Diffusive shock reacceleration at supernova remnant shocks

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CRA 2019 - L'Aquila

Cristofari & Blasi (MNRAS 2019)

GSSI

cta cherenkov telescope array

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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. »

(…)

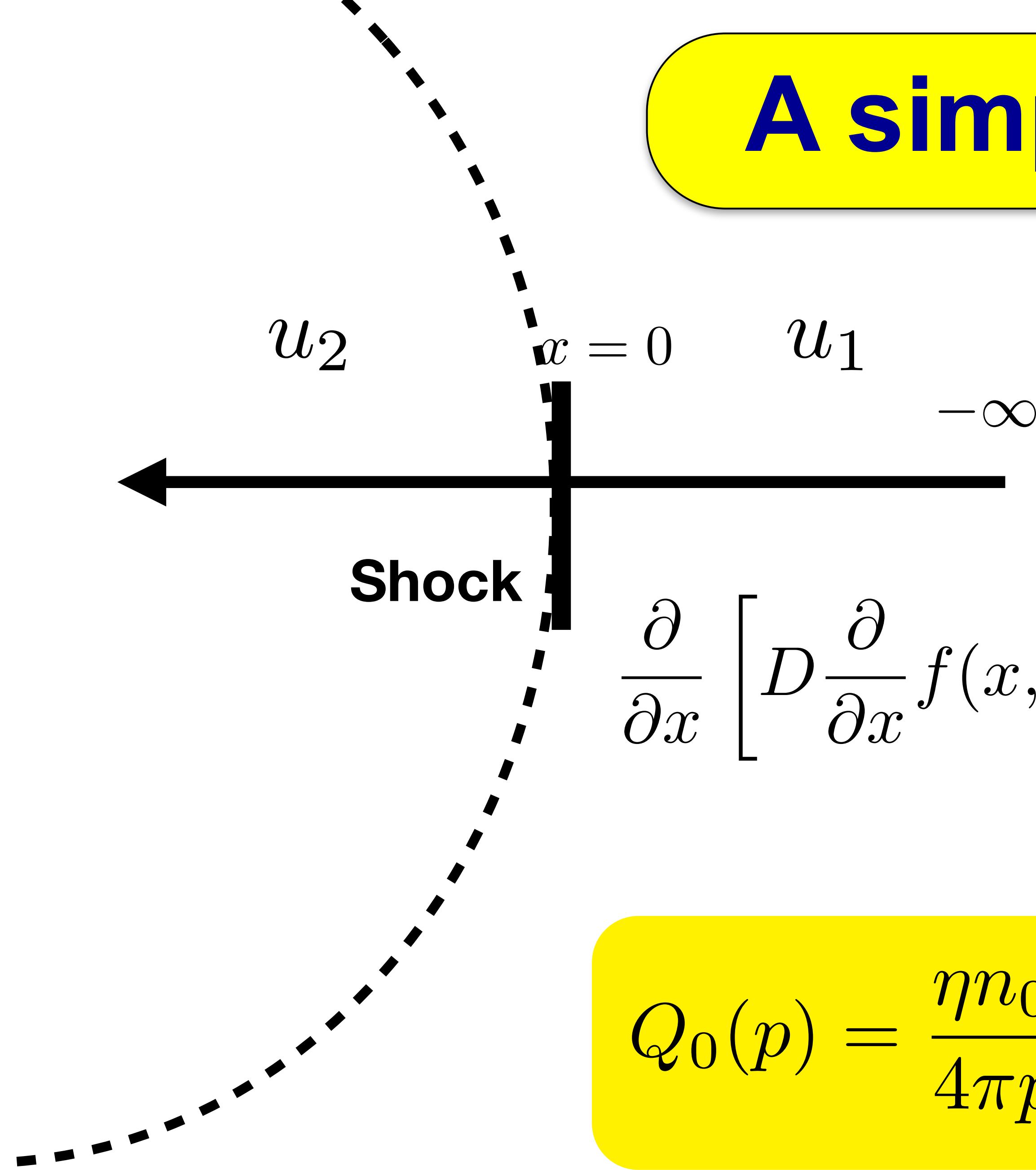
Pohl et. al (2015, A&A)

