

# Supernova remnants with the Cherenkov Telescope Array

**LPNHE**

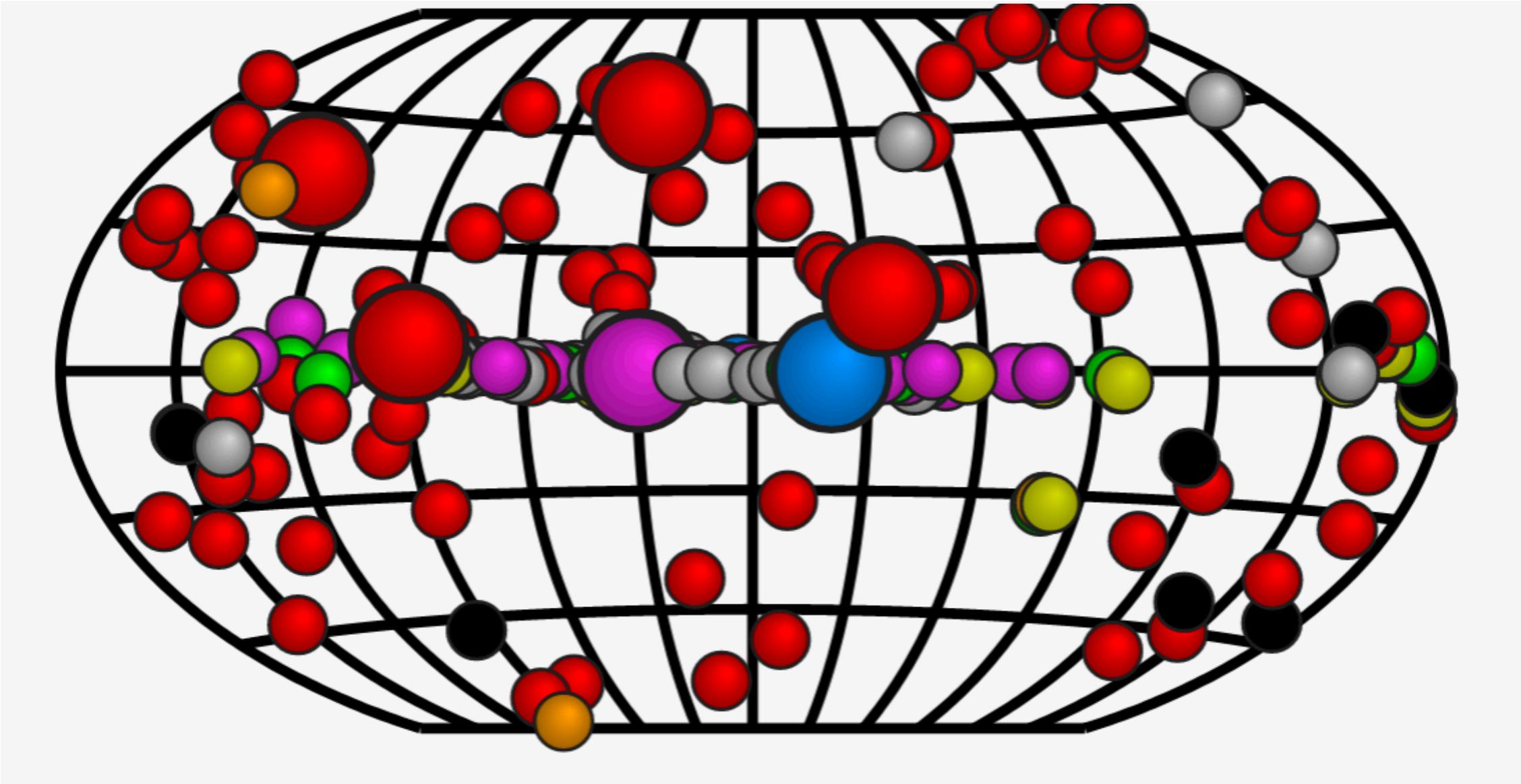
**March 2nd 2020**

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# Galactic supernova remnants



- PWN, PWN/TeV Halo, Composite SNR
- Shell, SNR/Molec. Cloud, Composite SNI
- PSR

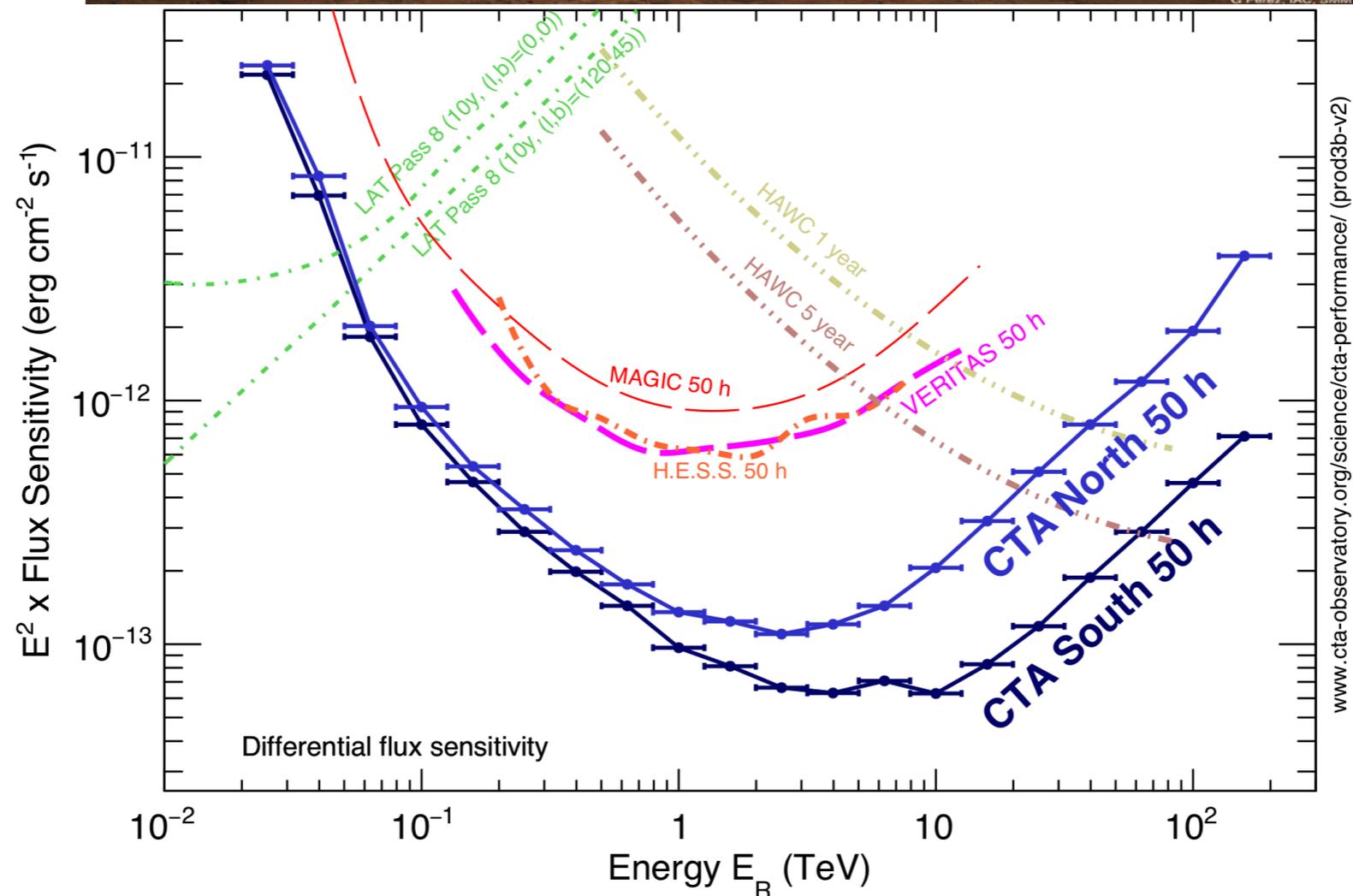
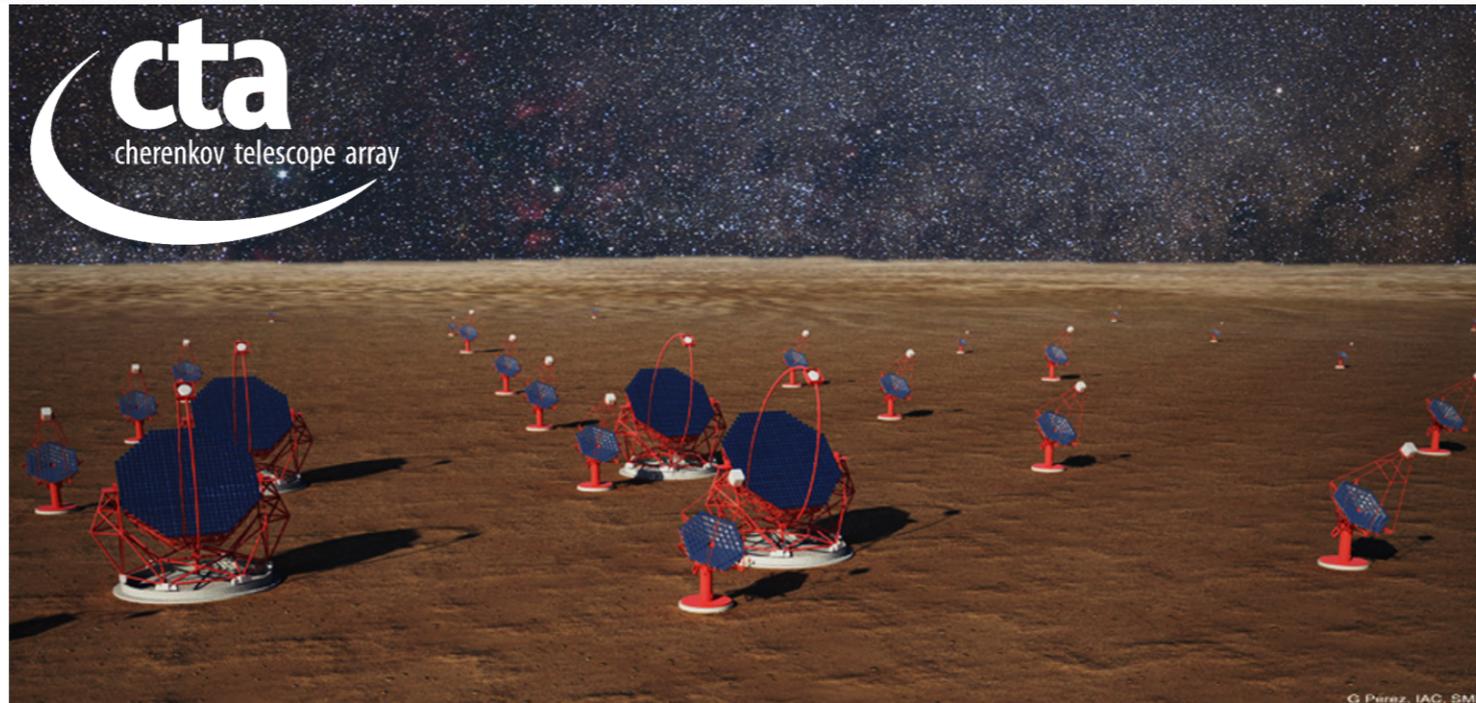
226 sources listed

57 « SNRs »

12 Shells

TeVCat (2020)

# TeV gamma-ray astronomy

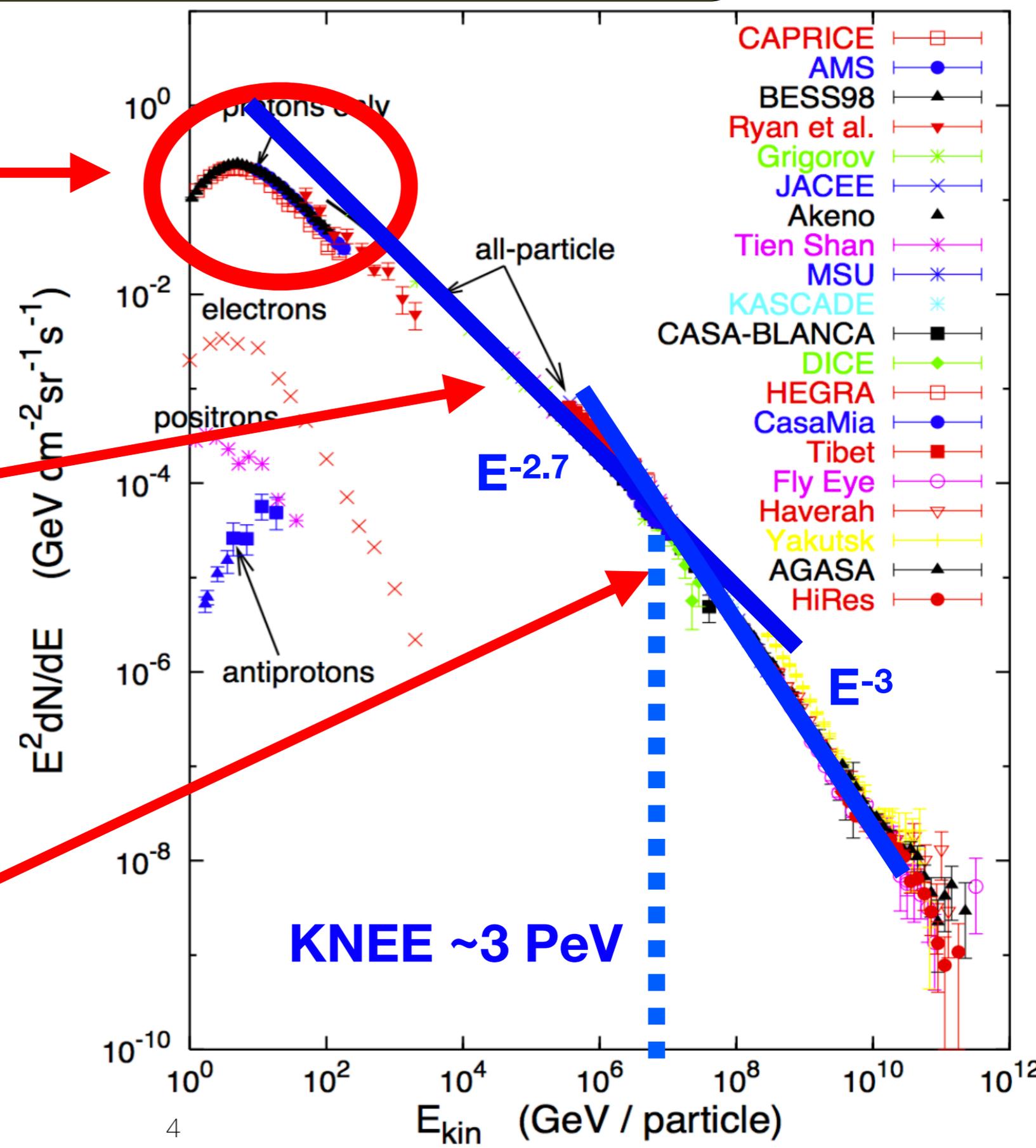


# Why supernova remnants?

**1. Bulk of CRs**  
 Energy density  $\sim 1$  eV/cm<sup>3</sup>  
 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**



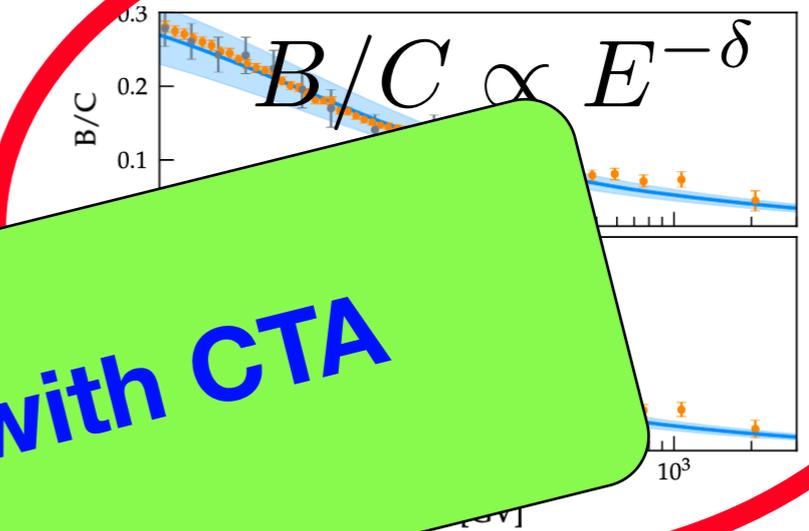
# What is wrong with supernova remnants?

