

Supernova Remnants as Accelerators of Galactic Cosmic Rays

From Modelling to Observations



Ludovica Crosato Menegazzi

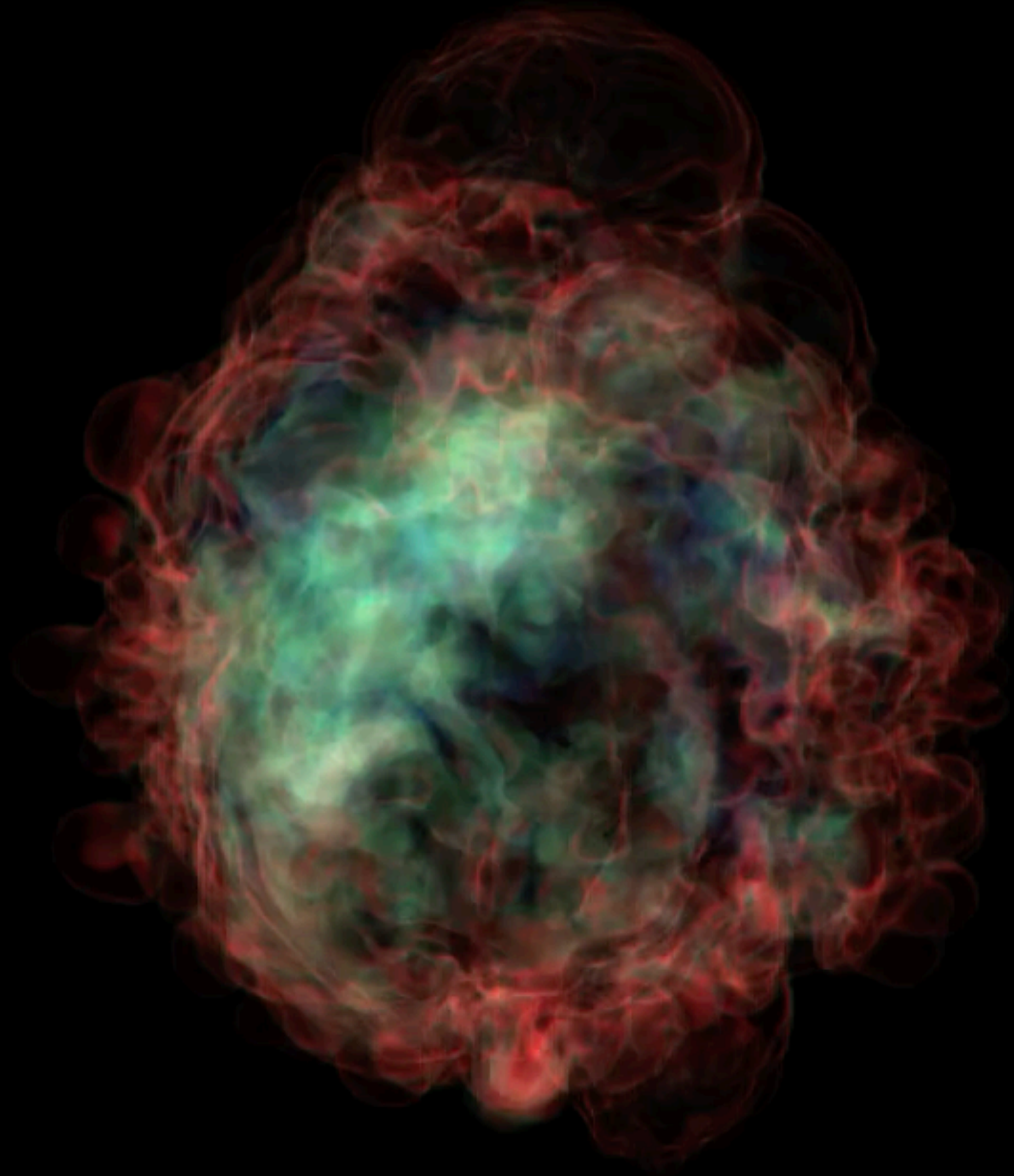
Collaborators: Robert Brose, Martin Pohl



GSI, Darmstadt 20.10.2026



Introduction



Galactic Cosmic-Rays

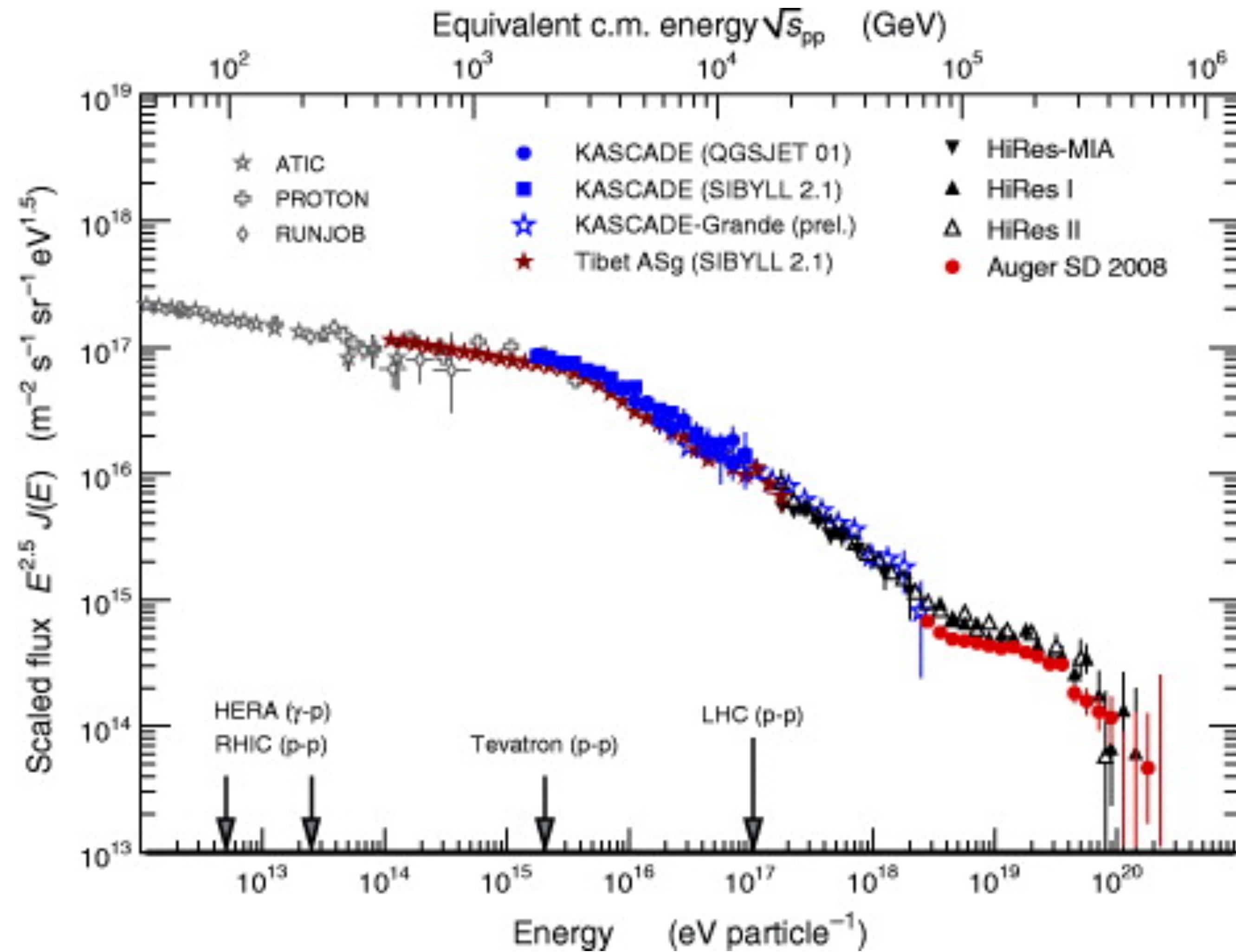


Figure: The cosmic ray spectrum (Blümer et al. 2019)

Galactic Cosmic-Rays

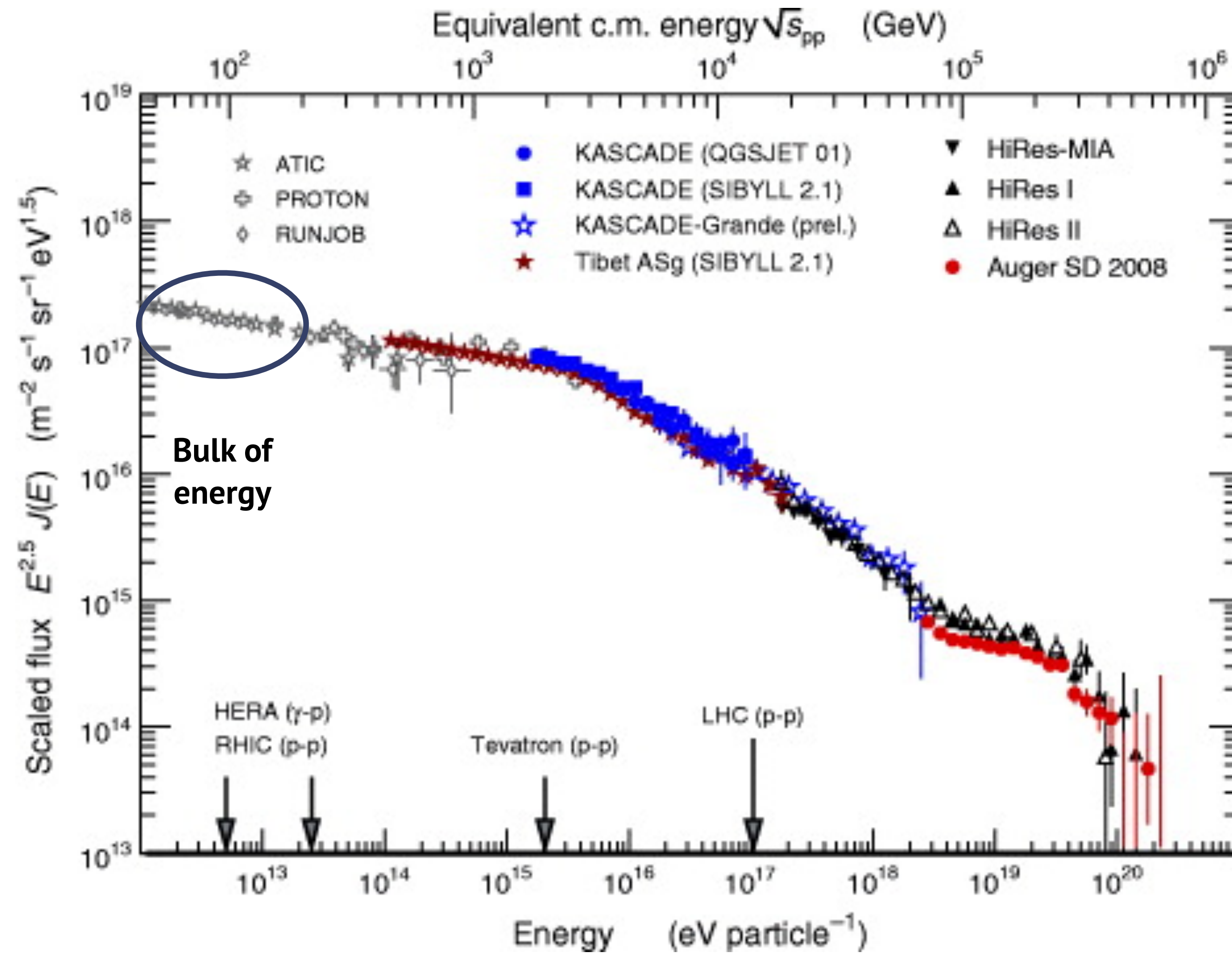


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Galactic Cosmic-Rays

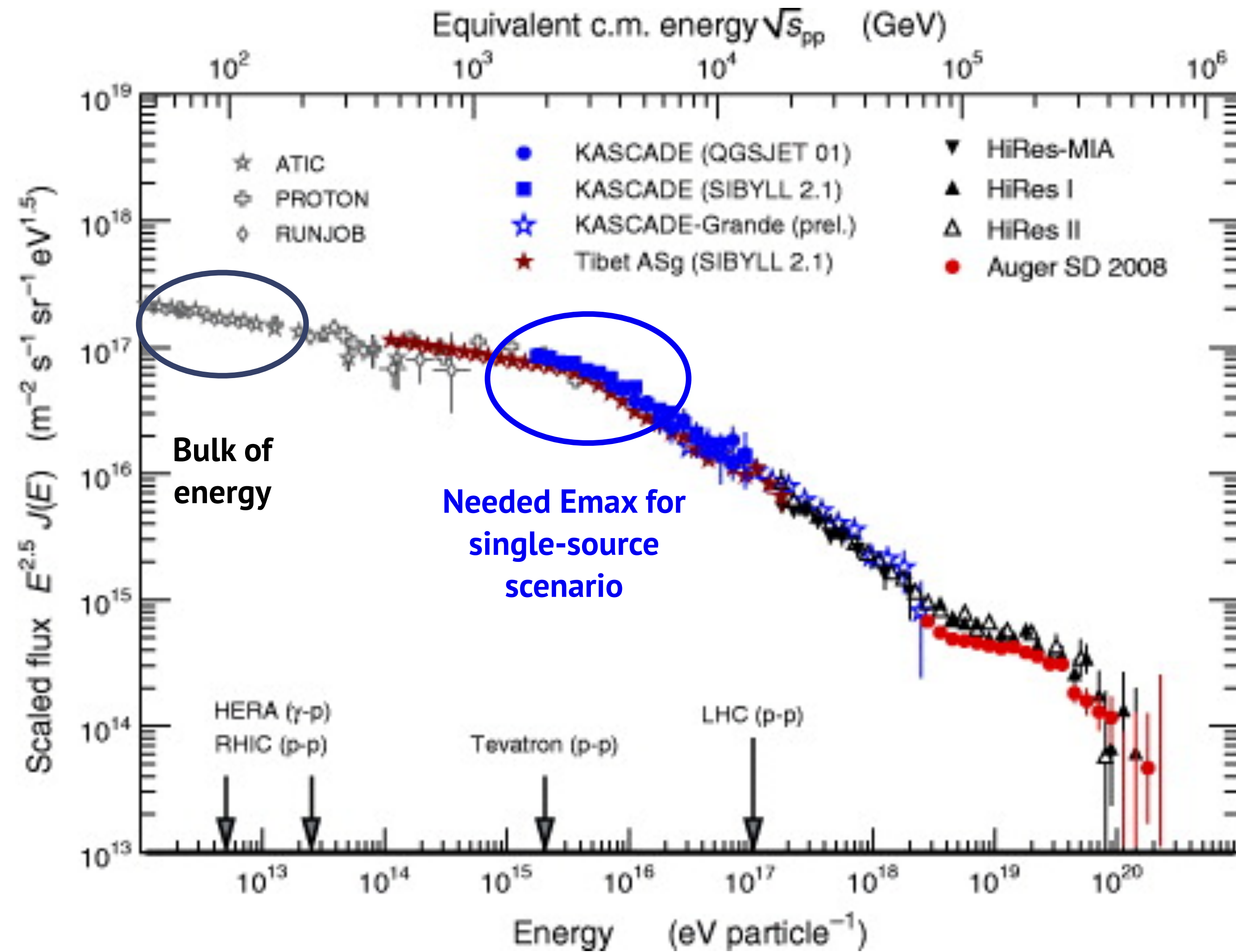


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Galactic Cosmic-Rays

Key questions:

- Can SNRs produce the right spectral shape? (And does it agree to observations?)

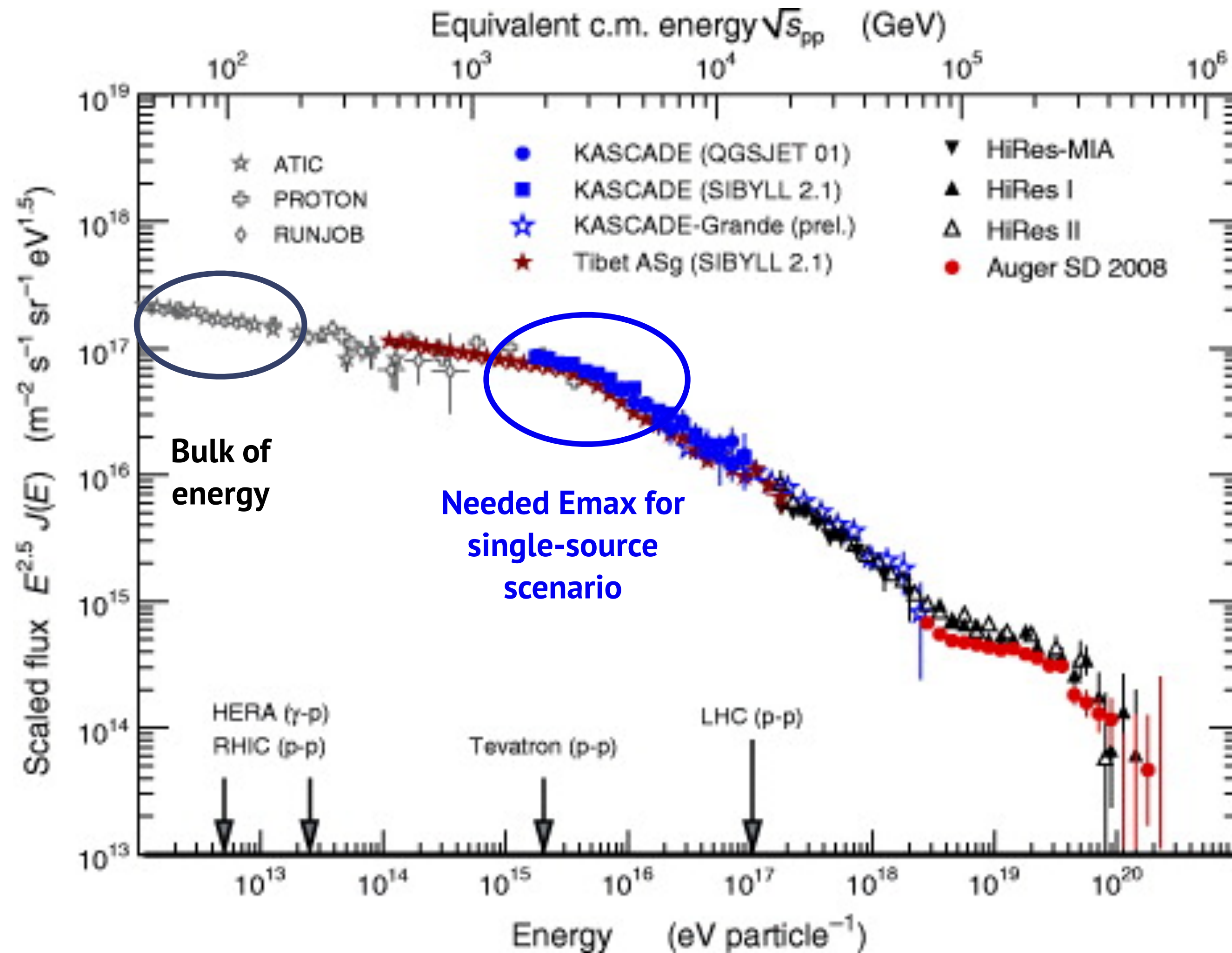


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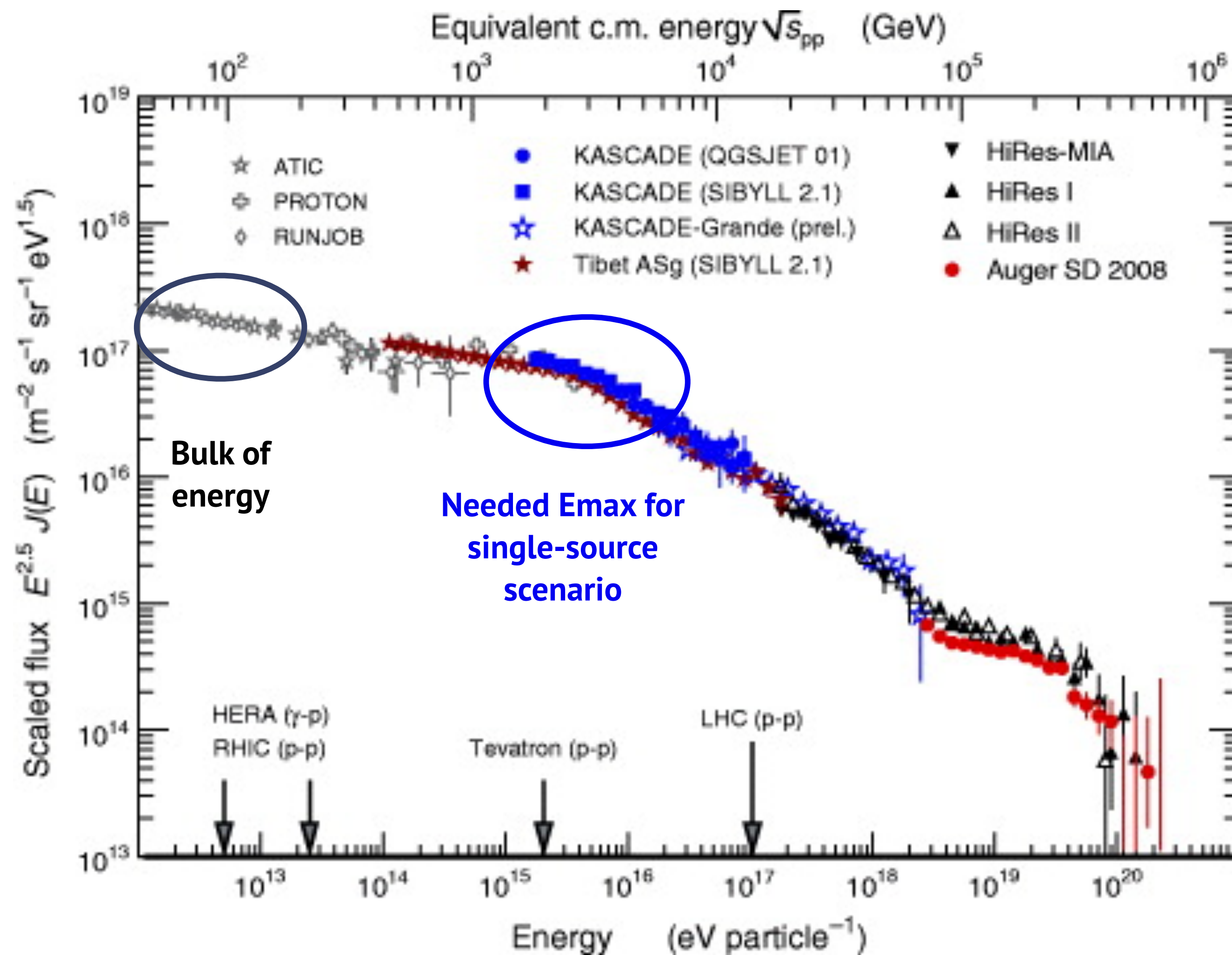


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Galactic Cosmic-Rays

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- Can SNRs produce the right spectral shape? (And does it agree to observations?)
- Can SNRs accelerate CRs to high-enough energies?
- What are signatures of the acceleration process?

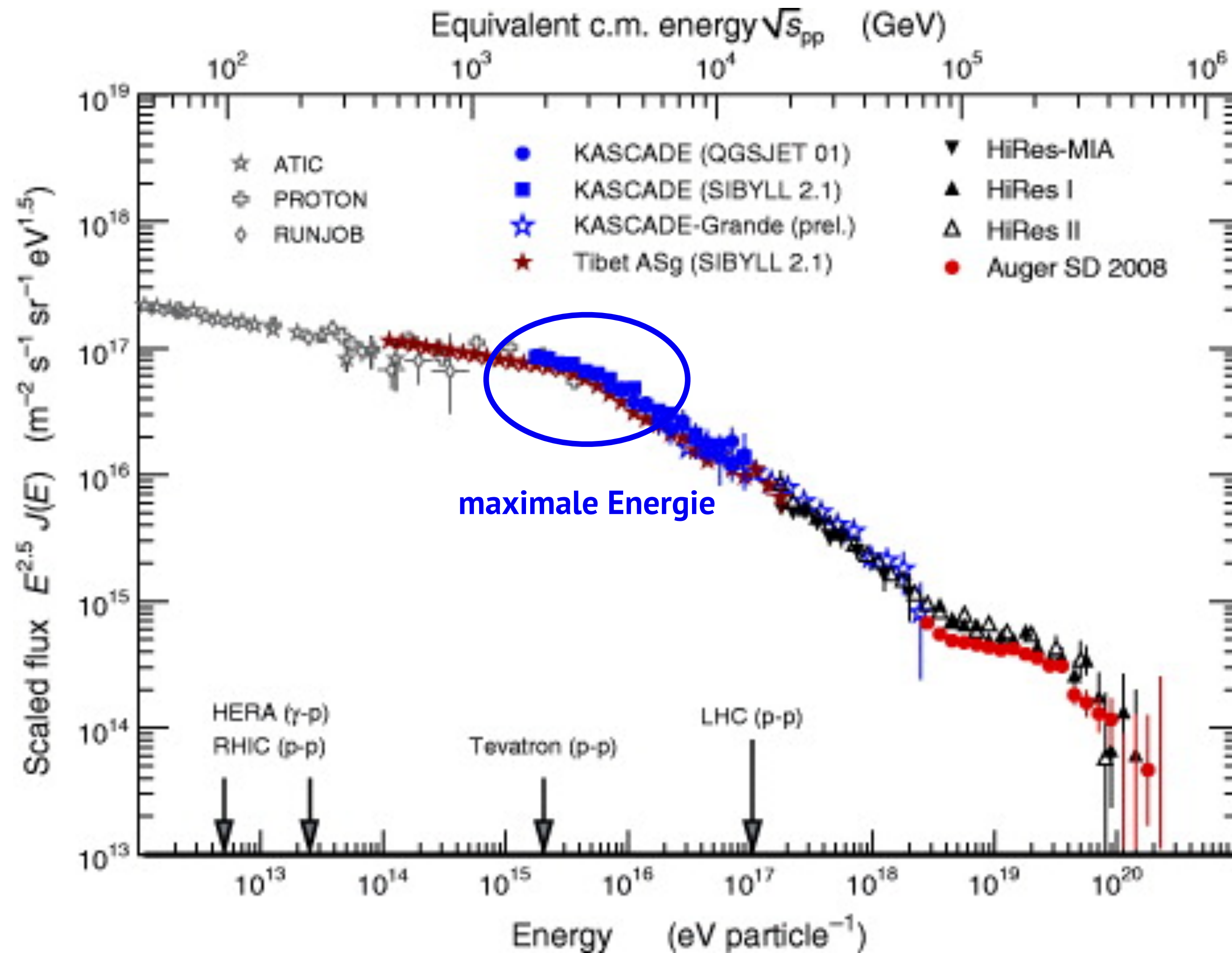
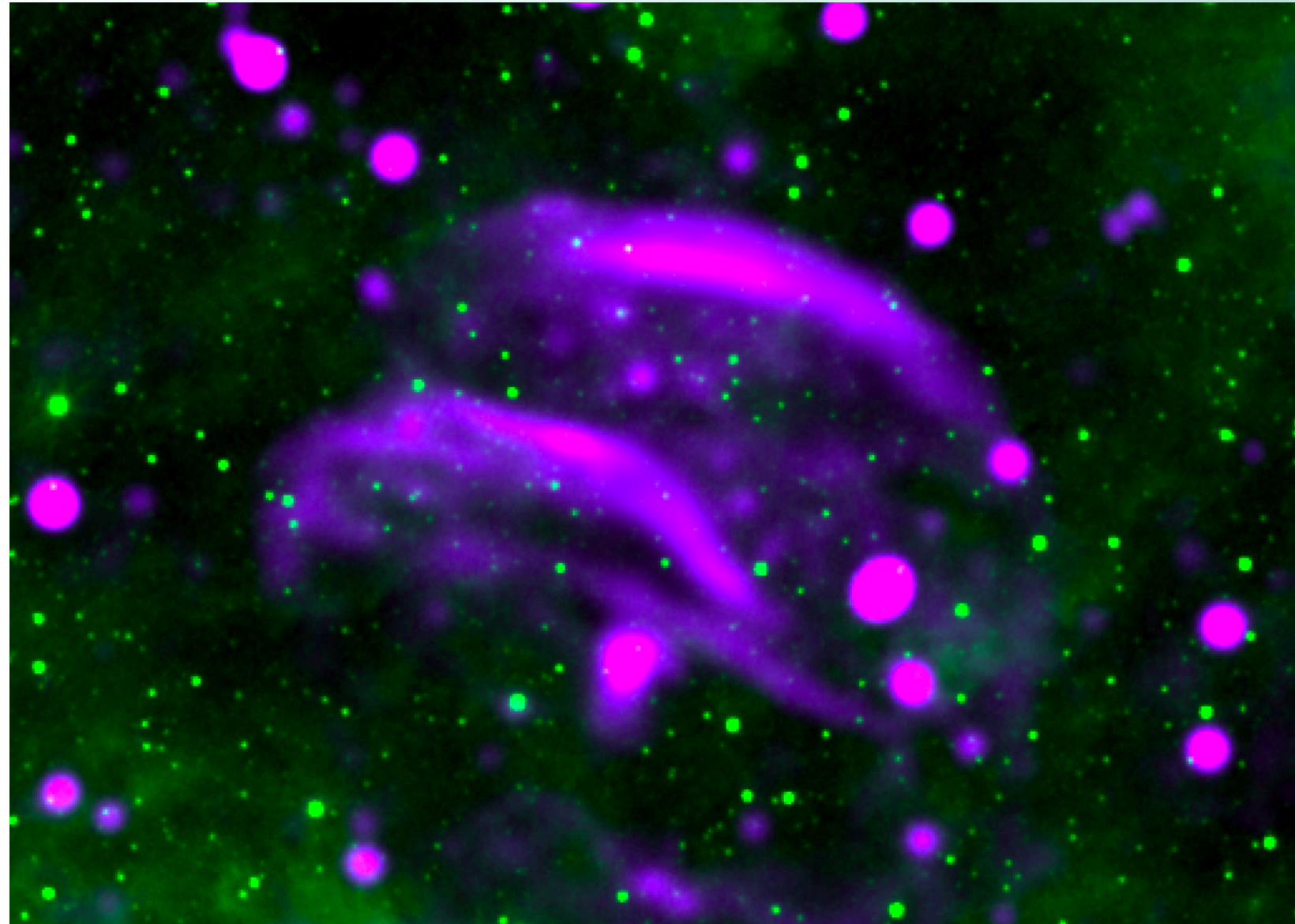
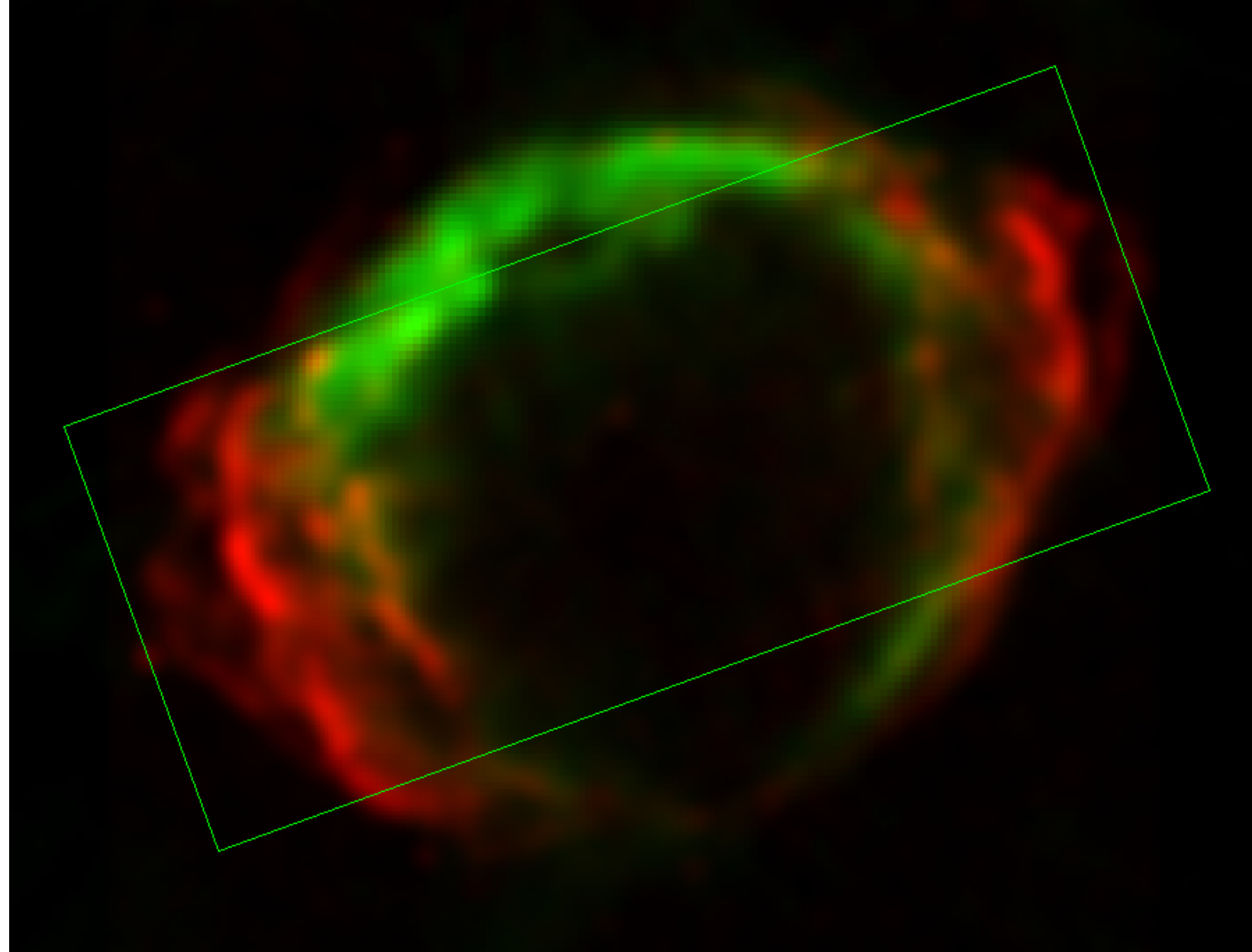


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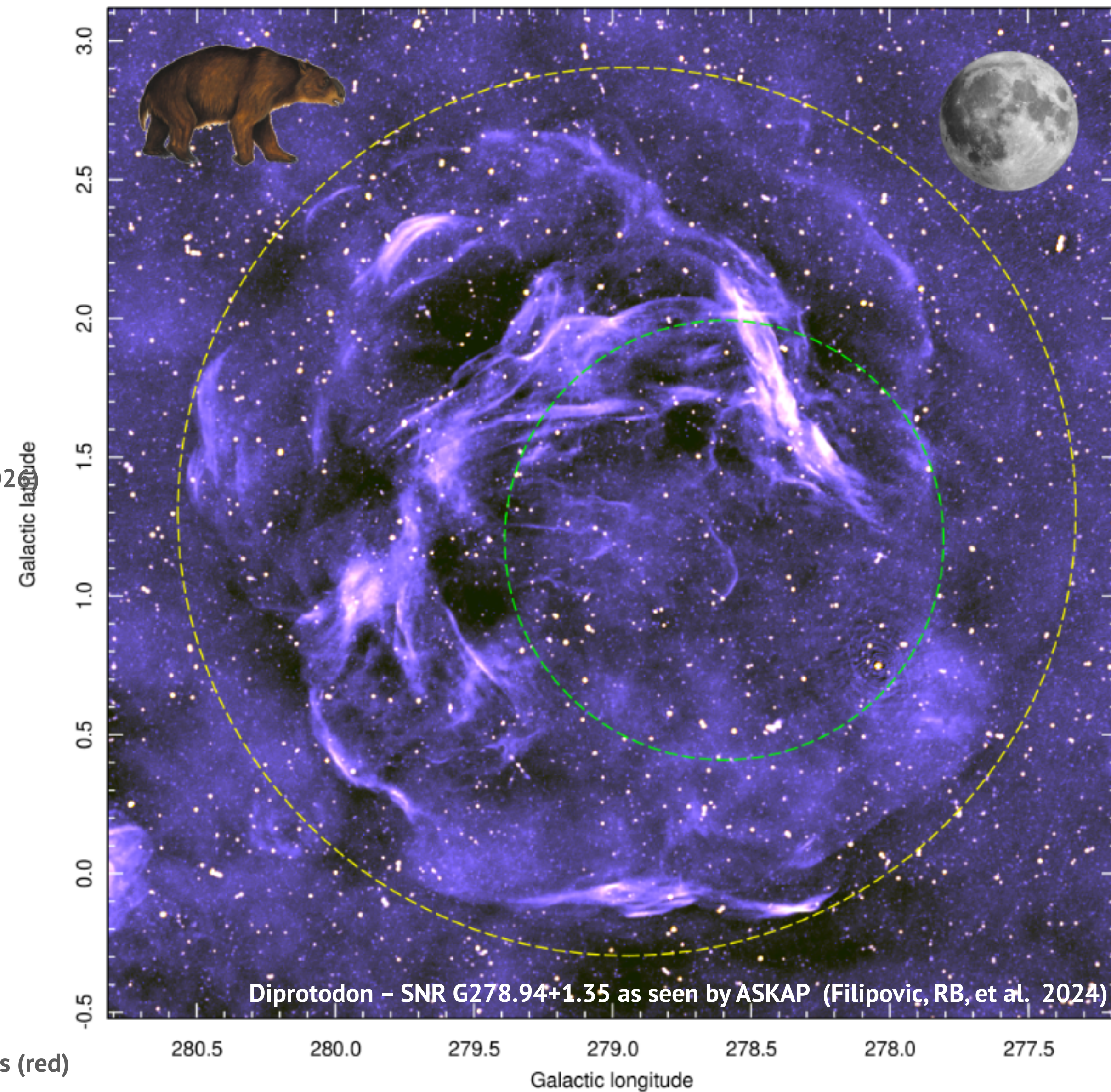
Why SNRs?



