Origin of Bright Gamma-ray and Radio Emission at Fast Cloud Shocks of Middle-aged Supernova Remnants

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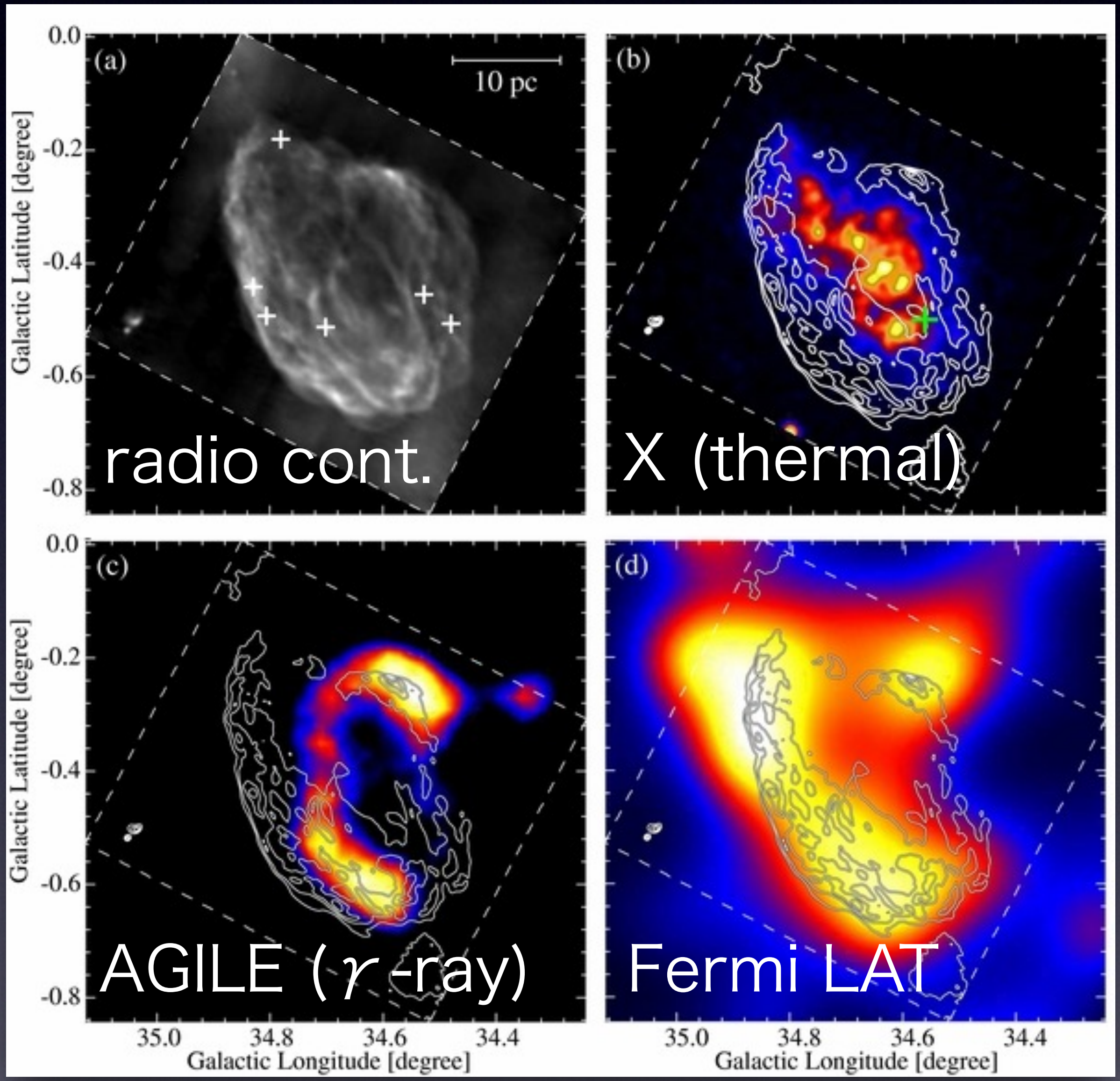
References

S.-H. Lee, D. J. Patnaude, J. C. Raymond et al., ApJ, 806, 71 (2015)
Y. Uchiyama, R. D. Blandford, S. Funk et al., ApJL, 723, L122 (2010)

Bright Radio and γ-rays from Middle-aged SNRs

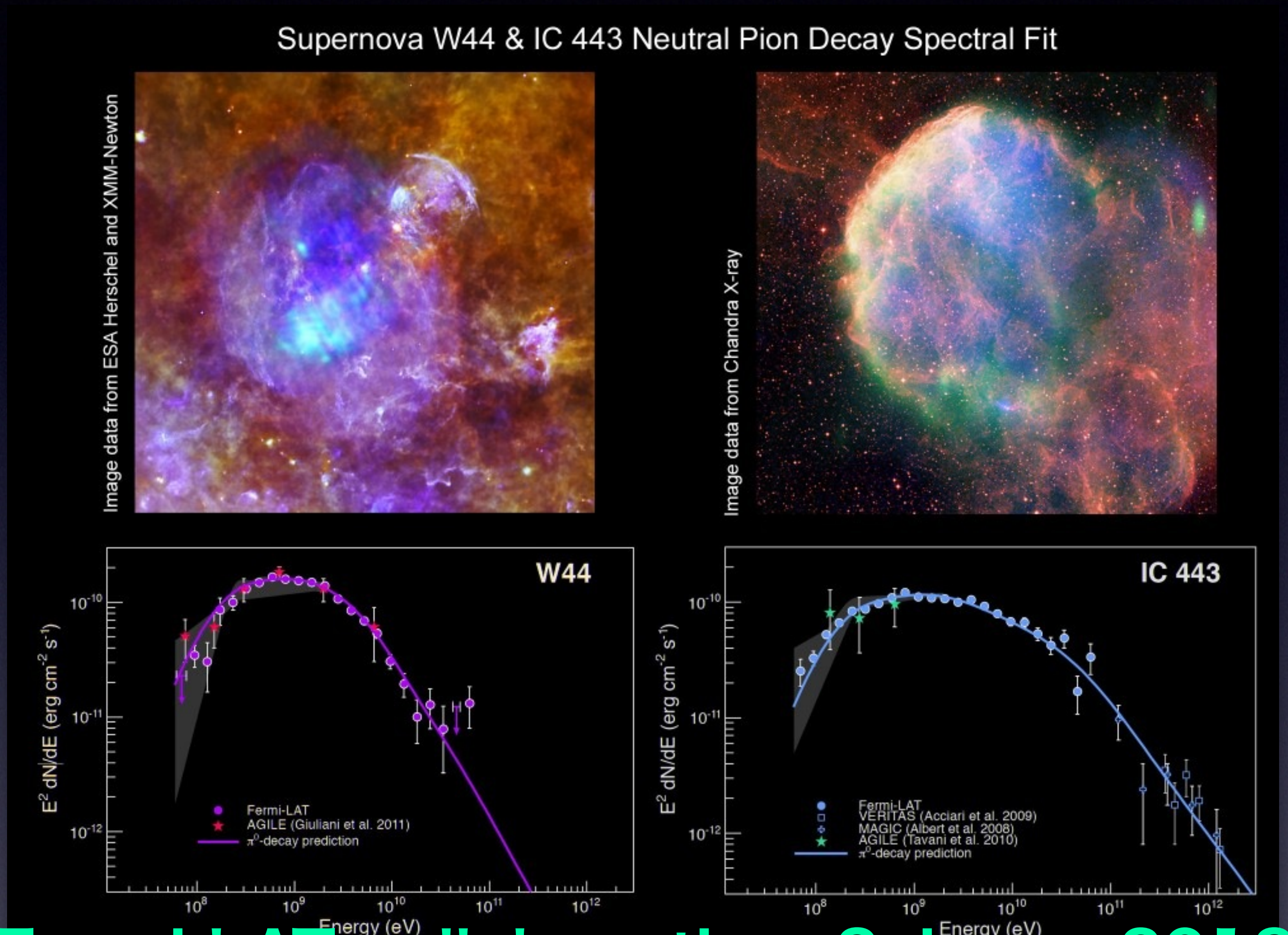
- ★ Many **GeV-bright SNRs** in our Galaxy found by AGILE, Fermi
- ★ Mostly **middle-aged SNRs** interacting with **molecular clouds**
- ★ Evolved, have slow shocks, but **bright non-thermal emission (radio, GeV γ-rays)**
- ★ Assume pure hadronic origin for luminous GeV γ-ray emission
  $\langle n_{gas} W_{CR} \rangle$ ~ a few 10^{50} to 10^{52} erg/cm^{-3}
  Lots of CR protons!
- ★ Bright non-thermal radio emission —> **B >> μG (i.e. >> ISM level)**

SNR W44 (Yoshiike+ 2013)

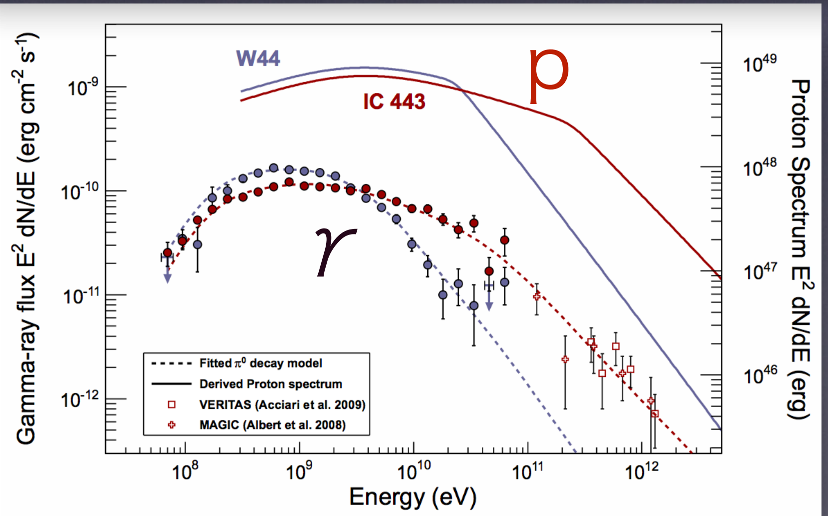


Characteristic γ-ray spectra of middle-aged GeV-bright SNRs

- ★ Cutoff detected around 250 MeV —> predominant **π^0 origin of γ-rays**
- ★ **Smoking gun evidence** for **SNR accelerating CR protons**!
- ★ **BUT! Many puzzles still remain**:
  - Origin of **copious CR protons**
    How are they **injected and accelerated**?
  - Unusual CR spectra, with momentum **break**
  - Origin of **amplified B-field**?
  - **Evolution stage of these GeV-bright guys?**
    Any connection with young ejecta-dominated and TeV-bright SNRs?



