

How do particles escape from accelerators?



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Plan of the lecture

- [1] Supernova remnants are spherical
- [2] Dynamical evolution of SNRs
- [3] Cosmic ray escape from SNRs (naive)

Supernova remnants

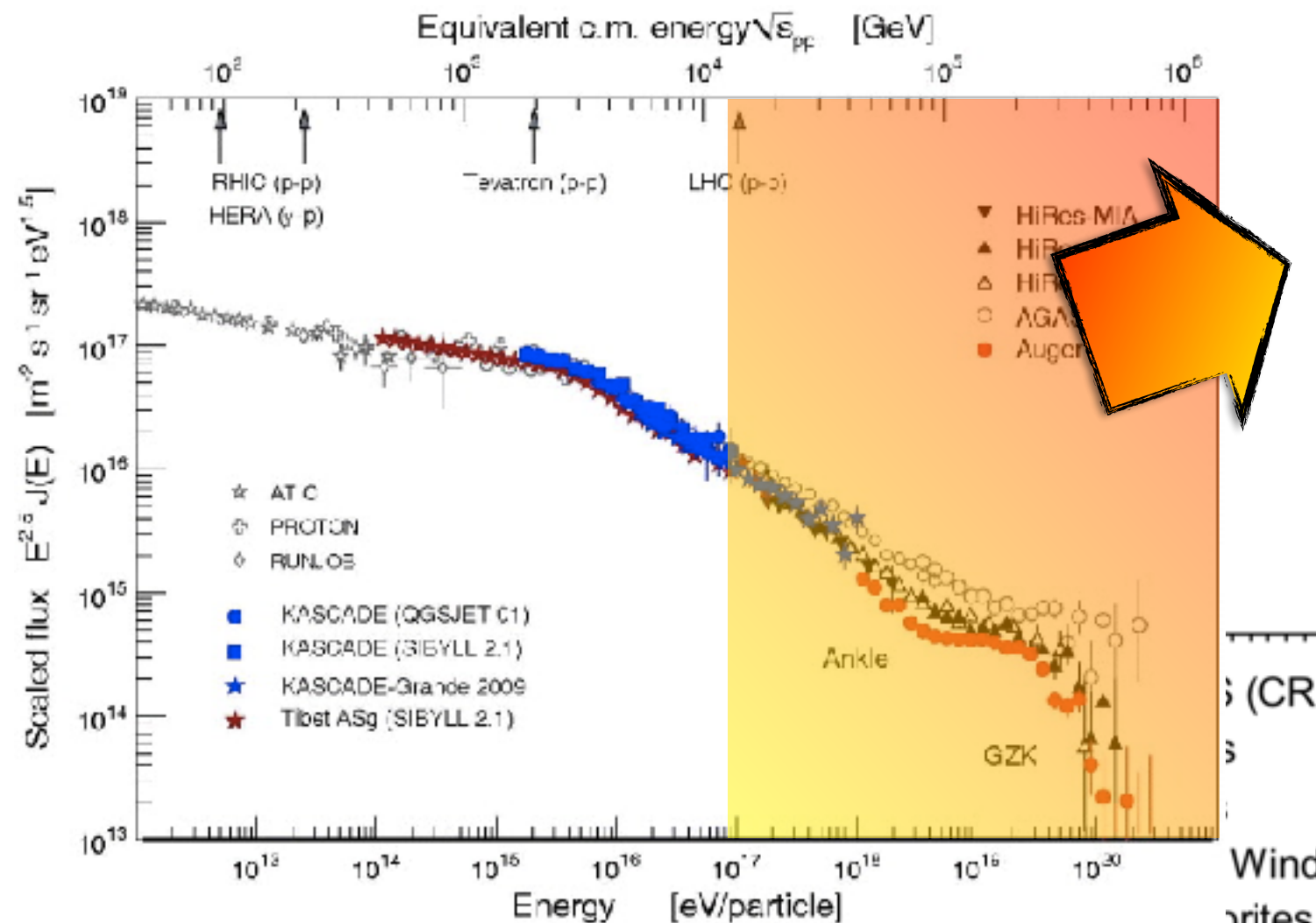
CR escape from sources

- [5] CR escape from SNRs (a bit more formal, but still quite hand wavy...)
- [6] maximum energy of accelerated CRs
- [7] spectrum of escaping CRs

Conclusions

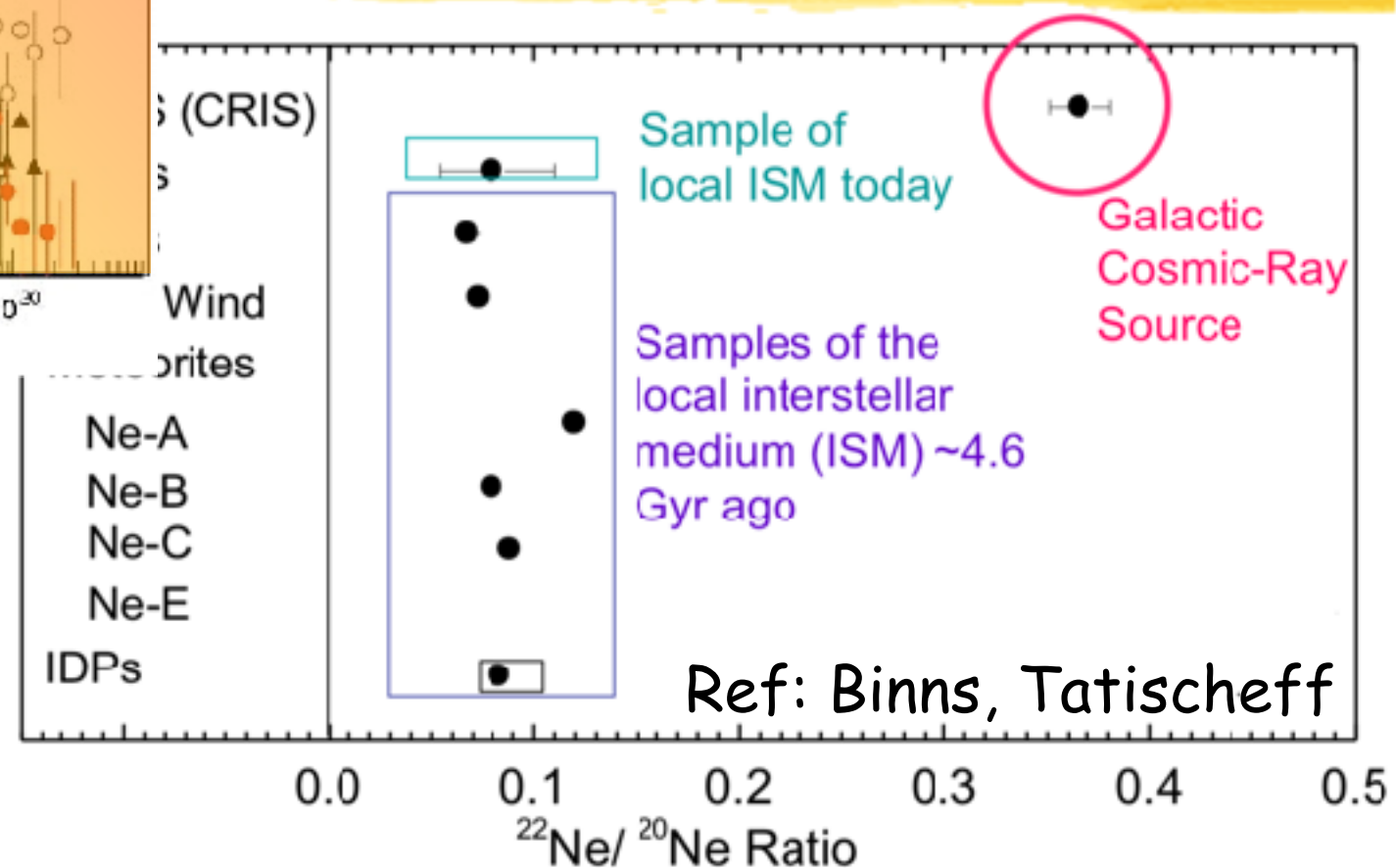
Supernova remnants

(At least) three serious issues remains



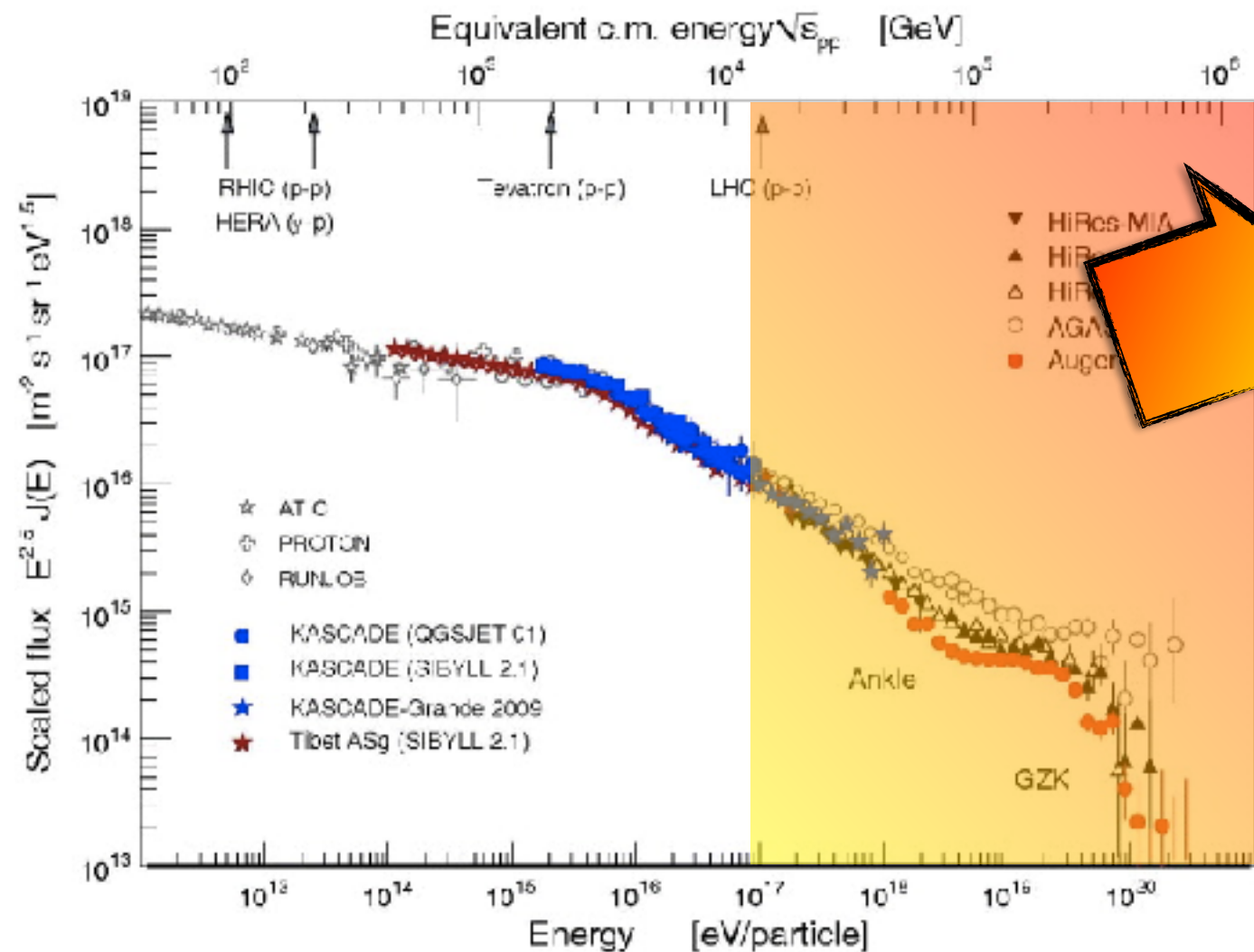
[1] can SNR shocks accelerate particles up to the largest observed energies?

[2] can the SNR paradigm explain the anomalous excess of the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio?

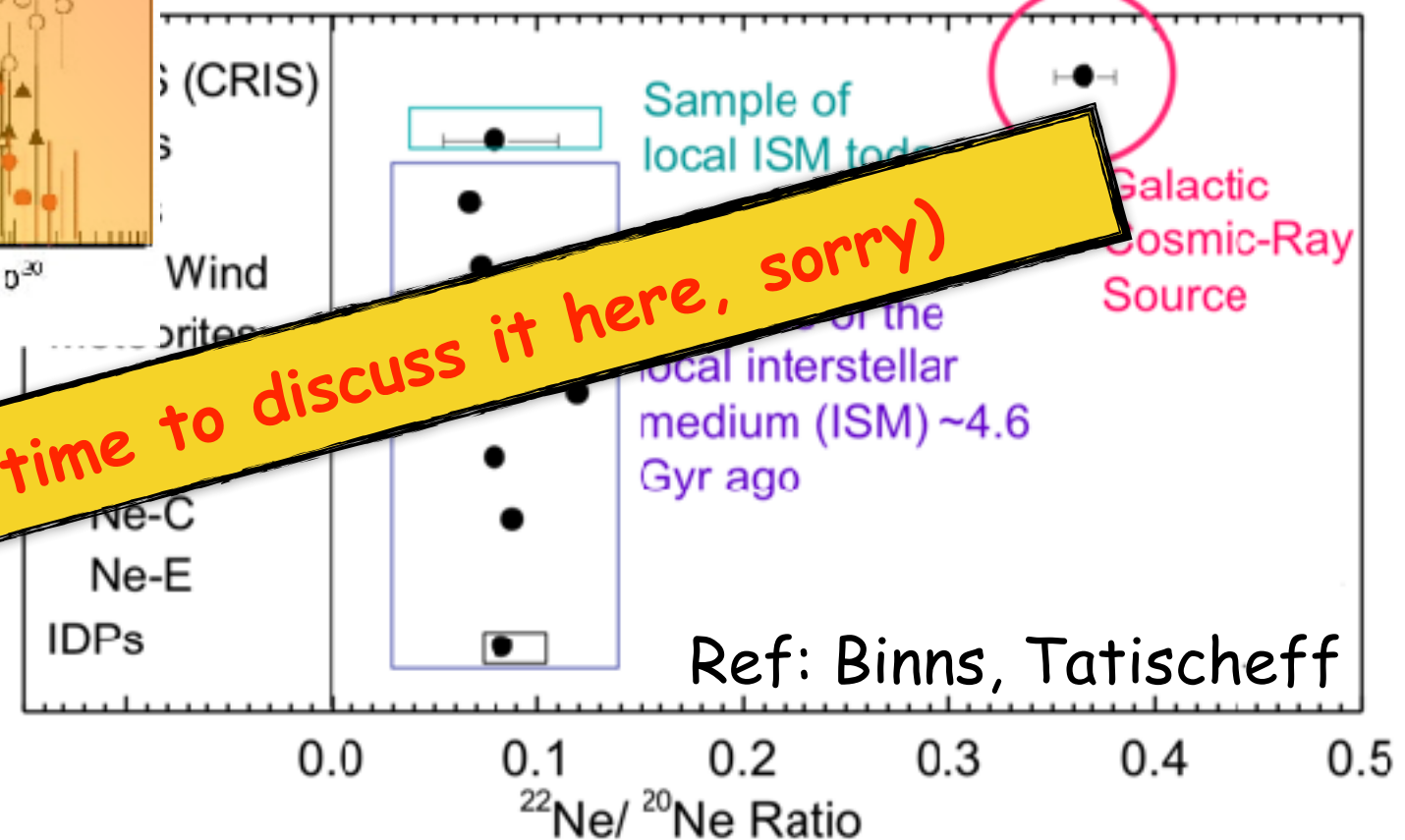


[3] DSA predicts E^{-2} spectra, but we need $E^{-2.2}$!

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[1] can SNR shocks accelerate particles up to the largest observed energies?

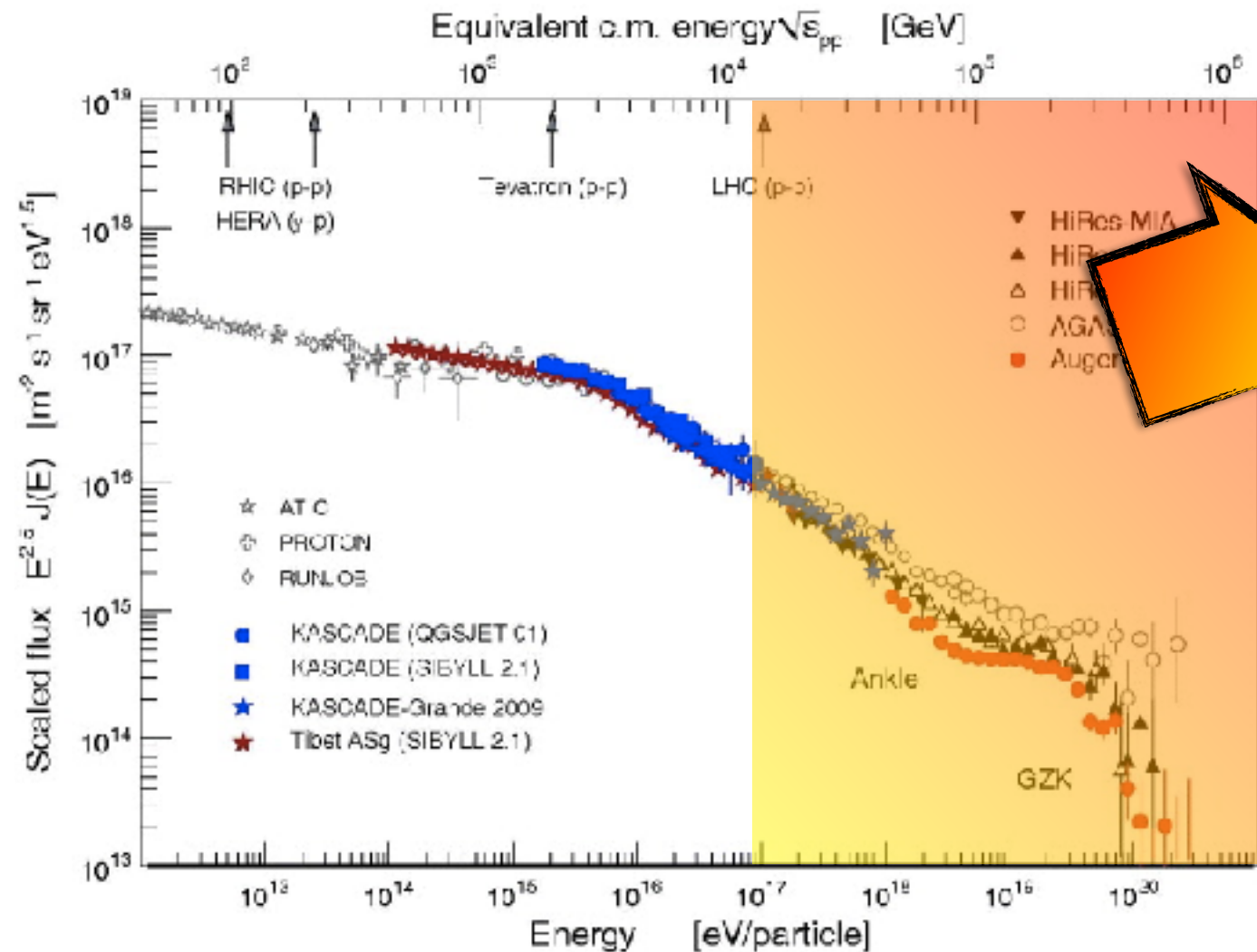


[2] can the SNR explain the excess of the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio?

stellar winds (no time to discuss it here, sorry)

[3] DSA predicts E^{-2} spectra, but we need $E^{-2.2}$!

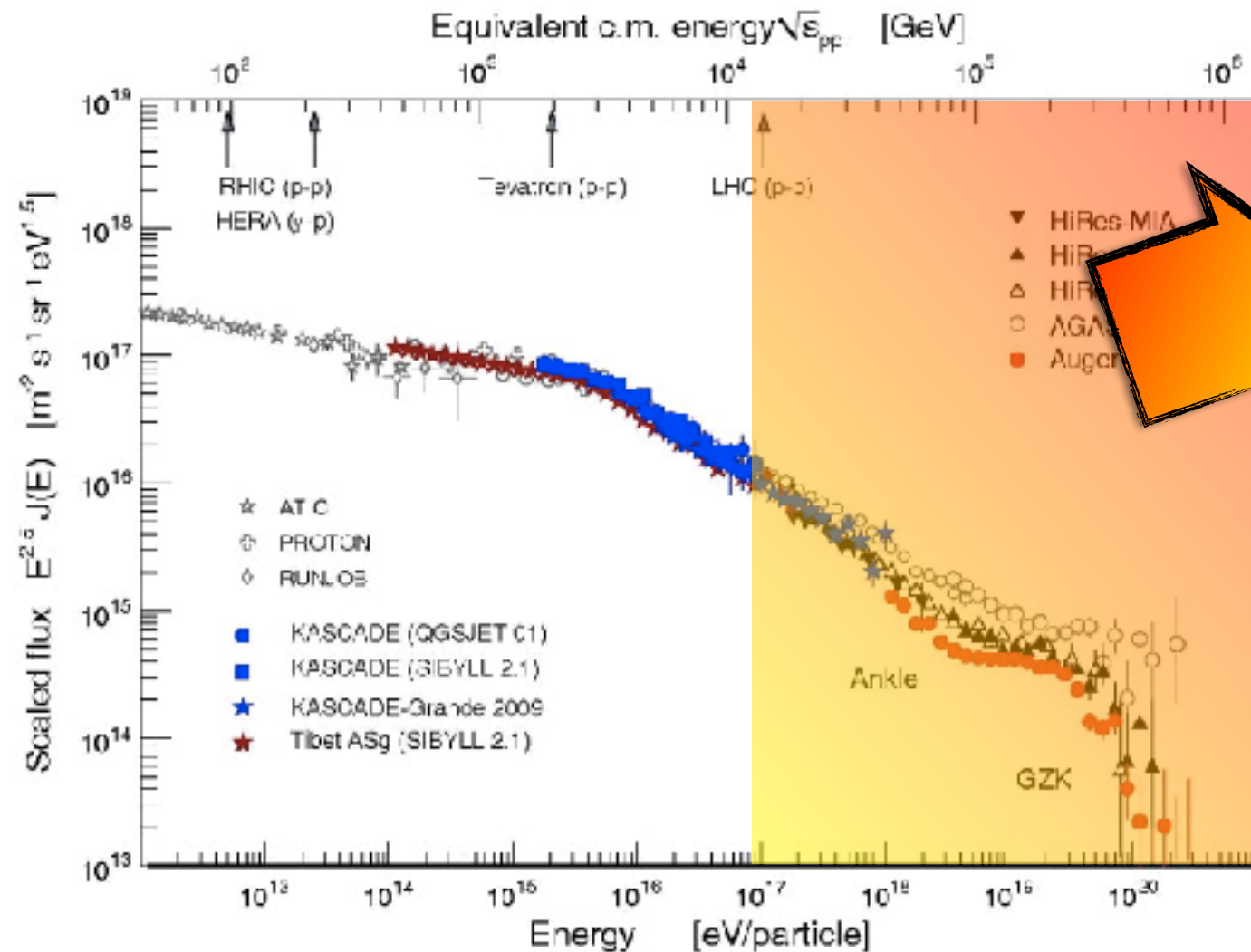
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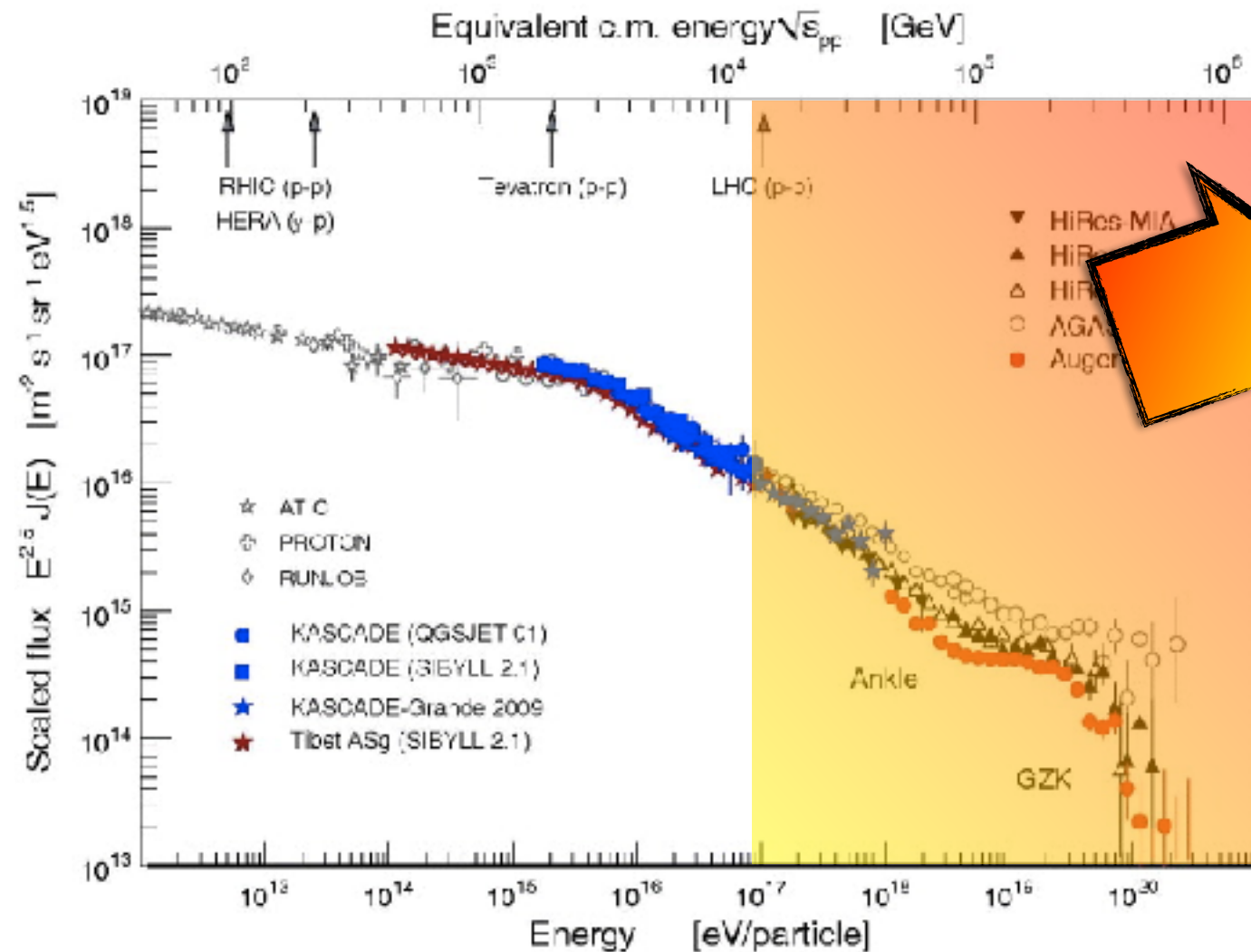


[1] can SNR shocks accelerate particles up to the largest observed energies?

to answer this one needs to understand particle escape from the accelerator

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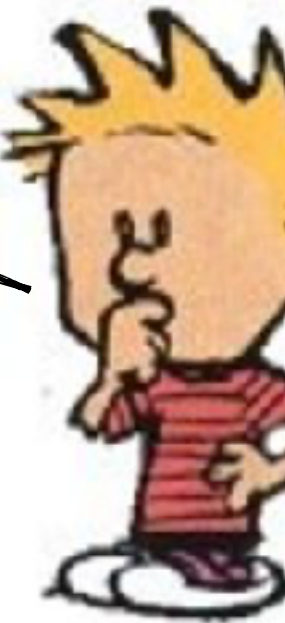


[1] can SNR shocks accelerate particles up to the largest observed energies?

think about the extreme case where particles NEVER escape the accelerator...

to answer this one needs to understand particle escape from the accelerator

[3] DSA predicts E^{-2} spectra, but we need $E^{-2.2}$!

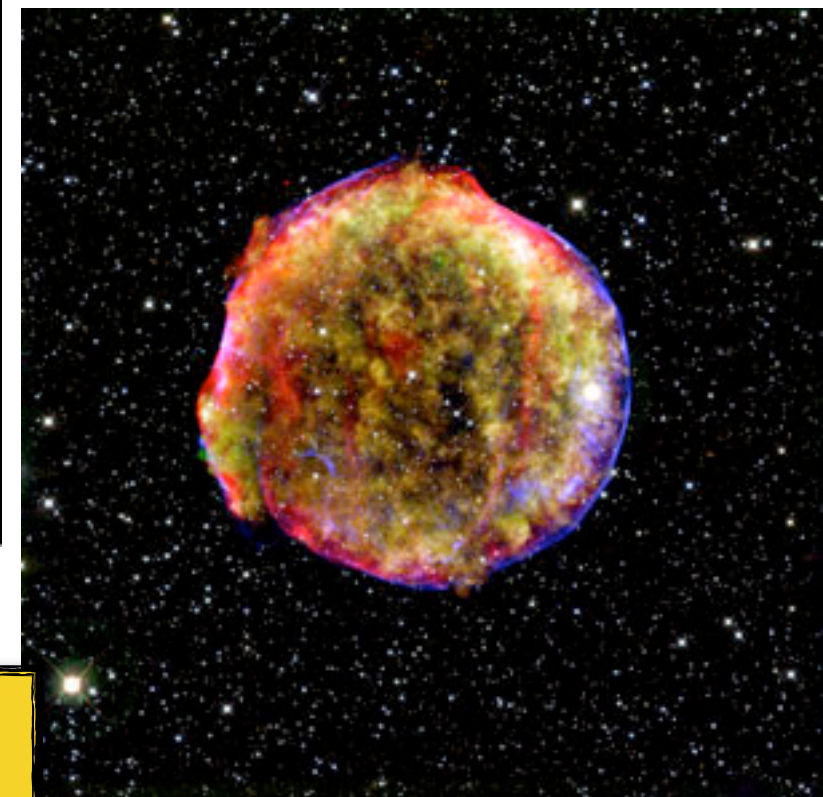
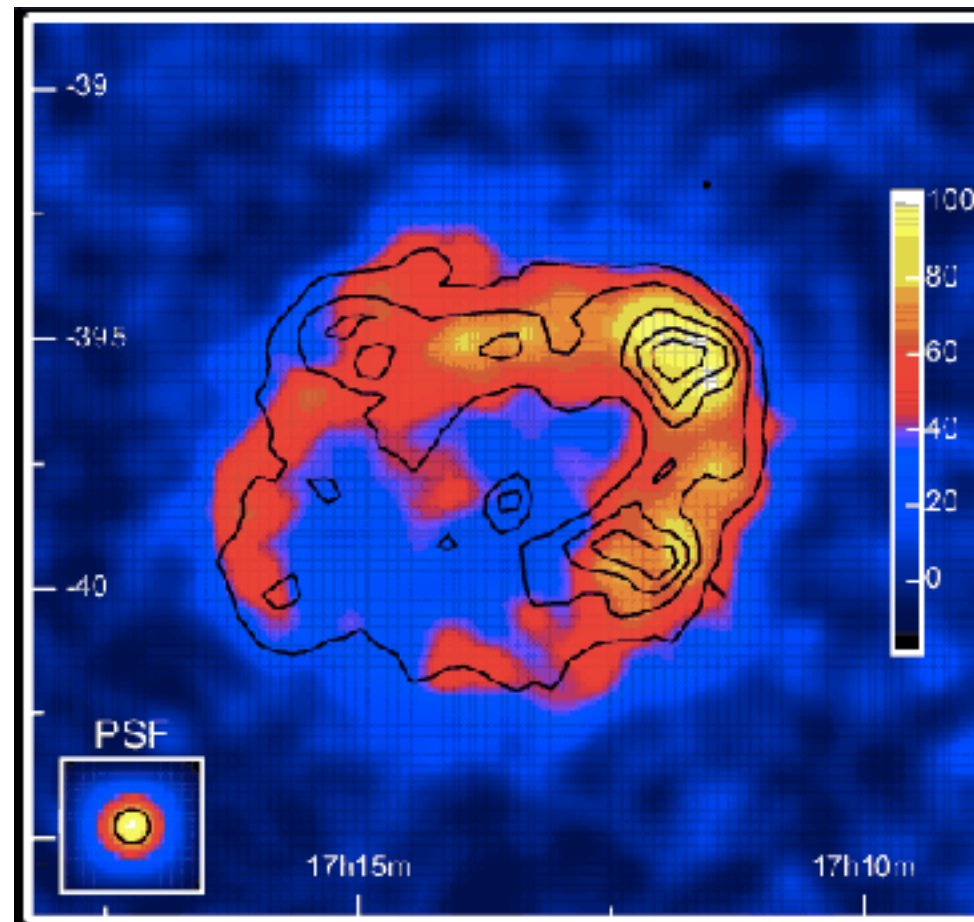
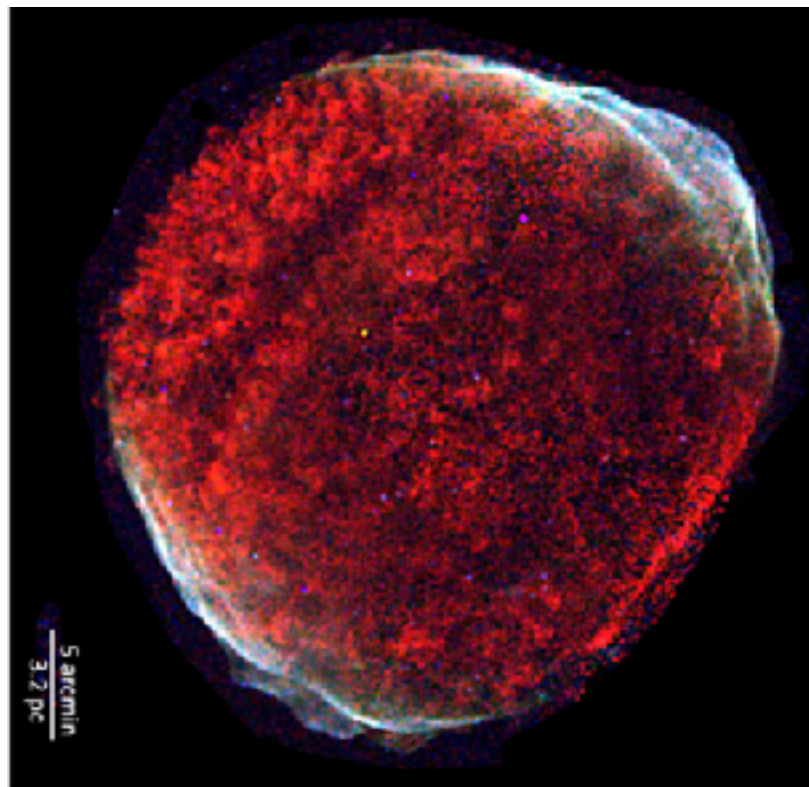


A small detail...

DSA: we considered a plane and infinite shock moving at constant speed

A small detail...

DSA: we considered a plane and infinite shock moving at constant speed



...SNRs are roughly spherical and the shock decelerates

Astrophysical explosions

interstellar medium

pressure

P

density

ρ



massive star

Astrophysical explosions

interstellar medium

mass of the ejecta

explosion energy

M_{ej} E_{SN} P ρ

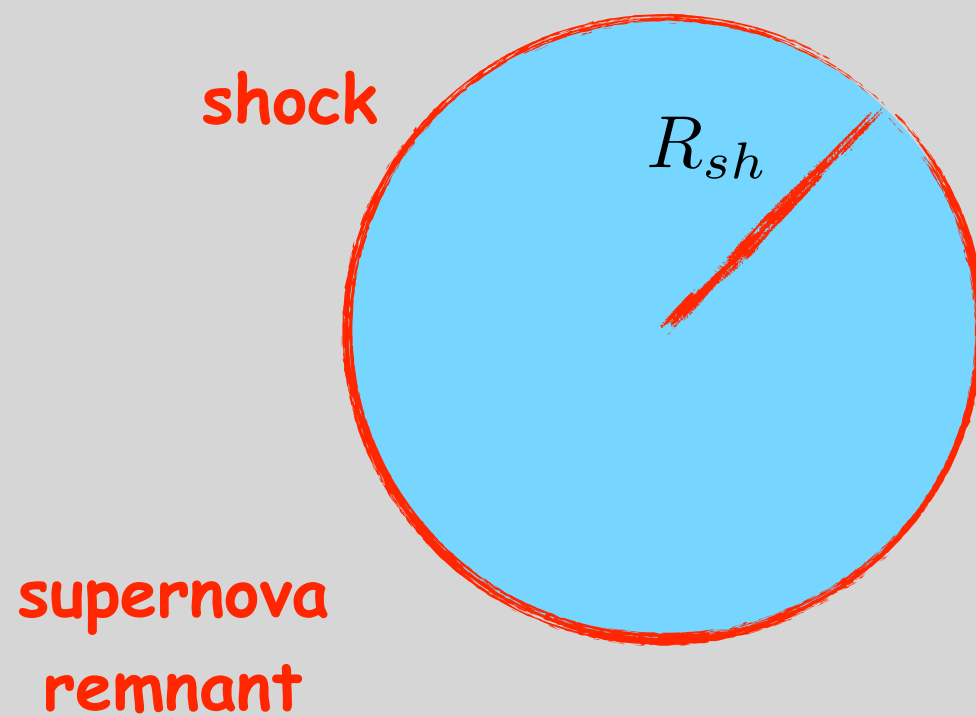
supernova



Astrophysical explosions

interstellar medium

$$M_{ej} \quad E_{SN} \quad P \quad \varrho$$



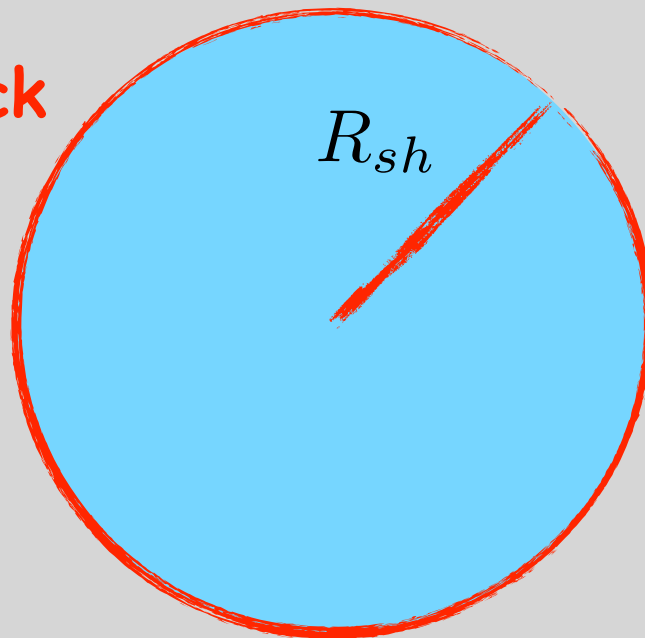
Astrophysical explosions

interstellar medium

$$M_{ej} \quad E_{SN} \quad P \quad \varrho$$

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$

shock



supernova
remnant

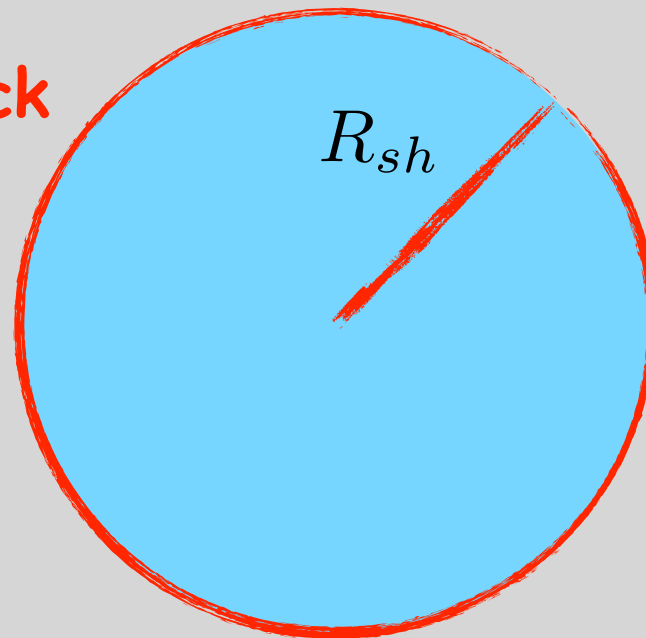
Astrophysical explosions

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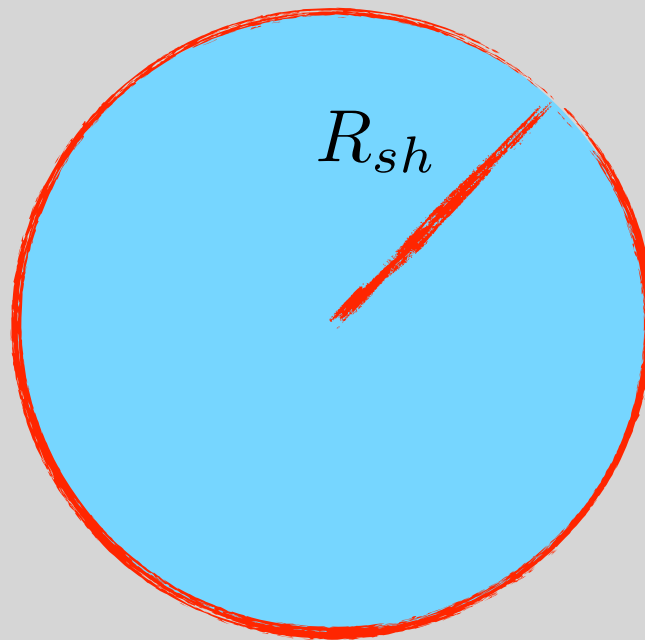
Astrophysical explosions

interstellar medium

$$M_{ej} \gg M_{sw}$$

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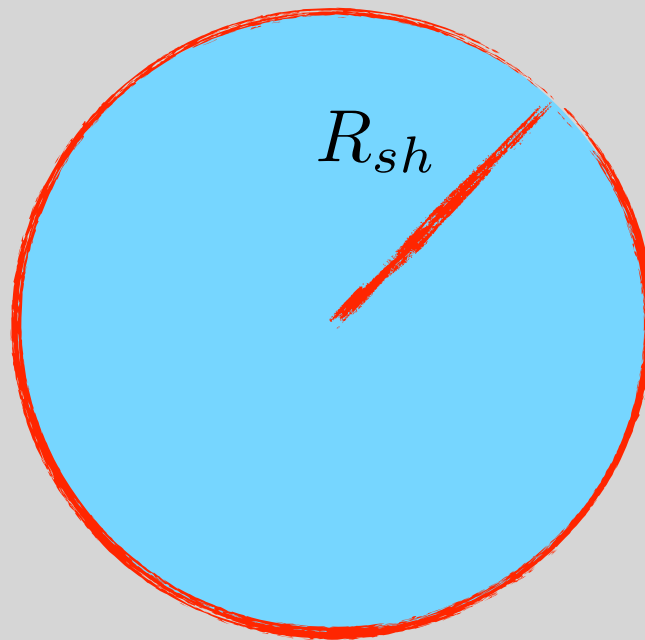
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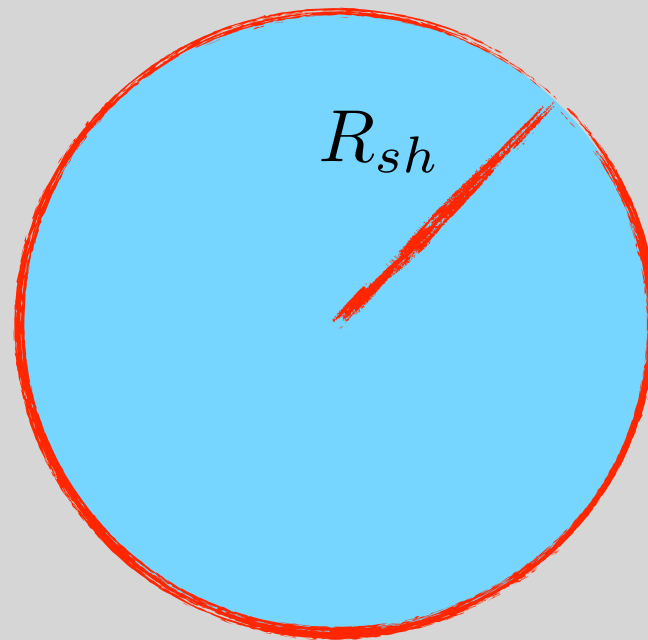
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$$M_{ej} \gg M_{sw}$$

$$M_{ej} \quad E_{SN} \quad \cancel{P} \quad \cancel{t}$$

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free expansion
(constant speed)

