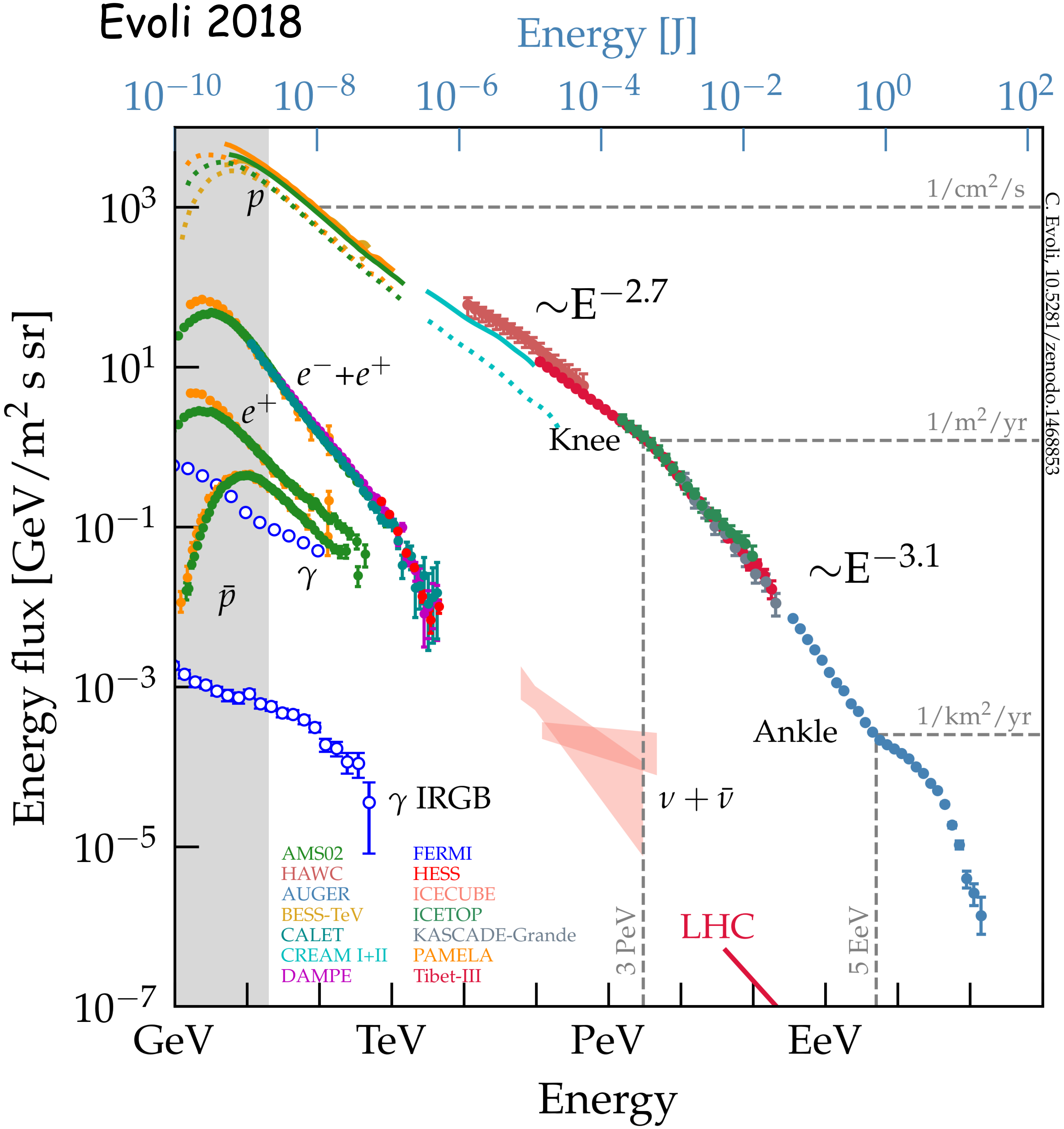
Supernova remnants and massive star clusters

Stefano Gabici
APC, Paris

The cosmic ray spectrum

Evoli 2018



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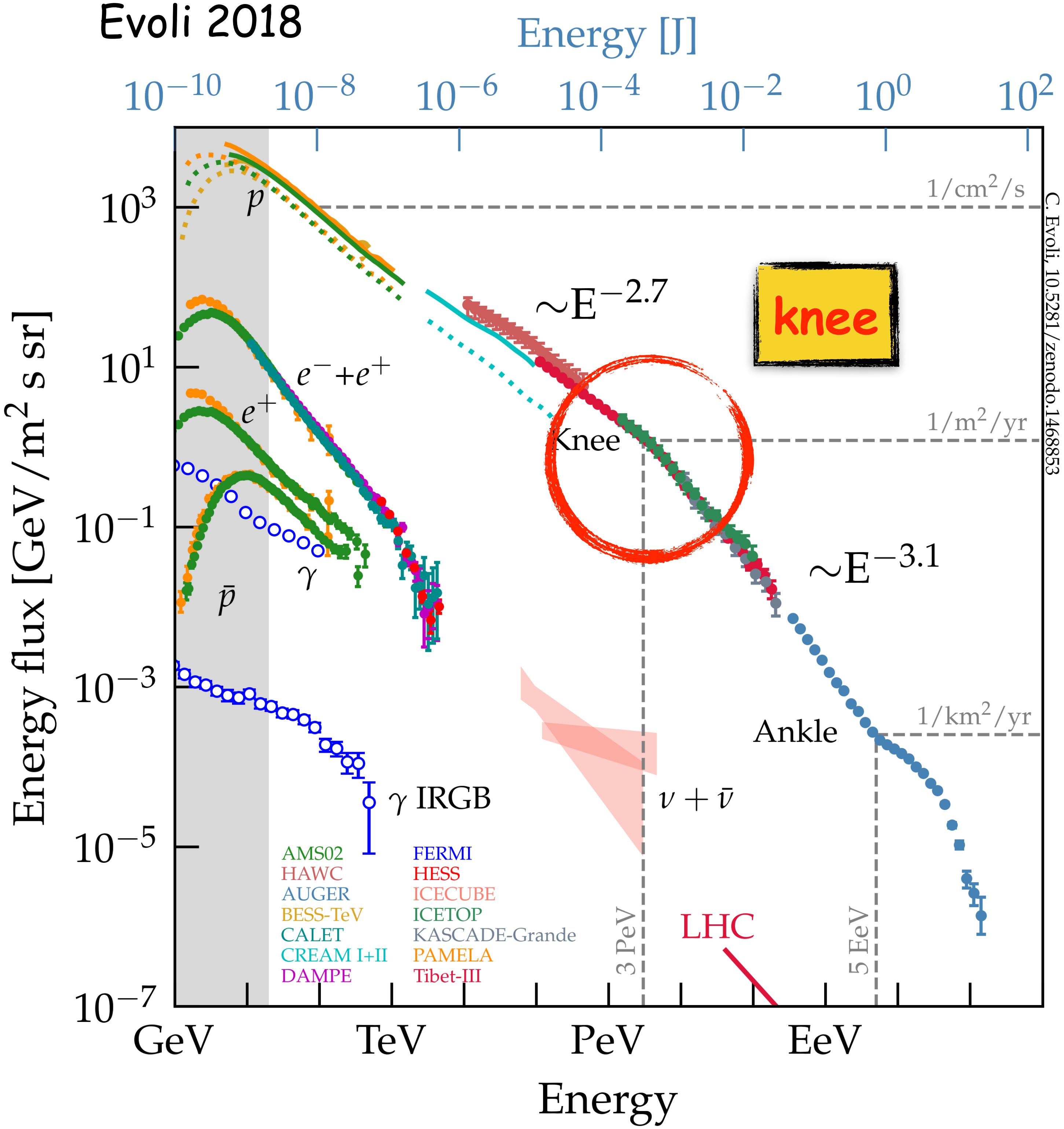

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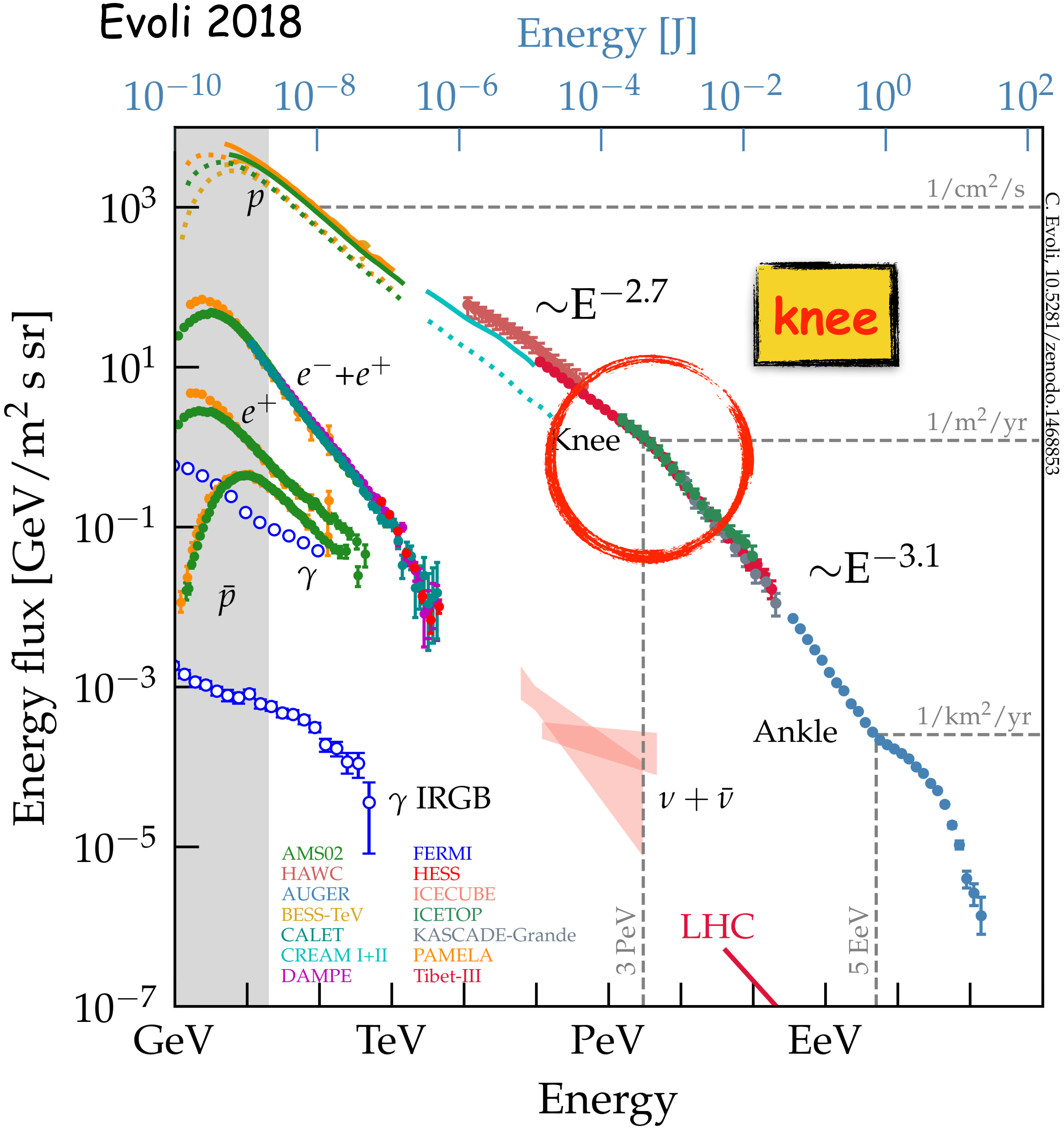

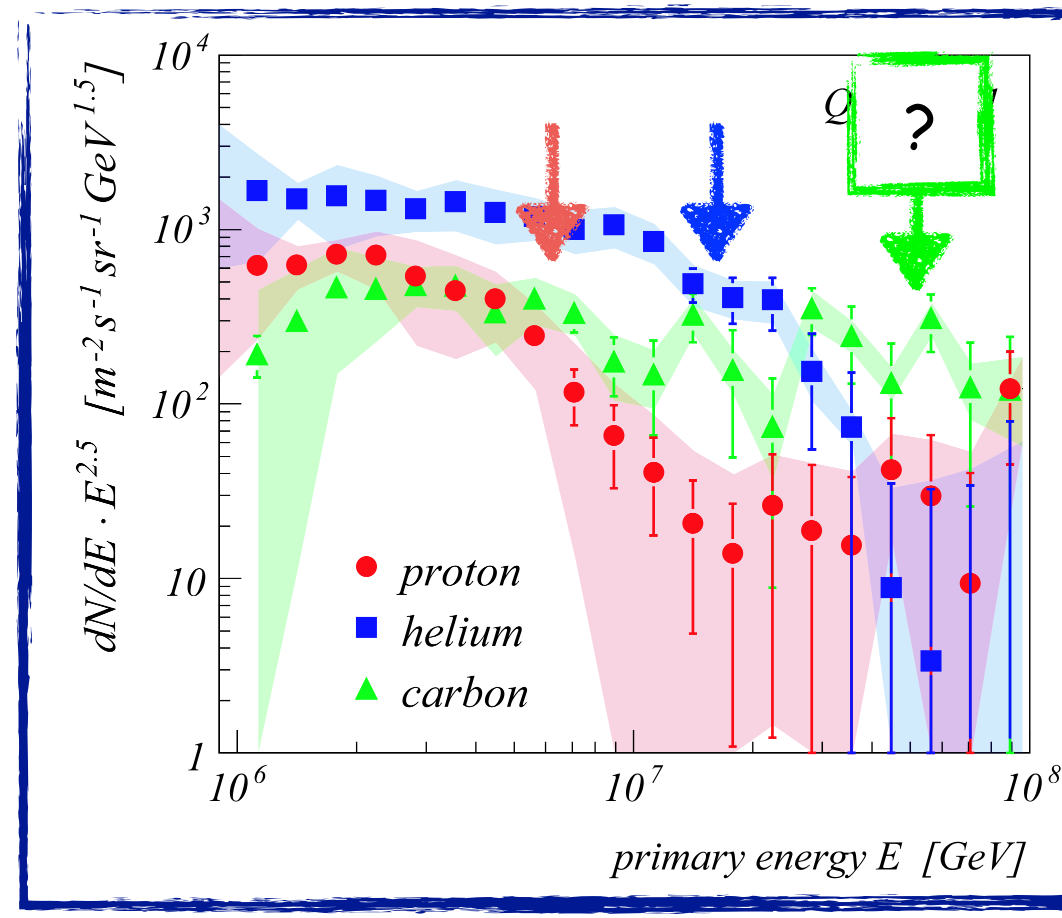

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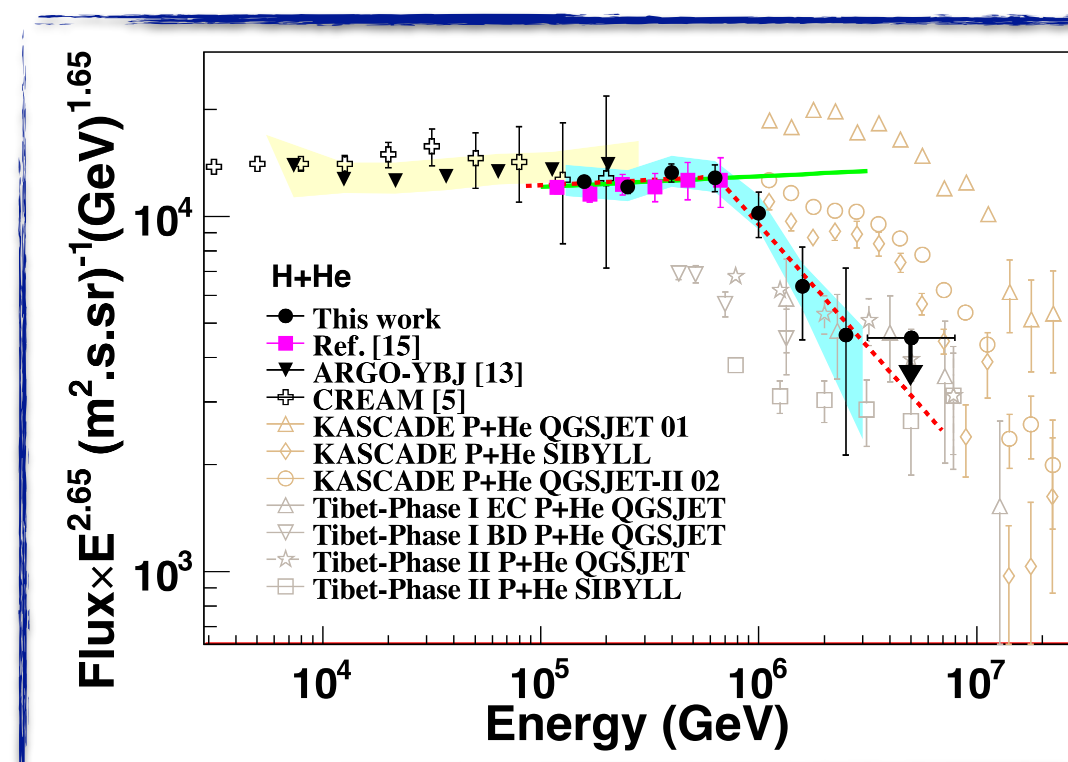

