Gamma-ray emission from middle aged supernova remnants interacting with molecular clouds

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06/06/2016

Victor Hess measured the ionization rate of our atmosphere with balloon experiments

M. Bertolotti, 2013
Celestial Messengers

Table 2.1 Summary of Hess' results

	Measured radiation (ions per cc per second)		
Mean height from ground (m)	Electrosc. 1	Electrosc. 2	Electrosc. 3
0	16.3	11.8	19.6
Up to 200	15.4	11.1	19.1
300–500	15.5	10.4	18.8
500–1,000	15.6	10.3	20.8
1,000–2,000	15.9	12.1	22.2
2,000–3,000	17.3	13.3	31.2
3,000–4,000	19.8	16.5	35.2
4,000–5,200	34.4	27.2	–

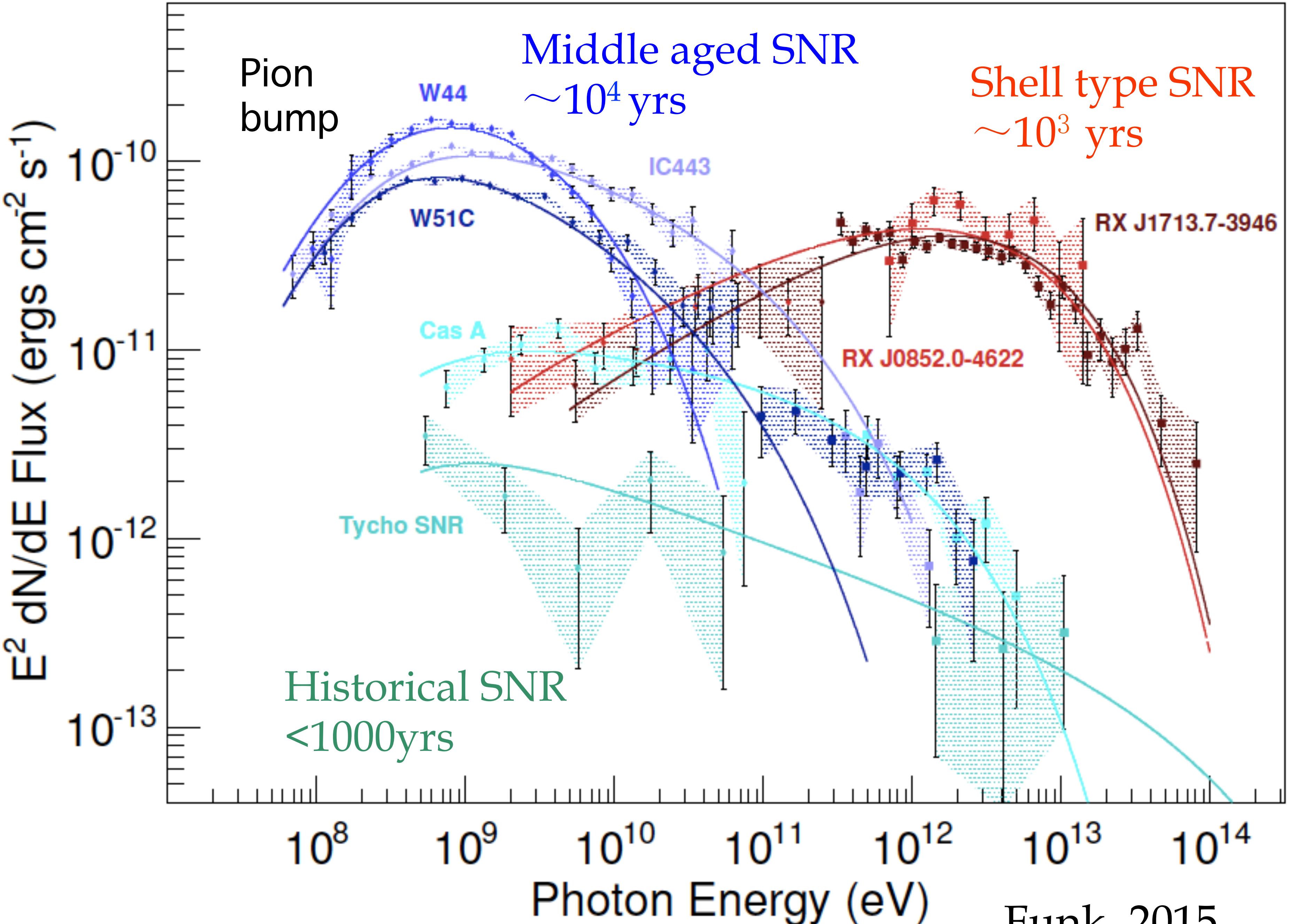
1934 Baade and Zwicky suggested that CR may originate from SN explosions based on the energy argument

(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

Identify SNRs as CR accelerators

Energetic electrons have been identified in SNRs through detection of synchrotron radiation in both radio and X-ray wavelengths.

Evidence for pion decay from accelerated protons is revealed in the γ-ray observation of SNRs recently.



Pion
bump
W44
Middle aged SNR
~10^4 yrs
Shell type SNR
~10^3 yrs
IC443
W51C
RX J1713.7-3946
Cas A
RX J0852.0-4622
Tycho SNR
Historical SNR
<1000yrs
E^2 dN/dE Flux (ergs cm^-2 s^-1)
10^-10
10^-11
10^-12
10^-13
10^8
10^9
10^10
10^11
10^12
10^13
10^14
Photon Energy (eV)