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



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

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

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

Boudary condition -> upstream infinity of the shock

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

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

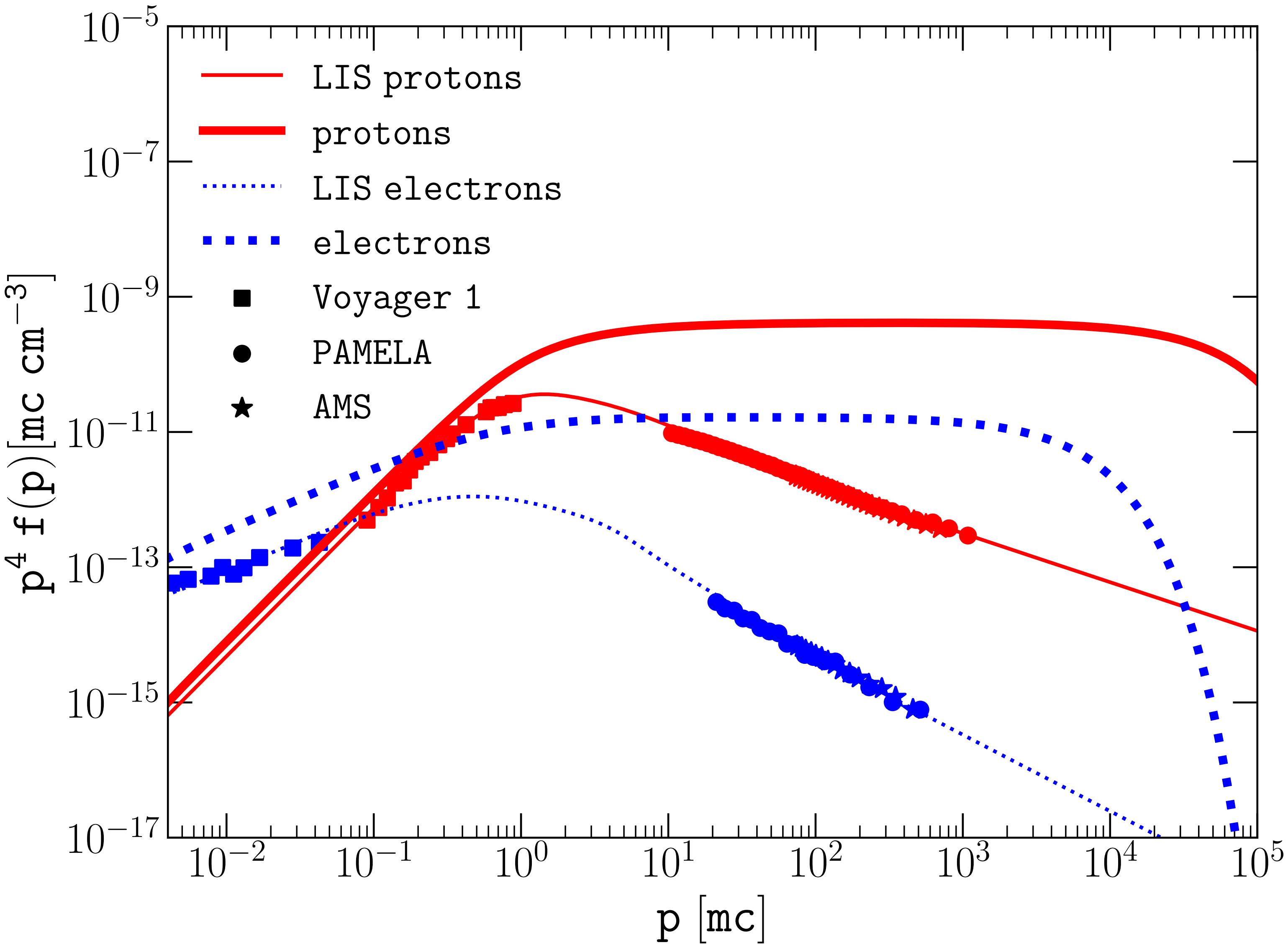
$$f_0(p) = s\frac{\eta n_1}{4\pi p_{\rm inj}^3}\left(\frac{p}{p_{\rm inj}}\right)^{-s} + s\int_{p_0}^{p}\frac{\mathrm{d}p'}{p'}\left(\frac{p'}{p}\right)^{s} g(p')$$

« Classic » diffusive shock acceleration

Reacceleration

Blasi (2004)

Reacceleration of Galactic CRs



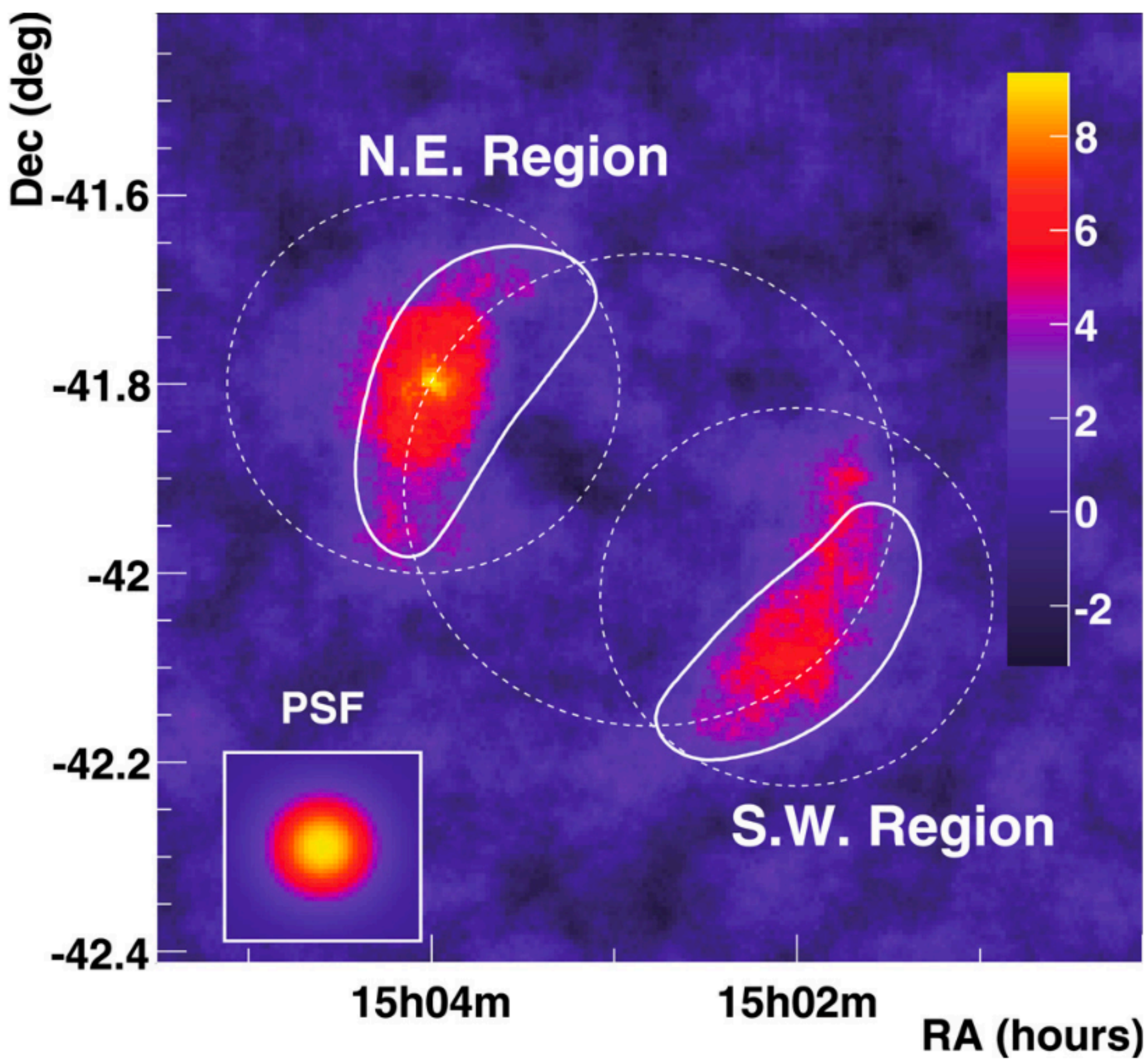
$$f_0^{\mathrm{reac}}(p) = s \int_{p_0}^{p} \frac{\mathrm{d}p'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$

