The hunt for pevatrons

Pierre Cristofari

KPAP 2026

Observatoire de Paris | PSL

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10^{15} eV

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1. Not easy to achieve

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2. The origin of Galactic cosmic rays

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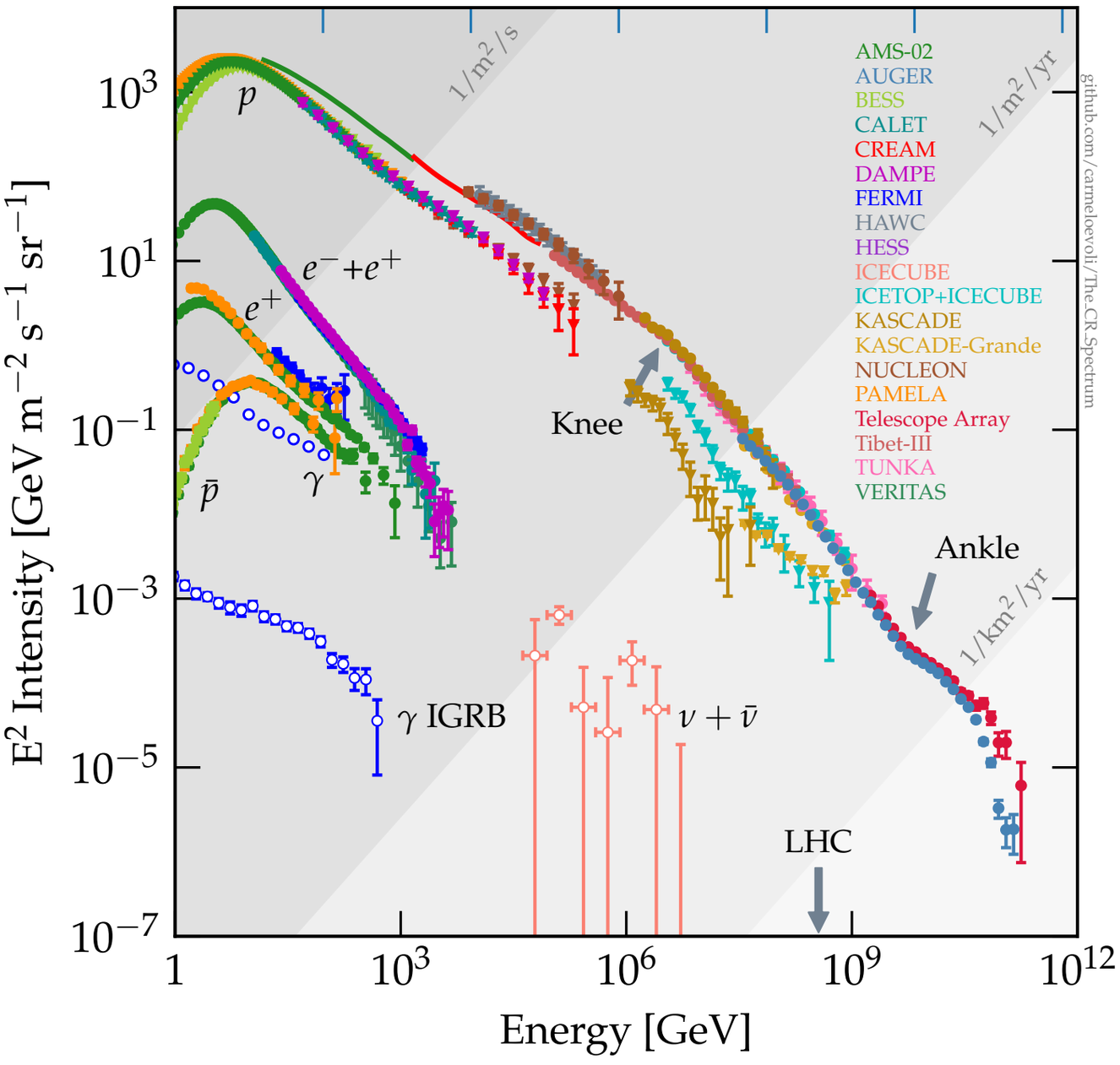

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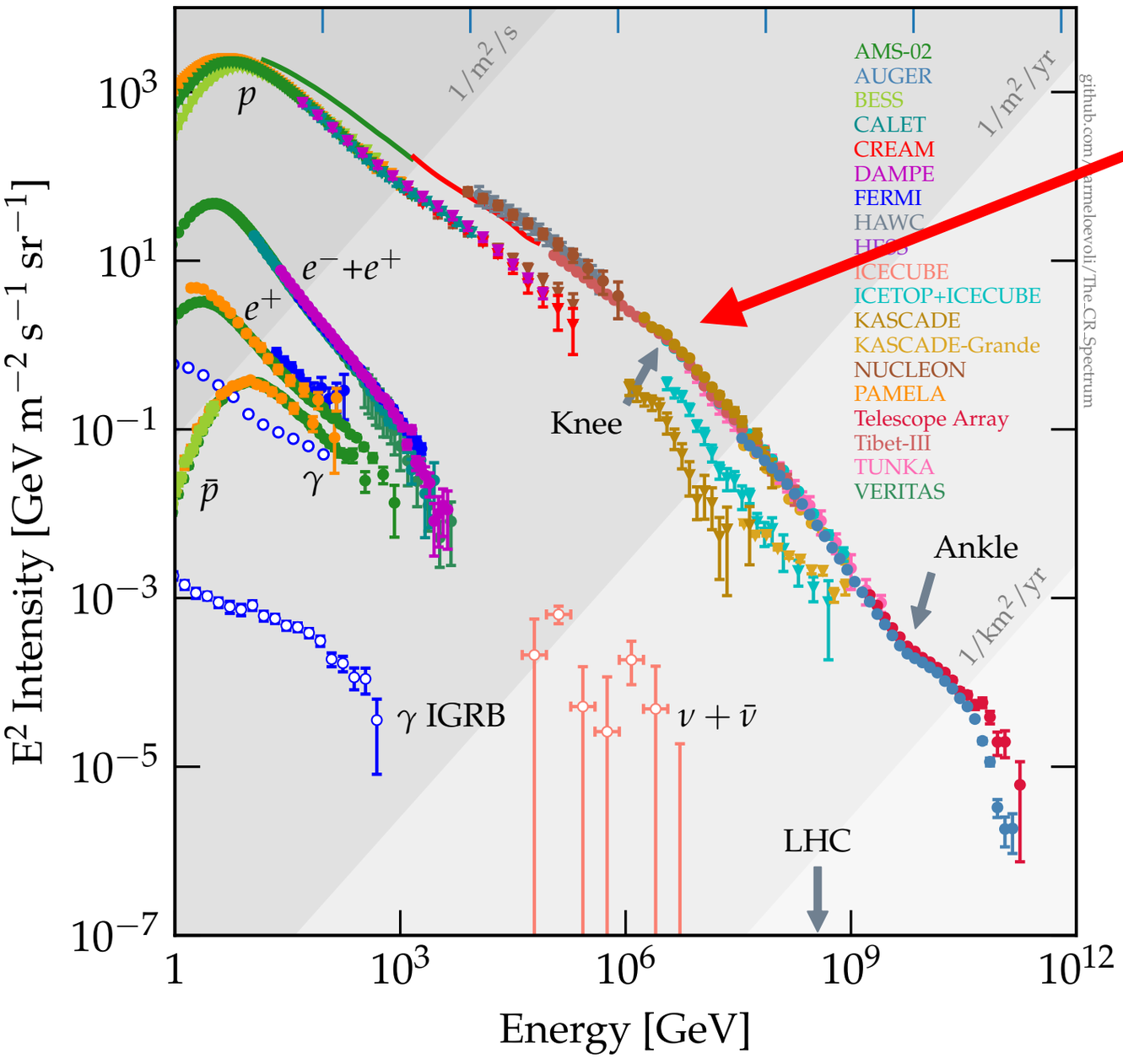

The « knee »
~3- 4 10^{15} eV

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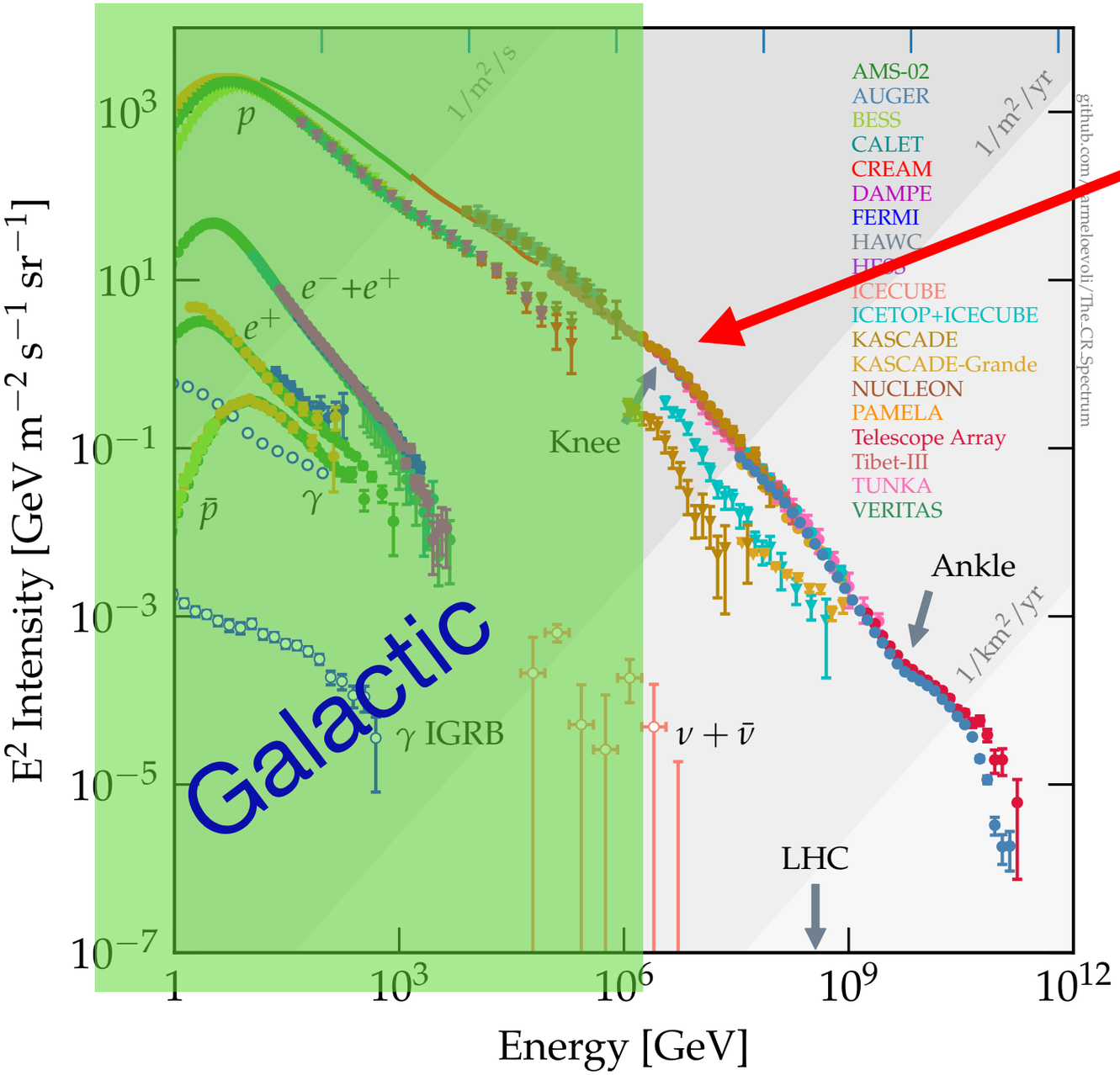

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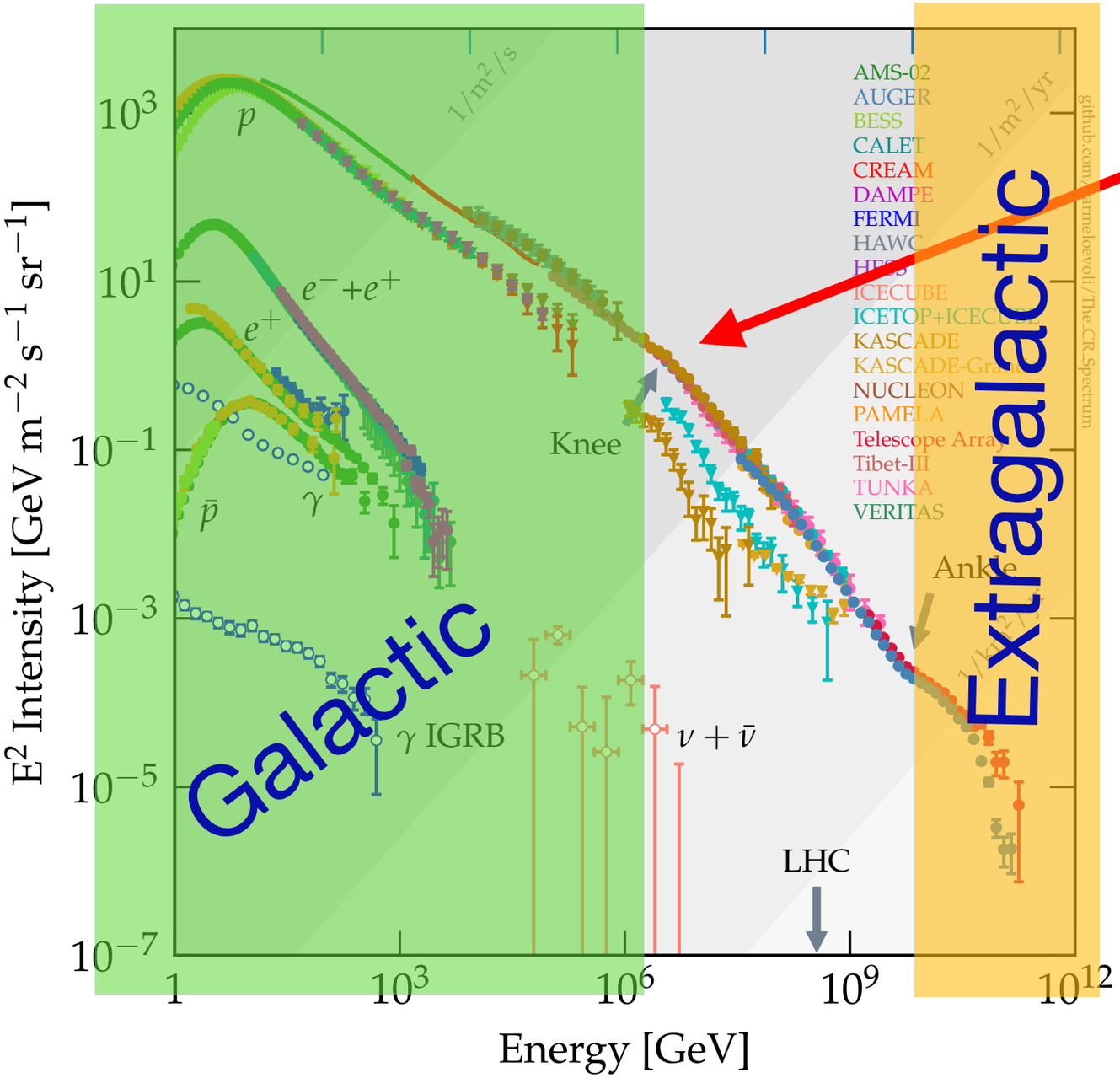

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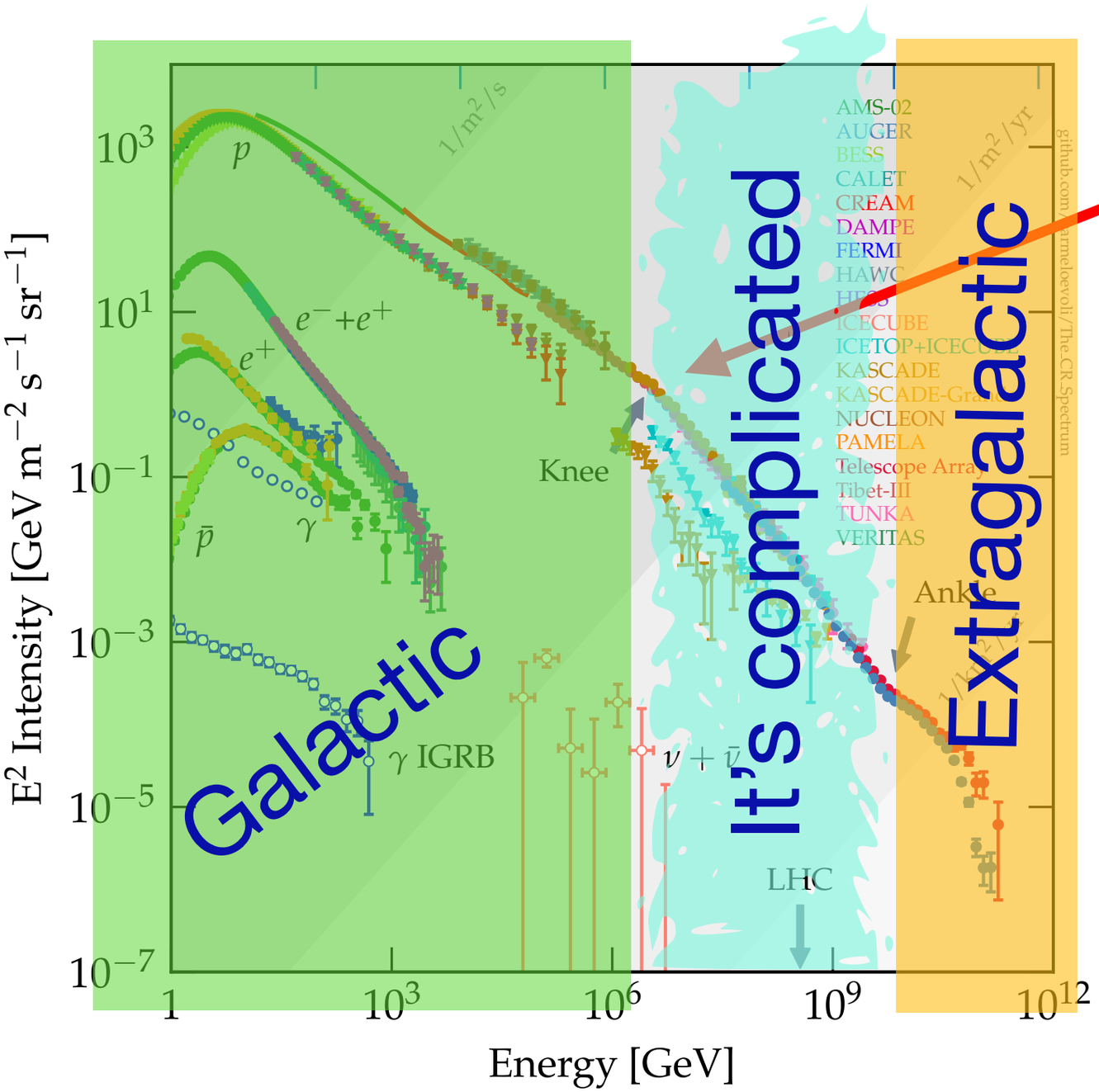

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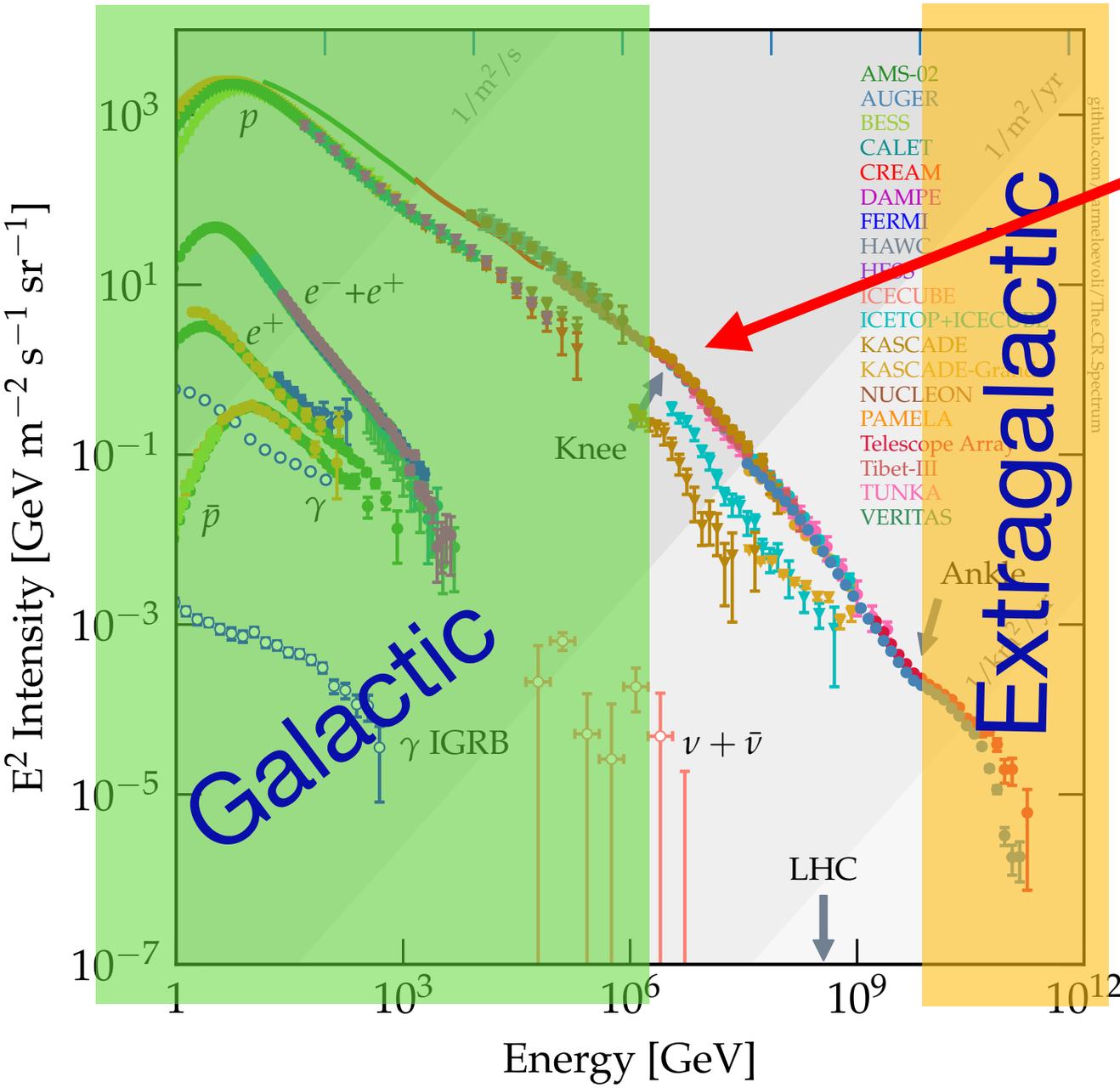

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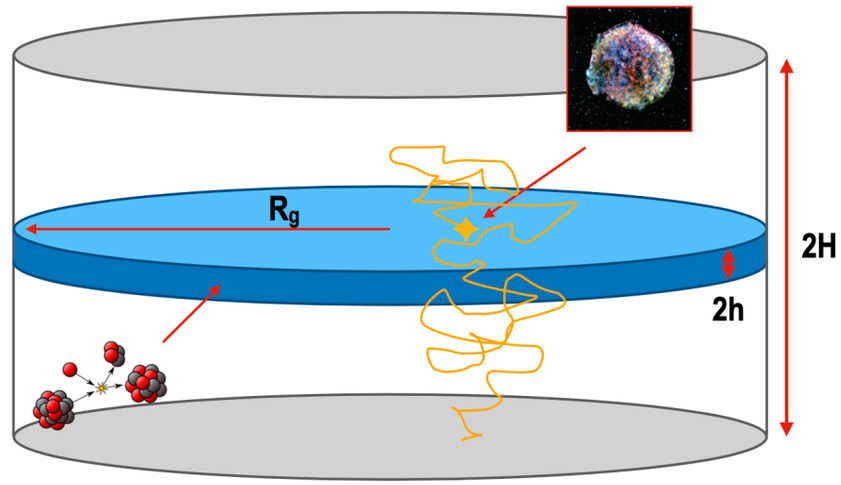

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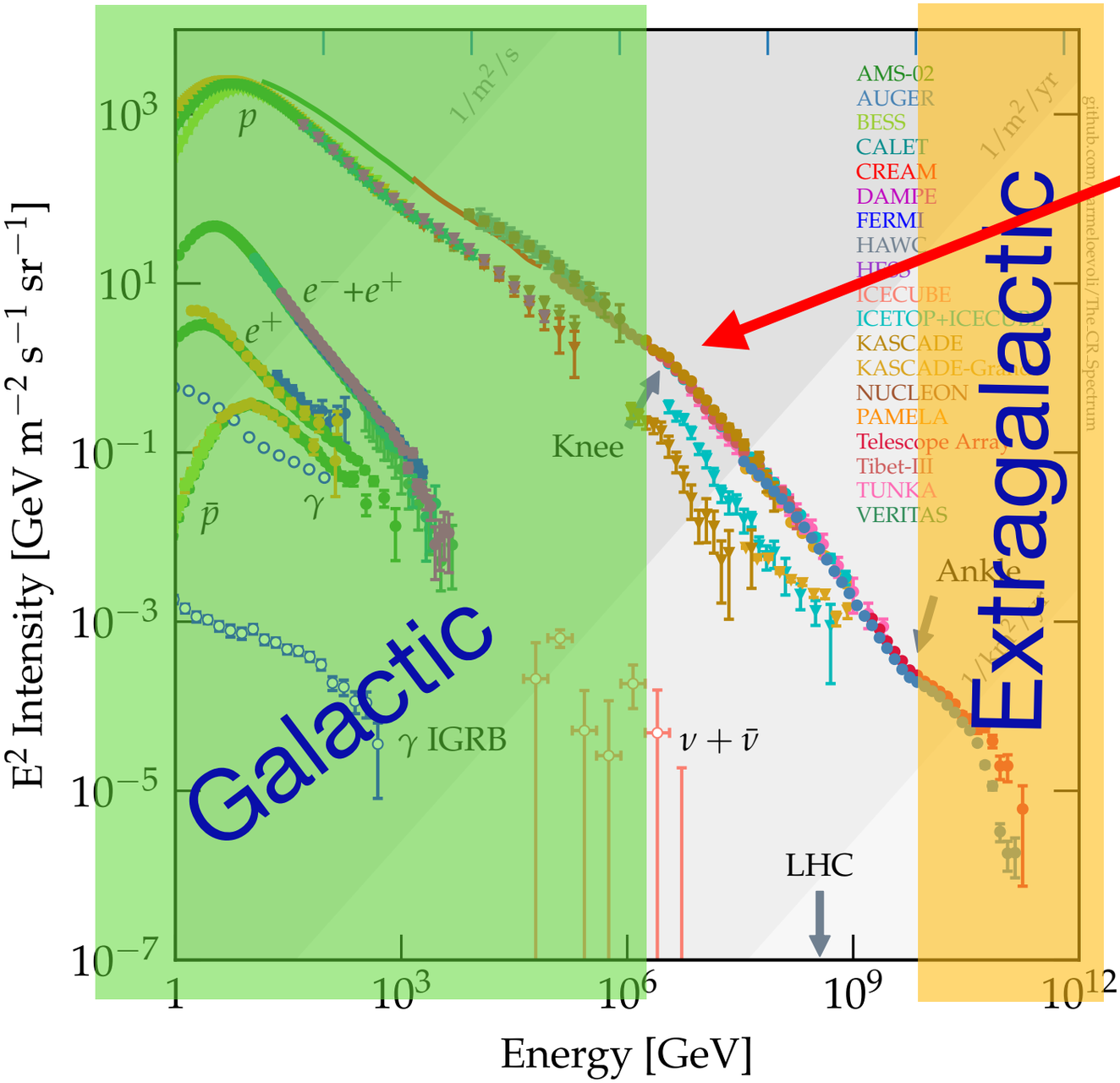

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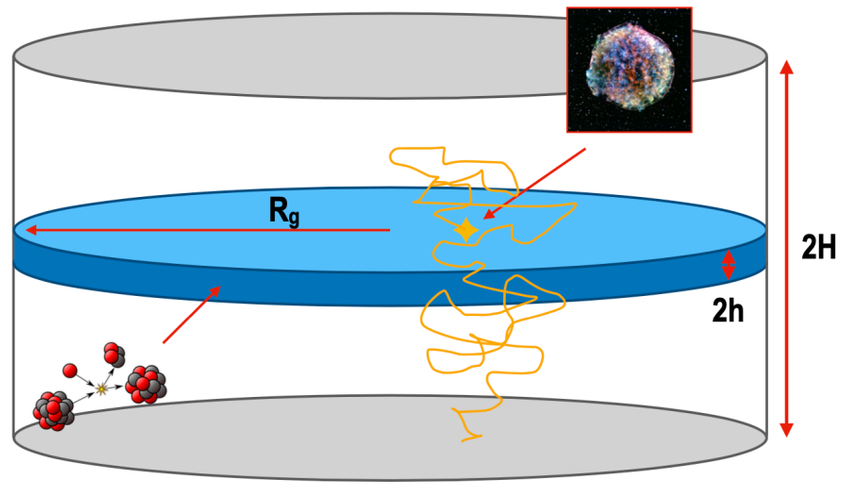

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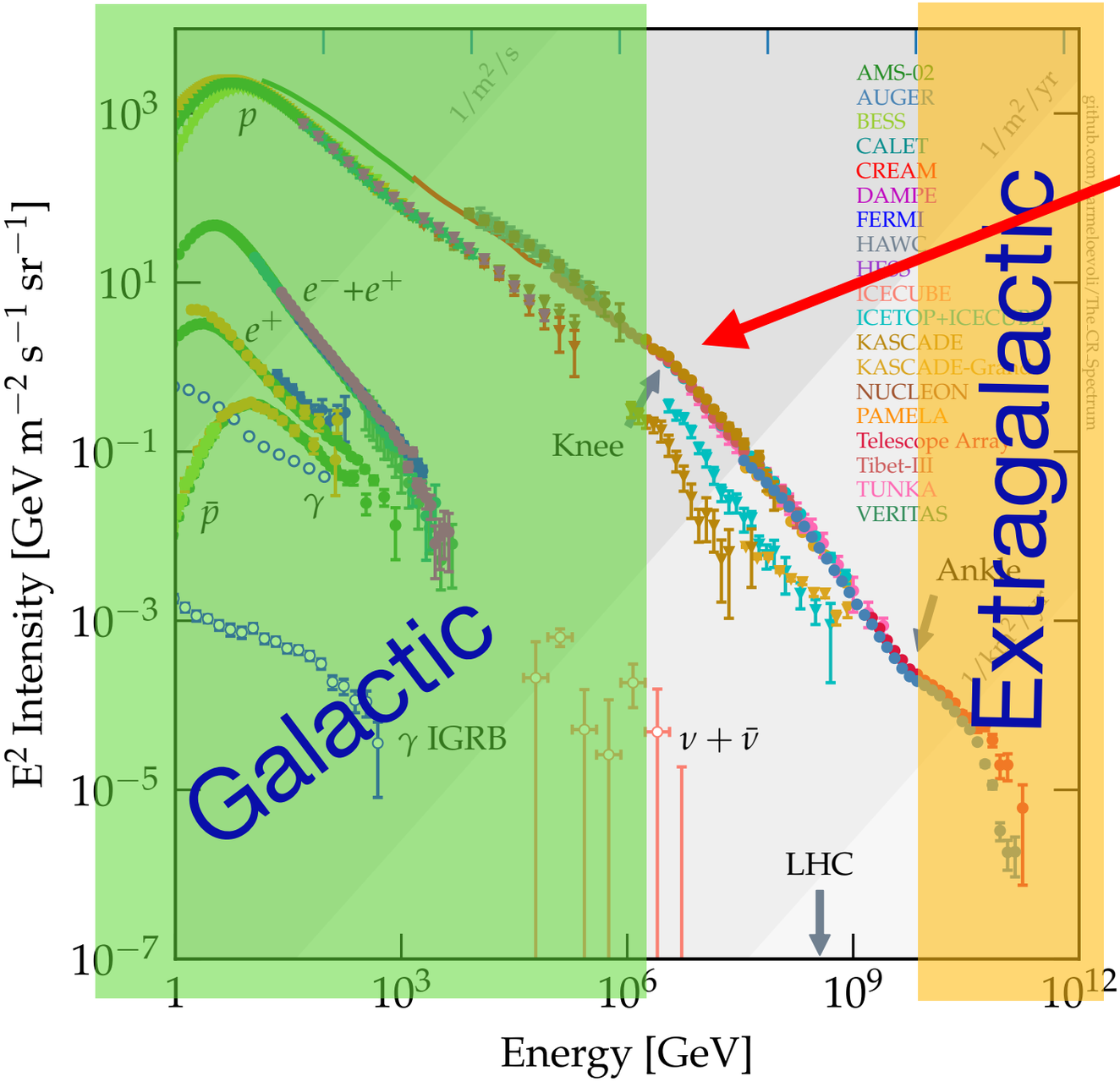

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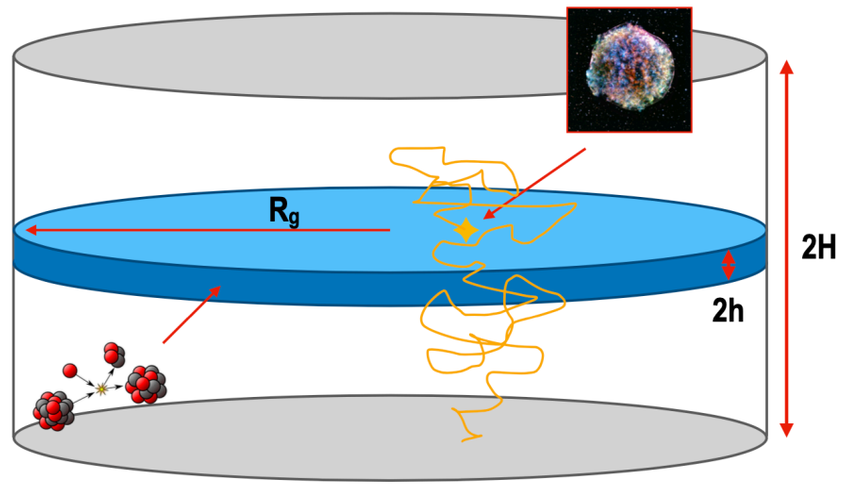

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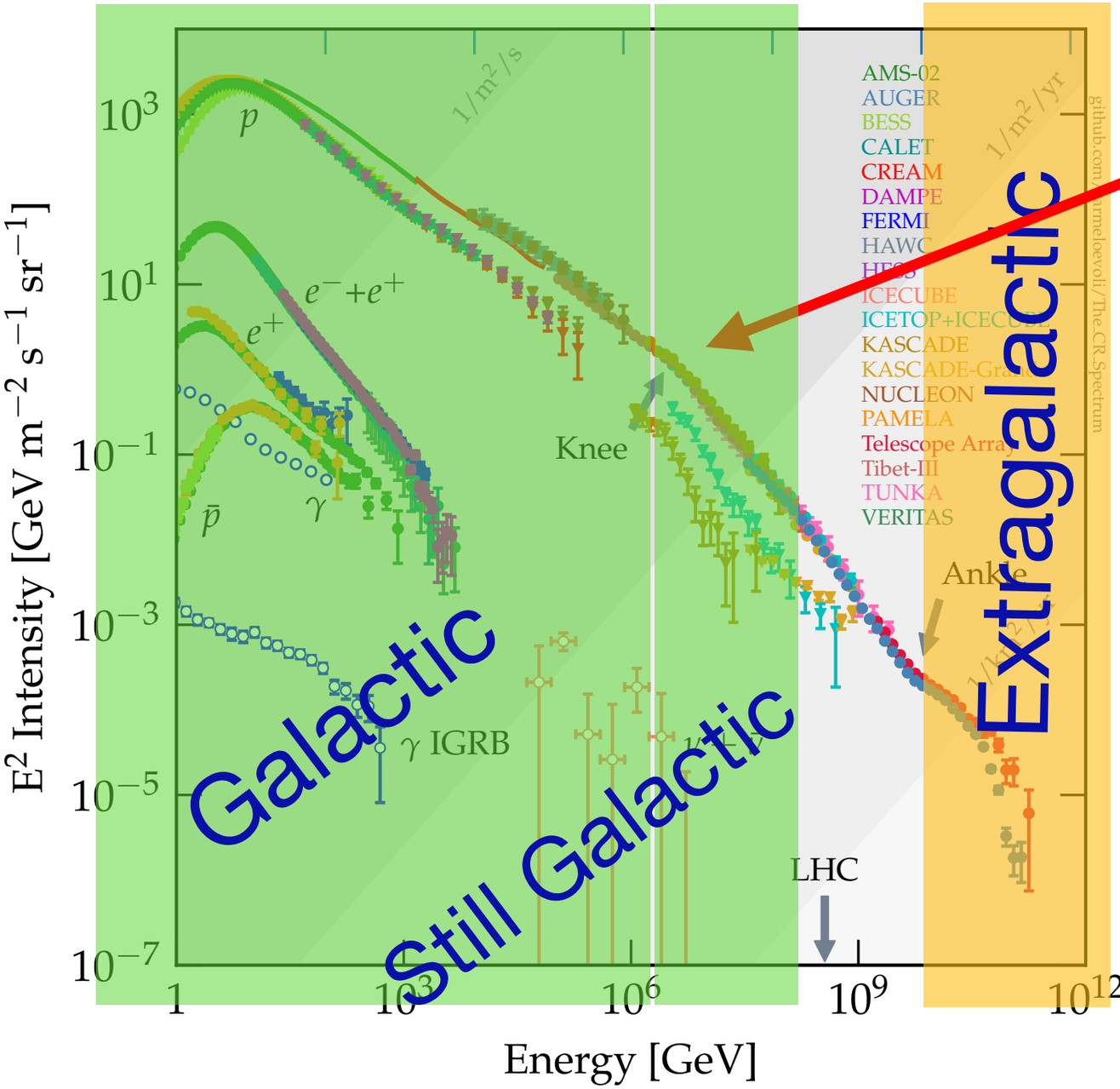

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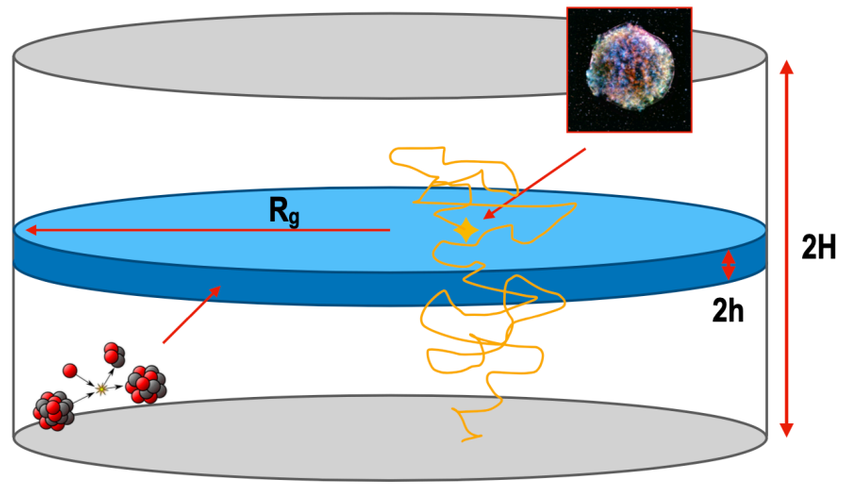

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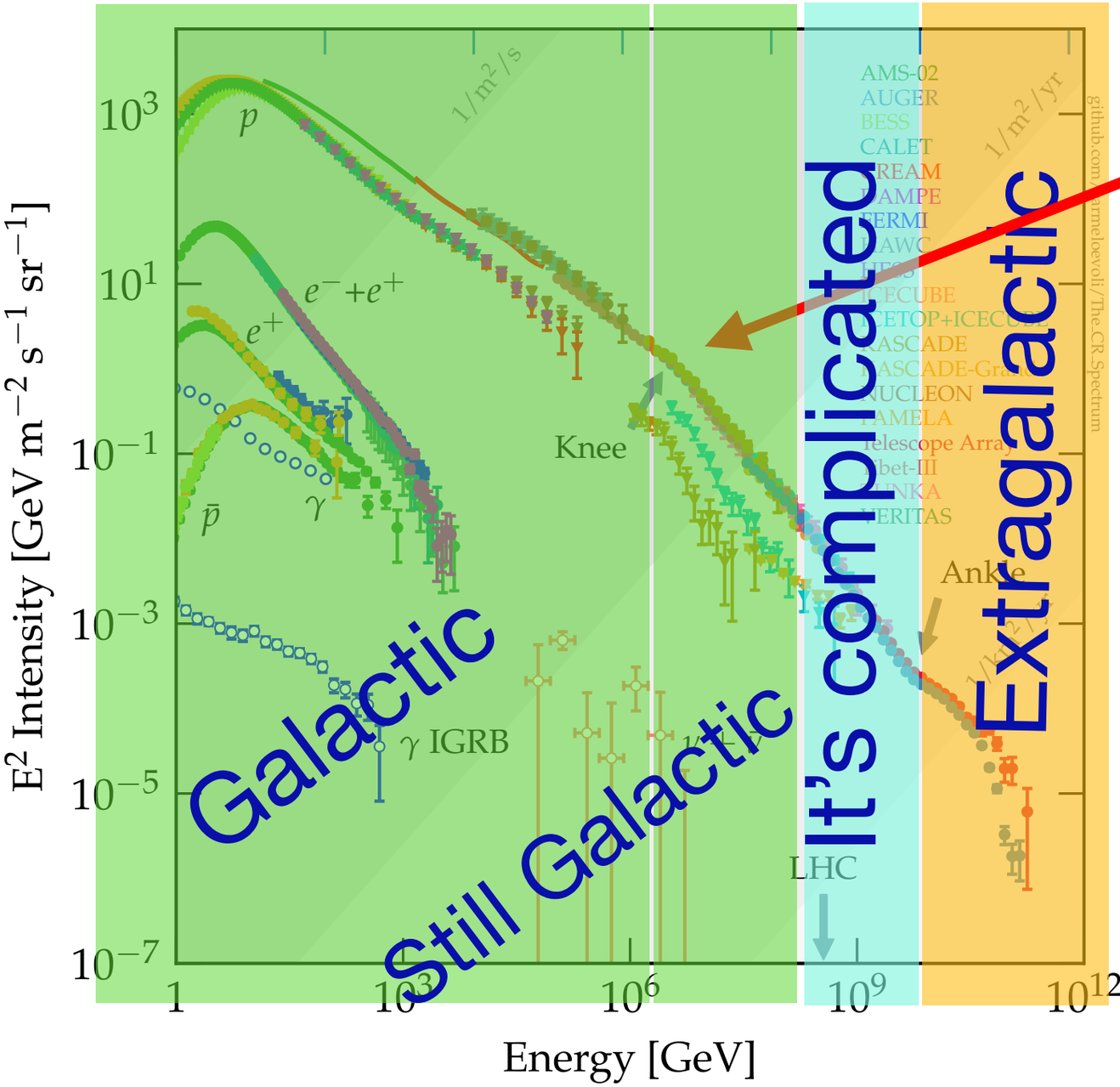

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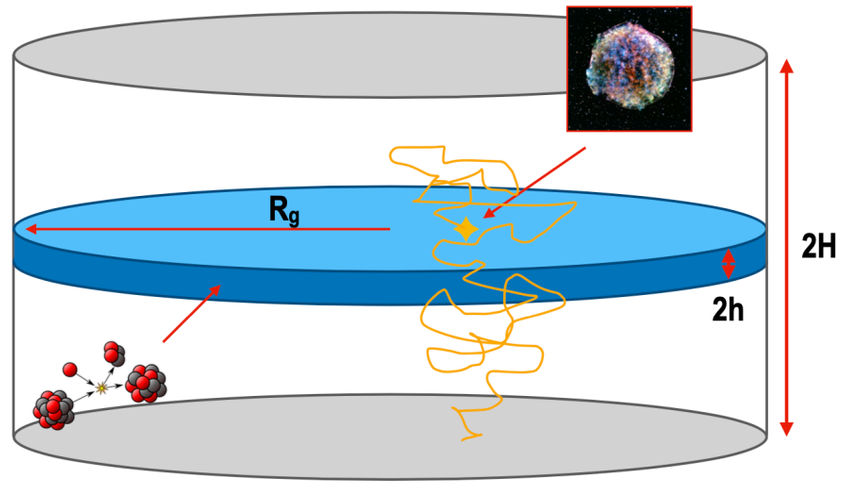

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Pevatrons in the last 10 years

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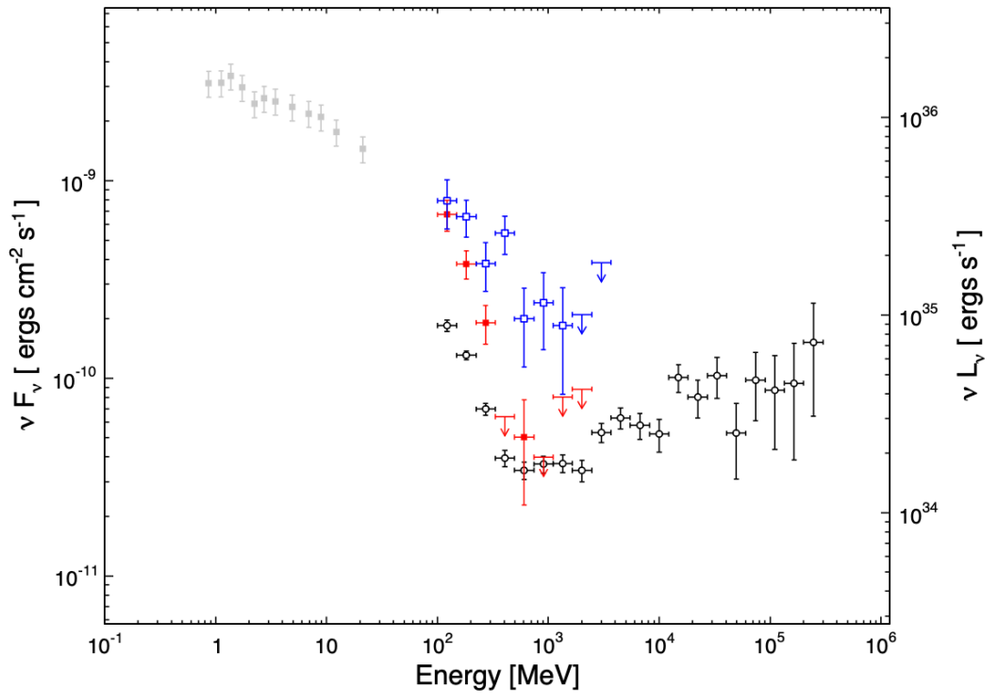
1. Crab electron pevatron (Fermi-LAT 2010):
   Flares 100 MeV due to PeV electrons



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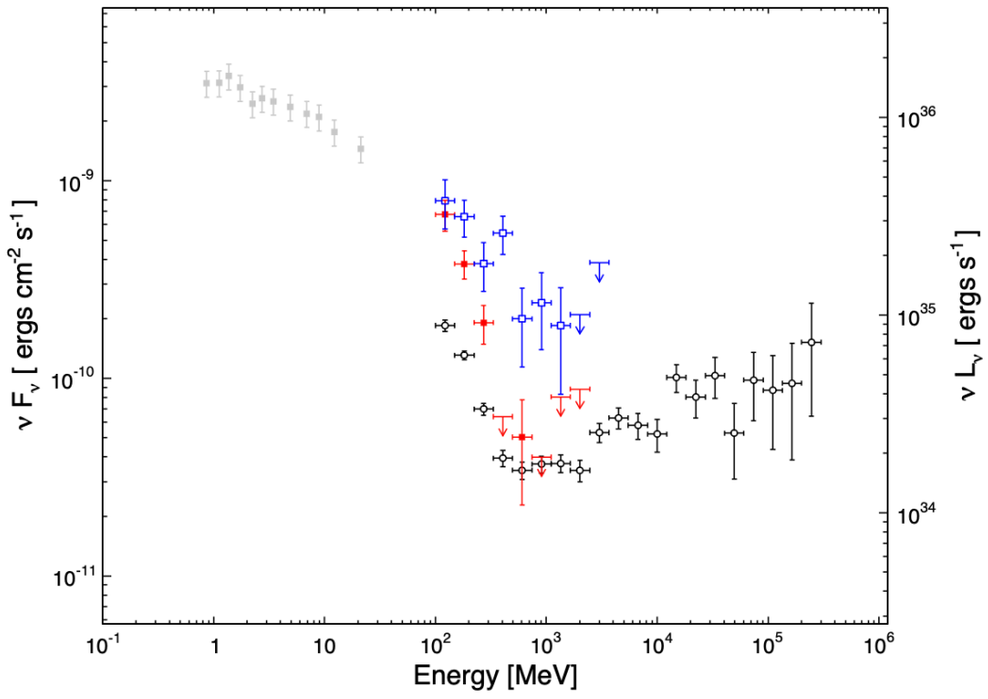


2. Galactic center Sgr. A* J1745-290
   (H.E.S.S. 2016)

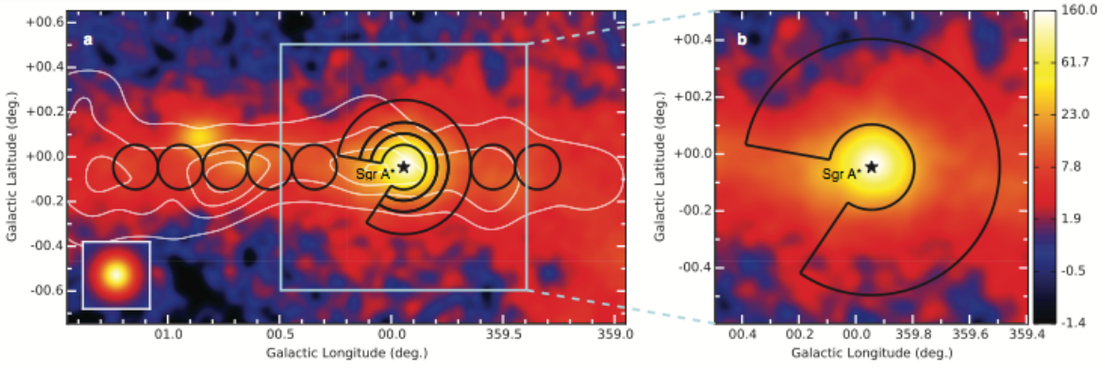
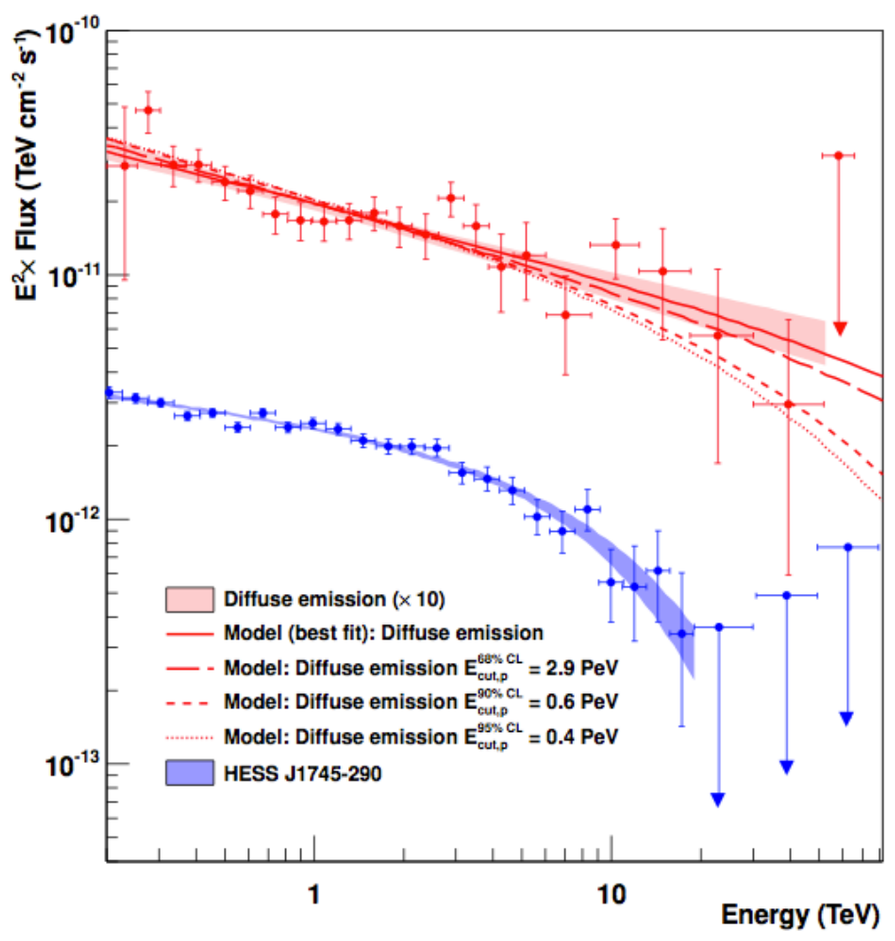


Figure 1: **VHE γ-ray image of the Galactic Centre region.** The colour scale indicates counts per 0.02° ×0.02° pixel.



