How do particles escape from accelerators?

Stefano Gabici
APC, Paris
gabici@apc.in2p3.fr

www.cnrs.fr

Plan of the lecture

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

Supernova remnants

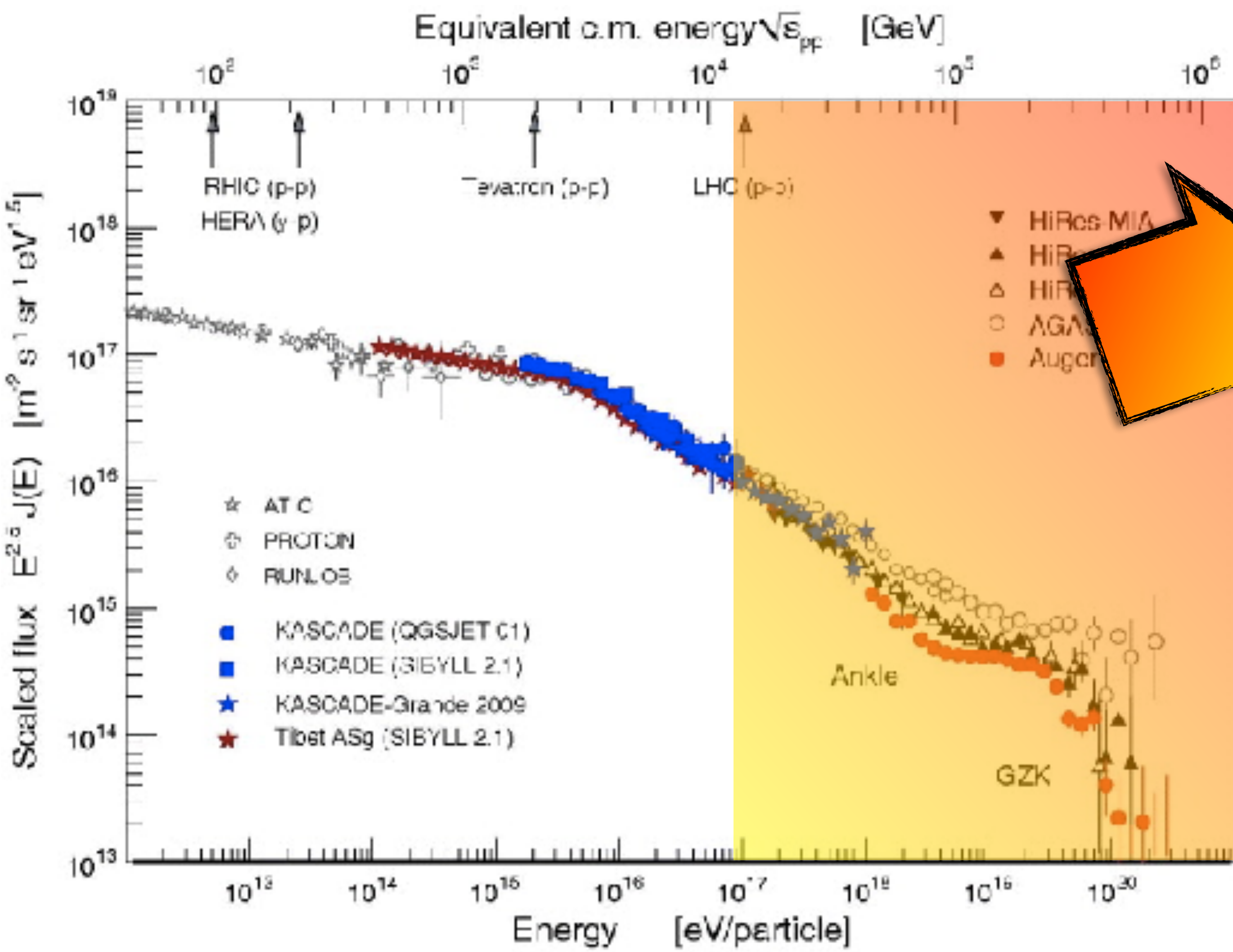
CR escape from sources

[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

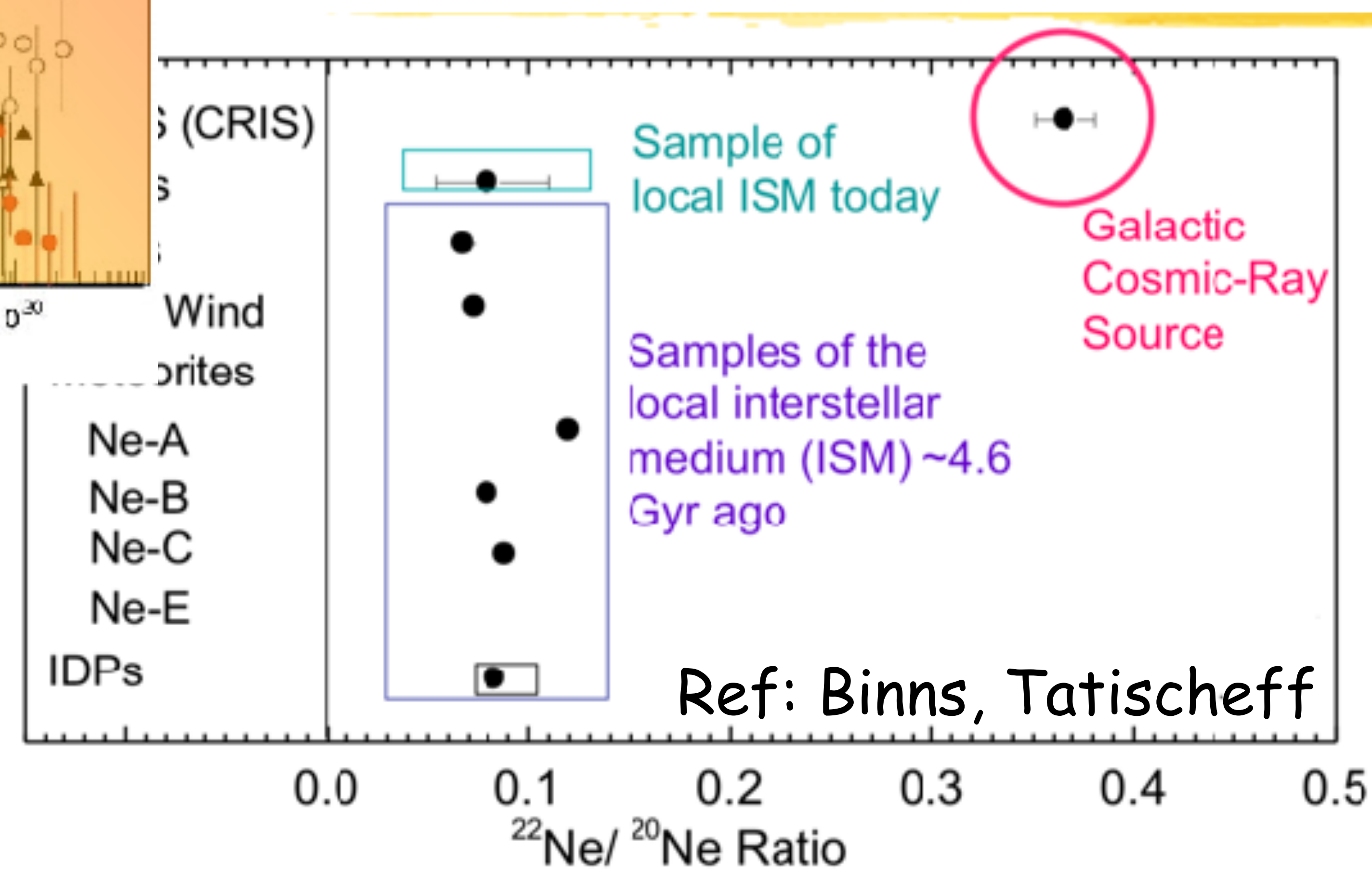
Conclusions

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 $^{22}Ne/^{20}Ne$ ratio?

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

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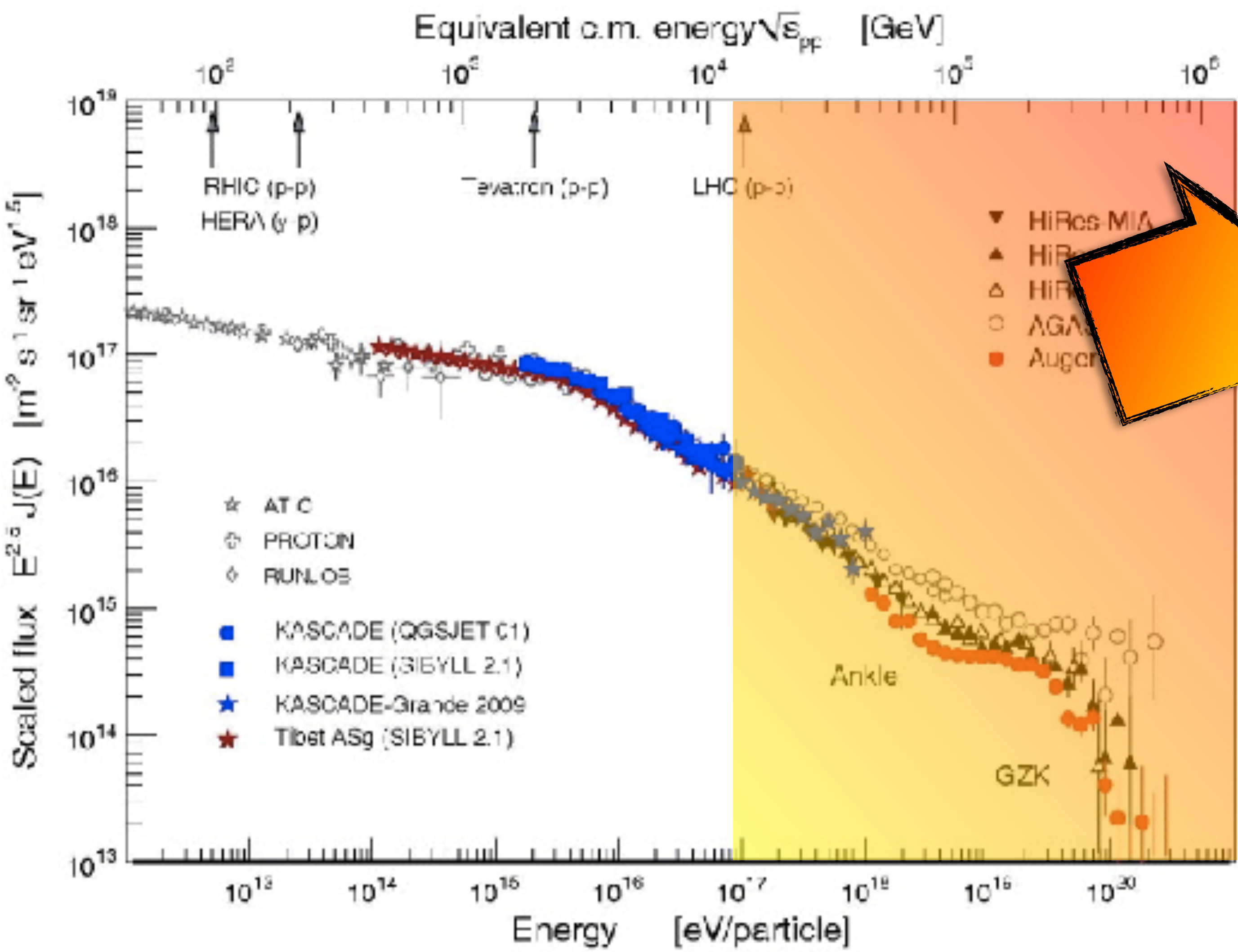

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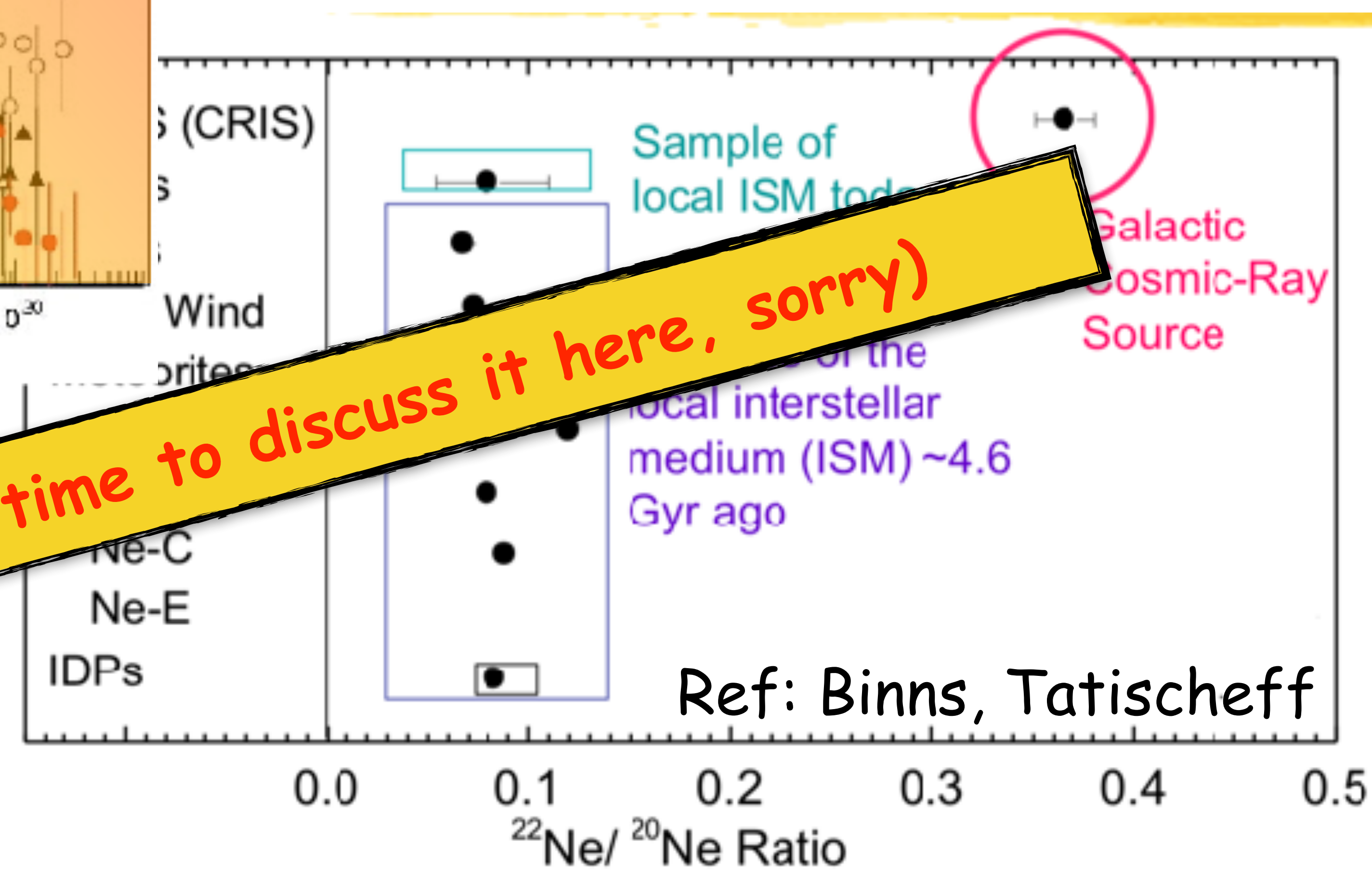

Ref: Binns, Tatischeff

[2] can the SNR par... explain the ... cess of the ^{22}... 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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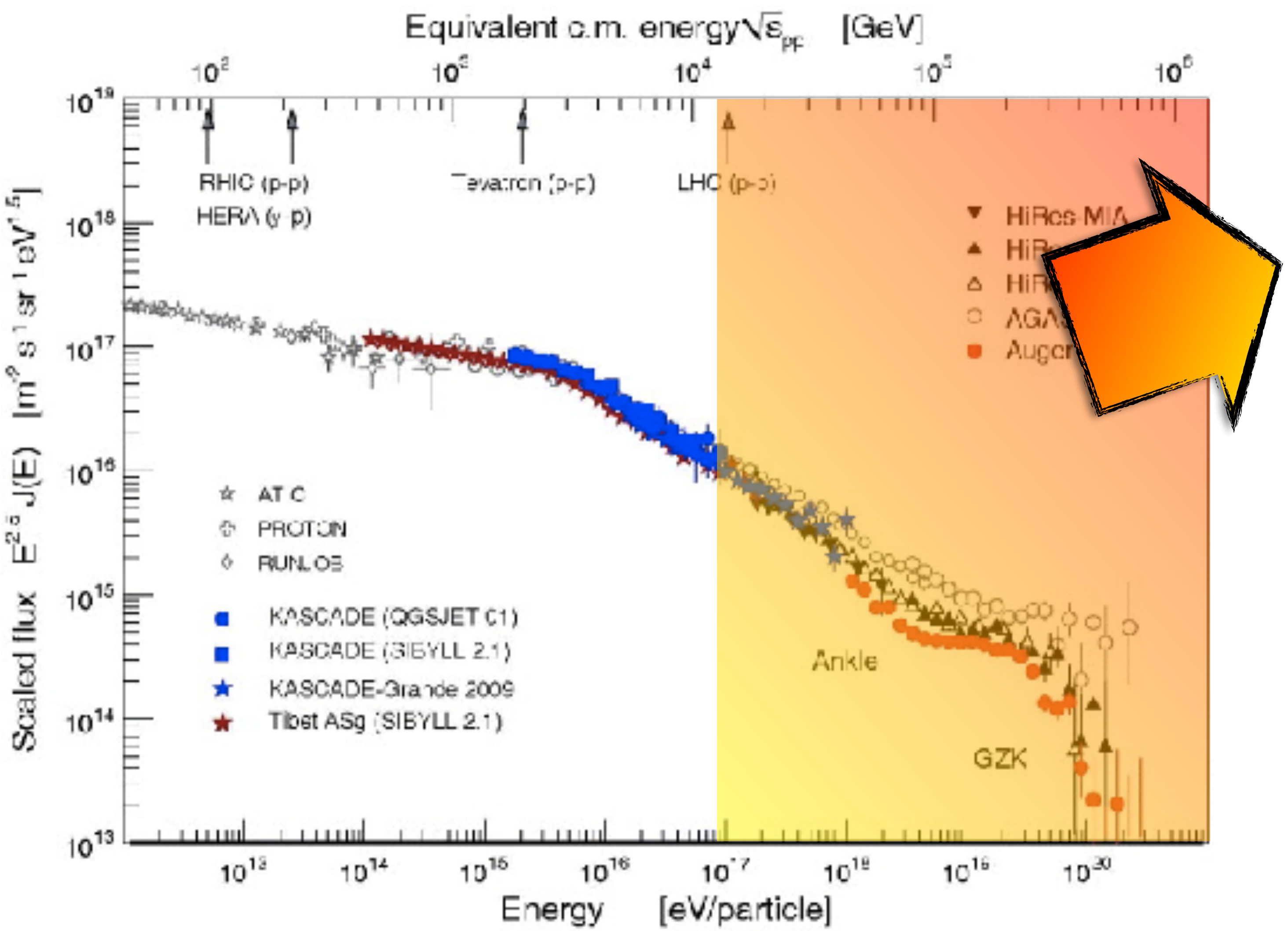

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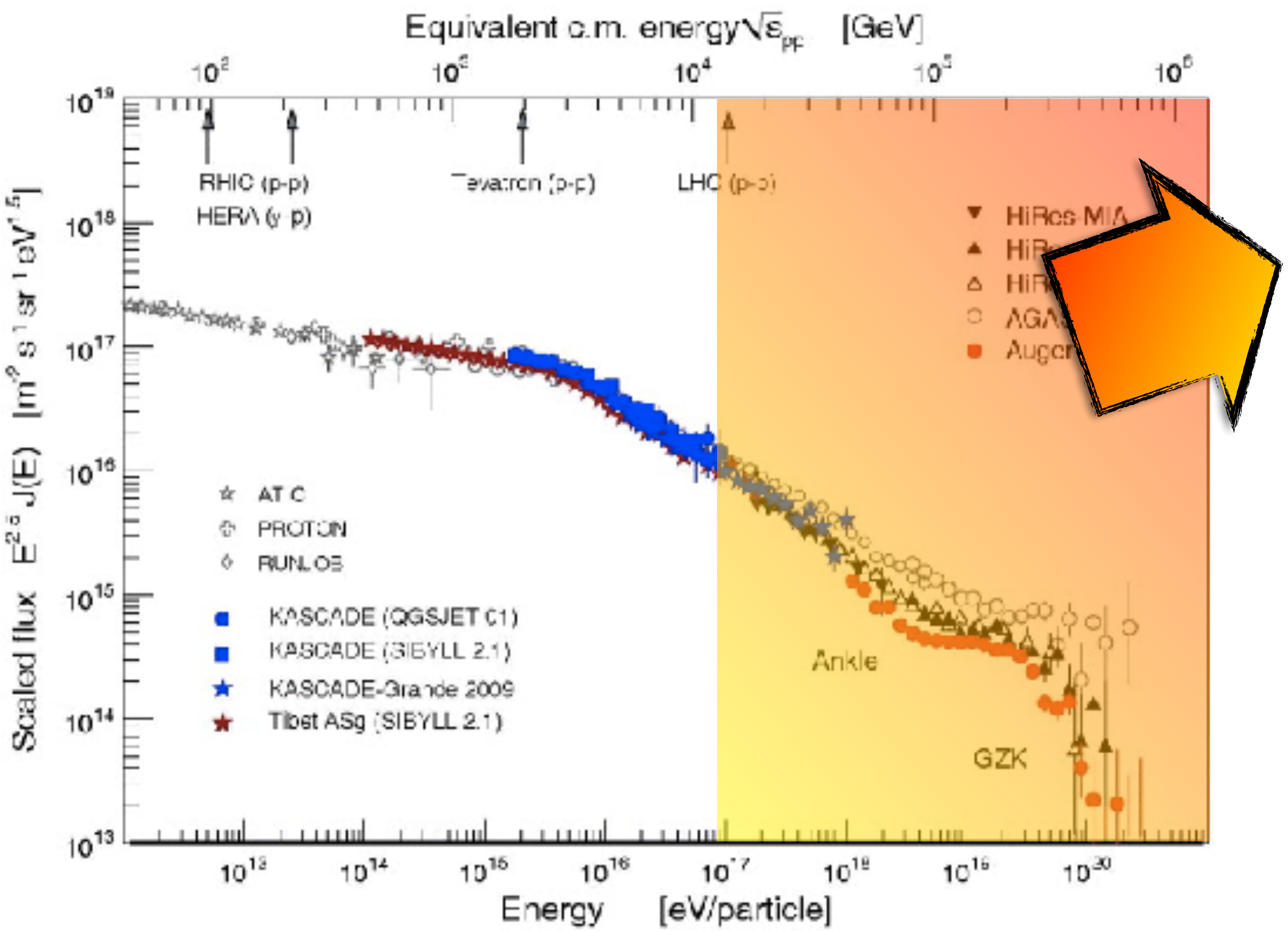

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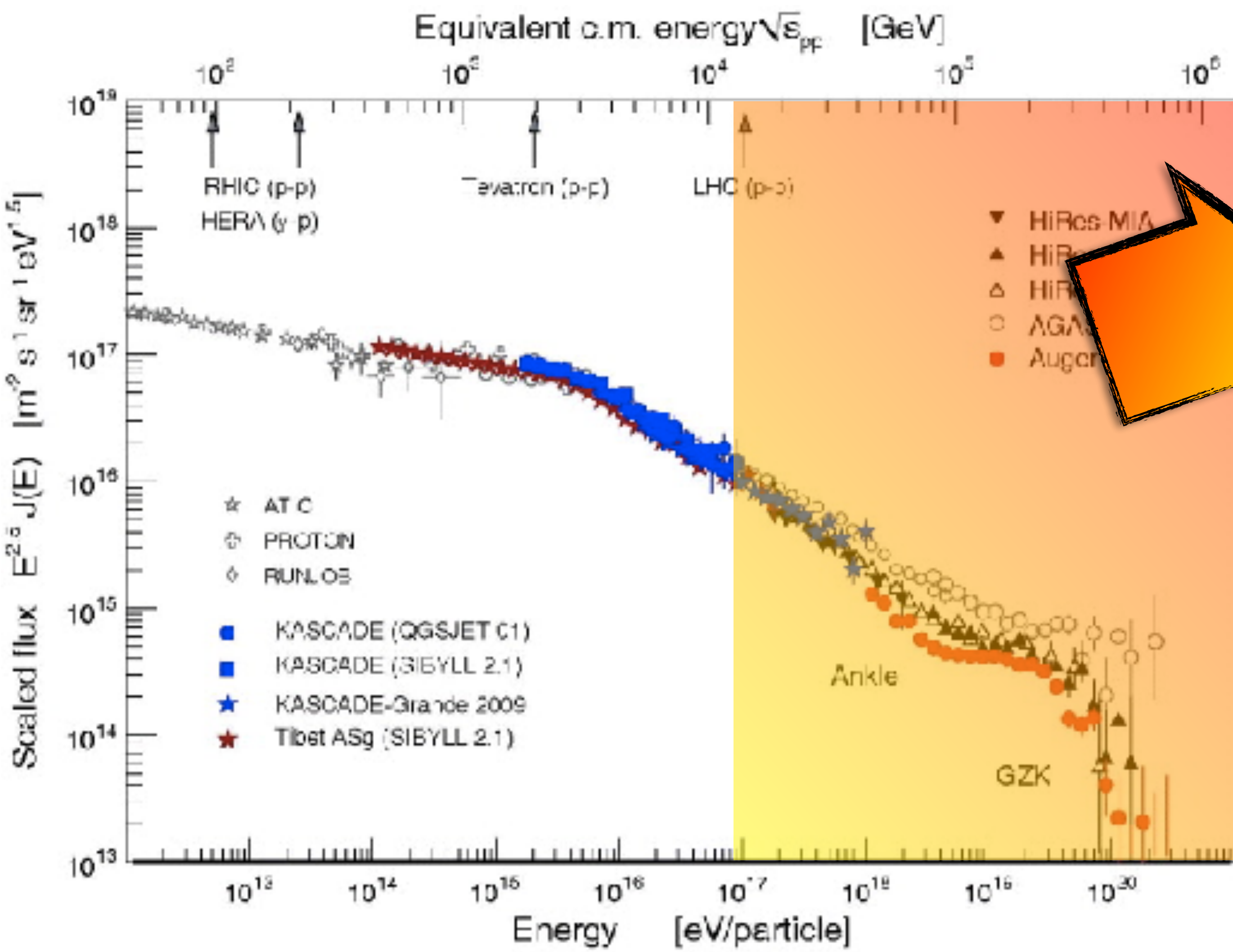
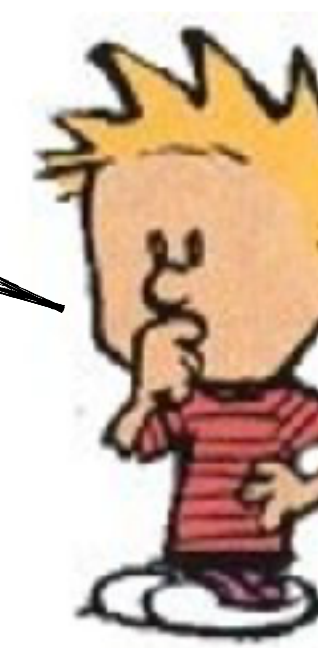


[1] can SNR shocks accelerate particles up to the largest observed energies?

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



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A small detail...

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

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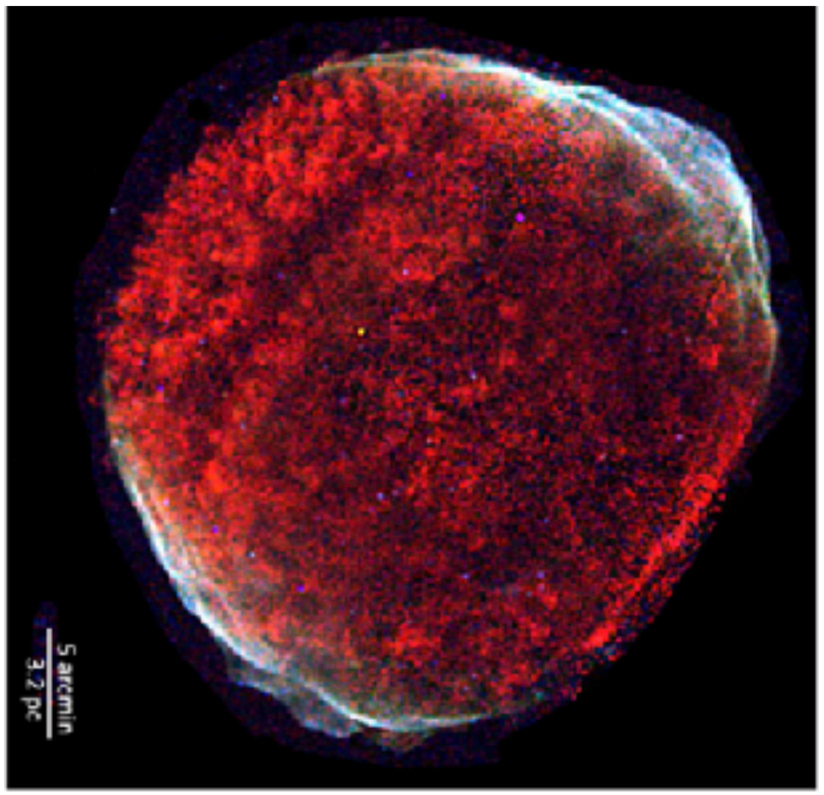

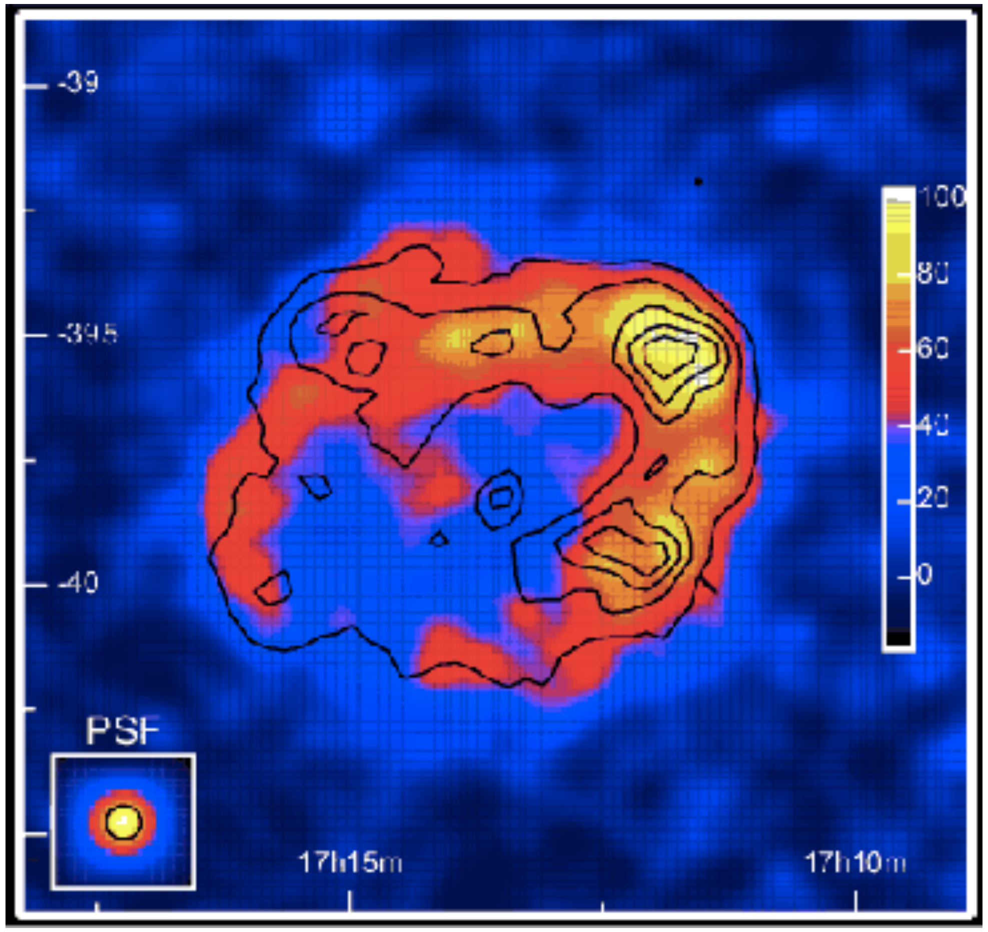

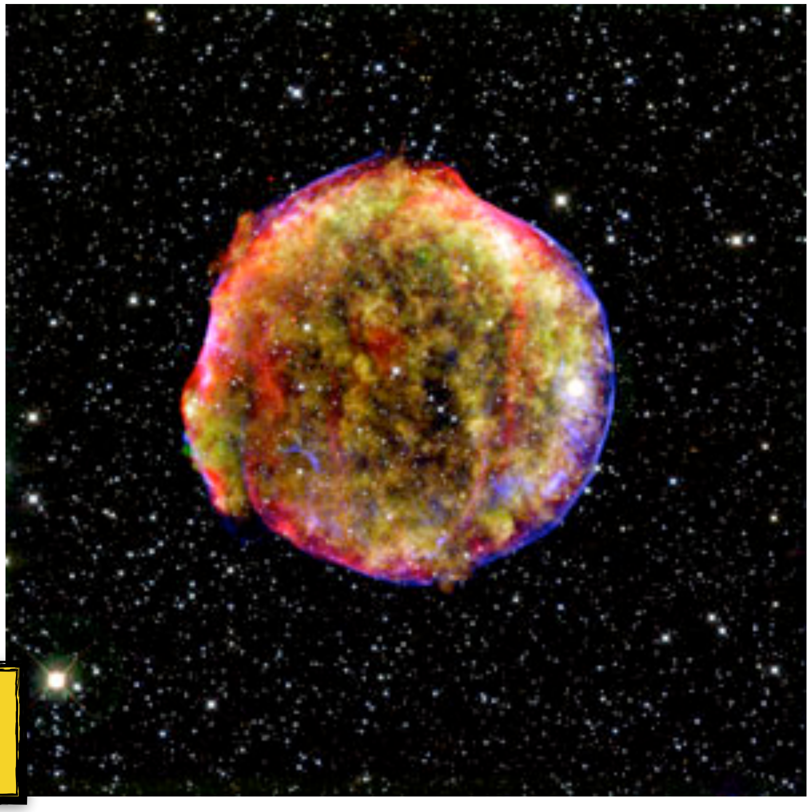

…SNRs are roughy spherical and the shock decelerates

Astrophysical explosions

interstellar medium

pressure P

density ϱ

massive star

Astrophysical explosions

interstellar medium

mass of the ejecta M_{ej}

explosion energy E_{SN}

P ϱ

supernova

Astrophysical explosions

interstellar medium

M_{ej} E_{SN} P ϱ

Astrophysical explosions

interstellar medium

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

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

Astrophysical explosions

interstellar medium

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

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Astrophysical explosions

interstellar medium

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

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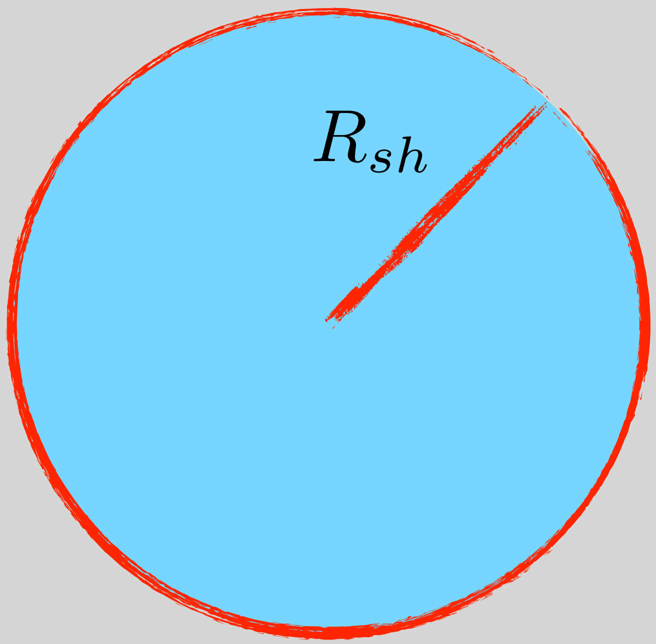

Astrophysical explosions

interstellar medium

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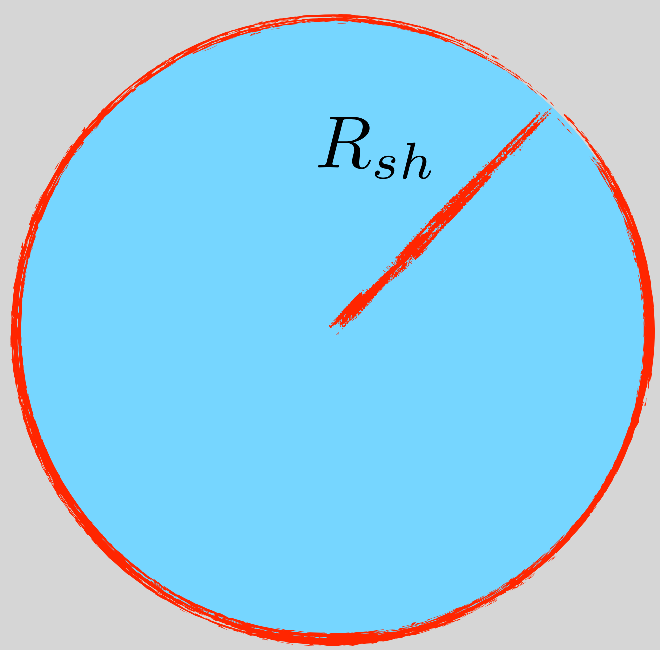

Astrophysical explosions

interstellar medium

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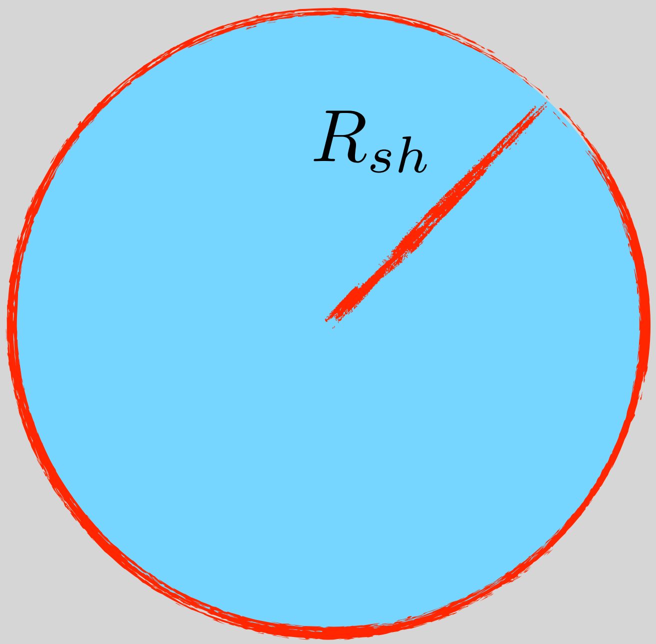

free expansion
(constant speed)

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

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

Astrophysical explosions

interstellar medium

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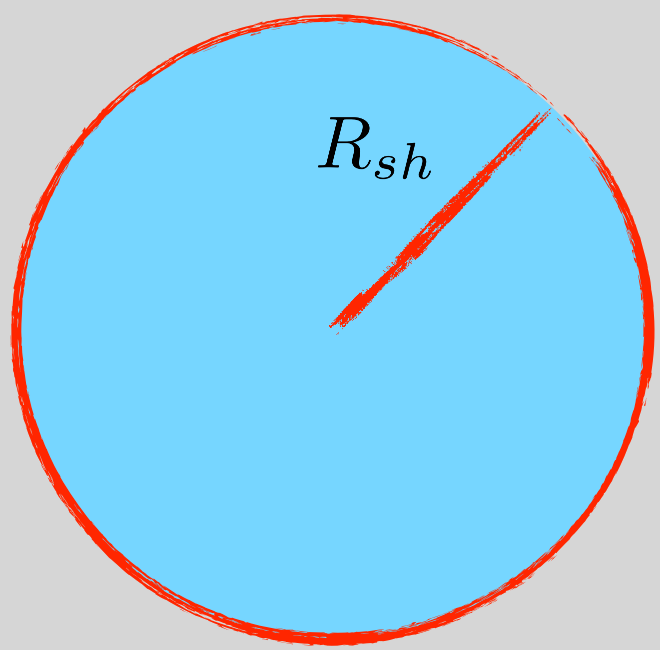

free expansion
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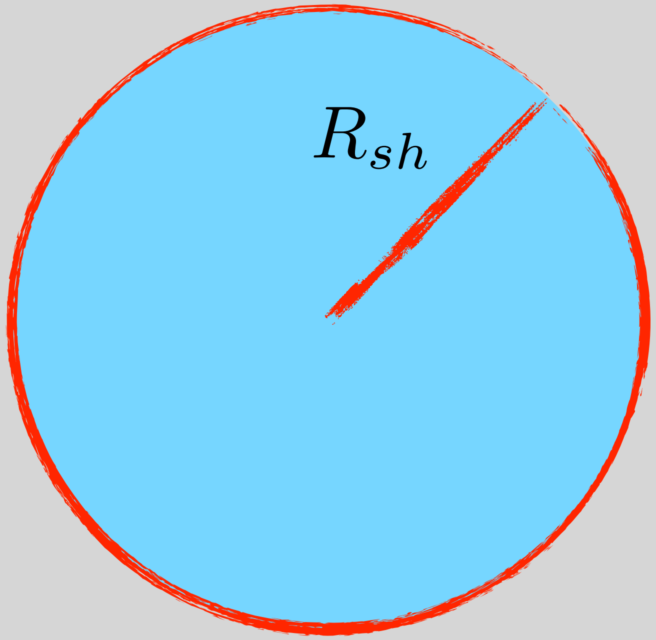
$$E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2 \longrightarrow v_{sh} = \sqrt{\frac{2E_{SN}}{M_{ej}}} \sim 10000 \left(\frac{M_{ej}}{M_\odot}\right)^{-1/2} \text{km/s}$$

