The transition from Galactic to extragalactic cosmic rays

Pierre Cristofari
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UHECR 2022

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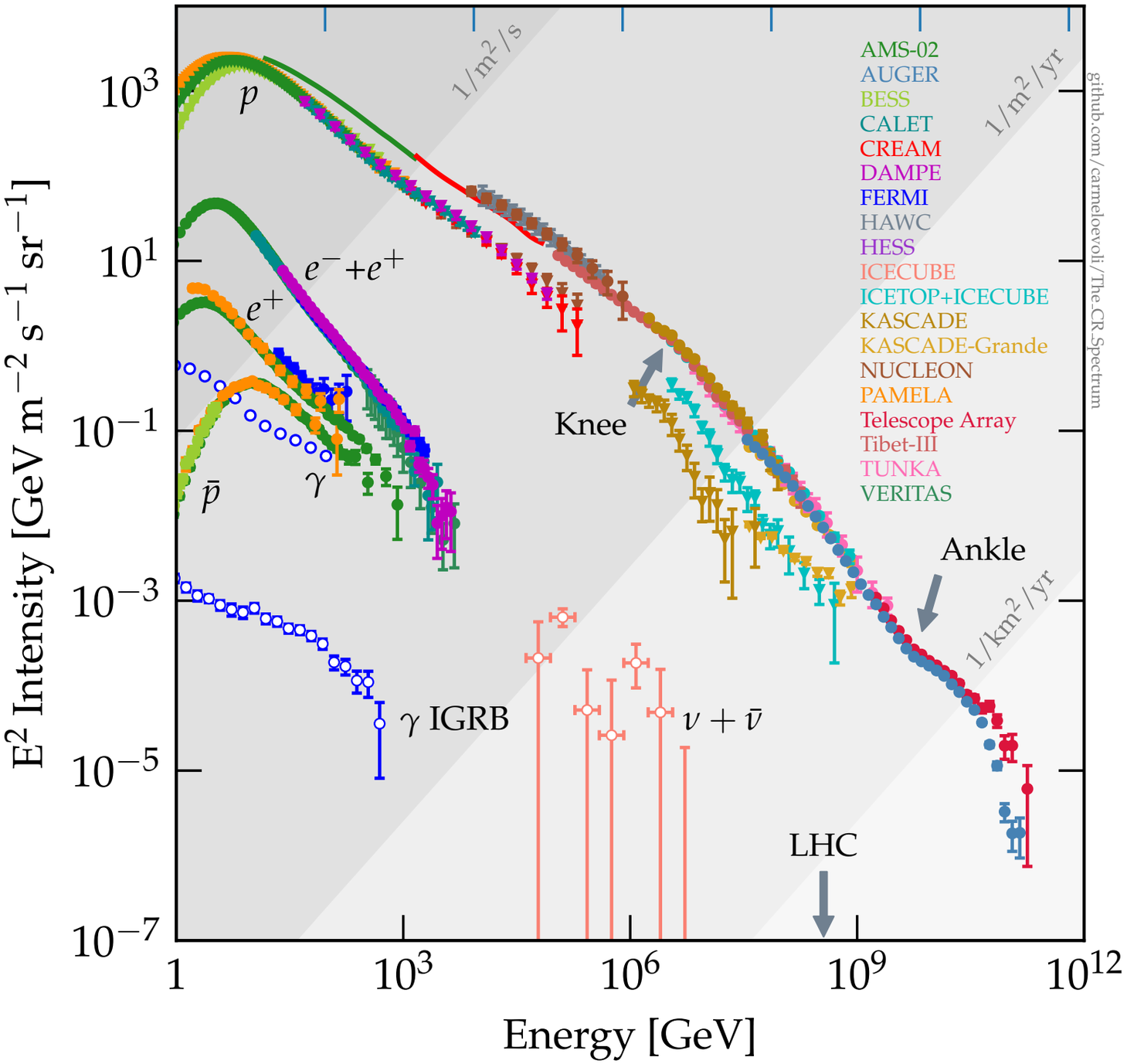

Evoli 2021

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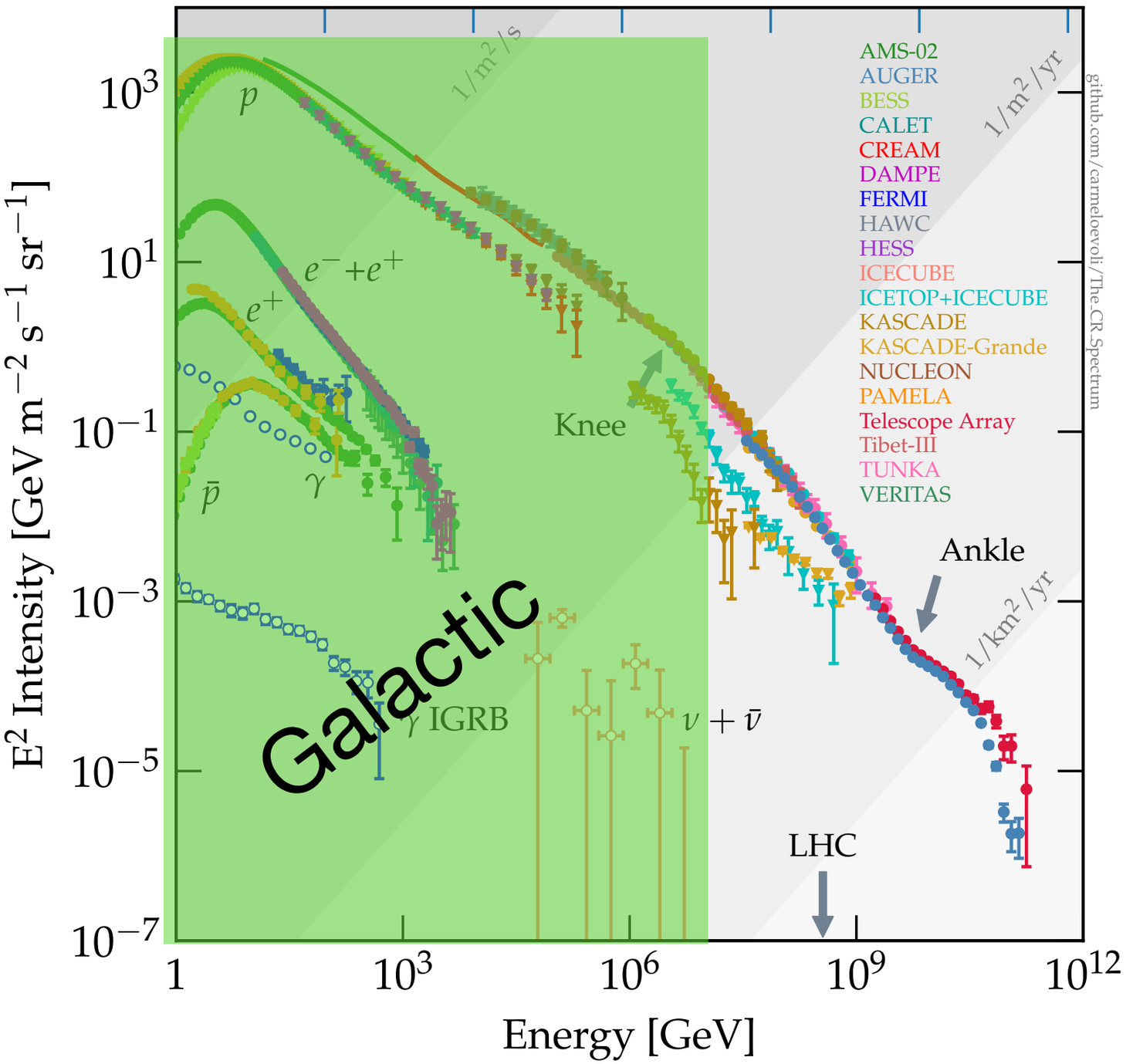

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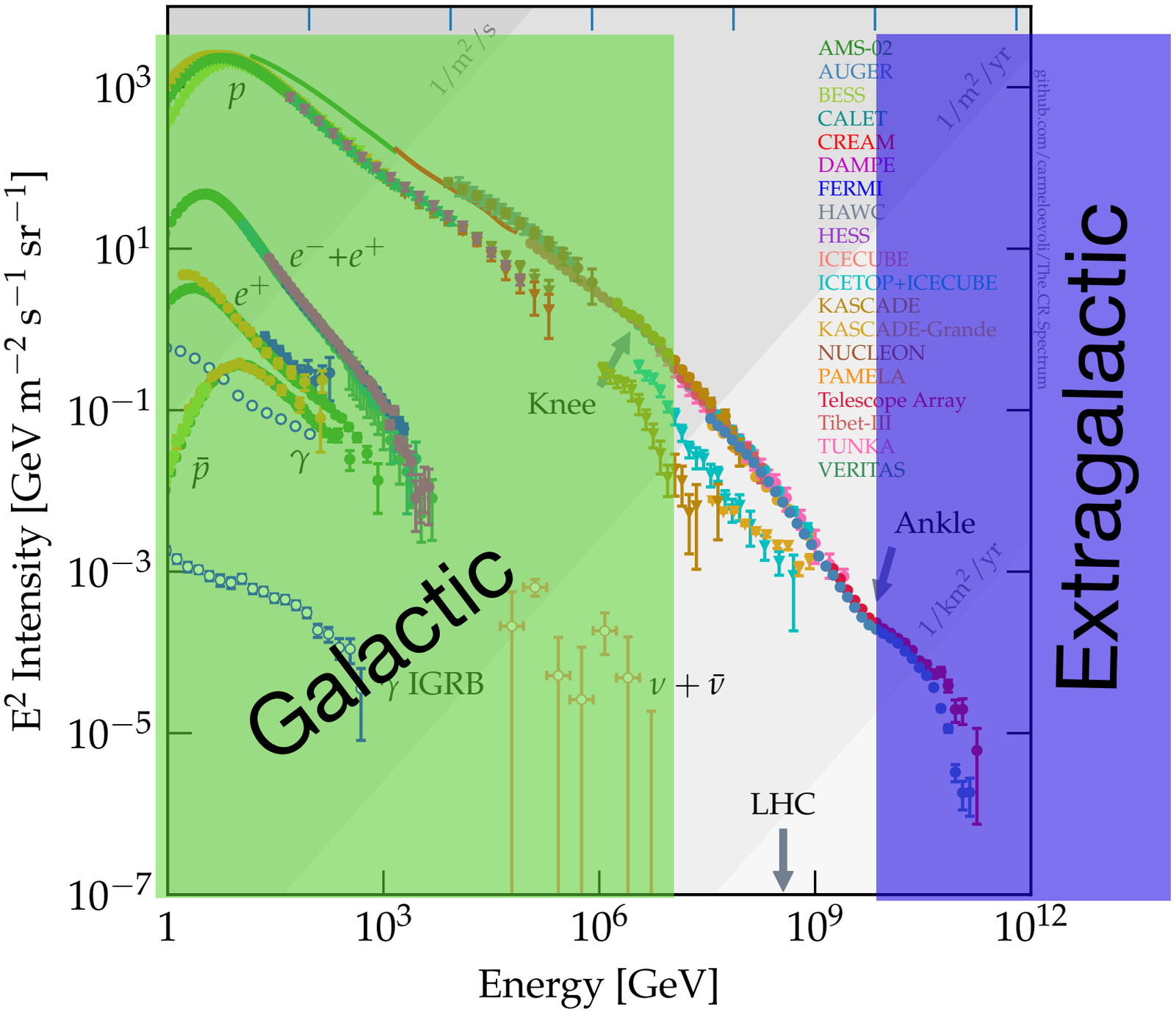

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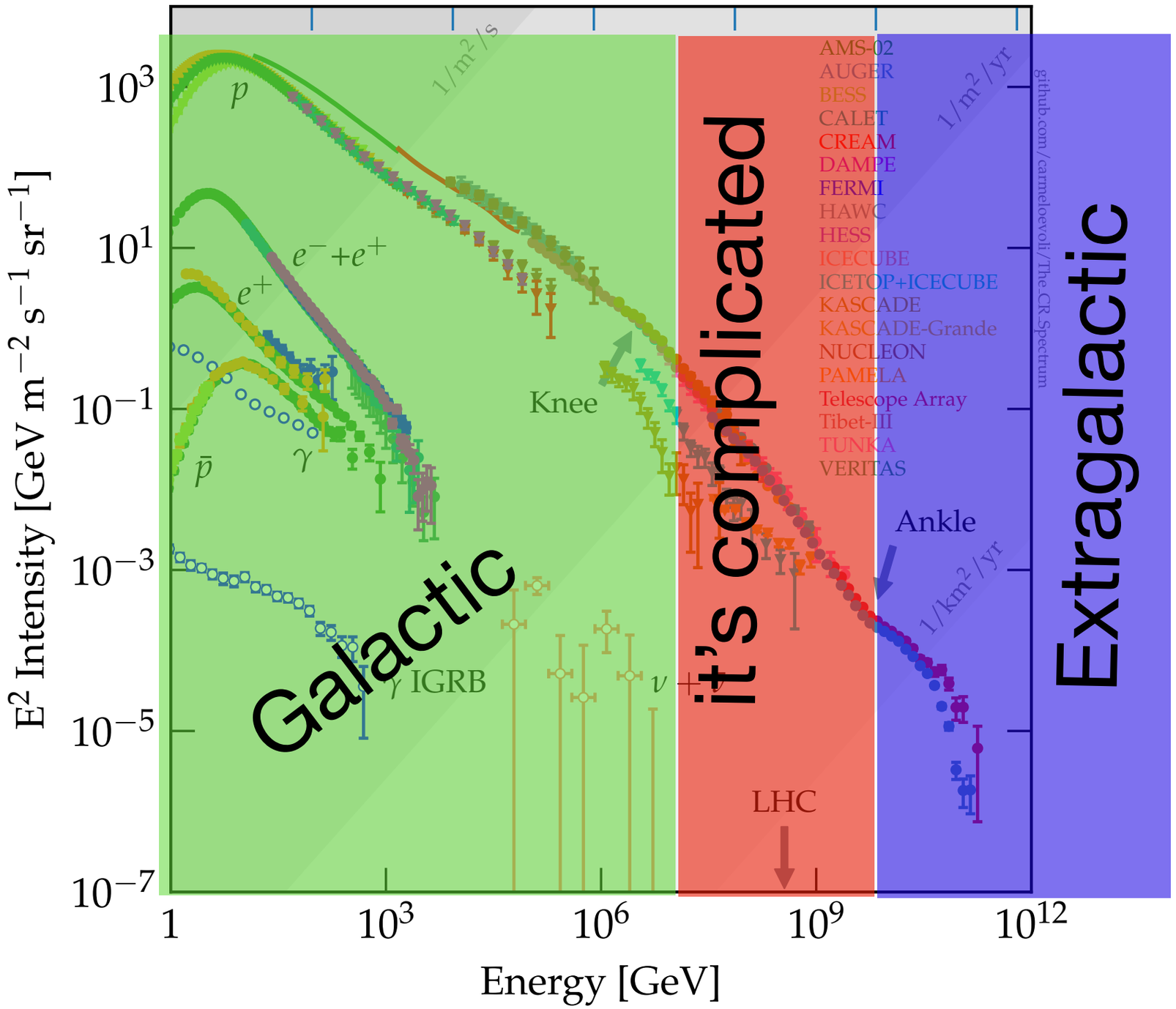

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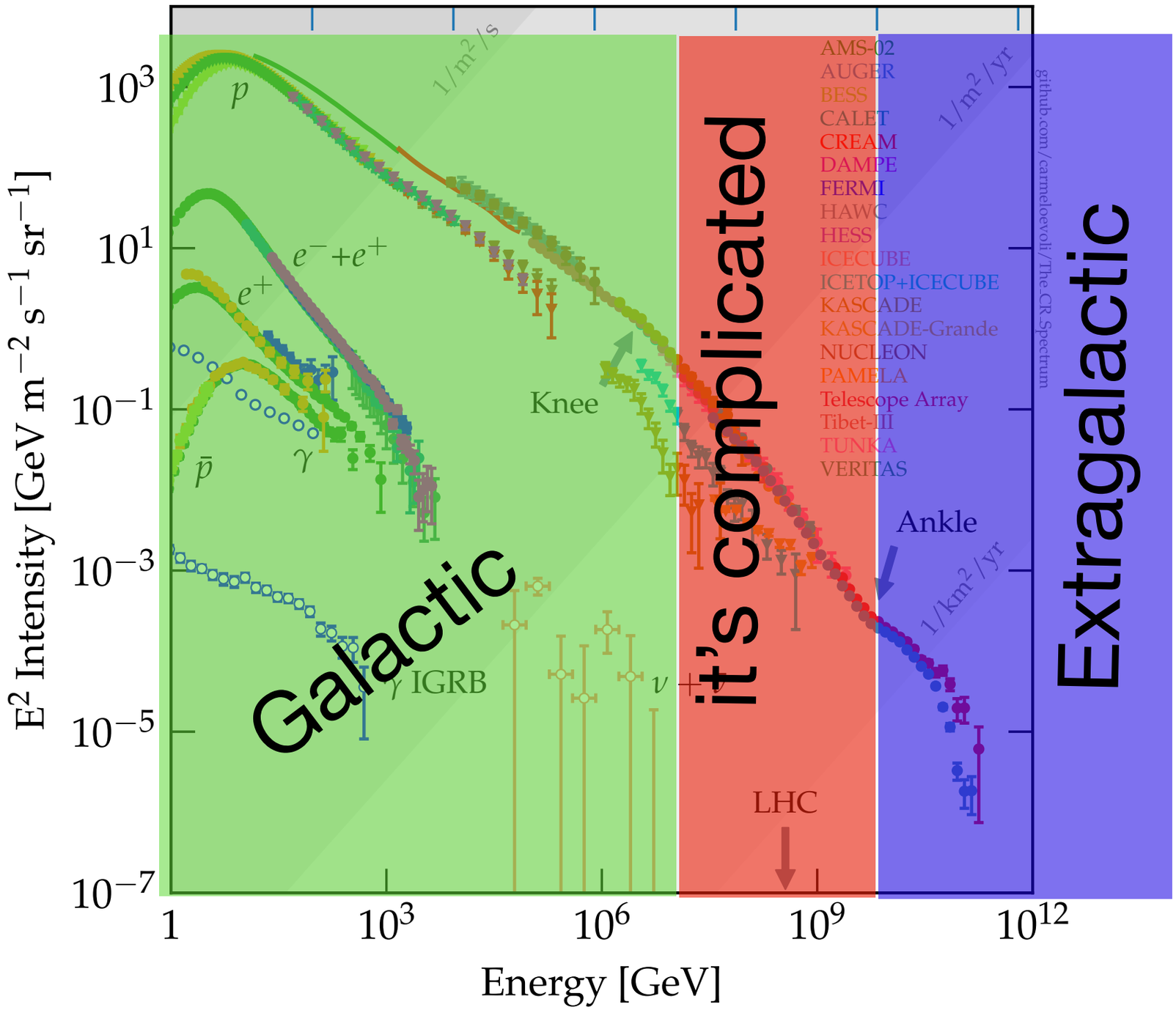

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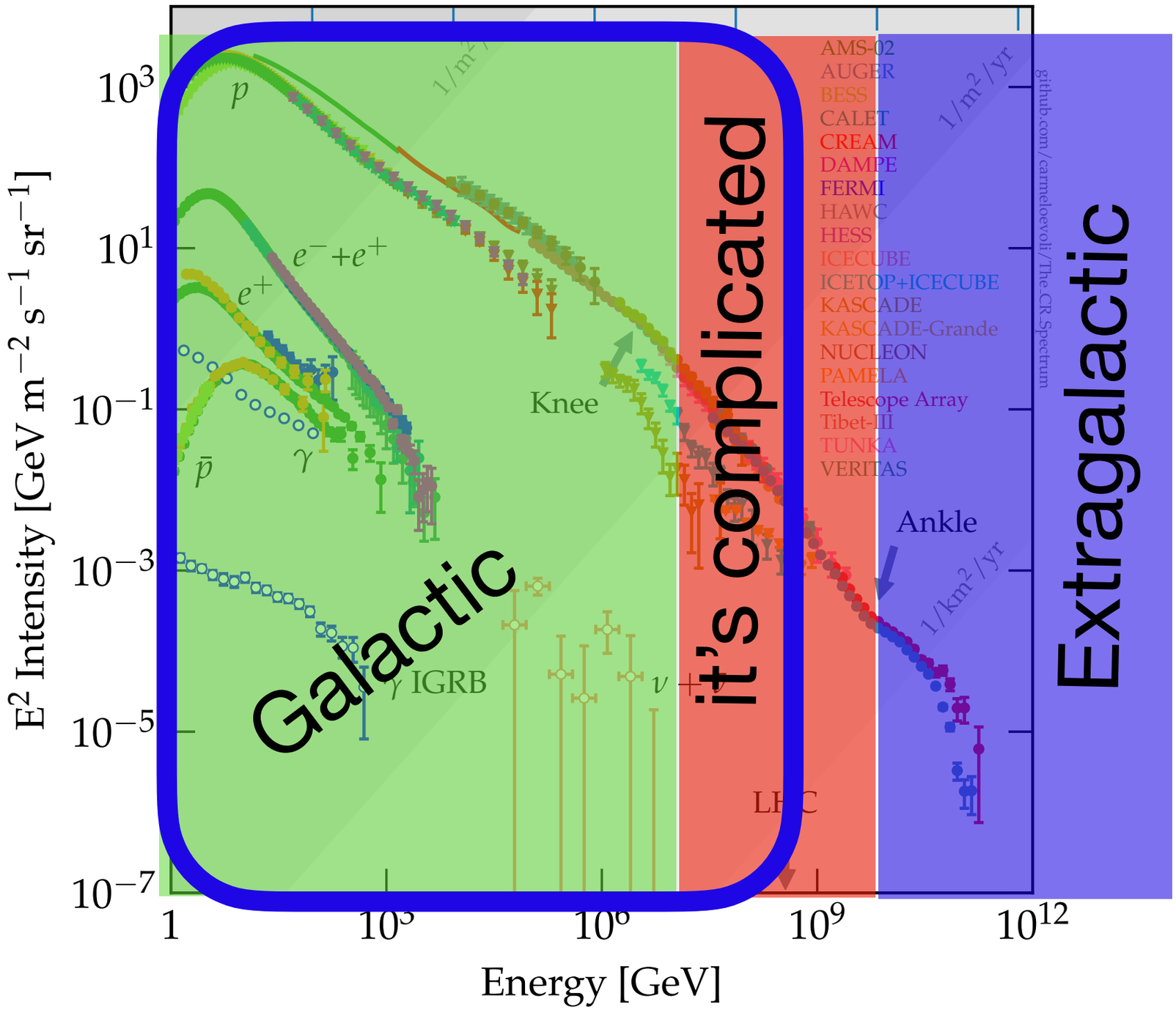

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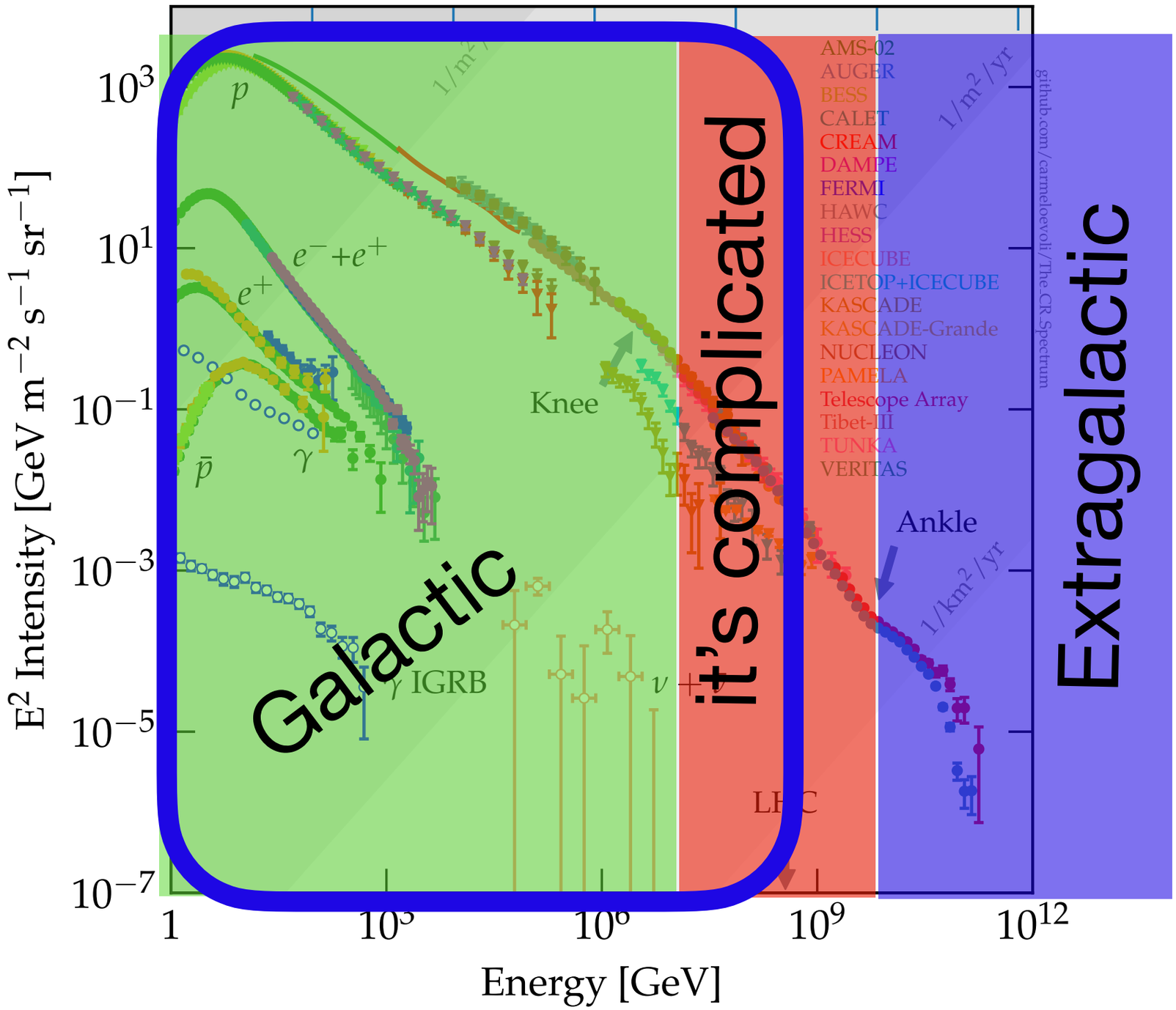

Reviews: Allard+ 2005, Berezinsky 2007, Aloisio+ 2012, Parizot 2014, Kachelrieß 2019 Evoli 2021

Sources of Galactic cosmic rays

Minimal requirements on proton sources:

★Sustain the total CR power
★Inject a spectrum that can account for proton spectrum
★Reach the knee (be pevatrons)

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SWGO
The Southern Wide-field Gamma-ray Observatory

Sources of Galactic cosmic rays

Minimal requirements on proton sources:

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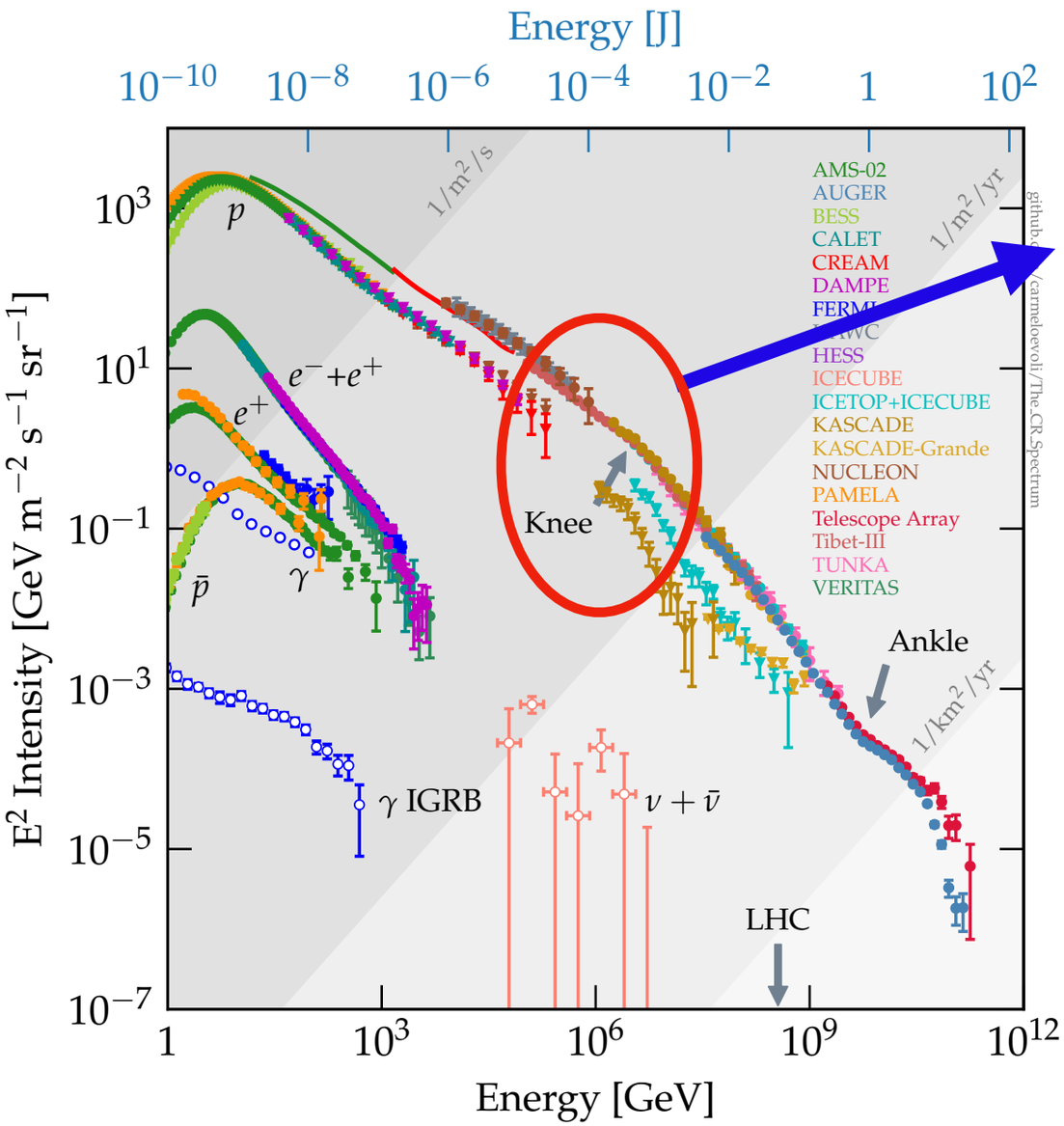
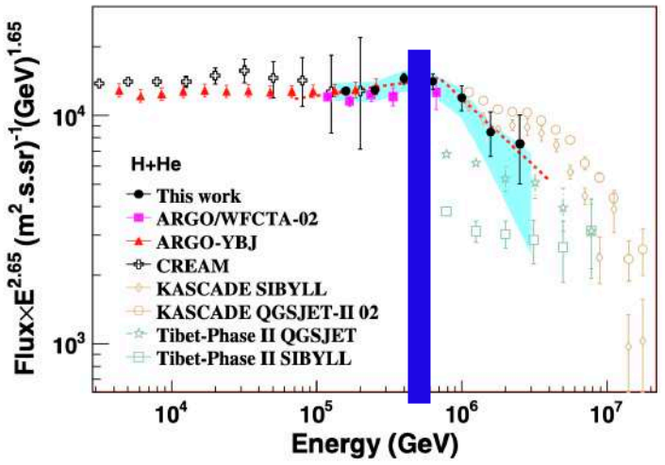
Key science project: the search, identification and characterization of pevatrons

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

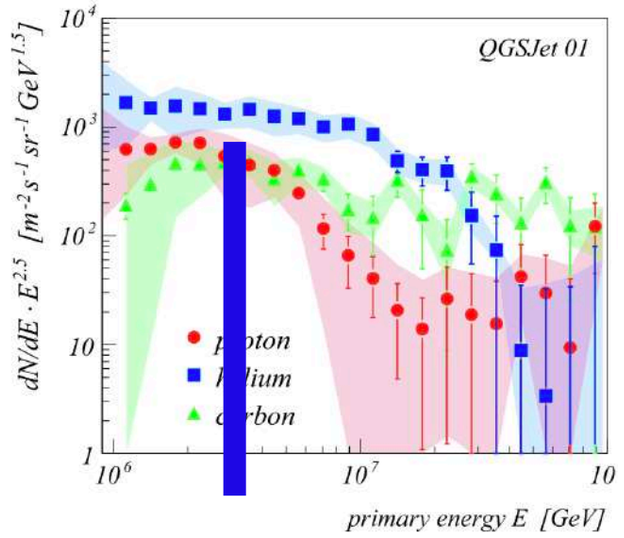
$$E_\gamma = 100\ \mathrm{TeV} \rightarrow E_p = 1\ \mathrm{PeV}$$

Pevatrons





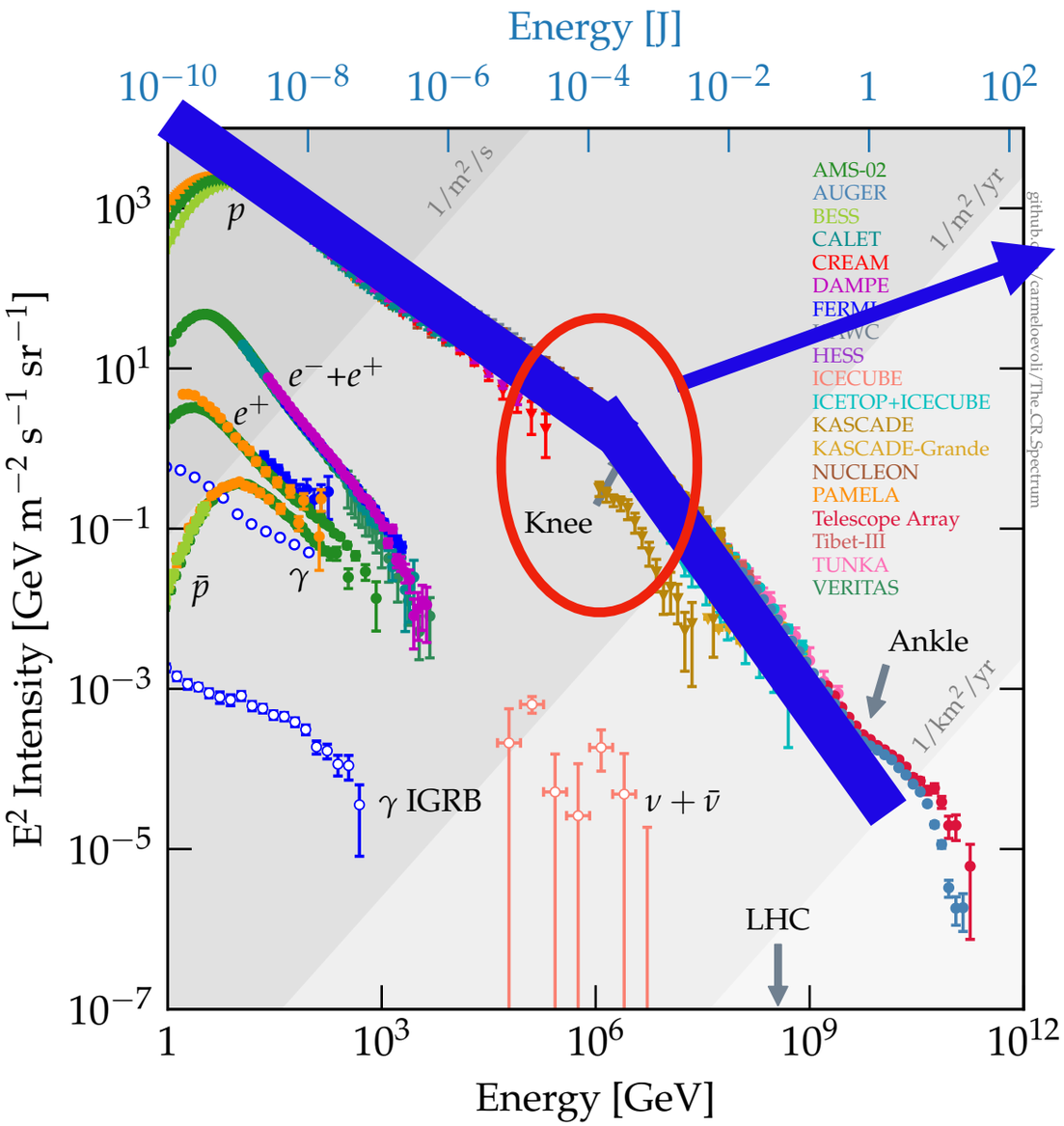
ARGO-YBJ
~700 TeV
Bartoli et al. 2015

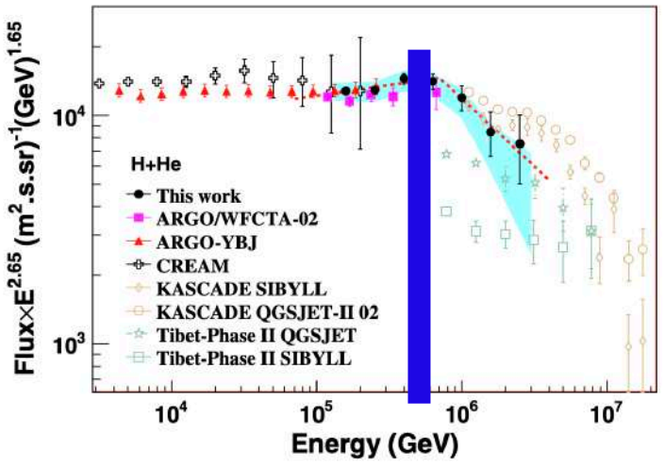


KASCADE
~3-4 PeV
Antoni et al. 2005

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

Pevatrons





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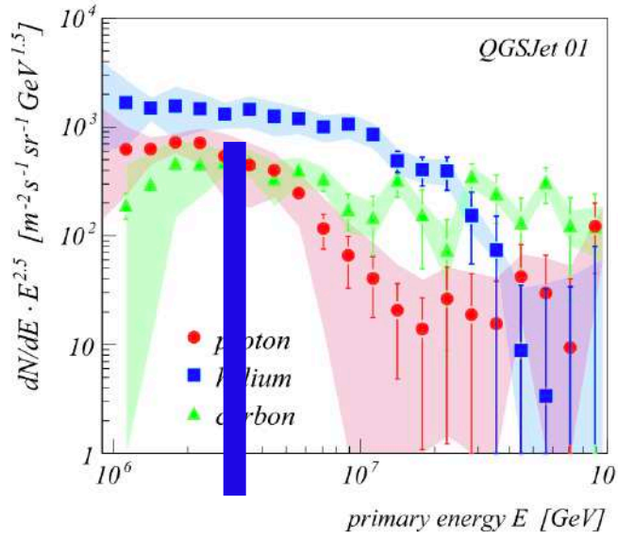

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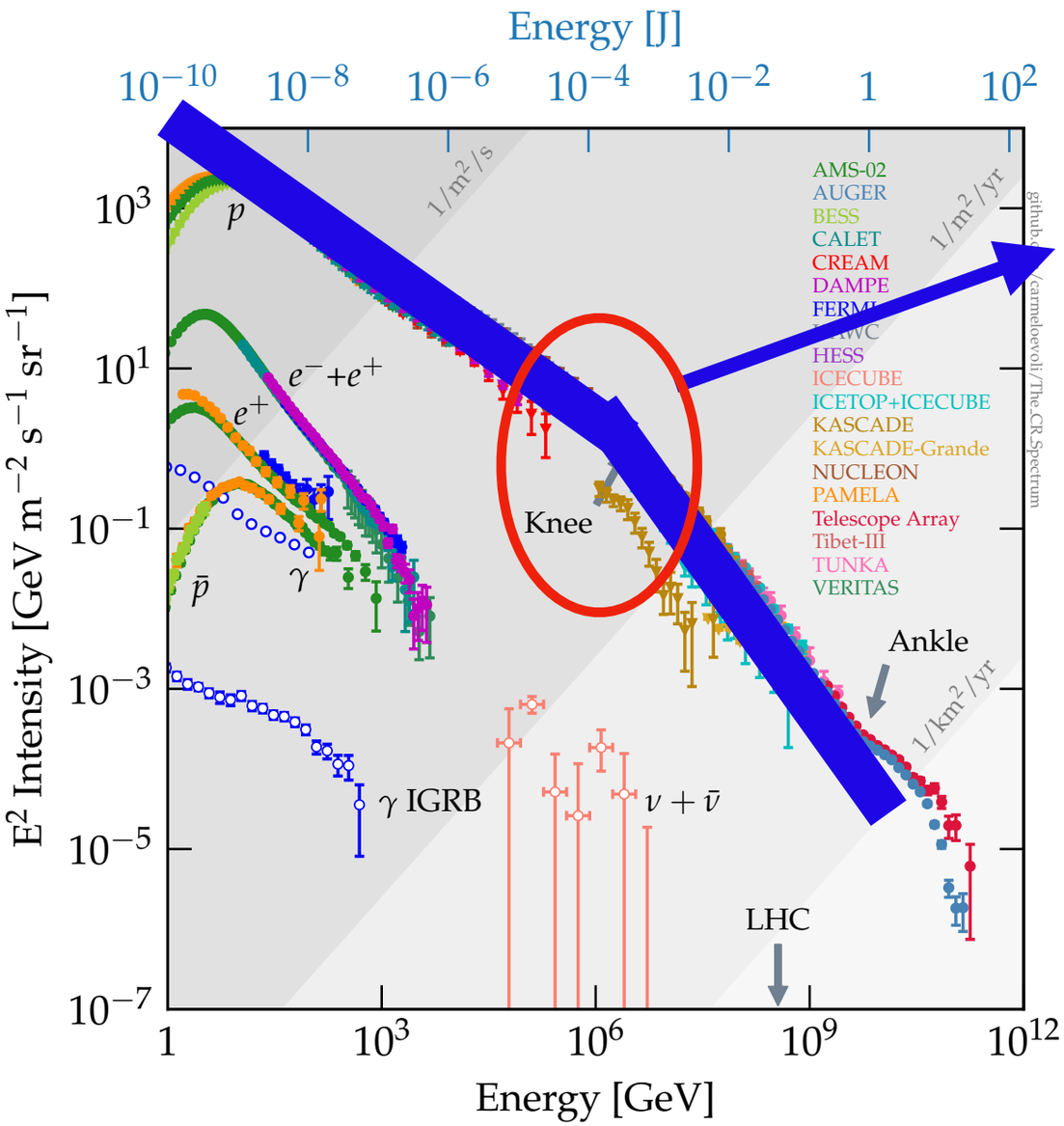

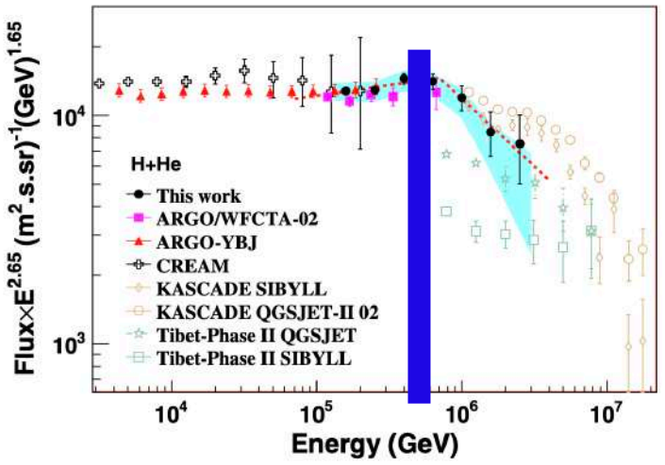

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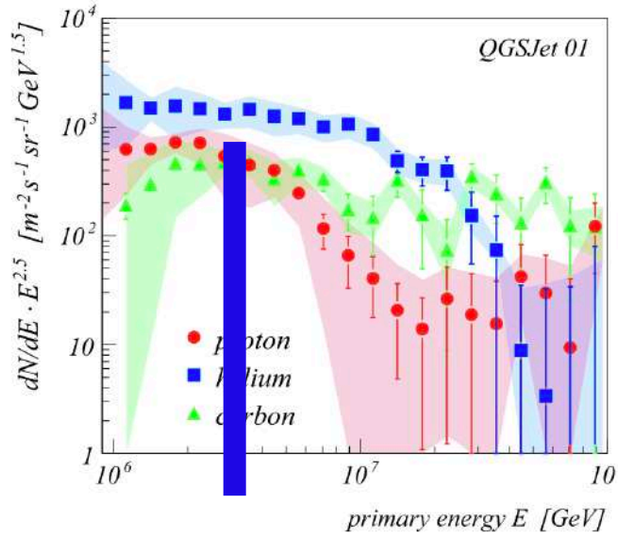

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Source of Galactic CRs must accelerate protons up to the knee!

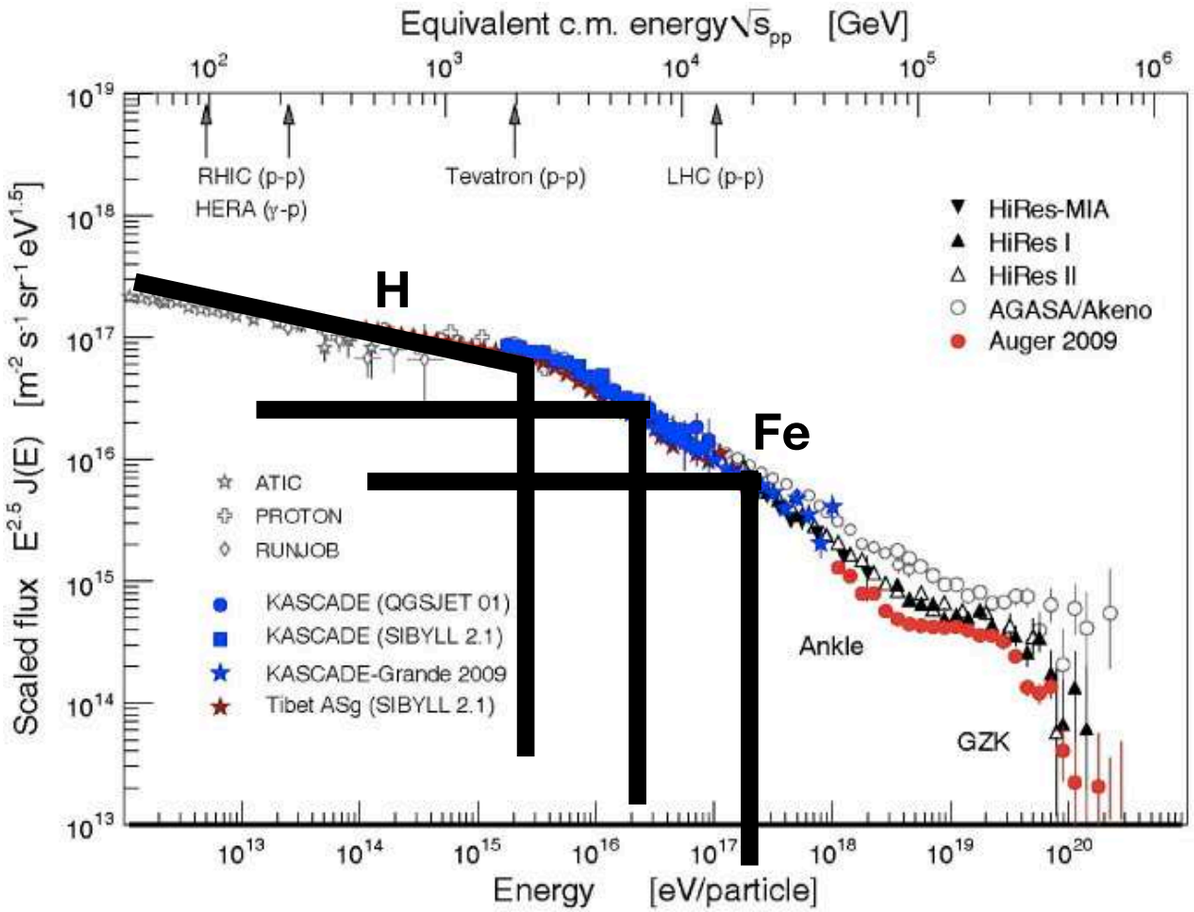
+ Z dependent knee

Pevatrons

MORE PRECISELY

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

~100 PeV



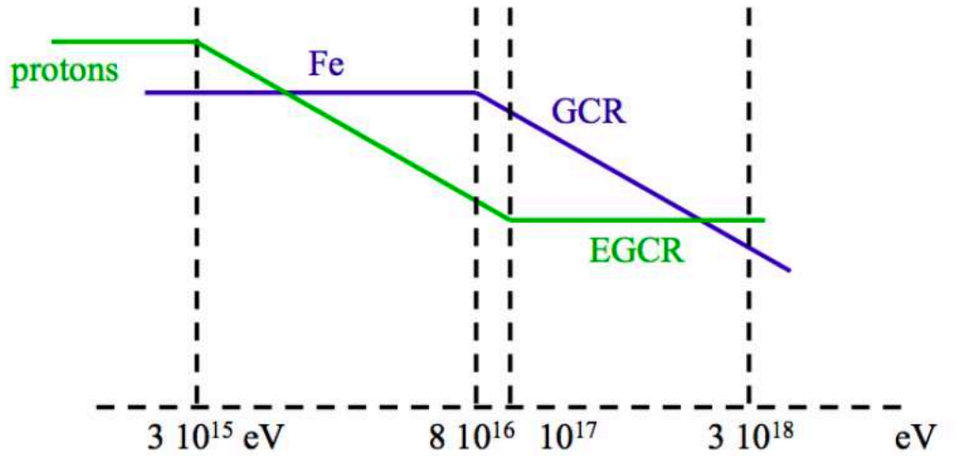


Figure 4: Sketch of the GCR/EGCR transition, with the proton and Fe components indicated (respectively in green and in blue on the color version of the figure). In ordinate, the CR flux is multiplied by E^x, where x is the logarithmic slope of the CR spectrum below the knee. (See also Fig. 3).