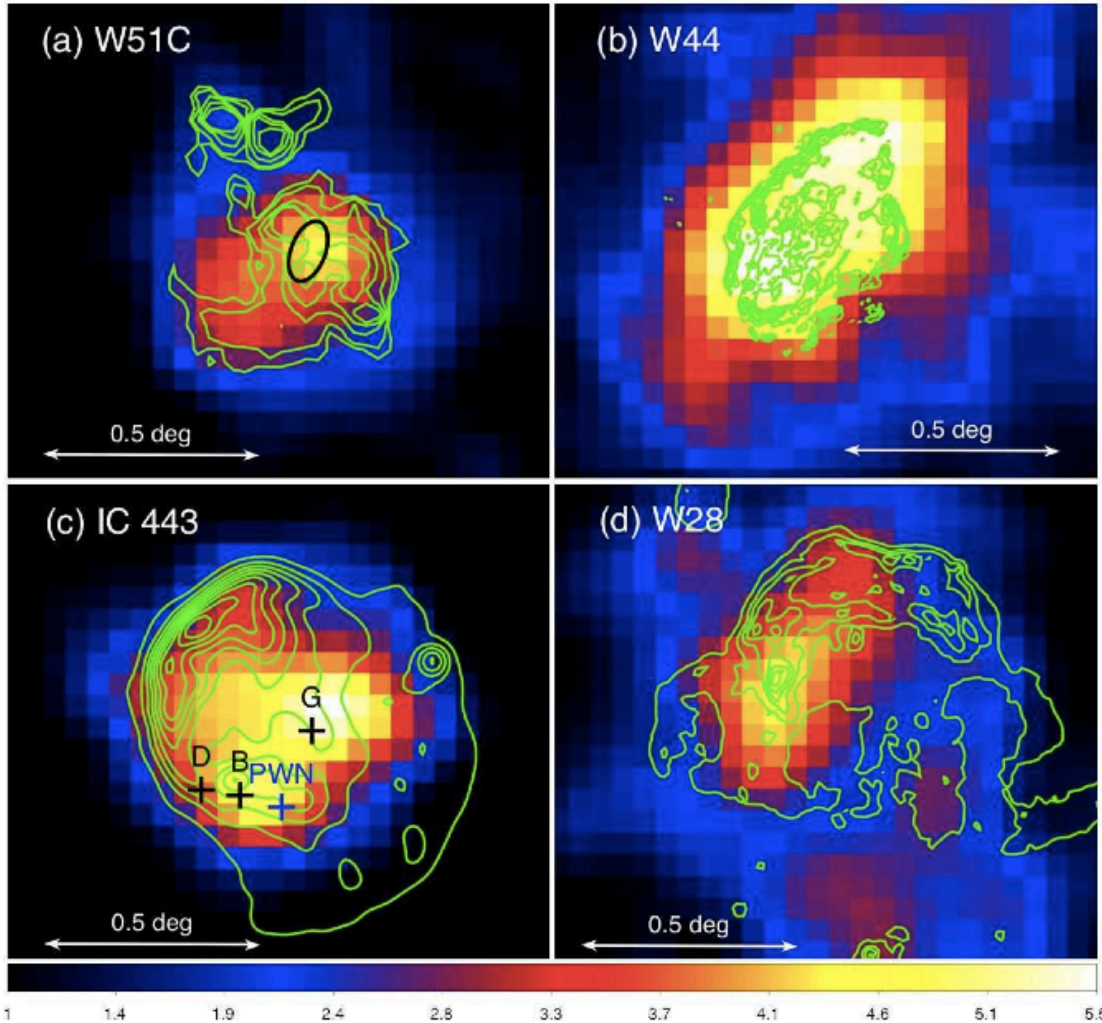
Funk 2015

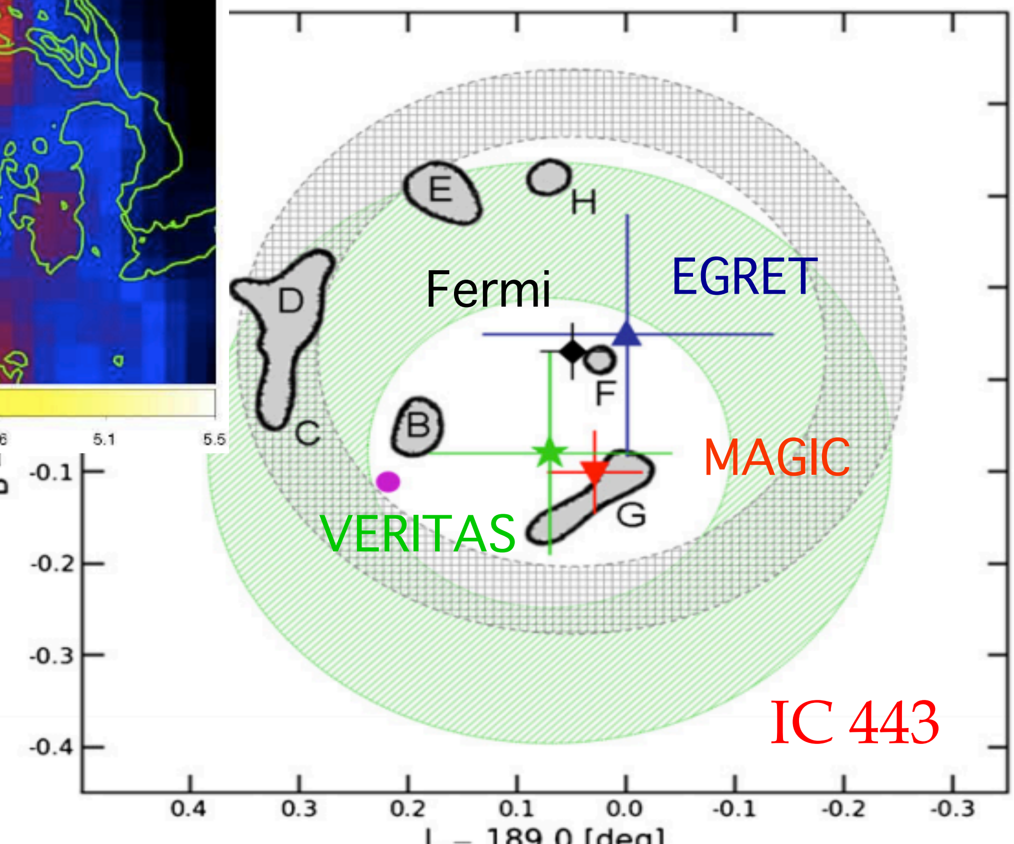
Implications based on observed spectral shape

Pion-decay signature → Dominated by hadronic emission

Smooth transition from GeV to TeV → One emission component or similar origin

Fermi LAT data→ color map
VLA radio maps →
green contours
shocked CO clumps →
black ellipse
OH masers → black crosses
Uchiyama 11