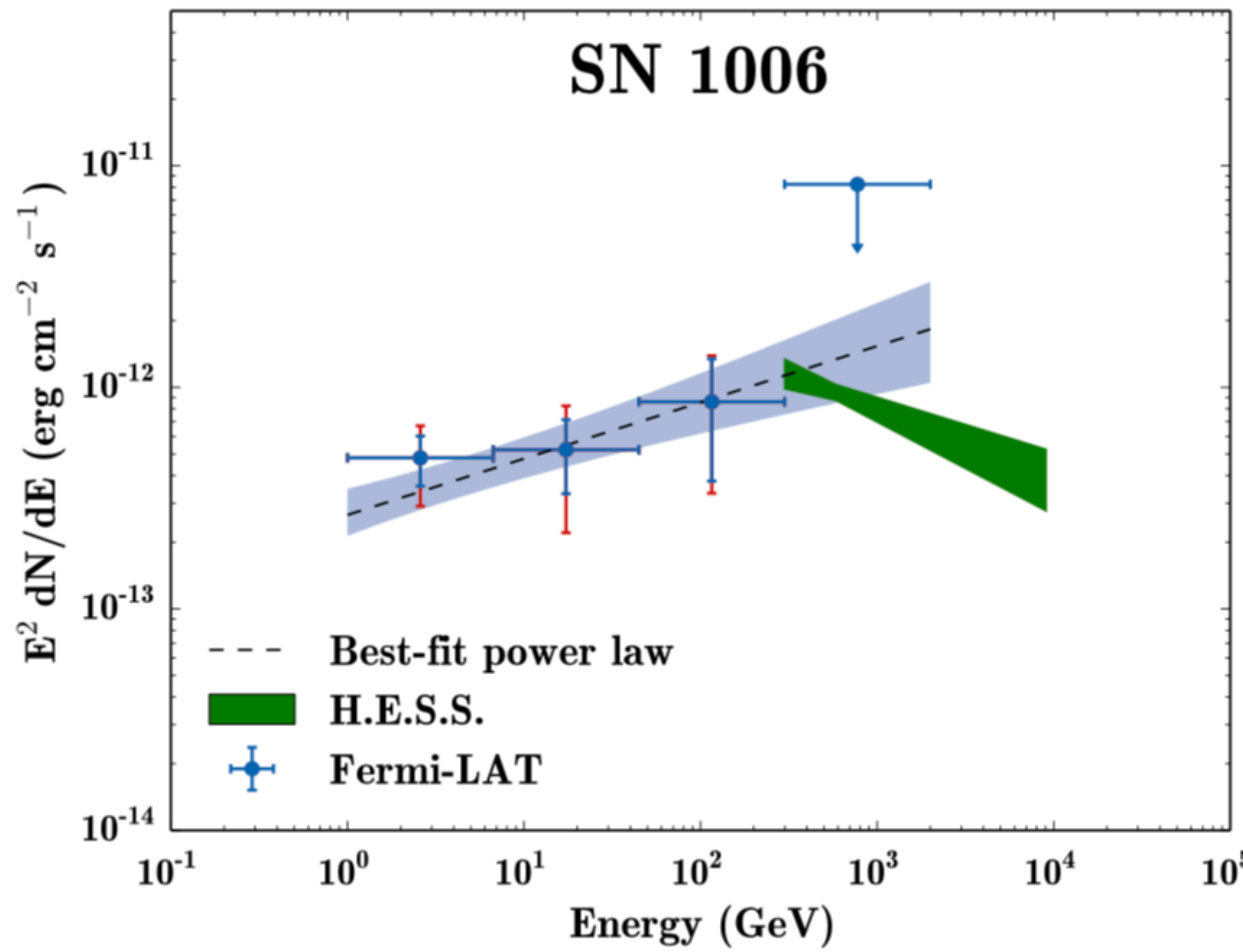
$$s = 4$$
$$p_0 \lesssim 1\ \mathrm{GeV}$$

Maximum energy of reaccelerated particles?

Bischoff et al. (2019)
Aguilar et al. (2019)
Cummings et al. (2016)
Adriani et al. (2011)

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 (2017)

Reaccelerated particles at SN 1006

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

Maximum energy of reaccelerated particles?

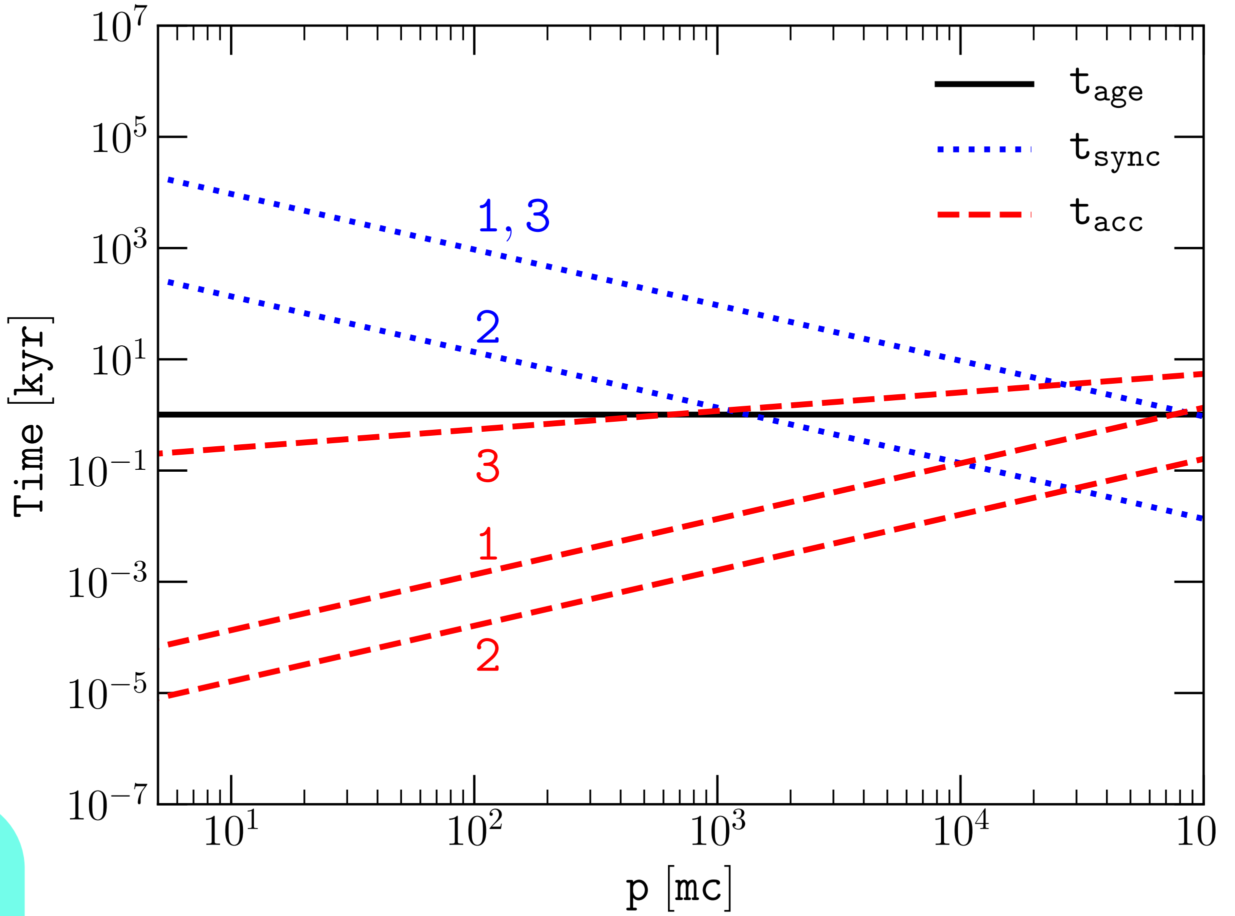
Protons?

