The hunt for PeVatrons

10^{15} eV

Supernova remnants

CEA DPhP

December 13th 2021

Pierre Cristofari

pierre.cristofari@obspm.fr

l'Observatoire de Paris | PSL

H.E.S.S.

SWGO The Southern Wide-field Gamma-ray Observatory

cta cherenkov telescope array

The hunt for PeVatrons

10^{15} eV

Supernova remnants

Cristofari, Blasi, Amato, Astro. Phy. , Dec. 2020

« The Low Rate of Galactic PeVatrons »

Nature, May 2021

« Ultrahigh-energy photons up to 1.4 PeV from
12 gamma-ray Galactic sources »

l'Observatoire de Paris | PSL

H.E.S.S.

SWGO The Southern Wide-field Gamma-ray Observatory

cta cherenkov telescope array

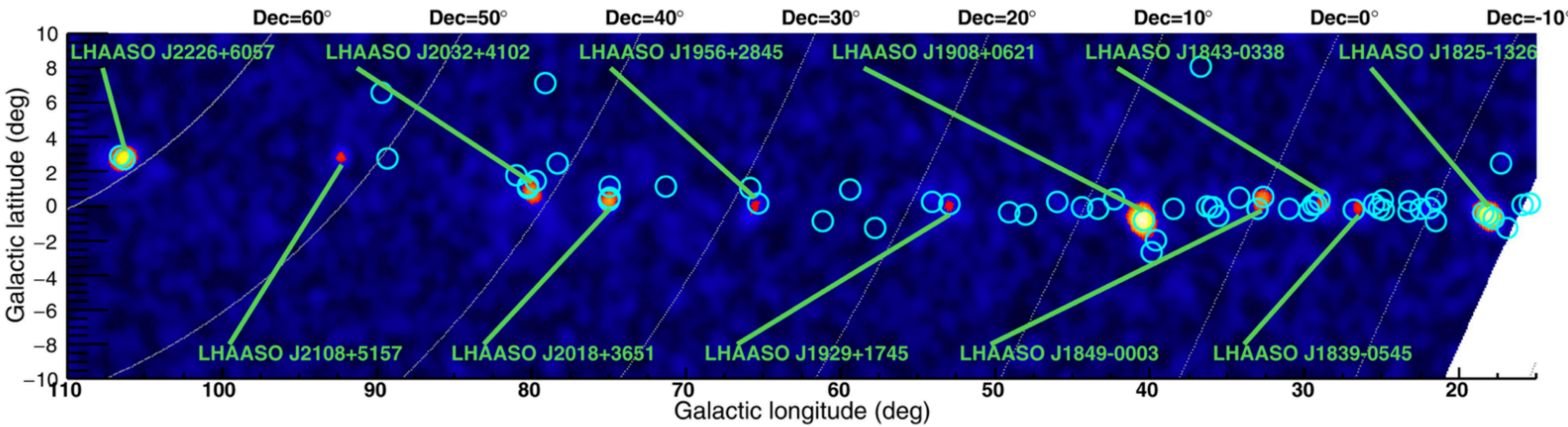
Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

https://doi.org/10.1038/s41586-021-03498-z

Received: 21 October 2020

Accepted: 26 March 2021

Published online: 17 May 2021



Why supernova remnants (SNR=' shock wave expanding after supernova')?

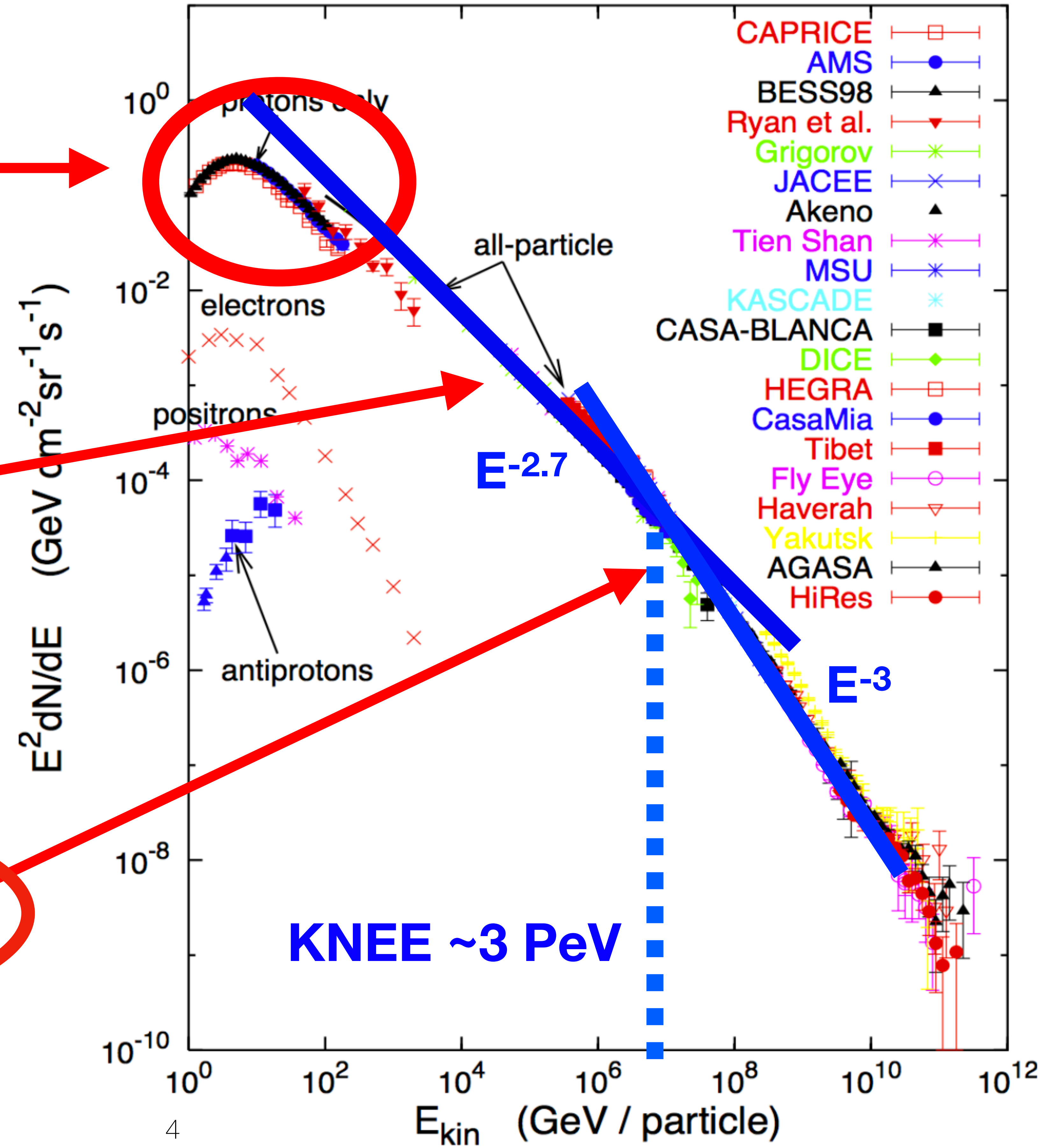
1. Bulk of CRs
Energy density ~1 eV/cm3
10% of SNR total explosion energy

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

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

Injection **Propagation**

3. Magnetic field amplification - pevatrons!



KM3NET 2014

Gamma rays from SNRs

Hadronic interactions :
Pion decay

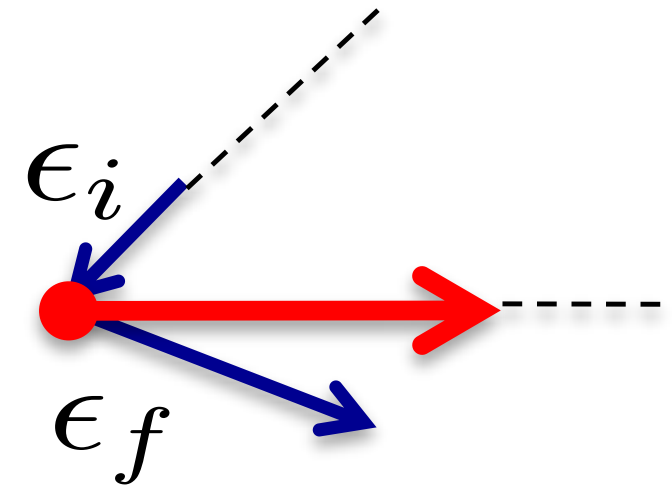
ISM

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

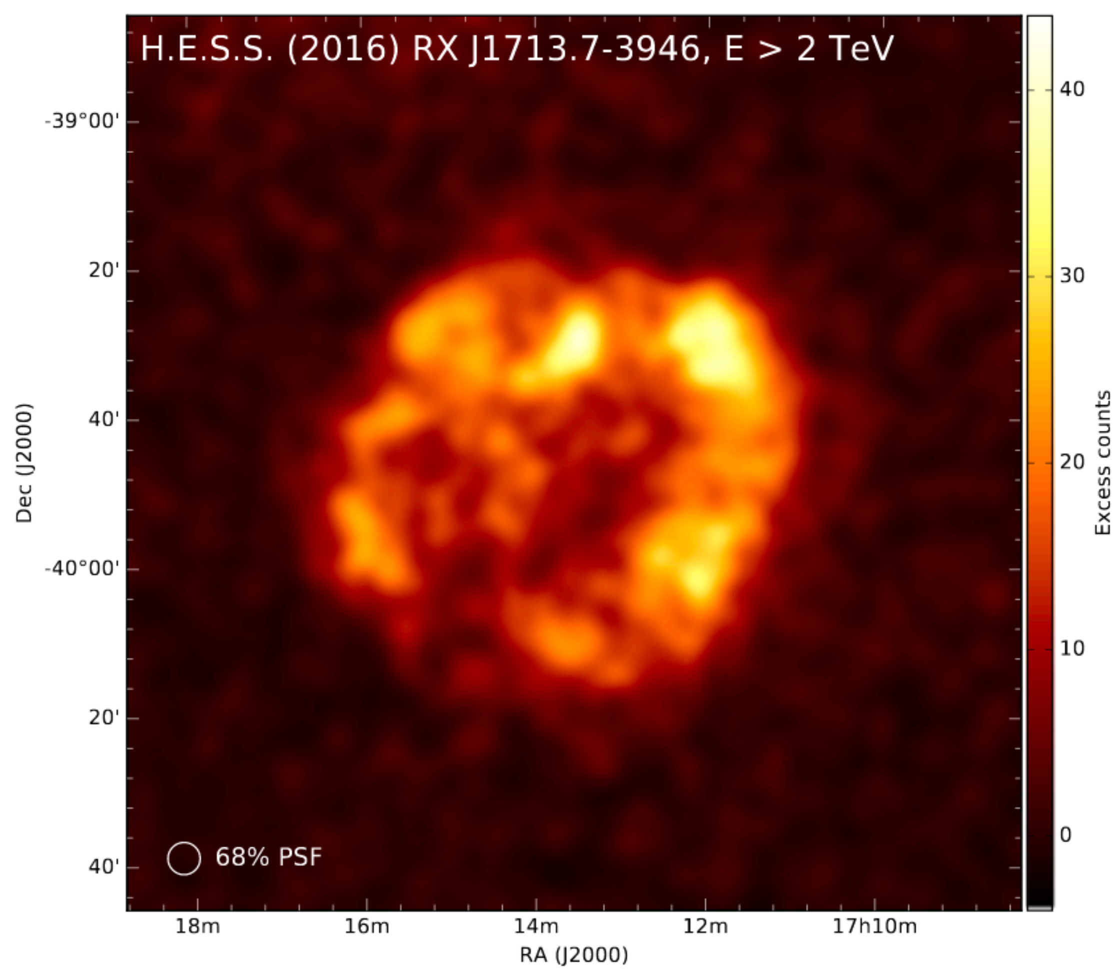
$$\pi^0 \rightarrow \gamma + \gamma$$

CR

Leptonic interactions :
Inverse Compton scattering



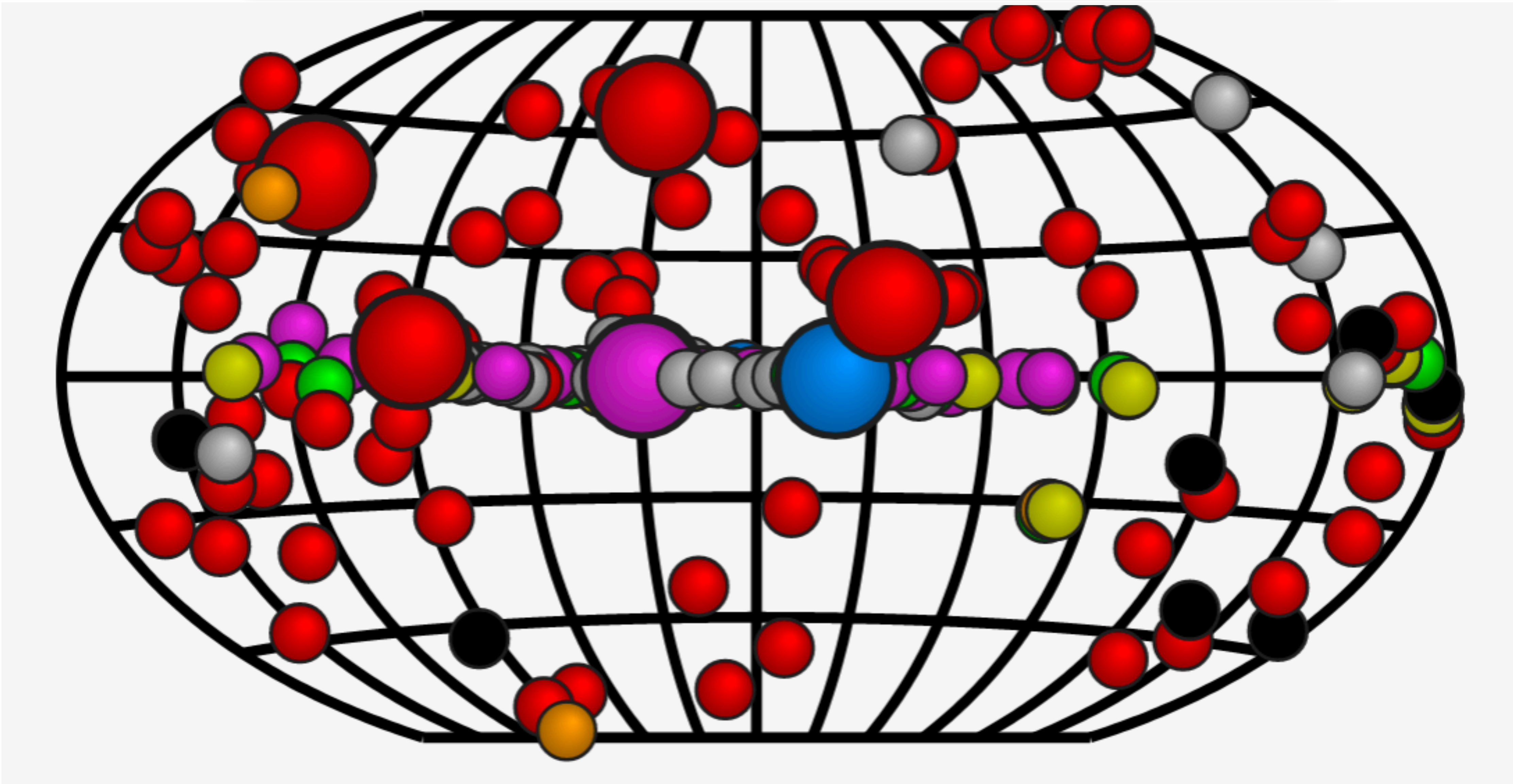
H.E.S.S. 2016



Efficient particle acceleration

Hadronic Vs Leptonic : situation unclear

Galactic supernova remnants



PWN, PWN/TeV Halo, Composite SNR

Shell, SNR/Molec. Cloud, Composite SNI

PSR

228 sources listed

58 « SNRs »

