

The hunt for PeVatrons

10^{15} eV

Supernova remnants

Marseille CPPM

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The hunt for PeVatrons

10^{15} eV

Supernova remnants

Cristofari, Blasi, Amato, *Astro. Phys.*, 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 »

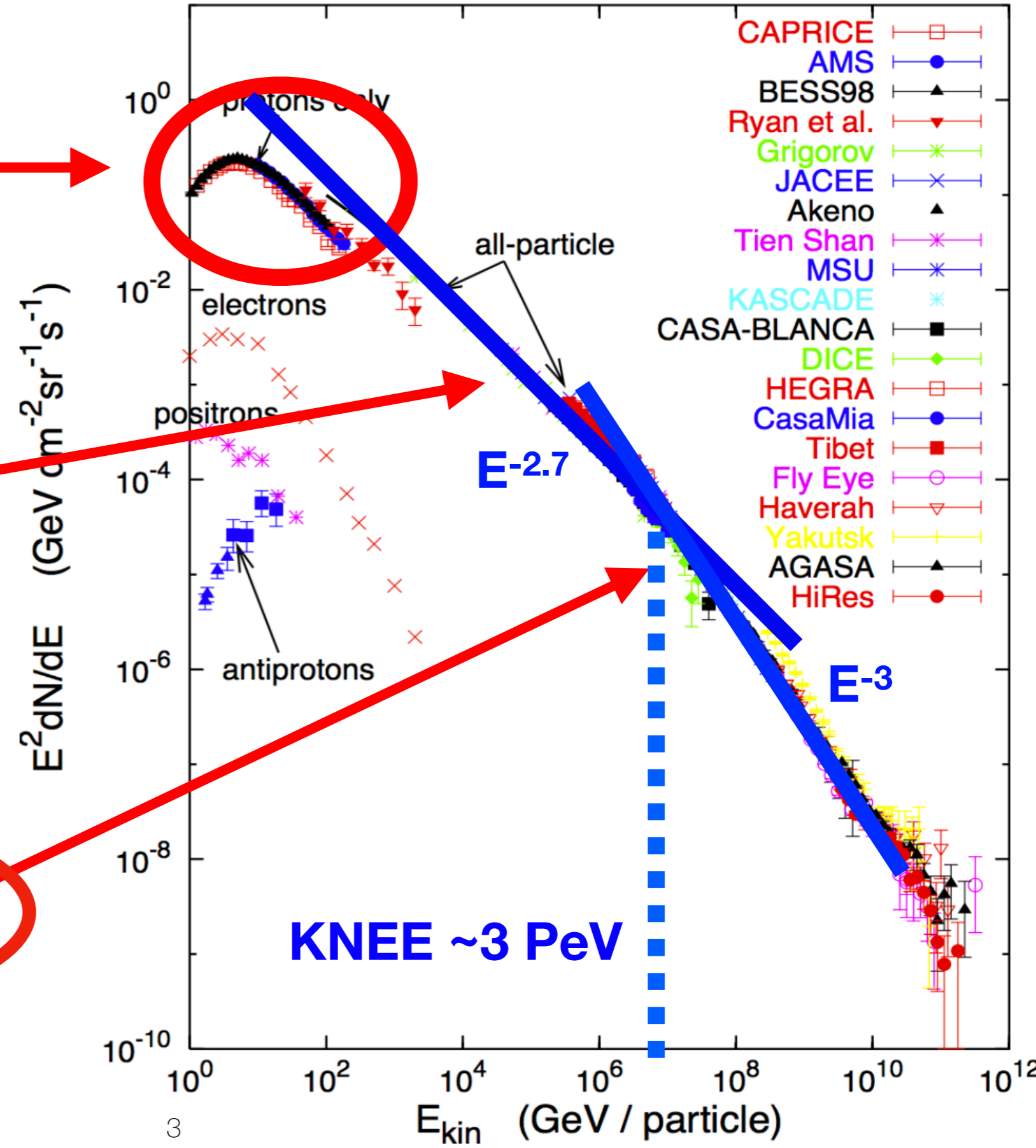


Why supernova remnants?

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

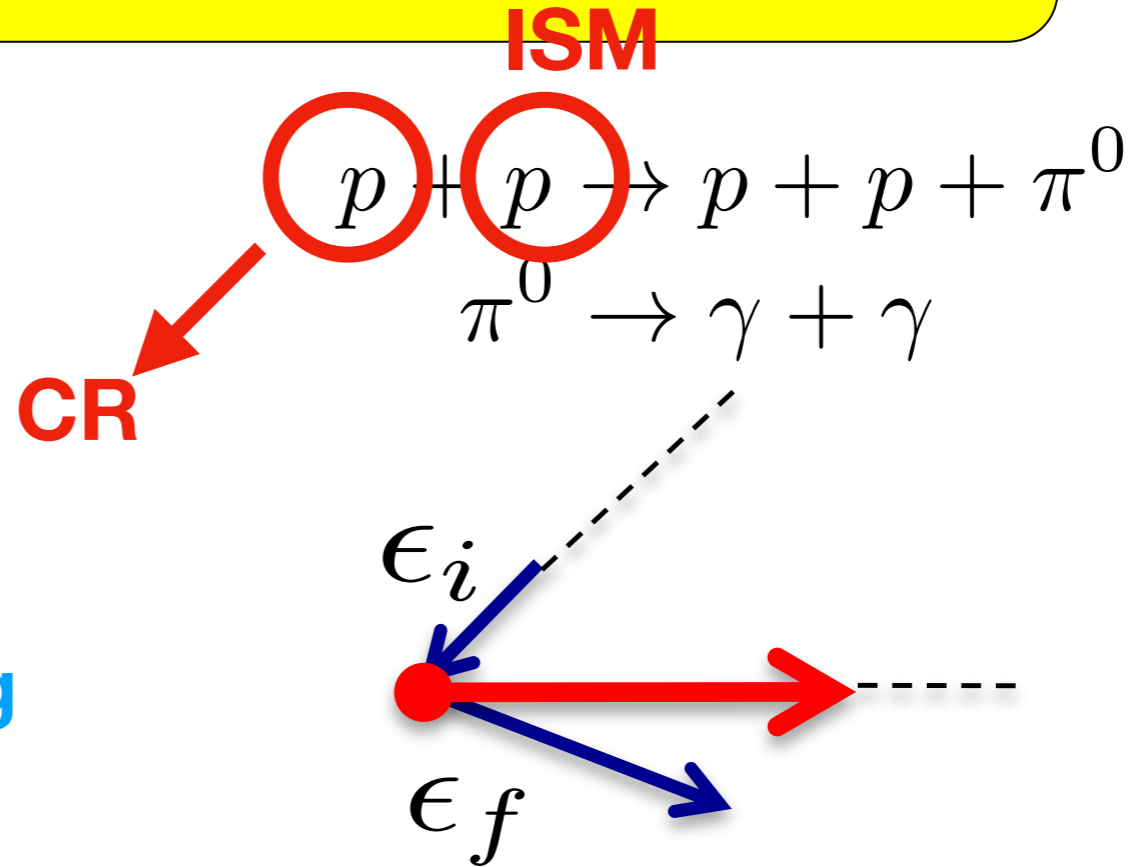
2. Slope $E^{-2.7}$
 Diffusive shock acceleration
 $E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$
 Injection Propagation

3. Magnetic field amplification - pevatrons!



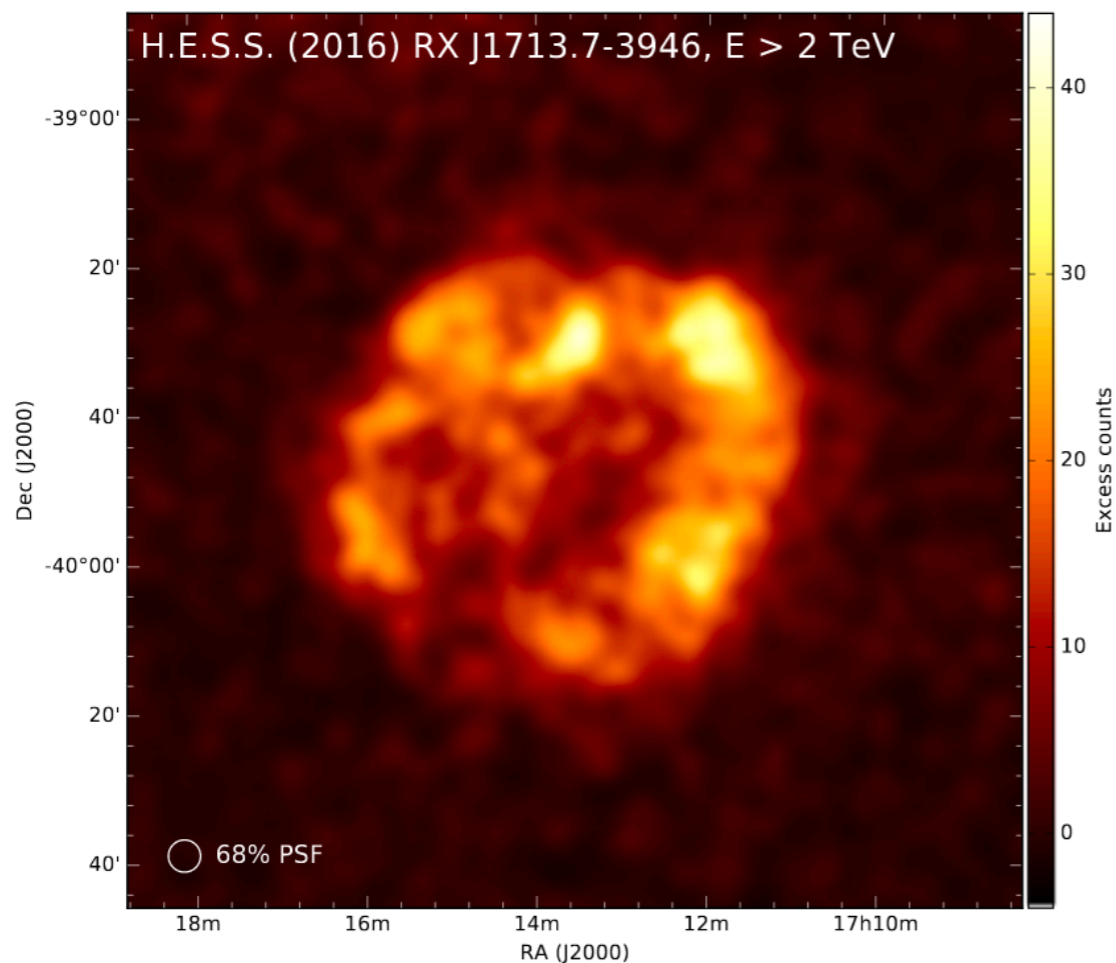
Gamma rays from SNRs

Hadronic interactions :
Pion decay



Leptonic interactions :
Inverse Compton scattering

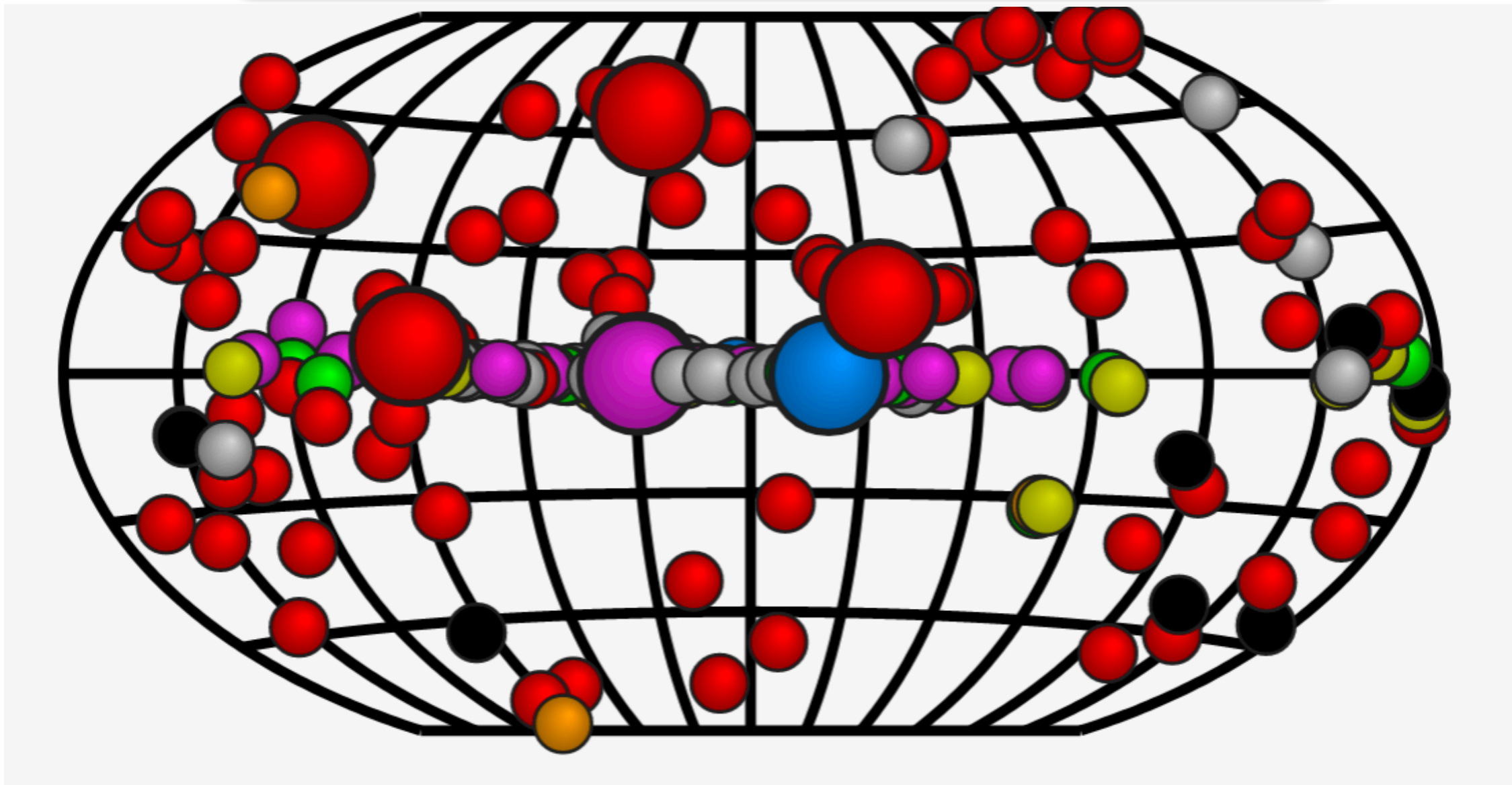
H.E.S.S. 2016



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

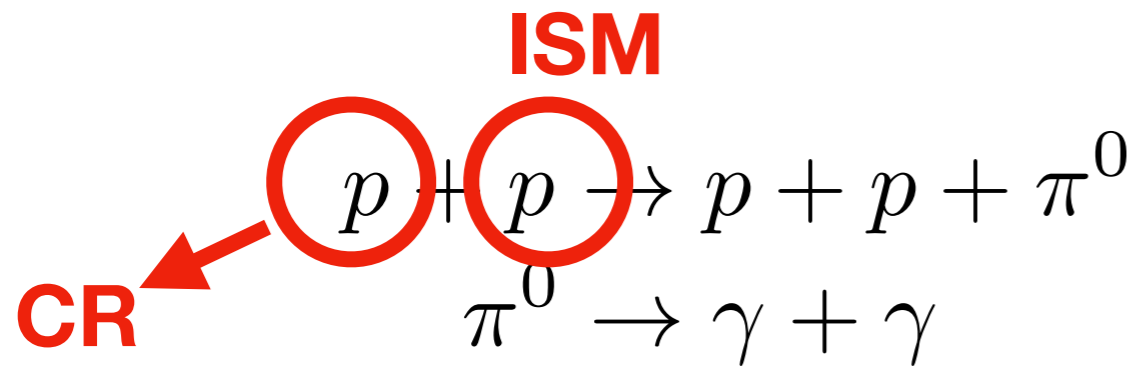
58 « SNRs »