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2$$

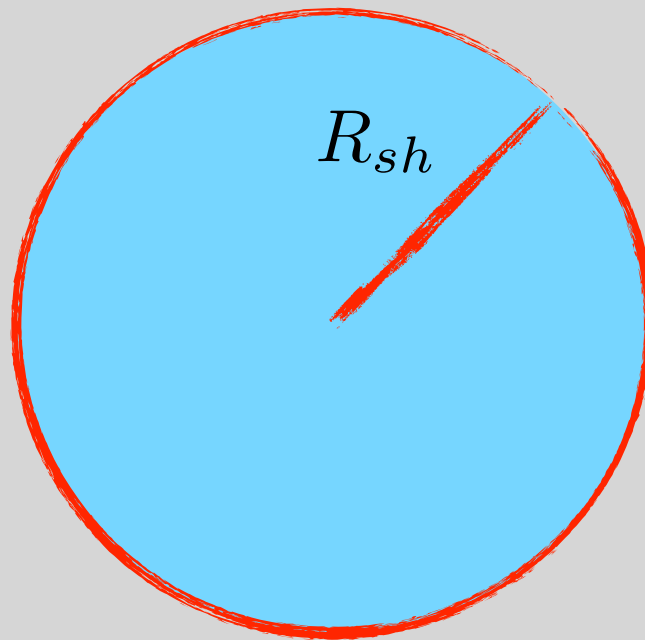
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$$M_{ej} \quad E_{SN} \quad \cancel{P} \quad \cancel{t}$$

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free expansion
(constant speed)

$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2 \longrightarrow v_{sh} = \sqrt{\frac{2E_{SN}}{M_{ej}}} \sim 10000 \left(\frac{M_{ej}}{M_{\odot}} \right)^{-1/2} \text{ km/s}$$

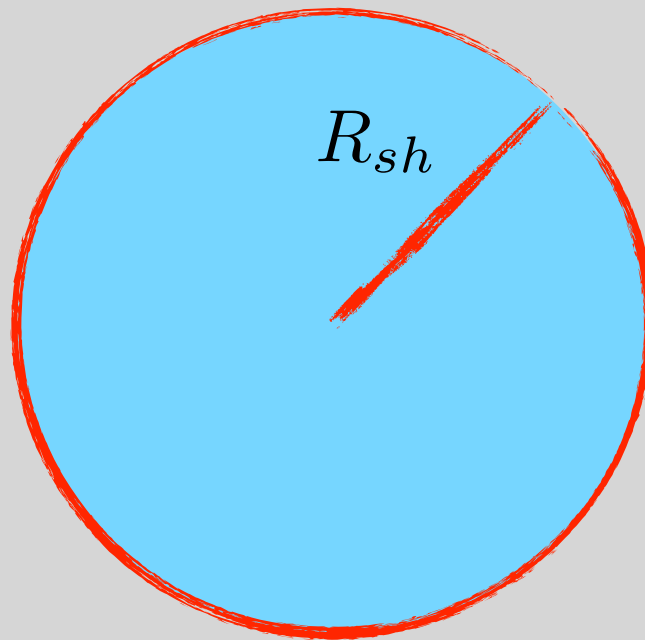
Astrophysical explosions

interstellar medium

$$M_{ej} = M_{sw}$$

$$M_{ej} \quad E_{SN} \quad \cancel{P} \quad \cancel{Q}$$

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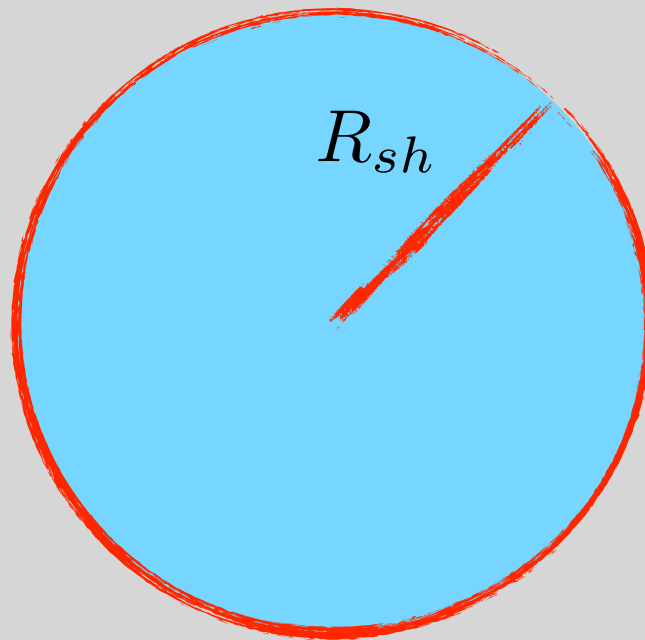
Astrophysical explosions

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$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \varrho$$



$$R_* = \left(\frac{3M_{ej}}{4\pi\varrho} \right)^{1/3} \sim 2 \left(\frac{M_{ej}}{M_{\odot}} \right)^{1/3} \left(\frac{n}{\text{cm}^{-3}} \right)^{-1/3} \text{ pc}$$

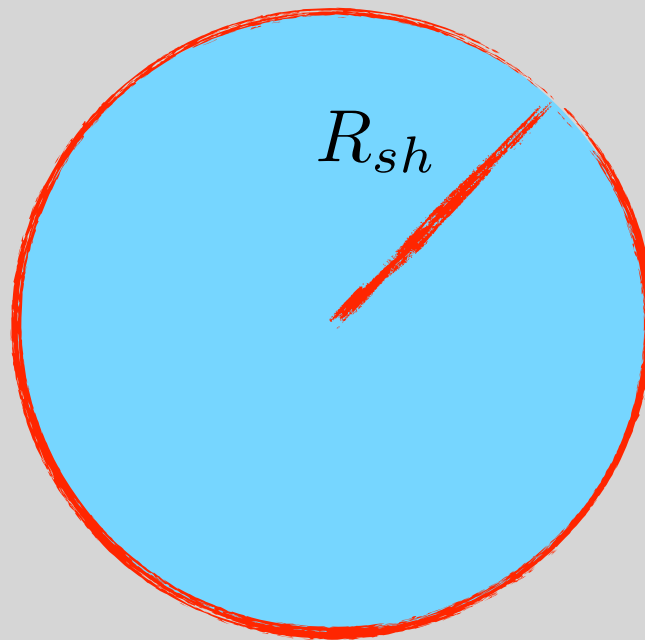
Astrophysical explosions

interstellar medium

$$M_{ej} = M_{sw}$$

$$M_{ej} \quad E_{SN} \quad \cancel{P} \quad \cancel{2}$$

$$M_{sw} = \frac{4\pi}{3} R_{sh}^3 \rho$$



it takes few centuries
to reach this moment

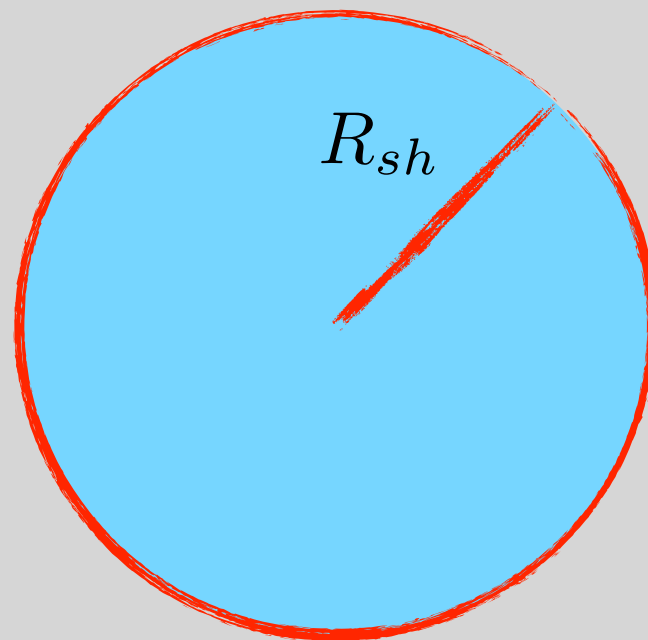
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Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

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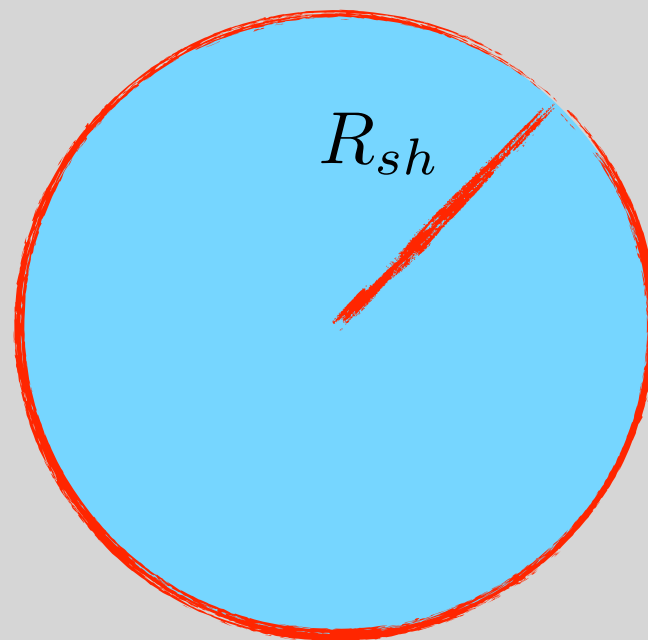


Astrophysical explosions

interstellar medium

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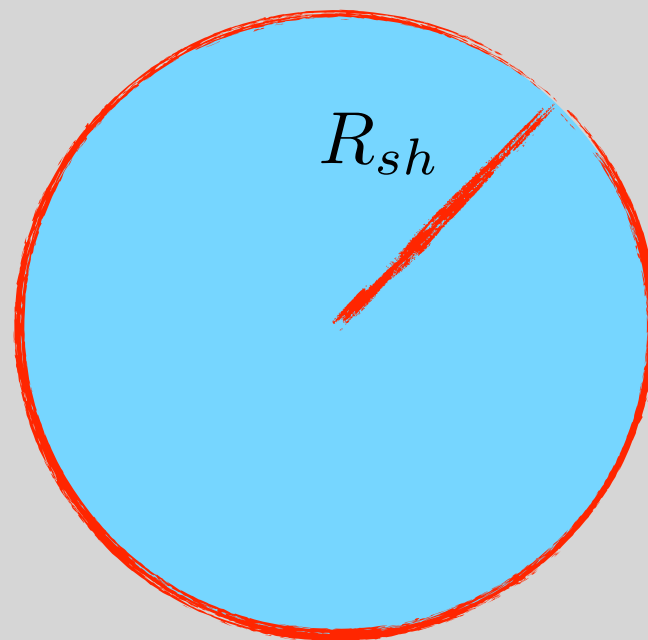
the shock begins to
feel the presence of
the ambient gas and
decelerates

Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad P \quad \rho$$



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Astrophysical explosions

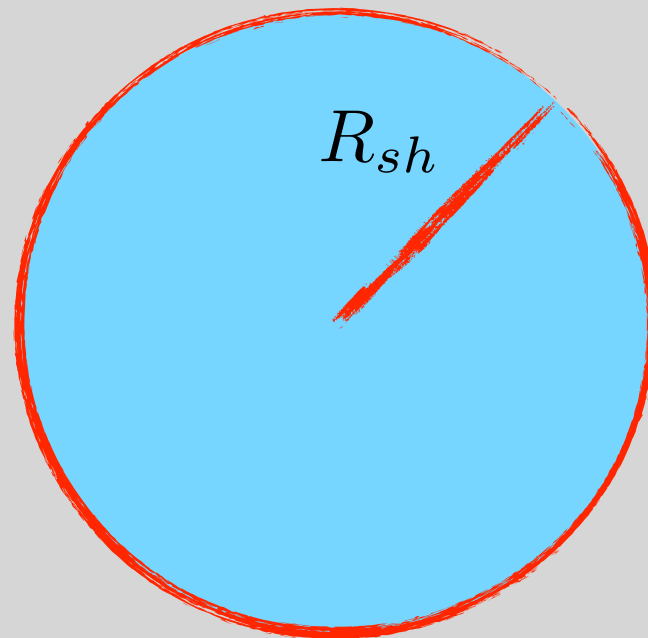
interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad P \quad \rho$$

$$c_s \approx 10 \text{ km/s}$$

strong shock



the shock begins to
feel the presence of
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Astrophysical explosions

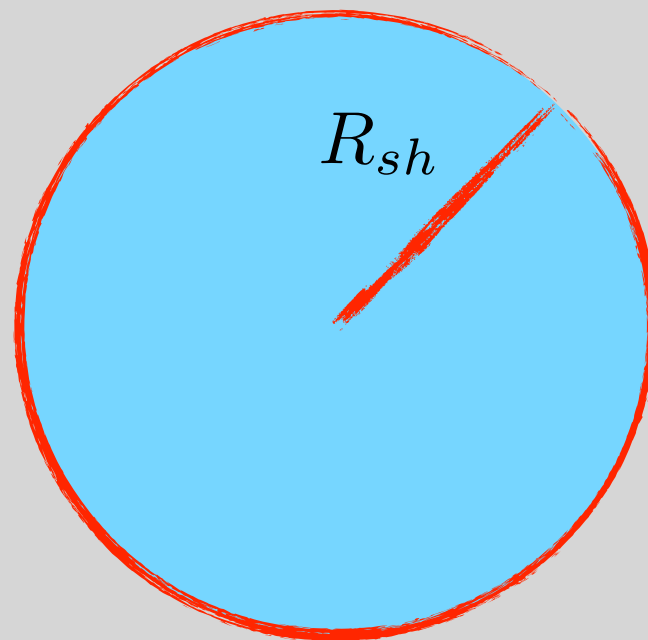
interstellar medium

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$$\cancel{M_{ej}} \quad E_{SN} \quad \cancel{v} \quad \rho$$

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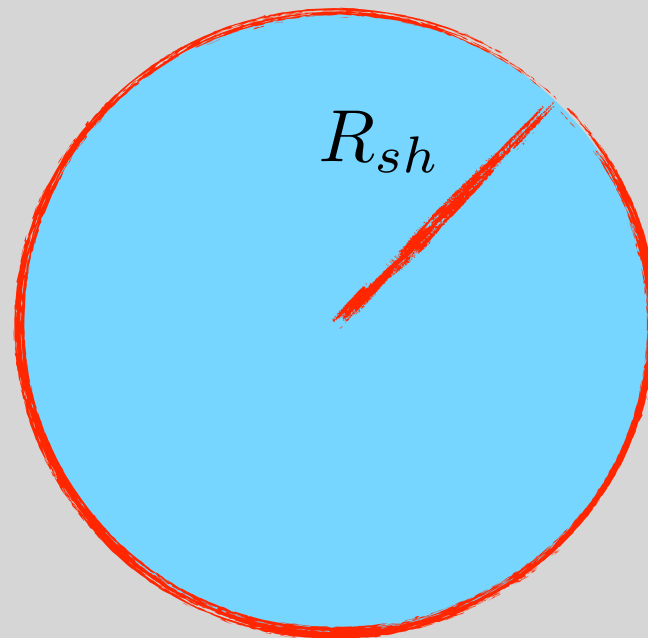
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the shock begins to feel the presence of the ambient gas and decelerates

non-dimensional quantity:

$$a = \frac{\rho R_{sh}^5}{E_{SN} t^2}$$

Astrophysical explosions

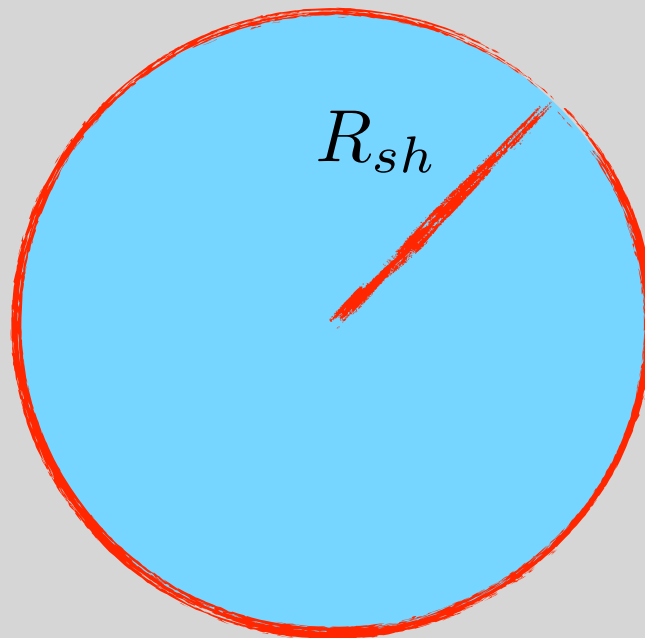
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non-dimensional quantity:

$$a = \frac{\rho R_{sh}^5}{E_{SN} t^2} \longrightarrow R_{sh} = \overset{\text{order unity}}{a} \left(\frac{E_{SN}}{\rho} \right)^{1/5} t^{2/5}$$

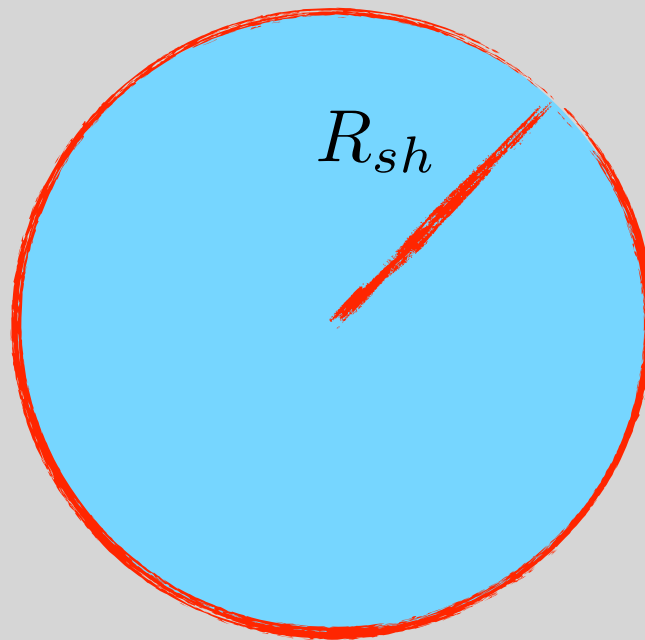
Astrophysical explosions

interstellar medium

$$M_{ej} \ll M_{sw}$$

$$\cancel{M_{ej}} \quad E_{SN} \quad \cancel{\rho} \quad \varrho$$

Sedov-Taylor solution



$$R_{sh} = a \left(\frac{E_{SN}}{\varrho} \right)^{1/5} t^{2/5}$$

$$u_{sh} = \frac{2}{5} \frac{R_{sh}}{t} \propto t^{-3/5}$$

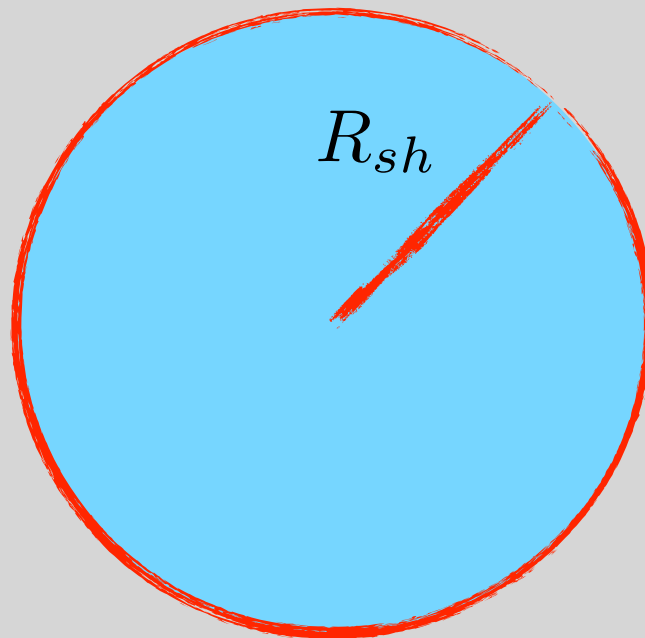
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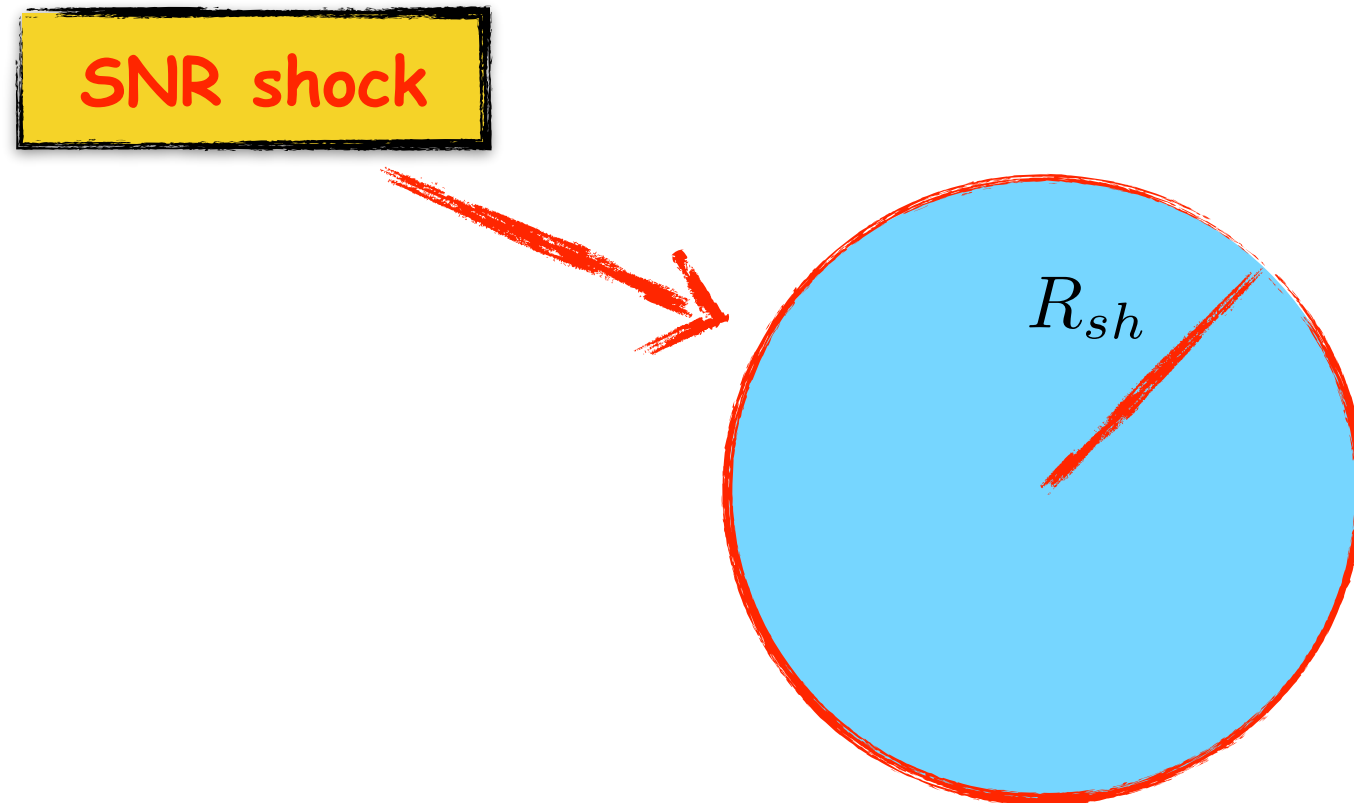
This solution holds until $t \sim 10^4 - 10^5$ yr, after that the SNR cools due to emission of X-ray photons

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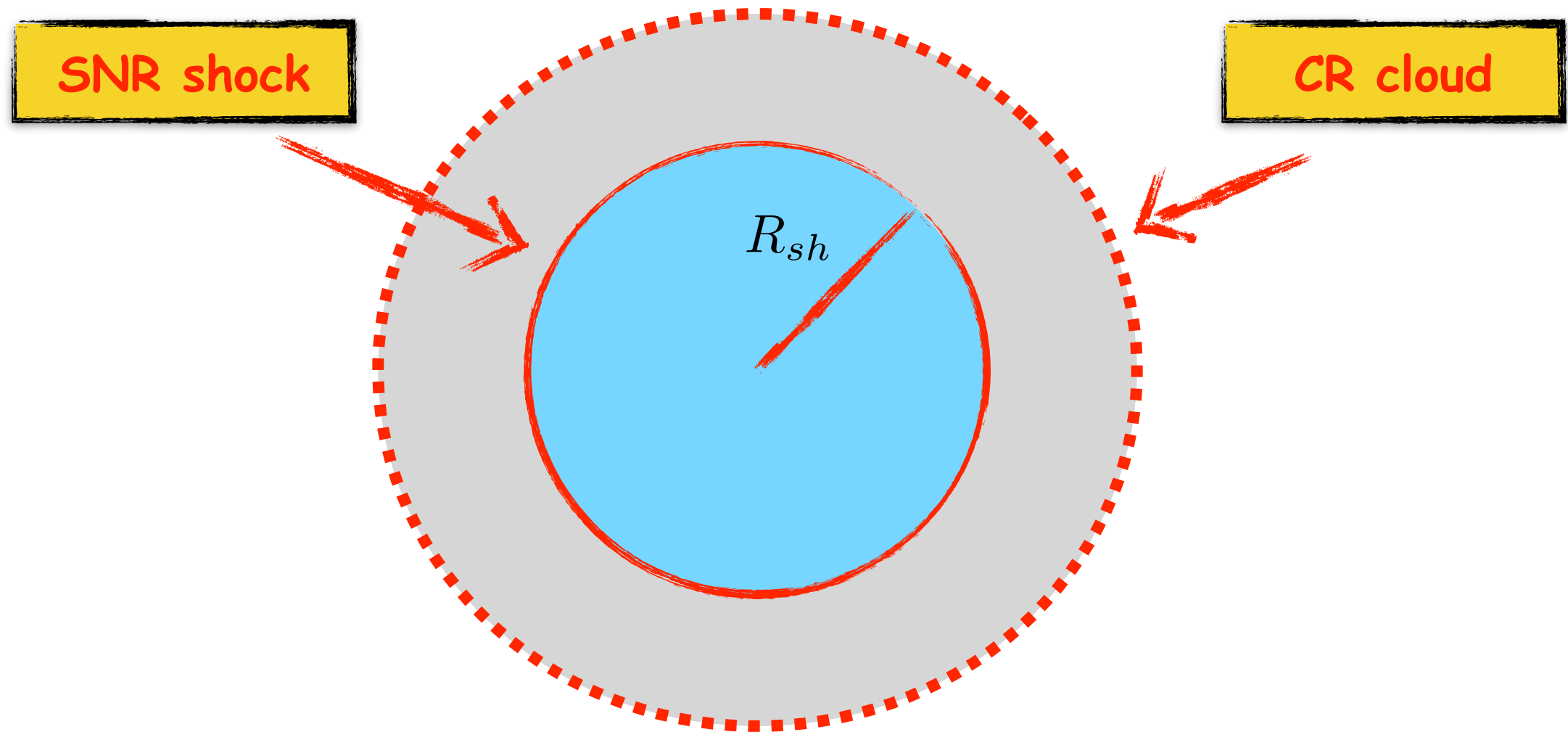
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How do cosmic rays escape
from their sources?

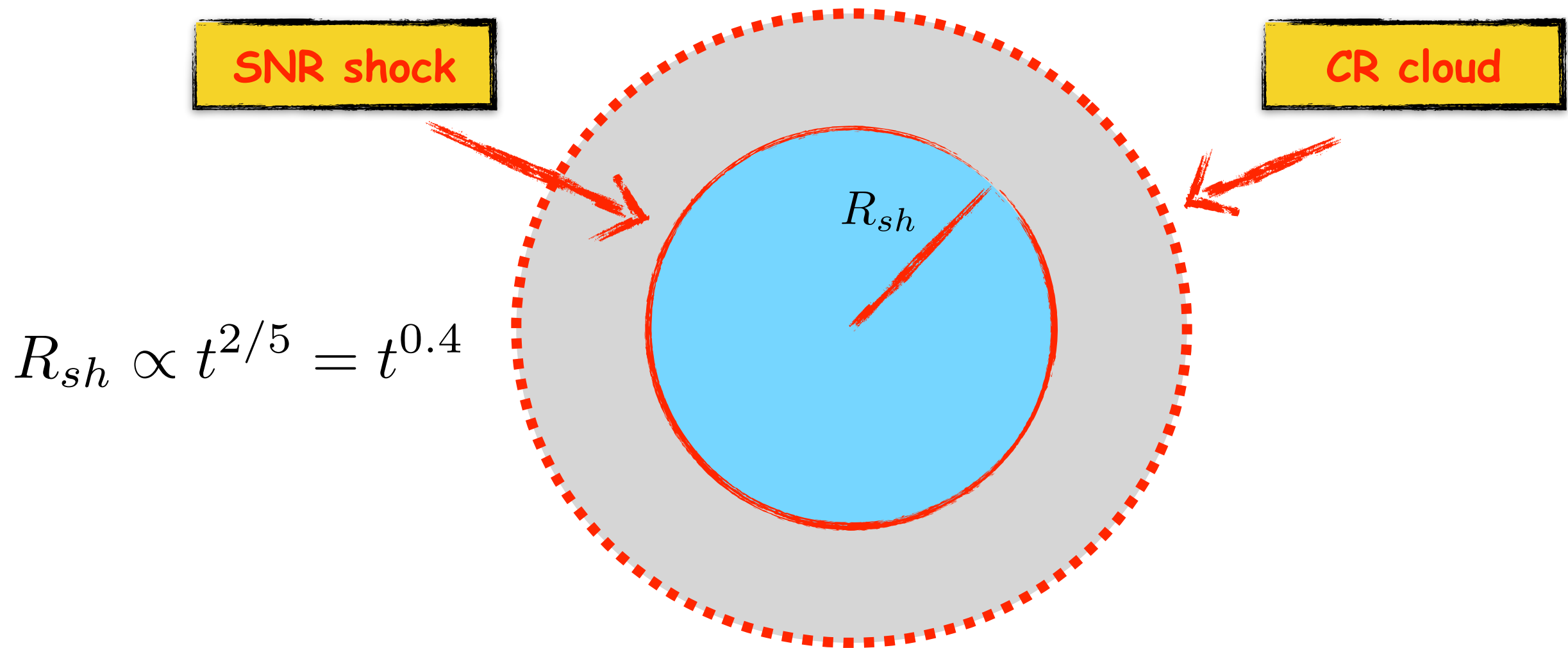
SNR shocks are spherical $\rightarrow$ CR escape



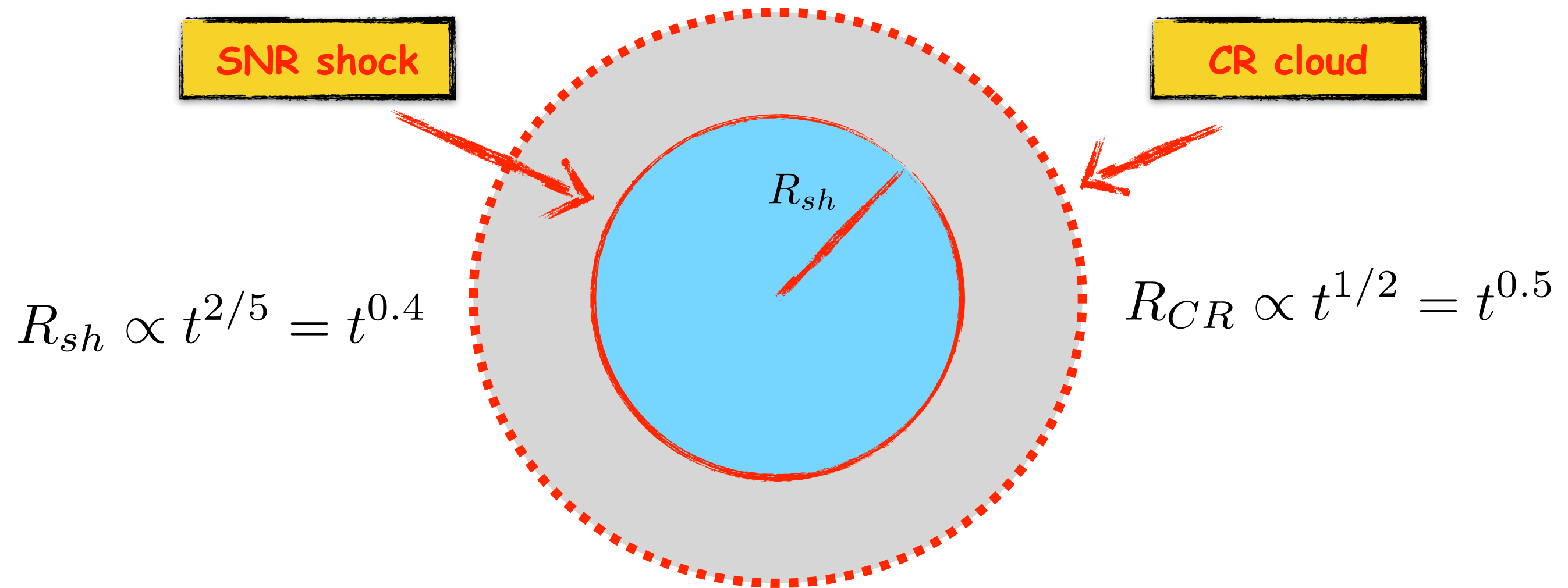
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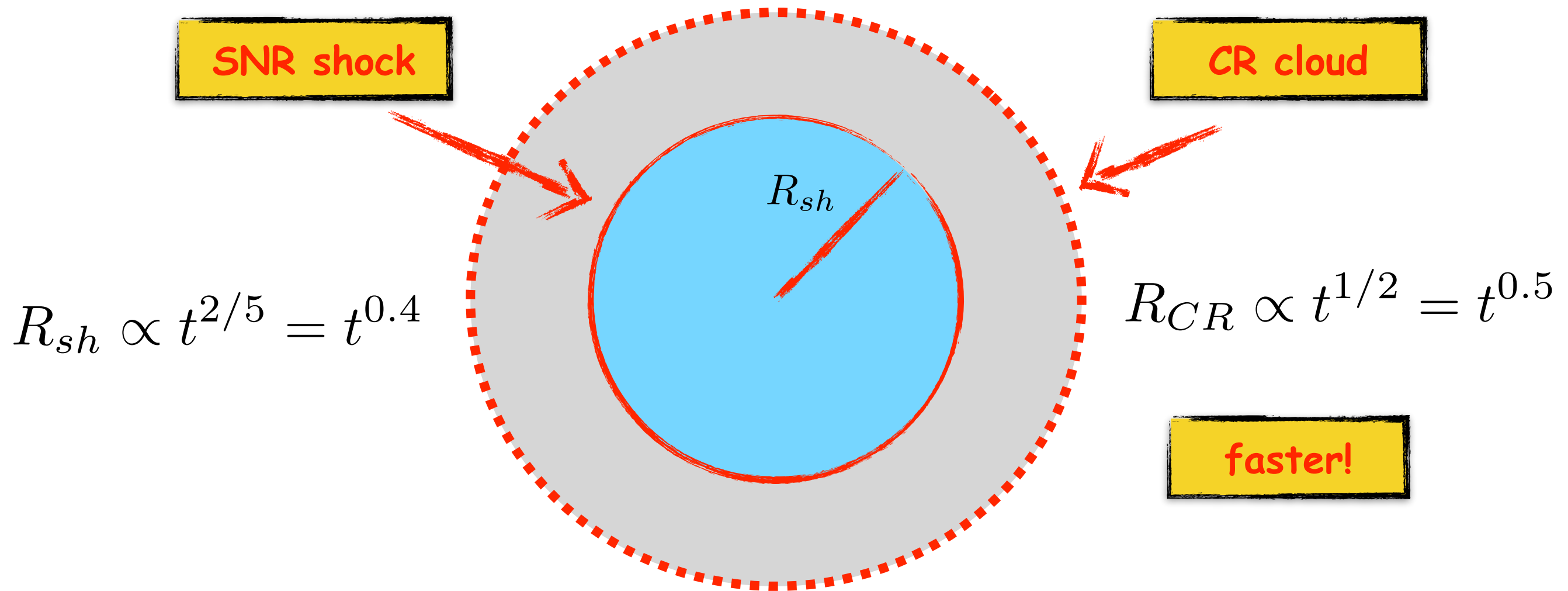
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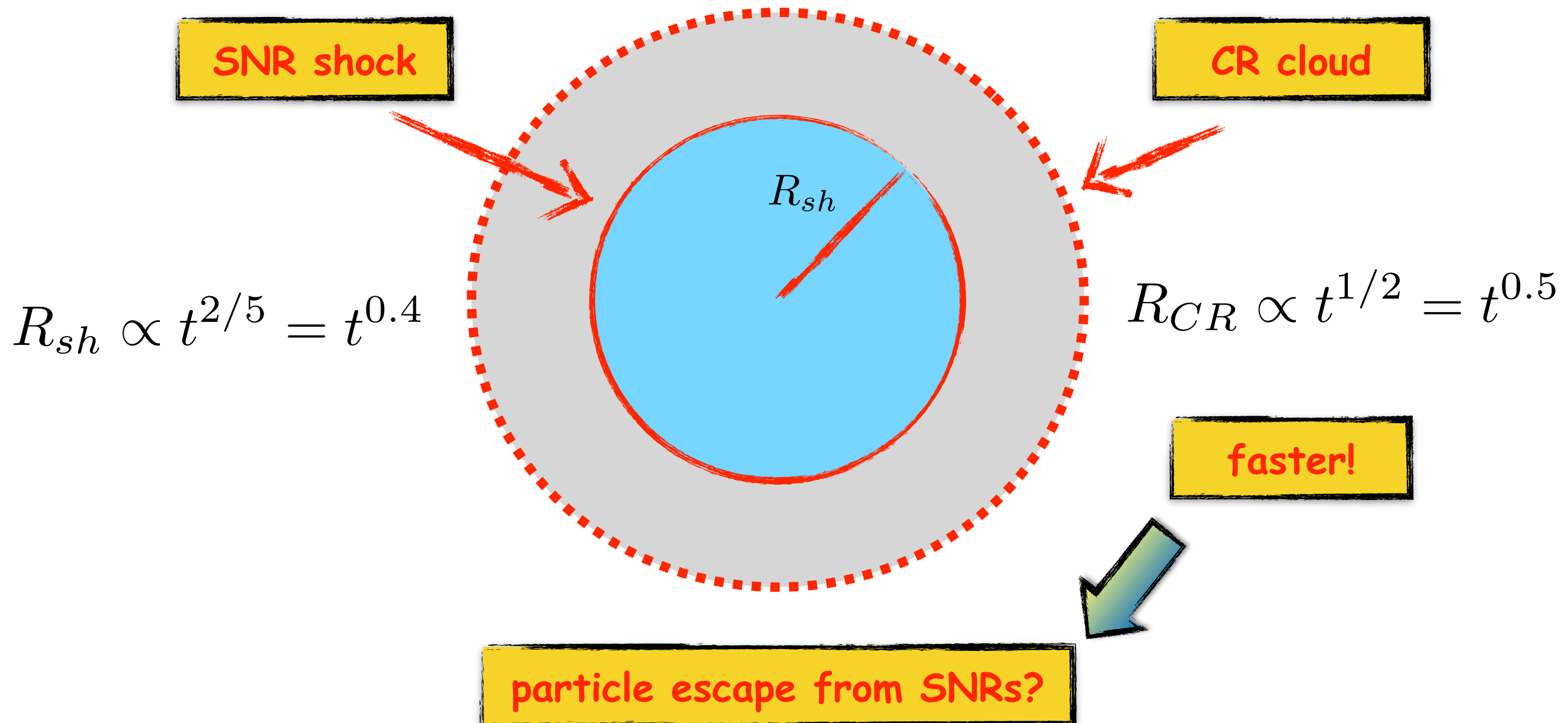
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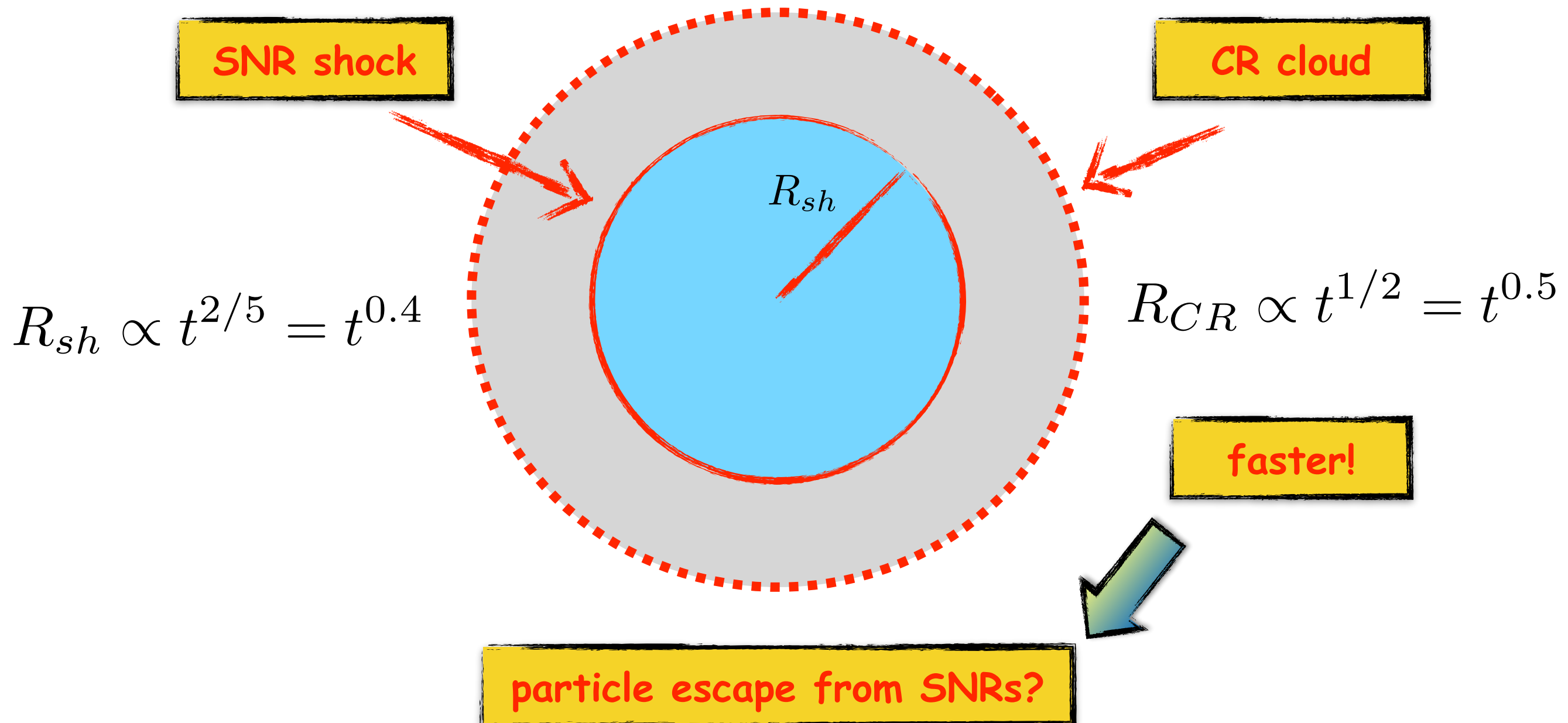
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SNR shocks are spherical $\rightarrow$ CR escape



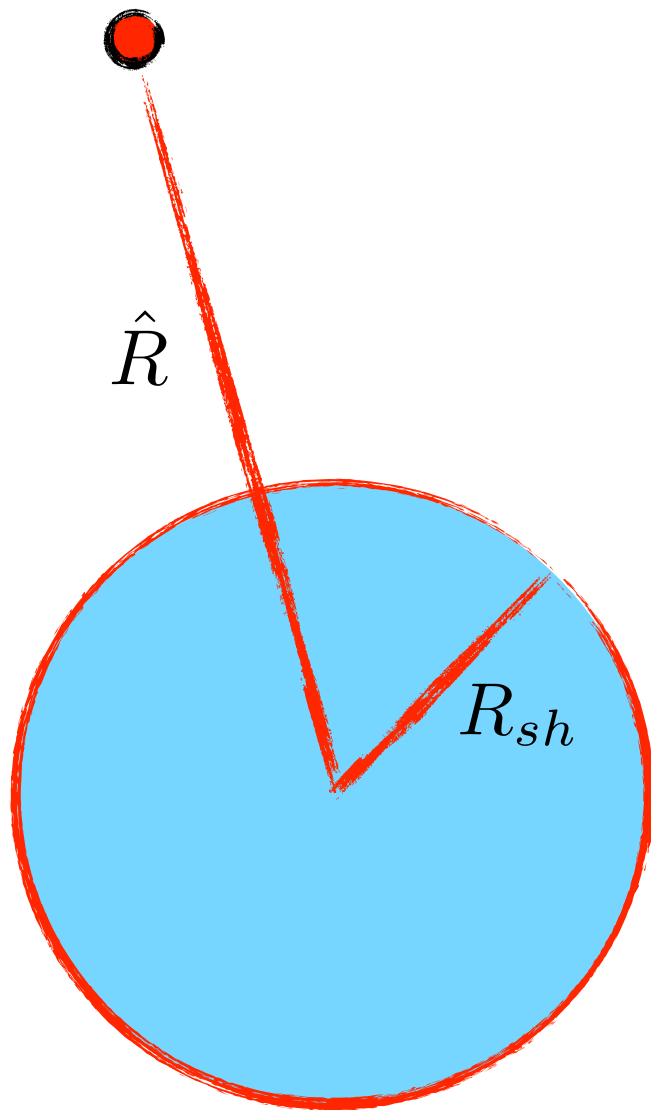
diffusion is faster for larger energies $\rightarrow$ high energy particles escape first?

