

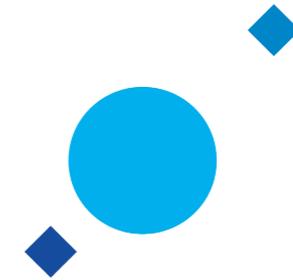
Particle escape from supernova remnants



Silvia Celli

silvia.celli@roma1.infn.it

Sapienza Università di Roma



INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

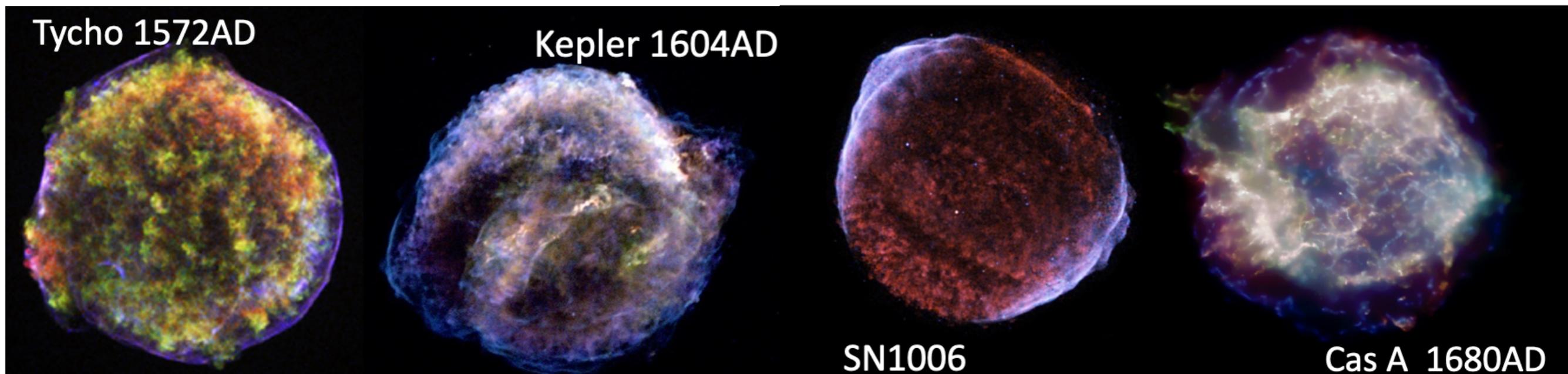
**The Symposium of Ultra-High-Energy Gamma Rays from
Supernova Remnants and the Origin of Galactic Cosmic Rays**

**February 26 to March 2, 2026
Yuxi CHINA**



Outline of the talk

- The **Supernova Remnant (SNR)** paradigm for the **origin of Galactic cosmic rays**:
 - the issue with maximum energy;
 - the role of particle escape in SNRs;
 - radiative signatures of SNR PeV activity.
- SNR-escaping particles **illuminating nearby molecular clouds**:
 - a catalog-based analysis of Galactic SNR-cloud pairs;
 - comparison with **LHAASO unidentified sources**.



The SNR paradigm for the origin of Galactic CRs

Enough power in SN explosions to explain CRs



Baade & Zwicky, PNAS 20 (1934) 259



Ginzburg & Syrovatsky, PTPS 20 (1961) 1

SNR shocks \rightarrow acceleration sites

Diffusive Shock Acceleration



Axford et al., ICRC1977, 11 132



Krymskii, AKSSRD 234 (1977) 1306



Bell, MNRAS 182 (1978) 147



Blandford & Ostriker, ApJ 221 (1978)

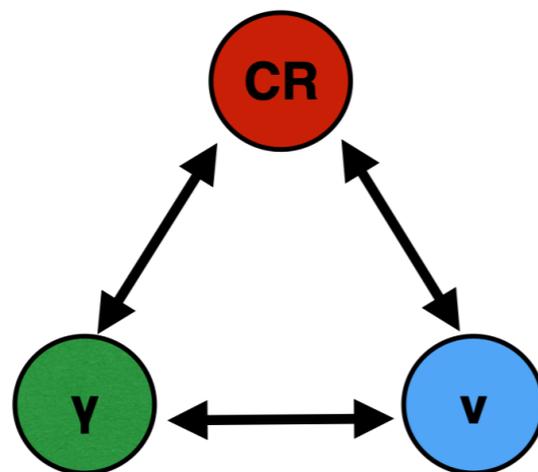
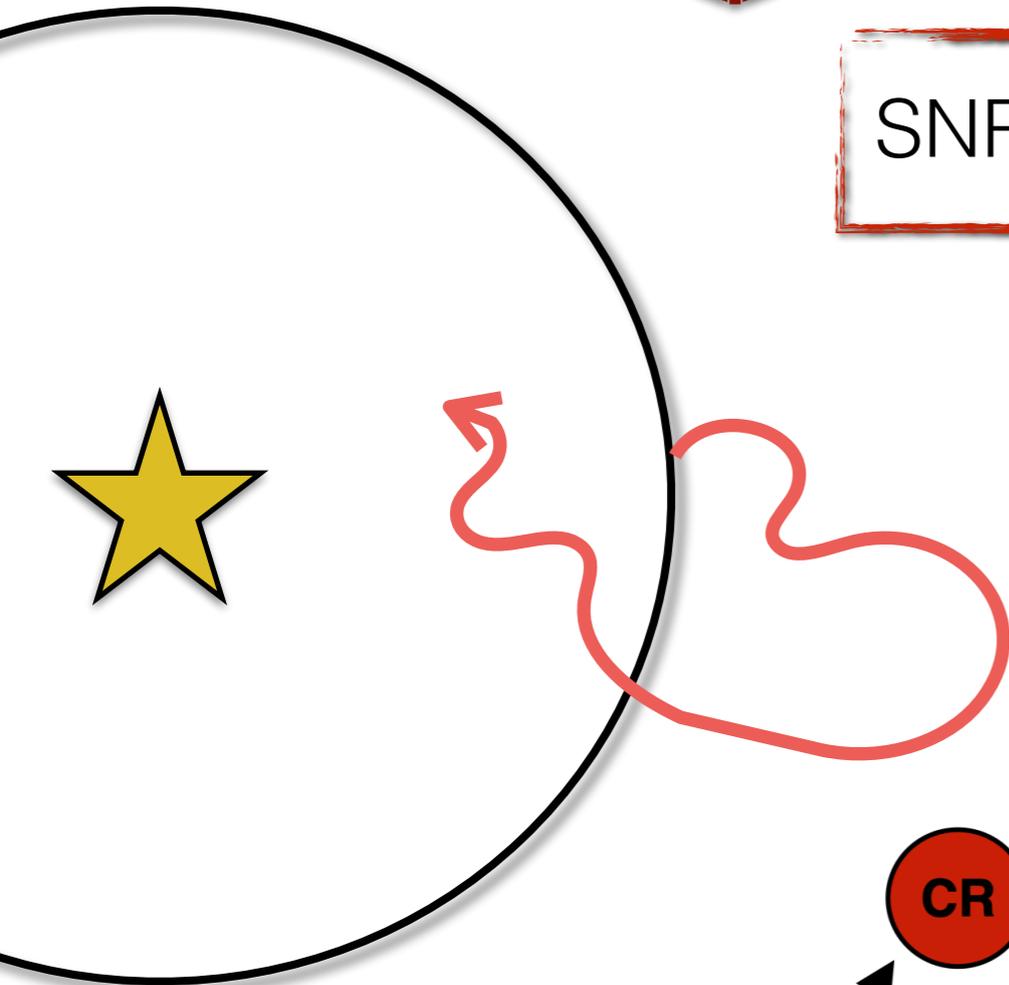
$$\rightarrow f_0(p) \propto p^{-4}$$

pp interaction \rightarrow γ rays and ν

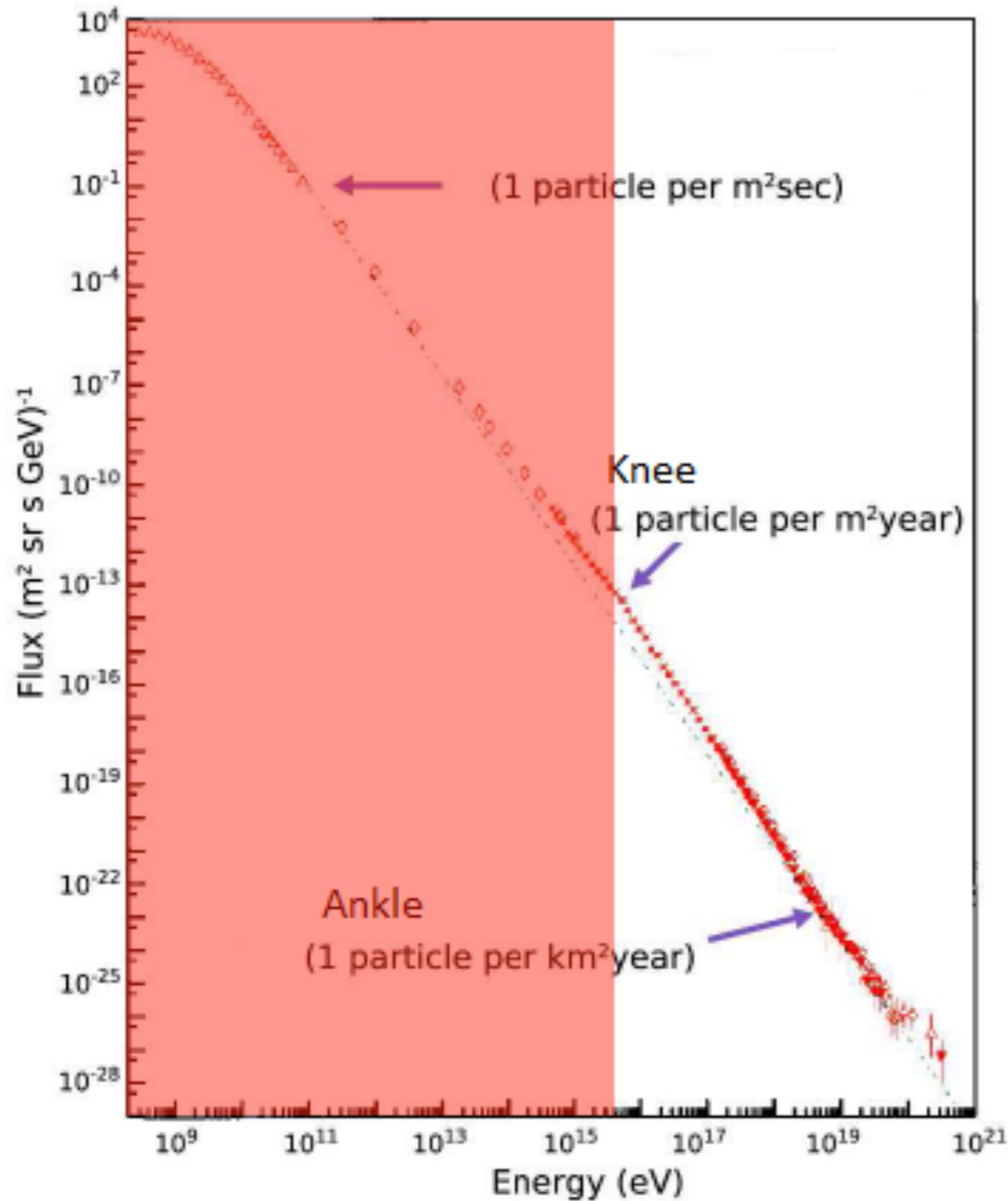


Aharonian et al., A&A 285 (1994) 645A

$$\rightarrow \frac{dN}{dE} \propto E^{-2}$$

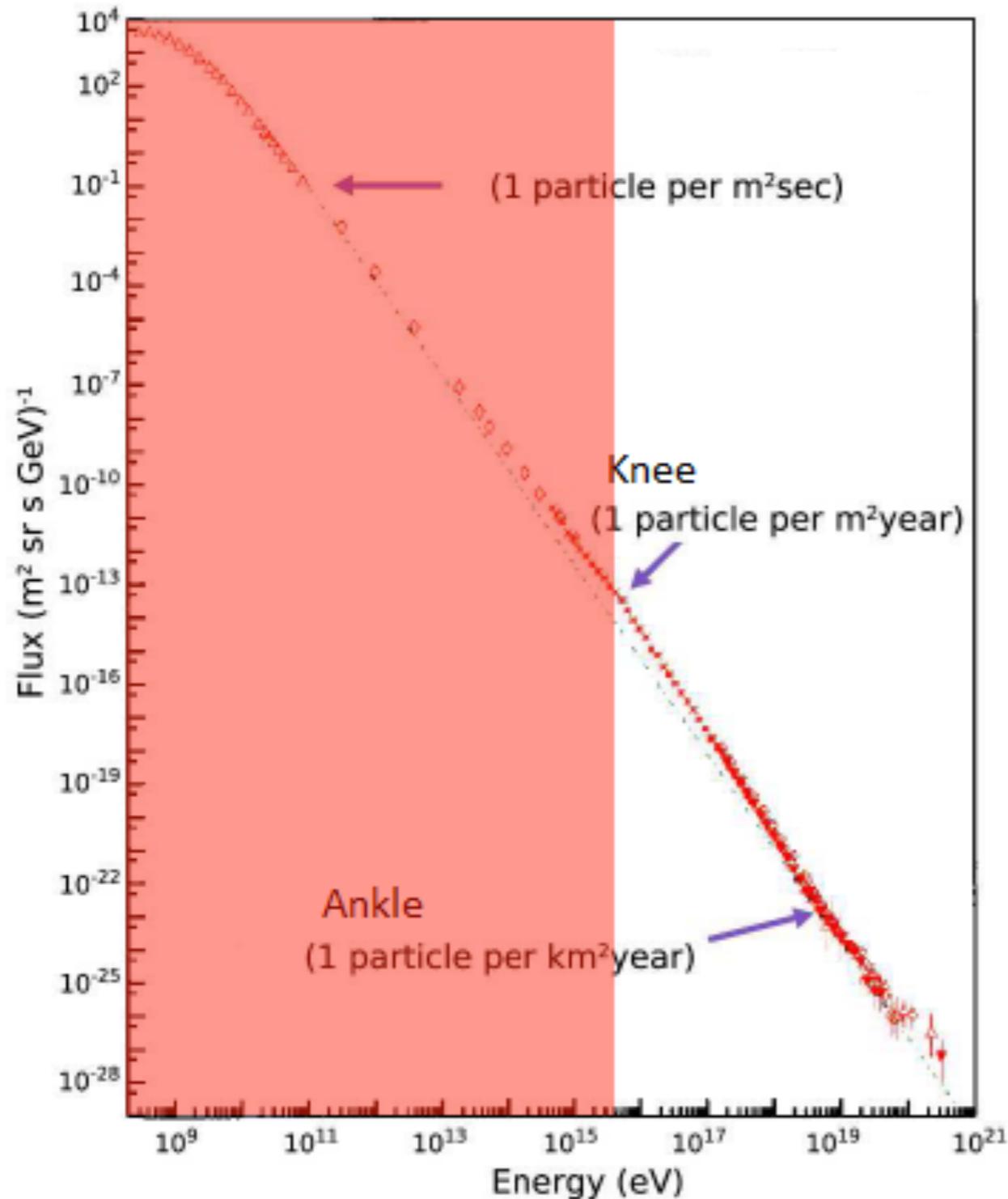


The SNR paradigm for the origin of Galactic CRs



$$U_{\text{CR}} = 0.5 \text{ eV/cm}^3$$
$$V = 400 \text{ kpc}^3$$
$$\tau_{\text{res}} = 5 \times 10^6 \text{ yr}$$
$$P_{\text{CR}} = \frac{U_{\text{CR}} V}{\tau_{\text{res}}} \sim 3 \times 10^{40} \text{ erg/s}$$