Astrophysical explosions

interstellar medium

$$\boxed{M_{ej} = M_{sw}}$$

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



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Astrophysical explosions

interstellar medium

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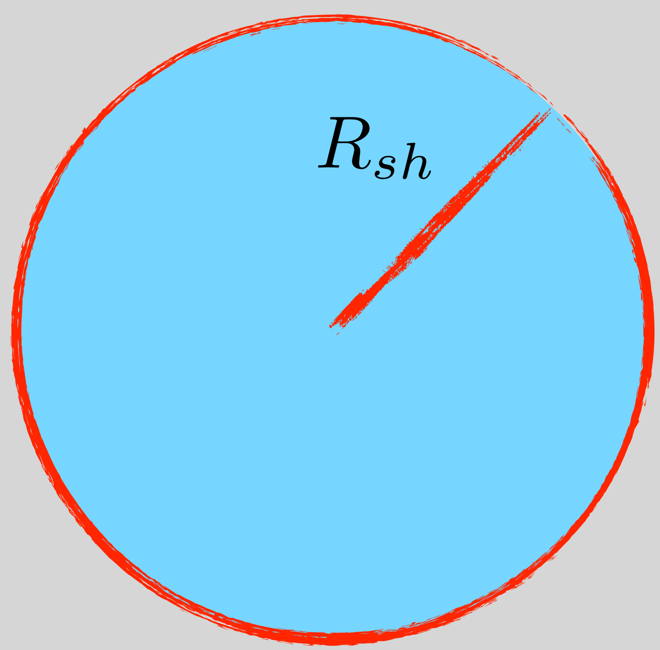

$$R_* = \left(\frac{3M_{ej}}{4\pi\varrho}\right)^{1/3} \sim 2\left(\frac{M_{ej}}{M_\odot}\right)^{1/3}\left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-1/3} \mathrm{pc}$$

Astrophysical explosions

interstellar medium

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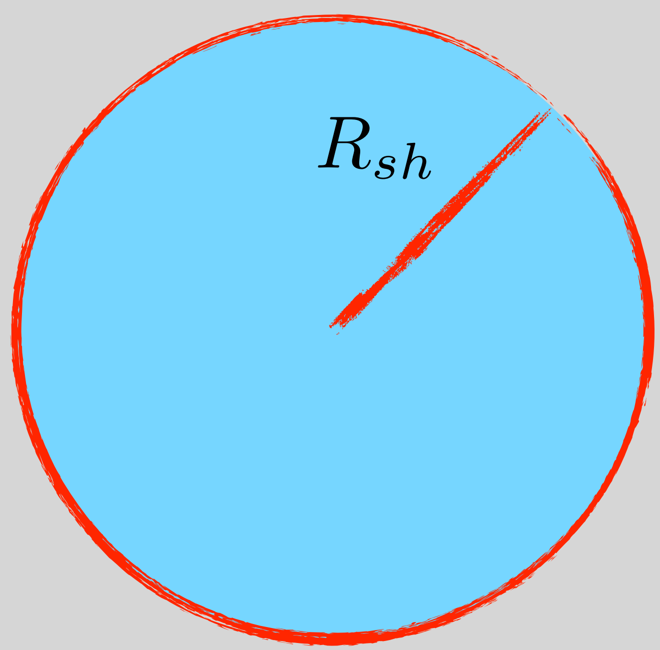

it takes few centuries to reach this moment

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Astrophysical explosions

interstellar medium

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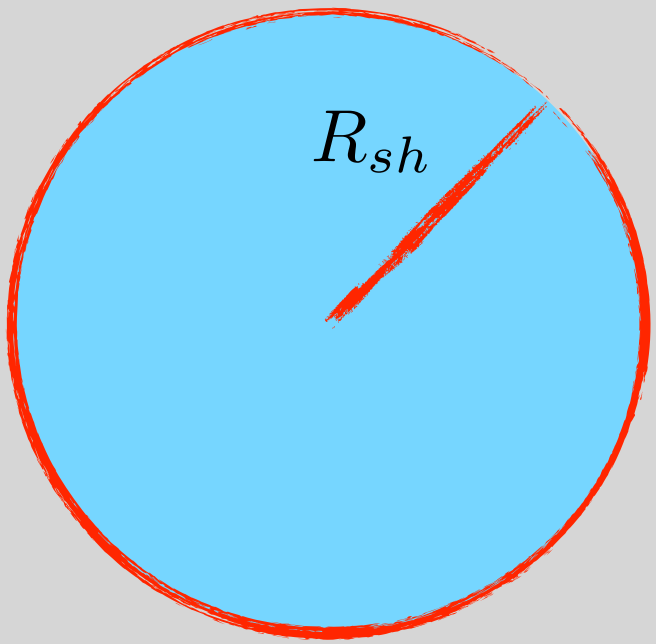
M_{ej} E_{SN} P ϱ



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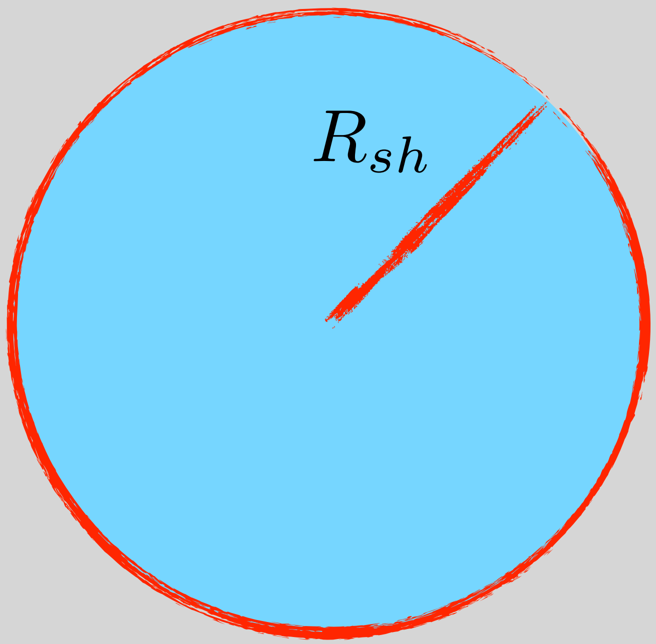

the shock begins to feel the presence of the ambient gas and decelerates

Astrophysical explosions

interstellar medium

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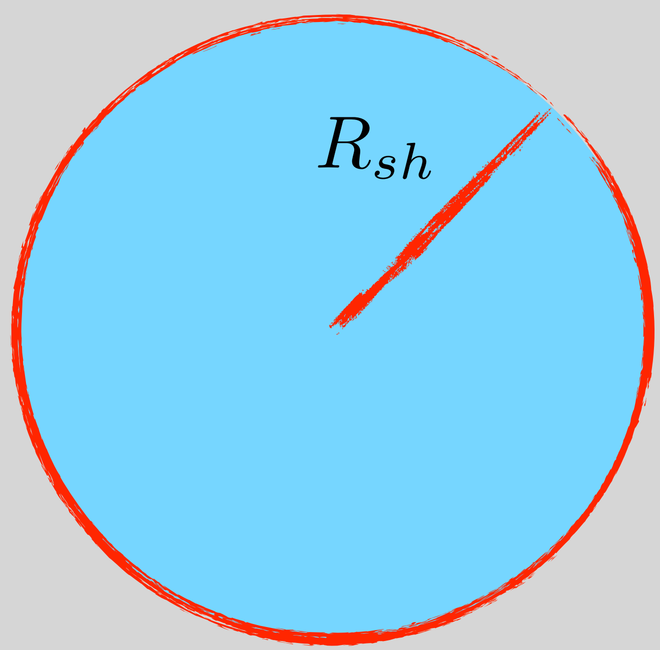

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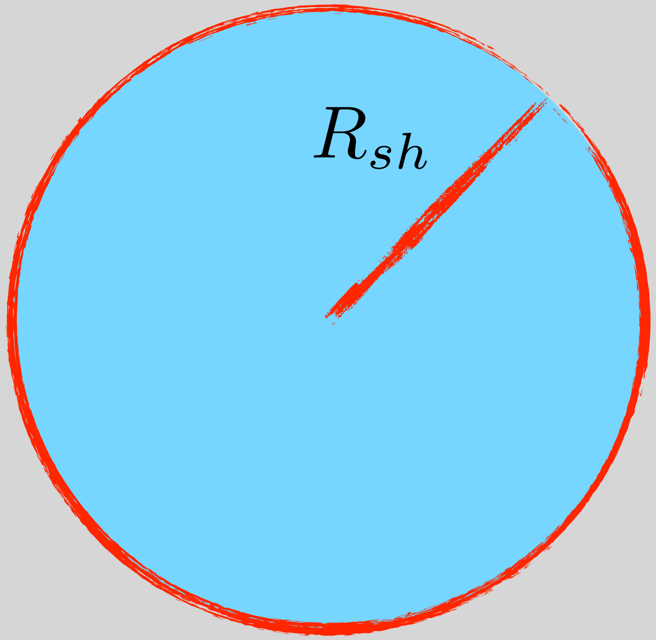
$c_s \approx 10 \text{ km/s}$

strong shock



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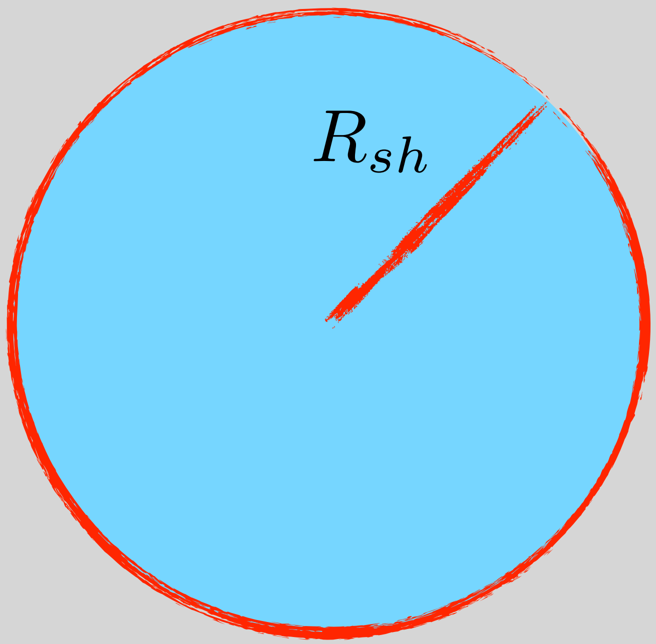

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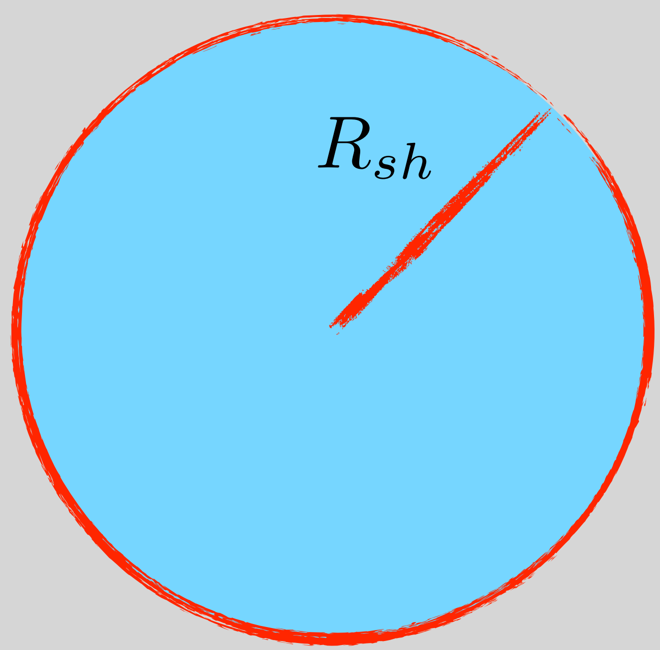

the shock begins to feel the presence of the ambient gas and decelerates

non-dimensional quantity: $a = \dfrac{\varrho \, R_{sh}^5}{E_{SN} \, t^2}$

Astrophysical explosions

interstellar medium

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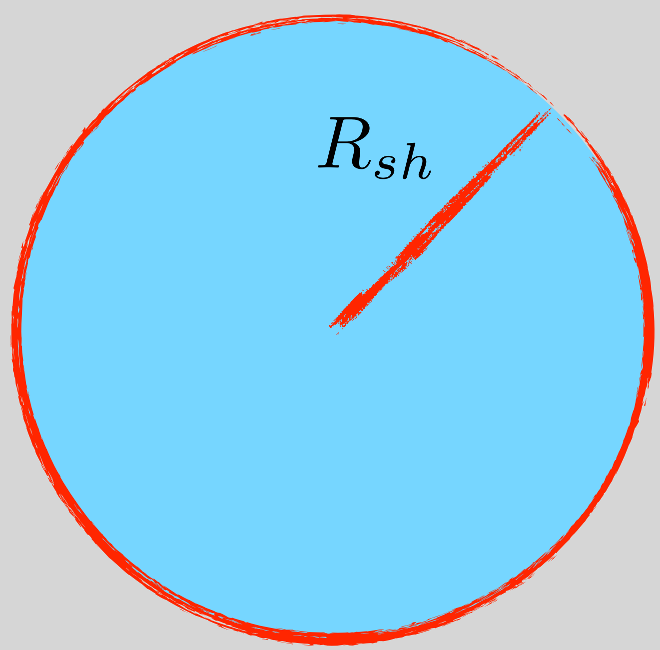

the shock begins to feel the presence of the ambient gas and decelerates

order unity

non-dimensional quantity: $a = \dfrac{\varrho\, R_{sh}^5}{E_{SN}\, t^2} \longrightarrow R_{sh} = a \left(\dfrac{E_{SN}}{\varrho}\right)^{1/5} t^{2/5}$

Astrophysical explosions

interstellar medium

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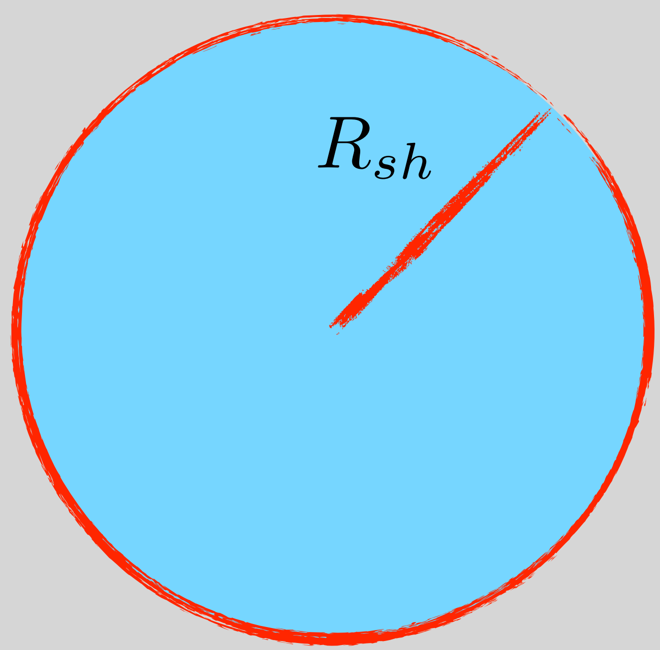

Sedov-Taylor solution

$$R_{sh} = a \left(\frac{E_{SN}}{\varrho} \right)^{1/5} t^{2/5} \qquad u_{sh} = \frac{2}{5} \frac{R_{sh}}{t} \propto t^{-3/5}$$

Astrophysical explosions

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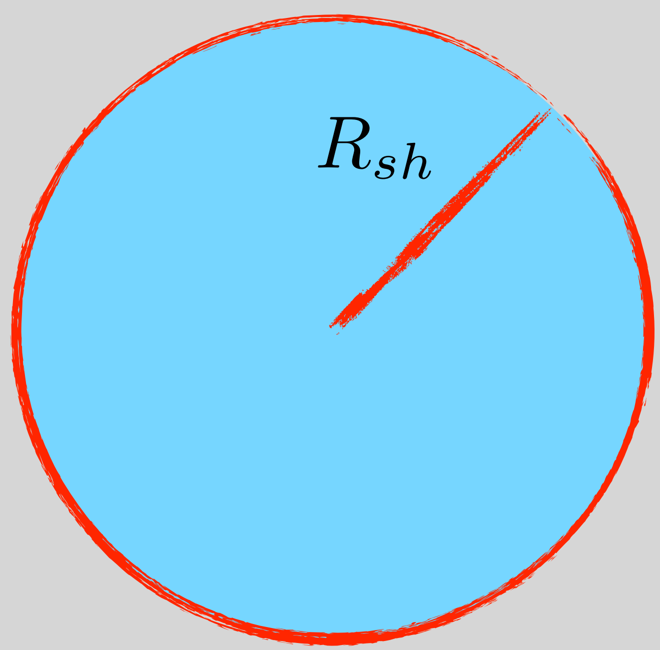
Sedov-Taylor solution



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

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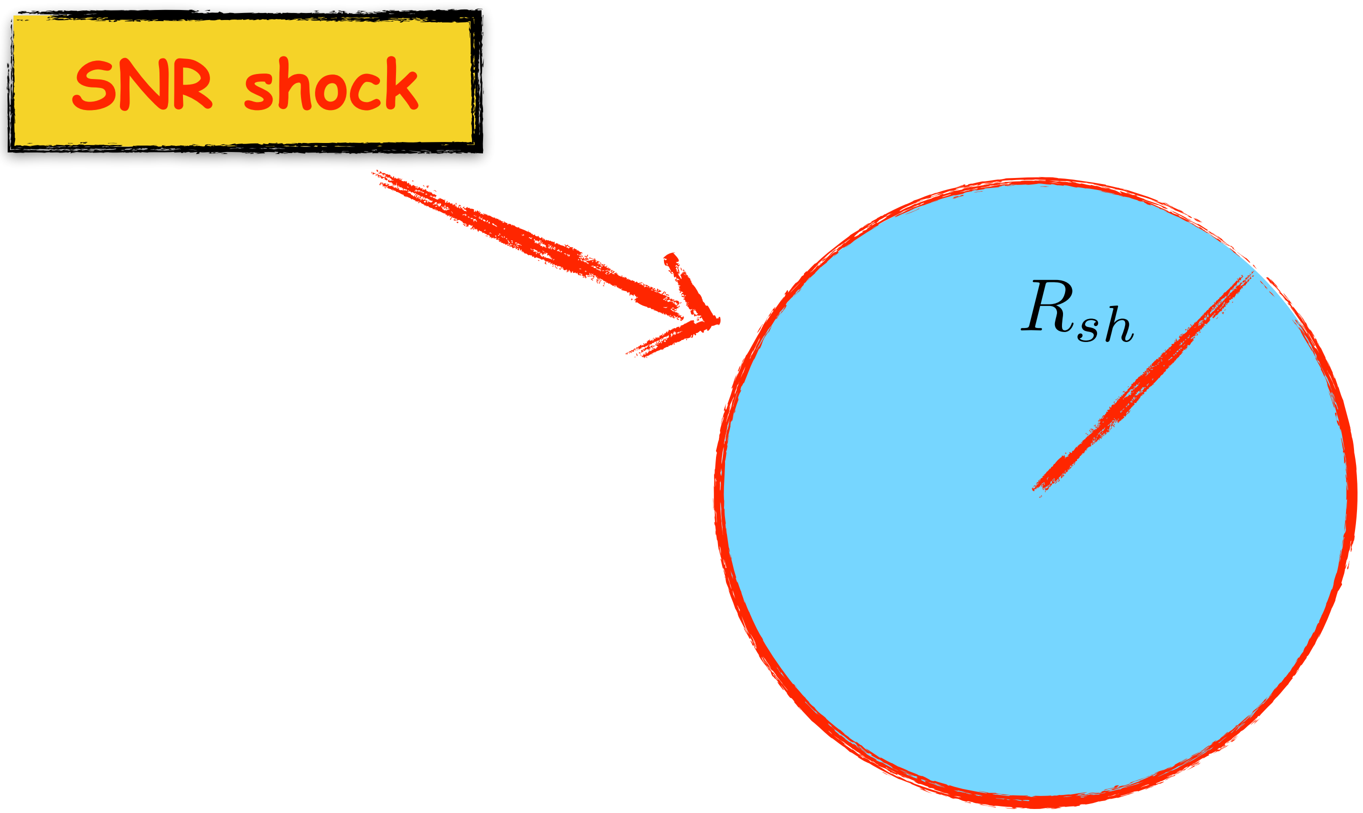
How do cosmic rays escape from their sources?

SNR shocks are spherical —> CR escape



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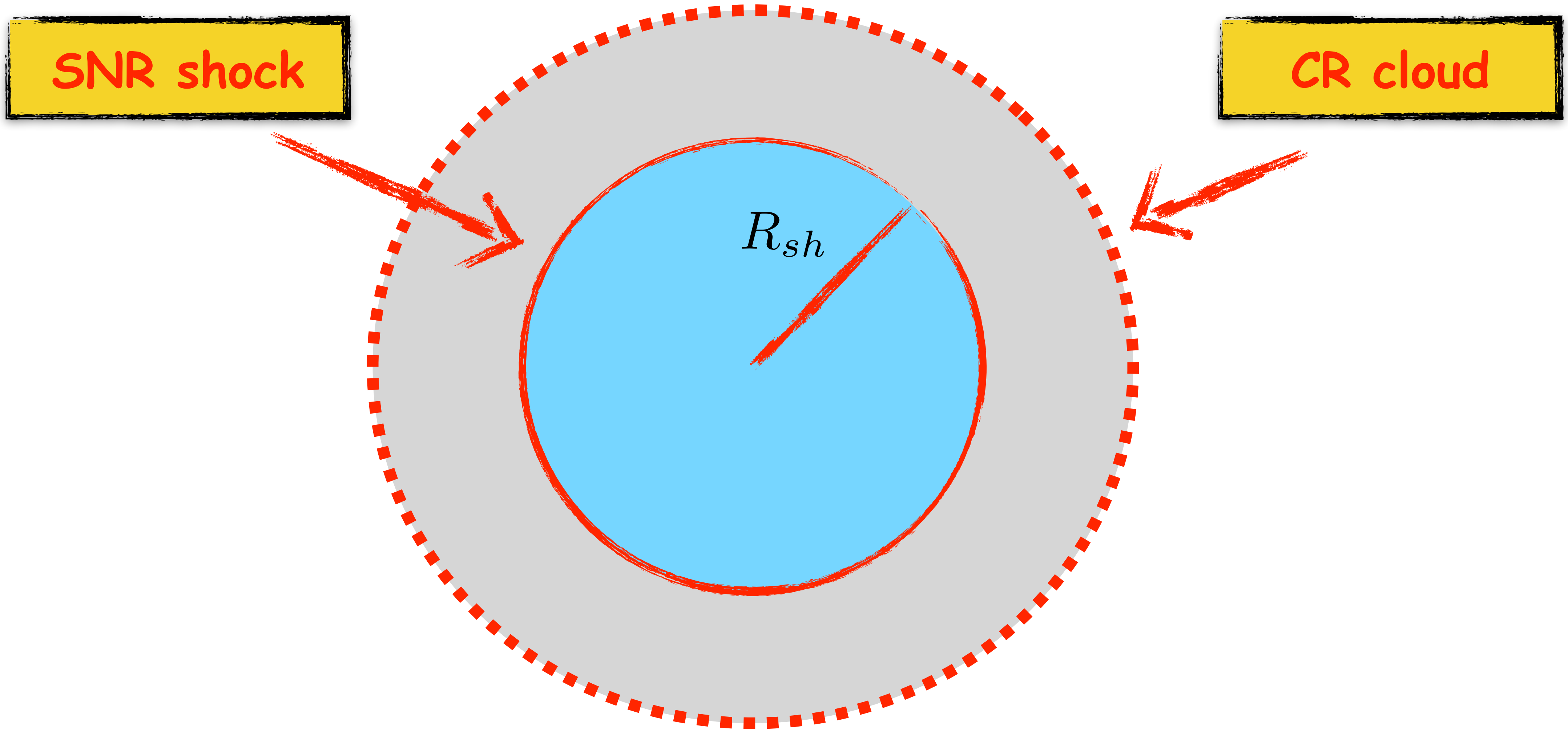
SNR shocks are spherical —> CR escape



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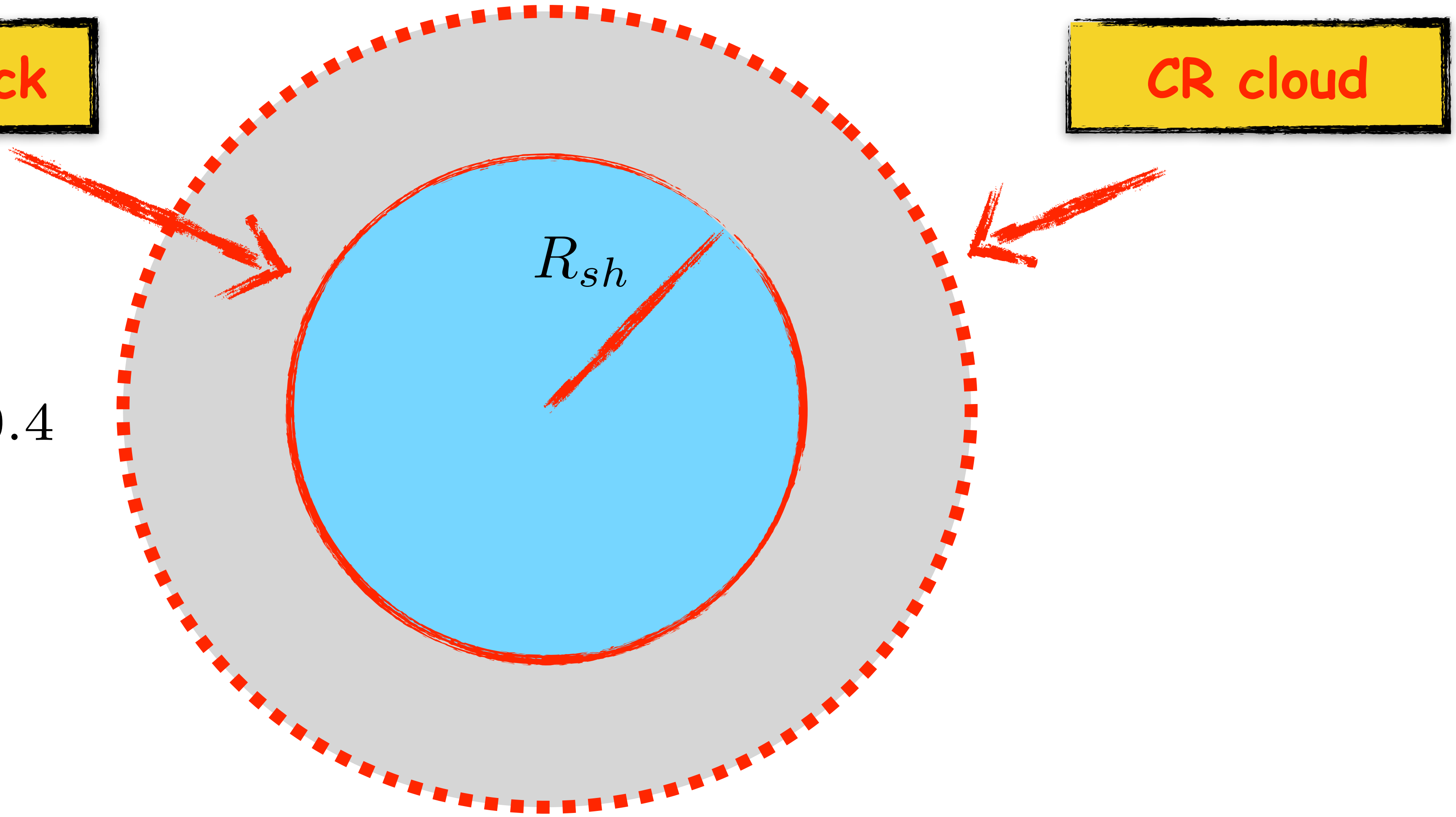

$$R_{sh} \propto t^{2/5} = t^{0.4}$$

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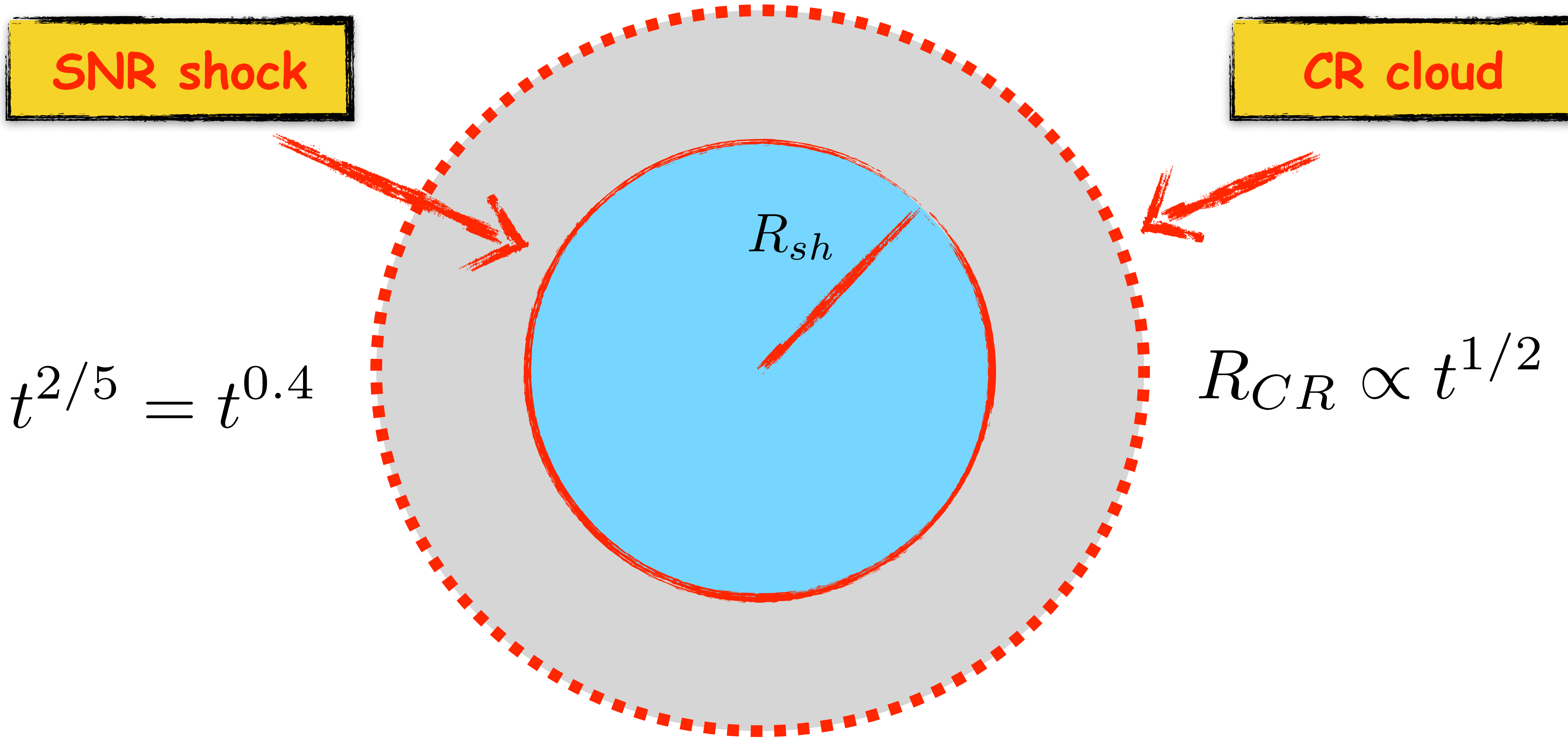
SNR shocks are spherical —> CR escape



$R_{sh} \propto t^{2/5} = t^{0.4}$

$R_{CR} \propto t^{1/2} = t^{0.5}$

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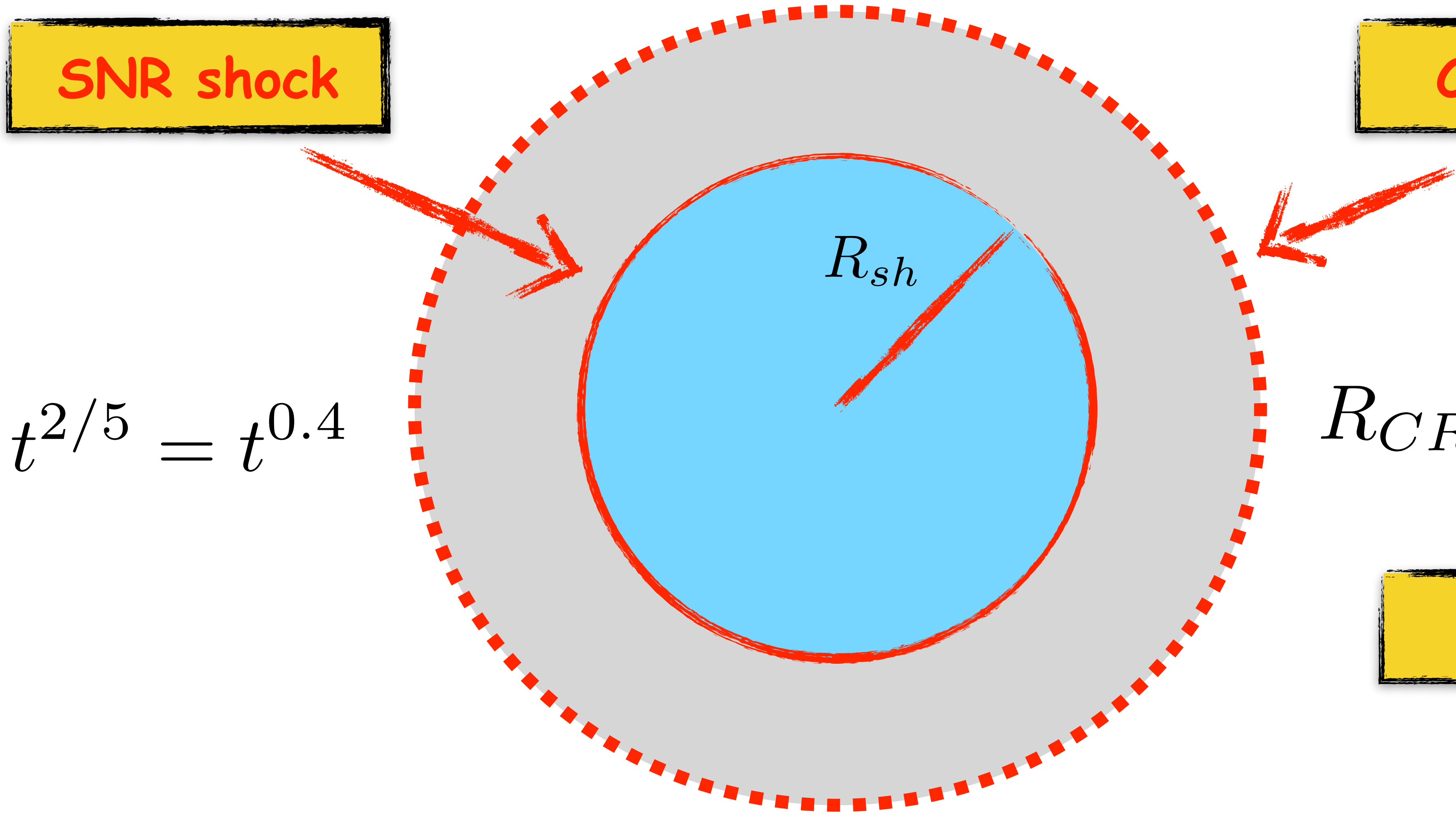
SNR shocks are spherical —> CR escape



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faster!

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SNR shocks are spherical —> CR escape

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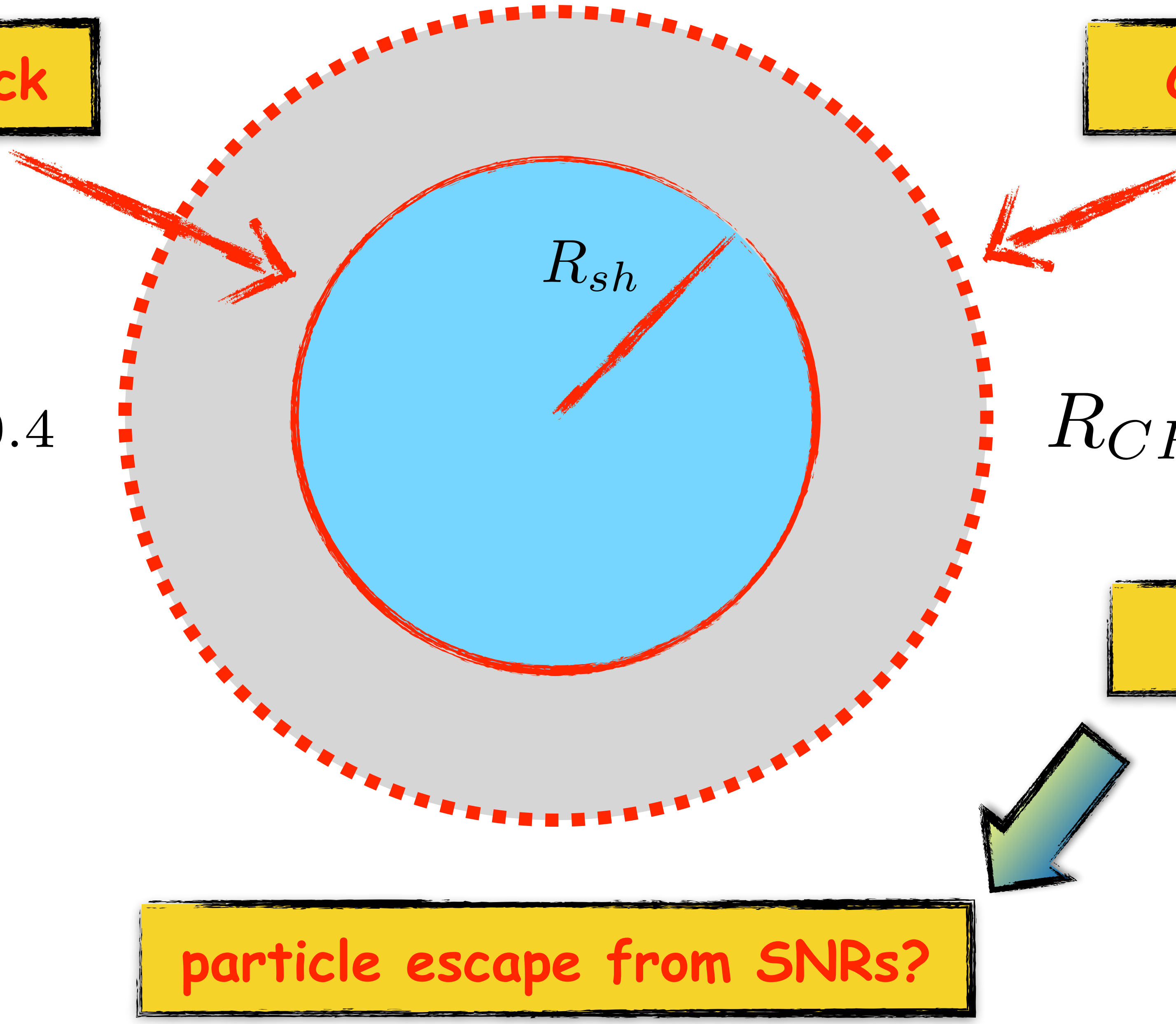

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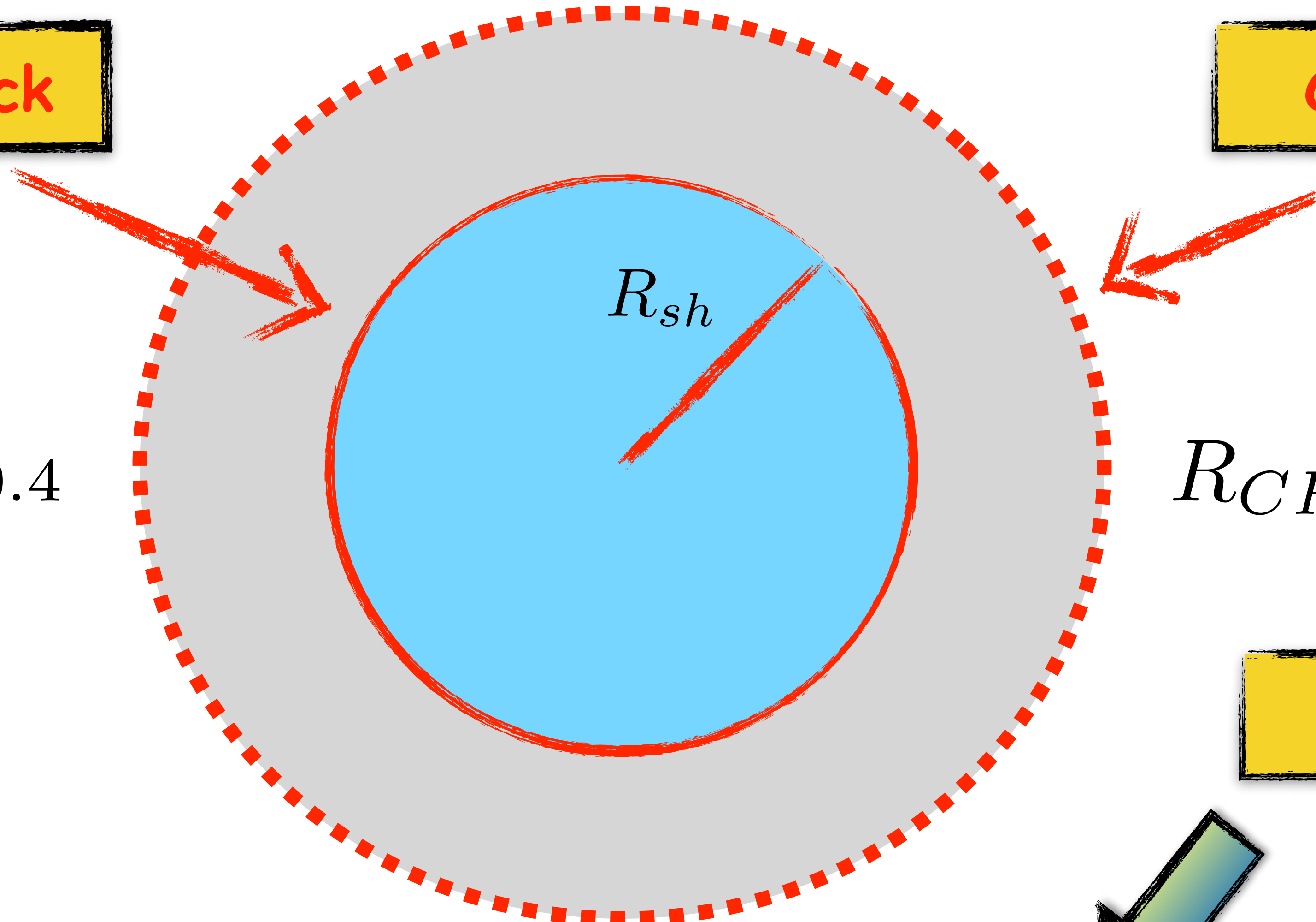
SNR shocks are spherical —> CR escape

SNR shock

CR cloud



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faster!

particle escape from SNRs?

diffusion is faster for larger energies —> high energy particles escape first?