ARGO coll. 2015

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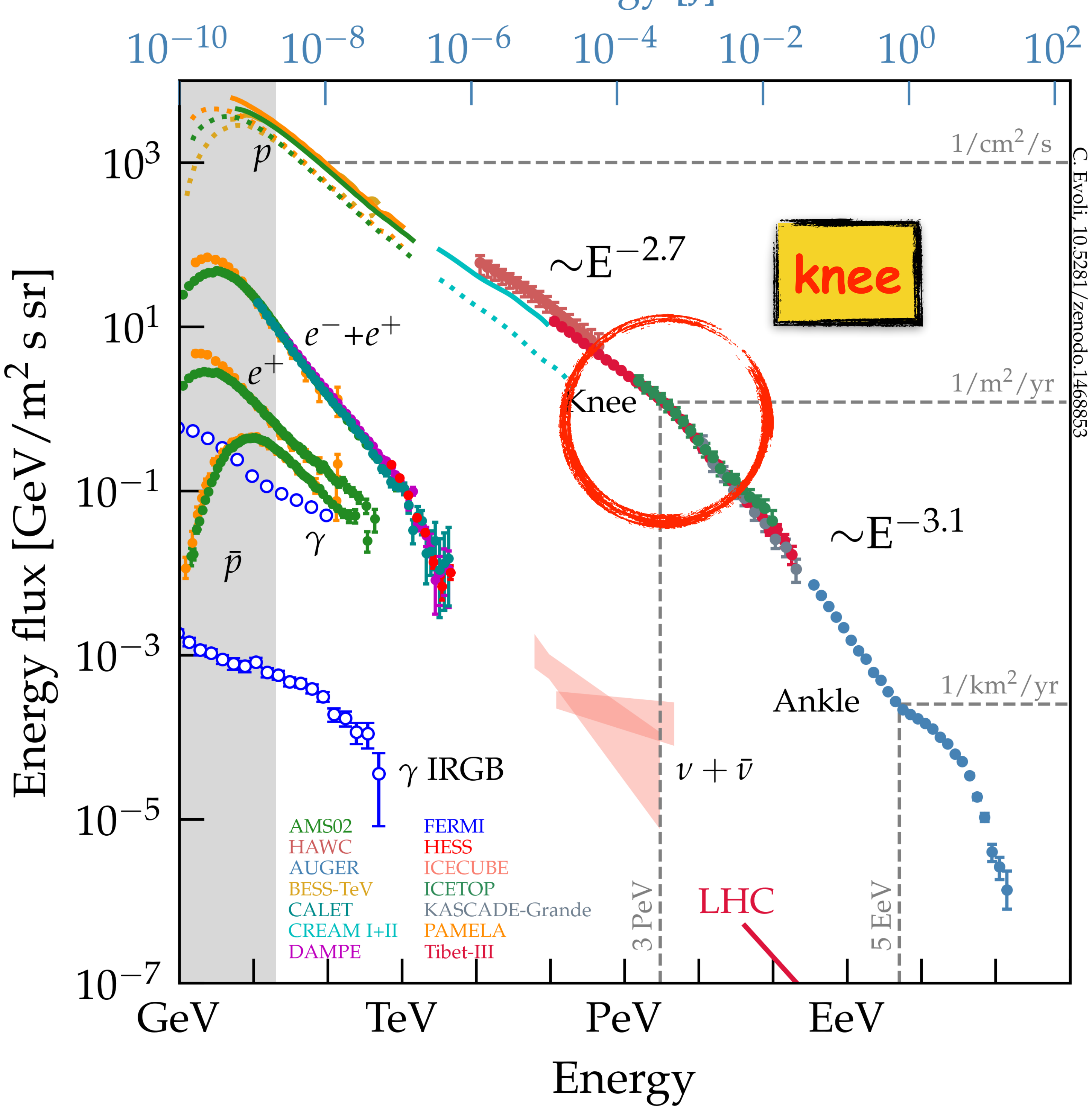

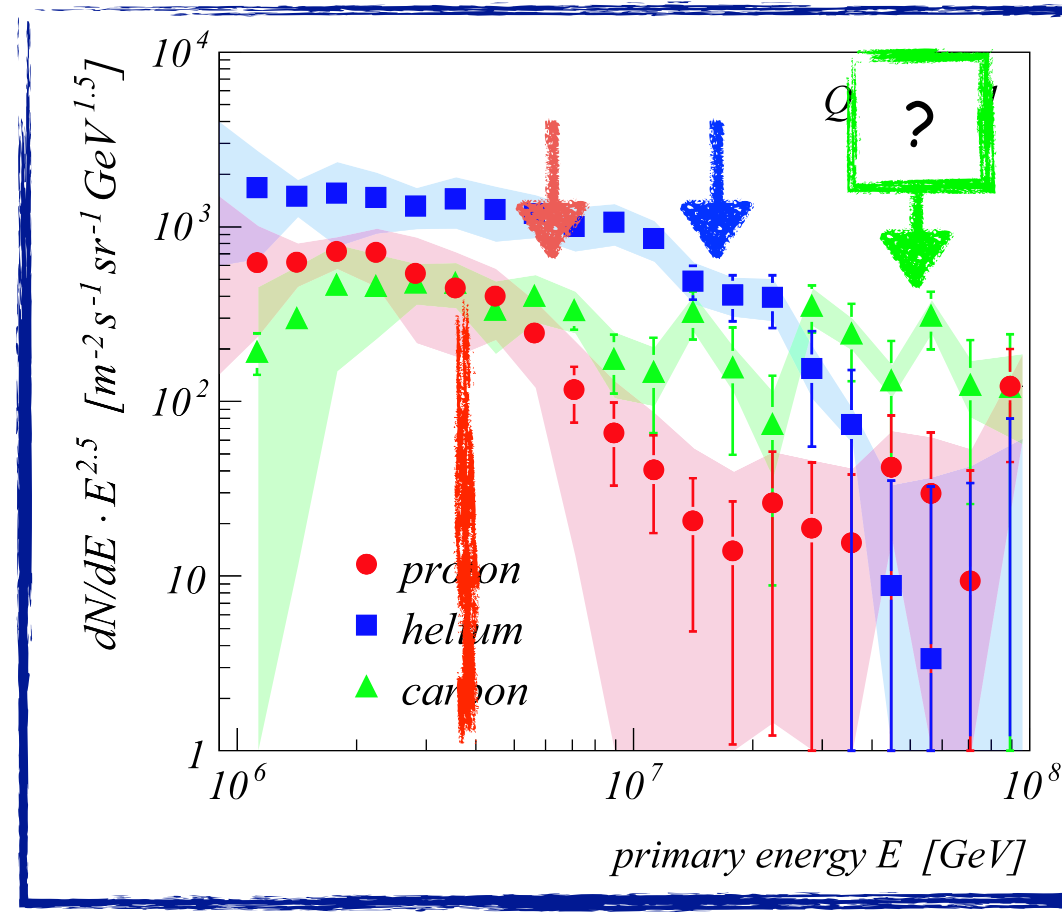

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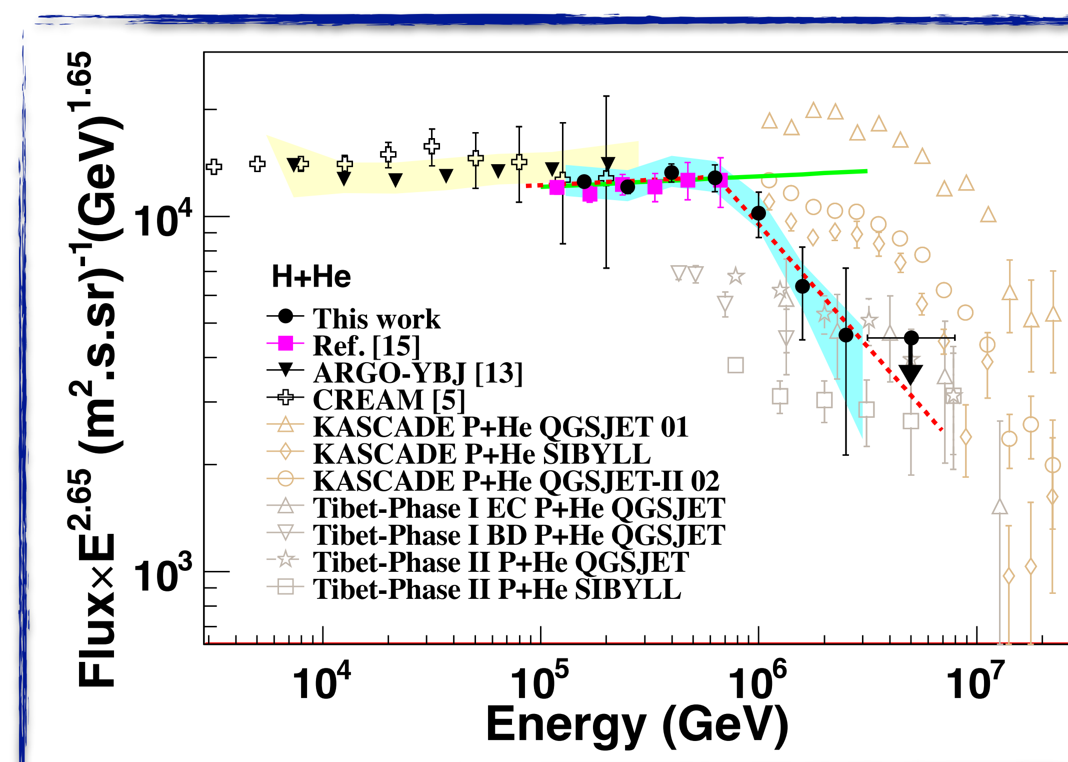

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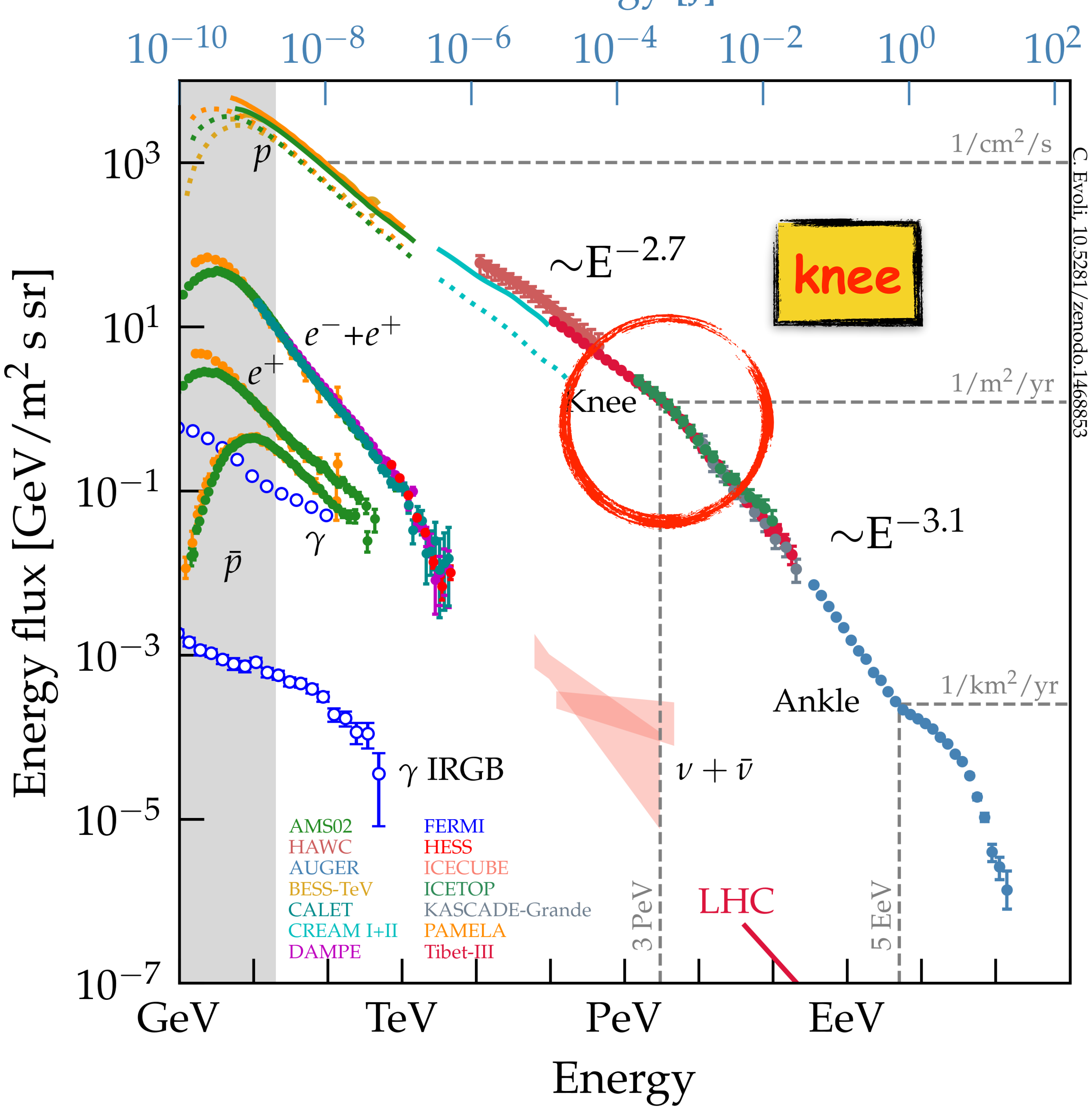

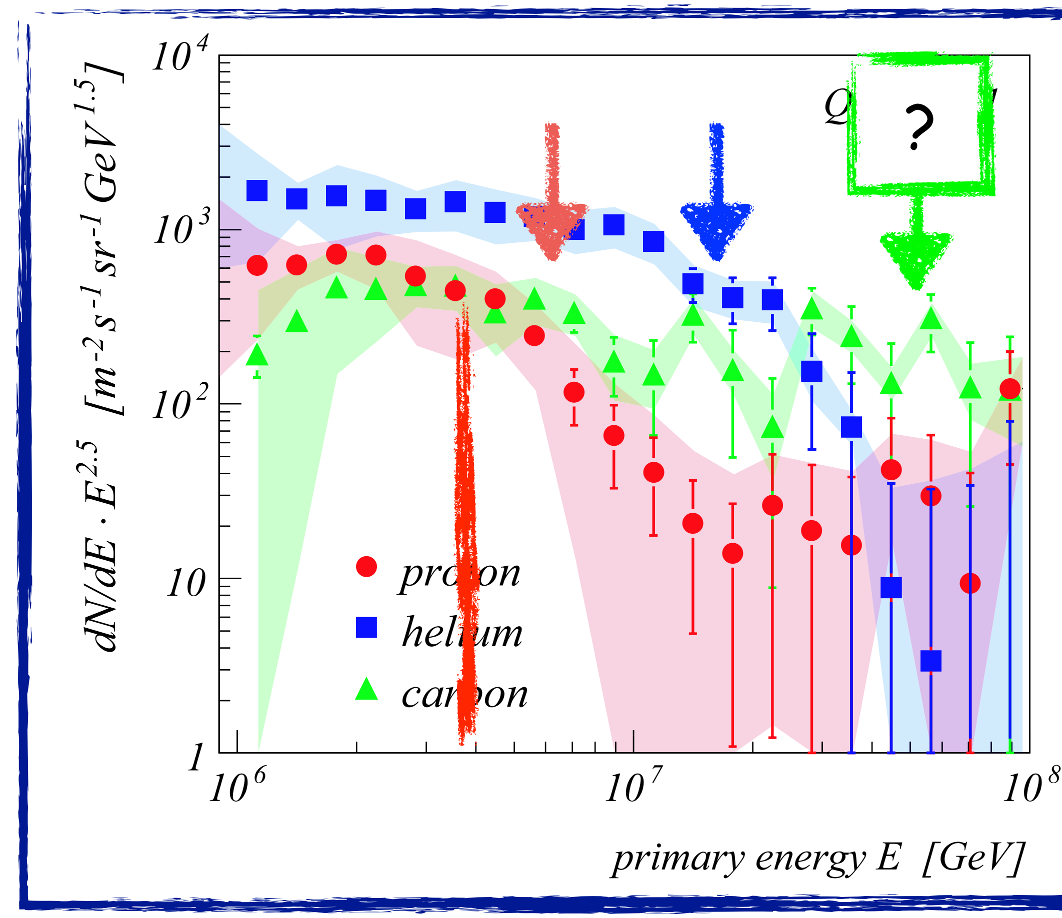

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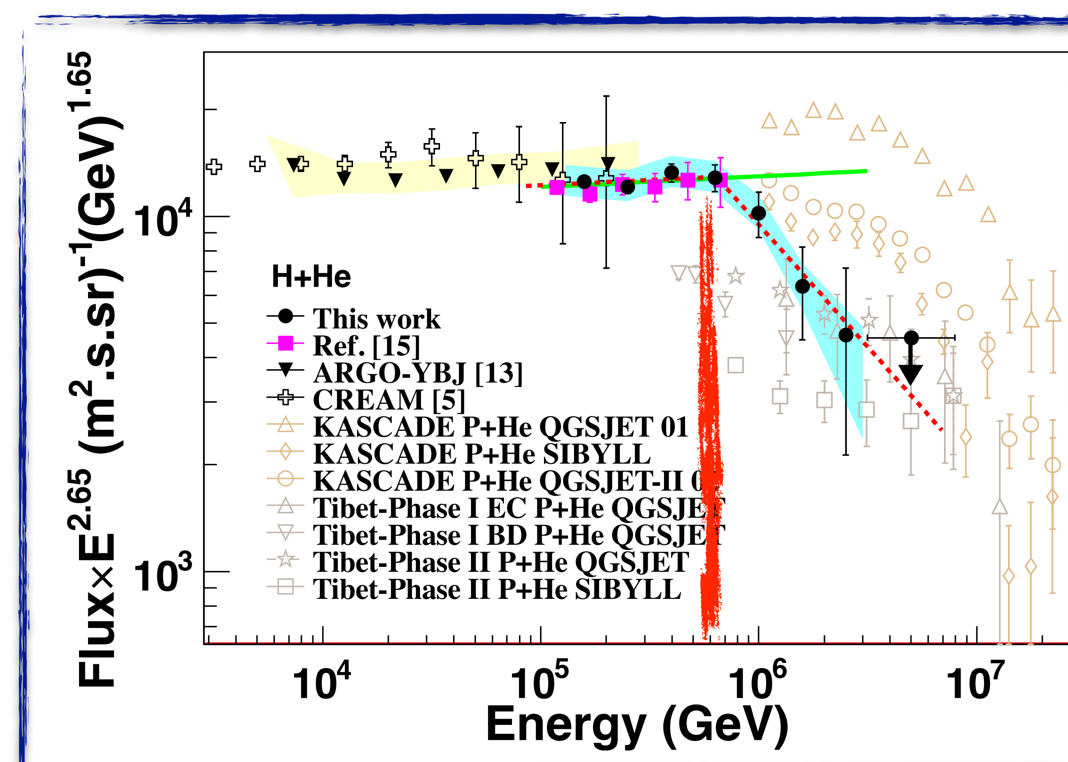