Z dependent knee ⟷ DSA depends on rigidity

Hillas 2006, Parizot 2014

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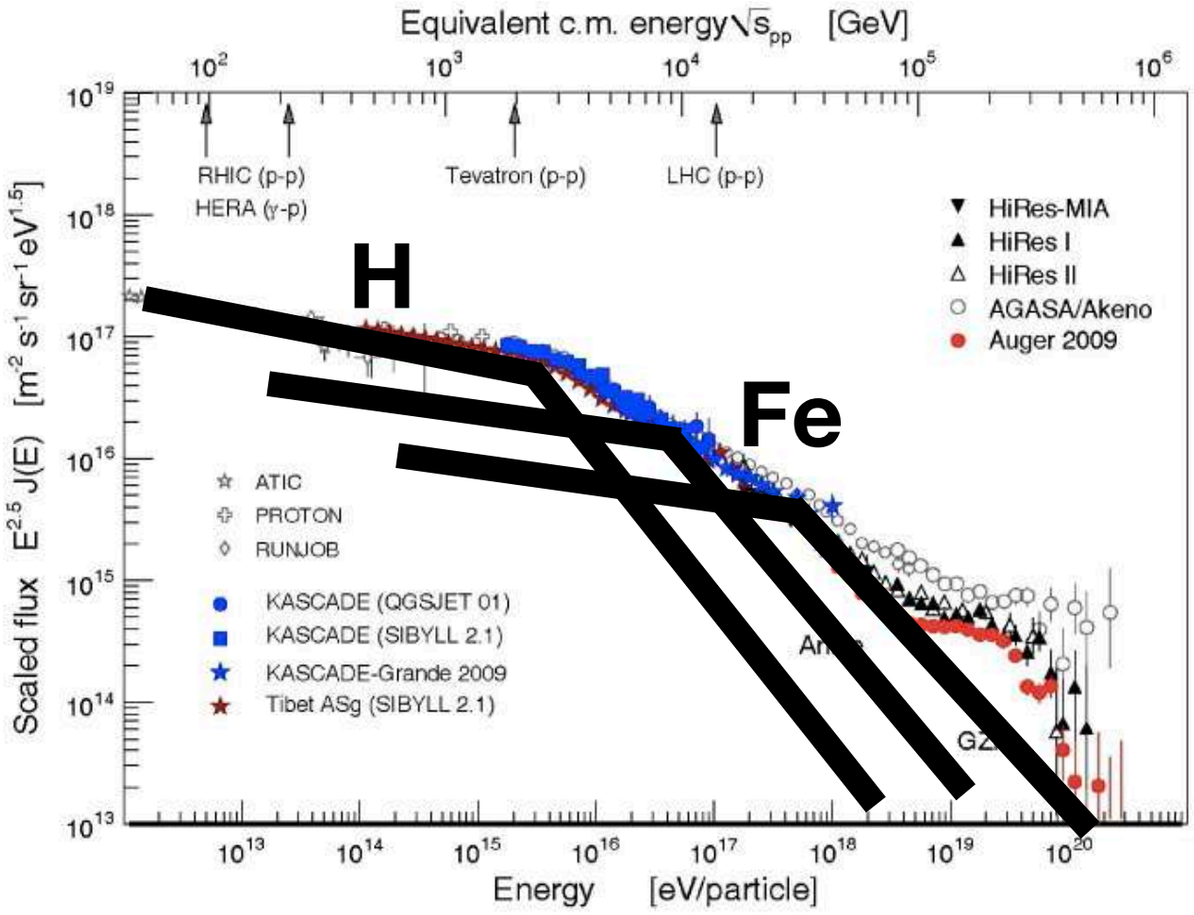

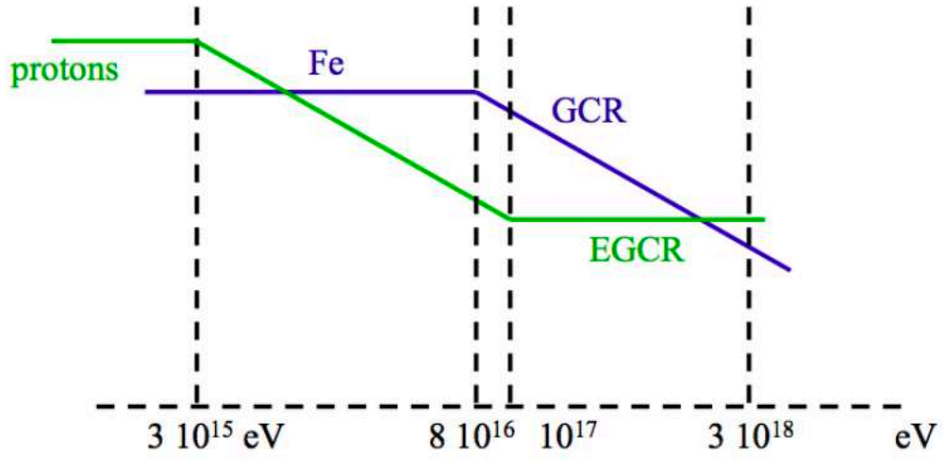

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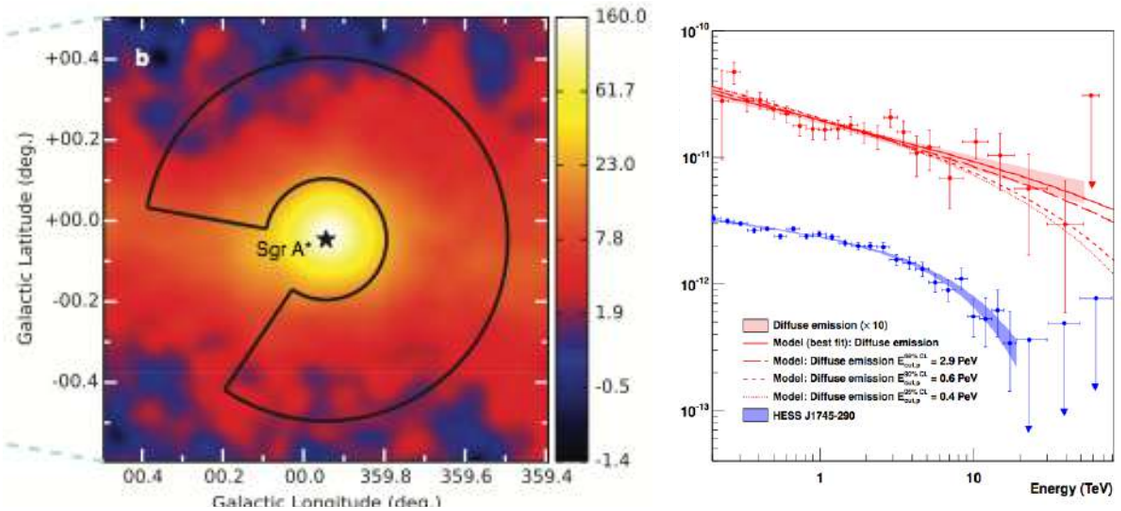
Smooth transition from Galactic to extraGalactic

Hillas 2006, Parizot 2014

What sources can be (proton) pevatrons?

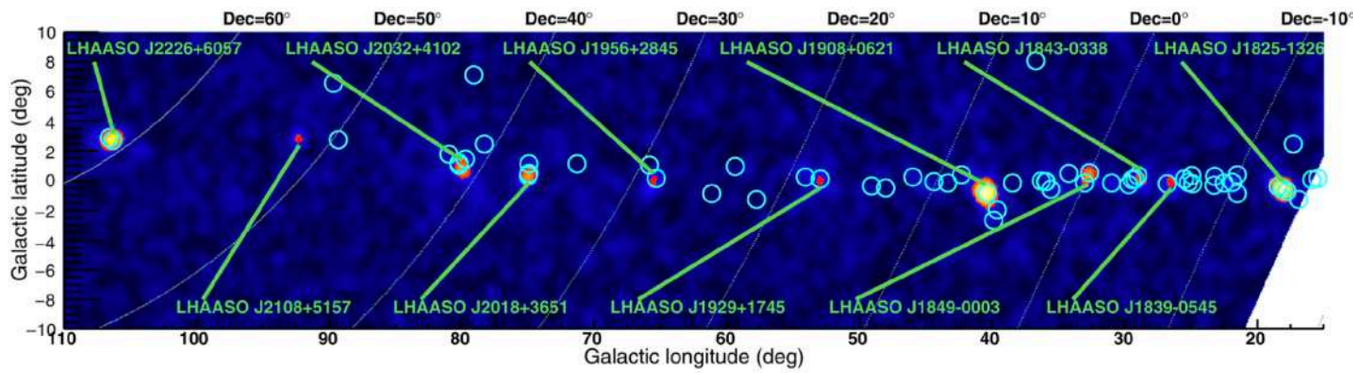
★ **Sufficient amount of PeV protons?**
★ **« Hard-enough » spectra above 10^{15} eV?**
★ **What sources can be (super)pevatrons? 10^{16} 10^{17} eV**

HESS J1745-290



HESS collab. 2016

LHAASO 12 Galactic pevatrons



Cao et al. 2021

De Ona Whilhelmi et al. (2022)

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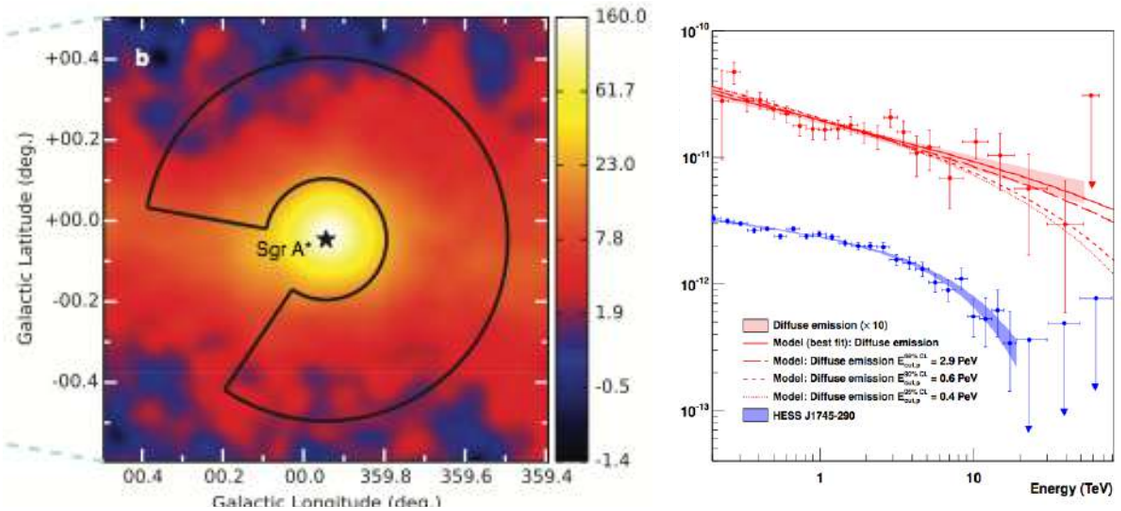

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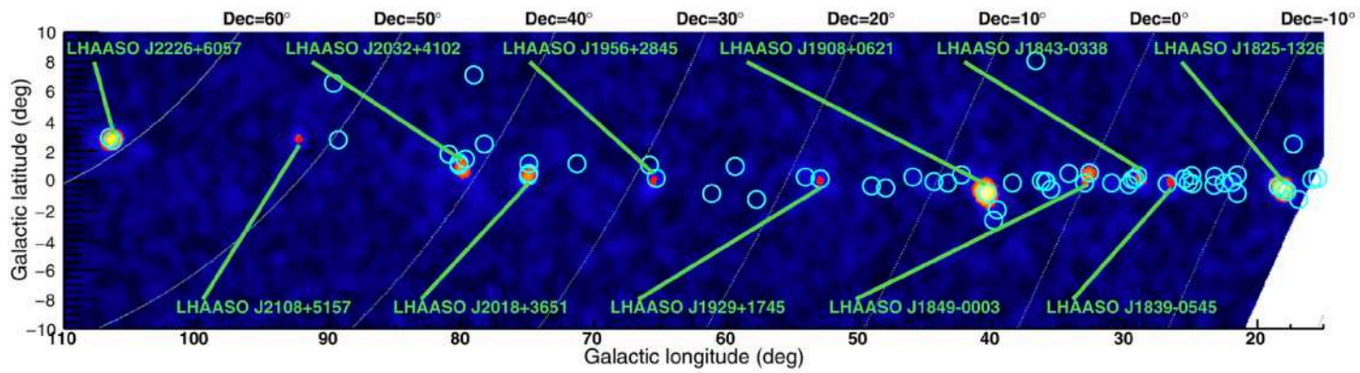


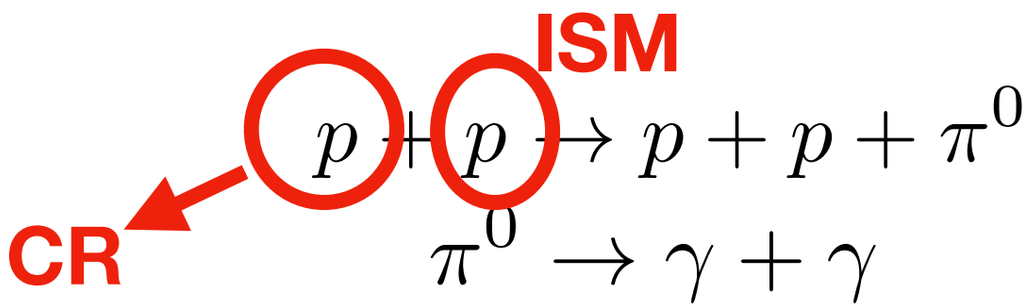
Cao et al. 2021

Not clear if hadronic or leptonic (probably leptonic for most sources)

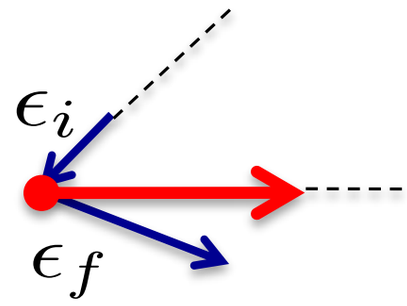
De Ona Whilhelmi et al. (2022)

What sources can be (proton) pevatrons?

Hadronic interactions : Pion decay



Leptonic interactions : Inverse Compton scattering



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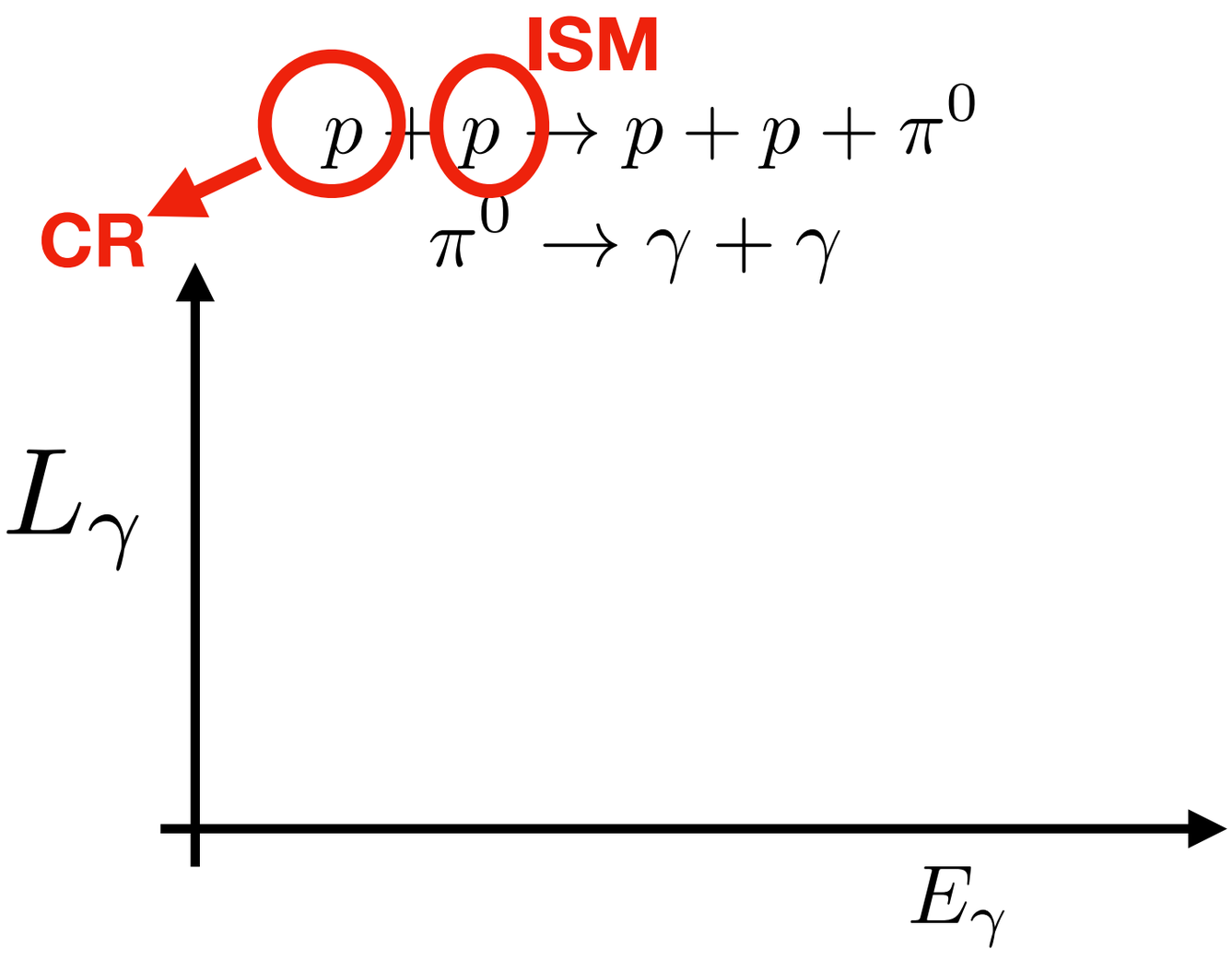

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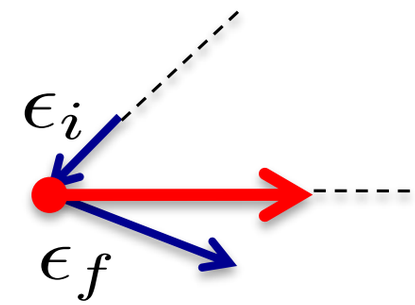

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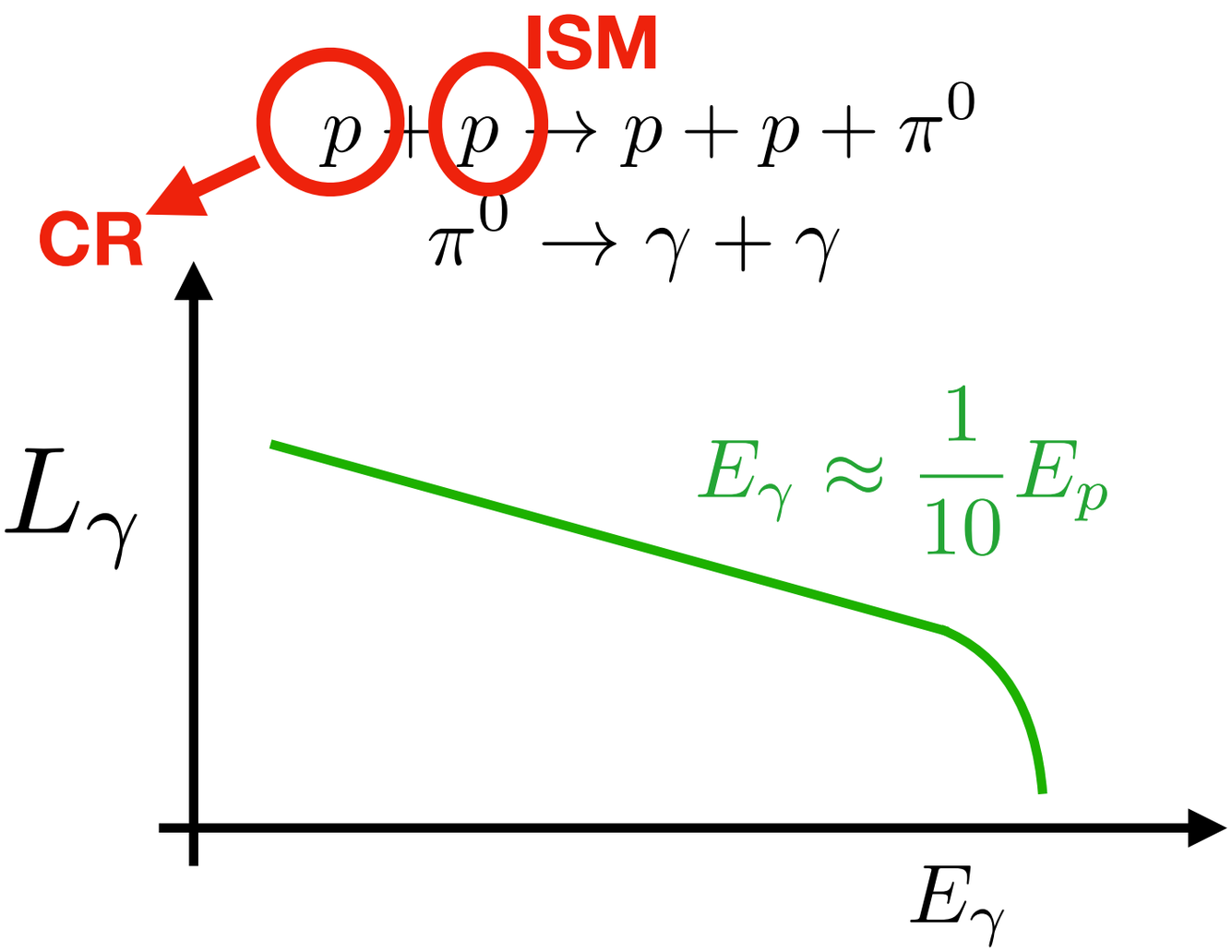

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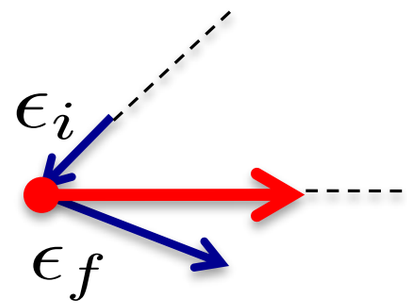

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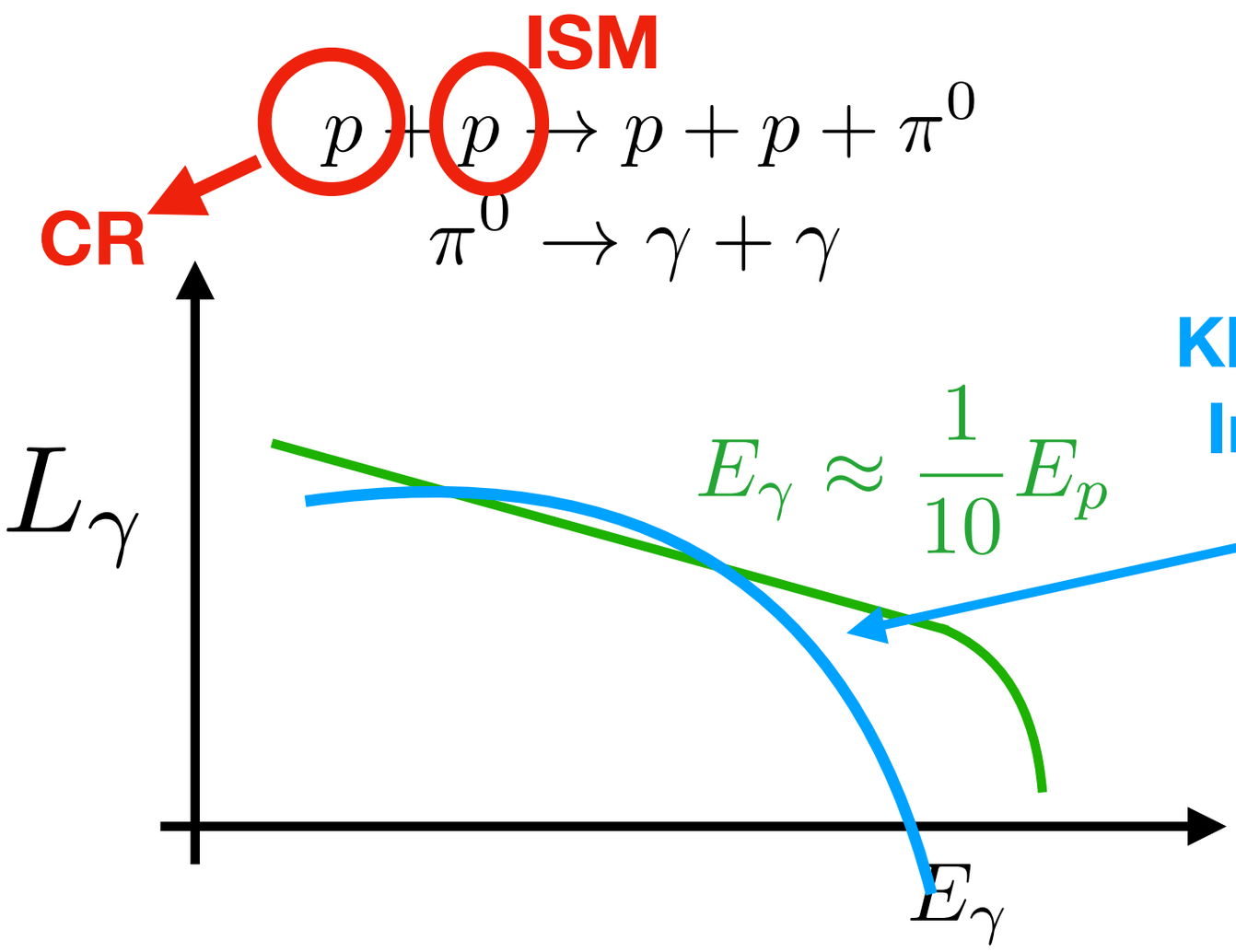

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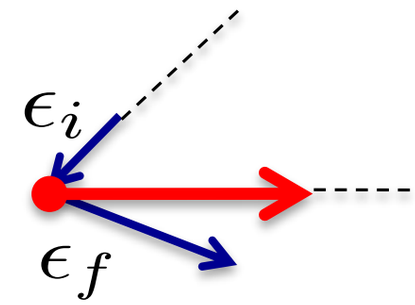

Klein-Nishina suppression: Inefficient above >50 TeV

De Ona Whilhelmi et al. (2022)

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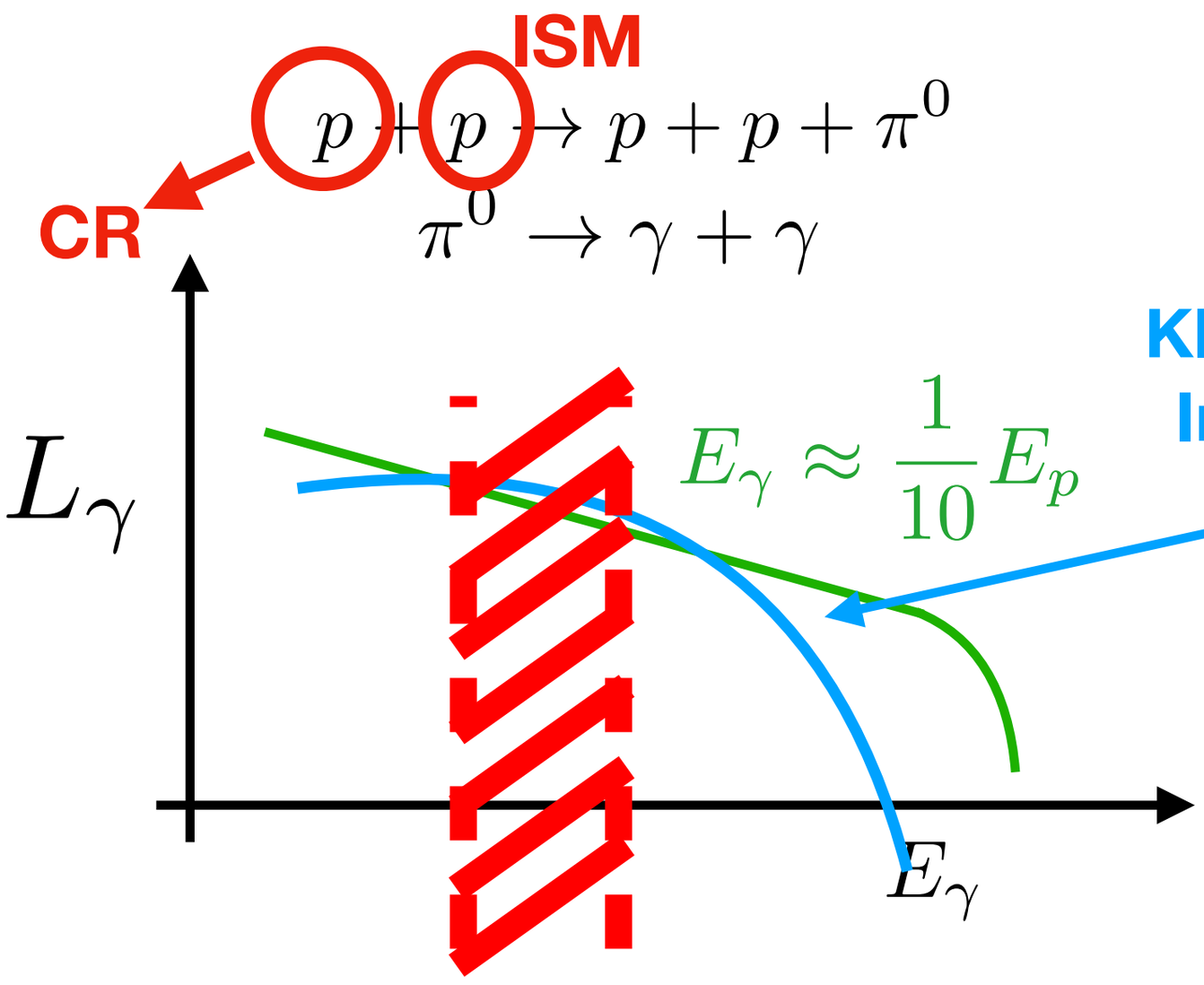

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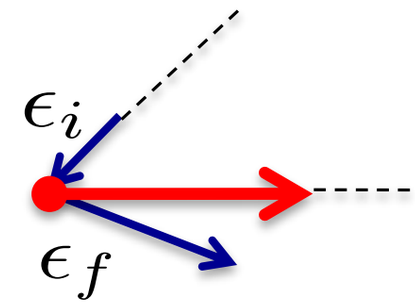

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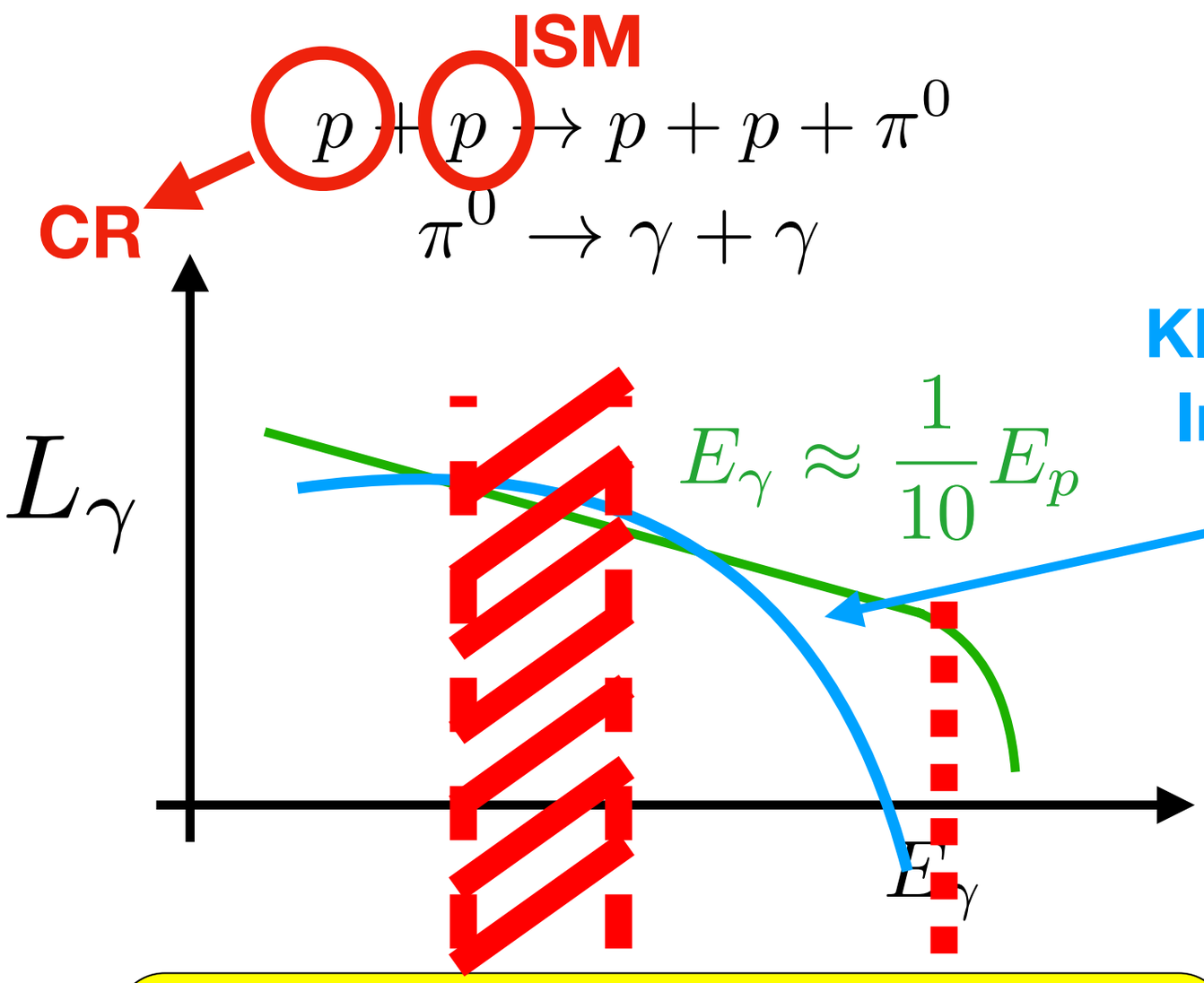

100 TeV gamma rays probe the acceleration of PeV protons (hadronic)

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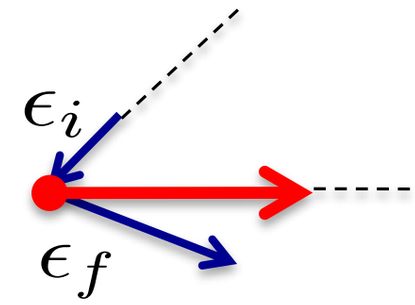

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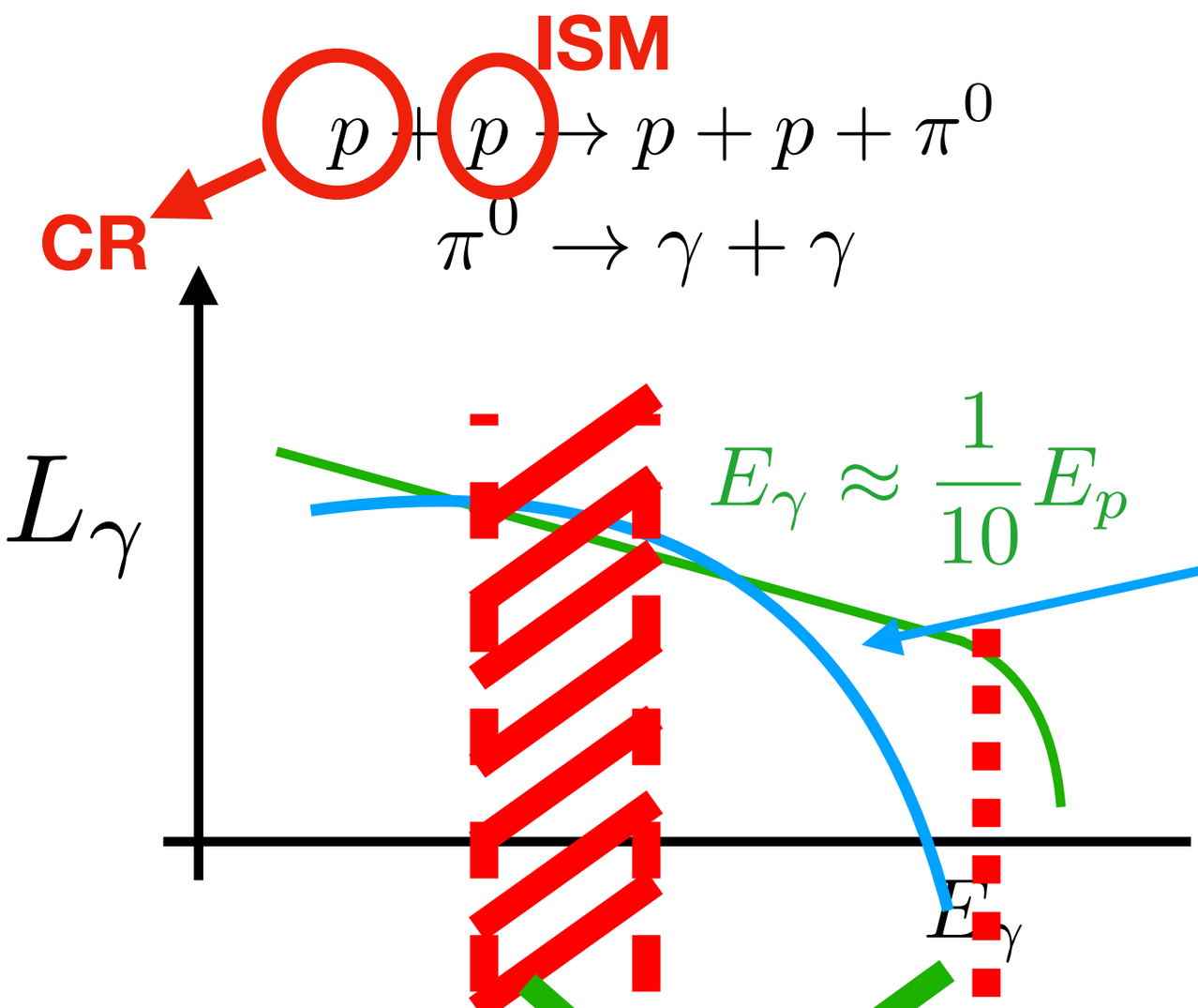

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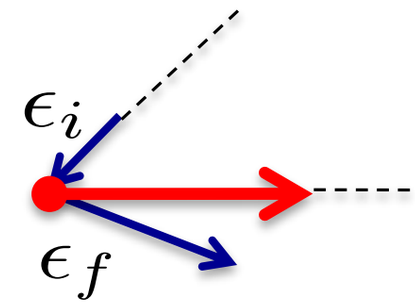

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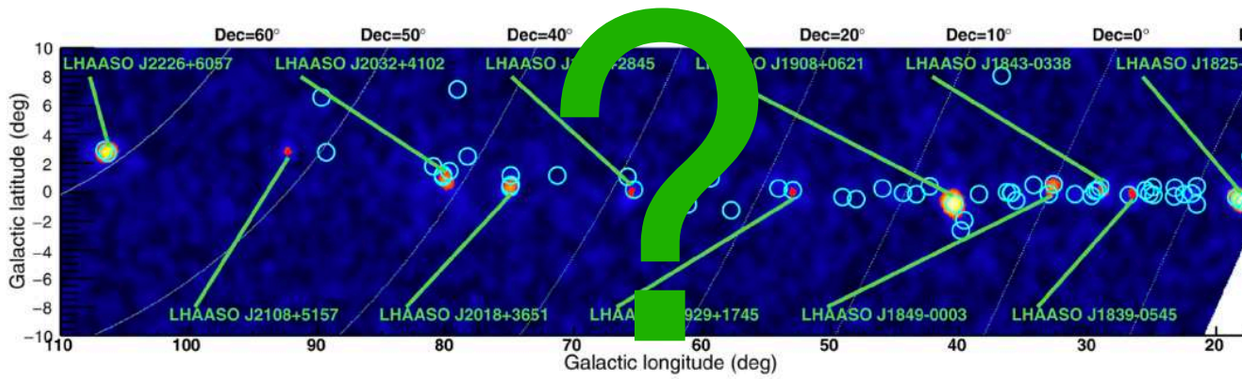

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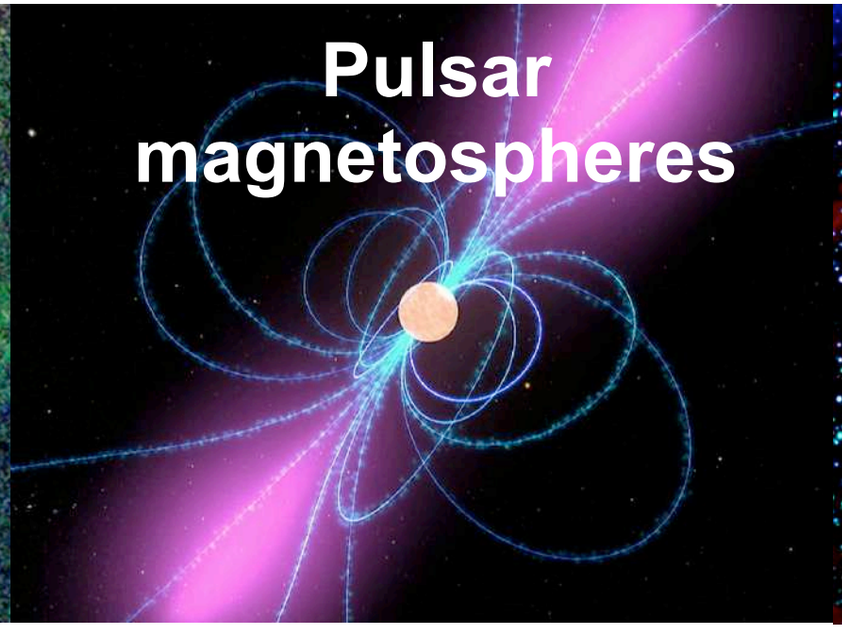
Vannoni et al. (2007), Brehaus et al. (2021)

De Ona Whilhelmi et al. (2022)

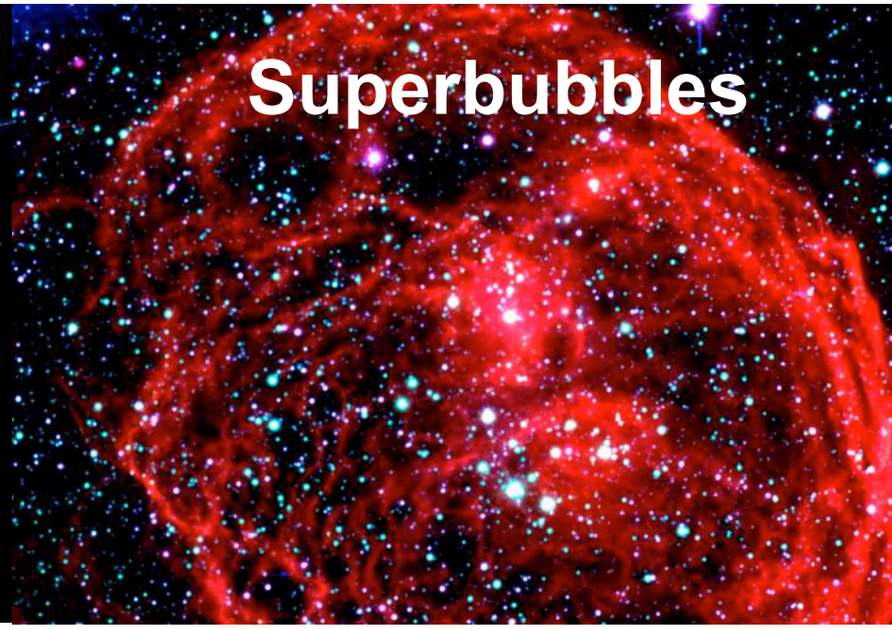
What sources can be (proton) pevatrons?

Theoretically?

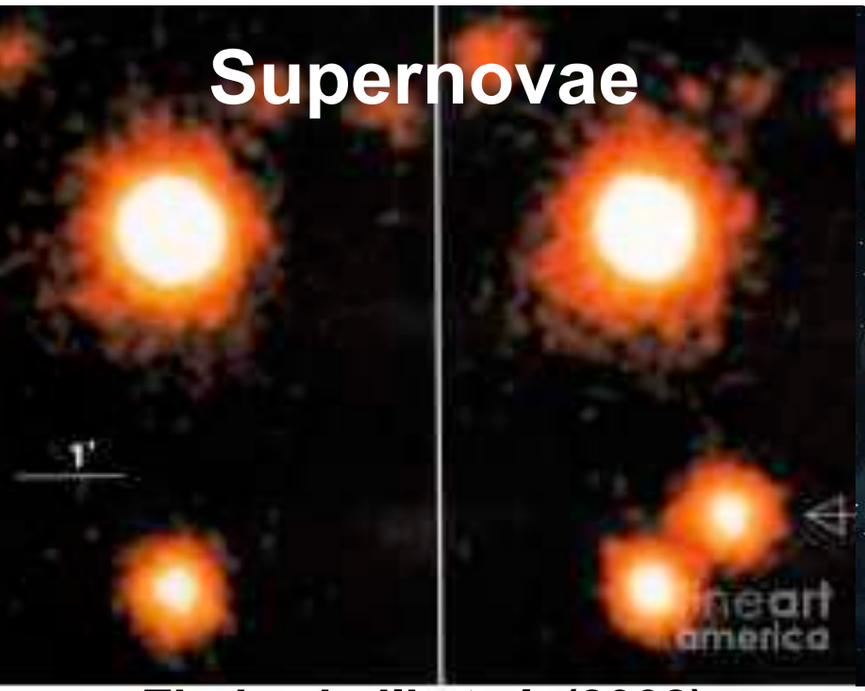
Aharonian et al.(2019)
Bykov et al. (2020)
Morlino et al. (2021)



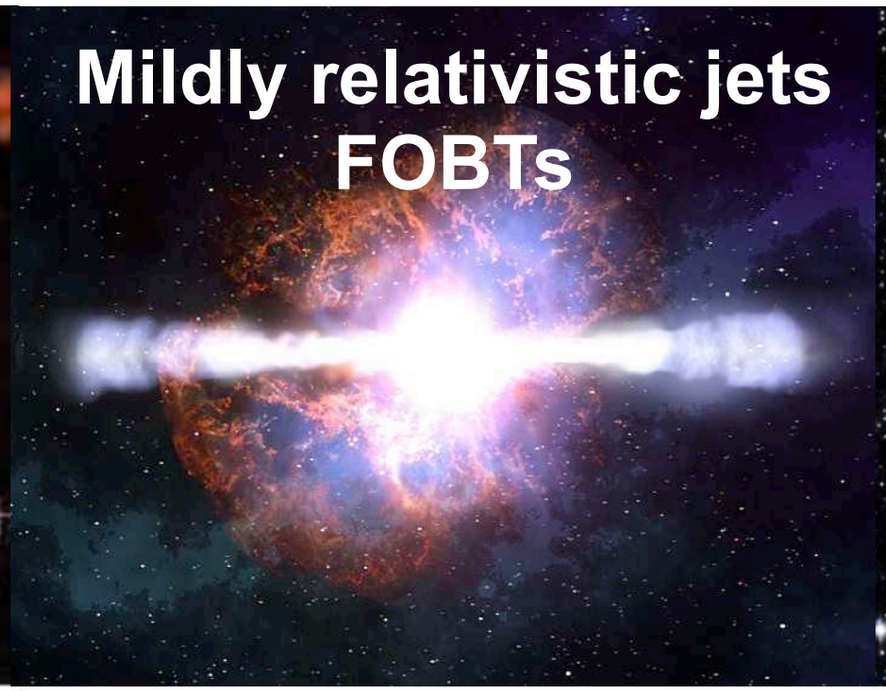
Guepin et al. (2020)



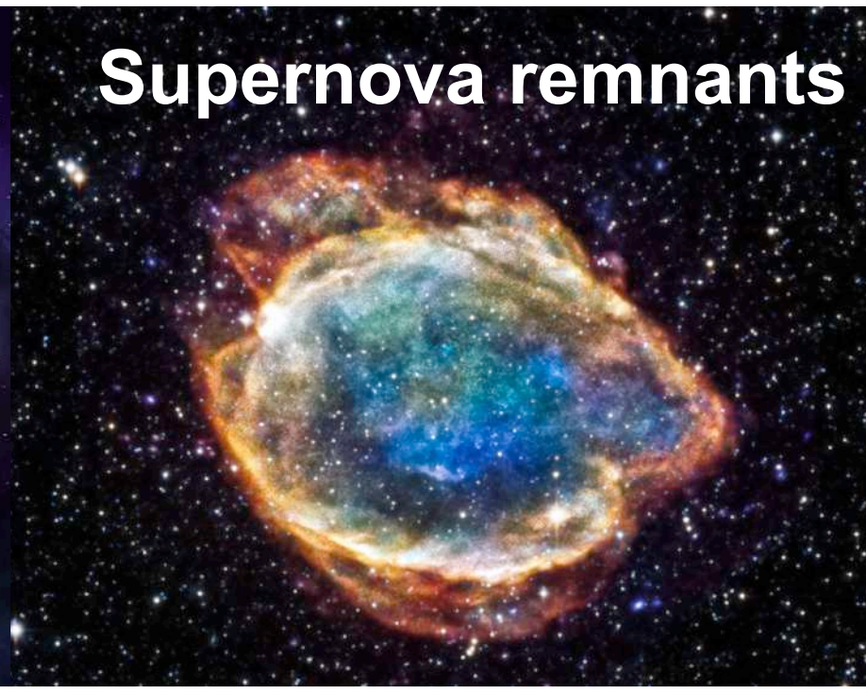
Vieu et al. (2020,2022)
Tatischeff et al. (2021)



Zirakashvili et al. (2008)
Bykov et al. (2018)



Bykov et al. (2022)



Bell et al. (2004, 2014)

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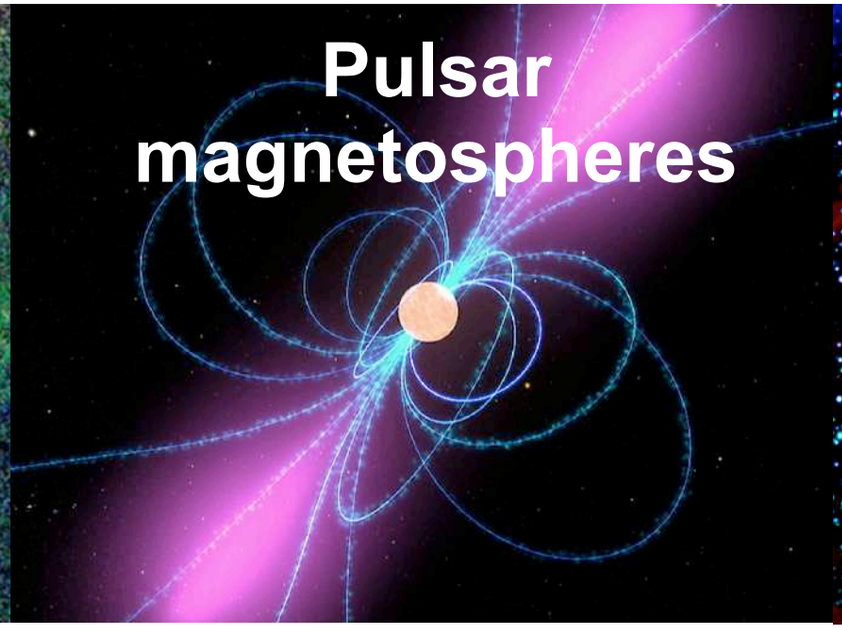