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

Maximum energy of reaccelerated electrons?

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

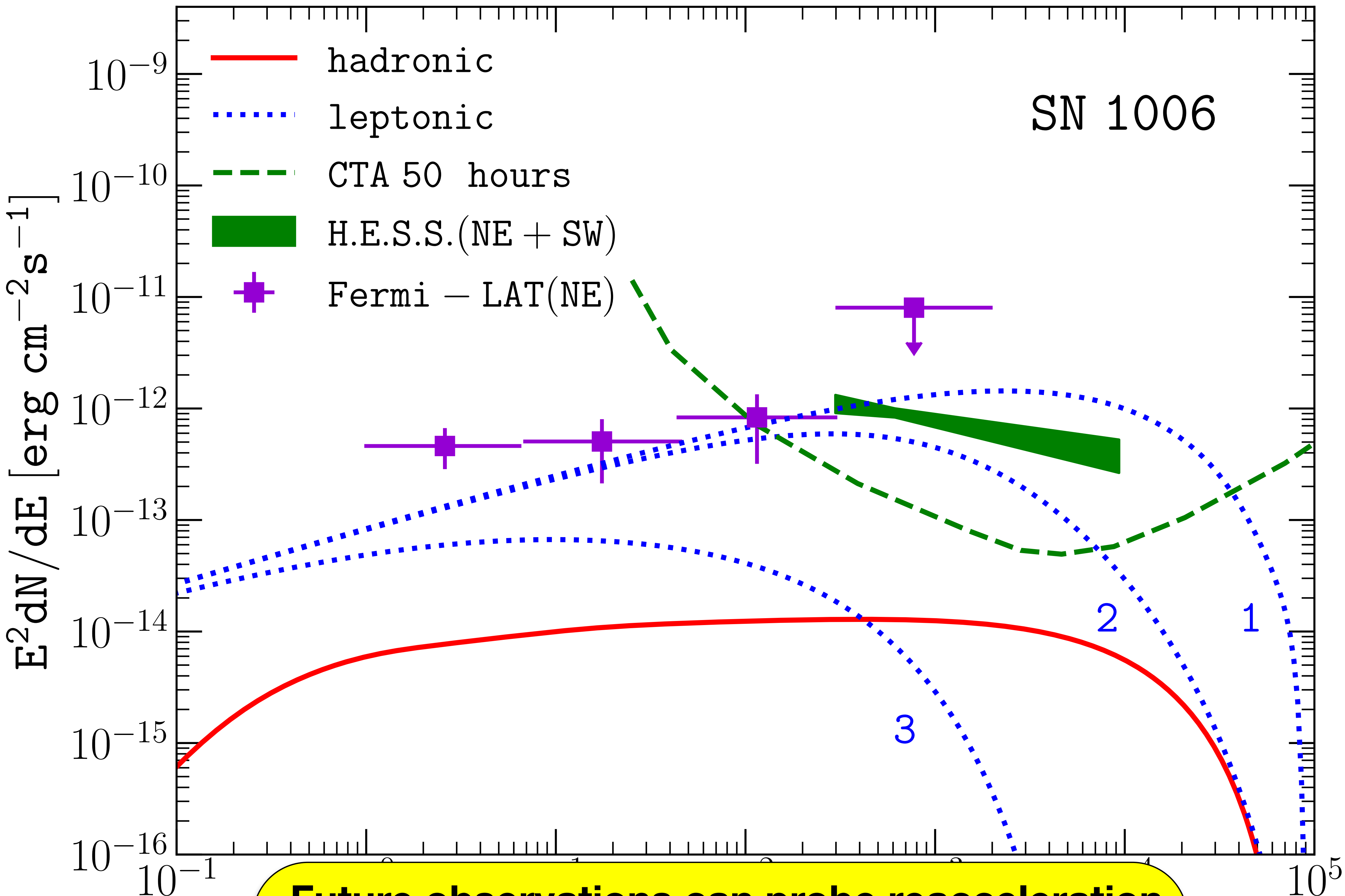
$$\tau_{\rm acc} = \frac{3}{u_1 - u_2} \int_0^p \frac{dp'}{p'} \left(\frac{D_1(p')}{u_1} + \frac{D_2(p')}{u_2}\right)$$