12 Shells

TeVCat (2021)

Gamma rays from SNRs

Hadronic interactions : Pion decay

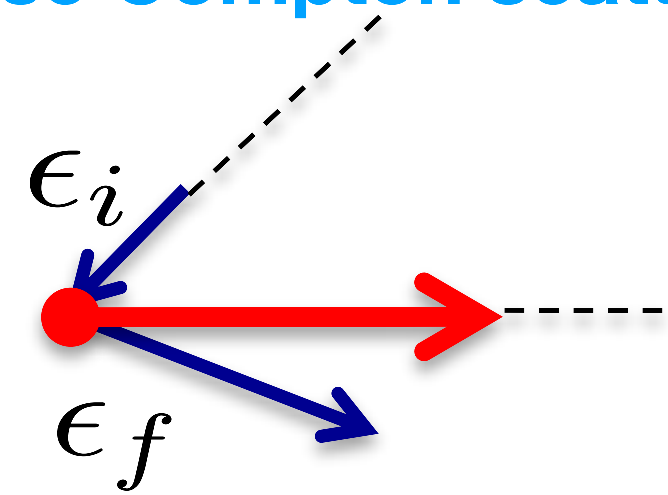
ISM

CR

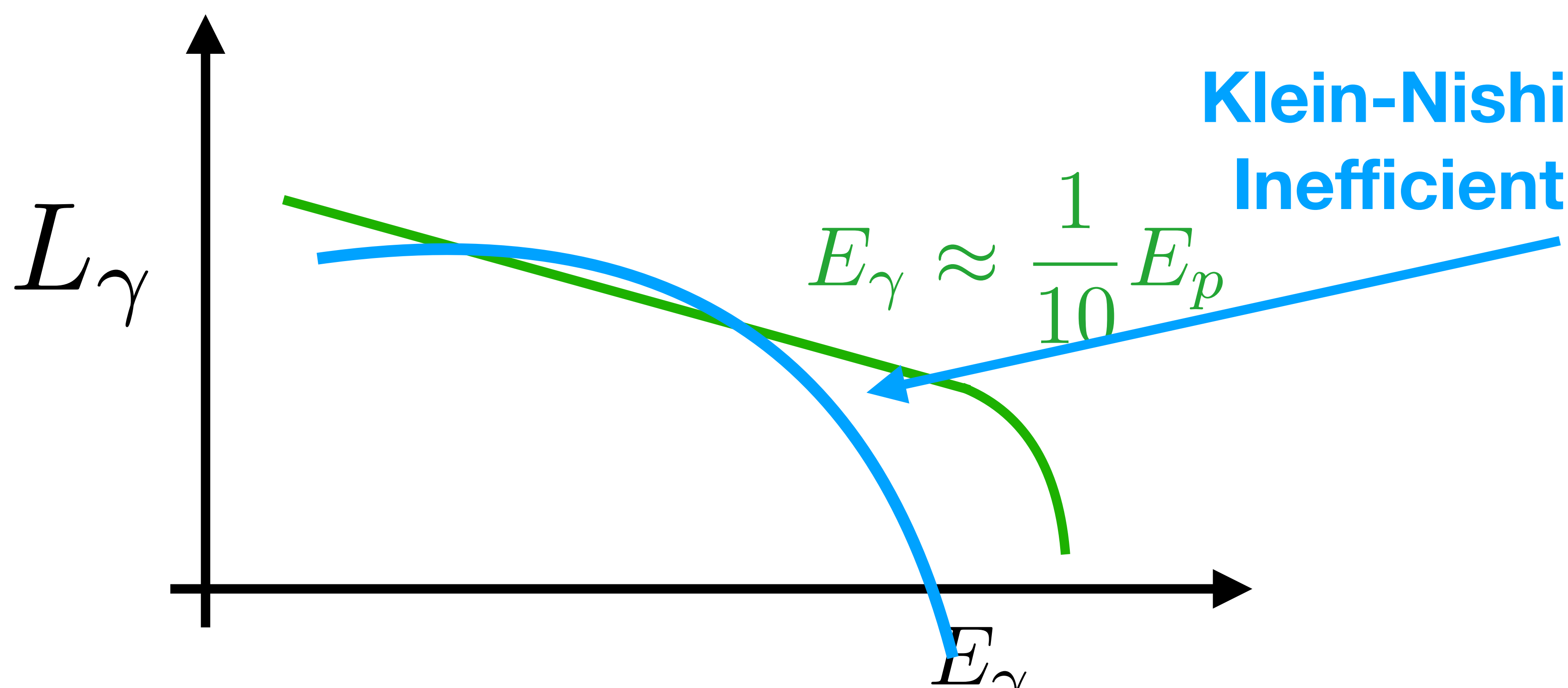
$$p + p \rightarrow p + p + \pi^0$$

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

Leptonic interactions : Inverse Compton scattering

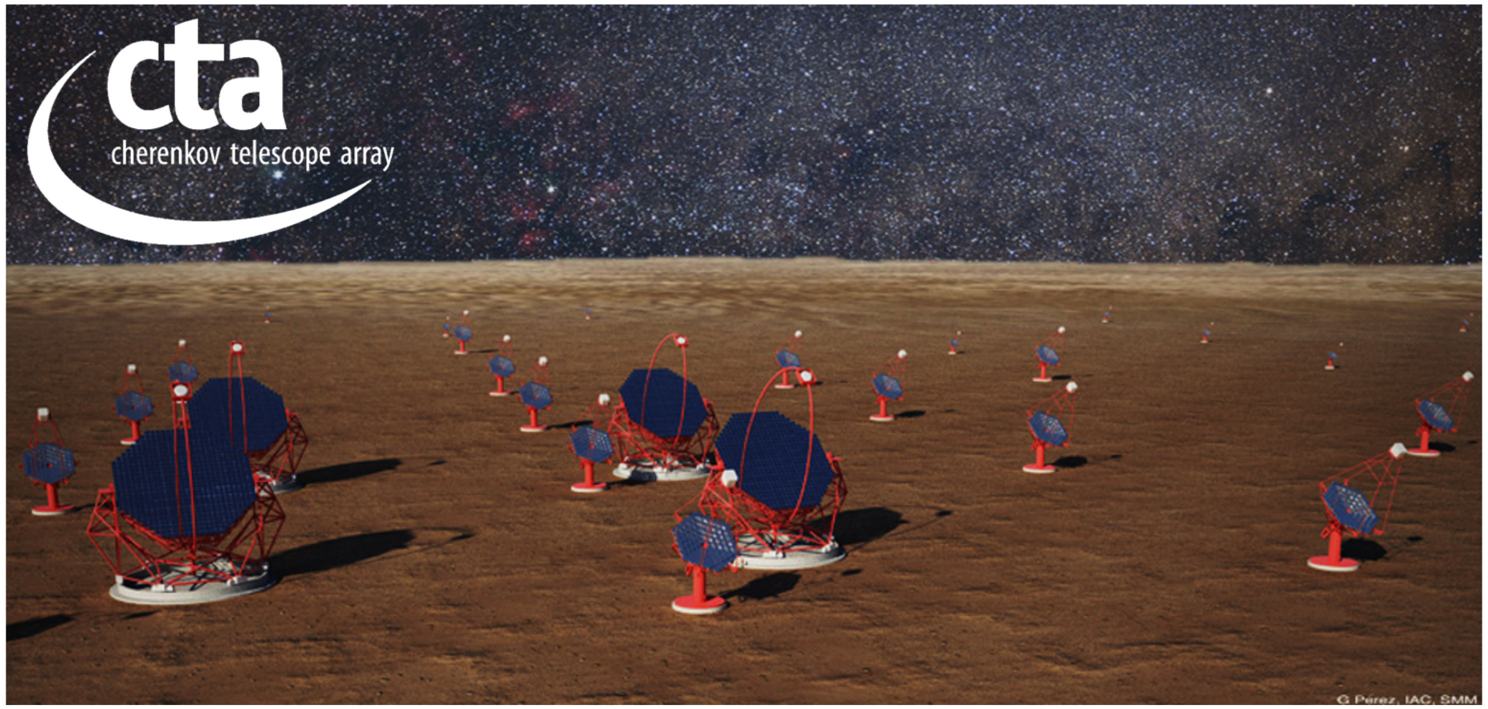


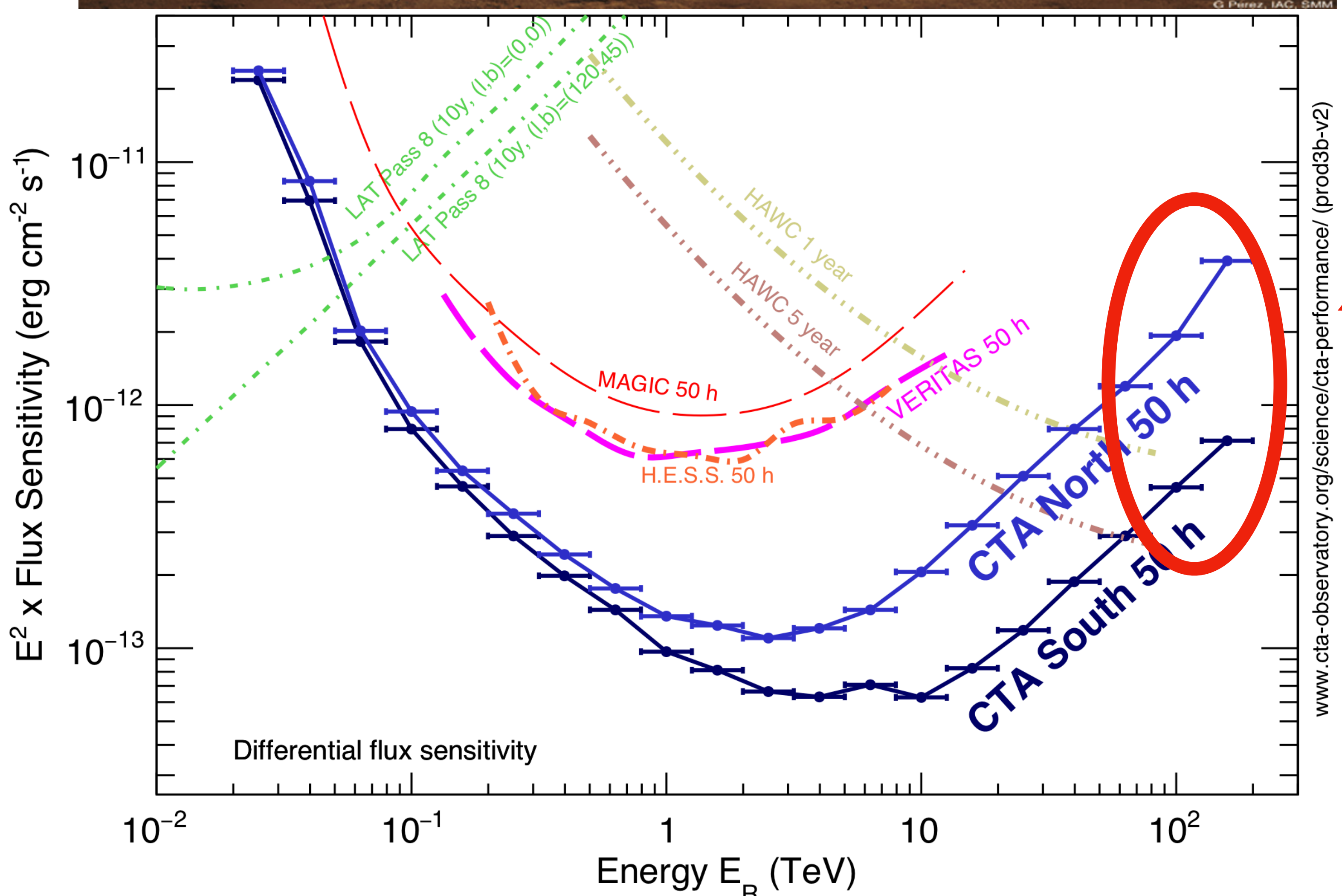
Klein-Nishina suppression: Inefficient above >50 TeV



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

TeV gamma—ray astronomy





100 TeV gamma rays -> acceleration of PeV protons (hadronic)

SNR Pevatrons with CTA

Why all the talking with PeV CRs at SNRs?

