The hunt for the sources of Galactic cosmic rays

Pierre Cristofari

June 8th 2022
SF2A

The hunt for the sources of Galactic cosmic rays

Particle acceleration at supernova remnants?

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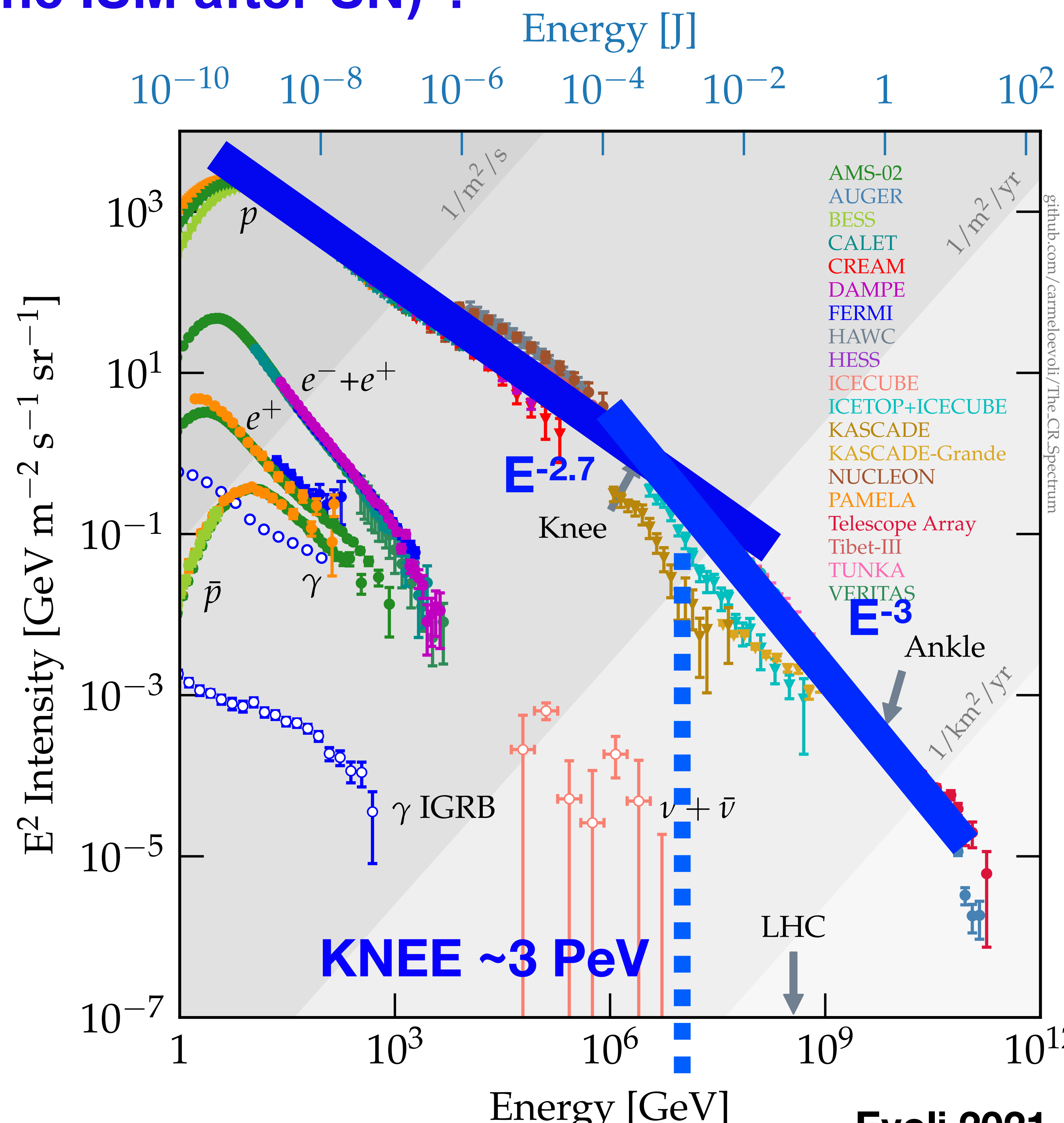
Why supernova remnants (=shock expanding in the ISM after SN) ?



Evoli 2021

Reviews: Blasi (2013,2019)
Tatischeff & Gabici (2018)
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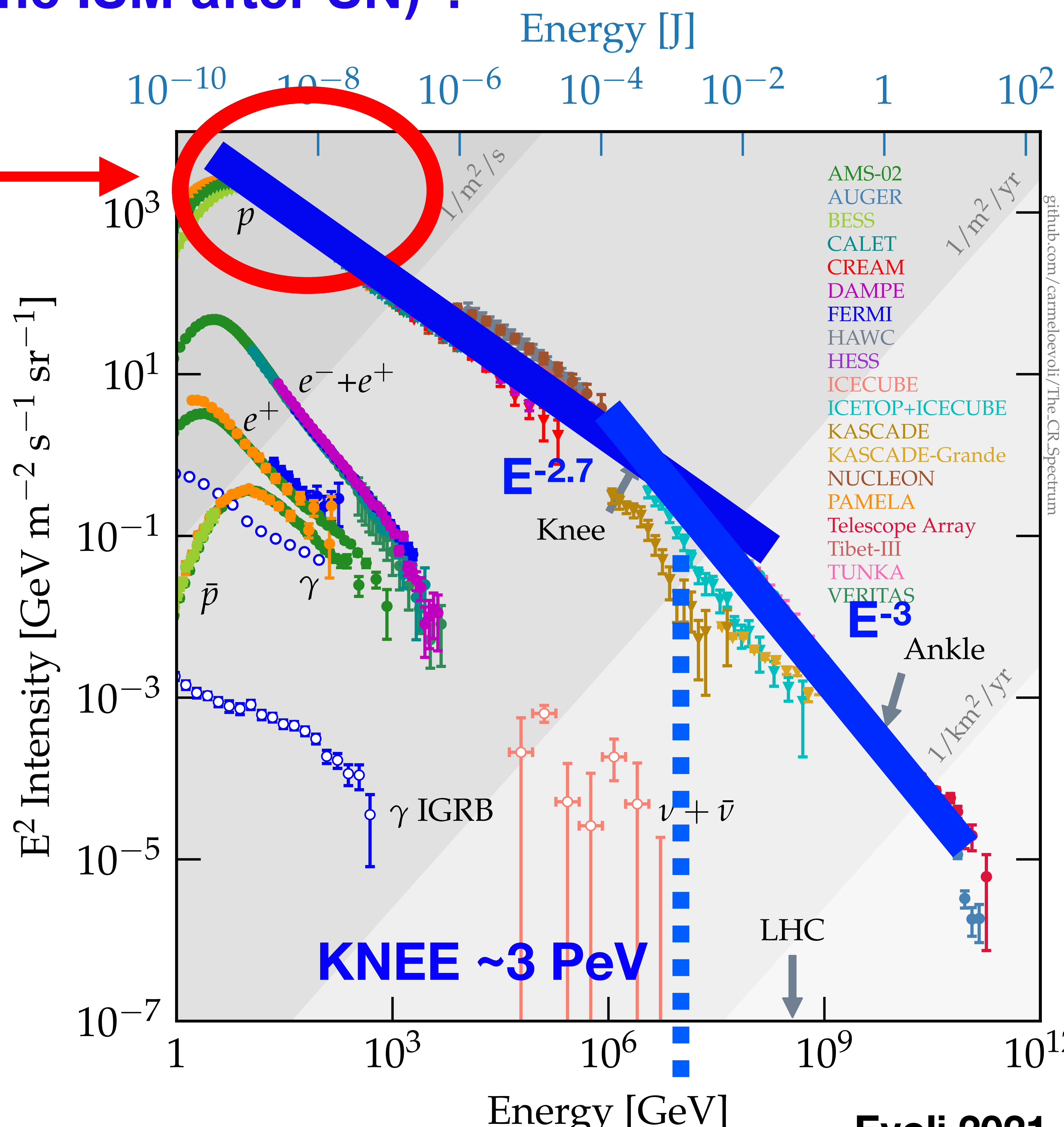
1. Bulk of CRs
Energy density ~1 eV/cm3
10% of SNR total explosion energy



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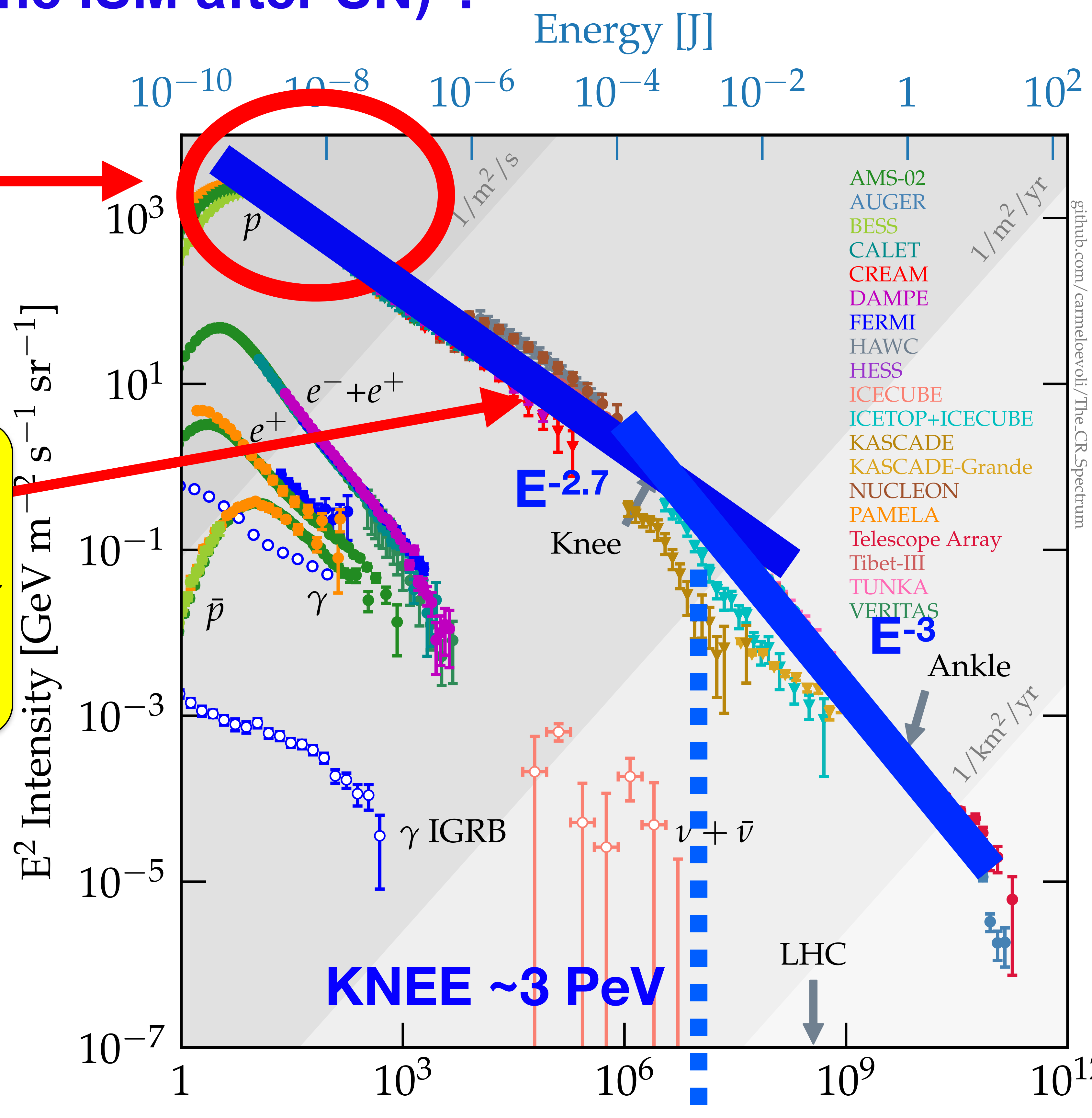
Diffusive shock acceleration

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

Injection **Propagation**



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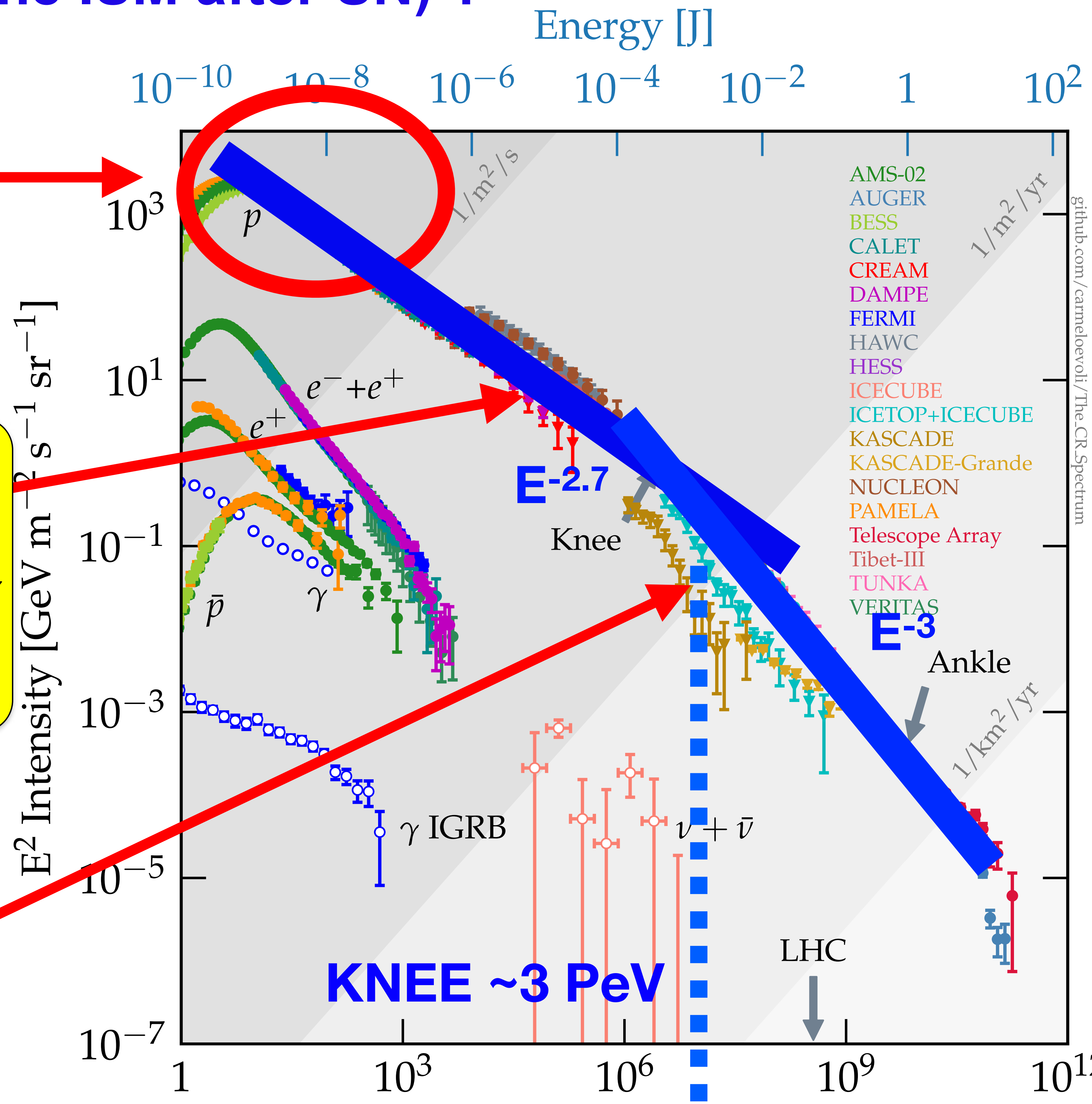
3. Magnetic field amplification



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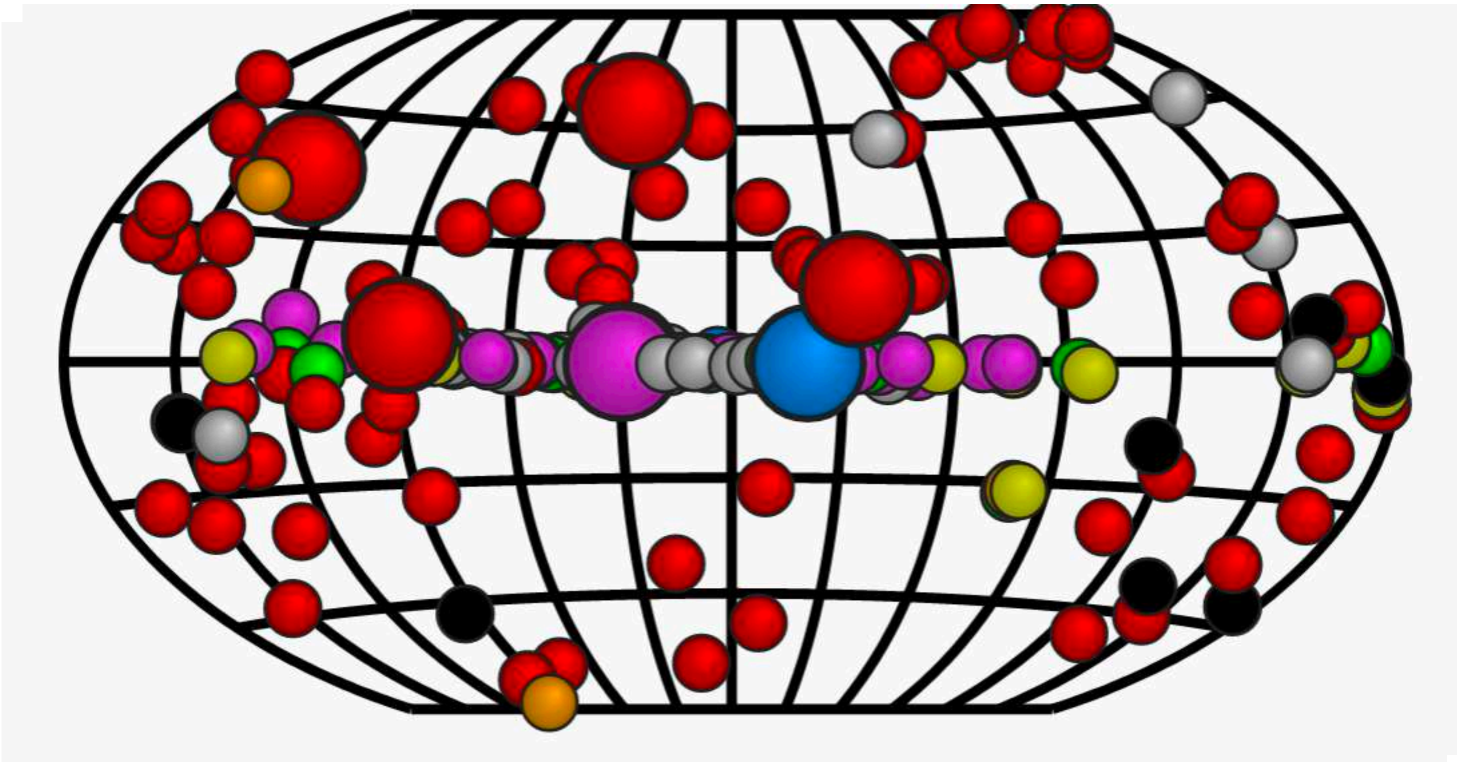
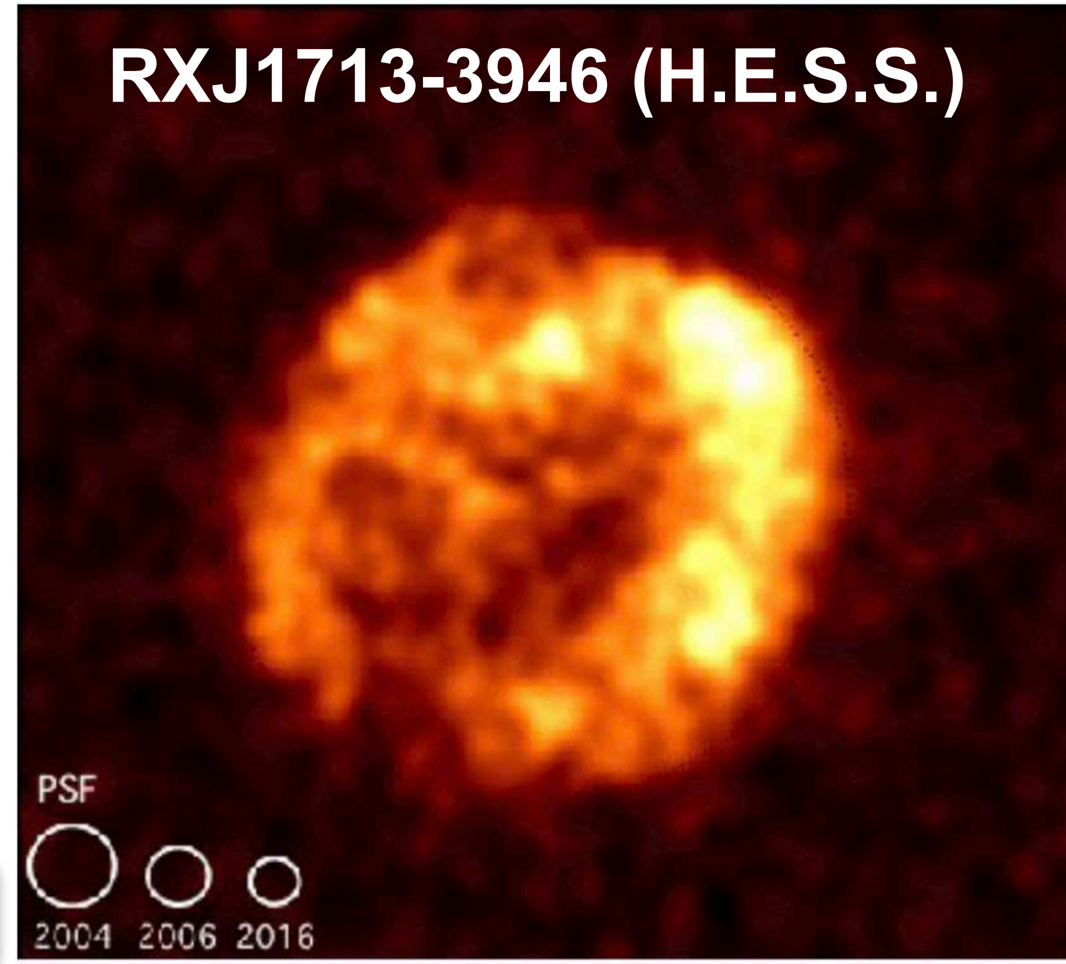
Evoli 2021

Detection of SNRs in the gamma-ray domain





PWN, PWN/TeV Halo, Composite SNR

Shell, SNR/Molec. Cloud, Composite SNI

228 sources listed

58 « SNRs »

12 Shells

ISM

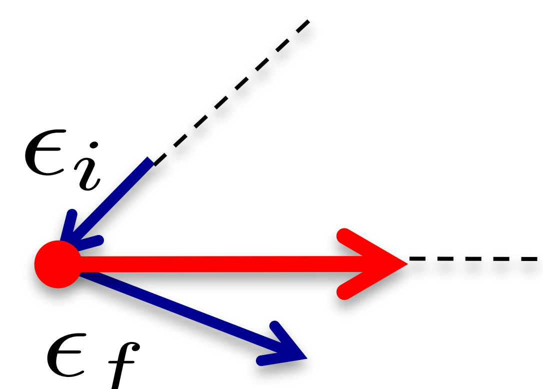
$$p + p \rightarrow p + p + \pi^0$$

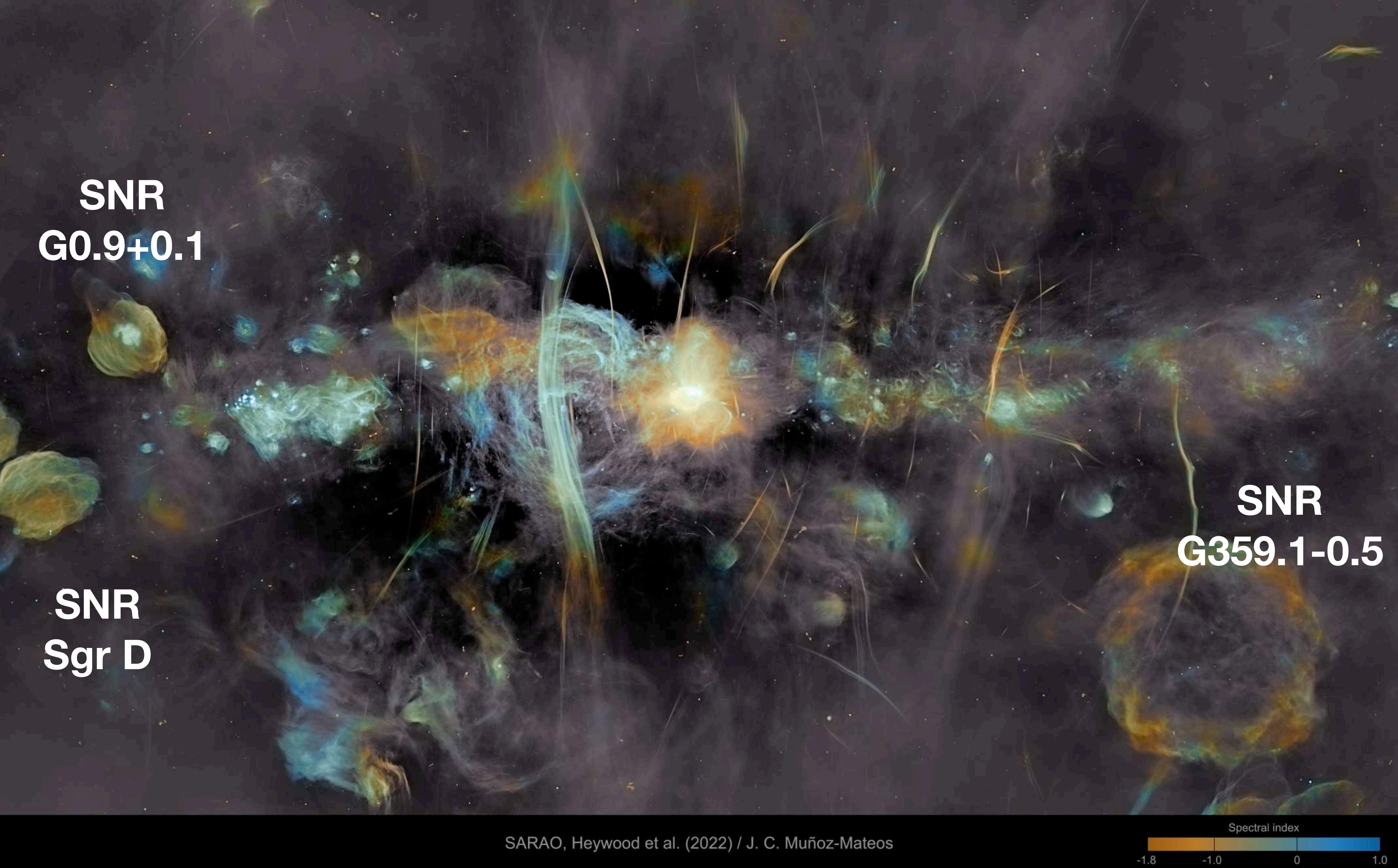
$$\pi^0 \rightarrow \gamma + \gamma$$

CR

Hadronic interactions:
Pion decay

Leptonic interactions:
Inverse Compton scattering

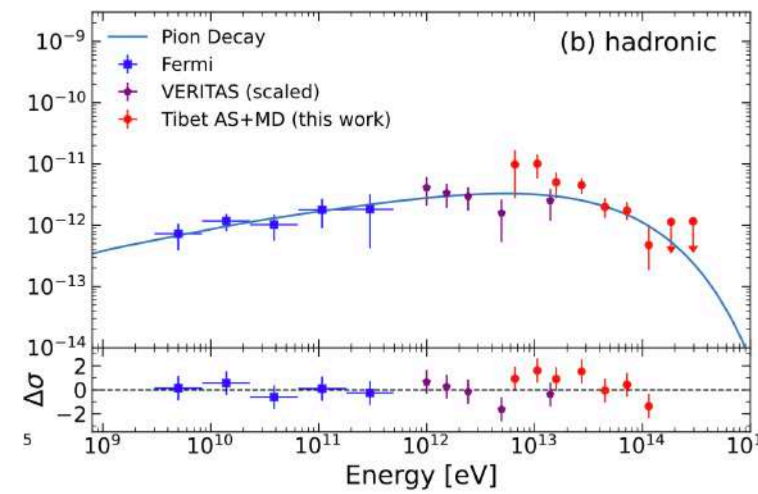




MeerKAT picture of the day Feb. 2nd 2022

What is wrong with supernova remnants?

1. All SNRs seem to not be pevatrons



SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

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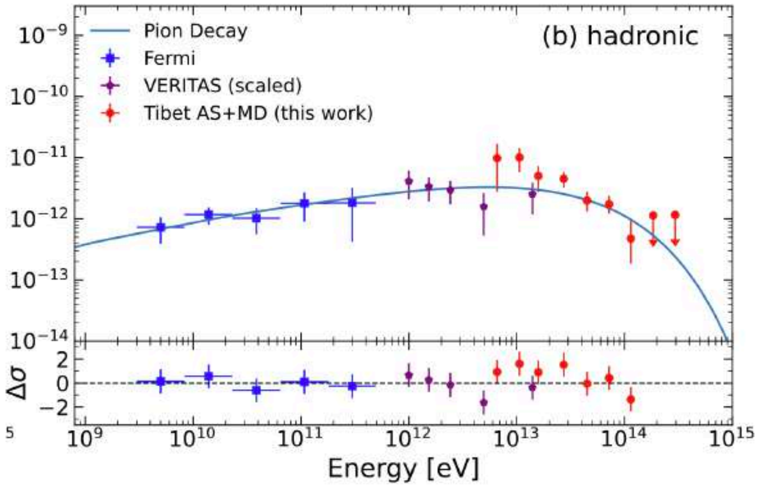

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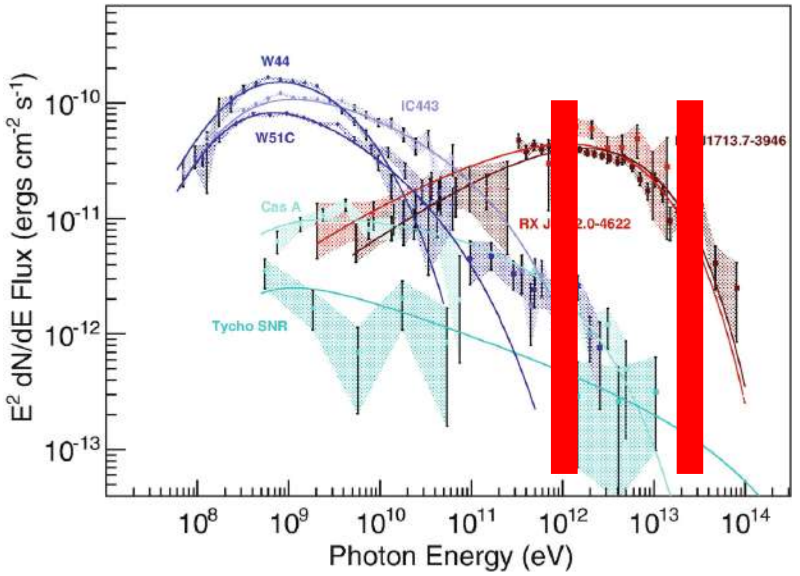
2. The slope of accelerated particles at SNR shocks

VHE domain steep spectra?



