The search for Galactic pevatrons

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NOW2022

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10^{15} eV

Why do we care?

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1. It is very difficult to explain acceleration up to 10^{15} eV (Galaxy)

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Why do we care?

1. It is very difficult to explain acceleration up to 10^{15} eV (Galaxy)

2. Origin of CRs

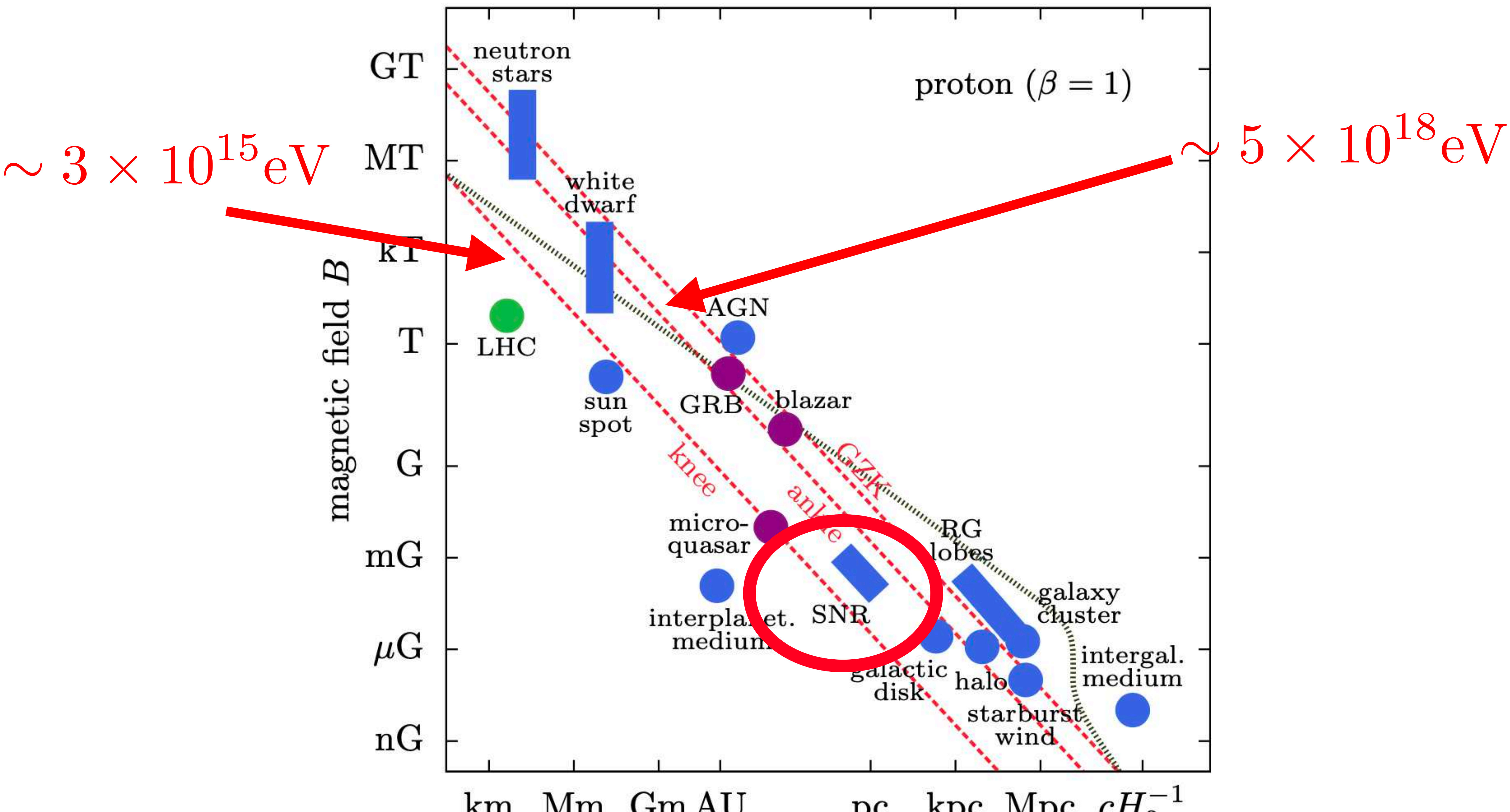
3. Now is the time: we can find them!

IJCLab Irène Joliot-Curie | l'Observatoire de Paris | PSL | H.E.S.S. | SWGO The Southern Wide-field Gamma-ray Observatory | cta cherenkov telescope array

1. It is difficult to explain acceleration up to 10^{15} eV (Galaxy)

Hillas criterion

$$E_{\max} \approx \xi \left(\frac{R_{\rm sh}}{\rm pc}\right)\left(\frac{u_{\rm sh}}{1000{\rm km/s}}\right)\left(\frac{B}{\mu\ {\rm G}}\right) {\rm TeV}$$



IceCube collaboration, 2017

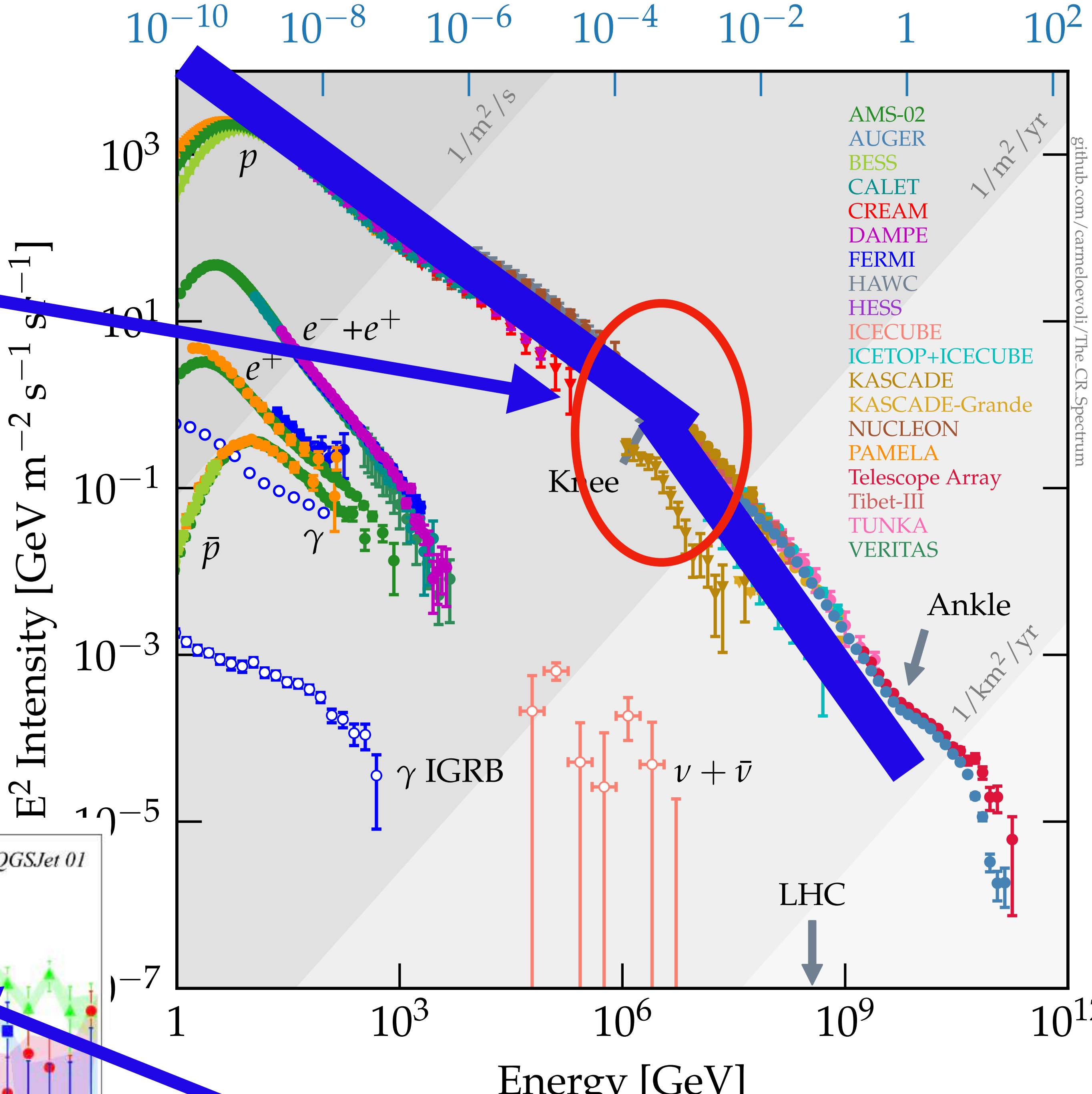
2. Origin of CRs

Blasi 2013, 2019 (reviews)
Gabici et al. 2019 (review)

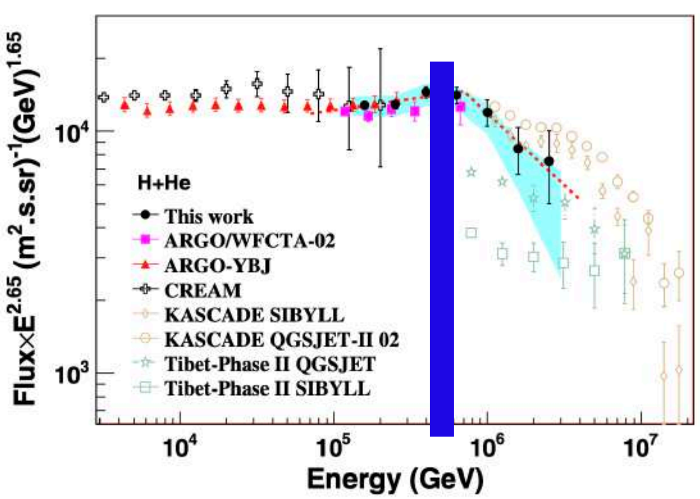
Reaching the « knee »

What is the energy of the knee?

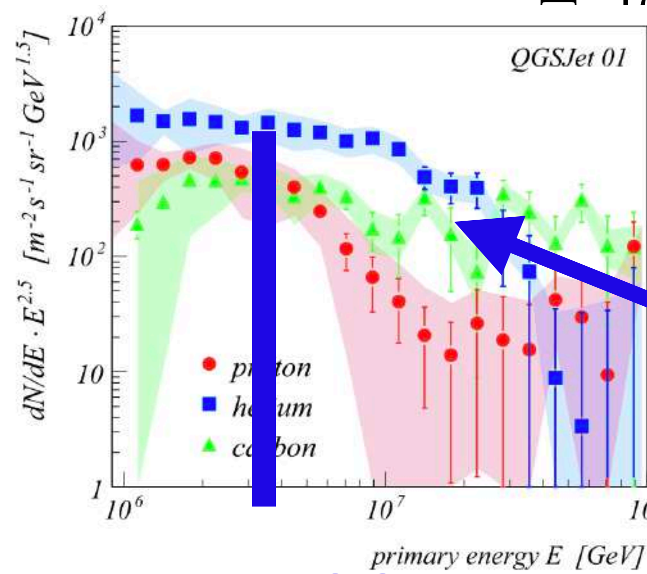
For protons:



Evoli 2021



ARGO-YBJ
~700 TeV
Bartoli et al. 2015



KASCADE
~3 PeV
Antoni et al. 2015

For heavier nuclei : Z dependent knees!

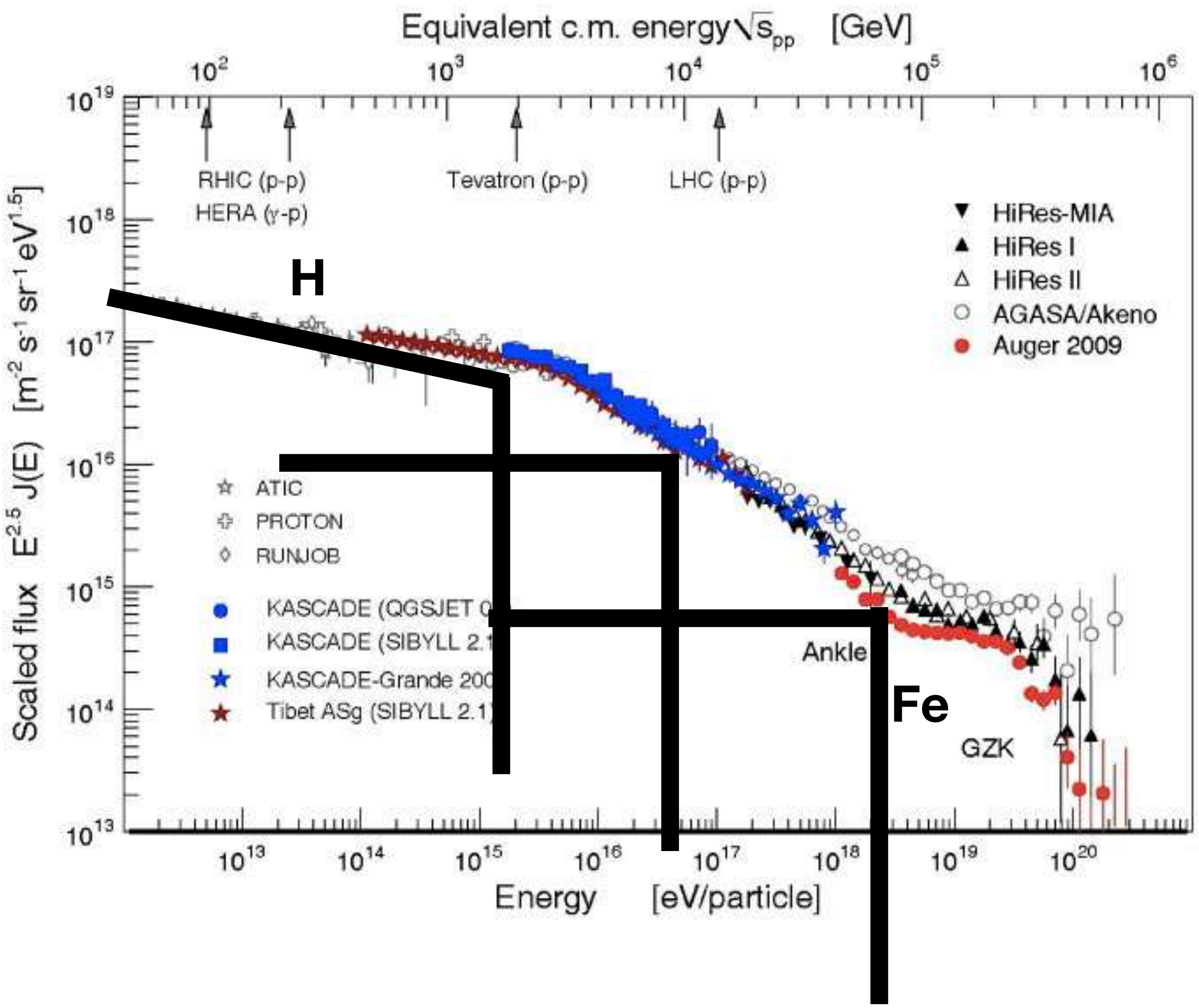
Source of Galactic CRs must accelerate protons up to the knee!

2. Origin of CRs

MORE PRECISELY

Source of Galactic CRs must accelerate up to AT LEAST the knee!

~100 PeV



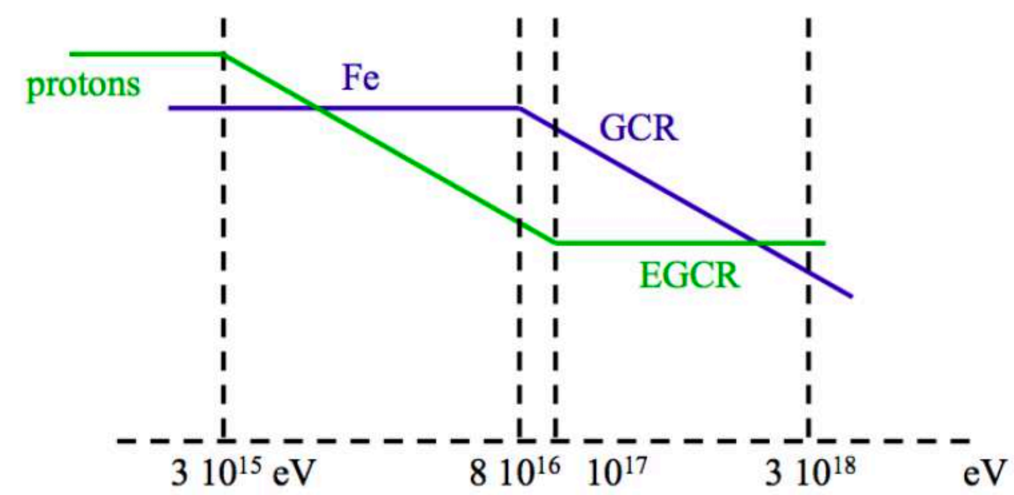


Figure 4: Sketch of the GCR/EGCR transition, with the proton and Fe components indicated (respectively in green and in blue on the color version of the figure). In ordinate, the CR flux is multiplied by E^x, where x is the logarithmic slope of the CR spectrum below the knee. (See also Fig. 3).

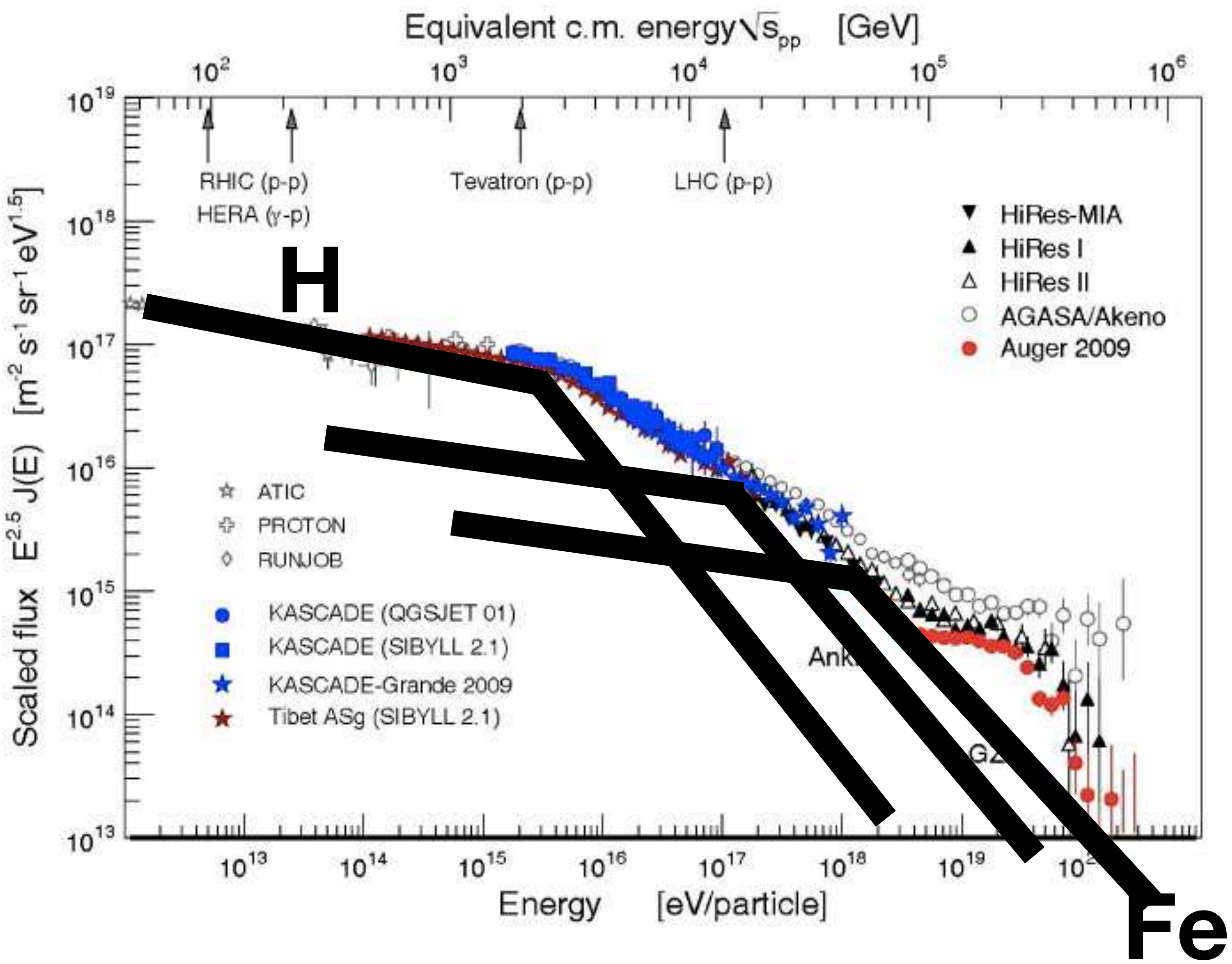
Parizot (Review) 2014

2. Origin of CRs

MORE PRECISELY

Source of Galactic CRs must accelerate up to AT LEAST the knee!