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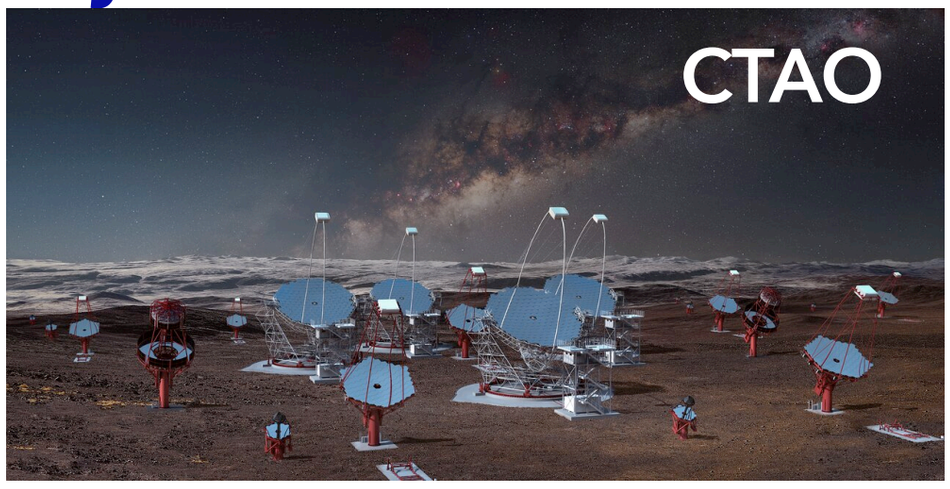
« Science with CTA 2017 »

Key Science project: detection of pevatrons



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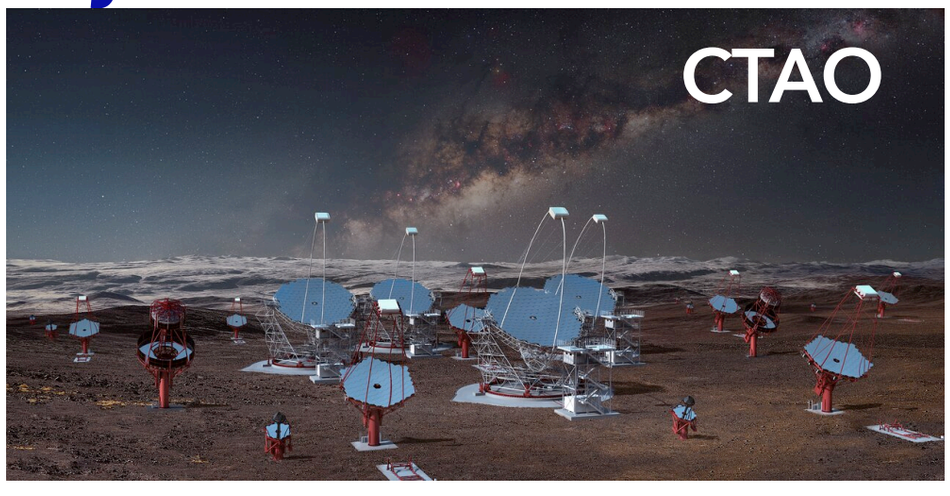

100 TeV gamma rays ⟷ PeV protons

Hadronic interactions :
Pion decay

CR **ISM**

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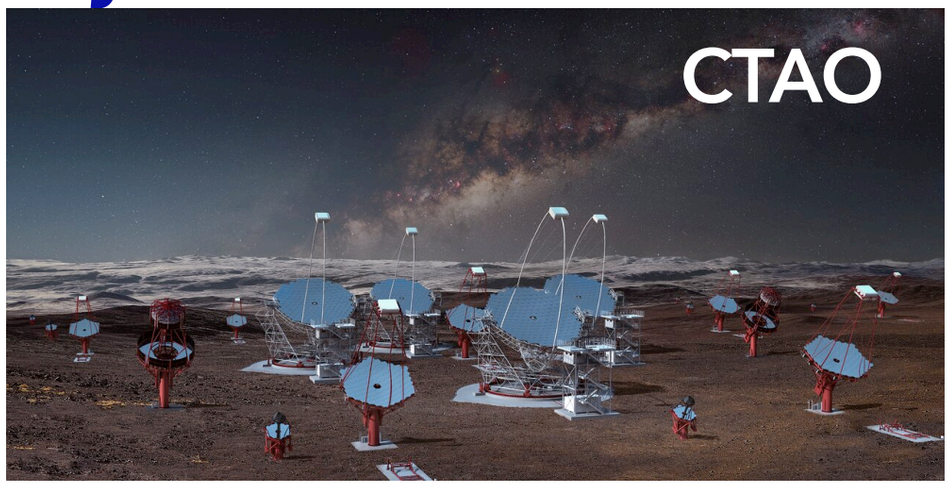

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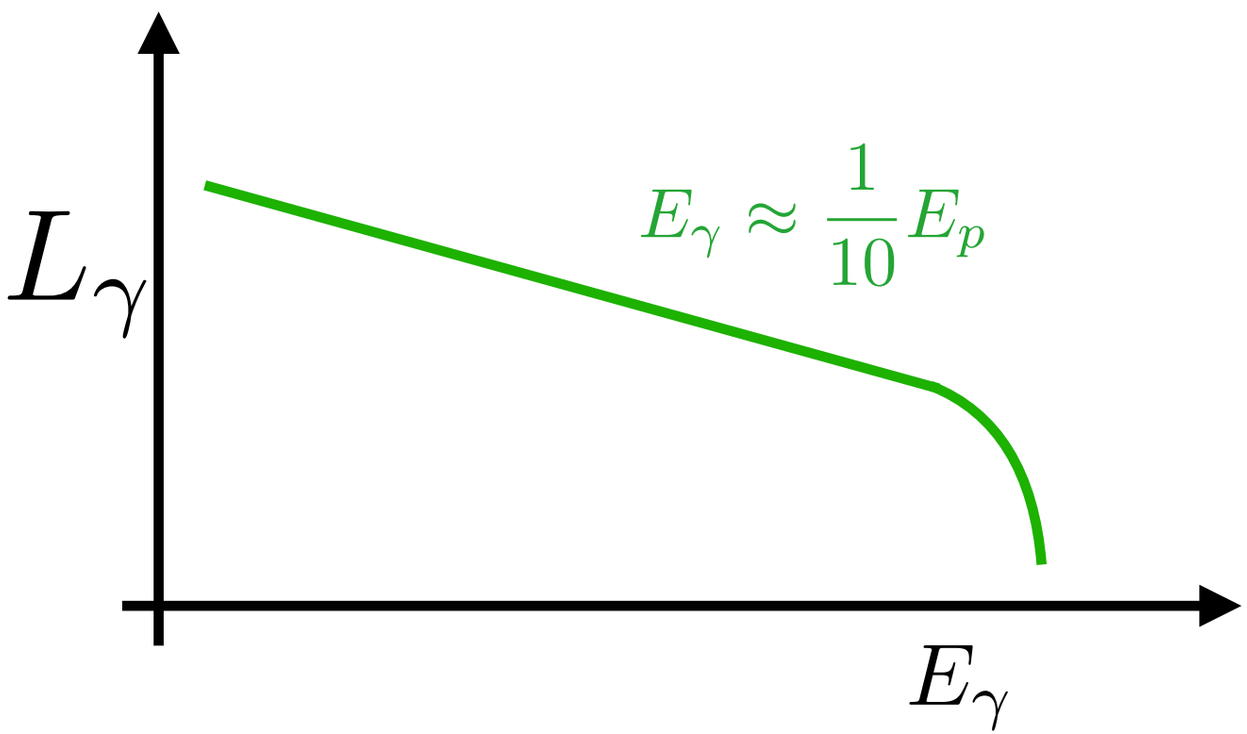

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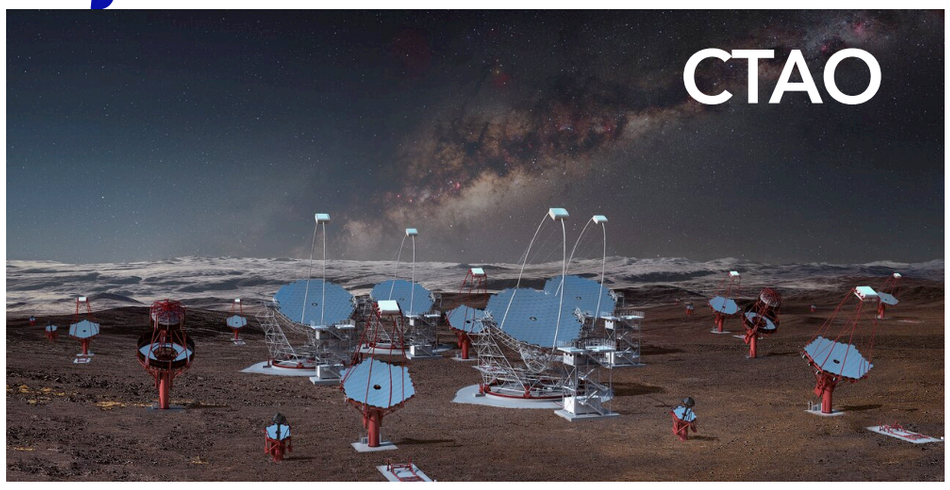

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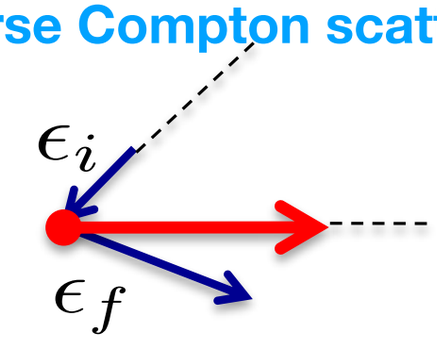

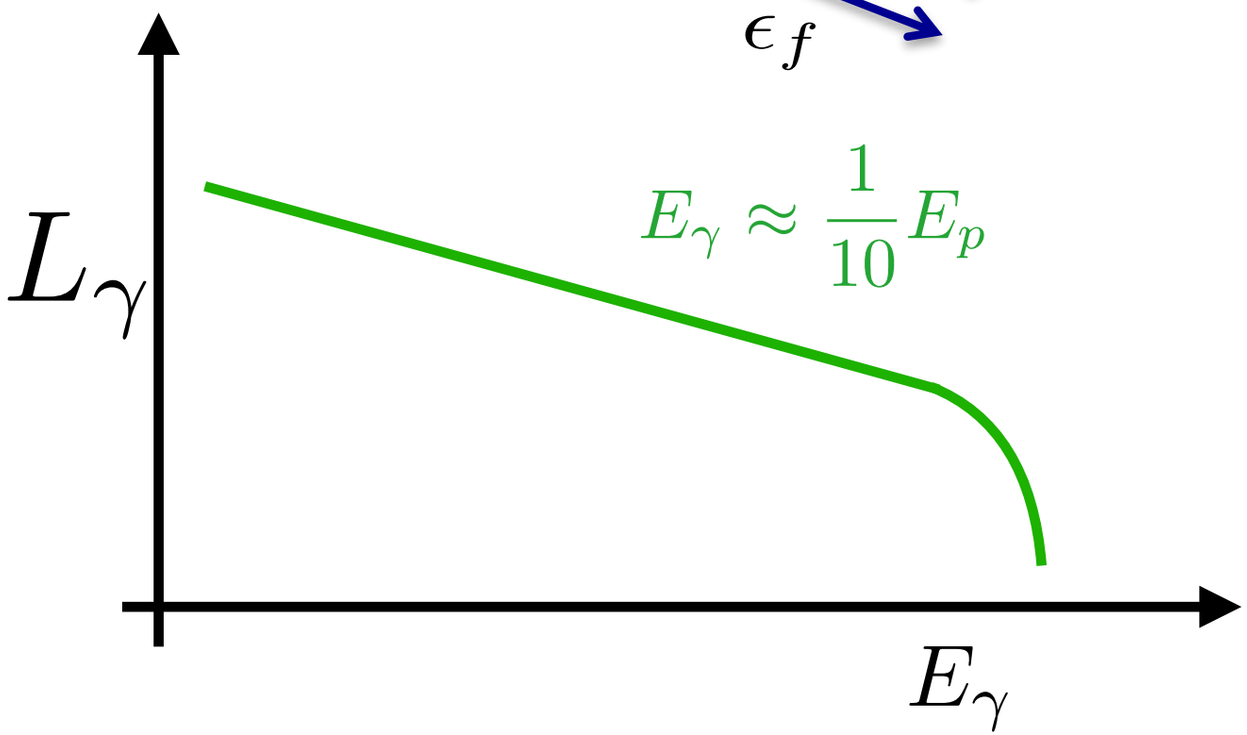

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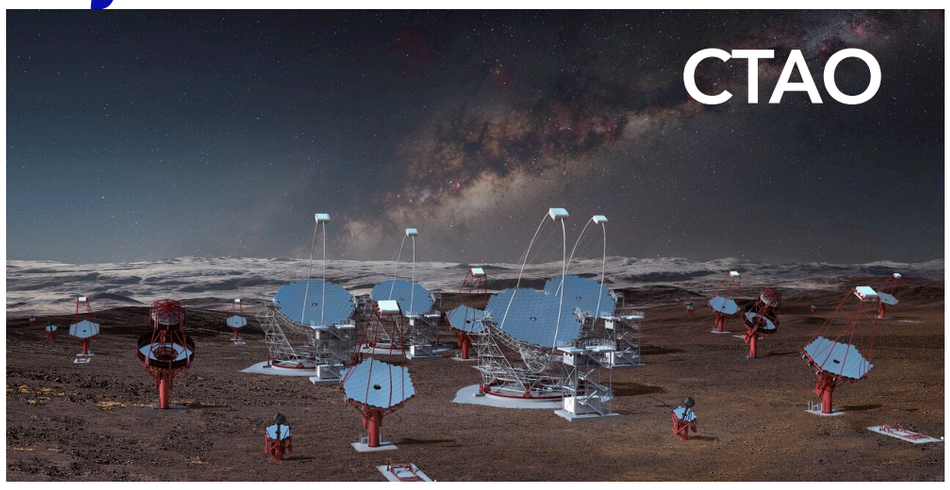

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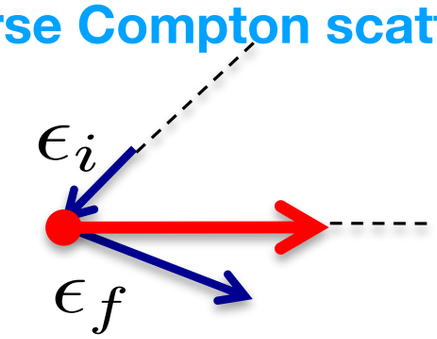

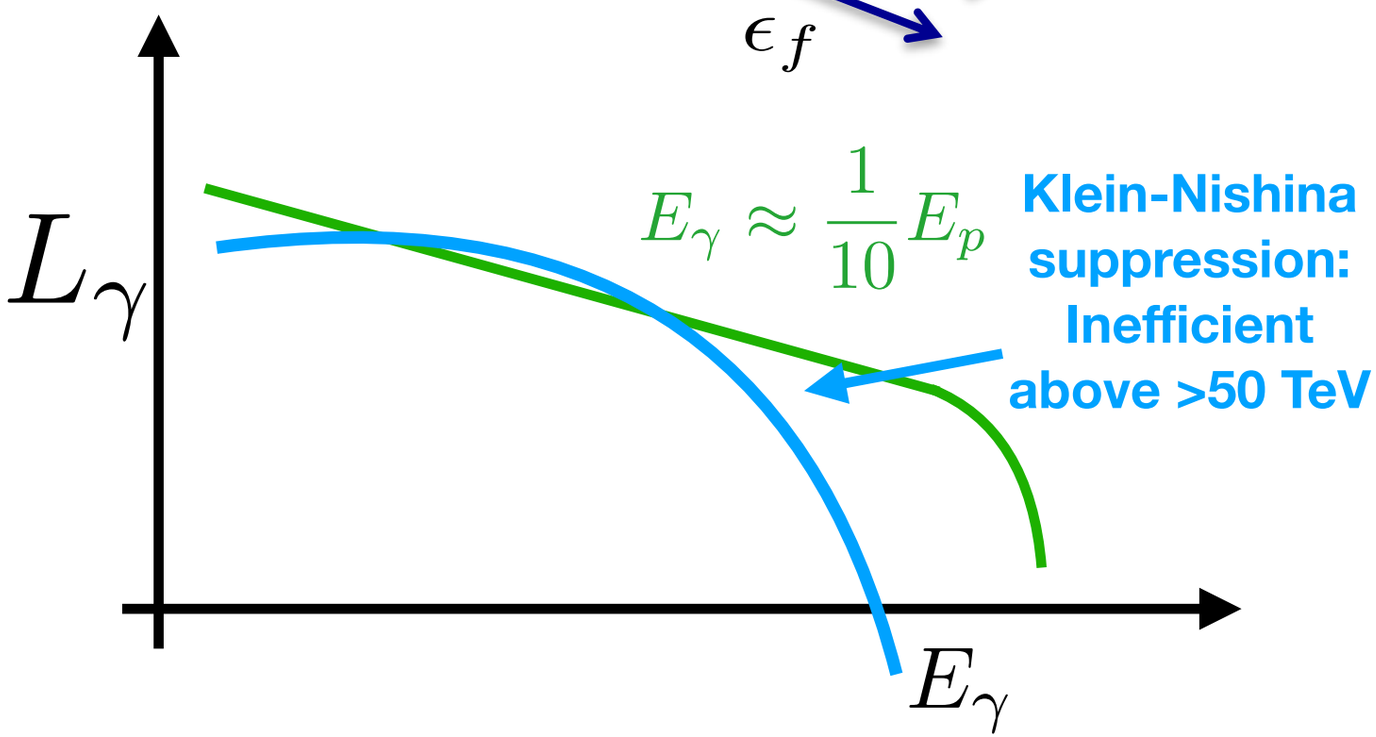

$$E_\gamma \approx \frac{1}{10} E_p$$

Klein-Nishina suppression: Inefficient above >50 TeV

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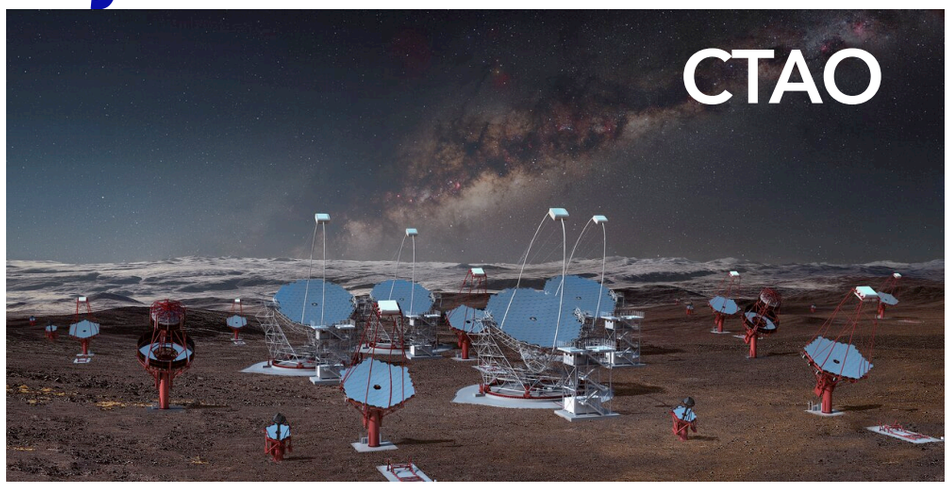

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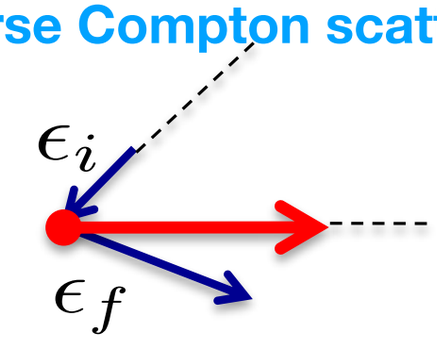

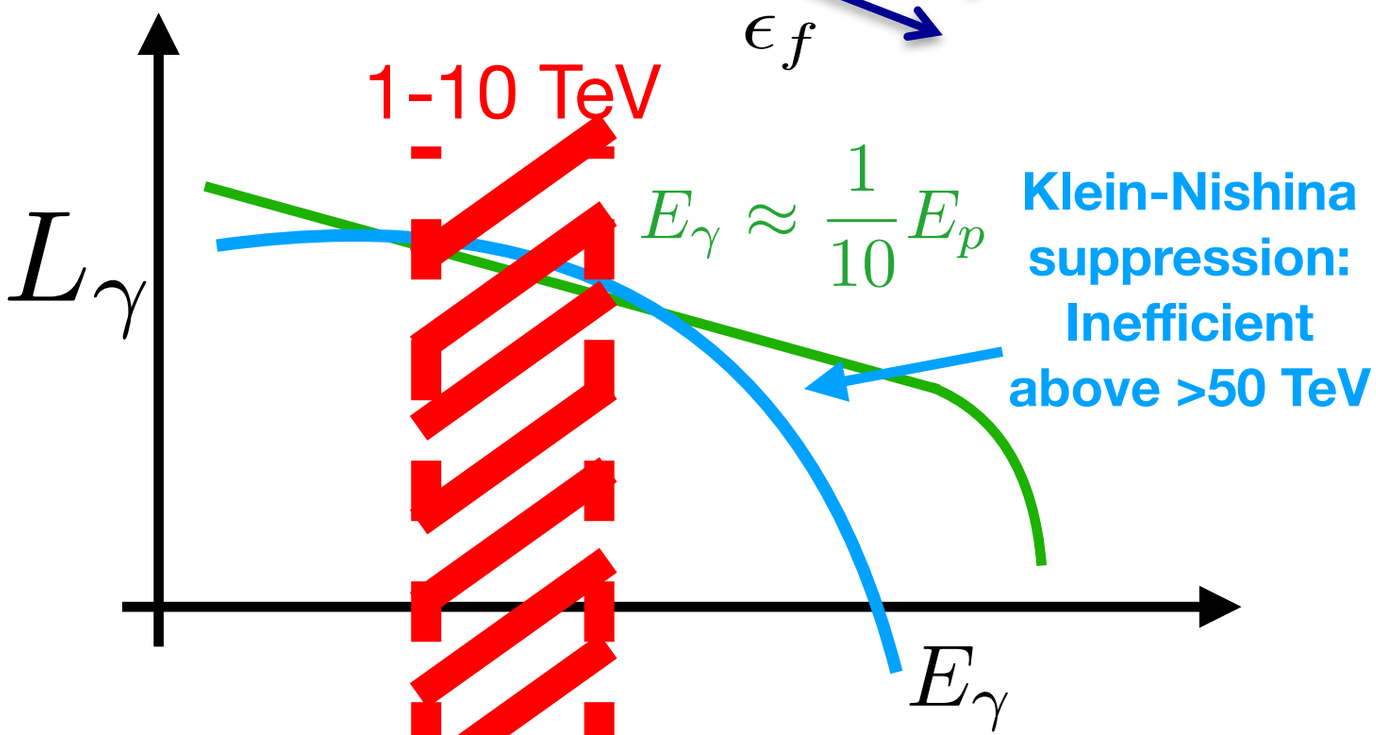

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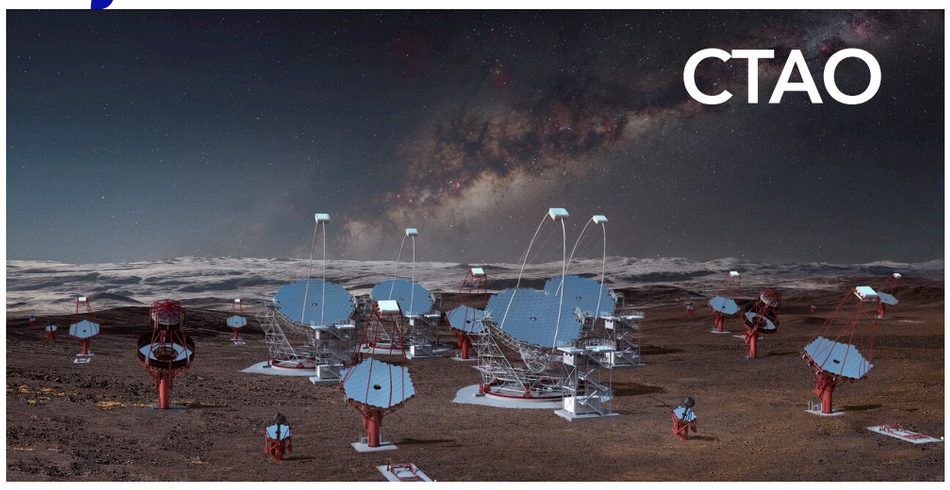

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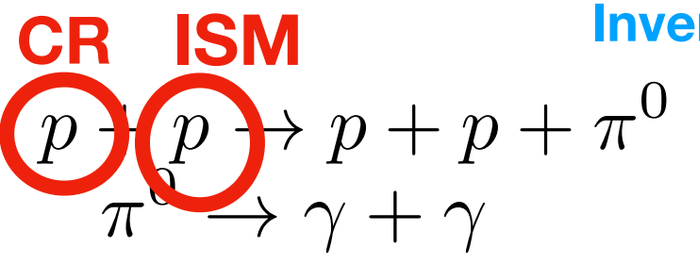

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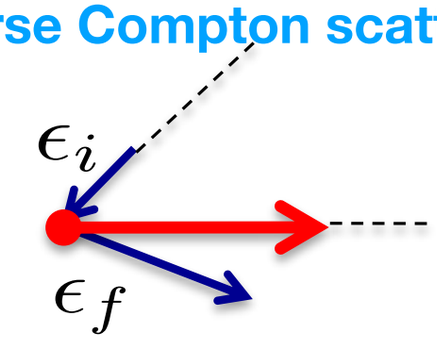

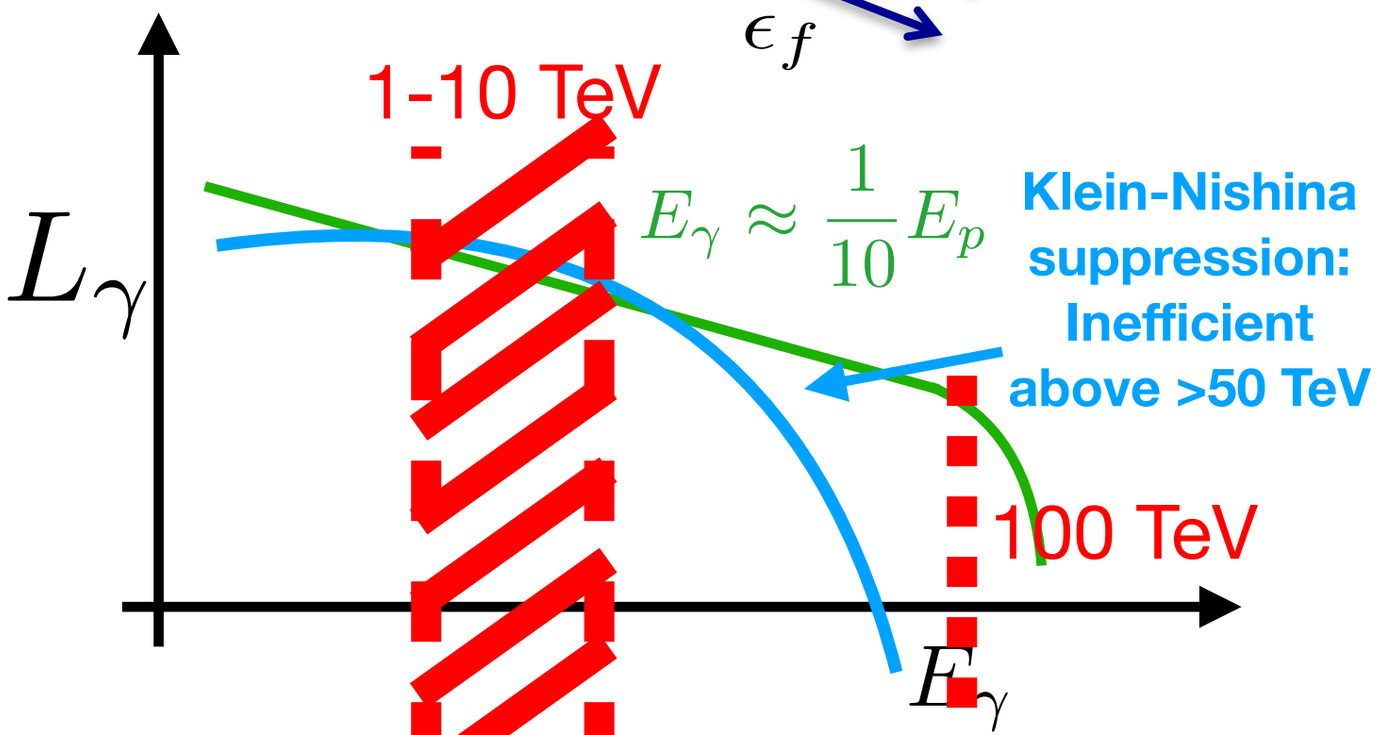

Pevatrons in the last 10 years

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Key Science project: detection of pevatrons

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Supernova remnant RXJ1713

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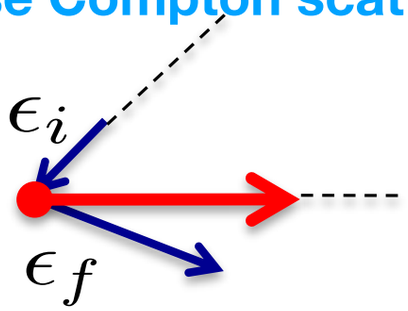

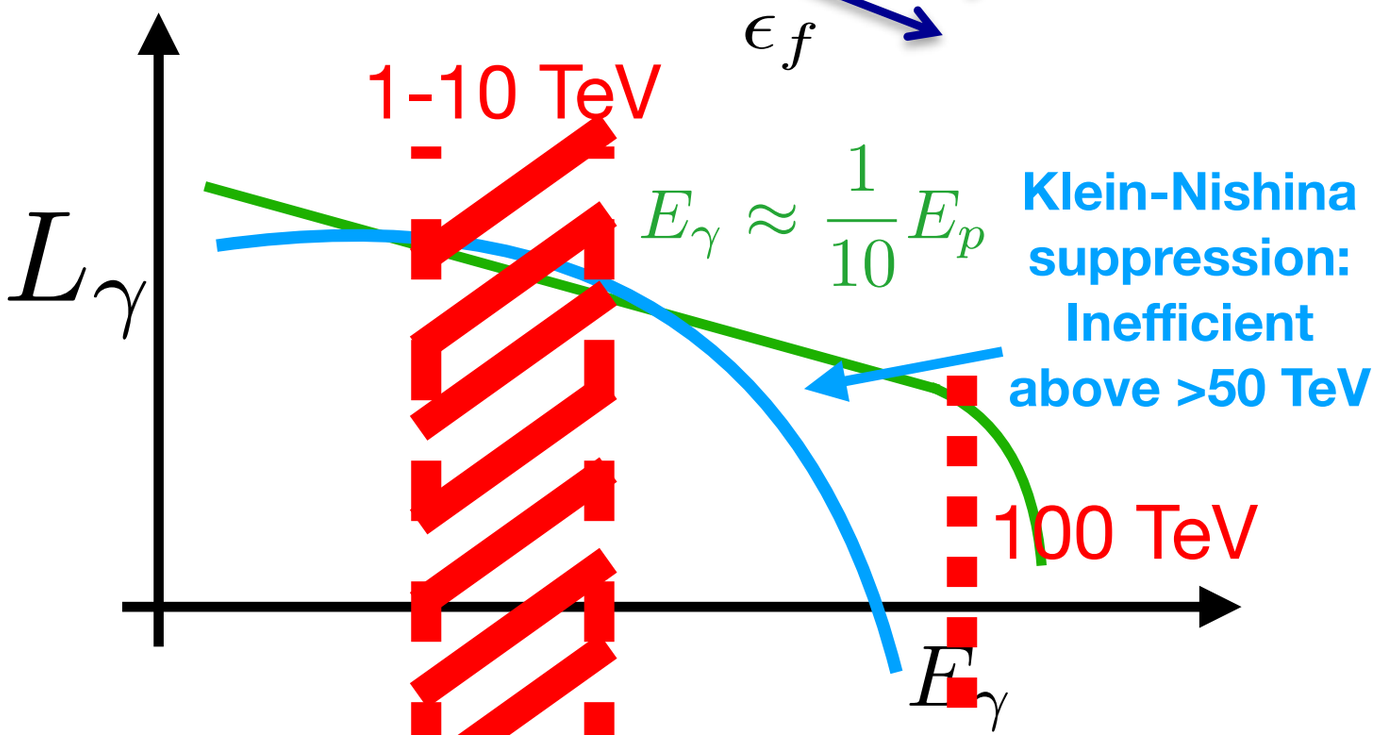

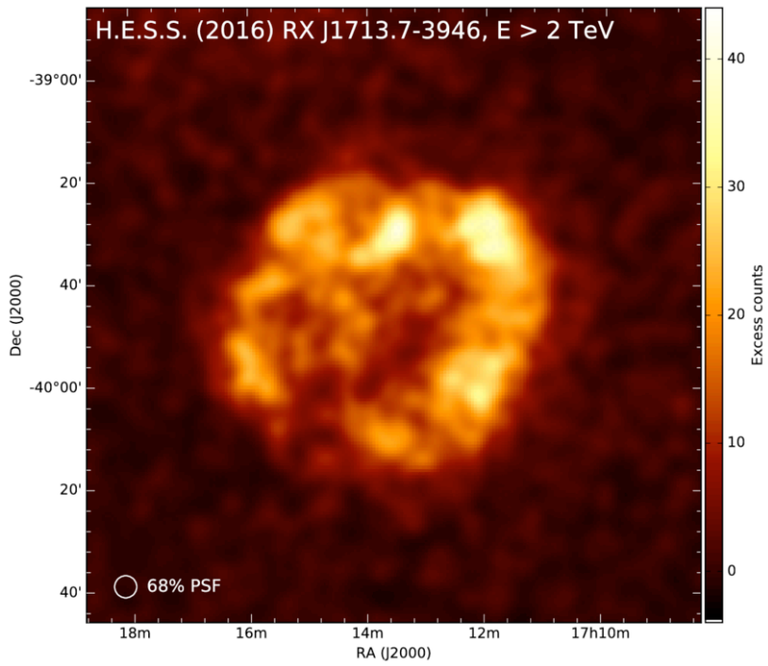

Preferred candidates for bulk of CR protons

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Key Science project: detection of pevatrons

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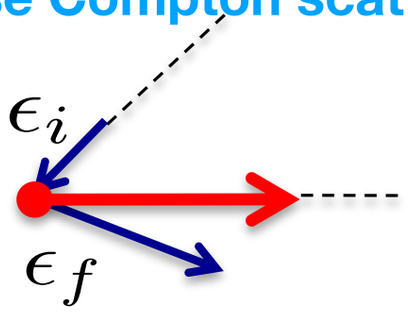

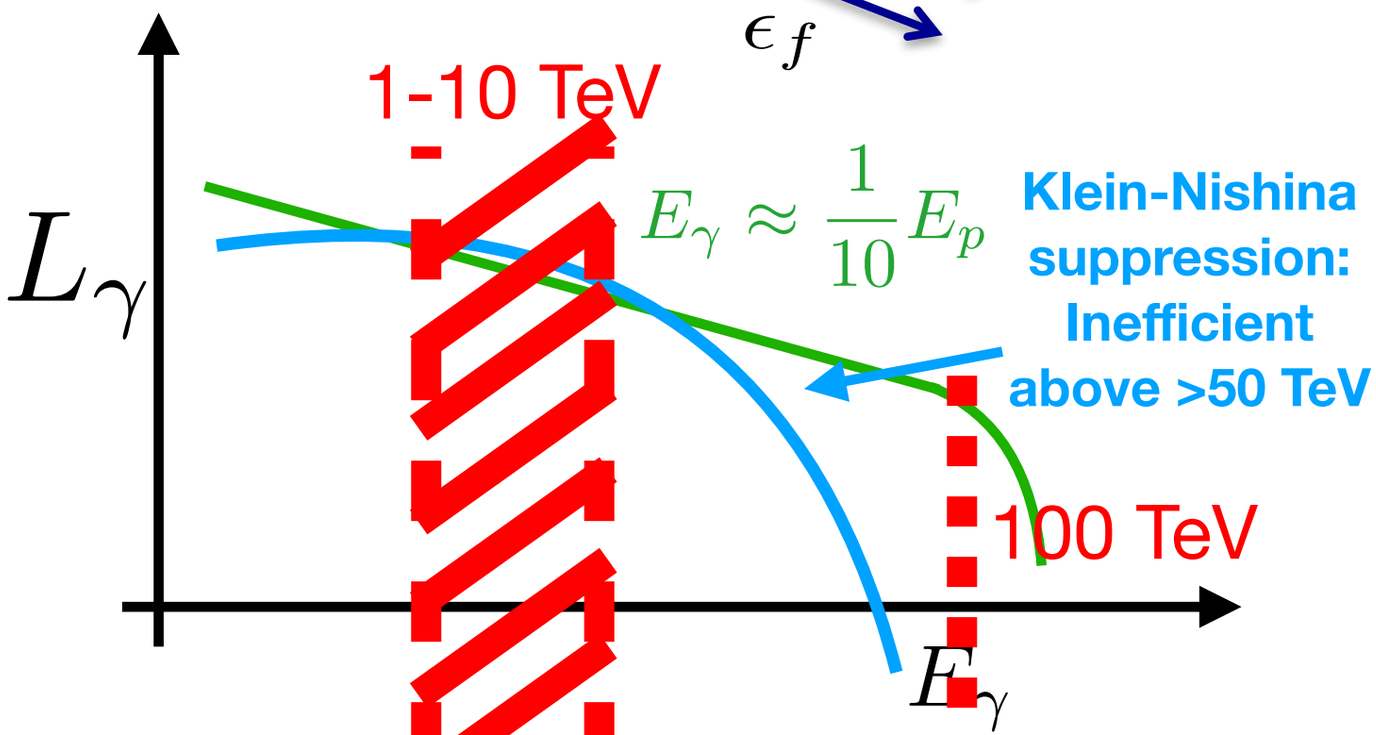

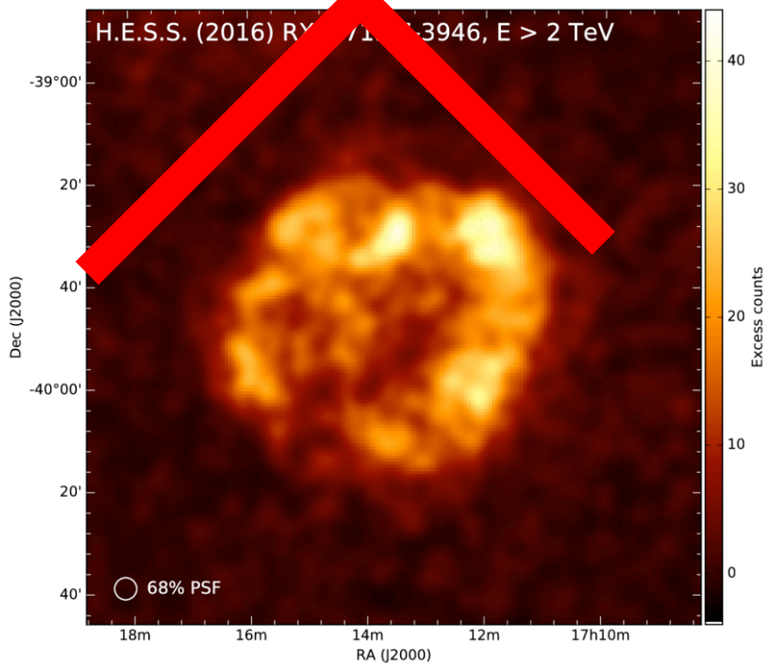

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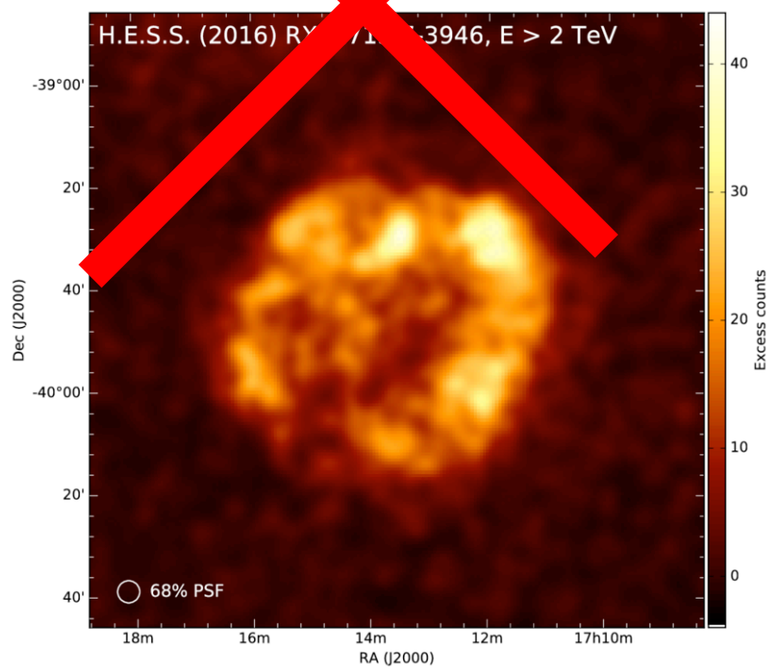
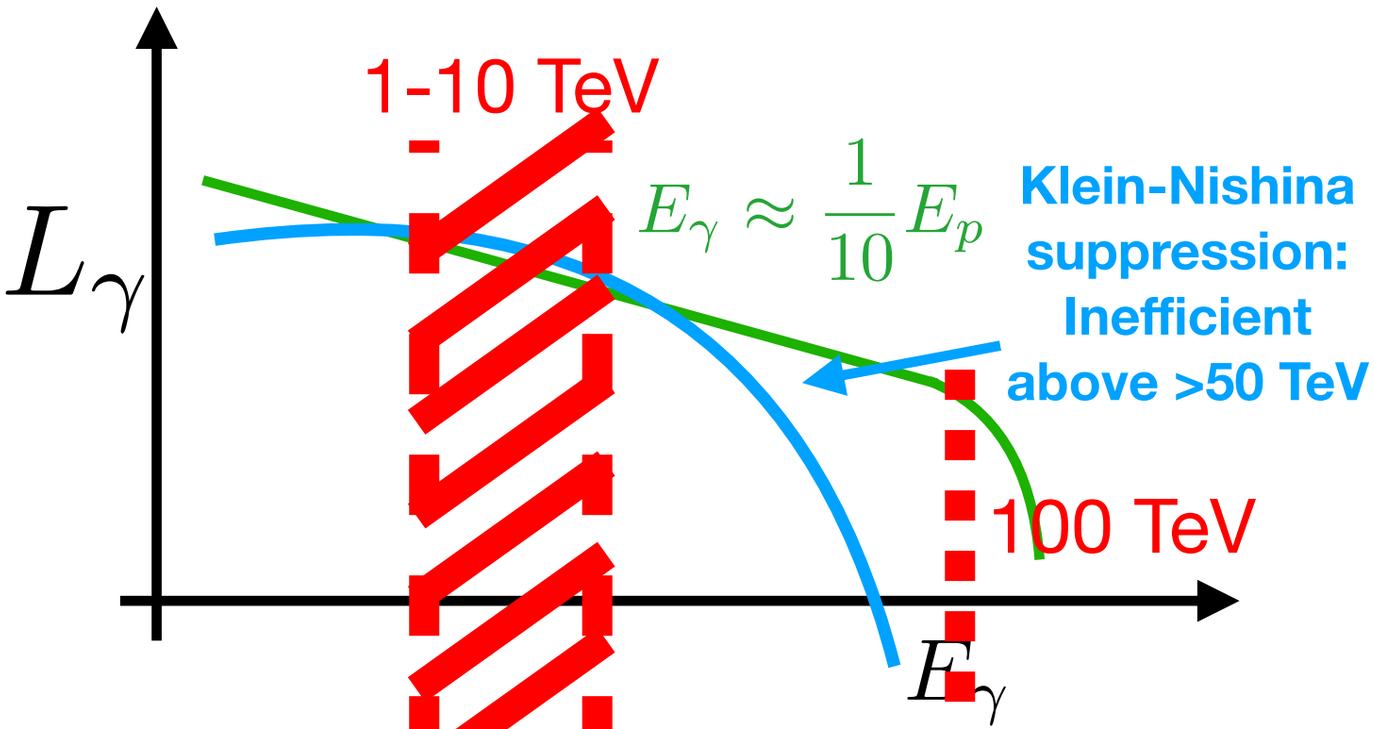
100 TeV gamma rays ⟷ PeV protons

