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Supernova remnants interacting with interstellar clouds

- ❑ Old large nearby SNRs
- ❑ Interaction with clouds
- ❑ Soft γ-ray spectra
- ❑ Reacceleration of ambient cosmic rays
- ❑ Application to the Cygnus Loop

CR acceleration in SNRs

- Maximum energy reached by Diffusive Shock Acceleration (DSA) increases fast with shock velocity

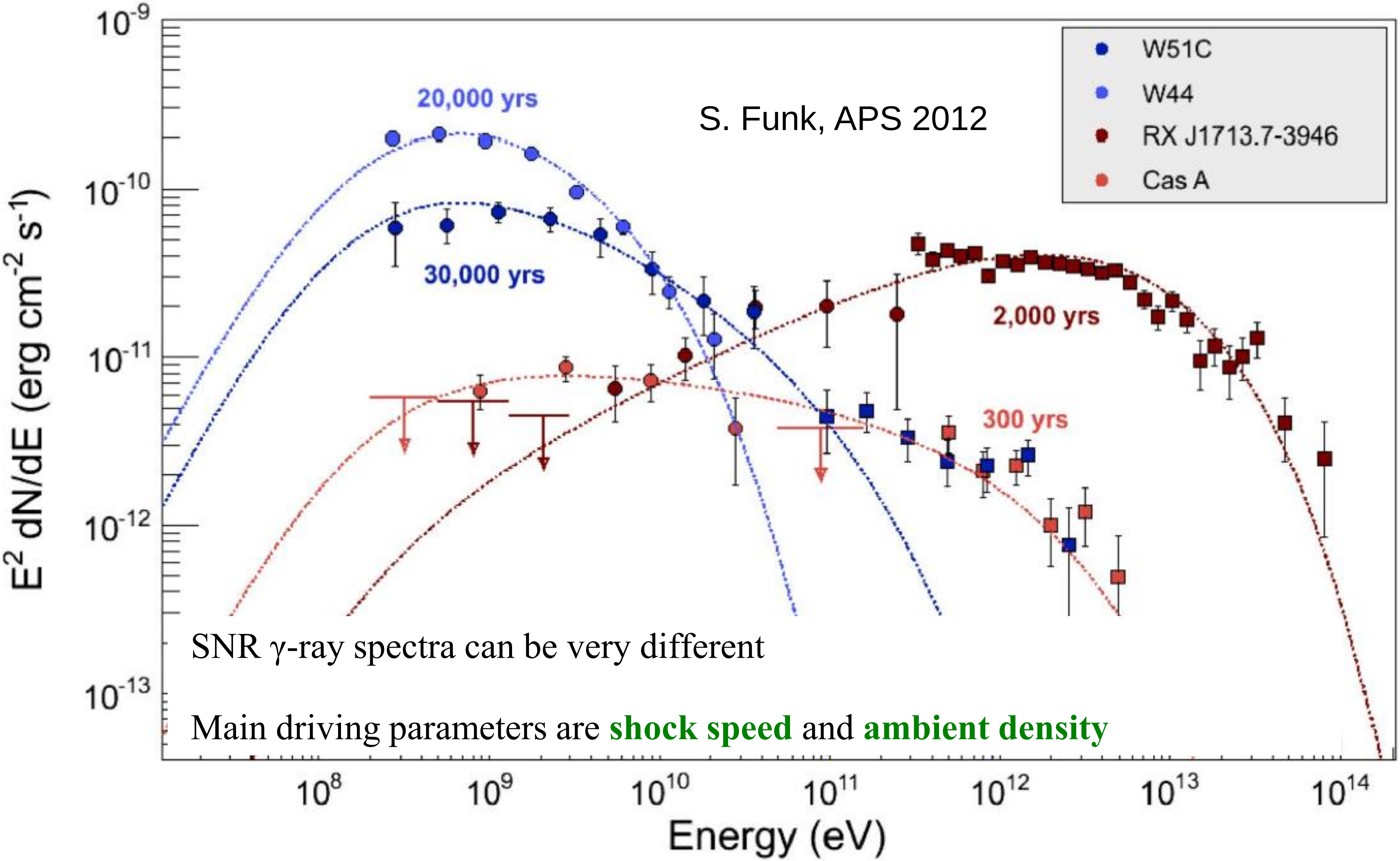
  $$p_{\rm max} = \frac{500}{\eta}\left(\frac{v_{\rm sh}}{100\ {\rm km/s}}\right)^2 \frac{t}{10\ kyr}\frac{B_0}{10\mu{\rm G}}\ {\rm GeV/c}$$