SNR shocks are spherical

return probability to the shock for a particle located upstream

CR particle

for simplicity let's take the shock to be at rest



SNR shocks are spherical

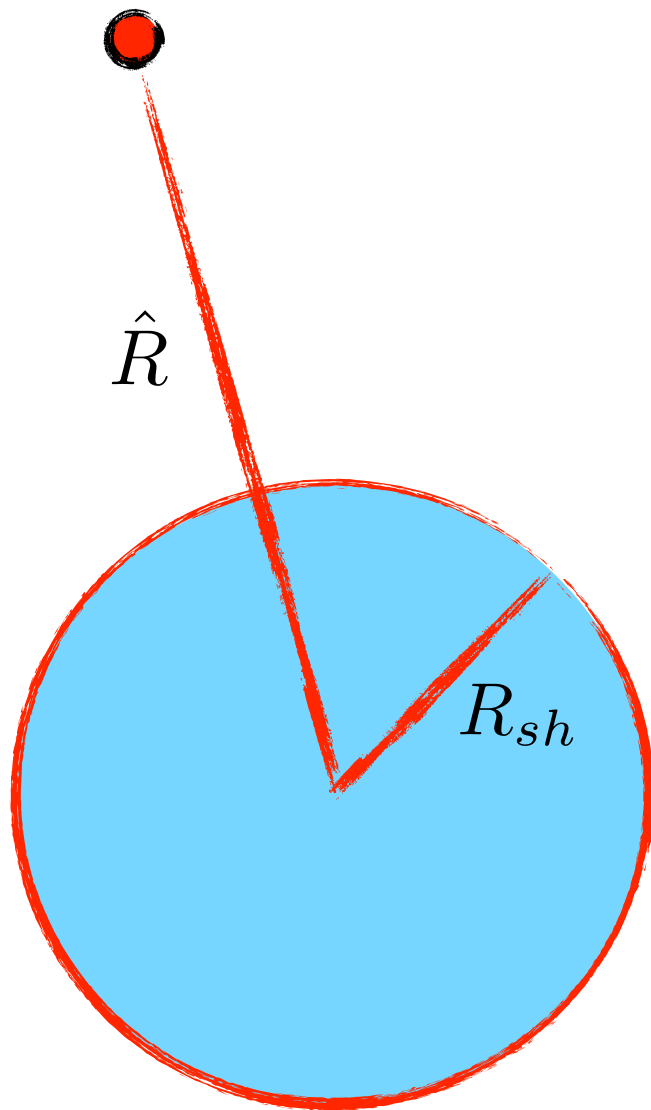
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diffusion equation

$$\frac{1}{R^2} \frac{\partial}{\partial R} \left(R^2 D \frac{\partial f}{\partial R} \right) = \delta(R - \hat{R})$$



SNR shocks are spherical

return probability to the shock for a particle located upstream

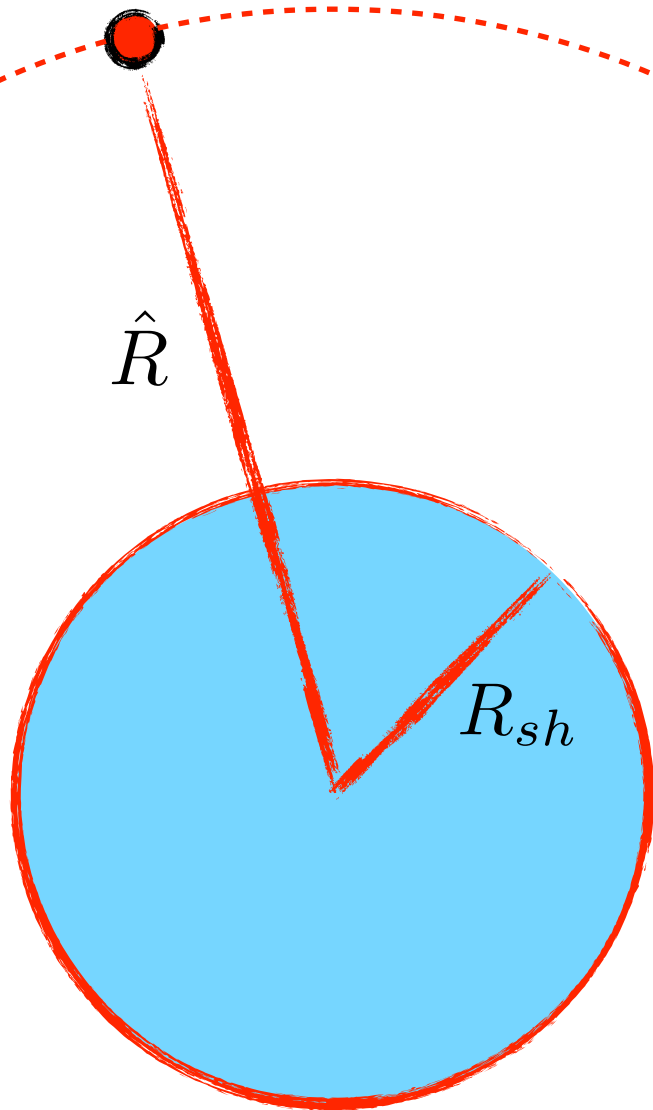
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fictitious source

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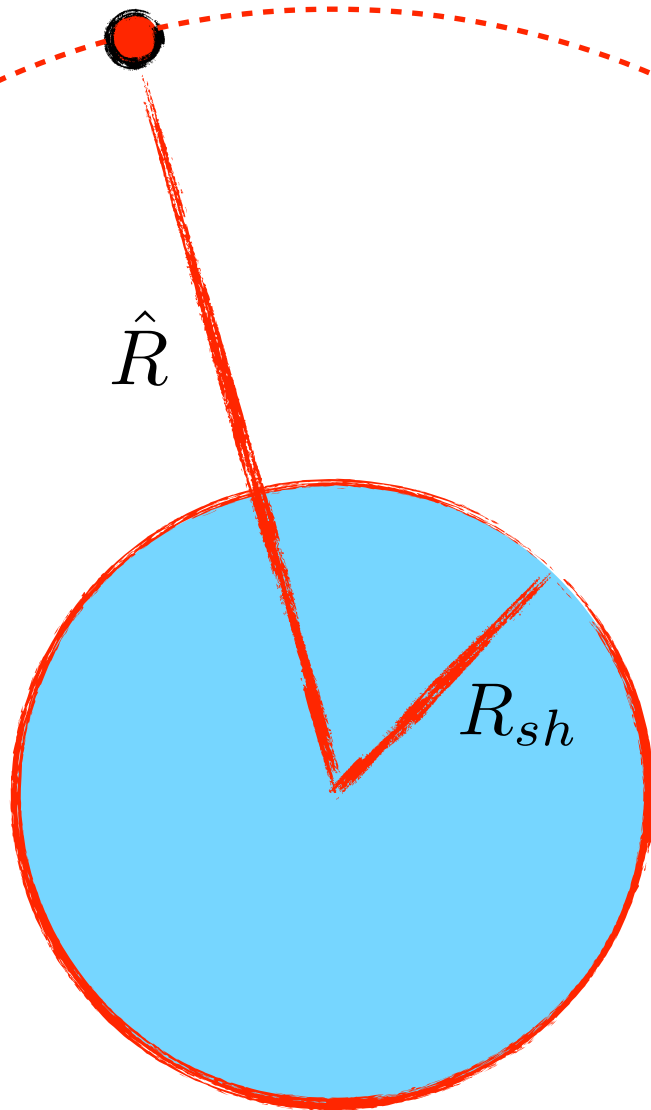
fictitious source

boundary conditions

$$\lim_{R \rightarrow \infty} f = 0$$

$$f(R_{sh}) = 0$$

we treat the shock as an absorbing boundary

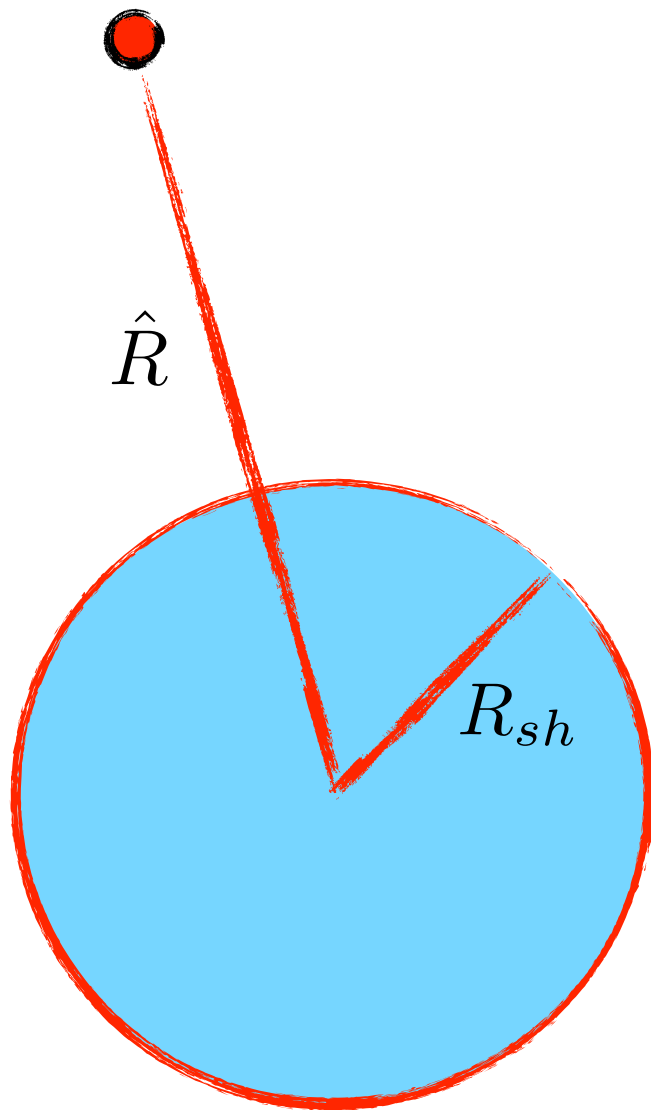


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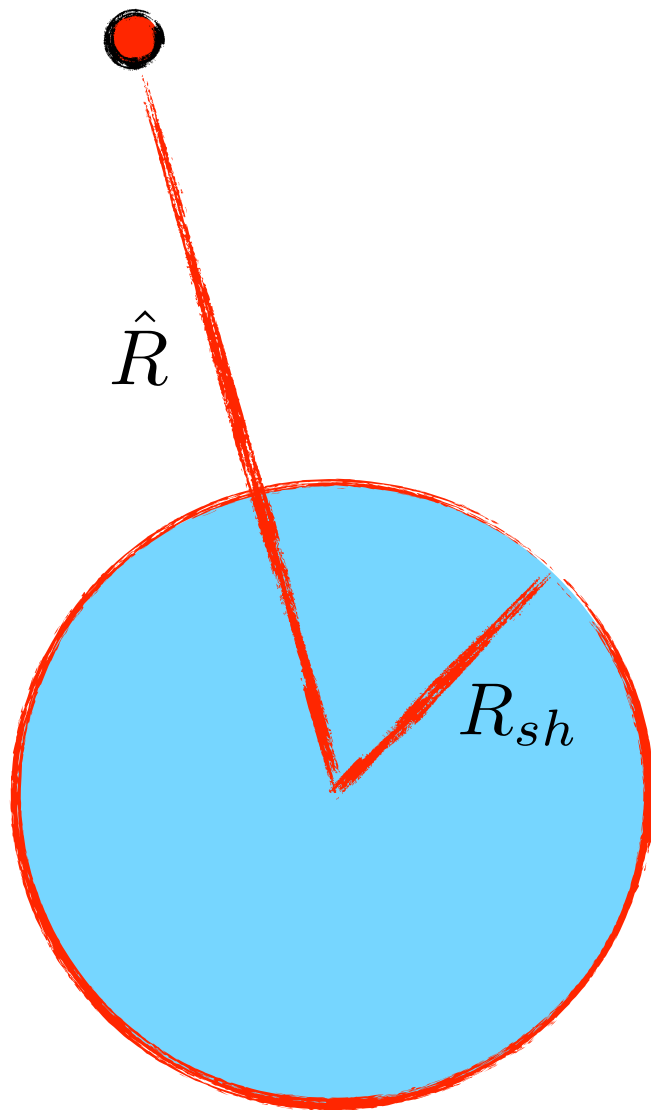
let's solve the equation for $R \neq \hat{R}$



SNR shocks are spherical

return probability to the shock for a particle located upstream

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let's solve the equation for $R \neq \hat{R}$

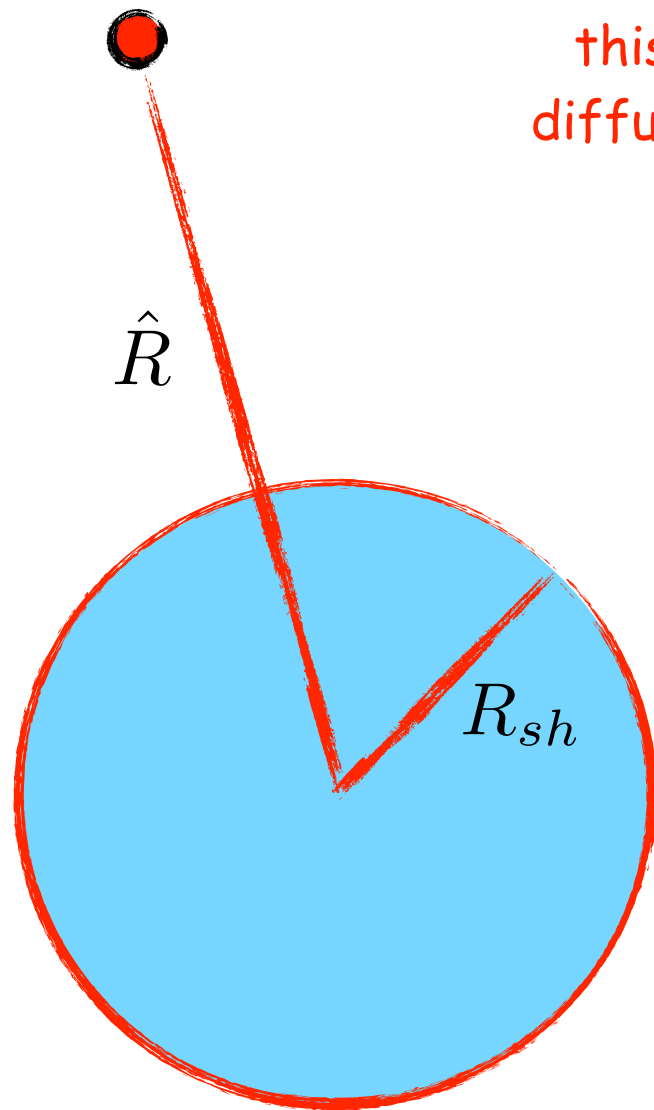
$$R^2 D \frac{df}{dR} = \phi \rightarrow f = -\frac{\phi}{D} \left(\frac{1}{R} + a \right)$$

constant

SNR shocks are spherical

return probability to the shock for a particle located upstream

CR particle



let's solve the equation for $R \neq \hat{R}$

this is the
diffusive flux

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$$\rightarrow f = -\frac{\phi}{D} \left(\frac{1}{R} + a \right)$$

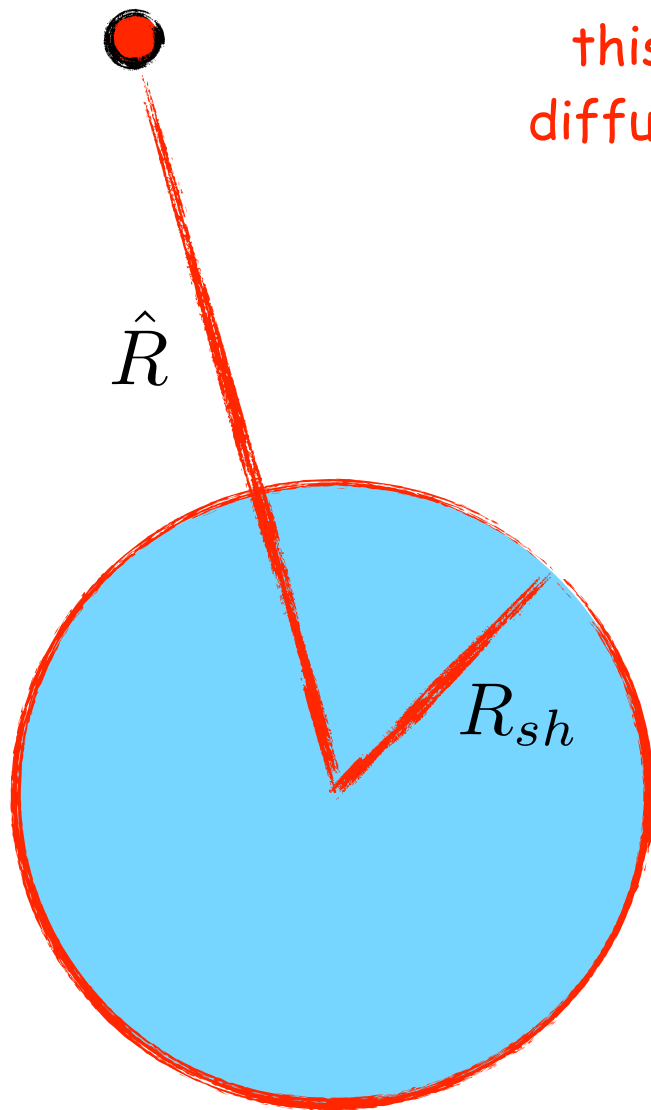
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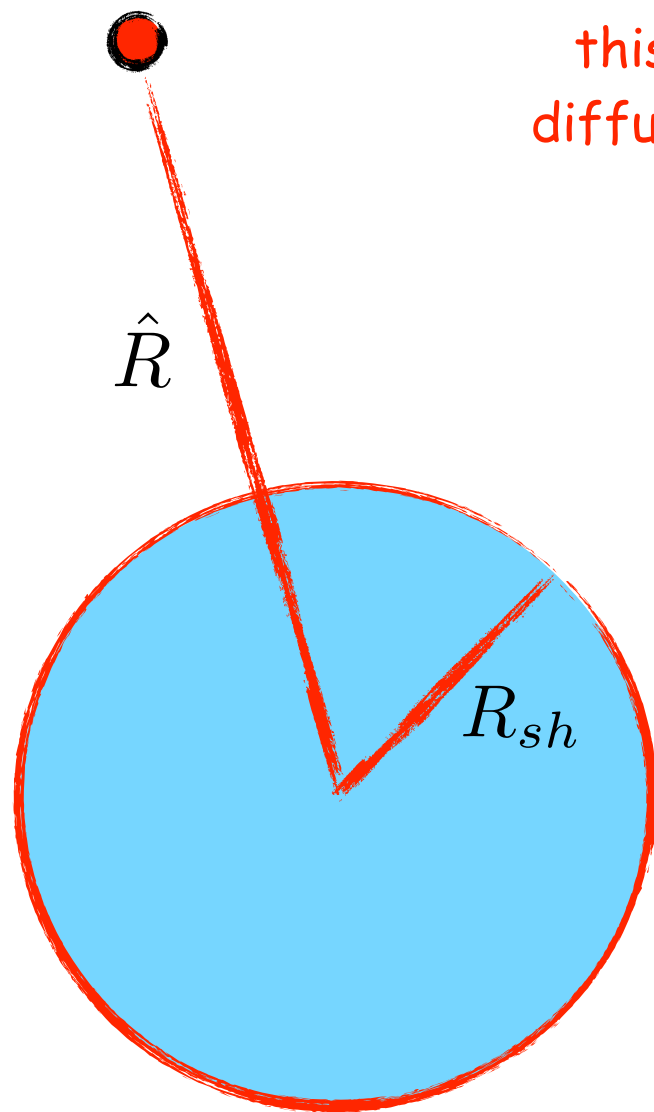
$$R_{sh} < R < \hat{R}$$

$$f(R_{sh}) = 0 \rightarrow f = -\frac{\phi_{sh}}{D} \left(\frac{1}{R} - \frac{1}{R_{sh}} \right)$$

SNR shocks are spherical

return probability to the shock for a particle located upstream

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let's solve the equation for $R \neq \hat{R}$

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diffusive flux

$$R^2 D \frac{df}{dR} = \phi \rightarrow f = -\frac{\phi}{D} \left(\frac{1}{R} + a \right)$$

constant

this is the diffusive flux

$$R_{sh} < R < \hat{R}$$

$$f(R_{sh}) = 0 \rightarrow f = -\frac{\phi_{sh}}{D} \left(\frac{1}{R} - \frac{1}{R_{sh}} \right)$$

$$R > \hat{R}$$

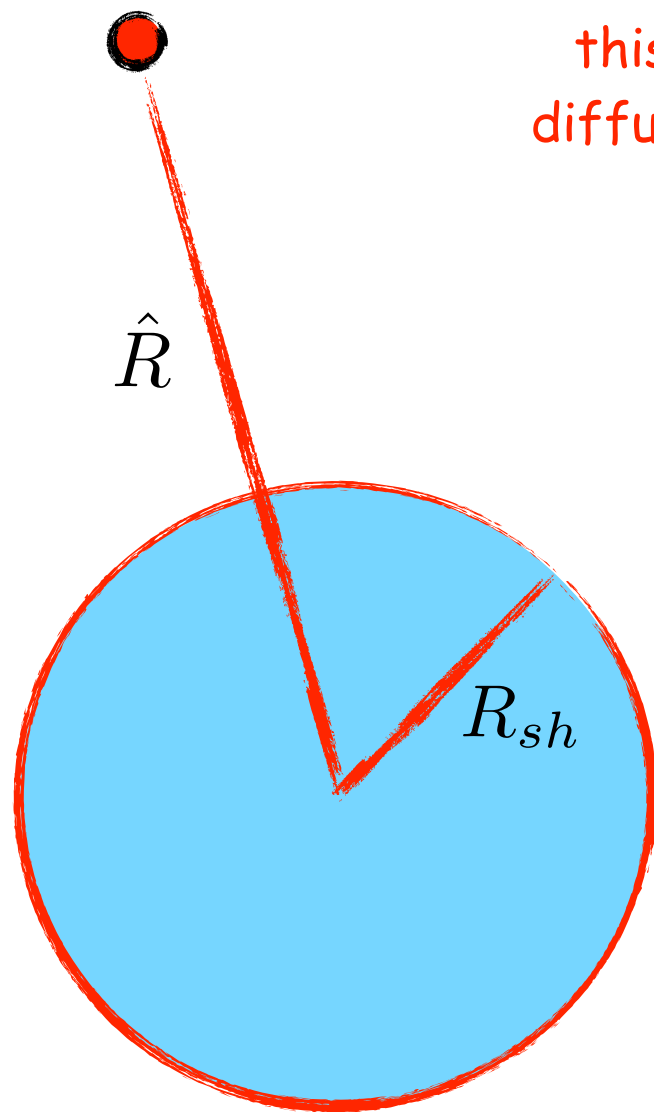
this is negative

$$f(R \rightarrow \infty) = 0 \rightarrow f = -\frac{\phi_{\infty}}{D} \frac{1}{R}$$

SNR shocks are spherical

return probability to the shock for a particle located upstream

CR particle



let's solve the equation for $R \neq \hat{R}$

this is the
diffusive flux

$$R^2 D \frac{df}{dR} = \phi \rightarrow f = -\frac{\phi}{D} \left(\frac{1}{R} + a \right)$$

constant

this is the diffusive flux

$$R_{sh} < R < \hat{R}$$

$$f(R_{sh}) = 0 \rightarrow f = -\frac{\phi_{sh}}{D} \left(\frac{1}{R} - \frac{1}{R_{sh}} \right)$$

$$R > \hat{R}$$

this is negative

$$f(R \rightarrow \infty) = 0 \rightarrow f = +\frac{\phi_{\infty}}{D} \frac{1}{R}$$

we make it positive

SNR shocks are spherical

return probability to the shock for a particle located upstream

the two solutions must be equal (continuity) in $R = \hat{R}$

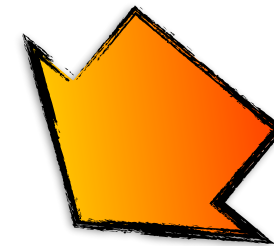
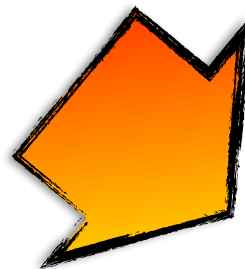
$$\boxed{R_{sh} < R < \hat{R}} \quad f = -\frac{\phi_{sh}}{D} \left(\frac{1}{R} - \frac{1}{R_{sh}} \right) \quad f = \frac{\phi_{\infty}}{D} \frac{1}{R} \quad \boxed{R > \hat{R}}$$

SNR shocks are spherical

return probability to the shock for a particle located upstream

the two solutions must be equal (continuity) in $R = \hat{R}$

$$\boxed{R_{sh} < R < \hat{R}} \quad f = -\frac{\phi_{sh}}{D} \left(\frac{1}{R} - \frac{1}{R_{sh}} \right) \quad f = \frac{\phi_{\infty}}{D} \frac{1}{R} \quad \boxed{R > \hat{R}}$$



$$-\frac{\phi_{sh}}{D} \left(\frac{1}{\hat{R}} - \frac{1}{R_{sh}} \right) = \frac{\phi_{\infty}}{D} \frac{1}{\hat{R}}$$

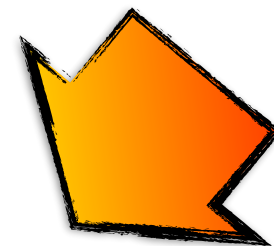
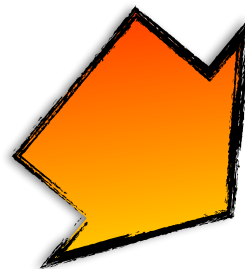
SNR shocks are spherical

return probability to the shock for a particle located upstream

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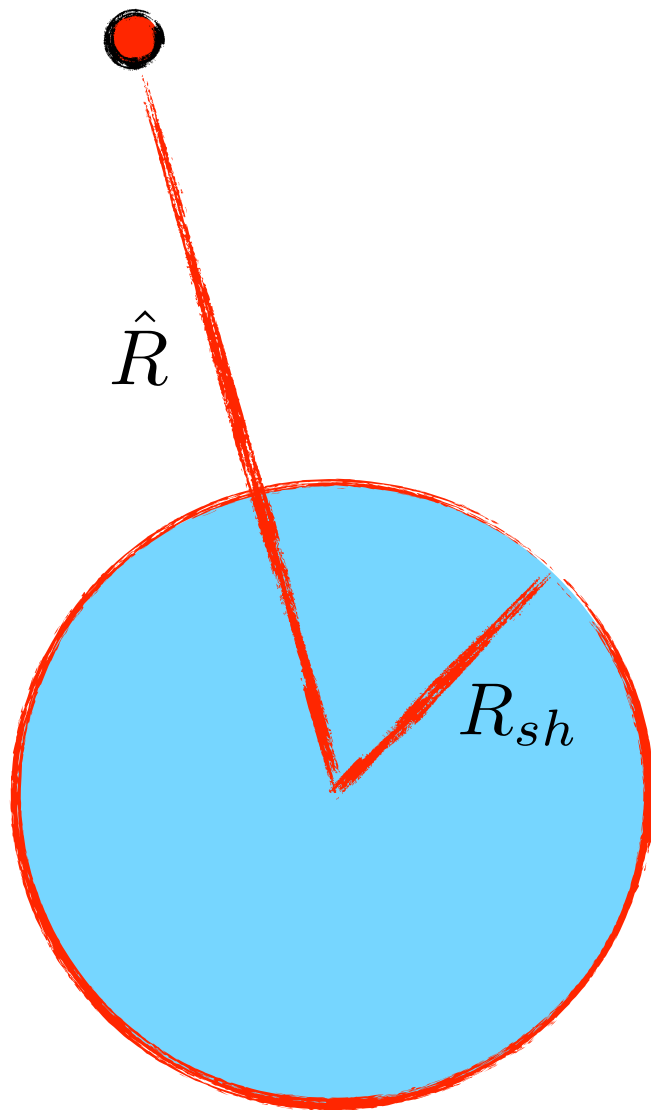


$$\phi_{\infty} = \phi_{sh} \left(\frac{\hat{R}}{R_{sh}} - 1 \right)$$

SNR shocks are spherical

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CR particle

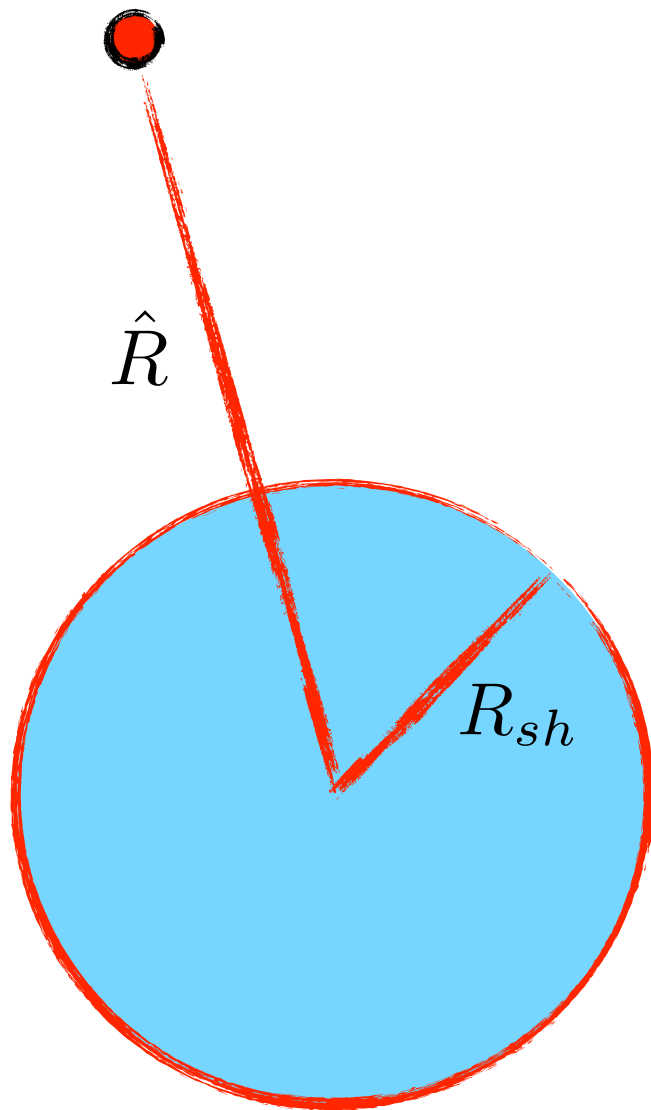


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$$\phi_{\infty} = \phi_{sh} \left(\frac{\hat{R}}{R_{sh}} - 1 \right)$$

$$P_{ret} = \frac{\phi_{sh}}{\phi_{sh} + \phi_{\infty}} = \frac{R_{sh}}{\hat{R}}$$

$$P_{esc} = 1 - \frac{R_{sh}}{\hat{R}}$$

SNR shocks are spherical

DSA theory → we computed the return probability for a plane shock

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plane shock (DSA)

$$P_{ret}^{DSA} = 1 - \frac{u_{sh}}{c}$$

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accelerated because it escapes
DOWNSTREAM (inside the SNR)

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spherical shock (geometry)

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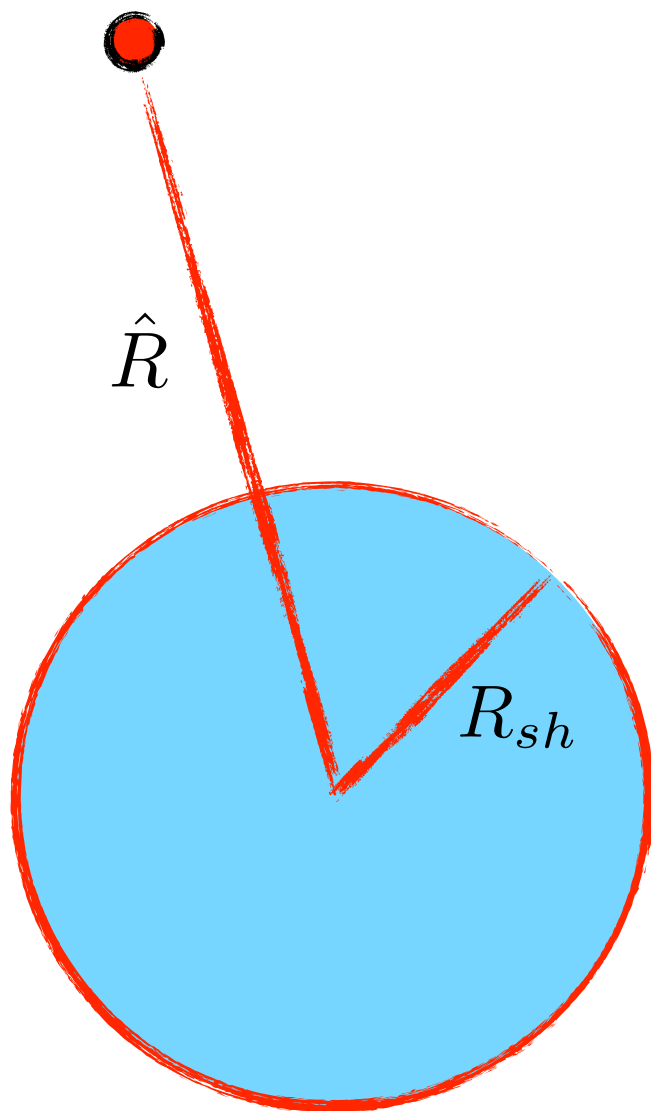
$$P_{esc}^{geom} \approx P_{esc}^{DSA} \longrightarrow \frac{\hat{R} - R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1$$

SNR shocks are spherical

consequences of what said so far...

$$1 - \frac{R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1$$

CR particle

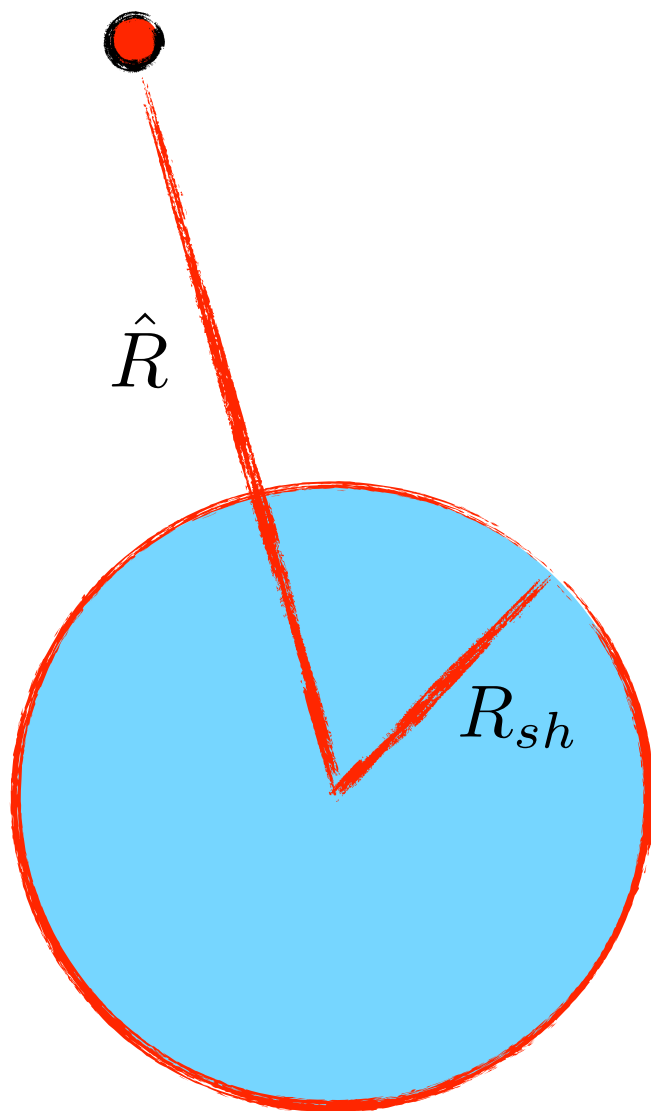


SNR shocks are spherical

consequences of what said so far...

$$1 - \frac{R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1 \longrightarrow \frac{\hat{R}}{R_{sh}} = \left(1 - \frac{u_{sh}}{c}\right)^{-1}$$

CR particle

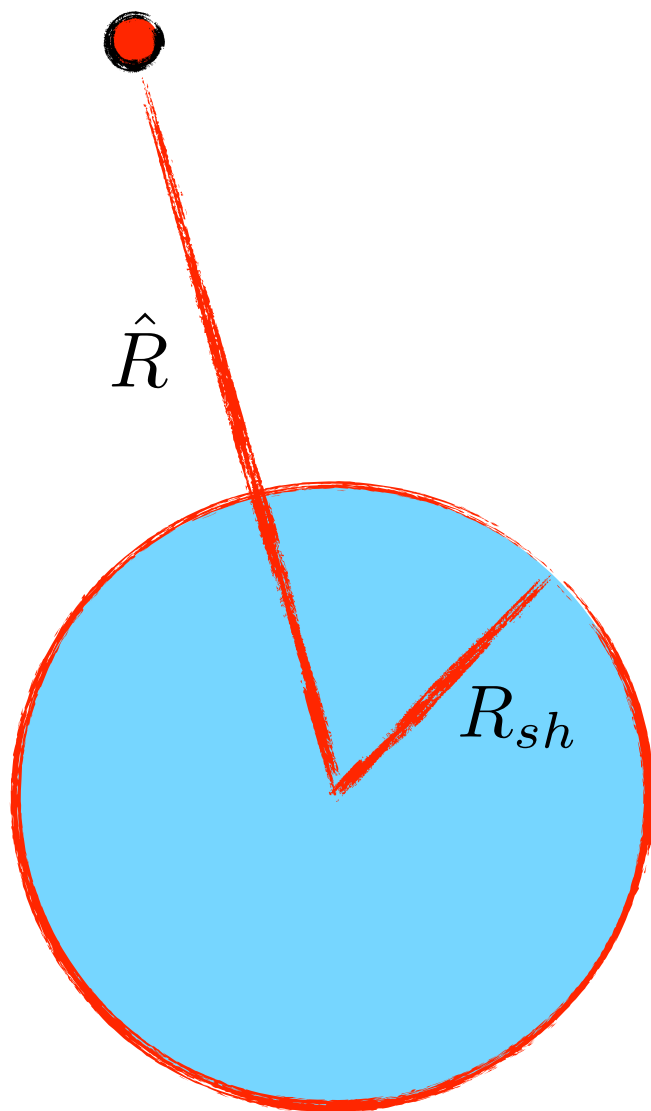


SNR shocks are spherical

consequences of what said so far...