Fermi LAT collaboration, Science 2013



Dynamically evolved SNRs

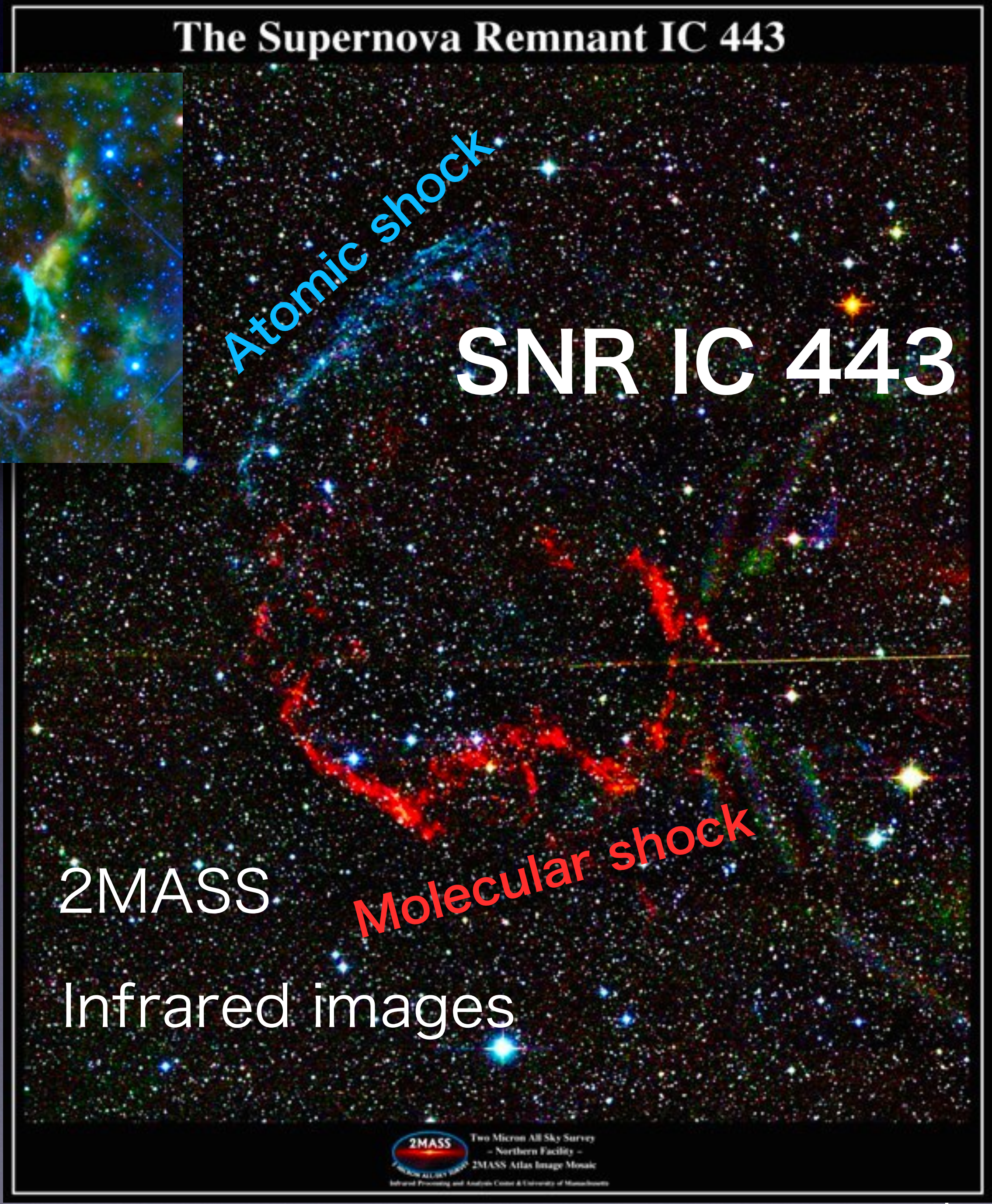
How can they emit bright gamma-rays!?

Radiative Shocks at Evolved SNRs

★ **Evolved SNRs often interacting with clouds**

★ **Typical properties:**

- v_{shock} > ~100 km/s
- $\langle n_0 \rangle$ ~ 100-1000 cm^{-3}
- T ~ a few 10^5 K behind shock, molecules dissociated and ionized
- Photoionization precursor by UV photons from downstream
- Bright optical/IR lines from recombining/excited gas
- Spots of OH masers from shocked dense clumps



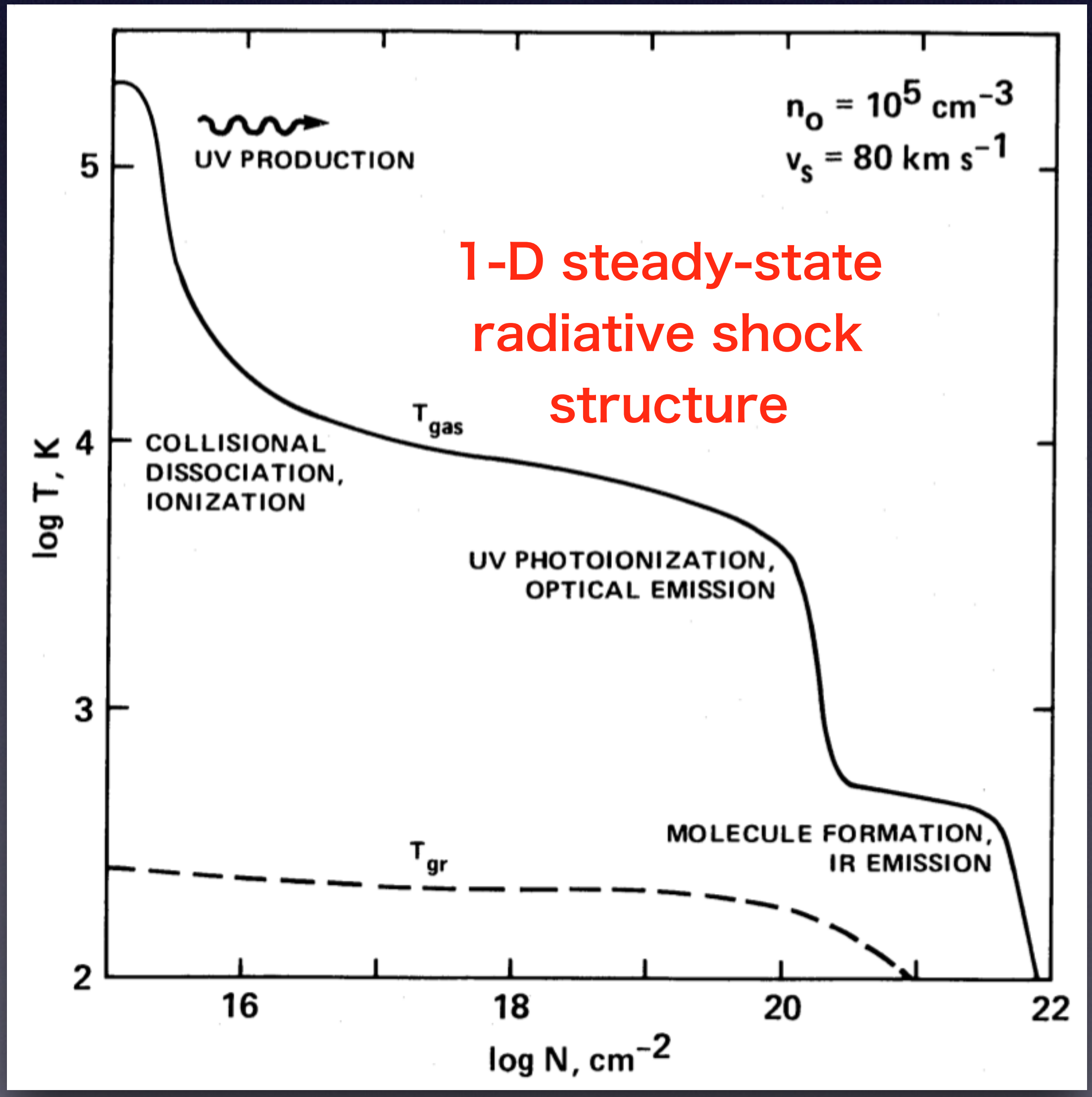
Basics of SNR Radiative Shocks

- ★ Transition from Sedov to radiative phase

  Transition timescale from $t_{cool} = t_{age}$: $t_{tr} \approx 2.9 \times 10^4 E_{51}^{4/17} n_0^{-9/17}$ yr (e.g., Blondin '98)