- Mass swept-up by SNR per unit ln(t) in the Sedov phase goes as $\rho v_{\rm sh} R^2 t \propto \rho R^3 \propto \rho t^{1.2} \propto \rho v_{\rm sh}^{-2}$
- Most of the CR acceleration in SNRs takes place at low shock velocities, a few 100 km/s
- We expect the bulk of GeV CRs to be accelerated in that phase
- 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 interstellar clouds
- Spatial resolution is no better than 0.1° (actually worse below 10 GeV). Cannot extract the spectrum of the shock itself, always integrated 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**

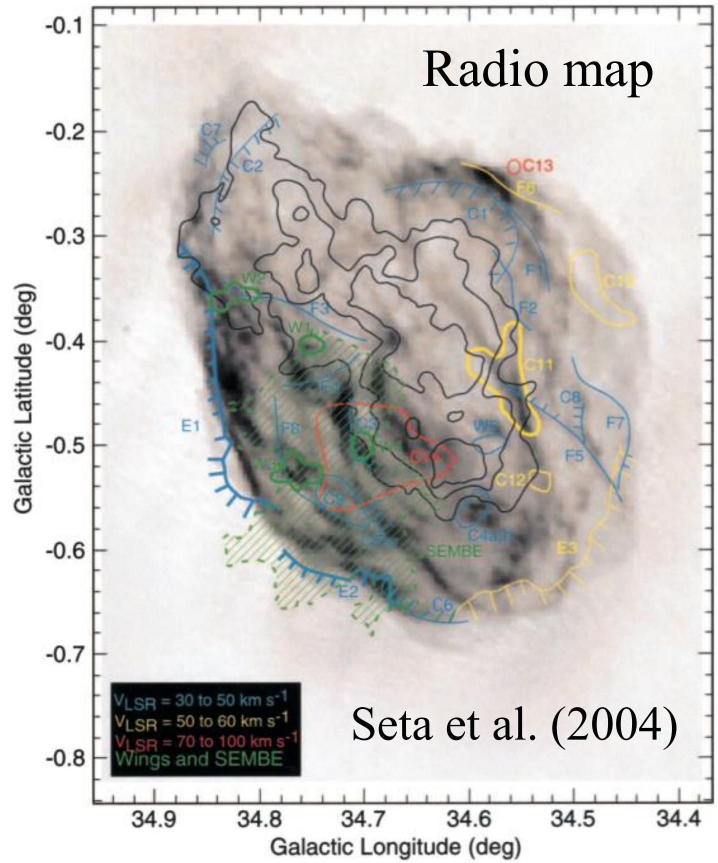
Middled-aged SNRs: W 44

Clear **hadronic** γ-ray emission (Ackermann et al 2013, Sci **339**, 807)