G289.6+5.8 (Lazarevic, RB, et al. 2020)



G1.9+0.3 in radio (green) and x-rays (red)
(Luken, RB, et al. 2019)



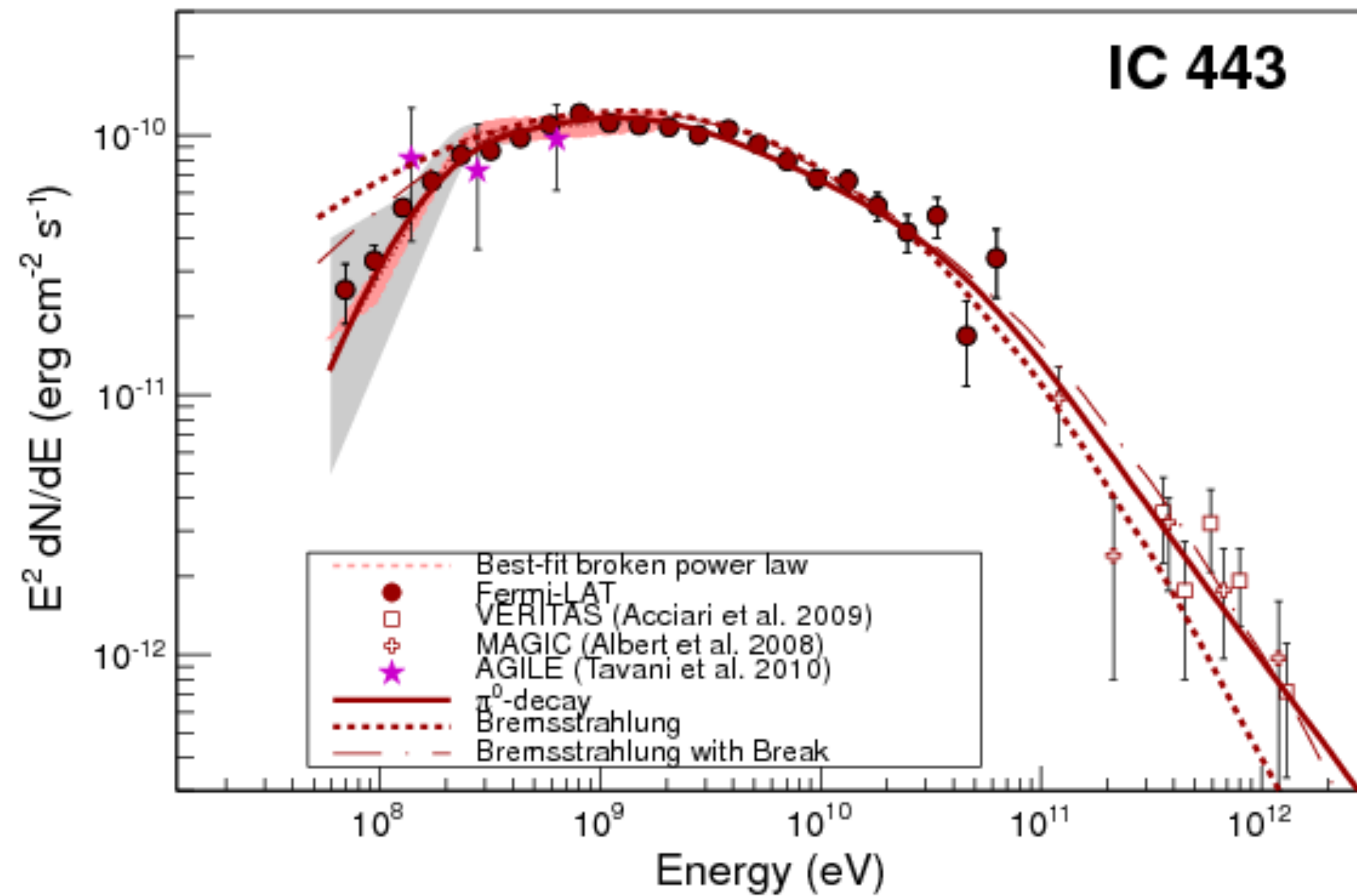
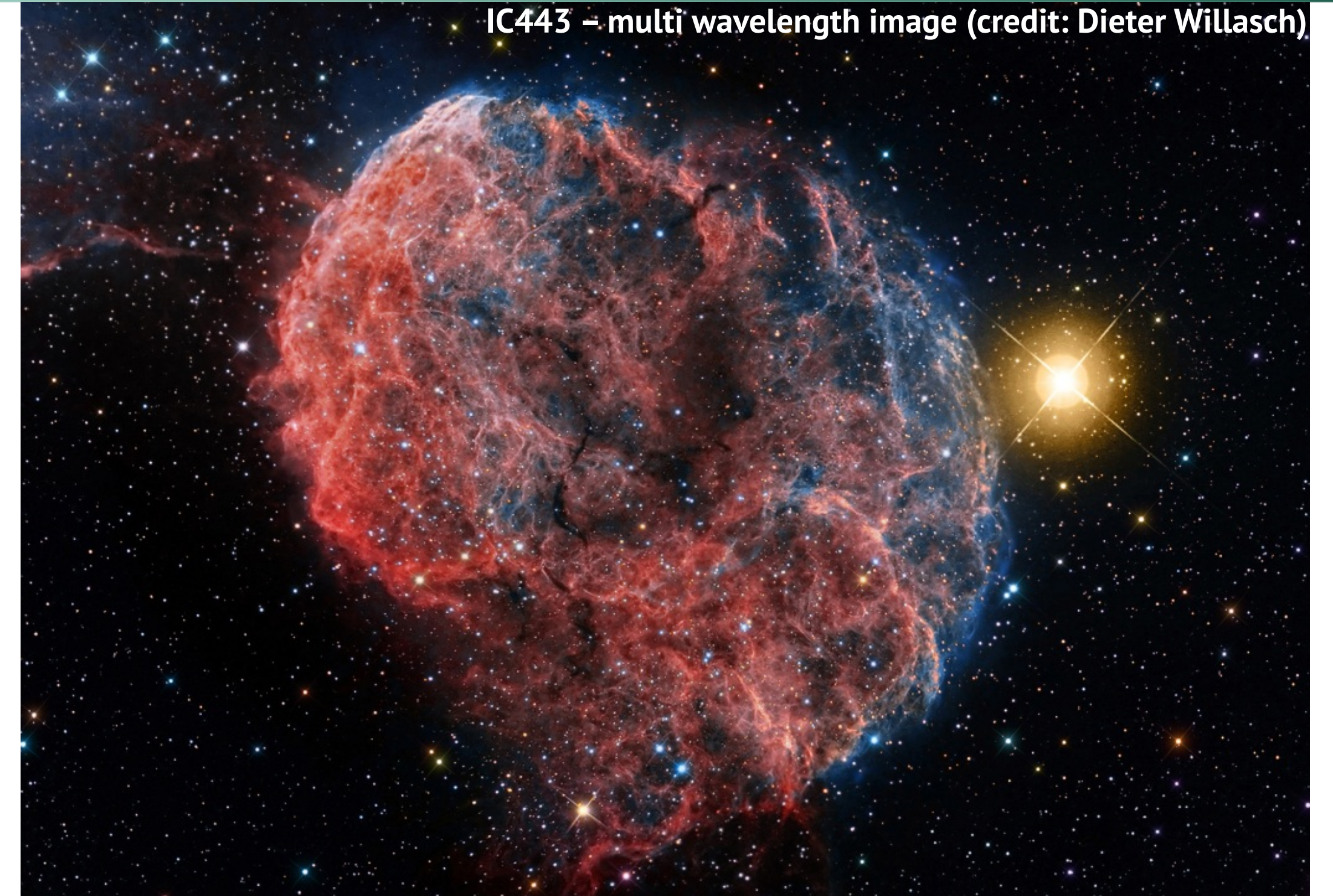
Diprotodon – SNR G278.94+1.35 as seen by ASKAP (Filipovic, RB, et al. 2024)

Why SNRs?

- Known to inject enough energy in the Galaxy

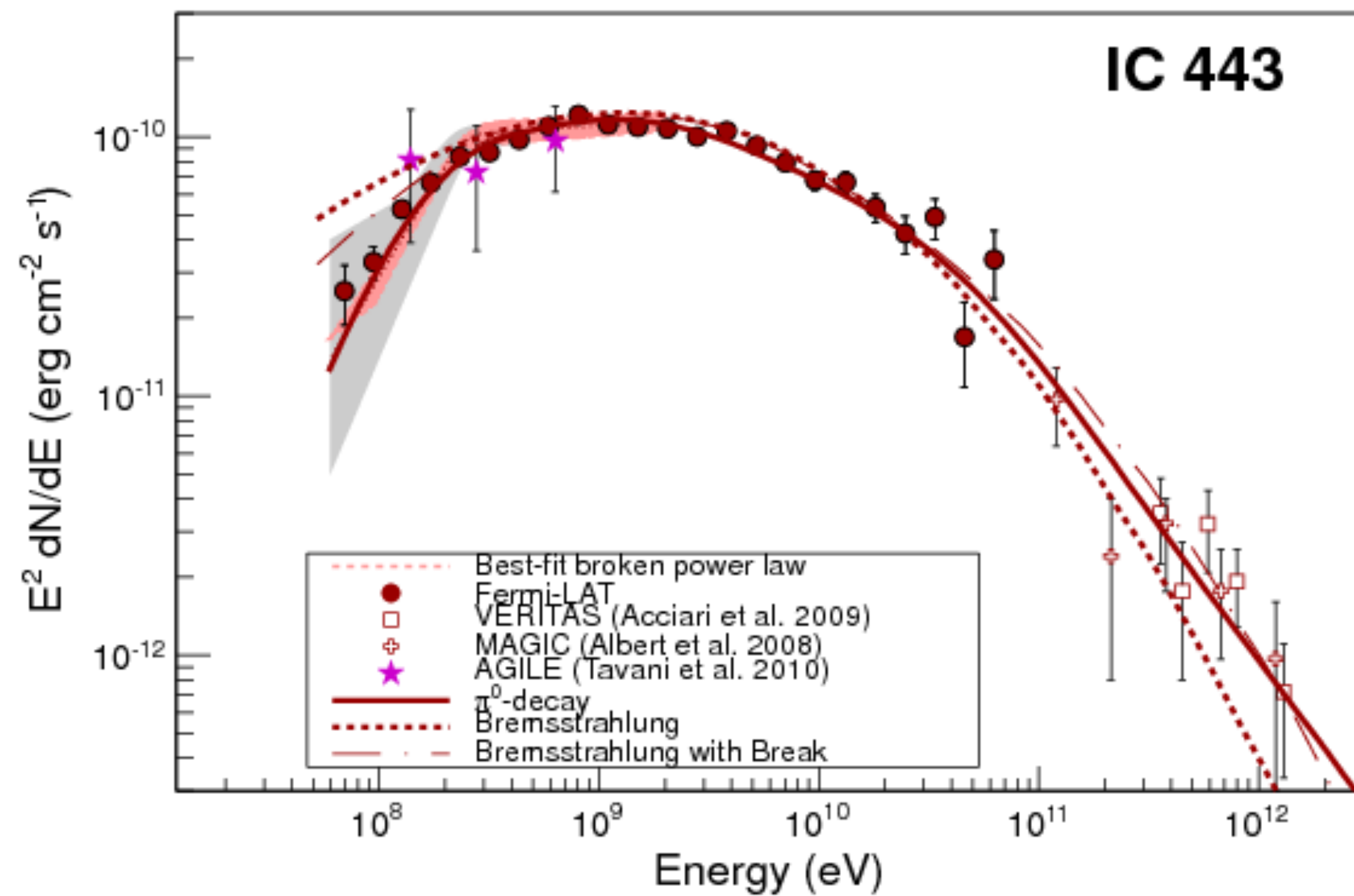
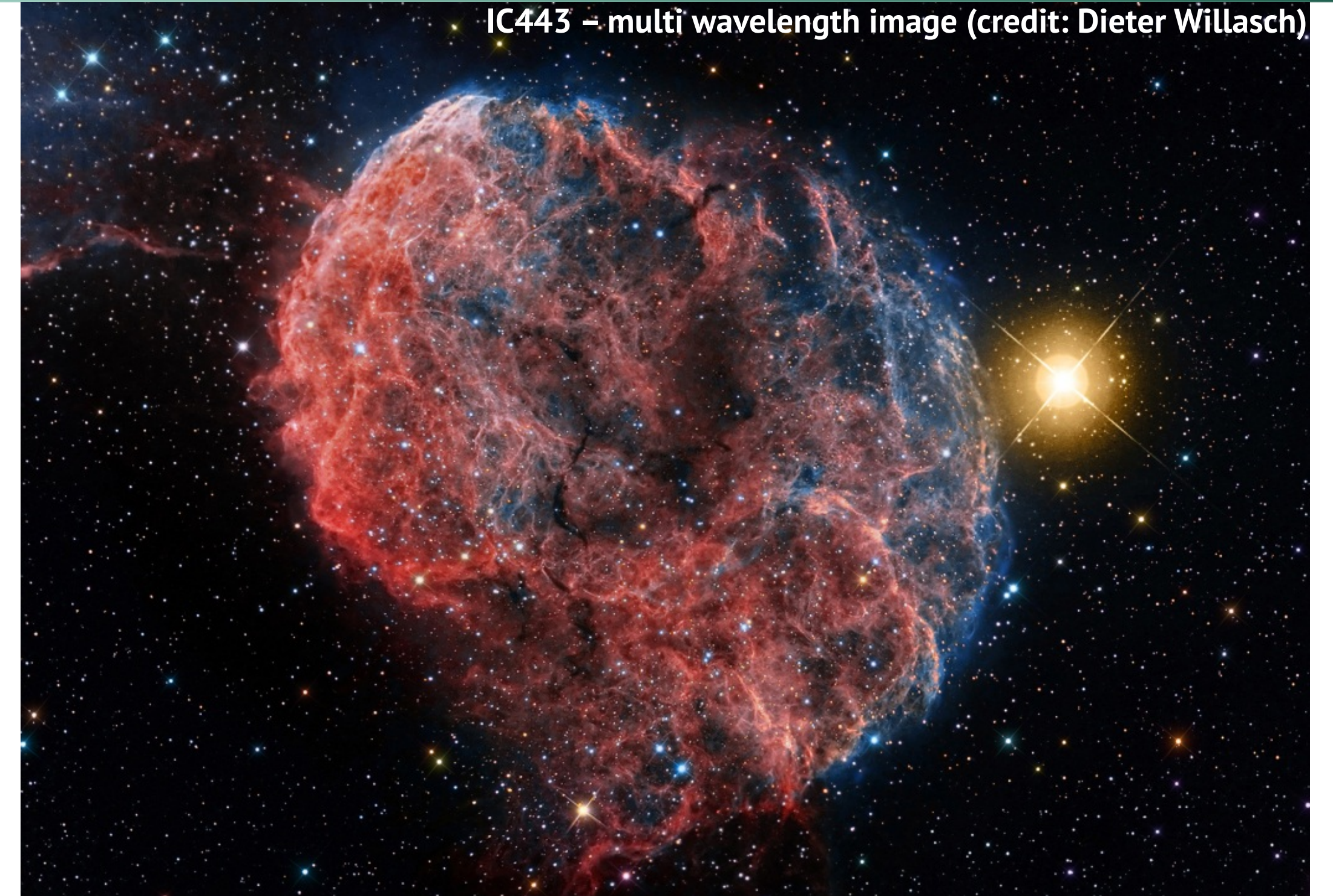
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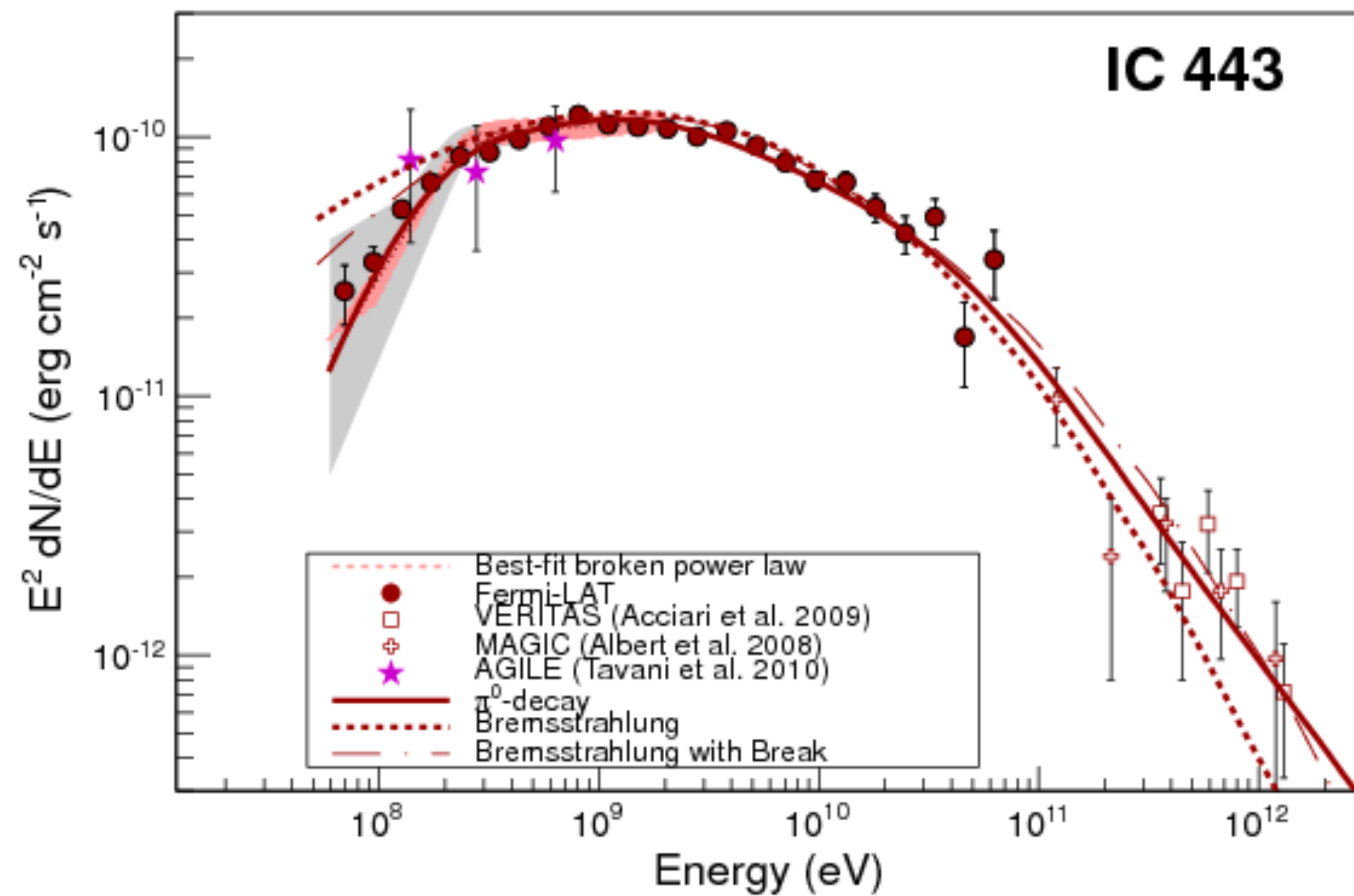
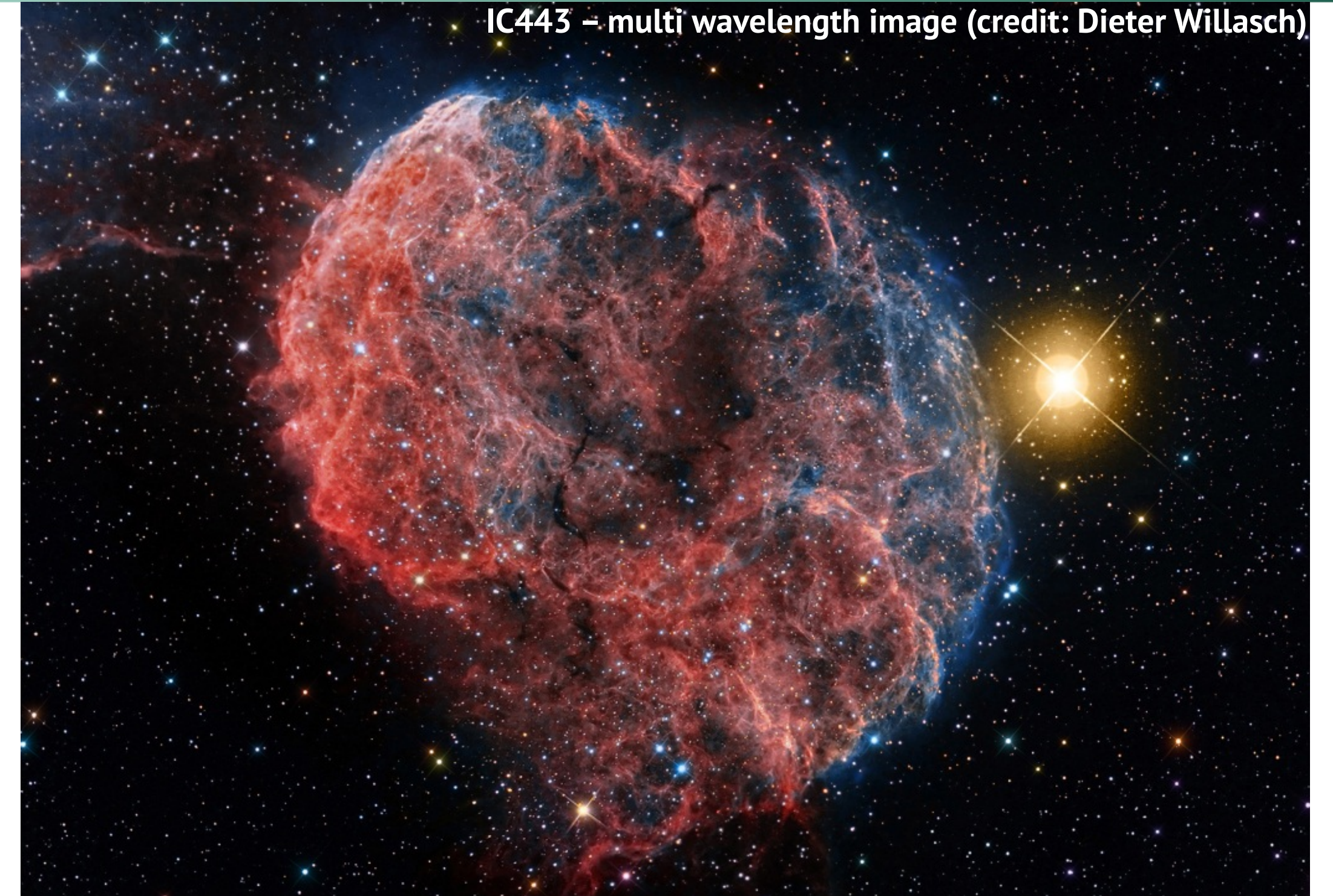
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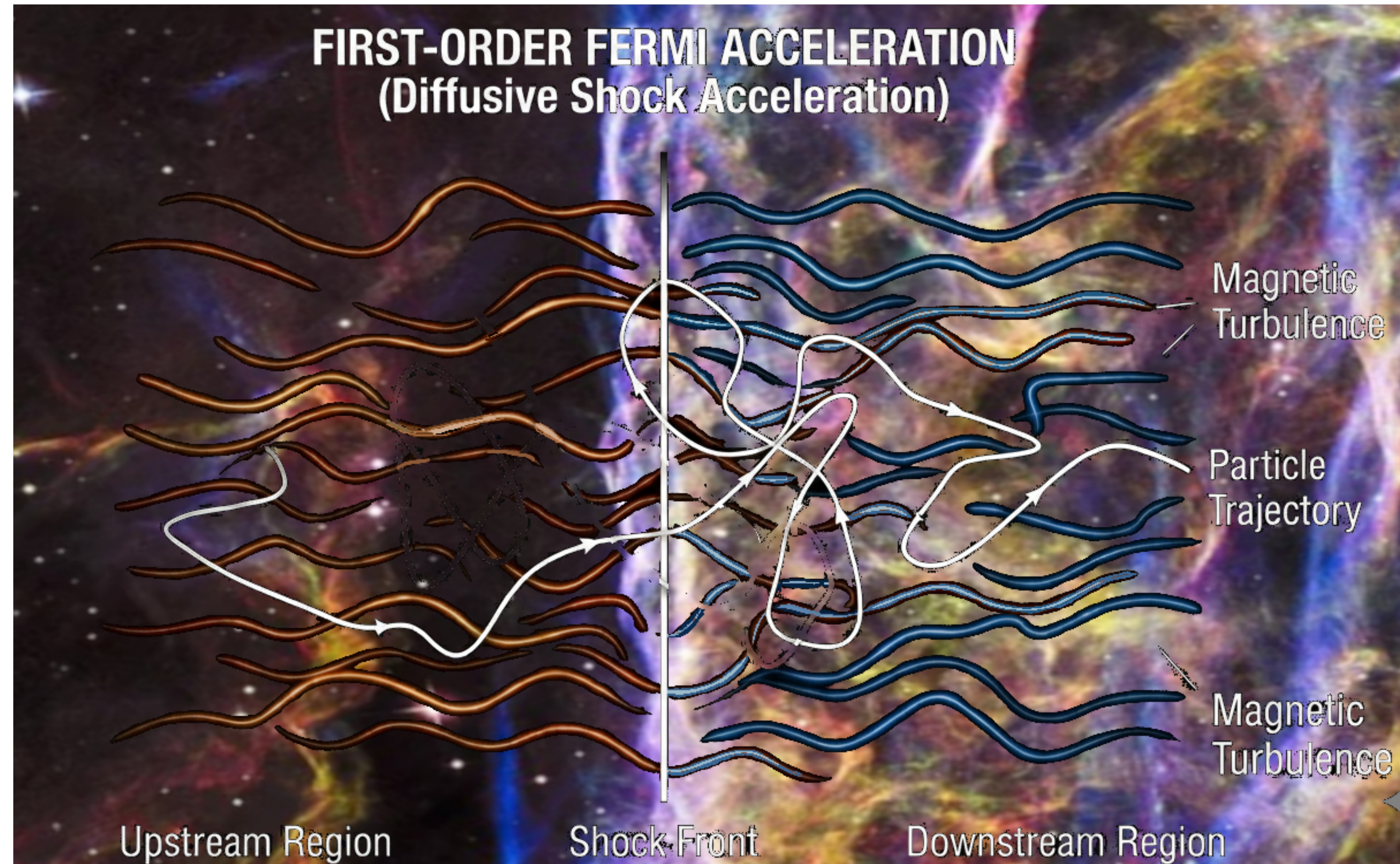


- Known accelerators of non-thermal electrons
- Viabale acceleration mechanism known

Diffusive shock acceleration

Ingredients:

- The Hydro evolution of the specific SNR
- The distribution of CRs
- The distribution of magnetic disturbances that scatter the CRs



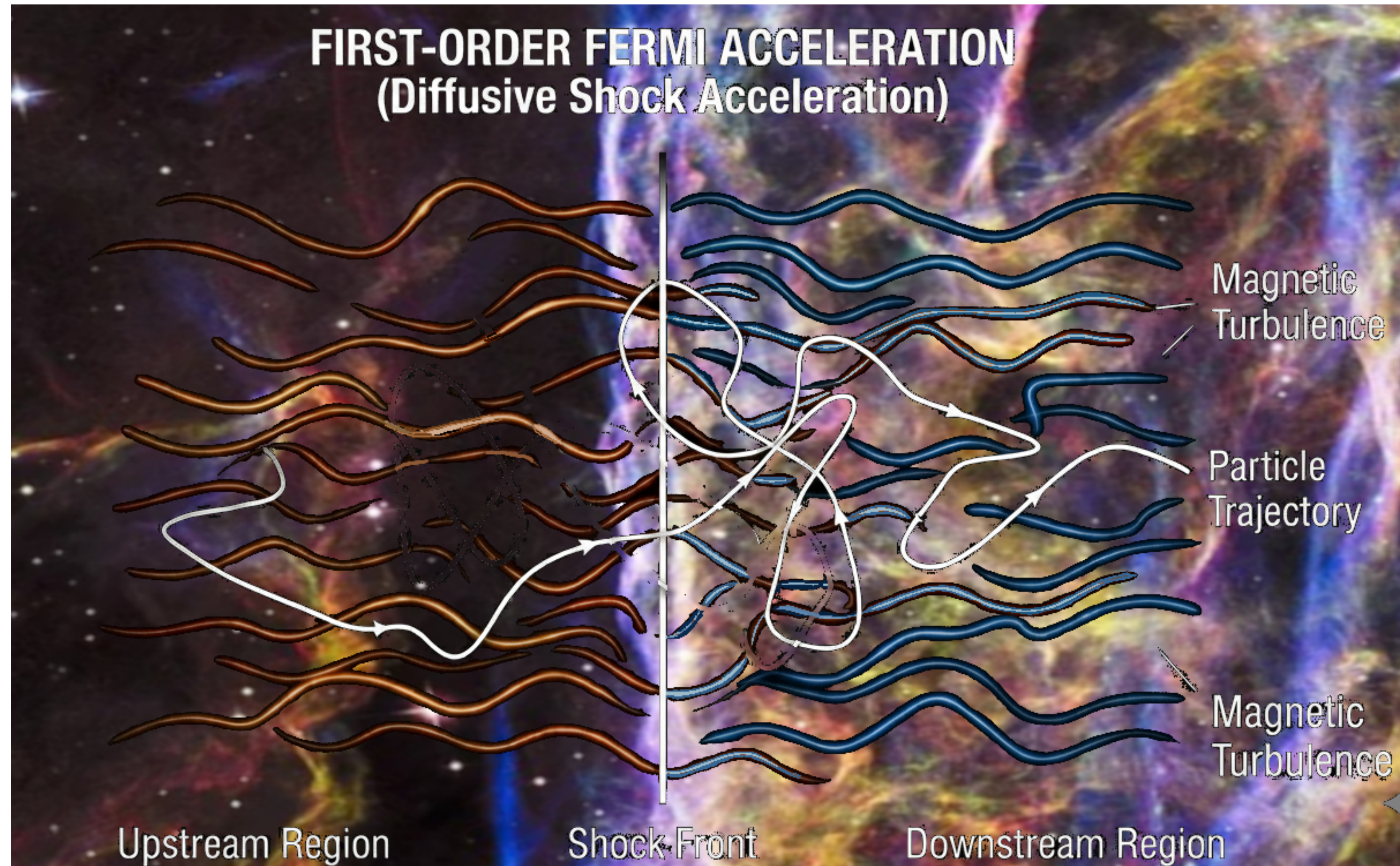
Diffusive shock acceleration

Ingredients:

- The Hydro evolution of the specific SNR
- The distribution of CRs
- The distribution of magnetic disturbances that scatter the CRs

→ non-thermal, power-law spectra

$$N(p) \propto p^{-\frac{r+2}{r-1}} N(p) \approx p^{-2}$$



1 PHYSICS

1.1 History

Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now, we've basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.