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

Resonant streaming of CRs
Skiling (1975)

Acoustic instability
Drury & Falle (1983)

Instability density fluctuations
Giacolone & Jokipii (2007)

....

Non-resonant streaming
Bell (2004)

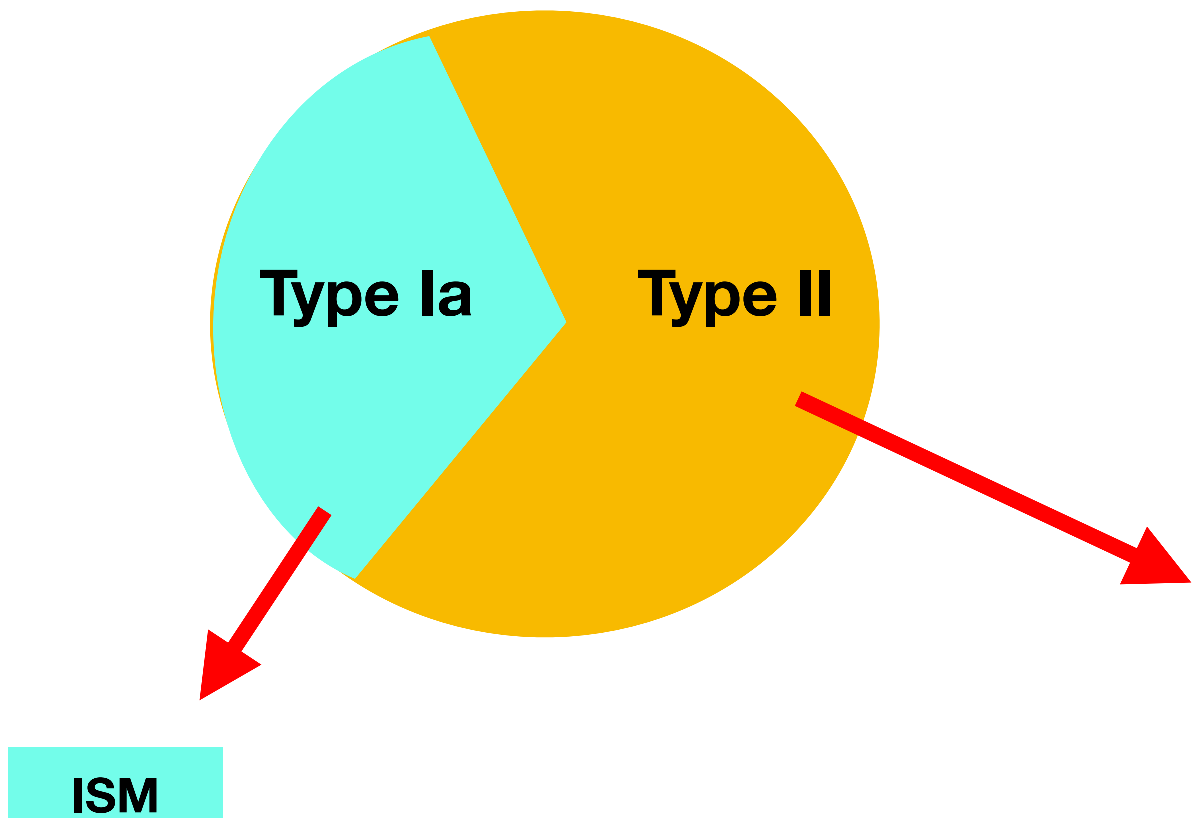
Non-resonant streaming of CRs

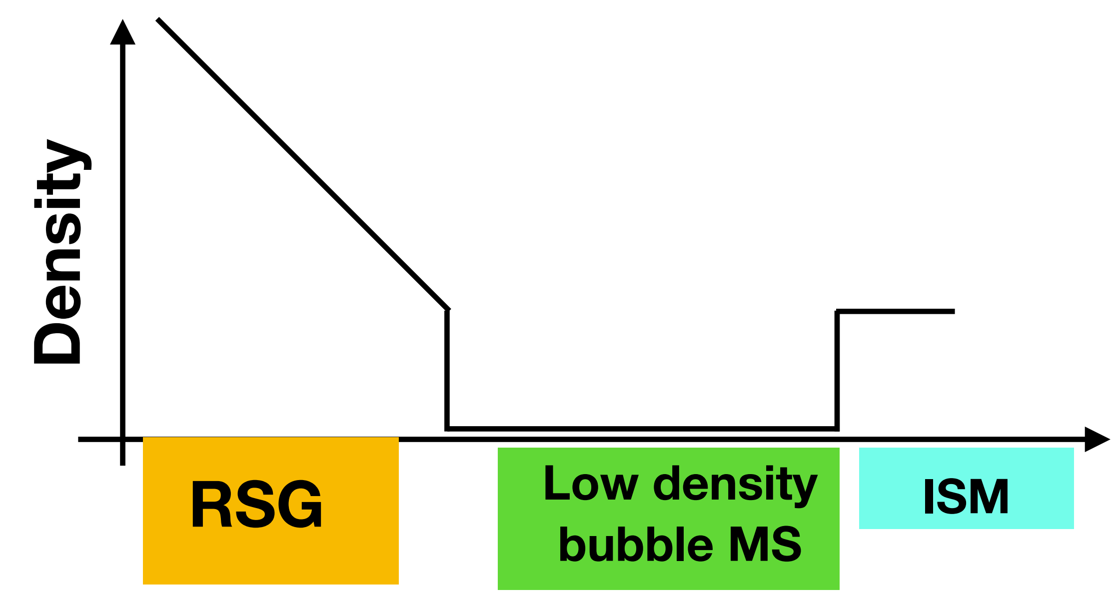
$$\int_0^t dt' \gamma_{\max}(t') \simeq 5$$

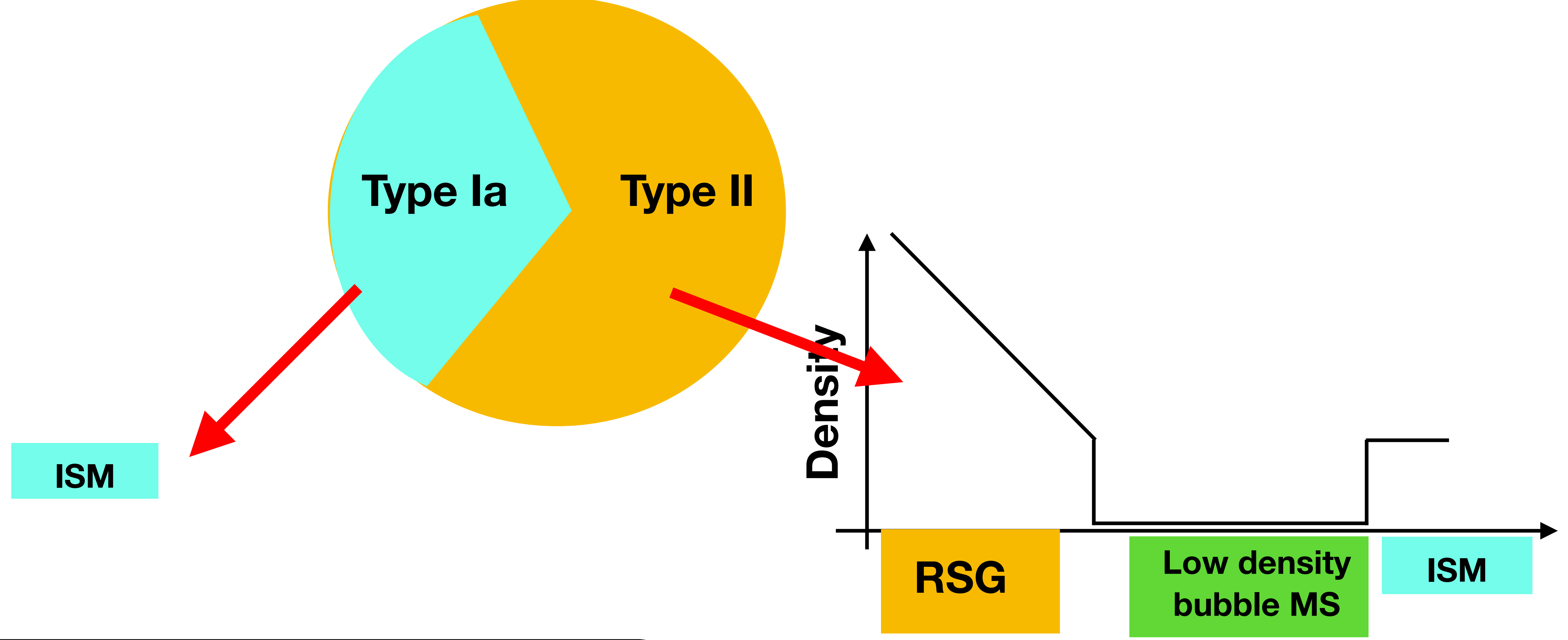
Growth rate of the non-resonant streaming instability

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

Different for different SNRs/SNe







$$R_{\rm sh} = 4.3 \left(\frac{\mathcal{E}_{51}^2}{n_0}\right)^{1/5} t_{\rm kyr}^{2/5} \left(1 - \frac{0.06 M_{\rm ej,\odot}^{5/6}}{\mathcal{E}_{51}^{1/2} n_0^{1/3} t_{\rm kyr}}\right)^{2/5} \ {\rm pc}$$

$$u_{\rm sh} = 1.7 \times 10^3 \left(\frac{\mathcal{E}_{51}^2}{n_0}\right)^{1/5} t_{\rm kyr}^{-3/5} \left(1 - \frac{0.06 M_{\rm ej,\odot}^{5/6}}{\mathcal{E}_{51}^{1/2} n_0^{1/3} t_{\rm kyr}}\right)^{-3/5} \ {\rm km/s}$$

Chevalier (1999) Tang (2017)

$$M_{\rm ej} = 1.4 M_\odot$$

$$E_{\rm SN} = 10^{51} {\rm erg}$$

$$n_0$$

$$\frac{\rm d}{{\rm d}t}(M u_{\rm sh}) = 4\pi R_{\rm sh}^2 P_{\rm in}$$

$$E = \frac{4\pi}{3(\gamma+1)} P_{\rm in} R_{\rm sh}^3 + \frac{1}{2} M u^2$$

$$R_{\rm sh}(t)$$

$$u_{\rm sh}(t)$$

Ostriker & McKee (1988)
Thin shell approximation

$$\dot{M}_{\rm RSG}, u_{\rm RSG}, E_{\rm SN}$$

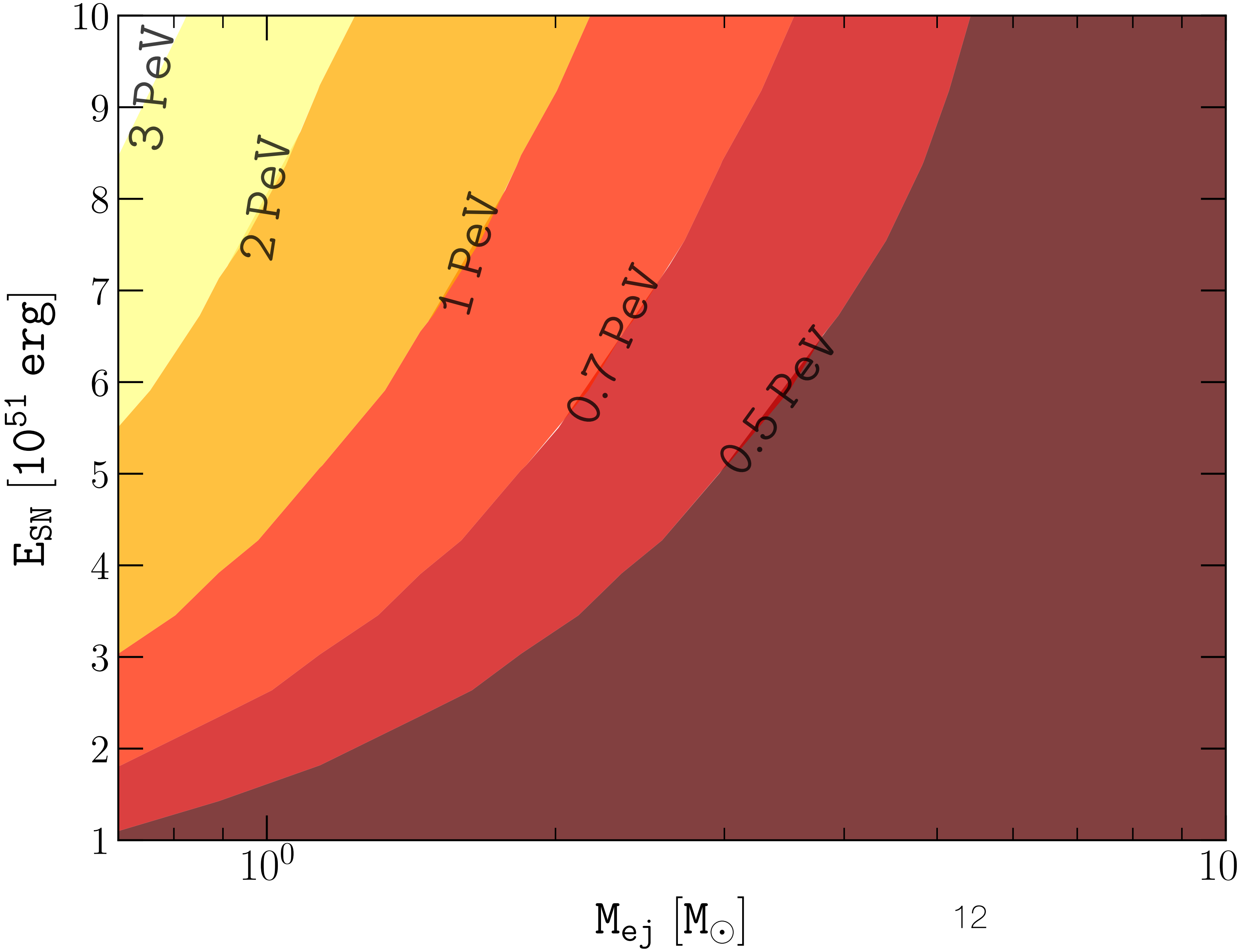
$$\dot{M}_{\rm MS}, u_{\rm MS}, n_0, M_{\rm ej},$$