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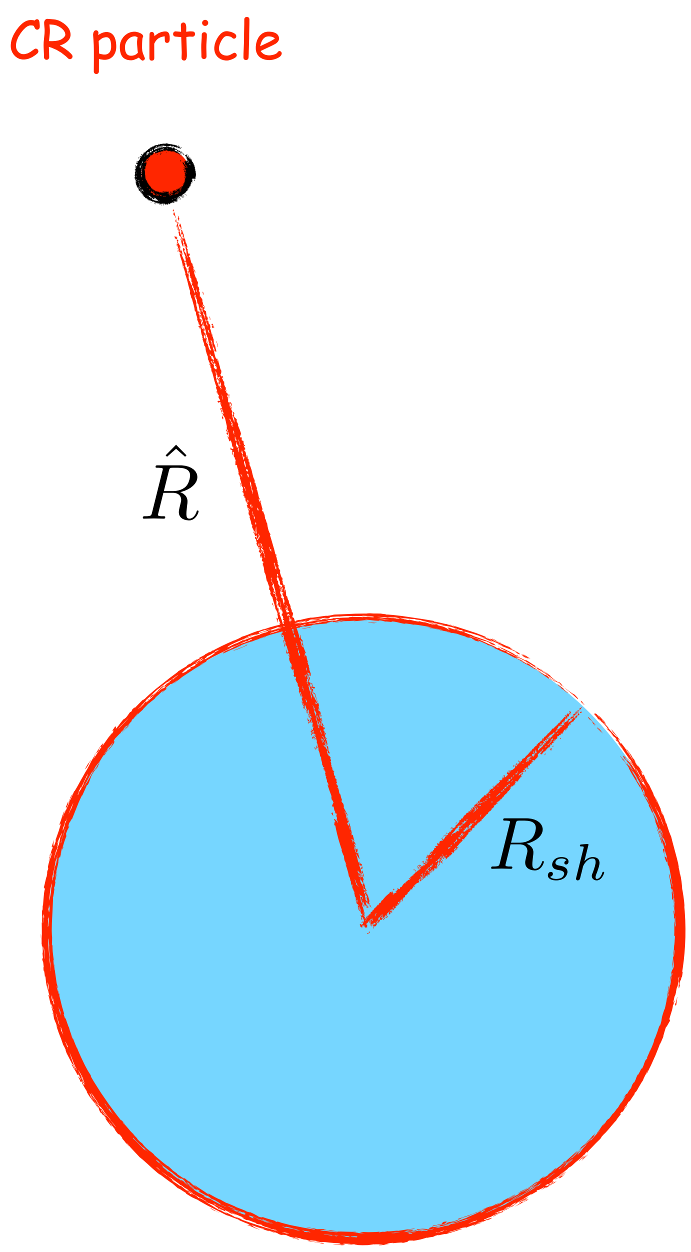
SNR shocks are spherical

return probability to the shock for a particle located upstream



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

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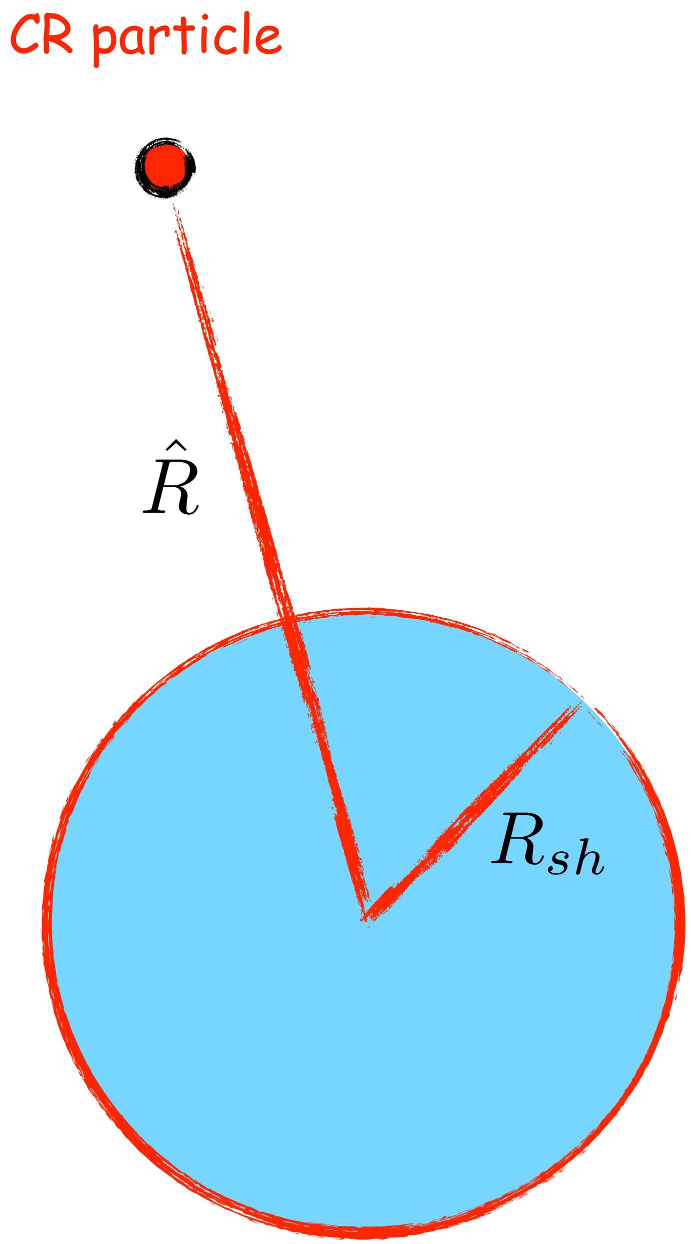

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diffusion equation

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

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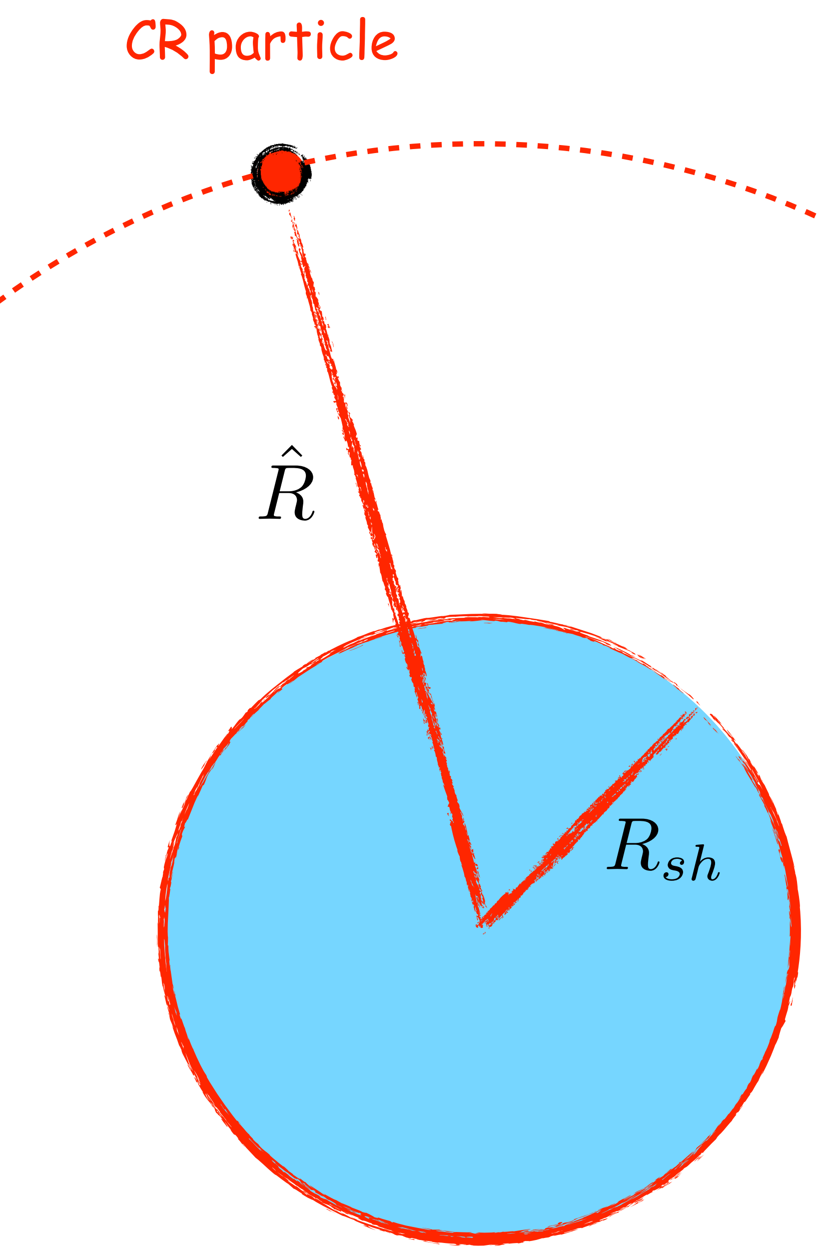

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fictitious source

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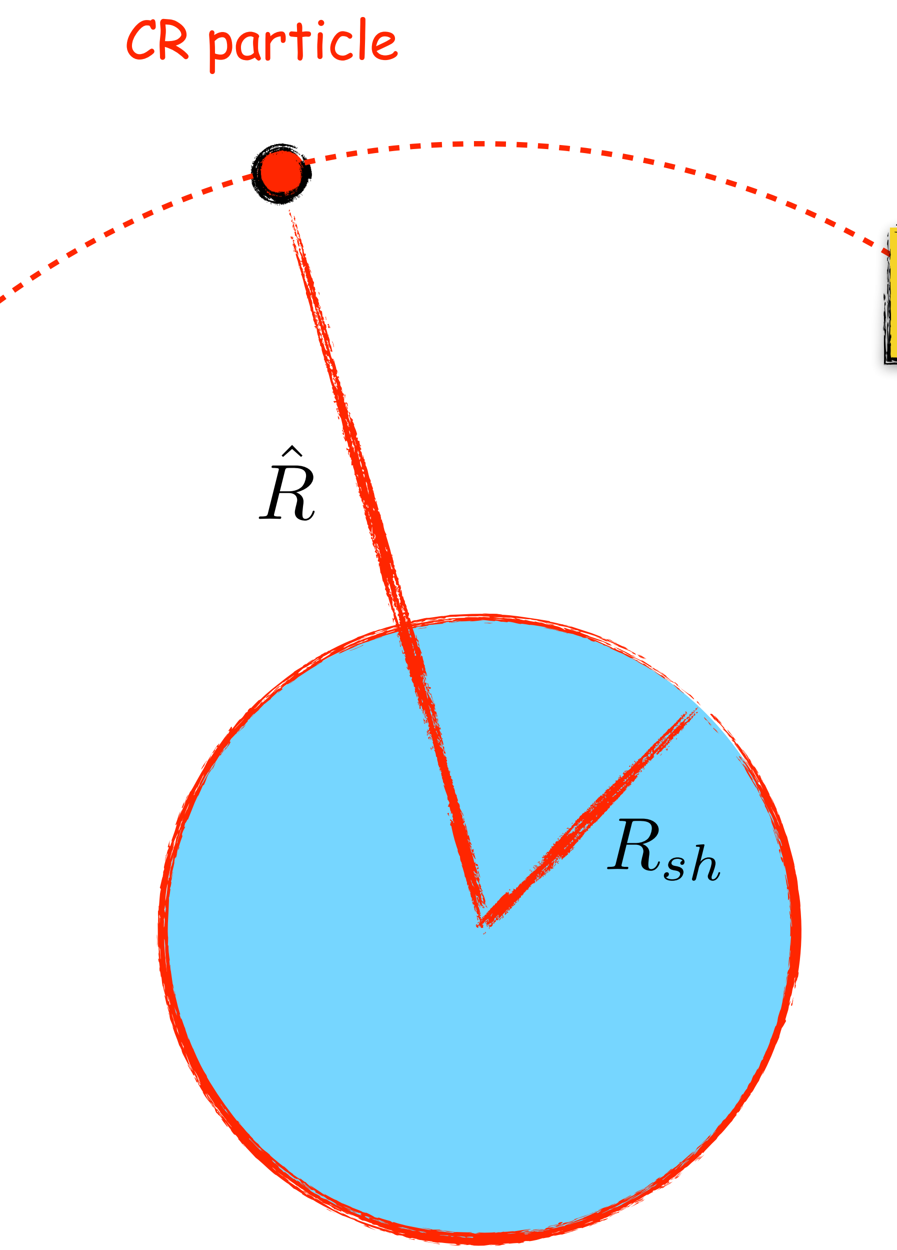

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boundary conditions

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

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

we treat the shock as an absorbing boundary

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SNR shocks are spherical

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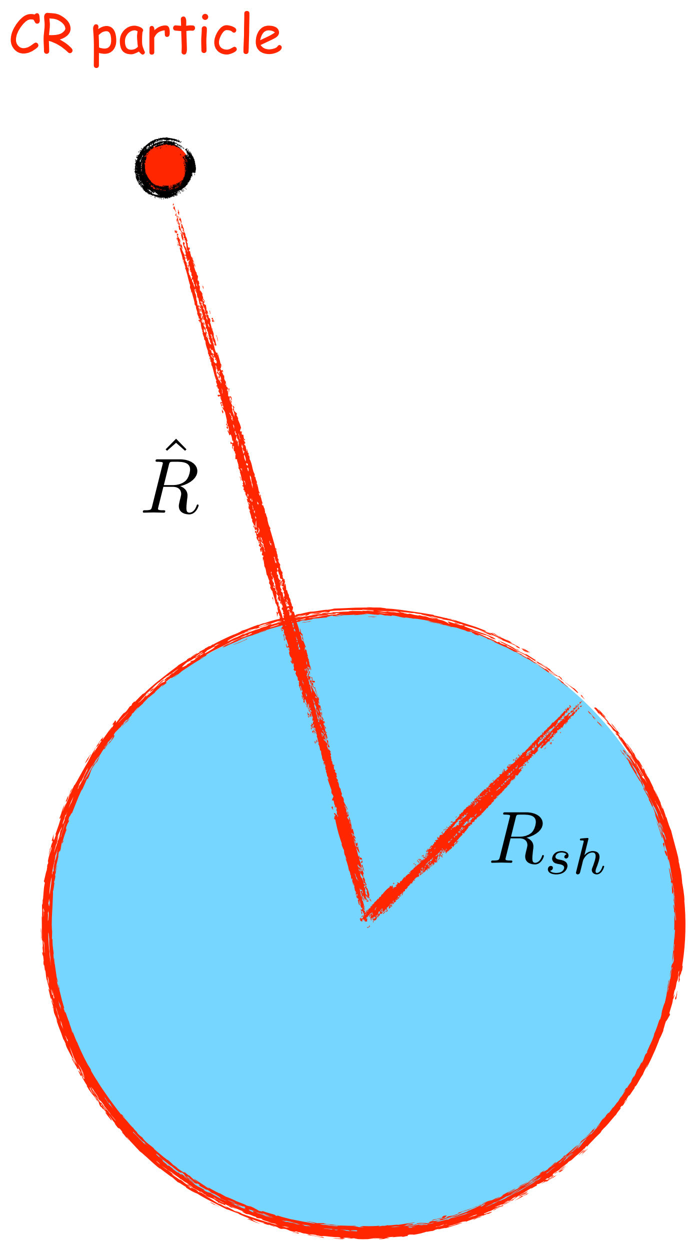

let's solve the equation for $R \neq \hat{R}$

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SNR shocks are spherical

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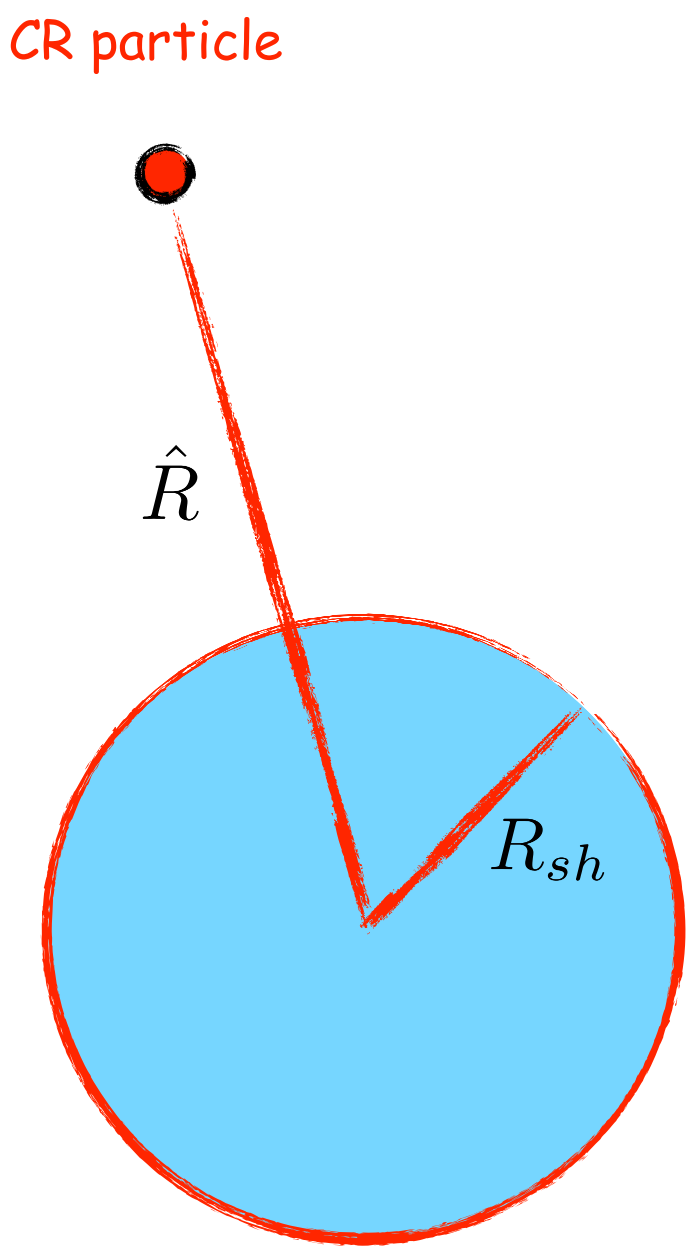

let's solve the equation for $R \neq \hat{R}$

constant

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

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SNR shocks are spherical

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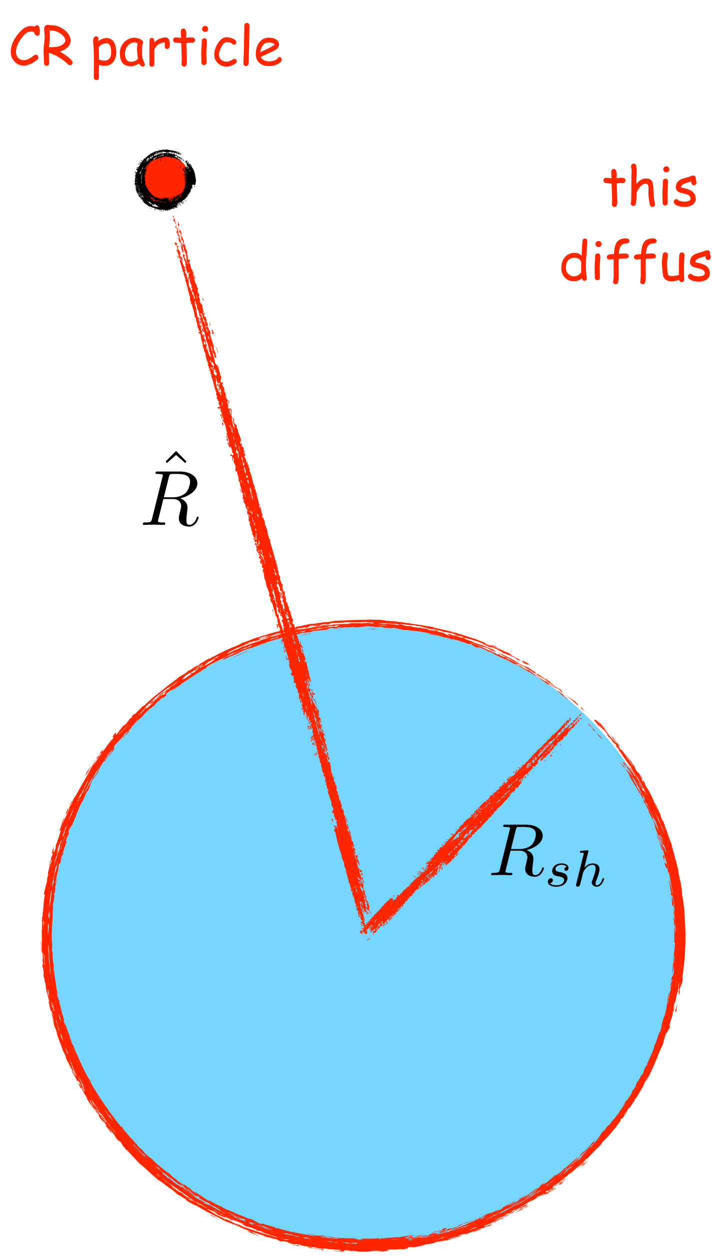

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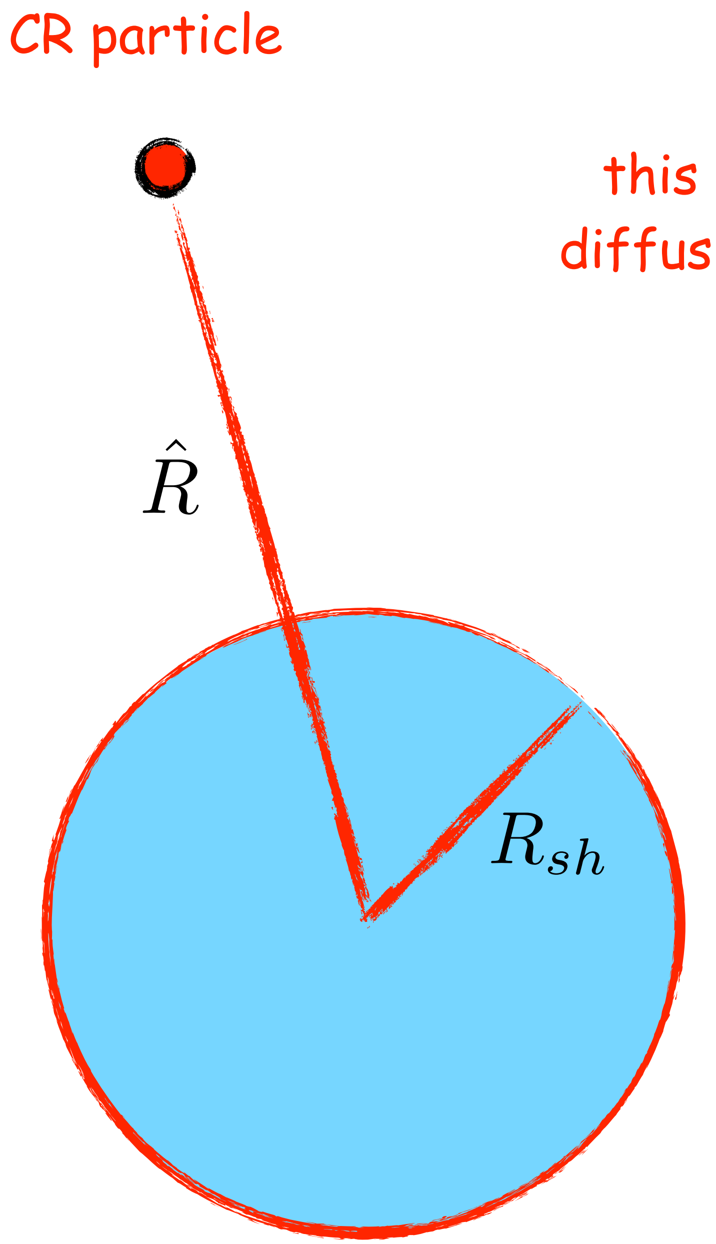

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this is the diffusive flux

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

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

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SNR shocks are spherical

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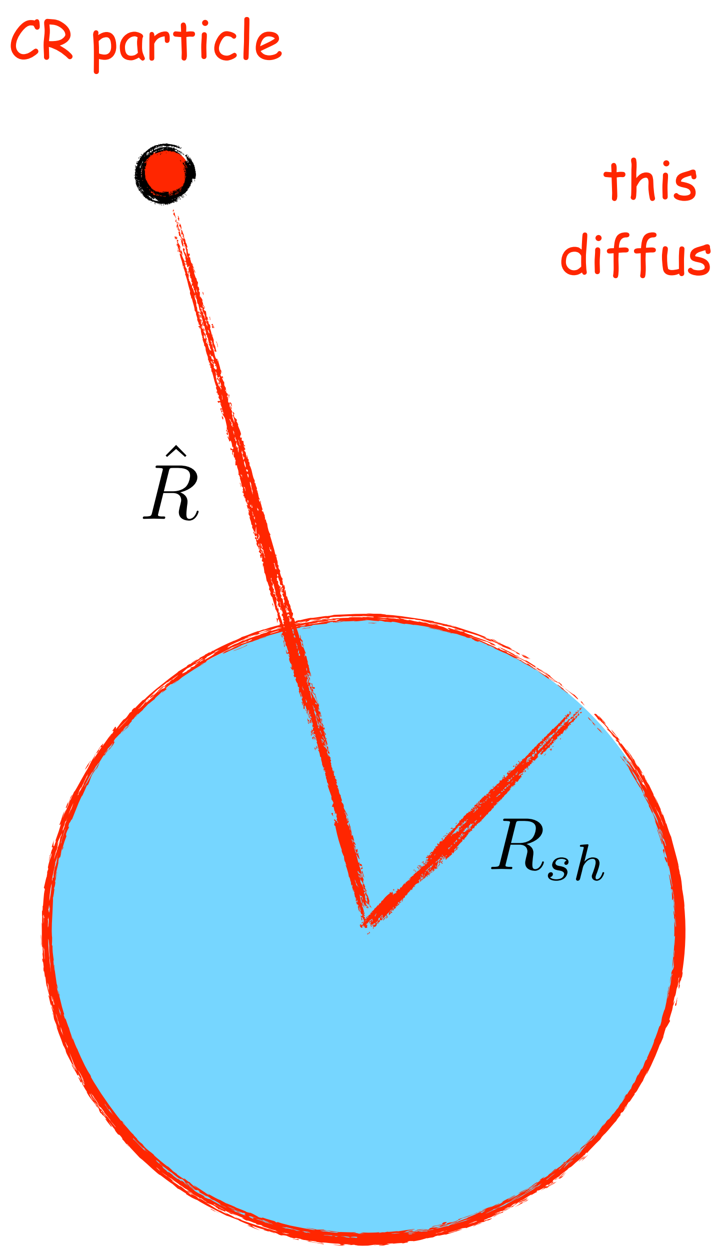

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$$f(R_{sh}) = 0 \rightarrow f = -\frac{\phi_{sh}}{D}\left(\frac{1}{R} - \frac{1}{R_{sh}}\right)$$

$$\boxed{R > \hat{R}}$$

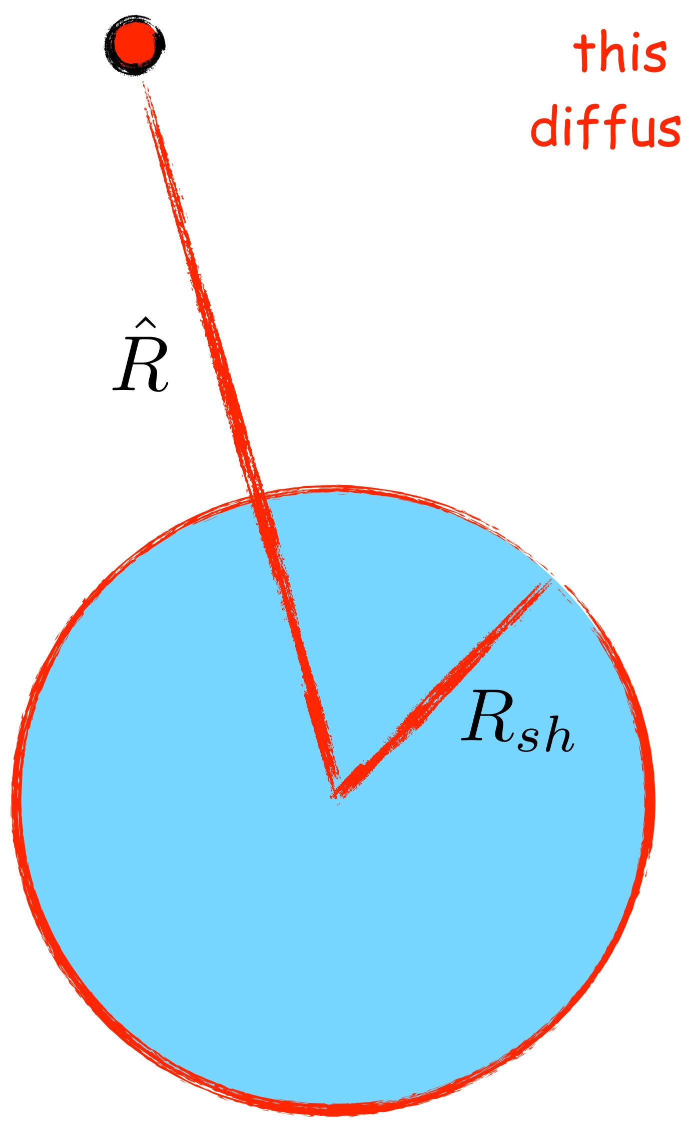
this is negative

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

Drury 2011

SNR shocks are spherical

return probability to the shock for a particle located upstream



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

this is the diffusive flux

constant

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

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

we make it positive

Drury 2011

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

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$\boxed{R > \hat{R}}$

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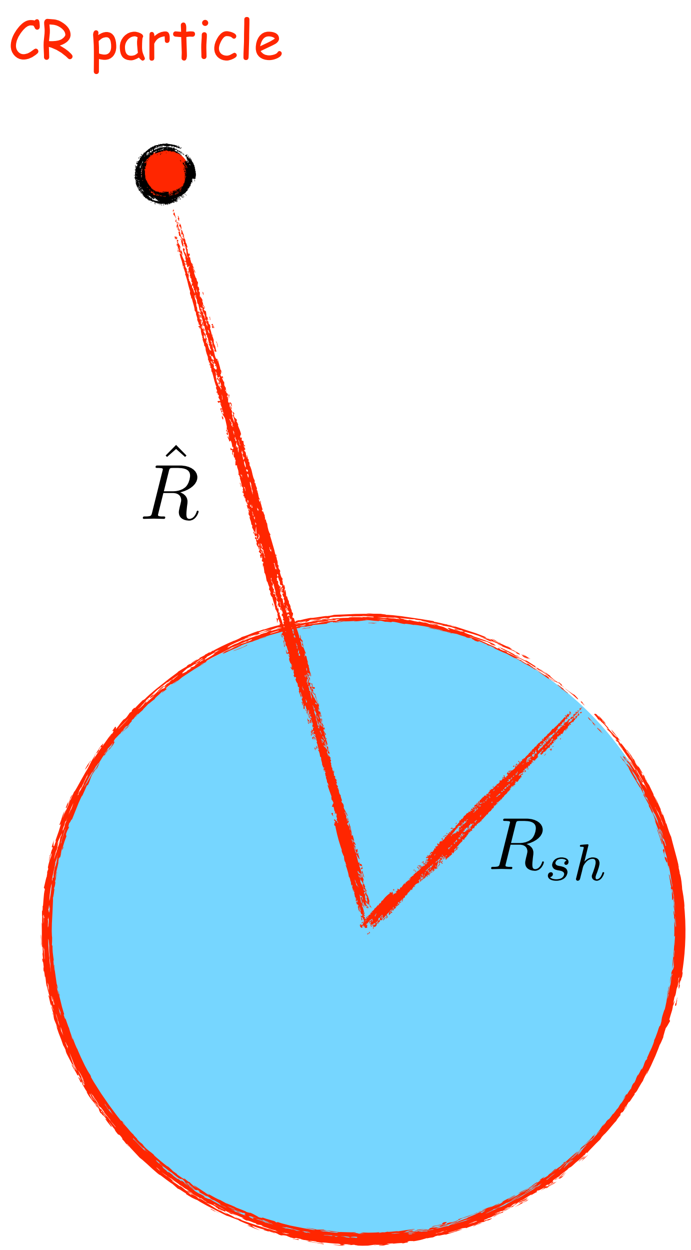

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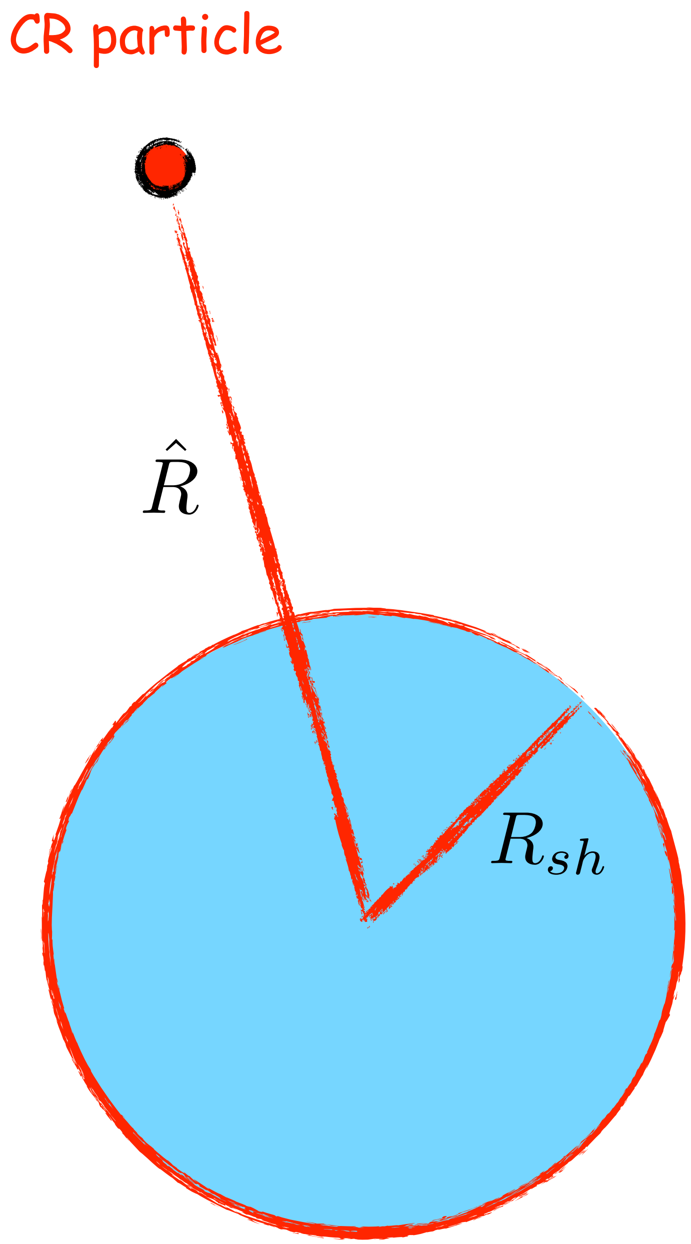

$$\boxed{\phi_\infty = \phi_{sh}\left(\frac{\hat{R}}{R_{sh}} - 1\right)}$$

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

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

Drury 2011

SNR shocks are spherical

DSA theory —> we computed the return probability for a plane shock

SNR shocks are spherical

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plane shock (DSA)

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

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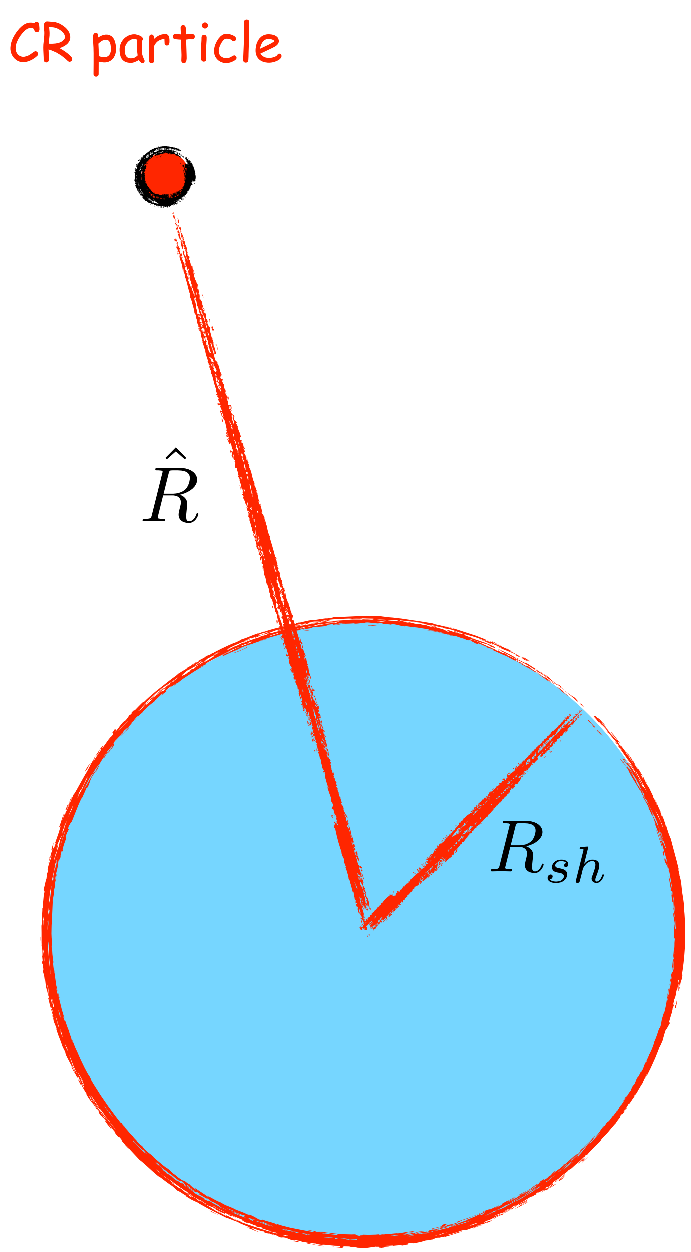
$$\boxed{P_{esc}^{geom} \approx P_{esc}^{DSA} \longrightarrow \frac{\hat{R} - R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1}$$

SNR shocks are spherical

consequences of what said so far...