- ★ Some relevant physical processes

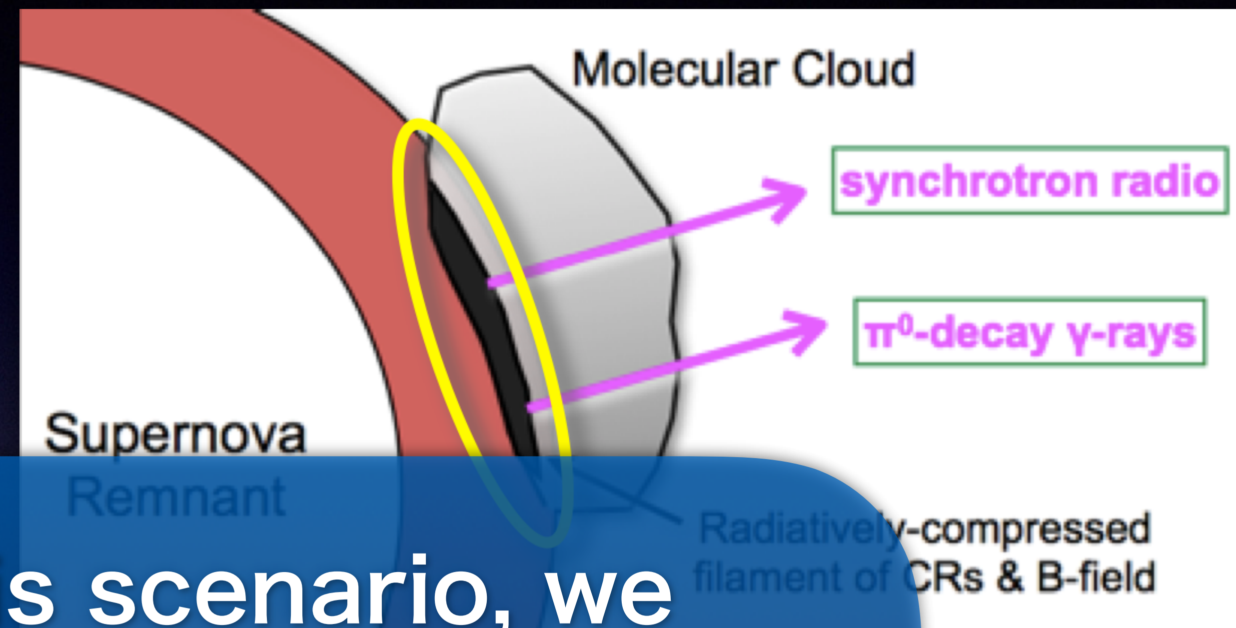
  - ☑ Recombining plasma
  - ☑ Radiative cooling (UV/optical continuum/lines)
  - ☑ Photoionization and heating
  - ☑ Thermal instability, shock oscillation
  - ☑ Molecular chemistry below a few 10^2 K
    Collisional cooling with dust grains



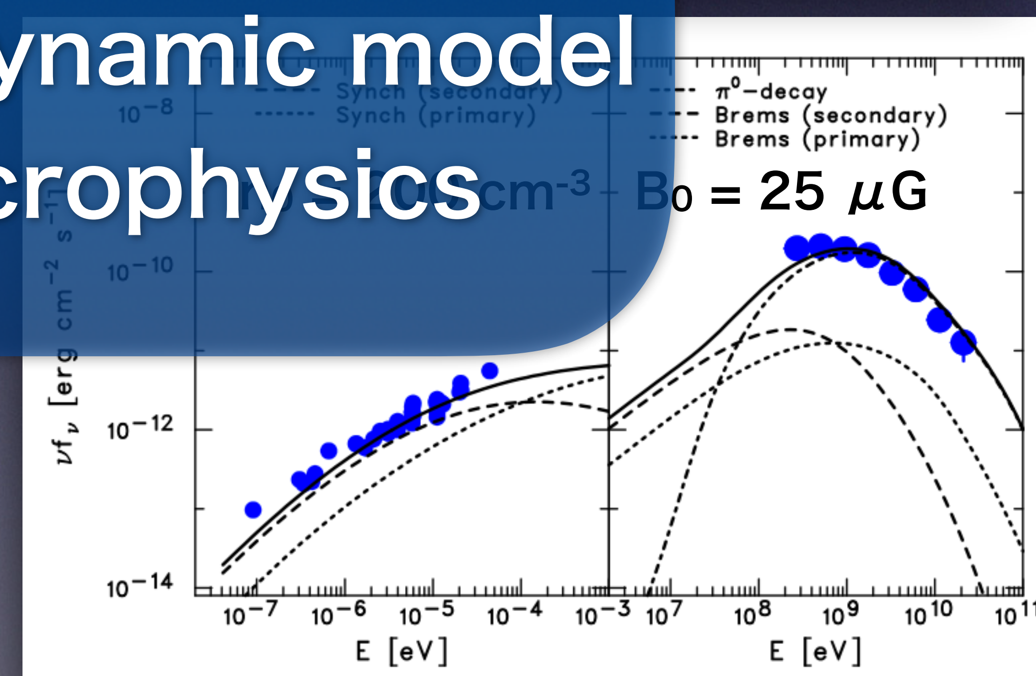
(Hollenbach & McKee '89)

“Crushed cloud” Scenario

- ★ Forward shock hits dense medium, drives a cloud shock into it
- ★ **Cold dense shell** forms behind decelerating cloud shock due to **fast radiative cooling**
- ★ **Re-acceleration of Galactic CR (GCR)** by >100km/s cloud shock is possible
- ★ **Gas**, **B-field** and **CRs** are rapidly **compressed**
- ★ Bright γ-ray from π^0-decay!
- ★ Bright radio synchrotron emission!



To test this scenario, we construct a hydrodynamic model with detailed microphysics



Analytic model for SMR W44 by Y. Uchiyama et al (2010)

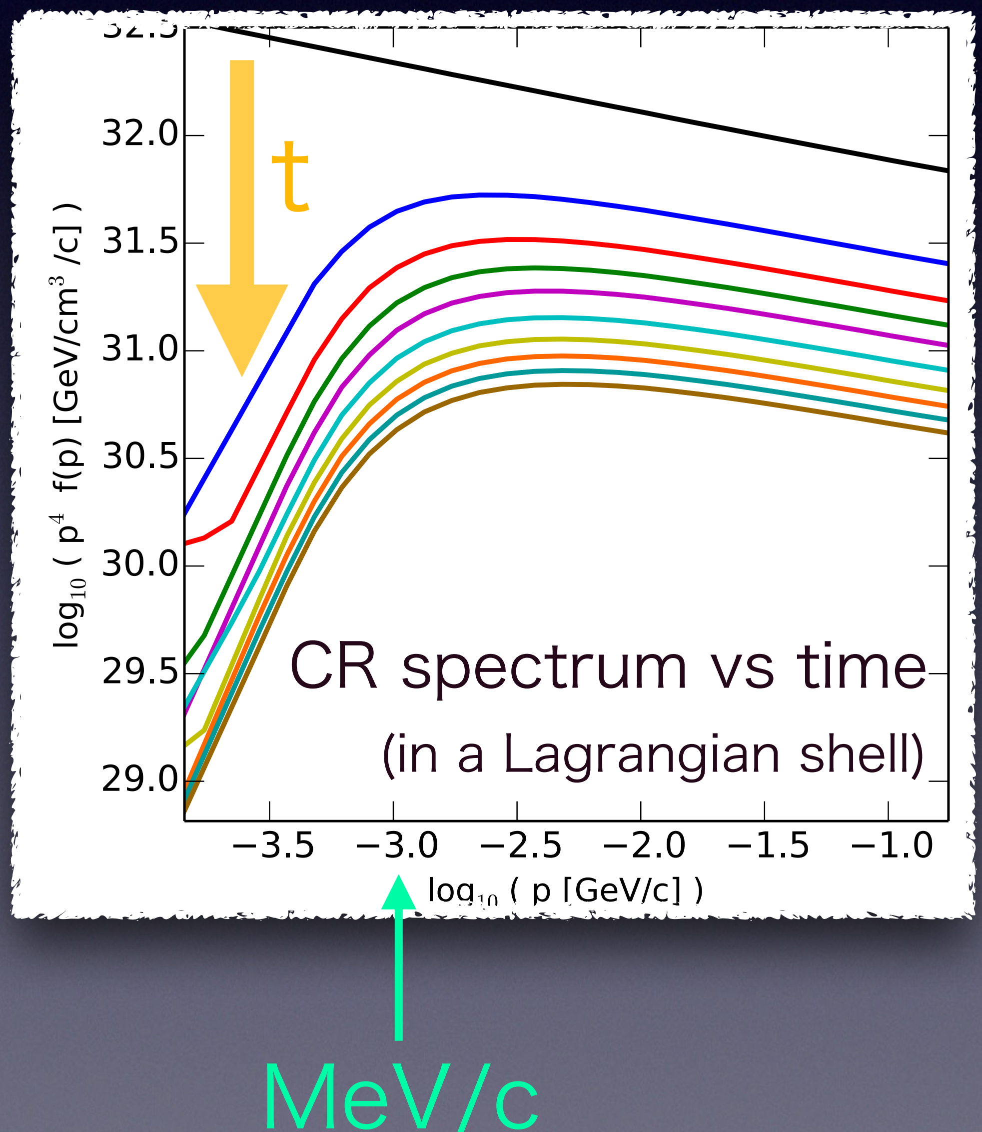
Particle acceleration scenarios at cloud shocks and potential problems

- ★ Two scenarios for particle acceleration through diffusive shock acceleration (DSA):
  (1) **Re-acceleration** of pre-existing CRs
  (2) **Fresh acceleration** of thermal particles

- ★ Fresh acceleration of thermal particles
  - Works quite well at young SNRs
  - Difficulties at radiative shocks of older SNRs

- ★ v_{sk} > ~100 km/s —> **Long t_{accel}** (~ v_{shock}^{-2}) to reach γ-ray emitting energies