$$1 - \frac{R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1 \longrightarrow \frac{\hat{R}}{R_{sh}} = \left(1 - \frac{u_{sh}}{c}\right)^{-1} \approx 1 + \frac{u_{sh}}{c} \sim 1 + 0.03 \left(\frac{u_{sh}}{10^4 \text{ km/s}}\right)$$

CR particle



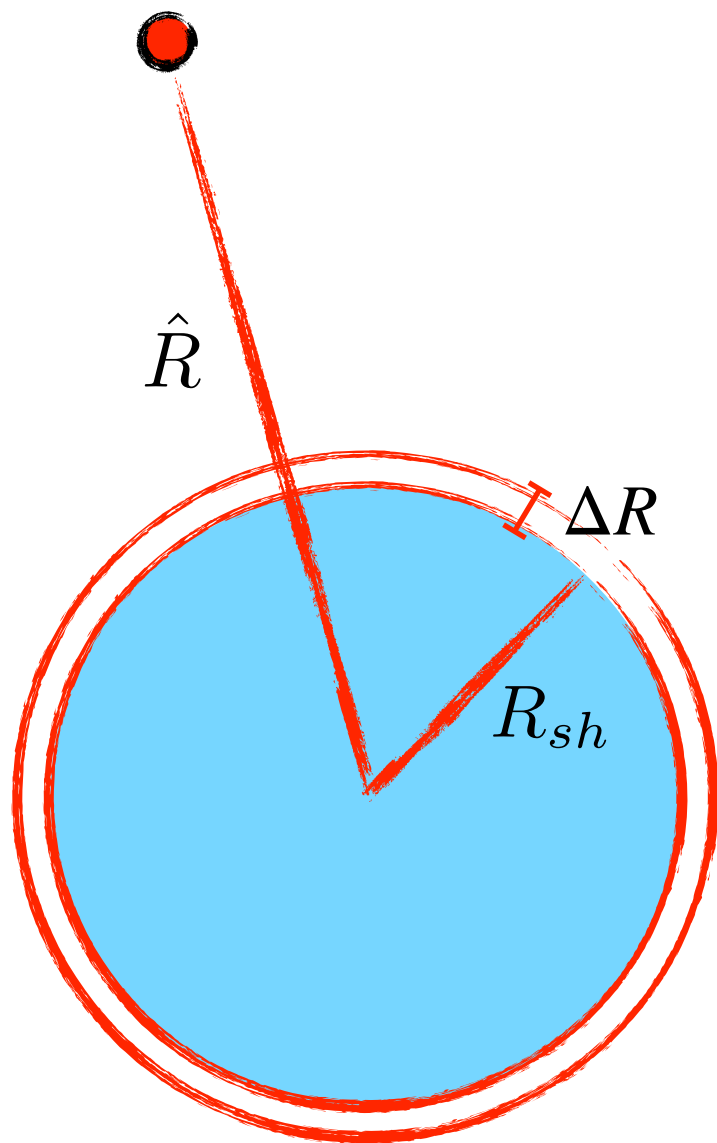
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this is very small

CR particle



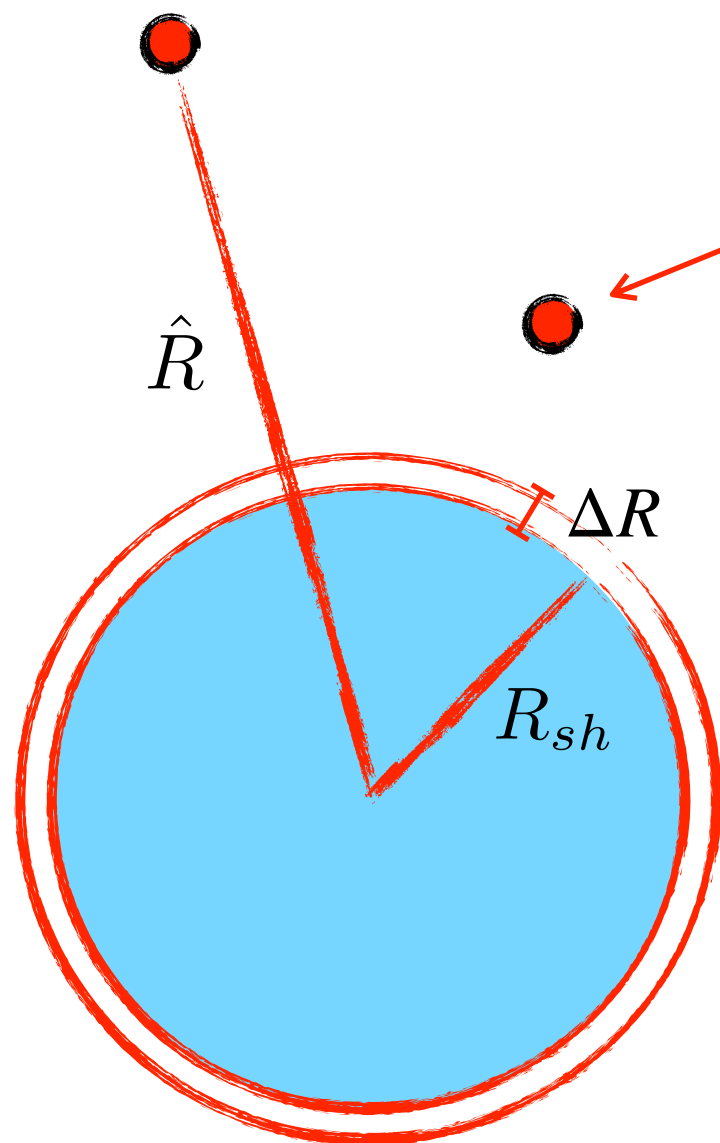
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CR particle



escape upstream is more likely
than escape downstream

SNR shocks are spherical

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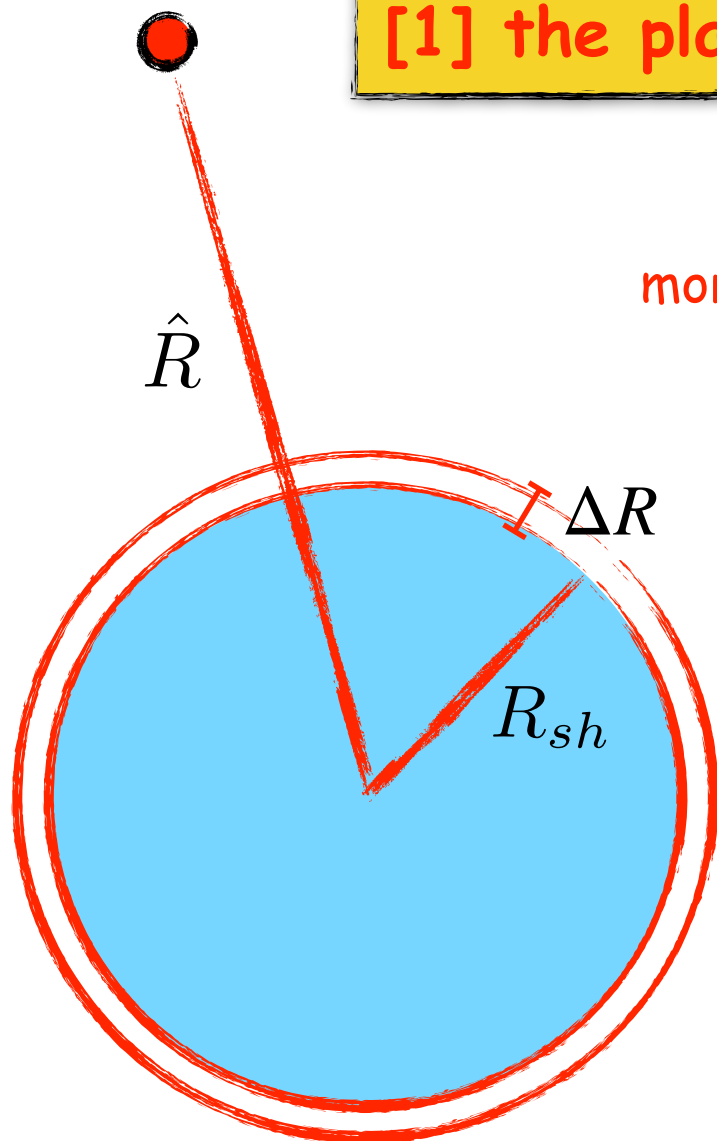
this is very small

CR particle

[1] the plane shock approximation is OK

more accurate estimate $\longrightarrow$

$$\frac{\Delta R}{R_{sh}} = \frac{\hat{R} - R_{sh}}{R_{sh}} \approx 5 - 10 \%$$



SNR shocks are spherical

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CR particle

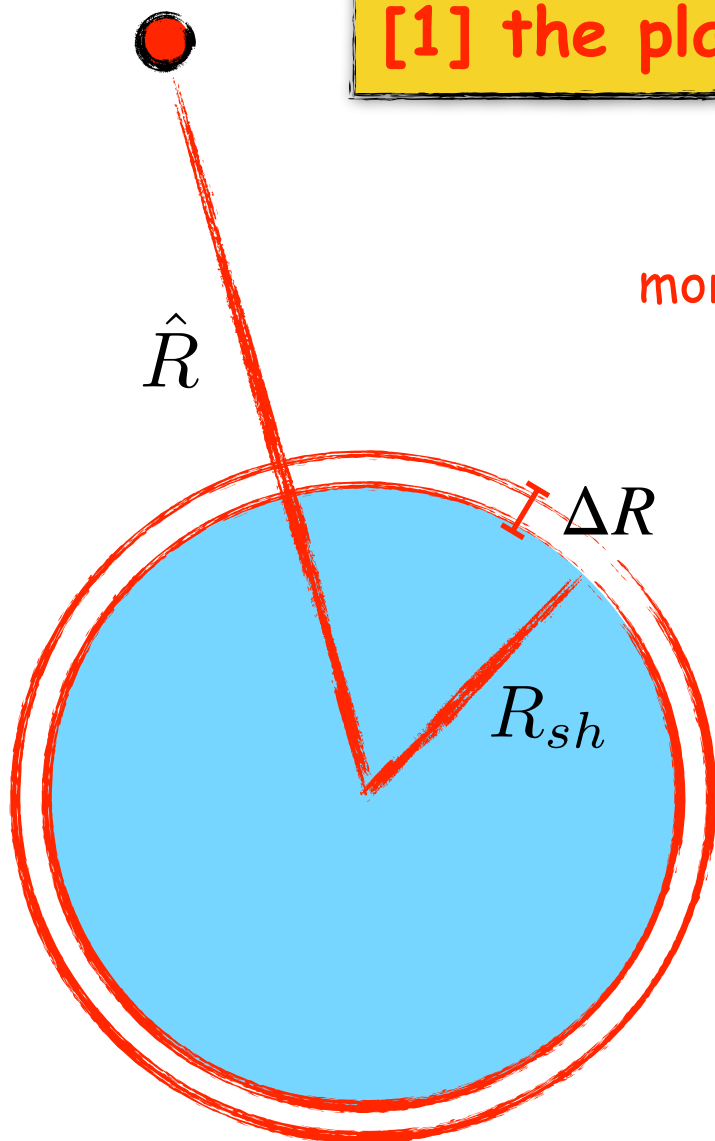
[1] the plane shock approximation is OK

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$$\frac{\Delta R}{R_{sh}} = \frac{\hat{R} - R_{sh}}{R_{sh}} \approx 5 - 10 \%$$

[2] in the Hillas criterion we should not use R_{sh} , but rather ΔR

$\longrightarrow E_{\max}$ goes down by ~ 1 order of magnitude



Plane (infinite) versus spherical shocks

plane (infinite)

spherical (finite)

■ particles can escape DOWNSTREAM ONLY → escape BOTH down and up-stream

Plane (infinite) versus spherical shocks

plane (infinite)

spherical (finite)

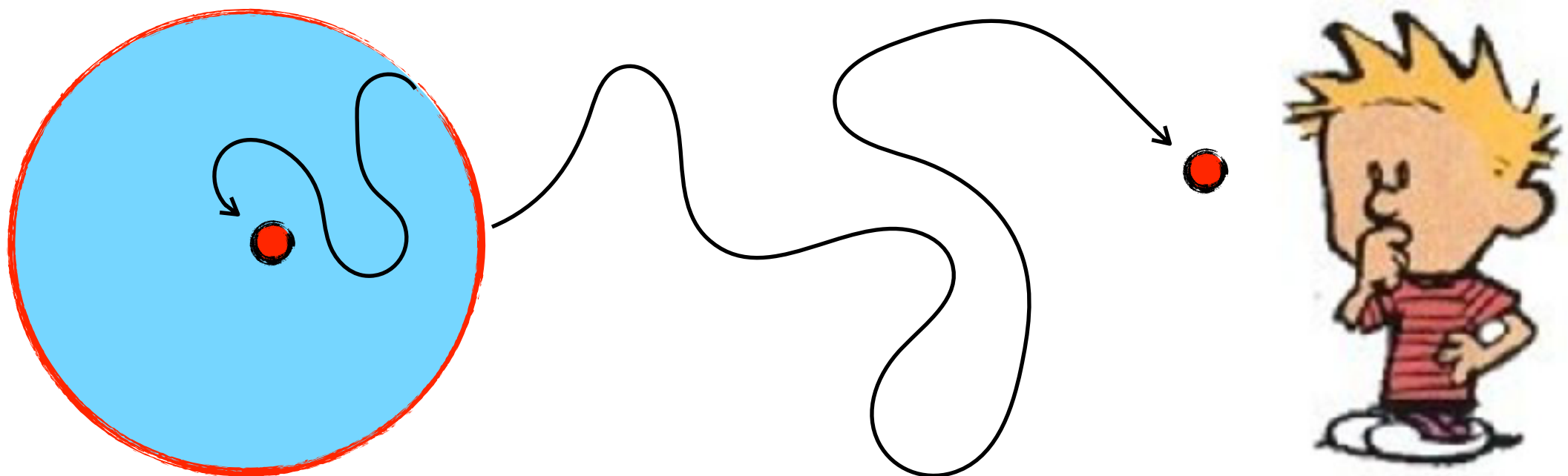
- particles can escape DOWNSTREAM ONLY → escape BOTH down and up-stream
- infinite time → arbitrarily large energy → escape upstream limits $E_{\max}$!

Plane (infinite) versus spherical shocks

plane (infinite)

spherical (finite)

- particles can escape DOWNSTREAM ONLY → escape BOTH down and up-stream
- infinite time → arbitrarily large energy → escape upstream limits $E_{\max}$!
- an observer at Earth sees → NOTHING! → what escapes upstream



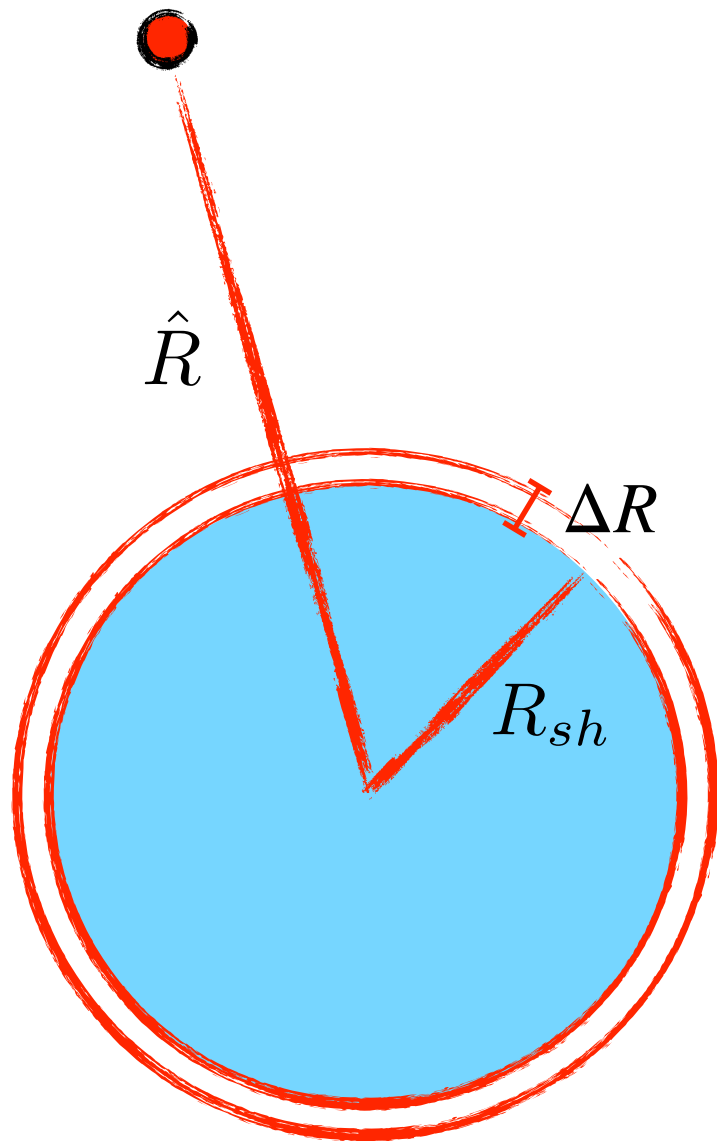
Which $E_{\max}$ at SNR shocks?

three possibilities:

[1] age limited $\rightarrow$

$$\tau_{acc}(E) = \tau_{age}$$

CR particle



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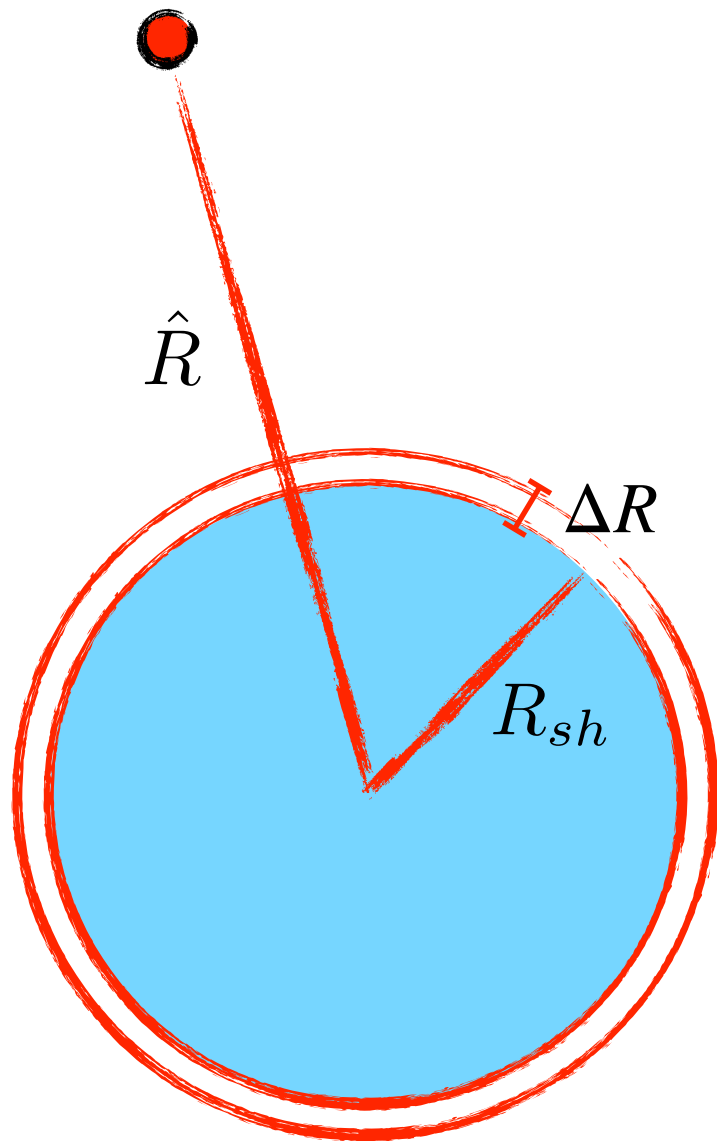
$$\tau_{acc}(E) = \tau_{age}$$

[2] size limited $\rightarrow$

$$l_d(E) = \Delta R$$

diffusion length

CR particle



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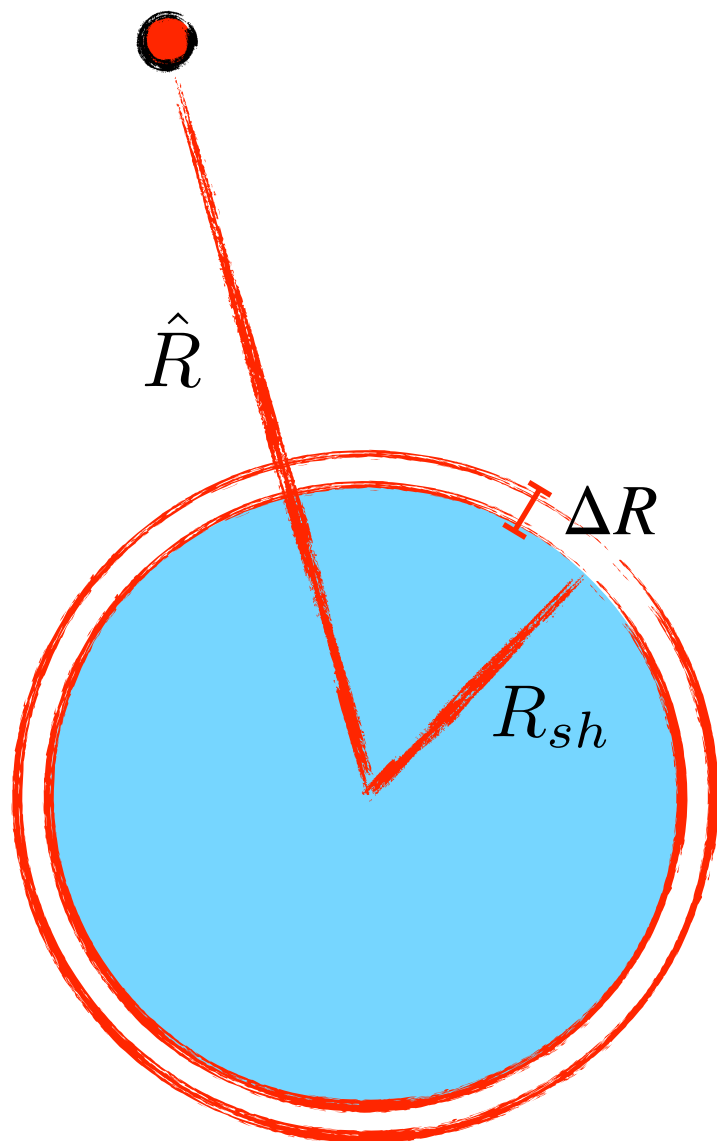
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diffusion length

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$$\tau_{acc}(E) = \tau_{loss}$$

CR particle



Which $E_{\max}$ at SNR shocks?

three possibilities:

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time

[2] size limited $\rightarrow$

$$l_d(E) = \Delta R$$

diffusion length

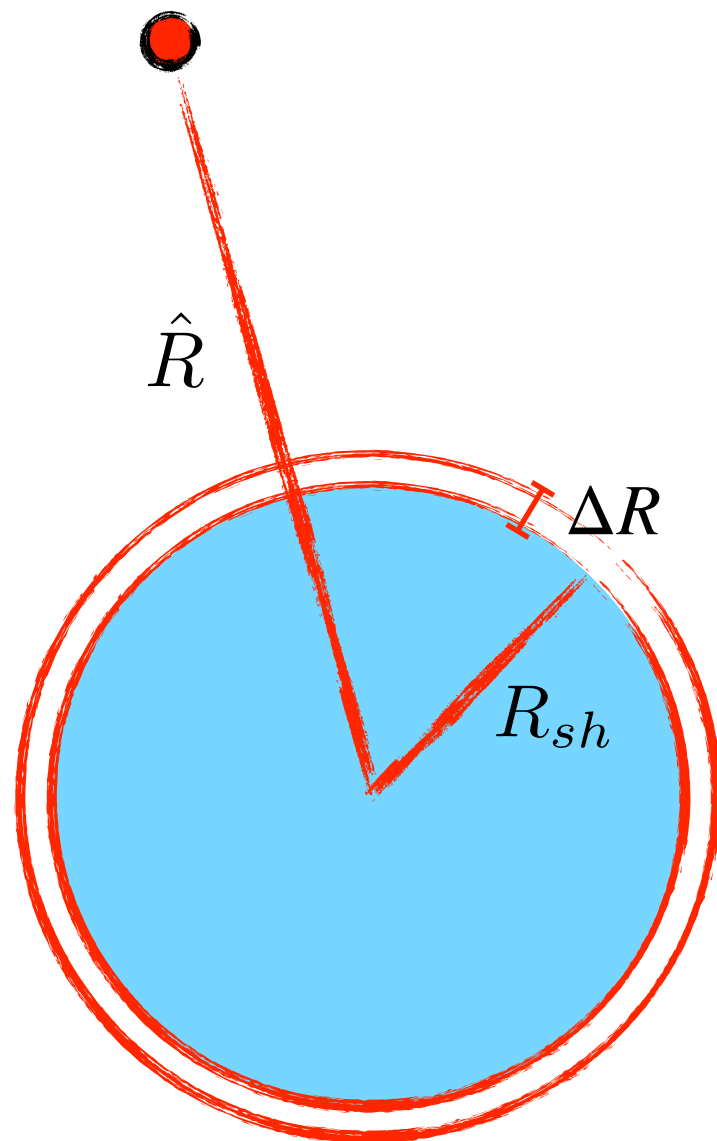
space

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energy

CR particle



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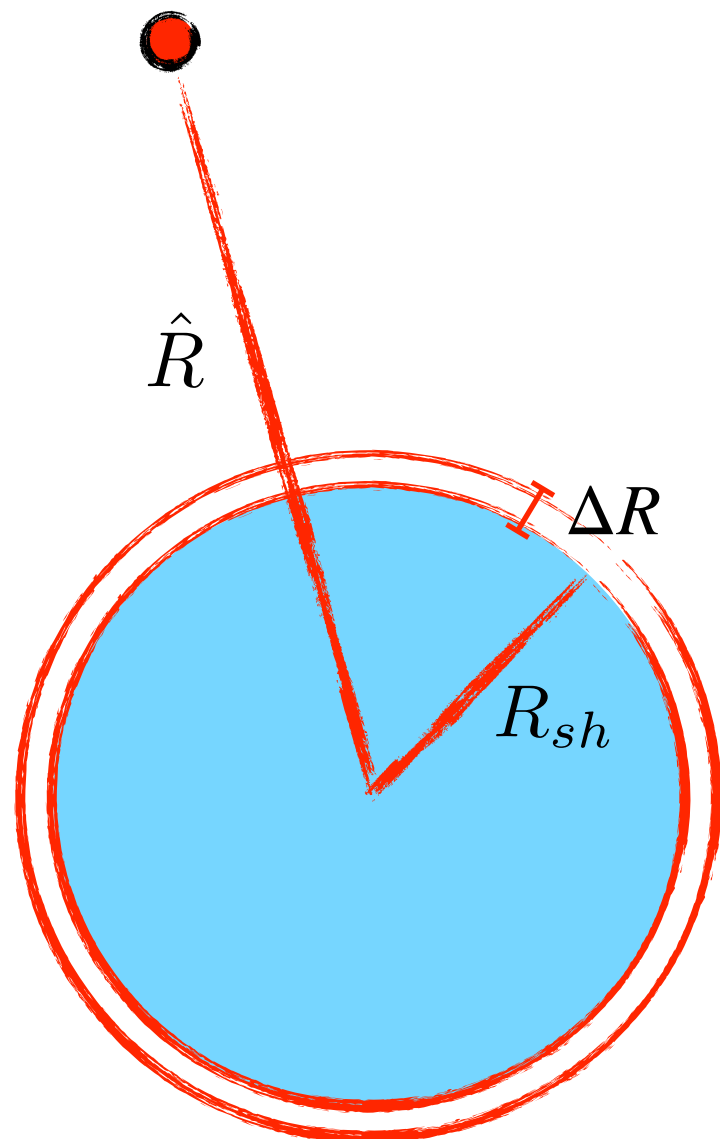
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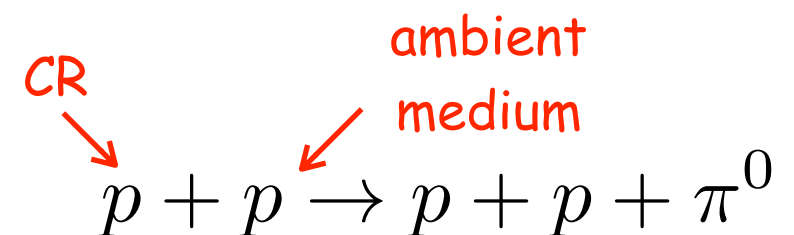
energy

CR particle



diffusion length

inelastic proton-proton interactions



$$t_{pp} = (n_{gas} \sigma_{pp} c k)^{-1} \approx 60 \left(\frac{n}{\text{cm}^{-3}} \right)^{-1} \text{Myr}$$

$4 \times 10^{-26} \text{ cm}^2$

0.45 (inelasticity)

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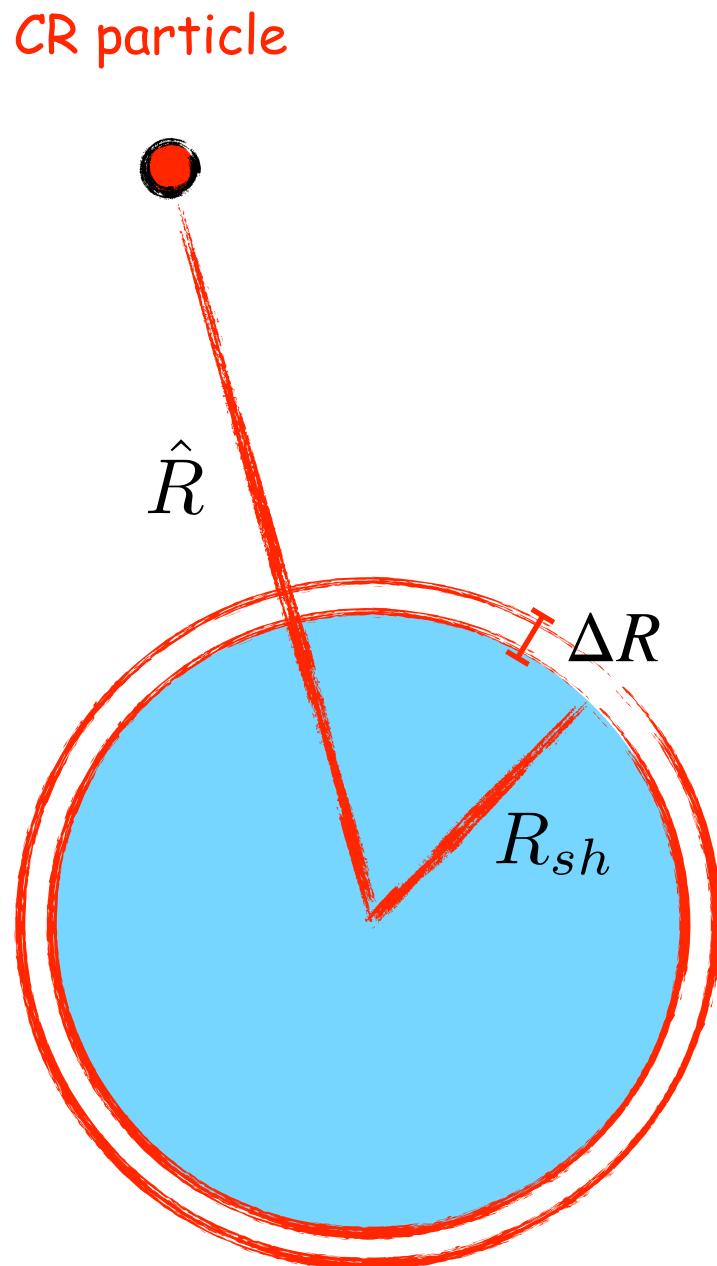
diffusion length

space

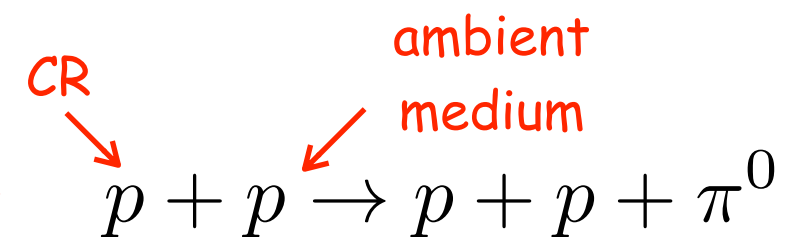
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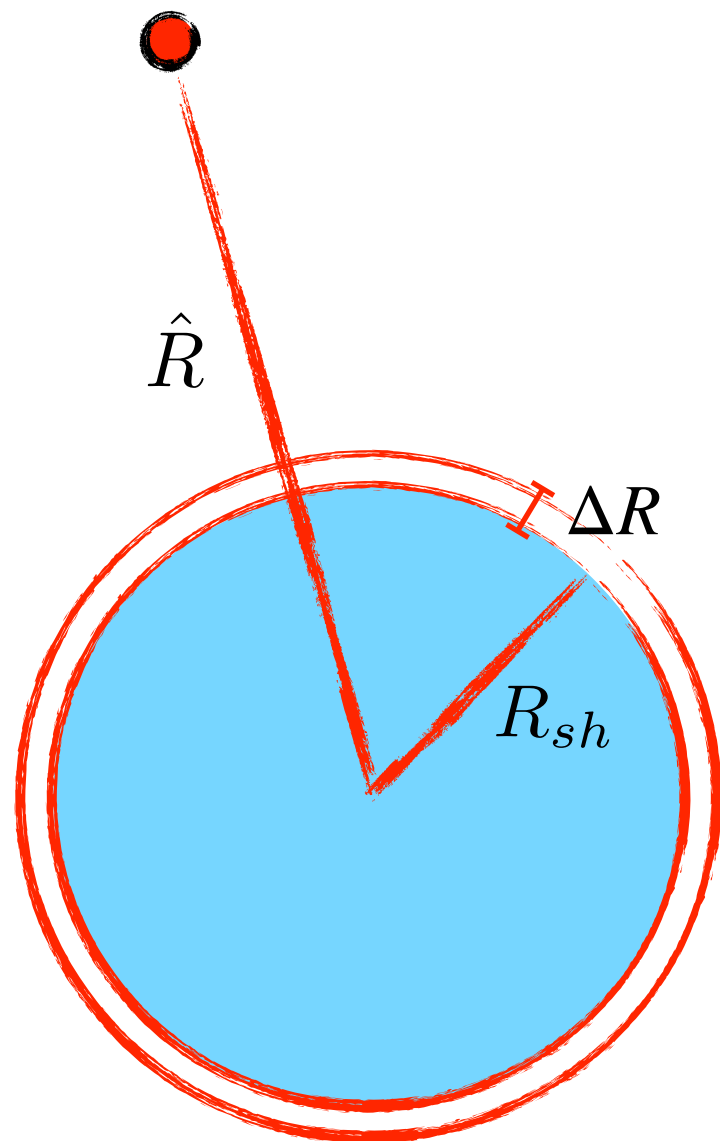
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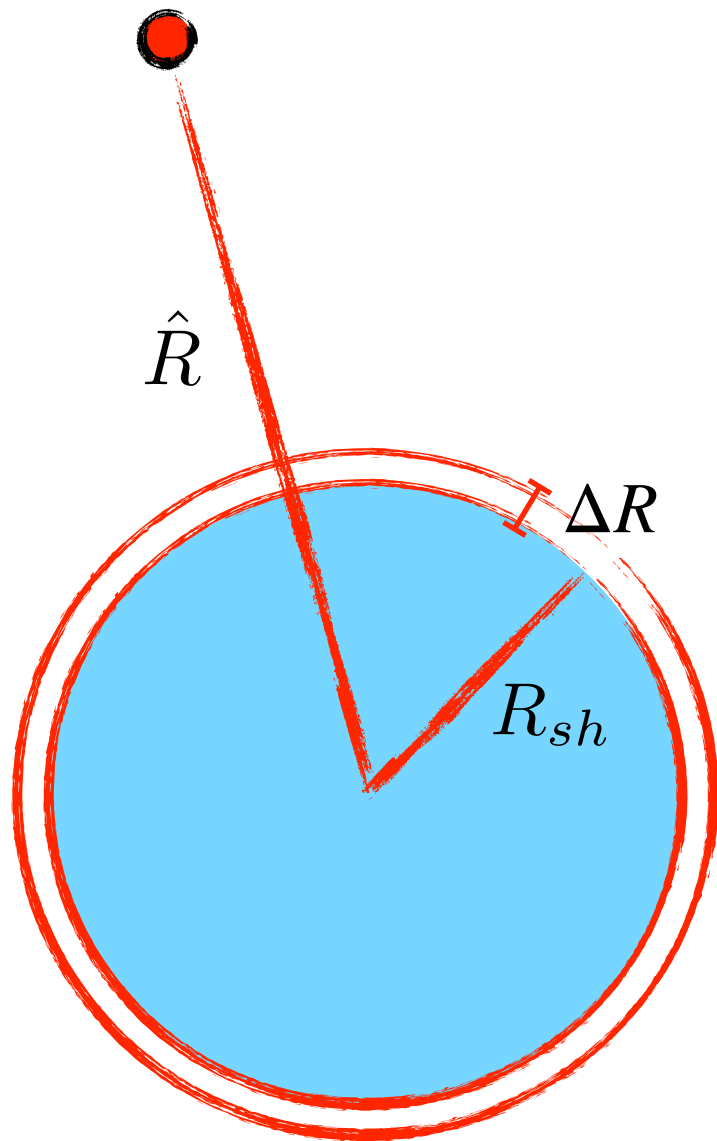
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$$\tau_{acc}(E) = \tau_{age}$$

$$\tau_{acc}(E) = \frac{1}{r_{acc}(E)} = 20 \frac{D(E)}{u_{sh}^2} = \frac{20R_L(E)c}{3u_{sh}^2}$$

CR particle



Which $E_{\max}$ at SNR shocks?