The SNR paradigm for the origin of Galactic CRs



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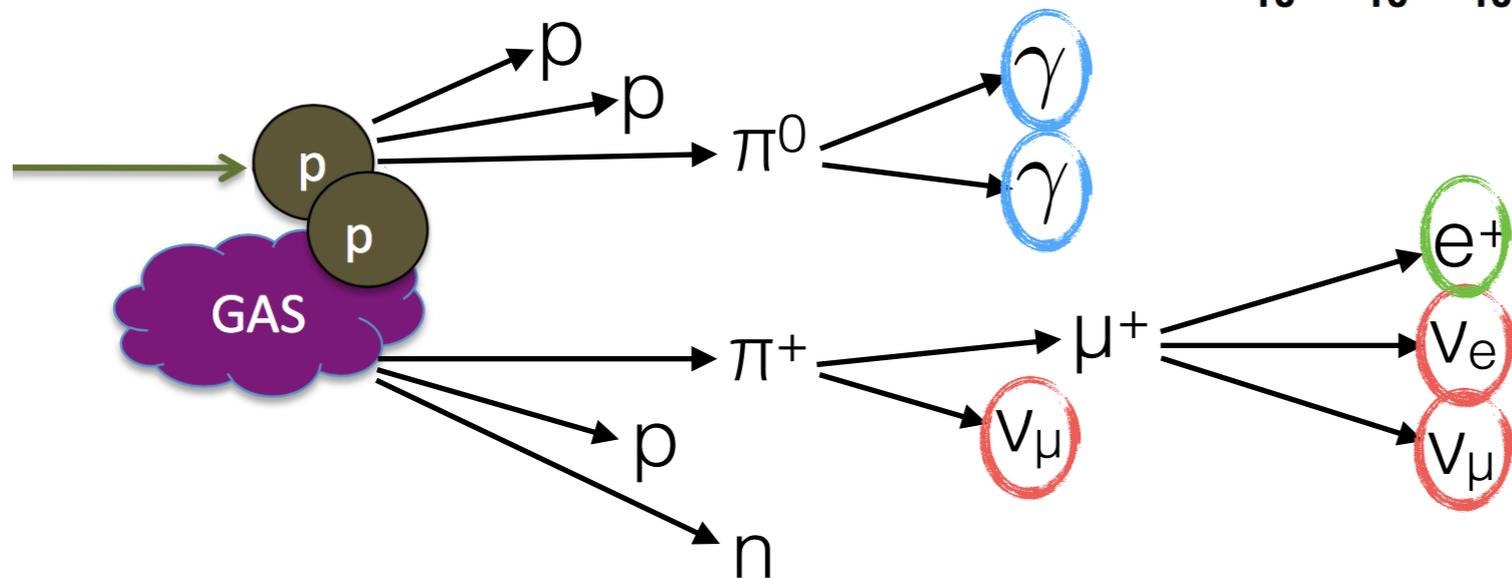
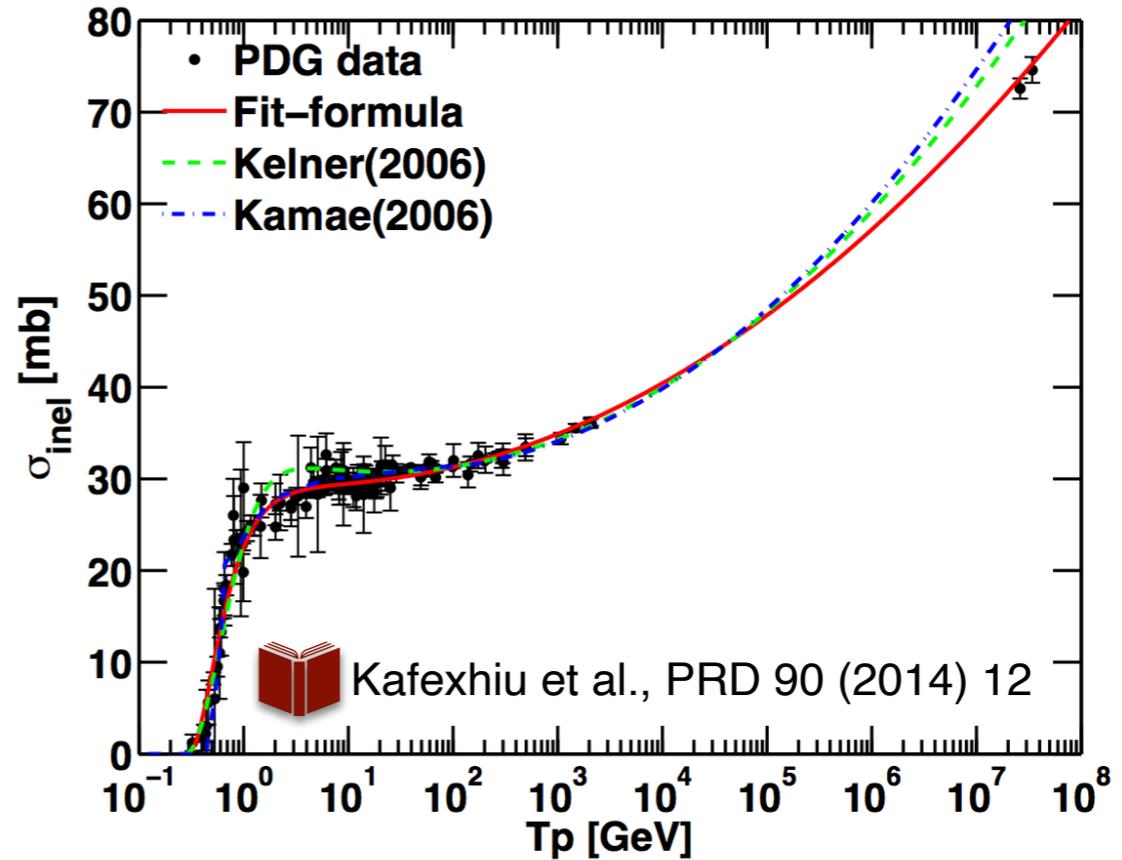
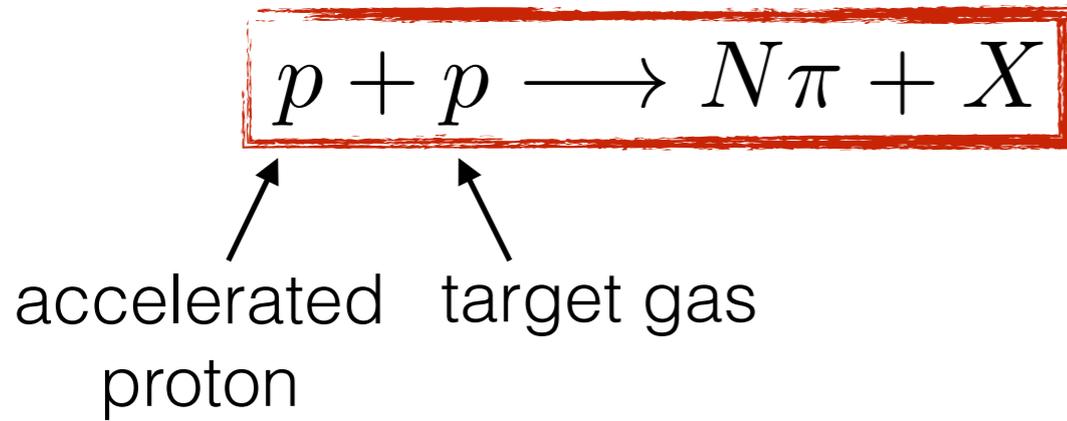
$$E_{\text{SN}} = 10^{51} \text{ erg}$$

$$R_{\text{SN}} = 0.03 \text{ yr}^{-1}$$

$$P_{\text{SN}} = R_{\text{SN}} E_{\text{SN}} \simeq 3 \times 10^{41} \text{ erg/s}$$

$\longrightarrow \xi_{\text{CR}} \simeq 10\%$

Proton-proton collisions

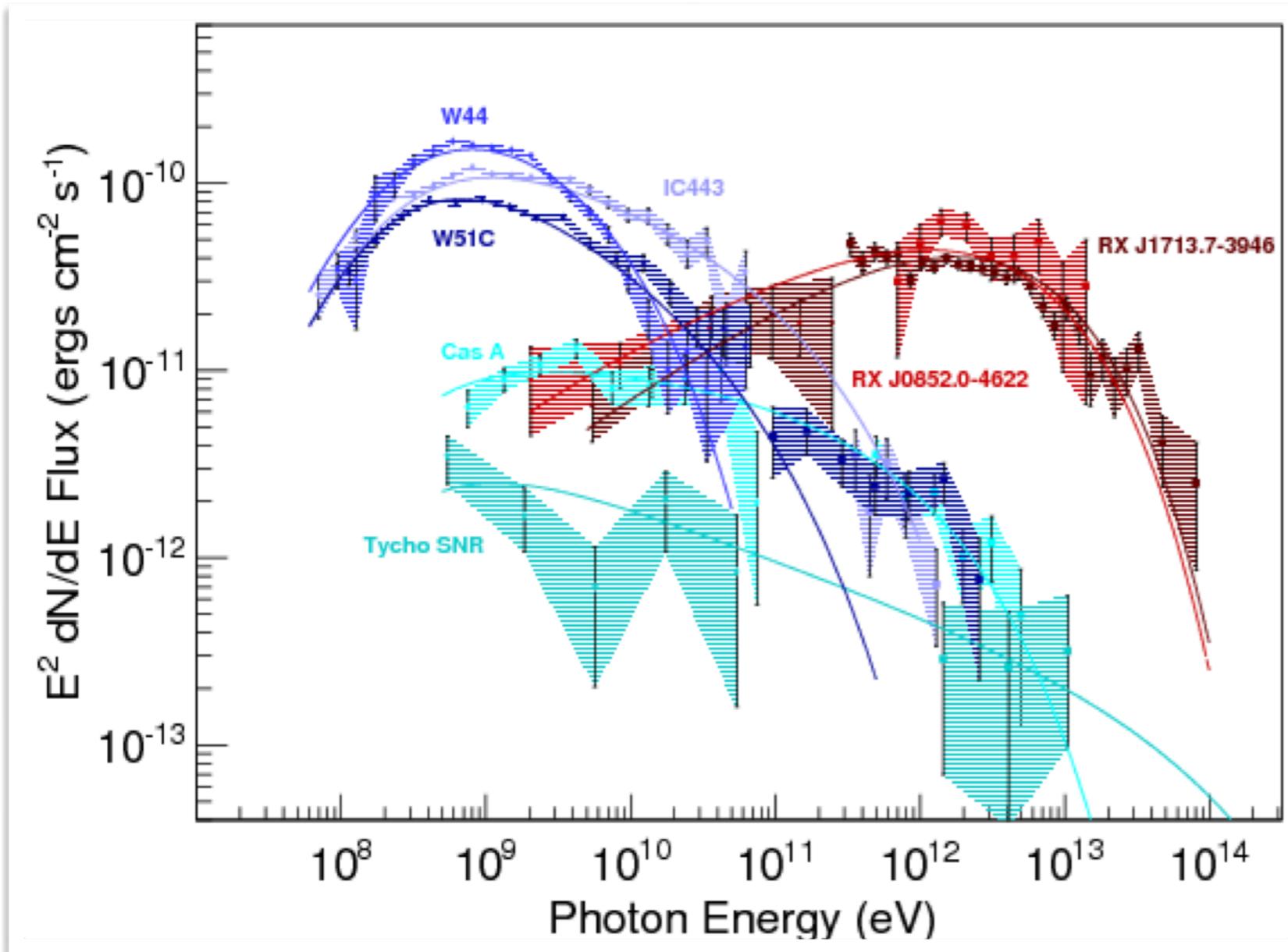


$$E_\gamma \simeq E_p / 10$$

$$E_\nu \simeq E_e \simeq E_p / 20$$

1 PeV proton \longrightarrow \sim 100 TeV gamma rays, \sim 50 TeV neutrinos/electrons

Gamma rays from SNRs



Middle-aged SNRs (20000 yrs)

- hadronic emission
- steep spectra
- $E_{\text{max}} < 1 \text{ TeV}$

Young SNRs (2000 yrs)

- hadronic/leptonic ?
- hard spectra
- $E_{\text{max}} = 10 - 100 \text{ TeV}$

Very young SNRs (300 yrs)

- hadronic ?
- steep spectra $E^{-2.3}$
- $E_{\text{max}} = 10 - 100 \text{ TeV}$



Drury et al., A&A 287 (1994) 959



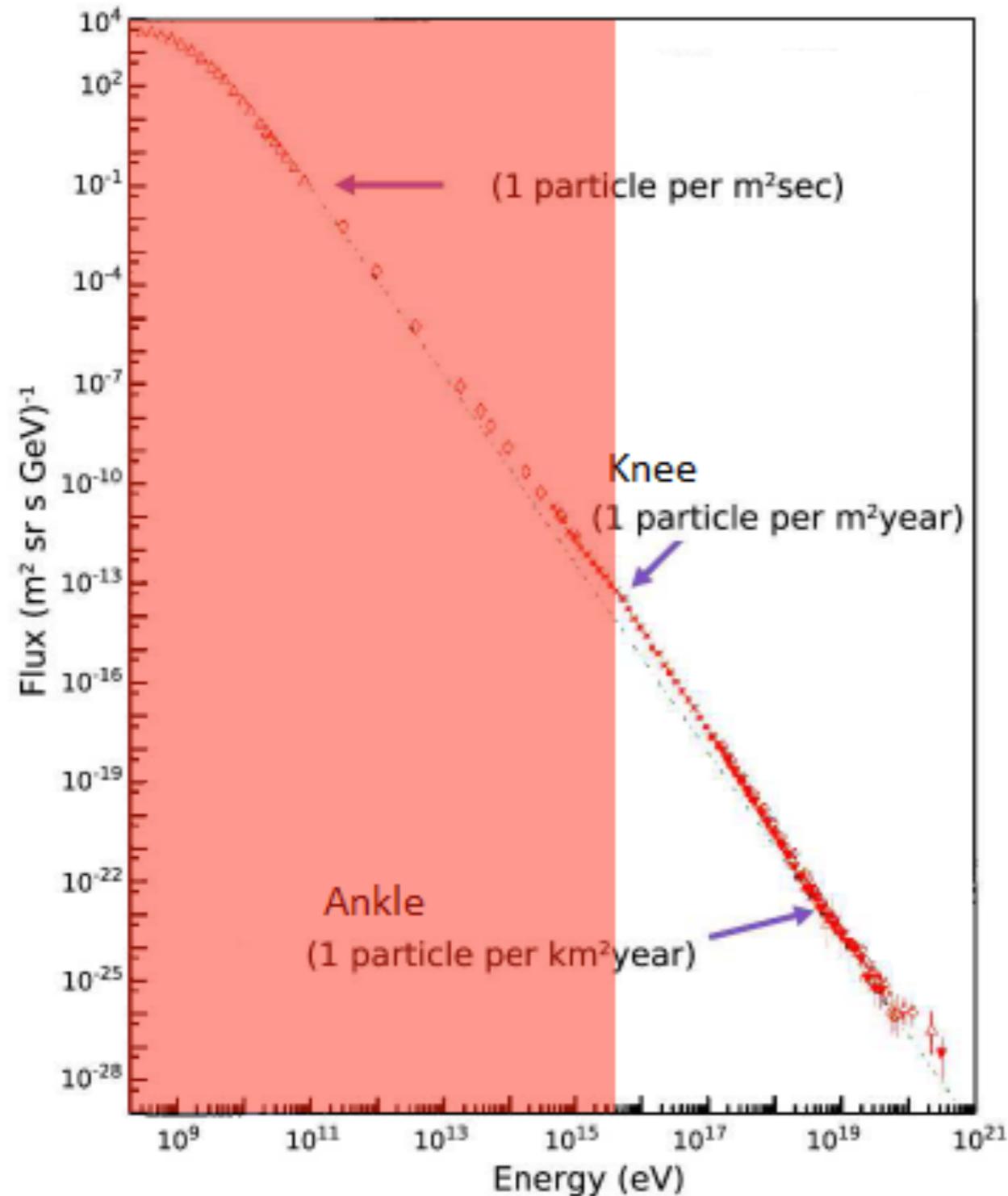
Tsuguya & Fumio, J. Phys. G 20 (1994) 477



Funk et al., ARNPS 65 (2015) 245F

Are SNRs proton PeVatrons?