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

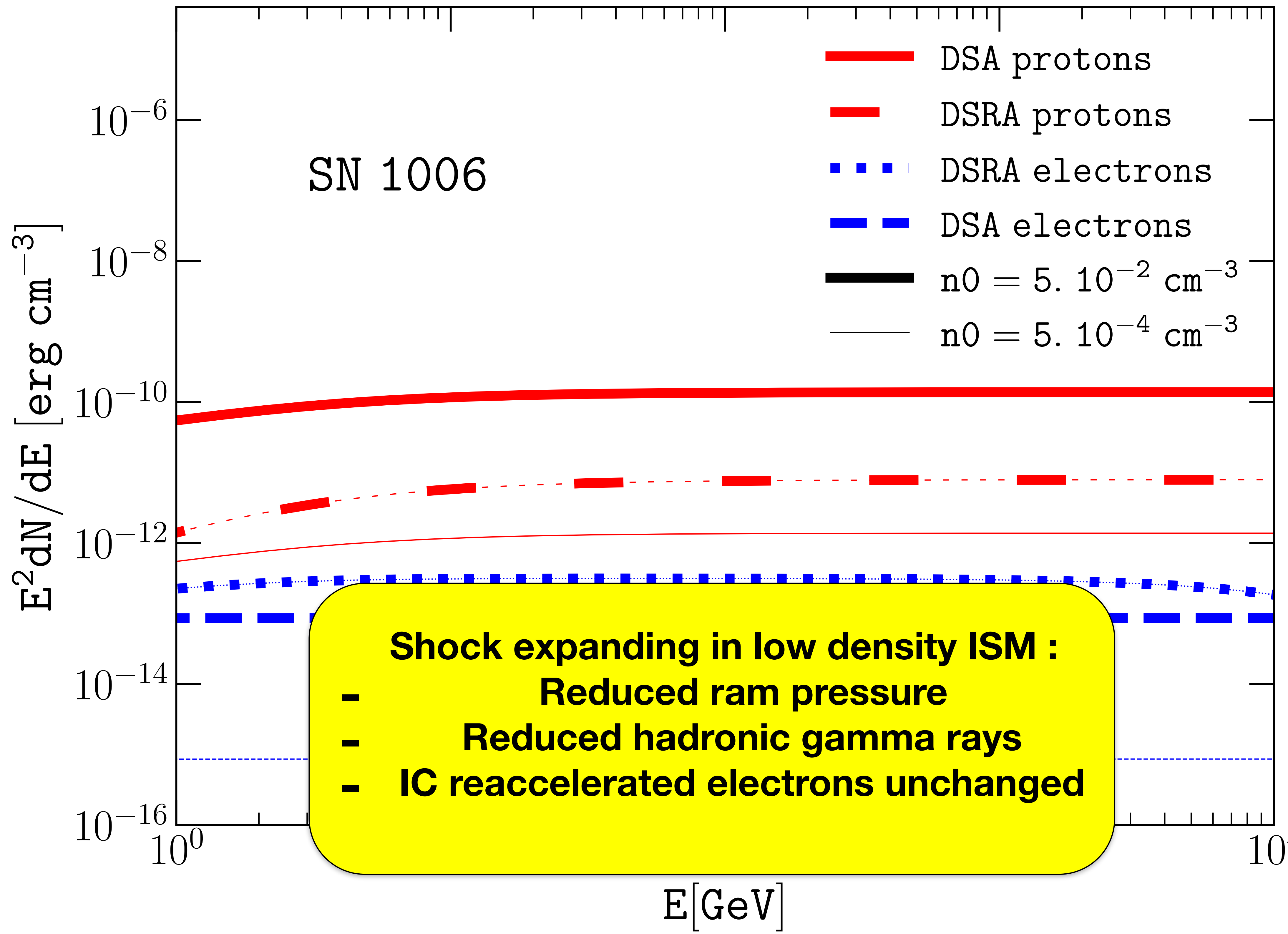
$$B_2 = rB_1$$

Gamma rays from SN 1006



Future observations can probe reacceleration and constrain the diffusion coefficient