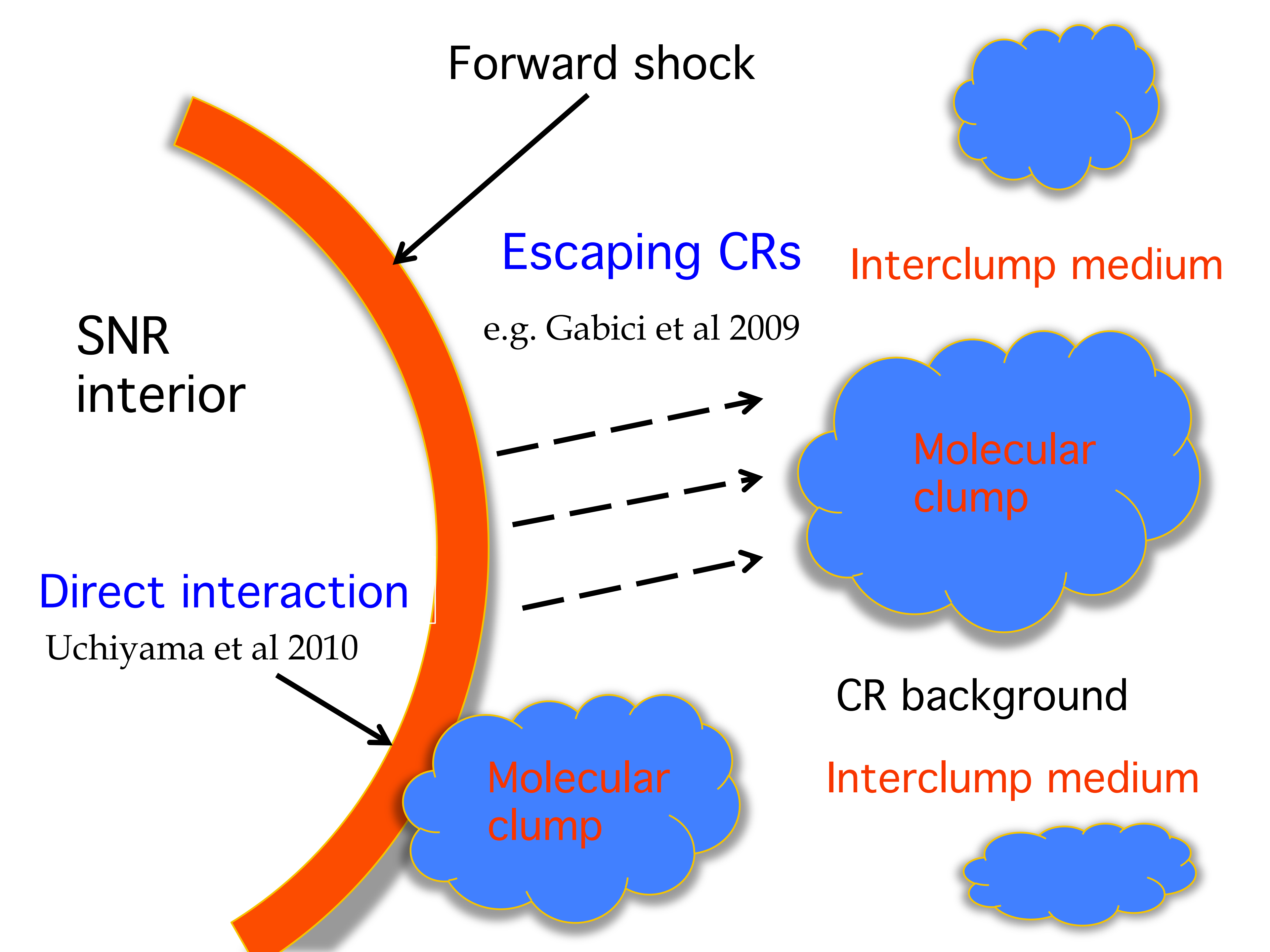
EGRET centroid ▲, MAGIC centroid ▼, VERITAS centroid ★, and Fermi LAT Centroid ◆.
Abdo et al 2010

Implication based on multi-wavelength image morphology

1. The GeV and TeV emission regions are well correlated with each other in space.

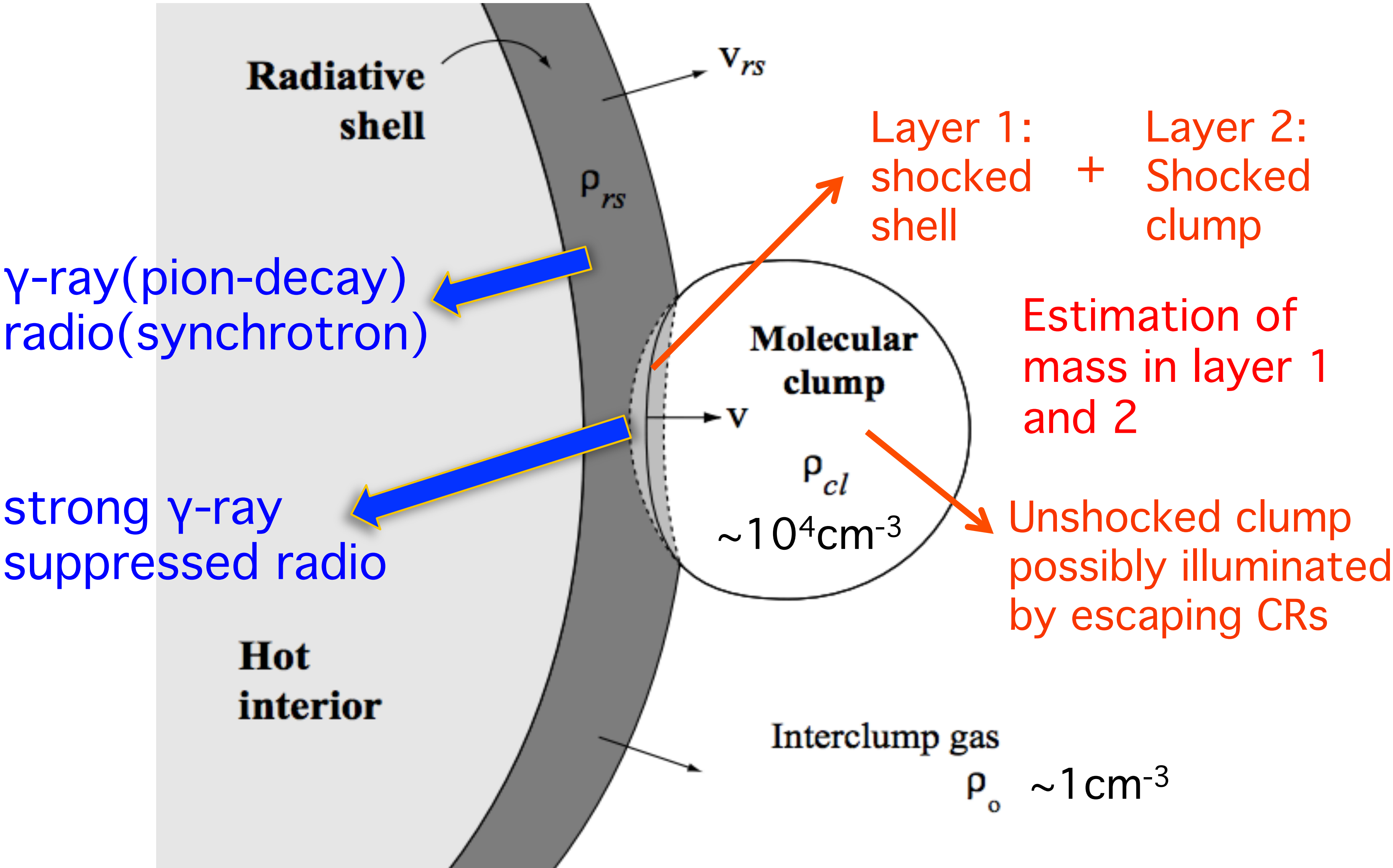
2. The high energy γ-ray emission region is spatially correlated with the molecular cloud interaction region.