Hillas criterion



$$E_{max} \simeq v_s R B$$

shock speed
radius
magnetic field

$$E_{max} \simeq 1 \left(\frac{v_s}{10^3 \text{ Km/s}} \right) \left(\frac{R}{\text{pc}} \right) \left(\frac{B}{\mu\text{G}} \right) \text{TeV}$$

3
3
10

$$E_{max} \simeq 100 \text{ TeV}$$

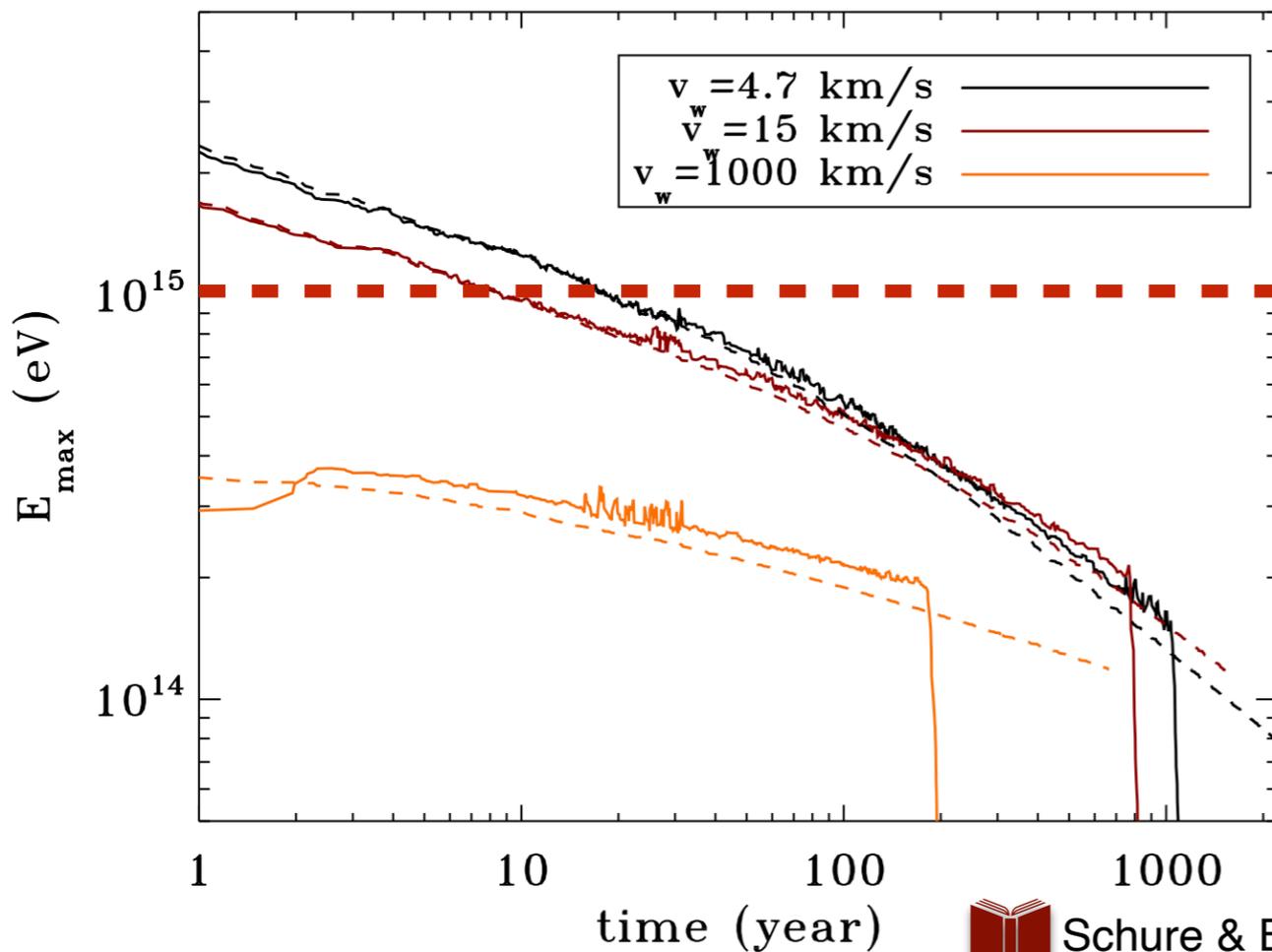
B-field amplification is required to achieve PeV energies



The problem of maximum energy in young SNRs

- Type Ia (e.g. Tycho) → expanding in constant density medium
- Core Collapse (e.g. CasA, RXJ1713.7-3946) → expanding in the dense slow wind of the progenitor star

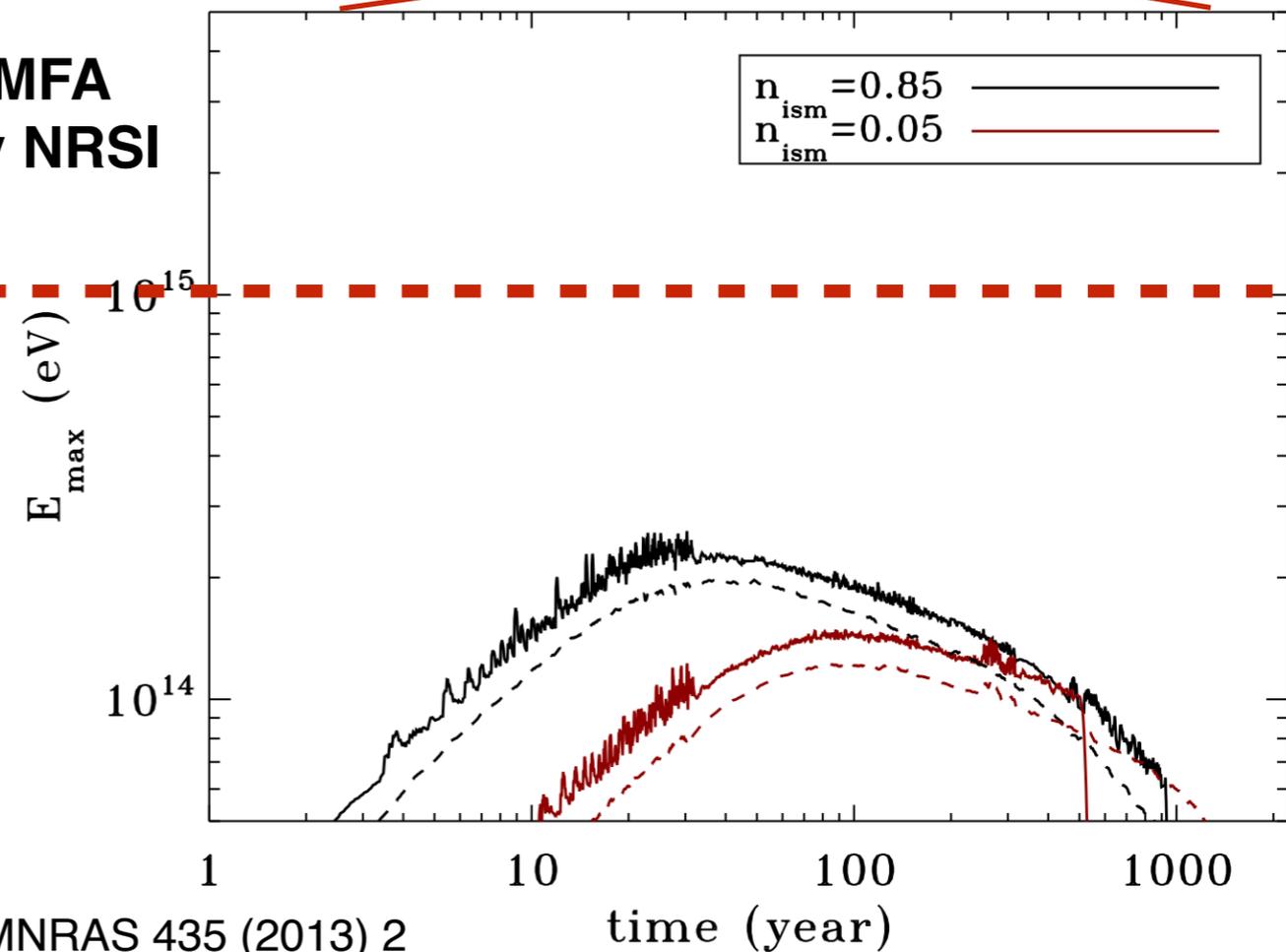
Remnants of type II



Schure & Bell, MNRAS 435 (2013) 2

~~Remnants of type Ia~~

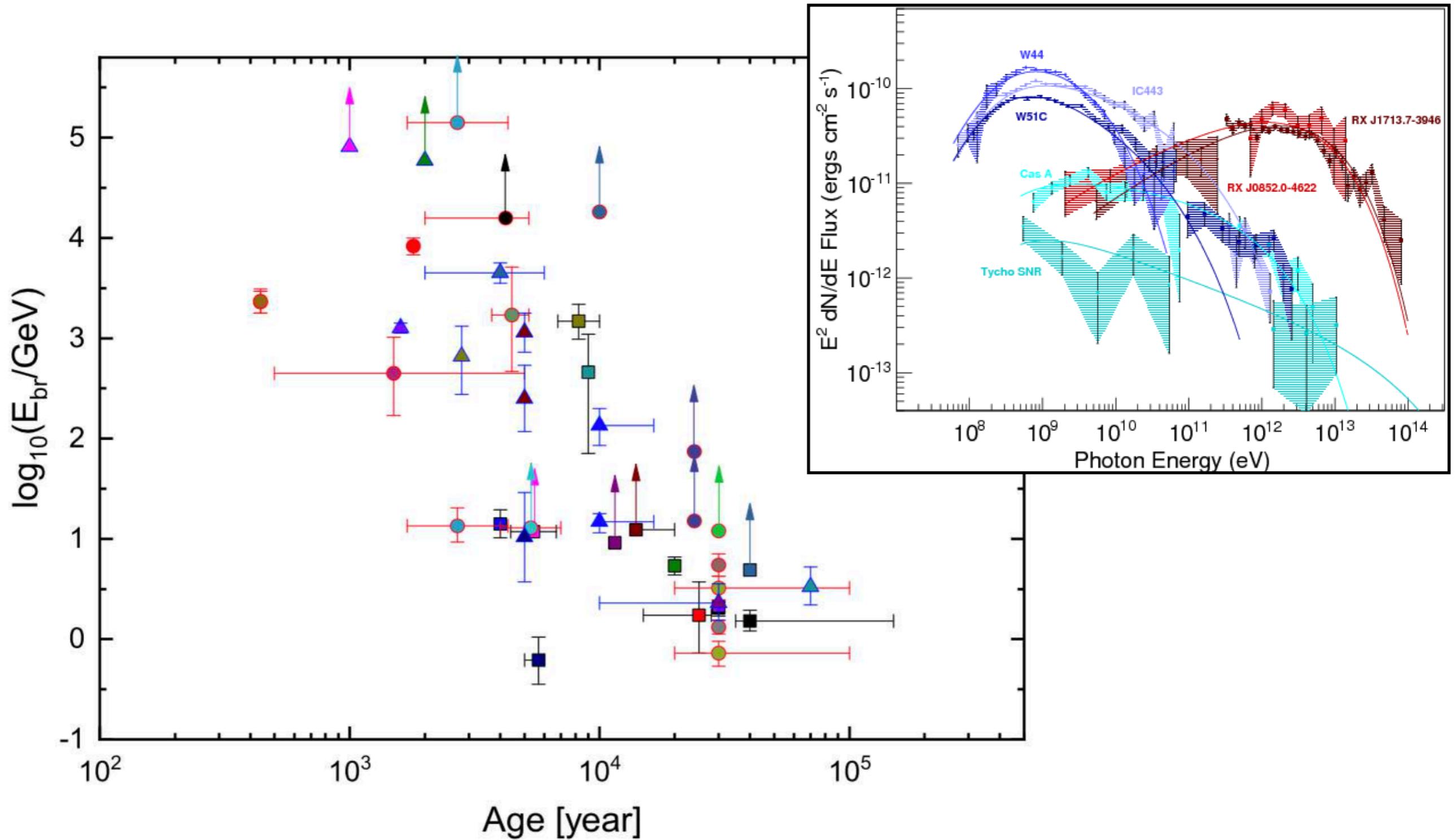
MFA
by NRSI



Only special explosions might achieve the knee



A population study of evolved SNRs



The role of particle escape or how do accelerated particles become CRs?

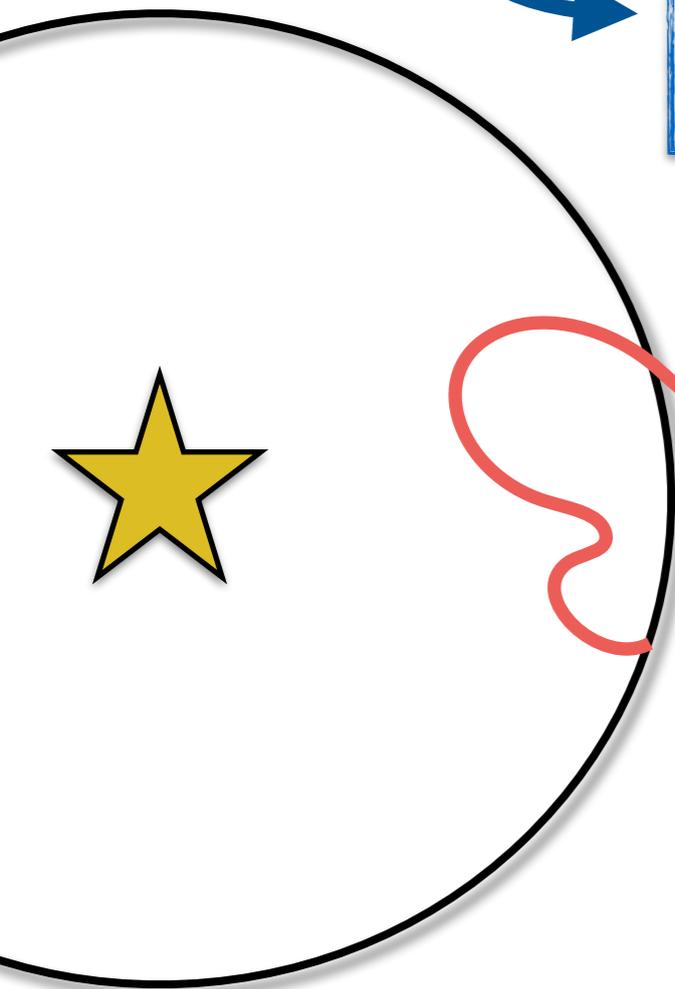
Acceleration at the shock: $f_0(p)$

$$f_0(p) \neq f_{\text{esc}}(p) \neq f_{\text{prop}}(p)$$

Escape from the shock: $f_{\text{esc}}(p)$

Propagation inside the Galaxy: $f_{\text{prop}}(p)$

Observation



The role of particle escape or how do accelerated particles become CRs?

