The contribution of supernova remnants to the Galactic cosmic ray spectrum

What's wrong with supernova remnants?

1st Workshop INTERCOS
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Why supernova remnants?

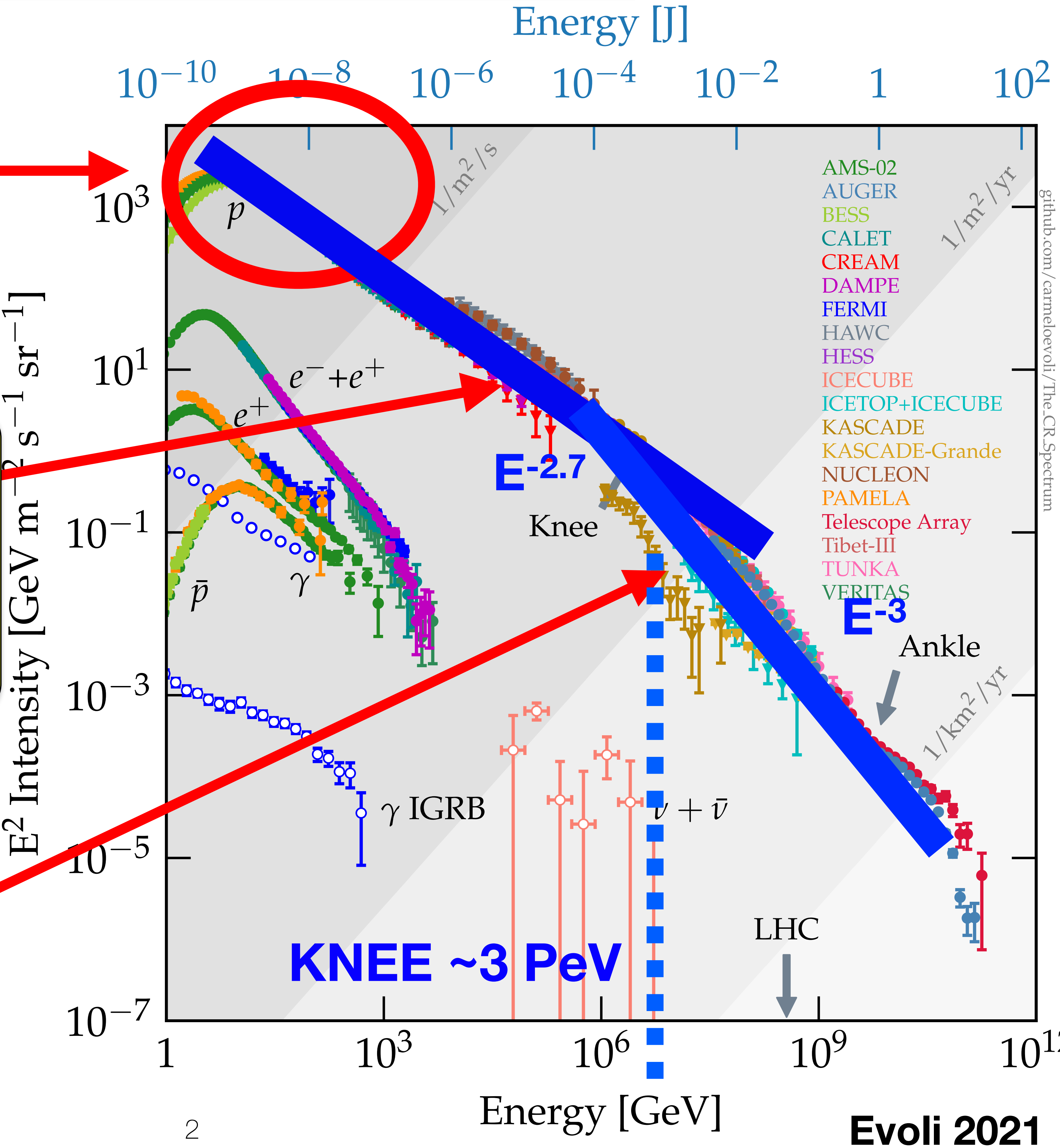
1. Bulk of CRs
Energy density ~1 eV/cm3
10% of SNR total explosion energy

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

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

Injection **Propagation**

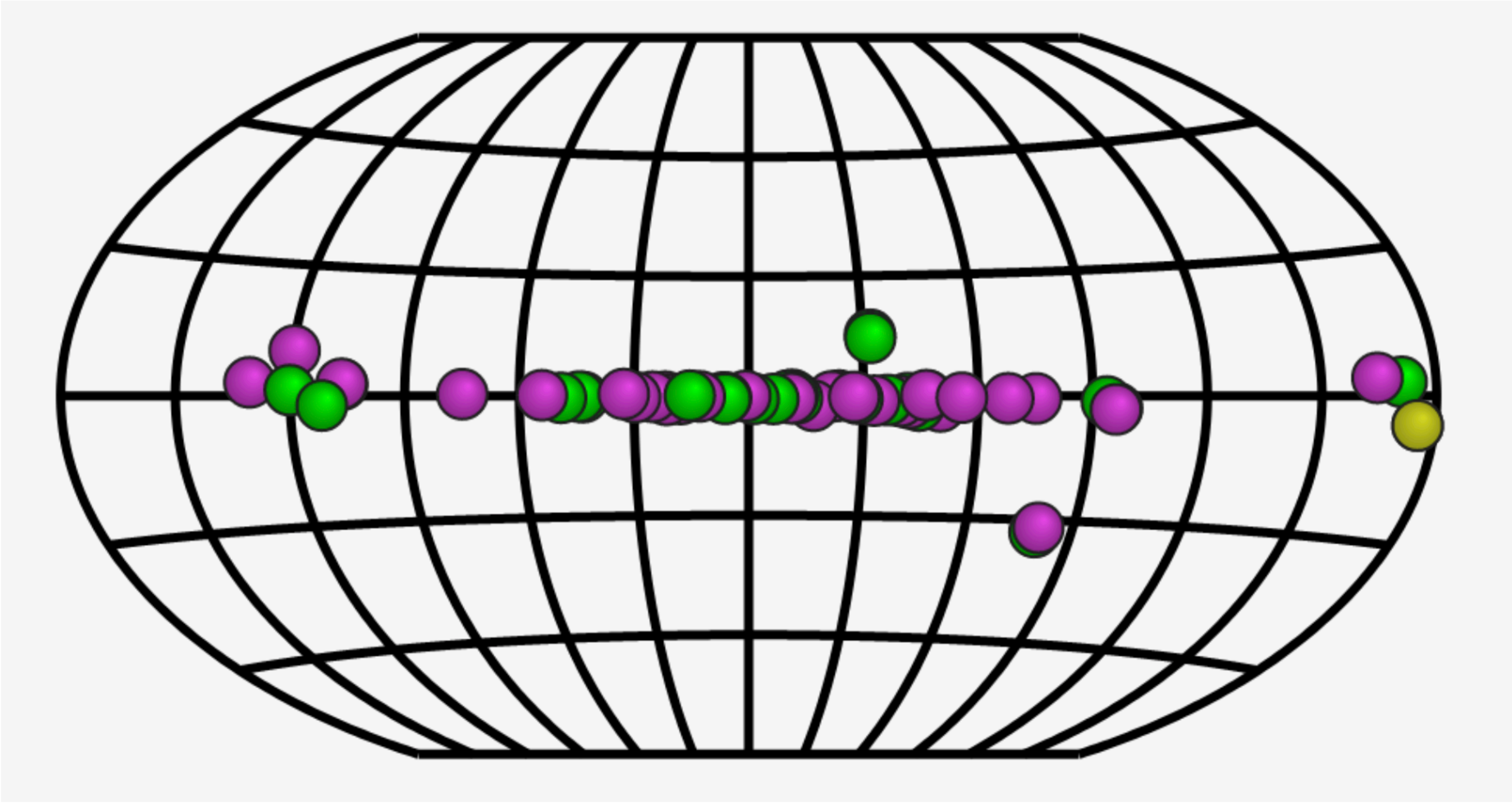
3. Magnetic field amplification



Evoli 2021

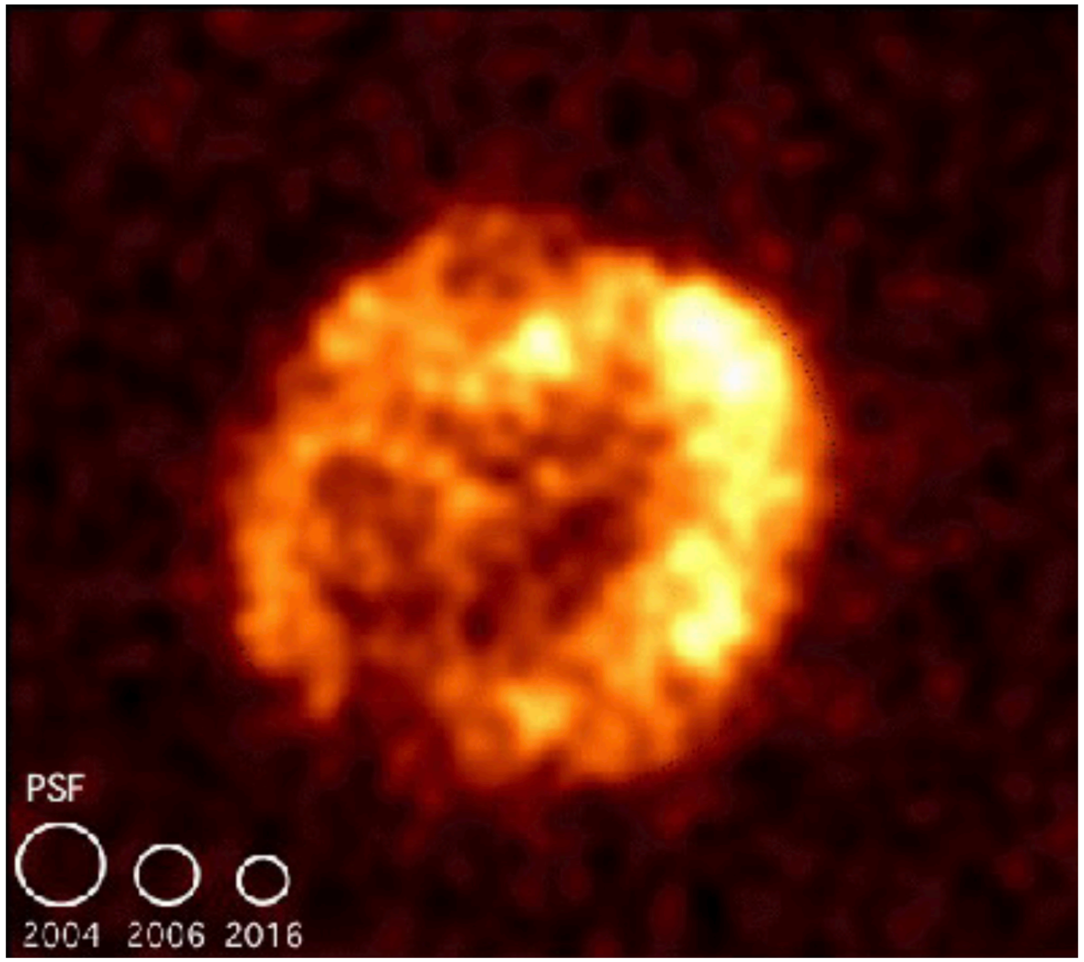
Reviews: Blasi (2013,2019)
Tatischeff & Gabici (2018)
Gabici et al. (2019)

Galactic supernova remnants



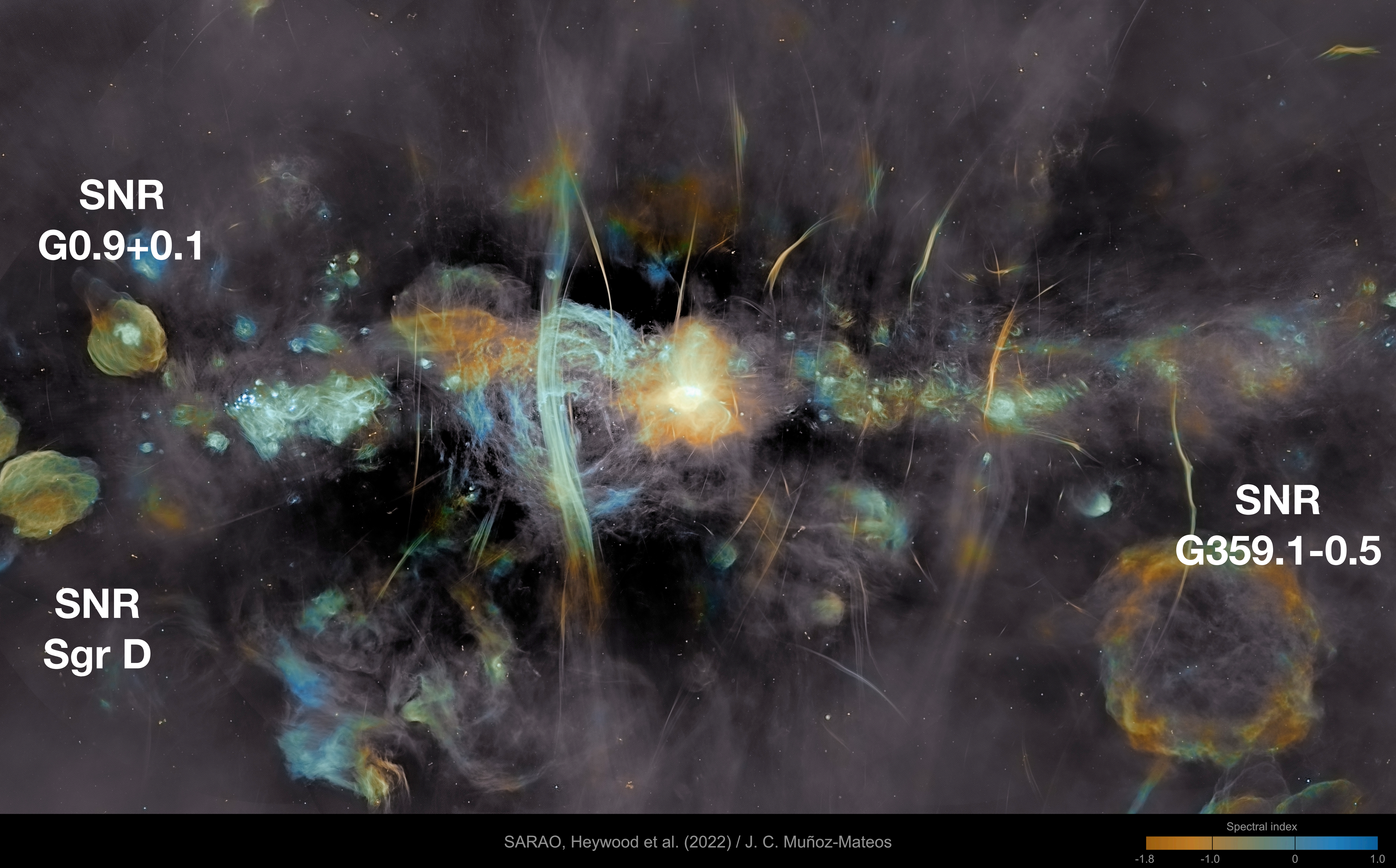
12 Shells

58 sources associated to SNRs



RXJ1713-3946 (H.E.S.S.)

TeVCat (2022)

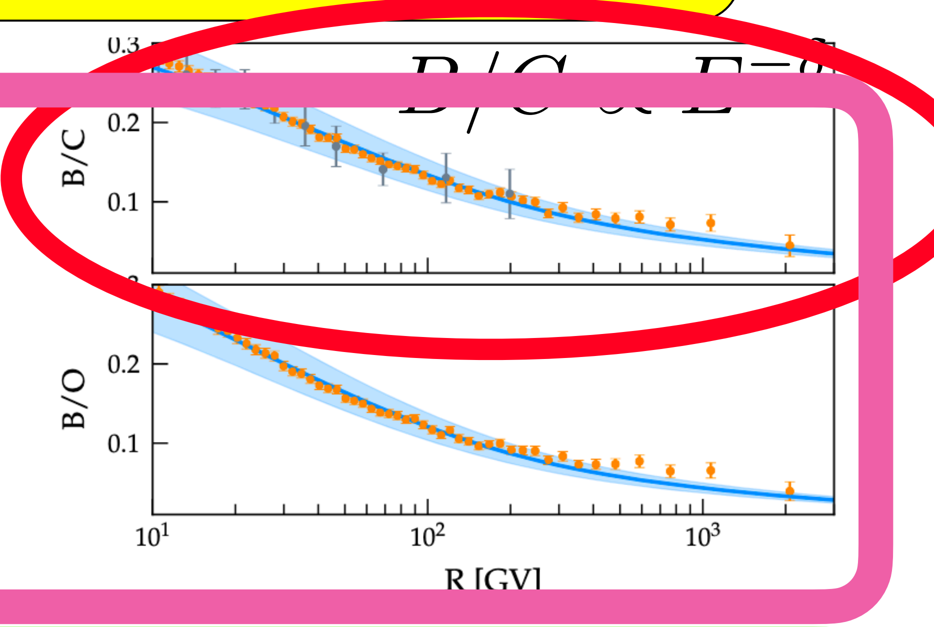


SARAO, Heywood et al. (2022) / J. C. Muñoz-Mateos

MeerKAT picture of the day Feb. 2nd 2022

What is wrong with supernova remnants?

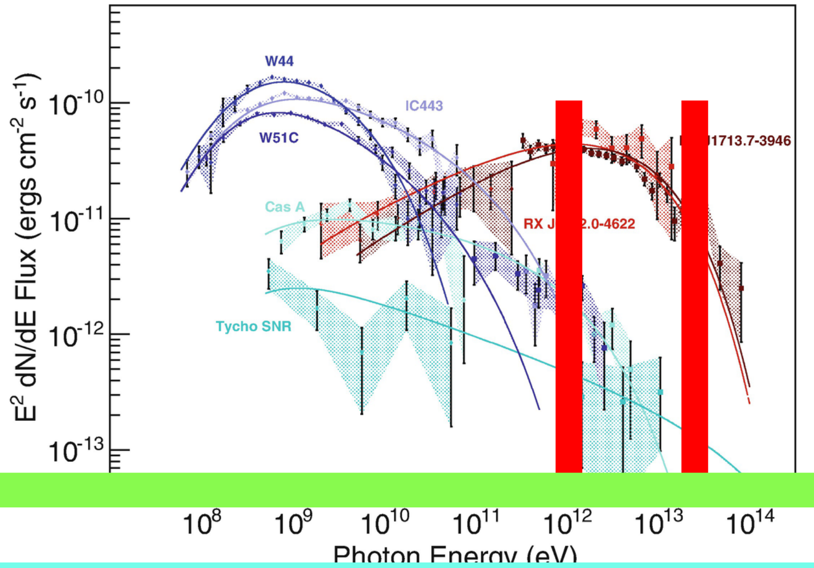
GOOD **NOT GOOD**



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

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

Injection Propagation



2. **Non-thermal emission from radio to gamma**

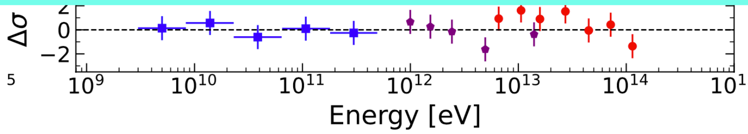
VHE domain steep spectra?

