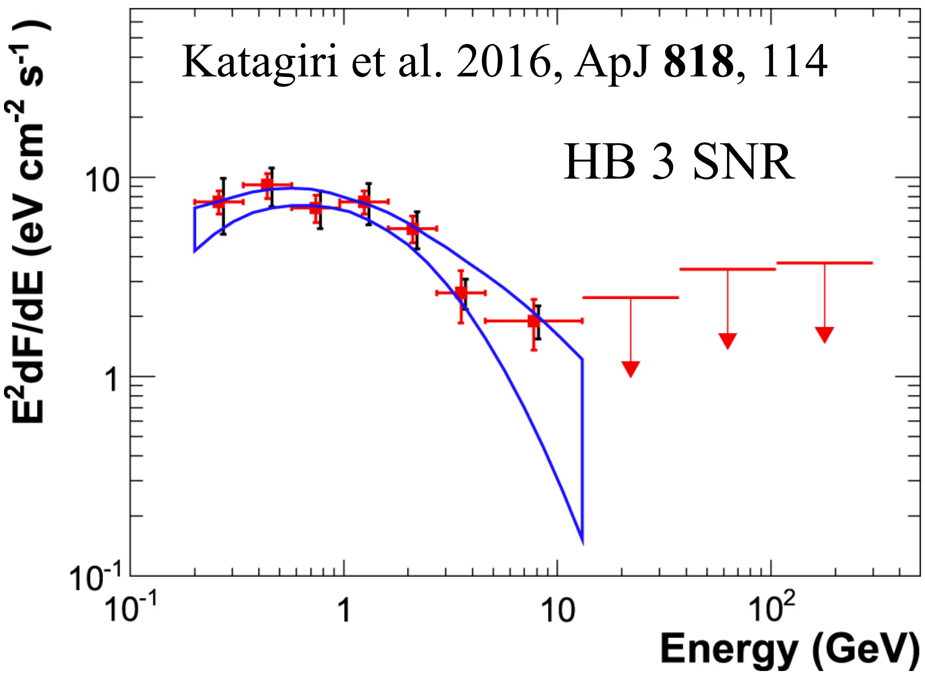
$V_{sh} \approx 330$ km/s from X-rays

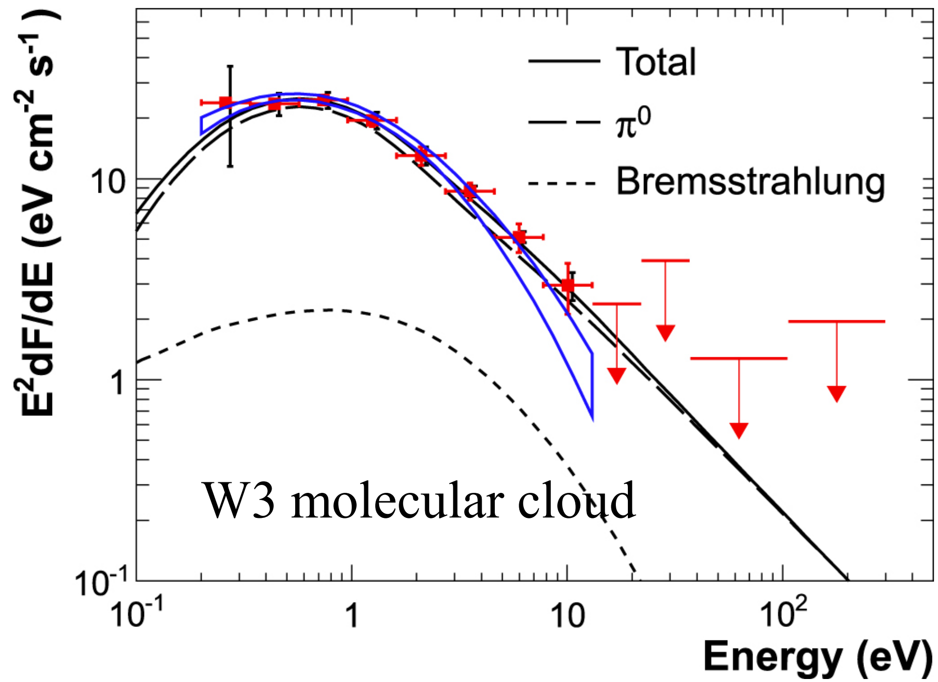
Break/cutoff < 10 GeV/c (particle momentum)

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: HB 3 + W3





Hadronic γ-ray emission from both the supernova remnant HB 3 (0.65° radius, $V_{sh} \approx 340$ km/s from X-rays) and the nearby W3 molecular cloud (≈ 2.2 kpc). Circumstantial evidence of interaction

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

Spectra consistent with the **same accelerated protons** (density, spectrum). 5% of supernova explosion energy

