Cosmic Rays from Supernova Remnants: What are we missing?

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Firenze - ITALY

The new era of multi-messenger astro-particle physics —
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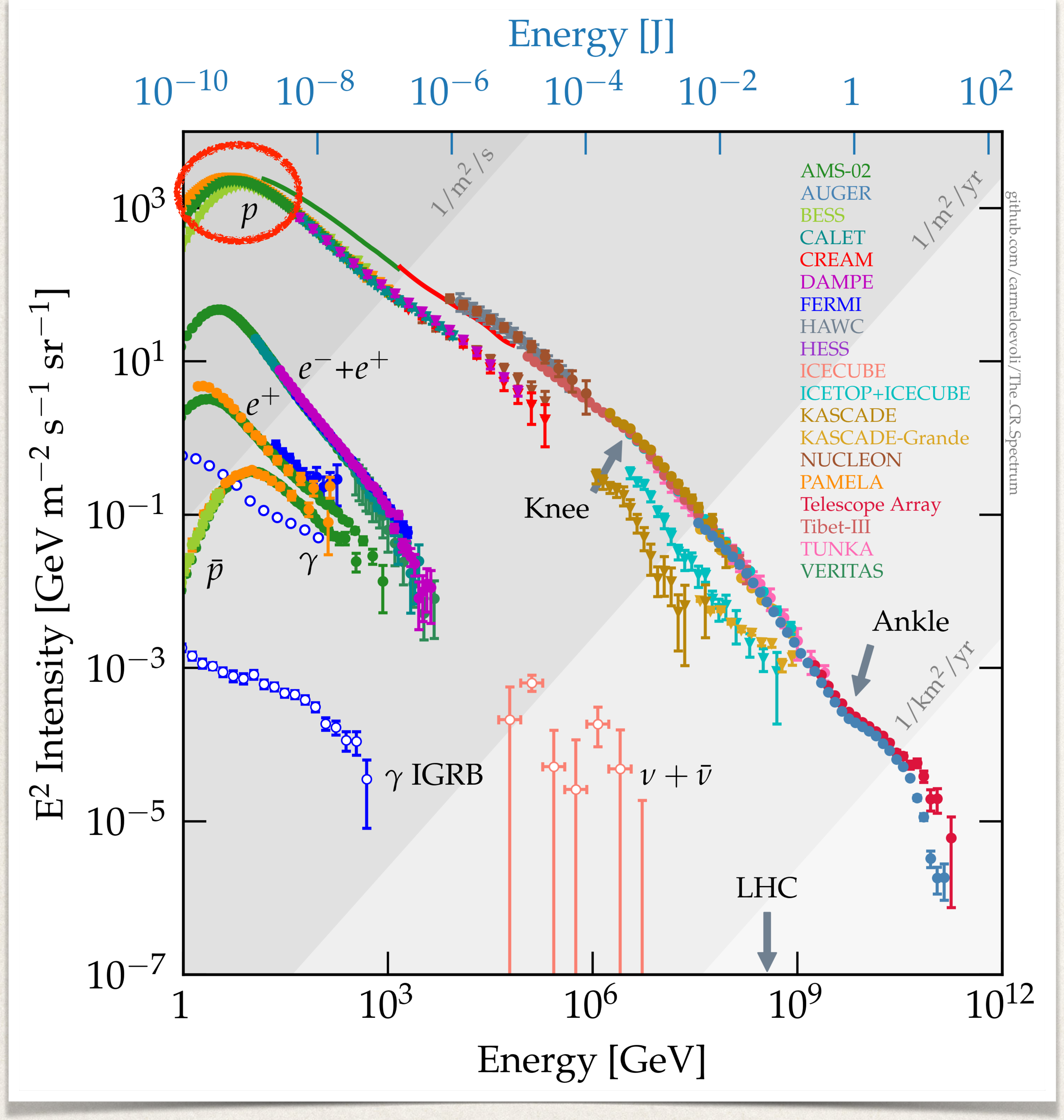
How to explain the origin of Galactic CRs



Requirements

- **Luminosity:** $\sim 10^{40}$ erg/s

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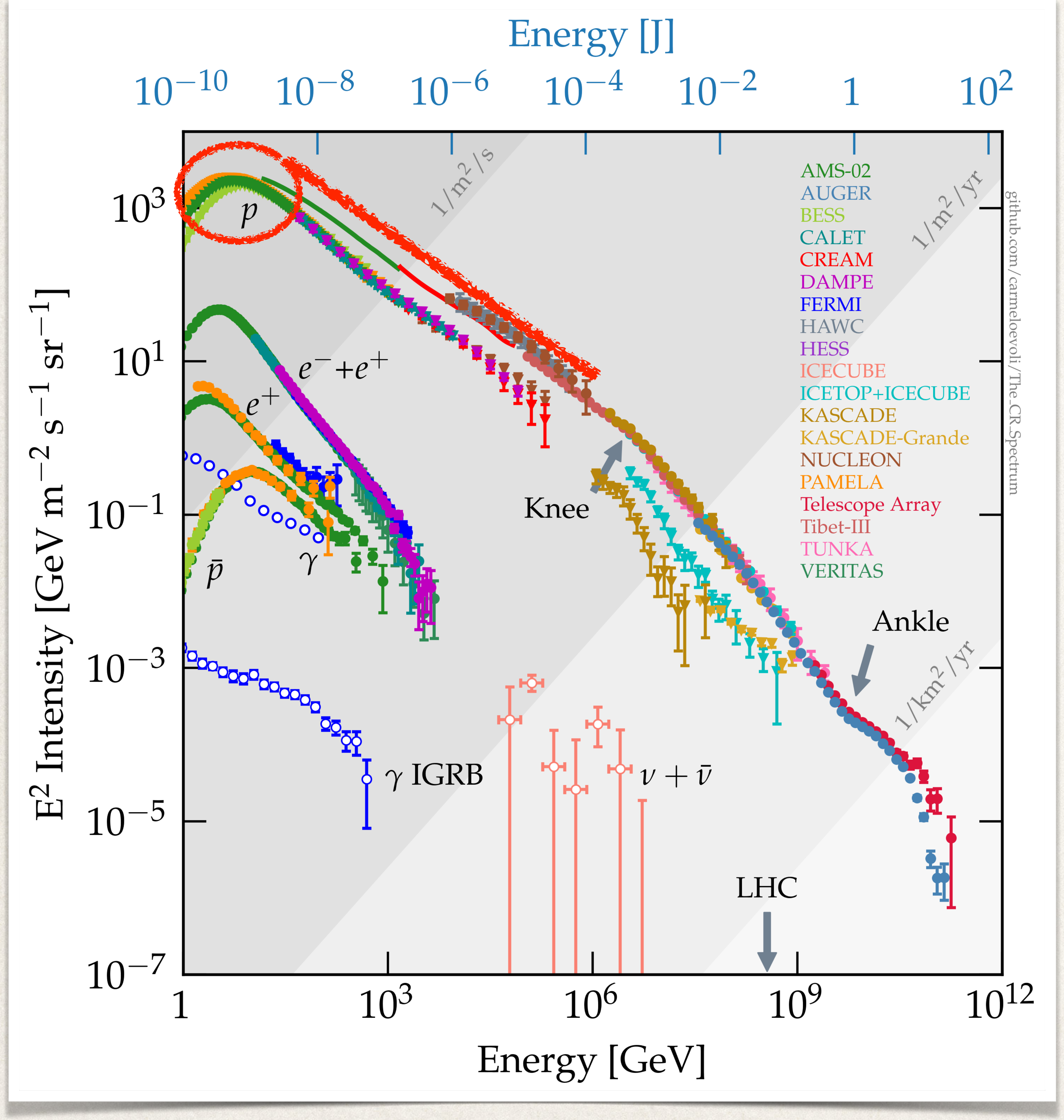

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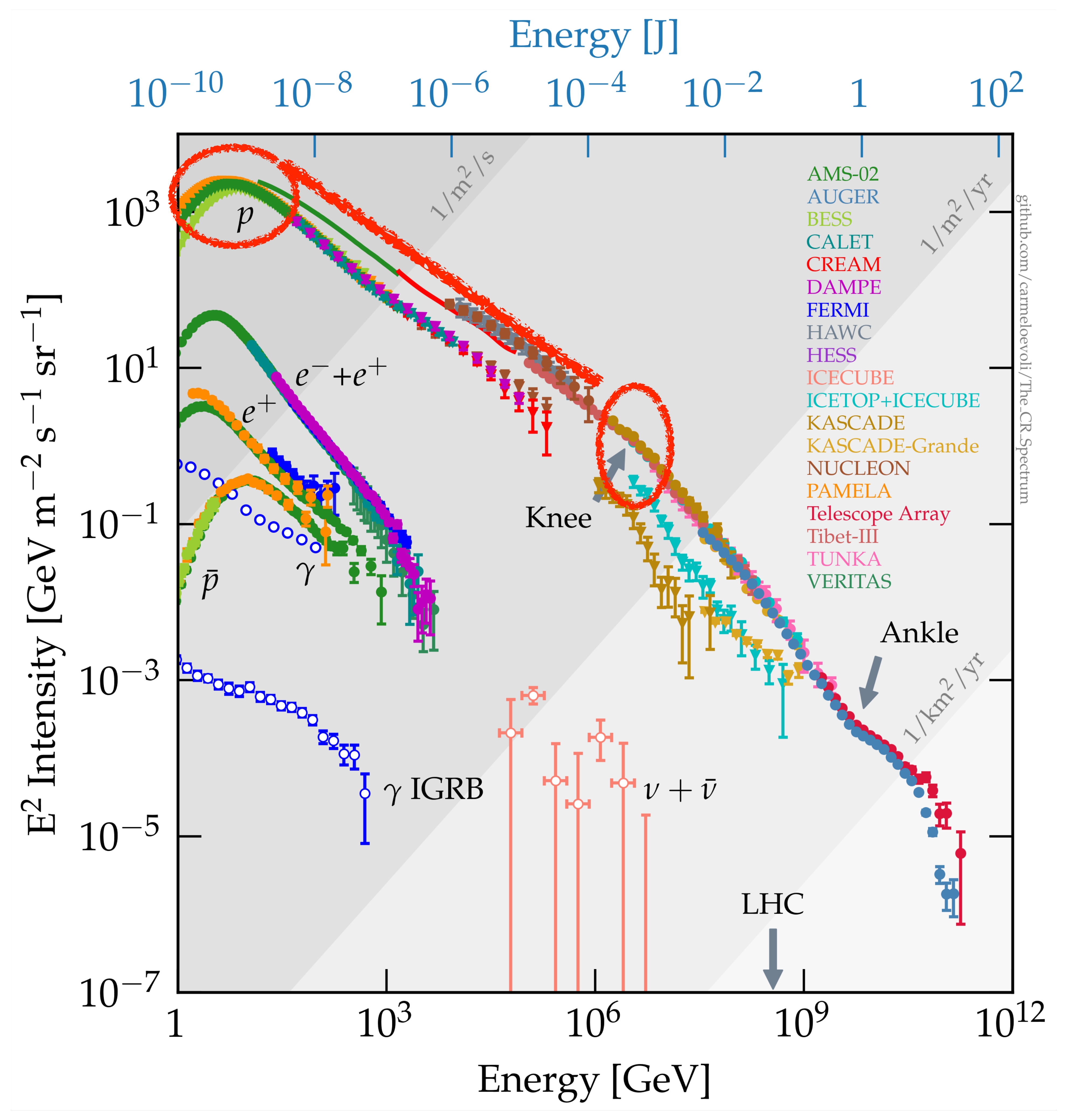

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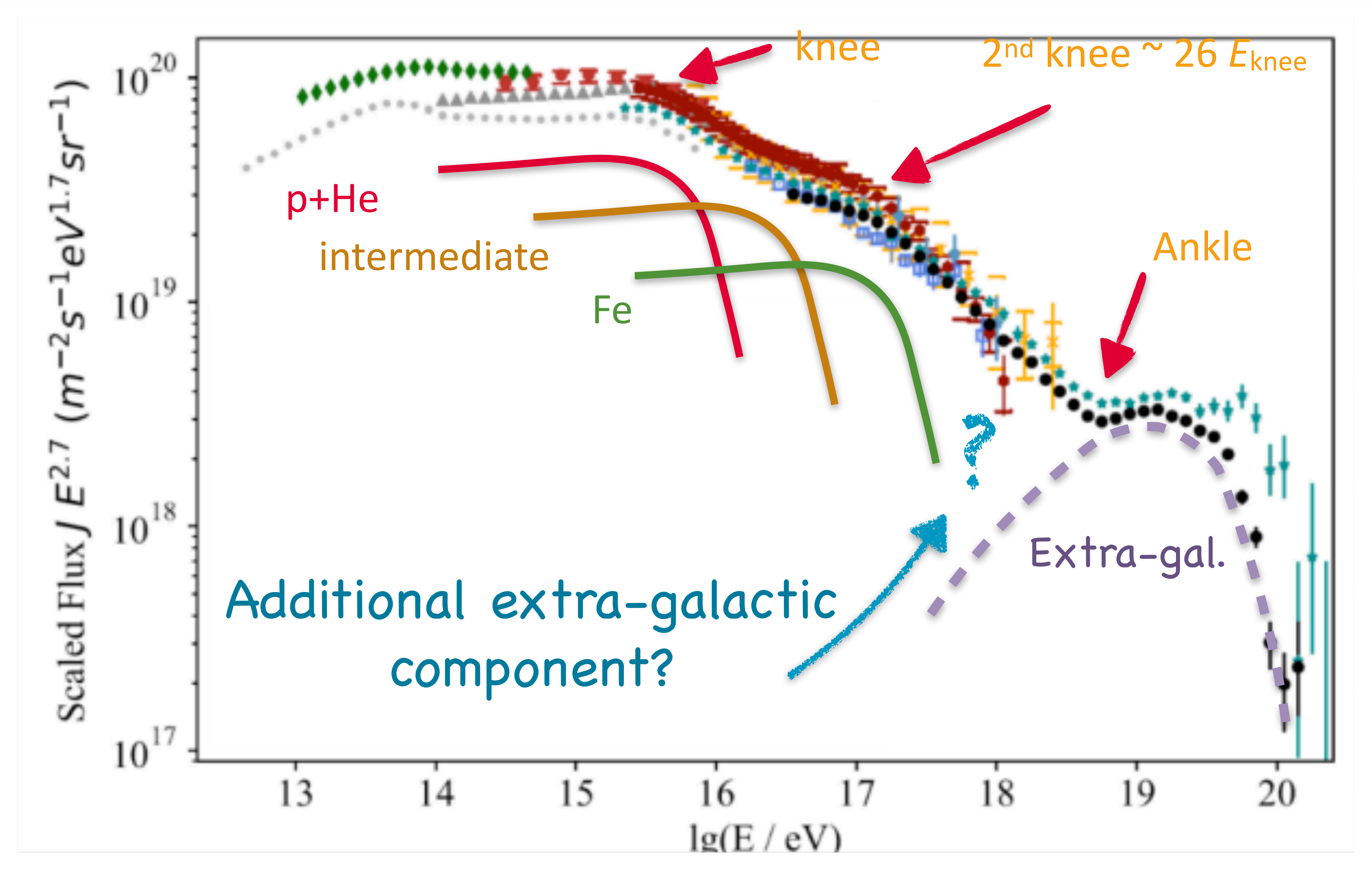

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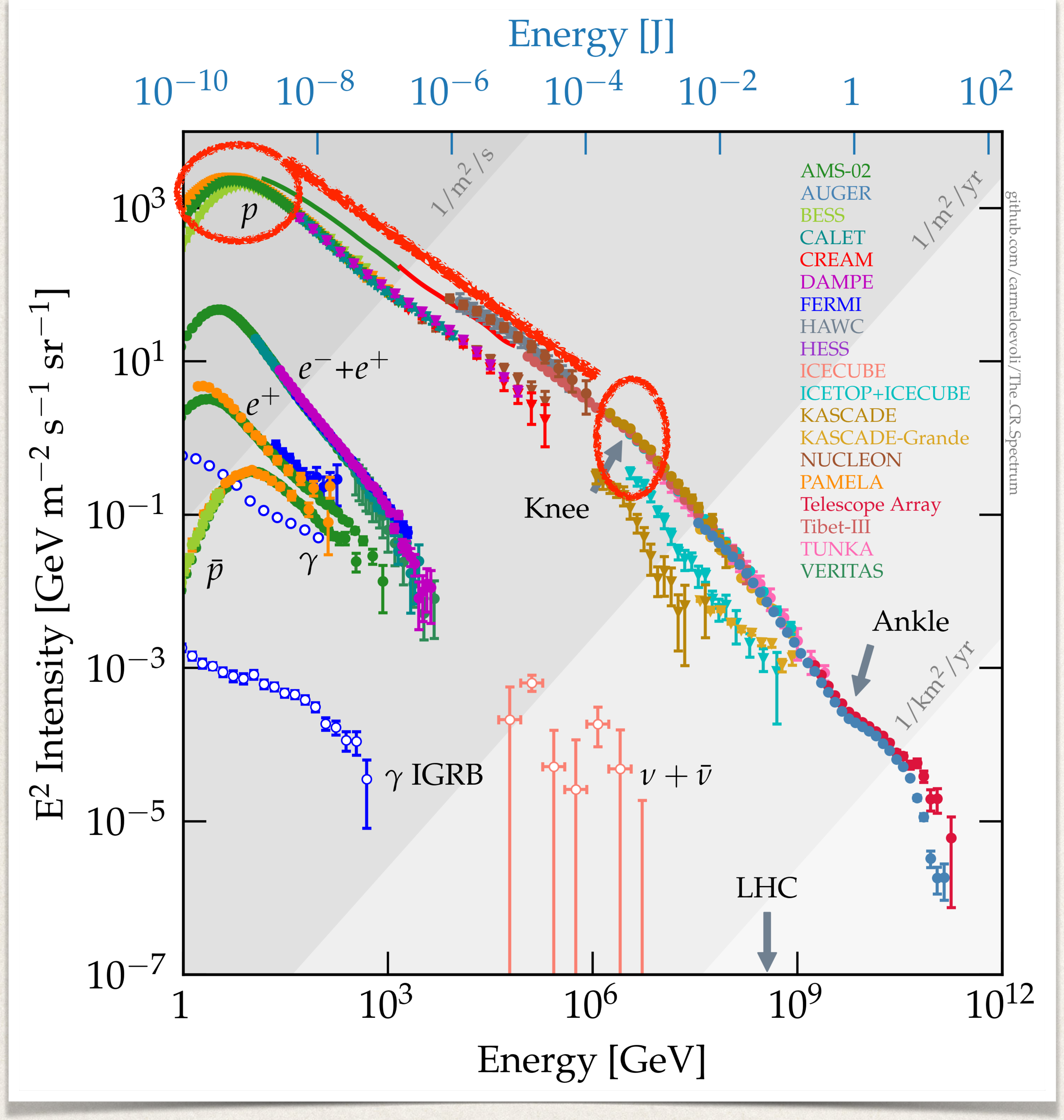

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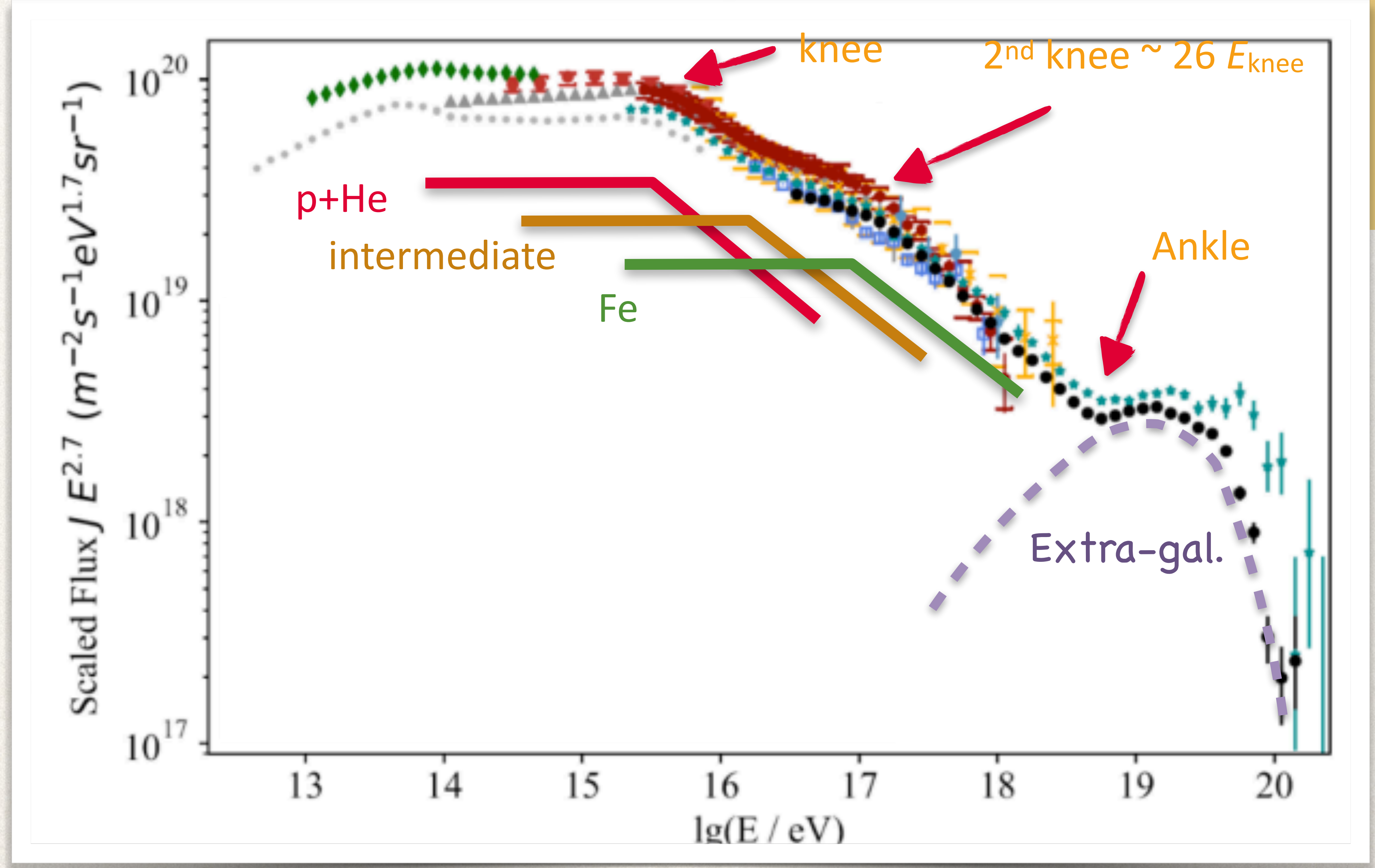

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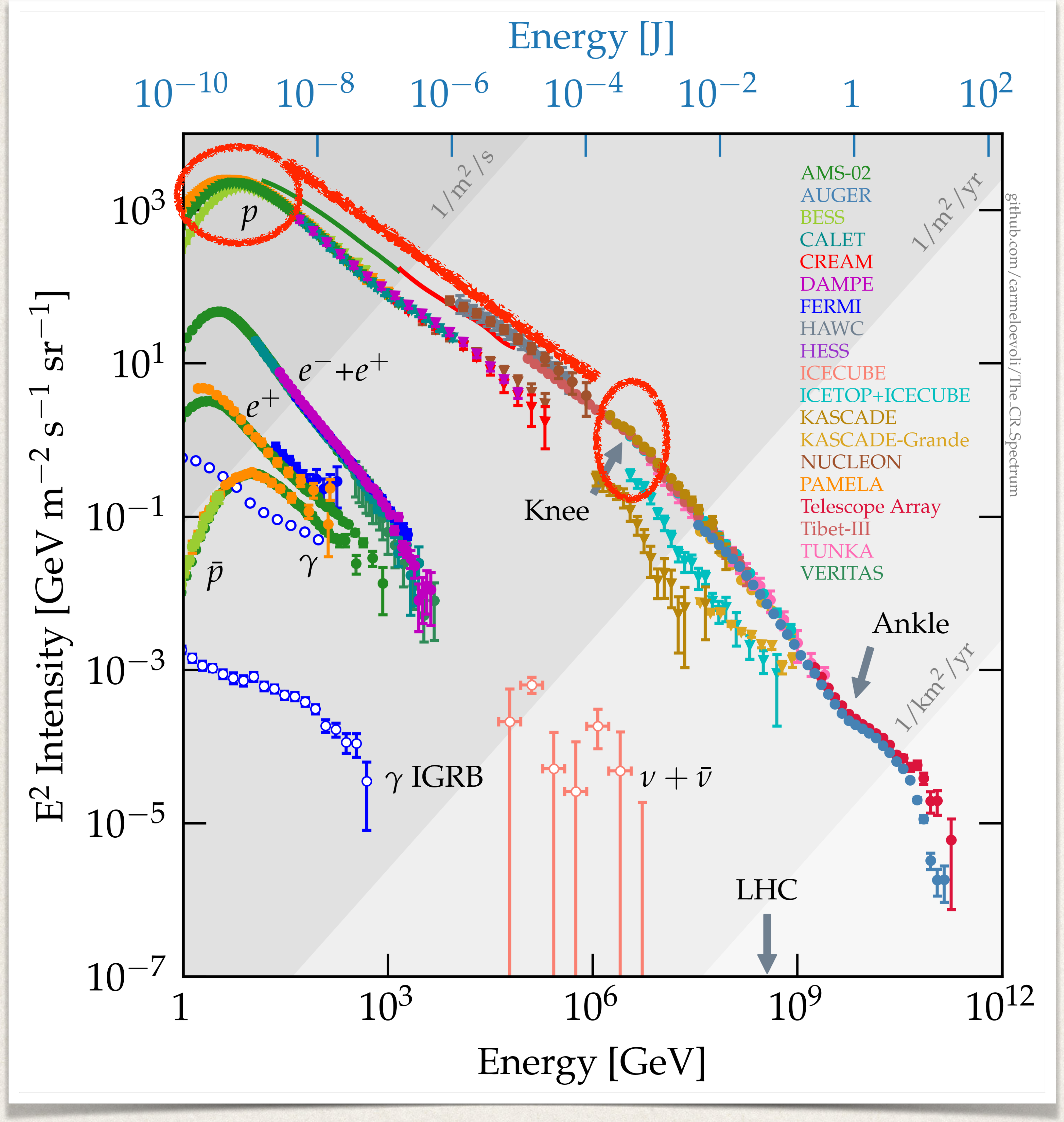