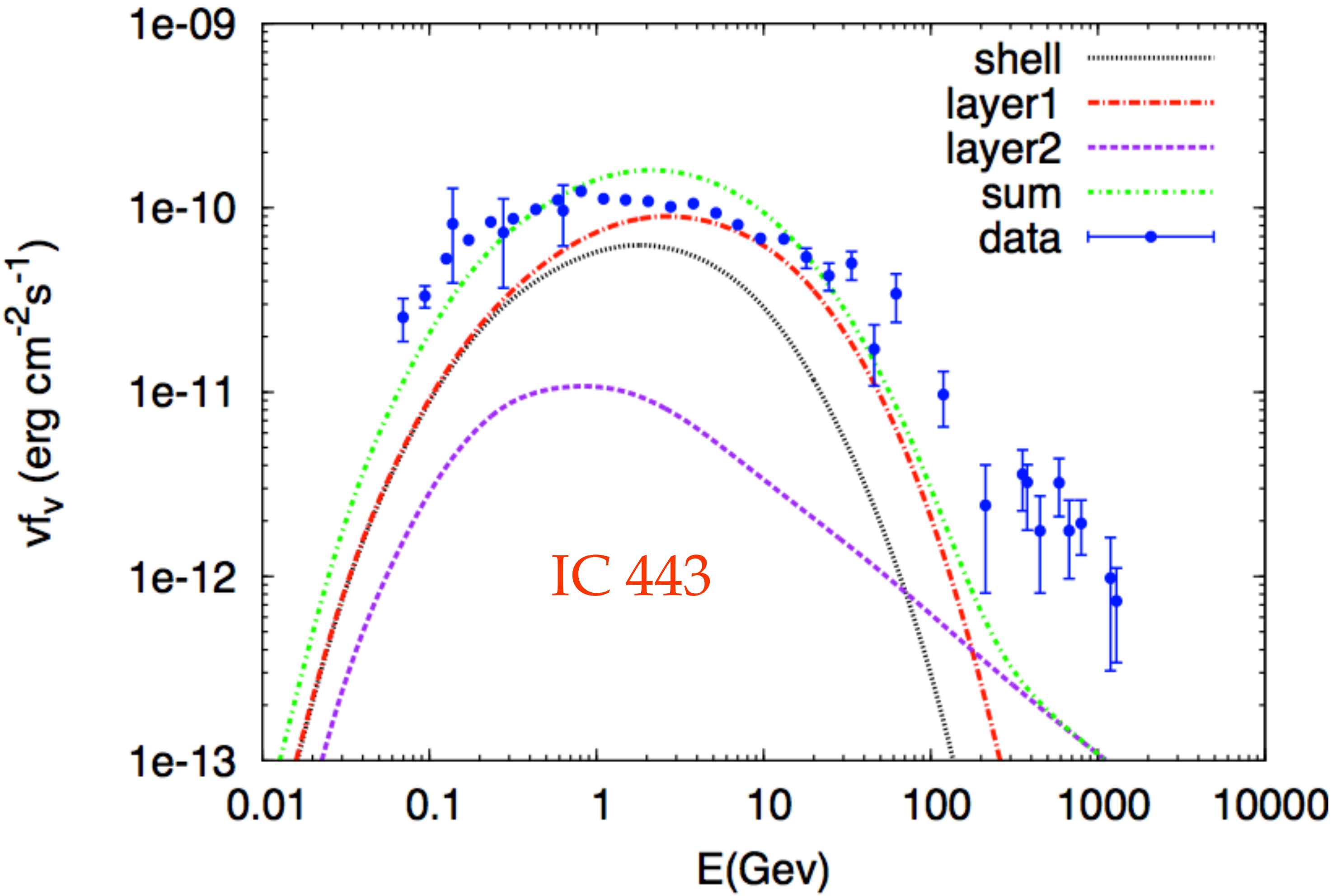
3. The brightest γ–ray emission region is not well correlated with non-thermal radio emission region.


Forward shock
Escaping CRs
e.g. Gabici et al 2009
Interclump medium
SNR
interior
Molecular
clump
Direct interaction
Uchiyama et al 2010
CR background
Molecular
clump
Interclump medium