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

Reacceleration in radiative shocks

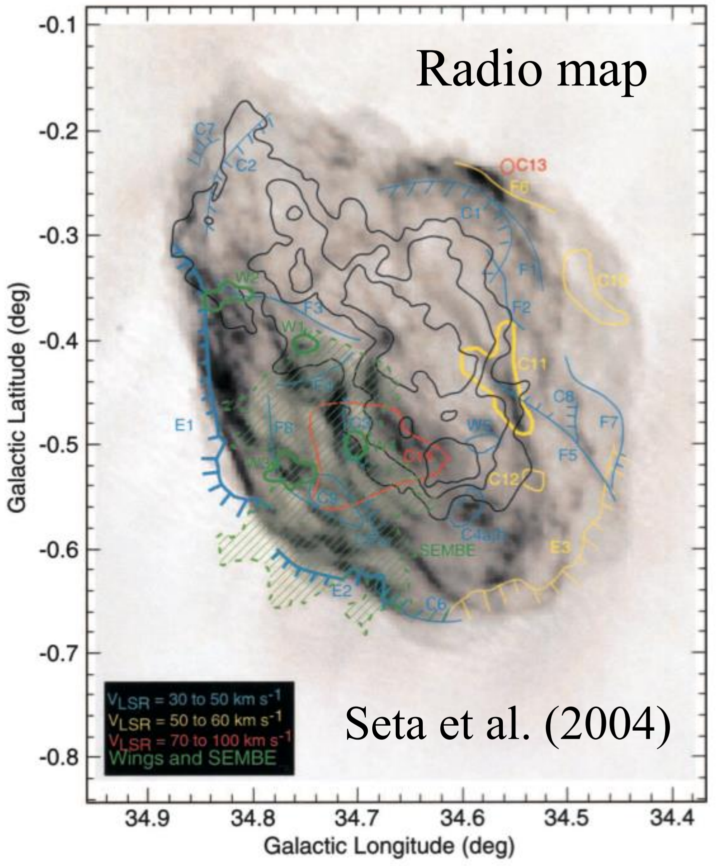
- ✓ Many bright GeV and radio SNRs are interacting with molecular clouds
- ✓ Chevalier 1999, ApJ **511**, 798; Uchiyama et al. 2010, ApJ **723**, L122
- ✓ Slow shocks (< 100 km/s); Fermi mechanism cannot reach TeV energies
- ✓ Complications due to neutral gas
- ✓ Injection from thermal gas difficult, but can work on existing Galactic CRs
- ✓ Radiative shocks ➔ strong compression downstream (limited by B field)
- ✓ 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

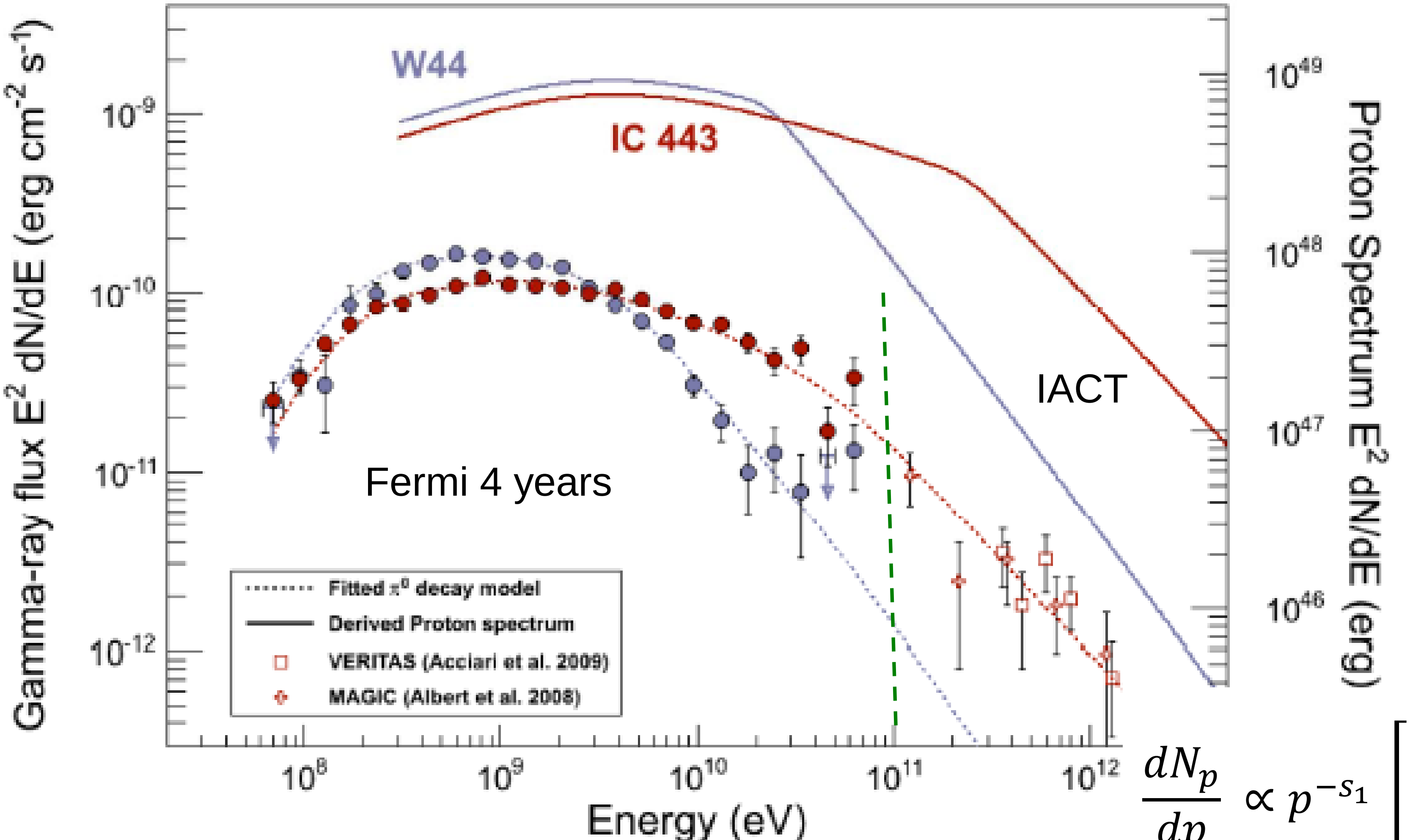
Consistent with CRs reaccelerated and compressed in **radiative shock**