Acceleration at the shock: $f_0(p)$

Escape from the shock: $f_{\text{esc}}(p)$

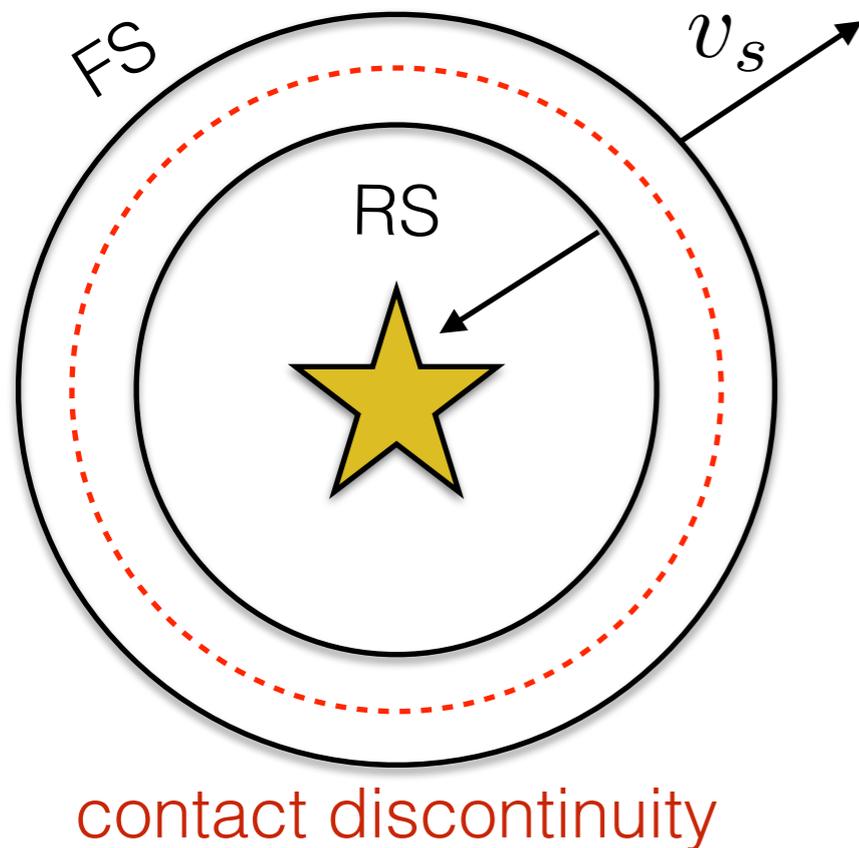
-  Ptuskin & Zirakashvili, A&A 429 (2005) 755
-  Gabici, Aharonian & Casanova, MNRAS (2009)
-  Ohira, Murase & Yamakazi, A&A (2010) 513
-  Bell & Shure, MNRAS 437 (2014) 2802
-  Cardillo, Amato & Blasi, APh 69 (2015) 1

Defines E_{max} and **spectral slope** of both **particles** and **radiation**

 A **phenomenological** model to investigate the particle **escape** through spectral and morphological features of evolved SNRs in the HE and VHE domain.

 Celli et al., MNRAS 490 (2019) 3

The hydrodynamical evolution of an SNR



I. Ejecta-dominated (ED) stage

$$M_{\text{ej}} \gg \frac{4}{3} \pi \rho R_s^3(t)$$

→ free expansion

II. Sedov-Taylor (ST) stage

$$M_{\text{ej}} \sim \frac{4}{3} \pi \rho R_s^3(t)$$

→ energy conservation

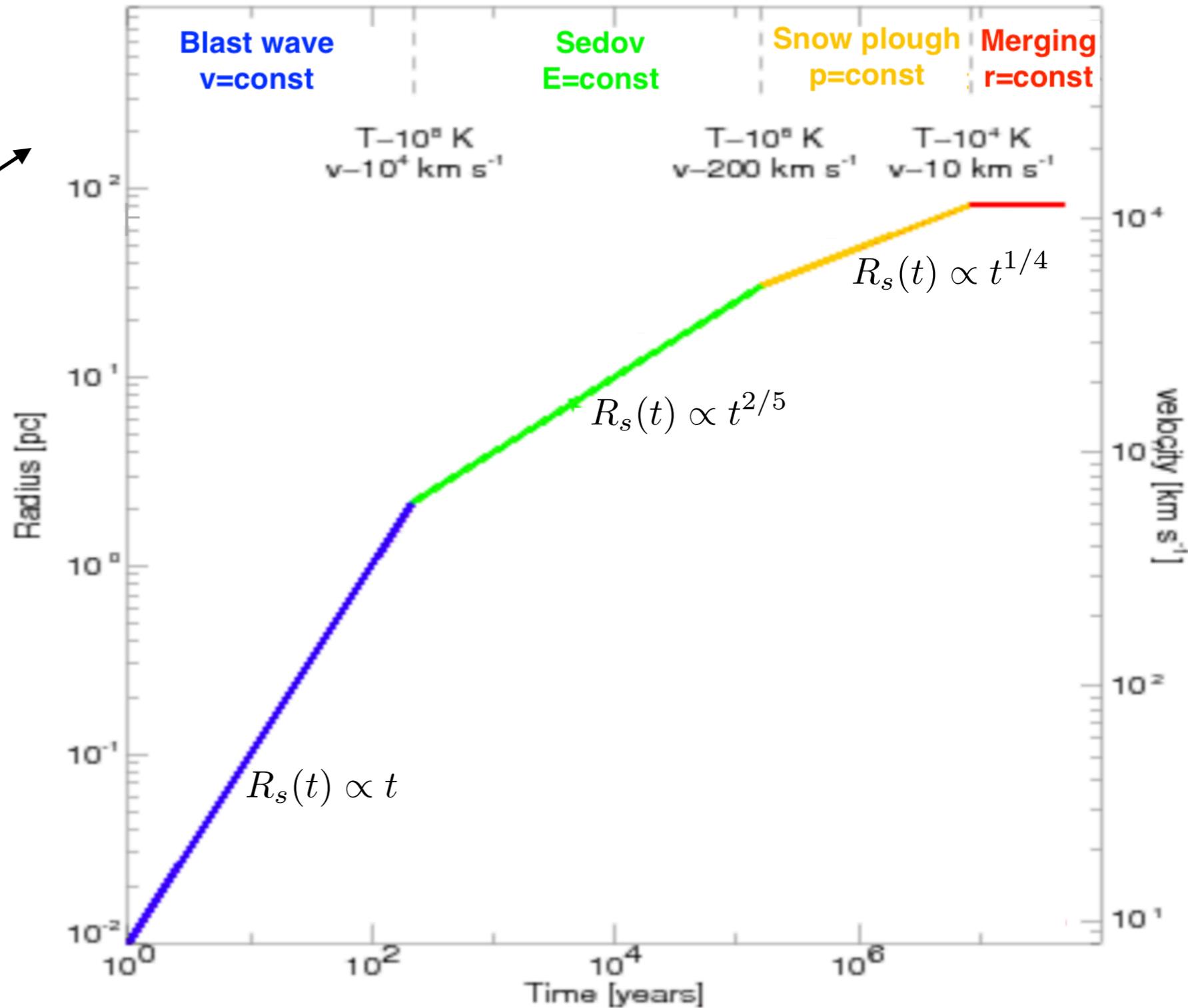
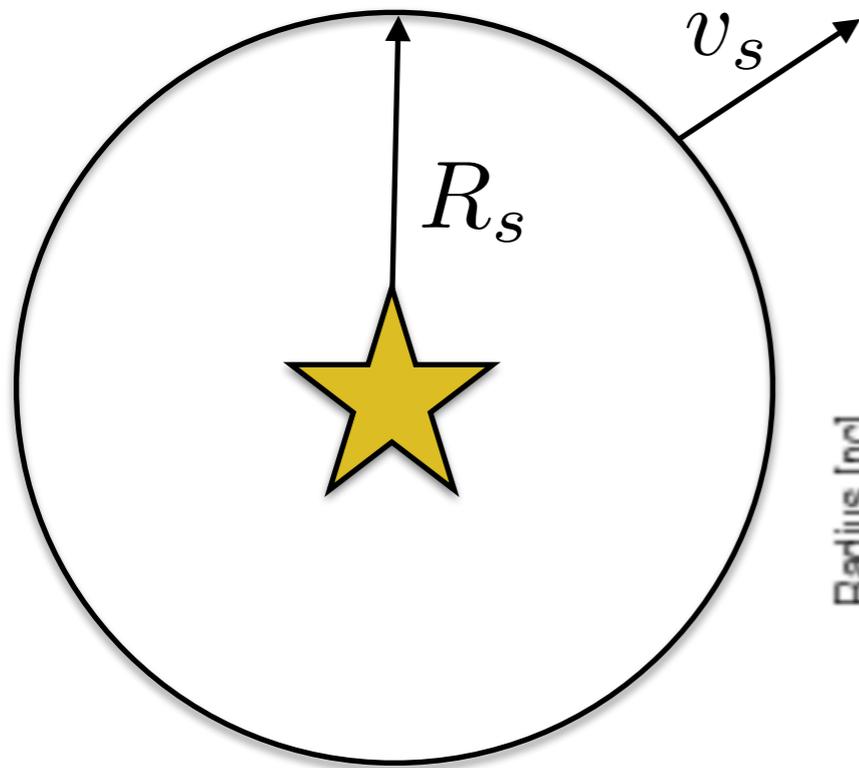
III. Radiative stage

→ momentum conservation

IV. Merging phase

→ pressure comparable to ISM

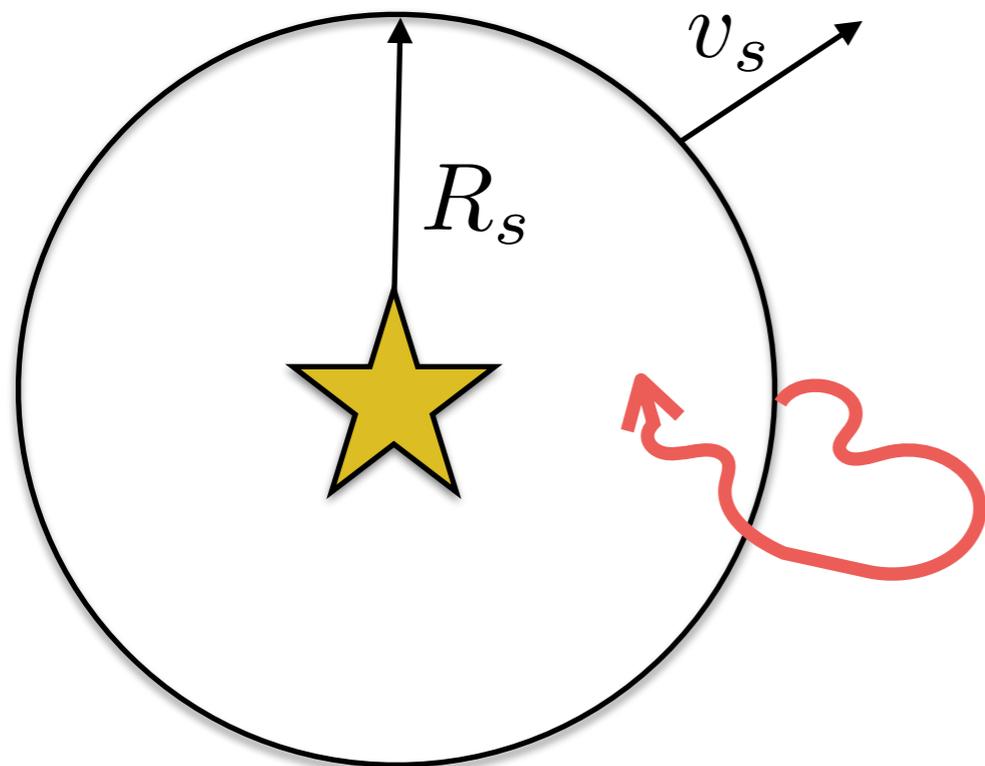
The hydrodynamical evolution of an SNR



 Vink, A&A Rev 20 (2012) 1

$$t_{\text{Sed}} \simeq 1.6 \times 10^3 \text{ yr} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{-1/2} \left(\frac{M_{\text{ej}}}{10 M_{\odot}} \right)^{5/6} \left(\frac{\rho_0}{1 m_{\text{p}}/\text{cm}^3} \right)^{-1/3}$$

Maximum energy in SNRs



- At Sedov time, particles at maximum energy E_M are still confined:

$$\lambda_d(E_M, t_{\text{Sed}}) \simeq R_s(t_{\text{Sed}})$$

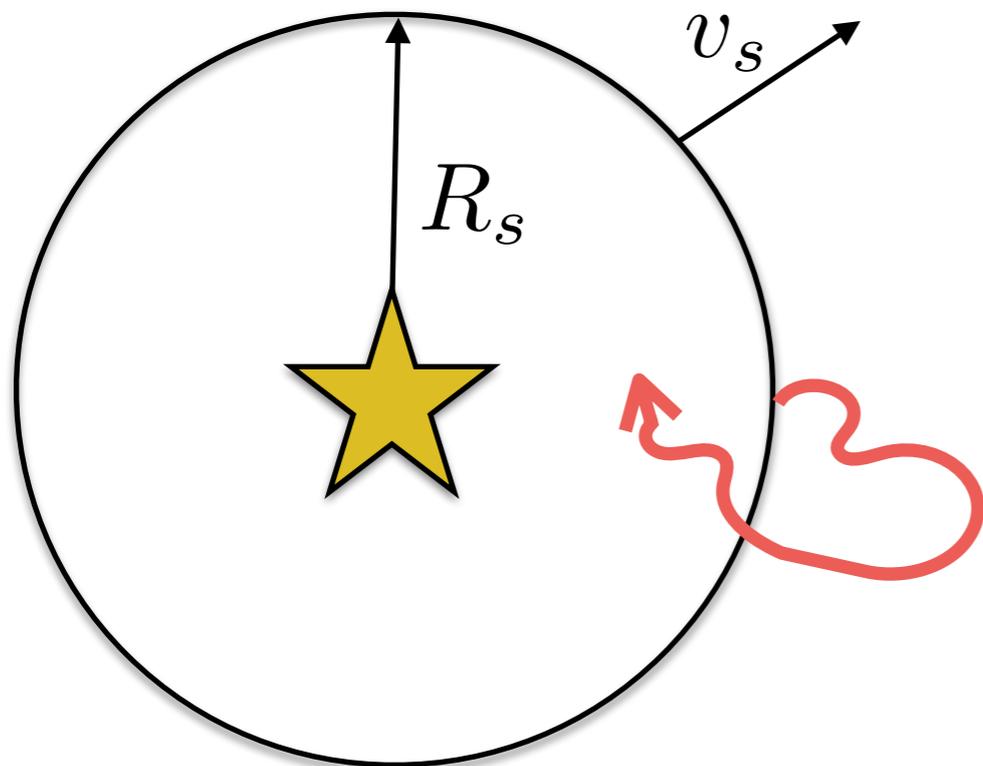
- Later in the evolution, particles diffusion length increases faster than SNR shock size:

$$\lambda_d \simeq D(E_M)/v_s \propto t^{3/5}$$

$$R_s \propto t^{2/5}$$

Particles previously confined will now violate Hillas criterion
→ **escape is expected to occur on shorter timescales for the highest energy particles, but it is not an instantaneous process**

Maximum energy in SNRs



$$t_{\text{acc}} = t_{\text{age}}$$

acceleration
limited by
remnant age

$$\frac{D(p_{\text{max}})}{v_s^2(t)} = t$$

$$\frac{p_{\text{max}}}{B_0 \mathcal{F}(t)} = v_s^2(t) t$$

$$\left(\frac{\delta B(\mathbf{x}, t)}{B_0} \right)^2 = \int \mathcal{F}(k, \mathbf{x}, t) d \ln k$$

$$p_{\text{max},0} \propto \mathcal{F}(t) v_s^2(t) t$$

→ **ED stage:**

$$v_s(t) \simeq \text{const}$$

$$p_{\text{max},0}(t) \propto \mathcal{F}(t) t$$

→ **ST stage:**

$$v_s(t) \simeq t^{-3/5}$$

$$p_{\text{max},0}(t) \propto \mathcal{F}(t) t^{-1/5} \propto t^{-\delta}$$

Maximum energy in SNRs

In the scenario where the maximum momentum of particles confined by the shock is a decreasing function of time, i.e.