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

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

**A. Re-acceleration with CTA**

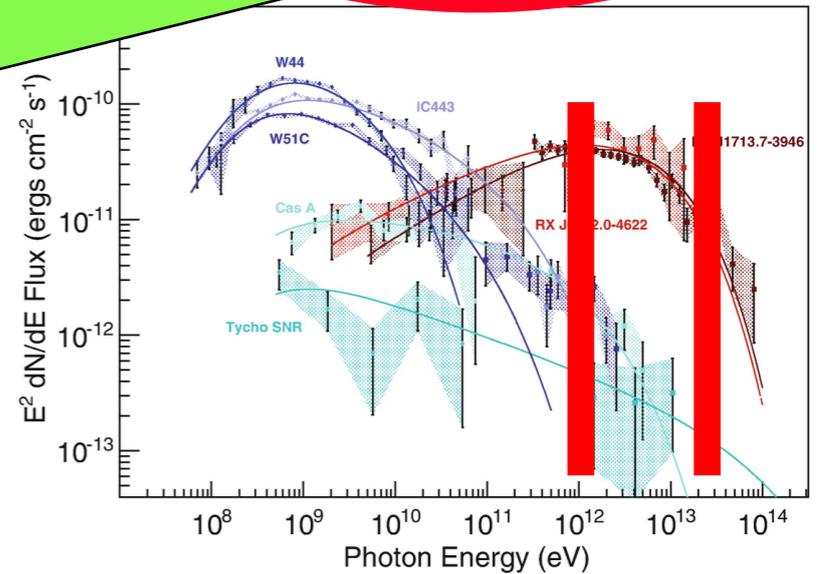
2. All gamma-ray spectra show spectra steeper than  $E^{-2}$



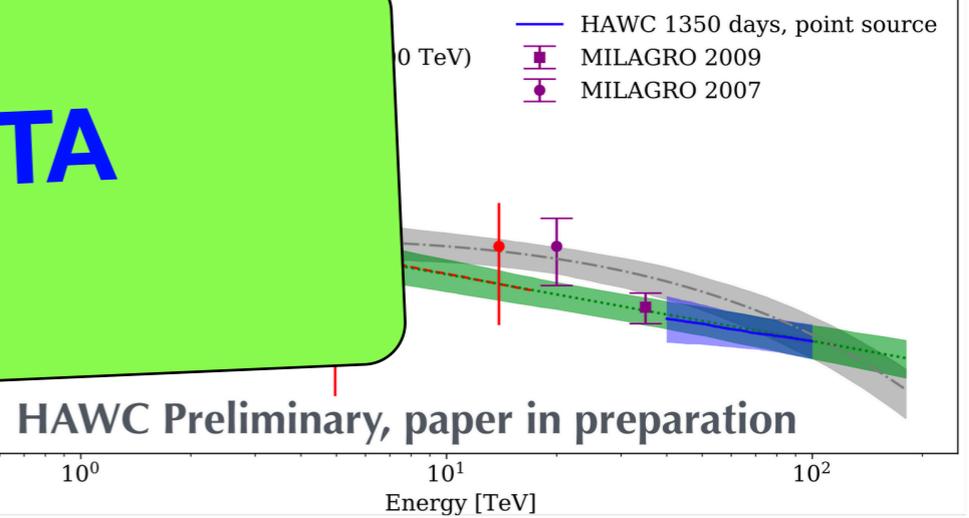
Fyoli et al. (2019)

3. No

**B. PeVatrons with CTA**



Funk (2017)



HAWC, Fleishhack  
 Texas Symp (2019)

**A. Diffusive shock reacceleration  
at supernova remnant shocks**

**B. Pevatrons with CTA**

**A. Diffusive shock reacceleration  
at supernova remnant shocks**

**B. Pevatrons with CTA**

# A. Diffusive shock reacceleration at supernova remnant shocks

Bell (1978, MNRAS, II.)

## 6. Effect of a shock front on pre-existing cosmic rays

« *In previous sections the injection of particles into the acceleration mechanism has been considered as taking place at low energy [...] An alternative source for the injection of particles is the cosmic ray population which already exists in the upstream gas.* »

(...)

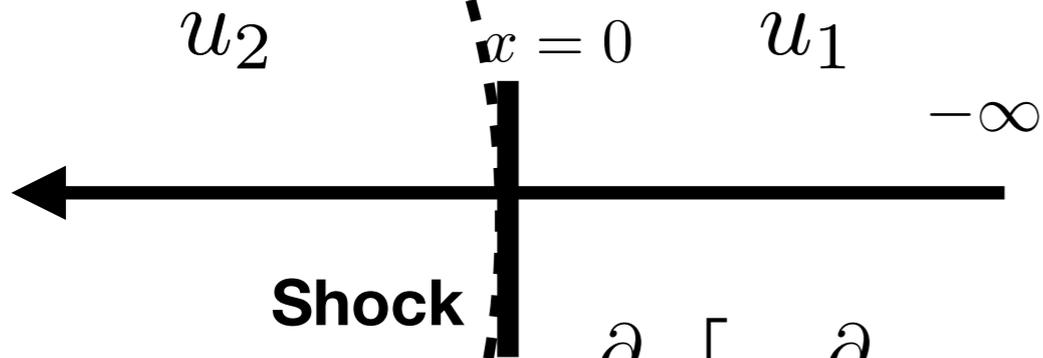
Pohl et. al (2015, A&A)

*Reacceleration of electrons in SNRs*

Blasi (2017, MNRAS), Bresci et al. (2019, MNRAS)

*The role of reacceleration on secondary nuclei.  
-> Anti-proton-to-proton and Boron-to-Carbon ratios*

# A simple description



$$\frac{\partial}{\partial x} \left[ D \frac{\partial}{\partial x} f(x, p) \right] - u \frac{\partial f(x, p)}{\partial x} + \frac{1}{3} \frac{du}{dx} p \frac{\partial f(x, p)}{\partial p} = -Q(x, p)$$

$$Q_0(p) = \frac{\eta n_0 u_1}{4\pi p_{inj}^2} \delta(p - p_{inj})$$

$$g(p) = f(-\infty, p)$$

**Boundary condition -> upstream infinity of the shock**

$$r = \frac{u_1}{u_2}$$

$$s = \frac{3r}{r-1}$$

$$f_0(p) = s \frac{\eta n_1}{4\pi p_{inj}^3} \left( \frac{p}{p_{inj}} \right)^{-s}$$

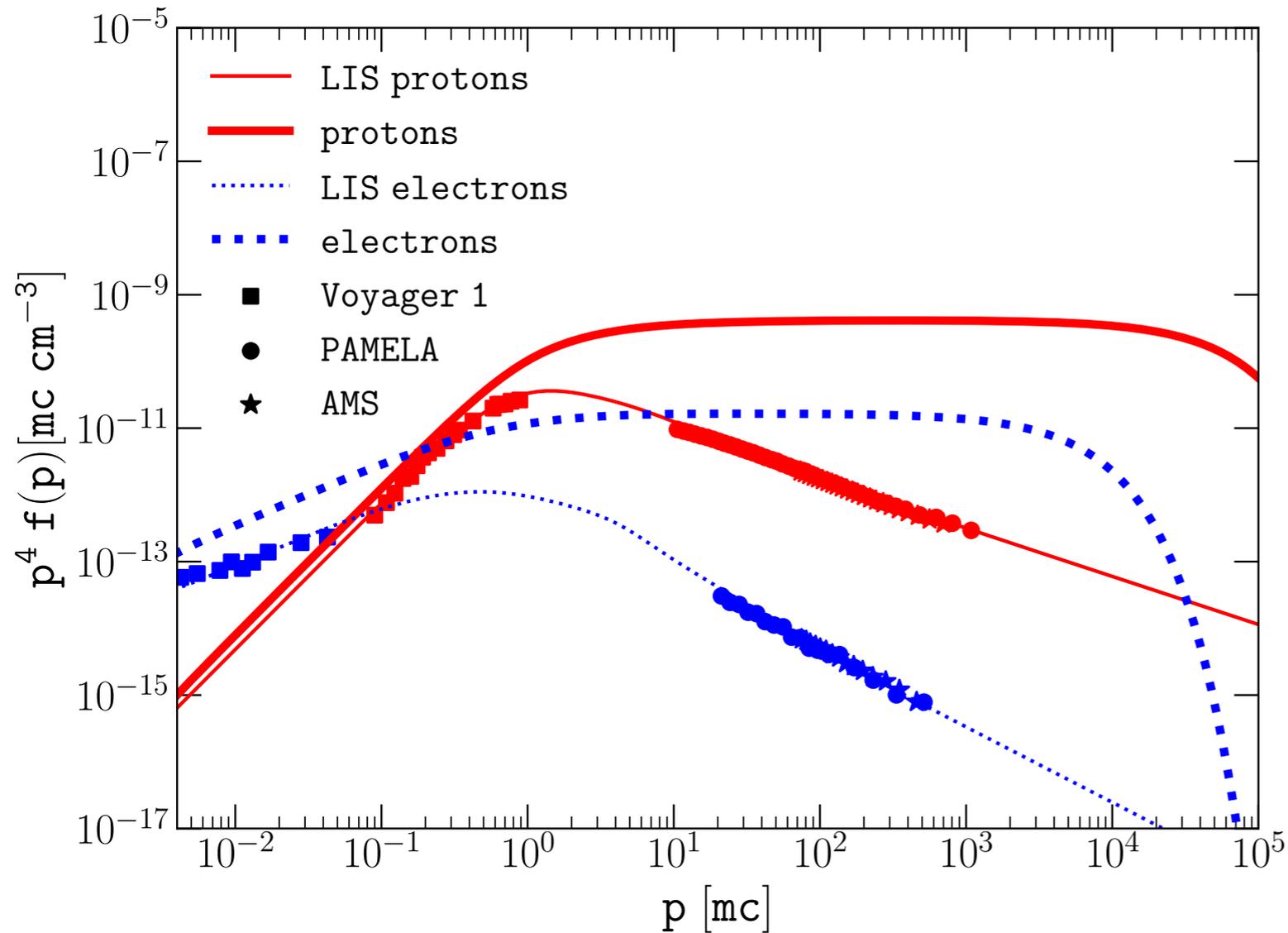
**« Classic »  
diffusive shock  
acceleration**

$$s \int_{p_0}^p \frac{dp'}{p'} \left( \frac{p'}{p} \right)^s g(p')$$

**Reacceleration**

**Blasi (2004)**

# Reacceleration of Galactic CRs



$$f_0^{\text{reac}}(p) = s \int_{p_0}^p \frac{dp'}{p'} \left( \frac{p'}{p} \right)^s g(p')$$

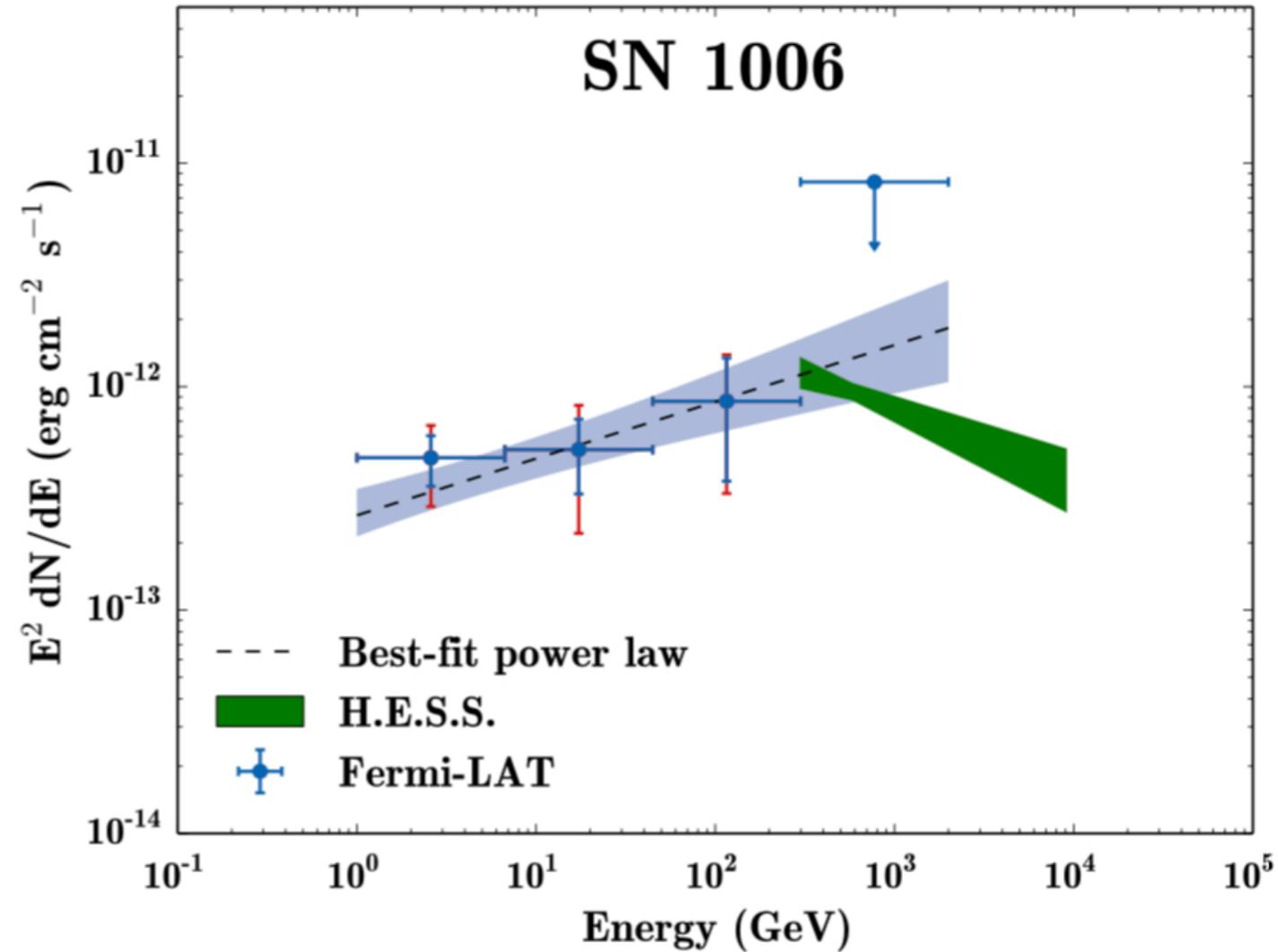
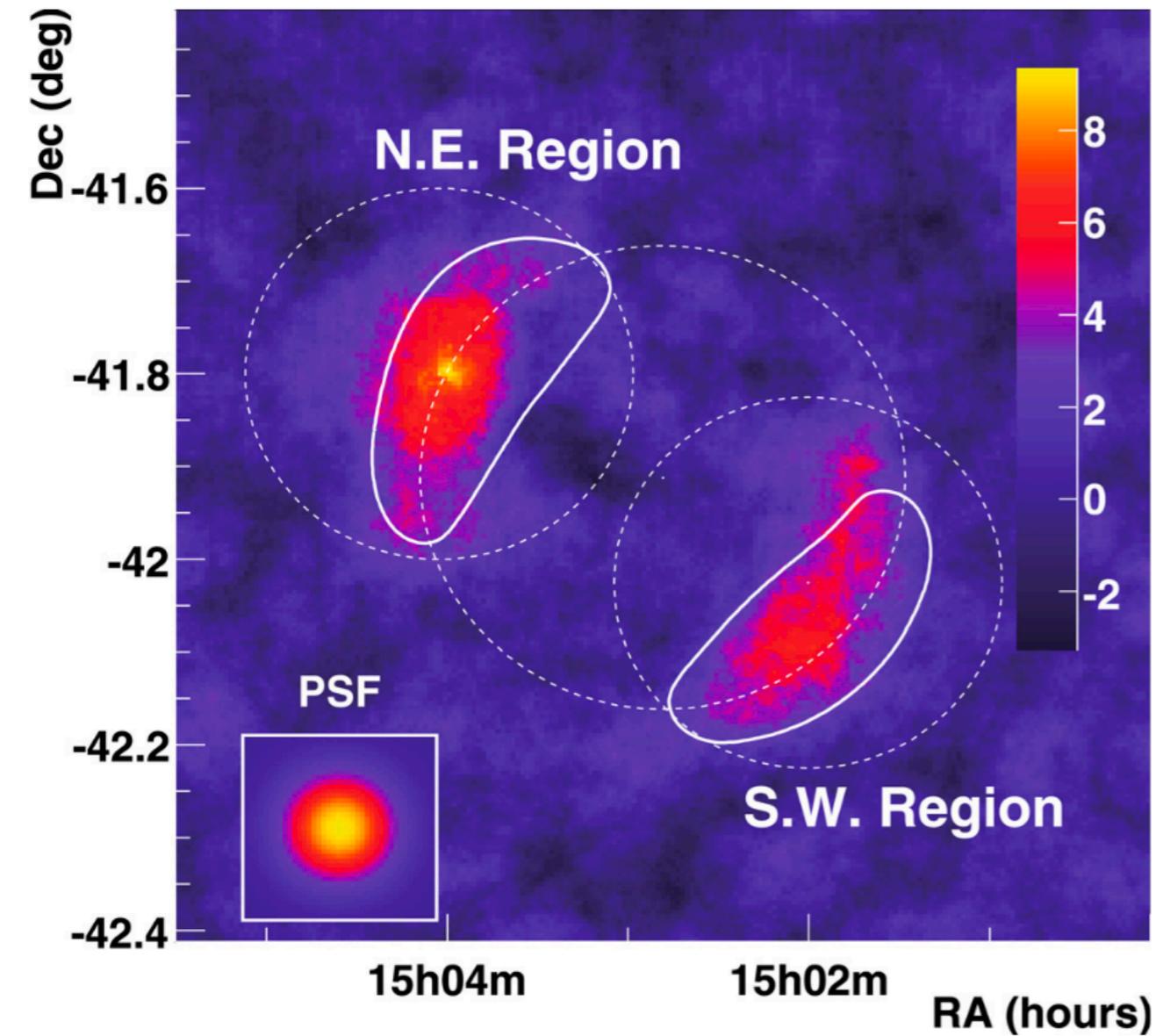
$$s = 4$$

$$p_0 \lesssim 1 \text{ GeV}$$

**Maximum energy of reaccelerated particles?**

**Bisschoff et al. (2019)**  
**Aguilar et al. (2019)**  
**Cummings et al. (2016)**  
**Adriani et al. (2011)**

# SN 1006



$$R_{\text{sh}} \approx 7 - 8 \text{ pc}$$

$$d \approx 1.8 - 2 \text{ kpc}$$

$$u_{\text{sh}} \approx 4.3 \cdot 10^8 \text{ cm/s}$$

$$n_0 \sim 10^{-2} - 10^{-1} \text{ cm}^{-3}$$

**H.E.S.S. (2010)**

**Condon (2017)**

# Reaccelerated particles at SN 1006

$$f_0^{\text{reac}}(p) = s \int_{p_0}^p \frac{dp'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$

Maximum energy of reaccelerated particles?