1 PHYSICS

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We have it all figured out but

- Magnetic turbulence
- Particle energization
- (Hydrodynamics)

Simplified CR Scattering

Wave-modes scattering CRs not fully clear.

A necessary assumptions in all models:

- Alfven waves (e.g. Skilling 1975)
- Bell's mode waves (Lucek & Bell 2000)
- Fast-mode waves (Yan & Lazarian 2004)
- Mirror-scattering (Bell 2025)
- Resonant curvature scattering (Kempski 2025)

Simplified CR Scattering

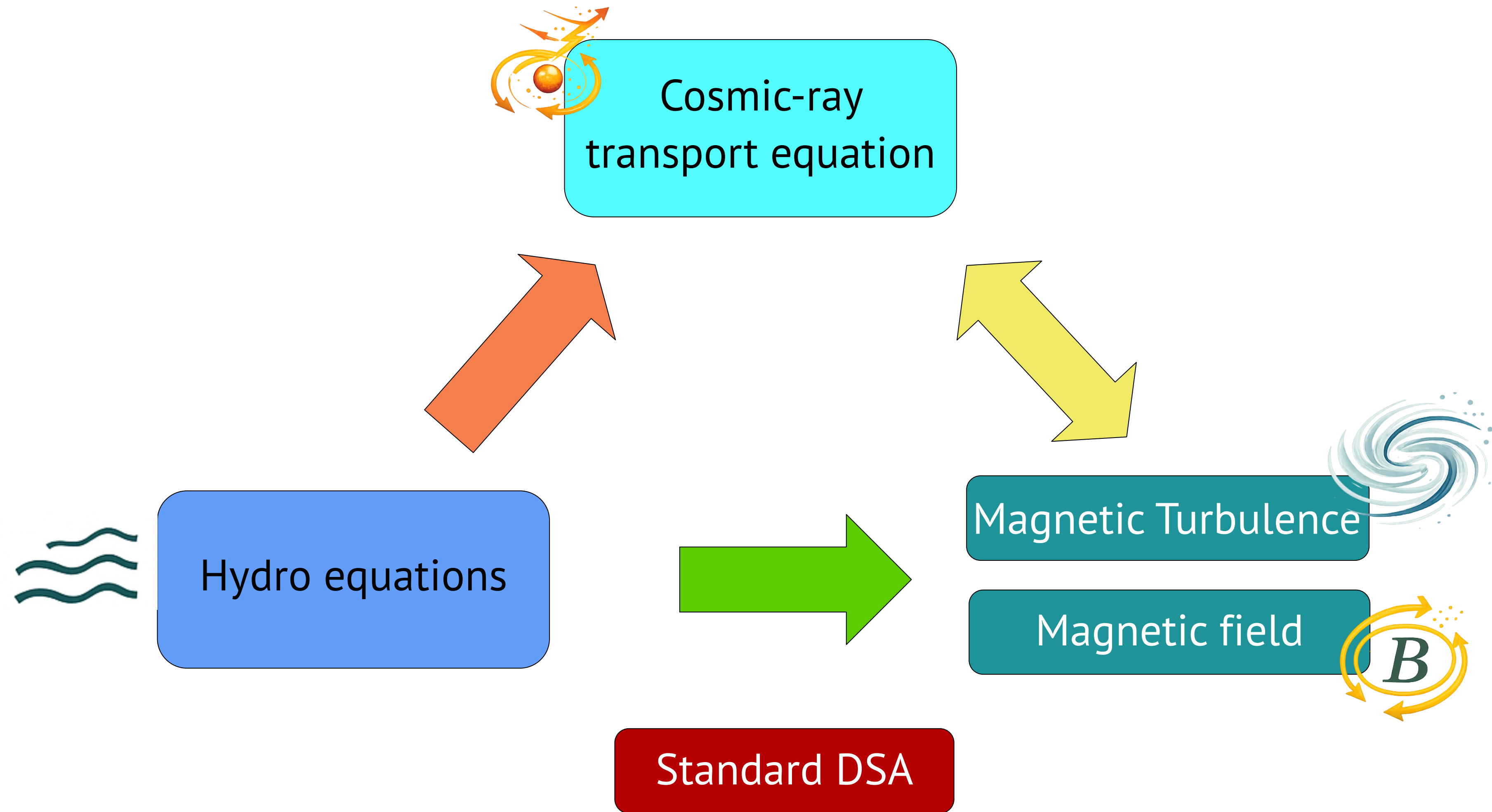
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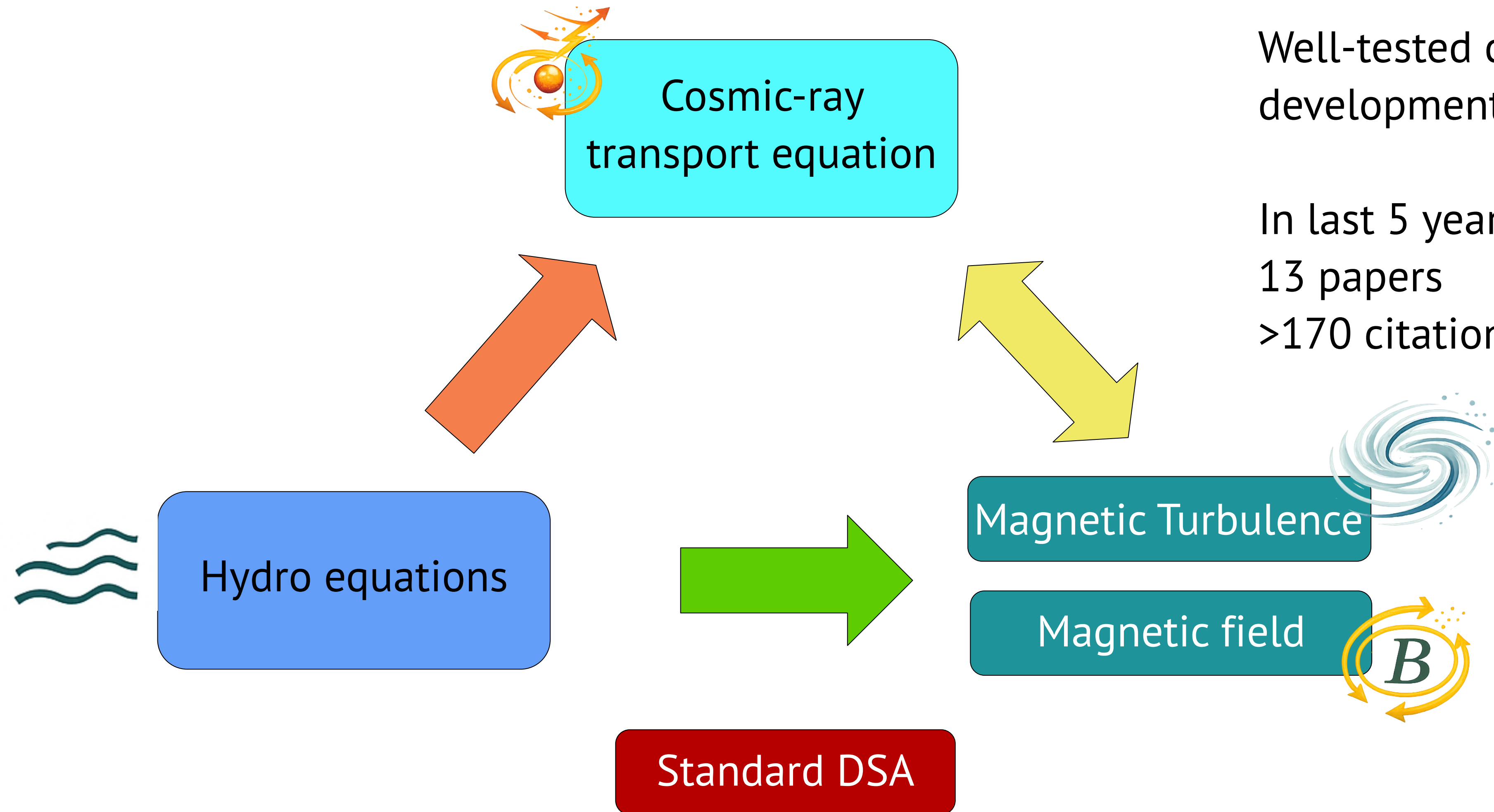
Type of turbulence/instability will ultimately affect the time-evolution of CR-acceleration

Radiation Acceleration Transport Parallel Code





Radiation Acceleration Transport Parallel Code



Well-tested code in development since 2012

In last 5 years:
13 papers
>170 citations

Galactic Cosmic-Rays

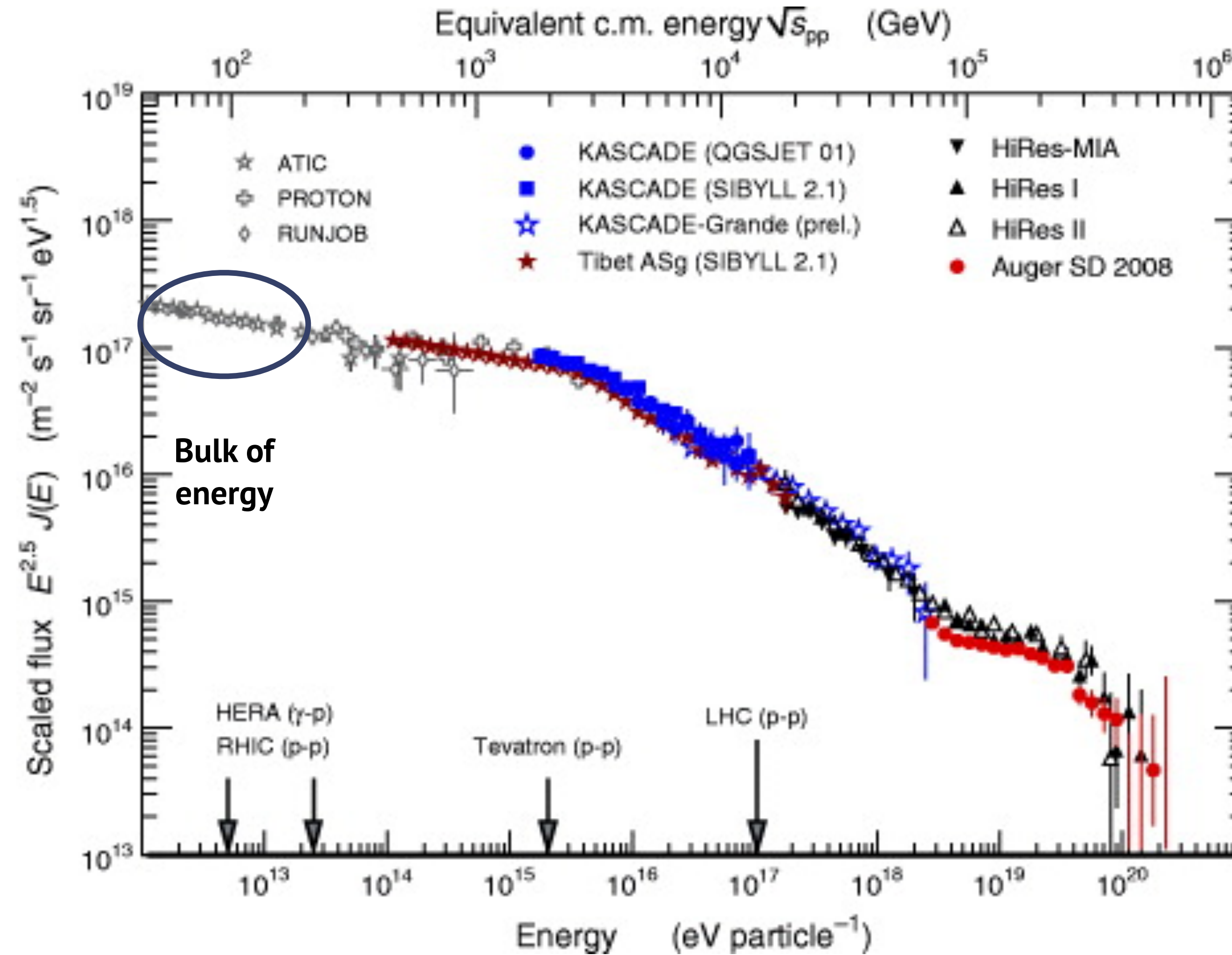


Figure: The cosmic ray spectrum (Blümer et al. 2019)

$$\frac{\partial N}{\partial t} = \underbrace{\nabla D_r \nabla N}_{\text{Diffusion}} - \underbrace{\nabla v N}_{\text{Advection}} - \underbrace{\frac{\partial}{\partial p} \left(N \dot{p} - \frac{v}{3} N p \right)}_{\text{Cooling Acceleration.}} + \underbrace{Q}_{\text{Injection}}$$

$$\frac{\partial E_W}{\partial t} = - \underbrace{(v \nabla_r E_W + c \nabla_r v E_W)}_{\text{Advection + Compression}} + \underbrace{k^3 \nabla_k D_k \nabla_k \frac{E_W}{k^3}}_{\text{Cascading}} + \underbrace{2(\Gamma_g - \Gamma_d) E_W}_{\text{Growth + Damping}}$$

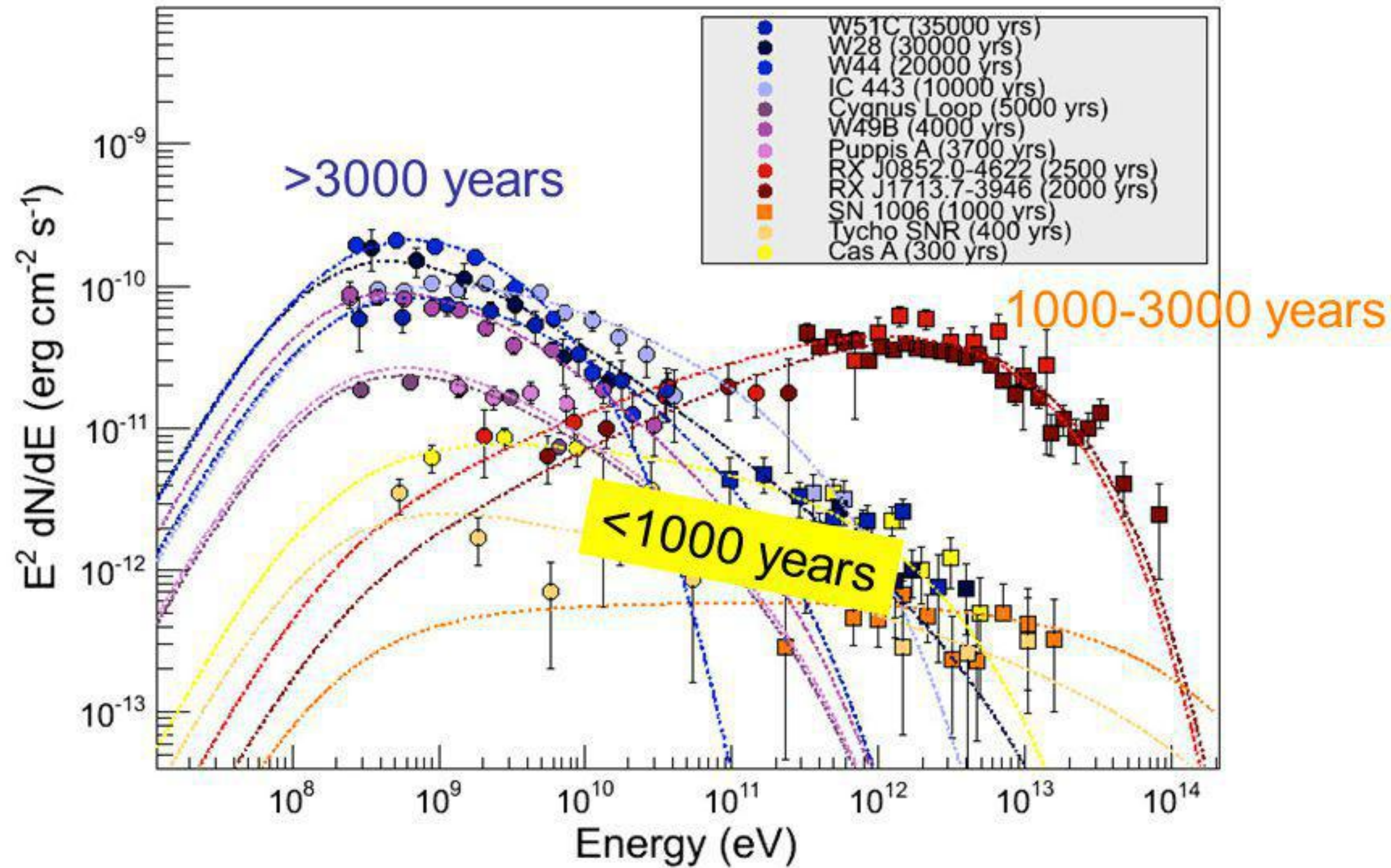
$$\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \mathbf{m} \\ E \end{pmatrix} + \nabla \begin{pmatrix} \rho \mathbf{v} \\ \mathbf{m} \mathbf{v} + (P) \mathbf{I} \\ (E + P) \mathbf{v} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ L \end{pmatrix} \quad \frac{\rho \mathbf{v}^2}{2} + \frac{P}{\gamma - 1} = E$$

The equations are solved:

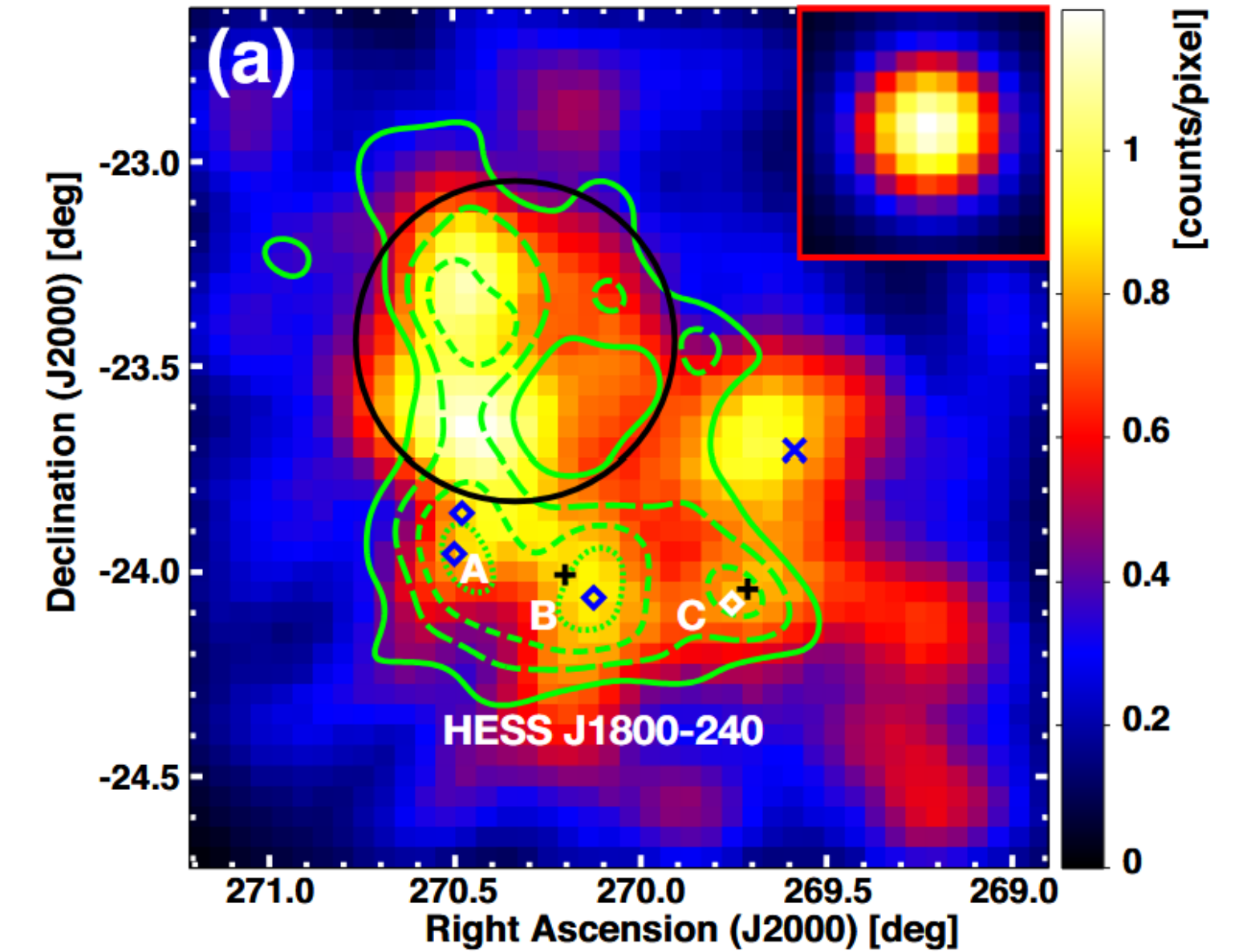
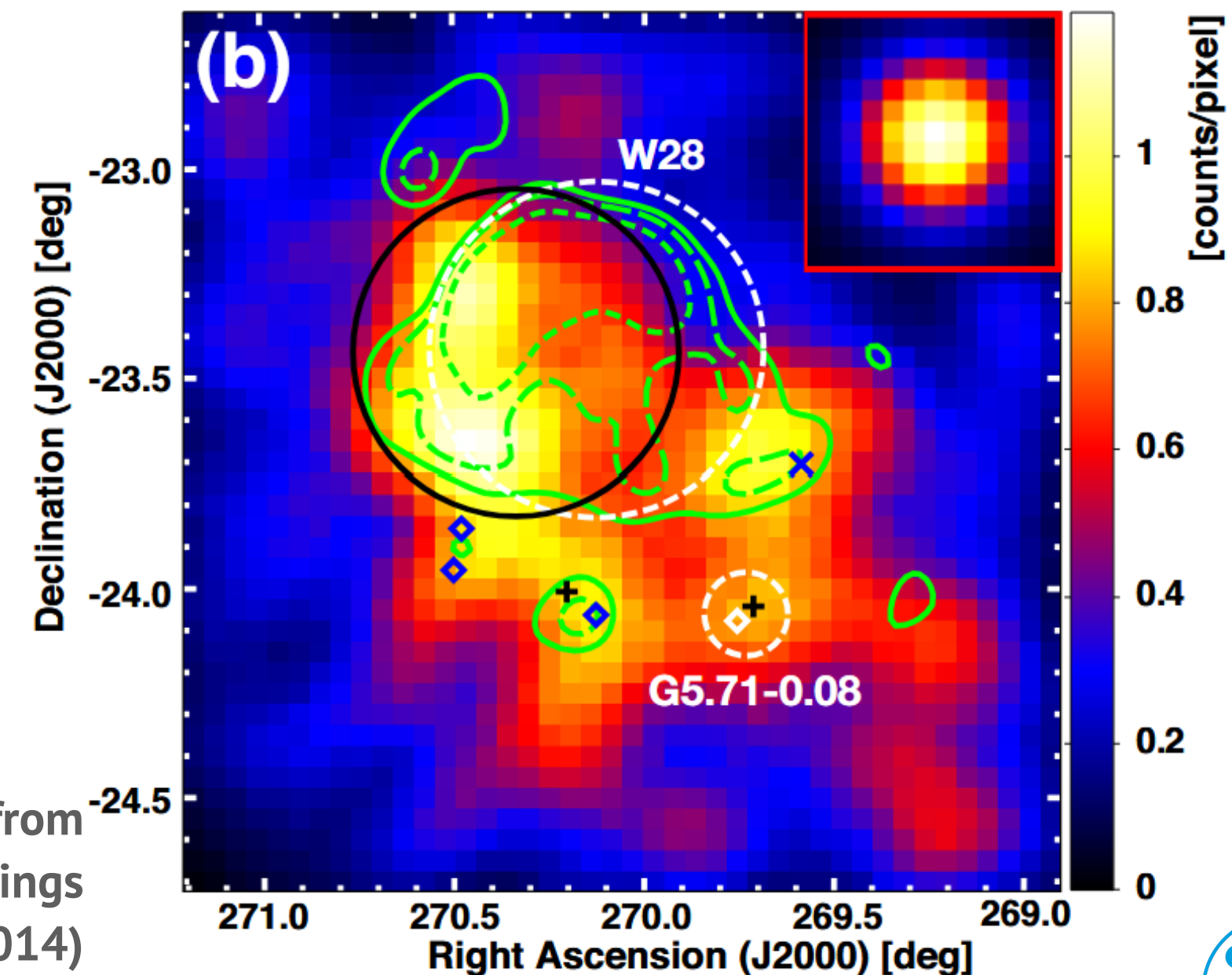
- One dimensional
- Spherically symmetric
- Monoenergetic injection
- Including Synchrotron and inverse-Compton cooling for electrons
- On a comoving, expanding grid for turbulence and CRs
→. no free escape boundary

Observational Signature

Evolution of particle acceleration in the shell-type SNRs



Gamma-ray flux from various SNRs (Funk, TeVPA 2011)

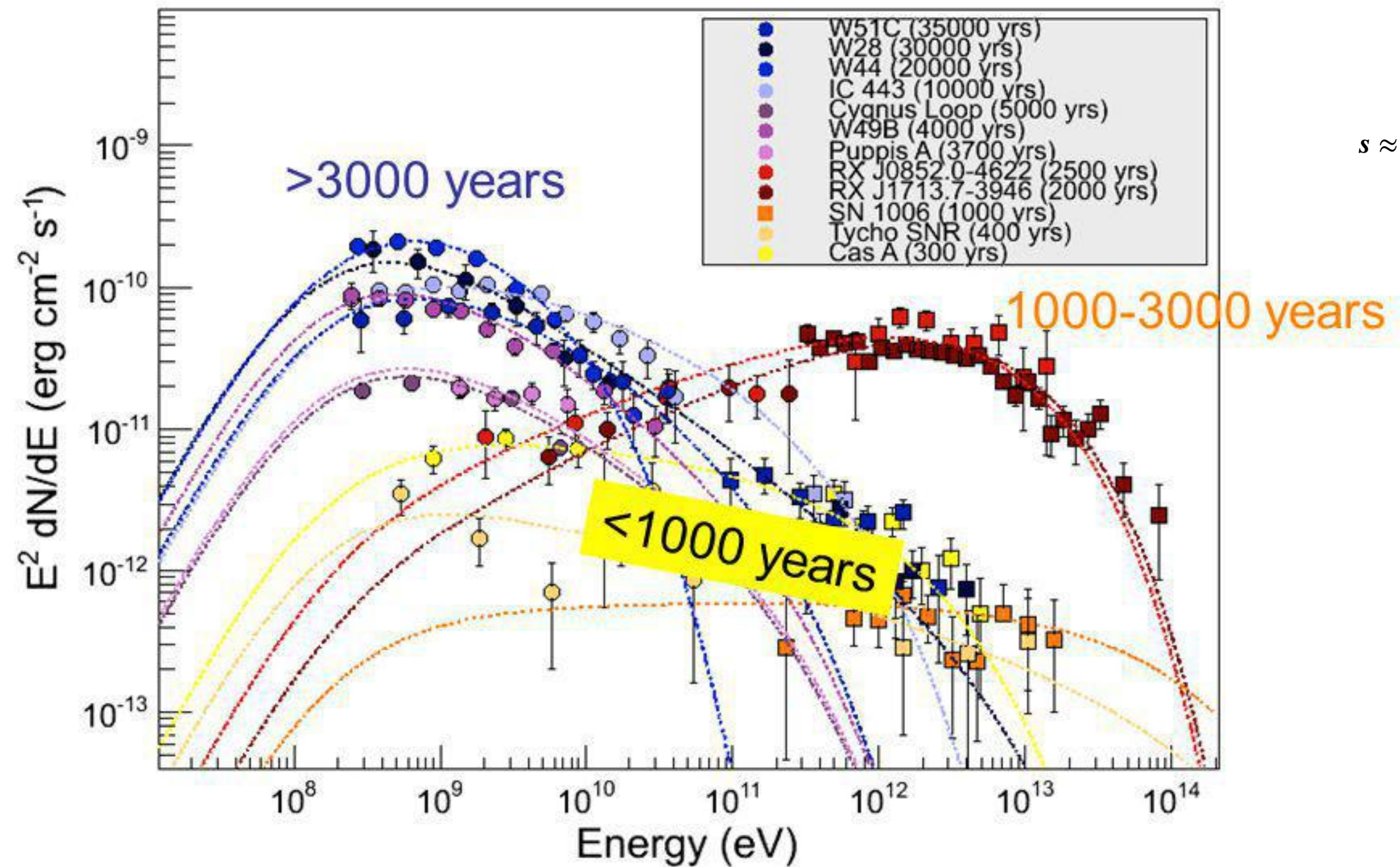


Gamma-ray emission from W28 and its surroundings (Hanabata et al. 2014)

Gamma-ray spectra

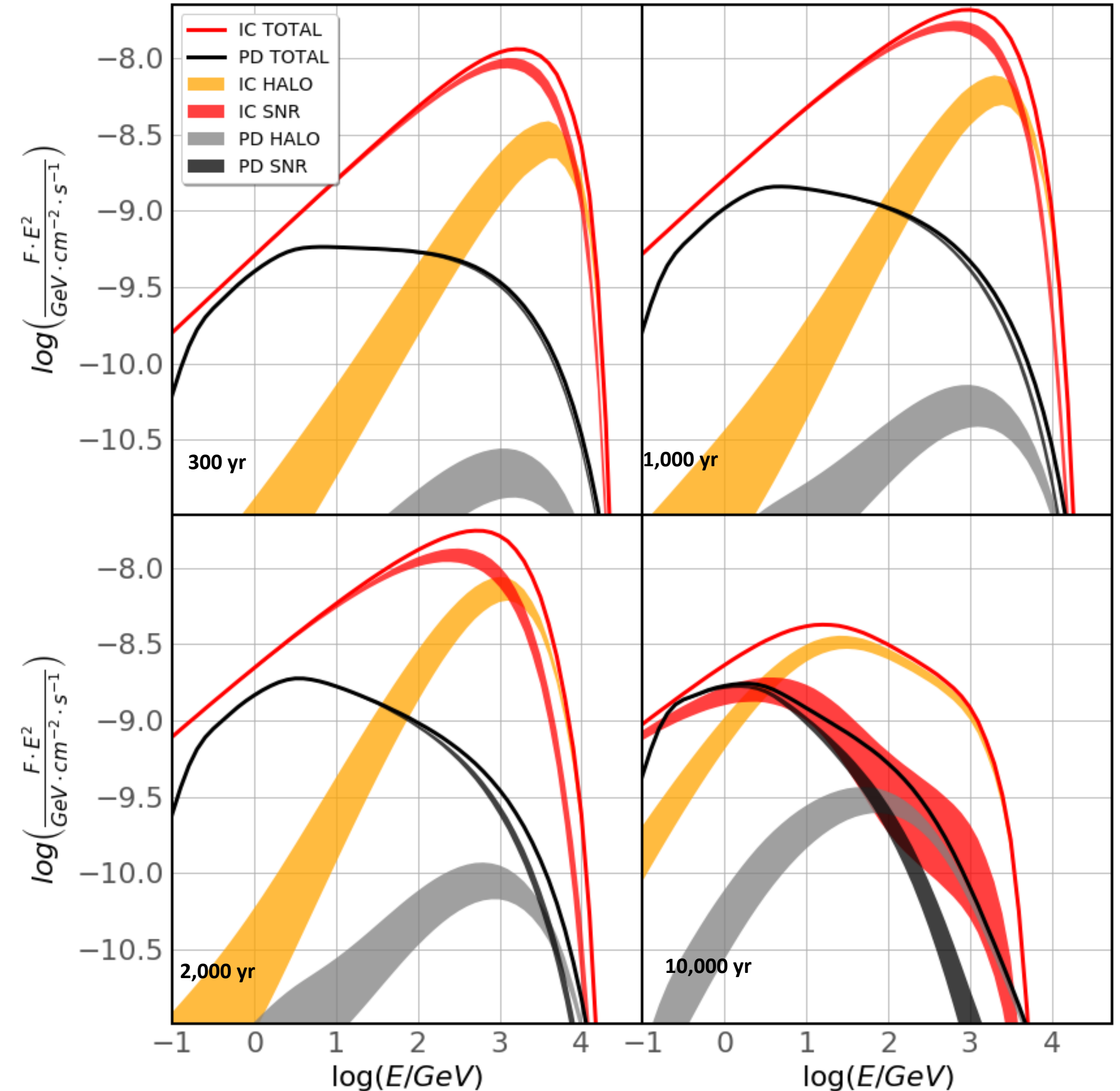
Observations:

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Model prediction (RB, et al. 2021):