$$p_{\max,0}(t) = p_M \left(\frac{t}{t_{\text{Sed}}} \right)^{-\delta} \longrightarrow t_{\text{esc}}(p) = t_{\text{Sed}} \left(\frac{p}{p_M} \right)^{-1/\delta}$$

 Ptuskin & Zirakashvili, A&A 429 (2005) 755

$\delta > 0$: high-energy particles escape earlier

- Magnetic field not amplified

$$p_{\max,0}(t) \propto t^{-1/5}$$

- Magnetic field amplification driven by resonant waves

$$p_{\max,0}(t) \propto t^{-7/5}$$

- Magnetic field amplification driven by non-resonant waves

$$p_{\max,0}(t) \propto t^{-2}$$

A model for particle propagation

Solution of the transport equation for accelerated **protons**

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f = \frac{p}{3} \frac{\partial f}{\partial p} \nabla \cdot \mathbf{v} + \nabla \cdot [D \nabla f]$$

**ANALYTICAL DESCRIPTION
WITH A DOWNSTREAM
VELOCITY PROFILE OF:**



Celli et al., MNRAS 490 (2019) 3

$$v(r, t) = \left(1 - \frac{1}{\sigma}\right) \frac{r}{R_s(t)} v_s(t)$$

Particles confined inside the SNR

$$\frac{\partial f_{\text{conf}}}{\partial t} + \mathbf{v} \cdot \nabla f_{\text{conf}} = \frac{p}{3} \frac{\partial f_{\text{conf}}}{\partial p} \nabla \cdot \mathbf{v}$$

$$p \leq p_{\text{max},0}(t)$$

Escaped particles

$$\frac{\partial f_{\text{esc}}}{\partial t} = \nabla \cdot [D \nabla f_{\text{esc}}]$$

$$p > p_{\text{max},0}(t)$$

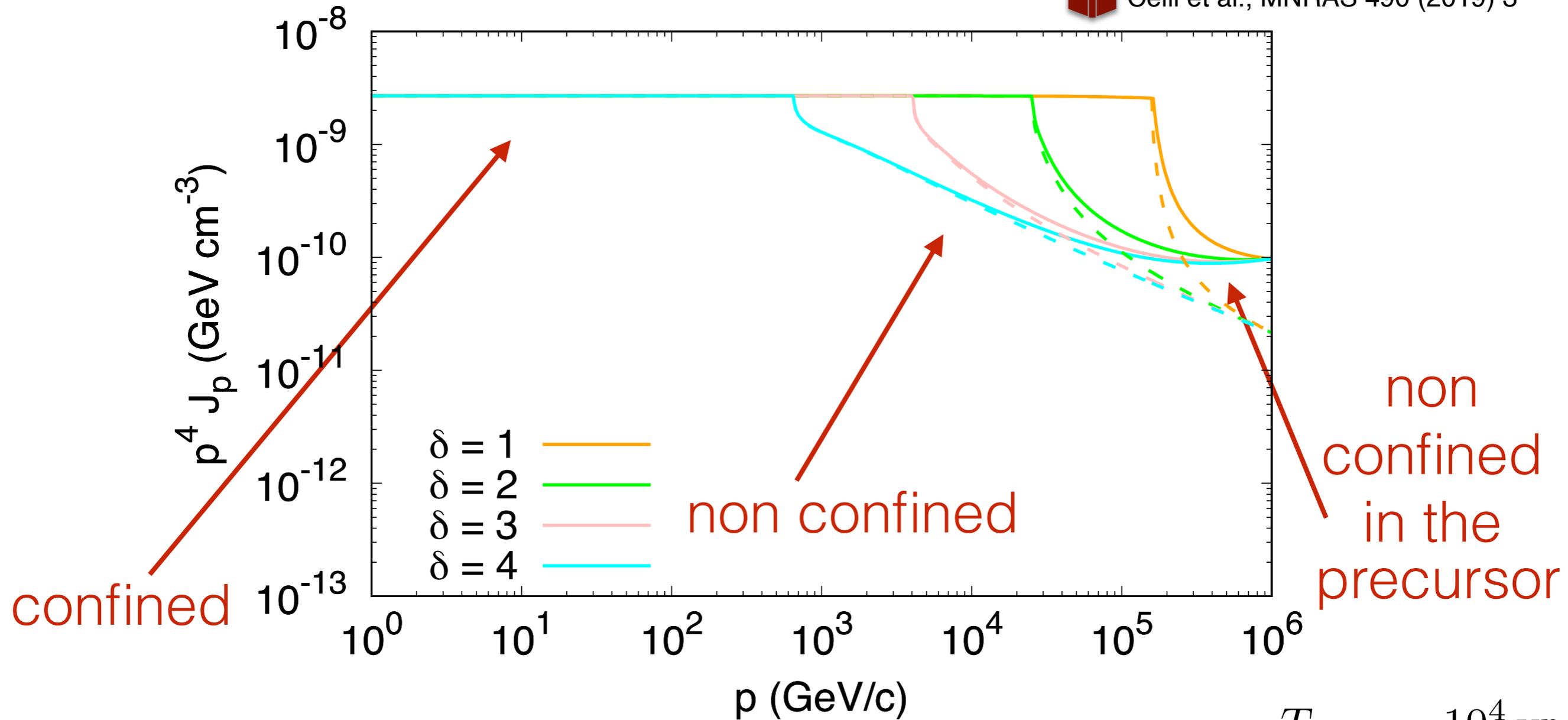
Matching condition: $f_{\text{esc}}(t_{\text{esc}}) = f_{\text{conf}}(t_{\text{esc}})$

The spectrum of protons inside the SNR

$$J_p^{\text{in}}(t, p) = \frac{4\pi}{V_{\text{SNR}}} \int_0^{R_{\text{sh}}(t)} [f_{\text{esc}}(t, r, p) + f_{p,\text{esc}}(t, r, p) + f_{\text{conf}}(t, r, p)] r^2 dr$$



Celli et al., MNRAS 490 (2019) 3



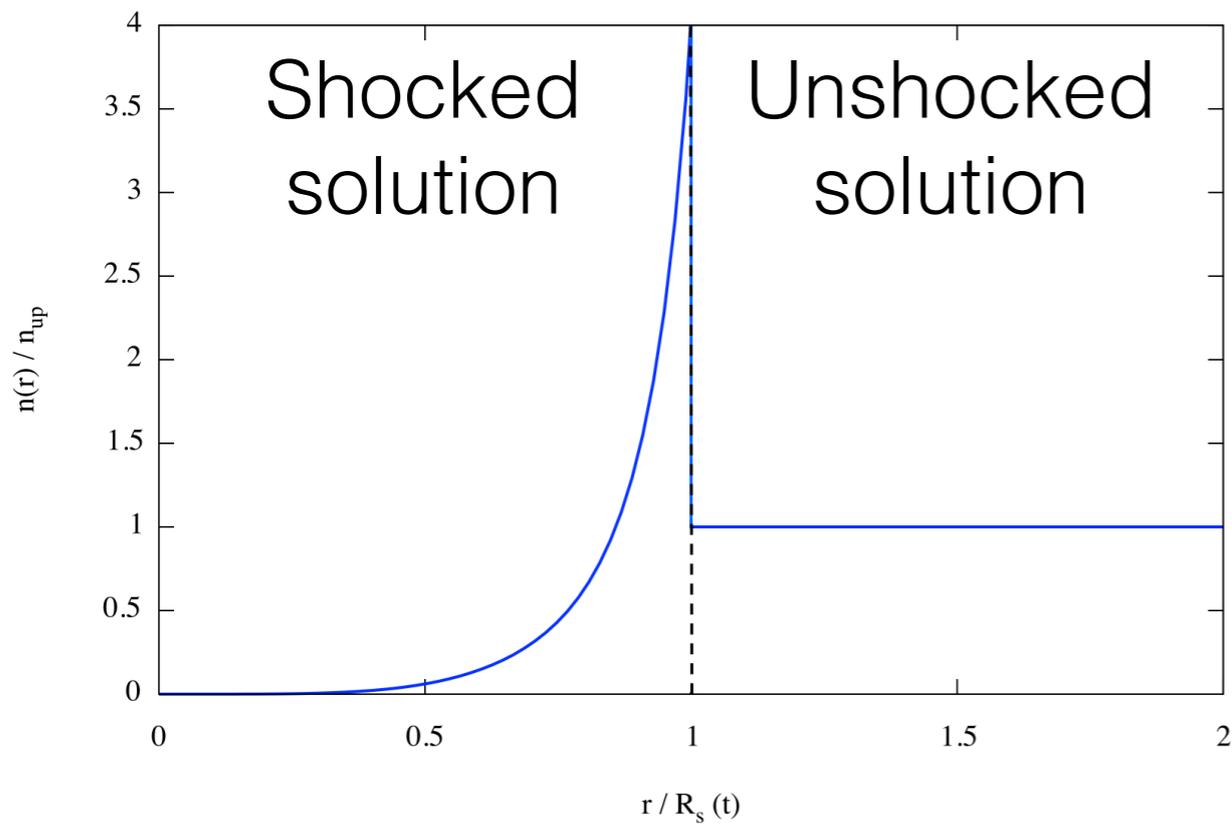
$$D(p) = 10^{27} \left(\frac{pc}{10 \text{ GeV}} \right)^{1/3} \text{cm}^2 \text{s}^{-1}$$

$$T_{\text{SNR}} = 10^4 \text{ yr}$$

$$\xi_{\text{CR}} = 10\%$$

$$n_{\text{up}} = 1 \text{ cm}^{-3}$$

Volume integrated gamma-ray emission from hadronic interactions

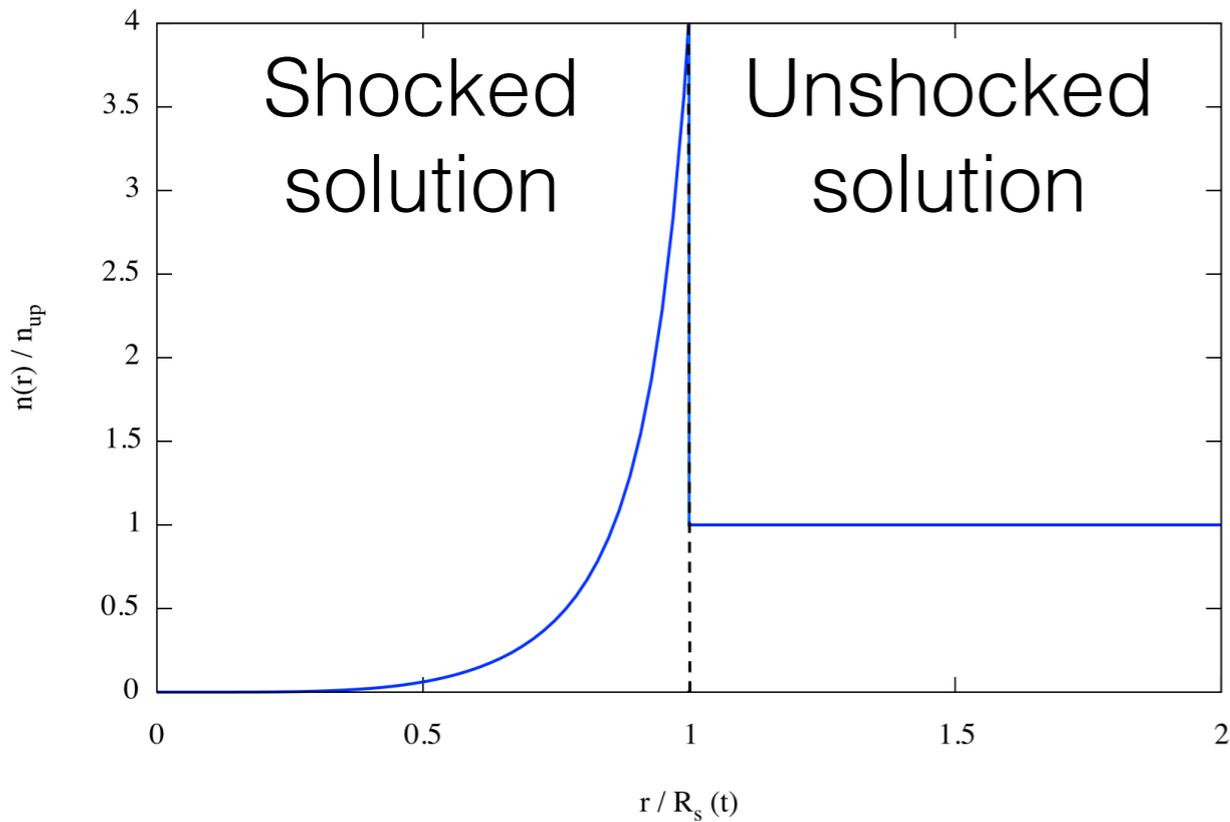


Density profile
of the CSM



Sedov, New York Academic Press (1959)