Other such SNRs: IC 443, W 51C, W 49B, W 28, 3C 391, G349.7+0.2, S 147



π^0-decay bump

Ackermann et al 2013, Science **339**, 807



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

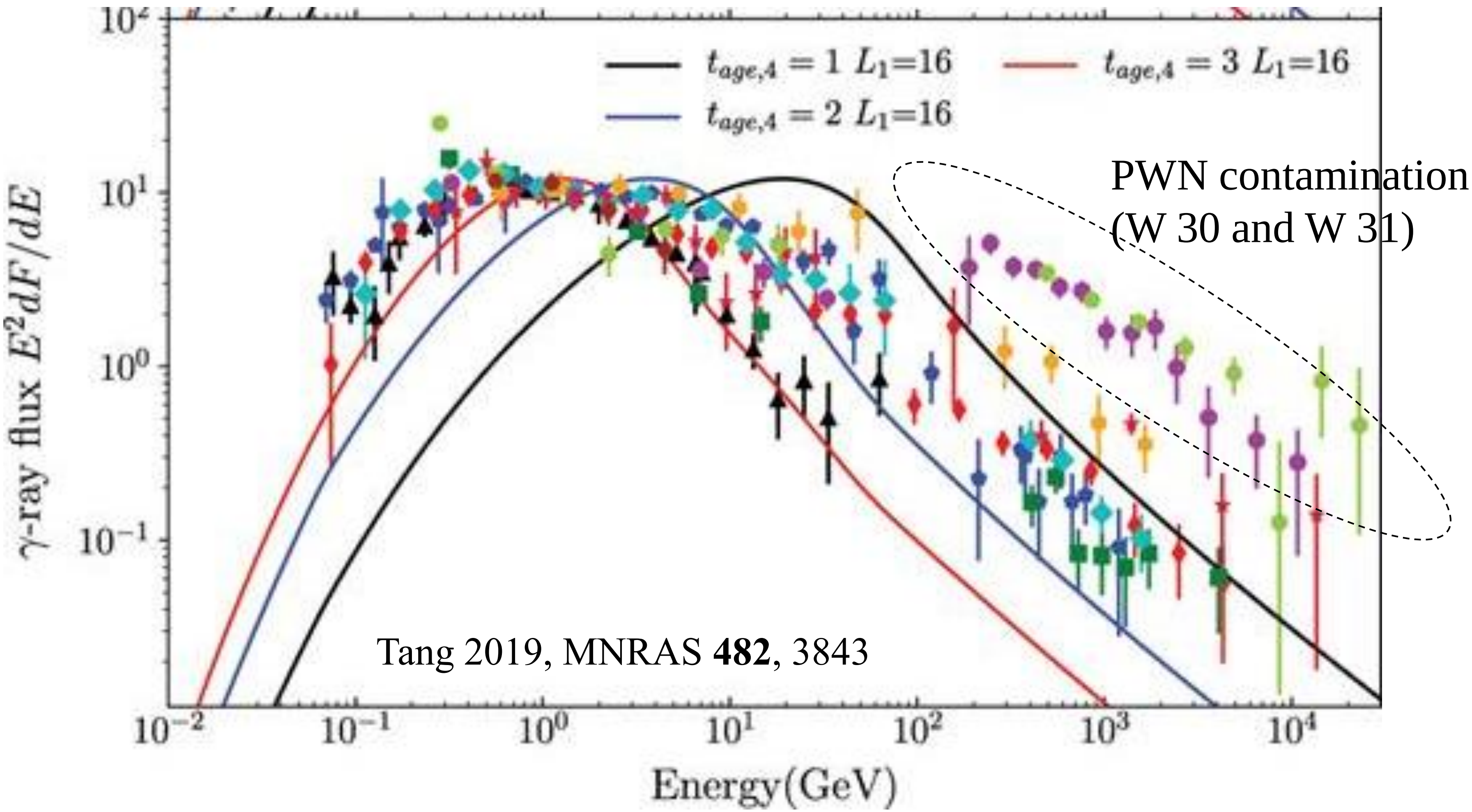
Full γ-ray spectrum: broken power-law in **momentum,** curve due to **transrelativistic** protons

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

IC 443: s_1 = 2.36 +/- 0.02, s_2 = 3.1 +/- 0.1, p_{br} = 240 +/- 70 GeV/c

Low-energy electron spectrum (from radio) is harder (1.74 and 1.72)