Supernova remnant RXJ1713





Preferred candidates for bulk of CR protons

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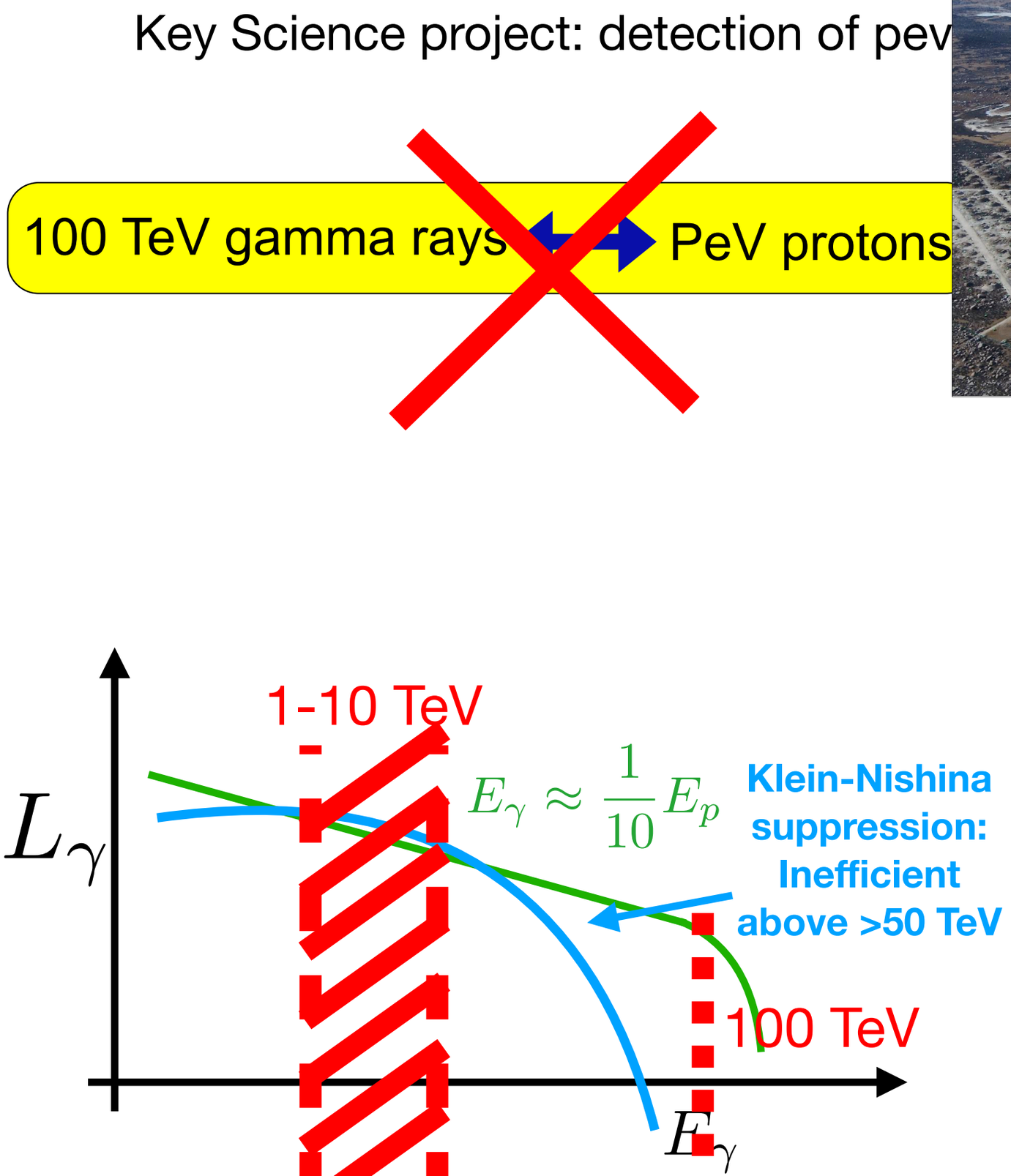
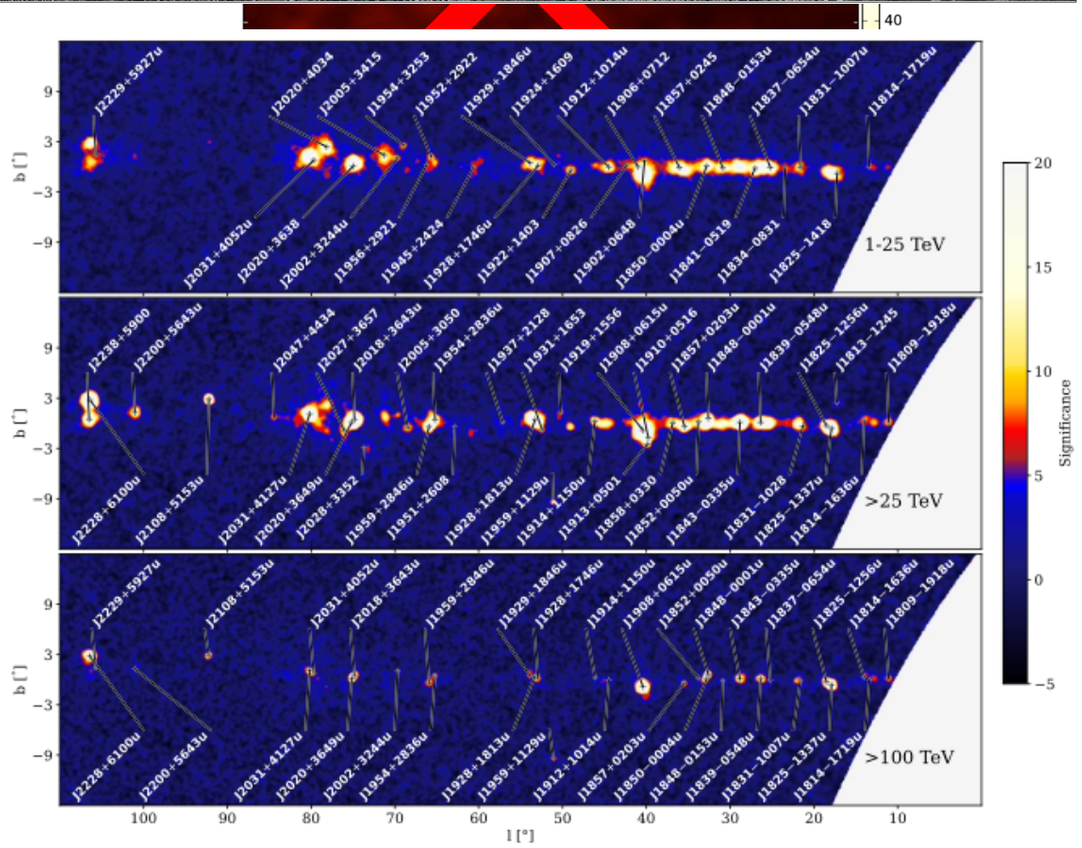
Key Science project: detection of pev

100 TeV gamma rays ⟷ PeV protons





LHAASO catalog Cao et al. 2024
43 sources >100 TeV

Pevatrons in the last 10 years

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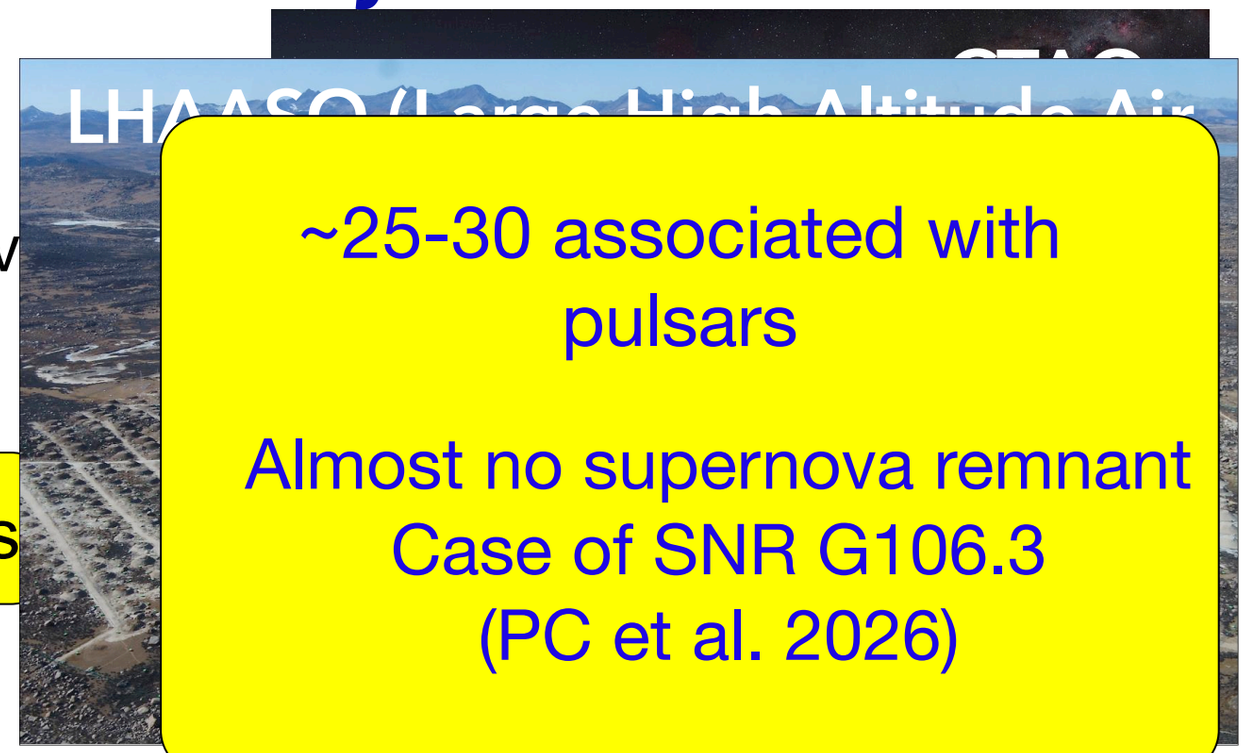
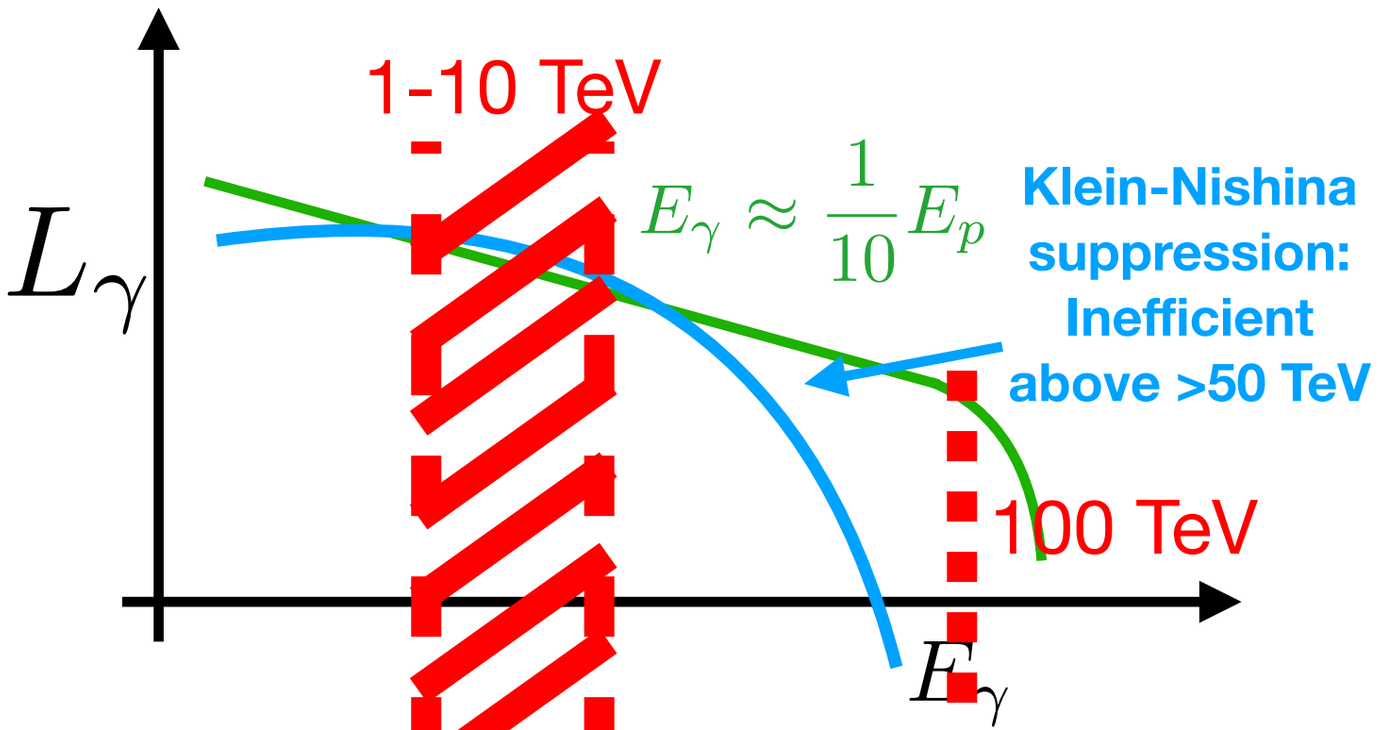
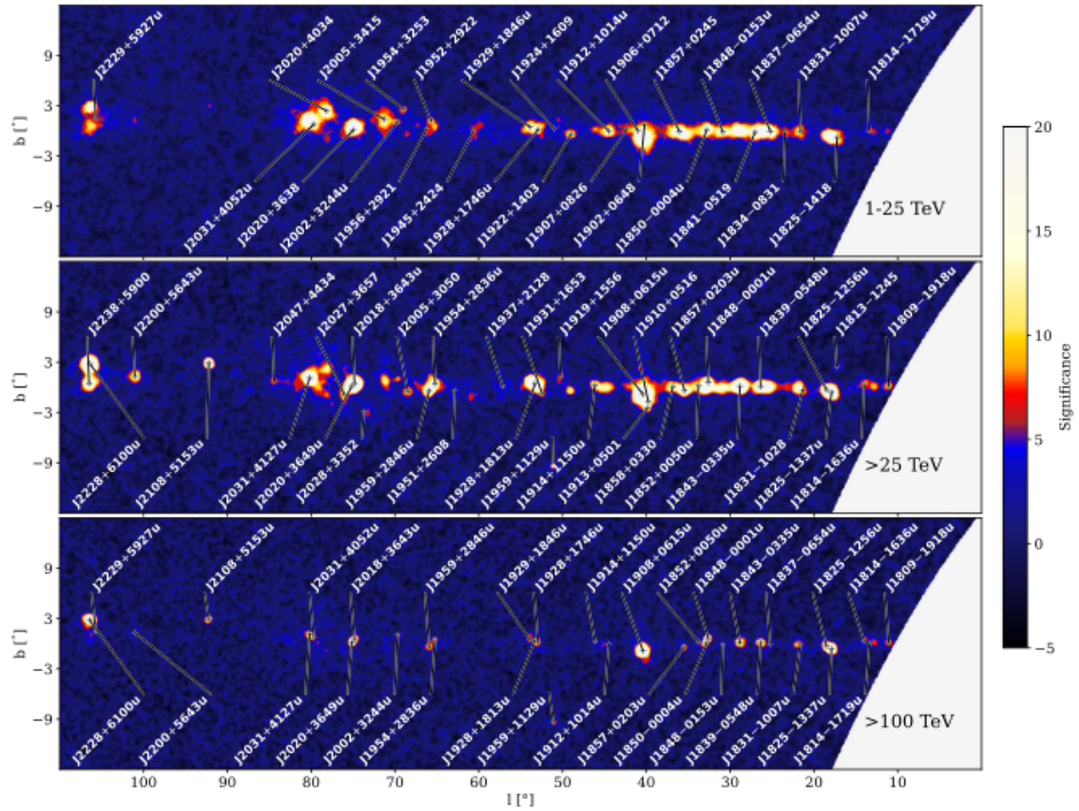
100 TeV gamma rays ⟷ PeV protons



~25-30 associated with pulsars

Almost no supernova remnant
Case of SNR G106.3
(PC et al. 2026)





LHAASO catalog Cao et al. 2024
43 sources >100 TeV

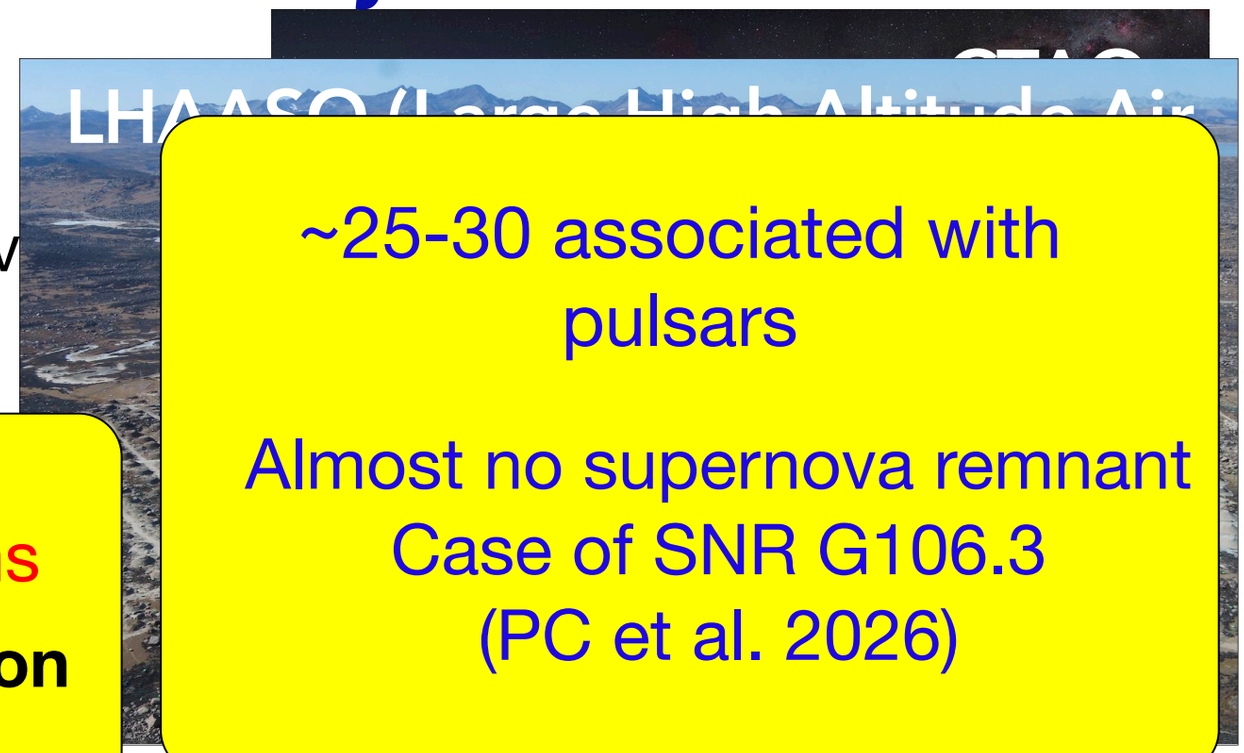
Pevatrons in the last 10 years

« Science with CTA 2017 »

Key Science project: detection of pev

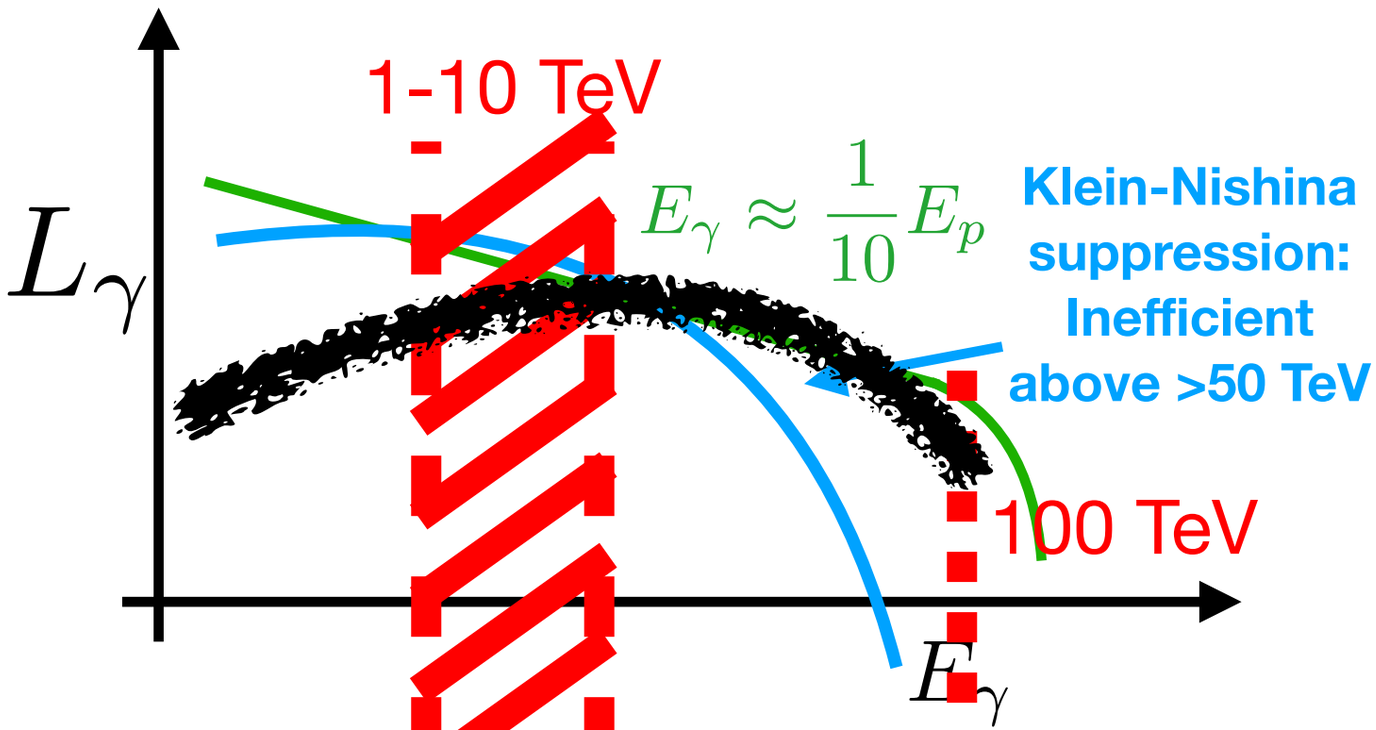
100 TeV gamma rays ⟷ Electrons

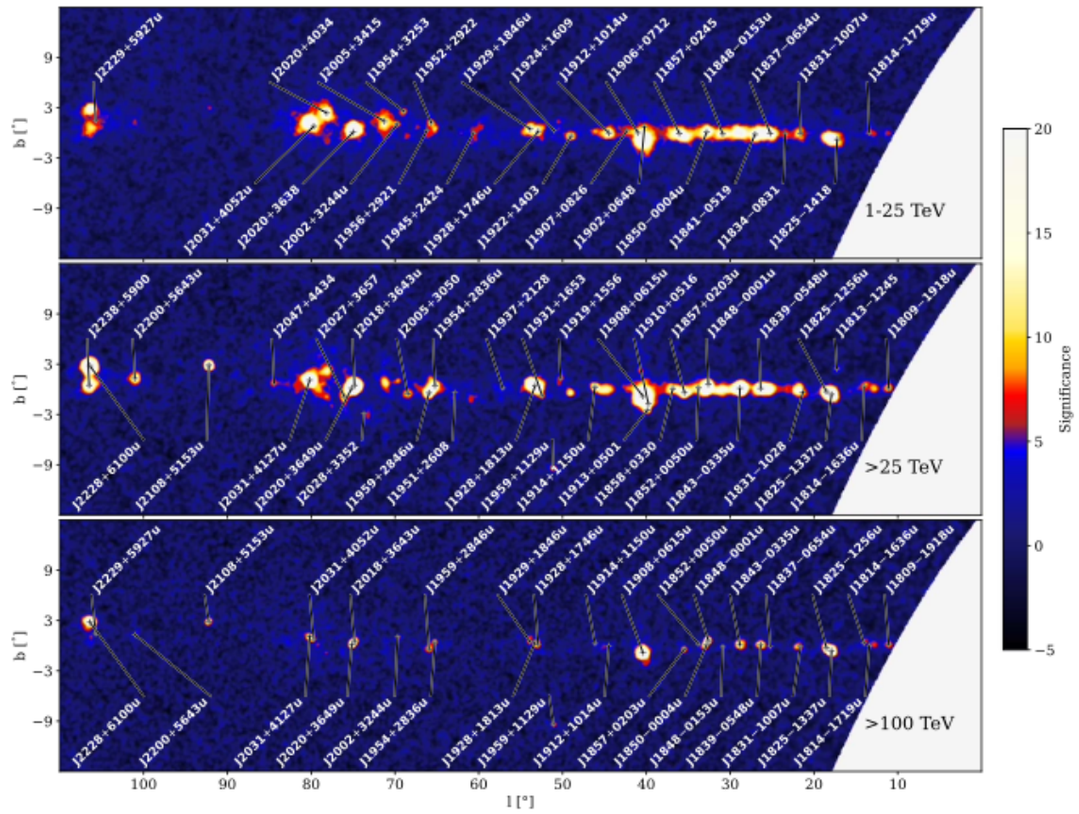
Hard spectra for electron with radiation dominated environment



~25-30 associated with pulsars

Almost no supernova remnant
Case of SNR G106.3
(PC et al. 2026)





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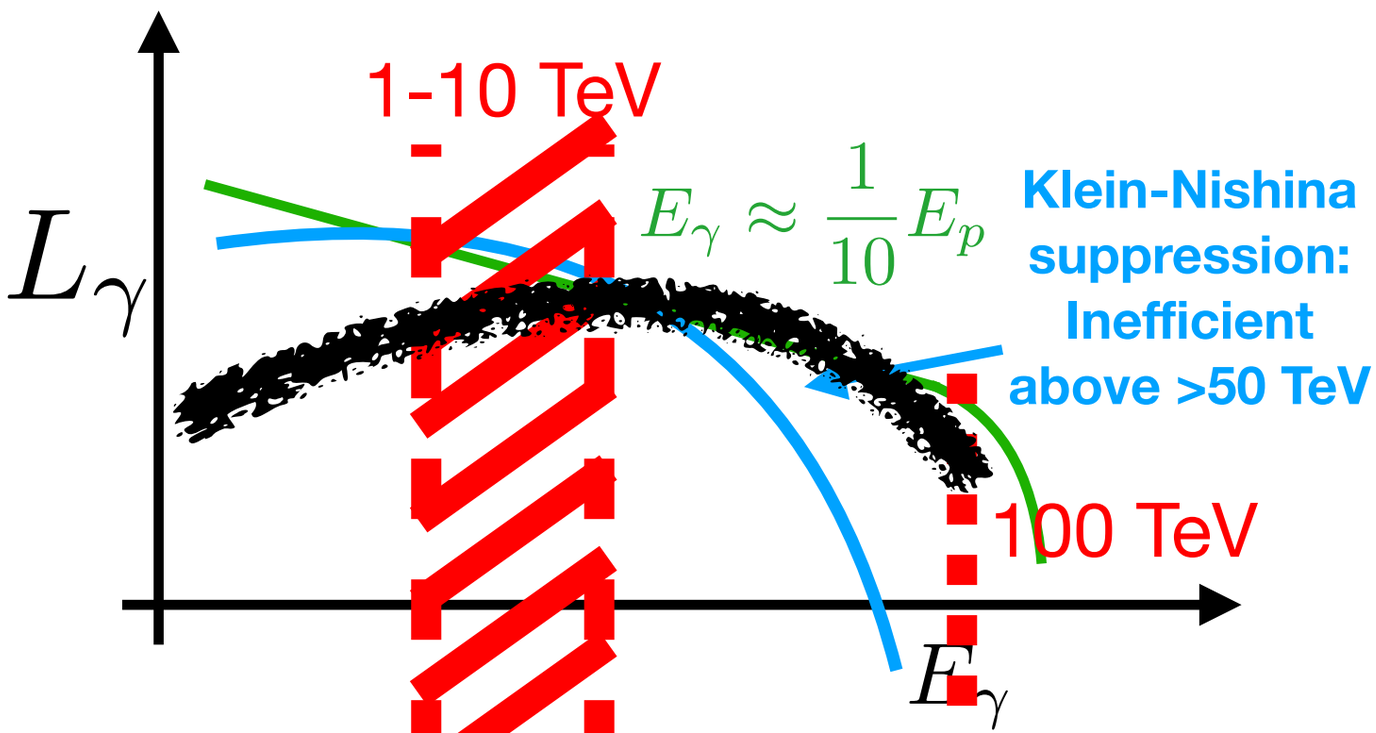
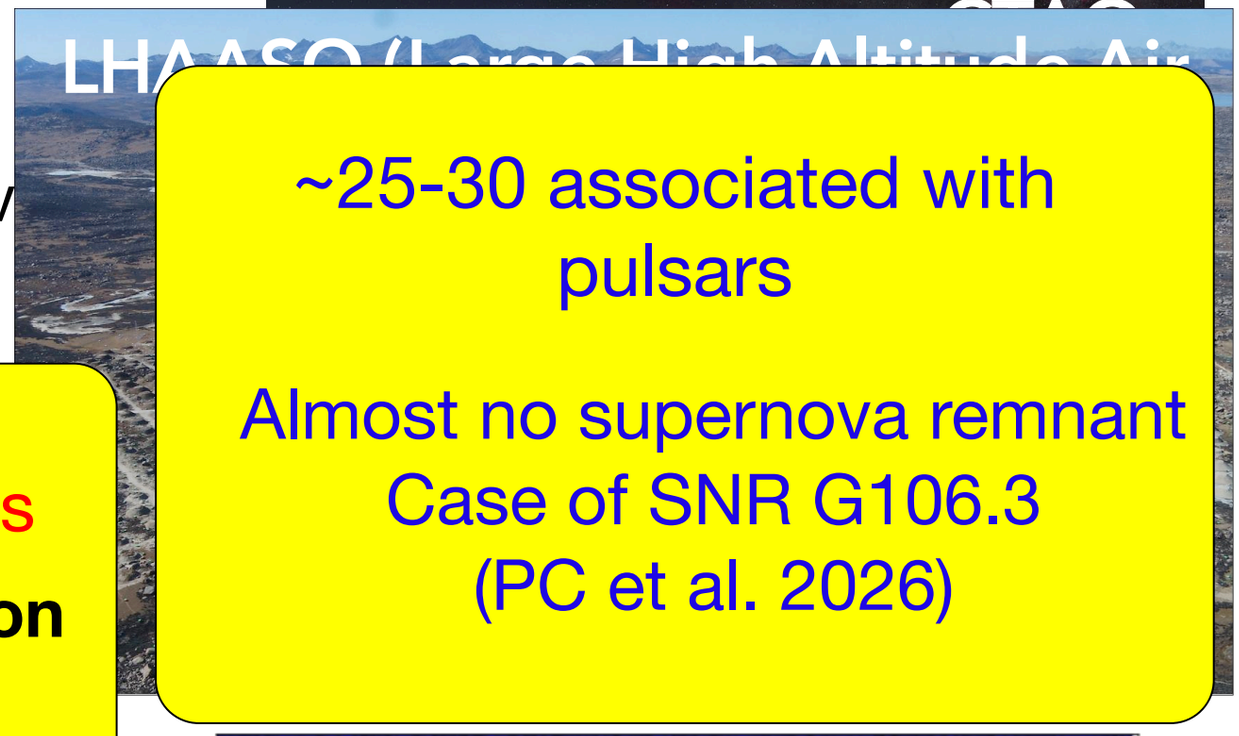
Vannoni et al. (2007), Brehaus et al. (2021)++





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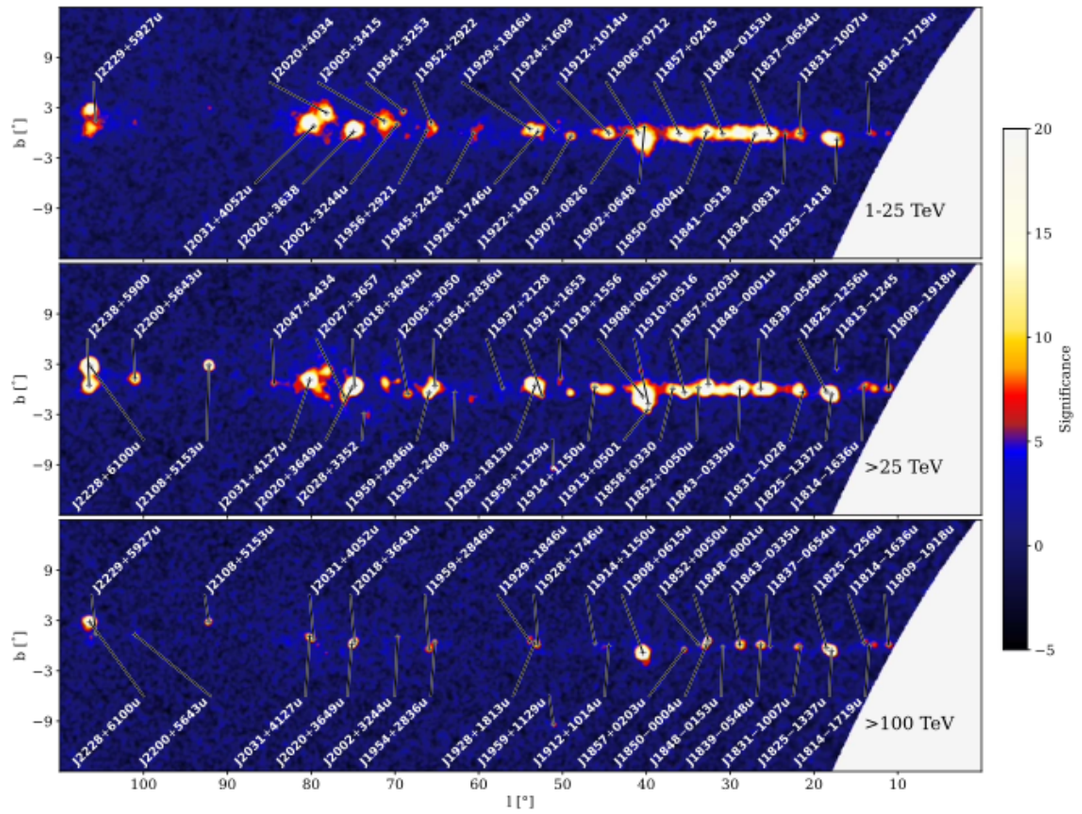

LHAASO catalog Cao et al. 2024
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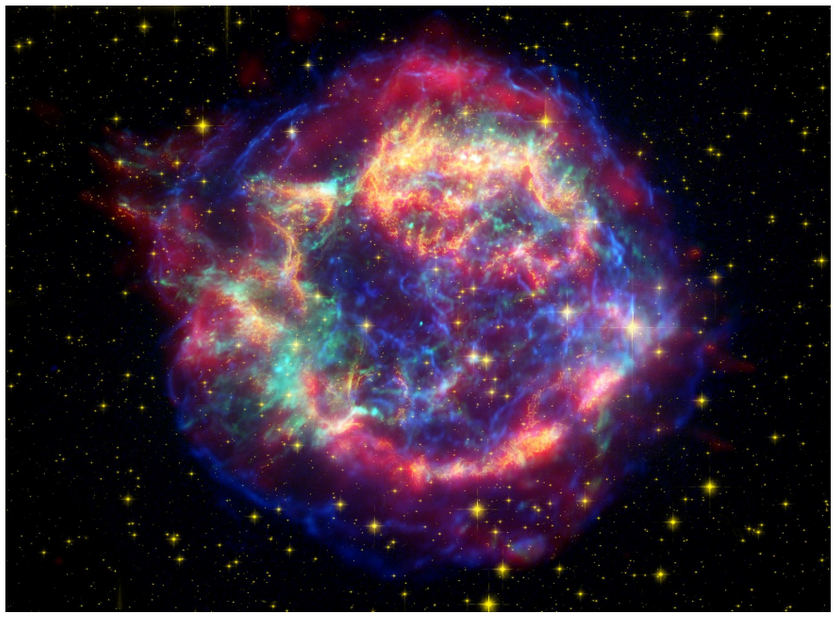
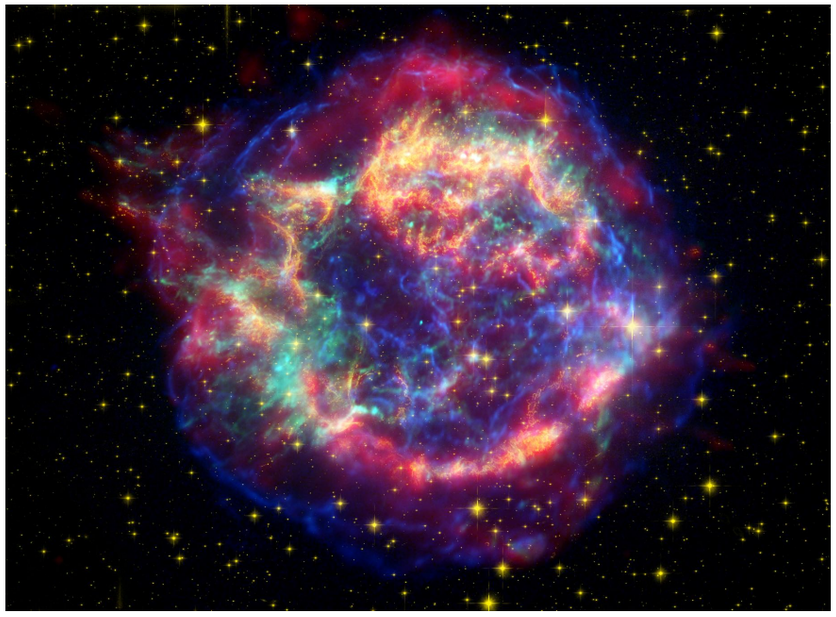
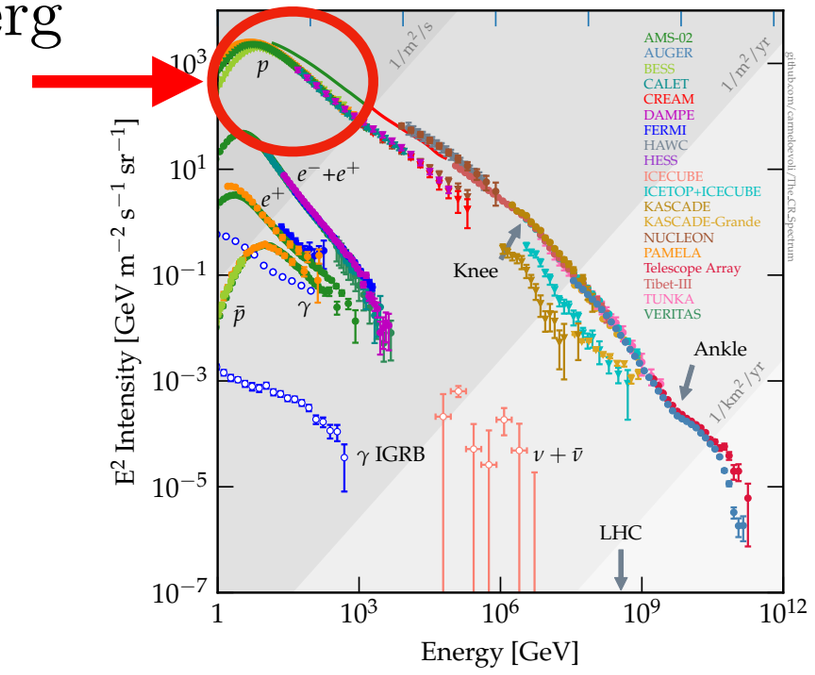
Supernova remnant pevatrons



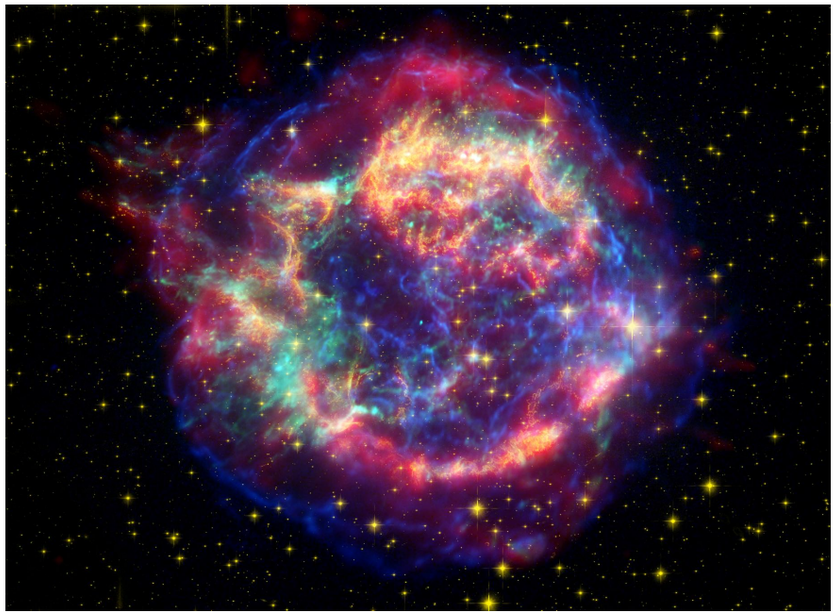
Supernova remnant pevatrons

$$10\% \times 3/\text{century} \times 10^{51}\text{erg}$$
$$w_{\text{CR}} \sim 1\text{eV.cm}^{-3}$$





Supernova remnant pevatrons



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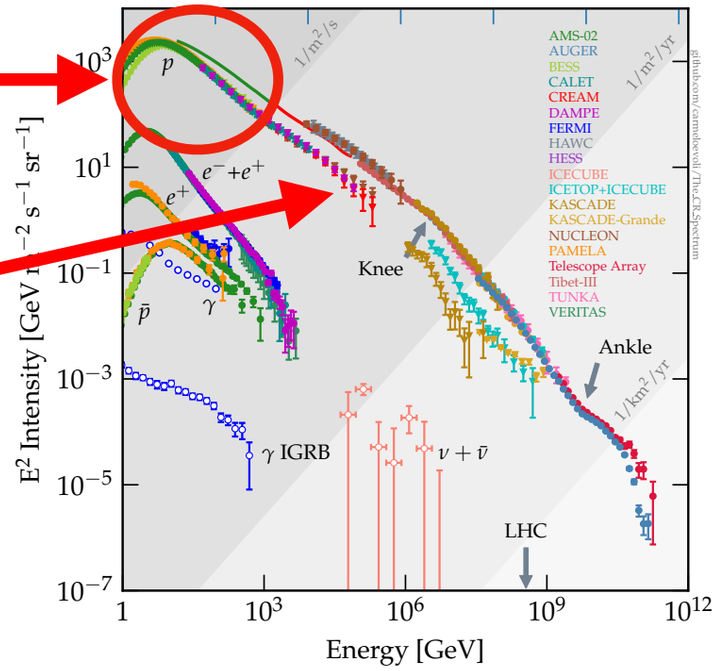
Slope (DSA)
$$\propto E^{-2.7}$$



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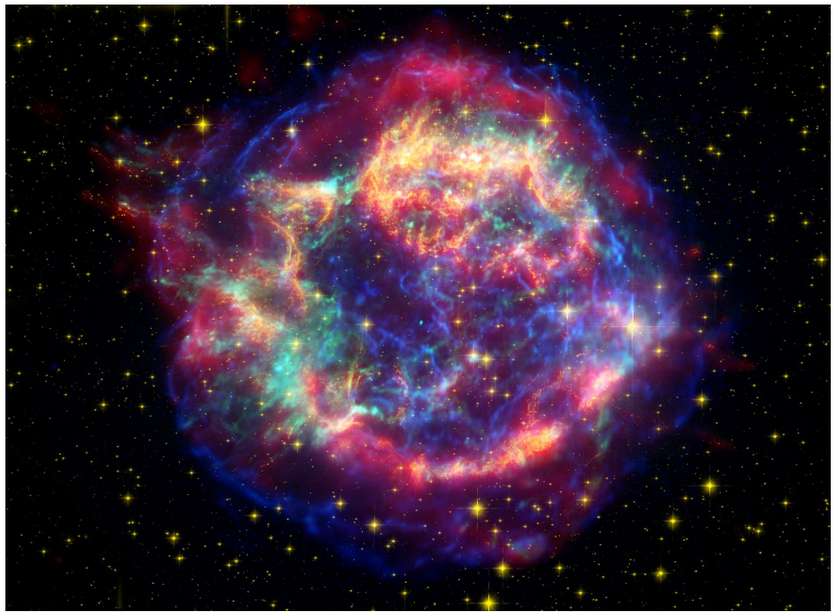

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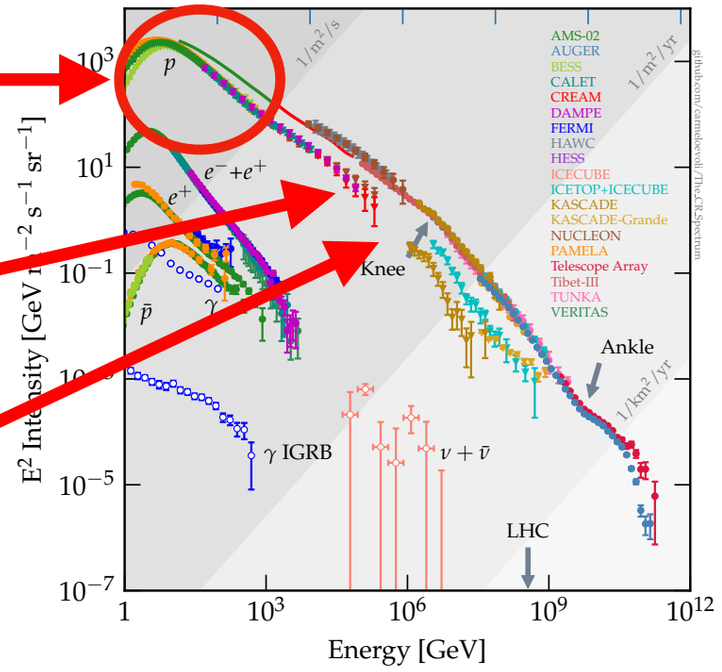
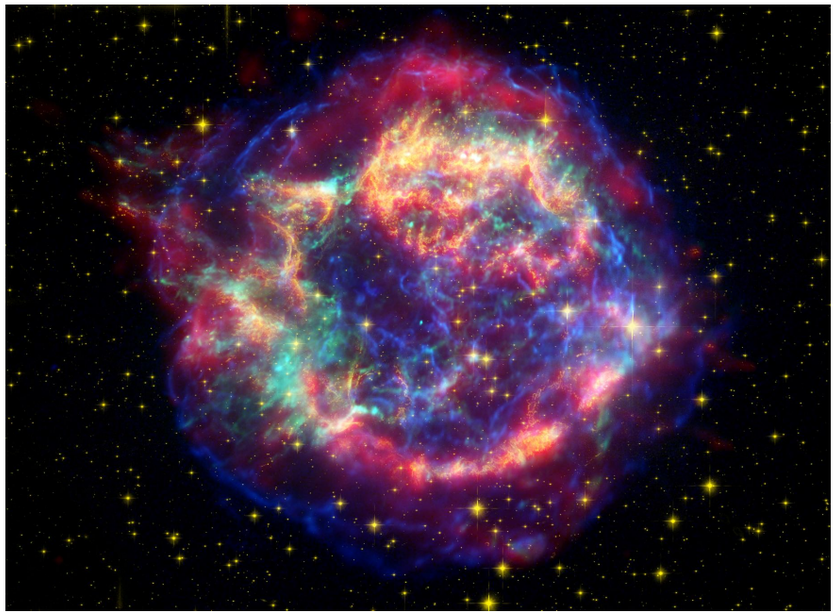
Knee?