~100 PeV



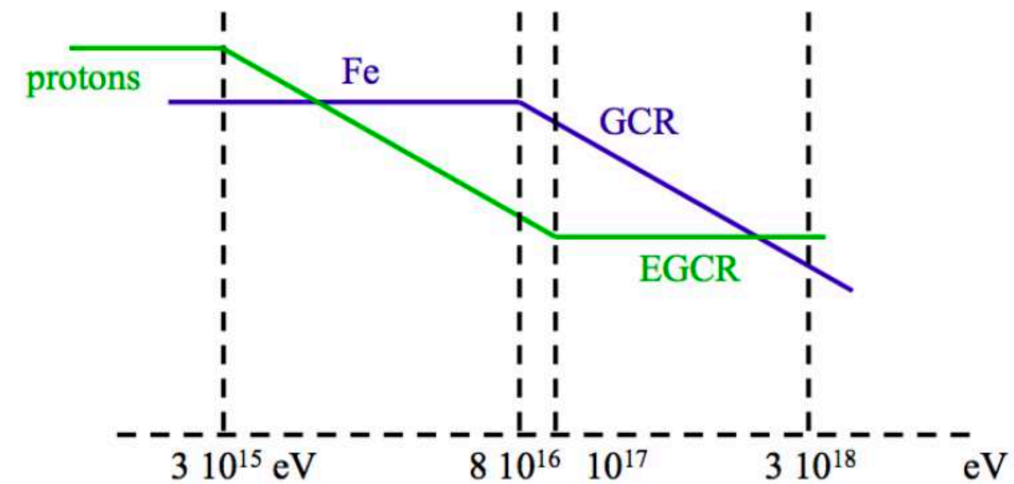


Figure 4: Sketch of the GCR/EGCR transition, with the proton and Fe components indicated (respectively in green and in blue on the color version of the figure). In ordinate, the CR flux is multiplied by E^x, where x is the logarithmic slope of the CR spectrum below the knee. (See also Fig. 3).

Smooth transition from Galactic to extraGalactic

Parizot (Review) 2014

Why supernova remnants (=shock expanding in the ISM after SN) ?

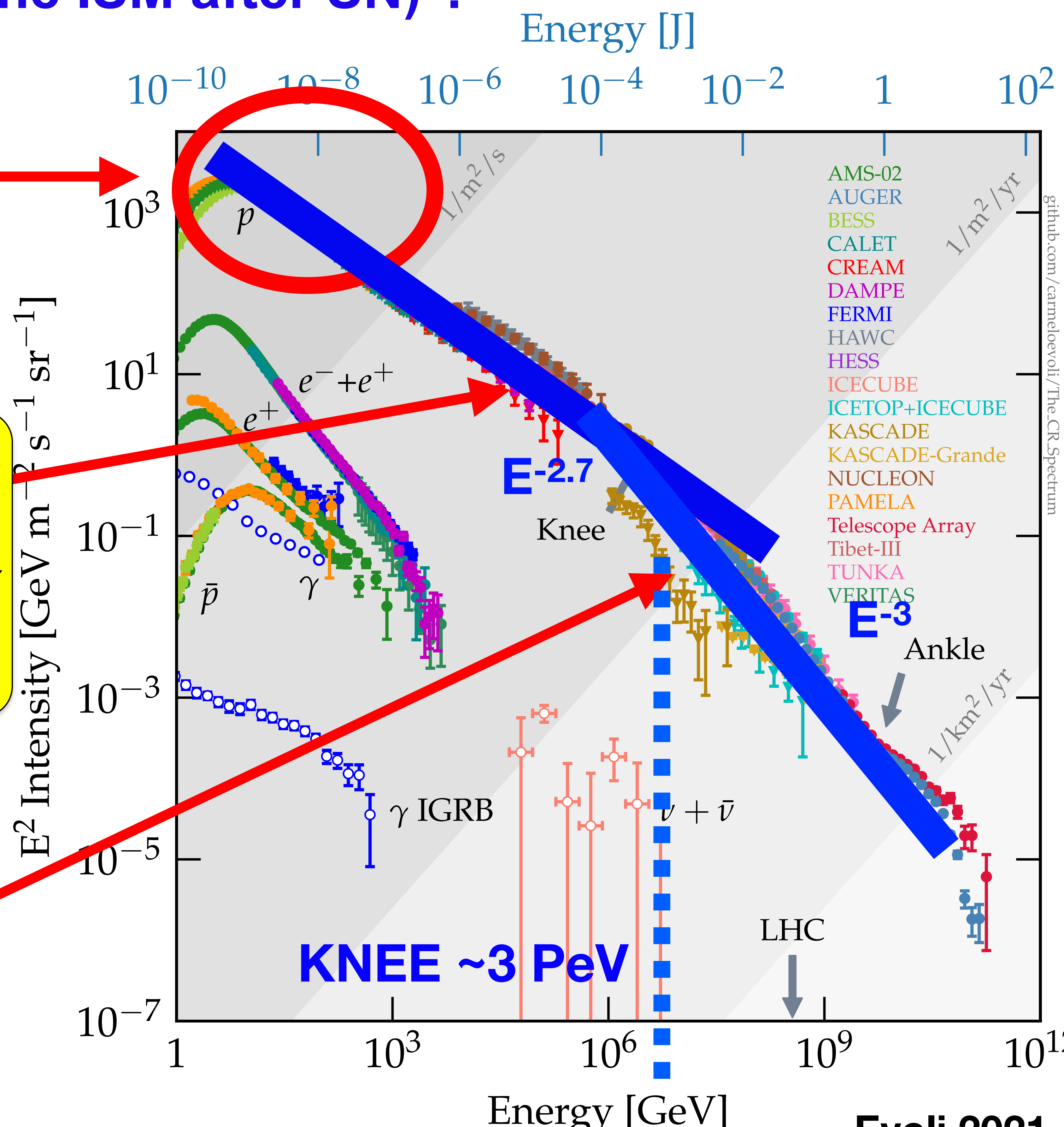
1. Bulk of CRs
Energy density ~1 eV/cm3
10% of SNR total explosion energy

2. Slope $E^{-2.7}$
Diffusive shock acceleration

$$E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$$

Injection **Propagation**

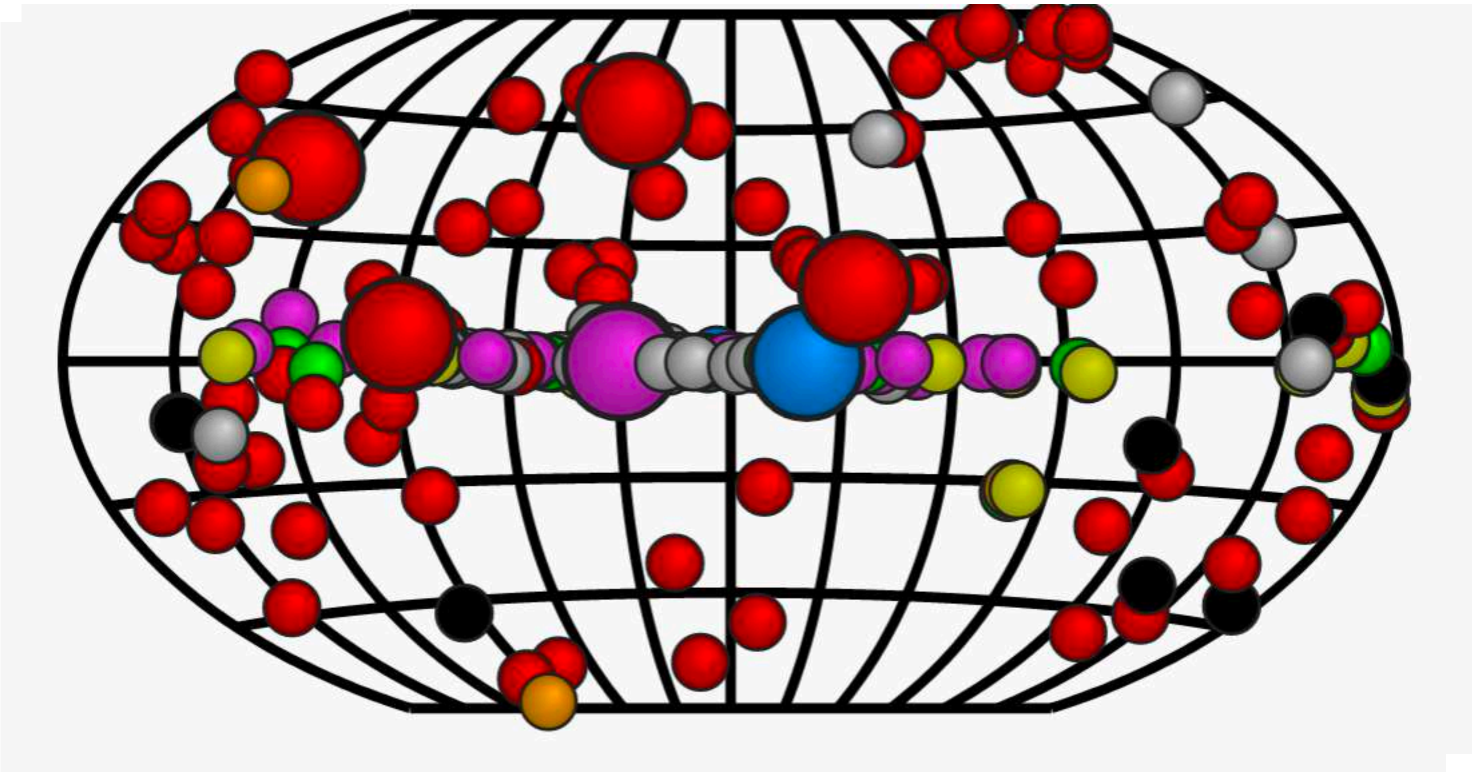
3. Magnetic field amplification



Evoli 2021

Reviews: Blasi (2013,2019)
Tatischeff & Gabici (2018)
Gabici et al. (2019)

Detection of SNRs in the gamma-ray domain



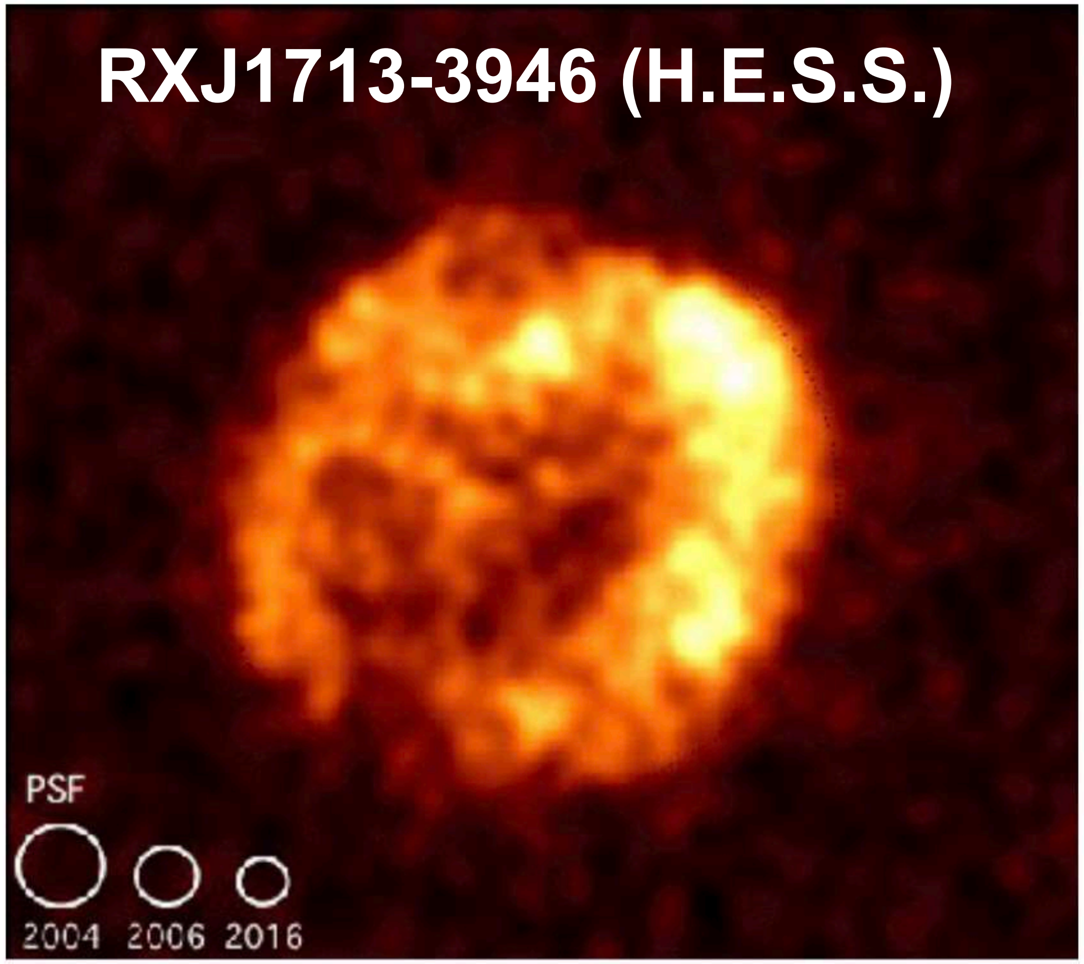
PWN, PWN/TeV Halo, Composite SNR

Shell, SNR/Molec. Cloud, Composite SNI

228 sources listed

58 « SNRs »

12 Shells



ISM

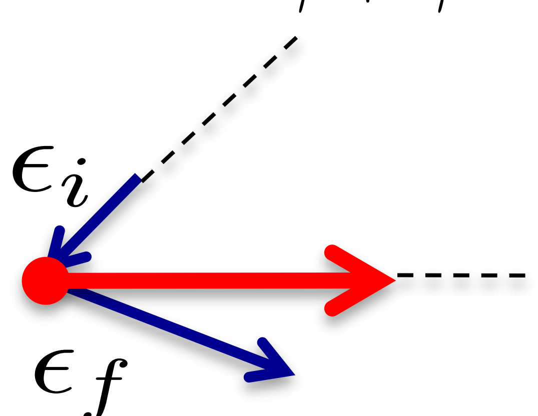
$$p + p \rightarrow p + p + \pi^0$$

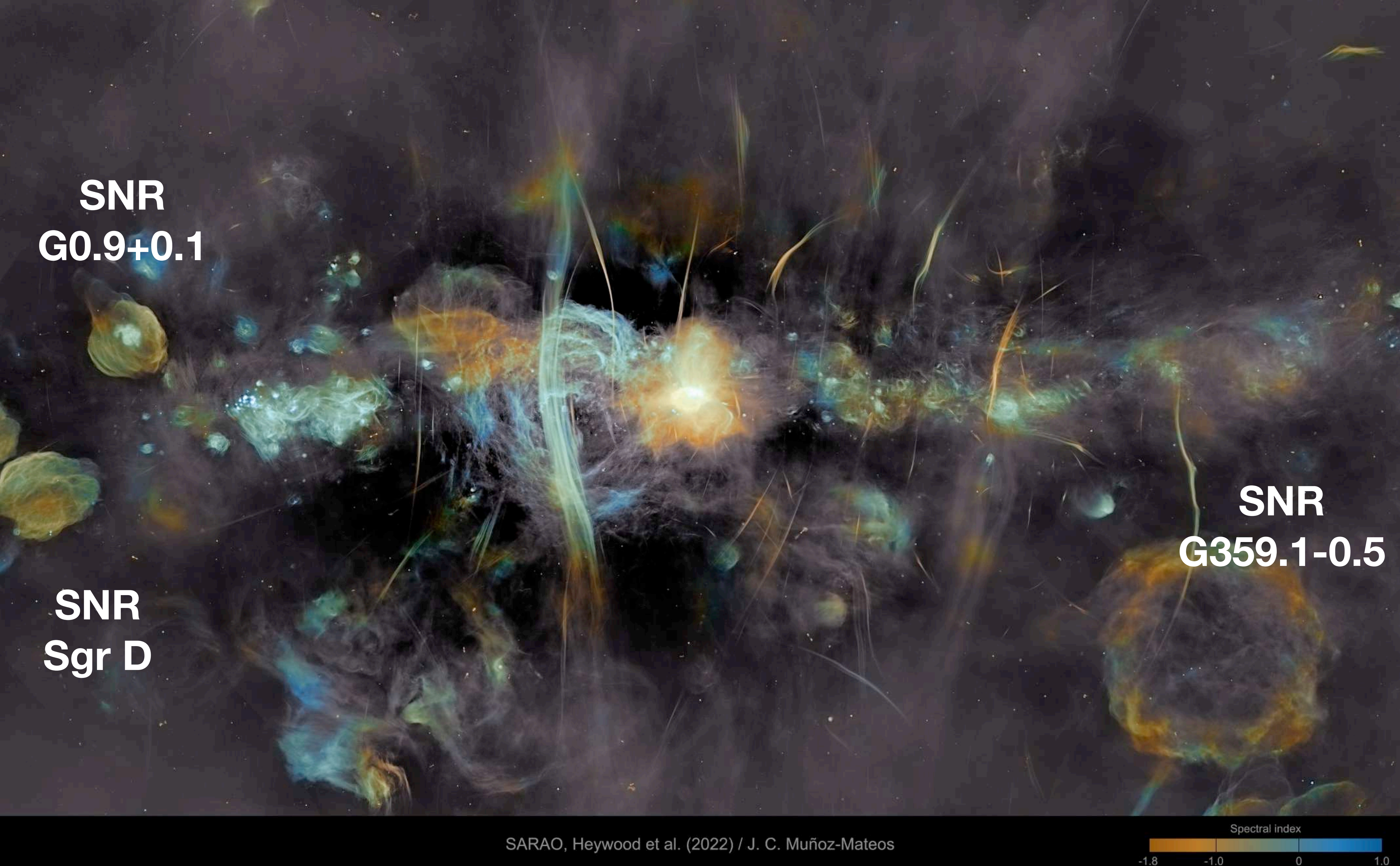
$$\pi^0 \rightarrow \gamma + \gamma$$

CR

Hadronic interactions:
Pion decay

Leptonic interactions:
Inverse Compton scattering





MeerKAT picture of the day Feb. 2nd 2022

Astronomy & Astrophysics manuscript no. output
September 1, 2022

Sensitivity of the Cherenkov Telescope Array to spectral signatures of hadronic PeVatrons