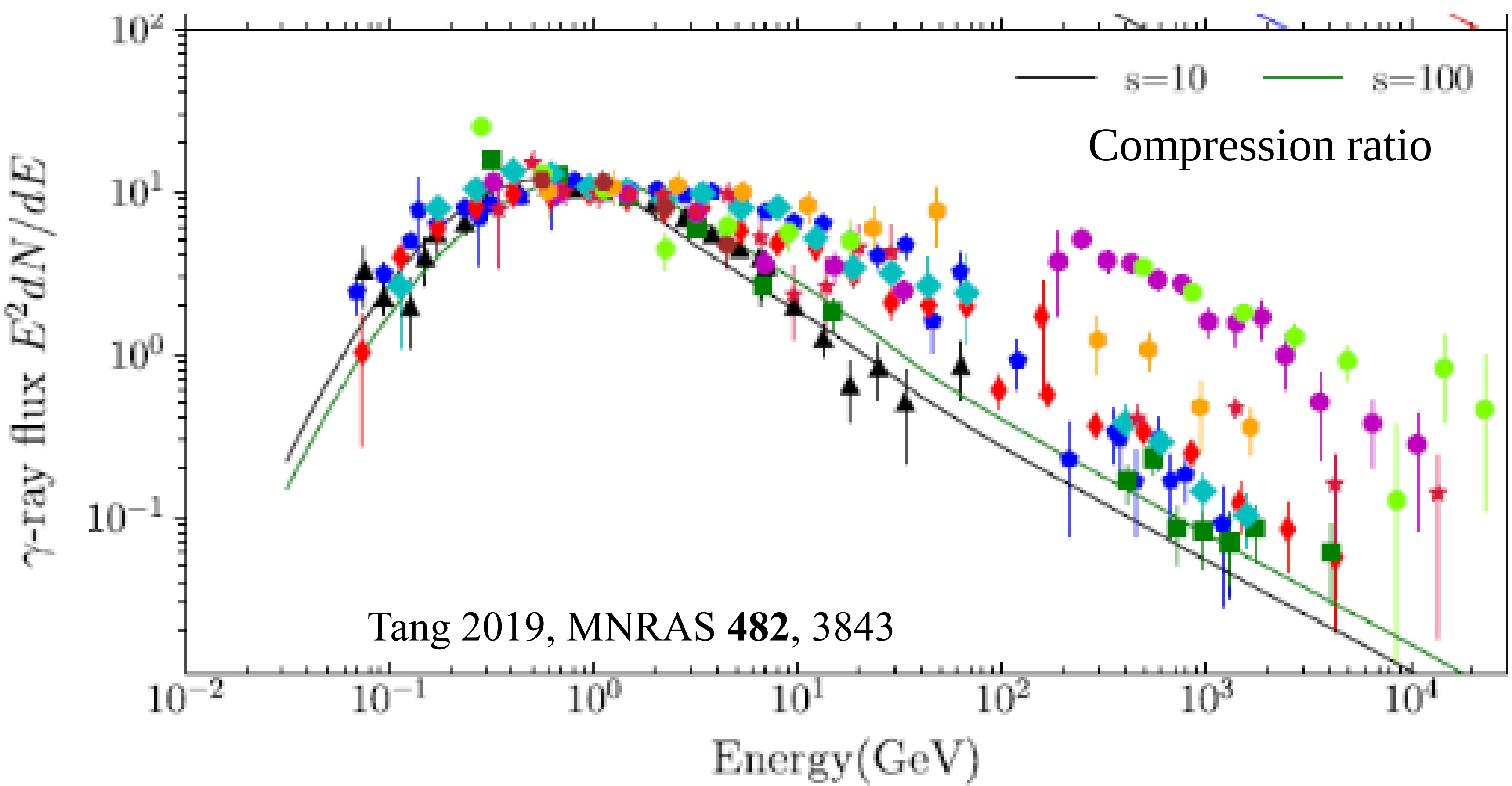
Interacting SNRs: Modeling



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

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

Interacting SNRs: Modeling



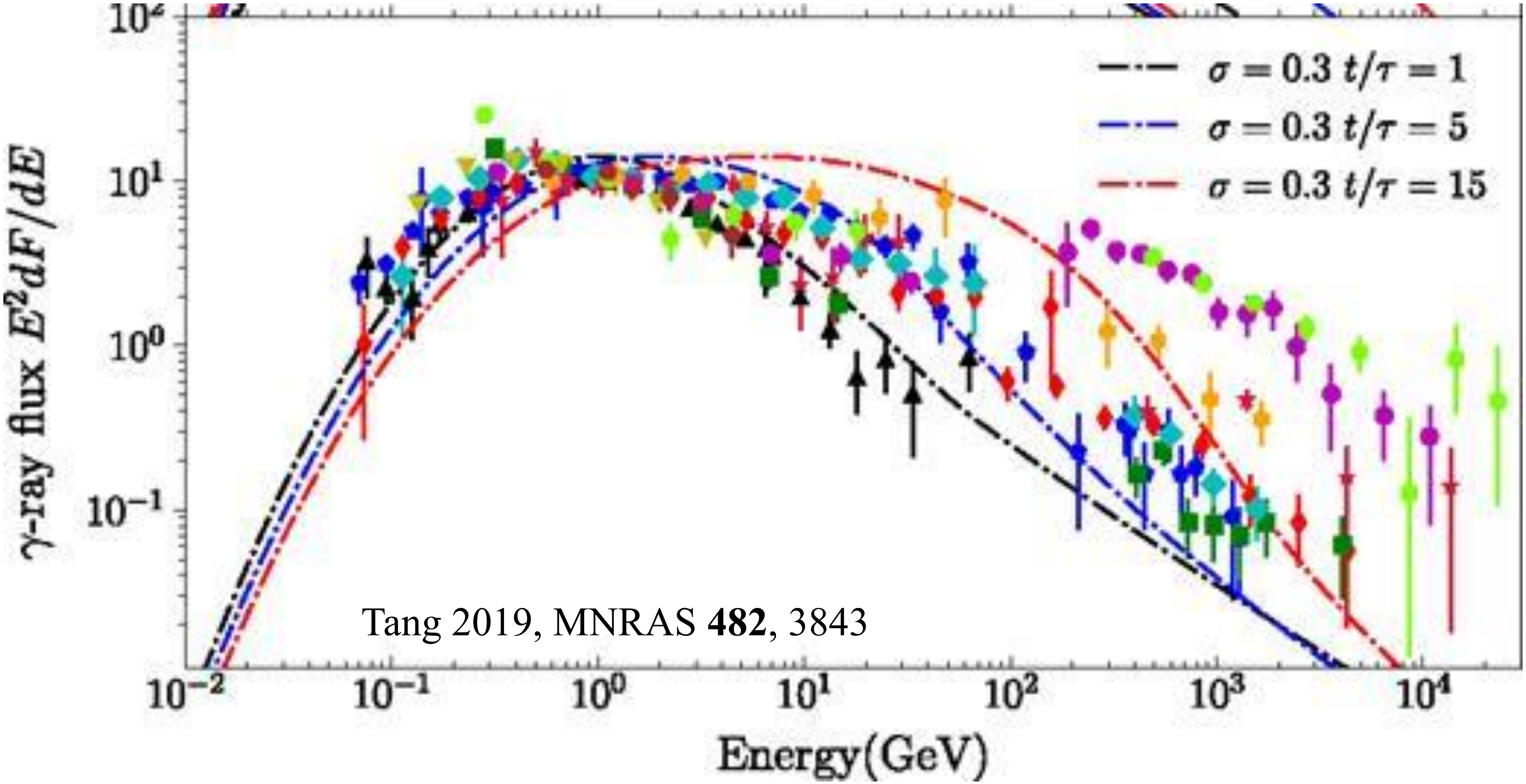
Radiative shock model with **pure adiabatic compression**

Van der Laan mechanism traditionally used in the radio

Could apply for **perpendicular B field**

Cannot account for breaks at large momentum like IC 443

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

The Cygnus Loop

Very well observed SNR (Raymond et al. 2020, ApJ **894**, 108)