Funk (2017)

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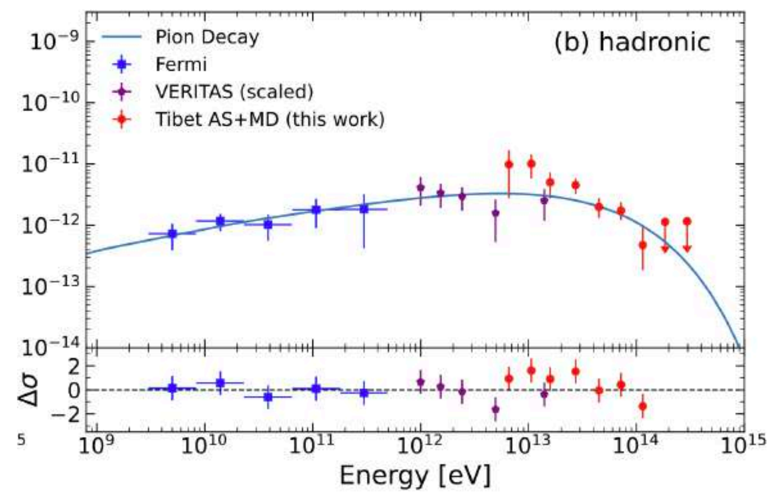

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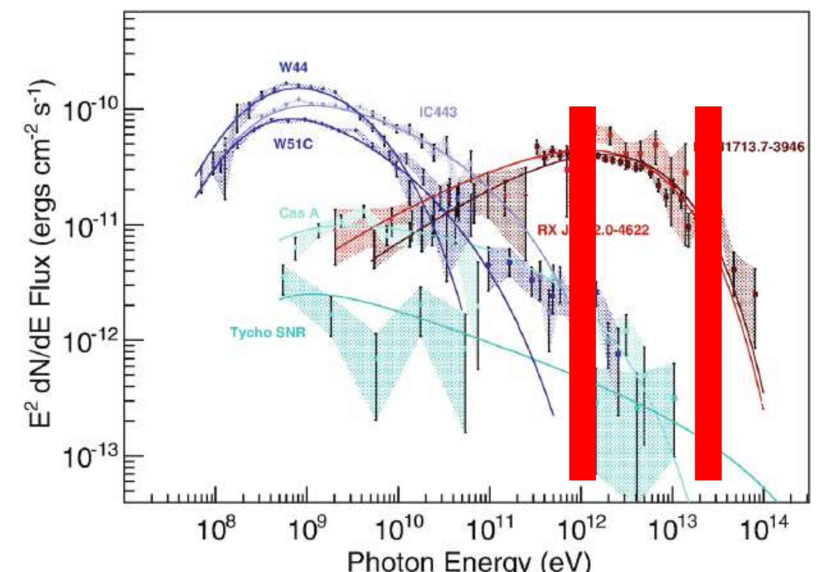

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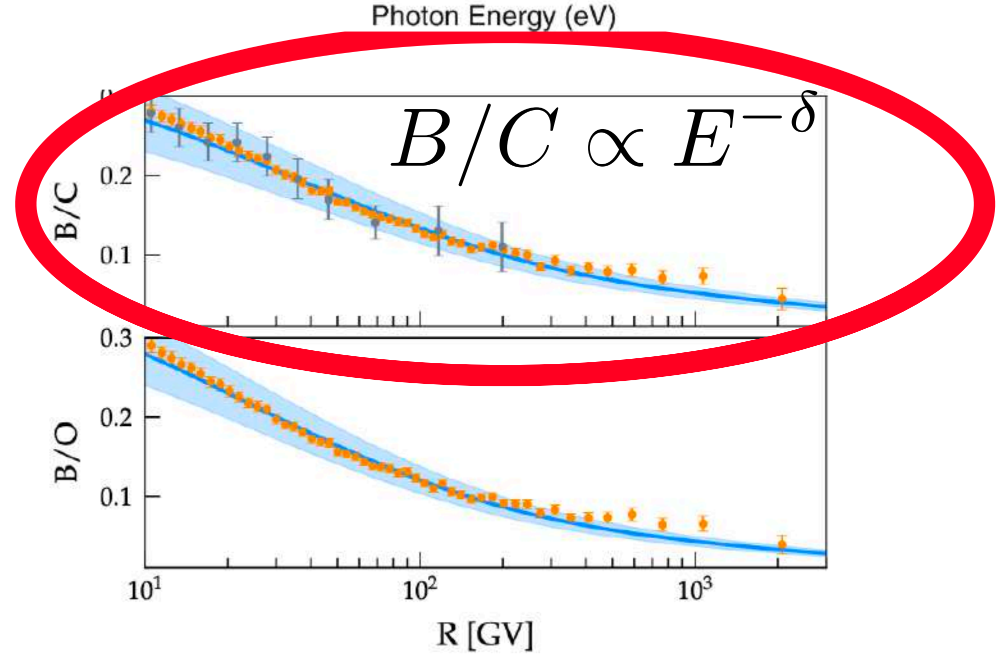
3. Particle spectra released in the ISM

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

Injection Propagation



How much e/p? For how long?

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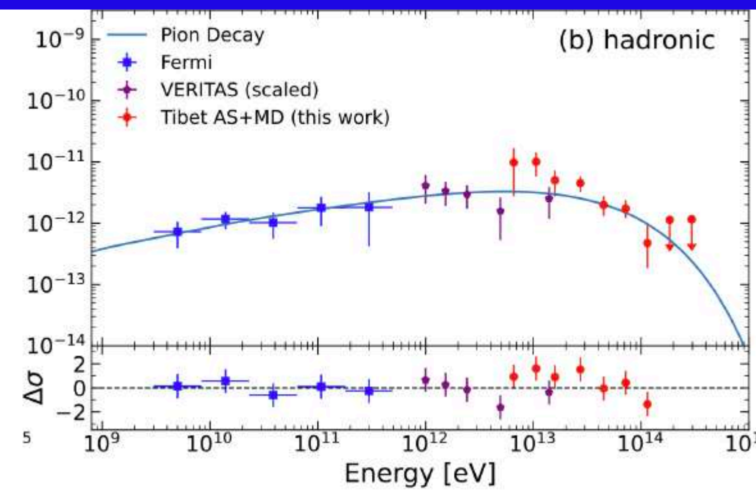

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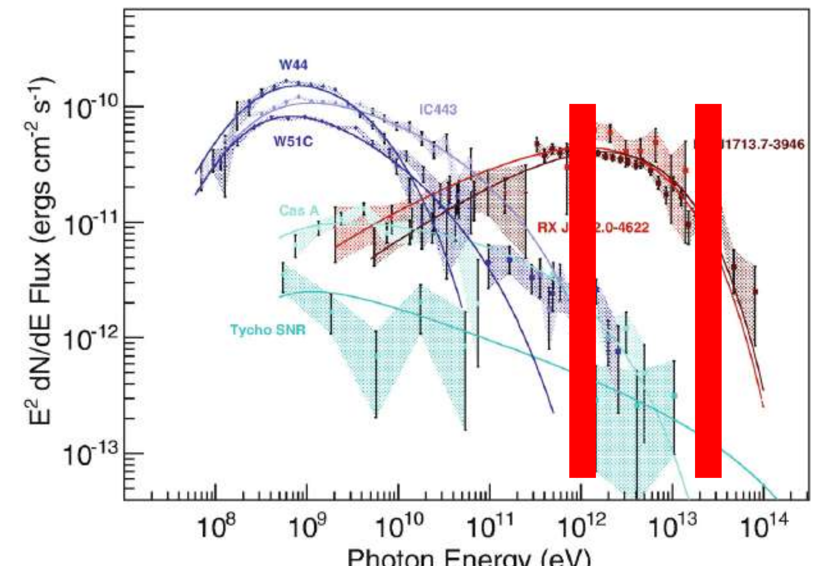

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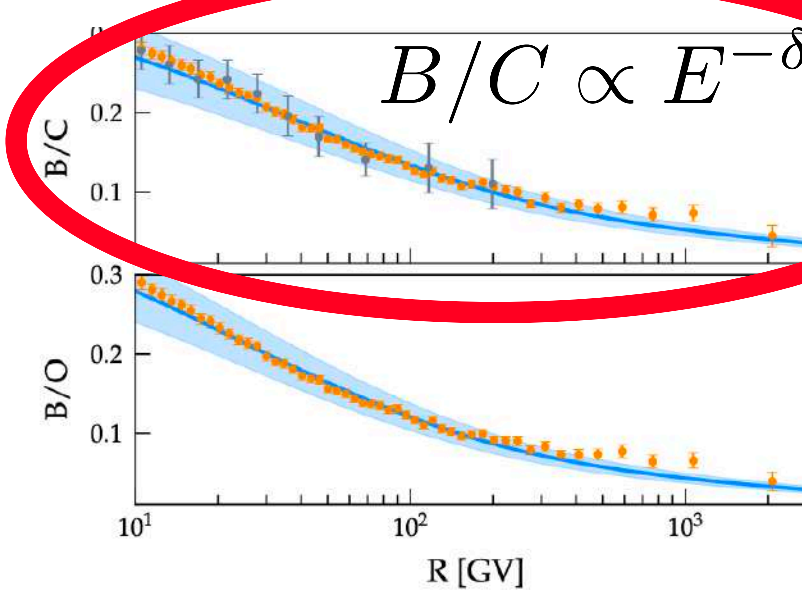

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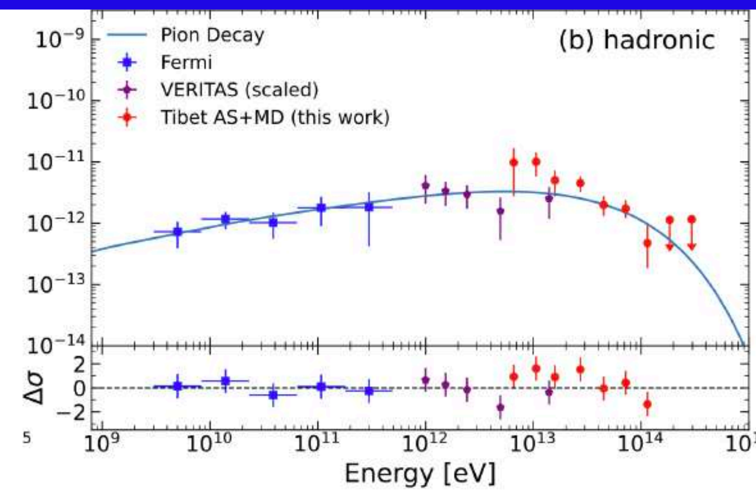

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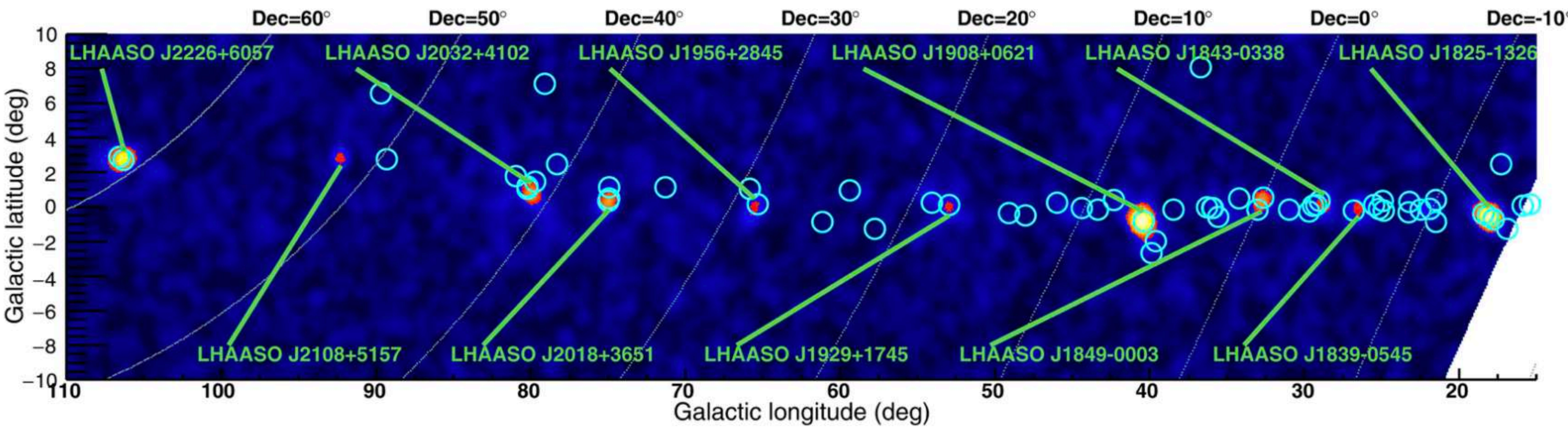
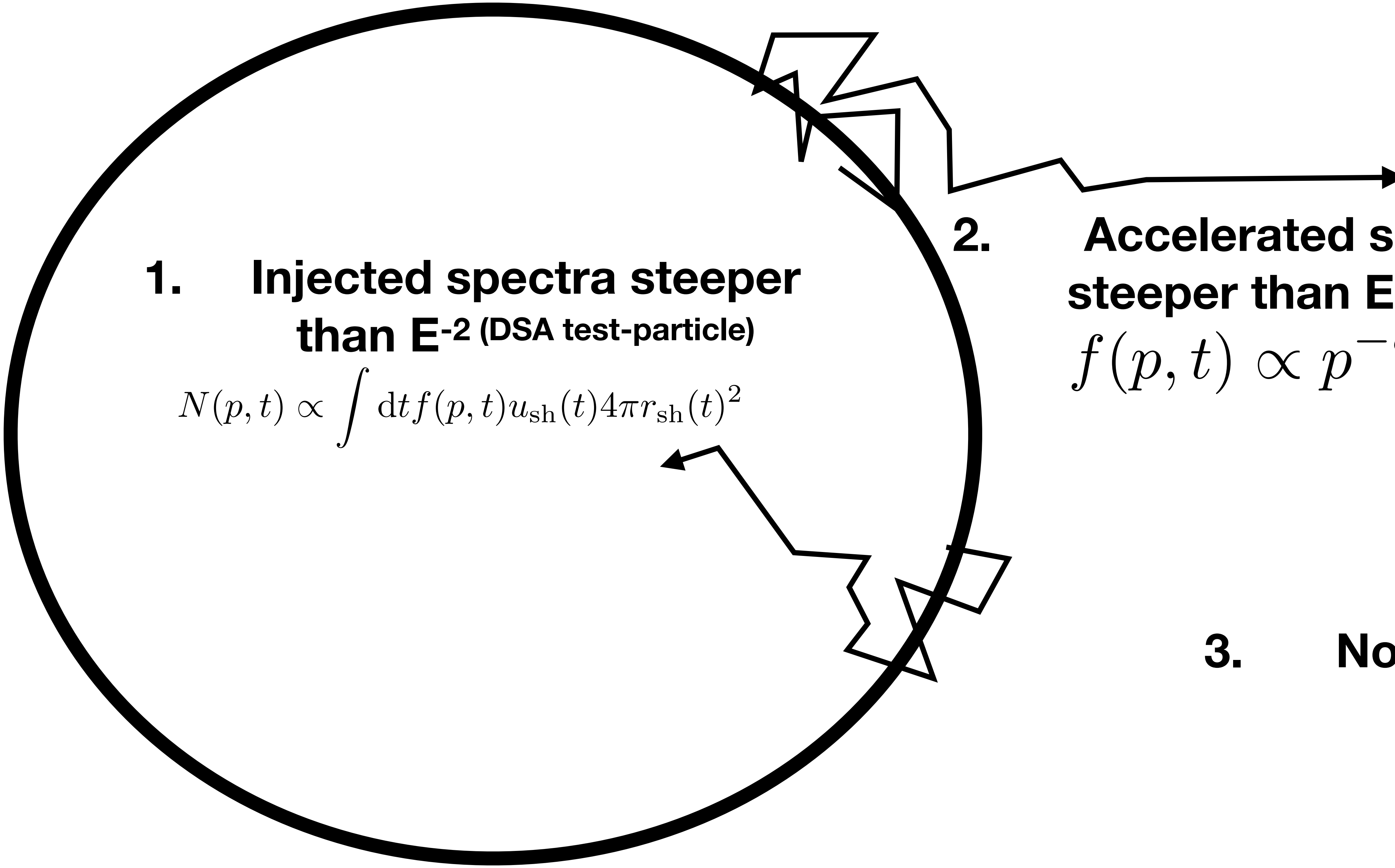


LHAASO Cao et al. (2021)

Three issues



1. **Injected spectra steeper than E^{-2} (DSA test-particle)**

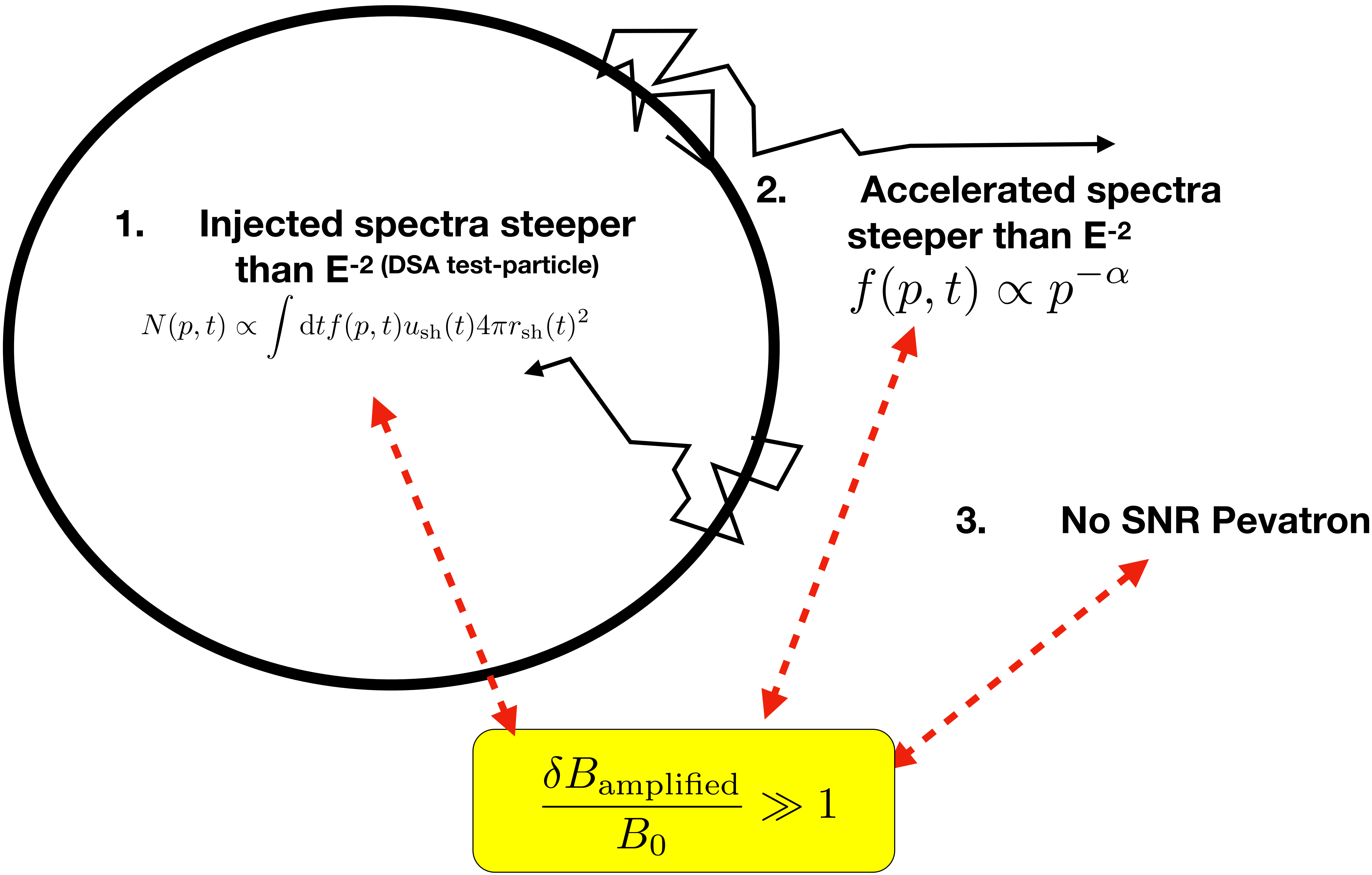
$$N(p,t) \propto \int \mathrm{d}t f(p,t) u_{\rm sh}(t) 4\pi r_{\rm sh}(t)^2$$

2. **Accelerated spectra steeper than E^{-2}**

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

3. **No SNR Pevatron**

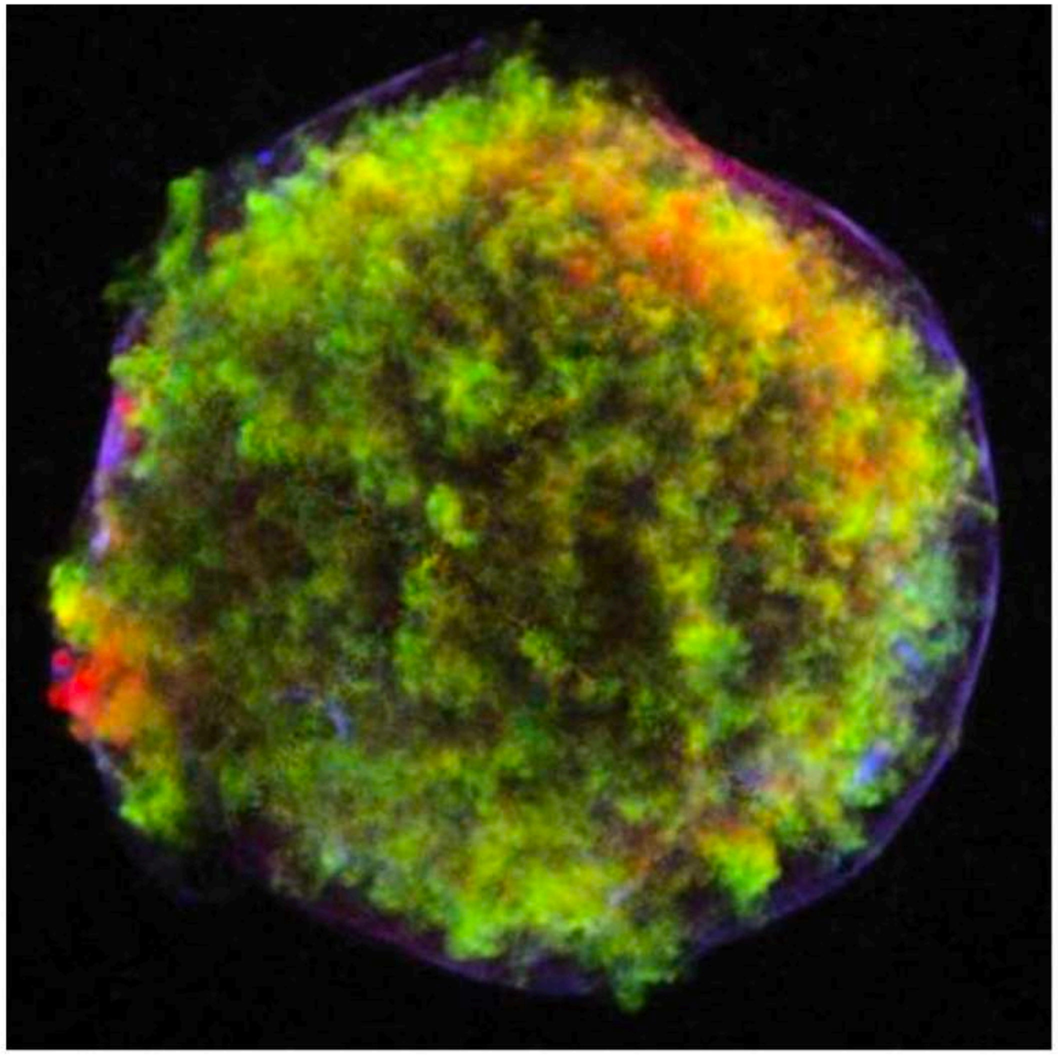
Three issues



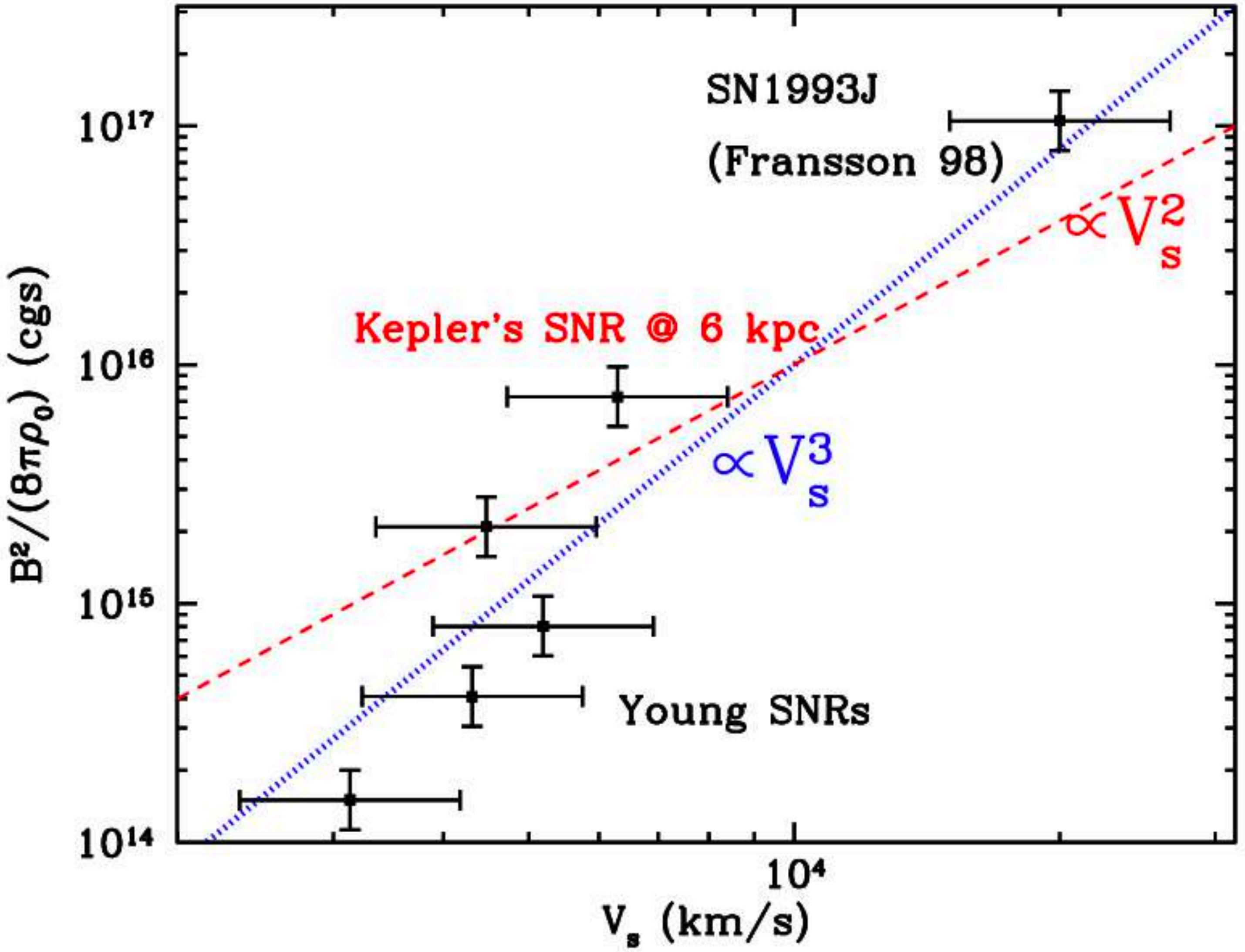
How to reach PeV energies at a SNR?

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

B >> B_ISM



Tycho with Chandra
Warren et al. (2005)



Vink (2012)

Possible for young and « energetic » SNRs!

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)

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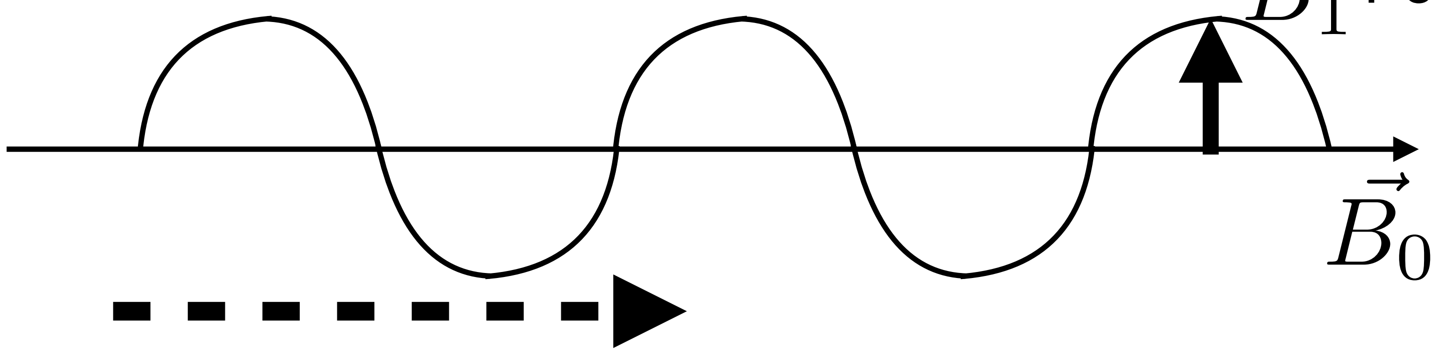
« Bell » non-resonant streaming instability



$\vec{B}_1$ Perturbed

$\vec{B}_0$ Unperturbed magnetic field

$\vec{j}_0$ Unperturbed current cosmic rays

$\vec{j}_1$ Perturbed

Streaming CRs exert a force on the MHD plasma: $\vec{j} \times \vec{B}$

Resonant

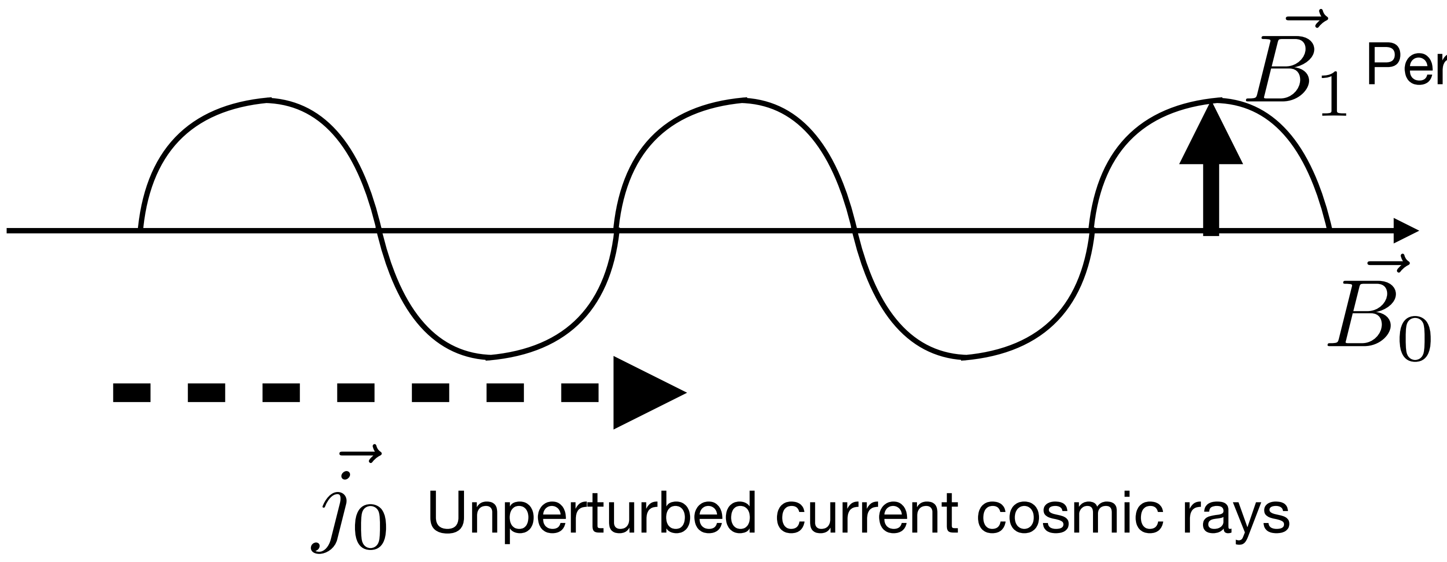
$\vec{j}_1 \times \vec{B}_0$

Non-resonant

$\vec{j}_0 \times \vec{B}_1$

Fastest growing instability
No requirement on resonance

« Bell » non-resonant streaming instability



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$$\vec{j}_1 \times \vec{B}_0$$

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Fastest growing instability
No requirement on resonance

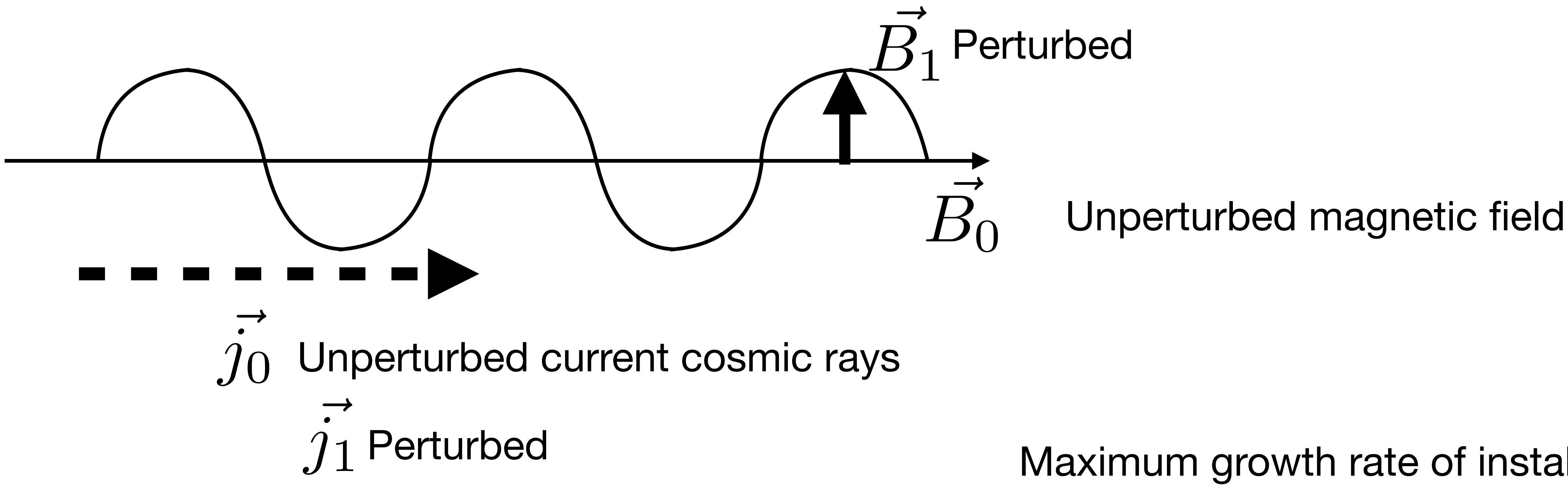
Momentum $$\rho \frac{\partial \vec{u}}{\partial t} = -\frac{\vec{j}_0 \times \vec{B}_1}{c} - \frac{1}{4\pi} \vec{B}_0 \times (\nabla \times \vec{B}_1)$$

Flux-freezing $$\frac{\partial \vec{B}_1}{\partial t} = \nabla \times (\vec{u} \times \vec{B}_0)$$

$$\gamma = \left(\frac{k B_0 j_0}{\rho c} \right)^{1/2}$$

Growth rate of instability

« Bell » non-resonant streaming instability



$$\gamma = \left(\frac{kB_0 j_0}{\rho c}\right)^{1/2}$$

Growth rate of instability

→

Maximum growth rate of instability:
Tension in magnetic field equates the driving force

$$\gamma_{\max} = \frac{1}{2}\left(\frac{4\pi}{\rho}\right)^{1/2}\frac{j_0}{c}$$

Bell (2004), Schure et al. (2012), Bell et al. (2013,2014), Schure et al. (2013,2014)