- ★ **Fast Coulomb loss** in dense cloud at super-thermal energies competes with early acceleration after injection



Shock Re-acceleration of Pre-existing Galactic CR (GCR)

- DSA re-acceleration of GCR with ambient spectra:

$n_{GCR,p}(p) = 4\pi J_p \beta^{1.5} p^{-2.76}$ $\quad p > 0.31$

$n_{GCR,e}(p) = 4\pi J_e p^{-2} (1 + p^2)^{-0.55}$ $\quad p > 0.02$ **(p in GeV/c)**

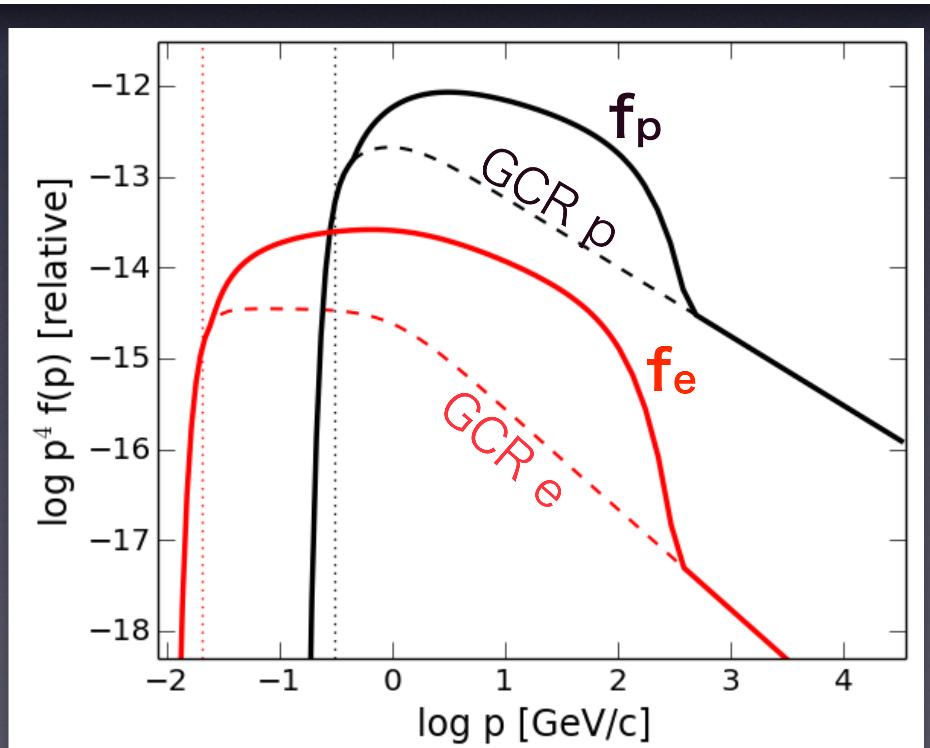
- Re-accelerated CR spectra (e.g., Blasi+ 2004, Lee+ 2012)

$$f_1^{cr}(p) = \frac{3S_{tot}}{S_{tot}U(p)-1}\left\{\frac{\eta n_0}{4\pi p_{inj}^3}\exp\left[-\int_{p_{inj}}^{p}\frac{dp'}{p'}\frac{3S_{tot}U(p')}{S_{tot}U(p')-1}\right]\right.$$

← fresh acceleration

$$\left. + \int_{p_{min}}^{p}\frac{dp''}{p''}f_\infty(p'')\exp\left[-\int_{p''}^{p}\frac{dp'}{p'}\frac{3S_{tot}U(p')}{S_{tot}U(p')-1}\right]\right\}$$

← re-acceleration



$4\pi p^2 f_{inf}(p) = n_{GCR}(p)$

S_{tot}: total shock compression ratio

U(p): gas velocity in precursor (in particle momentum space)

DSA in a partially neutral gas

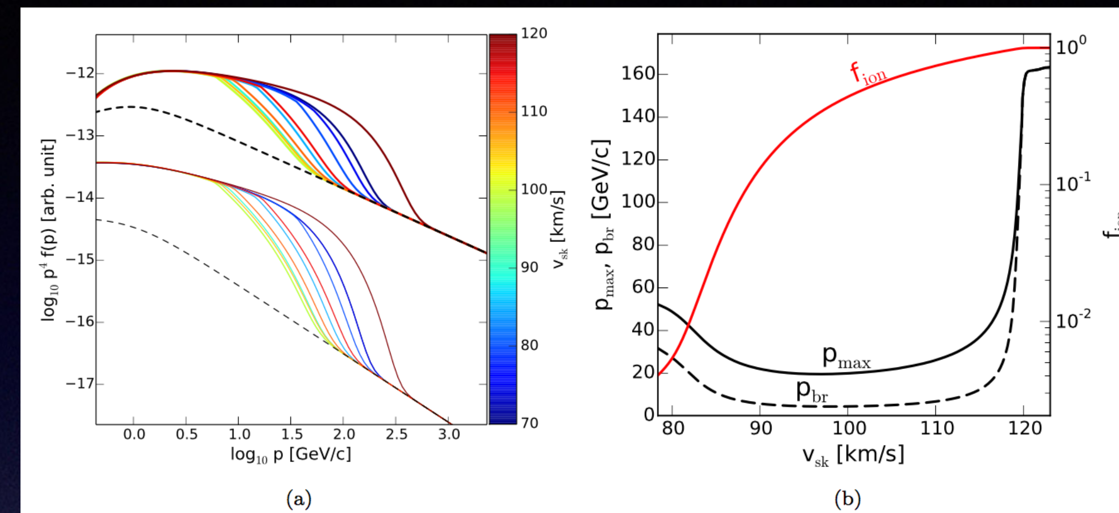
- ★ For v_{sk} ~ 100 km/s, ionization is partial in photoionization precursor, neutrals exist

- ★ Ion-neutral damping of magnetic turbulence
—> break in CR diffusion coefficient D(x,p)
—> break in CR spectrum (e.g. Bykov+ 2000)

- ★ D(x,p) —> D(x,p) (1 + p/p_{br}) (e.g. Zirakashvili & Ptuskin)
i.e., weaker α=2 scatterings for p > p_{br}
Reduces p_{max} by easier escape to upstream

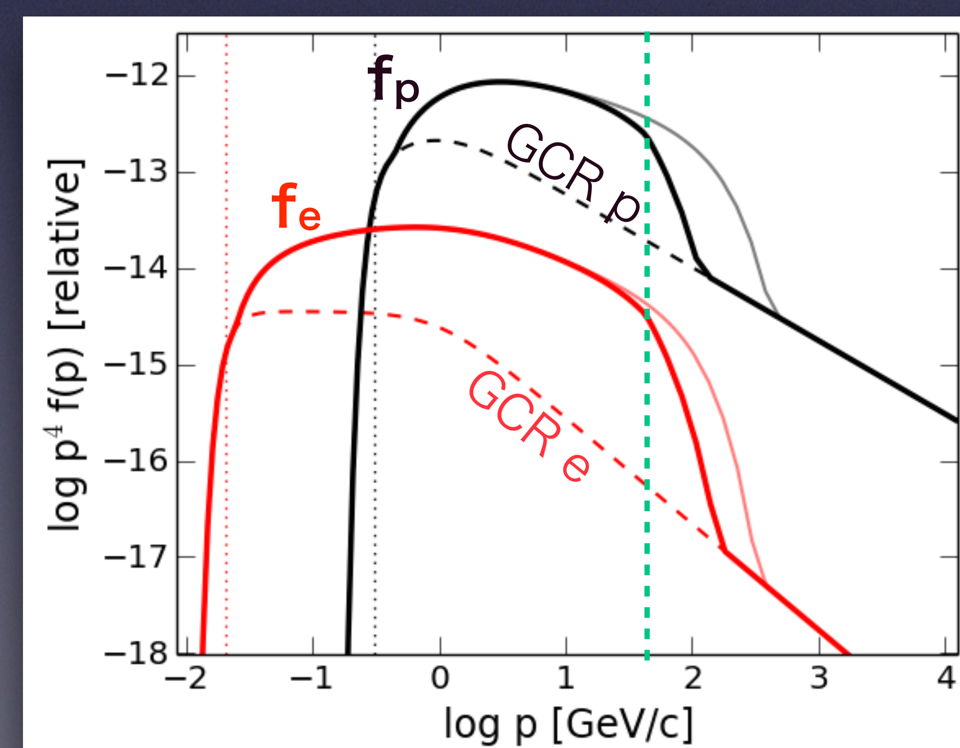
- ★ $f_{CR}(p)$ —> $f_{CR}(p)$ $(p/p_{br})^{-1}$ for p > p_{br}

- ★ **Fermi γ-ray spectra** of mid-aged SNRs **suggest a break @ ~10 GeV/c** in underlying proton spectrum



$$p_{br} = 10\left(T_4^{-0.4} n_0^{-1} n_i^{-0.5} B_\mu^2\right) m_p c$$

(Malkov+ 11, Lee+ 12)



Evolution of post-shock structure with full non-equilibrium ionization (NEI)

$$3/2\, k_B\, dT/dt = -(n_e n_p/n)\,\Lambda + \Gamma + (\kappa/n)\nabla^2 T$$

Cooling function

- ★ Follow NEI of 12 elements:
  H, He, CNO, Ne, Mg, Si, S, Ar, Ca, Fe
- ★ UV/optical continua and lines
- ★ Cooling is fast, close to isochoric

Heating function

- ★ Radiative transfer of strong UV lines and continua
- ★ Absorption, photoionization
- ★ Heating by photoelectrons