With application to searches for Galactic Supernova Remnant PeVatrons

The CTA Consortium, E.O. Angüner, G. Spengler, H. Costantini, P. Cristofari, T. Armstrong, L. Giunti

↓

CTA paper: Extensive discussion on the detectability of SNR pevatrons

Started 2016-2017, under collaboration review

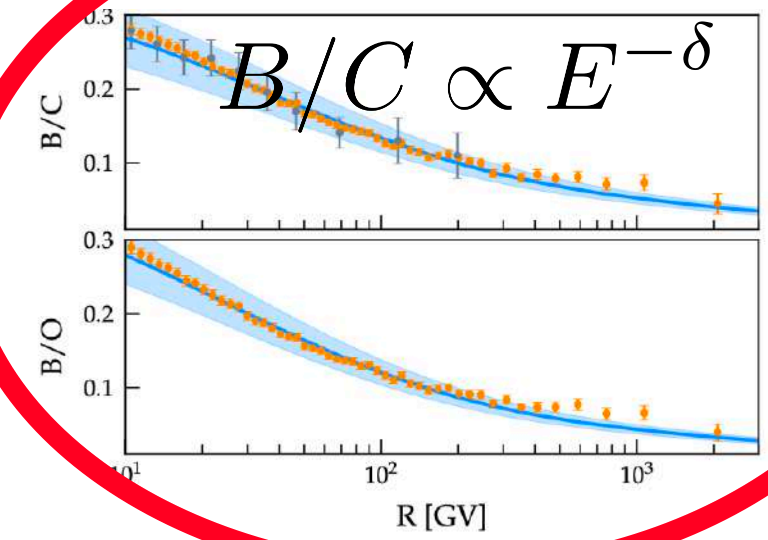
Bruno Khelifi, Gaia Verna, Cyril Trichard (2017) + many more

Tensions with the « Supernova remnants » hypothesis

1. Diffusive shock acceleration predicts E^{-2} at SNRs

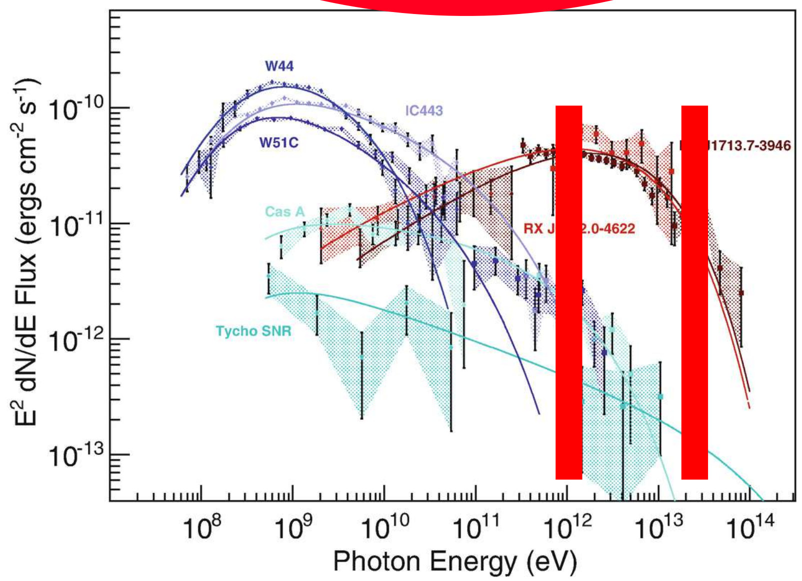
$$E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$$

Injection **Propagation**



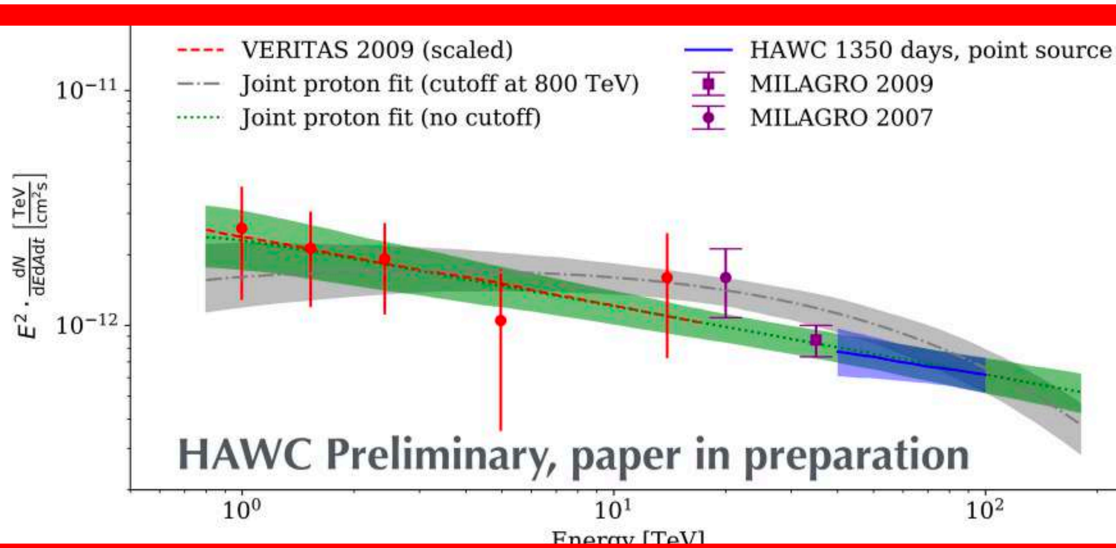
Evoli et al. (2019)

2. All gamma—ray spectra show spectra steeper than E^{-2}



Funk (2017)

3. No SNR Pevatron

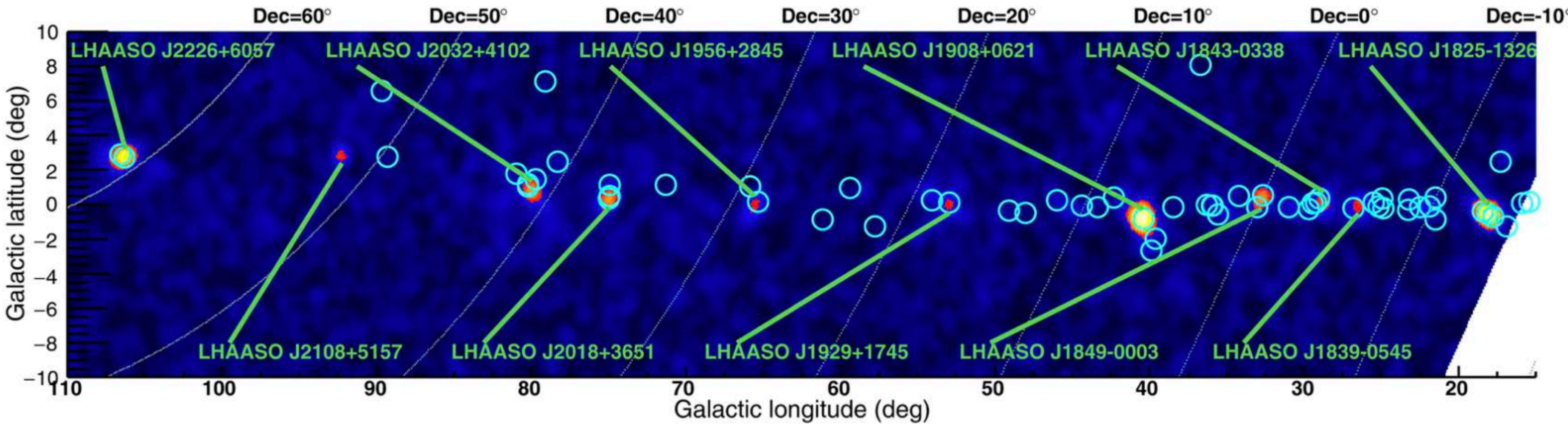


HAWC, Fleishhack Texas Symp (2019)

And… other pevatrons!

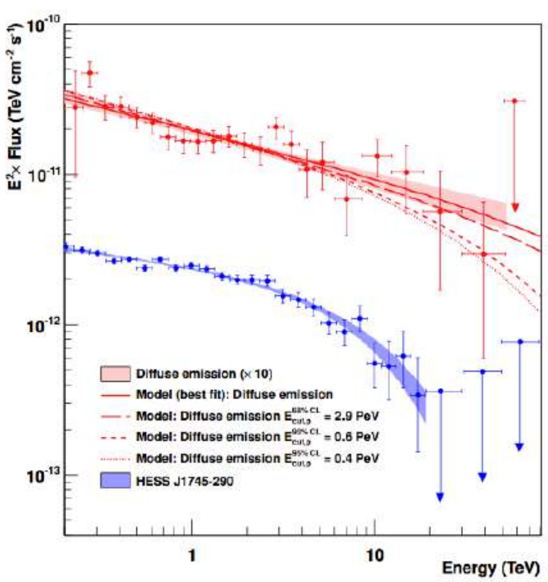
LHAASO 12 Galactic pevatrons

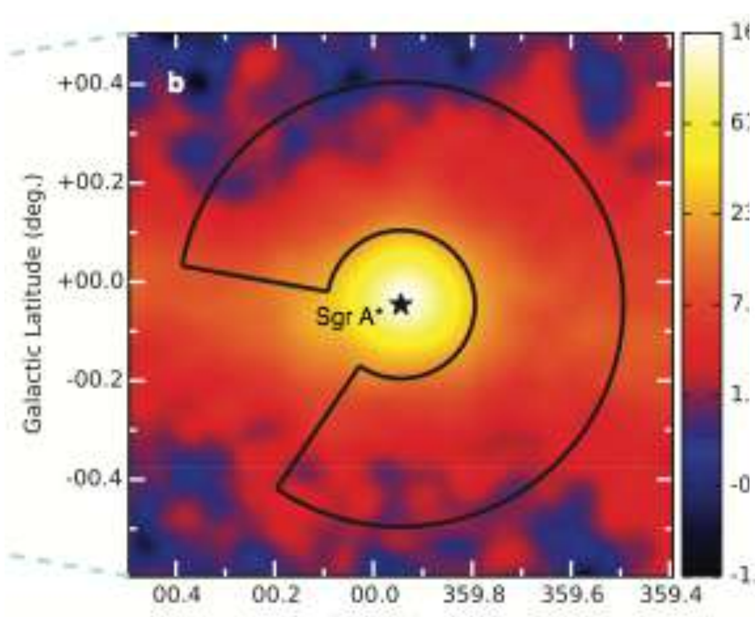
Cao et al. 2021

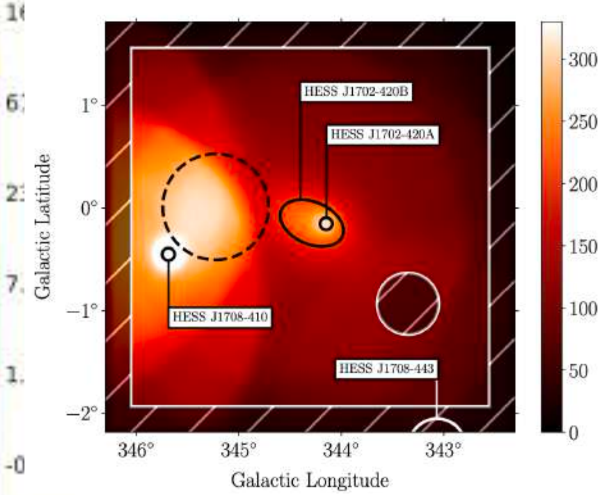


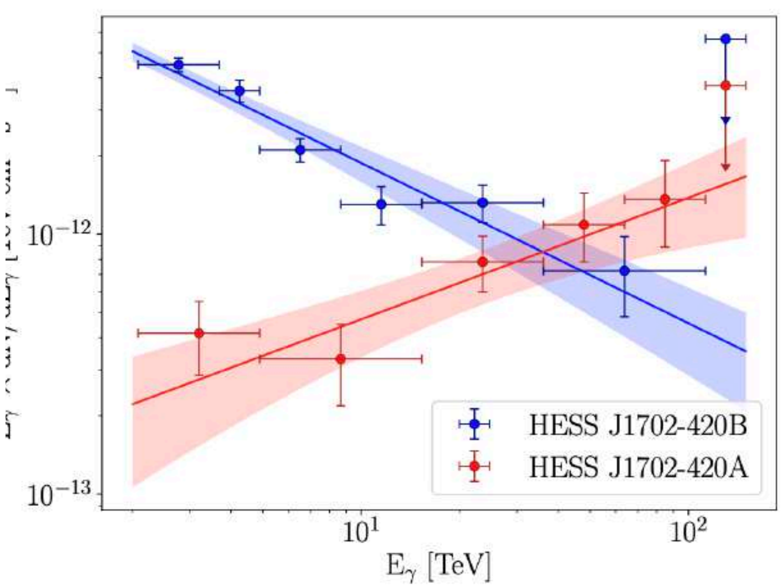
HESS J1745-290

HESS J1702-420









HESS collab. 2016

HESS collab. 2021

And… other pevatrons!

Crab: leptonic pevatron

Letter to the Editor

Twelve-hour spikes from the Crab Pevatron

M. Balbo[1,2], R. Walter[1,2], C. Ferrigno[1,2], P. Bordas[1,3]

Reviews:

Review

The Crab Pulsar and Nebula as seen in gamma-rays

Elena Amato [1,2], Barbara Olmi [1,3]

The theory of Pulsar Wind Nebulae: recent progress

Elena Amato*†

Numerous candidates (HAWC, TibetAsgamma)

HAWC J2227+610: a potential PeVatron candidate for the CTA in the northern hemisphere

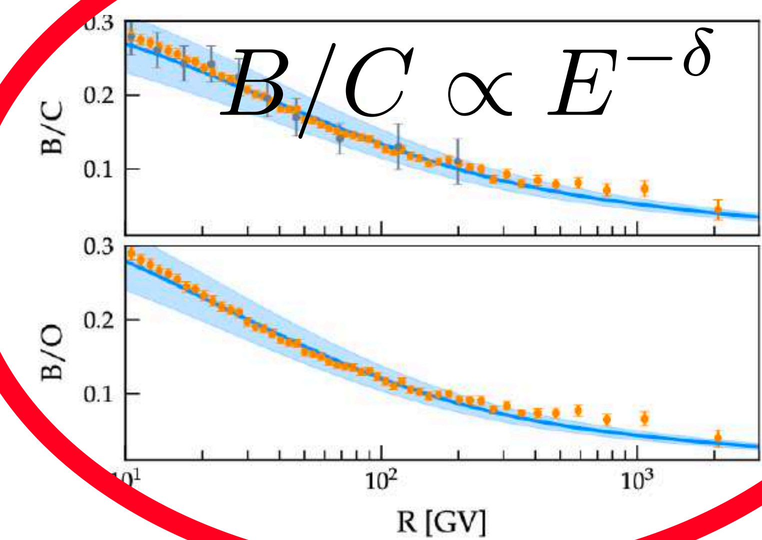
Gaia Verna,[a,*] Franca Cassol[a] and Heide Costantini[a] on behalf of the CTA Consortium

So what's wrong then?

1. Diffusive shock acceleration predicts E^{-2} at SNRs

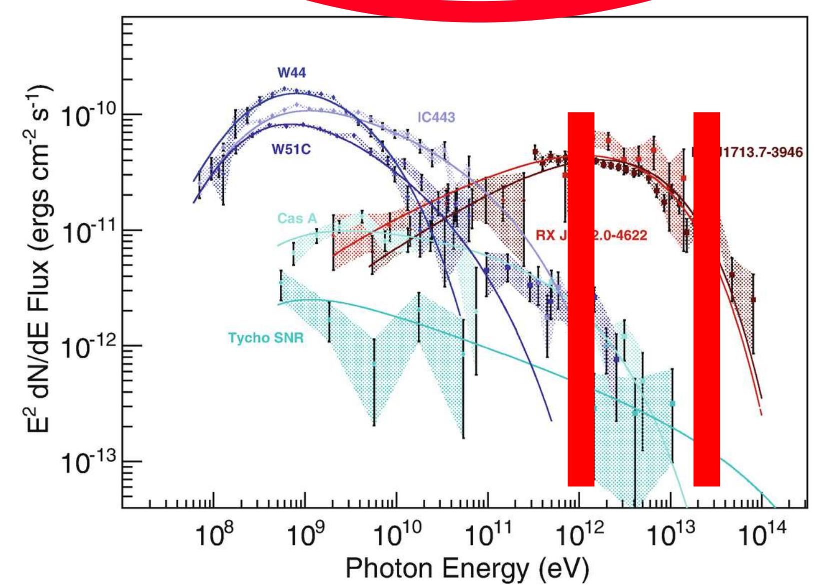
$$E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$$

Injection **Propagation**



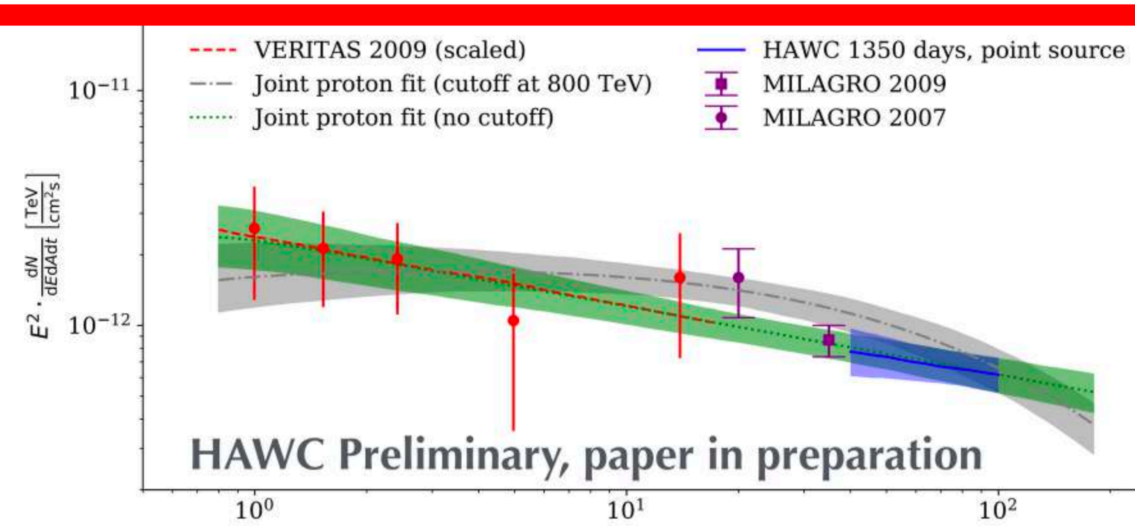
Evoli et al. (2019)

2. All gamma—ray spectra show spectra steeper than E^{-2}



Funk (2017)