Direct interaction scenario for radiative SNRs

Chevalier 99





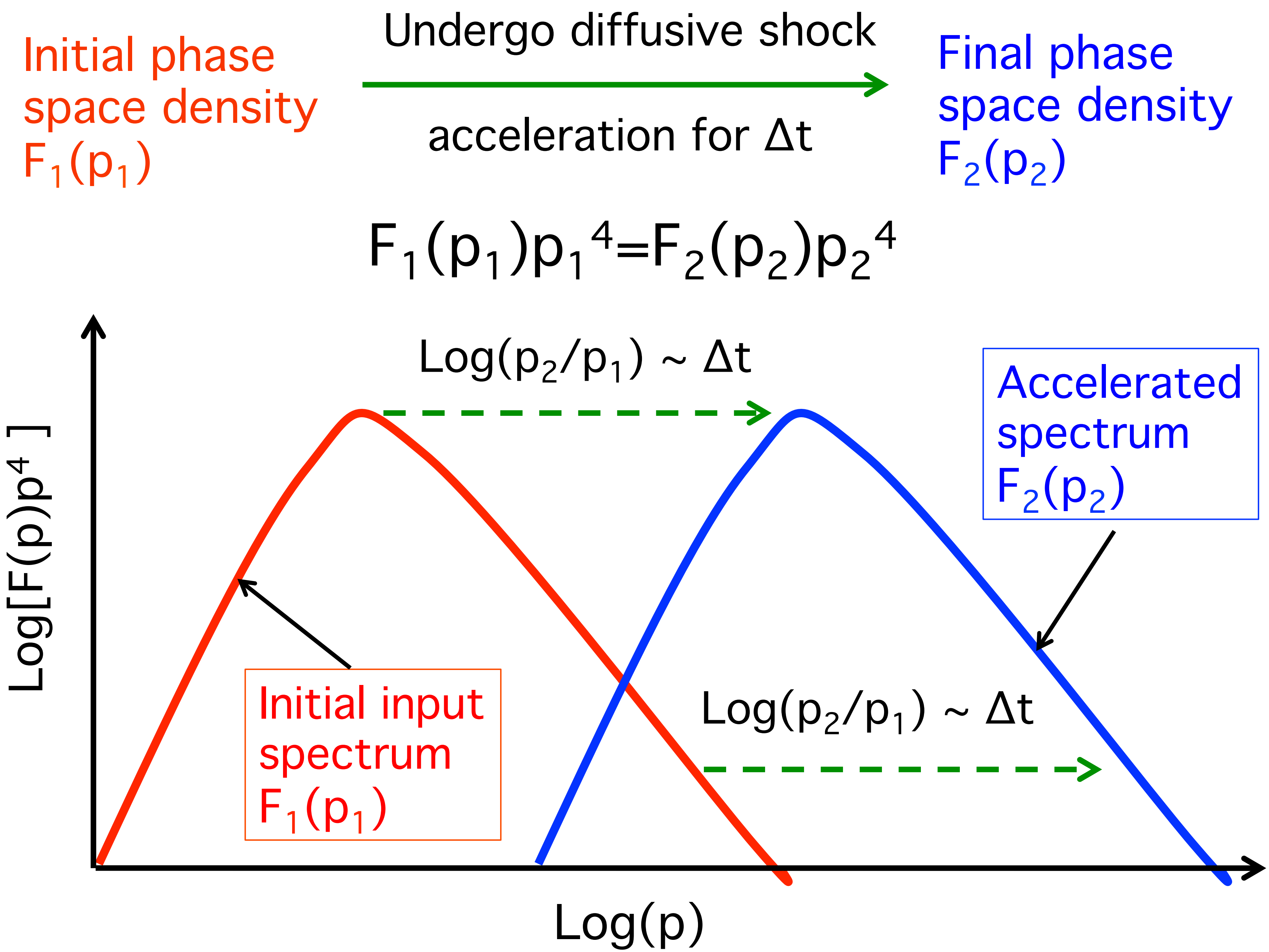
Diffusive shock acceleration plus adiabatic compression