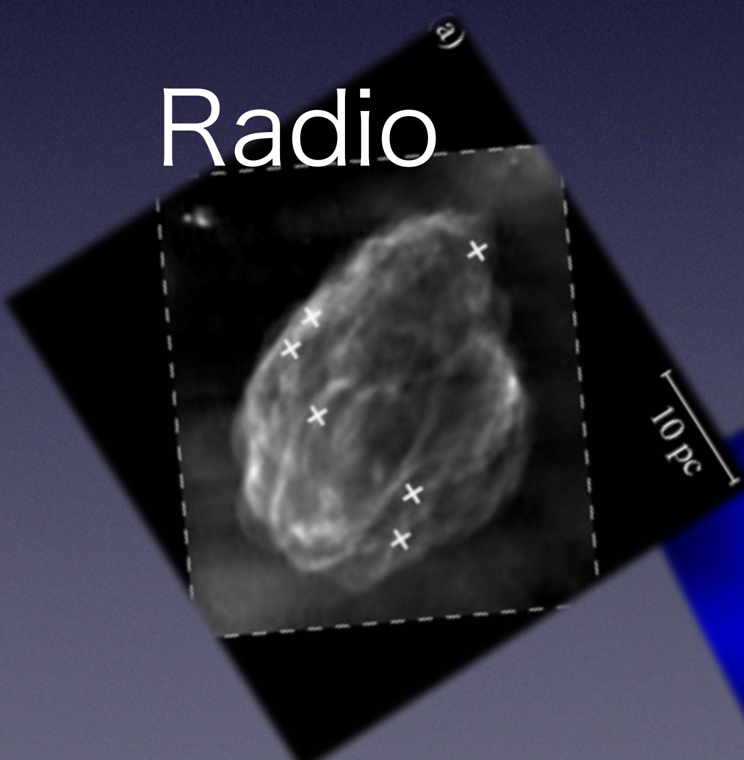
(e.g. Gnat & Steinberg 2009)

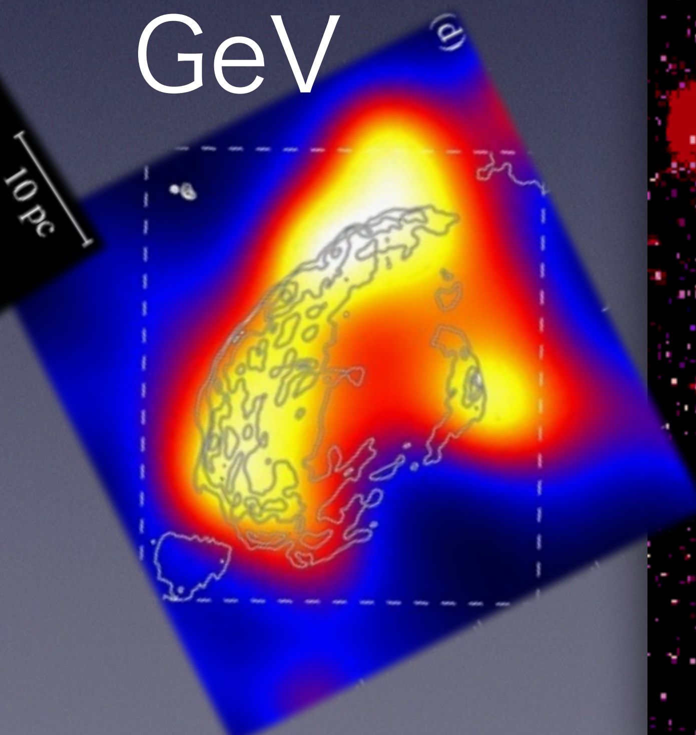
Thermal conduction

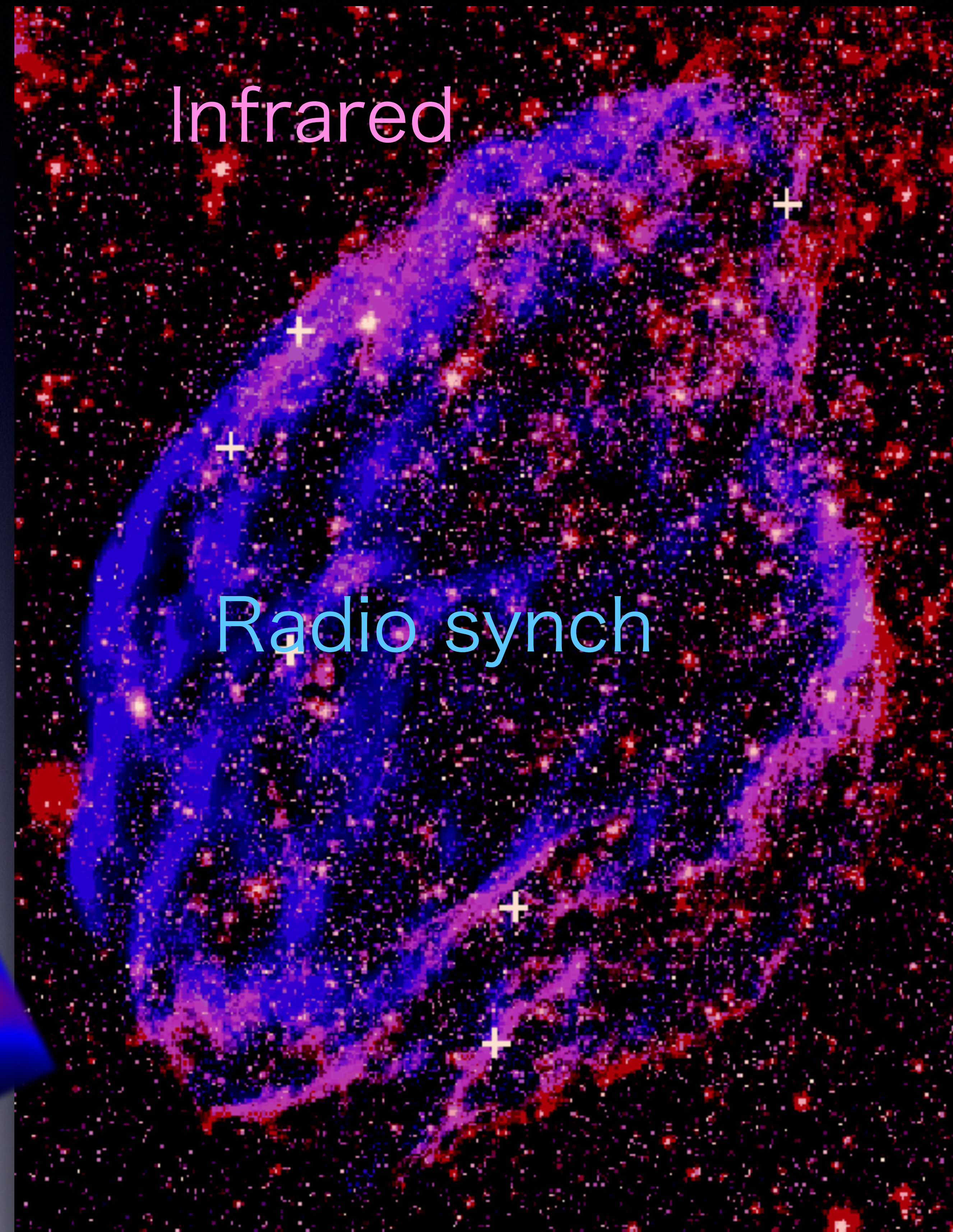
- ★ Conductivity $\kappa = f\,\kappa_{\rm Spitzer}$
- ★ f = 0.3 for collisionless plasma, hindrance by B-field

(e.g. Zakamska & Narayan '03, Bale+ '13)

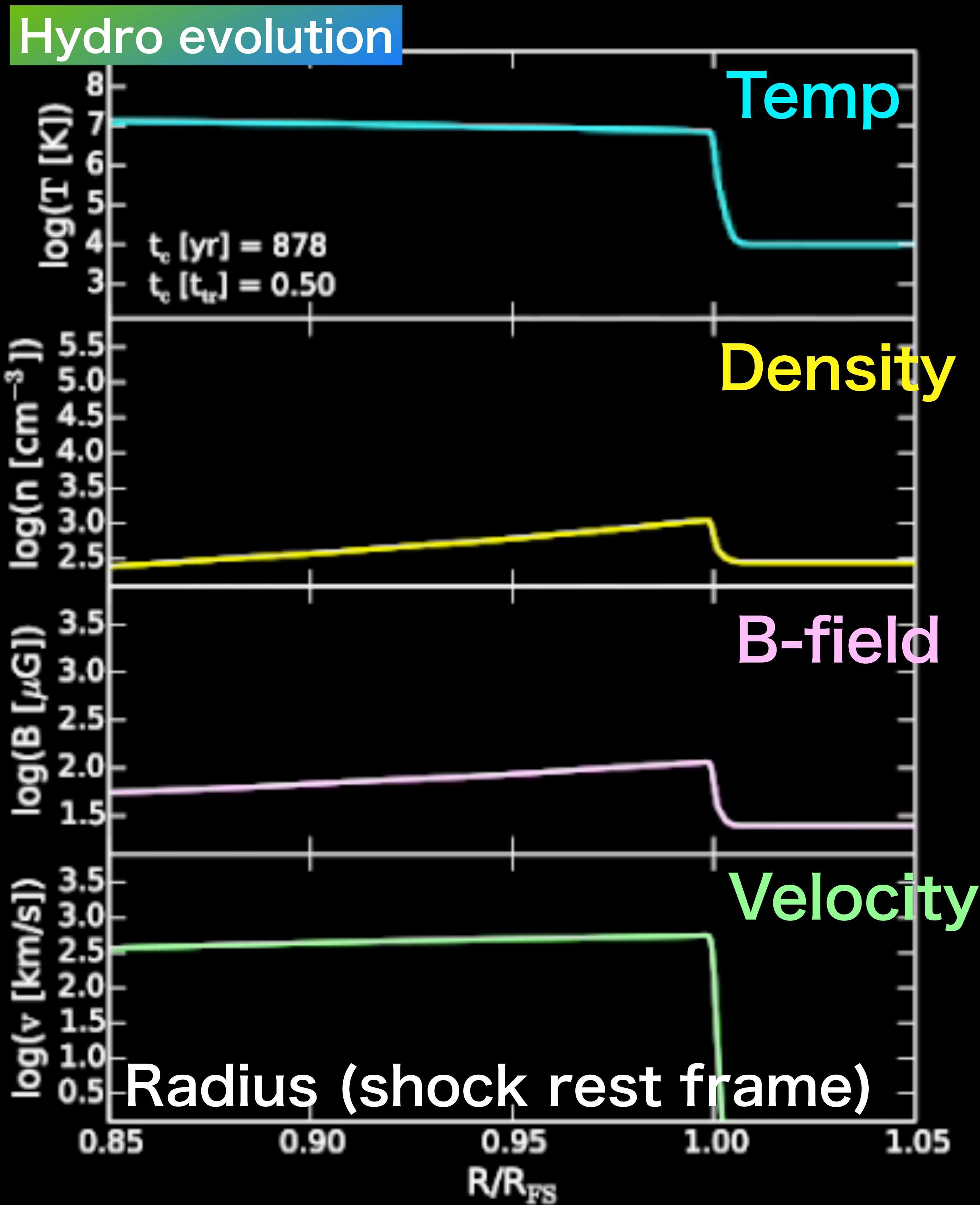
Compare model with SNR W44 broadband spectra