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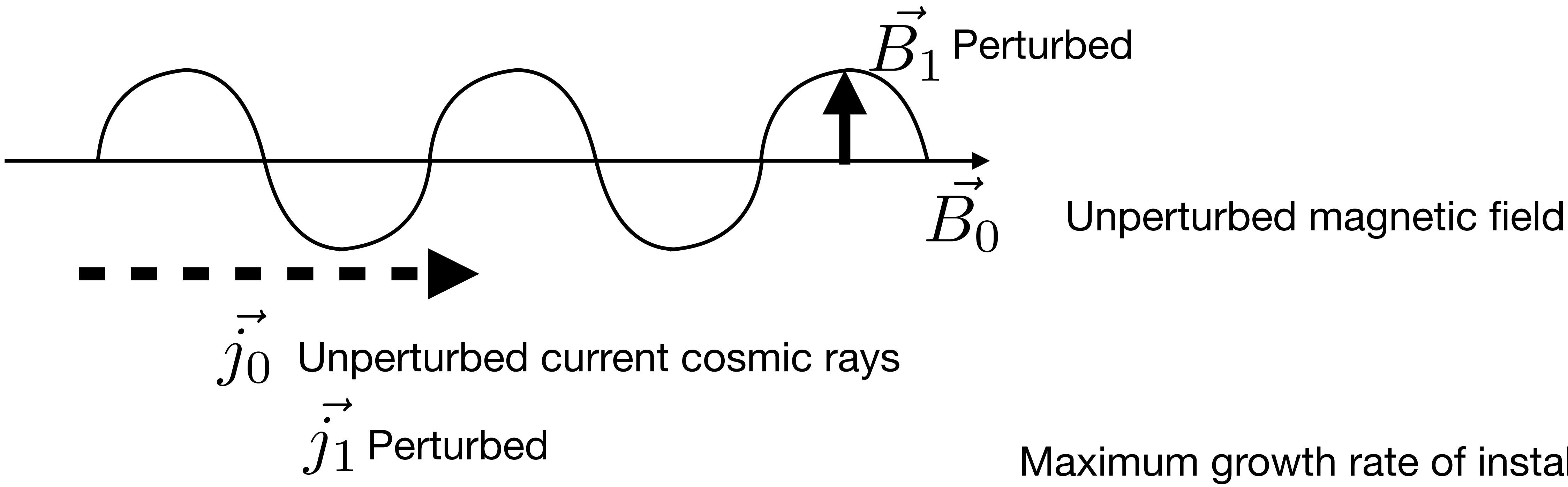

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$$\int_0^t dt' \gamma_{\max}(t') \simeq 5$$

Saturation at a few e-folds

$$\delta B \approx \sqrt{12\pi \frac{u_{\rm sh}}{c} \frac{\xi \rho u_{\rm sh}^2}{\ln\left(\frac{p_{\max}}{p_{\min}}\right)}}$$

Bell (2004), Schure et al. (2012), Bell et al. (2013,2014), Schure et al. (2013,2014)

Non-resonant streaming of CRs

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

Growth rate of the non-resonant streaming instability

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

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

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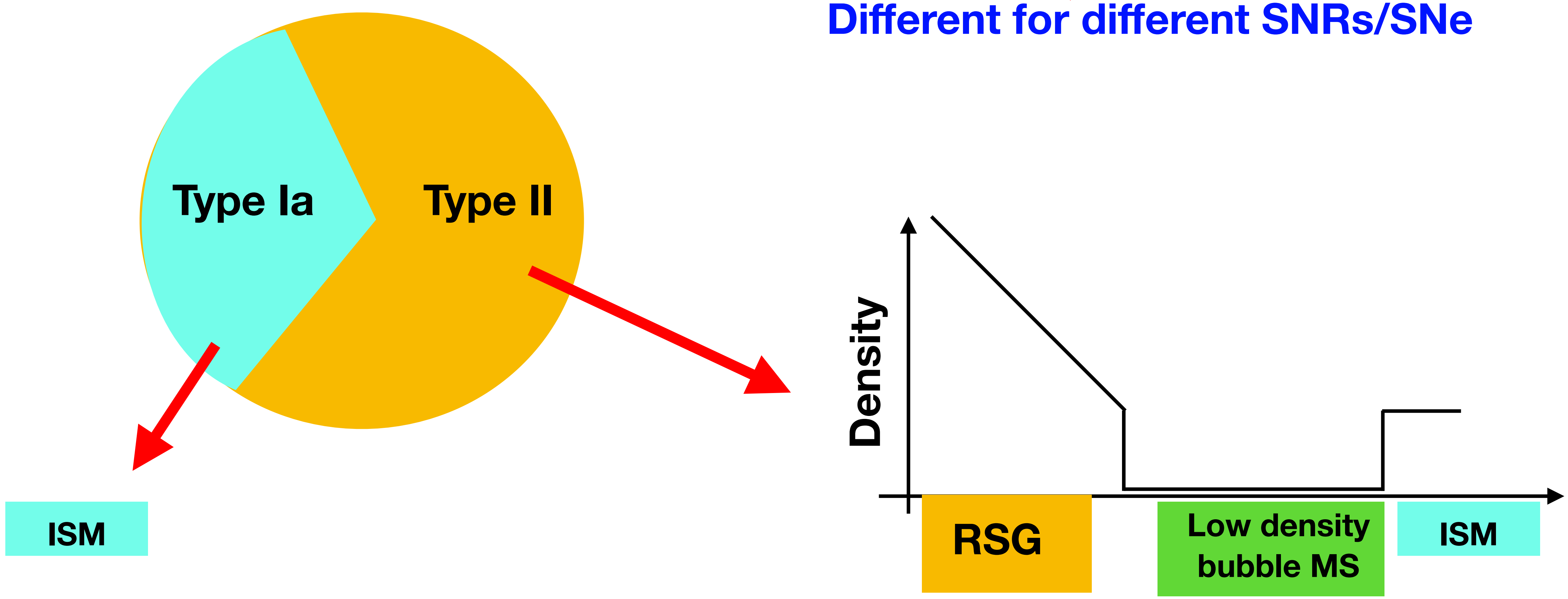
Different for different SNRs/SNe



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

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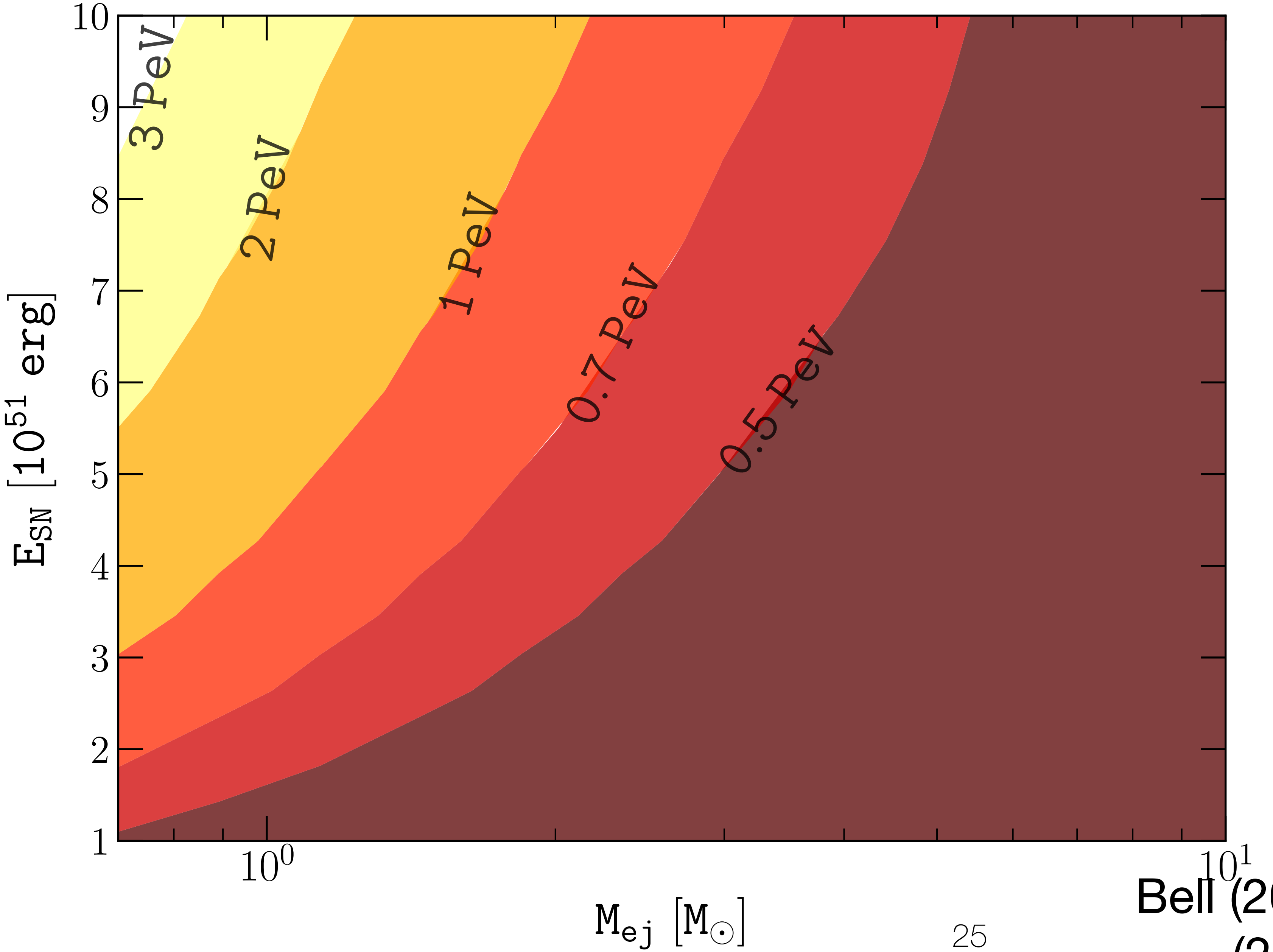
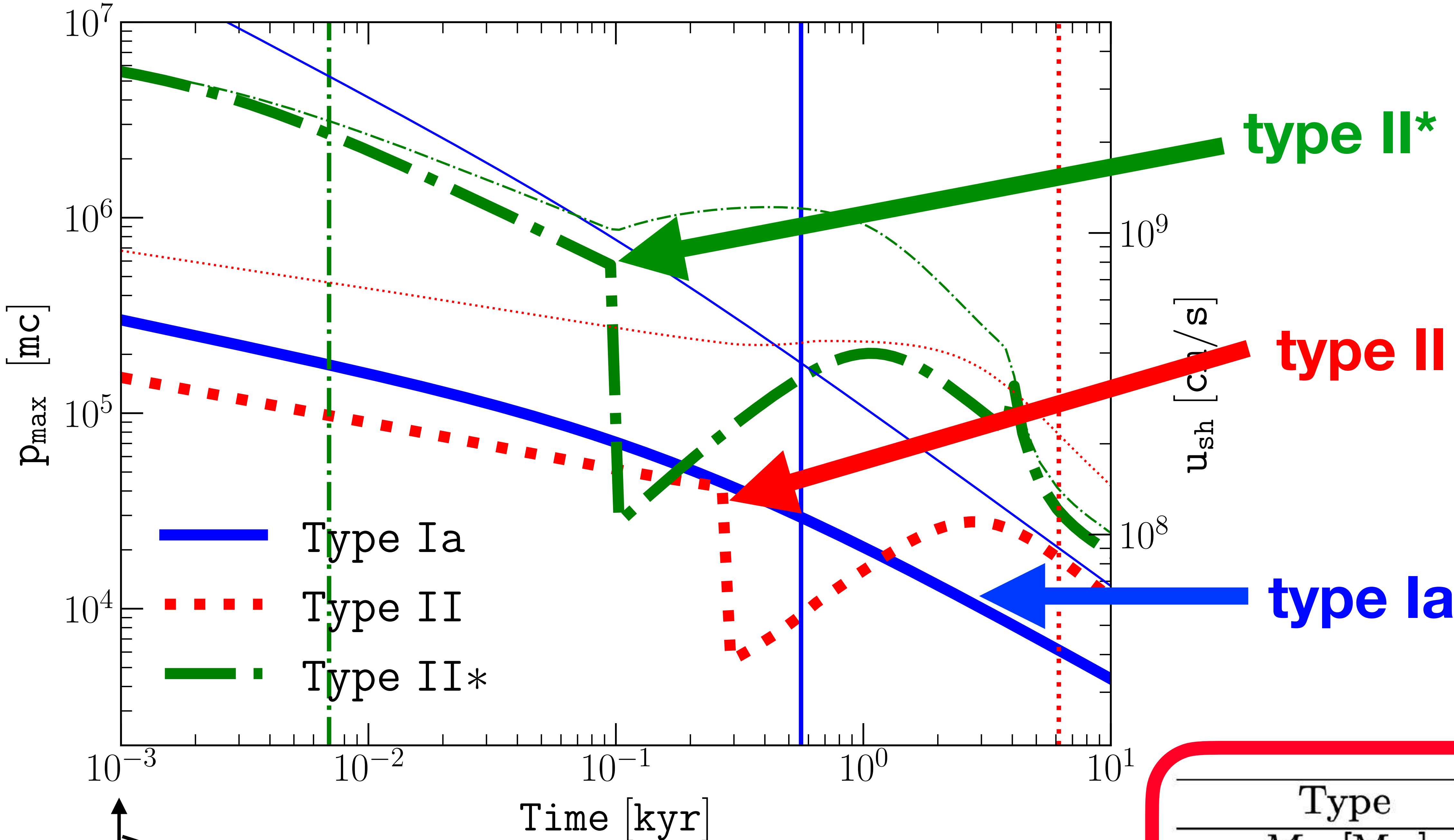


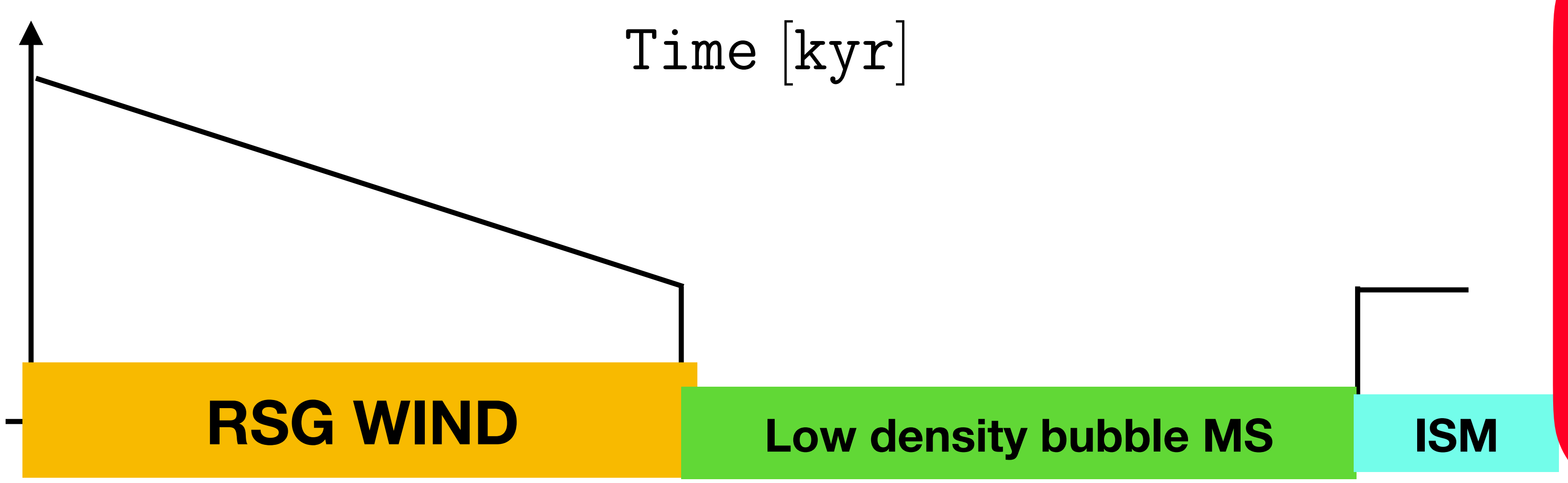
$$\dot{M}_{\rm RSG} = 10^{-4} M_\odot/{\rm yr}$$

$$\xi = 0.1$$

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

Type Ia, type II, type II*





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

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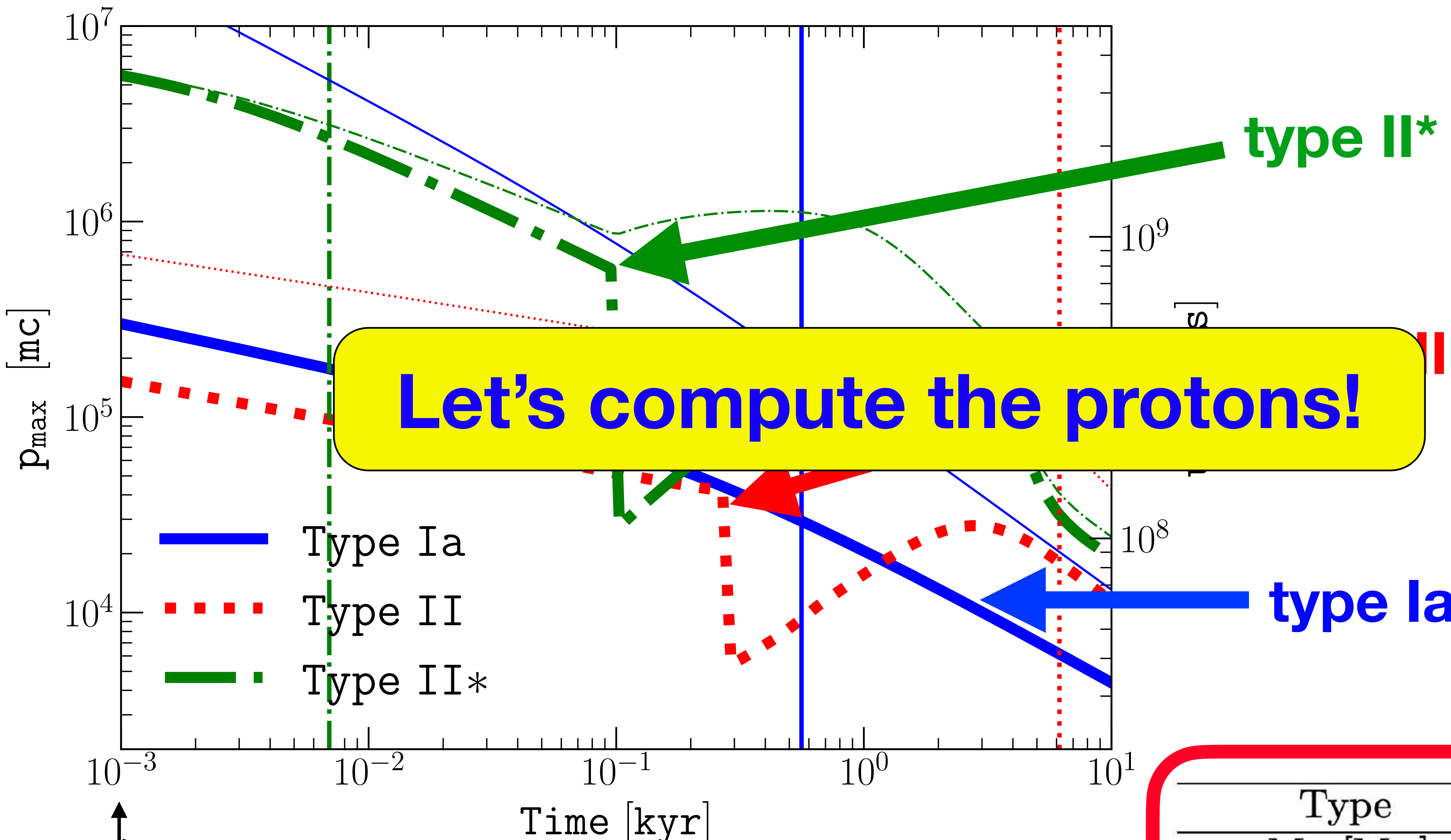

Let's compute the protons!

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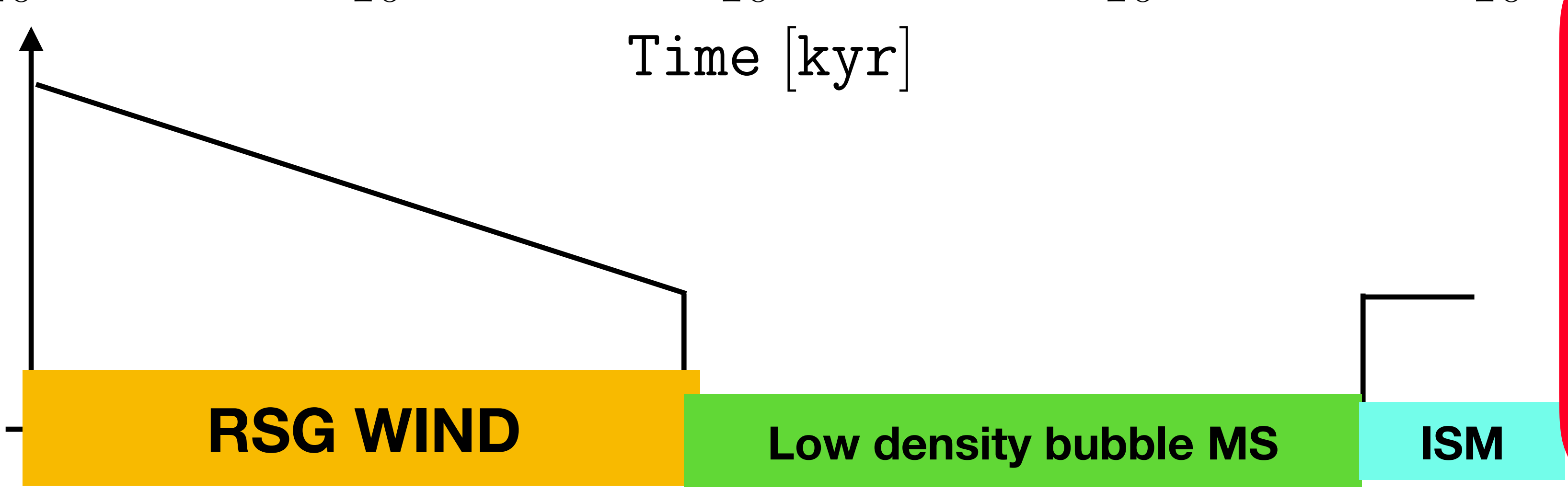
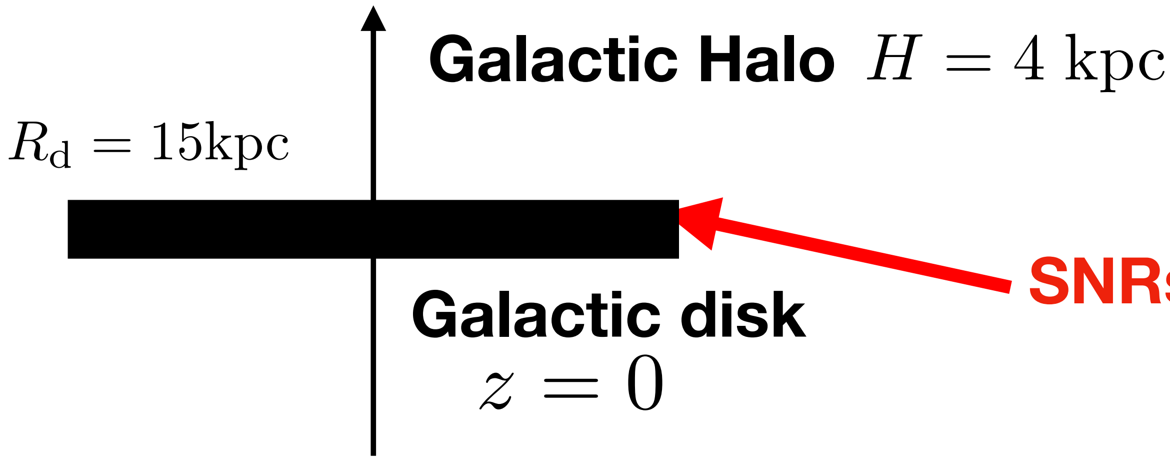