Volume integrated gamma-ray emission from hadronic interactions



$$f_0(p) \propto p^{-4}$$

$$D(10 \text{ GeV}/c) = 3 \times 10^{27} \text{ cm}^2/\text{s}$$

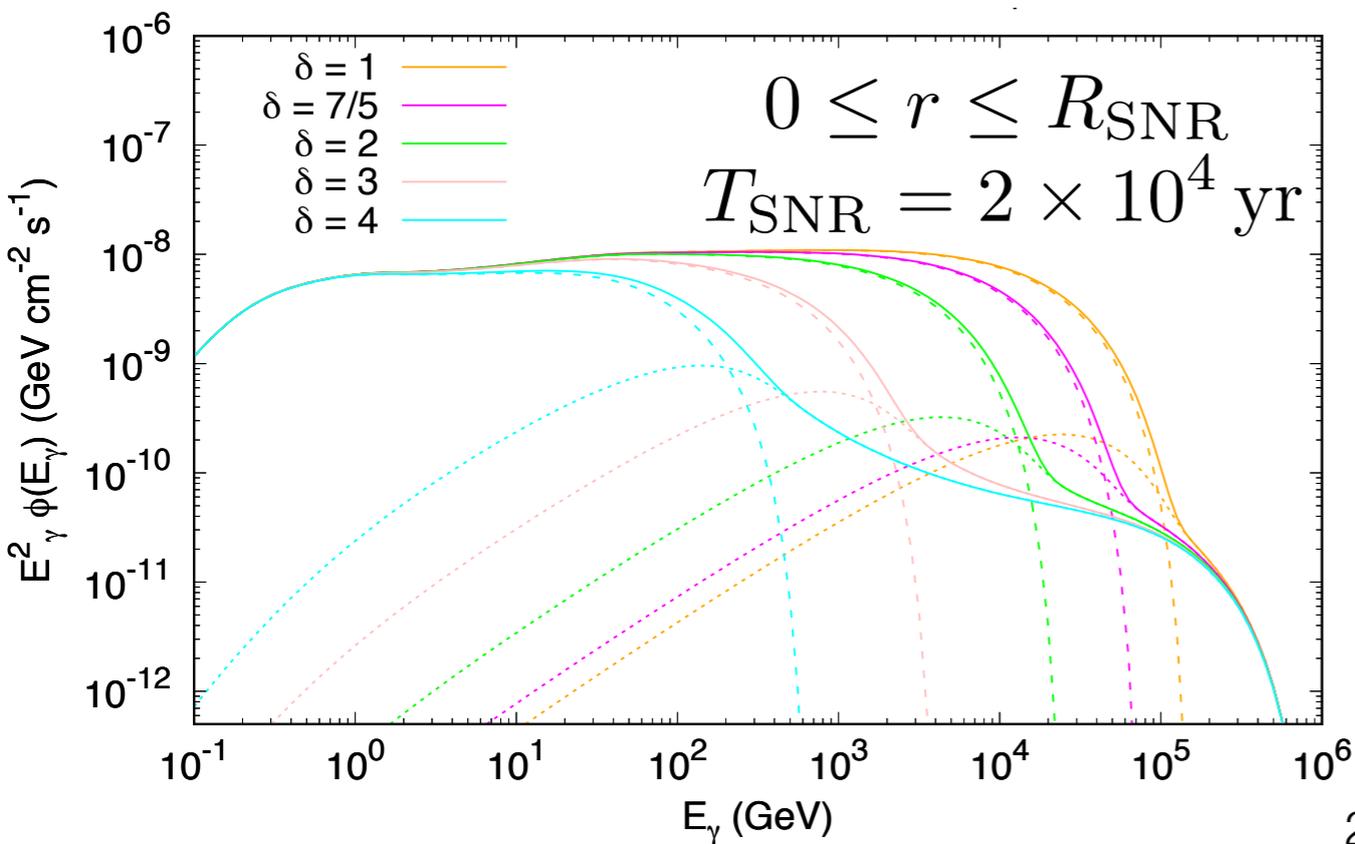
$$\xi_{\text{CR}} = 1\%$$

$$n_{\text{up}} = 1 \text{ cm}^{-3}$$

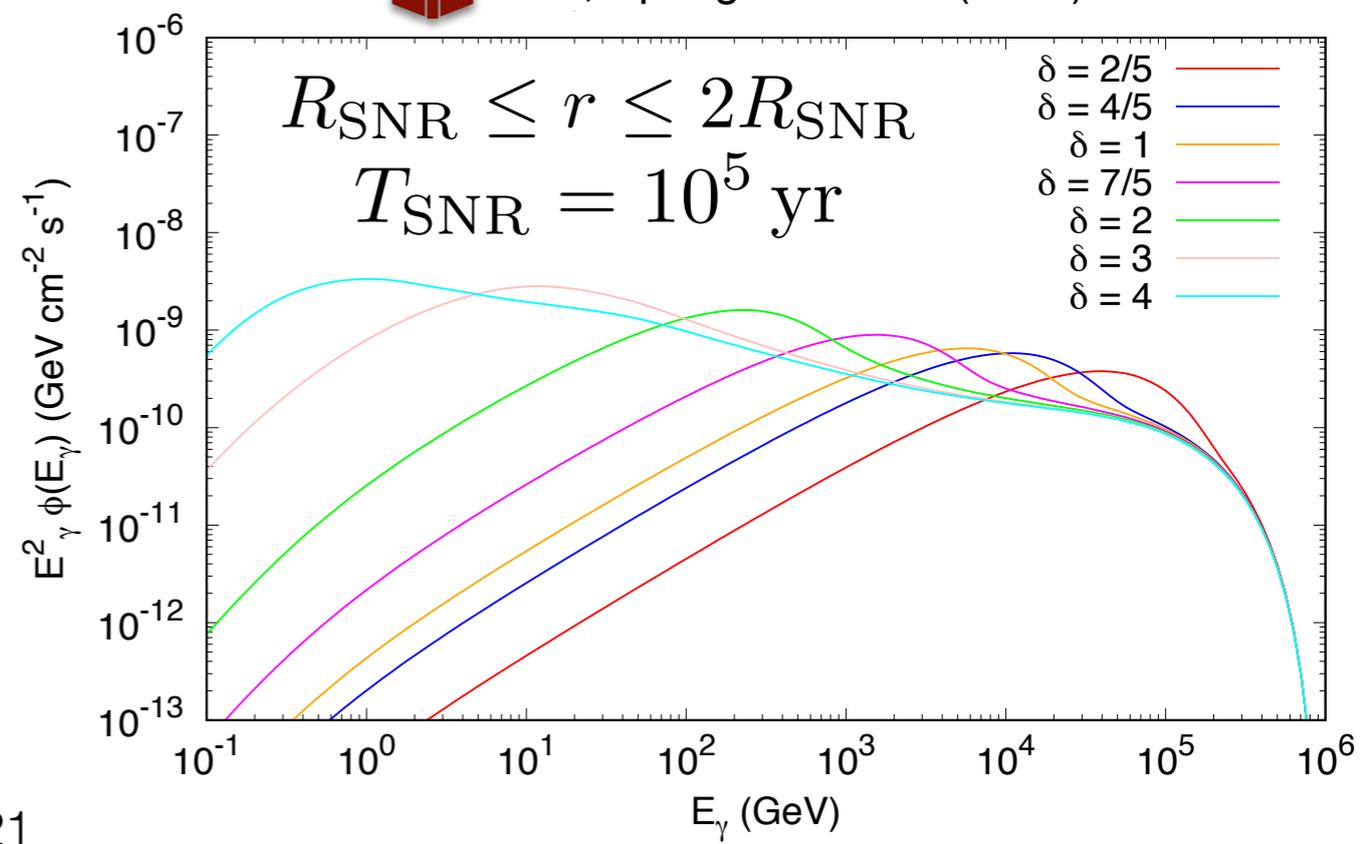
$$d = 1 \text{ kpc}$$



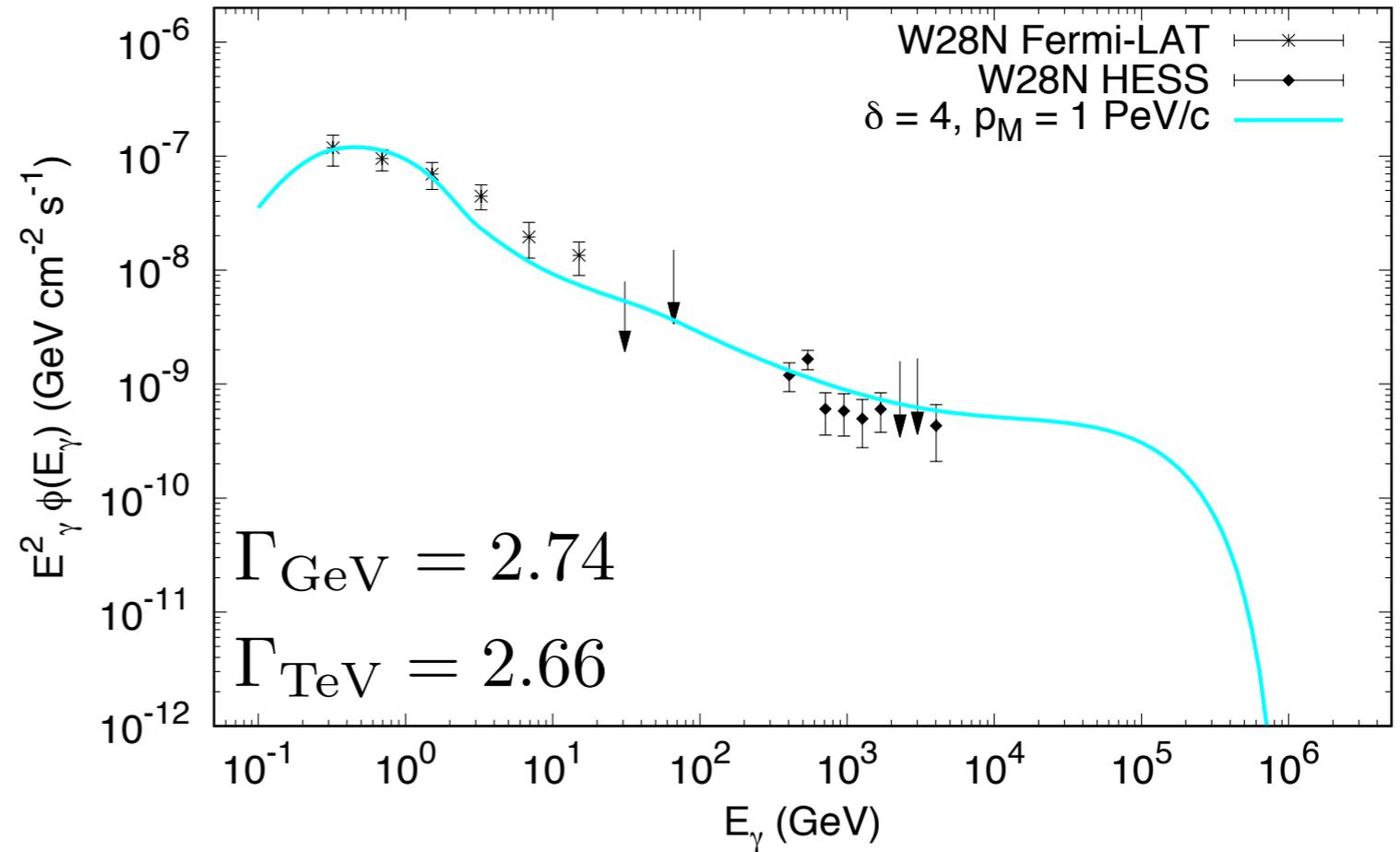
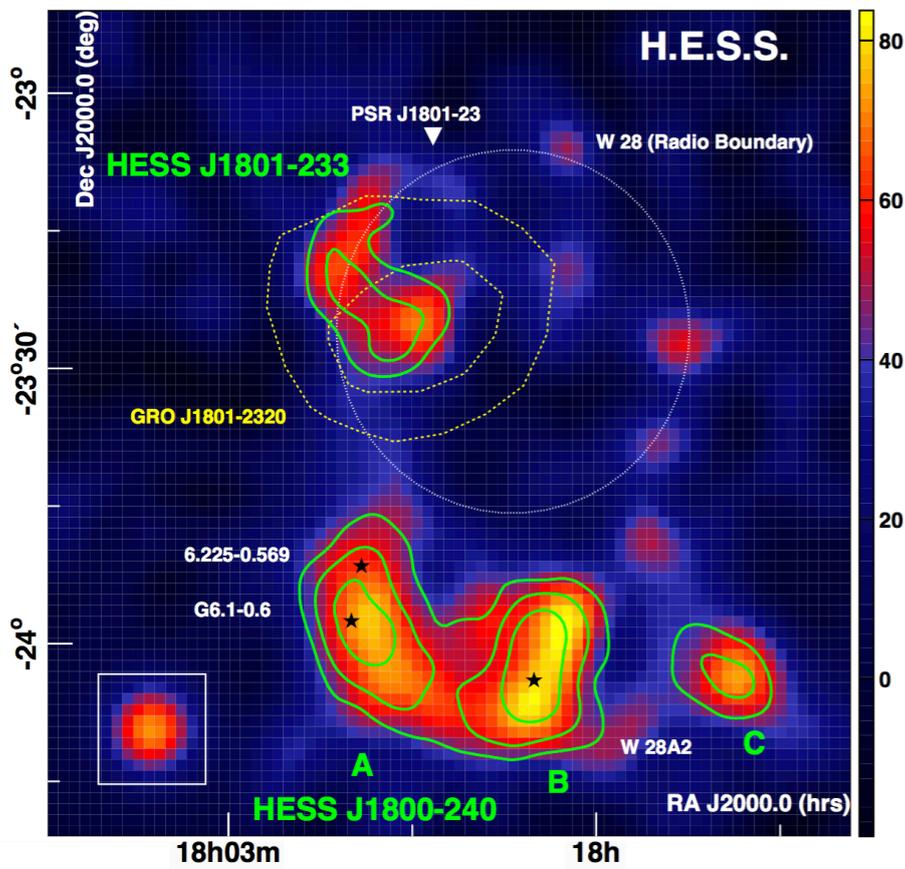
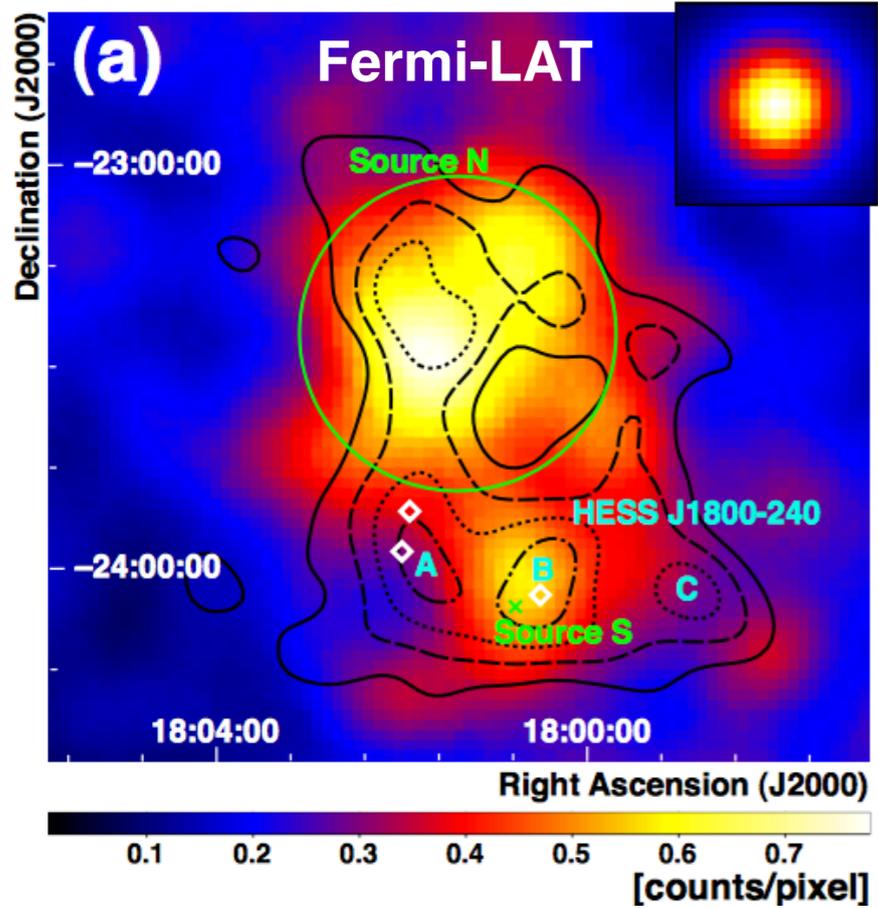
Celli, Springer Theses (2019)



21



Middle-aged SNRs: W 28N



$$f_0(p) \propto p^{-4}$$

$$T_{\text{SNR}} = 30 \text{ kyr}, n_{\text{up}} = 10 \text{ cm}^{-3}$$

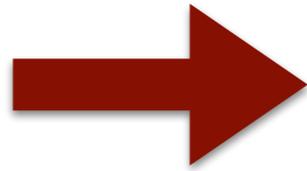
Kolm.

$$D(10 \text{ GeV/c}) = 3 \times 10^{27} \text{ cm}^2/\text{s}$$

$$\xi_{\text{CR}} \simeq 15\%$$



$$D/D_{\text{Gal}} \leq 0.3$$



Suppression of diffusion coefficient required:

- local turbulence?
- CR-induced turbulence (streaming instability)?



Malkov et al., ApJ 768 (2013) 63

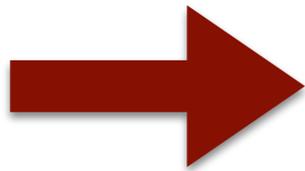


Nava et al., MNRAS 461 (2016) 3552N



D'Angelo et al., MNRAS 474 (2018) 1944D

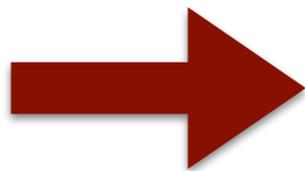
$$\delta \geq 2$$



How does magnetic turbulence evolve with time?