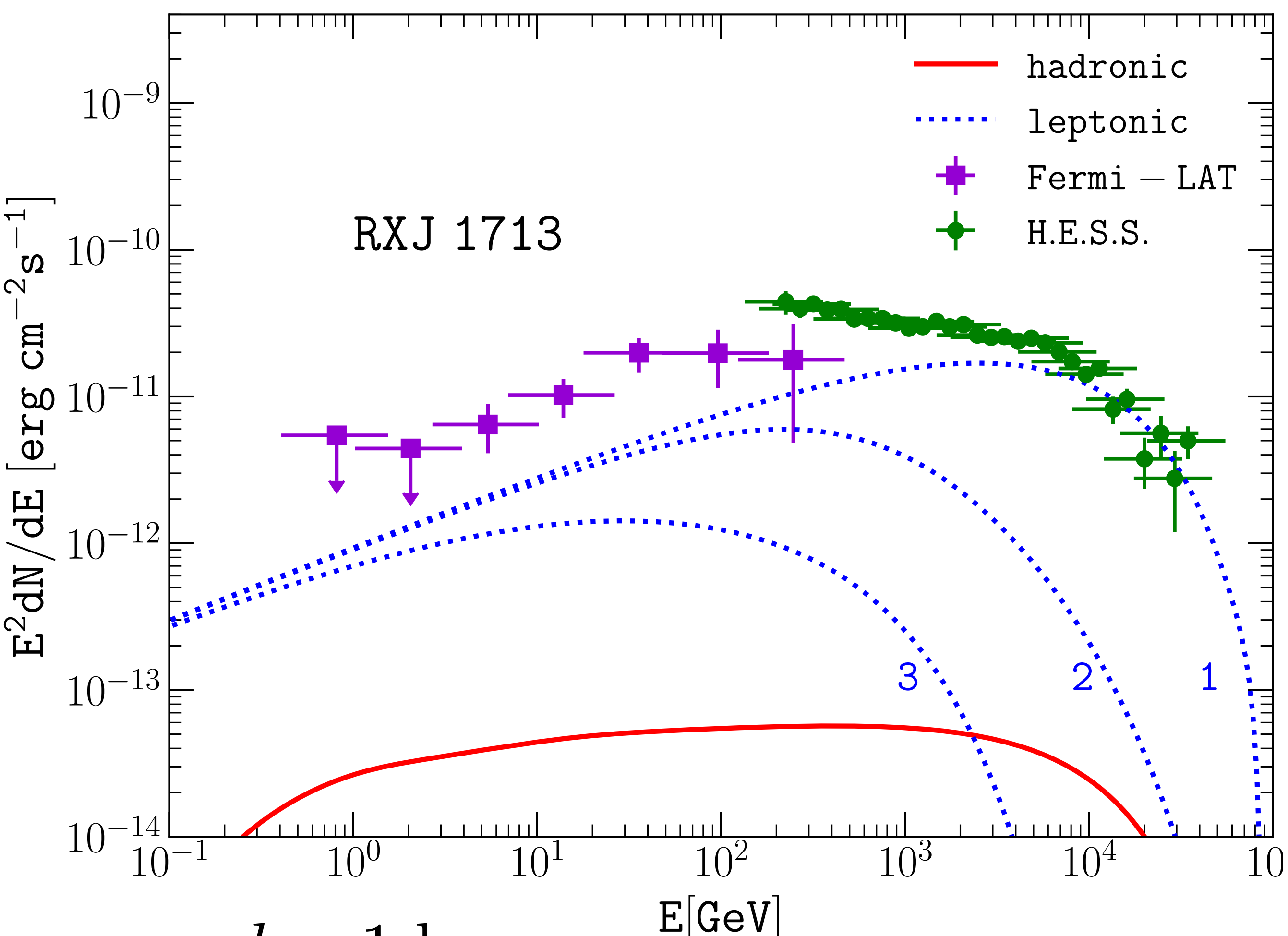
Reaccelerated particles at SN 1006



Shock expanding in low density ISM :

- **Reduced ram pressure**
- **Reduced hadronic gamma rays**
- **IC reaccelerated electrons unchanged**

RXJ1713 and Vela Jr

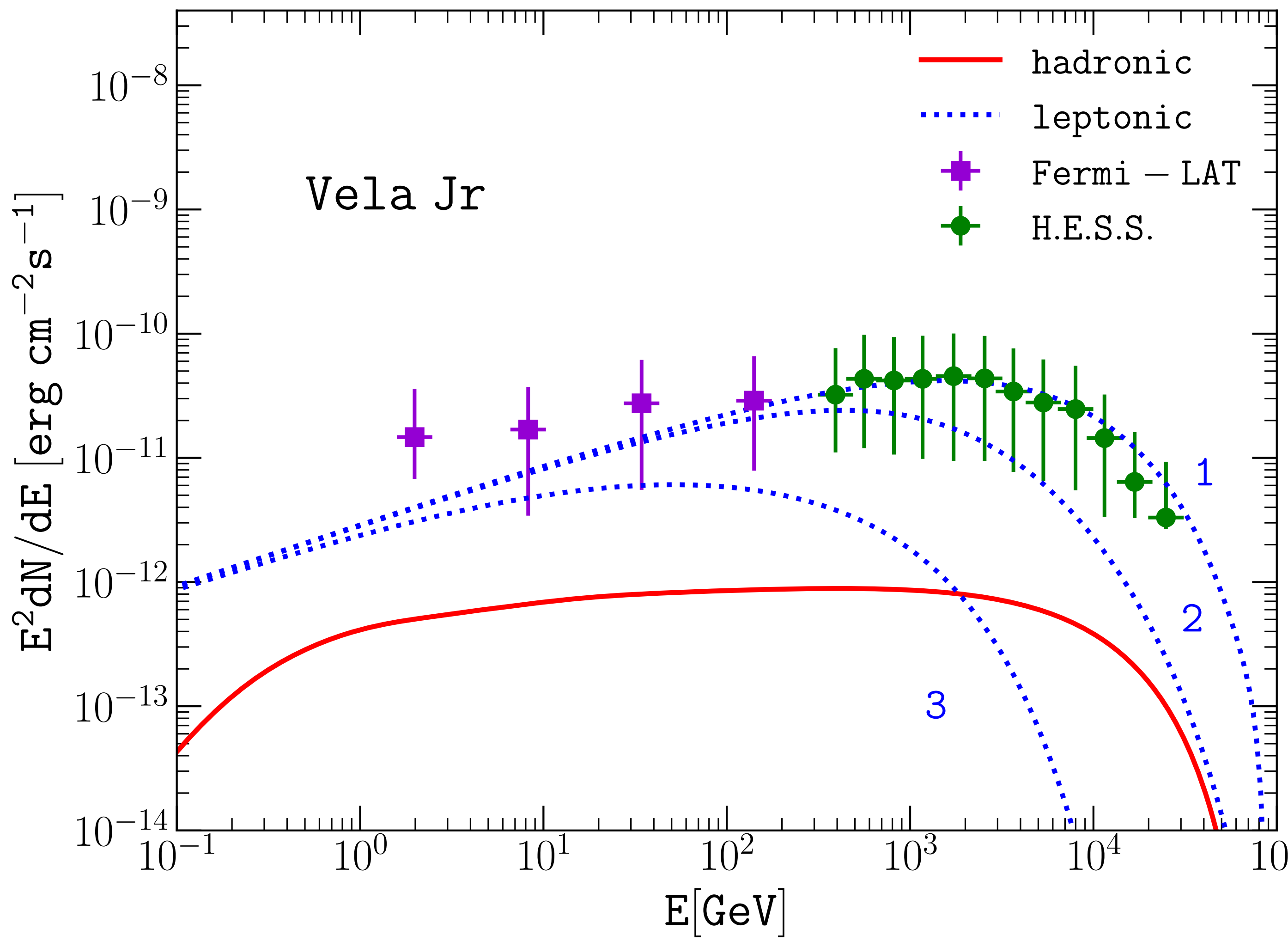


$d \approx 1$ kpc

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

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

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



$d \approx 0.750$ kpc

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

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

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

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

Reacceleration over the SNR lifetime

$$R_{\rm sh} \propto t^{2/5}$$
$$u_{\rm sh} \propto t^{-3/5}$$
$$p_{\rm max} = p_{\rm M} t^{-\alpha}$$

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

Number of freshly accelerated particles

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

Number of reaccelerated particles

$$n_{\rm reac}(p,t) \propto p^2 \; f_0^{\rm reac}(p)$$
$$\propto p^2 \; s \int_{p_0}^{p} \frac{{\rm d}p'}{p'} \left(\frac{p'}{p}\right)^s g(p')$$
$$\propto p^{-2} \exp\left[-\frac{p}{p_{\rm max}(t)}\right]$$