Protons after propagation in the Galaxy



SNRs injecting particles

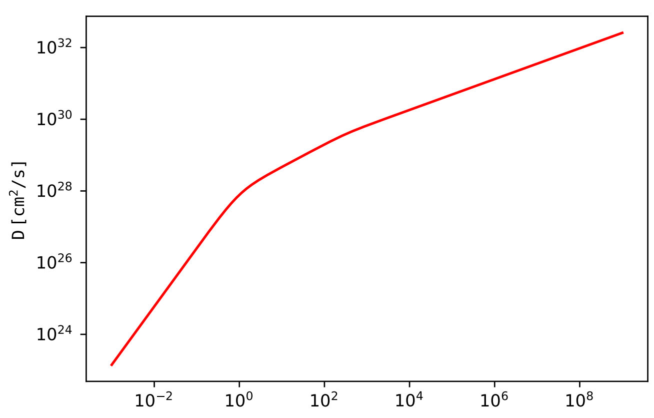
1D Galactic transport

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

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

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

Escaping

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

Protons from type Ia

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

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

Transport

Protons from type Ia

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

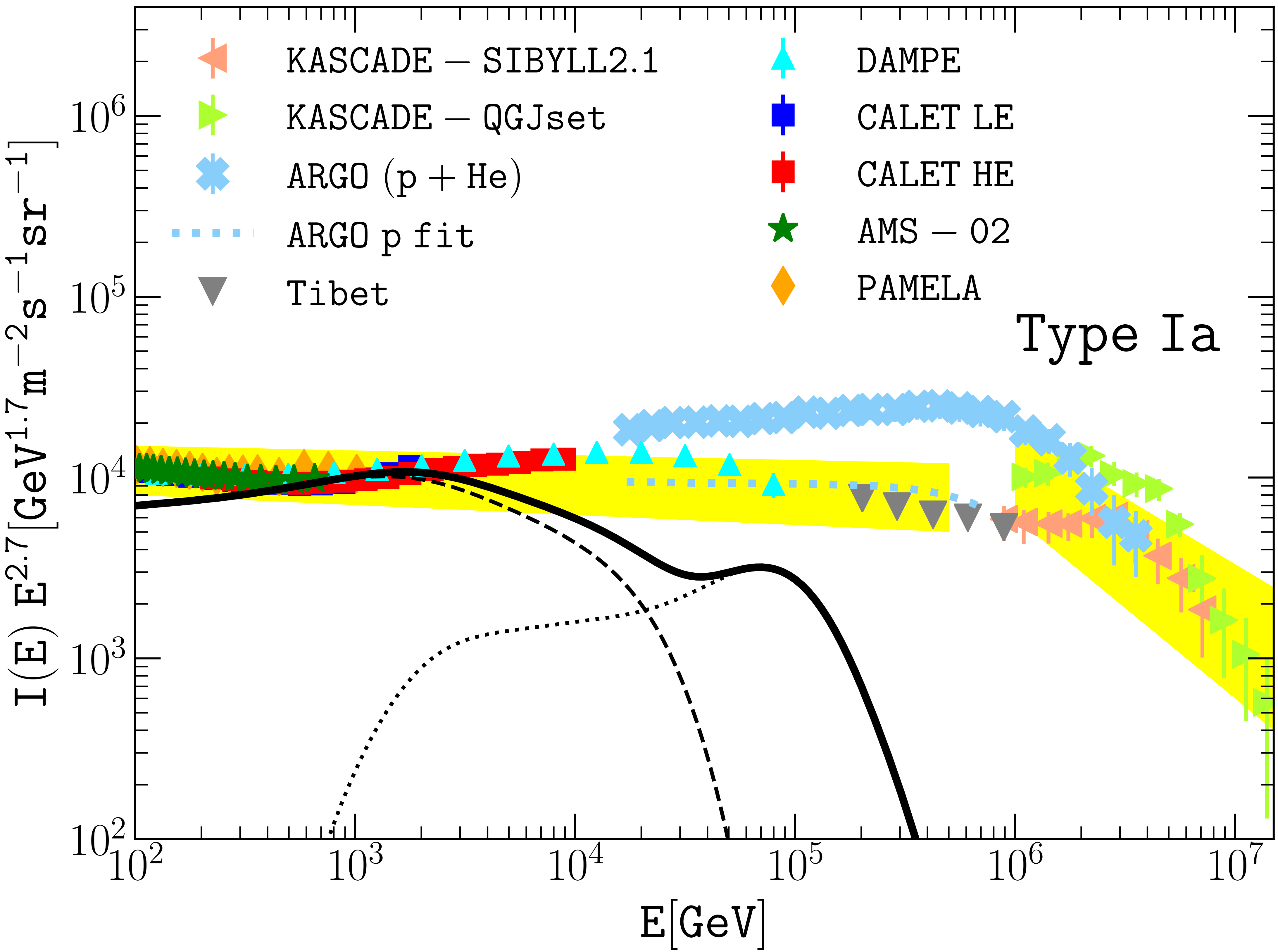
Diffusion coef

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

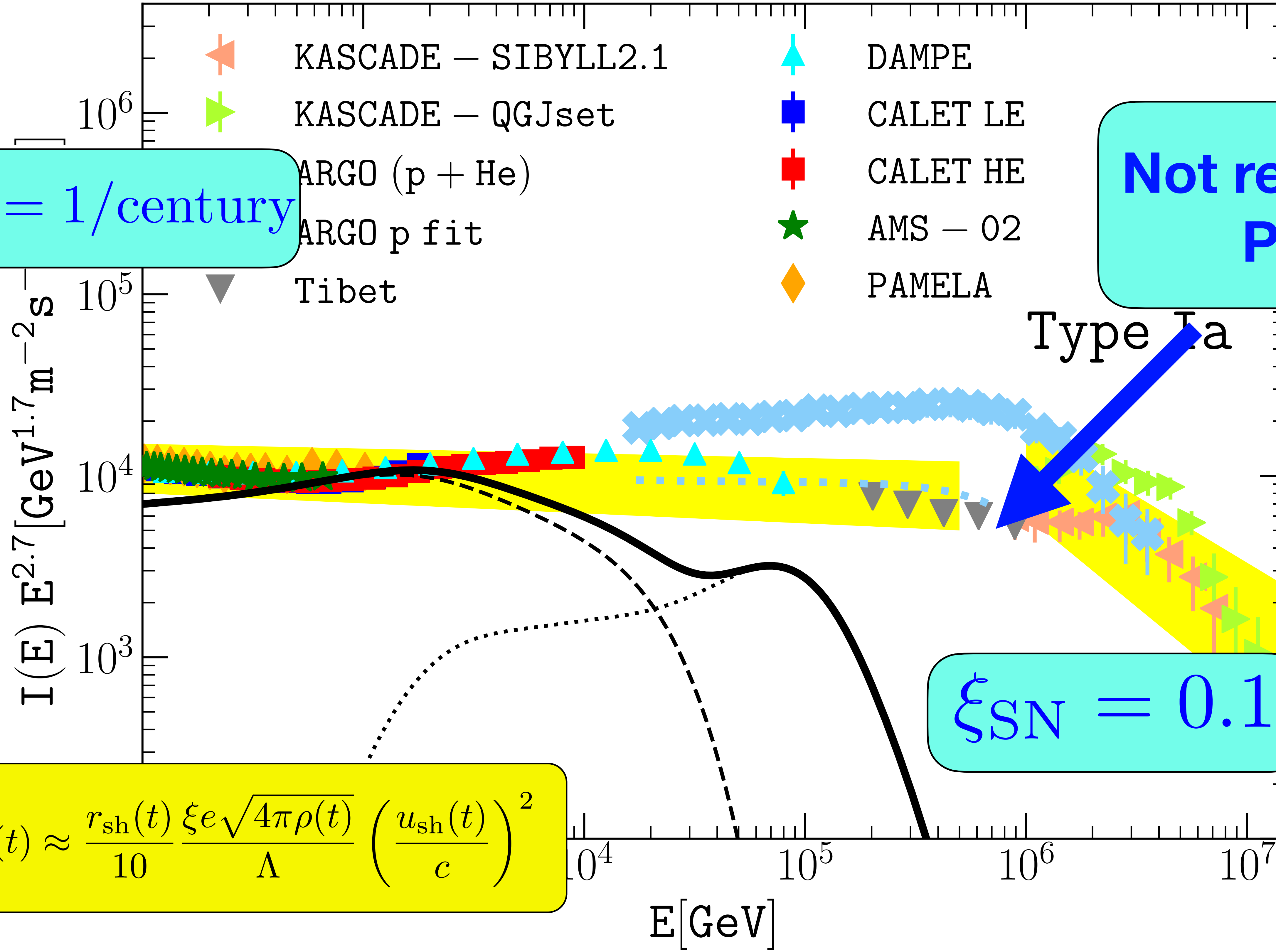
Transport

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

Protons from type Ia



Protons from type Ia



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

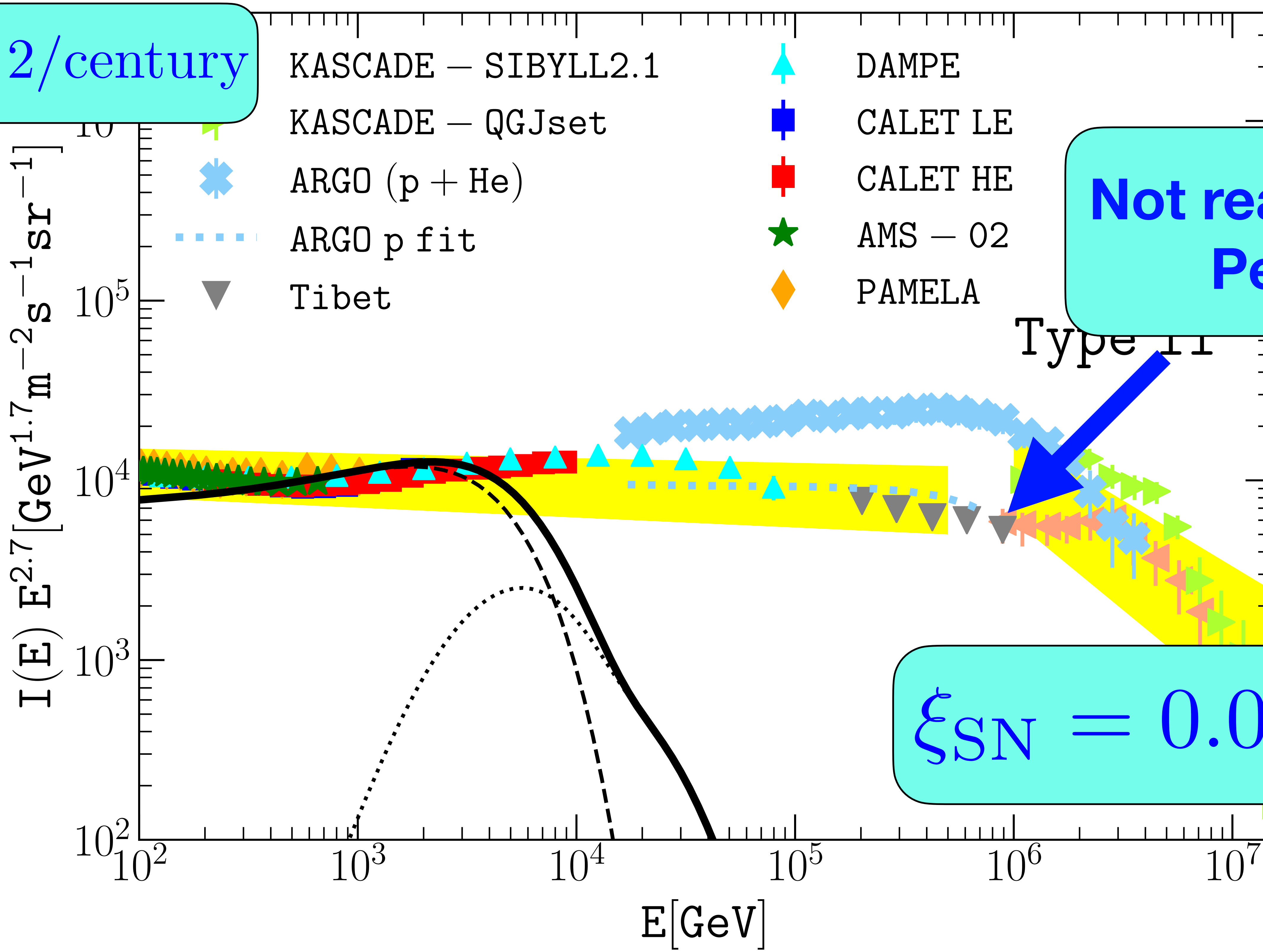
Not reaching PeV

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

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

Protons from type II

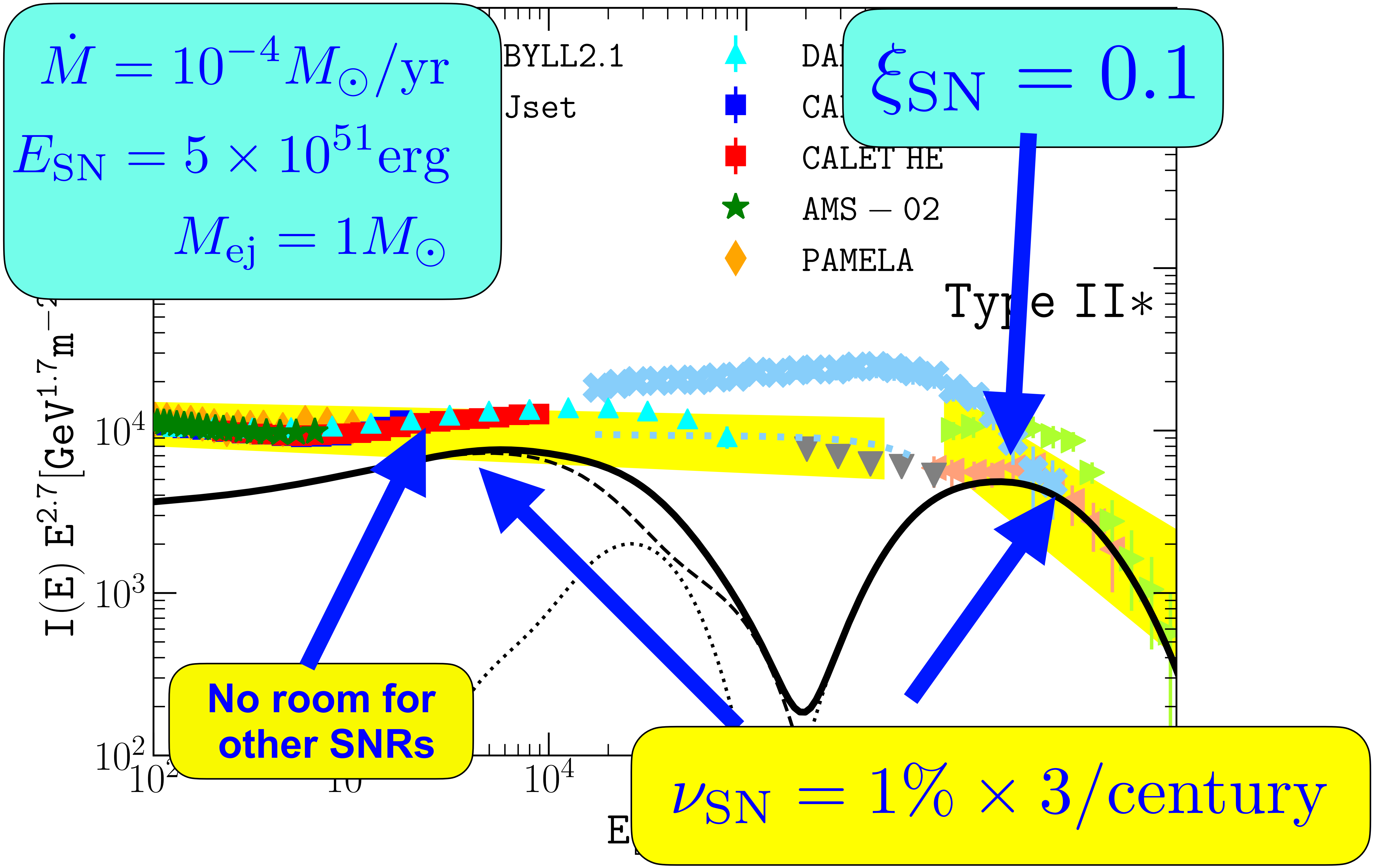
$\nu_{II} = 2/\mathrm{century}$



Not reaching PeV

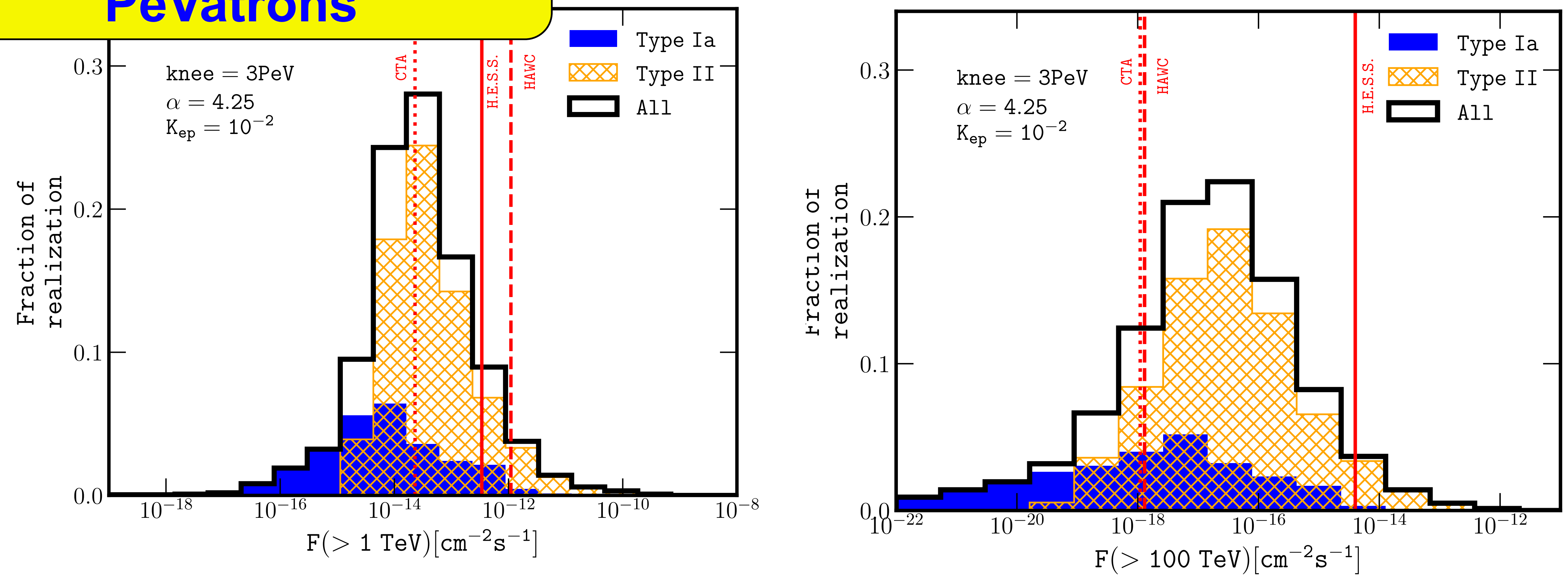
$\xi_{SN} = 0.06$

Protons from type II*



Pevatrons with CTA

Assuming all SNRs are PeVatrons



If only Type II* are Pevatrons

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

$$\to 0$$

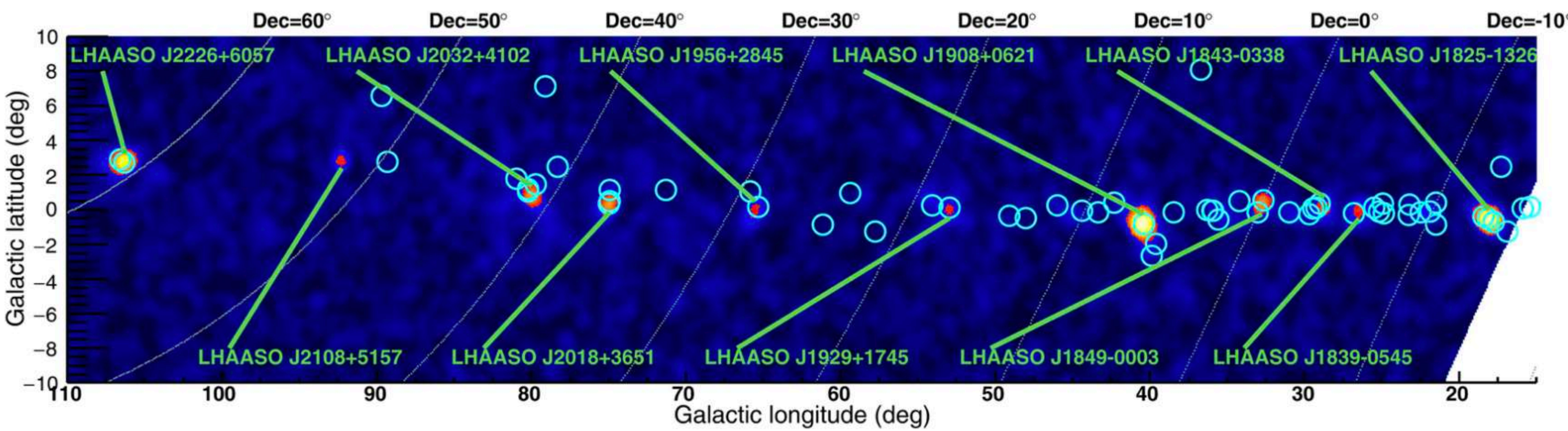
PC, Blasi, Amato (2020)

PC, Gabici, Terrier, Humensky (2018)

MAYBE:

What does this mean?

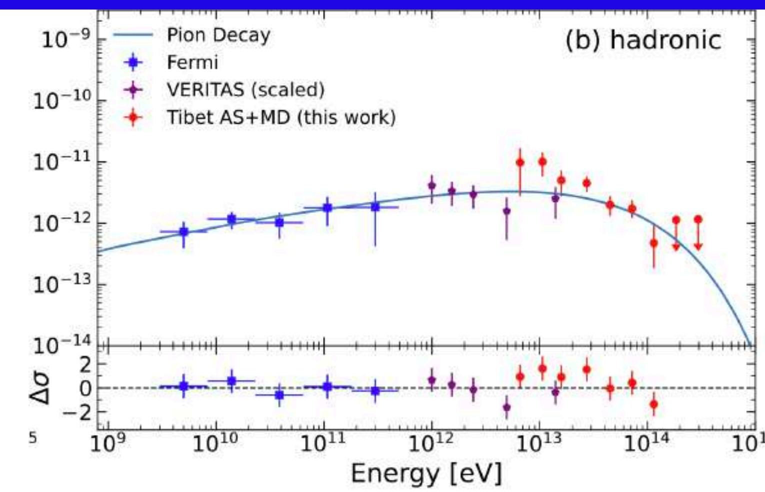
1. SNRs are OK but we won't see any PeVatrons with CTA
2. Another instability (not Bell) comes into play
3. Strong temporal dependance on one/several parameters



LHAASO Cao et al. (2021)

What is wrong with supernova remnants?

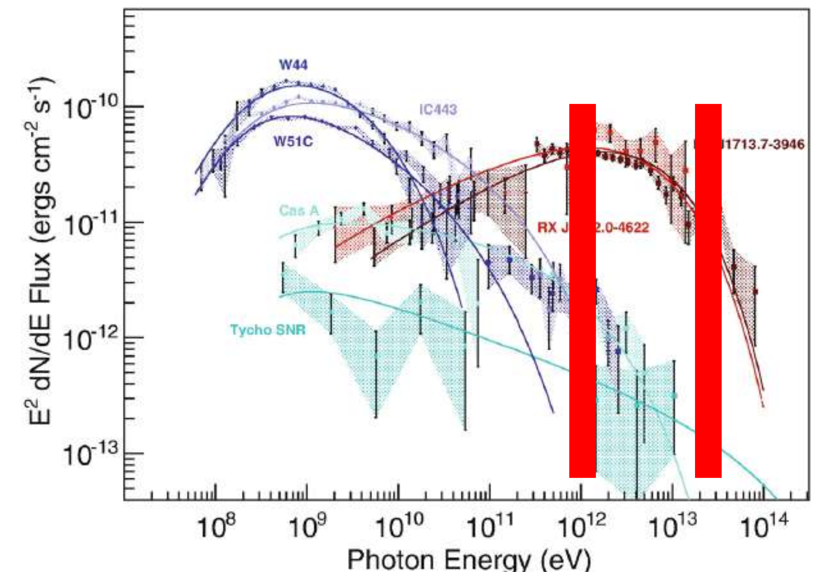
1. All SNRs seem to not be pevatrons



SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

2. The slope of accelerated particles at SNR shocks

VHE domain steep spectra?



Funk (2017)

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

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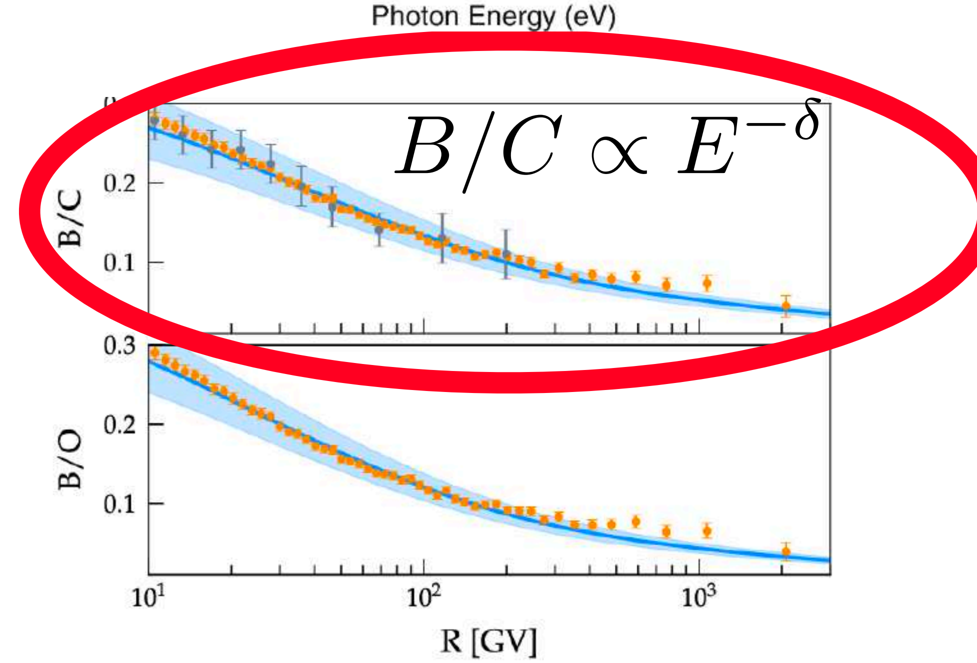

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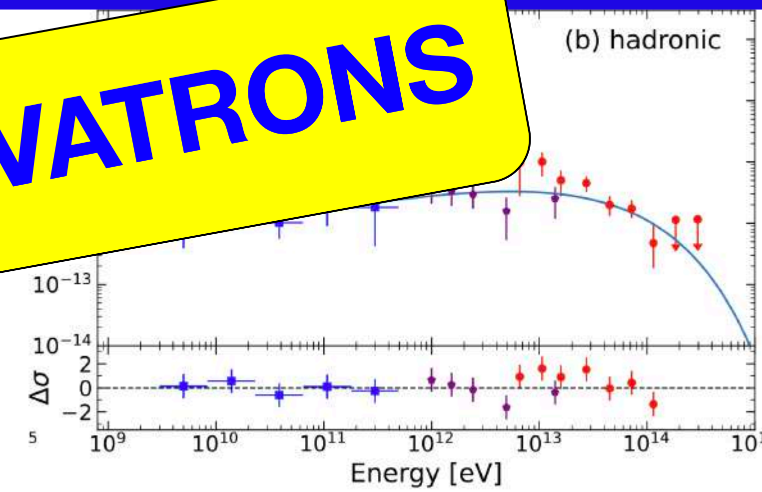
LOW NUMBER PEVATRONS



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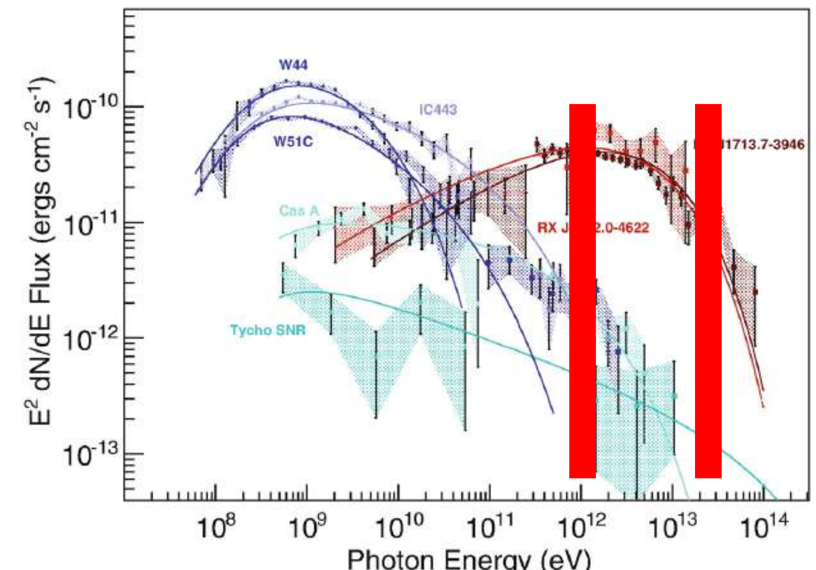

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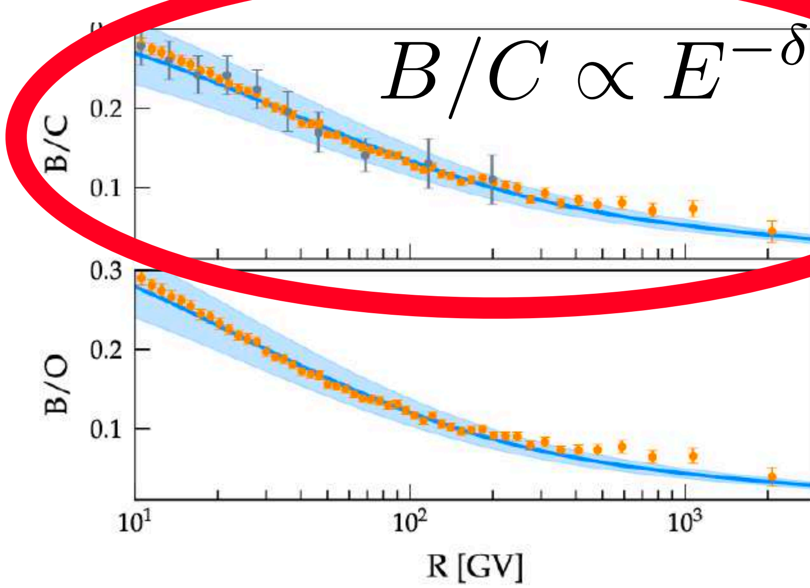

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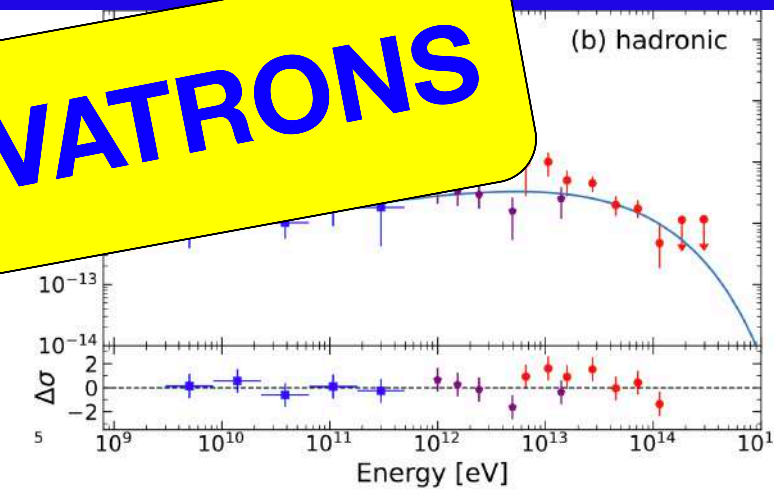

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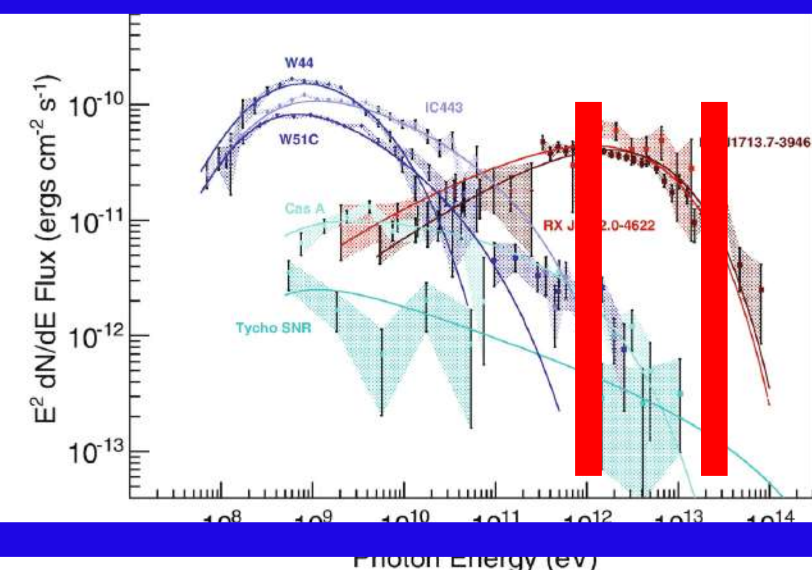

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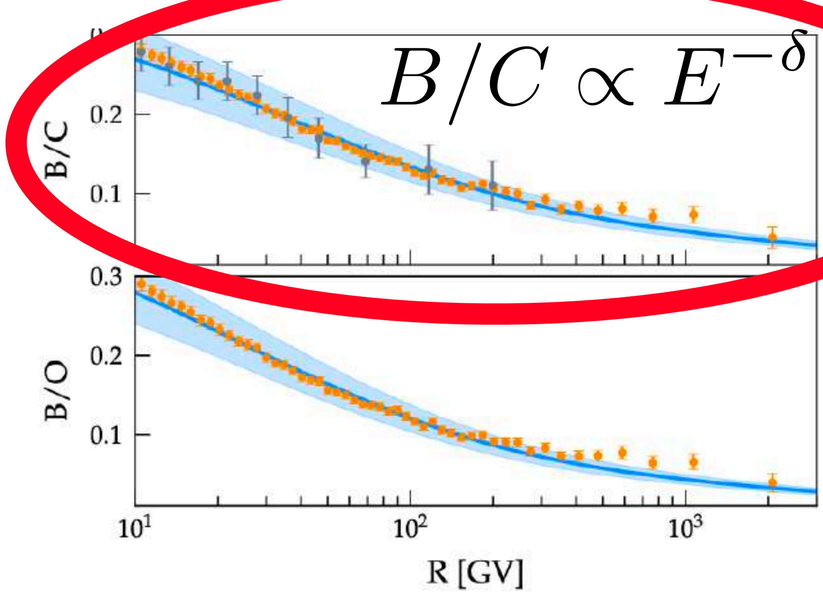

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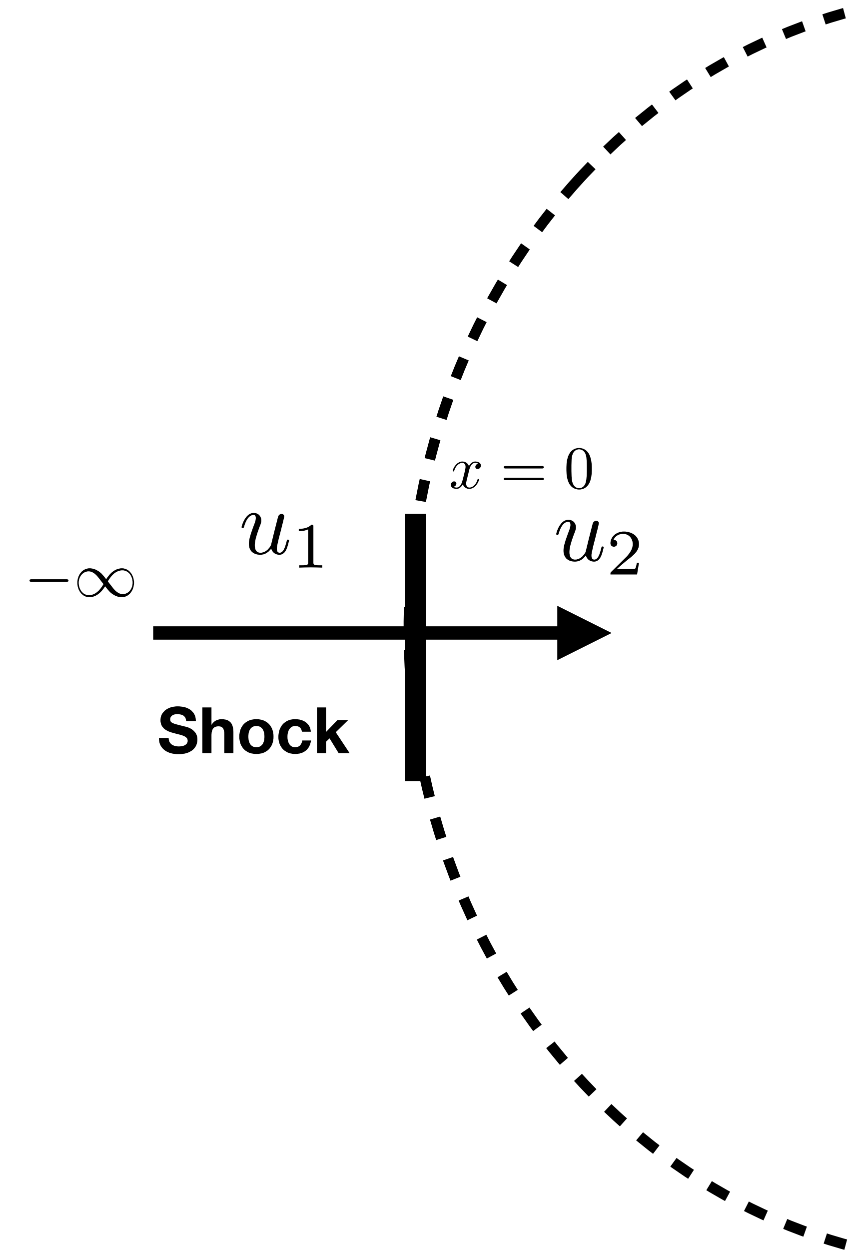

Drury& Völk (1980,1981), Bell (1987)
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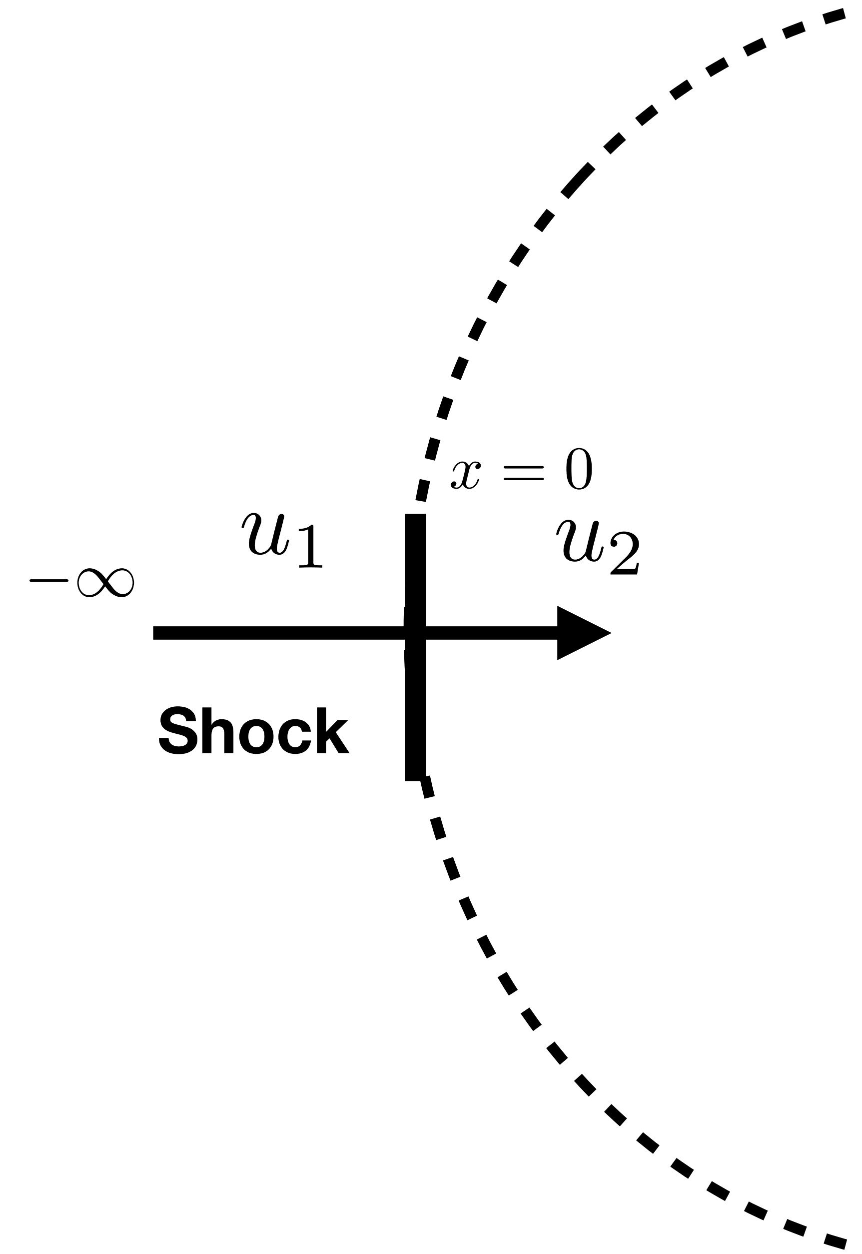