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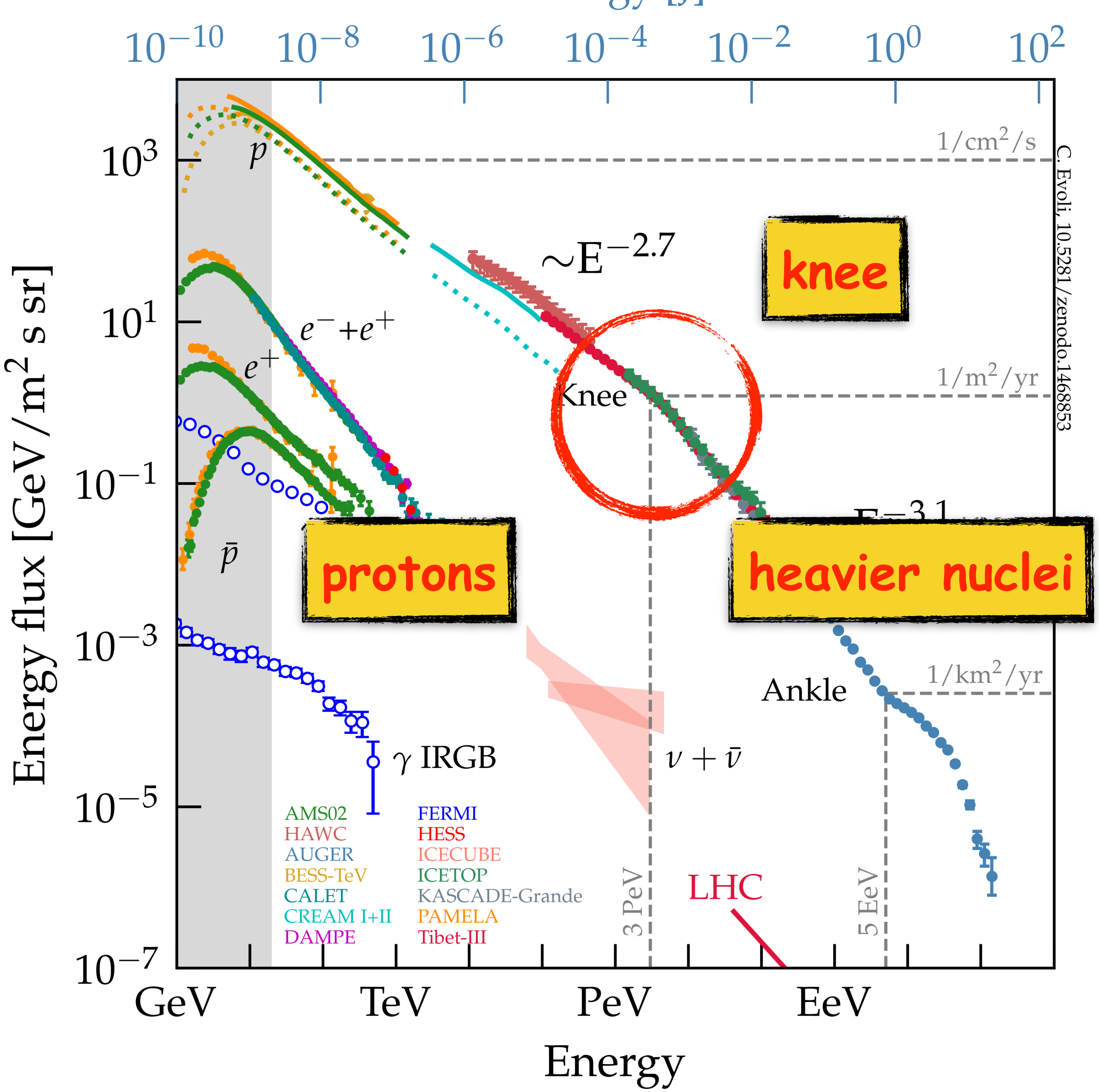

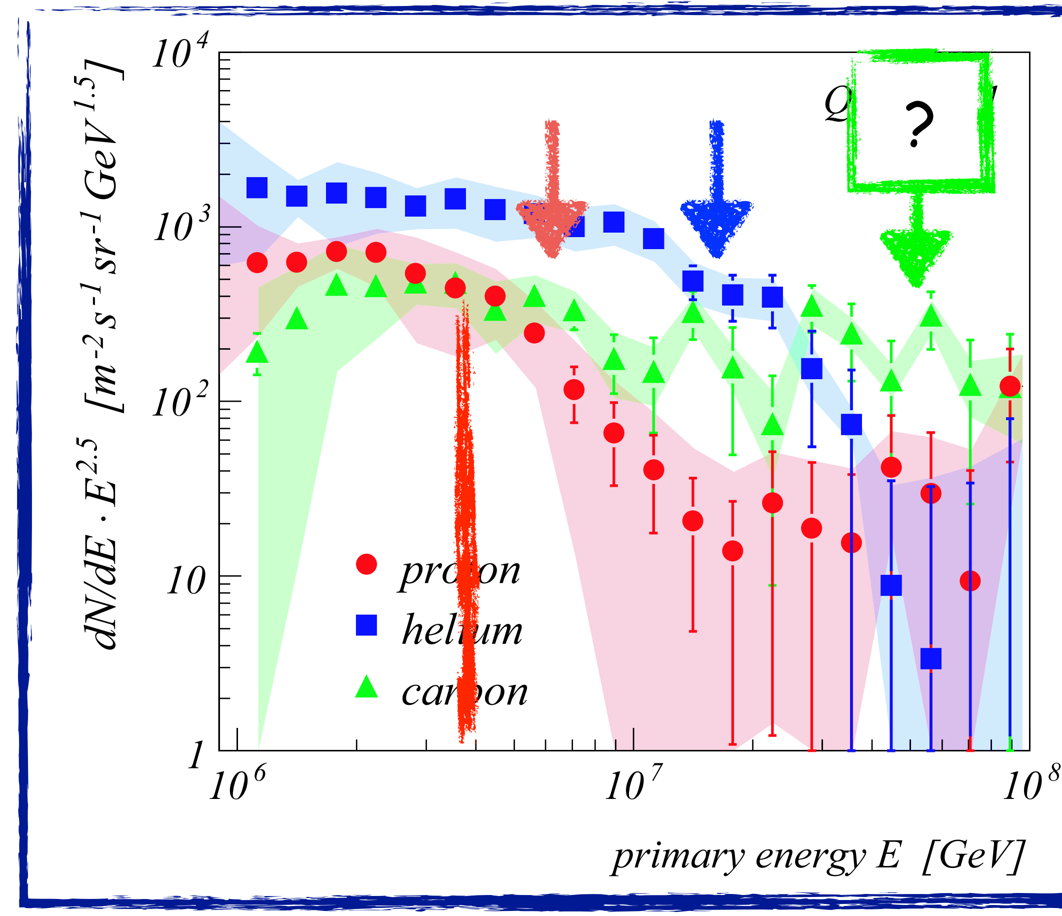

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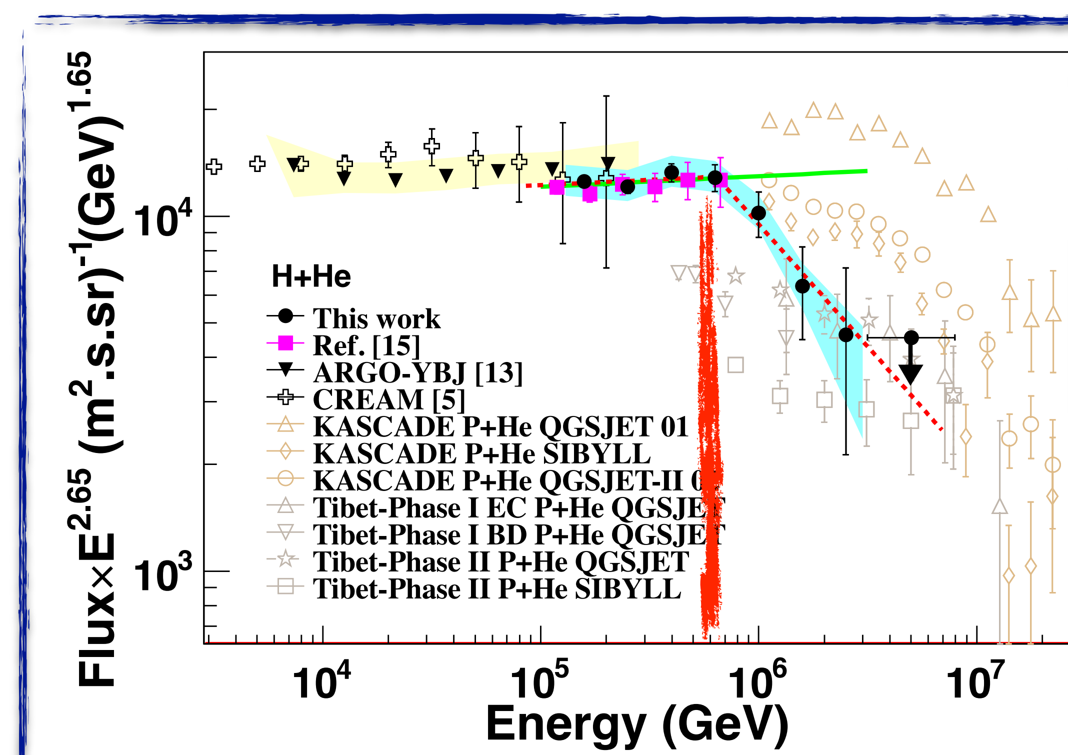

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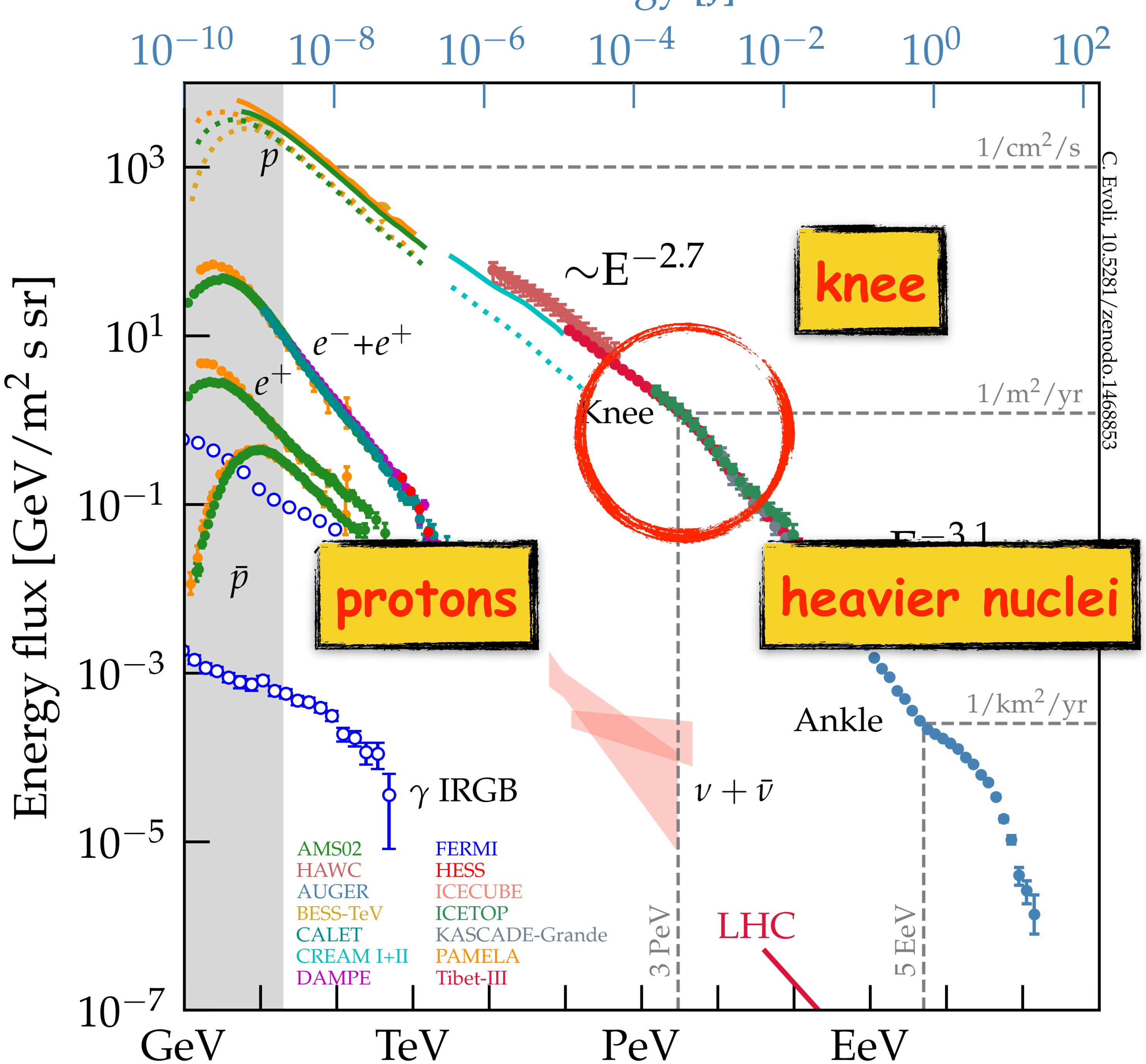
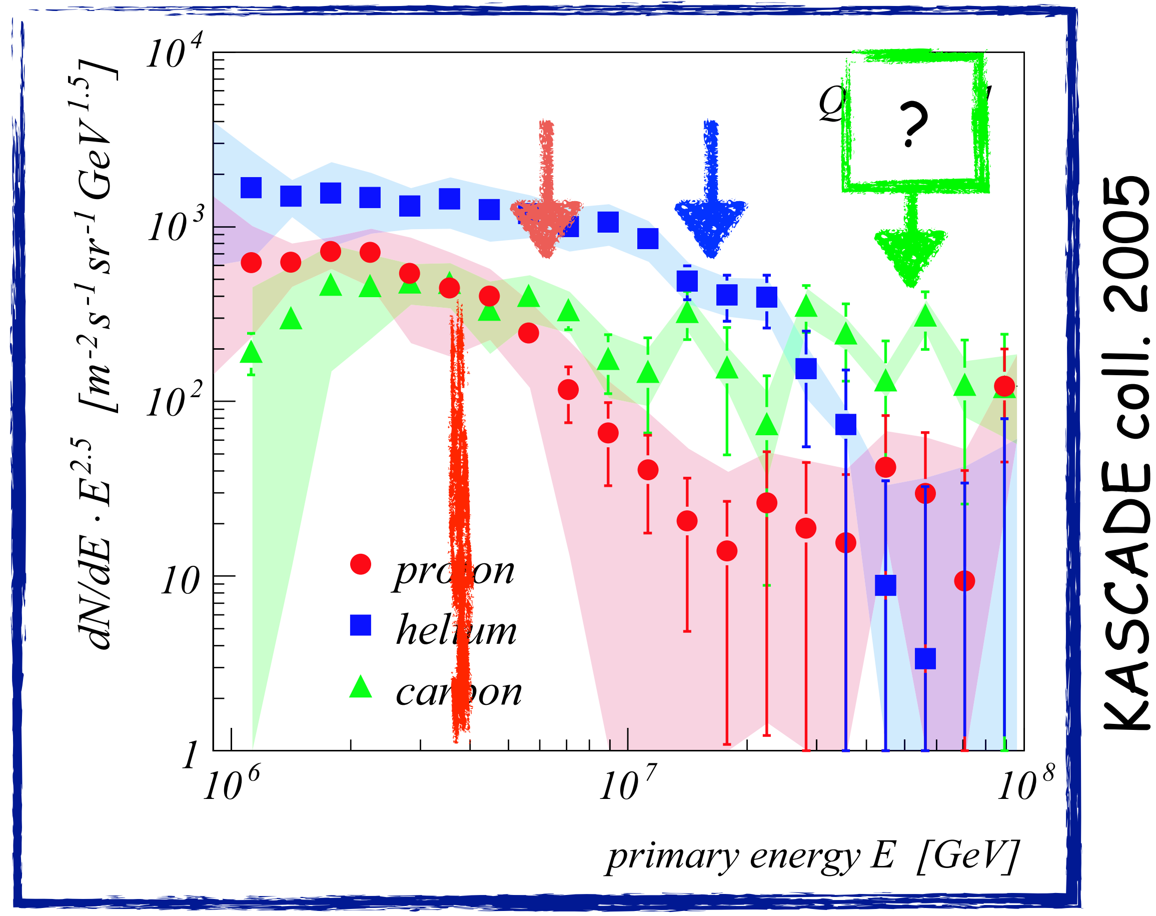
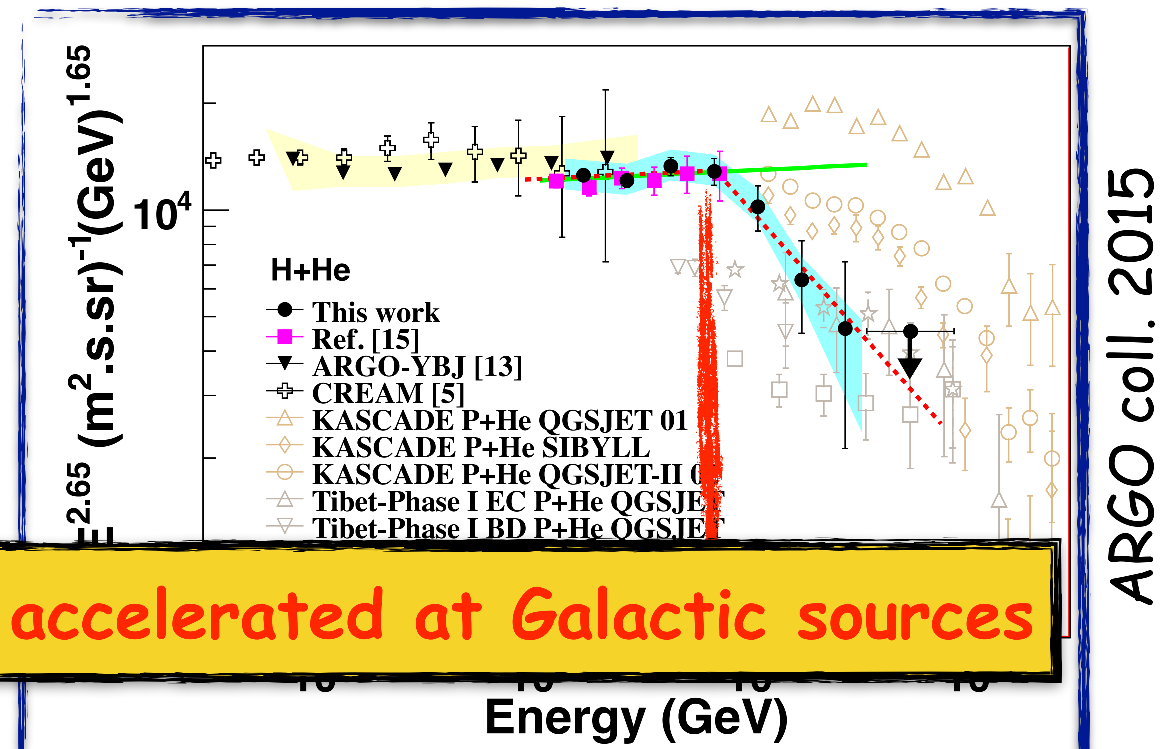
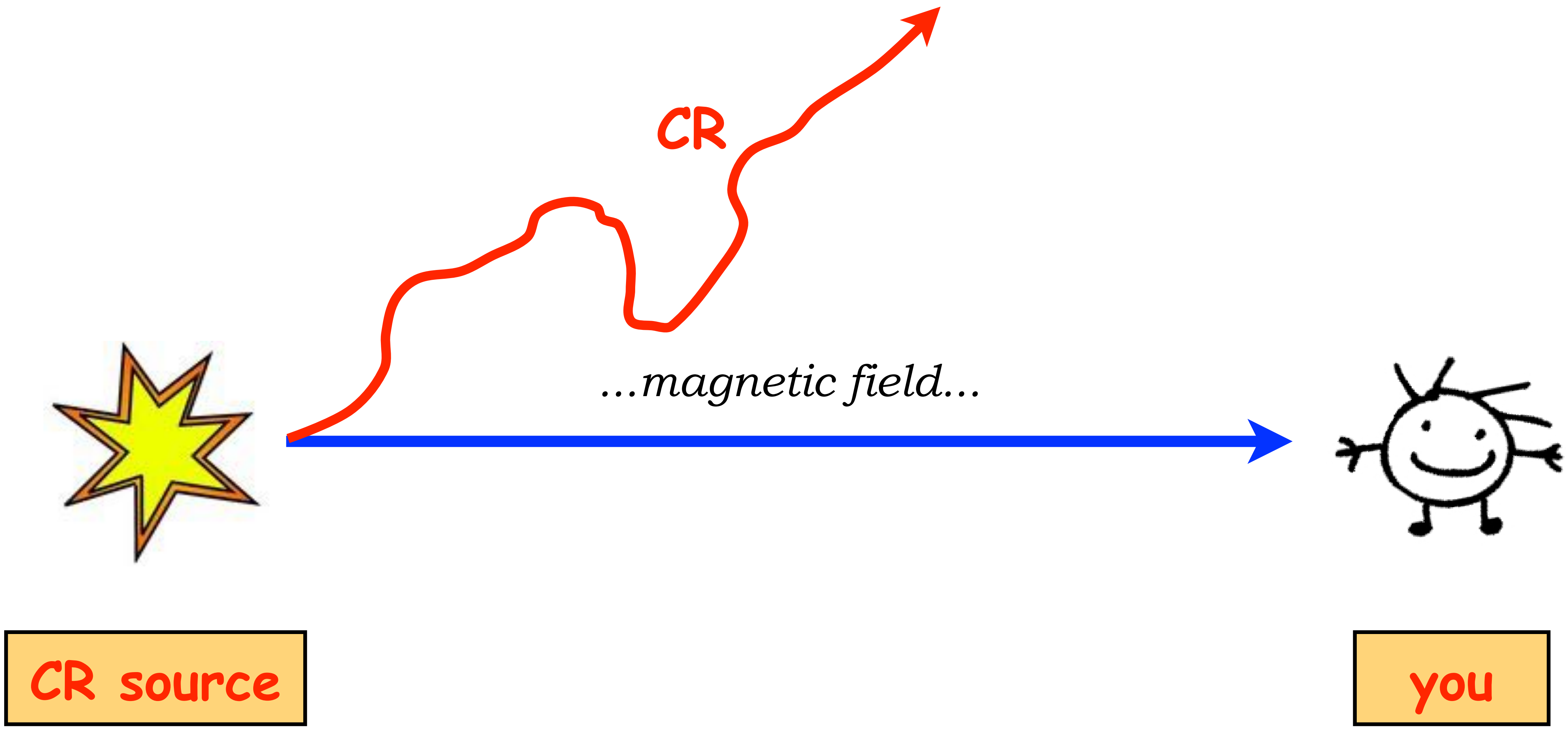






