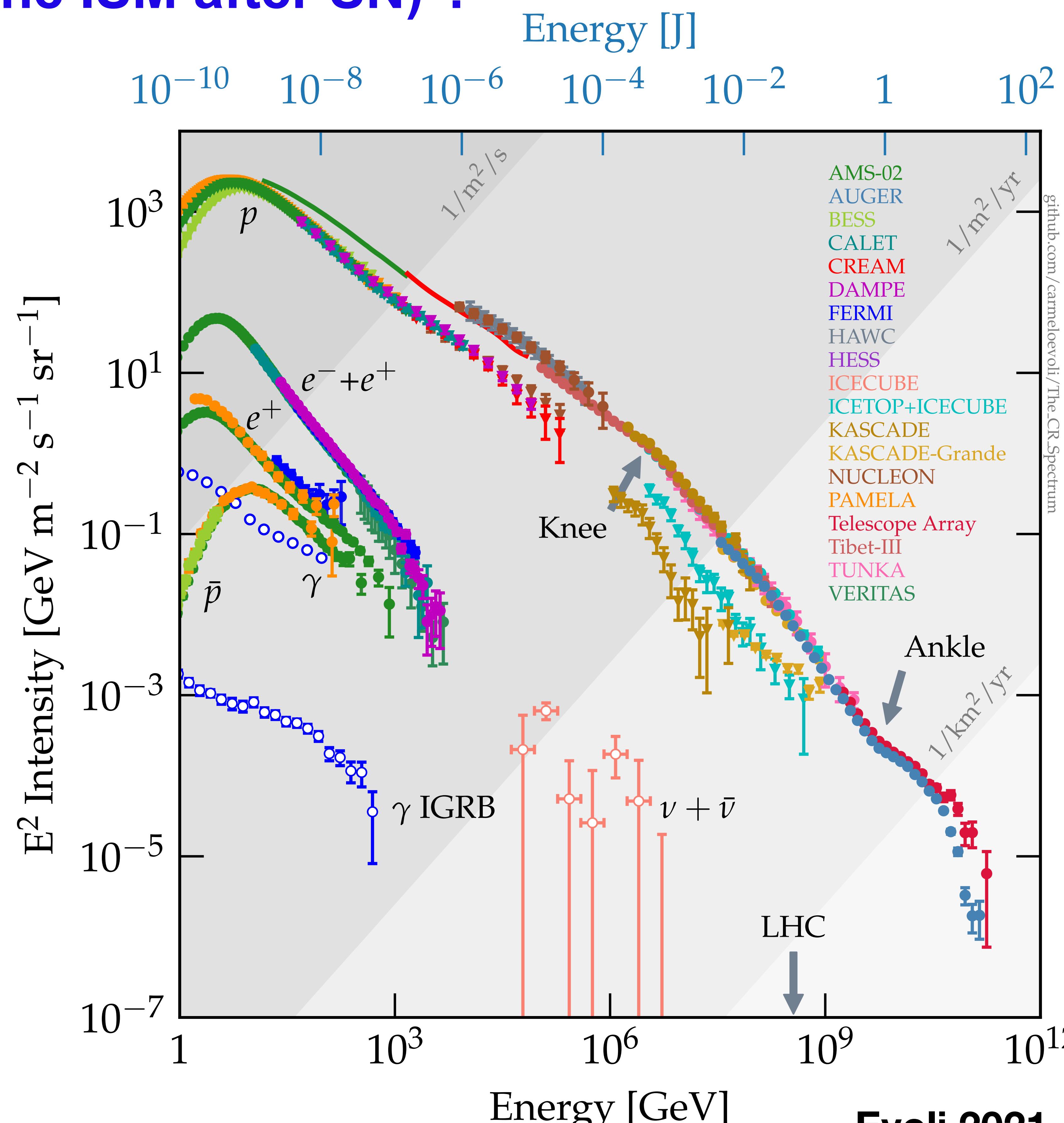
PARTICLE ACCELERATION AT SUPERNOVA REMNANTS: WHERE WE STAND AND WHERE WE GO

Pierre Cristofari

June 28th 2022
EAS

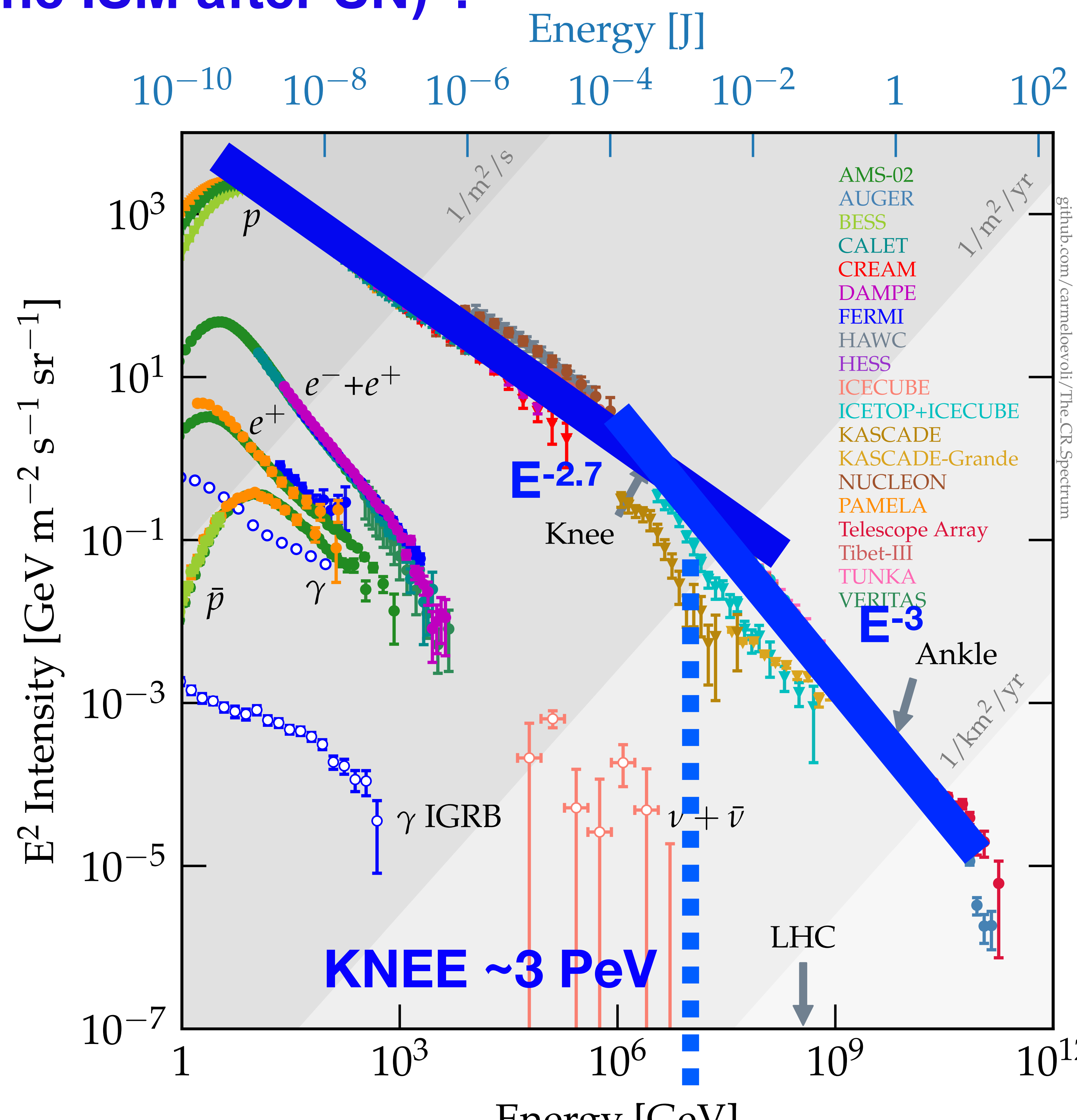
Why supernova remnants (=shock expanding in the ISM after SN) ?



Evoli 2021

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

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

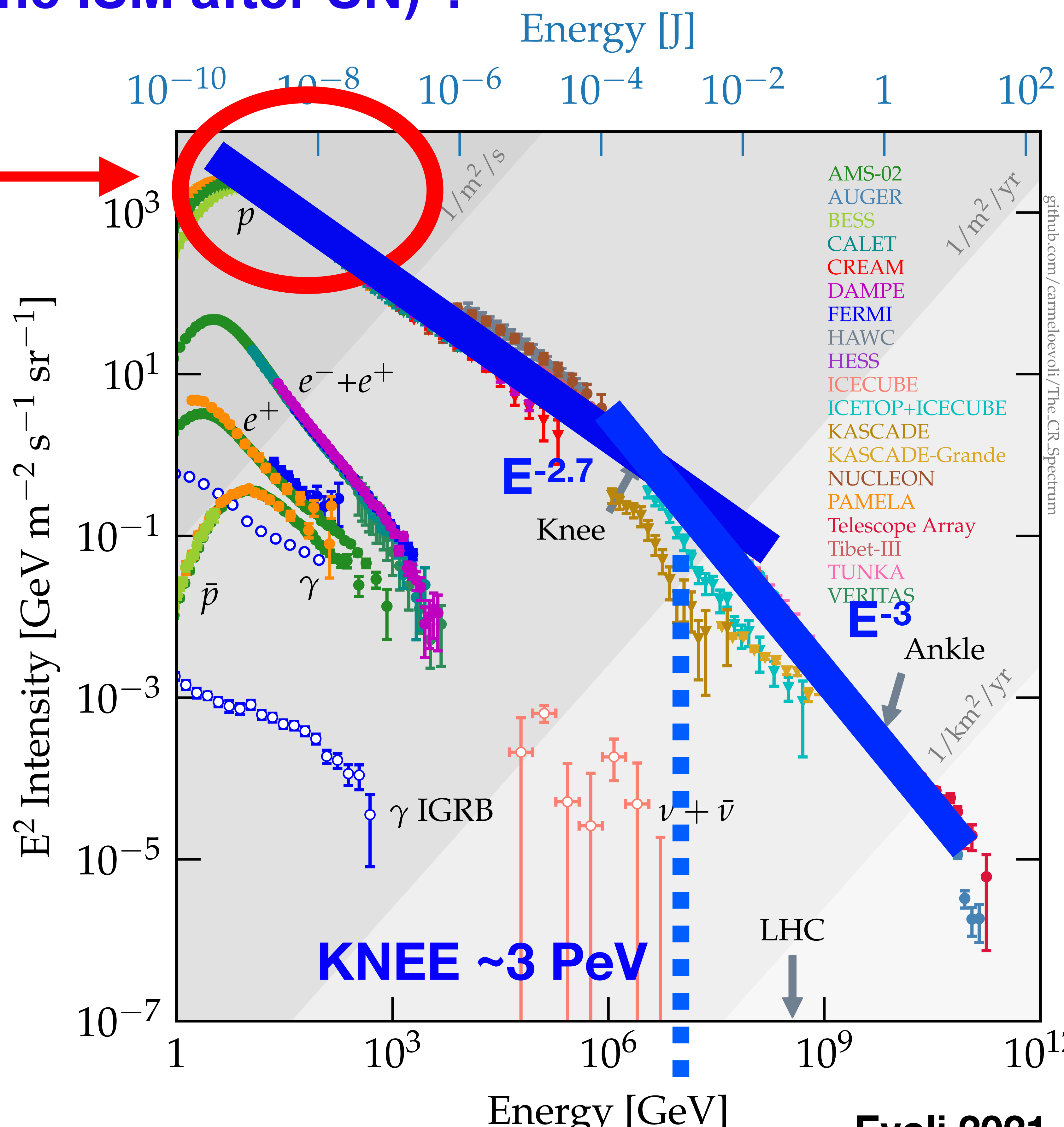


Reviews: Blasi (2013,2019)
Tatischeff & Gabici (2018)
Gabici et al. (2019)

Evoli 2021

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

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



Evoli 2021

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

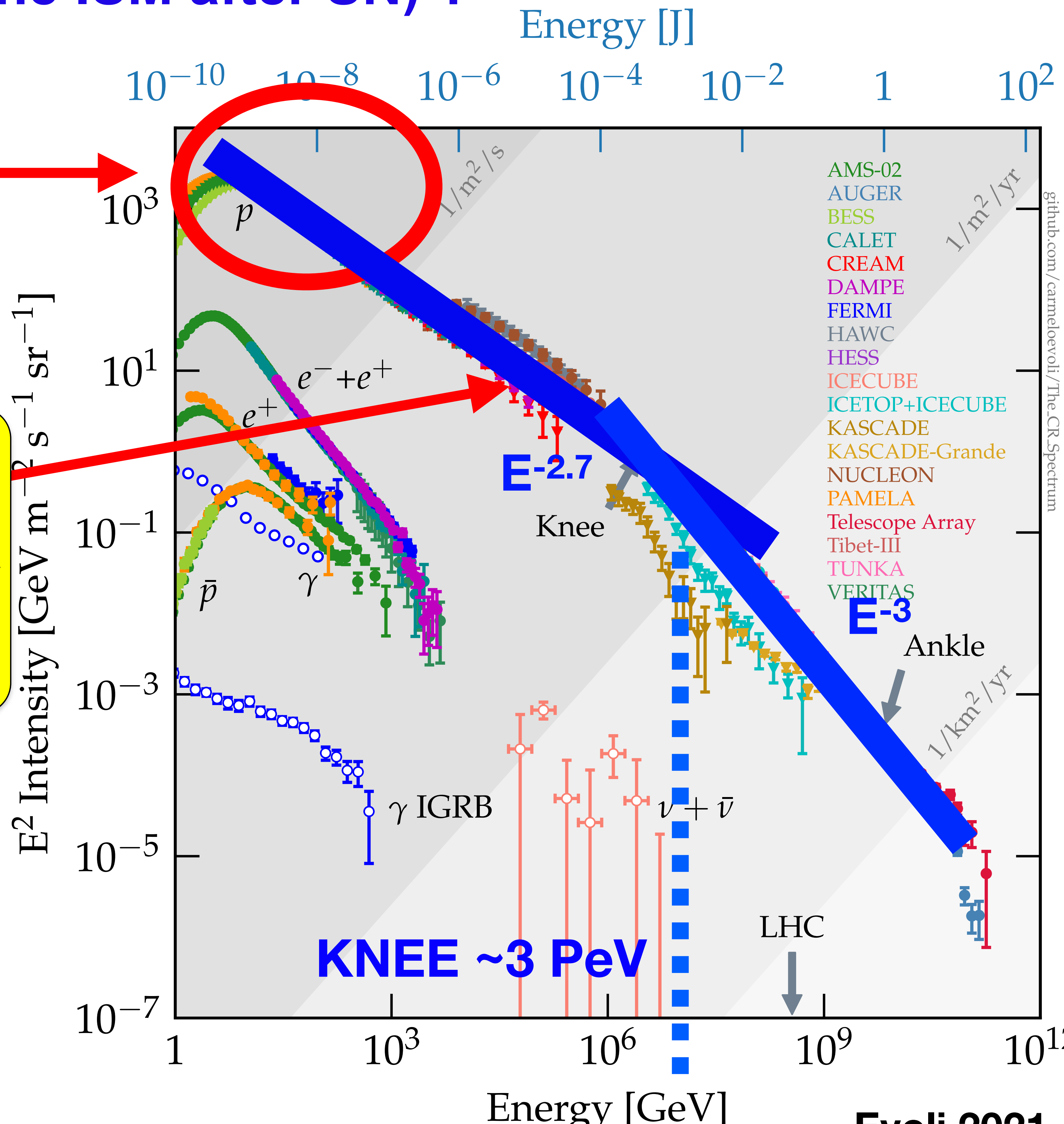
Why supernova remnants (=shock expanding in the ISM after SN) ?

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**



Evoli 2021

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

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

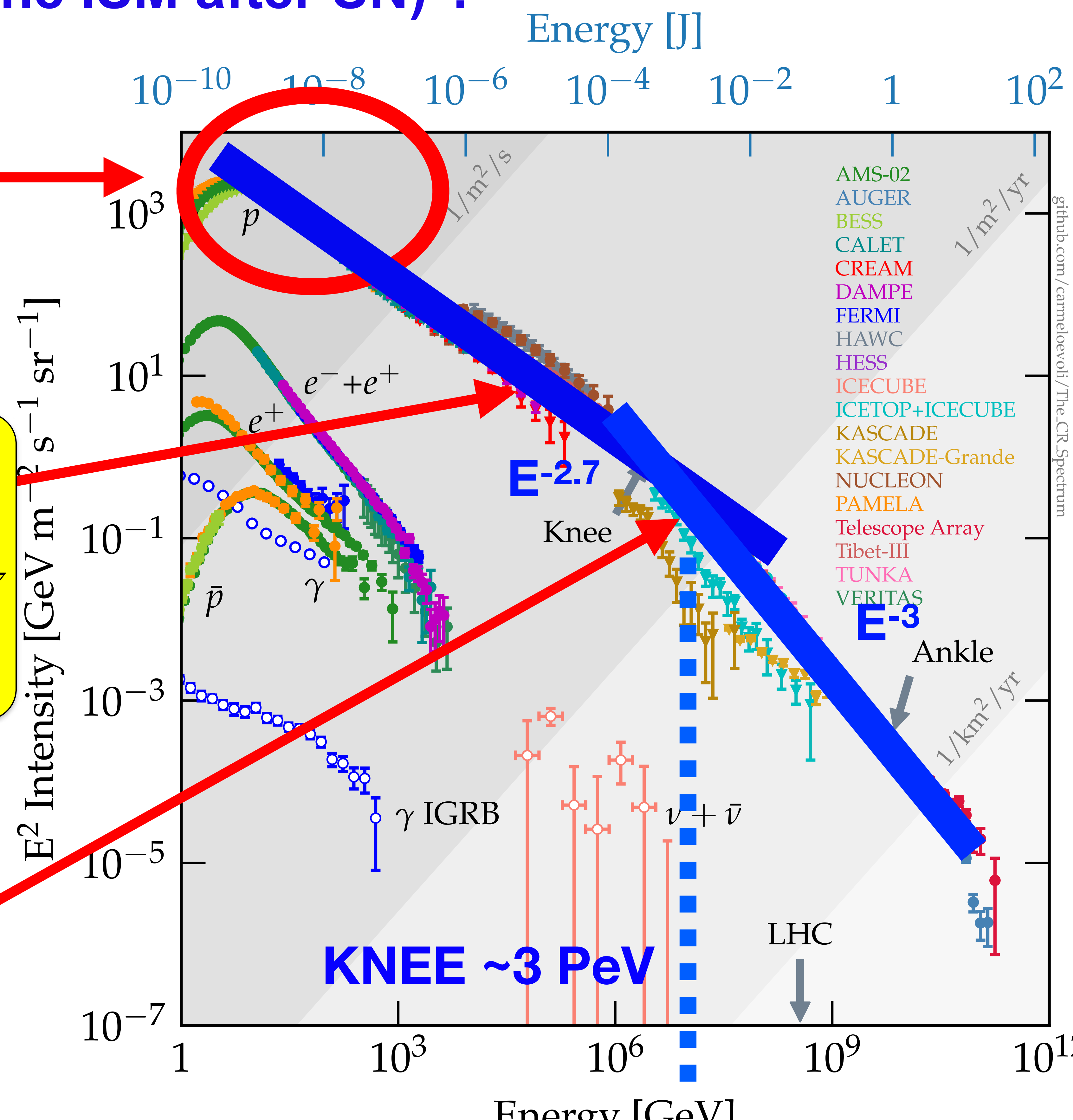
1. Bulk of CRs
Energy density ~1 eV/cm3
10% of SNR total explosion energy

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



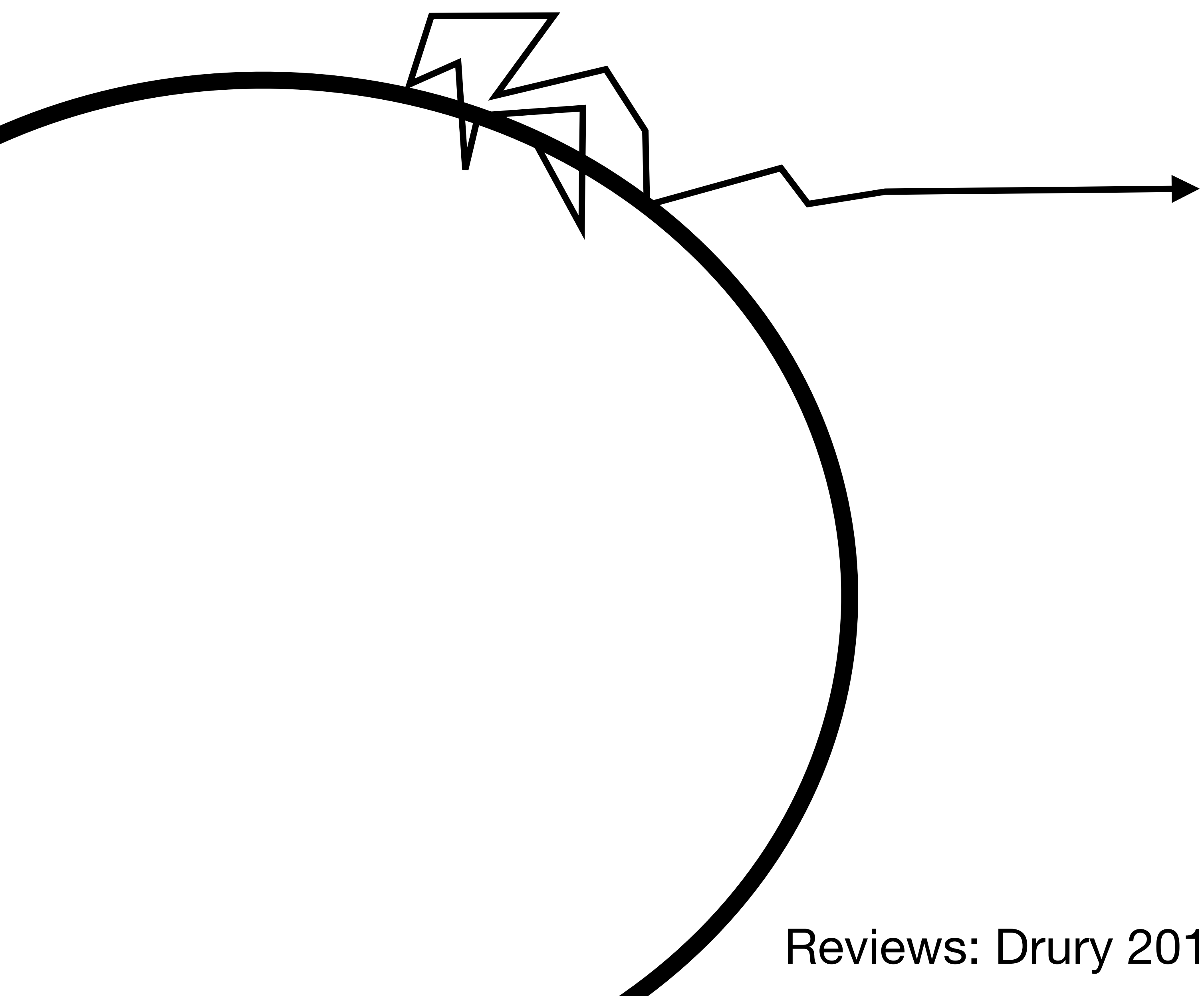
Reviews: Blasi (2013,2019)
Tatischeff & Gabici (2018)
Gabici et al. (2019)