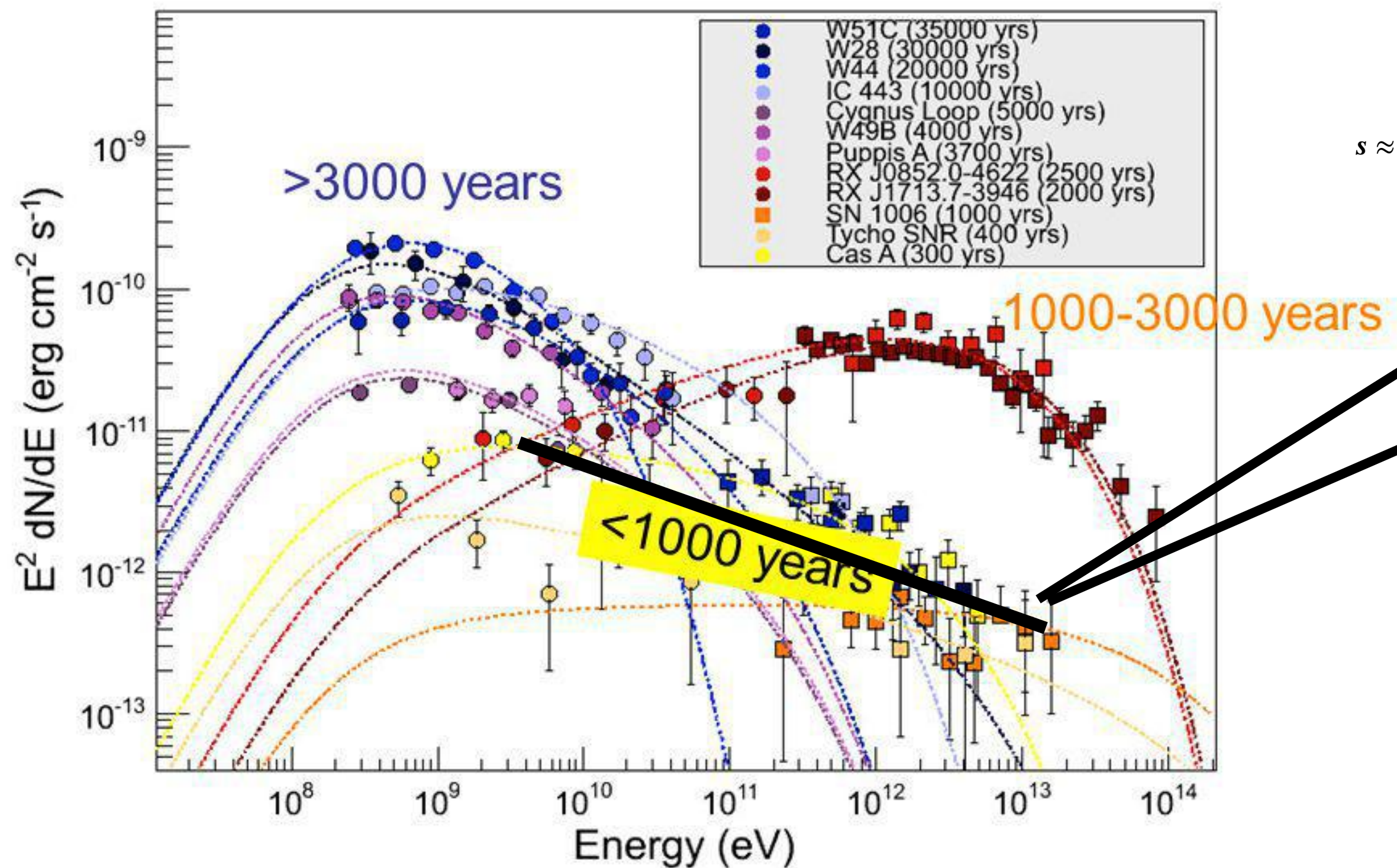


$s \approx 2$

Gamma-ray spectra

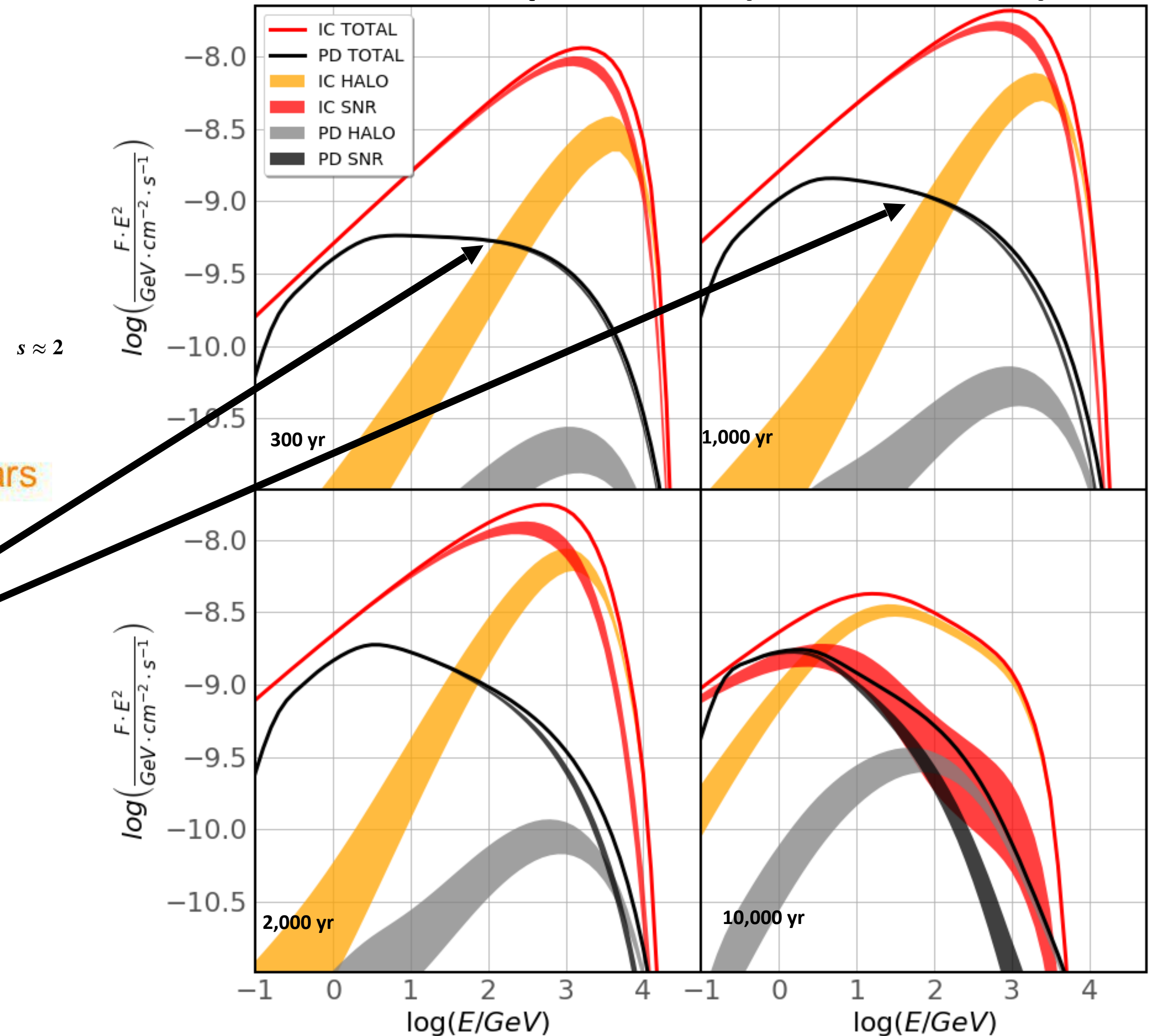
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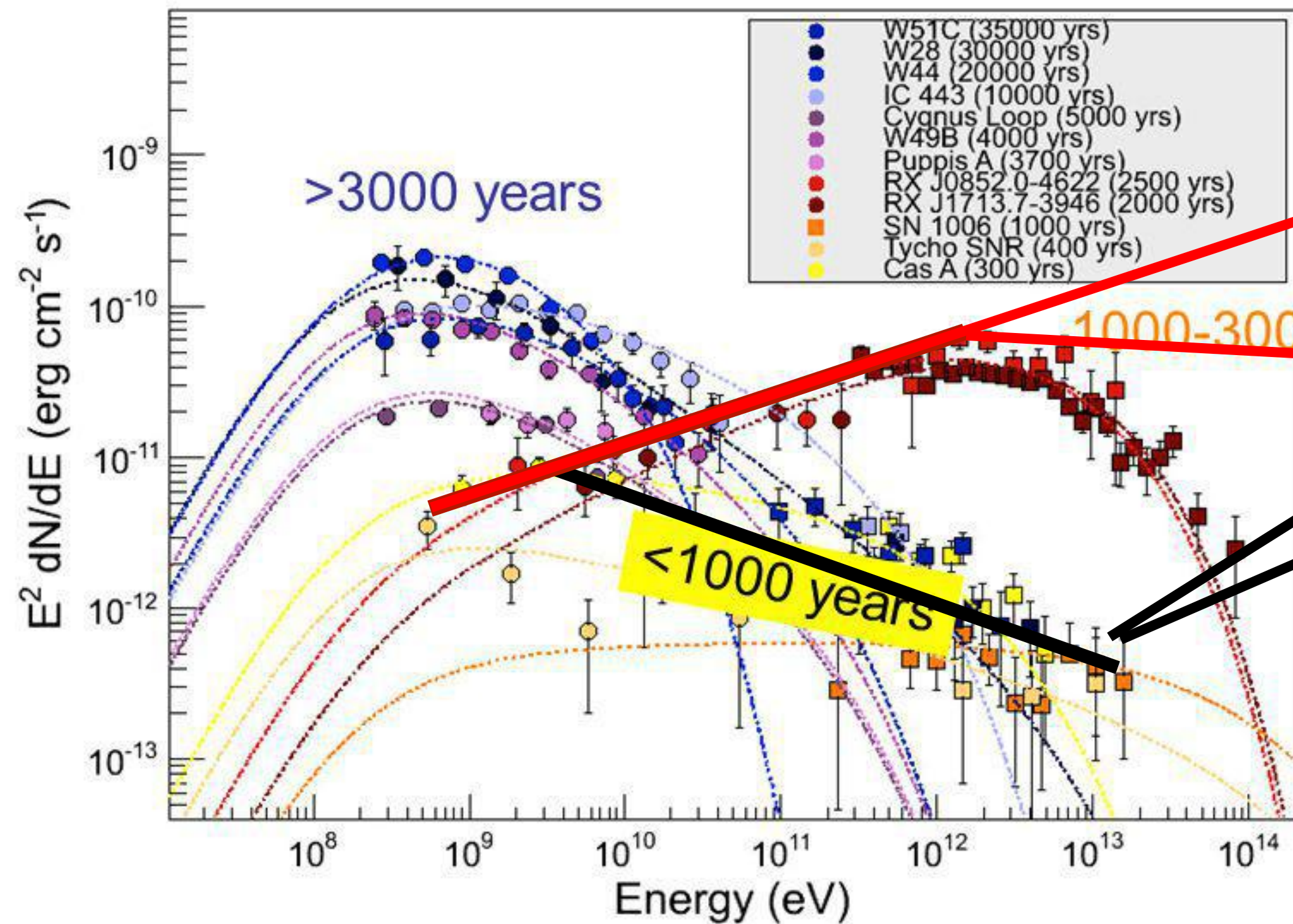
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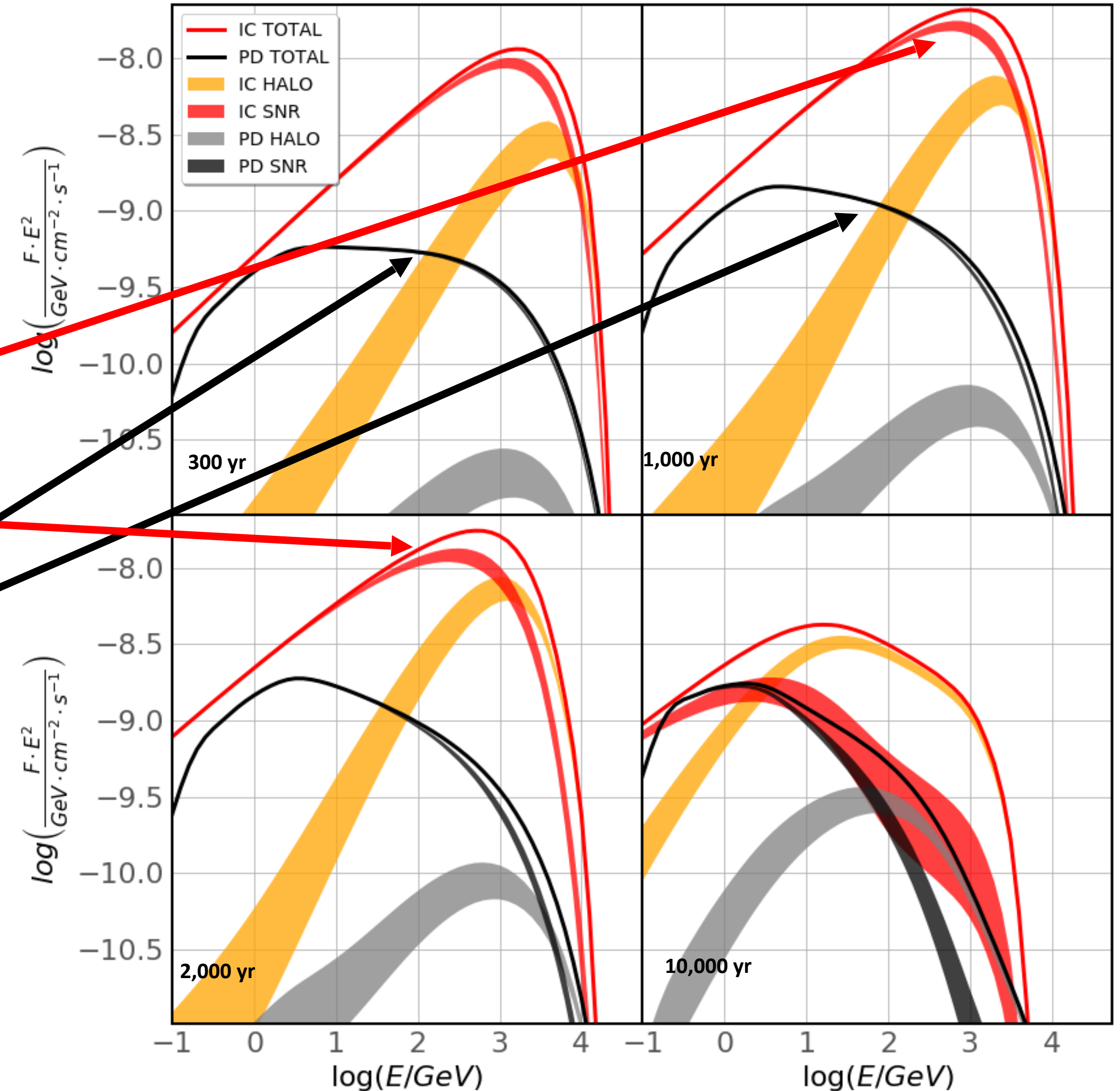
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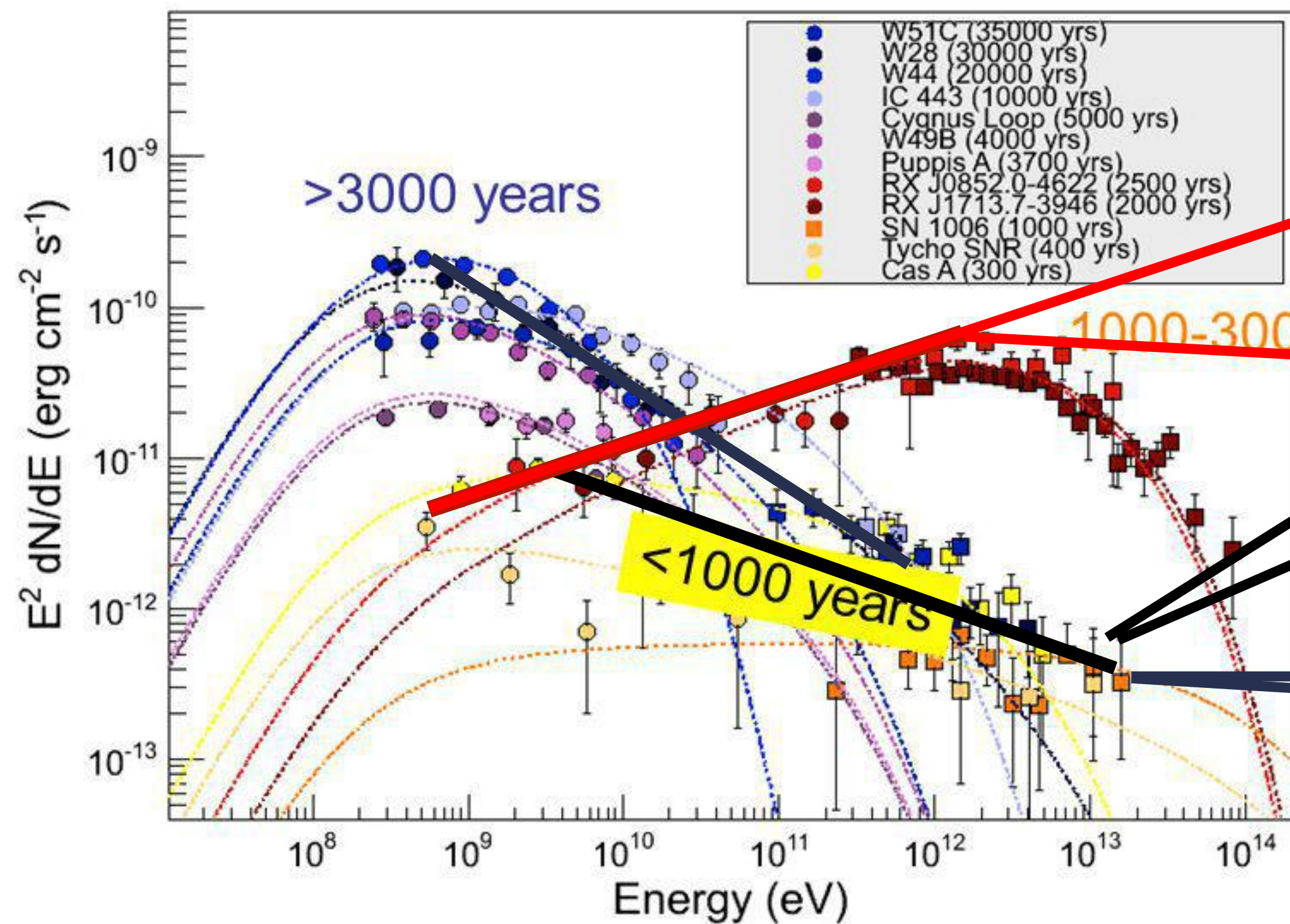
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Gamma-ray spectra

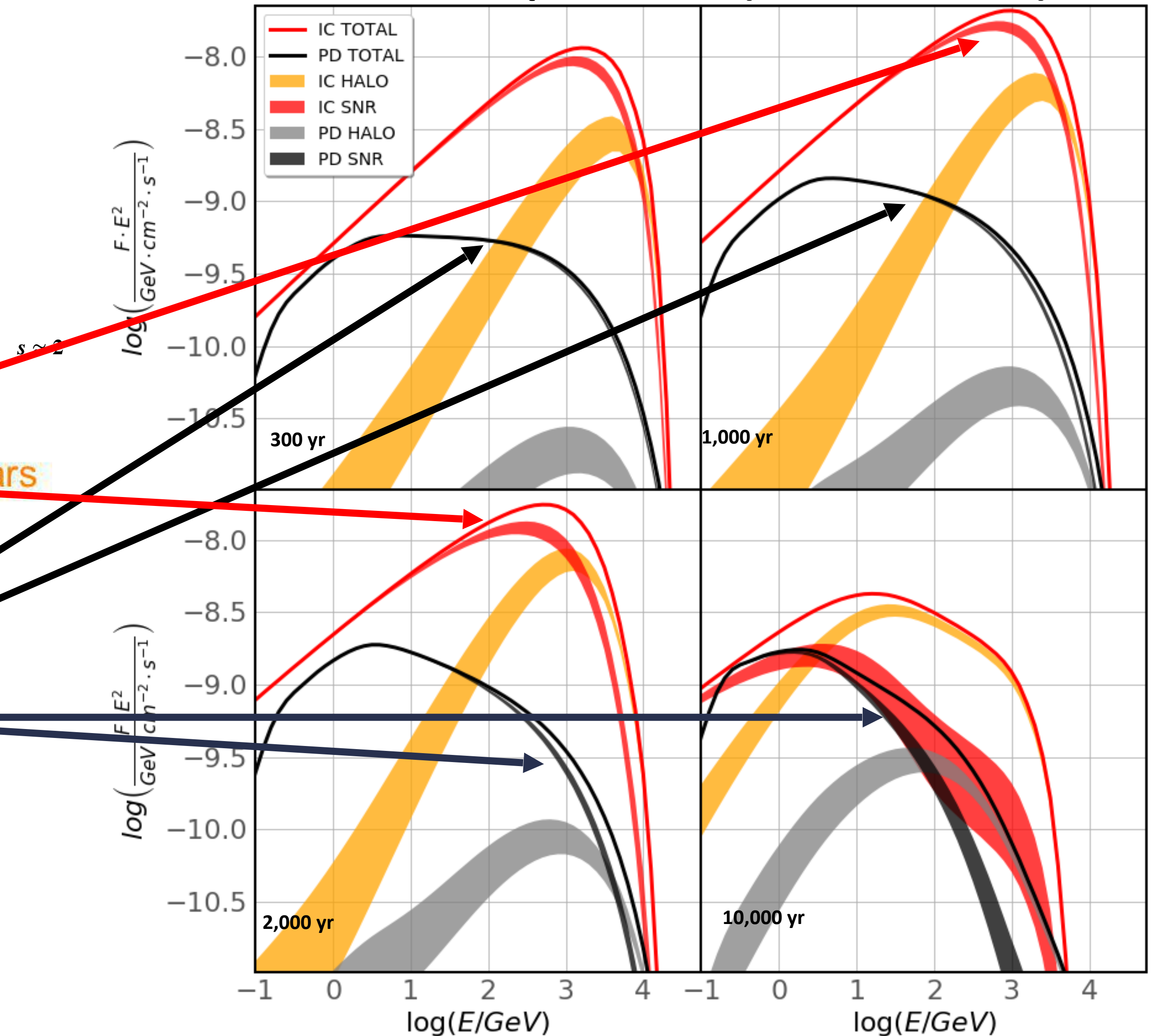
Observations:

Evolution of particle acceleration in the shell-type SNRs

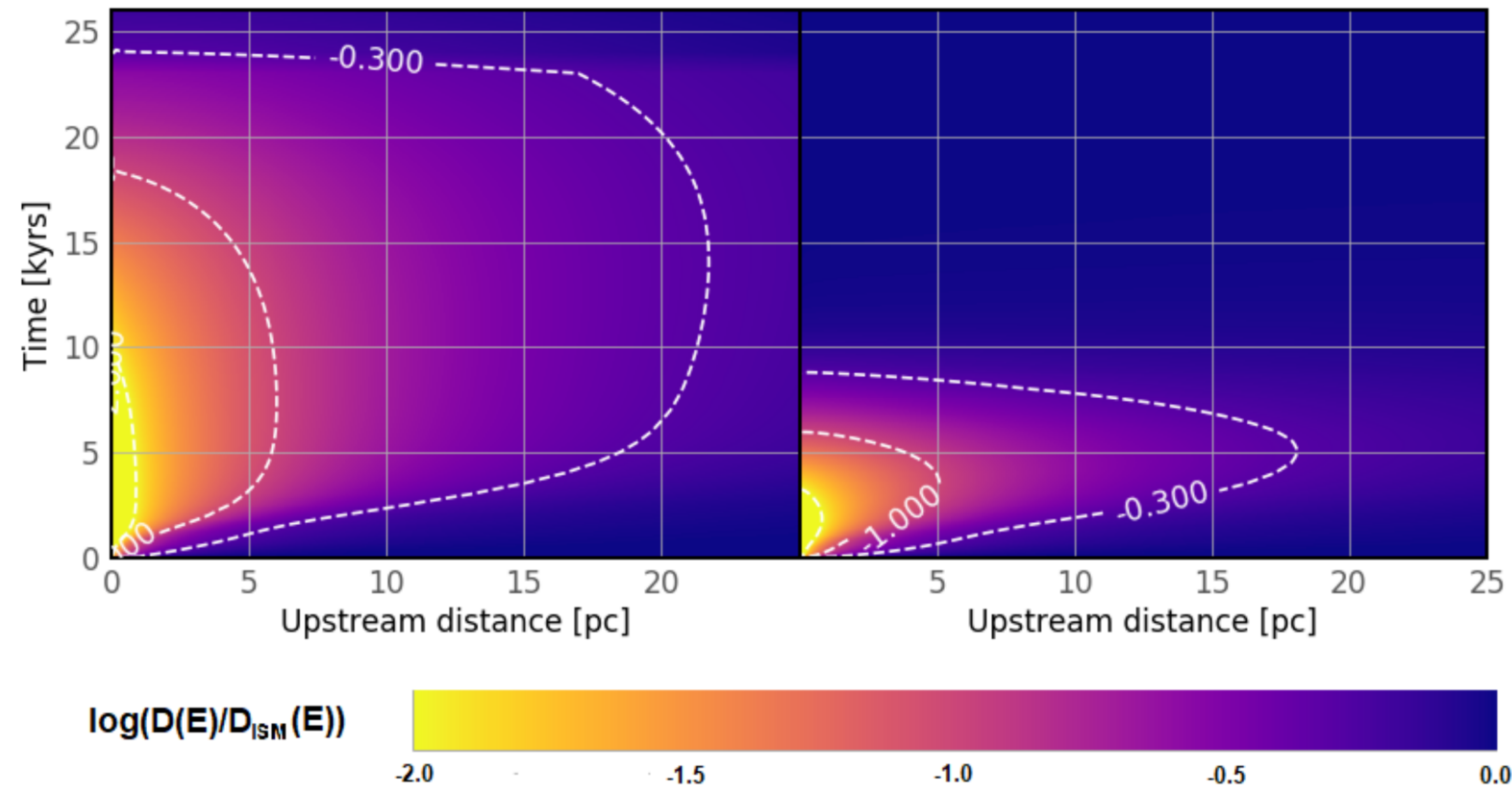


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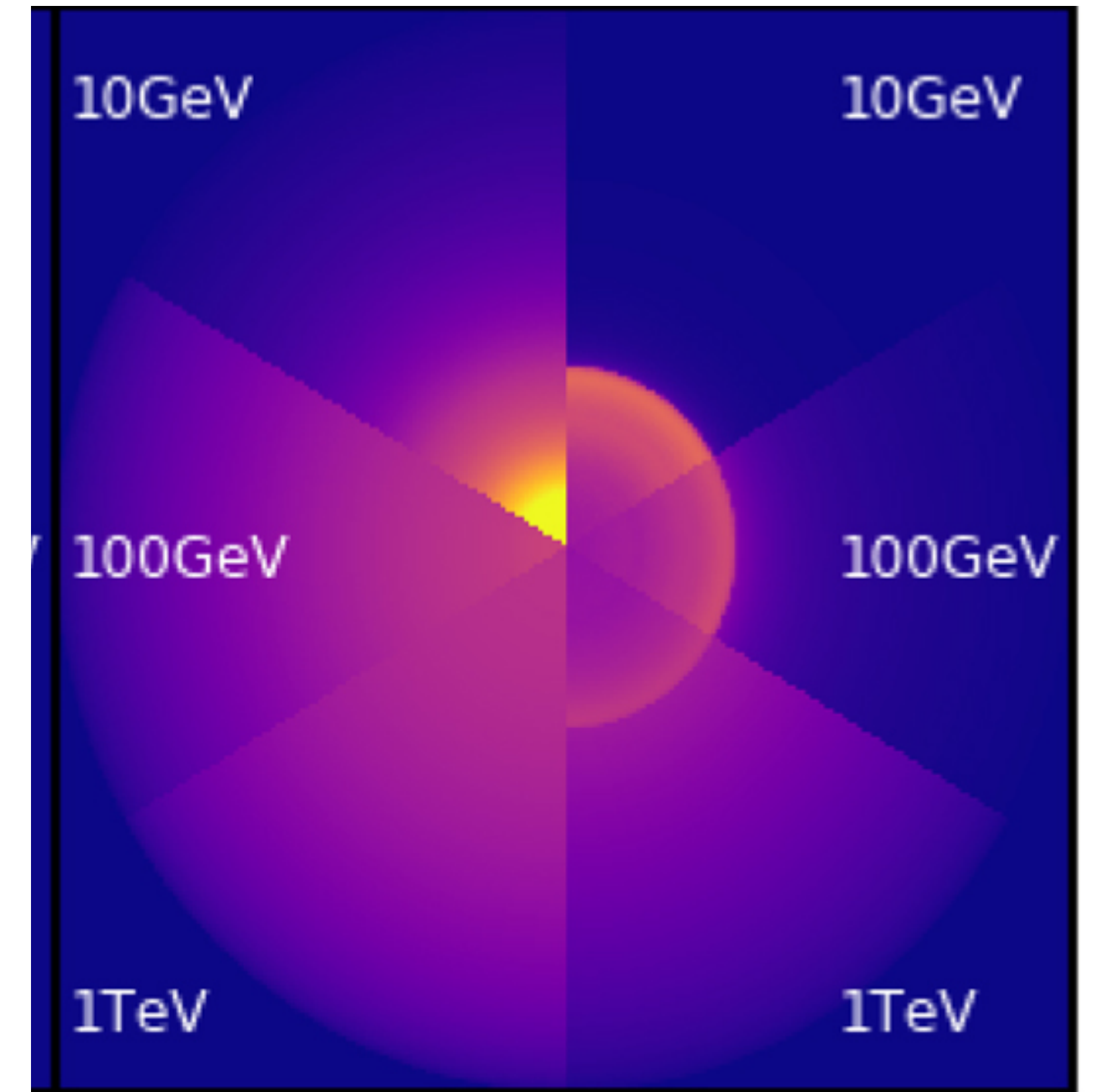
Model prediction (RB, et al. 2021):



Suppressed diffusion around SNRs



Diffusion around SNRs (RB, et al. 2021)



Gamma-ray halo around a 10kyr SNR (RB, et al. 2021)

Summary I

- A rapid decrease of E_{max} in the Sedov-phase triggers particle escape from deep downstream
- The downstream spectra are softer than the production spectra
- Both spectral indices are consistent with observations
- Formation of Halos due to suppressed diffusion around SNRs

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The spectral shape can be well explained