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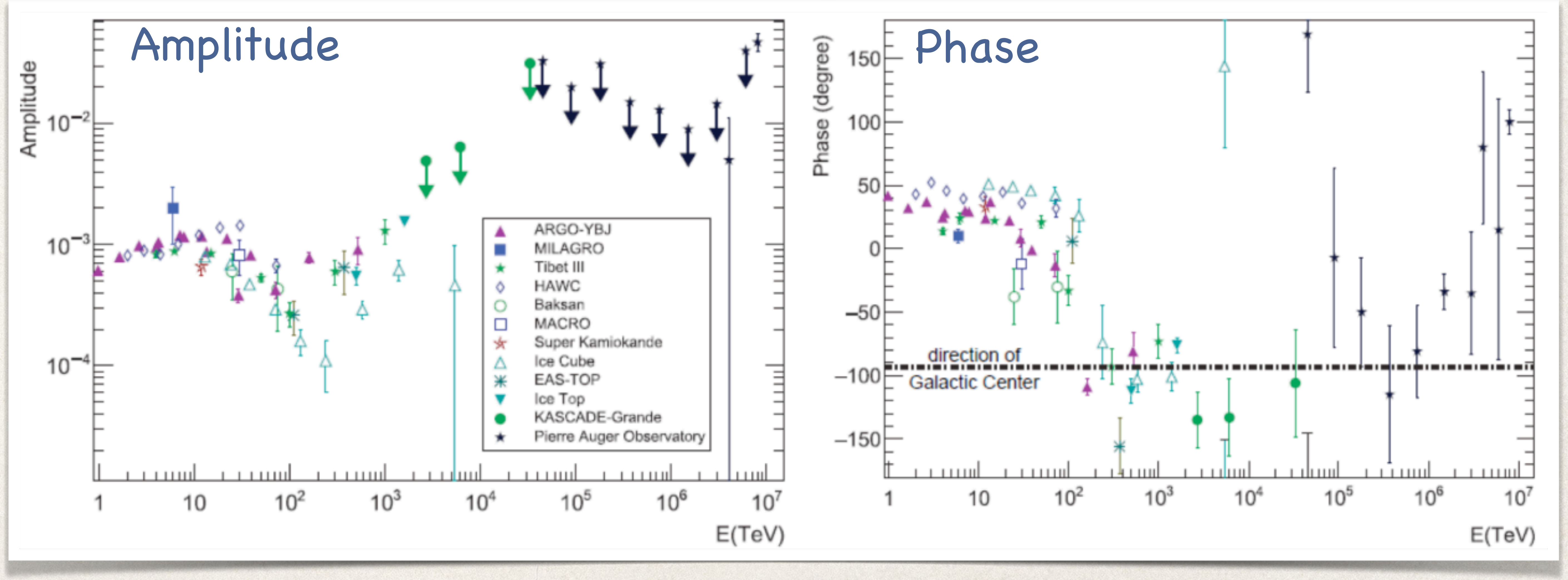

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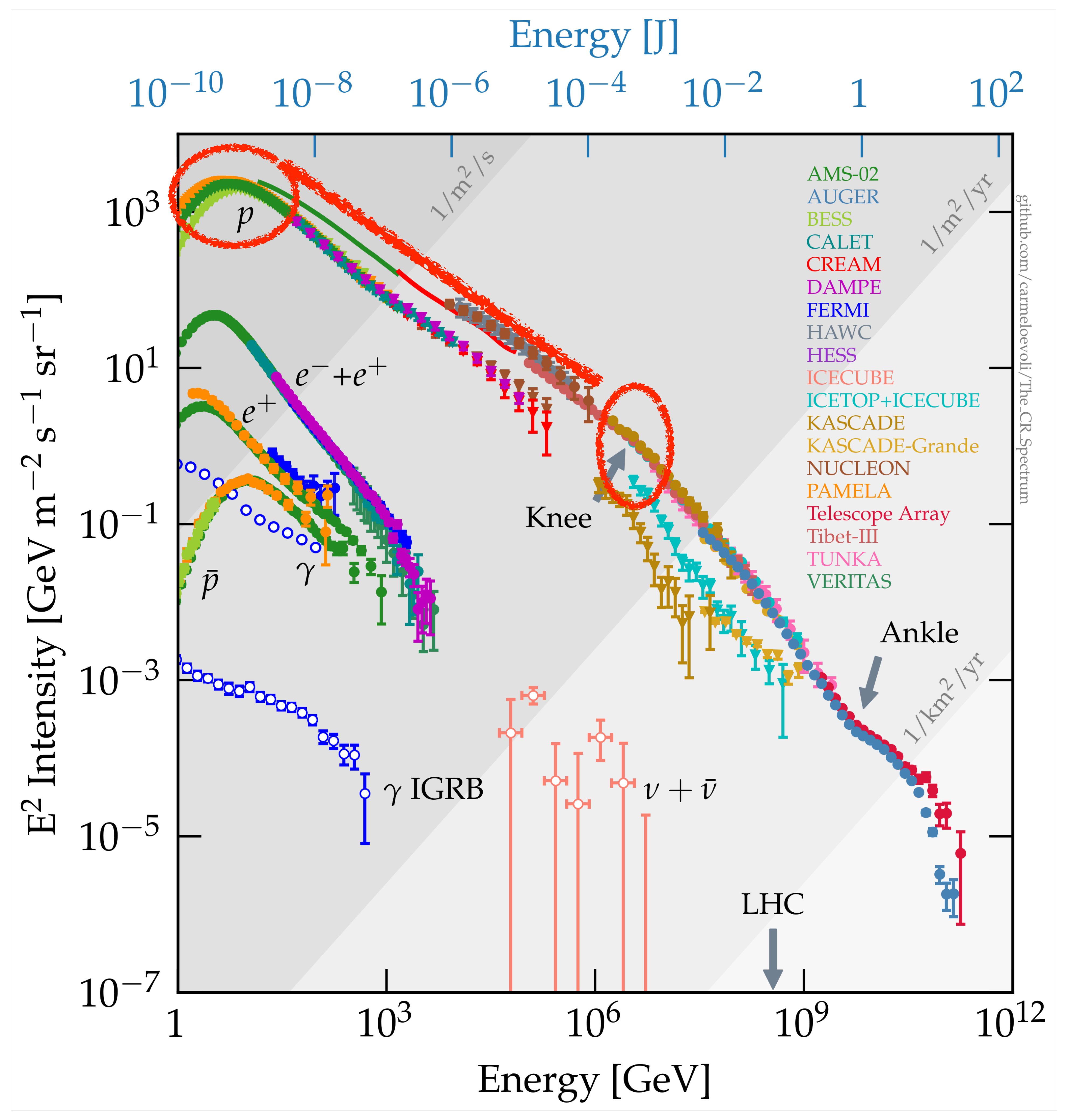

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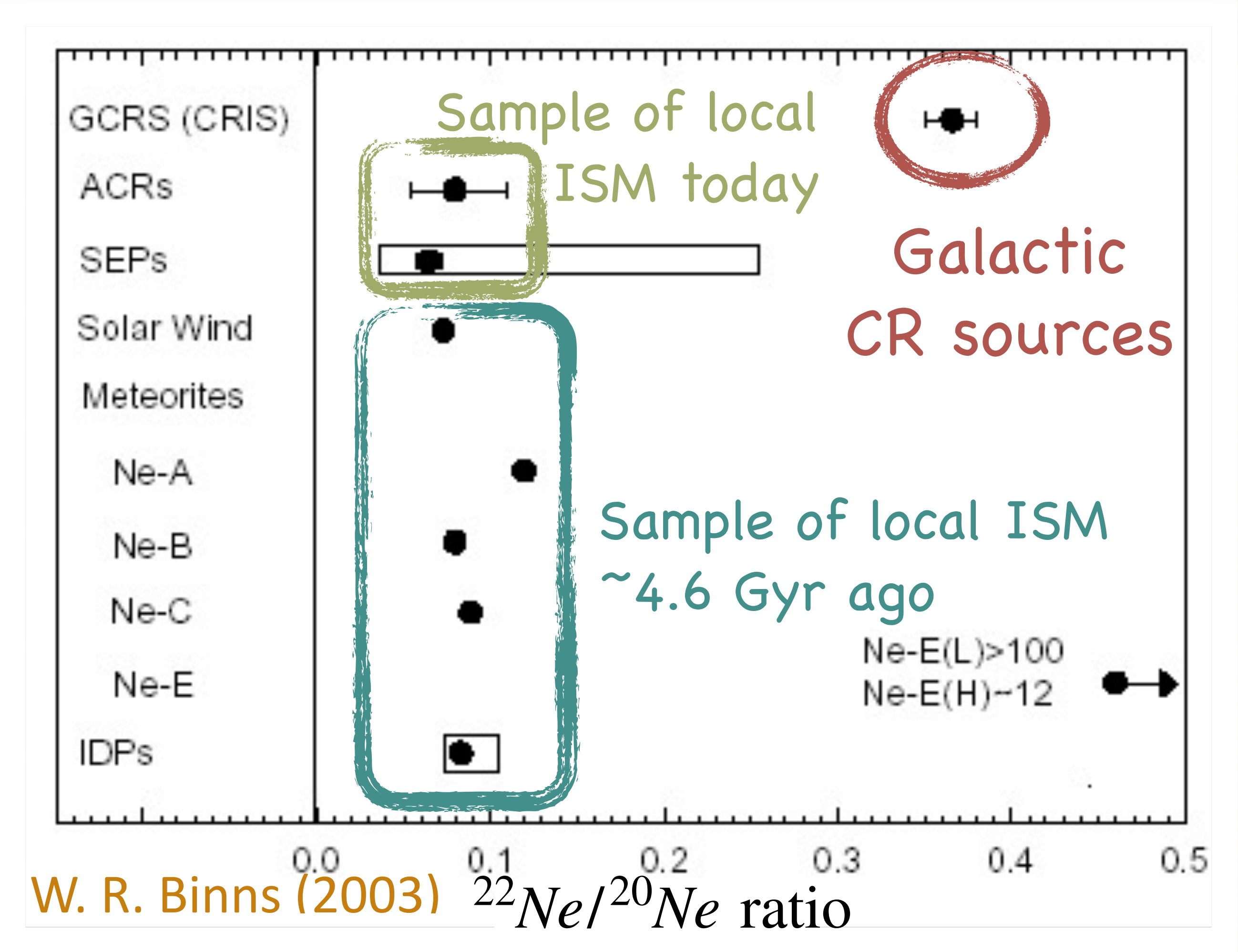
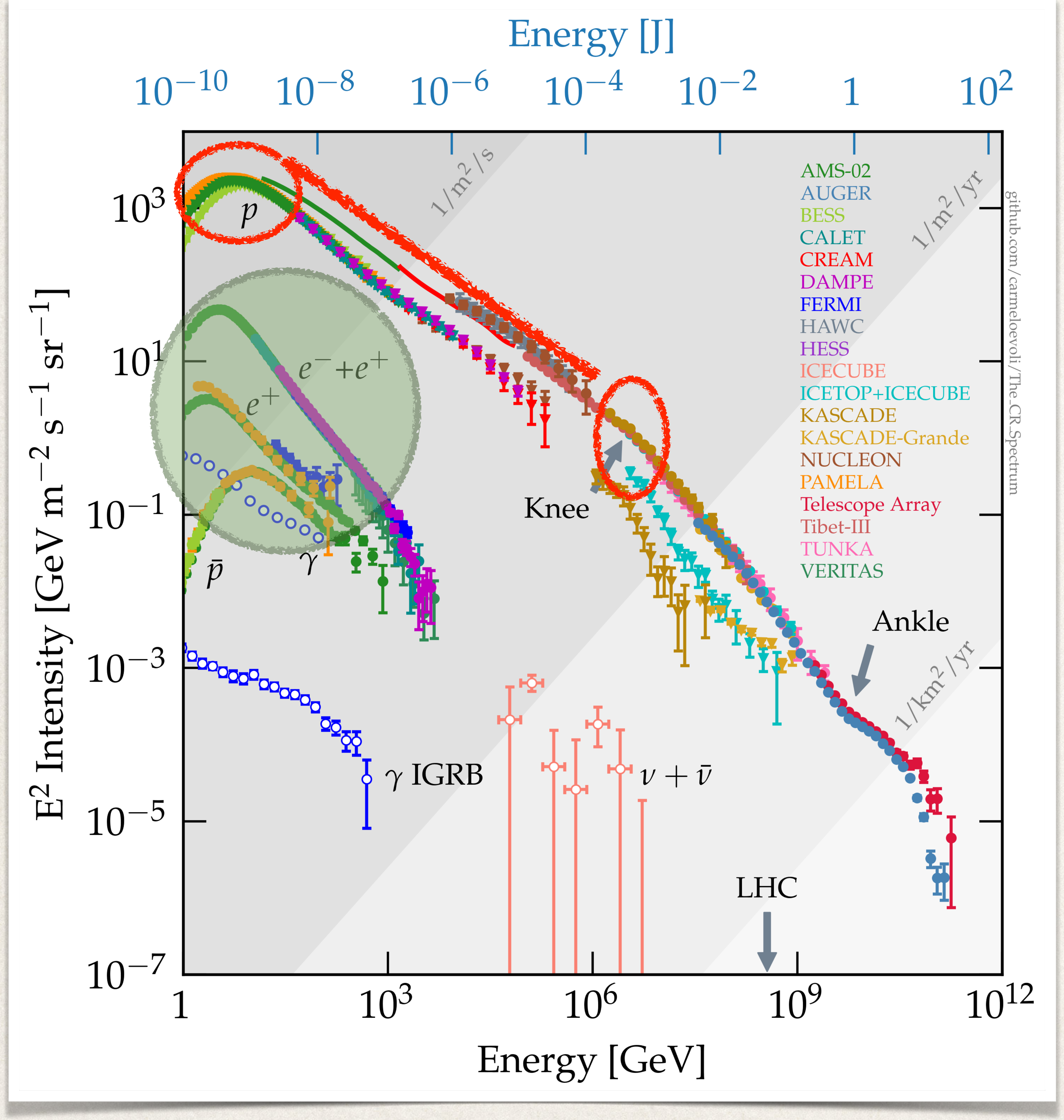


^{22}Ne / ^{20}Ne ratio

How to explain the origin of Galactic CRs



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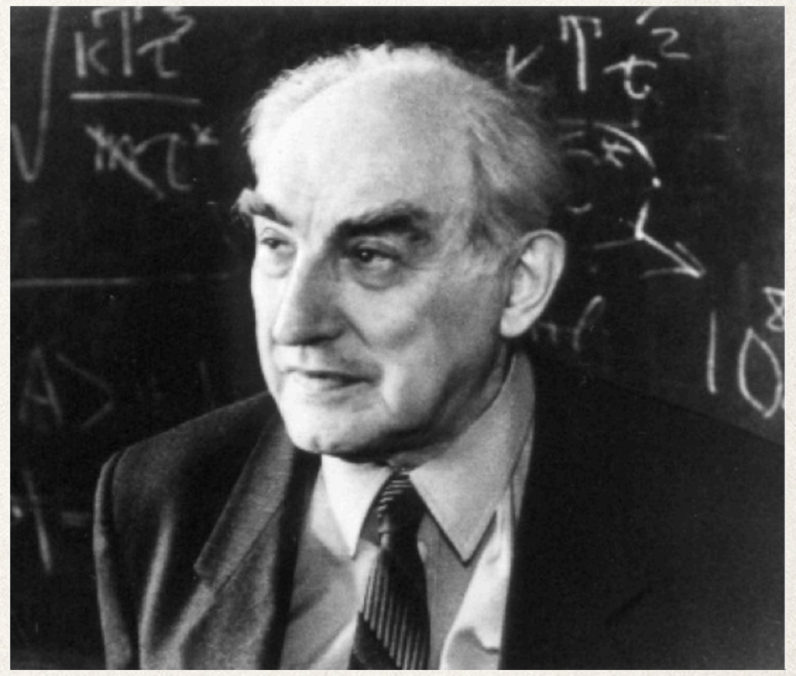
Leptons

Not completely clear their origin

- **Electrons:** SNR?
- **Positrons:** secondaries + Pulsars?

SNR-CR connection: an historical overview

- **1934** - Baade & Zwicky were the first to mention SNRs as sources of CRs, but arguing against them because CRs where thought to be extragalactic.
- **1942** - Alfvén theorised the existence of MHD waves
- **1949** - E. Fermi proposed stochastic acceleration for CRs (II order acceleration)
- **1964** - Ginzburg & Sirovatskii made the argument for SNRs as sources of Galactic CR in the 60's in a more quantitative form (10% kinetic energy needed to be converted in CRs).
- **'70** - Many authors apply Fermi's idea to SNR shocks (I order acceleration) [Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978; Krymskii 1977; Skilling 1975]
- Observational evidences:
  - **1949**: First radio observation of SNR (~300 sources known today)
  - **1995**: First non-thermal X-ray emission detected from SN1006 by ASCA (Since 2000: Chandra and XMM-Newton)
  - **2001**: first detection of shell type SNR in γ-rays by HEGRA



The SNR paradigm for the origin of CRs

Why SNR are so popular?

- Enough power to supply CR energy density (~10% of the explosion energy)
- Spatial distribution of SNRs compatible with the CR distribution
- Presence of non-thermal emission in SNRs
- A solid theory (DSA) applicable to SNR shocks

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Unsolved issues:

- No evidence of acceleration beyond ~100 TeV even in very young SNRs
- Predicted gamma-ray spectrum does not match the observed ones
- Escaping from sources not fully understood
- Anomalous CR chemical composition cannot be easily explained
- Spectral anomalies (p, He, CNO have different slopes)

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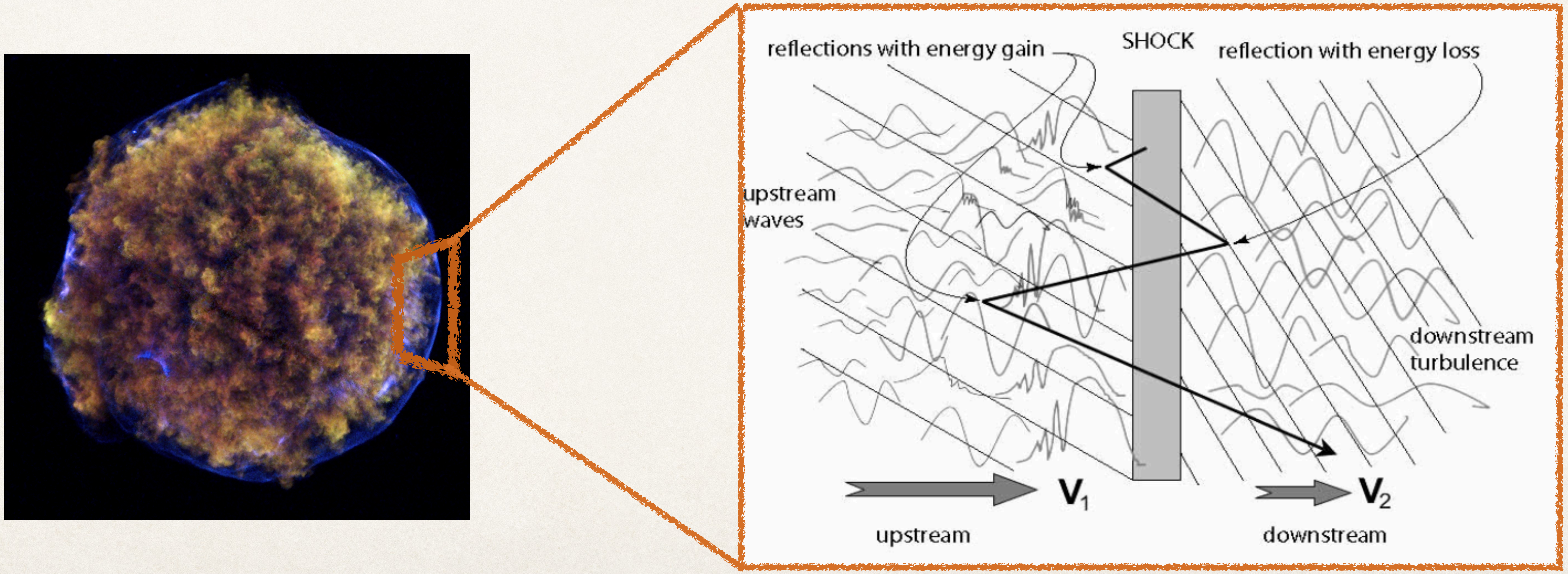
Where does the acceleration occurs?