the knee —> "maximum" energy of protons accelerated at Galactic sources

Cosmic ray sources: why is it so difficult?

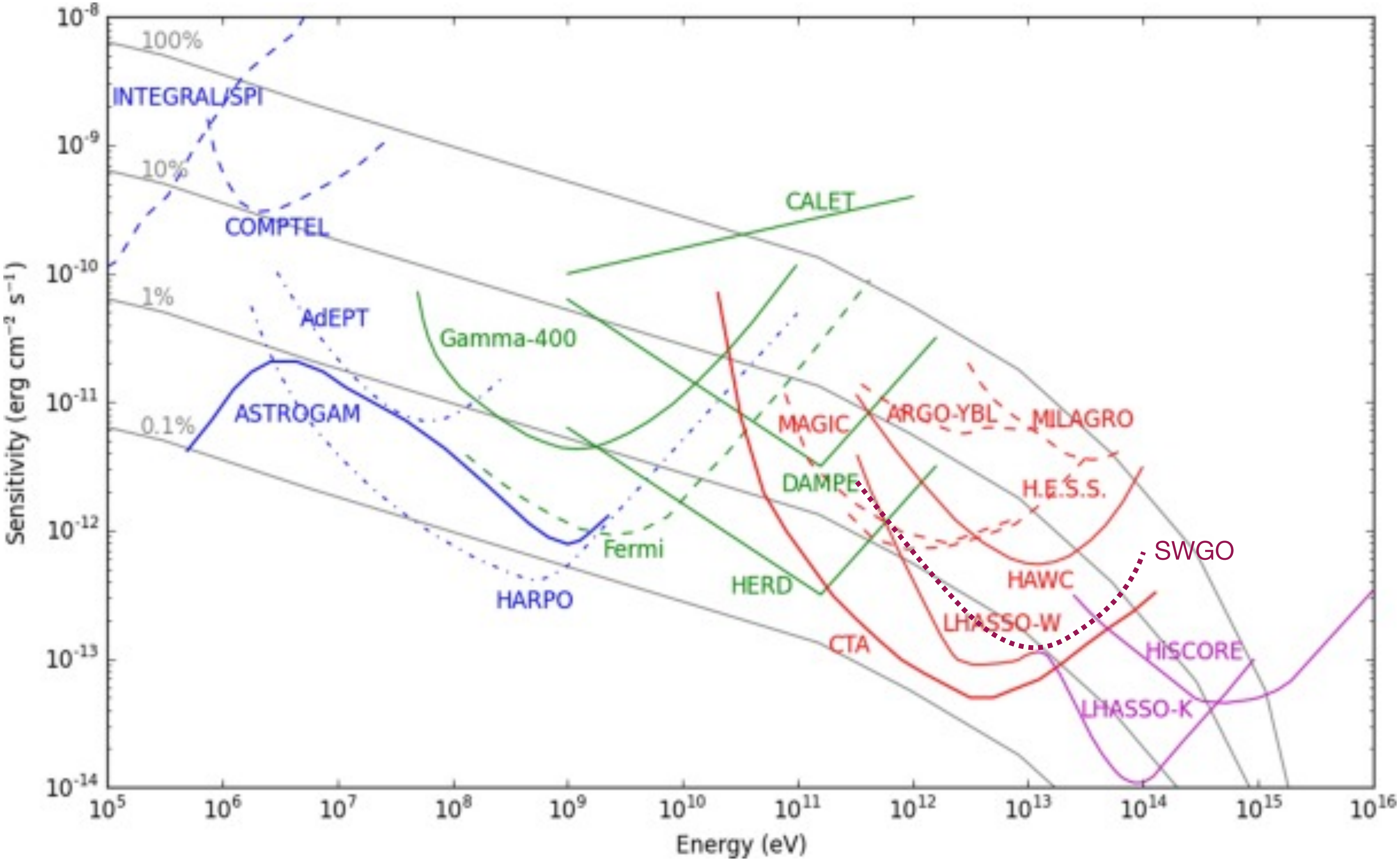


We cannot do CR Astronomy.

Need for indirect identification of CR sources.

Gamma-ray detectors

Knoedlseder 2016



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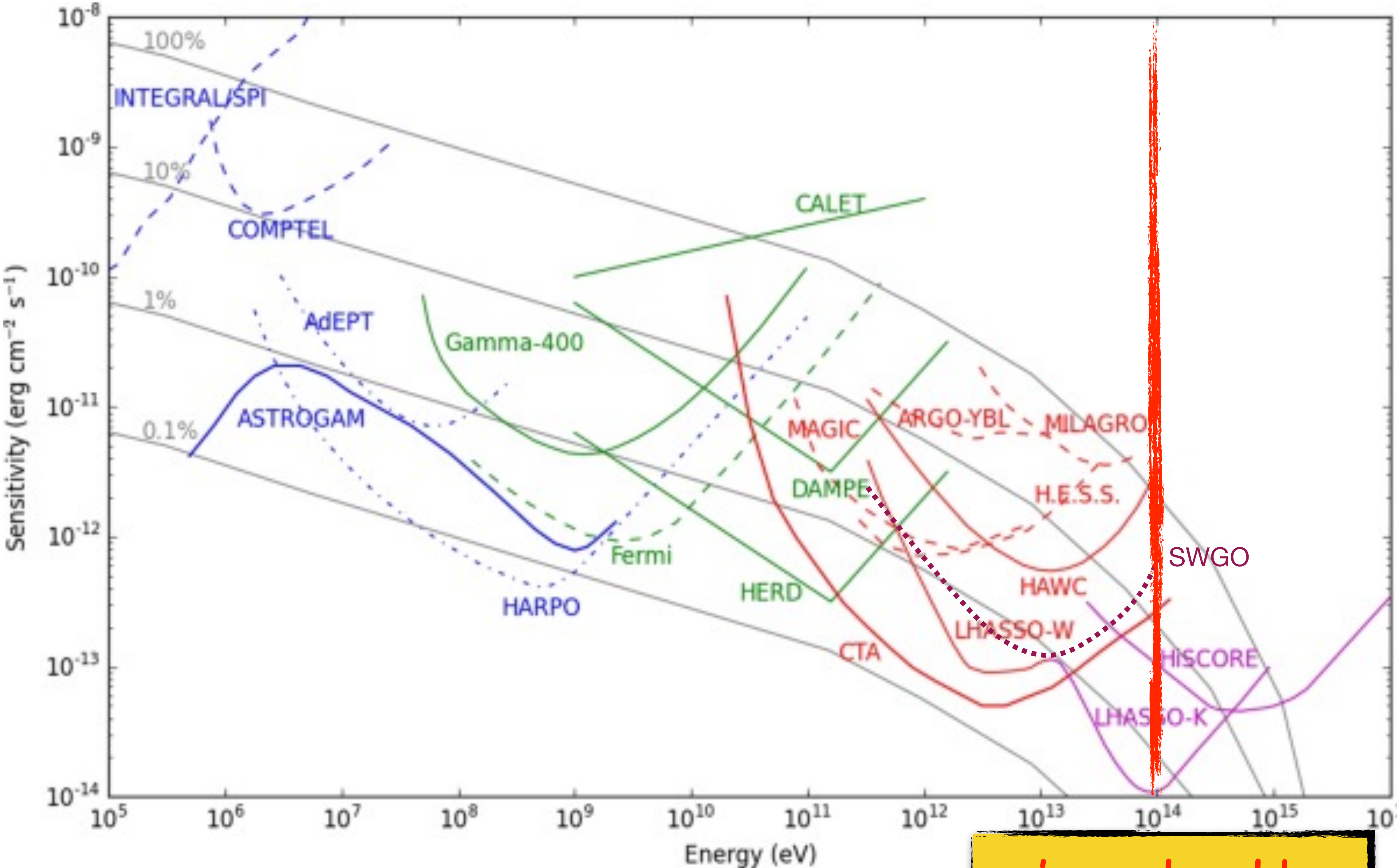
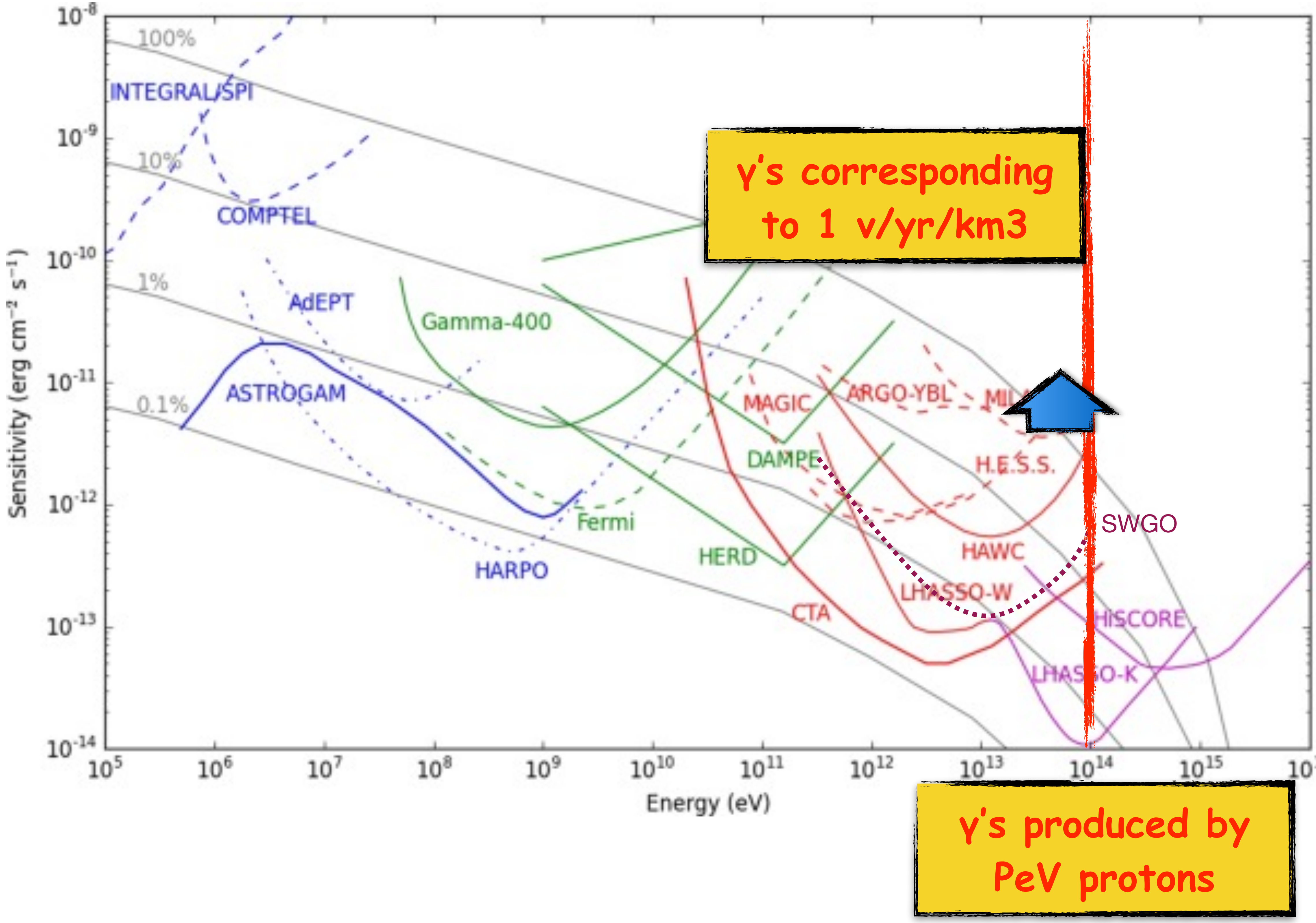