Supernova remnant pevatrons



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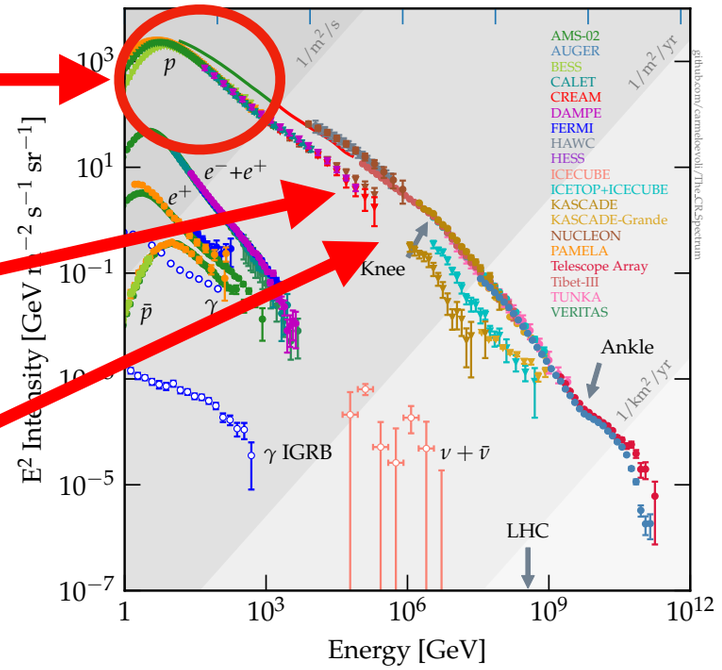
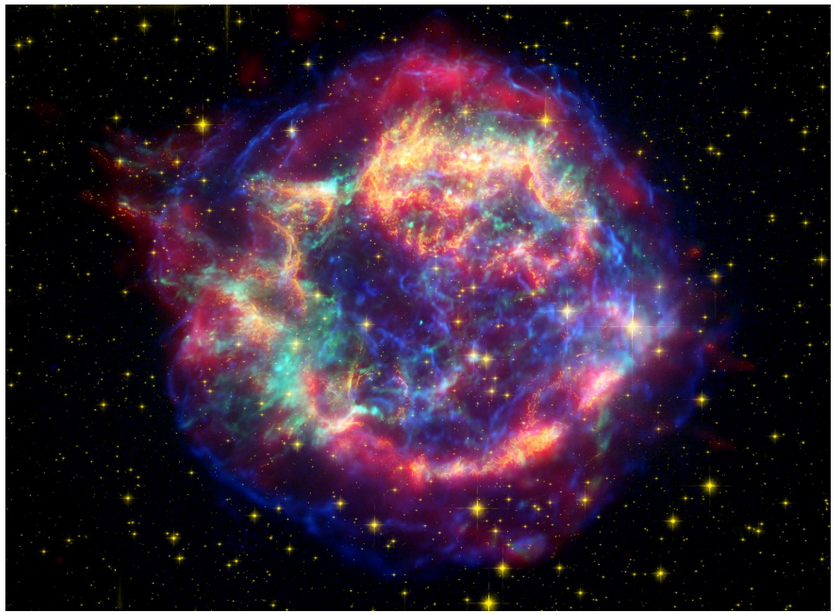


Hillas criterion

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

Supernova remnant pevatrons



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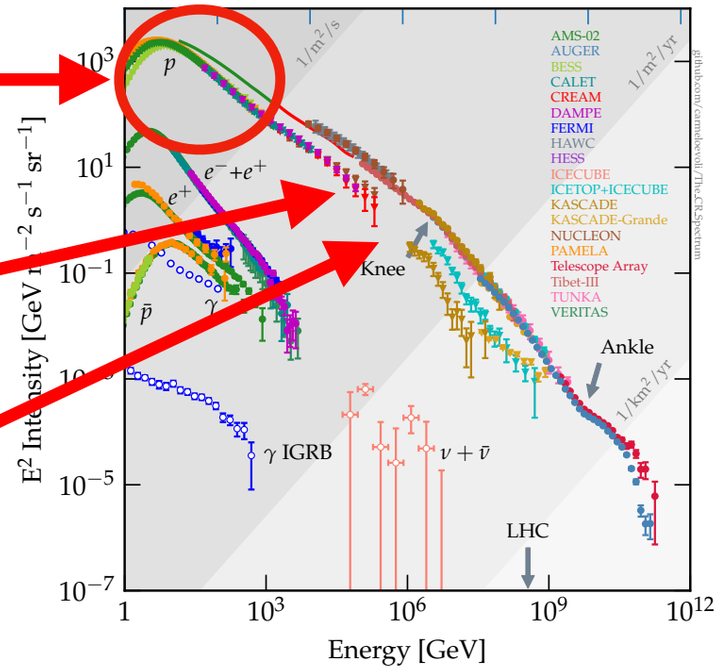

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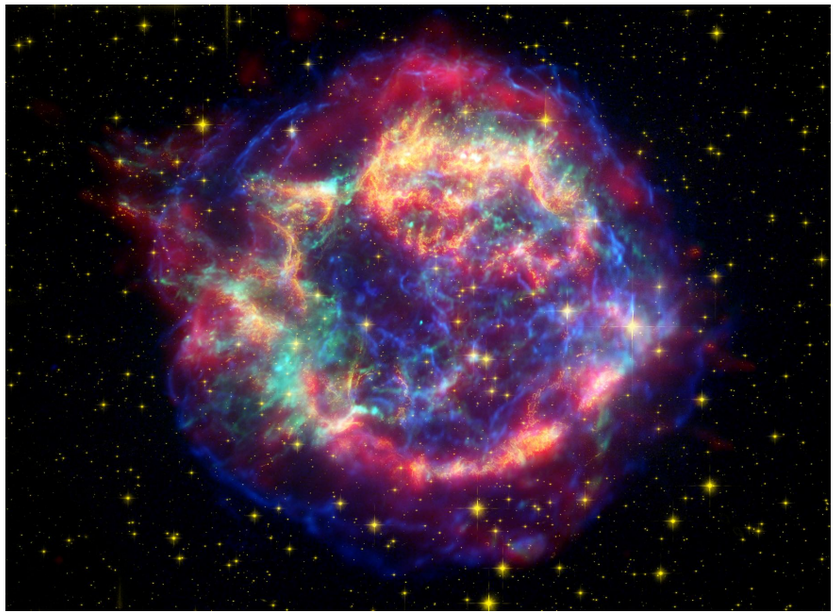

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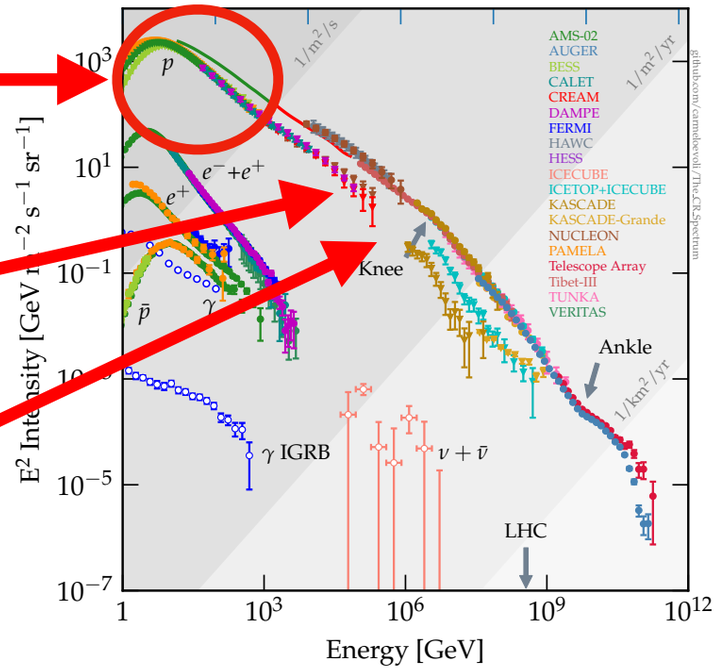

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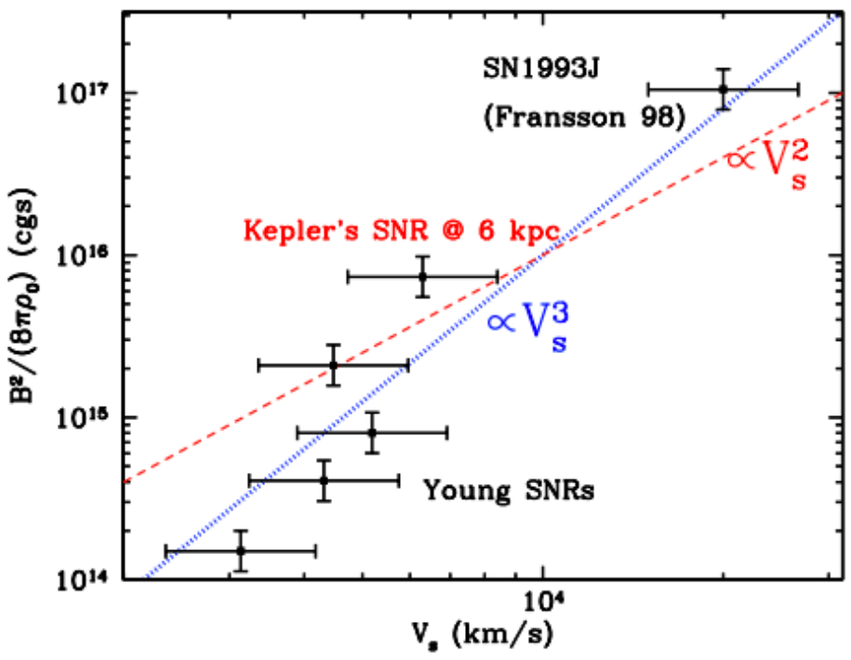
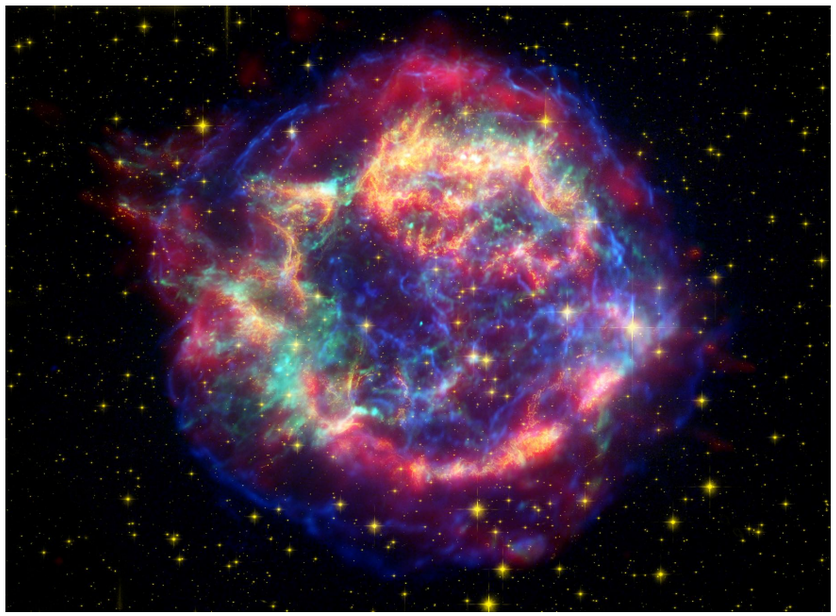


Supernova remnant pevatrons



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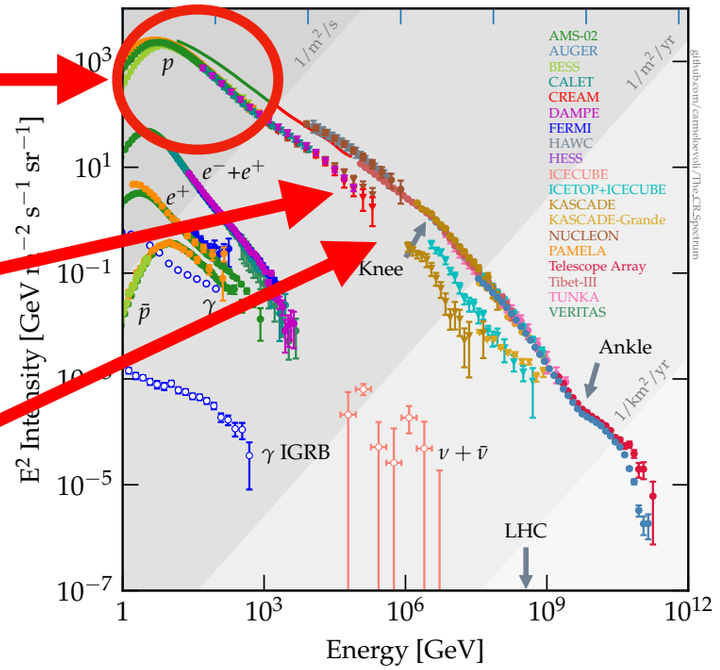

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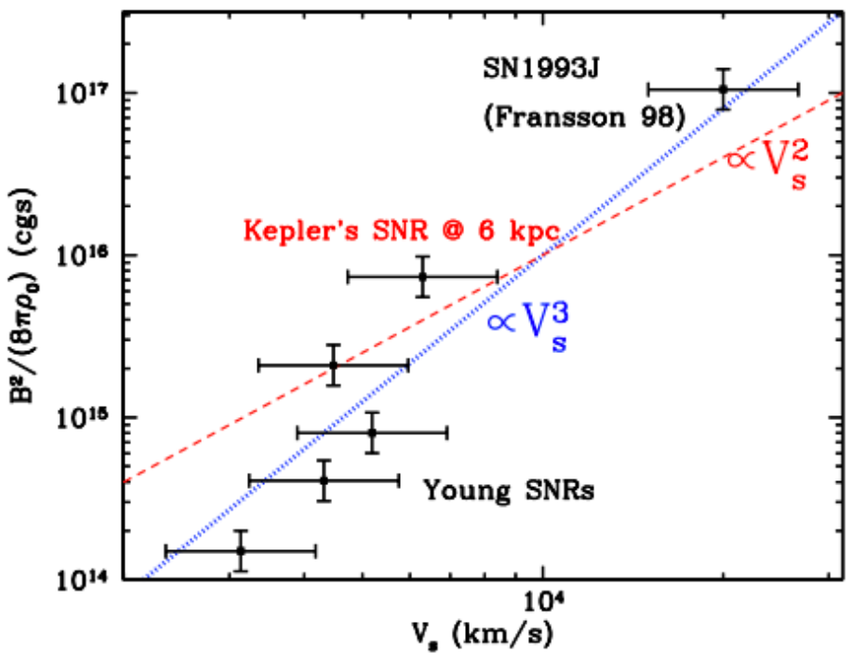

Growth of the non-resonant streaming instability

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

Different for different SNRs/SNe

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

Supernova remnant pevatrons

non-resonant streaming instability

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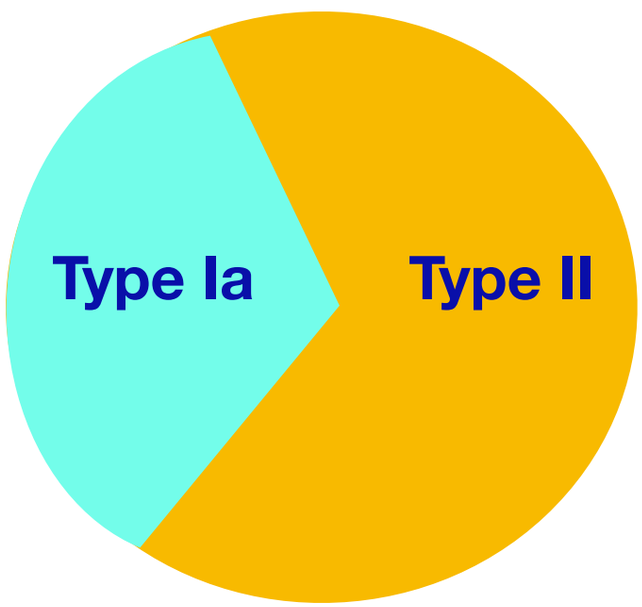

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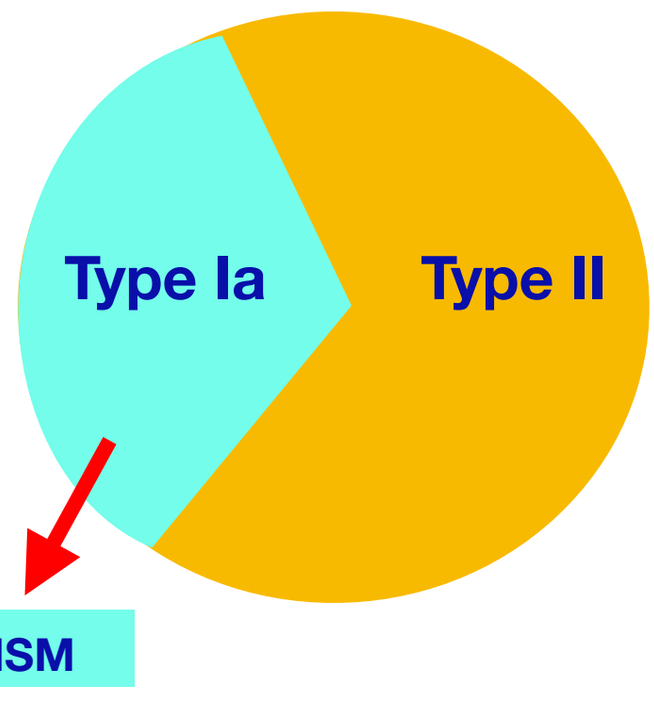

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Supernova remnant pevatrons

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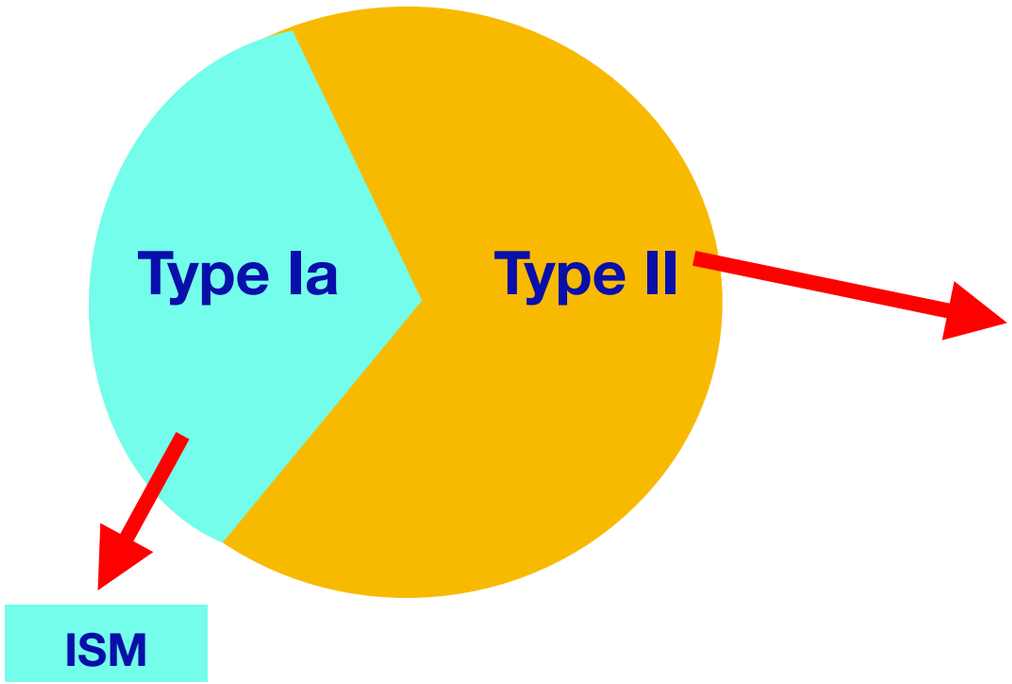

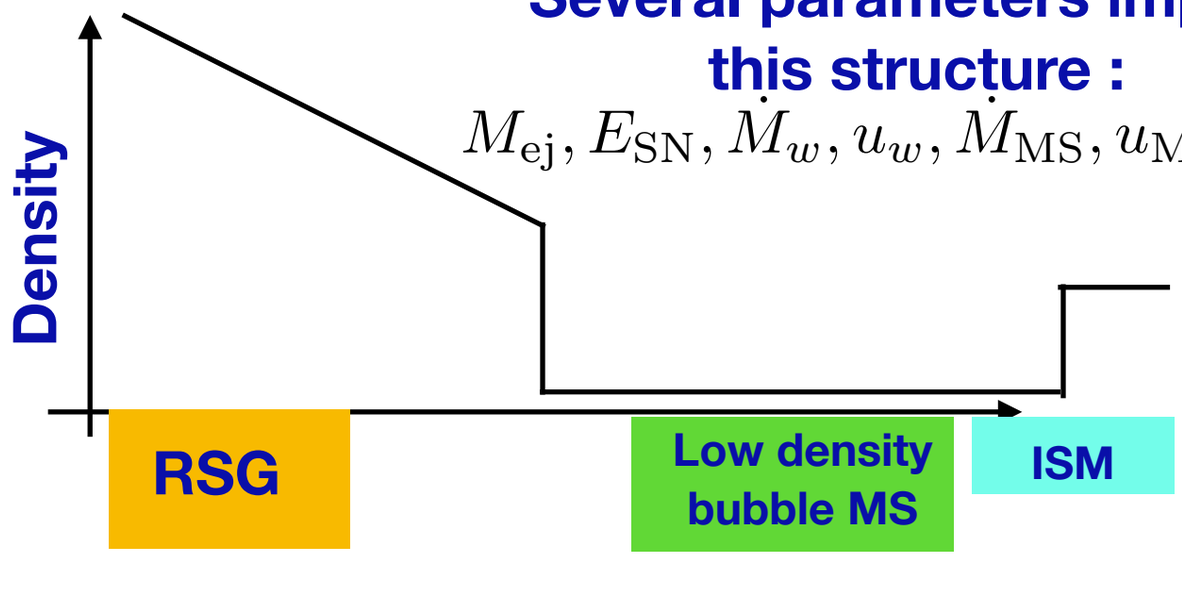

Several parameters impact this structure :

$M_{\rm ej}, E_{\rm SN}, \dot{M}_w, u_w, \dot{M}_{\rm MS}, u_{\rm MS}, t_{\rm RSG}$

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

Supernova remnant pevatrons

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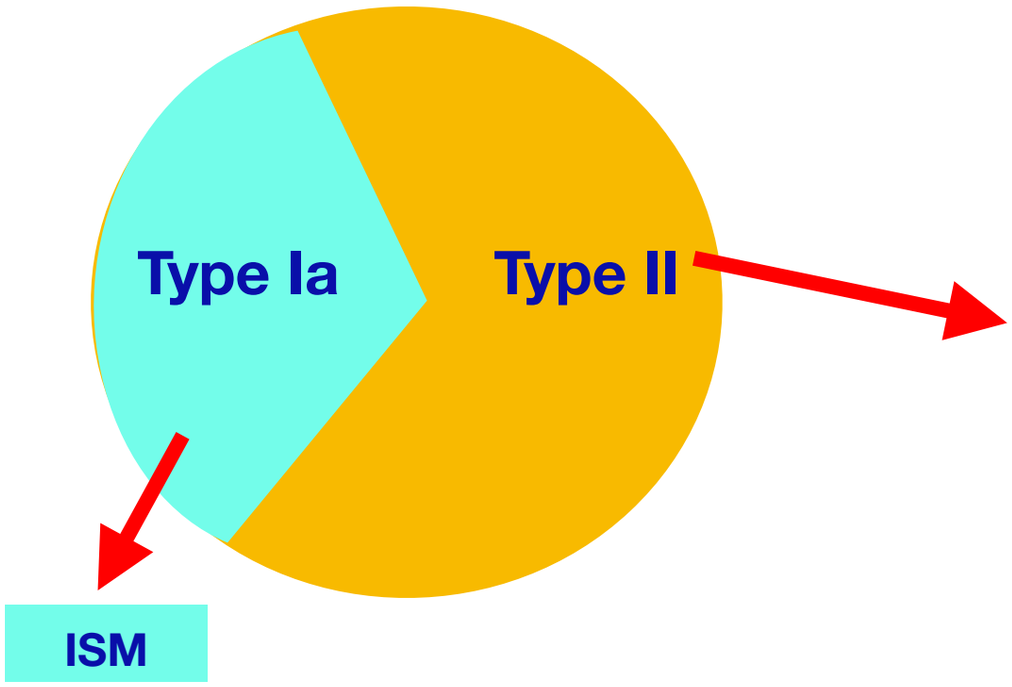

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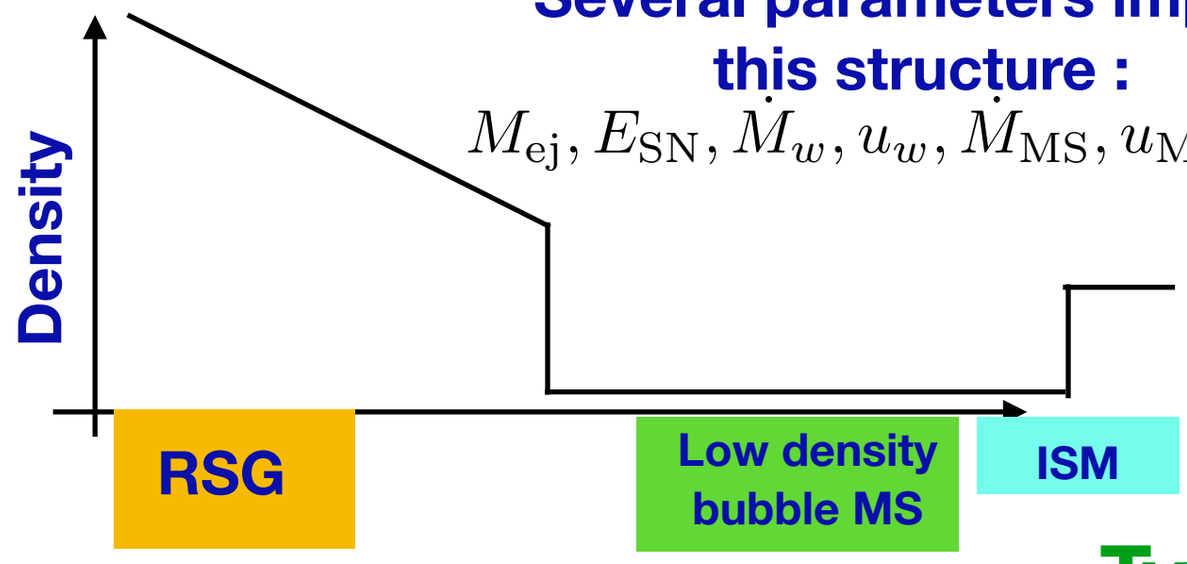
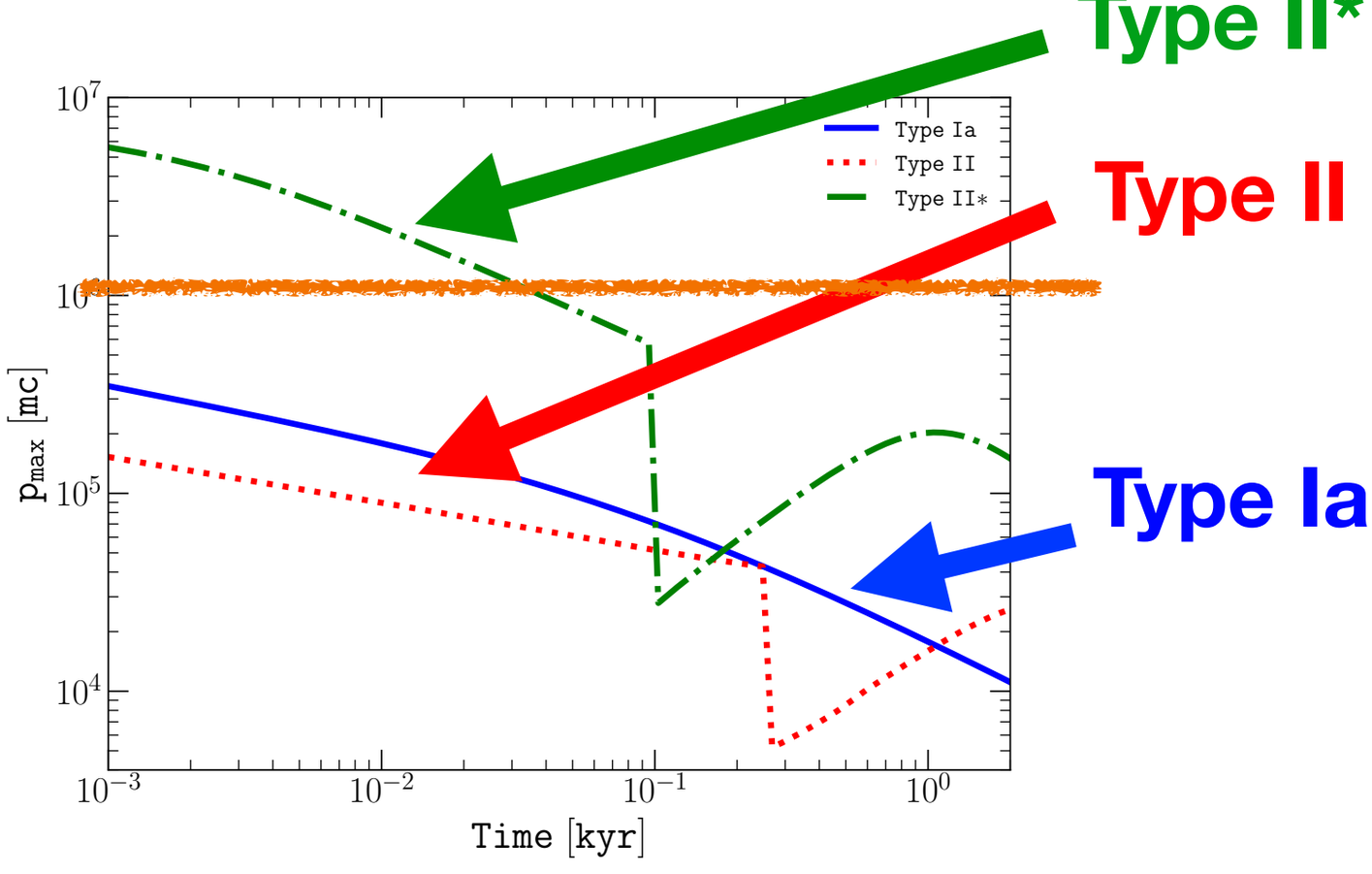


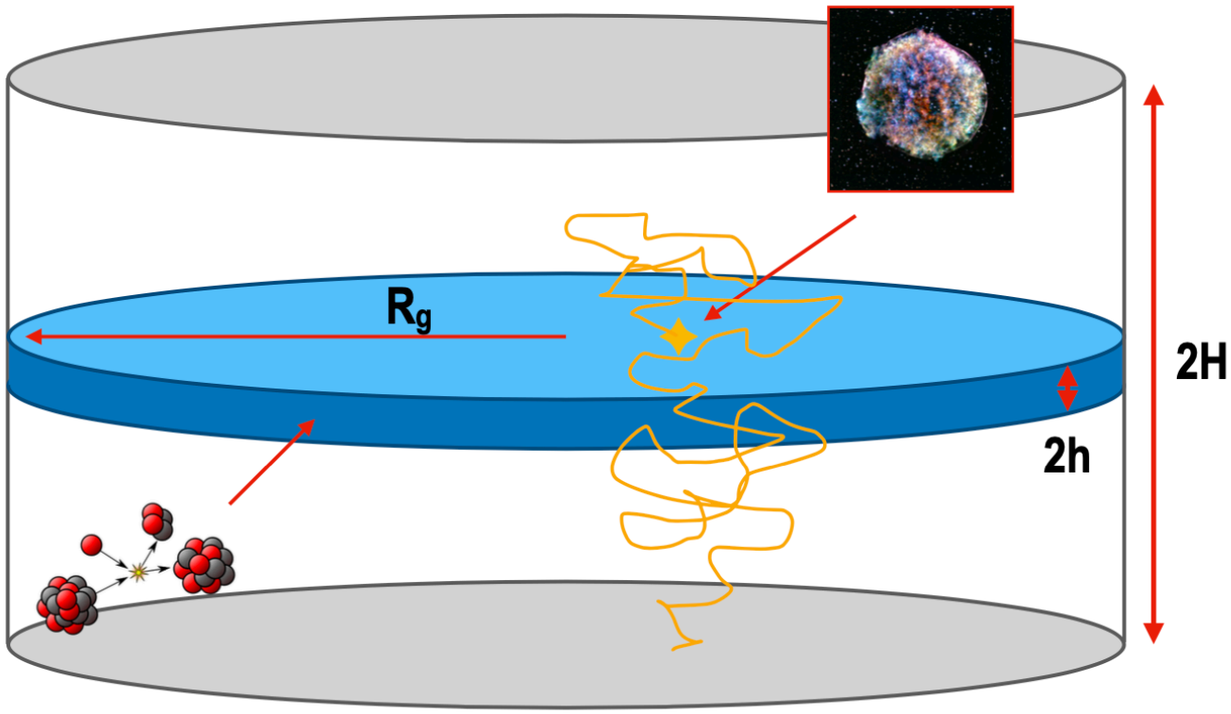
Typical SNRs : not pevatrons
Young and peculiar SNRs: pevatrons

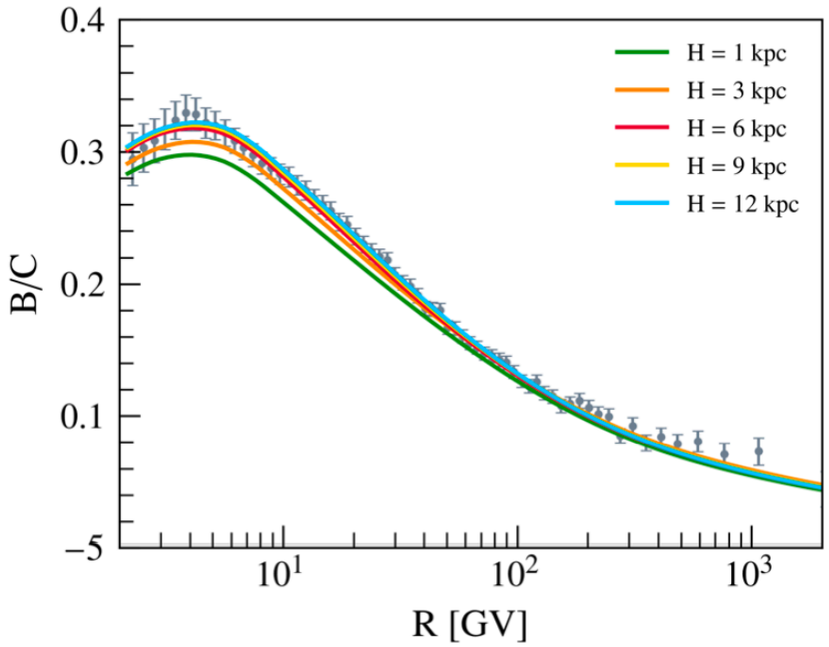


Bell (2004), Bell et al. (2013), Schure et al. (2014)

The case of supernova remnants

Consensus: Protons are injected in the disk and diffusively propagate in a magnetized halo





Secondary-to-primary ratio: properties of transport

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

Injection **Propagation**

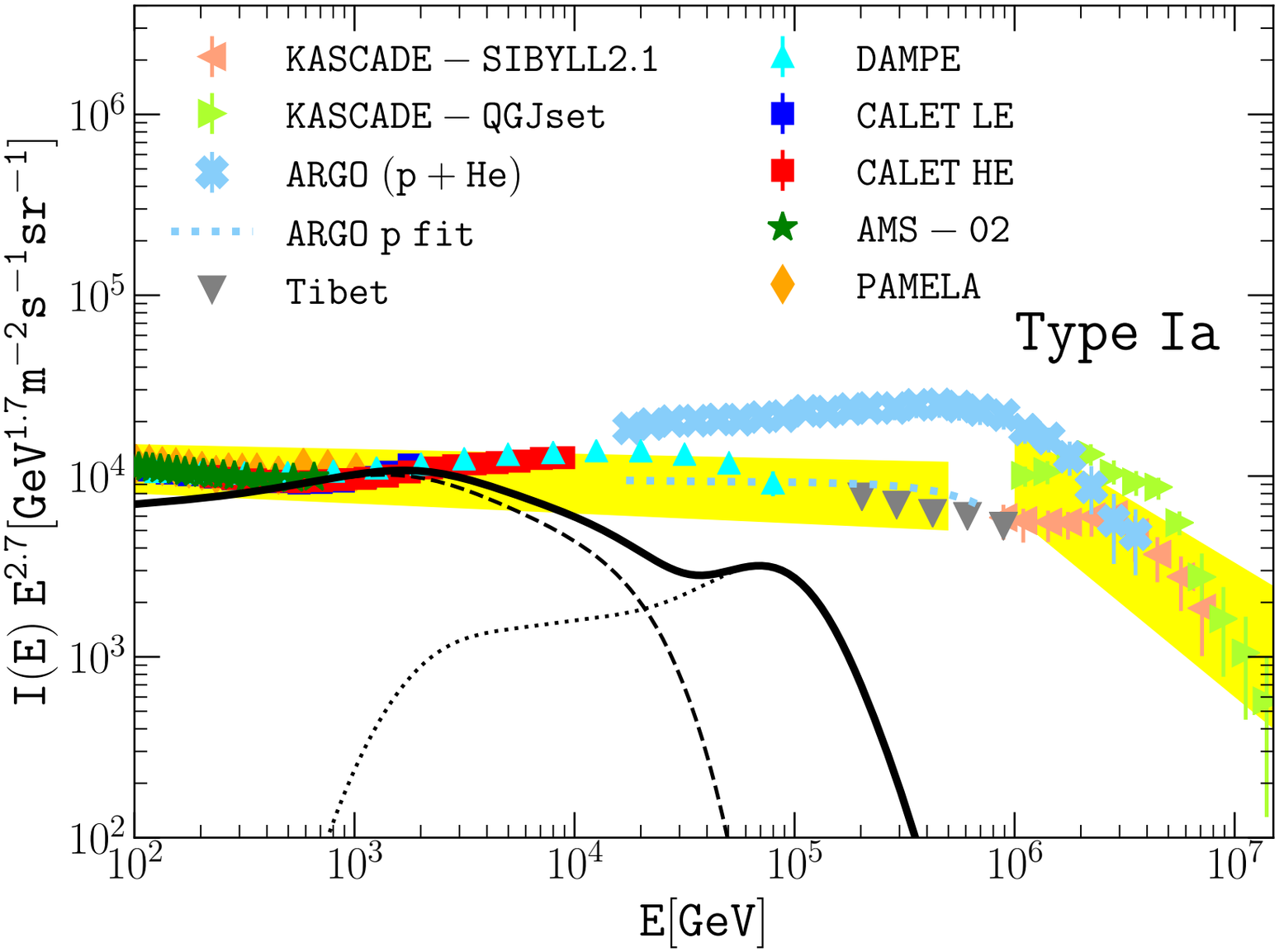
$$-\frac{\partial}{\partial z}\left[D(p)\frac{\partial f}{\partial z}\right] + u\frac{\partial f}{\partial z} - \frac{du}{dz}\frac{p}{3}\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\rm ion} f\right] = q(p,z)$$

Diffusion **Advection** **Ionisation losses** **Injection from SNRs**

Morrison, Olbert & Rossi 1954, Ginzburg & Syrovatskii 1964, Evoli et al. 2018, 2019

The case of supernova remnants

Protons after propagation:



PC, Blasi& Amato (2020)

The case of supernova remnants

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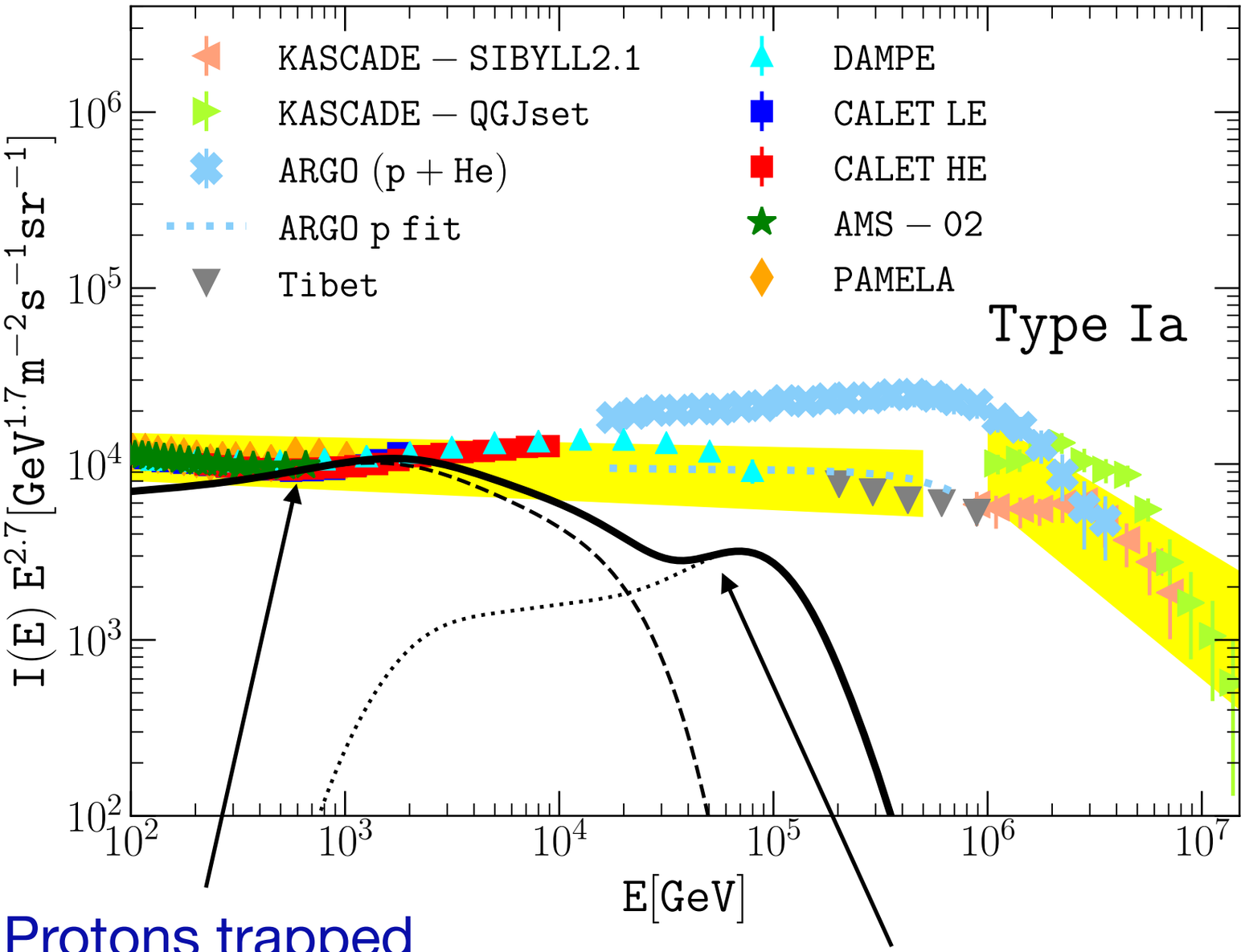