Nearby (735 pc), big (3°), off GP (b = -8.5°)

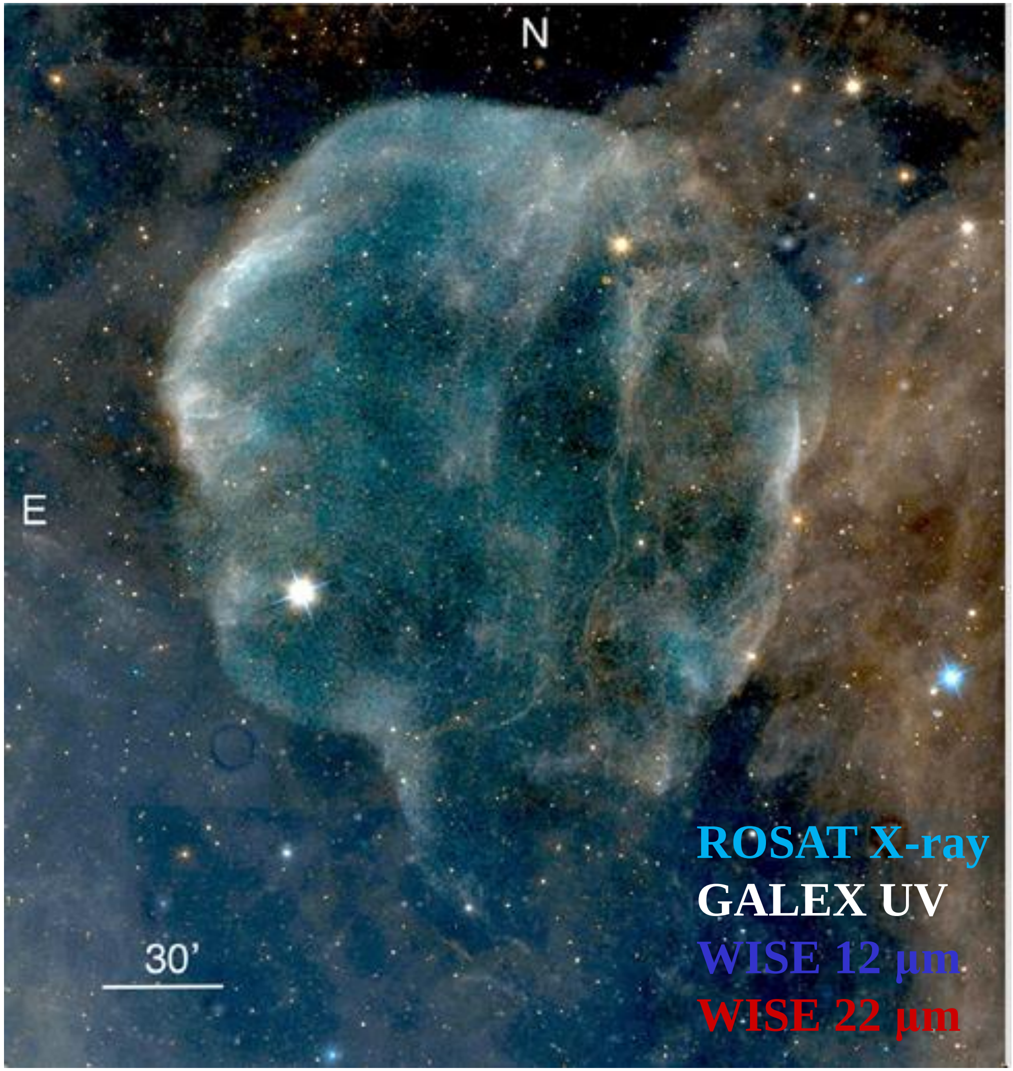
Radiative shocks (UV/Opt) around 130 km/s reach 300 cm^{-3}

Non-radiative shocks 240 km/s reach 6 cm^{-3}

Faster shocks (X-rays) around 350 km/s reach 1.6 cm^{-3}

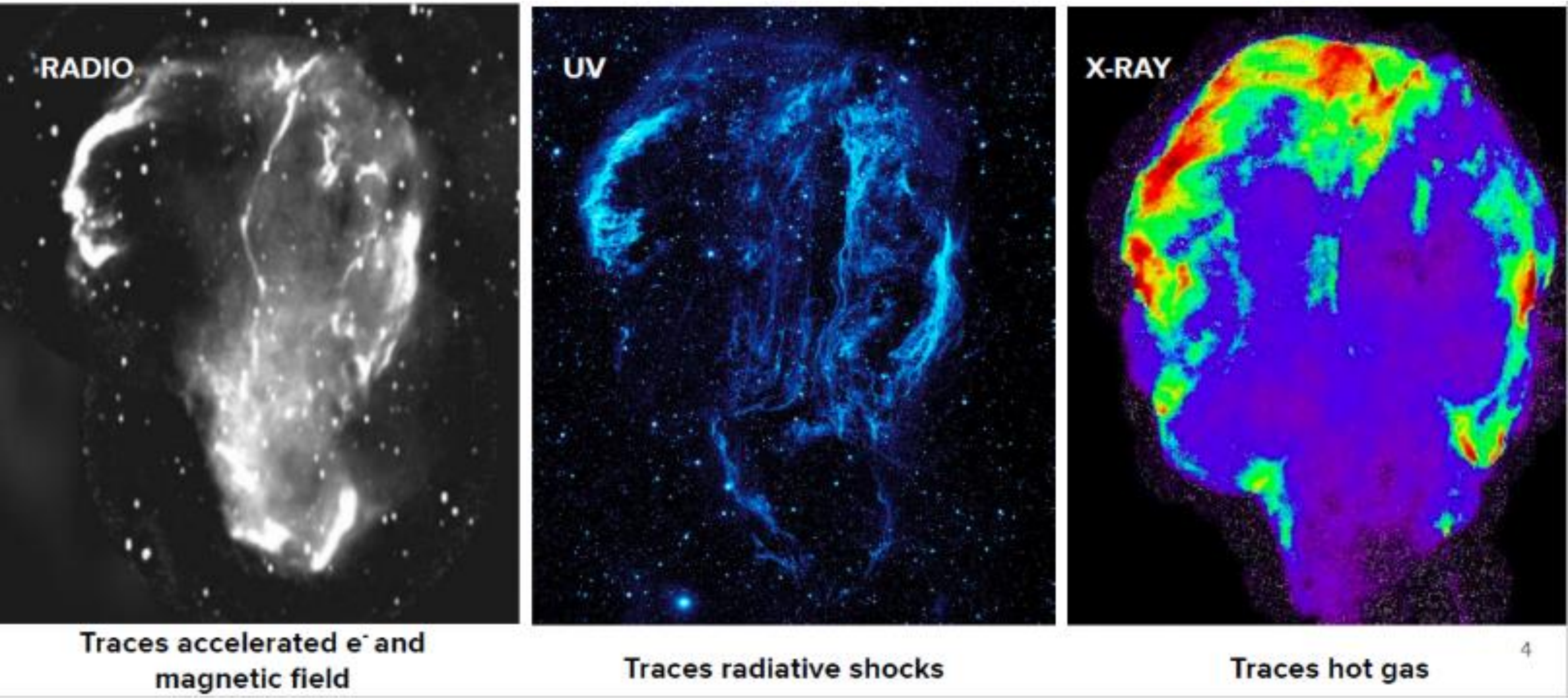
(post shock densities)