Galactic Cosmic-Rays

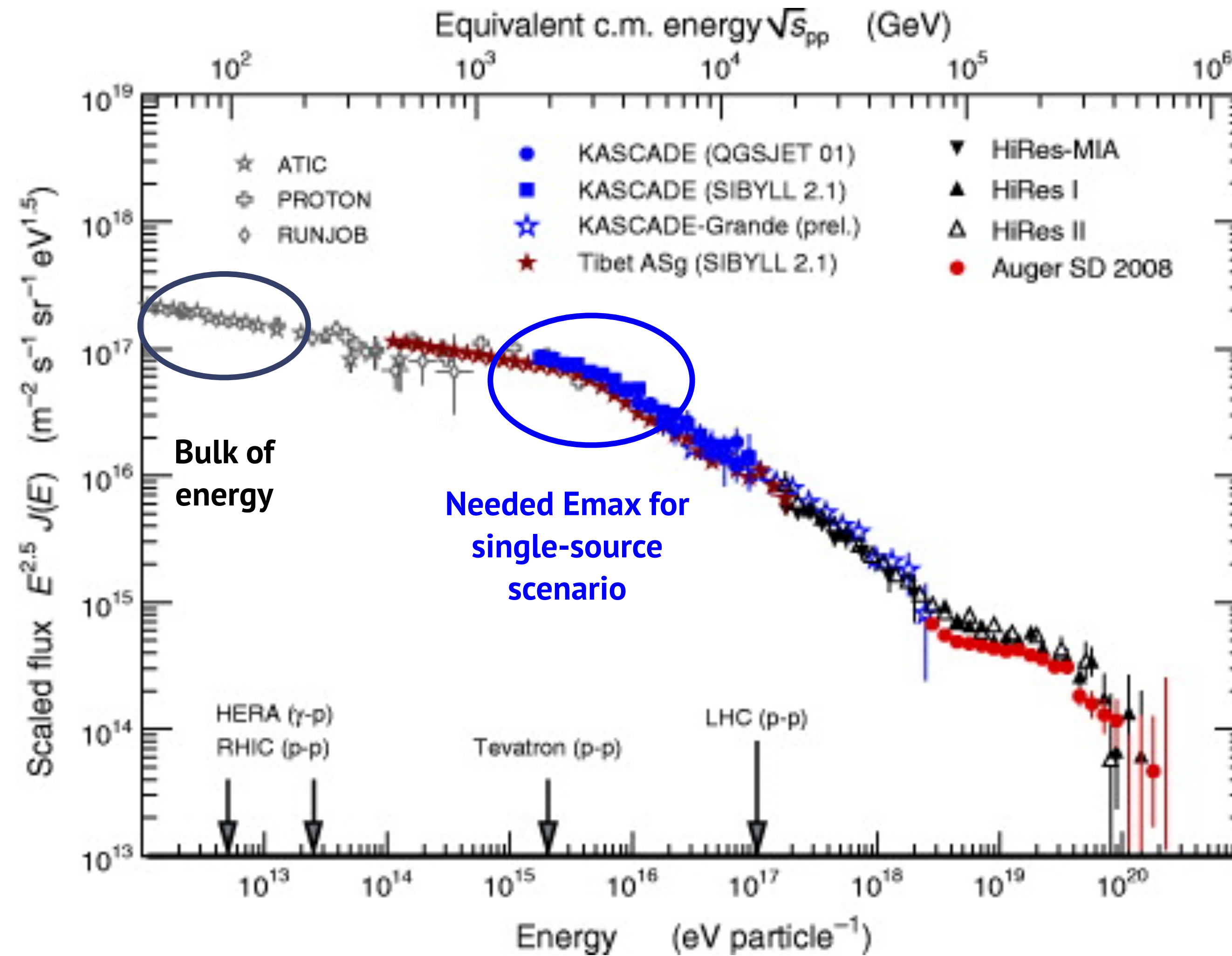
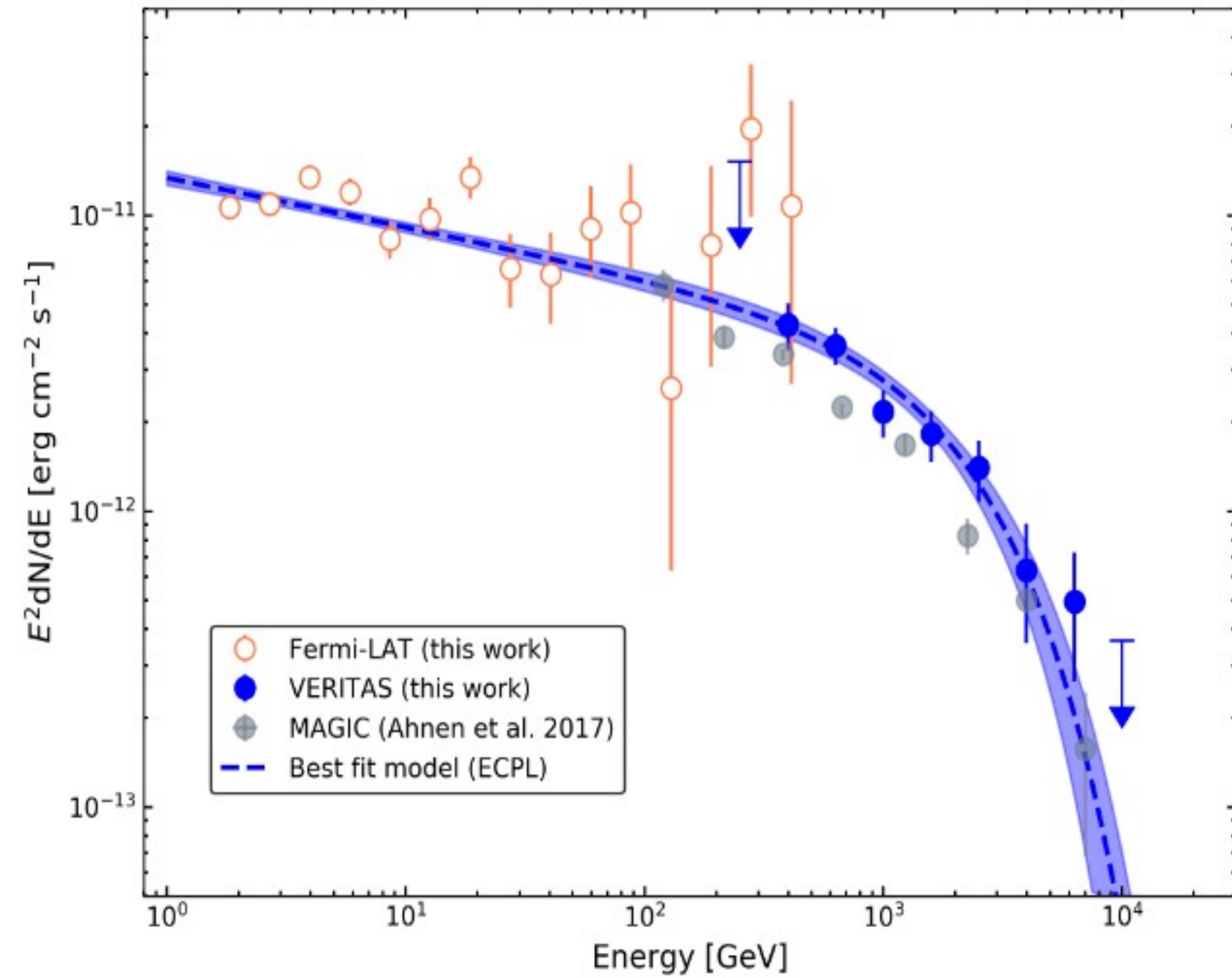


Figure: The cosmic ray spectrum (Blümer et al. 2019)

Maximum Energy - General problem

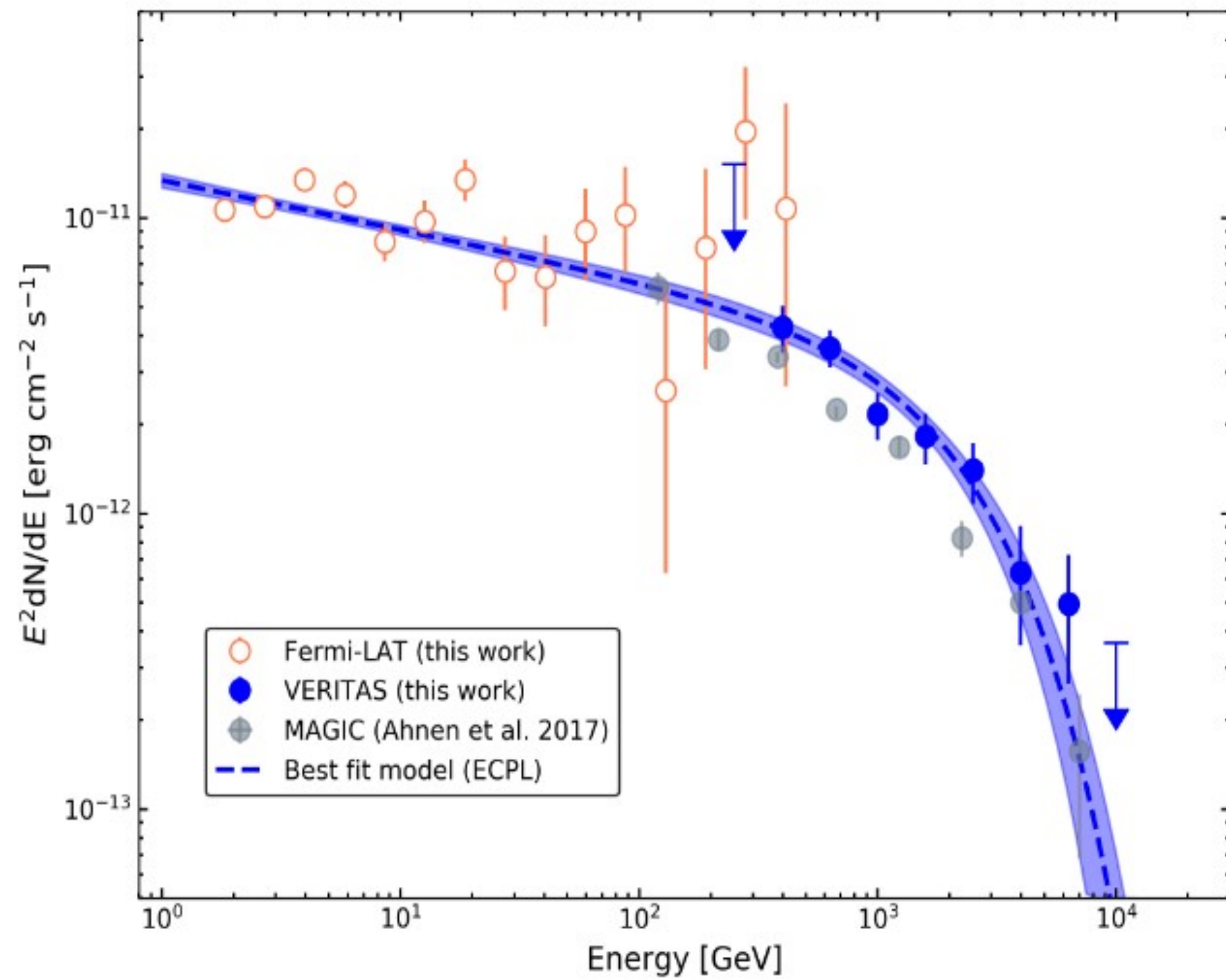
Observations



Gamma-ray SED of Cas A (VERITAS 2018)

Maximum Energy - General problem

Observations



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Hillas criterium

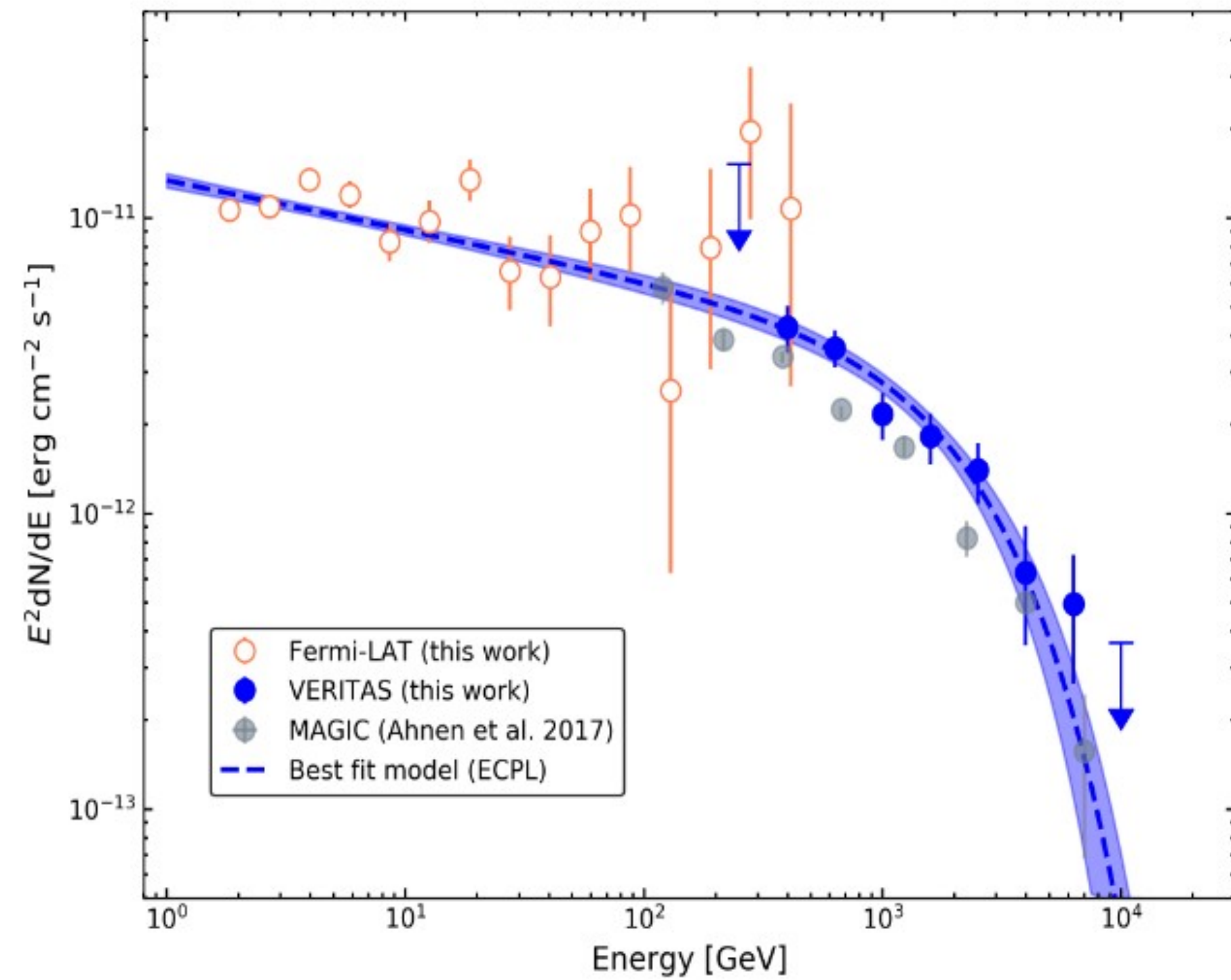
$$E_{max} \approx qv_{sh}BL/4c$$

SNRs:

$$B(t \sim 400yr) \approx 700\mu G$$

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The Story seems more complicated

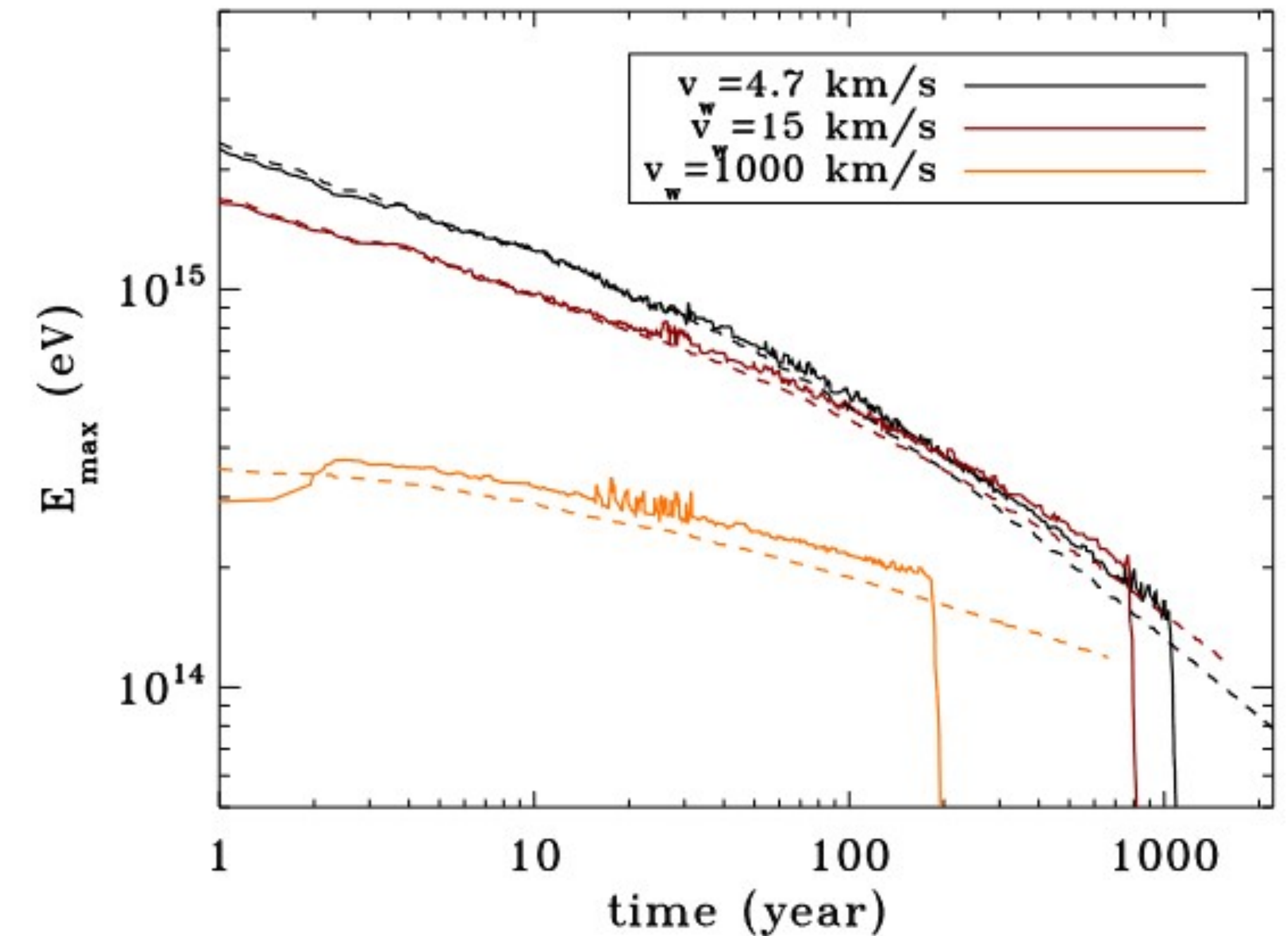
Maximum Energy - General problem

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- Saturated field strong enough to go to PeV energies in very young SNRs ($t < 20\text{yr}$) (e.g. Schure&Bell 2013 (MHD))



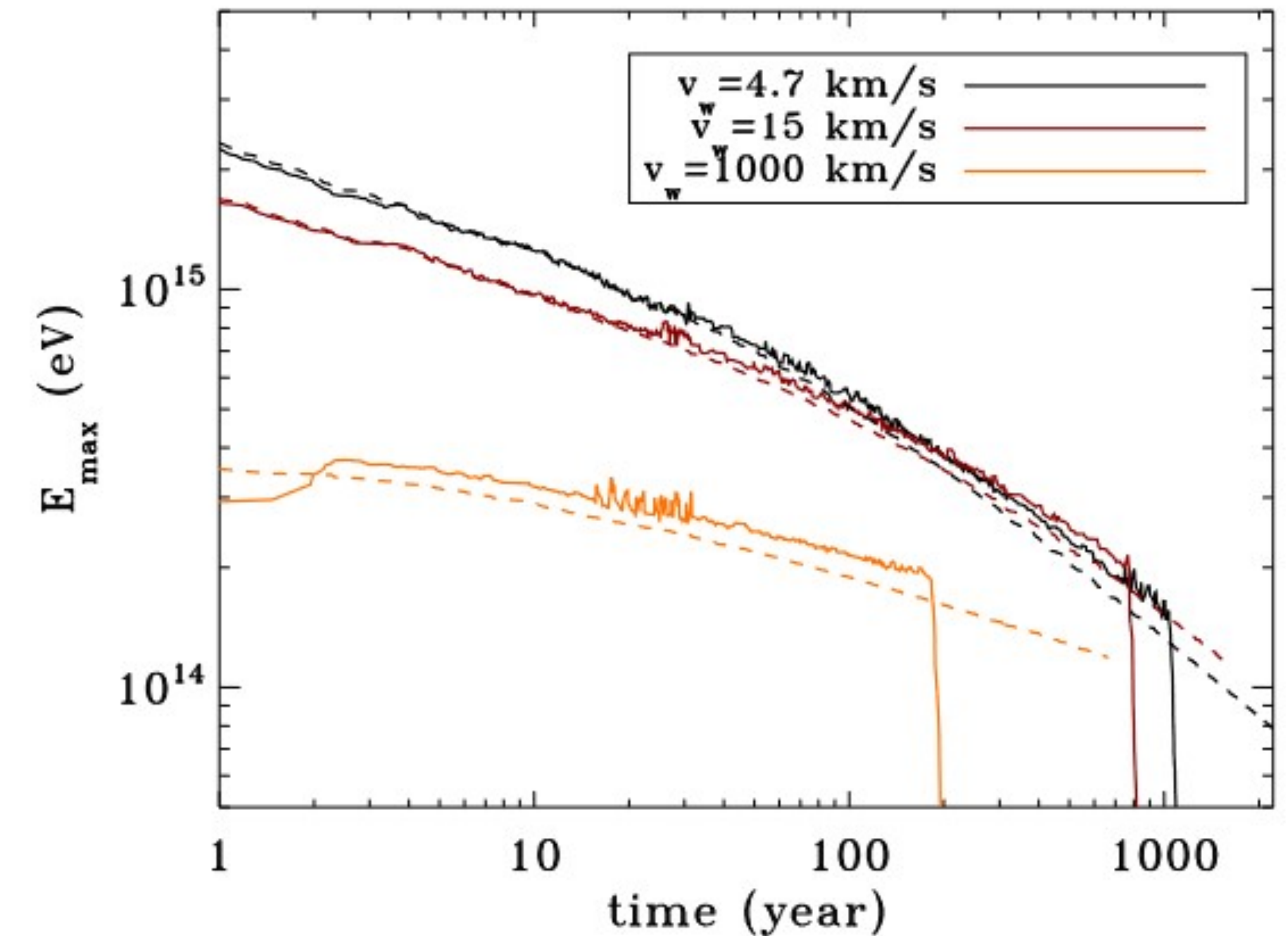
Schure&Bell (2013)

Maximum Energy - General problem

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- Saturated field strong enough to go to PeV energies in very young SNRs ($t < 20yr$) (e.g. Schure&Bell 2013 (MHD))
- Kinetic studies “confirm” SNRs as PeVatrons (e.g.: Inoue+ (2021), Marcowith+ (2018), Ptuskin+(2010))

→ Assumes Bohm diffusion in amplified field

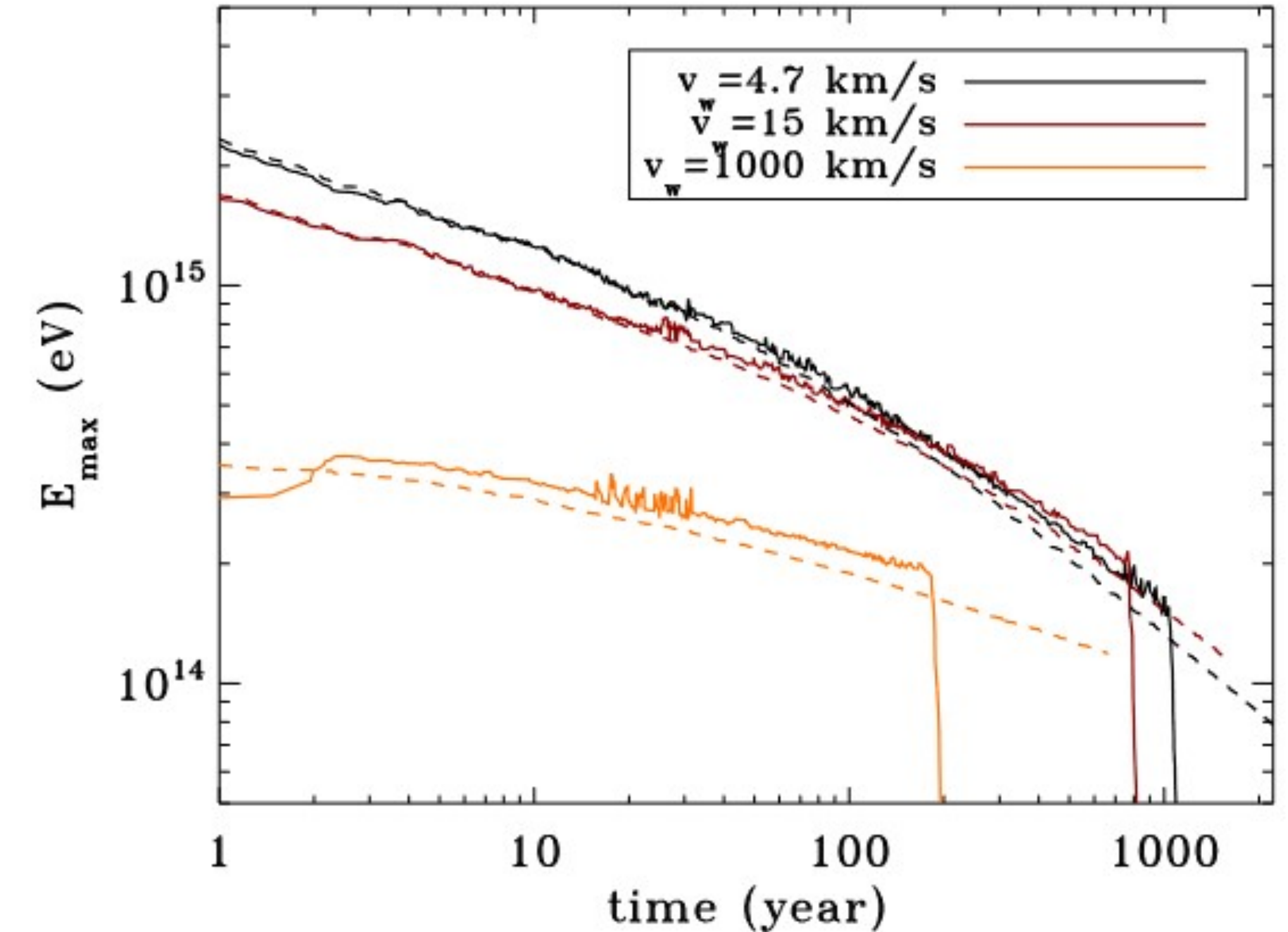


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SNRs as CR Sources

- High magnetic fields required → Self-consistent amplification:

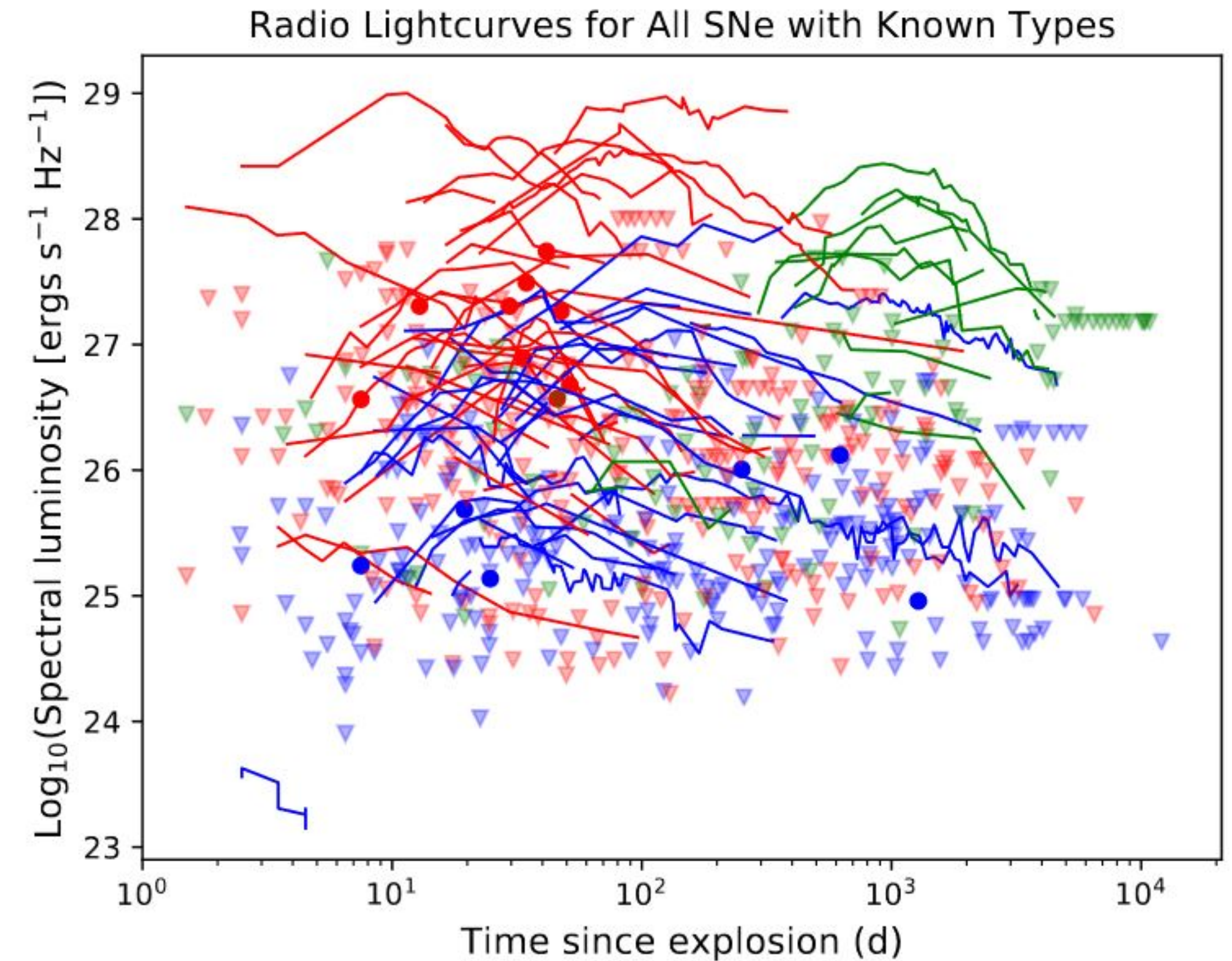
$$\Gamma_{\delta B} \propto \frac{\partial N_{CR}}{\partial r} \propto \rho_{CSM}$$

→ Progenitor stars with extreme mass-loss:

LBVs ↔ **Type-IIn SNe**

RSGs ↔ **Type-IIP SNe**

- Theoretical models predict high-energy radiation if particle acceleration is efficient (e.g., Murase+2011, Marcowith+2018,..);
but only smooth winds so far



Early-time Radio emission from SNs of various types
(Bietenholz et al.2021)

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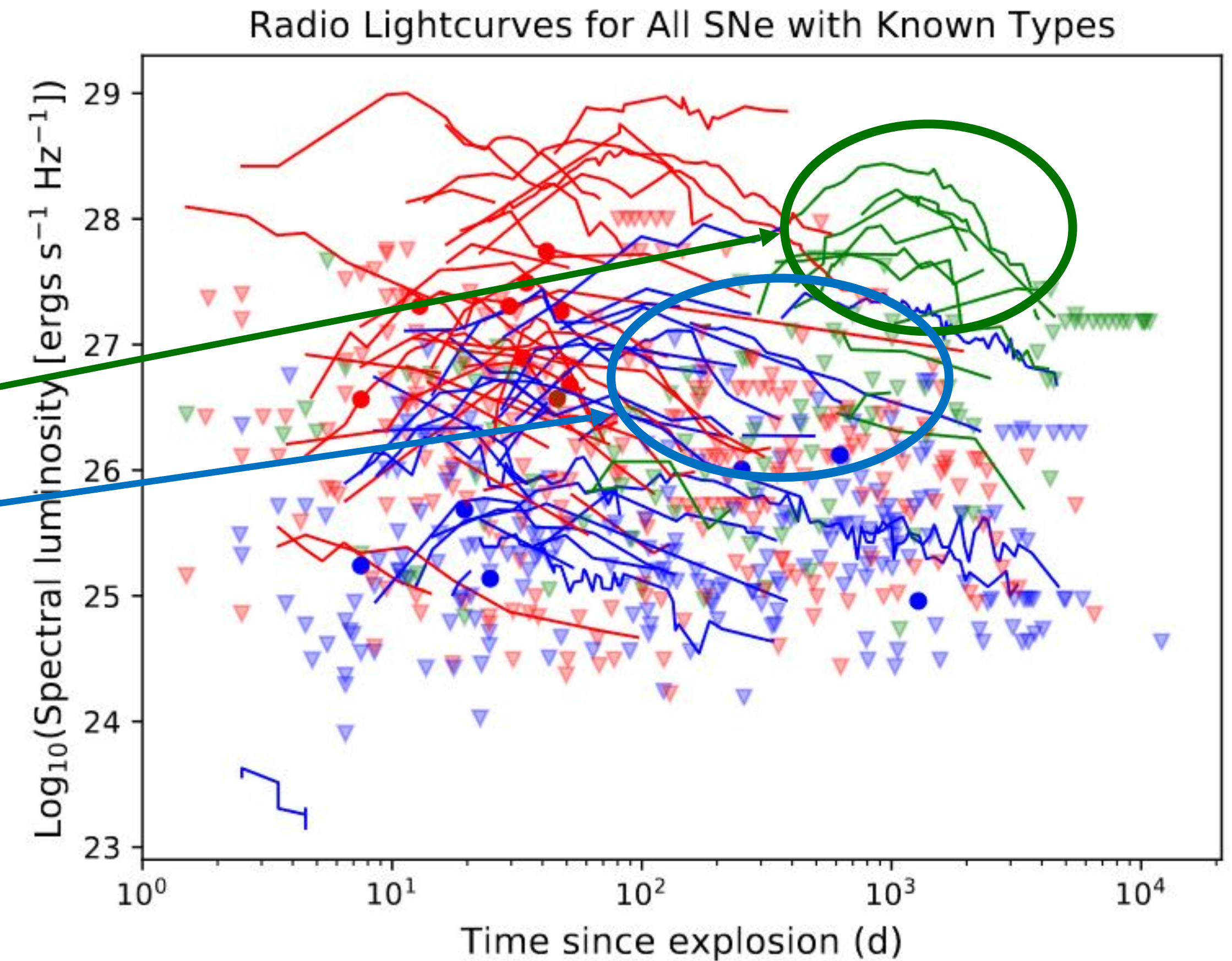
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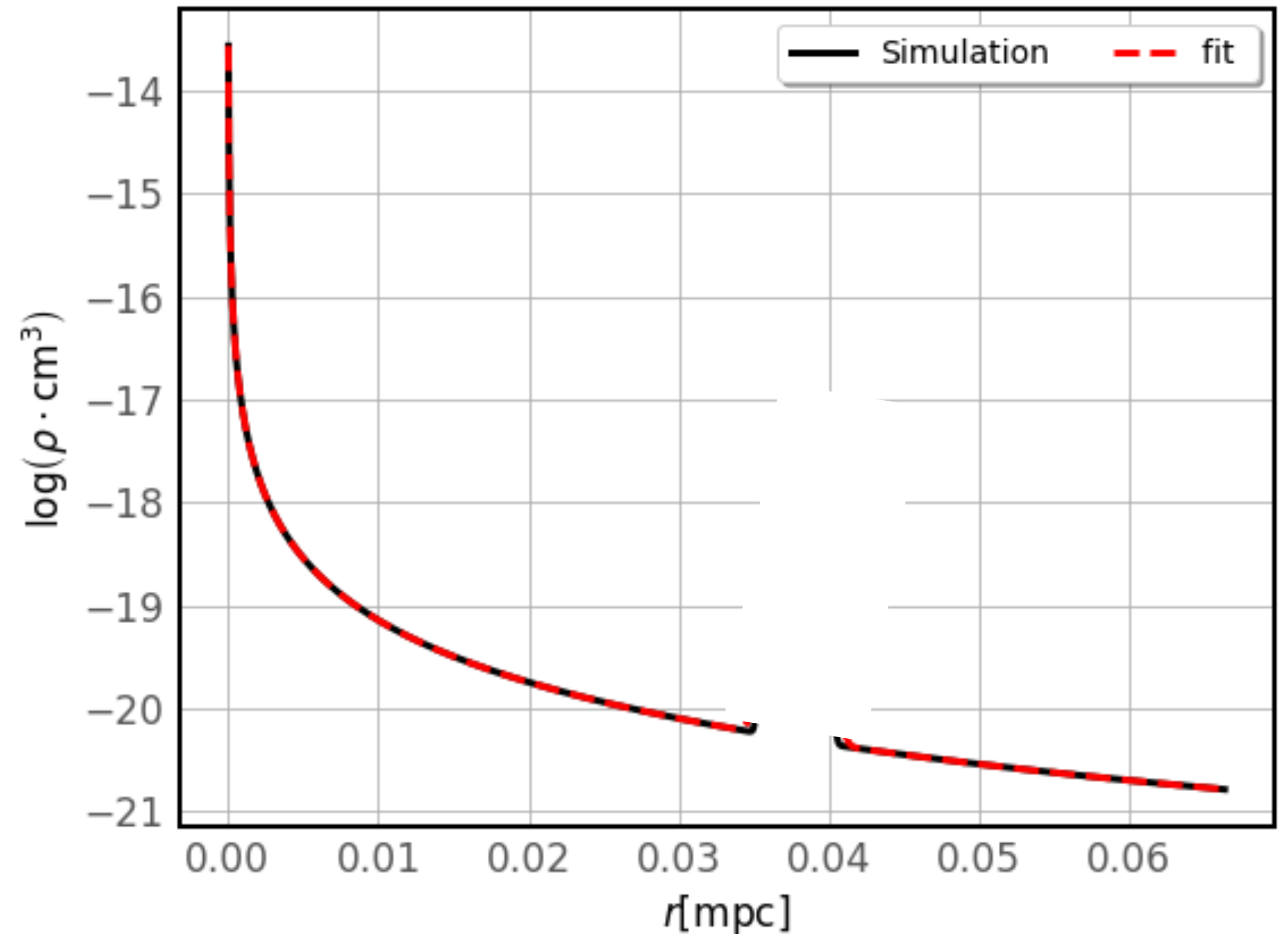
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Smooth Wind Case