12 Shells

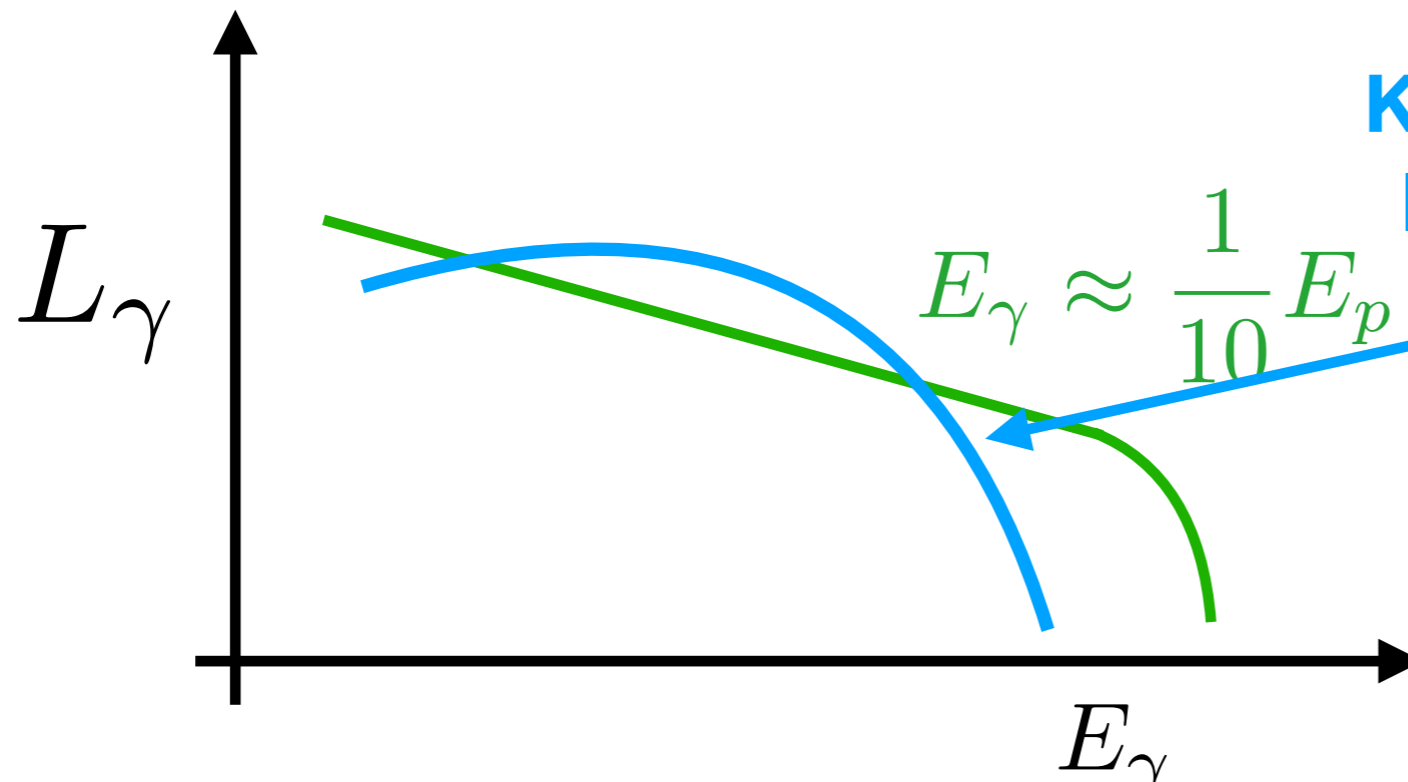
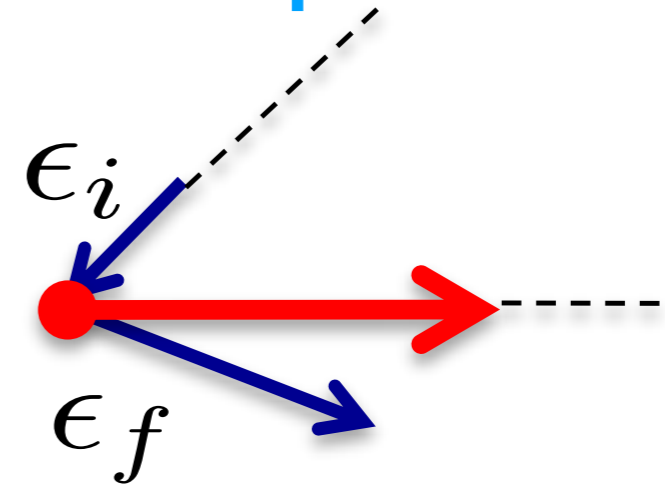
TeVCat (2021)

Gamma rays from SNRs

Hadronic interactions :
Pion decay



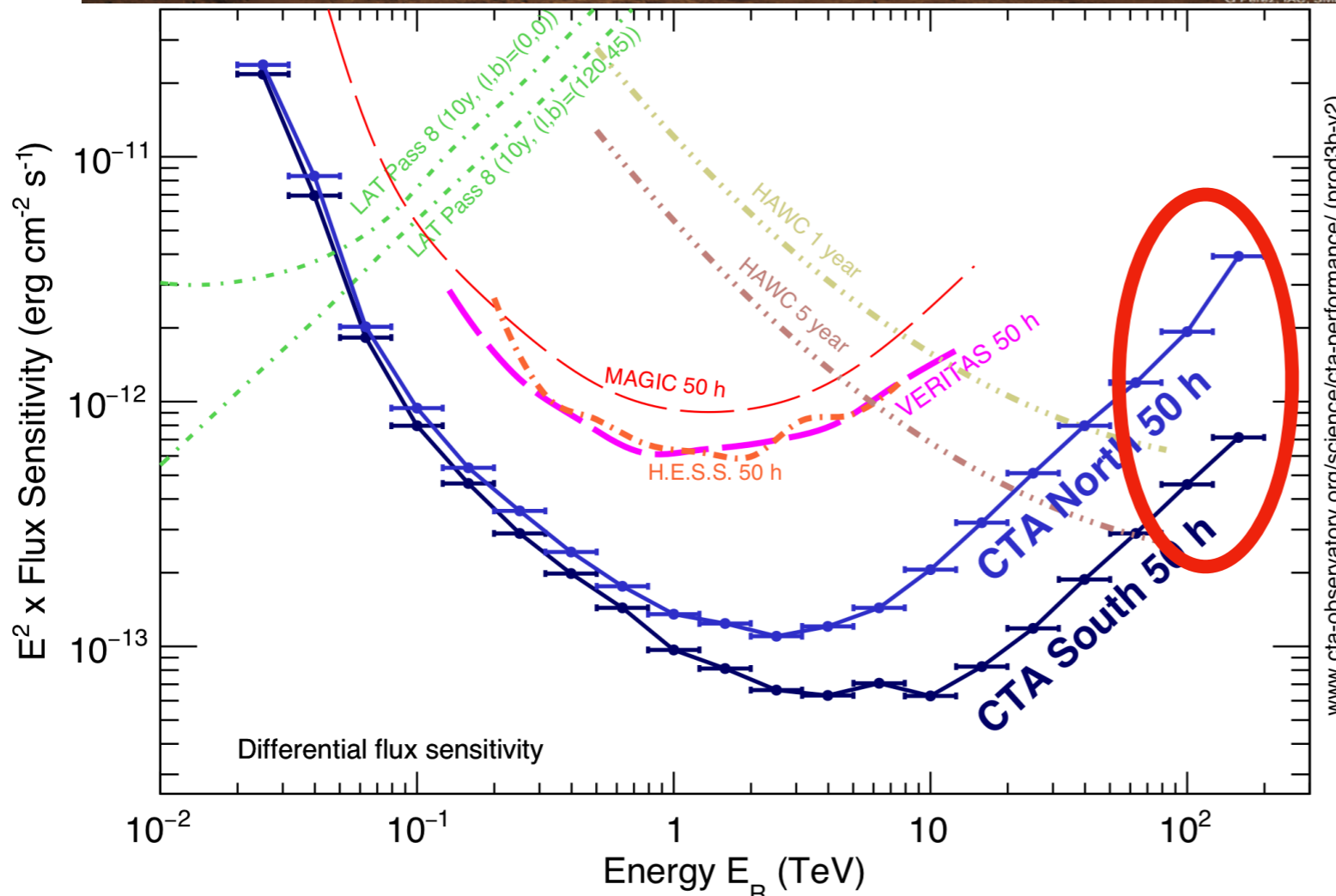
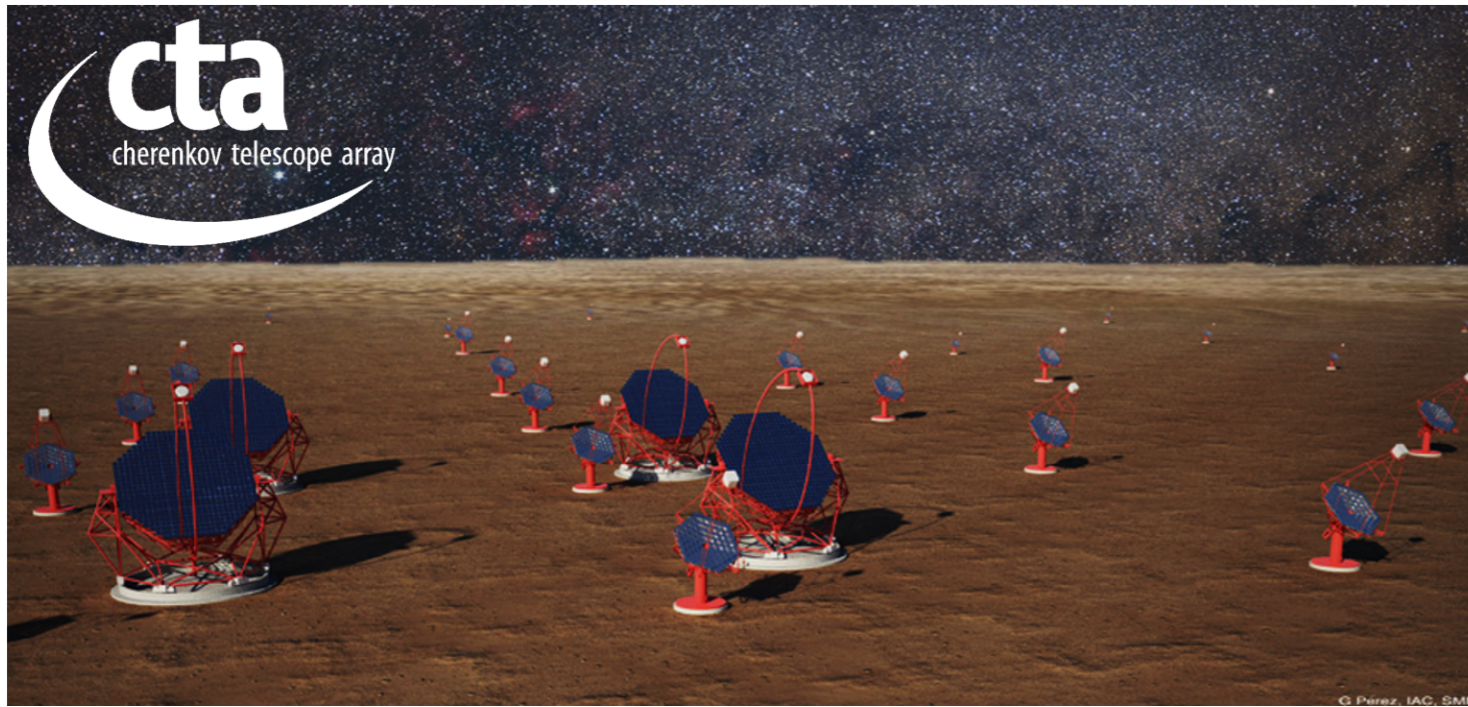
Leptonic interactions :
Inverse Compton scattering



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?

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

**Resonant
streaming of CRs
Skilling (1975)**

**Instability
density fluctuations
Giacolone & Jokipii (2007)**

**Acoustic instability
Drury & Falle (1983)**

....