Particle content: protons/electrons?

3. **Energy budget (~5-10 % total**

The low rate of supernova remnant pevatrons

NO SNR pevatron



SN

Tibe

The low rate of supernova remnant pevatrons

How to reach PeV energies at a SNR?

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

Resonant streaming of CRs
Skiling (1975)

Acoustic instability
Drury & Falle (1983)

Instability
density fluctuations
Giacolone & Jokipii (2007)

Non-resonant streaming
Bell (2004)

....

Reviews: Drury (1994)
Blasi (2013,2019)
Gabici et al. (2019)

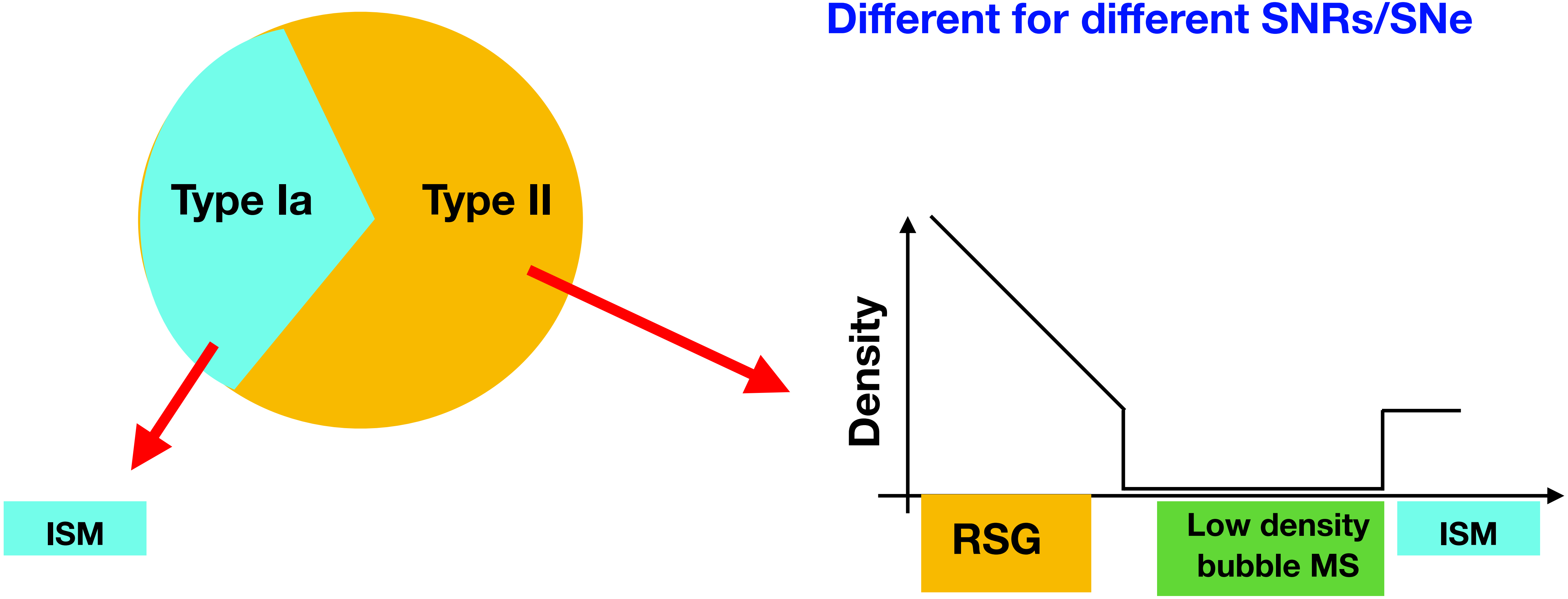
Non-resonant streaming of CRs

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

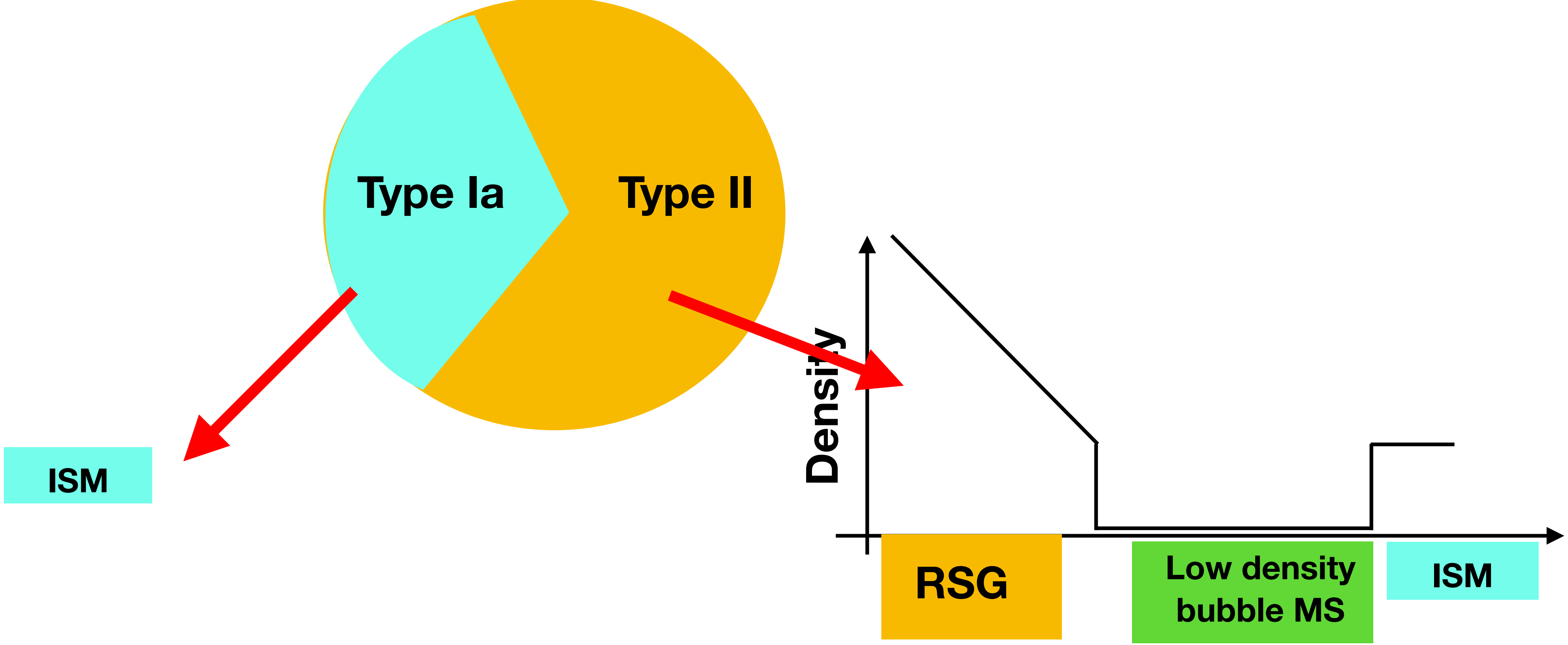
Growth rate of the non-resonant streaming instability

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

Different for different SNRs/SNe



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



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

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

Chevalier (1999) Tang (2017)

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

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

$$n_0$$

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

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

Ostriker & McKee (1988)
Thin shell approximation

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

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

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

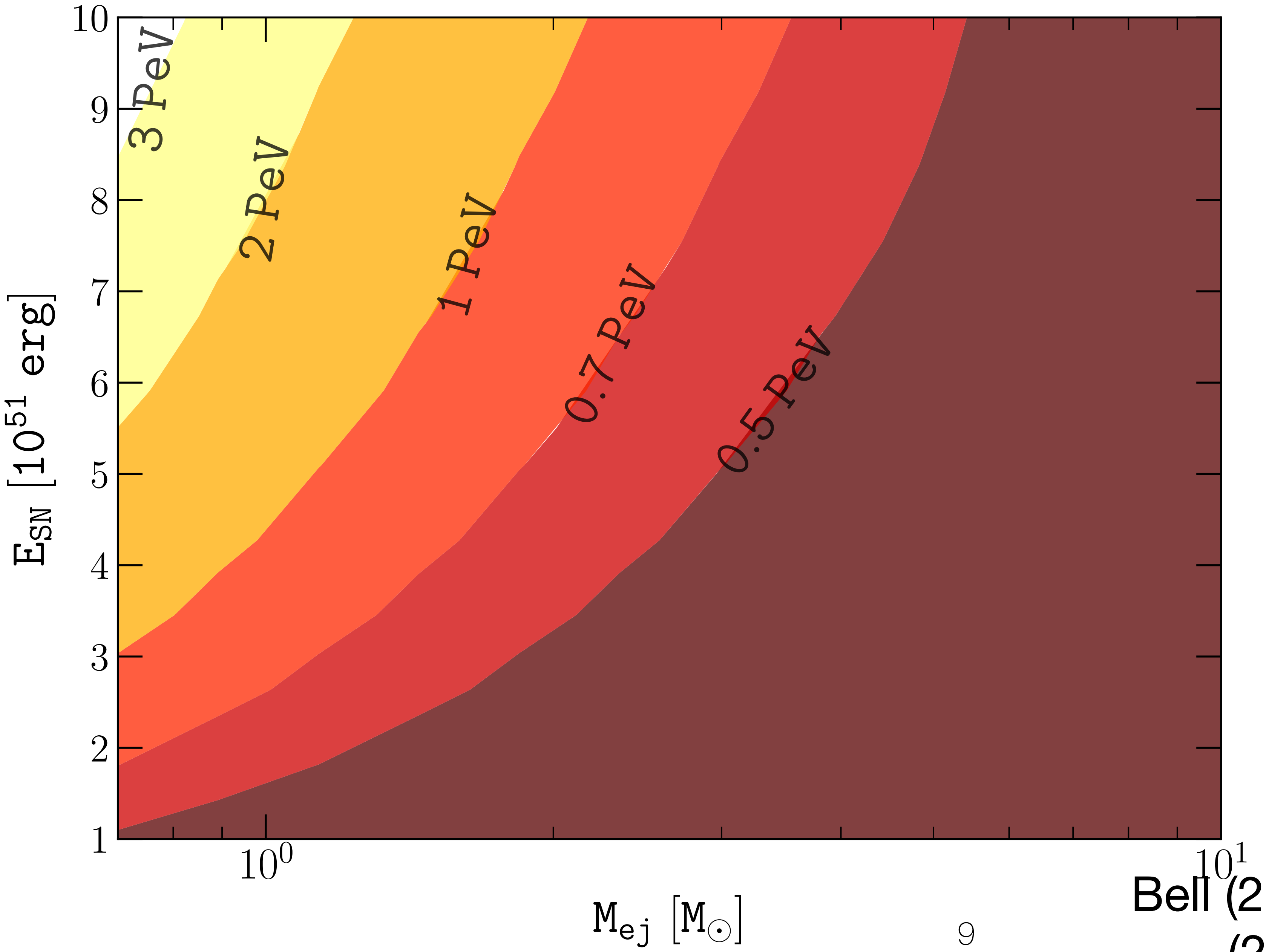
$$\dot{M}_{\rm MS}, u_{\rm MS}, n_0, M_{\rm ej},$$

Non-resonant streaming of CRs

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

Growth rate of the non-resonant streaming instability

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

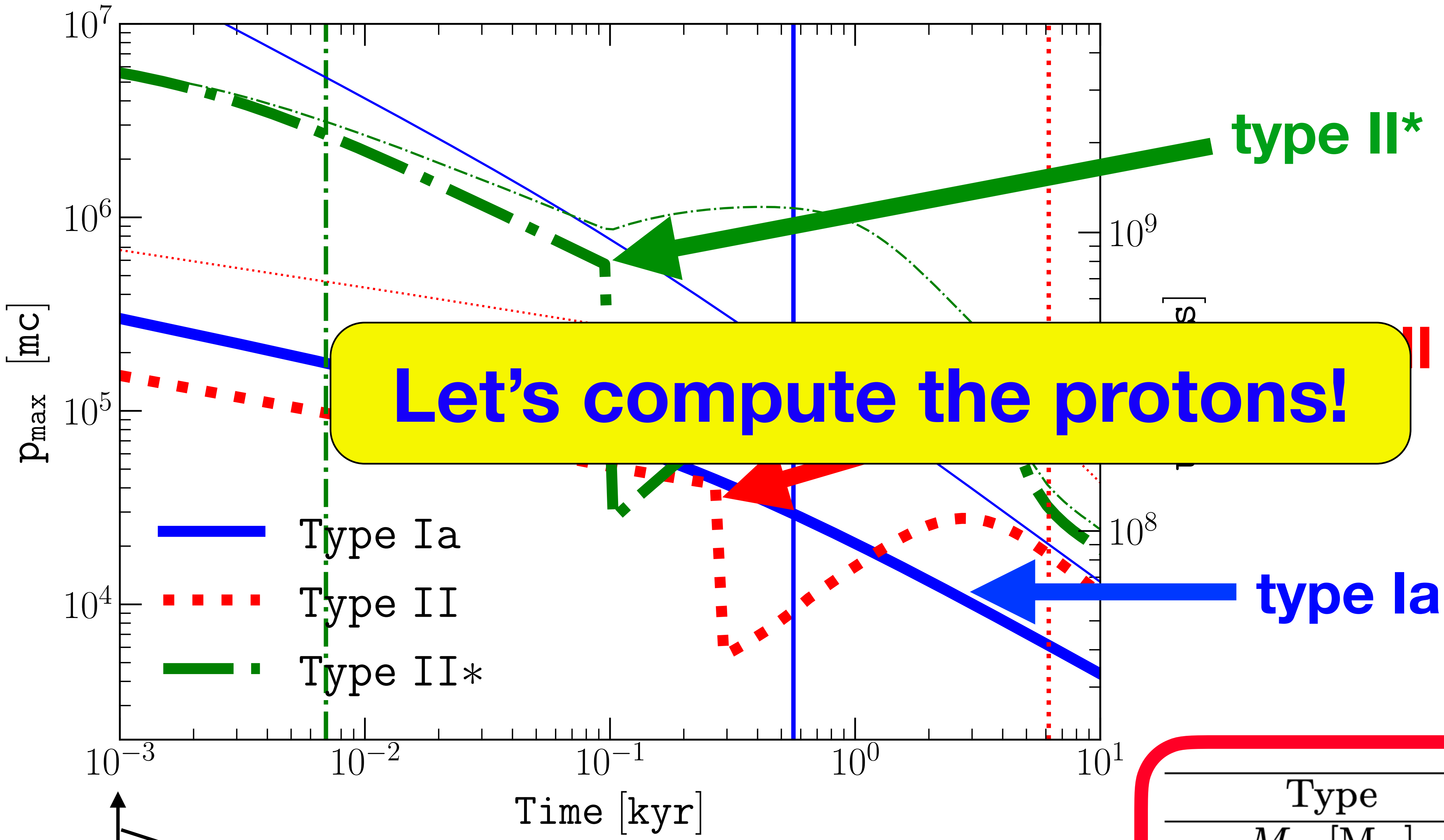


$$\dot{M}_{\rm RSG} = 10^{-4} M_\odot/{\rm yr}$$

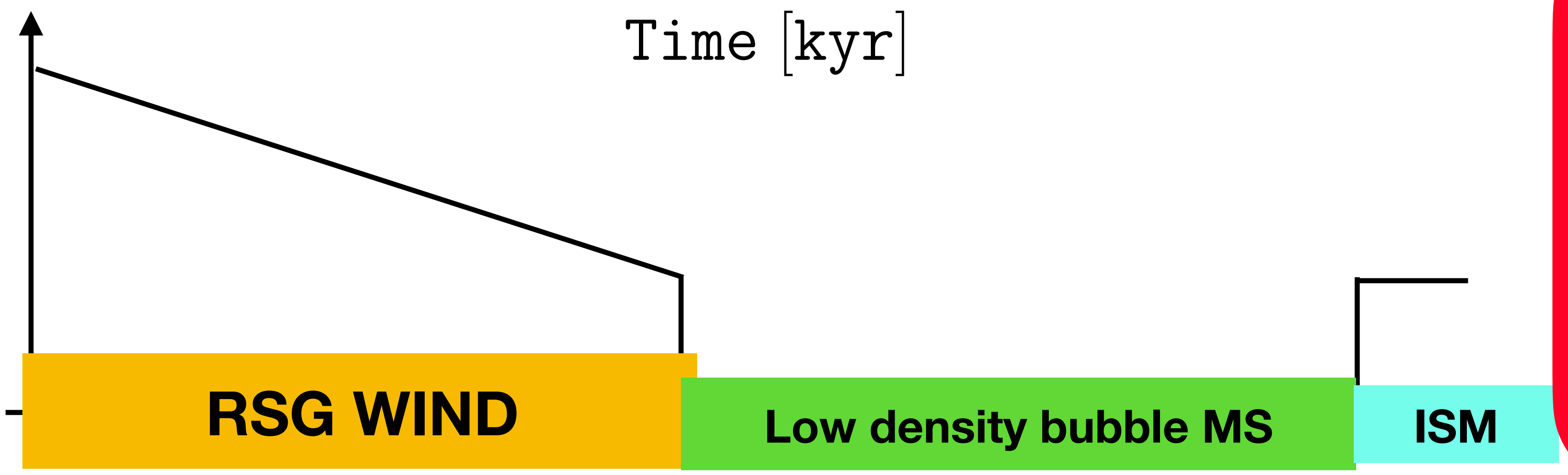
$$\xi = 0.1$$

Bell (2004), Bell et al. (2013), Schure et a
(2014), PC, Blasi & Amato (2020)

Type Ia, type II, type II*

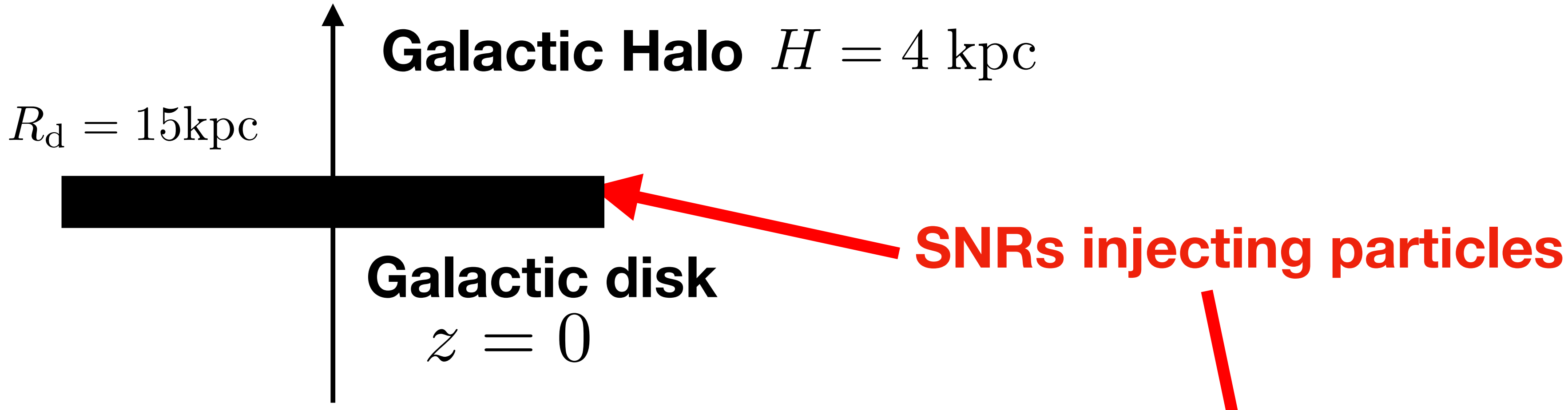


Let's compute the protons!