Evoli 2021

What we know: the general picture

1. Strong collision-less non-relativistic shock wave: diffusive shock acceleration

$$\mathcal{M} >> 1$$
$$r = 4$$



Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

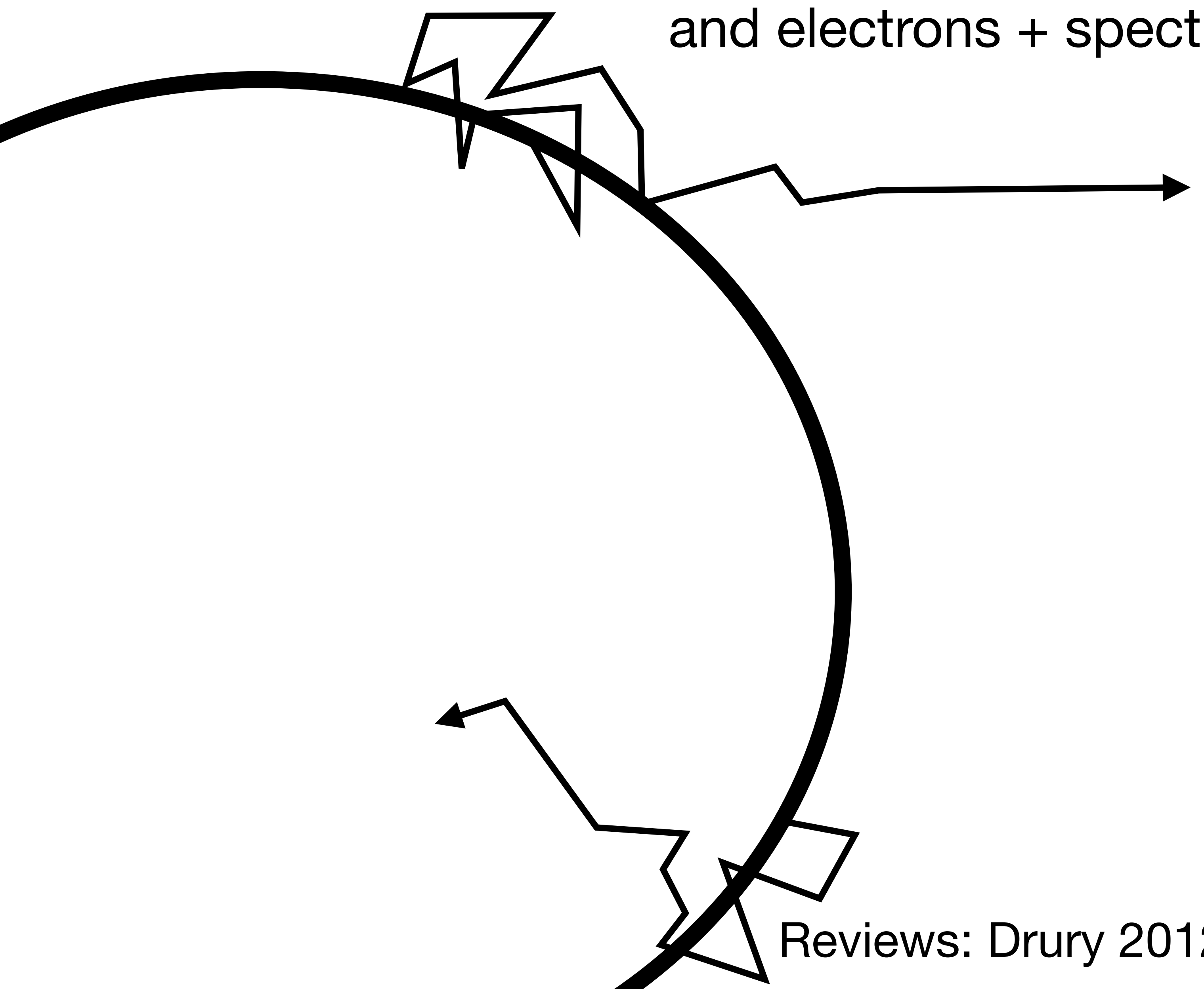
What we know: the general picture

1. Strong collision-less non-relativistic shock wave: diffusive shock acceleration

$$\mathcal{M} >> 1$$
$$r = 4$$

2. Acceleration of protons and electrons + spectra

$$f(p,t) \propto p^{-4} \propto E^{-2}$$
$$\xi_{\rm CR} \sim 1 - 10\%$$



Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

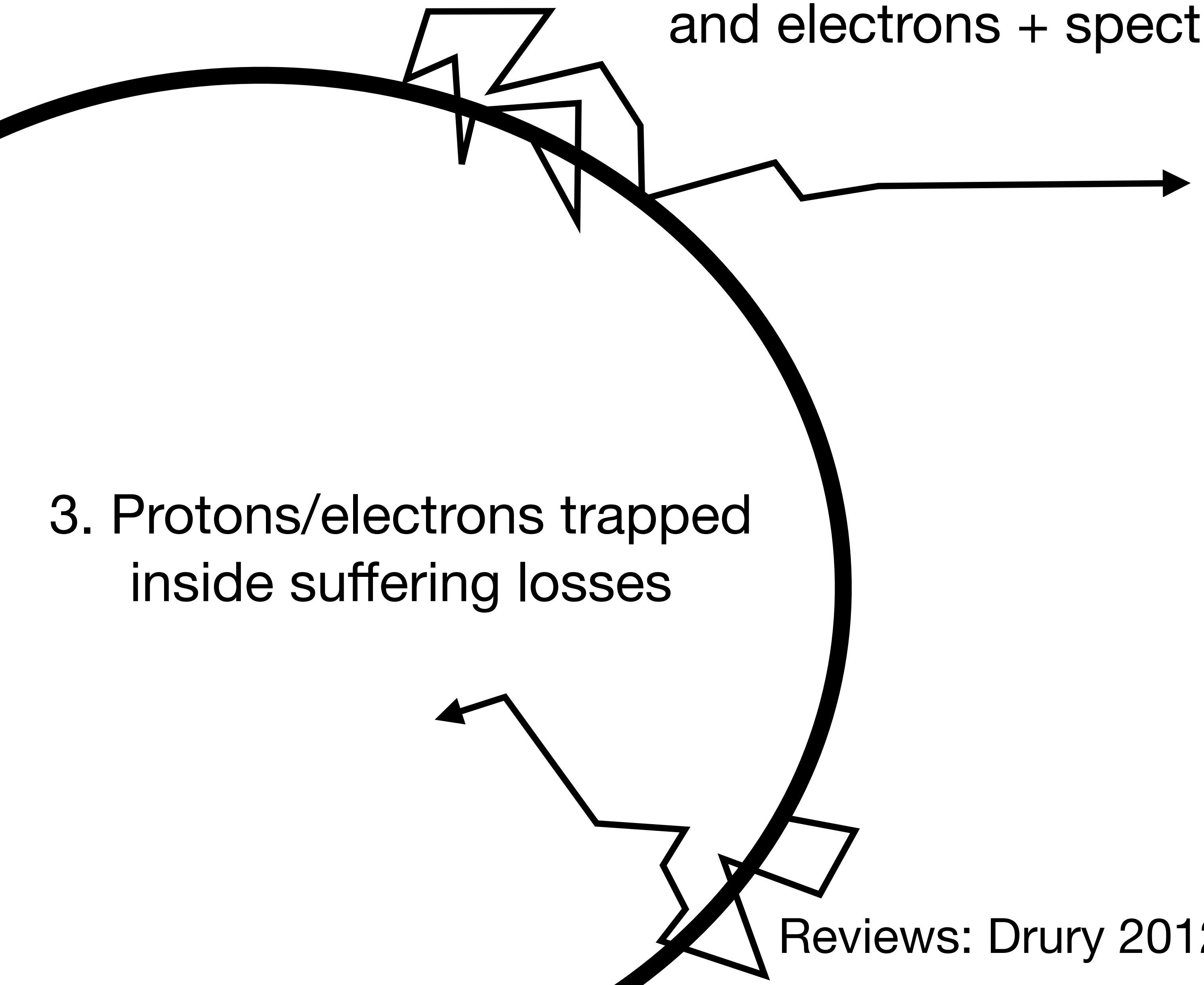
What we know: the general picture

1. Strong collision-less non-relativistic shock wave: diffusive shock acceleration

$$\mathcal{M} >> 1$$
$$r = 4$$

2. Acceleration of protons and electrons + spectra

$$f(p,t) \propto p^{-4} \propto E^{-2}$$
$$\xi_{\rm CR} \sim 1 - 10\%$$



3. Protons/electrons trapped inside suffering losses

Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

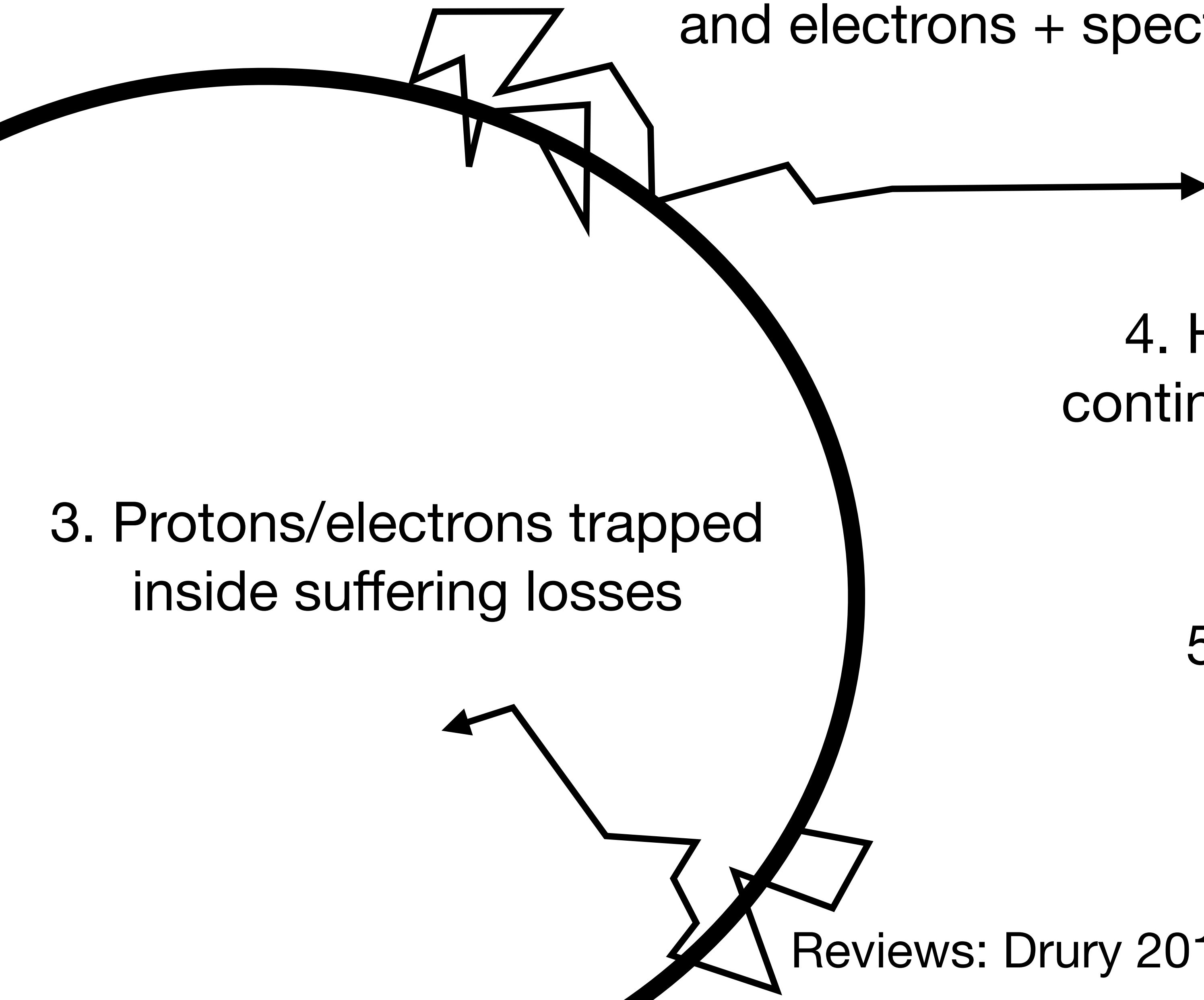
What we know: the general picture

1. Strong collision-less non-relativistic shock wave: diffusive shock acceleration

$$\mathcal{M} >> 1$$
$$r = 4$$

2. Acceleration of protons and electrons + spectra

$$f(p,t) \propto p^{-4} \propto E^{-2}$$
$$\xi_{\rm CR} \sim 1 - 10\%$$

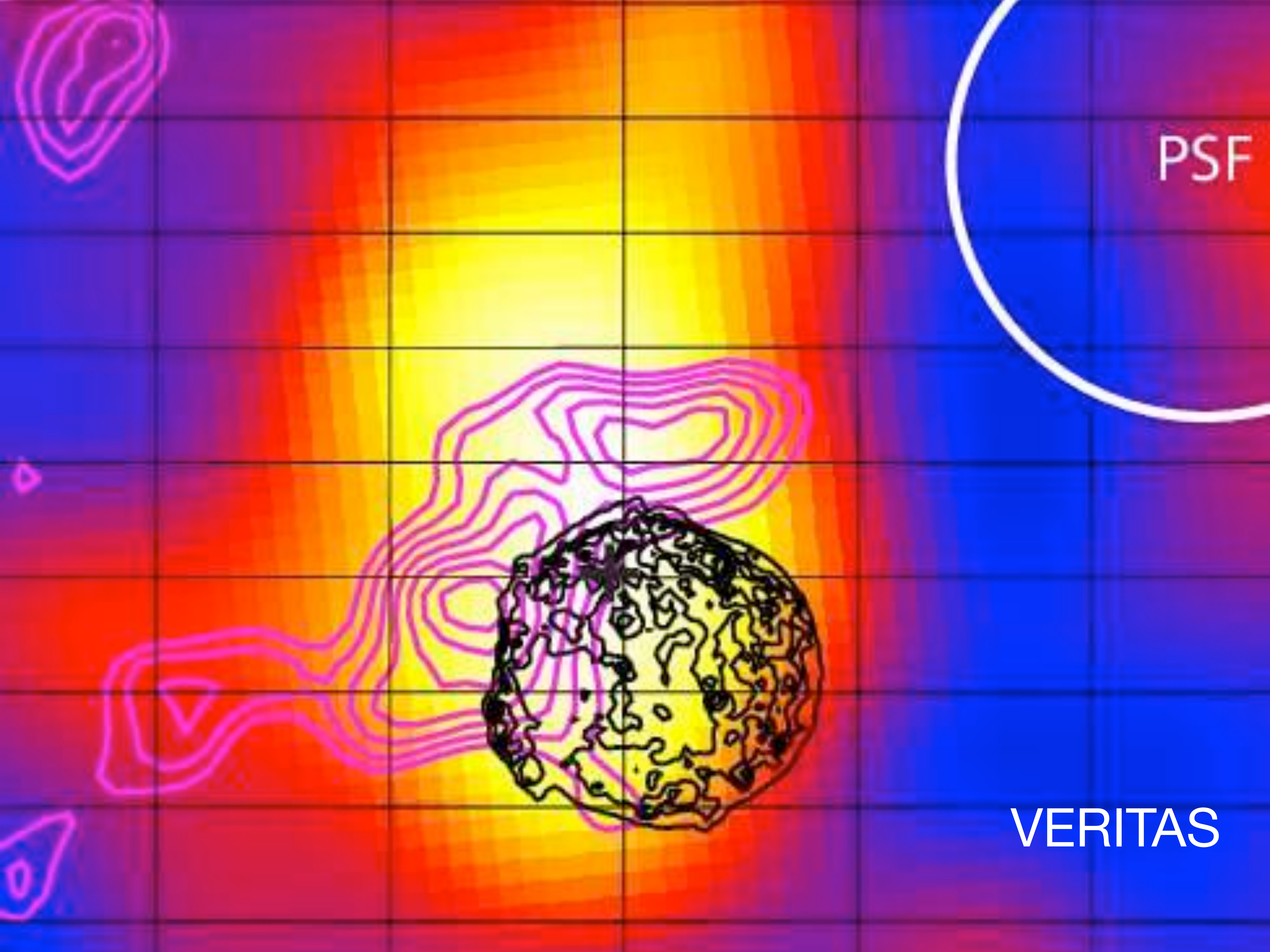


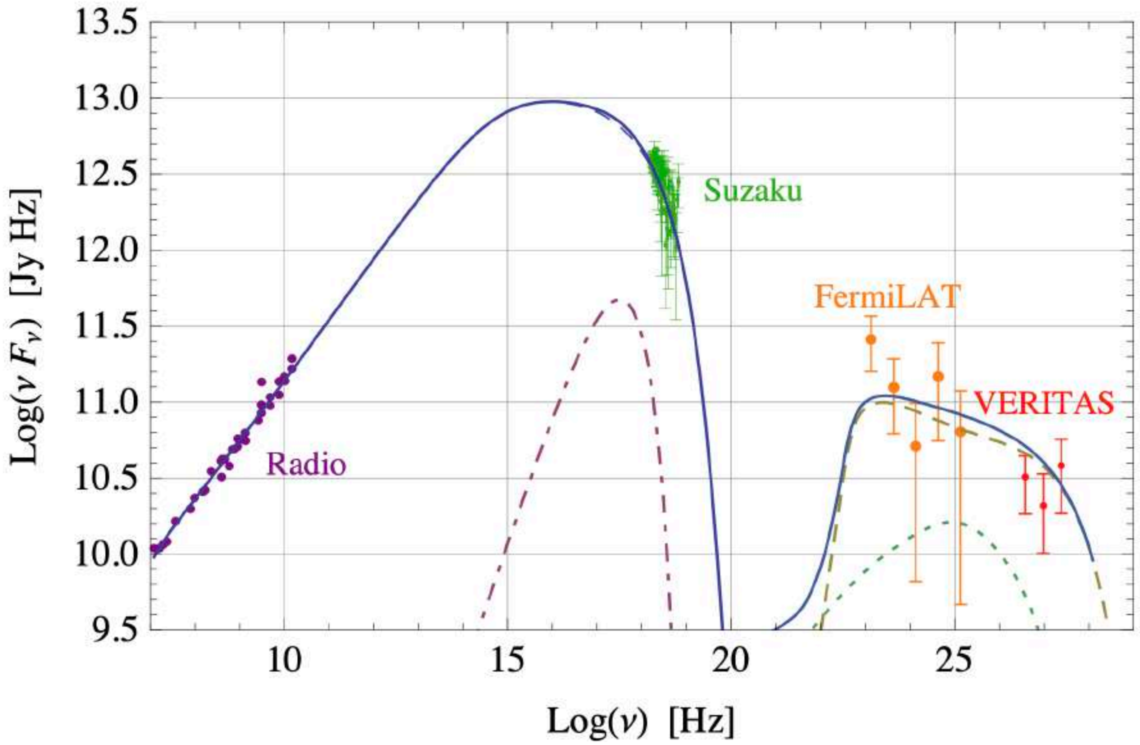
4. High momenta particles continuously escaping the SNR

3. Protons/electrons trapped inside suffering losses

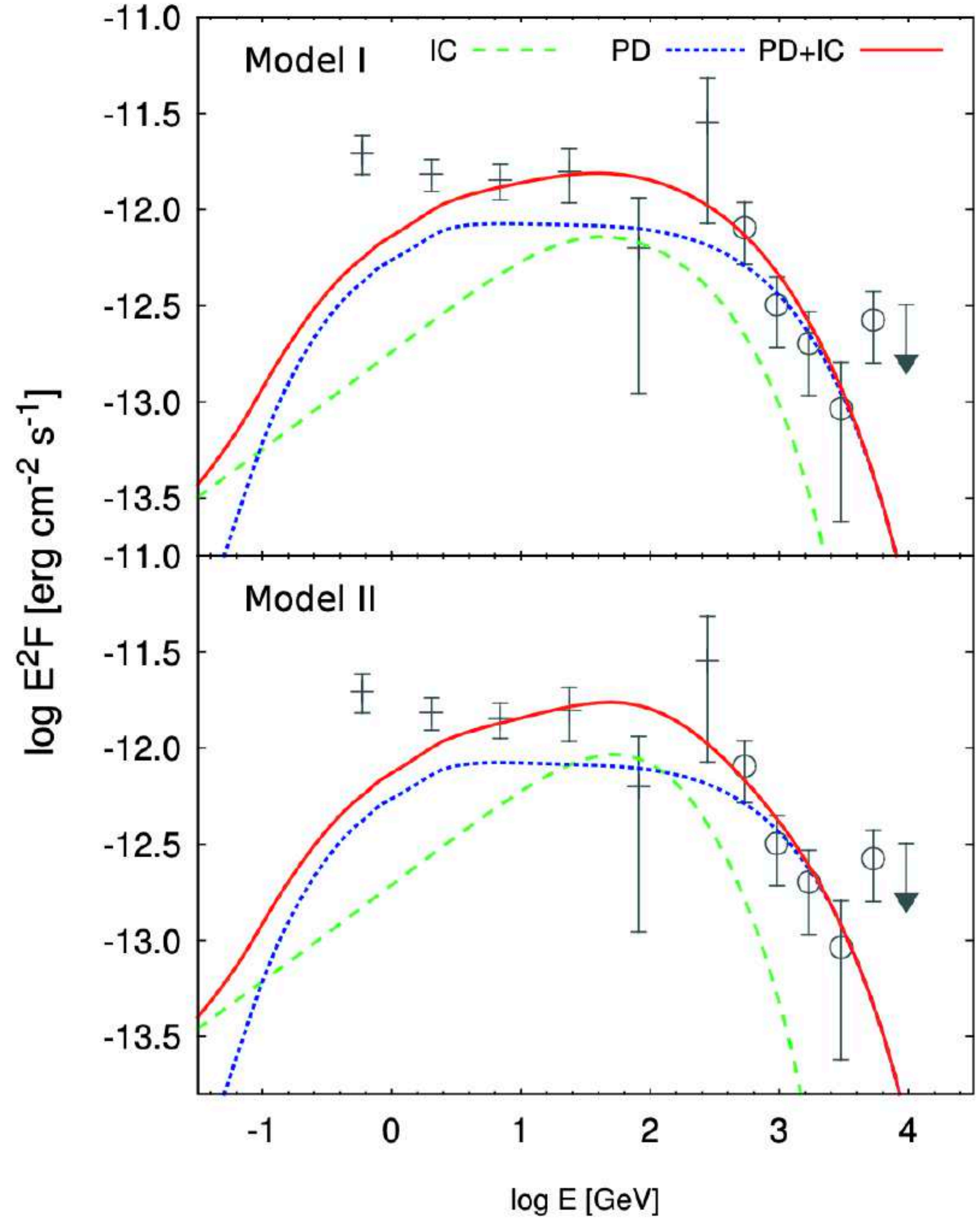
5. Magnetic field amplification to reach the PeV range

Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

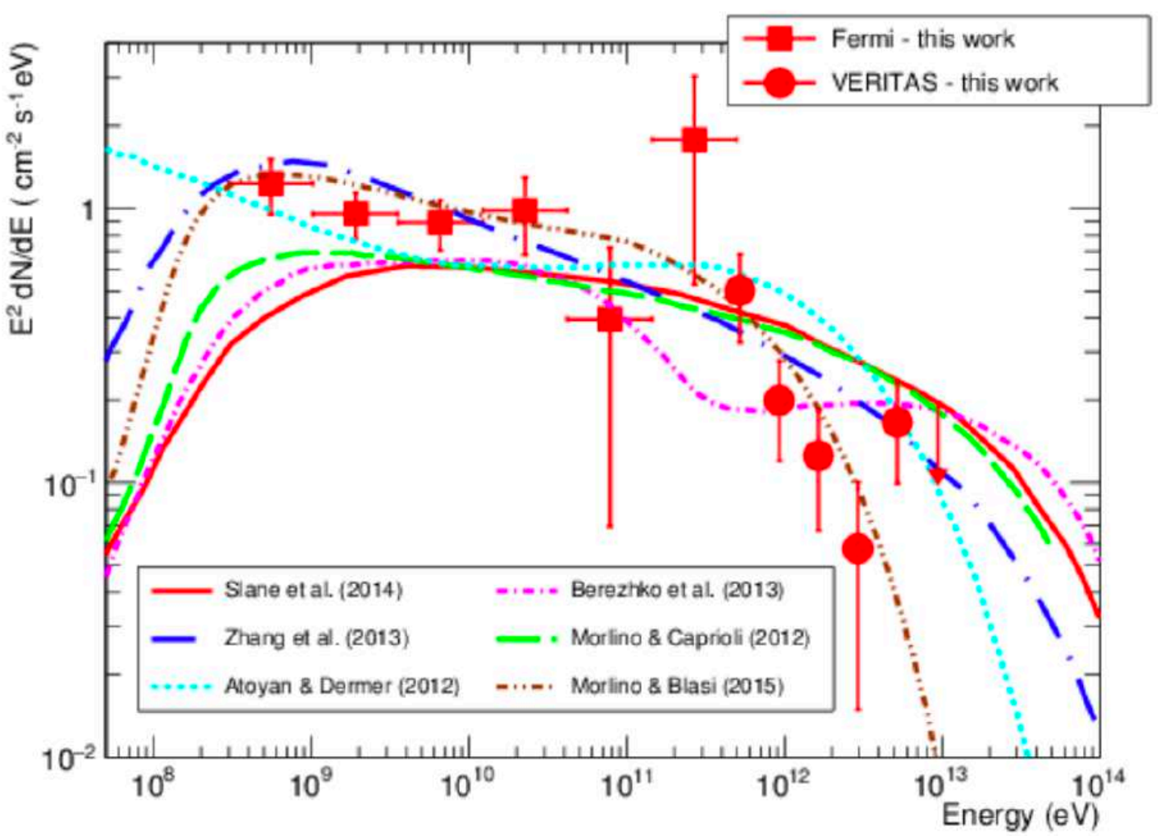

PSF
VERITAS



Morlino & Caprioli 2012



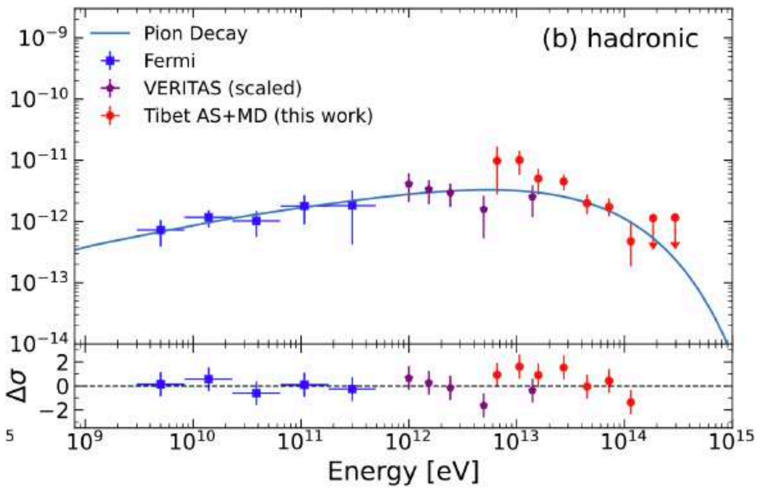
Wilhelm et al. 2020



Archambault et al. 2017

What is wrong?

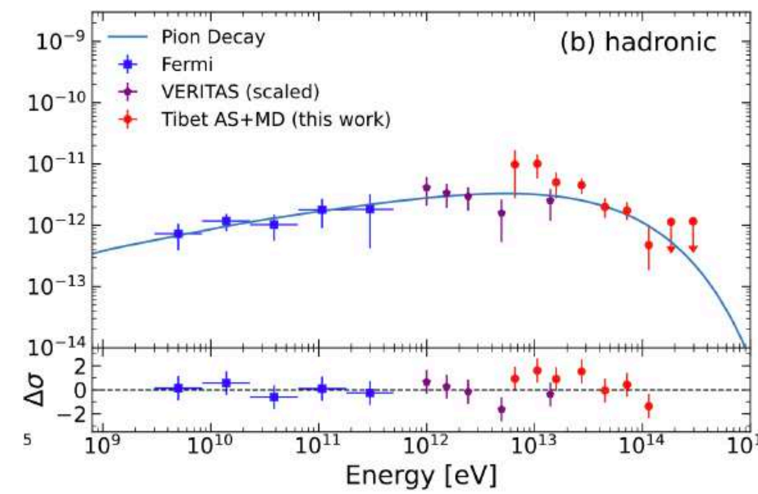
1. All SNRs seem to not be pevatrons



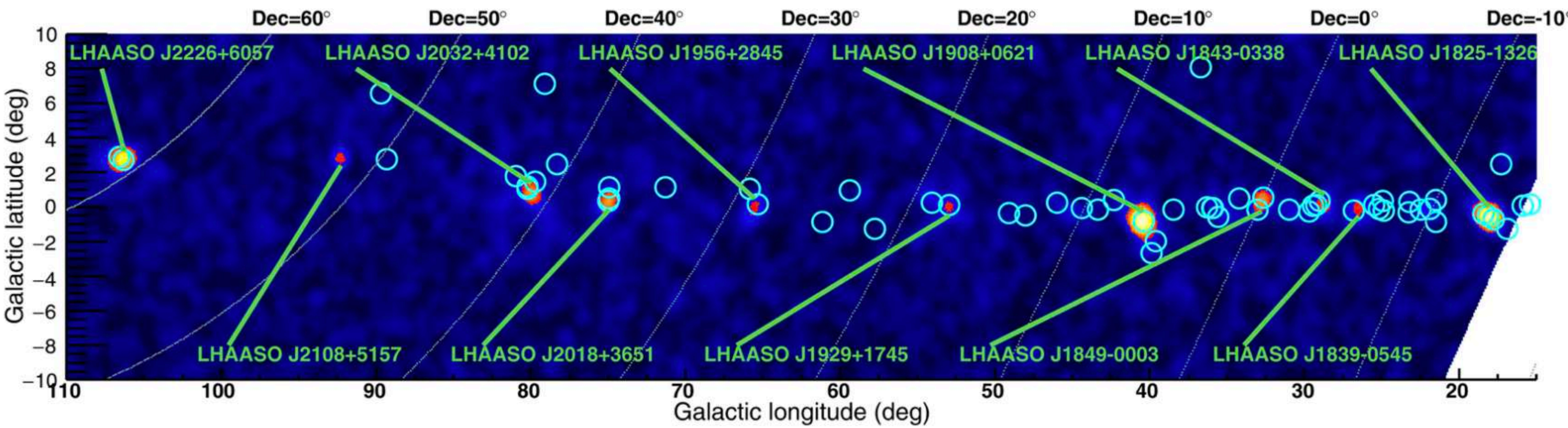
SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)

What is wrong?

1. All SNRs seem to not be pevatrons



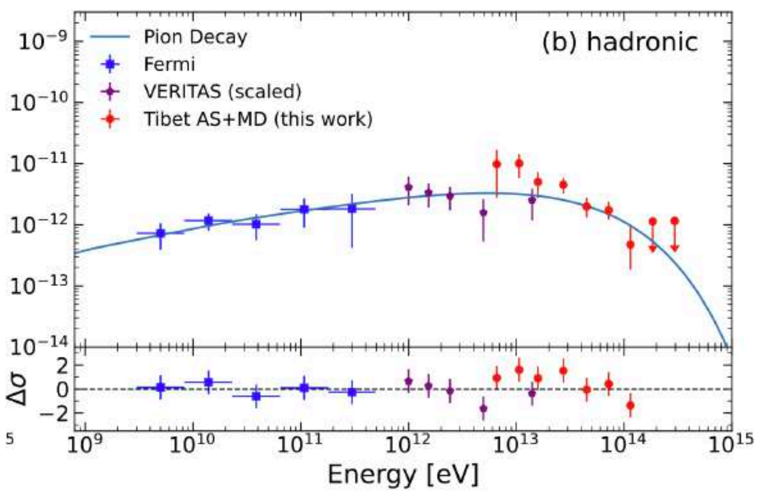
SNR G106.3+ 2.7
HAWC 2020
Tibet (Nature 2021)



LHAASO Cao et al. (2021)

What is wrong?

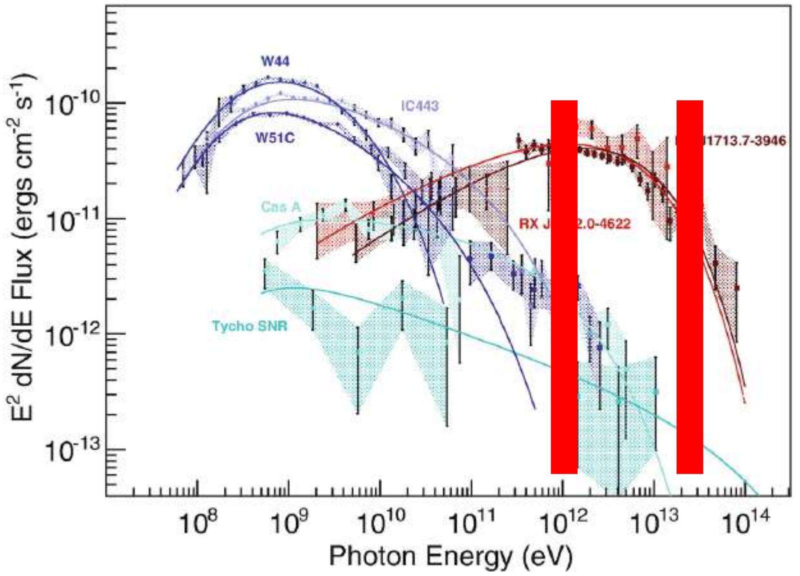
1. All SNRs seem to not be pevatrons



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

2. The slope of accelerated particles at SNR shocks

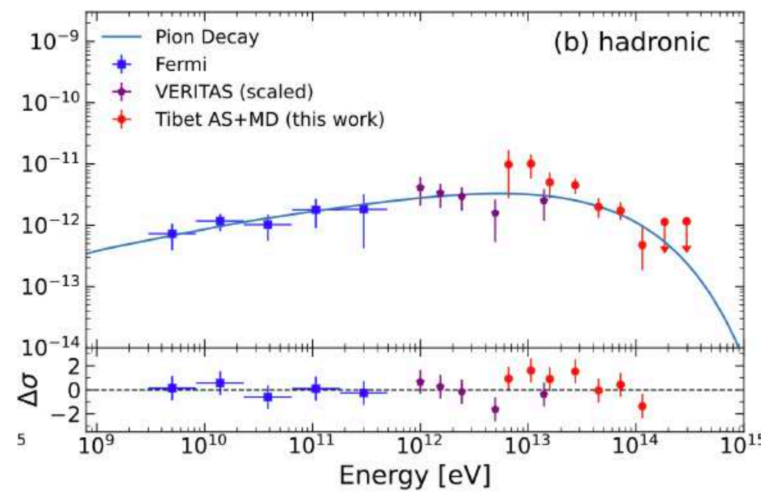
VHE domain steep spectra?



Funk (2017)

What is wrong?

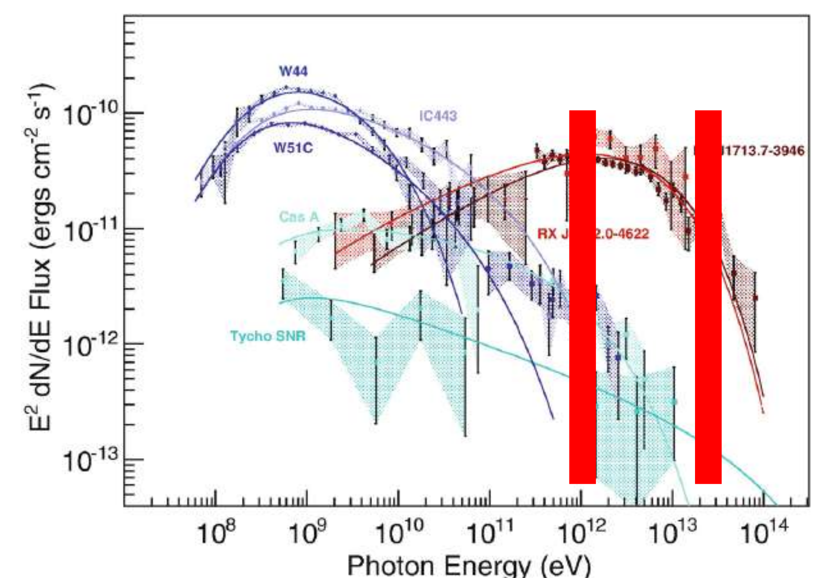
1. All SNRs seem to not be pevatrons



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

2. The slope of accelerated particles at SNR shocks

VHE domain steep spectra?

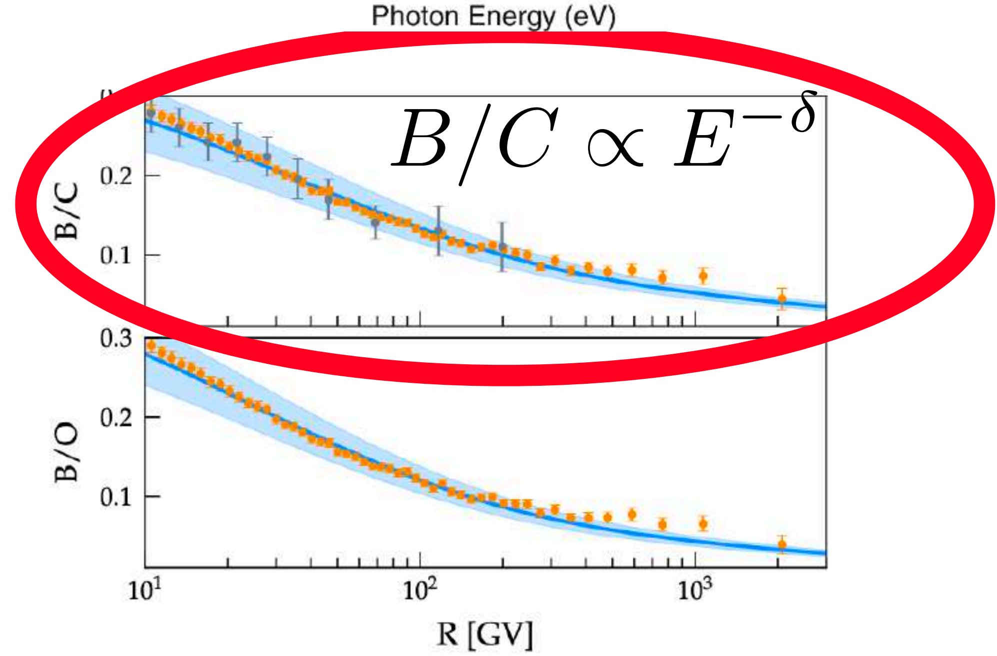


Funk (2017)

3. Particle spectra released in the ISM

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

Injection Propagation



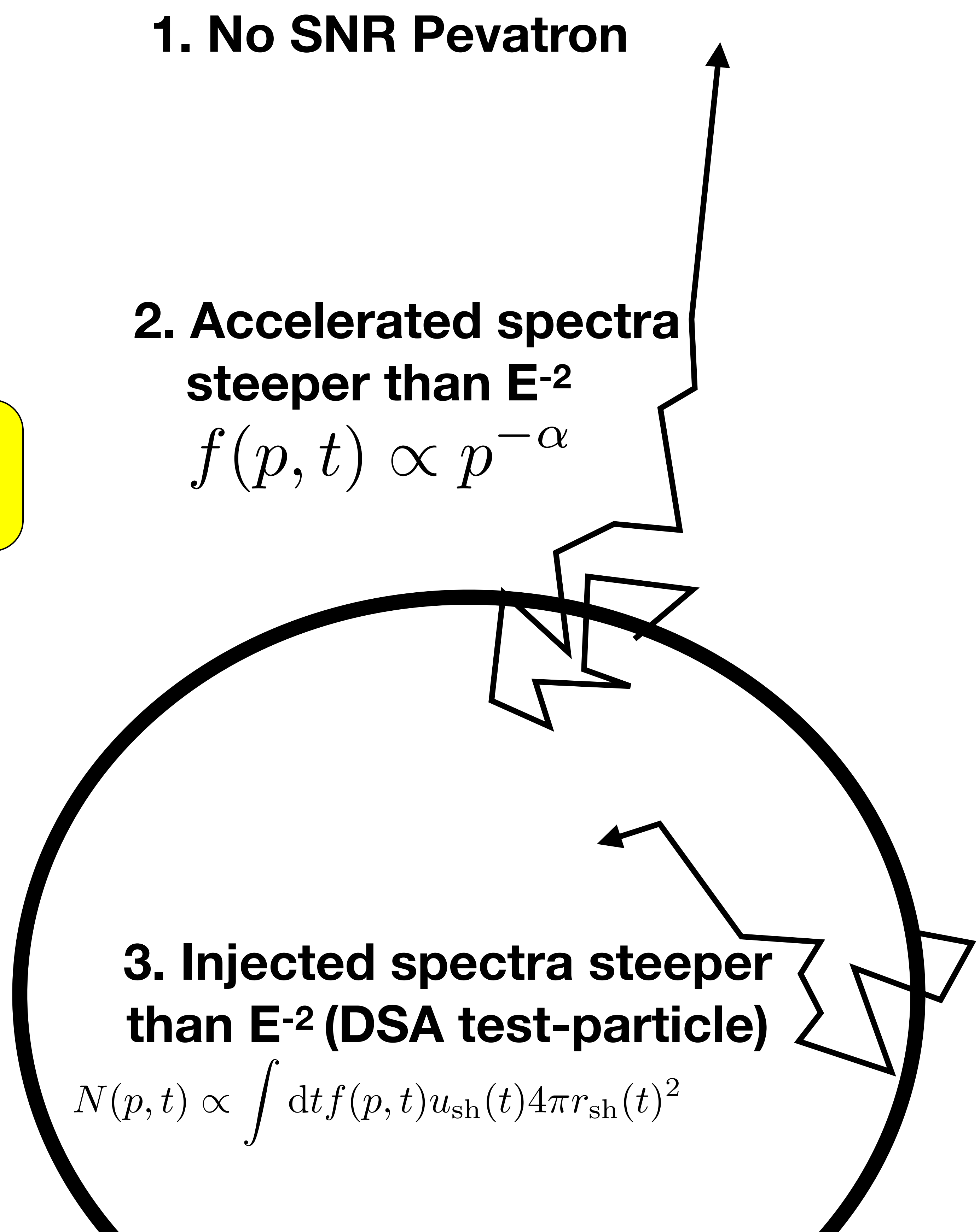
How much e/p? For how long?