**Non-resonant streaming
Bell (2004)**

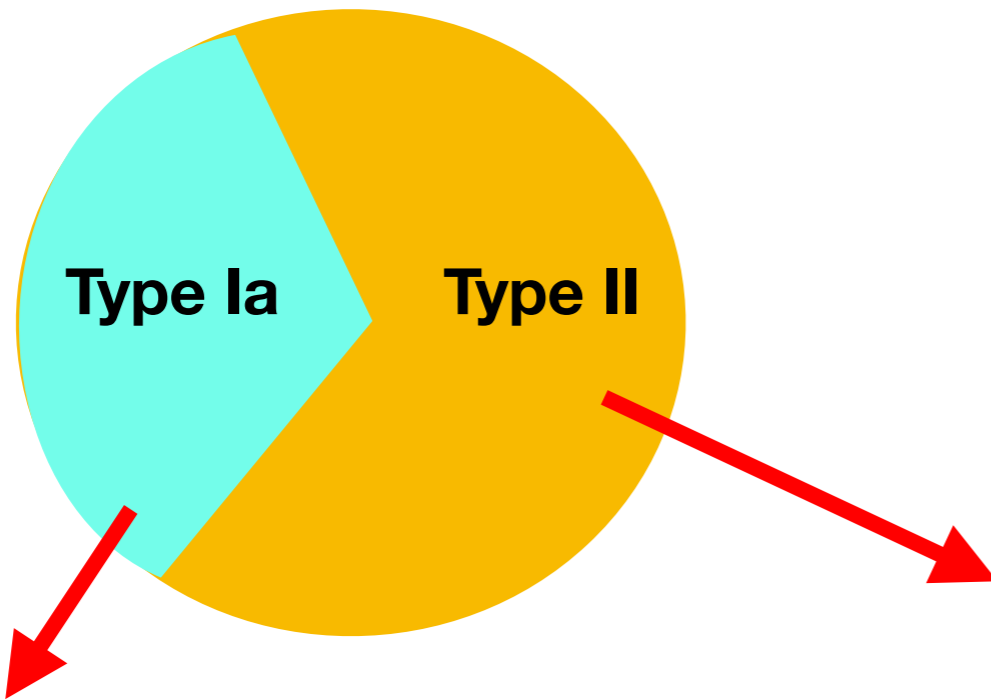
Non-resonant streaming of CRs

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

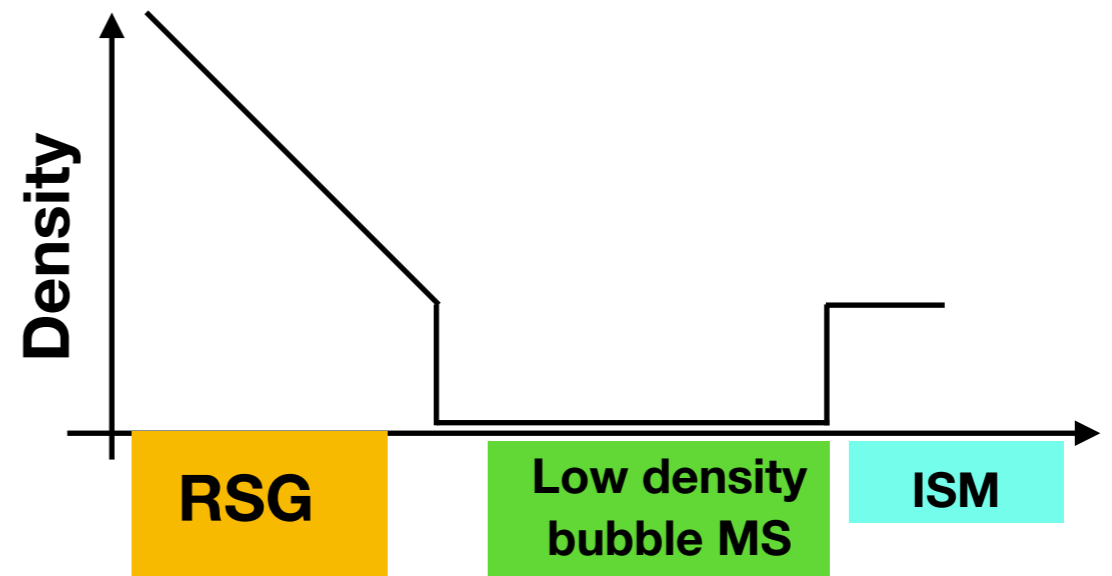
Growth rate of the non-resonant streaming instability

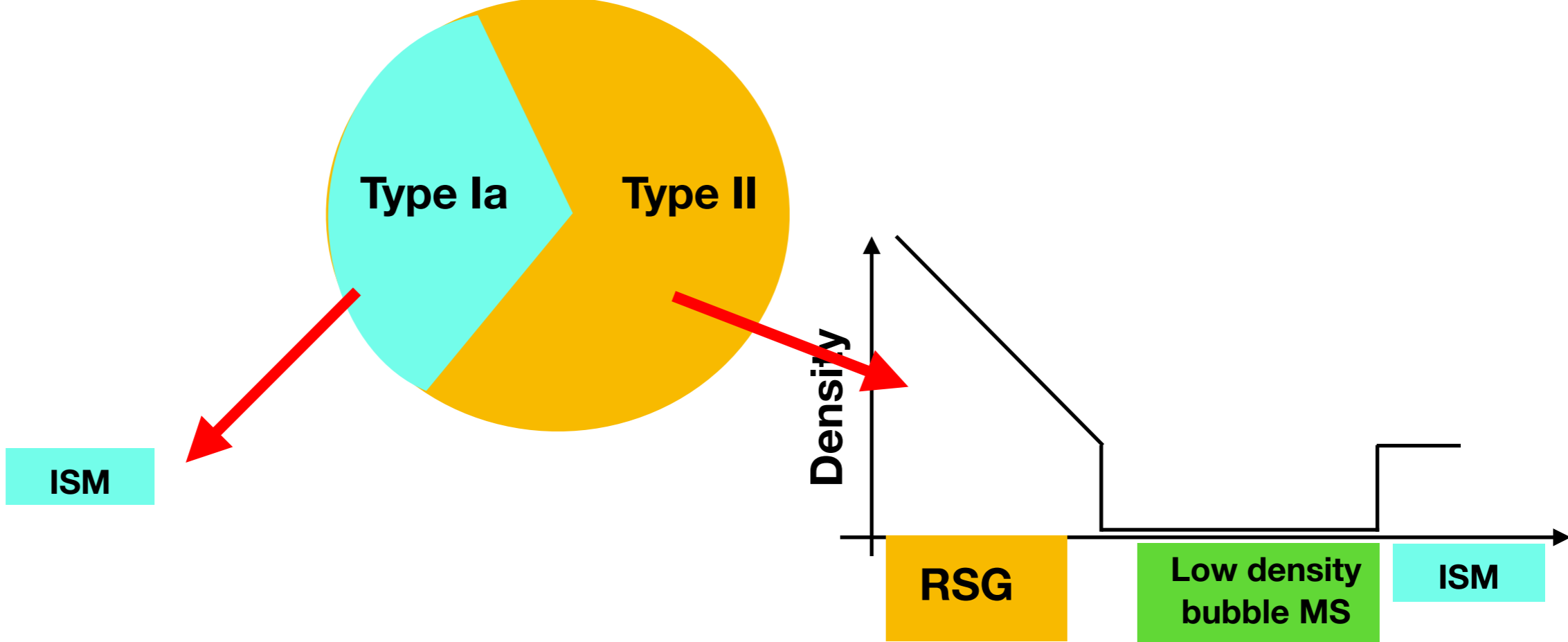
$$p_{\max}(t) \approx \frac{r_{\text{sh}}(t)}{10} \frac{\xi e \sqrt{4\pi\rho(t)}}{\Lambda} \left(\frac{u_{\text{sh}}(t)}{c} \right)^2$$

Different for different SNRs/SNe



ISM





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

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

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

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

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

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

Chevalier (1999) Tang (2017)

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

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

$$n_0$$

Ostriker & McKee (1988)
Thin shell approximation

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

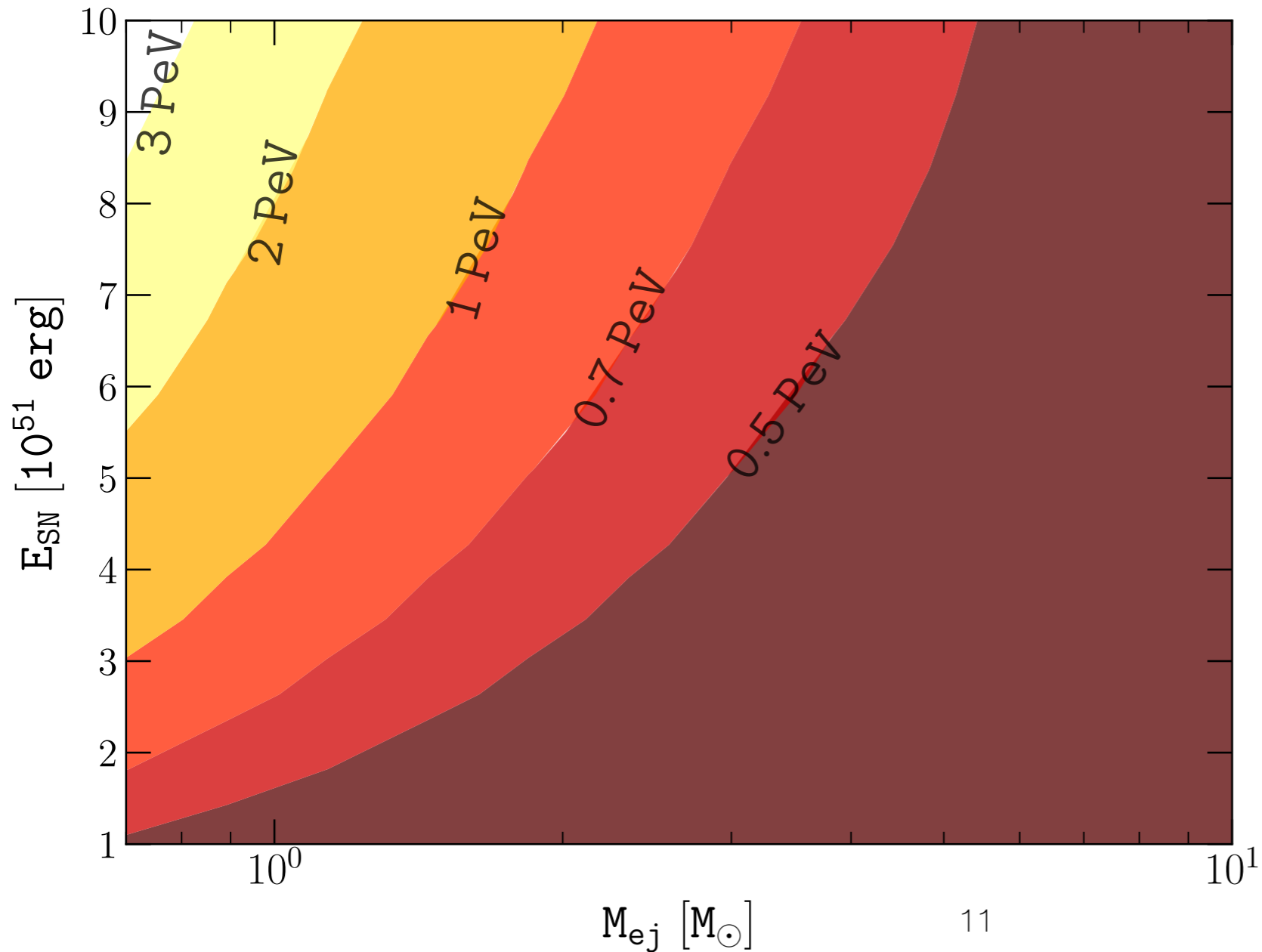
$$\dot{M}_{\text{MS}}, u_{\text{MS}}, n_0, M_{\text{ej}},$$

Non-resonant streaming of CRs

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

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

Growth rate of the non-resonant streaming instability



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

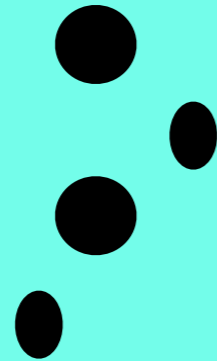
$$\xi = 0.1$$

Protons from SNRs?