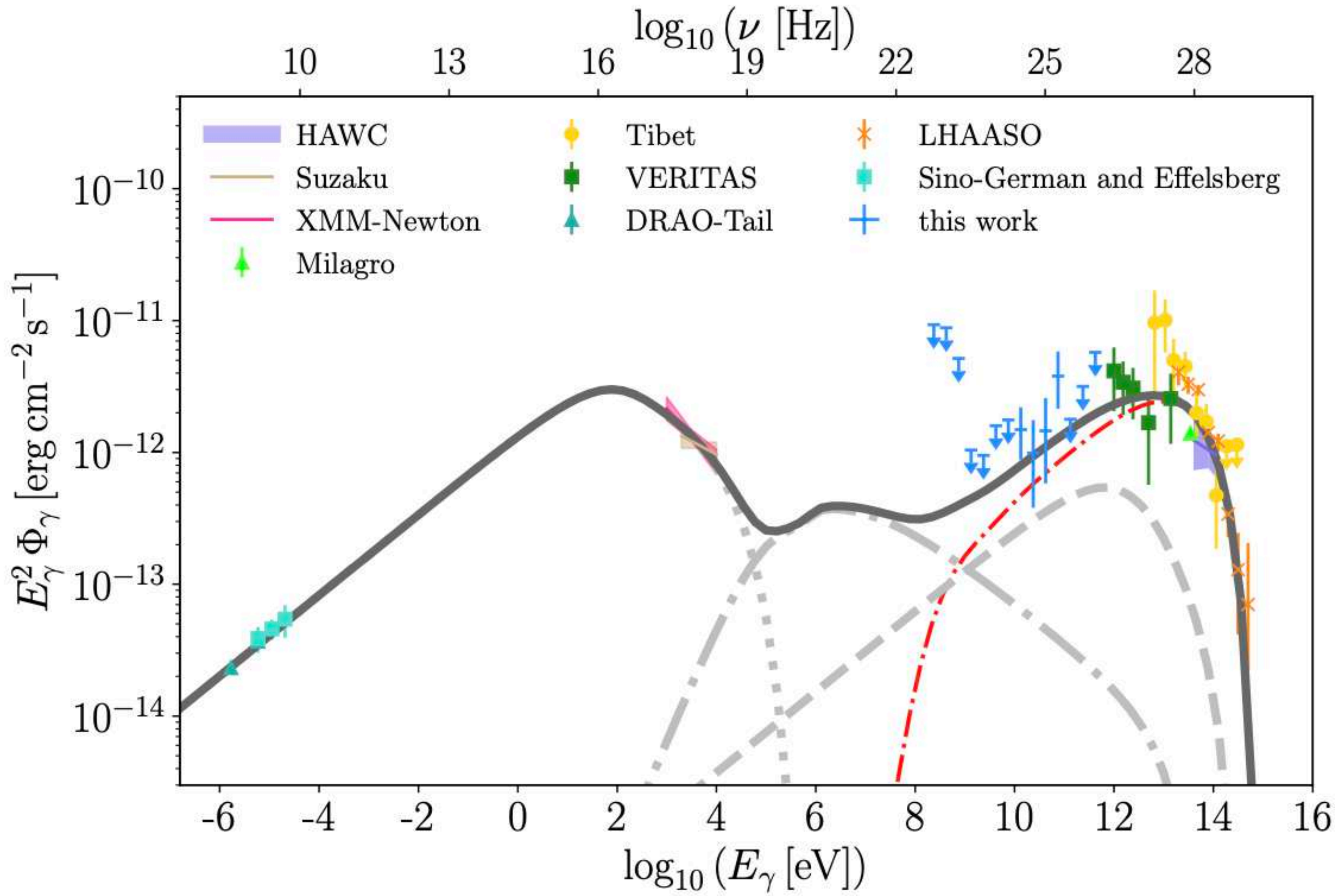
3. No SNR Pevatron



HAWC, Fleishhack Texas Symp (2019)

Evidence for PeV Proton Acceleration from Fermi-LAT Observation of SNR G106.3+2.7

Ke Fang,[1] Matthew Kerr,[2] Roger Blandford,[3,4] Henrike Fleischhack,[5,6,7] and Eric Charles[4,3]

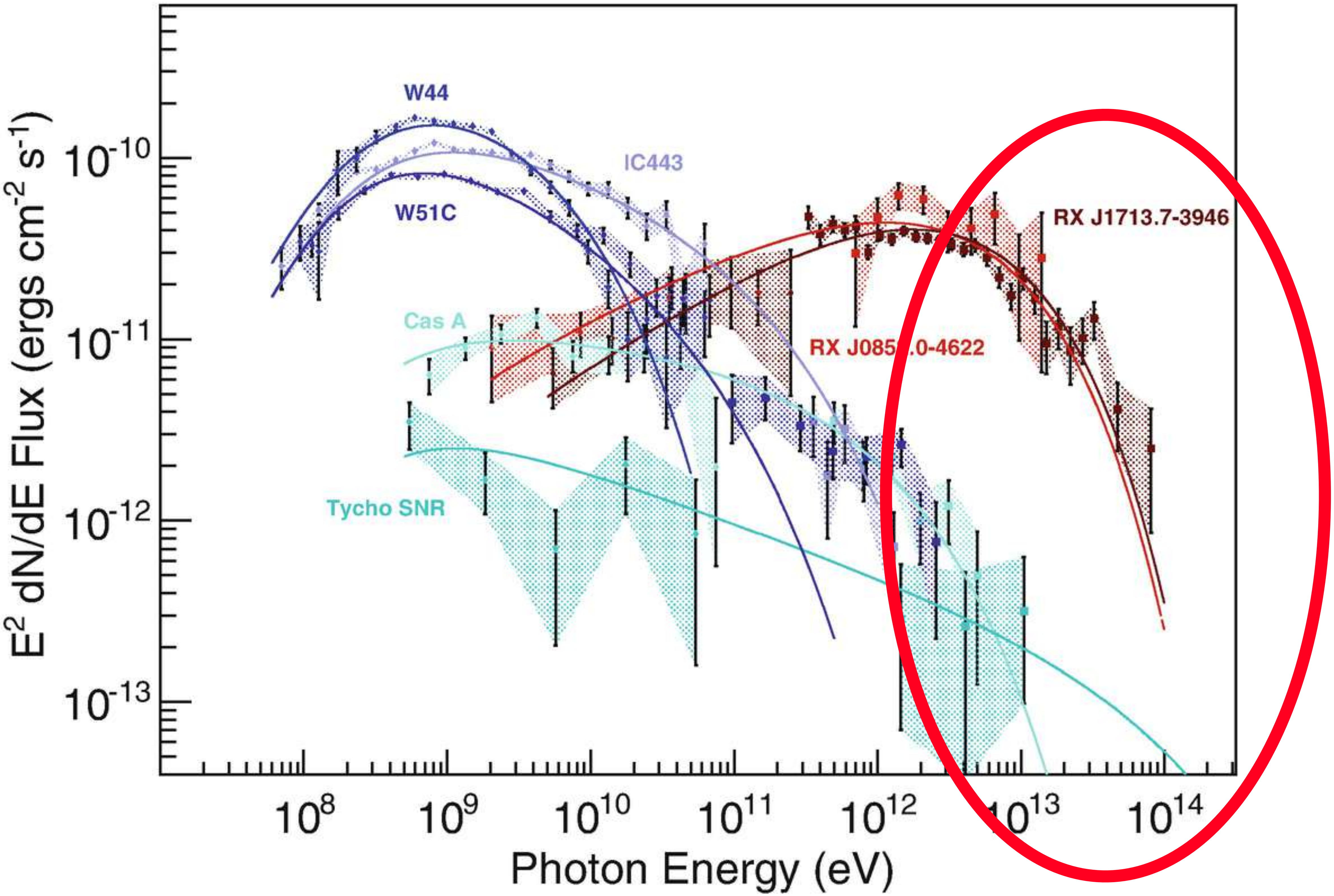


12 years data Fermi-LAT : Hard GeV-TeV spectrum : protons!

+ Celli, Aharonian, Gabici 2020

2022

So far, all SNRs seem to not be pevatrons



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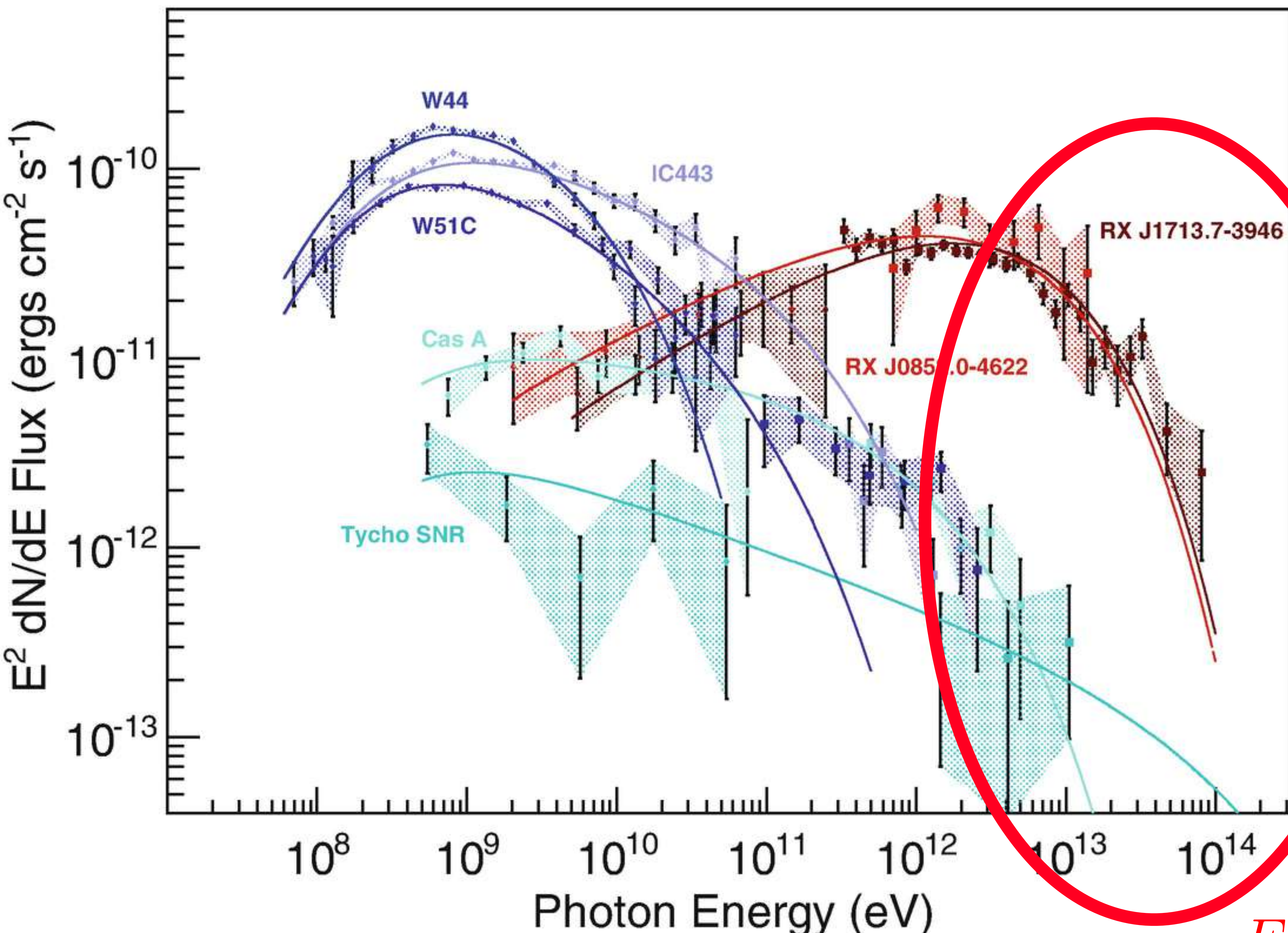
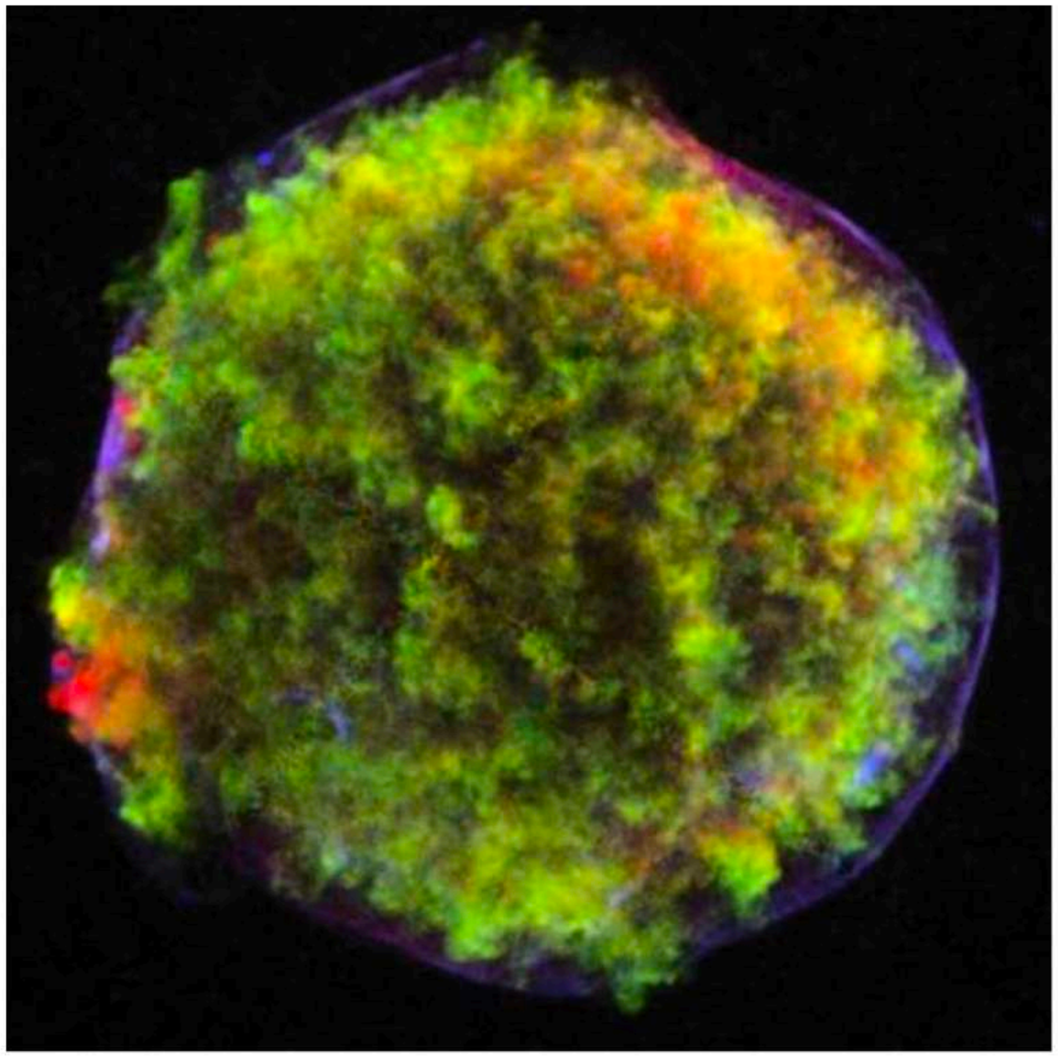


$$E_\gamma \approx \frac{E_p}{10}$$

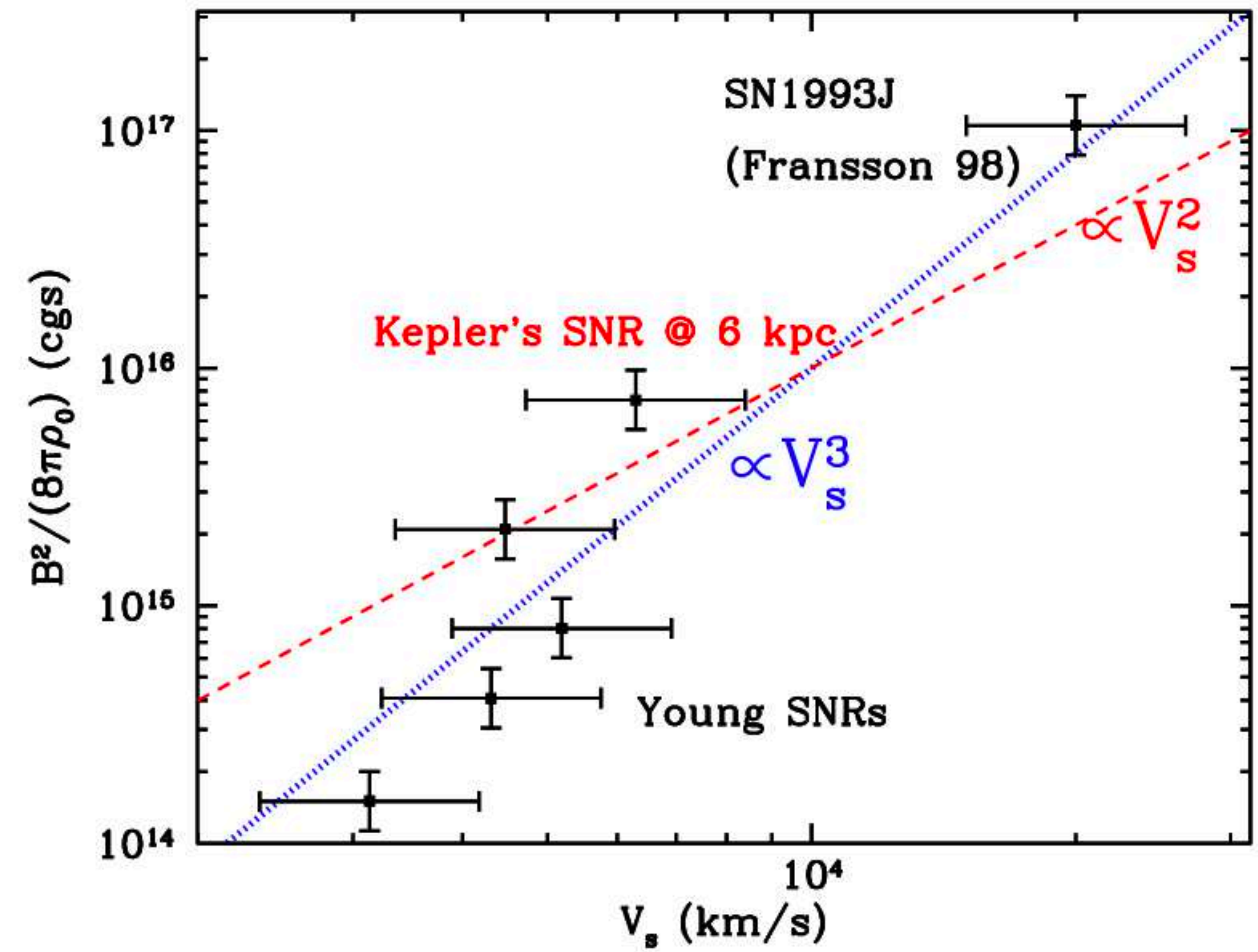
How to reach PeV energies at a SNR?

$$E_{\rm max} \approx \xi \left(\frac{R_{\rm sh}}{\rm pc}\right)\left(\frac{u_{\rm sh}}{1000{\rm km/s}}\right)\left(\frac{B}{\mu\ {\rm G}}\right) {\rm TeV}$$

B >> B_ISM



Tycho with Chandra
Warren et al. (2005)



Vink (2012)

Possible for young and « energetic » SNRs!

How to reach PeV energies at a SNR?

$$E_{\max} \approx \xi \left(\frac{R_{\rm sh}}{\rm pc}\right)\left(\frac{u_{\rm sh}}{1000{\rm km/s}}\right)\left(\frac{B}{\mu\ {\rm G}}\right) {\rm TeV}$$

Resonant streaming of CRs
Skiling (1975)

Acoustic instability
Drury & Falle (1983)

Instability density fluctuations
Giacolone & Jokipii (2007)

....