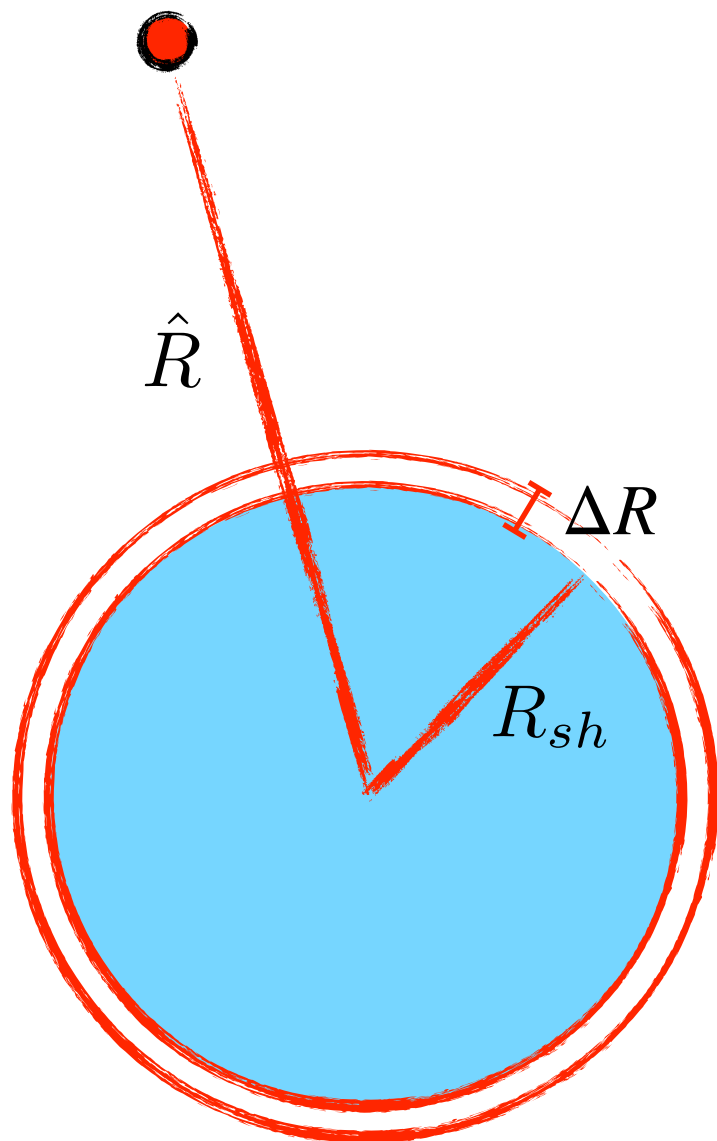
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$$R_L(E_{\max}) = \frac{3}{20} \left(\frac{u_{sh}}{c} \right) u_{sh} \tau_{age}$$

CR particle



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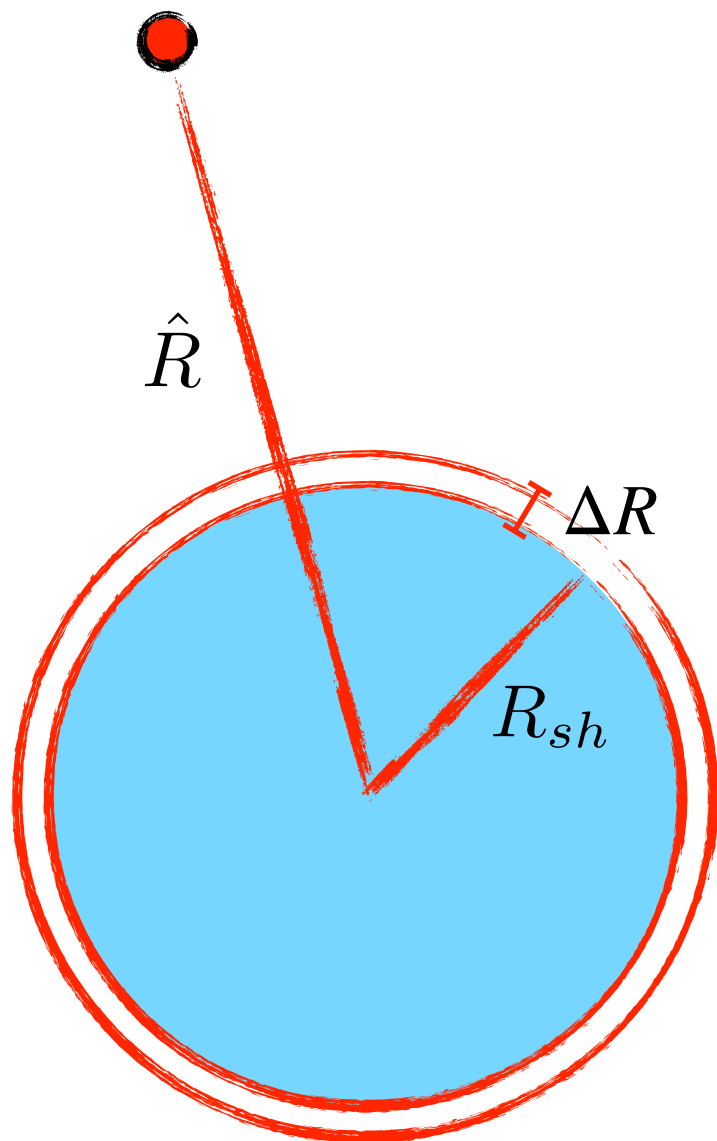
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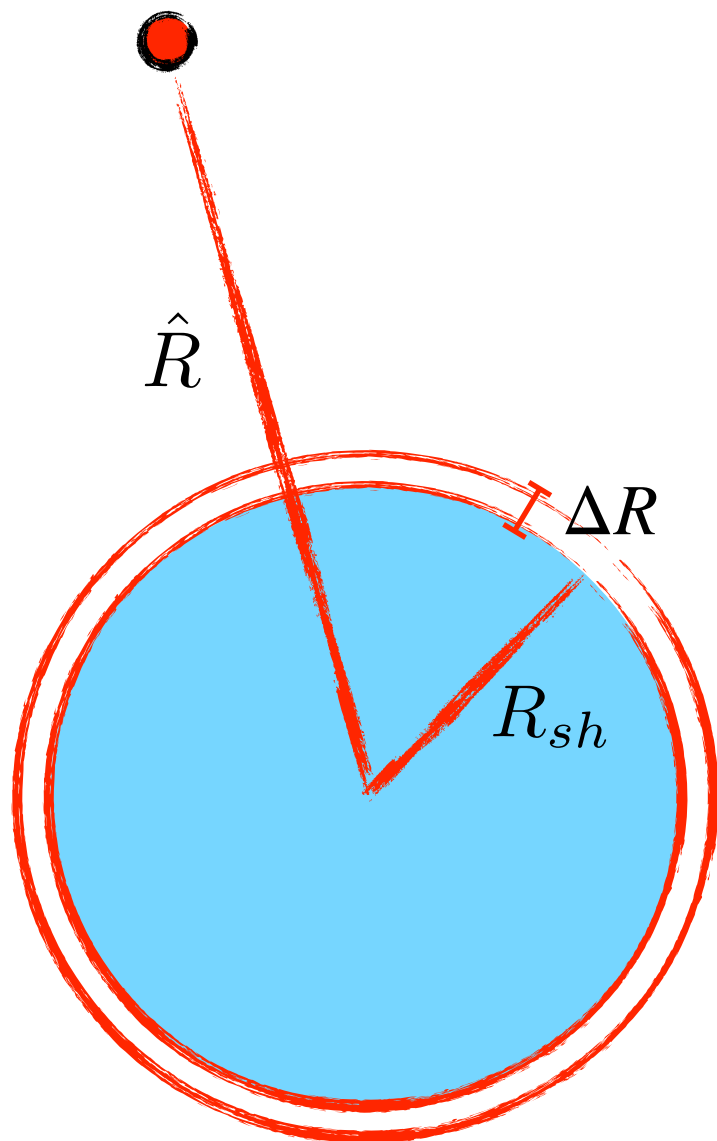
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[2] size limited $\rightarrow$

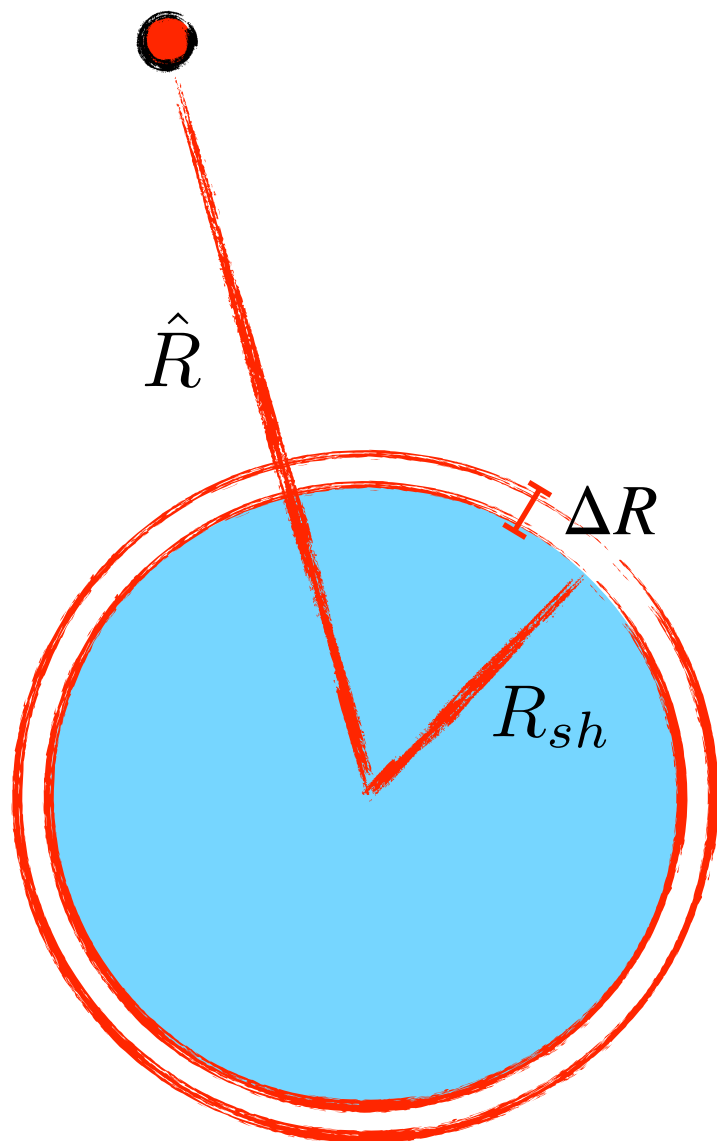
$$l_d(E) = \Delta R = \overset{\sim 5\%}{\downarrow} \eta R_{sh}$$

$$\parallel$$

$$l_d(E) = \frac{D(E)}{u_{sh}} = \frac{R_L(E) c}{3 u_{sh}}$$

$$R_L(E_{\max}) = 3 \eta \left(\frac{u_{sh}}{c} \right) R_{sh}$$

CR particle



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SNR evolution $\rightarrow$

$$R_{sh} \propto \tau_{age}^{\alpha} \longrightarrow u_{sh} = \alpha \frac{R_{sh}}{\tau_{age}}$$

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← virtually identical

virtually identical →

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Q.
Q.



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$$\alpha = 1 \rightarrow R_L(E_{\max}) \propto E_{\max} \propto \tau_{age}$$

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free expansion →

$$\alpha = 1 \rightarrow R_L(E_{\max}) \propto E_{\max} \propto \tau_{age}$$

Sedov-Taylor →

$$\alpha = \frac{2}{5} \rightarrow R_L(E_{\max}) \propto E_{\max} \propto \tau_{age}^{-1/5}$$

Q.
Q.



Which $E_{\max}$ at SNR shocks?

$$R_L(E_{\max}) = 3\eta \left(\frac{u_{sh}}{c} \right) R_{sh}$$

Which $E_{\max}$ at SNR shocks?

$$R_L(E_{\max}) = 3\eta \left(\frac{u_{sh}}{c} \right) R_{sh}$$


$$R_L(E) = \frac{E(\text{eV})}{300 B(\text{G})} \text{ cm}$$

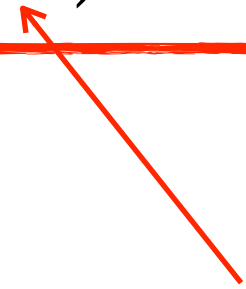

$$E_{\max} \approx 30 \left(\frac{\eta}{0.1} \right) \left(\frac{B}{3 \mu\text{G}} \right) \left(\frac{u_{sh}}{10^4 \text{ km/s}} \right) \left(\frac{R_{sh}}{\text{pc}} \right) \text{ TeV}$$

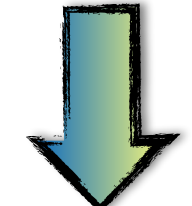
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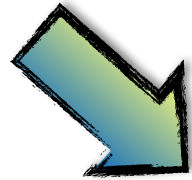

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$$R_* = R_{sh}(\tau_{age}^*) \approx 2 \text{ pc}$$



$$E_{\max} \approx 60 \text{ TeV}$$

Which $E_{\max}$ at SNR shocks?

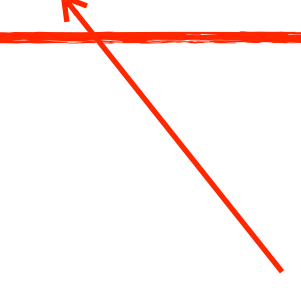
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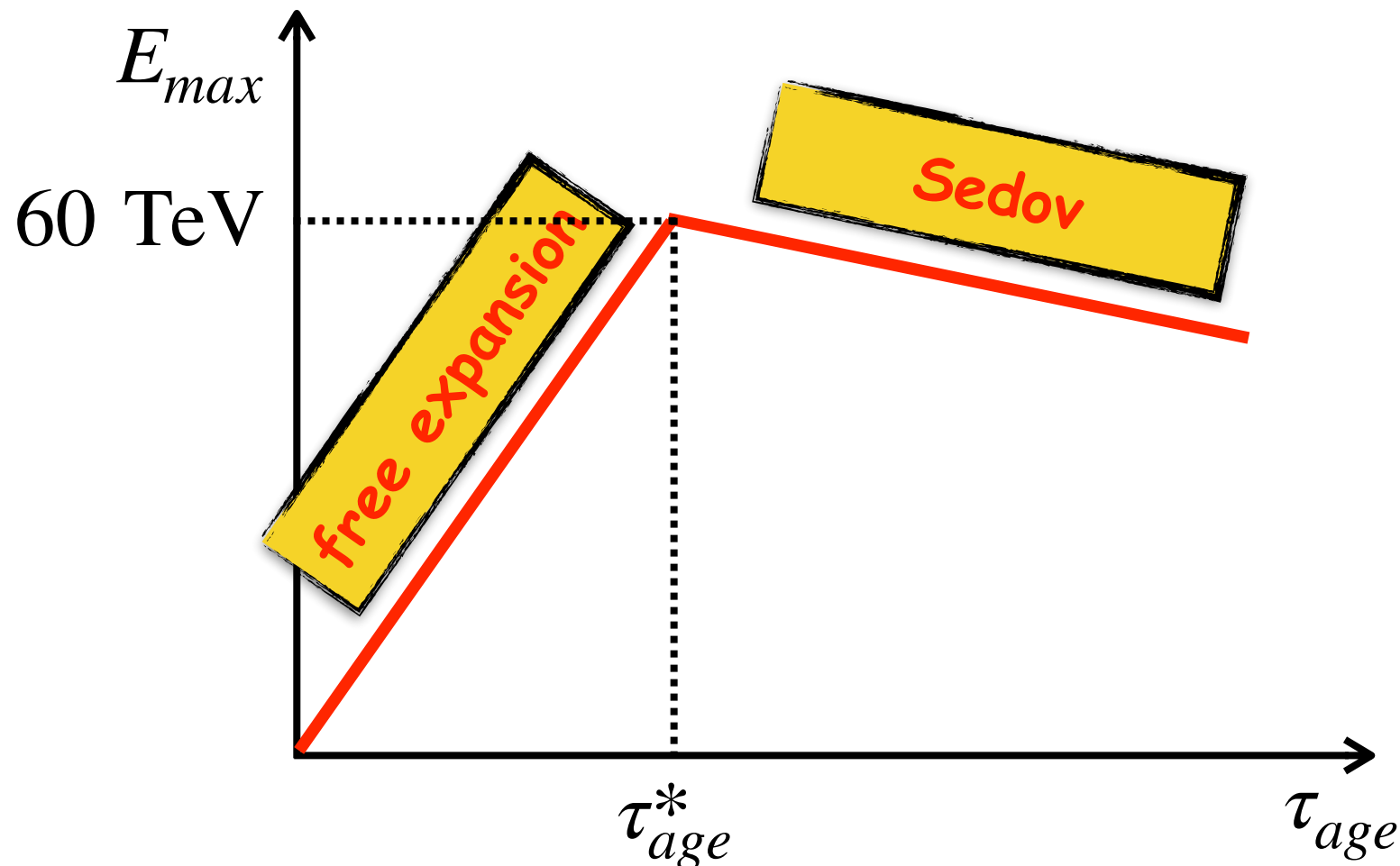
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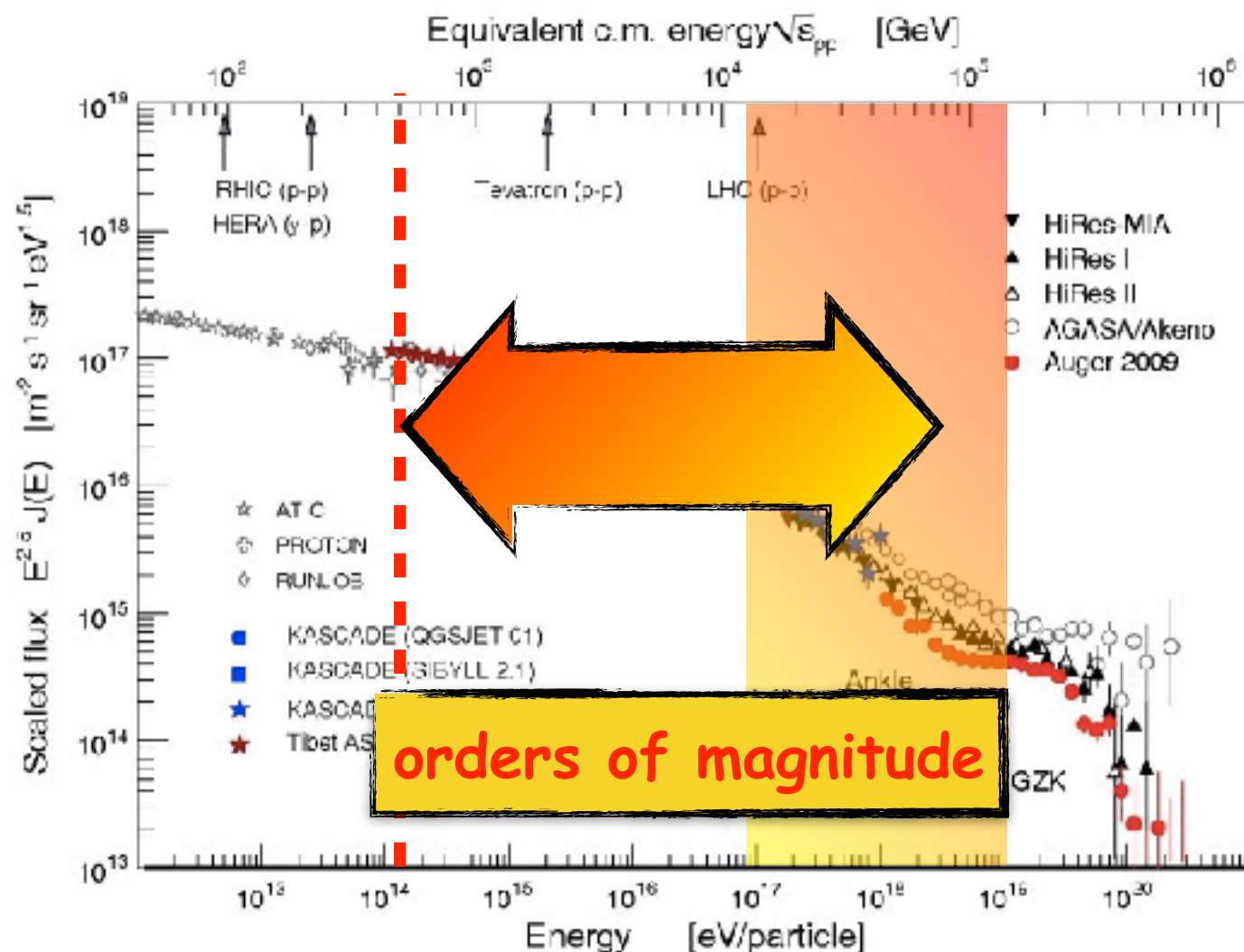


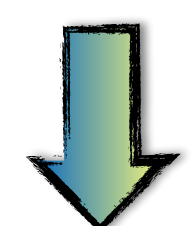
Which E_{max} at SNR shocks?

$$R_L(E_{max}) = 3\eta \left(\frac{u_{sh}}{c} \right) R_{sh}$$


$$R_L(E) = \frac{E(\text{eV})}{300 B(\text{G})} \text{ cm}$$

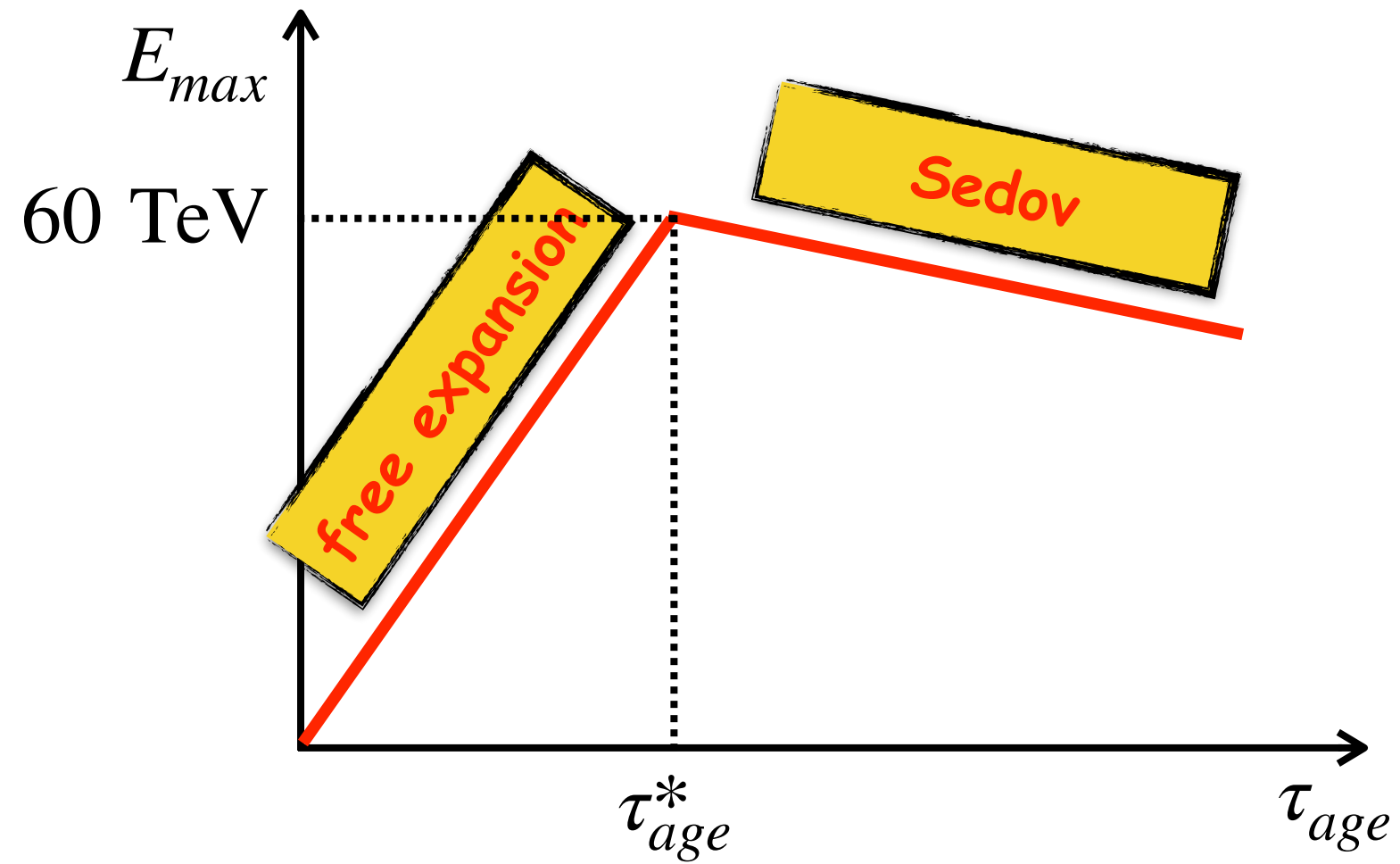

$$E_{max} \approx 30 \left(\frac{\eta}{0.1} \right) \left(\frac{B}{3 \mu\text{G}} \right) \left(\frac{u_{sh}}{10^4 \text{ km/s}} \right) \left(\frac{R_{sh}}{\text{pc}} \right) \text{ TeV}$$



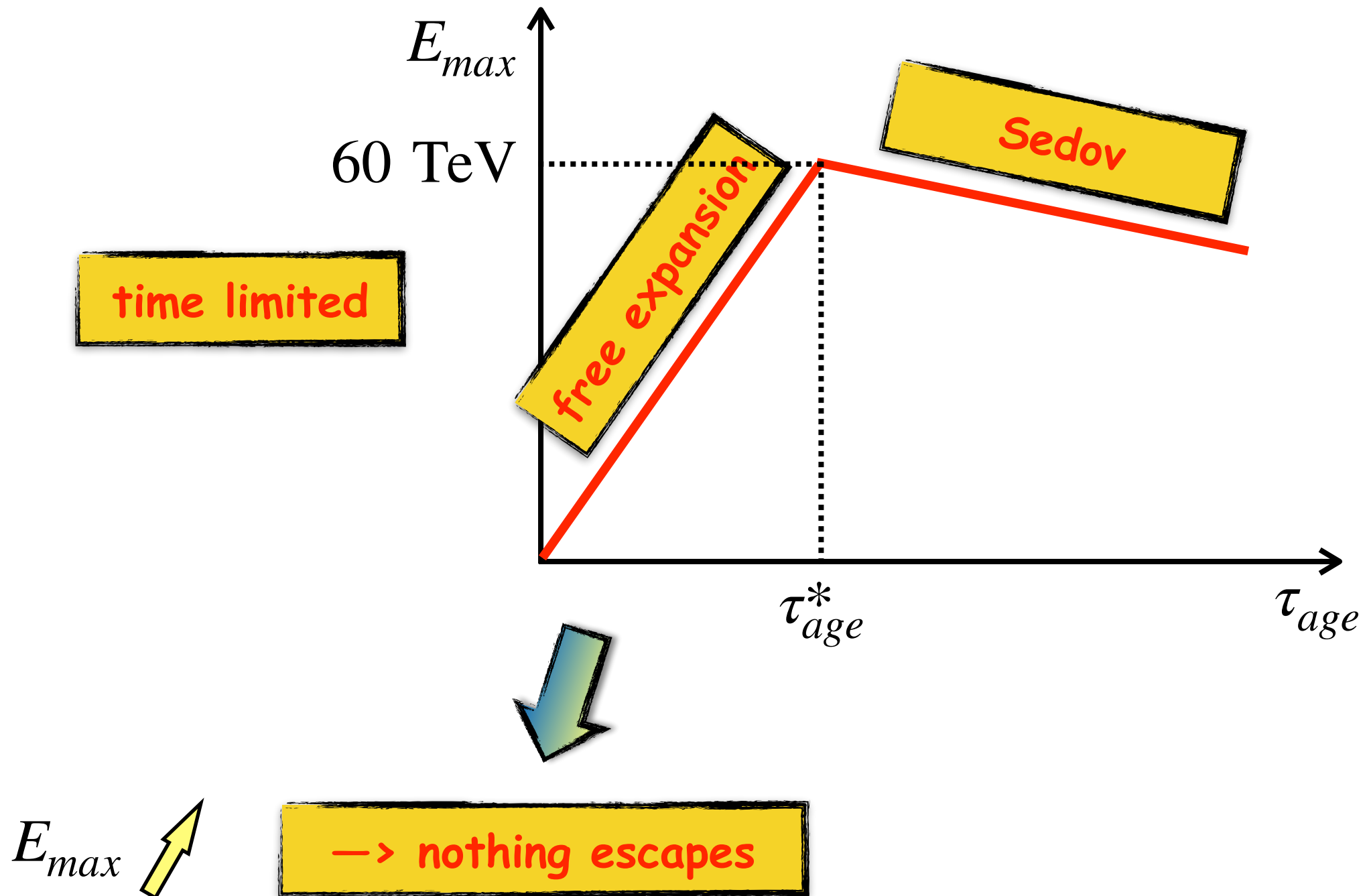
$$R_* = R_{sh}(\tau_{age}^*) \approx 2 \text{ pc}$$


$$E_{max} \approx 60 \text{ TeV}$$

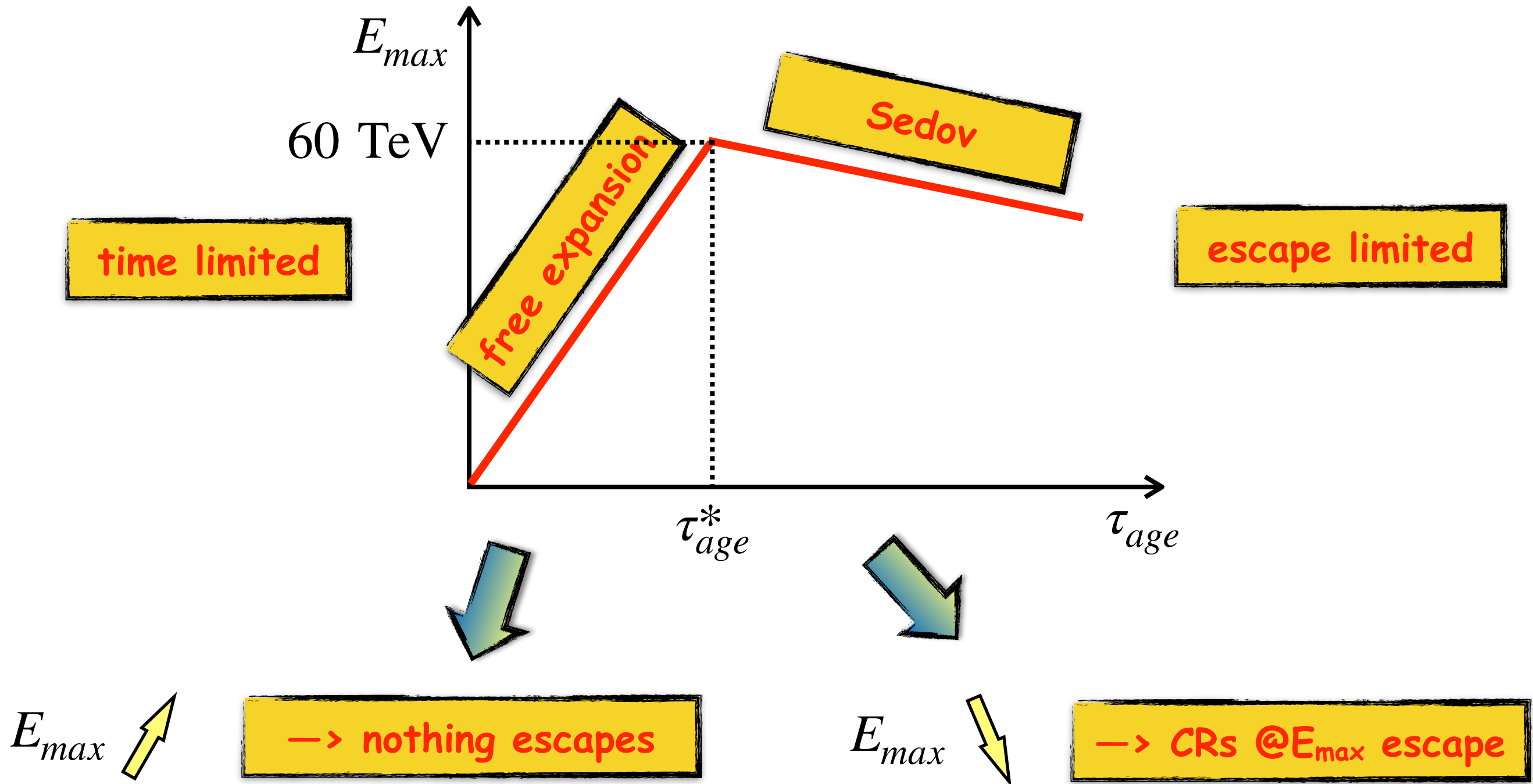
Gradual release of CRs



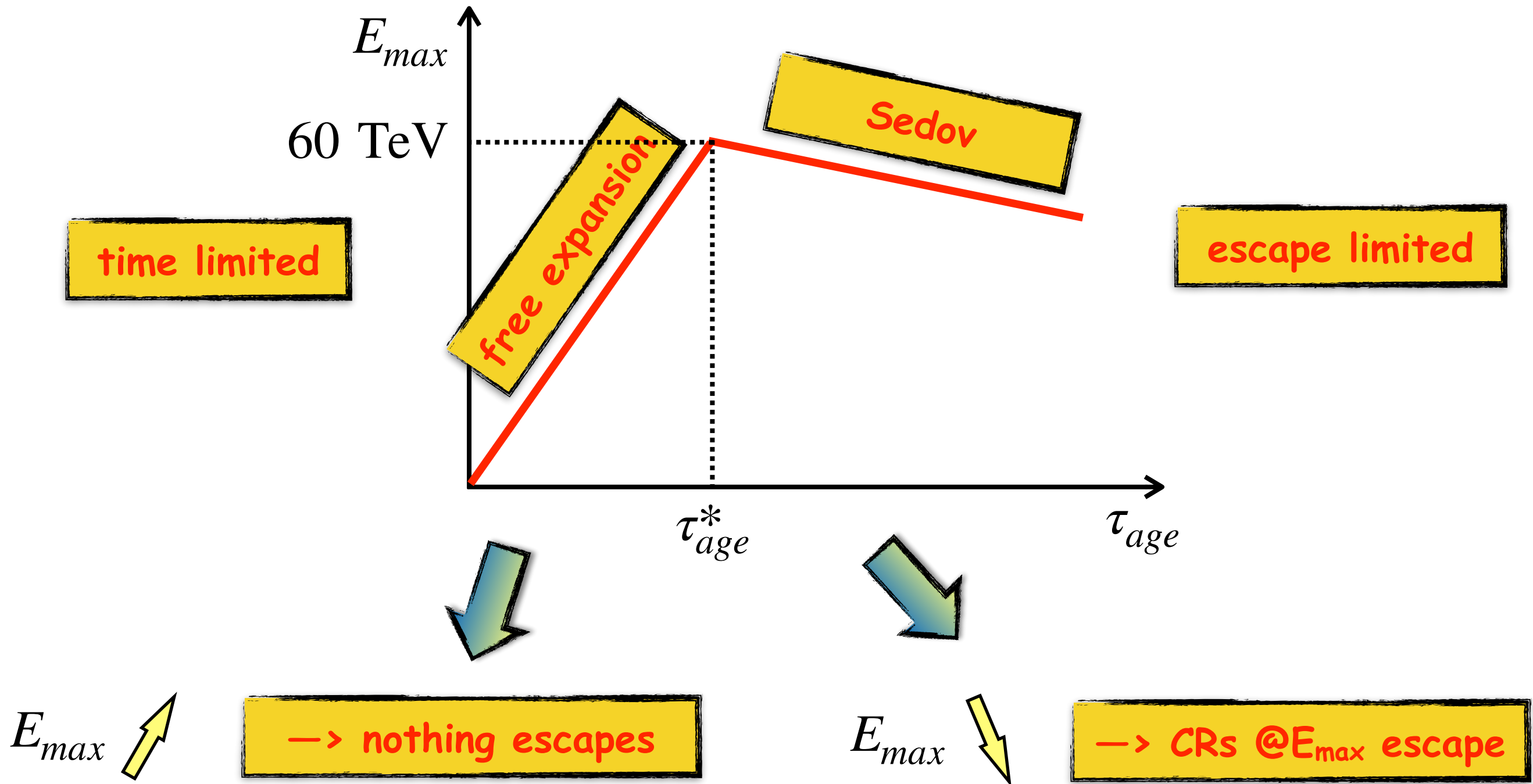
Gradual release of CRs



Gradual release of CRs



Gradual release of CRs



real life: u_{sh} not necessarily constant in free expansion, it may slowly decelerate —> few CR escape also during this phase

Way outs?

$$E_{max} \approx 30 \left(\frac{\eta}{0.1} \right) \left(\frac{B}{3 \mu\text{G}} \right) \left(\frac{u_{sh}}{10^4 \text{ km/s}} \right) \left(\frac{R_{sh}}{\text{pc}} \right) \text{TeV}$$

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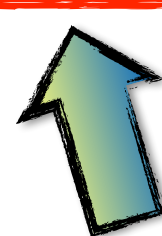
these are very well
measured/constrained

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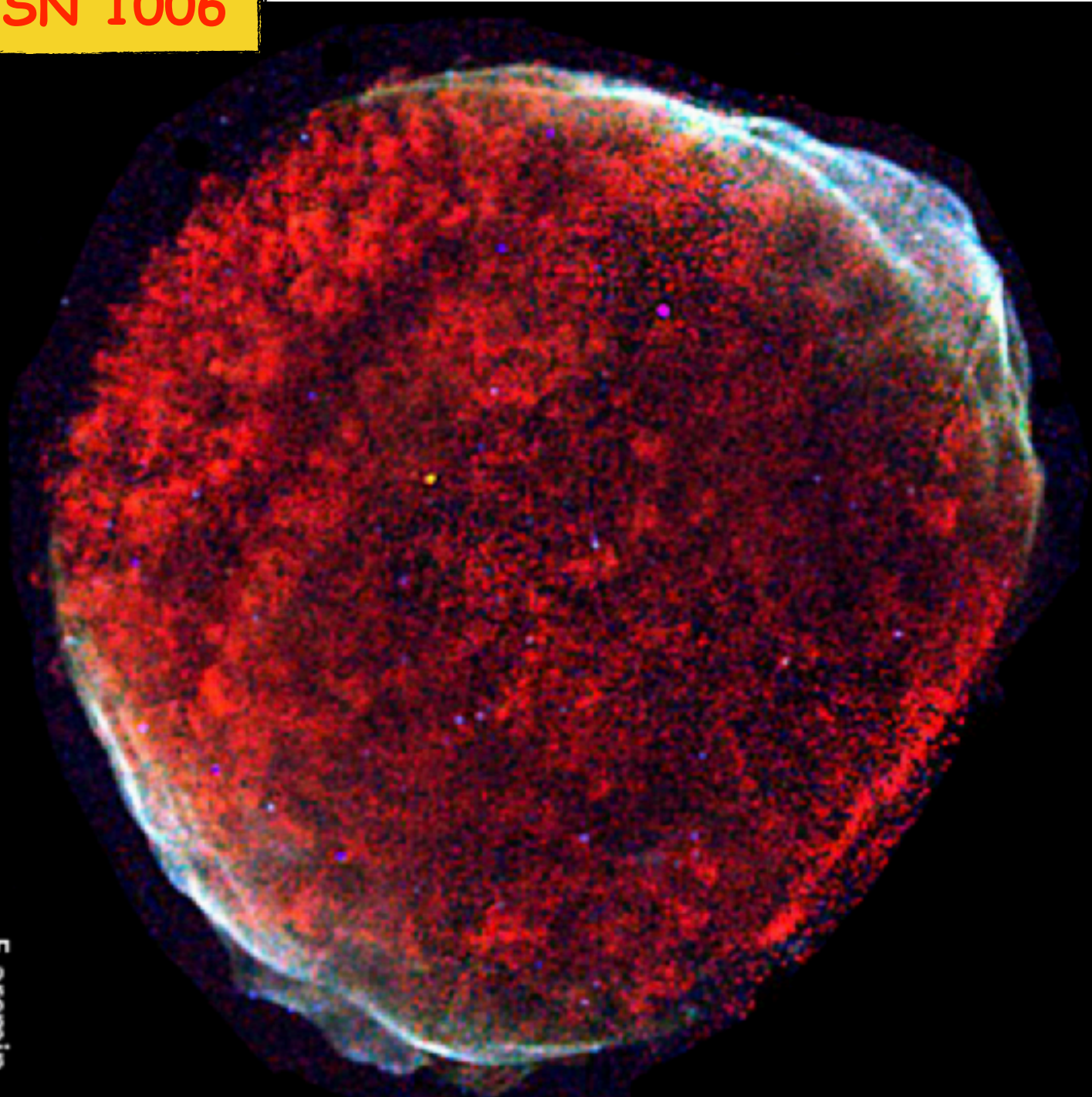
this is (was) not



these are very well
measured/constrained

Large B fields are observed!
(~100xISM values)

SN 1006

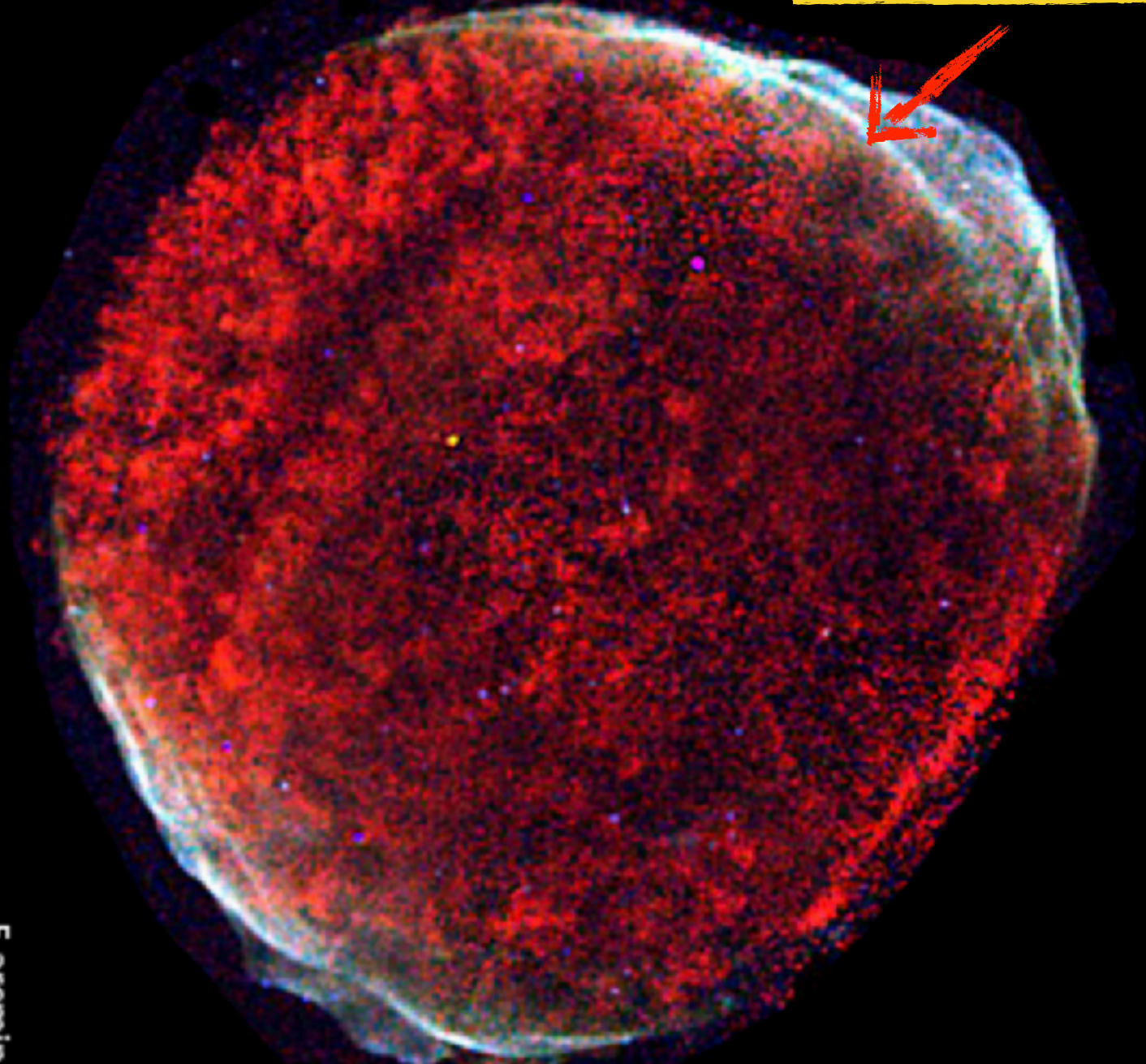


5 arcmin
3.2 pc

Large B fields are observed! ($\sim 100\times$ ISM values)

SN 1006

narrow X-ray
synchrotron filaments



5 arcmin
3.2 pc

Large B fields are observed! (~100xISM values)

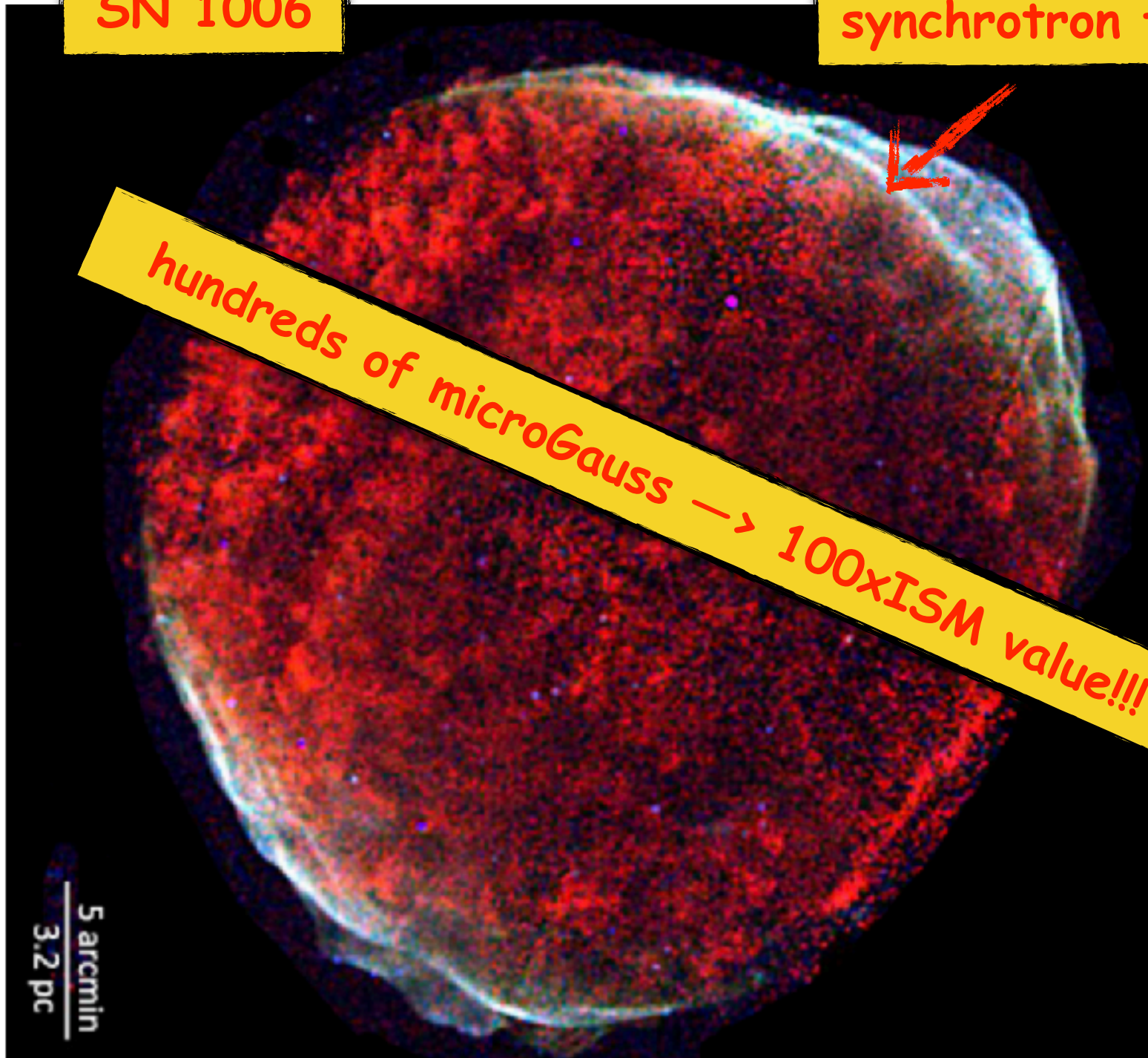
SN 1006

narrow X-ray
synchrotron filaments



hundreds of microGauss $\rightarrow$ 100xISM value!!!