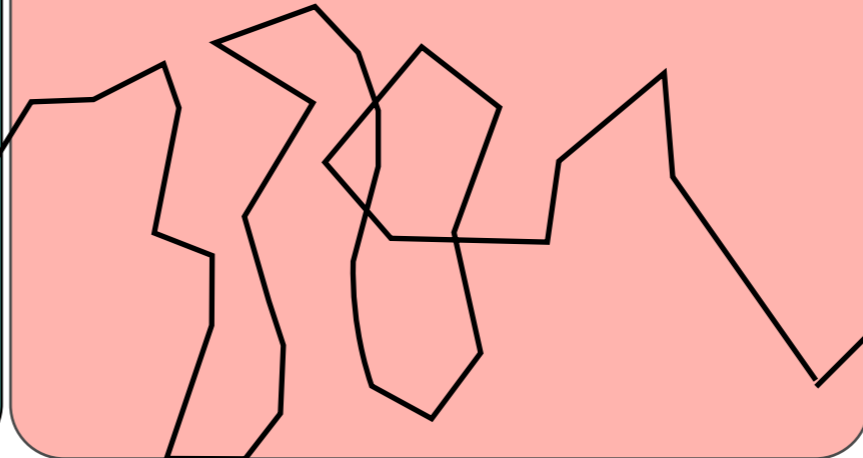
SNRs



**Inject protons
in the ISM**



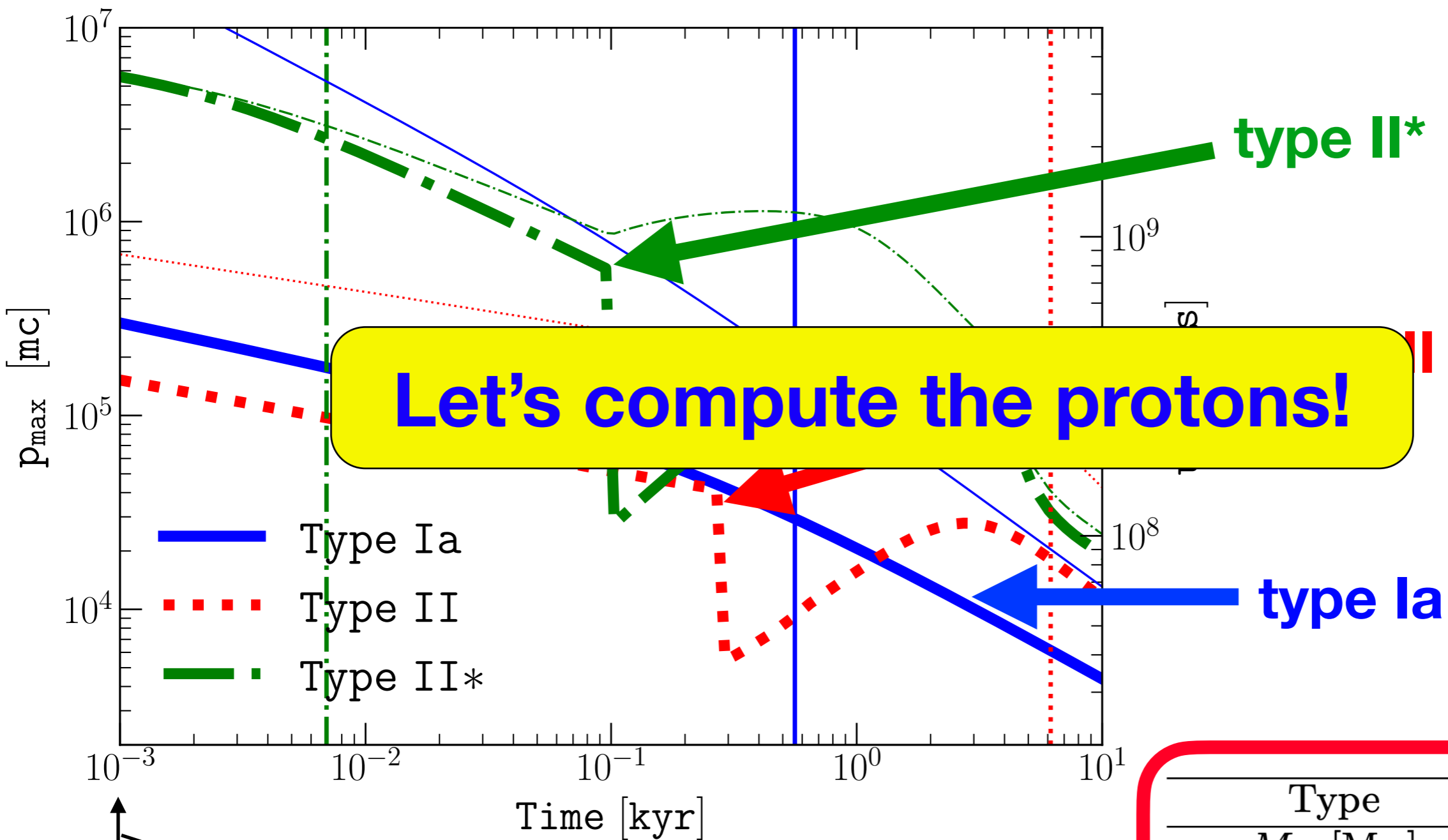
**Protons propagate
to us in the Galaxy**



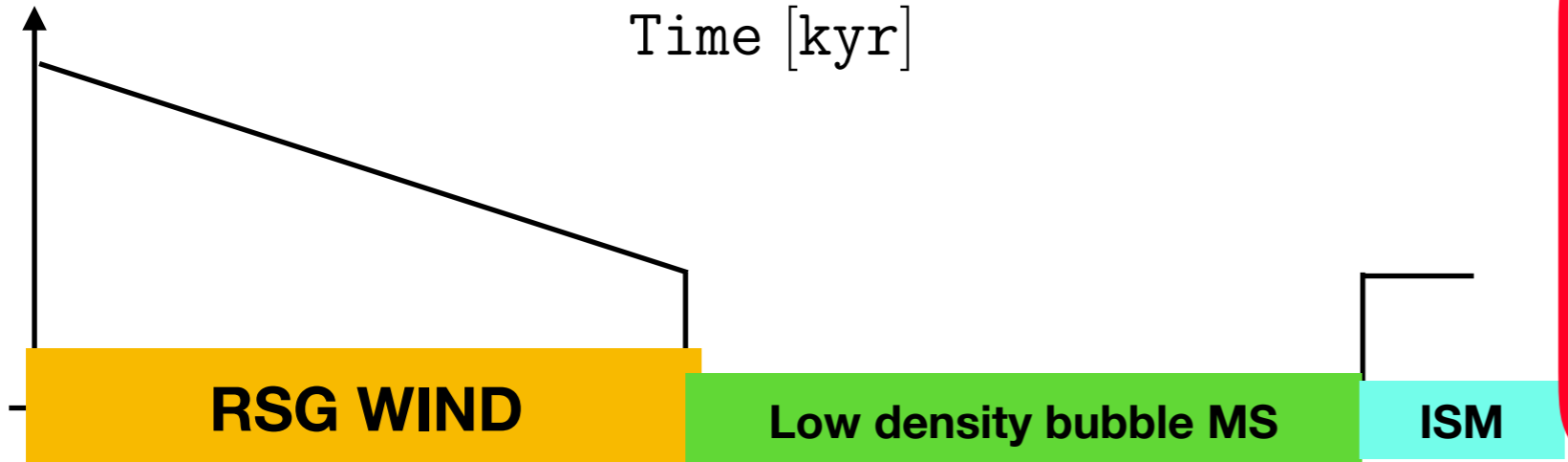
**Compare to
spectrum of CRs**



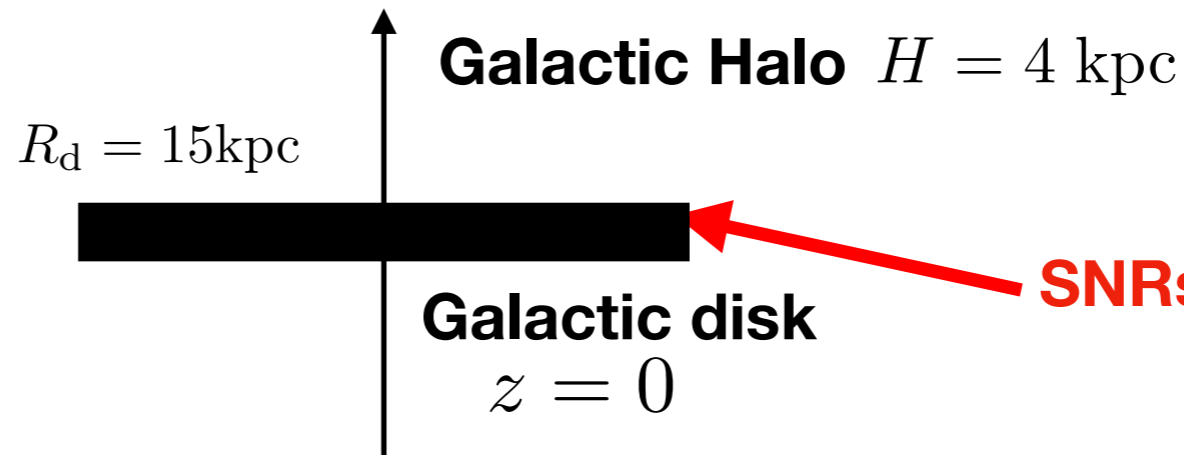
Type Ia, type II, type II*



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



Protons after propagation in the Galaxy



1D Galactic transport

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

Diffusion

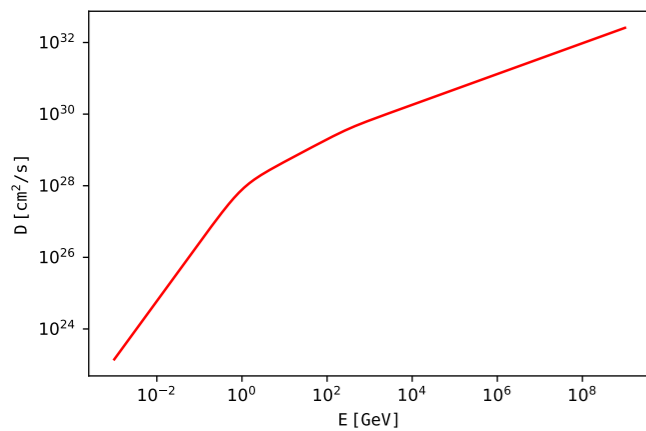
Advection

Ionisation losses

Injection from SNRs

$$D(p) = D_0 \frac{v(p)}{c} \frac{(p/mc)^\delta}{[1 + (p/p_b)^{\Delta\delta/r}]^r}$$

In agreement with AMS-02 measurements
Evoli (2019)



Trapped

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

Escaping

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

Protons from supernova remnants

List of parameters:

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

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

Injection from SNRs

Galactic dimensions

Diffusion coef

H, R_d, h, D, n_0

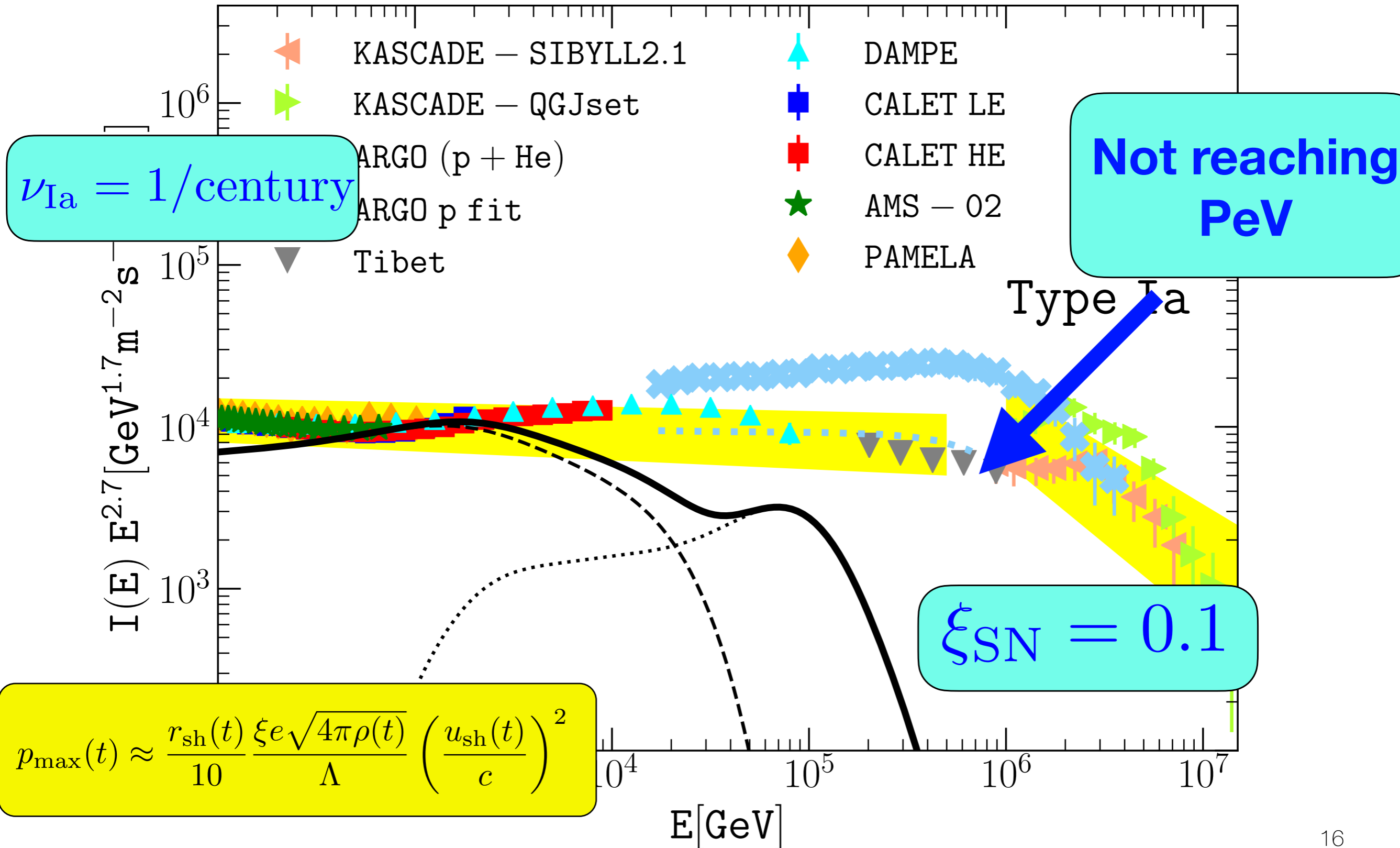
Transport

Rate of SNe

Efficiency of particle acceleration

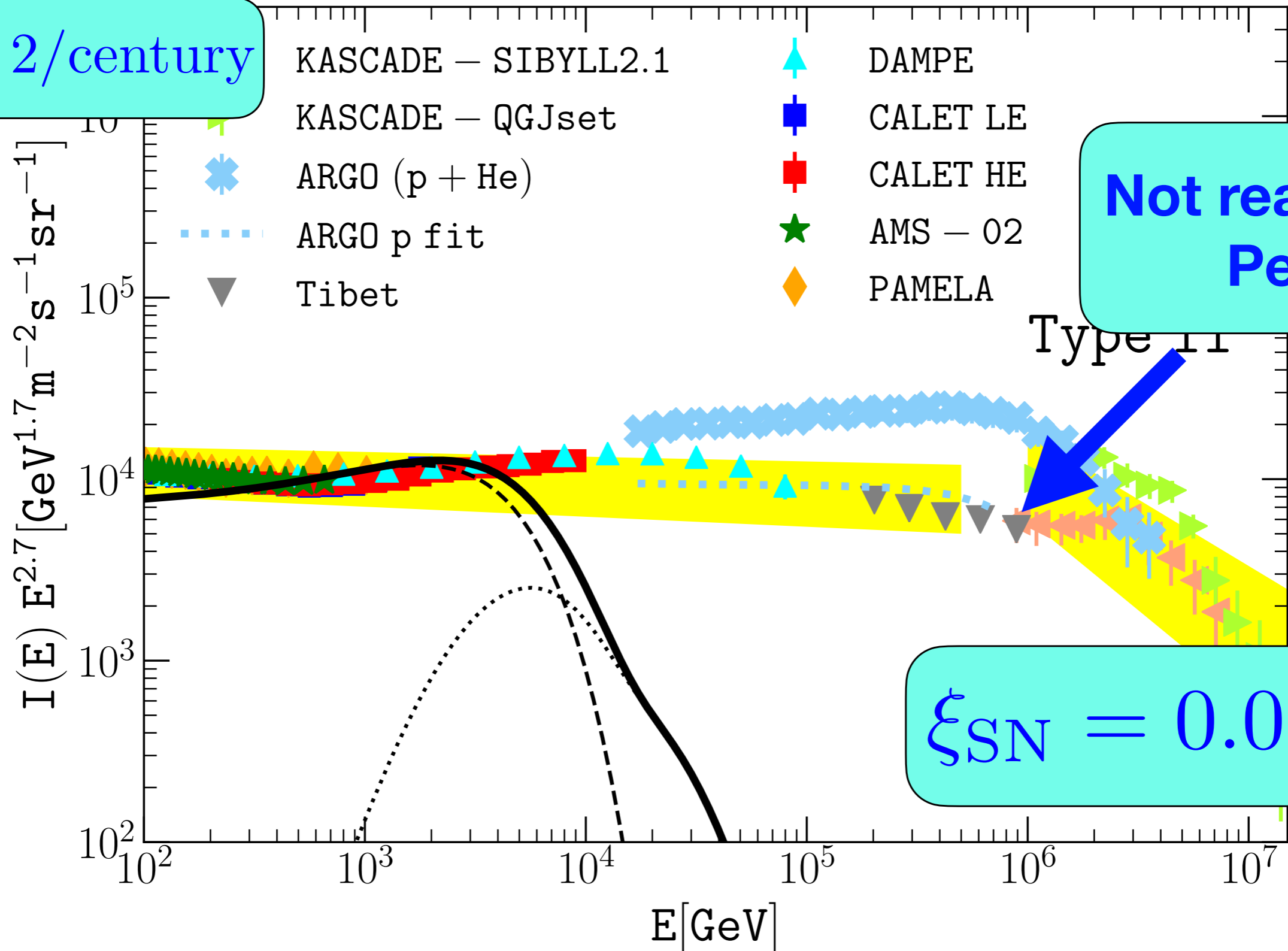
$$E_{\text{max}} \propto \xi_{\text{CR}}$$
$$\text{Norm} \propto \xi_{\text{CR}} \times \nu_{\text{SN}}$$

Protons from type Ia



Protons from type II

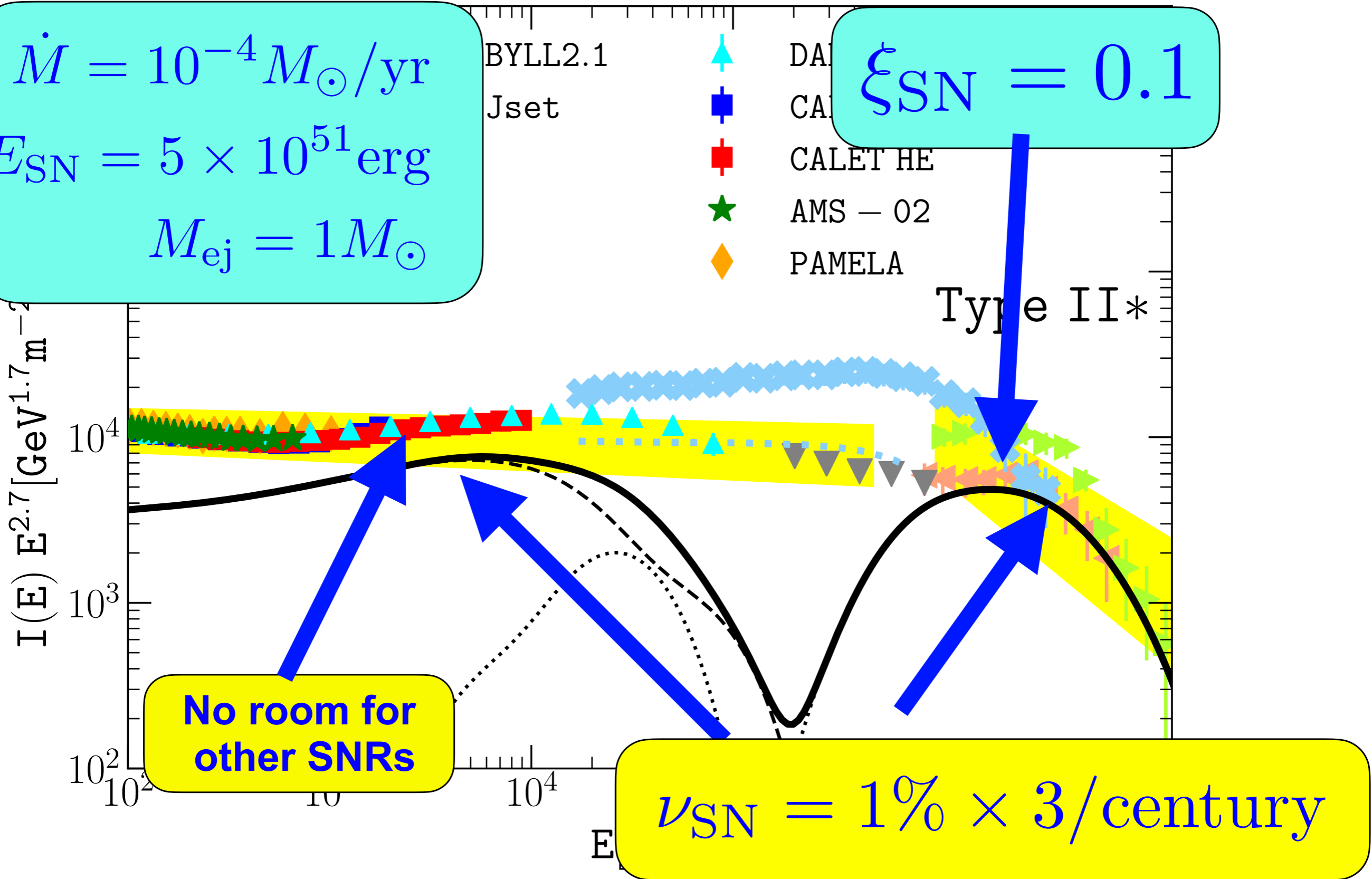
$\nu_{II} = 2/\text{century}$



Protons from type II*

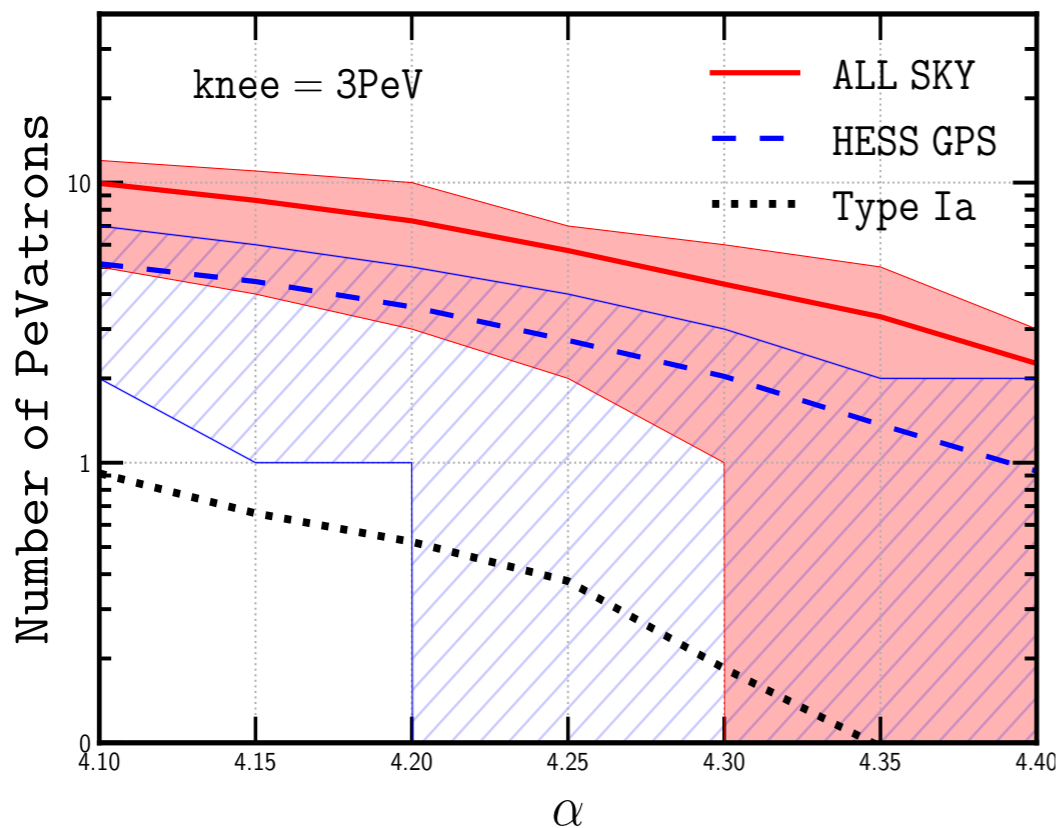
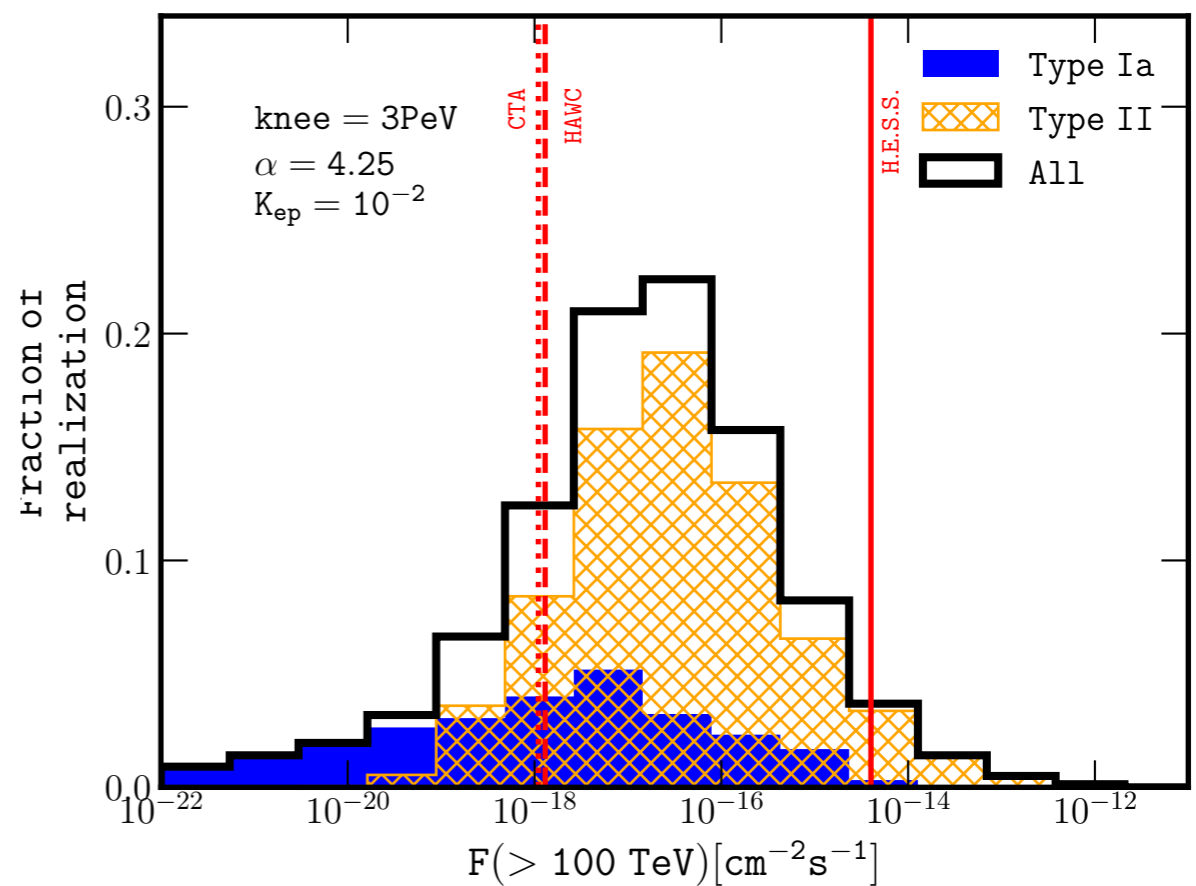
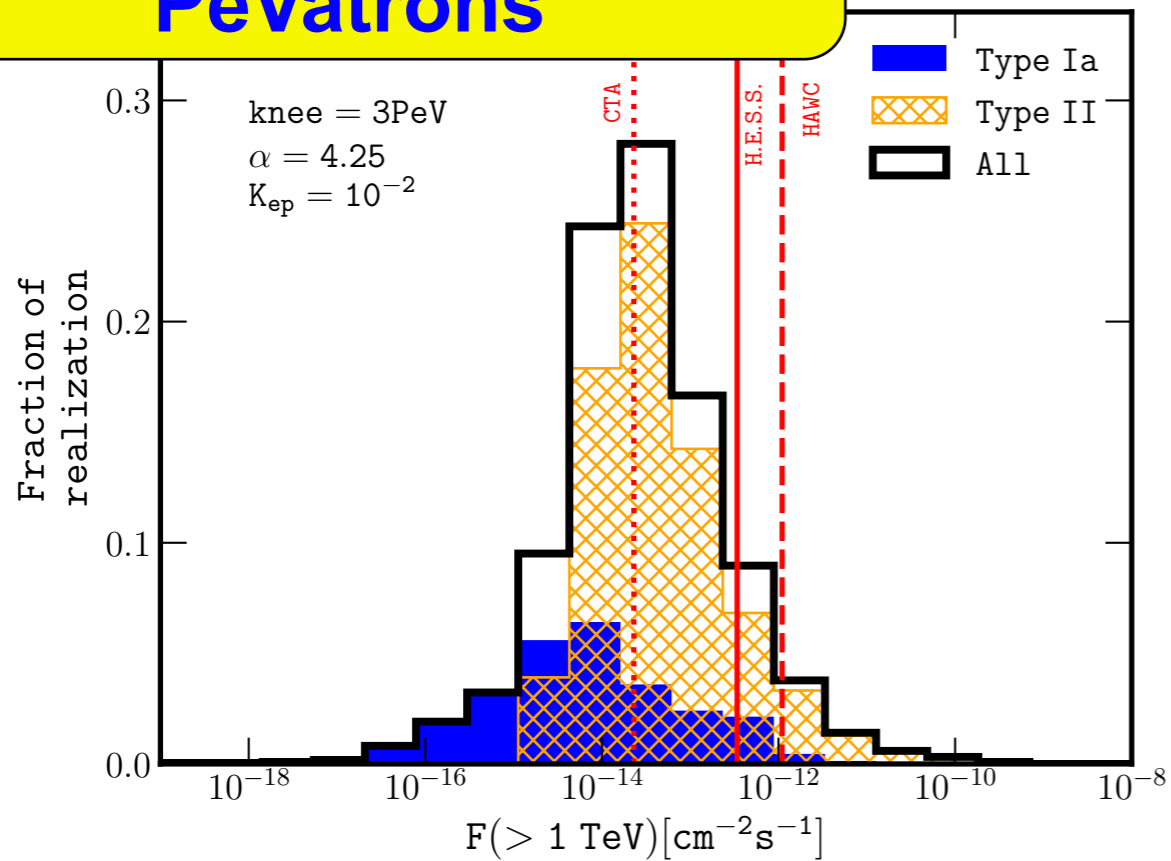
$\dot{M} = 10^{-4} M_{\odot}/\text{yr}$
 $E_{\text{SN}} = 5 \times 10^{51} \text{ erg}$
 $M_{\text{ej}} = 1 M_{\odot}$