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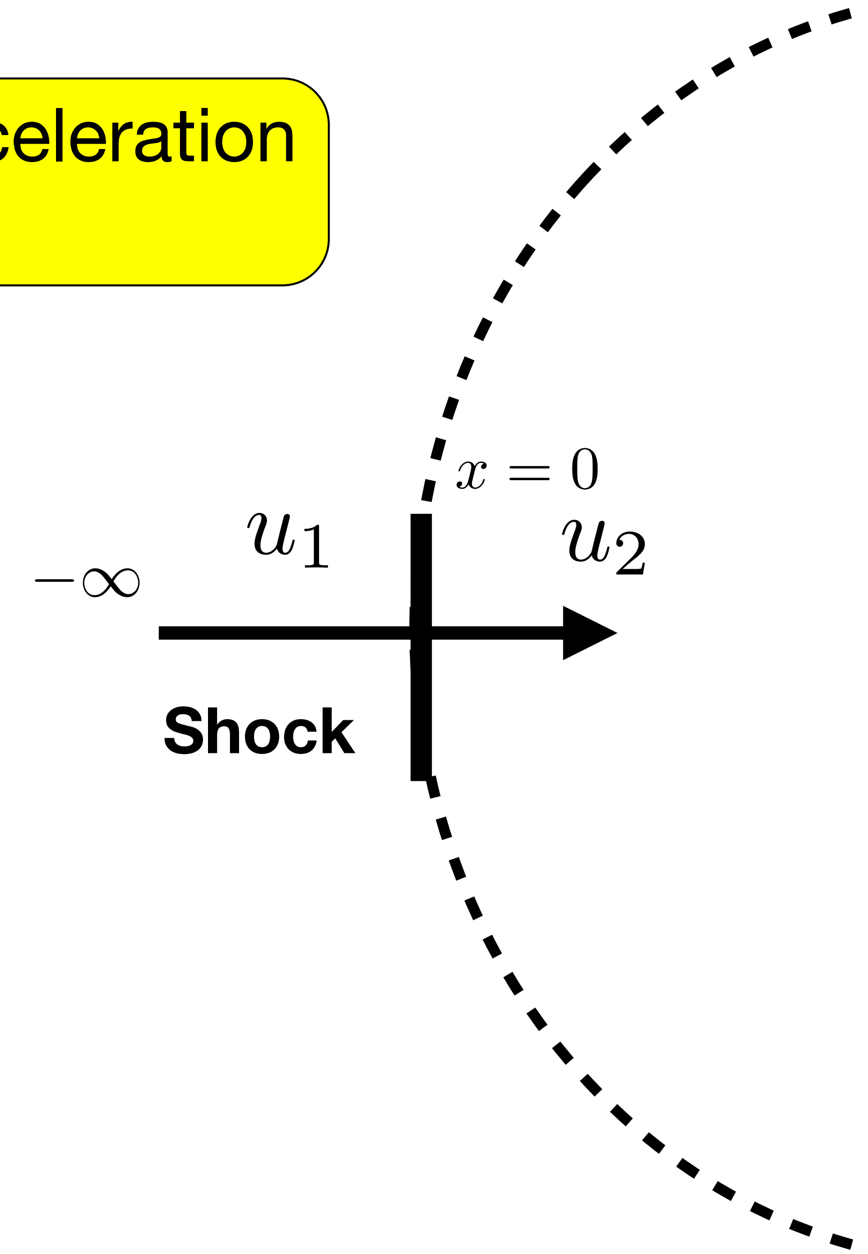

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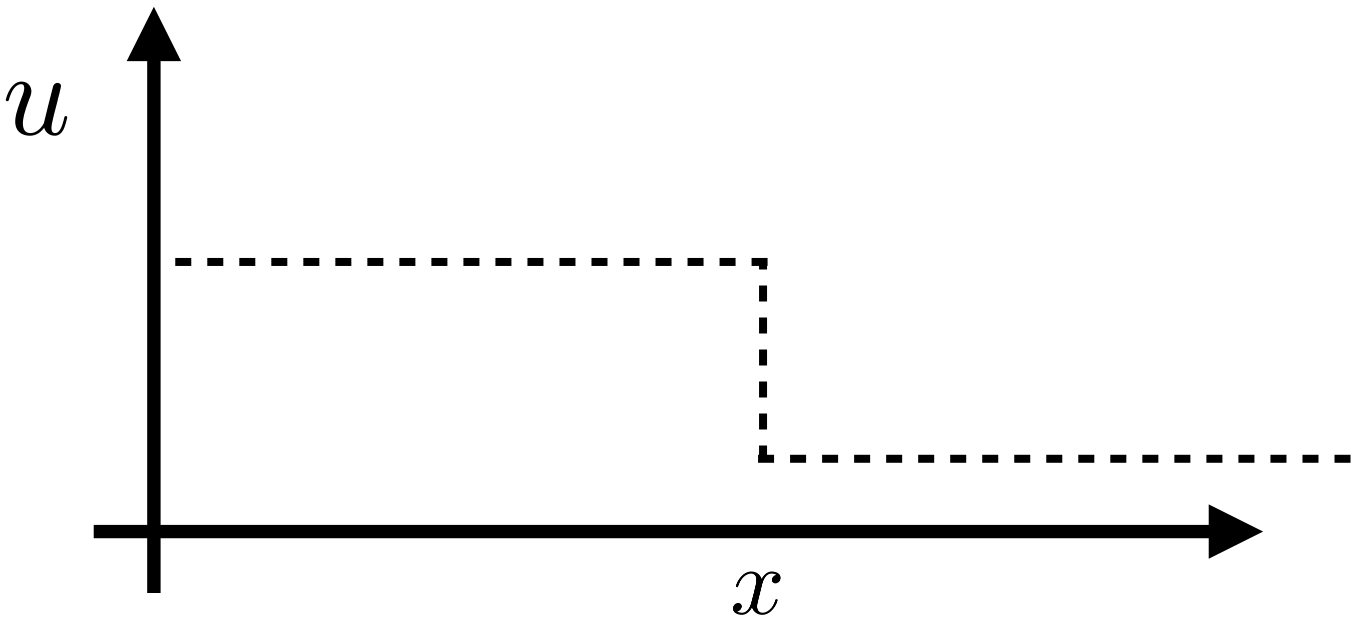

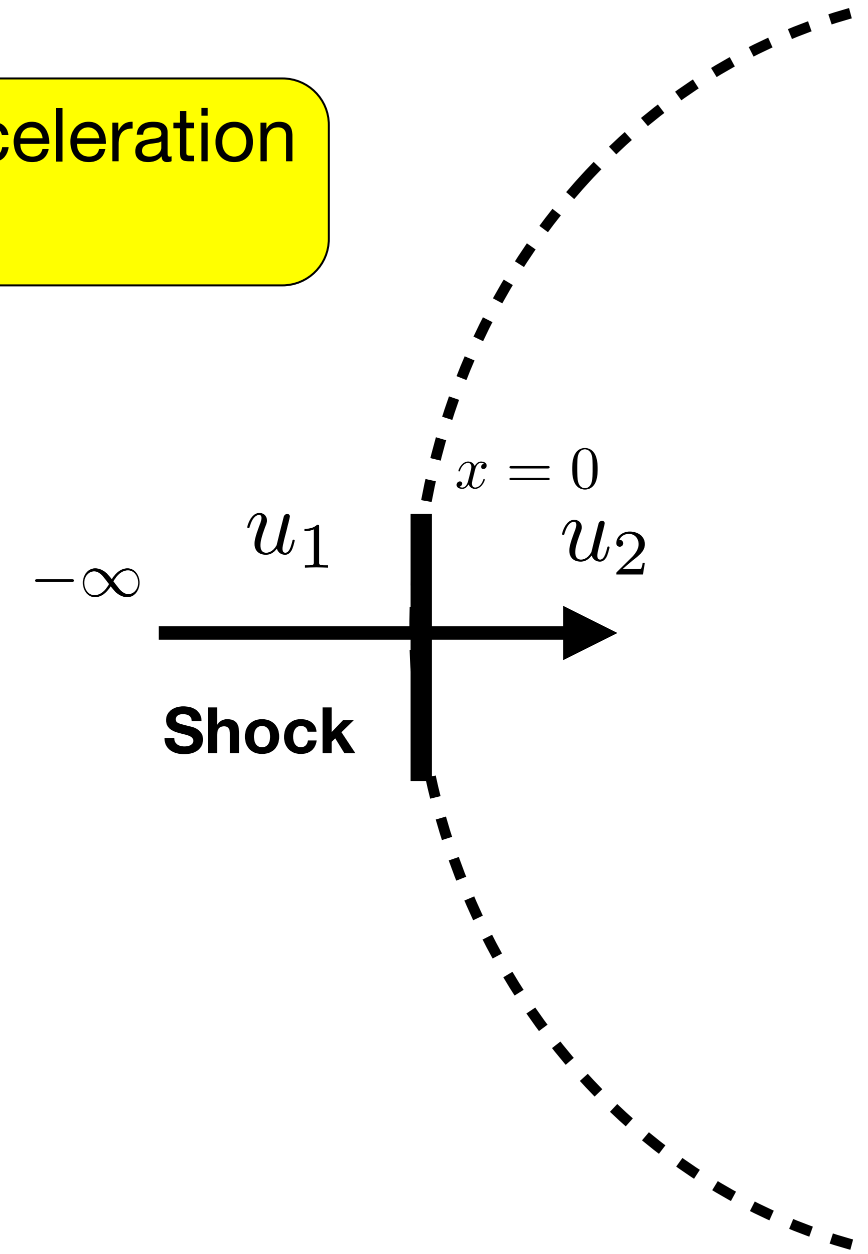

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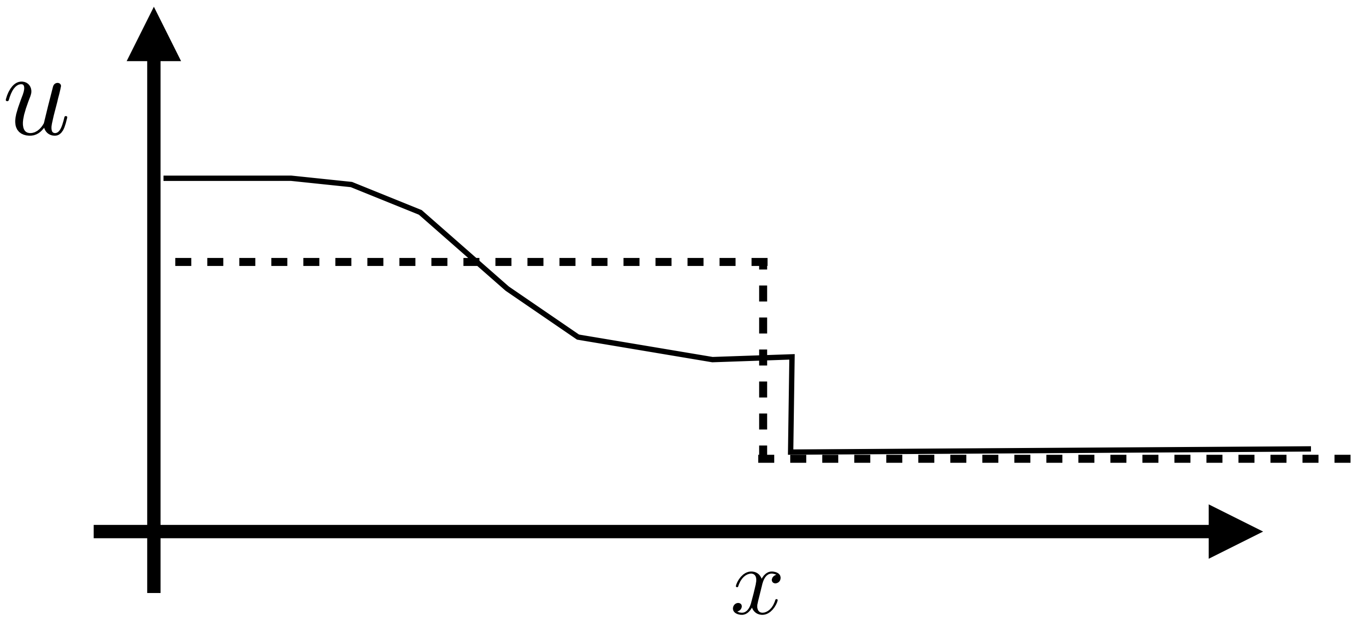

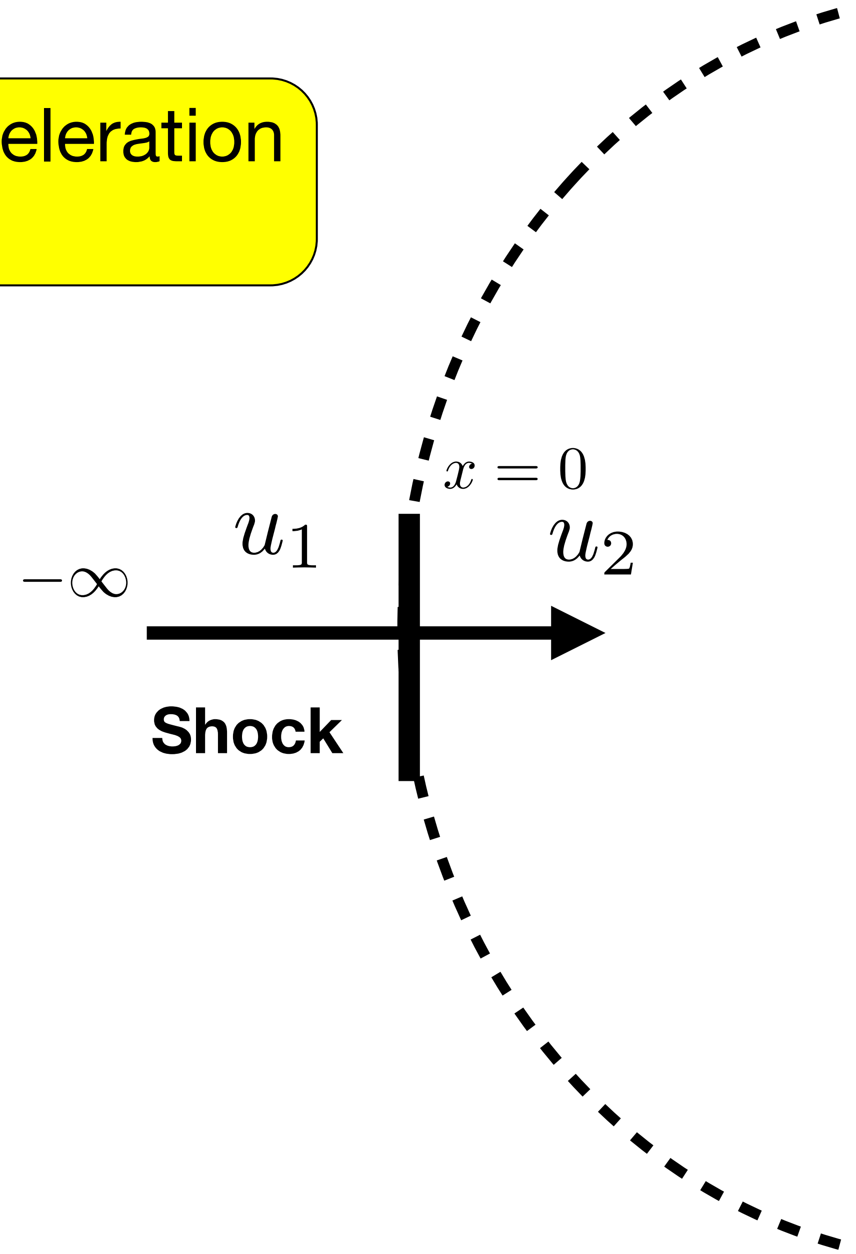

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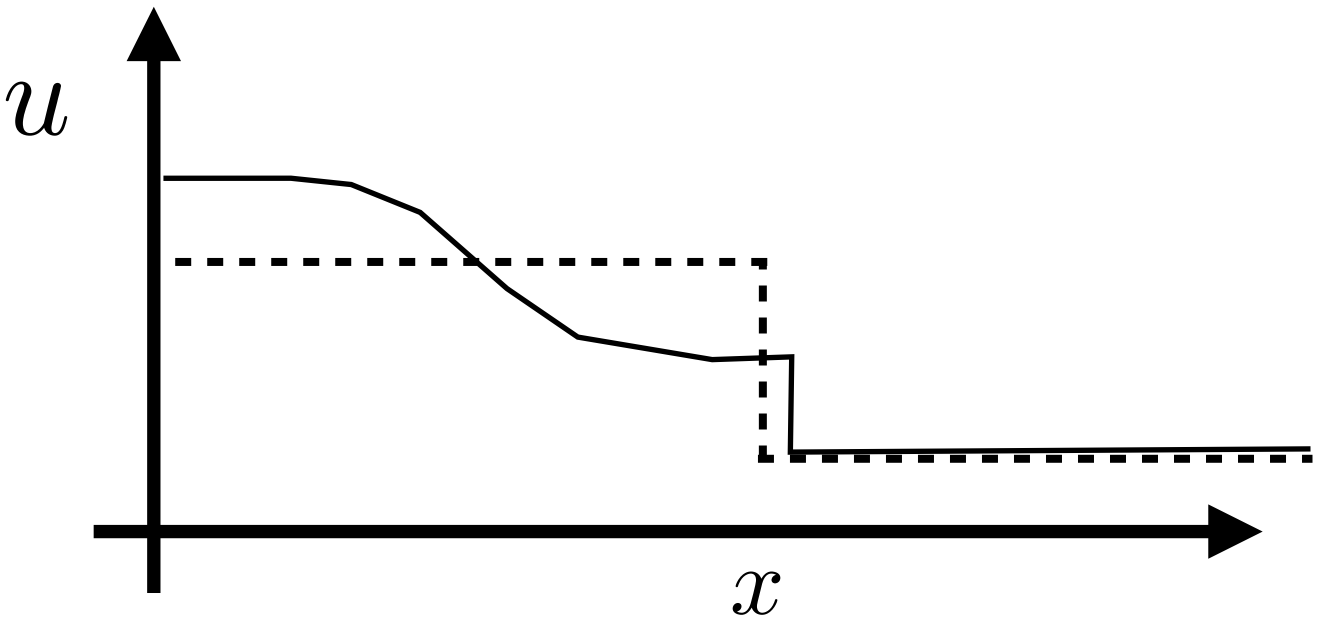

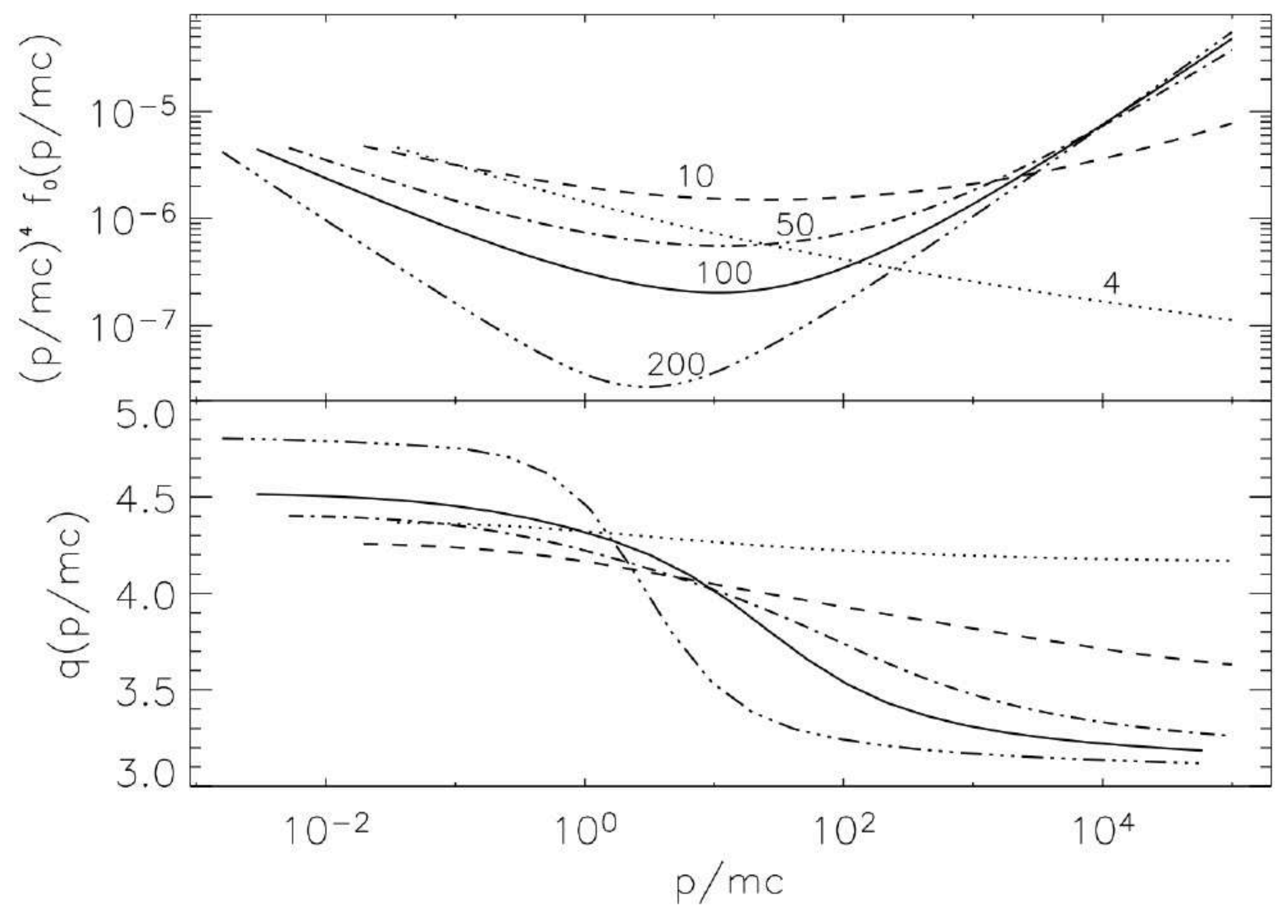

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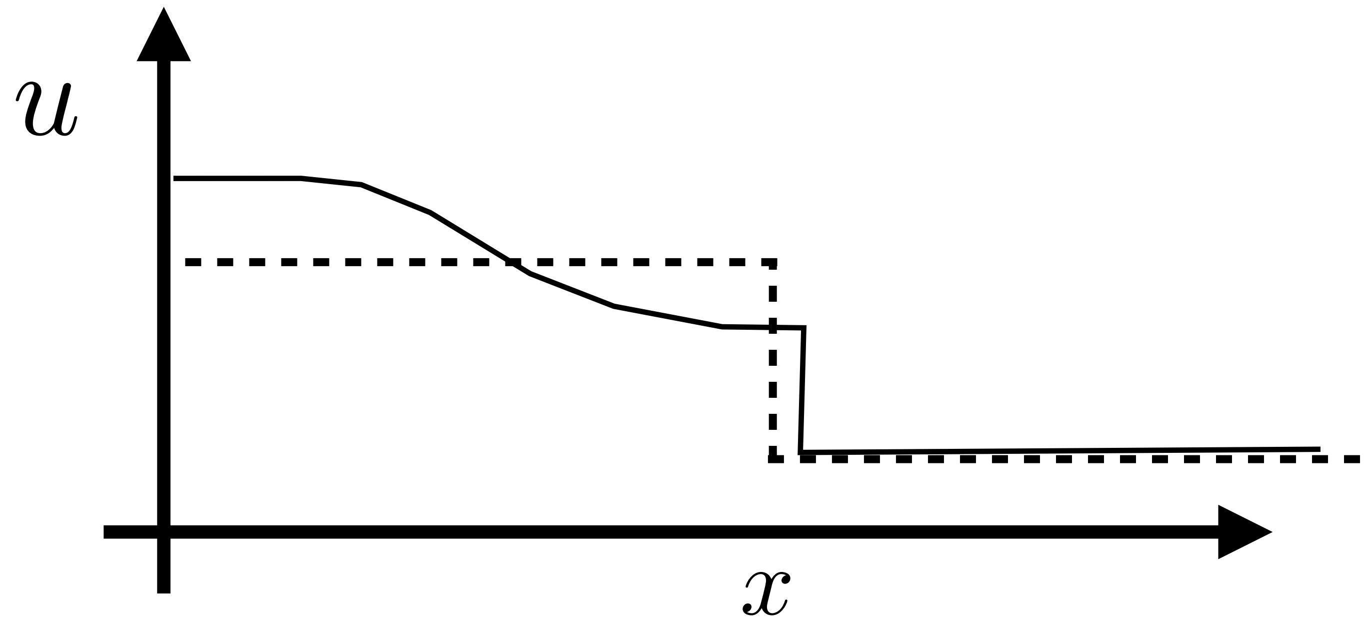

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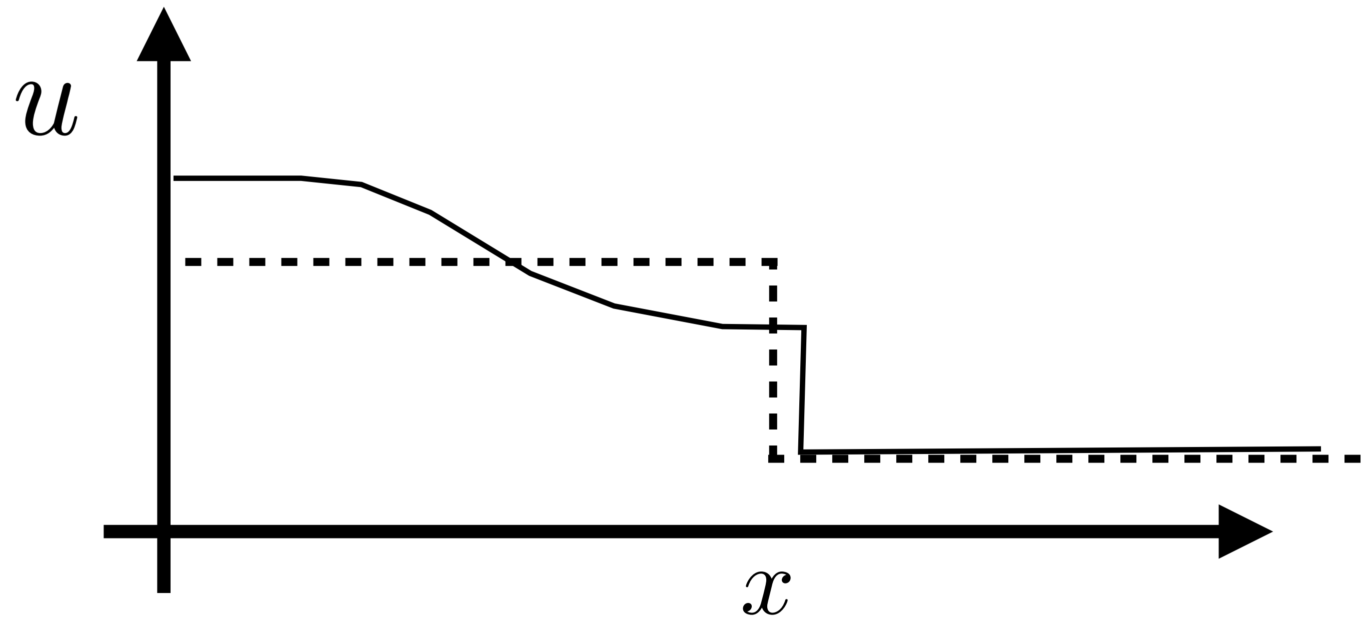

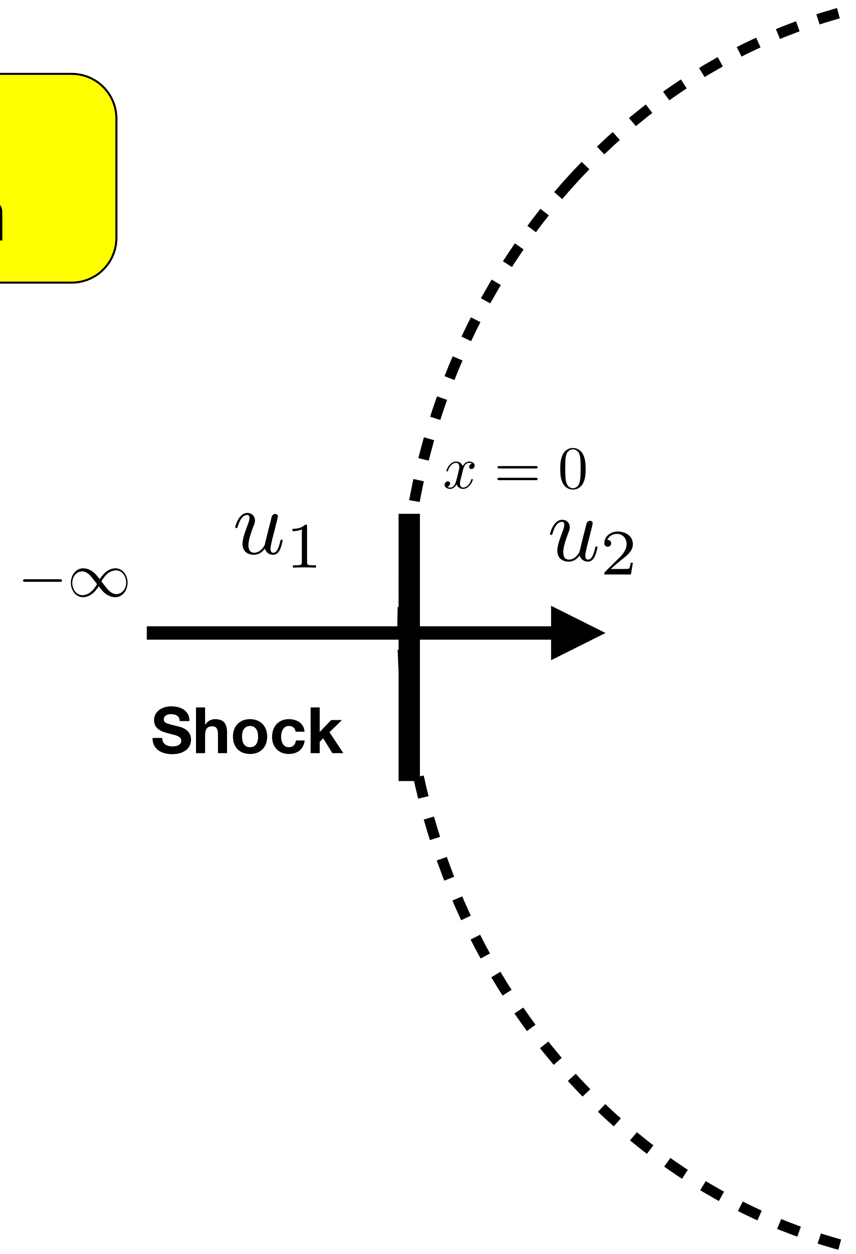

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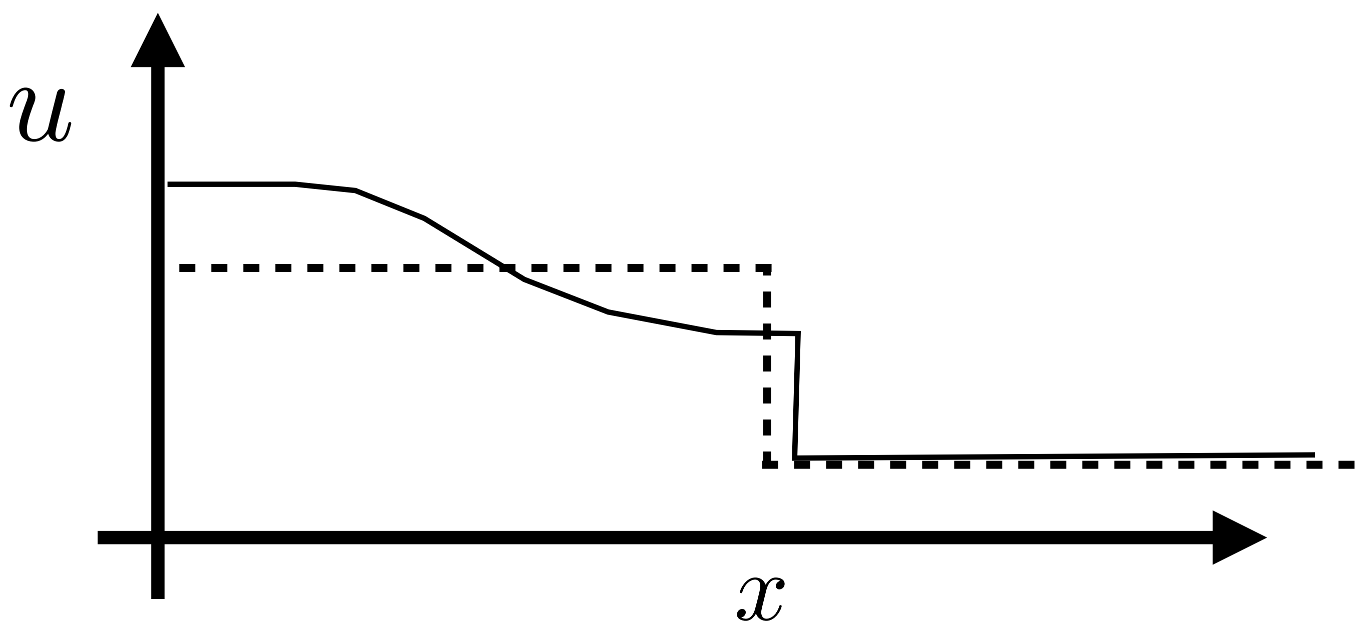