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

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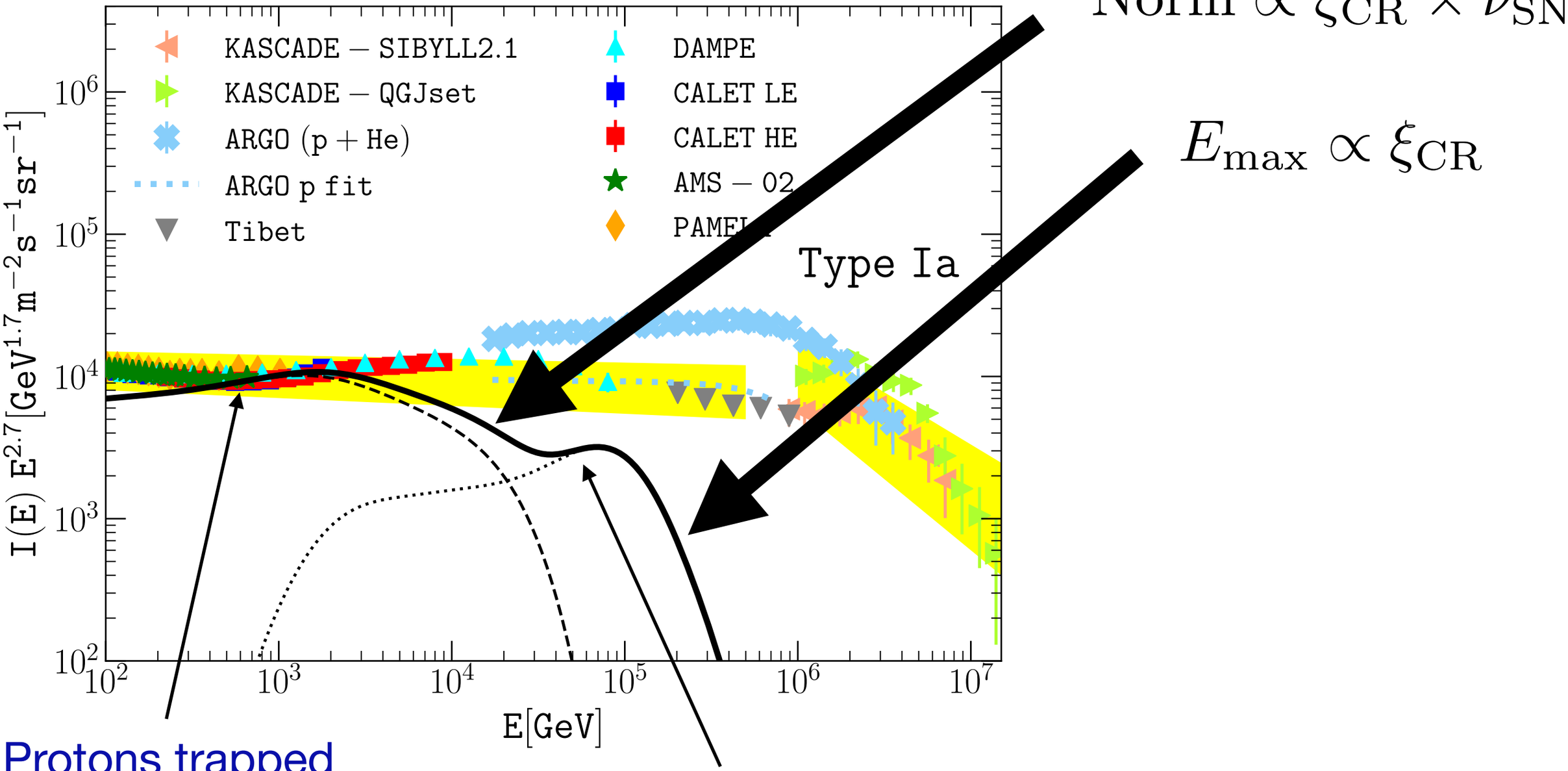

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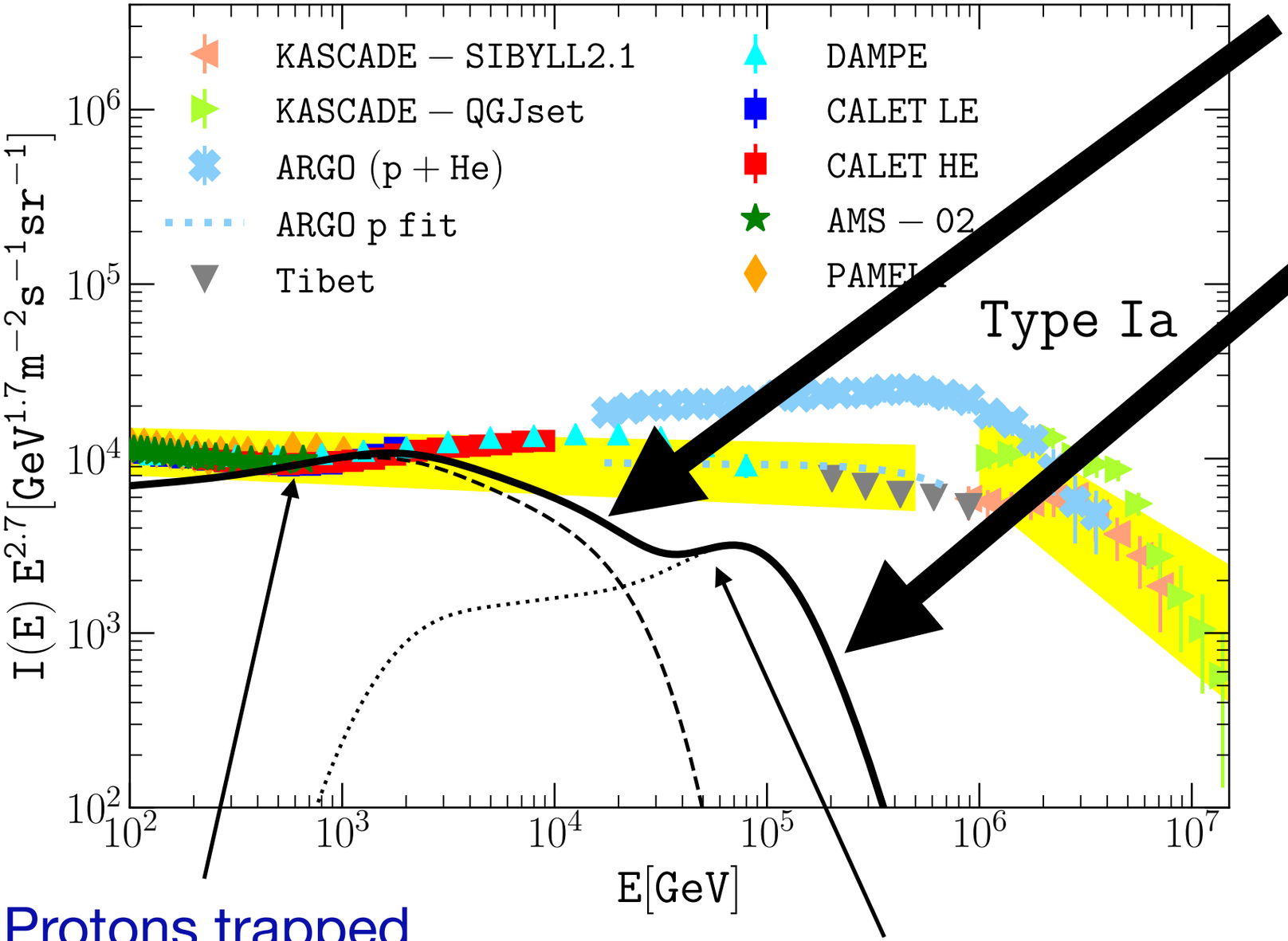

$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

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

$$\nu_{\mathrm{Ia}} = 1/\mathrm{century}$$

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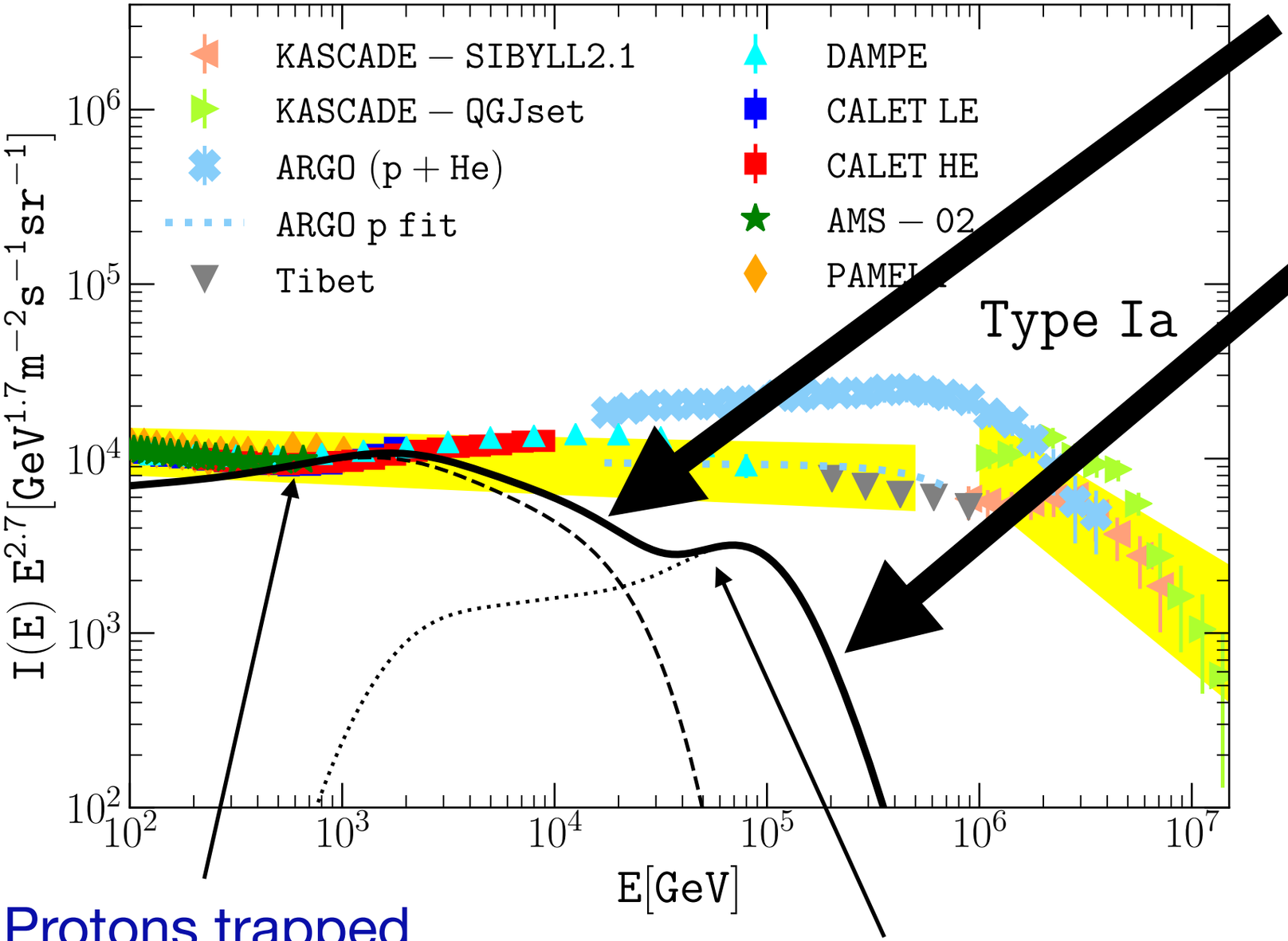


$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

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

$$\nu_{\mathrm{Ia}} = 1/\mathrm{century}$$

$$\xi_{\mathrm{SN}} = 0.1$$

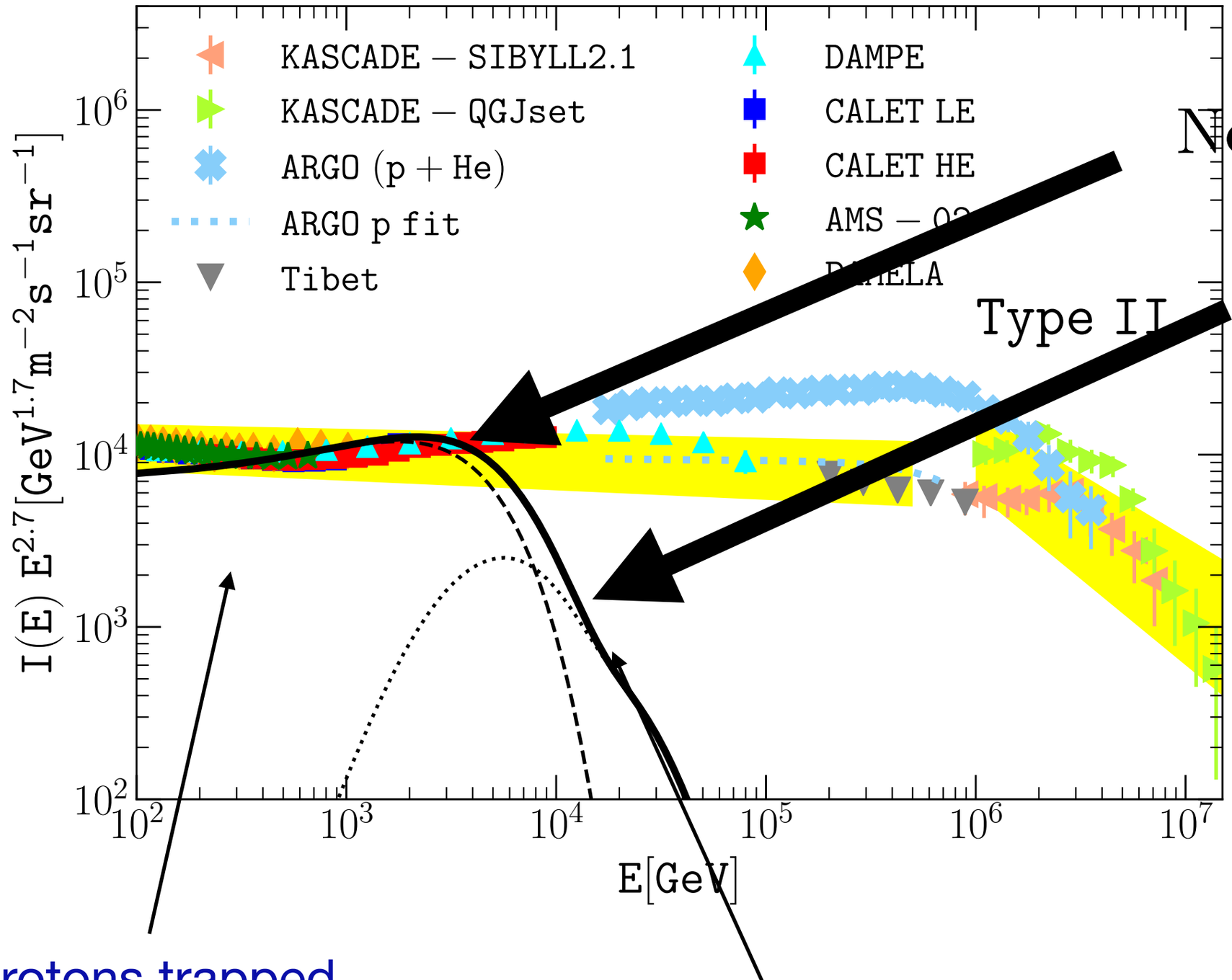
Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:



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

Type II

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

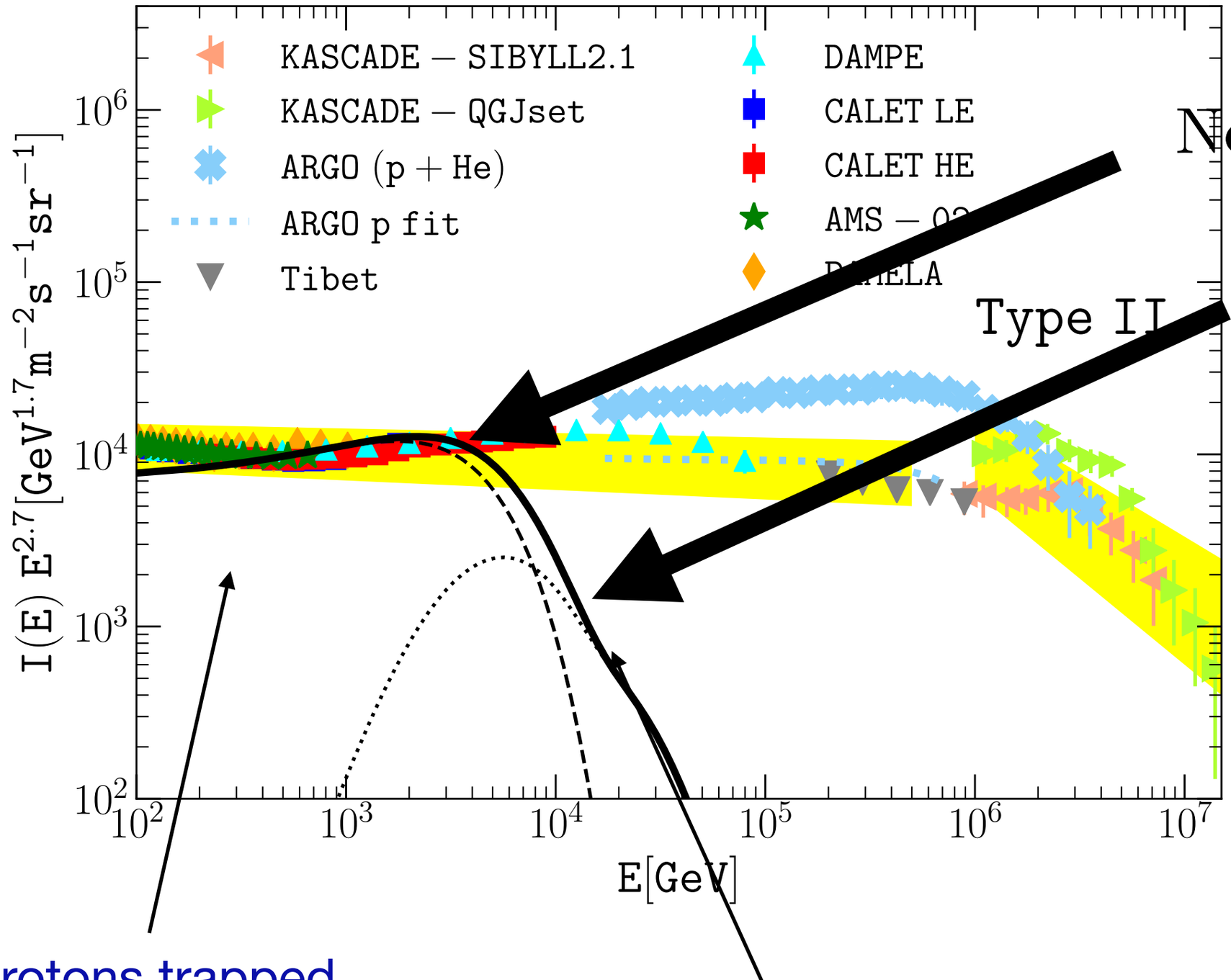
Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:



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

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Protons trapped inside SNR

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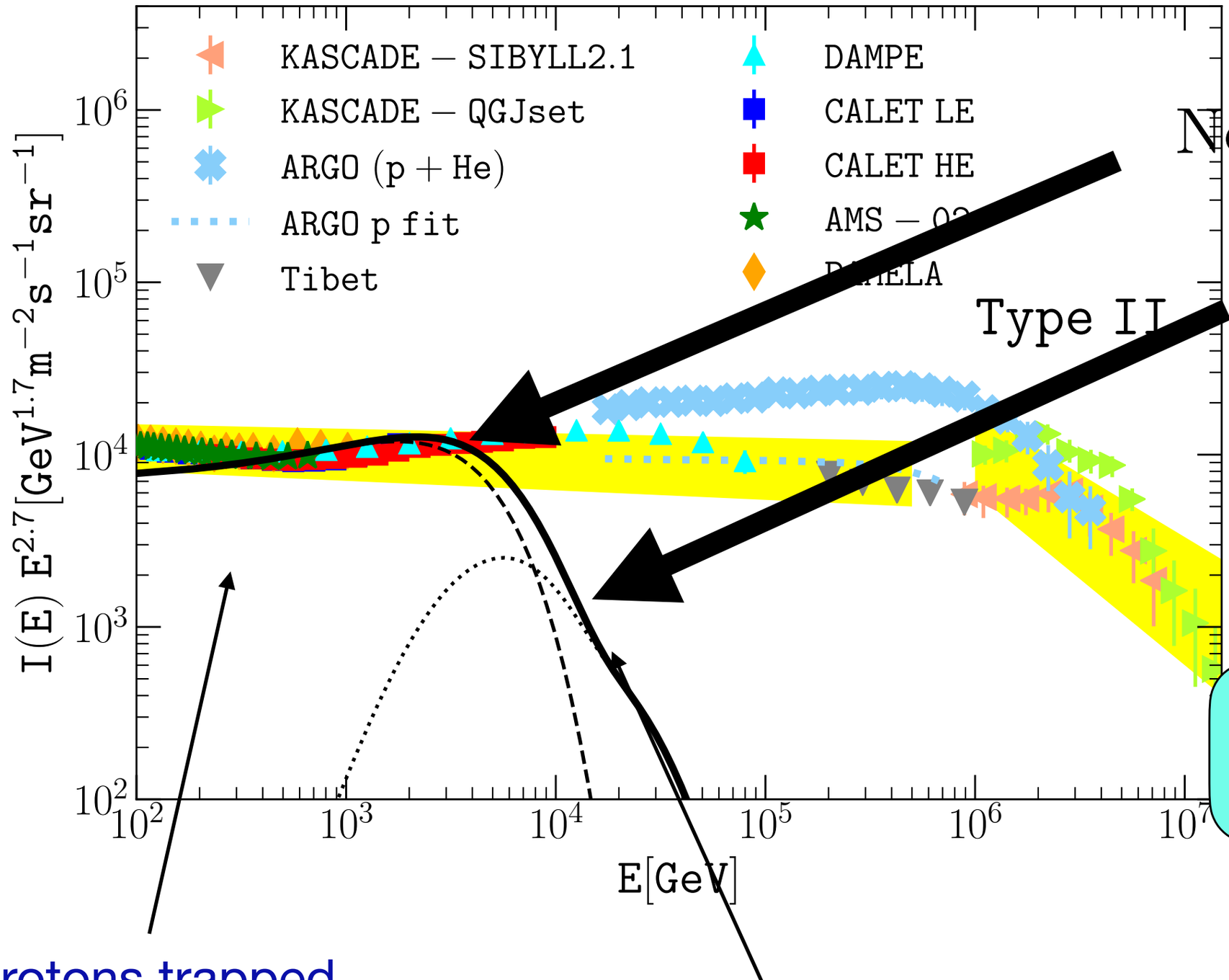

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$$E_{\mathrm{max}} \propto \xi_{\mathrm{CR}}$$

$$\nu_{\mathrm{II}} = 2/\mathrm{century}$$

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

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

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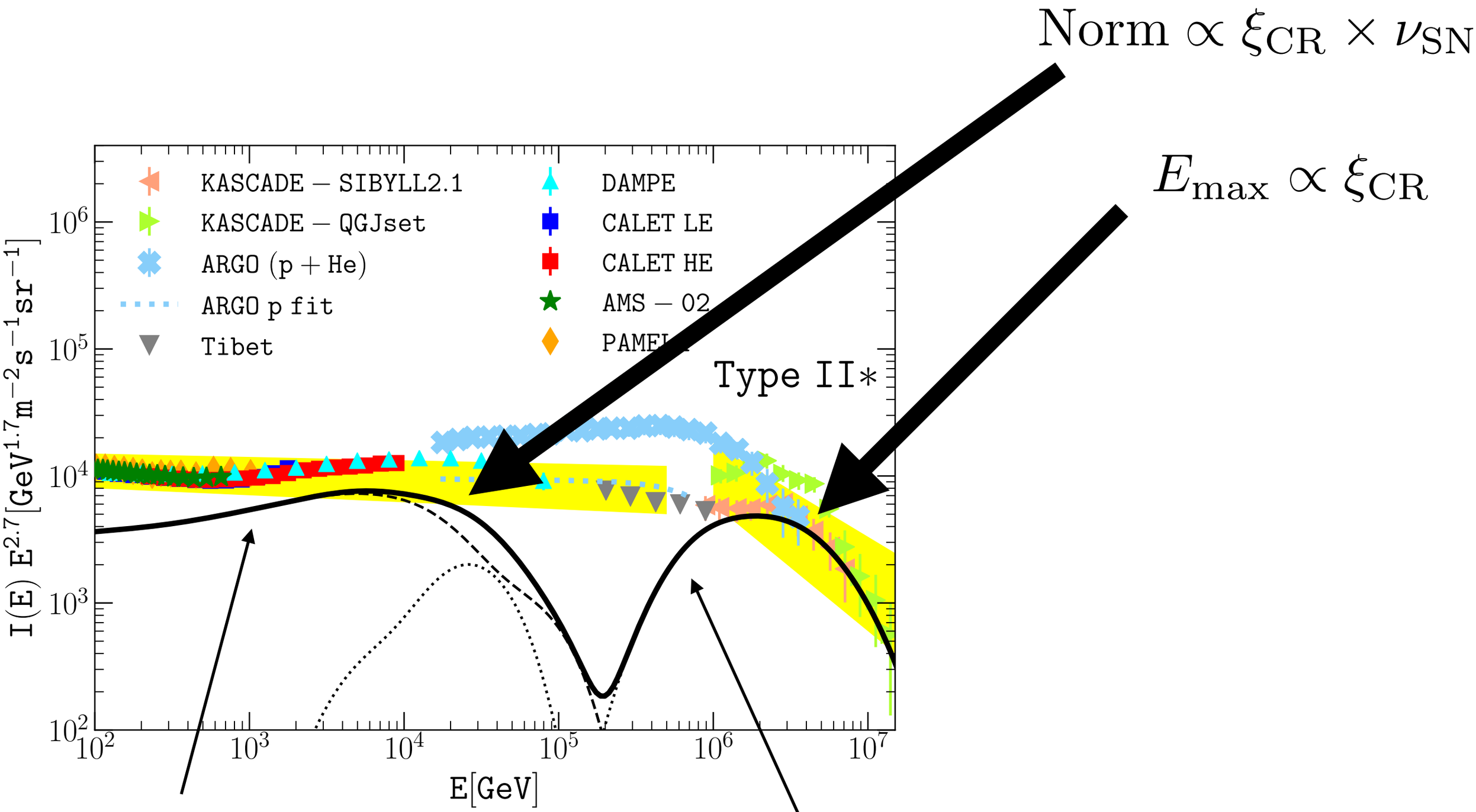

Protons trapped inside SNR

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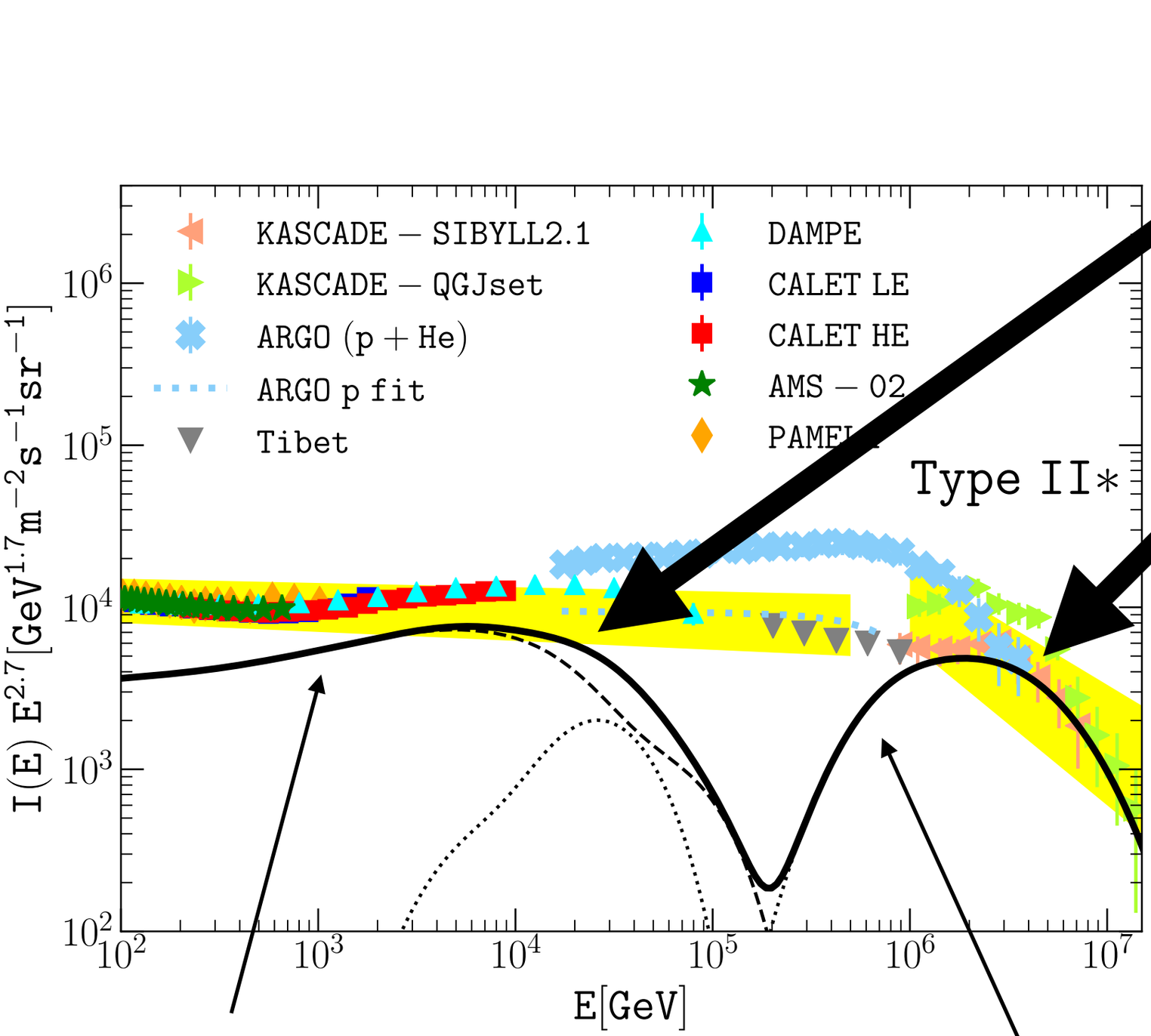
The case of supernova remnants

Protons after propagation:



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

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

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

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

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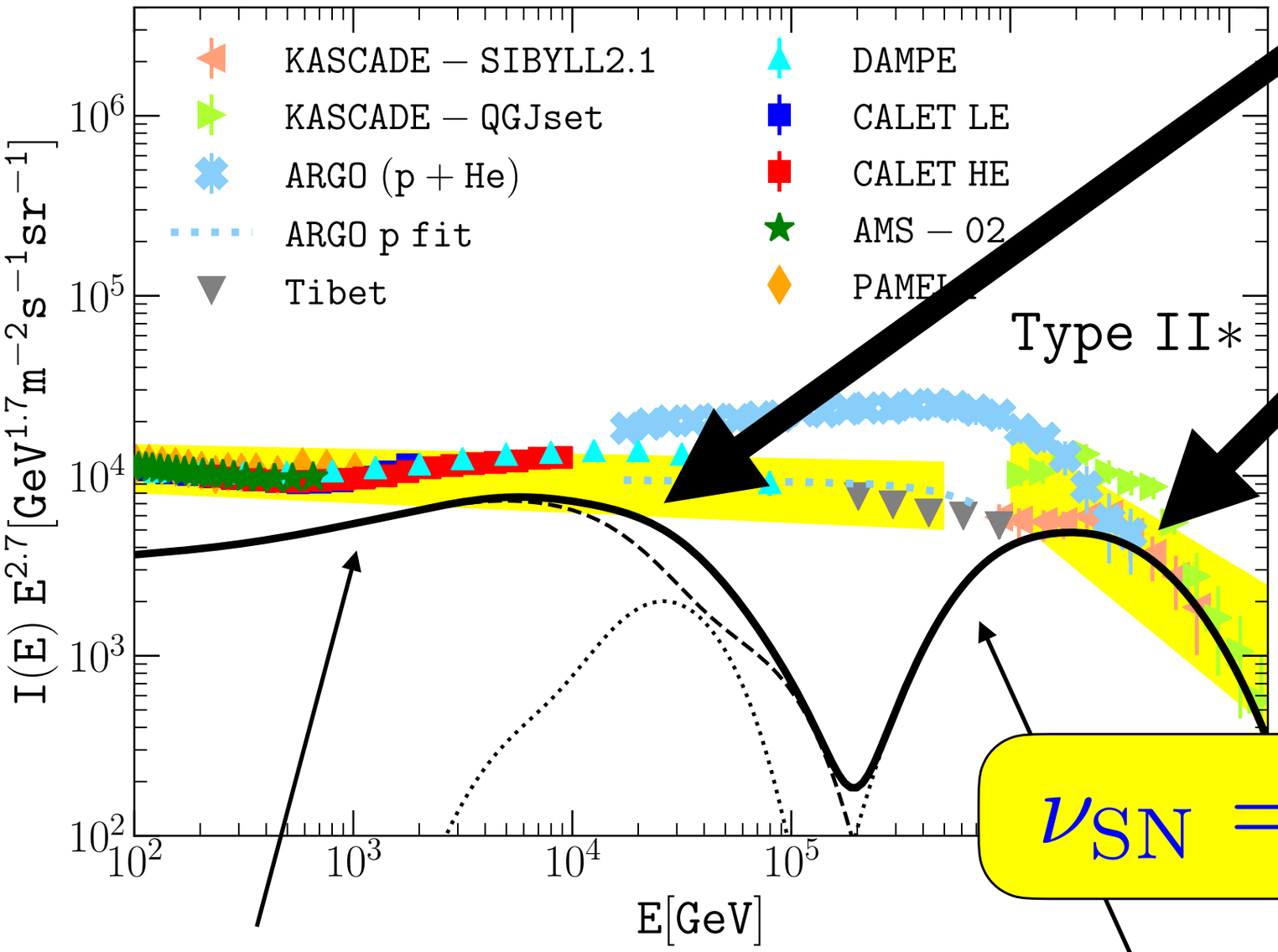
Reach PeV and not overproduce the CR spectrum:



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

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

1. Possible to account for PeV protons with rare unusual SNRs (1-5% 3/ century, hard to catch!) - specific environments and diversity of SNe investigated in several works (Gabici et al. 2019, Kamijina& Ohira 2024, Das et al. 2024, Vieu et al. 2023, Bykov et al. 2024 + many more, (Sushsch et al. 2025), SNe close to stellar clusters (Vieu&Reville 2024)?)

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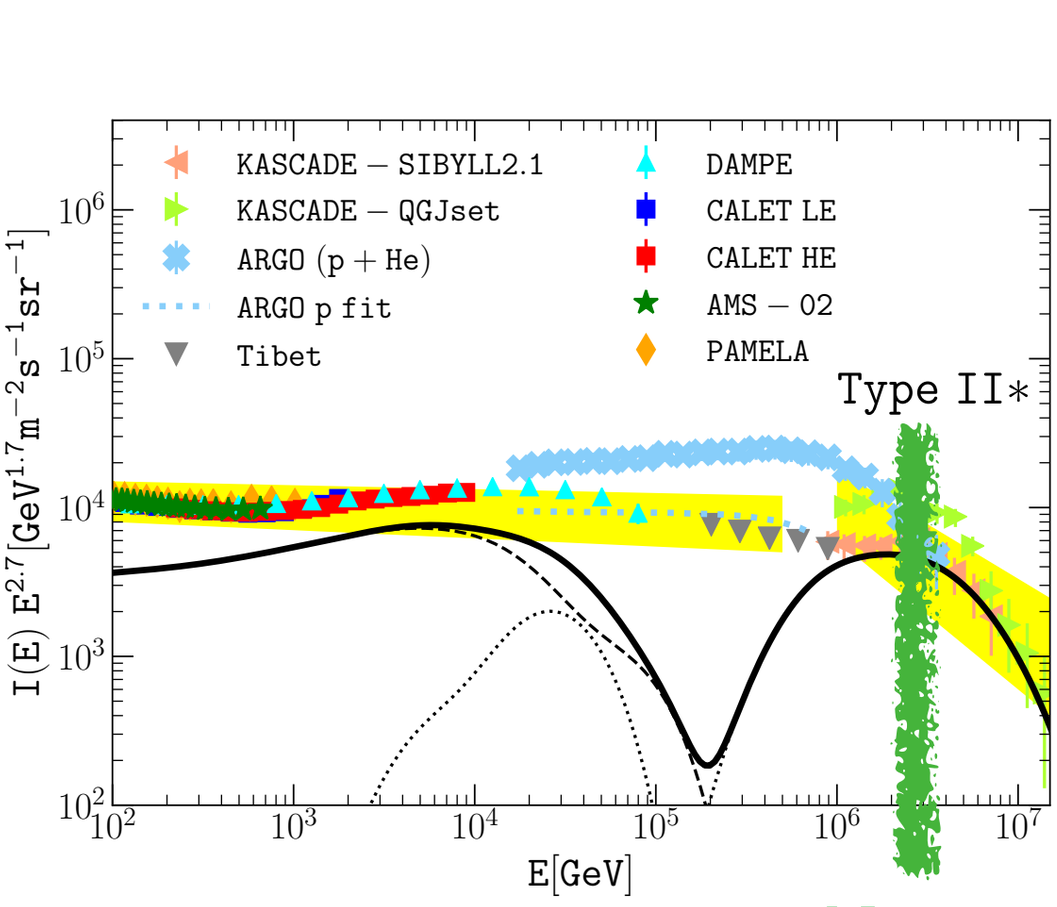
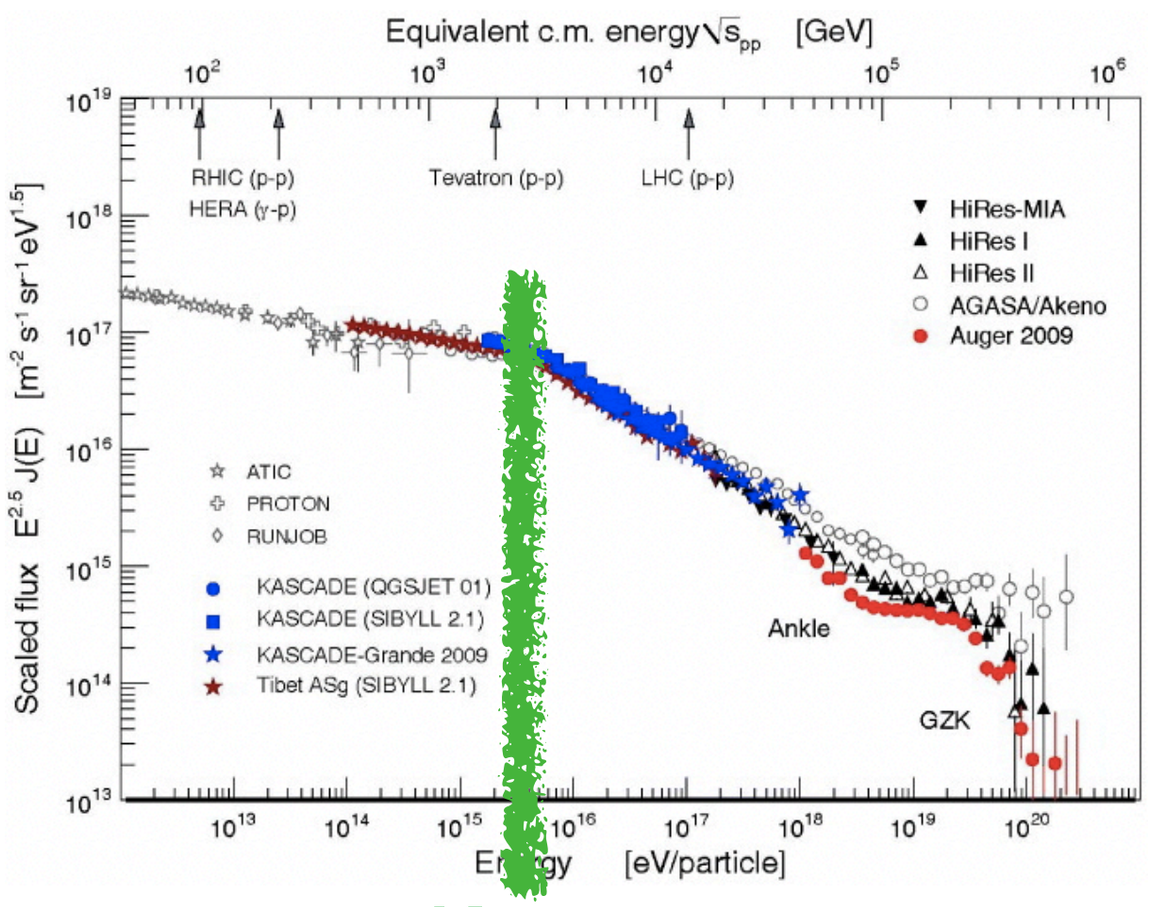


Knee



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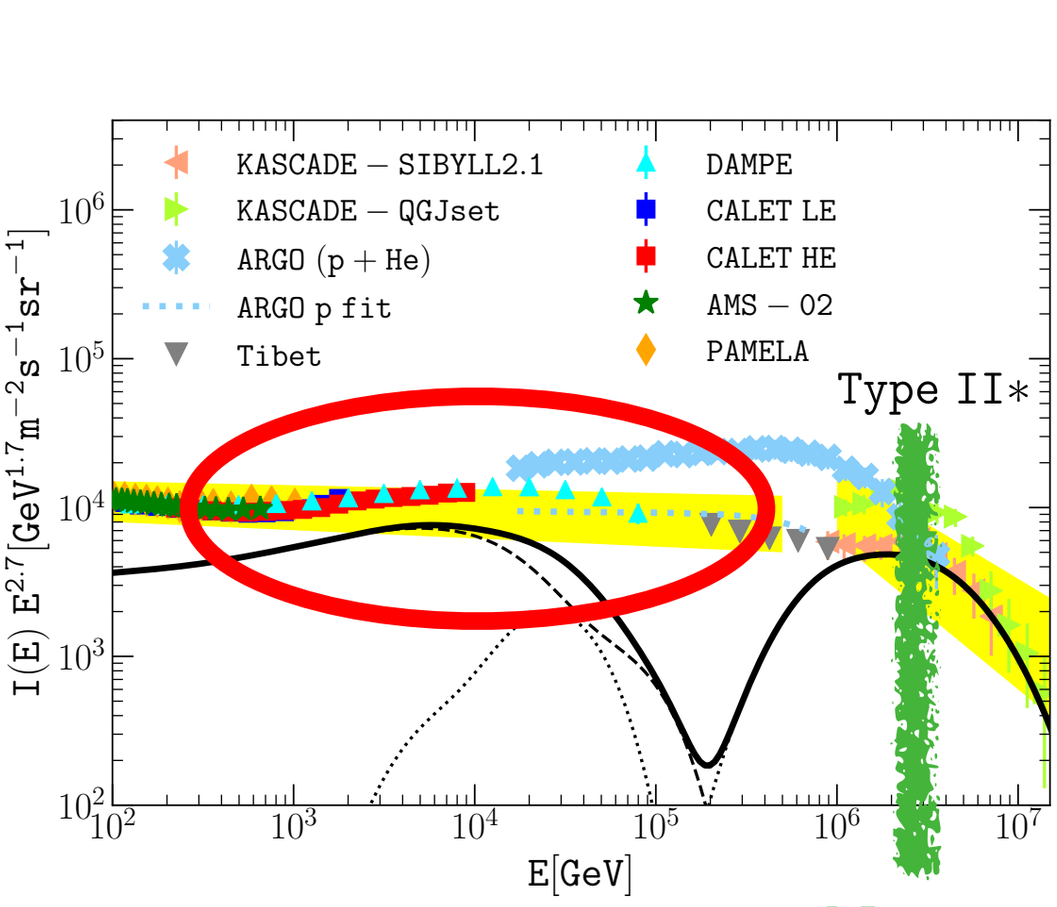

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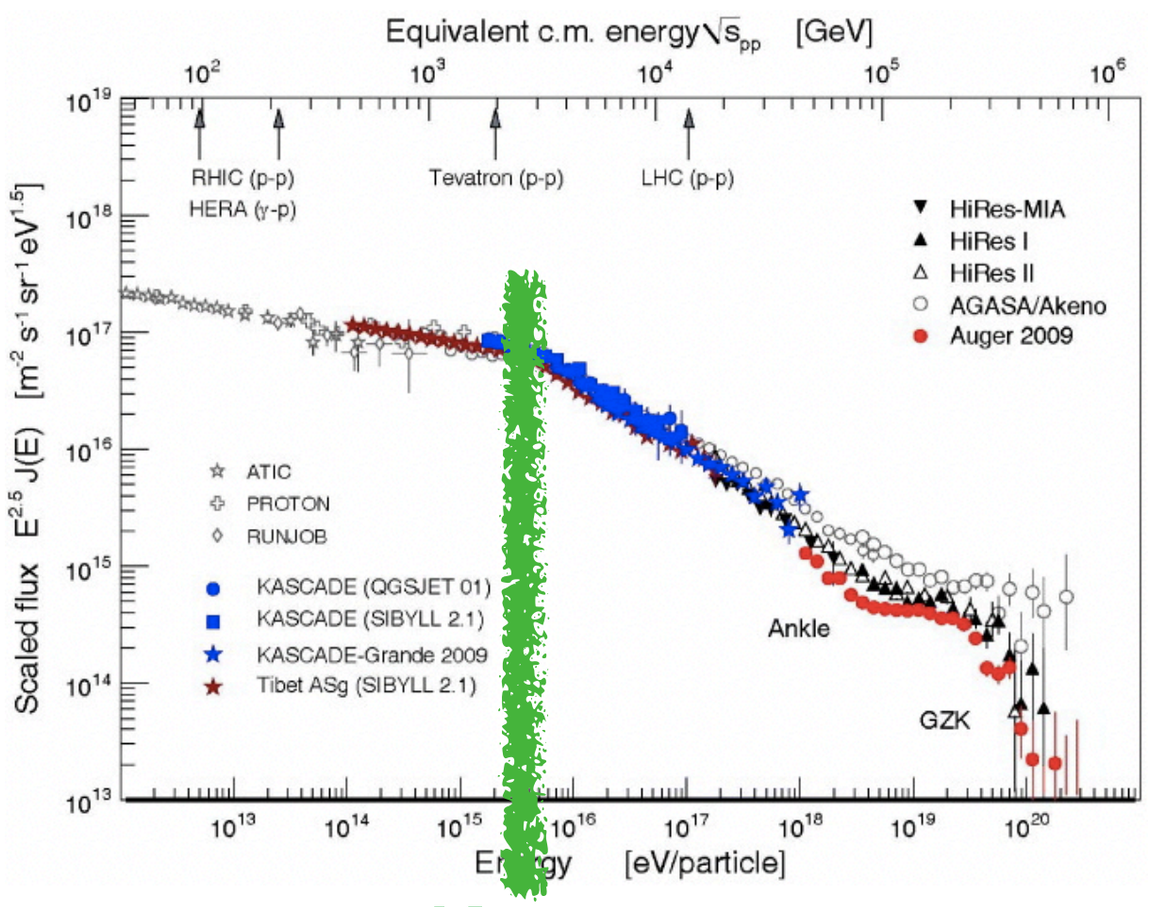