5 arcmin
3.2 pc



Large B fields observed!

($\sim 100 \times B_{\text{ISM}}$)

SN 1006

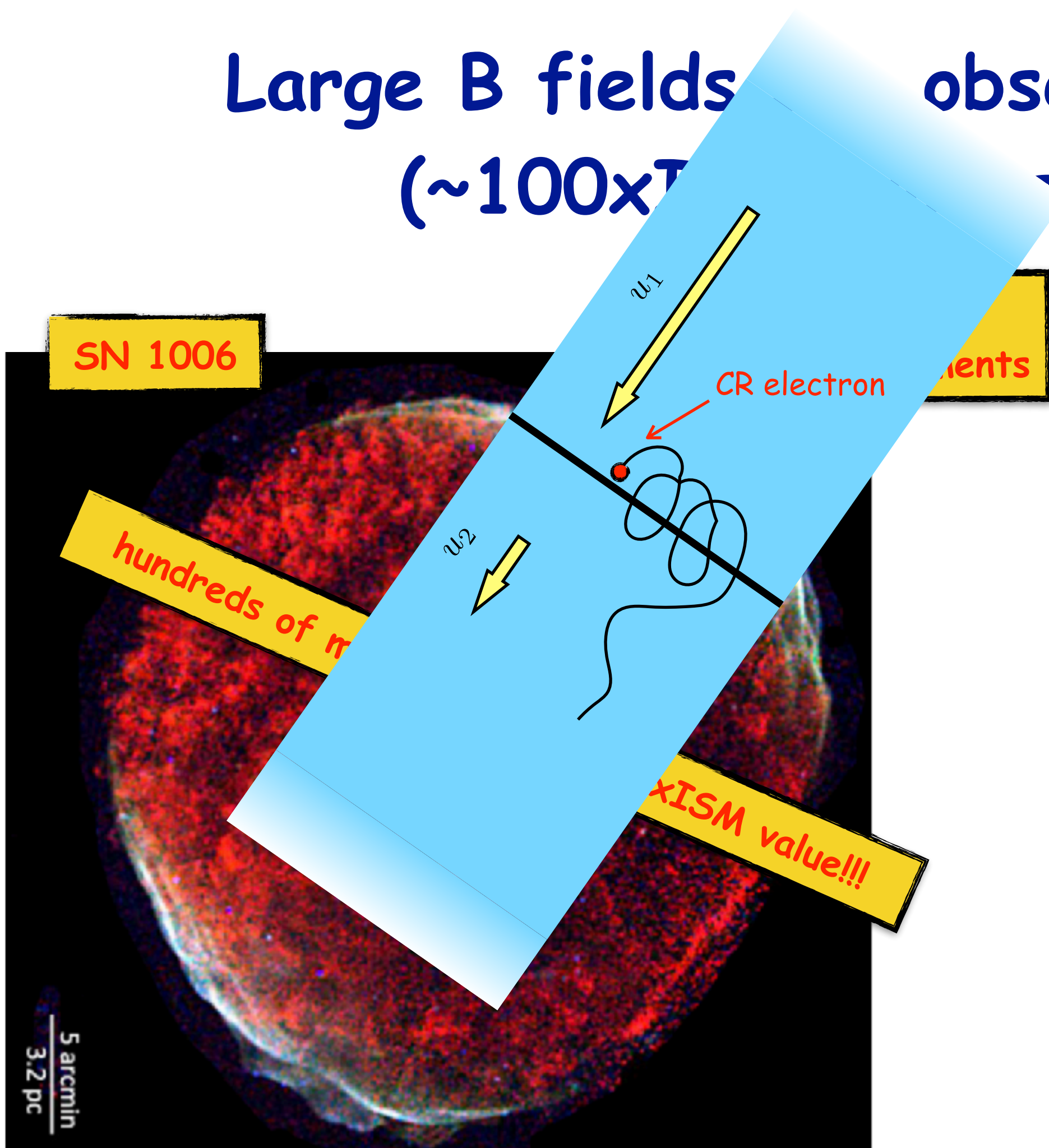
ments

CR electron

hundreds of m

xISM value!!!

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dies due to $\nearrow$
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($\sim 100 \times T$)

SN 1006

ments

CR electron

hundreds of m

thickness of
X-ray
filament

lue!!!

dies due to $\nearrow$
synchrotron losses

Large B fields observed!

($\sim 100 \times 10^{12}$ G)

SN 1006

hundreds of m

CR electron

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synchrotron losses

thickness of
X-ray
filament

narrow filament $\rightarrow$ large B field!

Large B fields observed!

($\sim 100 \times B_{\text{ISM}}$)

SN 1006

$$B_d \approx 100 \times B_{\text{ISM}}$$

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CR electron

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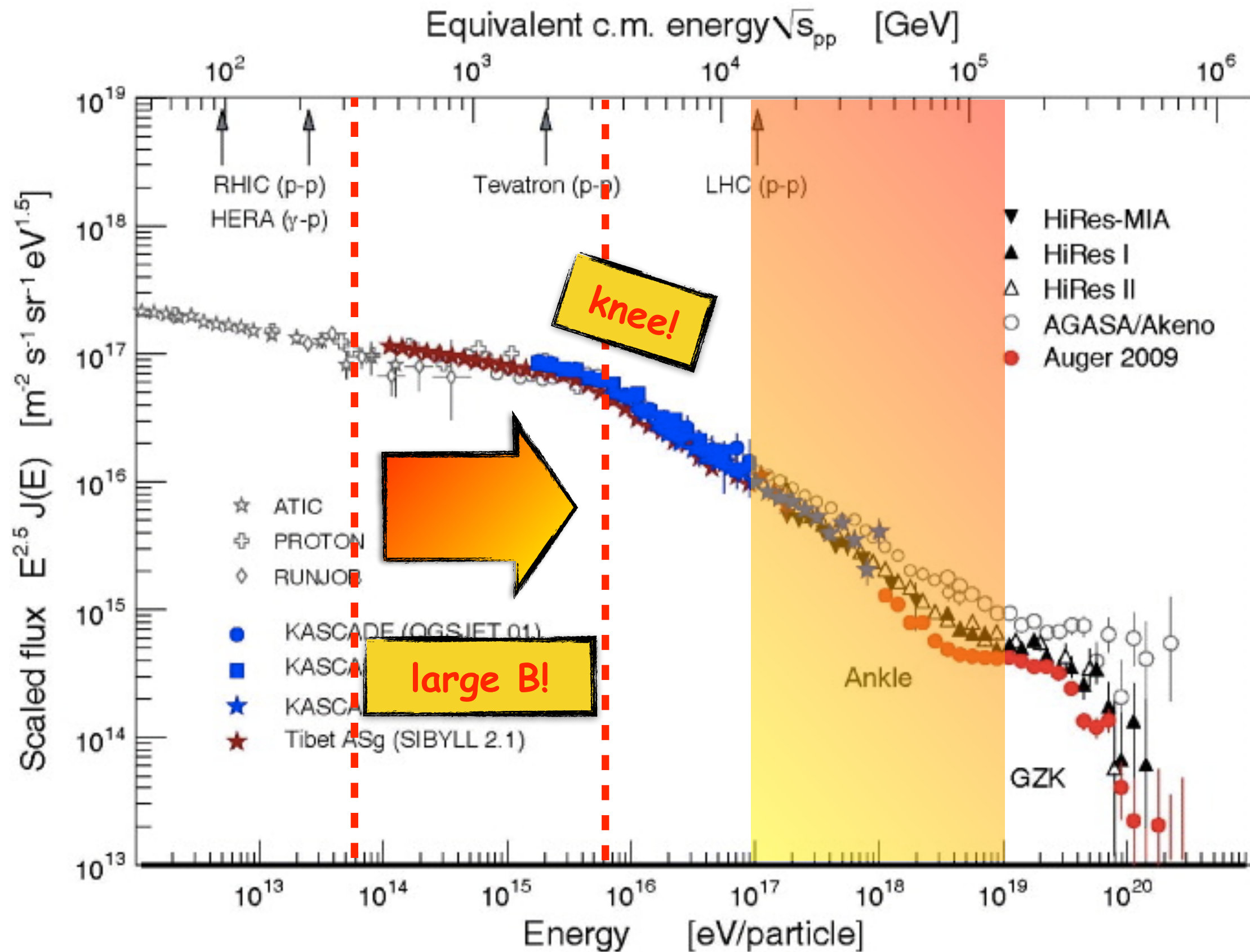
thickness of X-ray filament

narrow filament $\rightarrow$ large B field!

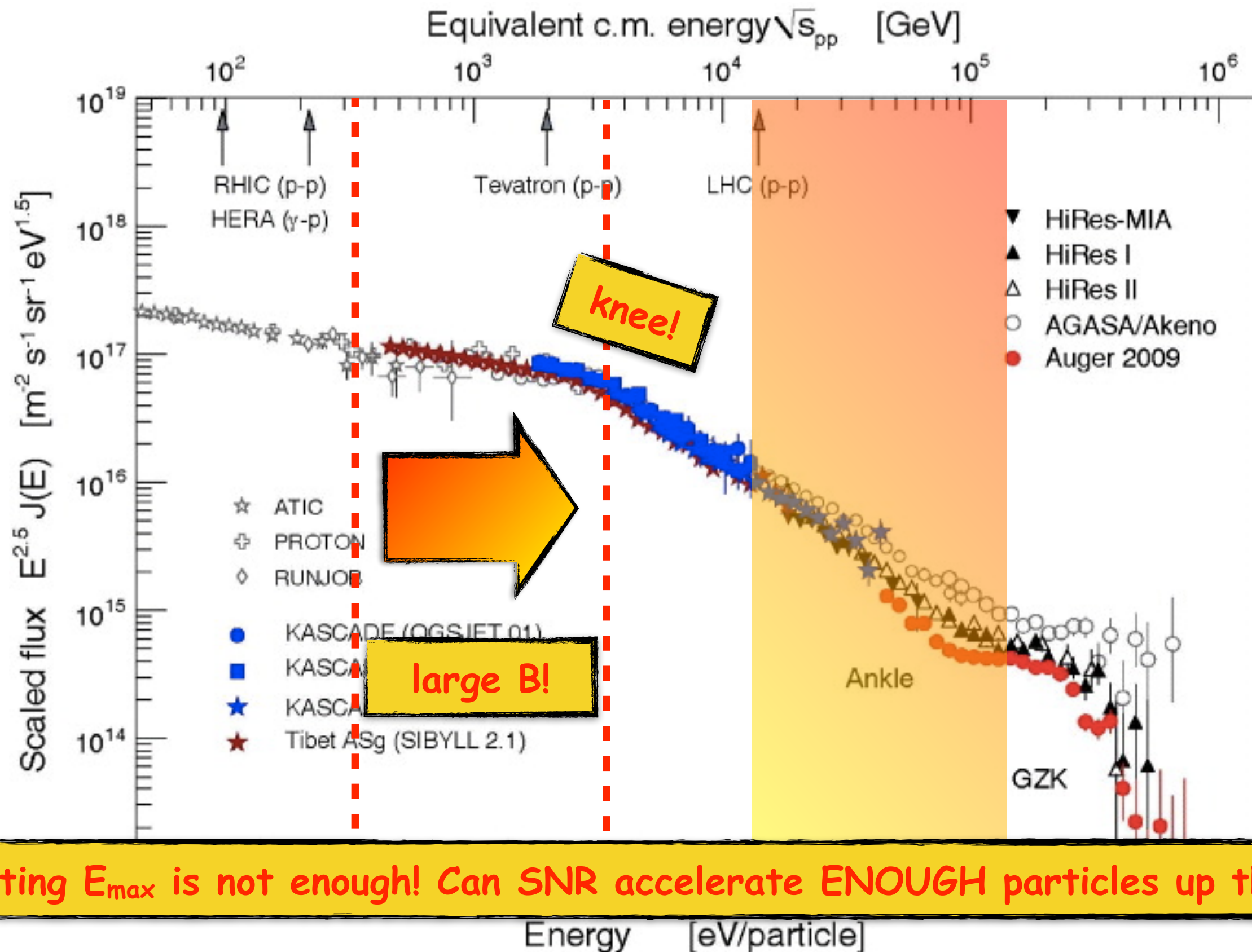
NON LINEAR!

- CR acceleration
- $\rightarrow$ CR escape
- $\rightarrow$ electric current
- $\rightarrow$ plasma instability
- $\rightarrow$ B is amplified

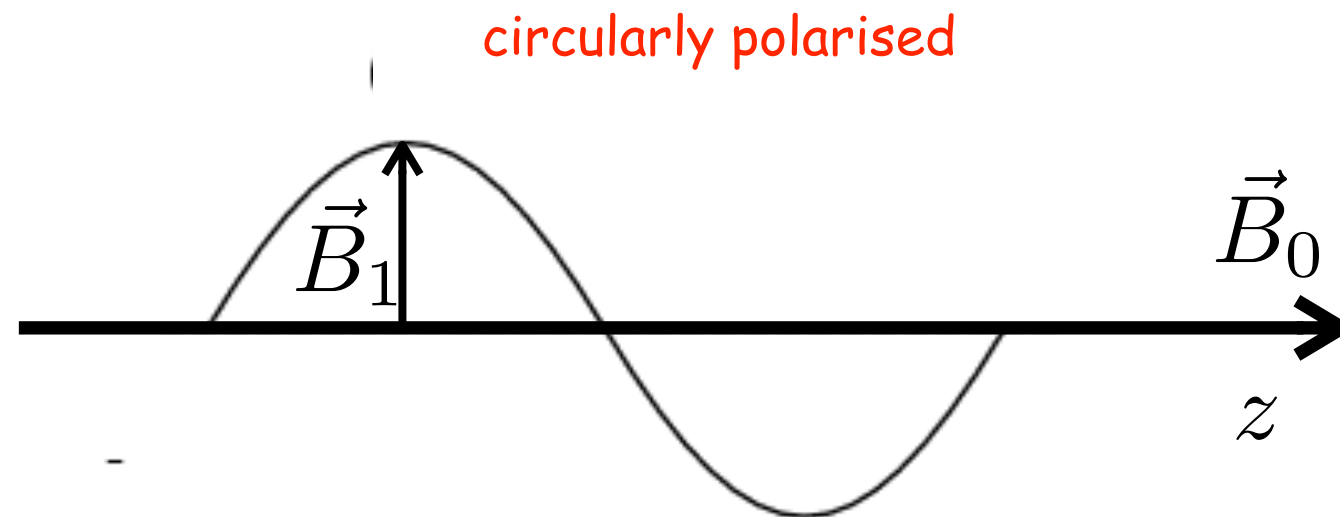
Getting close...



Getting close...



How is that? Non-resonant “Bell” instability



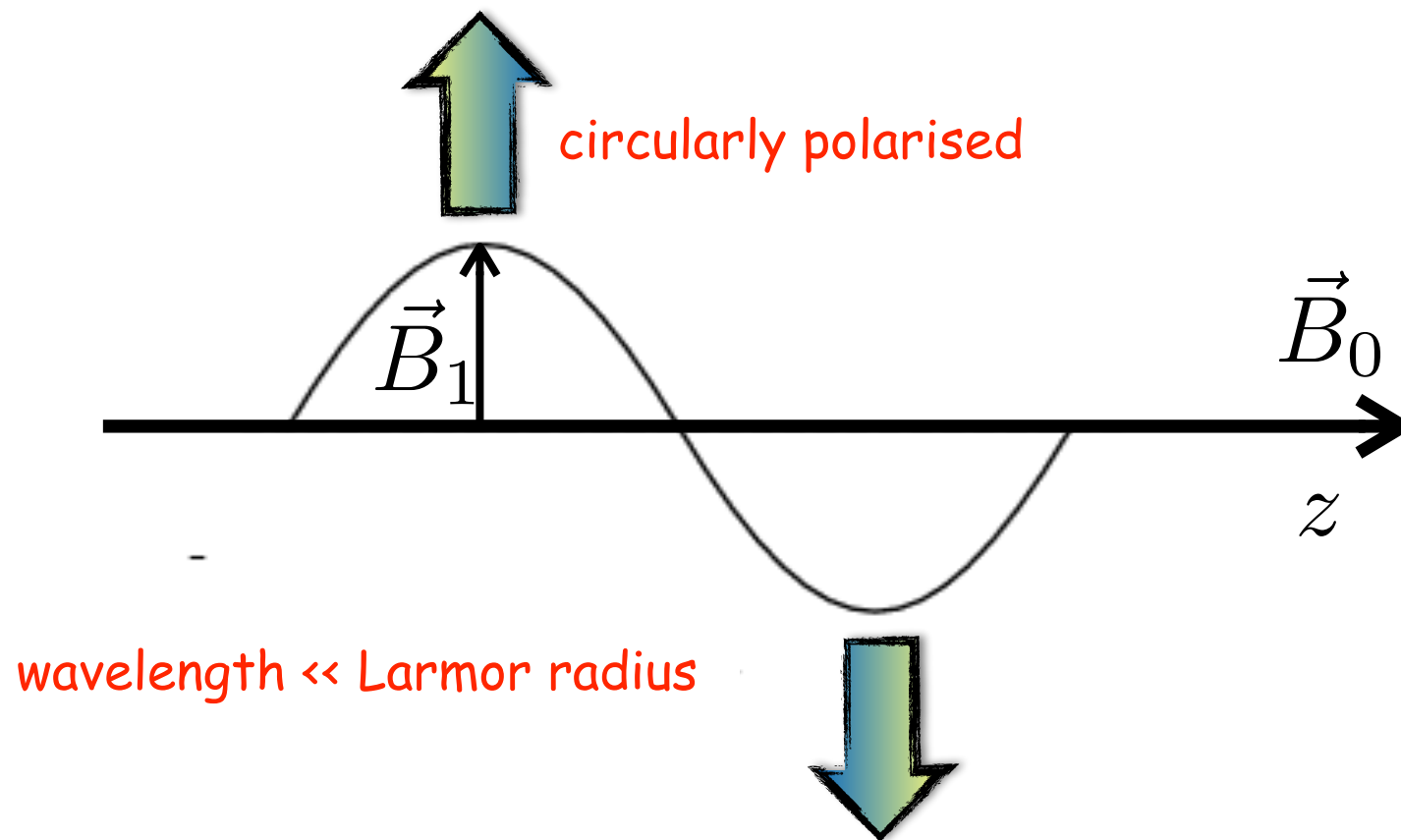
wavelength $\ll$ Larmor radius

escaping CRs barely deflected
→ CR current j along B_0
→ return current in the opposite direction

Bell 2004 ... Bell et al 2013

see also earlier works (space plasma community): Sentman+ 81, Winske & Leroy 84, Gary 93

How is that? Non-resonant “Bell” instability



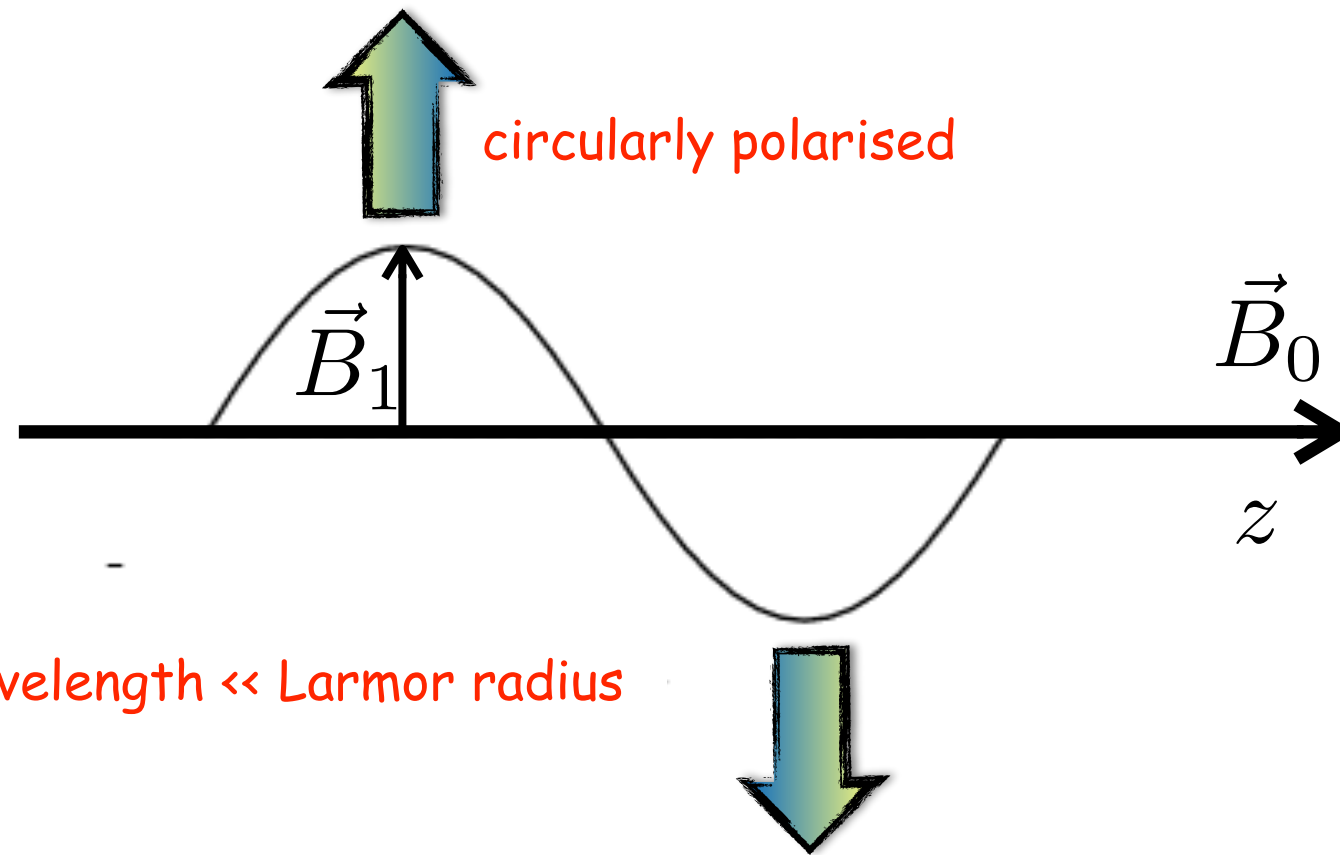
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$-\vec{j} \times \vec{B}_1$ force acting on the plasma → expands the helical perturbation of B

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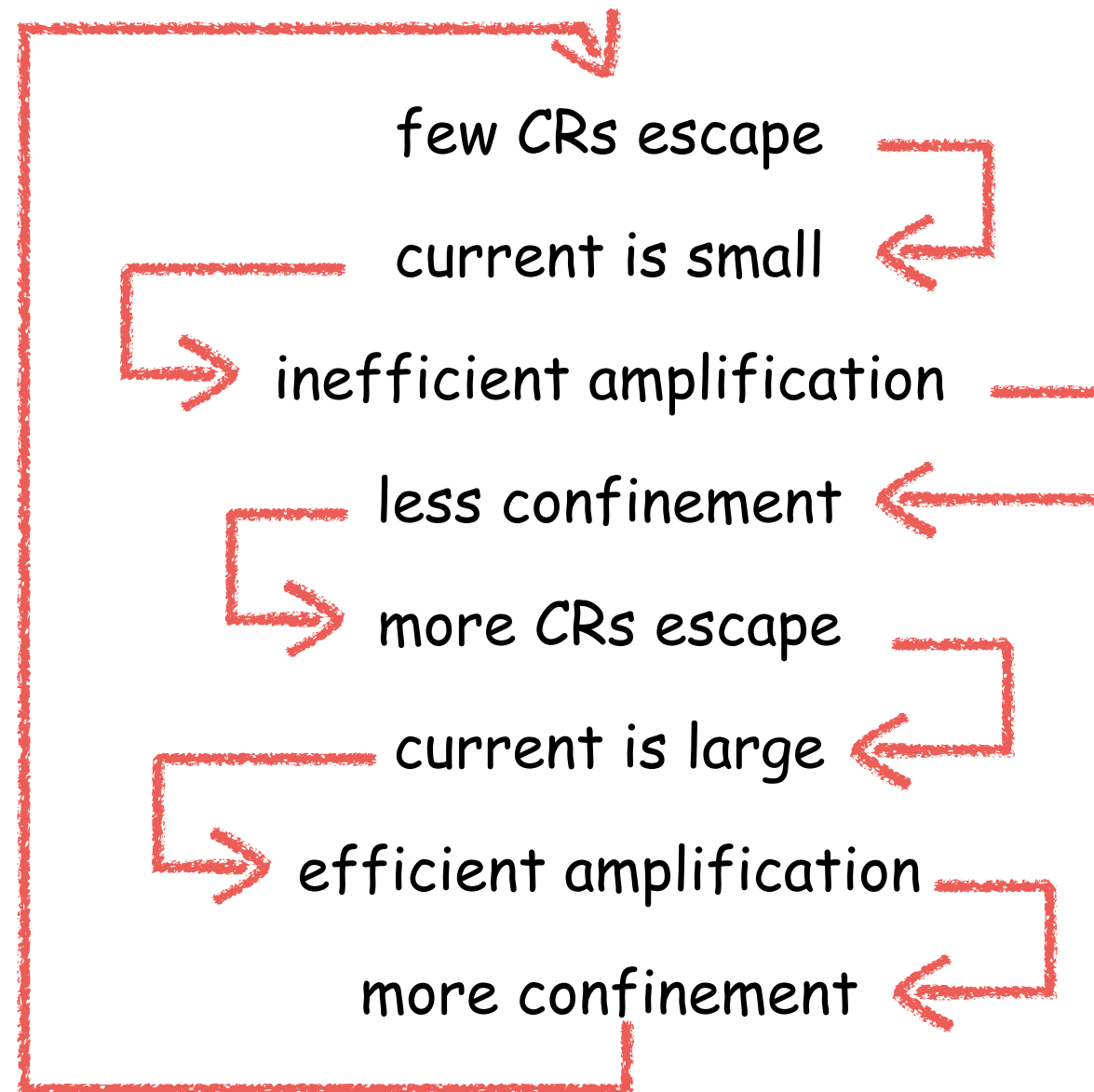
(until the size of the perturbation is of the order of the Larmor radius or magnetic tension balances it)

Bell 2004 ... Bell et al 2013

see also earlier works (space plasma community): Sentman+ 81, Winske & Leroy 84, Gary 93

A non-linear (self regulating) process...

CR current-driven instability: a self-regulating mechanism



Bell 2004

Bell et al. 2013

Iterative methods...

assumption: particles with $E < E_{\text{max}}$ are diffusively confined within the shock,
while particles with $E > E_{\text{max}}$ can freely escape

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10% SNR energy $\rightarrow$ A

~ 4 $\leftarrow q$

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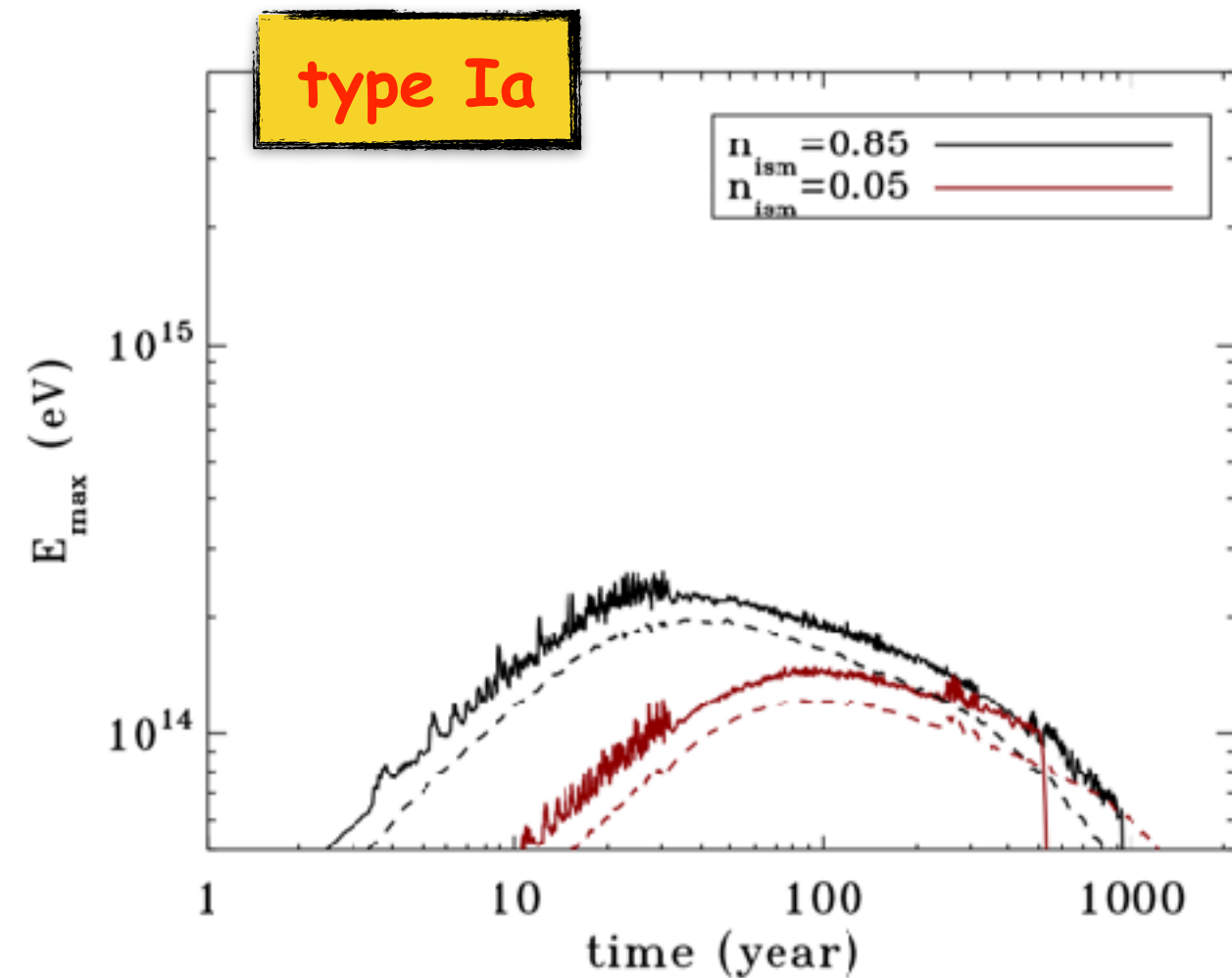
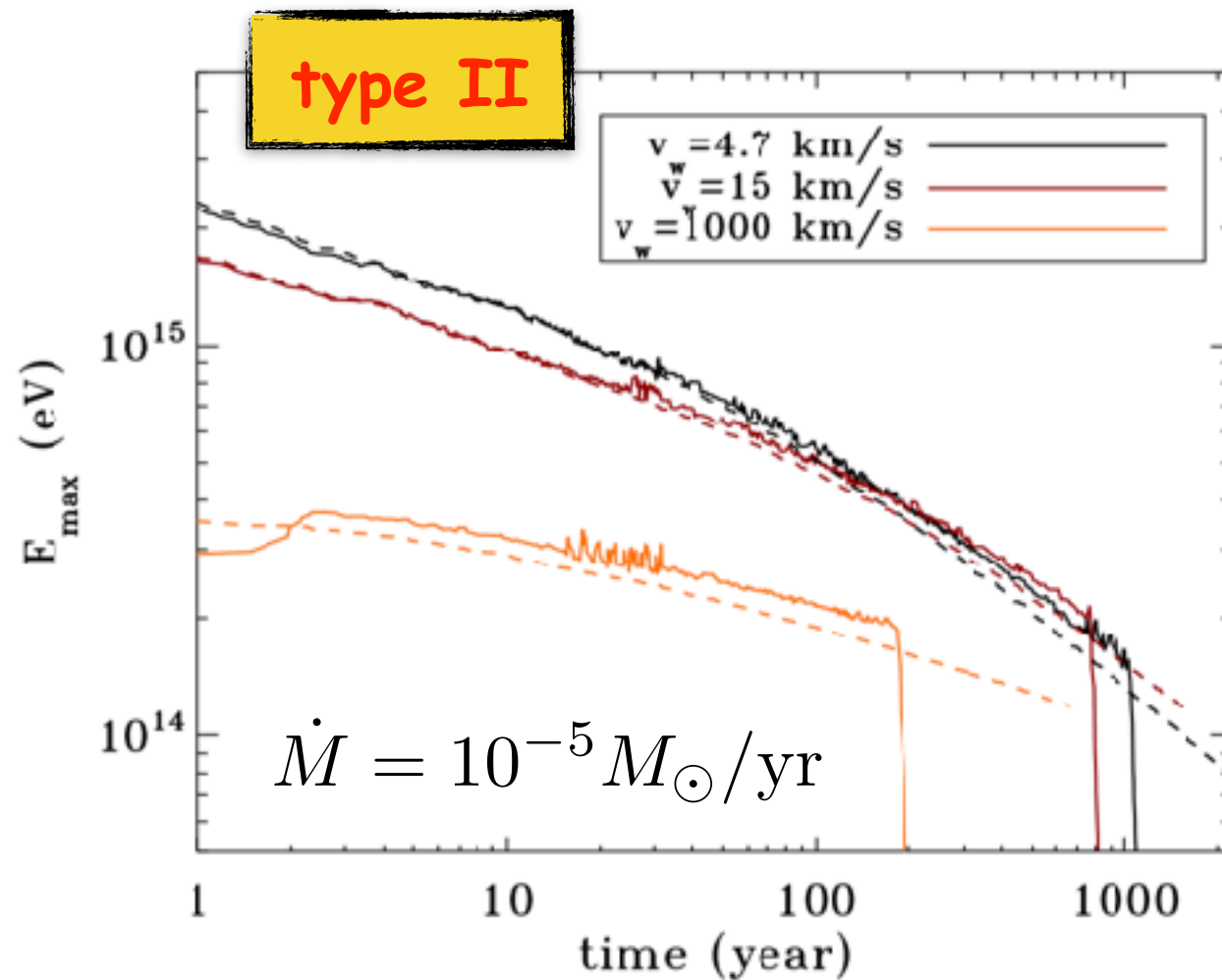
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try a $p_{\max} \rightarrow$ determine current $j \rightarrow$ get $B \rightarrow$ get a new $p_{\max} \rightarrow$ adjust and restart

note that in the case B depends on time $\rightarrow$ different scalings for $E_{\max}(t)$

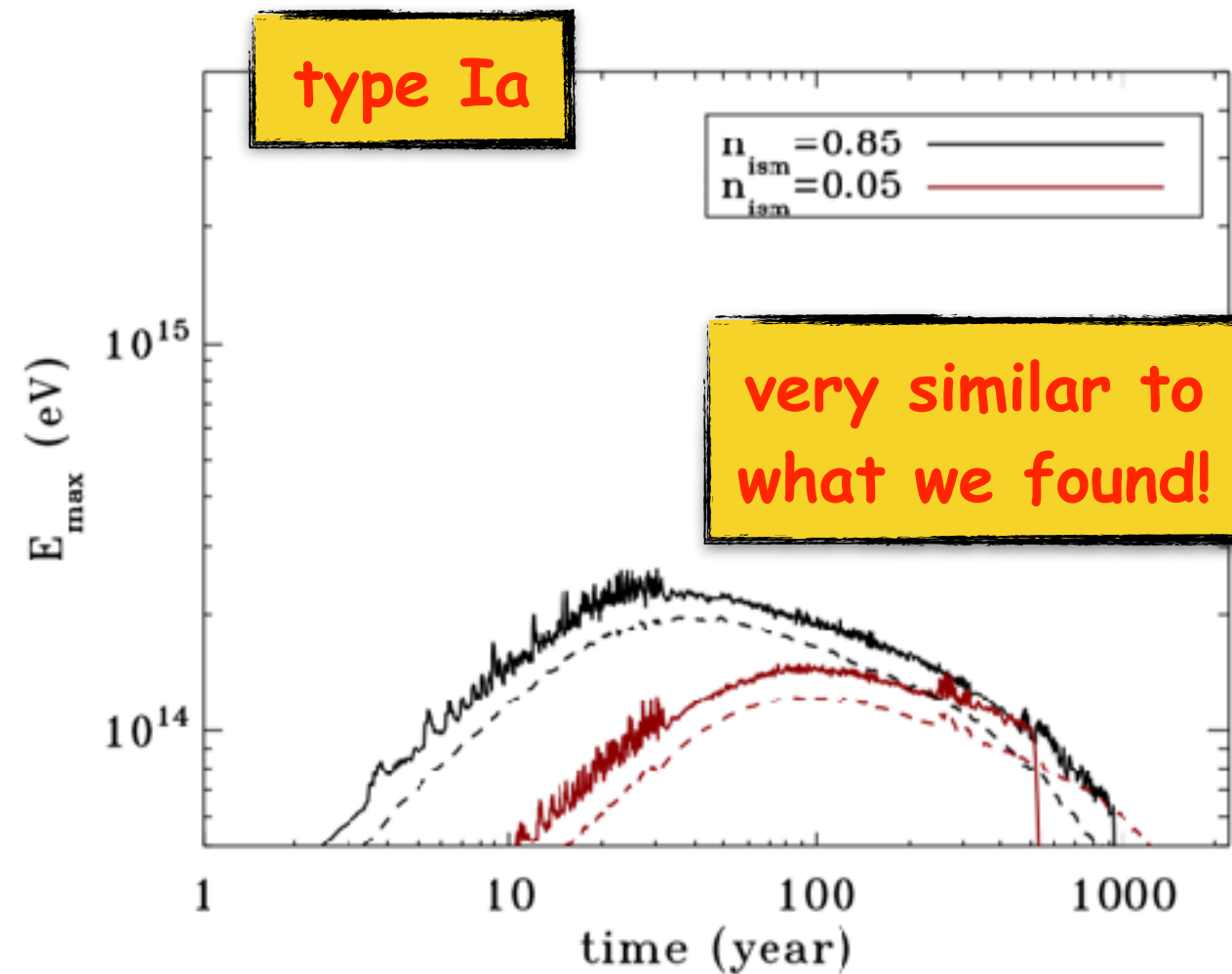
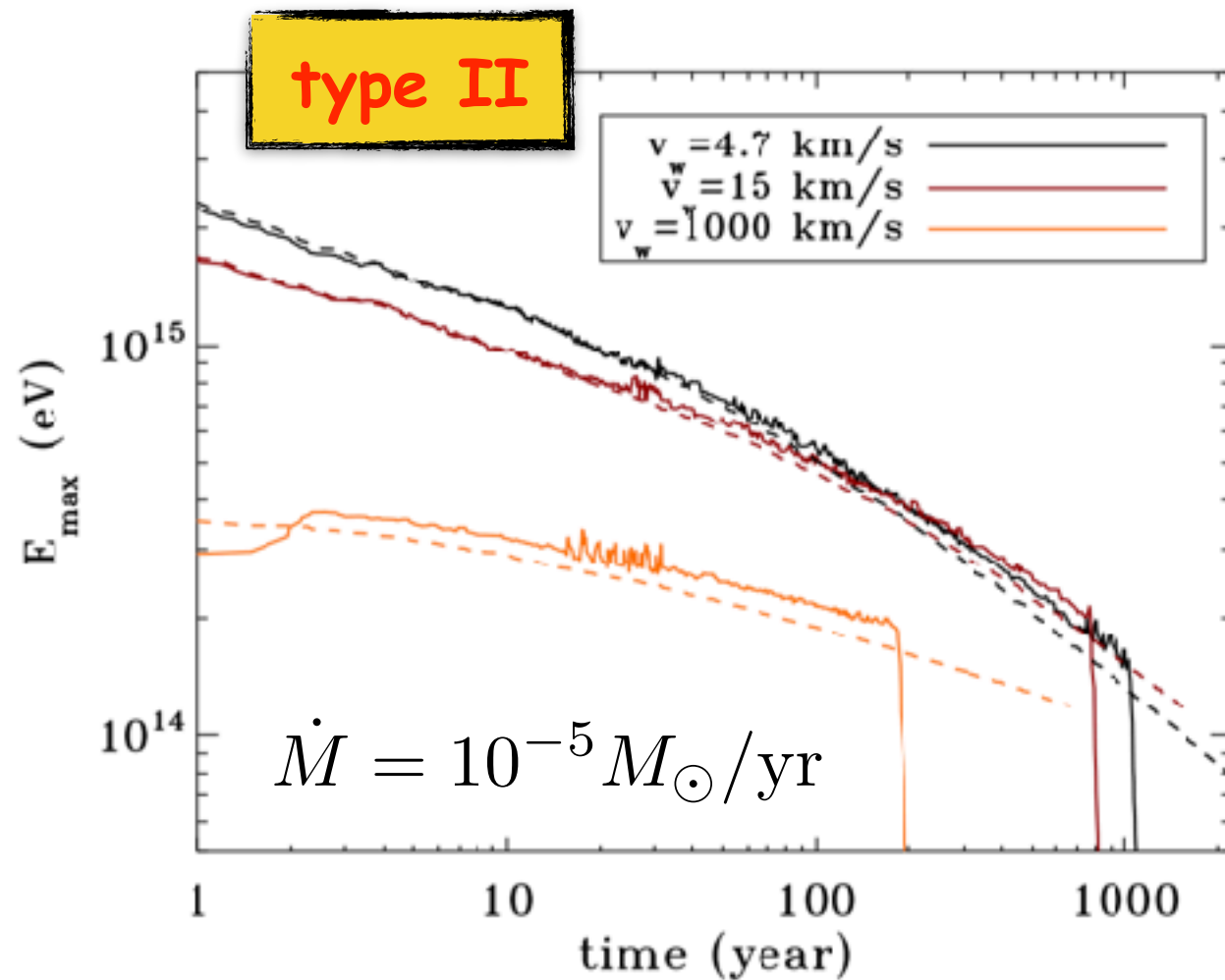
Only very young SNRs accelerate to PeV