Excellent target to **resolve radiative and non-radiative shocks in the same SNR**



Fesen et al 2018, MNRAS **481**, 1786

Multiwavelength view



About half of the radio emission (south) is not correlated with other wavelengths.
Spectrum does not look different though ➔ constant reduction factor

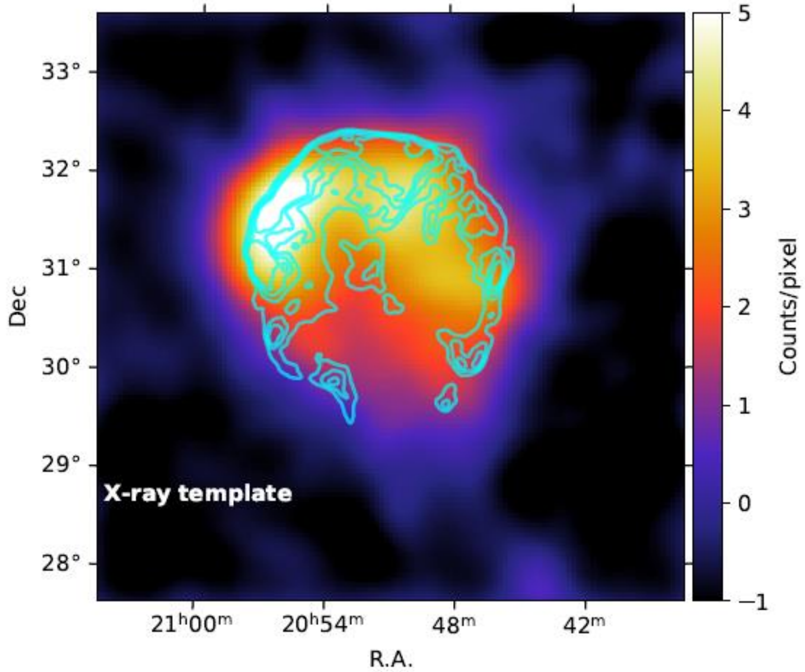
γ-ray emission

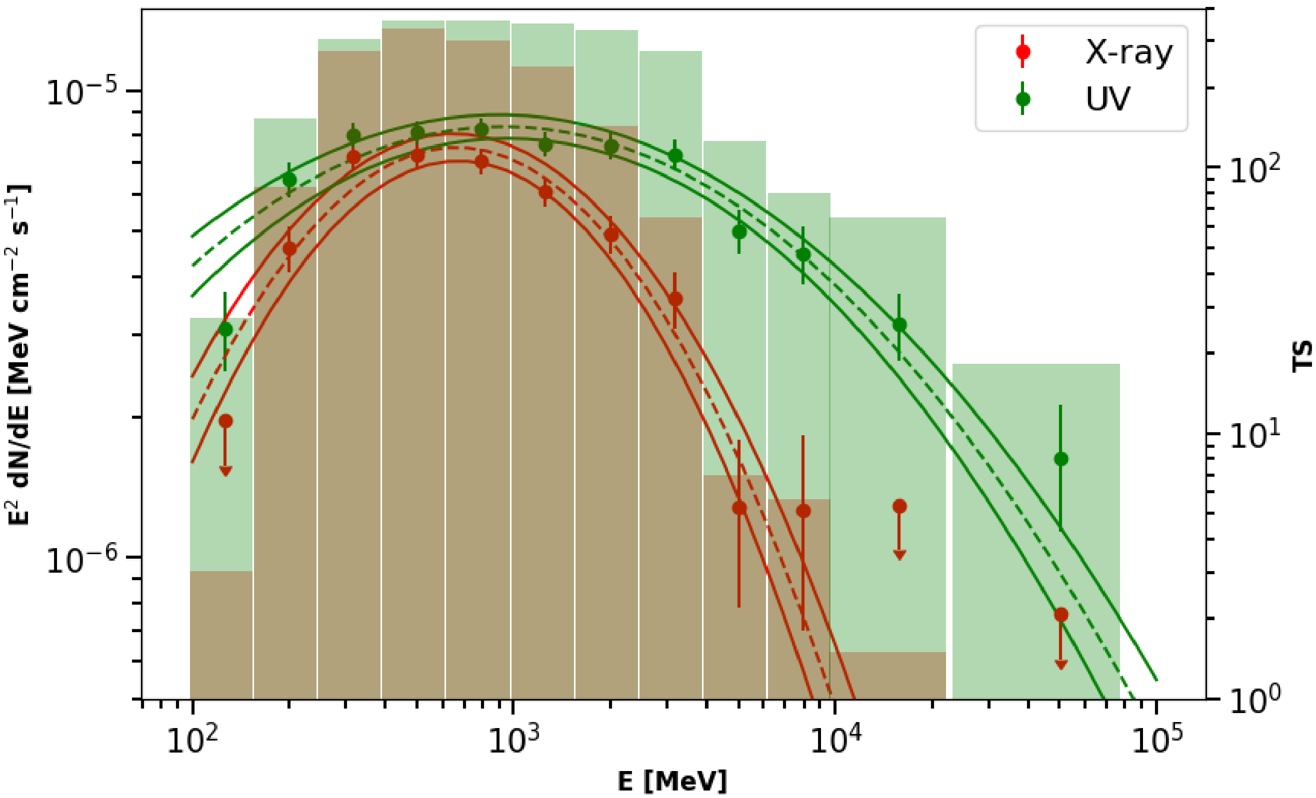
Tutone, Ballet, Acero, submitted to A&A

Well resolved with Fermi LAT > GeV