Many works in the last years:

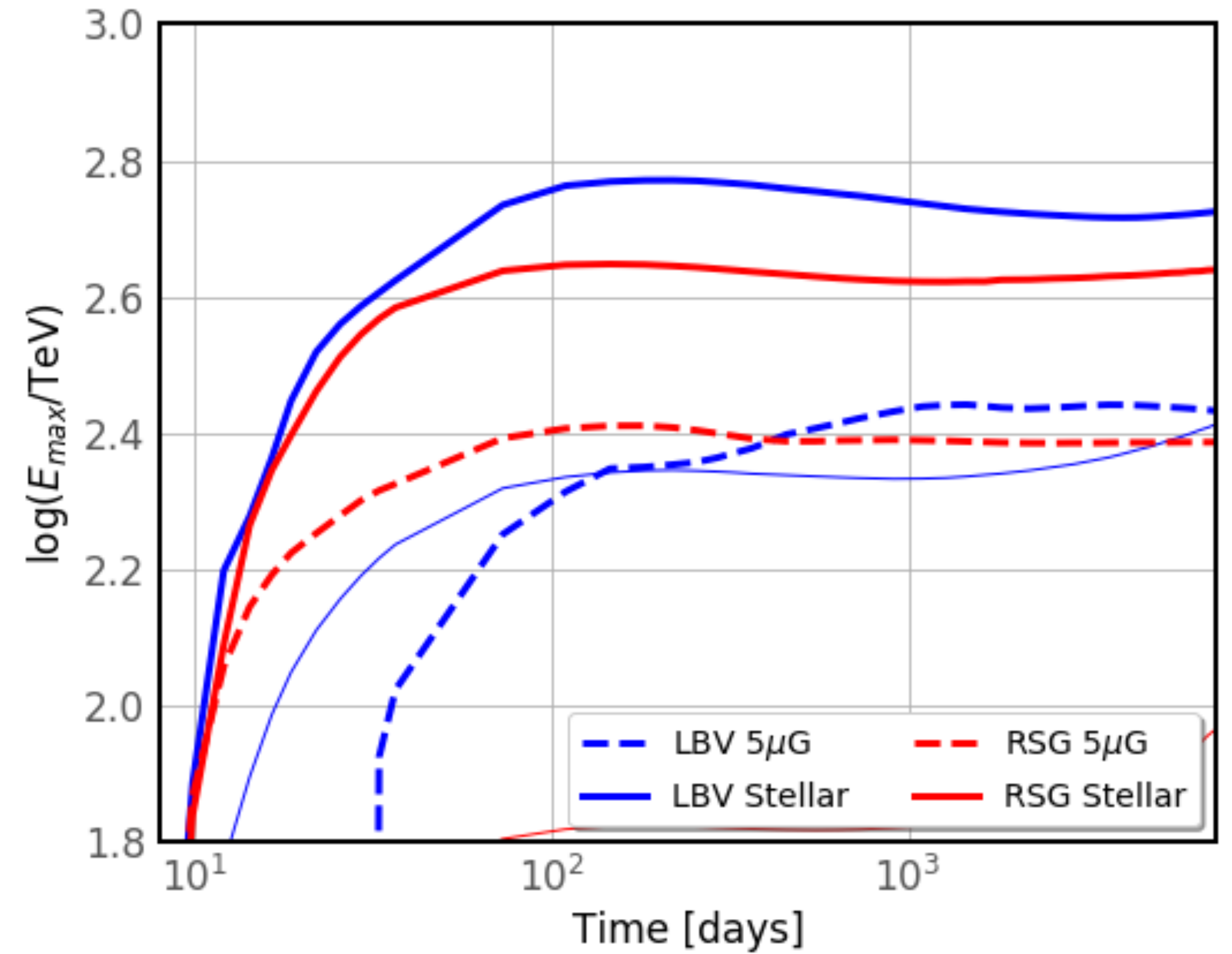
- Murase et al. (2011, 2014), Bell et al. (2013), Marcowith et al. (2018); Cristofari et al. (2020), Inoue et al. (2021), Cristofari et al. (2022), **RB22**
- $E_{max} = 100\text{TeV} - 10\text{PeV}$

Unrealistically high parameter values needed



CSM-structure for a LBV with a smooth wind (example plot)

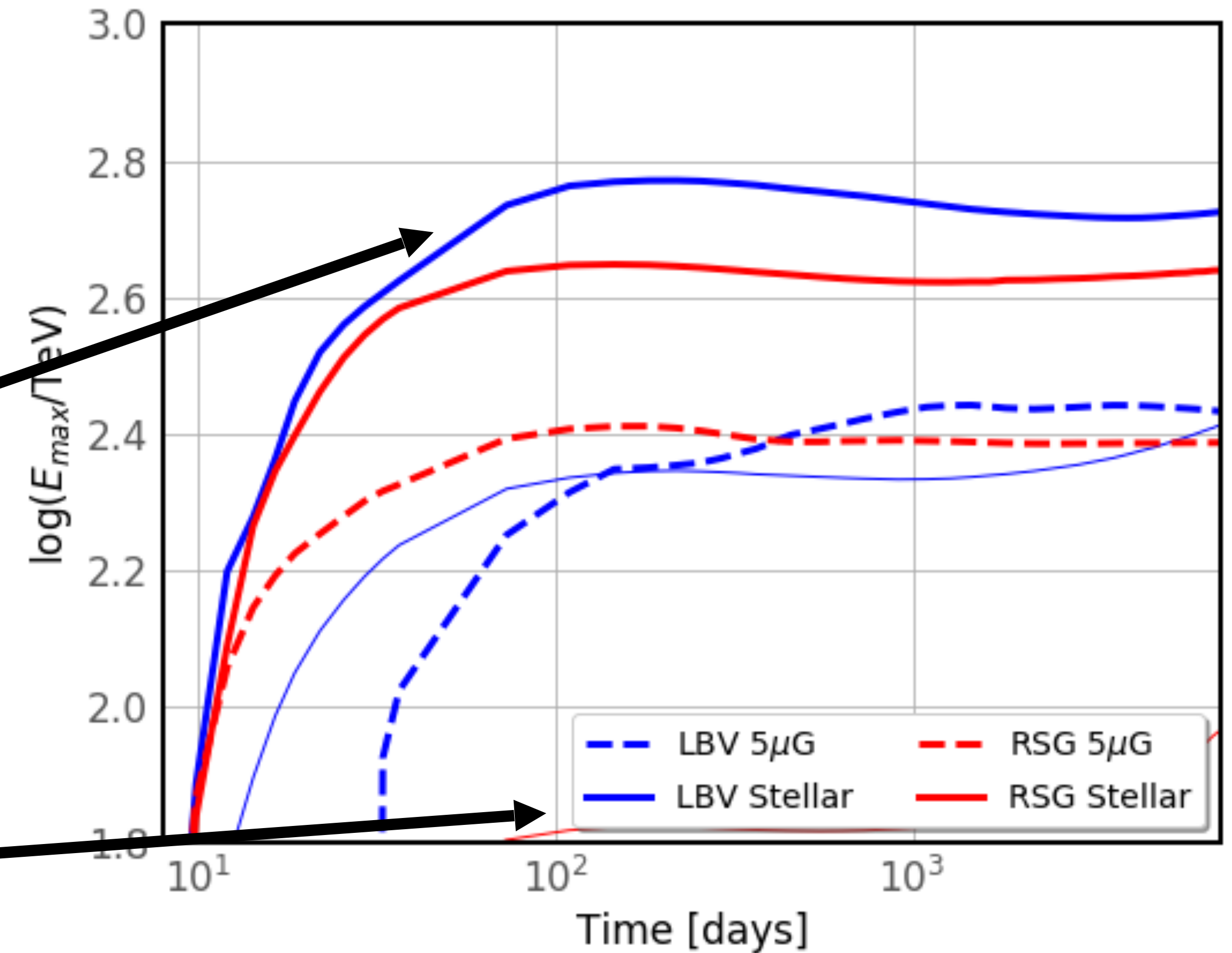
Results - $E_{\max}$



Maximum energy over time for Type-IIn and Type-IIP SNe in smooth winds (RB, et al. 2022)

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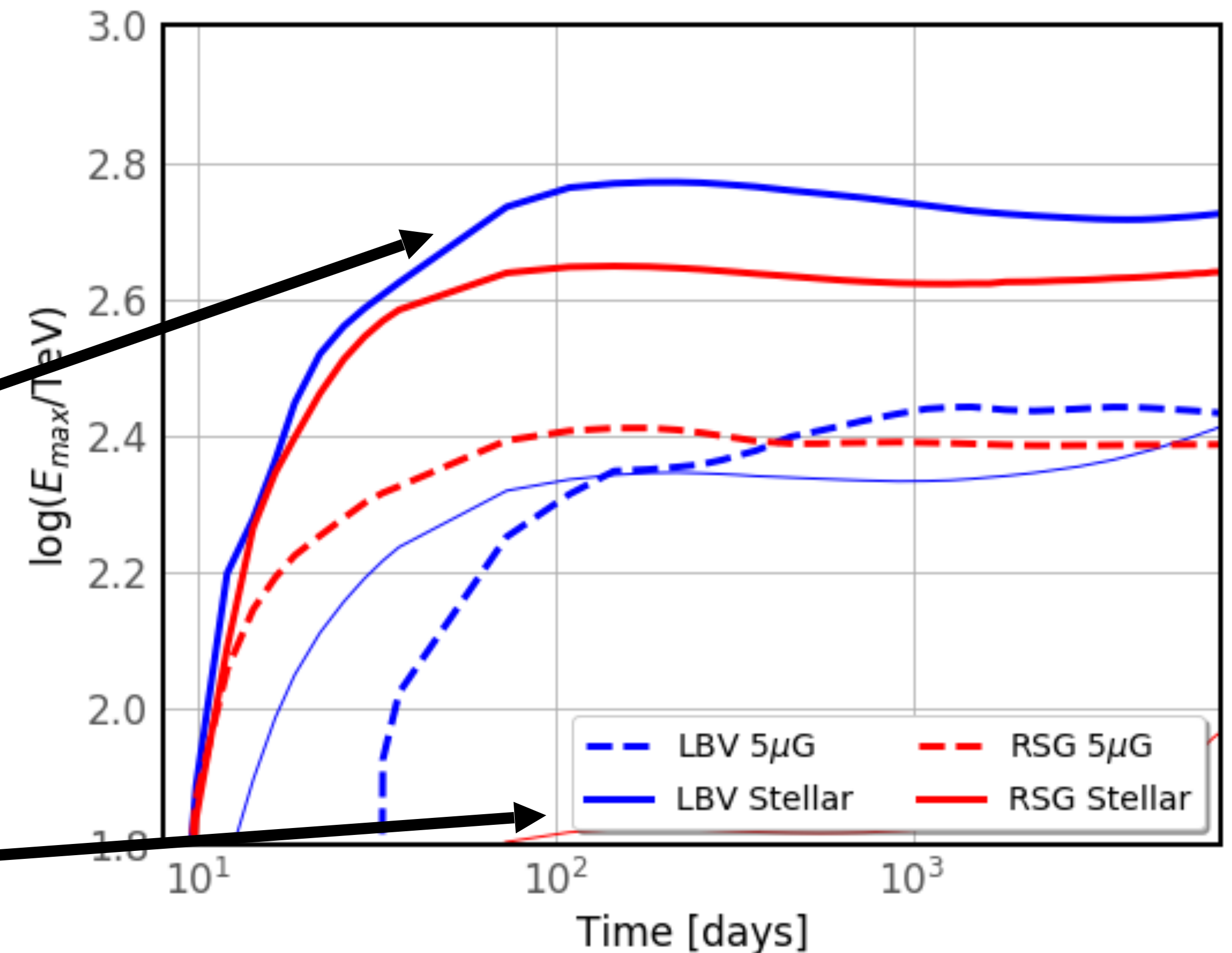
- Fit spectrum with power-law plus exponential cutoff $\rightarrow E_{\max}$
- **Acceleration time** is **~ 1 month** to get to quasi-steady state
- $E_{\max} \approx 600$ TeV for LBV (high $\dot{M}$, $B \propto r^{-1}$)
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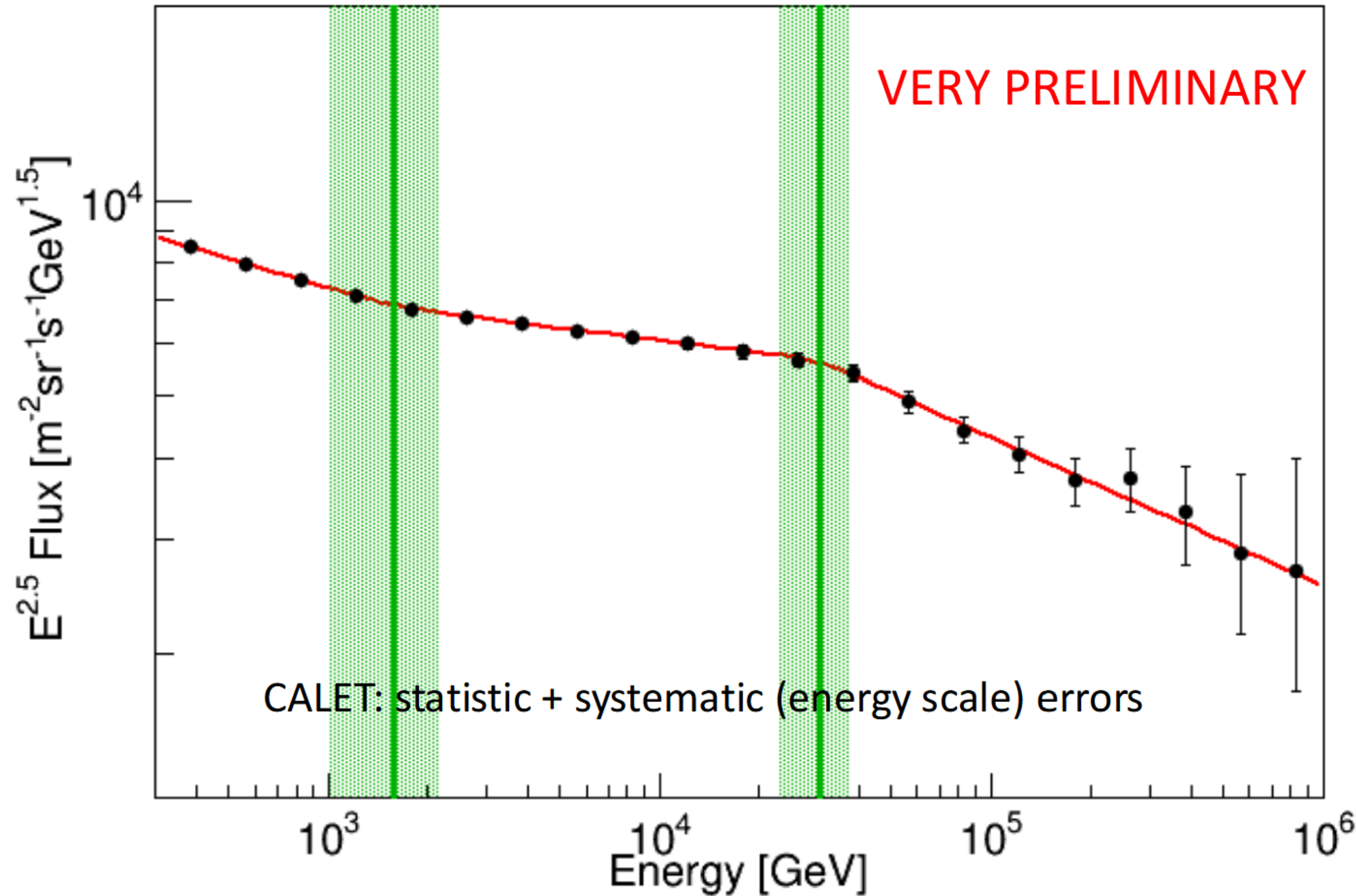
No model assumption gives

$$E_{\max} \geq 1 \text{ PeV}$$

Maximum energy over time for Type-IIn and Type-IIP SNe in smooth winds (RB, et al. 2022)

Measured CR spectra

$$\Phi(E) = C \left(\frac{E}{\text{GeV}} \right)^\gamma \left[1 + \left(\frac{E}{E_0} \right)^s \right]^{\frac{\Delta\gamma}{s}} \left[1 + \left(\frac{E}{E_1} \right)^{s_1} \right]^{\frac{\Delta\gamma_1}{s_1}}$$



Fitting Parameters

$$\gamma = -2.65 \pm 0.03$$

$$E_0 = 1.57 \pm 0.58 \text{ TeV}$$

$$\Delta\gamma = 0.09 \pm 0.03$$

$$s = 6.6 \text{ (Fix)}$$

$$E_1 = 30.6 \pm 7.4 \text{ TeV}$$

$$\Delta\gamma_1 = -0.17 \pm 0.04$$

$$s_1 = 10 \text{ (Fix)}$$

Galactic Cosmic-Rays

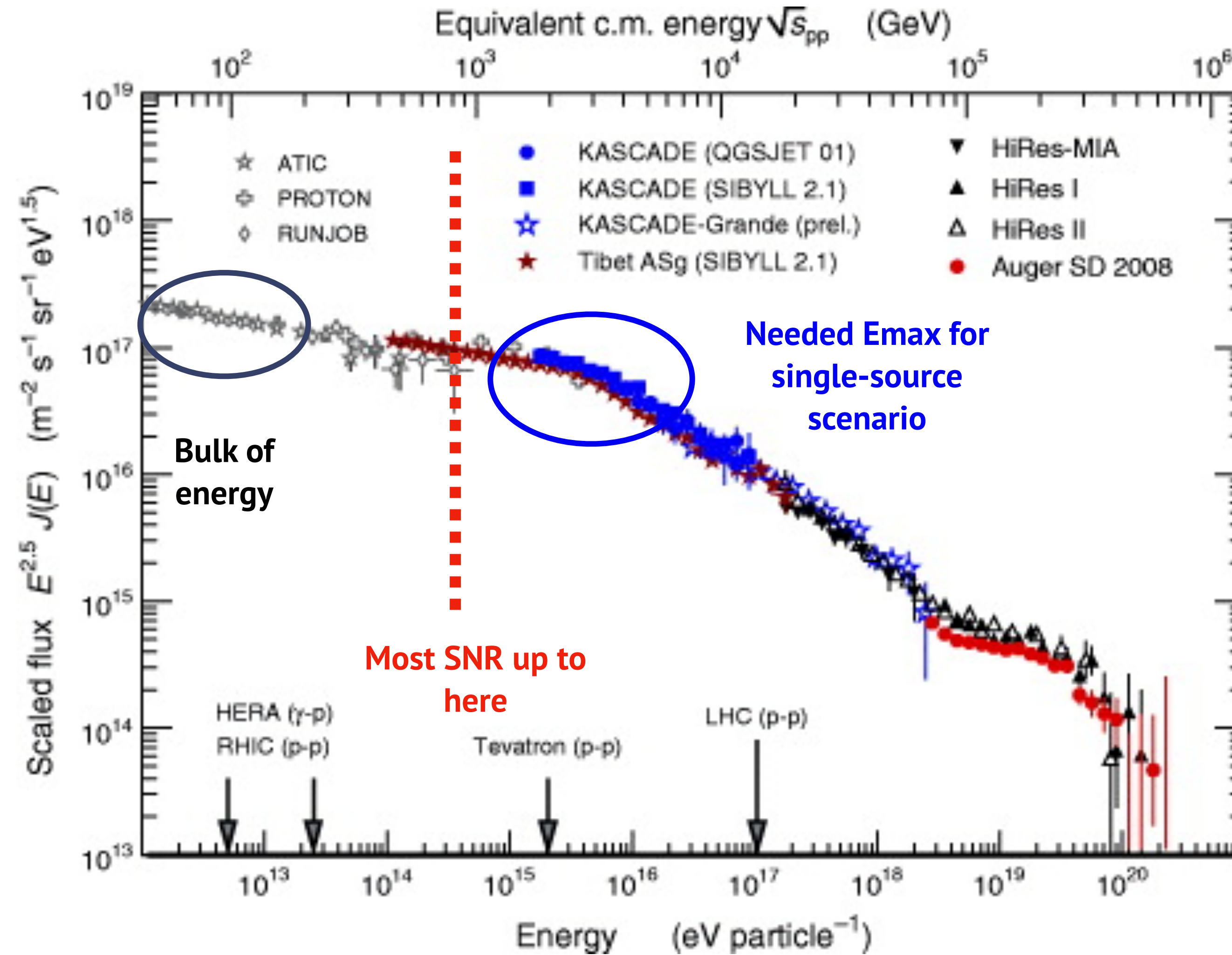


Figure: The cosmic ray spectrum (Blümer et al. 2019)

Structured CSM

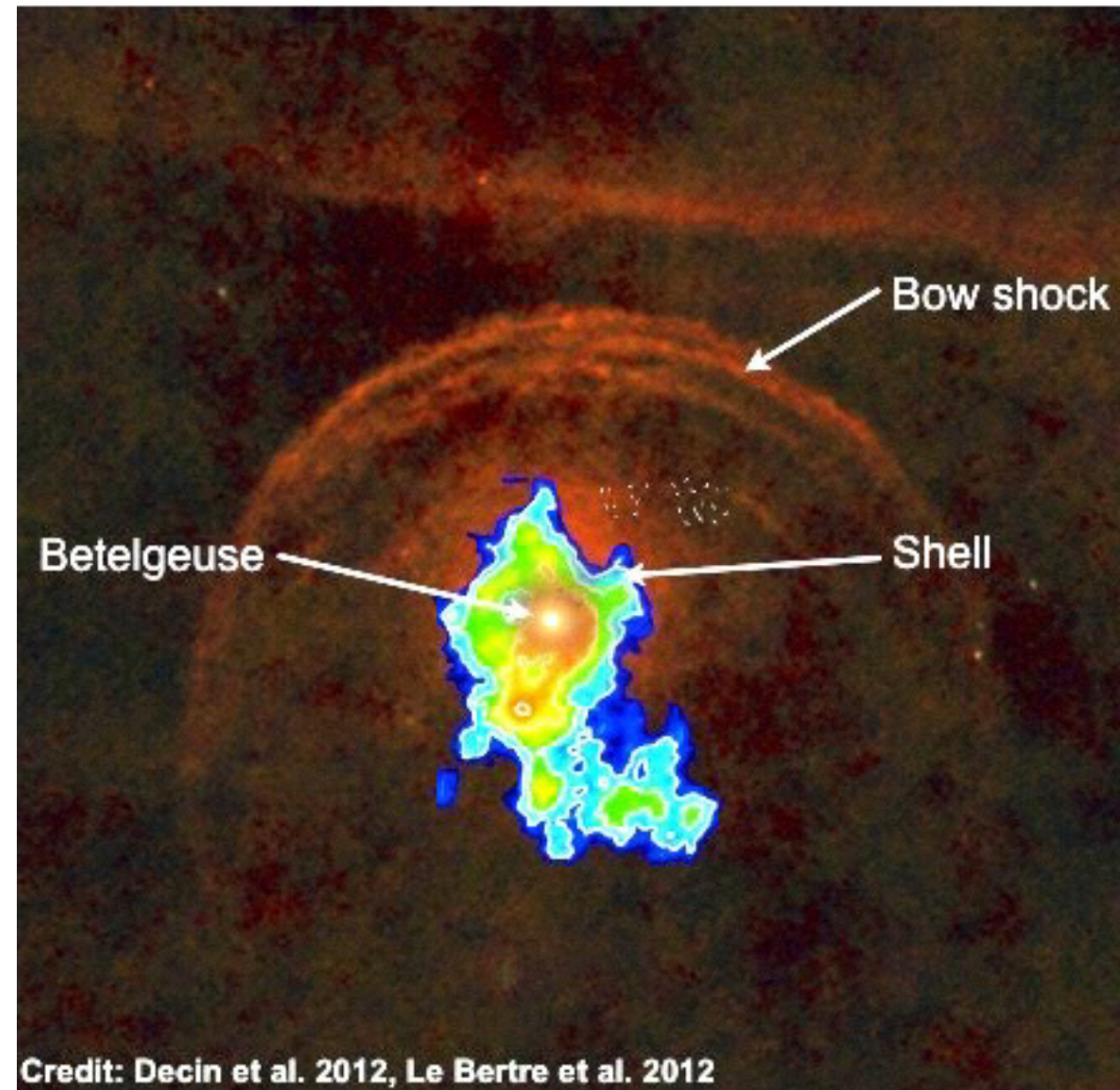
RSGs:

- Shell created by dense winds + intense ambient photon field

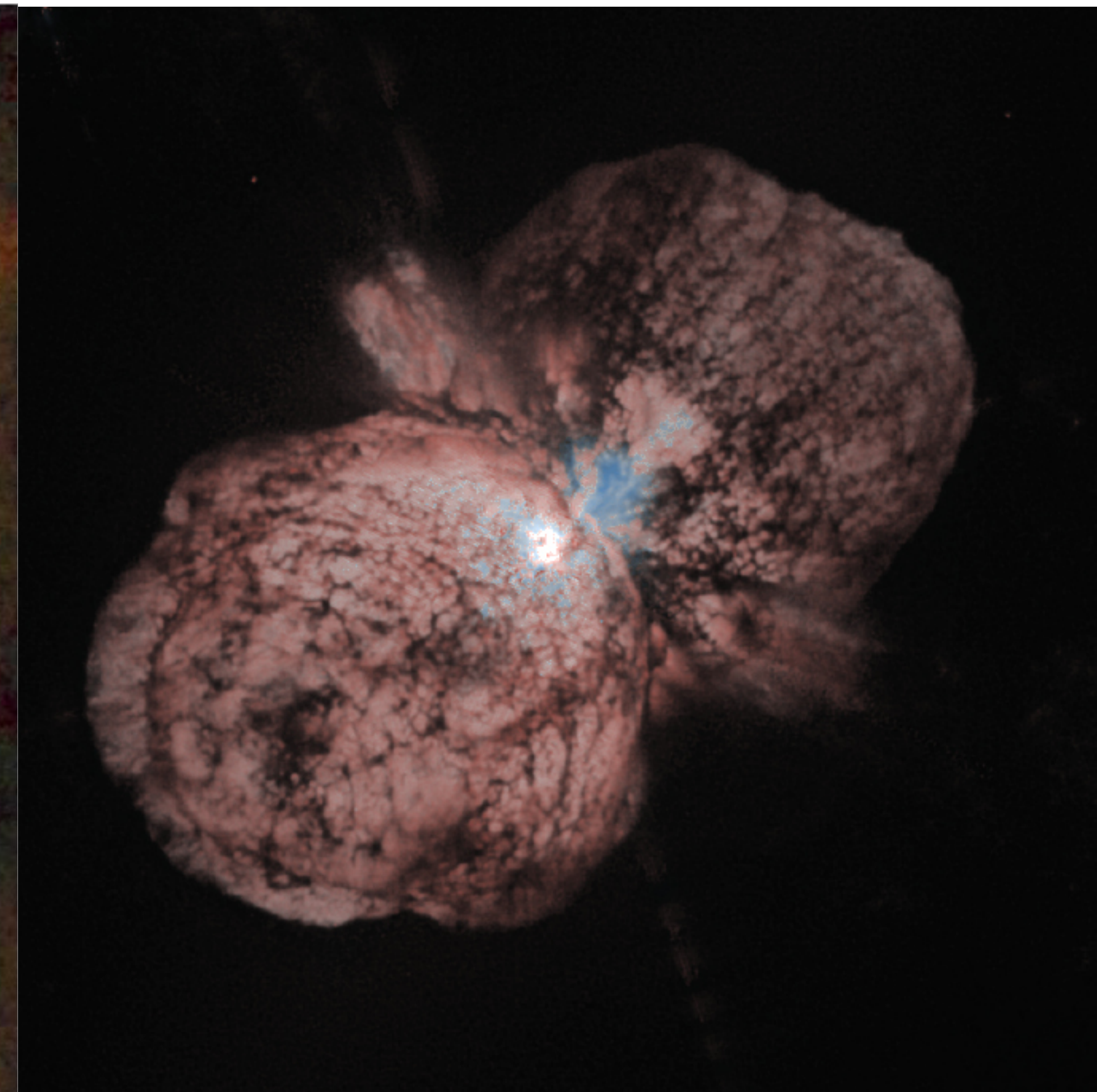
→ Photoionization confined shells

LBVs:

- Highly unstable mass-loss
- Dense shells with few $M_{\odot}$



Herschel view of Betelgeuse



HST view of η Carinae (NASA, STScI)

Structured CSM - Shell Setup

- Adding a (gaussian) CSM-shell with:

$$M_{\text{shell}} = 2M_{\odot}$$

$$R_{\text{shell}} \approx 3 - 60\text{mpc}$$

$$D_{\text{shell}} \approx 0.5\text{mpc}$$

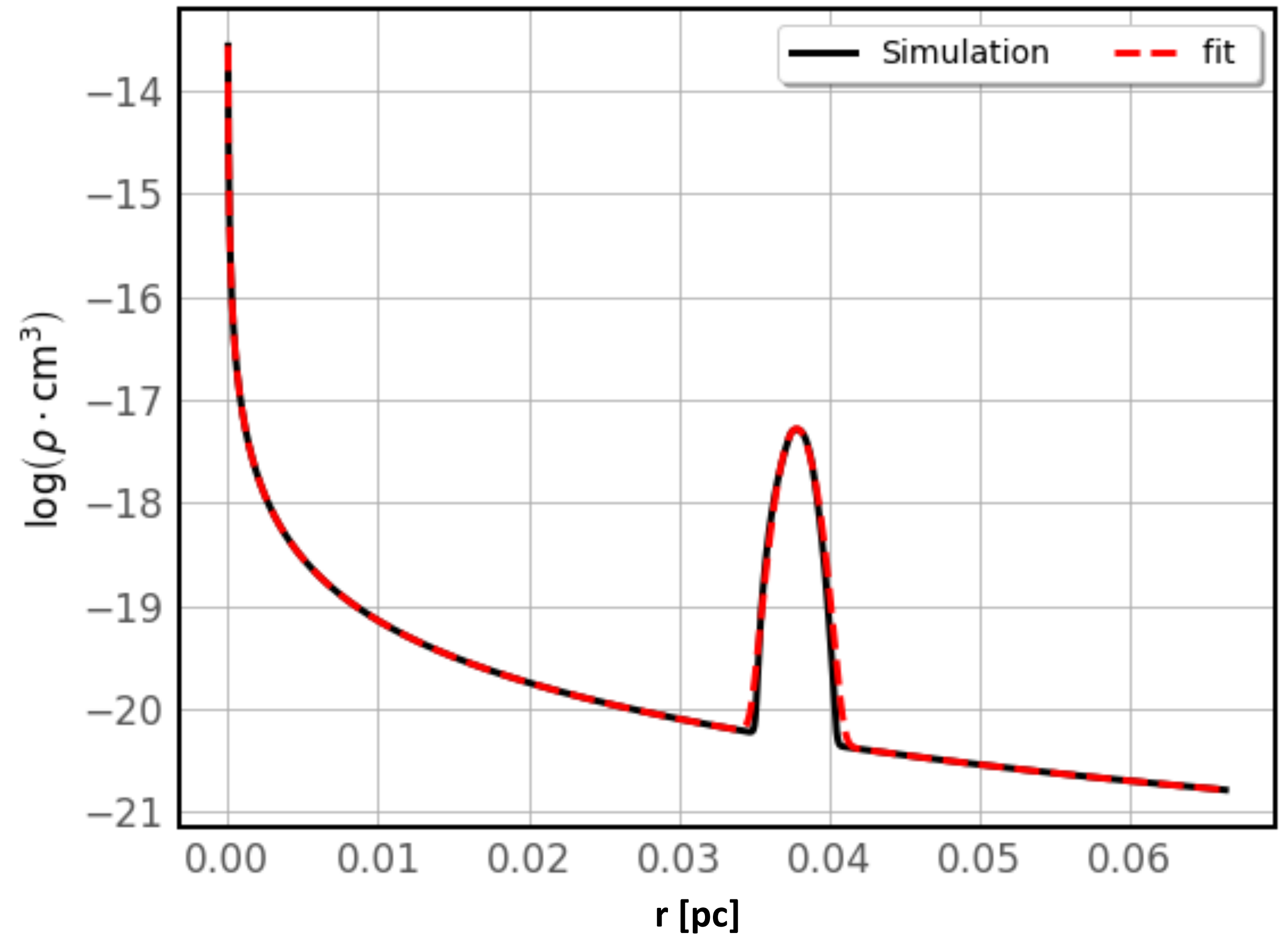
- Modest steady mass-loss with:

$$\dot{M} = 10^{-4}M_{\odot}/\text{yr}$$

- Shock-shell interaction after

$$\approx 30 - 3000\text{days}$$

- Interaction triggers reflected shocks –
shock-shock interactions after



CSM-structure for a LBV with a episode of high mass-loss in the past (example plot)