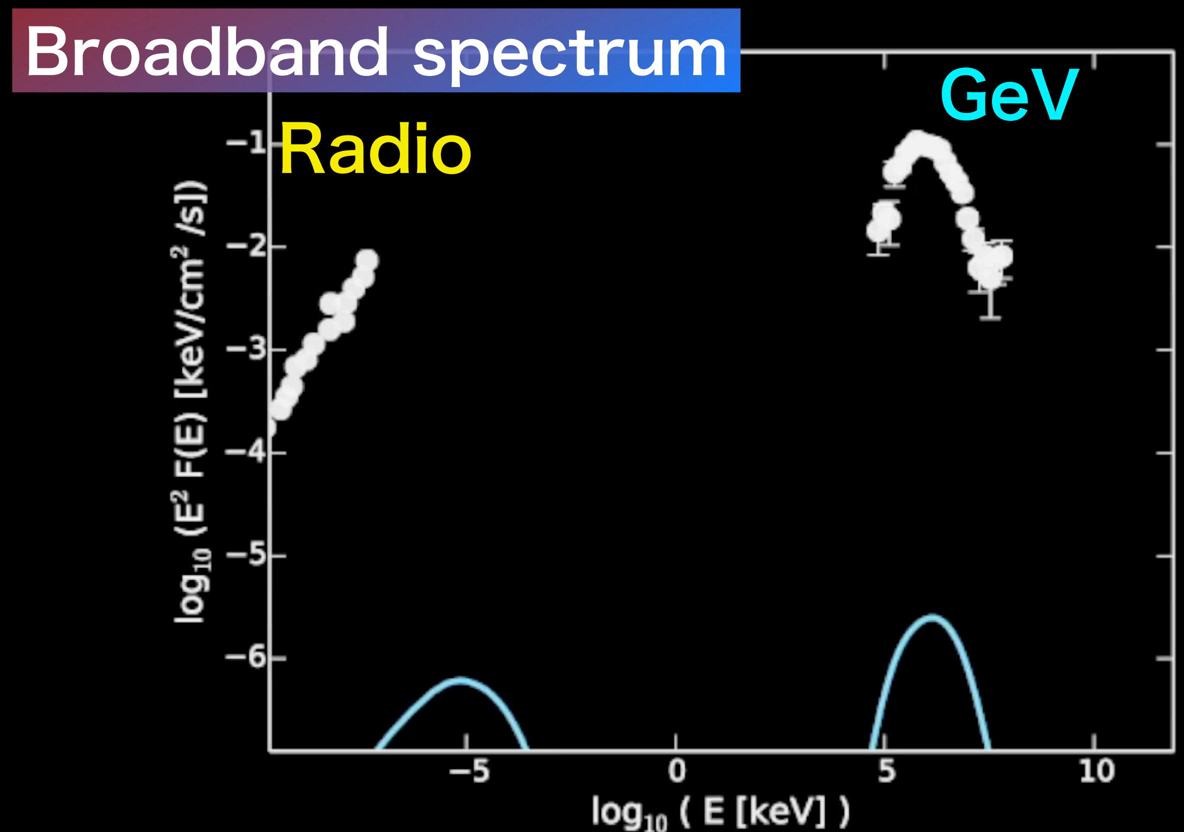


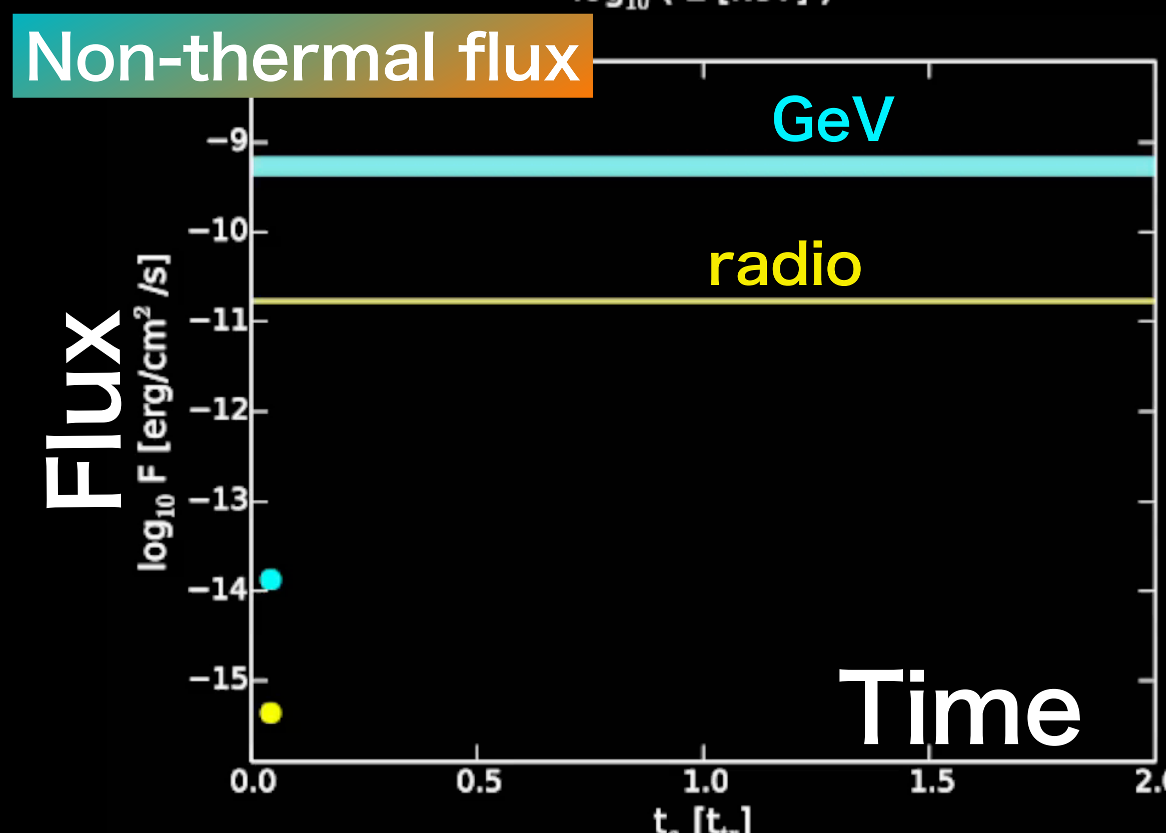




Hydrodynamics and Spectral Evolution

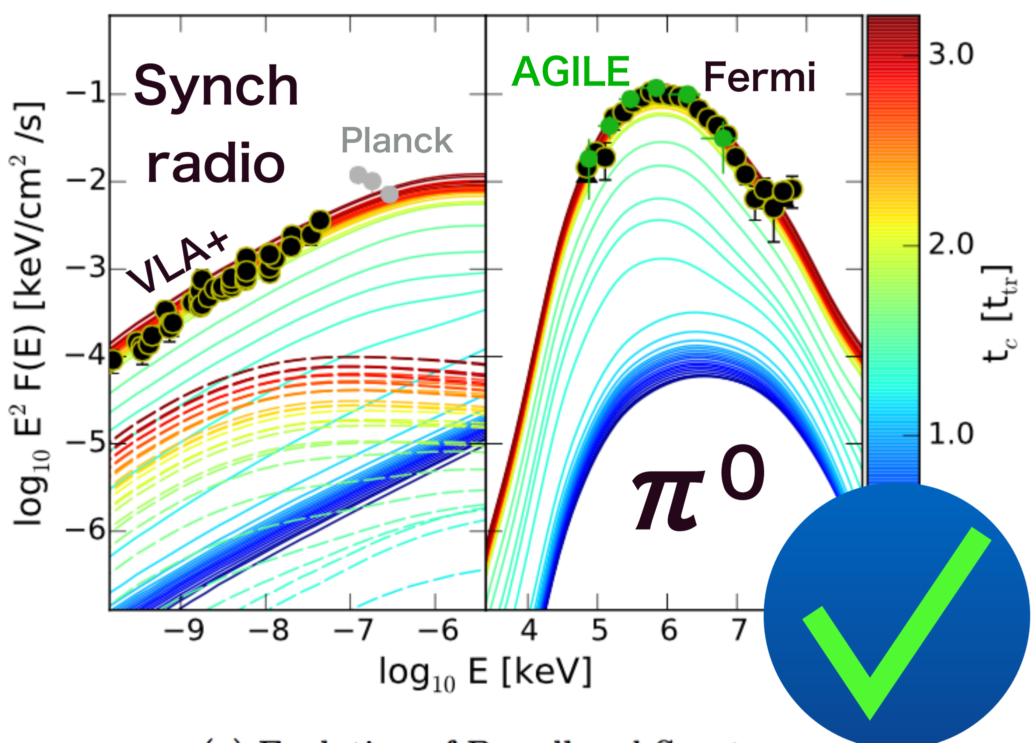




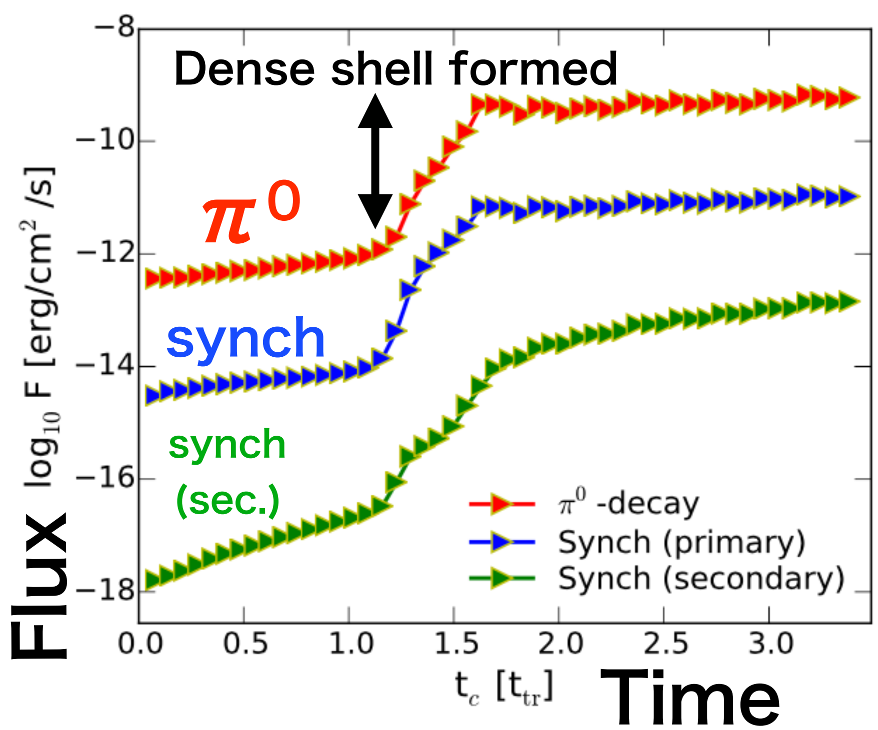


Broadband Spectral Evolution again

GCR re-acceleration model

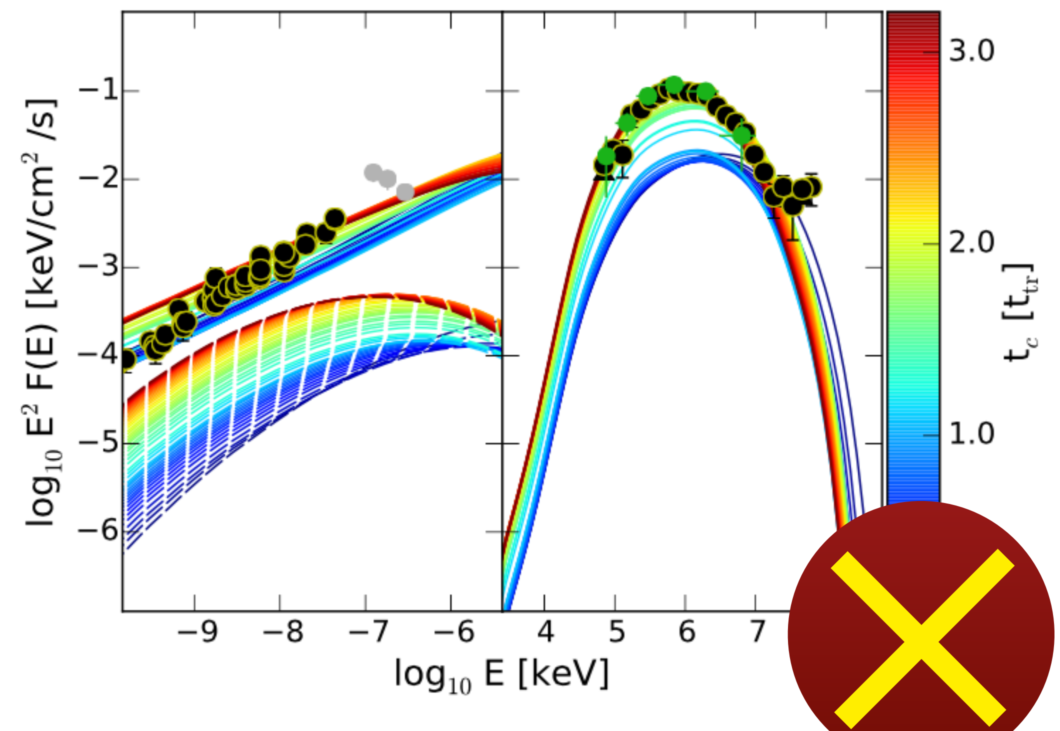