~~Protons?~~

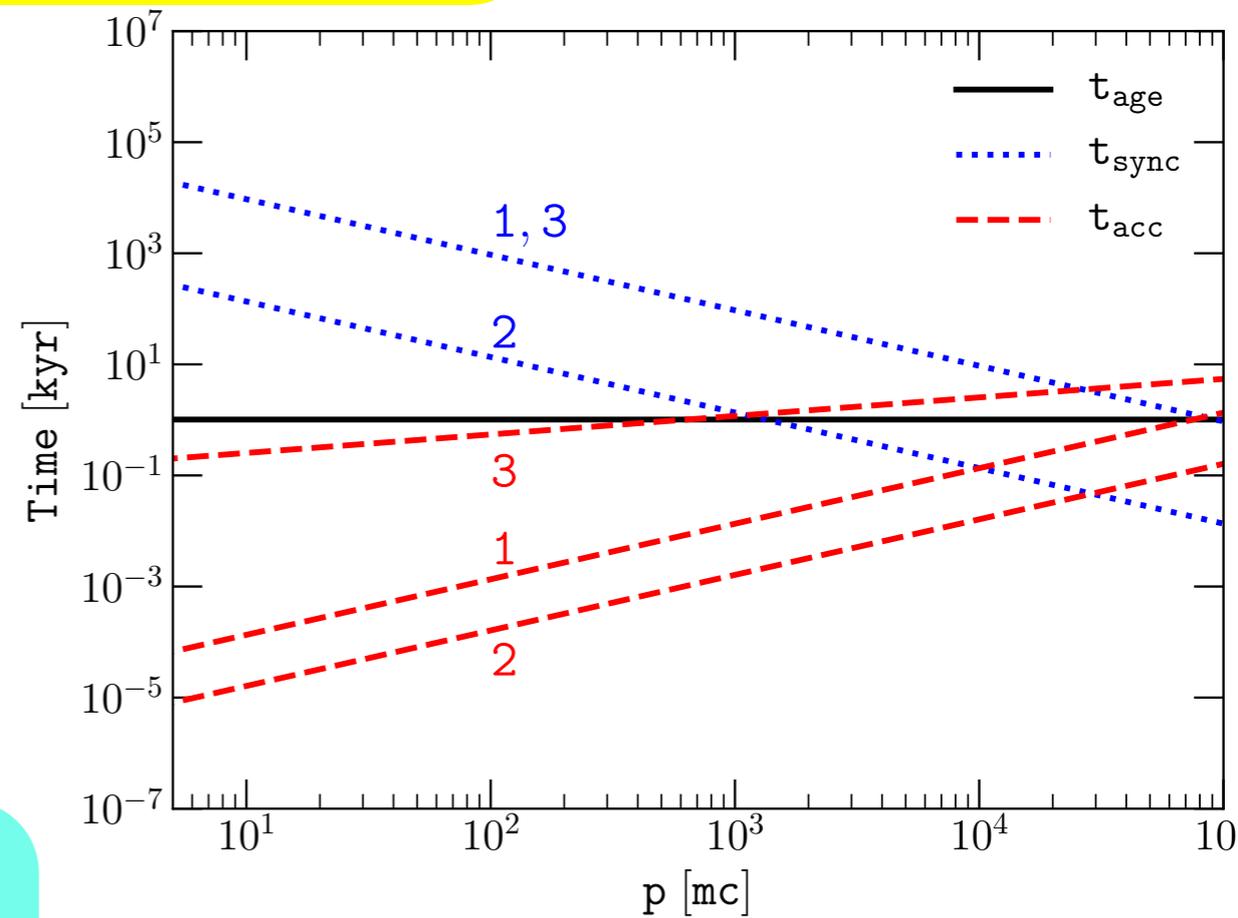
~~$$n_0 \sim 10^{-2} - 10^{-1} \text{ cm}^{-3}$$~~

Maximum energy of reaccelerated electrons?

$$\tau_{\text{acc}} = \min(\tau_{\text{sync}}, t_{\text{age}})$$

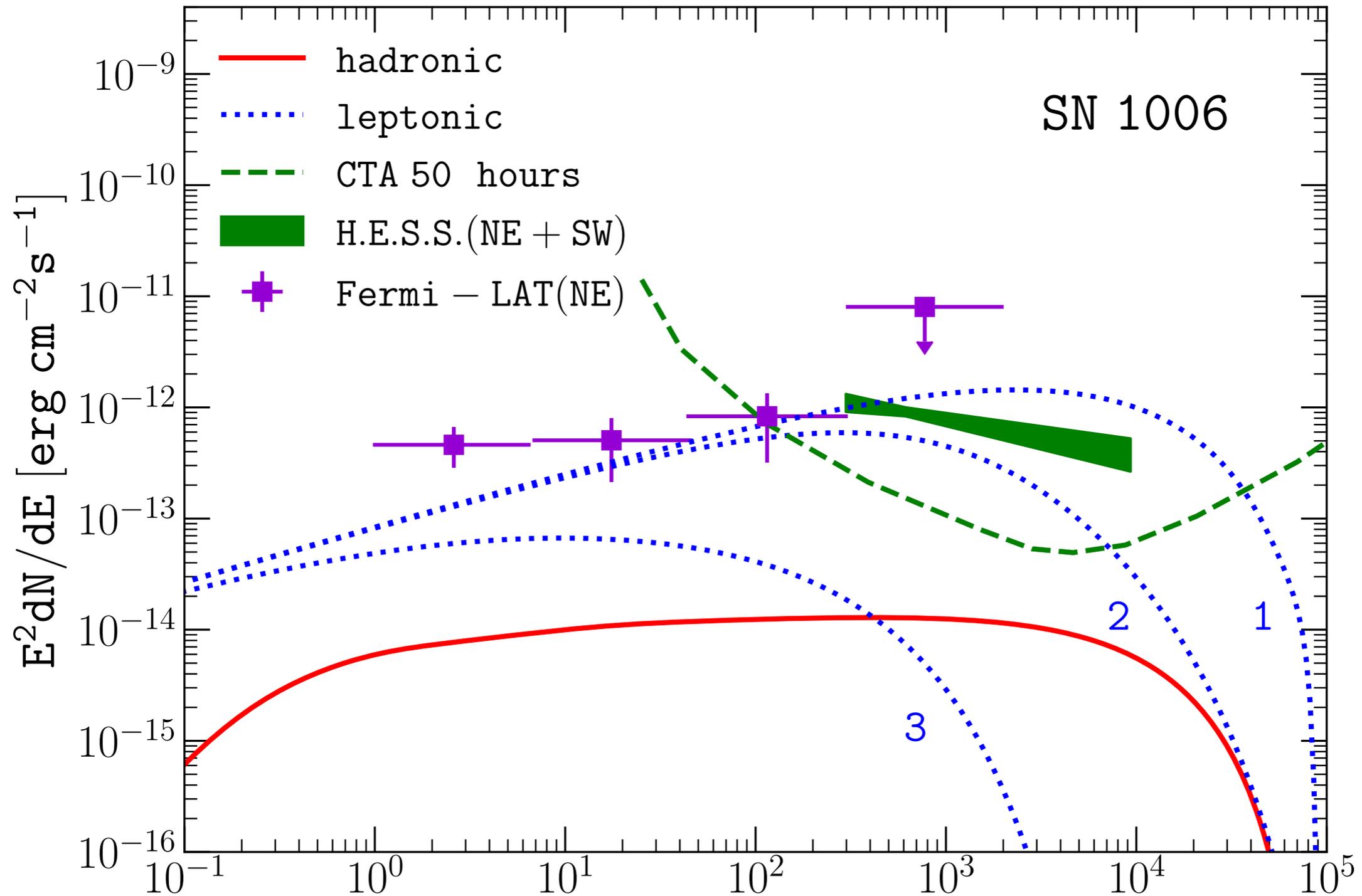
$$\tau_{\text{acc}} = \frac{3}{u_1 - u_2} \int_0^p \frac{dp'}{p'} \left( \frac{D_1(p')}{u_1} + \frac{D_2(p')}{u_2} \right)$$

- |    |                        |                        |
|----|------------------------|------------------------|
| 1. | $D(p) \propto p$       | $B_2 = 12\mu\text{G}$  |
| 2. | $D(p) \propto p$       | $B_2 = 100\mu\text{G}$ |
| 3. | $D(p) \propto p^{1/3}$ | $B_2 = 12\mu\text{G}$  |



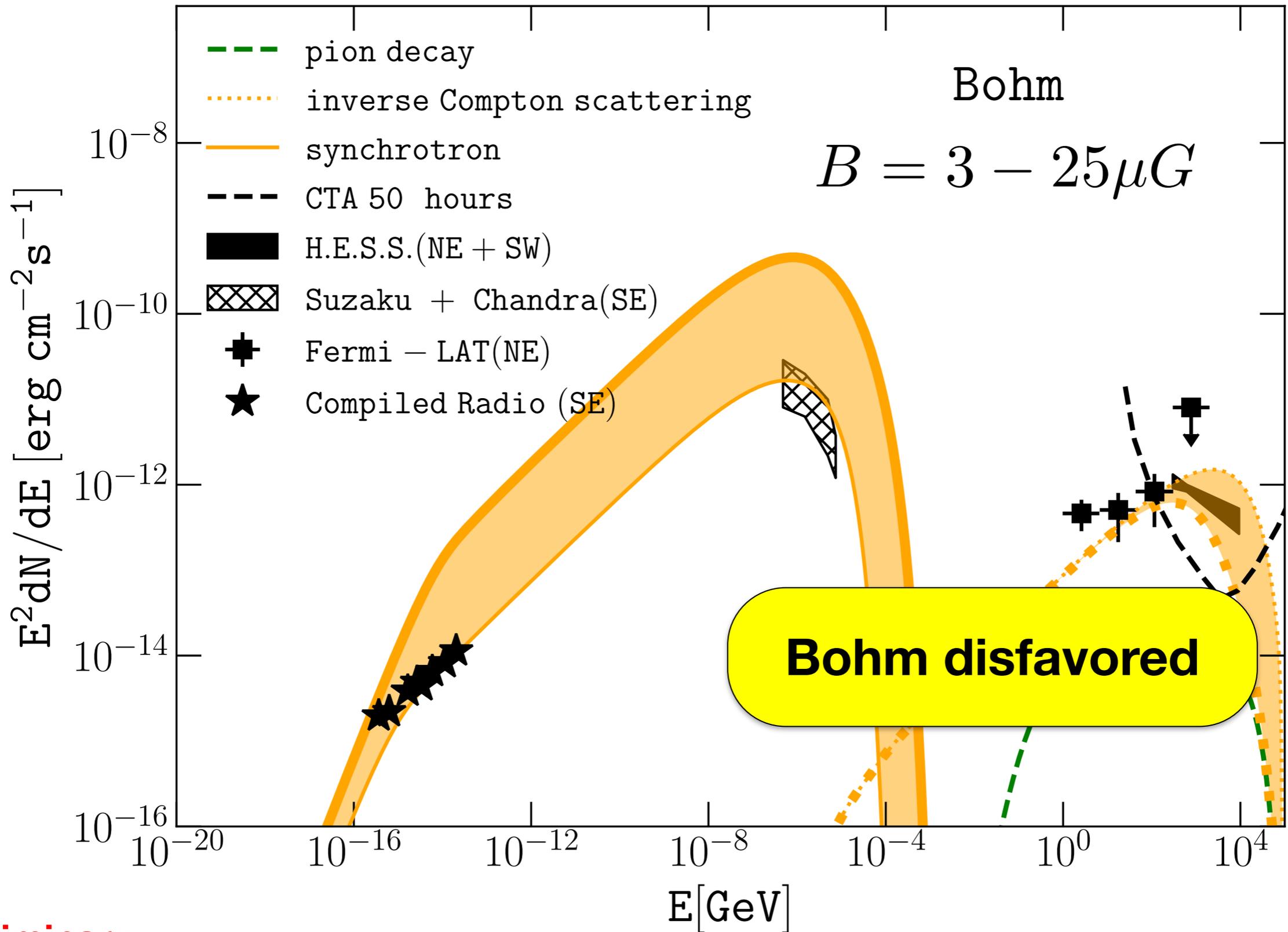
$$B_2 = r B_1$$

# Gamma rays from SN 1006



**Future observations can probe reacceleration and constrain the diffusion coefficient**

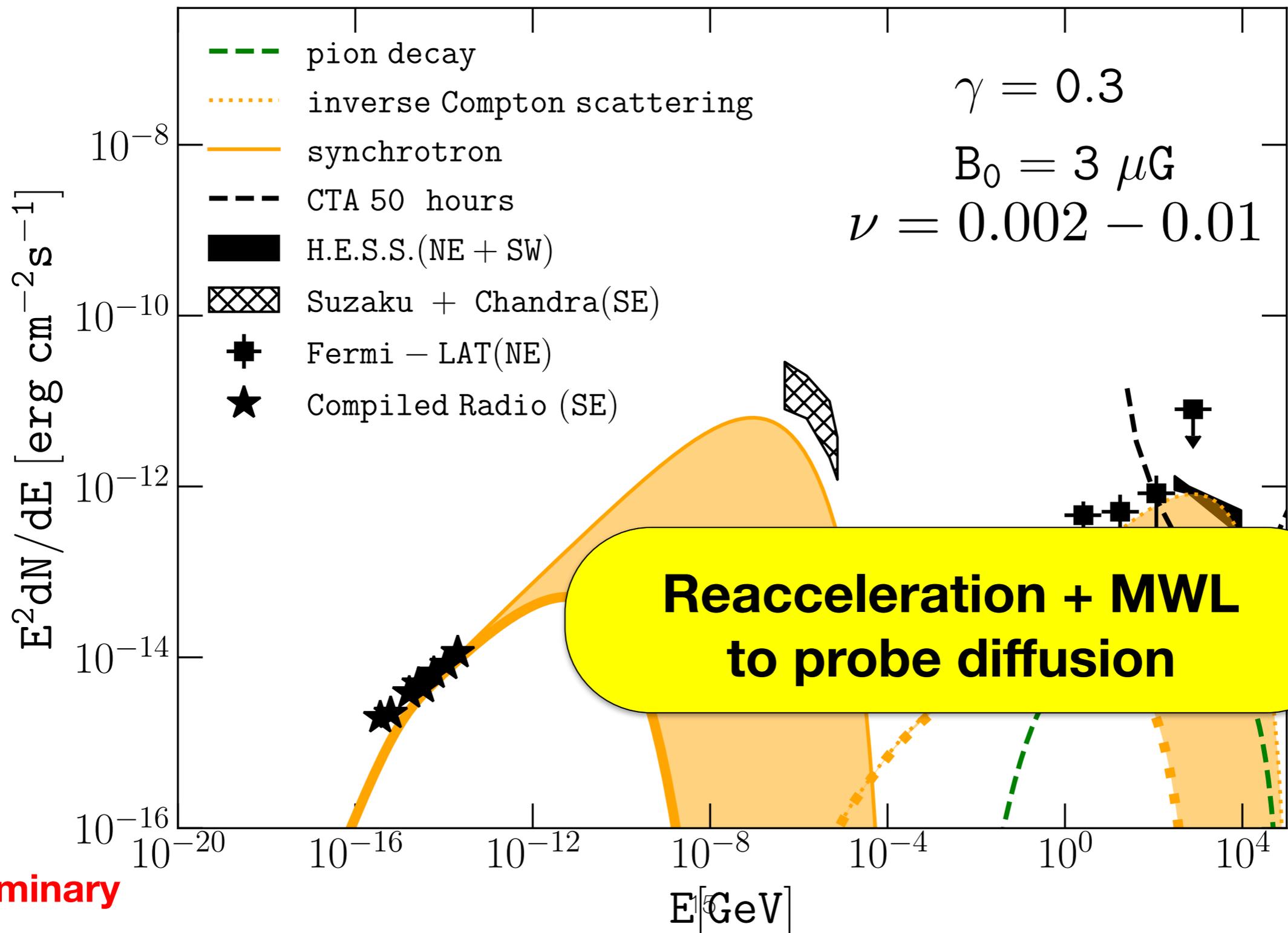
# Diffusion at SN1006



Preliminary

# Diffusion at SN1006

$$D = \nu 3 \times 10^{27} \left( \frac{p}{\text{GeV}} \right)^\gamma \left( \frac{B}{3\mu\text{G}} \right)^{-\gamma}$$