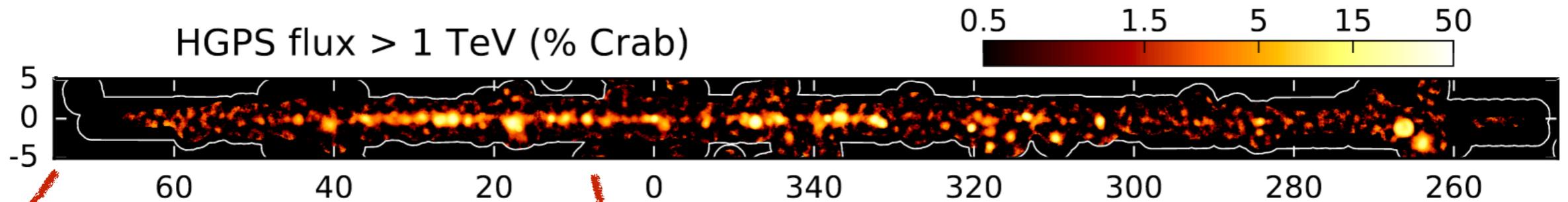
Needs to include damping effects (MHD cascade, ion-neutral friction).

$$\xi_{\text{CR}} \simeq 2 - 20\%$$

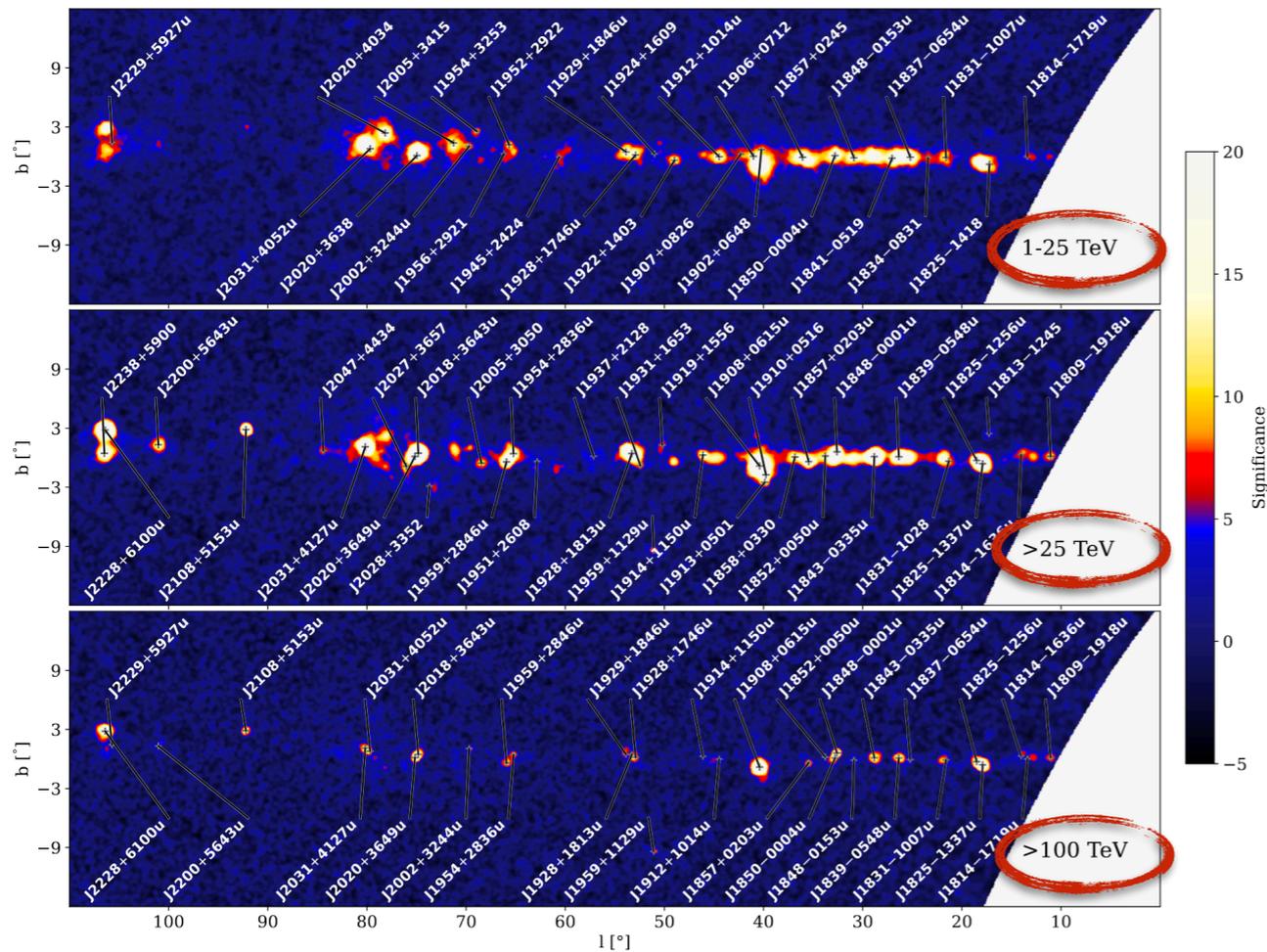


Standard assumption in the SNR paradigm for the origin of GCRs.

VHE & UHE gamma-ray sources in the Galaxy



LHAASO significance maps



- Galactic Plane Survey by **H.E.S.S.**

- 78 sources detected

- **47 unidentified**

 Abdalla et al., A&A 612 (2018) A1

- 1st **LHAASO** catalog:

- 90 sources detected

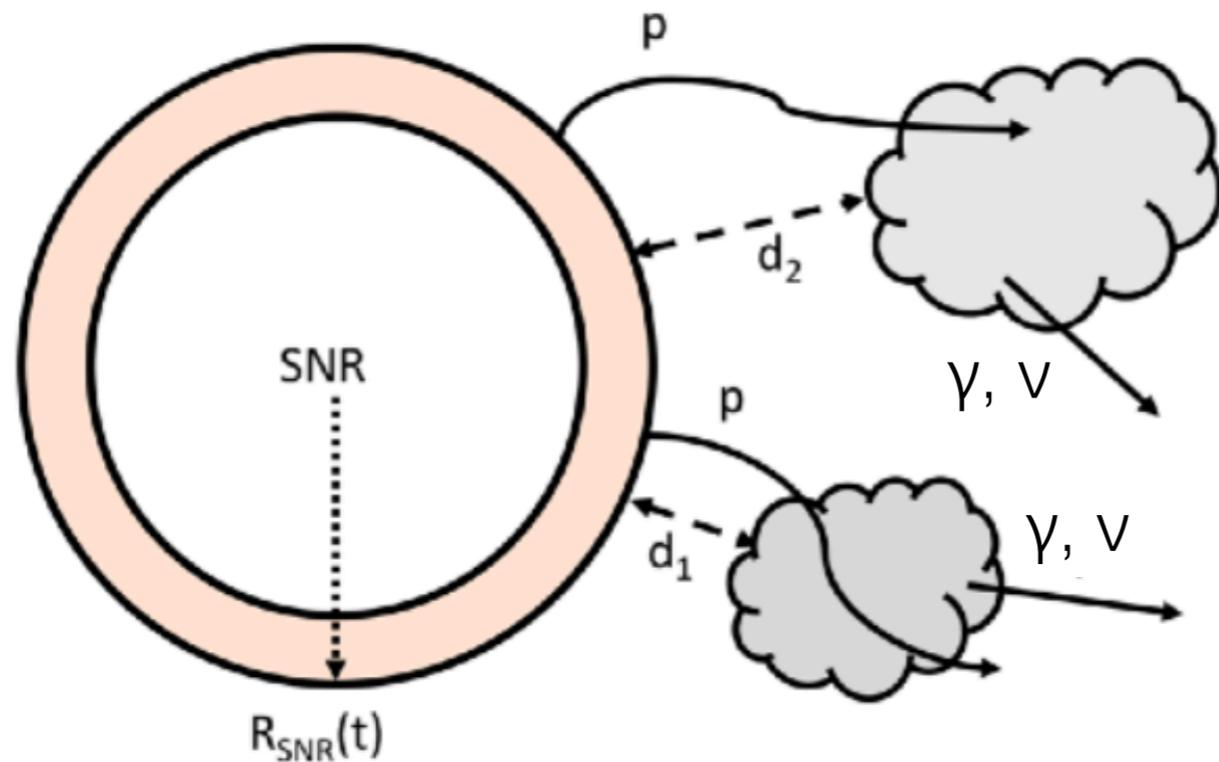
- 43 with UHE emission ($\sigma > 4$ @ $E > 100$ TeV)

- **32 new TeV sources**

 Cao et al., ApJSS 271 (2024) 25

Are UNID sources related to molecular clouds as illuminated by SNR-escaping CRs?

Escaping particles & molecular cloud illumination



- **Delayed emission** from **molecular clouds** could help us understanding whether nearby **SNRs** have ever behaved as **PeVatron**

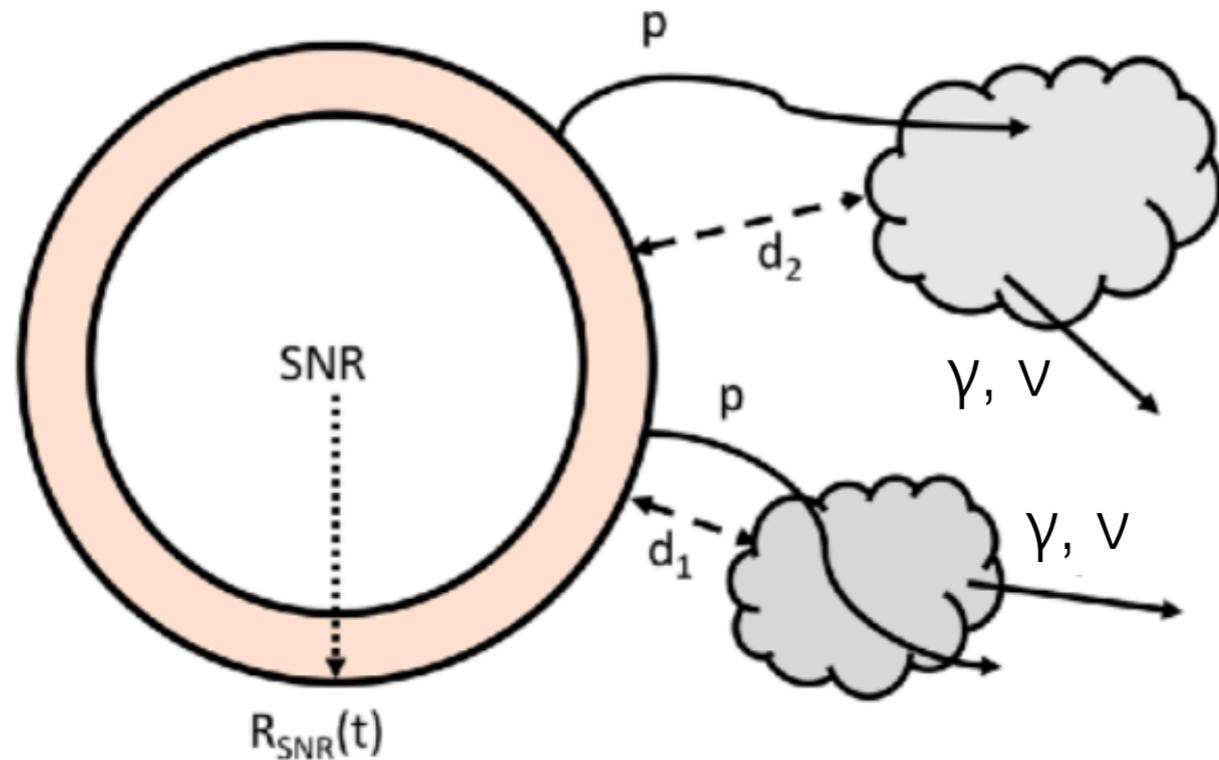
 Gabici et al., MNRAS 396 (2009) 1629G

 Mitchell & Celli, JHEA 44 (2024) 340

Methods

- SNRs from both **GreenCat** & **SNRCat** catalogs;
- Molecular Clouds detected through ^{12}CO line from **Rice catalog**: measured distance, size and density (with uncertainties);
- **SNR-MC pairing** requires angular separation and distance to imply a physical separation < 100 pc;
 - If SNR distance is unknown, it is considered at cloud distance and only angular separation is used as a selection criterion.

Escaping particles & molecular cloud illumination



 Mitchell & Celli, JHEA 44 (2024) 340

CR injection model @ SNRs:

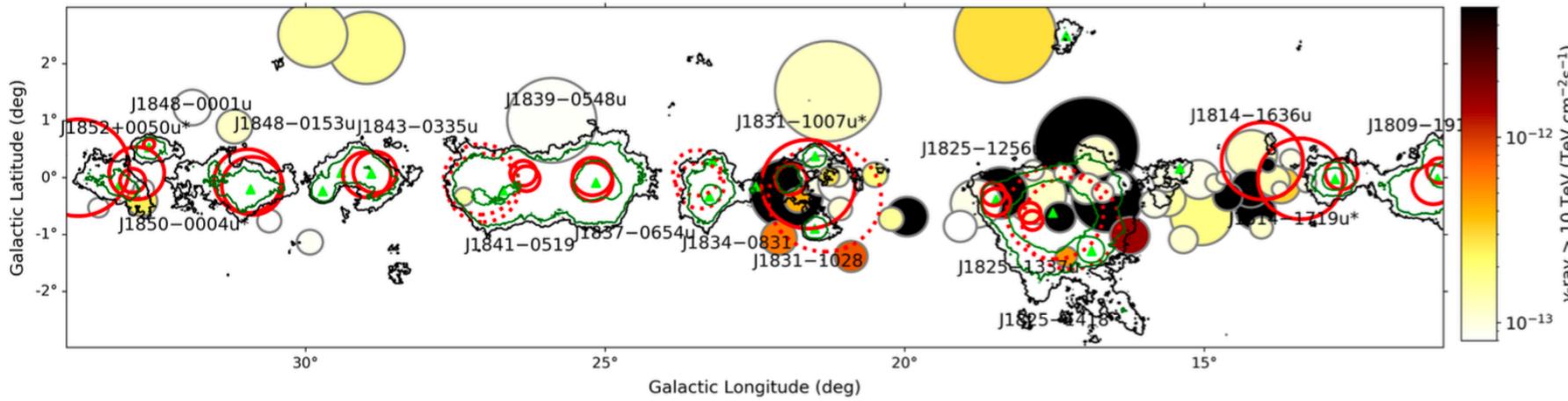
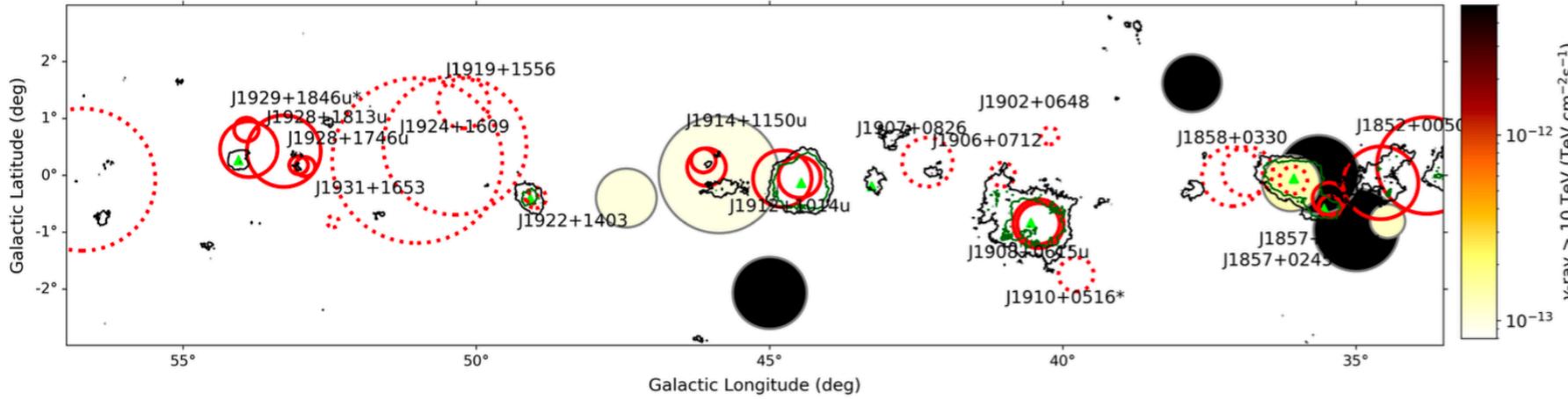
$$f(E, r, t) = \frac{f_0 E^{-\alpha}}{\pi^{3/2} R_d(E)^3} \exp \left[-\frac{r^2}{R_d^2(E)} \right]$$

- Acceleration slope **$\alpha=2$** ;
- Conversion efficiency **$\xi_{\text{CR}}=0.1$** ;
- Both **type IA** and **type II** SN modelling, with different t_{sed} ;
- Time-dependent escape with **$\delta=2.5$** and **$p_M=3 \text{ PeV}/c$** ;
- Transport in **Kolmogorov**-like diffusion coefficient, locally suppressed @ $D_0(1\text{GeV})=3 \times 10^{26} \text{ cm}^2/\text{s}$.