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



Galactic Halo $H = 4$ kpc

$R_{\rm d} = 15$kpc

Galactic disk

$z = 0$

SNRs injecting particles

1D Galactic transport

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

Diffusion

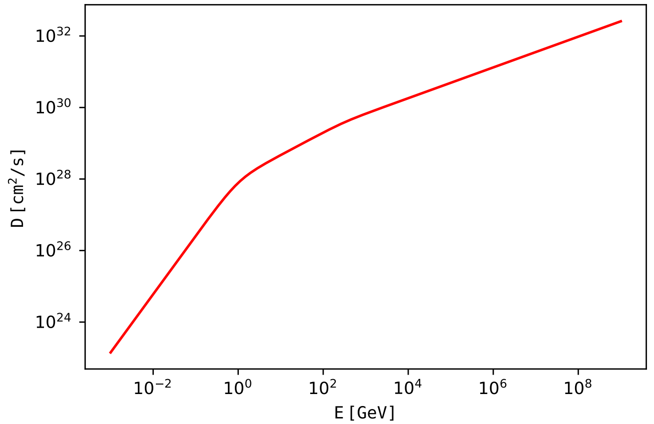
Advection

Ionisation losses

Injection from SNRs

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

In agreement with AMS-02 measurements
Evoli (2019)



Trapped

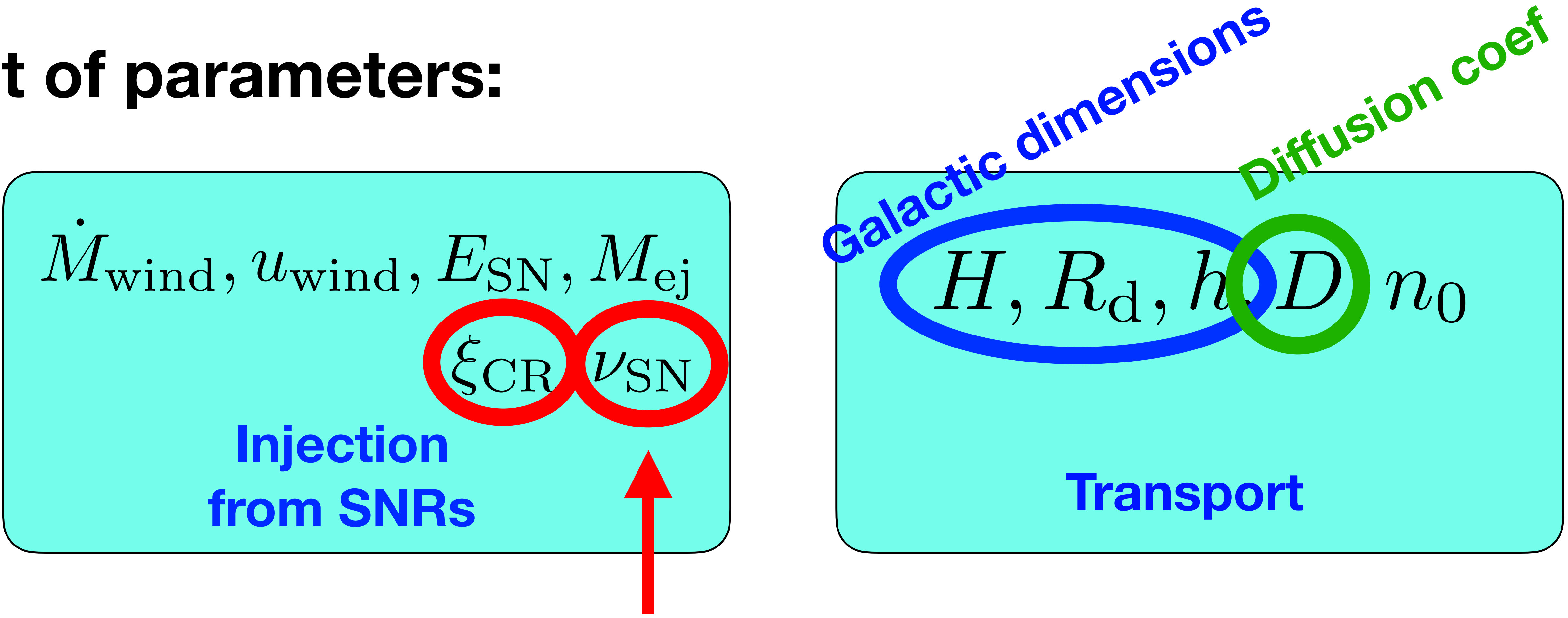
$$q_{\rm acc}(p)dp = \frac{\nu_{\rm SN}}{\pi R_{\rm d}^2}\int_{t_0}^{T_{\rm S}} dt\frac{4\pi}{\sigma}r_{\rm sh}^2(t)u_{\rm sh}(\;)f_0(p',t)dp'$$

Escaping

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

Protons from type Ia

List of parameters:



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

ξ_{CR} ν_{SN}

Injection from SNRs

Galactic dimensions

Diffusion coef

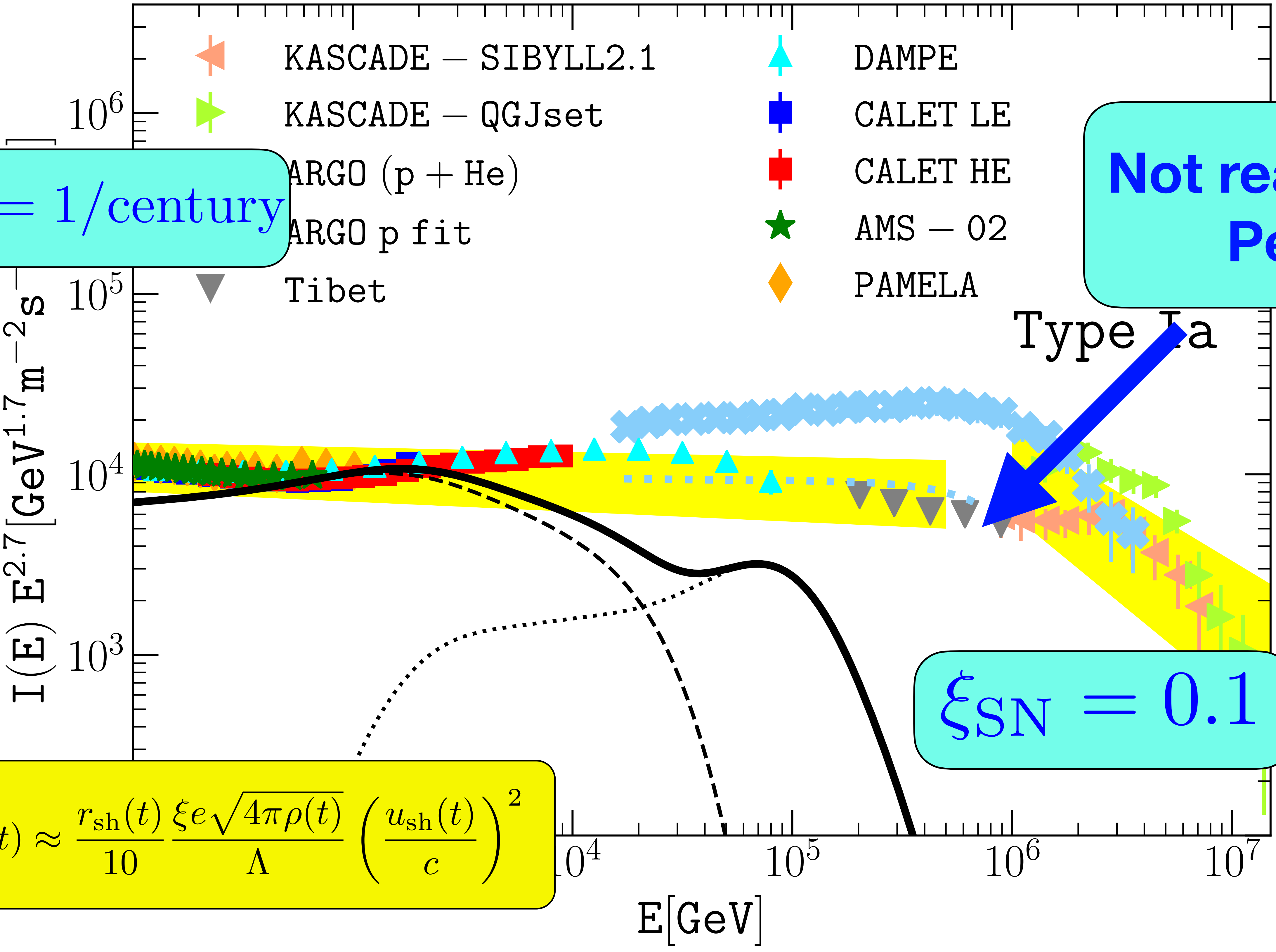
$H, R_{\mathrm{d}}, h, D \; n_0$

Transport

Rate of SNe= 1/century (total 3/century)