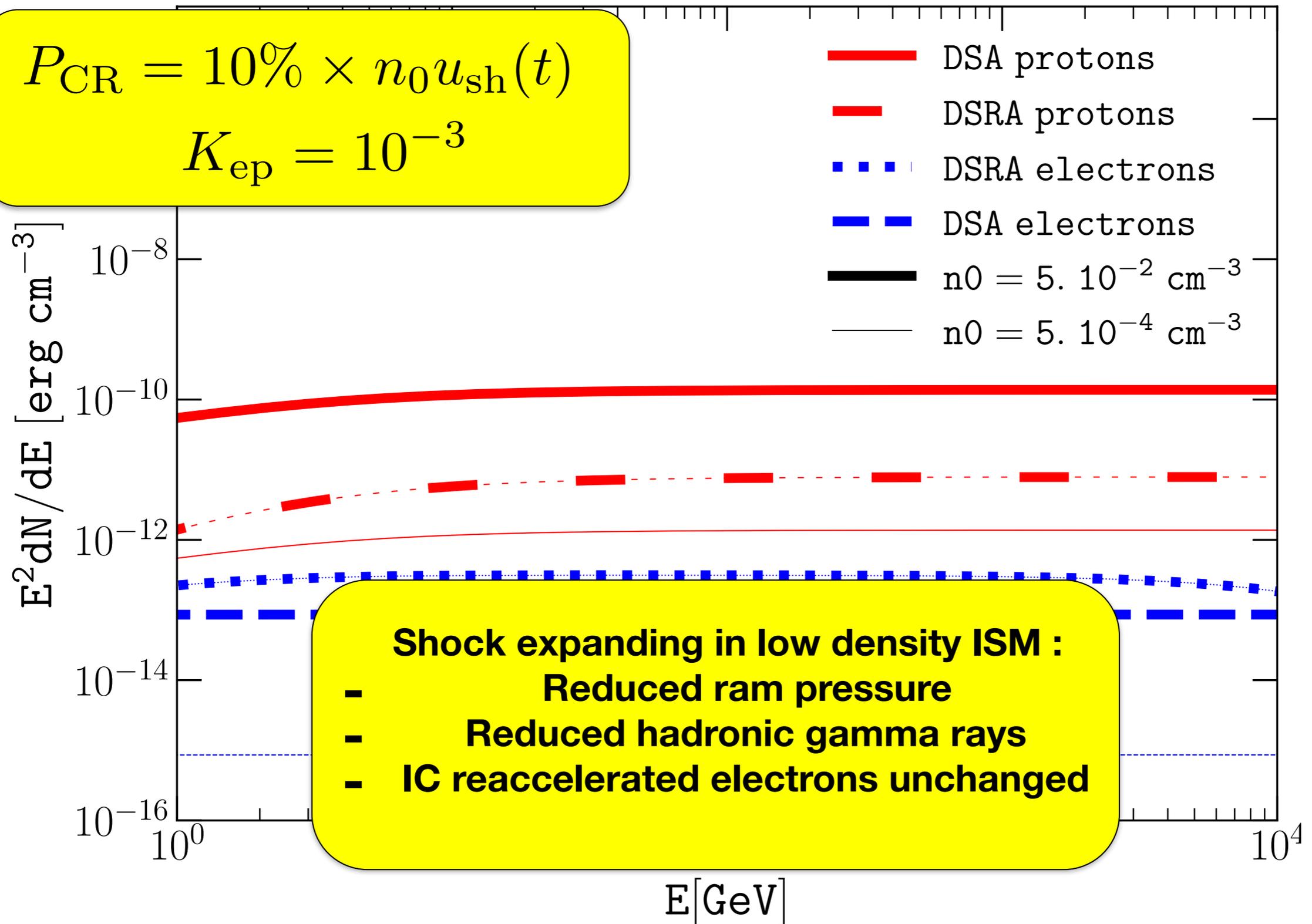


Preliminary

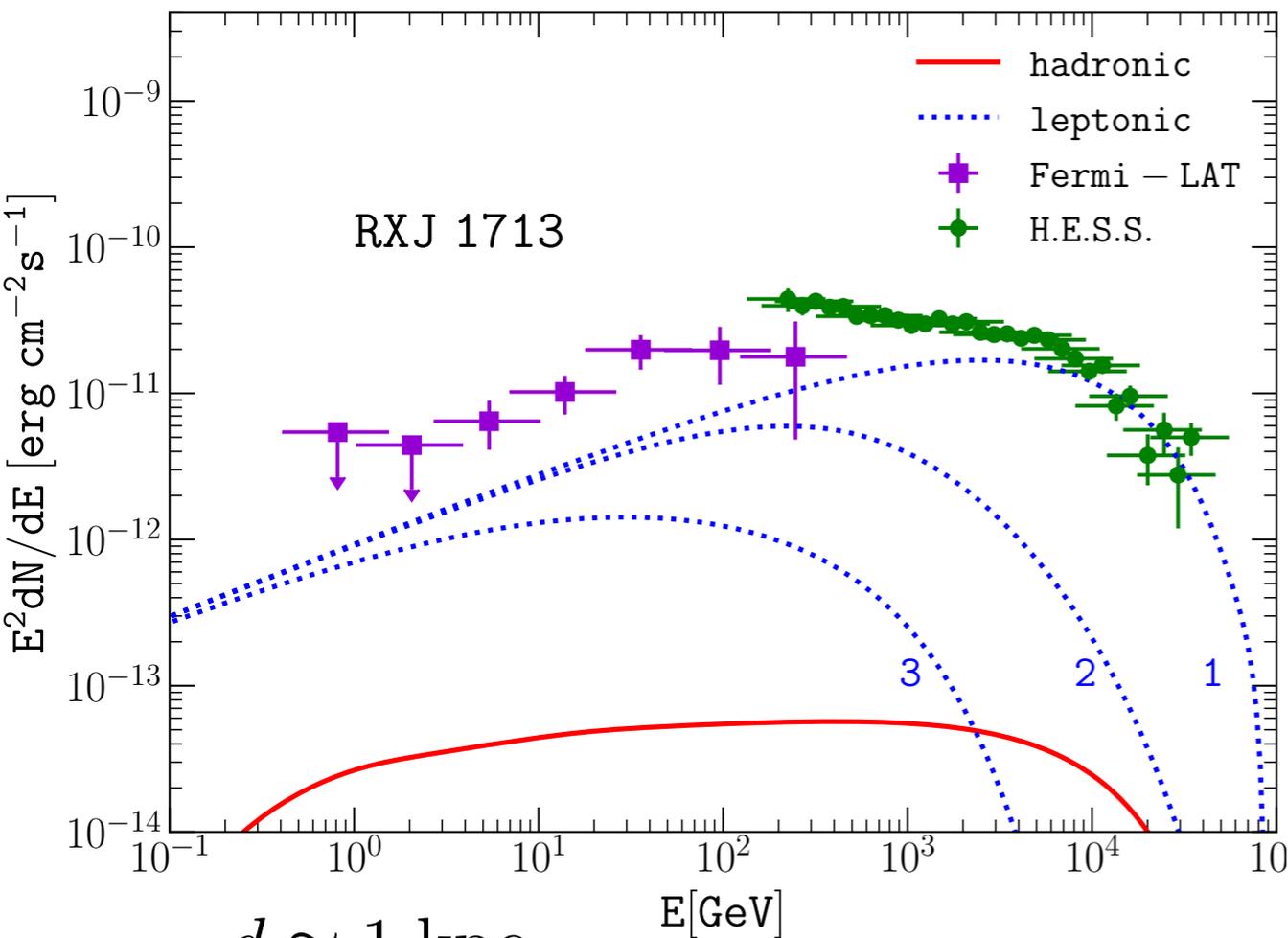
# Reaccelerated particles at SN 1006

$$P_{\text{CR}} = 10\% \times n_0 u_{\text{sh}}(t)$$

$$K_{\text{ep}} = 10^{-3}$$



# RXJ1713 and Vela Jr

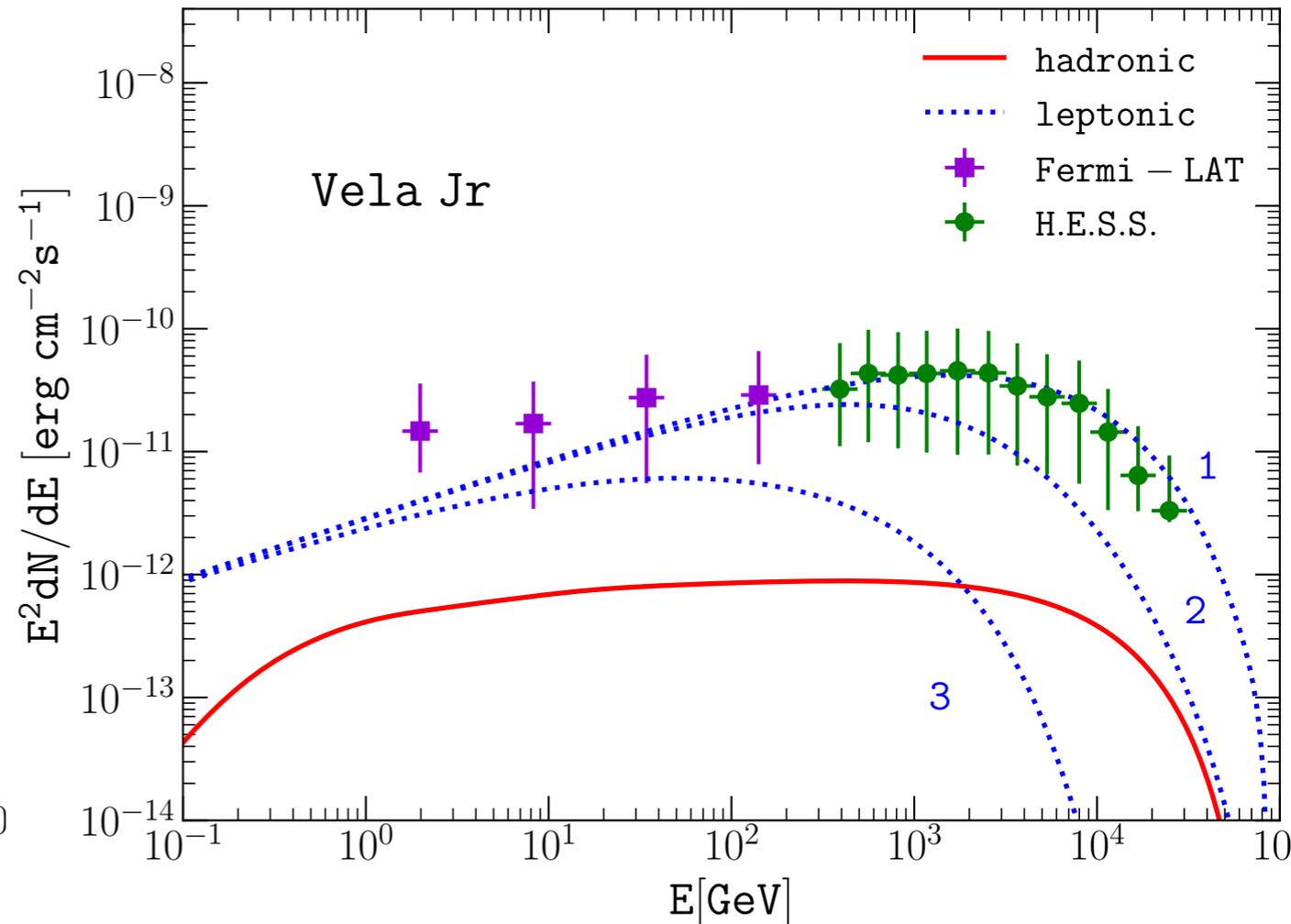


$d \approx 1$  kpc

$n_0 \approx 10^{-2} \text{ cm}^{-3}$

$R_{\text{sh}} \approx 10$  pc

$u_{\text{sh}} \approx 4 \cdot 10^8$  cm/s



$d \approx 0.750$  kpc

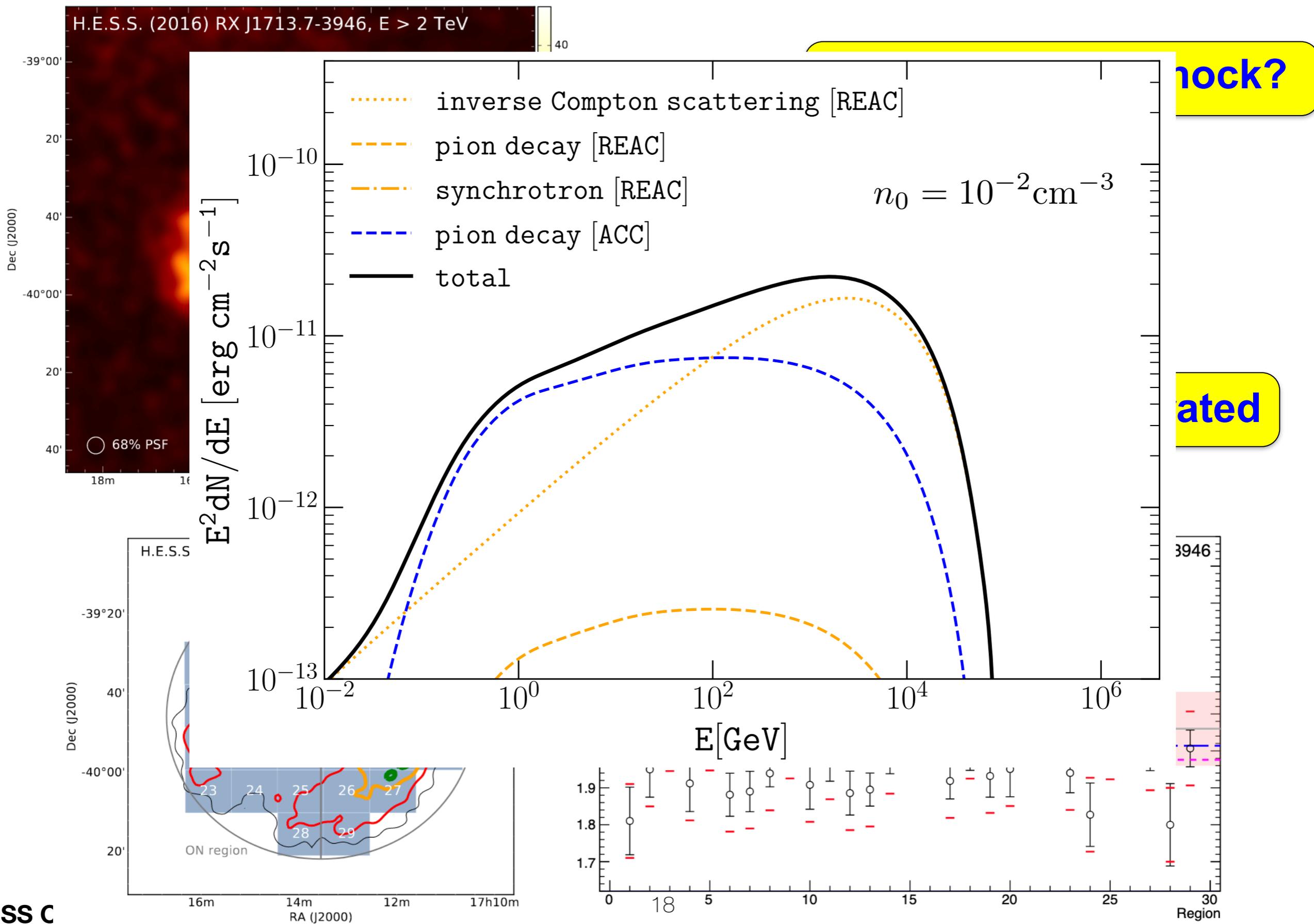
$n_0 \approx 10^{-1} \text{ cm}^{-3}$

$R_{\text{sh}} \approx 12$  pc

$u_{\text{sh}} \approx 3 \cdot 10^8$  cm/s

**Gamma rays from reaccelerated particles ~somewhat at the level of gamma rays from 'freshly' accelerated particles**

# The particle content



# Reacceleration over the SNR lifetime

$$R_{\text{sh}} \propto t^{2/5}$$

$$u_{\text{sh}} \propto t^{-3/5}$$

$$p_{\text{max}} = p_{\text{M}} t^{-\alpha}$$

$$N(p) = \int_{t_0}^{T_{\text{SN}}} dt n(p, t) 4\pi R_{\text{sh}}^2(t) u_{\text{sh}}(t)$$

**Number of freshly accelerated particles**

$$n_{\text{acc}}(p, t) \propto \xi n_0 u_{\text{sh}}^2(t) p^{-2} \exp\left[-\frac{p}{p_{\text{max}}(t)}\right]$$

**Total integrated spectrum**

$$N_{\text{acc}}(p) \propto \xi E_{\text{SN}} p^{-2} \ln\left(\frac{p_{\text{M}}}{p}\right)$$

**Number of reaccelerated particles**

$$n_{\text{reac}}(p, t) \propto p^2 f_0^{\text{reac}}(p) \\ \propto p^2 s \int_{p_0}^p \frac{dp'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$

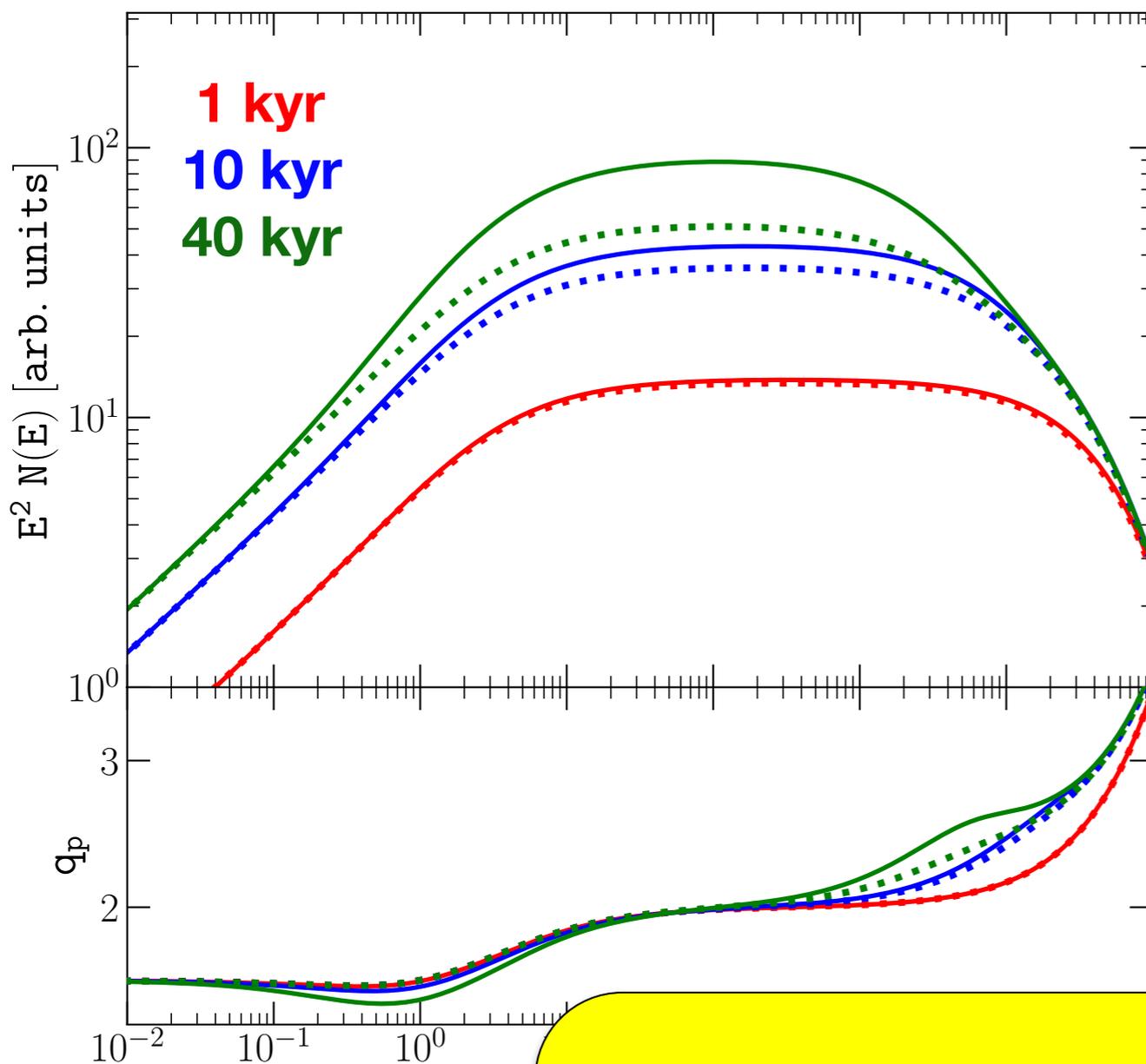
$$\propto p^{-2} \exp\left[-\frac{p}{p_{\text{max}}(t)}\right]$$