Non-resonant streaming of CRs

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

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

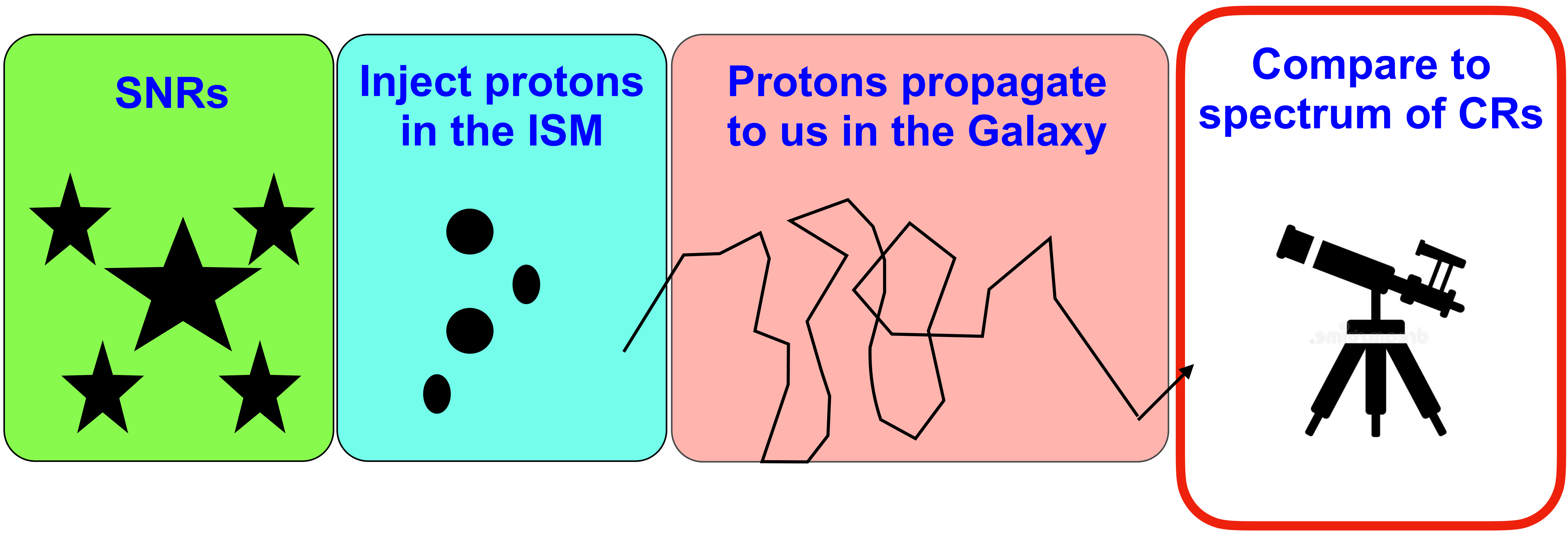
Growth rate of the non-resonant streaming instability



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

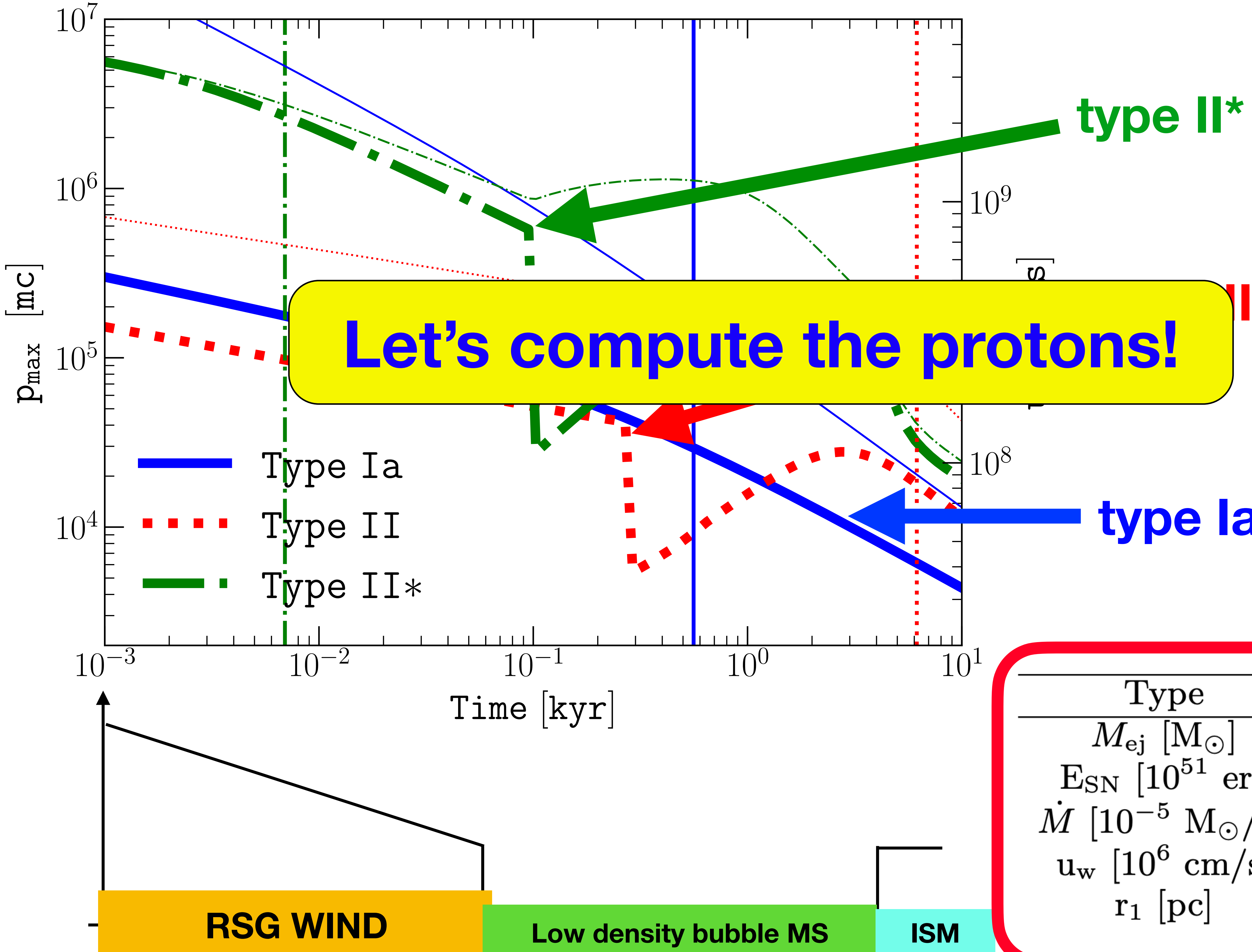
$$\xi = 0.1$$

Protons from SNRs?



PC, Blasi, Amato 2020

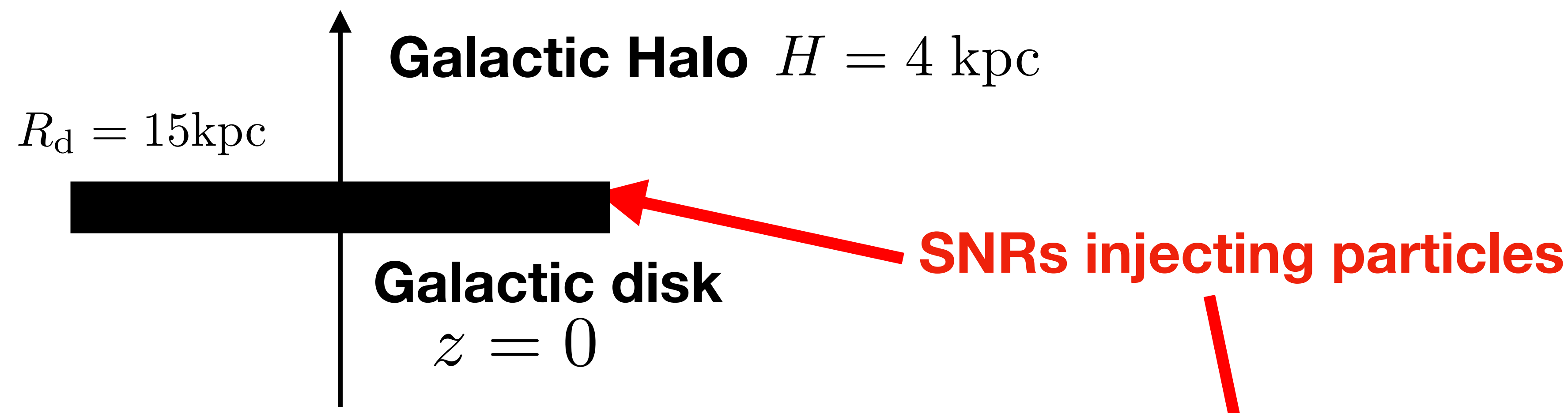
Type Ia, type II, type II*



Let's compute the protons!

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

Protons after propagation in the Galaxy



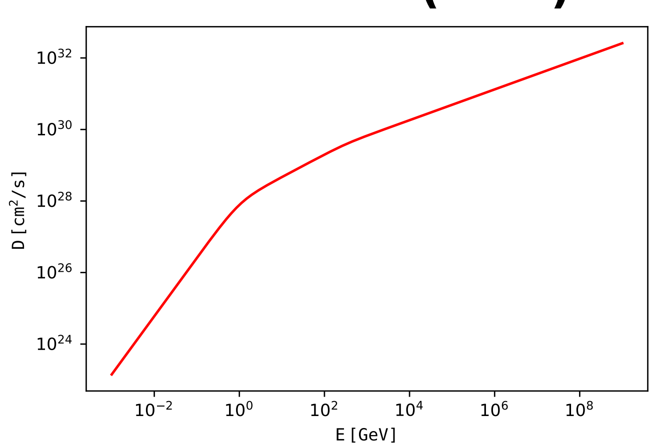
1D Galactic transport

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

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

$$D(p) = D_0 \frac{v(p)}{c}\frac{(p/mc)^\delta}{\left[1+(p/p_\mathrm{b})^{\Delta\delta/r}\right]^r}$$

In agreement with AMS-02 measurements
Evoli (2019)



Trapped

$$q_\mathrm{acc}(p)dp = \frac{\nu_\mathrm{SN}}{\pi R_\mathrm{d}^2}\int_{t_0}^{T_\mathrm{SN}} dt\frac{4\pi}{\sigma}r_\mathrm{sh}^2(t)u_\mathrm{sh}(t)f_0(p',t)dp'$$

Escaping

$$q_\mathrm{esc}(p) = \frac{\nu_\mathrm{SN}}{\pi R_\mathrm{d}^2}\int_{t_0}^{T_\mathrm{SN}} dt\frac{4\pi}{\sigma}r_\mathrm{sh}^2(t)u_\mathrm{sh}(t)f_0(p,t)\delta(p,p_\mathrm{max}(t))$$

Protons from supernova remnants

List of parameters:

$\dot{M}_{\rm wind}, u_{\rm wind}, E_{\rm SN}, M_{\rm ej}$

$\xi_{\rm CR}, \nu_{\rm SN}$

Injection from SNRs

Galactic dimensions

Diffusion coef

$H, R_{\rm d}, h, D, n_0$

Transport

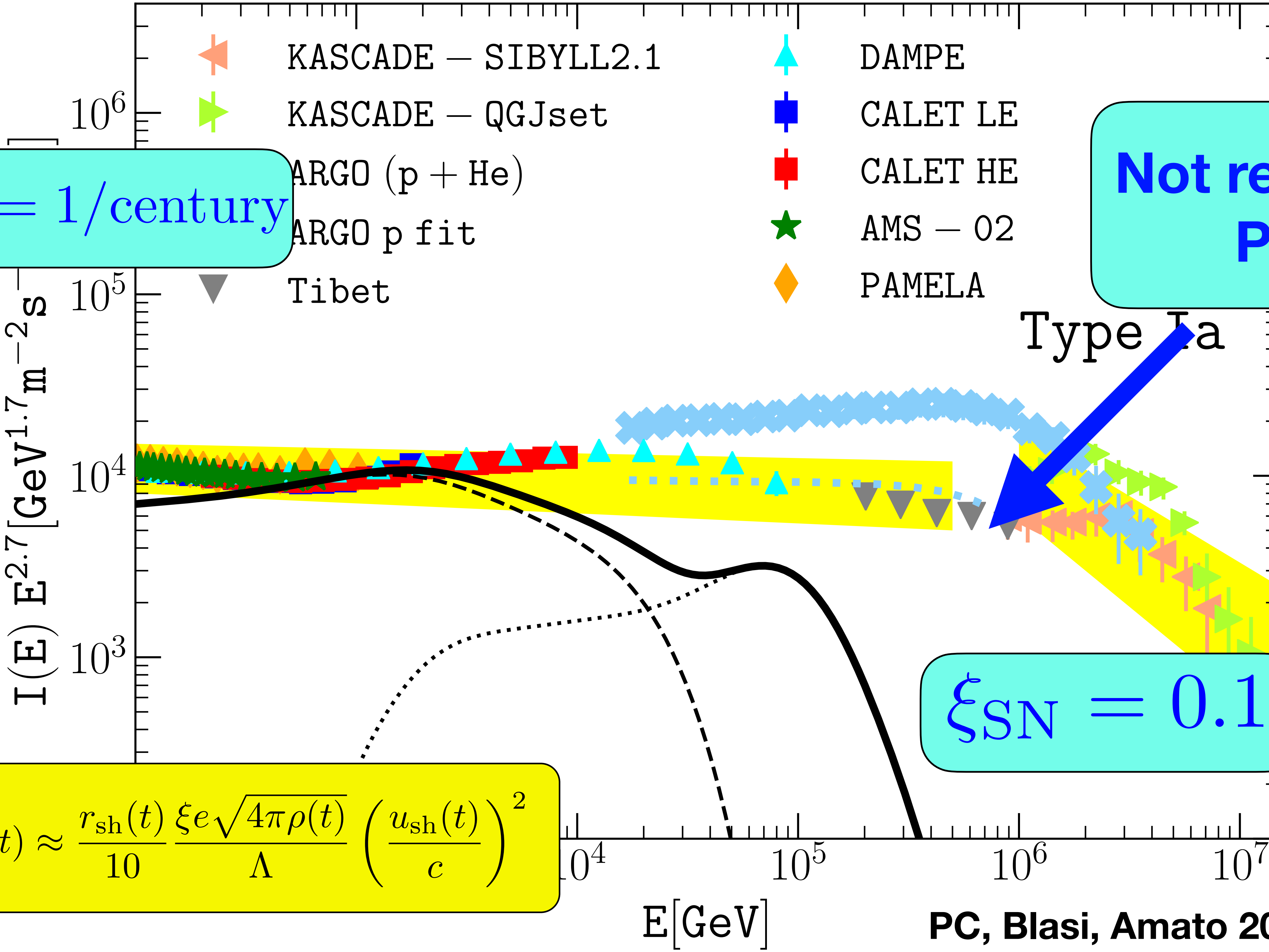
Rate of SNe

Efficiency of particle acceleration

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

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

Protons from type Ia



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

Not reaching PeV

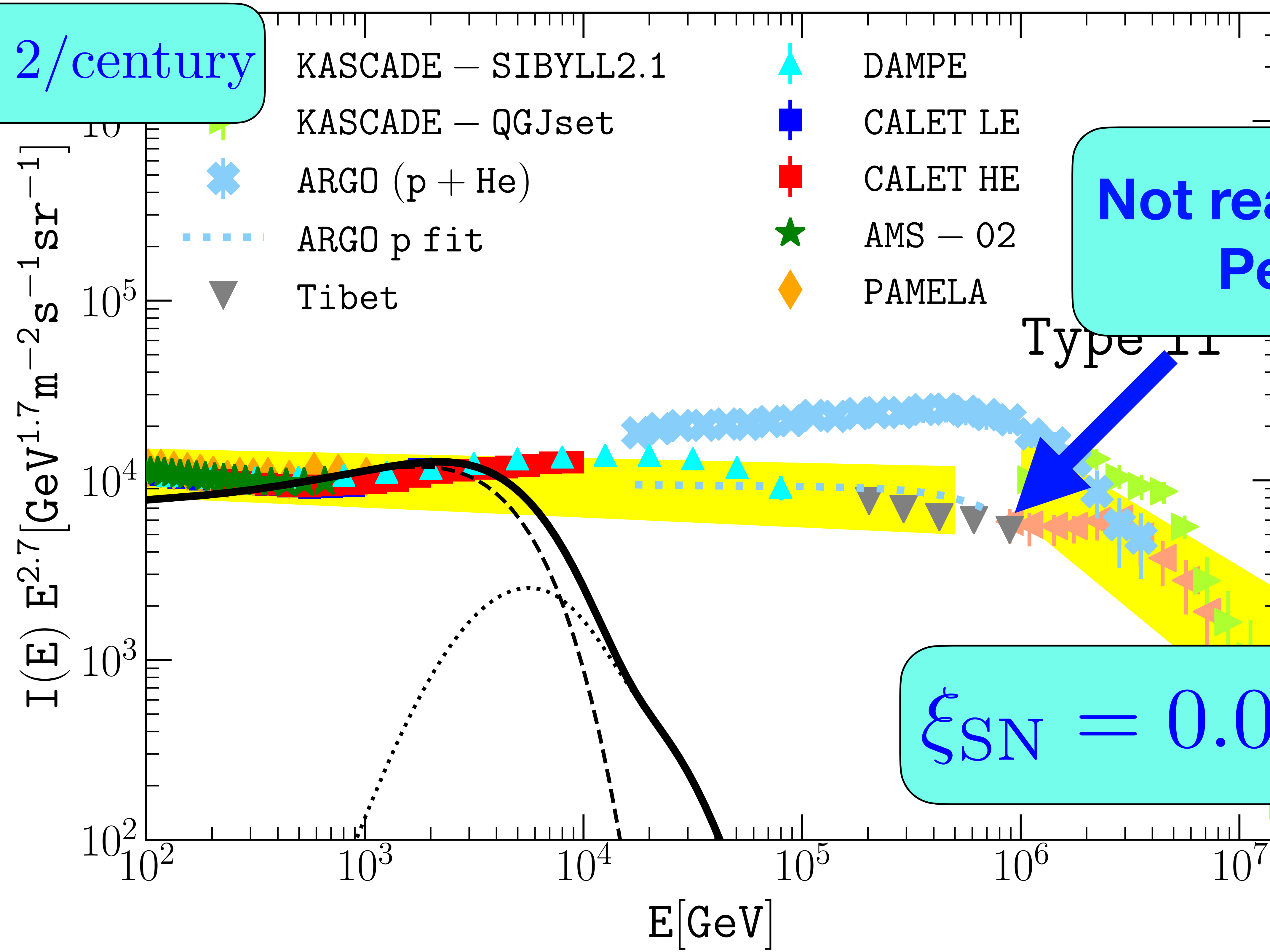
$\xi_{\mathrm{SN}} = 0.1$

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

PC, Blasi, Amato 2020

Protons from type II

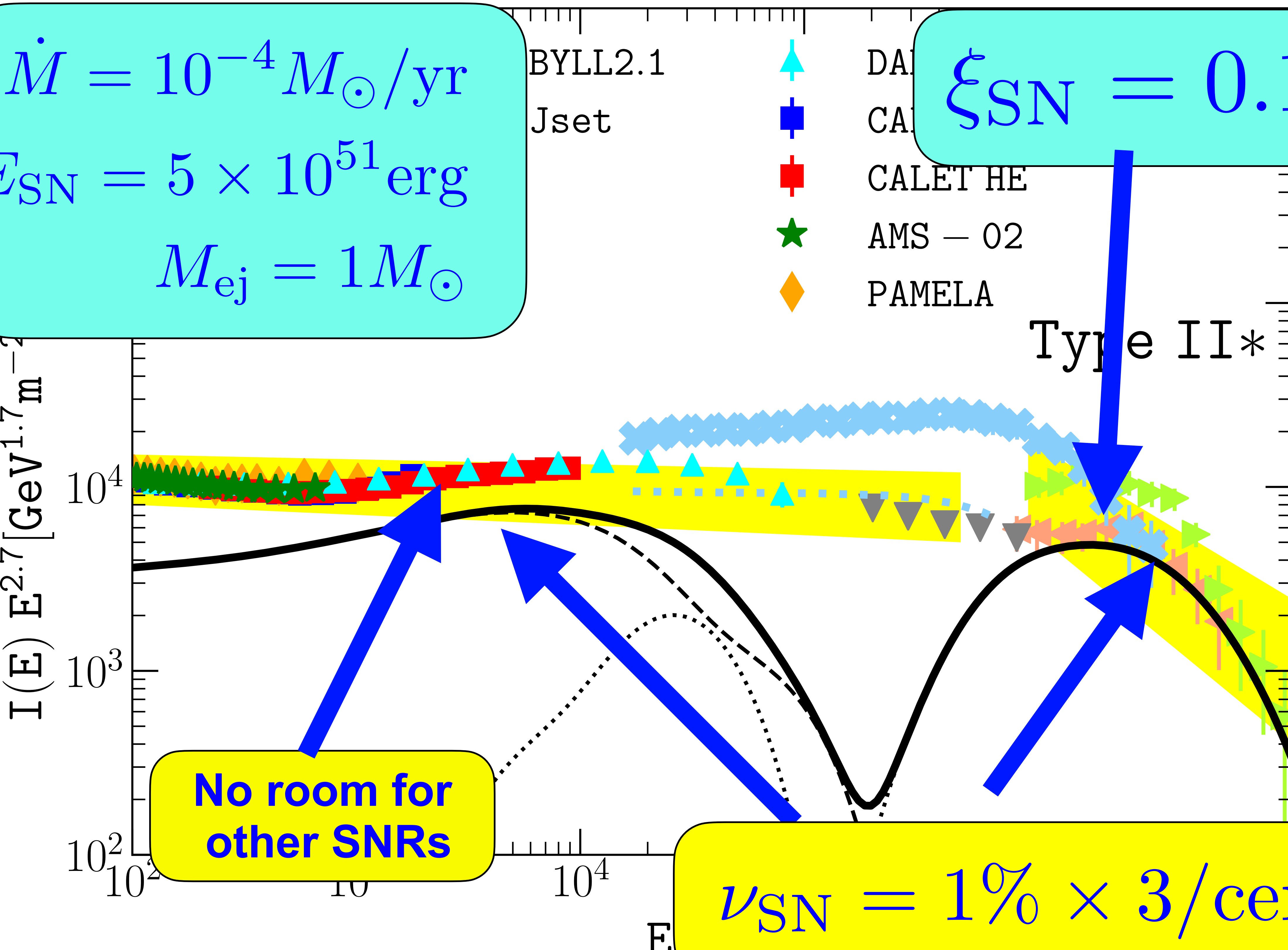
$\nu_{\text{II}} = 2/\text{century}$



Not reaching PeV

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

Protons from type II*



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

$E_{\mathrm{SN}} = 5 \times 10^{51}\mathrm{erg}$