- Repeated multiple scatterings with magnetic turbulence produce small energy gain at each shock crossing (*I order Fermi acceleration*)
- Balance between energy gain and escape probability results into a featureless power-law spectrum



Diffusive shock acceleration (DSA)

Basic predictions of Diffusive Shock Acceleration (DSA):

1. Spectrum $f(p) \propto p^{-4} \;\rightarrow\; f(E) \propto E^{-2}$ (for relativistic energies)

2. Acceleration efficiency $\xi_{CR} \approx 10\,\%$

3. Maximum energy (equating acceleration time with the end of the ejecta dominated phase)

$$E_{\max} = 50\, Z\, \mathscr{F}(k_{\rm res}(E)) \left(\frac{B_0}{\mu G}\right) \left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{1}{6}} \left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)^{\frac{1}{2}} \left(\frac{n_0}{{\rm cm}^{-3}}\right)^{-\frac{1}{3}} {\rm TeV}$$

Magnetic turbulence spectrum

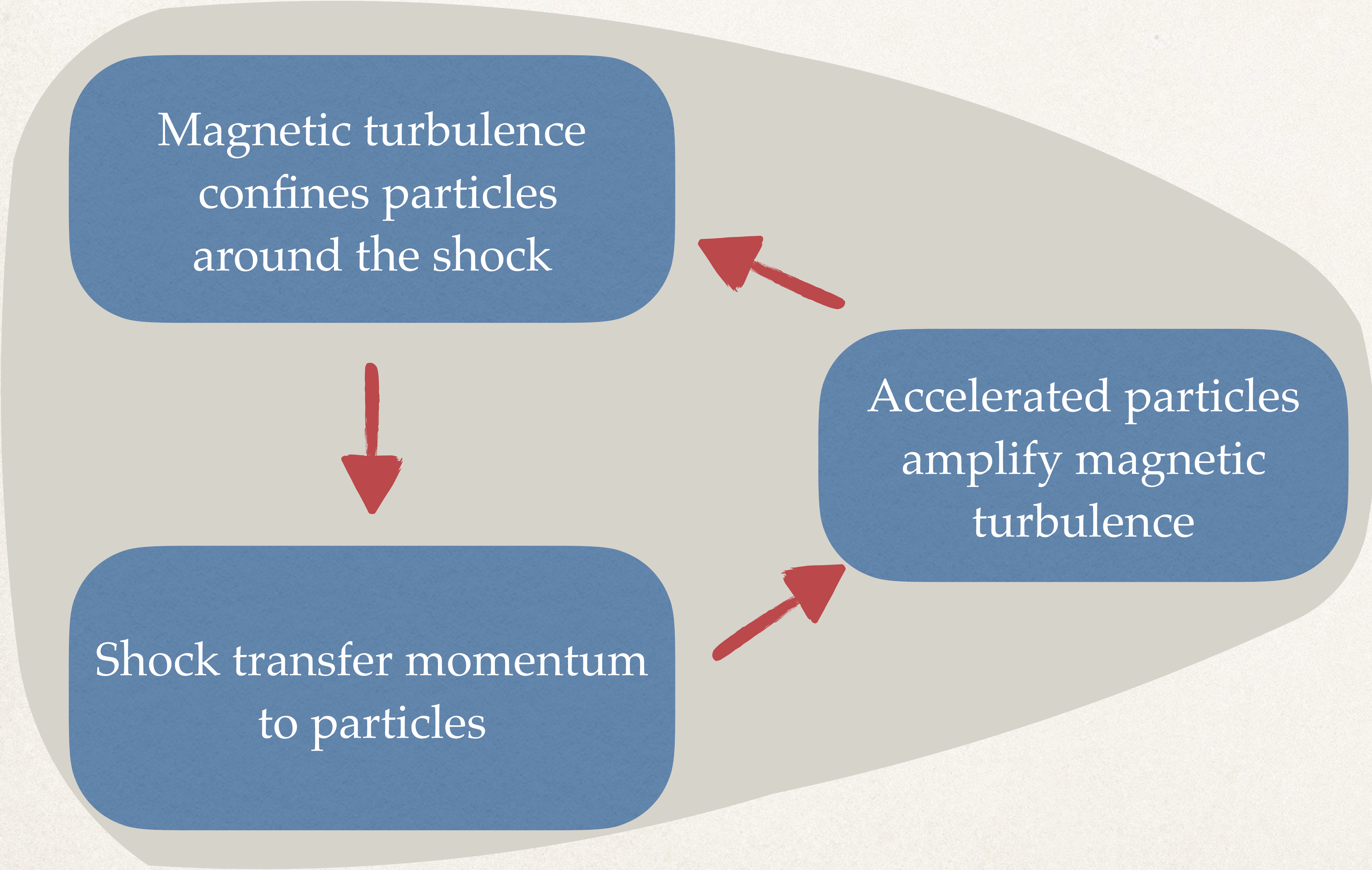
$$\mathscr{F}(k) = \left(\frac{kP(k)}{B_0^2/8\pi}\right)$$

Weak dependence on other parameters

Reaching PeV energies requires strong magnetic field amplification $\delta B \gg B_0$

The non-linear fashion of DSA

What makes DSA a non-trivial theory is the non-linearity due to CR feedback onto the shock dynamics



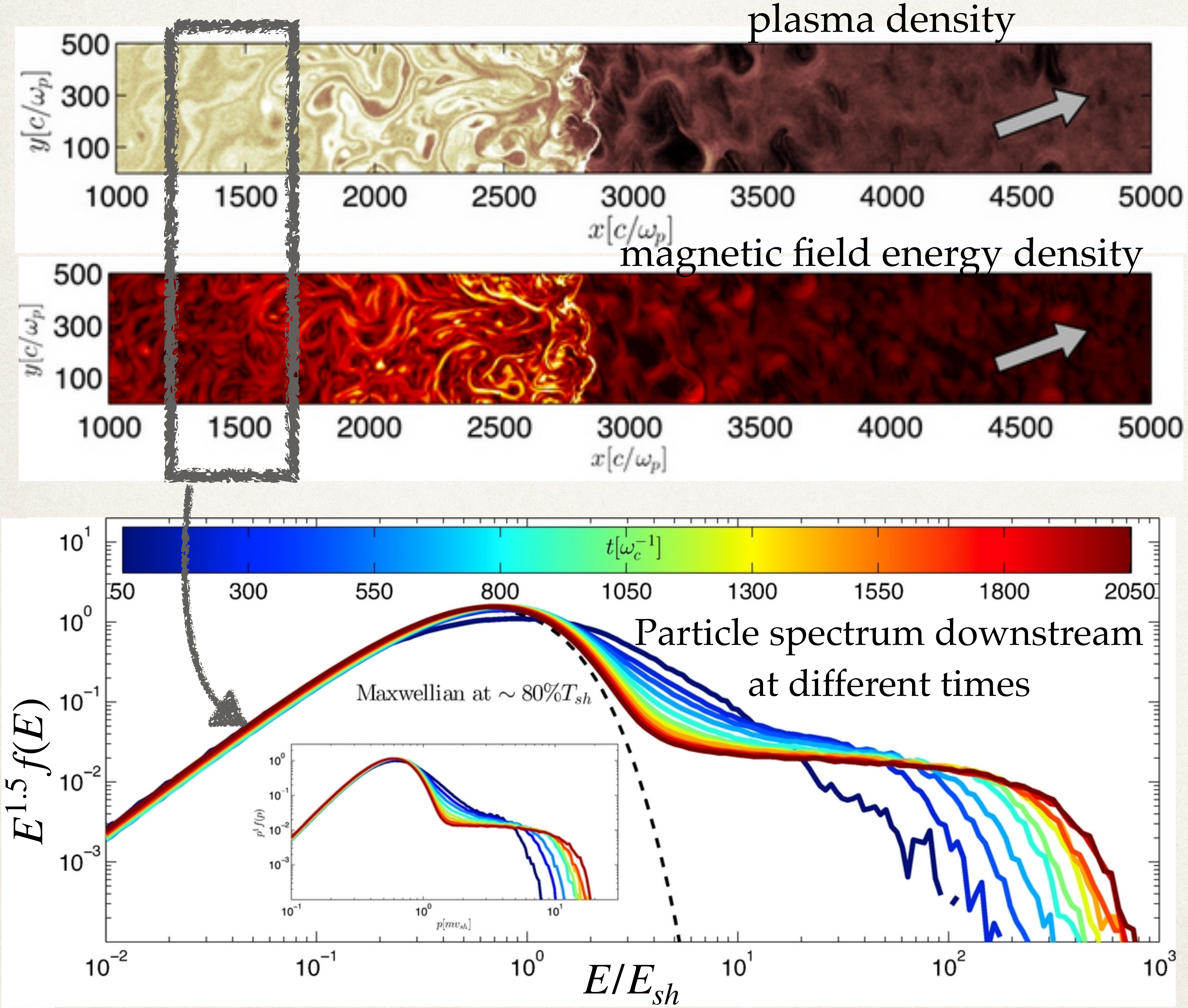
This chain of processes determines simultaneously:

- Acceleration efficiency
- Spectral slope
- Maximum energy
- Particle escape

The key aspect of the whole process is the magnetic field amplification

DSA from PIC simulations

[Caprioli & Spitkovsky, ApJ 2014]

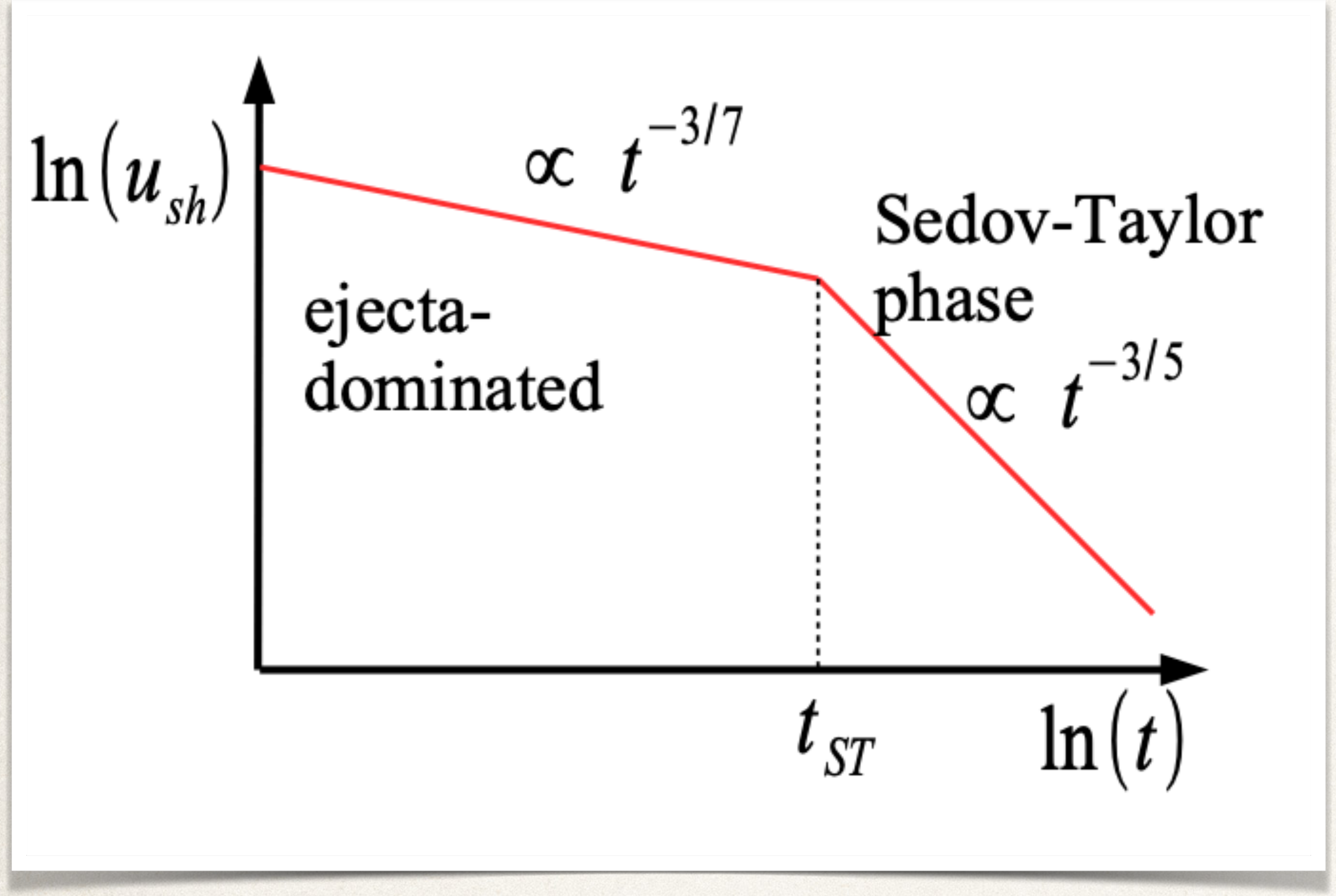


- A nice confirmation of DSA predictions comes from *particle in cell* (PIC) simulations
  - ✓ Large efficiency ~ 10-20%
  - ✓ Spectrum ~ p^{-4} (~ $E^{-1.5}$ at non-relativistic energies)
  - ✓ self-generated magnetic turbulence
- However, PICs can only simulate the beginning of the acceleration process (small dynamical range: E_{max} << 1 GeV)

  ⇒ No conclusion on E_{max}

Maximum energy in DSA applied to SNRs

Maximum energy can only increase during the ejecta dominated phase of the SNRs because $u_{\rm sh} \sim {\rm const}$.



Shock radius
$$\begin{cases} R_{\rm sh} \propto t^{4/7} & \text{ejecta-dominated} \\ R_{\rm sh} \propto t^{2/5} & \text{Sedov-Taylor phase} \end{cases}$$

But particle diffuse ahead of the shock: $\langle d \rangle \propto \sqrt{Dt}$

$$\langle d \rangle > R_{sh}$$

During the ST phase the highest energy particles cannot be reached by the shock and escape towards upstream

Estimate of the beginning of the ST phase: $M_{swept-up} = M_{ejecta}$

$$\begin{cases} t_{ST} = R_{ST}/u_{sh} \\ E_{SN} = 1/2\, M_{ej} u_{sh}^2 \end{cases}$$

$$t_{ST} \simeq 50 \left(\frac{M_{ej}}{M_\odot}\right)^{5/6} \left(\frac{E_{\rm SN}}{10^{51}\,{\rm erg}}\right)^{-1/2} \left(\frac{n_{\rm ism}}{{\rm cm}^{-3}}\right)^{-1/3} \, {\rm yr}$$

Magnetic field amplification: observations

[Hwang+ 2002; Bamba+, 2005; Ballet 2006; Vink 2012]

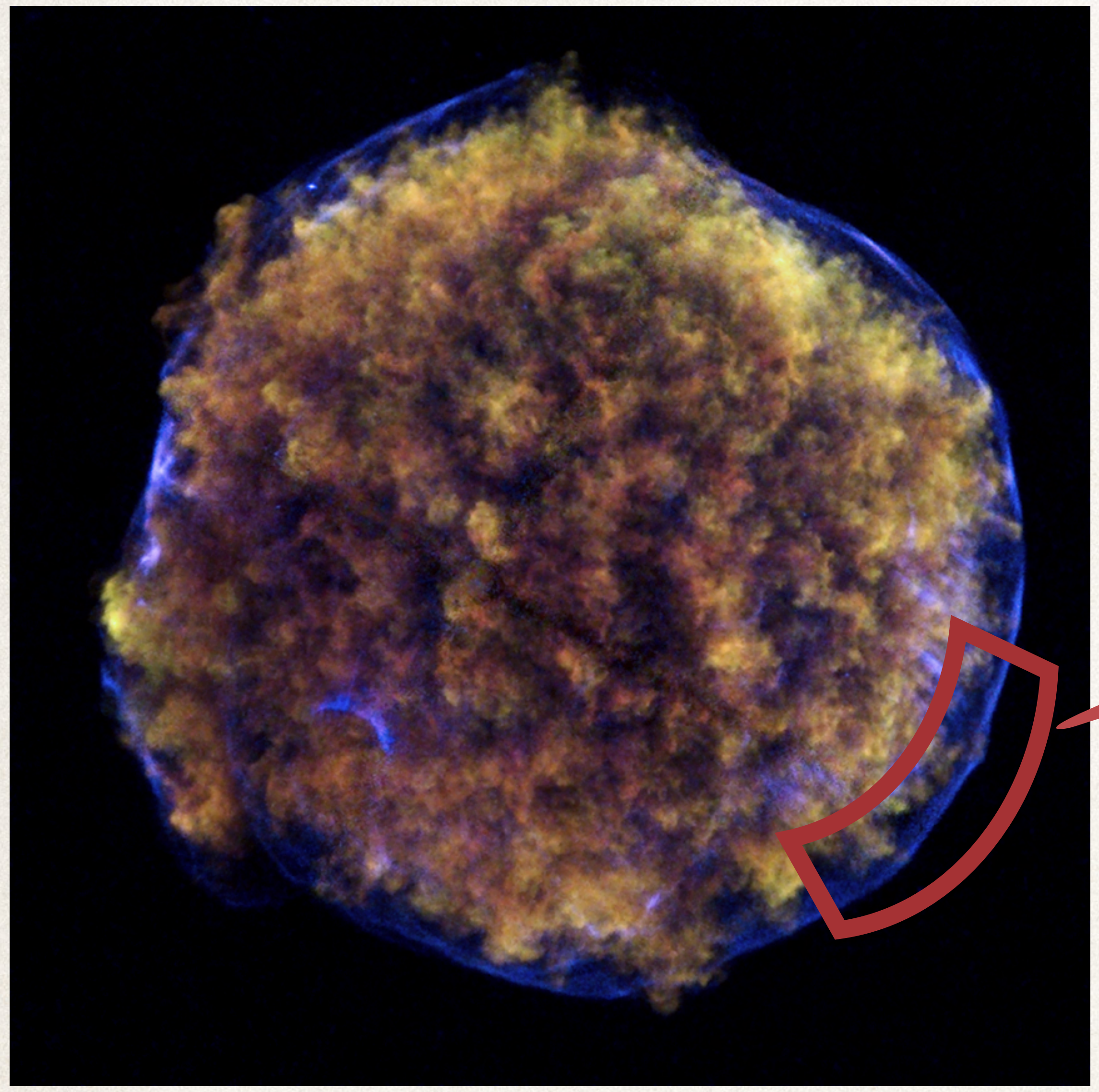
Thin non-thermal X-ray filaments provide existence for efficient magnetic field amplification

Equating the thickness of X-ray filaments with the synchrotron losses length-scale:

$$\begin{cases} D = r_L c/3 \propto E/B \\ \tau_{\rm syn} = \dfrac{3 m_e c^2}{4 \sigma_{\rm Tom} c \gamma \beta^2 U_B} \propto 1/(EB^2) \end{cases}$$

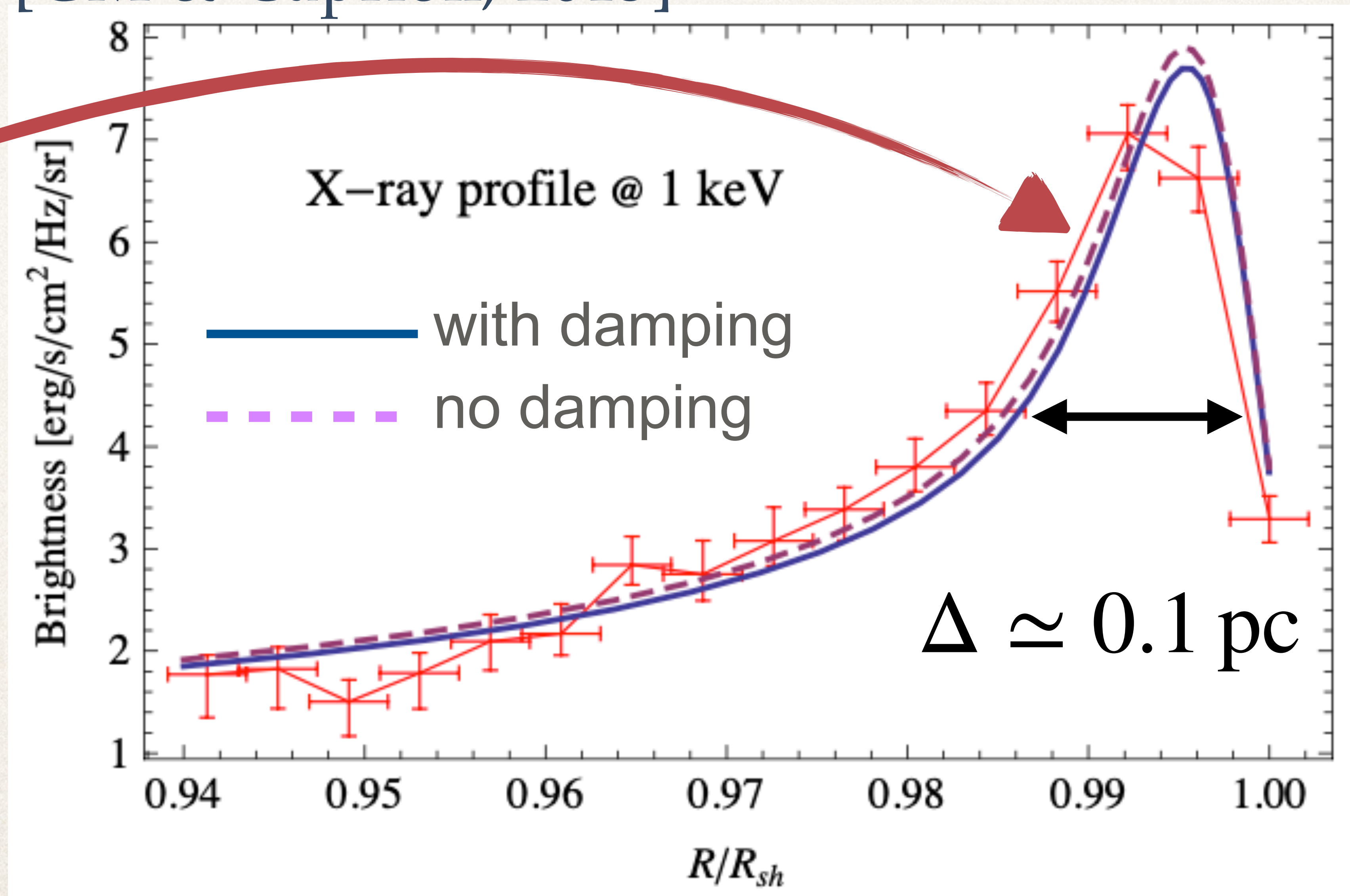
$$\Delta \simeq \sqrt{D \tau_{\rm syn}} \propto B^{-3/2}$$

$$B \simeq 100 - 300\ \mu G \gg B_{\rm ISM}$$



Chandra X-ray map of Tycho SNR. Data from the red sector are from Cassam-Chenai et al. (2007)

[GM & Caprioli, 2013]



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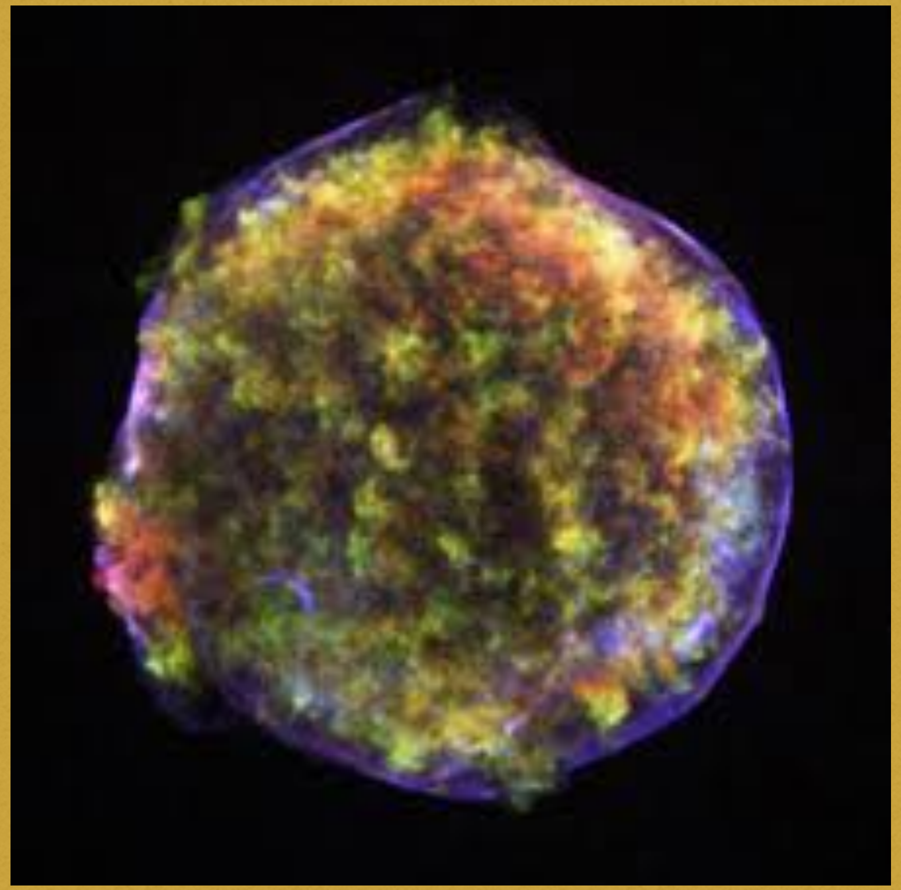
Thin non-thermal X-ray filaments provide existence for efficient magnetic field amplification

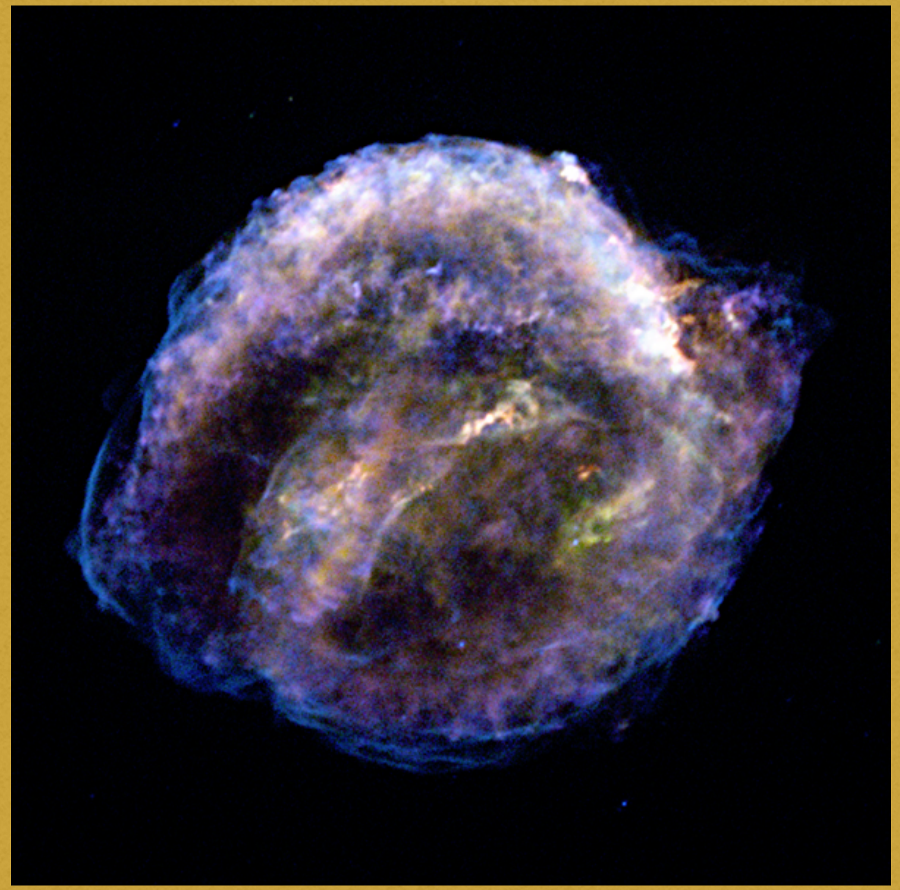
Similar filaments are observed in almost all young SNRs