Hadronic (pp) collisions in clouds:

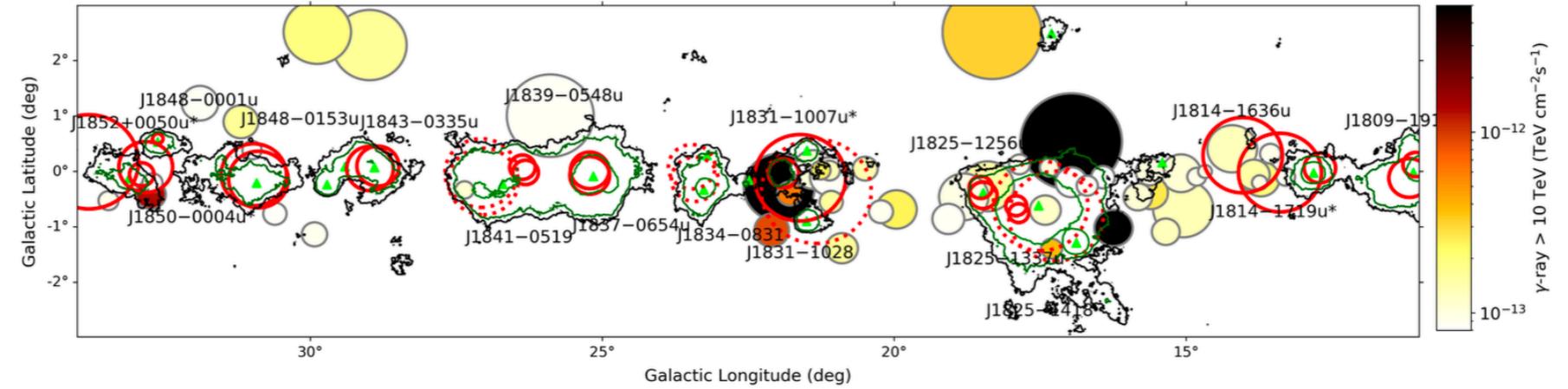
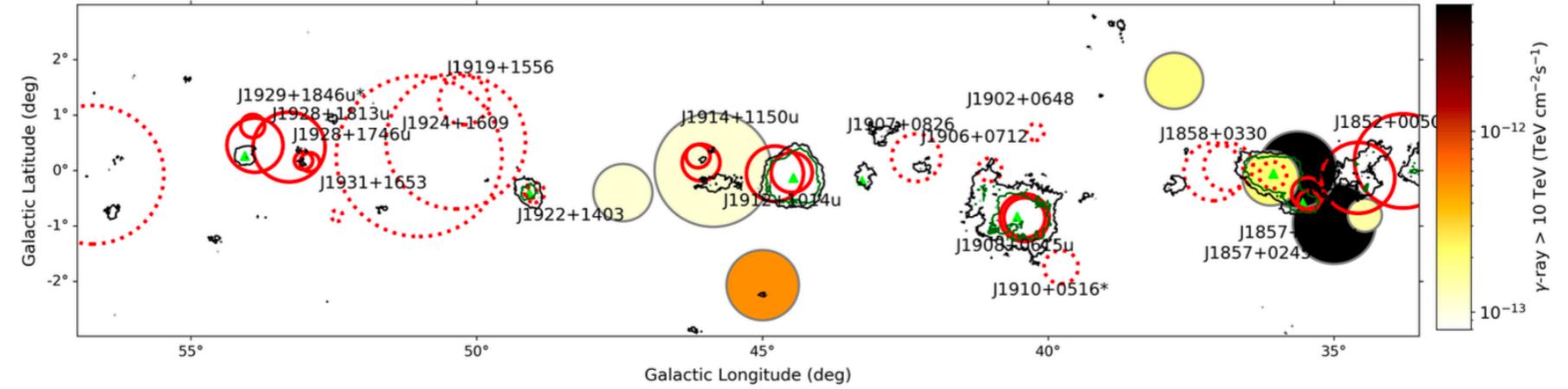
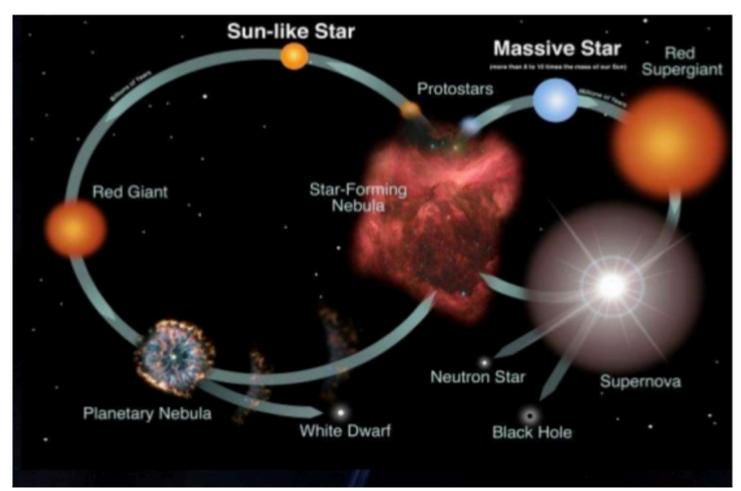
- Computation of emerging gamma rays and neutrinos;
- Additional contribution from CR sea;
- Spectral analysis of spatially coincident **LHAASO unidentified sources**.

Type Ia SN scenario



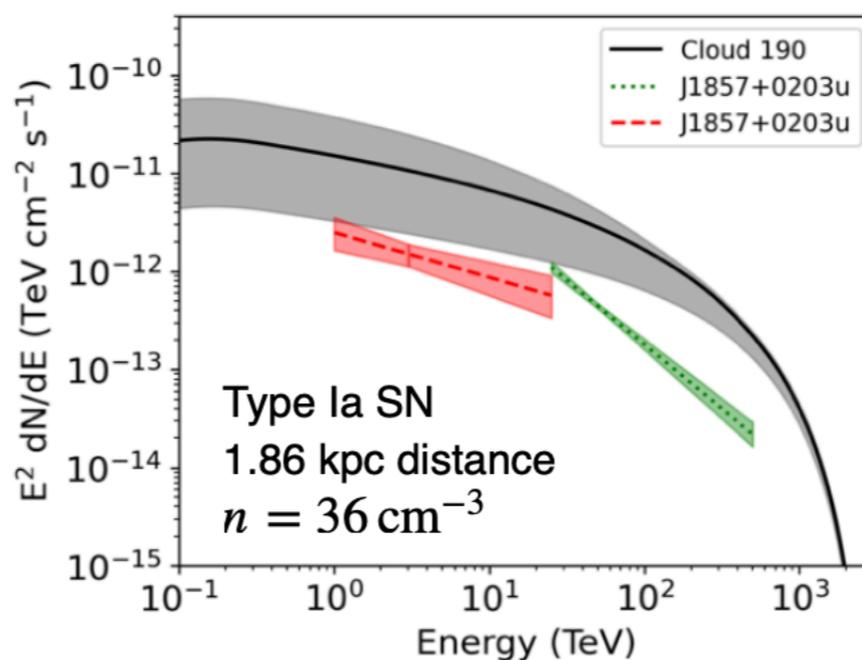
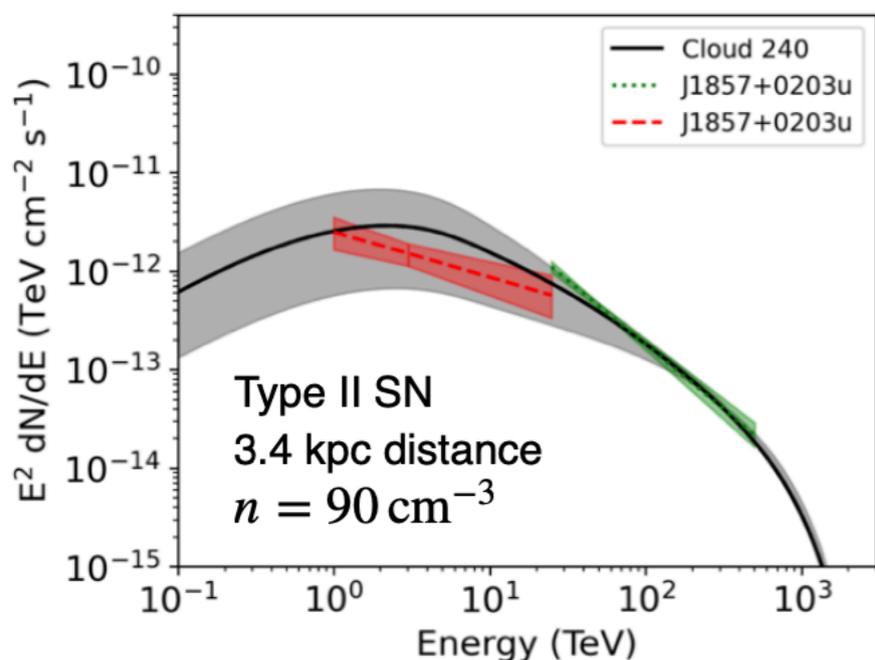
Mitchell & Celli, JHEA 44 (2024) 340

Type II SN scenario



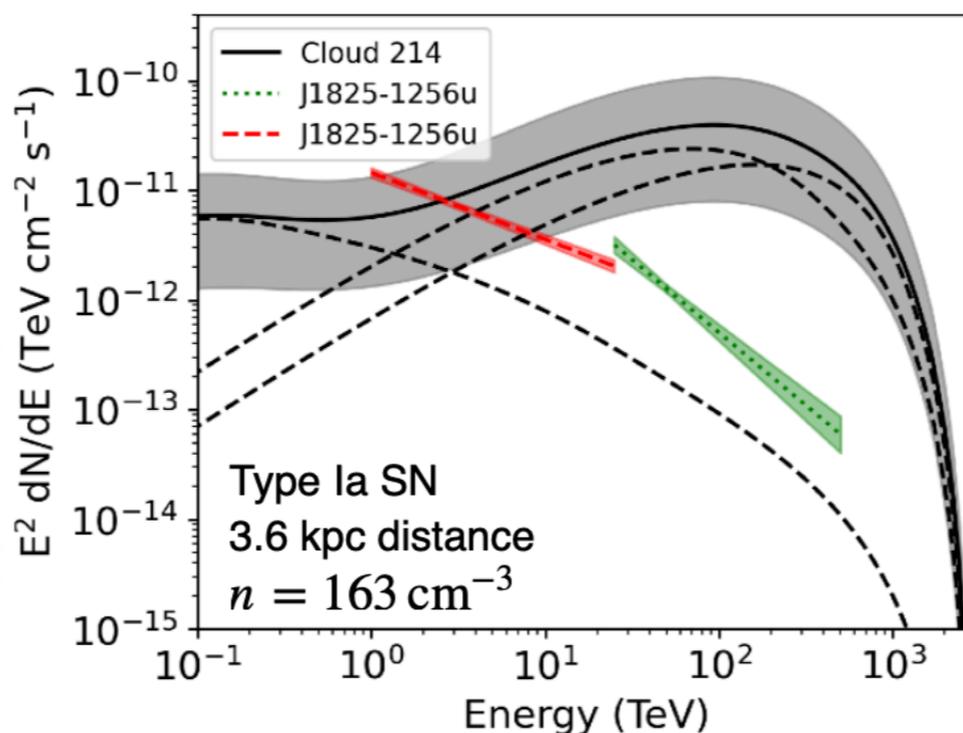
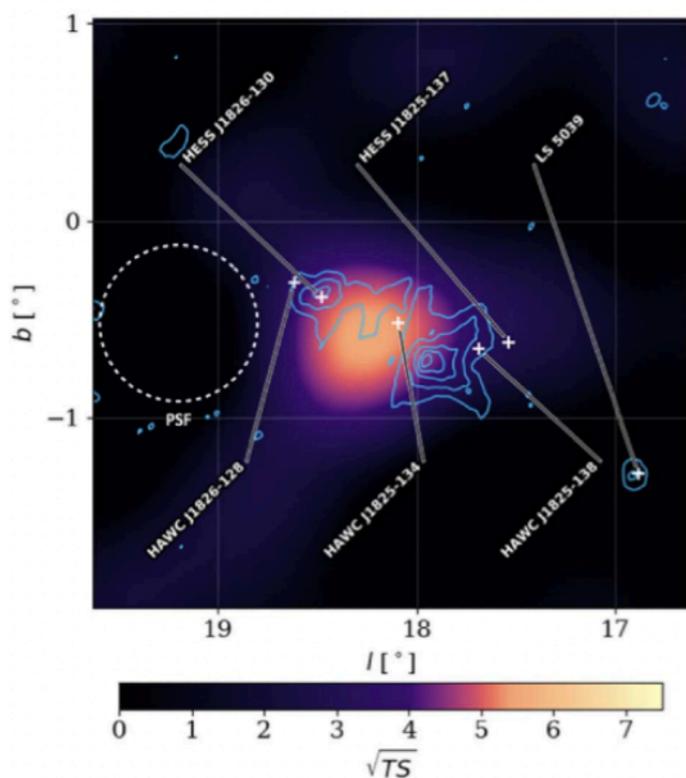
1LHAASO J1857+0203u

- Coincident with HESS UNID source J1858+020
- Spatially coincident with clouds 240 & 190, illuminated by SNR G036.6-0.7



- These are not fits, but model prediction with benchmark parameters
- 10% CR efficiency here assumed, a lower value would be more consistent with data!

1LHAASO J1825-1256u



- **A formally UNID source in a complex sky region**
- Here, **multiple SNRs** contribute to the total flux, namely G017.0-0.0, G017.4-0.1, **G019.1+0.2**
 - each contribution should rather be considered individually.

Conclusions

- The most energetic particles — approaching **~PeV energies** — are expected to **escape** their source **at early times**;
- The **maximum energy** of confined particles inside of middle-aged SNRs is responsible for the measured cut-off energy in these systems;
- Escaping particles could be traced via illuminated nearby molecular clouds:
 - The spectrum of particles penetrating the molecular cloud is different from that injected by the accelerator;
 - A **new population** of high energy sources may be emerging, coincident with **target** material rather than accelerators themselves;
- The scenario of molecular clouds illuminated by nearby SNRs appears viable to explain several **unidentified UHE sources**;
- Confirming this scenario would require **MWL as well as neutrino observations**.

Thanks for your kind attention!

**The Symposium of Ultra-High-Energy Gamma Rays from
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