Non-resonant streaming
Bell (2004)

Reviews: Drury (1994)
Blasi (2013,2019)
Gabici et al. (2019)

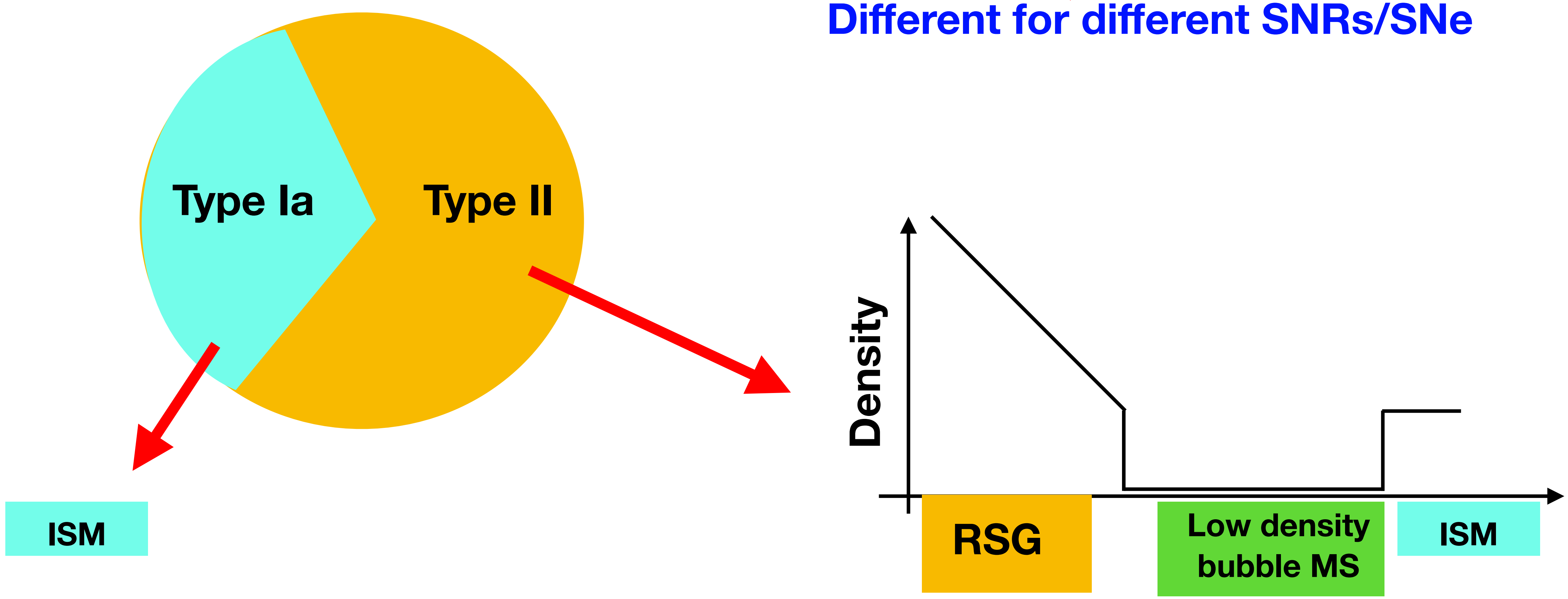
Non-resonant streaming of CRs

$$\int_0^t dt' \gamma_{\max}(t') \simeq 5$$

Growth rate of the non-resonant streaming instability

$$p_{\max}(t) \approx \frac{r_{\rm sh}(t)}{10} \frac{\xi e \sqrt{4\pi\rho(t)}}{\Lambda} \left(\frac{u_{\rm sh}(t)}{c}\right)^2$$

Different for different SNRs/SNe



Bell (2004), Bell et al. (2013), Schure et al. (2014)

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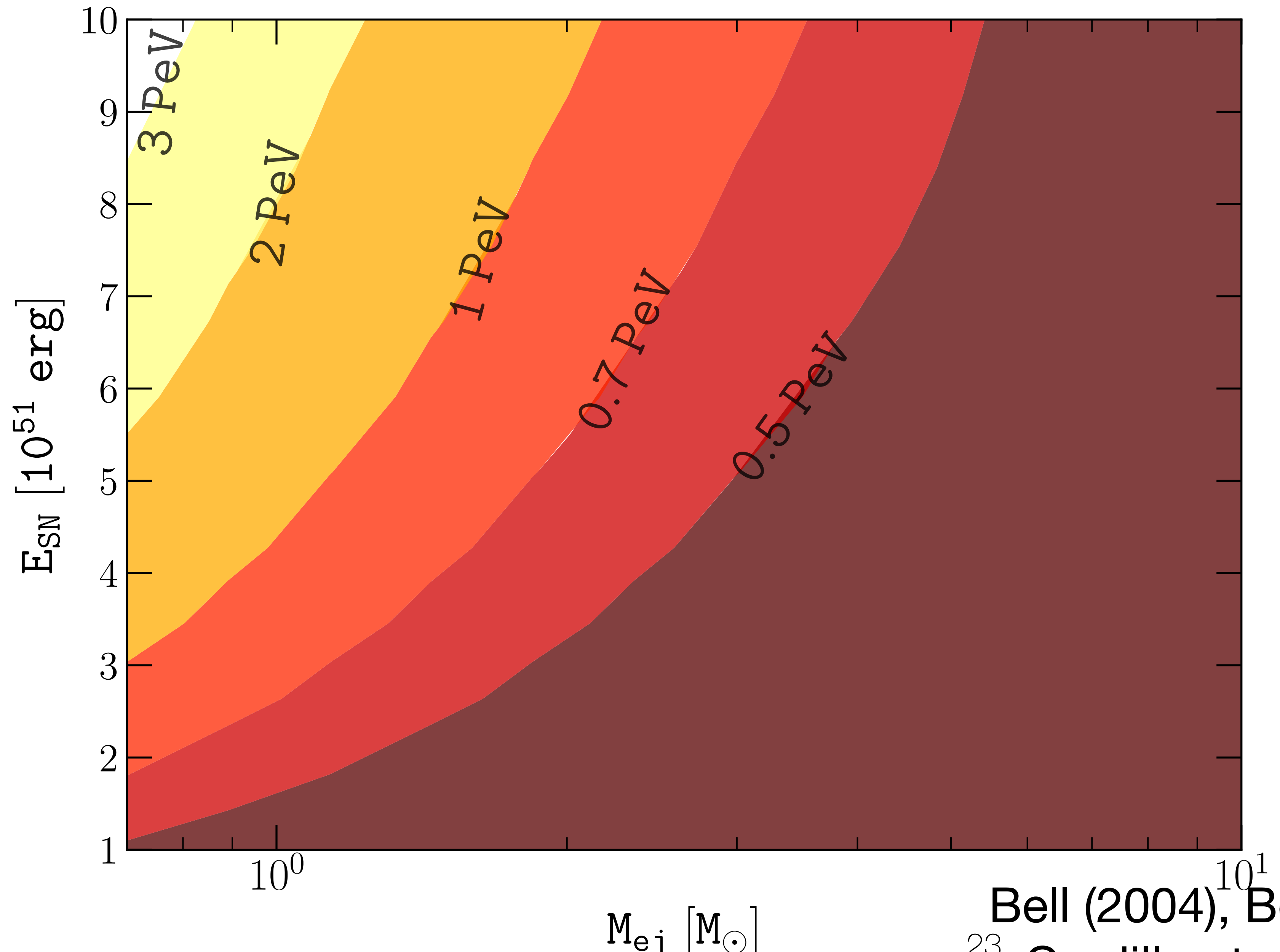
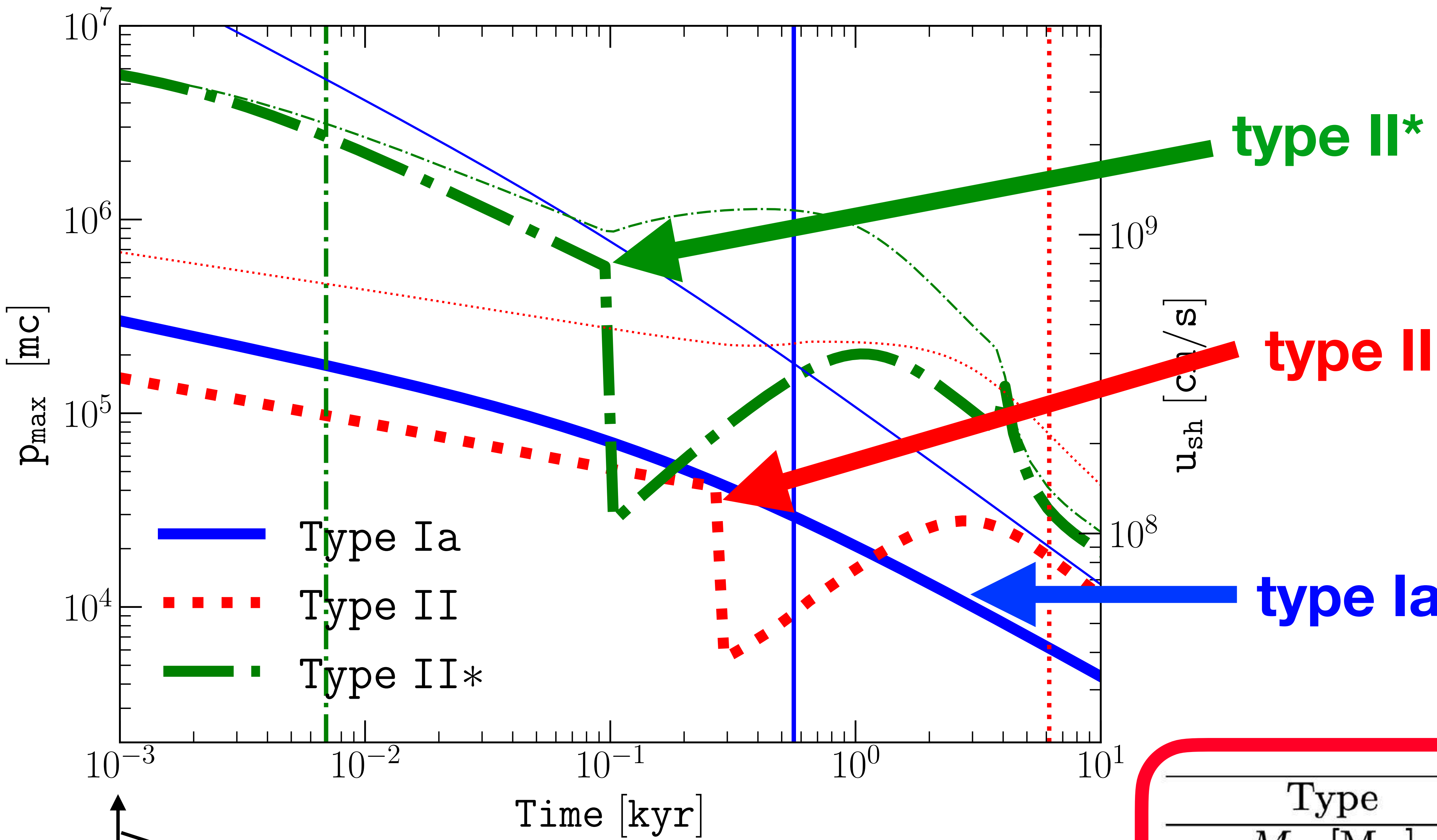


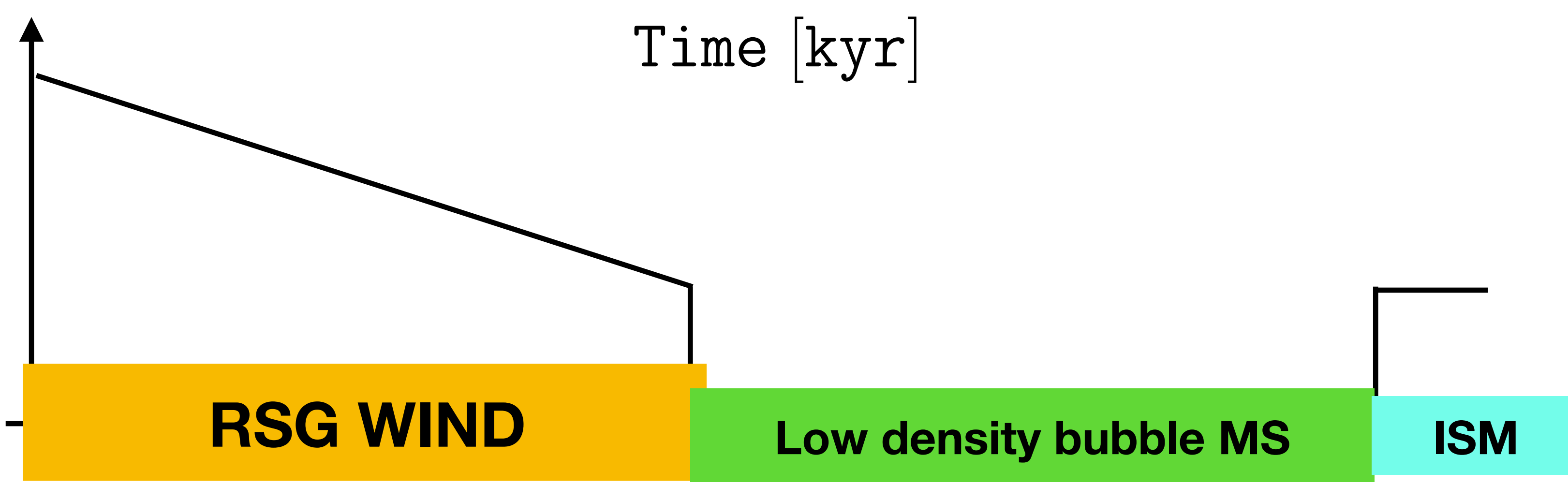
$$\dot{M}_{\rm RSG} = 10^{-4} M_\odot/{\rm yr}$$

$$\xi = 0.1$$

Bell (2004), Bell et al. (2013), Schure et al. (2014
Cardillo et al. (2016) PC, Blasi & Amato (2020)

Type Ia, type II, type II*

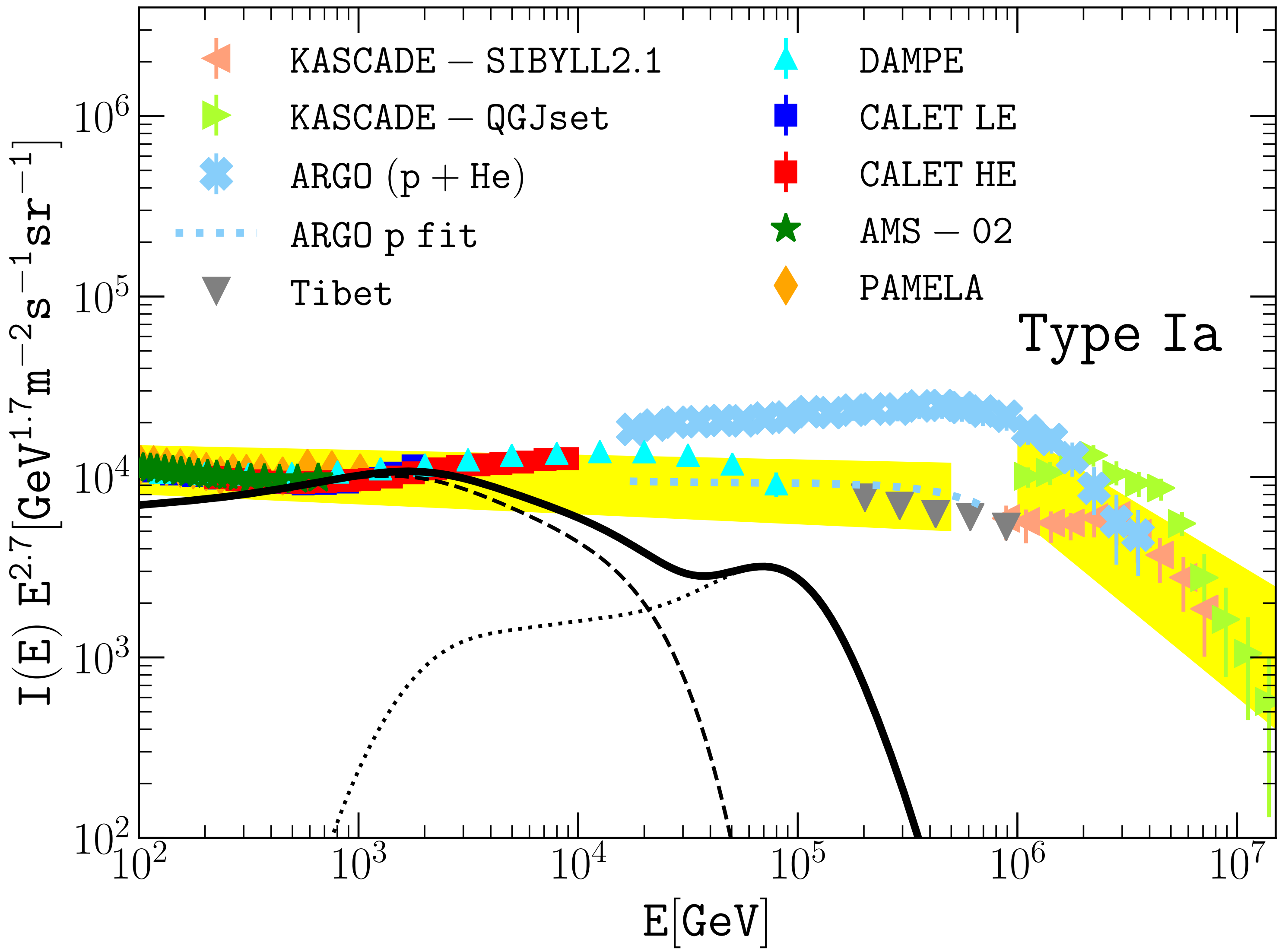




Type	Ia	II	II*
M_{ej} [$M_\odot$]	1.4	5	1
E_{SN} [10^{51} erg]	1	1	10
$\dot{M}$ [10^{-5} $M_\odot$/yr]	–	1	10
u_w [10^6 cm/s]	–	1	1
r_1 [pc]	–	1.5	1.3