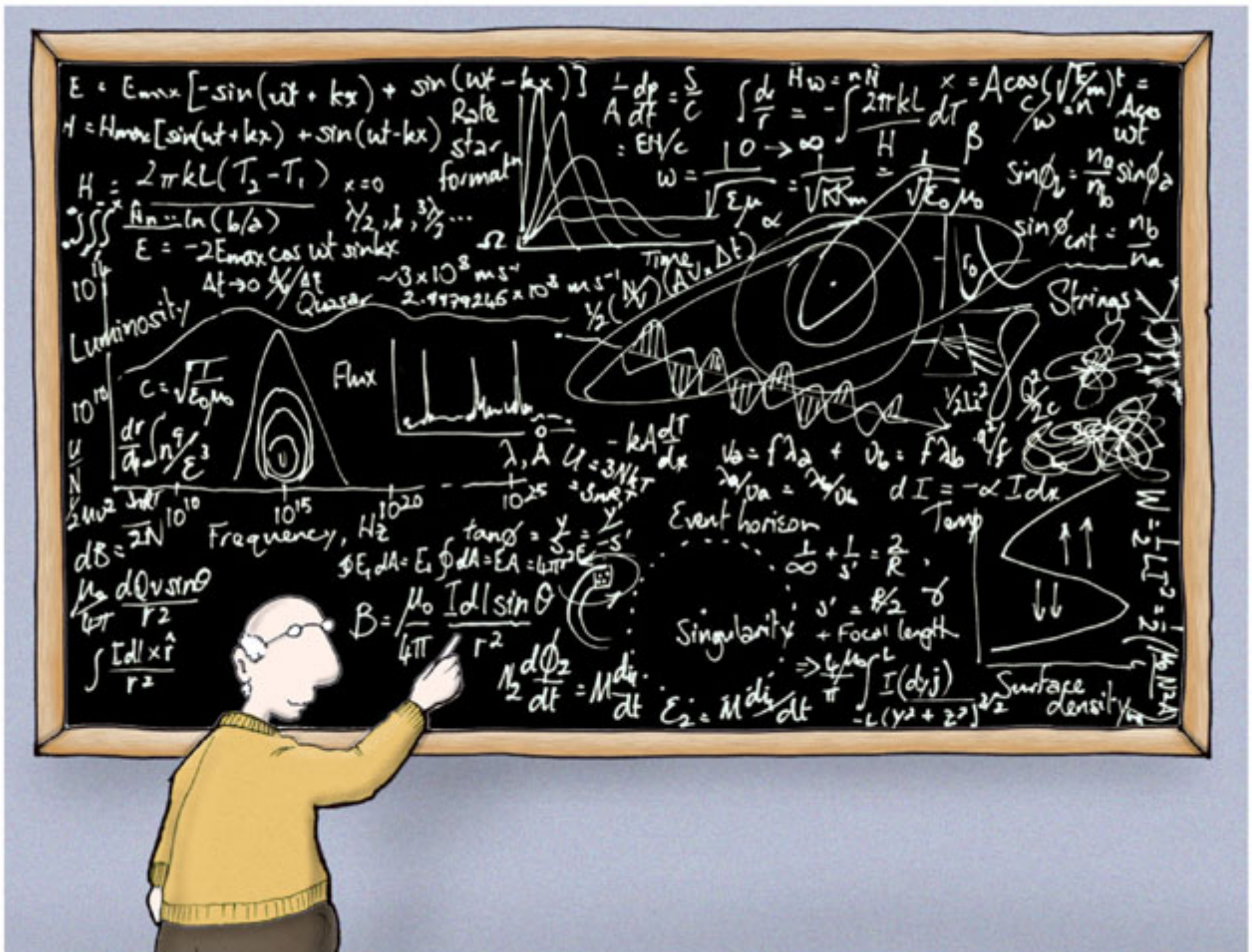
γ's produced by PeV protons

Gamma-ray detectors

Knoedlseder 2016



Why is it so difficult to study PeVatrons?



Astrophysics made simple

Charged particles and electromagnetic fields

cosmic rays are charged particles —> they are affected by electromagnetic fields

$$\vec{E}(\vec{r}, t) \qquad \vec{B}(\vec{r}, t)$$

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Simplifying assumption —> consider only constant fields

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A particle of charge q moving at a velocity u fill experience a force:

$$\vec{F} = \frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = q\left(\vec{E} + \frac{\vec{u}}{c} \times \vec{B}\right)$$

relativistic momentum $\vec{p} = \gamma m \vec{u}$

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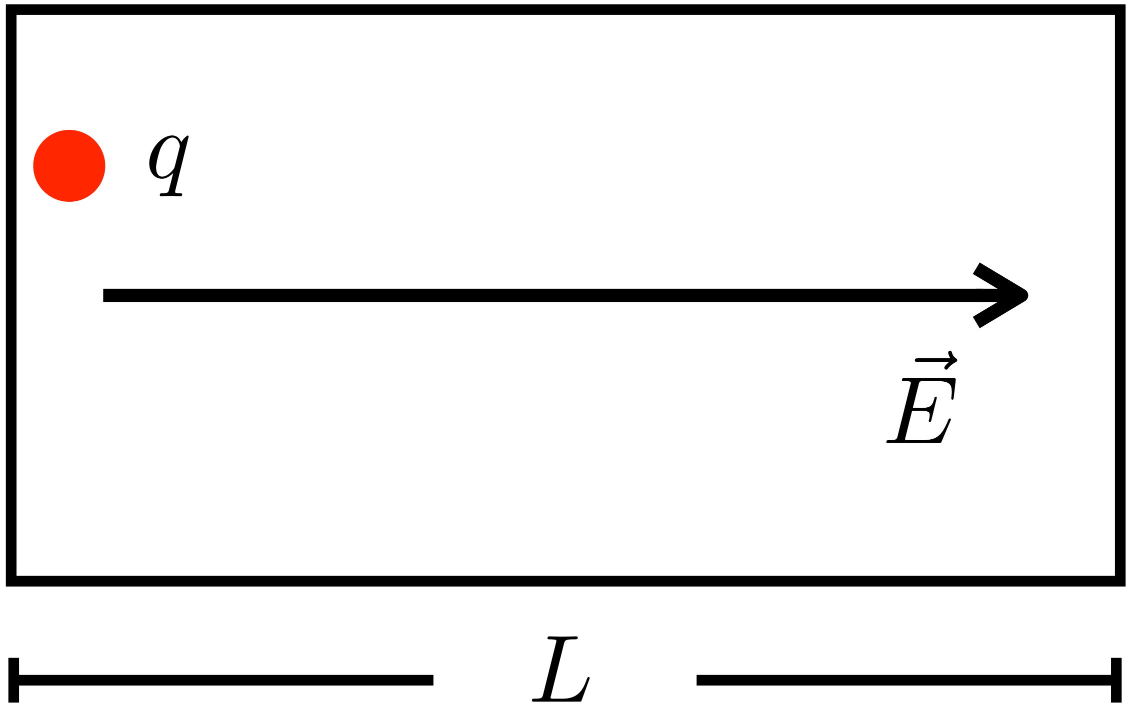
Lorentz force
$\perp$ to velocity —>
doesn't change
the particle energy!

relativistic momentum $\vec{p} = \gamma m \vec{u}$

Maximum energy

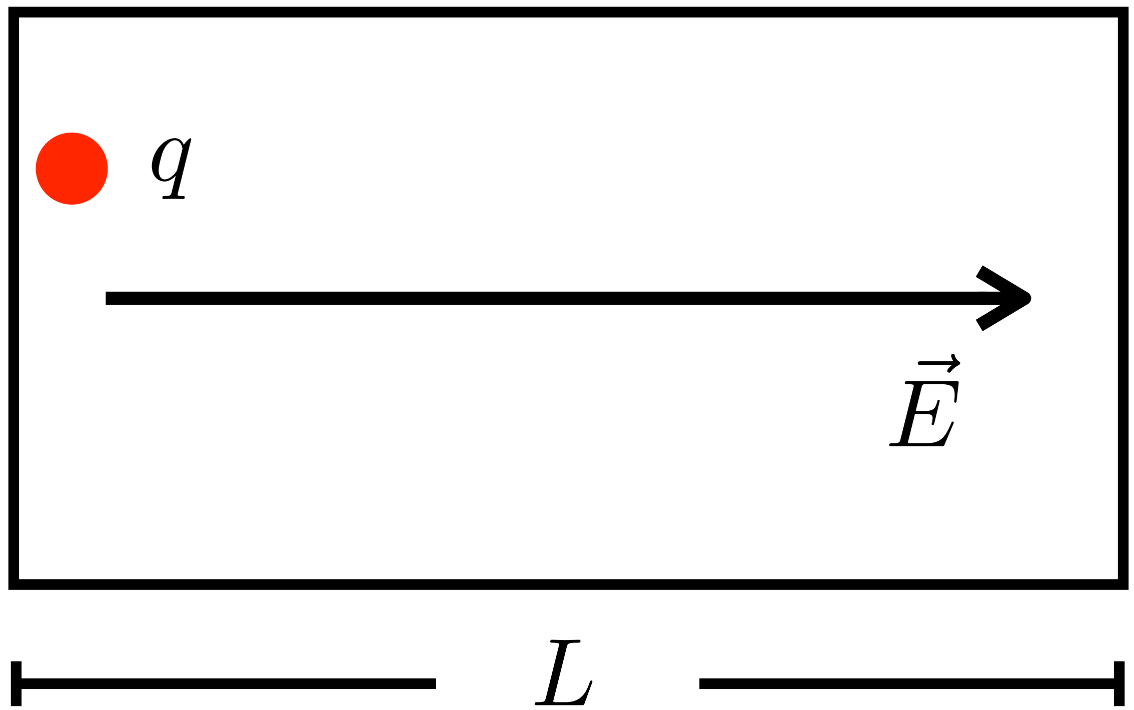
this is an accelerator



$$L \gg \frac{mc^2}{qE}$$

Maximum energy

this is an accelerator



$$L \gg \frac{mc^2}{qE}$$

$$E_t^{max} = qEtc = qEL$$

large charge

strong E field

large accelerator

Can we keep a static and uniform electric field in an astrophysical plasma?

unfortunately, that's quite difficult…

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An excess of electrical charge is needed to maintain a static electric field. However we should remember…

> "…a basic property of plasma, its tendency towards electrical neutrality. If over a large volume the number of electrons per cubic centimeter deviates appreciably from the corresponding number of positive ions, the electrostatic forces resulting yield a potential energy per particle that is enormously greater than the mean thermal energy. Unless very special mechanisms are involved to support such large potentials, the charged particles will rapidly move in such a way as to reduce these potential difference, i.e., to restore electrical neutrality."

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So, the answer is no…

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So, the answer is no...

...but there is still maybe some hope?

Way-out: time varying B

We DO need electric fields to accelerate particles!

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Maxwell equations

$$\nabla \vec{E} = 4\pi\varrho$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{4\pi}{c}\vec{j} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

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$$\nabla \vec{E} = 4\pi\varrho = 0$$ —> plasma quasi-neutrality

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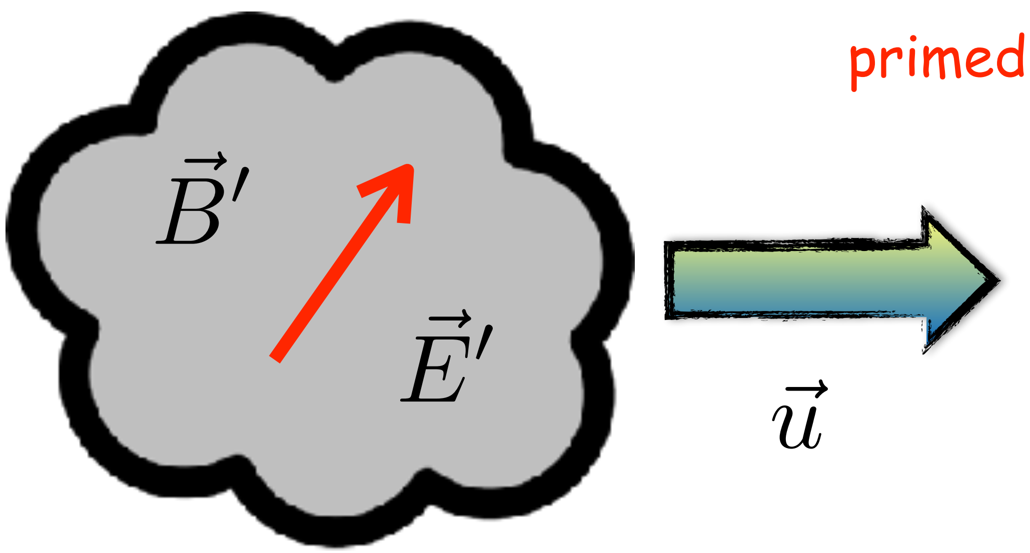
A time varying magnetic field acts as a source of electric field!

An equivalent way: change rest frame

Consider a magnetised cloud of plasma moving at a (non relativistic) velocity u



primed quantities —> cloud frame

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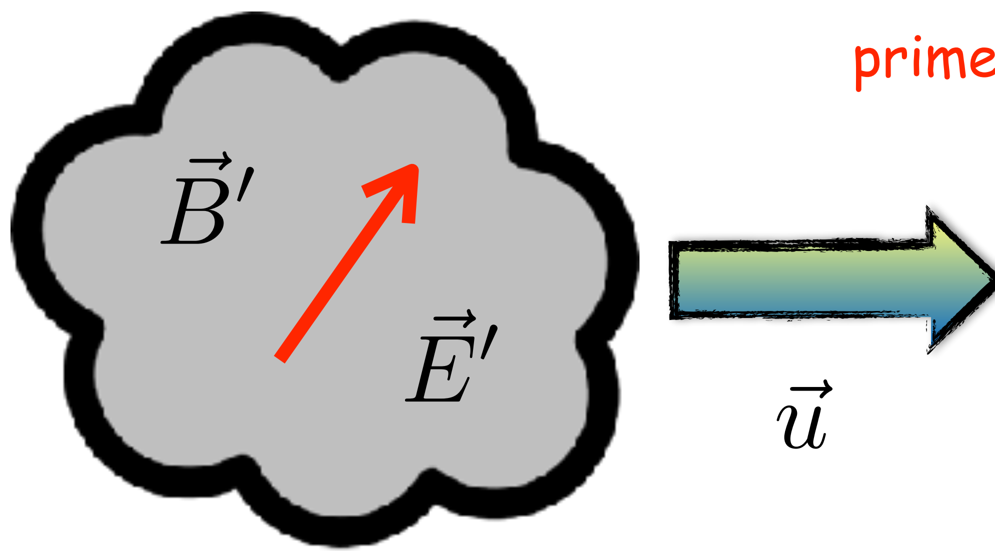

Lorentz transformation

$$\vec{E}' = \vec{E} + \frac{\vec{u}}{c} \times \vec{B}$$

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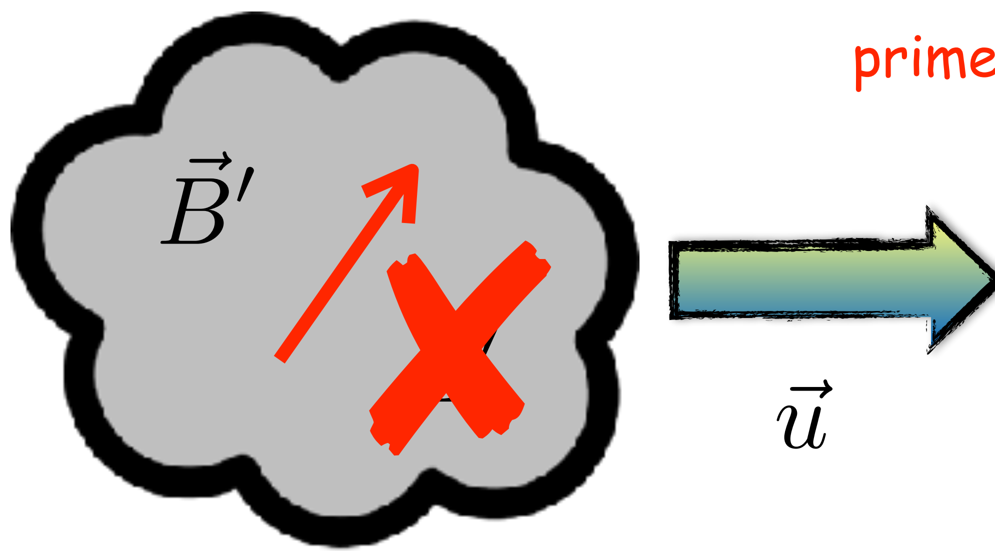

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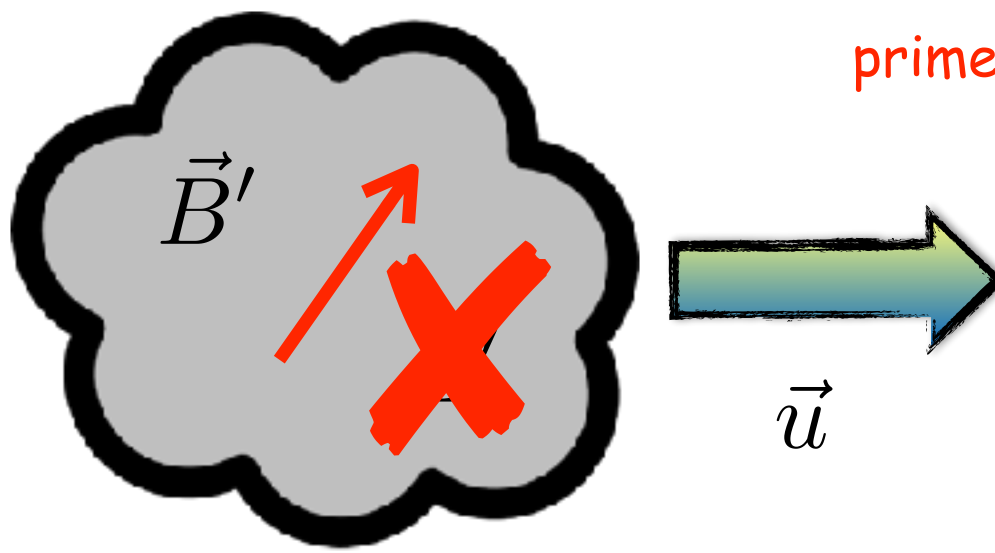

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an observer in the lab frame sees an electric field!