$M_{\mathrm{ej}} = 1 M_\odot$

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

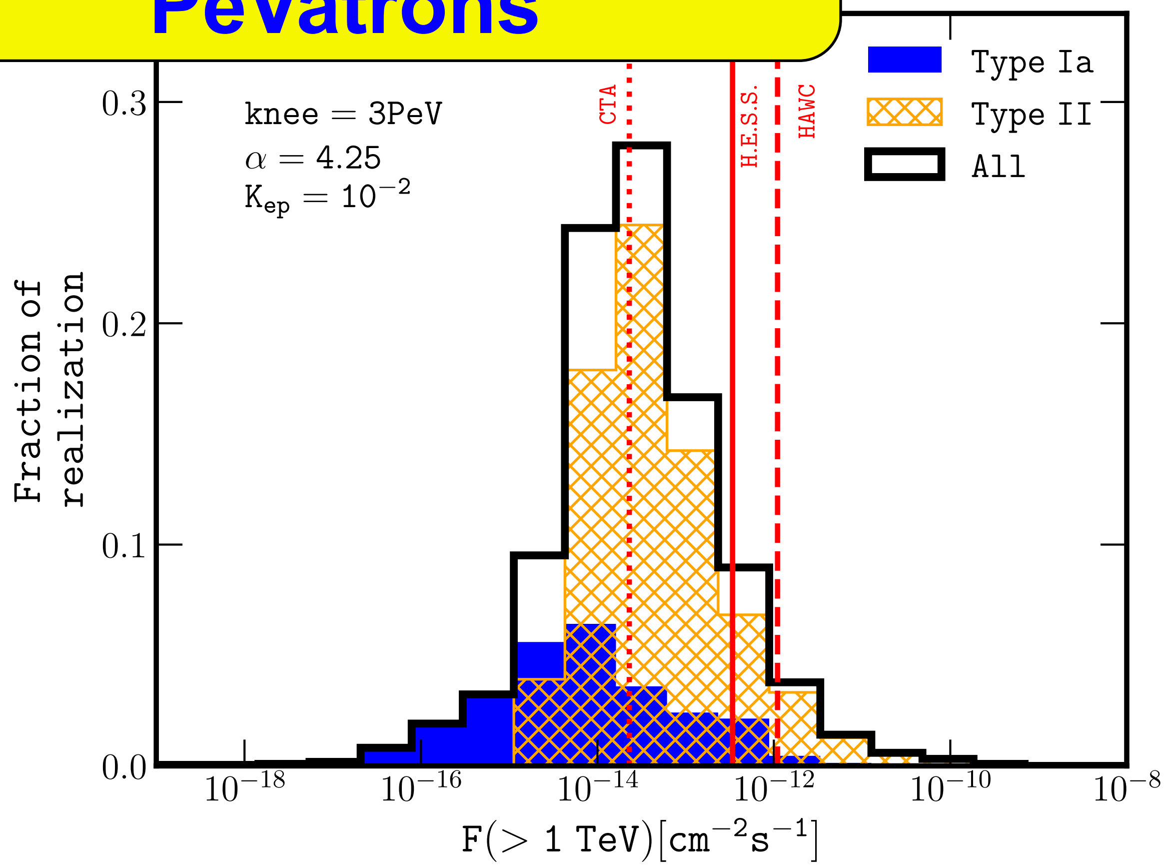
No room for other SNRs

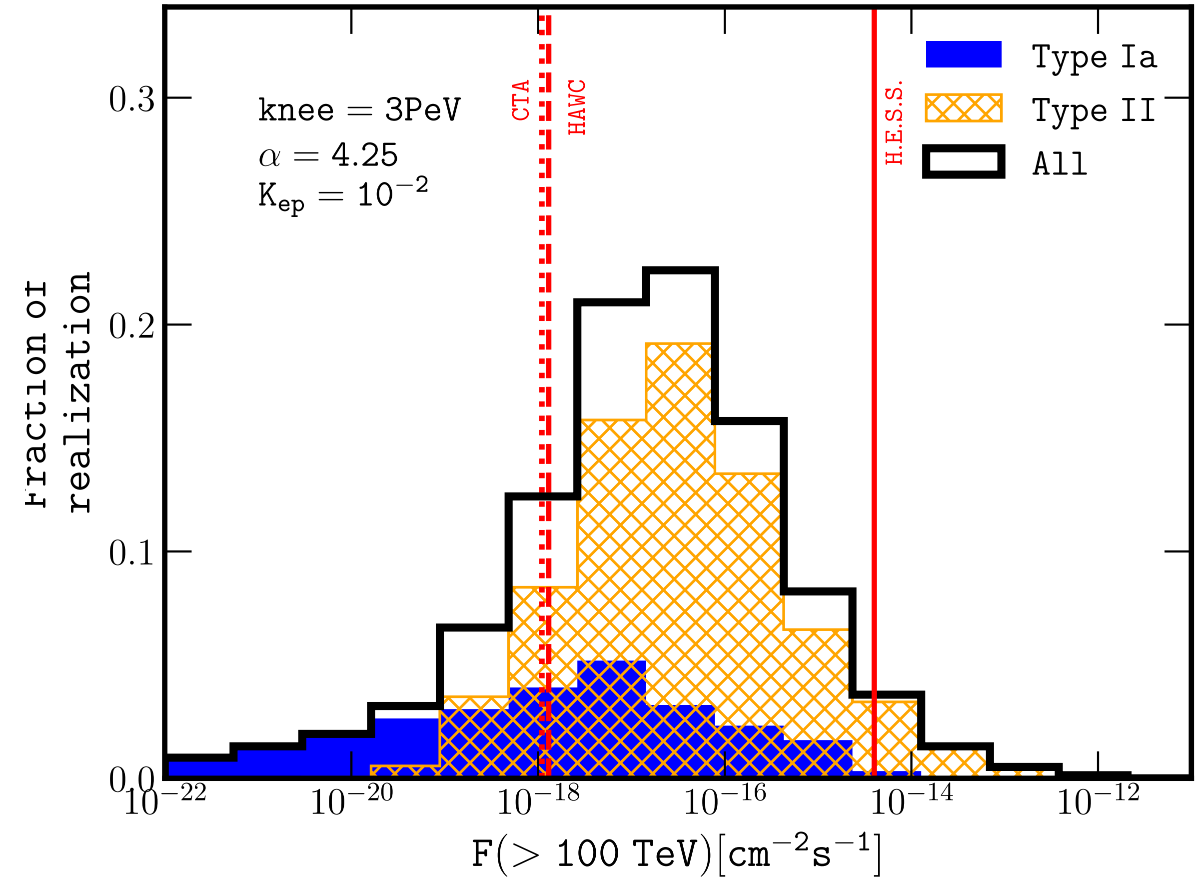
$\nu_{\mathrm{SN}} = 1\% \times 3/\mathrm{century}$

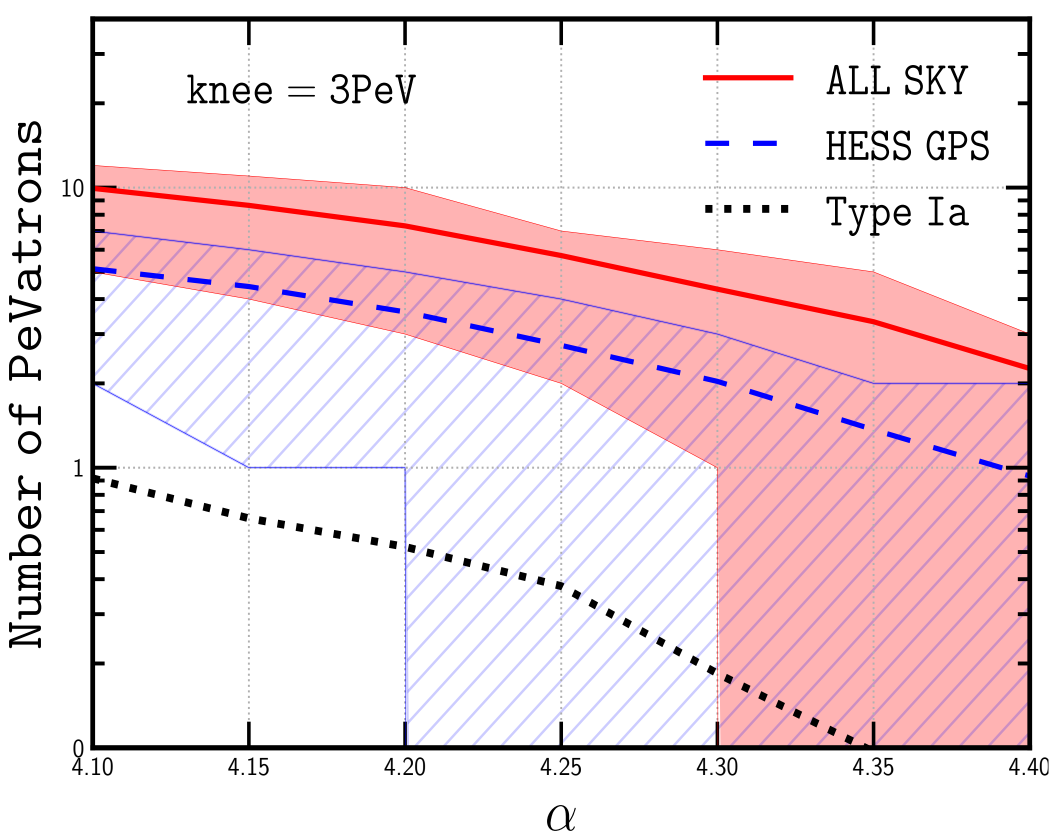
PC, Blasi, Amato 2020

Pevatrons with CTA

Assuming all SNRs are PeVatrons







If only Type II* are Pevatrons

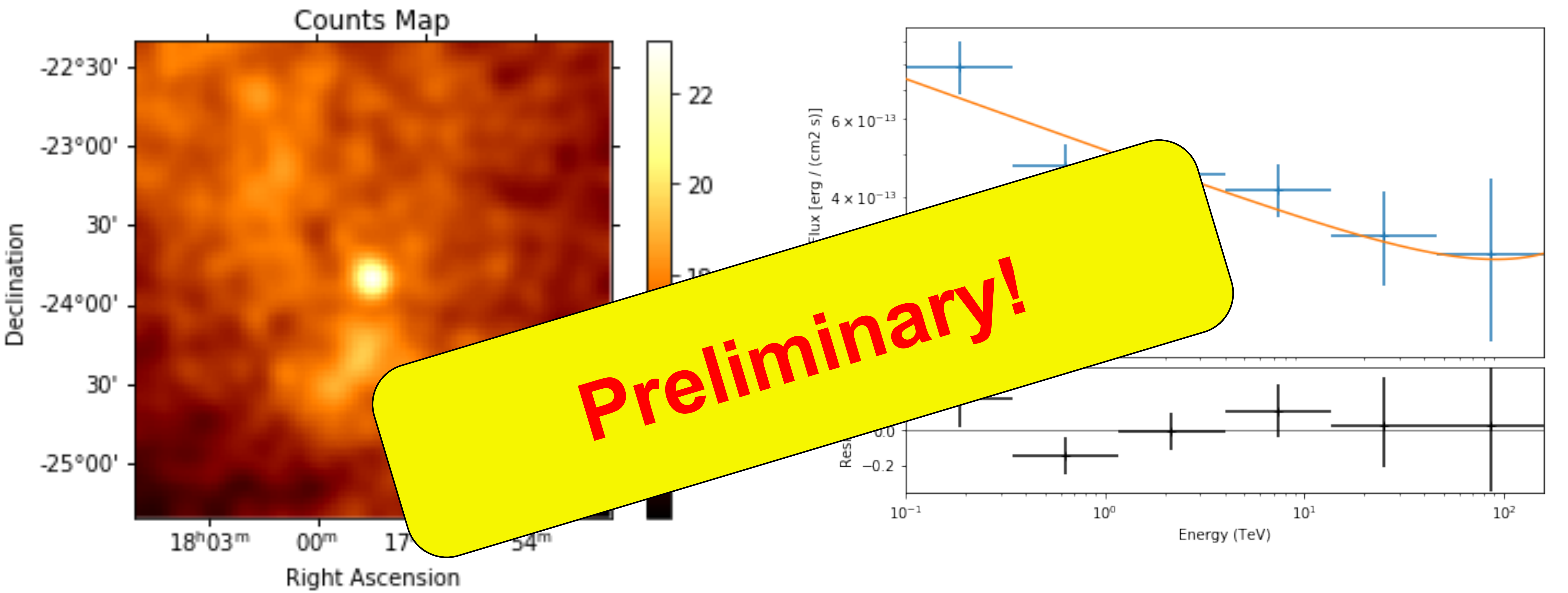
$$\nu_{\mathrm{SN}} = 1\% \times 3/\mathrm{century}$$

$$\rightarrow 0$$

PC, Blasi, Amato (Astro. Part. Phy. 2020)

PC, Gabici, Terrier, Humensky (MNRAS, 2018)

Pevatrons with CTA

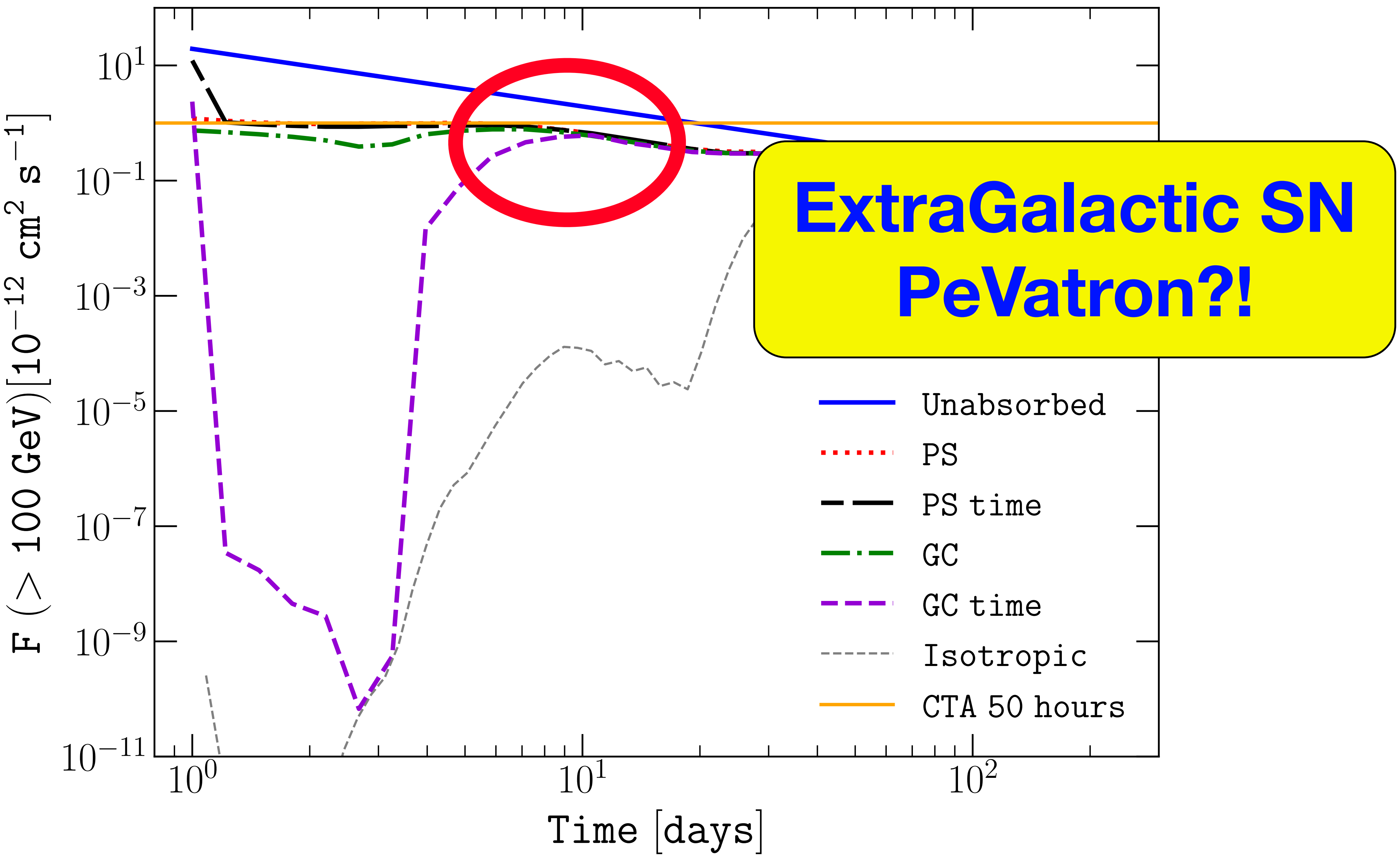


Pevatron working group: Acero, Anguner, Cassol, Costantini, Giunti, Khelifi, Trichard, Verna, PC

CTA Consortium paper in preparation

Pevatrons with CTA

SN1993J Type IIb SN in M81 (3.6 Mpc) - ExtraGalactic SNe/SNRs?