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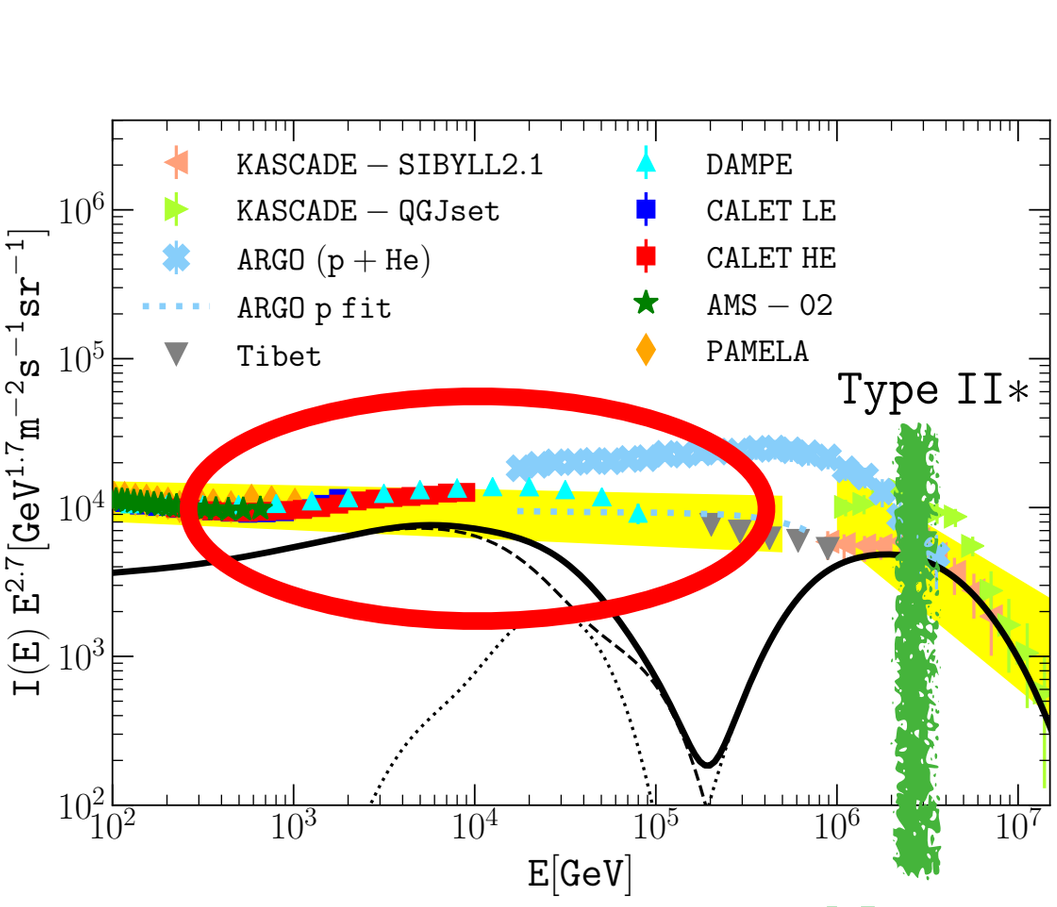

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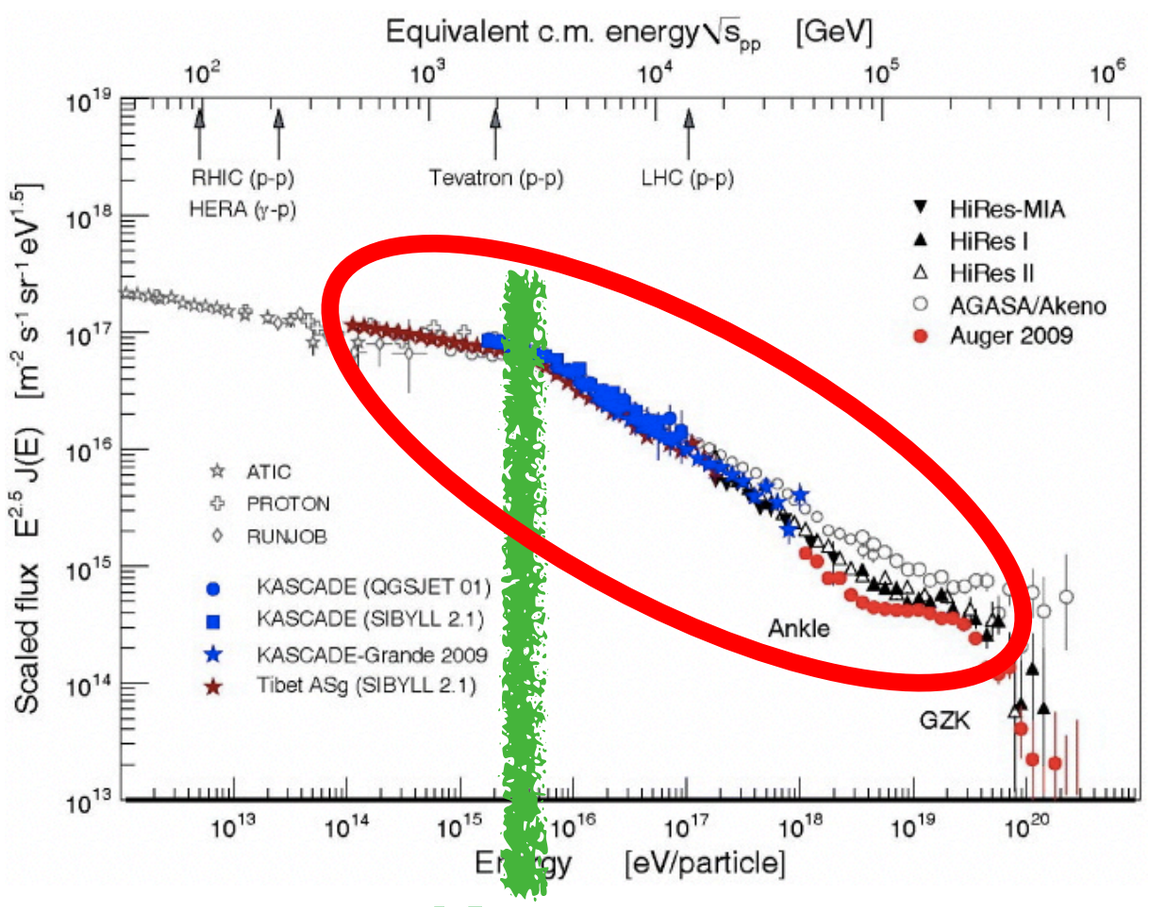

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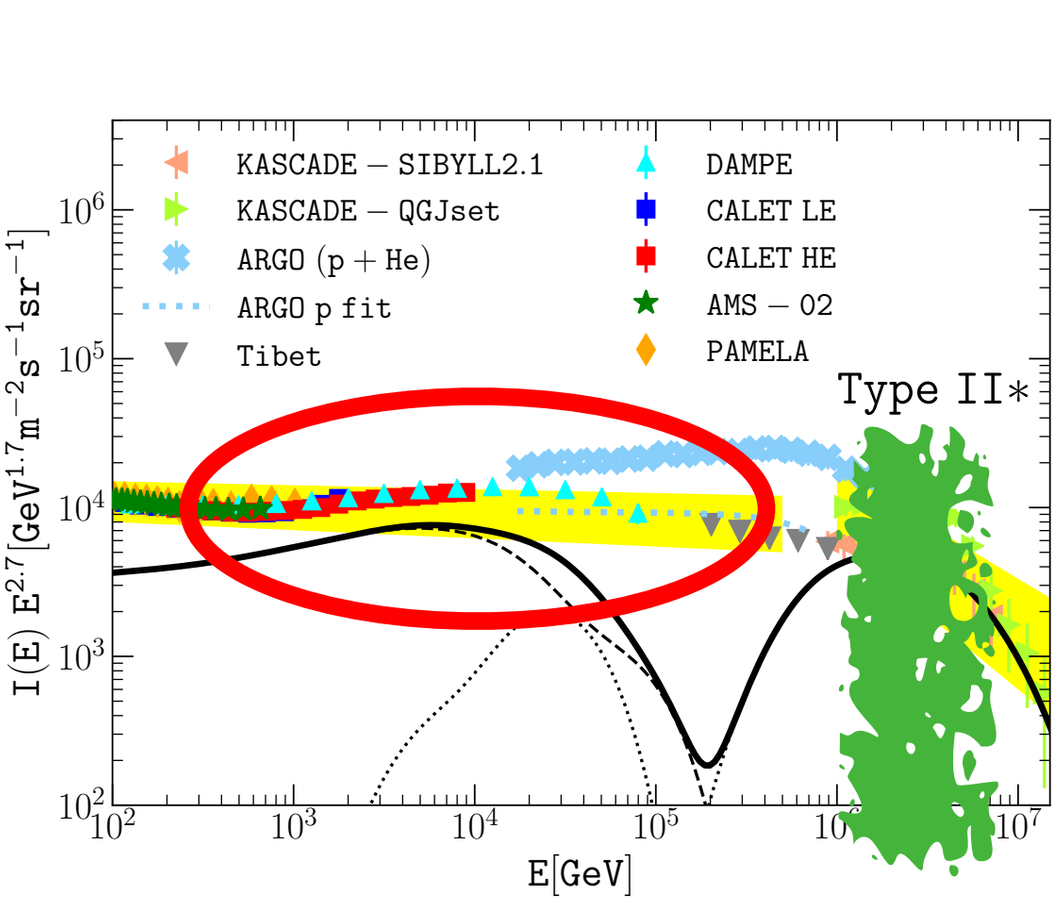

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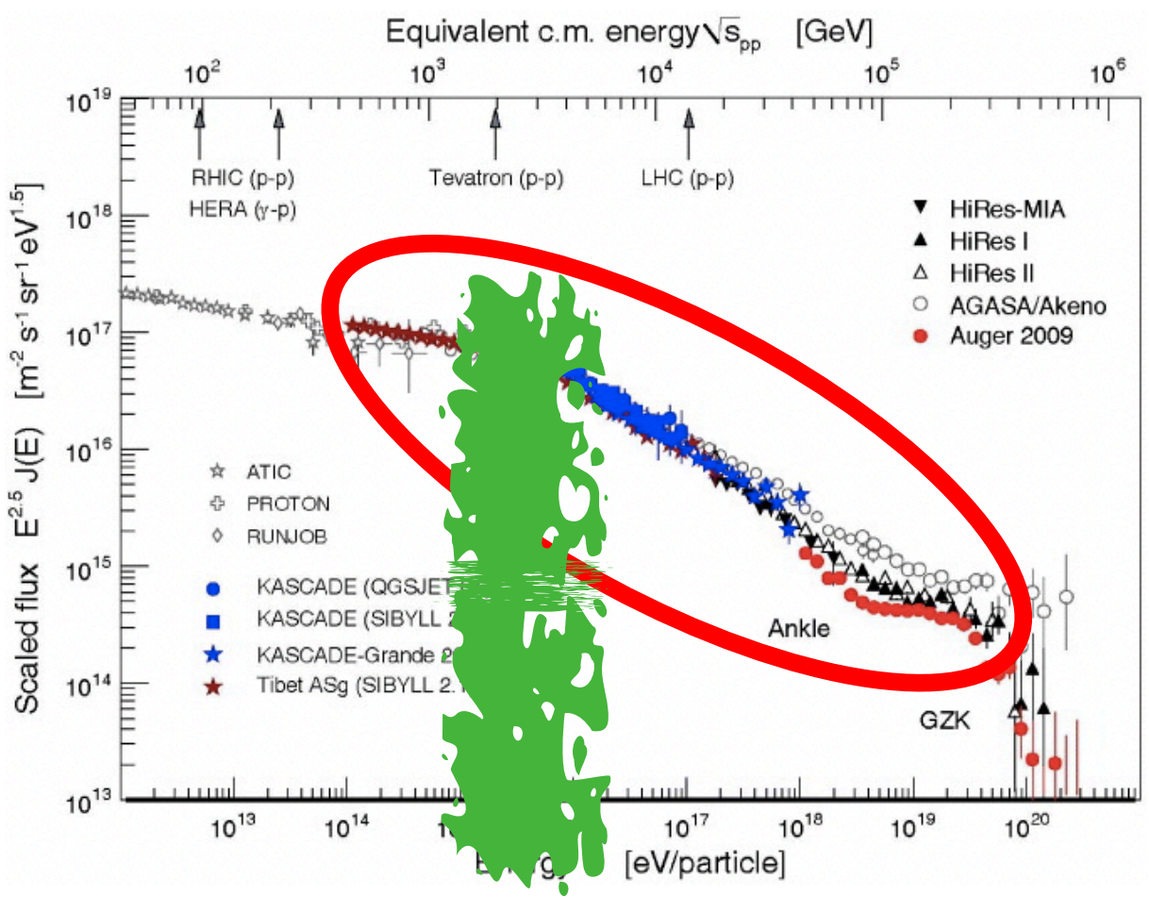
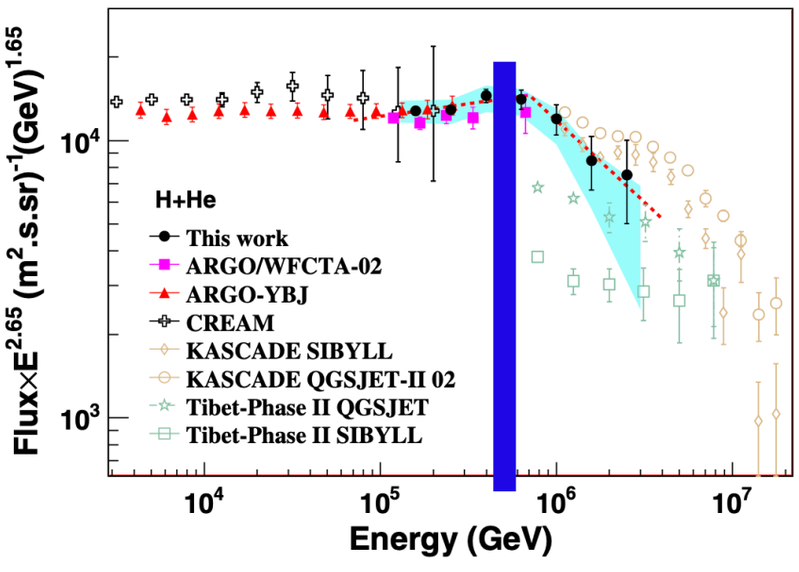


Knee

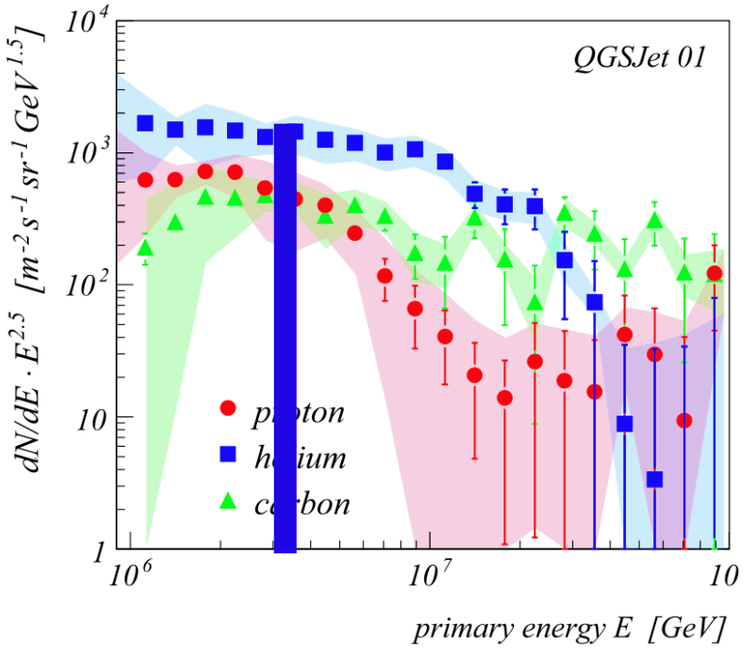
The proton « knee »



ARGO-YBJ

~700 TeV

Bartoli et al. 2015

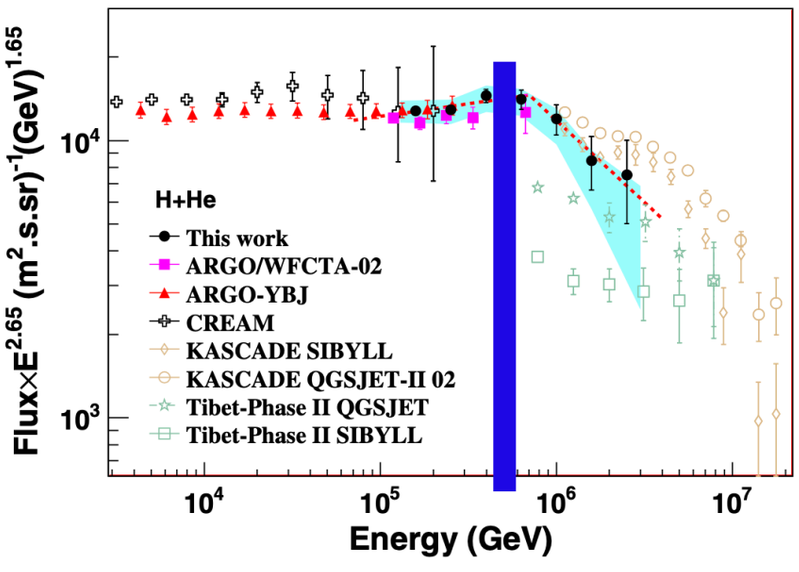


KASCADE

~3-4 PeV

Antoni et al. 2005

The proton « knee »



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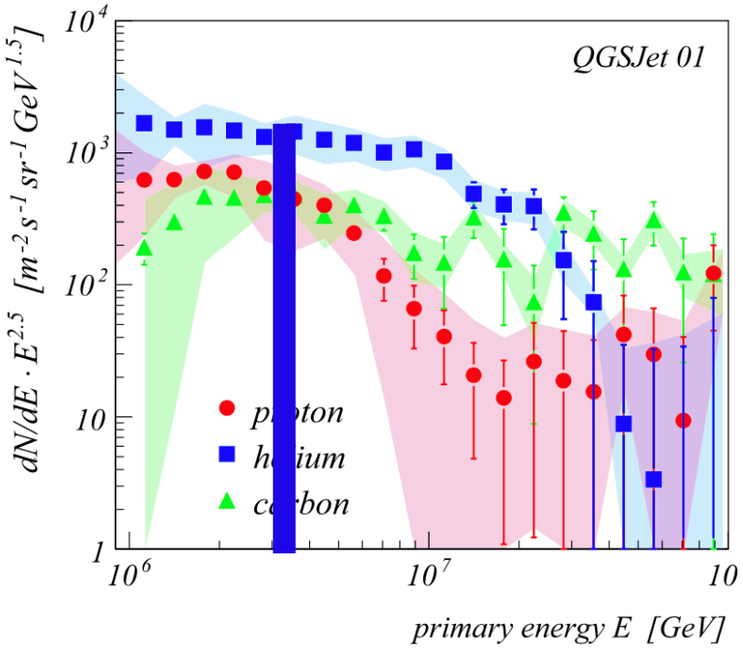

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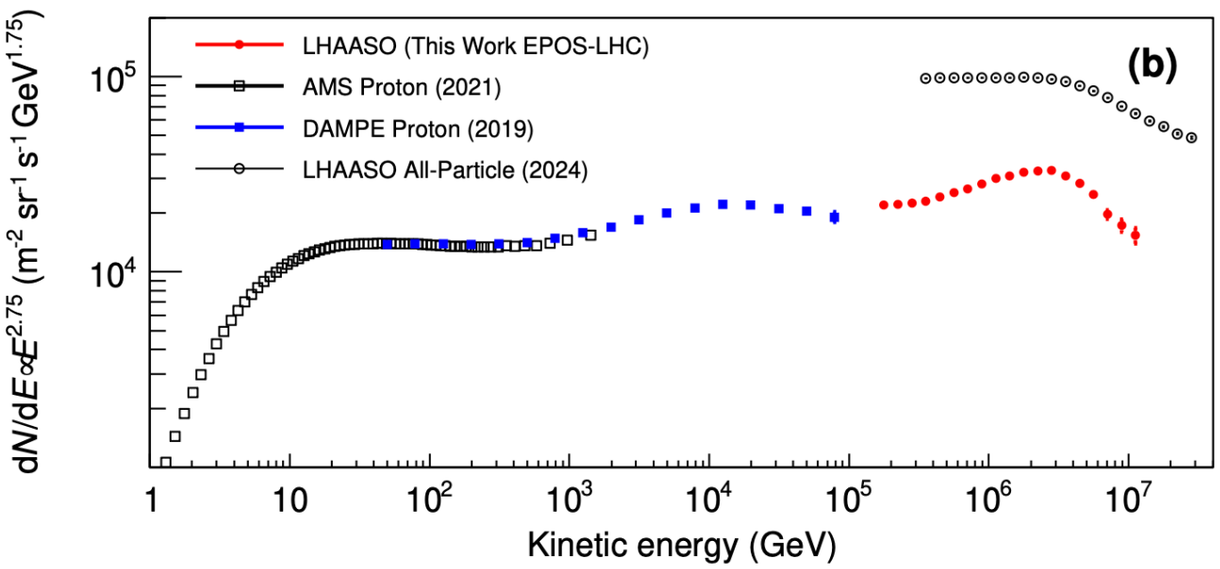
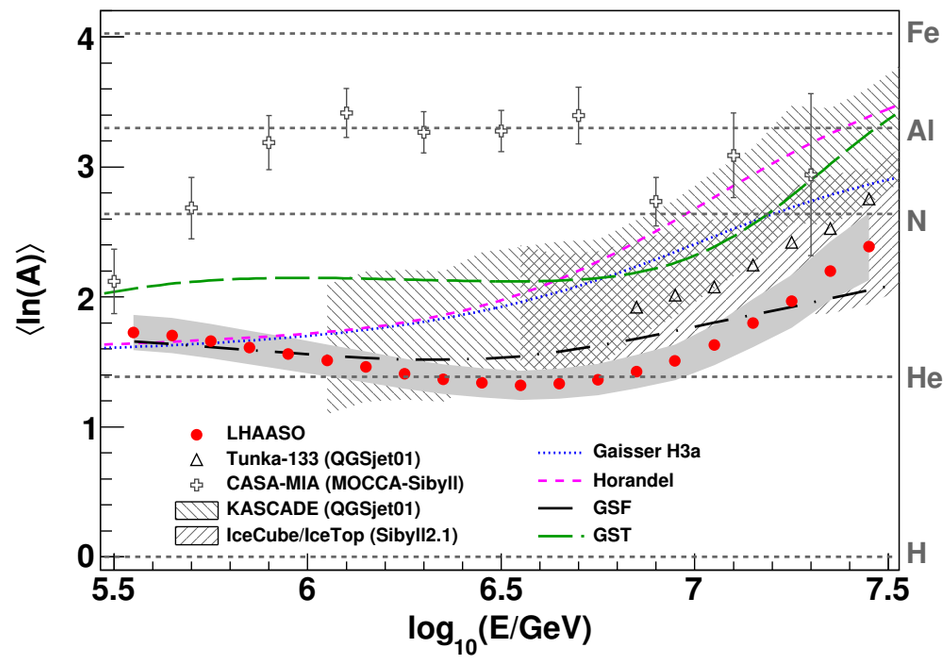


LHAASO Cao et al. 2025 ~3 PeV

Hints for rigidity-dependent knee

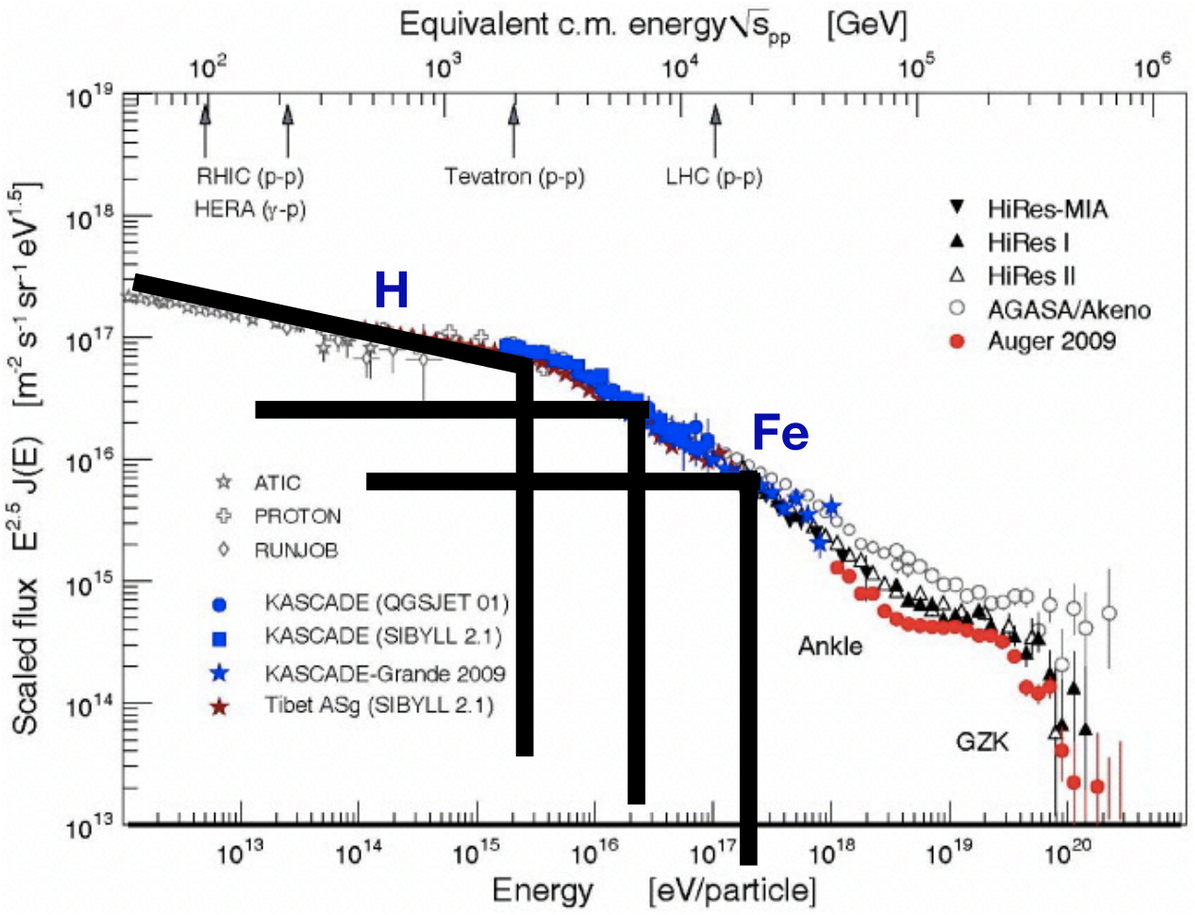


LHAASO Cao et al. 2024

The « knee »

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

~100 PeV



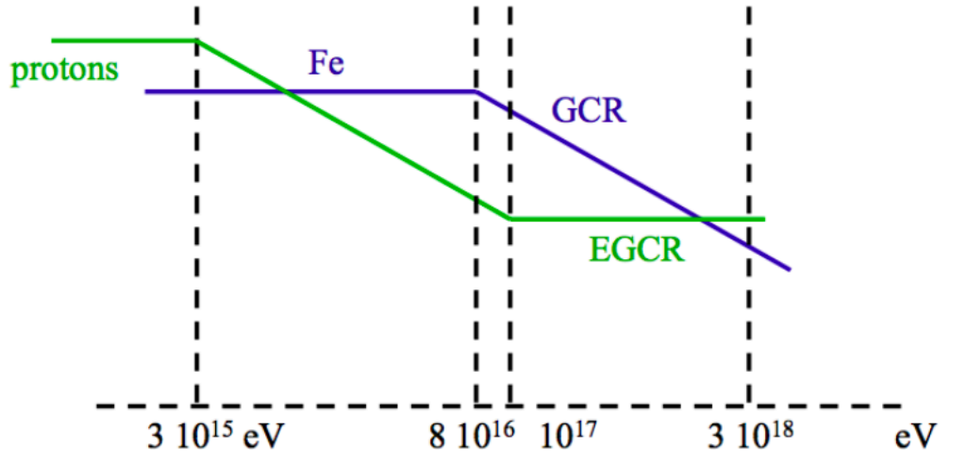


Figure 4: Sketch of the GCR/EGCR transition, with the proton and Fe components indicated (respectively in green and in blue on the color version of the figure). In ordinate, the CR flux is multiplied by E^x, where x is the logarithmic slope of the CR spectrum below the knee. (See also Fig. 3).

Z dependent knee ⟷ DSA depends on rigidity

Hillas 2006, Parizot 2014

The « knee »

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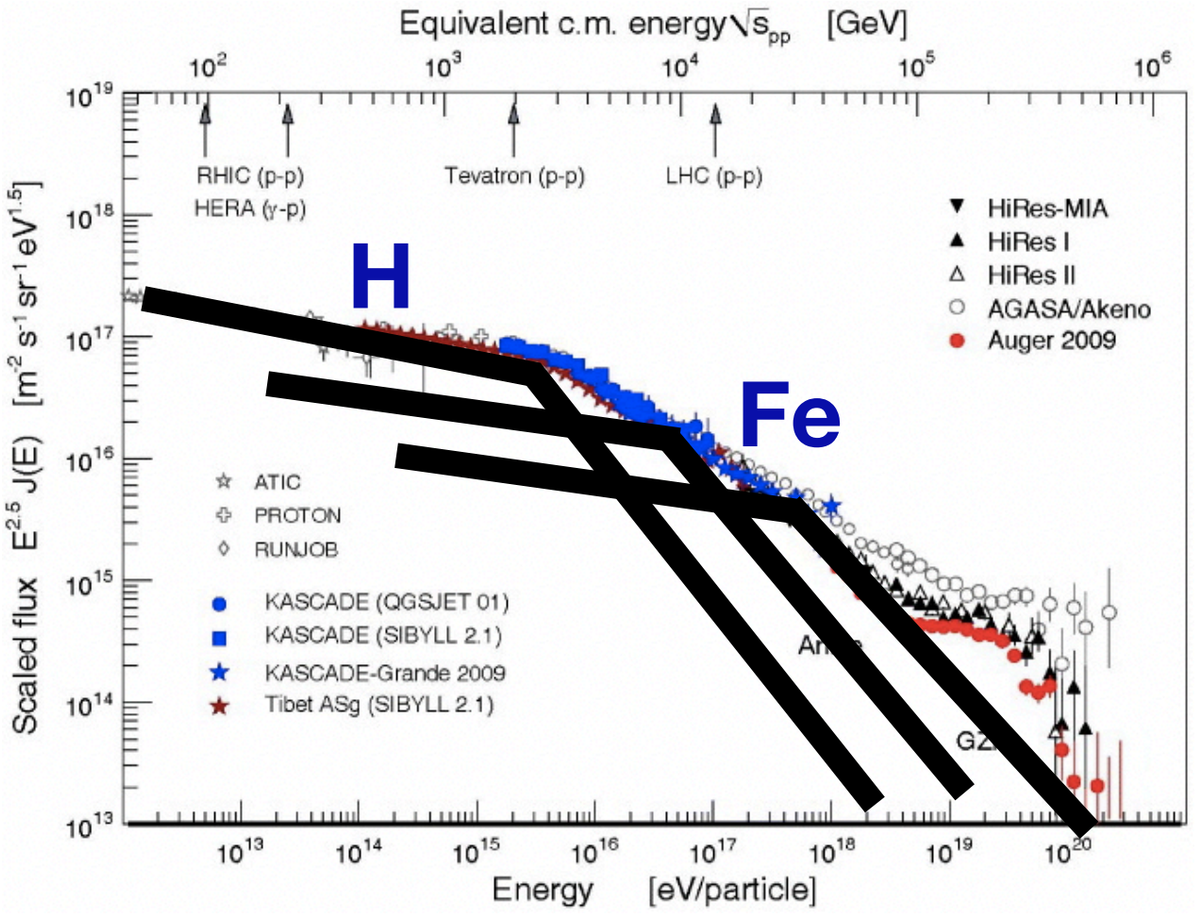

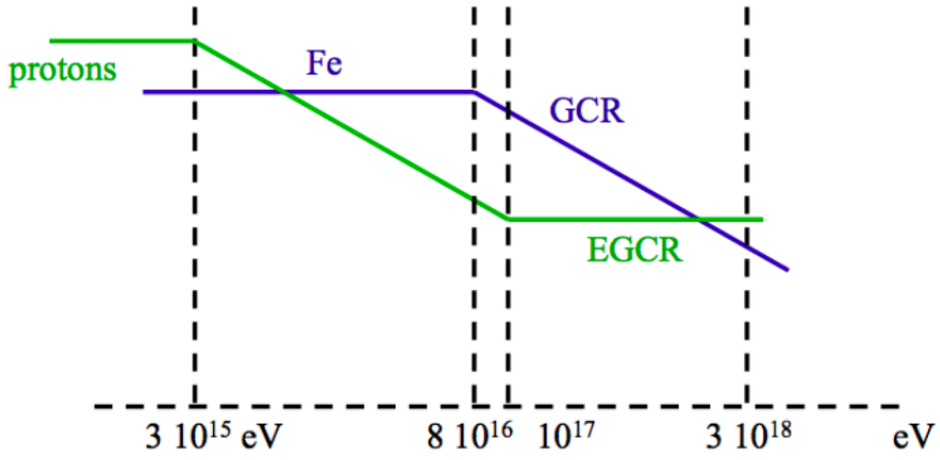

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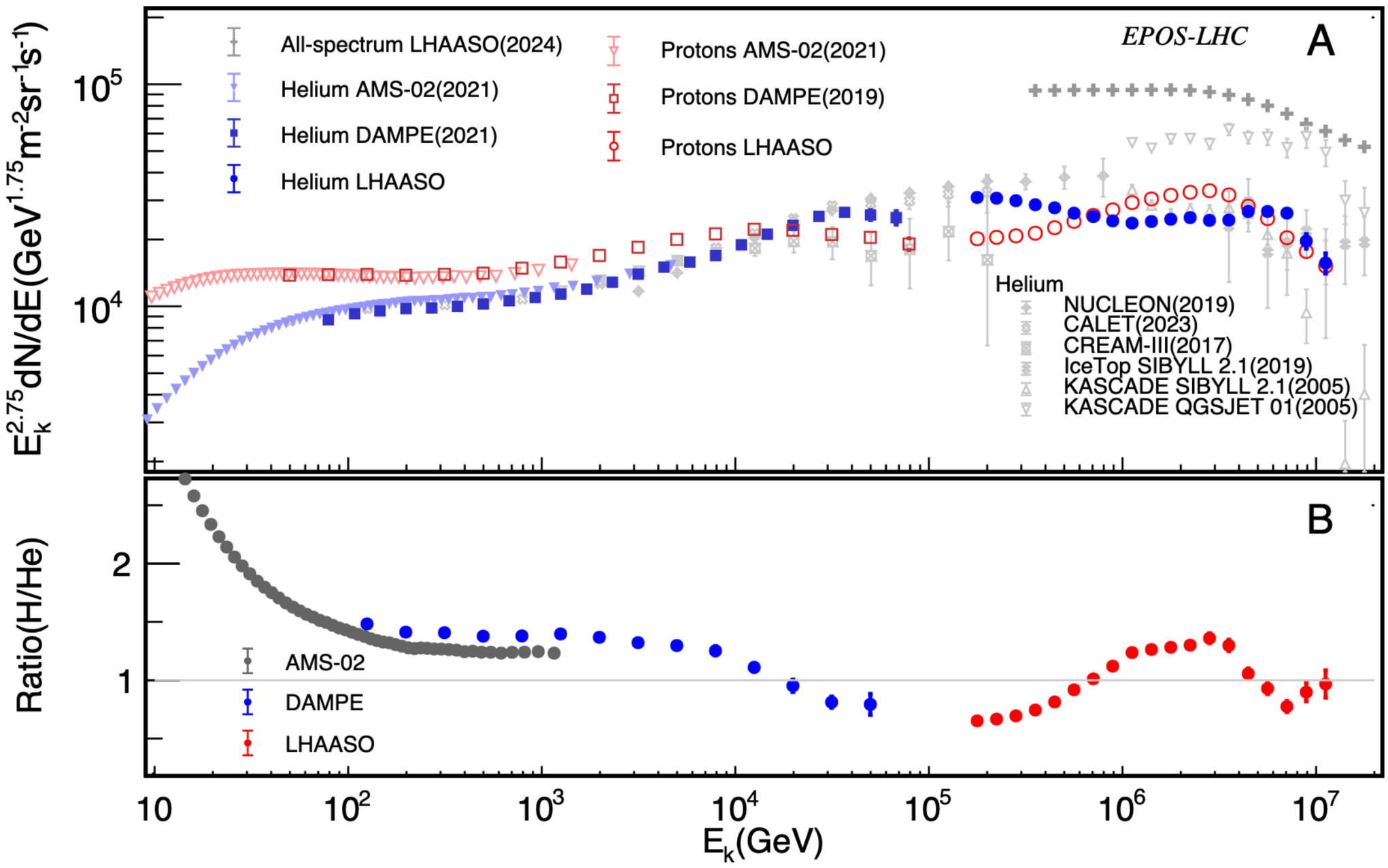
Smooth transition from Galactic to extraGalactic

Hillas 2006, Parizot 2014

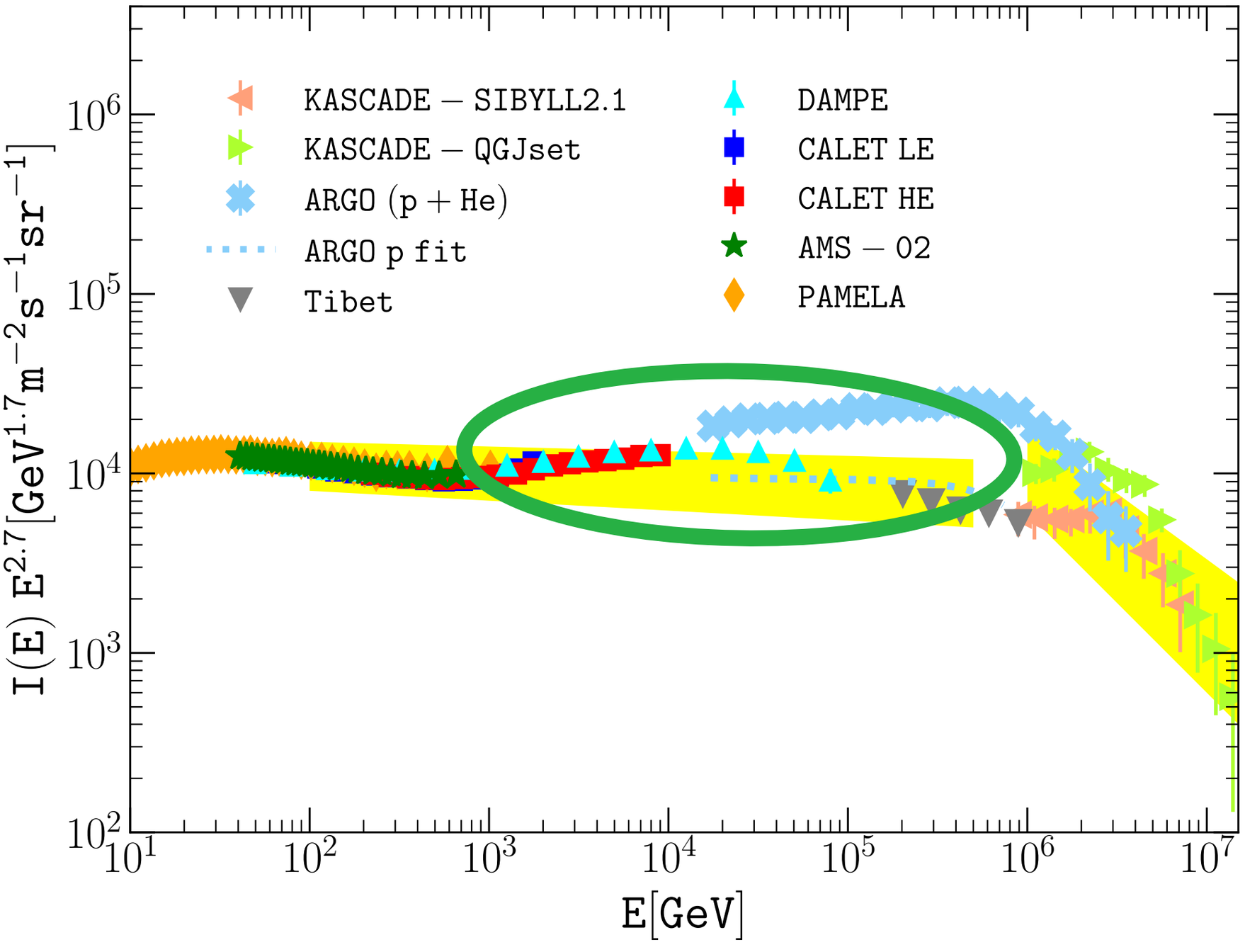
The proton and Helium « knee »



Complex behavior (not like the smooth all-particle spectrum)
Interpretation: Several sources of Galactic cosmic rays (not only one)

LHAASO Cao et al. 2026

And … below the knee?