Three issues

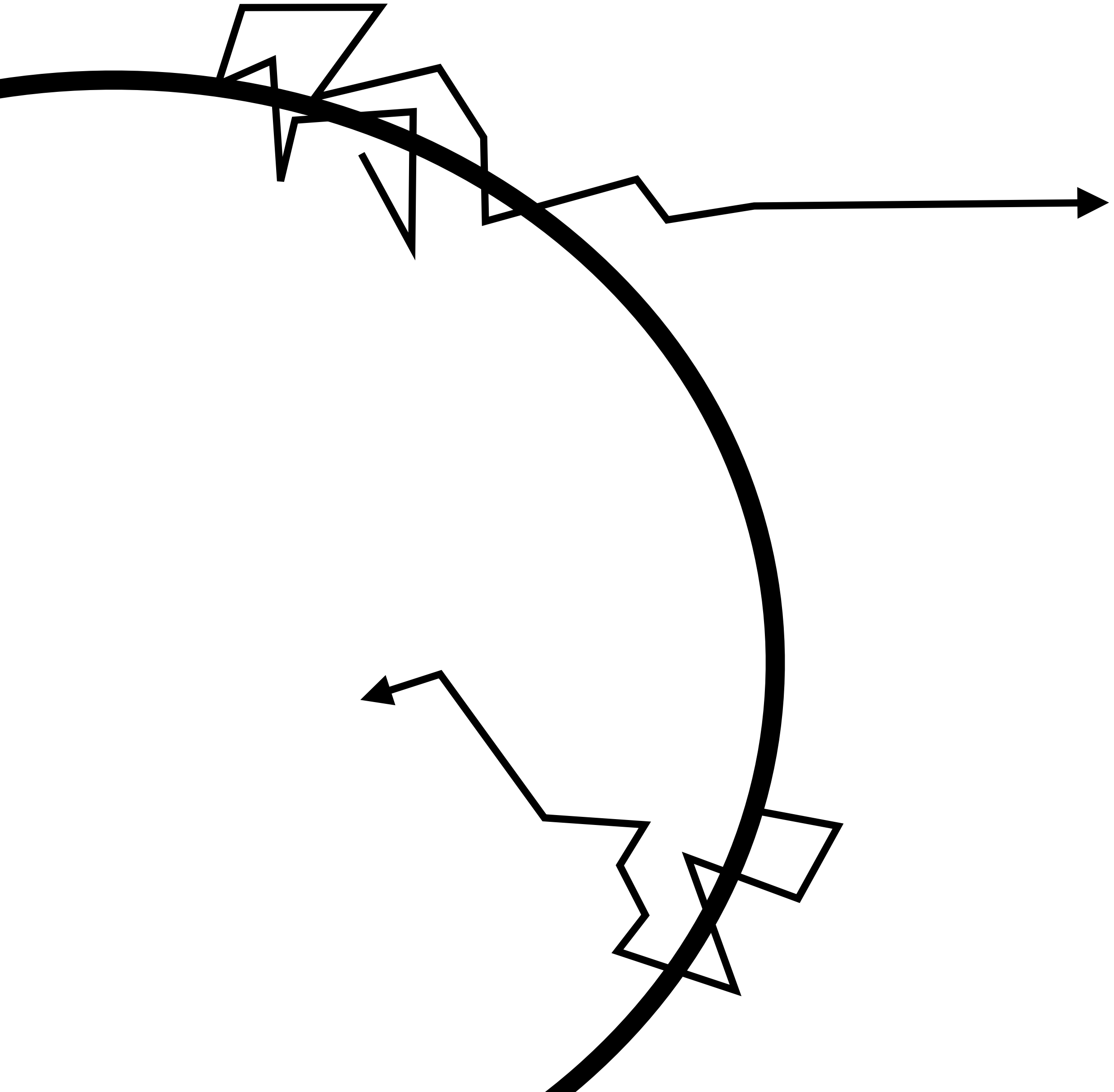
1. All SNRs seem to not be pevatrons

2. The slope of accelerated particles at SNR shocks

3. Particle spectra released in the ISM



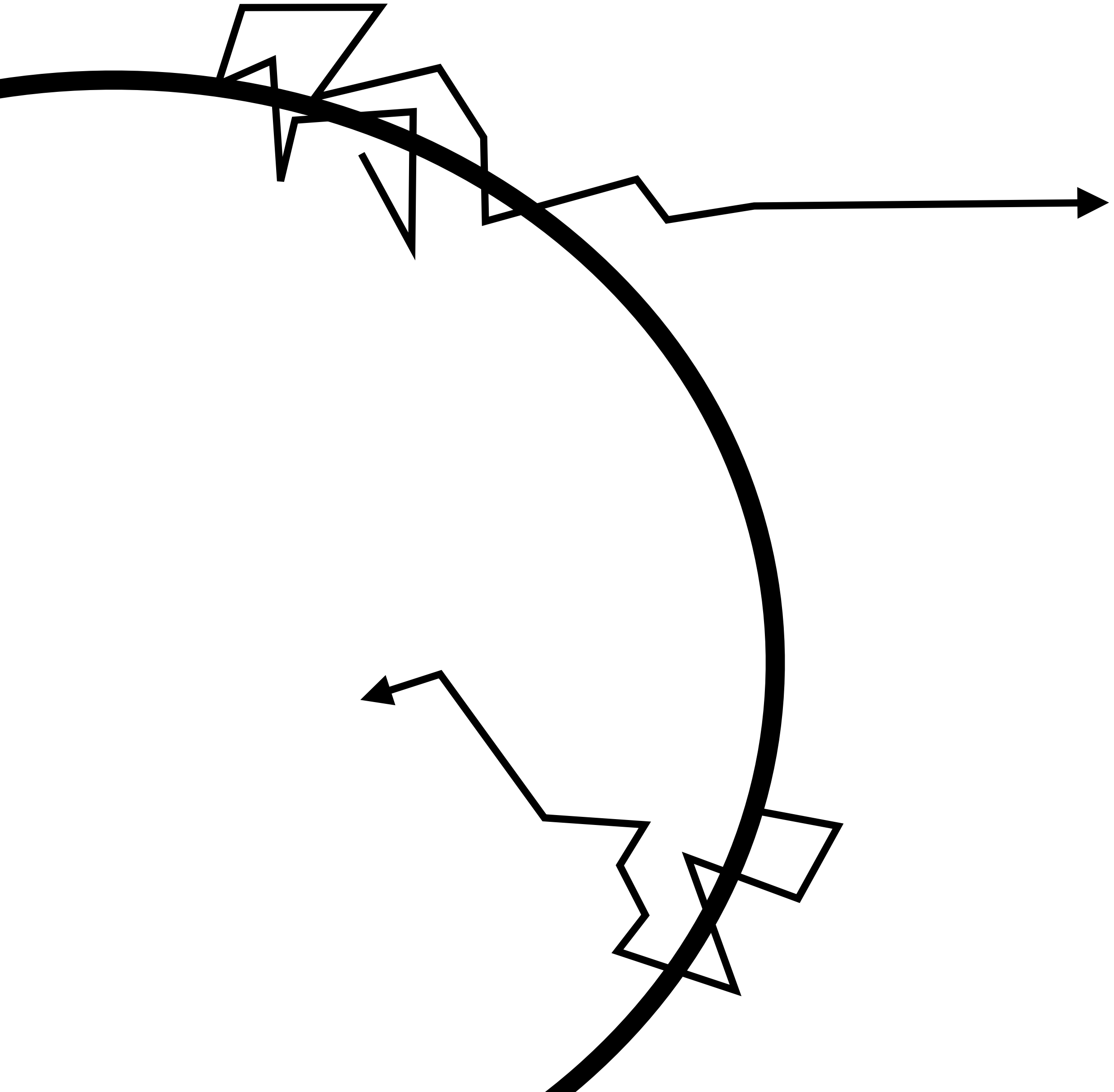
What we still don't really know



What we still don't really know

1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

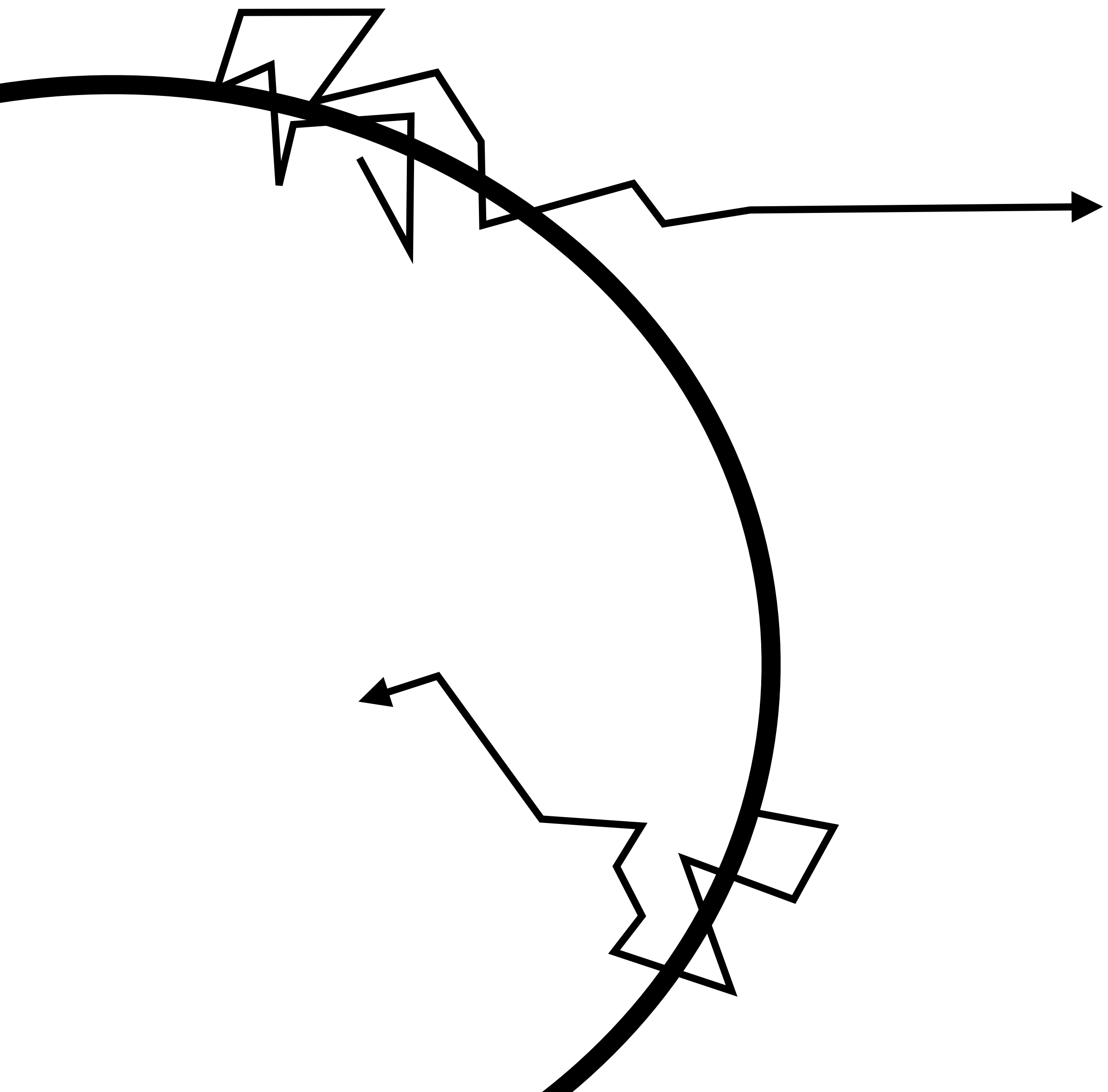


What we still don't really know

1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?



What we still don't really know

1. How are particles injected in the accelerator?

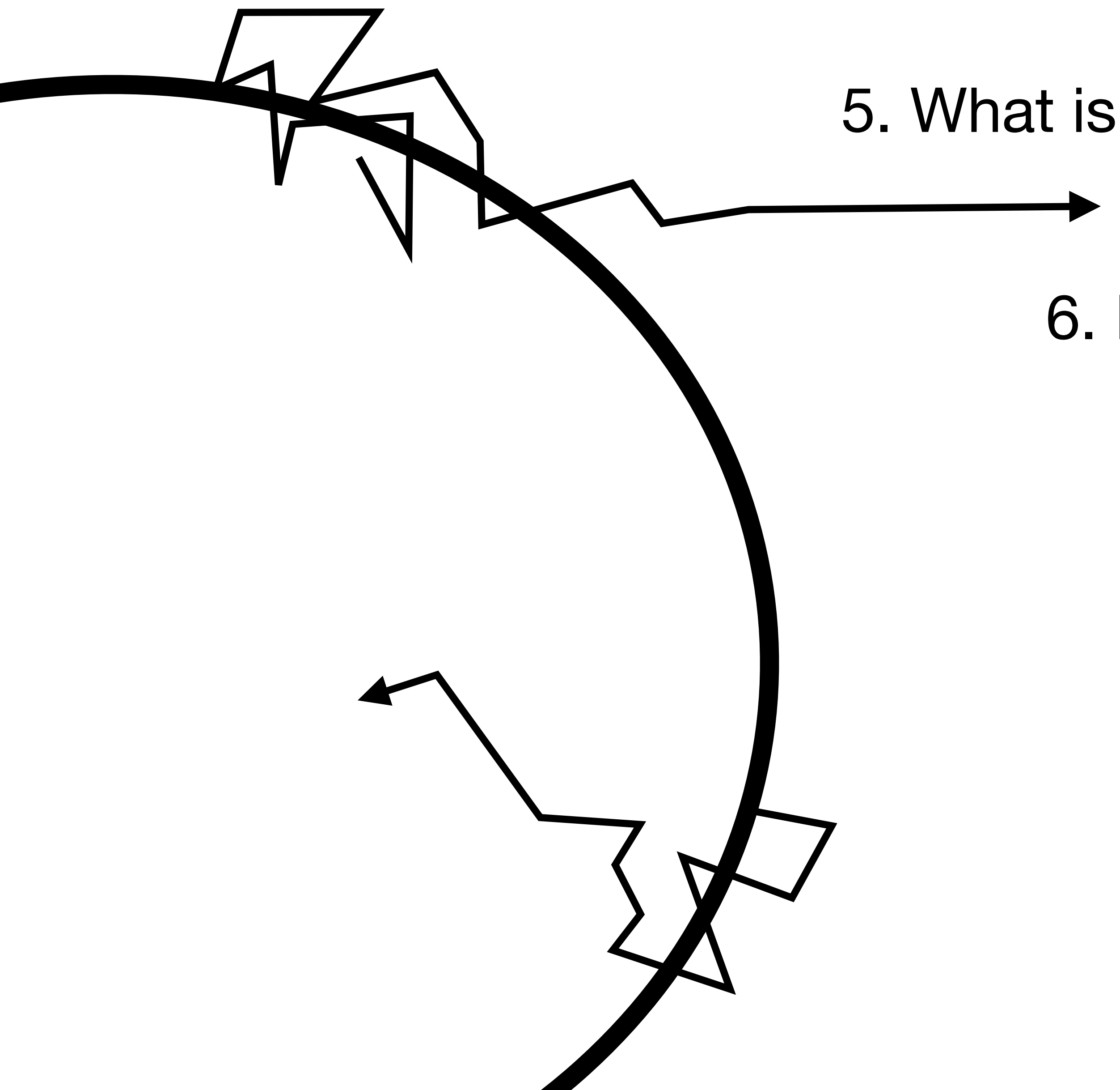
2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?

4. Protons? Electrons? Ratio?

5. What is the effect of losses on the trapped particles?

6. How long does the acceleration phase last?



What we still don't really know

1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?

4. Protons? Electrons? Ratio?

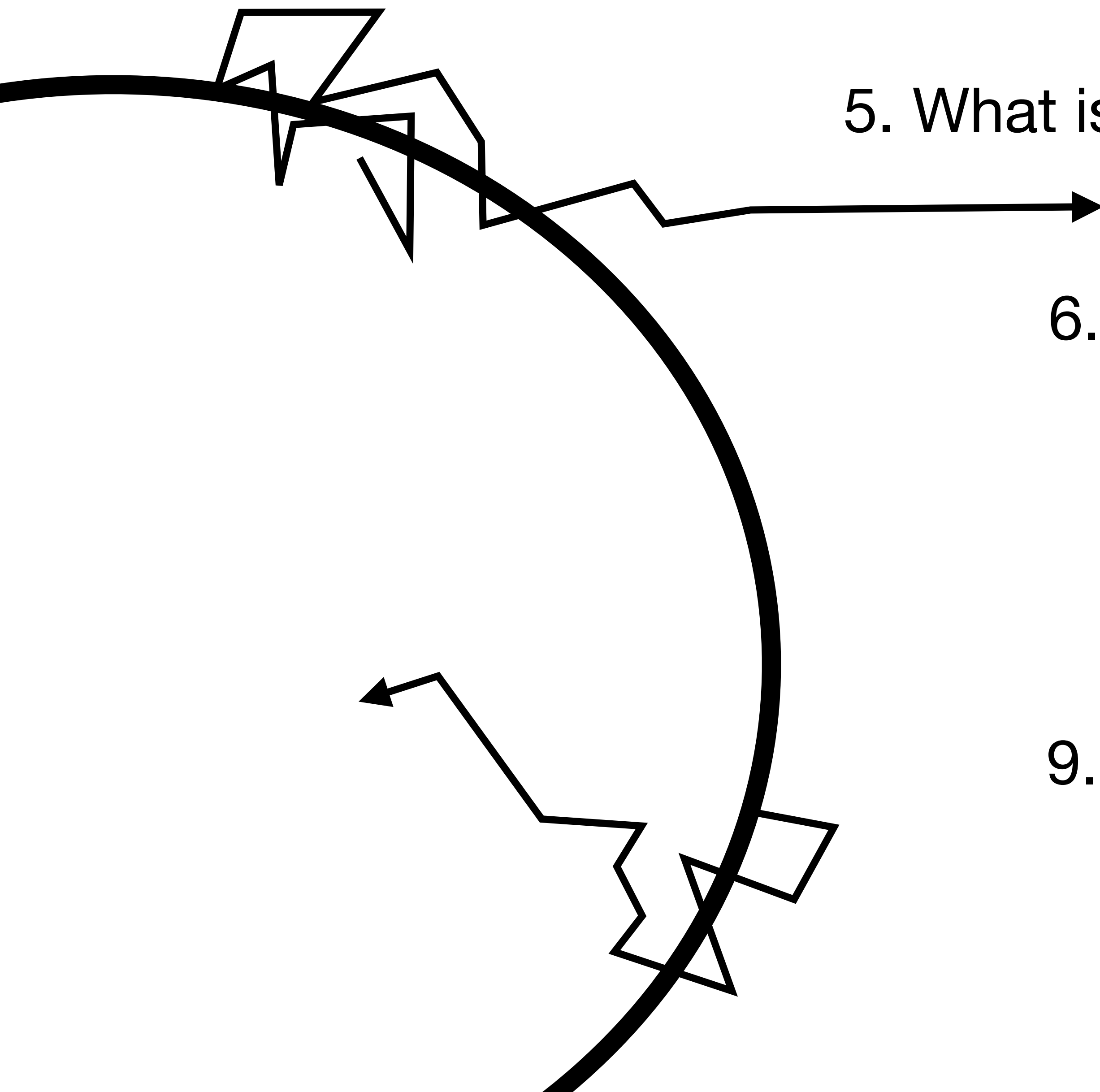
5. What is the effect of losses on the trapped particles?

6. How long does the acceleration phase last?

7. How do particles escape the SNR?

8. How is the magnetic field amplified?

9. What is the maximum energy of accelerated particles?



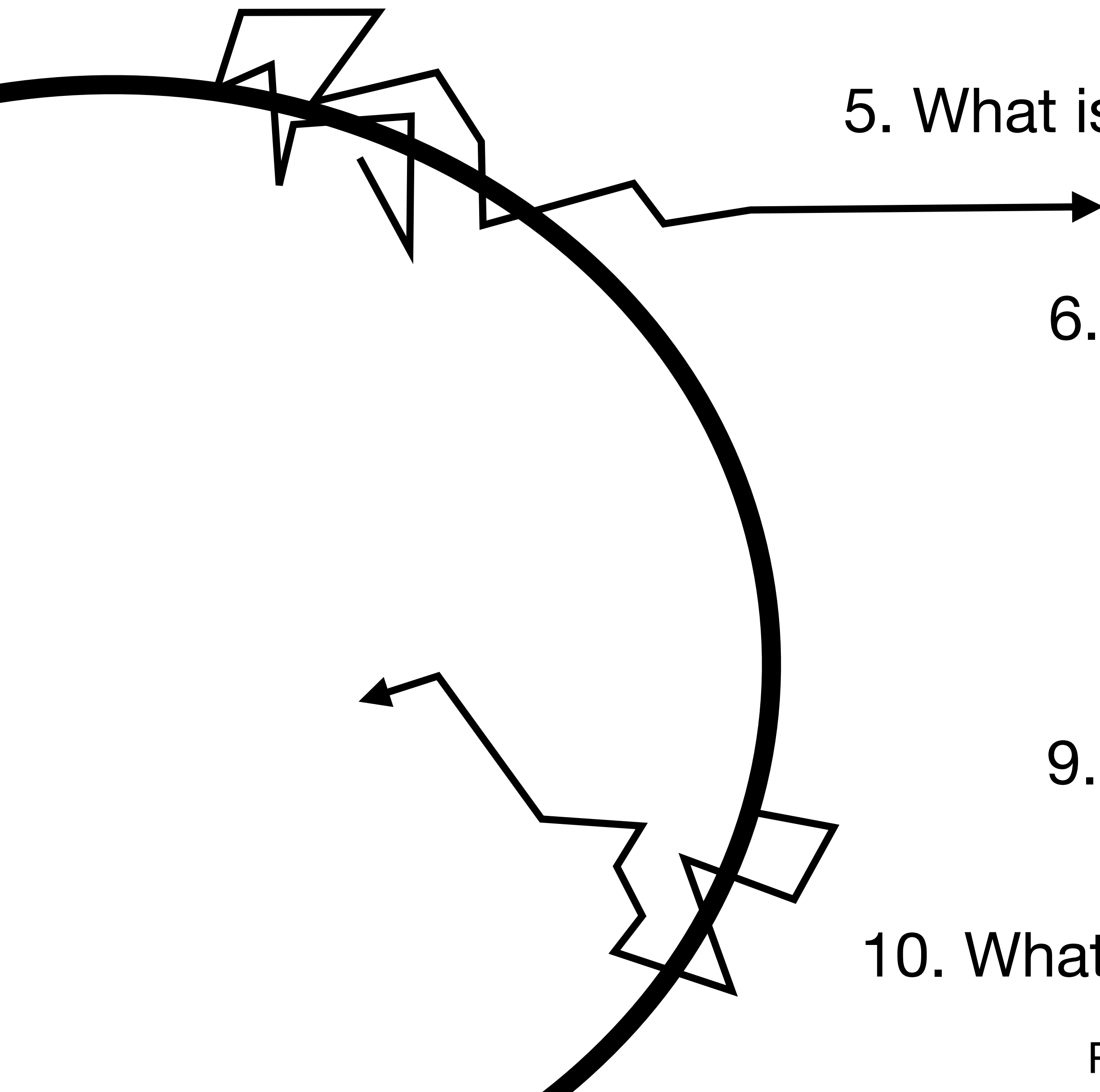
What we still don’t really know

1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?