(a) Evolution of Broadband Spectrum



(b) Evolution of Integrated Flux

NLDSA (thermal injection) model



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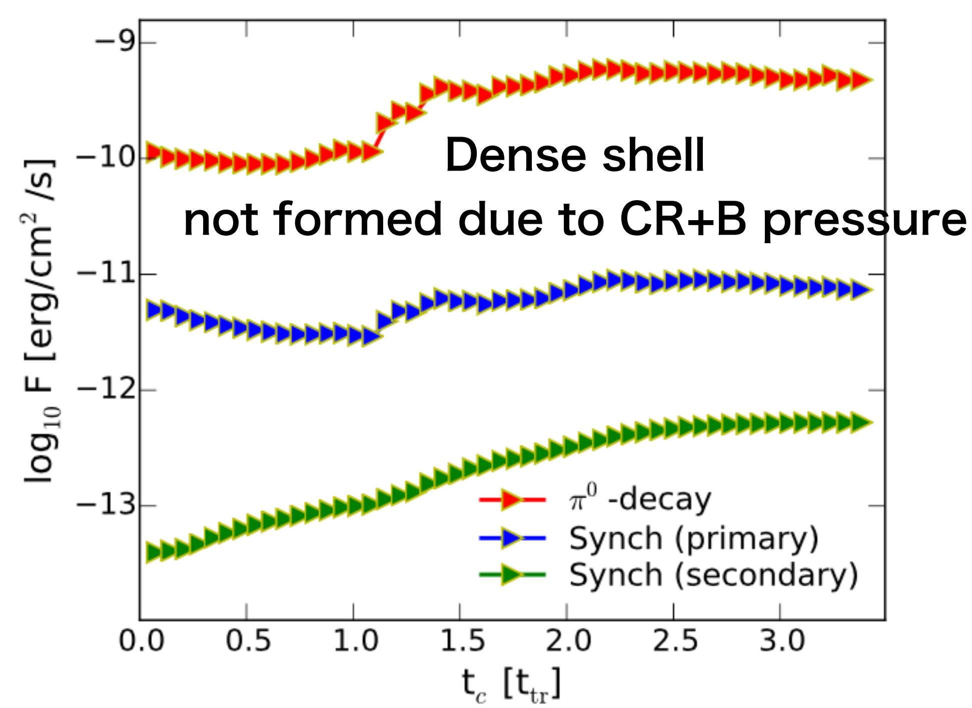
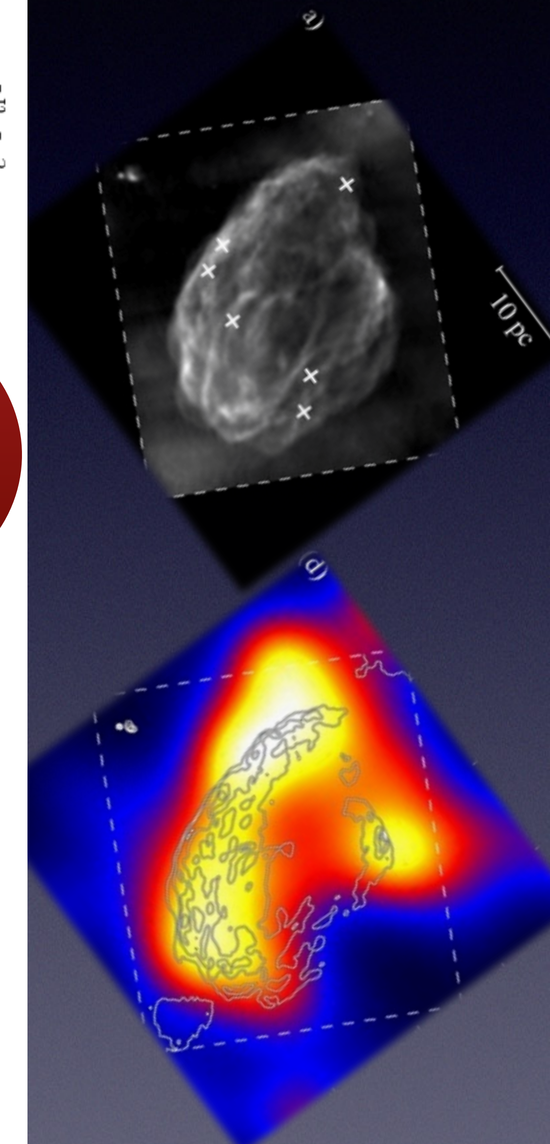
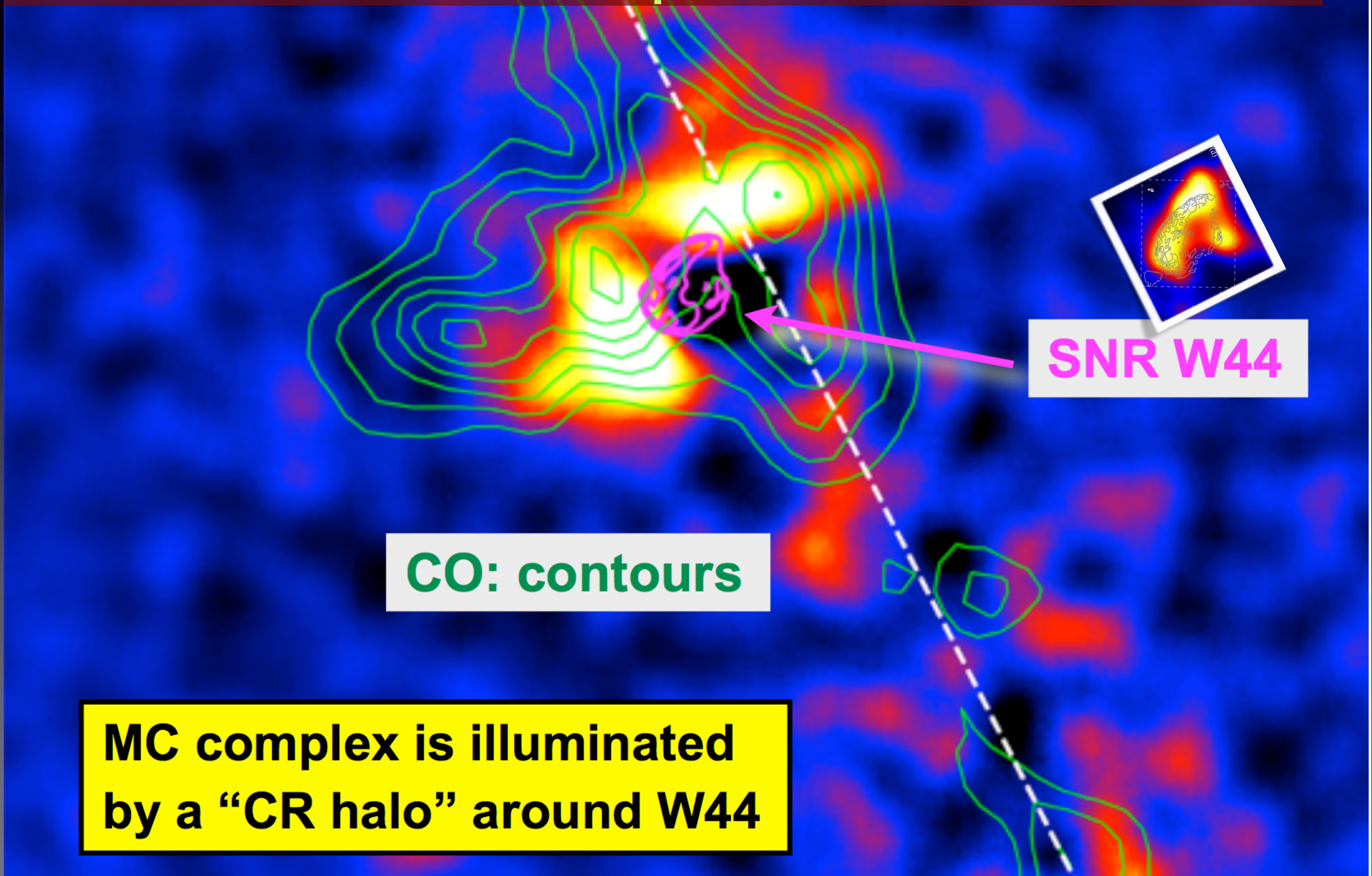