Total integrated spectrum

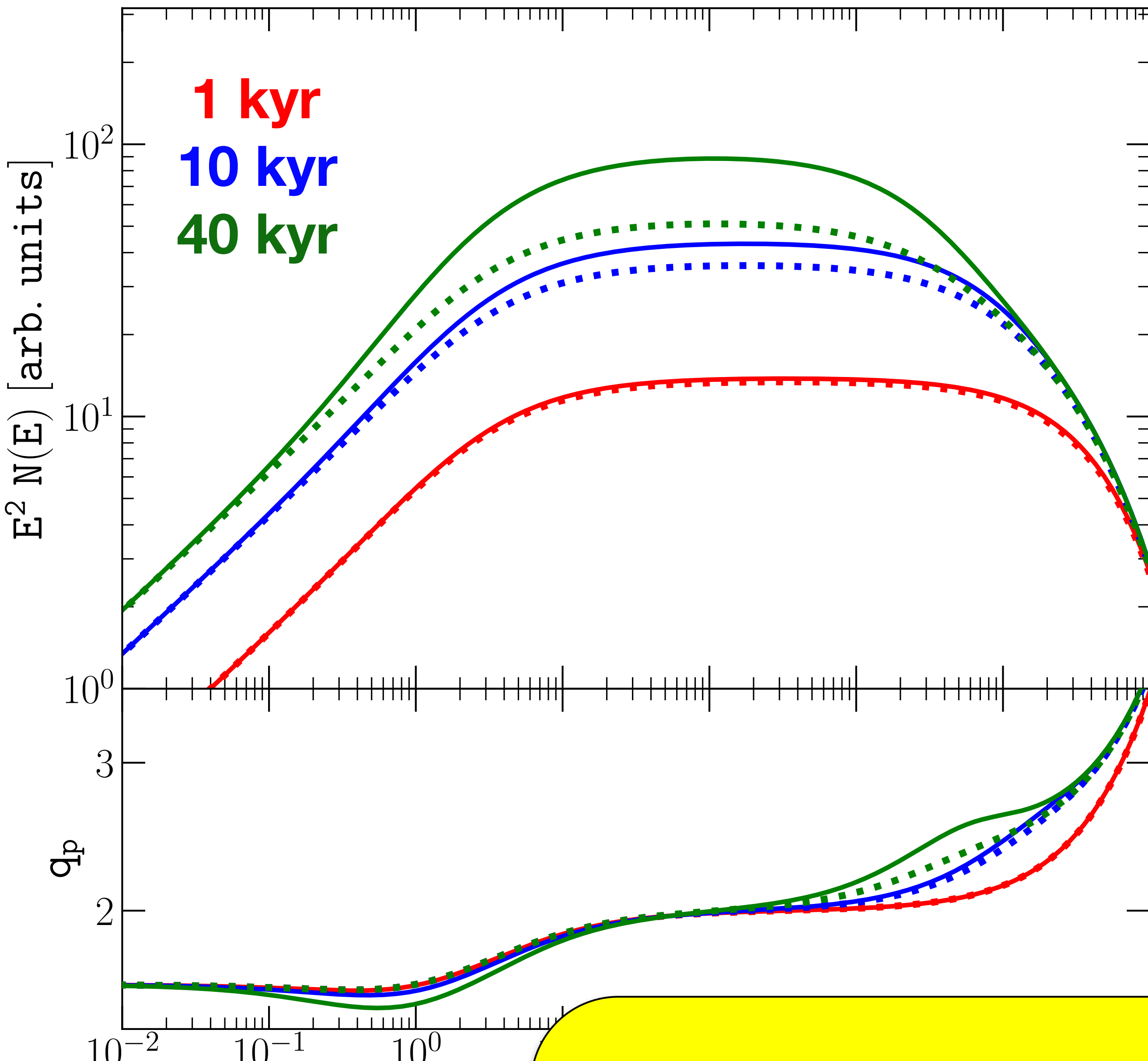
$$N_{\rm acc}(p) \propto \xi E_{\rm SN} \; p^{-2} \ln\left(\frac{p_{\rm M}}{p}\right)$$