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$$R_{\text{shell}} \approx 3 - 60\text{mpc}$$

$$D_{\text{shell}} \approx 0.5\text{mpc}$$

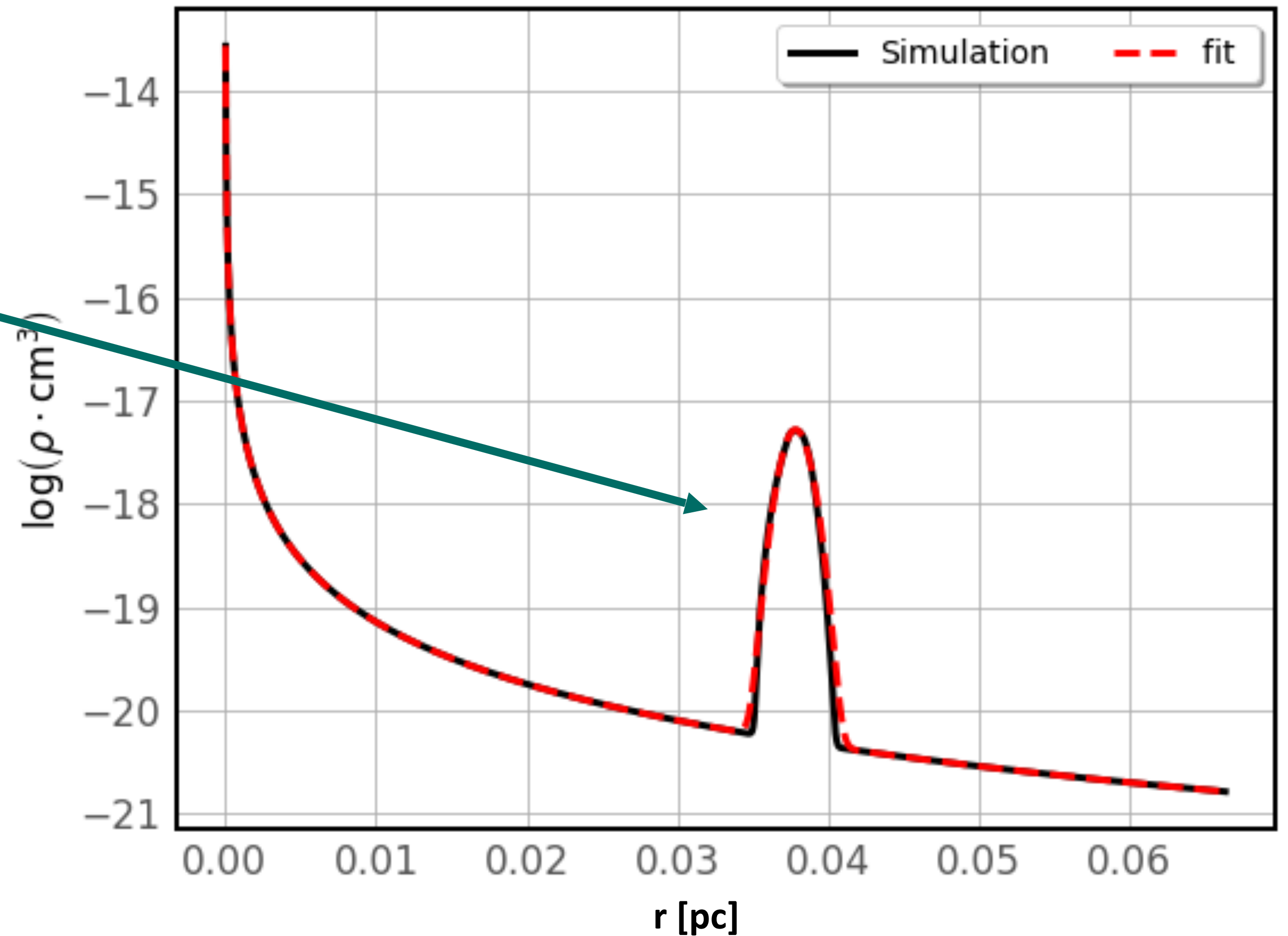
- Modest steady mass-loss with:

$$\dot{M} = 10^{-4}M_{\odot}/\text{yr}$$

- Shock-shell interaction after

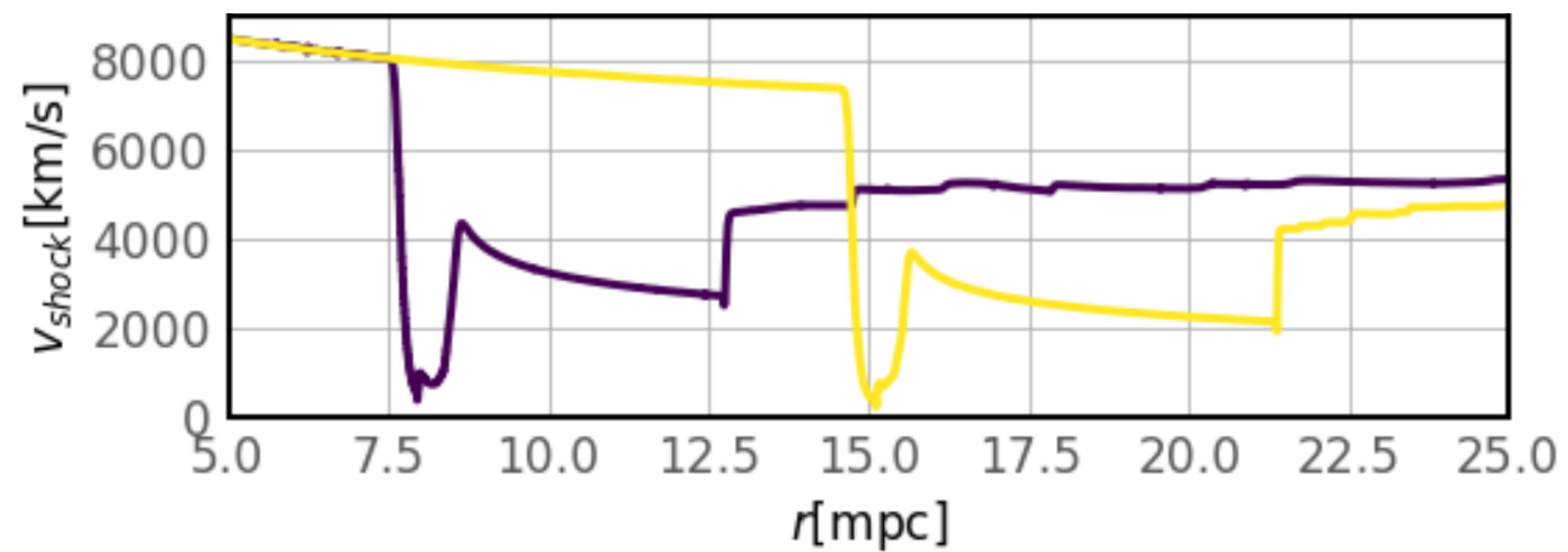
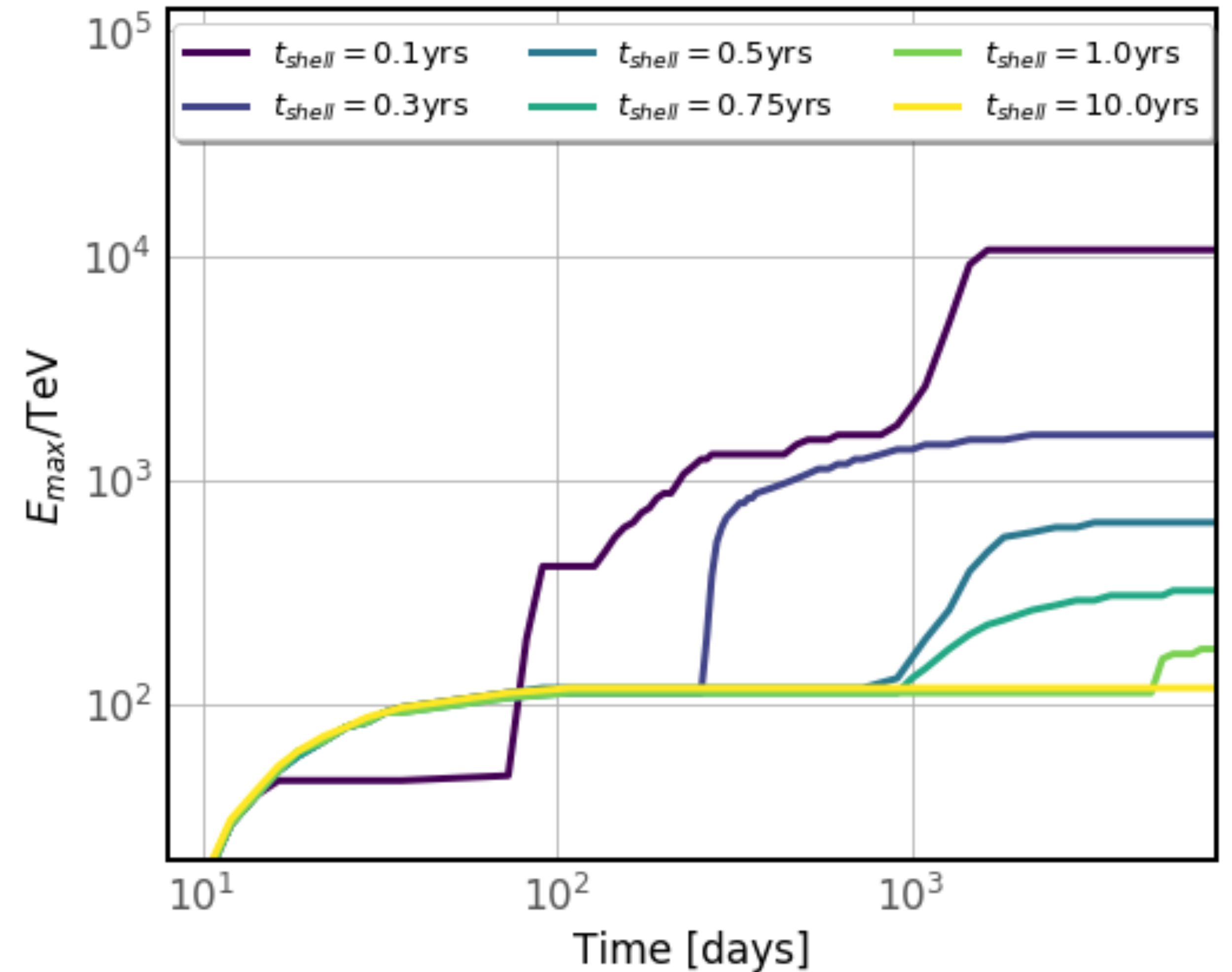
$$\approx 30 - 3000\text{days}$$

- Interaction triggers reflected shocks –
shock-shock interactions after



CSM-structure for a LBV with a episode of high mass-loss in the past (example plot)

Results: $E_{\max}$ (LBVs)

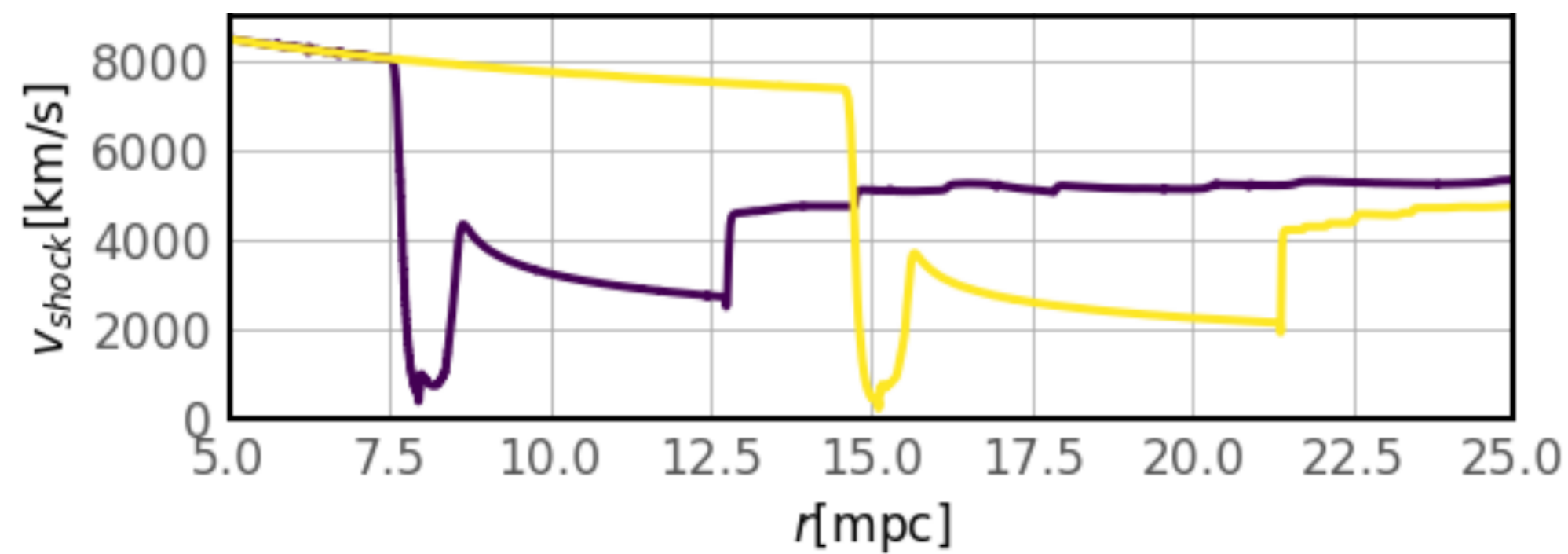


Maximum energy over time for Type-Ia SNe interacting with dense shells (RB, et al. 2025)

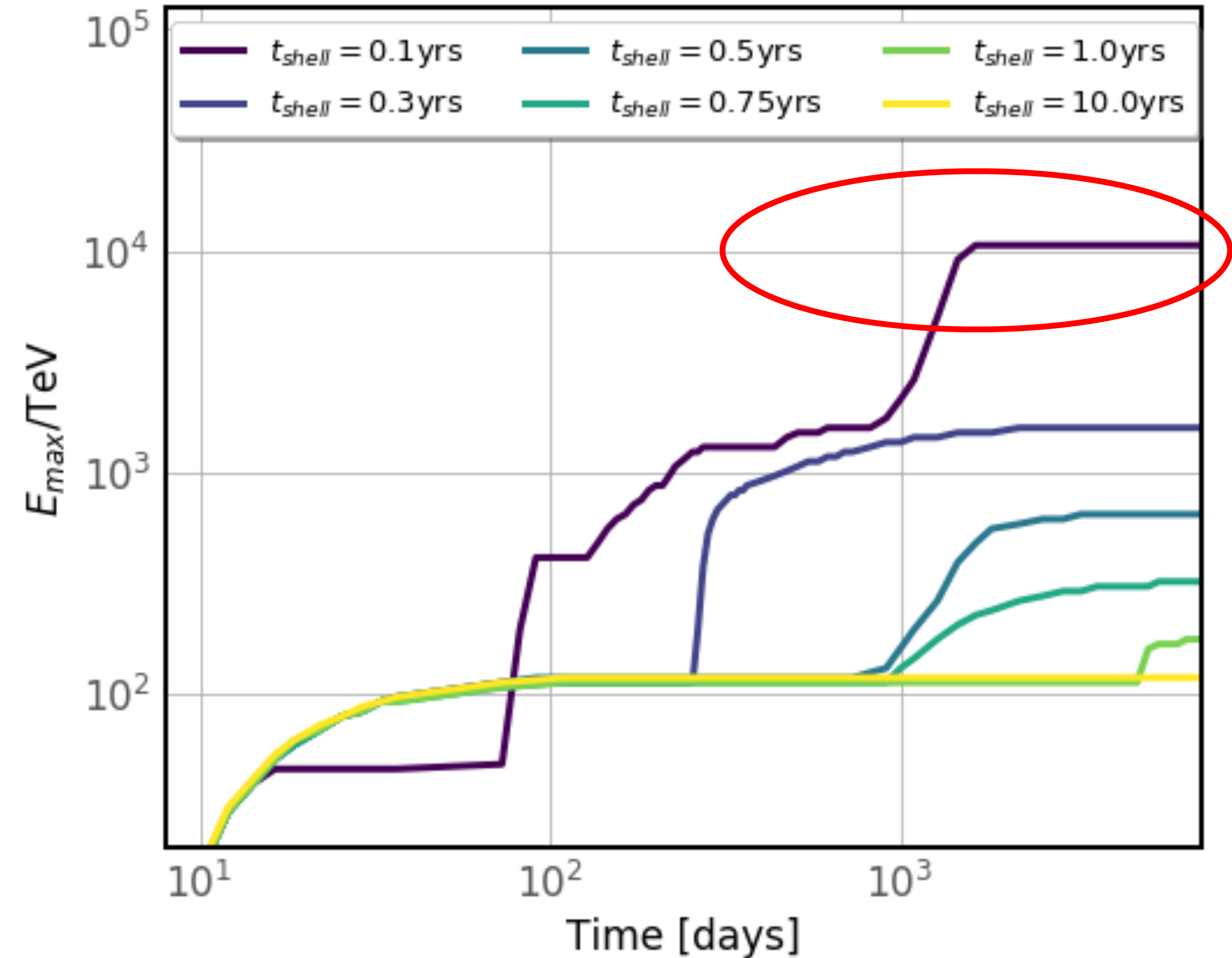
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Shell:

- Shock-shell interaction reduces $E_{\max}$ of freshly accelerated CRs



- Reaccelerated shock after shell passage propagates into amplified field of previously escaped CRs → Boost to $E_{\max}$ ($E_{\max}$ limited by shock-capture time)

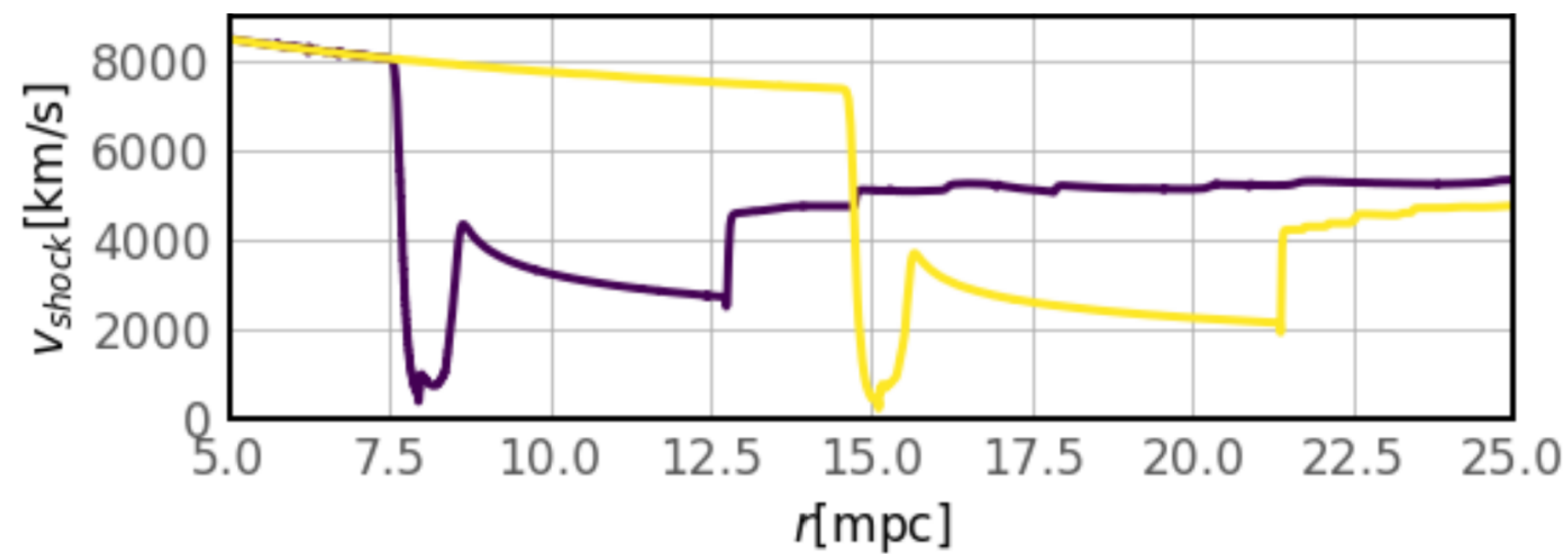


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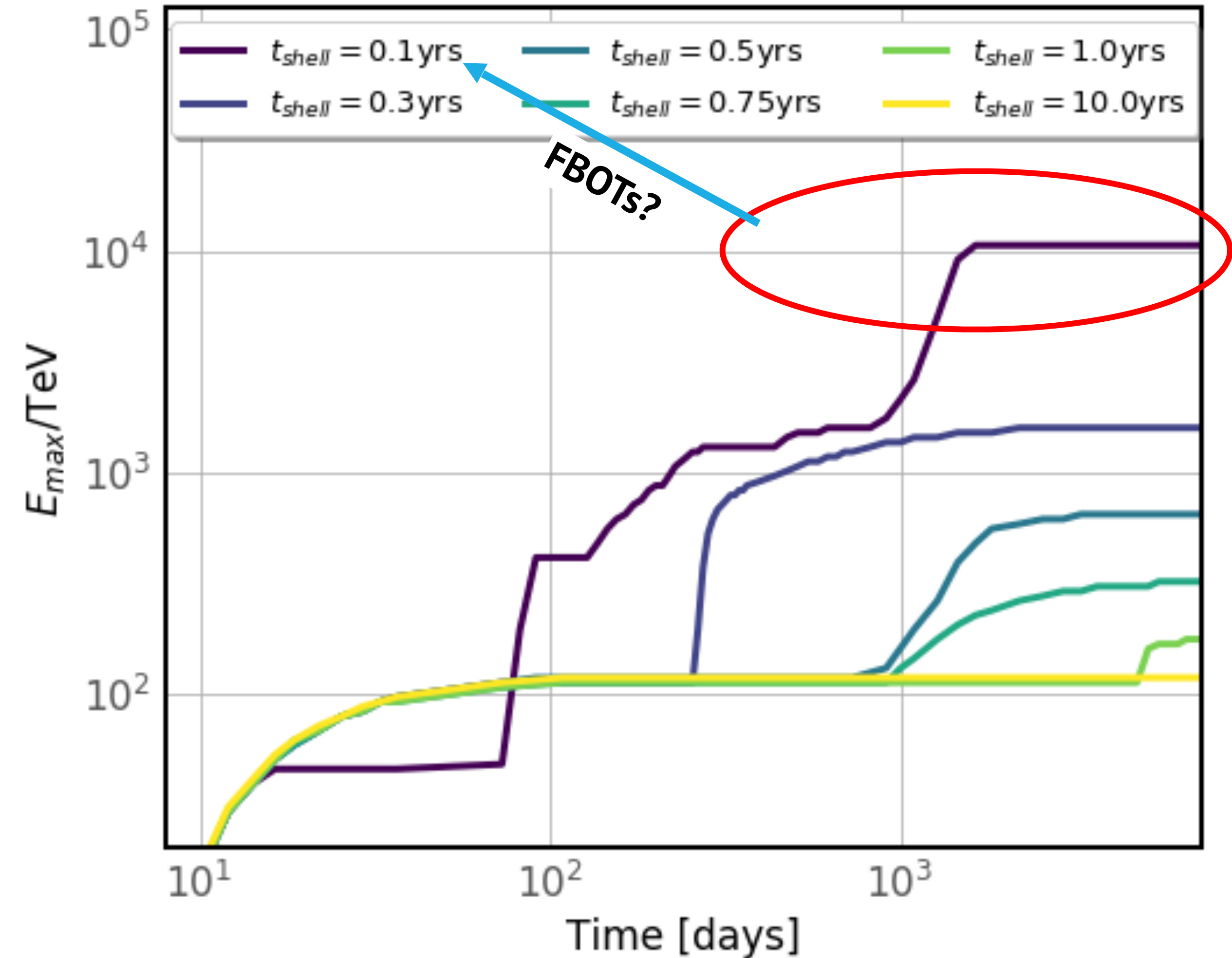
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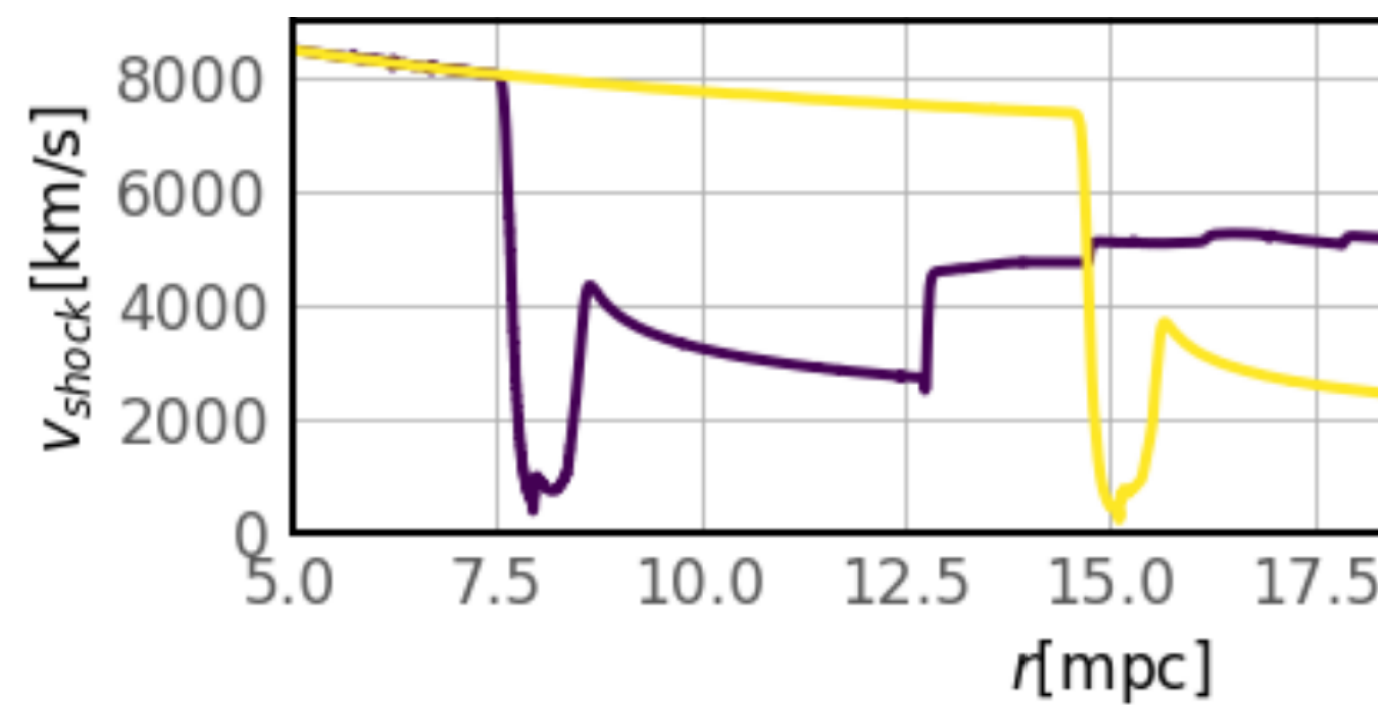


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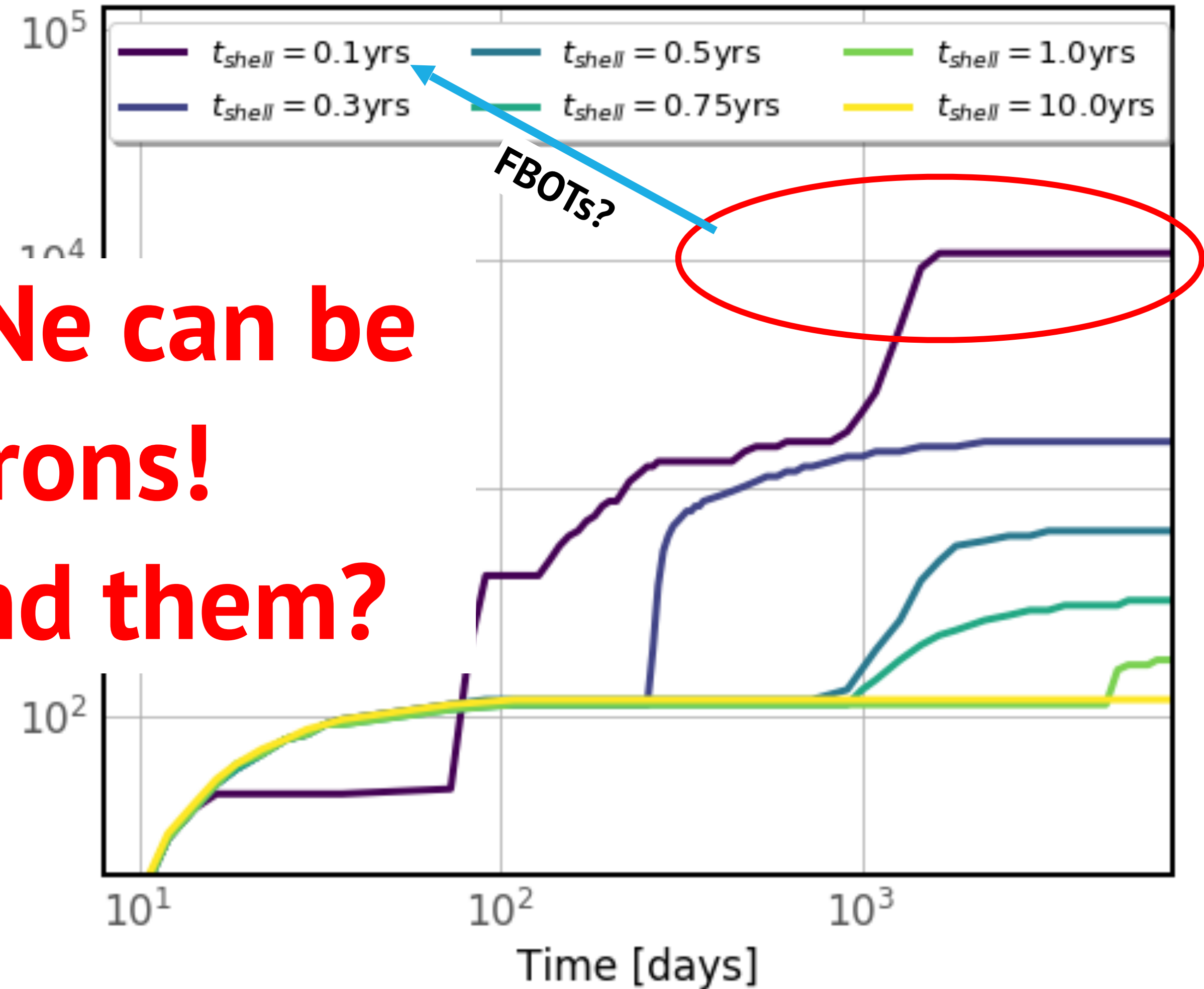
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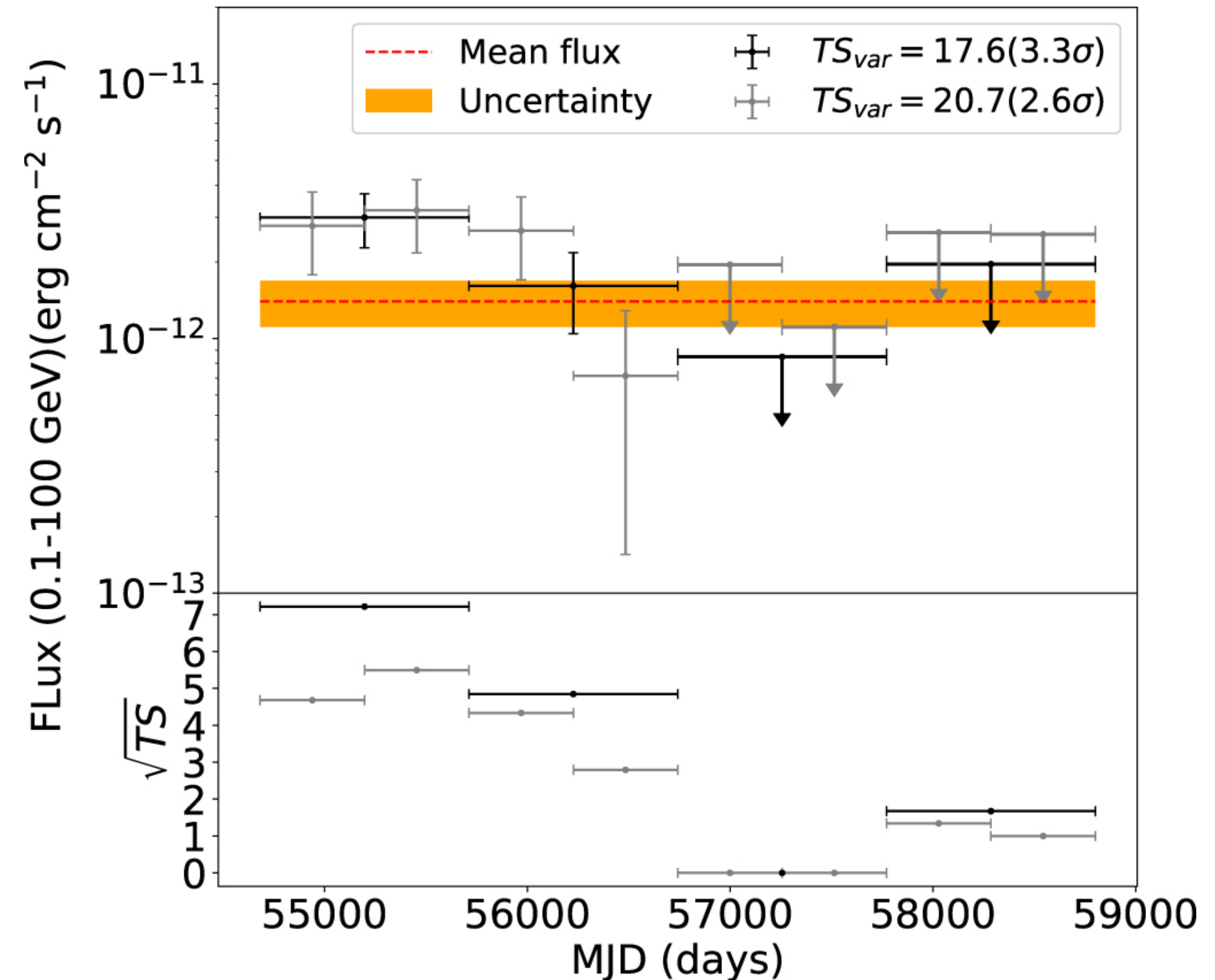
Type-IIn SNe can be PeVatrons!
How to find them?