**Total integrated spectrum**

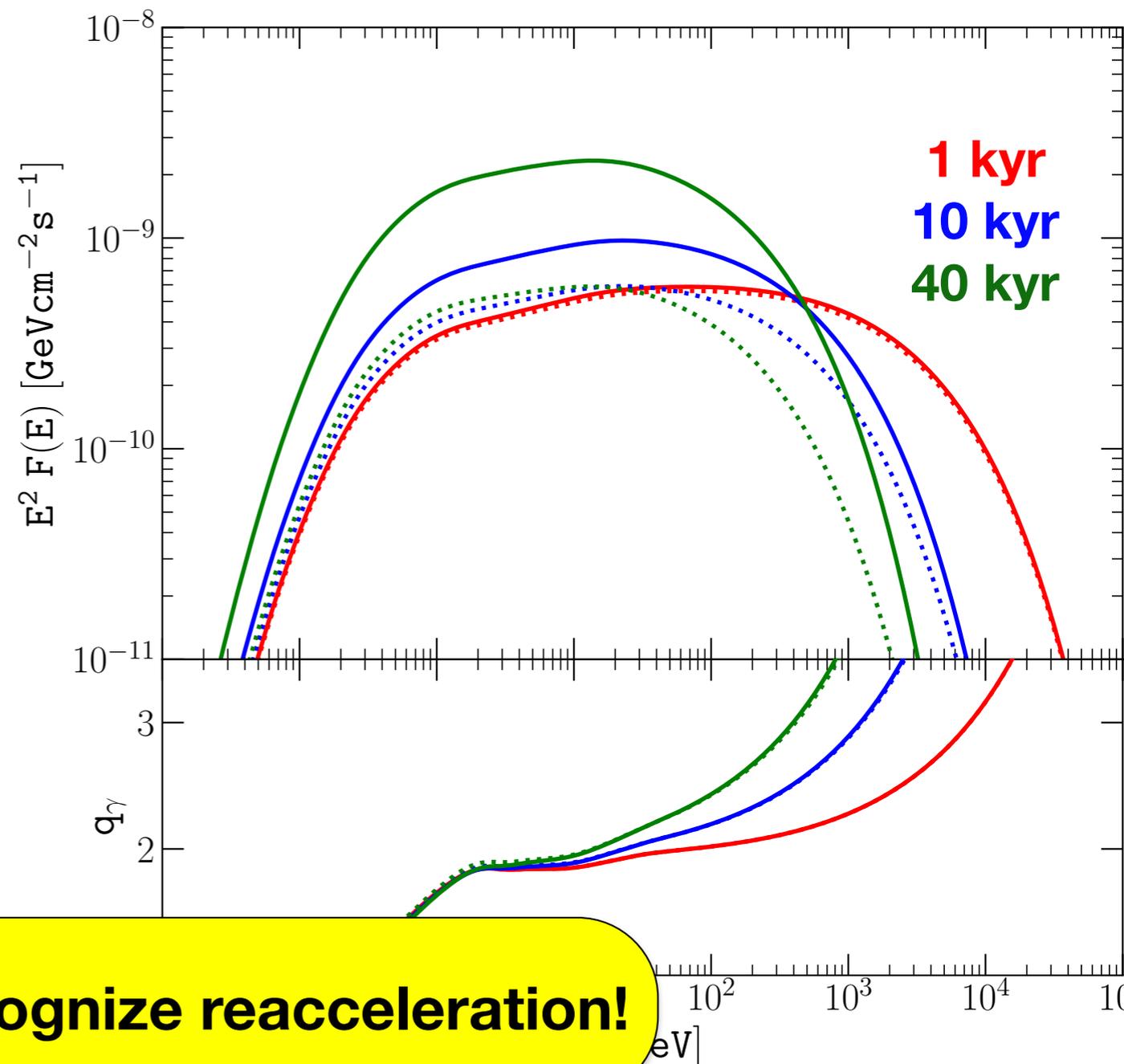
$$N_{\text{reac}}(p) \propto V_{\text{SN}} \left(\frac{T_{\text{SN}}}{t_0}\right)^{6/5} p^{-2} \exp\left[-\frac{p}{p_{\text{max}}(T_{\text{SN}})}\right]$$

# Reacceleration over the SNR lifetime

## Protons



## Gamma-rays

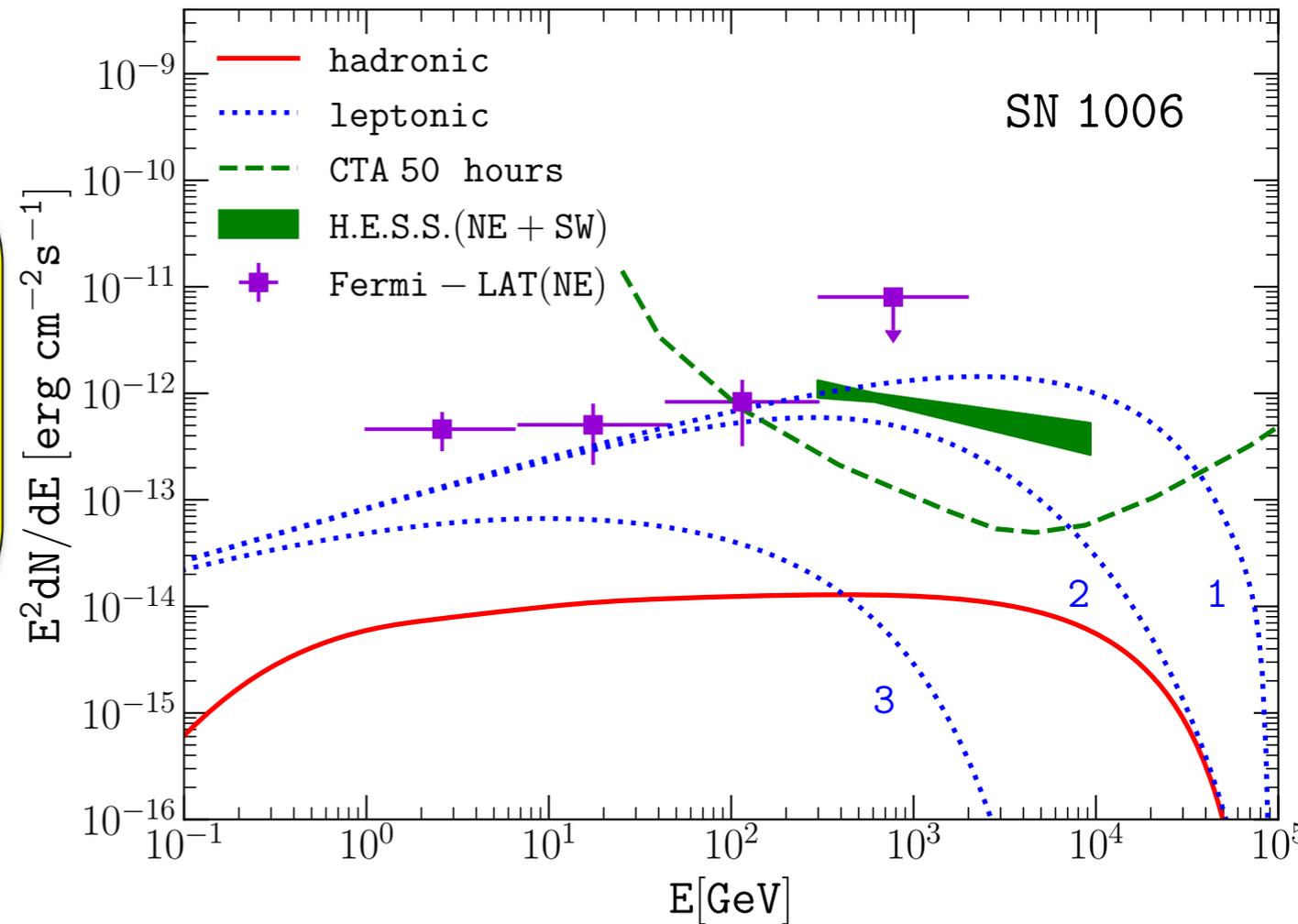


**It is not easy to recognize reacceleration!**

# Partial Conclusions

## Minimal assumptions:

- CR spectrum around SN 1006
- Diffusion regime/magnetic field
- Compression factor at the shock



1. The importance of reacceleration at SNRs
2. Possible tests with gamma-ray observations
3. SNRs low density environment
4. Open questions: contribution to the CR spectrum, maximum energy, secondaries

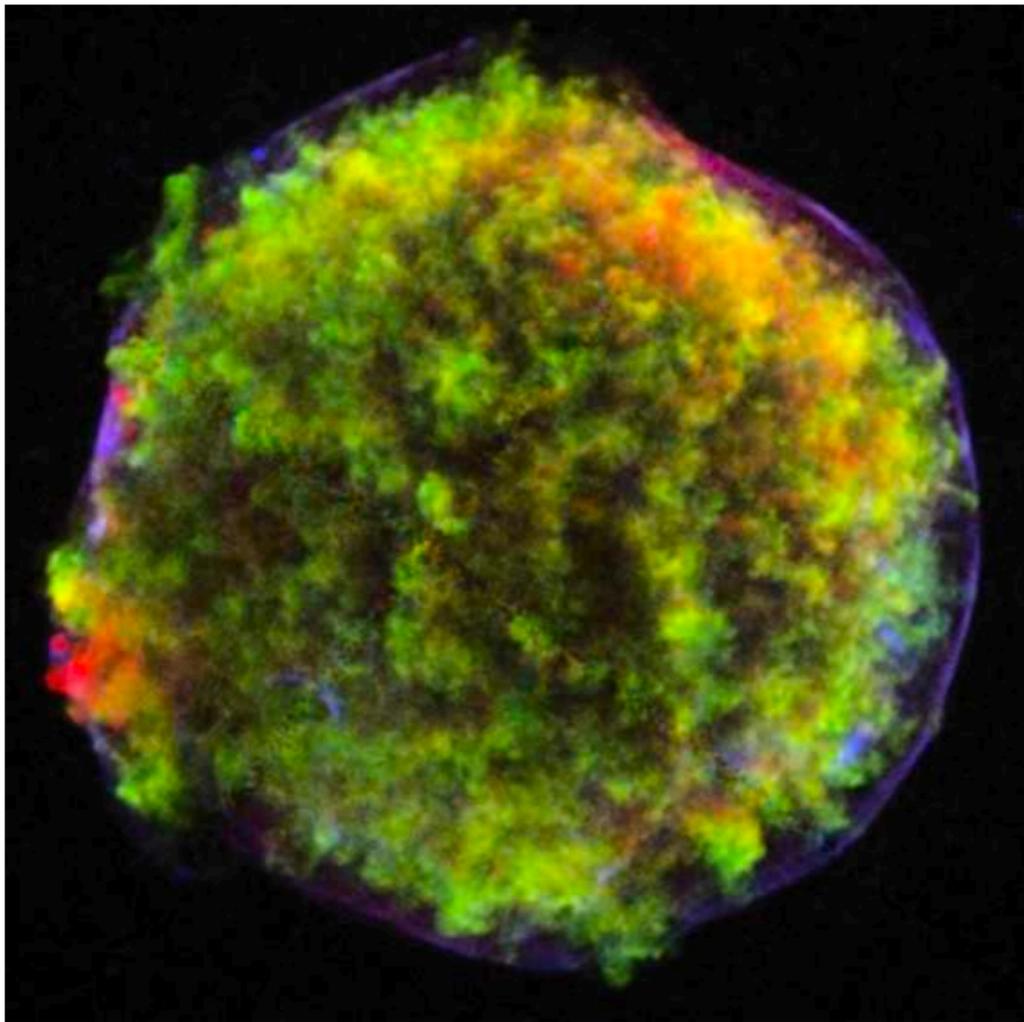
**A. Diffusive shock reacceleration  
at supernova remnant shocks**

**B. Pevatrons with CTA**

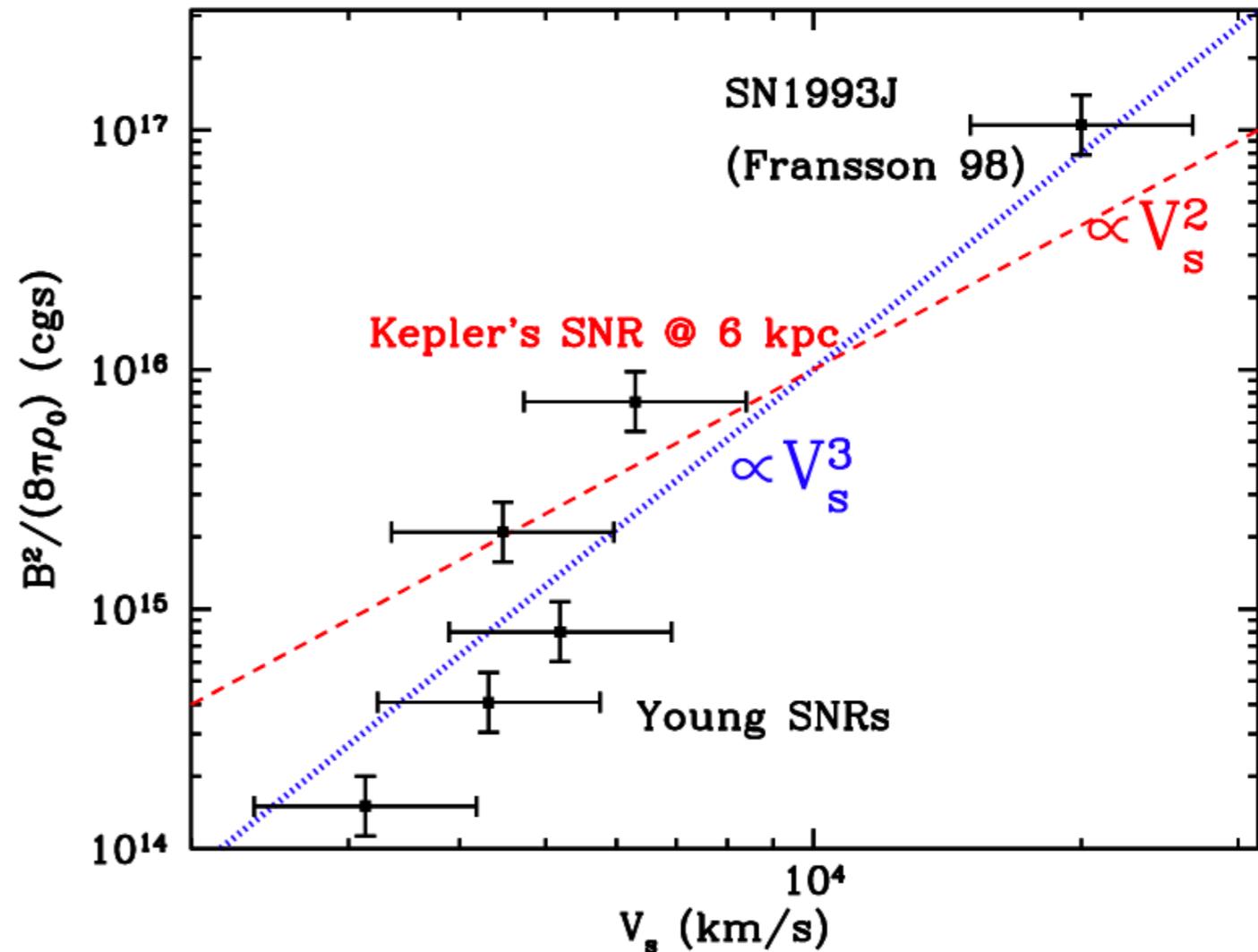
## B. SNR Pevatrons with CTA

How to reach PeV energies at a SNR?