Tycho



SN 1006

Kepler



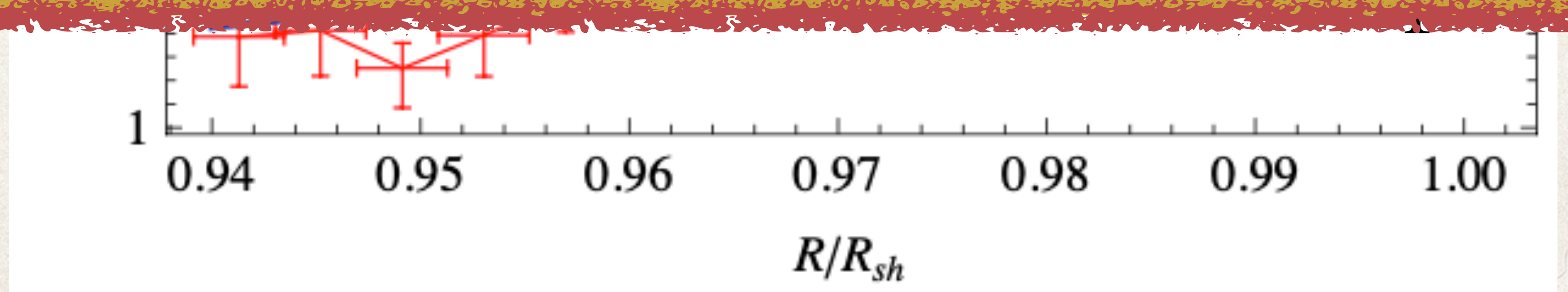
Cas A

Blue → non-thermal X-rays

C

Data

from Cassam-Chenai et al. (2007)

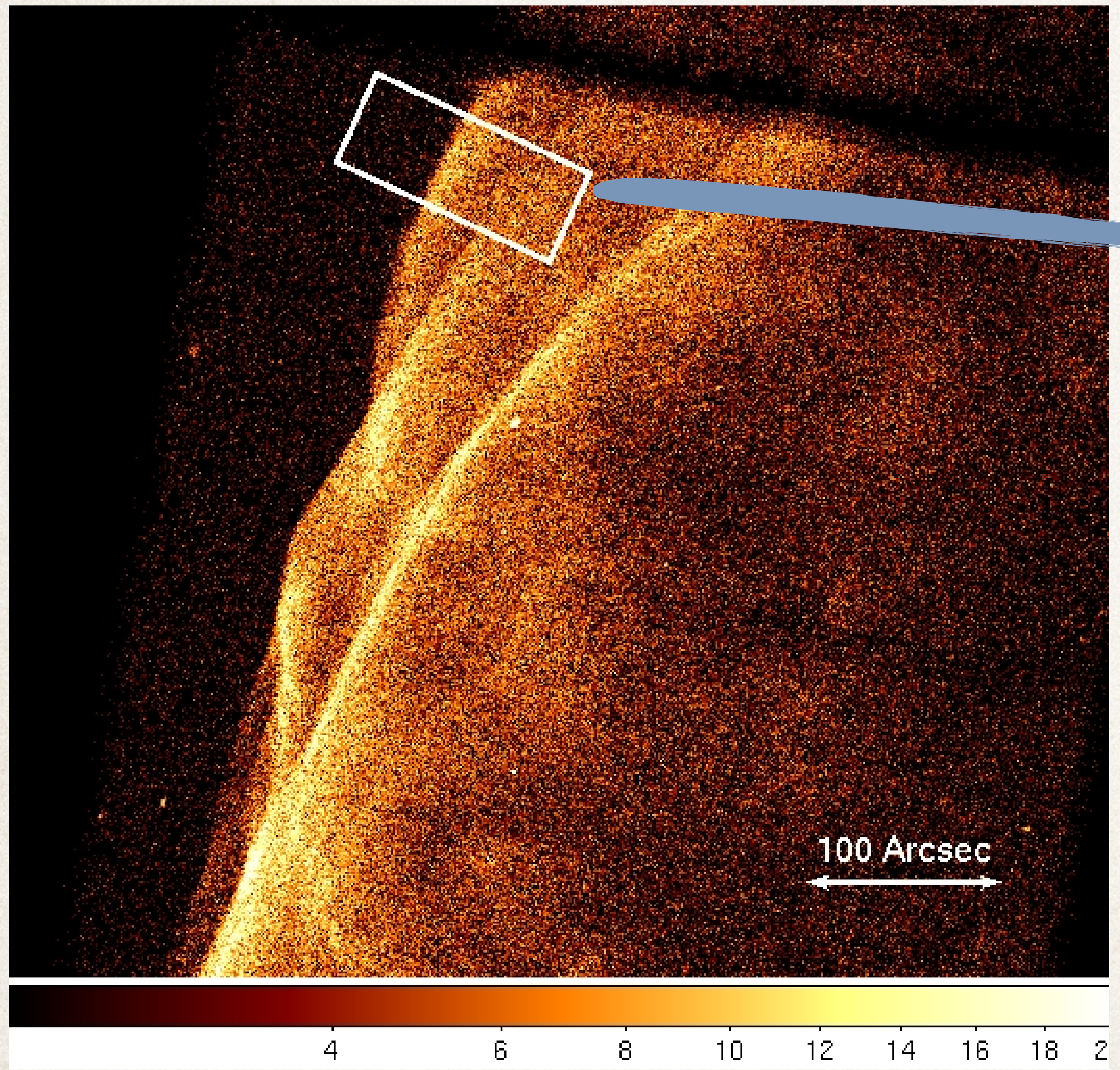


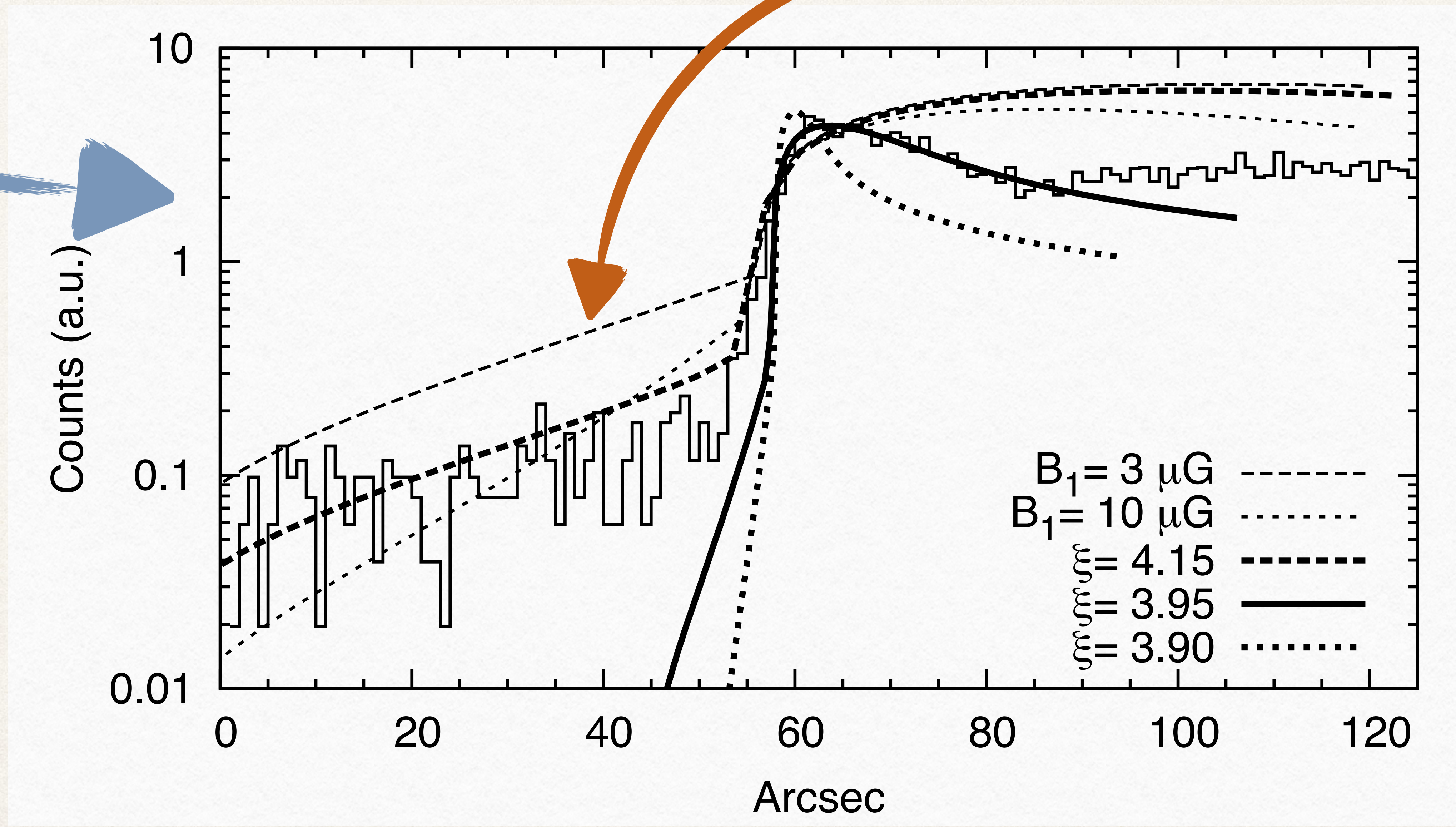
Where is the magnetic field amplified?

[GM, Amato, Blasi, MNRAS 2009]

- **Downstream**: MHD instabilities (shear-like)
- **Upstream:** only through instabilities driven by CRs
- Amplification is needed both *upstream* and *downstream* to reach high energies

SN 1006





Non-thermal X-ray emission form SN 1006 (Chandra)

Low magnetic field upstream produces a more extended emission NOT OBSERVED!

Magnetic field has to be amplified also upstream

Magnetic field amplification: theory

Isolated SNRs:
Possible CR-driven instabilities:

- Resonant streaming instability
  Skilling 1975; Bell & Lucek 2001; Amato & Blasi 2006; Blasi 2014
- Non-resonant (Bell) instability
  Bell 2004; Bell et al. 2013, 2014; Amato & Blasi 2009
- Turbulent amplification
  Drury & Downes 2012; Xu & Lazarian 2017

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SNRs in complex environments:
(MFA due to other processes)

- SNRs exploding in super bubbles
  (MFA due to wind-wind collisions)
  e.g. Vieu & Reville 2023;

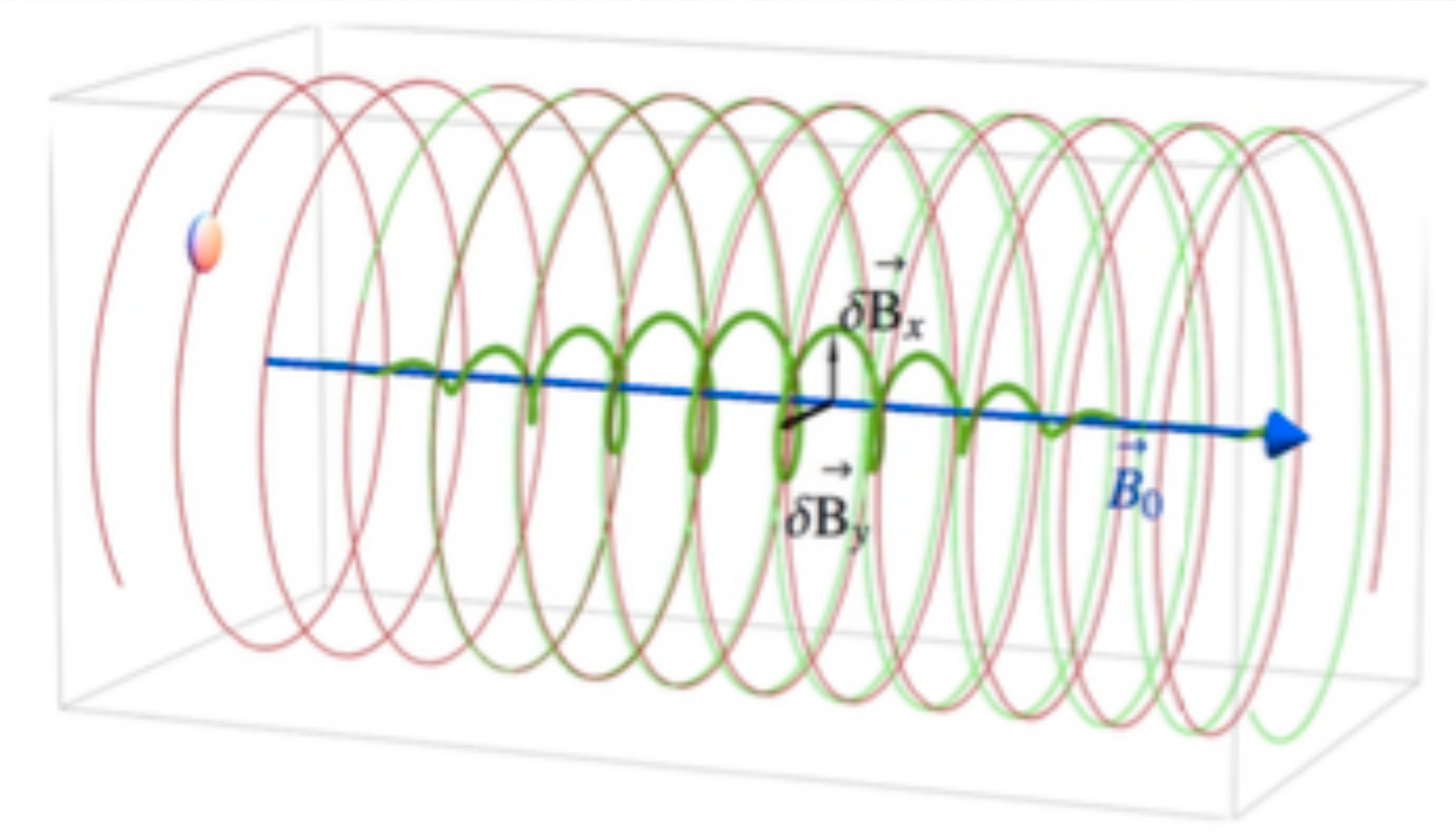
Not fully understood yet

Magnetic field amplification: theory

Resonant streaming instability

[Skilling 1975; Bell & Lucek 2001; Amato & Blasi 2006; Blasi 2014]

- Amplification is due to resonant interaction between CR with Larmor radius r_L and waves with wave-number $k = 1/r_L$.



- Fast growth rate $$\Gamma_{CR}(k) = \frac{v_A}{B_0^2/8\pi} \frac{1}{kW(k)} \frac{\partial P_{CR}(>p)}{\partial x}$$

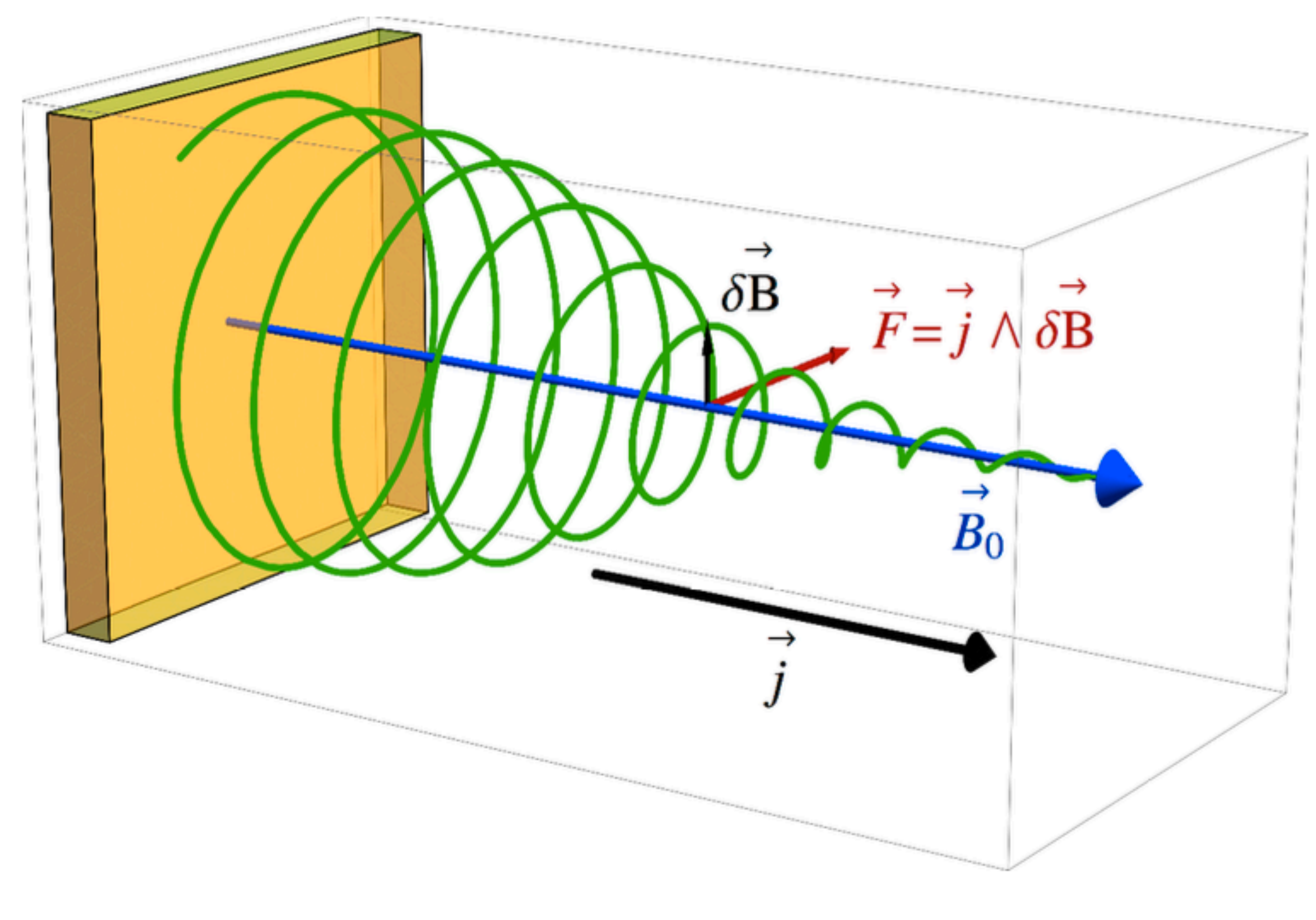
(~10 yr for typical SNR shocks)

A factor ~20 below the *knee*

- But saturation level at $\delta B/B_0 \lesssim 1$ → $E_{max} \approx 50$ TeV

Magnetic field amplification: theory
Non-resonant (*Bell*) instability

[Bell 2004; Bell et al. 2013, 2014; Amato & Blasi 2009]



- Amplification due to $\vec{j}_{CR} \times \delta\vec{B}$ force of escaping CR current with magnetic field perturbations
- Fast growth rate but excites small wavelength waves (⇒ **need of inverse cascade?**)
- $E_{\rm max} \propto \sqrt{\rho_{\rm csm}}$ → high level of amplification only in dense environments (Type II SNe exploding into dense progenitor stellar winds)

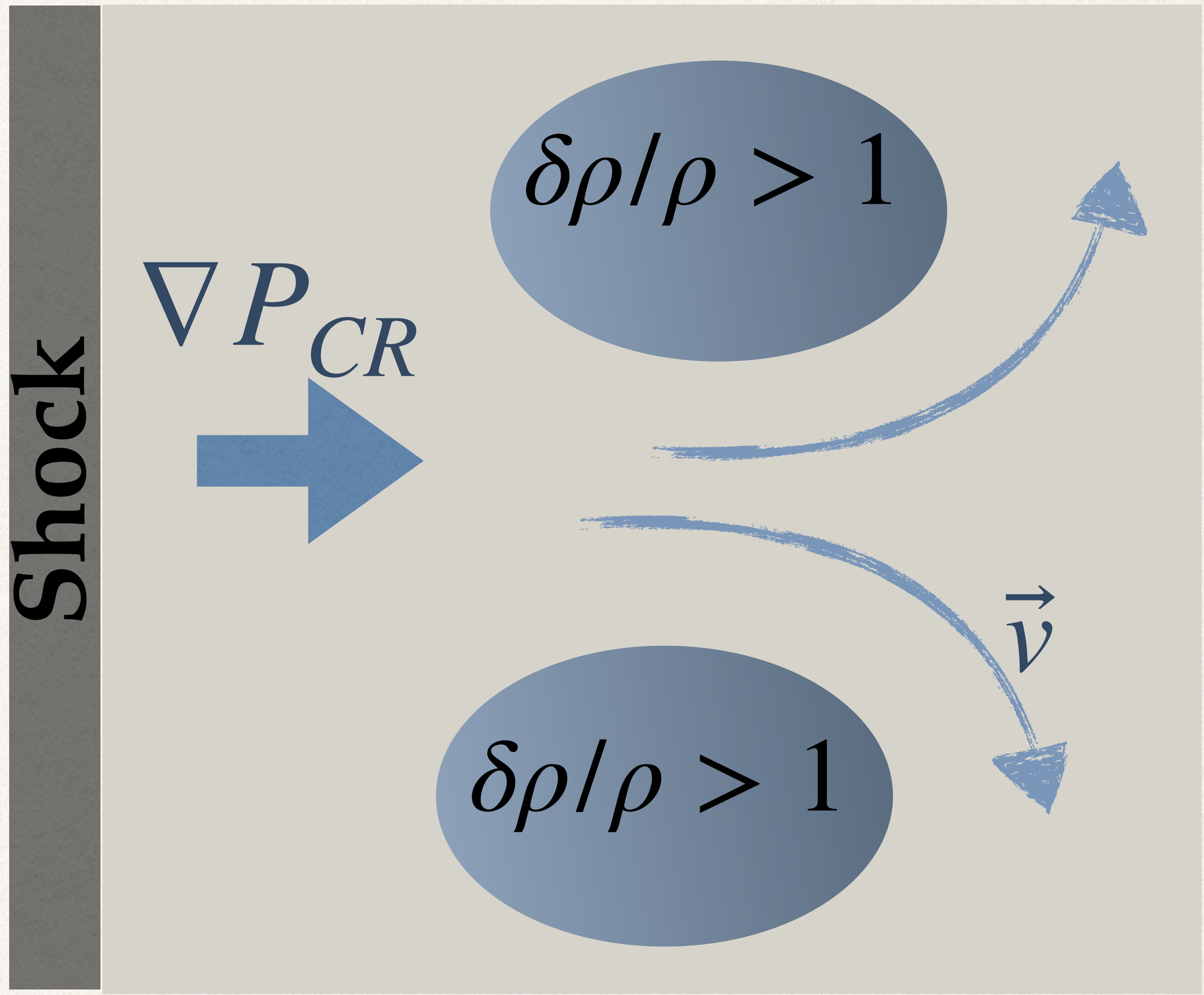
$$E_{\rm max} \simeq \frac{e\,\xi_{cr}}{10\,c} \frac{\sqrt{4\pi\rho}}{\Lambda} v_{sh}^2 R_{sh} \simeq 30\,{\rm TeV} \left(\frac{\xi_{cr}}{0.1}\right) \left(\frac{\rho/m_p}{{\rm cm}^{-3}}\right)^{1/2} \left(\frac{v_{sh}}{5000\,{\rm km/s}}\right)^2 \left(\frac{R_{sh}}{\rm pc}\right)$$

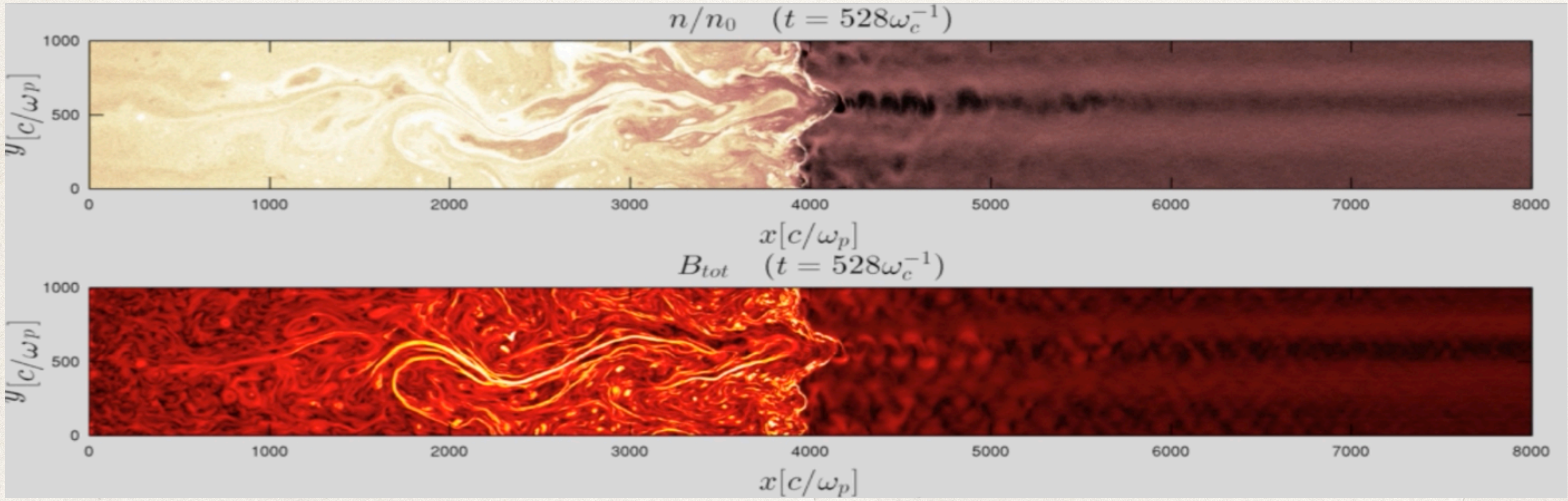
Magnetic field amplification: theory

Turbulent amplification

[Drury & Downes 2012; Xu & Lazarian 2017]