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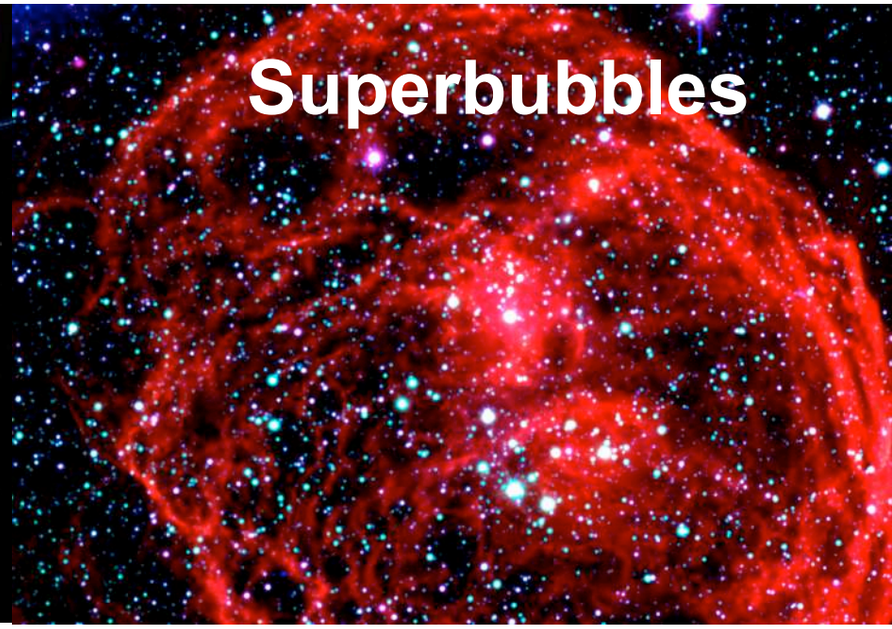

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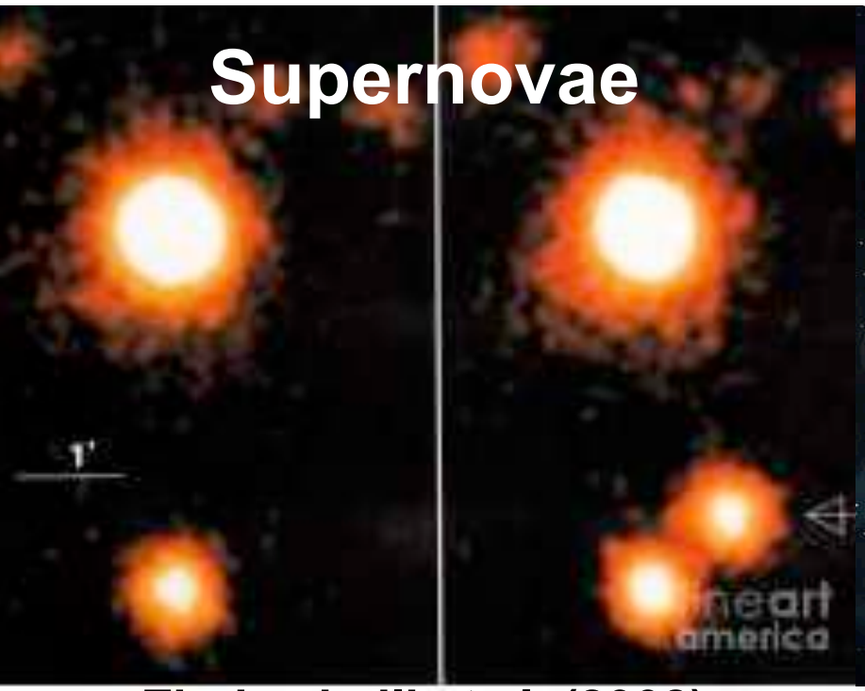

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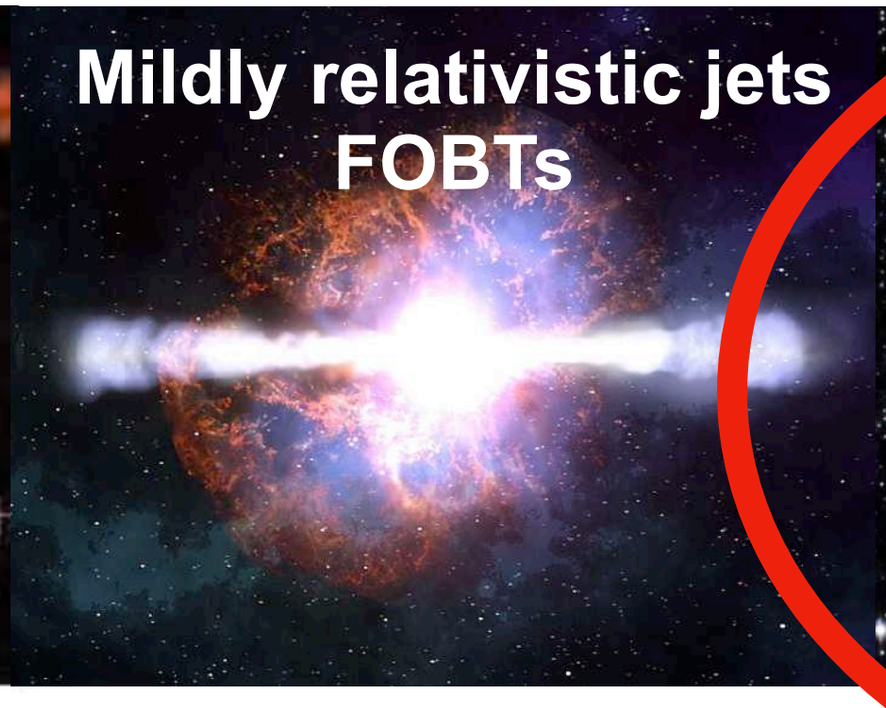
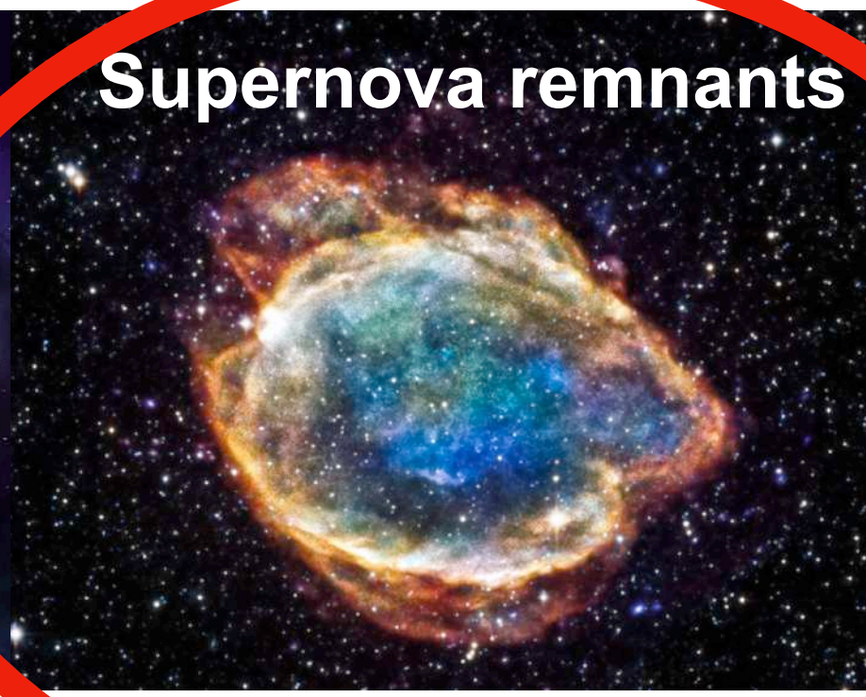


Bykov et al. (2022)



Bell et al. (2004, 2014)

The case of supernova remnants

Minimal requirements on proton sources:

★Sustain the total CR power
★Inject a spectrum that can account for proton spectrum
★Reach the knee (be pevatrons)

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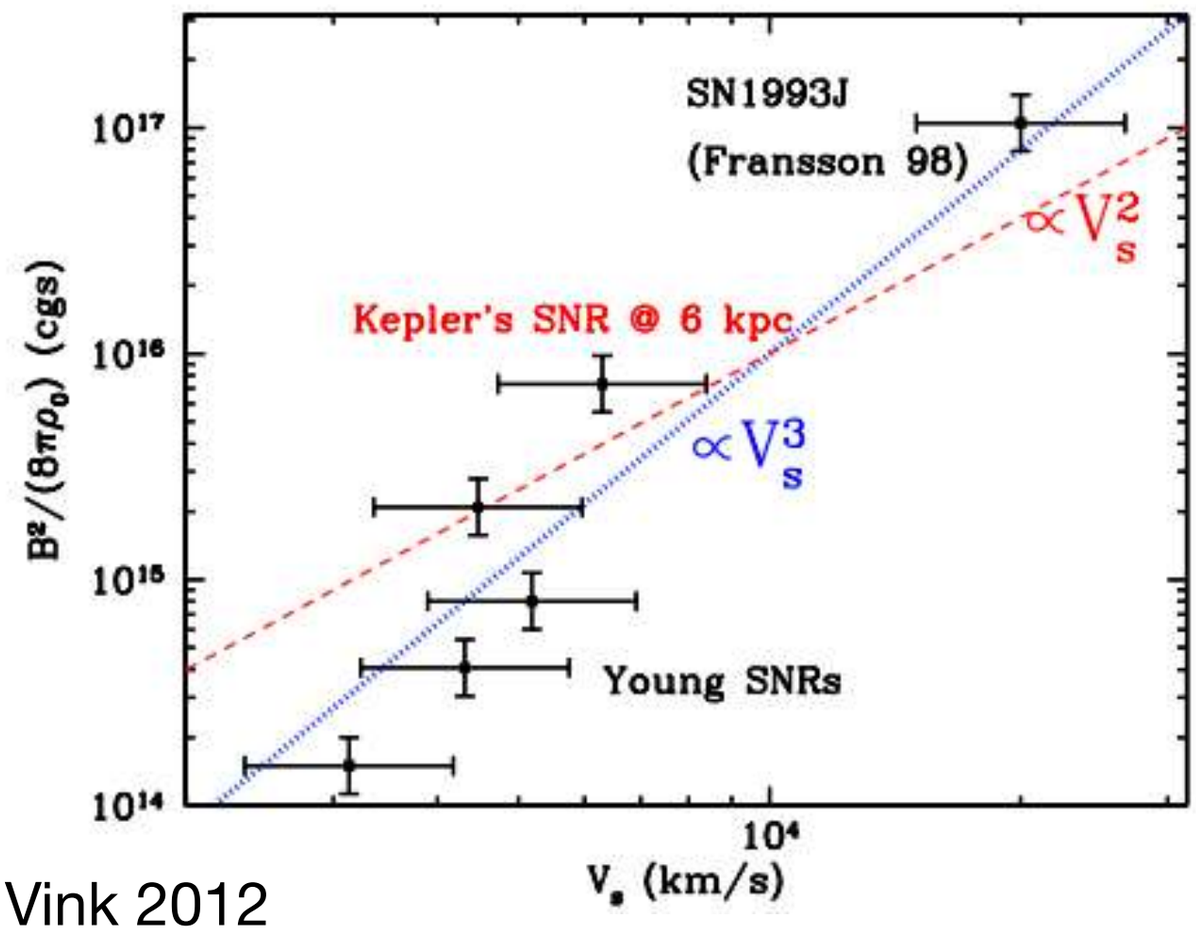

Vink 2012

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Growth of the non-resonant streaming instability

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

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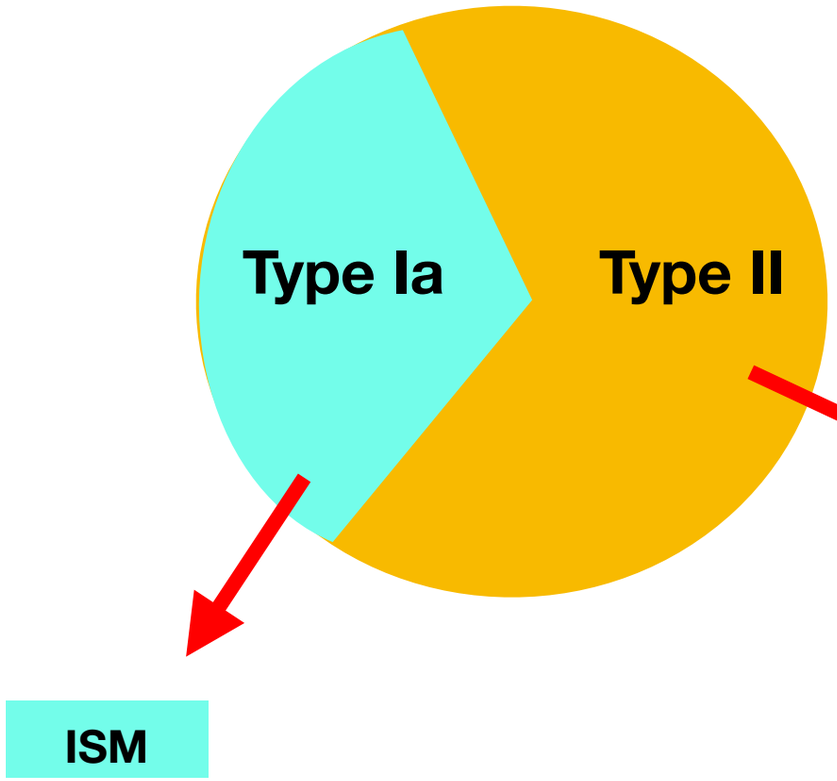

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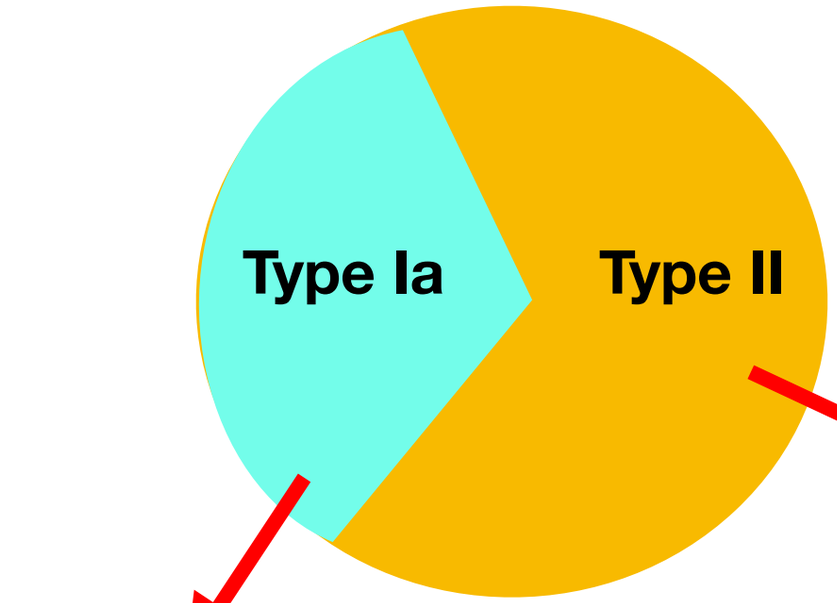

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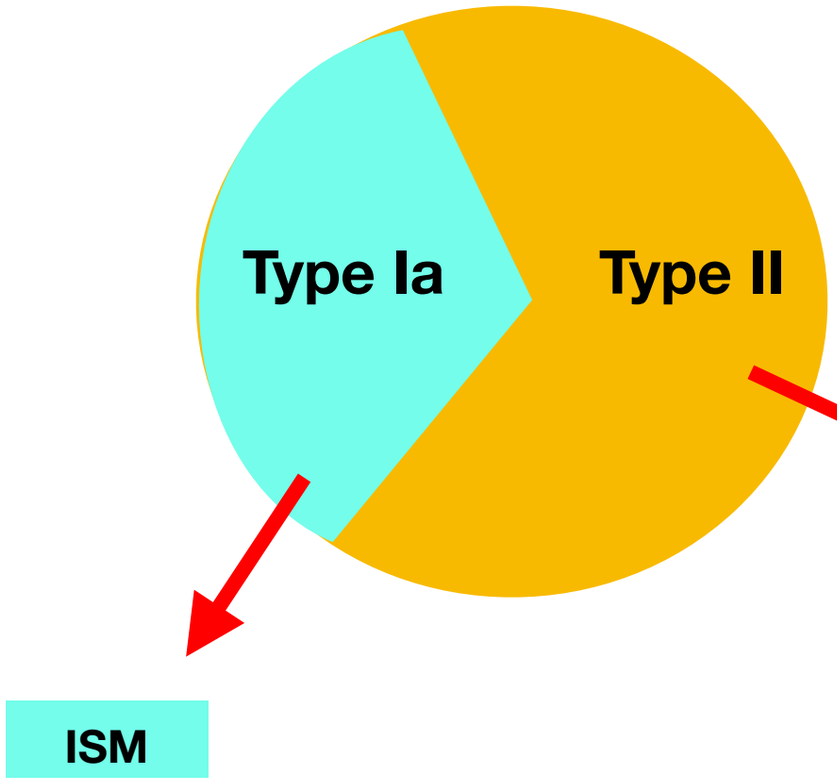

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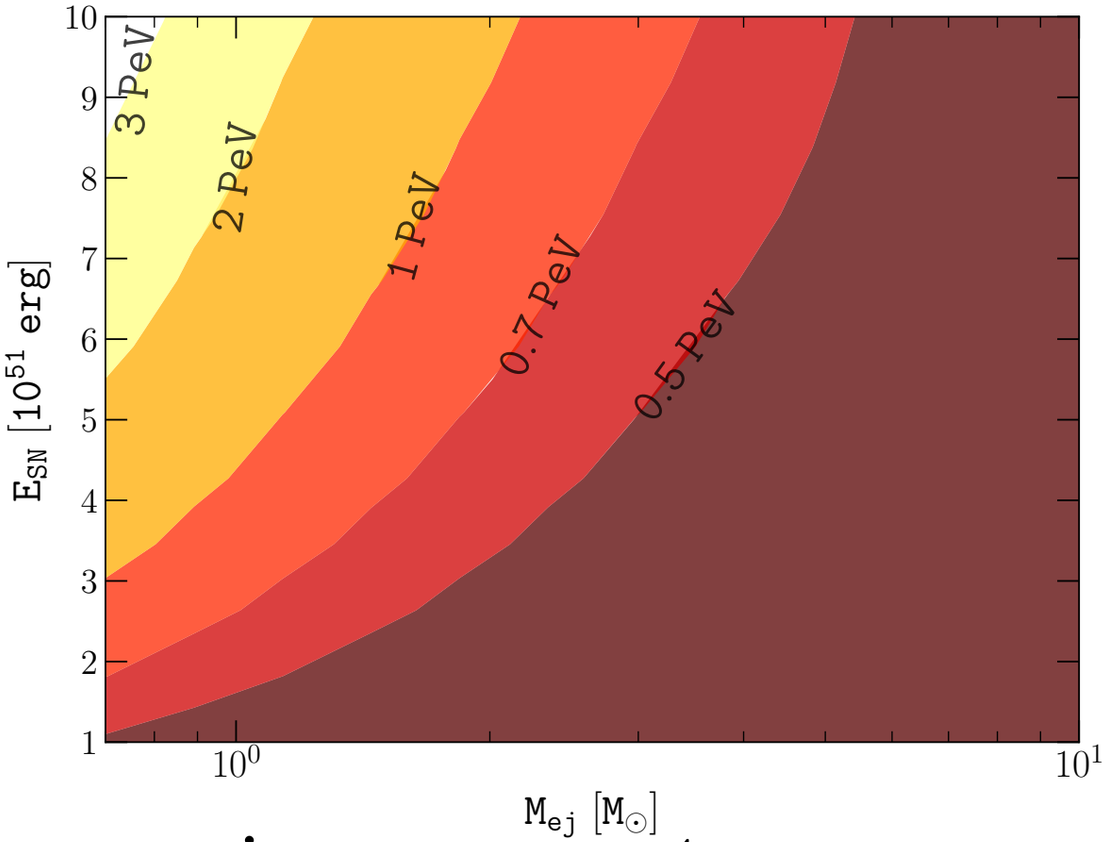
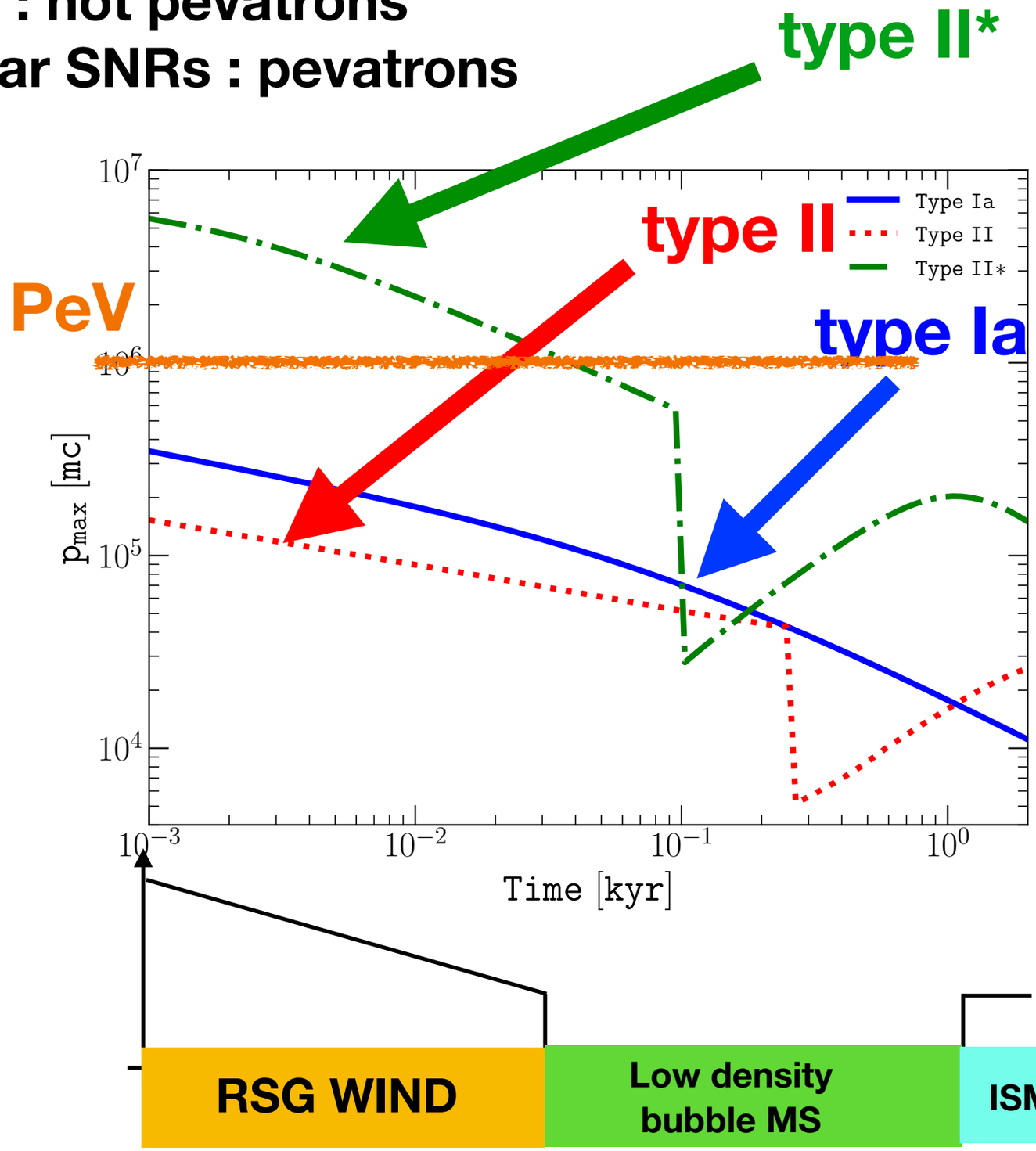
The case of supernova remnants

Typical SNRs : not pevatrons
Young and peculiar SNRs : pevatrons



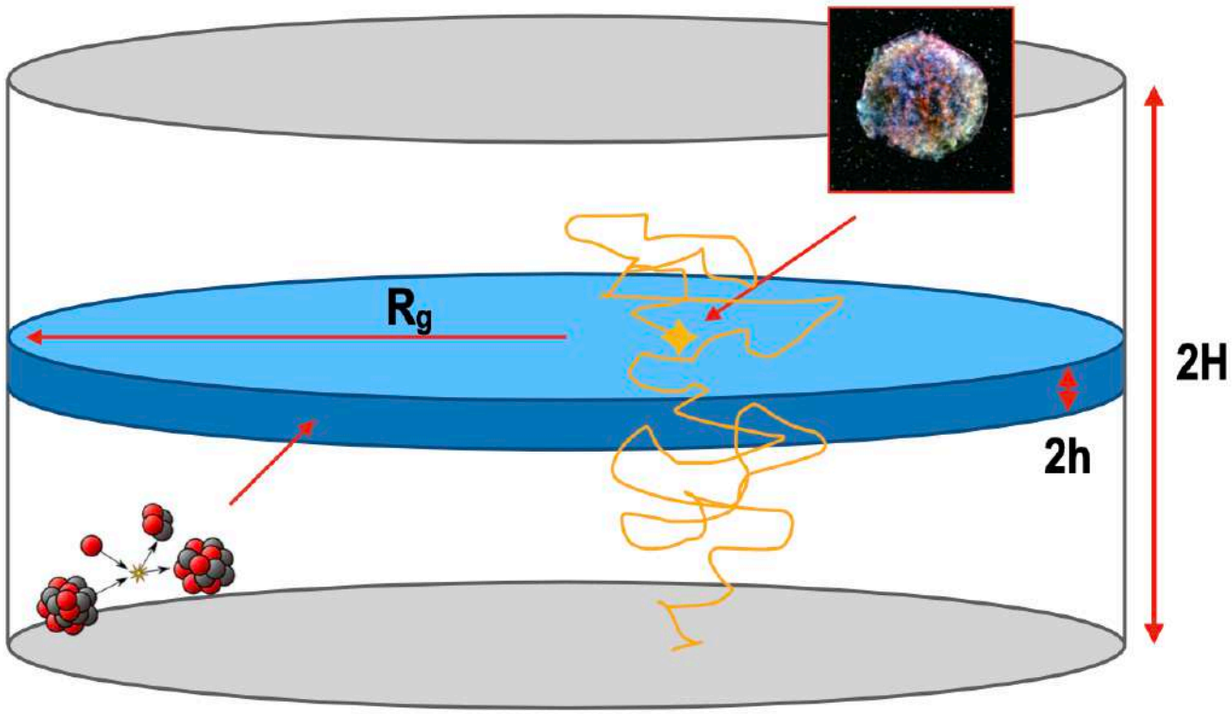
$$\dot{M}_{\rm RSG} = 10^{-4} M_\odot/{\rm yr}$$
$$\xi = 0.1$$



Bell (2004), Bell et al. (2013), Schure et al. (2014), Ptuskin et al. (2010), Cardillo et al. (2016) PC, Blasi & Amato (2020)

The case of supernova remnants

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



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

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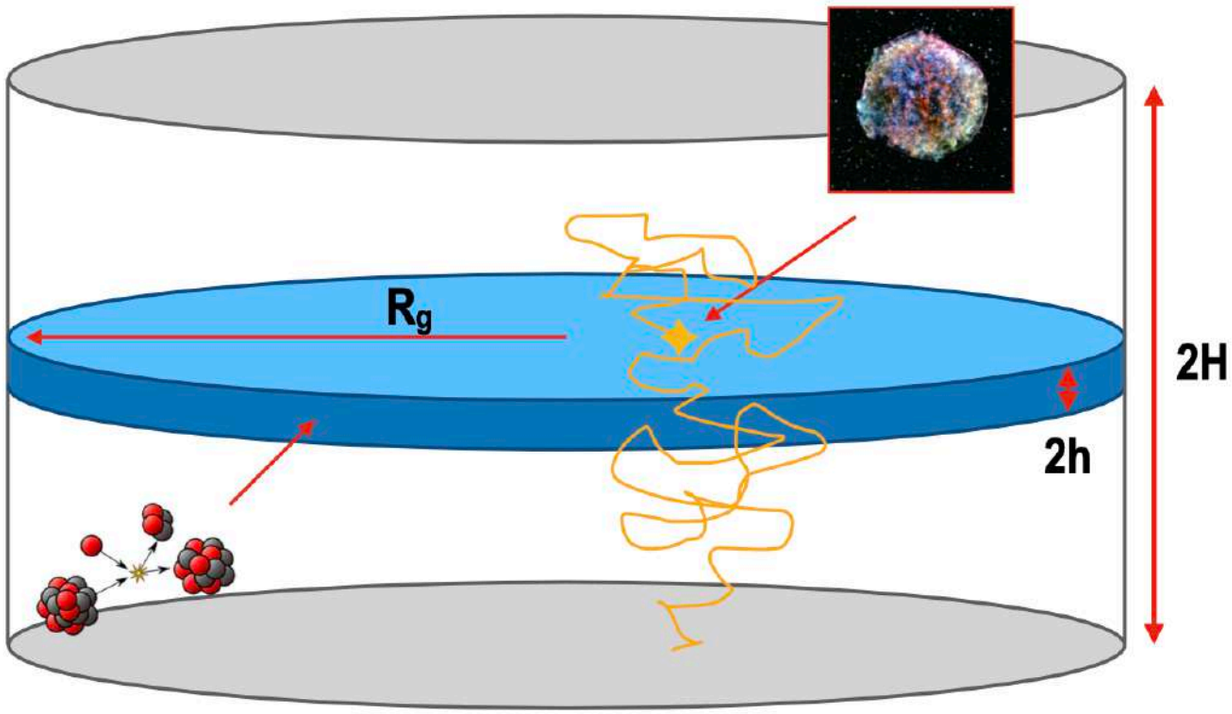

$$-\frac{\partial}{\partial z}\left[D(p)\frac{\partial f}{\partial z}\right]+u\frac{\partial f}{\partial z}-\frac{du}{dz}\frac{p}{3}\frac{\partial f}{\partial p}+\frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\rm ion}f\right]=q(p,z)$$

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

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

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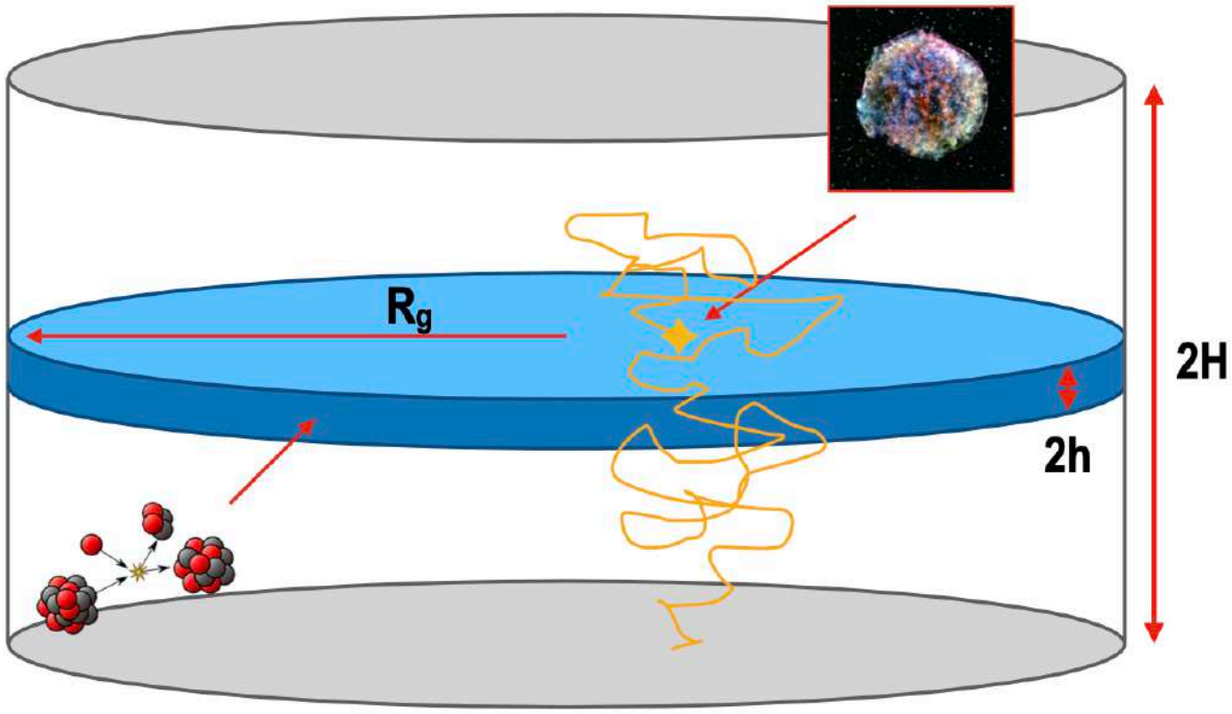

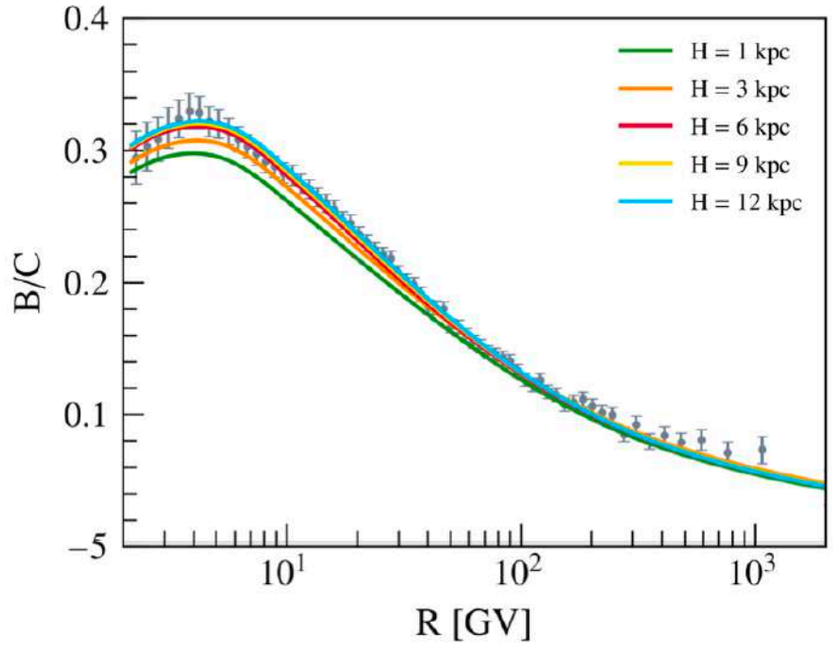

Secondary-to-primary ratio: properties of transport

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

Injection **Propagation**

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

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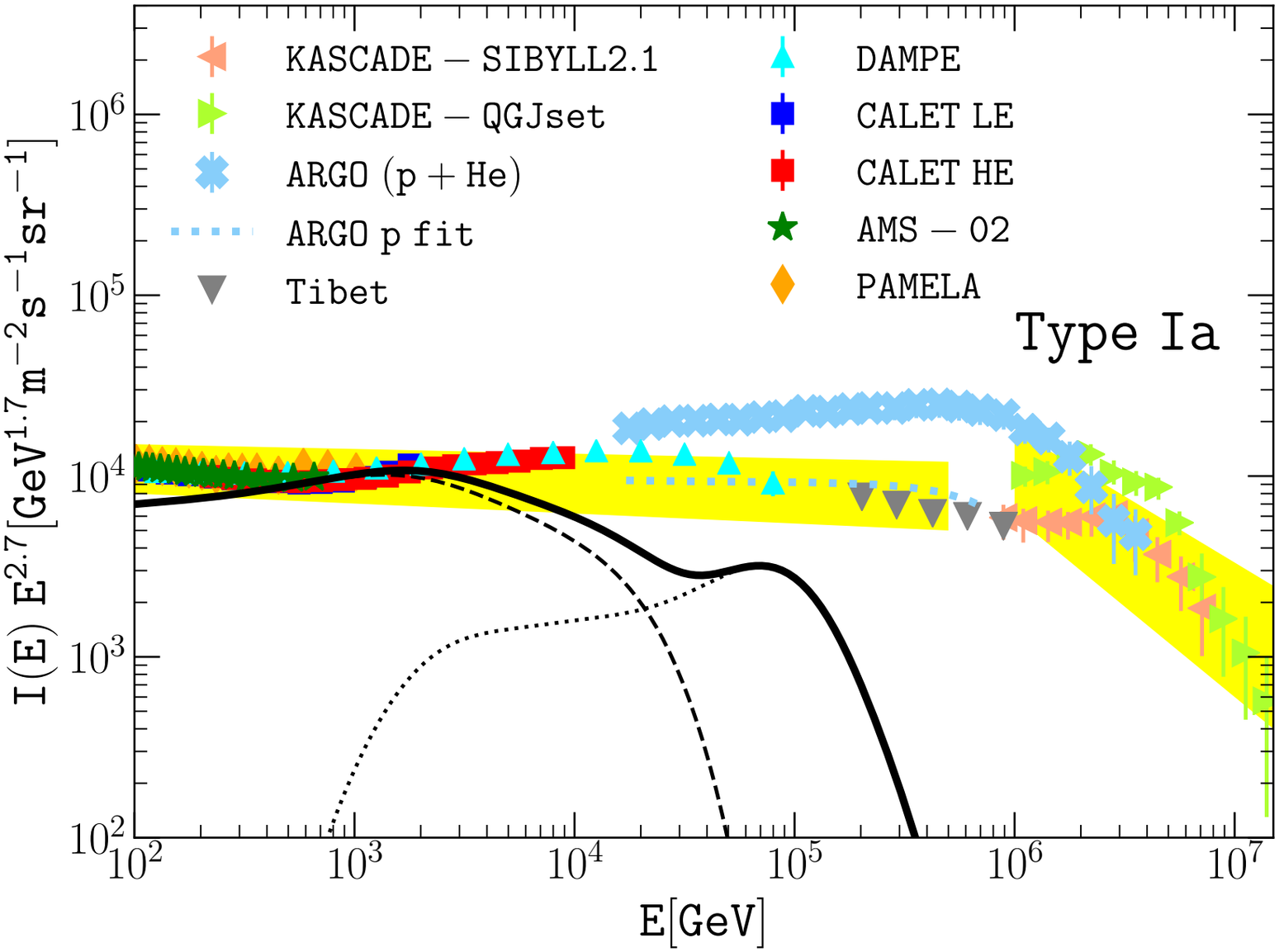
The case of supernova remnants

Protons after propagation:



PC, Blasi& Amato (2020)

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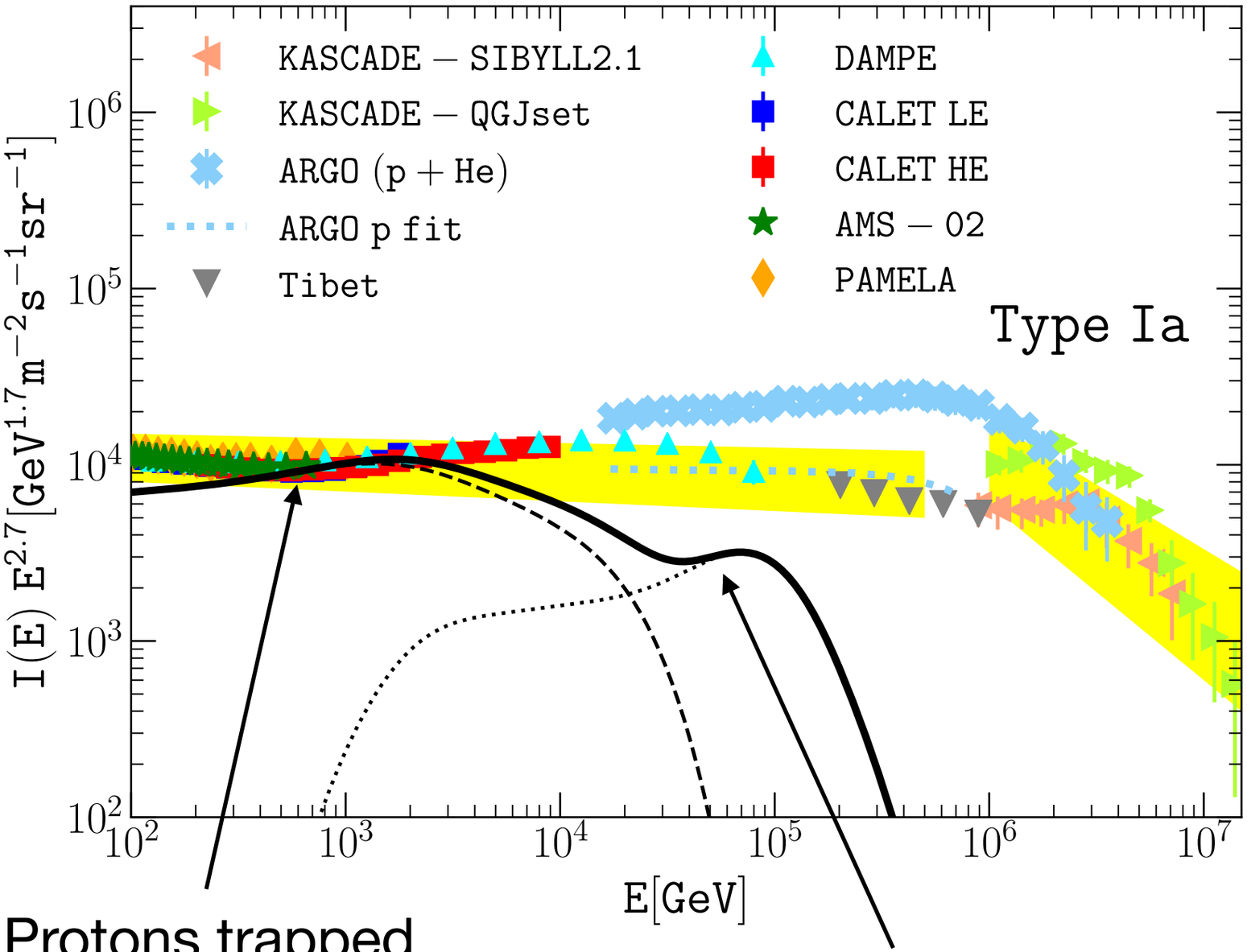

Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

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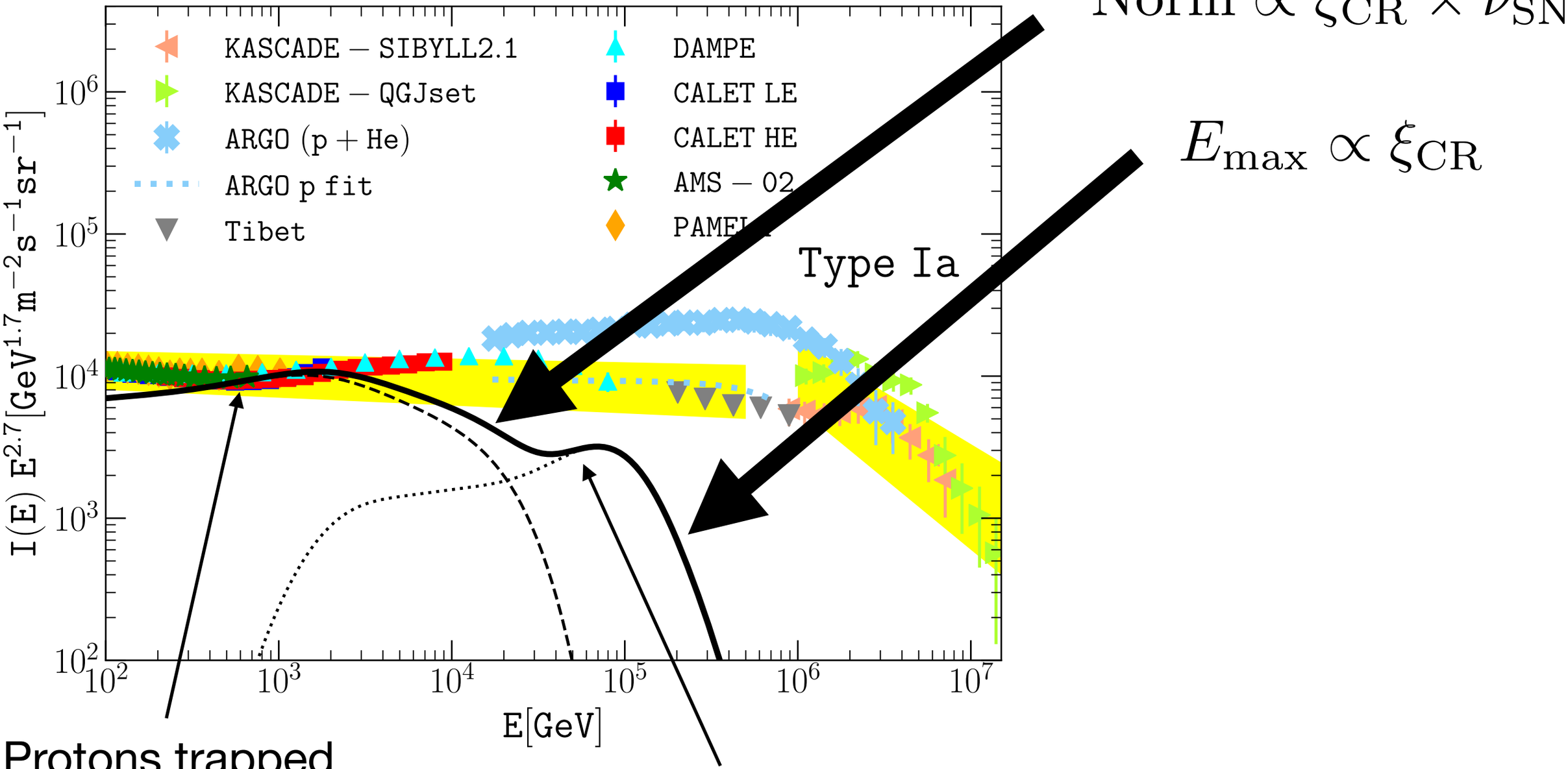

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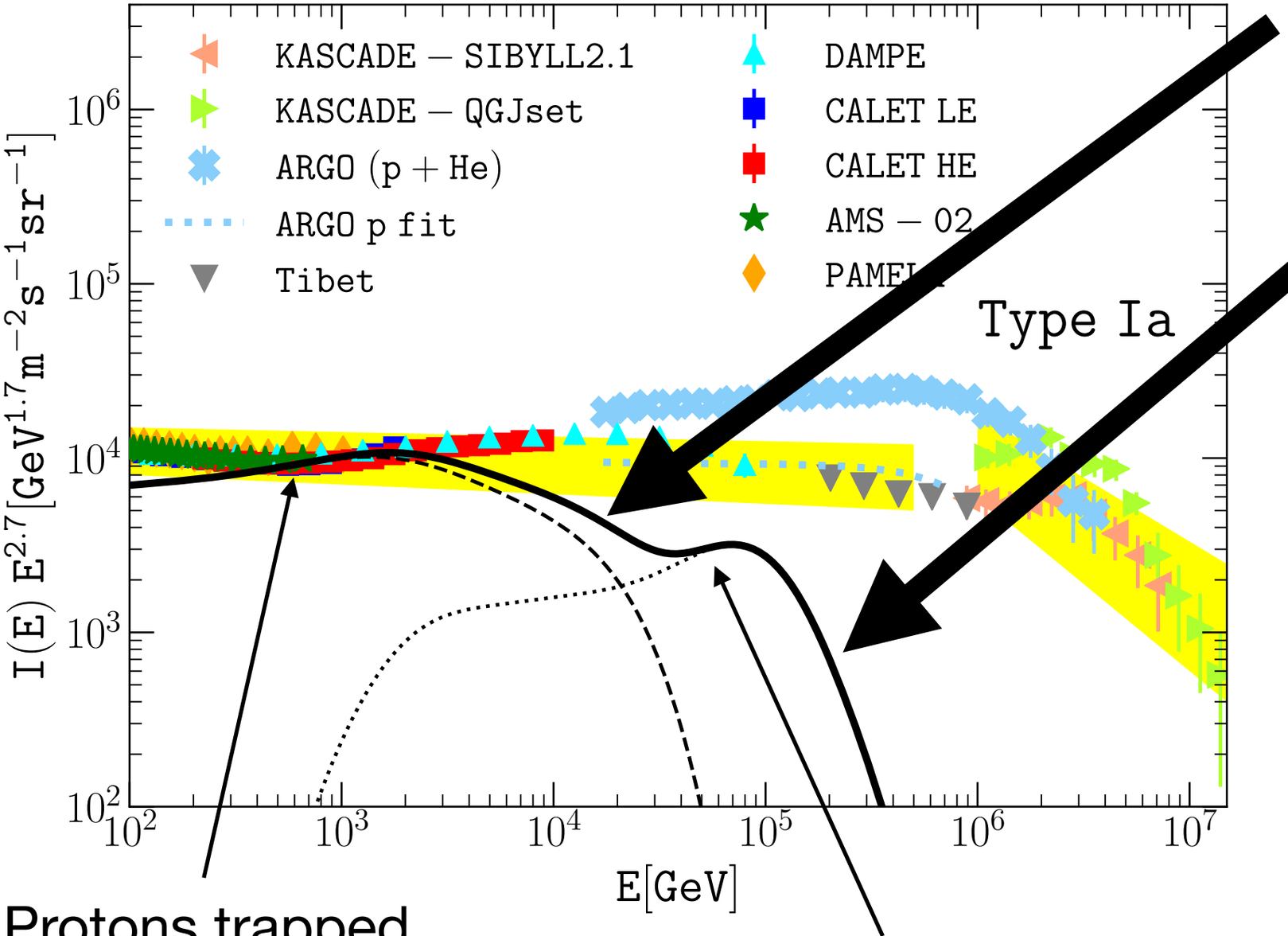

$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

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

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

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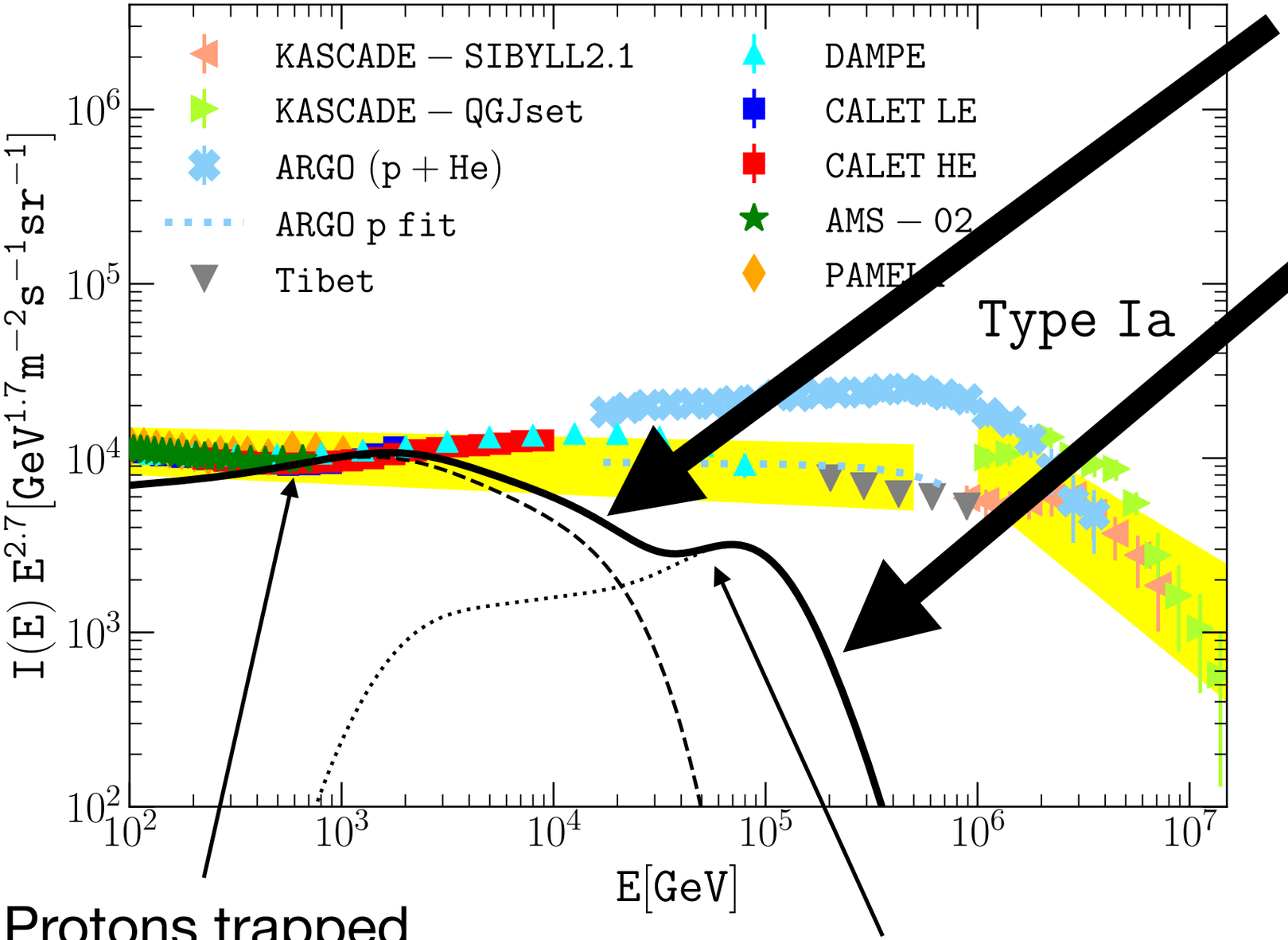