Protons from type Ia

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



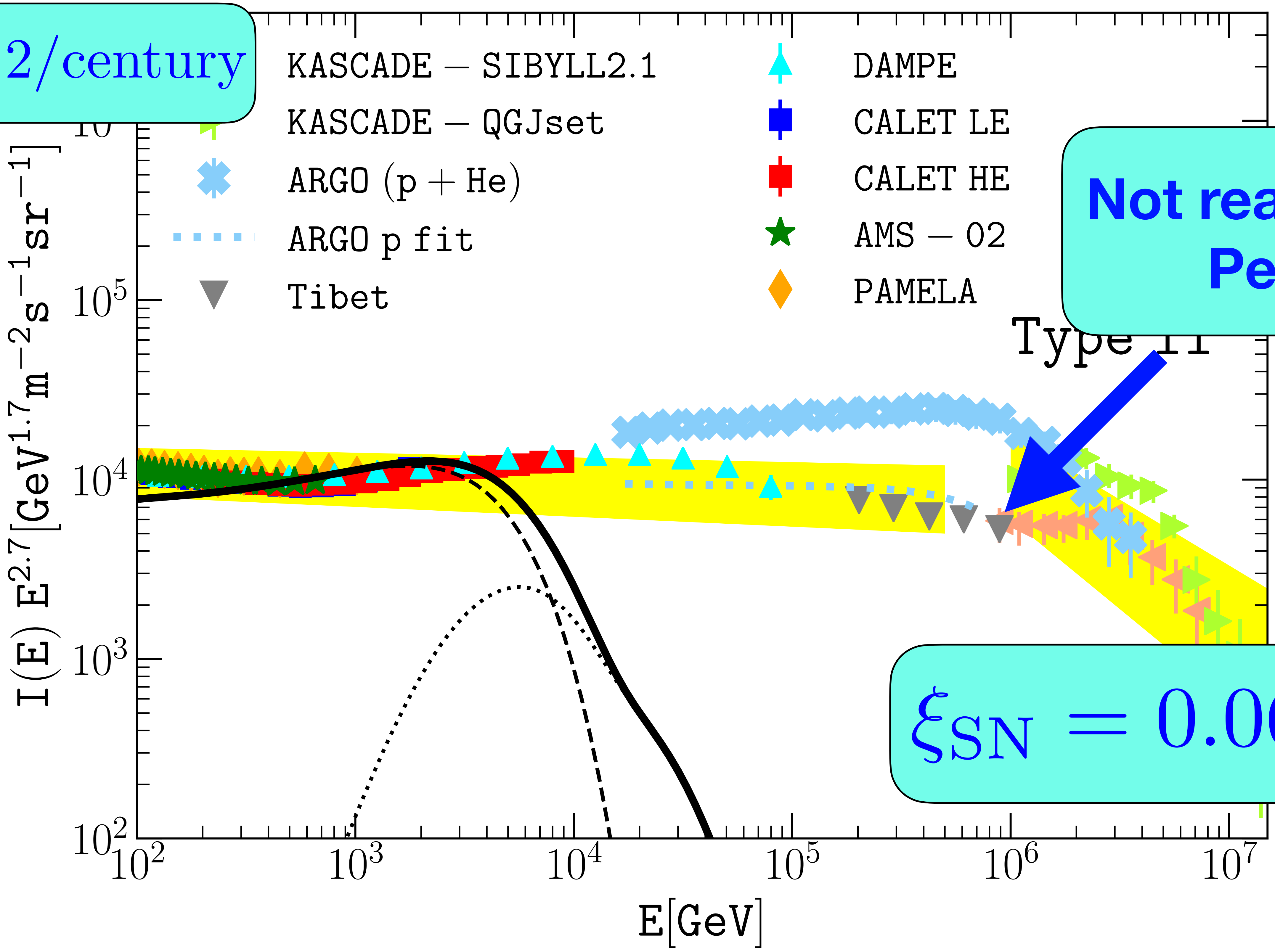
Not reaching PeV

$\xi_{\rm SN} = 0.1$

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

Protons from type II

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



Not reaching PeV

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

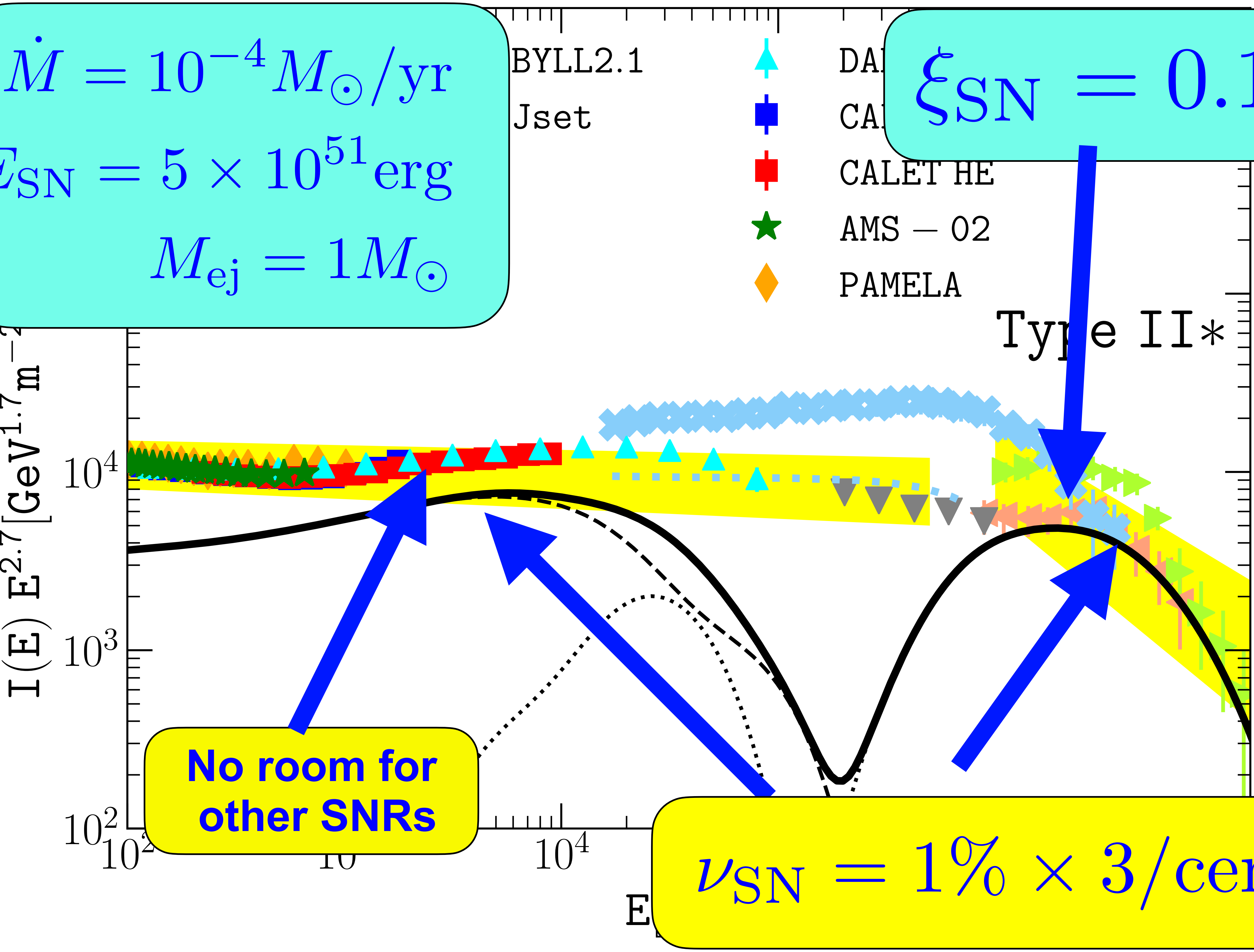
Protons from type II*

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

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

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

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

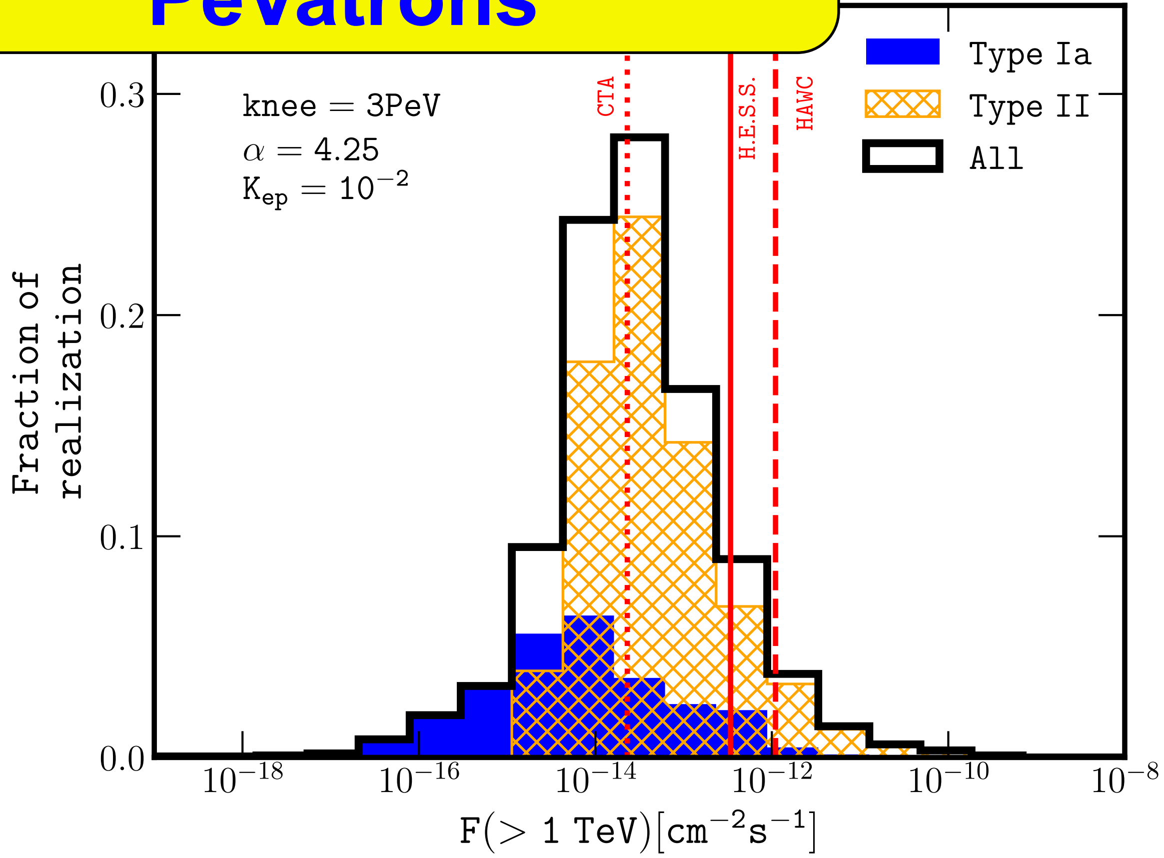


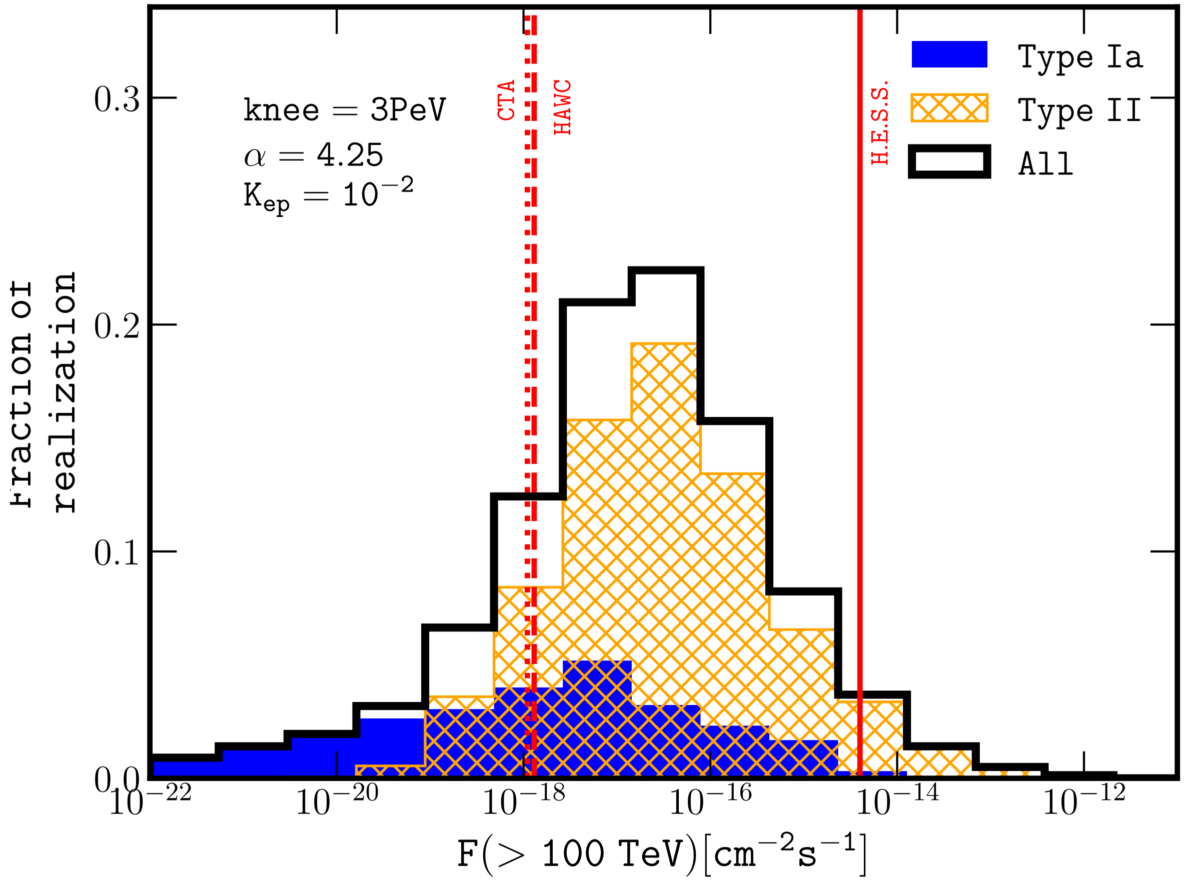
No room for other SNRs

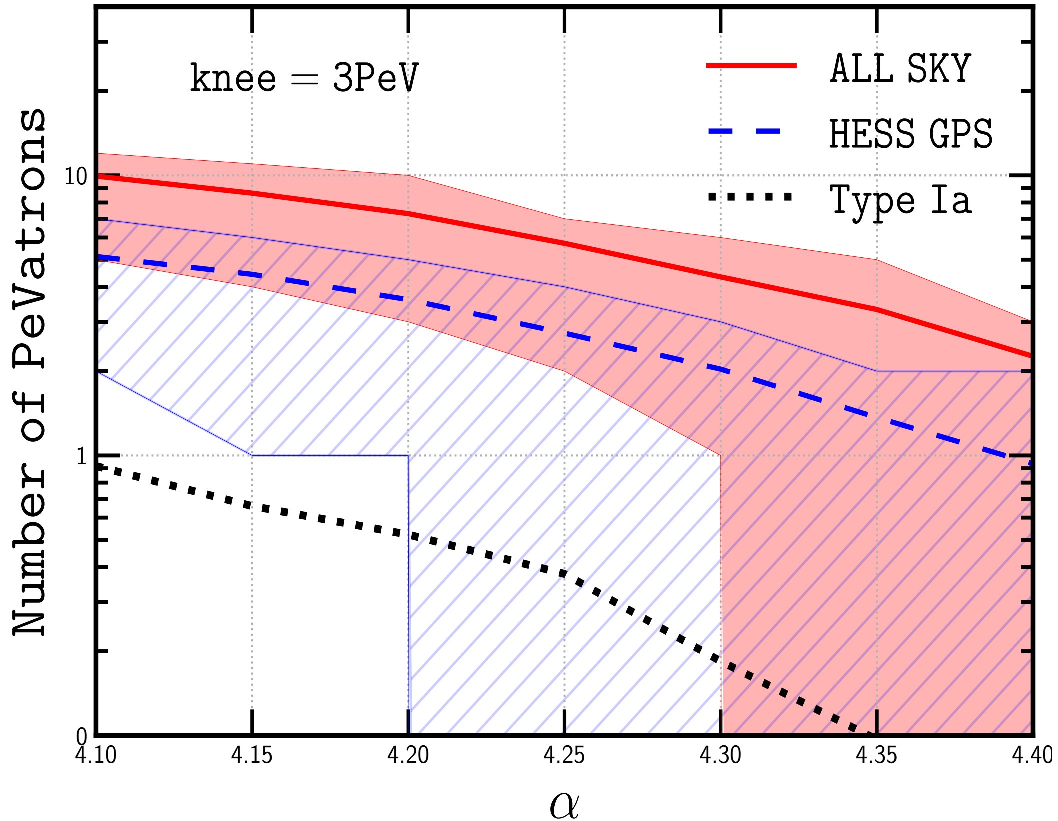
$$\nu_{\mathrm{SN}} = 1\% \times 3/\mathrm{century}$$

Pevatrons with CTA

Assuming all SNRs are PeVatrons







If only Type II* are Pevatrons

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

$$\to 0$$

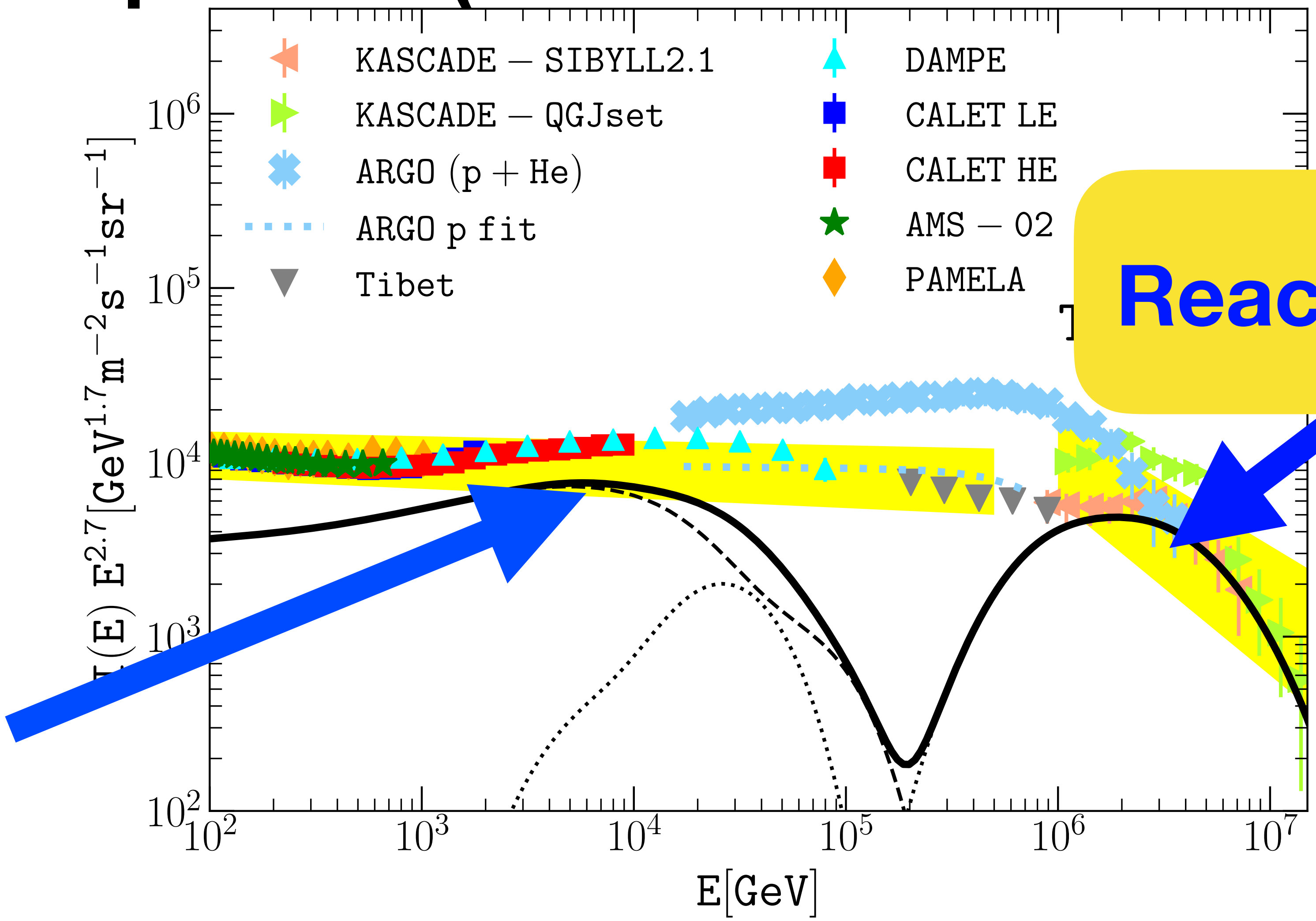
PC, Blasi, Amato (submitted 2020)

PC, Gabici, Terrier, Humensky (2018)

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. **If PeV range with II* -> not much room for others! Efficiency< few percent (not 10-15% sim. /observations)**



Reaching PeV

Mimicking bump?

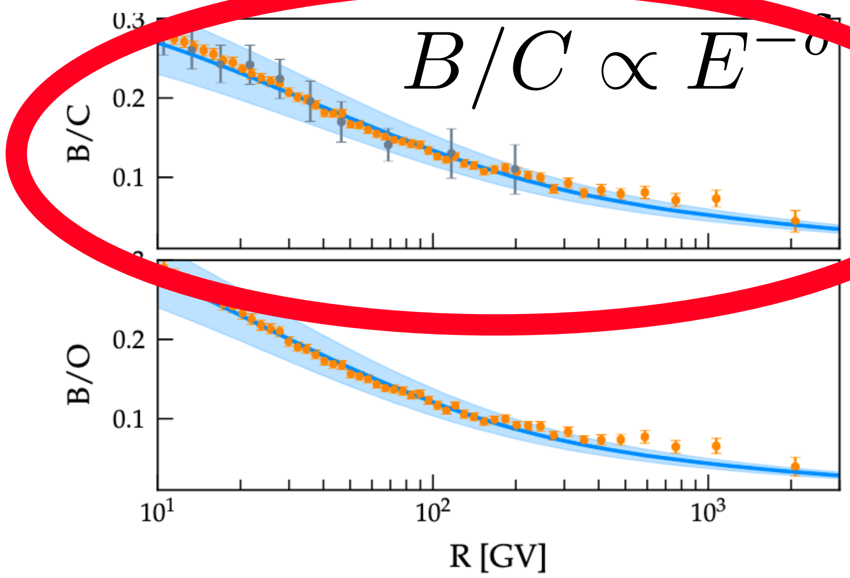
What is wrong with supernova remnants?

GOOD **NOT GOOD**

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

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

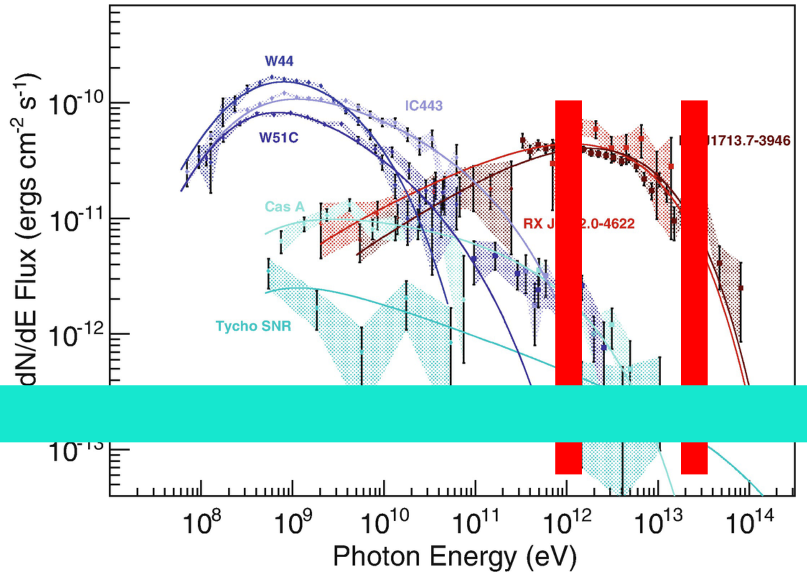
Injection Propagation


$B/C \propto E^{-\delta}$

2. Non-thermal emission from radio to gamma

VHE domain steep spectra?

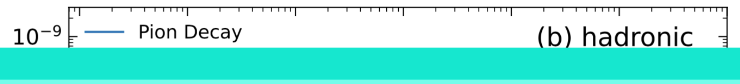
Particle content: protons/electrons?



Funk (2017)

3. Energy budget (~5/10% total explosion energy)

How much precisely? For how long?



21)

The low rate of supernova remnant pevatrons

The steep gamma-ray spectra (particle content)

Diffusive shock reacceleration

Bell (1978, MNRAS, II.)