Underproduce TeV emision

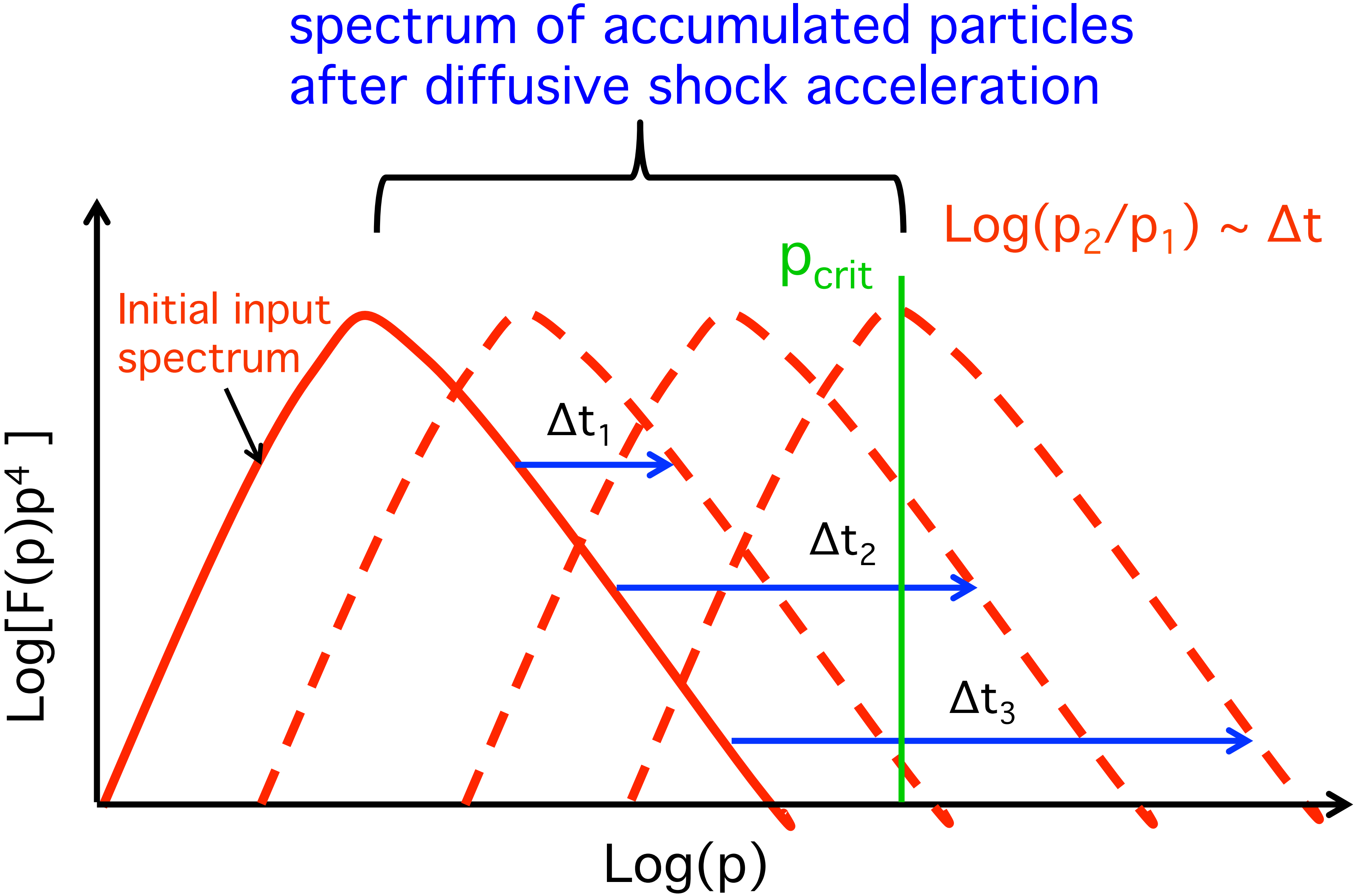
Tang&Chevalier 14 with modification

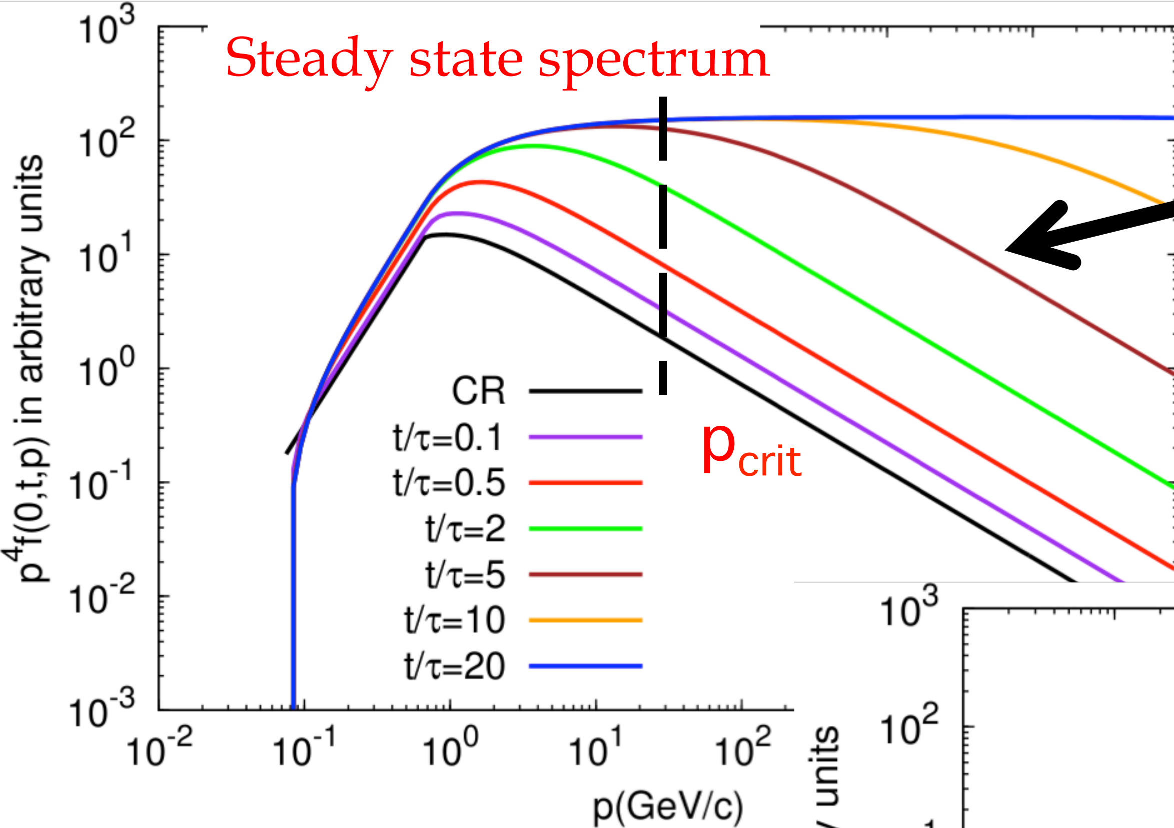
Exponential cutoff due to limited age of the remnant, same as Uchiyama et al 10

Time dependent diffusive shock acceleration in the test particle limit


Initial phase space density $F_1(p_1)$
Undergo diffusive shock
acceleration for Δt
Final phase space density $F_2(p_2)$
$F_1(p_1)p_1^4=F_2(p_2)p_2^4$
Log(p2/p1) ~ Δt
Accelerated spectrum $F_2(p_2)$
Initial input spectrum $F_1(p_1)$
Log(p2/p1) ~ Δt
Log[F(p)p4]
Log(p)

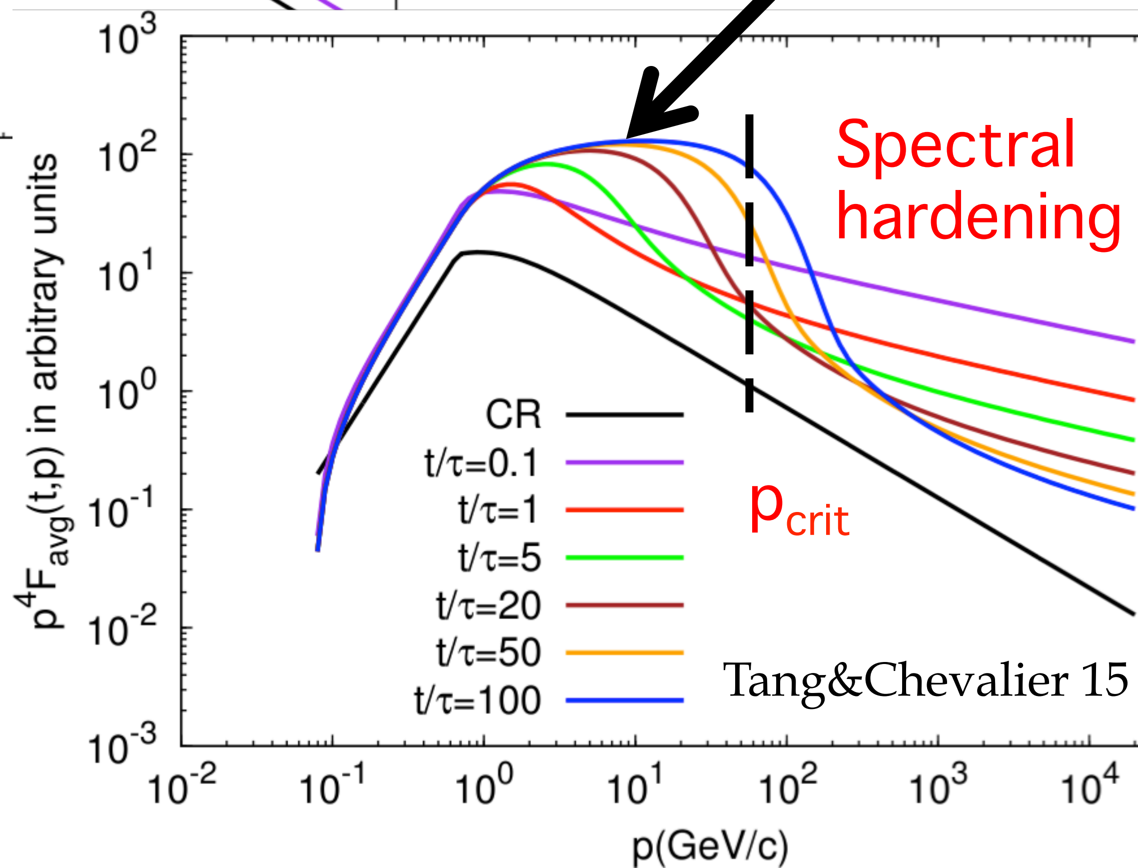
Continuous injection of the same input spectrum