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



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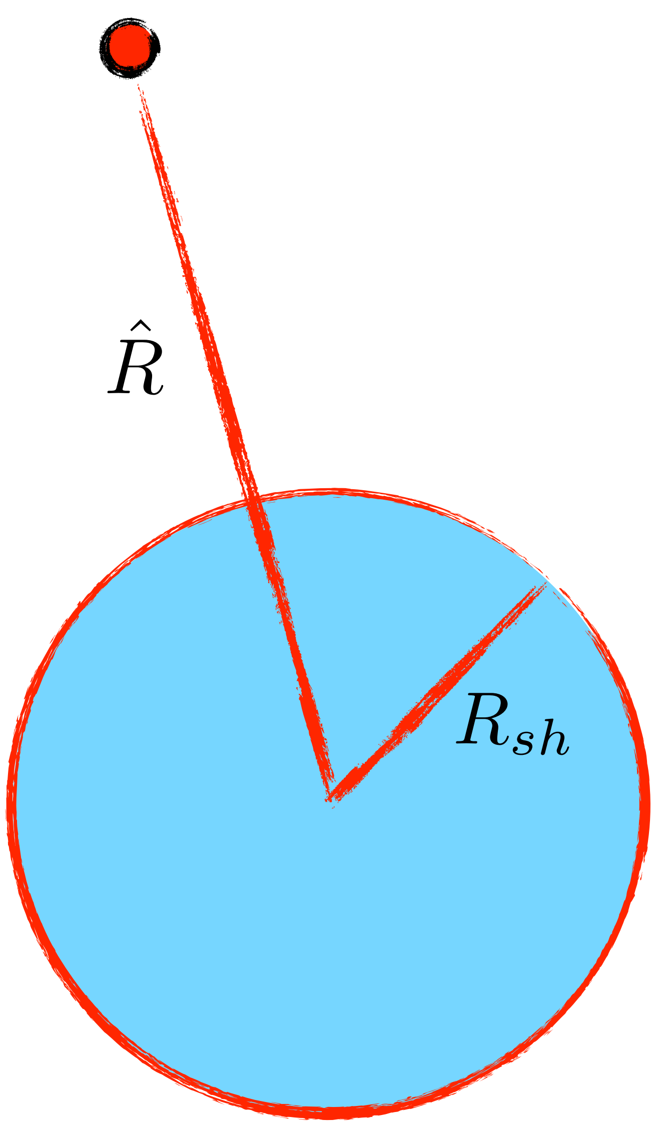
$$1 - \frac{R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1 \longrightarrow \frac{\hat{R}}{R_{sh}} = \left(1 - \frac{u_{sh}}{c}\right)^{-1}$$

CR particle



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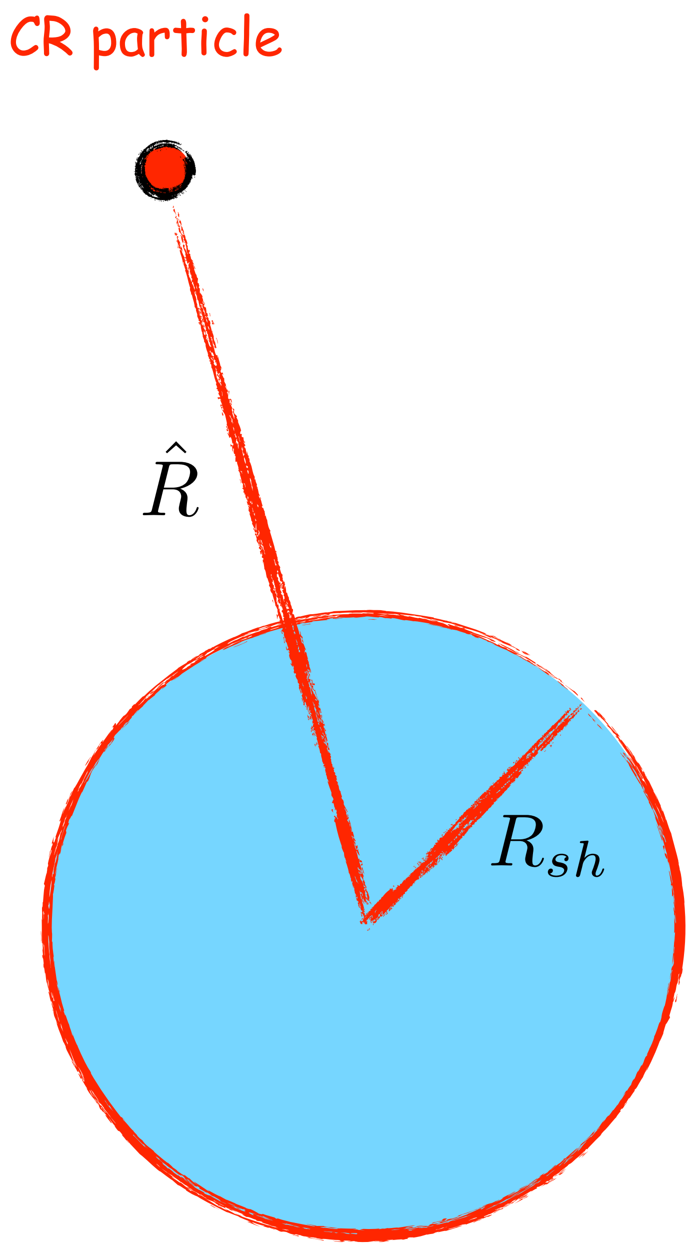
$$1 - \frac{R_{sh}}{\hat{R}} = \frac{u_{sh}}{c} \ll 1 \longrightarrow \frac{\hat{R}}{R_{sh}} = \left(1 - \frac{u_{sh}}{c}\right)^{-1} \approx 1 + \frac{u_{sh}}{c} \sim 1 + 0.03 \left(\frac{u_{sh}}{10^4 \text{ km/s}}\right)$$



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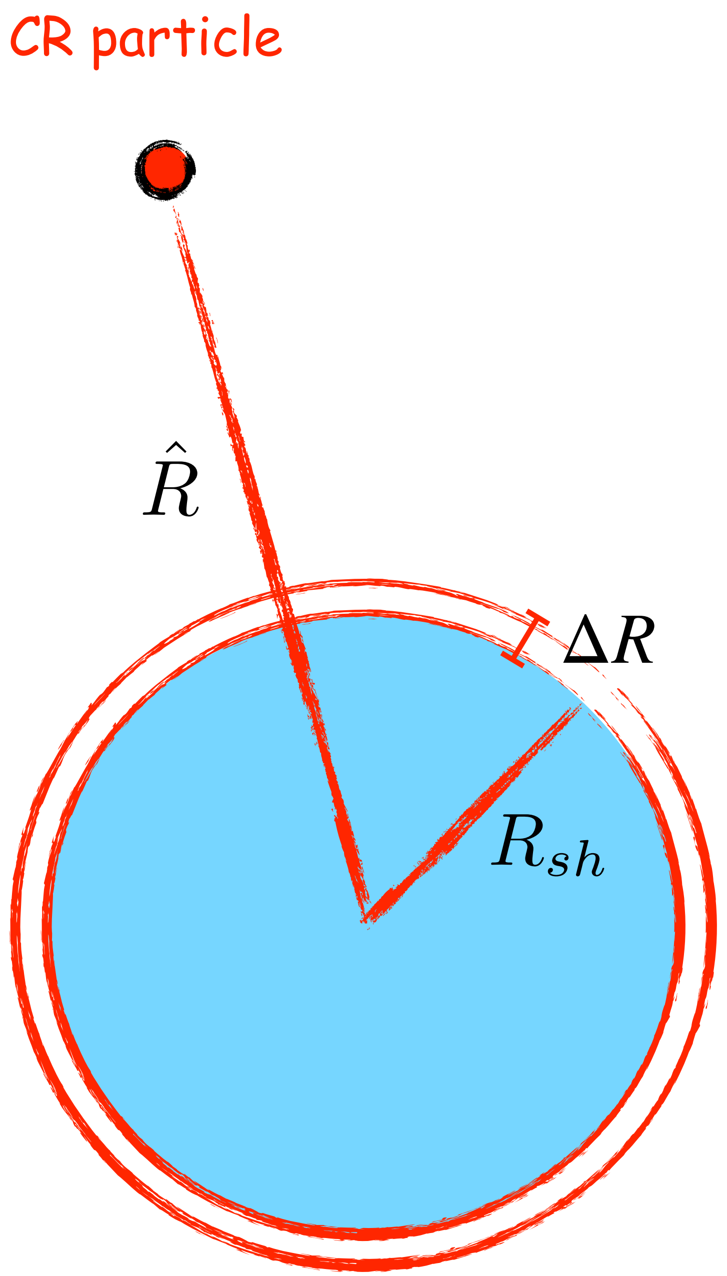

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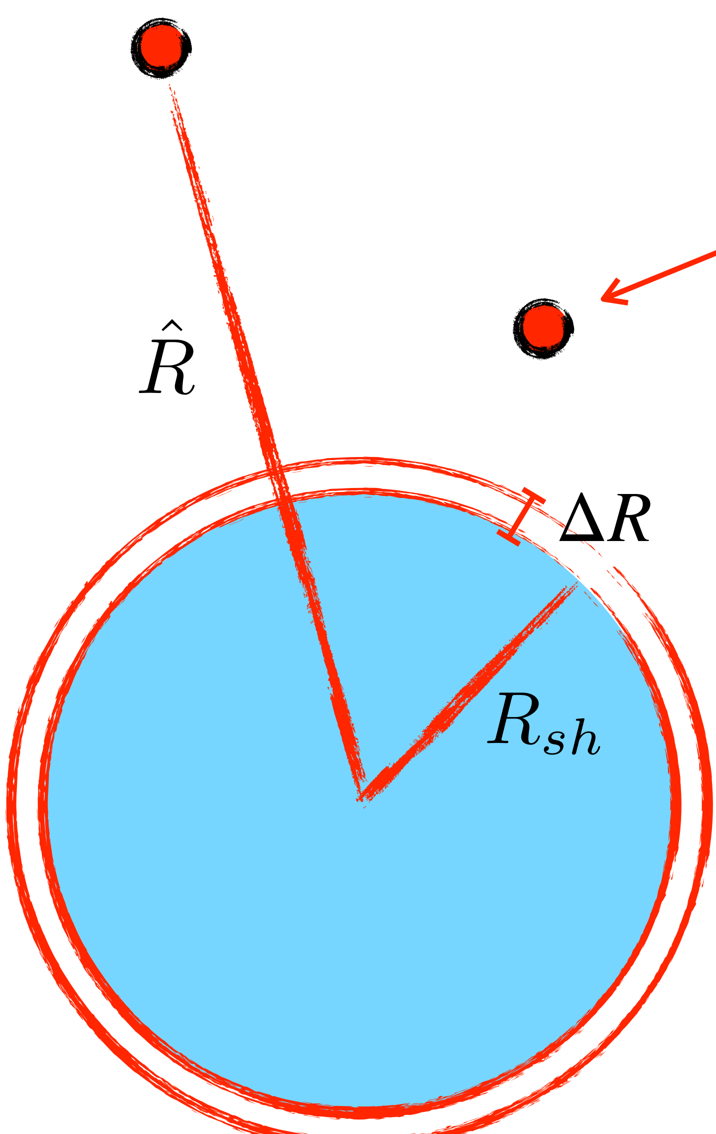

escape upstream is more likely
than escape downstream

SNR shocks are spherical

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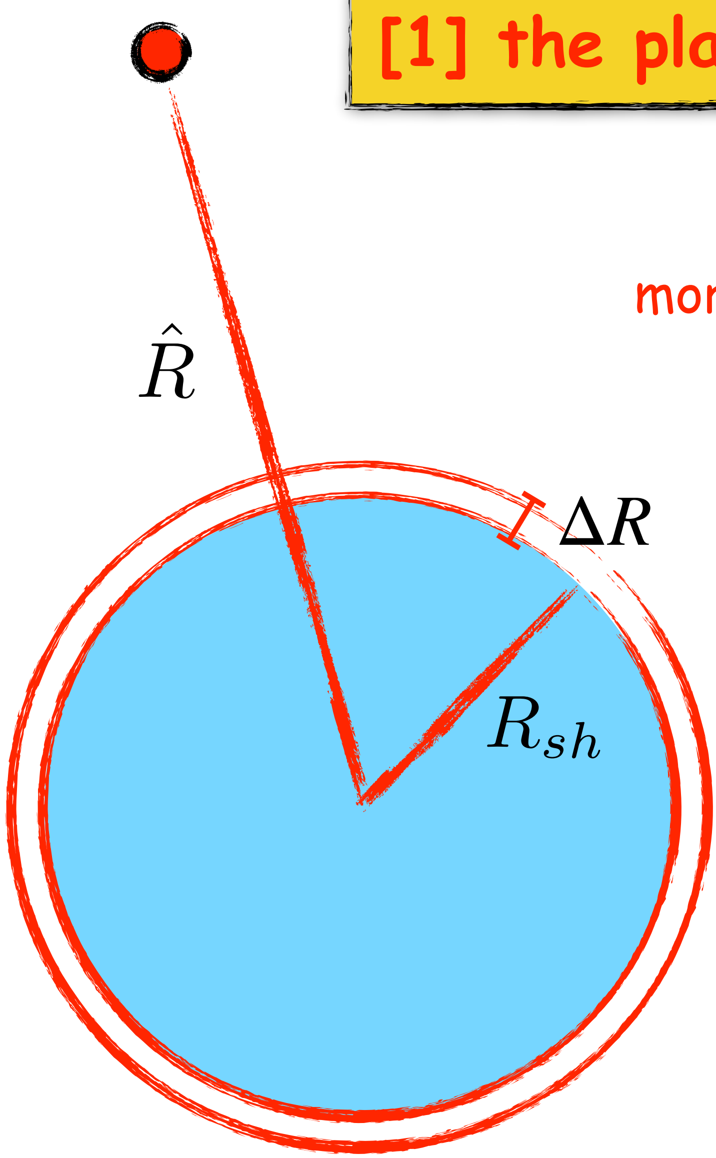
[1] the plane shock approximation is OK



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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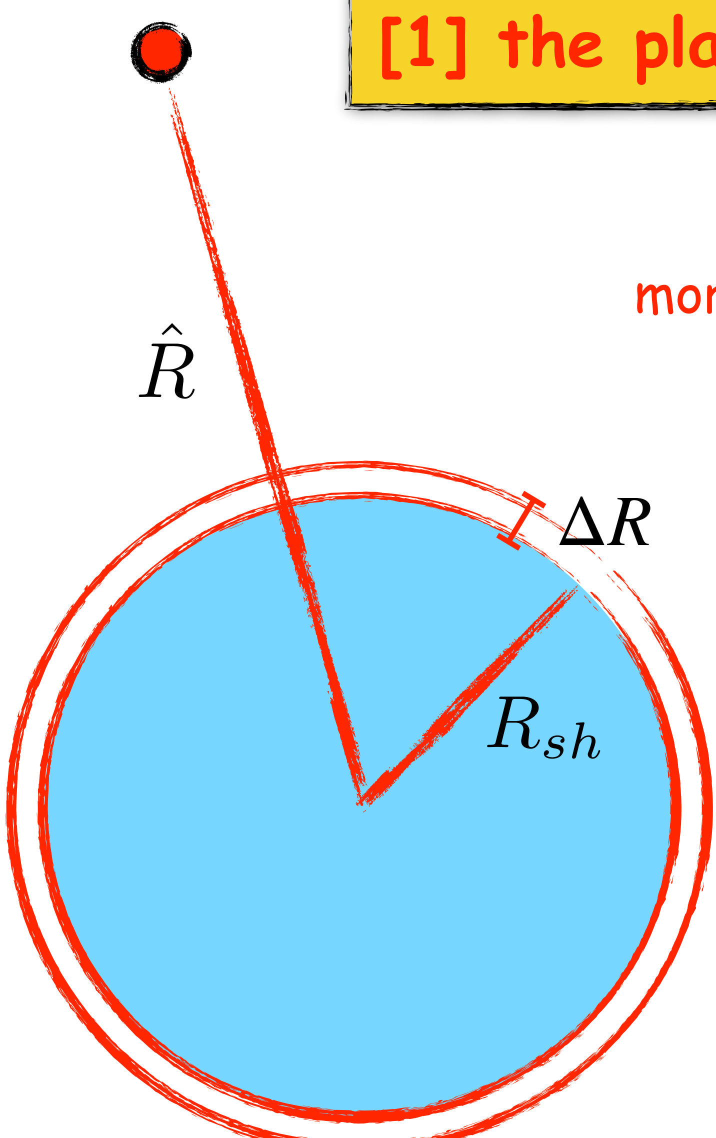

more accurate estimate $\longrightarrow$ $$\frac{\Delta R}{R_{sh}} = \frac{\hat{R} - R_{sh}}{R_{sh}} \approx 5 - 10\,\%$$

[2] in the Hillas criterion we should not use Rsh, but rather ΔR

—> 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

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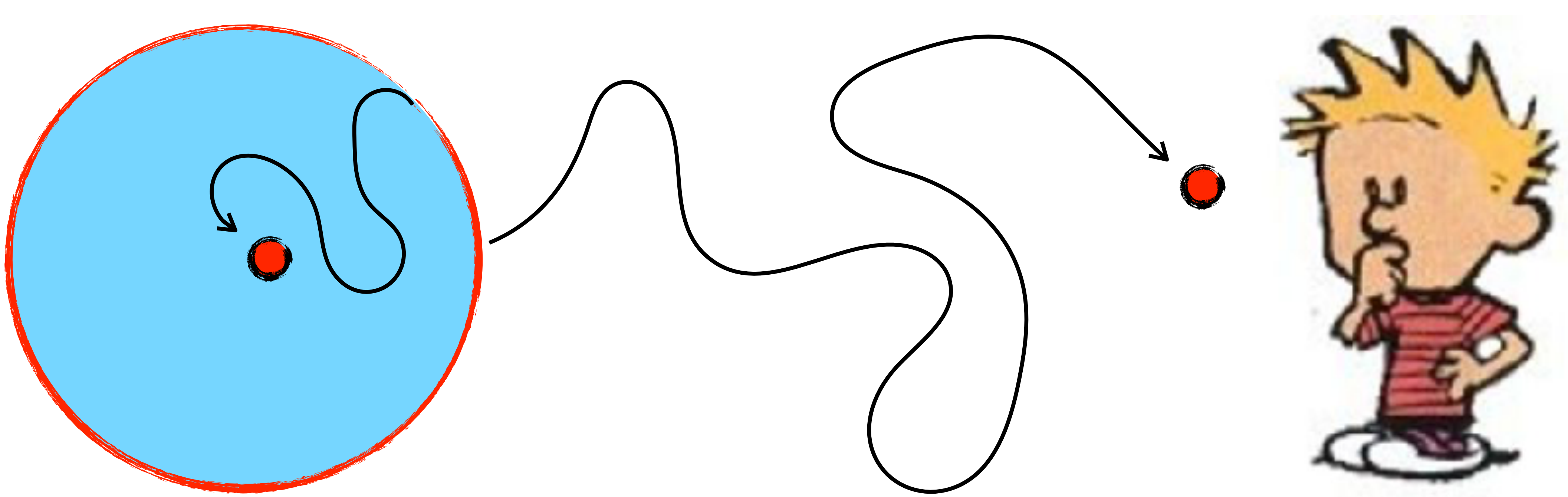
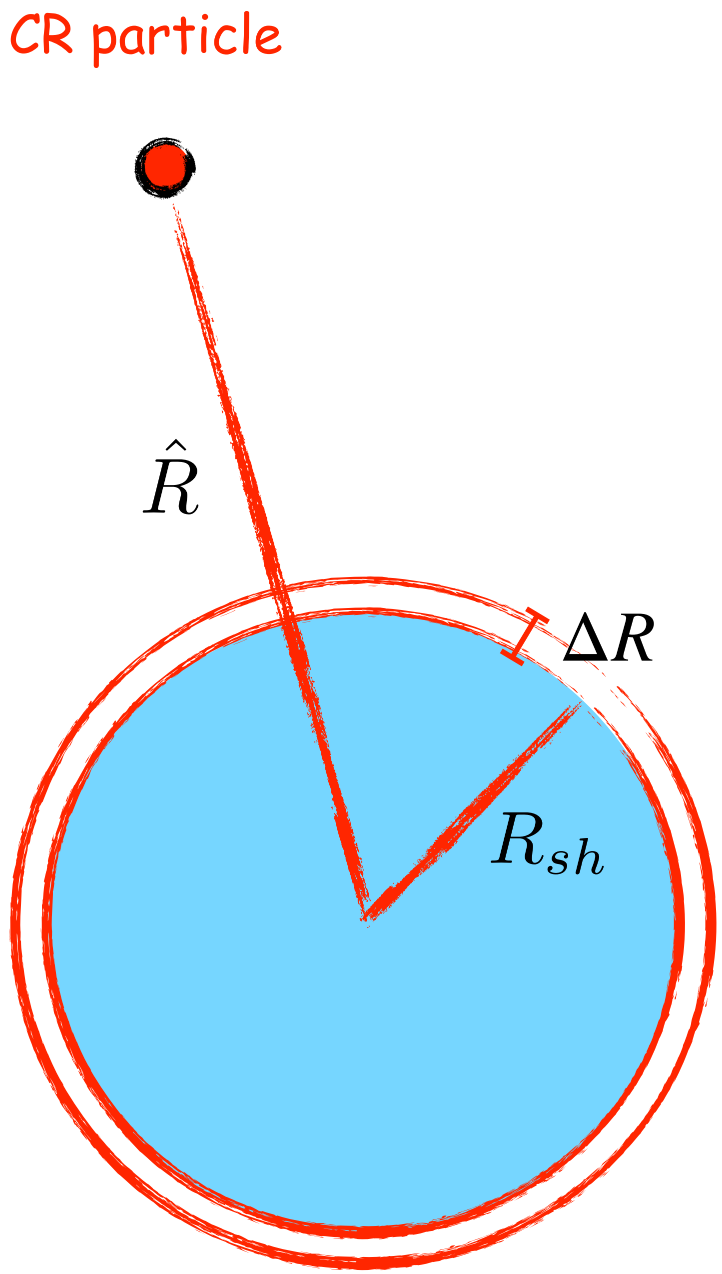
Plane (infinite) versus spherical shocks

	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 —>

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

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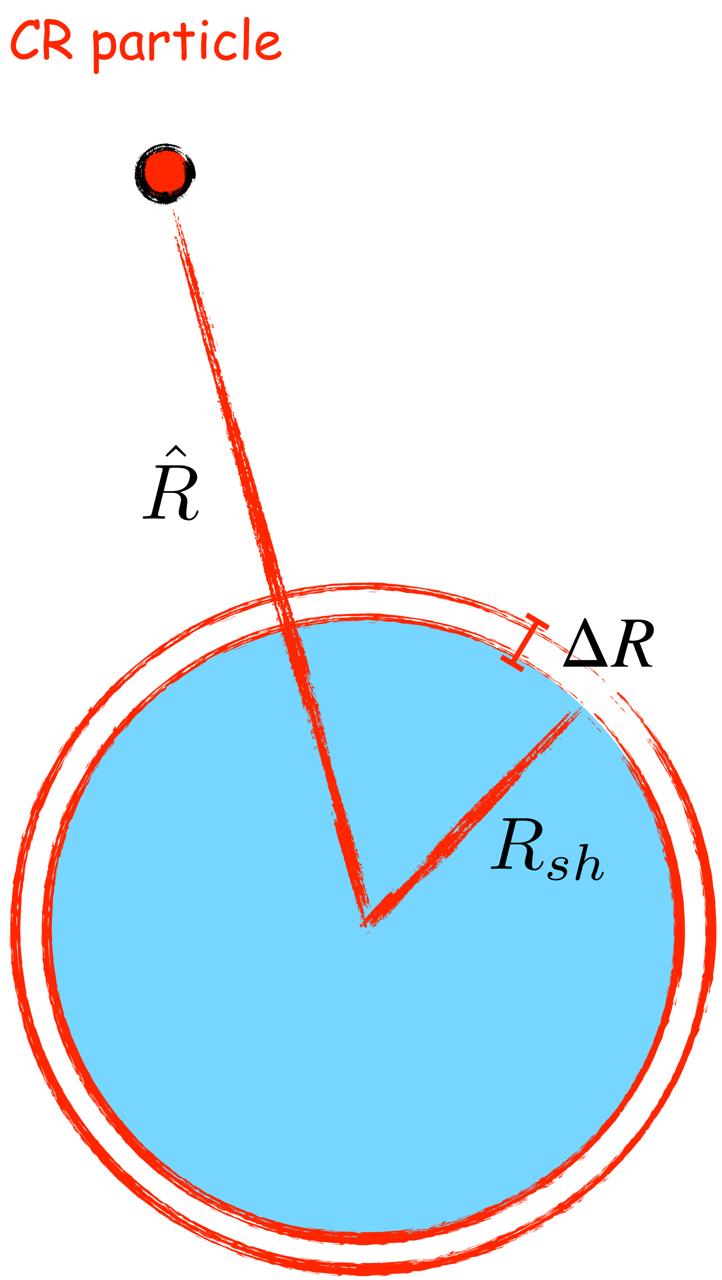
diffusion length

[2] size limited —> $l_d(E) = \Delta R$



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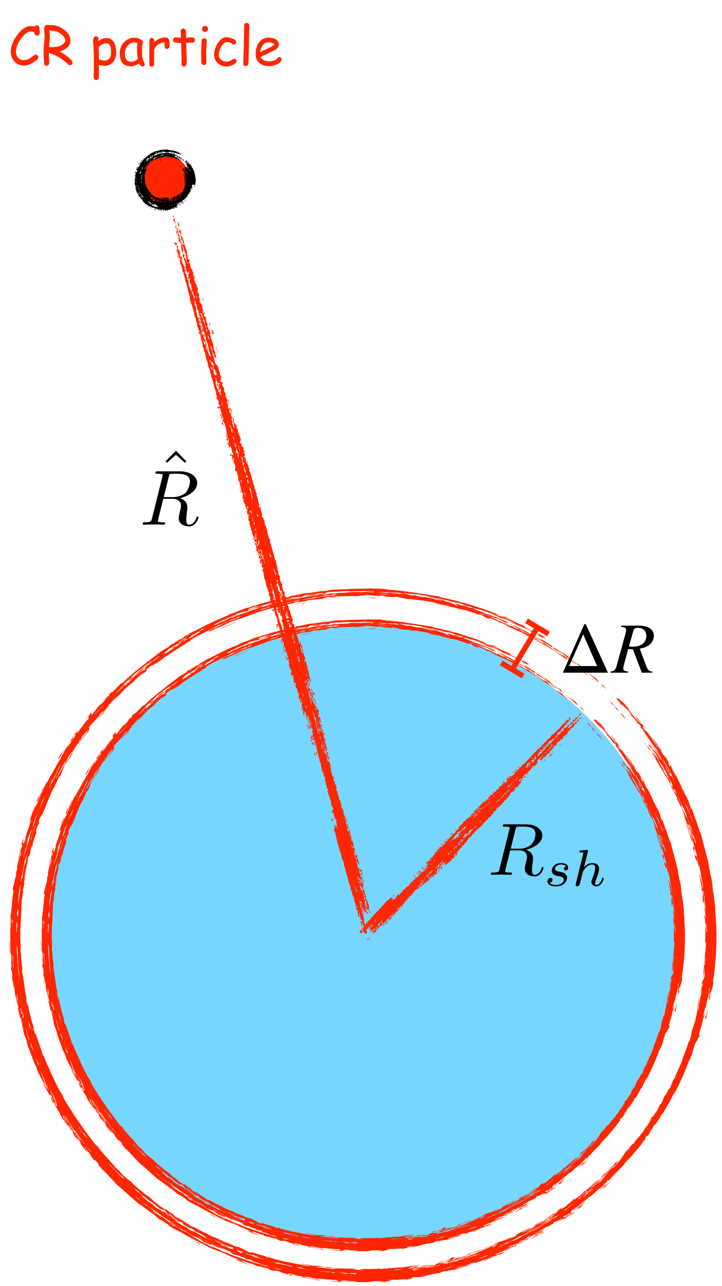


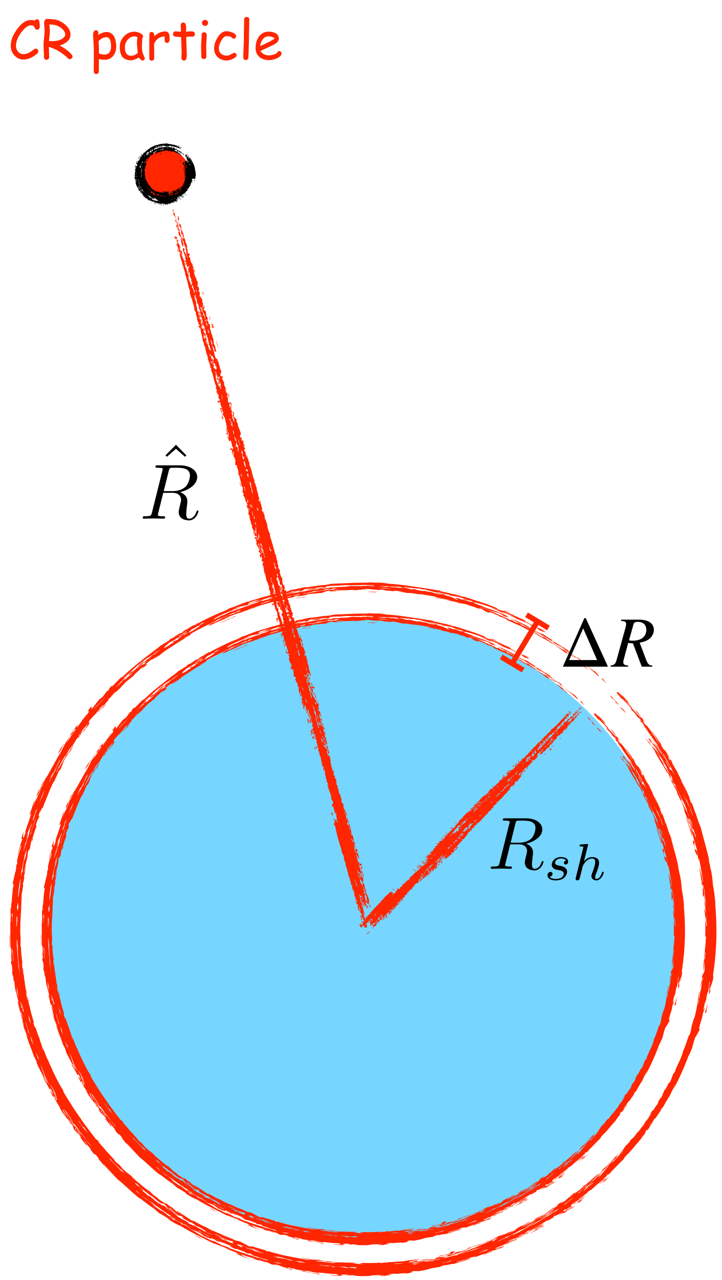
three possibilities:

[1] age limited —> $\tau_{acc}(E) = \tau_{age}$

[2] size limited —> $l_d(E) = \Delta R$ diffusion length

[2] loss limited —> $\tau_{acc}(E) = \tau_{loss}$

Which E_{max} at SNR shocks?



three possibilities:

[1] age limited —> $\tau_{acc}(E) = \tau_{age}$ **time**

diffusion length

[2] size limited —> $l_d(E) = \Delta R$ **space**

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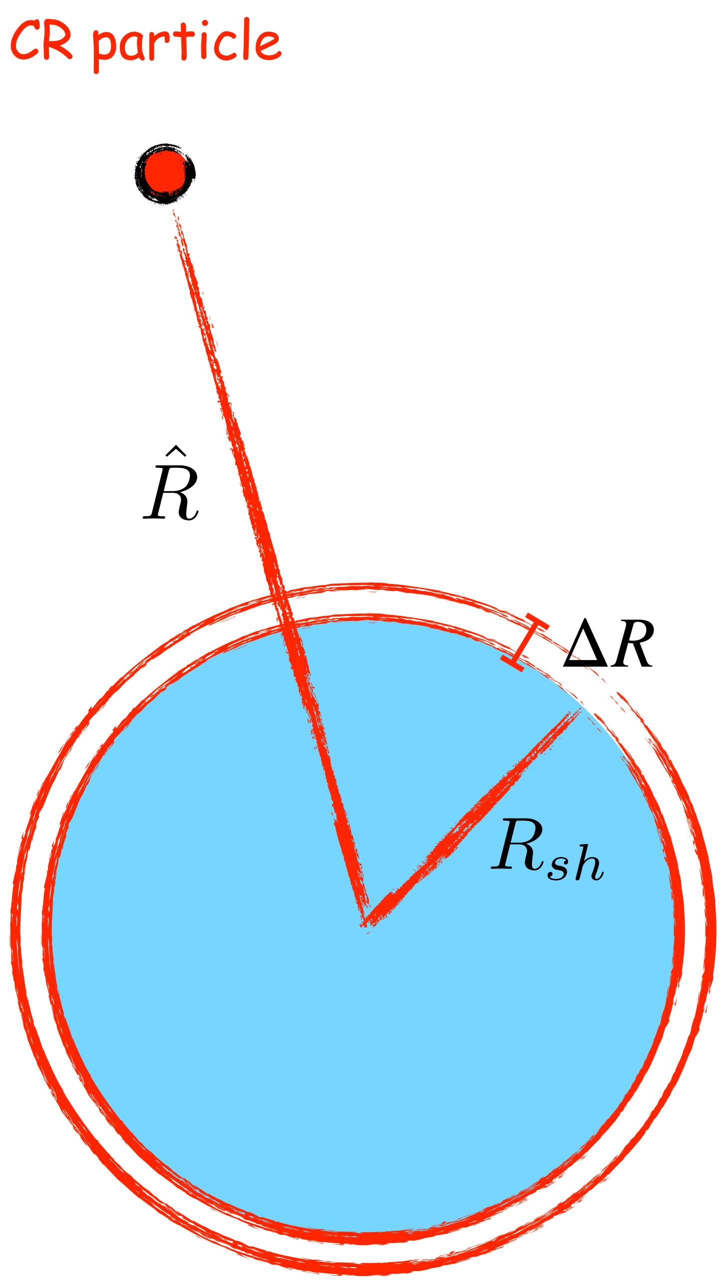

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CR

ambient medium

inelastic proton-proton interactions $p + p \rightarrow p + p + \pi^0$

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

4×10^{-26} cm^2 0.45 (inelasticity)

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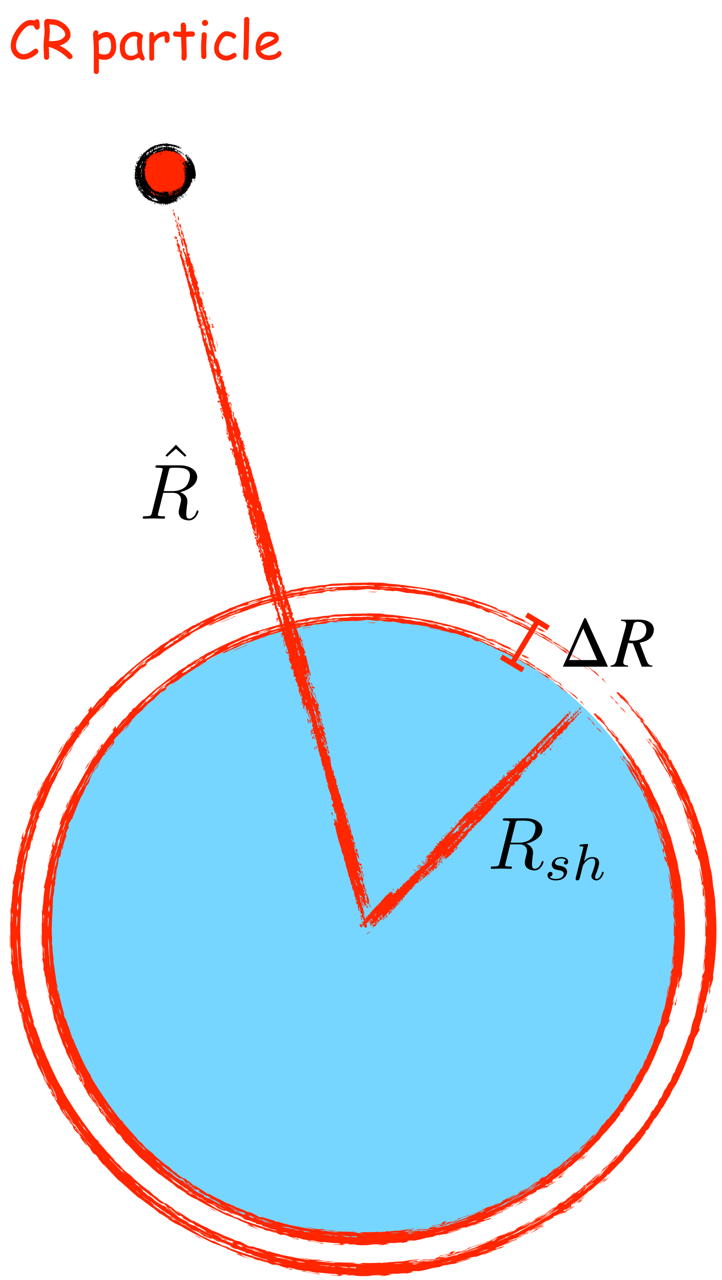

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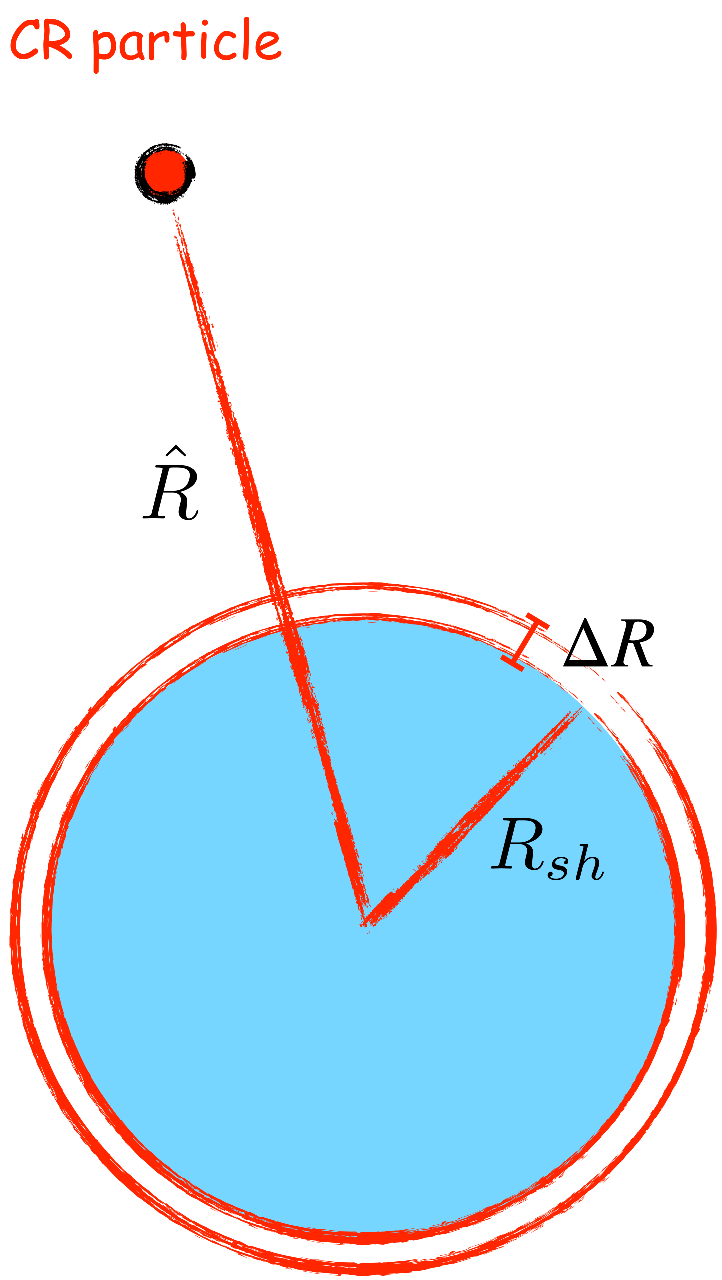

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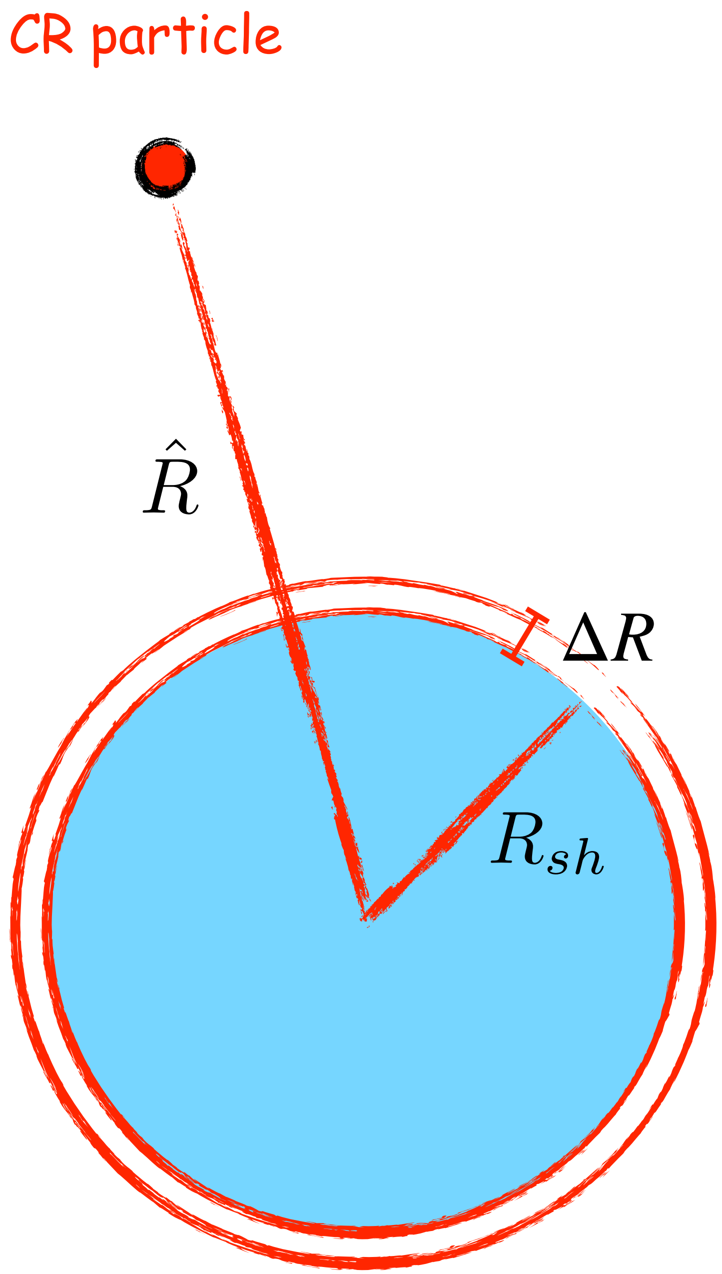

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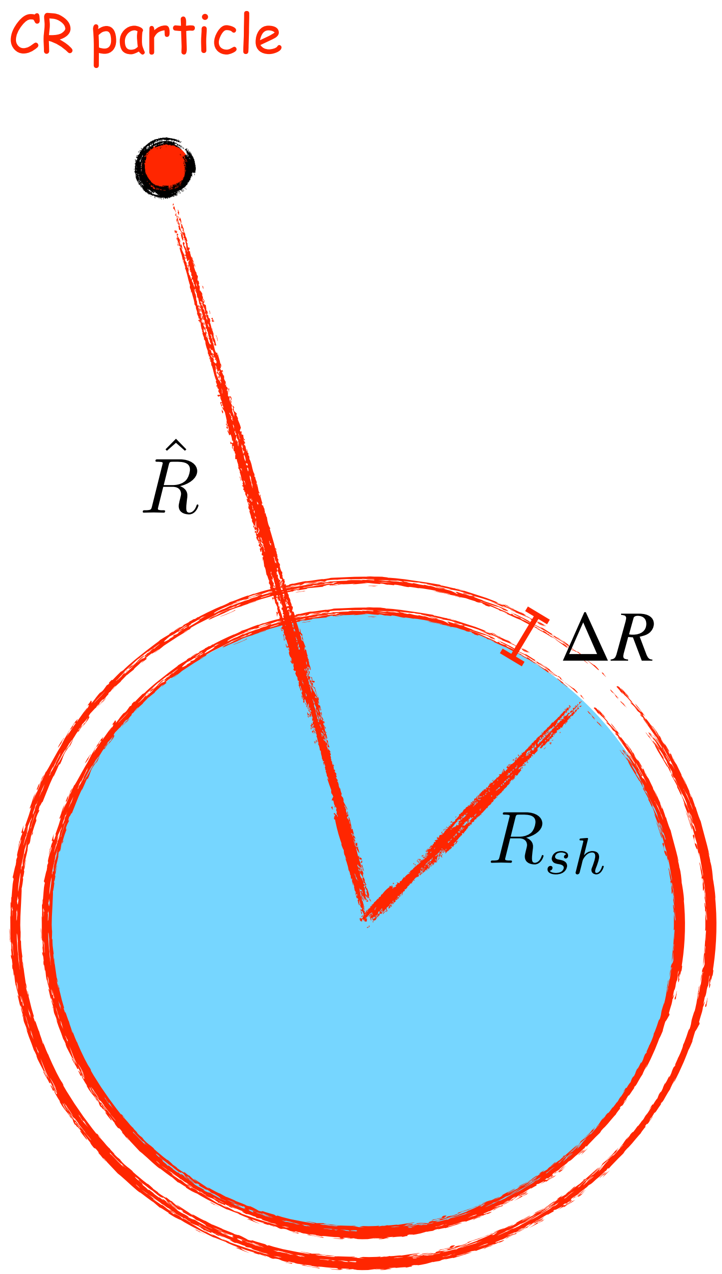

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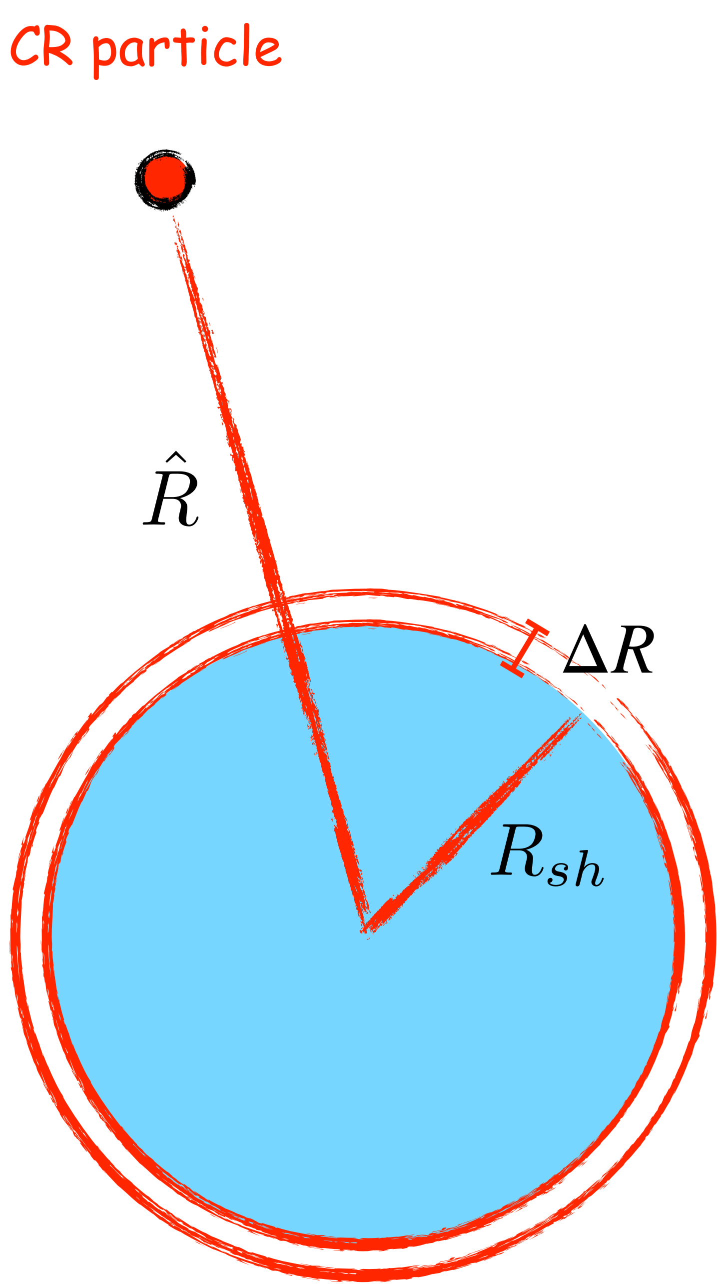