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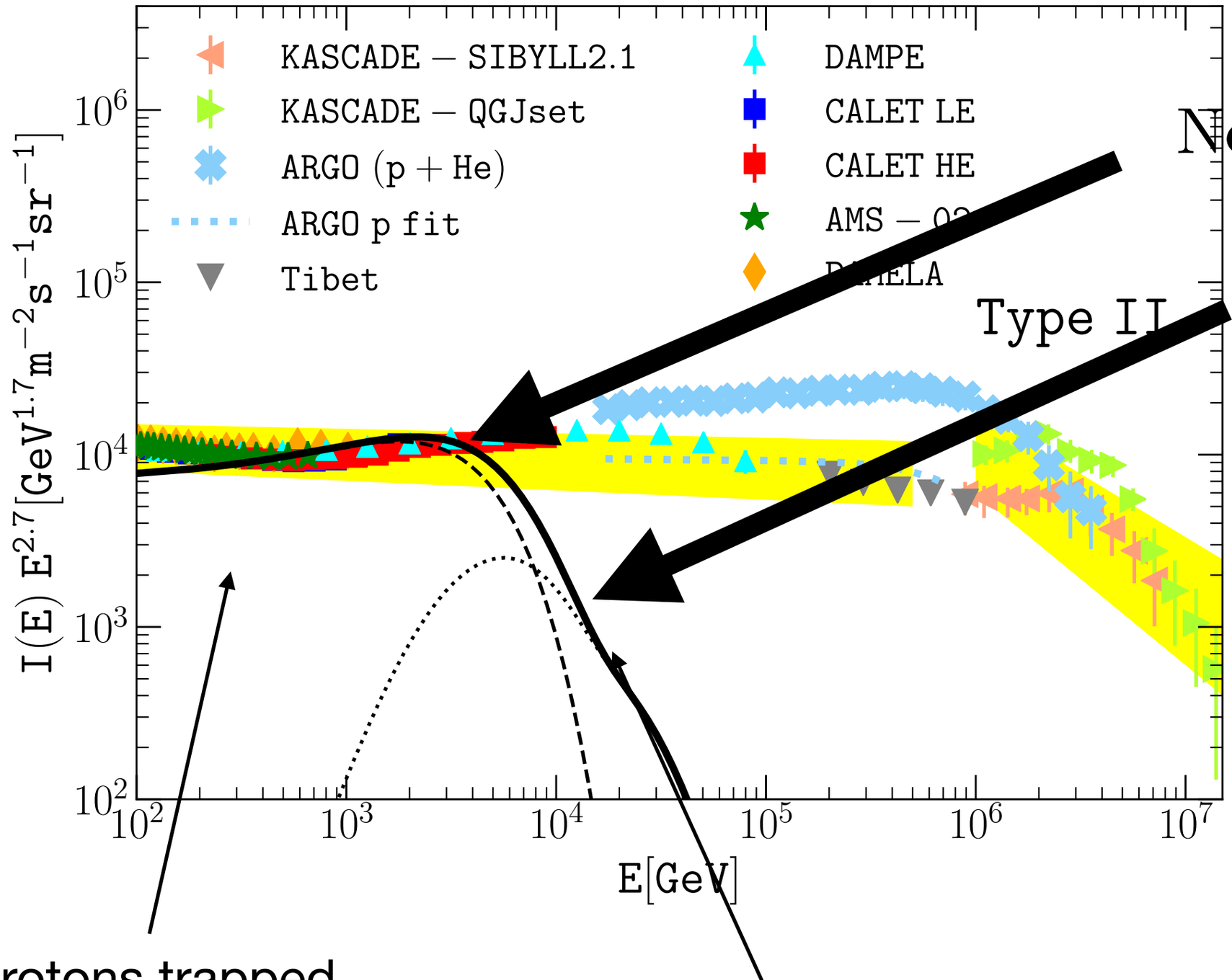

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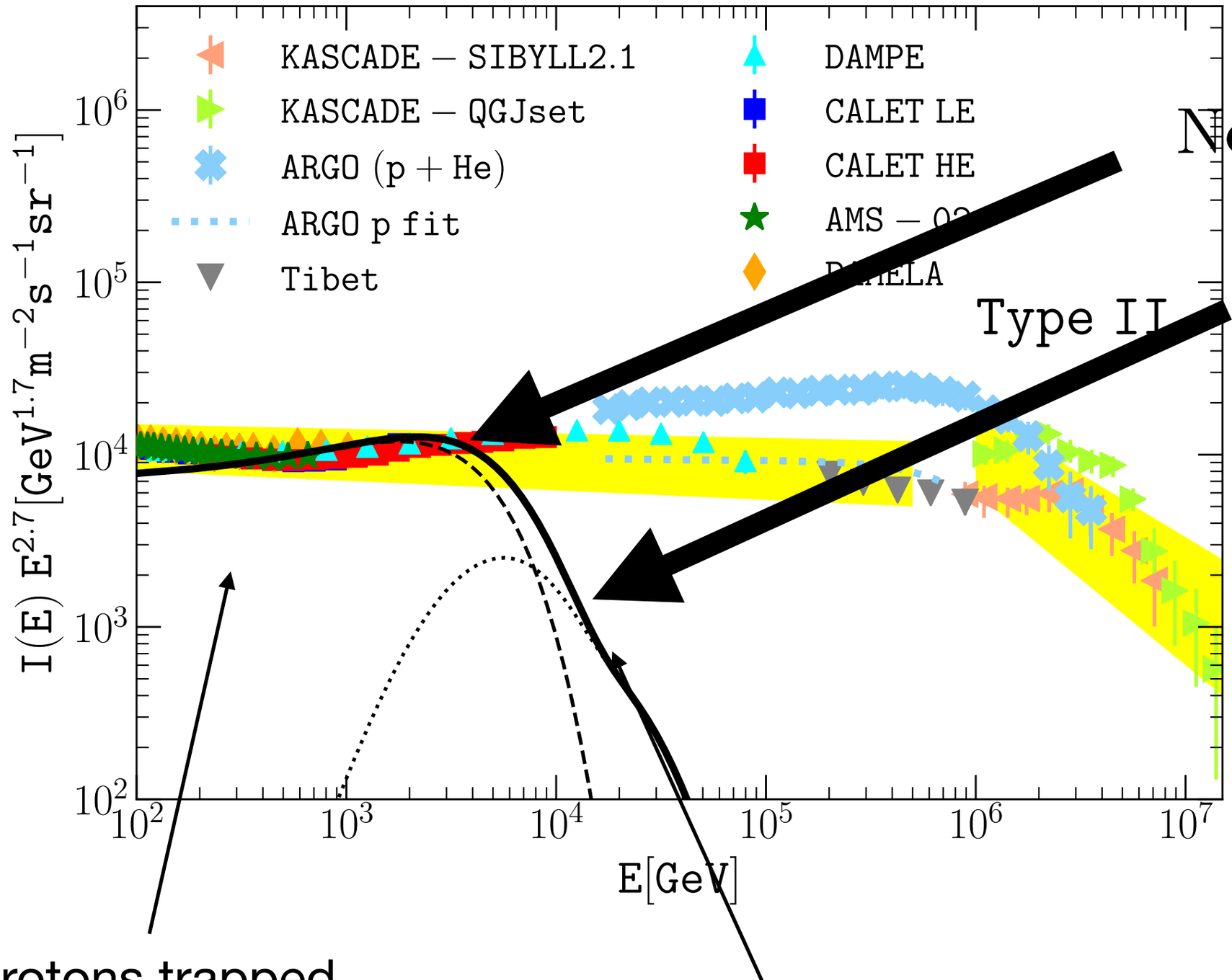

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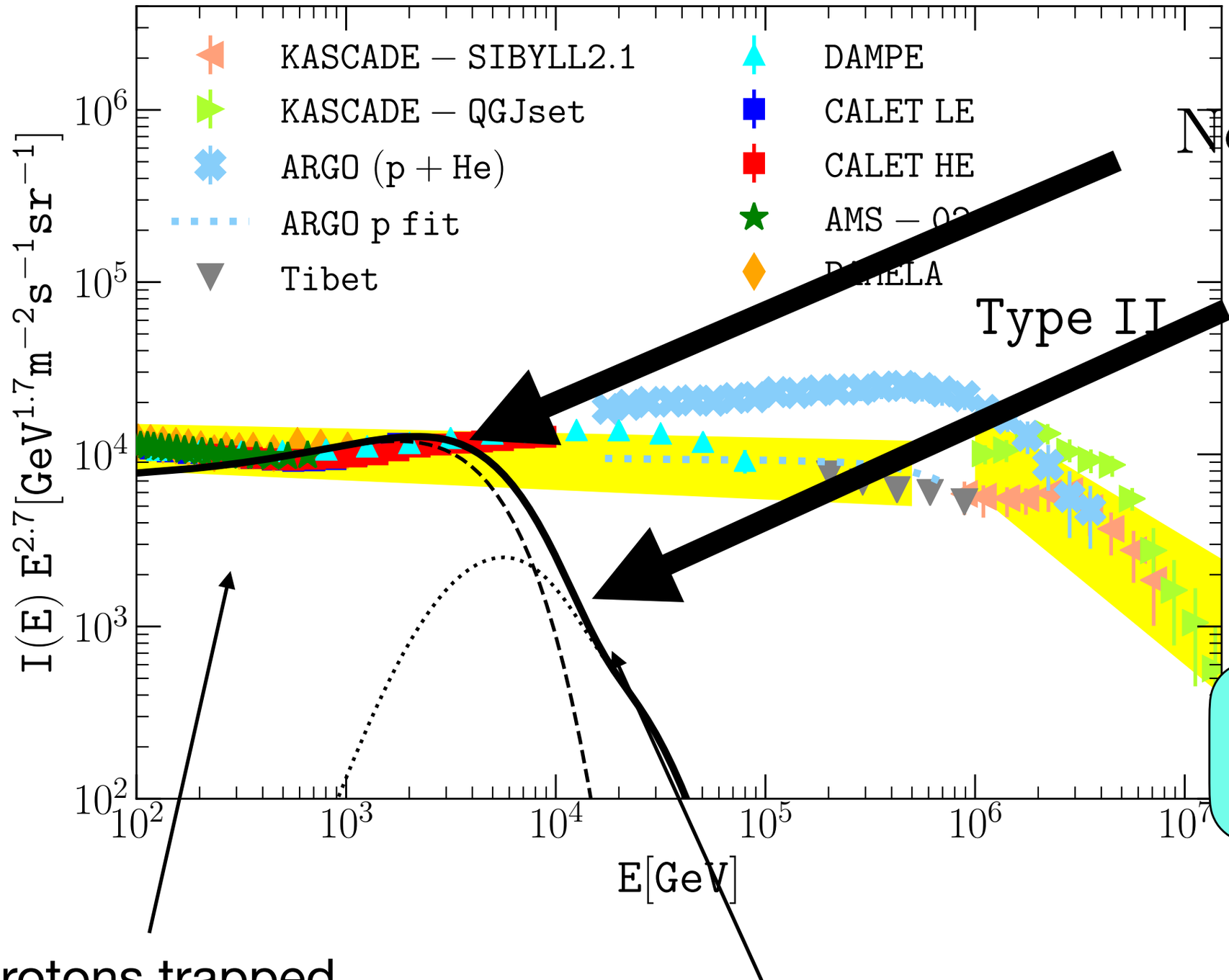


$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

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

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

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

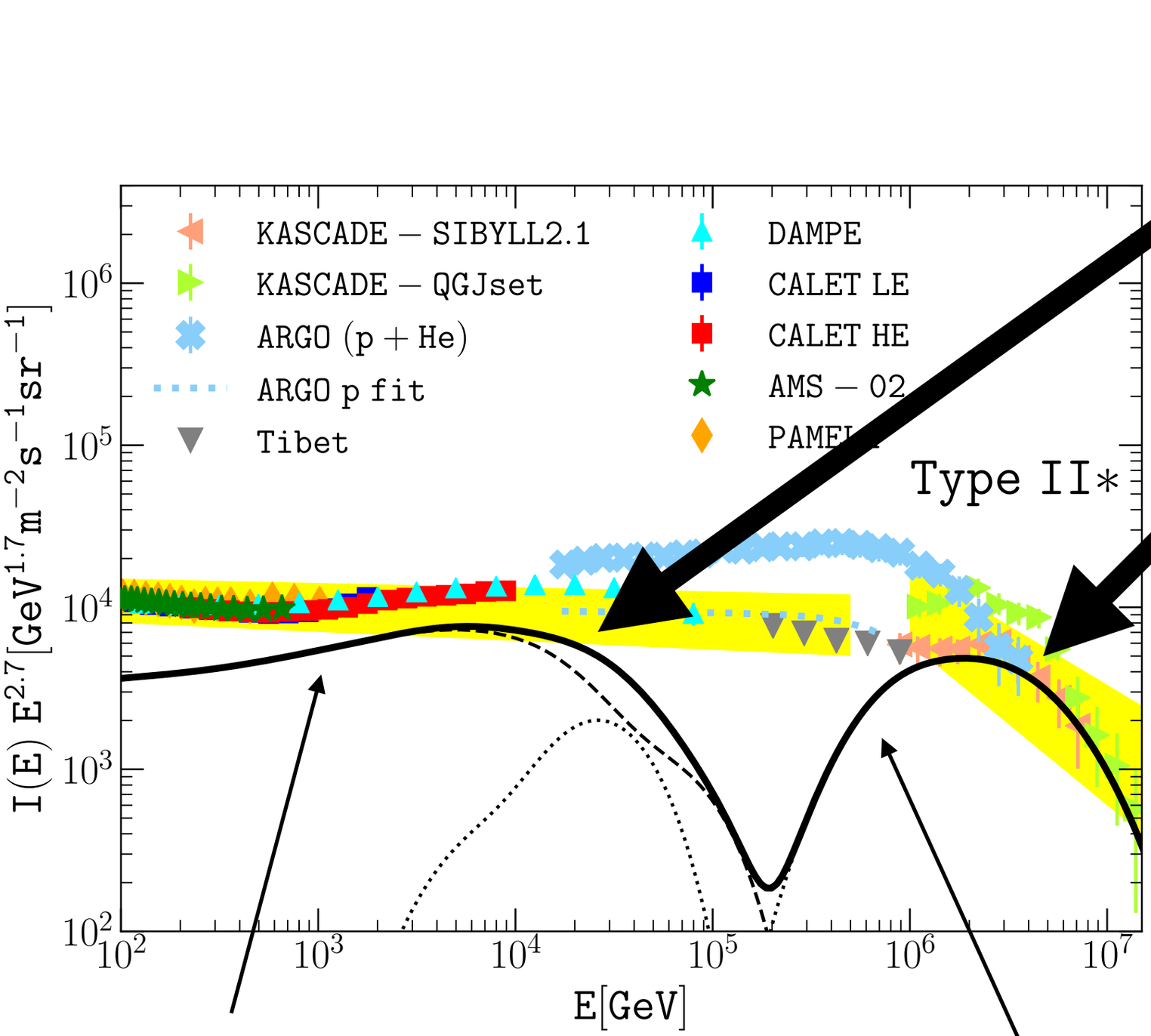
Protons trapped inside SNR

Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

Protons after propagation:



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Type II*

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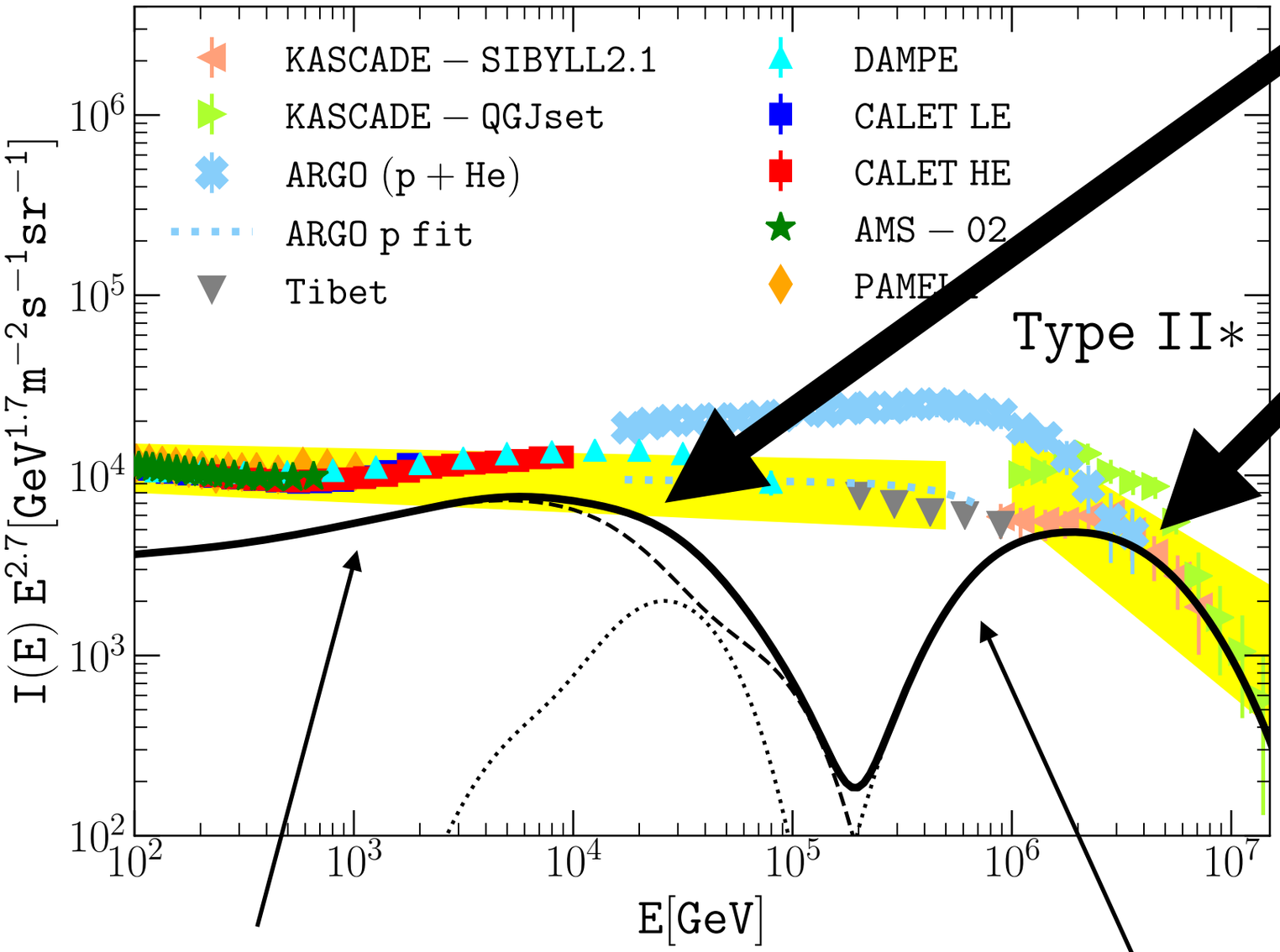
$$\mathrm{Norm} \propto \xi_{\mathrm{CR}} \times \nu_{\mathrm{SN}}$$

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

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



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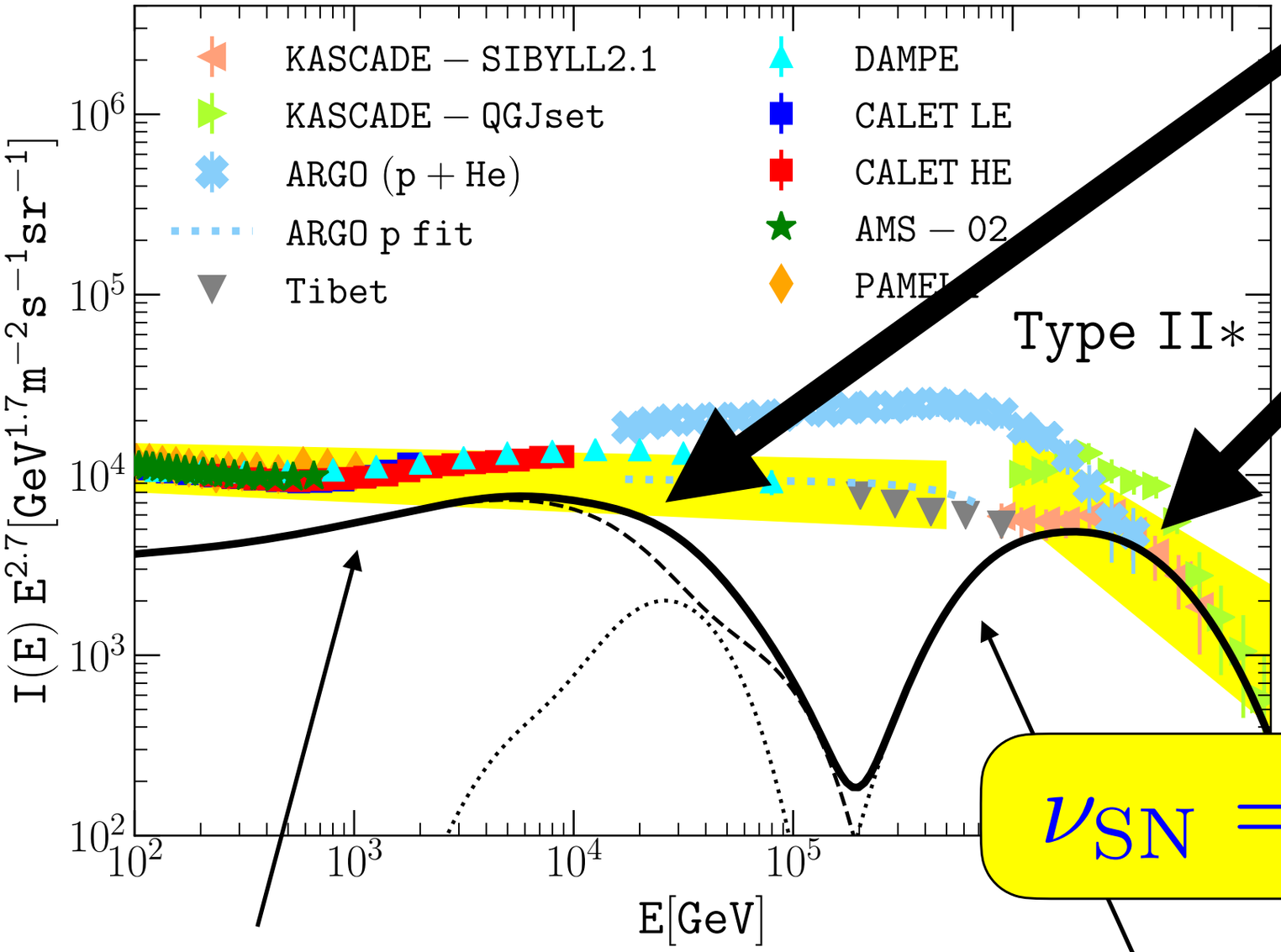

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Reach PeV and not overproduce the CR spectrum:

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

Protons trapped inside SNR

Protons continuously escaping

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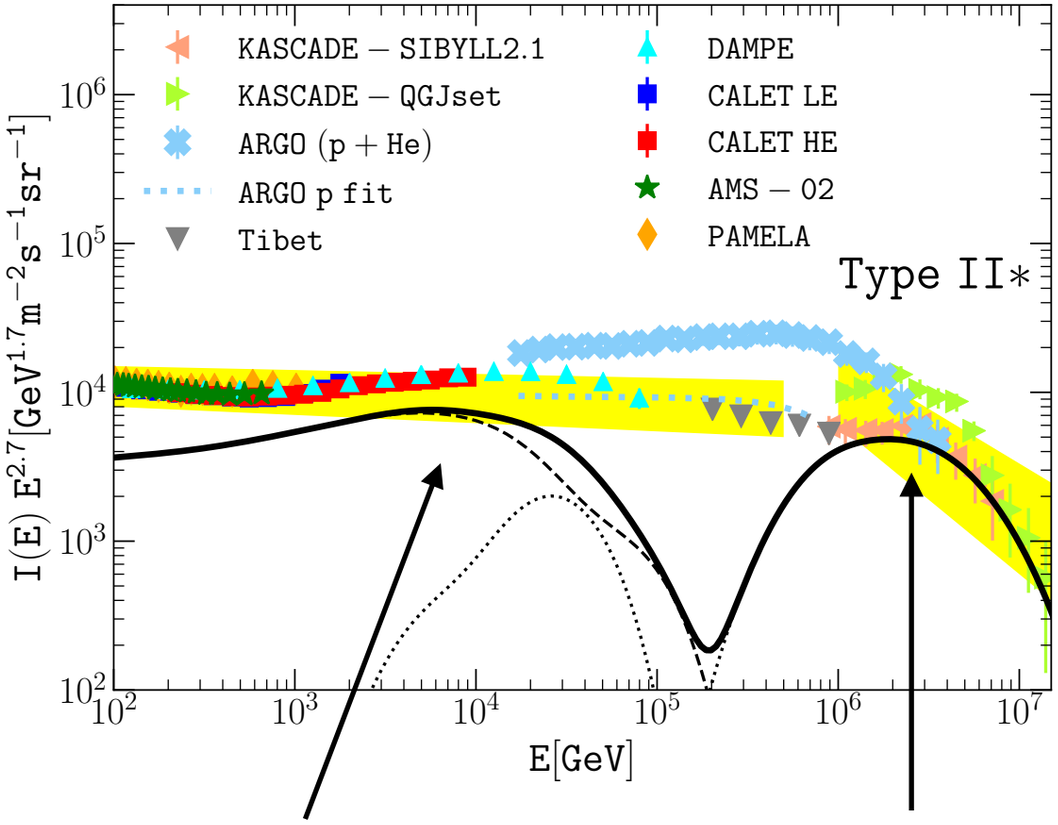
1. Possible to account for PeV protons with rare unusual SNRs (1% 3/century, hard to catch!)



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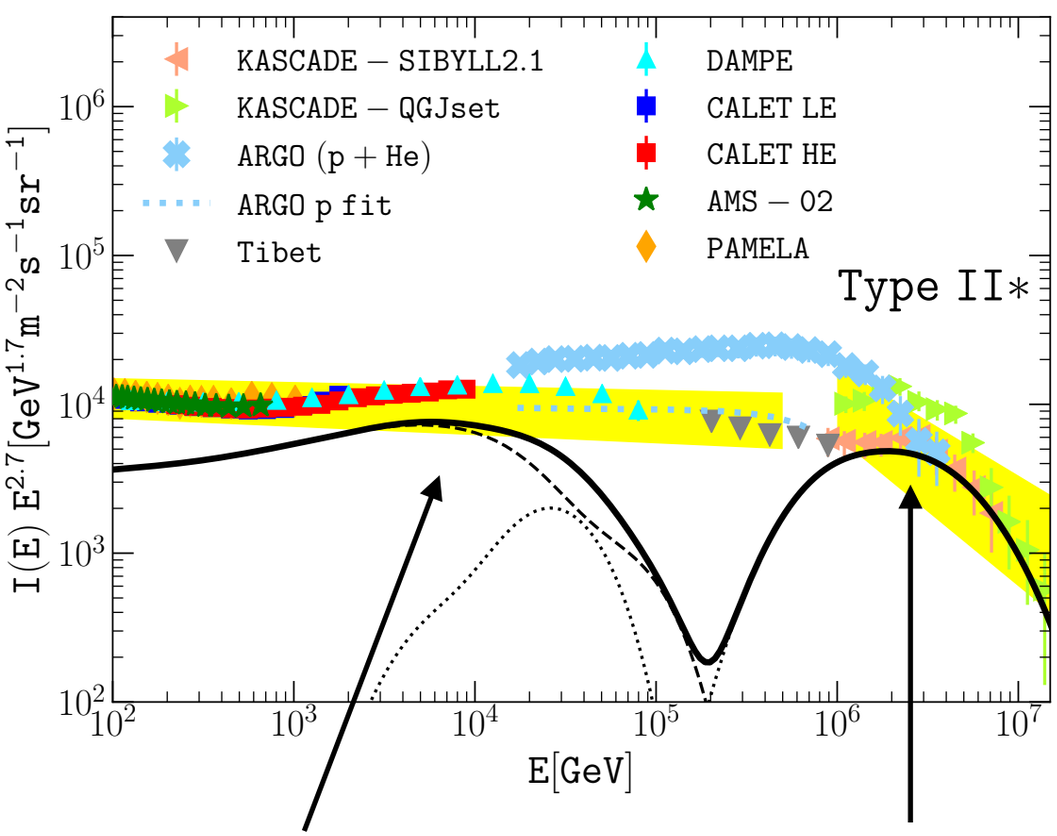

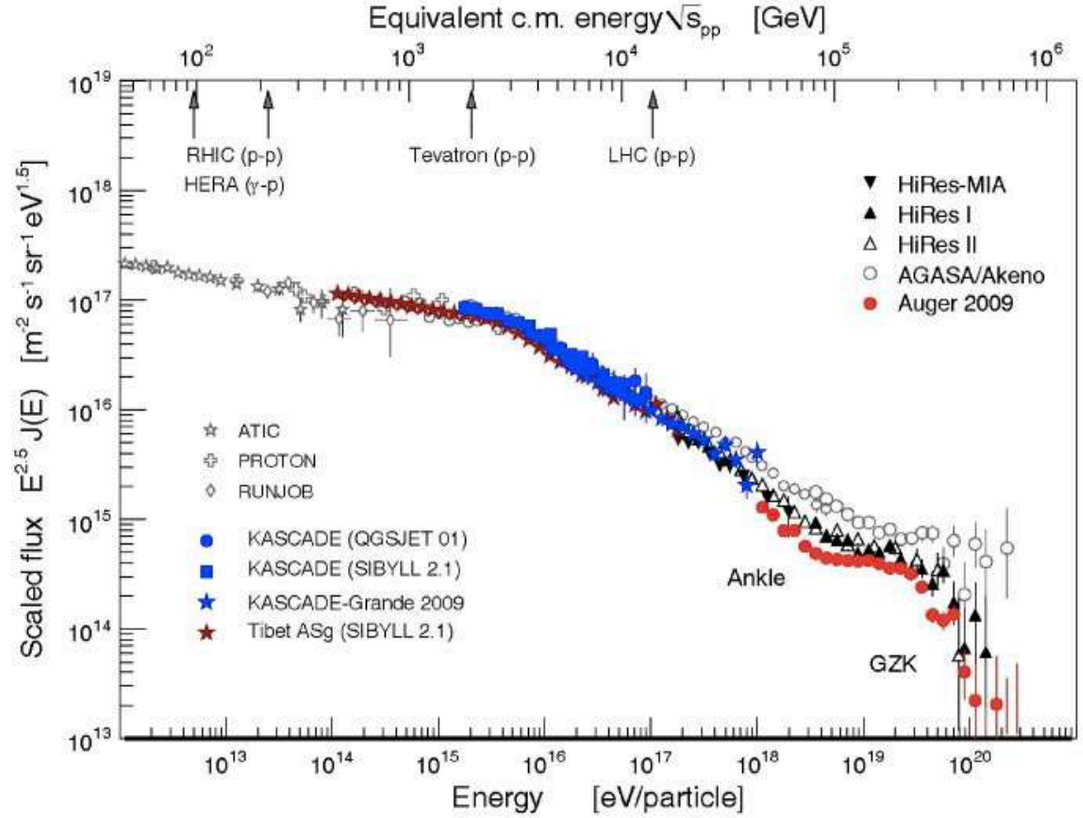

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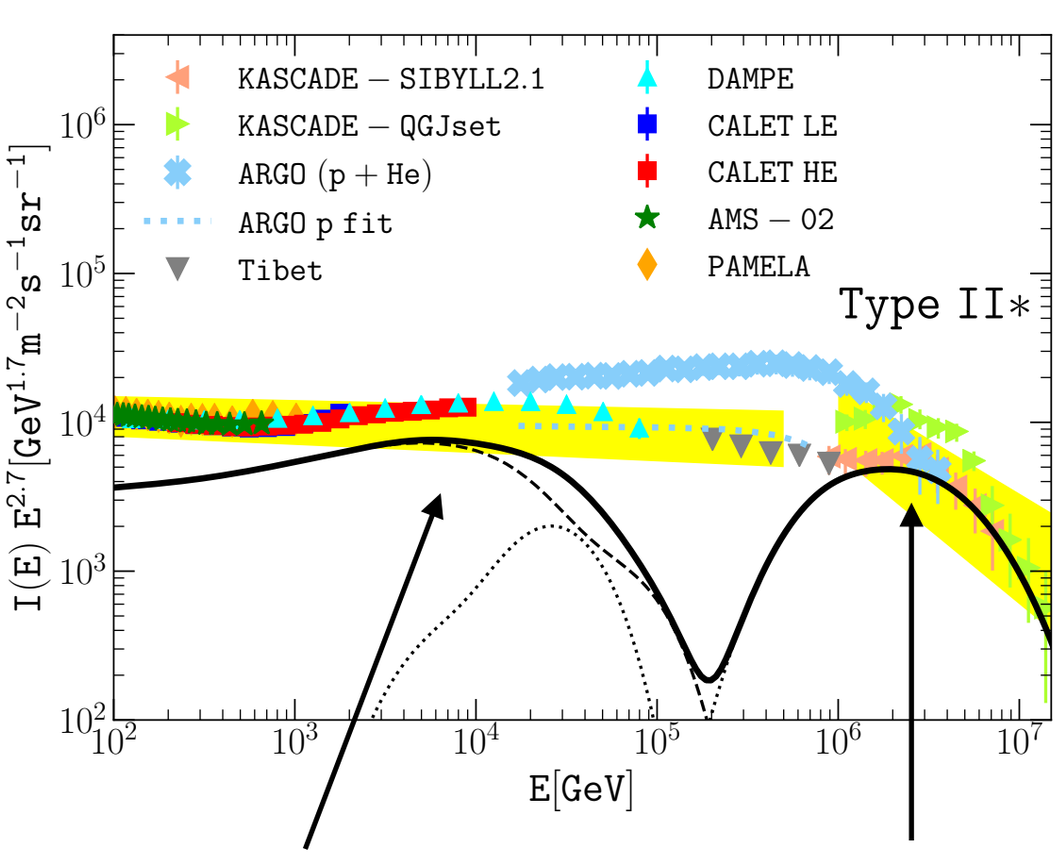

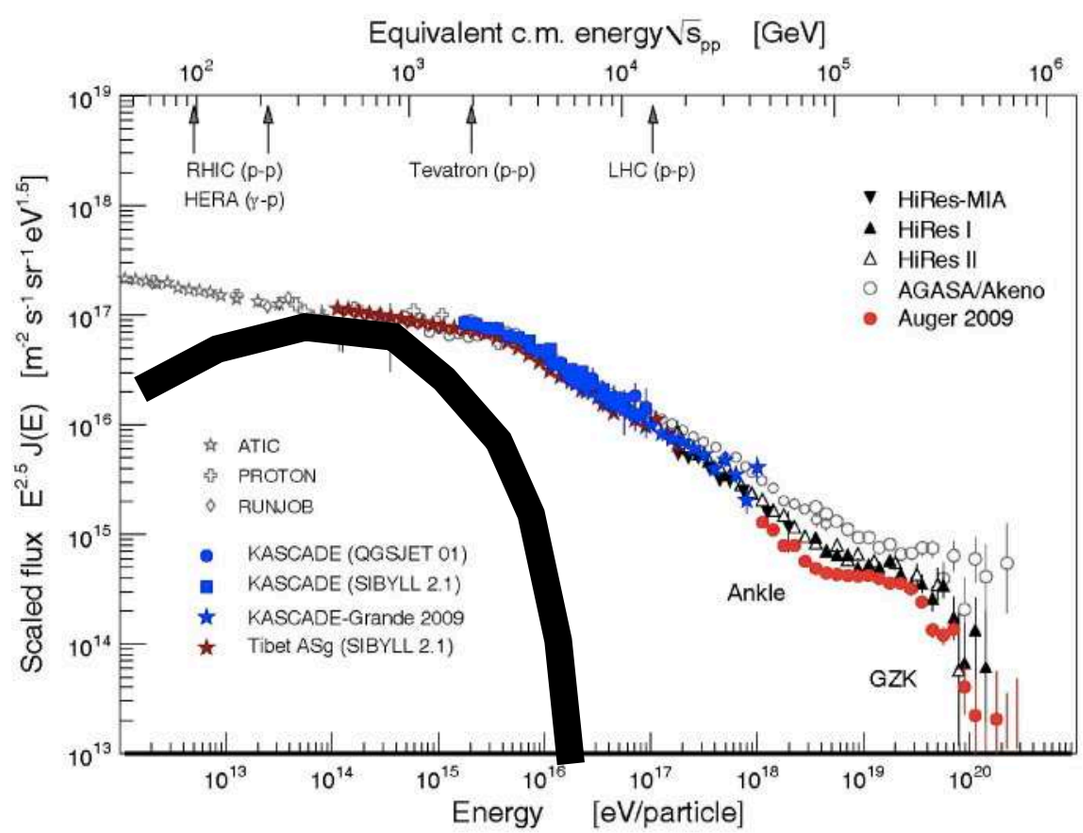

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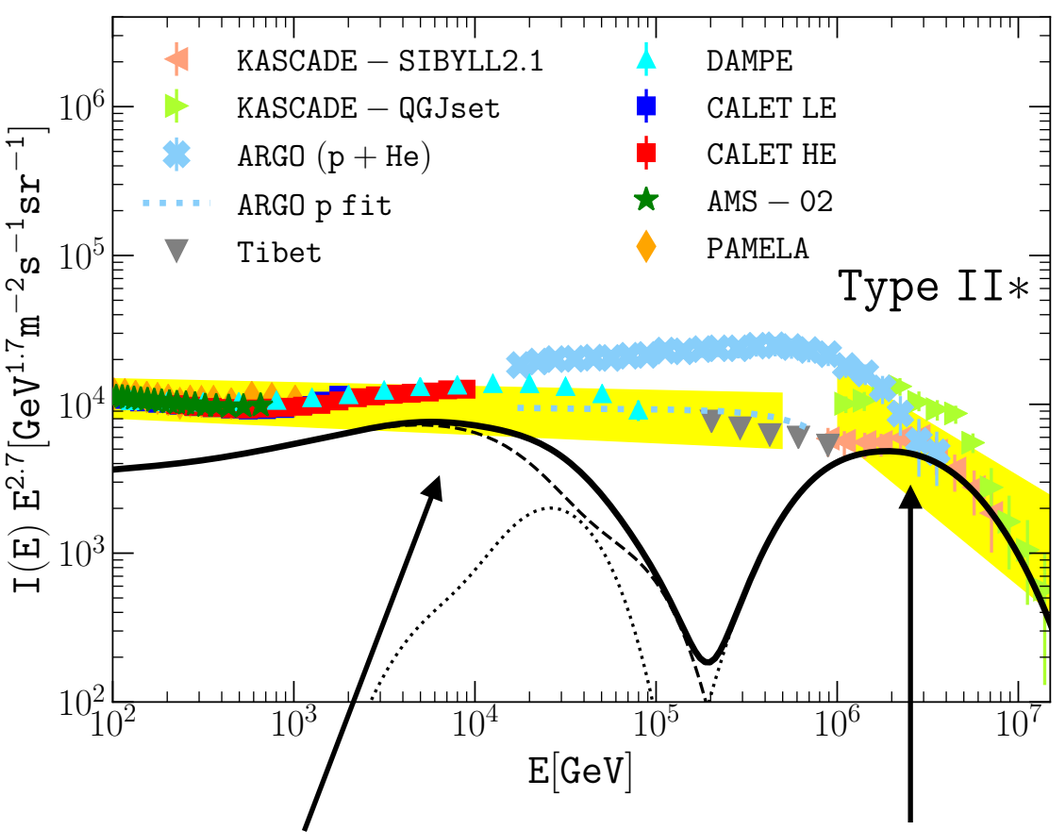

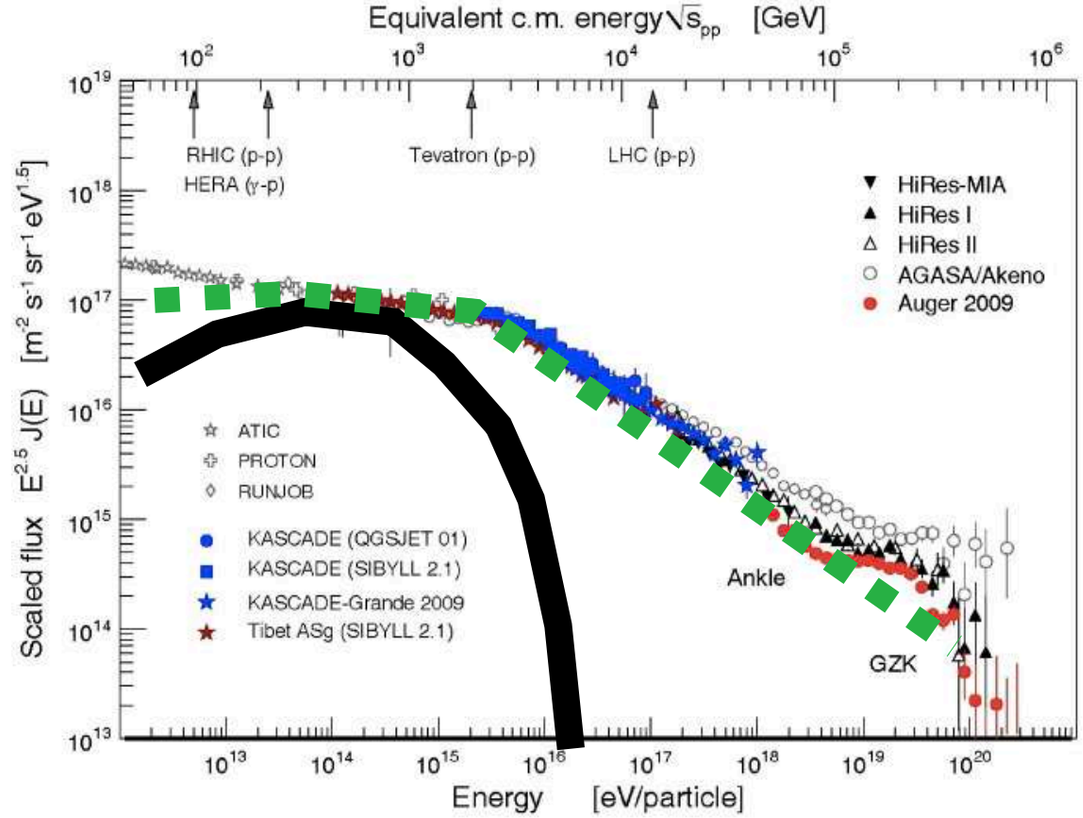

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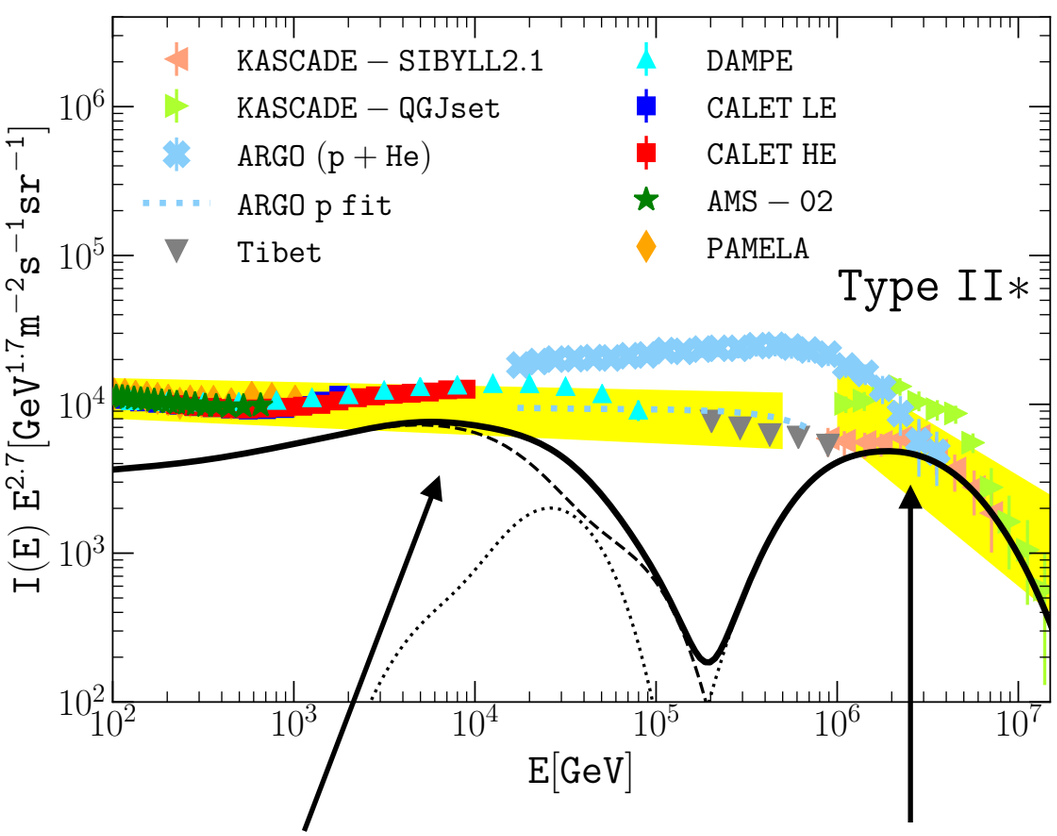
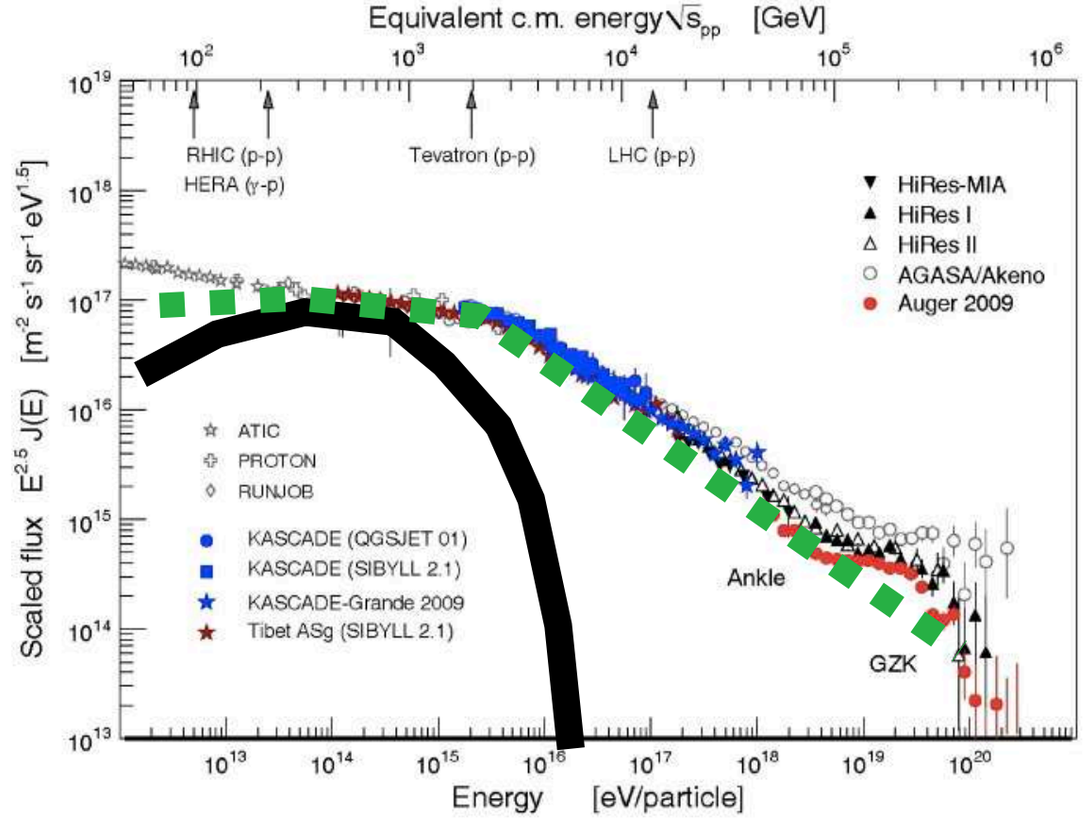
3. Issues with the spectrum BELOW PeV!