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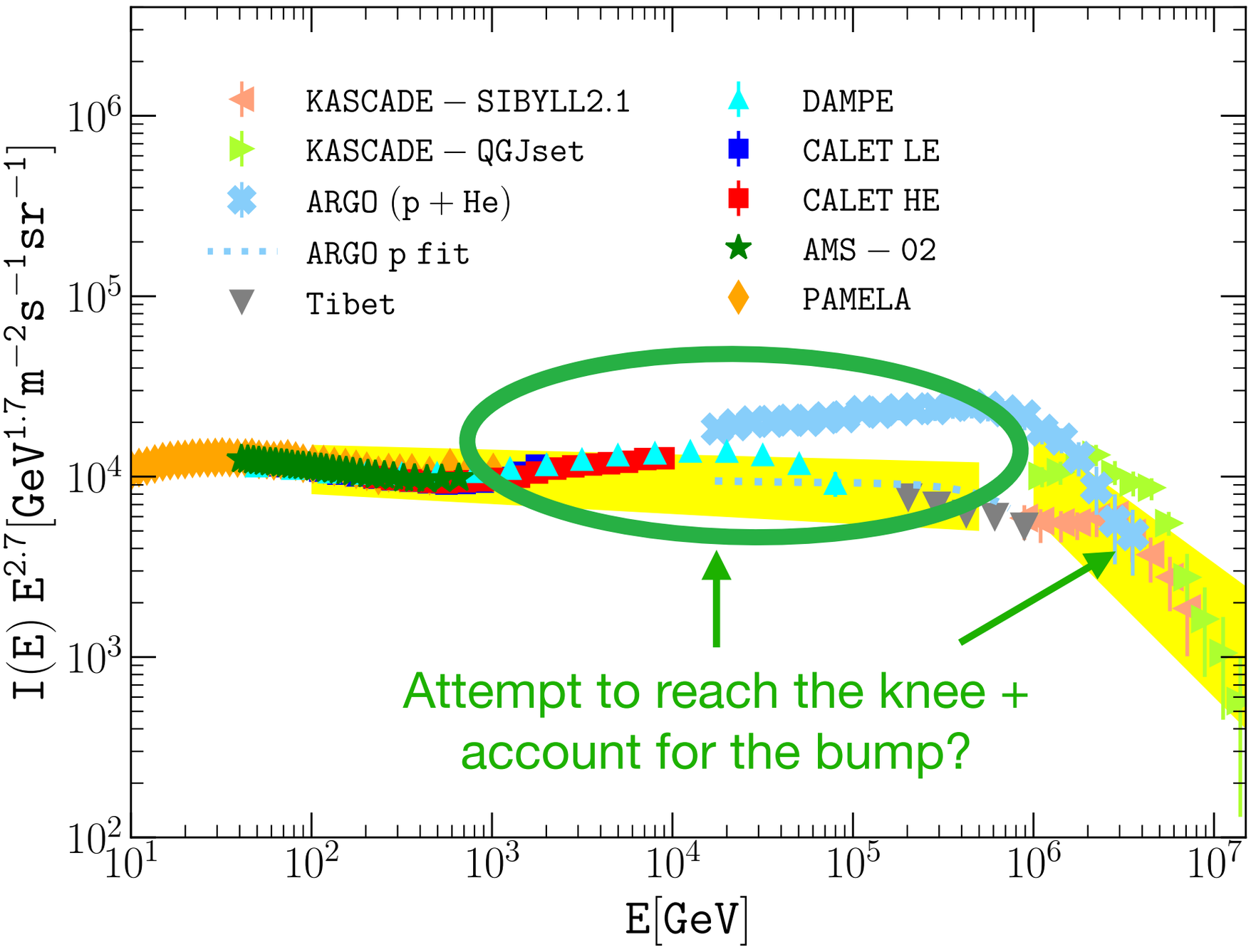

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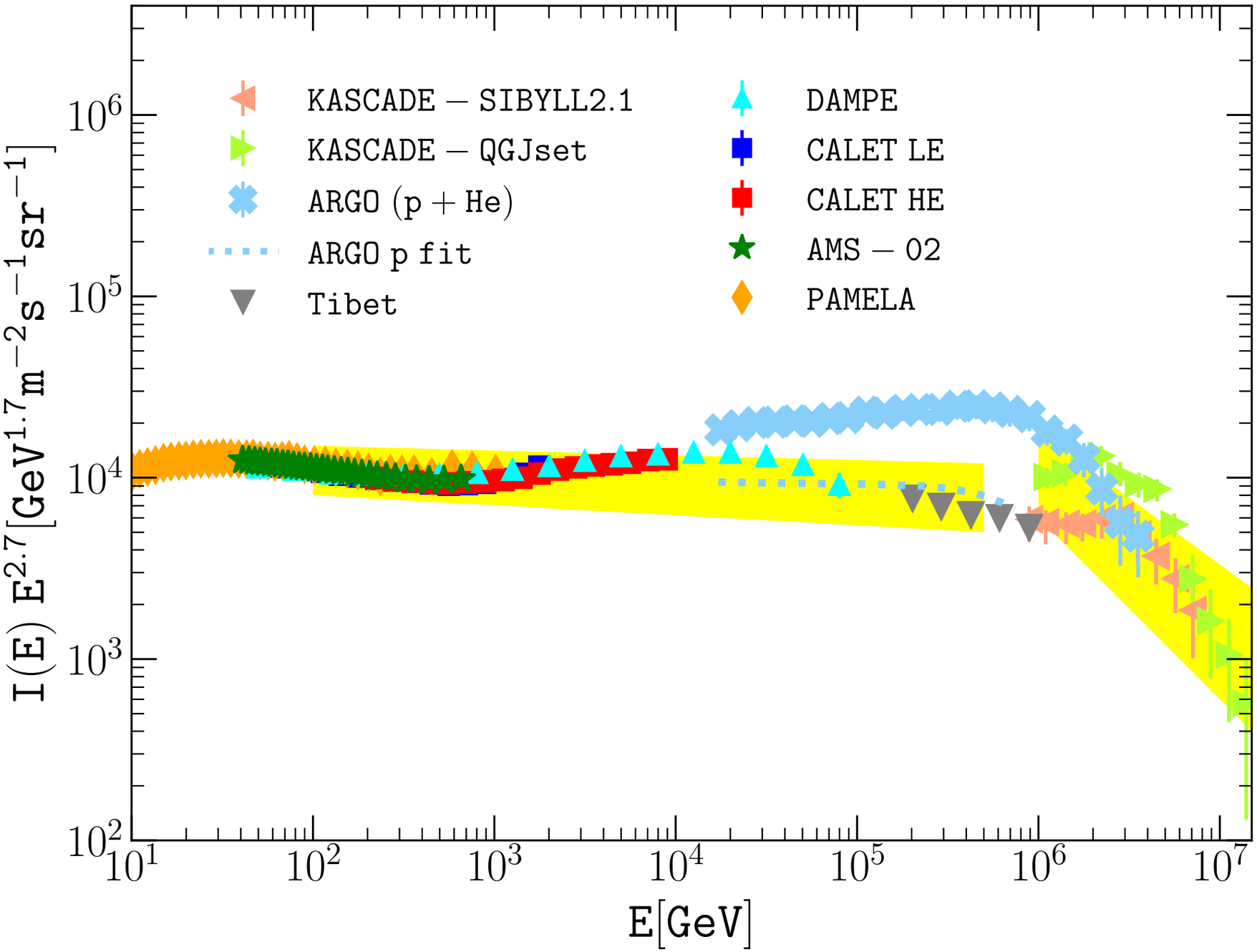
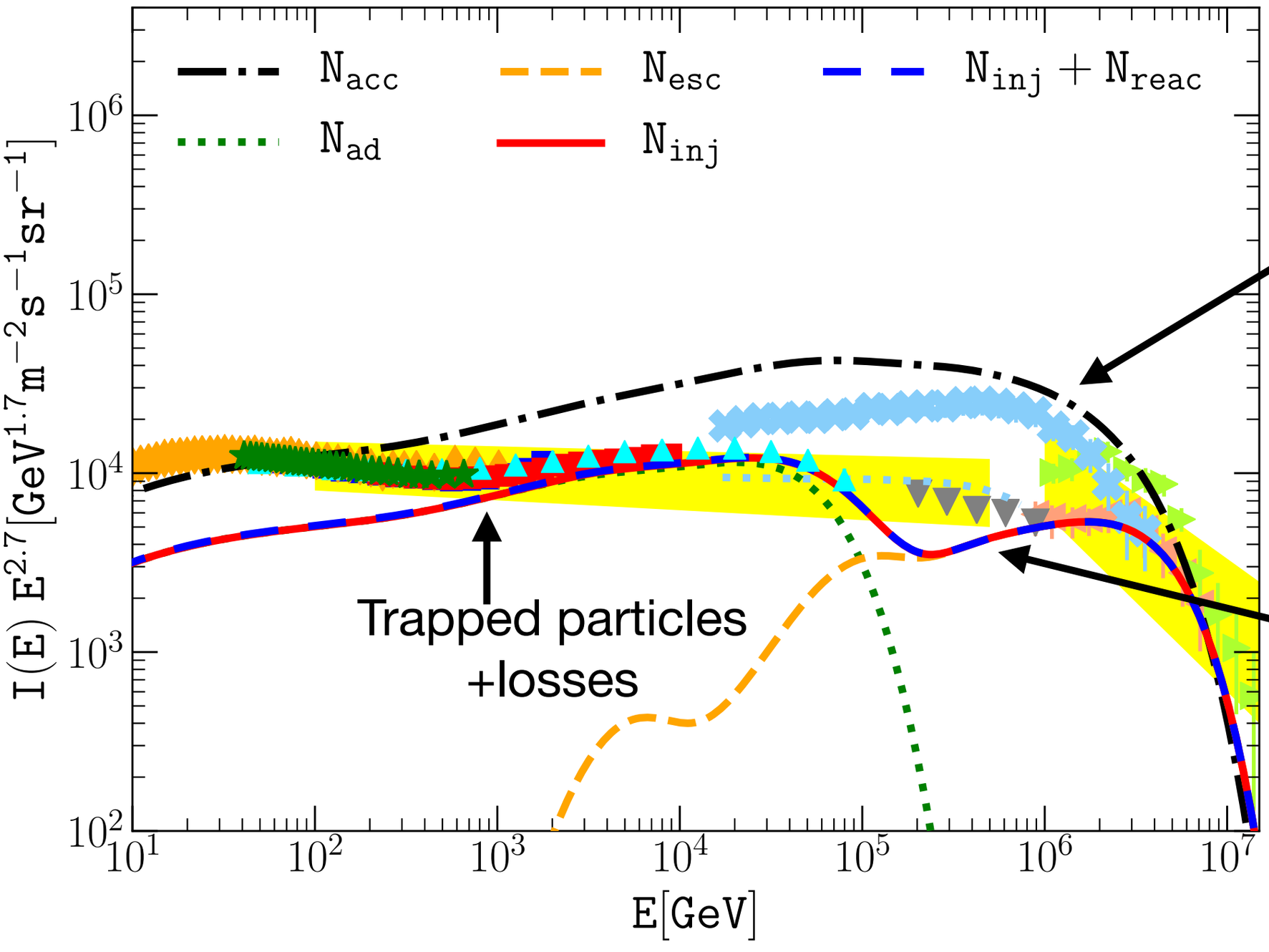


With only one object?

$$\mathrm{Type\ II} * \left[E_{SN} = 1 - 10\ 10^{51}\mathrm{erg}\right]$$

$$\dot{M} = 10^{-4} M_\odot/\mathrm{yr} \qquad \xi = 5\%$$



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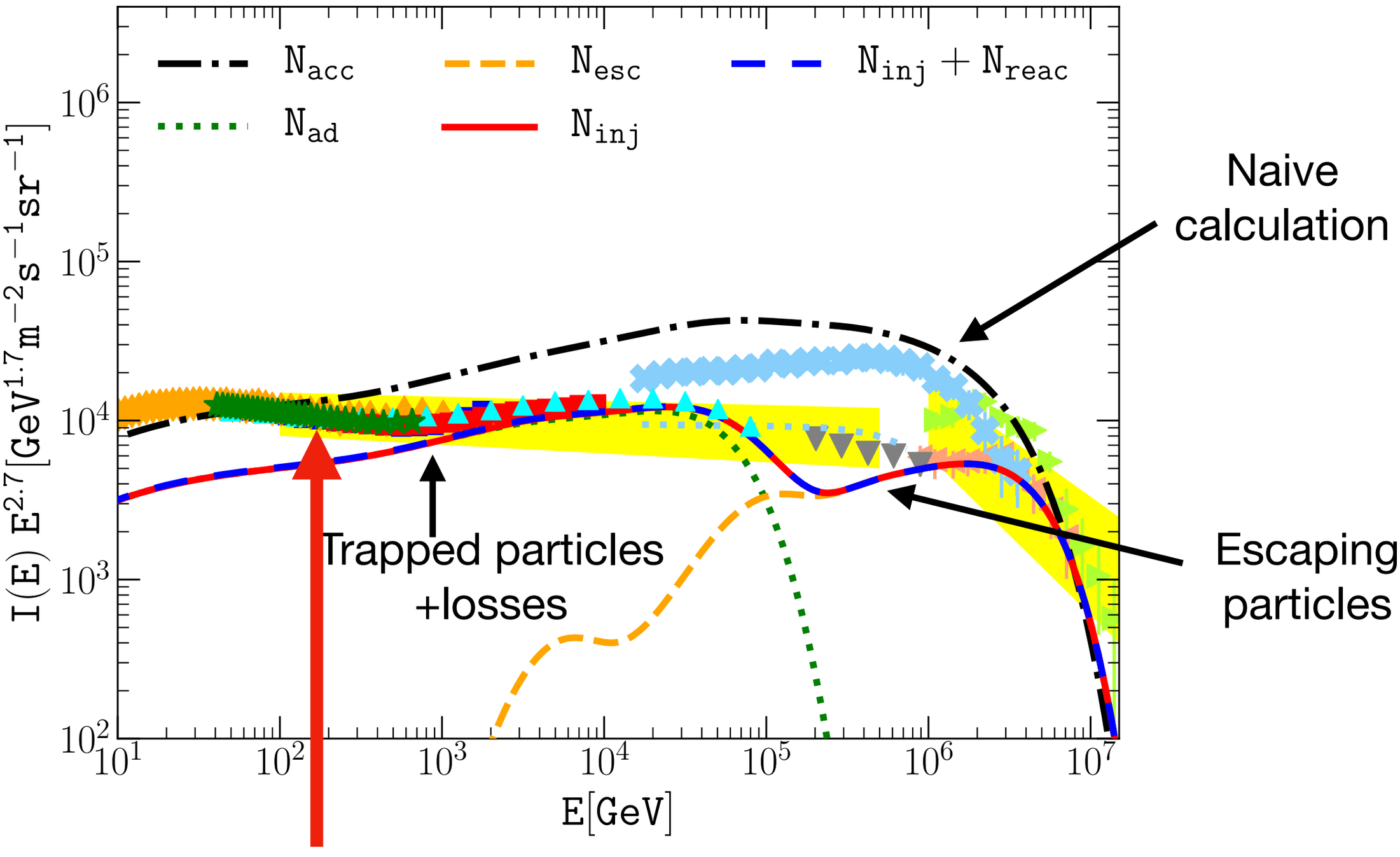
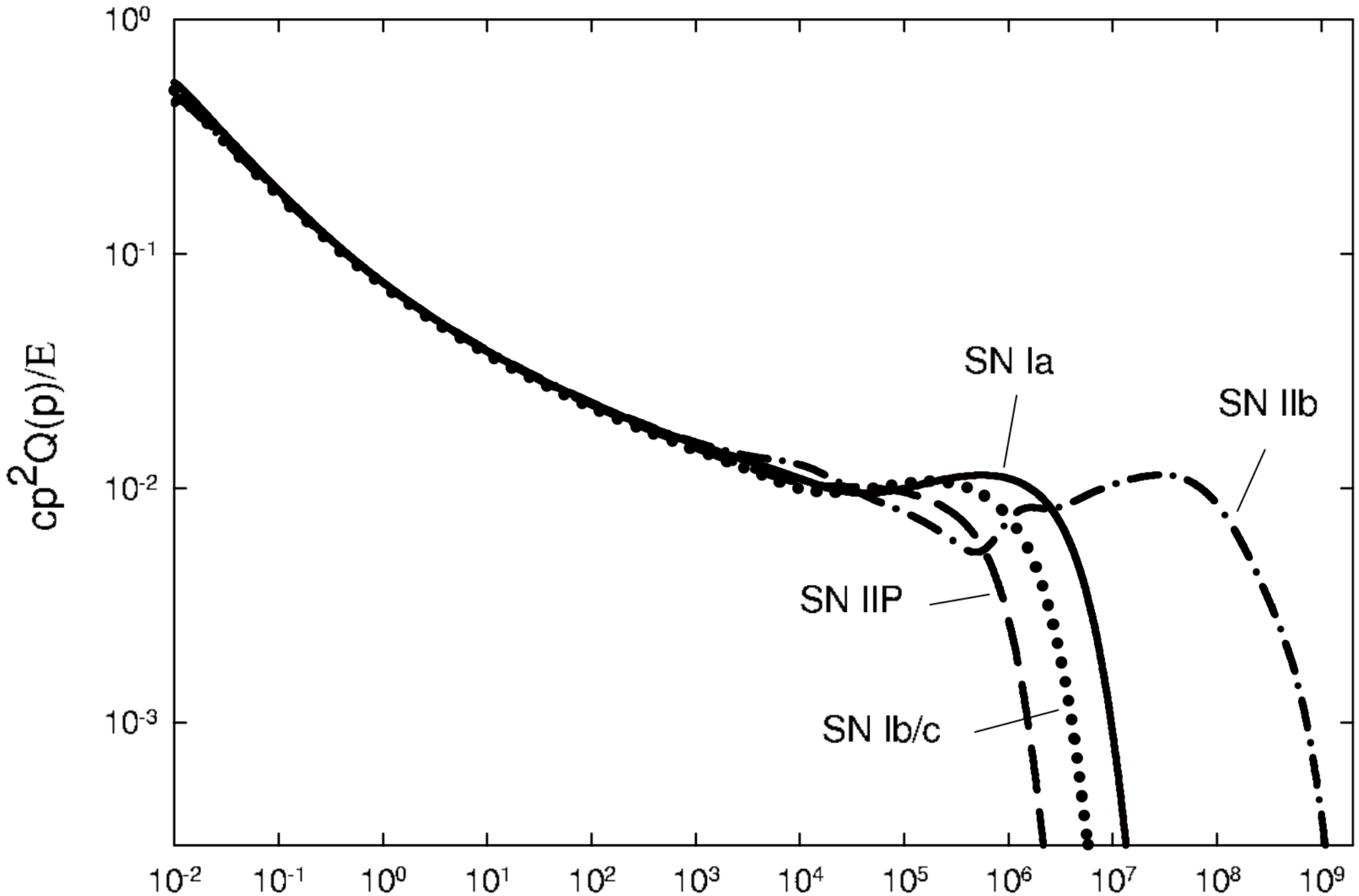


Major problem: no room for other SNRs/ other accelerators

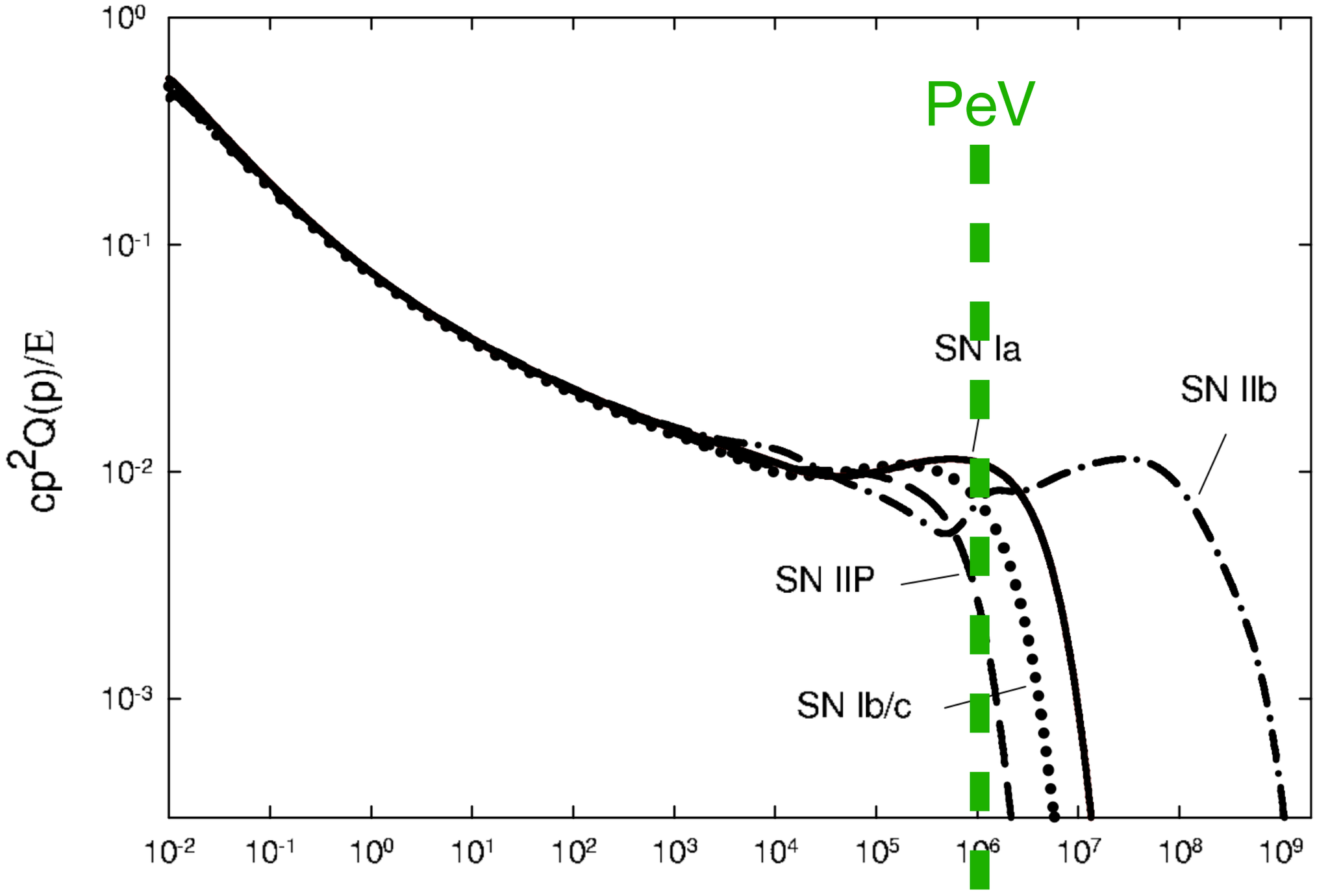
And … below the knee?



With several ‘components’

Ptuskin, Zirakashvili & Seo 2010

And … below the knee?



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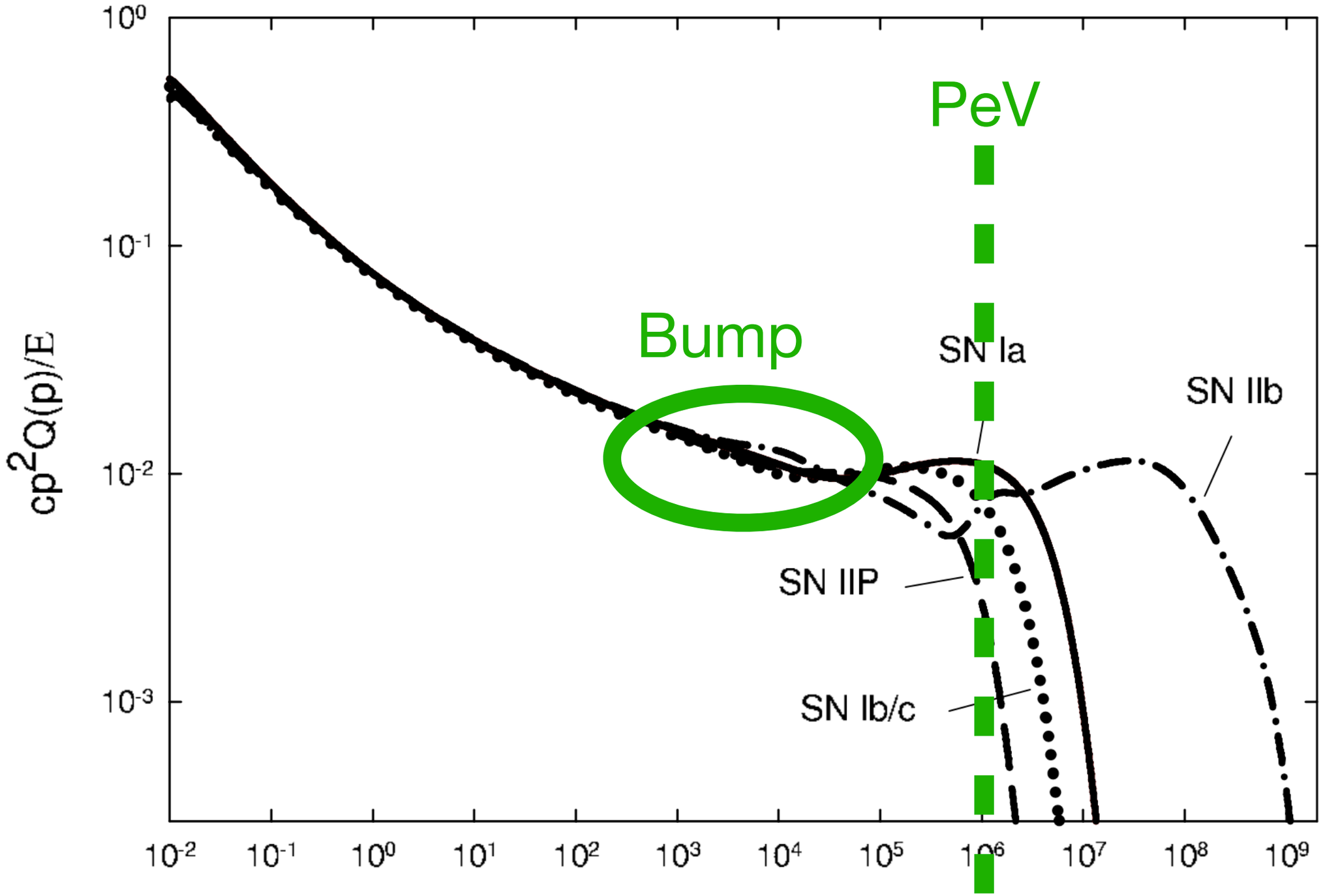

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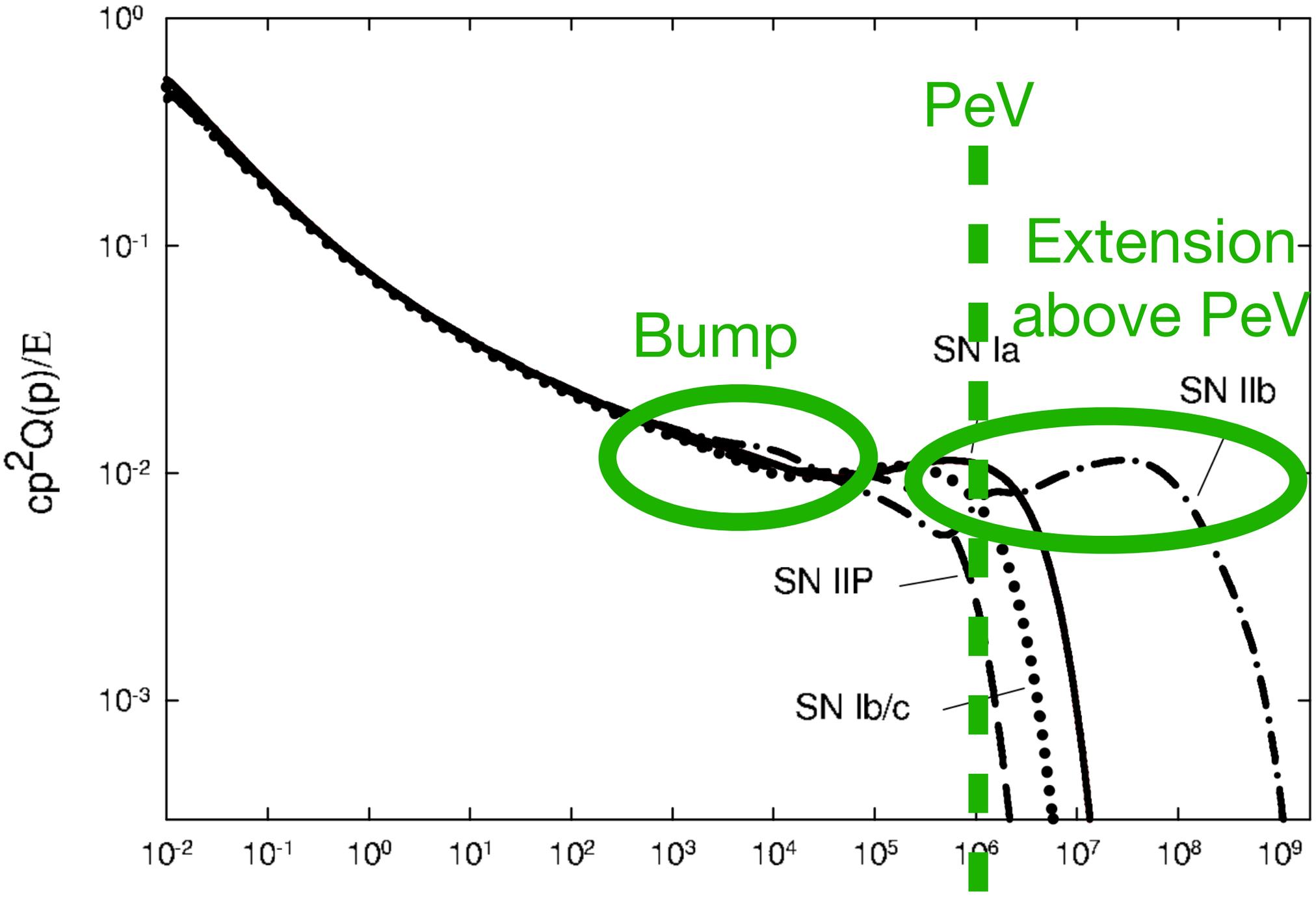

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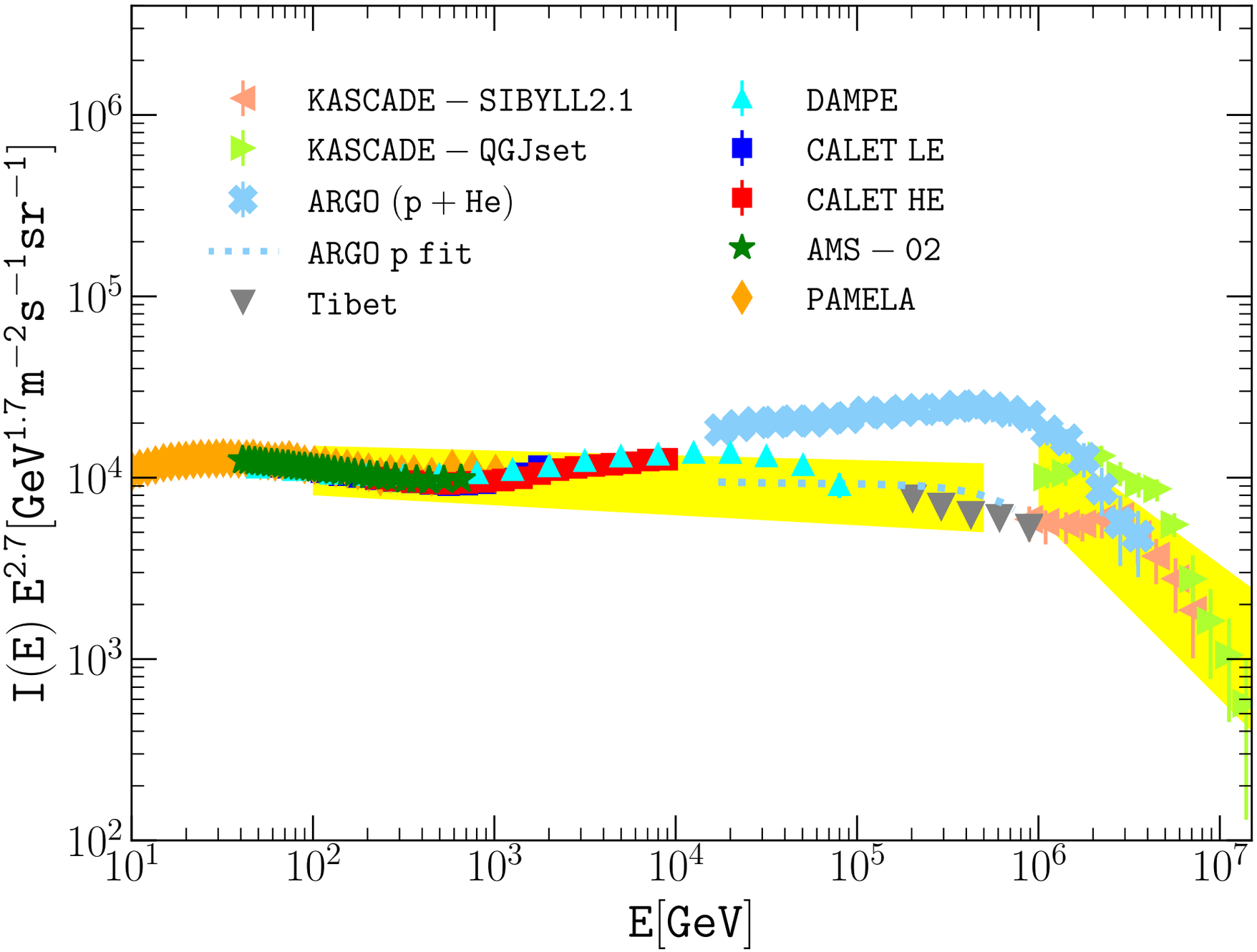

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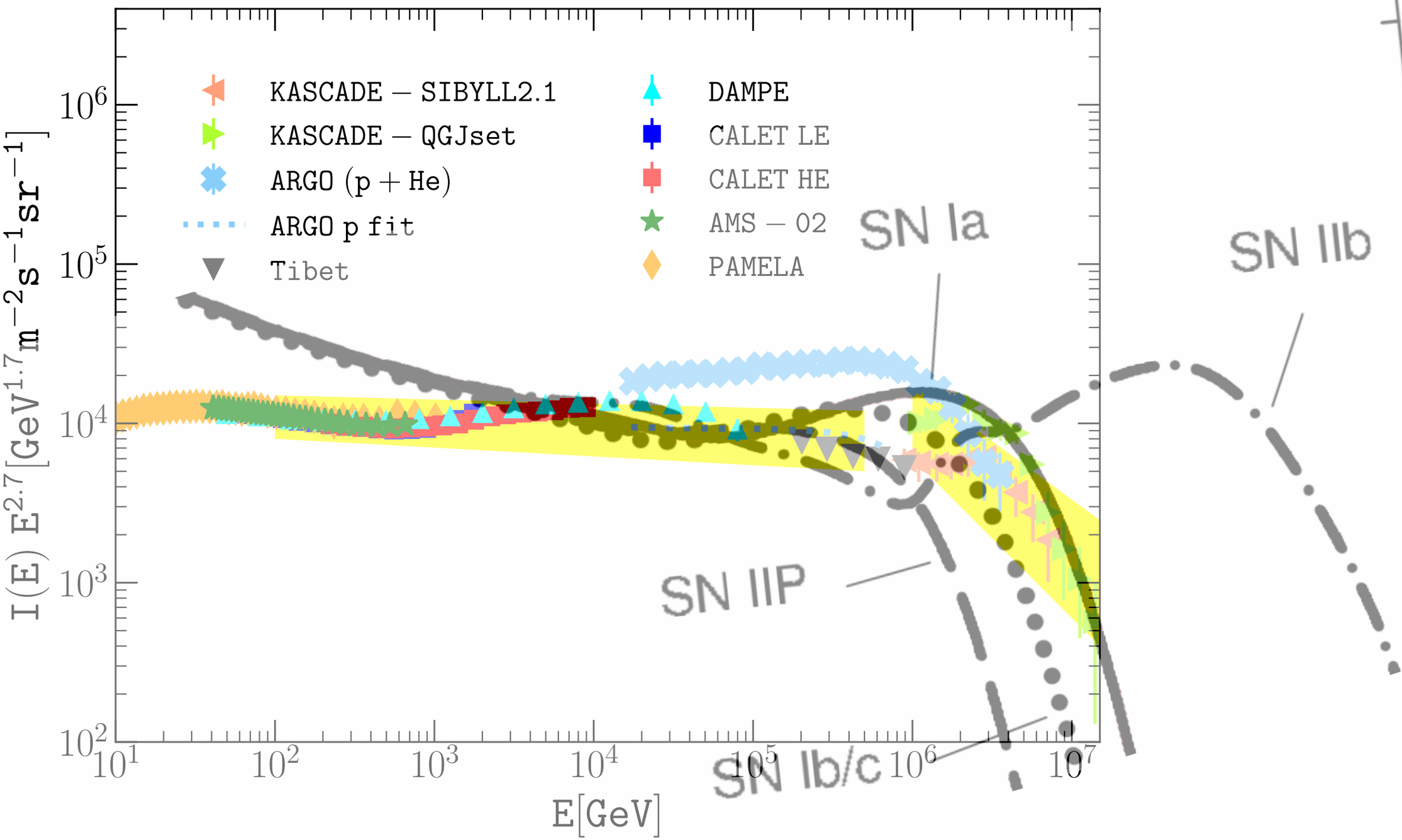

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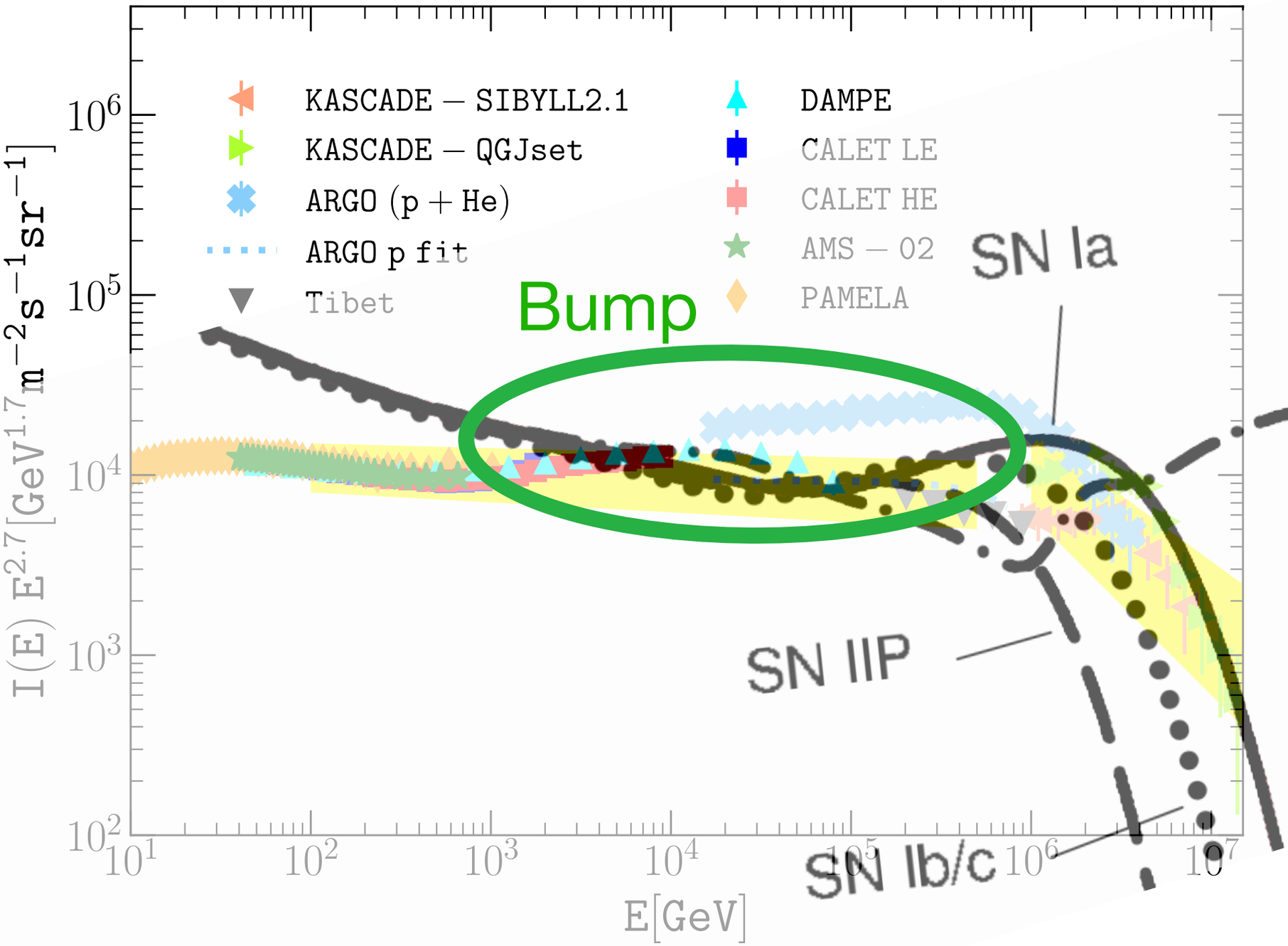

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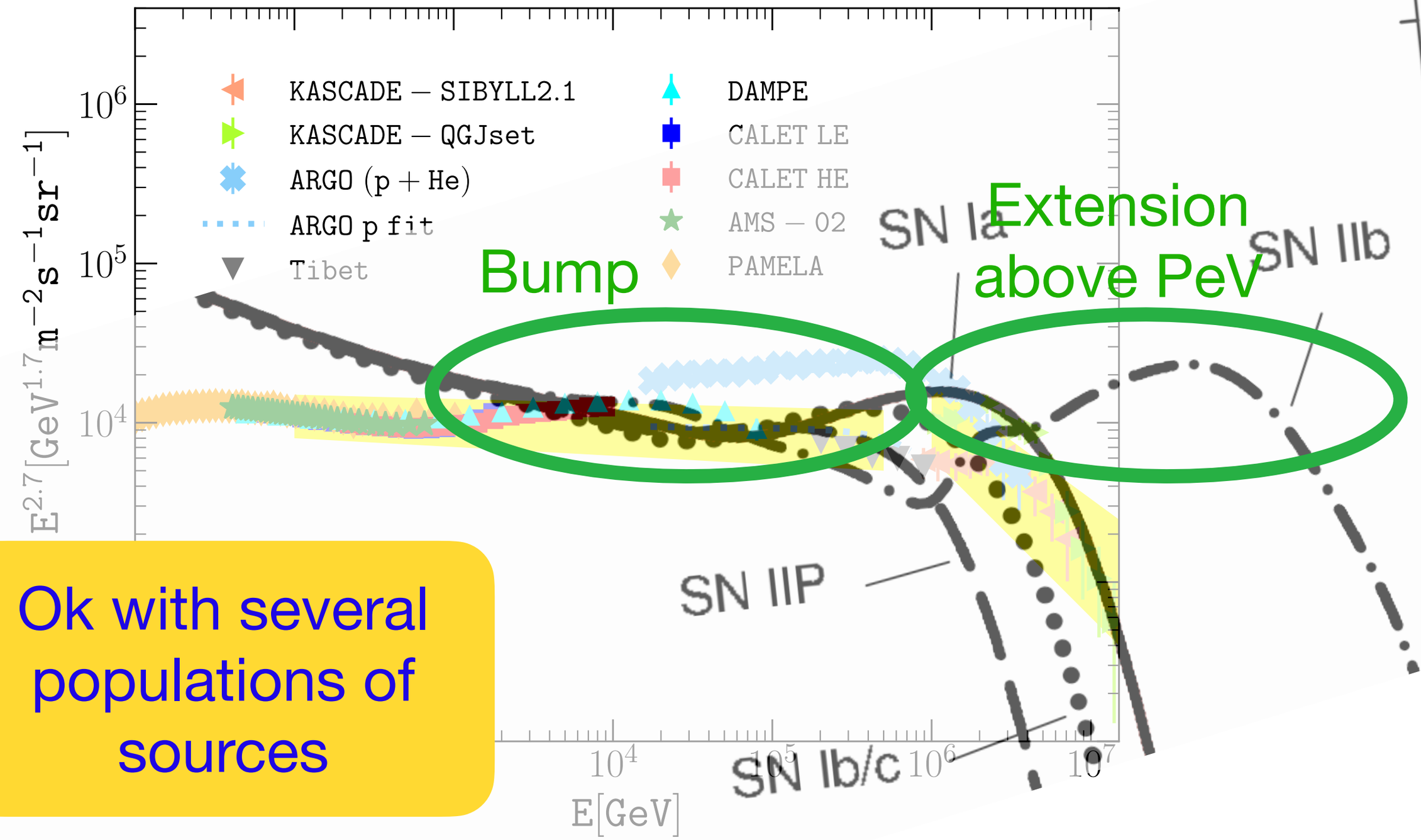
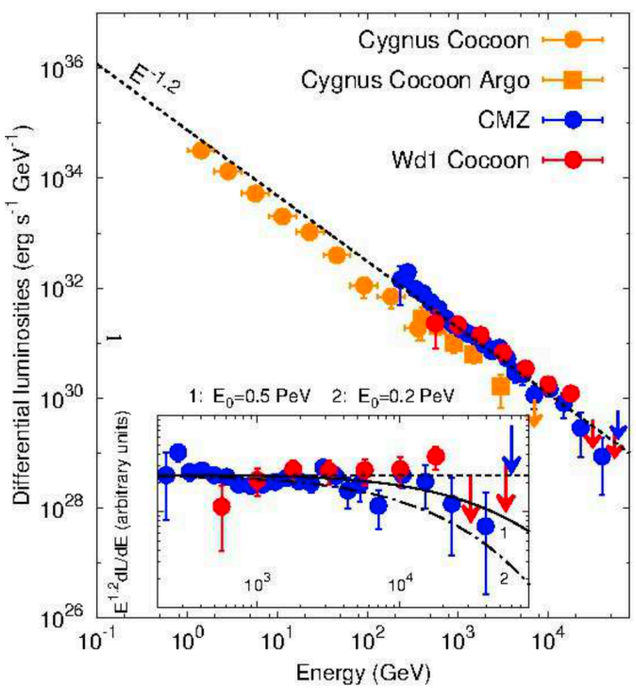
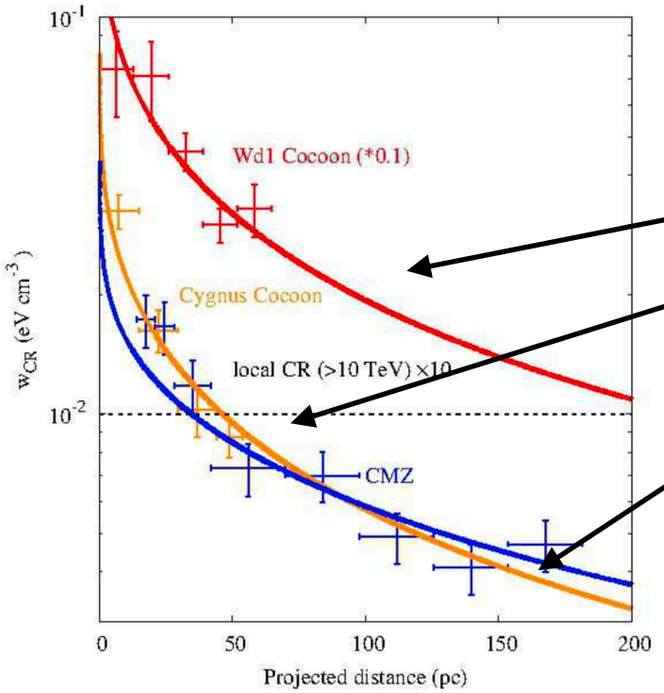


Ok with several populations of sources

Ptuskin, Zirakashvili & Seo 2010

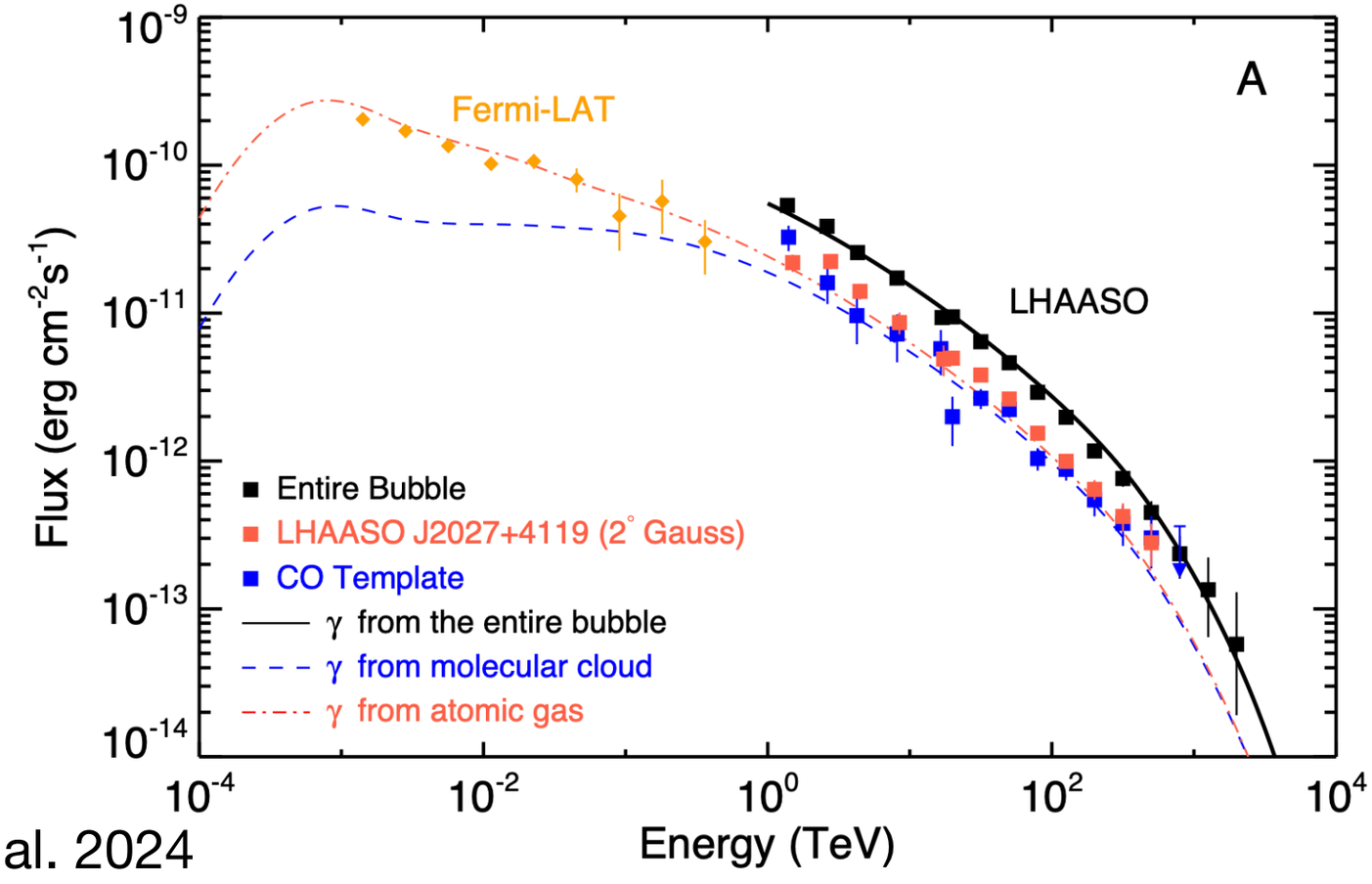
Massive stars and stellar clusters





1/R profile as expected in continuous injection from sources

Aharonian et al. 2019, Yang et al. 2021

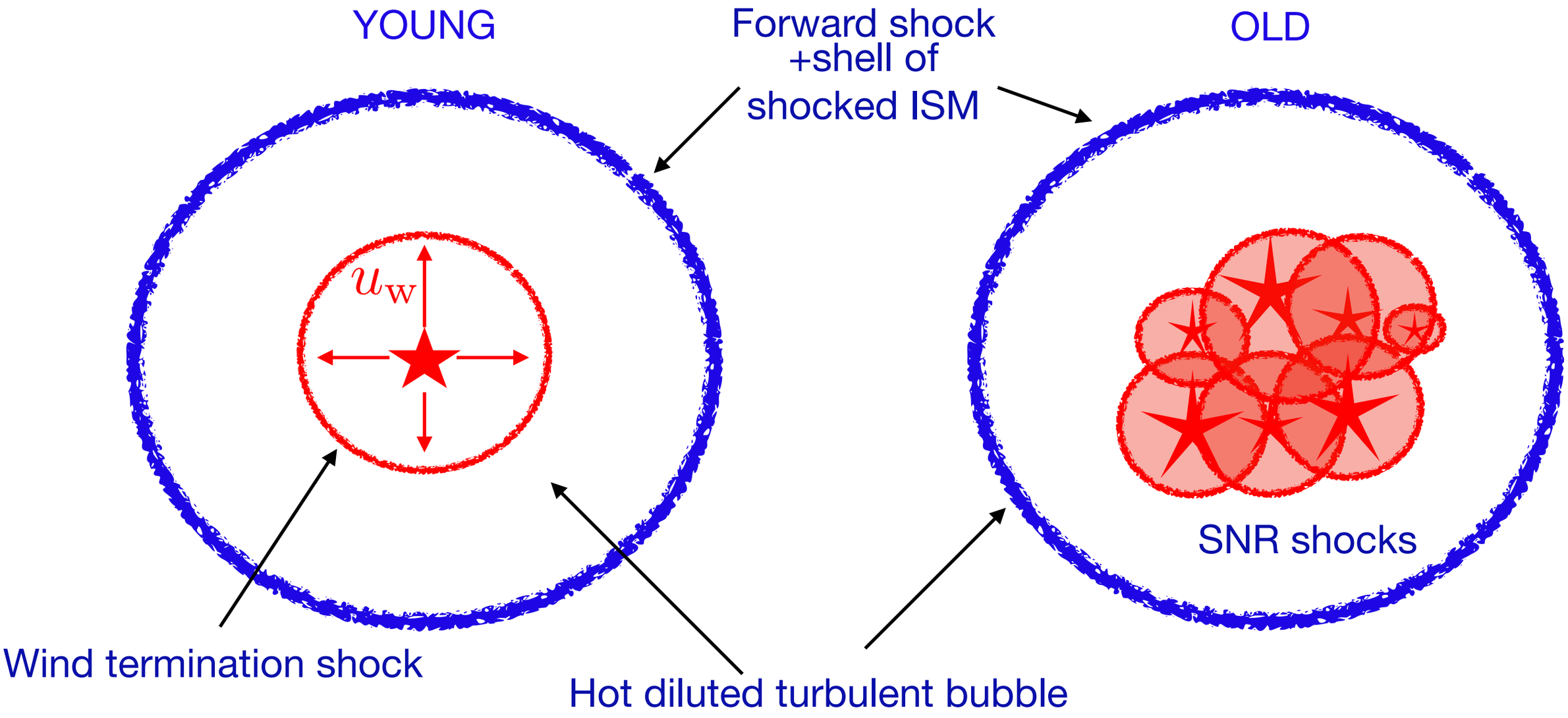


PeV photons!