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



Pevatrons with CTA

Assuming all SNRs are PeVatrons

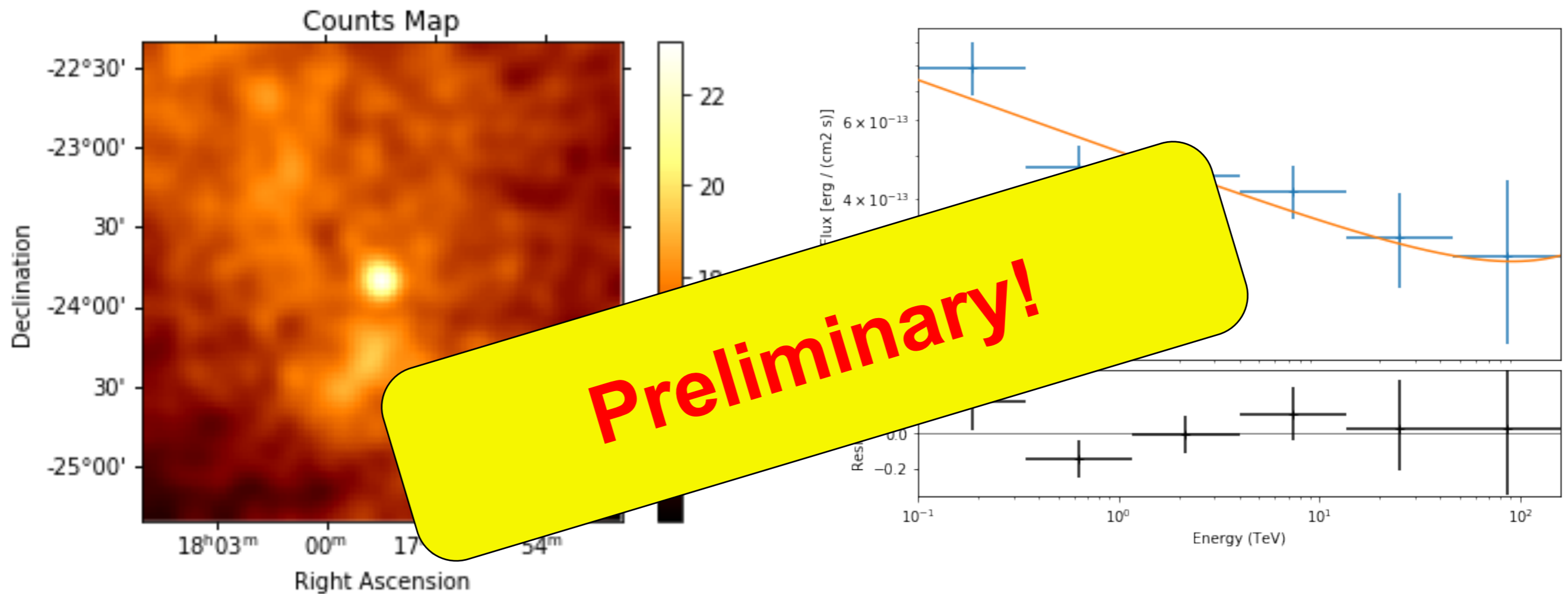


If only Type II* are Pevatrons
 $\nu_{\text{SN}} = 1\% \times 3/\text{century}$
 $\rightarrow 0$

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

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

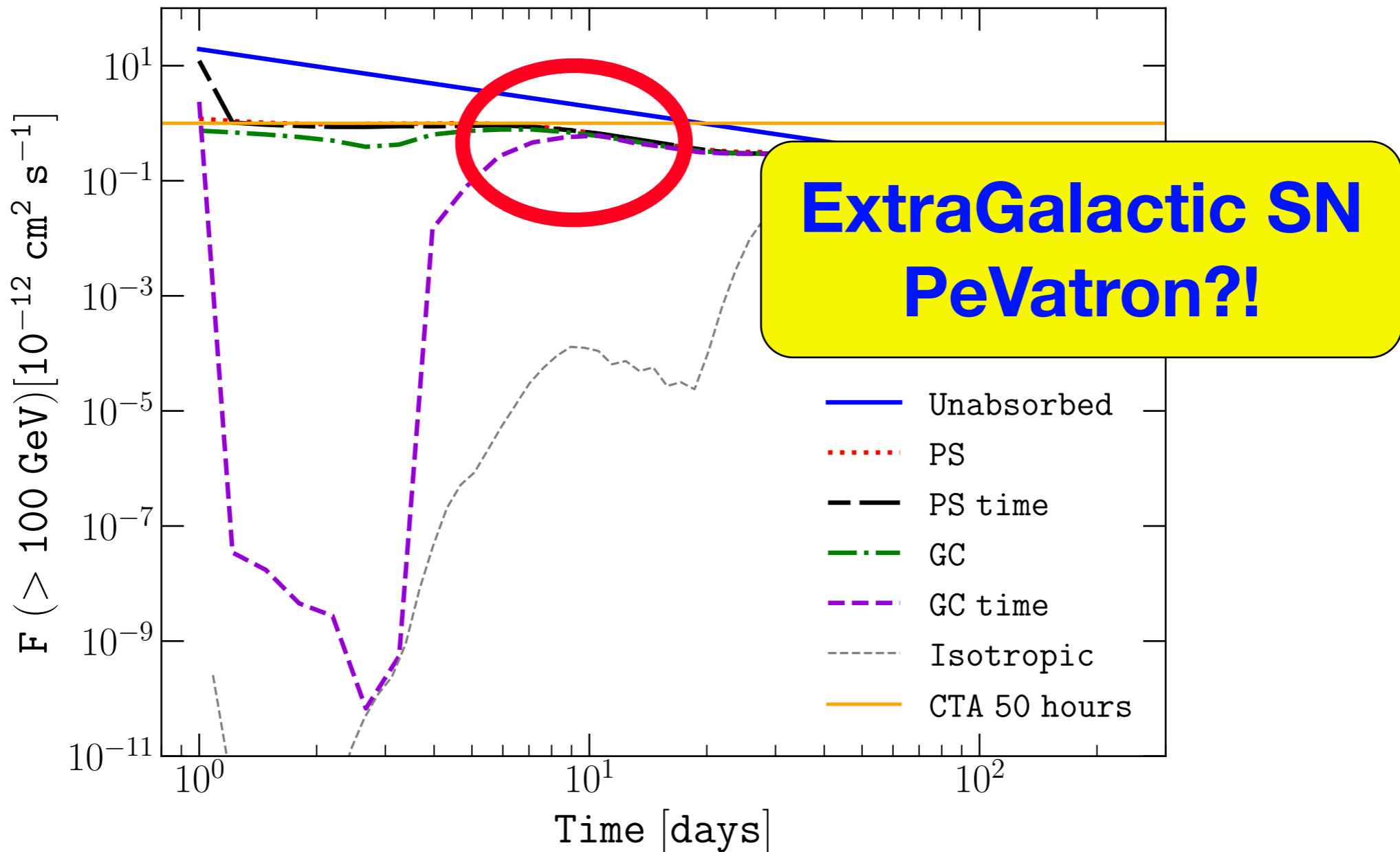
Pevatrons with CTA



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

Pevatrons with CTA

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

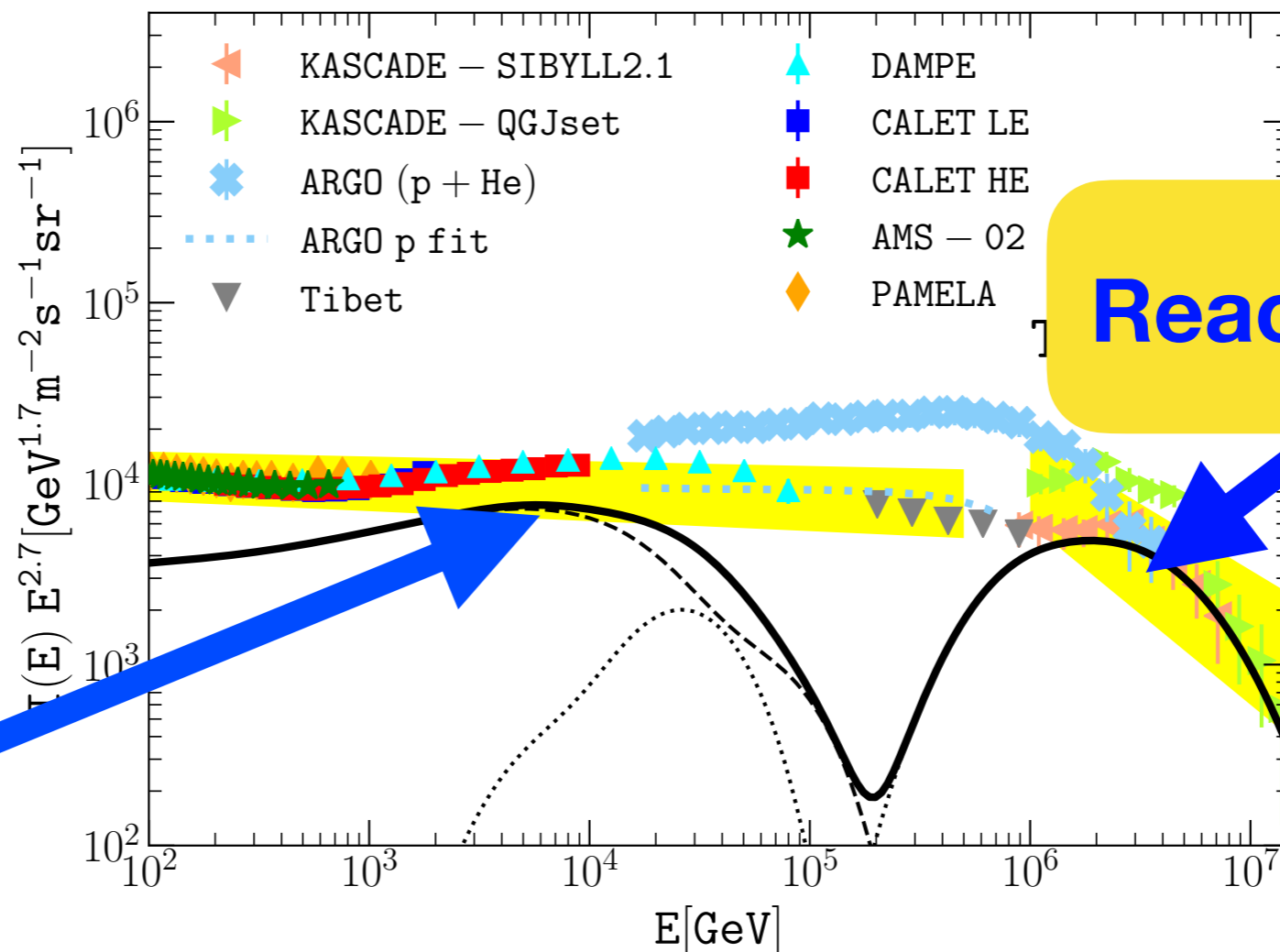


Pevatron working group: Acero, Anguner, Cassol, Costantini, Giunti, Khelifi, Trichard, Verna, PC

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?