- In presence of density inhomogeneities, the different CR force acting onto plasma can generate vorticity
- This mechanism is effective only in large precursors (hence E_{max} already large enough and flat spectrum ~E^{-2})
- The density discontinuities can be generated even through the non-resonant instability → filamentation
- In realistic situations: $\delta B/B \lesssim 1$





Filamentation instability observed in 2D hybrid simulations
[Caprioli & Spitkovsky, 2013]

Only very young SNRs can accelerate up to PeV

Schure & Bell (2013)

Using non-resonant instability:

$$\frac{B_{\rm sat}^2}{B_0^2} \sim \frac{U_{\rm CR}}{U_{B_0}} \frac{v_d}{c} \propto n_0 v_{sh}$$

→

Efficient amplification requires:
- large densities
- large shock speed

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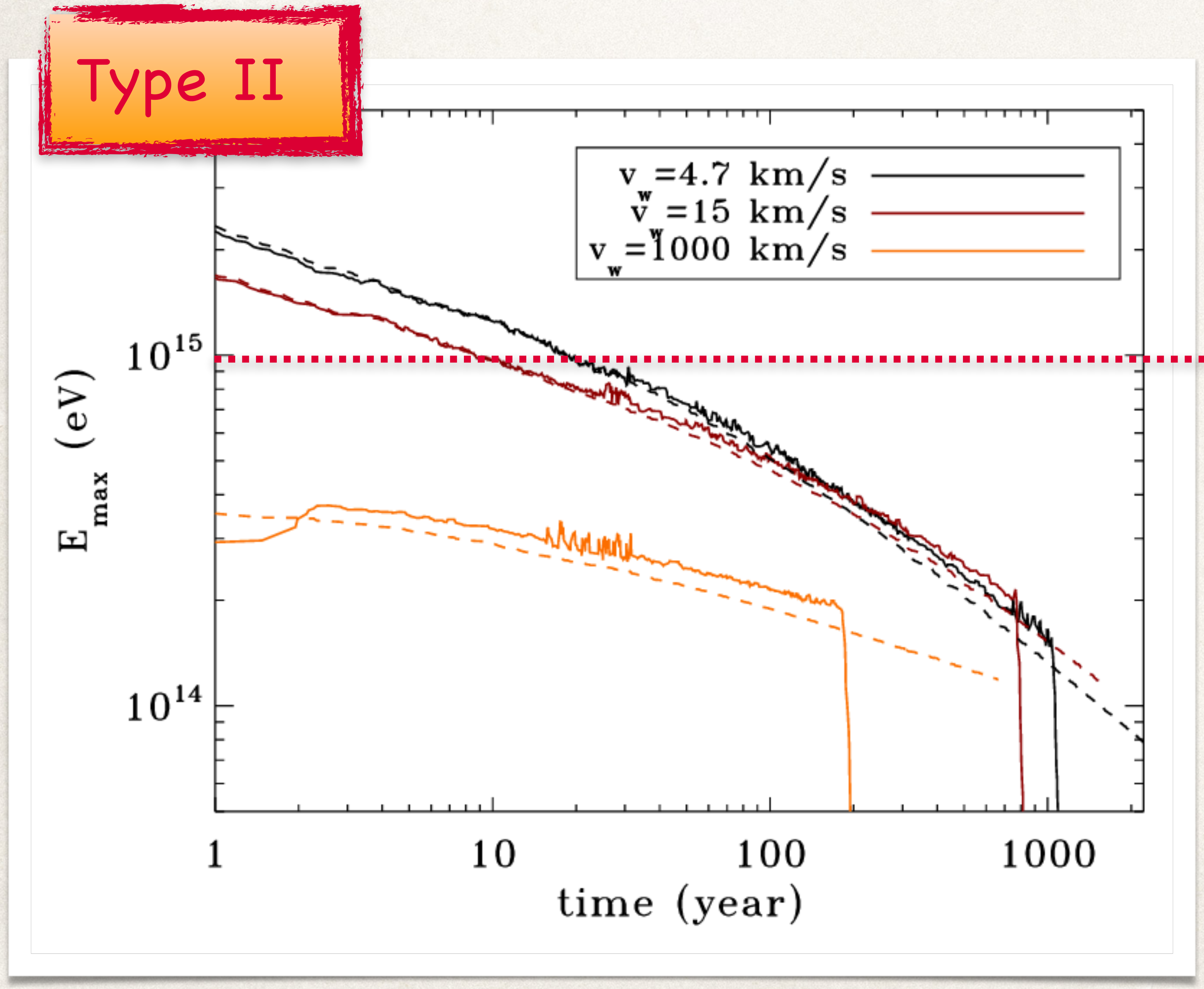
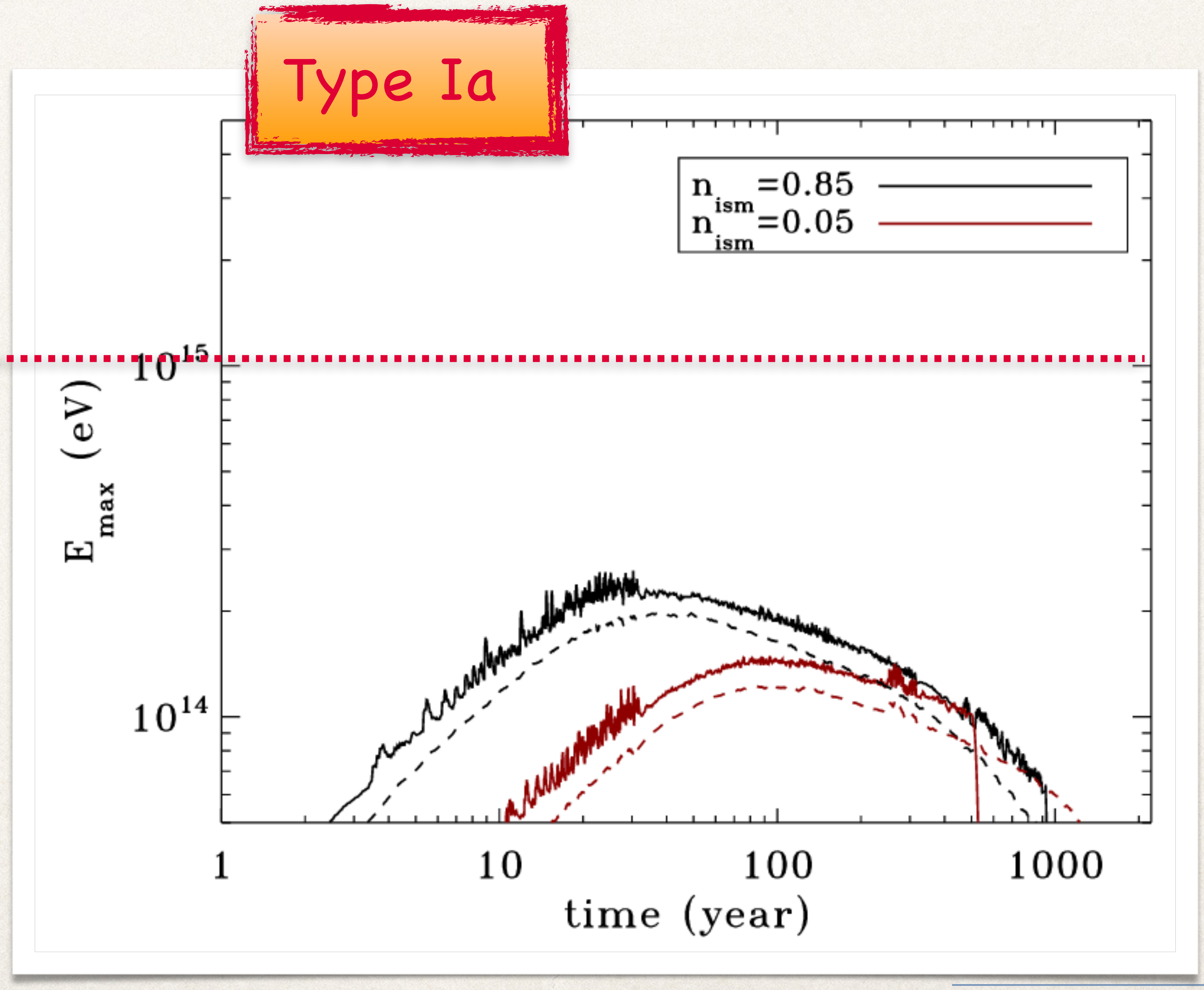
PeV energies can be reached:
- Only by core-collapse SN expanding into dense environment (slow and dense progenitor's wind)
- During the very early phase (age $\lesssim 50$ years)



1 PeV



Assumed ejecta mass:

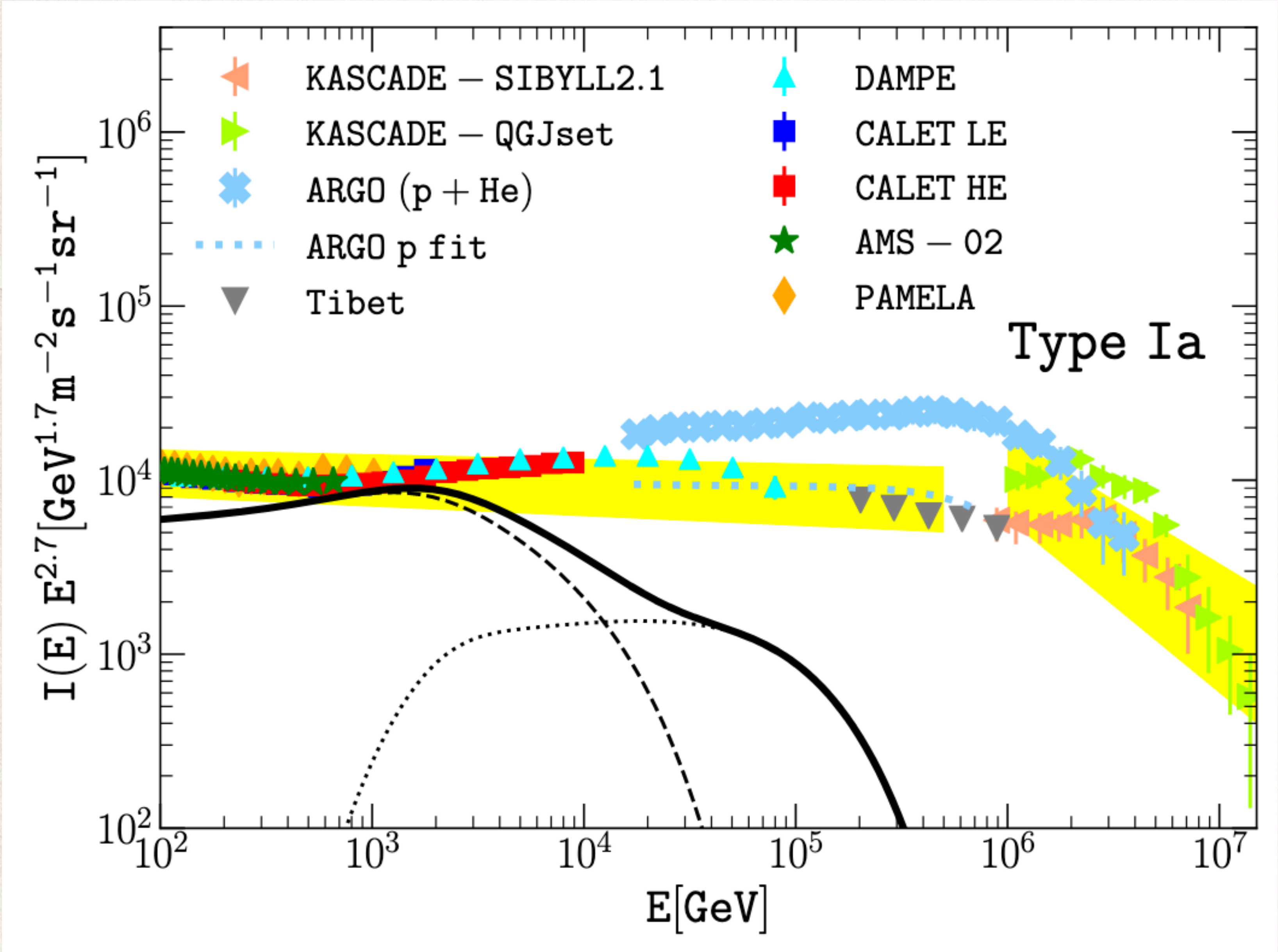
$M_{ej} \simeq 1\,M_\odot$

Application of Bell instability to different type of SNRs: comparison with CR spectrum at Earth

[Cristofari, Blasi, Amato, APh 2020]

Assumed acceleration efficiency $\xi_{cr} \approx 0.10$

	Type Ia	Type II	Type II*
E_{SN} [10^{51} erg]	1	1	$5 \div 10$
$\dot{M}_{wind}$ [$M_\odot/yr$]	$--$	10^{-5}	10^{-4}
M_{ej} [$M_\odot$]	1.4	10	1.0
ν_{SN} [yr^{-1}]	10^{-2}	2×10^{-2}	3×10^{-4}



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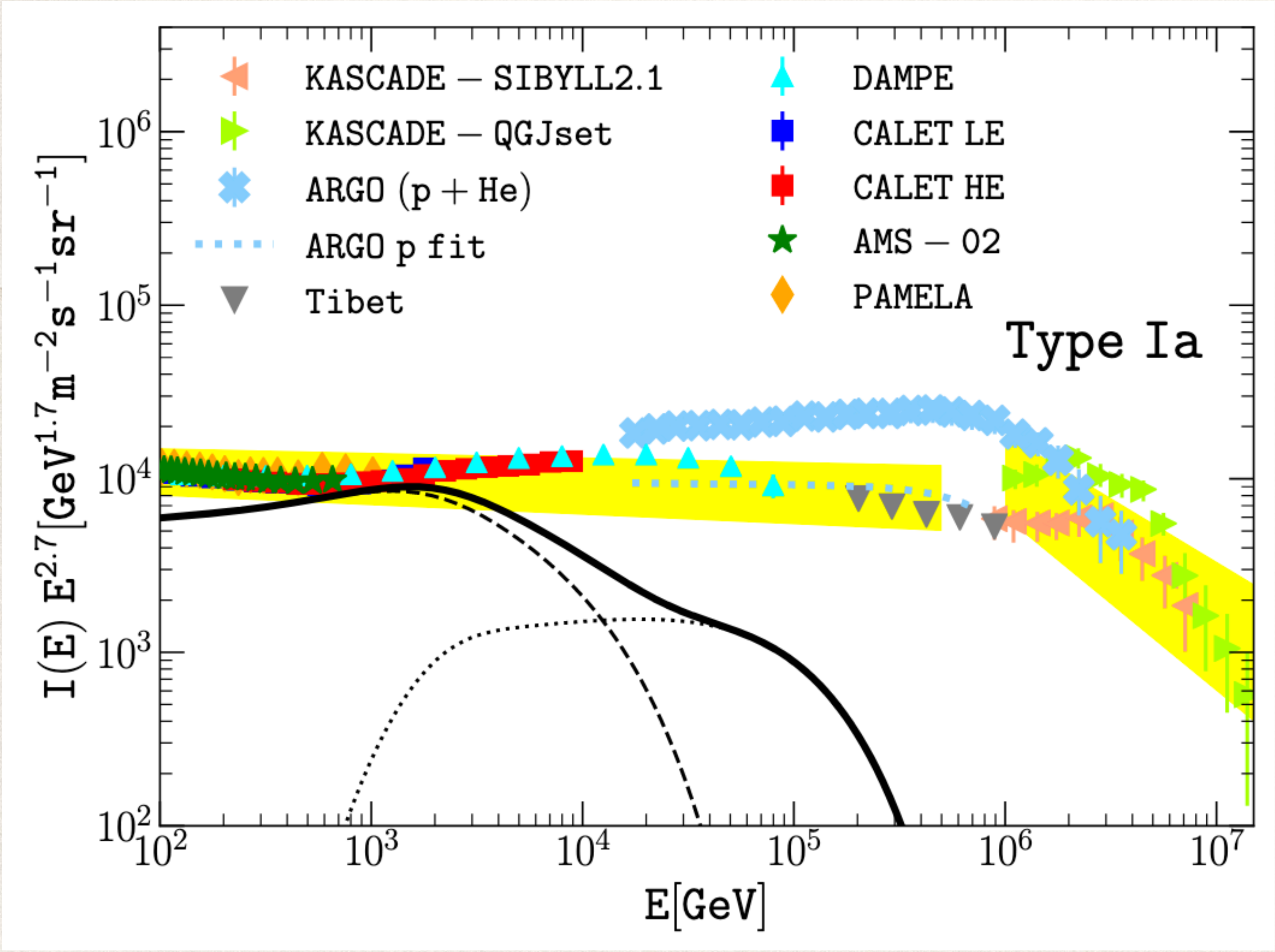