Order of magnitude estimates of the induced electric field

time-varying B-field

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characteristic length

$$\nabla \times \quad \rightarrow \quad \frac{1}{L}$$

$$\frac{\partial}{\partial t} \quad \rightarrow \quad \frac{1}{T}$$

characteristic time

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$$E \approx \frac{L}{T}\frac{B}{c} \approx \frac{U}{c}B$$

characteristic velocity

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Let's go back to the results obtained for the electrostatic accelerator

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electric charge → $\left(\frac{q}{c}\right)$

B-field → B

velocity → U

size → L

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electric charge (q), velocity (U), B-field (B), size (L)

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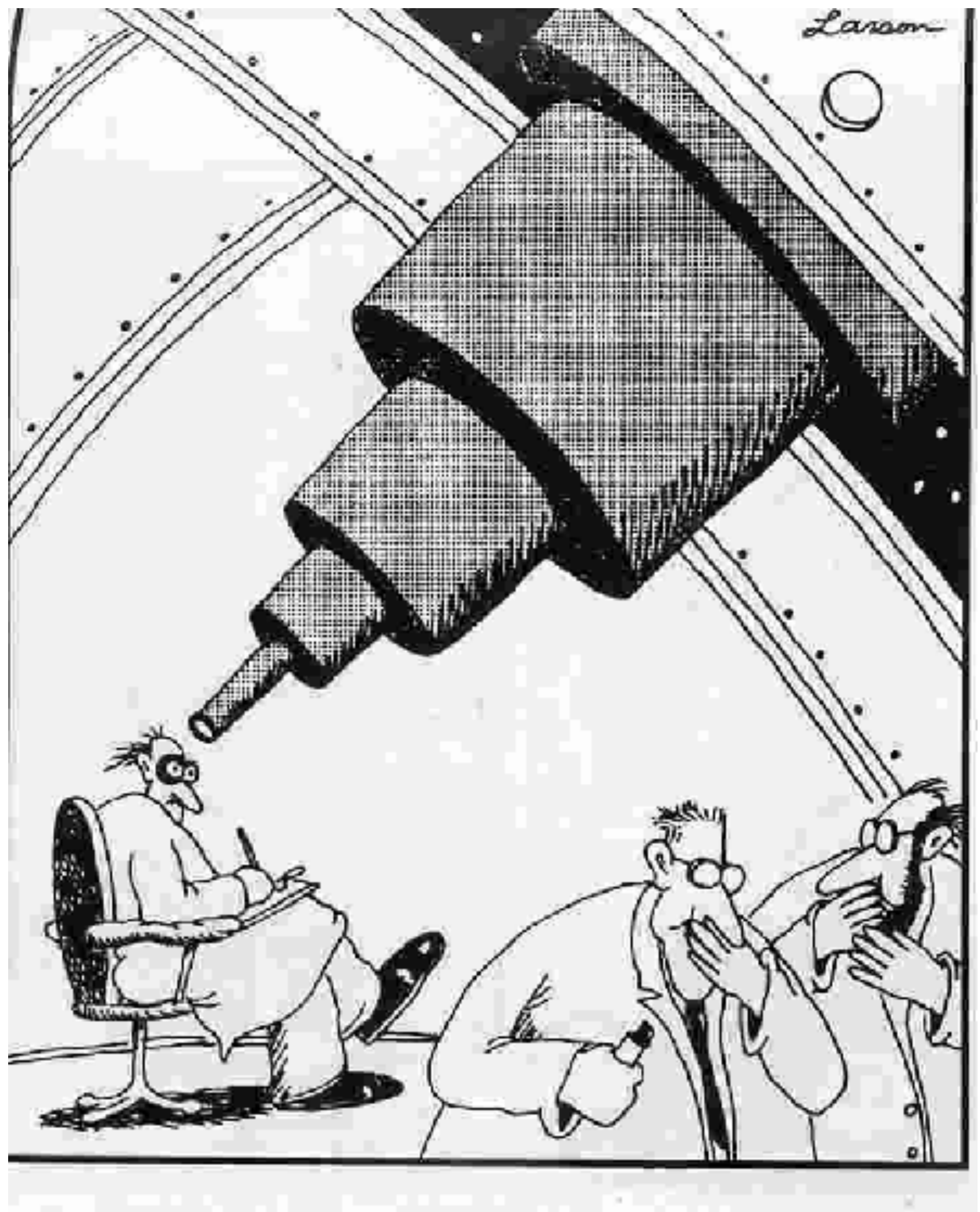
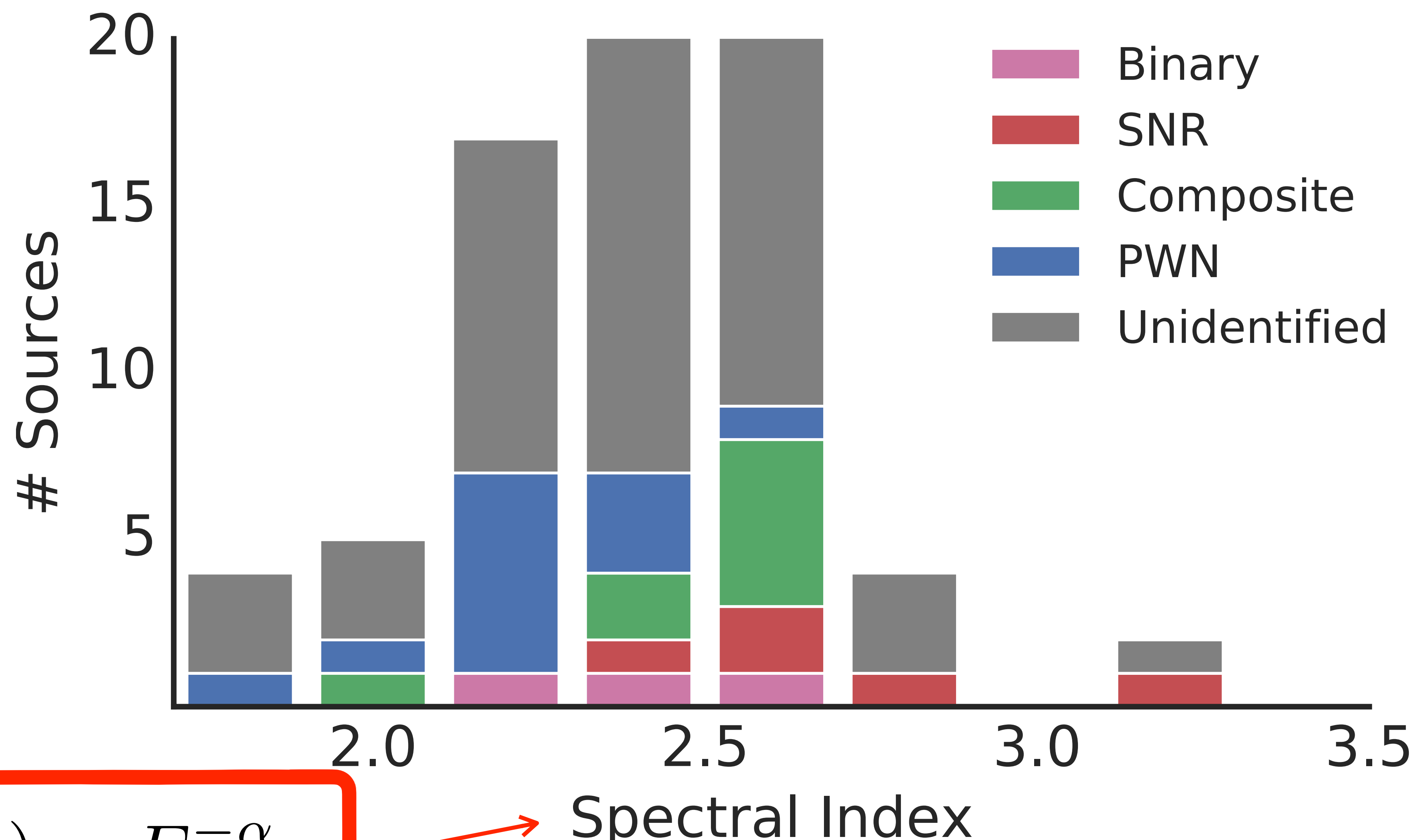


Gamma-ray spectra are steep!

$$F_\gamma(E_\gamma) \propto E_\gamma^{-\alpha}$$

Gamma-ray spectra are steep!

Galactic plane survey performed by HESS above ~100 GeV



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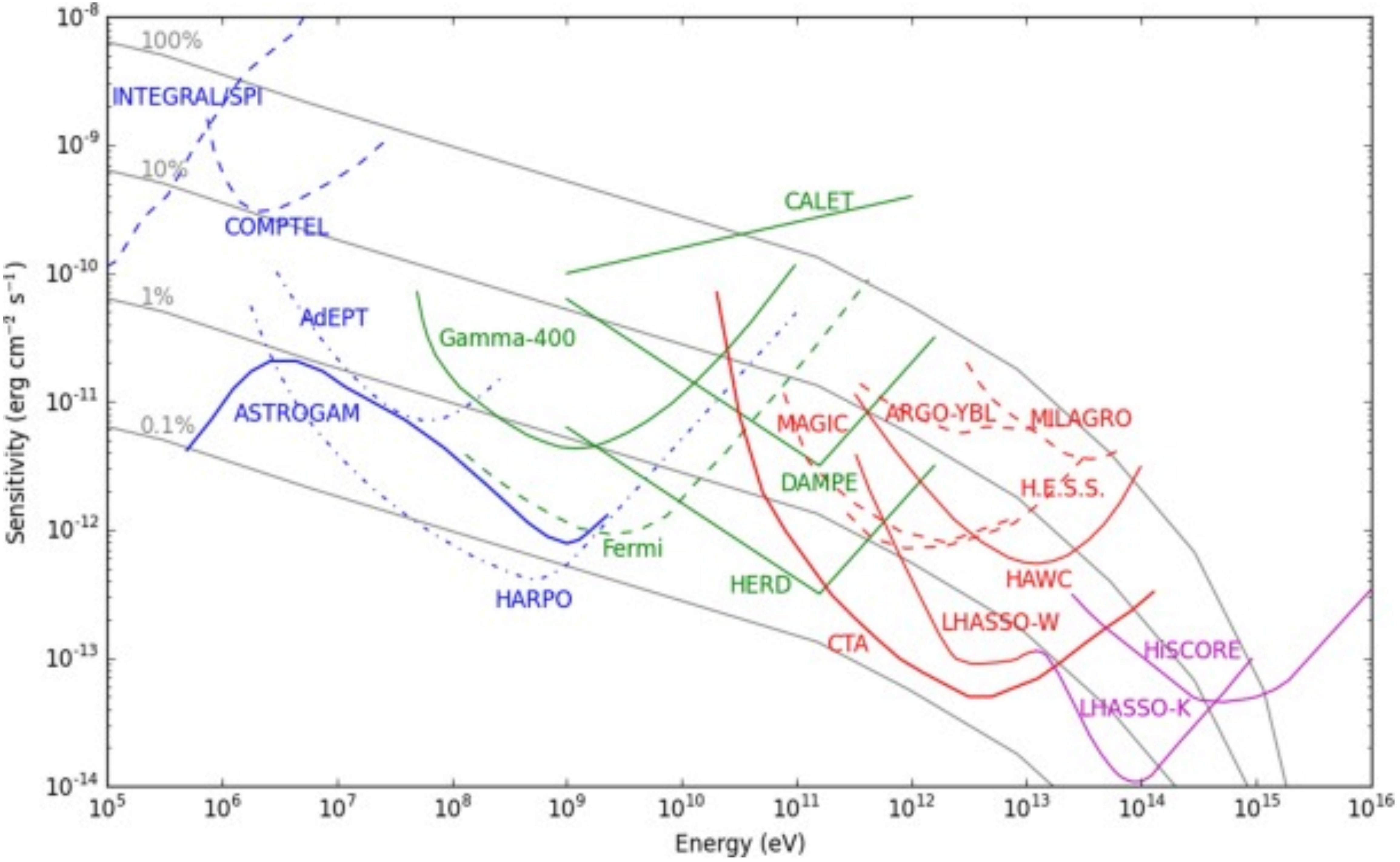
HESS Collaboration 2018

Gamma-ray detectors

Knoedlseder 2016



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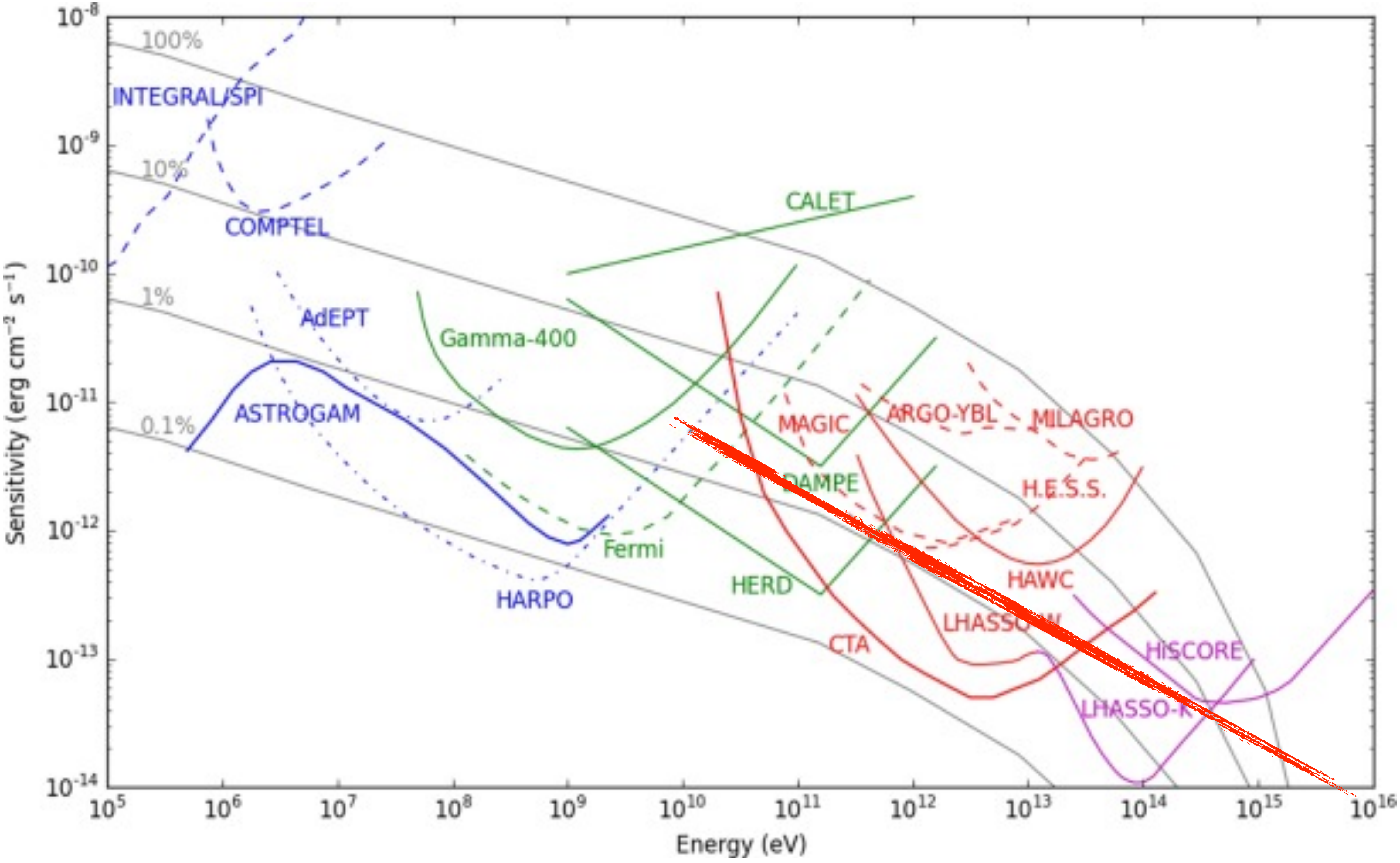