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



Tycho with Chandra  
Warren et al. (2005)



Vink (2012)

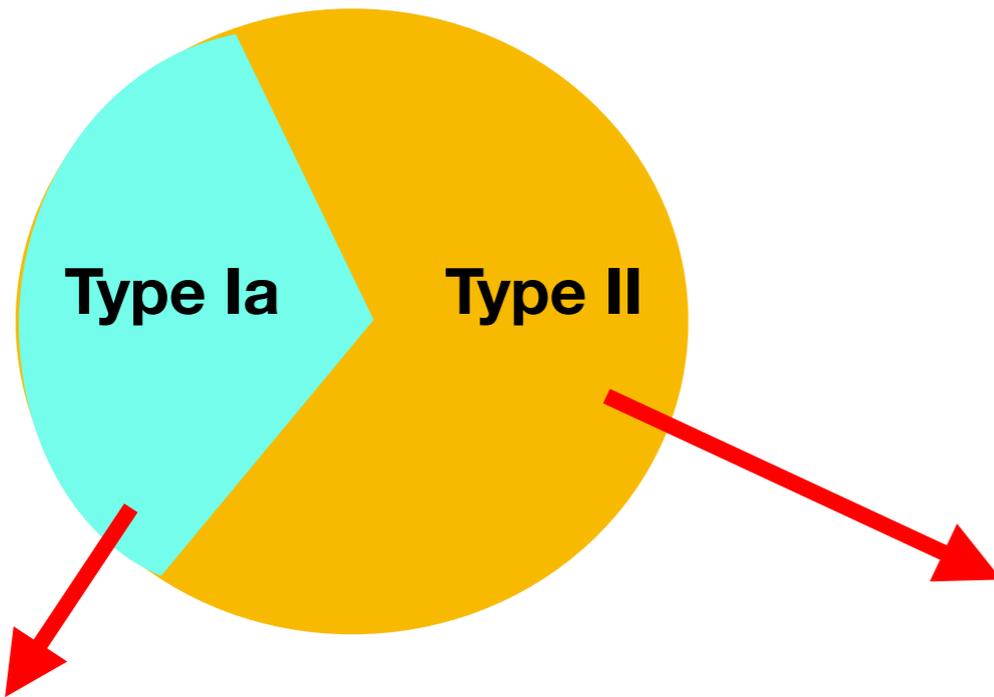
# Non-resonant streaming of CRs

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

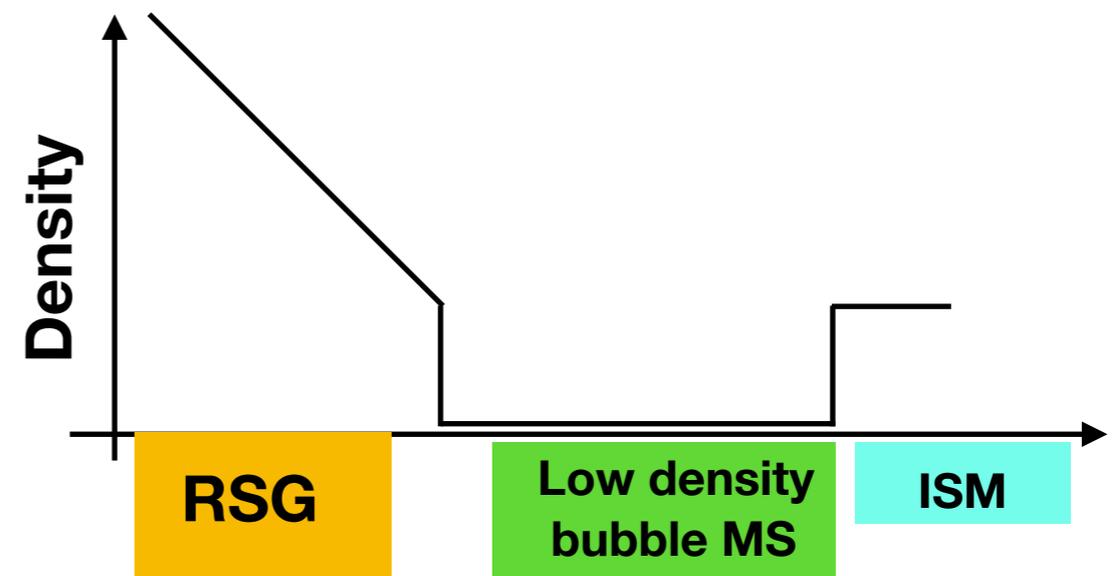
Growth rate of the non-resonant streaming instability

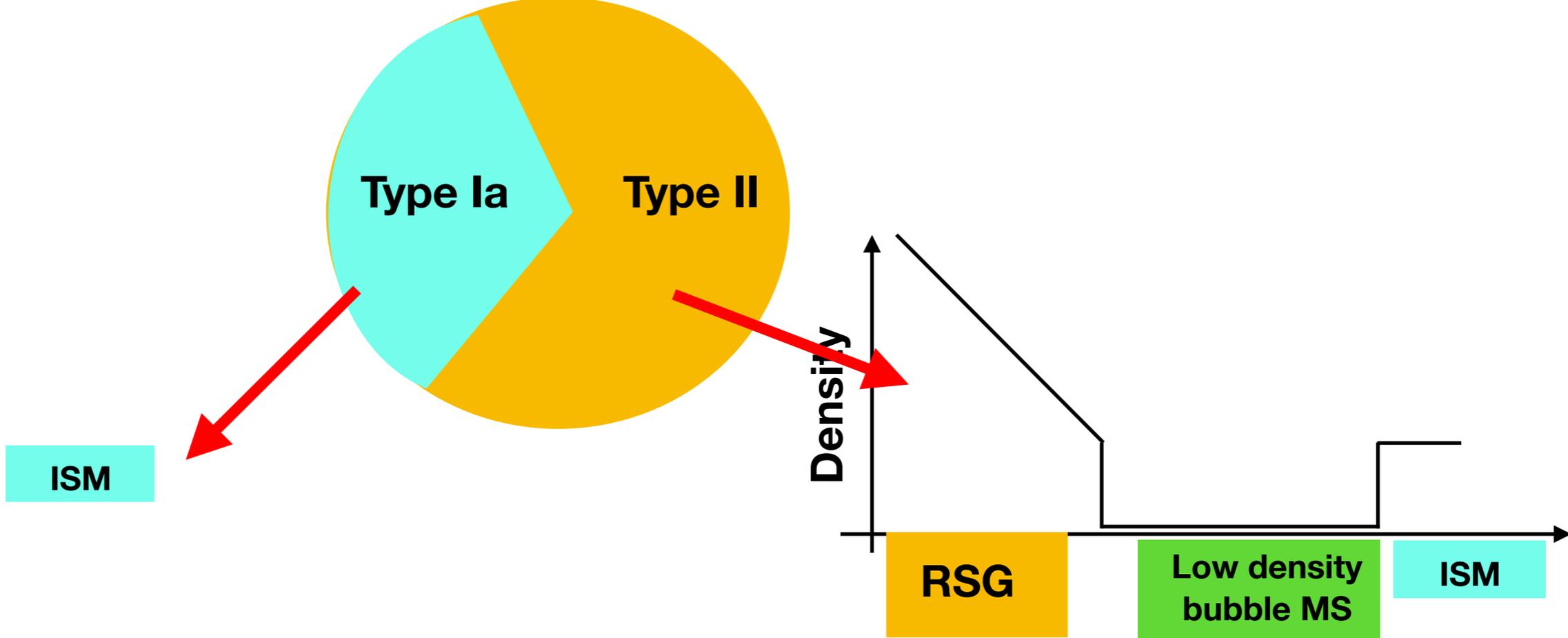
$$p_{\max}(t) \approx \frac{r_{\text{sh}}(t)}{10} \frac{\xi e \sqrt{4\pi\rho(t)}}{\Lambda} \left( \frac{u_{\text{sh}}(t)}{c} \right)^2$$

Different for different SNRs/SNe



ISM





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

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

**Chevalier (1999) Tang (2017)**

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

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

$$n_0$$

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

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

**Ostriker & McKee (1988)**  
Thin shell approximation

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

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

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

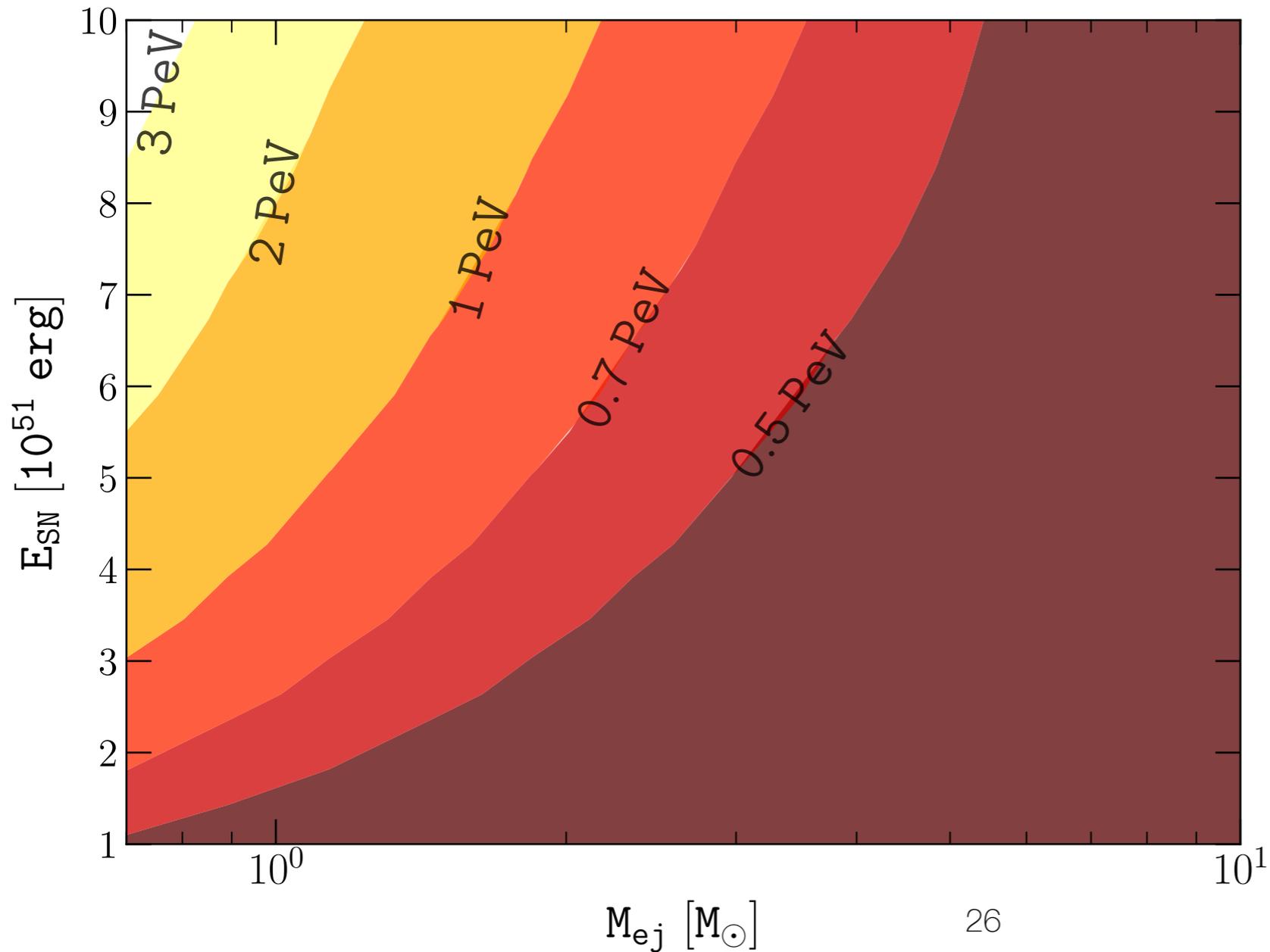
$$\dot{M}_{\text{MS}}, u_{\text{MS}}, n_0, M_{\text{ej}},$$

# Non-resonant streaming of CRs

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

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

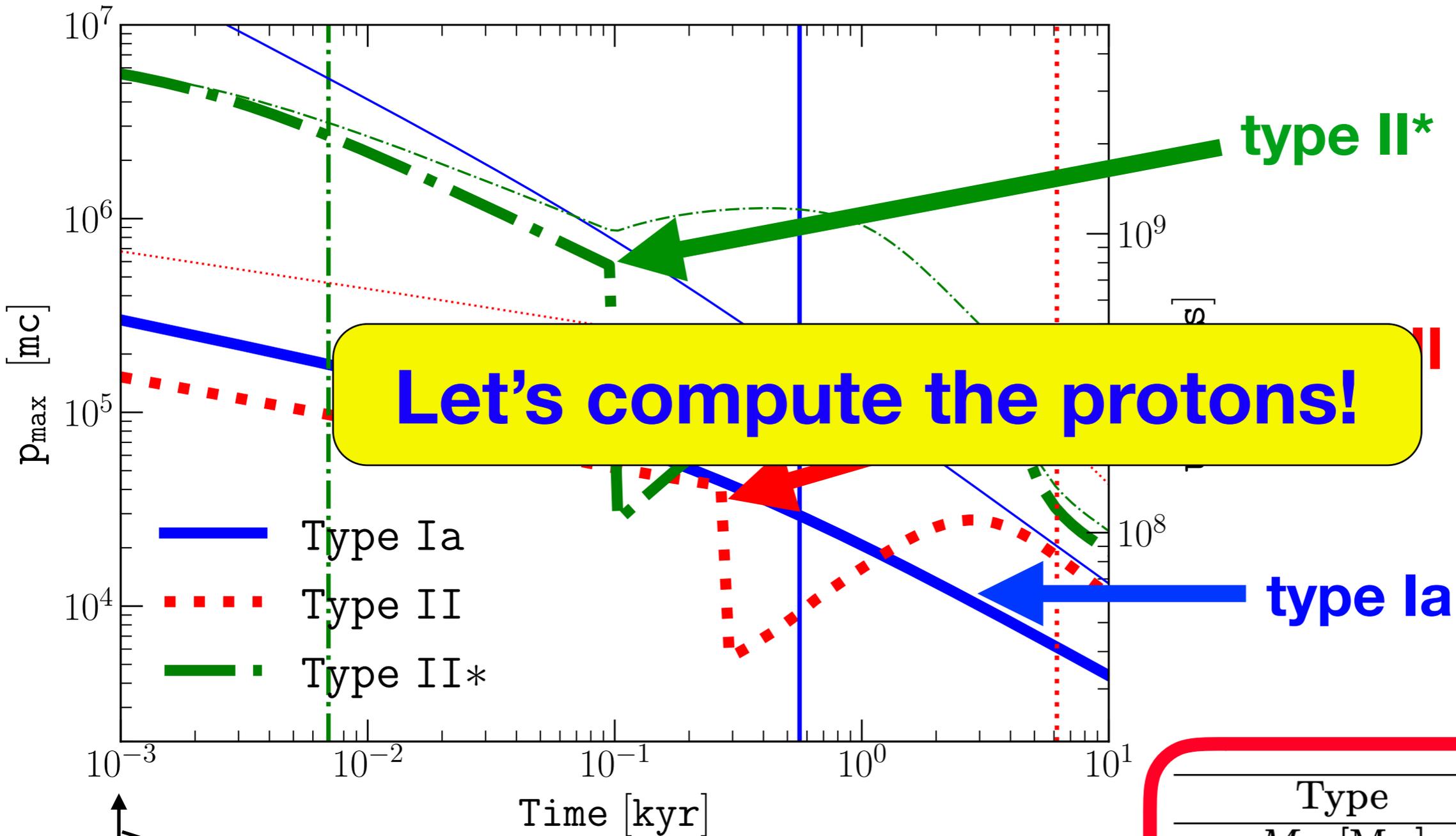
**Growth rate of the non-resonant streaming instability**