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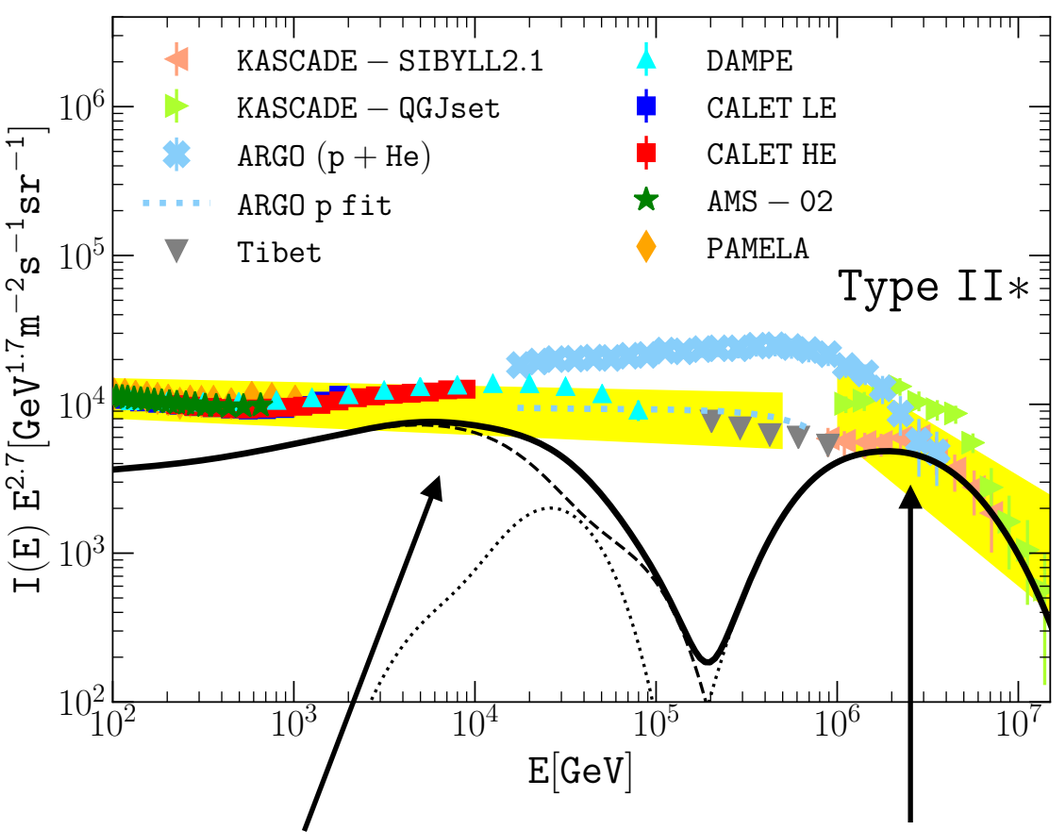
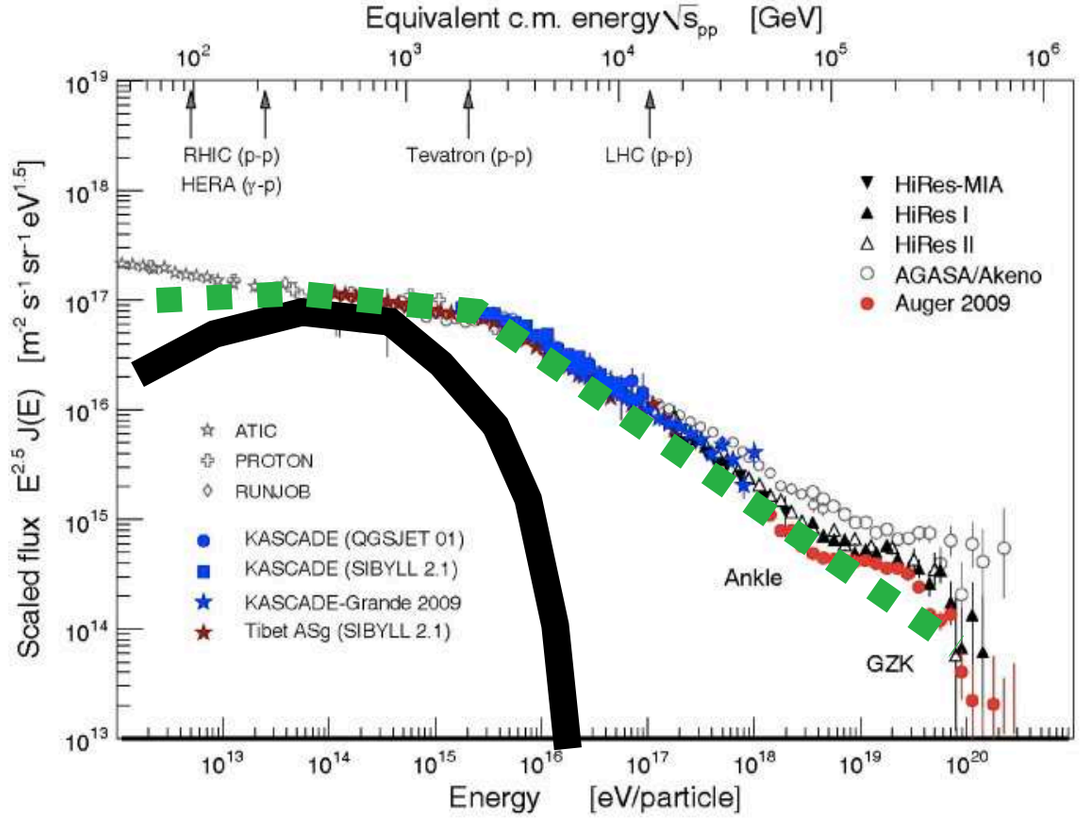




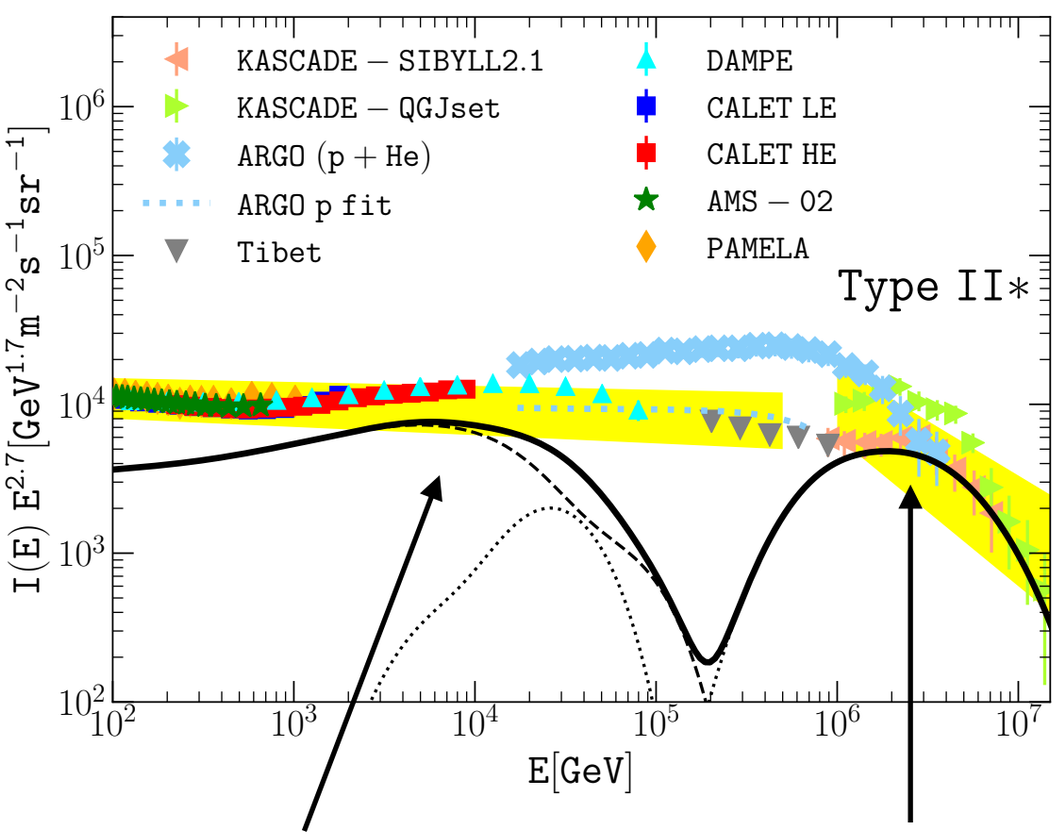
Protons trapped inside SNR

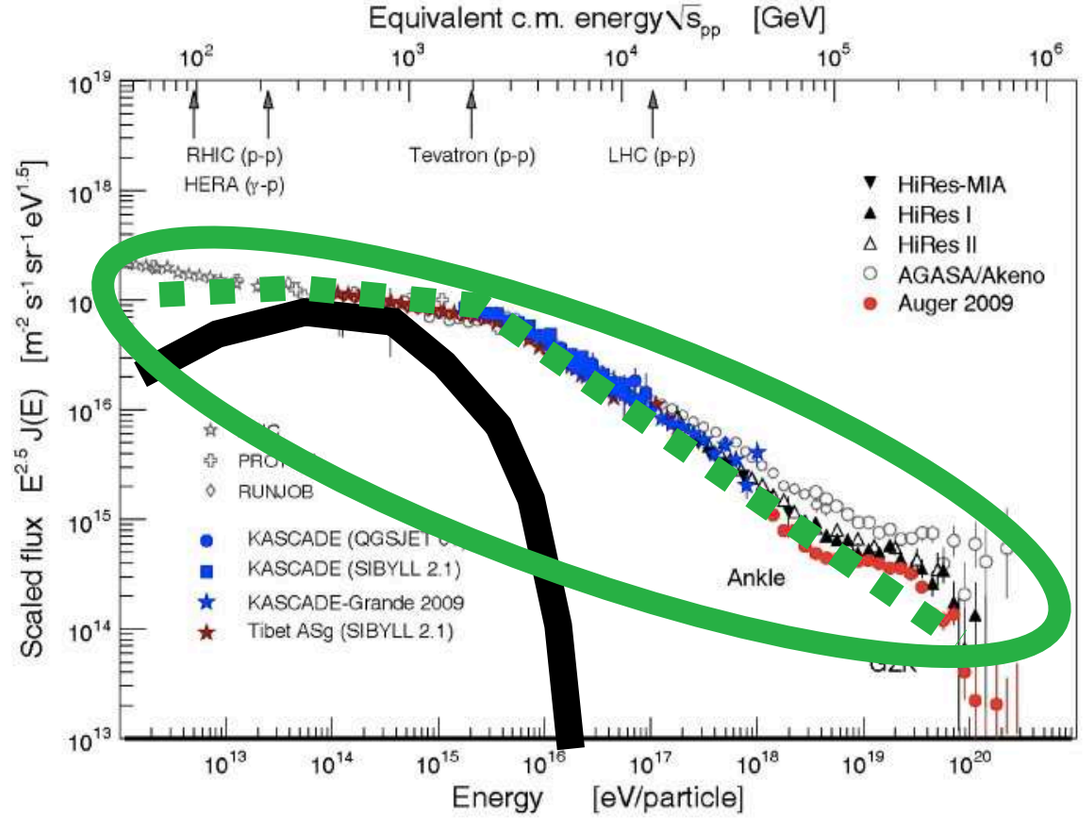
Protons continuously escaping

PC, Blasi& Amato (2020)

The case of supernova remnants

1. Possible to account for PeV protons with rare unusual SNRs (1% 3/century, hard to catch!)
2. Exponential cut-off (expected from escape of protons)
3. Issues with the spectrum BELOW PeV!





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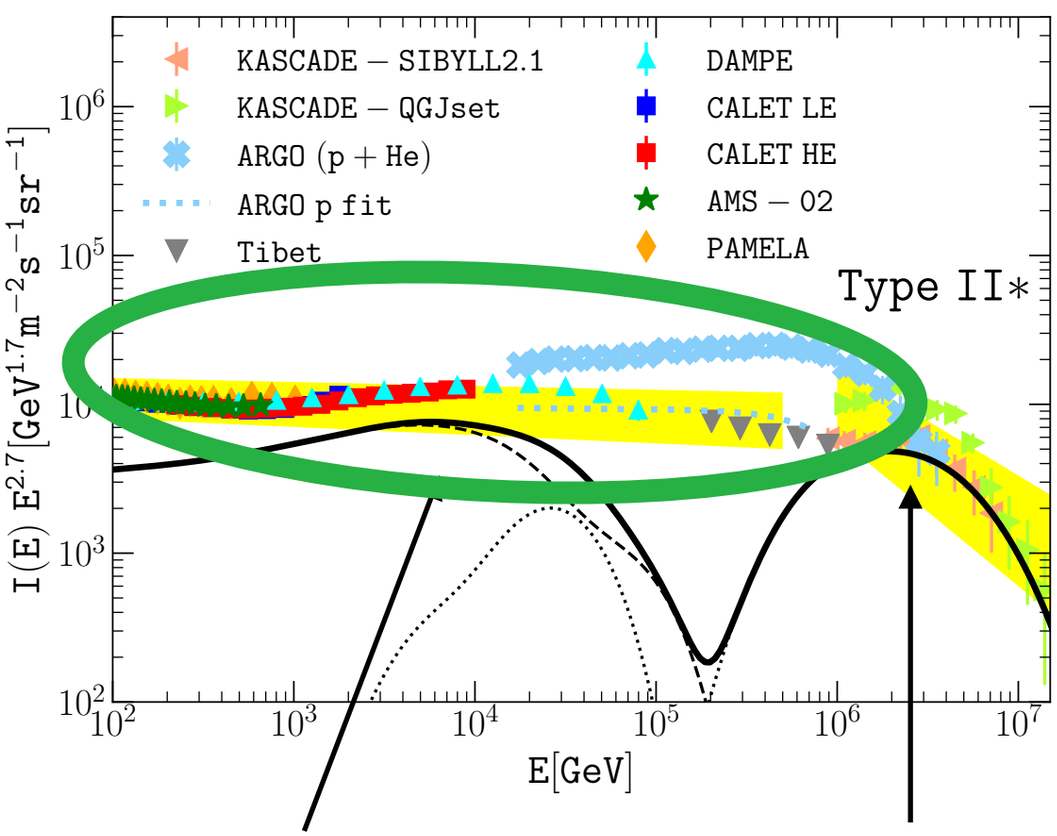

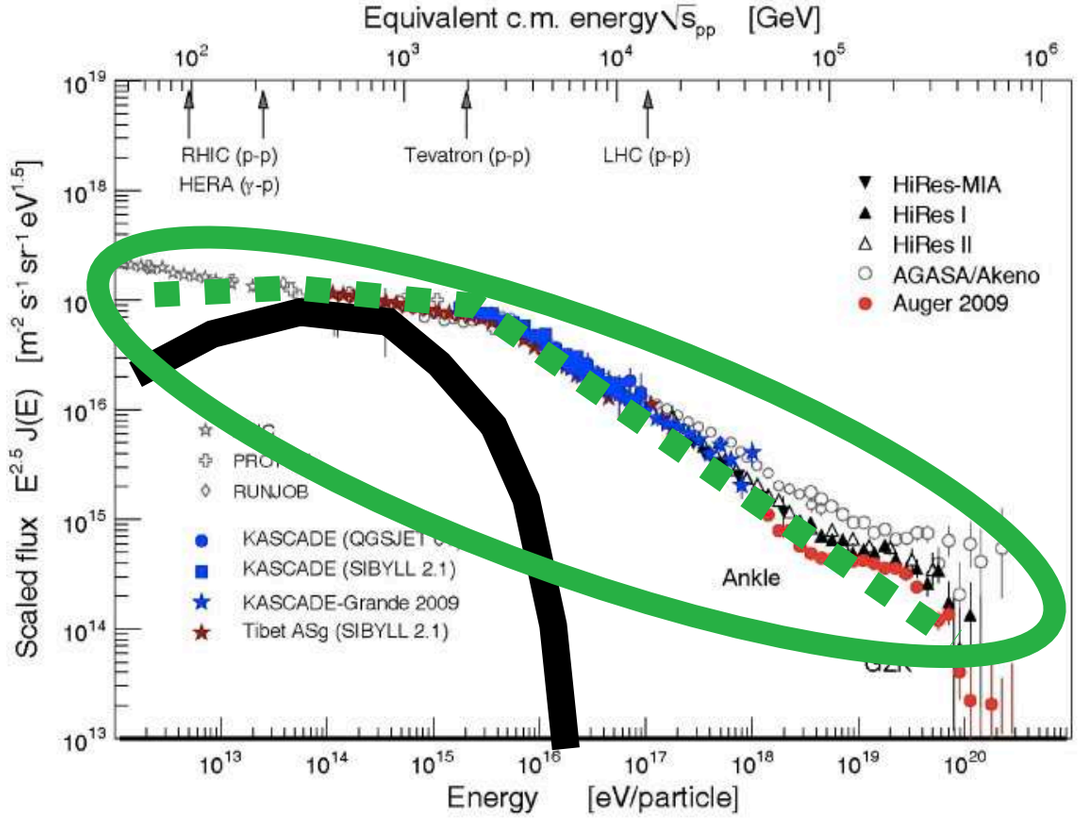

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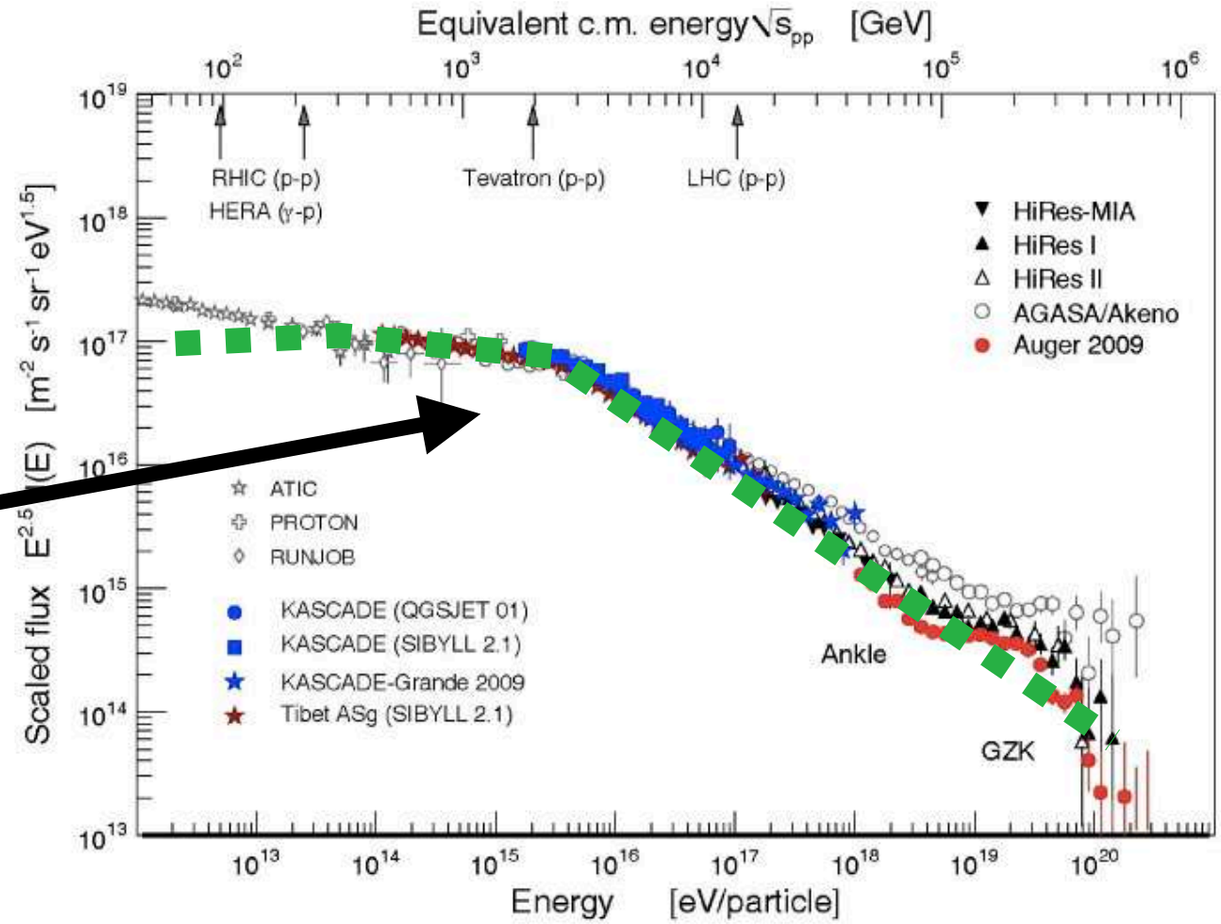
‘Hard enough’ spectra above the knee

How to produce this?



1. Break during propagation

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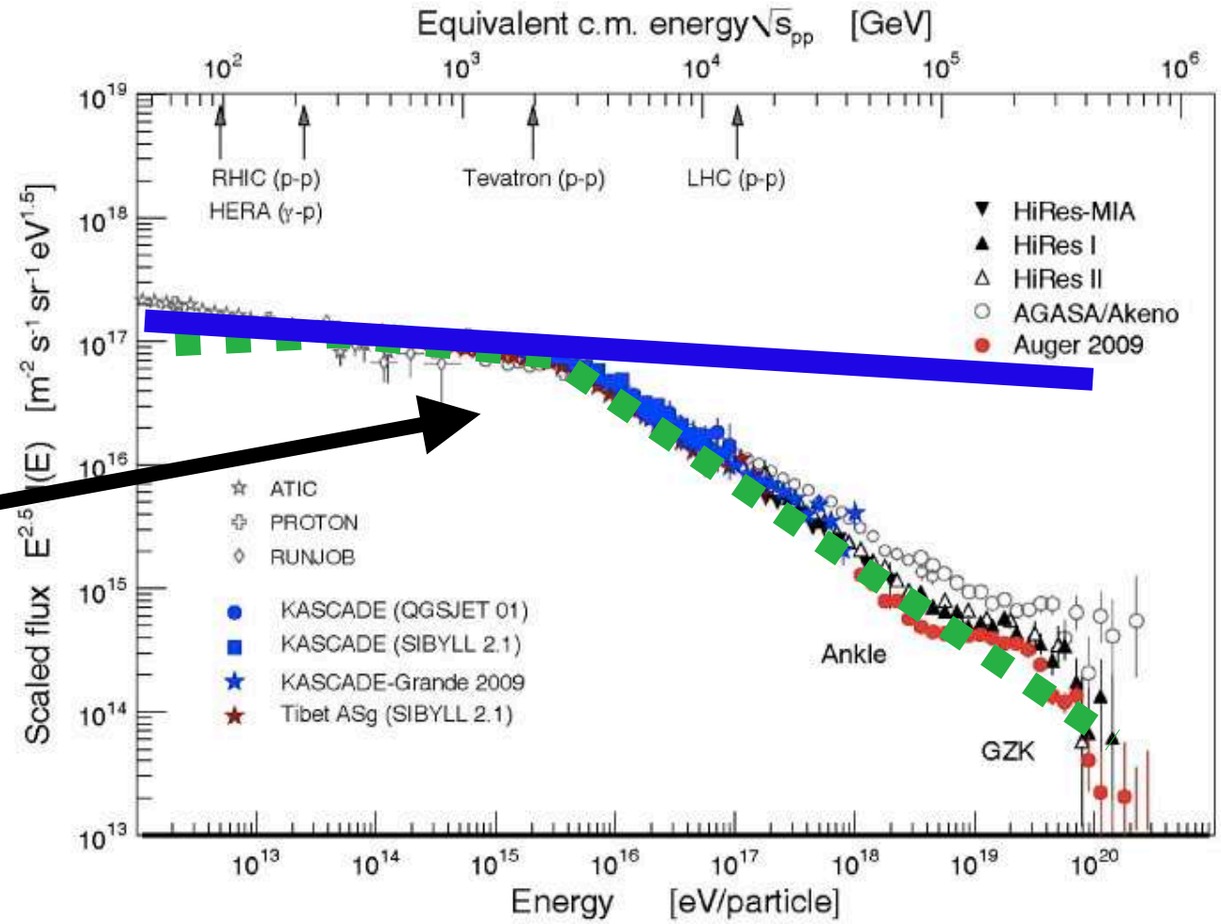

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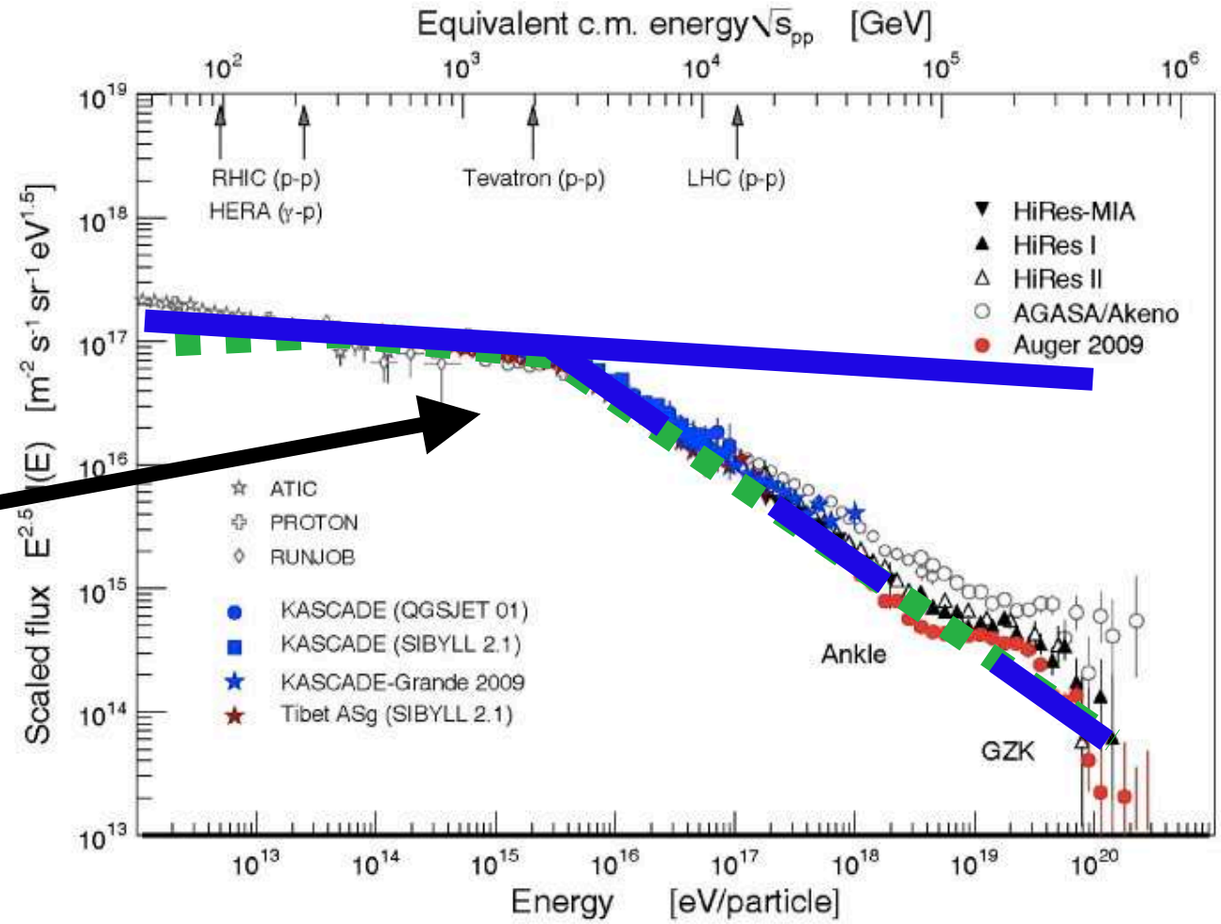

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Alex Kääpä’s talk

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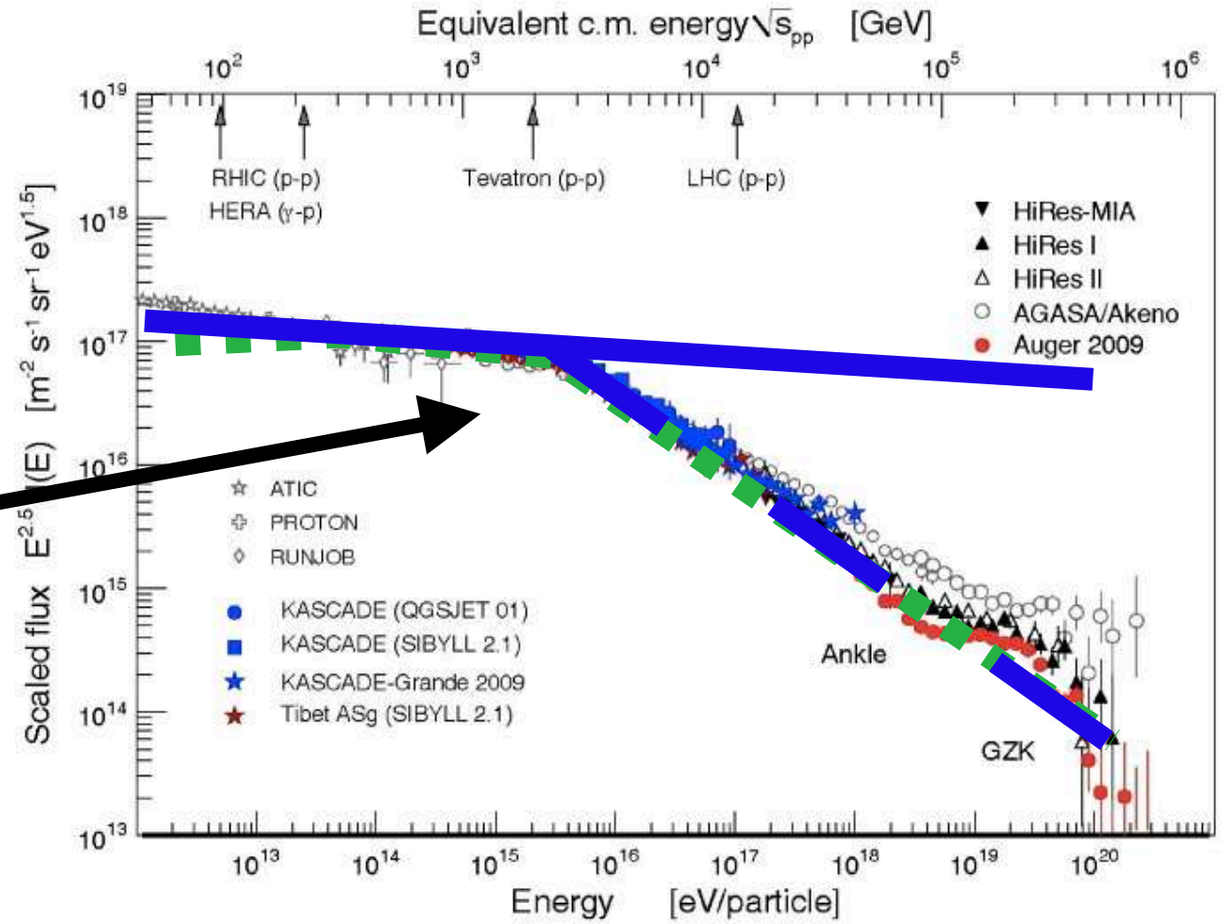

1. Break during propagation

2. Two (or more) ‘classes’ of sources overlapping

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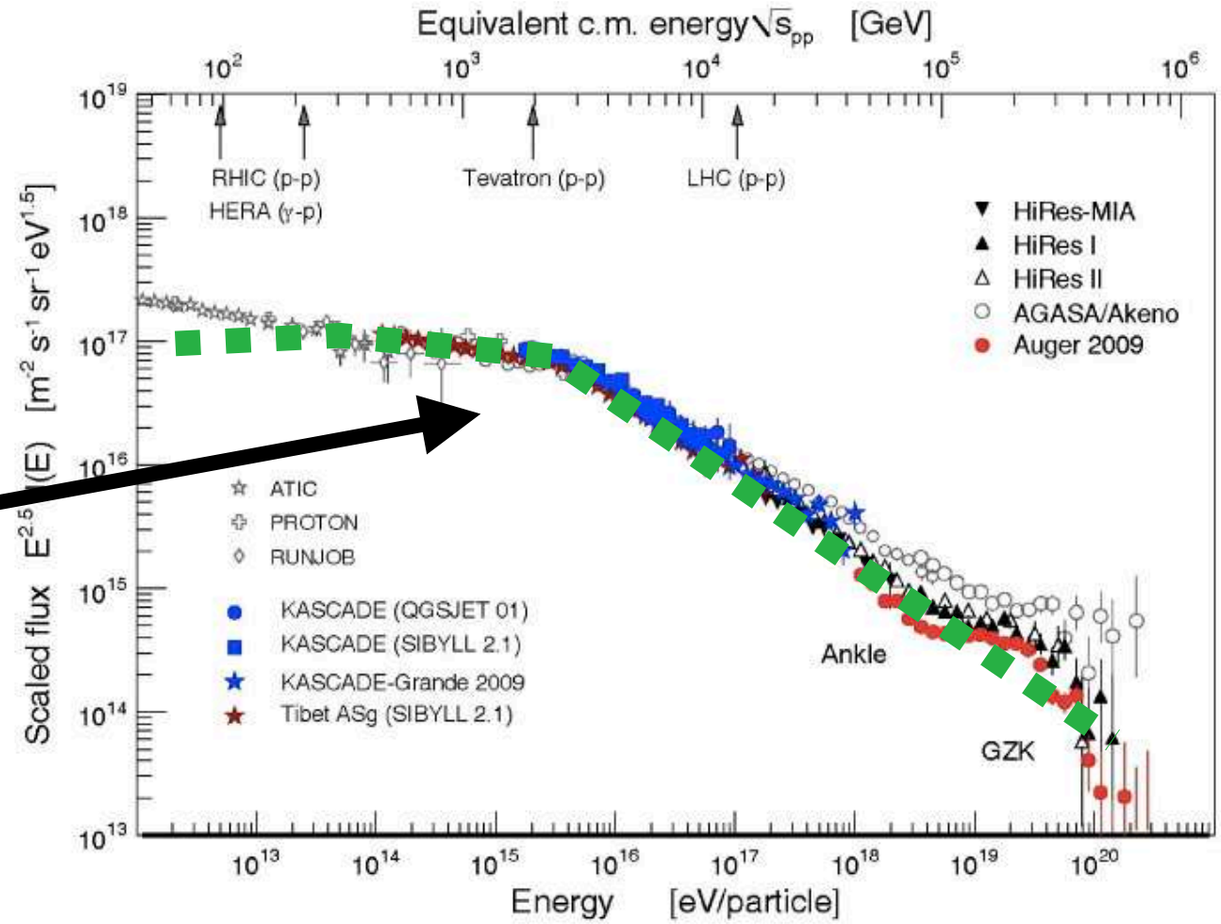

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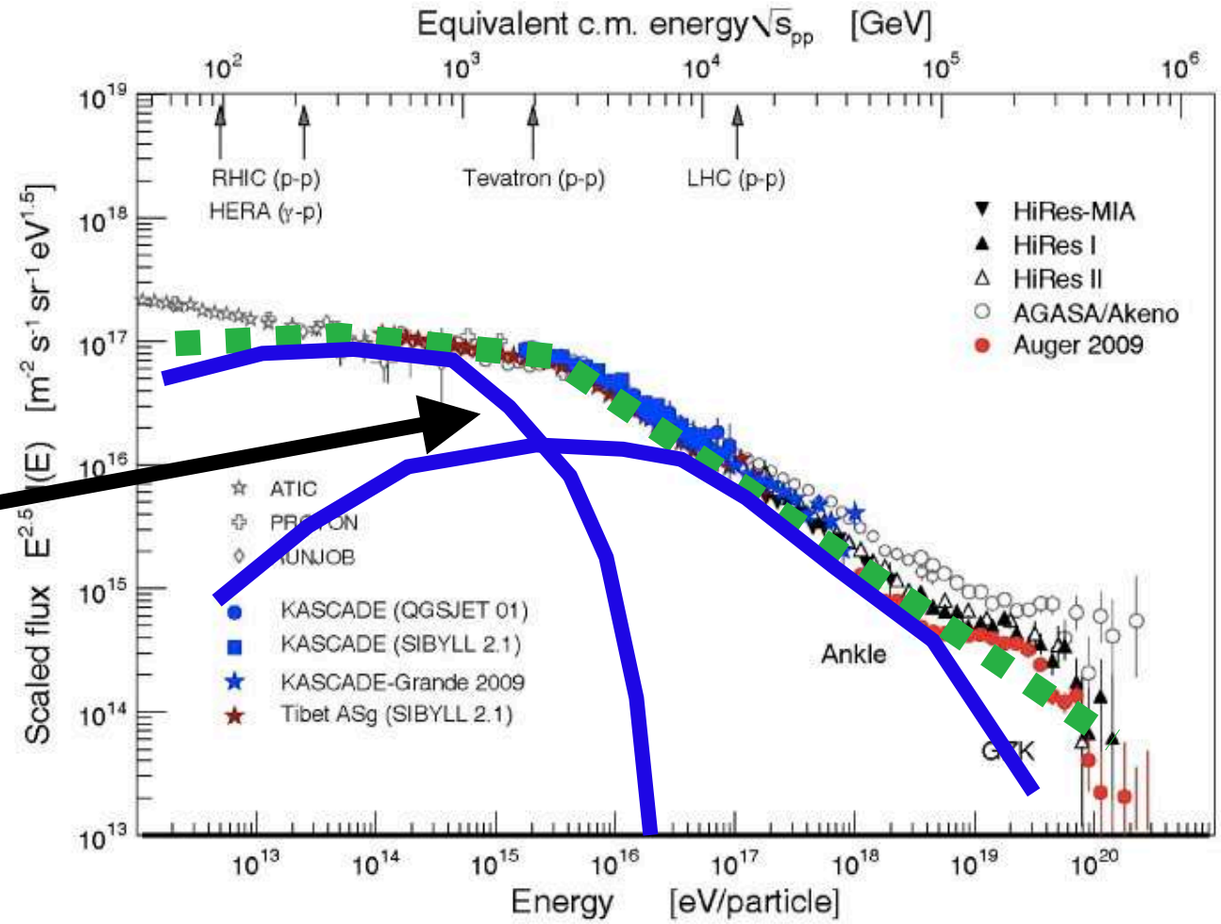

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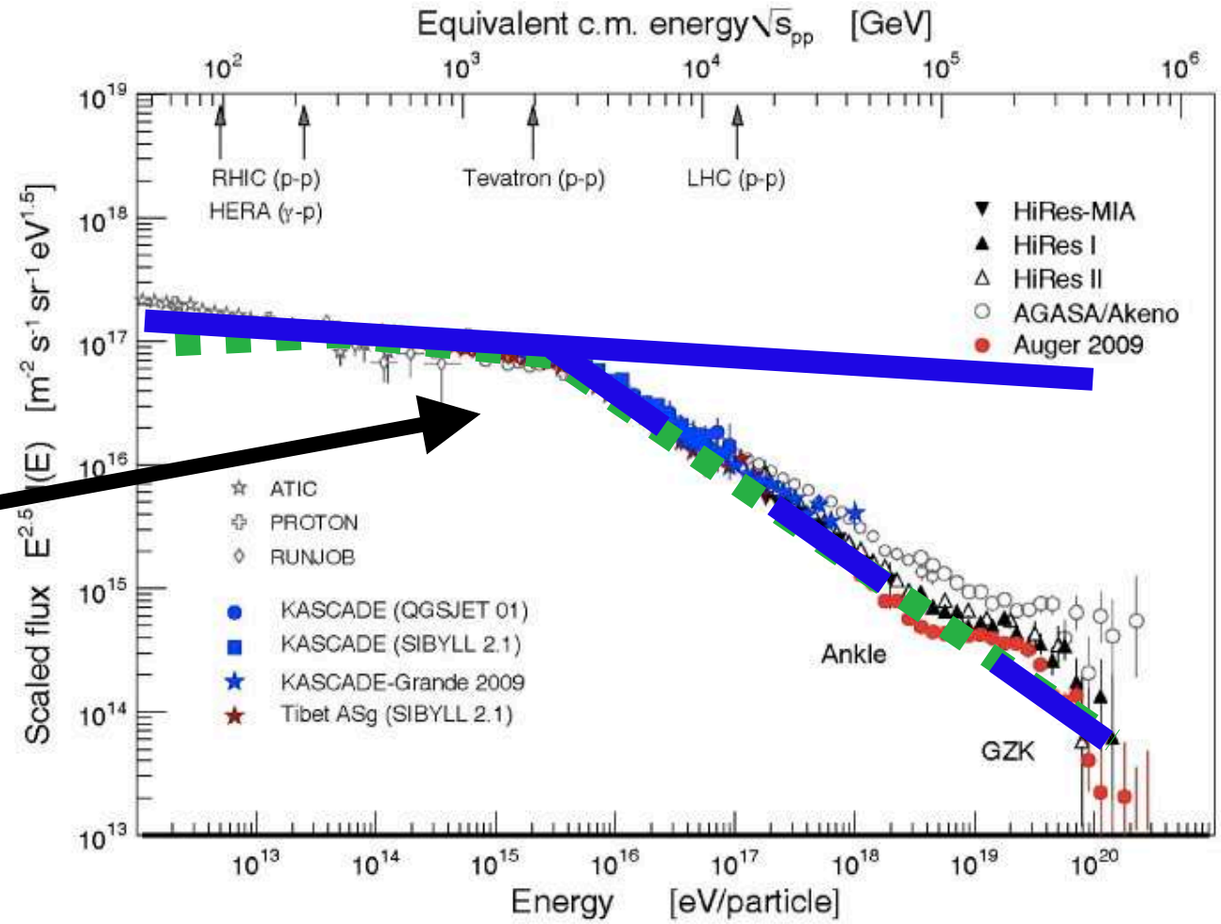

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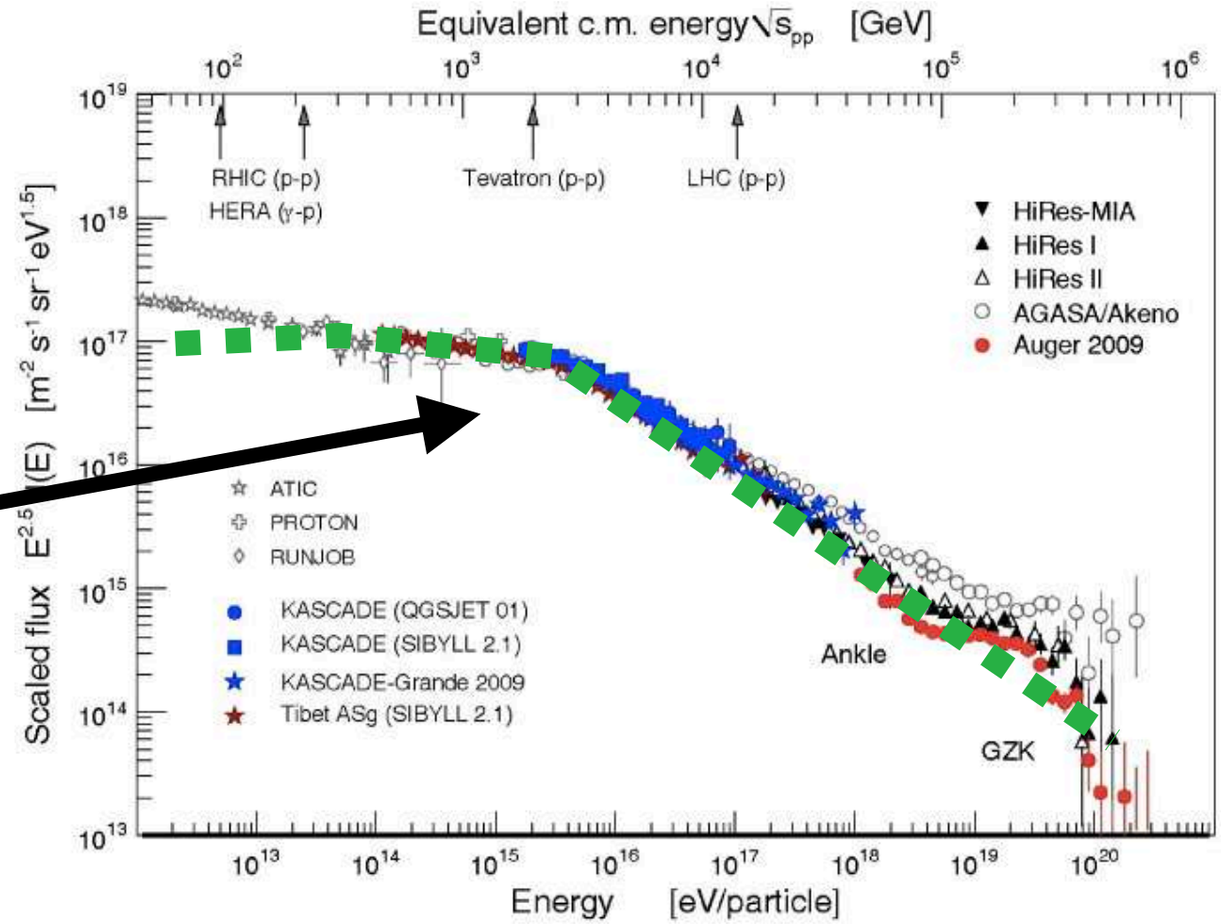

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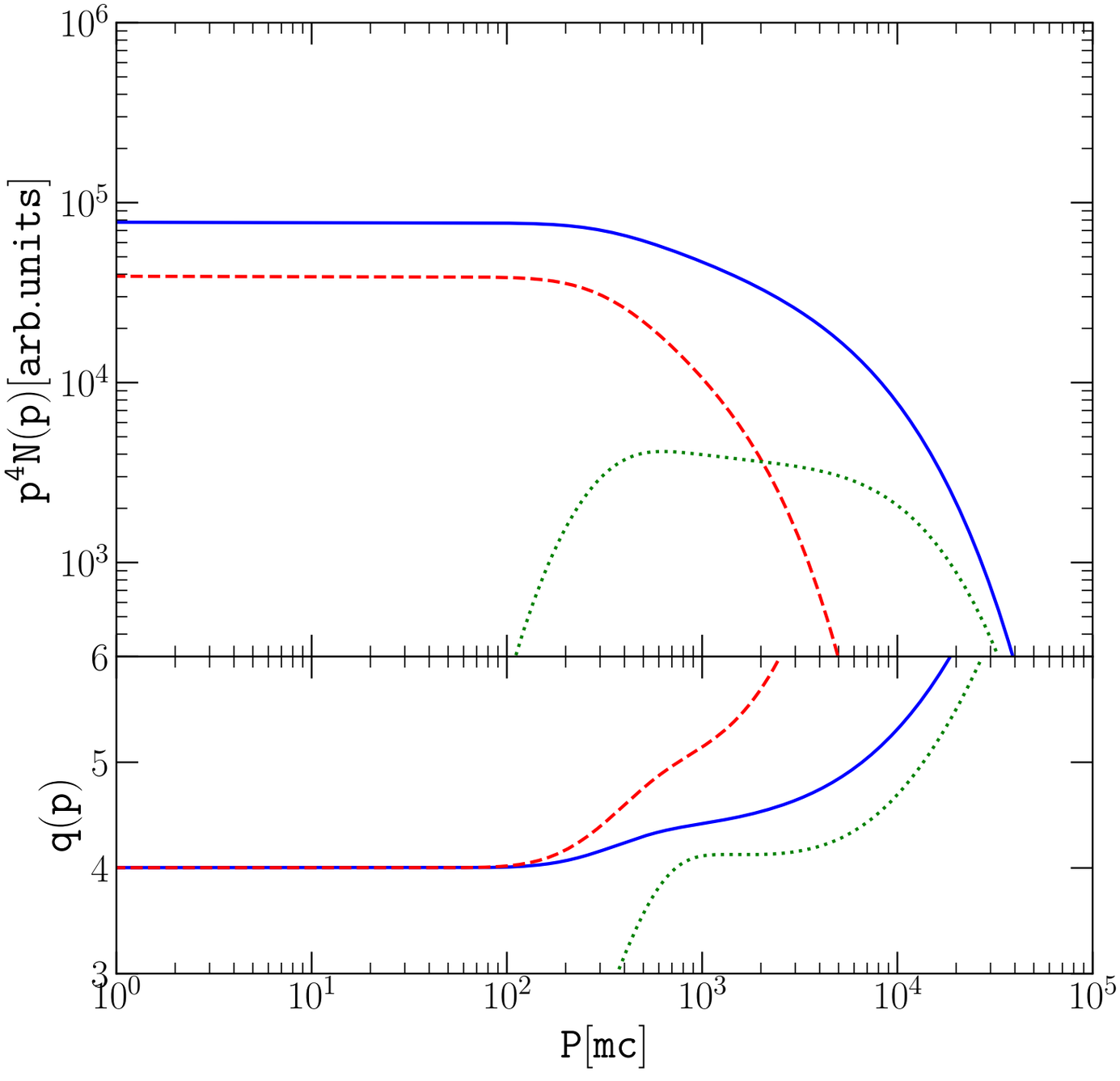
SNRs from Type Ia



Ptuskin & Zirakashvili 2008, Caprioli et al. 2010, Blasi 2013, PC et al. 2021, Morlino et al. 2021

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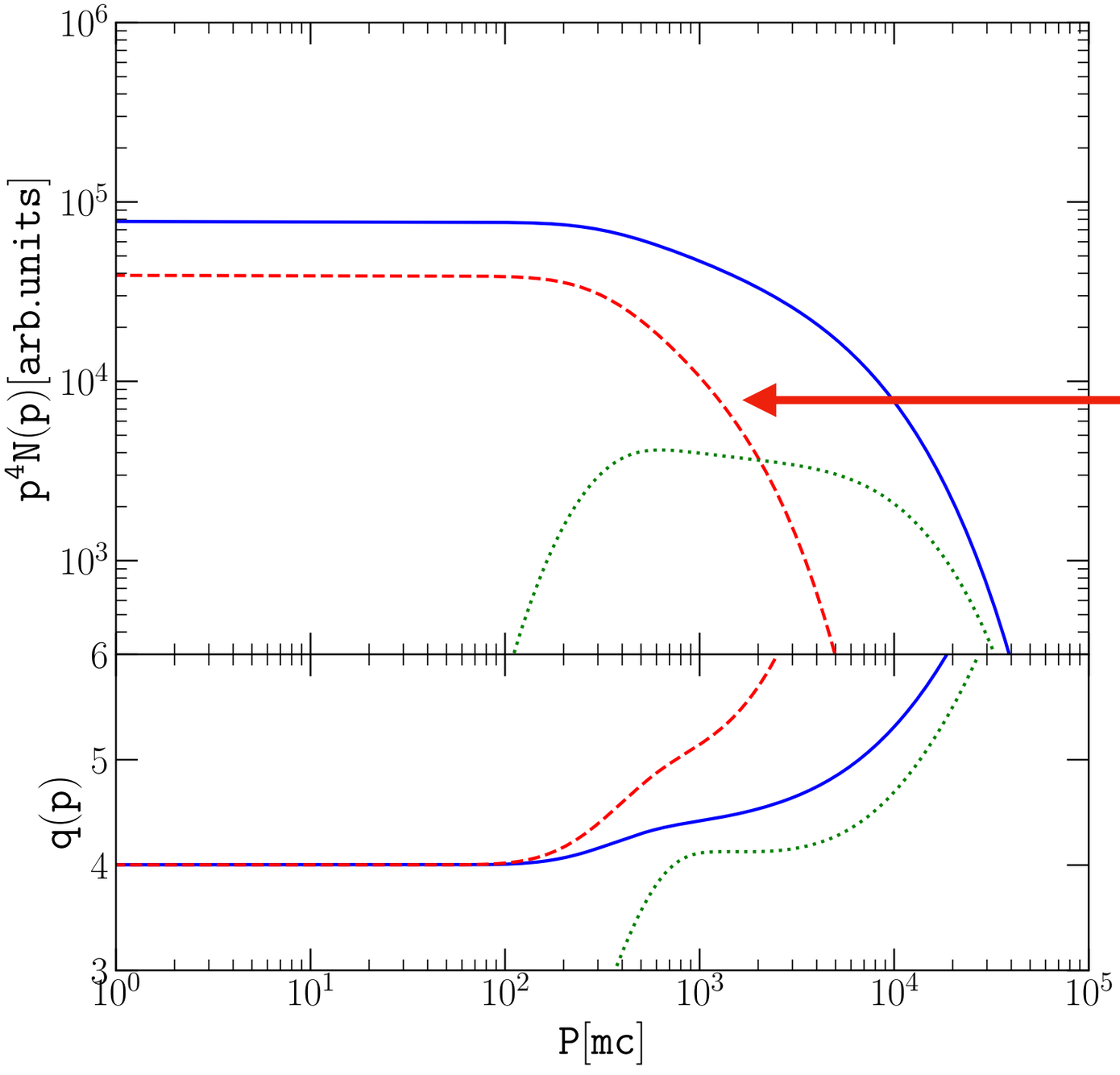