Remains the original input CR spectrum above p_{crit}

Reaches the steady state DSA spectrum below p_{crit}



F large p, t/τ is small, diffusion dominates advection

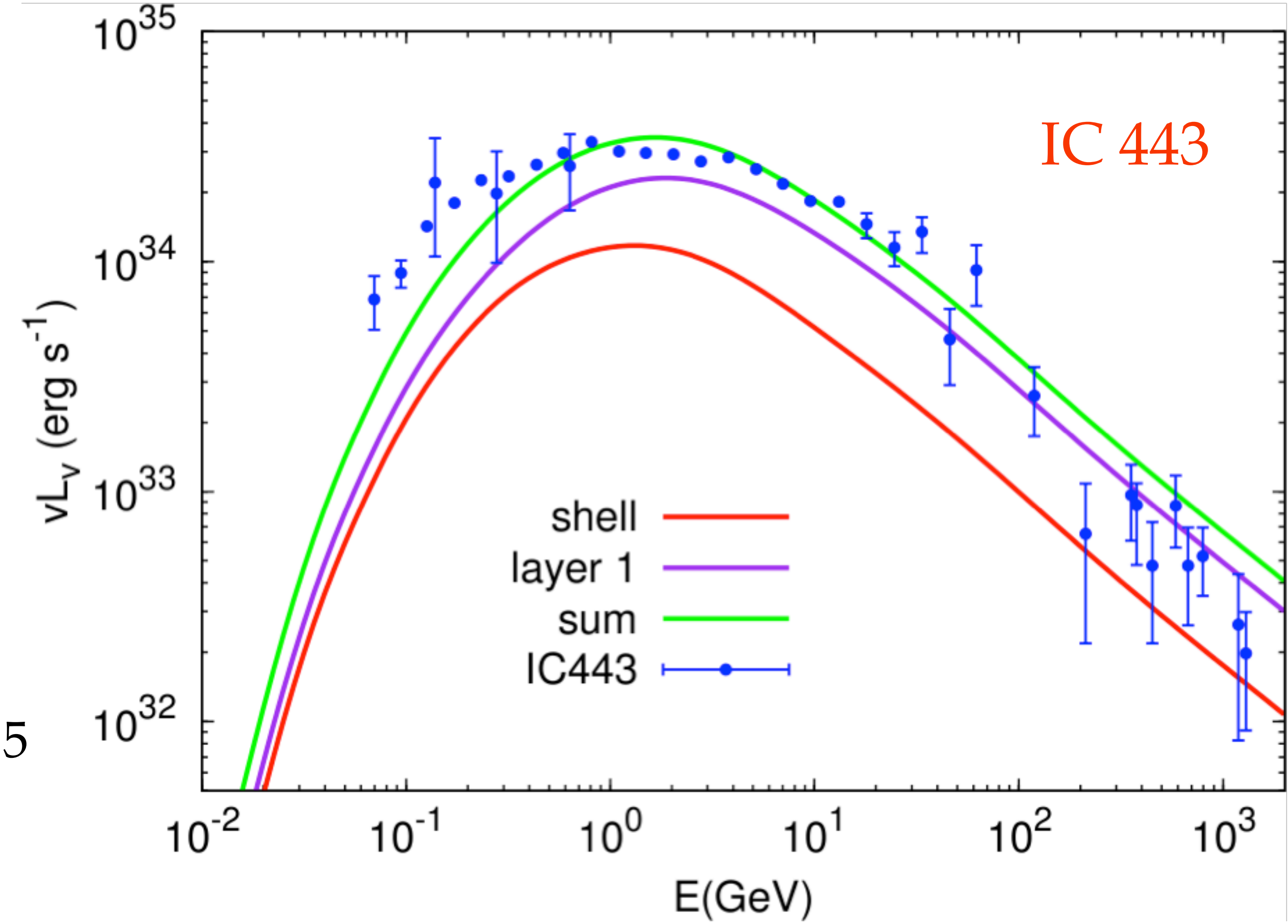
If $\kappa \sim p^{\sigma}$, spectral hardening at high energy $\sim 0.5\sigma$

Energy independent diffusion with $t_{age}/\tau=2t_{MC}/\tau=2$ and filling factor f =0.2