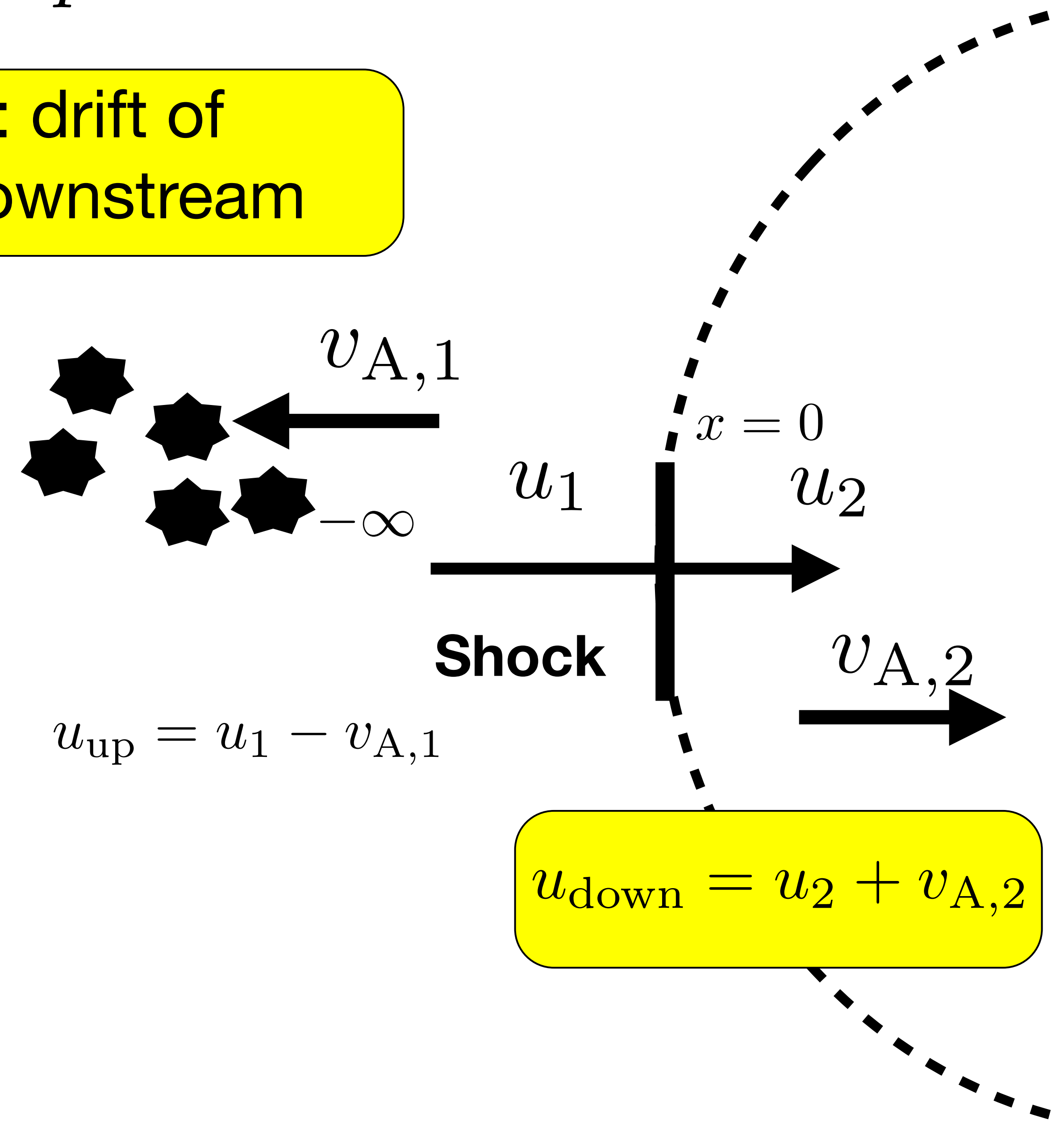

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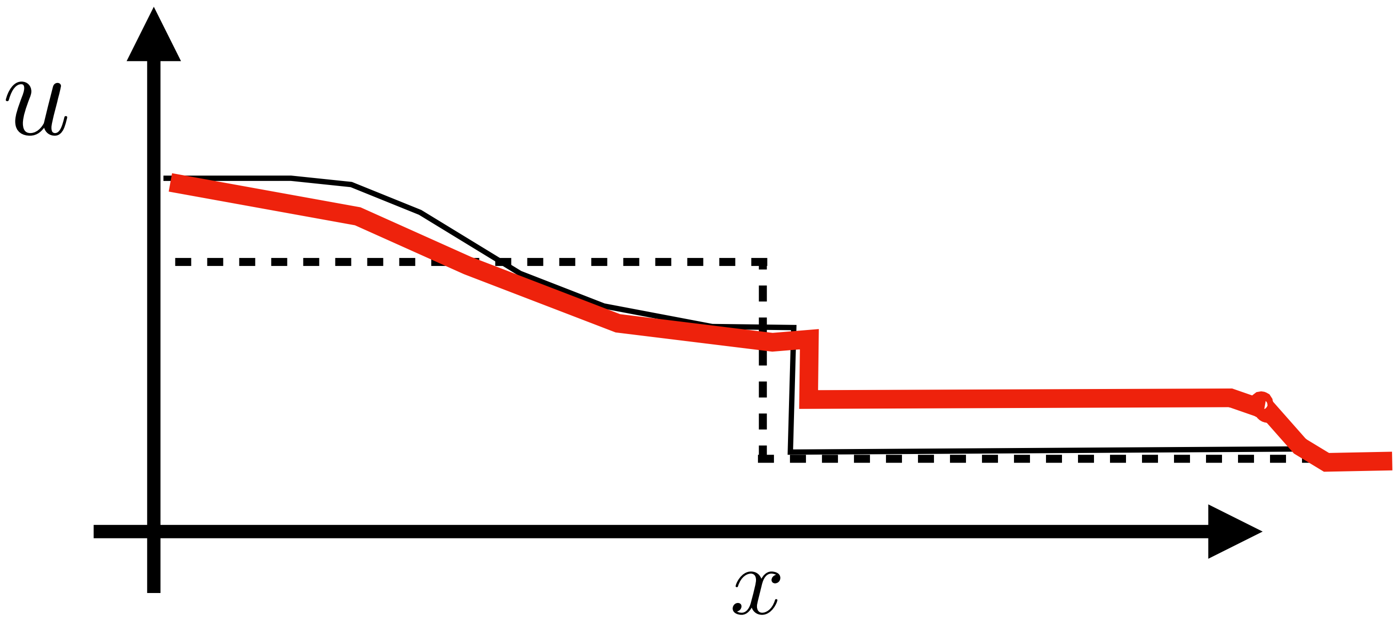

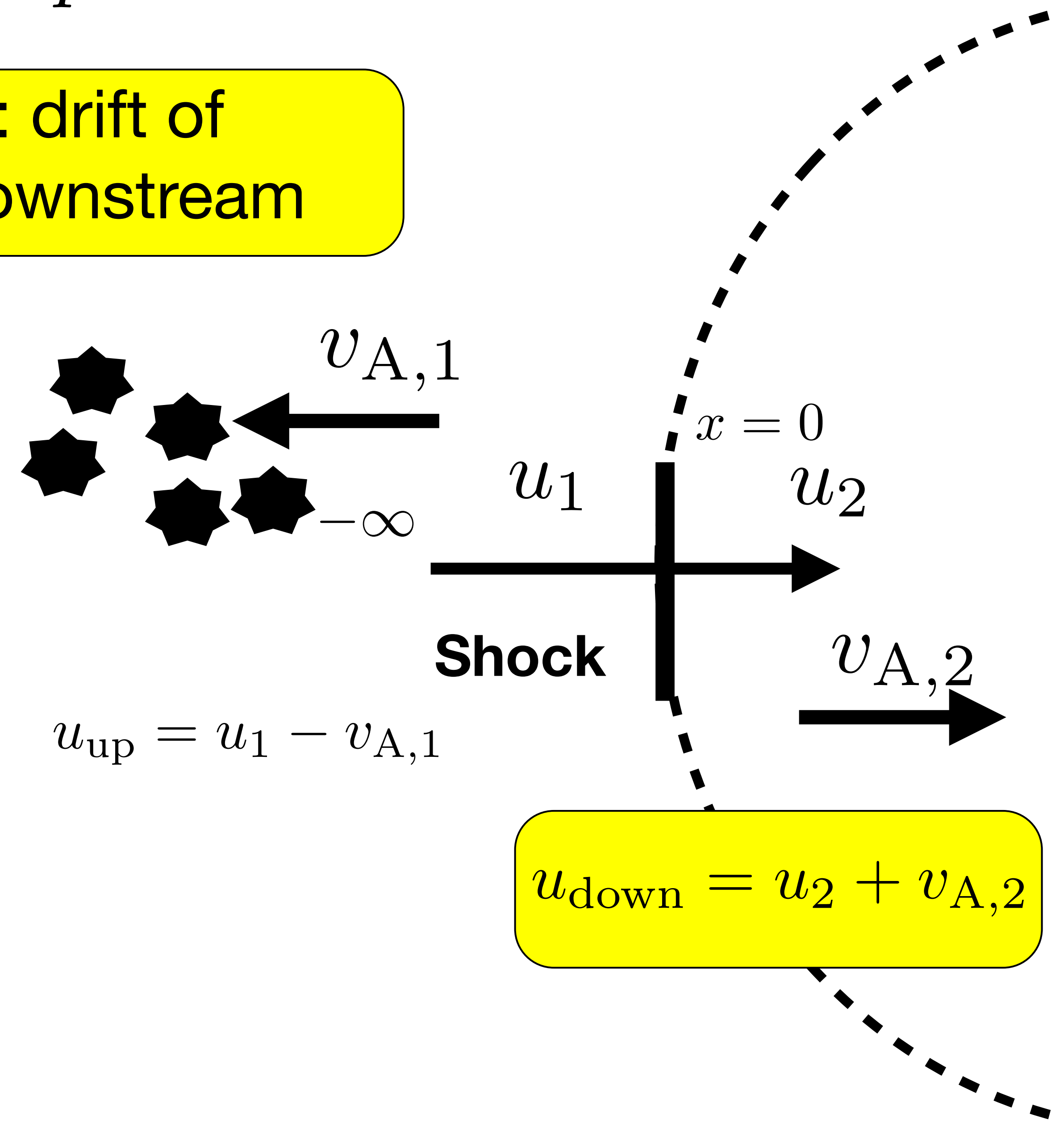

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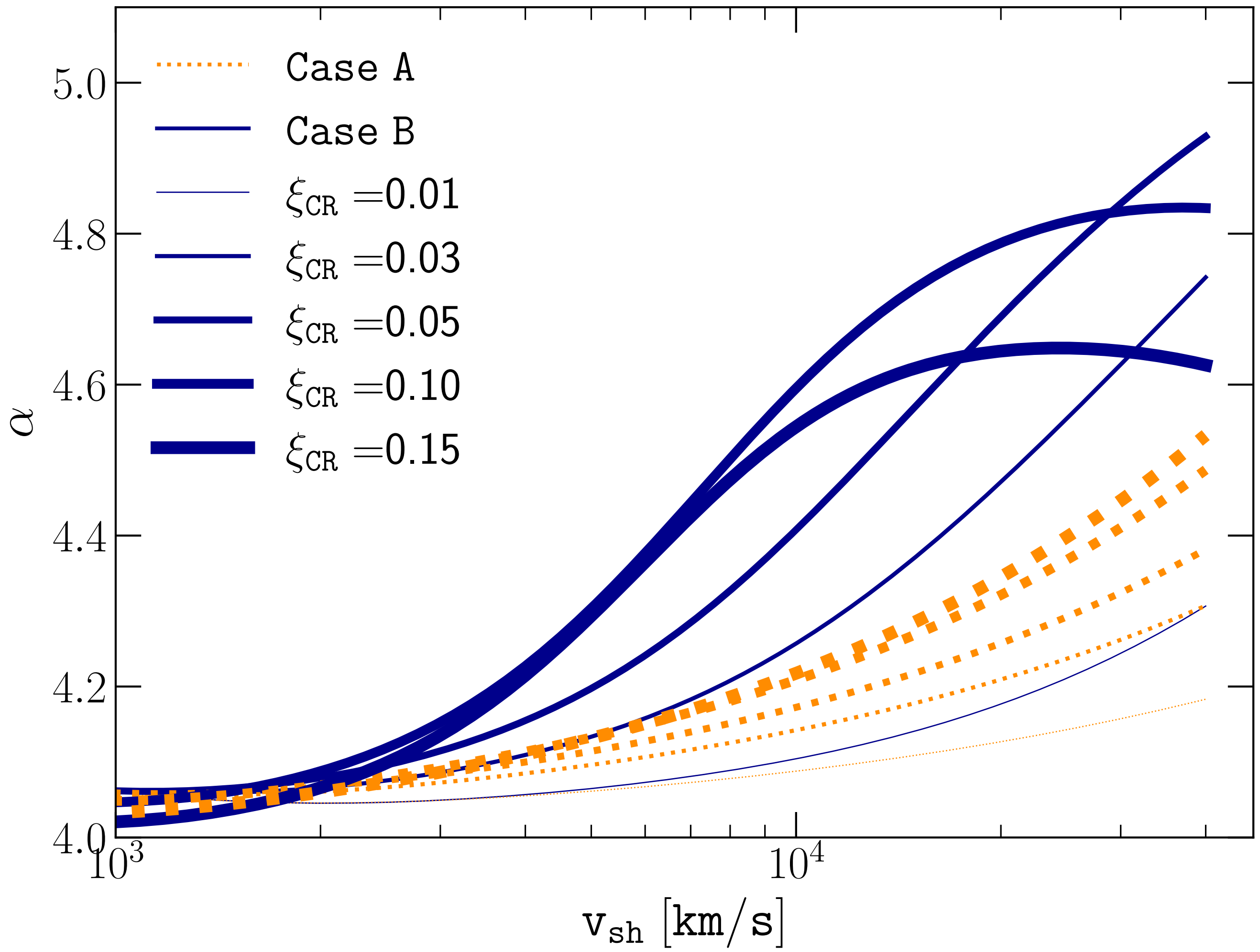
Bell: current from all particles (maximum value B)



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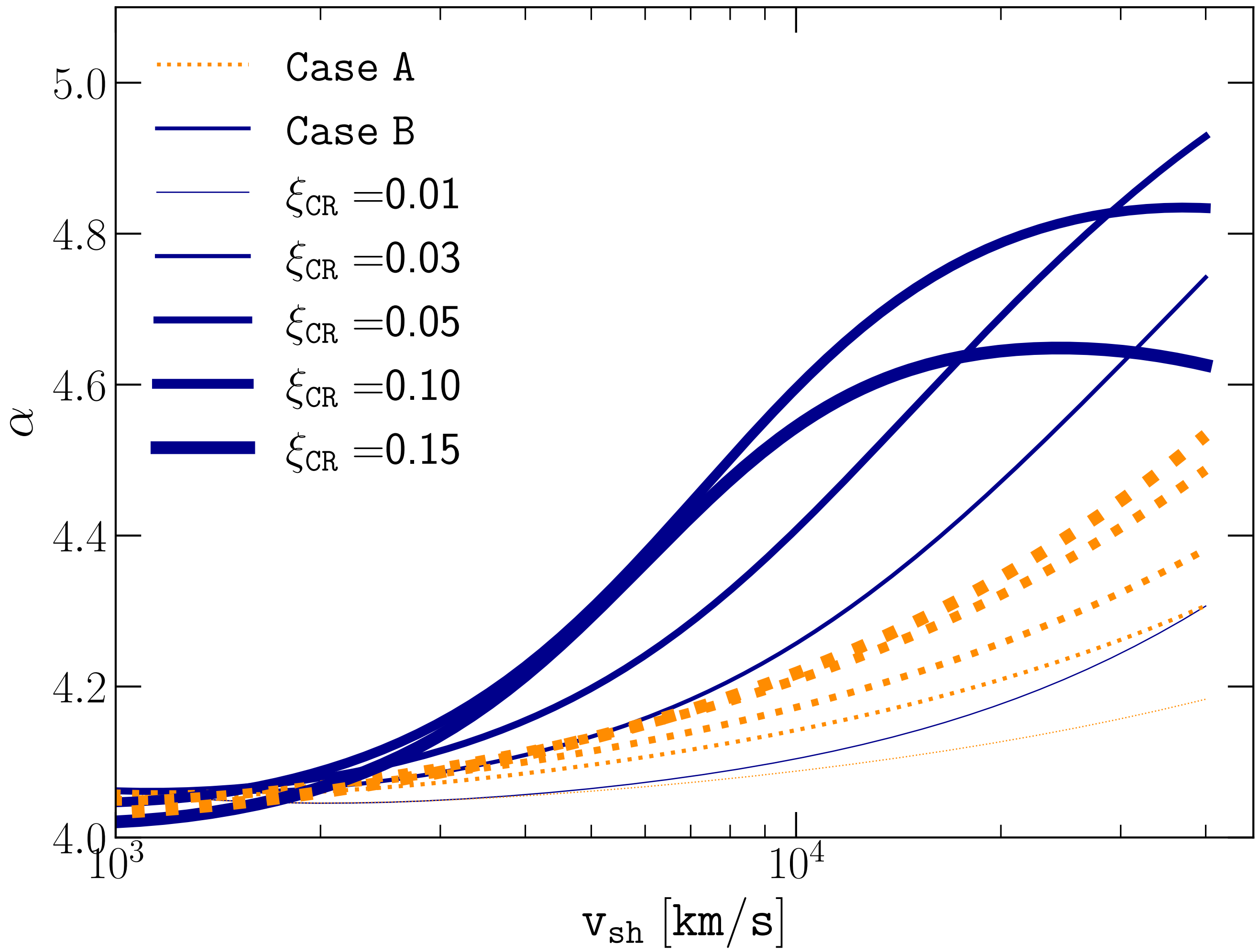

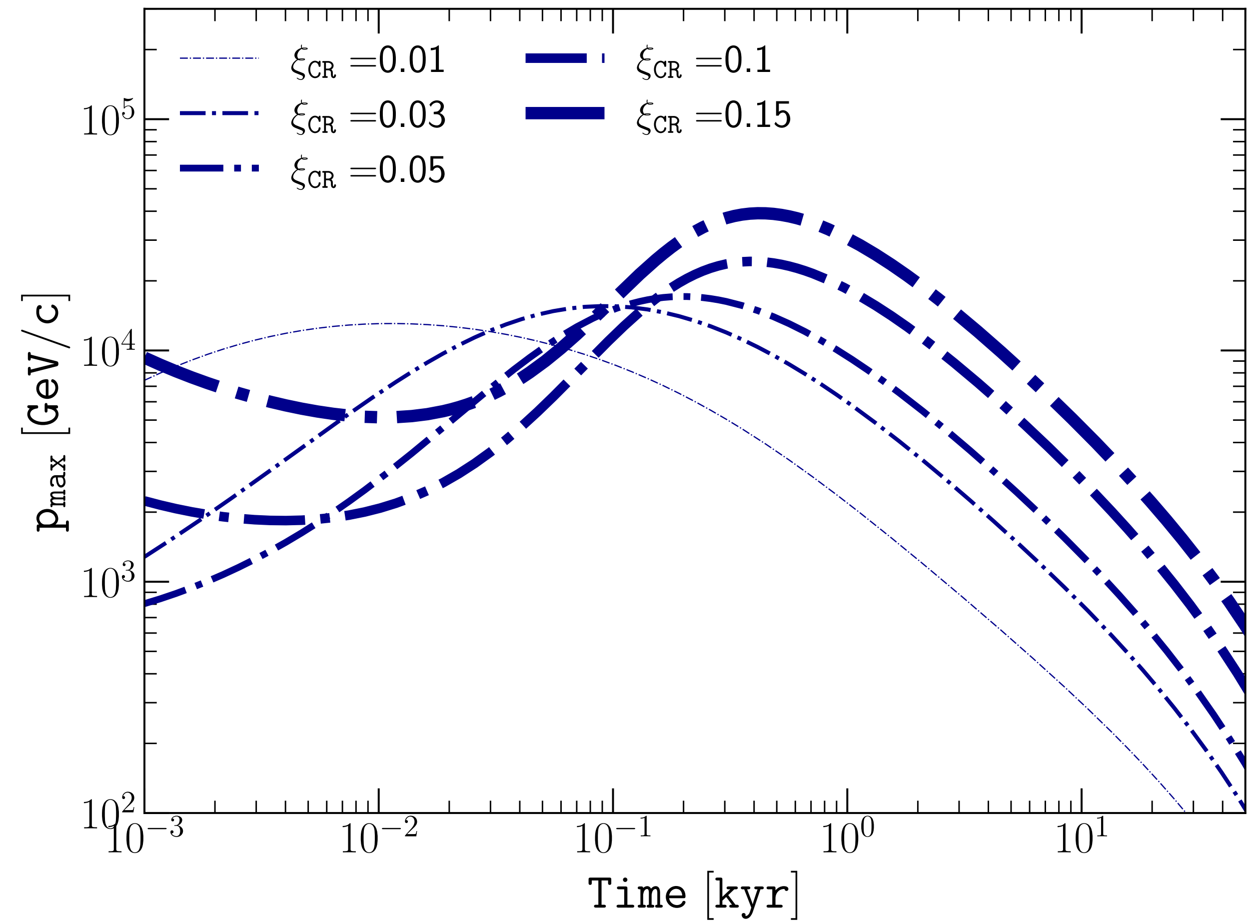

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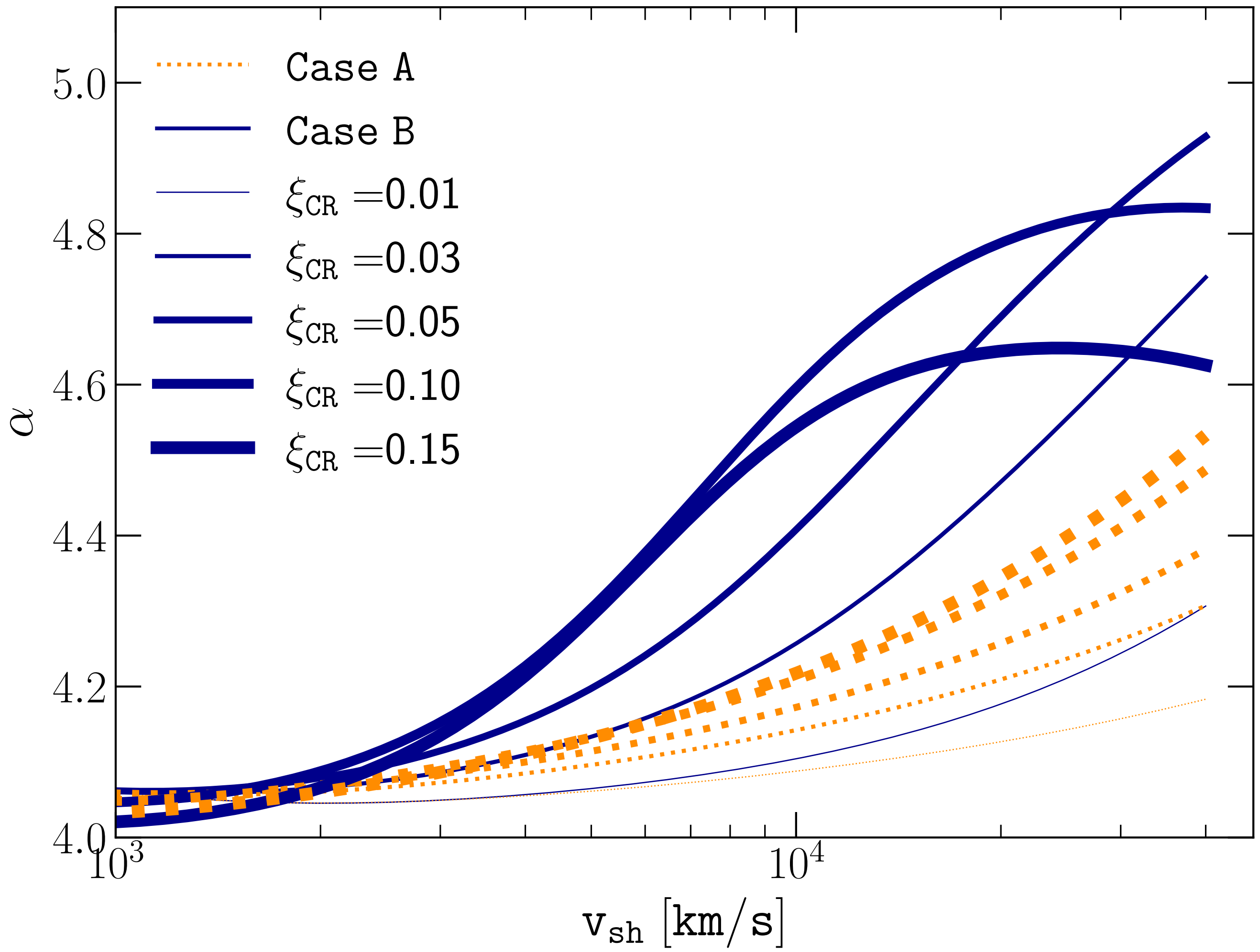

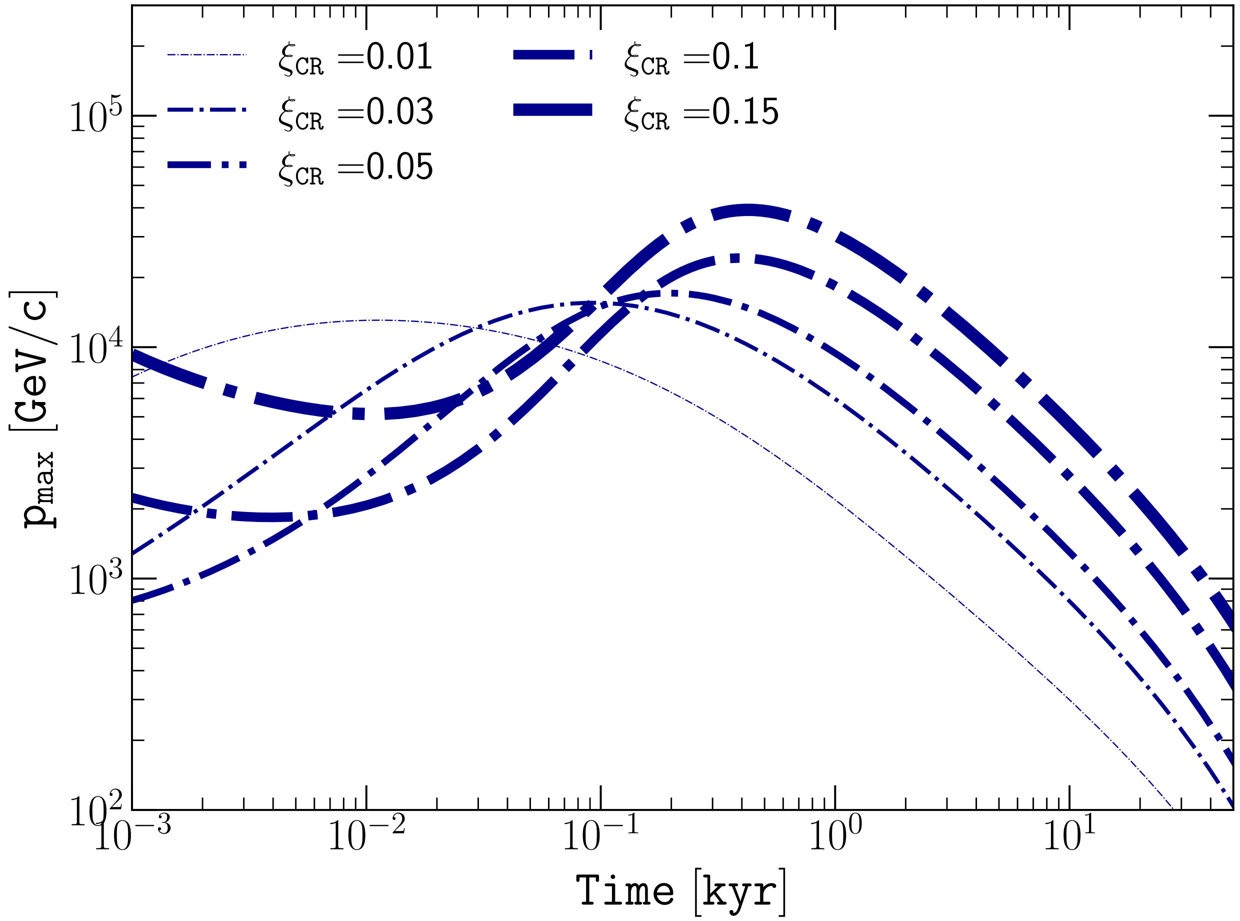

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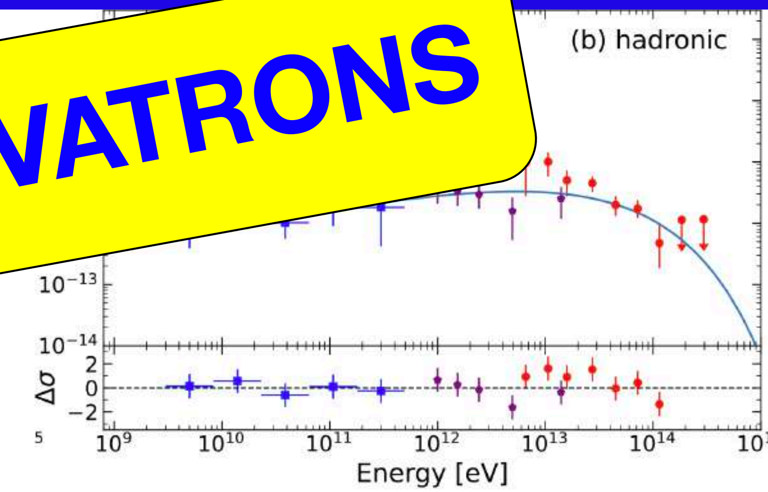
Consequences on pmax!

Drury (1983), Kirk (1990) Caprioli, Haggerty & Blasi (2020), Diesing & Caprioli (2021), PC, Blasi & Caprioli (2022)

What is wrong with supernova remnants?

1. All SNRs seem to not [text partly covered by overlaid banner]

LOW NUMBER PEVATRONS



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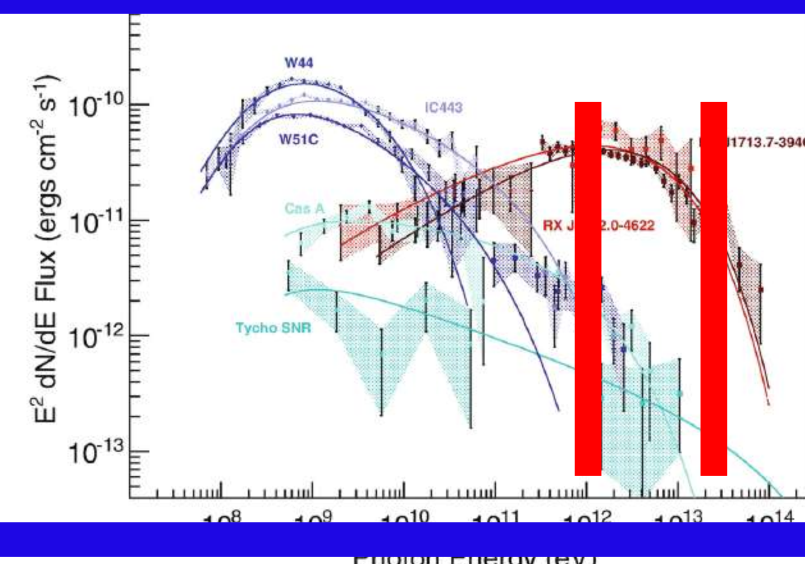

Funk (2017)

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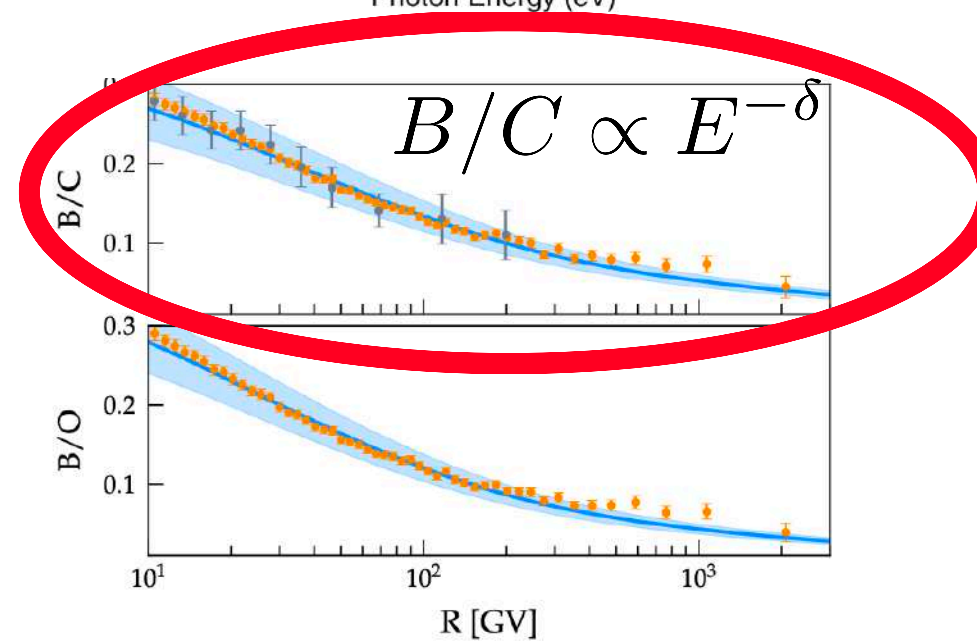

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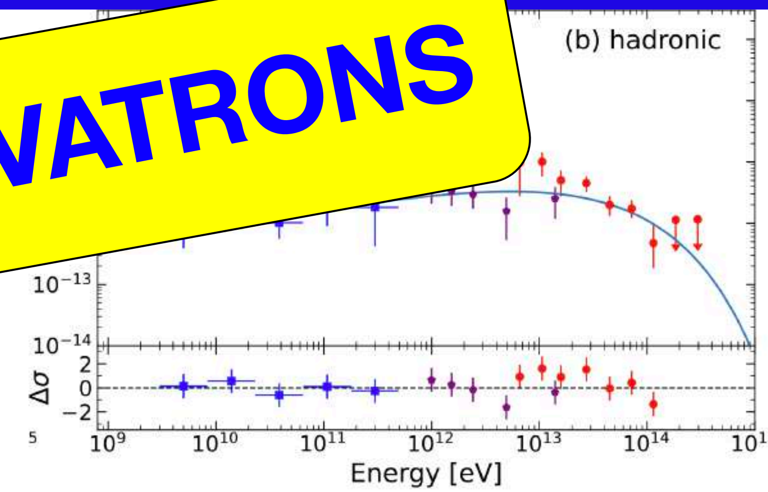

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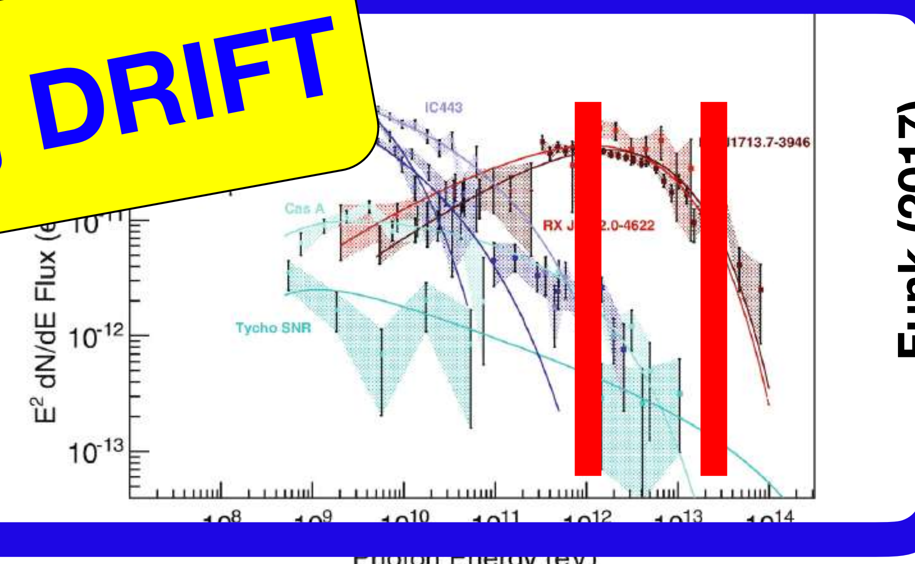
VH... ...spectra?