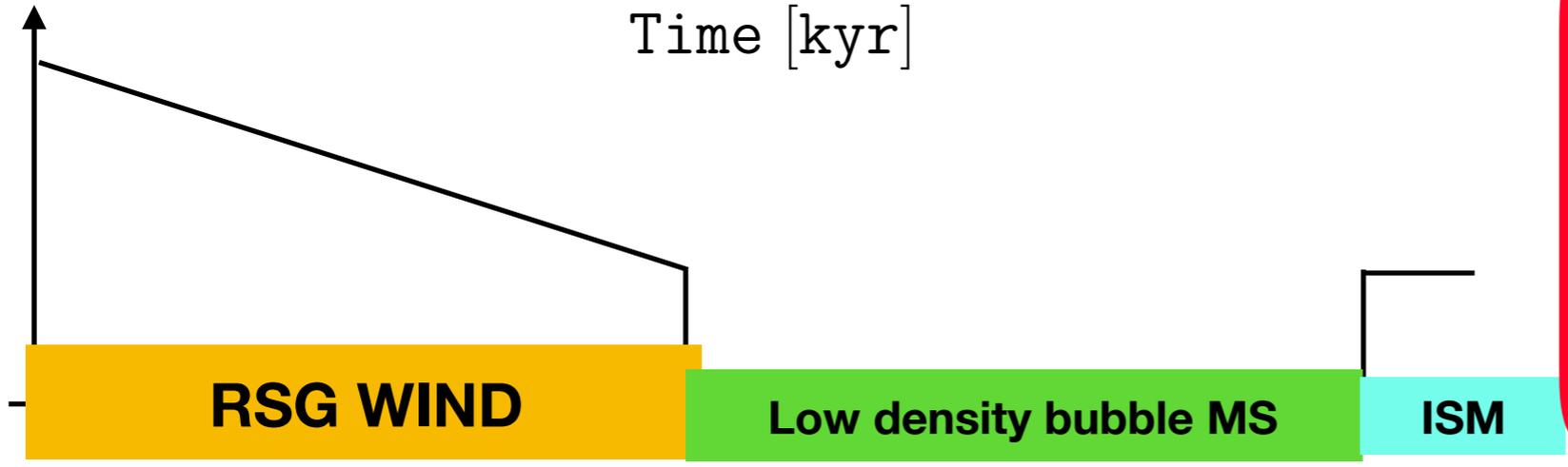
$$\dot{M}_{\text{RSG}} = 10^{-4} M_{\odot}/\text{yr}$$

$$\xi = 0.1$$

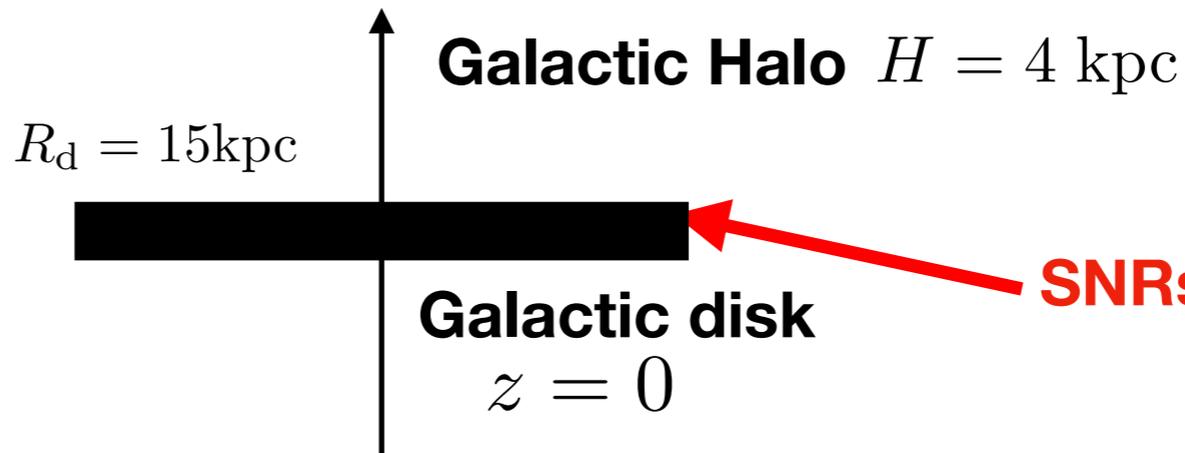
# Type Ia, type II, type II\*



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

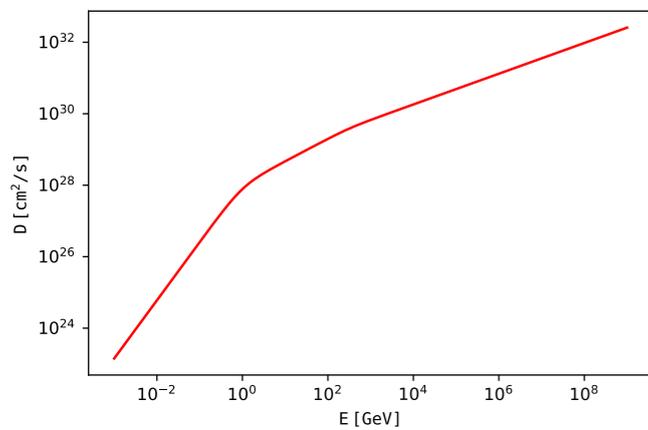
Advection

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

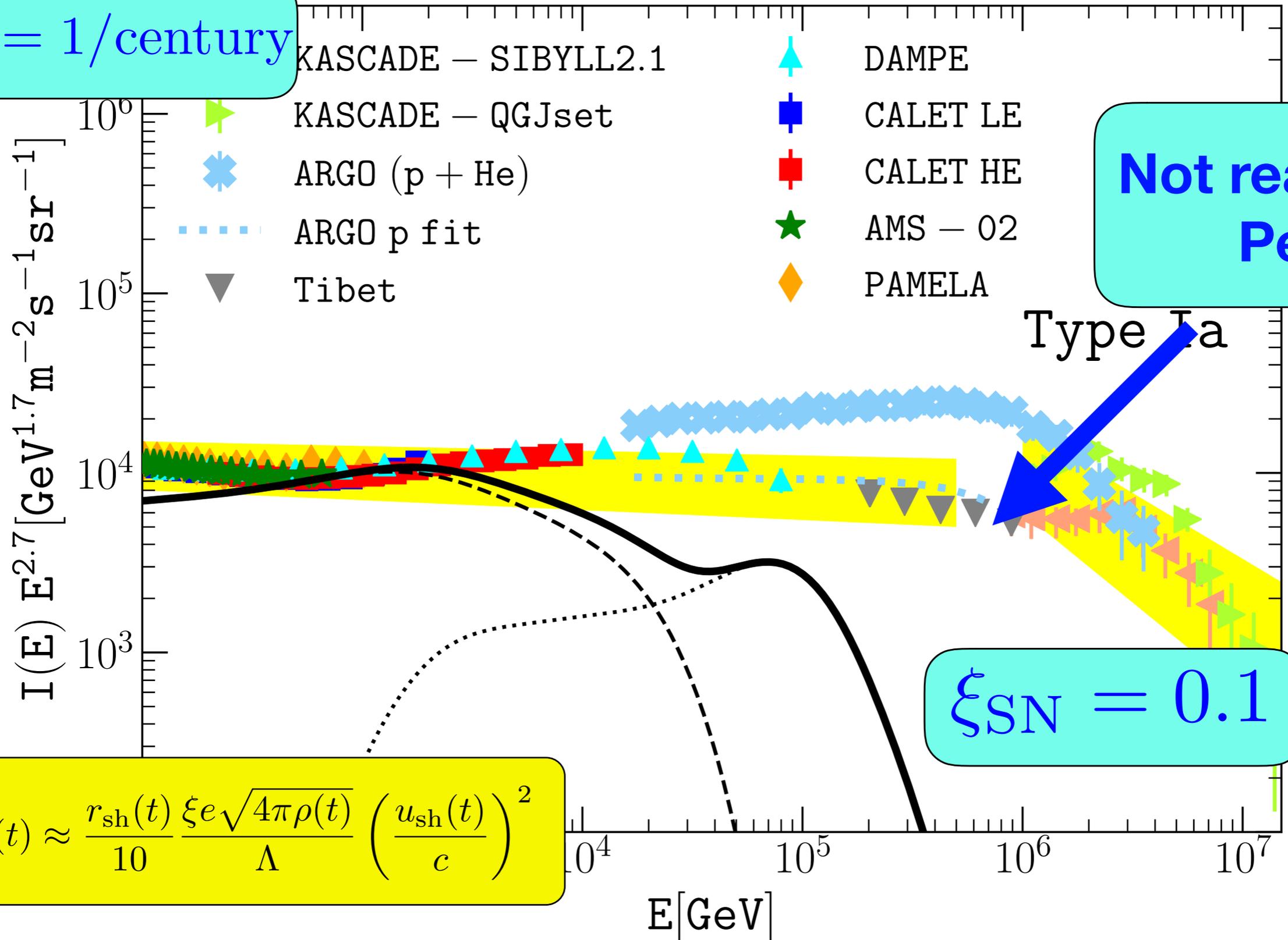
$$q_{\text{acc}}(p) dp = \frac{\nu_{\text{SN}}}{\pi R_d^2} \int_{t_0}^{T_{\text{SN}}} dt \frac{4\pi}{\sigma} r_{\text{sh}}^2(t) u_{\text{sh}}(t) f_0(p', t) dp'$$