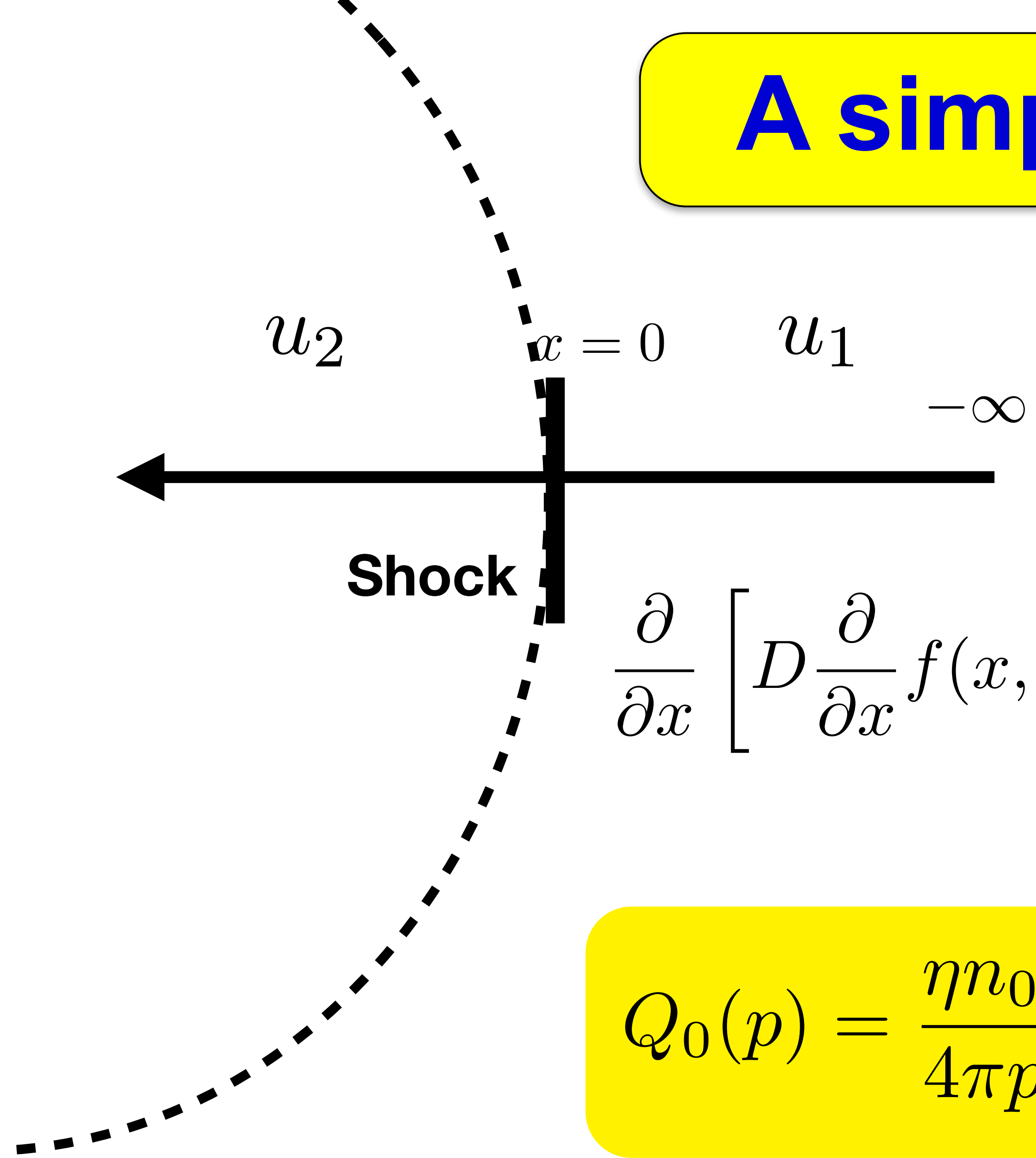
6. Effect of a shock front on pre-existing cosmic rays

> ***« 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. »***

Stochastic reacceleration (2nd order Fermi)

DSReacceleration (1st order Fermi)

A simple description



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

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

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

Boudary condition -> upstream infinity of the shock

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

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

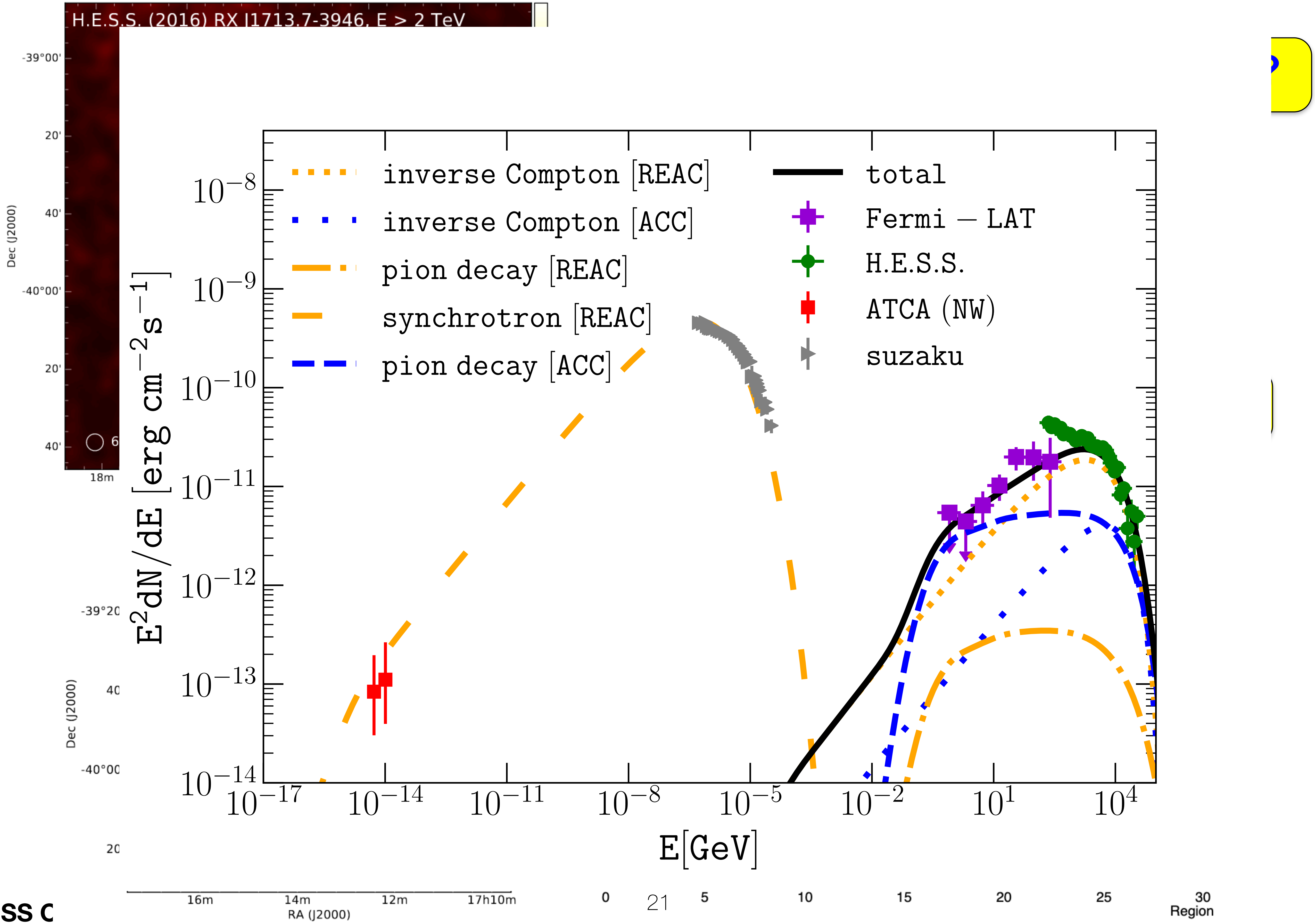
$$f_0(p) = \cancel{s\frac{\eta n_1}{4\pi p_{\mathrm{inj}}^3}\left(\frac{p}{p_{\mathrm{inj}}}\right)^{-s}} + s\int_{p_0}^{p}\frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^{s} g(p')$$

« Classic » diffusive shock acceleration

Reacceleration

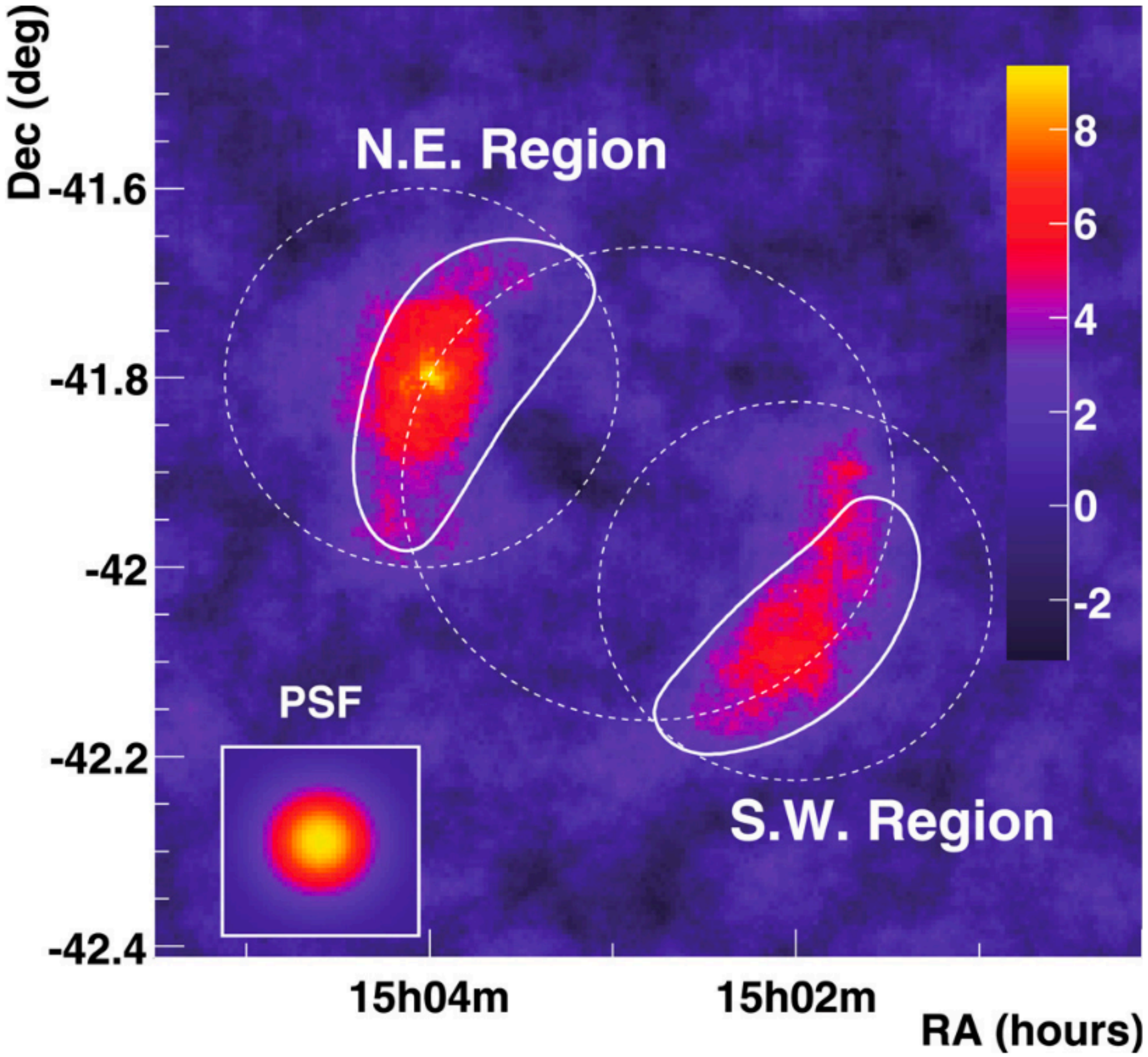
Blasi (2004)

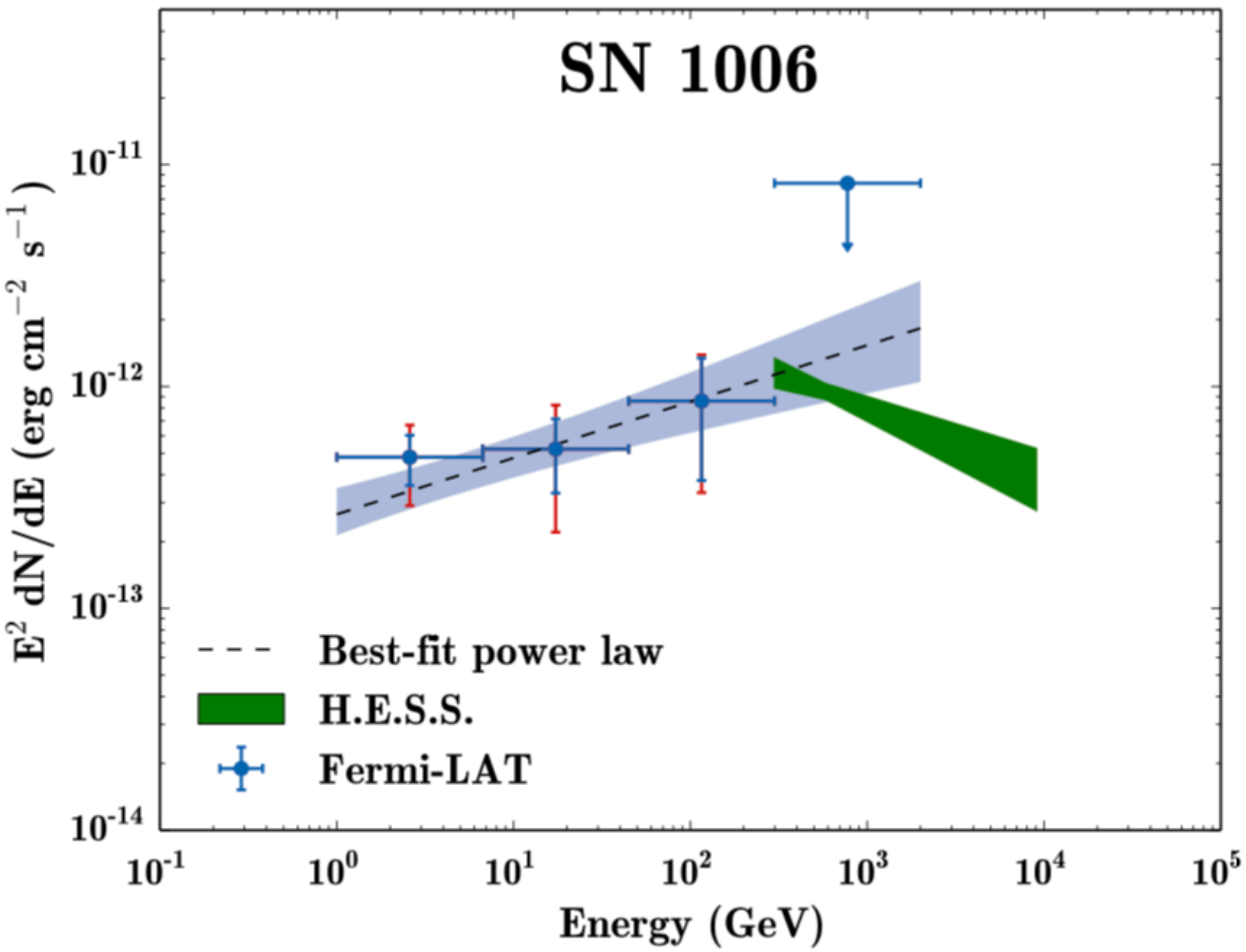
The particle content



HESS C

SN 1006





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

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

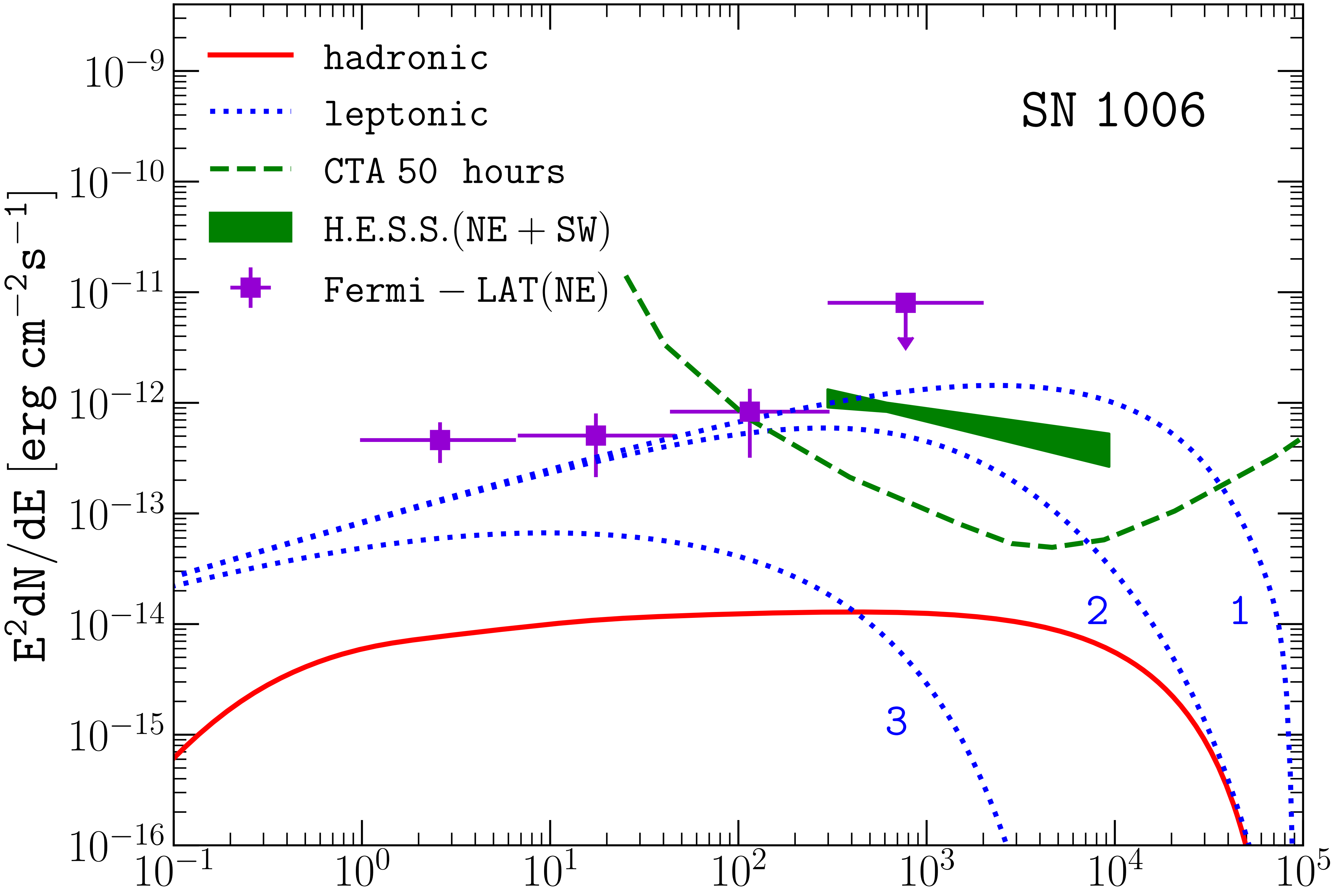
$$u_{\rm sh} \approx 4.3 \ 10^{8} {\rm cm/s}$$

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

H.E.S.S. (2010)

Condon et al. (2017)