Protons after propagation in the Galaxy

Using 1D semi-analytical model for transport



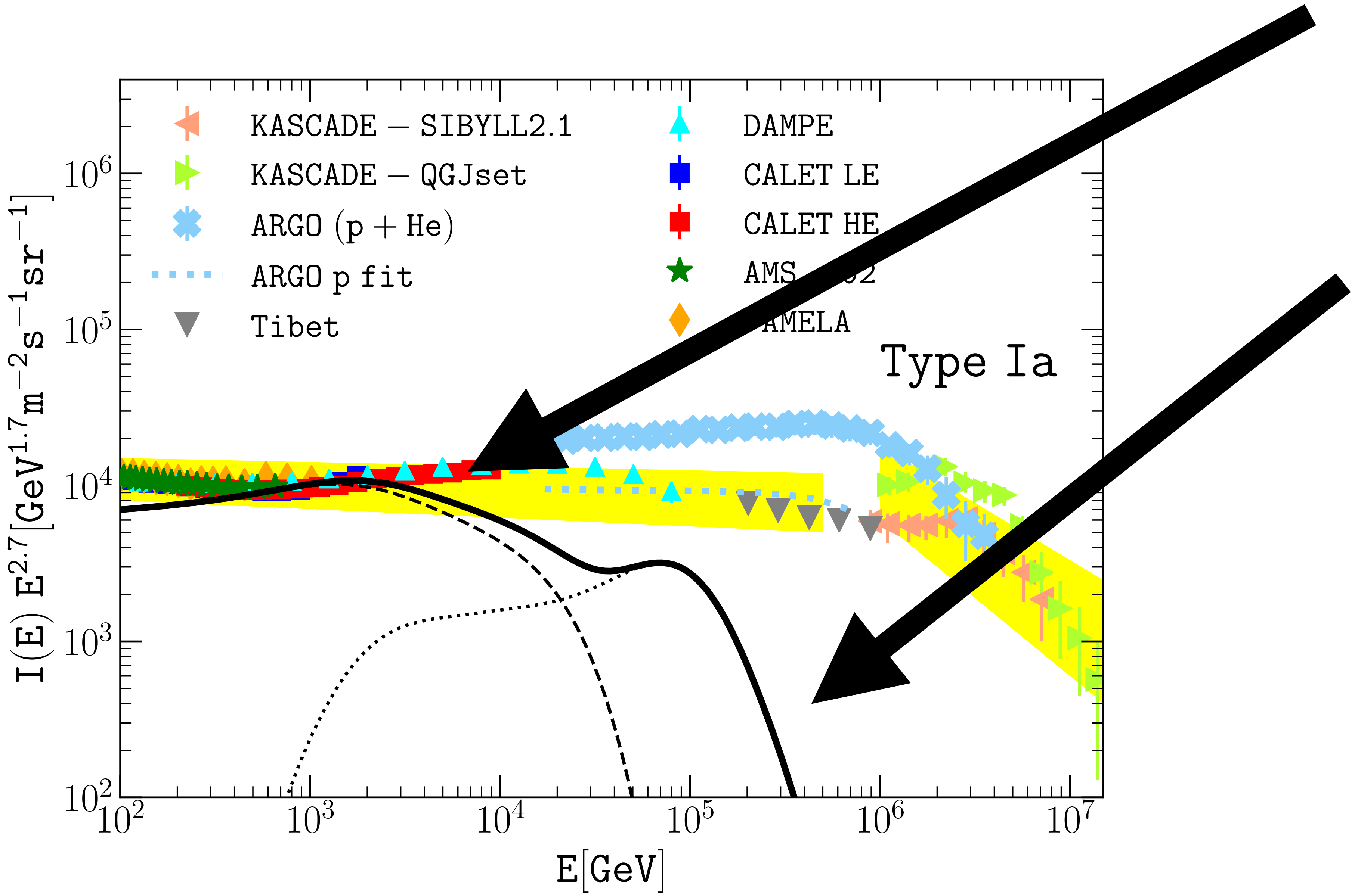
Cristofari, Blasi& Amato (2020)

Protons after propagation in the Galaxy

Using 1D semi-analytical model for transport

$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

$$E_{\max} \propto \xi_{\mathrm{CR}}$$



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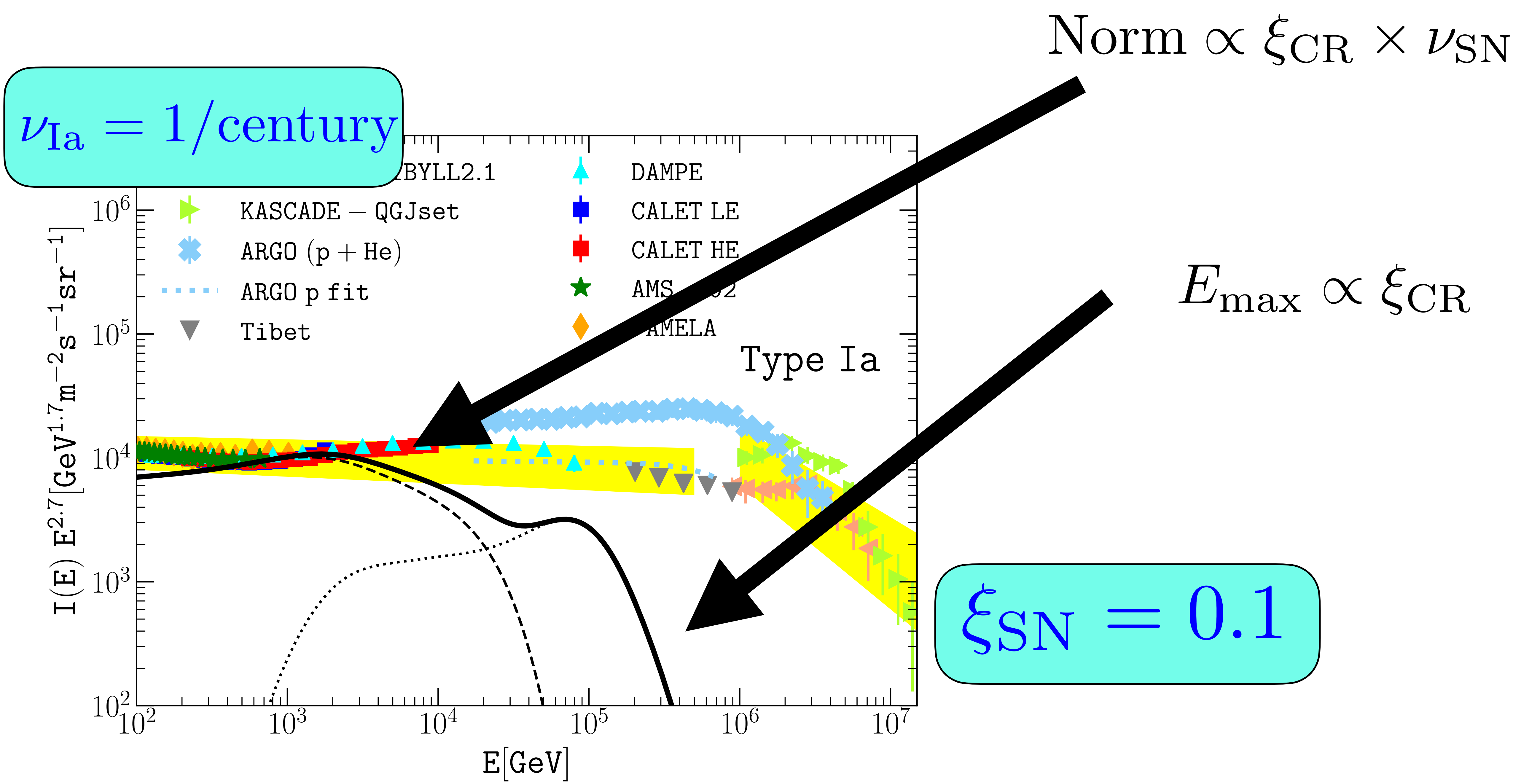


Cristofari, Blasi& Amato (2020)

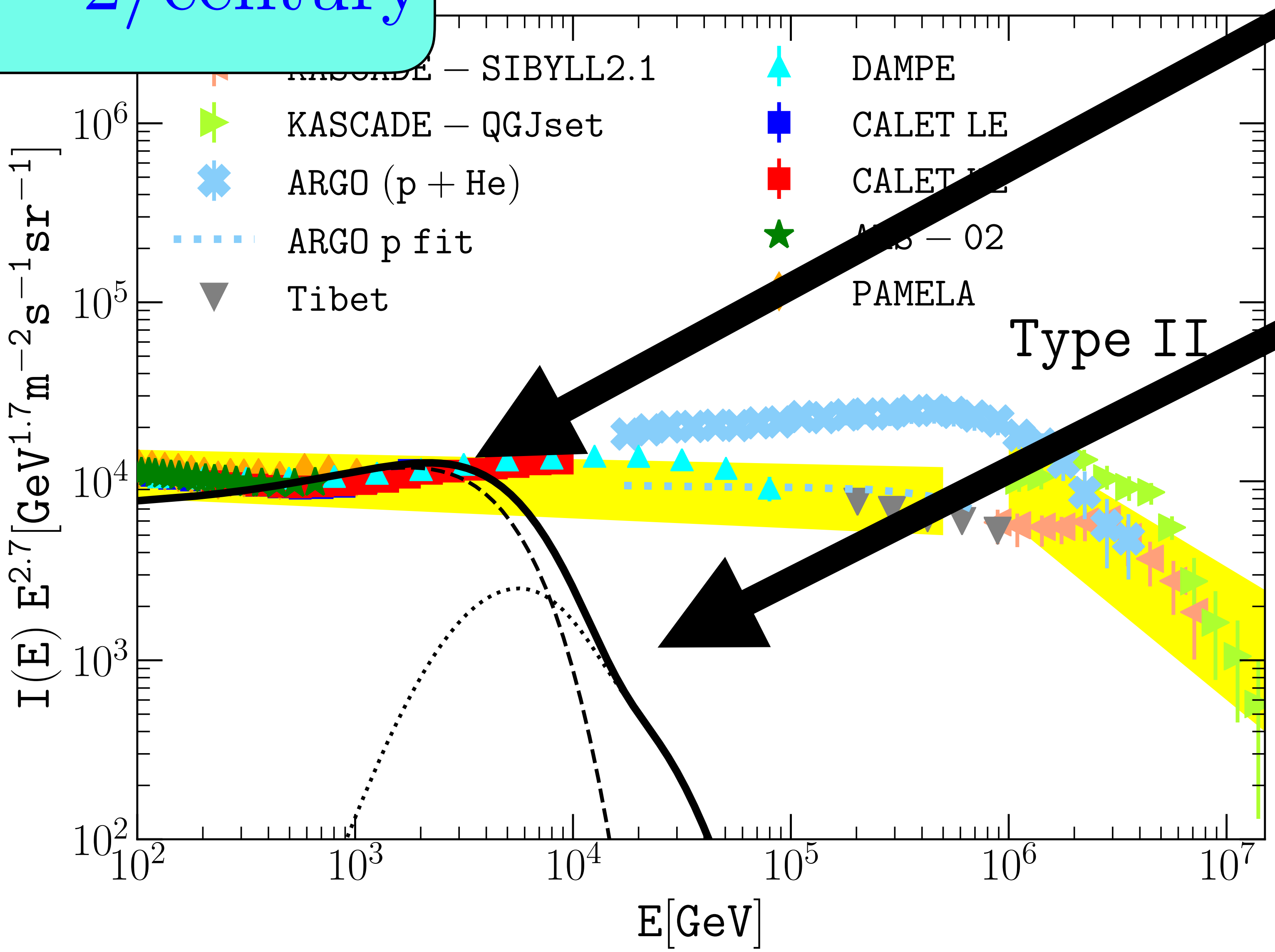
Protons after propagation in the Galaxy

Using 1D semi-analytical model for transport

$$\nu_{\rm II} = 2/\text{century}$$

$$\text{Norm} \propto \xi_{\rm CR} \times \nu_{\rm SN}$$

$$E_{\max} \propto \xi_{\rm CR}$$



$$\xi_{\rm SN} = 0.06$$

Cristofari, Blasi& Amato (2020)

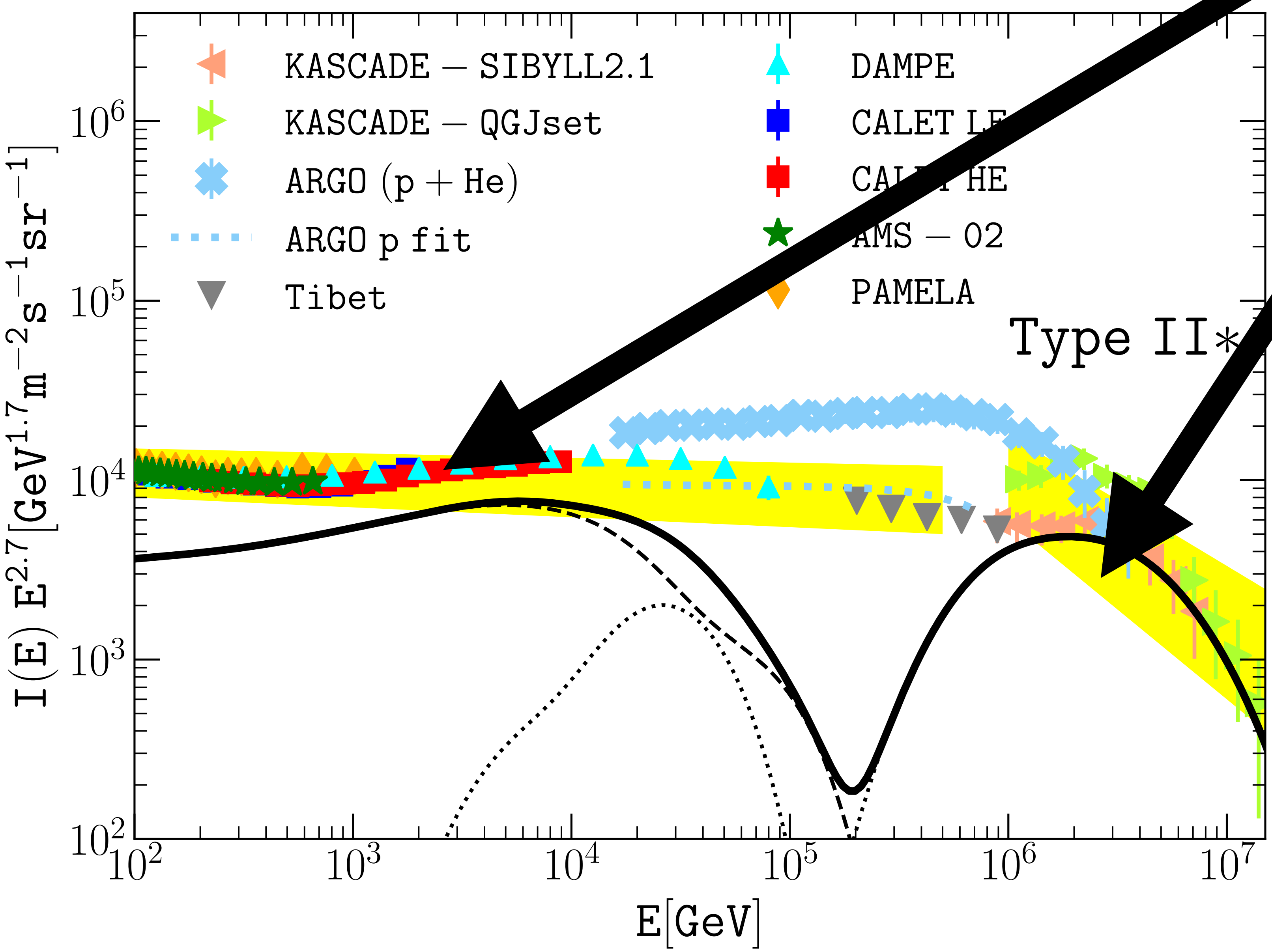
Protons after propagation in the Galaxy

Using 1D semi-analytical model for transport

$\text{Norm} \propto \xi_{\text{CR}} \times \nu_{\text{SN}}$

$E_{\max} \propto \xi_{\text{CR}}$

$\xi_{\text{CR}} \sim 5 - 10\%$



Cristofari, Blasi& Amato (2020)

Protons after propagation in the Galaxy

Using 1D semi-analytical model for transport

$$\text{Norm} \propto \xi_{\rm CR} \times \nu_{\rm SN}$$

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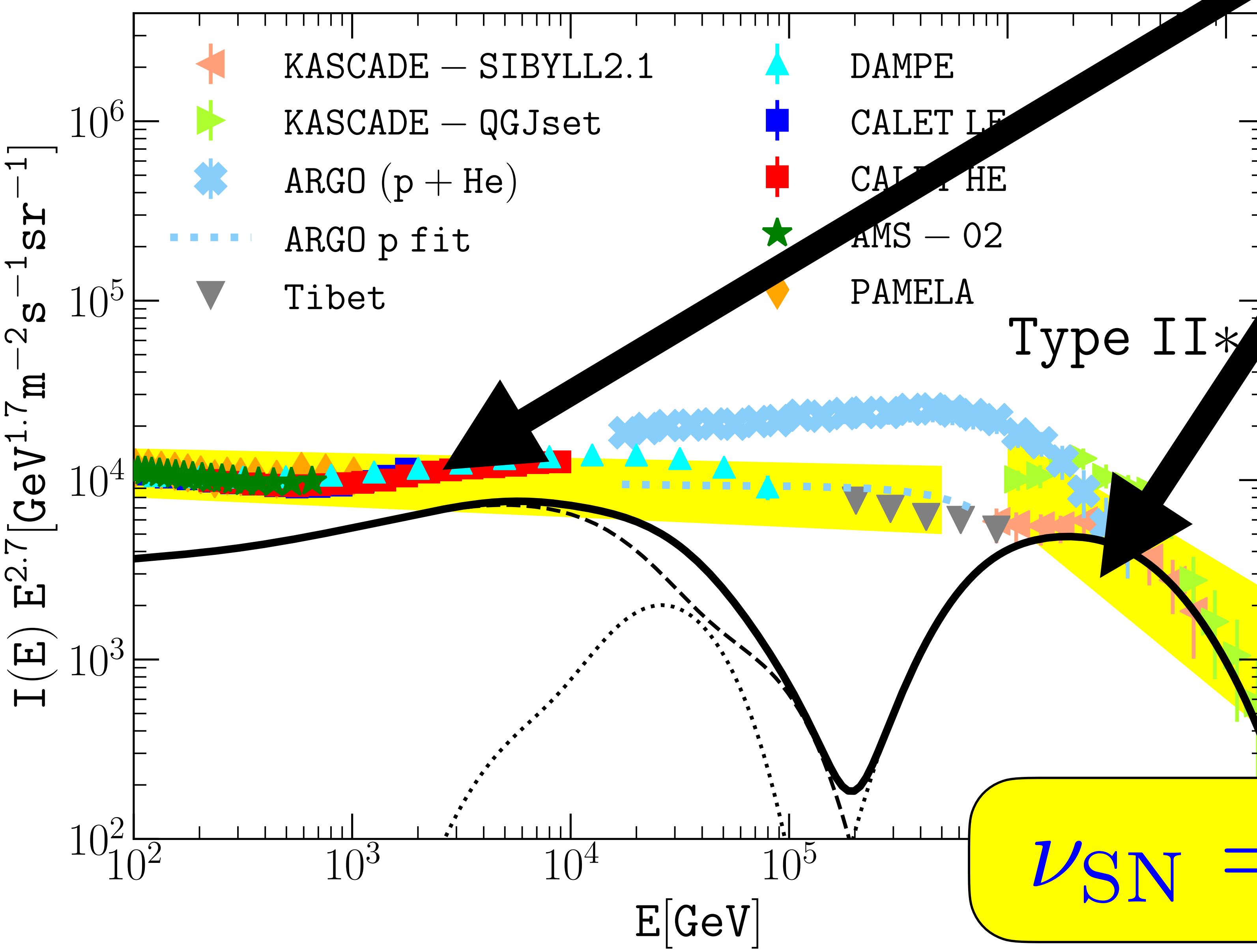


Reach PeV and not overproduce the CR spectrum:

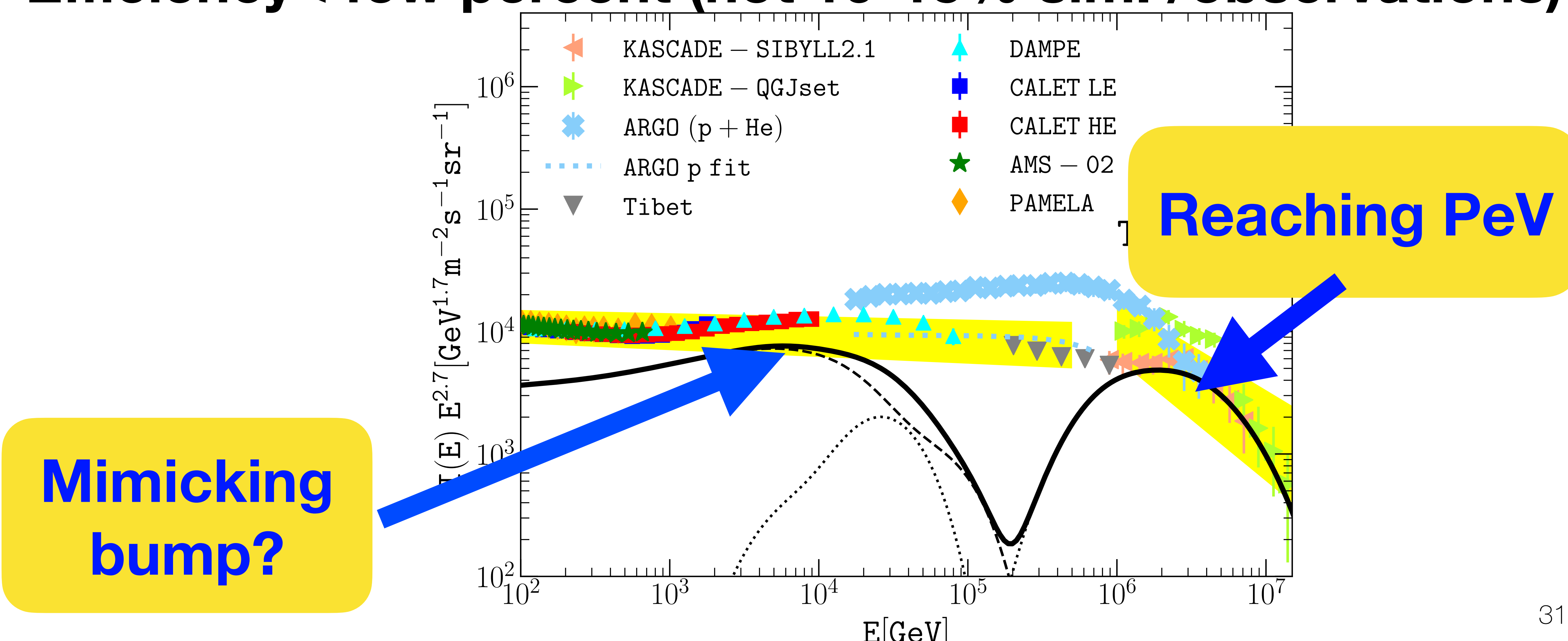
$$\nu_{\rm SN} = 1\% \times 3/\text{century}$$

Cristofari, Blasi& Amato (2020)

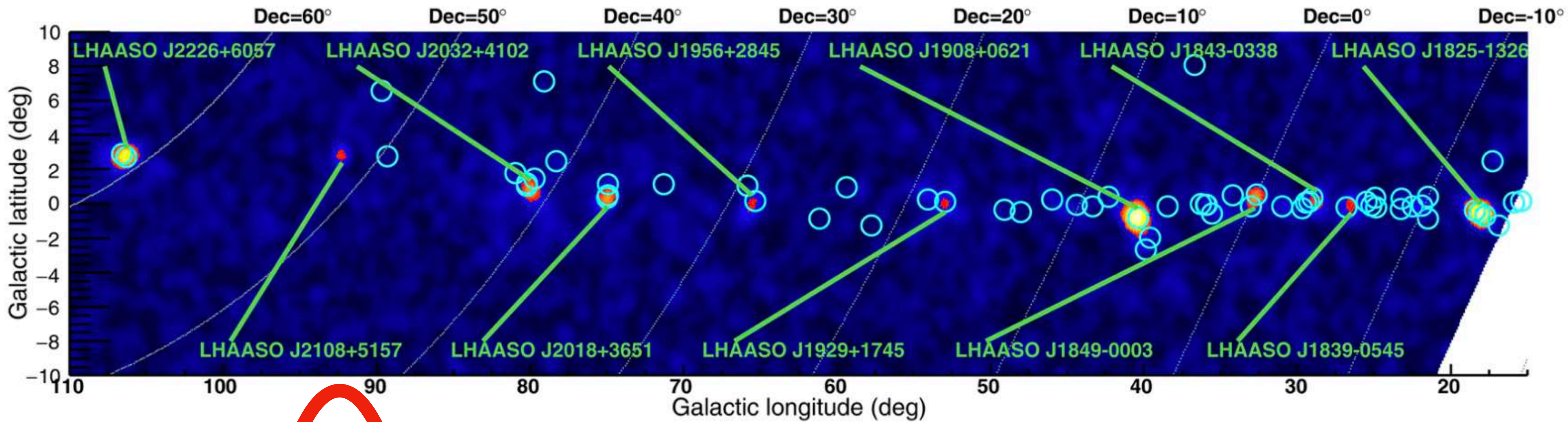
What does this mean?

MAYBE:

1. **SNRs are OK but we won’t see any PeVatrons with CTA**
2. **Another instability (not Bell) comes into play**
3. **Strong temporal dependance on one/several parameters**
4. **SNRs are not dominant sources of CRs up to the knee (role of other objects/stellar clusters/ massive stars/?)**
5. **If PeV range with II* -> not much room for others! Efficiency< few percent (not 10-15% sim. /observations)**



Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic 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	$.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	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	NR 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,
Not many SNRs

https://doi.org/10.1038/s41586-021-03498-z
Received: 21 October 2020
Accepted: 26 March 2021
Published online: 17 May 2021

When instruments were optimized in the 1-10 TeV range

Hadronic interactions : Pion decay

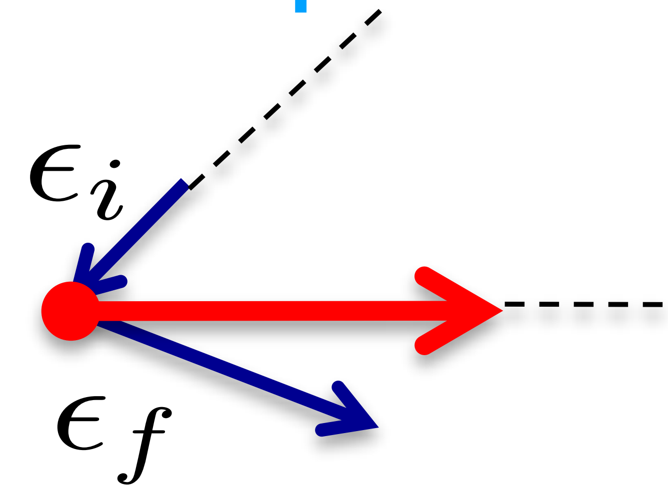
ISM

$$p + p \rightarrow p + p + \pi^0$$

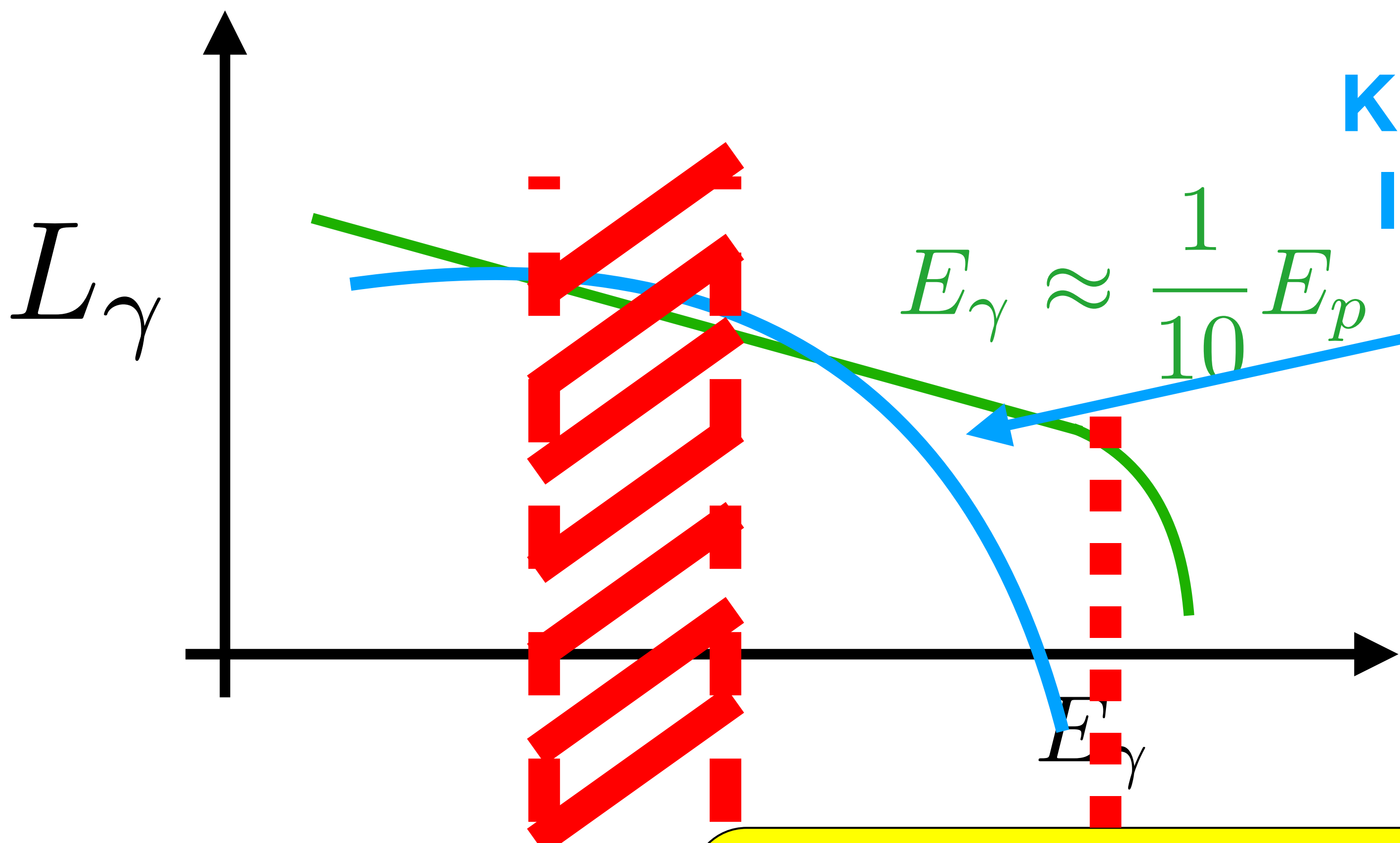
CR

$$\pi^0 \rightarrow \gamma + \gamma$$

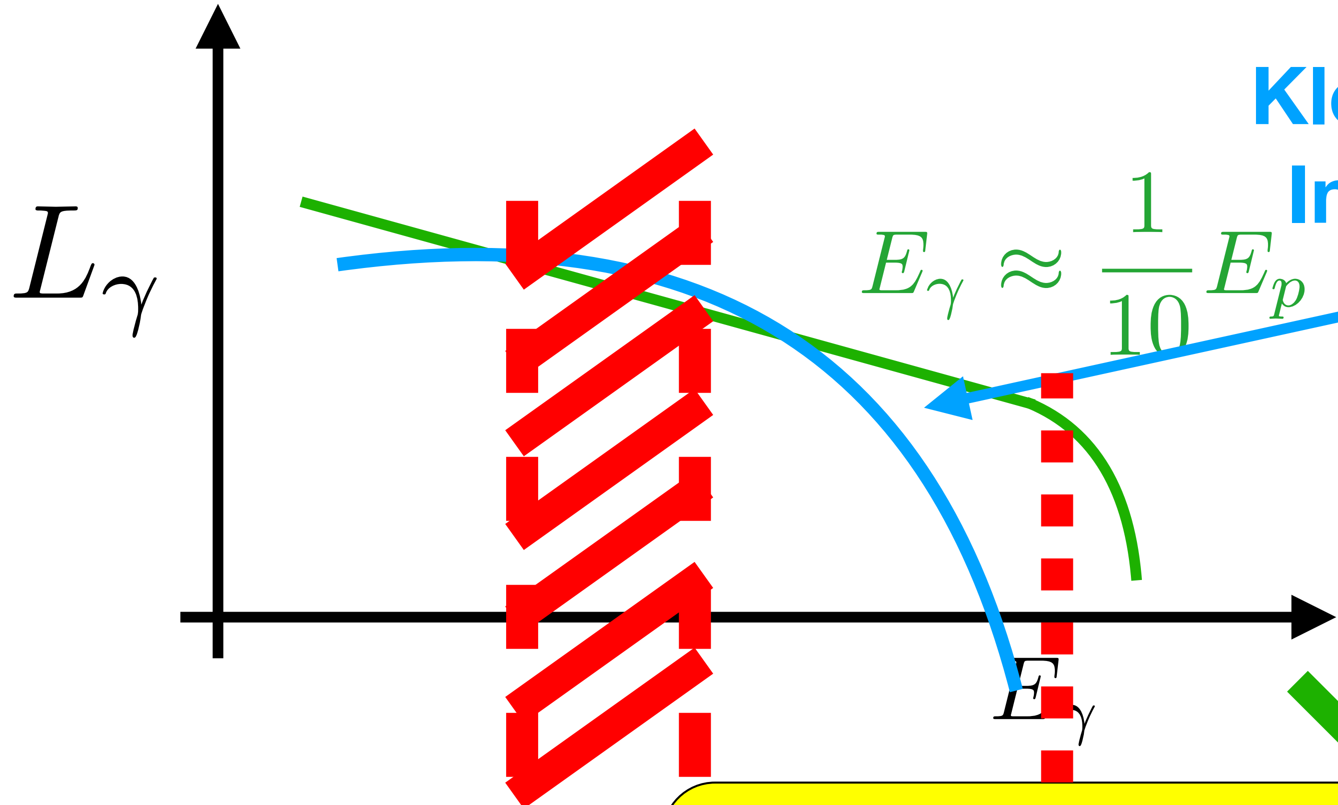
Leptonic interactions : Inverse Compton scattering



Klein-Nishina suppression: Inefficient above >50 TeV



100 TeV gamma rays probe the acceleration of PeV protons (hadronic)



Klein-Nishina suppression:
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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}	

Very uncertain nature of these sources?
Proton acceleration? Electron acceleration?
Not many SNRs in this list!

Hadronic vs. Leptonic

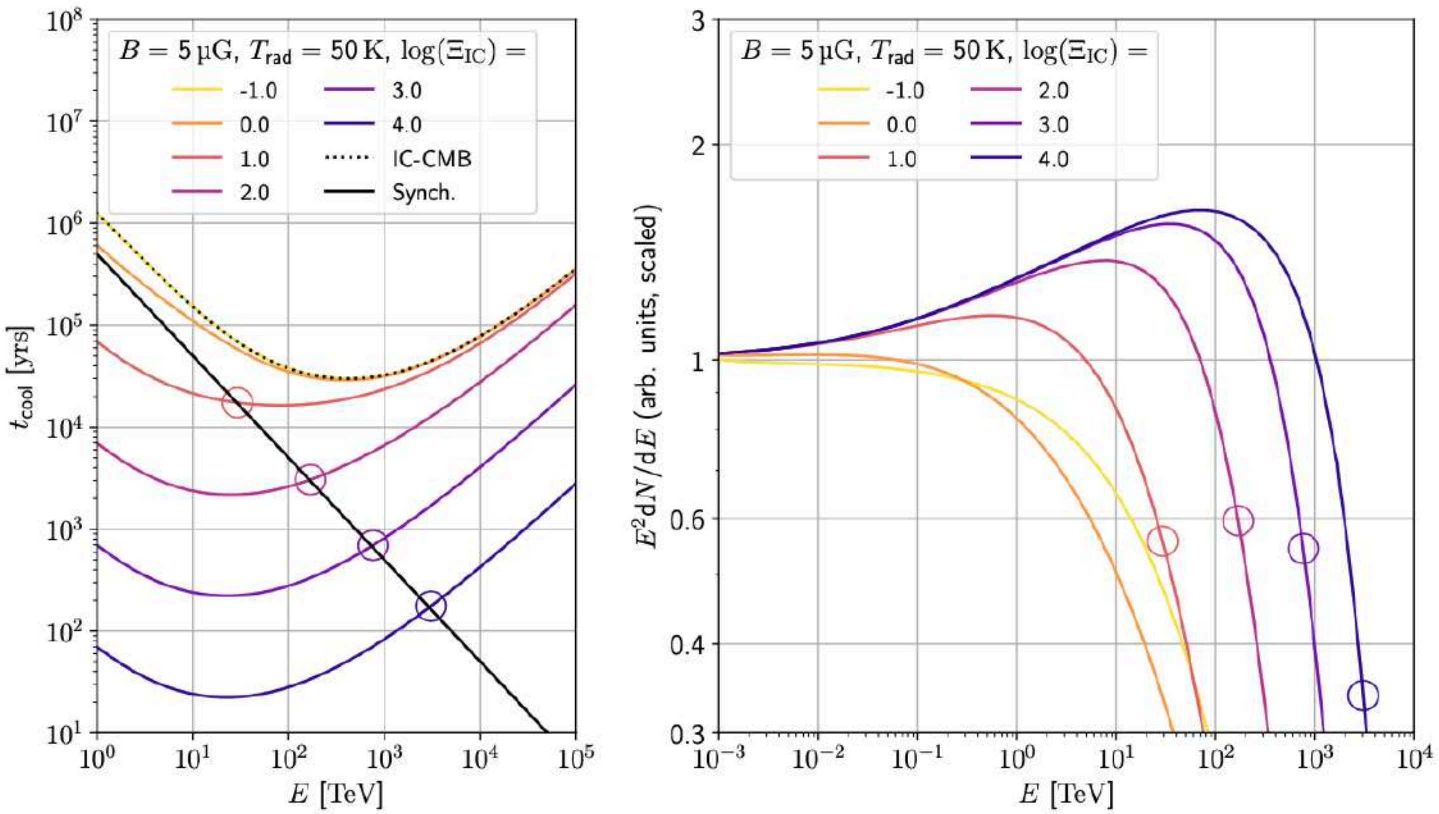
Ultra-high energy Inverse Compton emission from Galactic electron accelerators

M. Breuhaus [1], J. Hahn [1,*] C. Romoli [1], B. Reville [1], G. Giacinti [1], R. Tuffs [1] and J. A. Hinton [1]

[1] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

(Received XXX, 2020; Revised yyy, 2020; Accepted zzz, 2020)

It is generally held that >100 TeV emission from astrophysical objects unambiguously demonstrates the presence of PeV protons or nuclei, due to the unavoidable Klein-Nishina suppression of inverse Compton emission from electrons. However, in the presence of inverse Compton dominated cooling, hard high-energy electron spectra are possible. We show that the environmental requirements for such spectra can naturally be met in spiral arms, and in particular in regions of enhanced star formation activity, the natural locations for the most promising electron accelerators: powerful young pulsars. Our scenario suggests a population of hard ultra-high energy sources is likely to be revealed in future searches, and may also provide a natural explanation for the 100 TeV sources recently reported by HAWC.



Vannoni, Gabici &Aharonian 2007

And… other candidates!