NON-LINEAR EFFECTS, DRIFT



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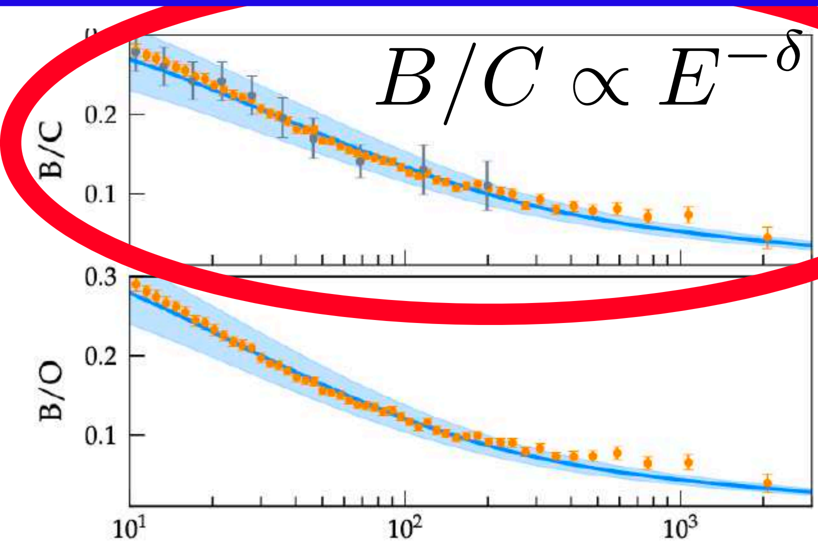

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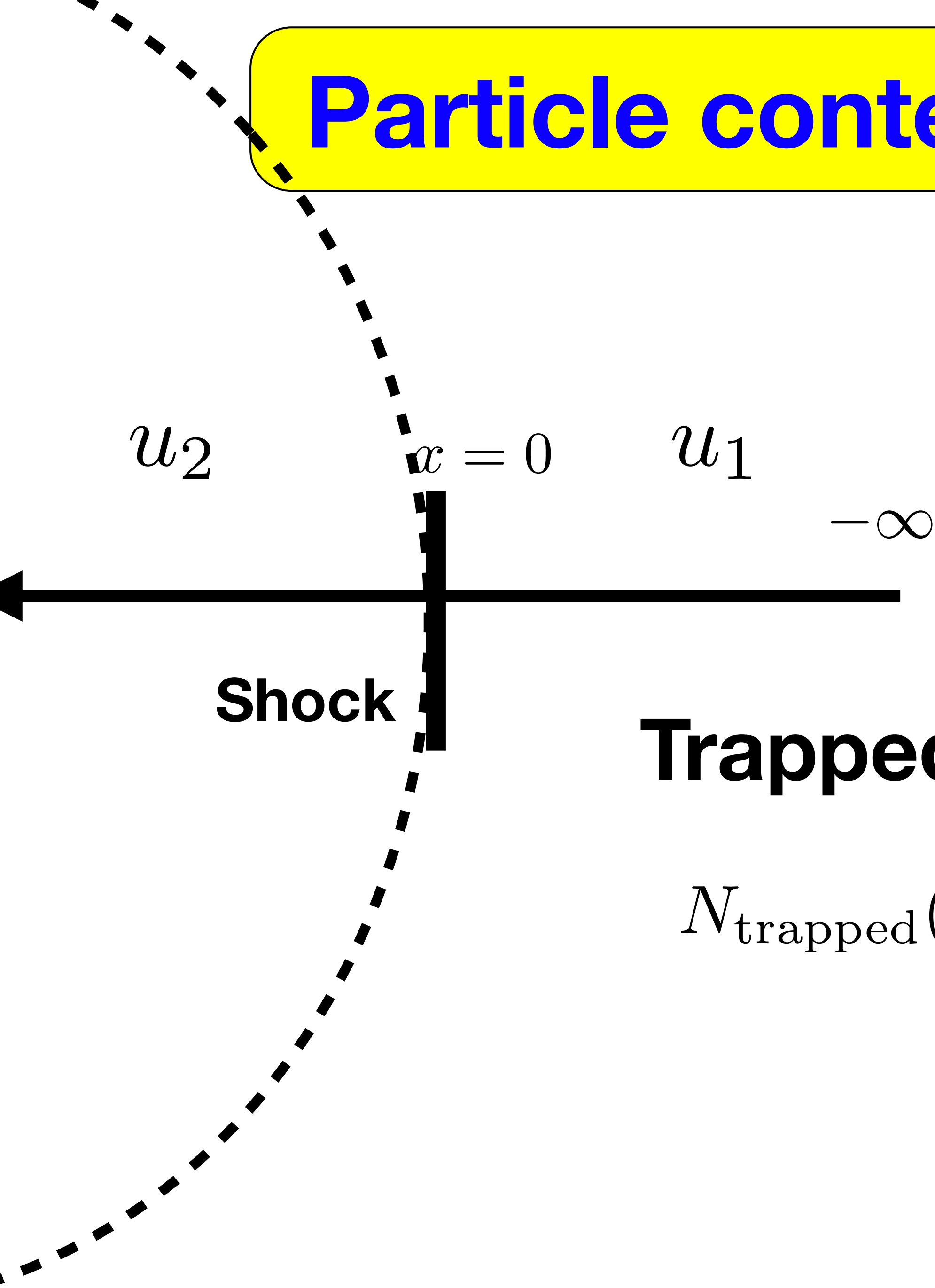

DSA $f(p) \propto p^{-\alpha}$

Trapped particles

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PC, Blasi, Caprioli (2021)

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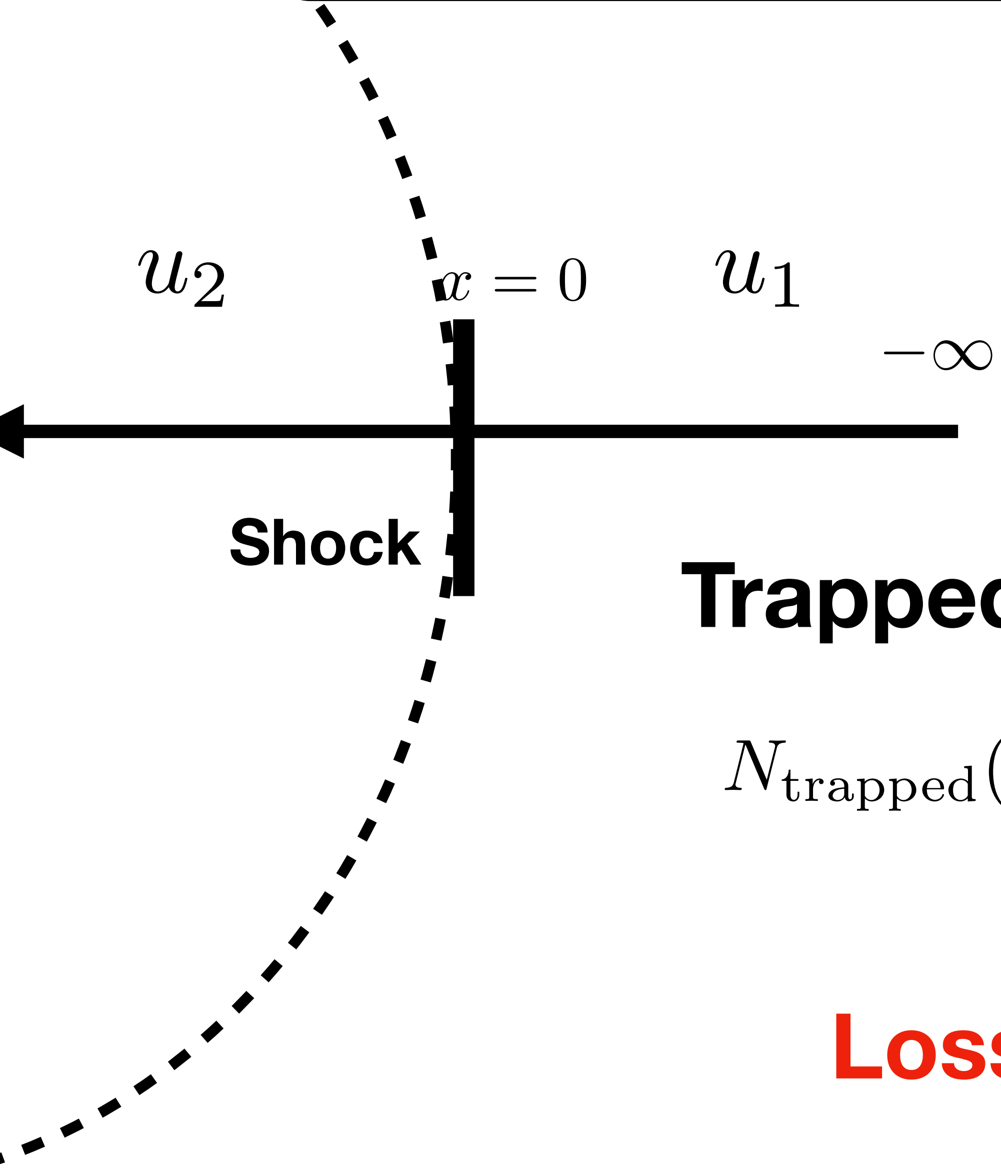

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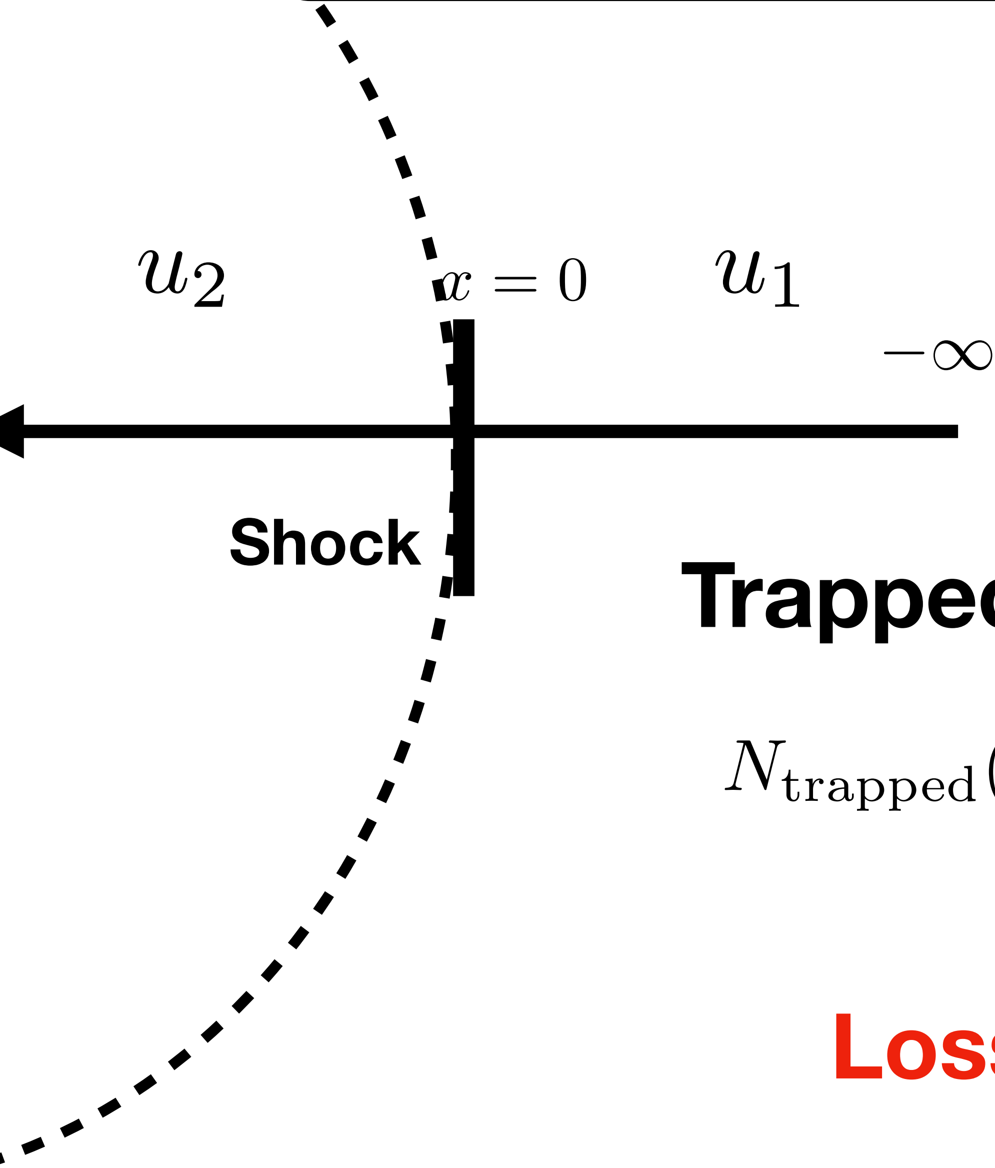

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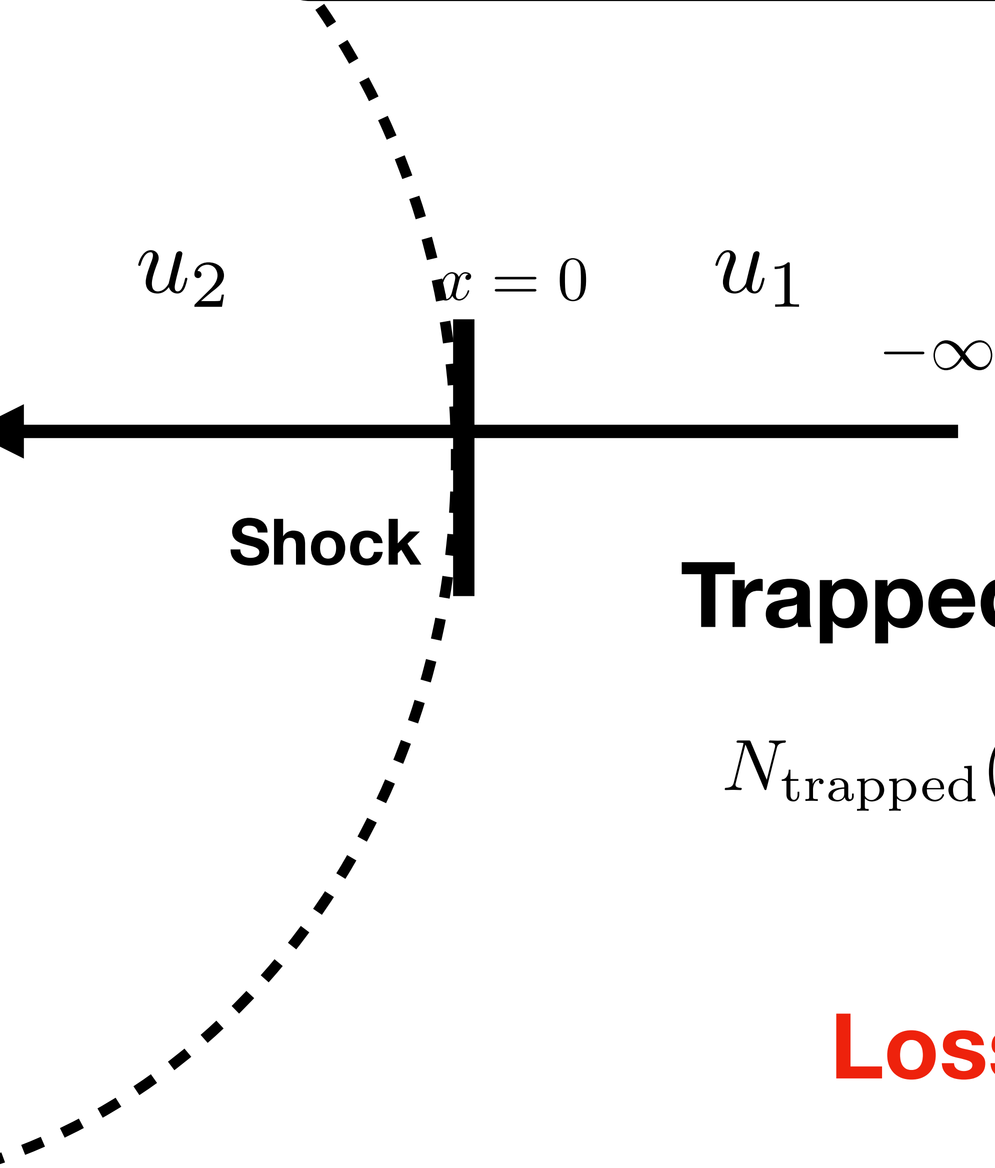

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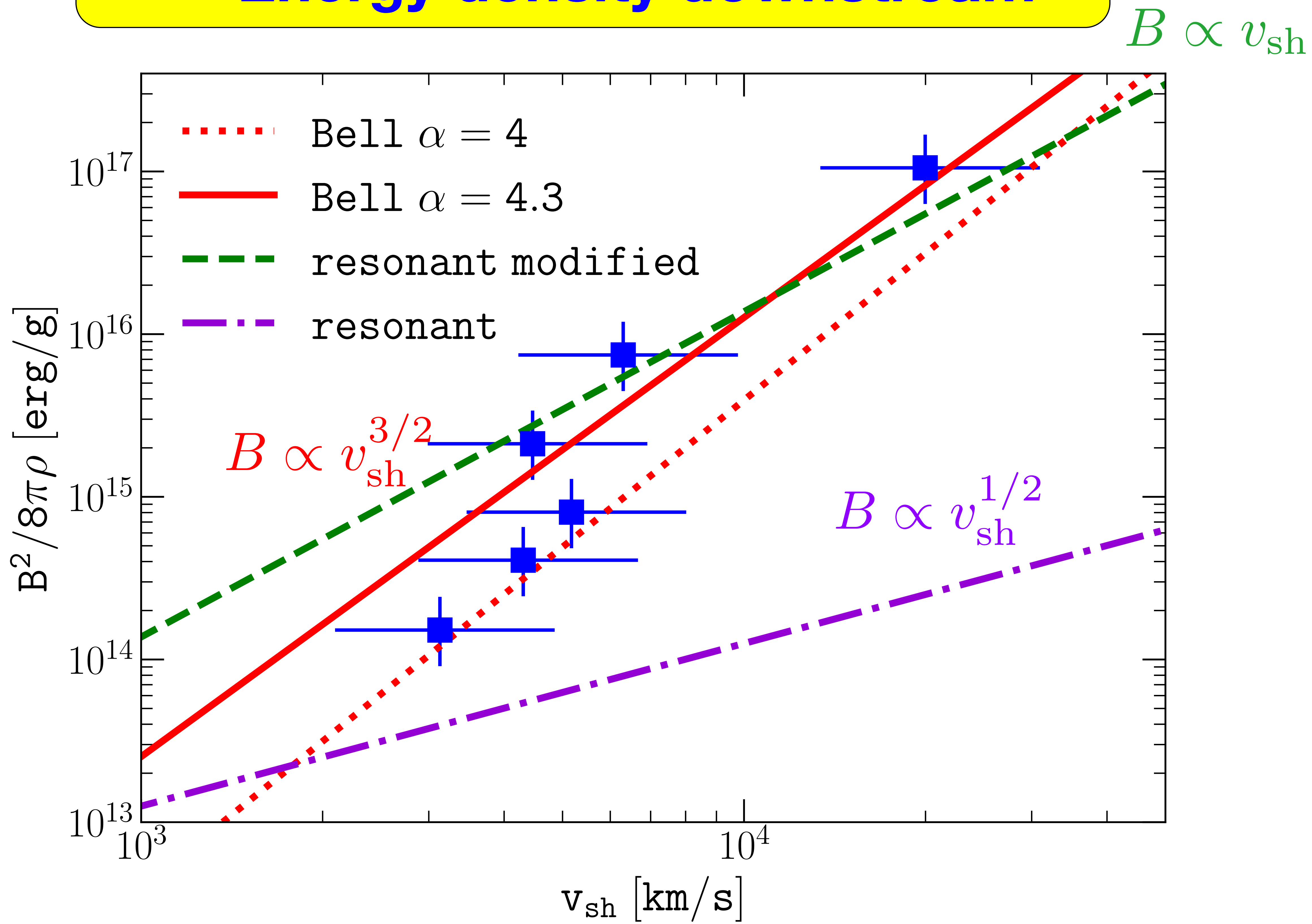
Energy density downstream



Important for losses!

Vink 2012

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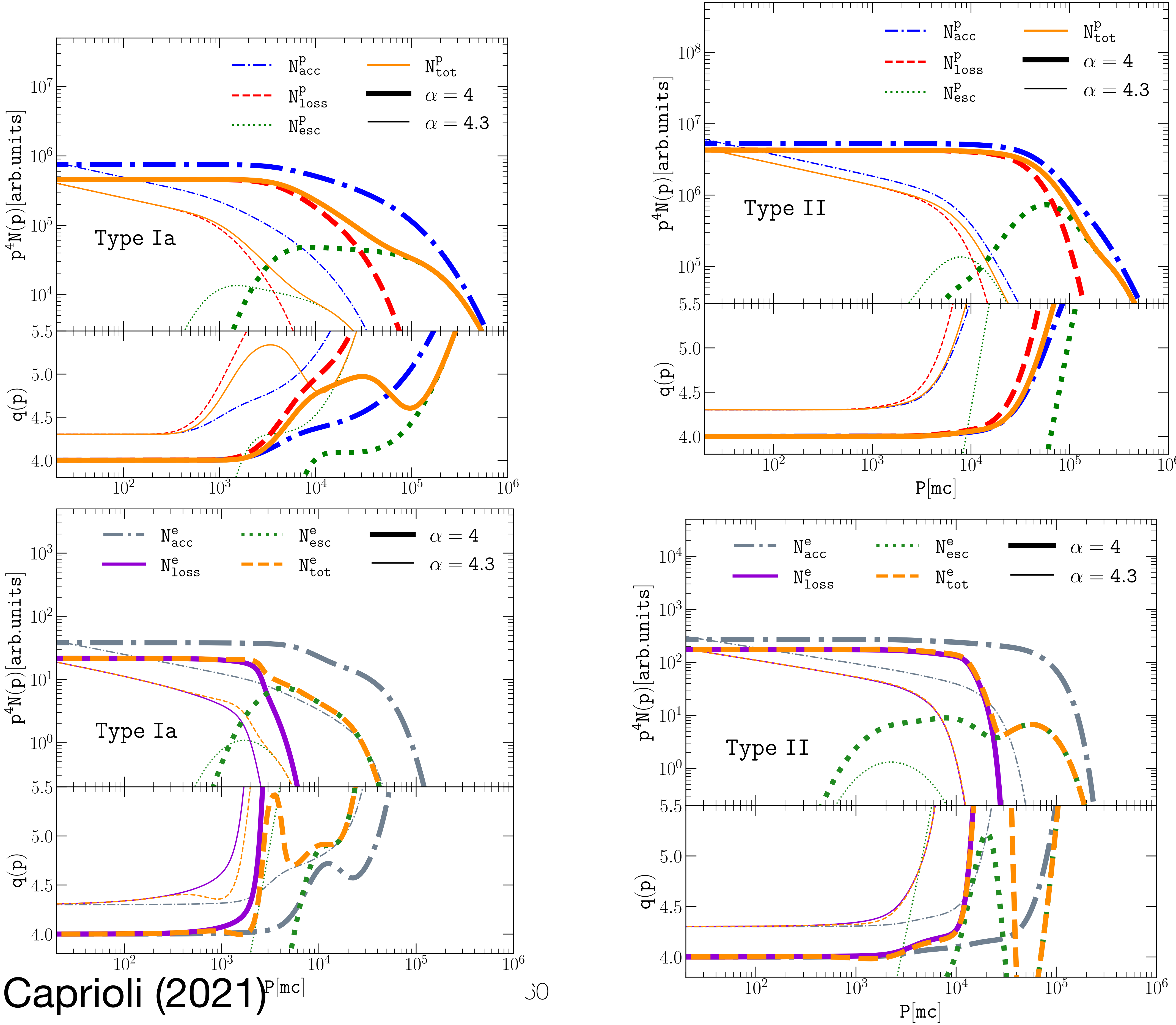
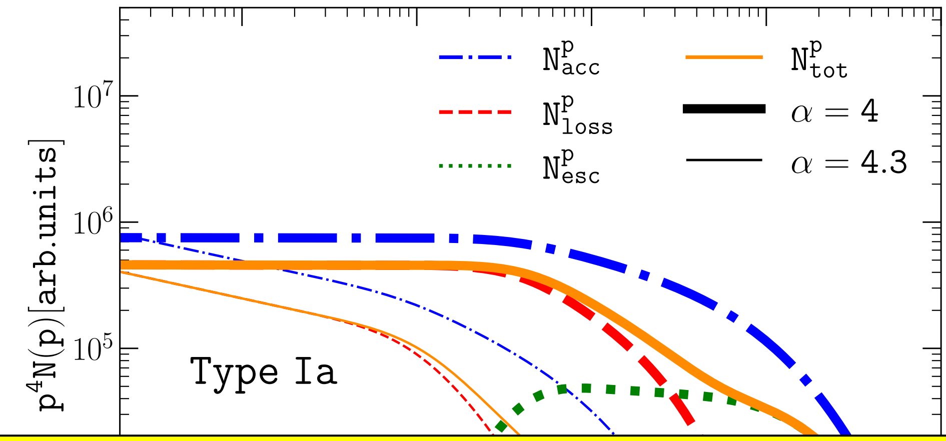
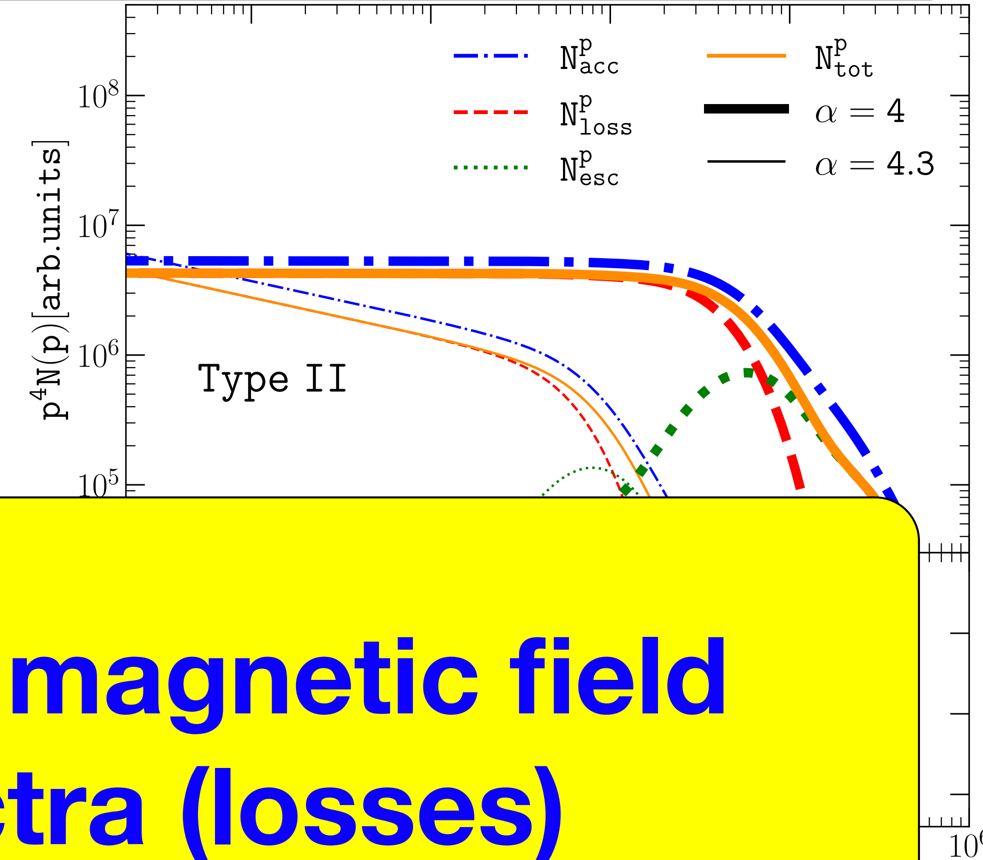


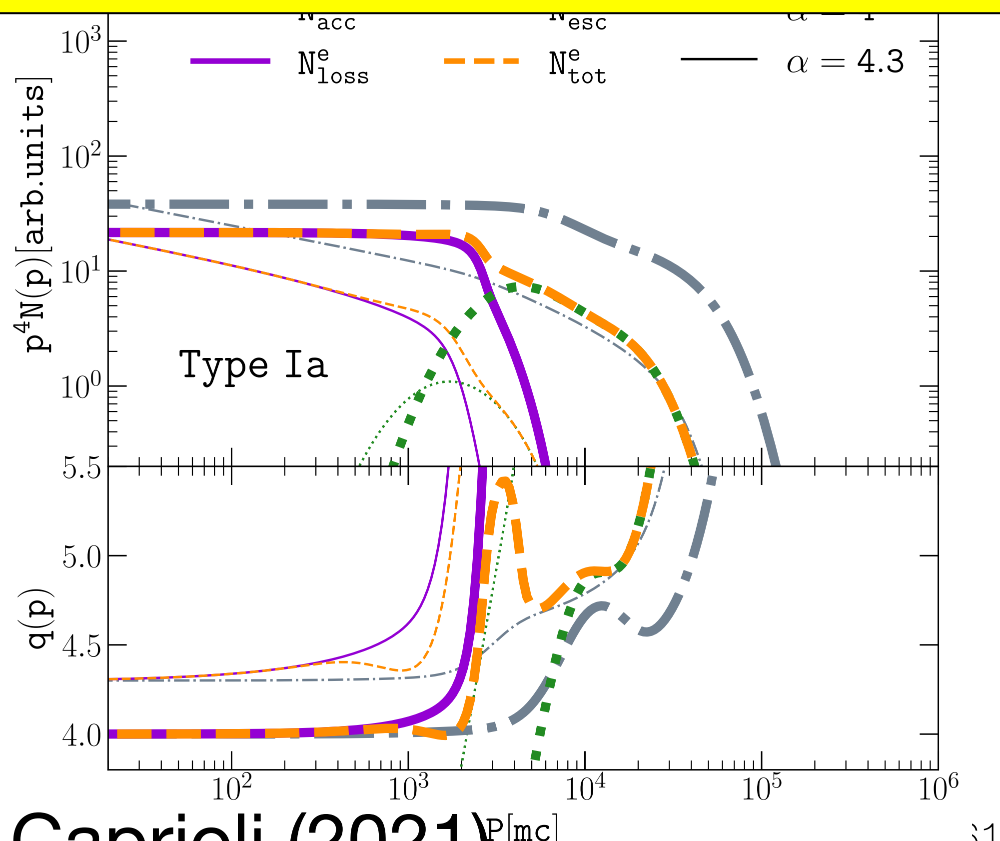
PC, Blasi, Caprioli (2021)

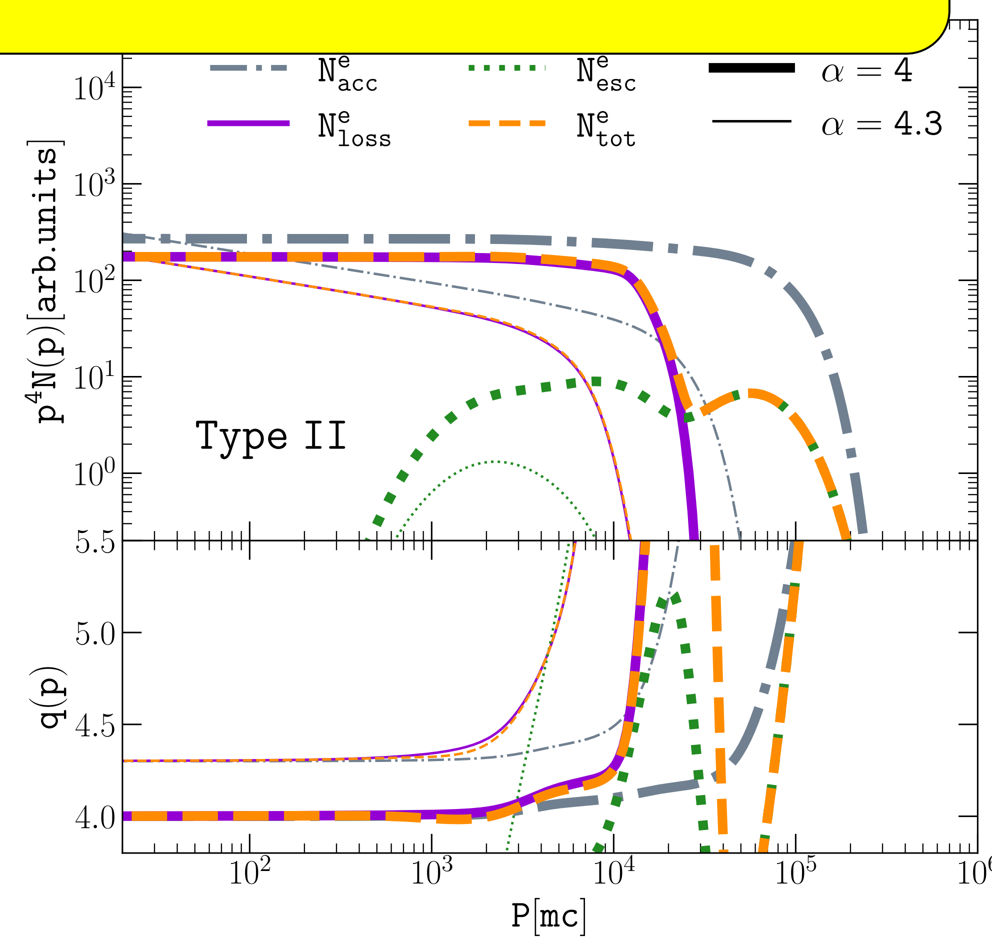
Particle content: accelerated vs. injected?