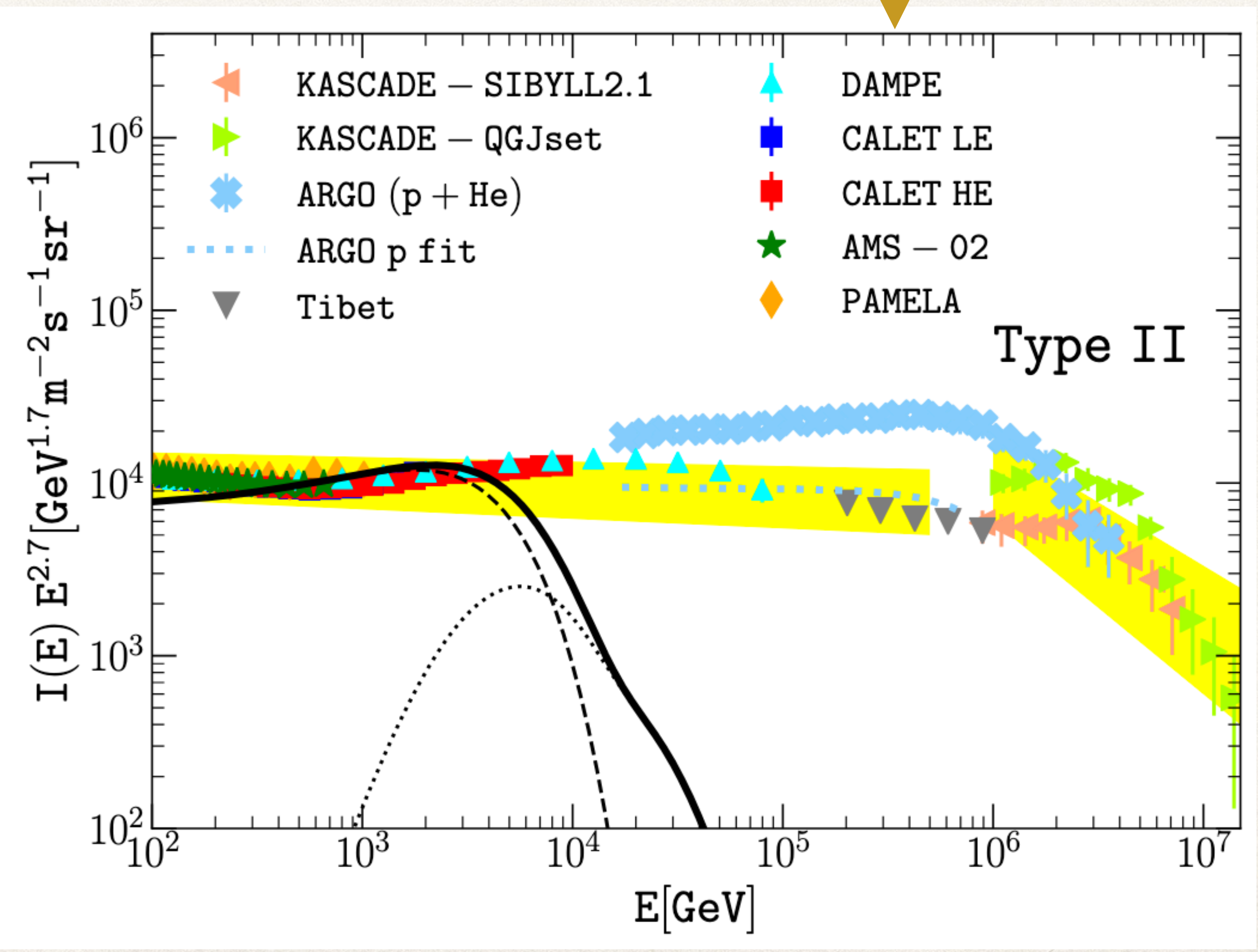

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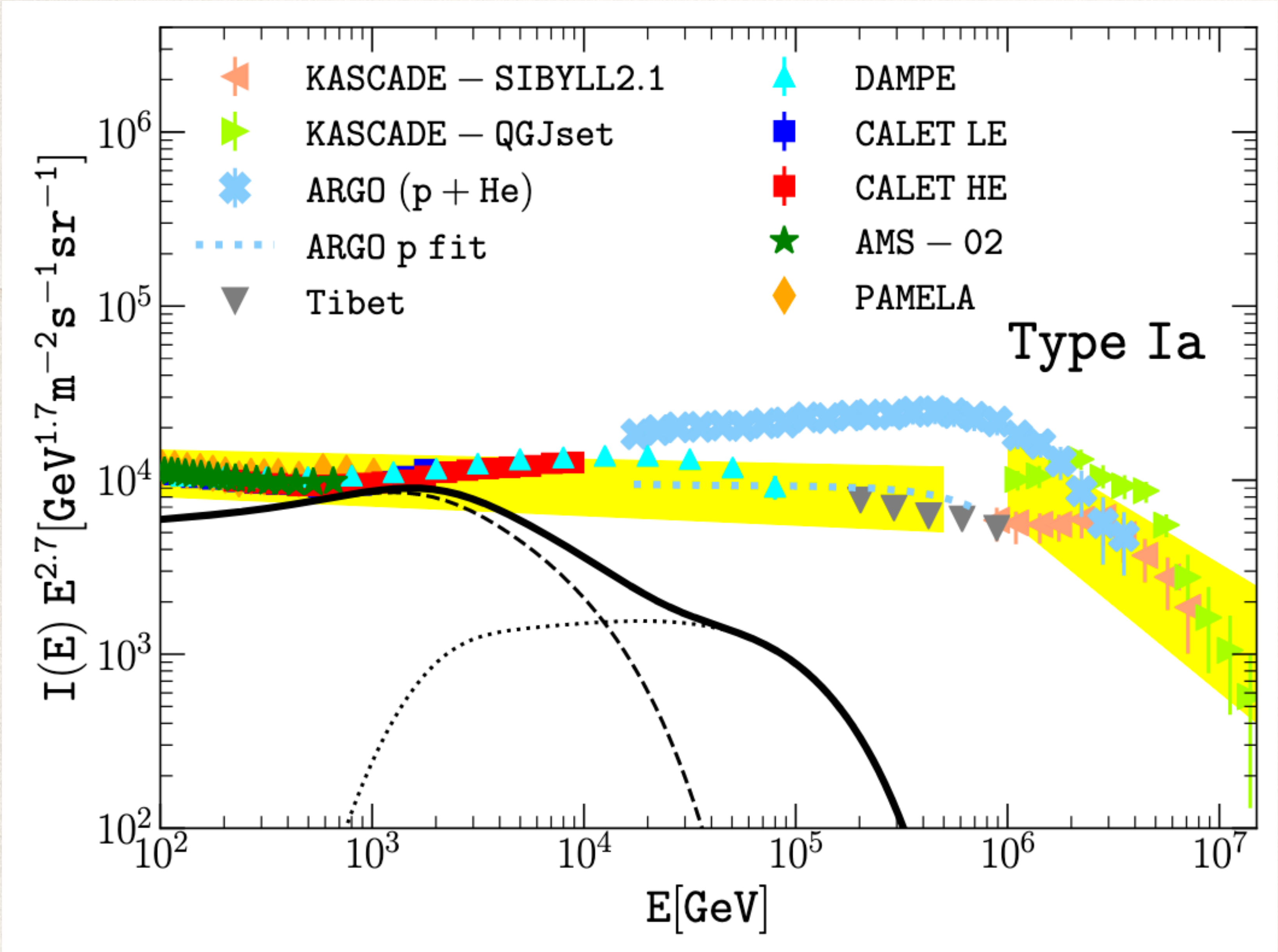
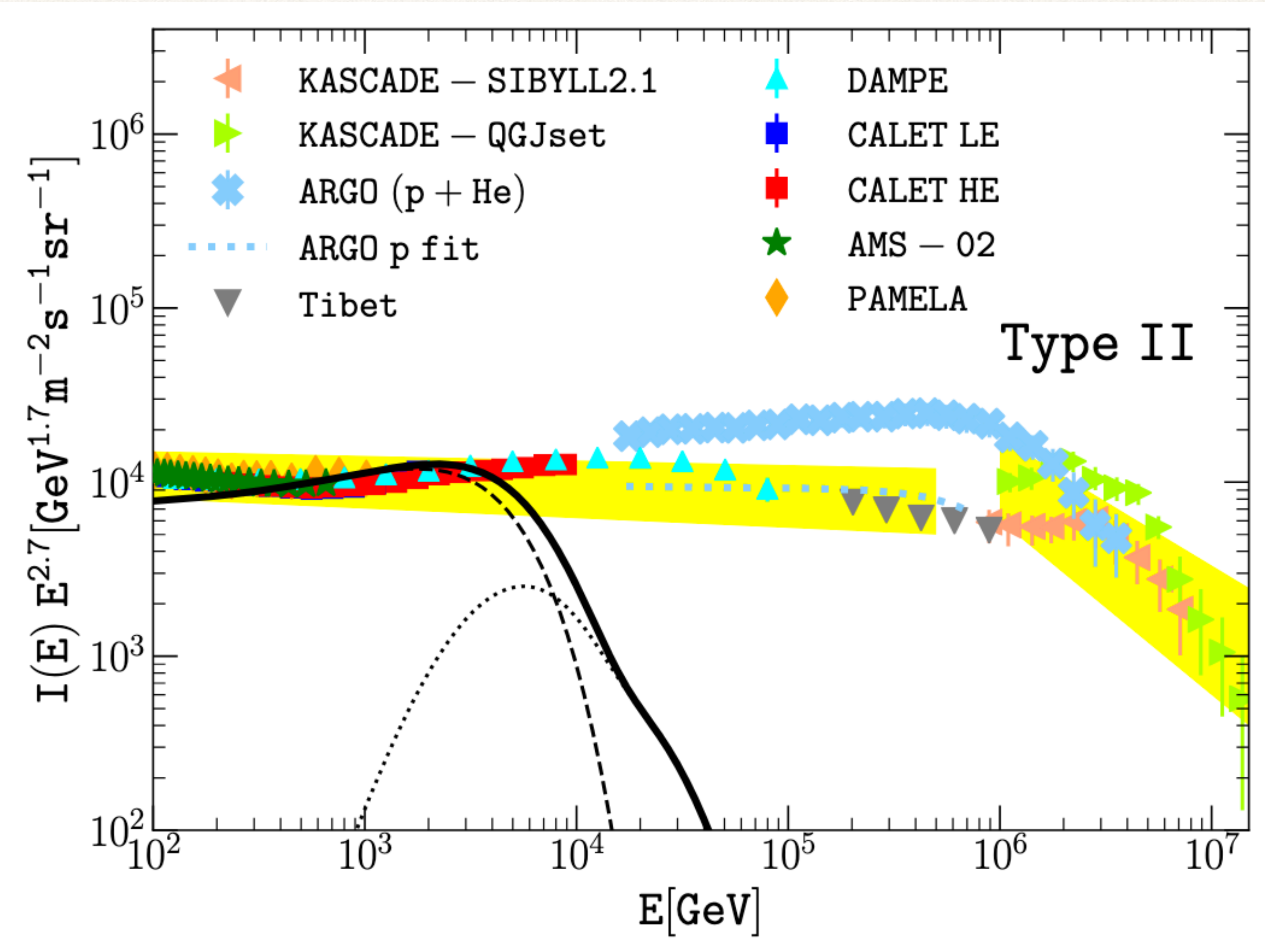
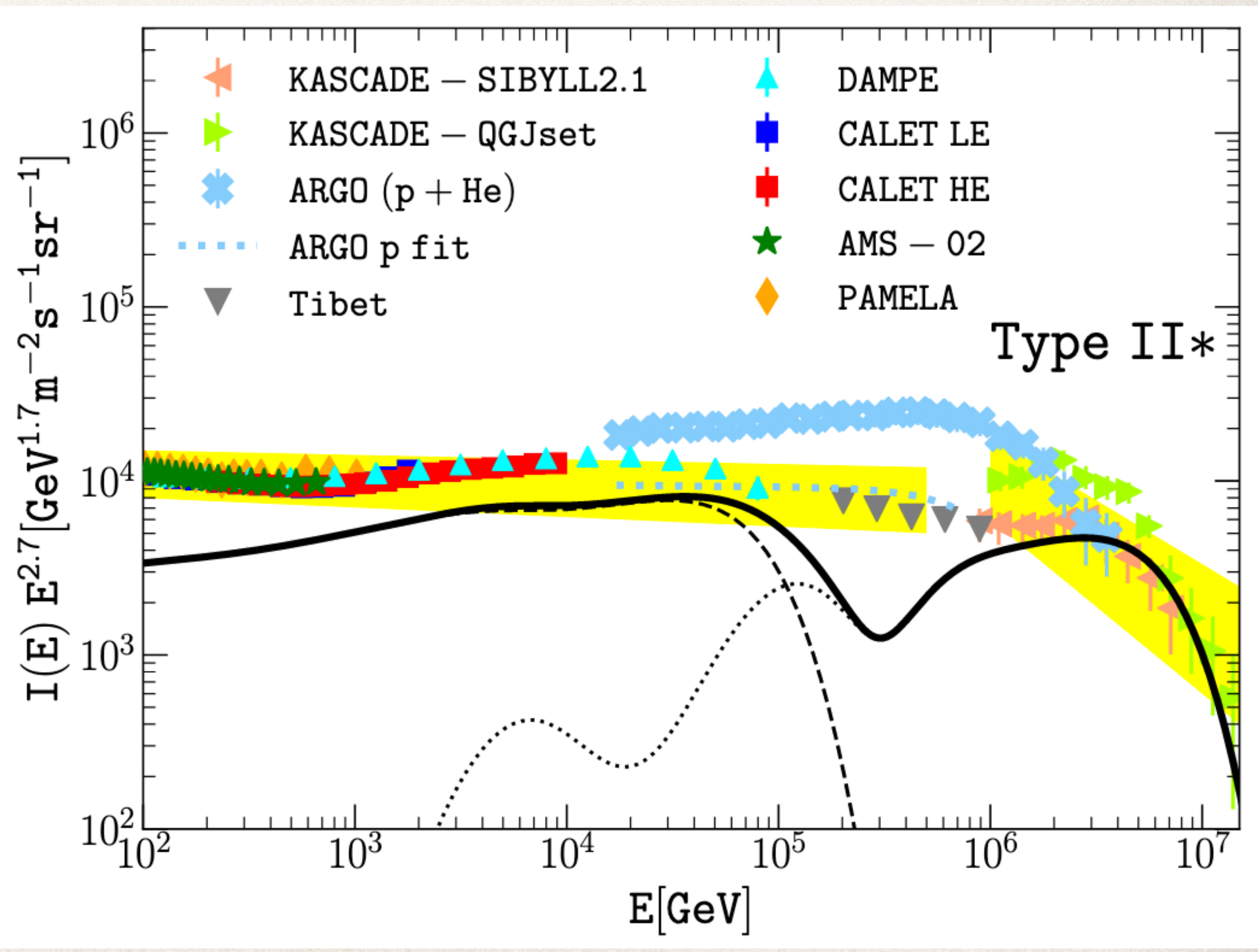
Only very rare and powerful events can account for PeV particles







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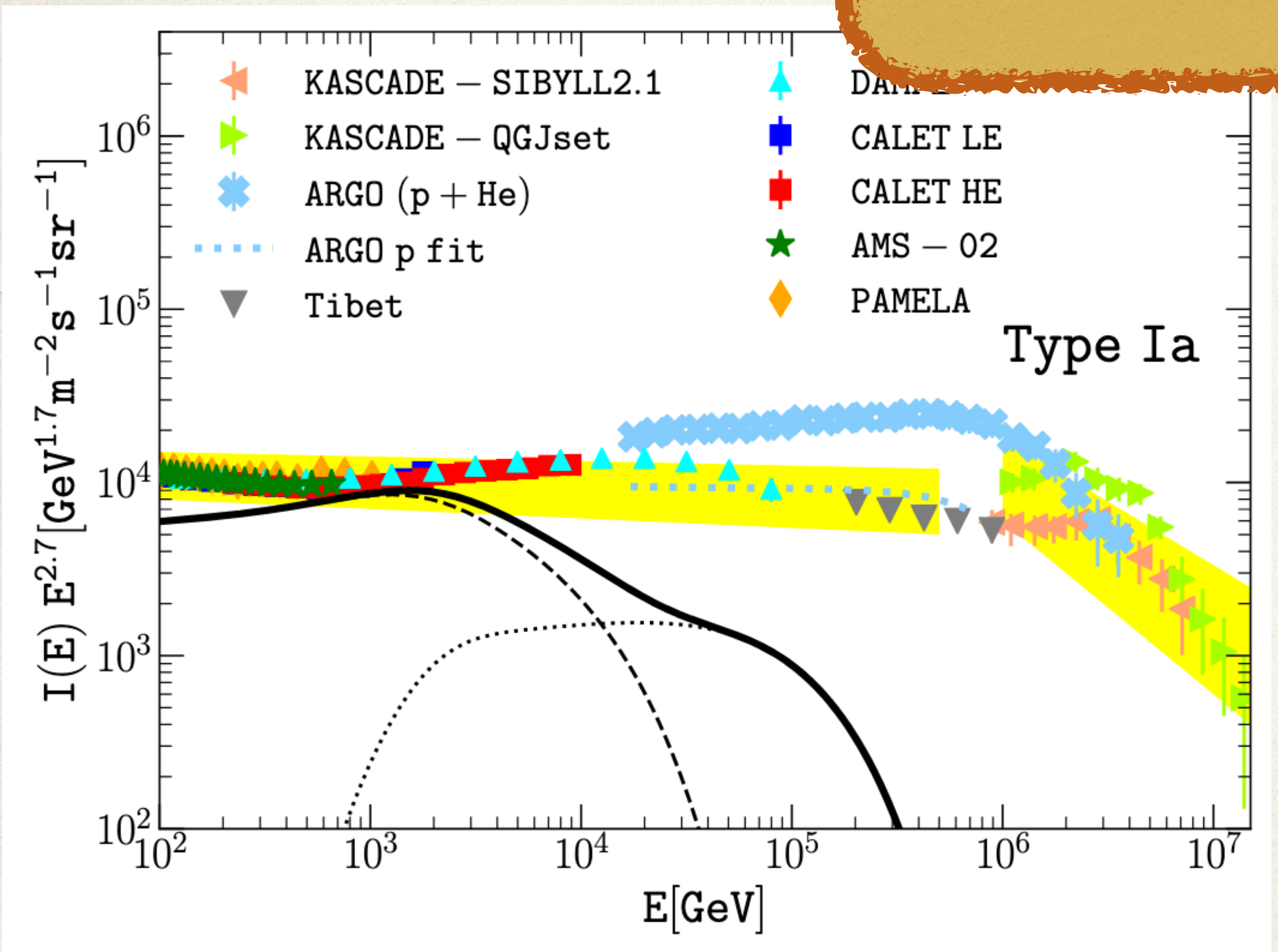
	Type Ia	Type II	Type II*

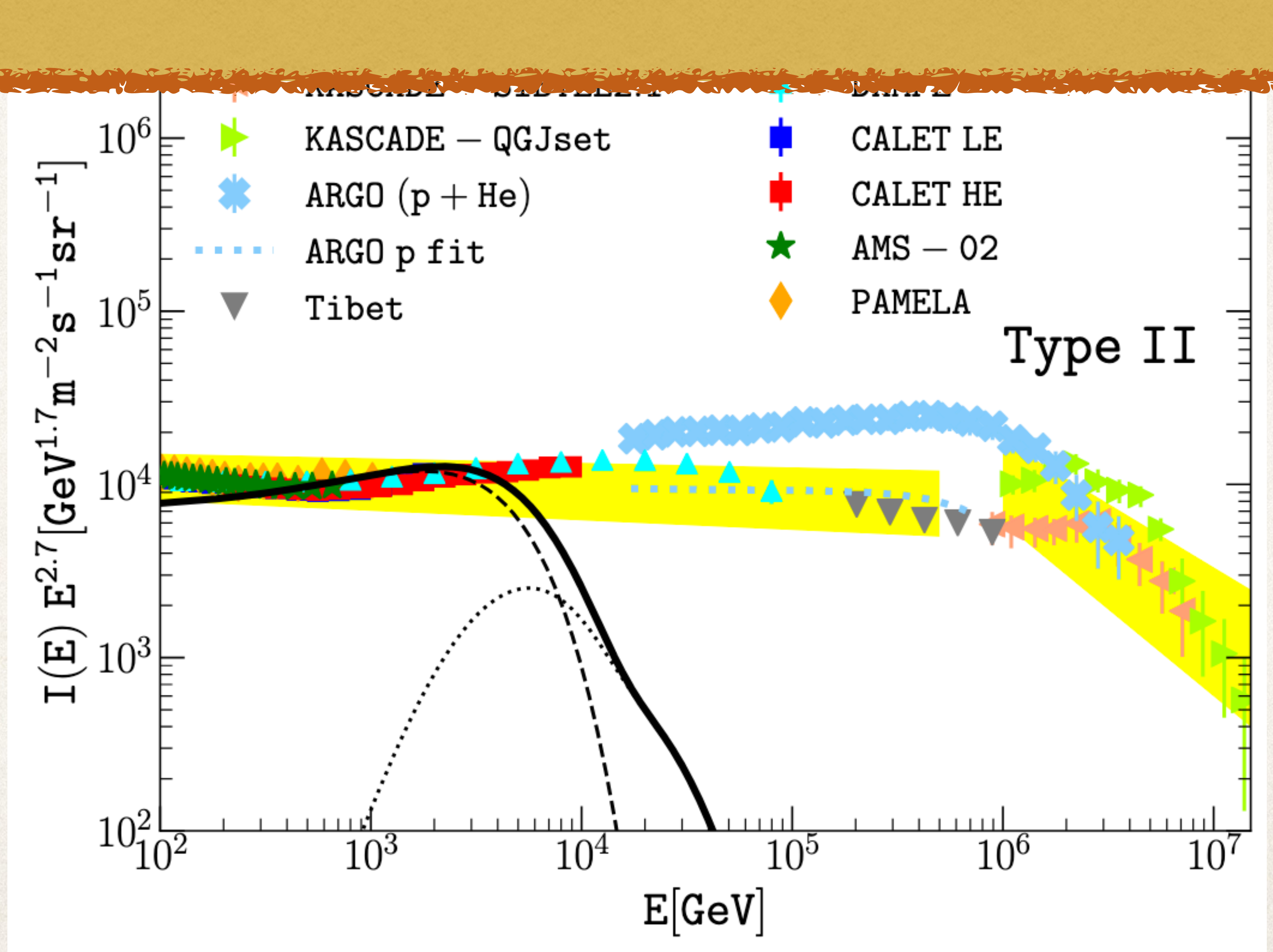
Assumed acc... efficiency ξ_c

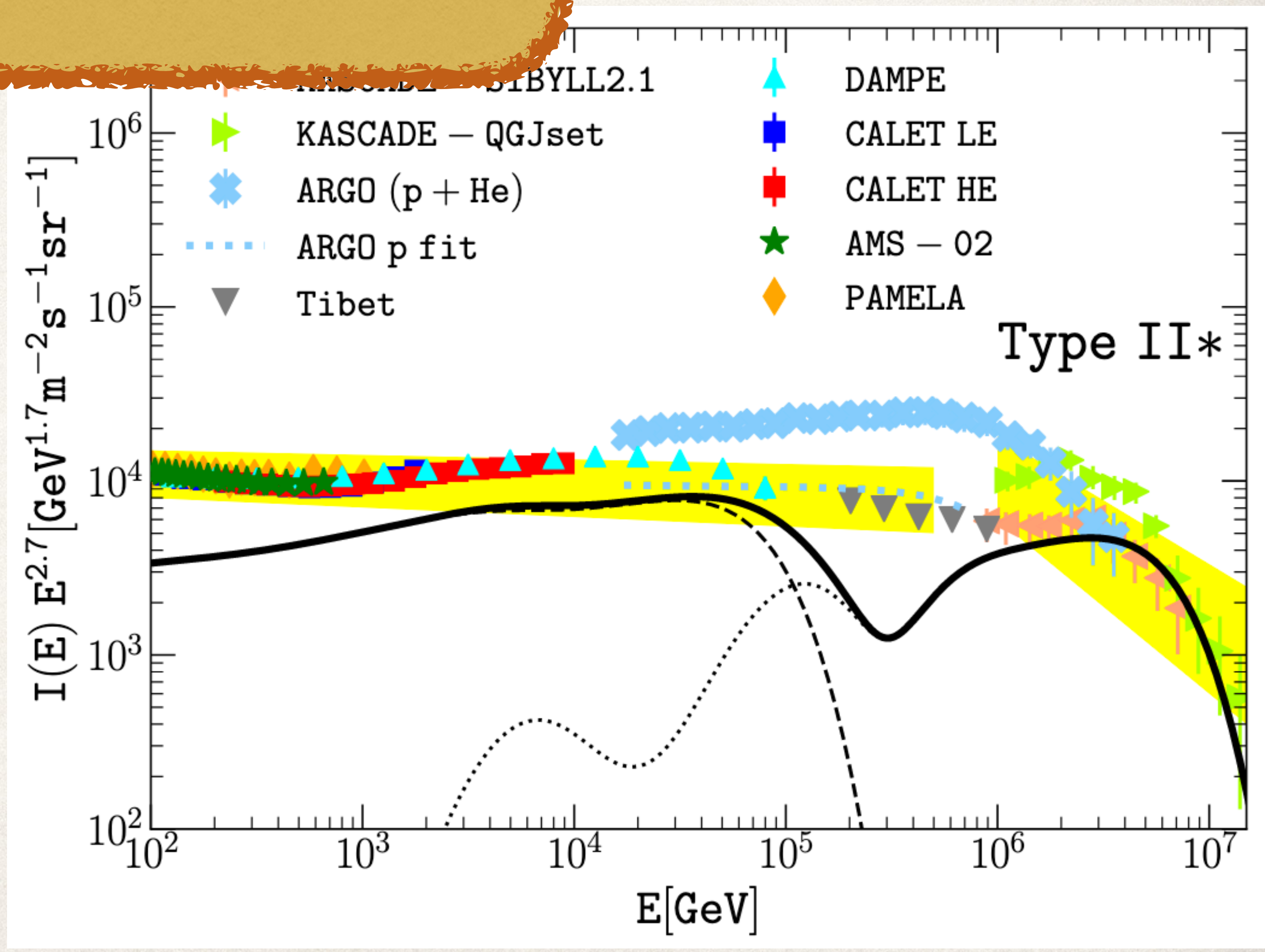
Only very rare and powerful ...ts can account ...PeV particles

If Type II* SNRs are responsible for the production of PeV particles, they also dominate the flux at ~10^2 - 10^4 GeV

⇒ **little room is left to ordinary SNRs!**







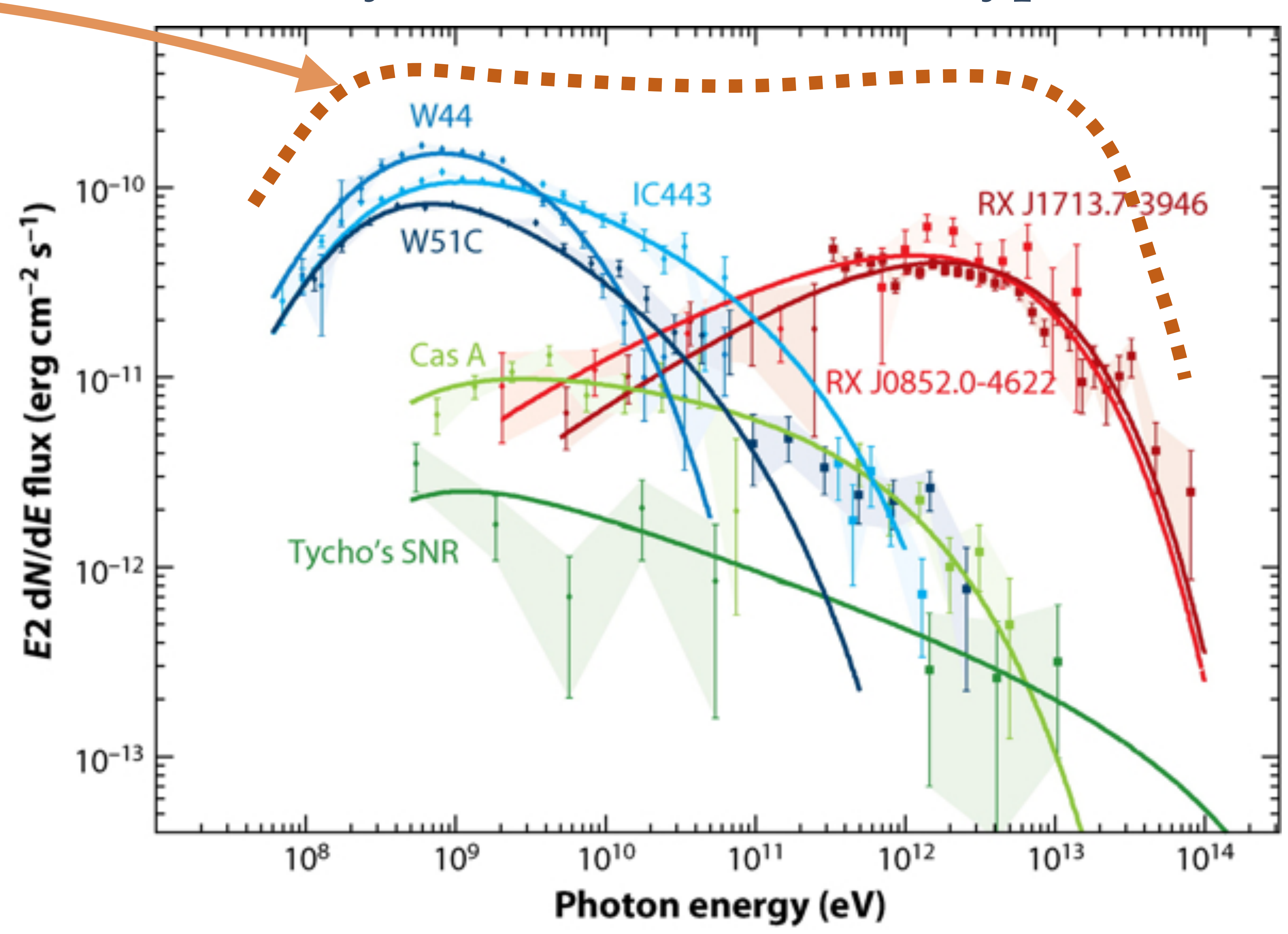
Gamma-rays from SNRs: what's wrong with DSA?