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

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

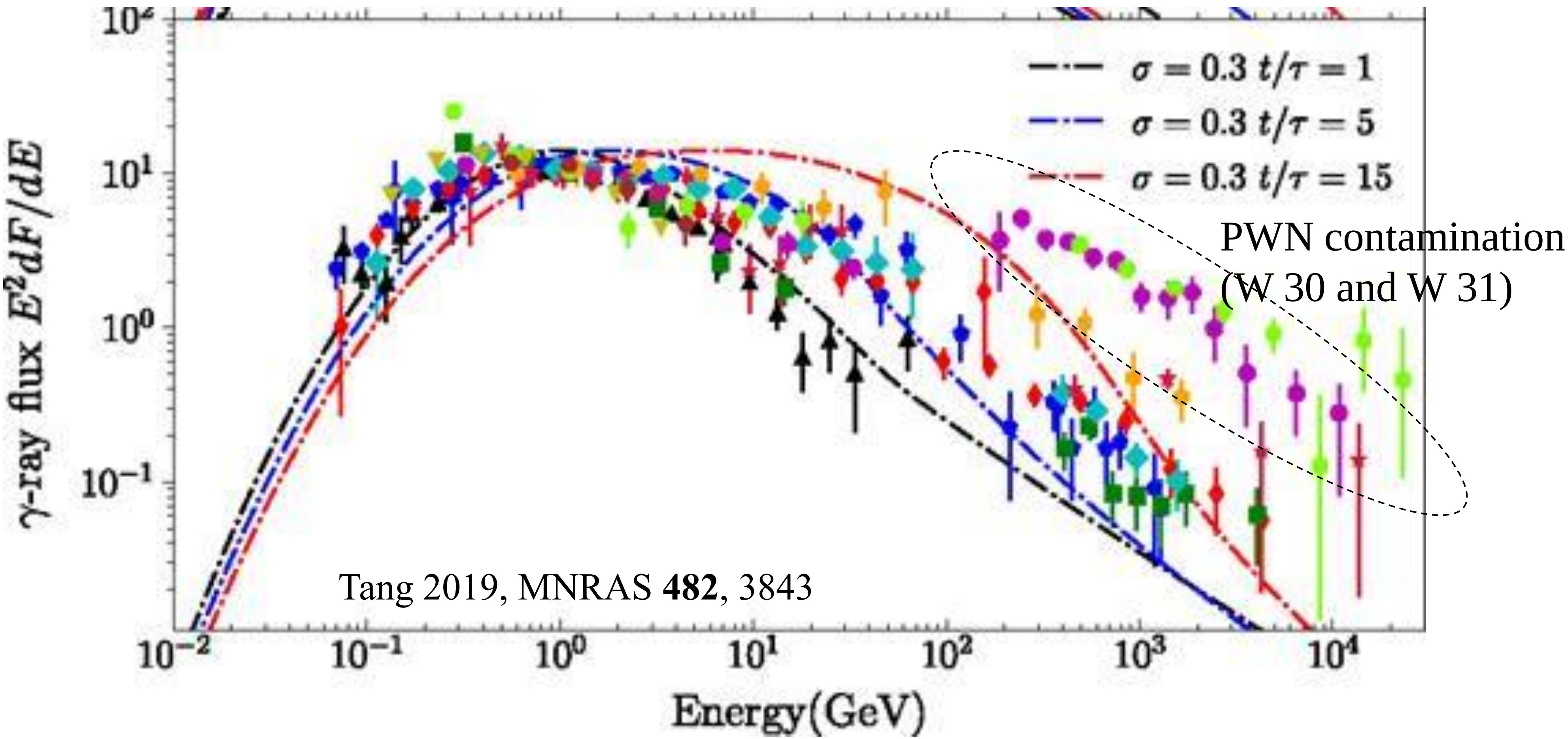
Other such SNRs: IC 443, W 51C, W 49B, W 28, 3C 391, G349.7+0.2



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: **Reacceleration of pre-existing ambient CRs** (RPCR)
  $n_{\mathrm{acc}}(p) = (\delta + 2) p^{-\delta} e^{-p/p_{\max}} \int_0^p n_{\mathrm{GCR}}(x) x^{\delta-1} dx$ (δ=2 in standard DSA)
- ✓ Radiative shocks ➔ strong compression downstream (limited by B field)
  $n_{\mathrm{ad}}(p) = s^{2/3} n_{\mathrm{acc}}(s^{-1/3} p)$ (s is the radiative compression, > 10)
- ✓ Compresses together the accelerated particles, the magnetic field (synchrotron) and the gas (π^0-decay)
- ✓ **Very large emissivity over very small volume**

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 inflexion to power law (compressed GCR) after peak