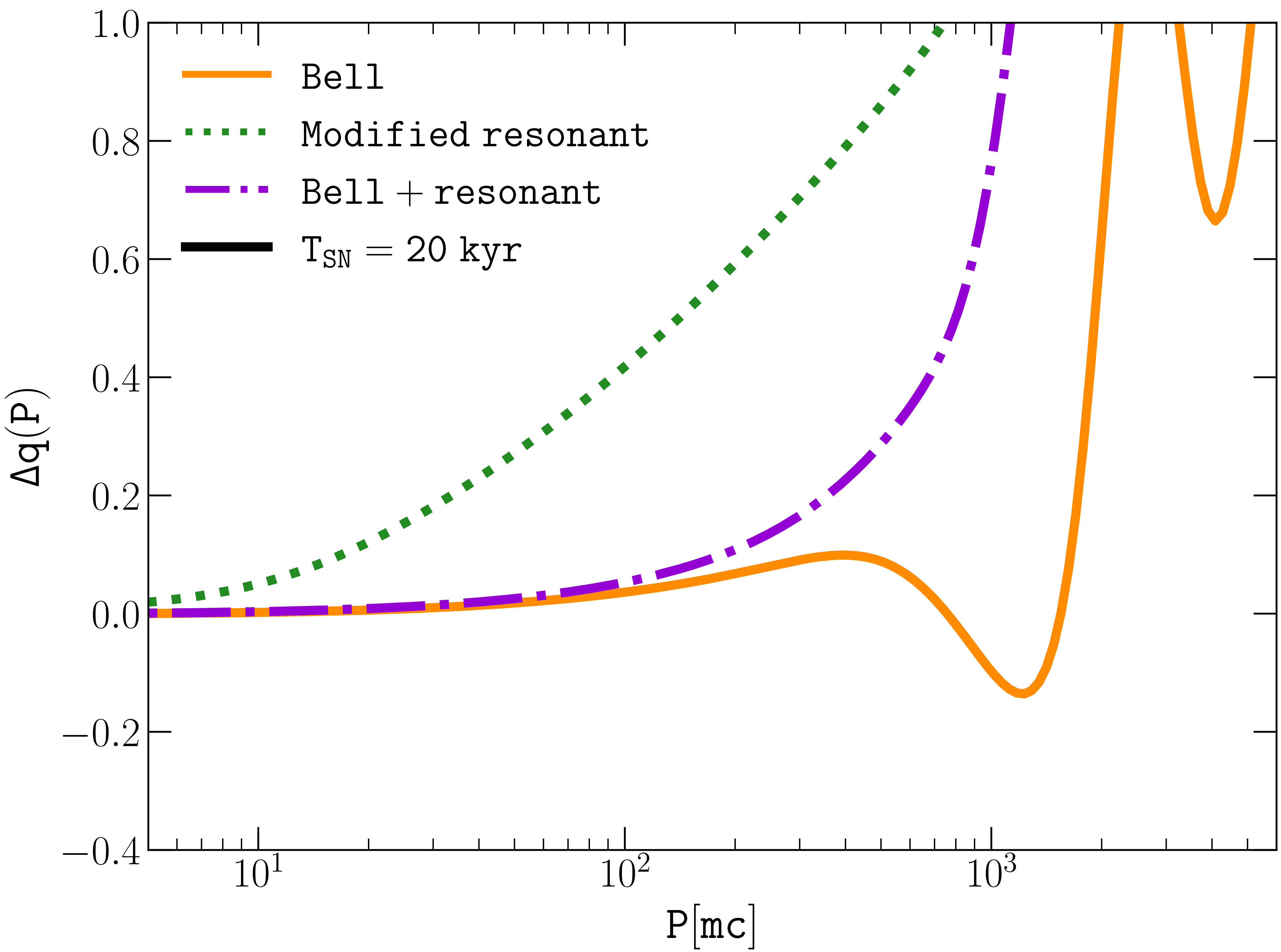
The importance of the magnetic field in shaping the spectra (losses)





PC, Blasi, Caprioli (2021)

Difference total spectrum electron vs. proton

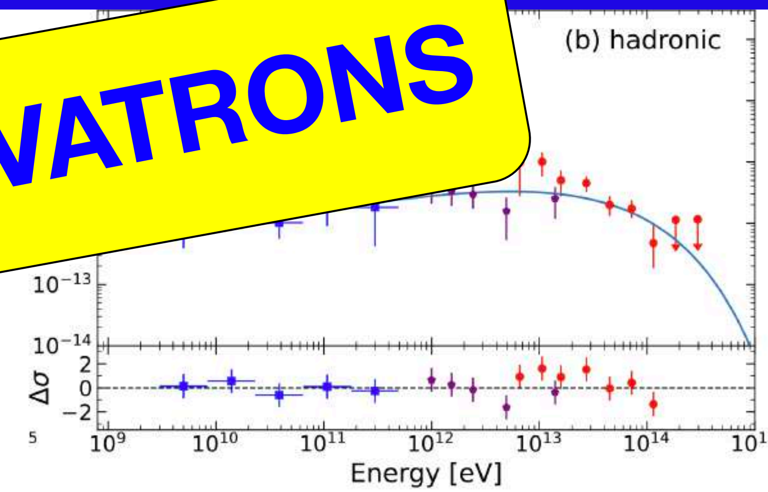


PC, Blasi, Caprioli (2021)

What is wrong with supernova remnants?

1. All SNRs seem to not b…

LOW NUMBER PEVATRONS

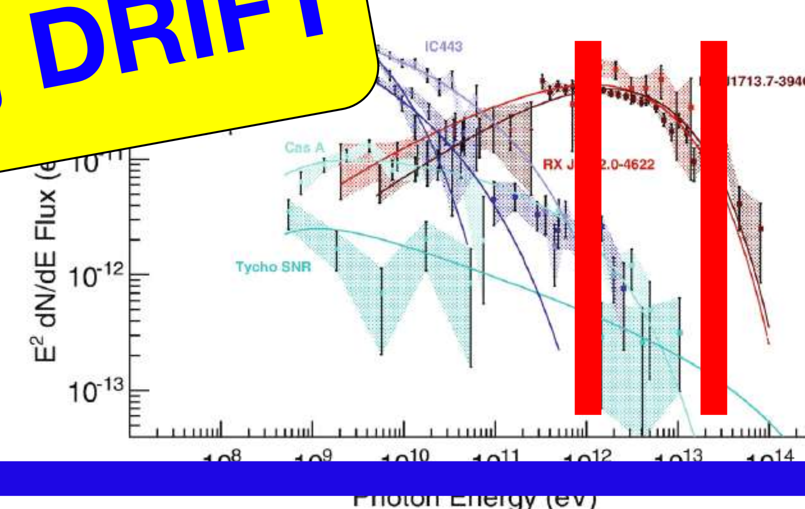


SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

2. The slope of accelerated partic…
at SNR sh…

NON-LINEAR EFFECTS, DRIFT

VH… …spectra?



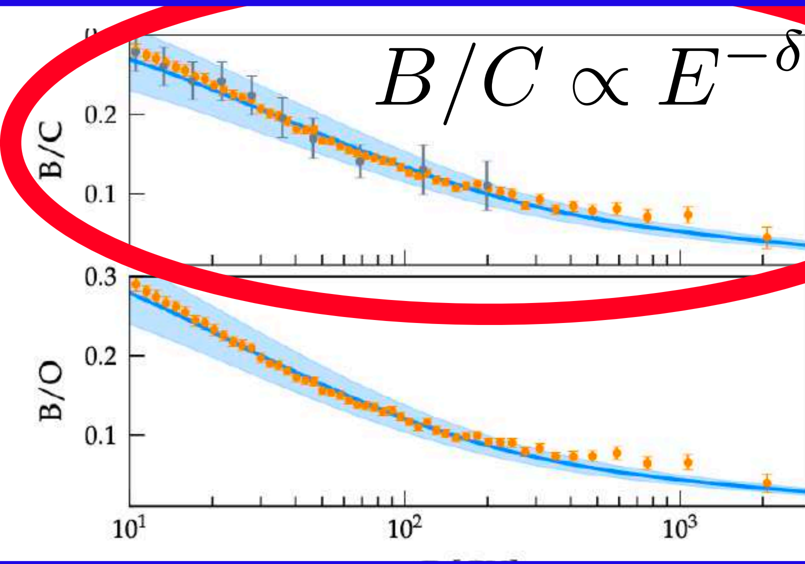
Funk (2017)

3. Particle spectra released in the ISM

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

Injection Propagation

How much e/p? For how long?



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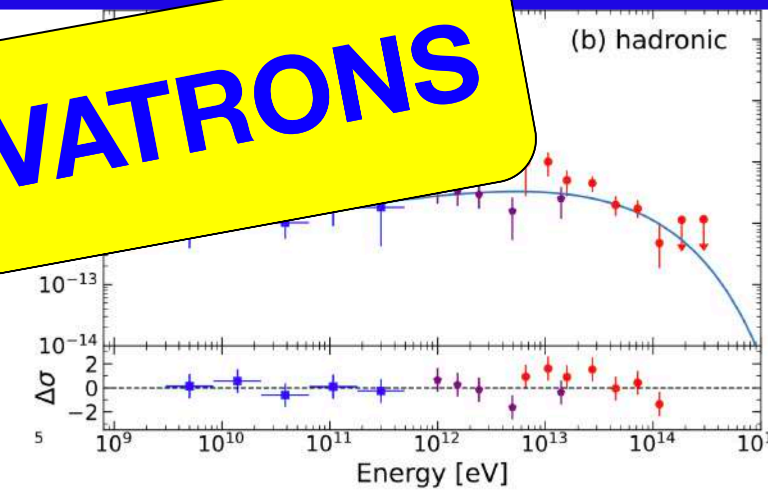

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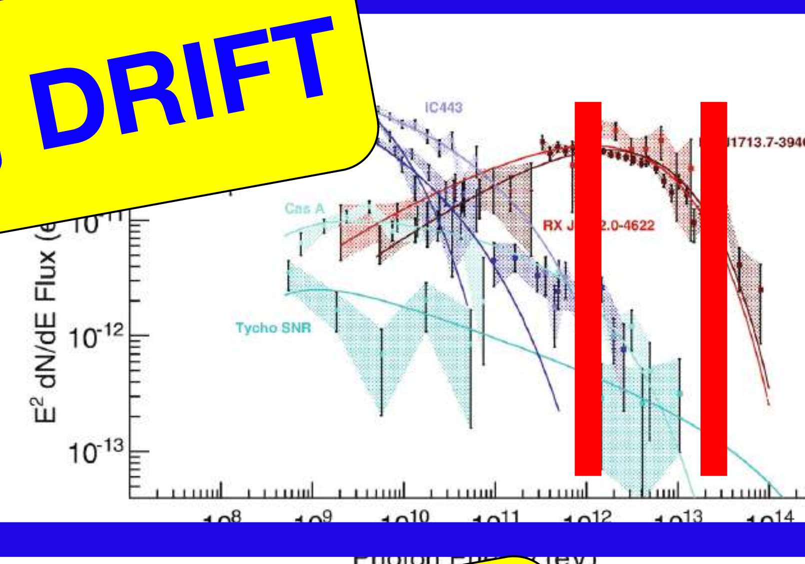


Funk (2017)

3. Particle spectra released in the ISM

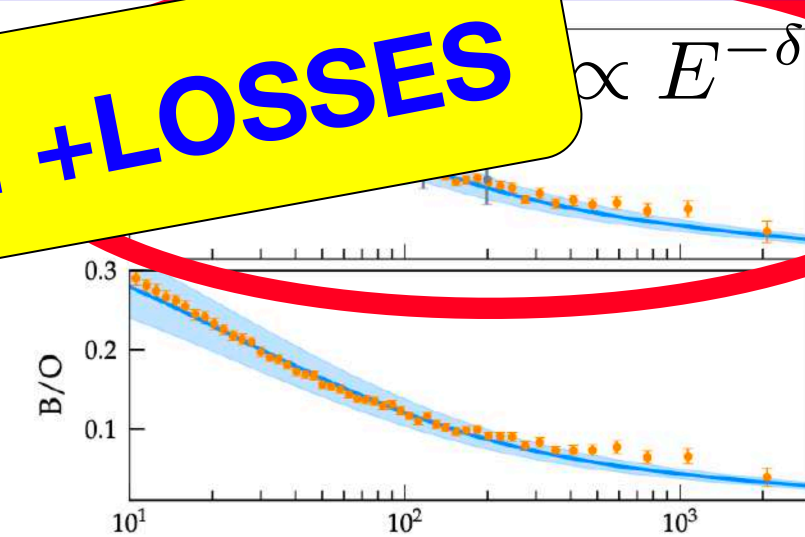
CUMULATED SPECTRUM +LOSSES

$\propto E^{-\delta}$

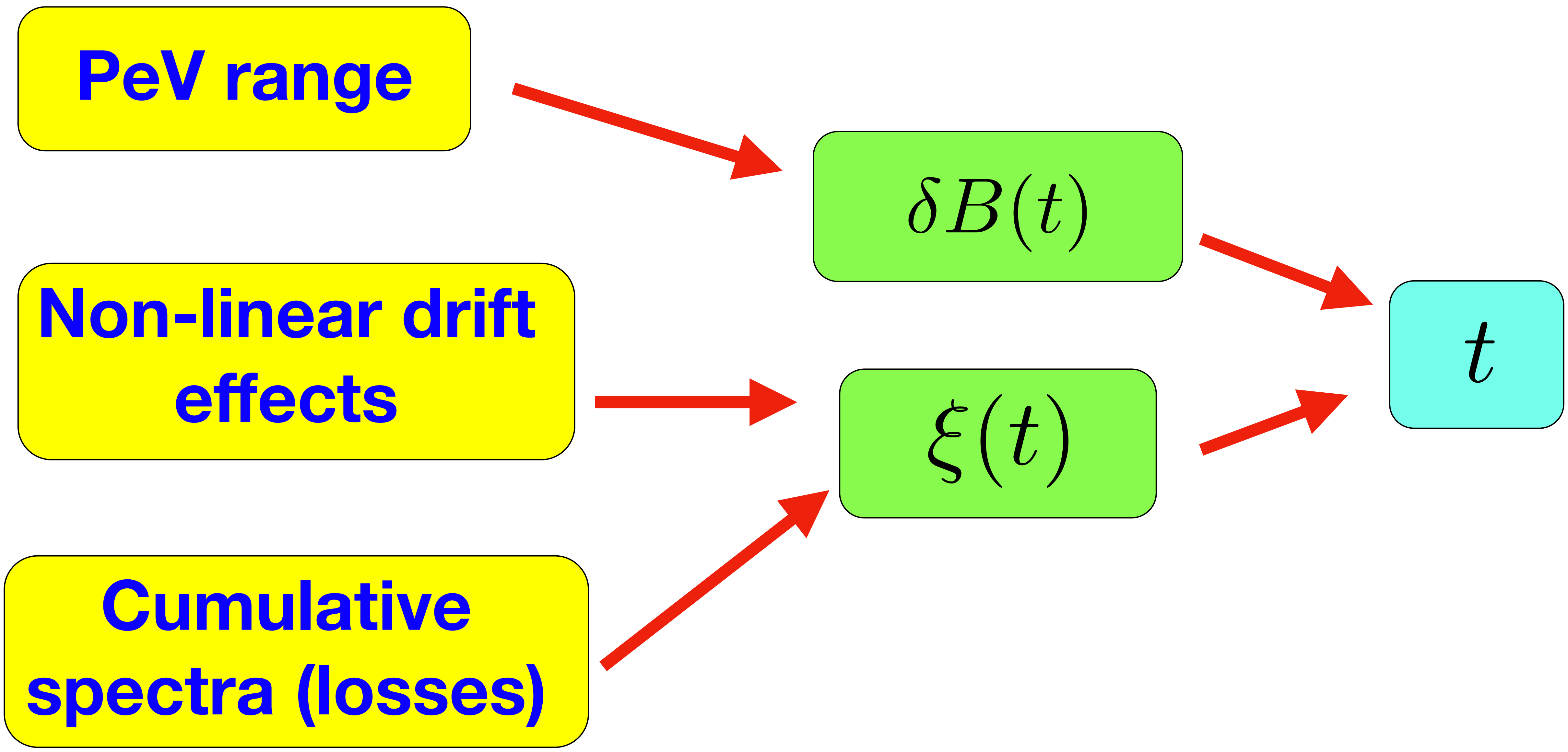
$E^{-2.7}$

Propagation

How much e/p? For how long?

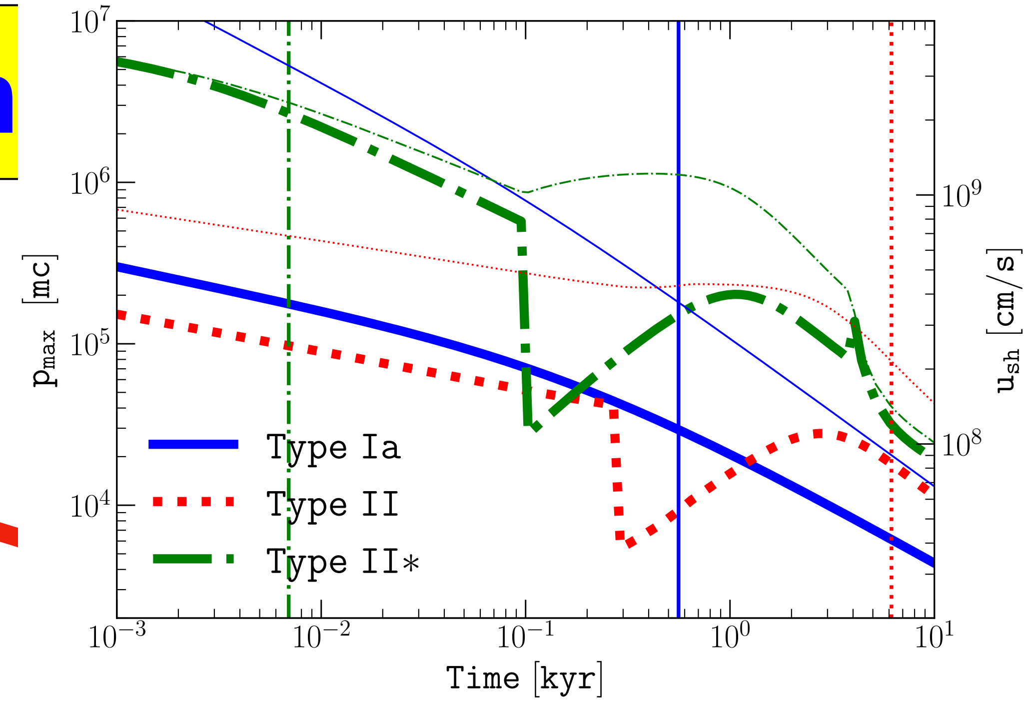


Intricate issues



Early times!

In



PeV range

Non-linear drift effects

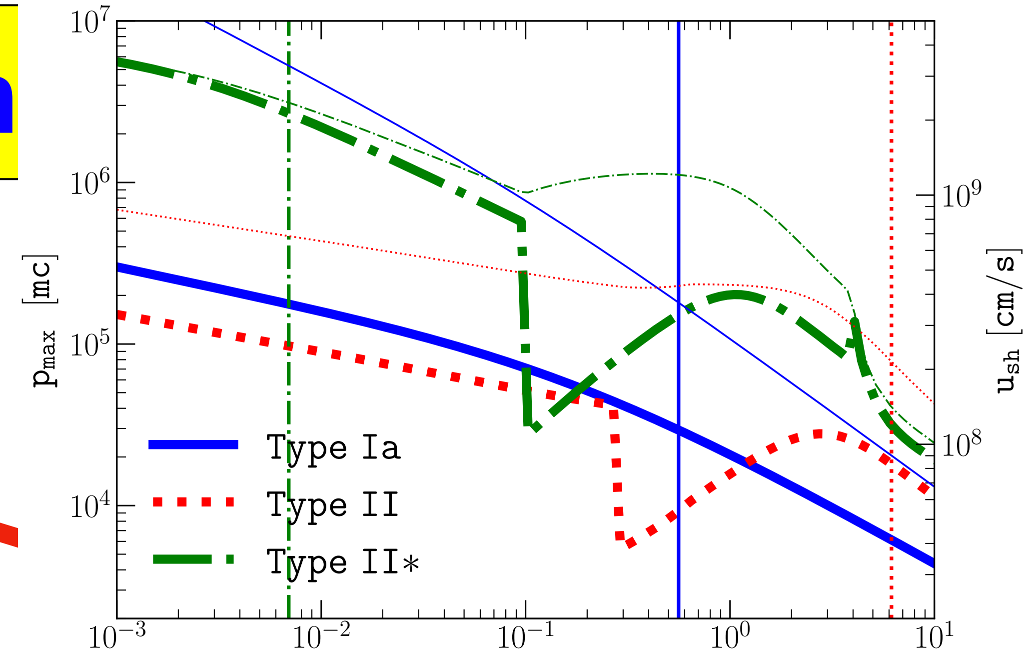
Cumulative spectra (losses)

$\xi(t)$

t

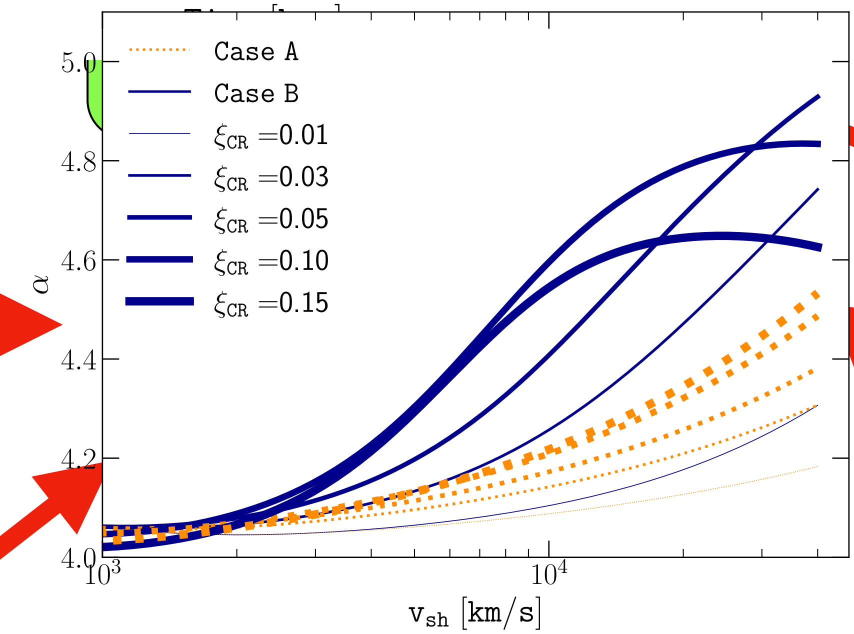
Early times!

In



PeV range

Non-linear drift effects



Cumulative spectra (losses)

t

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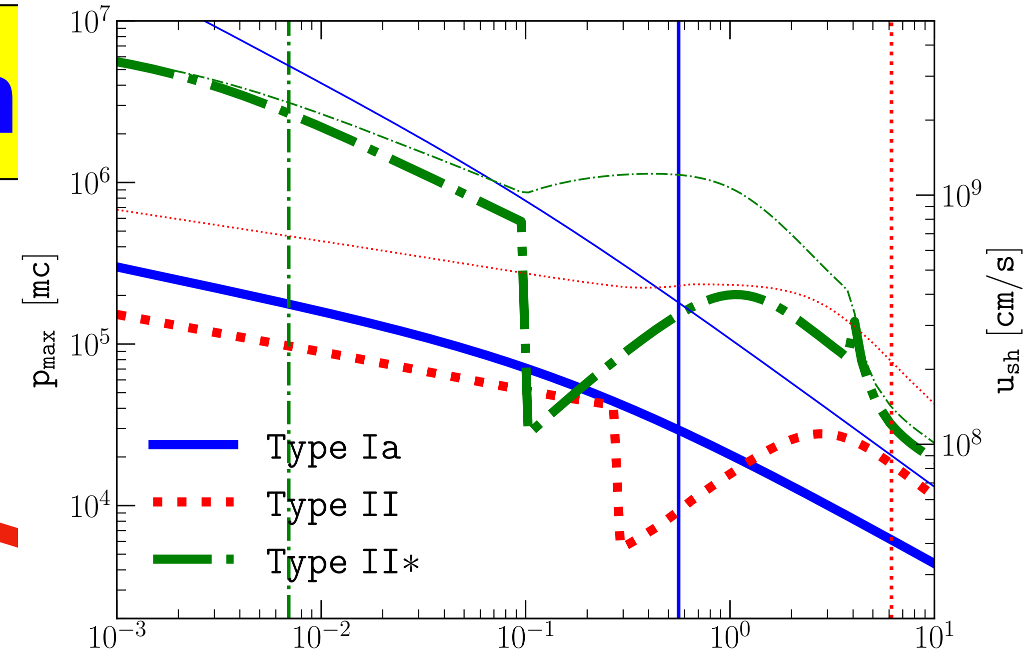
In

PeV range



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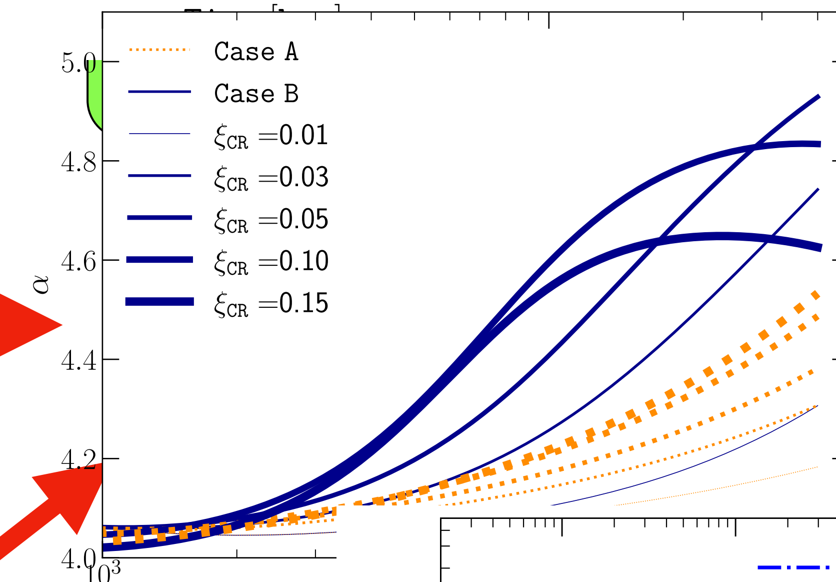
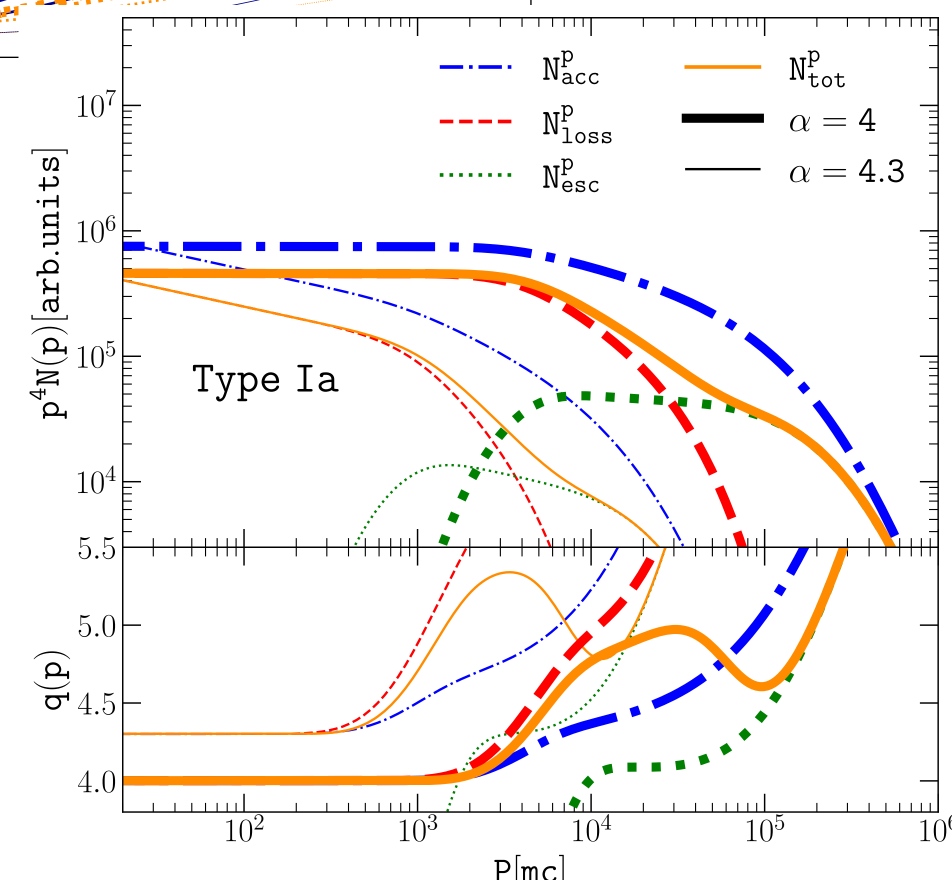


Cumulative spectra (losses)



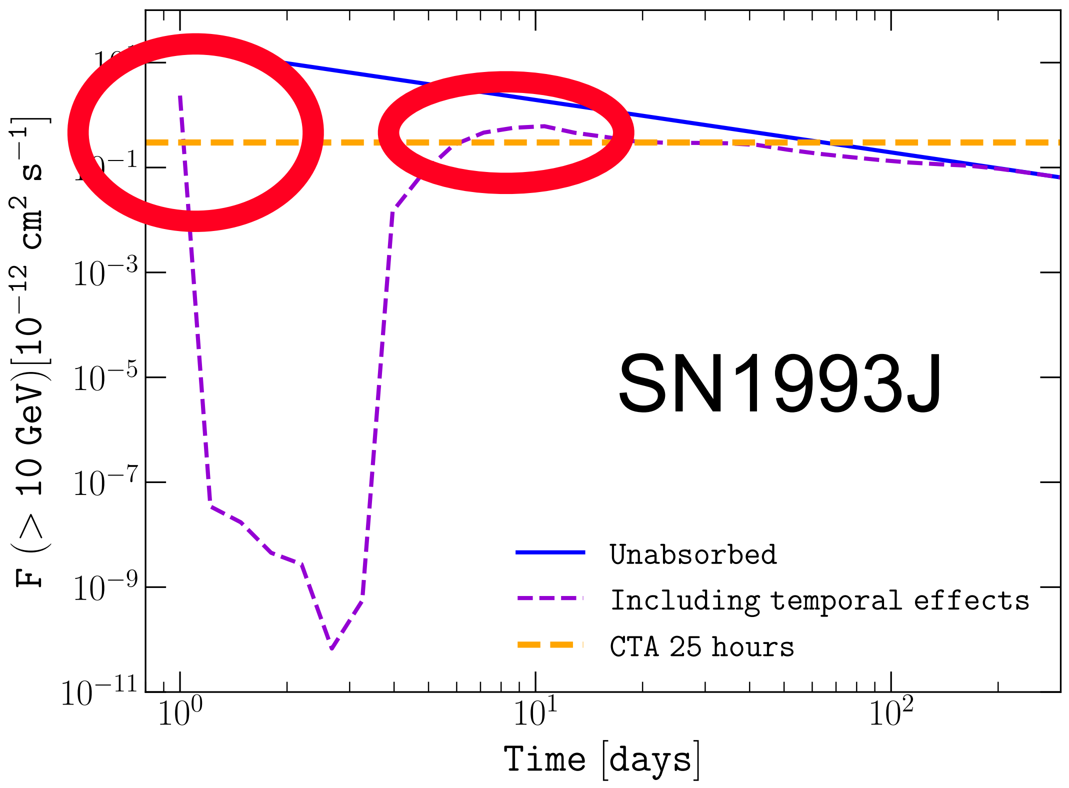
Early times!

t

Conclusions: particle acceleration at supernovae (gamma-ray domain CTA?)

1. Slope of accelerated particles?
2. Maximum energy?
3. Efficiency?
4. Magnetic field?

Early times to get rid of cumulative effects



Conclusions: particle acceleration at supernovae (gamma-ray domain CTA?)

1. **Slope of accelerated particles?**
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