Particle trapped inside
SNR + losses

Ptuskin & Zirakashvili 2008, Caprioli et al. 2010, Blasi 2013, PC et al. 2021, Morlino et al. 2021

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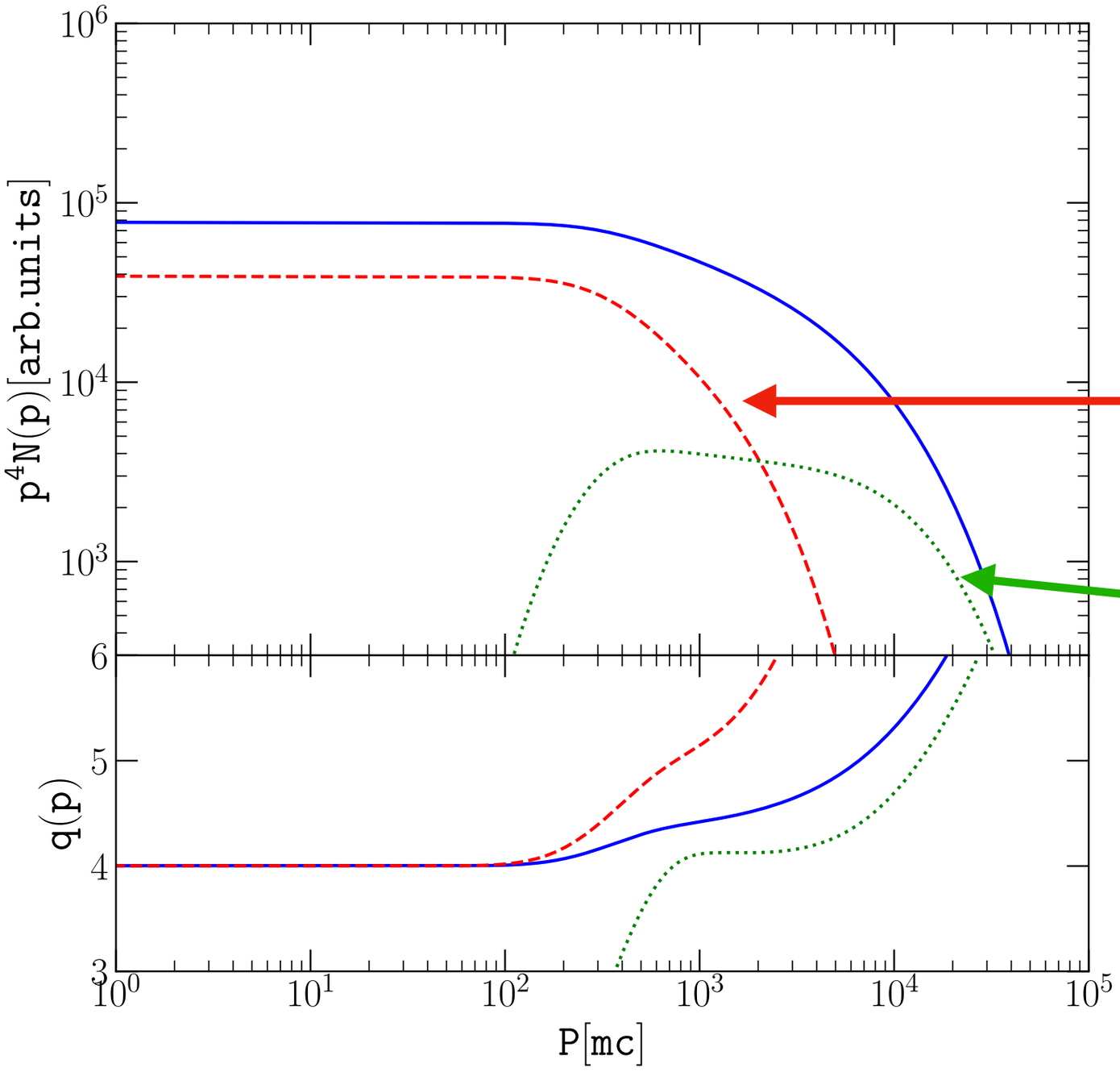

Particle trapped inside SNR + losses

Particle constantly escaping in the ISM

Ptuskin & Zirakashvili 2008, Caprioli et al. 2010, Blasi 2013, PC et al. 2021, Morlino et al. 2021

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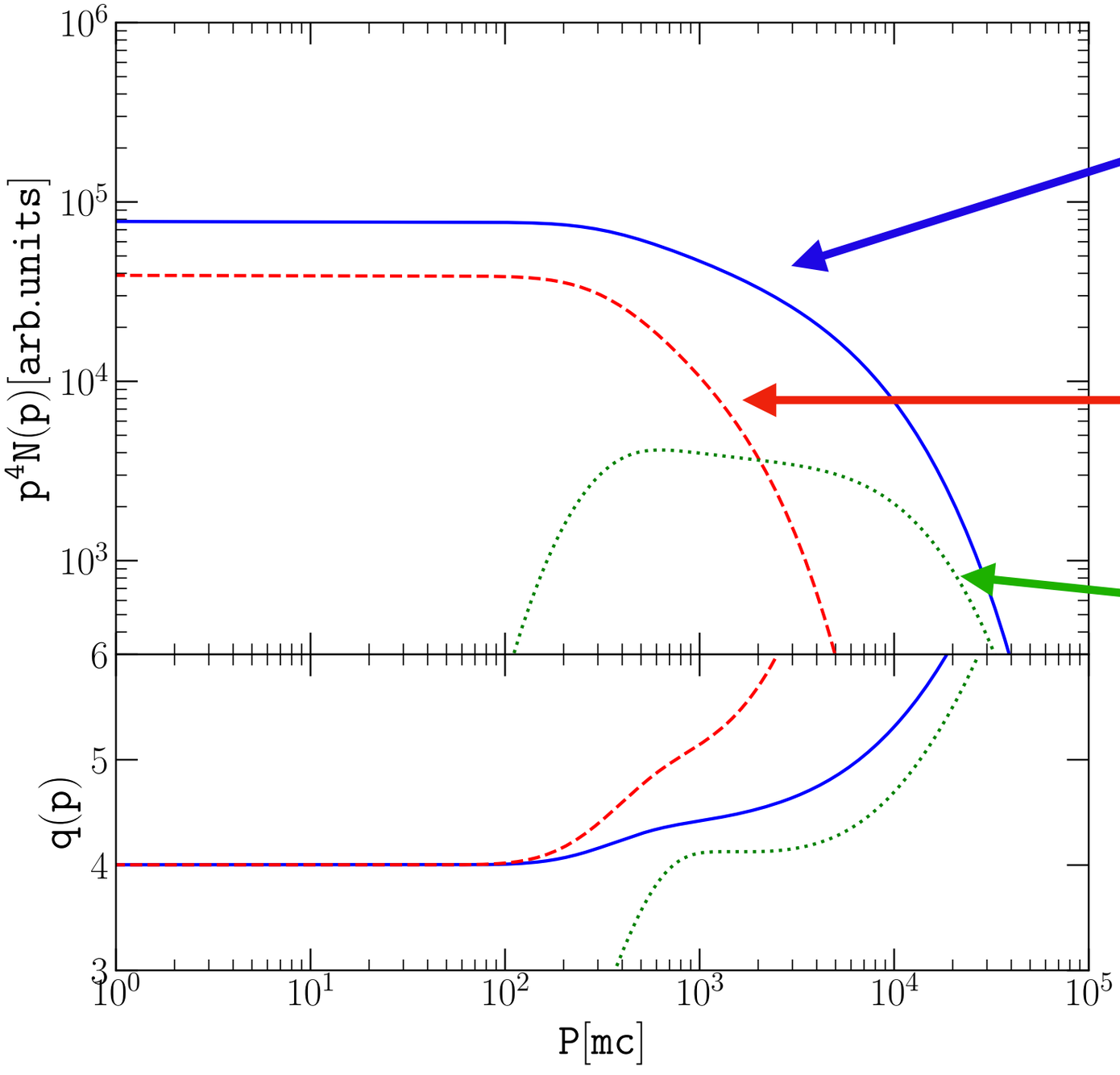

Sum

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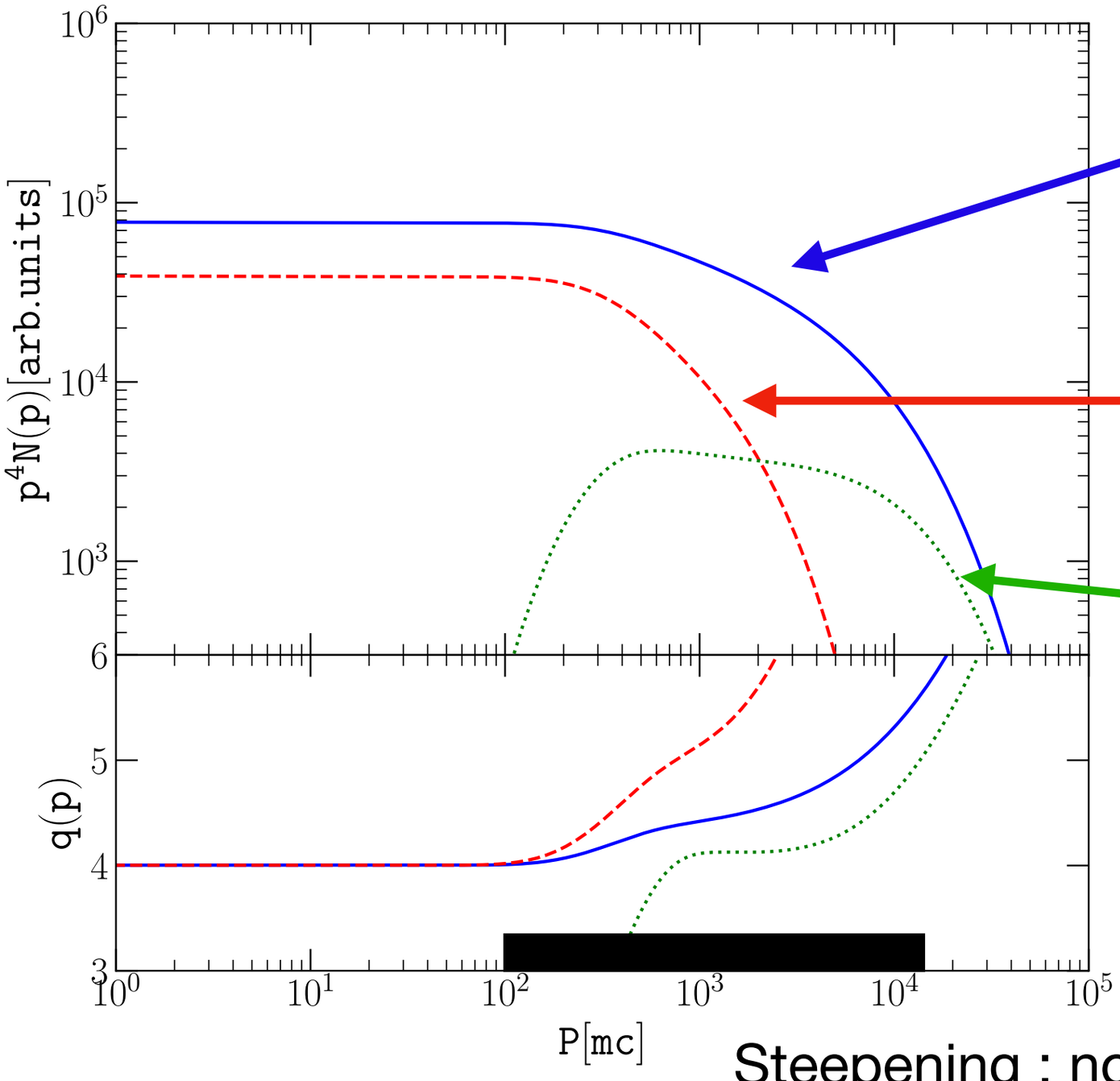


Sum

Particle trapped inside SNR + losses

Particle constantly escaping in the ISM

Steepening : not the energy range we want, same idea for other sources?

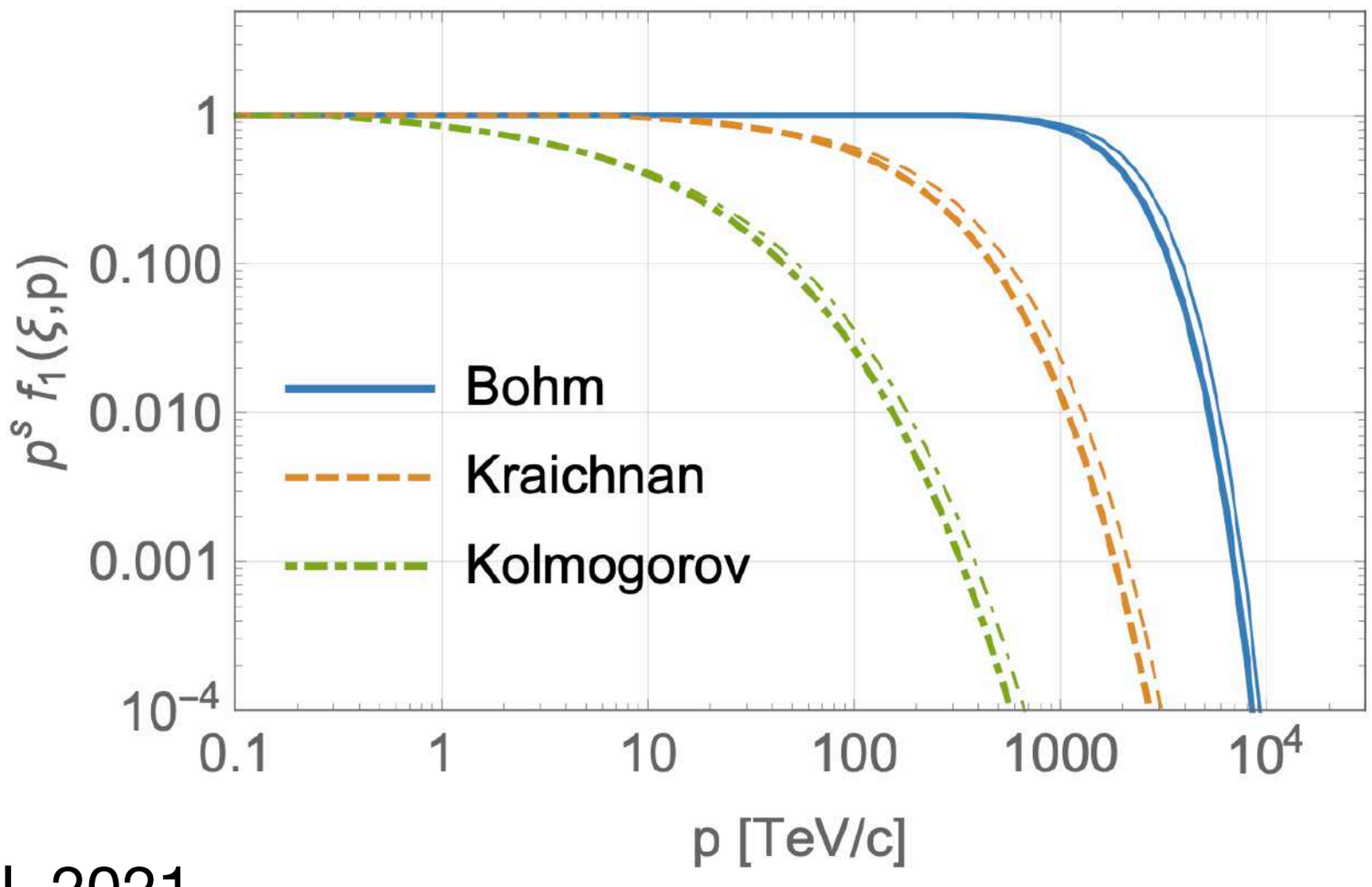
Ptuskin & Zirakashvili 2008, Caprioli et al. 2010, Blasi 2013, PC et al. 2021, Morlino et al. 2021

‘Hard enough’ spectra above the knee

Reaching PeV range (SNRs or other objects): **may not be a problem**

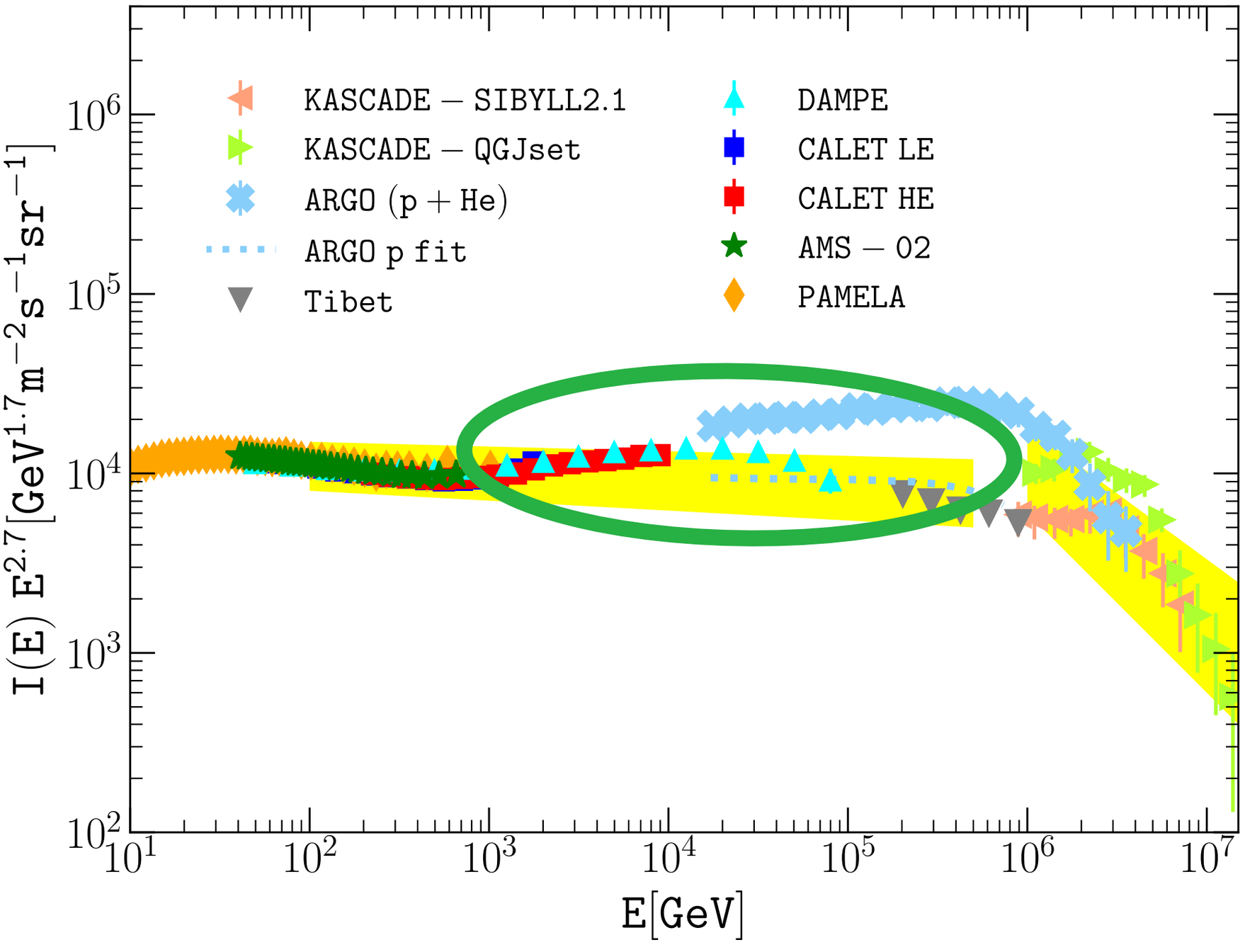
Problem : produce enough PeV protons (nuclei) +
« hard enough » spectrum above the PeV range

Stellar clusters: « hard enough » spectrum above PeV : Losses, escaping particles, diffusion coefficient?



Morlino et al. 2021

And… below the knee?



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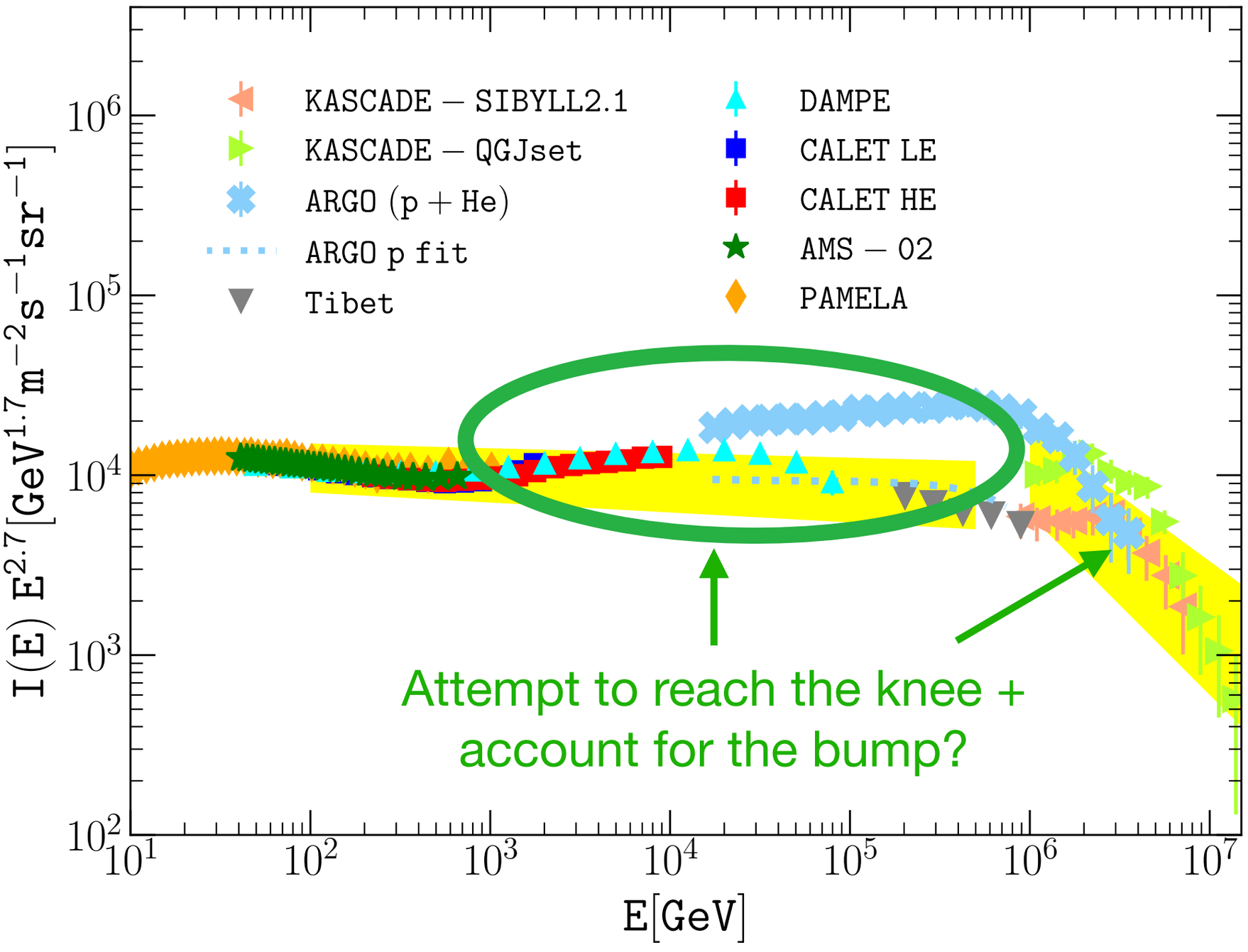

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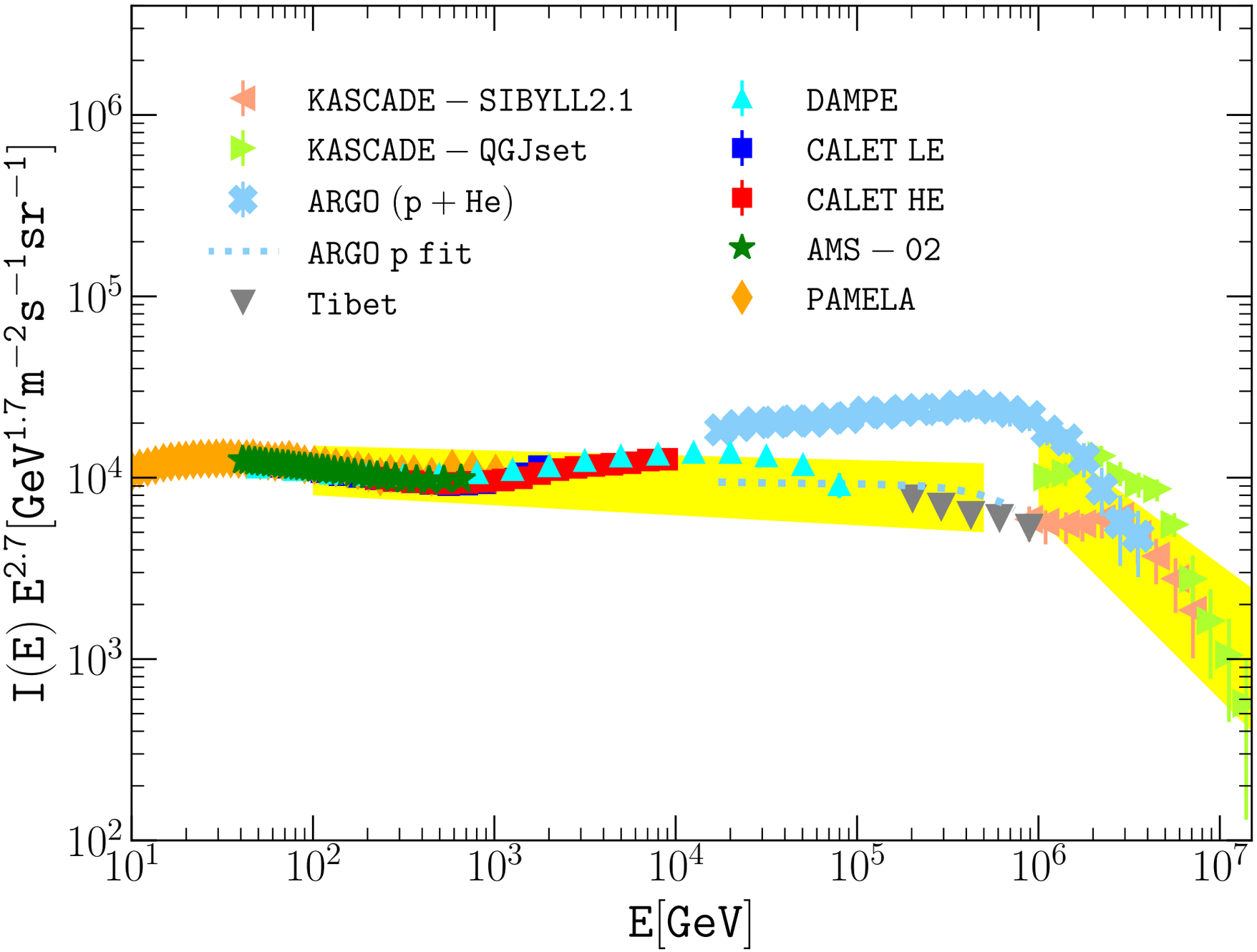

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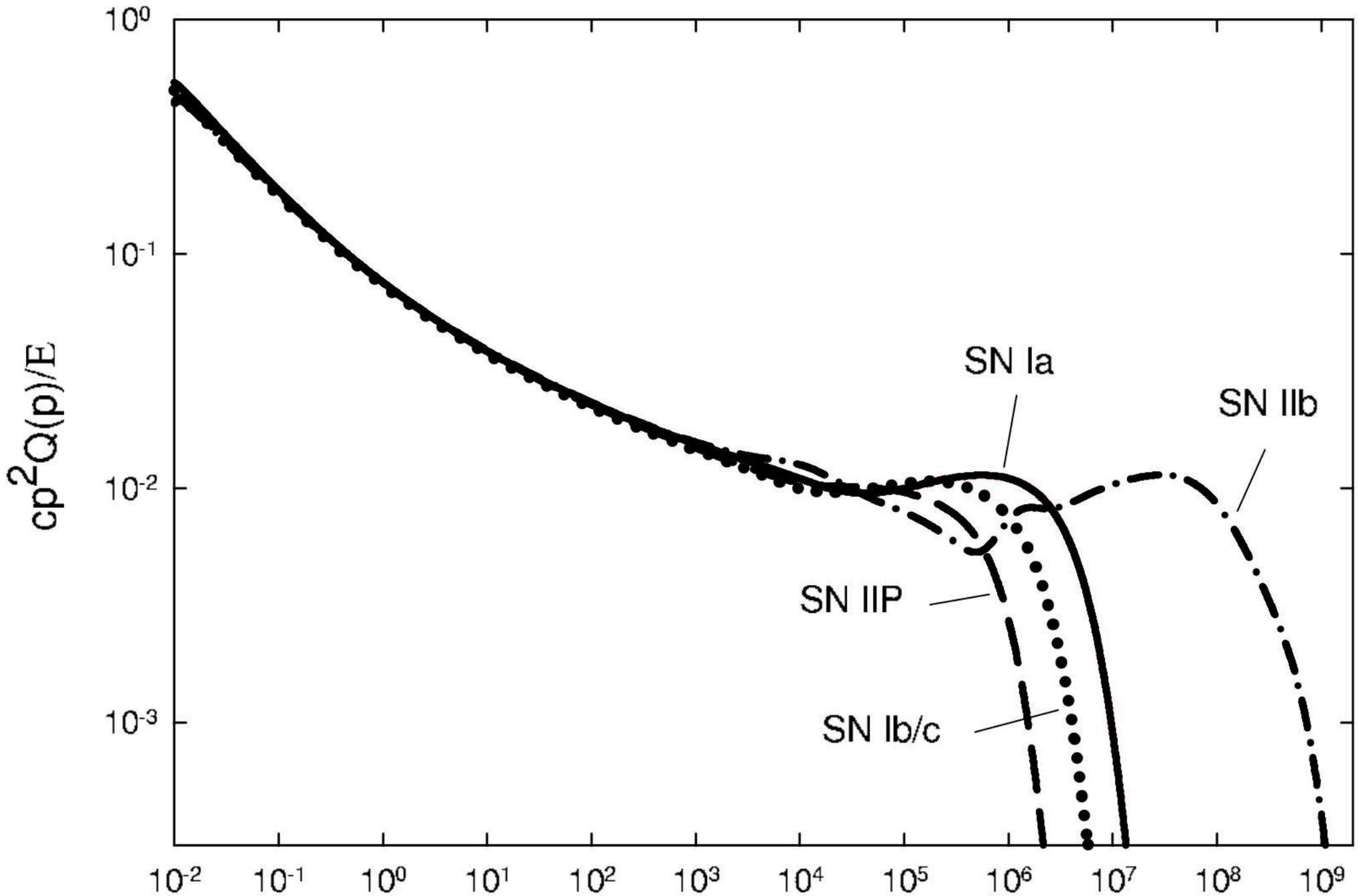

With several ‘components’

Ptuskin, Zirakashvili & Seo 2010

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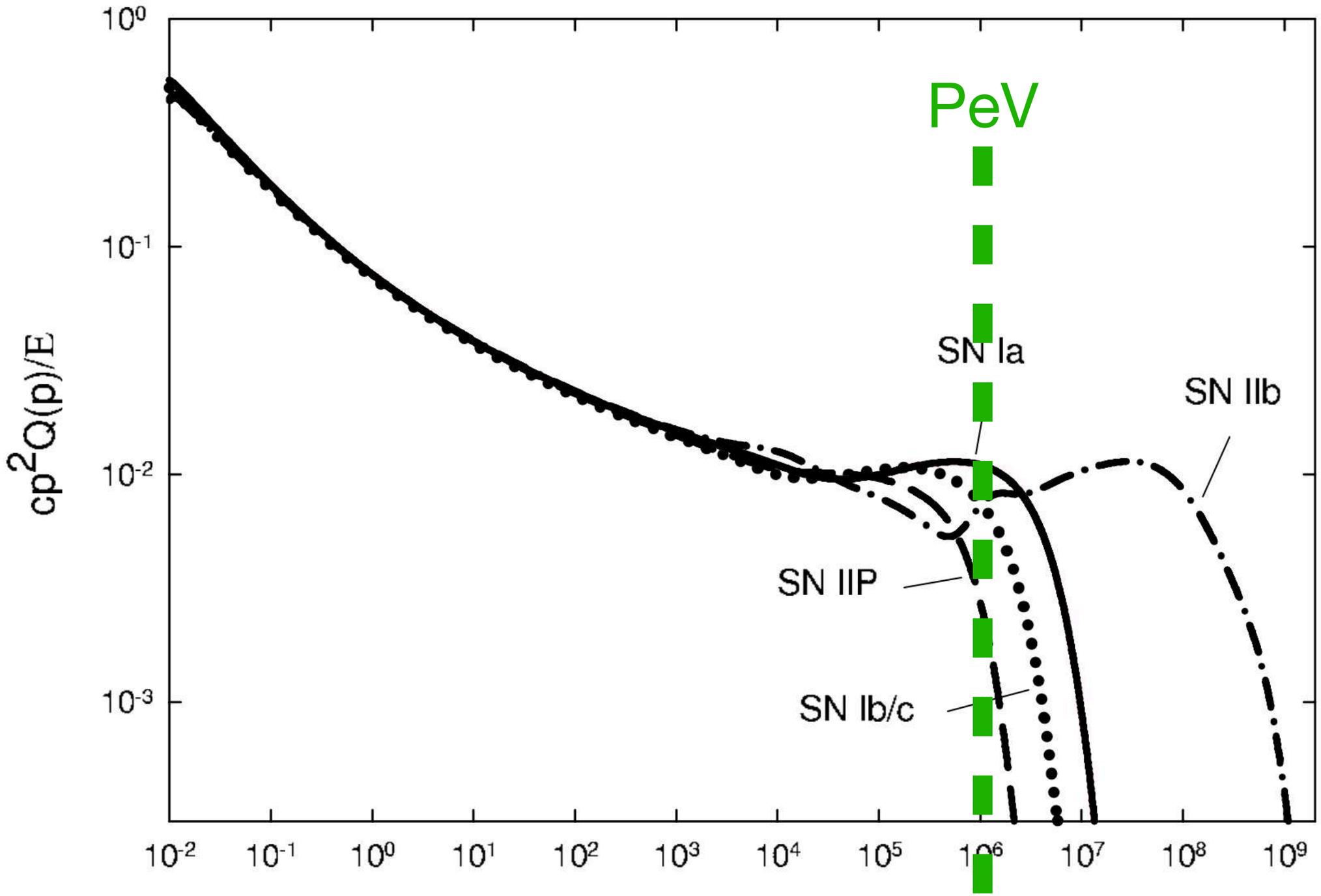

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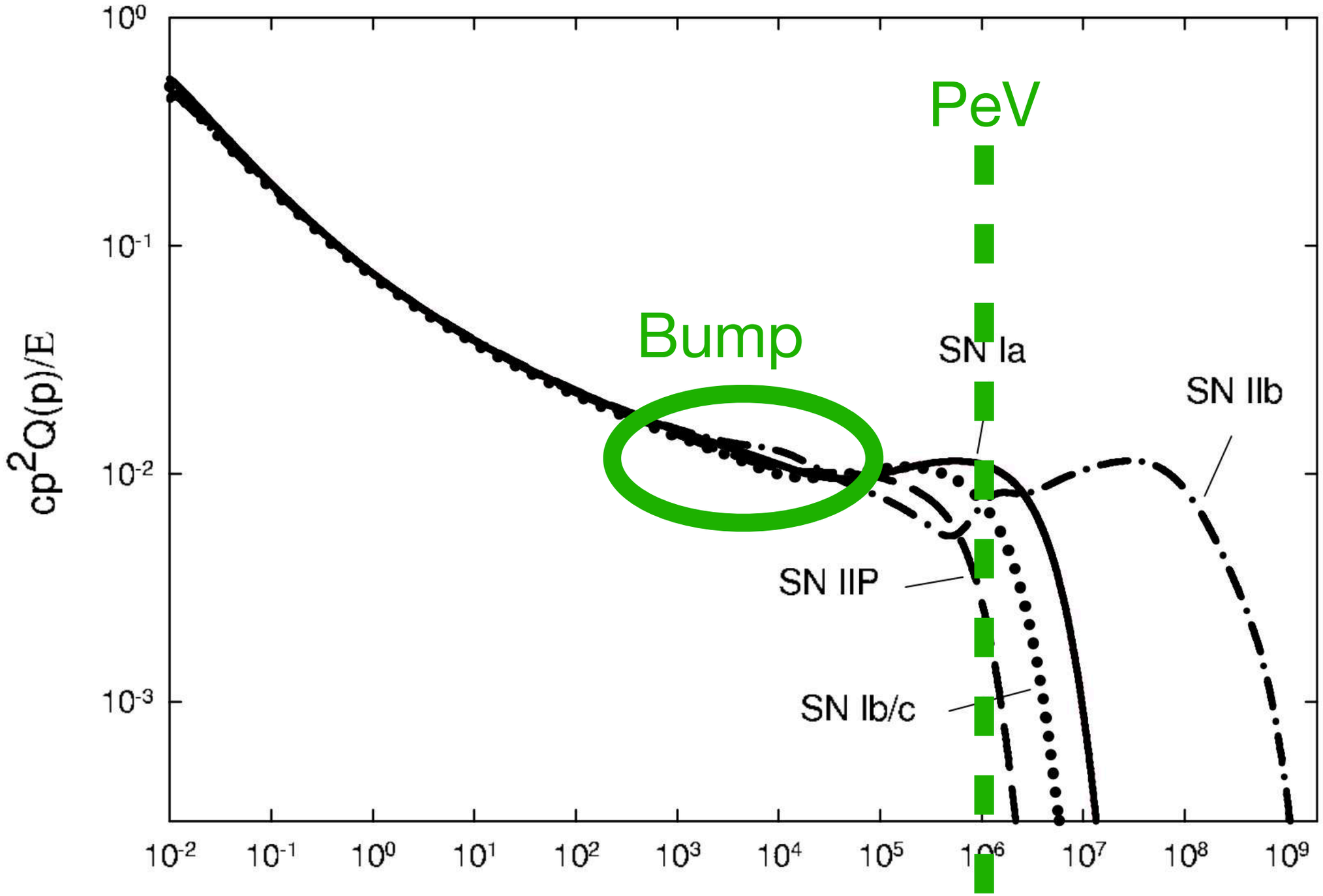

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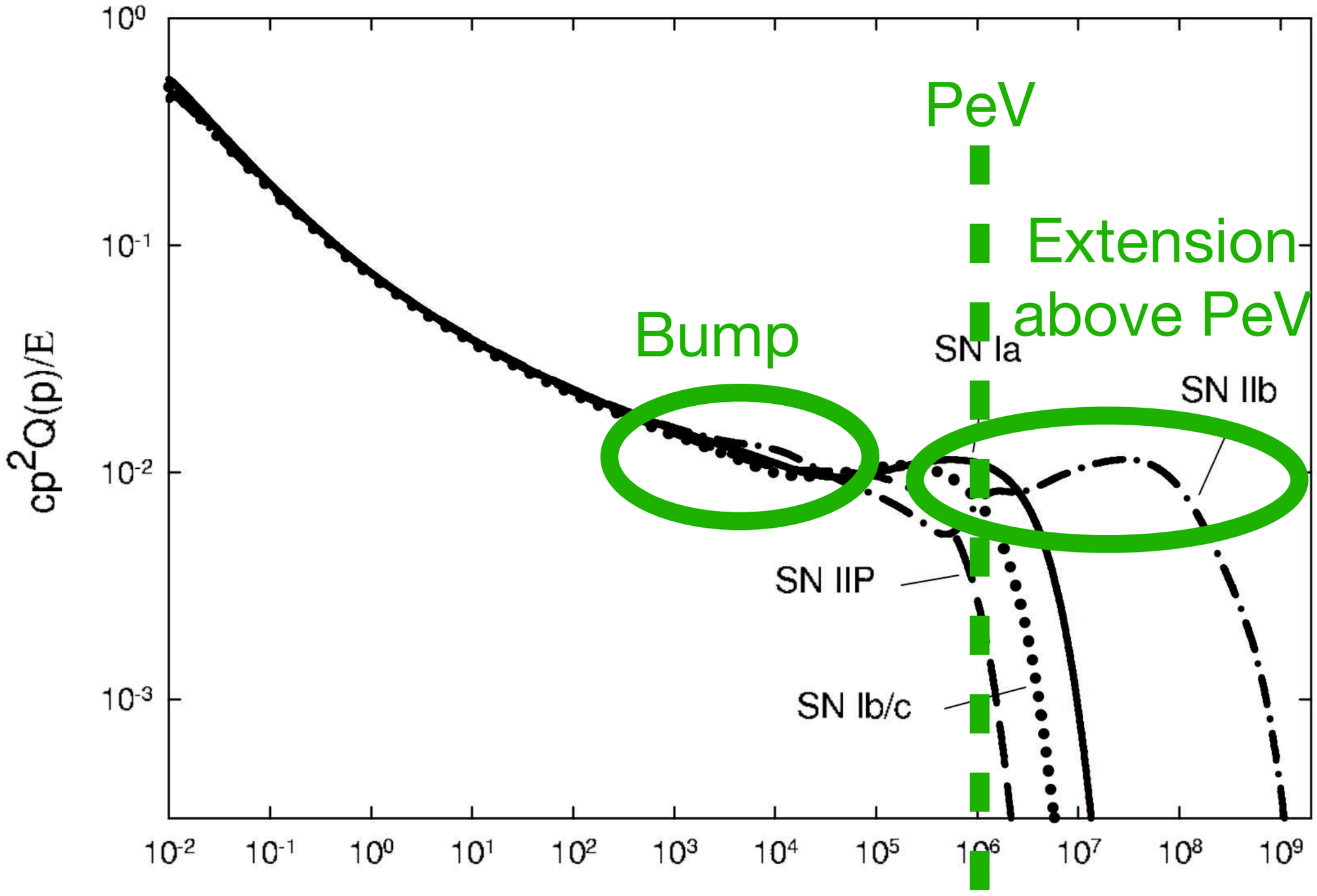

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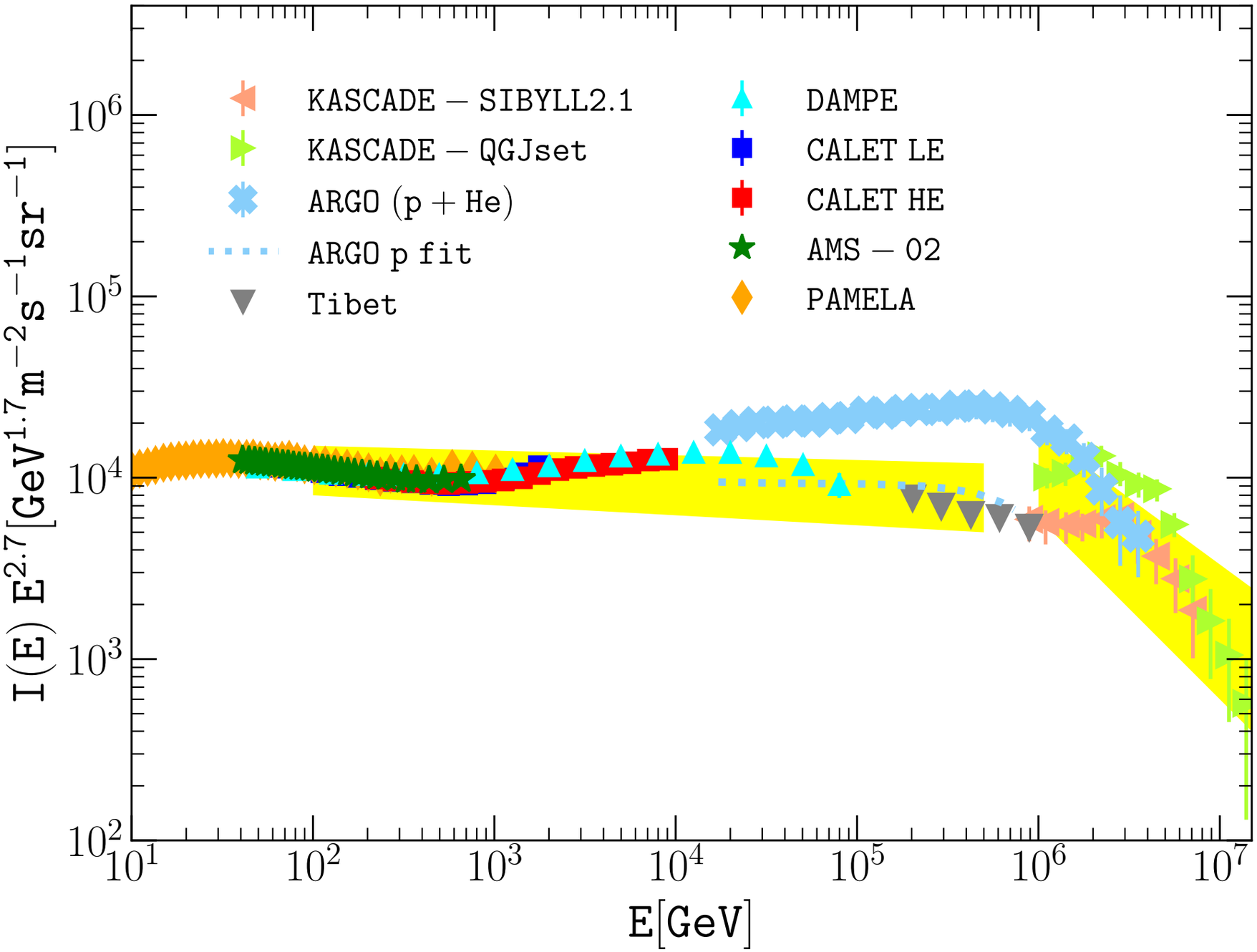

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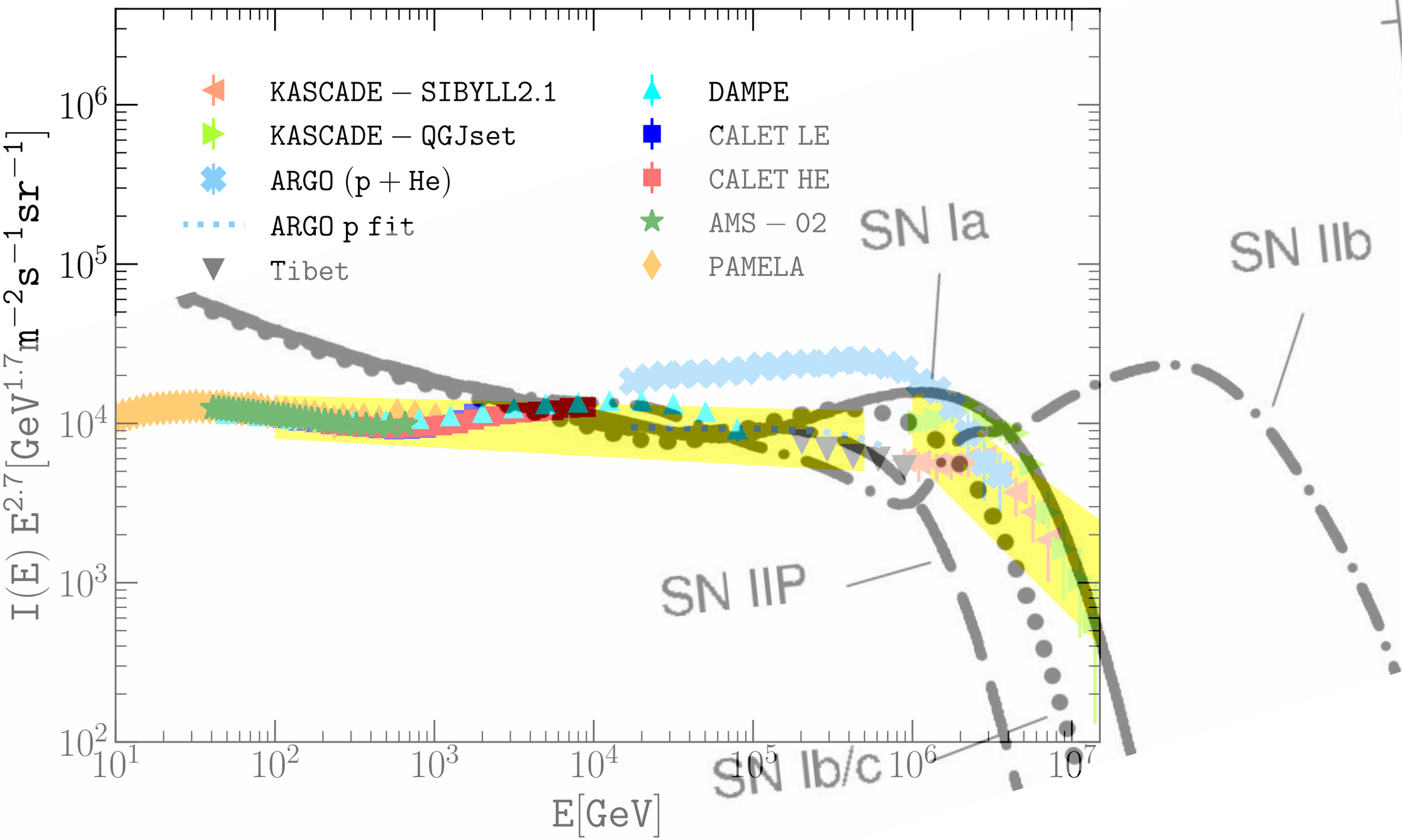