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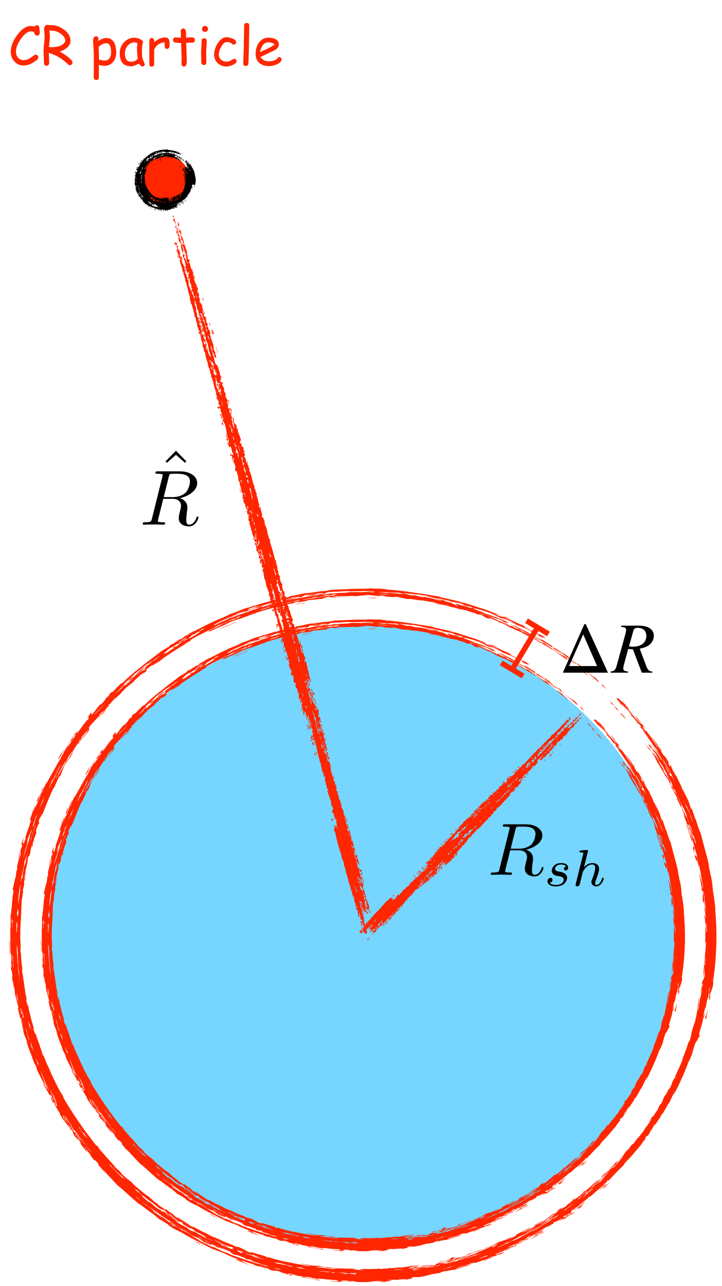

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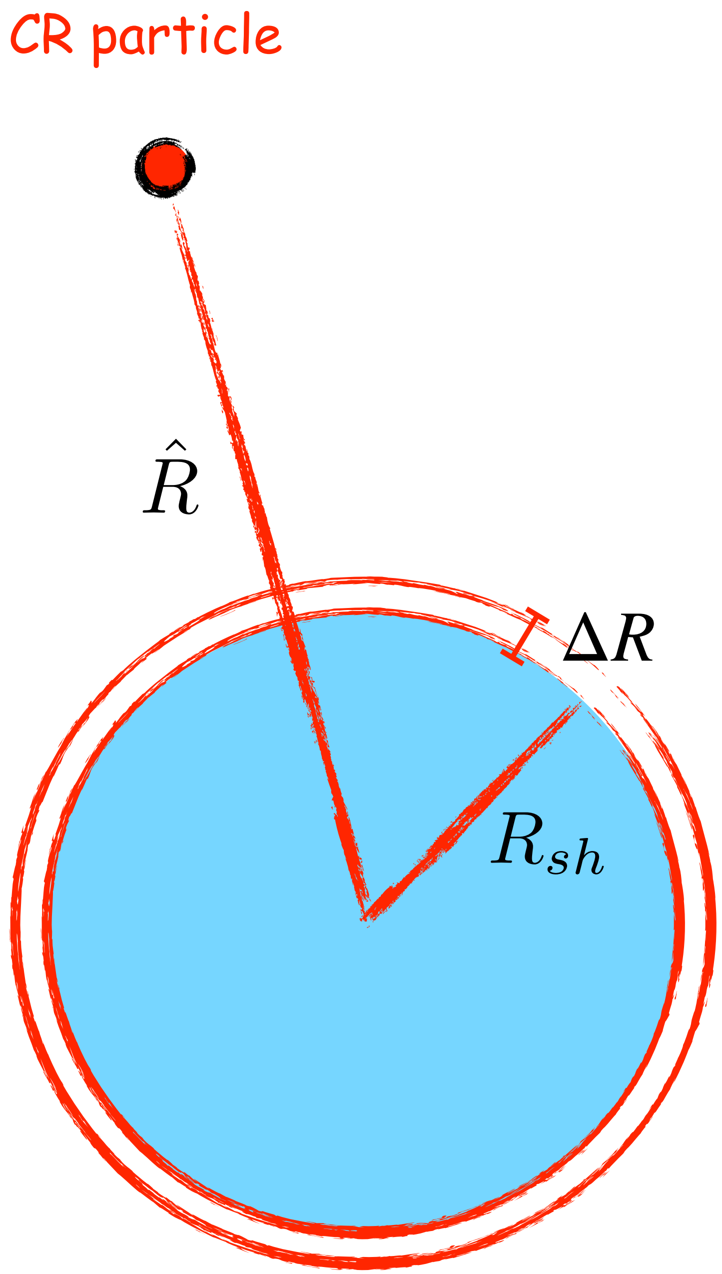

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$$l_d(E) = \Delta R = \eta R_{sh}$$

~5%

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

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SNR evolution —>

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

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Sedov-Taylor —>

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

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?

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

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

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

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

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

Which E_{max} at SNR shocks?

$$R_L(E_{max}) = 3\eta \left(\frac{u_{sh}}{c}\right) R_{sh} \qquad R_L(E) = \frac{E(\mathrm{eV})}{300\ B(\mathrm{G})}\ \mathrm{cm}$$

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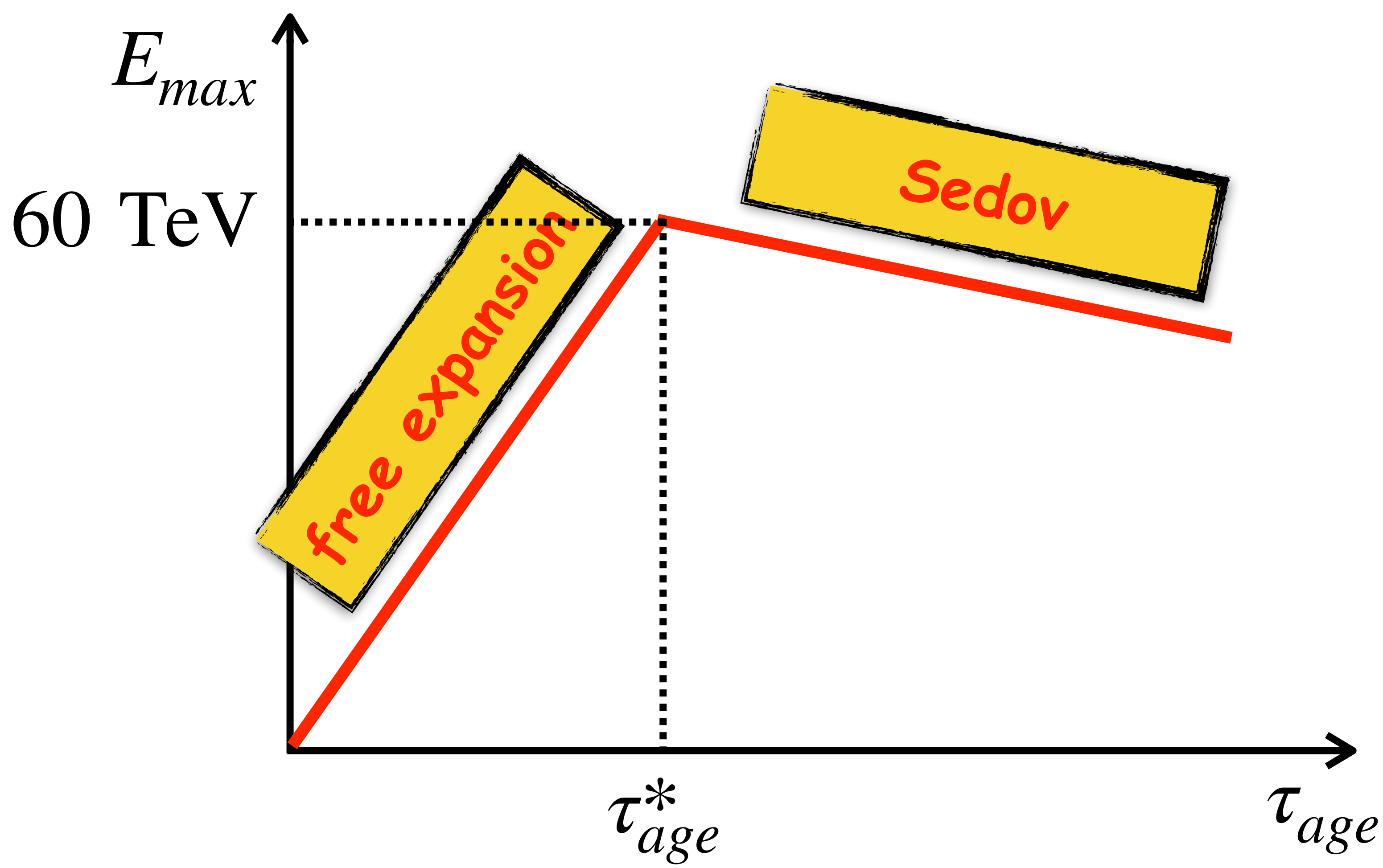

$$R_* = R_{sh}(\tau^*_{age}) \approx 2\ \mathrm{pc}$$

$$\boxed{E_{max} \approx 60\ \mathrm{TeV}}$$

Which E_{max} at SNR shocks?

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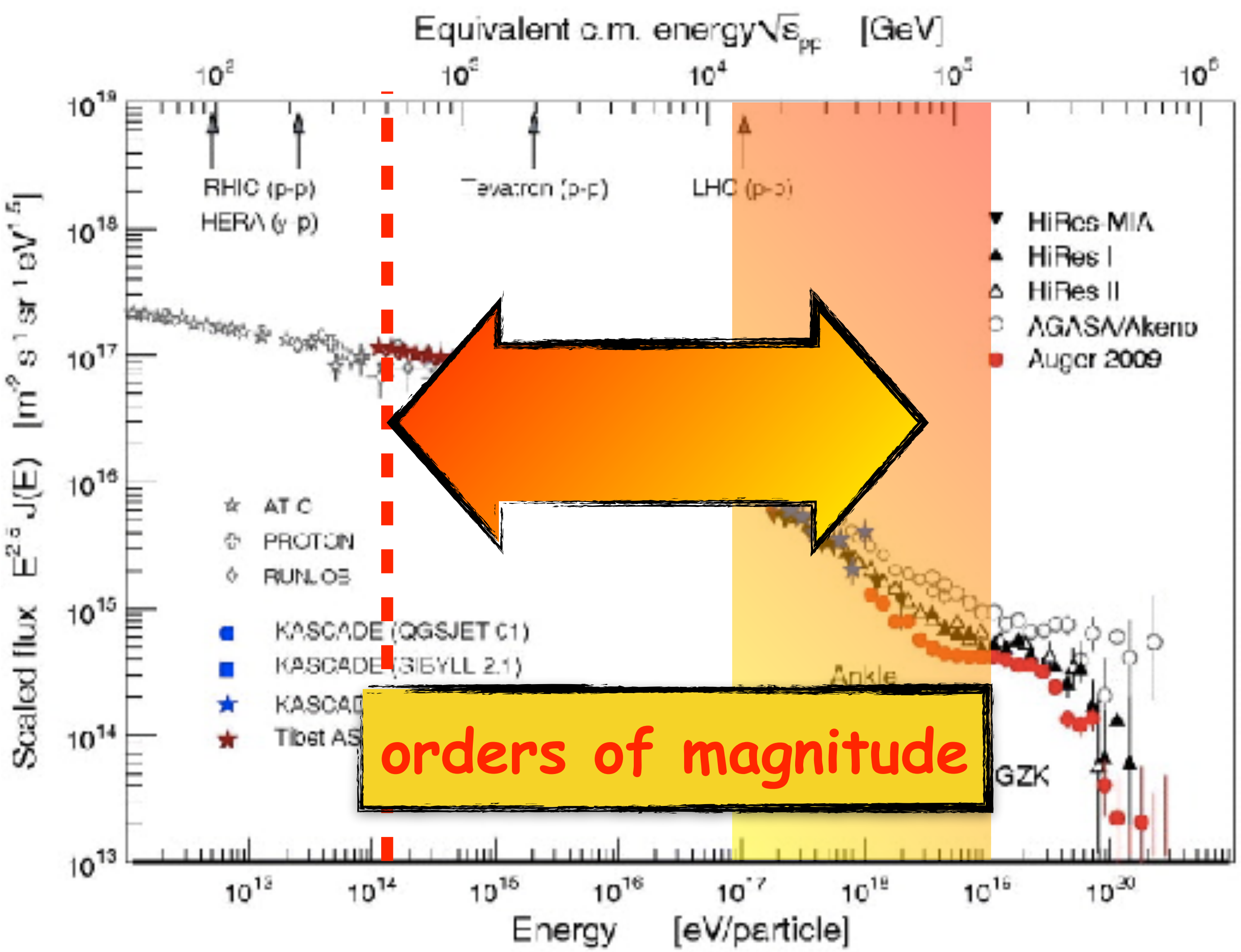

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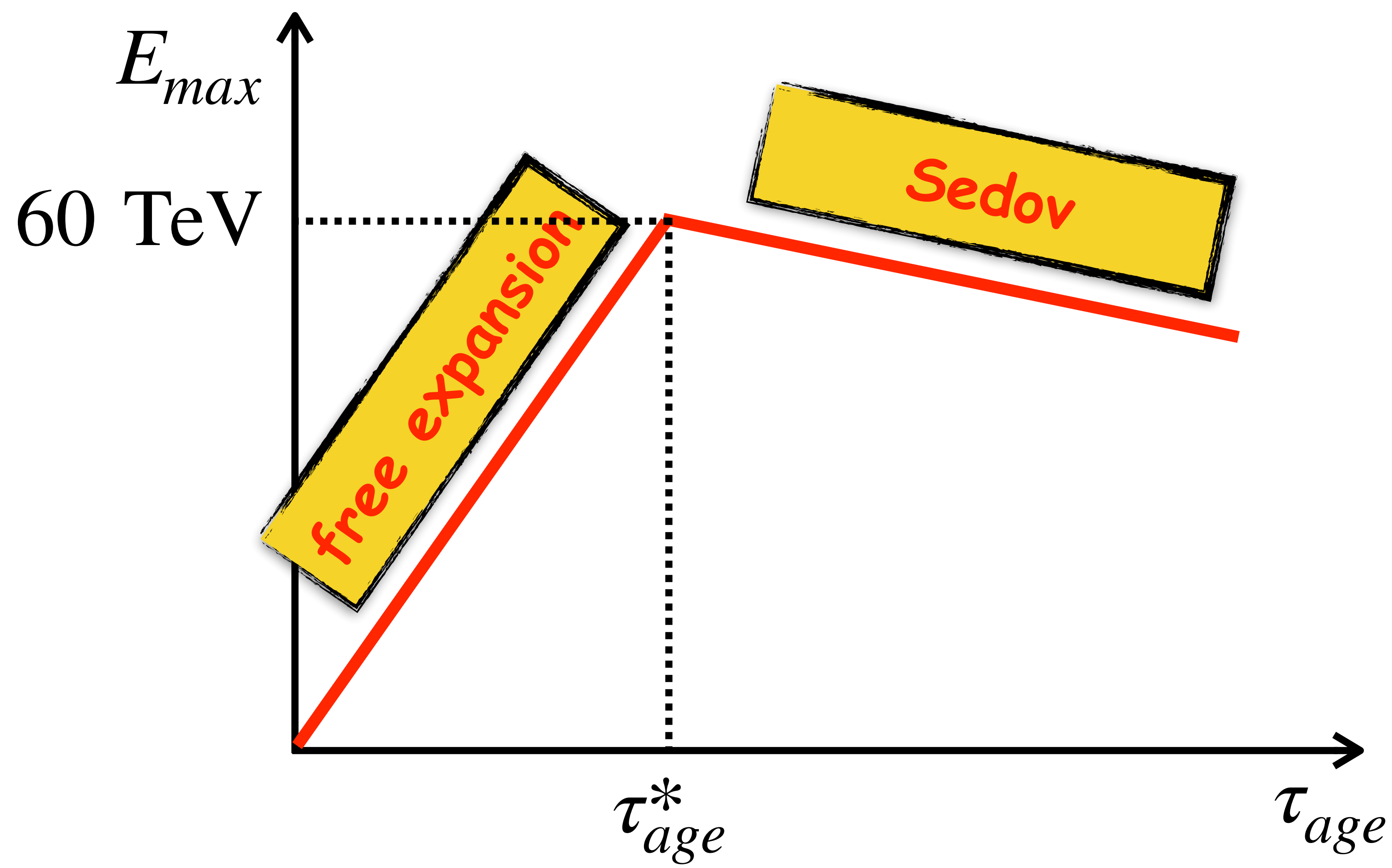
Lagage & Cesarsky 1983

Gradual release of CRs



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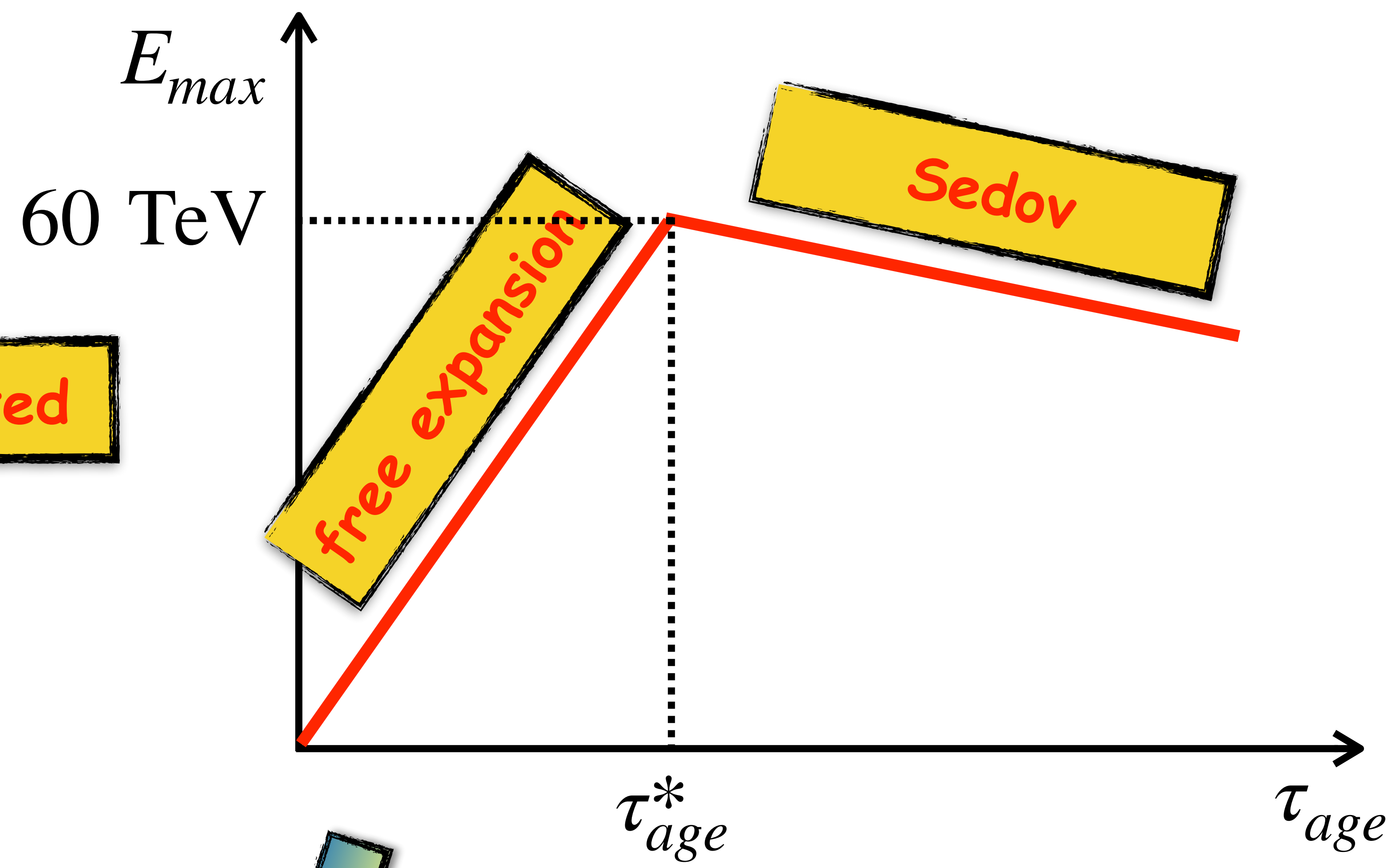

time limited

E_{max} ↑ —> nothing escapes

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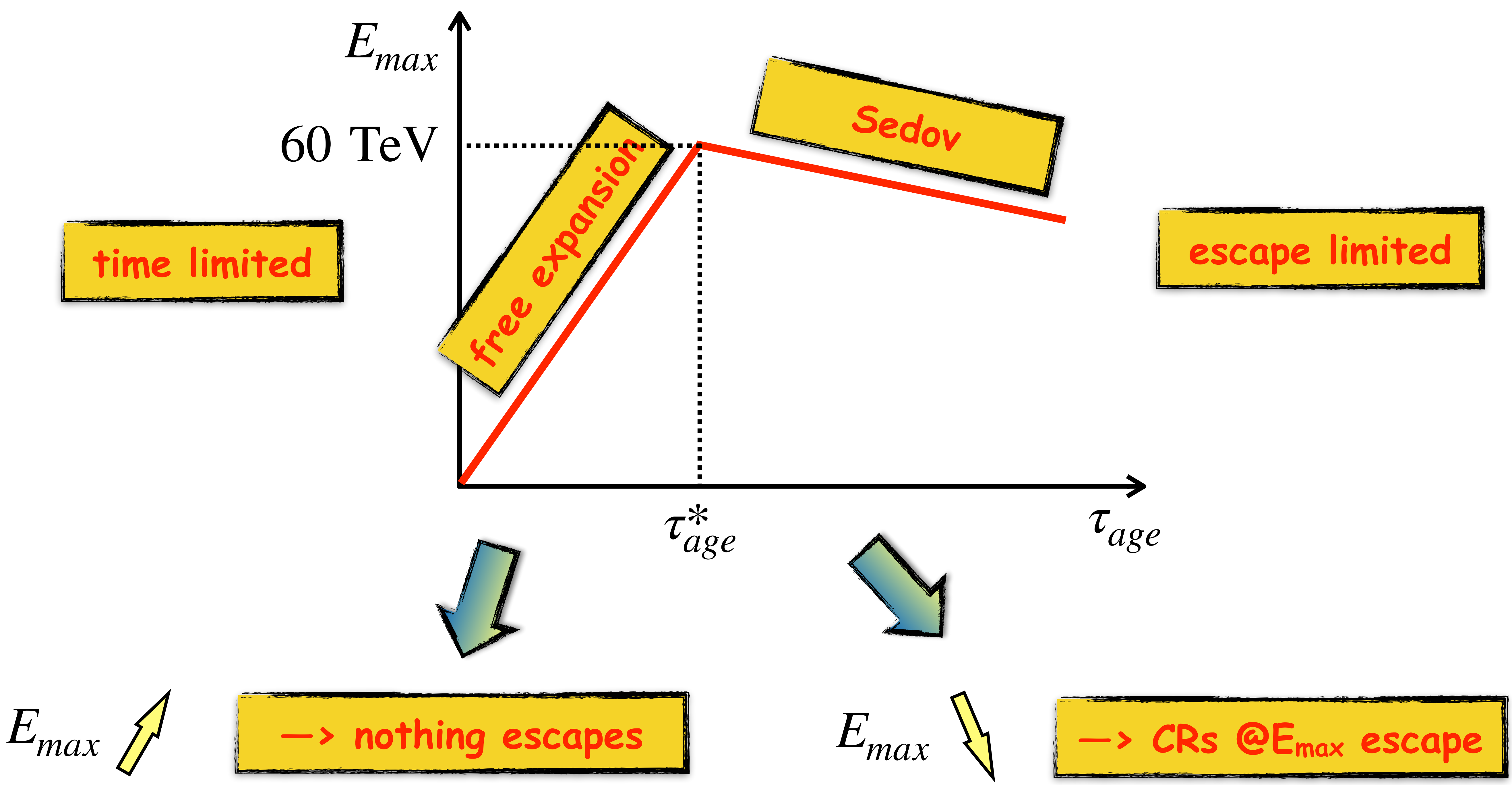

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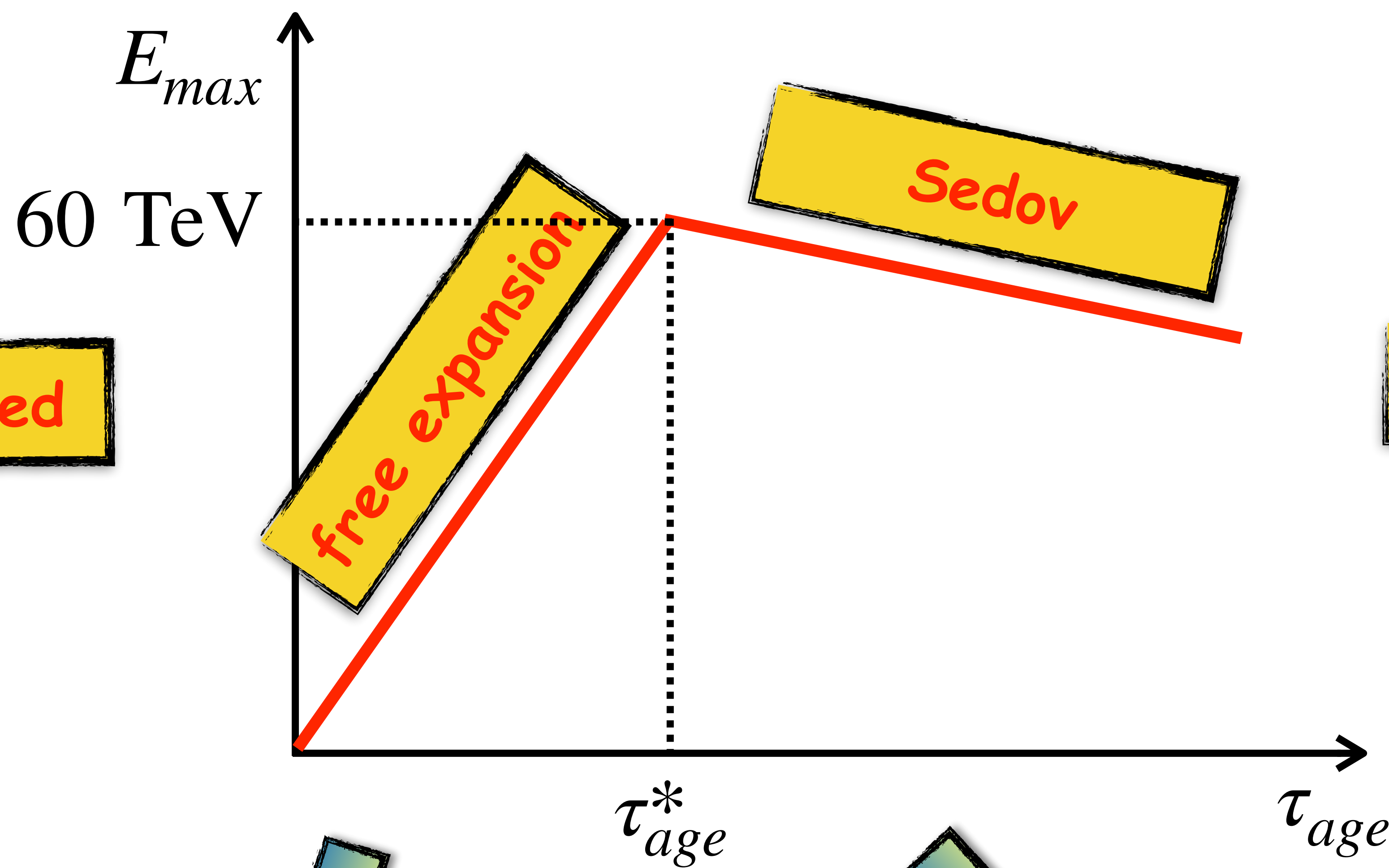

escape limited

E_{max} —> nothing escapes

E_{max} —> CRs @E_{max} escape

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

Way outs?

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

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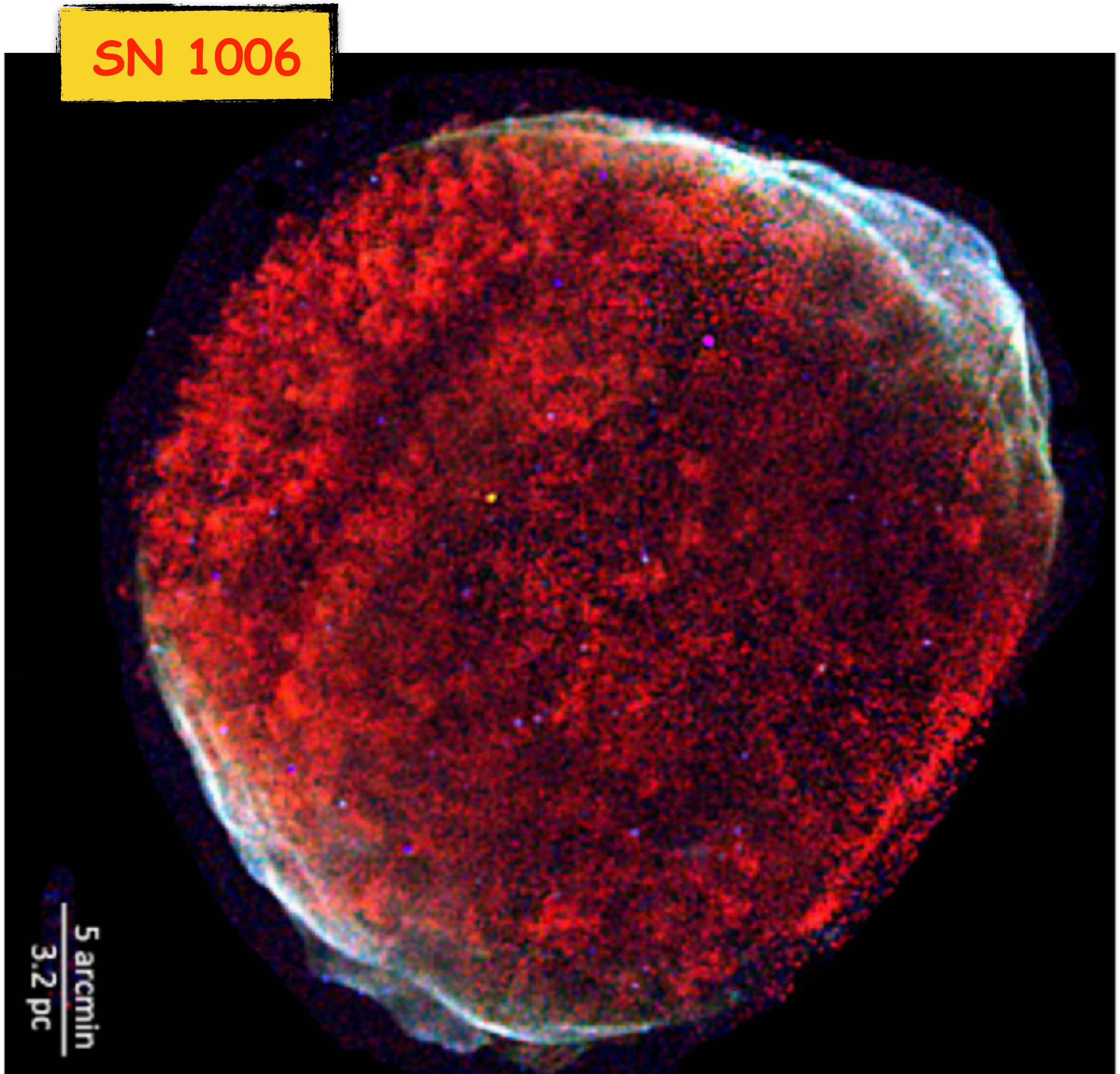
this is (was) not

these are very well measured/constrained

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



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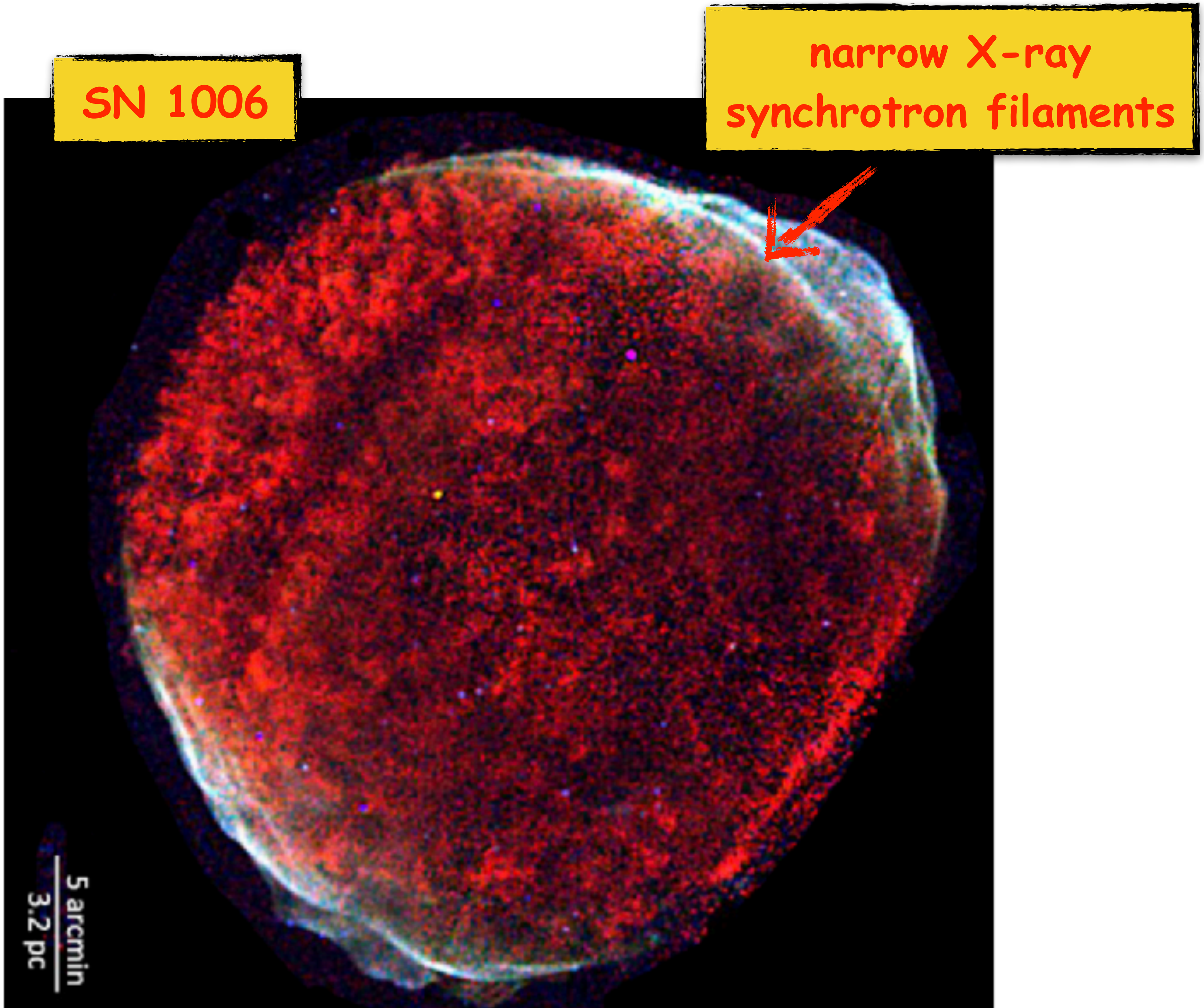

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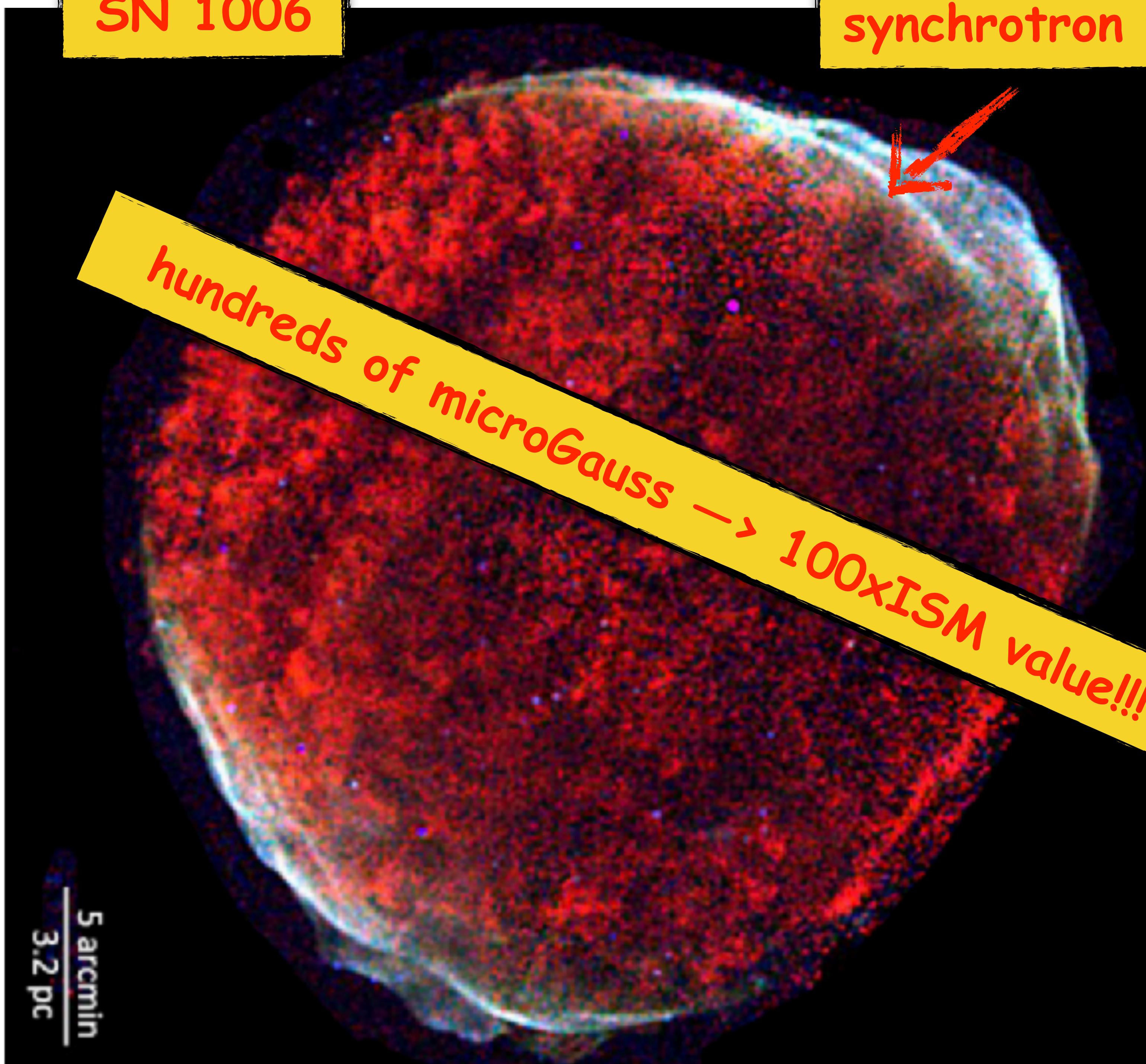
SN 1006

narrow X-ray synchrotron filaments

hundreds of microGauss —> 100xISM value!!!