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}

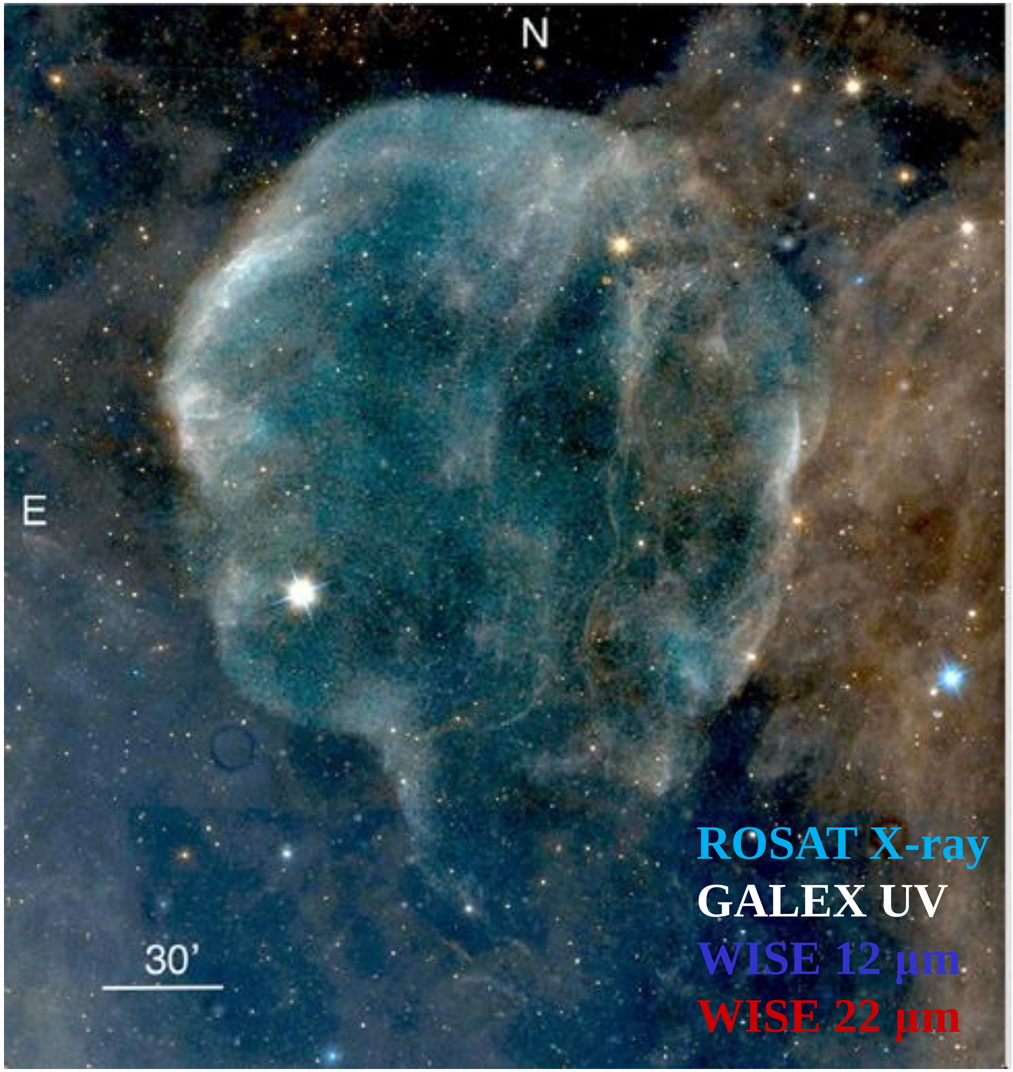
Non-radiative shocks 240 km/s reach 6 cm^{-3}

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

(post shock densities)