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 type Ia

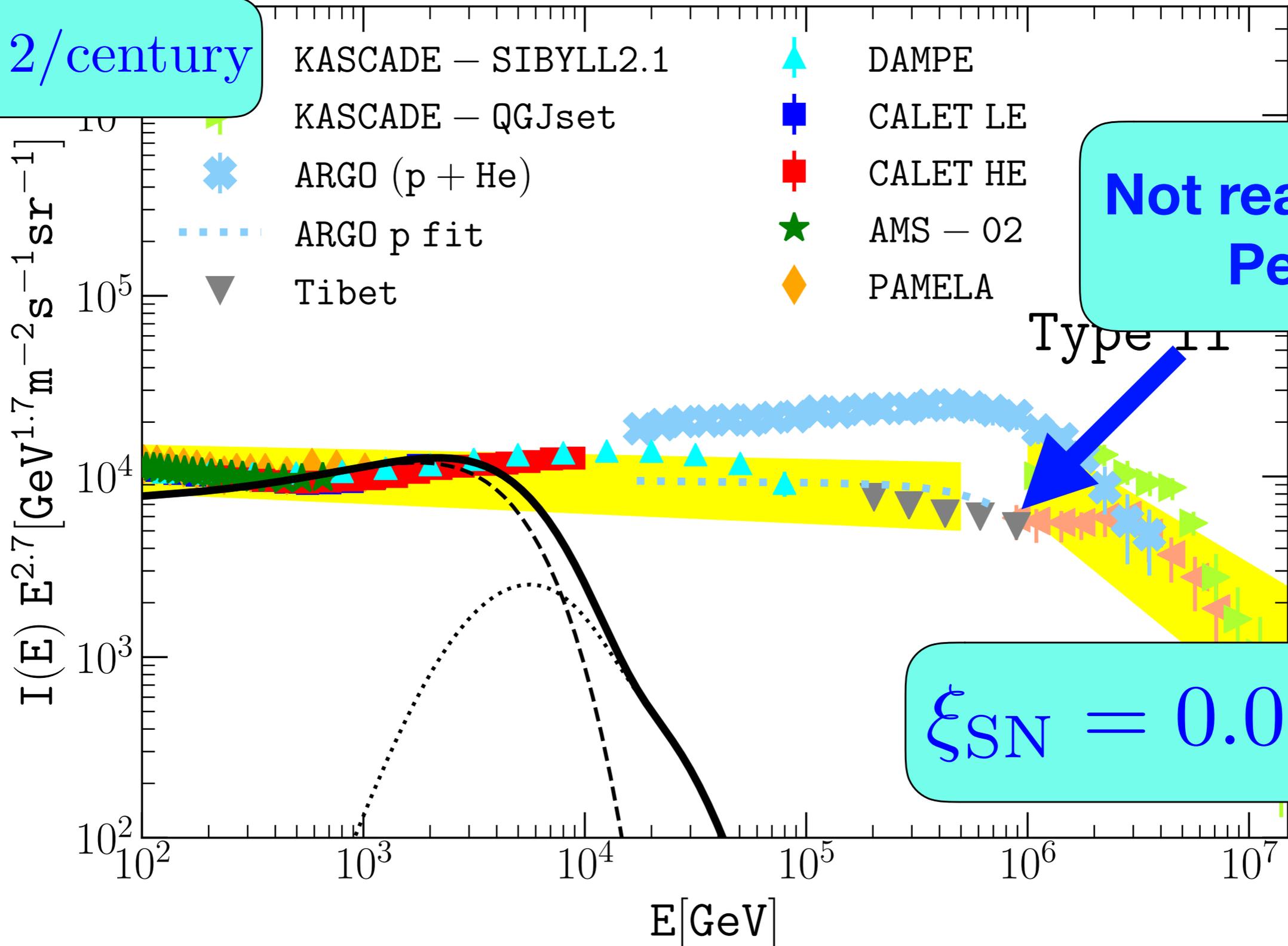
$\nu_{\text{Ia}} = 1/\text{century}$



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

# Protons from type II

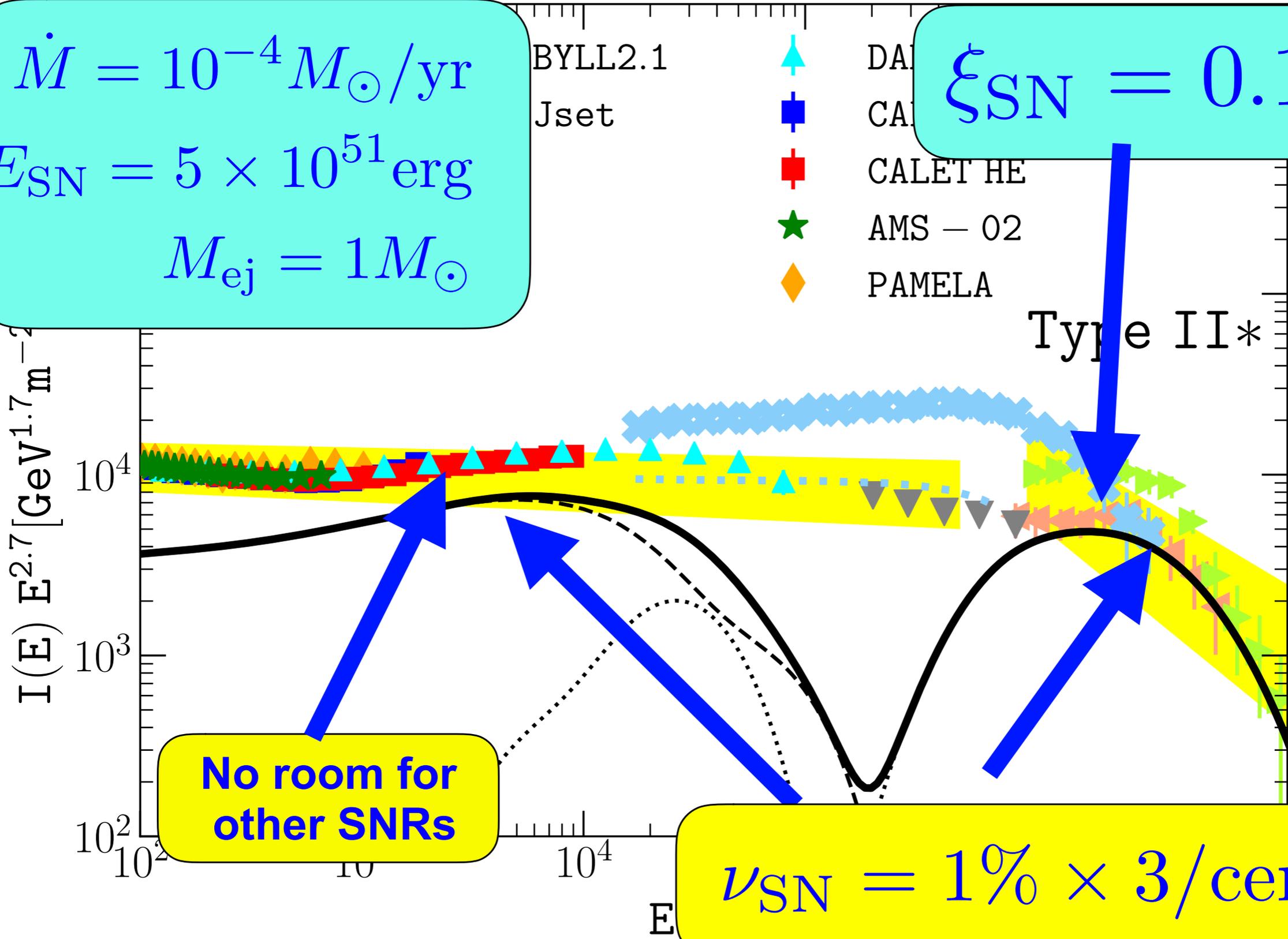
$\nu_{II} = 2/\text{century}$



# Protons from type II\*

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

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

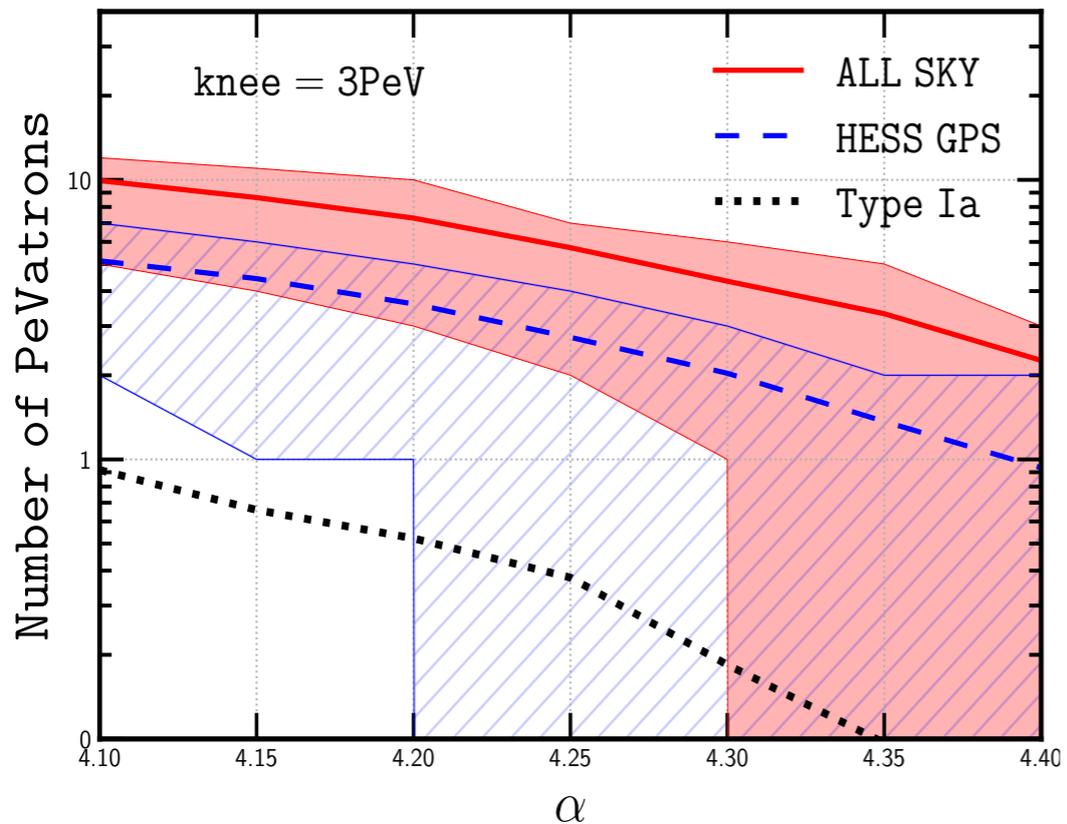
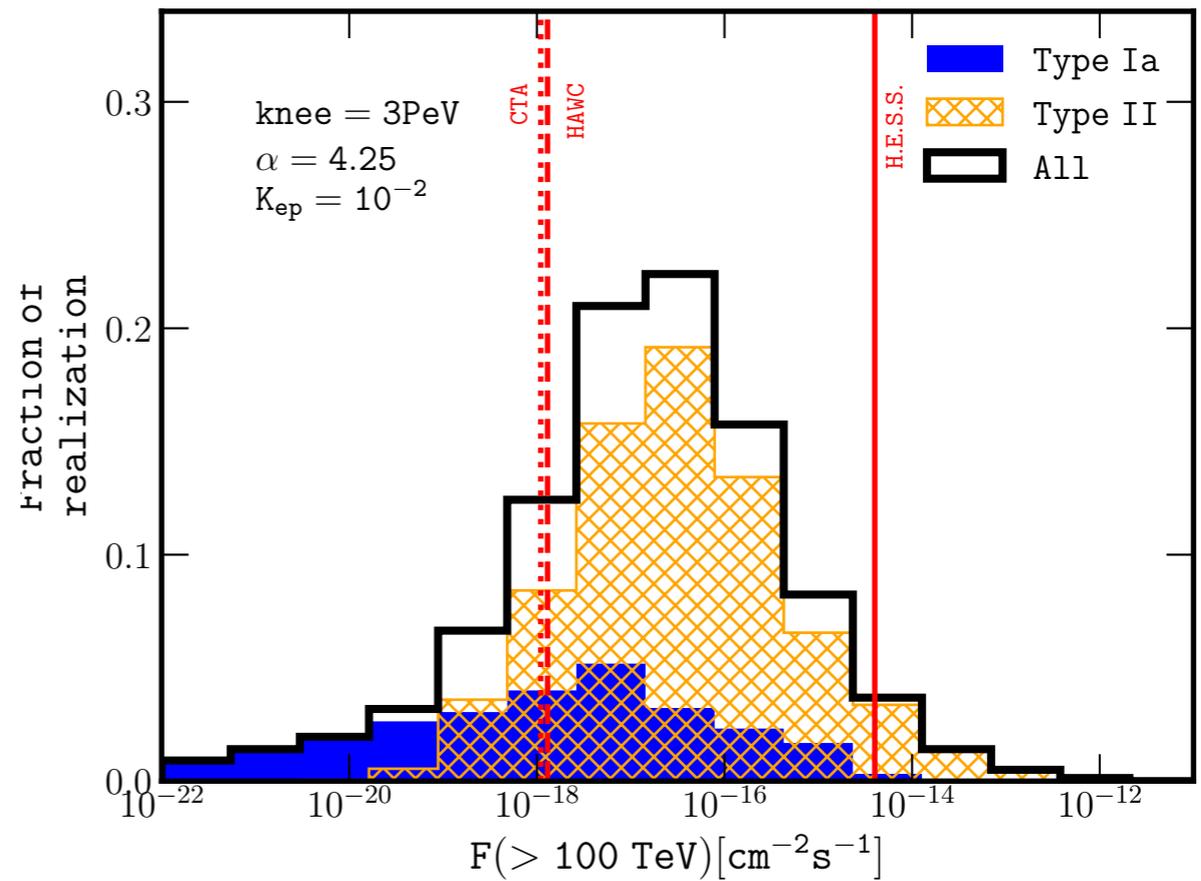
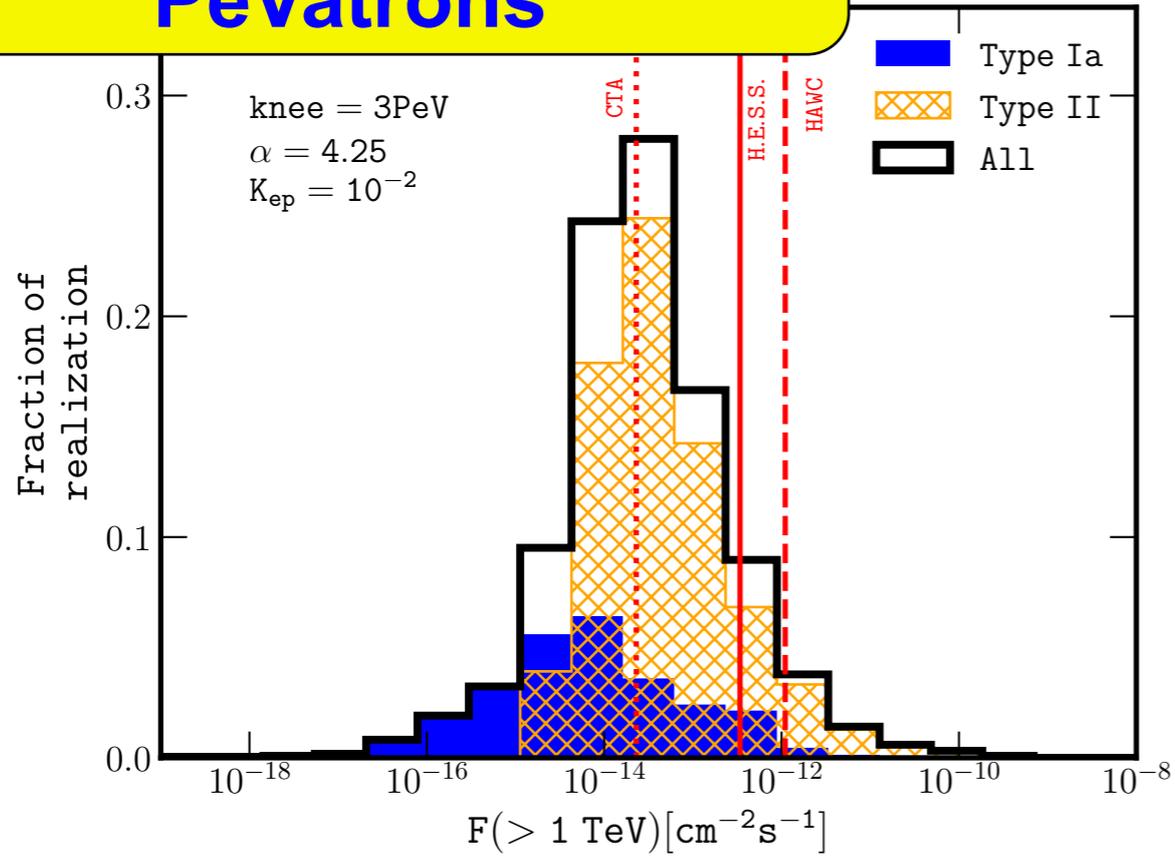


No room for other SNRs

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

# Pevatrons with CTA

Assuming all SNRs are PeVatrons

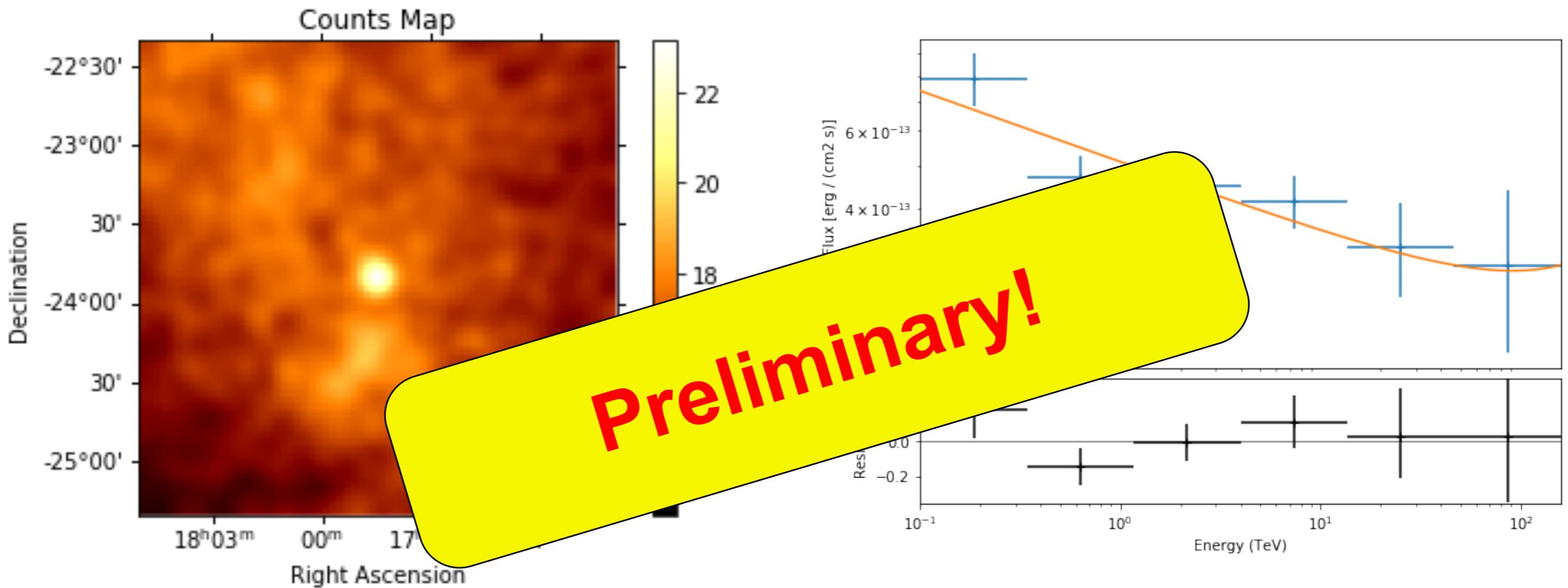


If only Type II\* are Pevatrons  
 $\nu_{SN} = 1\% \times 3/\text{century}$   
 $\rightarrow 0$

PC, Blasi, Amato ( submitted 2020)

PC, Gabici, Terrier, Humensky (2018)

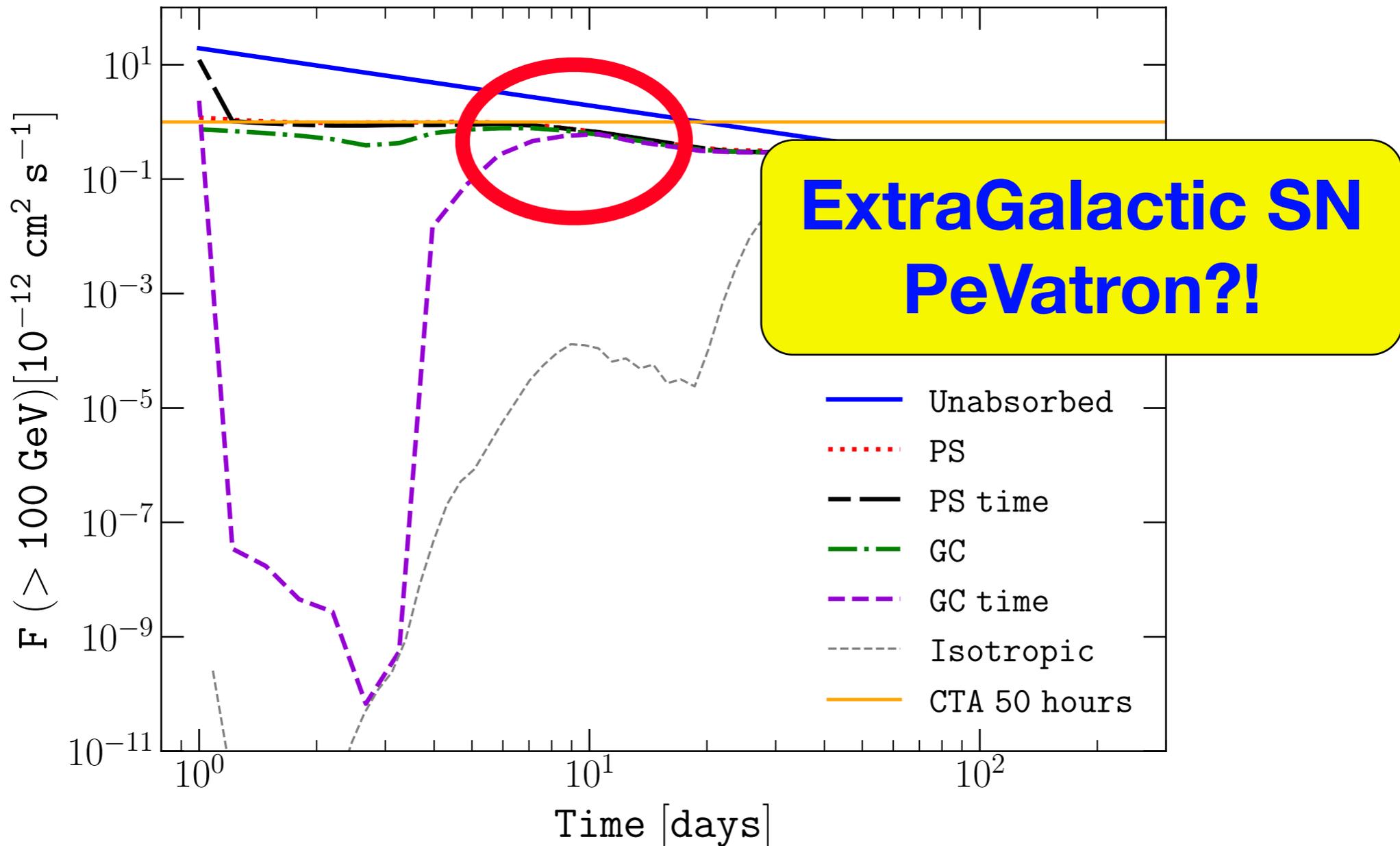
# Pevatrons with CTA



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?

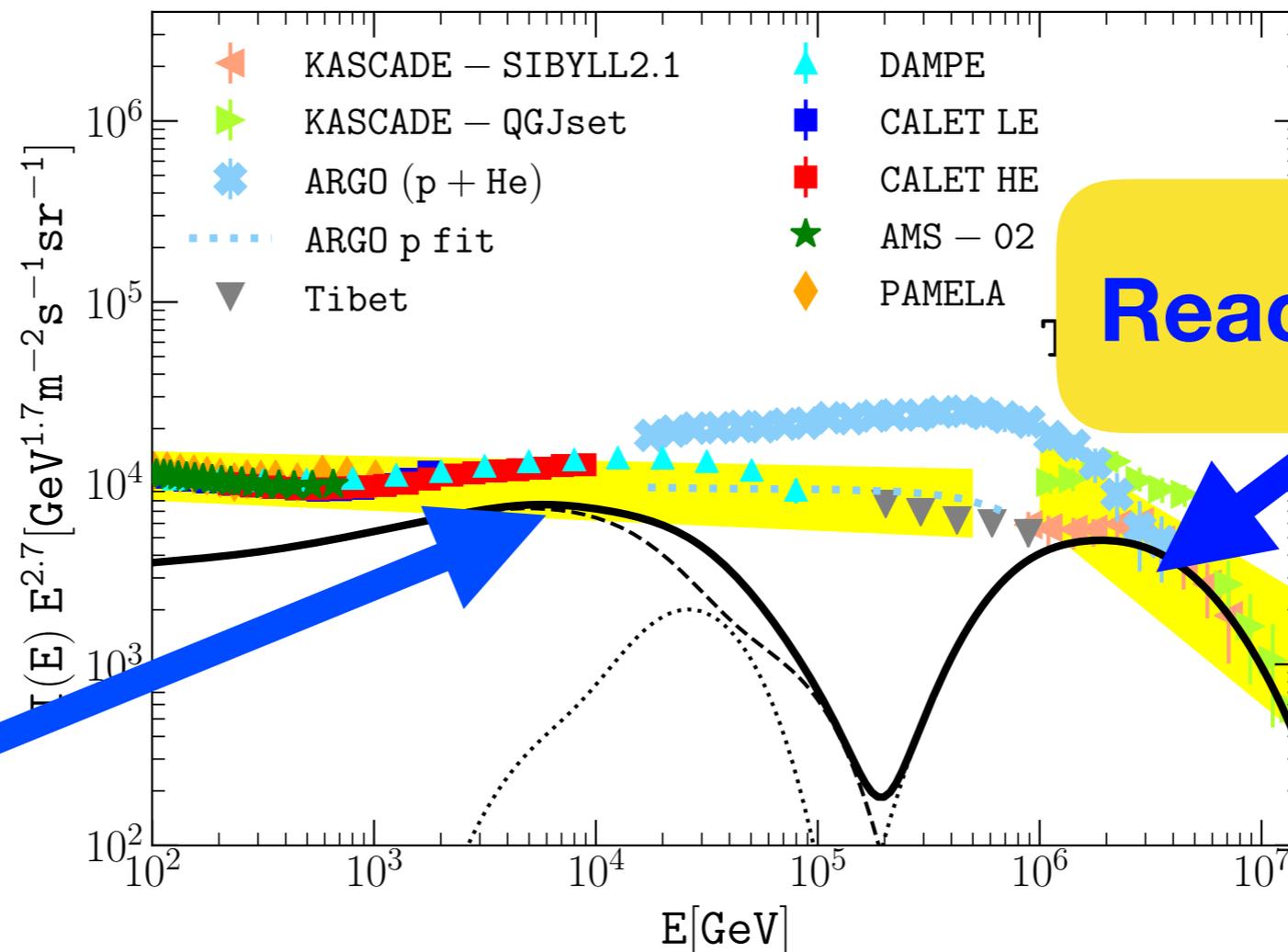


Pevatron working group: Acero, Anguner, Cassol, Costantini, Giunti, Khelifi, Trichard, Verna, PC

# 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/?)
5. The Knee is not the knee (He?)



**Mimicking bump?**

**Reaching PeV**

# Conclusions

## A. Diffusive shock reacceleration at supernova remnant shocks

- \* Could play an important role (e.g. SN1006)
- \* Help make sense of steep gamma-ray spectra?
- \* What particle content do we see in SNRs?

## B. SNR PeVatrons with CTA

### Not detected

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

### Detected

- \* What mechanism? (Bell?)
- \*  $\xi_{CR}$ /  $\dot{M}$  function of time?
- \* When? How many?
- \* Other Astrophysical objects?