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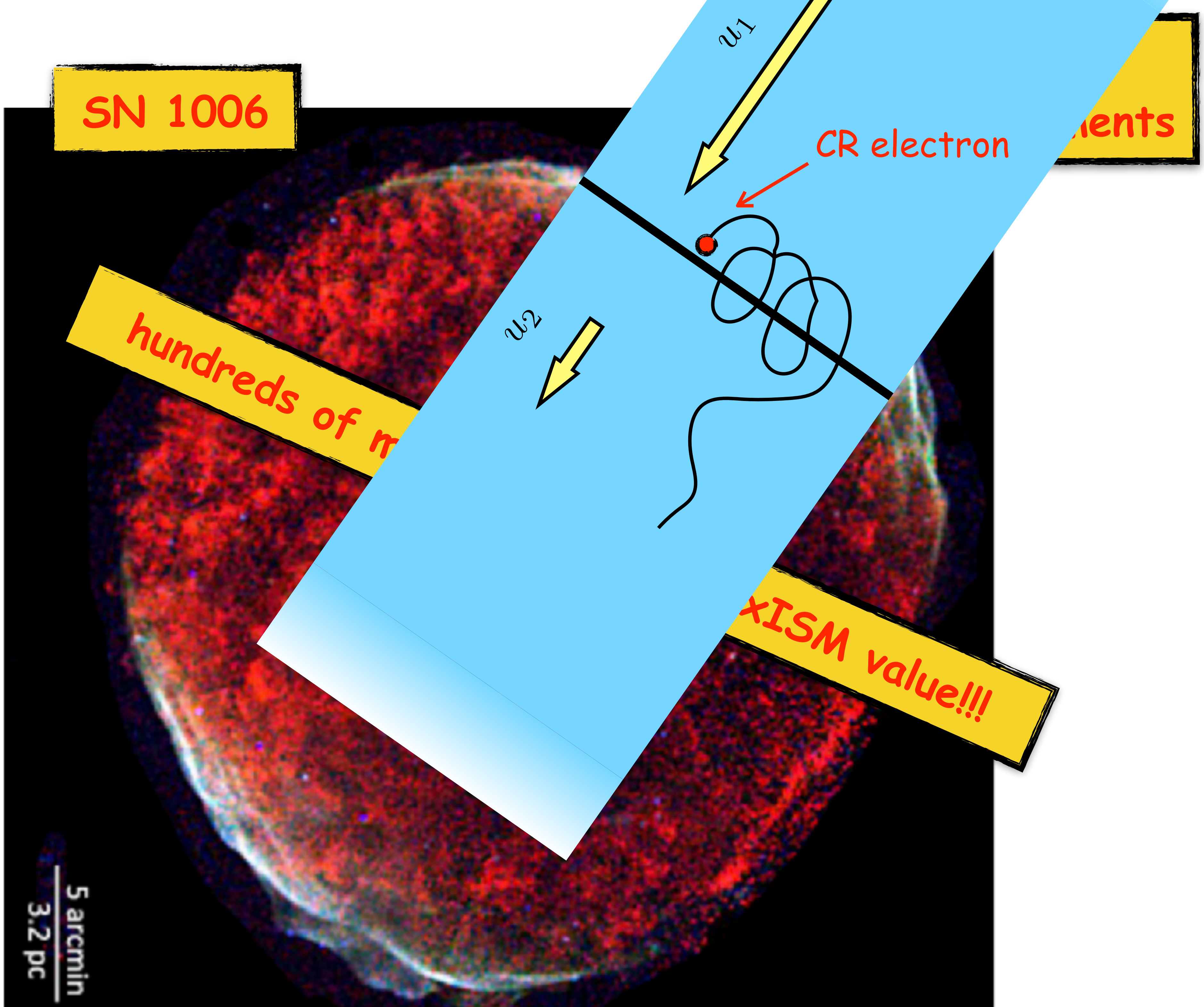

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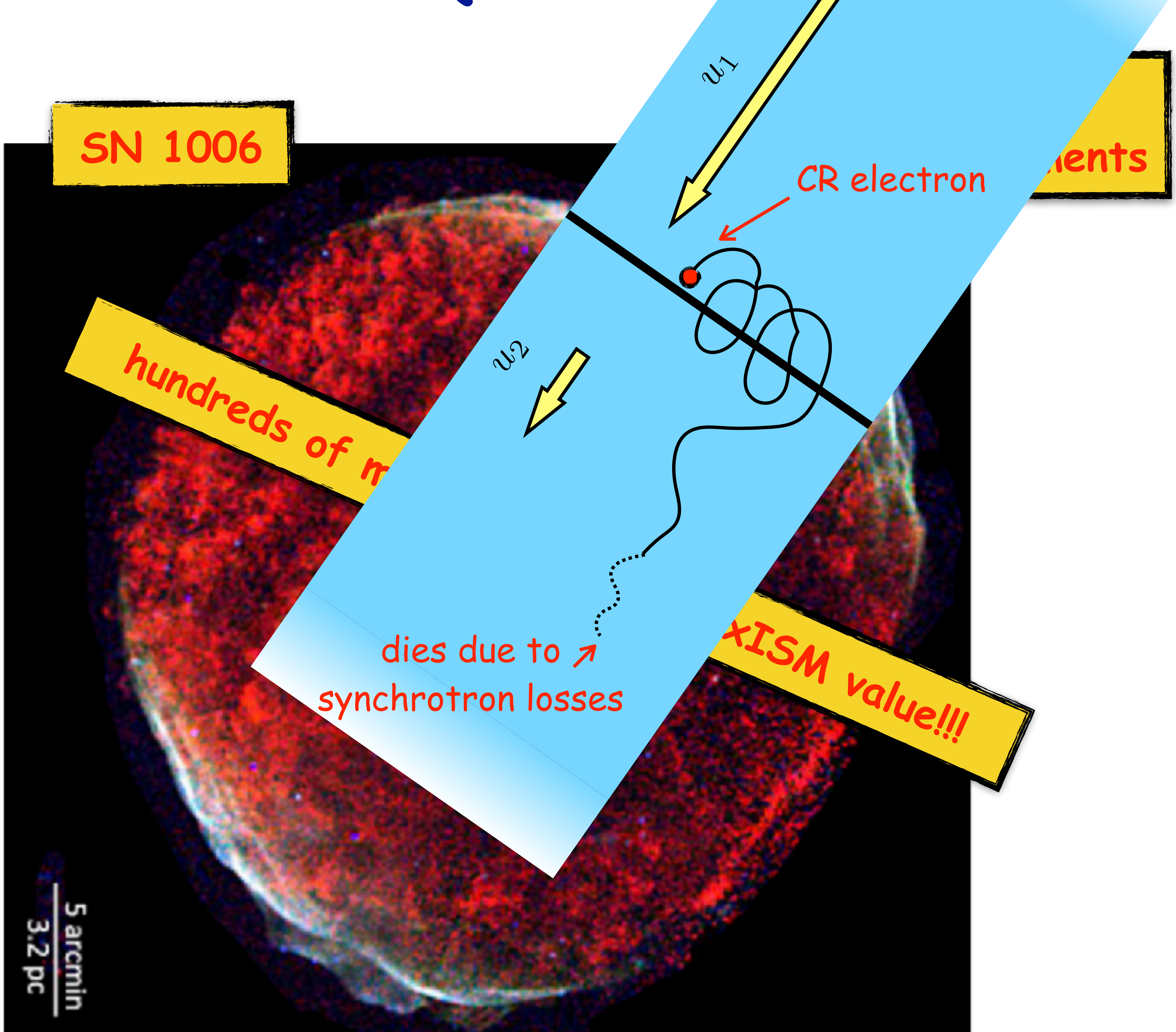

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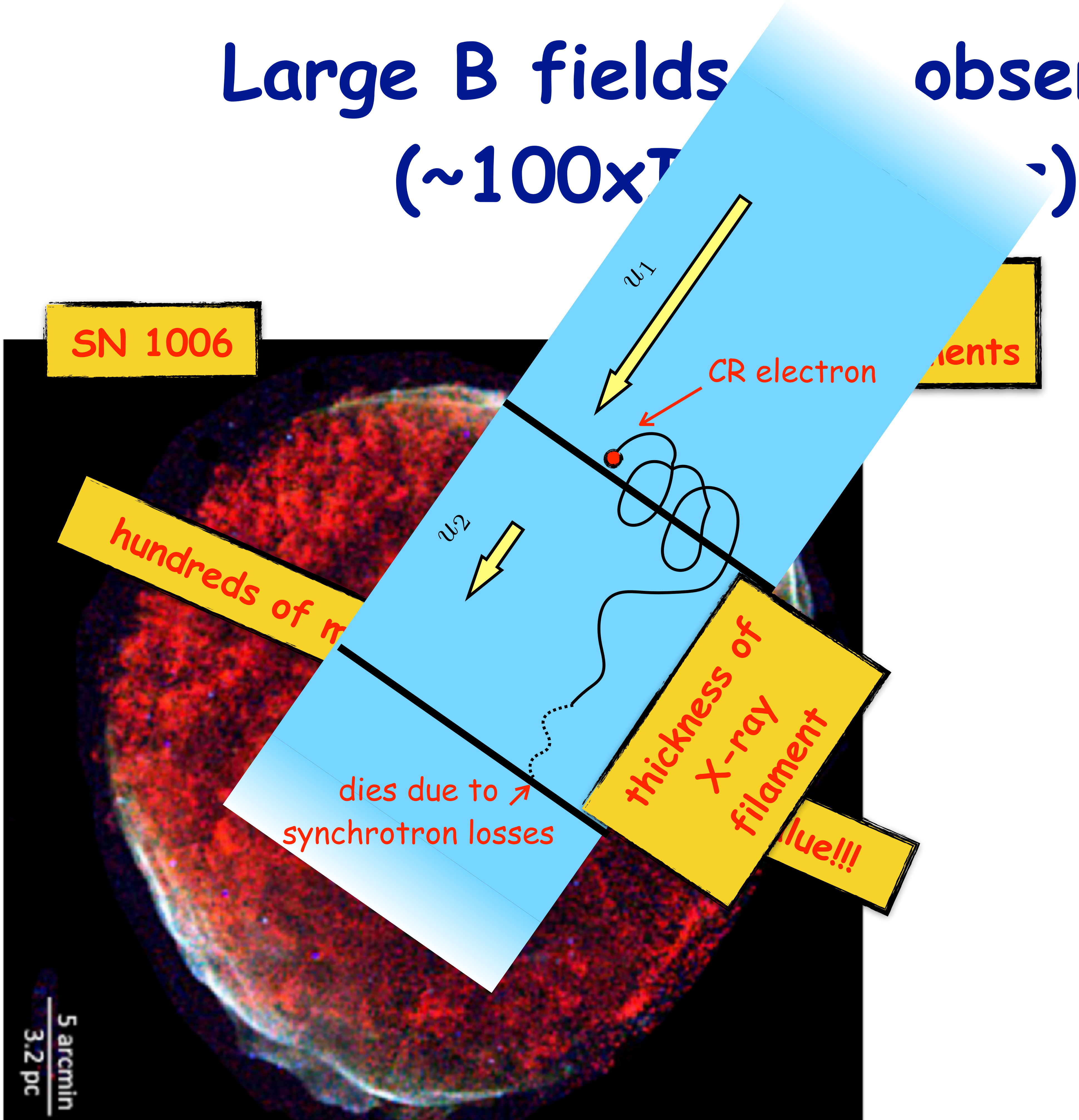

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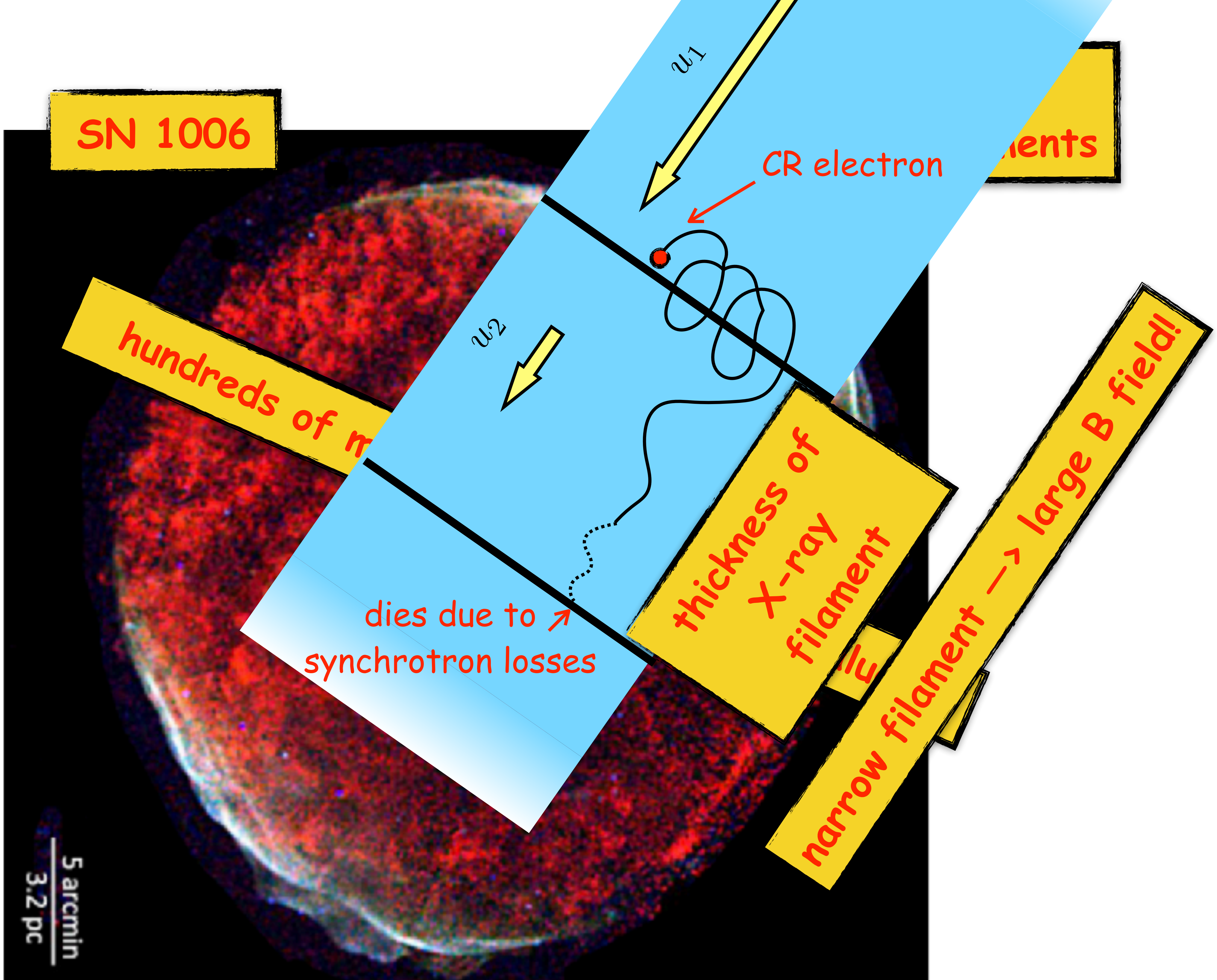

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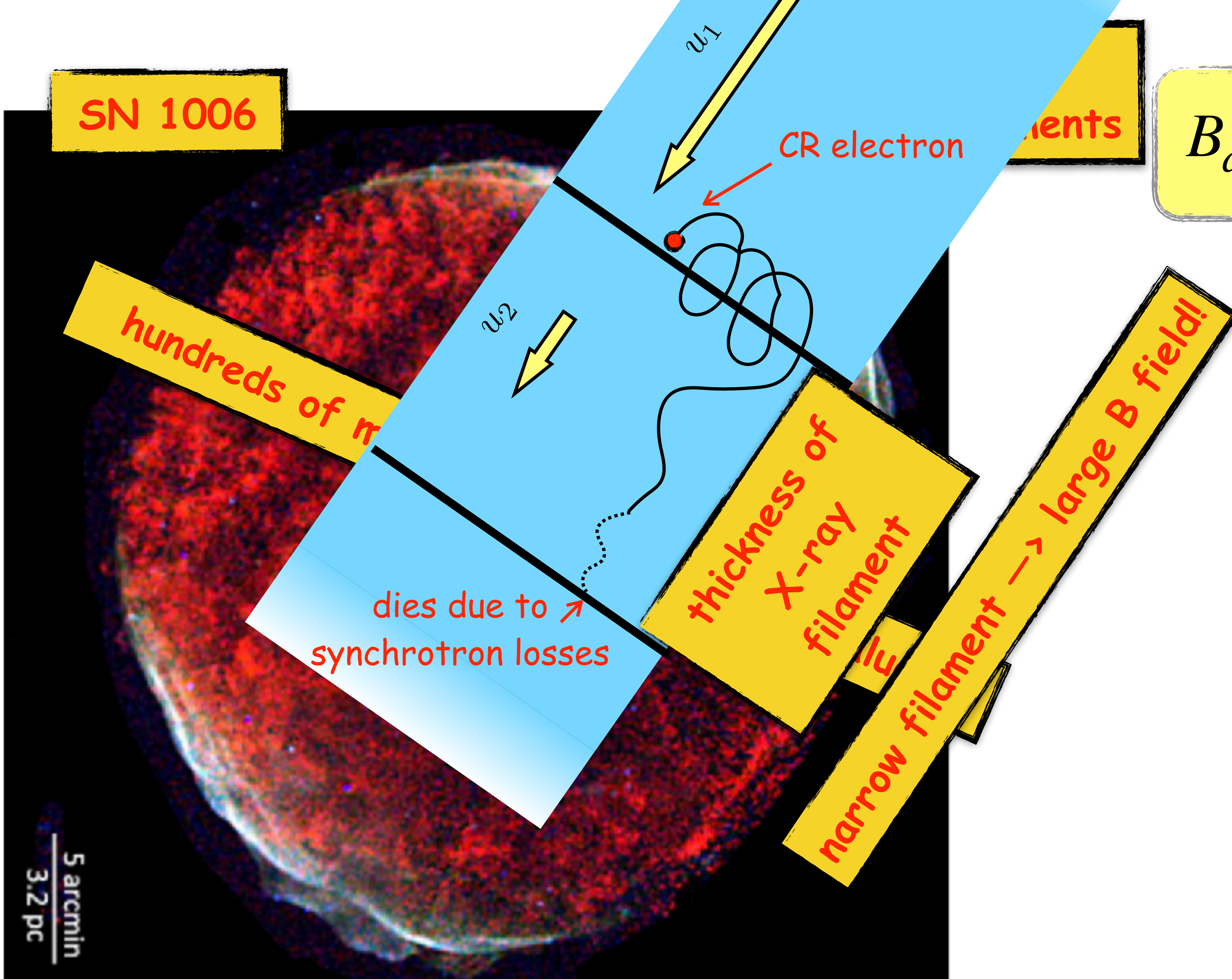

$$B_d \approx 100 \times B_{ISM}$$

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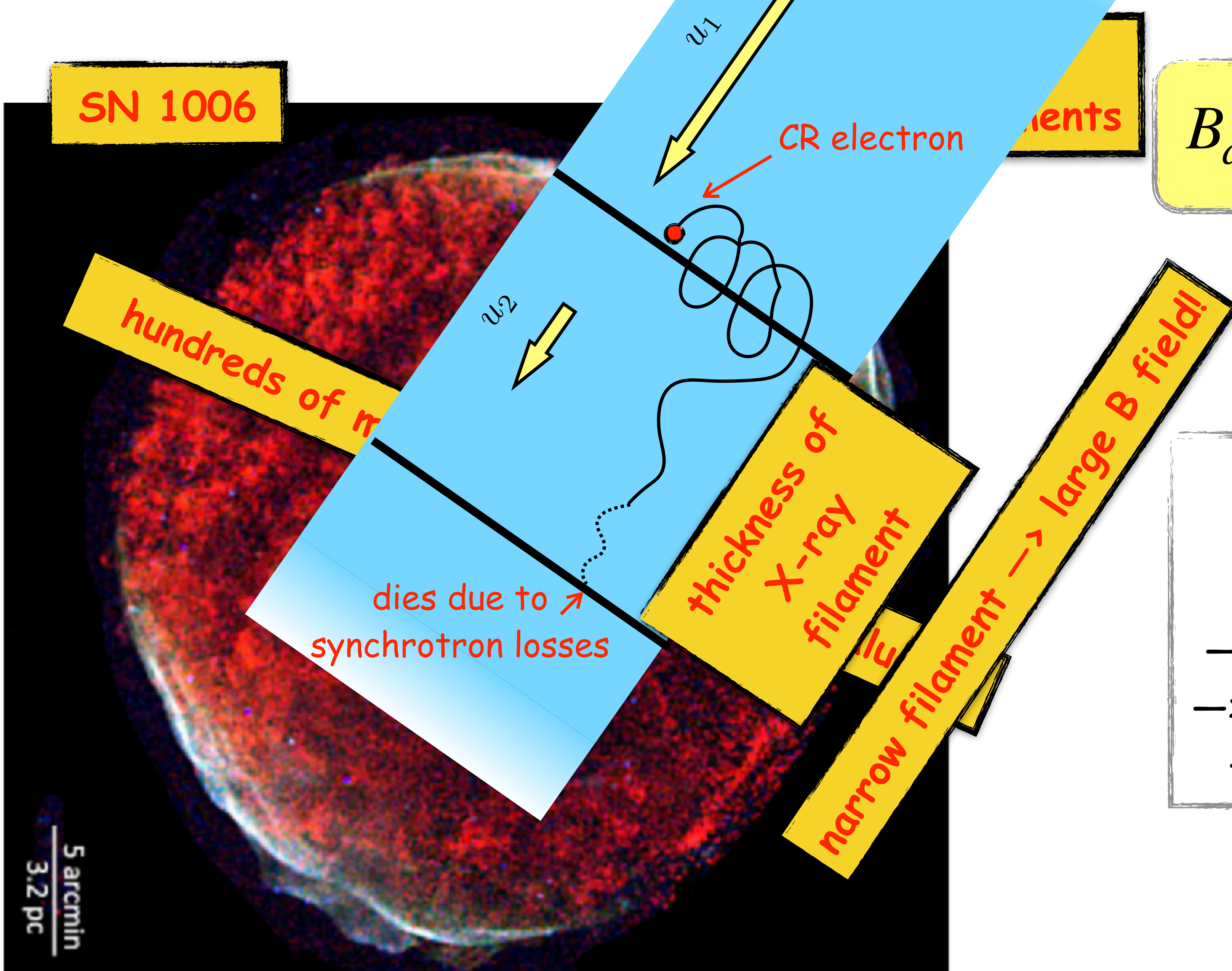

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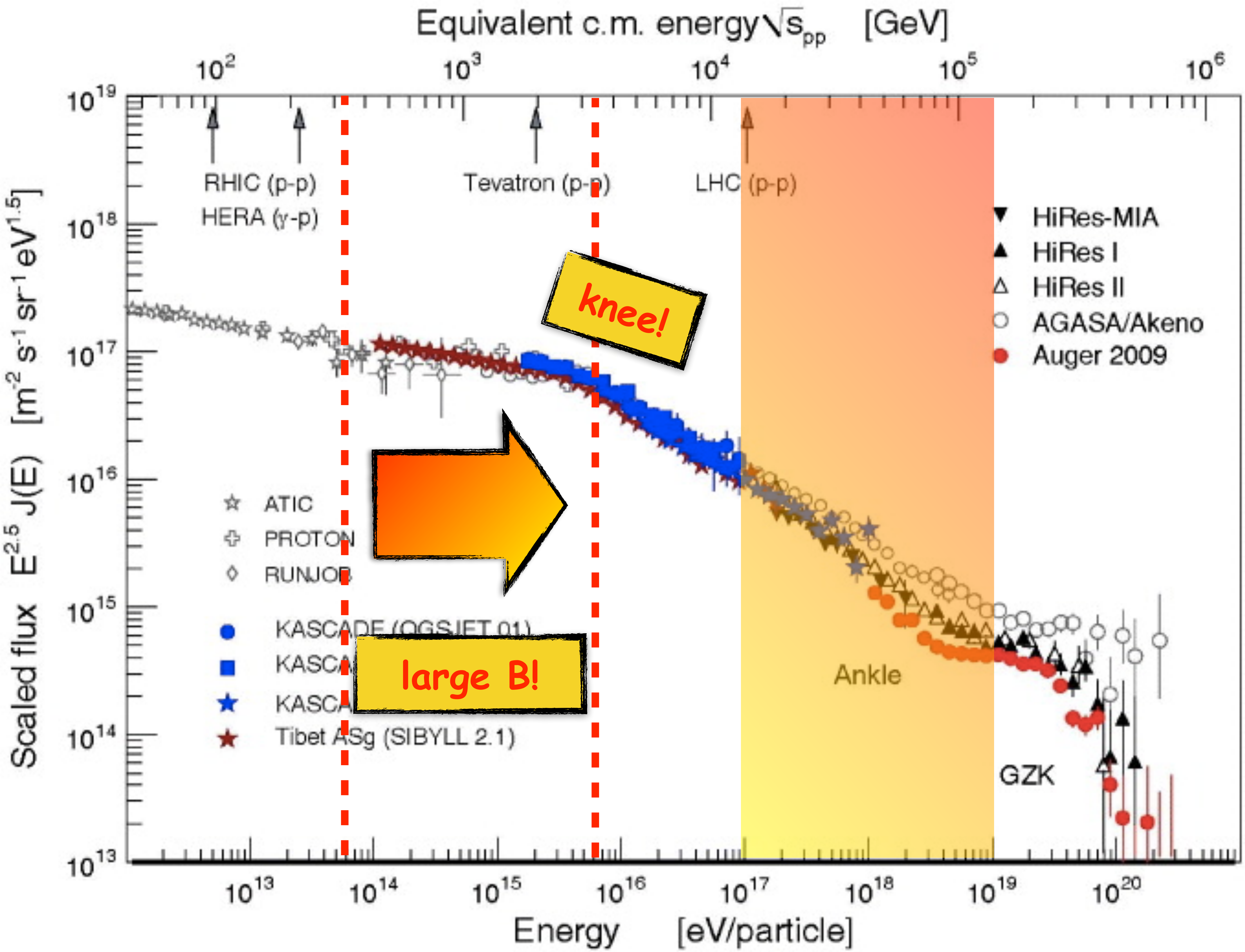
NON LINEAR!
CR acceleration
—> CR escape
—> electric current
—> plasma instability
—> B is amplified

Getting close...



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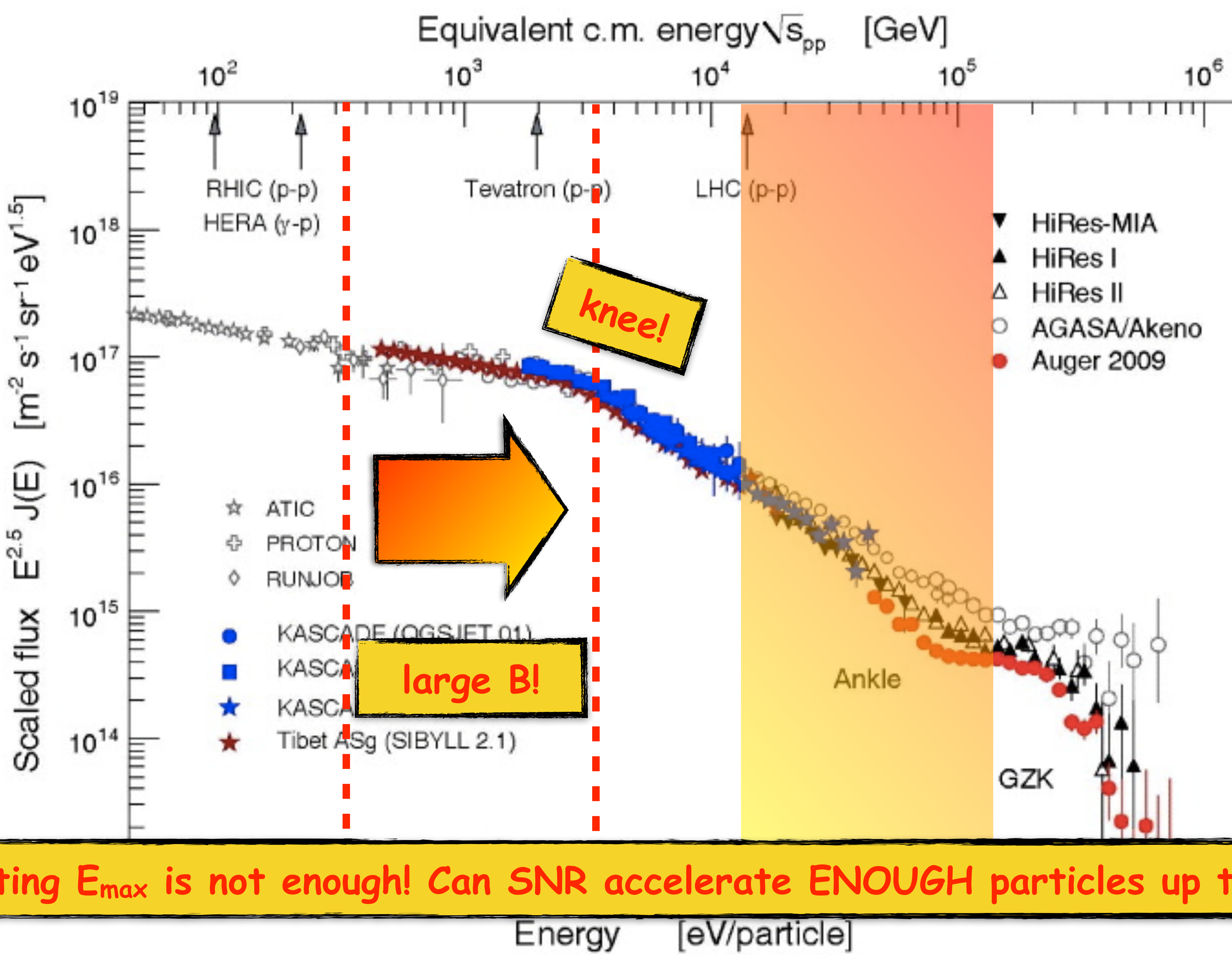
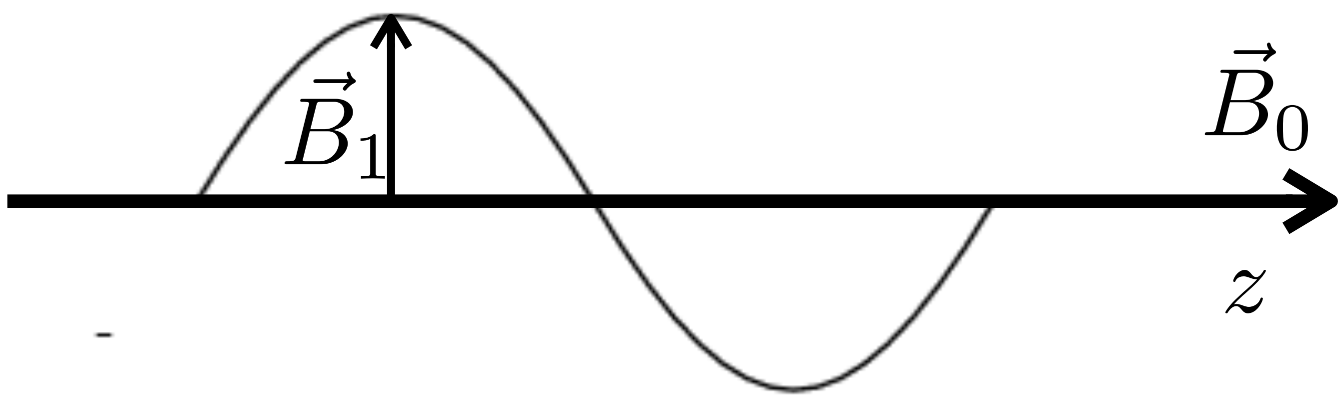


boosting E_{max} is not enough! Can SNR accelerate ENOUGH particles up there?

How is that? Non-resonant "Bell" instability

circularly polarised



wavelength << 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

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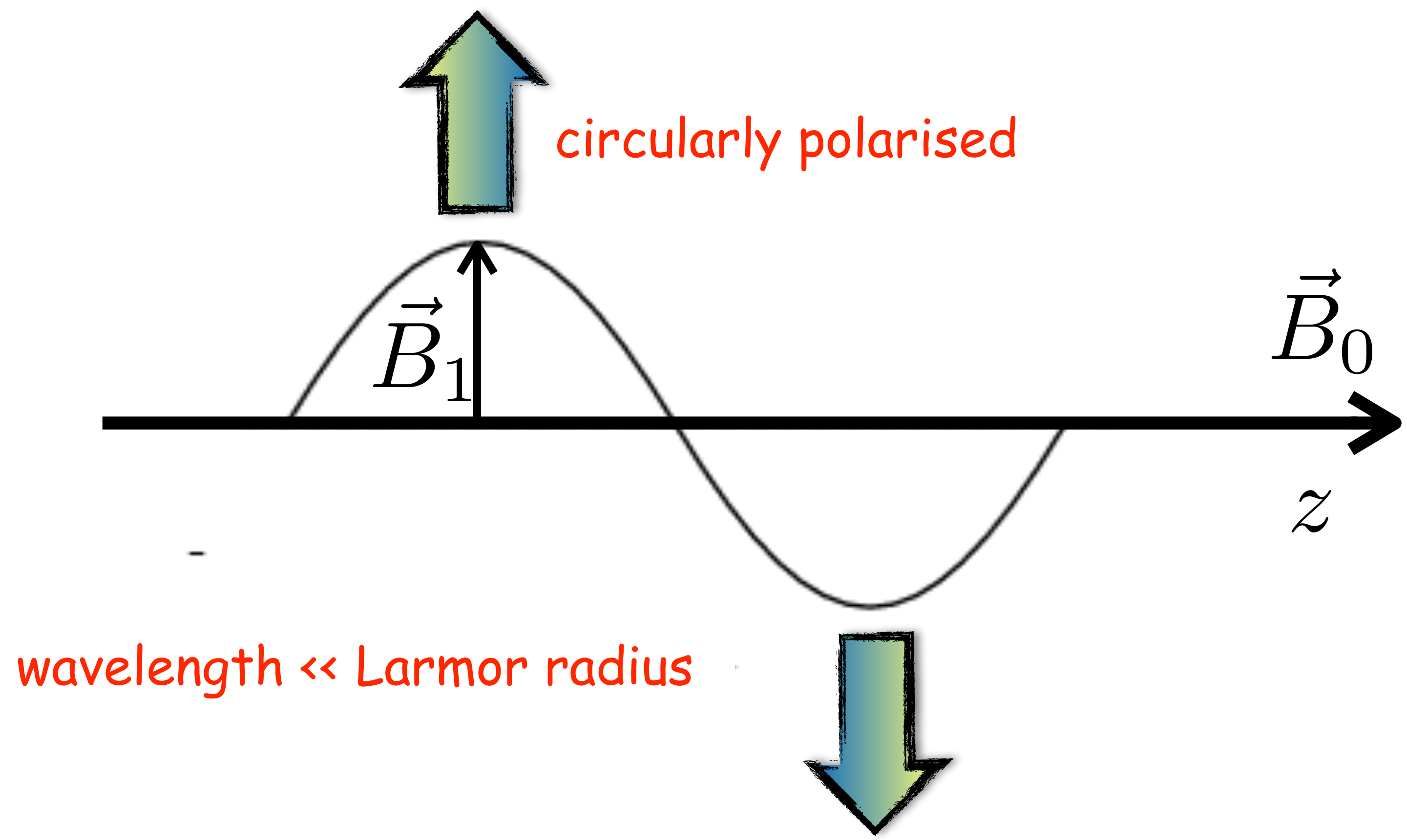

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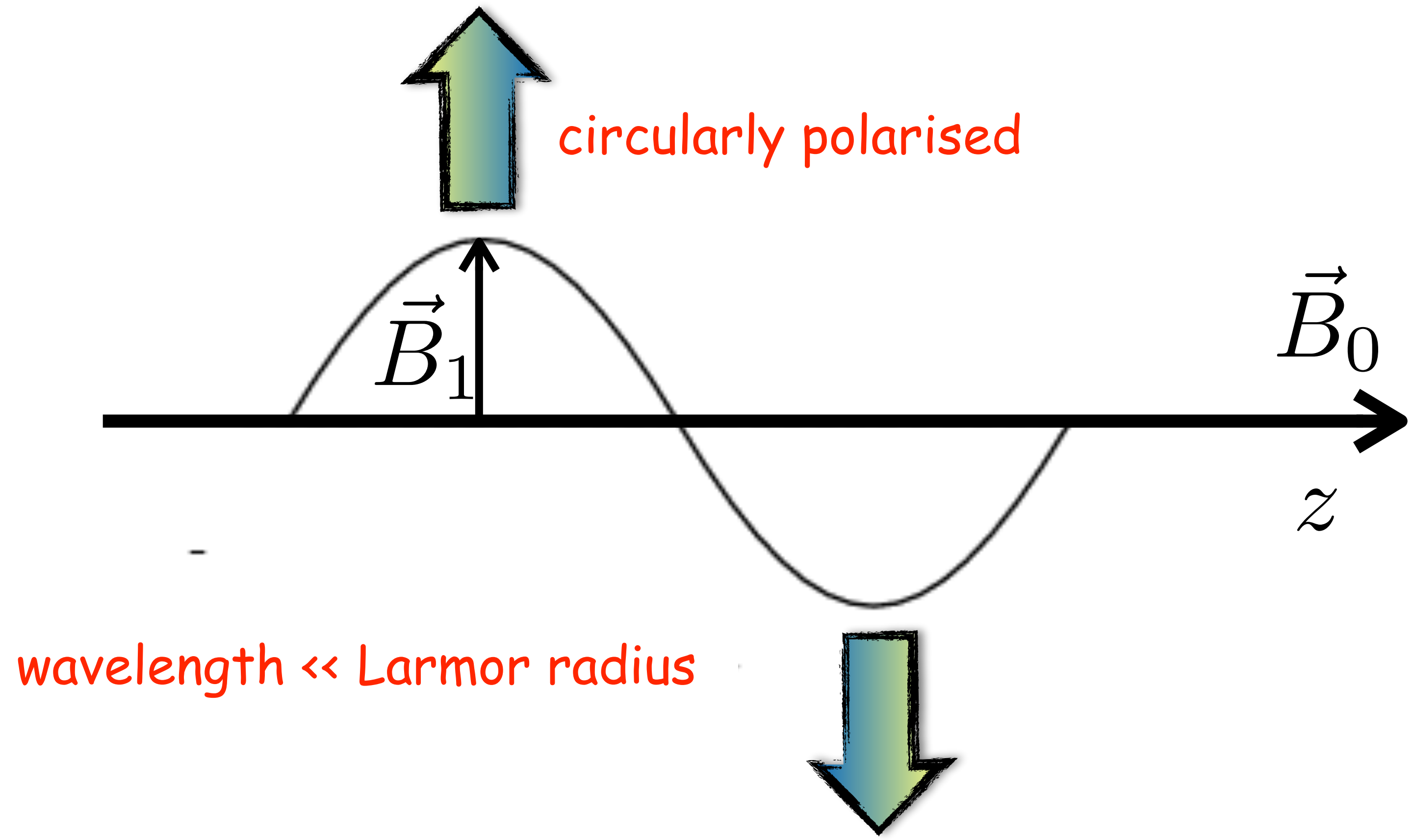

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$-\vec{j} \times \vec{B}_1$ **force acting on the plasma —> expands the helical perturbation of B**

(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

few CRs escape

current is small

inefficient amplification

less confinement

more CRs escape

current is large

efficient amplification

more confinement

Bell 2004

Bell et al. 2013

Iterative methods…

assumption: pareticles with E < Emax are diffusively confined within the shock,
while particles with E > Emax can freely escape

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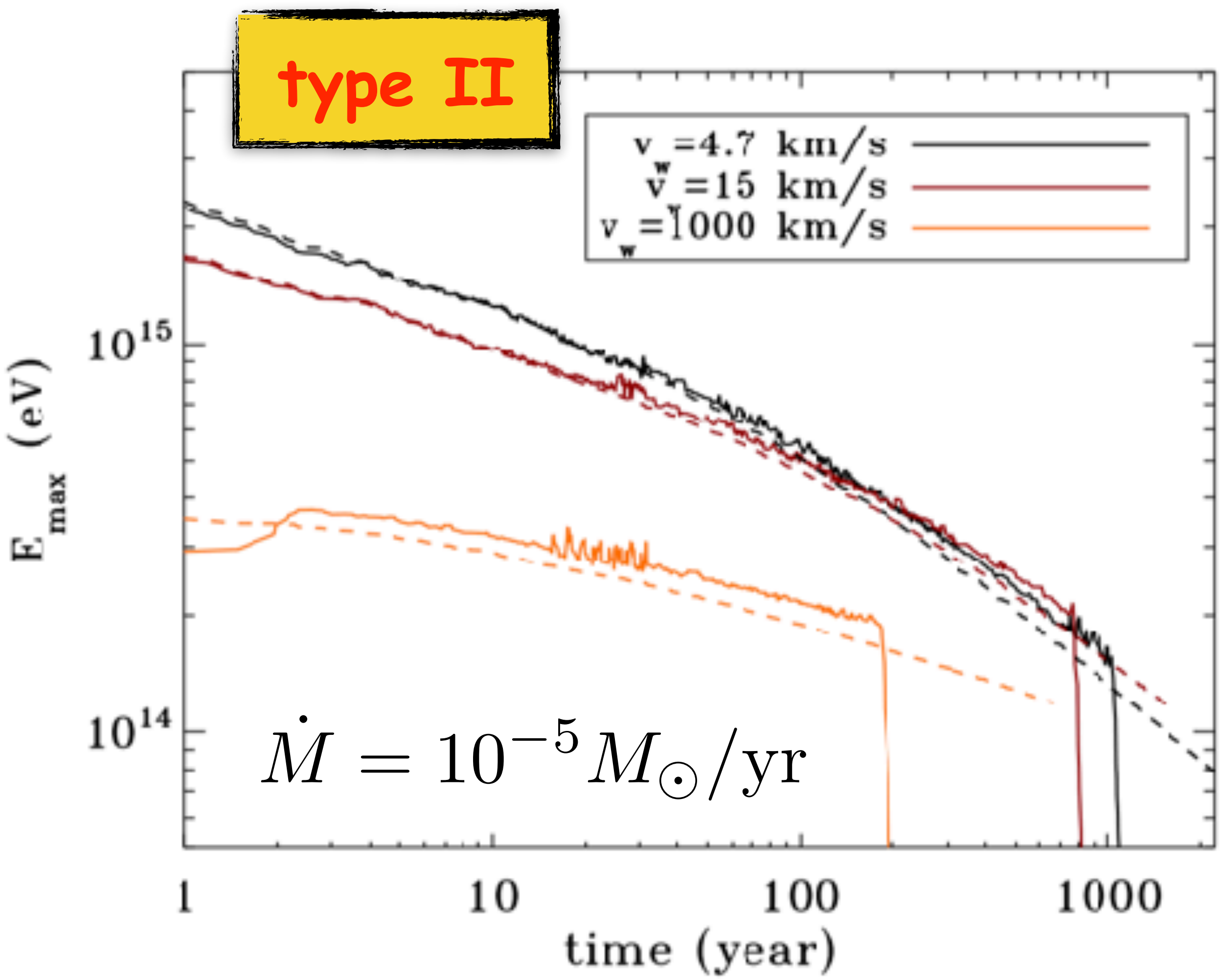
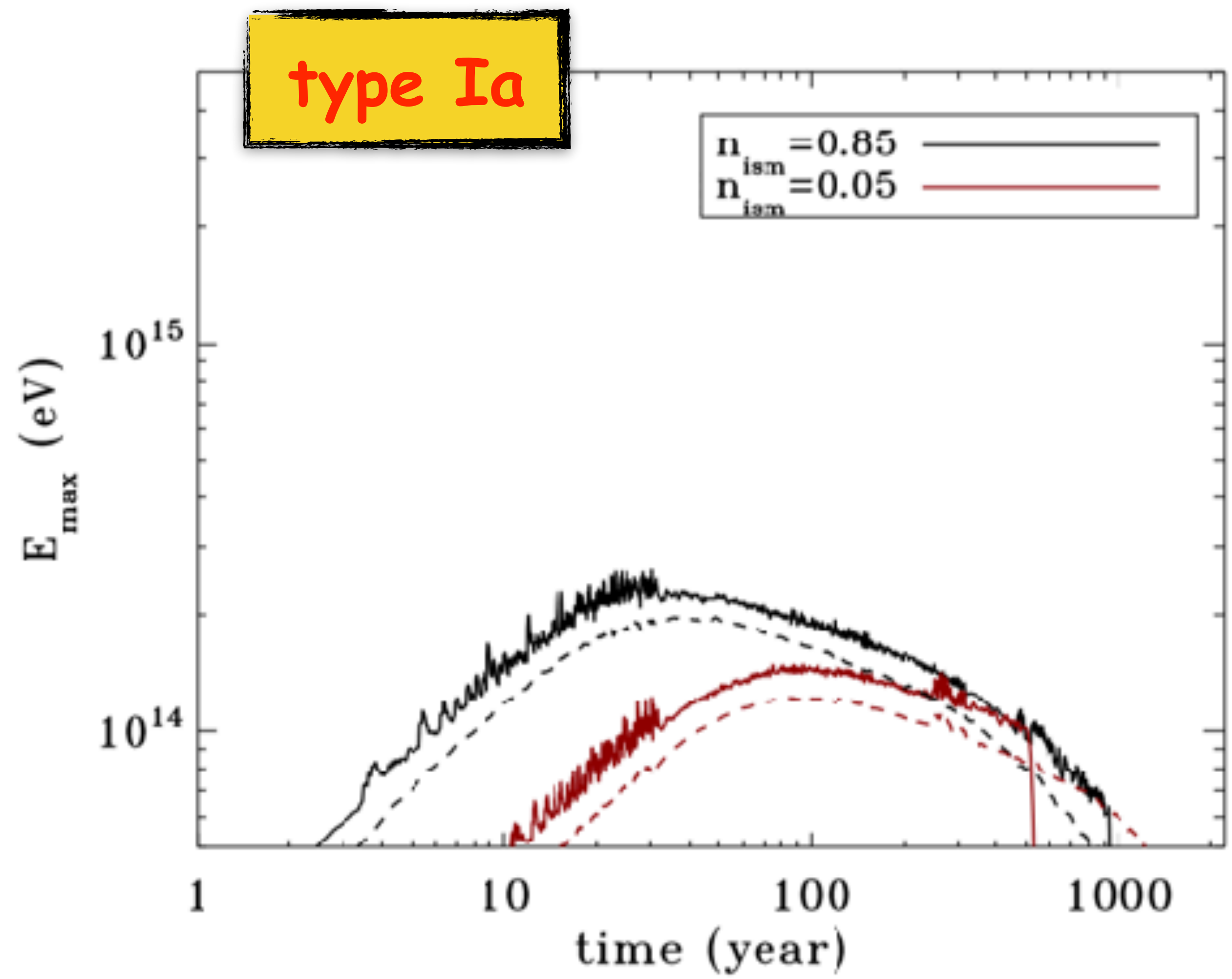
note that in the case B depends on time —> different scalings for $E_{max}(t)$