Looks like X-ray or UV, not like radio

Best template is UV, significantly better with **combination of UV and X-rays**



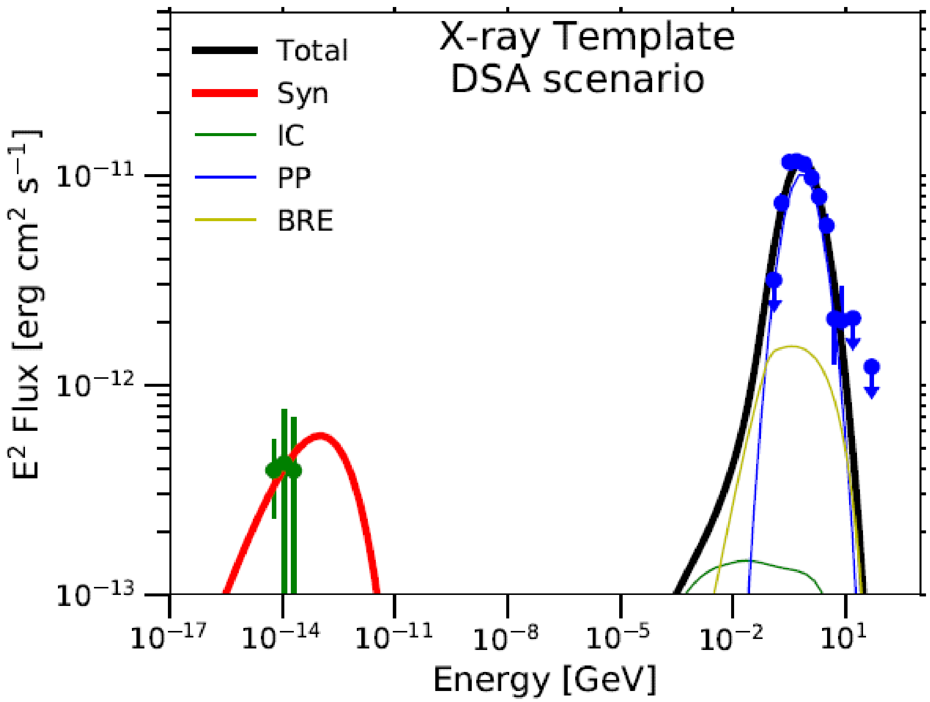


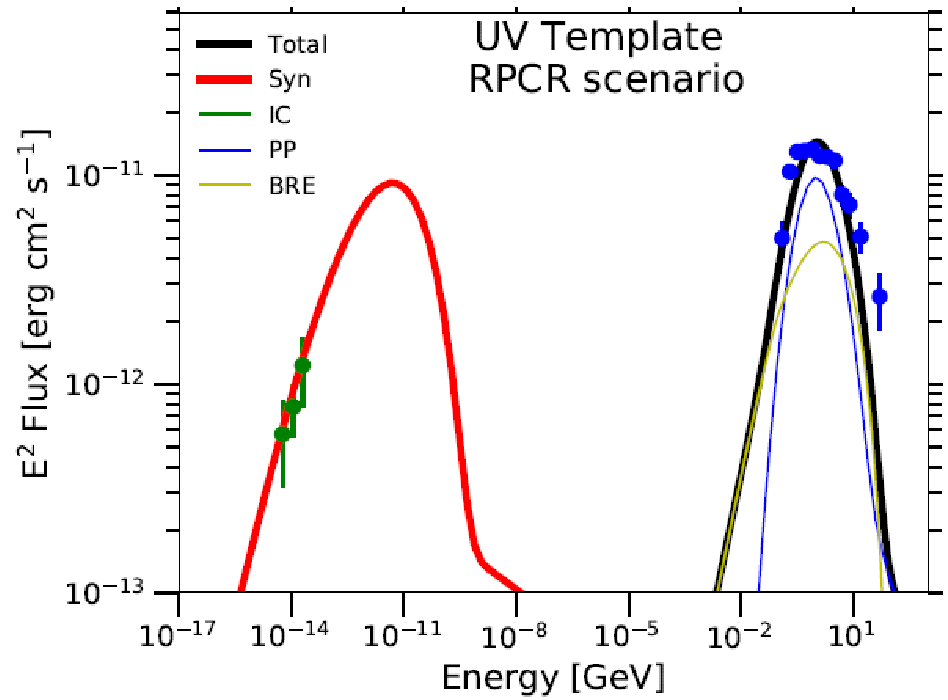
Fit with UV and X-ray templates

Both spectra are strongly curved toward low energy, implying hadronic emission

UV-associated (radiative) extends to higher energies. Asymptotic index ≈ 3

Modelling the γ -ray emission





Model UV-associated and X-ray associated spectra (same decomposition for radio)