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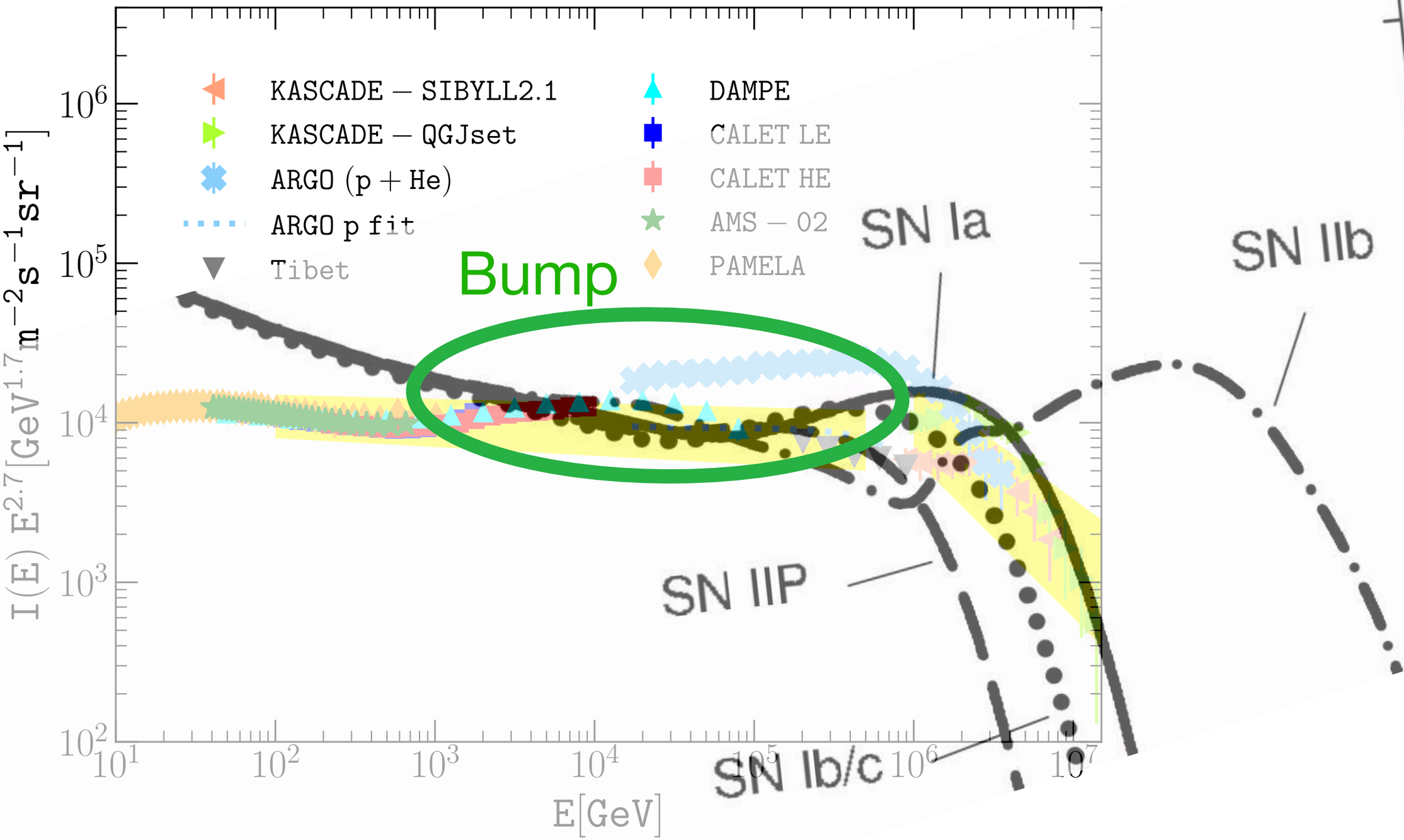

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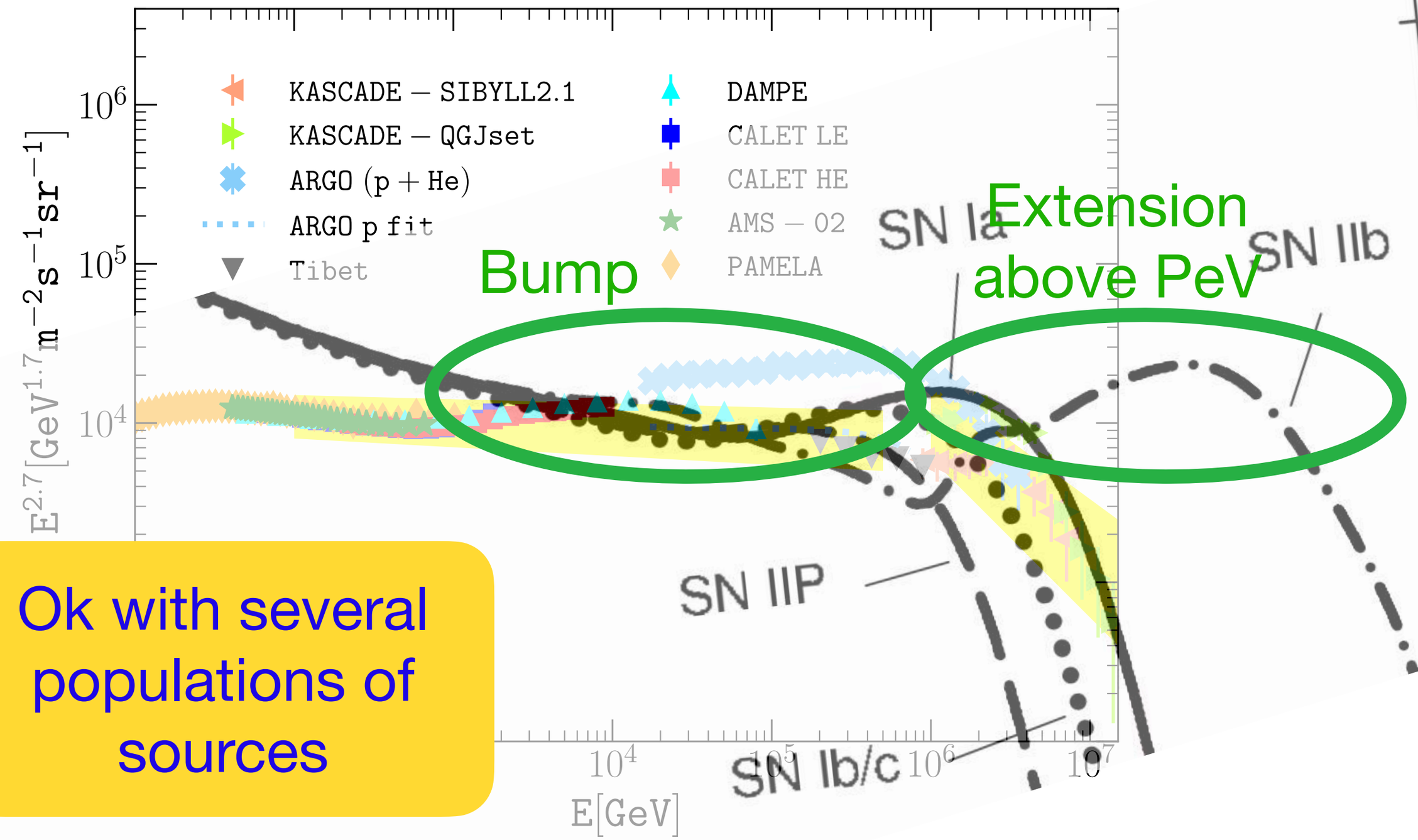


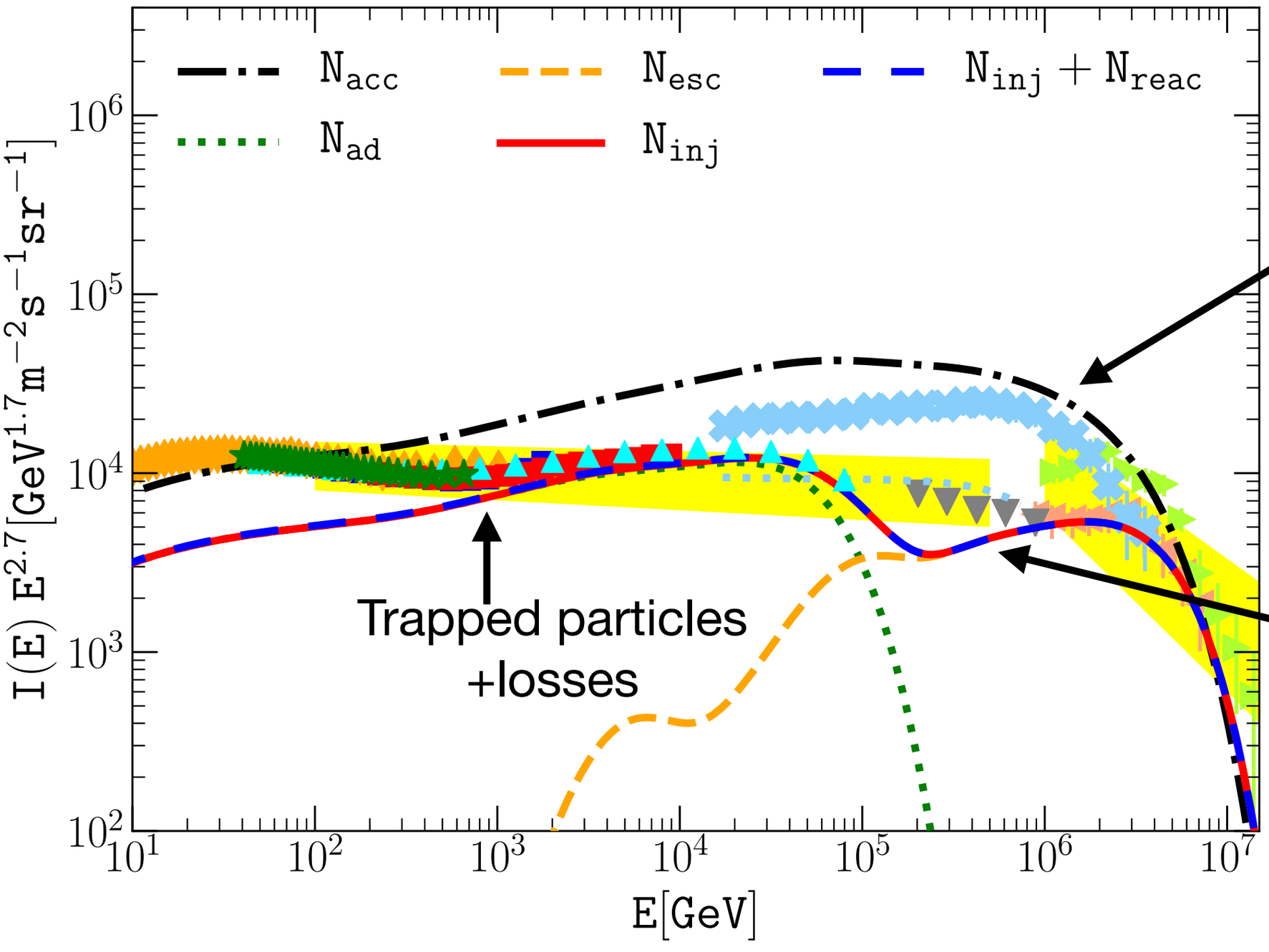
Ok with several populations of sources

Ptuskin, Zirakashvili & Seo 2010

With only one object?

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

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



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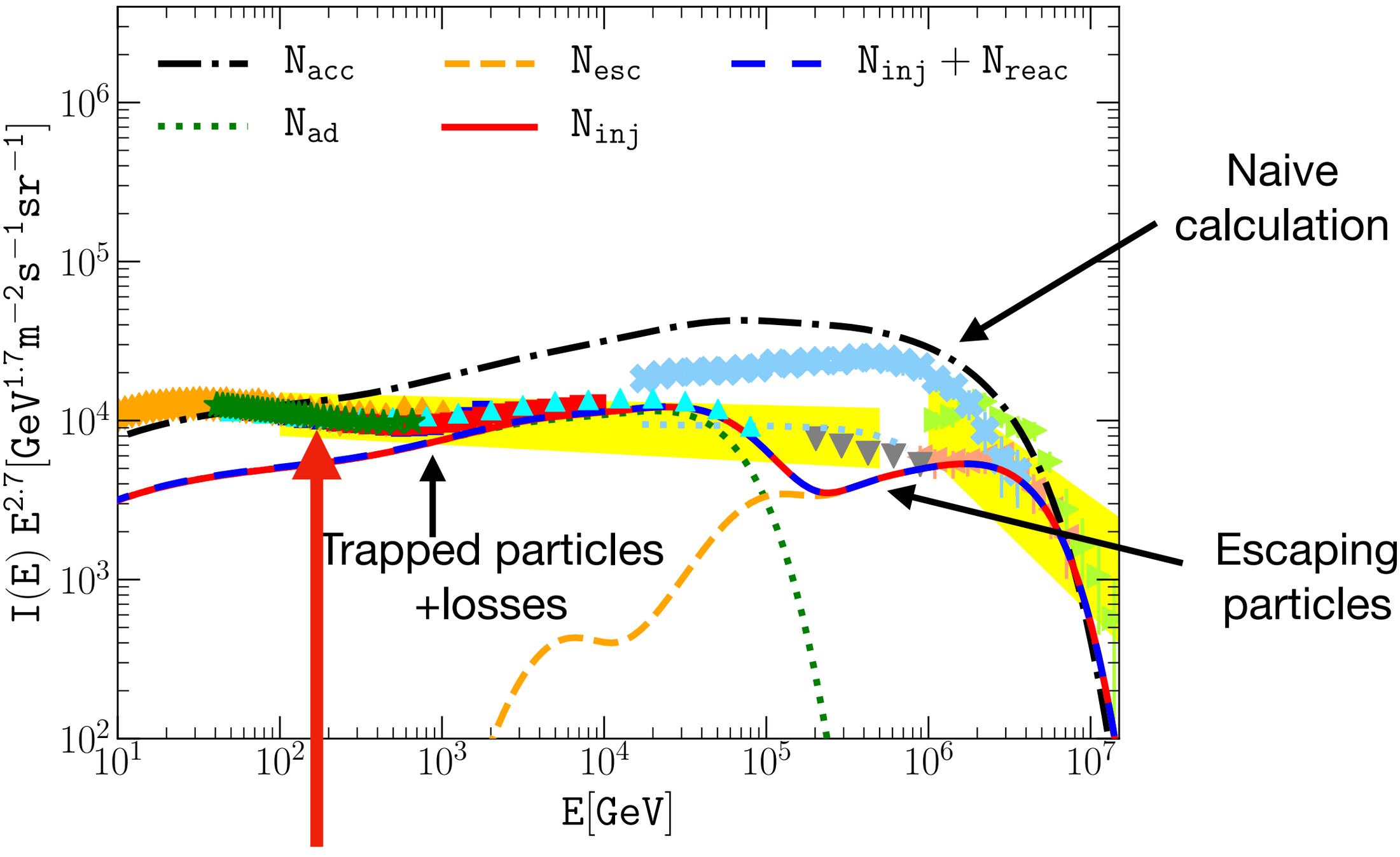


Major problem: no room for other SNRs/ other accelerators

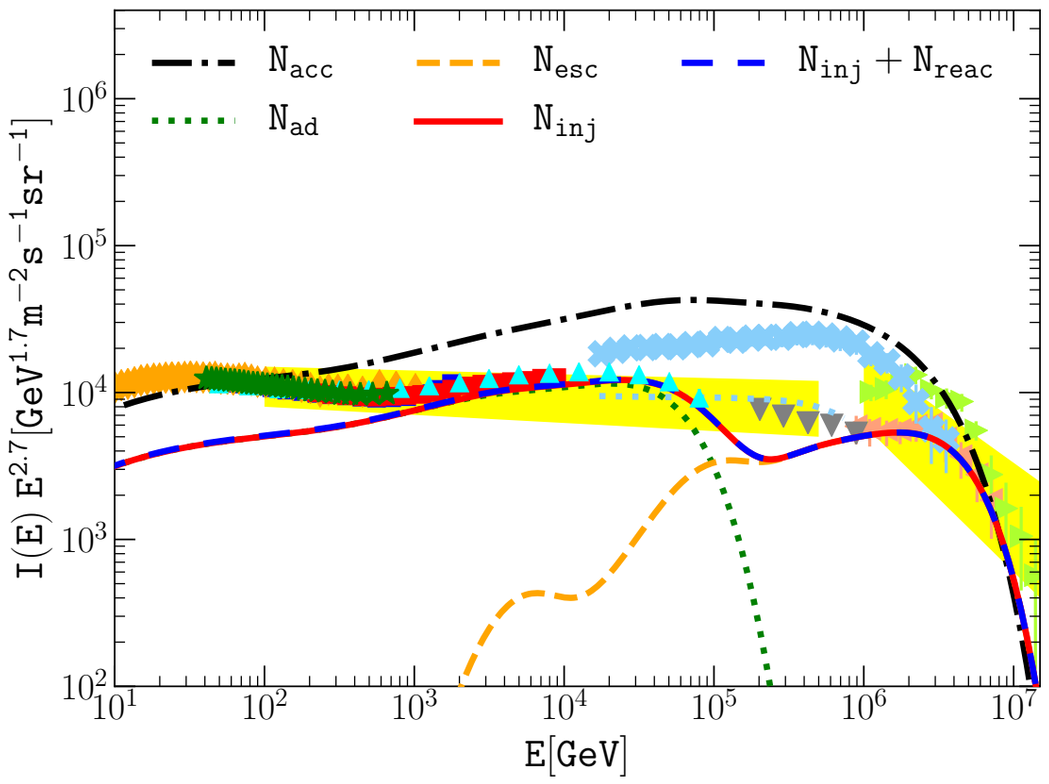
Origin of Galactic protons

Which sources could be pevatrons?

1. Probably SNRs (few and rare)
2. Many other sources (Massive stars, superbubbles,etc.)

How to produce ‘enough’ protons + ‘hard enough’ spectra above PeV?

1. Role of other SNRs? Efficiency of 5-10% in type II* leaves little room
2. What about other accelerators?
3. What about fine features (10 TeV bump?)



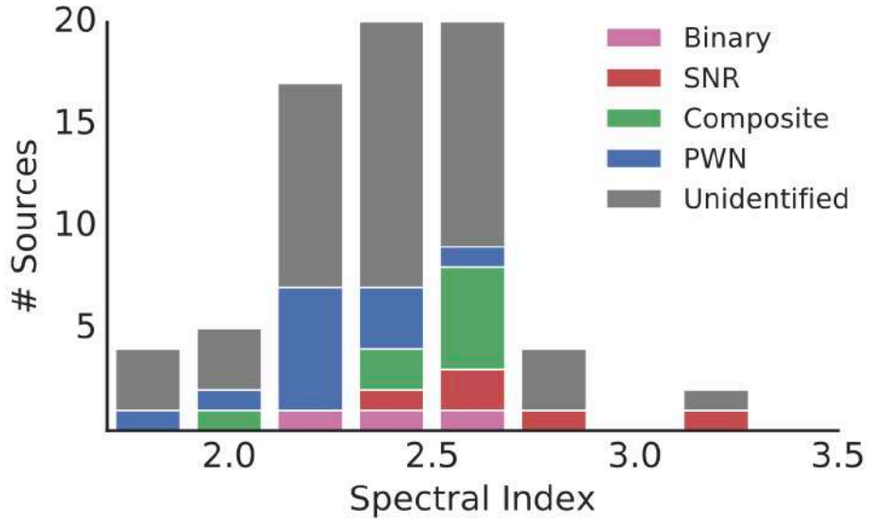
Supernova remnants (important issues)

1. What is the spectrum of accelerated protons?

$$f(p) \propto p^{-\alpha}$$

$$\alpha = 4 \qquad \alpha > 4$$

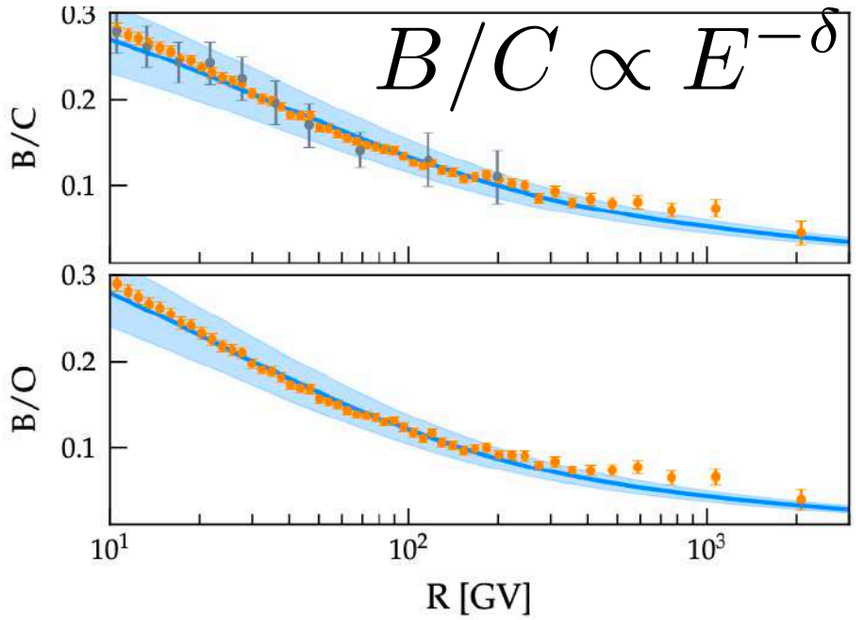
TeV range H.E.S.S. 2018



2. What is the spectrum of protons released in the ISM?

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

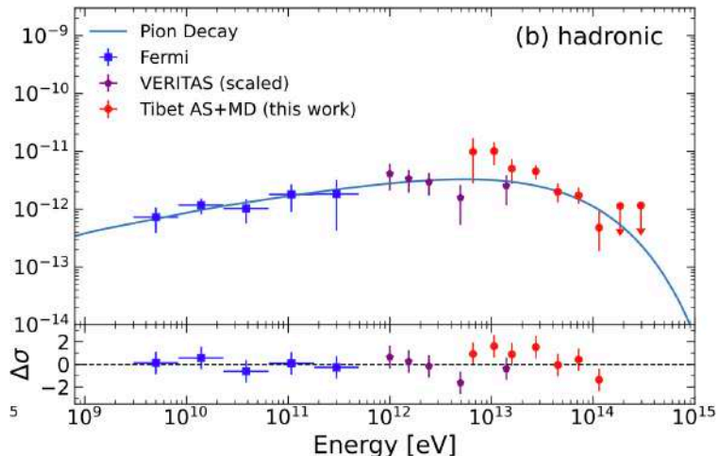
Injection **Propagation**



Evoli et al. 2019

3. What is the maximum energy? (PeV, above?)

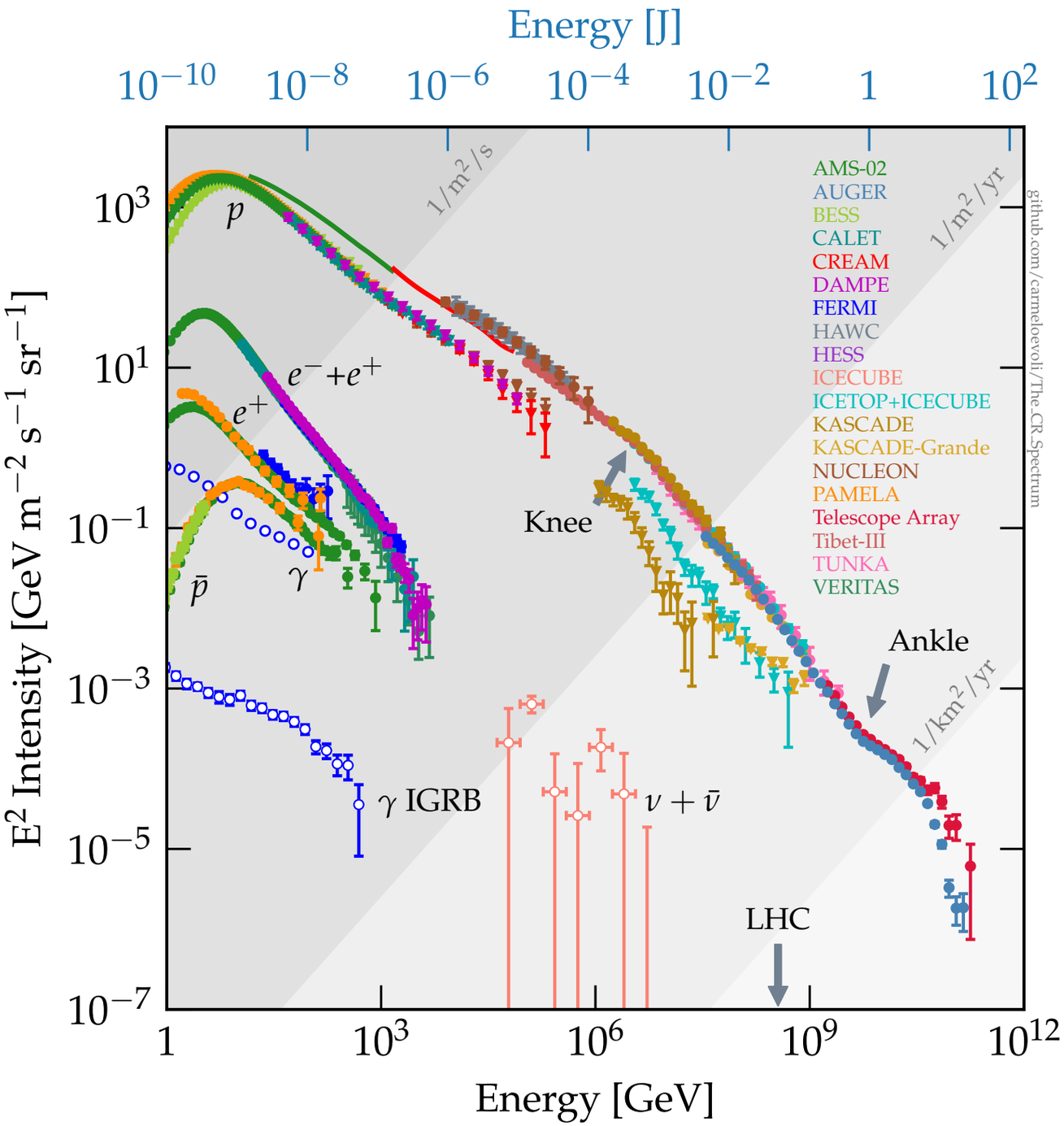
NO SNR pevatron
Fang et al. 2022?



SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

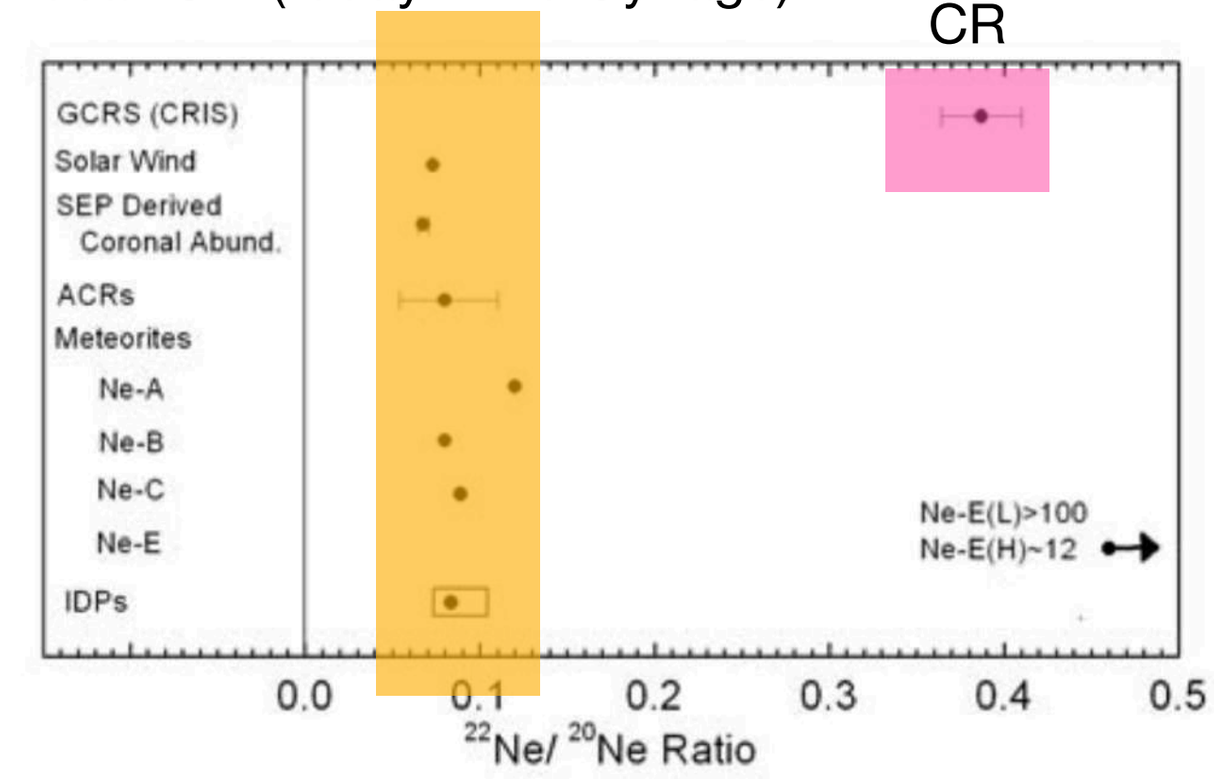
Drury 2012, Blasi 2013, 2019, Gabici et al. 2019

More than protons



Evoli 2021

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



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

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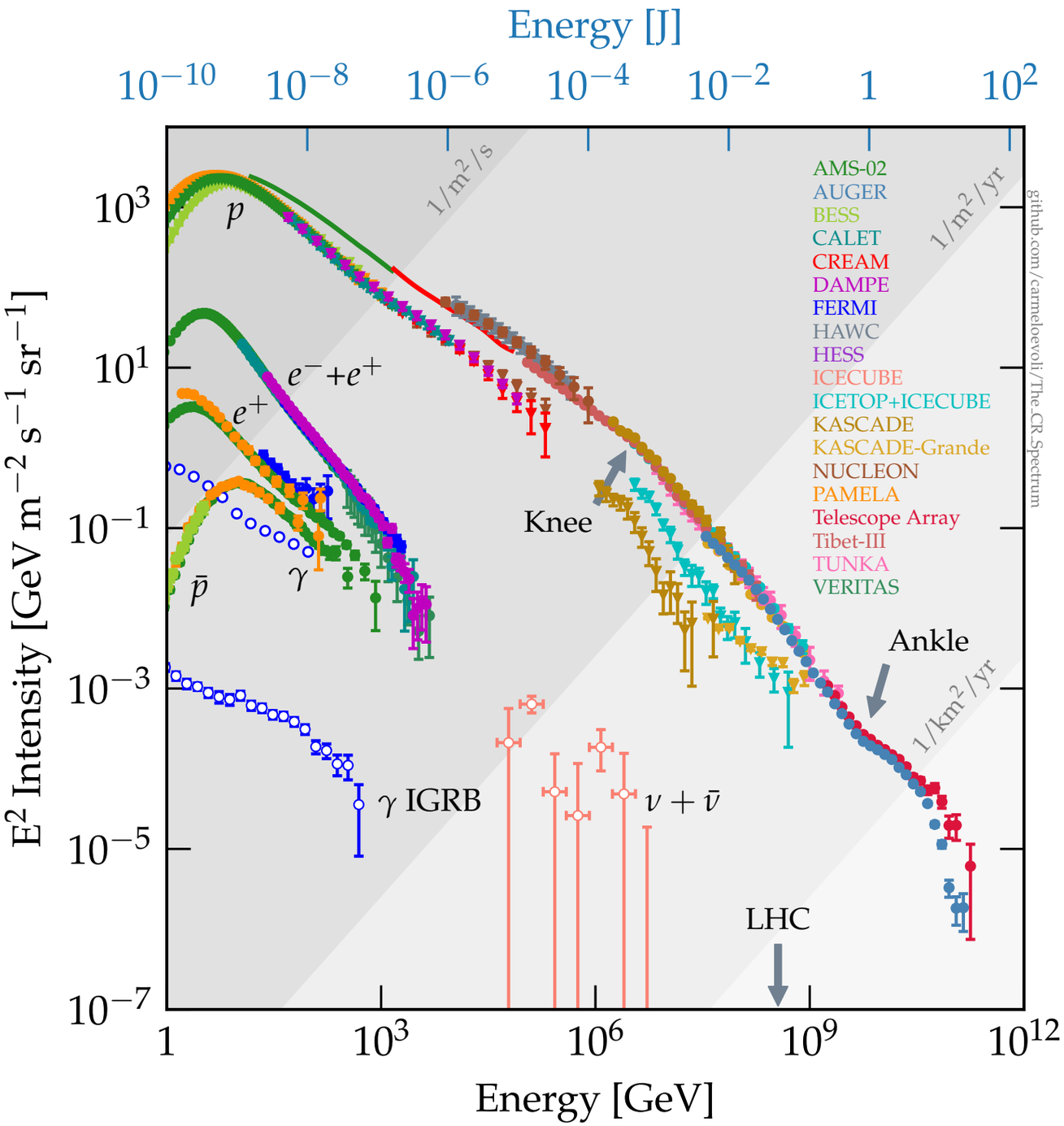
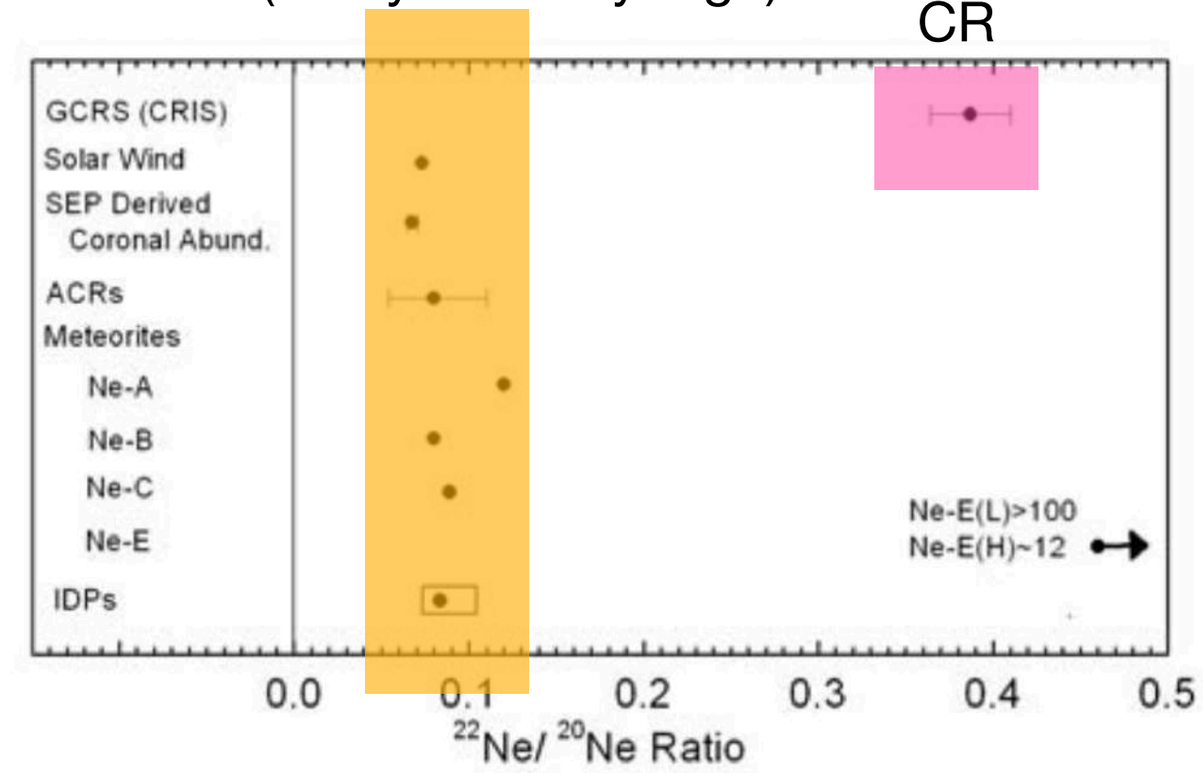


Evoli 2021

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

Local ISM (today + 4.5 Gyr ago)

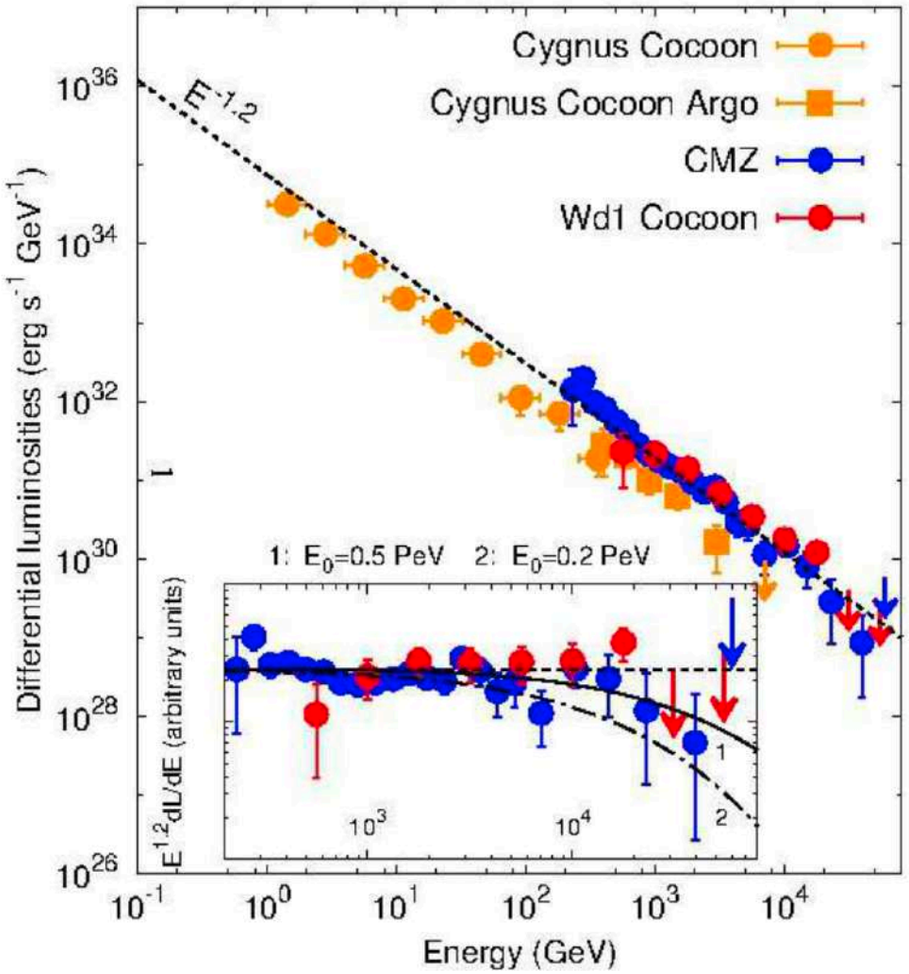


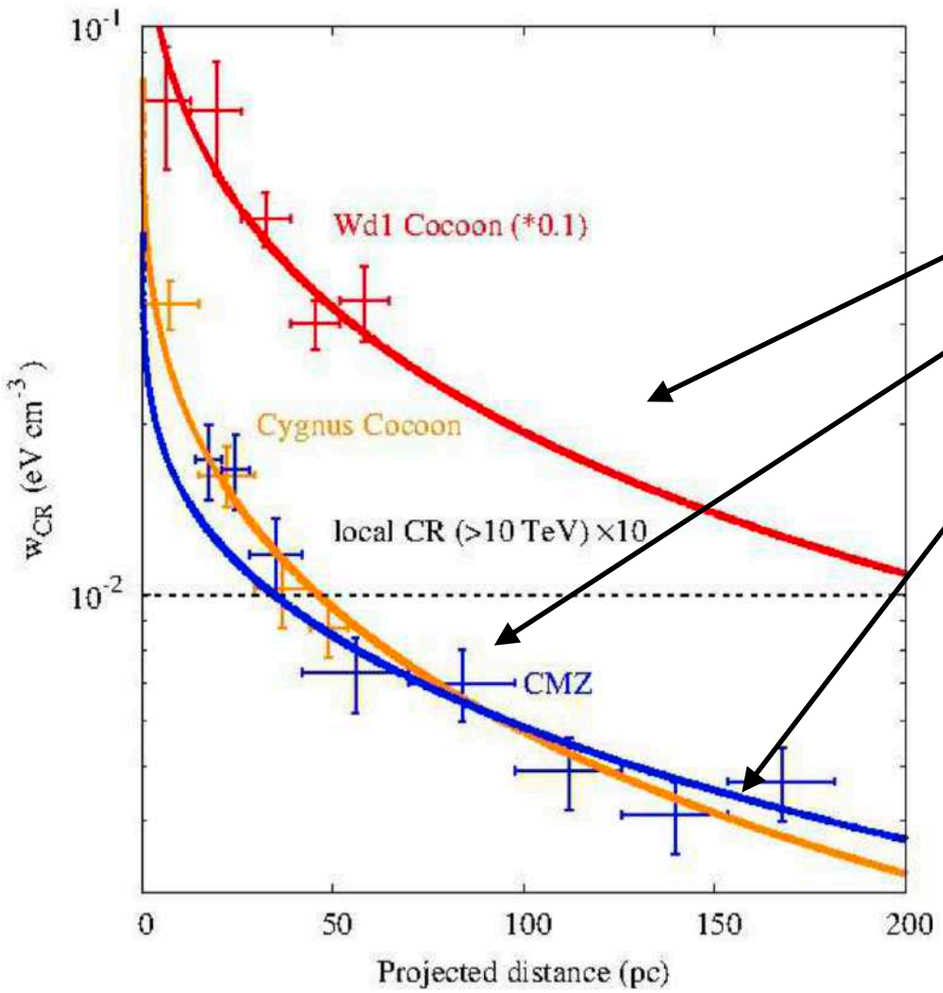
Stellar winds termination shocks

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

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

CRs from young stellar clusters





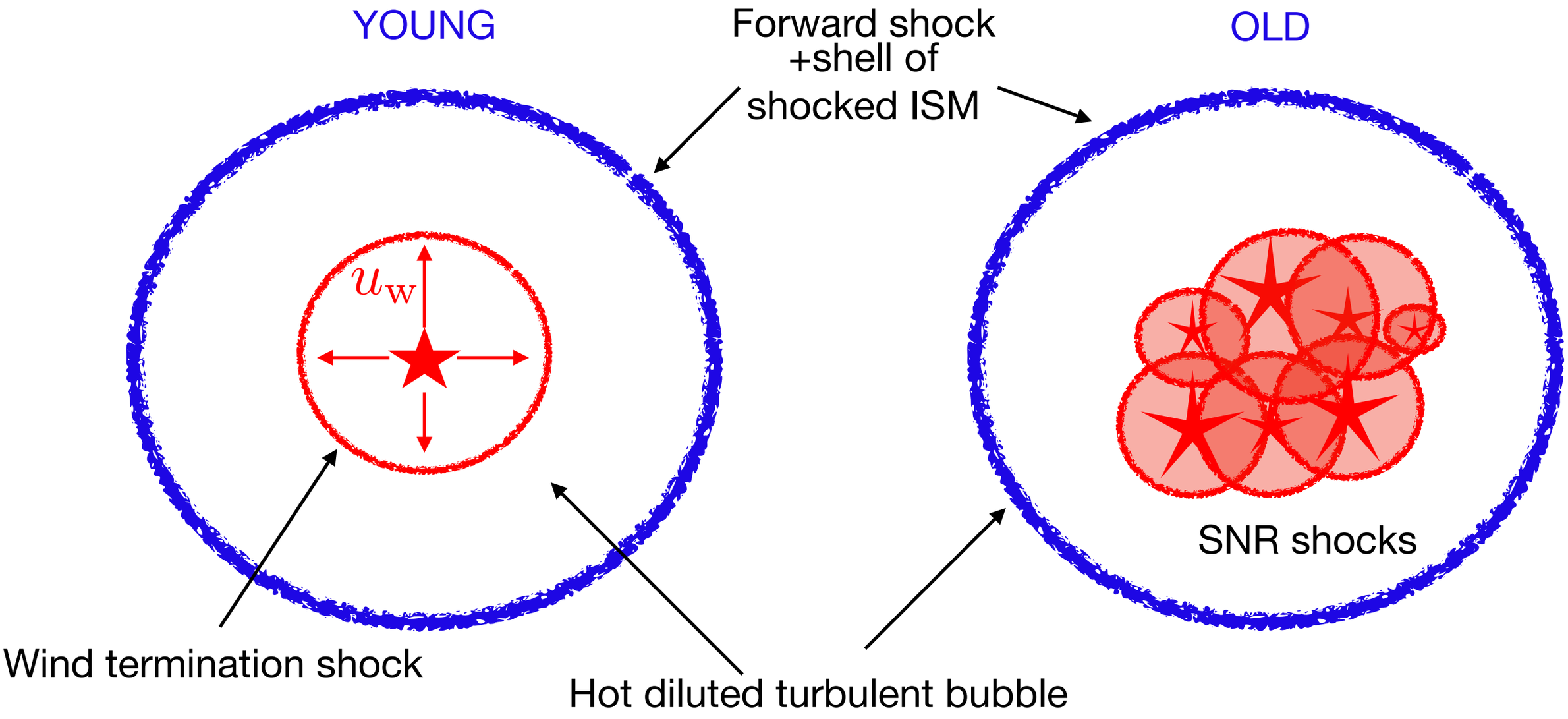
1/R profile as expected in continuous injection from sources

Gamma rays from massive stars demonstrate particle acceleration

Aharonian et al. 2019, Yang et al. 2021

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



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

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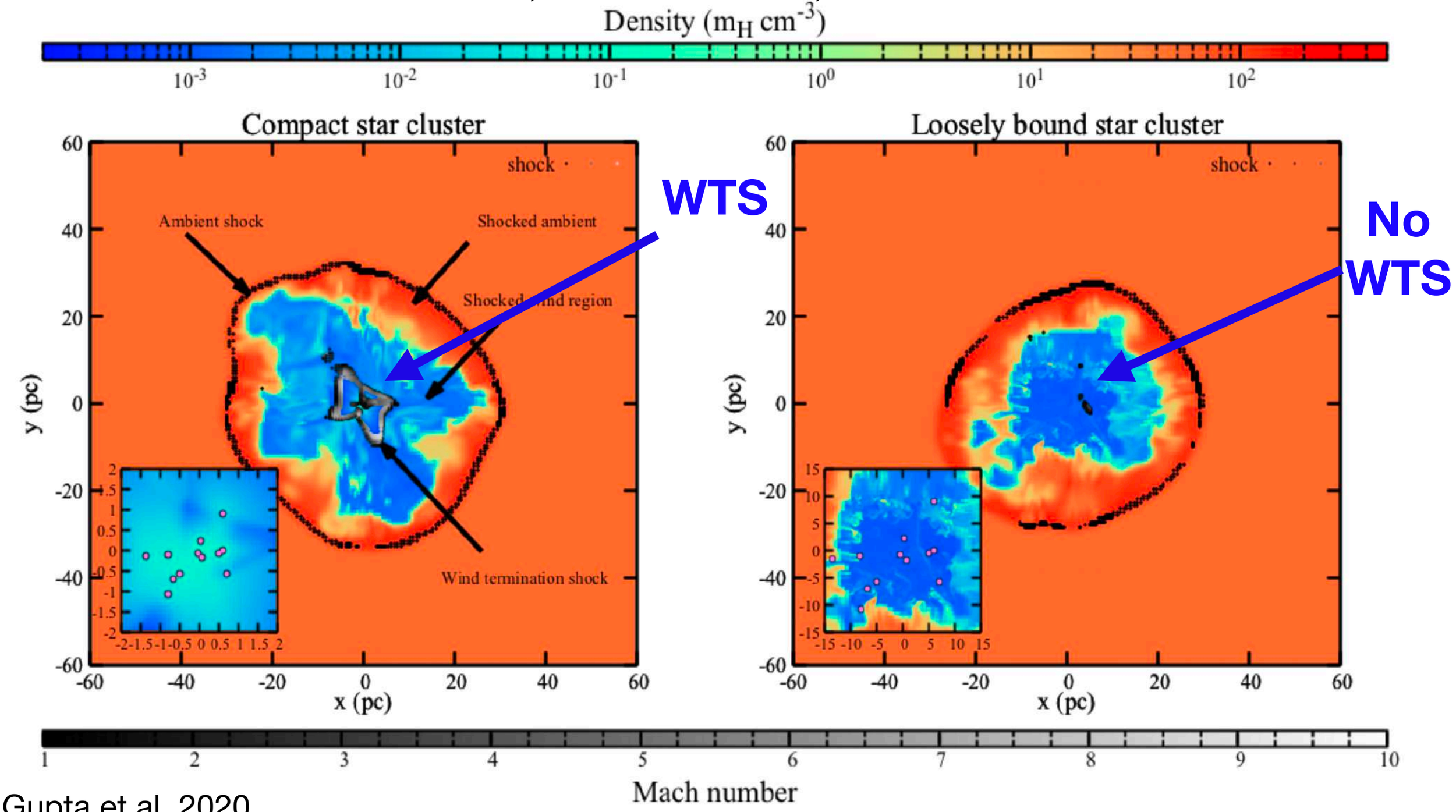

Gupta et al. 2020

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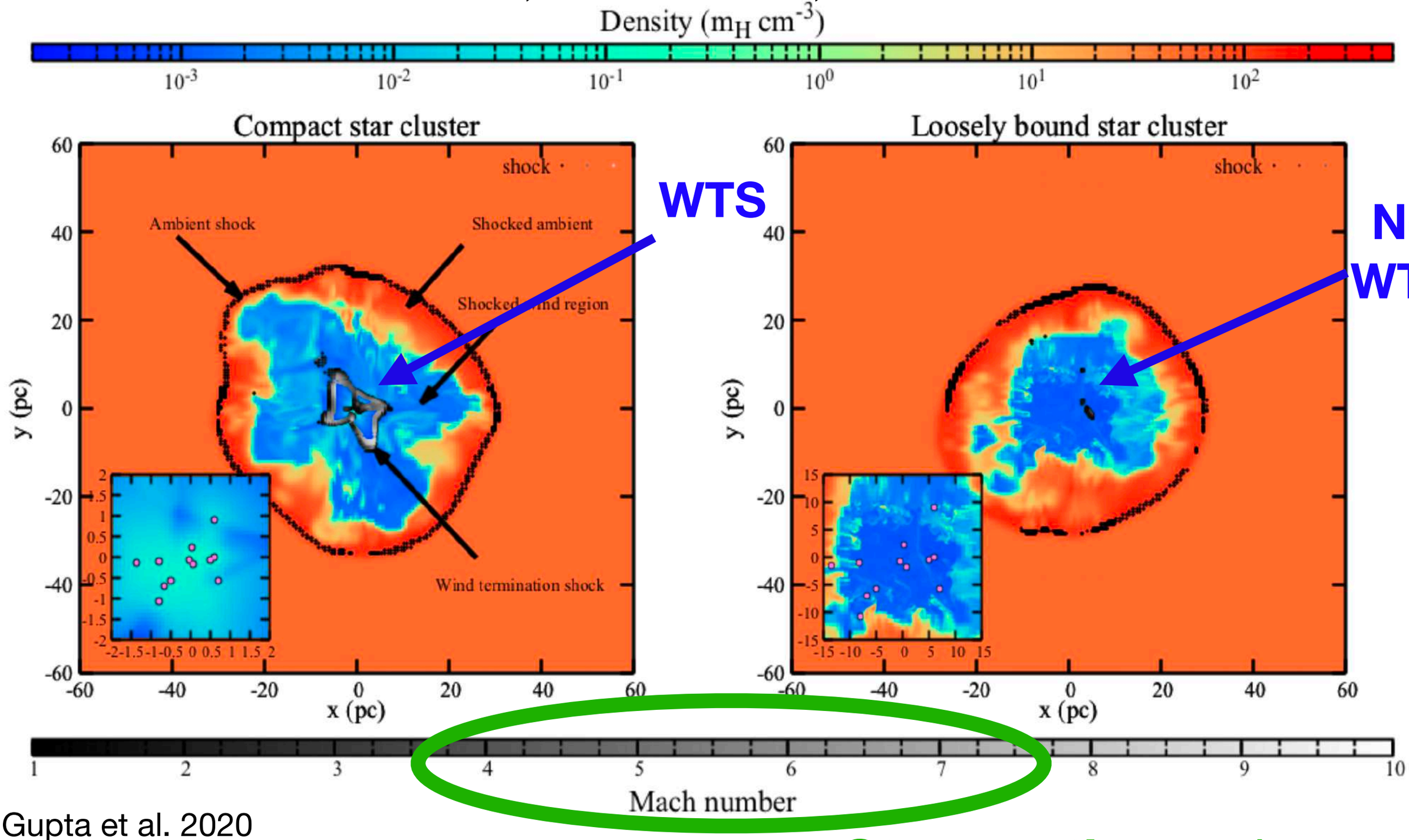

Gupta et al. 2020

Weak shocks → Steeper than p^{-4}

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

SNRs Wind TS Superbubbles

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

	SNRs	Wind TS	Superbubbles
Energetics			
Injected spectrum			
PeV			
Enough PeV protons + Above PeV + hard enough spectrum above PeV			
‘DAMPE’ 10 TeV Bump			

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

	SNRs	Wind TS	Superbubbles
Energetics			
Injected spectrum			
PeV			
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$^{22}Ne/^{20}Ne$			

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

	SNRs	Wind TS	Superbubbles
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Injected spectrum			
PeV	Enough PeV protons + Above PeV + hard enough spectrum above PeV		
‘DAMPE’ 10 TeV Bump			
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	SNRs	Wind TS	Superbubbles
Energetics	Yes	No	Yes
Injected spectrum	≈	≈	≈
PeV	Enough PeV protons + Above PeV + hard enough spectrum above PeV		
	‘DAMPE’ 10 TeV Bump		
$^{22}Ne/^{20}Ne$			

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

	SNRs	Wind TS	Superbubbles
Energetics	Yes	No	Yes
Injected spectrum	≈	≈	≈
PeV	Probably	Probably	Probably

Enough PeV protons +
Above PeV + hard enough
spectrum above PeV

‘DAMPE’ 10 TeV Bump

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

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Energetics	Yes	No	Yes
Injected spectrum	≈	≈	≈
PeV	Probably	Probably	Probably
Enough PeV protons + Above PeV + hard enough spectrum above PeV	?	?	?
‘DAMPE’ 10 TeV Bump			

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	SNRs	Wind TS	Superbubbles
Energetics	Yes	No	Yes
Injected spectrum	≈	≈	≈
PeV	Probably	Probably	Probably
Enough PeV protons + Above PeV + hard enough spectrum above PeV	?	?	?
‘DAMPE’ 10 TeV Bump	Maybe	Unclear	Maybe
$^{22}Ne/^{20}Ne$	No	Yes	No

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

	SNRs	Wind TS	Superbubbles
Energetics	Yes	No	Yes
Injected spectrum	≈	≈	≈
PeV	Probably	Probably	Probably
Enough Pe			
Above PeV - spectrum			
'DAMPE' 1			ybe
$^{22}Ne/^{20}Ne$	No	Yes	No

No easy way to solve everything with one class of sources

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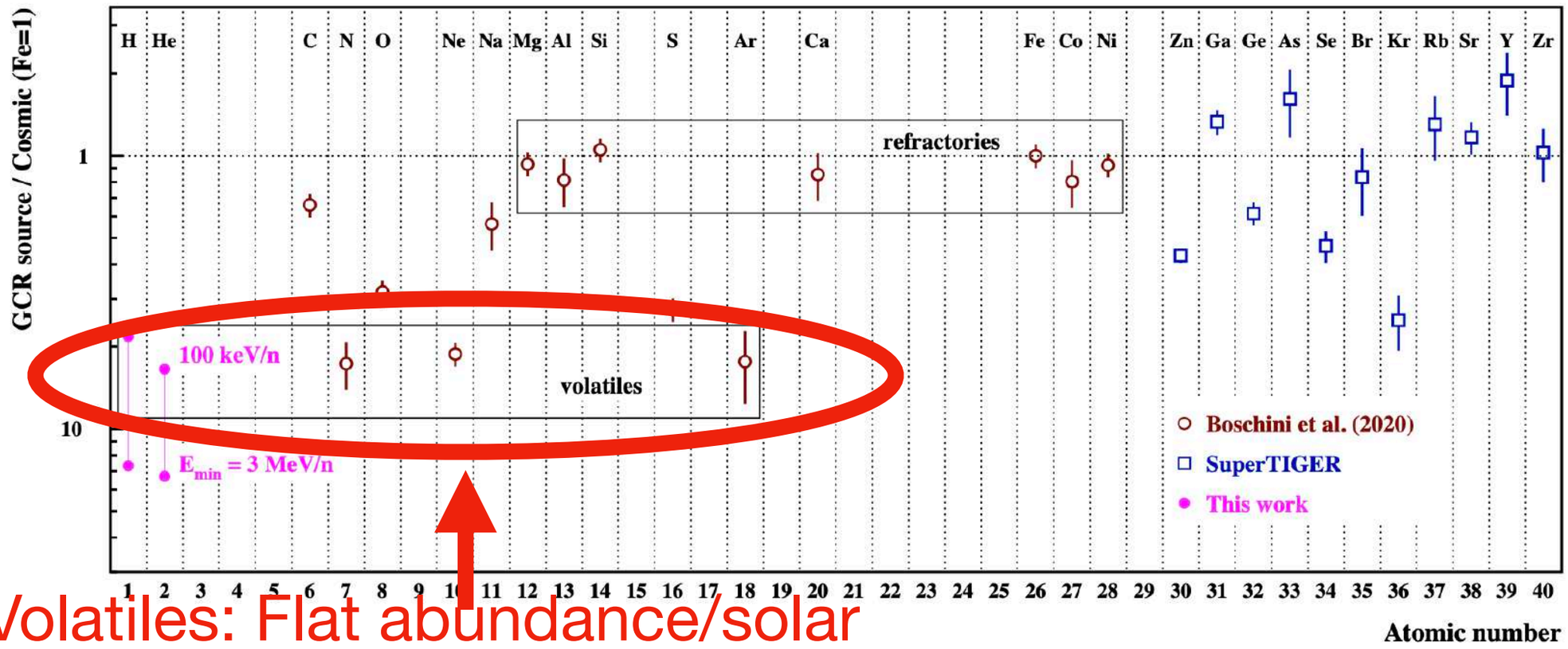
No easy way to solve everything with one class of sources

Mixed contributions?