Total integrated spectrum

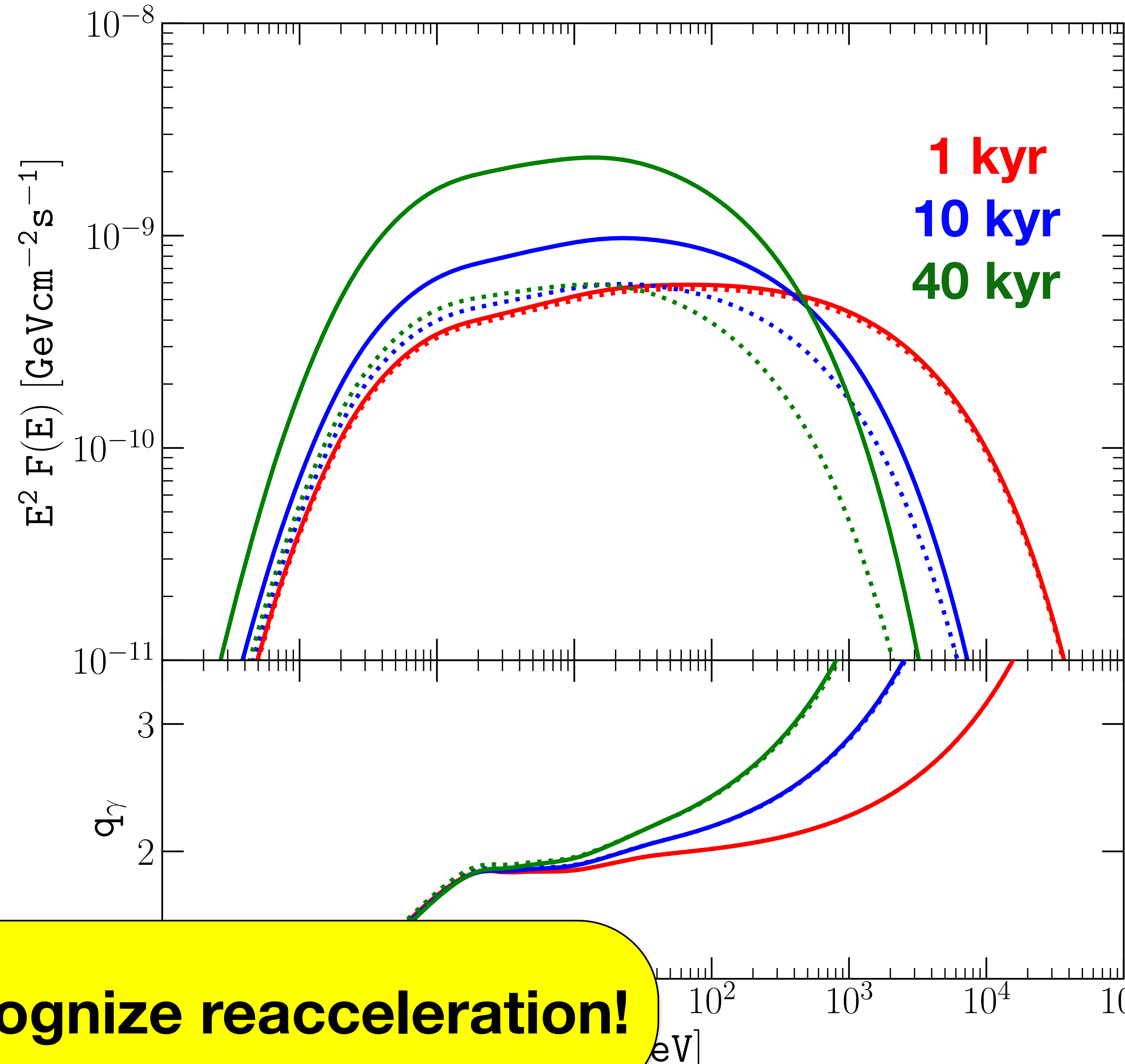
$$N_{\rm reac}(p) \propto V_{\rm SN} \left(\frac{T_{\rm SN}}{t_0}\right)^{6/5} p^{-2} \exp\left[-\frac{p}{p_{\rm max}(T_{\rm SN})}\right]$$

Reacceleration over the SNR lifetime

Protons



Gamma−rays

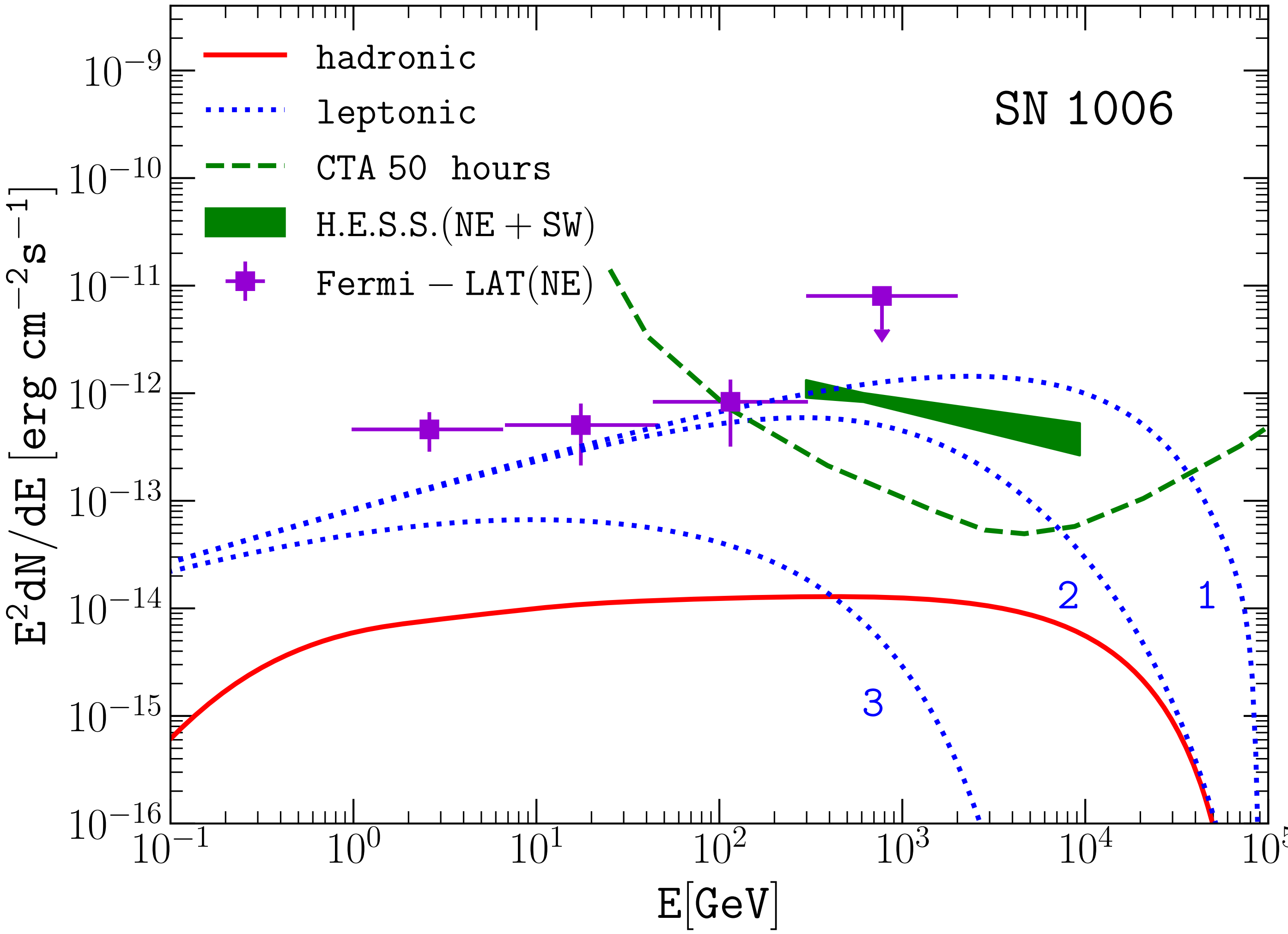


It is not easy to recognize reacceleration!

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