Schure & Bell 2013



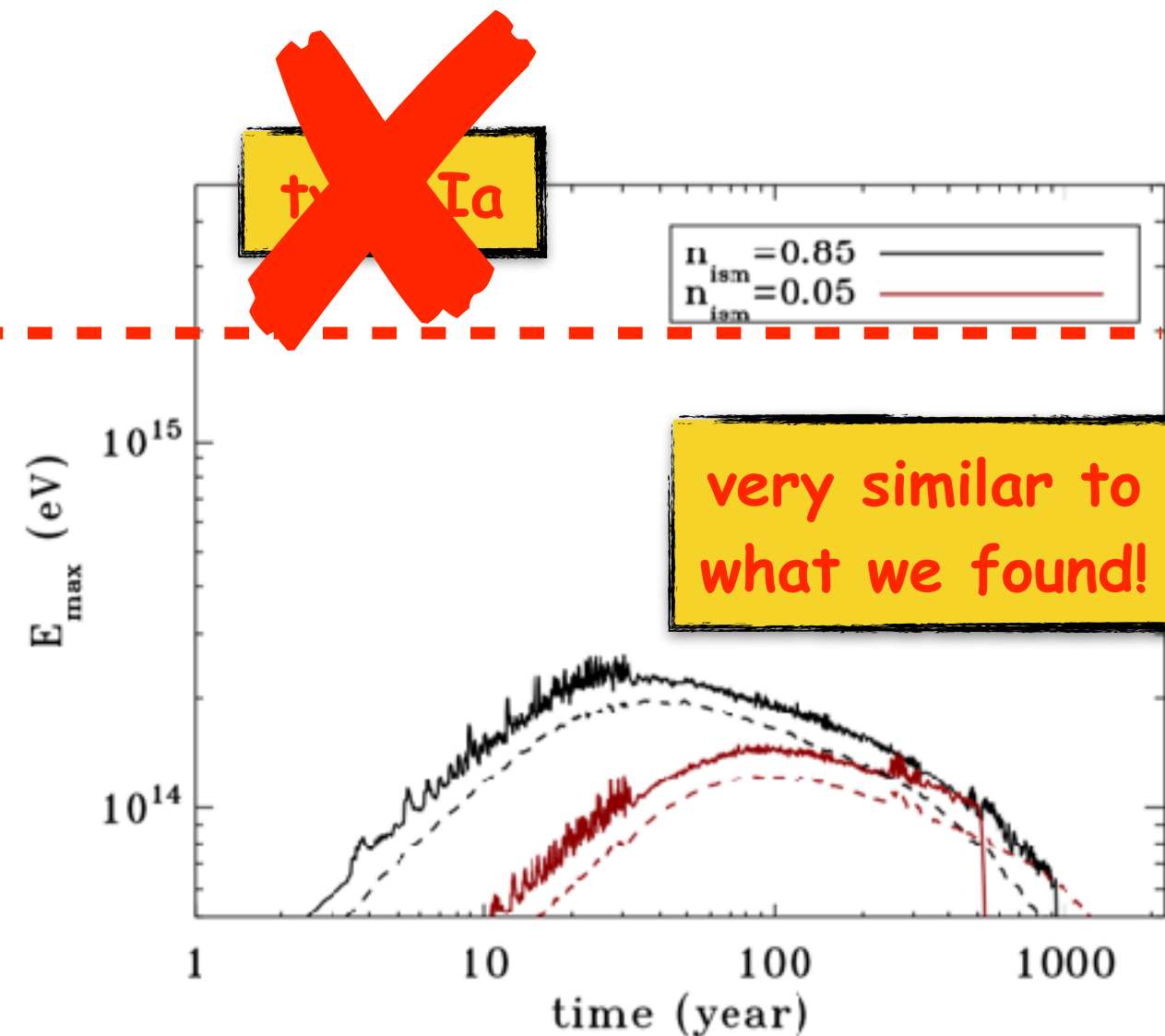
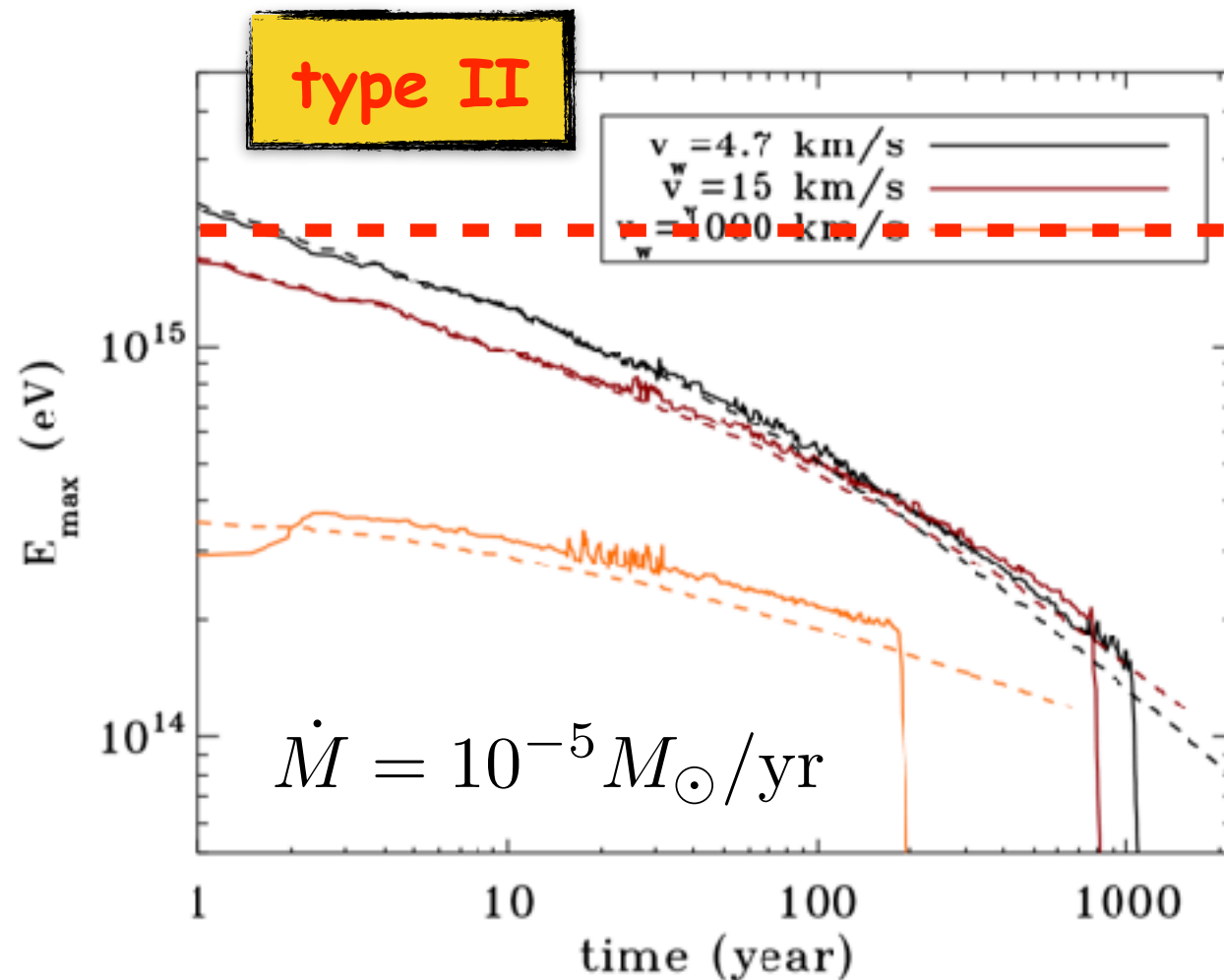
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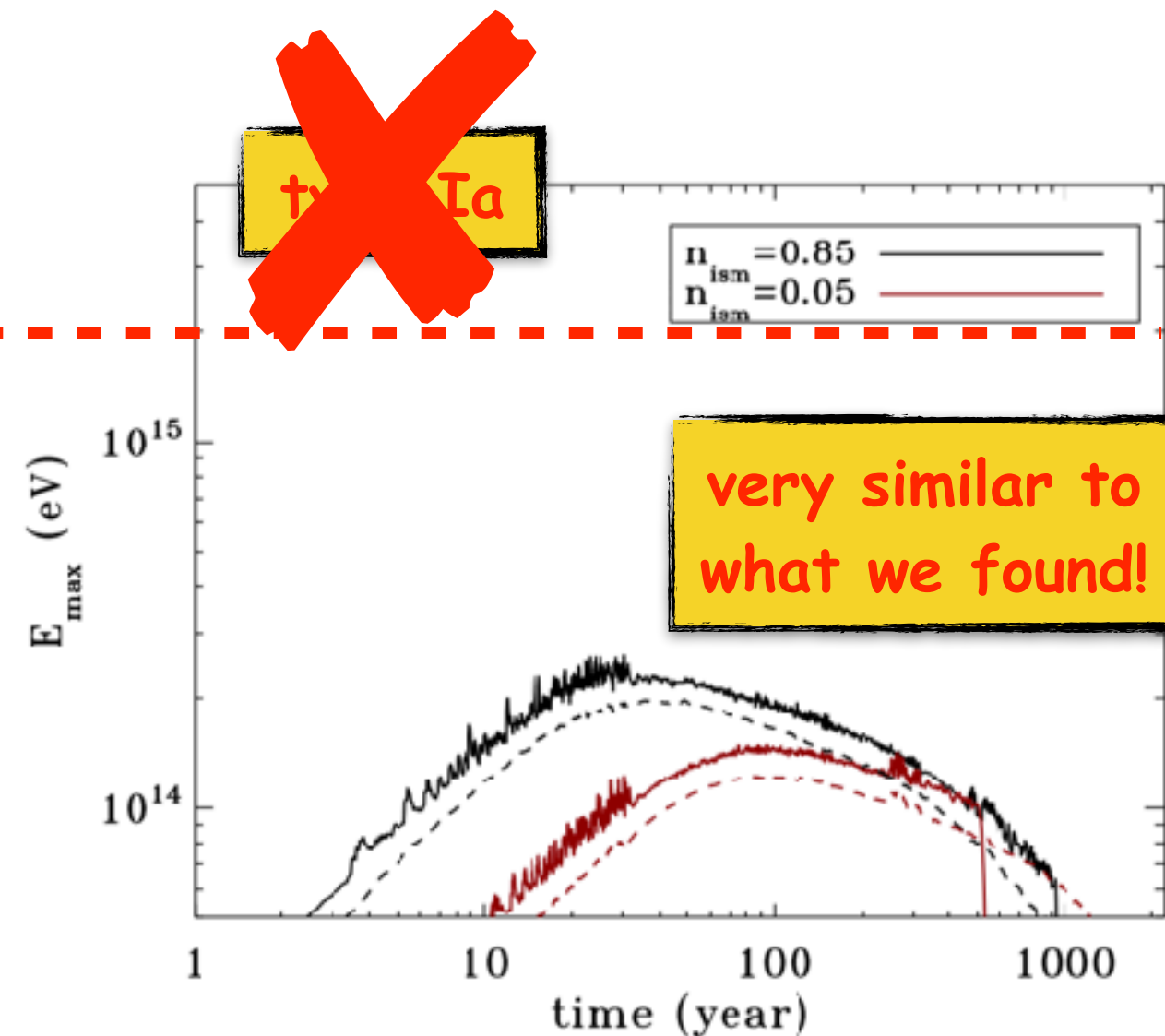
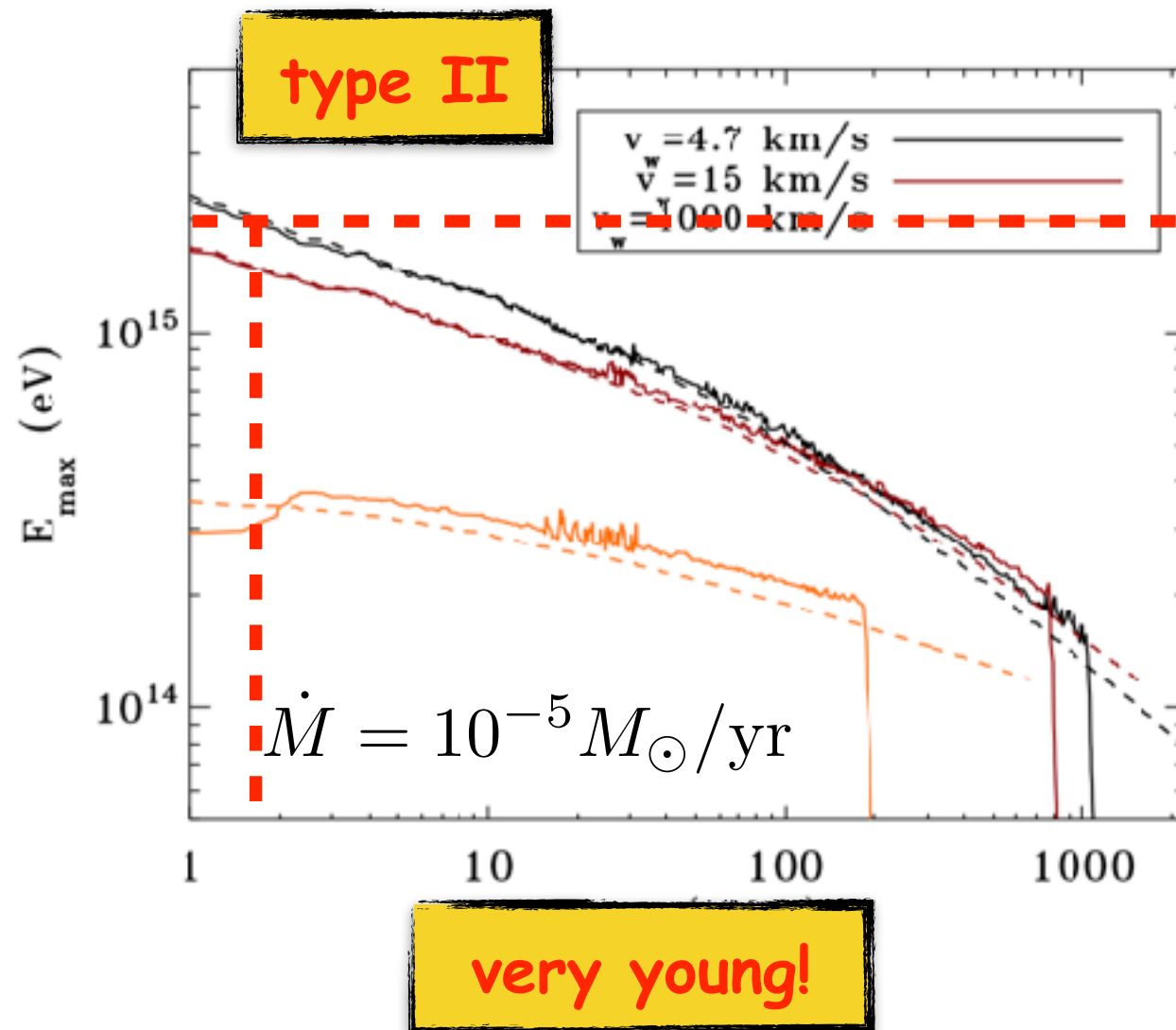
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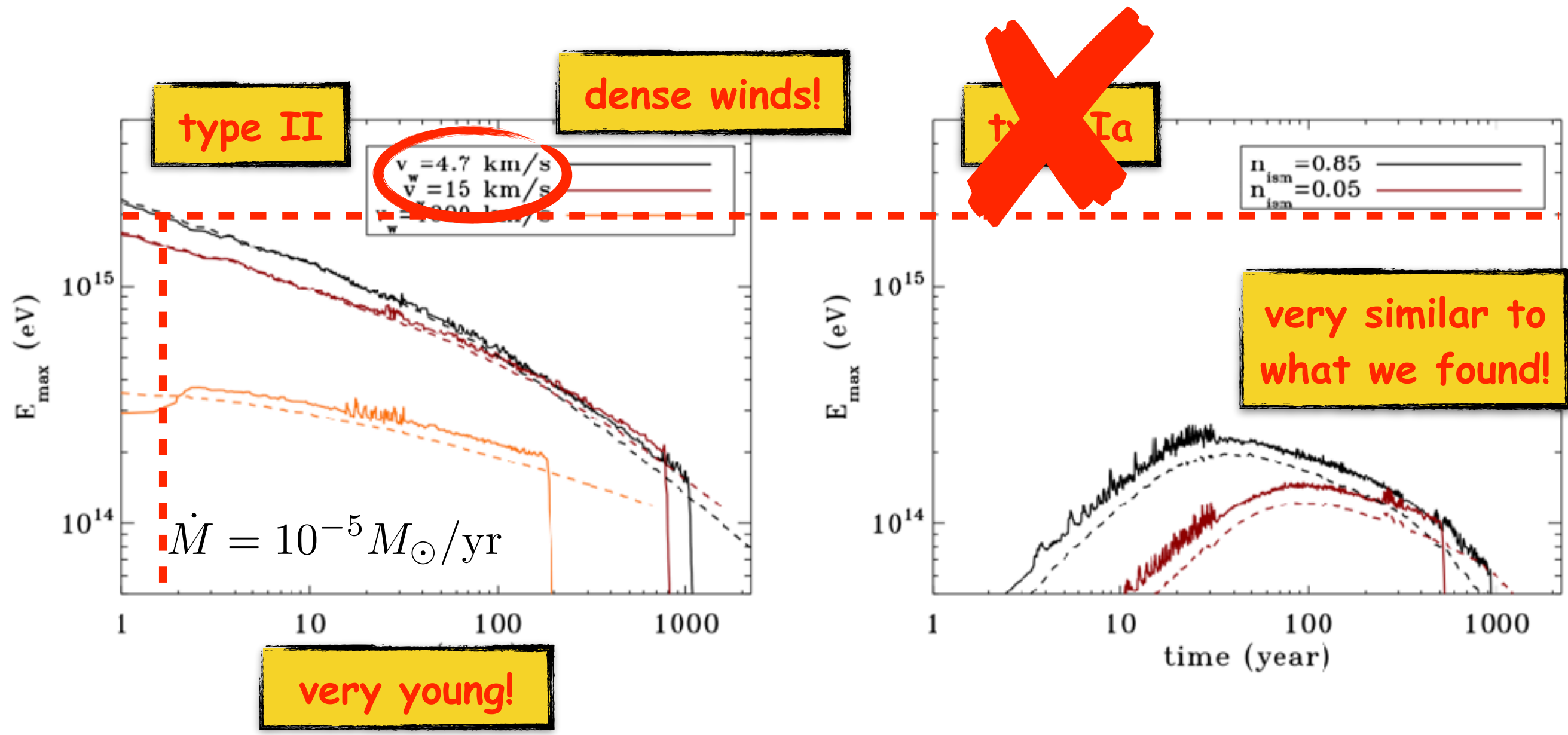
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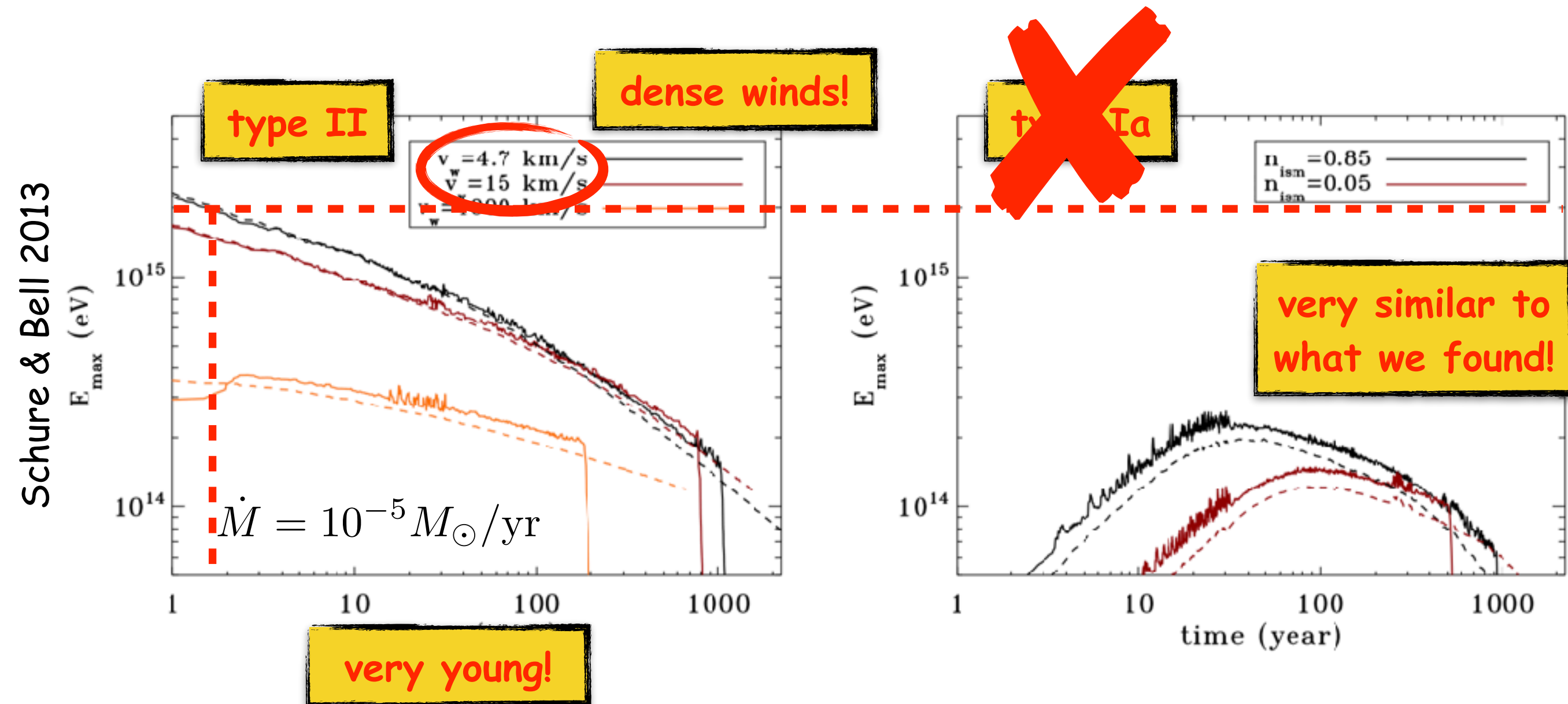


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Only very young SNRs accelerate to PeV



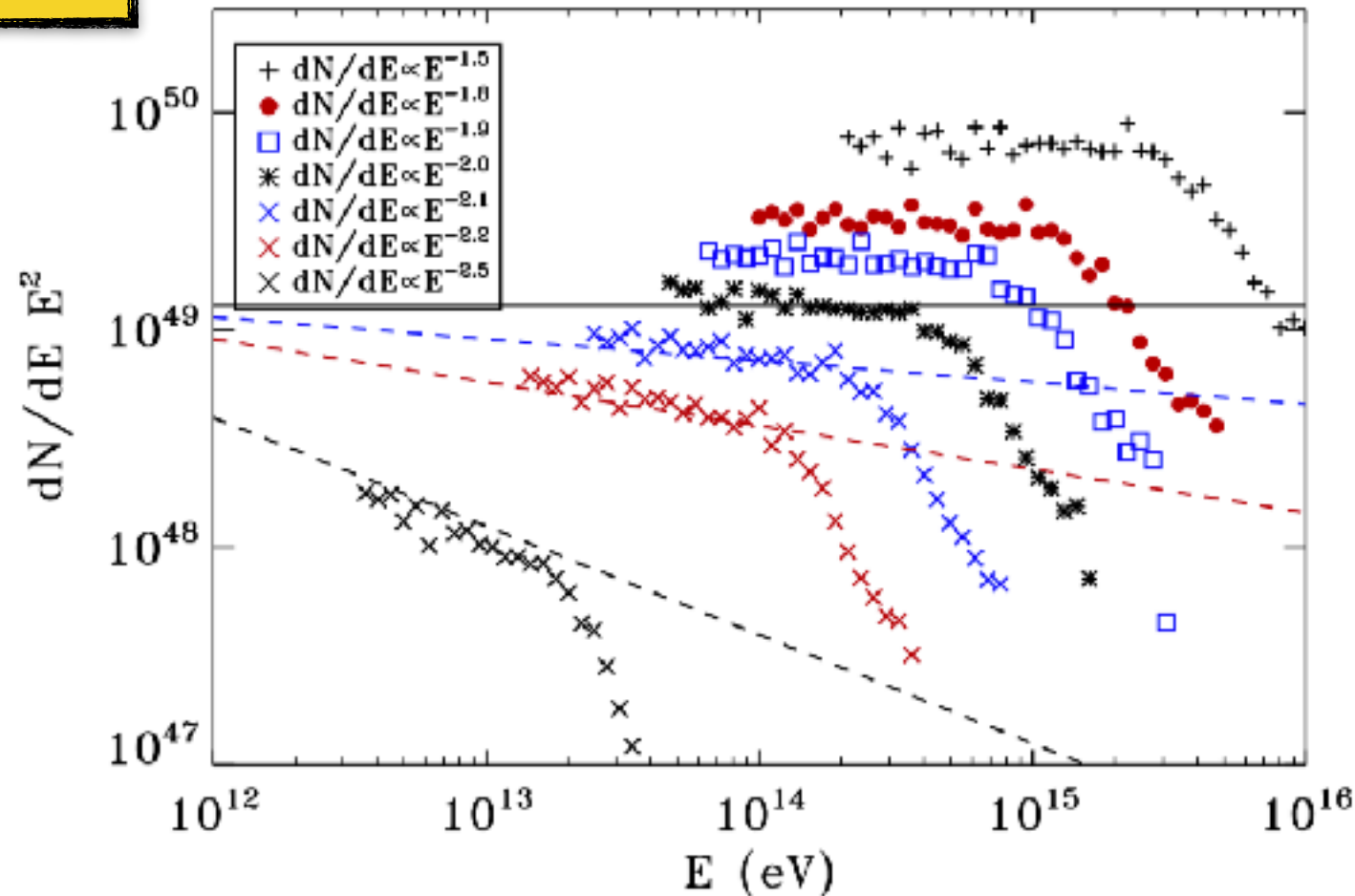
3 consequences:

- ☐ can SNR accelerate CRs up to the knee and beyond? → **most likely yes!**
- ☐ **very rare events** → # of **active PeV SNRs** = 0 → enough CRs? → maybe not?
- ☐ “**knee**” in the spectrum from one SNR at **transition to Sedov**

One can't have everything...

spectrum of CRs released in the ISM during the entire SNR life

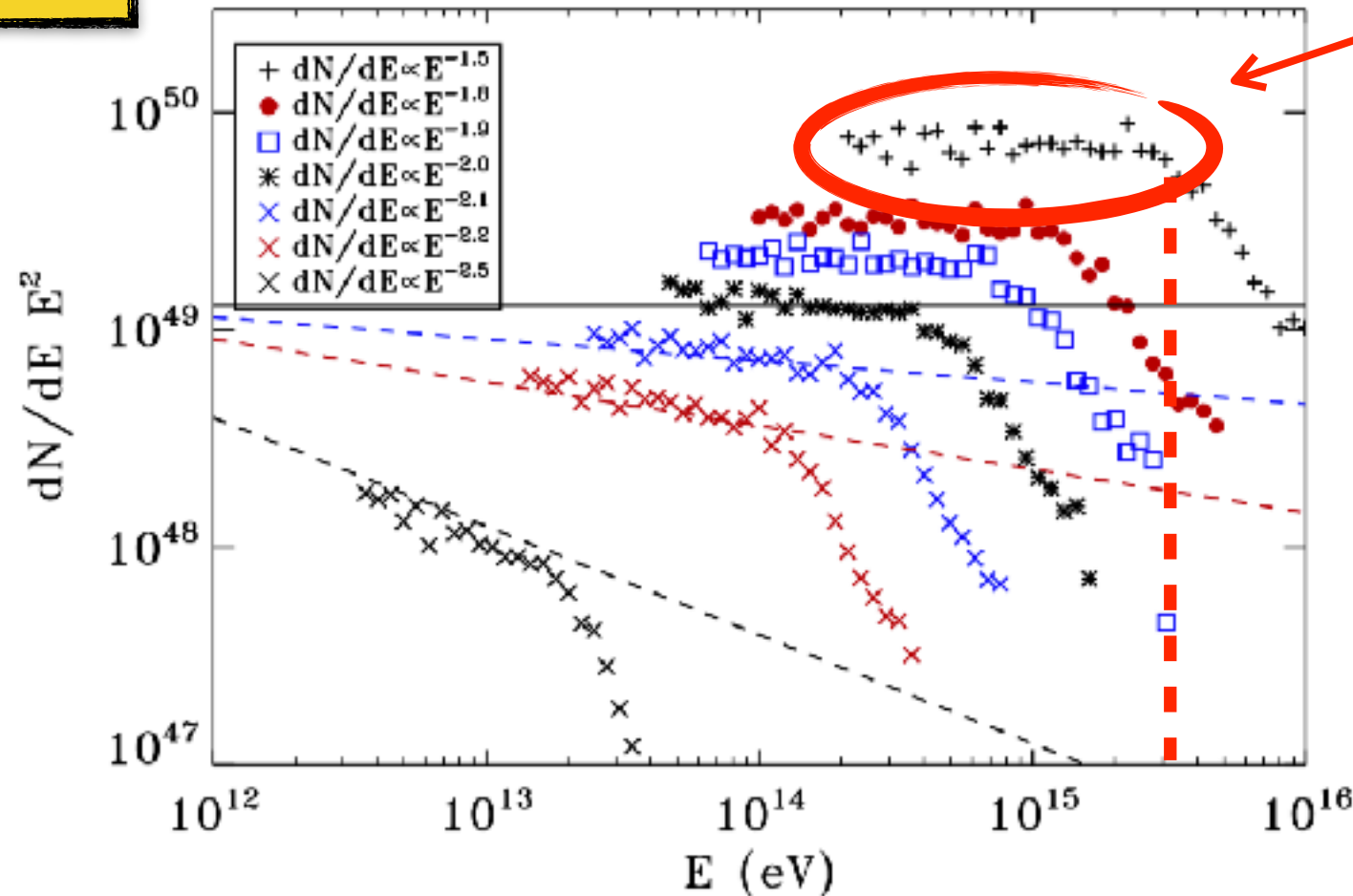
type II



One can't have everything...

spectrum of CRs released in the ISM during the entire SNR life

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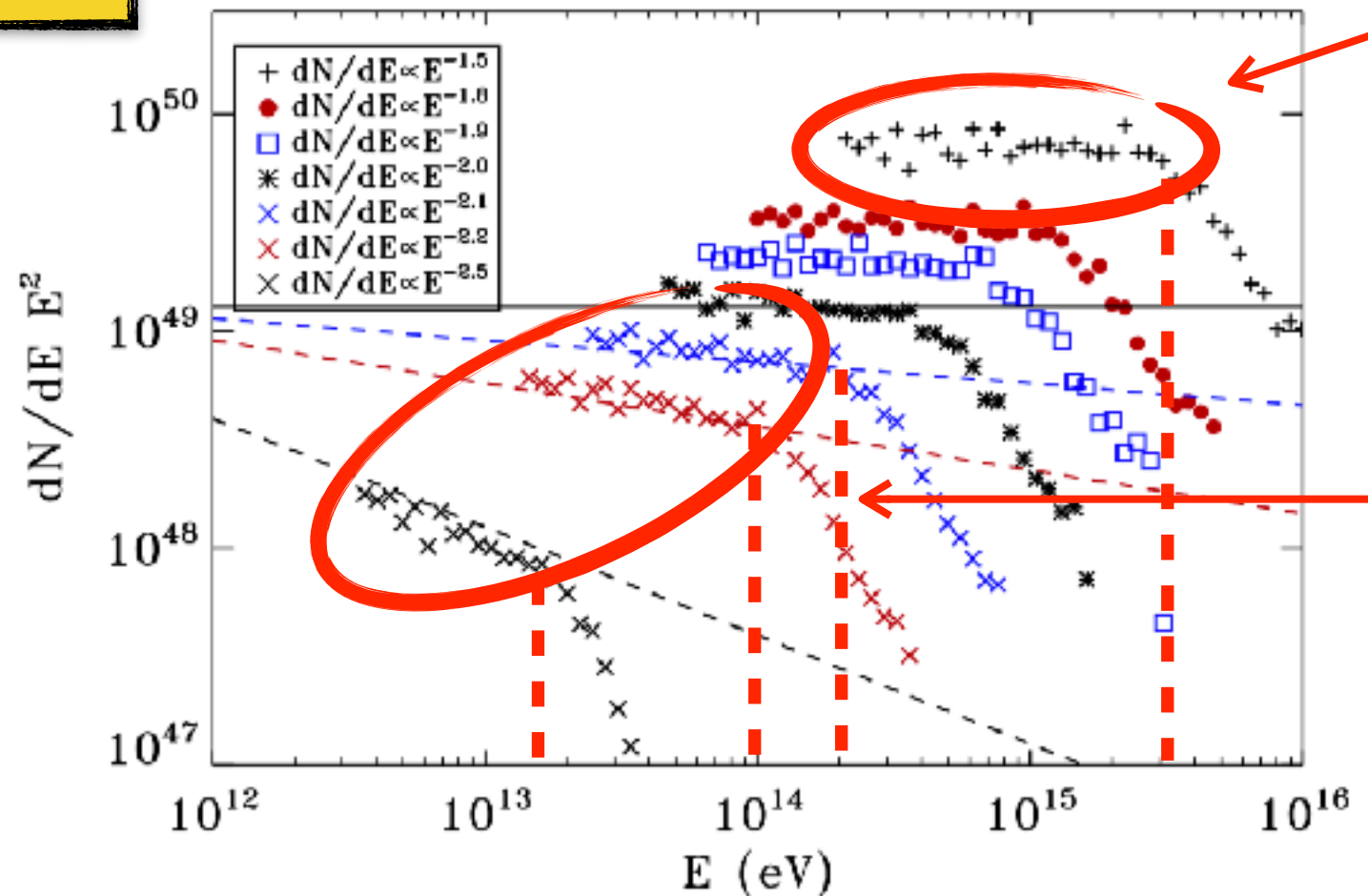


knee at the right place
→ injection too hard

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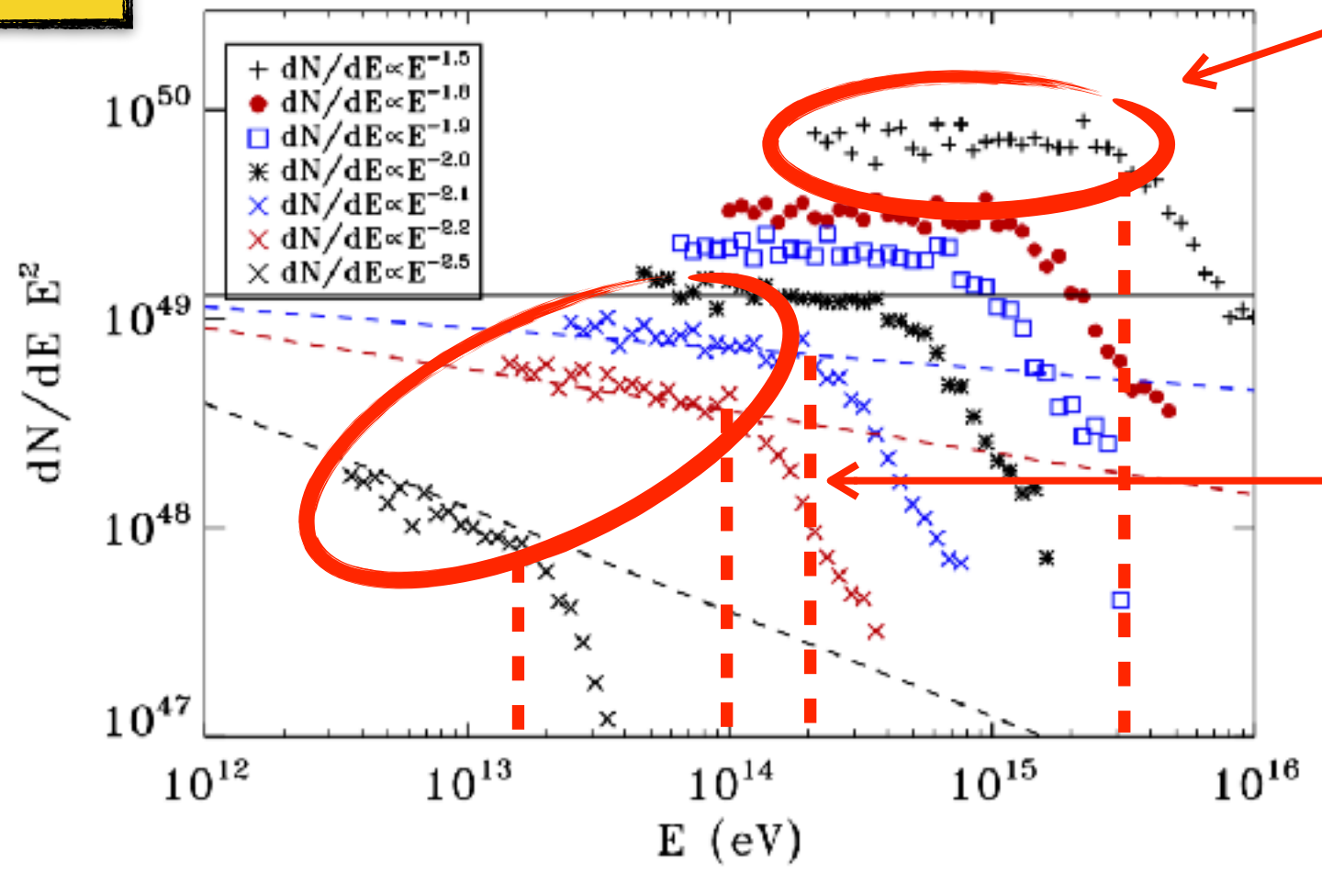
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injection spectrum
steeper than 2
→ not enough to reach
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Schure & Bell 2014

can we
tune it?

It is also worth noticing that none of the types of SNRs considered here is able alone to describe the relatively smooth CR spectrum that we measure over many decades in energy. In a way, rather than being surprised by the appearance of features, one should be surprised by the fact that the CR spectrum is so regular.

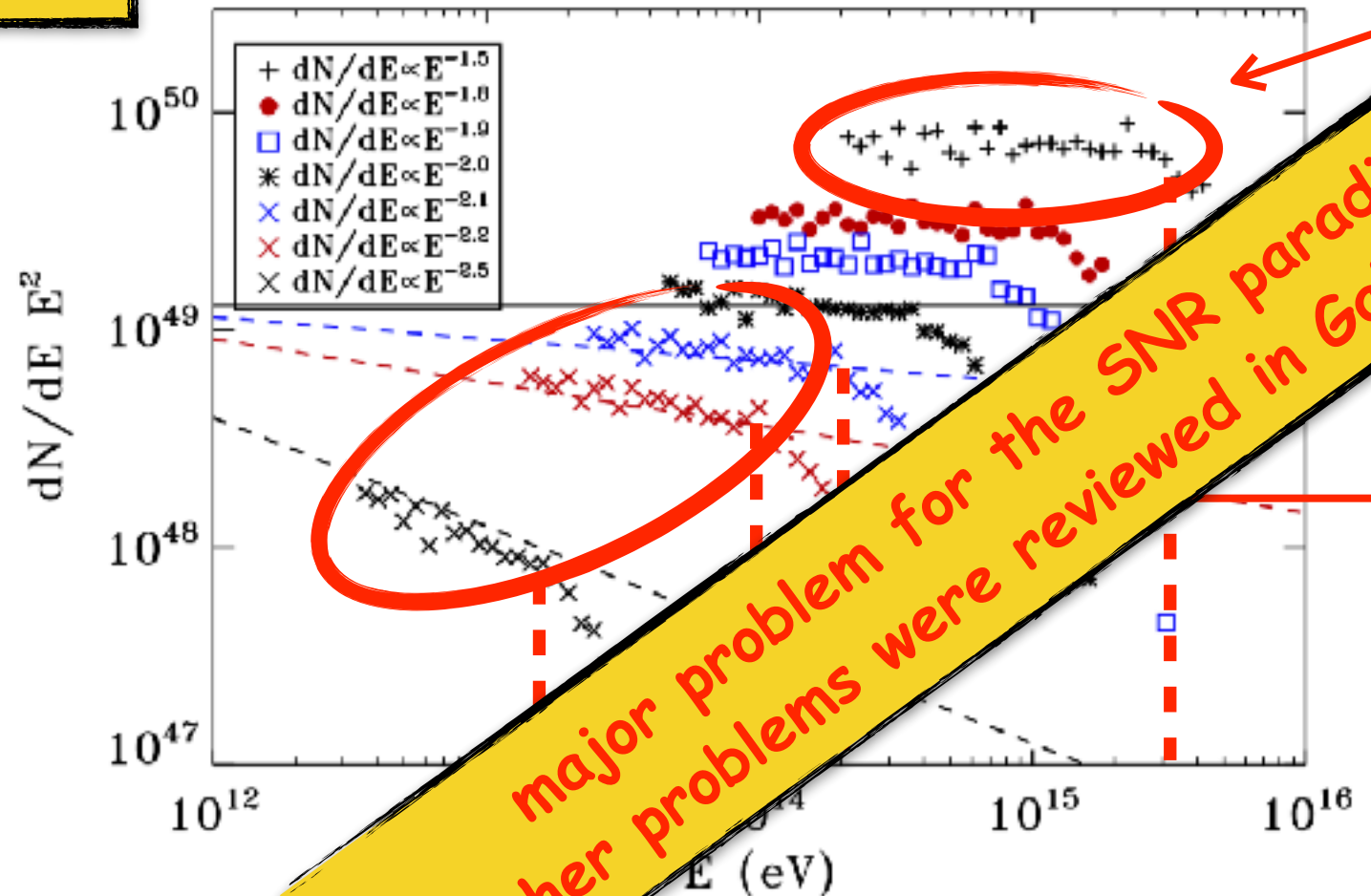
(Cristofari+ 2020)

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Schure & Bell 2014



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(Cristofari+ 2020)



How to conclude?