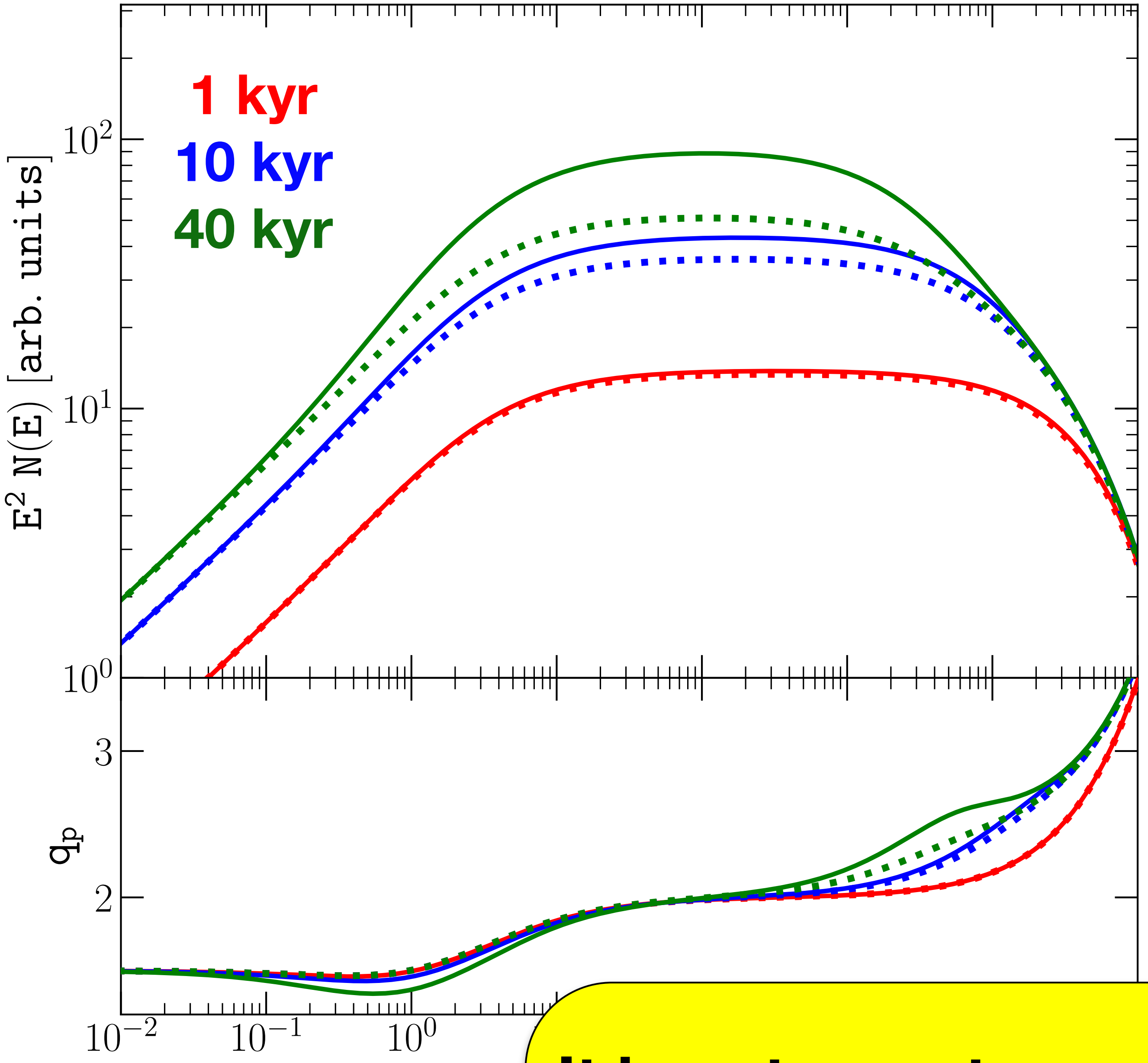
Gamma rays from SN 1006



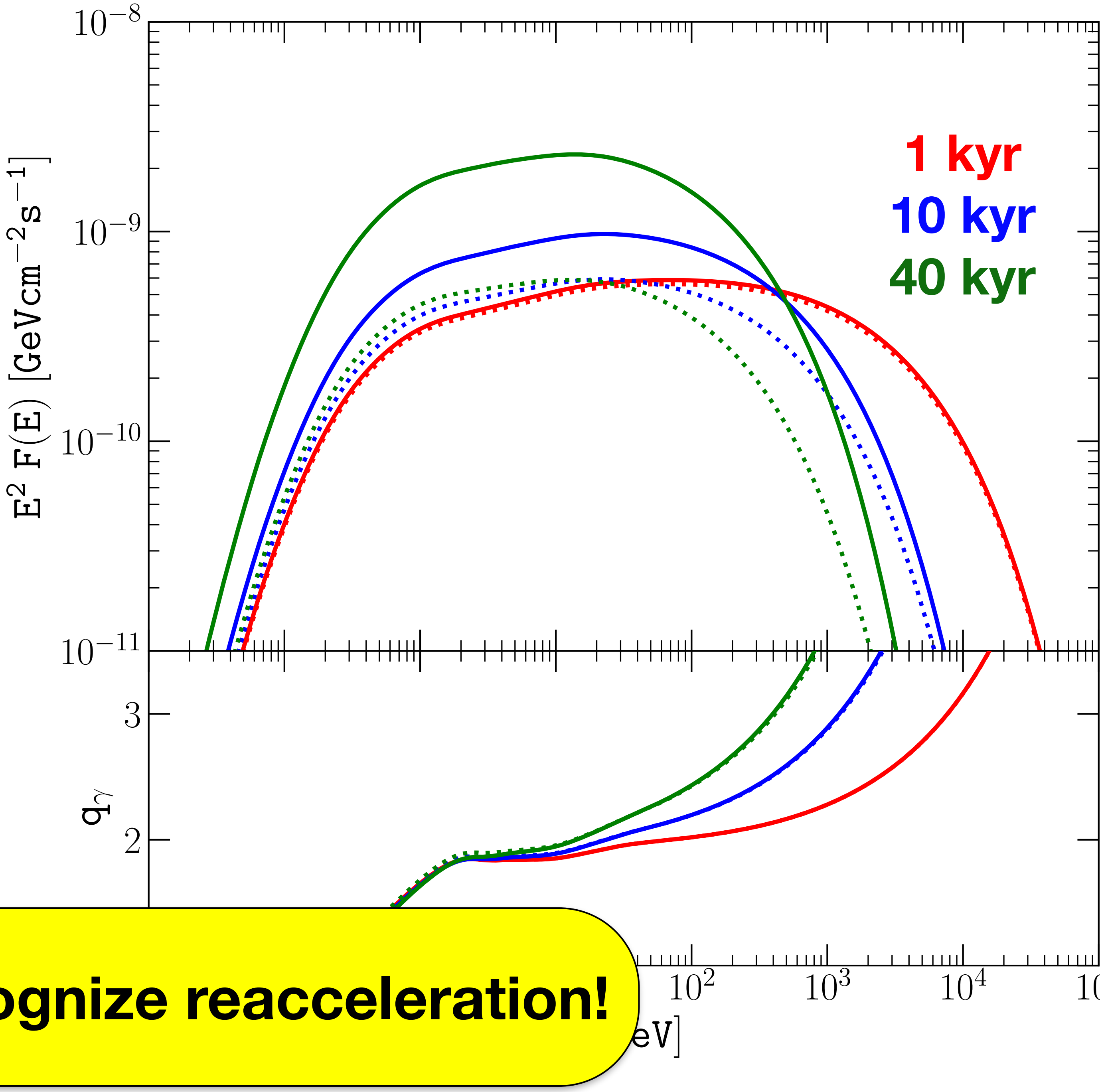
Future observations can probe reacceleration and constrain the diffusion coefficient

Reacceleration over the SNR lifetime

Protons



Gamma—rays



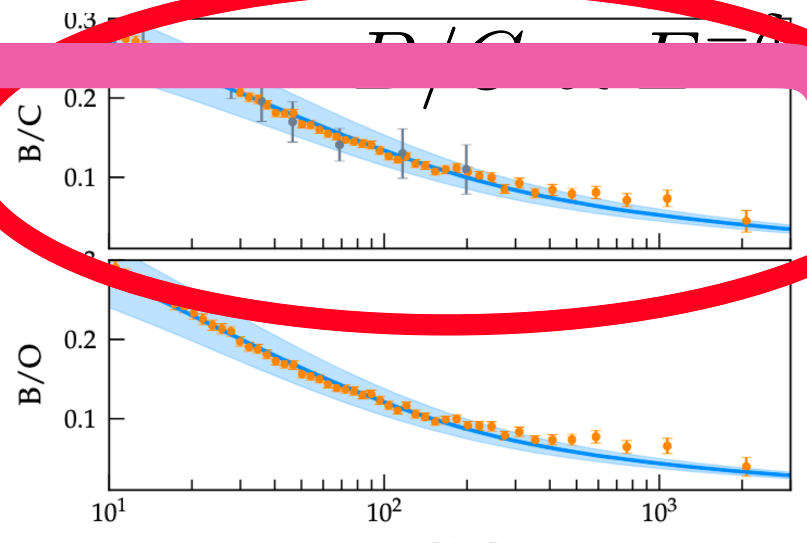
It is not easy to recognize reacceleration!

What is wrong with supernova remnants?

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

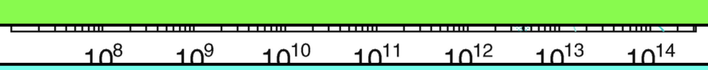
$$E^{-(2.4..2.1)} \times E^{-(0.3..0.6)} = E^{-2.7}$$

Injection **Propagation**

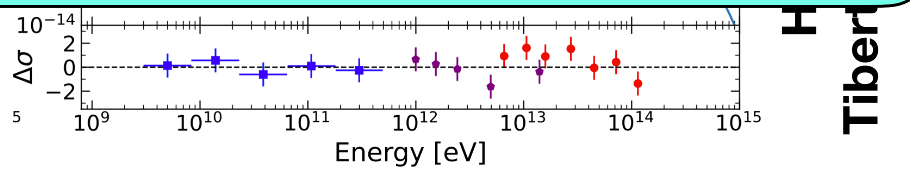


DSReacceleration

3. Energy budget (~5/10% total

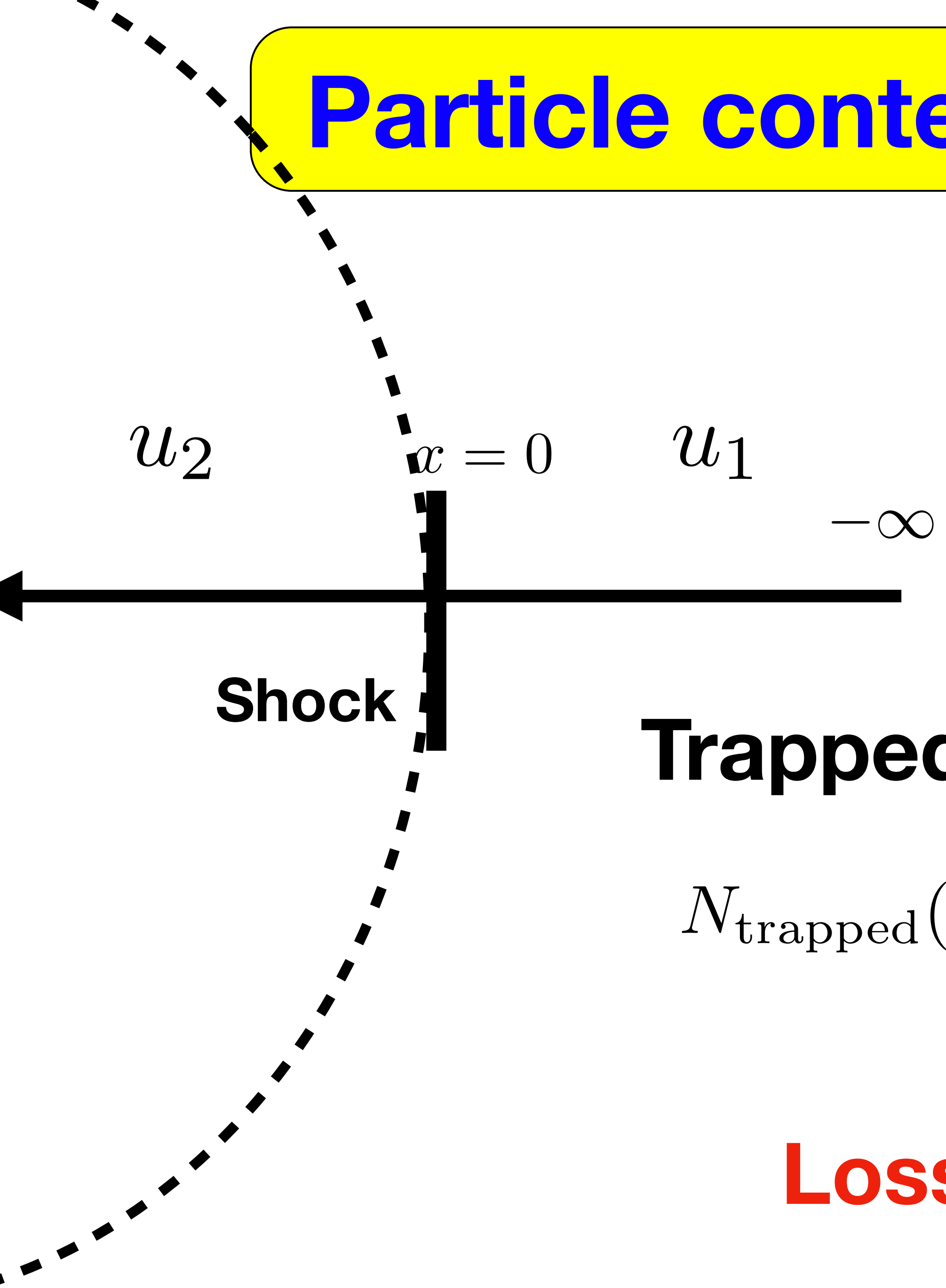


The low rate of supernova remnant pevatrons



NO SNR pevatron

Particle content: accelerated vs. injected?



DSA

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

Trapped particles

$$N_{\rm trapped}(p) = \int_{t_0}^{T_{\rm SN}} {\rm d}t \frac{4\pi}{r} R_{\rm sh}^2(t)\ v_{\rm sh}(t) \left(\frac{p'}{p}\right)^2 f(p', t) \frac{{\rm d}p'}{{\rm d}p}$$

Losses

$$\frac{{\rm d}p}{{\rm d}t} = -\frac{p}{\mathcal{L}}\frac{{\rm d}\mathcal{L}}{{\rm d}t} + \frac{4}{3}\sigma_{\rm T} c \left(\frac{p}{m_{\rm e} c}\right)^2 \frac{B_2^2(t)}{8\pi},$$

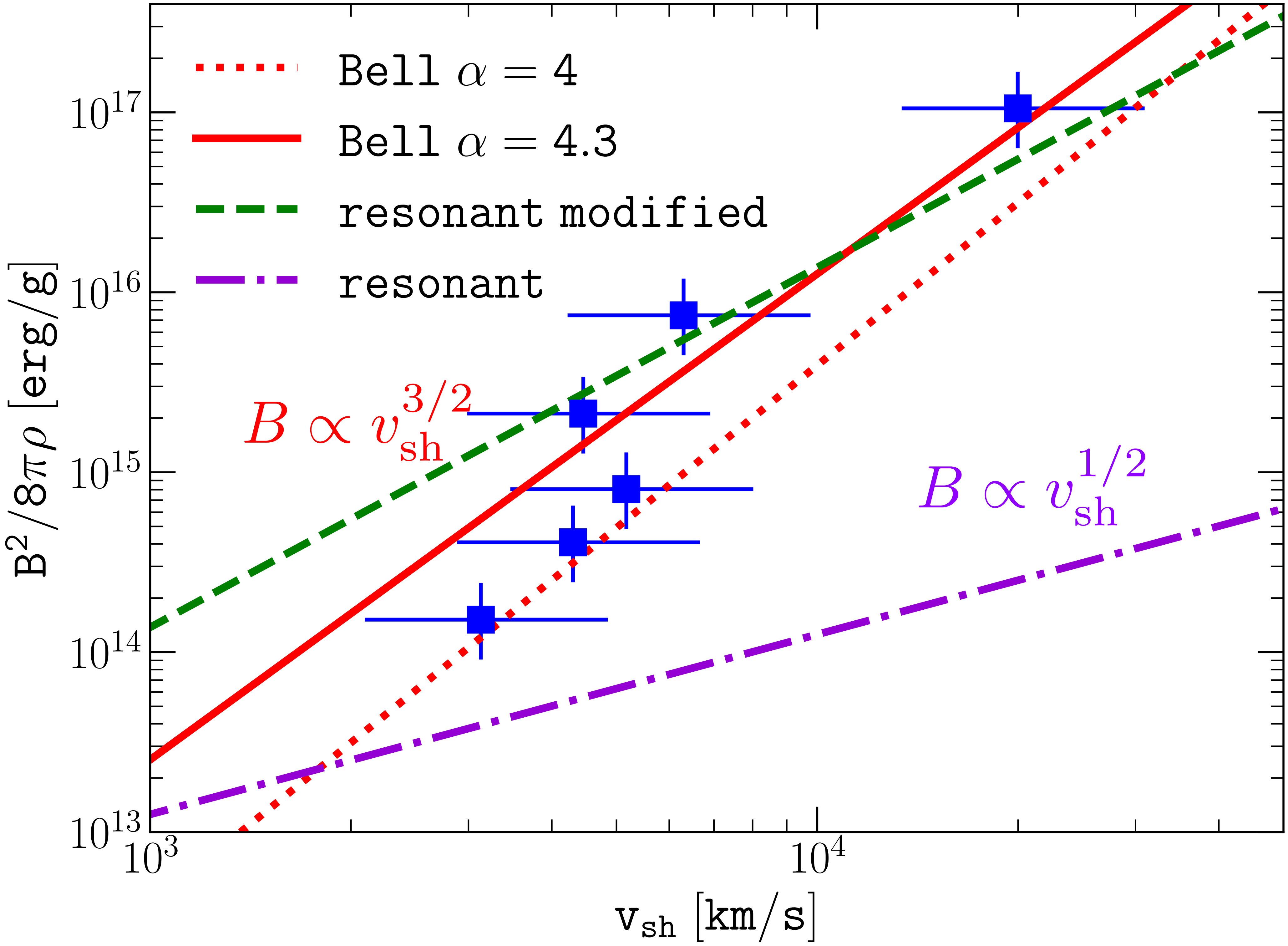
Escaping particles

$$N_{\rm esc}(p) = \int_{t_0}^{\rm T_{SN}} {\rm d}t' \frac{4\pi}{r} r_{\rm sh}^2(t') v_{\rm sh}(t') f(p, t') G(p, t')$$

PC, Blasi, Caprioli (2021)

Energy density downstream

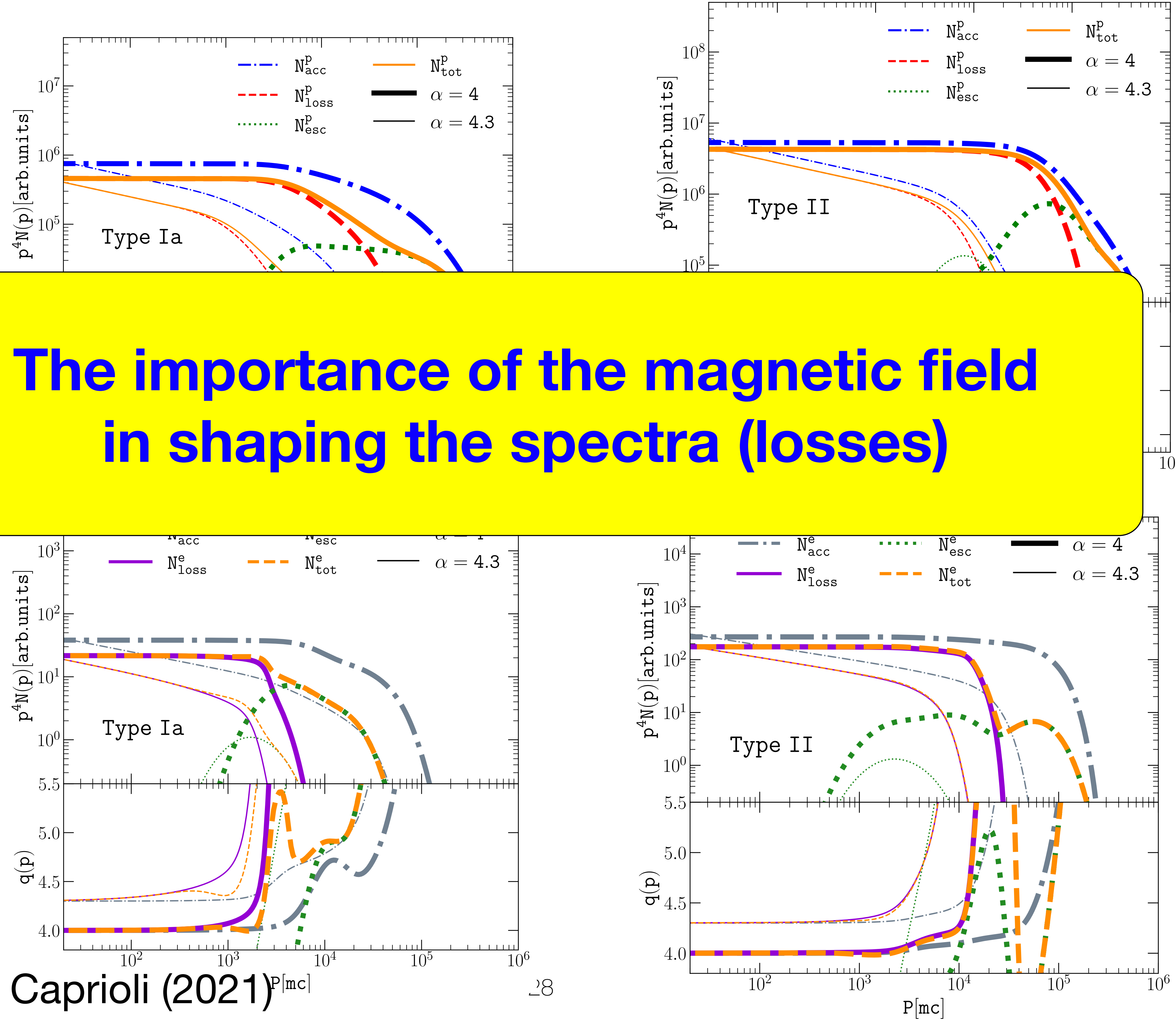
$B \propto v_{\rm sh}$



Important for losses!