Prediction from test particle theory

	Very young (~300 yr)	Young (~2000 yr)	Middle-age (~10^4 yr)
Emission type	hadronic	unclear (had./lept.)	hadronic
spectrum	soft (~$E^{-2.3}$)	hard (~$E^{-1.5}$ - $E^{-1.8}$)	soft (~E^{-3})
E_{max} (protons)	10-100 TeV	10-100 TeV	<~10 TeV

Not enough to explain the knee at ~PeV

Gamma-ray emission from shell-type SNRs

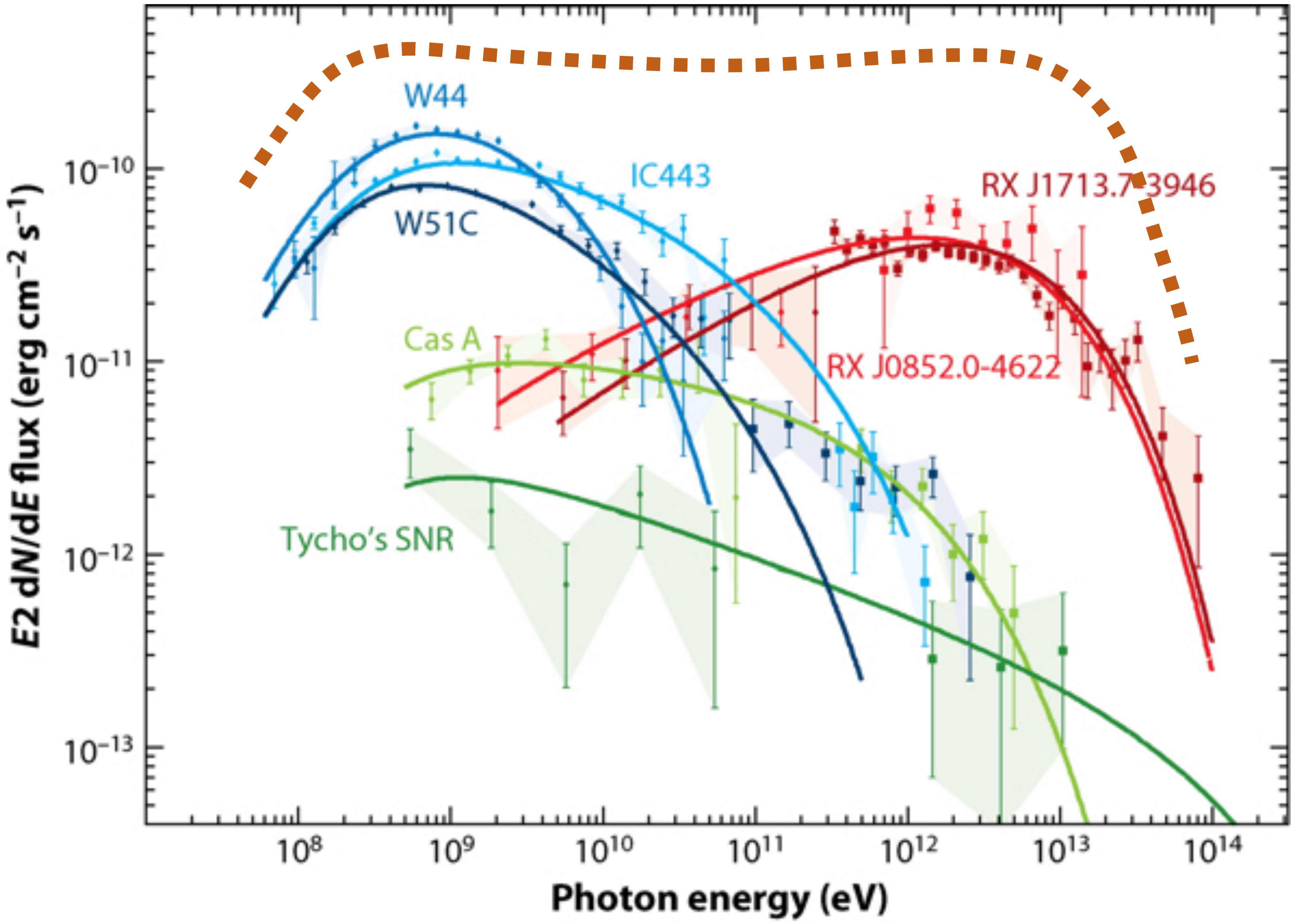


Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

Modification of spectral slope

How to get gamma-ray spectra different from E^{-2} ?

Gamma-ray emission from shell-type SNRs



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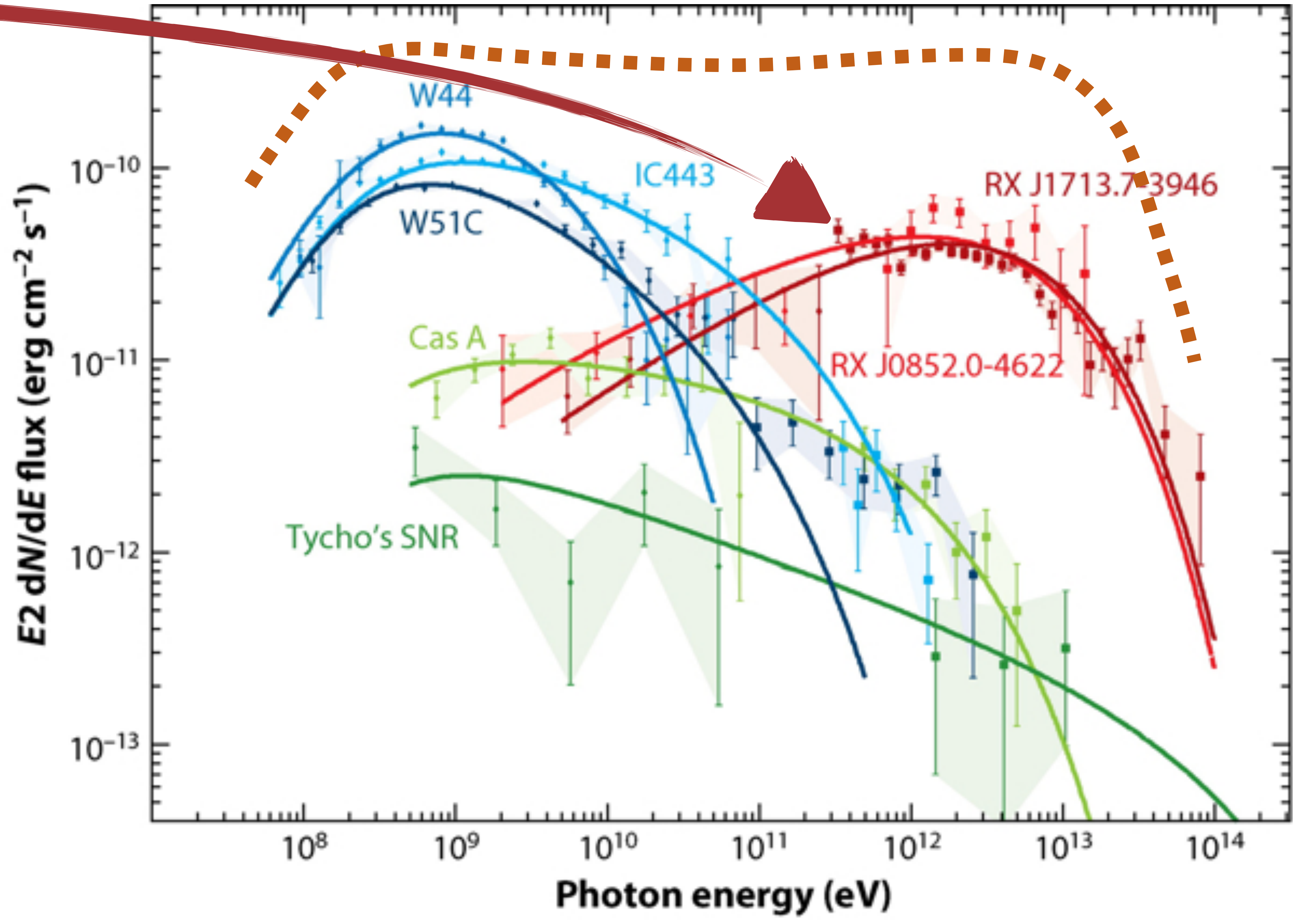
Modification of spectral slope

How to get gamma-ray spectra different from E^{-2} ?

- **Spectra harder than E^{-2}:**
  - Leptonic origin (predicts flux ~ $E^{-1.5}$)
  - Hadronic with shock expanding in clumpy media

Gamma-ray emission from shell-type SNRs



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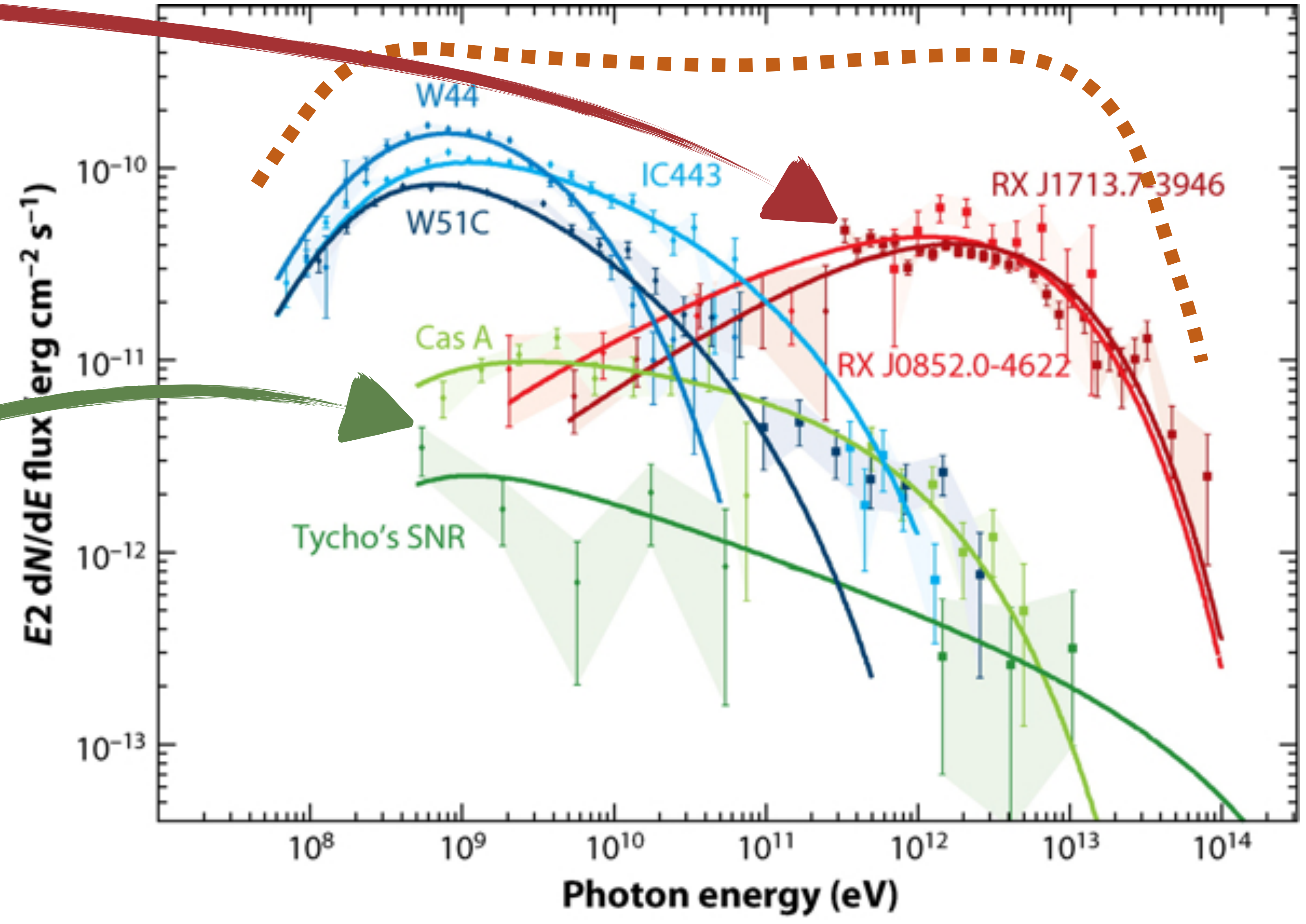
- **Spectra steeper than E^{-2}:**
  - Modified velocity of scattering centres
  - Energy losses during acceleration
  - Break of CR isotropy (only for $v_{sh} \gtrsim 10^4$ km/s)

Gamma-ray emission from shell-type SNRs



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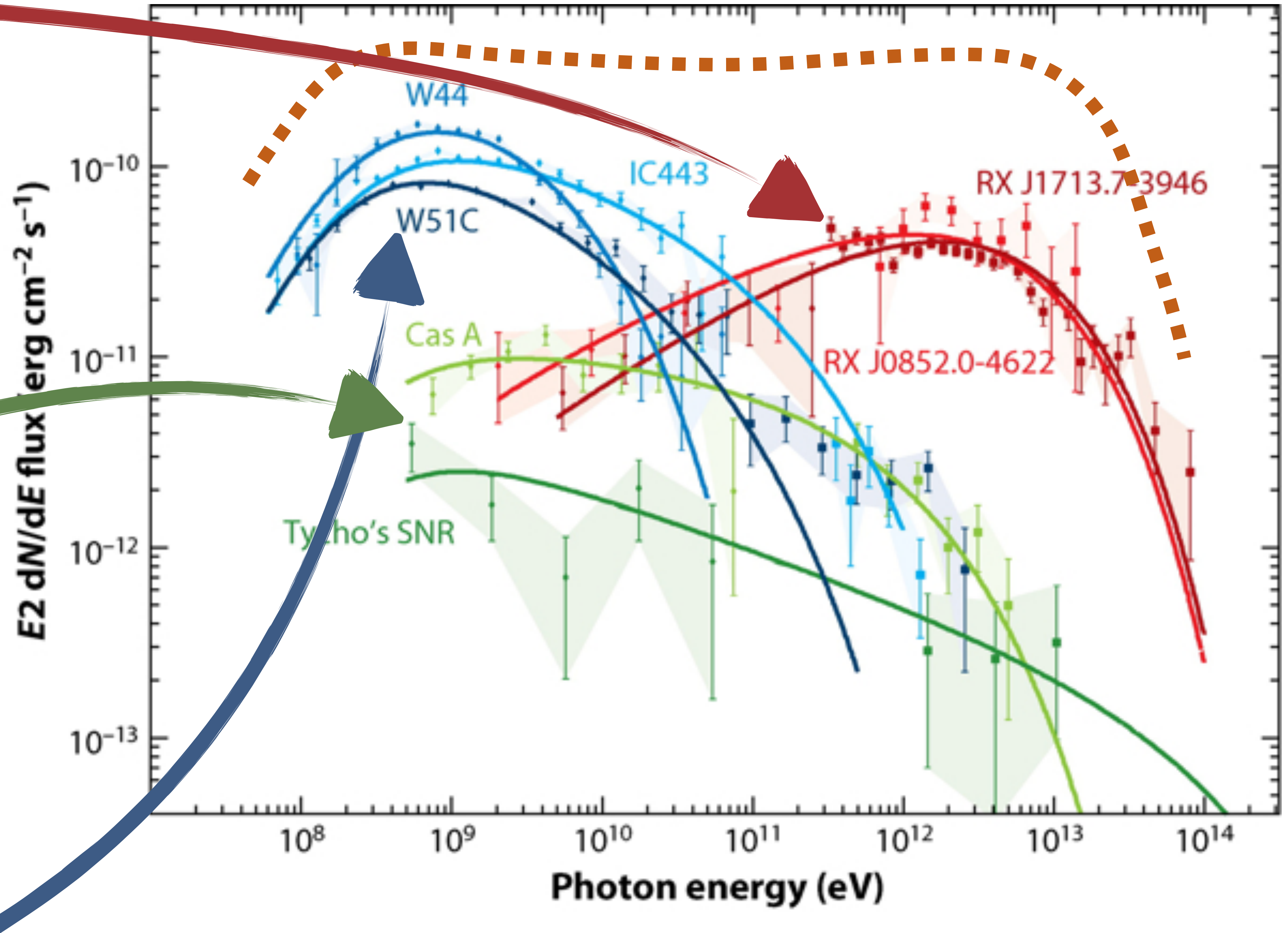
- **Spectra steeper than E^{-2}:**
  - Modified velocity of scattering centres
  - Energy losses during acceleration
  - Break of CR isotropy (only for $v_{sh} \gtrsim 10^4$ km/s)
  - Shock structure modified by neutral Hydrogen (only for $v_{sh} \lesssim 3000$ km/s)
  - Particle escaping (only for middle-aged SNRs)

Gamma-ray emission from shell-type SNRs



Funk S. 2015.
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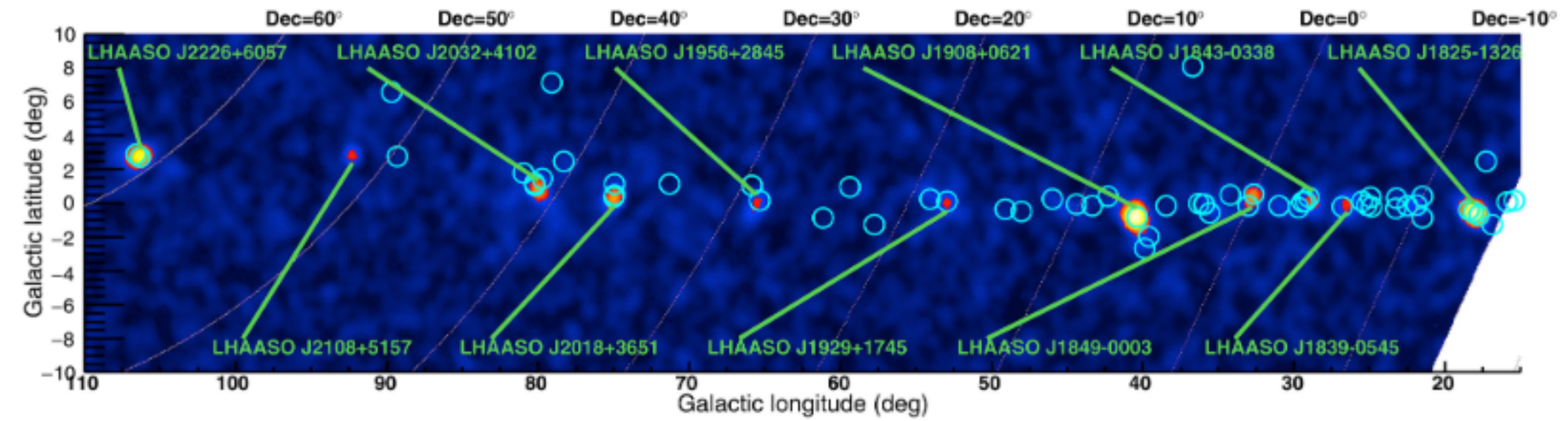
SNRs associated LHAASO sources



Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)[a]	L_s (erg/s)[b]	Potential TeV Counterpart[c]
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030, 2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\,d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\,l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

Uncertain nature of sources due to poor angular resolution

- **Many PSRs (not a surprise: probability of one PSR in LHAASO PSF ~1)**
- **2 young massive stellar clusters**
- **Not many SNRs (all middle-age mainly interacting with molecular clouds)**

SNR Name	Age [kyr]	Distance [kpc]	Type	Cloud interaction	Pulsar
G28.6-0.1	14	7 – 9.6	shell	Yes	?
G40.5-0.5	20	3.4 – 5.1	shell	Yes	Yes
G54.1+0.3	1.5 – 2.4 PSR: 2.9	4.1 – 7.2 PSR: 6.2	Composite	?	Yes
G66.0-0.0	?	2.3 – 4	shell	?	No
G79.8+1.2 (Candidate)	?	?	—	—	—
G106.3+2.7 (Boomerang)	> 3900 PSR: 10	0.7 — 0.8 PSR: 3	Composite	Yes	Yes

A simple model for particle escape from SNRs

[Celli, GM, Gabici & Aharonian 2019]

1) Simple expression for the proton maximum energy

$$p_{\max}(t) = p_M \left(\frac{t}{t_{ST}} \right)^{-\delta}$$

2) assumption:

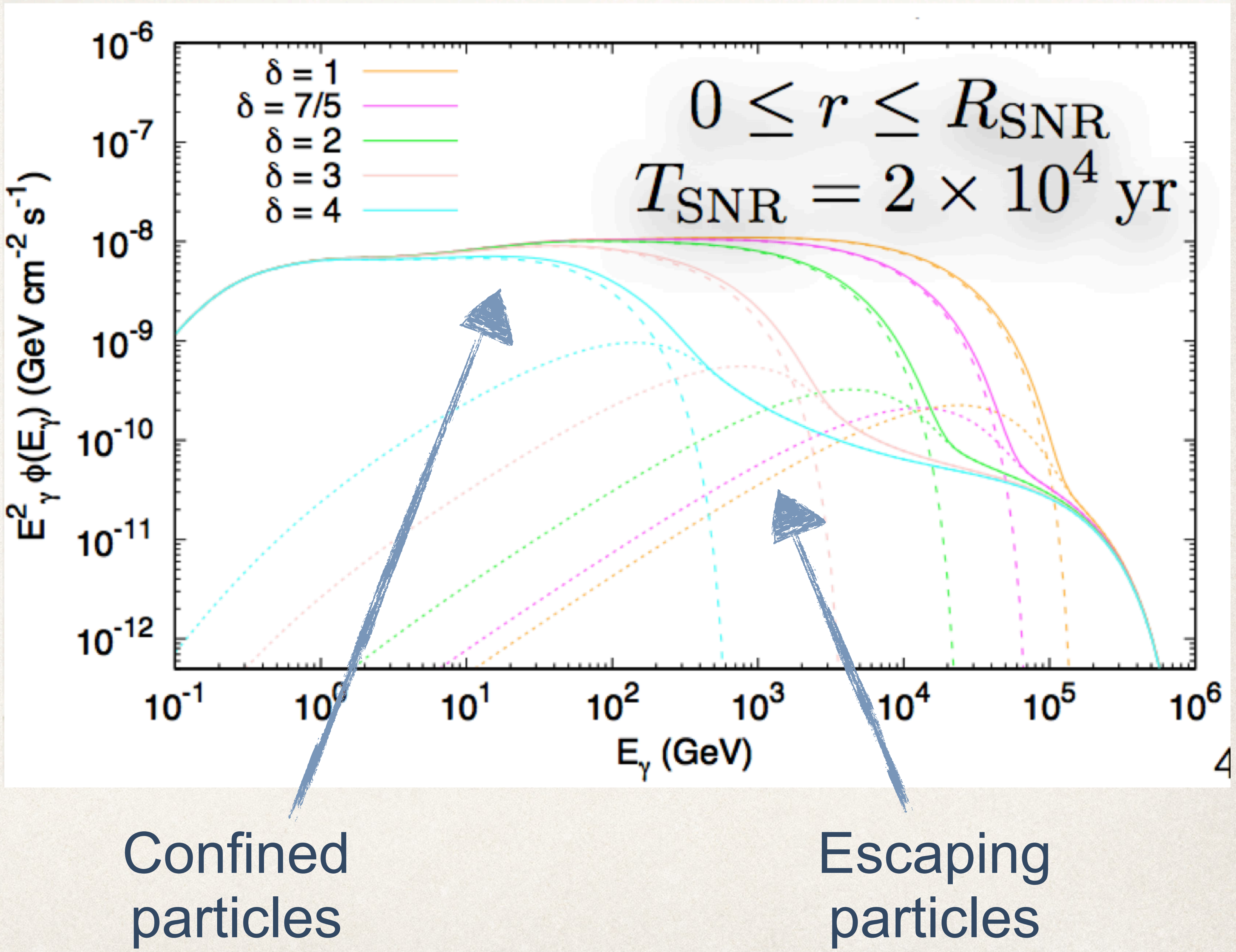
$p < p_{\max}(t) \Rightarrow$ particles are confined inside the SNR

$p > p_{\max}(t) \Rightarrow$ particles escape and diffuse

3) If $D_{\rm ext} \ll D_{\rm gal}$, escaping particles can interact with the SNR interior for long time

High energy emission can be present also in middle-aged SNRs

Example of gamma-ray emission from a middle aged SNR



Particle escape from SNRs

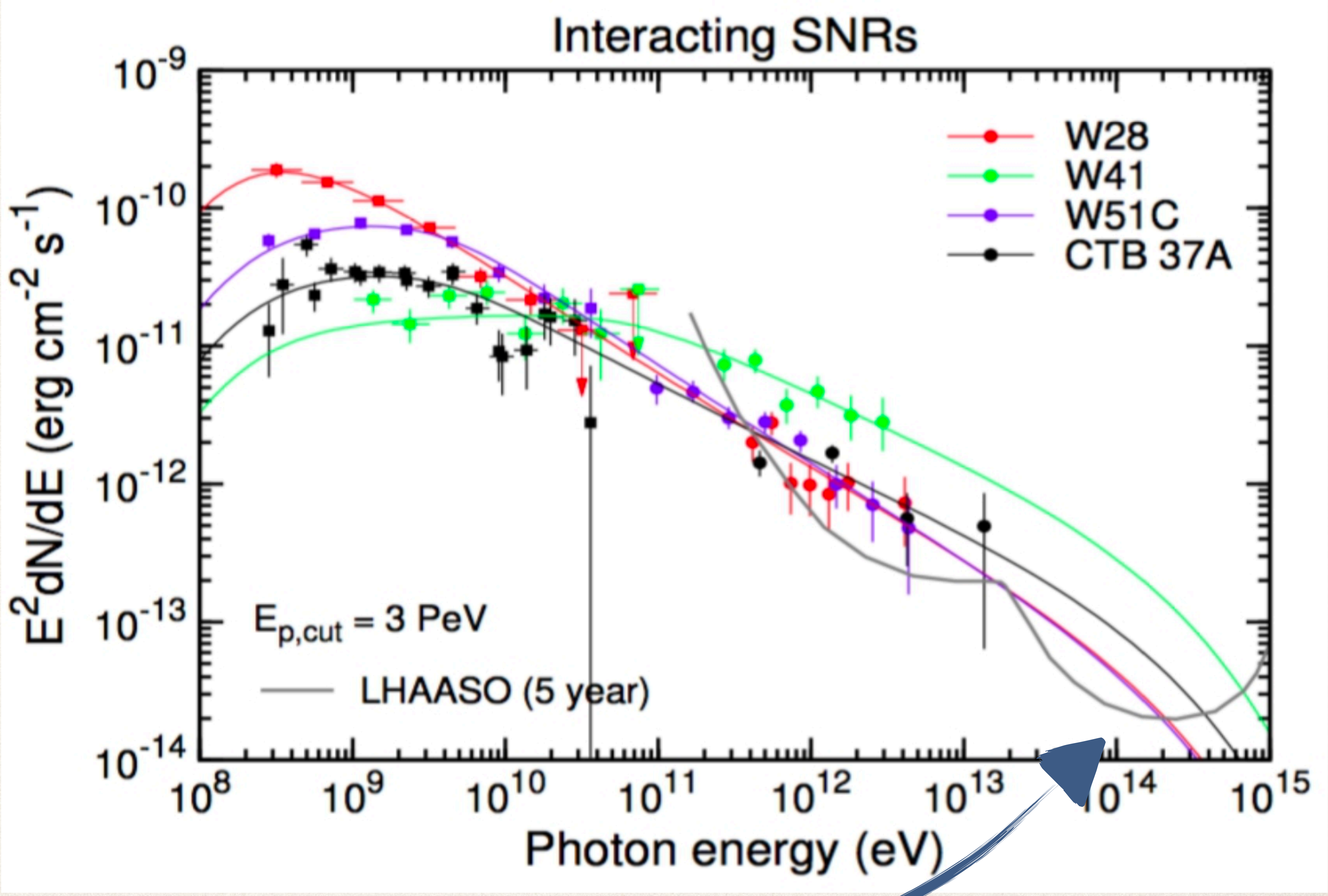
For middle-aged SNR:

- Escaping particles can produce large halos around SNRs (similar to the one observed from some PWNe)
- Confinement can be enhanced thanks to streaming instability of run away particles
- If the external diffusion is suppressed:
  - Observed steep spectra can be due to escape
  - High energy particles are still around the SNR:

$$\tau_{\rm esc} \simeq 10 \left(\frac{d}{50\,\rm pc}\right)^2 \left(\frac{D_{\rm csm}}{D_{\rm Gal}/100}\right)^{-1} \rm kyr$$

- LHAASO can probe this scenario thanks to the high energy sensitivity

LHAASO Science White Paper
arXiv:1905.02773v1

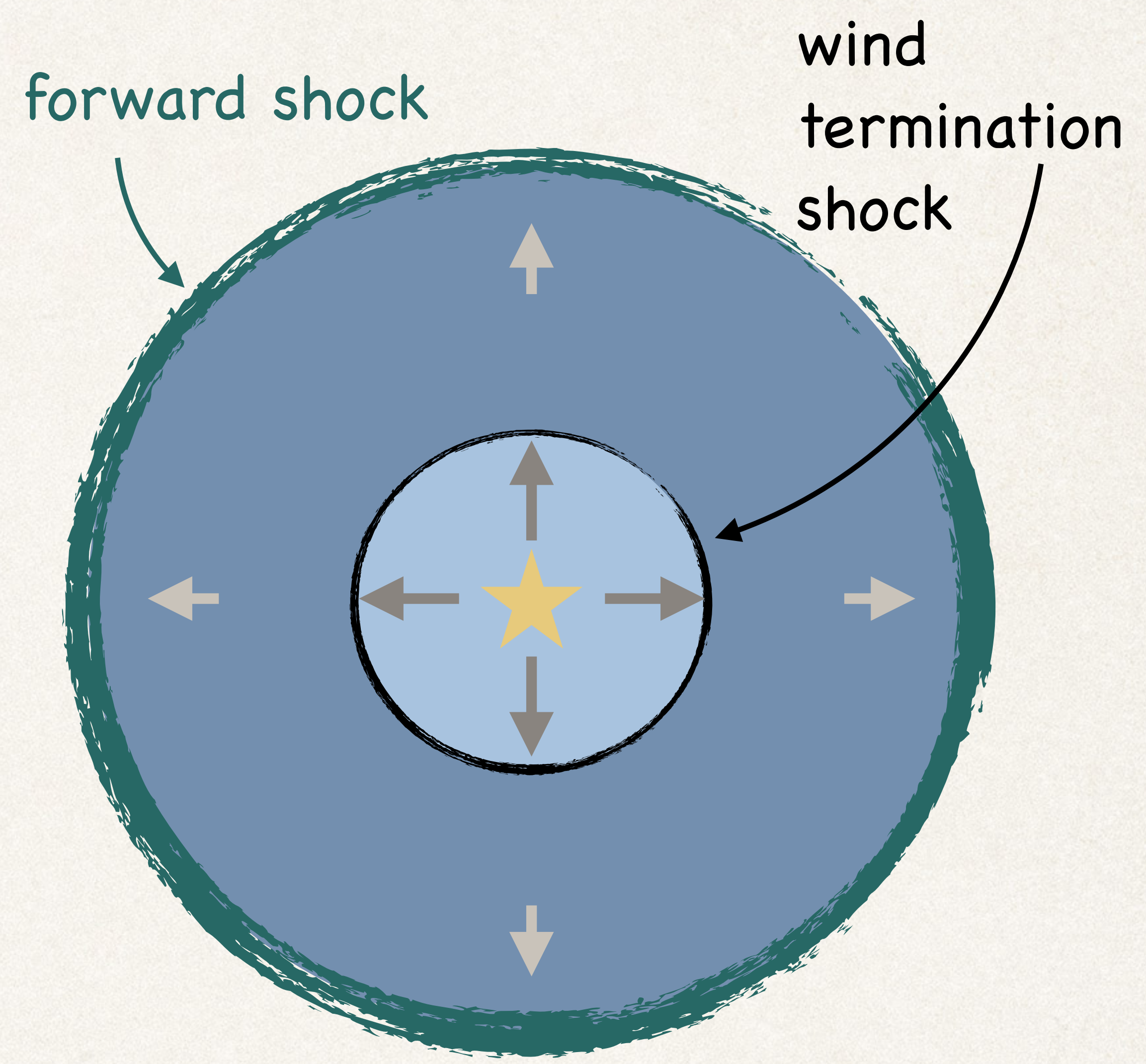


Stellar clusters and super-bubbles (the elephant in the room)

Why Star clusters are important?

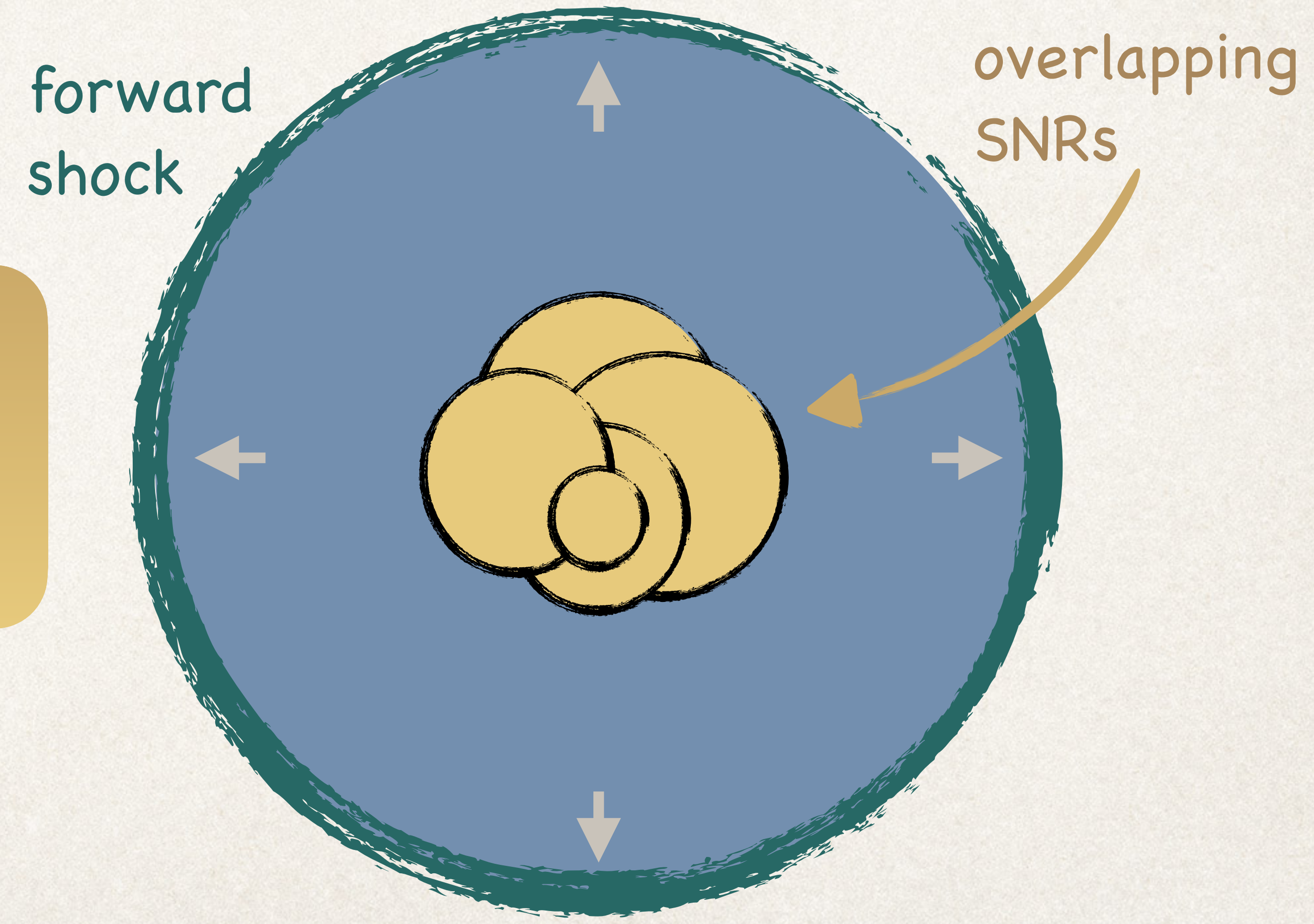
- Massive stars born in Star Clusters
  - **~80%** of CC SNe explode in SCs
  - **~20%** explode as isolated (probably associated to runaway stars)

$t \lesssim 3\,\mathrm{Myr}$
only stellar winds



- Expands into an environment different from the "regular" ISM
  - Lower density ($n \sim 10^{-3} - 0.1$)
  - Higher temperature ($T \sim 10^{6} - 10^{8}\,\mathrm{K}$)
  - Highly turbulent (+ advection)

$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$
stellar wind + SNe



SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number

<u>Example: first SN expanding into the shocked wind</u>

Shocked wind temperature: $k_B T_b = \frac{3}{16} m_p v_w$

Sound speed: $c_{\rm sound} = \sqrt{\gamma k_B T_b / m_p}$

$$\Rightarrow M = \frac{v_{sh}}{c_s} = 3.6 \left(\frac{v_{sh}}{5000\,\mathrm{km/s}} \right) \left(\frac{v_w}{2500\,\mathrm{km/s}} \right)^{-1}$$

CAVEAT:
Temperature may decrease due to radiative losses/heat conduction

$$\tau_{\rm cool} \simeq 6 \left(\frac{T}{10^6\,K} \right)^{1.7} \left(\frac{n}{0.01\,\mathrm{cm}^{-3}} \right)^{-1} \mathrm{Myr}$$

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
   - low Alfvénic Mach number

Example: first SN expanding into the shocked wind

If the magnetic field is produced by wind turbulence:

$$\frac{B^2}{4\pi} v_w = \eta_B L_w \;\Rightarrow\; B_b \simeq 10,\mu\mathrm{G}$$

Than the Alfvénic Mach number is

$$M_A = \frac{v_{\rm sh}}{v_{\rm A}} = \sqrt{\frac{4}{11\eta_B}\frac{v_{\rm sh}}{v_w}} \gtrsim 4$$

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
   - low Alfvénic Mach number
   - faster acceleration time

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Than the Alfvénic Mach number is

$$M_A = \frac{v_{\rm sh}}{v_{\rm A}} = \sqrt{\frac{4}{11\eta_B}\frac{v_{\rm sh}}{v_w}} \gtrsim 4$$

The maximum energy increases:

$$E^p_{\rm max} \simeq 2\,\mathscr{F} \left(\frac{B_0}{10\mu G}\right)\left(\frac{M_{\rm ej}}{M_\odot}\right)^{-\frac{1}{6}}\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)^{\frac{1}{2}}\left(\frac{n_0}{0.01{\rm cm}^{-3}}\right)^{-\frac{1}{3}} \mathrm{PeV}$$

Diffusion needs to be Bohm-like

SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
   - low Alfvénic Mach number
   - faster acceleration time
   - enhanced syn. losses

Synchrotron loss time: $\tau_{\rm syn} = \frac{9 m_e^2}{4 r_0^2 c\, B^2} E^{-1}$

Advection time: $\tau_{\rm adv} = \frac{4 R_b}{3 v_w} \left(\frac{R_b}{R_s} \right)^2$

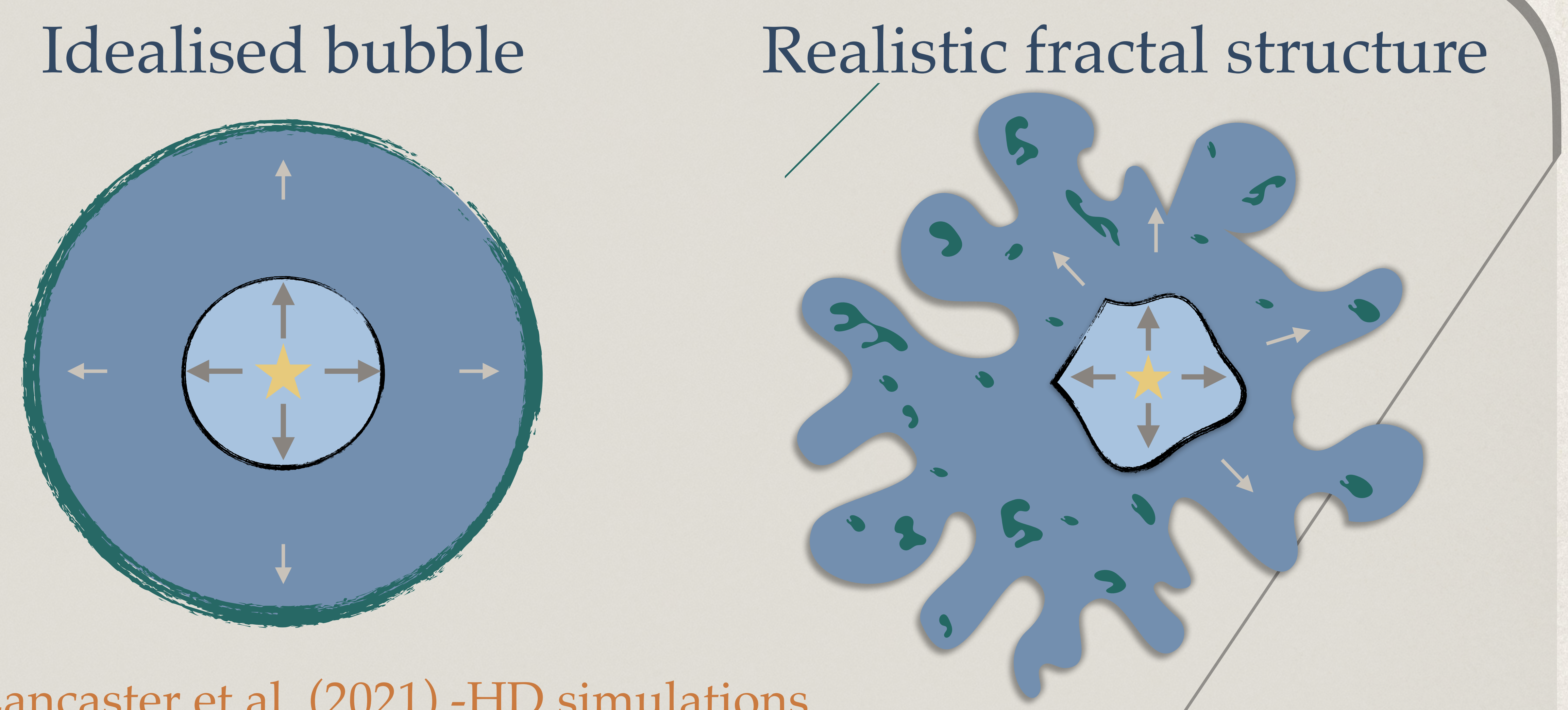
$$\tau_{adv} = \tau_{\rm syn} \;\Rightarrow\; E_{\rm esc} \lesssim 200 \left(\frac{B}{10\,\mu G} \right)^{-2} \text{GeV}$$

High energy electrons cannot escape from the bubble

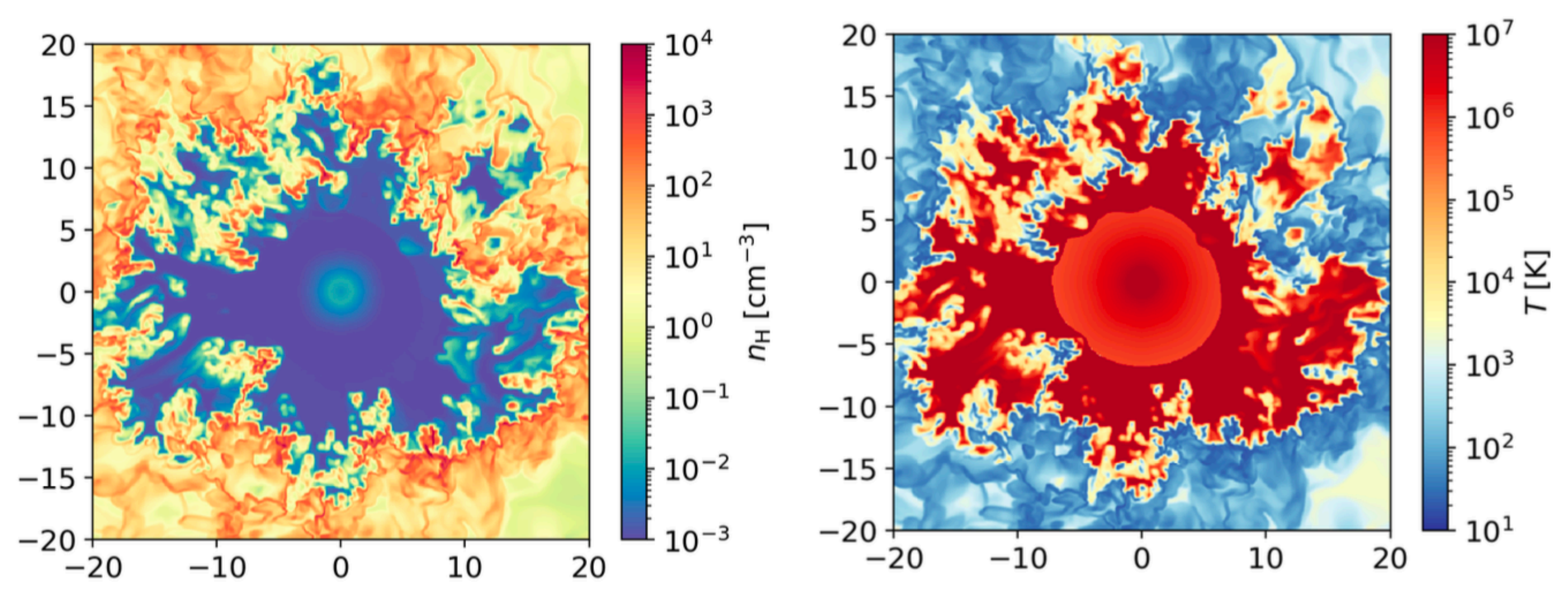
SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
   - low Alfvénic Mach number
   - faster acceleration time
   - enhanced syn. losses
3. Fractal structure of dense shell
   - Increase of cooling by conduction



L. Lancaster et al. (2021) -HD simulations

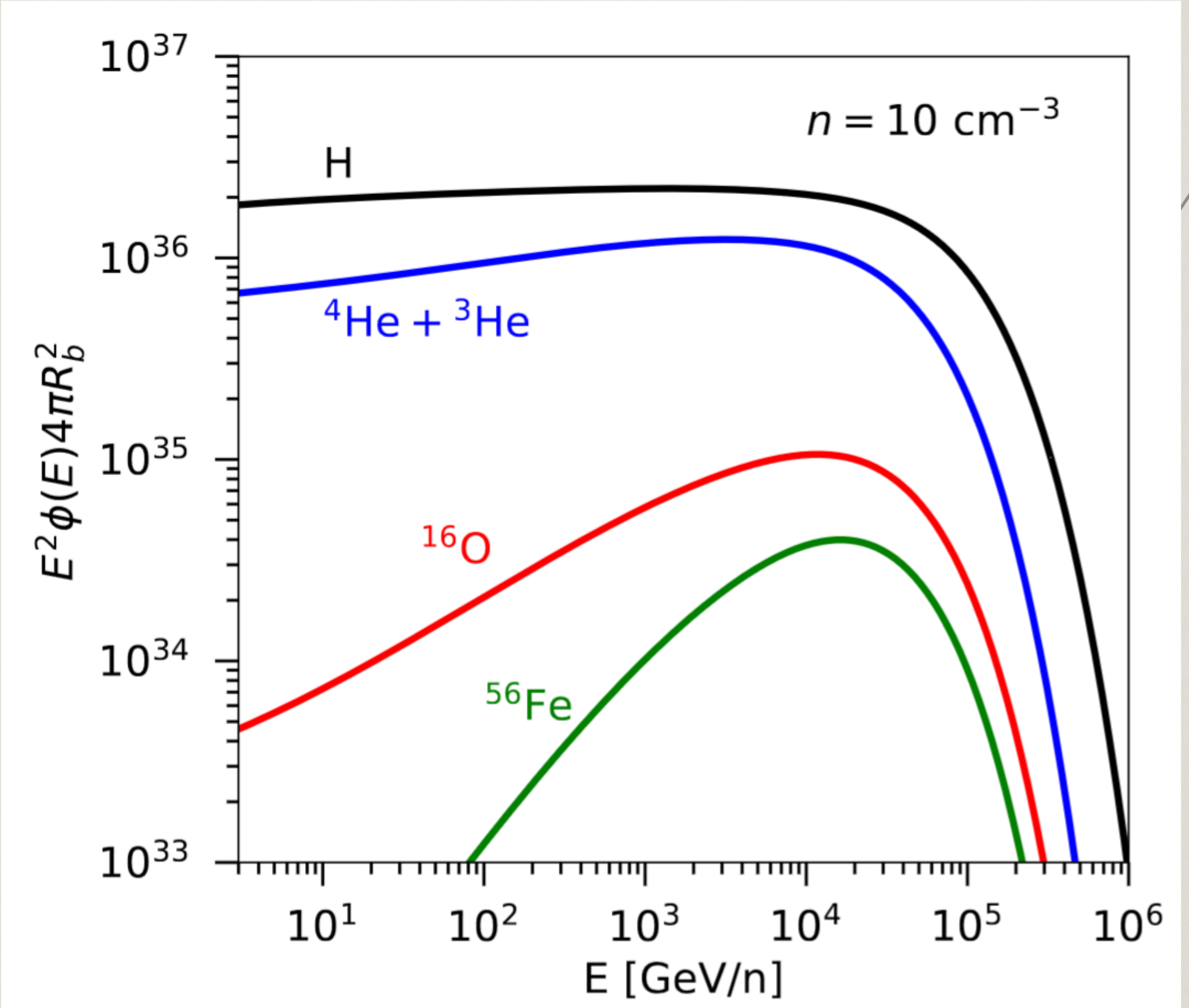


SNR expanding into super-bubbles

Main effects on the SNR evolution

1. High temperature ⇒ low Mach number
2. High turbulence ⇒ high magnetic field
   - low Alfvénic Mach number
   - faster acceleration time
   - enhanced syn. losses
3. Fractal structure of dense shell
   - Increase of cooling by conduction
   - Possible increase of grammage

Spectrum of different species escaping the bubble: effect of spallation
(The case of Cygnus cocoon $L_{\rm wind} \gtrsim 10^{38}$ erg/s)



[P. Blasi, GM (2024) submitted]

Some conclusions

DSA applied to SNR shocks is the most solid framework to explain the origin of Gal. CRs. <u>BUT</u> some fundamental problems remain unsolved

- From SNRs emission, the standard spectrum $n(E) \sim E^{-2}$ is never observed
  - Do we lack of some fundamental aspect of the theory? (*velocity of magnetic turbulence and energy losses due to amplification of magnetic field point towards steeper spectra*)
  - Important environmental effects? (*Clumpy media, presence of neutral Hydrogen, …*)
- Maximum energies above few tens of TeV never observed
  - Resonant instability allows only $\delta B/B_0 \lesssim 1 \rightarrow E_{max} \lesssim 100$ TeV
  - Non-resonant instability applied to common SNRs also gives $E_{max} \lesssim 100$ TeV
    - ➡ PeV energies require very rare (~10^{-4} yr^{-1}), powerful events ($E_{SN} \sim 10^{52}$ erg; $M_{ej} \sim 1\, M_{sol}$)
  - Pre-amplified magnetic field in super-bubbles may solve the problem
- Middle-aged SNR can be promising target for PeV search if diffusion is suppressed