Pion-decay emission maintains the pre-existing CR spectrum shape at high energy

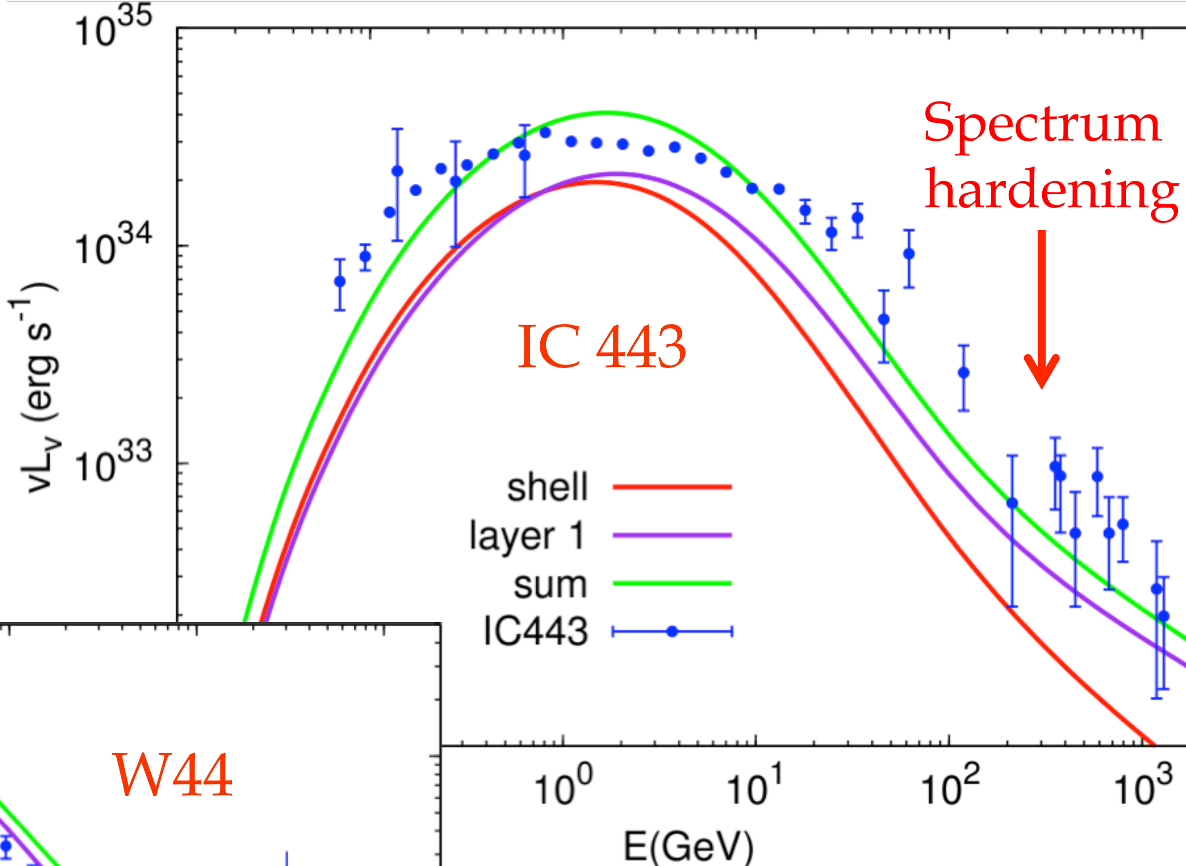
Could be extended to crushed cloud model Uchiyama et al 10

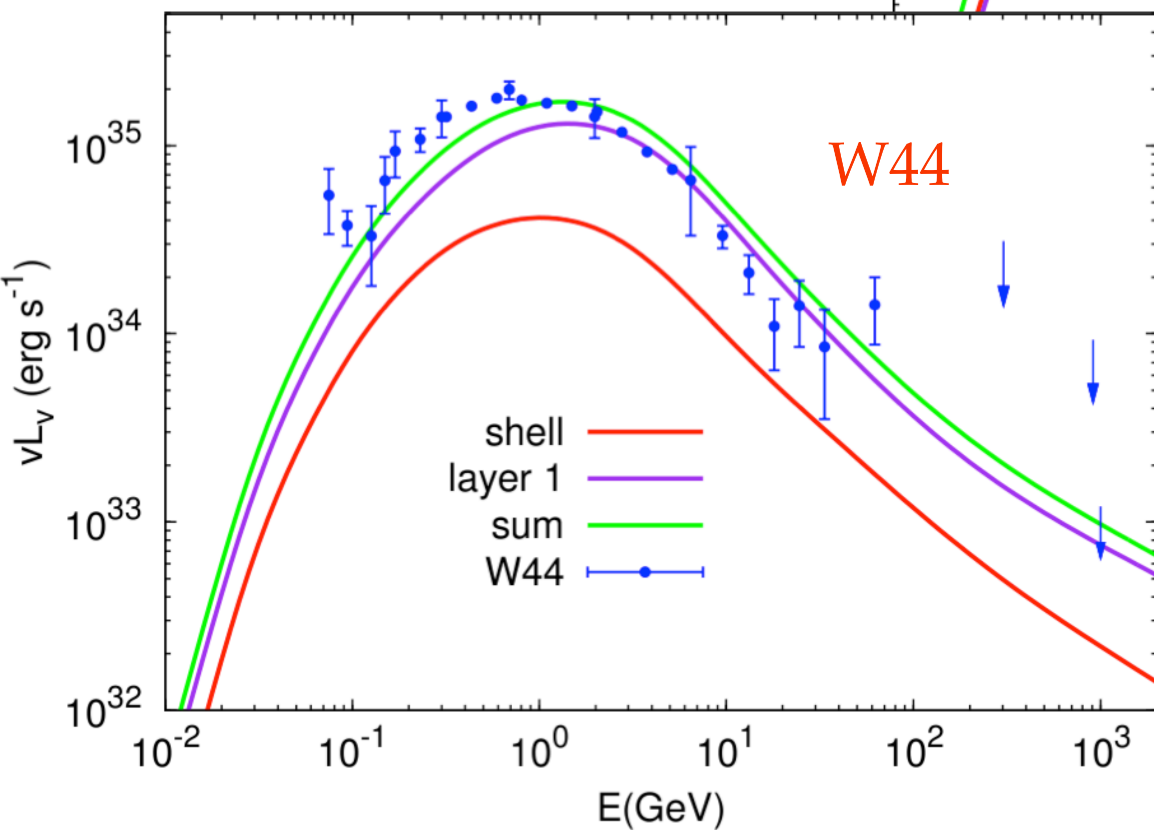
Tang & Chevalier15



Energy dependent diffusion with σ=0.5 and filling factor f=0.15

Tang&Chevalier 15





Energy dependent diffusion with σ=0.5 and filling factor f=0.3

Tang&Chevalier 15

Summary and future work

A shell-clump interaction model focusing on radiative SNRs could explain the radio and γ–ray morphology of SNRs like IC 443.

Time dependent DSA solution could help explain the γ-ray emission from GeV to TeV band. It also implies a spectral hardening around 100 GeV for strong energy dependent diffusion.

Transition from thermal injection dominated seed particles to pre-existing CR particles.

Unification of escaping scenario (escaping and upstream particles) and direct interaction scenario (downstream particles).