An example: mixed contribution

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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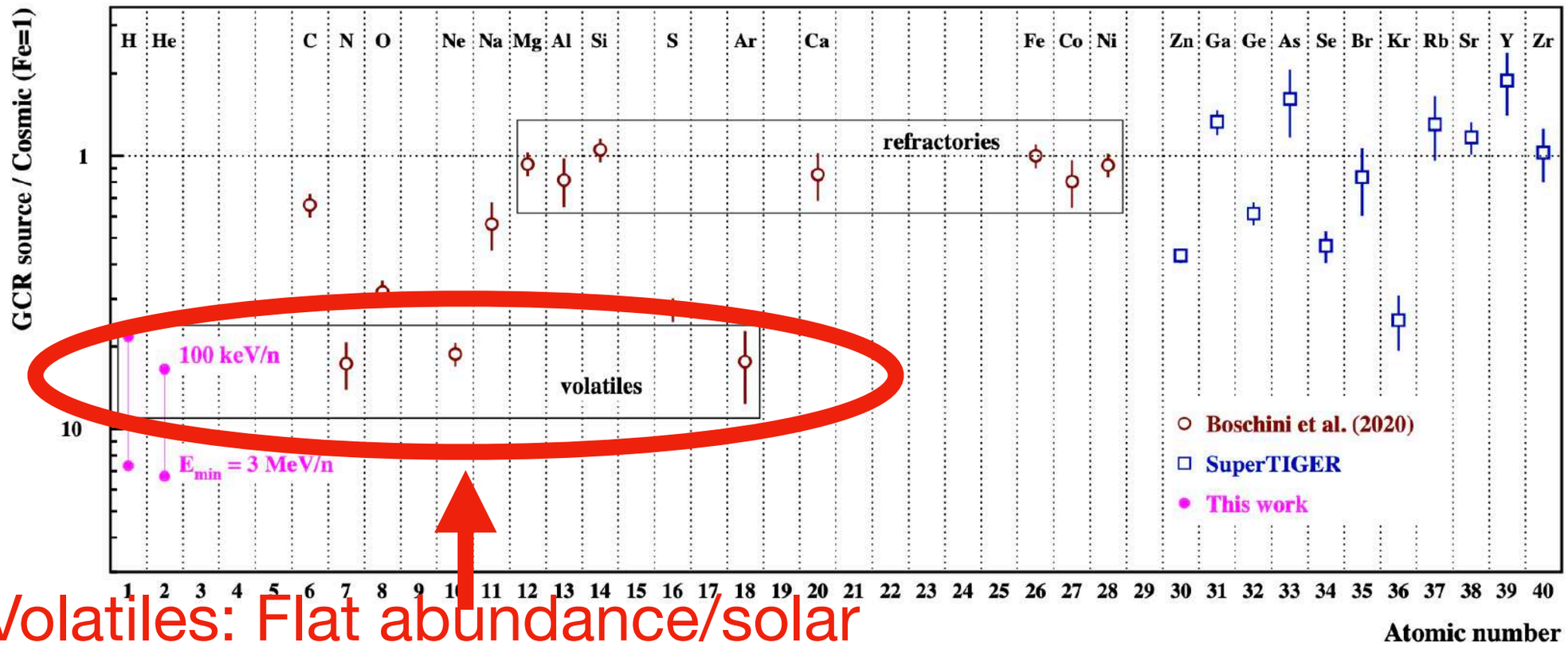

Volatiles: Flat abundance/solar ratio, A/Q ~2 for all elements

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 S	Accelerated wind	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

An example: mixed contribution

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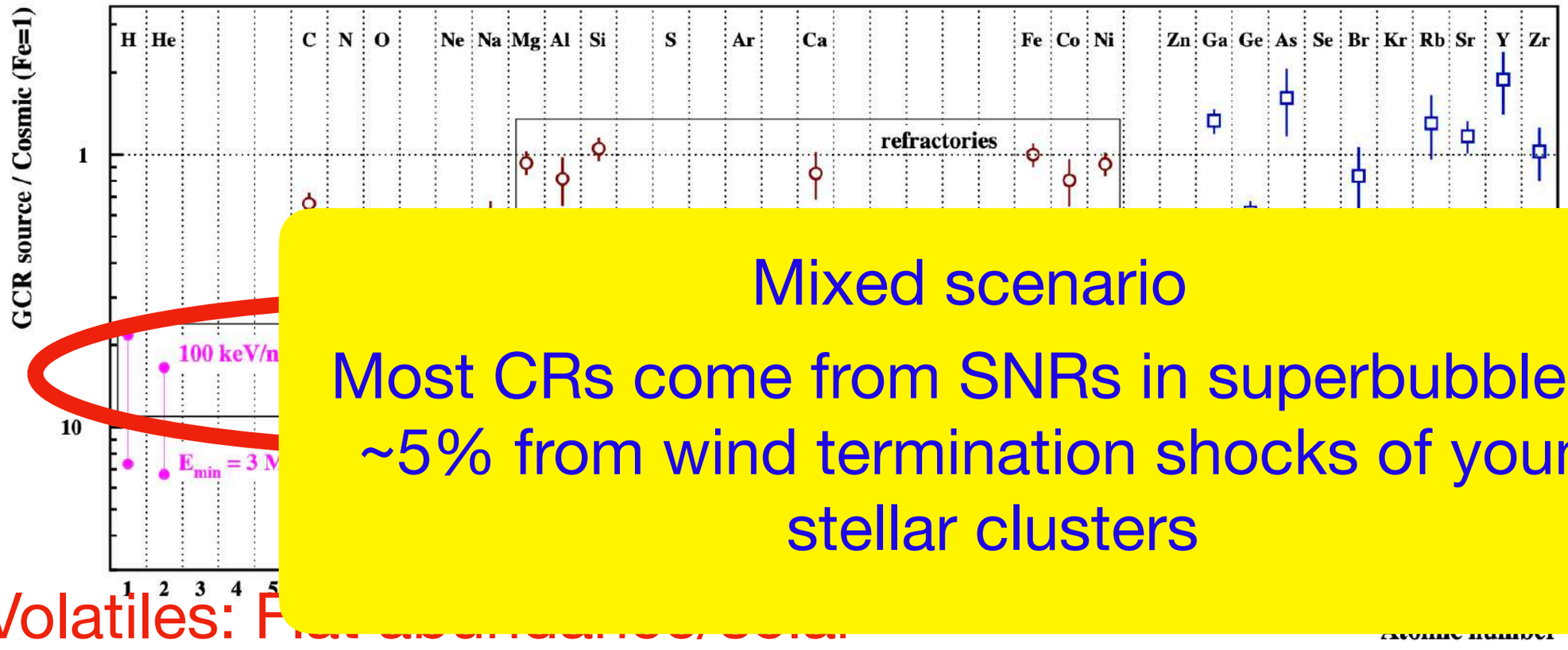

Mixed scenario

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

Volatiles: F[illegible] abundances, solar ratio, A/Q ~2 for all elements

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	Model 1	Model 2	Model 3	Model 4	Model 5
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Tatischeff et al. 2021

Other issues!

SNRs Wind TS Superbubbles

Other issues!

1. Spectral hardening towers the Galactic center

Other issues!

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2. Small spatial gradients of CRs

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5. He spectra different than H

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	SNRs	Wind TS	Superbubbles
Other issues!	?	?	?

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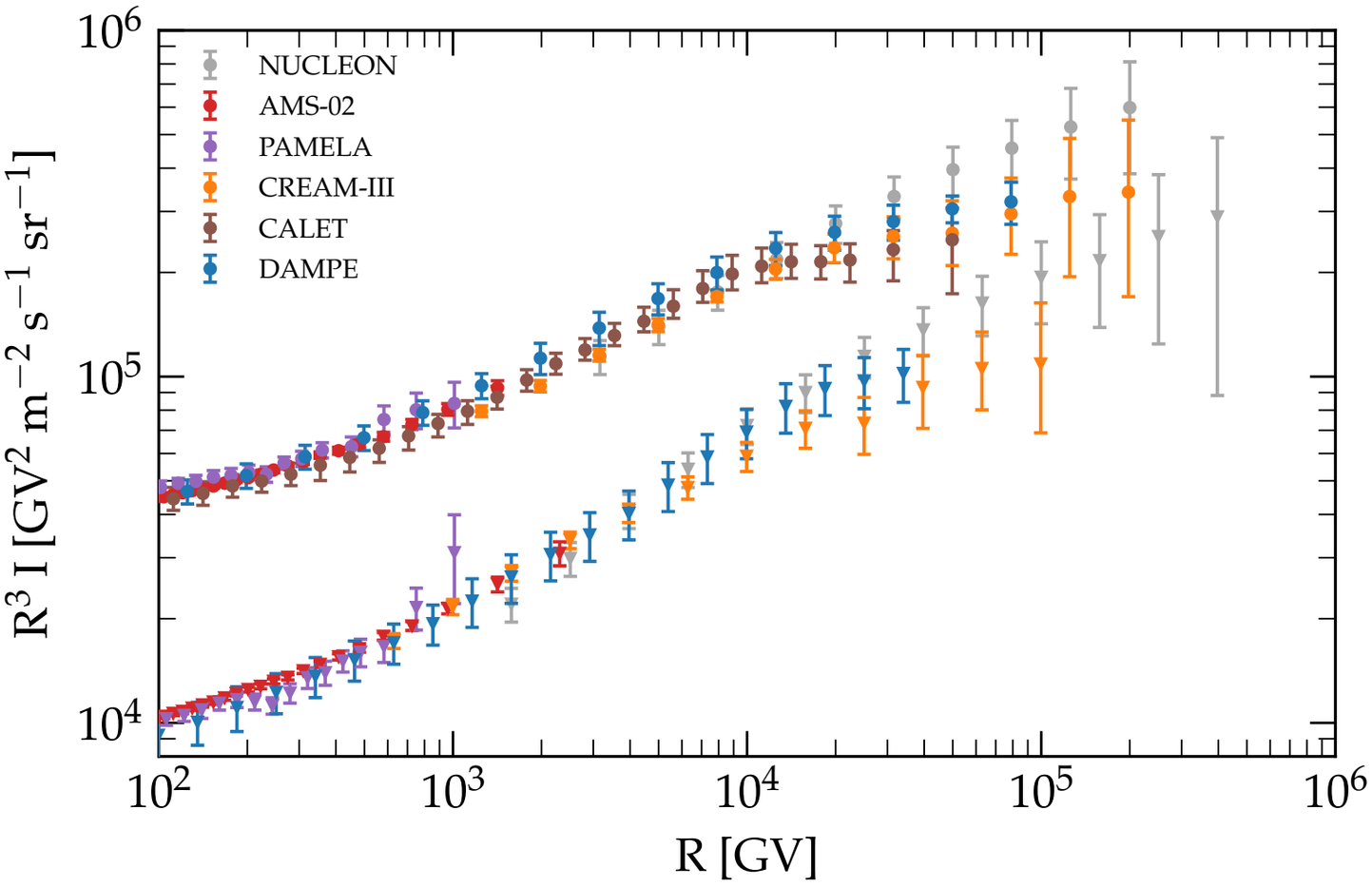
Review: Gabici, Evoli, Gaggero, Mertsch, Orlando, Strong, Vittino 2019

He and H


NUCLEON
AMS-02
PAMELA
CREAM-III
CALET
DAMPE
$R^3\,I\,[GV^2\,m^{-2}\,s^{-1}\,sr^{-1}]$
R [GV]
10^6
10^5
10^4
10^2
10^3
10^4
10^5
10^6

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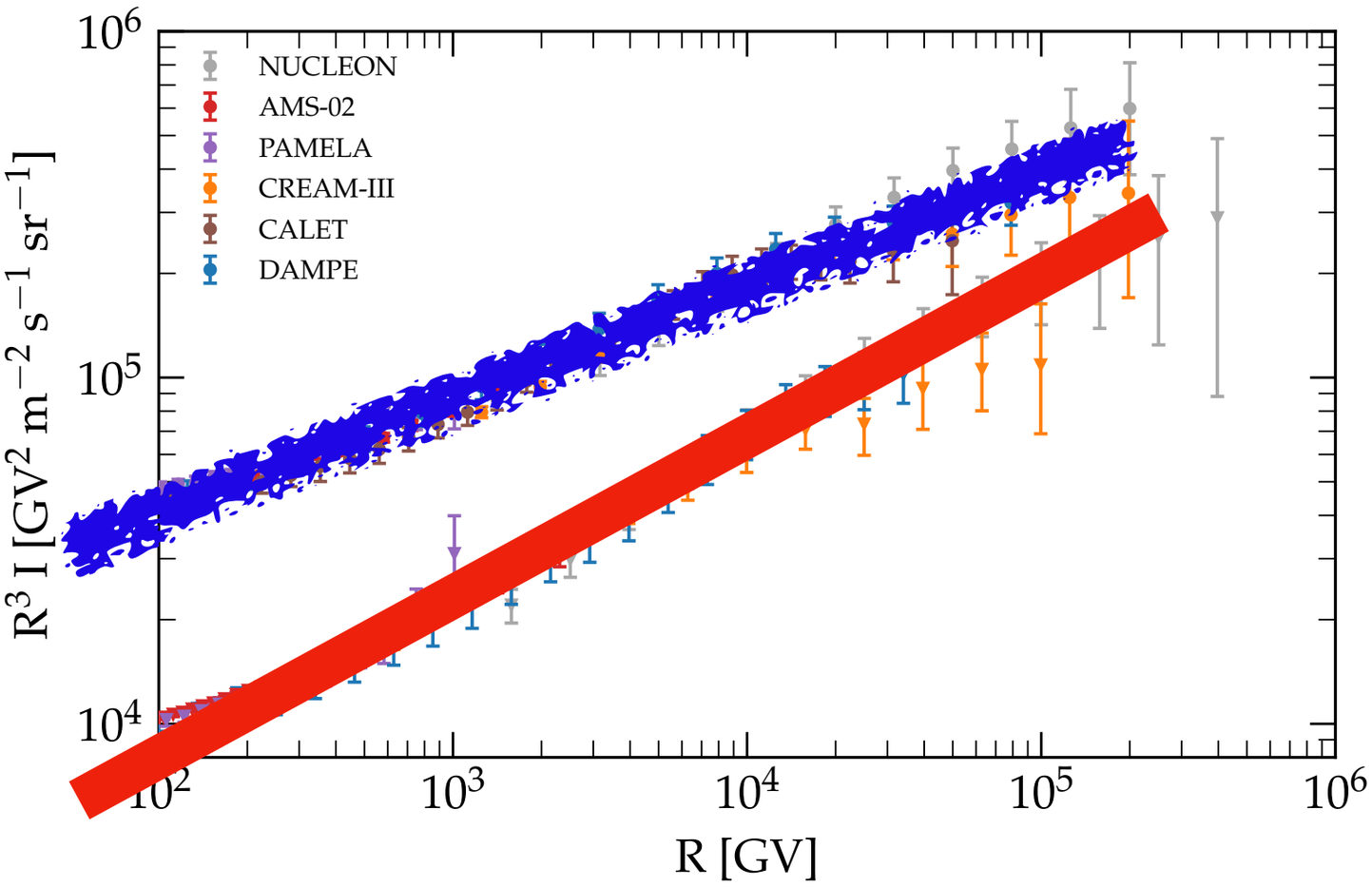
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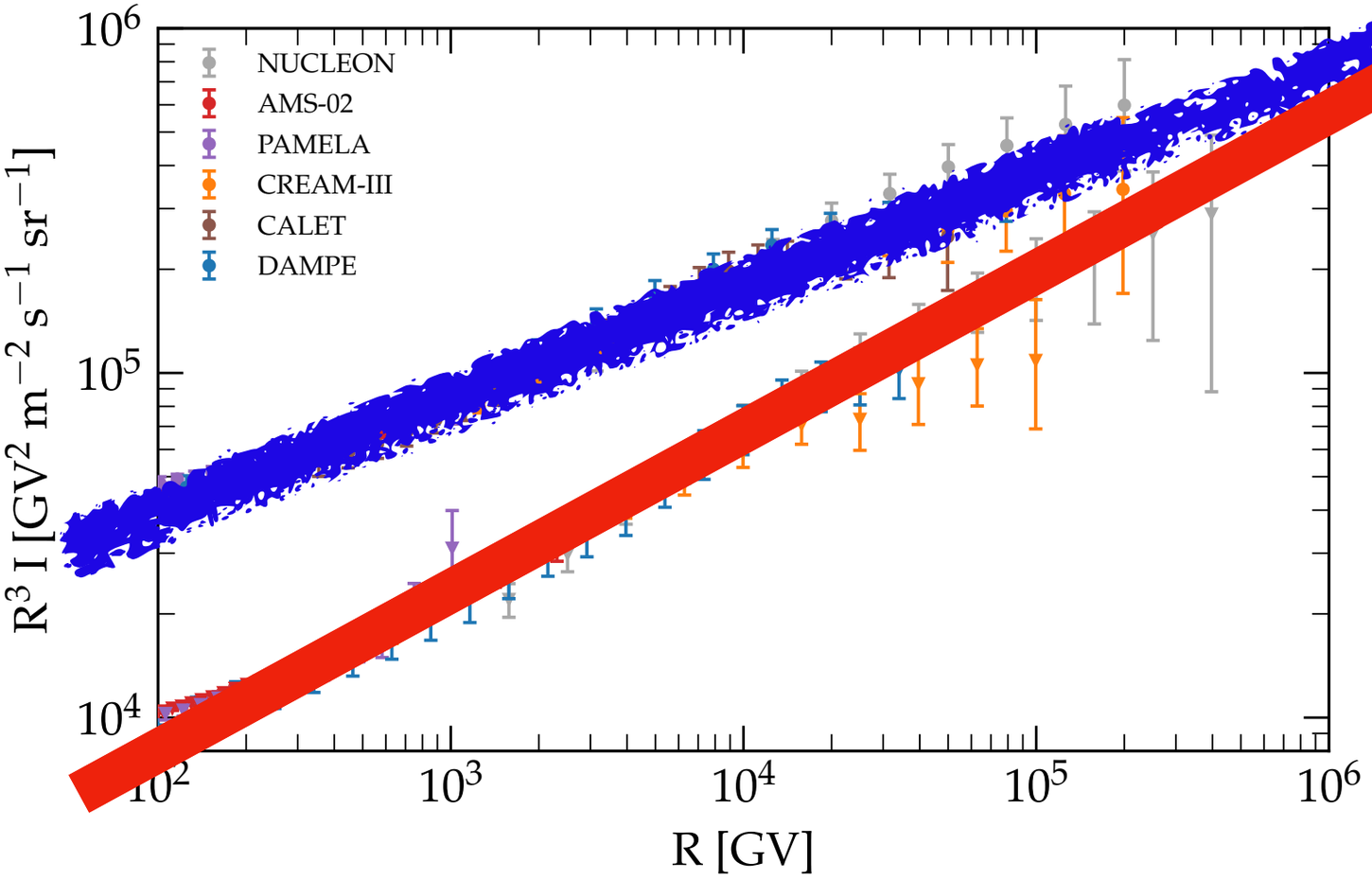
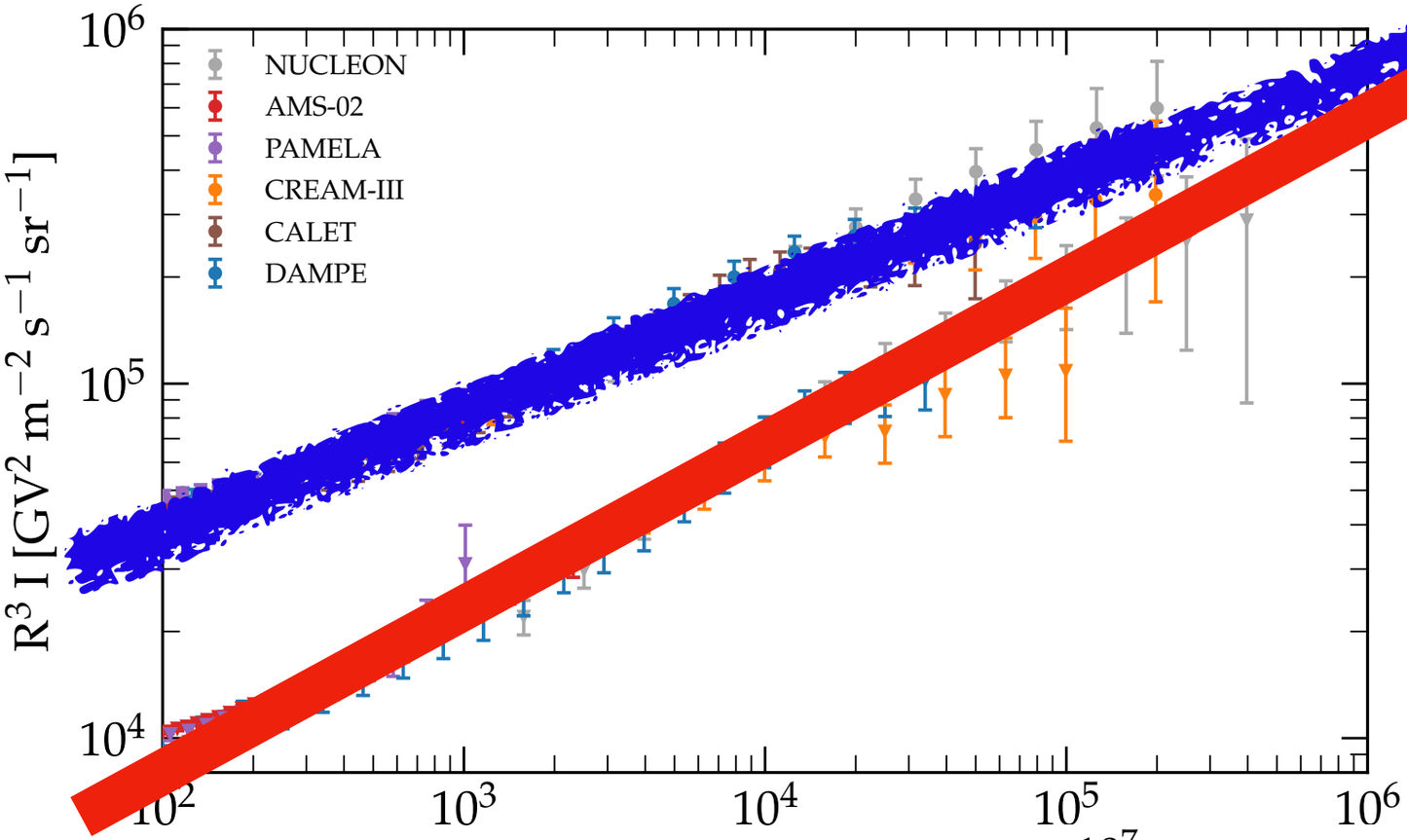


Wild extrapolation: He dominant in the PeV range? Composition of the knee?

Evoli 2022

He and H



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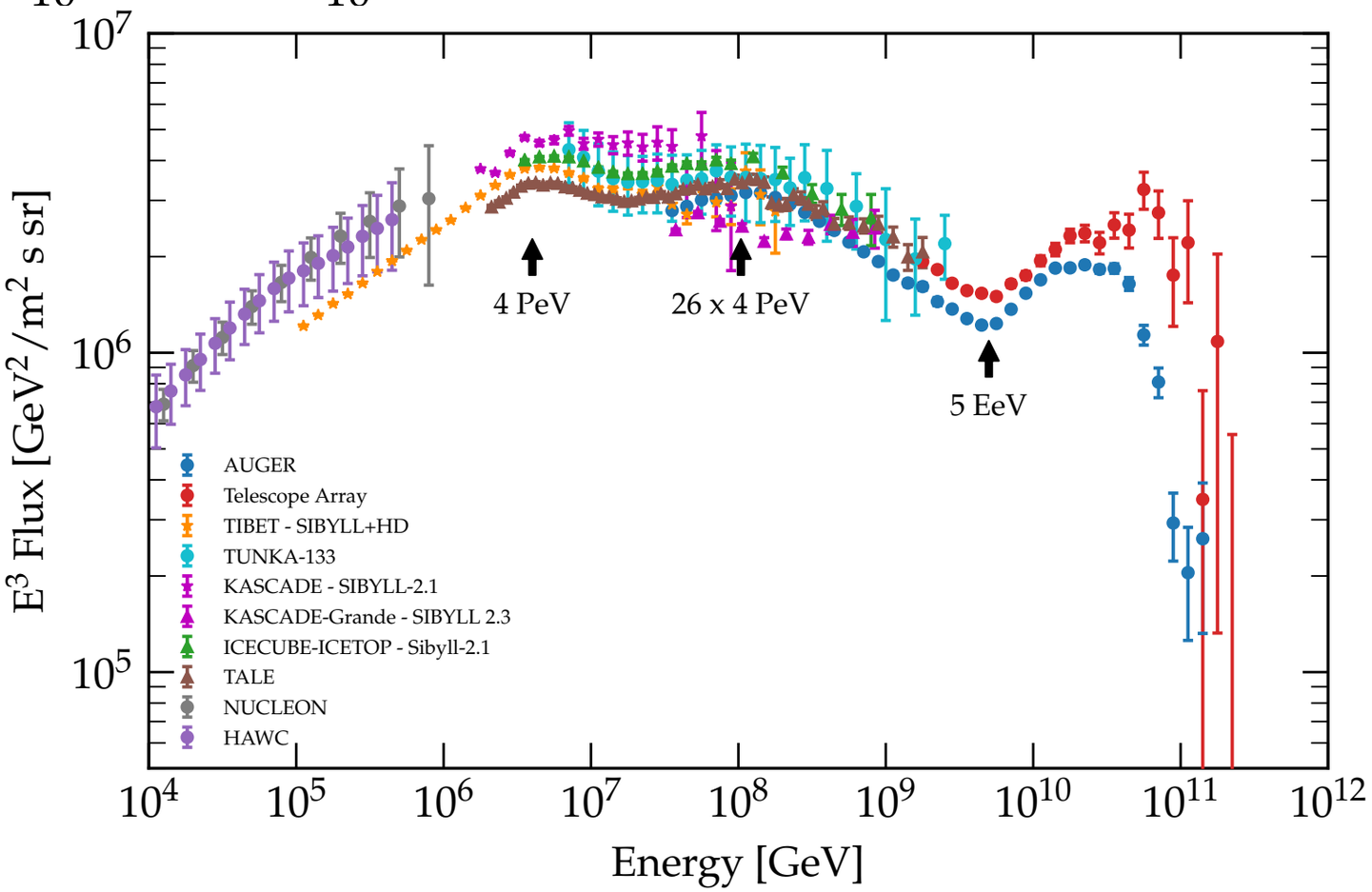
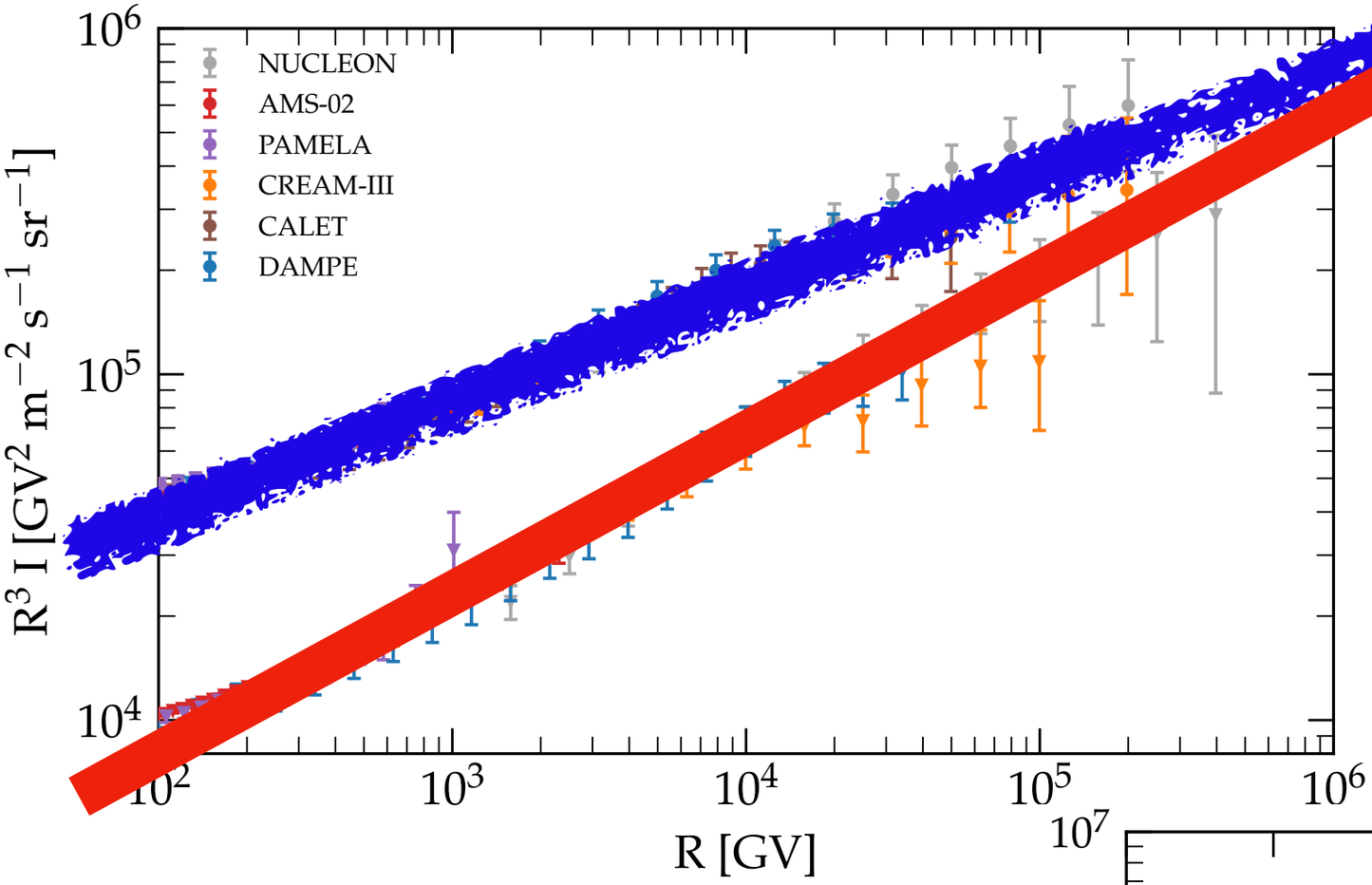


Evoli 2022

He and H



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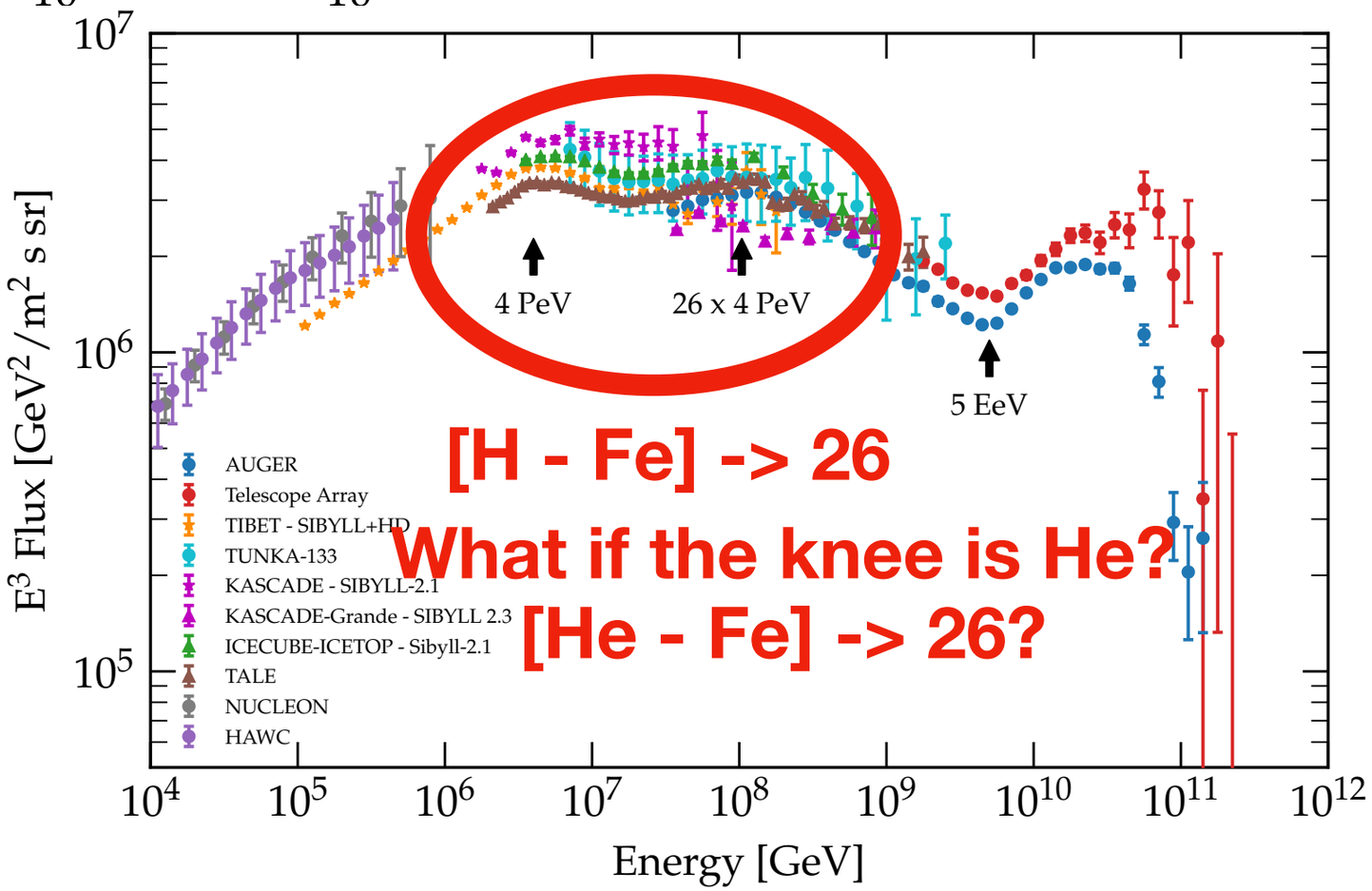

[H - Fe] -> 26

What if the knee is He?

[He - Fe] -> 26?

Evoli 2022

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

The SNR paradigm faces problems

1. Spectra of accelerated particles
2. Spectra released in ISM
3. Up to and beyond PeV?
4. Features in spectrum

Star clusters accelerate particles

1. Wind termination shocks
2. Superbubbles

Mixed scenarios seem favored

it’s a pity, because allows for fine tuning

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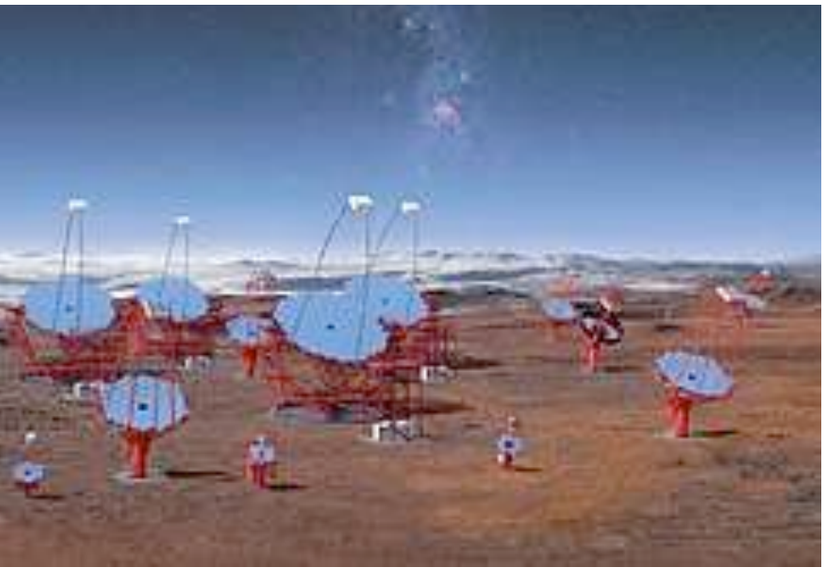

Star clusters accelerate particles

1. Wind termination shocks
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Mixed scenarios seem favored

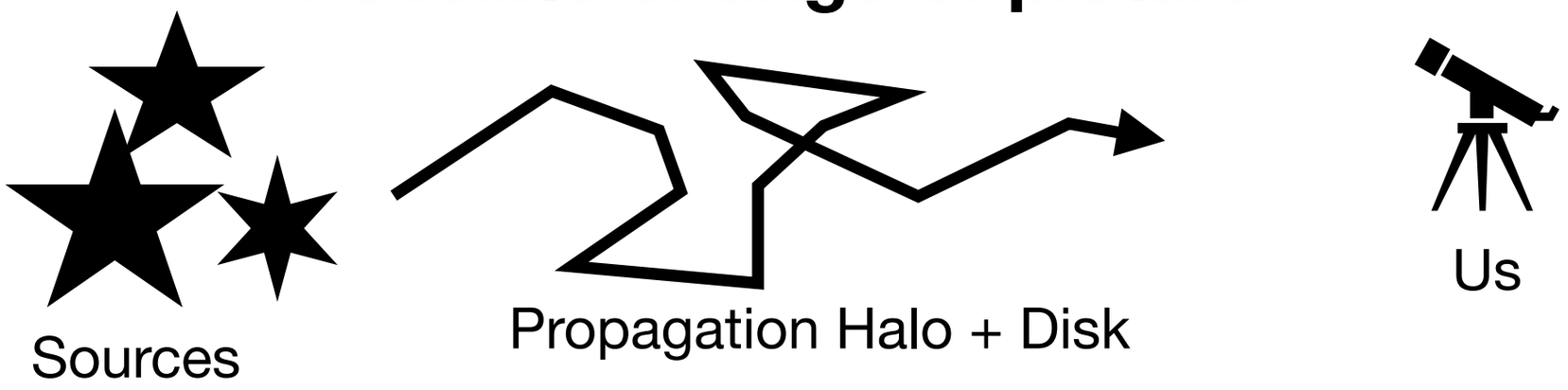
it's a pity, because allows for fine tuning

Next years: differential spectra in the 100 TeV range needed

1. From SNRs and star clusters
2. To understand their role in the origin of CRs + essential questions on shock acceleration (efficiency, spectra around the knee, etc.)

~~The transition from~~ Galactic ~~to extragalactic~~ cosmic rays

Possible change of picture



Different classes of sources Diffusive reacceleration

Reviews origin of Galactic CRs: Blasi et al. 2013 & 2019, Gabici et al. 2019, PC 2021

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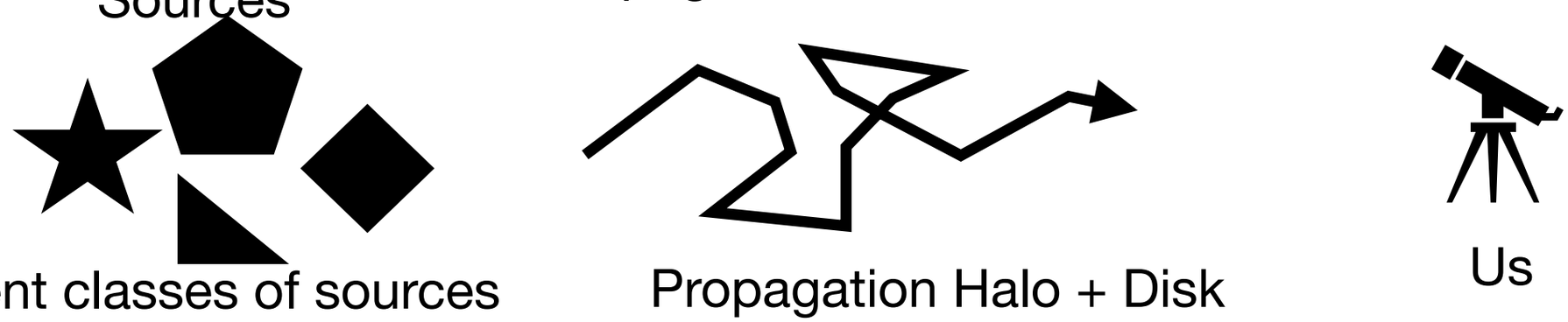

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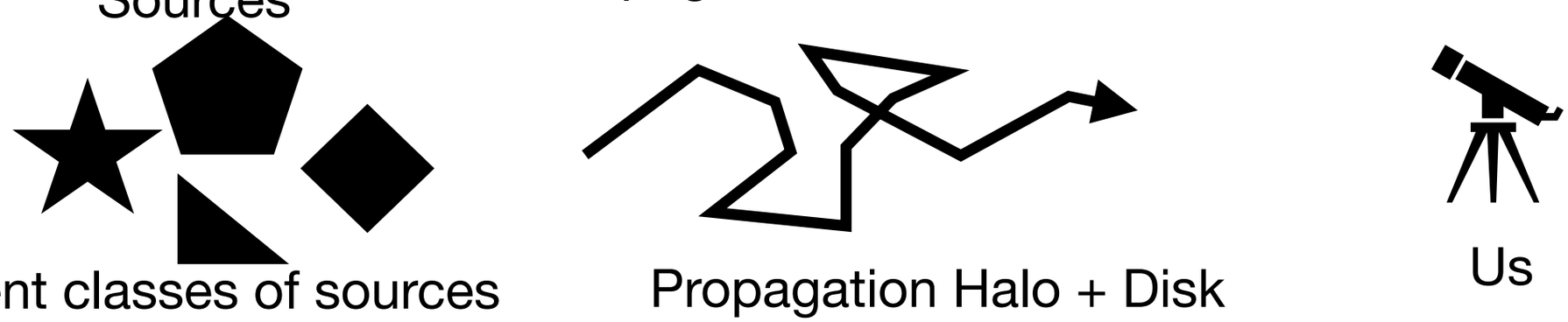

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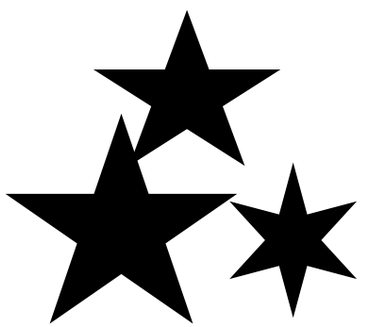
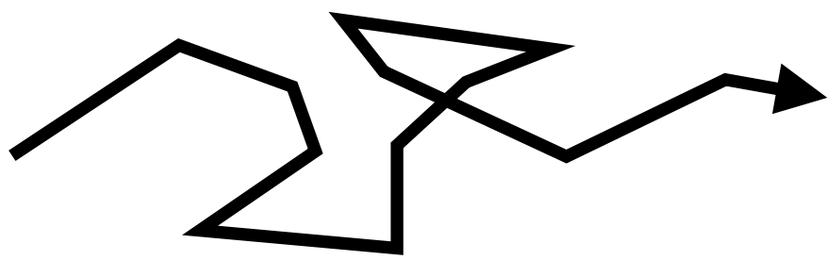
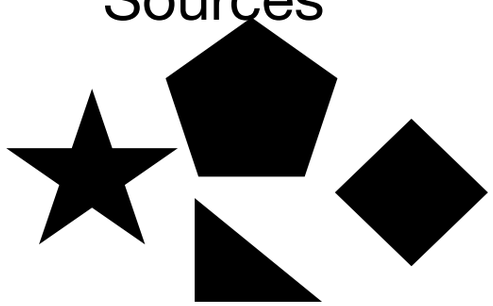


Sources



Propagation Halo + Disk

Us



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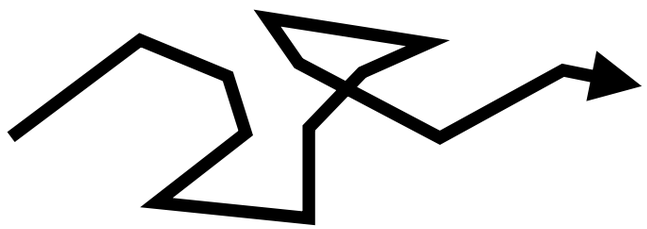

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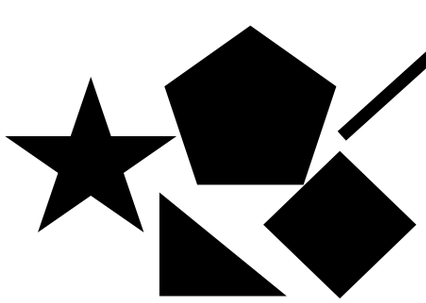

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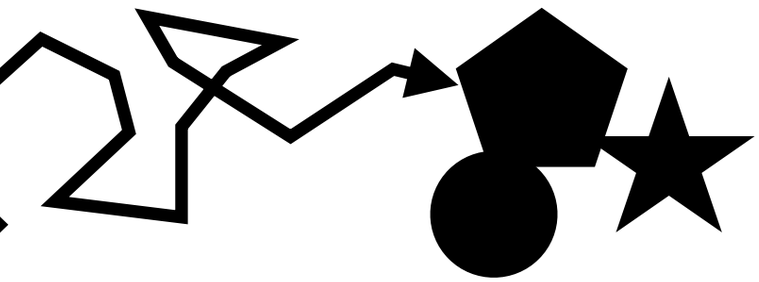
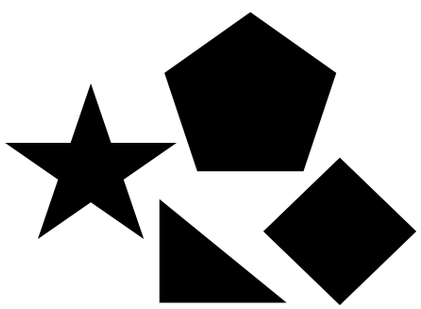


DSA Reacceleration

Us



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