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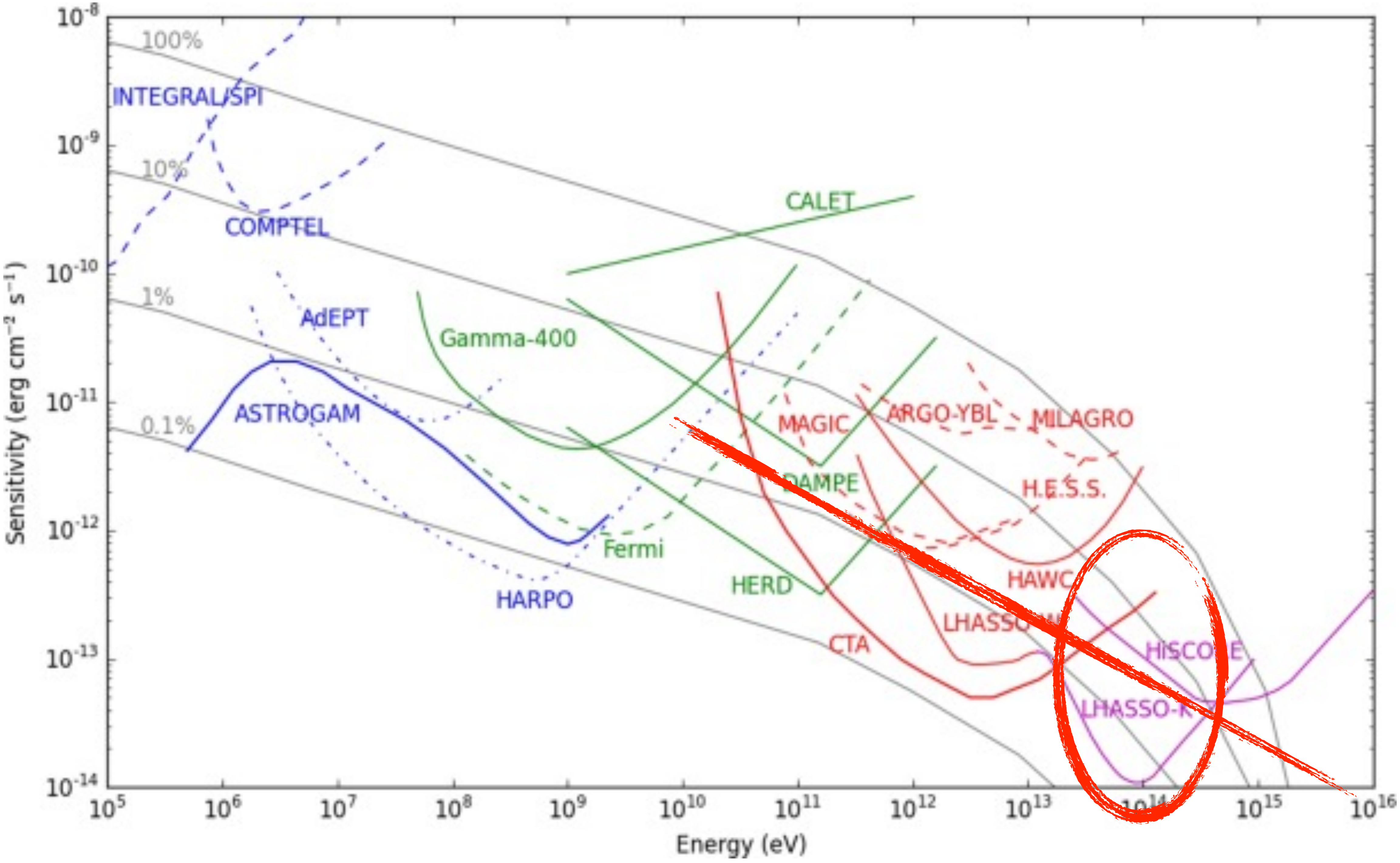
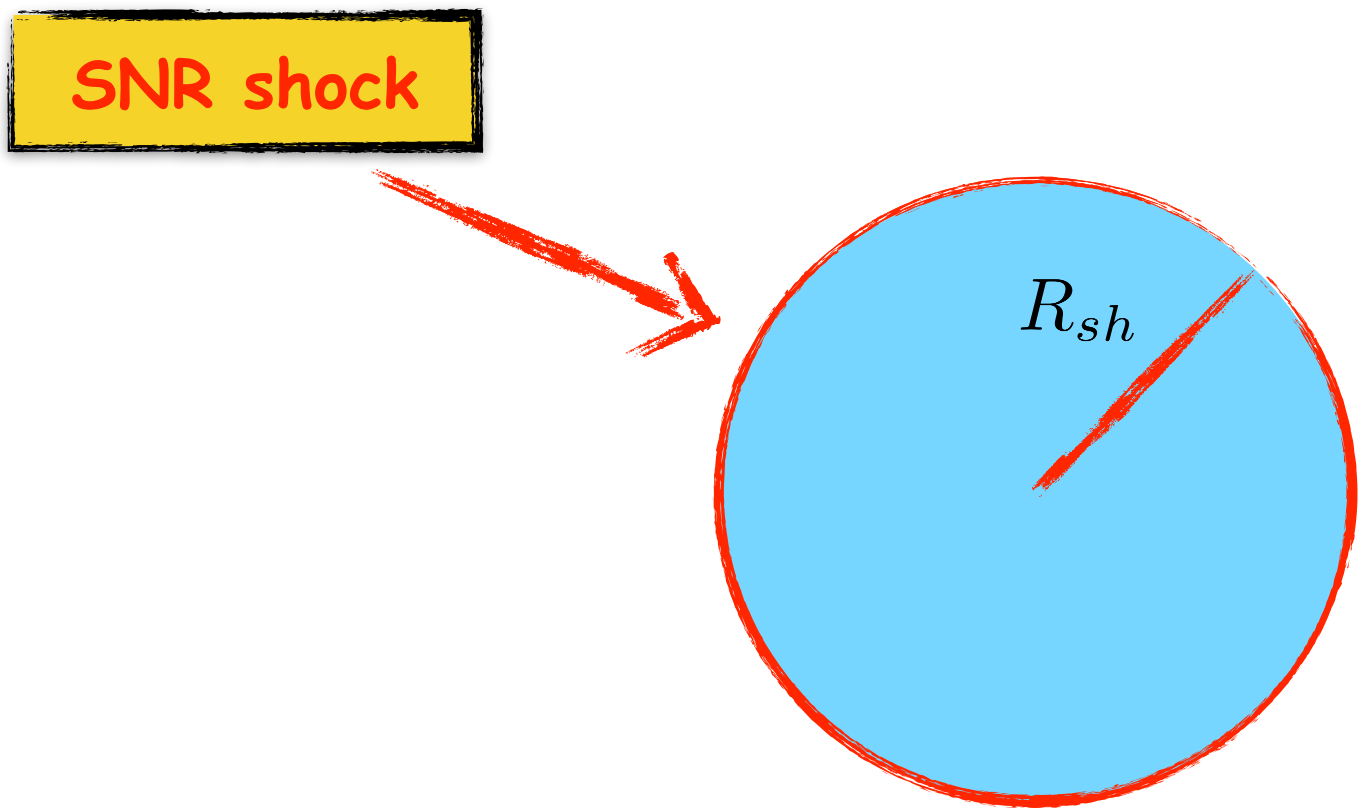


Supernova remnants

SNRs are spherical —> CR escape!



e.g. Drury 2011

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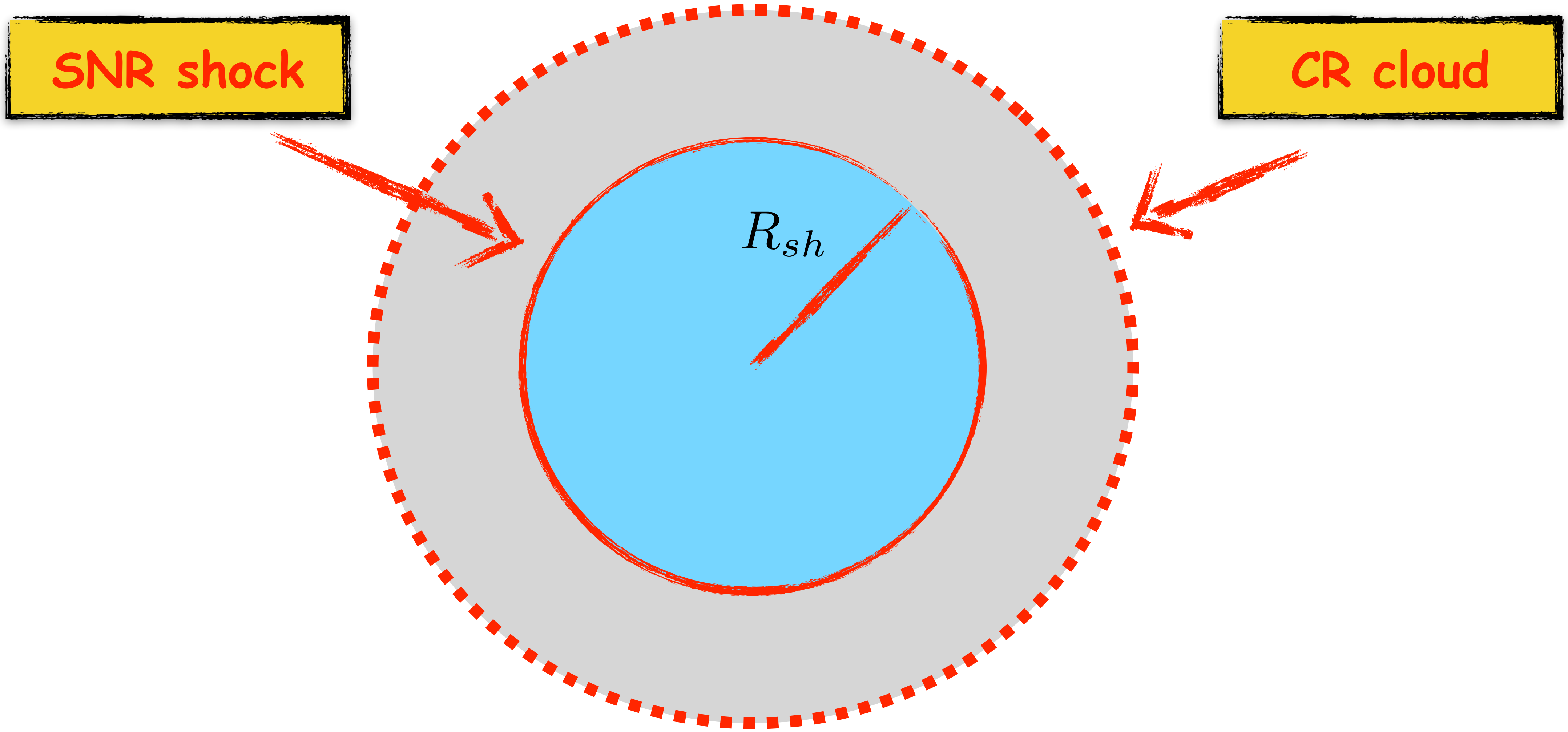

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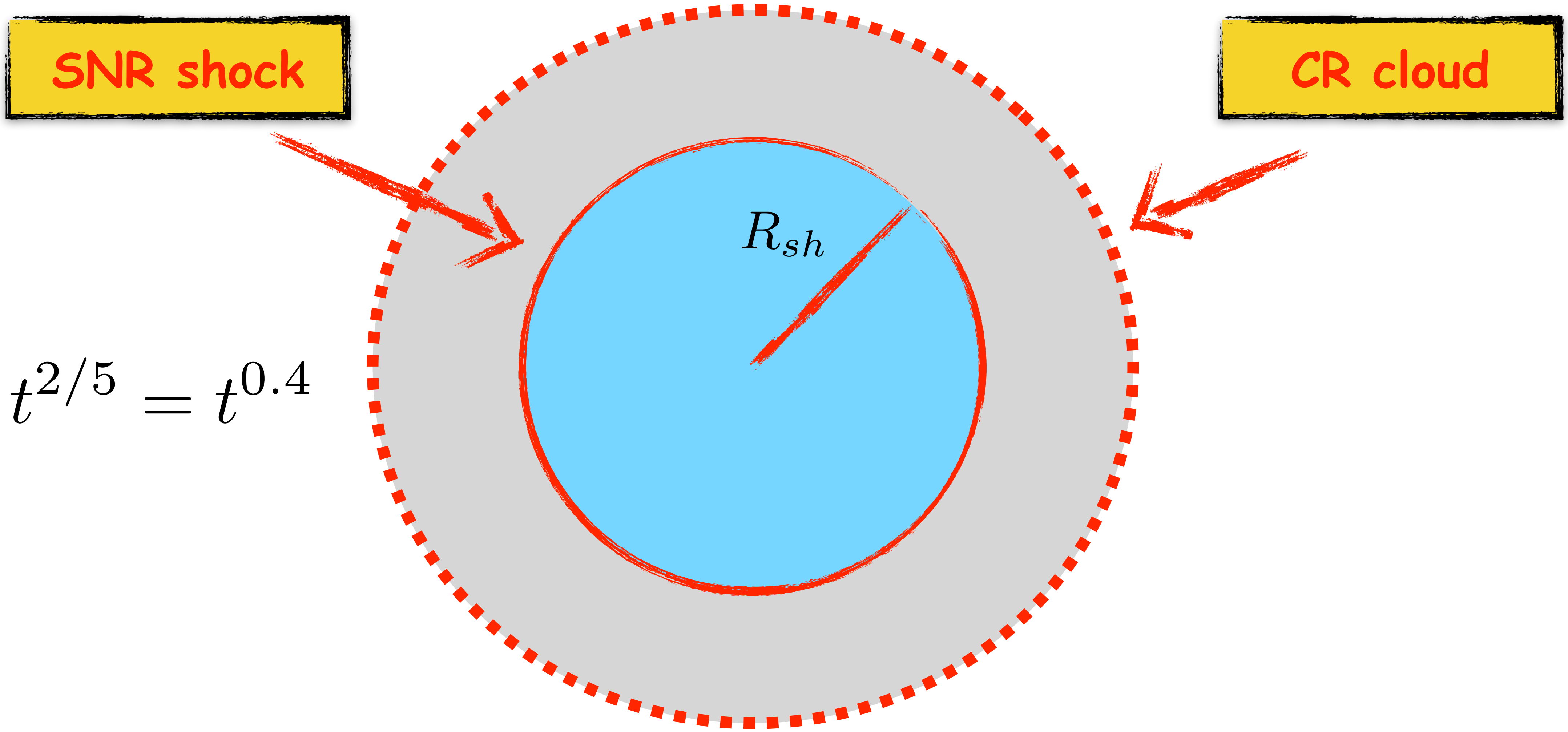

$$R_{sh} \propto t^{2/5} = t^{0.4}$$

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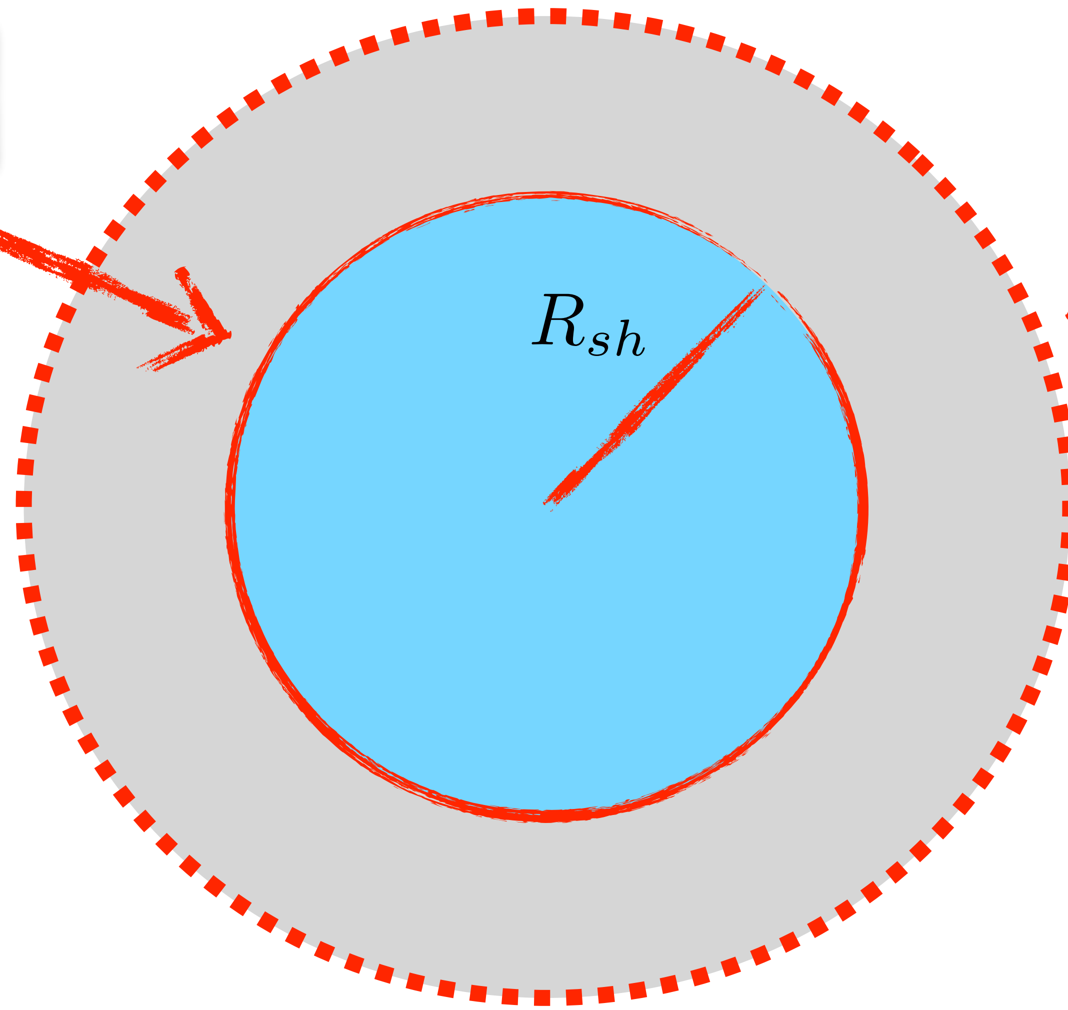
SNR shock

CR cloud



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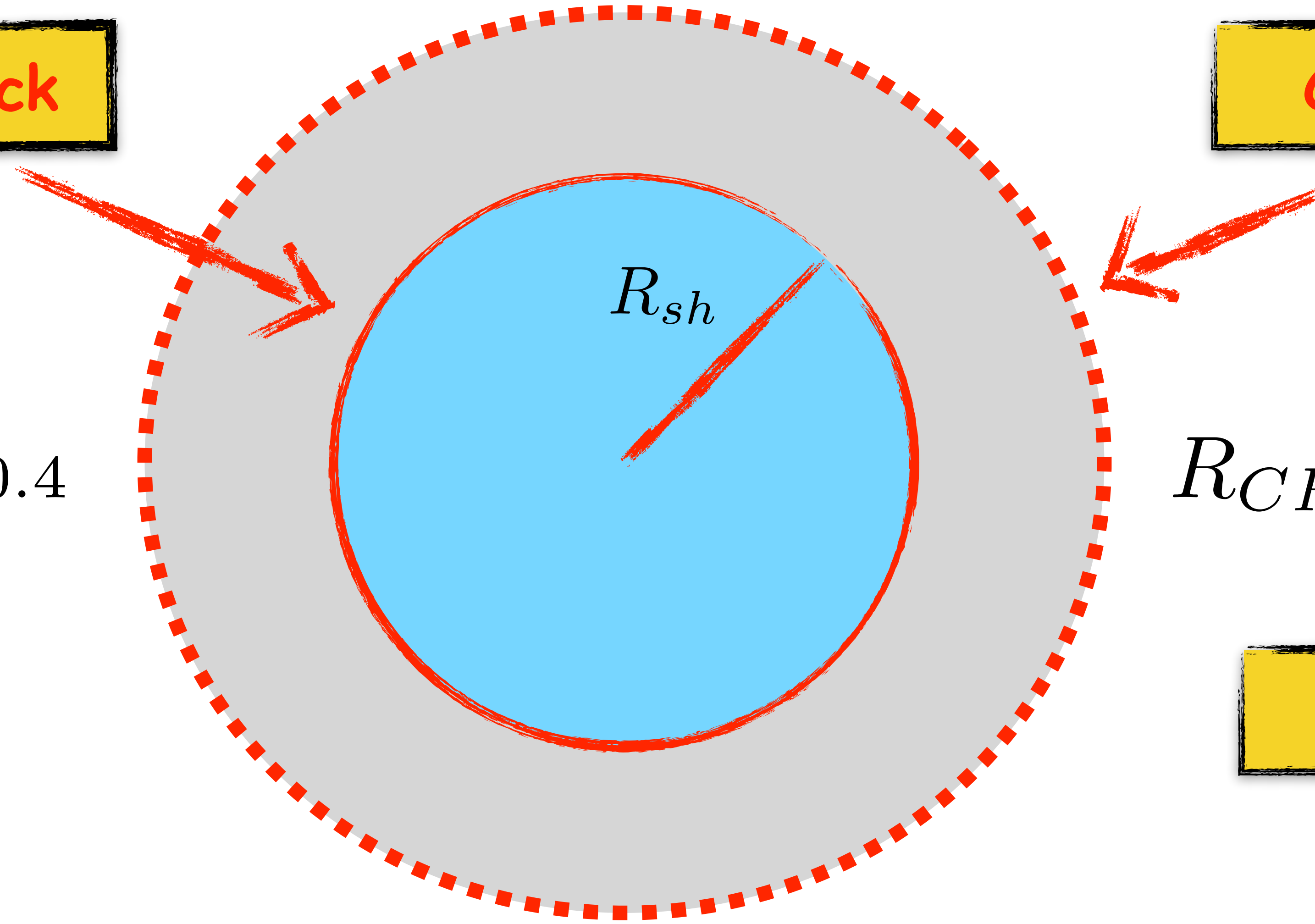