Massive stars as sources of cosmic rays

Massive Stars as Major Factories of Galactic Cosmic Rays

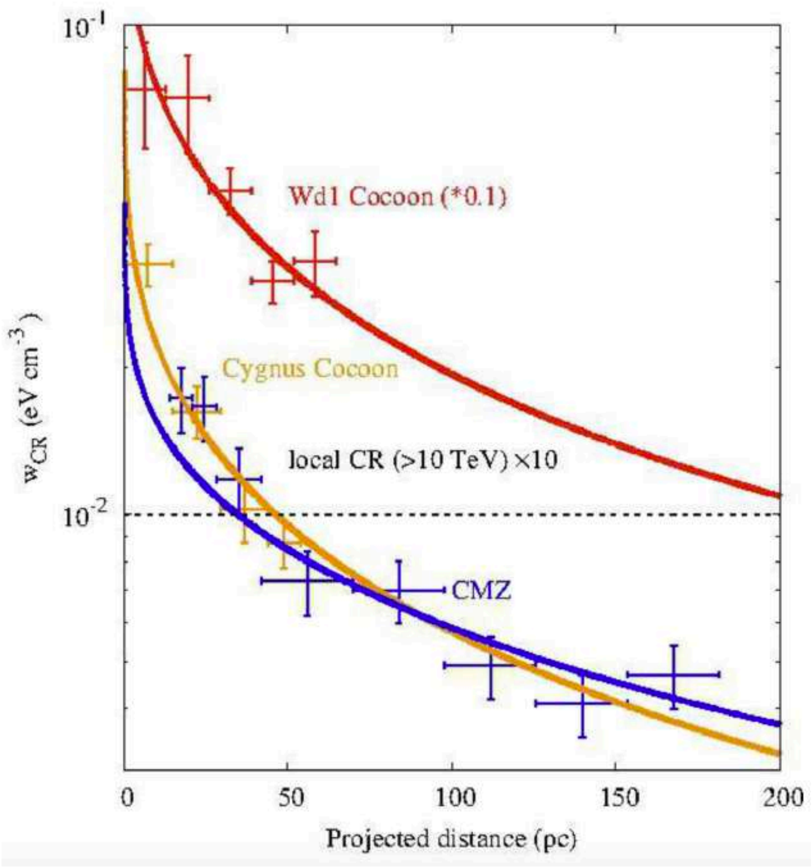
Felix Aharonian[1,2,3], Ruizhi Yang[2], Emma de Oña Wilhelmi[4,5,6] **2019**

Particle acceleration in winds of star clusters

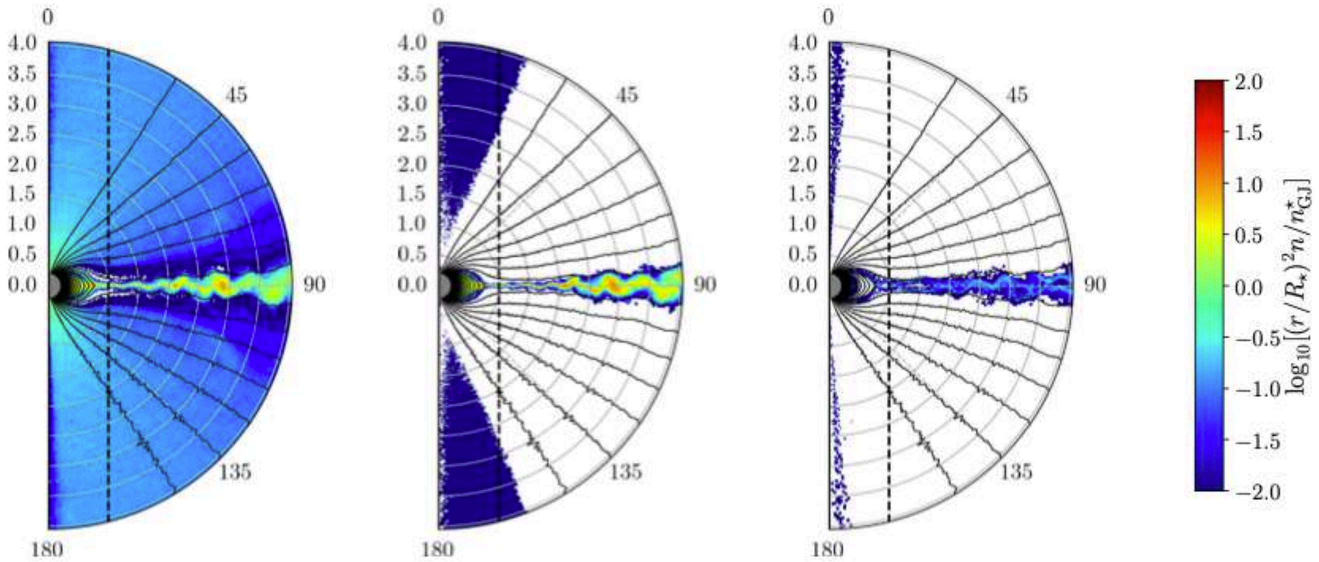
2021

G. Morlino [1]★, P. Blasi[2,3]†, E. Peretti[4,2]‡ & P. Cristofari[2,3]§

+ Gupta et al. (2020)
+ Menchiari et al. (2022)



'Leptonic' pevatrons also 'hadronic' sources?



Proton acceleration in pulsar magnetospheres

Claire Guépin[1,2,3], Benoît Cerutti[4], and Kumiko Kotera[1]

2020

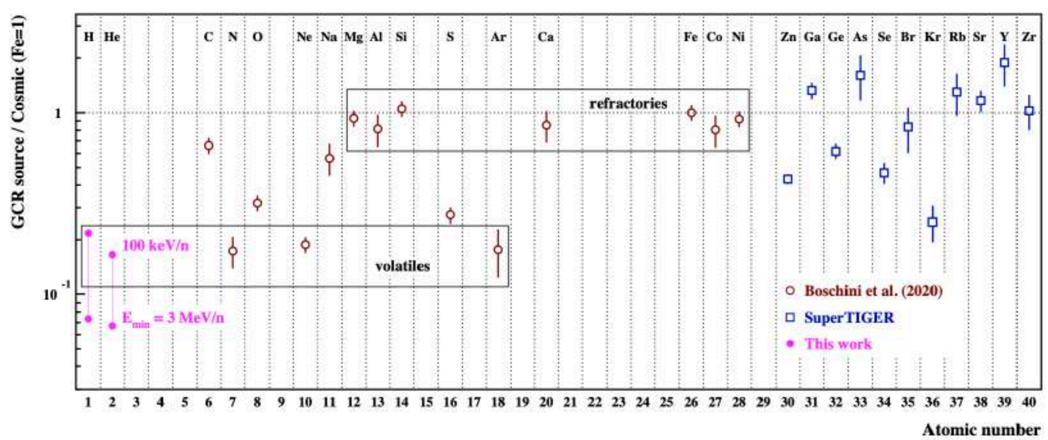
And… other candidates!

Superbubbles

The Origin of Galactic Cosmic Rays as Revealed by their Composition

Vincent Tatischeff,[1★] John C. Raymond,[2] Jean Duprat[3] Stefano Gabici[4] and Sarah Recchia[1,5]

2021



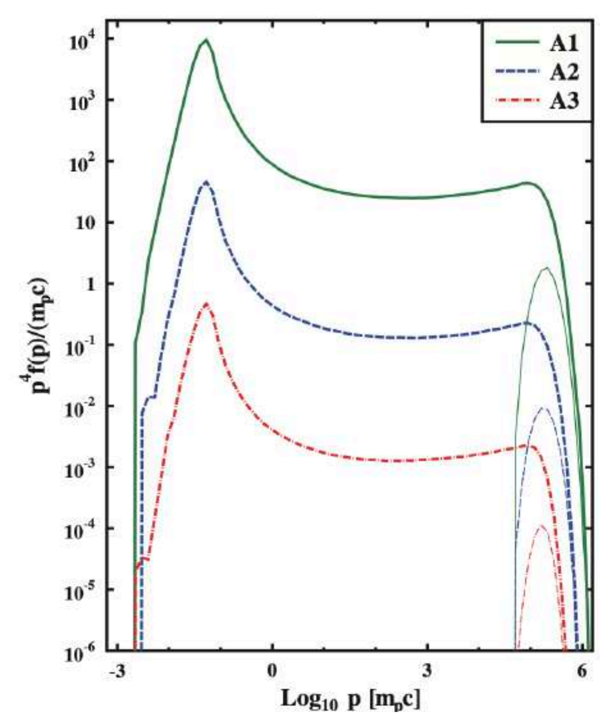
Parizot et al. 2004
Ferrand & Marcowith 2010
Vieu, Gabici, Tatischeff 2021,2022
Vieu, Reville, Aharonian 2022

Article

Particle Acceleration in Mildly Relativistic Outflows of Fast Energetic Transient Sources

Andrei Bykov *, Vadim Romansky and Sergei Osipov

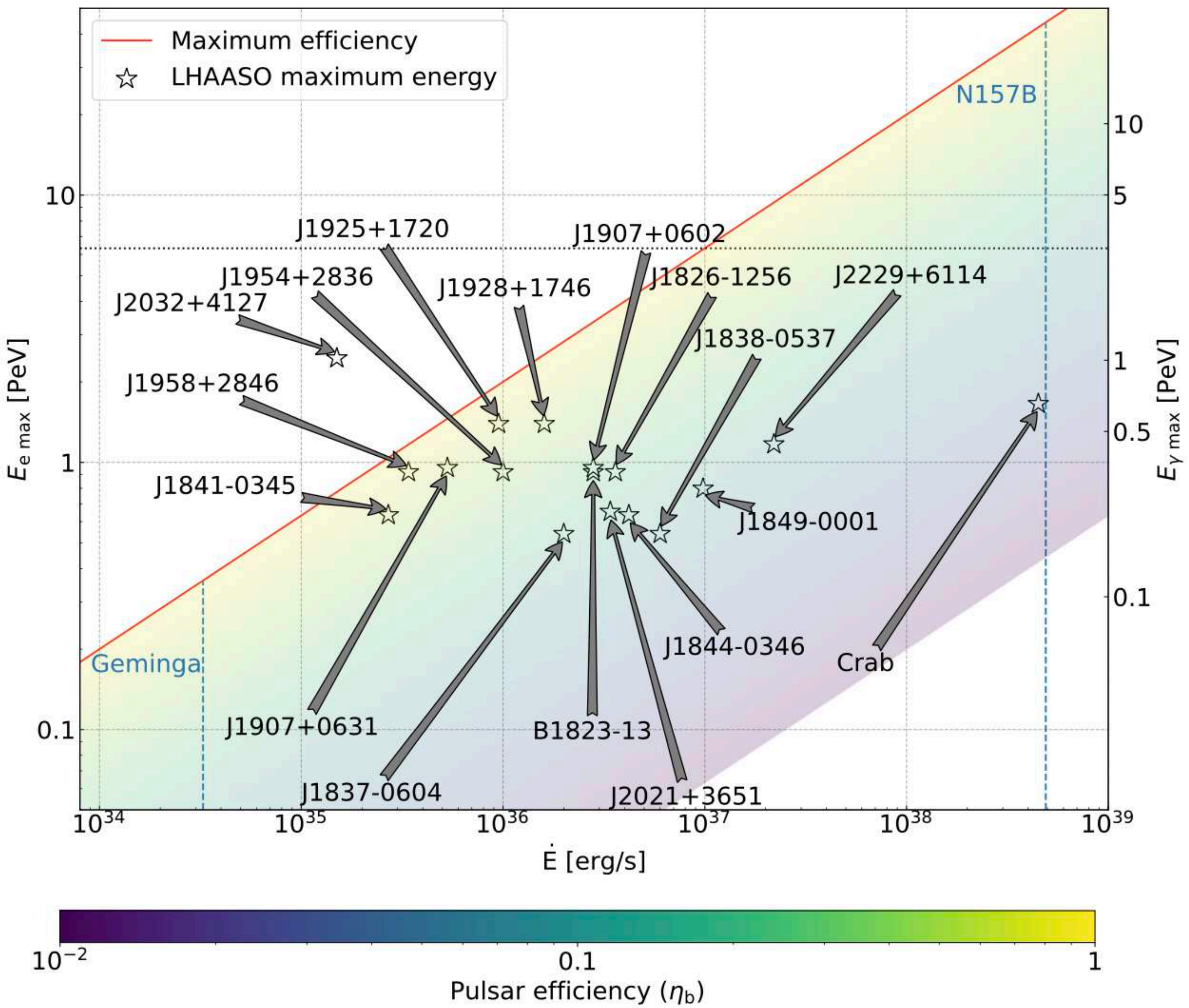
2022



And… other candidates!

On the potential of bright, young pulsars to power ultra-high gamma-ray sources

Emma de Oña Wilhelmi[1] Rubén López-Coto[2,3] Elena Amato[4,5] and Felix Aharonian[6,7]

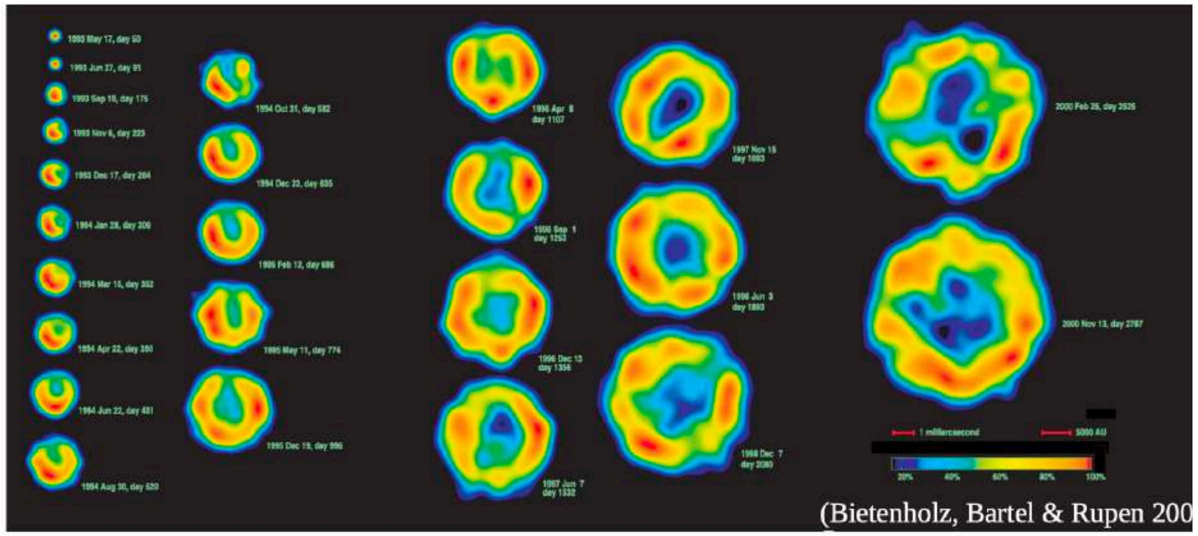


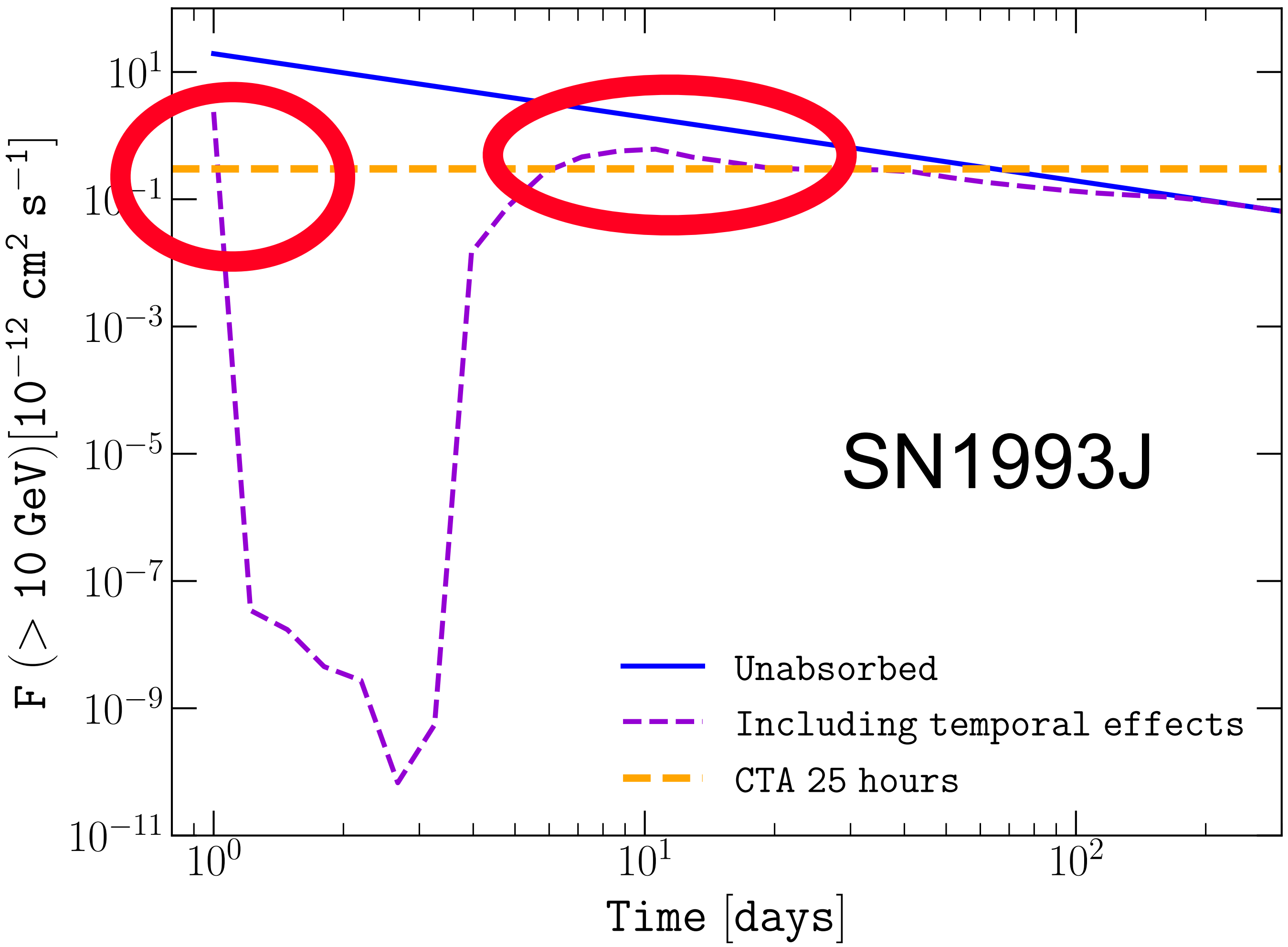
And… other candidates!

Core collapse supernovae

Gamma rays in the first days after the SN explosion

$$\gamma\gamma \to e^+e^-$$





The potential for detection with CTA (Consortium paper in preparation)
F. Acero, C. Boisson, J. Devin, V. Dwarkadas, G. Giacinti, N. Komin, A. Marcowith, M. Renaud, S. Ohm, J. Vink, H. Sol, T. Stolarczyk, V. Tatischeff

Brose, Pohl, Sushch (2021)
Brose, Sushch, Mackey (2022)
PC et al. (2020,2022)

Summary

For a long time:
 1.'detecting pevatrons' ~ 'finding supernova remnant pevatrons'
2. Detection in the 100 TeV gamma-ray range (relatively hard spectra)= hadronic pevatrons

Now:
 1. many pevatron candidates (superbubbles, stellar clusters, leptonic sources, supernovae, SNRs)
2. 'Interpretation of 100 TeV gamma rays' is tricky Improved angular/spectral studies + multi-wavelength studies
3. CTA paper on pevatrons: useful tools and discussion on how to identify pevatrons (on the example of SNR populations)

'Theory and phenomenology of pevatrons' (lecture/seminar CDY, Stefano Gabici)

'The hunt for pevatrons: the role played by supernova remnants' (short review, PC)