Reaching PeV

**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?)**
- * **ξ_{CR} / \dot{M} function of time?**
- * **When? How many?**
- * **Other Astrophysical objects?**

H.E.S.S. J1745-290

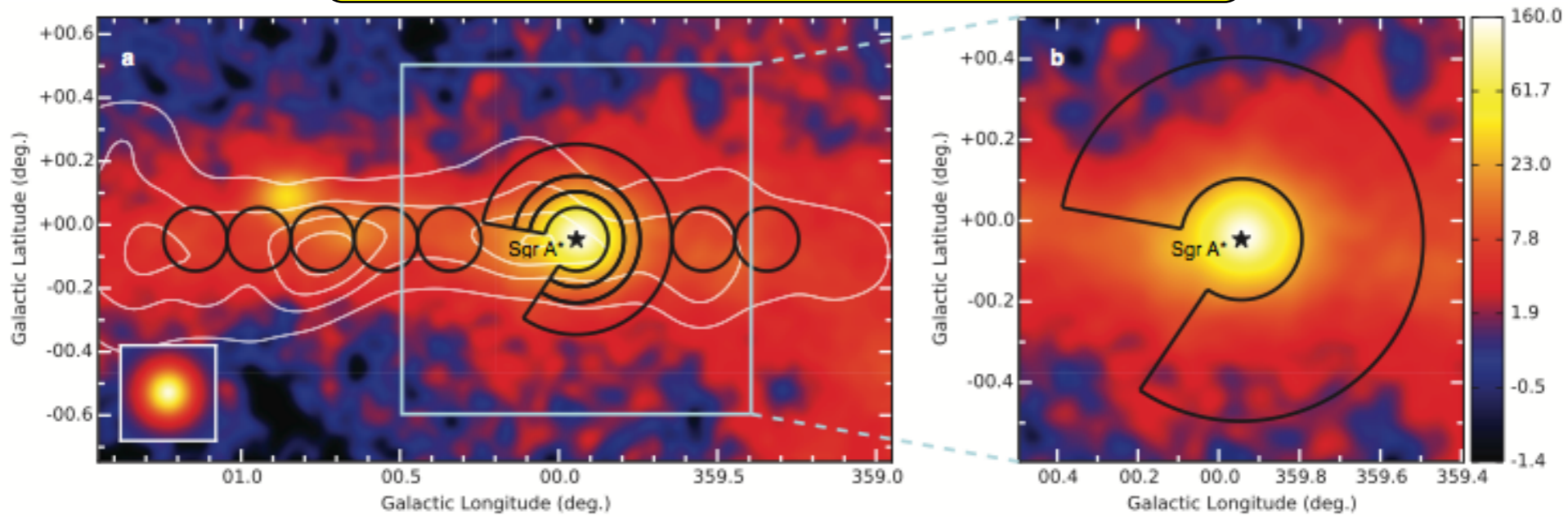
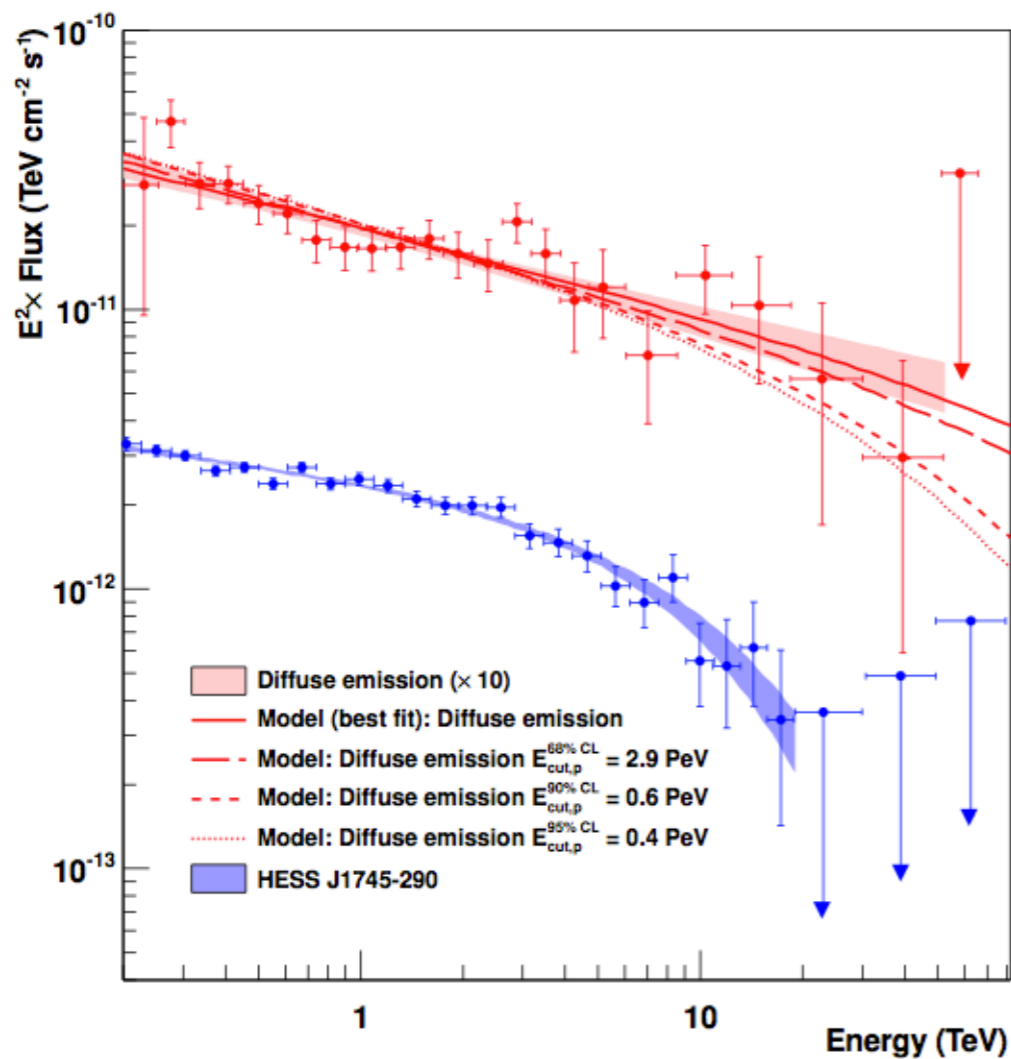
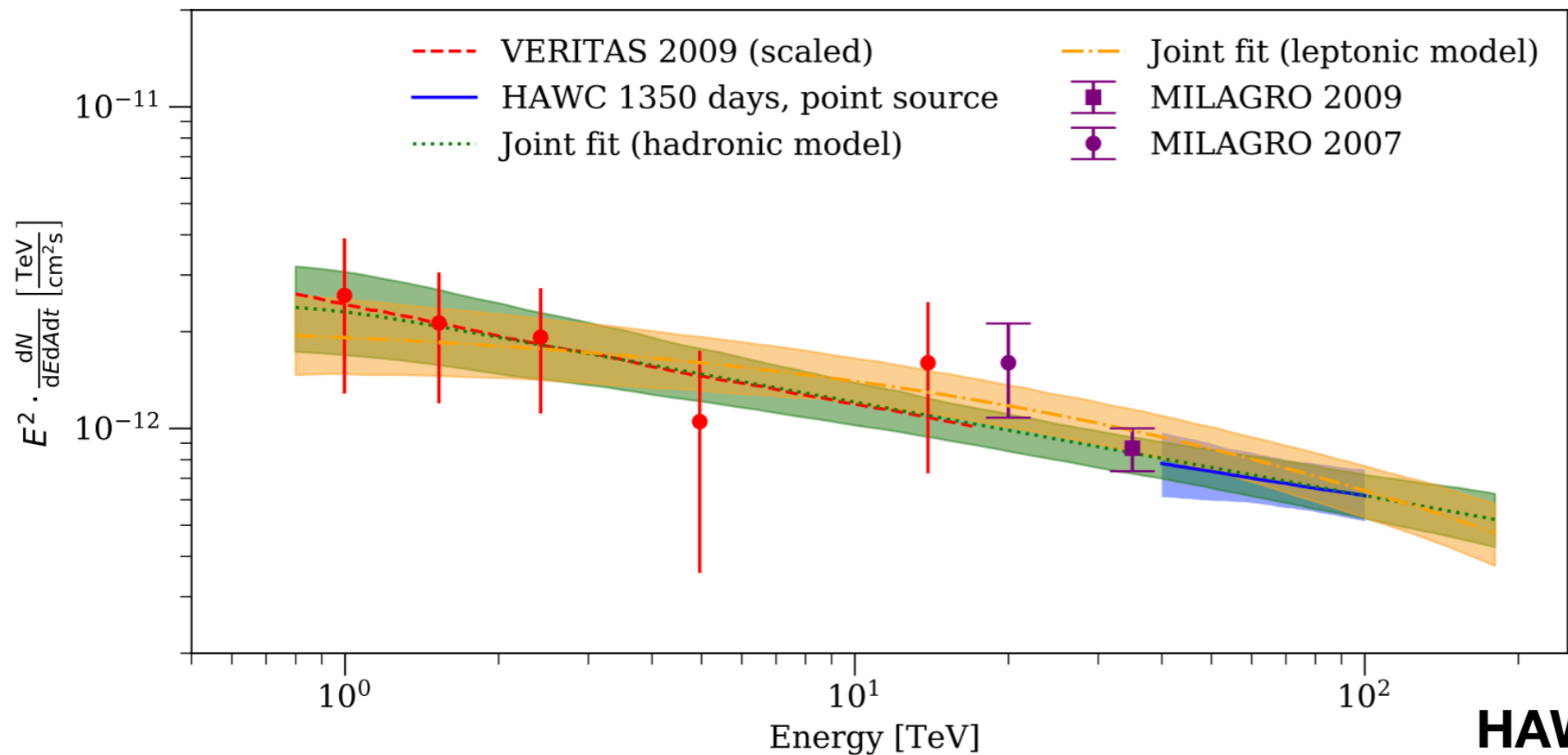
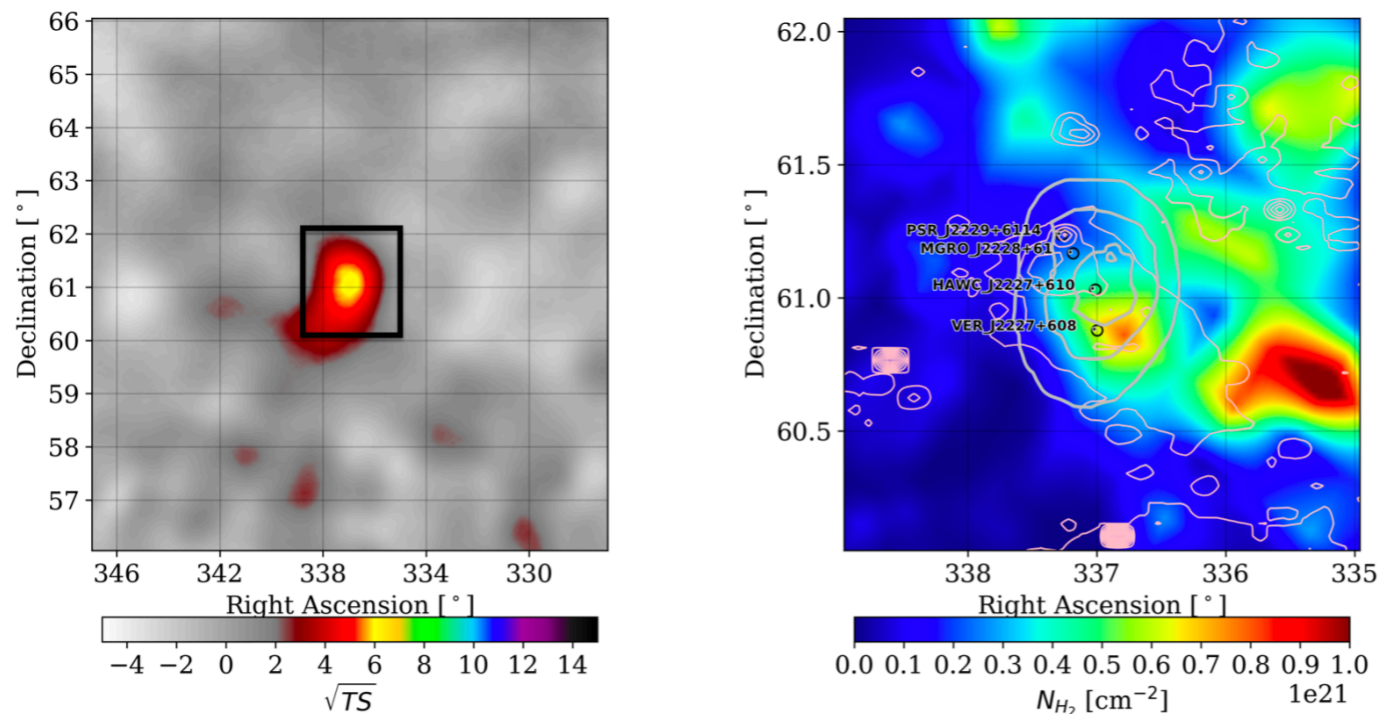


Figure 1: VHE γ -ray image of the Galactic Centre region. The colour scale indicates counts per $0.02^\circ \times 0.02^\circ$ pixel.