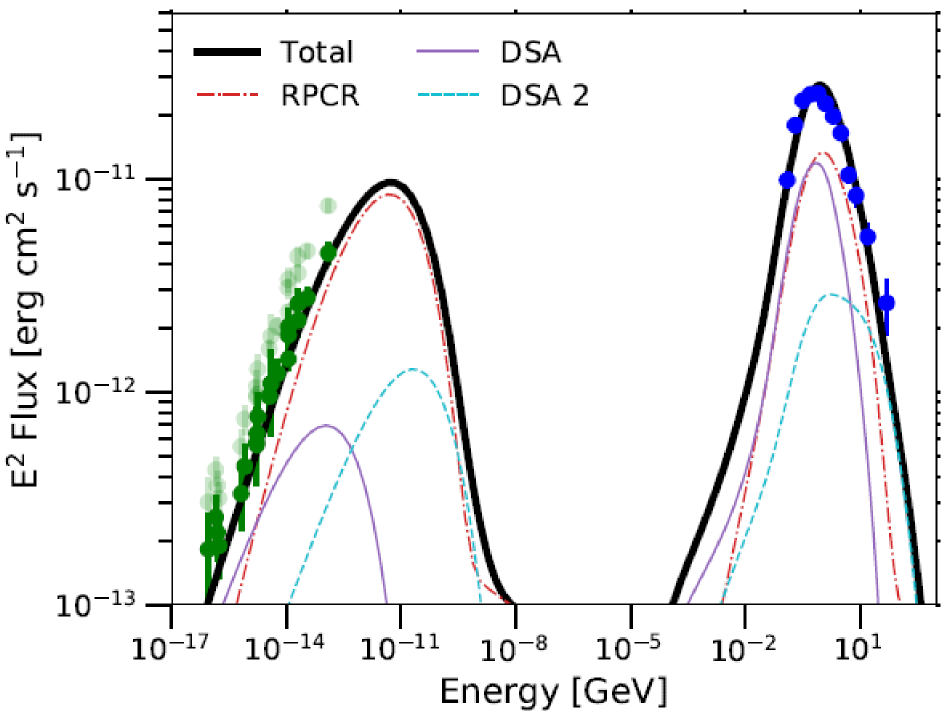
Use **observationally-determined physical parameters** for each (density, velocity, B)

Fit total energy in protons/He (1.2 10^{49} erg) and electron fraction (1%) in NR shocks

Fit filling factor of radiative clouds (1.3%). Energy in reaccelerated CRs only 4 10^{46} erg

Fit p_{max} (15 GeV in DSA and 20 GeV in RPCR)

Total γ -ray spectrum



Sum the radiative (reacceleration RPCR) and non-radiative (accelerated from thermal gas DSA) contributions

Explain 50 GeV point with small contribution (DSA2) from fastest X-ray shocks in more tenuous gas

Radio dominated by radiative shocks (larger B)

Good overall fit with only 4 free parameters (ignoring DSA2)

Open questions:

- ✓ RPCR contribution is somewhat too peaked. Local low-energy CR spectrum too low?
- ✓ High-energy tail is well fit by a power law, but is fit here by the sum of three cutoff power laws. Coincidence?

Discussion 1

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

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

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

My current understanding

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

Discussion 2

- **Those SNRs with radiative shocks are very bright at GeV, but are they important to the Galactic ecology?**

That process is limited to the cloud volume where the radiative shock develops (smaller than the total SNR volume)

Appears to reach several % in Fermi sources, but not active in all SNRs

Estimated total energy < 10^{48} erg, even in fully radiative SNRs like S 147

Those CRs have not escaped yet, they will lose energy during reexpansion. The width of the compressed regions is a few 10 mpc, but the compressed B field is transverse so escape is hard

My current understanding

✓ **Probably no**

Discussion 3

- **Why is the maximum momentum smaller in main SNR than in radiative shocks, compared to DSA prediction?**

$p_{\max} = 33\, s^{1/3}\, t_4\, V_{100}^2\, B_{\mu G}\, /\eta$ GeV/c (s is radiative compression)

My current understanding

✓ **Age limitation may not be relevant in old SNRs**

					P_{max} or P_{br}	
SNR	V_{sh} (100 km/s)	B (μG)	t (10^4 yr)	$S^{1/3}$	pred	obs
Monoceros	330	1 ?	3	1	1000/η	a few
HB 3	340	1 ?	3	1	1100/η	10
Cyg Loop	250	3	2.1	1	1300/η	15
W 44	100	25	0.5	2.4	1000/η	22
MSH 15-56	150	4	0.8	2.3	700/η	> 50
Cyg Loop	130	6	0.12	2.3	100/η	20

Discussion 4

- **What is the origin of the power-law extension after the break in radiative shocks, with a slope around 3?**

1. Adiabatic compression of Galactic CRs? PL should emerge as additional component after cutoff, not what is seen
2. Break due to turbulence decay in neutrals? Predicts $\Delta s = 1$, more than is observed if low-energy slope is 2.3-2.4
3. Relic of acceleration in SNRs at earlier times, only partly escaped? Should appear as additional component rather than an extension
4. No reacceleration, only illumination? Why is spectrum softer in non-radiative parts of the Cygnus Loop?

My current understanding

✓ **Spectrum looks like a single component**

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 accelerated at blast wave **illuminate** clouds, but difficult to use quantitatively because of complications due to diffusion
- **Reacceleration** at radiative shocks often dominates GeV emission
- **Regular DSA** appears to be still active at 400 km/s

Backup

Recent theoretical work on reacceleration

- ✓ Cristofari & Blasi 2019 (MNRAS **489**, 108) insisted on reacceleration in low density media (not what I am interested in here)
- ✓ Caprioli et al 2018 (J. Plasma Phys. **84**, 715840301) discussed how reacceleration could help injection
- ✓ In interstellar clouds gas is largely neutral, injection is difficult and it is reasonable to expect that reacceleration is the dominant mechanism