Only very young SNRs accelerate to PeV

Schure & Bell 2013





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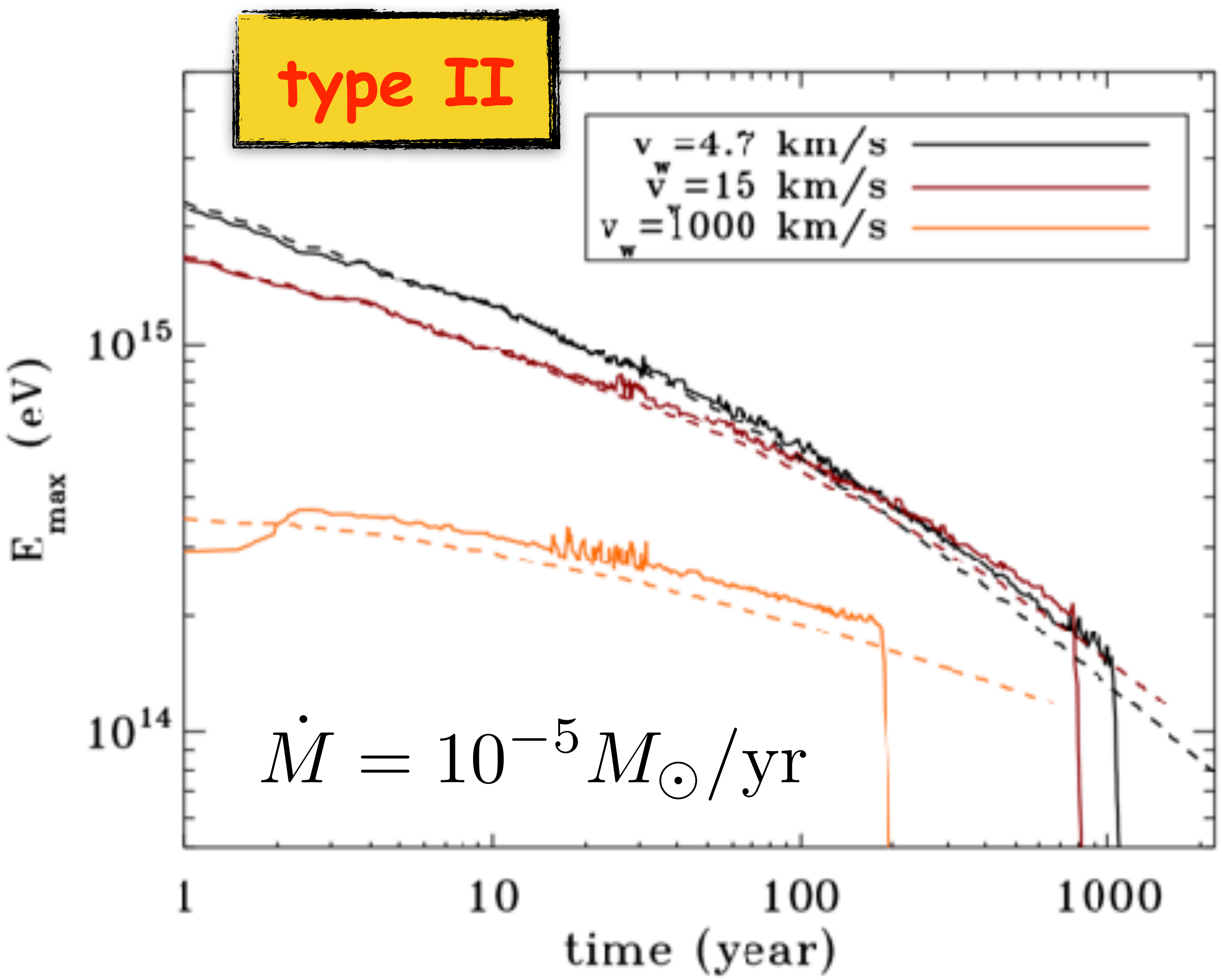

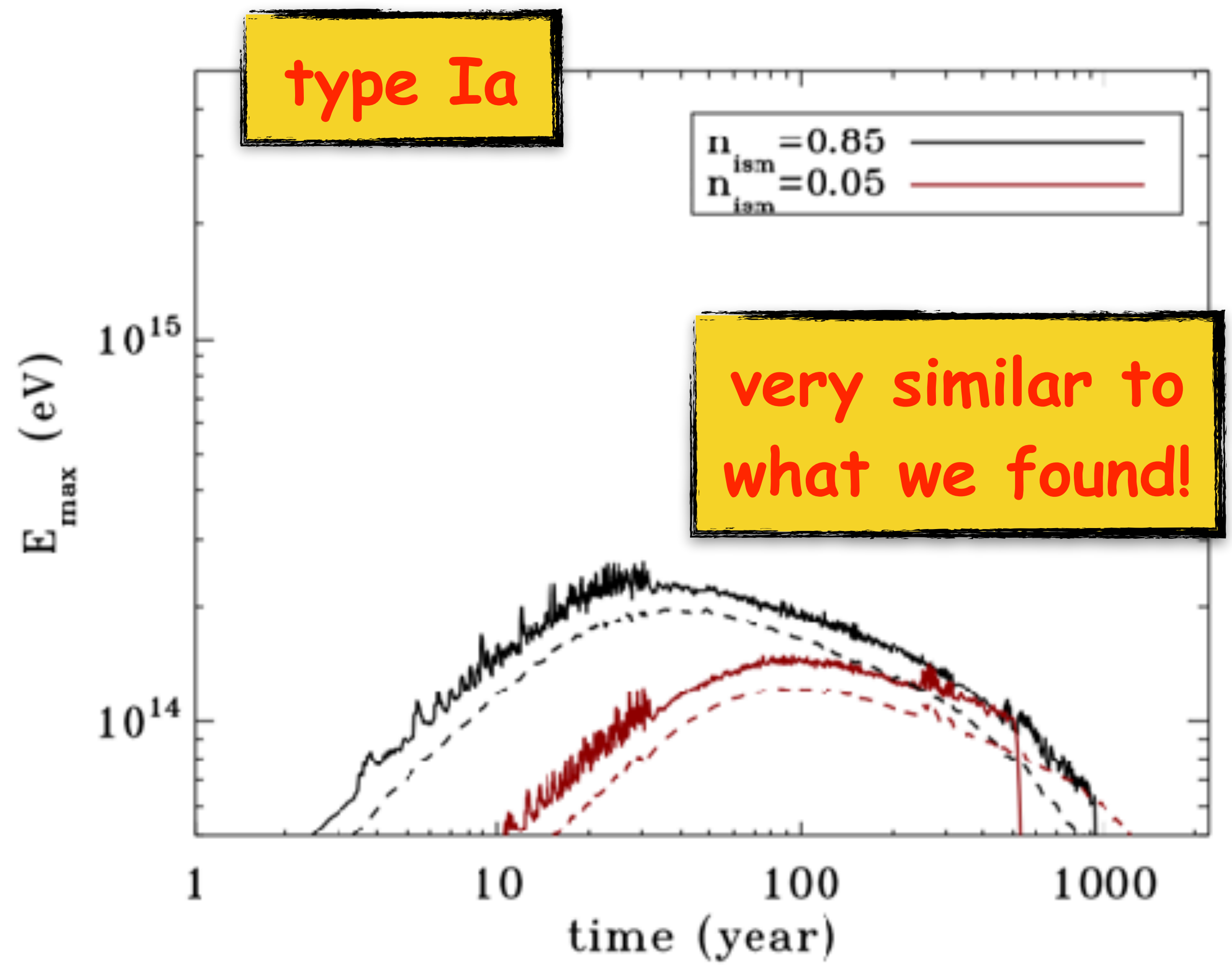

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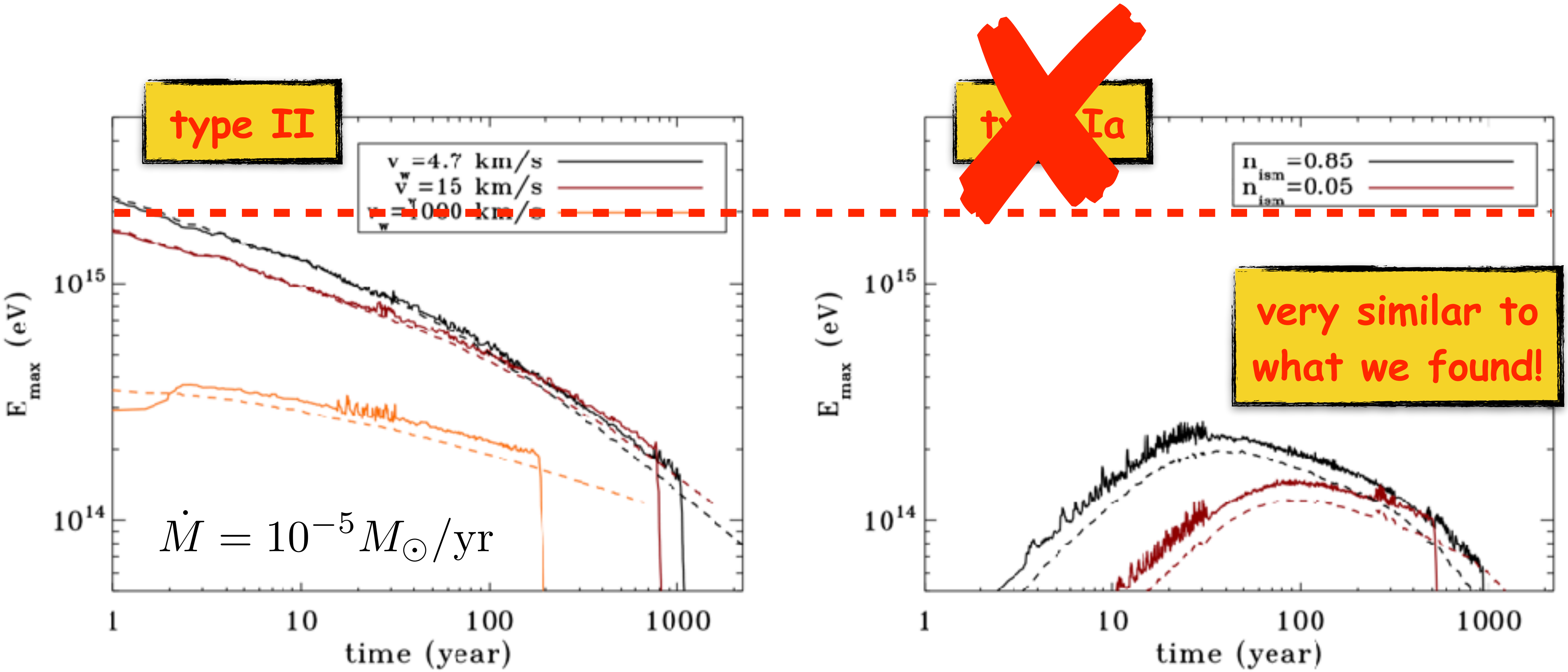

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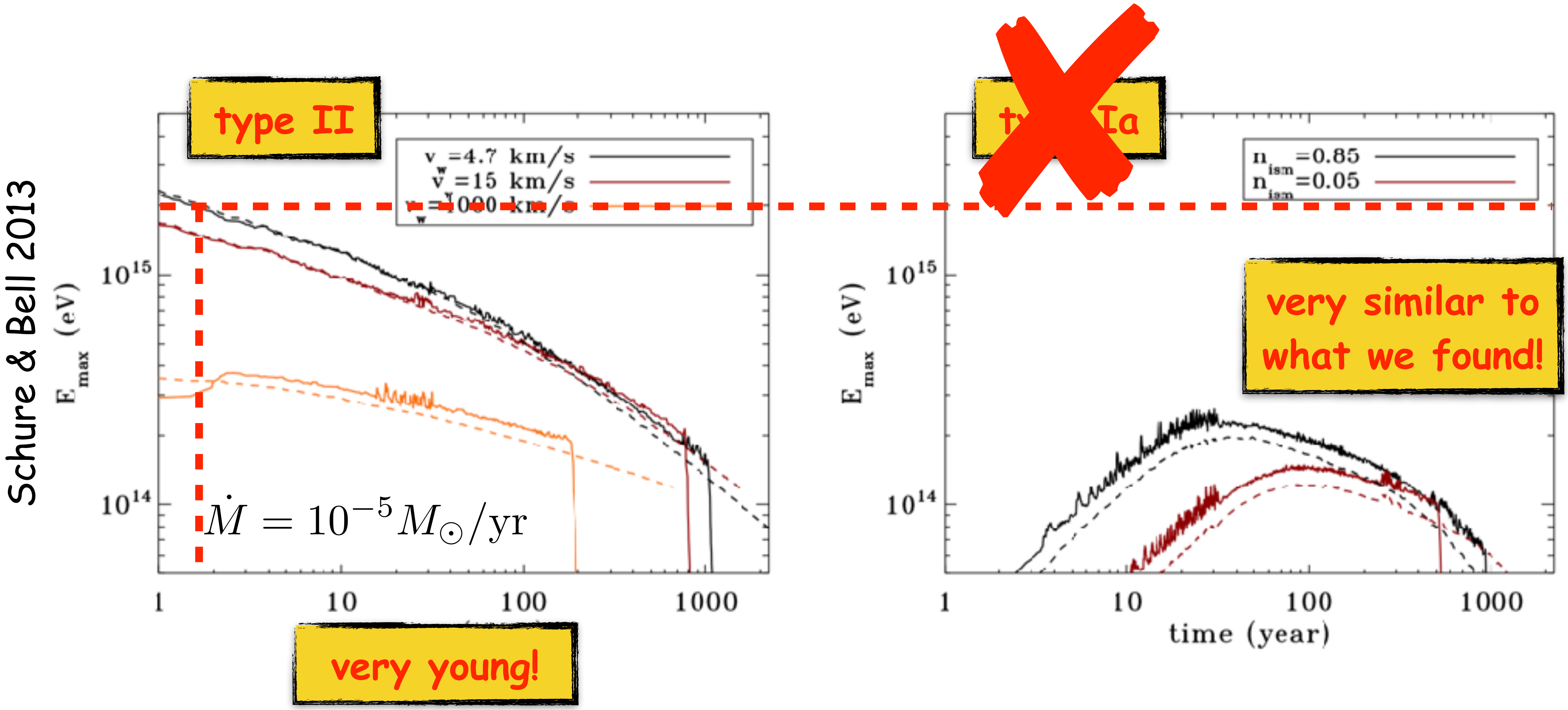

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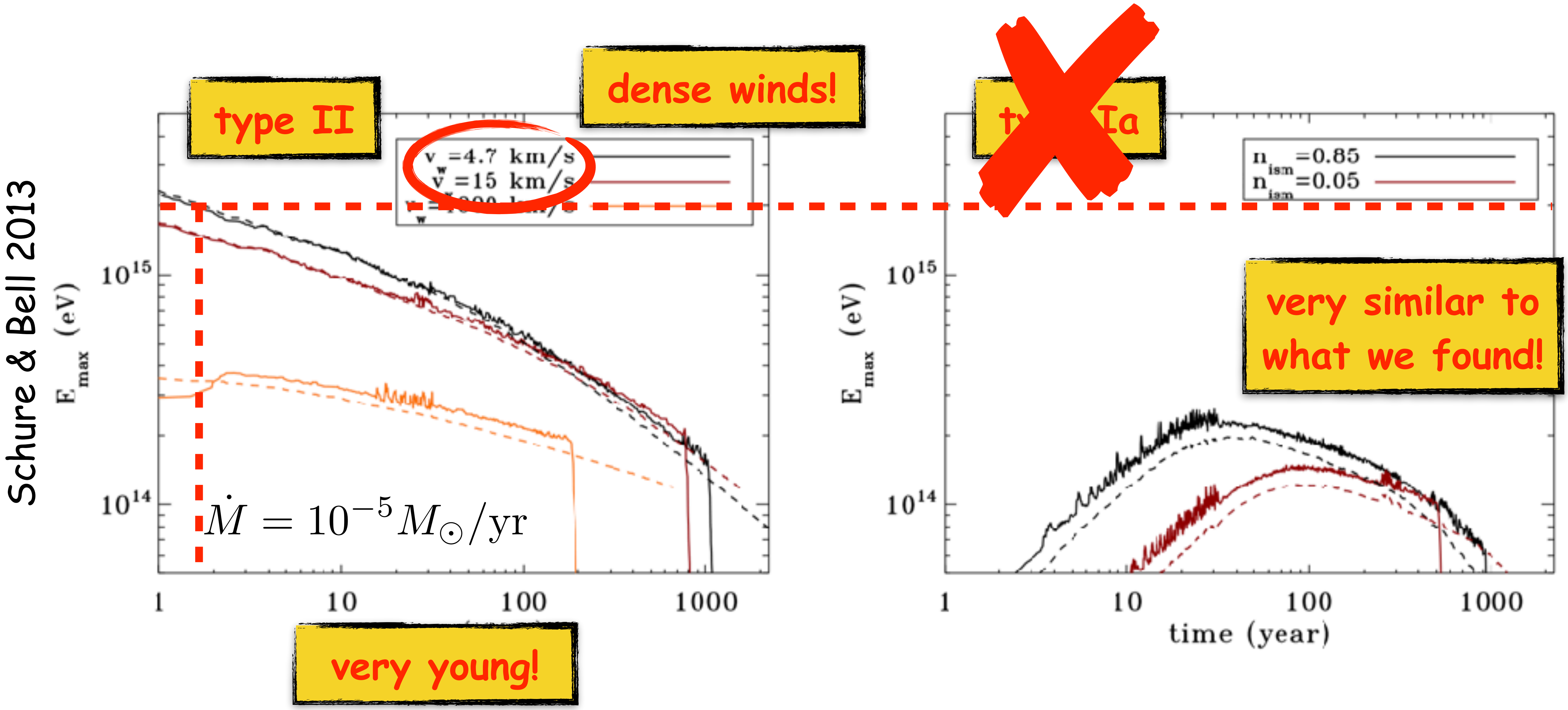

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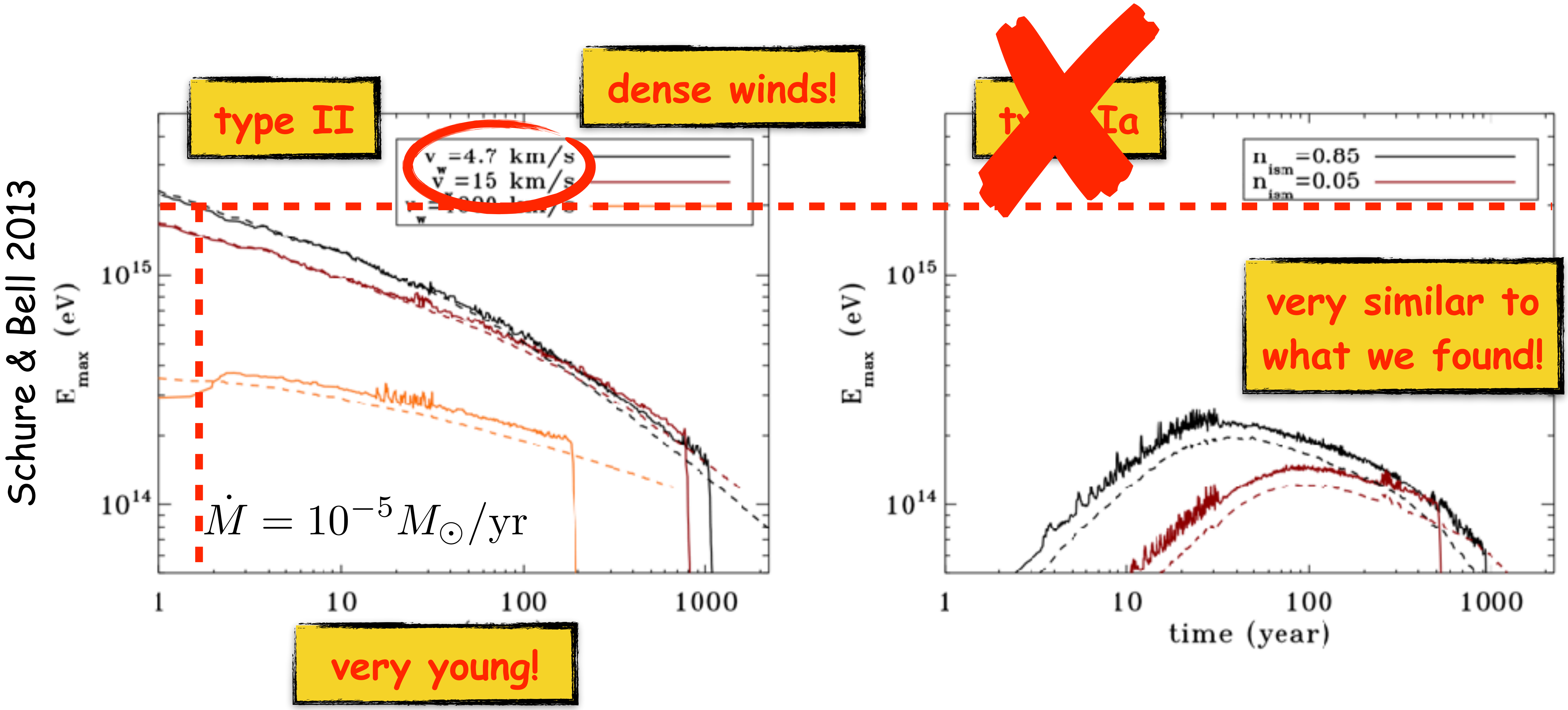


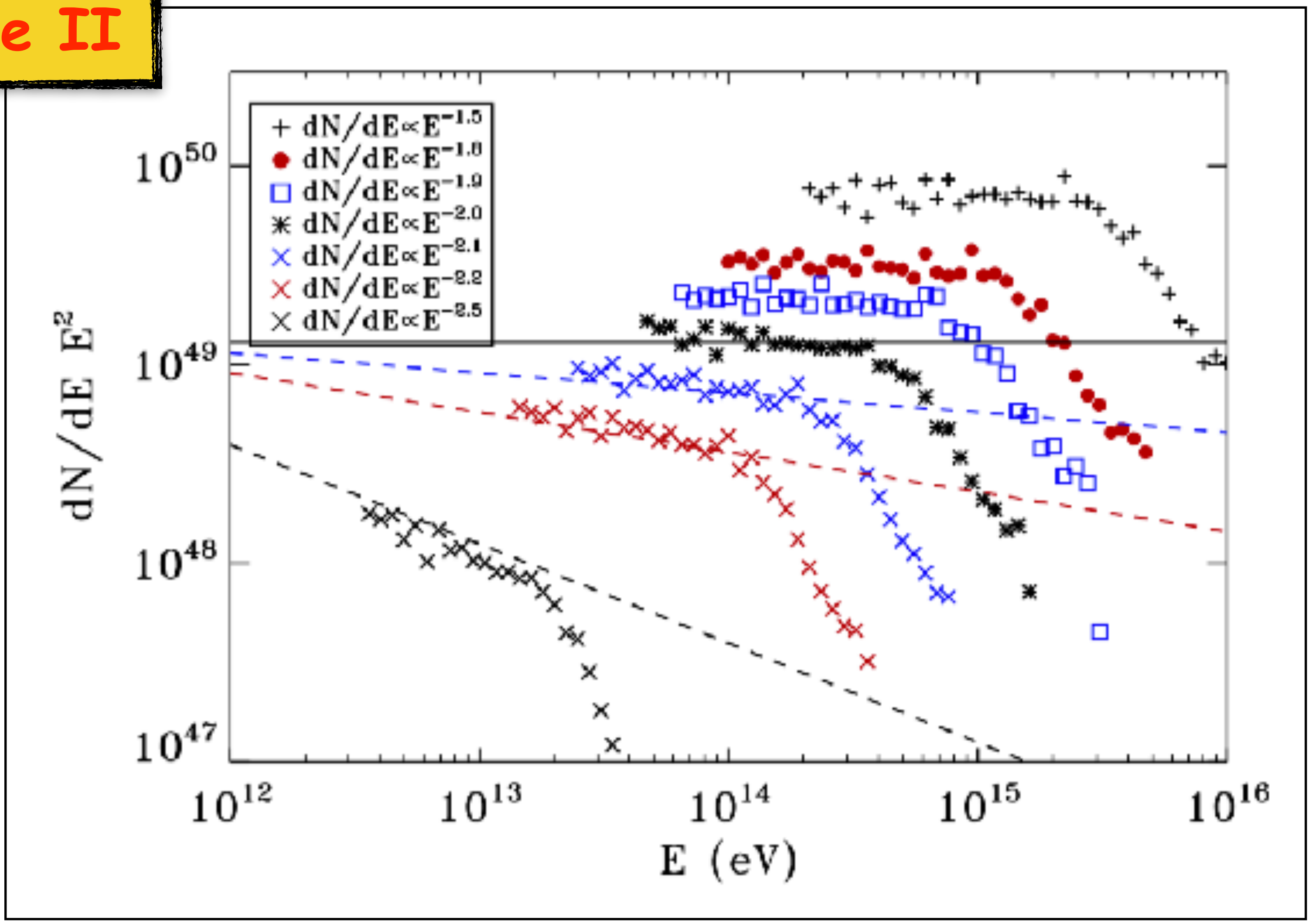
3 consequences:

- 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



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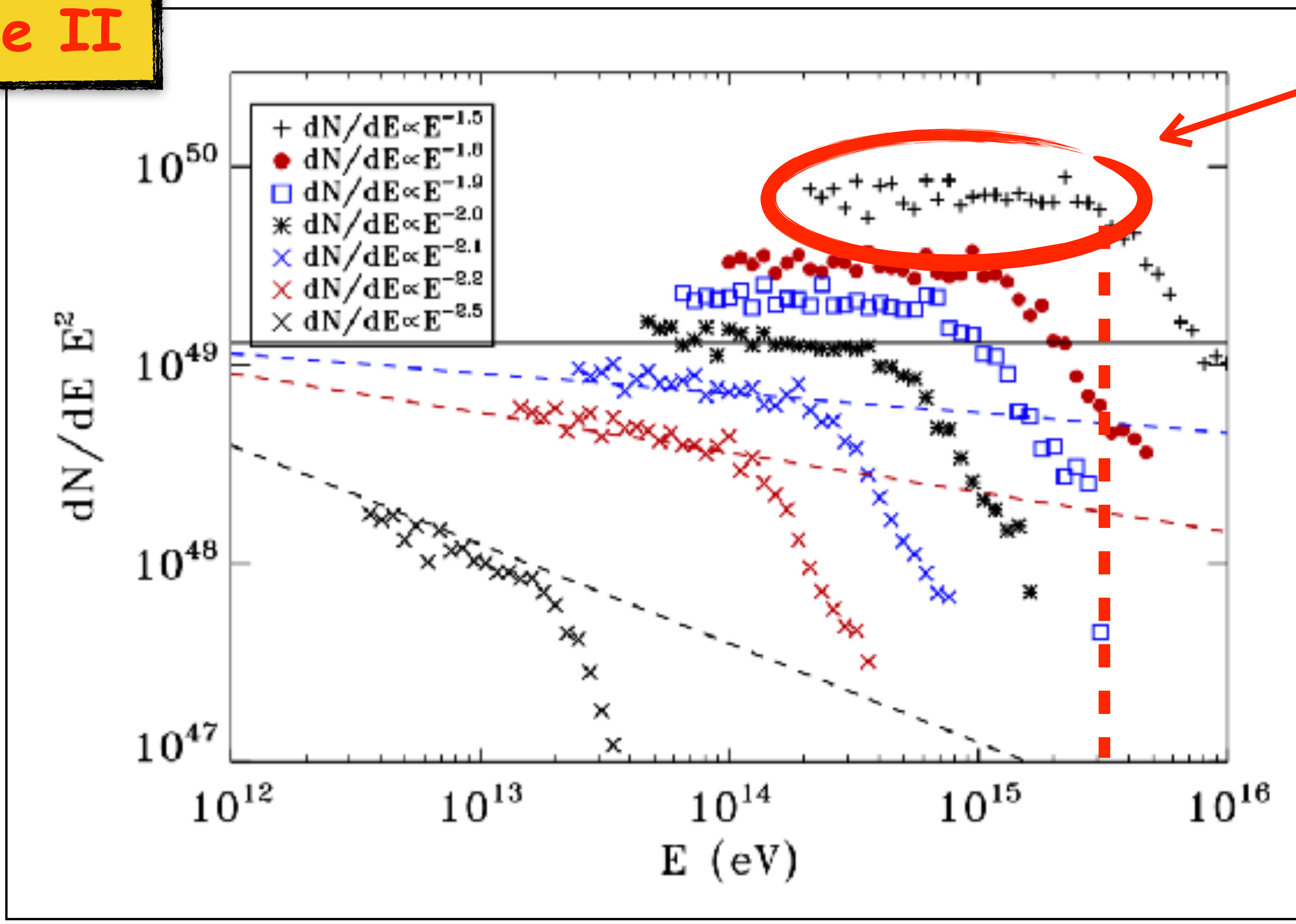

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knee at the right place

—> injection too hard

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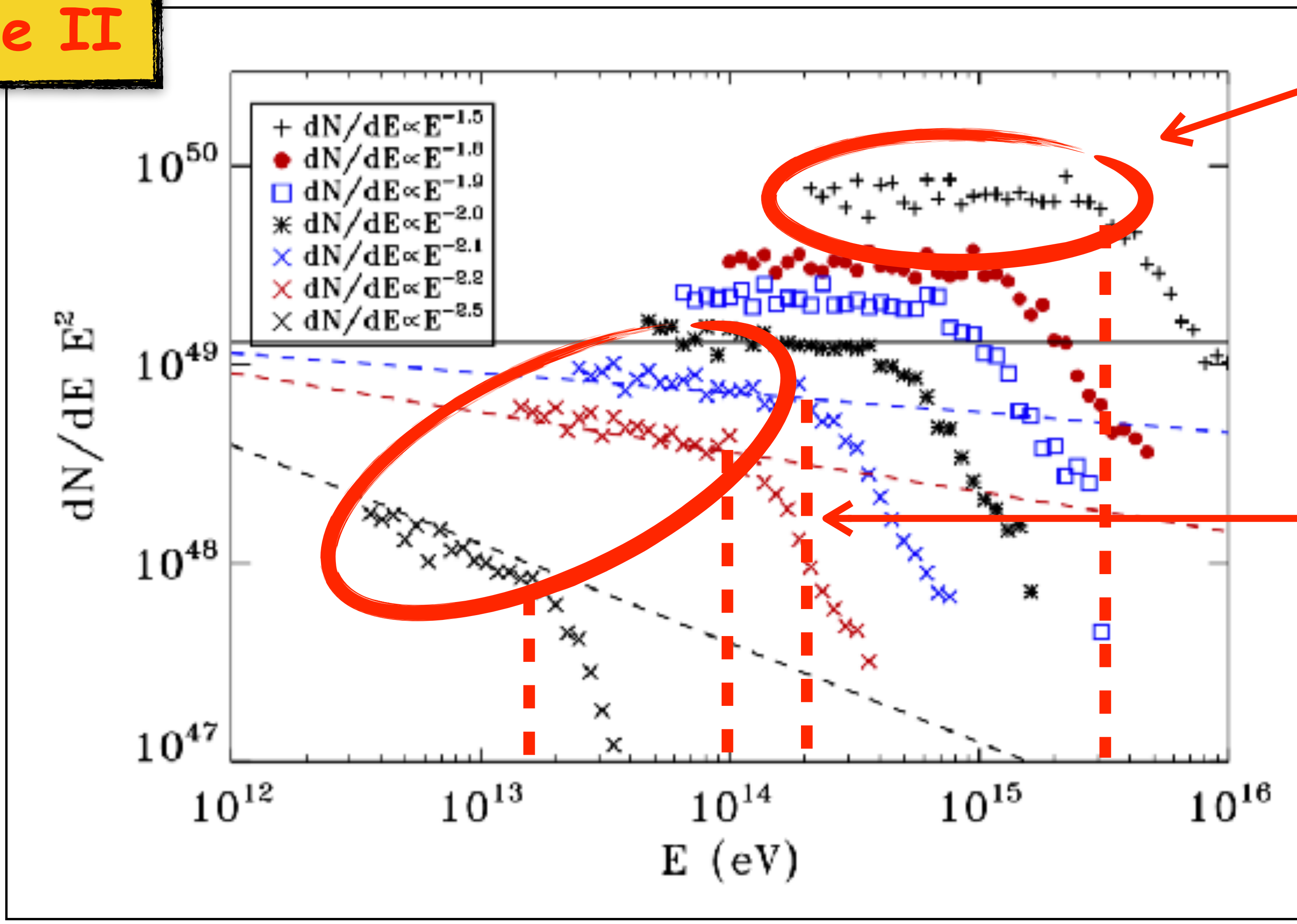

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steeper than 2

—> not enough to reach

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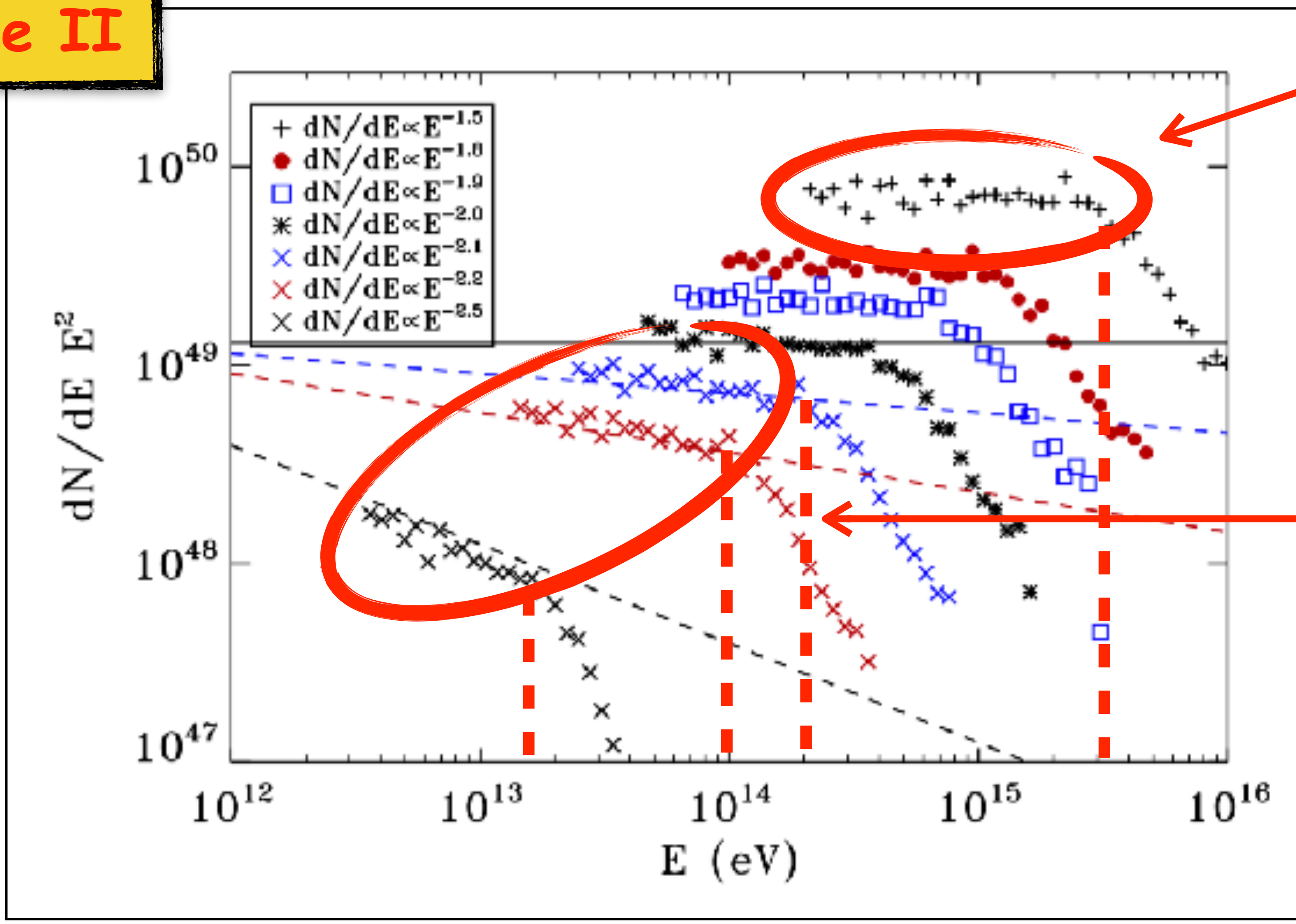

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can we tune it?