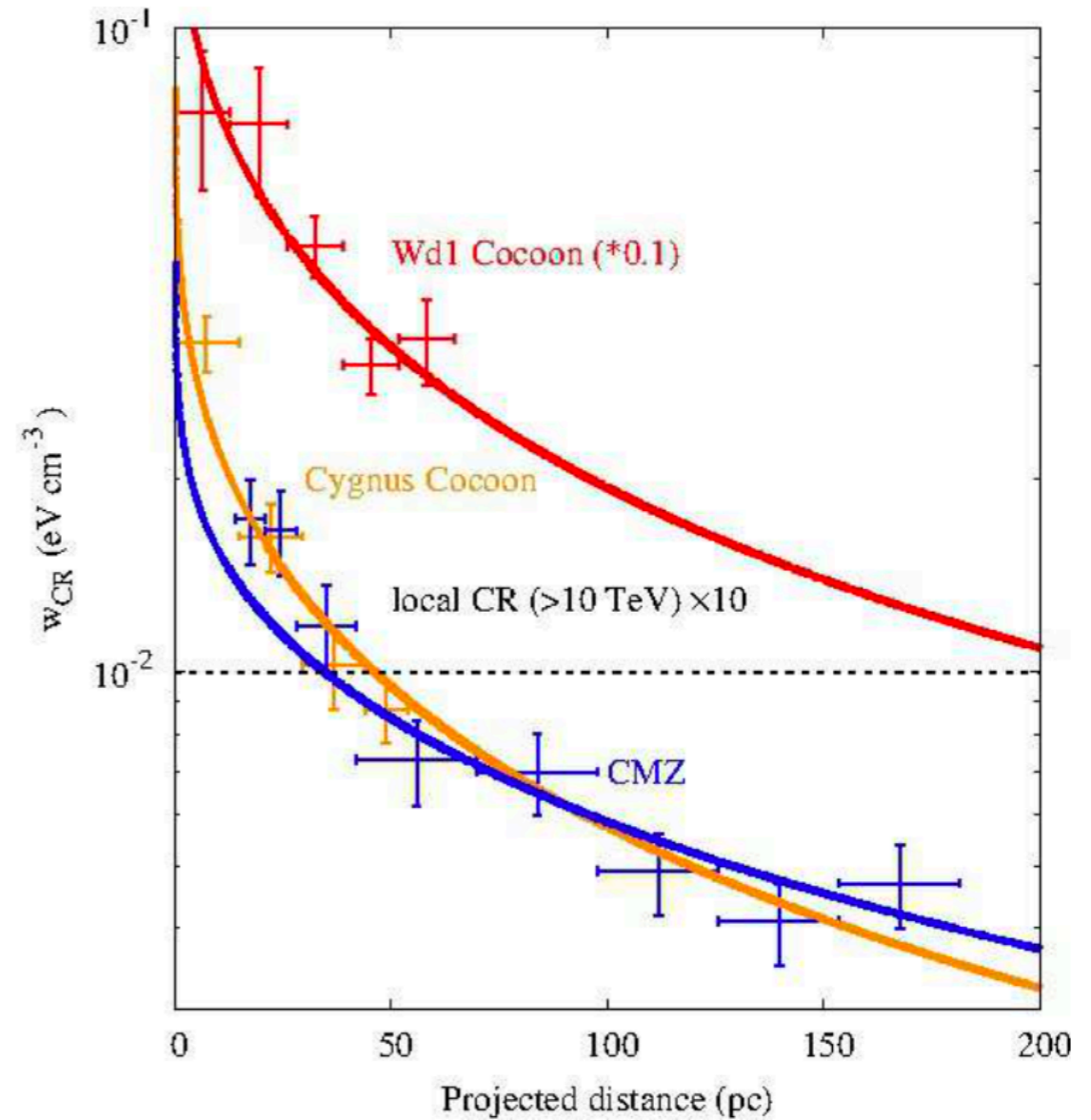
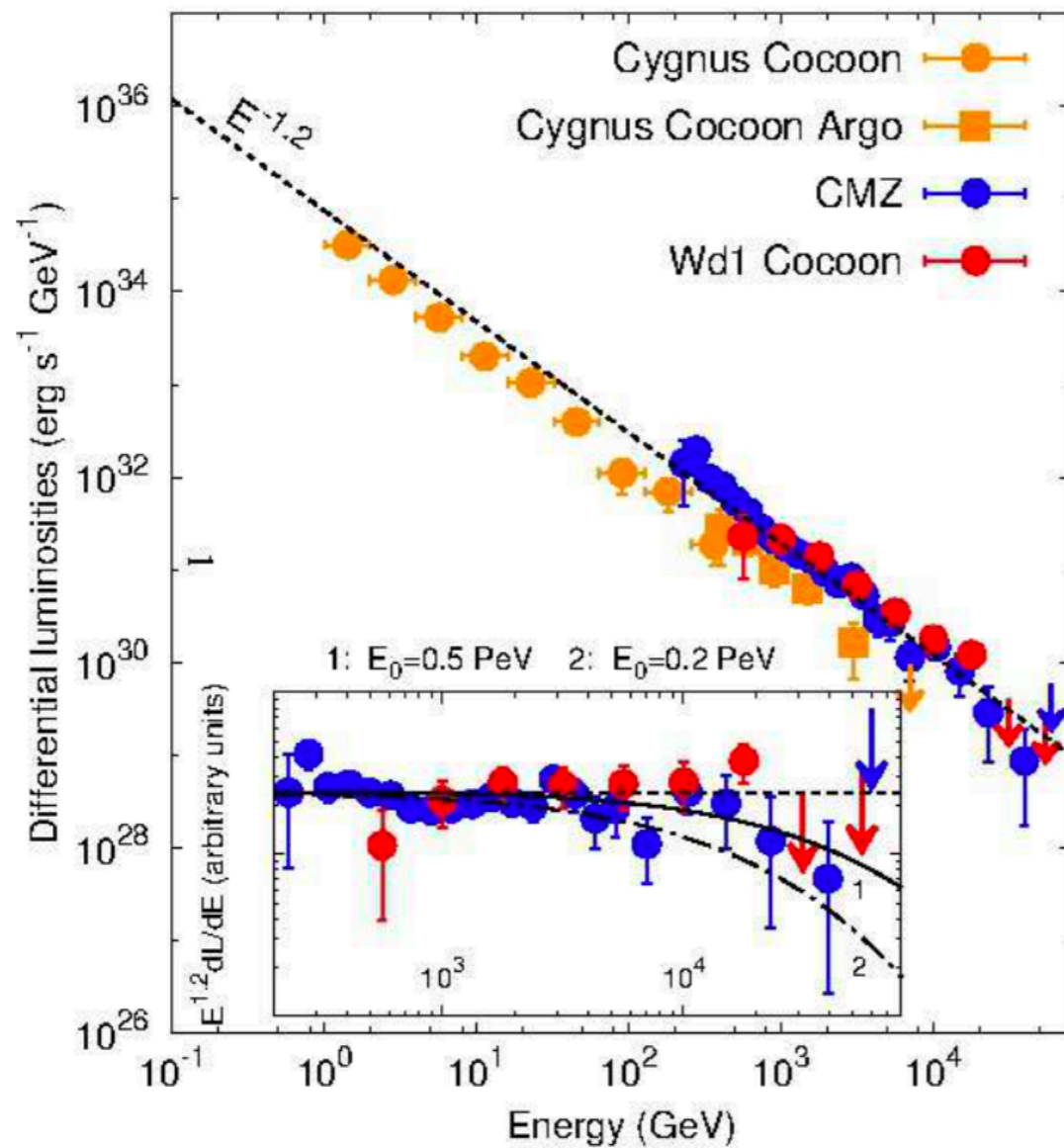


H.E.S.S. collaboration (Nature, 2016)

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



Massive stars as CR factories?



Aharonian et al. (Nature Astro. 2019)

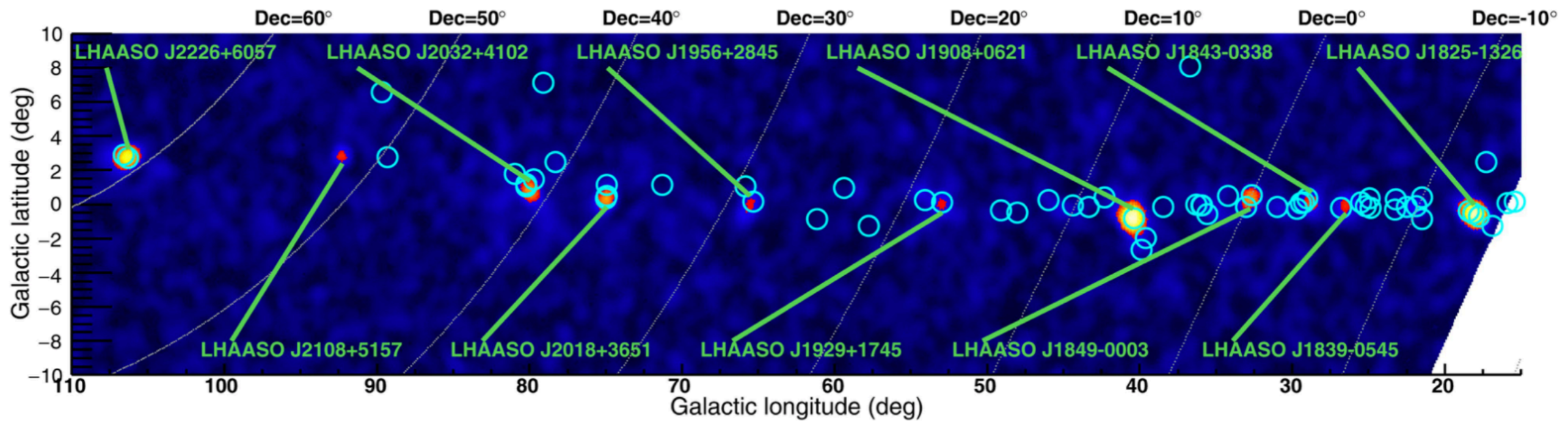
Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

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

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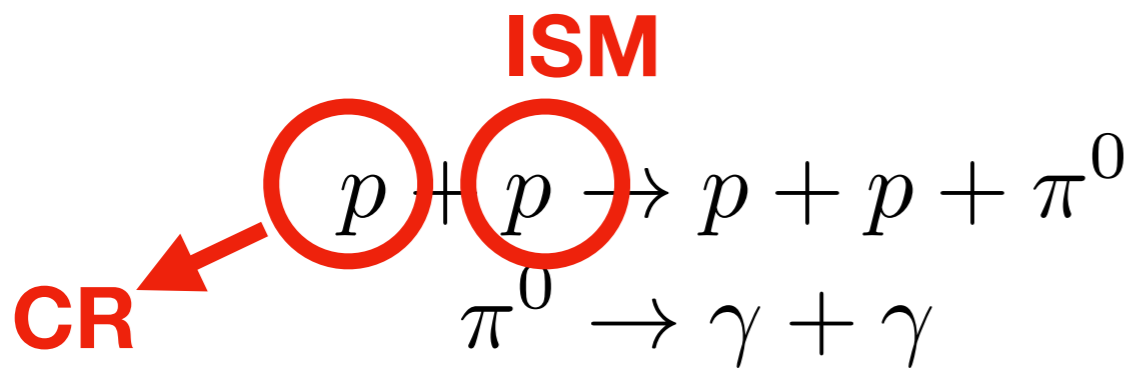
Ultra-high-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources

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, 2HWC J1825-134
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069, HESS J1841-055
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	
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, ARGO J1907+0627, VER J1907+062, 2HWC 1908+063
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188, HESS J1930+188, VER J1930+188
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	
	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, VER J2016+371
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157, MGRO J2031+41, 2HWC J2031+415, VER J2032+414
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	
	SNR G79.8+1.2	NR candidate	—	—	—	
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

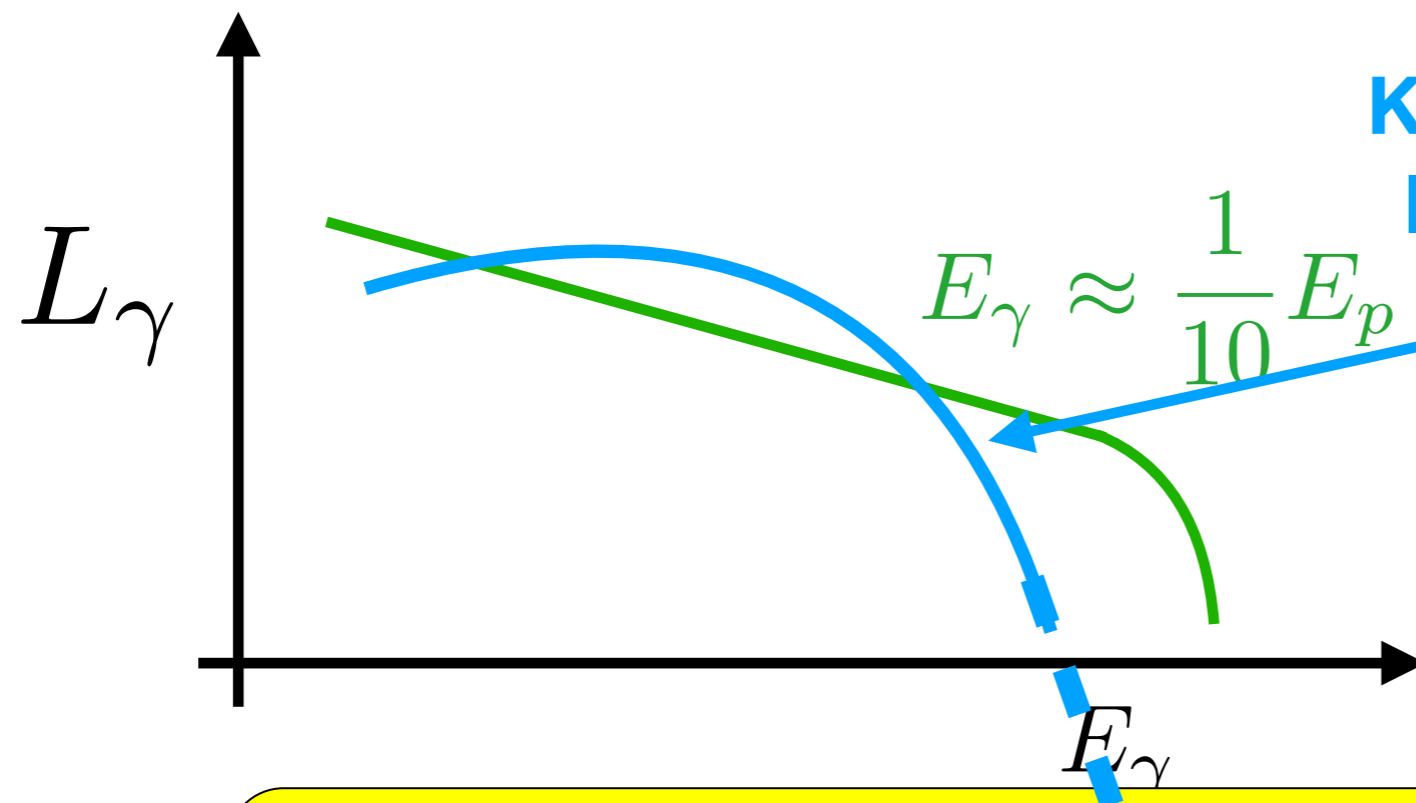
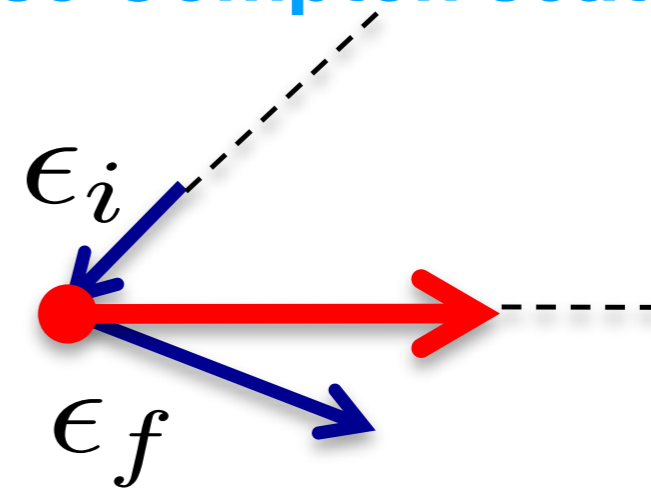
**Very uncertain nature of these sources?
Proton acceleration? Electron acceleration?
Not many SNRs in this list!**

Gamma rays from SNRs

Hadronic interactions :
Pion decay



Leptonic interactions :
Inverse Compton scattering



Klein-Nishina suppression:
Inefficient above >50 TeV

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

**Conclusions : the hunt for pevatrons,
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Cristofari, Blasi, Amato, Astro. Phy. , Dec. 2020