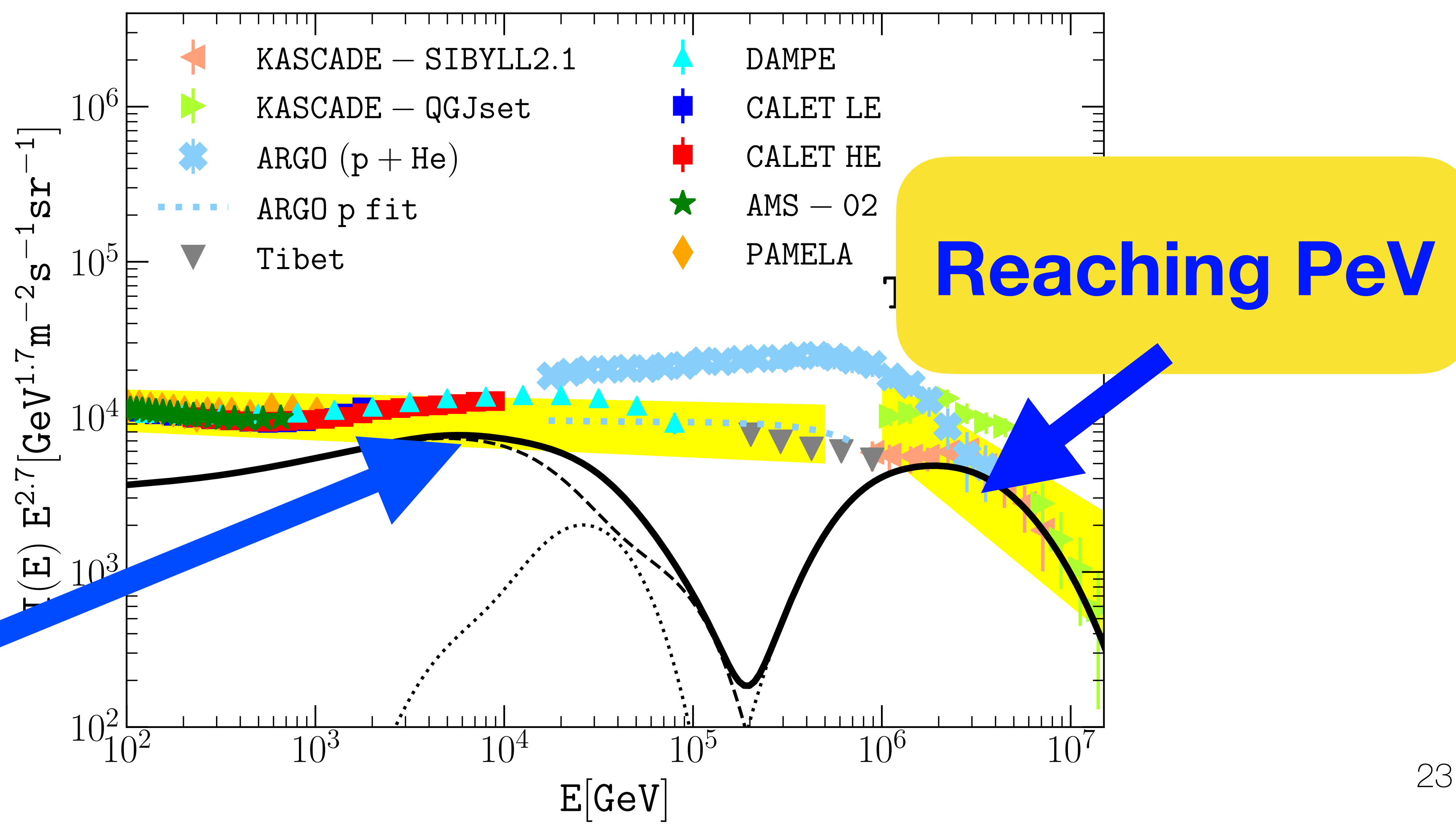
Pevatron working group: Acero, Anguner, Cassol, Costantini, Giunti, Khelifi, Trichard, Verna, PC

Cristofari, Marcowith, Renaud, Dwarkadas, Tatischeff, MNRAS (2020)

What does this mean?

MAYBE:

1. **SNRs are OK but we won’t see any PeVatrons with CTA**
2. **Another instability (not Bell) comes into play**
3. **Strong temporal dependance on one/several parameters**
4. **SNRs are not dominant sources of CRs up to the knee (role of other objects/stellar clusters/ massive stars/?)**



Mimicking bump?

Conclusions : the hunt for pevatrons, closing the SNR case?

SNR PeVatrons with gamma-ray instruments (HAWC, H.E.S.S, CTA, LHAASO, SWGO)

Not detected

- That's OK
- What role for SNRs?
- Really PeV? Knee? Composition?
- DAMPE bump?

Detected

- What mechanism? (Bell?)
- xi_CR/ Mdot function of time?
- When? How many?
- Other Astrophysical objects?

H.E.S.S. J1745-290

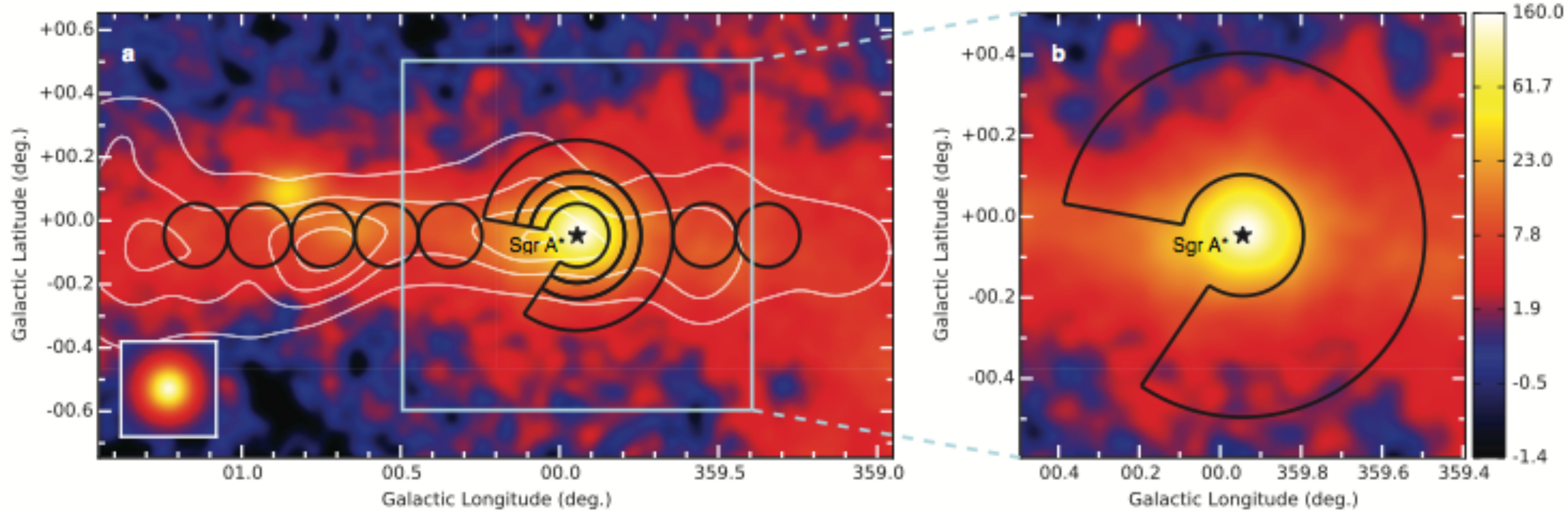
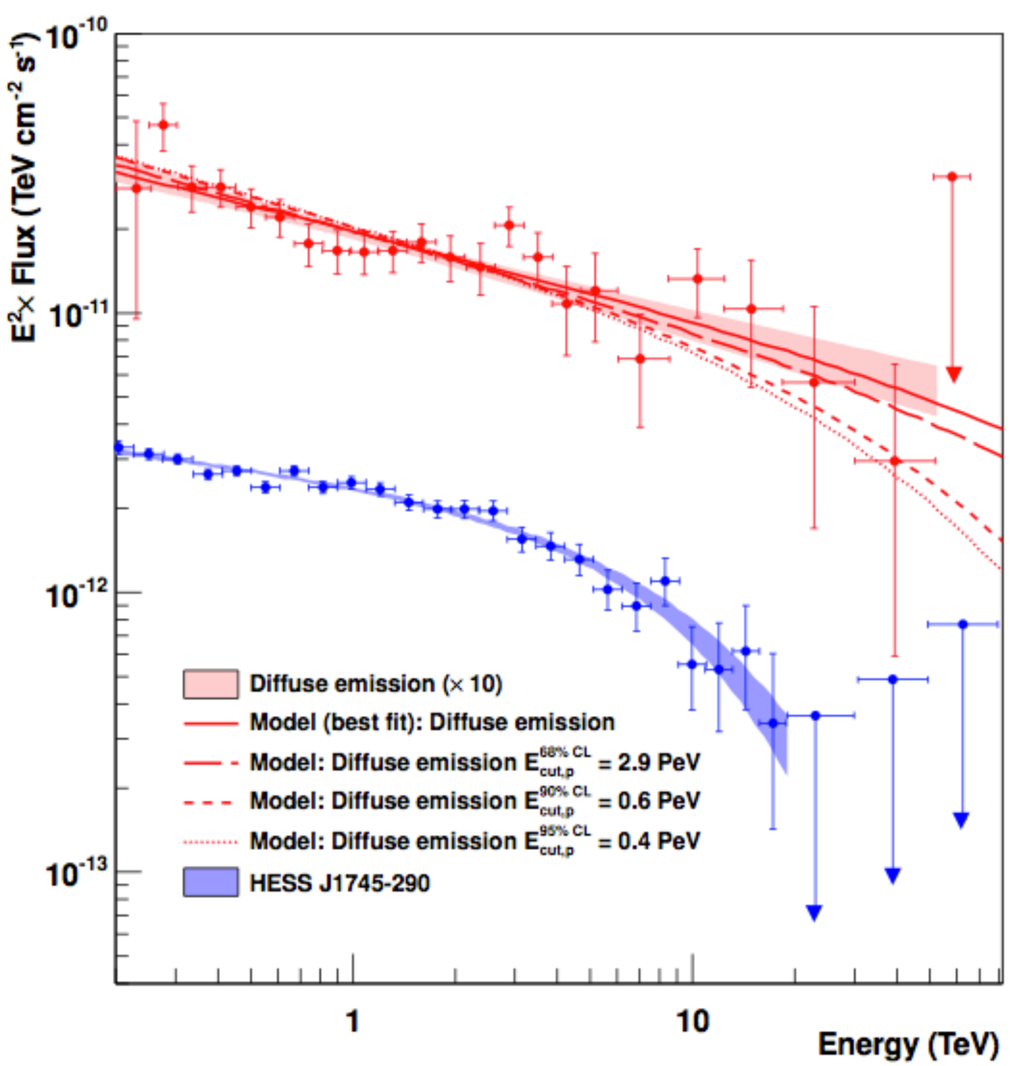
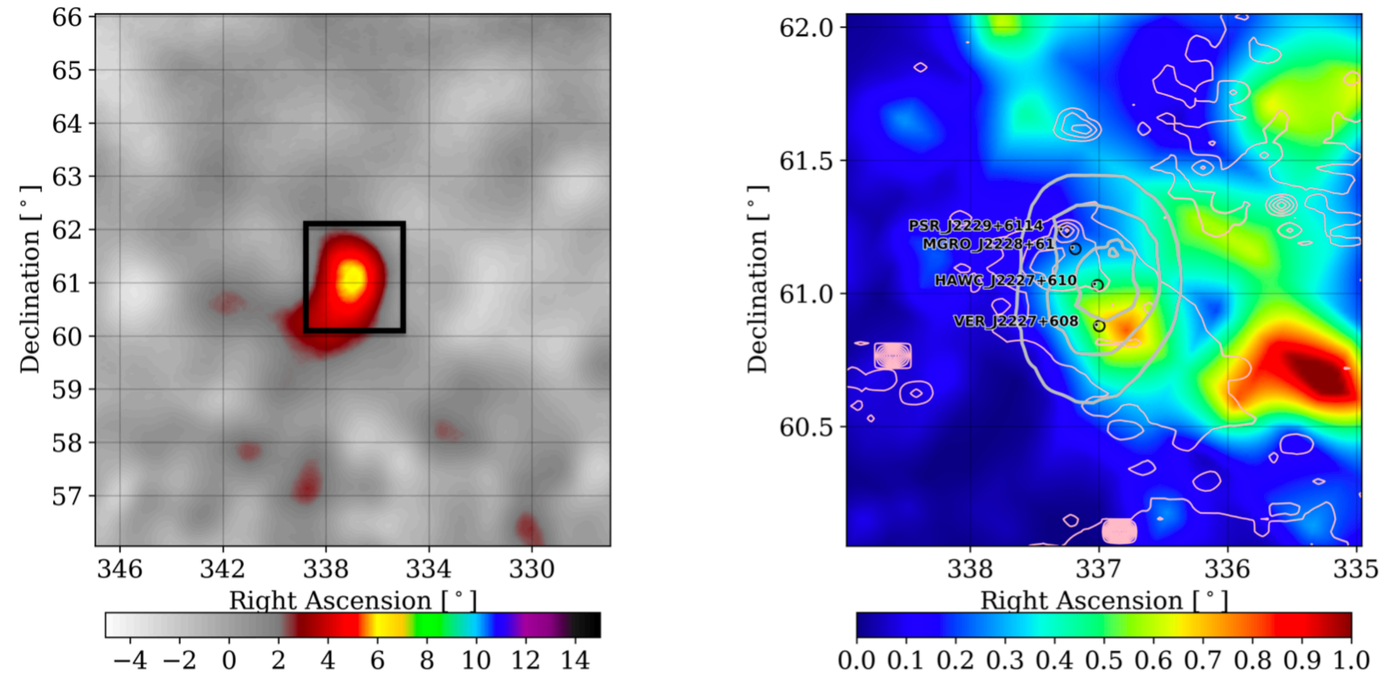