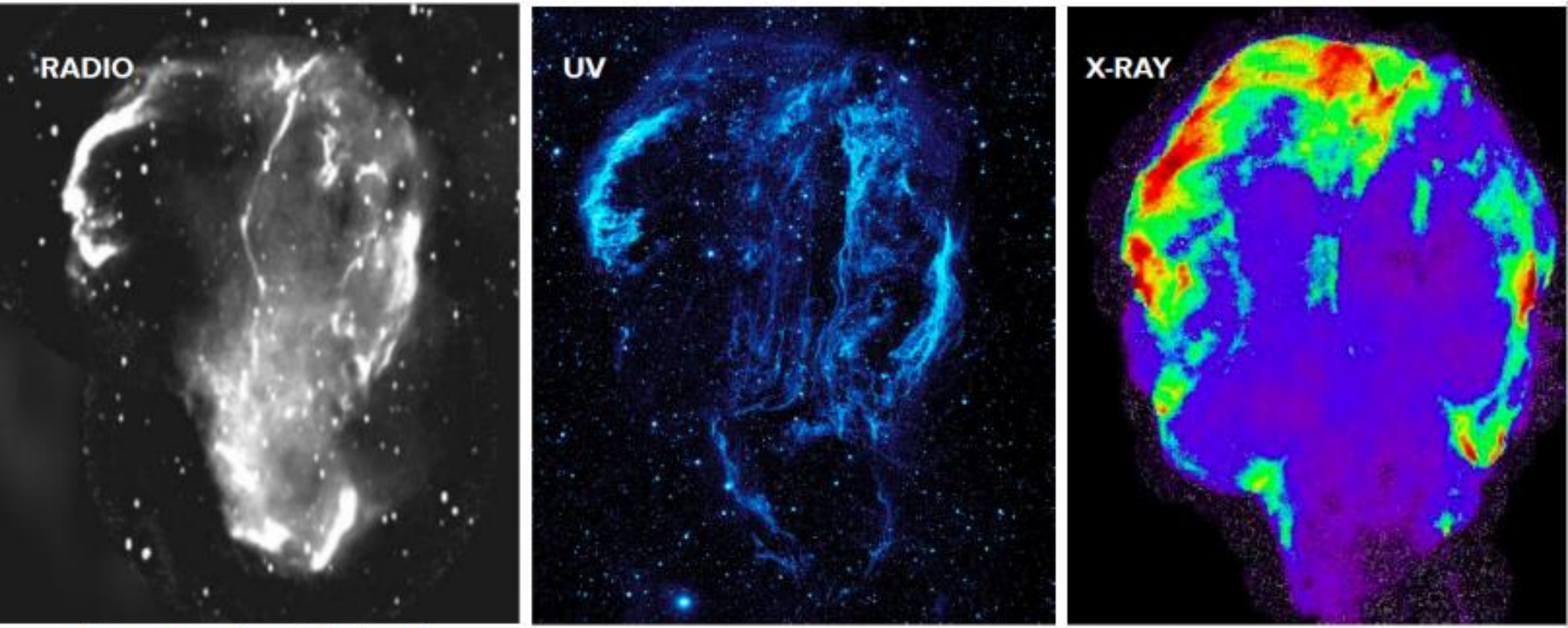
Excellent target to study both **radiative and non-radiative shocks in the same SNR**

Previous studies on MSH 15-56 (Devin et al 2018, A&A **617**, A5) and CTB 37A (Abdollahi et al 2020, ApJ **896**, 76) but more confusion and dominated by radiative emission



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

Multiwavelength view



Traces accelerated e^- and magnetic field | Traces radiative shocks | Traces hot gas