4. Protons? Electrons? Ratio?



5. What is the effect of losses on the trapped particles?

6. How long does the acceleration phase last?

7. How do particles escape the SNR?

8. How is the magnetic field amplified?

9. What is the maximum energy of accelerated particles?

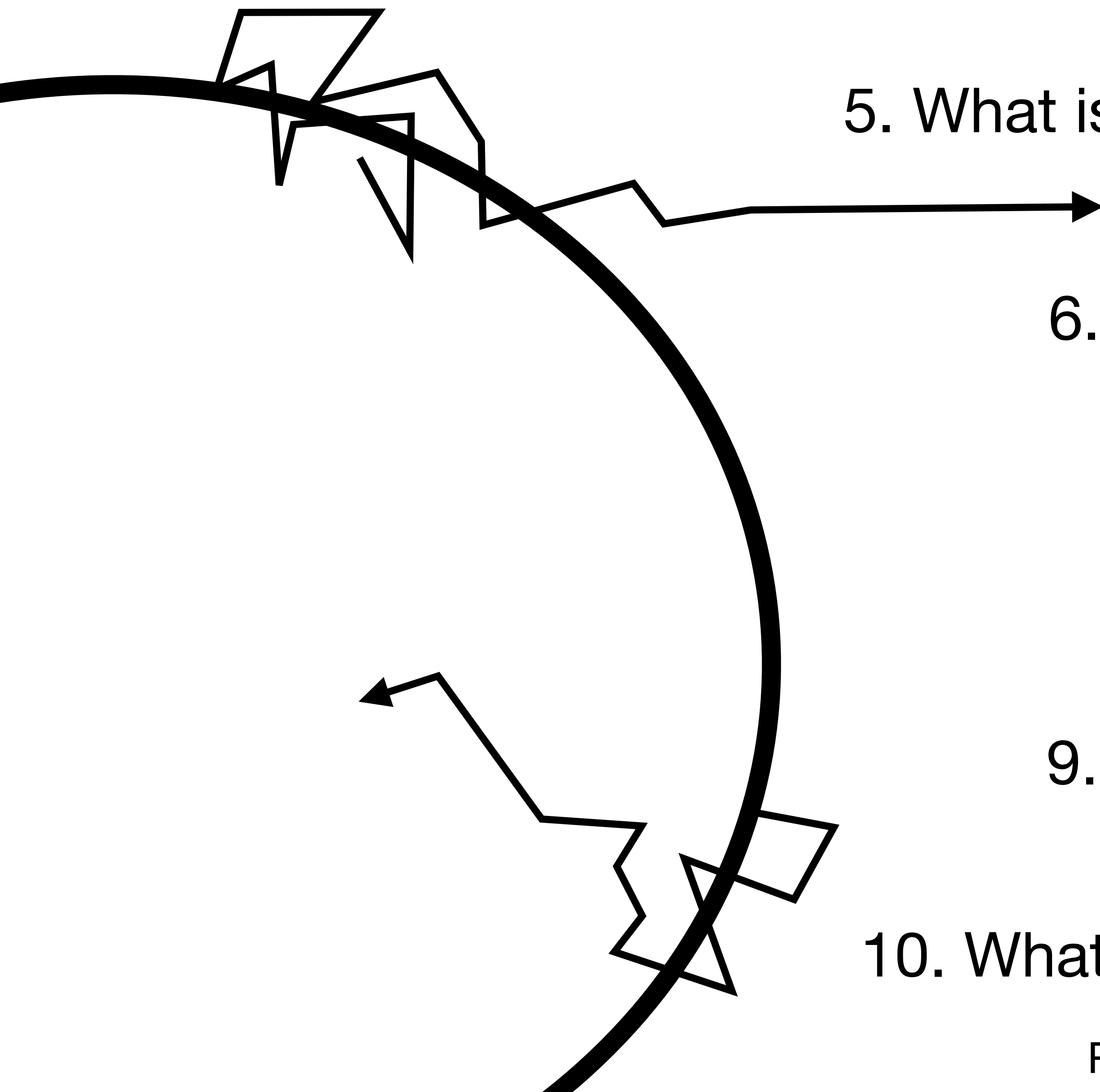
10. What is the role of pre-existing CRs (reacceleration?)

Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

What we still don't really know

All connected !

1. How are particles injected in the accelerator?
2. What is the efficiency of particle acceleration?
3. What is the spectrum of accelerated particles at the shock?
4. Protons? Electrons? Ratio?
5. What is the effect of losses on the trapped particles?

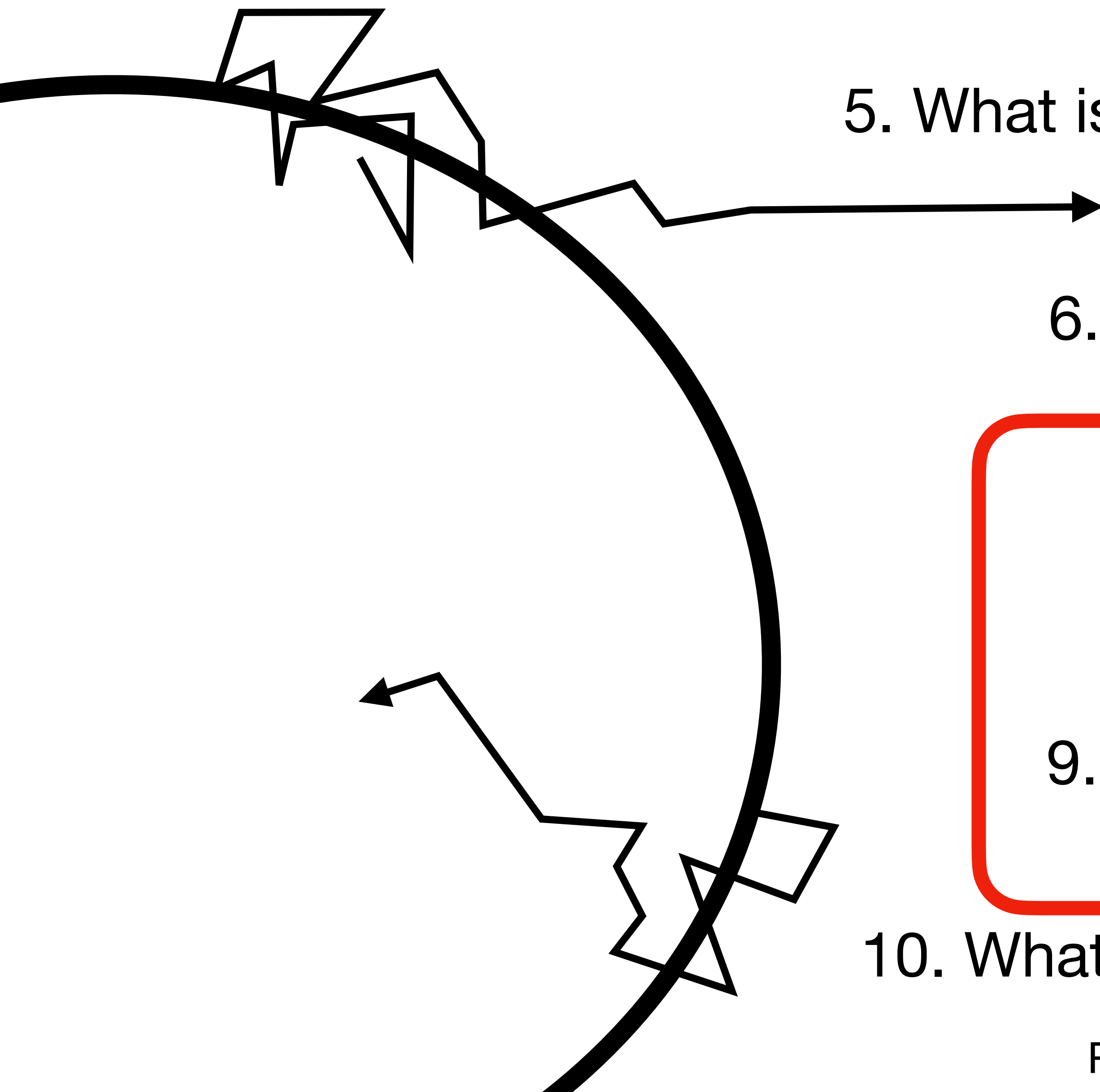


6. How long does the acceleration phase last?
7. How do particles escape the SNR?
8. How is the magnetic field amplified?
9. What is the maximum energy of accelerated particles?
10. What is the role of pre-existing CRs (reacceleration?)

Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

What we still don't really know

1. How are particles injected in the accelerator?
2. What is the efficiency of particle acceleration?
3. What is the spectrum of accelerated particles at the shock?
4. Protons? Electrons? Ratio?



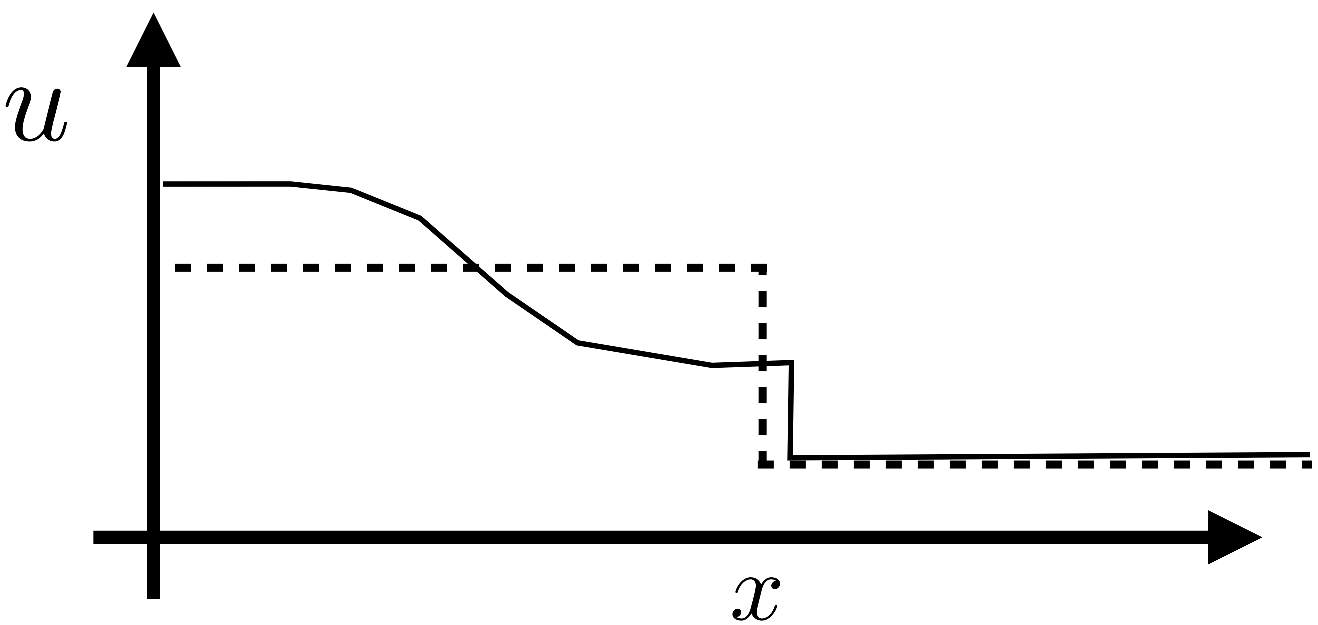
5. What is the effect of losses on the trapped particles?
6. How long does the acceleration phase last?
7. How do particles escape the SNR?
8. How is the magnetic field amplified?
9. What is the maximum energy of accelerated particles?
10. What is the role of pre-existing CRs (reacceleration?)

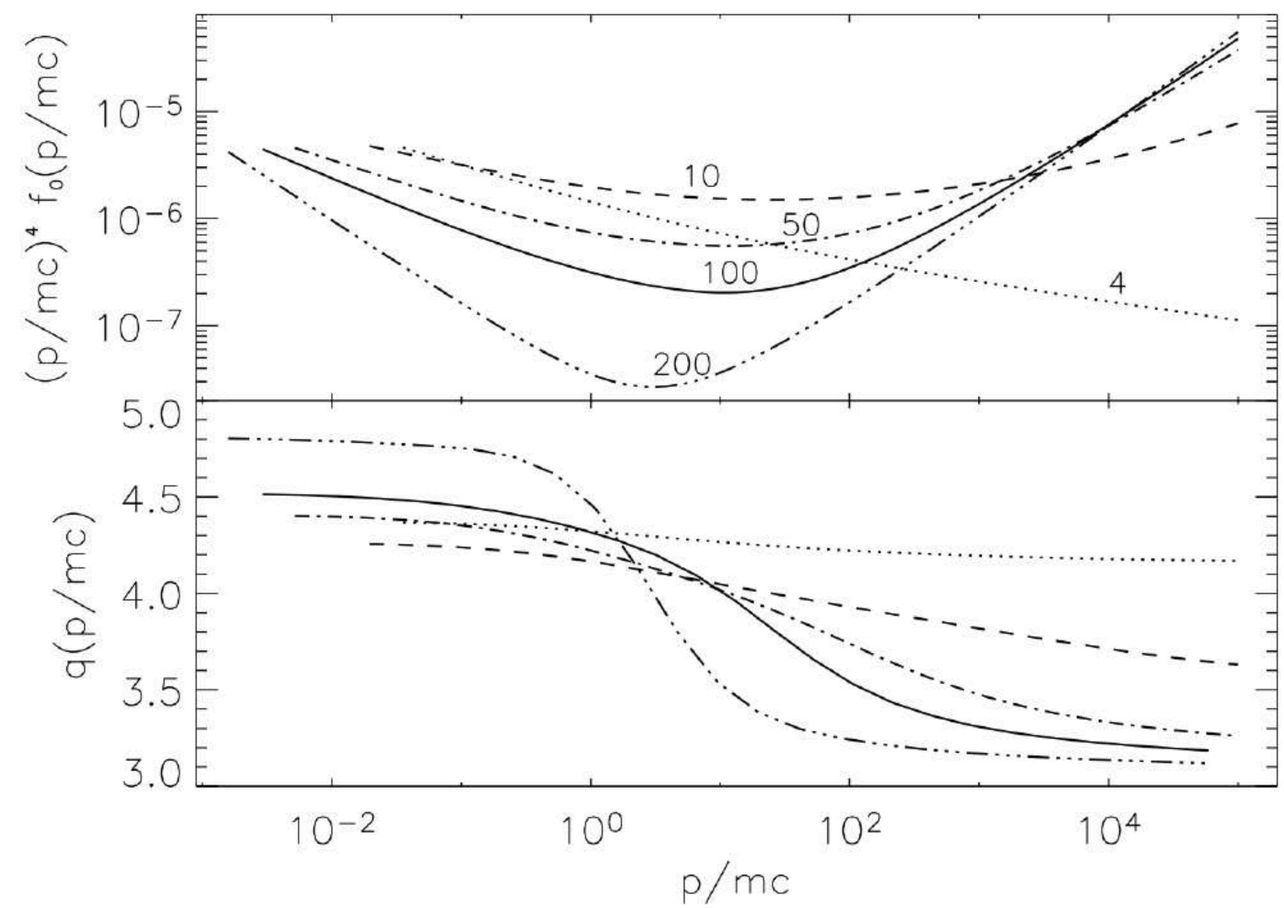
Reviews: Drury 2012, Blasi 2013, Blasi 2019, Gabici et al. 2019

Spectrum at the shock?

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

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





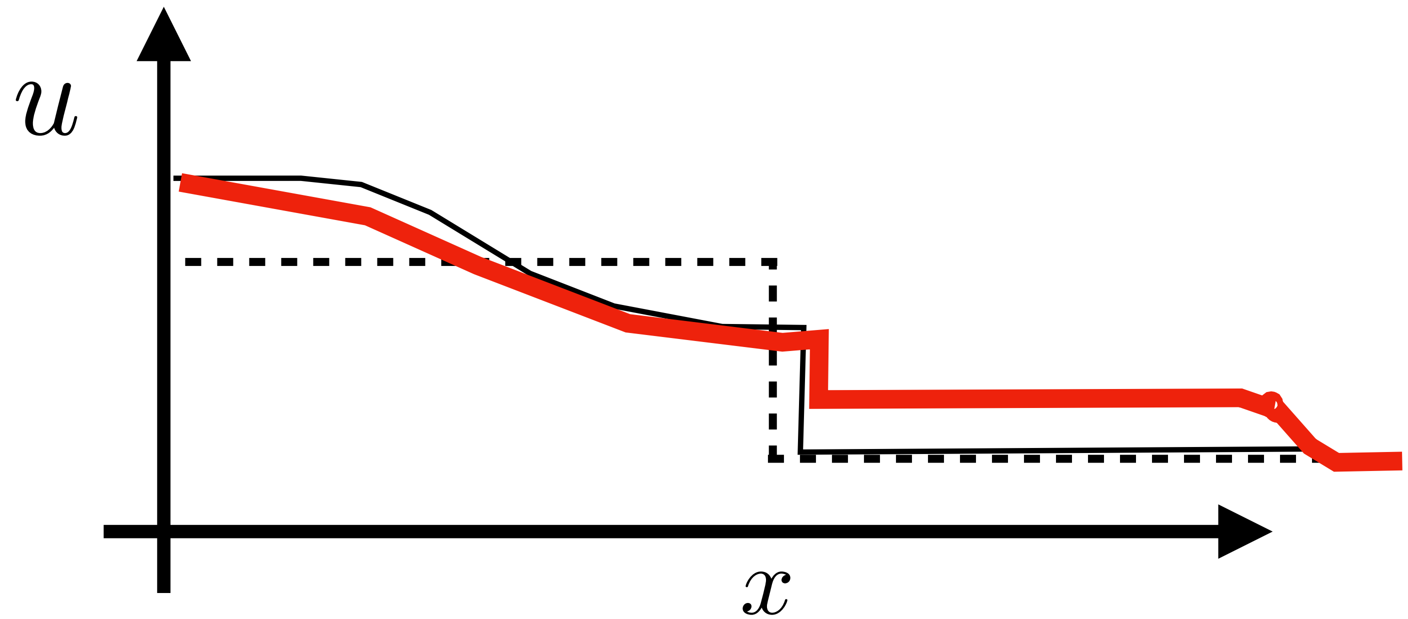
Drury& Völk (1980,1981), Bell (1987)
Jones & Ellison (1991), Ellison, Möbius & Paschamnn (1990), Ellison, Baring & Jones (1995, 1995) Kang & Jones (1997, 2005) Kang, Jones & Gieseler (2002), Malkov (1997), Malkov, Diamond & Völk (2000)
Blasi (2002), Amato & Blasi (2005,2006)

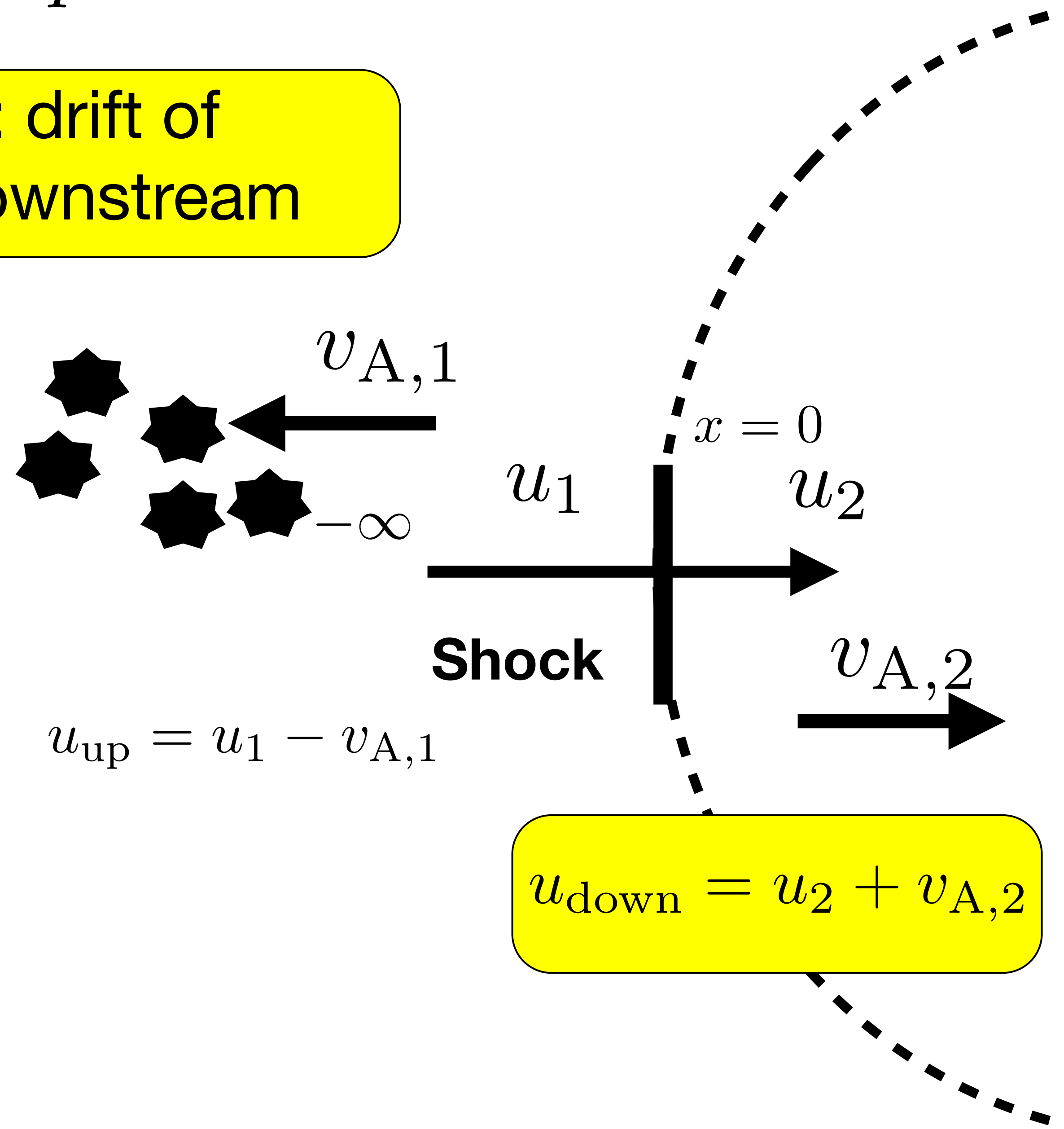
Spectrum at the shock?