Vink 2012

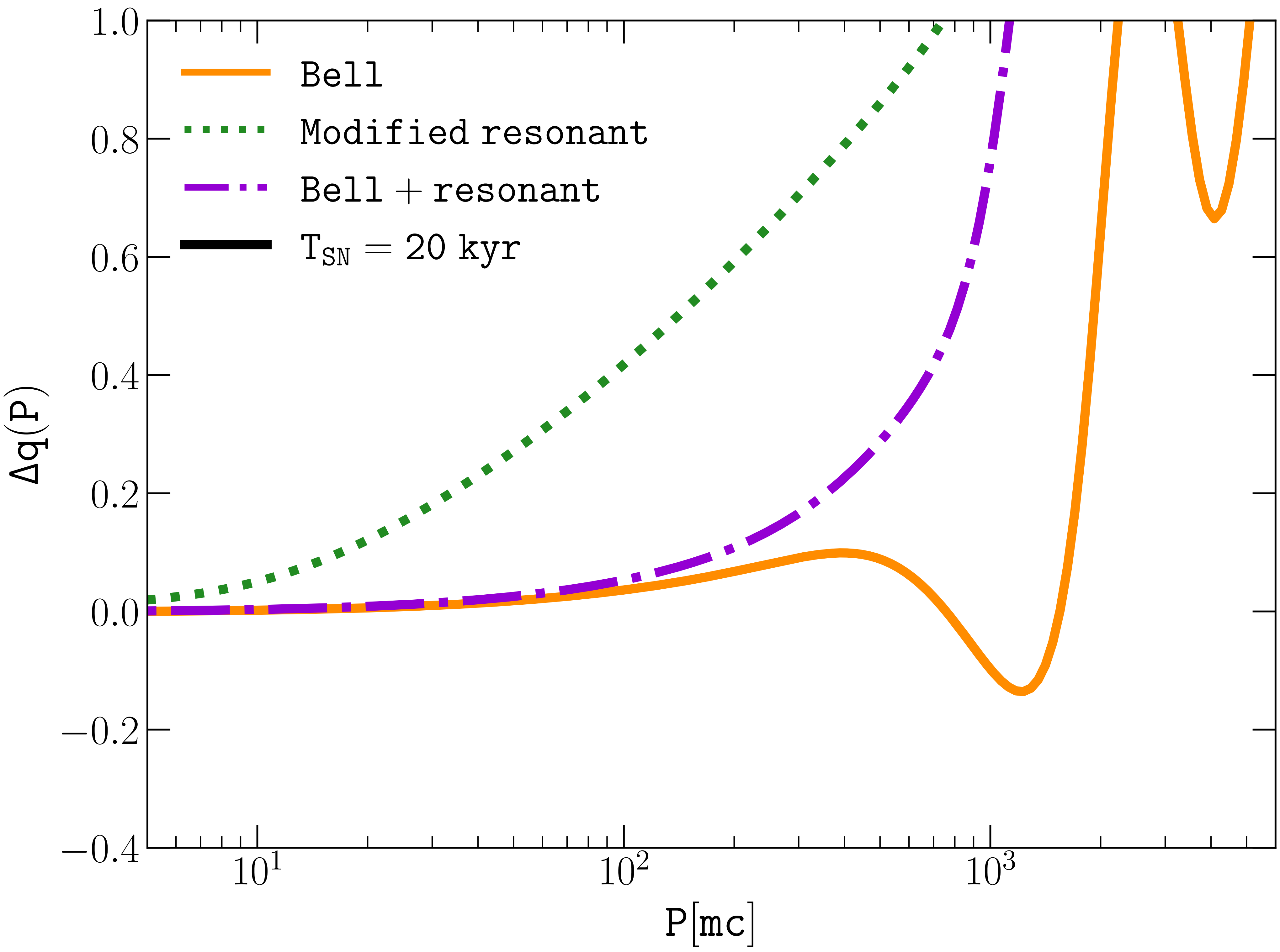
Particle content: accelerated vs. injected?



The importance of the magnetic field in shaping the spectra (losses)

PC, Blasi, Caprioli (2021)

Difference total spectrum electron vs. proton



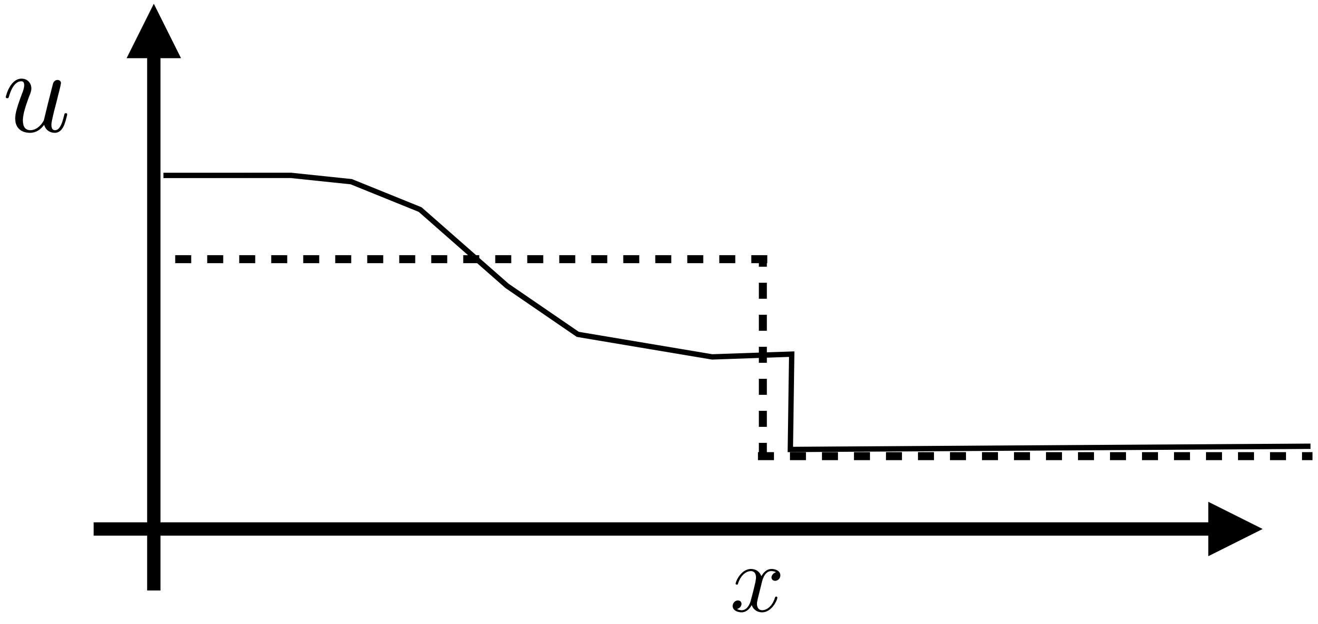
PC, Blasi, Caprioli (2021)

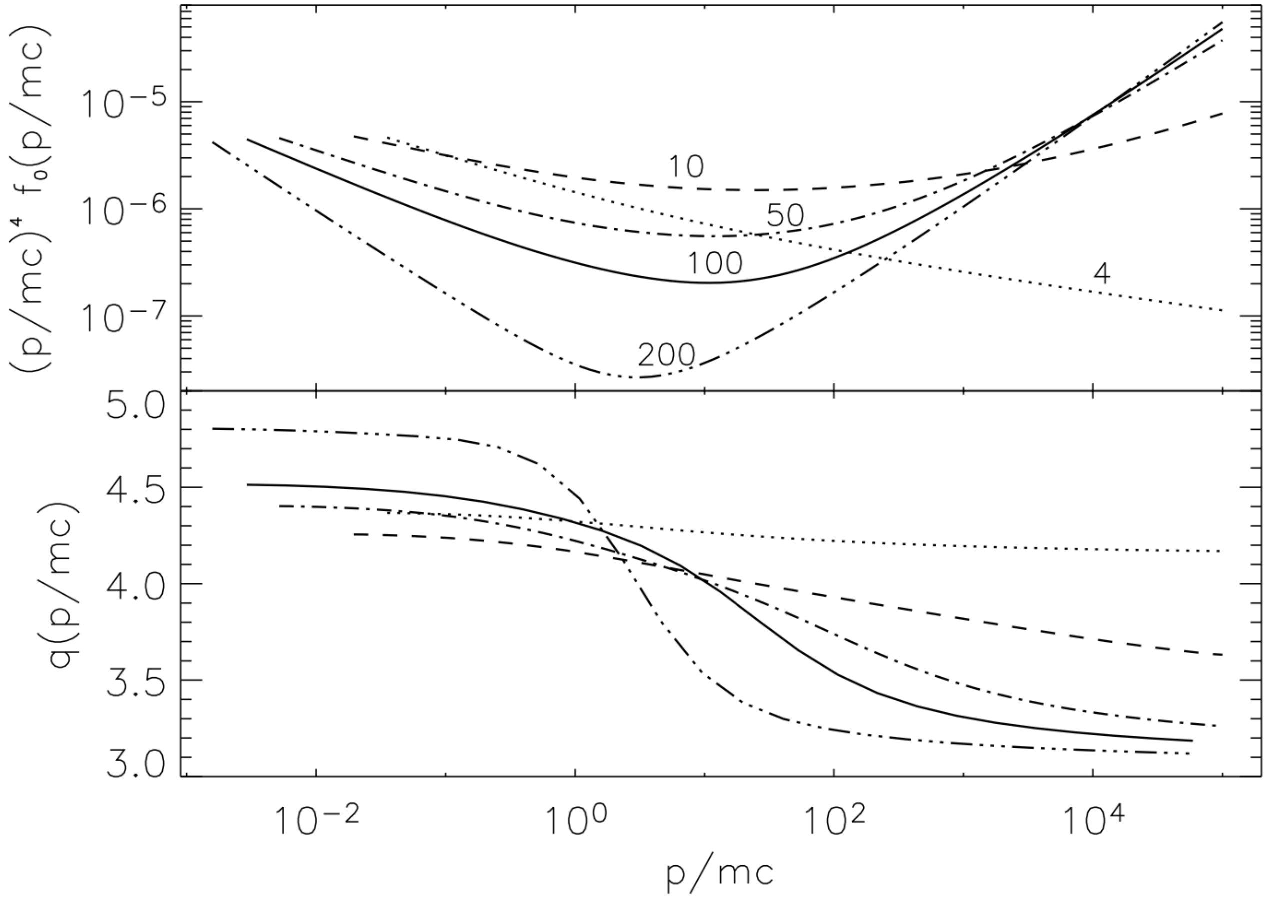
Spectrum at the shock?

Until now: fixed slope at the shock produced steeper summed injected spectrum.

$$f(p) \propto p^{-\alpha} \qquad\qquad f(p) \propto p^{-\alpha(t)} \quad \alpha \neq 4$$

Non-linear effects: efficient particle acceleration acting on the shock structure





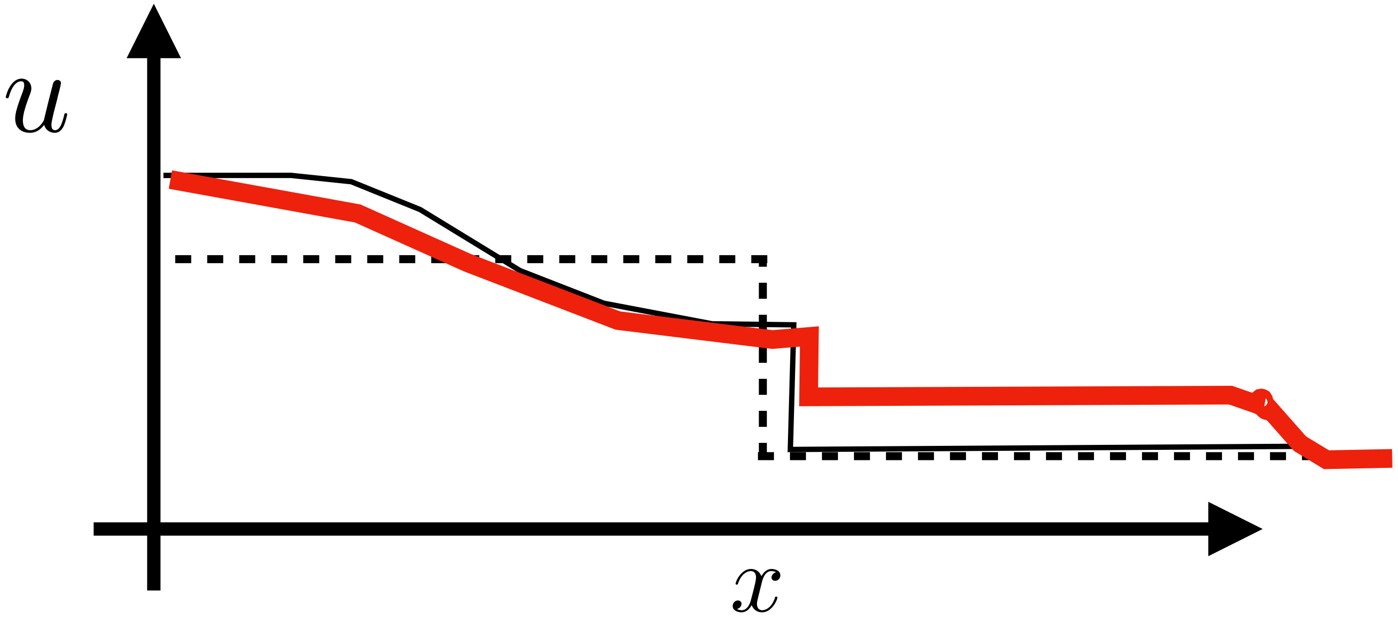
Drury& Völk (1980,1981), Bell (1987)
Jones & Ellison (1991), Ellison, Möbius & Paschamnn (1990), Ellison, Baring & Jones (1995, 1995) Kang & Jone
(1997, 2005) Kang, Jones & Gieseler (2002), Malkov (1997), Malkov, Diamond & Völk (2000)
Blasi (2002), Amato & Blasi (2005,2006)

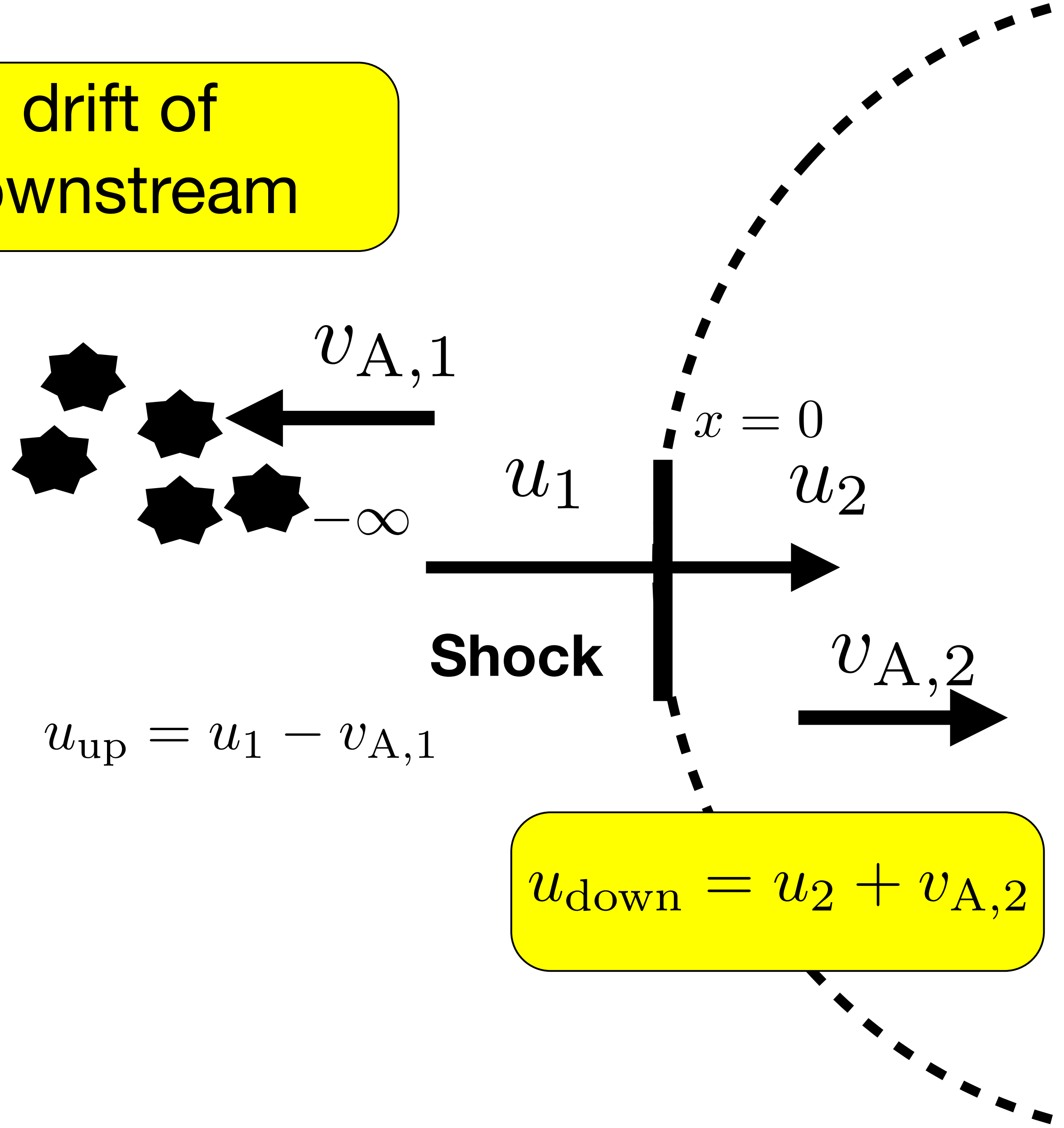
Spectrum at the shock?