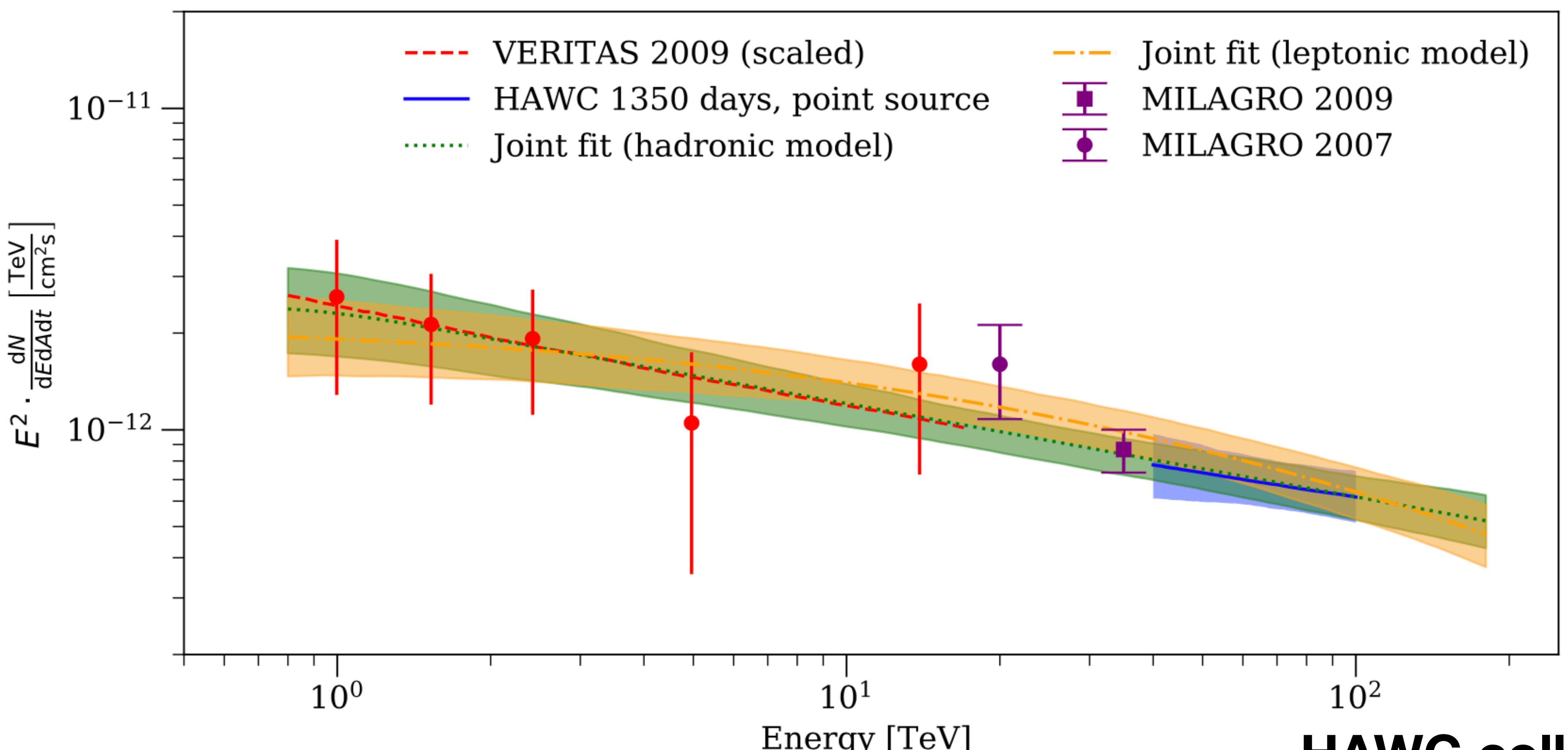
Figure 1: **VHE γ-ray image of the Galactic Centre region.** The colour scale indicates counts per 0.02° ×0.02° pixel.



H.E.S.S. collaboration (Nature, 2016)

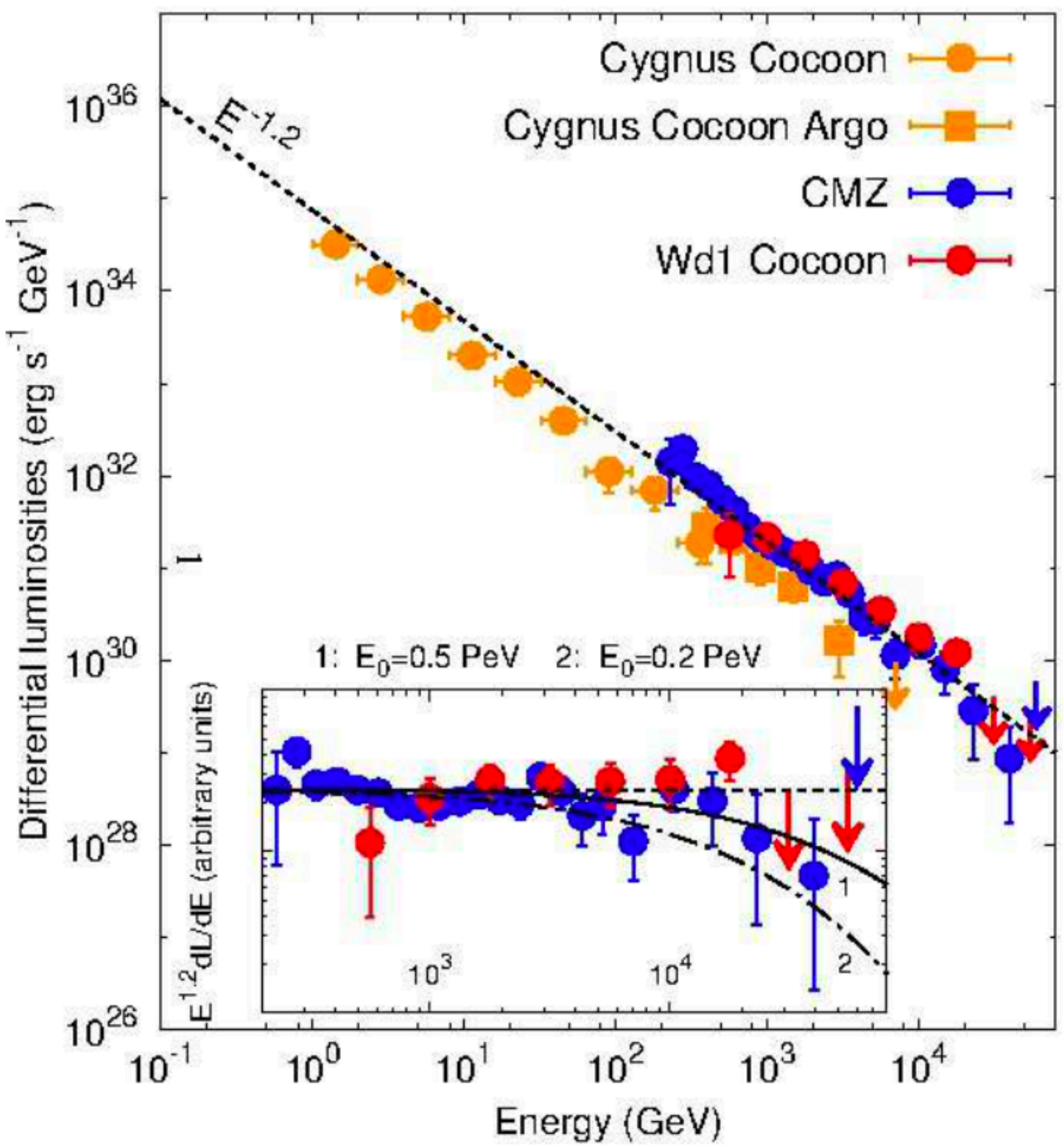
HAWC J2227+610 (associated with SNR G106.3+2.7?)

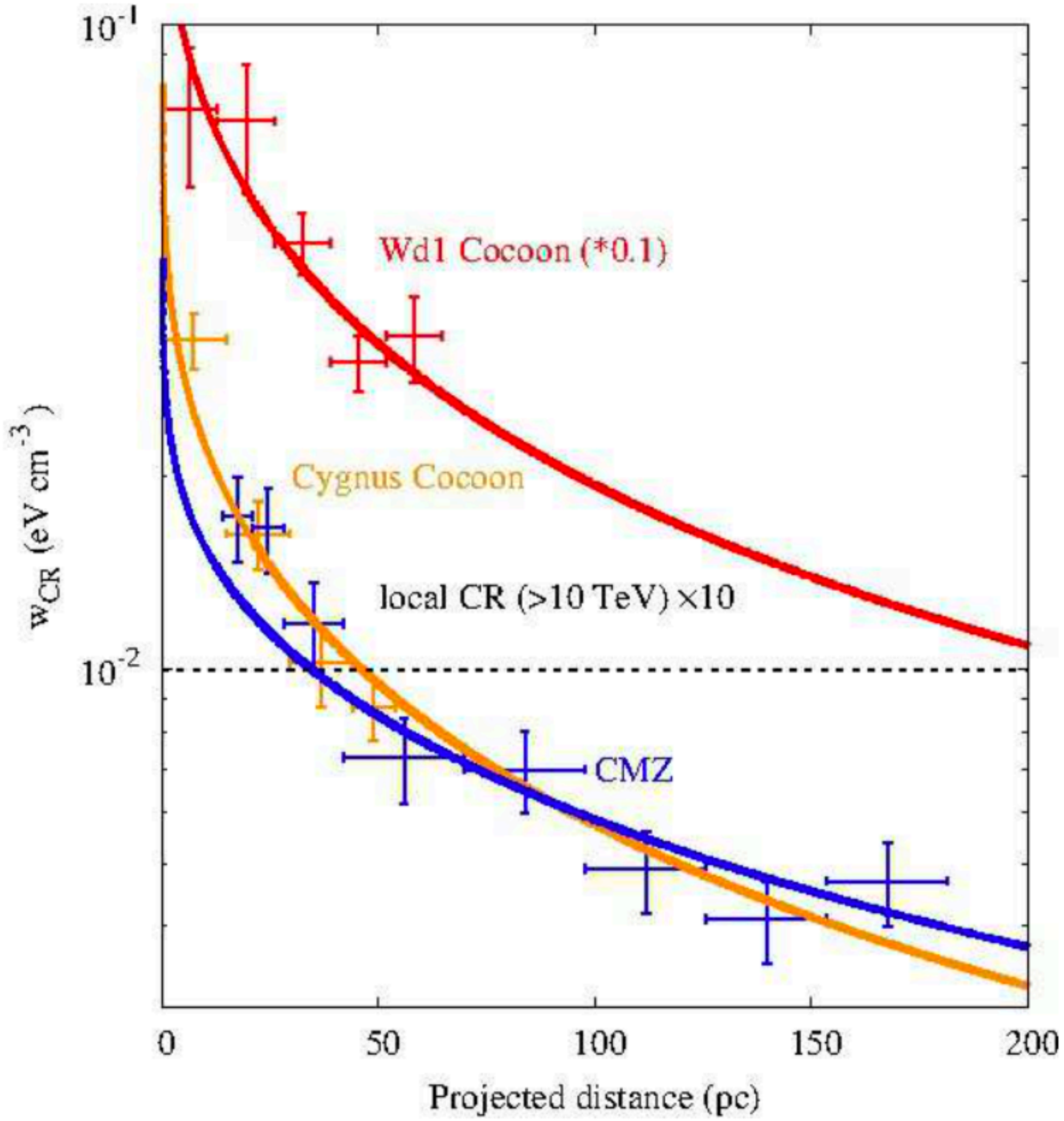




HAWC collaboration ApJ 2020

Massive stars as CR factories?





Aharonian et al. (Nature Astro. 2019)

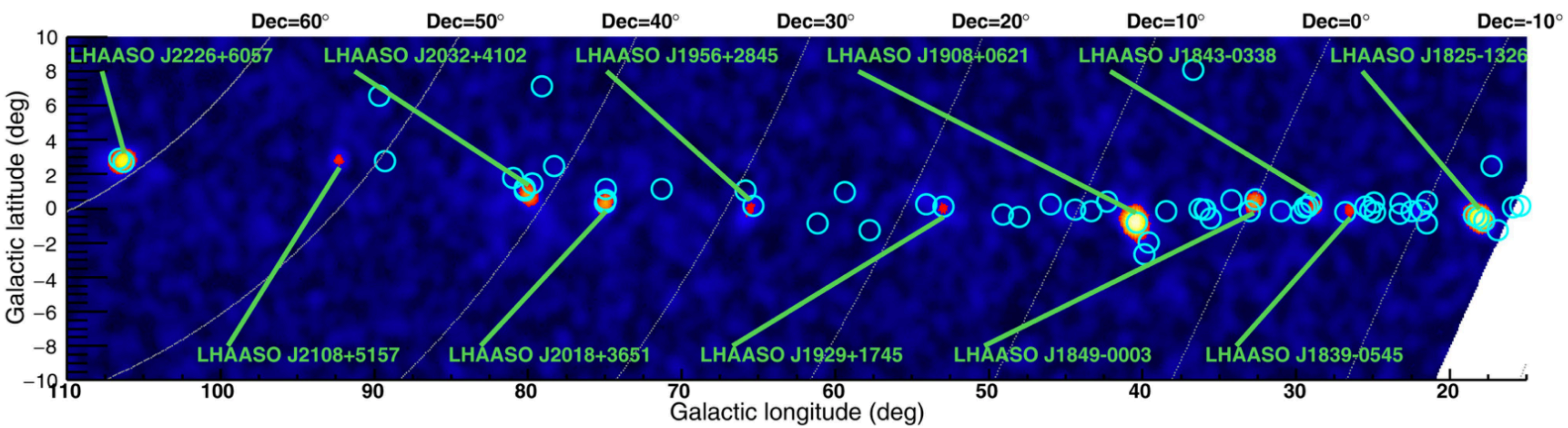
Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

https://doi.org/10.1038/s41586-021-03498-z

Received: 21 October 2020

Accepted: 26 March 2021

Published online: 17 May 2021



Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

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

Very uncertain nature of these sources?

Proton acceleration? Electron acceleration?

Not many SNRs in this list!

Conclusions : the hunt for pevatrons, closing the SNR case?

SNR PeVatrons with gamma-ray instruments (HAWC, H.E.S.S, CTA, LHAASO, SWGO)

Not detected

- That’s OK
- What role for SNRs?
- Really PeV? Knee? Composition?
- DAMPE bump?

Detected

- What mechanism? (Bell?)
- xi_CR/ Mdot function of time?
- When? How many?
- Other Astrophysical objects?

pierre.cristofari@obspm.fr

PC, Blasi, Amato, Astro. Phy. , Dec. 2020
PC, Universe, review 2020