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





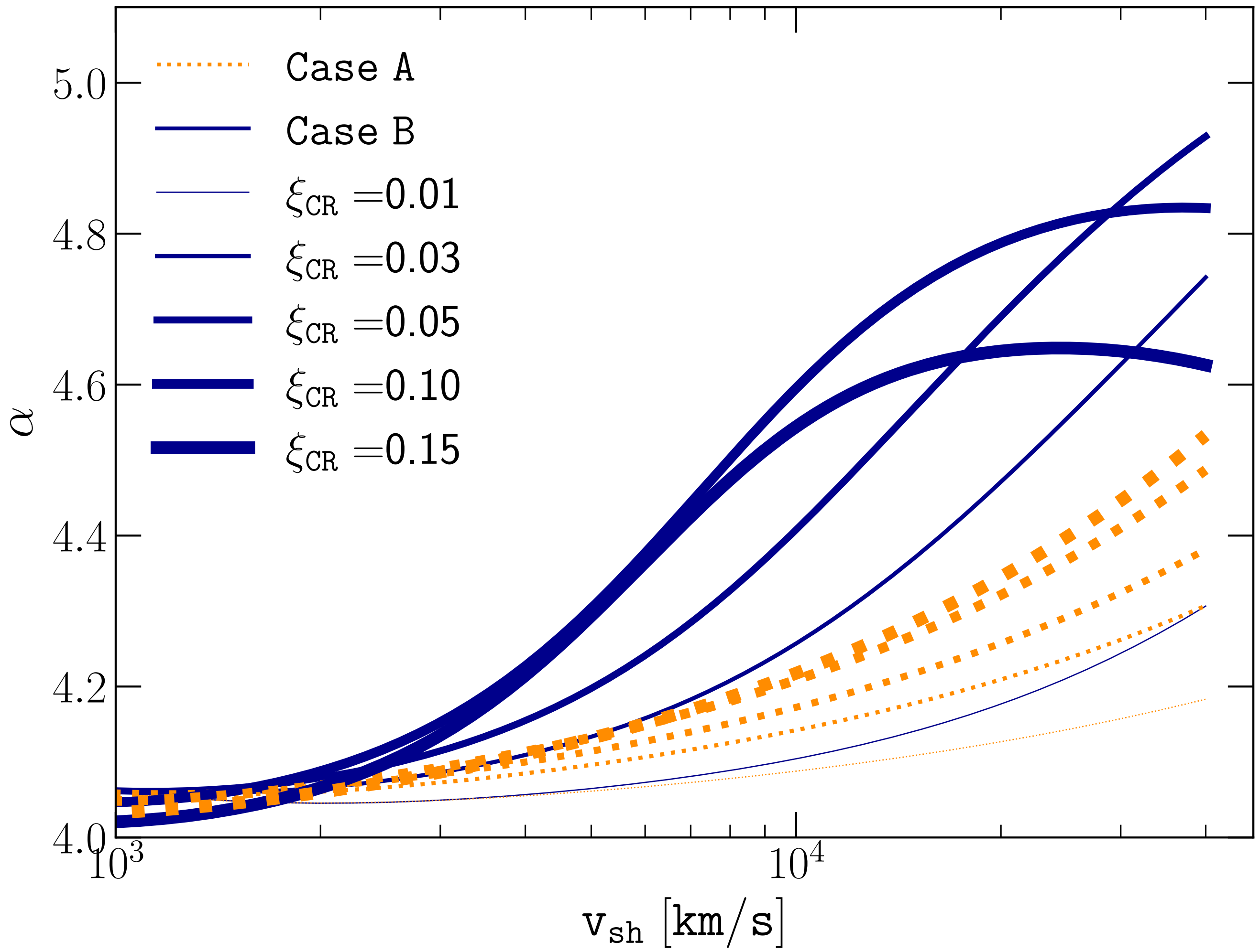
Zirakashvili & Ptuskin (2008), Kirk (1990)

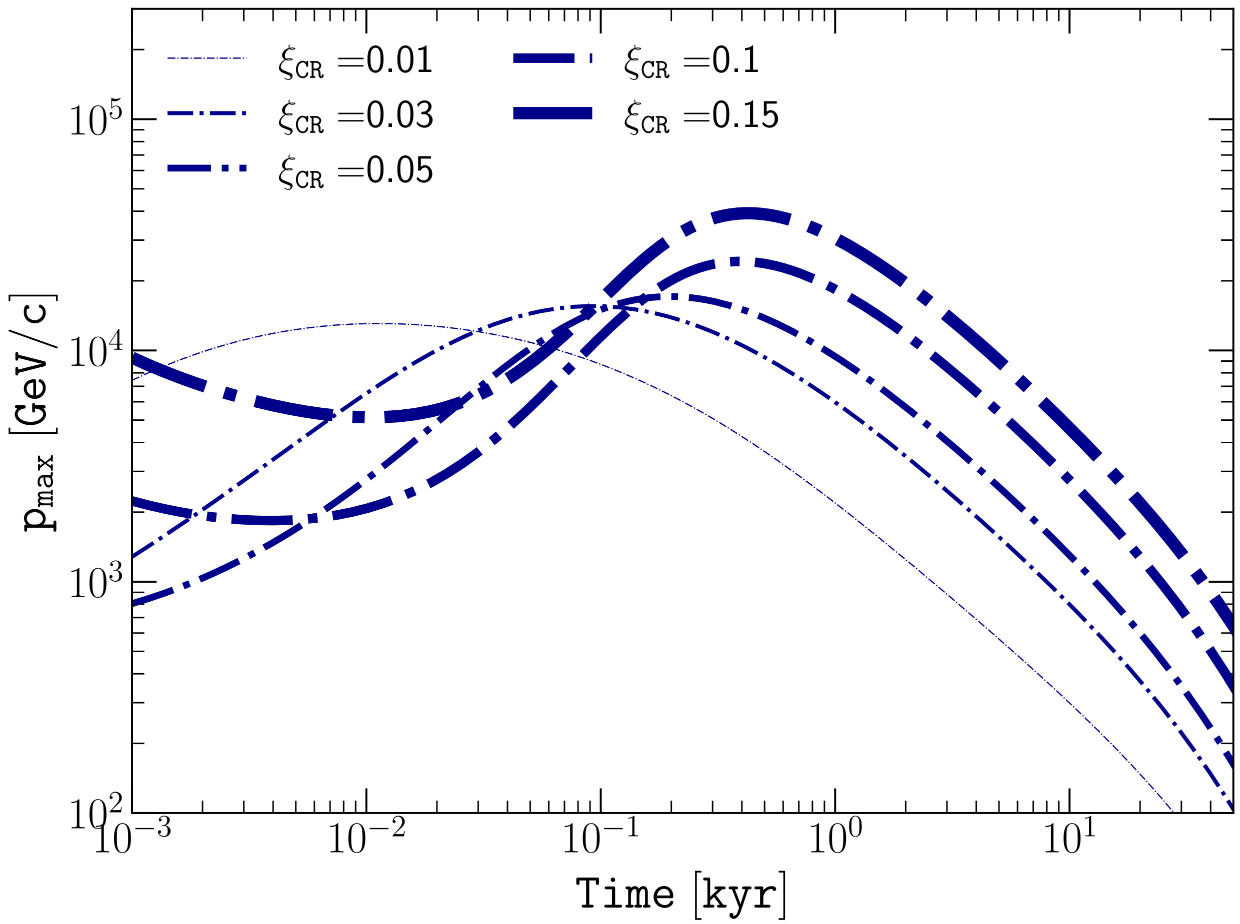
Drury (1983), Caprioli, Haggerty & Blasi (2020), Diesing & Caprioli (2021), PC, Blasi & Caprioli (2022)

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

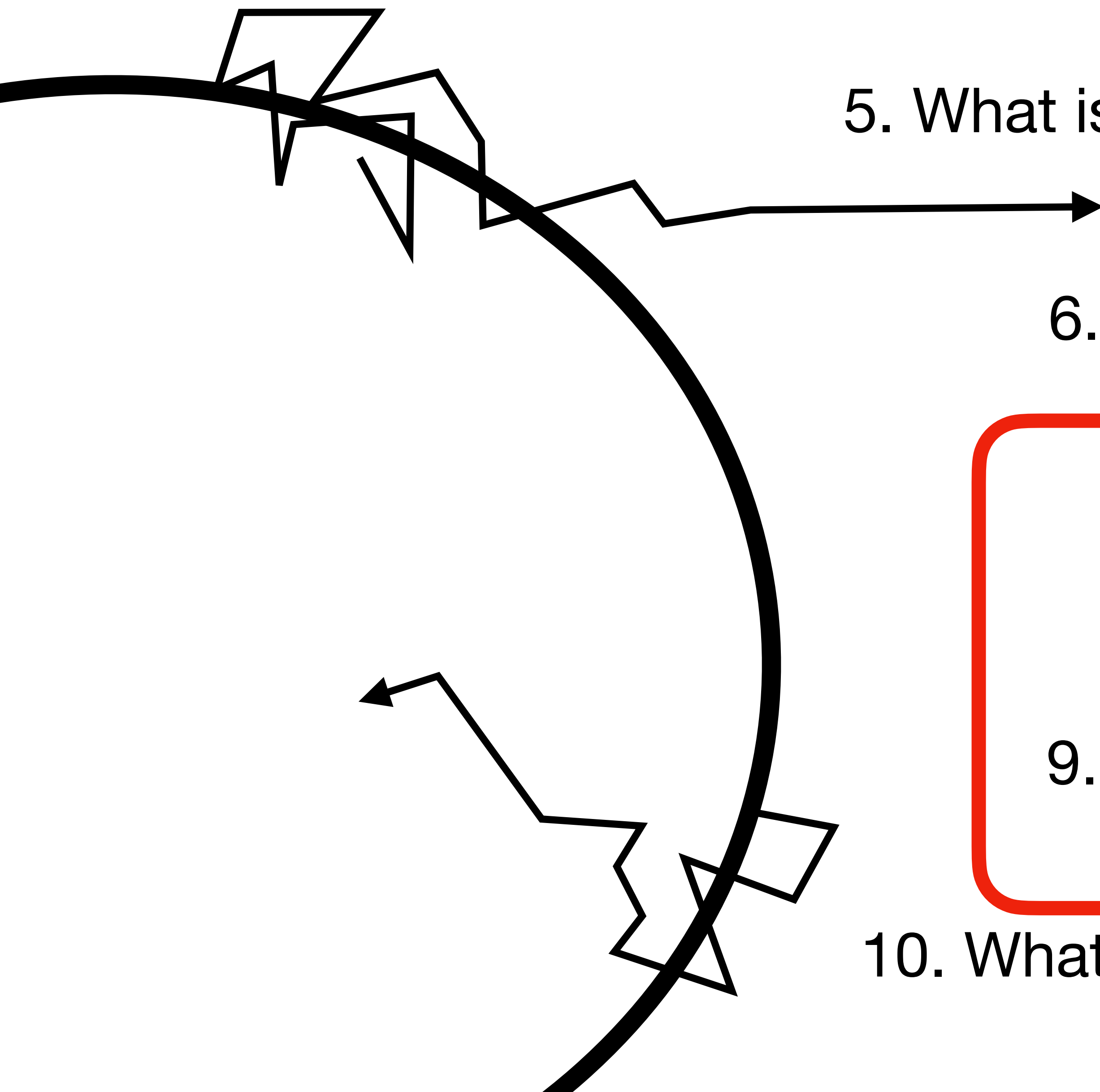
What we still don’t really know

1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?

4. Protons? Electrons? Ratio?



5. What is the effect of losses on the trapped particles?

6. How long does the acceleration phase last?

7. How do particles escape the SNR?

8. How is the magnetic field amplified?

9. What is the maximum energy of accelerated particles?

10. What is the role of pre-existing CRs (reacceleration?)

What we still don't really know

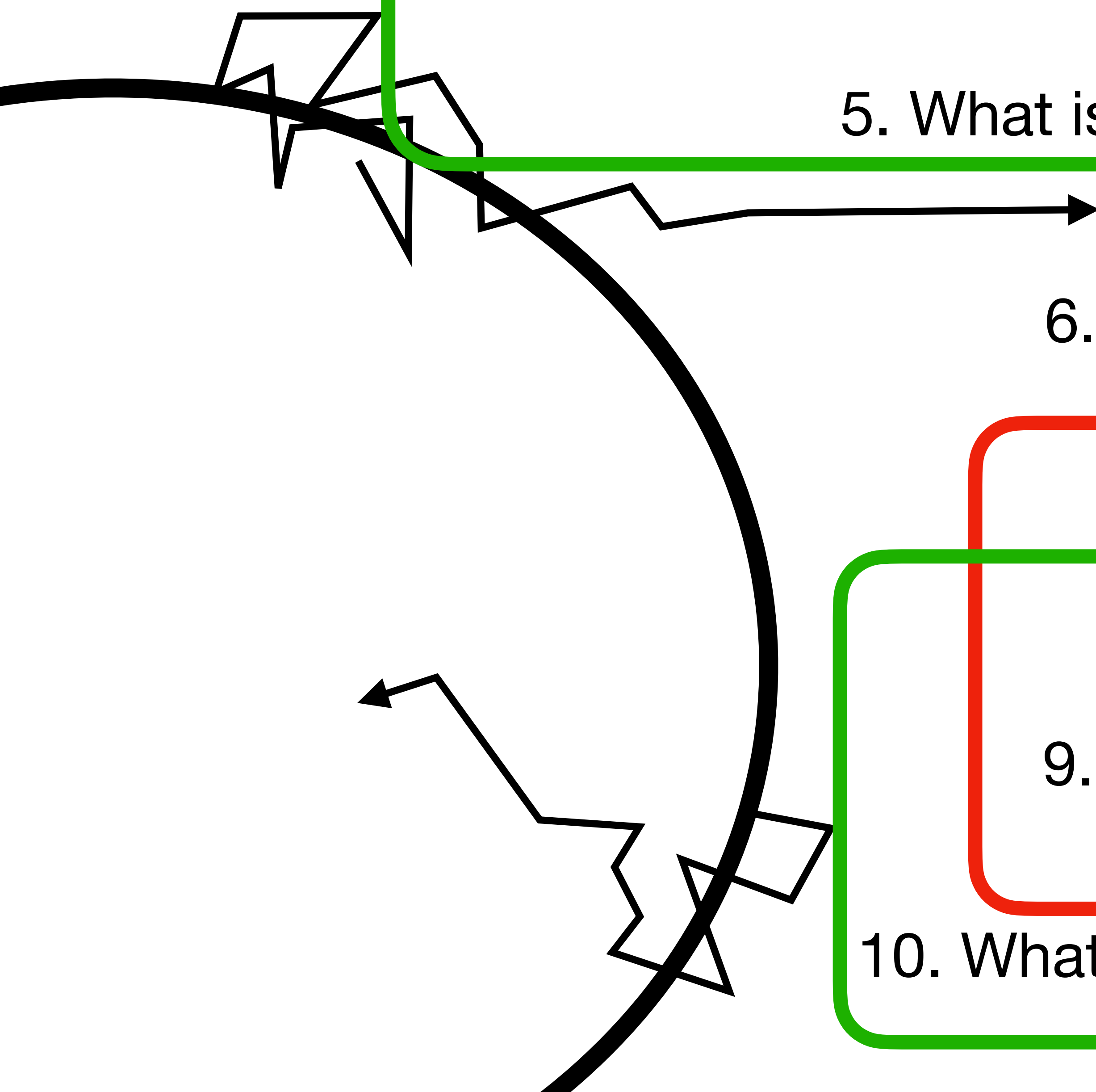
1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?

4. Protons? Electrons? Ratio?

5. What is the effect of losses on the trapped particles?



6. How long does the acceleration phase last?

7. How do particles escape the SNR?

8. How is the magnetic field amplified?

9. What is the maximum energy of accelerated particles?

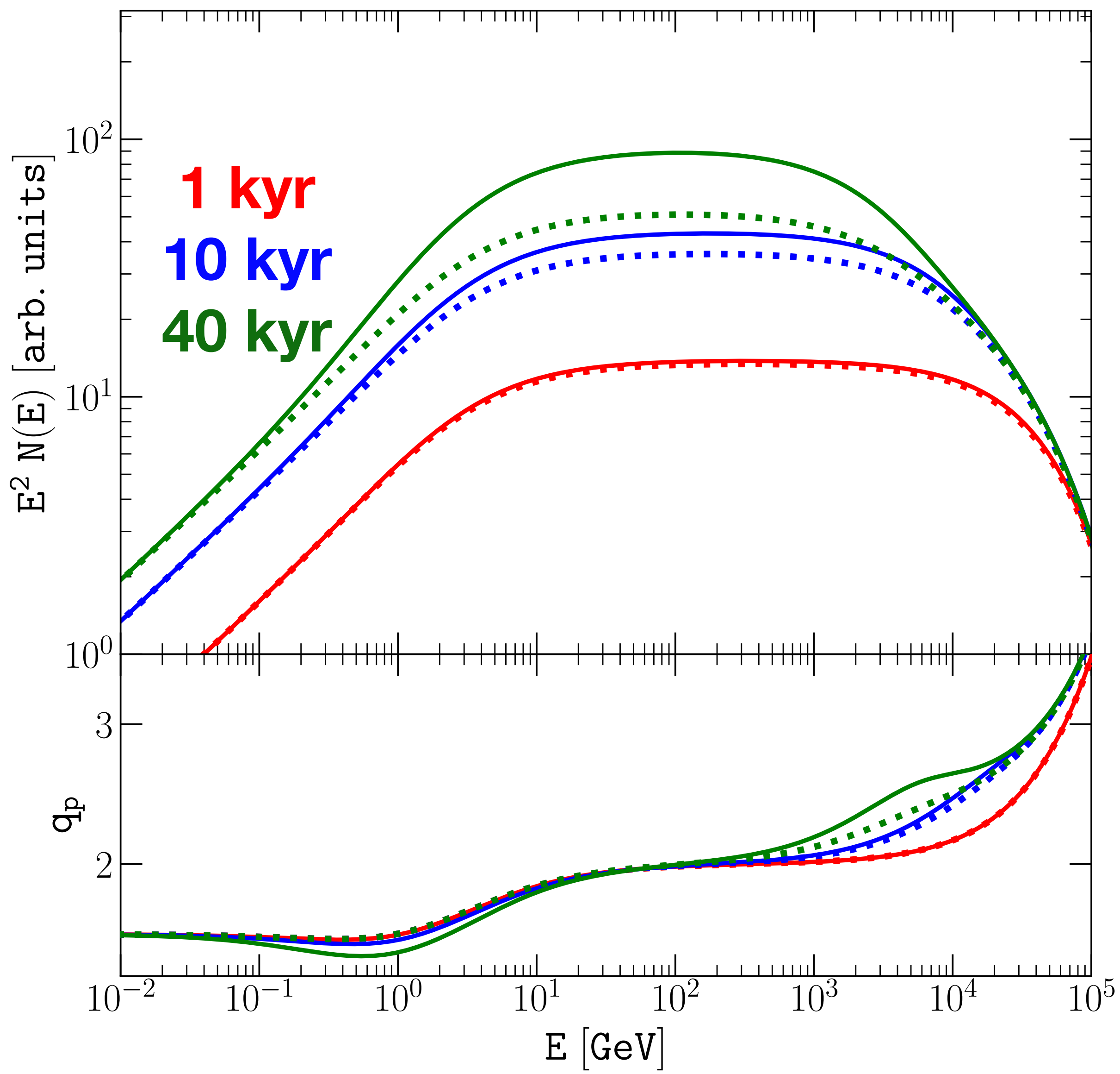
10. What is the role of pre-existing CRs (reacceleration?)

Reacceleration over the SNR lifetime

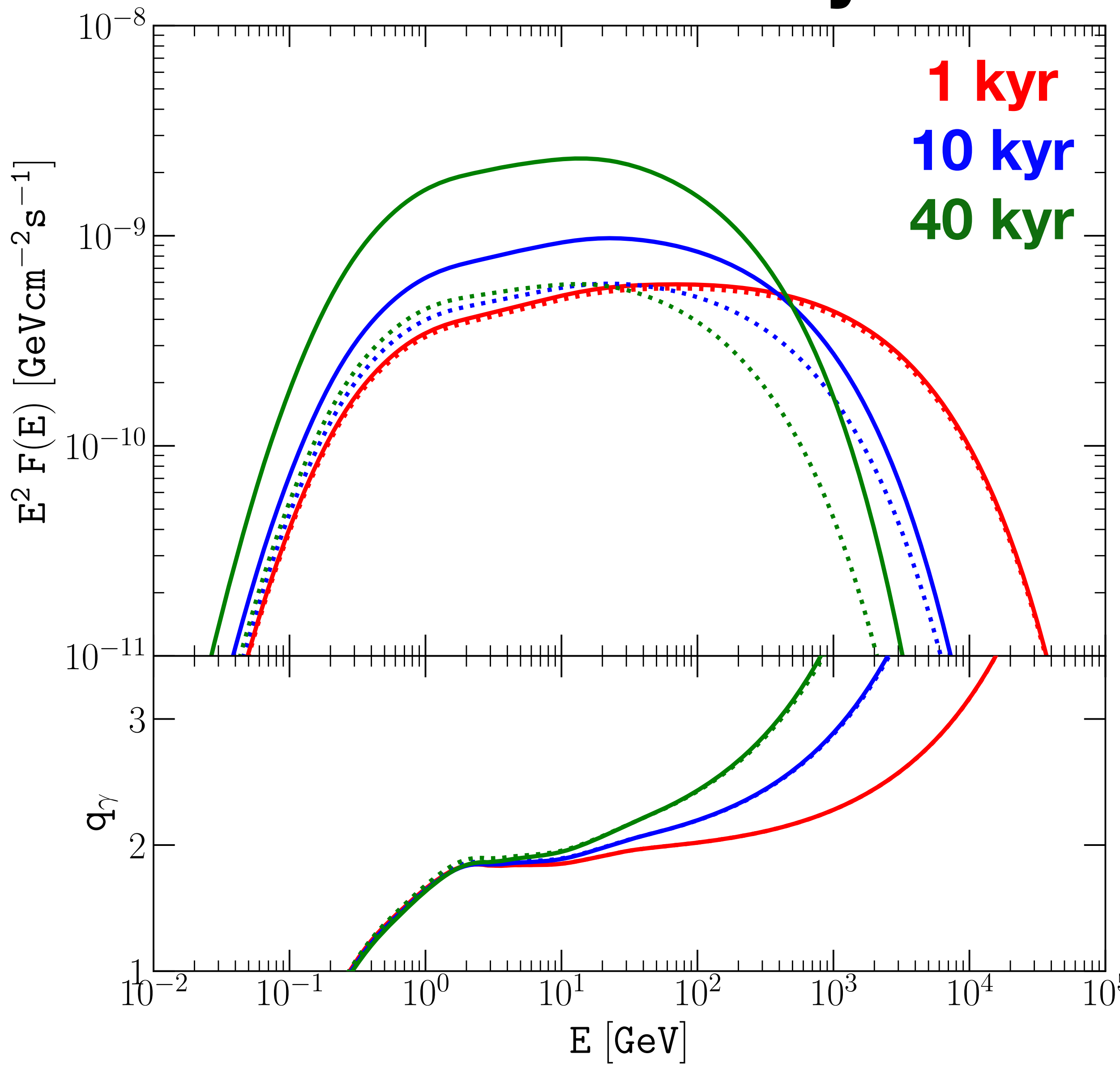
Bell (1978, II.)