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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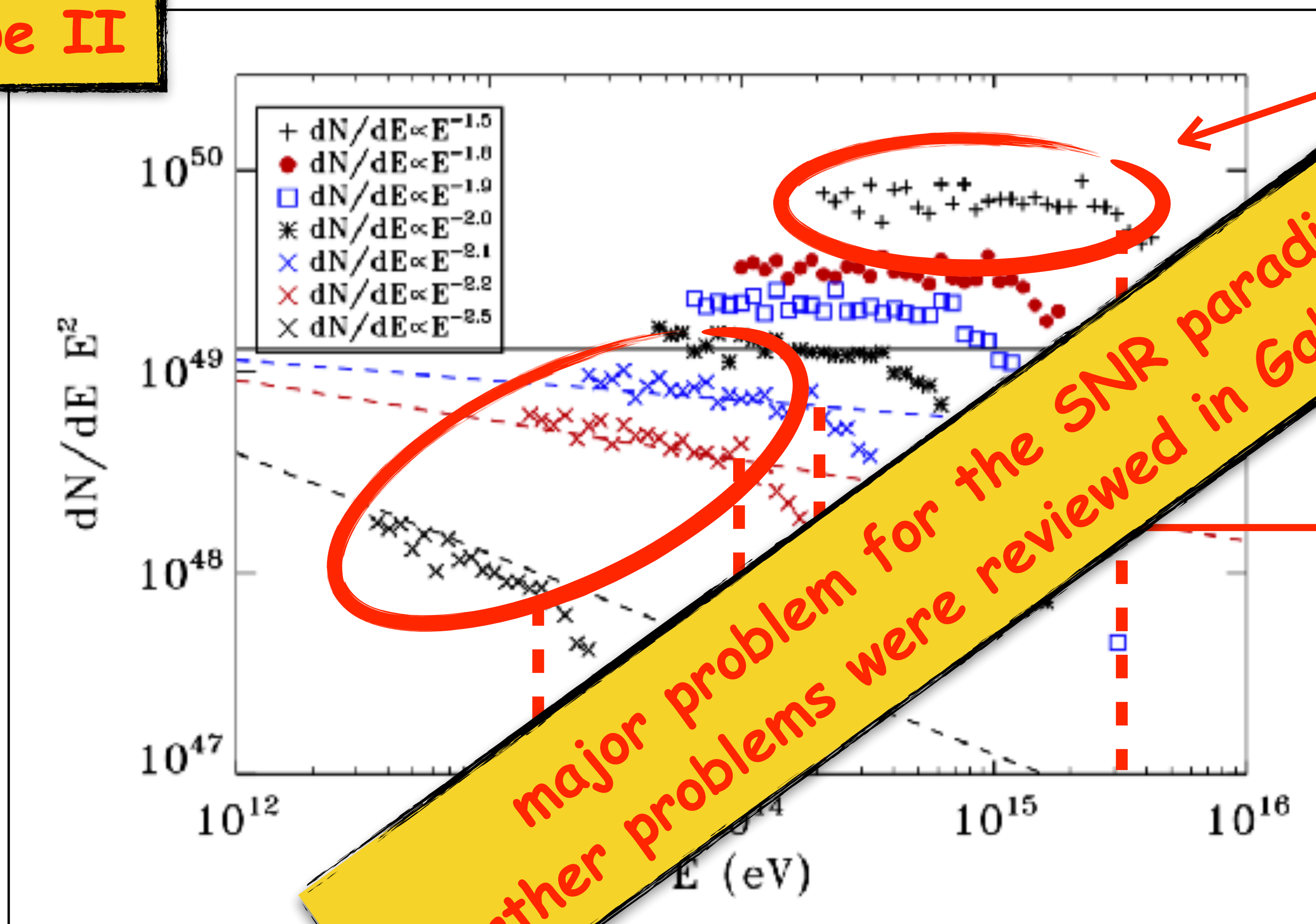

major problem for the SNR paradigm
(further problems were reviewed in Gabici+ 2019)

kn at the right place

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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

- The bulk of the energy of ... ...ginates from ... ...sions in the Galactic disk

Do SNRs accelerate ALL CRs? (PeV and beyond)

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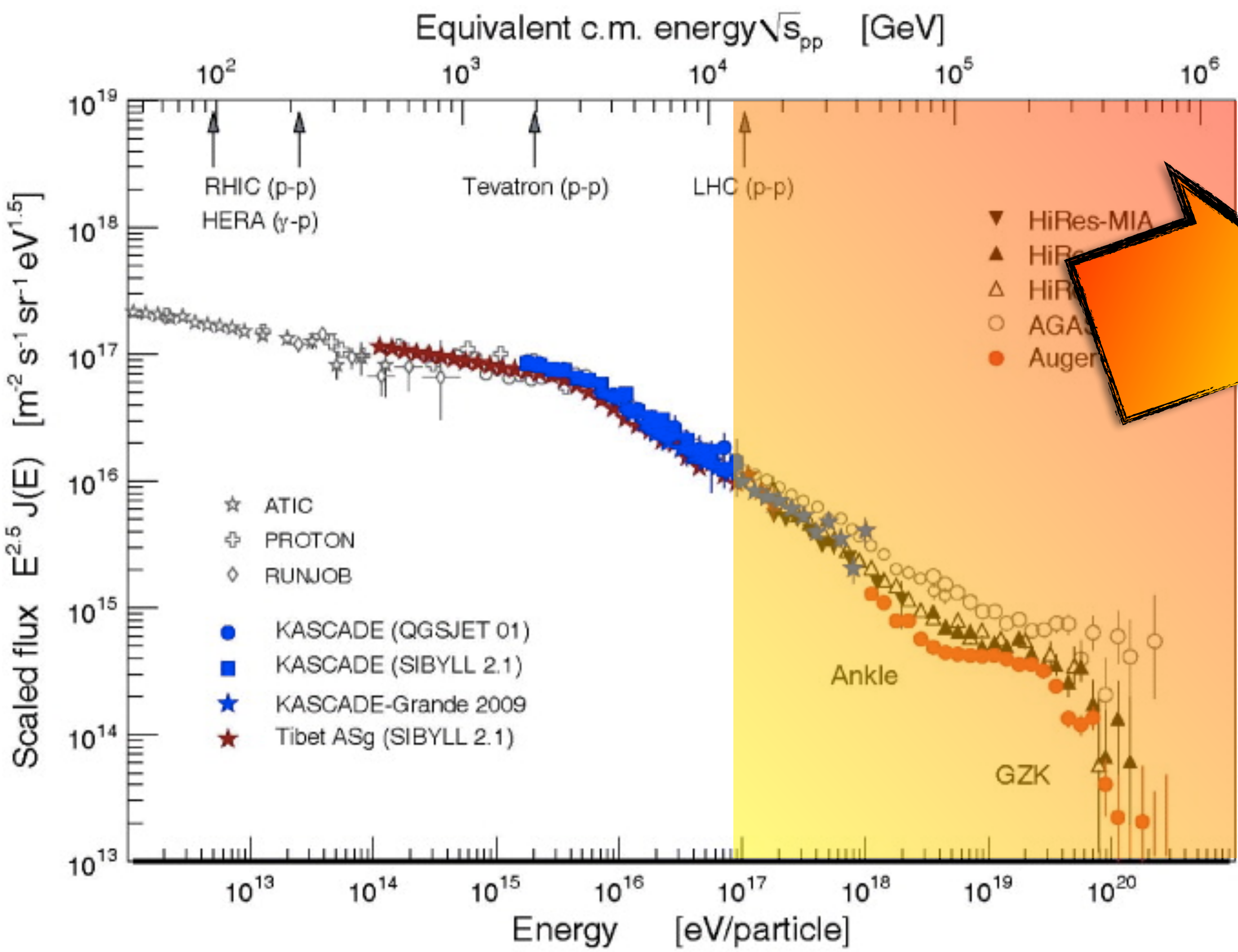
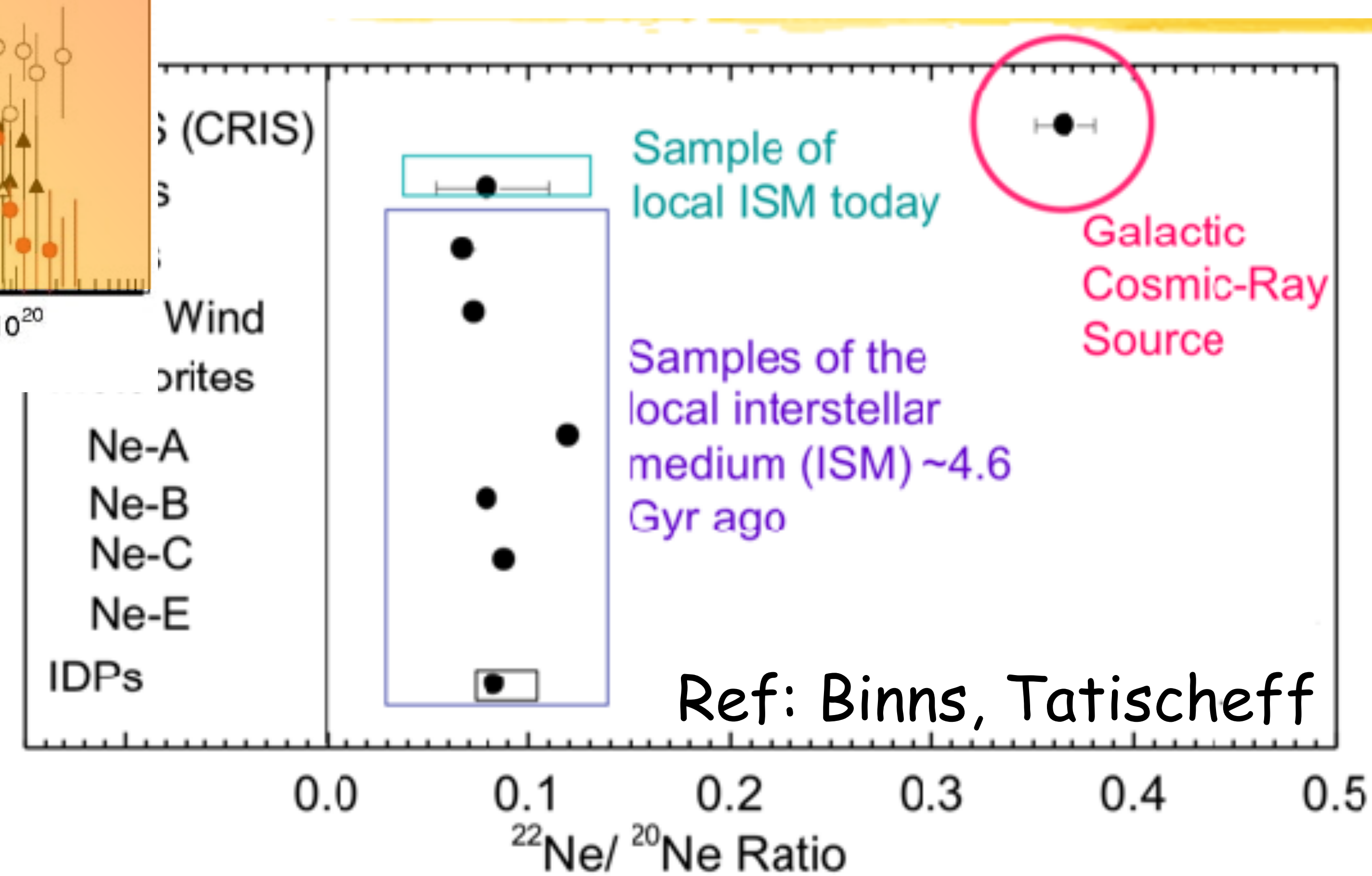
  interstellar medi … diffusive shock
  accel … supernova remnants

what about ^{22}Ne/^{20}Ne? —> 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 $^{22}Ne/^{20}Ne$ ratio?

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

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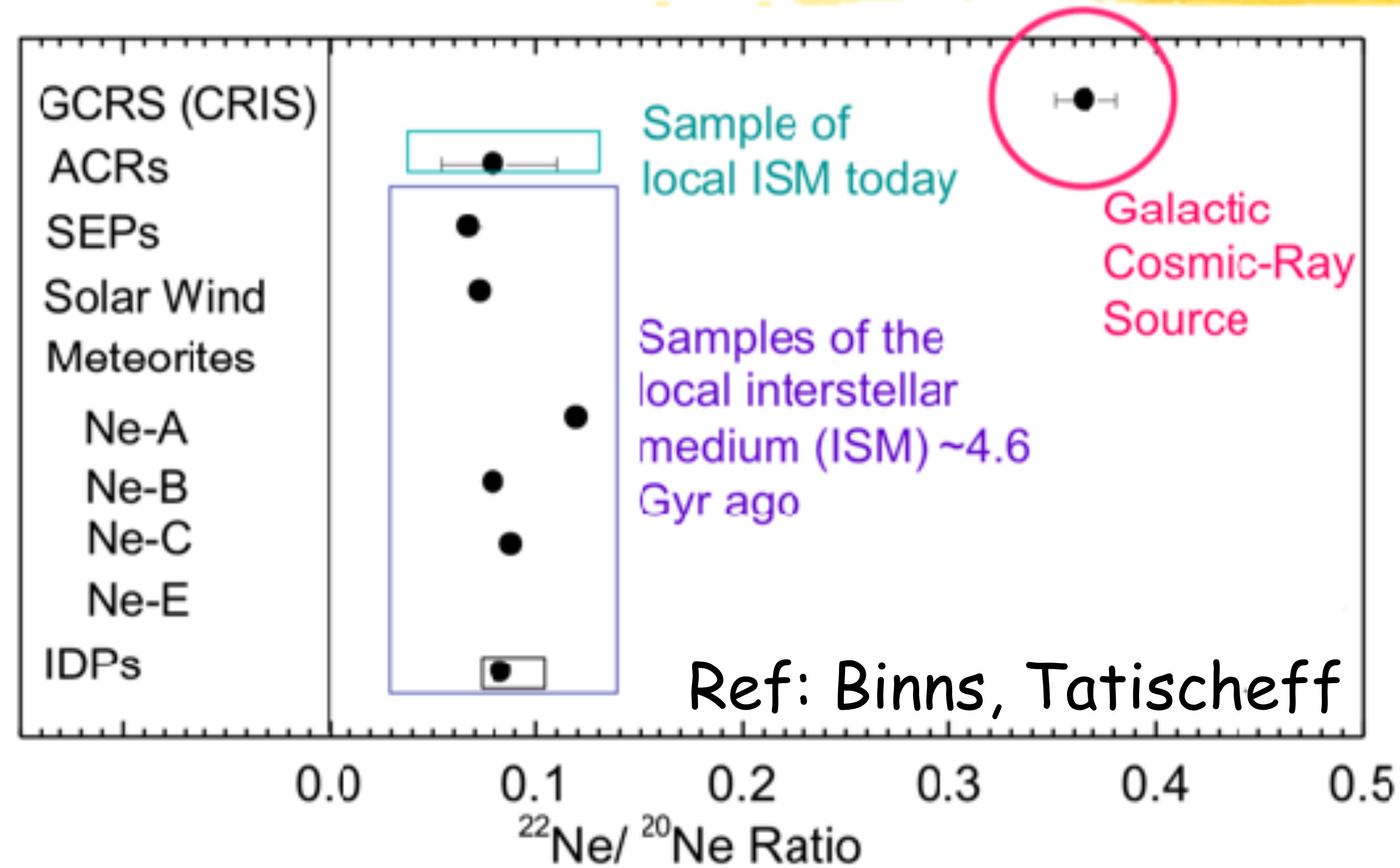

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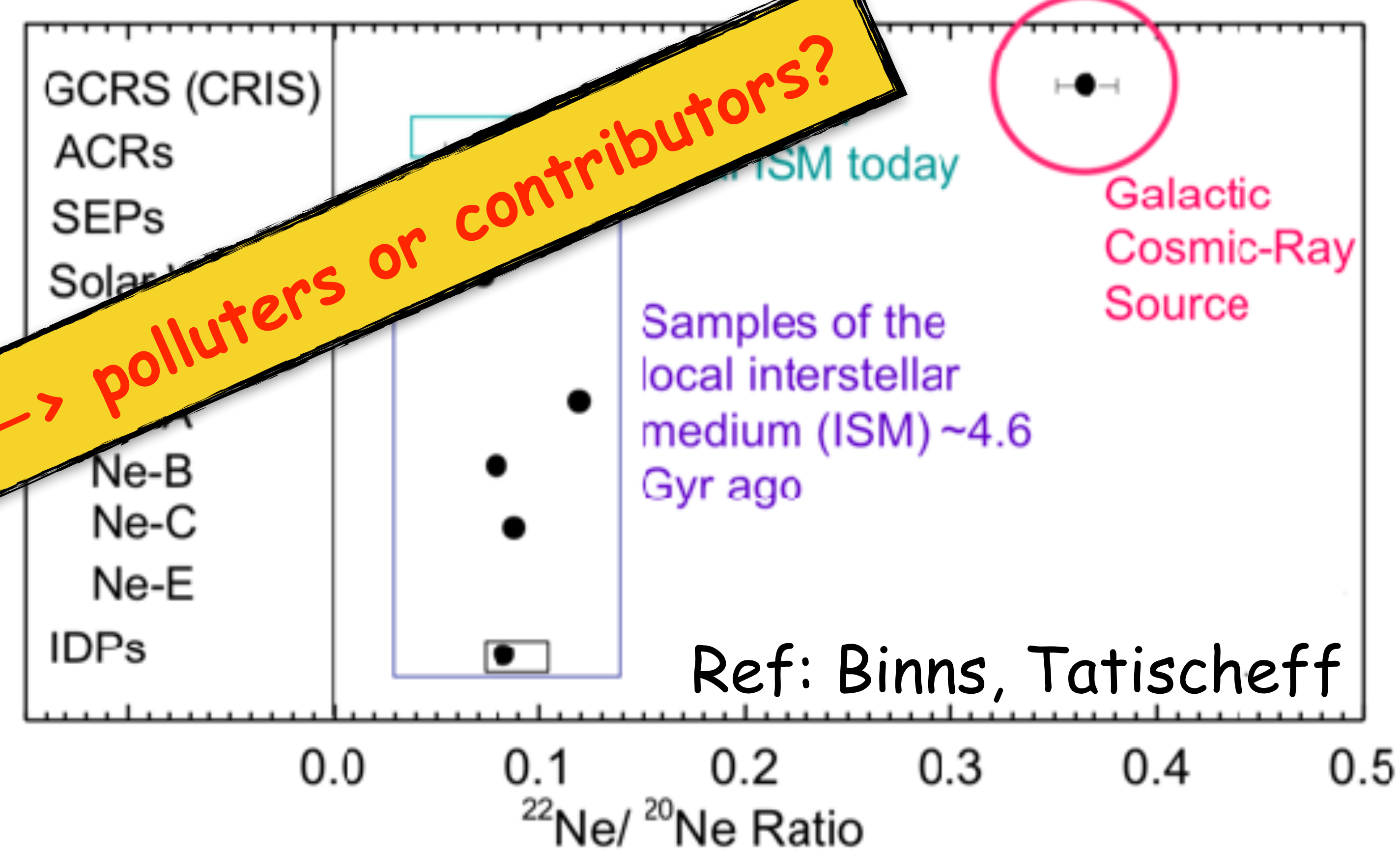
[2] can the SNR par… explain the ano… excess of the 22… ratio?

role of stellar winds —> polluters or contributors?



Ref: Binns, Tatischeff

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90% SNR + 10% stellar winds might work

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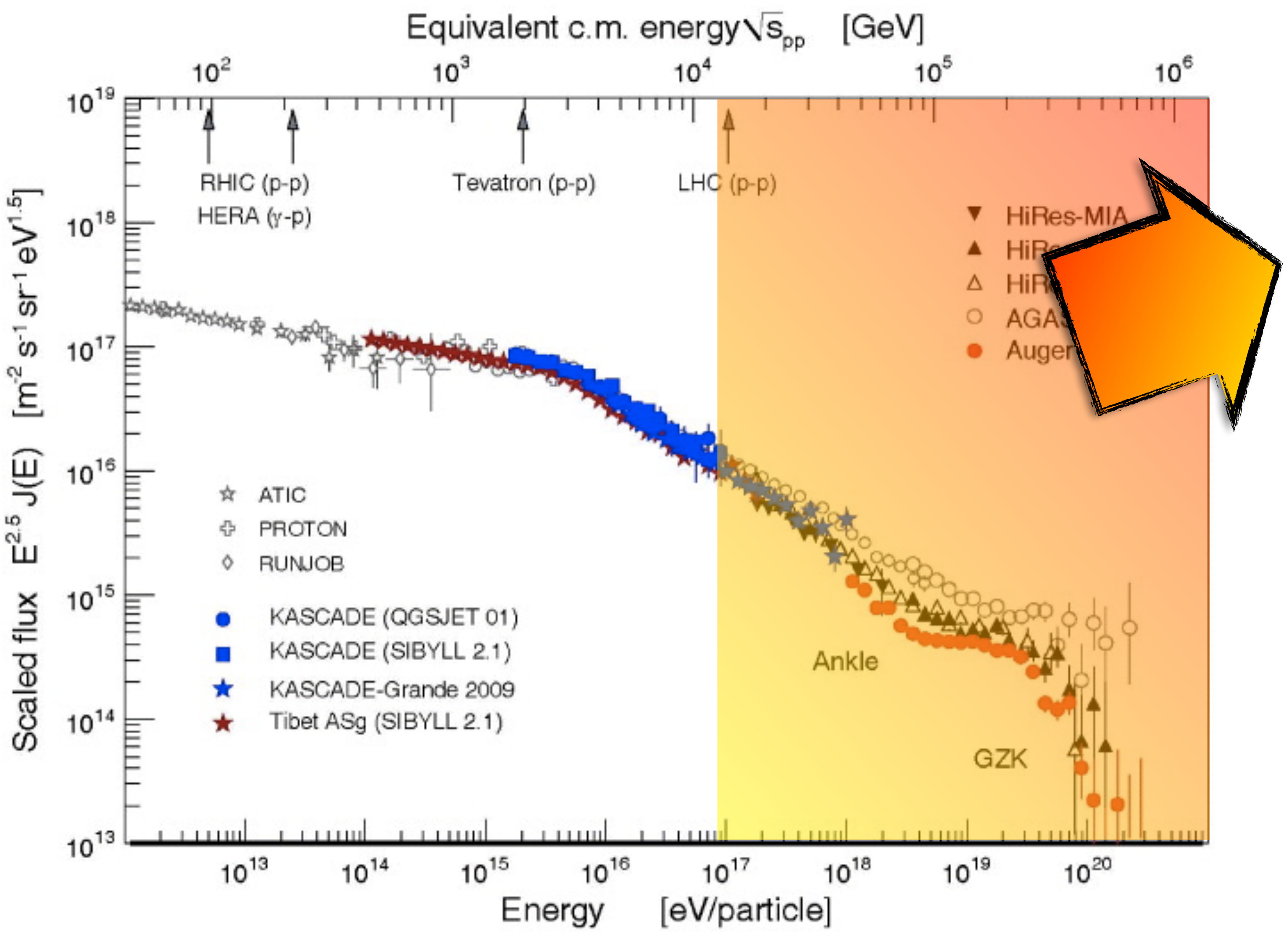

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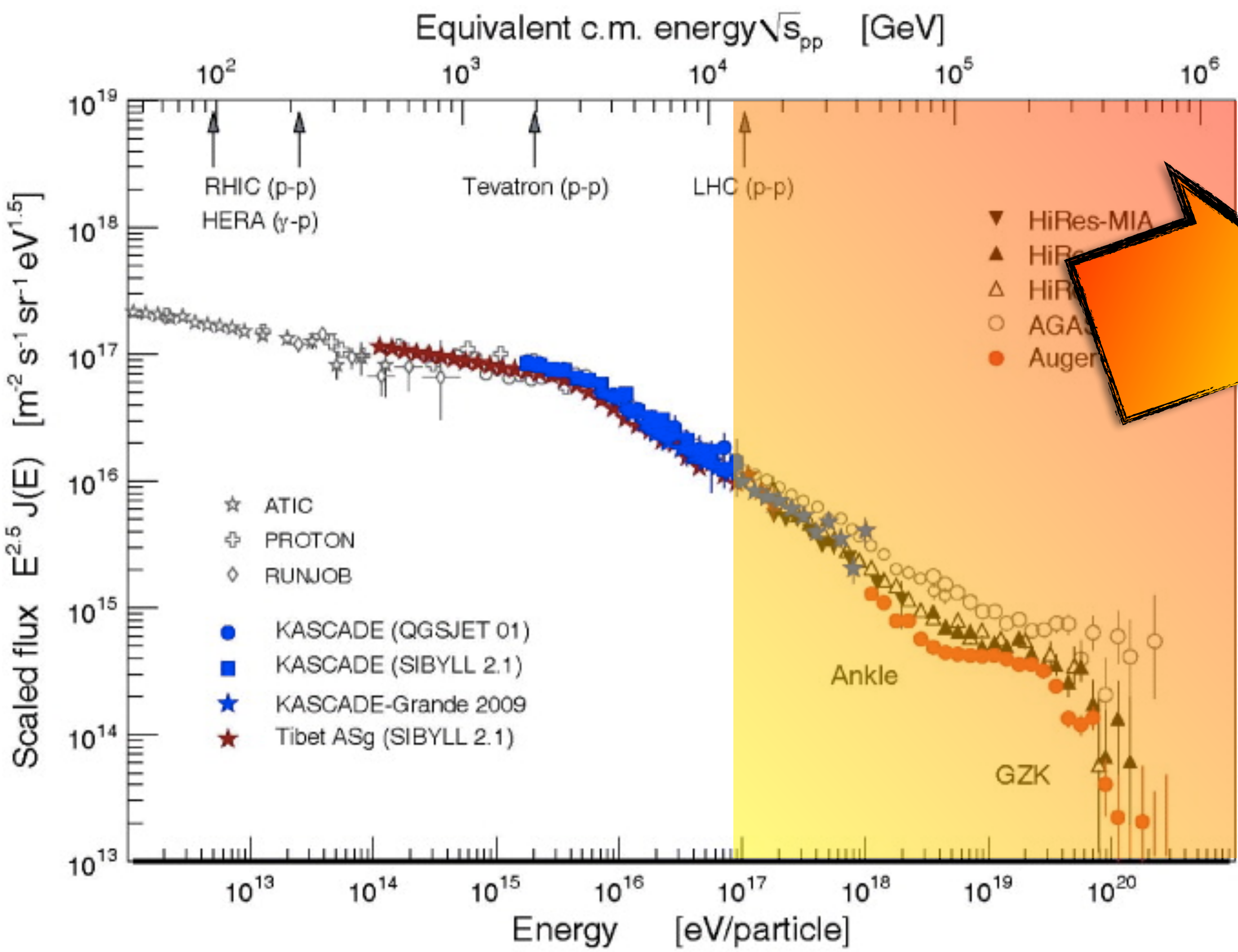

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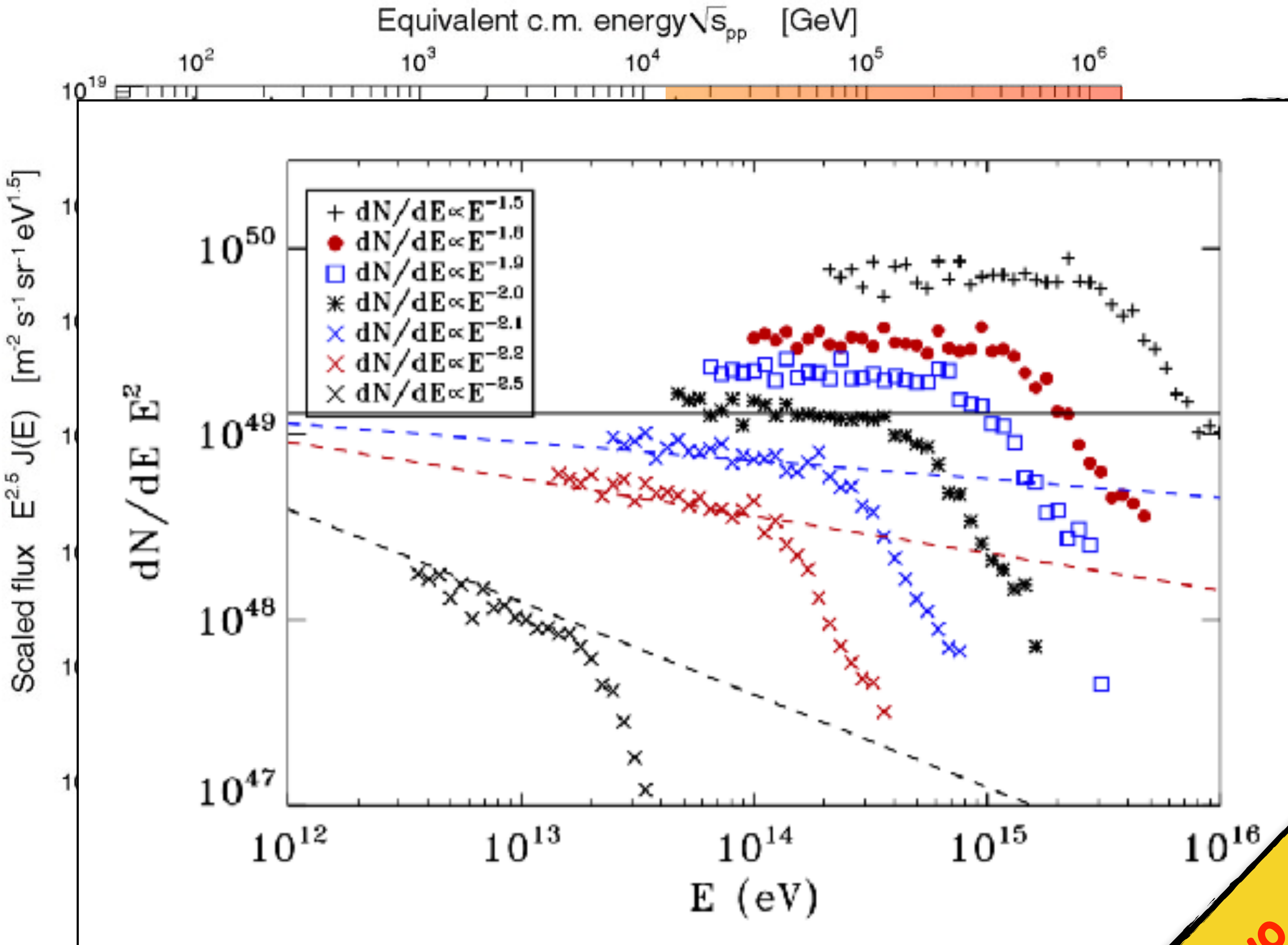

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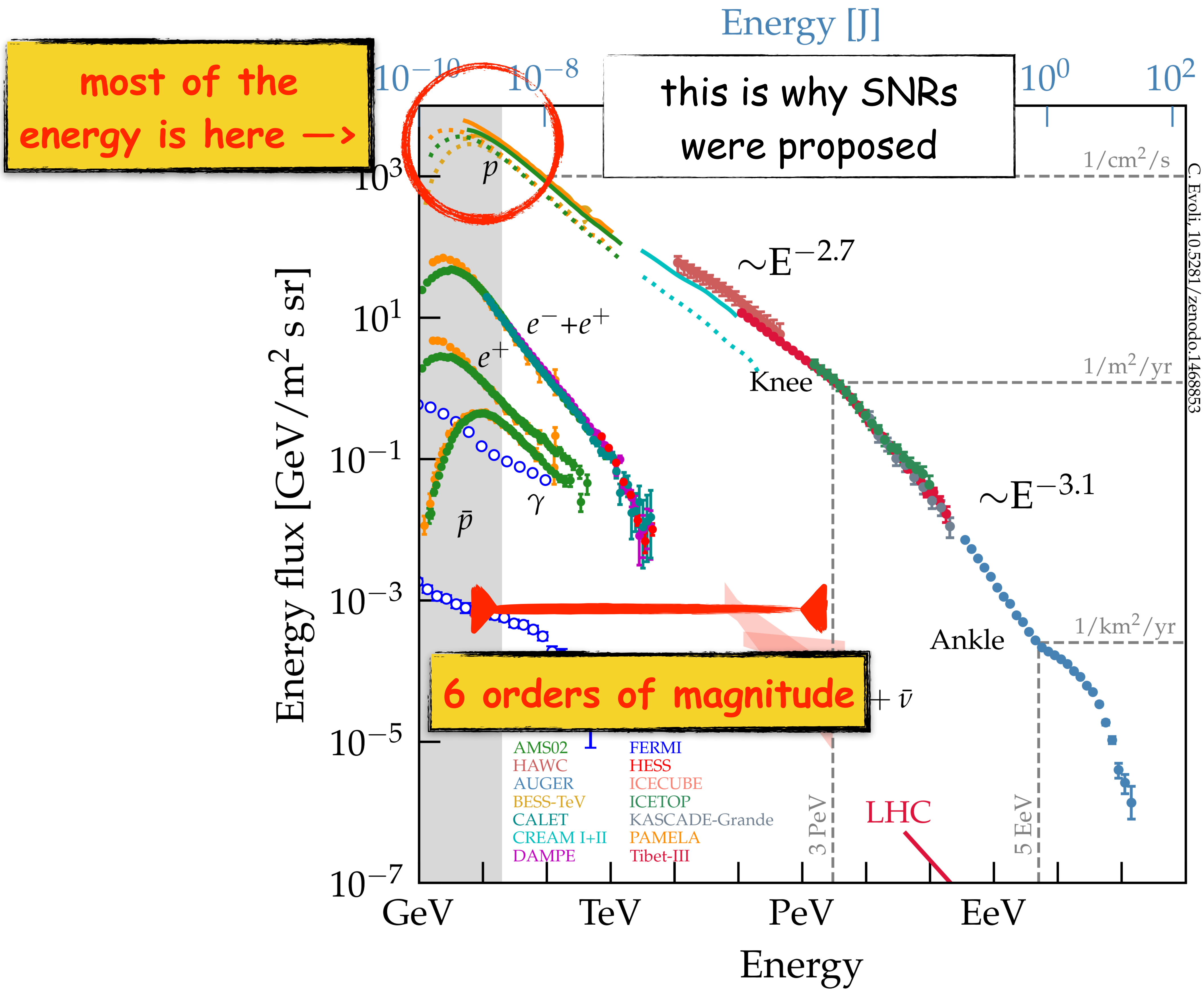
Note on energetic



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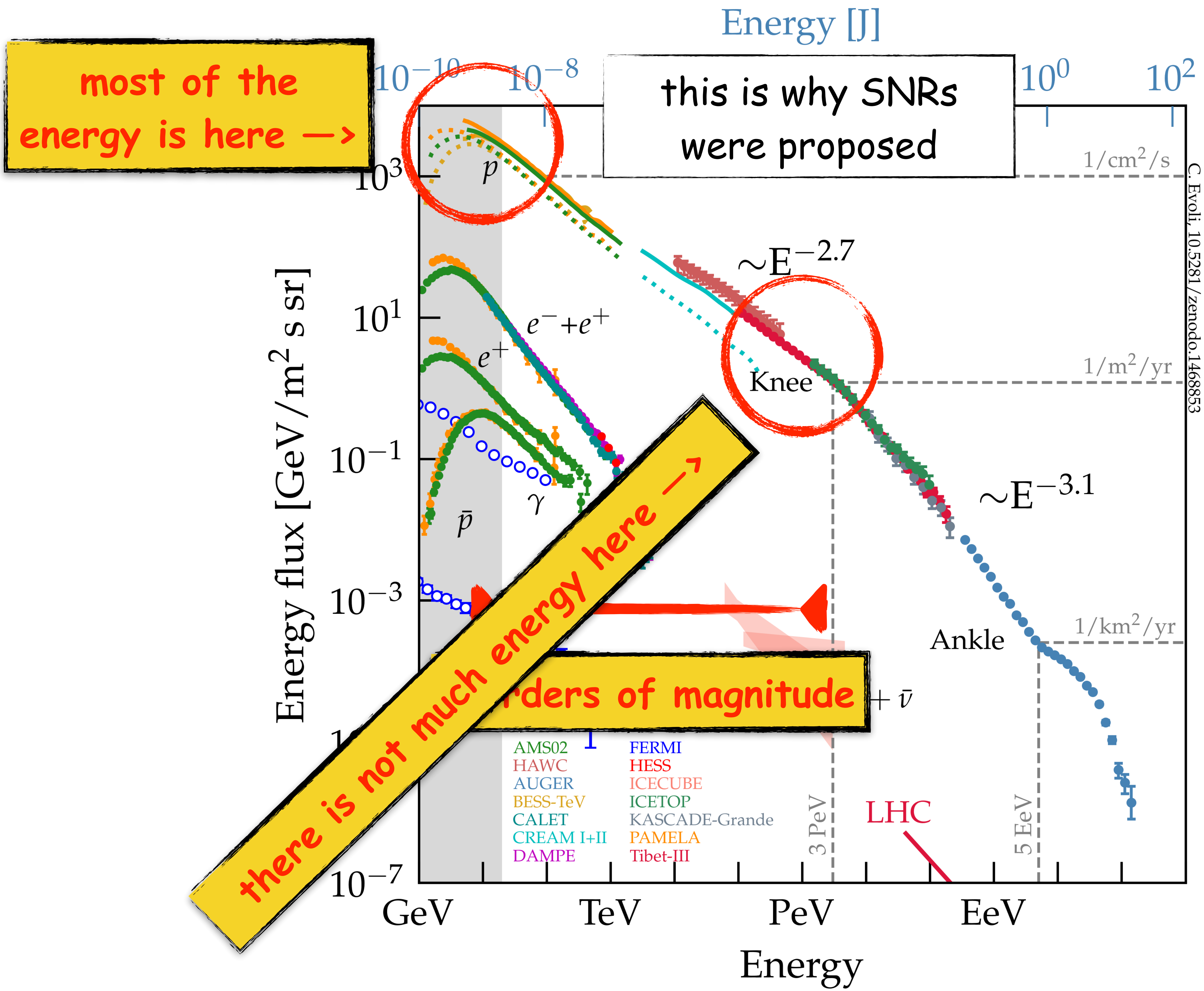

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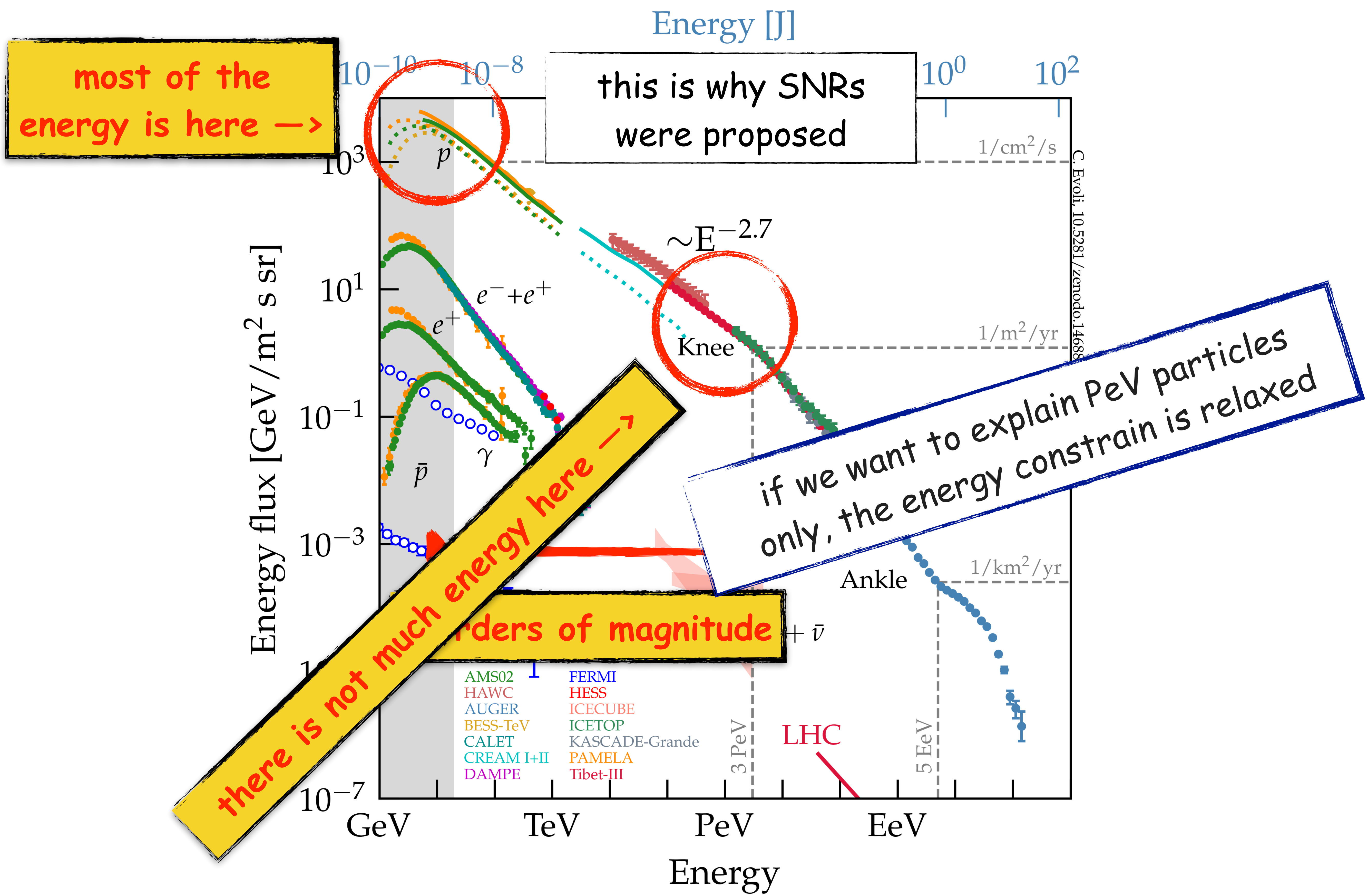

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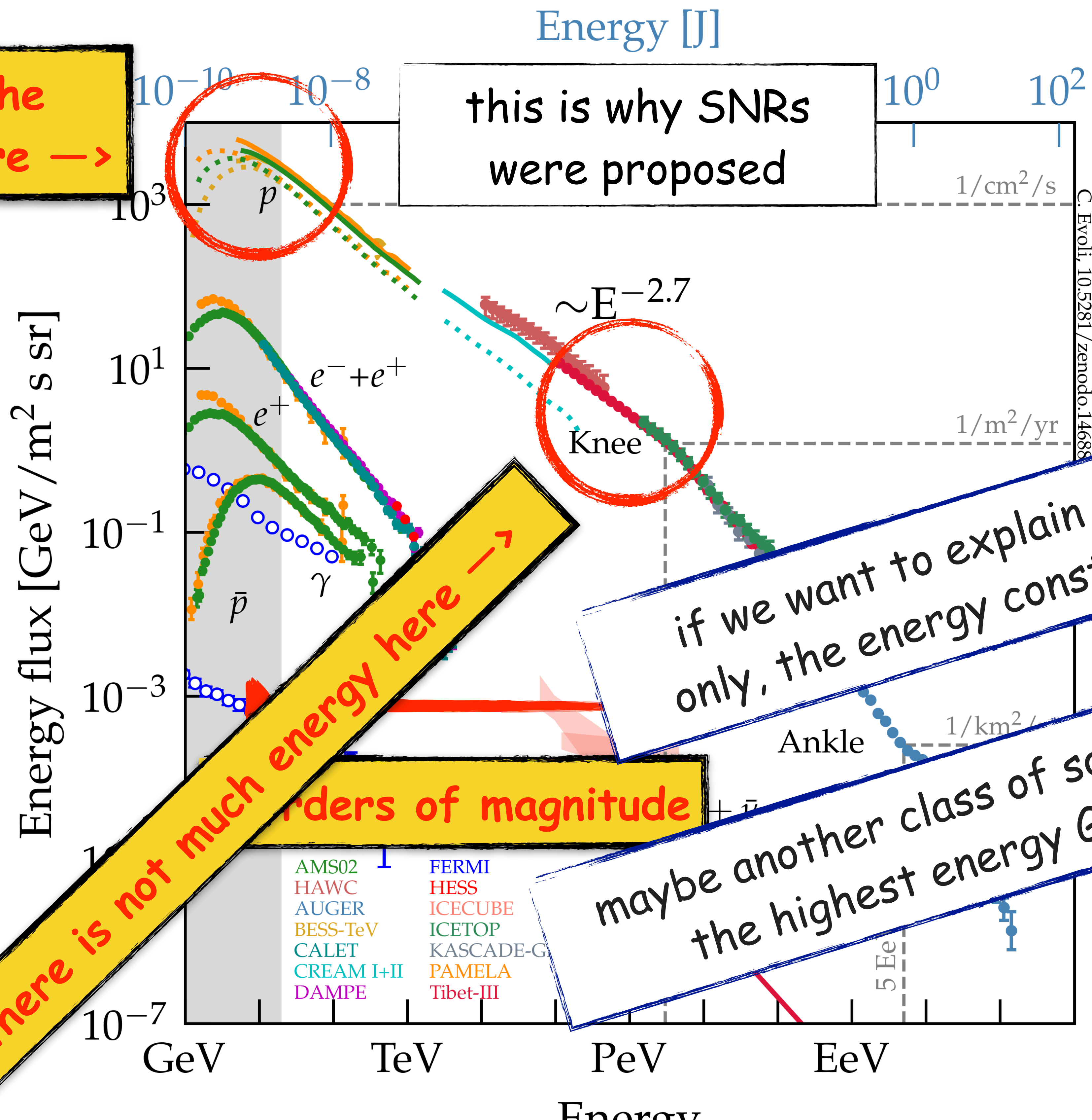

most of the energy is here —>

this is why SNRs were proposed

there is not much energy here —>

...rders of magnitude

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

maybe another class of sources produces the highest energy Galactic CRs?

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90% SNR + 10% stellar winds might work

The three pillars of orthodoxy

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  ns in the Galactic disk

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
  e (dusty)
  interstellar medi
  gh diffusive shock
  accel
  supernova remnants

90% SNR + 10% stellar winds might work