Until now: fixed slope at the shock produced steeper summed injected spectrum.

$$f(p) \propto p^{-\alpha} \qquad\qquad f(p) \propto p^{-\alpha(t)} \quad \alpha \neq 4$$

Non-linear effects: drift of scattering centers downstream





$$u_{\mathrm{up}} = u_1 - v_{\mathrm{A},1}$$

$$u_{\mathrm{down}} = u_2 + v_{\mathrm{A},2}$$

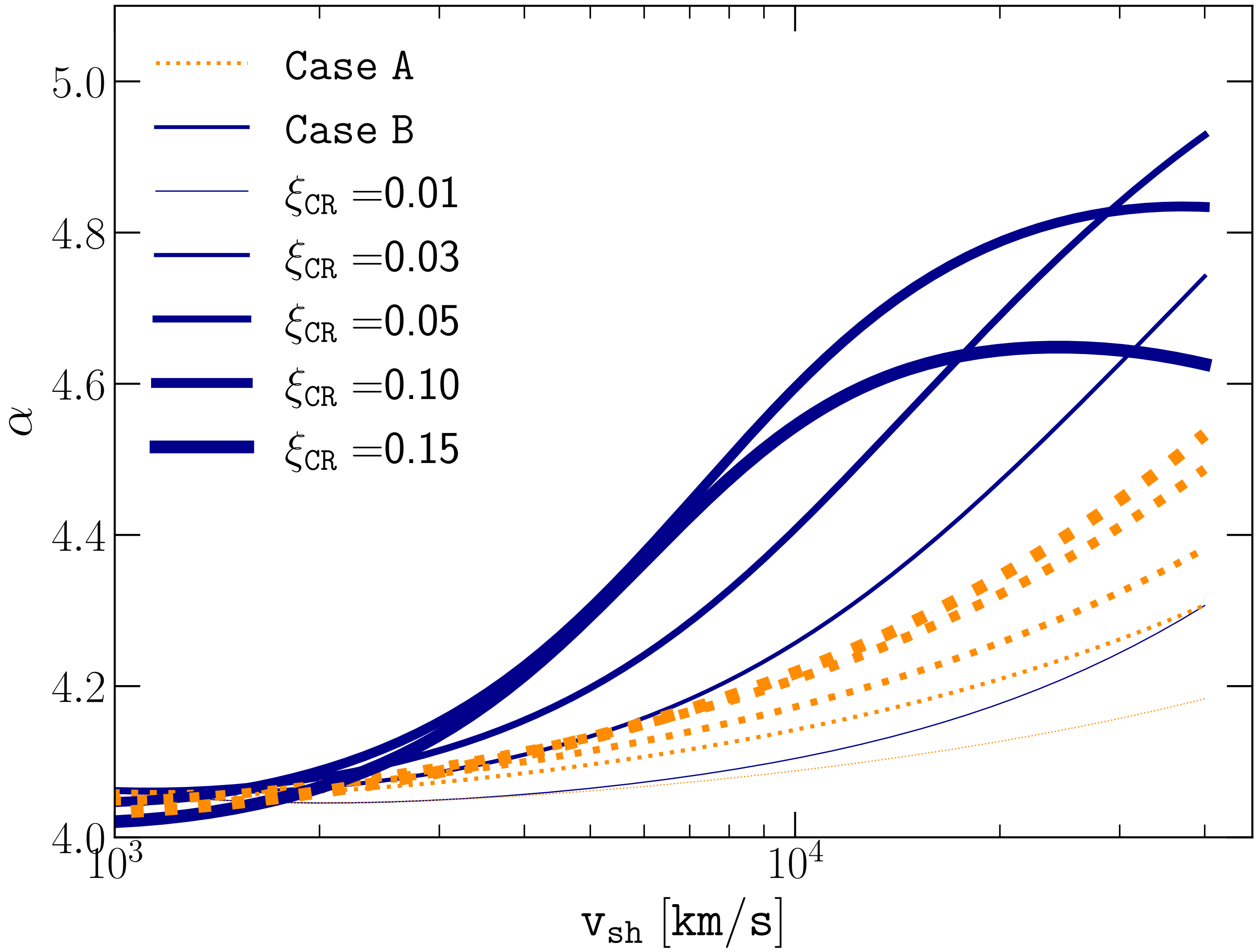
Zirakashvili & Ptuskin (2008)

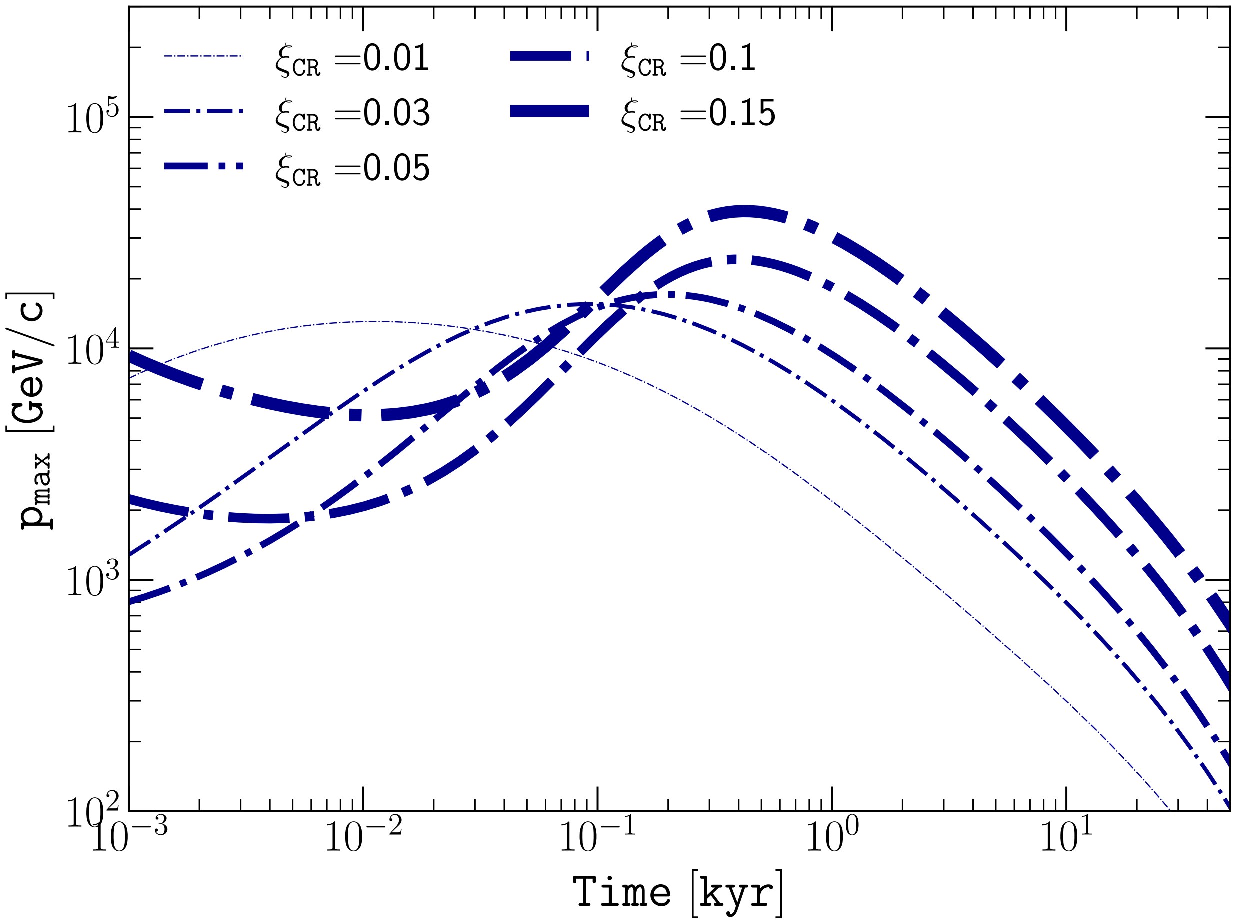
Drury (1983), Caprioli, Haggerty & Blasi (2020), Diesing & Caprioli (2021), PC, Blasi & Caprioli (submitted 2022)

Spectrum at the shock?

$$v_{A,2} = R_{\rm tot}\frac{\delta B_2}{\sqrt{4\pi\rho}}$$

Bell: current from all particles
(maximum value B)





Bell: current escaping
particles upstream infinity

Consequences on pmax!

Drury (1983), Caprioli, Haggerty & Blasi (2020), Diesing & Caprioli (2021), PC, Blasi & Caprioli (submitted 2022)

What is wrong with supernova remnants?

1. Diffusive shock acceleration predicts E-2 at SNRs

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

Injection Propagation

2. Non-thermal emission from radio to gamma

3. Energy budget (~5/10% total explosion energy)

How much precisely? For how

4. SNR Pevatron

NO SNR pevatron

Non-linear effects, drift scattering centers

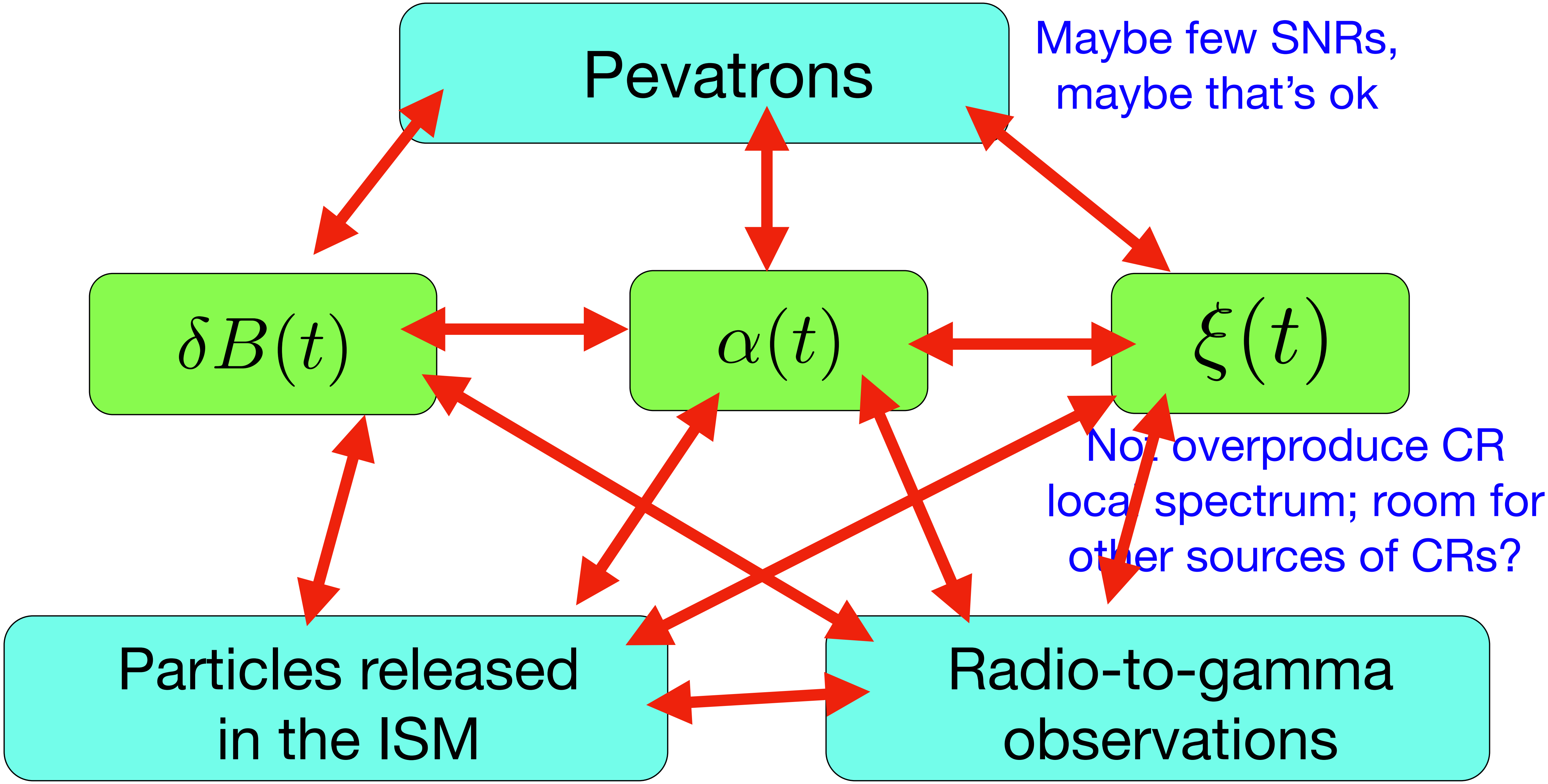
Cumulative effects including losses (B?)

Diffusive shock Reacceleration?

Time evolution? Duration phases? Acceleration at late times?

Maybe very few SNRs + short phase

Summary



Pevatrons

Maybe few SNRs,
maybe that’s ok

$\delta B(t)$

$\alpha(t)$

$\xi(t)$

Not overproduce CR
local spectrum; room for
other sources of CRs?

Particles released
in the ISM

Radio-to-gamma
observations

What’s ~~wrong~~ unclear with supernova remnants?

1. What is pmax(t)? Pevatrons?
2. Magnetic field (time)?
3. Content accelerated/reaccelerated?
4. Efficiency (time)?
5. Slope (precursor/postcursor)?
6. Spectrum released in the ISM?

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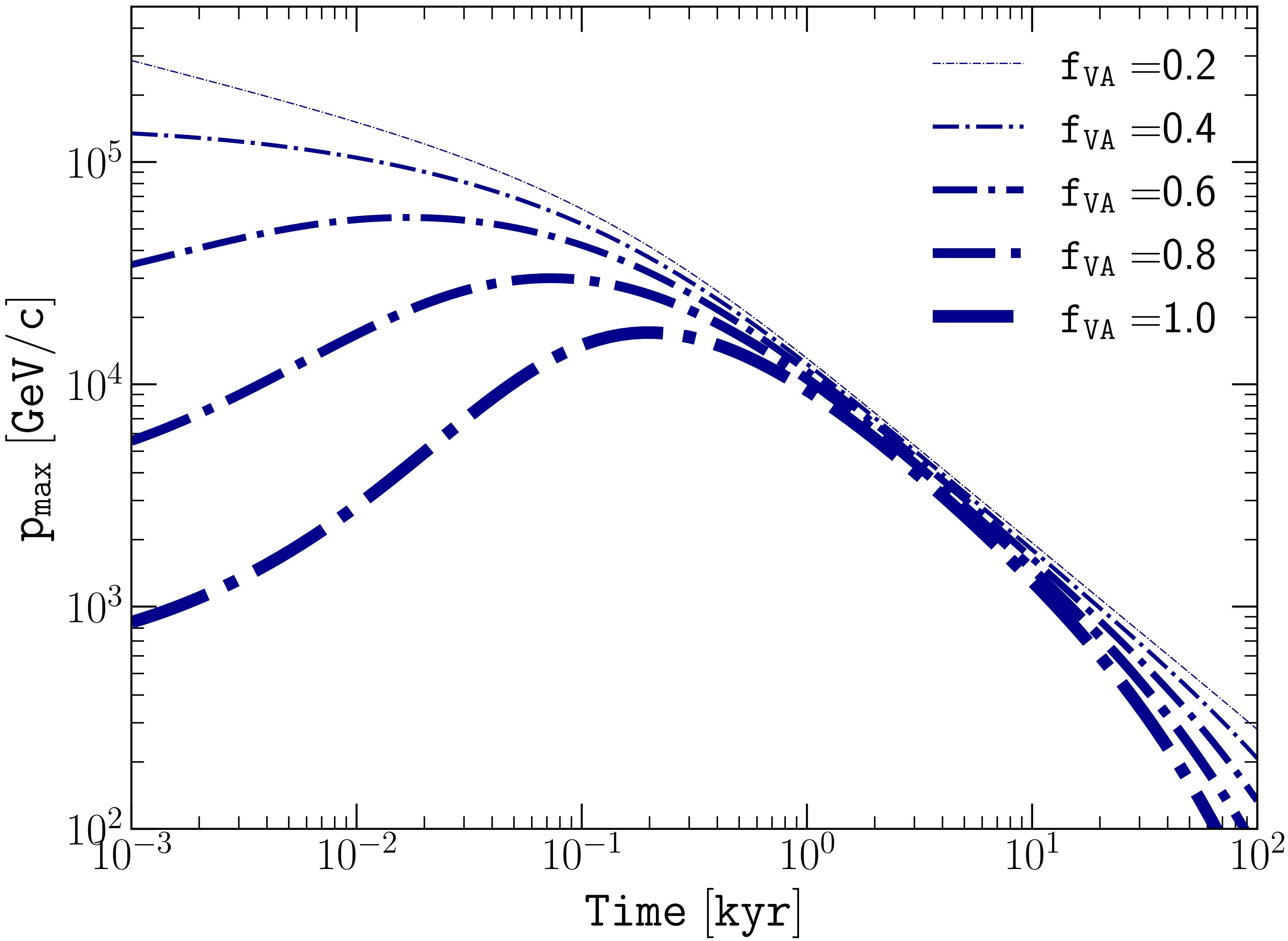

f_{VA} =0.2
f_{VA} =0.4
f_{VA} =0.6
f_{VA} =0.8
f_{VA} =1.0
p_{max} [GeV/c]
10^5
10^4
10^3
10^2
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
Time [kyr]