« 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. »

Protons



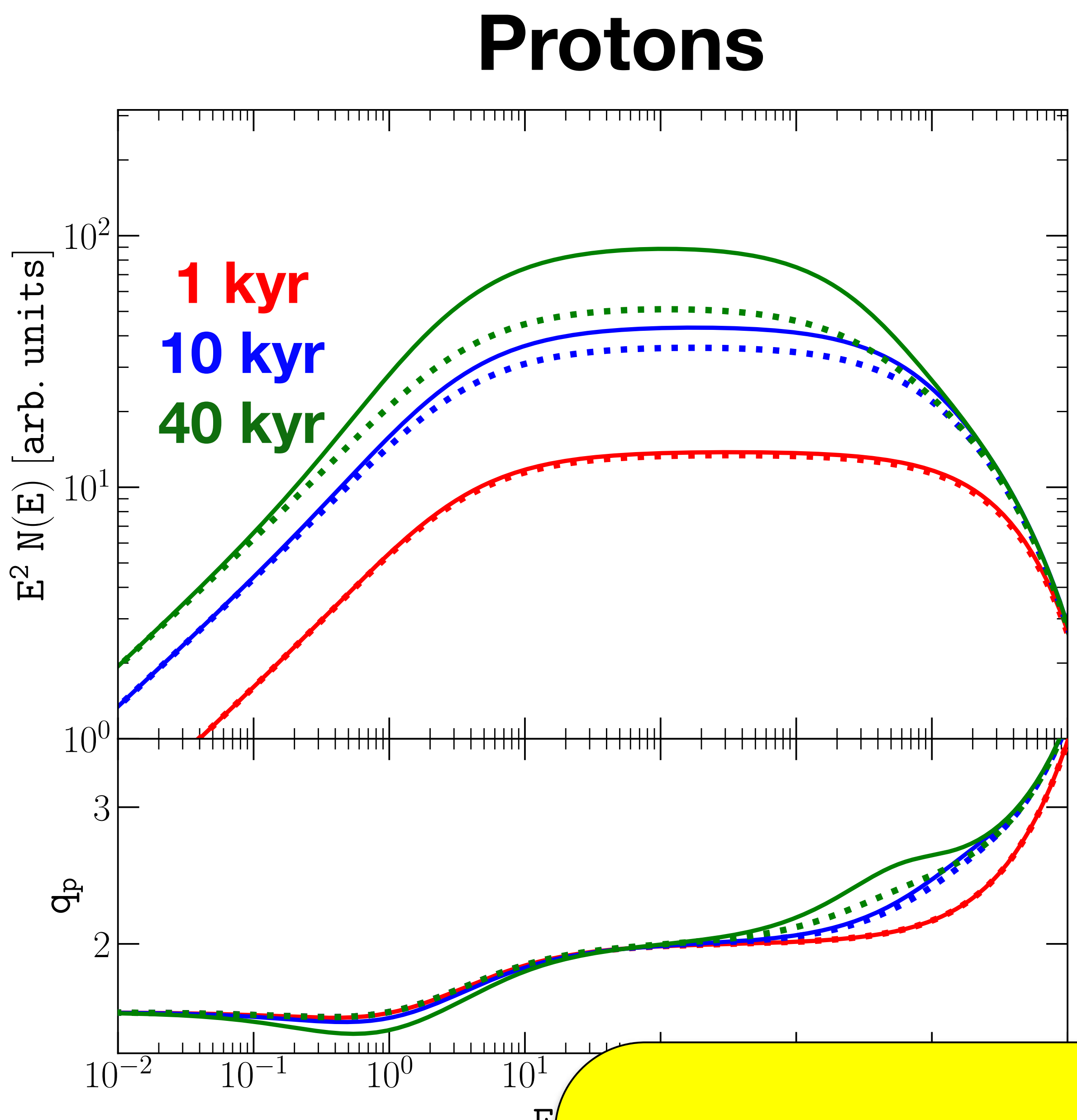
Gamma—rays

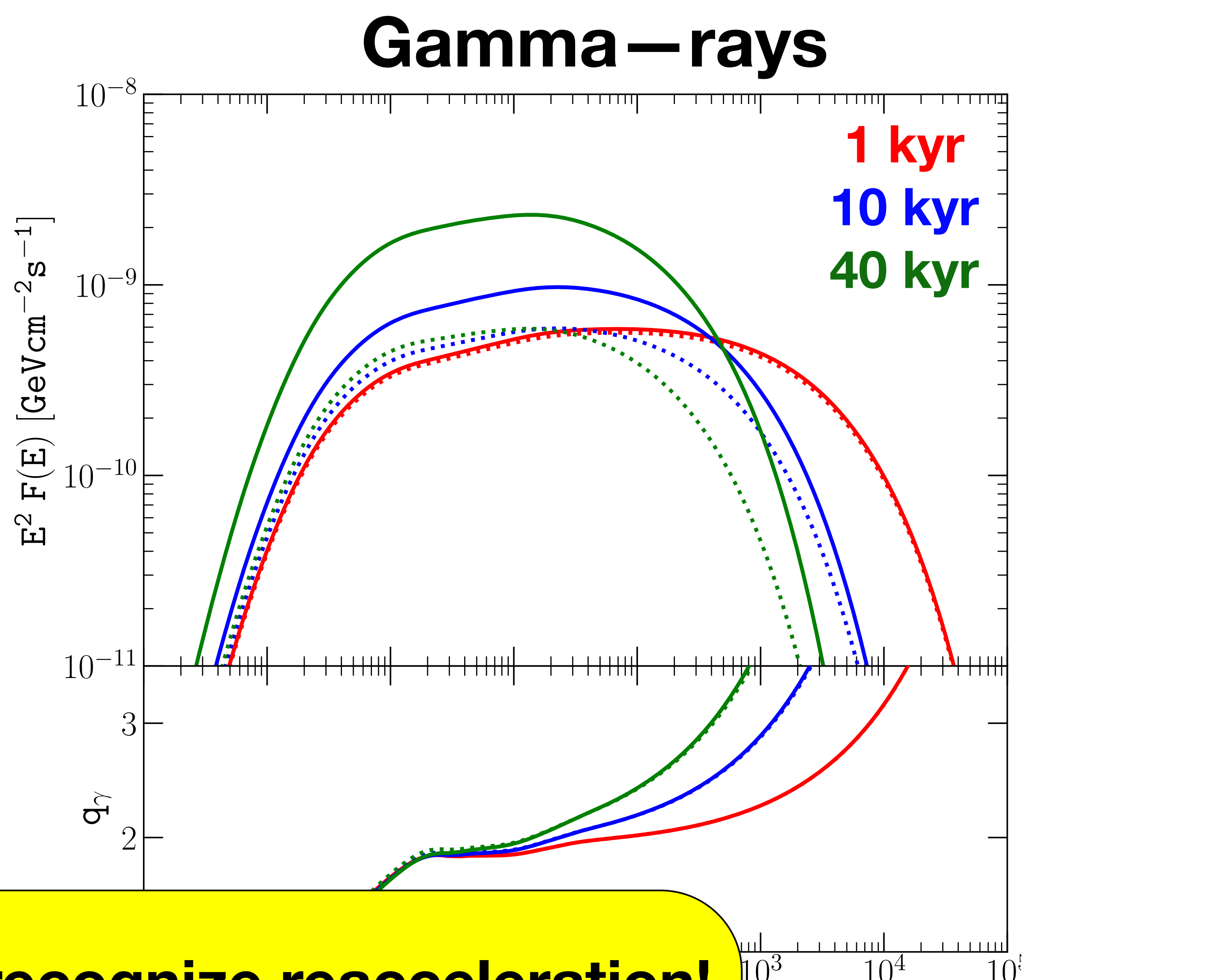


Reacceleration over the SNR lifetime

Bell (1978, II.)

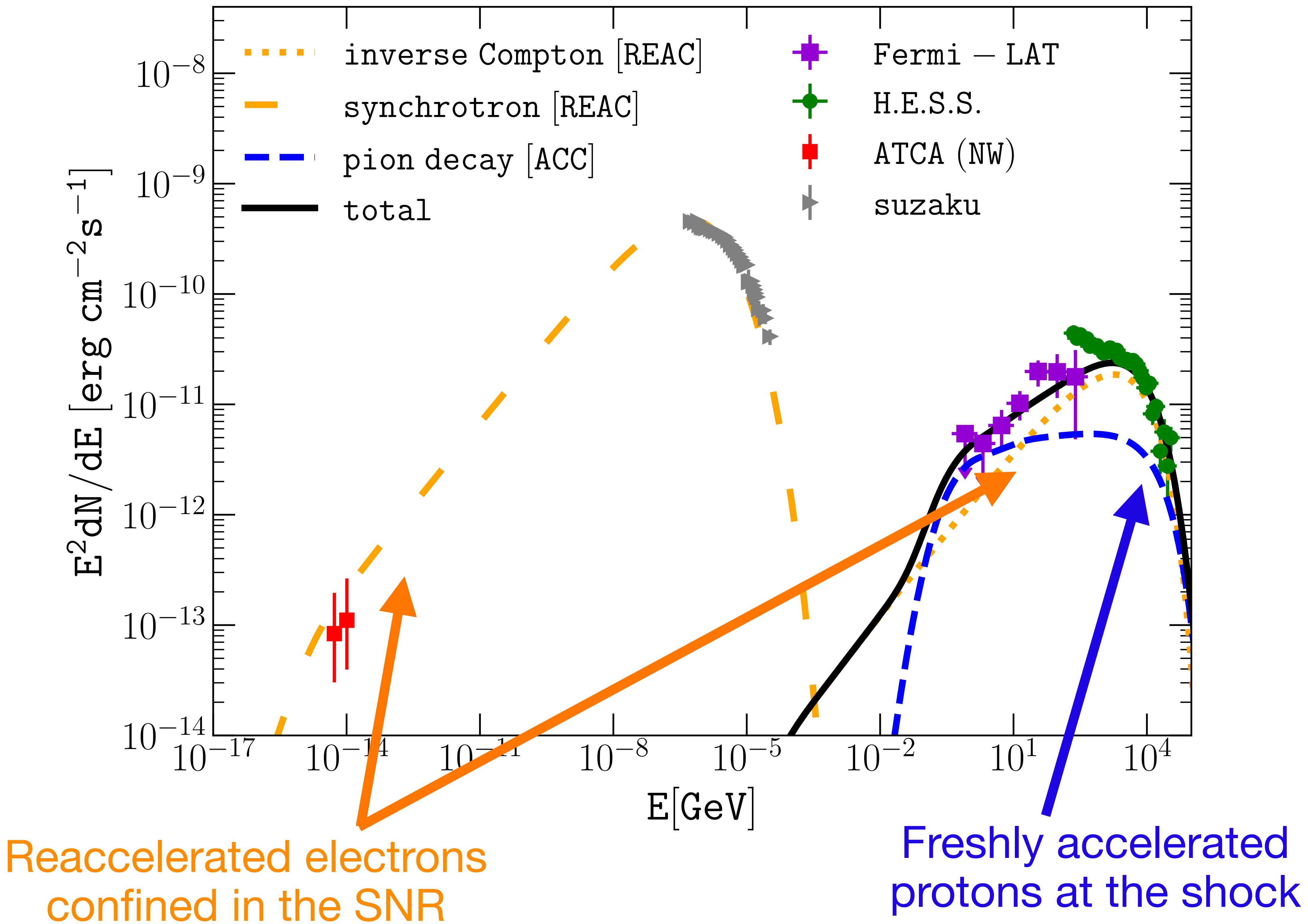
« In previous sections the injection of particles into the acceleration mechanism has been considered as taking place at low energy […] An alternative source for the injection of particles is the cosmic ray population which already exists in the upstream gas. »





It is not easy to recognize reacceleration!

RXJ1713-3946: the contribution of reaccelerated electrons



PC, Gabici, Niro 2021

What we still don't really know

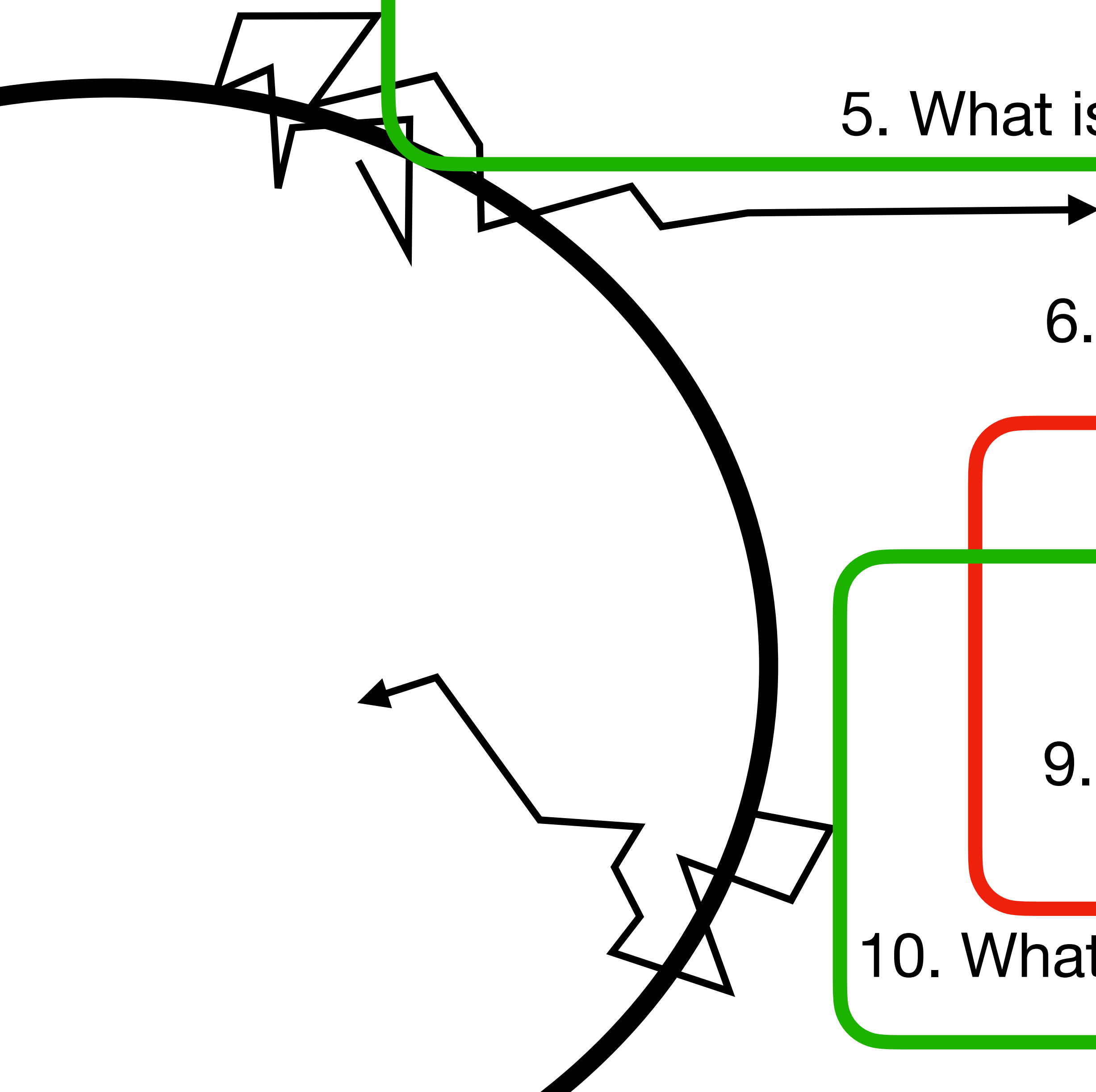
1. How are particles injected in the accelerator?

2. What is the efficiency of particle acceleration?

3. What is the spectrum of accelerated particles at the shock?

4. Protons? Electrons? Ratio?

5. What is the effect of losses on the trapped particles?



6. How long does the acceleration phase last?

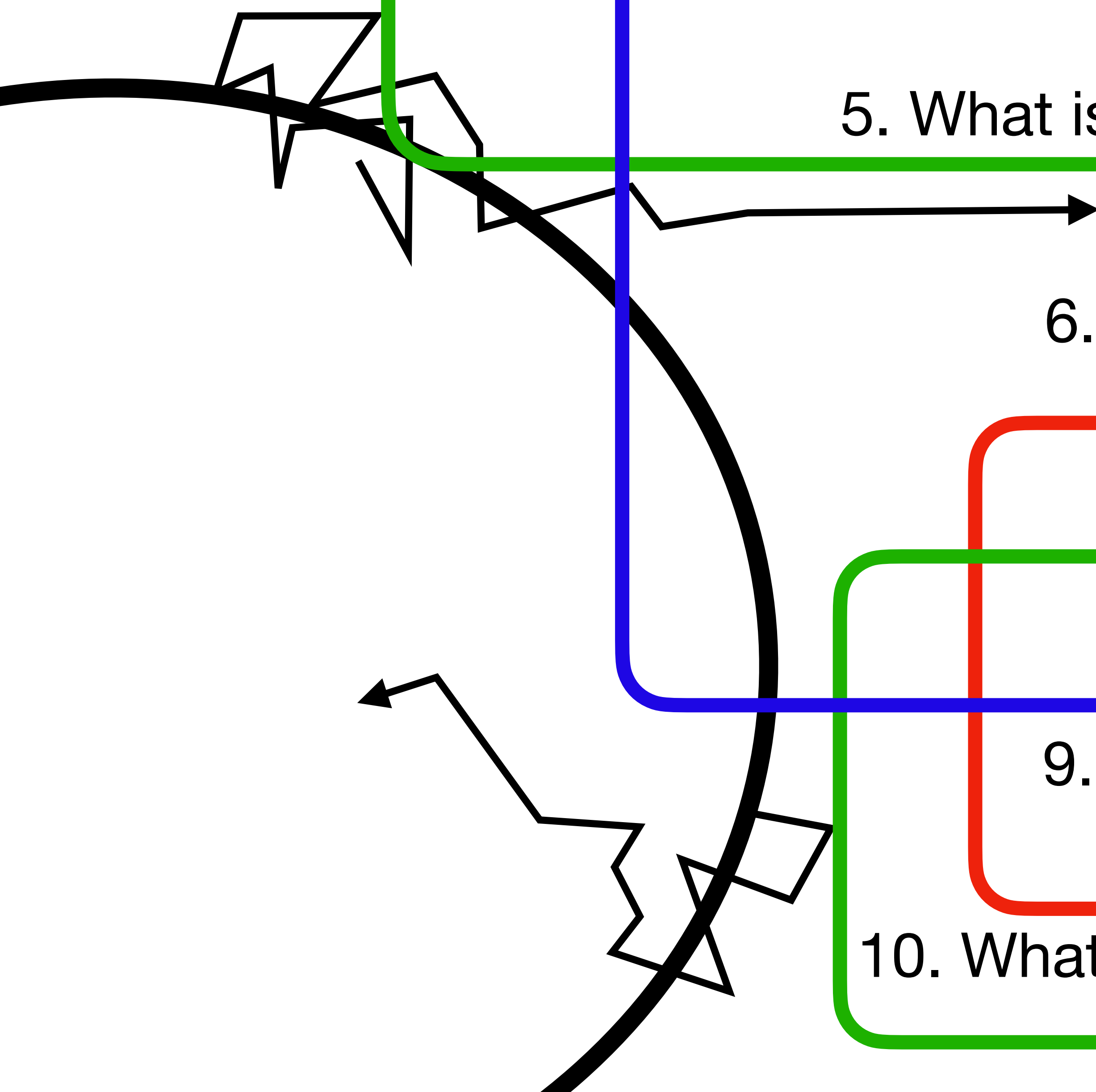
7. How do particles escape the SNR?