LHAASO Cao et al. 2024

CRs from stellar clusters and interstellar bubbles

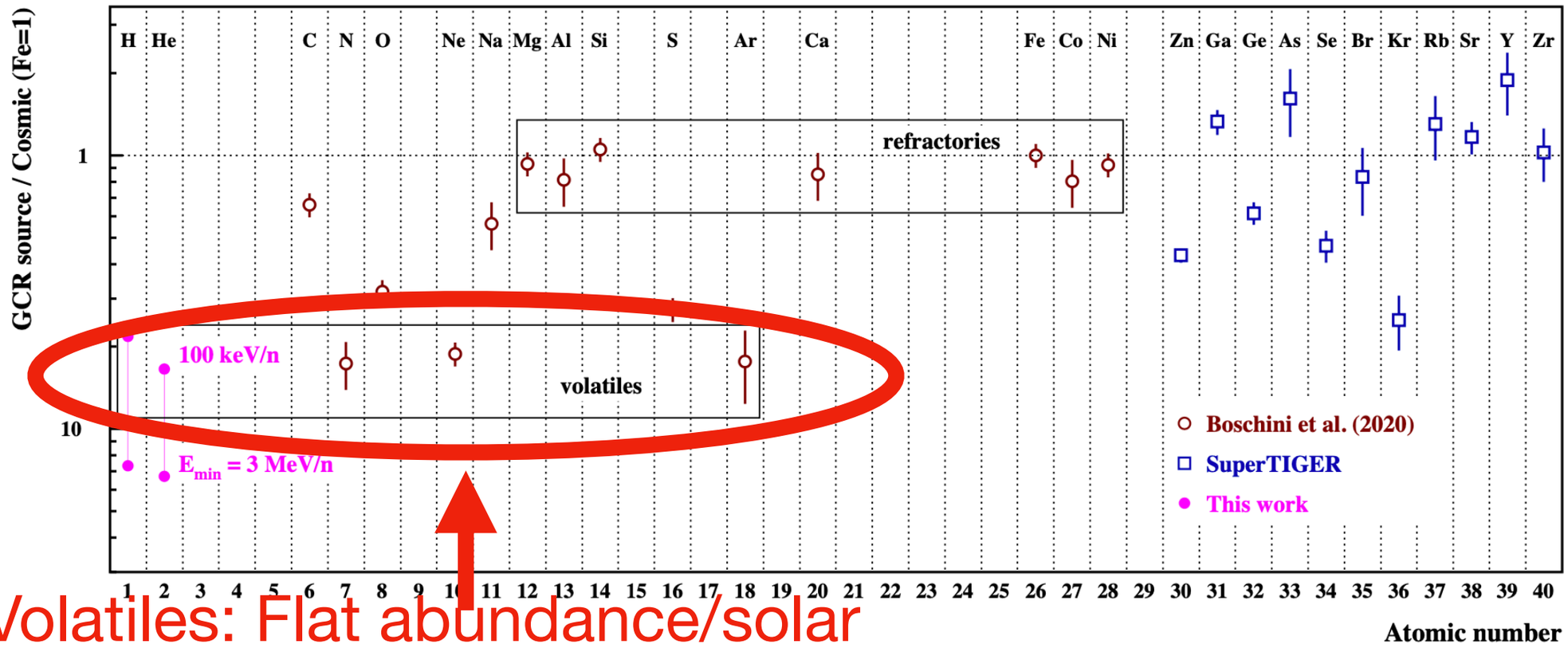
Cassé & Paul 1980,1982; Volk& Forman 1982, Cesarsky & Montmerle 1983; Webb et al. 1985, Bykov et al. 2001 ++, Parizot et al. 2004, Ferrand & Marcowith 2010, Morlino et al. 2021, Vieu et al. 2022, 2023, 2024, Härer et al. 2025 ..



Castor et al. 1975, Weaver et al. 1977, MacCray&Kafatos 1987, MacLow&McCray 1988, Koo&McKee 1992

Explaining the CR composition

CR abundances relative to solar composition (Voyager/AMS/SuperTIGER)



Volatiles: Flat abundance/solar ratio, A/Q ~2 for all elements

Injection from hot medium (superbubbles?)

Tatischeff et al. 2021

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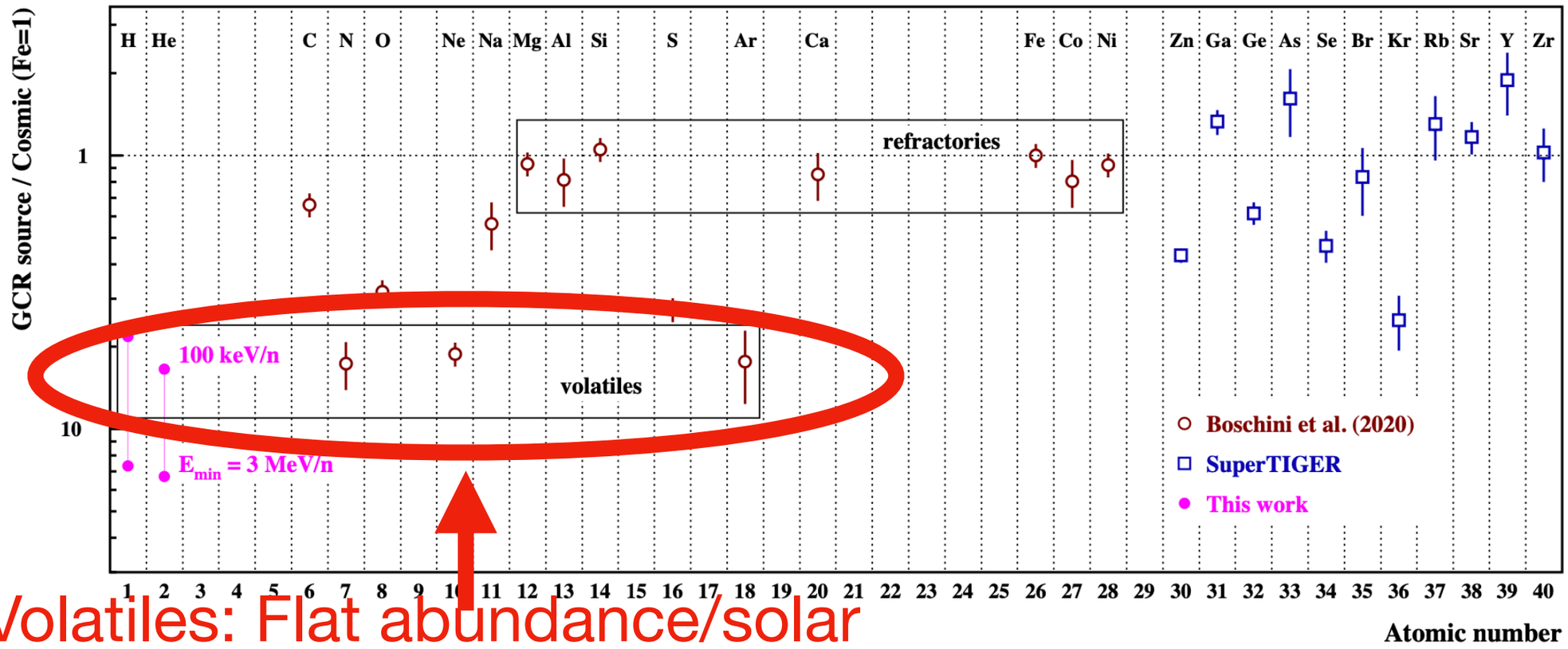


Volatiles: Flat abundance/solar ratio, A/Q ~2 for all elements

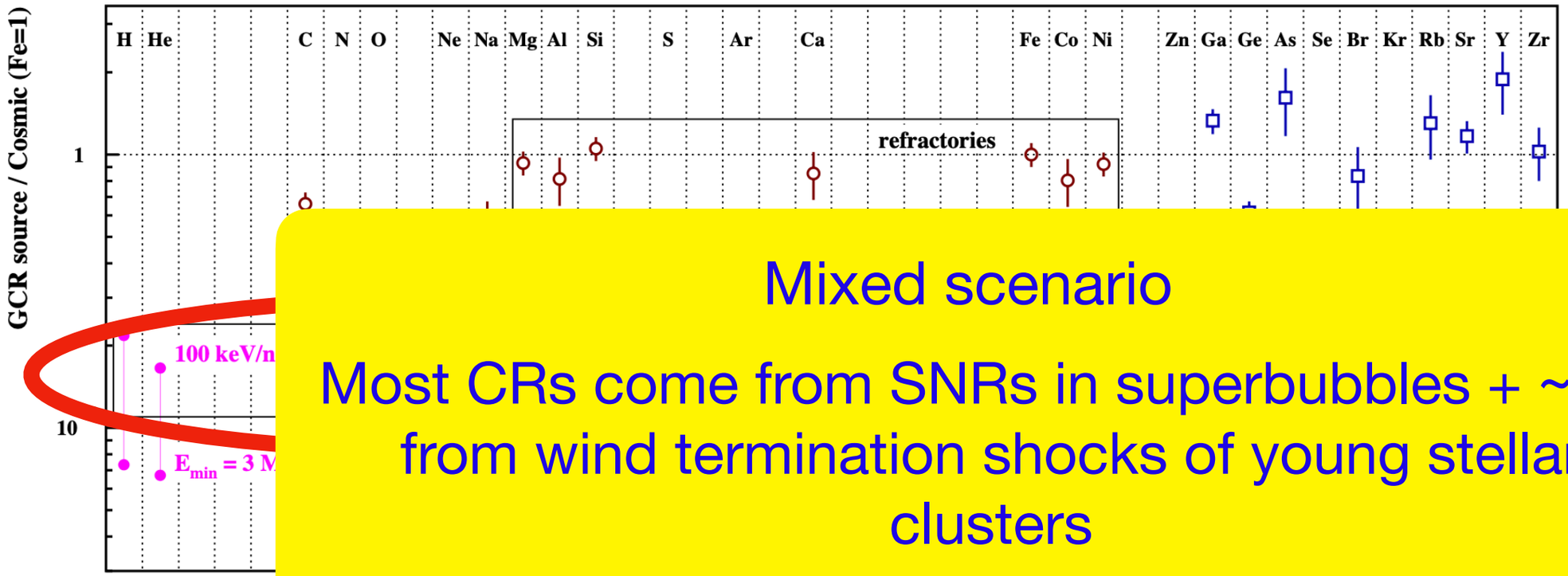
Injection from hot medium (superbubbles?)

	Model 1	Model 2	Model 3	Model 4	Model 5
GCR gas source of SC compo.	70% WNM, 30% WIM	SB	SB	60% SB, 28% WNM, 12% WIM	60% SB, 28% WNM, 12% WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{SB})^a$	–	6.50 ± 0.2	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	26.0 ± 13	17.9 ± 9.7	27.0 ± 13.2	22.8 ± 10.6
W.-R. wind contribution $x_w{}^c$	10.3%	48.9%	(5.1 – 6.1)%	$(55.6^{+1.3}_{-0.3})$%	(7.3 – 7.9)%
χ^2_{min}(GCR dust source)^d	24.6	26.9	25.9	26.0	24.8
χ^2_{min}(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	23.2 ± 9.4	20.2 ± 7.2	24.6 ± 10.2	24.4 ± 9.2
W.-R. wind contribution $x_w{}^c$	10.3%	48.9%	5.9%	56.0%	7.7%
χ^2_{min}(GCR dust source)^d	24.6	28.0	26.9	26.4	25.0
χ^2_{min}(GCR gas source)^e	24.7	32.3	13.2	32.4	18.3

Tatischeff et al. 2021

Explaining the CR composition

CR abundances relative to solar composition (Voyager/AMS/SuperTIGER)



Mixed scenario

Most CRs come from SNRs in superbubbles + ~5% from wind termination shocks of young stellar clusters

Volatiles: Flat abundances, solar ratio, A/Q ~2 for all elements

Injection from hot medium (superbubbles?)

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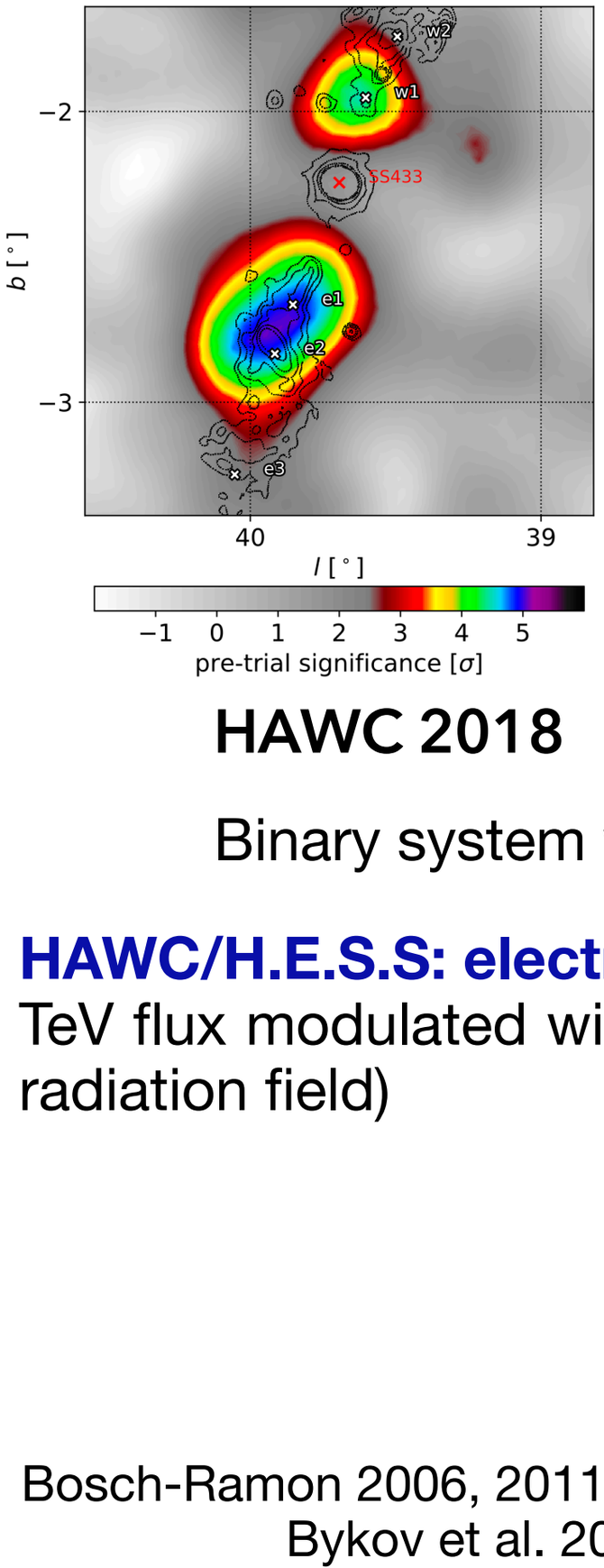
GCR gas source of SC compo.	70% WNM, 30% WIM	SB	SB	60% SB, 28% WNM, 12% WIM	60% SB, 28% WNM, 12% WIM
^{22}Ne-rich GCR gas source	Accelerated winds	Winds in SB	Accelerated winds	Winds in SB	Accelerated winds
SB temperature $\log(T_{SB})^a$	–	6.50 ± 0.2	> 6.45	$6.5^{+0.3}_{-0.2}$	> 6.35
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	26.0 ± 13.2	17.9 ± 9.7	27.0 ± 13.2	22.8 ± 10.6
W.-R. wind contribution $x_w{}^c$	10.3%	48.9%	(5.1 – 6.1)%	$(55.6^{+1.3}_{-0.3})$%	(7.3 – 7.9)%
χ^2_{min}(GCR dust source)^d	24.6	26.9	25.9	26.0	24.8
χ^2_{min}(GCR gas source)^e	24.7	31.1	12.2	31.4	16.7
SB temperature $\log(T_{SB})$	–	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)	6.6 (fixed)
Relative eff. $\epsilon = \epsilon_{dust}/\epsilon_{gas}{}^b$	33.8 ± 13.4	23.2 ± 9.4	20.2 ± 7.2	24.6 ± 10.2	24.4 ± 9.2
W.-R. wind contribution $x_w{}^c$	10.3%	48.9%	5.9%	56.0%	7.7%
χ^2_{min}(GCR dust source)^d	24.6	28.0	26.9	26.4	25.0
χ^2_{min}(GCR gas source)^e	24.7	32.3	13.2	32.4	18.3

Tatischeff et al. 2021

Microquasars: the case of SS433



HAWC 2018

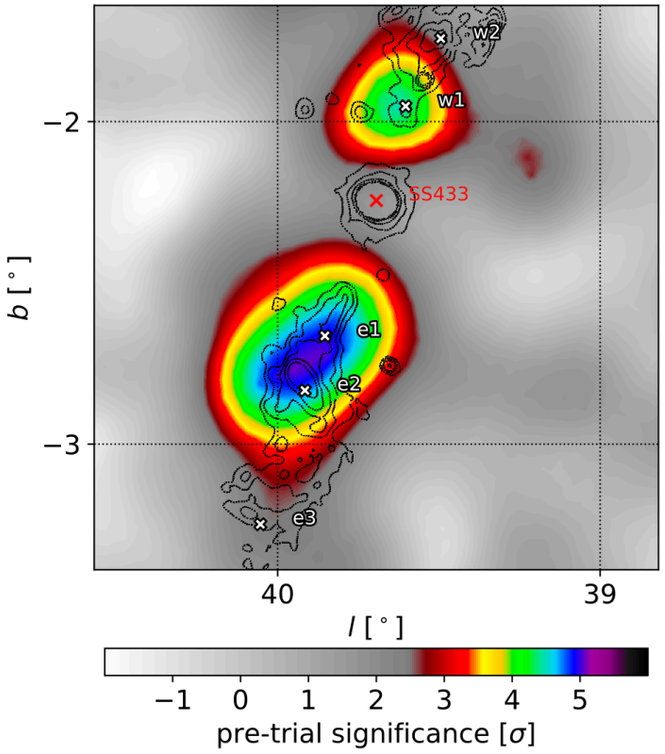
Binary system with black hole, accretion disk, jets

HAWC/H.E.S.S: electrons?

TeV flux modulated with orbital period (very fast cooling due to intense stellar radiation field)

Bosch-Ramon 2006, 2011, Orelanna et al. 2007, Vila&Romero 2010, Khangulyan et al. 2024, Bykov et al. 2024, Peretti et al. 2025, Fujita et al. 2026 + many more

Microquasars: the case of SS433



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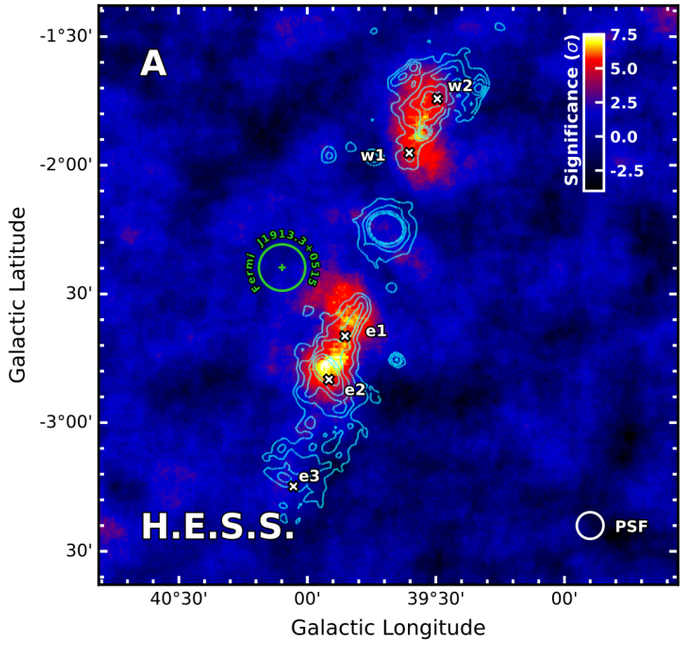
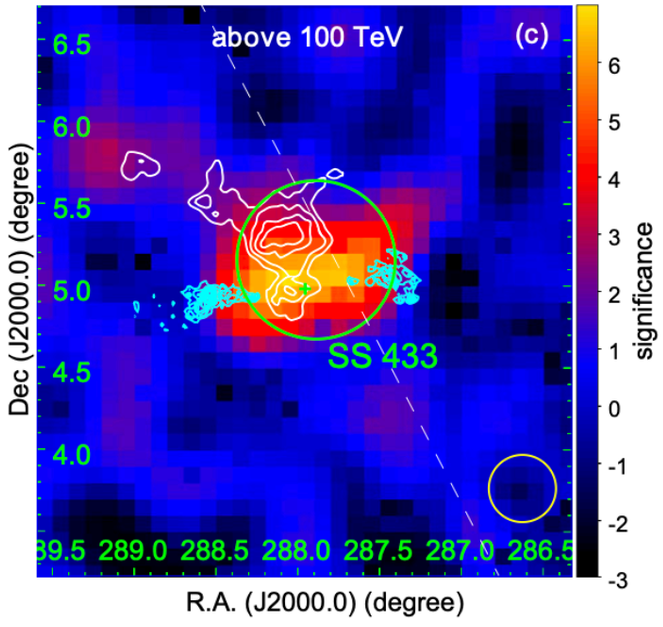


HESS 2024



LHAASO 2025

+3 others

Binary system with black hole, accretion disk, jets

HAWC/H.E.S.S: electrons?

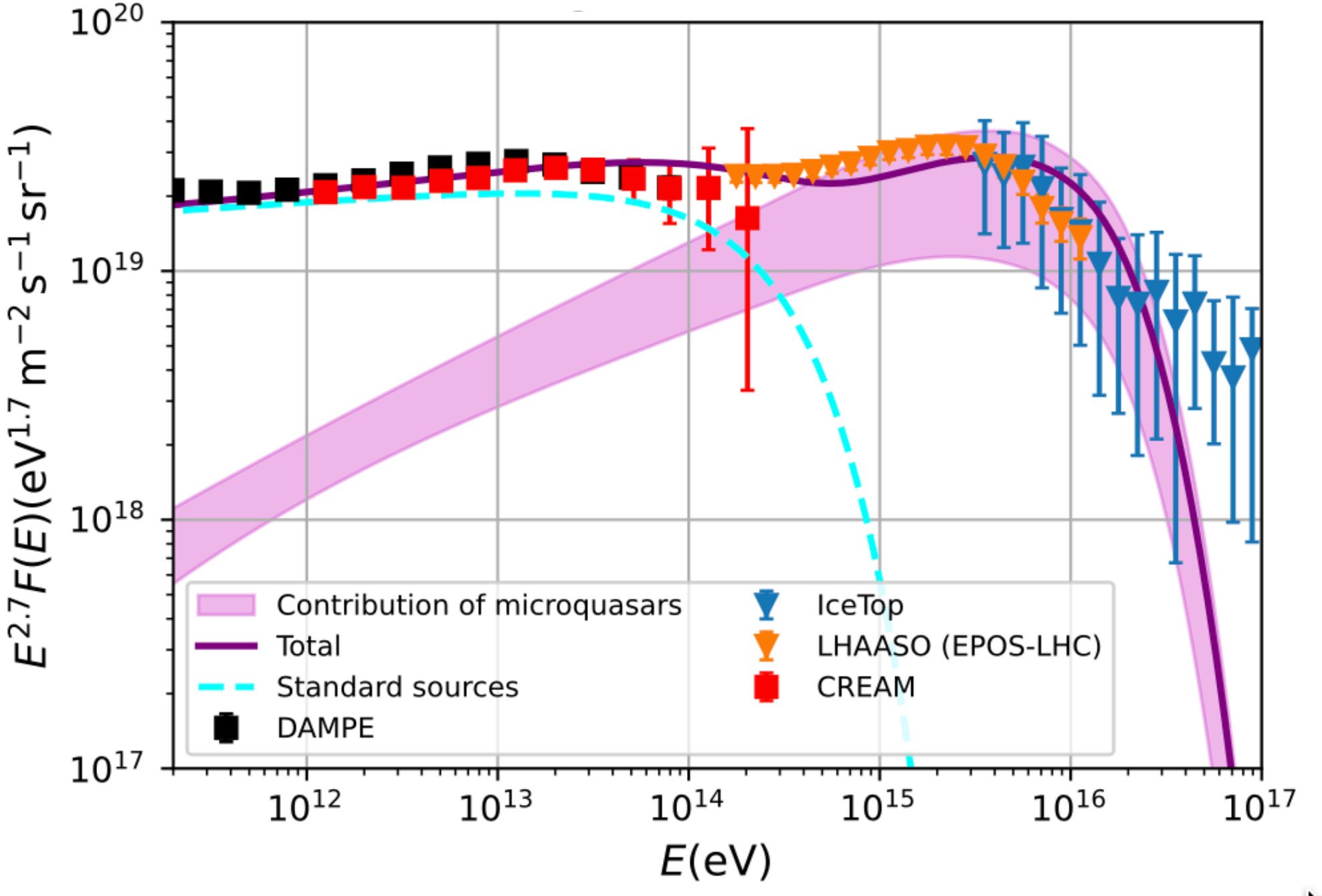
TeV flux modulated with orbital period (very fast cooling due to intense stellar radiation field)

LHAASO: electrons + protons

Particle acceleration: DSA? At which shocks (internal, forward, recollimation shocks?)? Fermi II? Shear acceleration? Magnetic reconnection?

Bosch-Ramon 2006, 2011, Orelanna et al. 2007, Vila&Romero 2010, Khangulyan et al. 2024, Bykov et al. 2024, Peretti et al. 2025, Fujita et al. 2026 + many more

Mixed contribution?

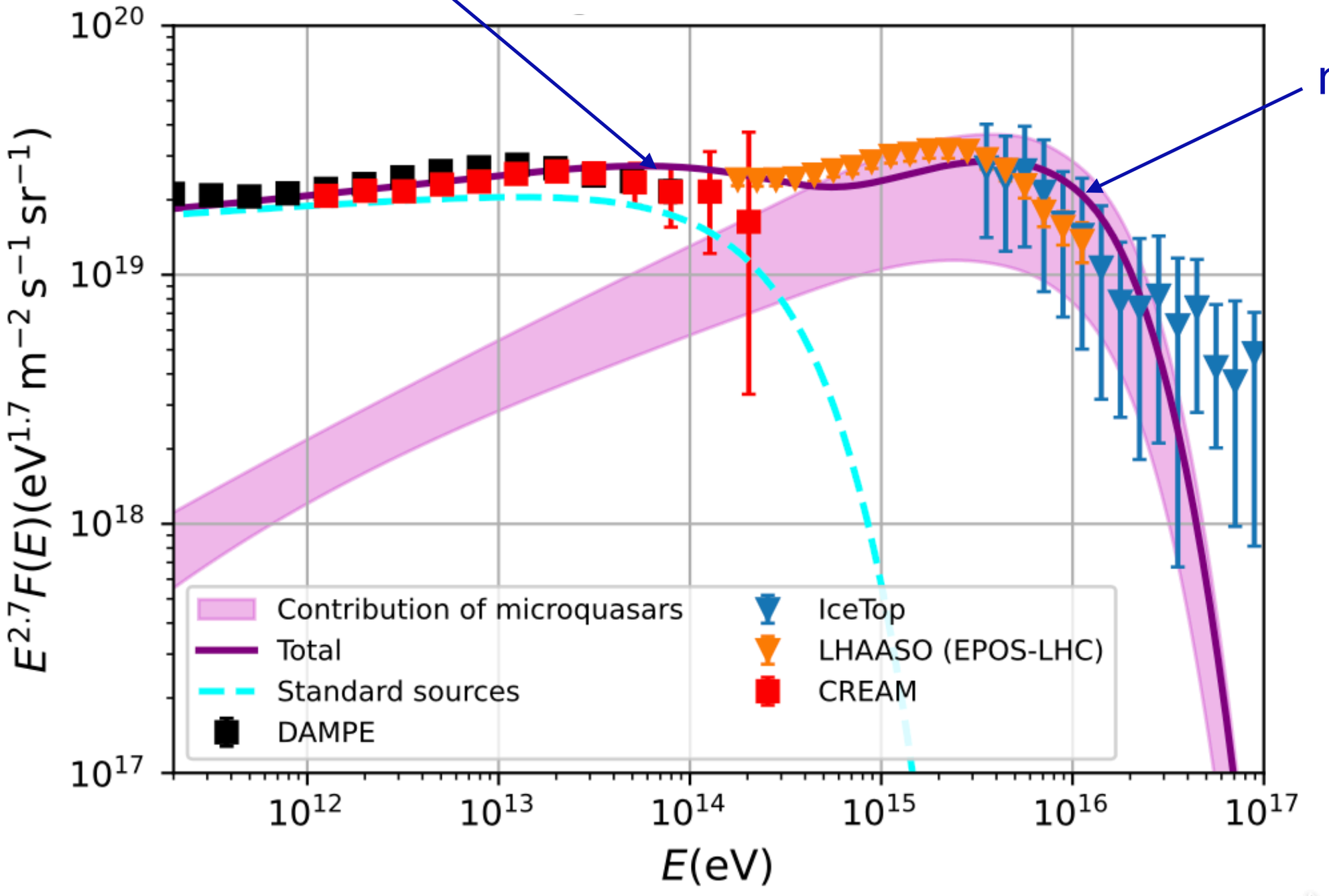


Kaci et al. 2025

Mixed contribution?

Massive stars, SNRs?

10 Powerful microquasars



Kaci et al. 2025

Consensual pictures

Supernova remnants

must play a role in producing Galactic of CRs, but face issues (exact spectrum accelerated and injected, efficiency)

could be pevatrons (rare and unusual events, or specific environments?)

Massive stars, star clusters, winds

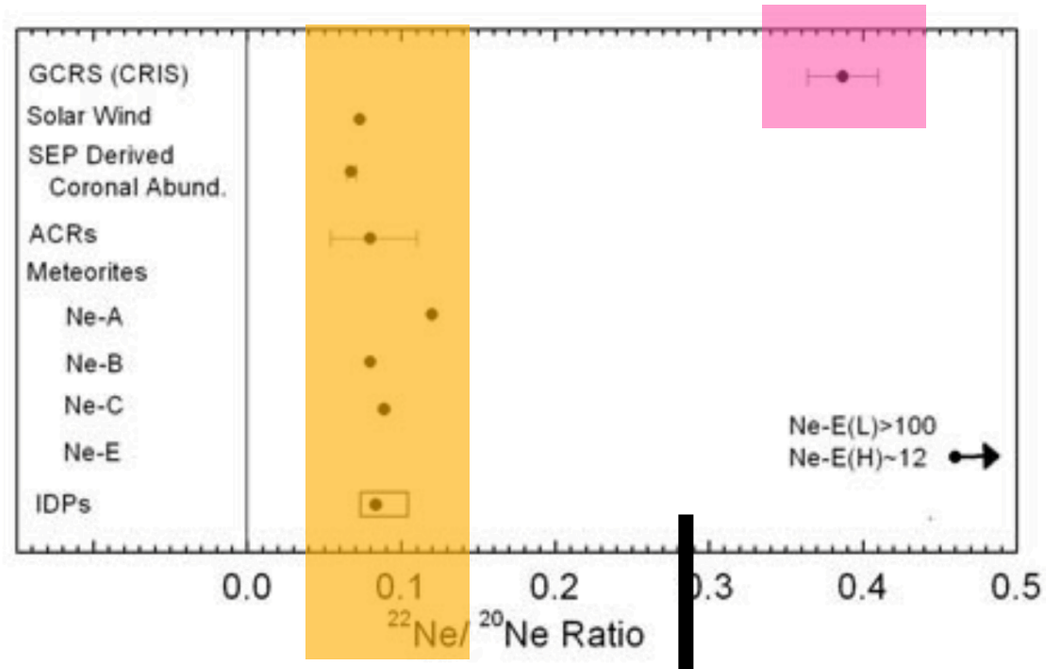
play a role in producing Galactic of CRs
needed to account for CR composition
pevatrons, but efficient enough?

Microquasars

definitely pevatrons
contribution lower energy?
superpevatrons?

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

Local ISM (today + 4.5 Gyr ago)



Stellar winds termination shocks

Wolf-Rayet winds (^{22}Ne enriched)

Binns et al. 2005, Prantzos 2012,
Tatischeff et al. 2018

Summary

Supernova remnants, massive stars, star clusters, superbubbles, wind termination shocks, unusual objects

Several open problems (spectrum? Efficiency? Escape around sources?) for all of these candidates: interesting even if not pevatrons!

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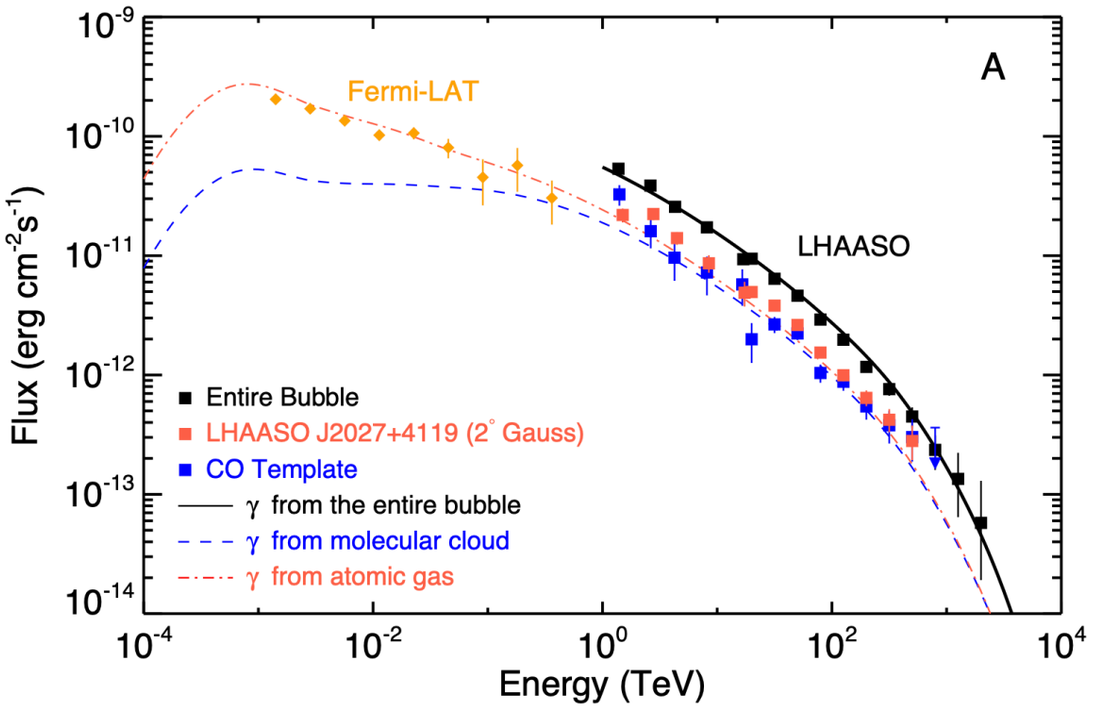

Cygnus cocoon LHAASO 2024

Summary

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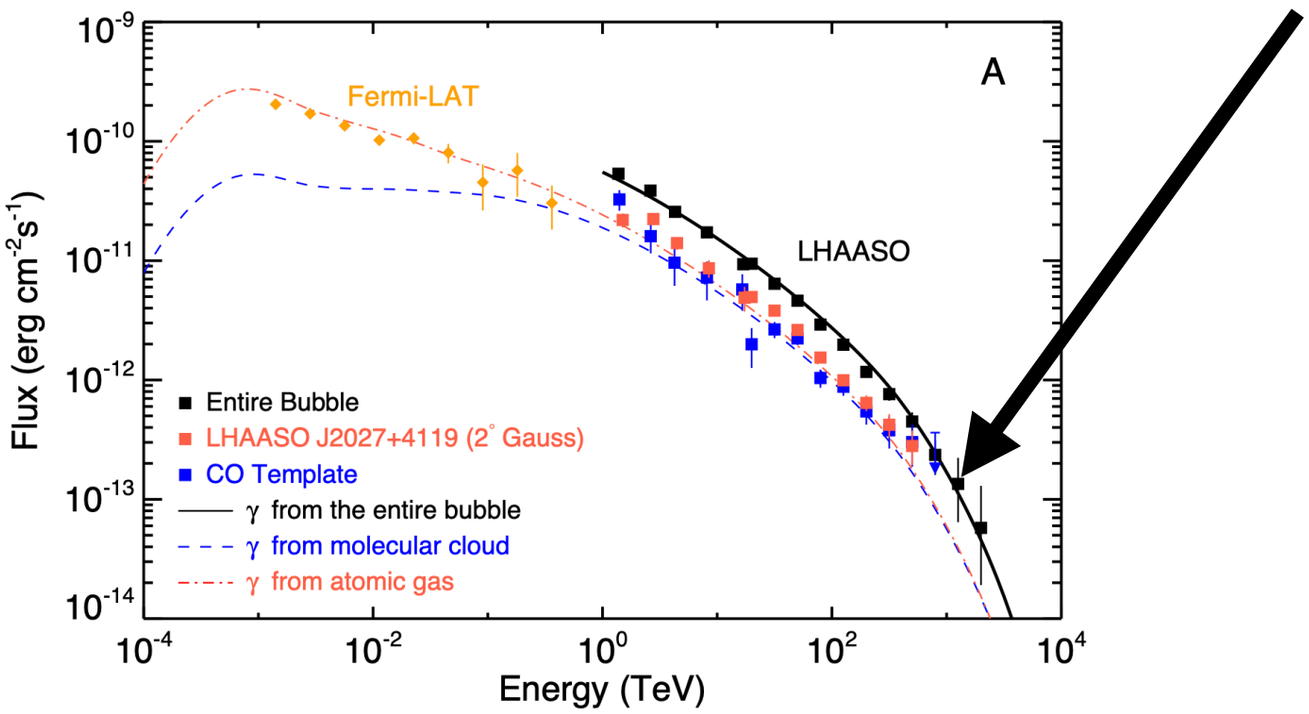


Cygnus cocoon LHAASO 2024

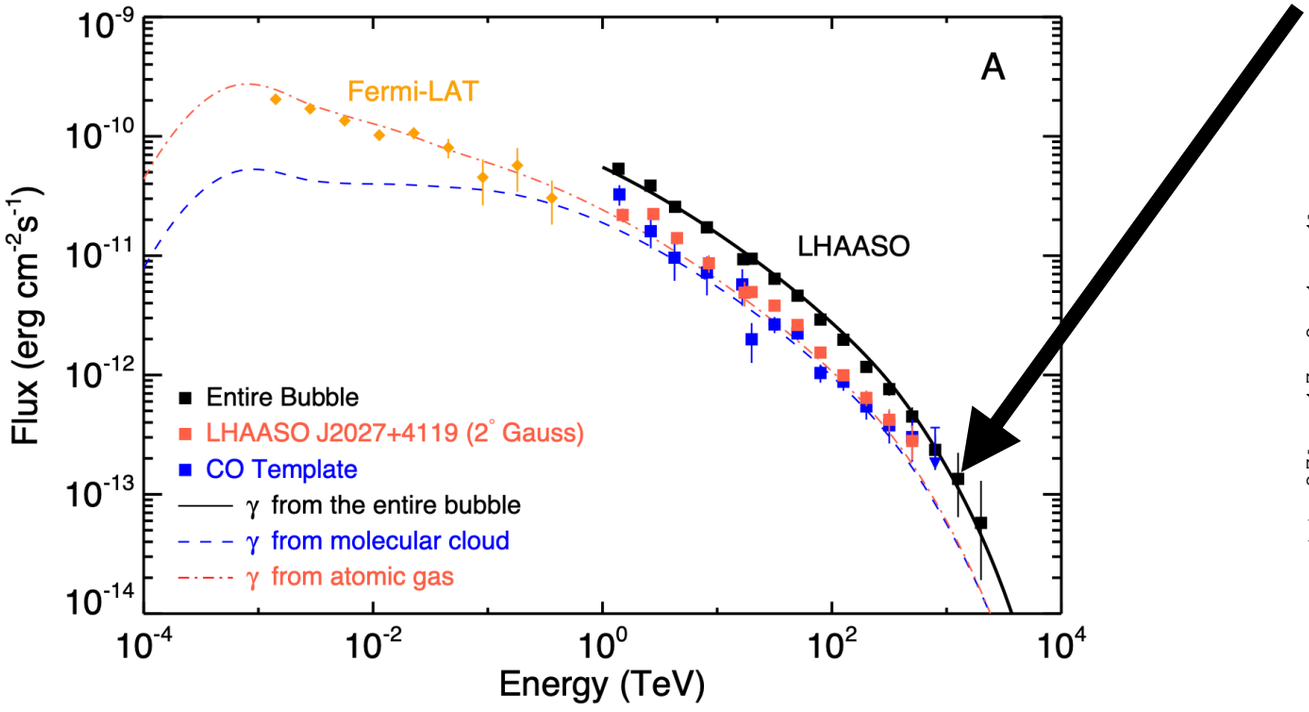
Summary

Supernova remnants, massive stars, star clusters, superbubbles, wind termination shocks, unusual objects

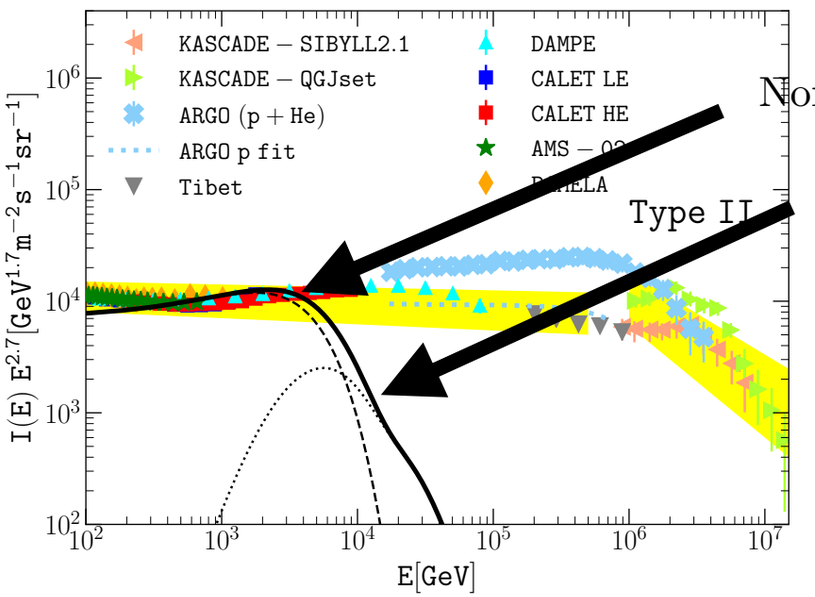
Several open problems (spectrum? Efficiency? Escape around sources?) for all of these candidates: interesting even if not pevatrons!

What does it mean to be a pevatron?

Very sensitive instruments can detect very few PeV particles important for CR: Efficient pevatrons-superpevatrons



Cygnus cocoon LHAASO 2024



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

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

THE END