(b) Evolution of Integrated Flux

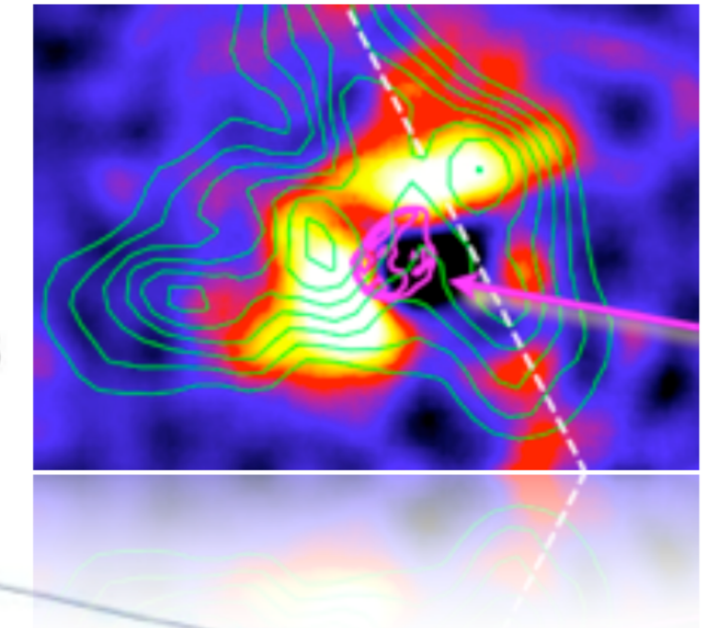


W44 is known to be surrounded by a complex of MCs.
Size ~100 pc, Mass ~10^6 M_{sun} (Dame+1986)

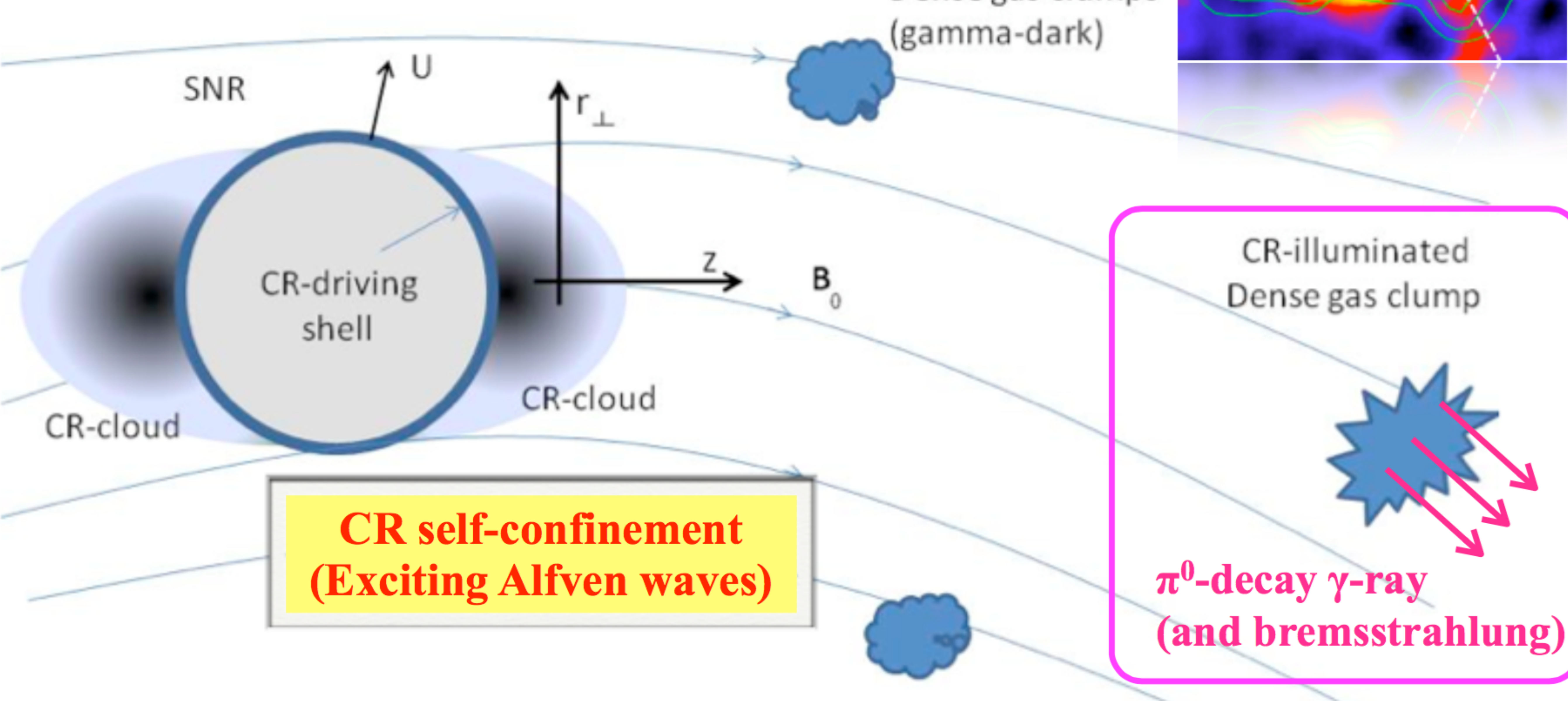
Fermi detects γ-rays from vicinity of W44
Must have a different production mechanism



Gamma-ray Evidence for Leaking CRs



(c) M. Malkov (2012)



After leaving SNR W44, CRs diffuse along the external B-field direction ➜ bipolar morphology

Conclusions

- Fast radiative shocks in clouds can produce bright GeV and radio emission, despite their not-so-impressive velocities
- **Re-acceleration and compression of pre-existing cosmic rays in a dense radiatively cooling shell** are the keys
- Probably major contributor to GeV + radio emission from shell of mid-aged SNRs directly interacting with molecular clouds
- Mechanisms are quite different from younger SNRs
- For SNR W44, cloud shock in $\langle n_0 \rangle = 200\ \mathrm{cm}^{-3}$ partially ionized medium can produce observed radio and γ-ray fluxes