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

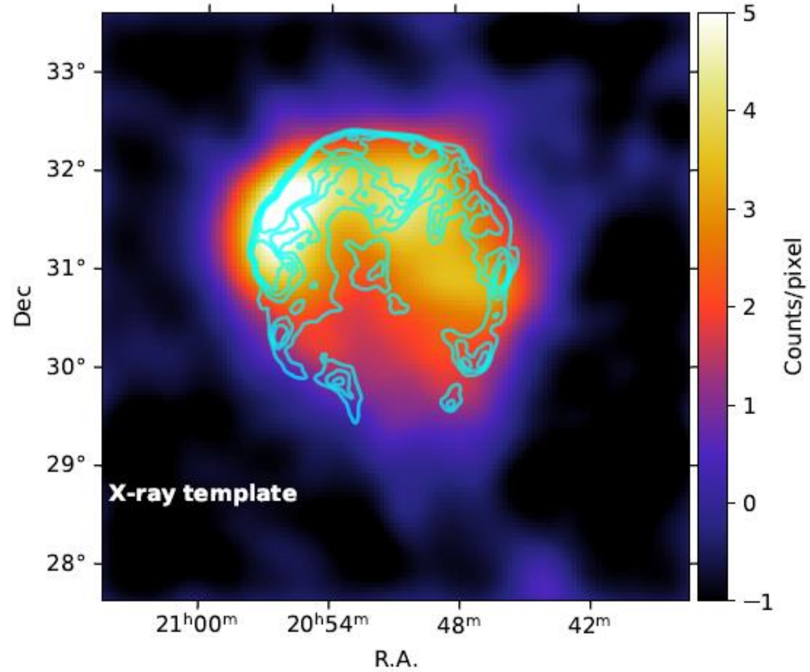
γ-ray emission

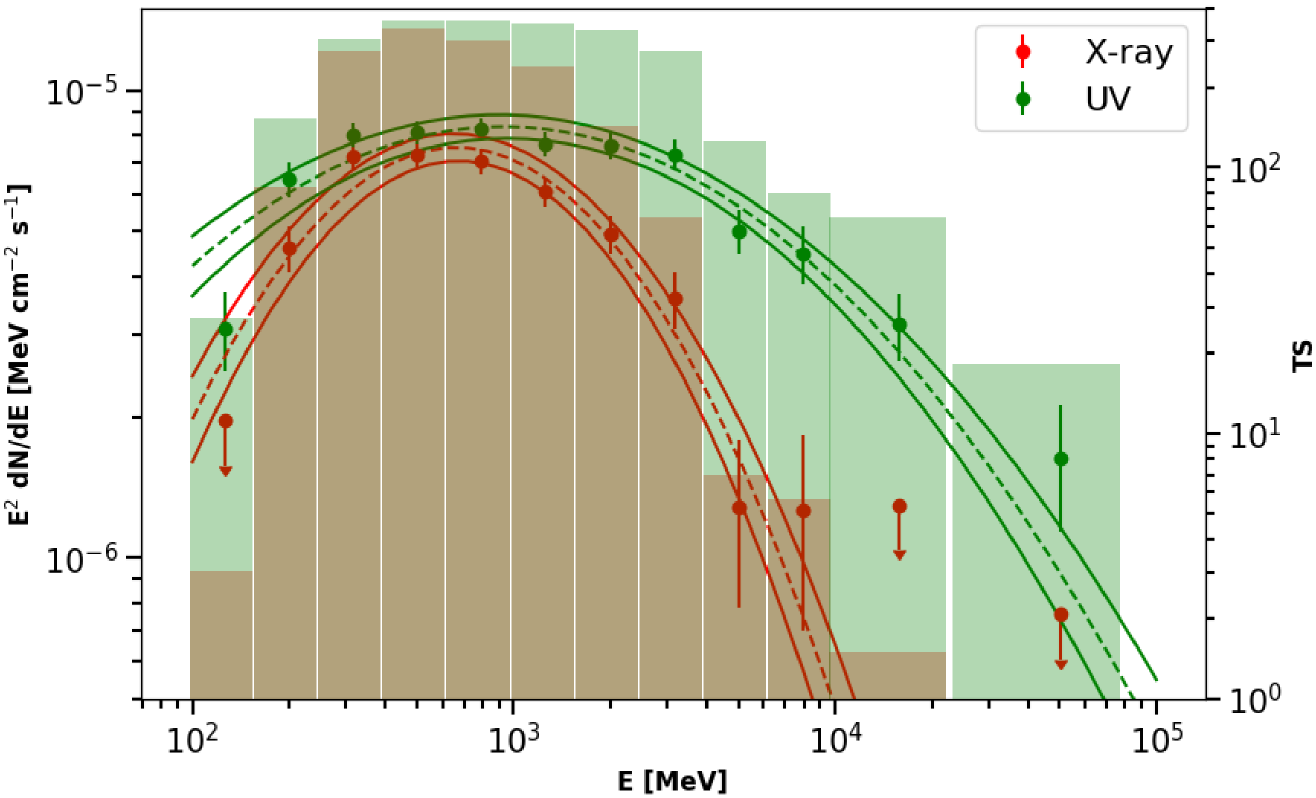
Tutone, Ballet, Acero, submitted to A&A

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**



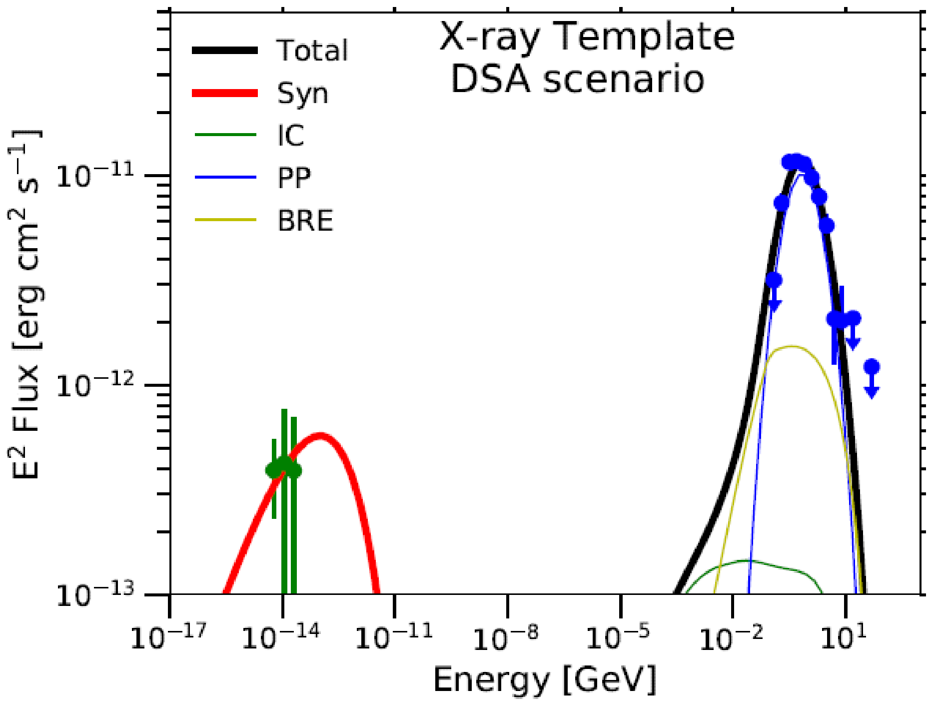


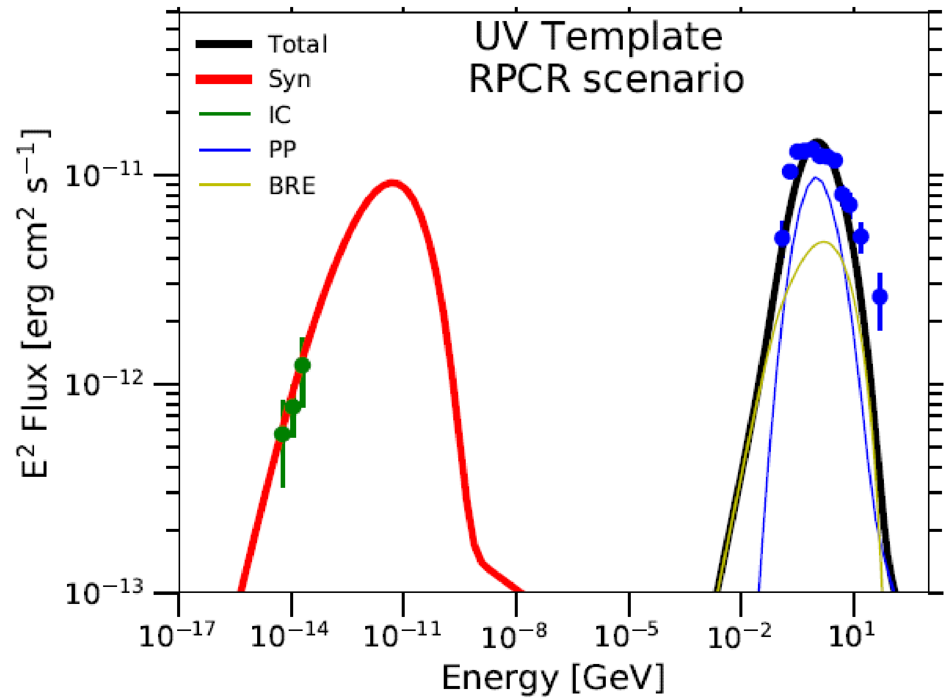
Fit with UV and X-ray templates

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

UV-associated (radiative) extends to higher energies