8. How is the magnetic field amplified?

9. What is the maximum energy of accelerated particles?

10. What is the role of pre-existing CRs (reacceleration?)

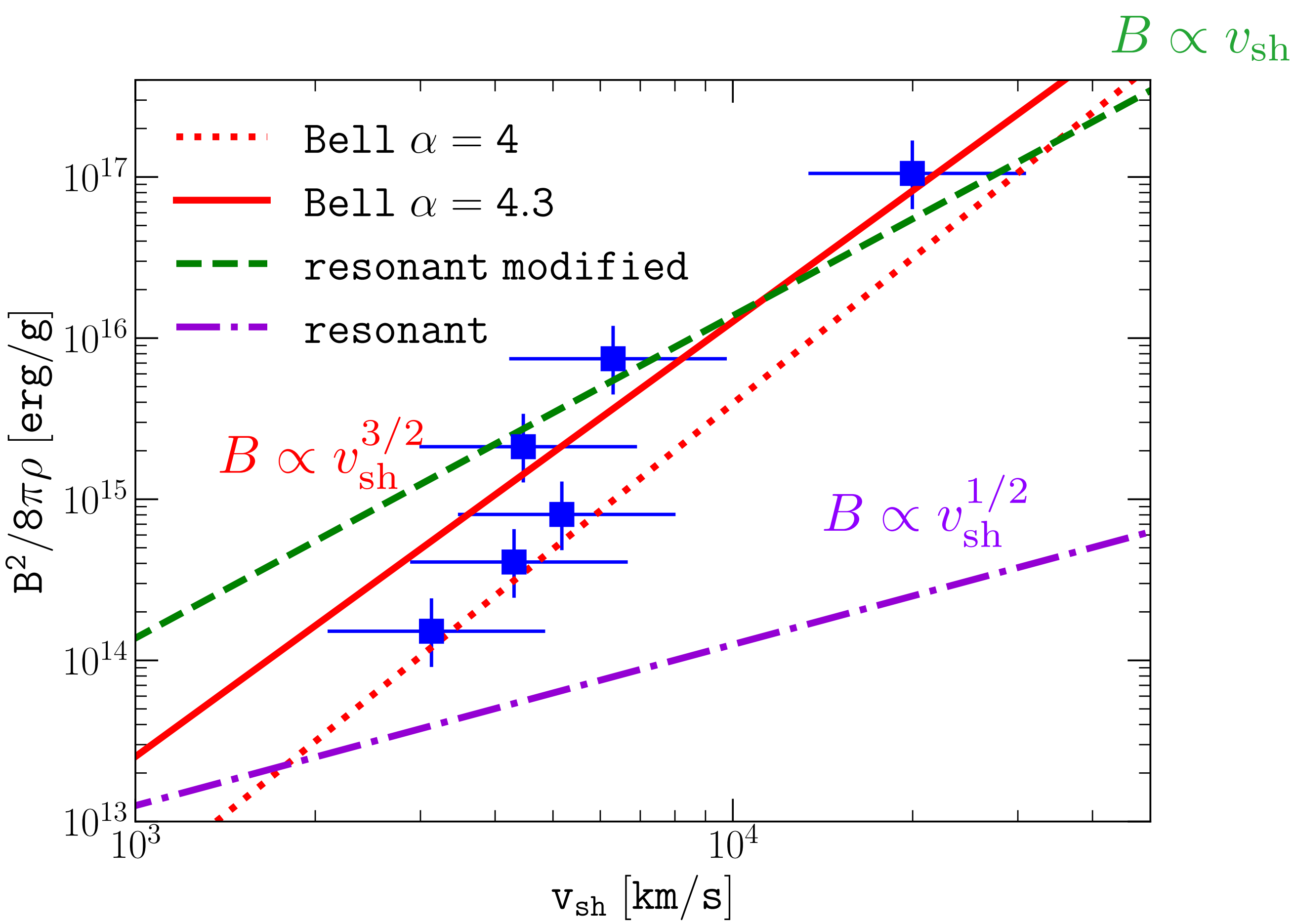
What we still don't really know

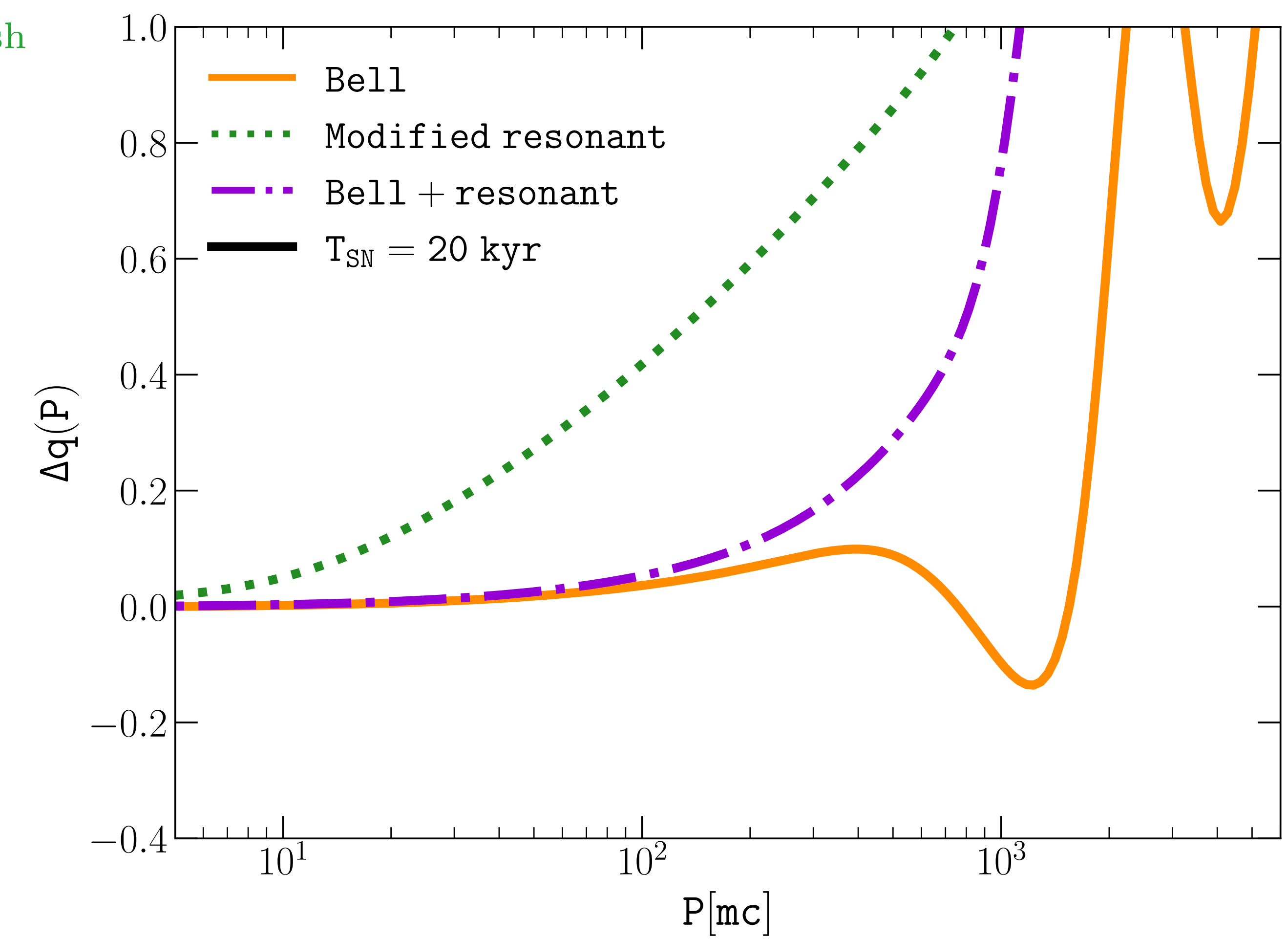


1. How are particles injected in the accelerator?
2. What is the efficiency of particle acceleration?
3. What is the spectrum of accelerated particles at the shock?
4. Protons? Electrons? Ratio?
5. What is the effect of losses on the trapped particles?
6. How long does the acceleration phase last?
7. How do particles escape the SNR?
8. How is the magnetic field amplified?
9. What is the maximum energy of accelerated particles?
10. What is the role of pre-existing CRs (reacceleration?)

Slope of proton/electron spectra injected in the ISM

Electron spectra steeper than protons could help make sense of the positron fraction (PAMELA, AMS-02)





Importance of the time of confinement/acceleration

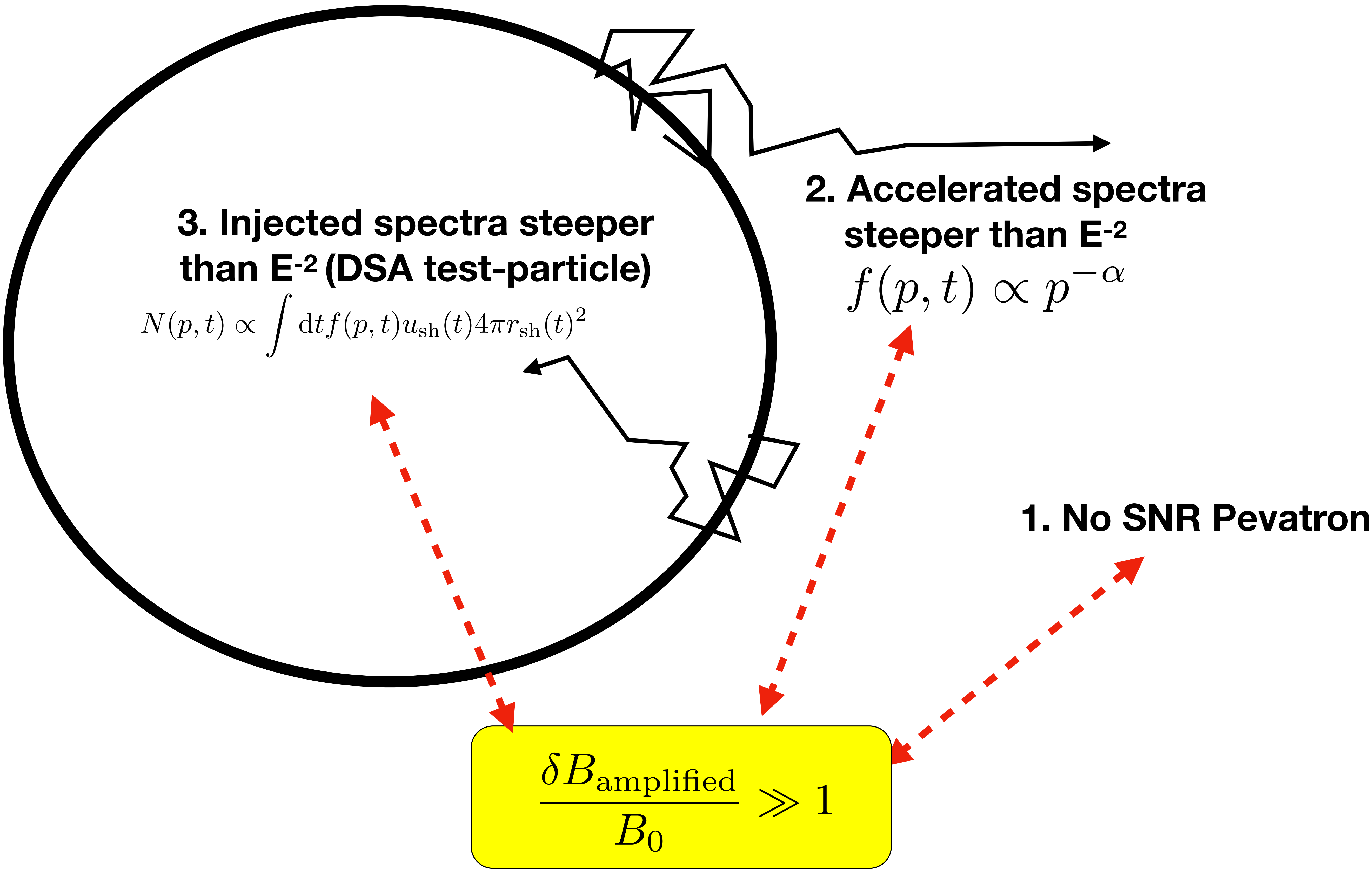
Importance of magnetic field + efficiency of acceleration

Amato & Blasi (2012)

Diesing & Caprioli (2019)

PC, Blasi, Caprioli (2021)

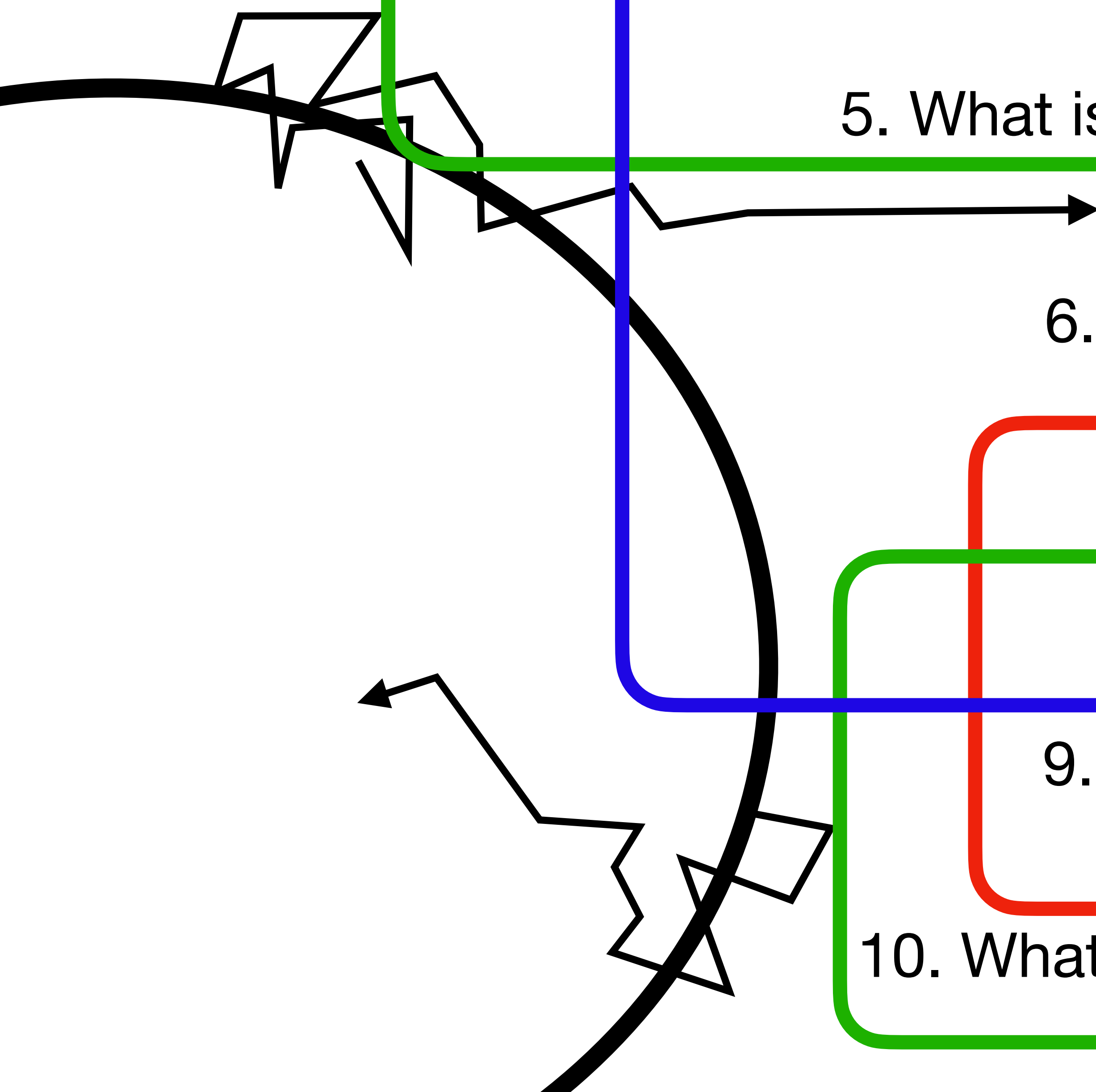
Three issues



Conclusions: need to answer these questions + others!

All connected !

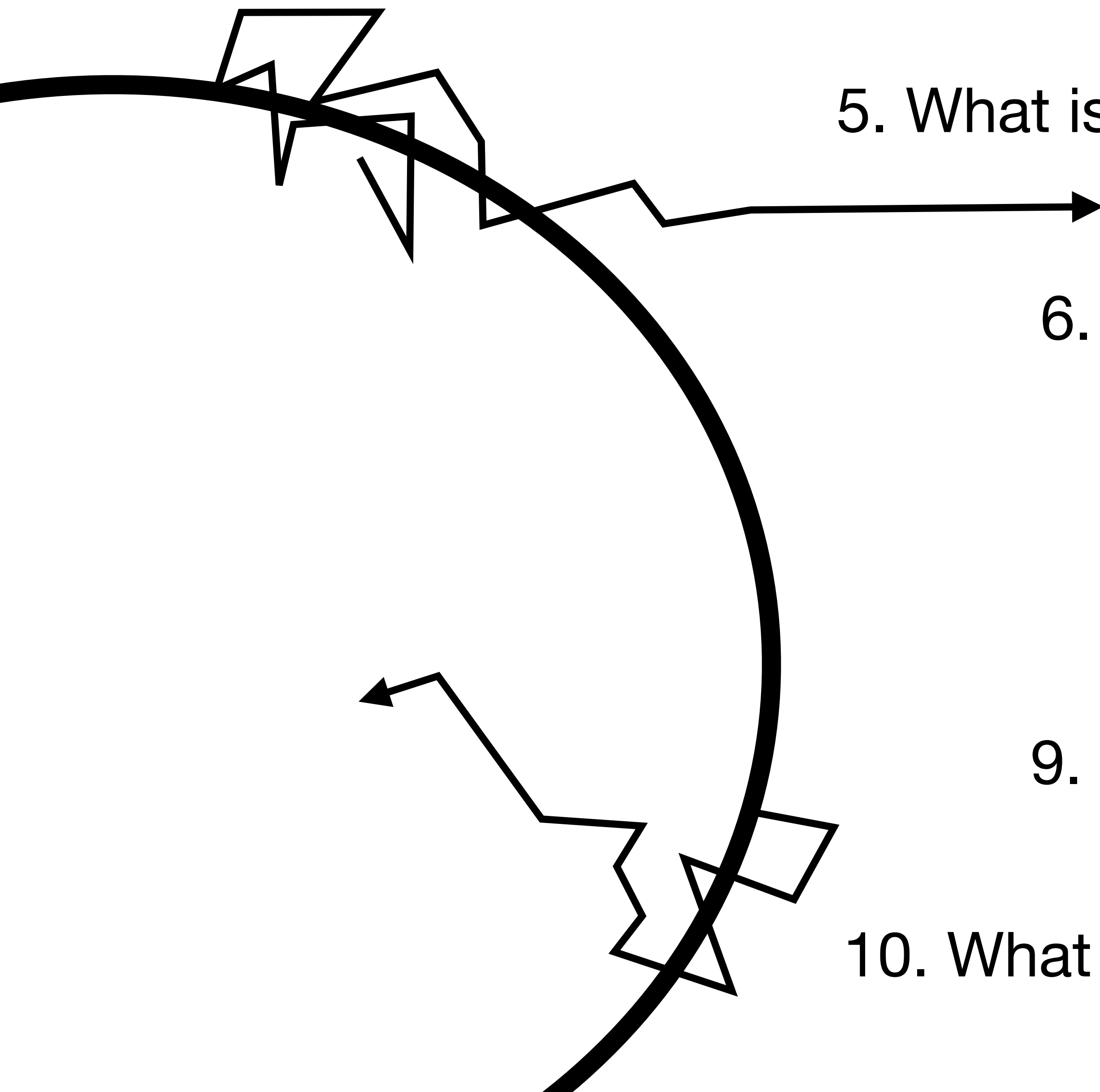
1. How are particles injected in the accelerator?
2. What is the efficiency of particle acceleration?
3. What is the spectrum of accelerated particles at the shock?
4. Protons? Electrons? Ratio?
5. What is the effect of losses on the trapped particles?
6. How long does the acceleration phase last?
7. How do particles escape the SNR?
8. How is the magnetic field amplified?
9. What is the maximum energy of accelerated particles?
10. What is the role of pre-existing CRs (reacceleration?)



Conclusions: need to answer these questions + others!

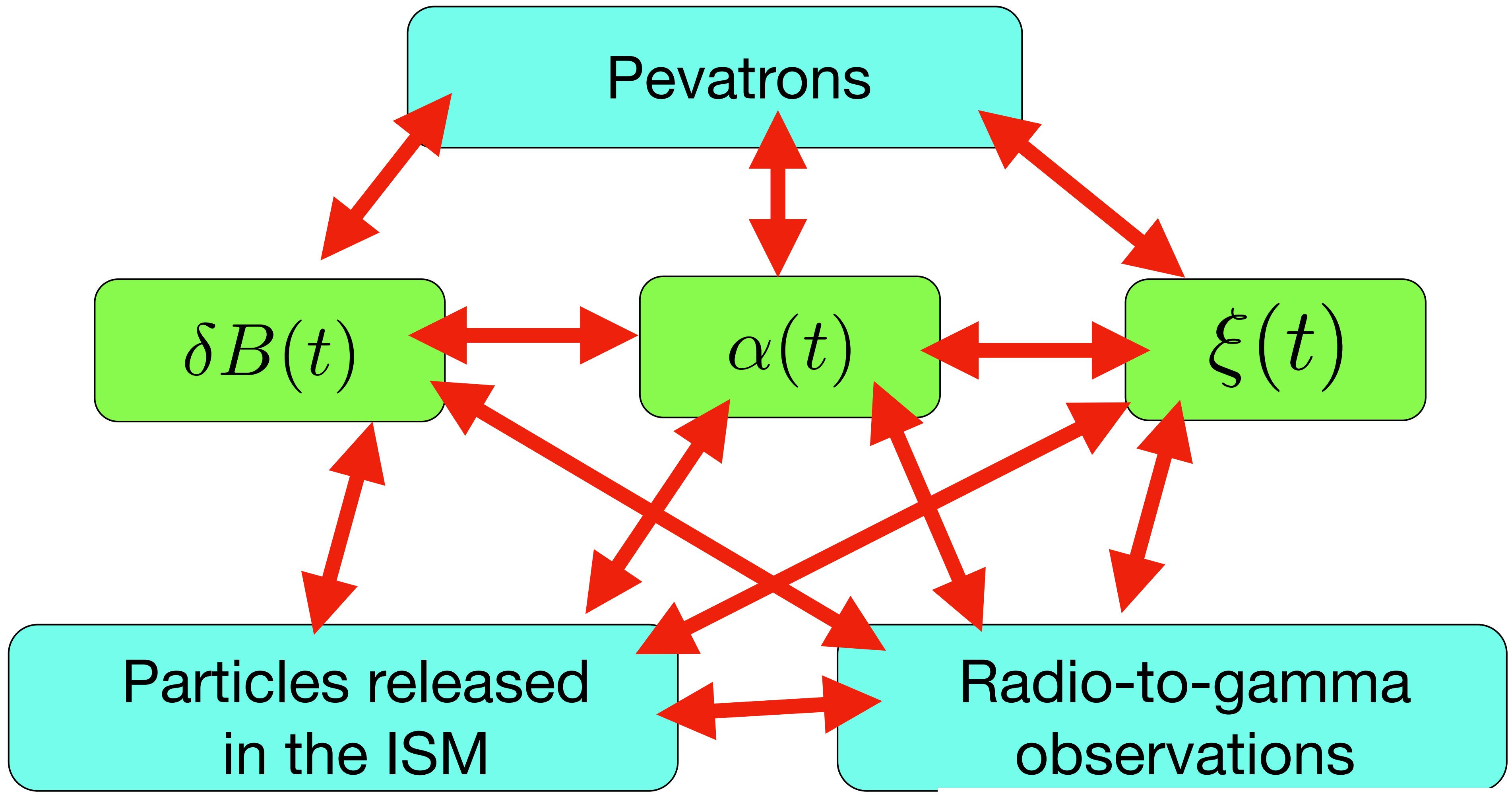
All connected !

1. How are particles **injected** in the accelerator?
2. What is the **efficiency** of particle acceleration?
3. What is the **spectrum of accelerated** particles at the shock?
4. **Protons? Electrons?** Ratio?
5. What is the effect of losses on the **trapped** particles?



6. **How long** does the acceleration phase last?
7. How do particles **escape** the SNR?
8. How is the **magnetic field amplified**?
9. What is the **maximum energy** of accelerated particles?
10. What is the role of pre-existing CRs (**reacceleration**?)

Particle acceleration at supernovae: gamma-ray domain with the Cherenkov Telescope Array?



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

Early times to get rid of cumulative effects