The three pillars of orthodoxy

▶ The bulk of the energy of cosmic rays originates from supernova explosions in the Galactic disk

▶ Cosmic rays are diffusively confined within an extended and magnetised Galactic halo

▶ Cosmic rays are accelerated out of the (dusty) interstellar medium through diffusive shock acceleration in supernova remnants

The three pillars of orthodoxy

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Do SNRs accelerate ALL CRs? (PeV and beyond)

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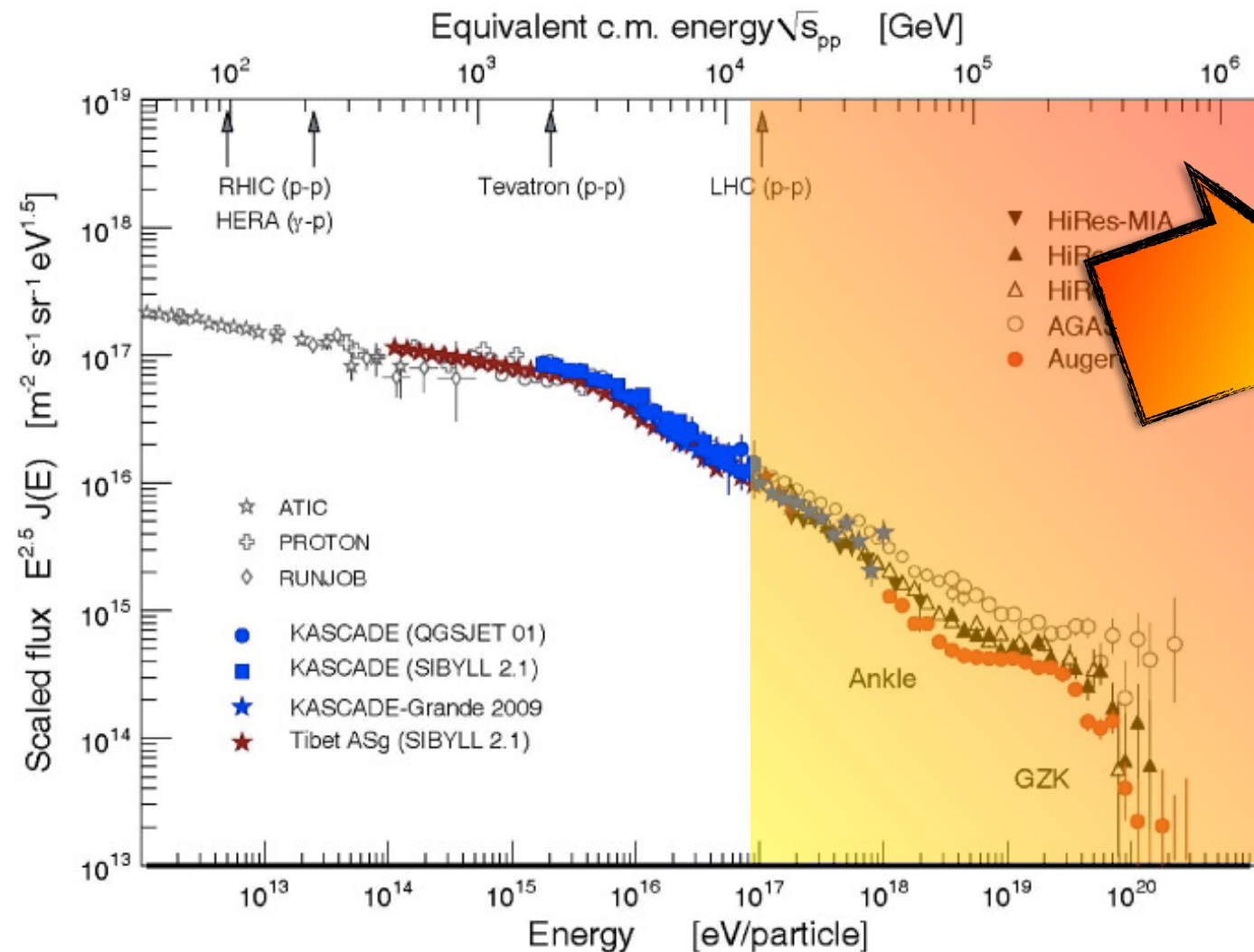
Do SNRs accelerate ALL CRs? (PeV and beyond)

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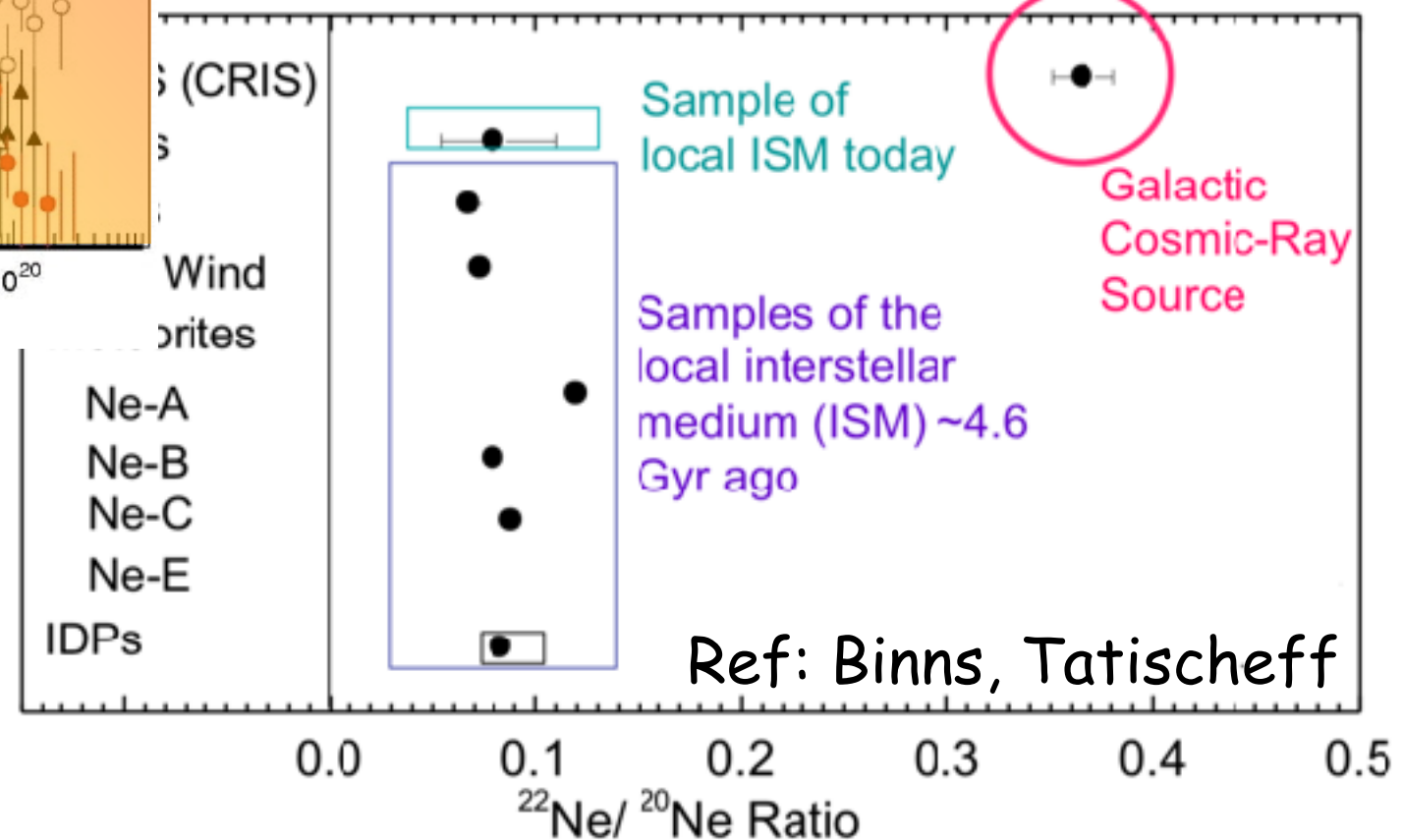
what about $^{22}\text{Ne}/^{20}\text{Ne}$? $\rightarrow$ stellar winds

(At least) three serious issues remains



[1] can SNR shocks accelerate particles up to the largest observed energies?

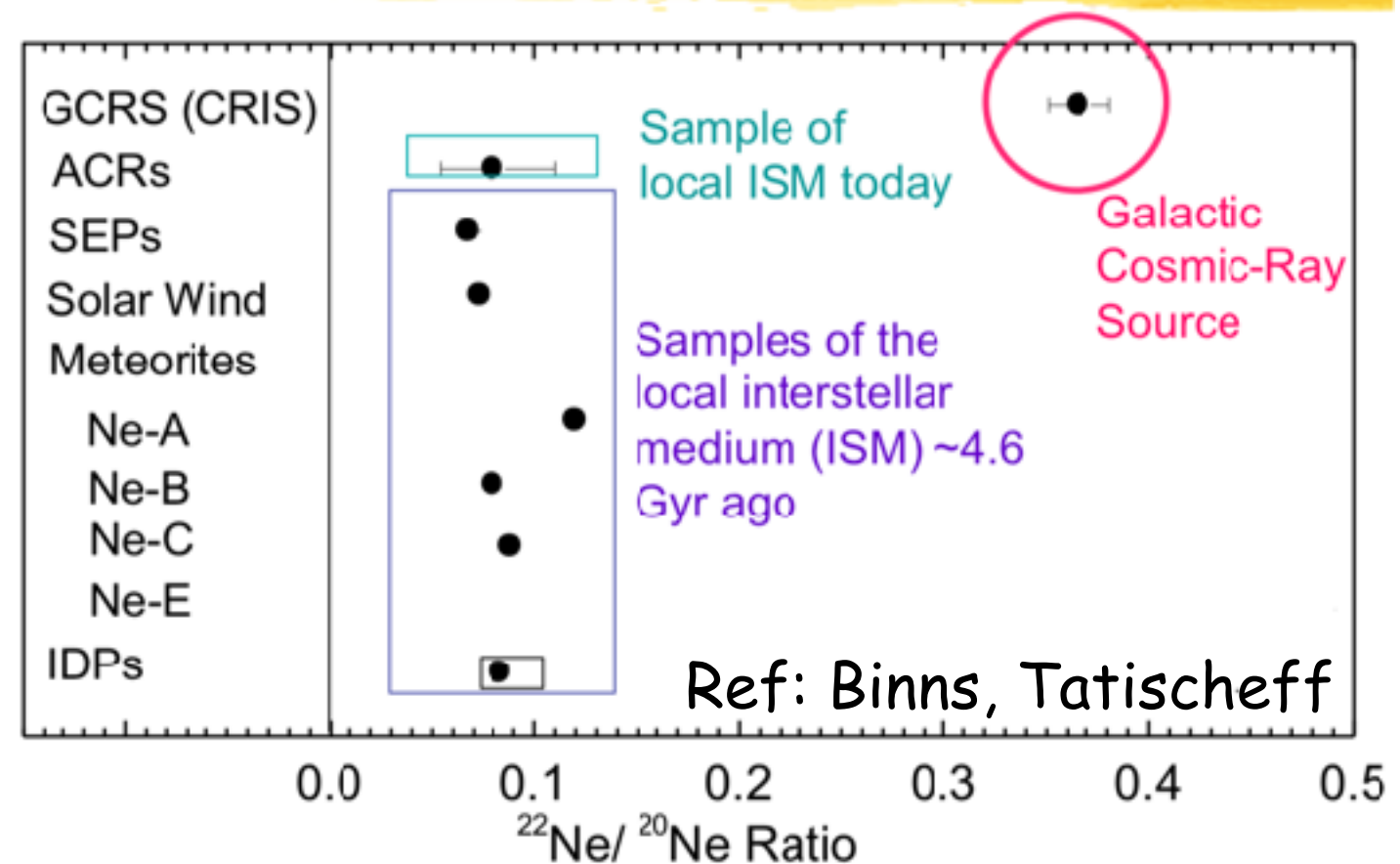
[2] can the SNR paradigm explain the anomalous excess of the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio?



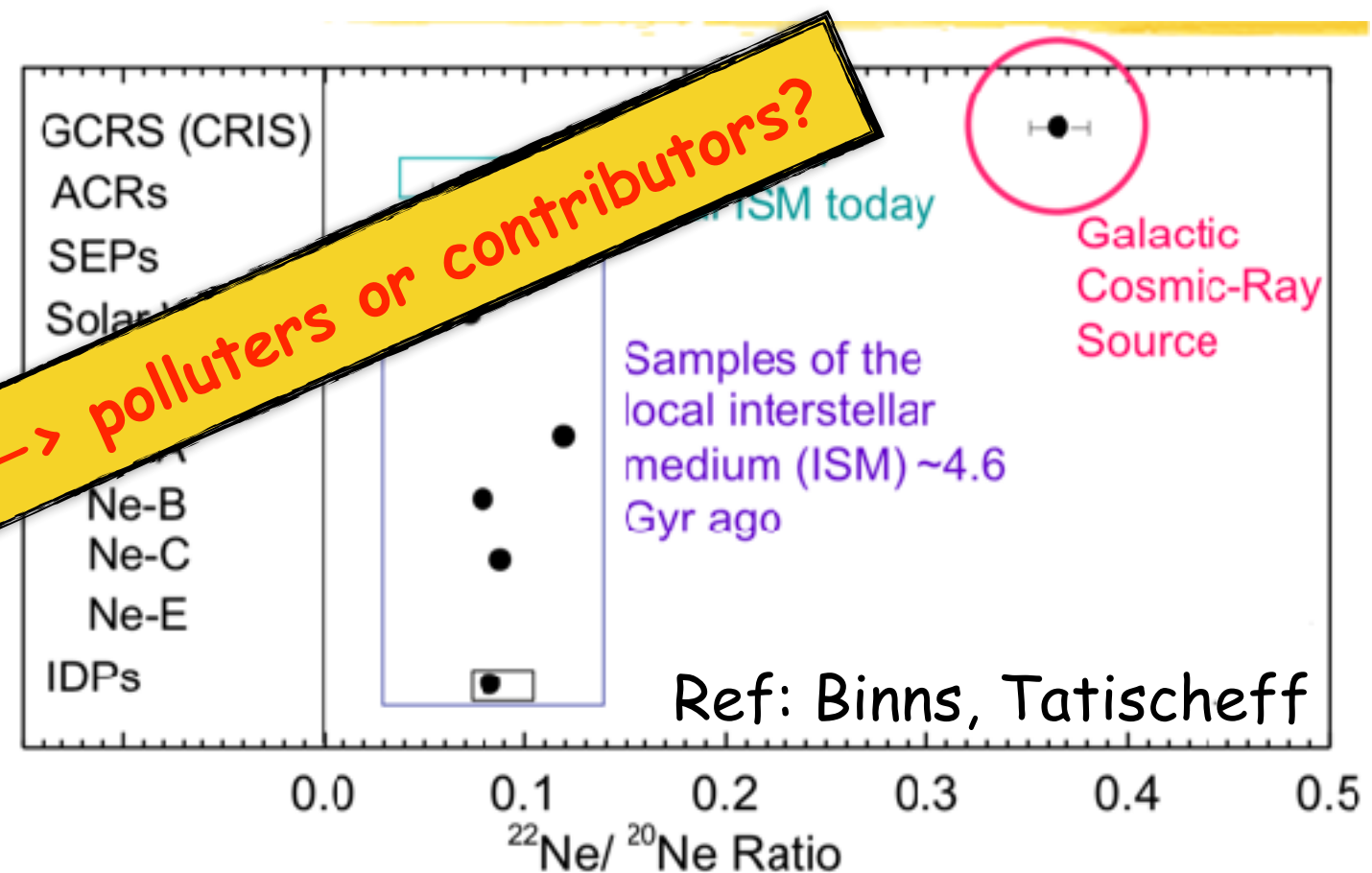
[3] DSA predicts E^{-2} spectra, but we need $E^{-2.2}$!

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role of stellar winds $\rightarrow$ polluters or contributors?

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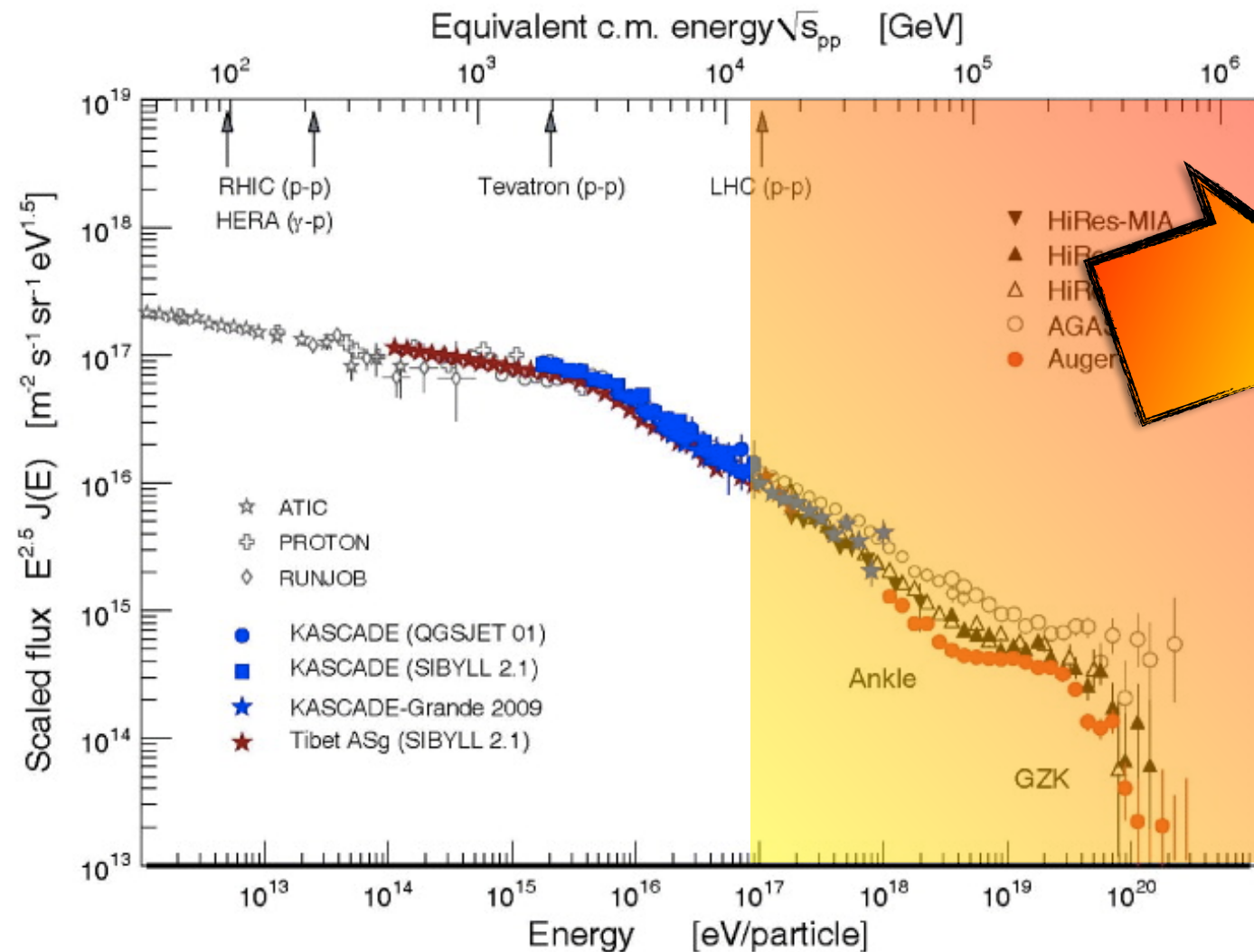
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90% SNR + 10% stellar winds might work

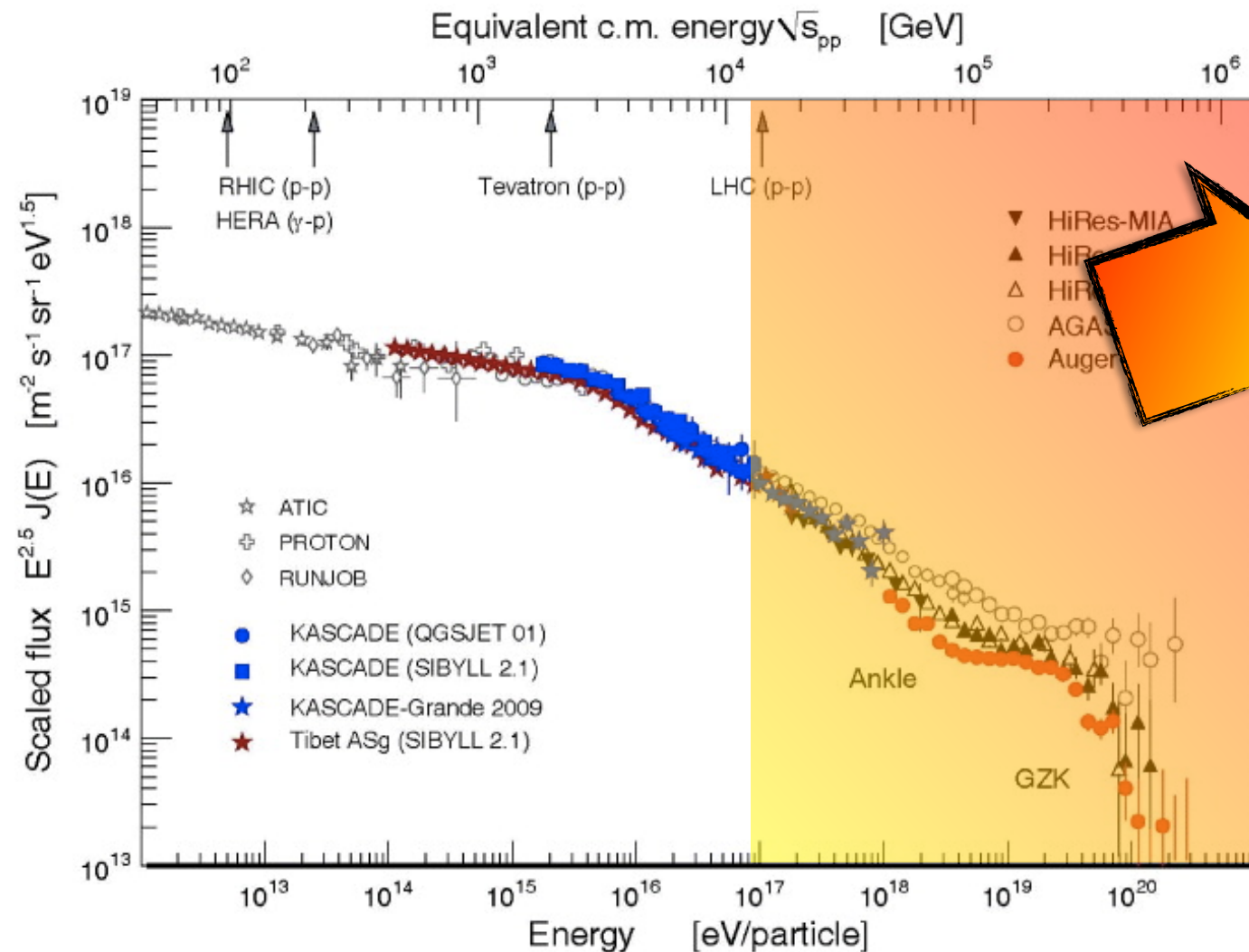
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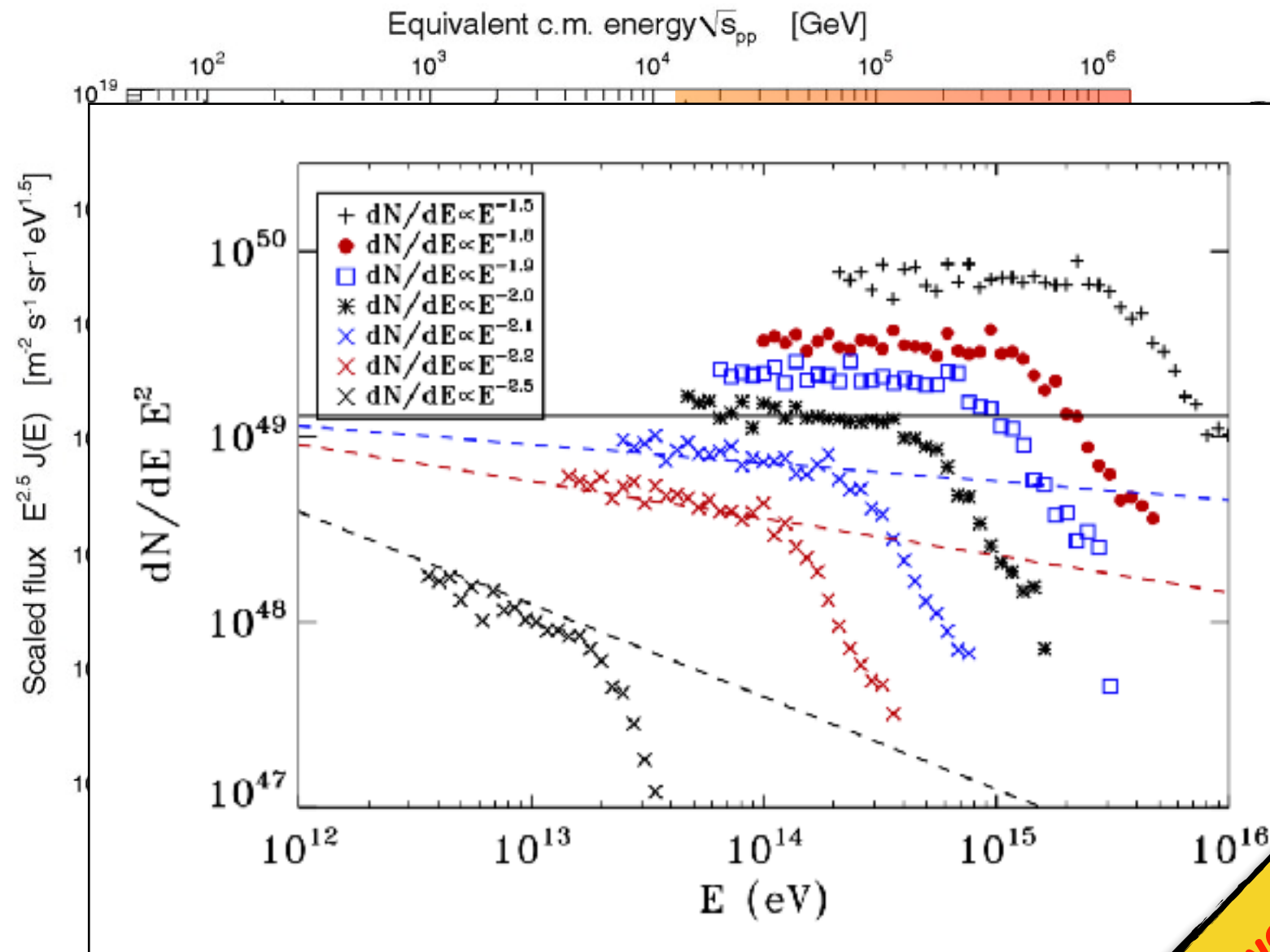


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these two aspects are related

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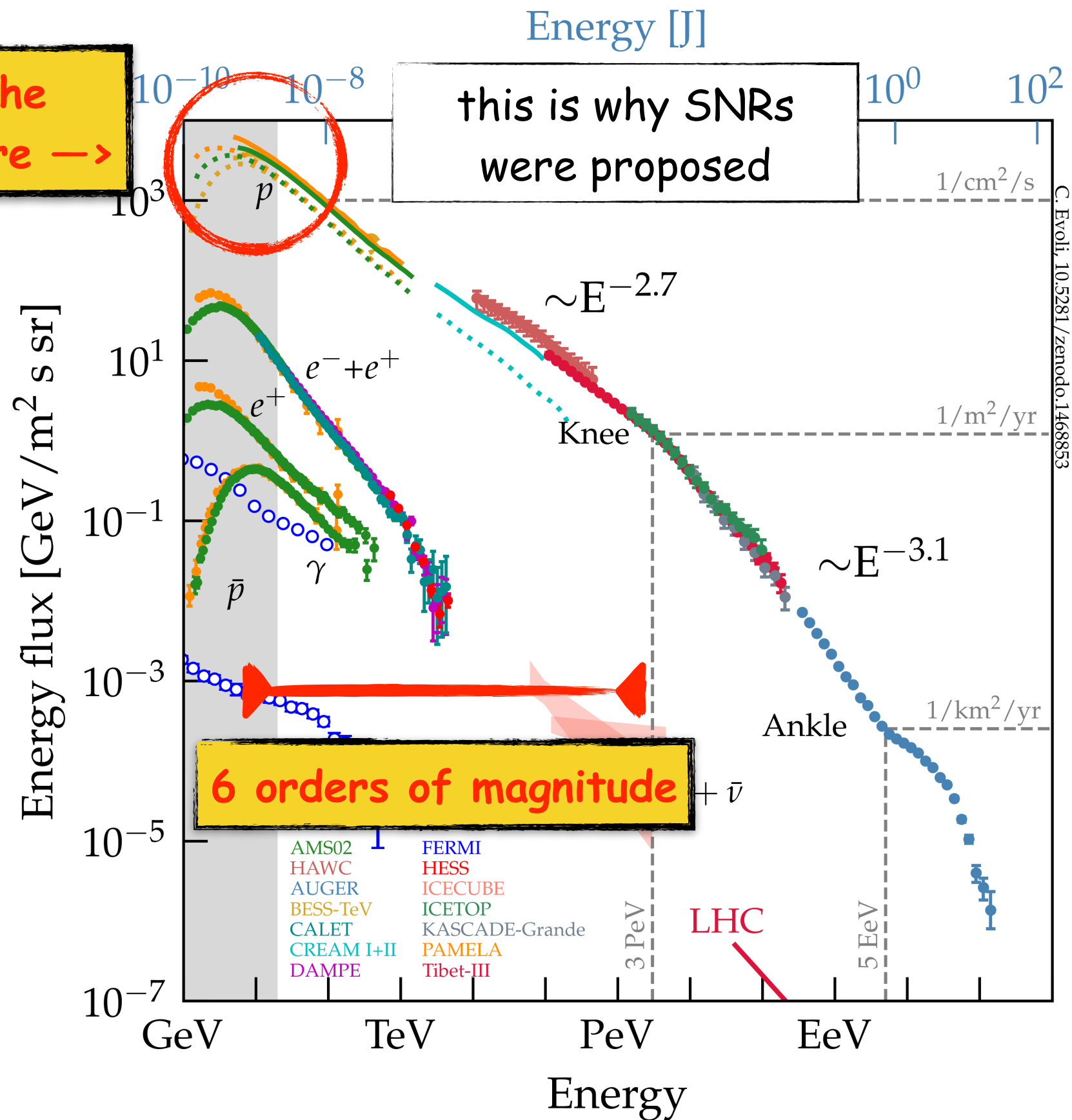
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Note on energetic

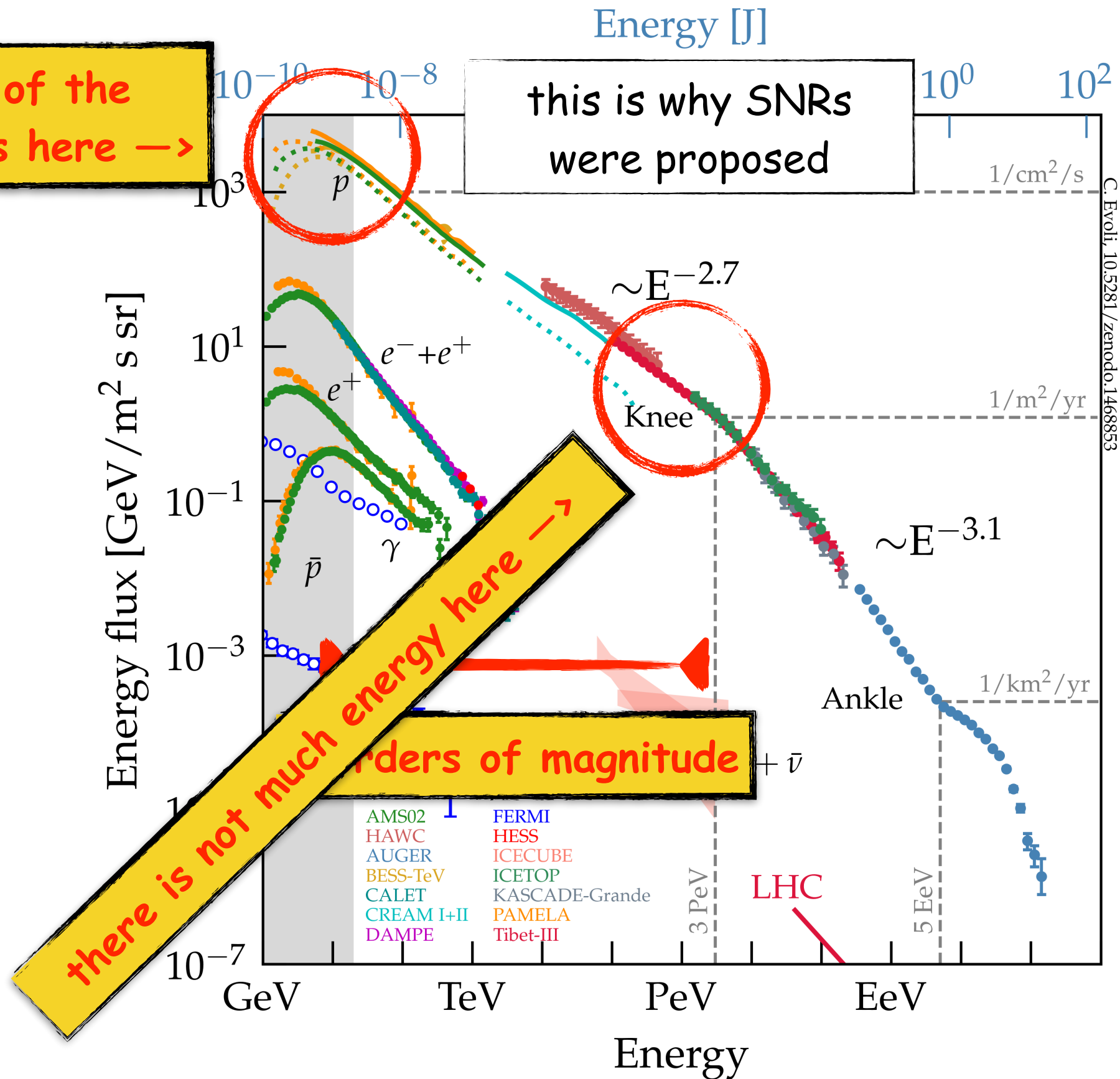
most of the energy is here —>

this is why SNRs were proposed



Note on energetic

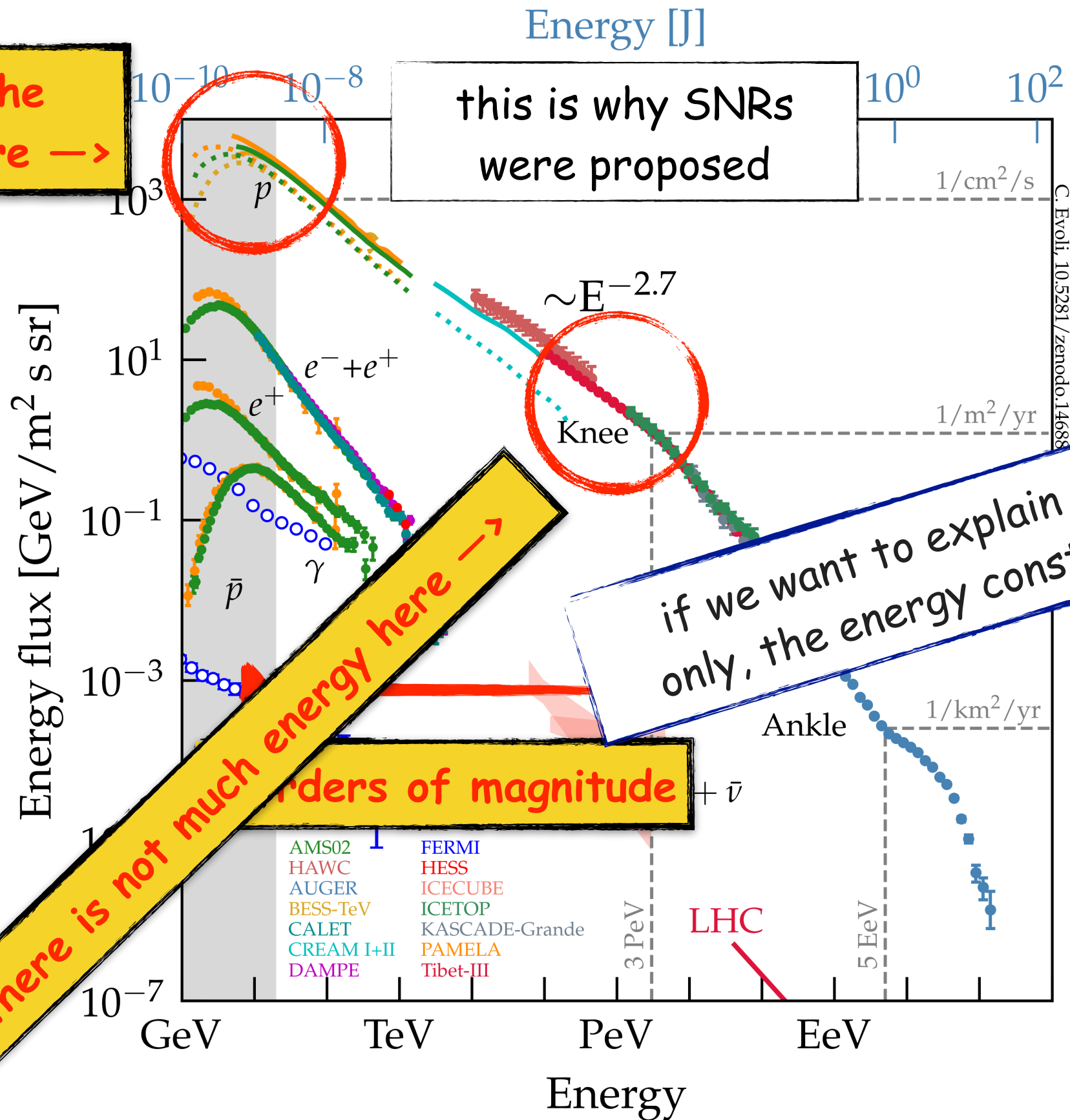
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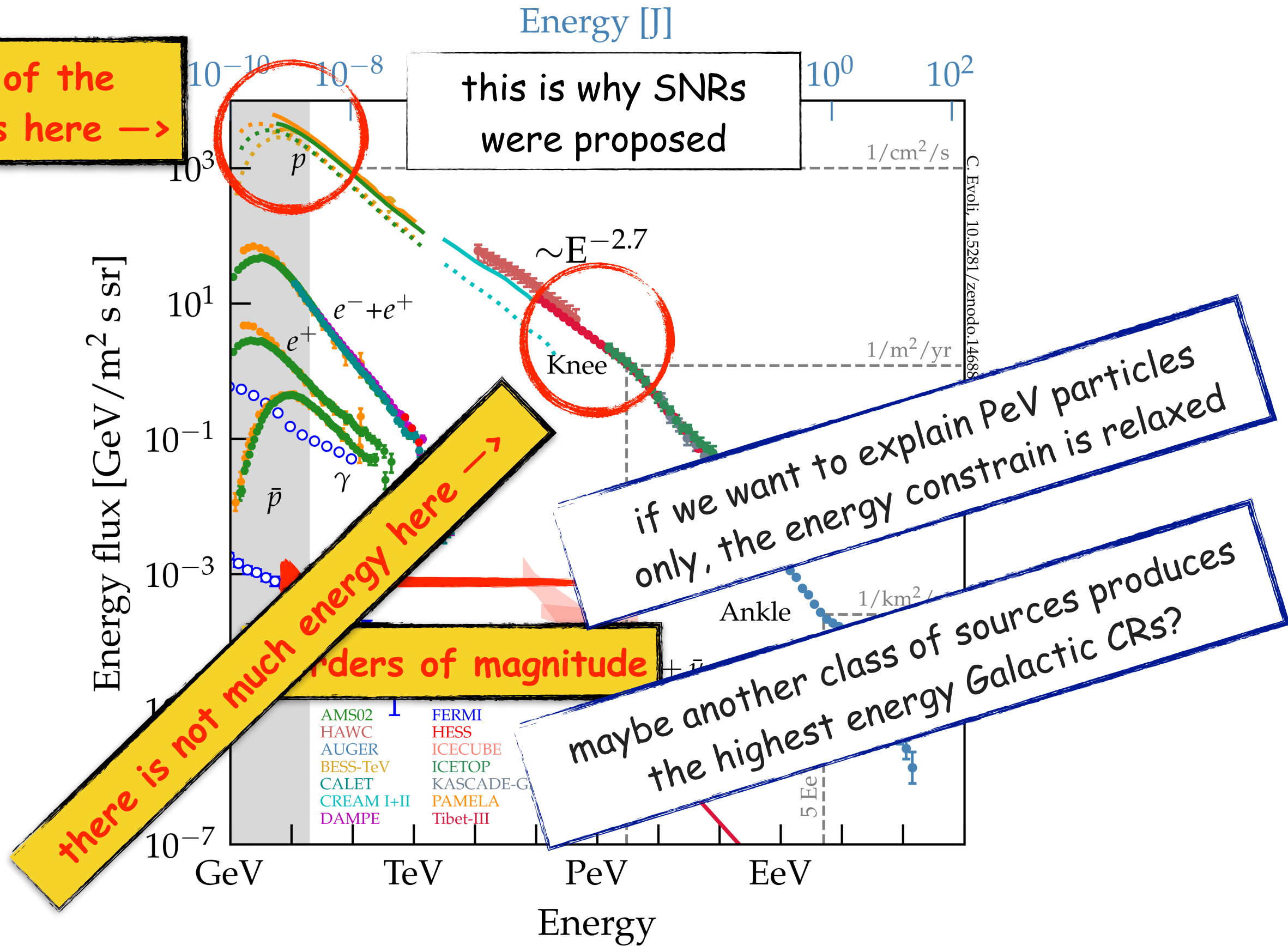


there is not much energy here →

orders of magnitude

if we want to explain PeV particles only, the energy constrain is relaxed

Note on energetic



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The bulk of the

another class of sources to explain PeV and beyond
(rare SNRs, star clusters... most fashionable now microquasars)



Cosmic rays are diffusively confined within an
extended and magnetised Galactic halo



Cosmic rays are accelerated in the (dusty)
interstellar medium by high diffusive shock
acceleration in supernova remnants

90% SNR + 10% stellar winds might work