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)

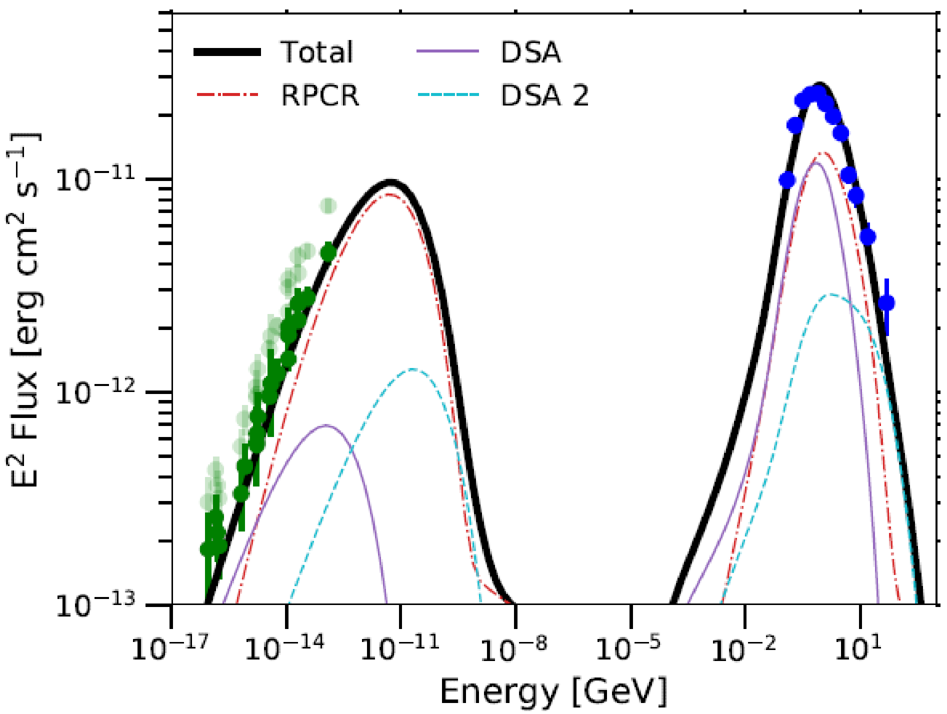
Harder radiative spectrum because B is larger (compensates lower velocity), additional compression increases max energy, and more bremsstrahlung

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%)

Fit p_{max} corresponding to Bohm factor η = 7 (same in DSA and 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?

Conclusions

- ✓ **Many old interacting SNRs** observed at GeV, bright because of large target density in interstellar clouds, good MWL constraints
- ✓ The Cygnus Loop is a particularly good example (well resolved)
- ✓ The γ-ray emission in the Cygnus Loop is consistent, both spatially and spectrally, with the original idea that **both newly accelerated CRs and reaccelerated CRs in radiative shocks contribute**

Reaccelerated CRs occupy only a small volume, ~ 4 10^{46} erg total energy
➔ not as important to CR budget as to γ-ray emission

Hampered by poor angular resolution below 1 GeV ($R_{68} = 2°$ at 350 MeV)