Maximum energy over time for Type-IIn SNe interacting with dense shells (RB, et al. 2025)

SNRs as CR Sources

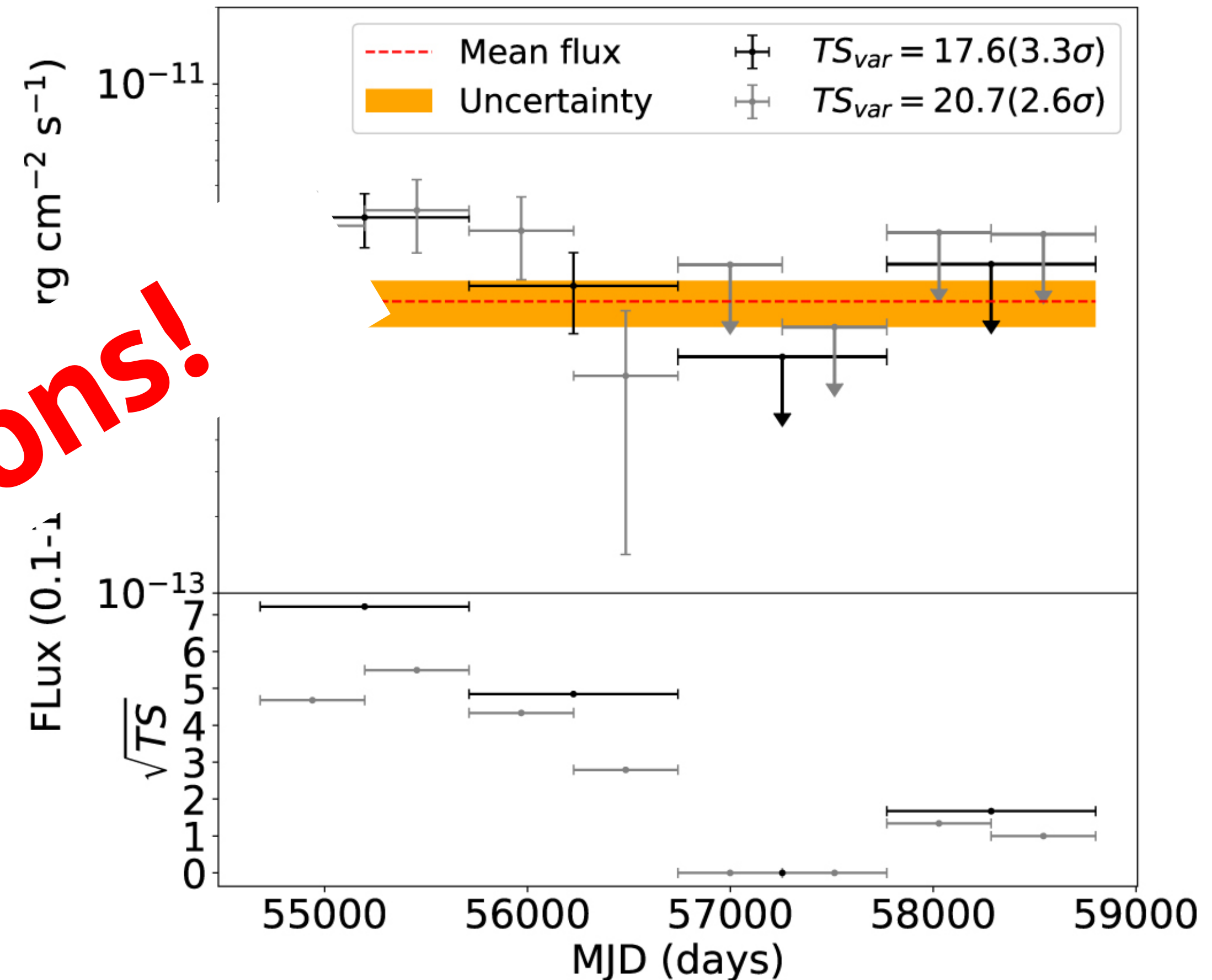
- H.E.S.S. Collaboration (2019) obtained upper limits on TeV emission from nearby CCSNe
- Ongoing HESS ToO programme so far has no detections
- Xi+(2020) detected γ -rays from the location of SN 2004dj, a bright and nearby SN IIP, with FERMI-LAT
- A recent variability analysis of FERMI-LAT data found evidence in support of 2 further detections (Prokhorov+2021).
- Also suggestion of increasing flux from SN1987A with FERMI-LAT (Malyshev+2019)
- Non detection of SN 2023ixf at $\sim 7\text{Mpc} \rightarrow E_{\text{CR}} < 10^{49}\text{erg}$ (Martí-Devesa+2024)



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No detections!



Summary II

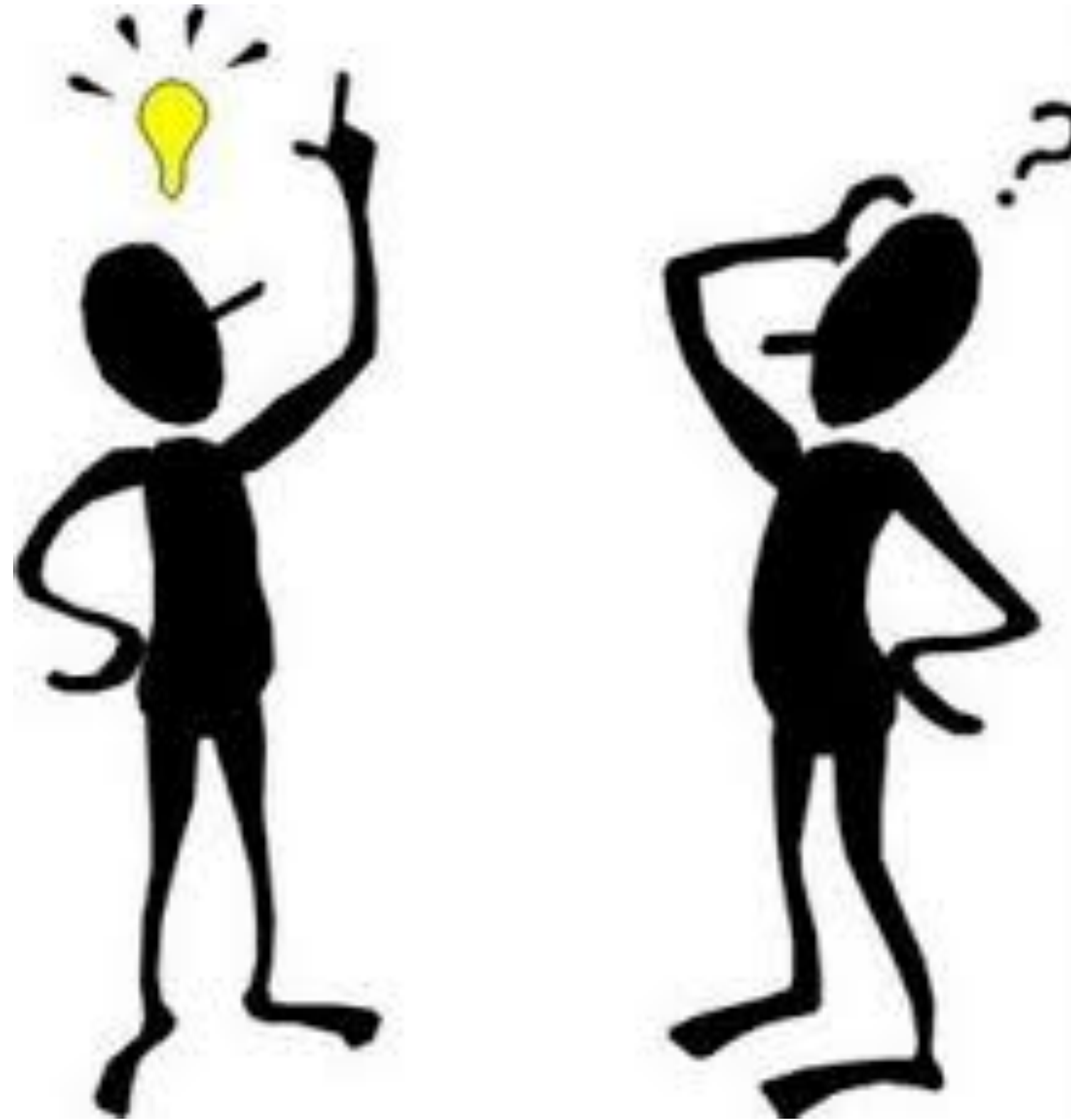
- SNRs usually reach too low $E_{\max}$
- BUT $E_{\max}$ coincides (roughly) with features in GCR-spectrum
- Exceptional cases early-on might operate as PeVatrons
- Shell-interactions might greatly boost gamma-ray signals

Summary II

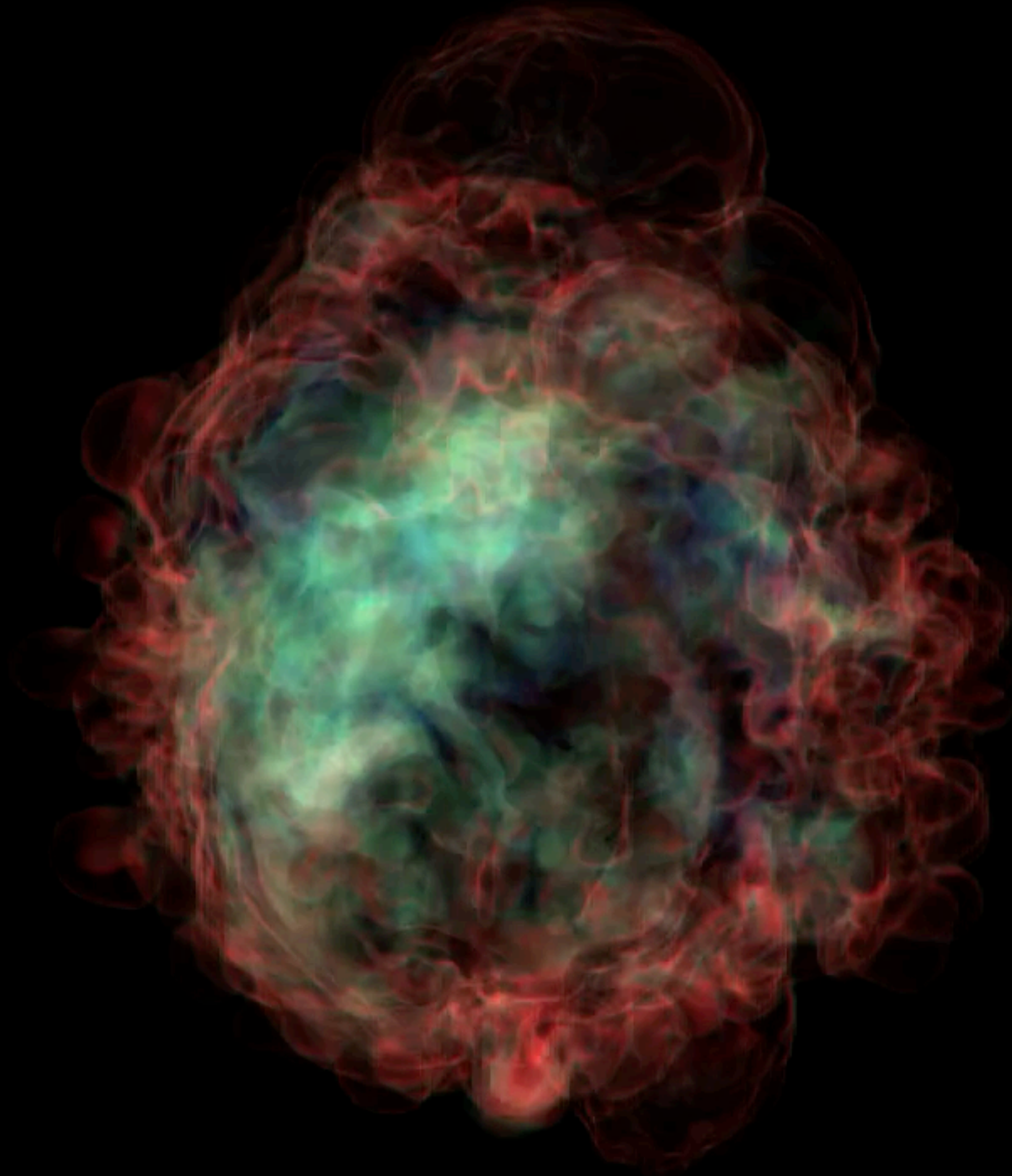
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Multi-wavelength strategies needed

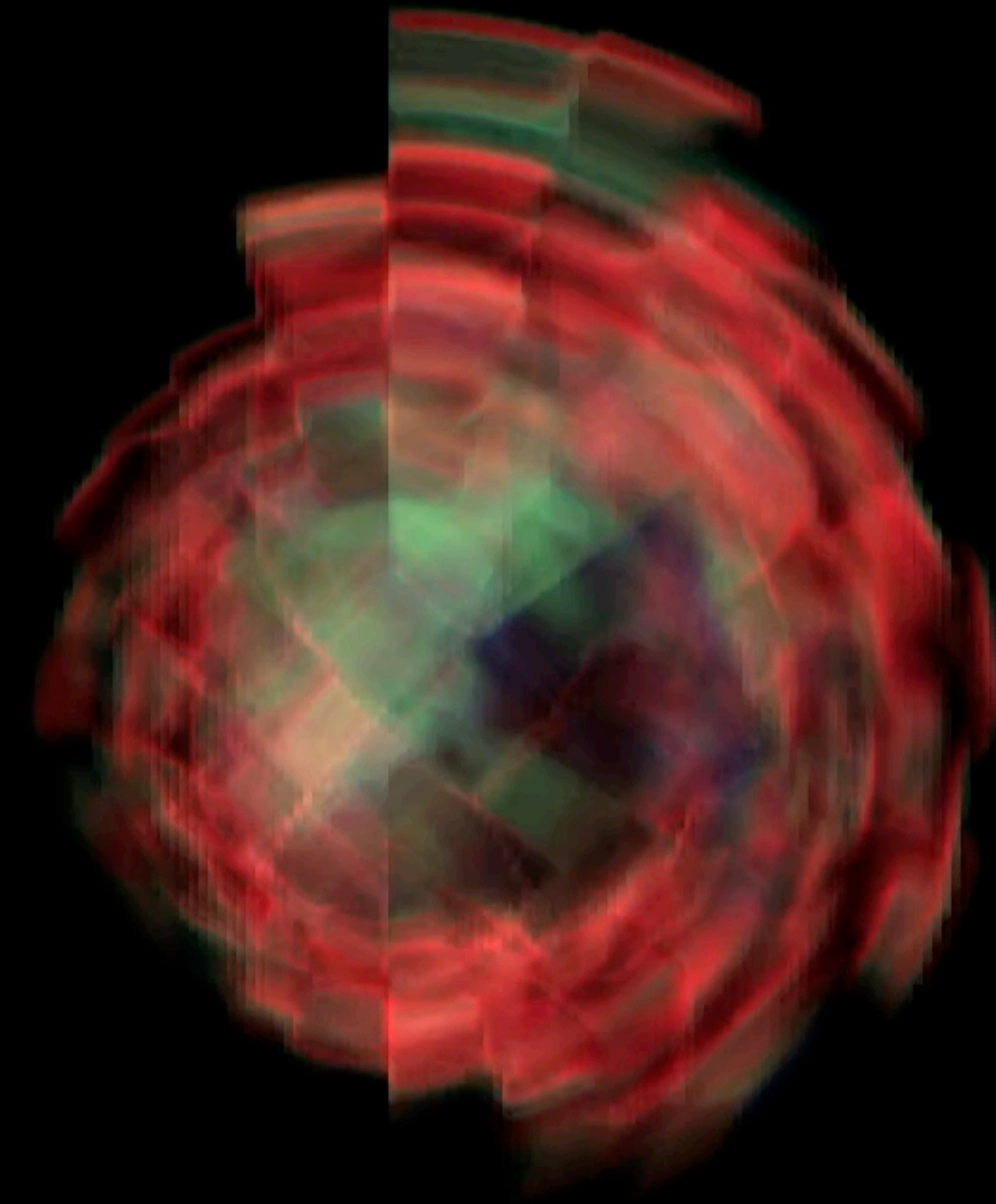
What else?



Pseudo-3D models: ^{60}Fe distribution



Schulreich, M. M. Et al. (2023)

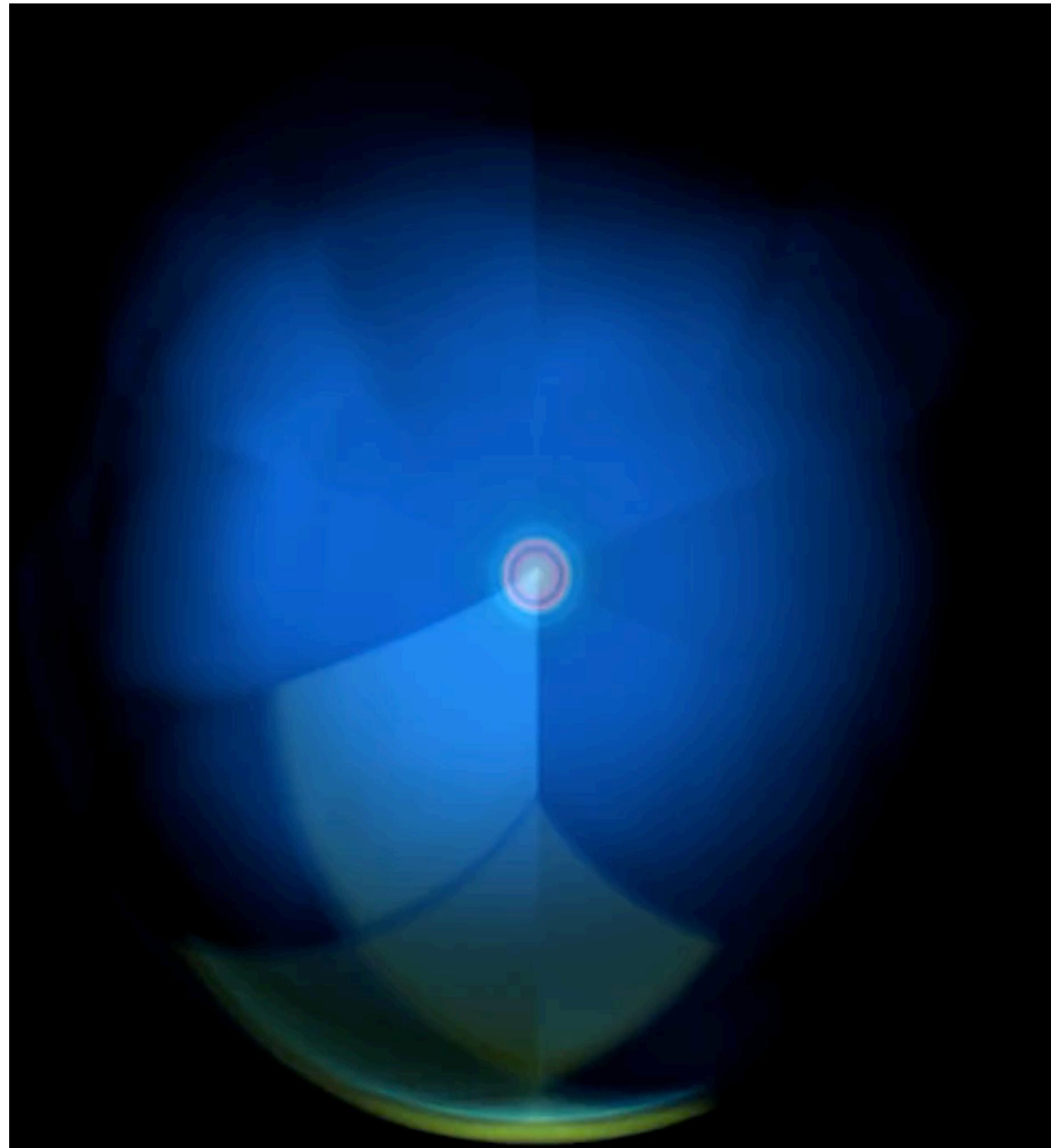


Rendering with HEALPix and RATPaC

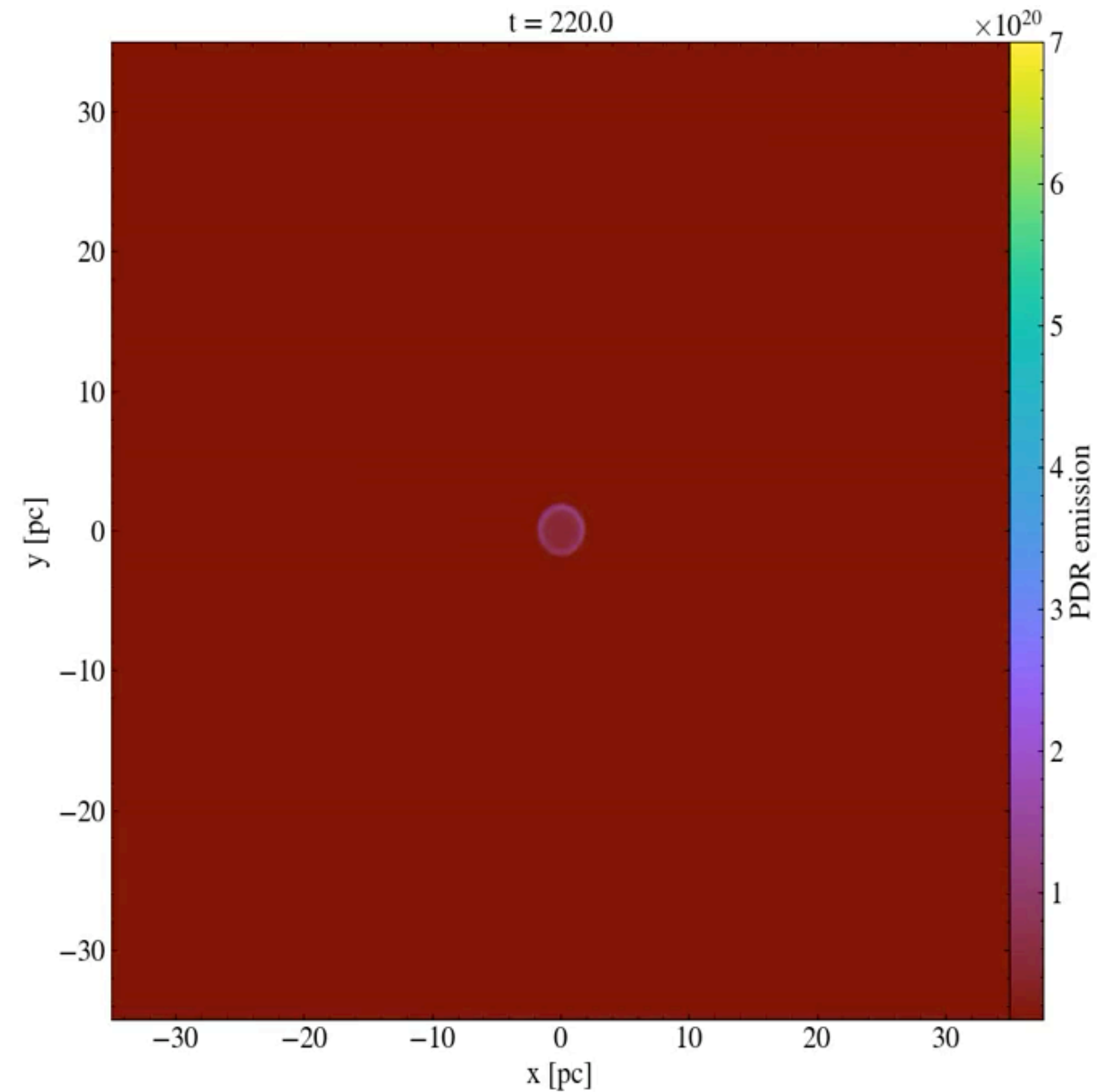
Application: ^{60}Fe distribution with 192 pixels

Time evolution

3D map



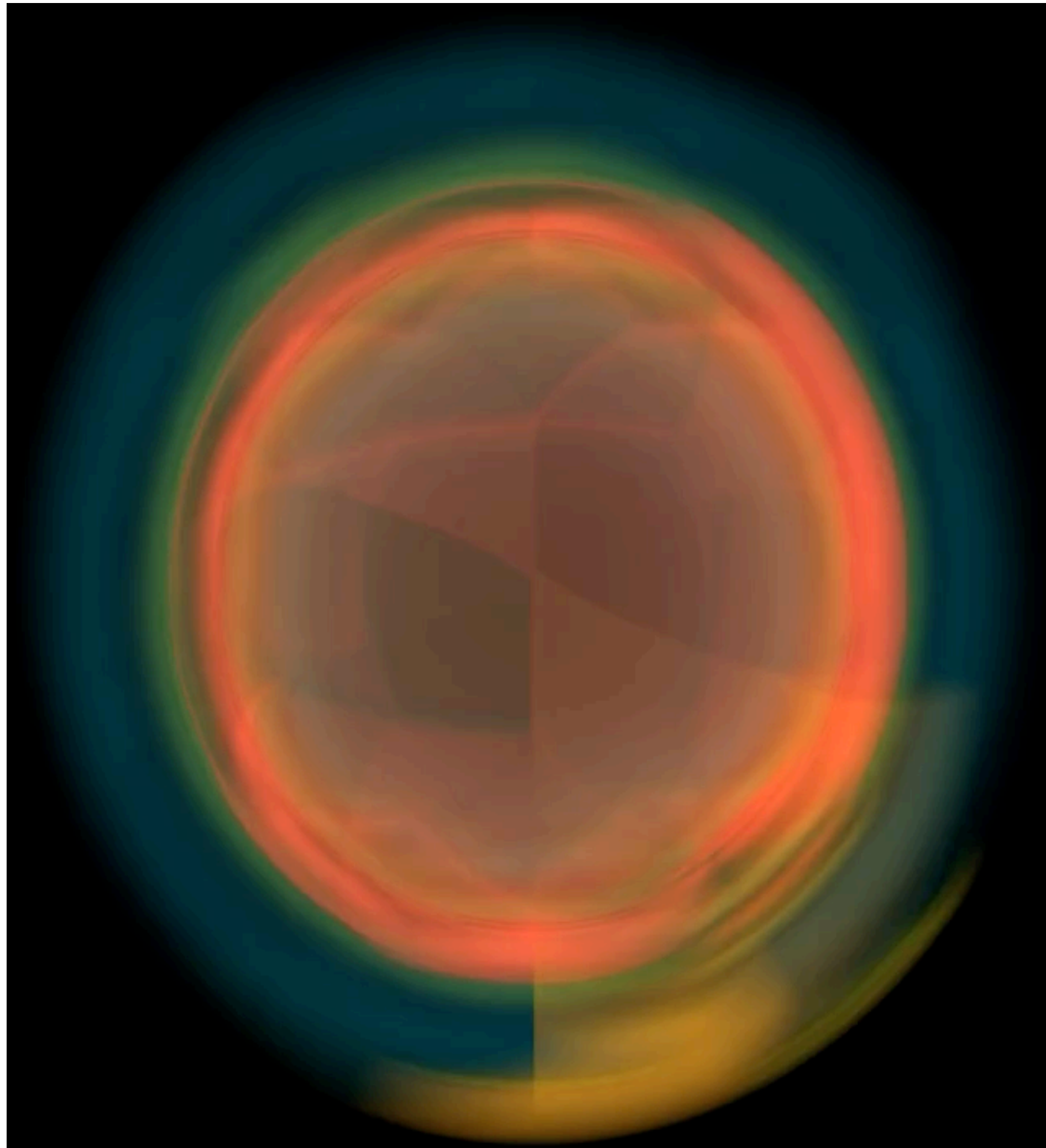
Projection



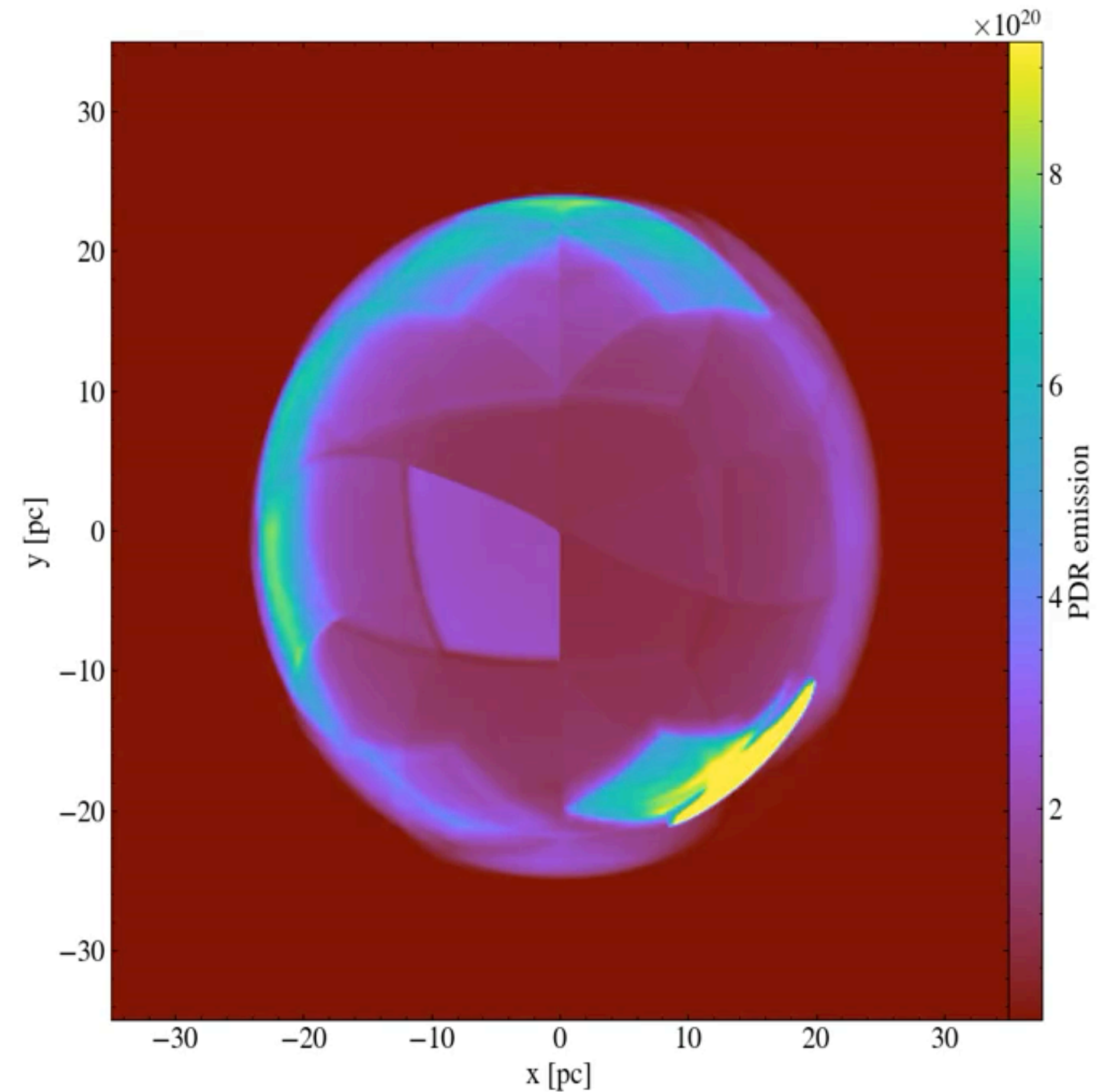
Application: Pion decay emission

Rotation at 10kyr

3D map



Projection



Conclusion and outlook

Particle Escape

- SNRs can produce the right spectra
- Gamma-ray halos should form as a consequence

$$E_{\max}$$

- $E_{\max}$ for Type IIPs of ~ 70 TeV is in rough agreement with spectral break in Galactic CR-spectrum
- Type-IIn SNe with early shell-interaction is possible PeVatrons $\rightarrow$ rare event
- Gamma-ray detection of interacting SNe require multi-wavelength efforts!

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Many more

- Time-variable emission might occur in SNRs on short timescales
- The environment structure can severely change spectra $\rightarrow$ population matters
- Possible link of source-environments to CR-abundance features
- Models of SNRs (and particle accelerations) still behind quality of observations