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faster!

e.g. Drury 2011

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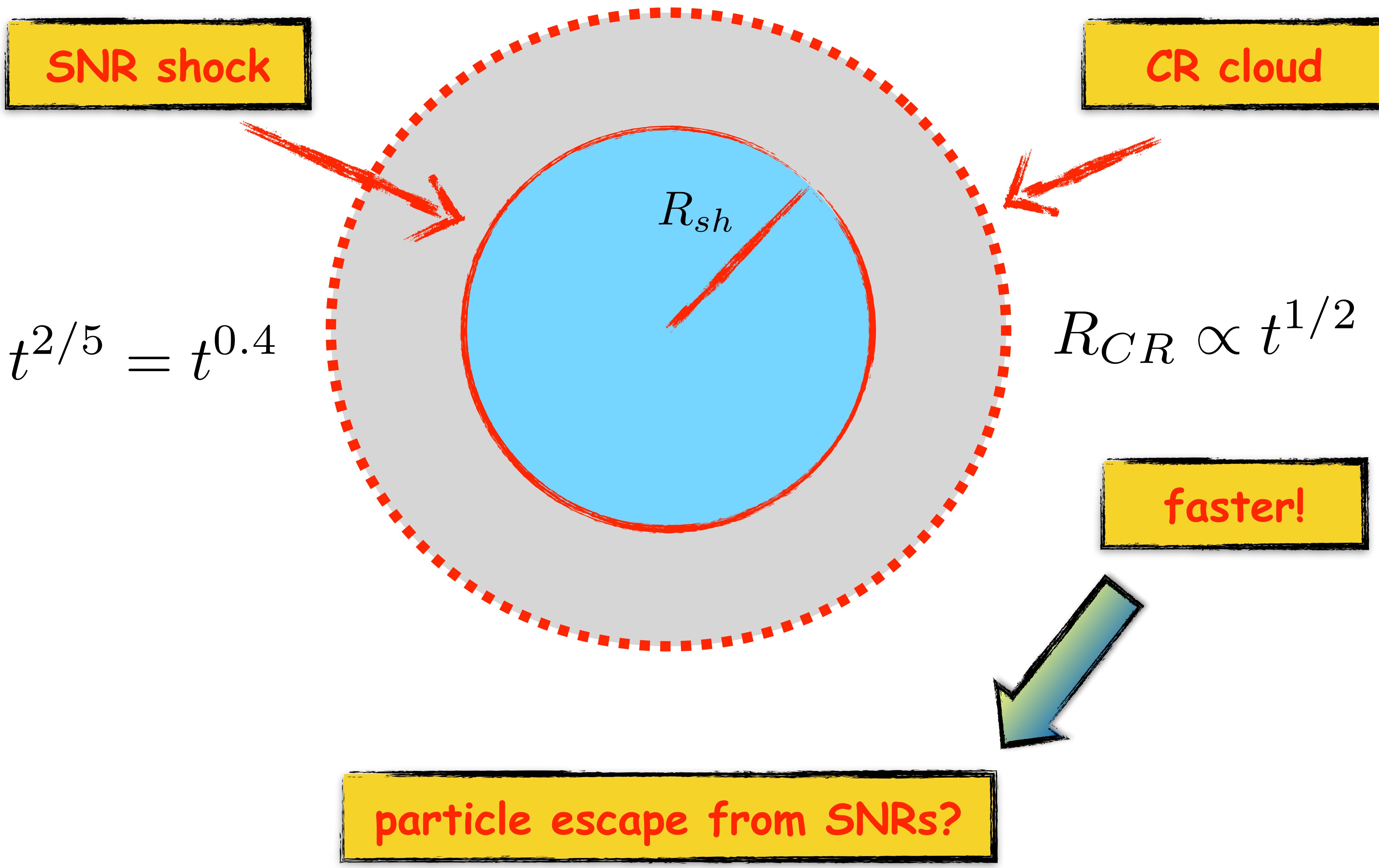

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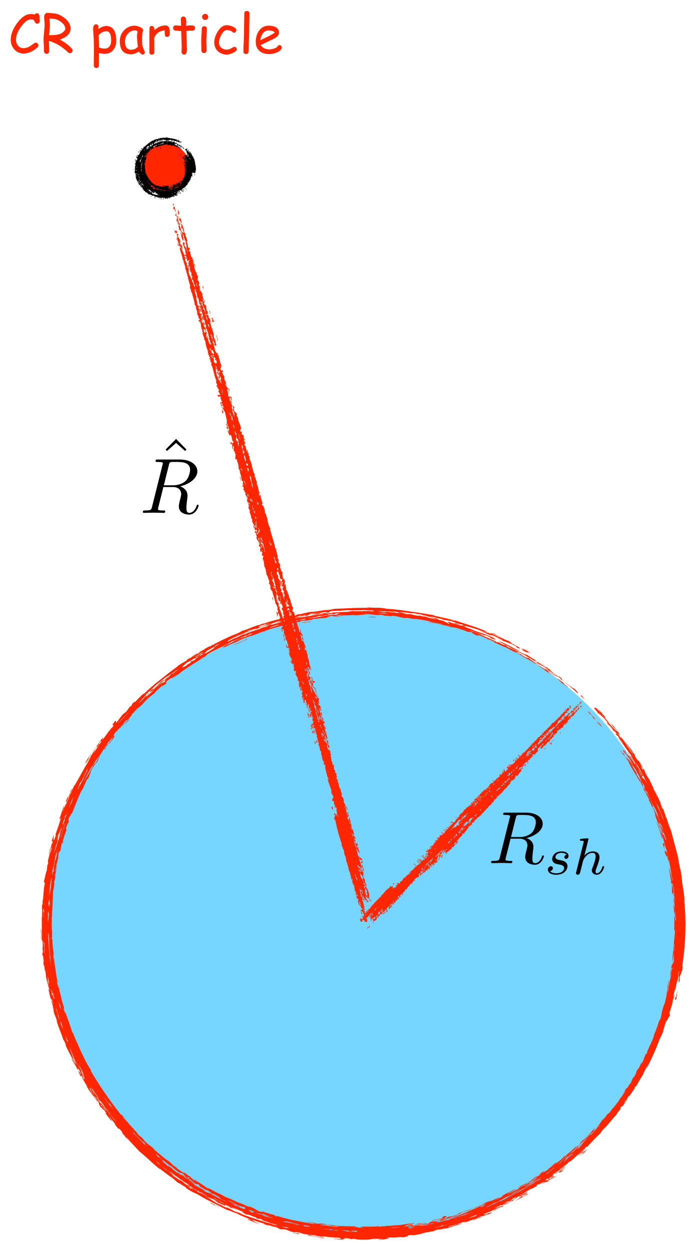
SNRs are spherical —> CR escape!

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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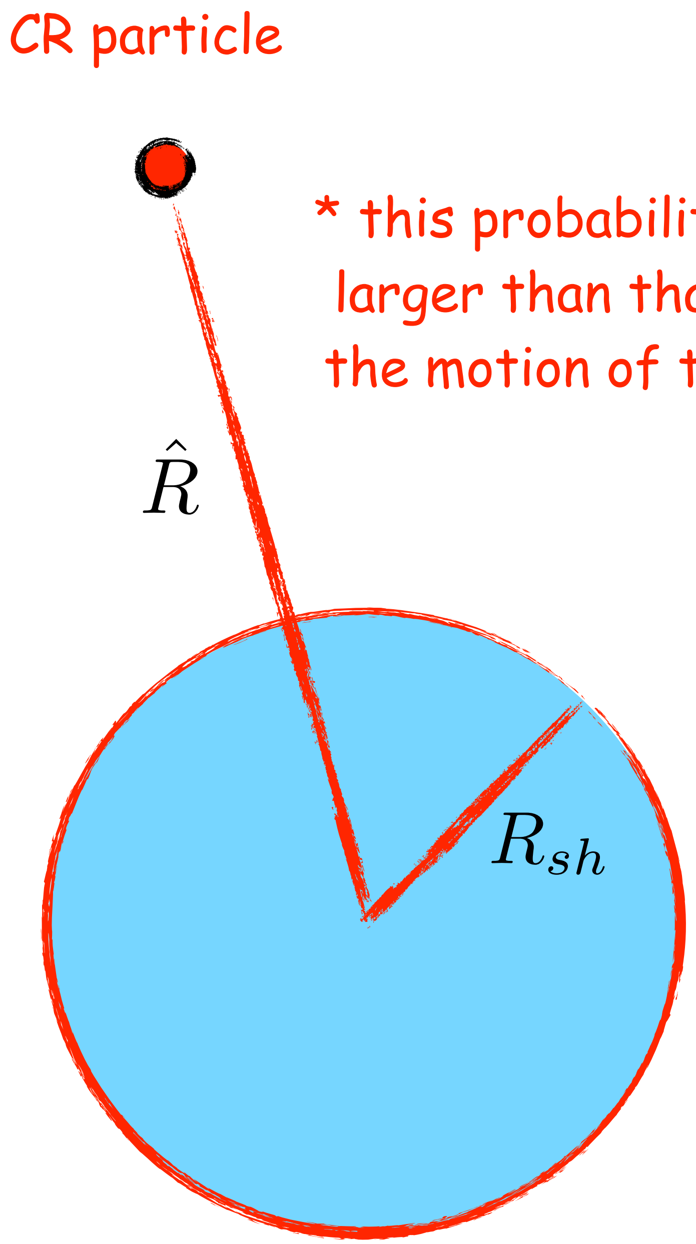

* this probability is a bit larger than that due to the motion of the shock

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

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particles have a non-vanishing probability to return to the shock even if they are quite far from it

Drury 2011

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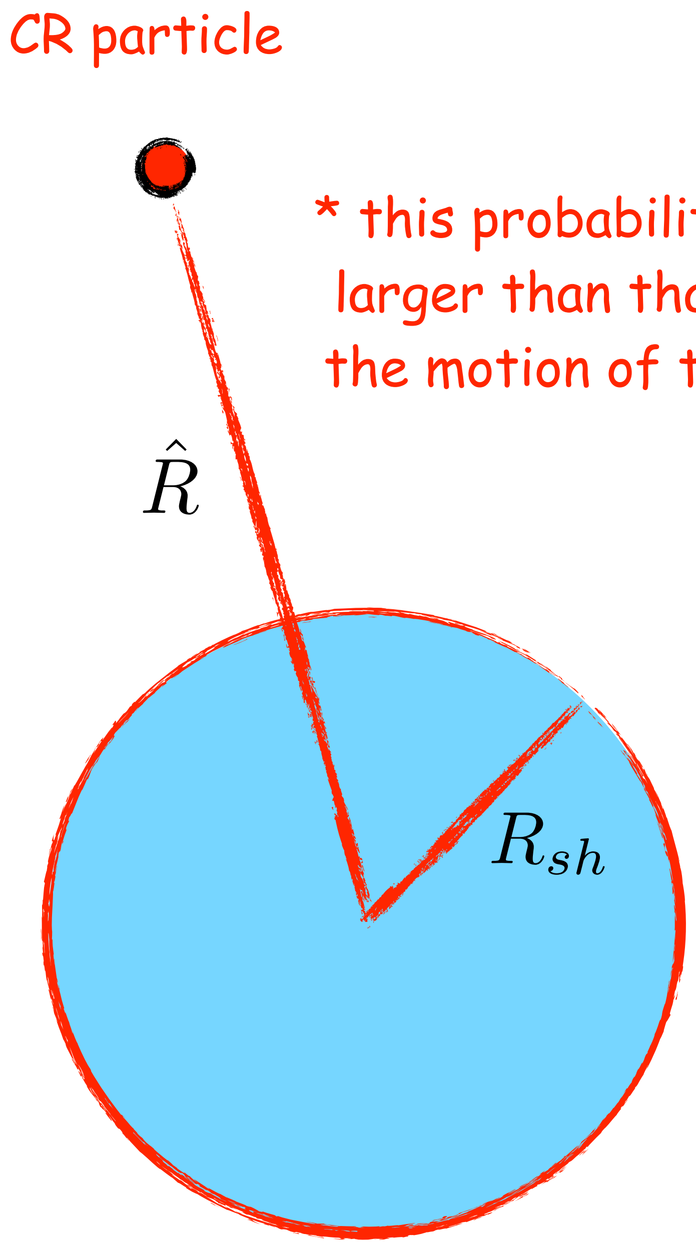

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in order to maintain an effective acceleration, such probability should be very close to 1

$$P_{ret} = 1 - \frac{u_{sh}}{c} \gtrsim 0.97$$

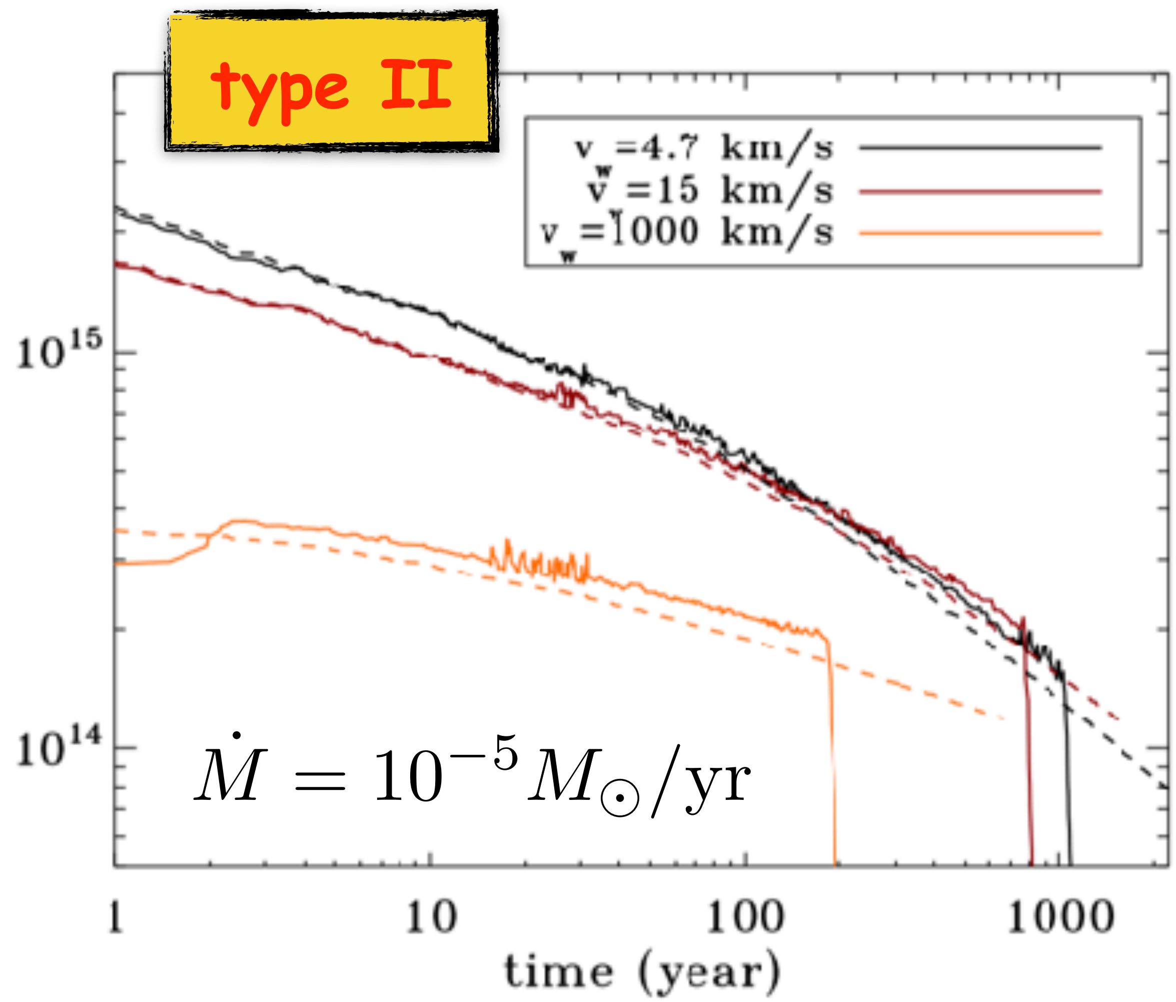
← free expansion

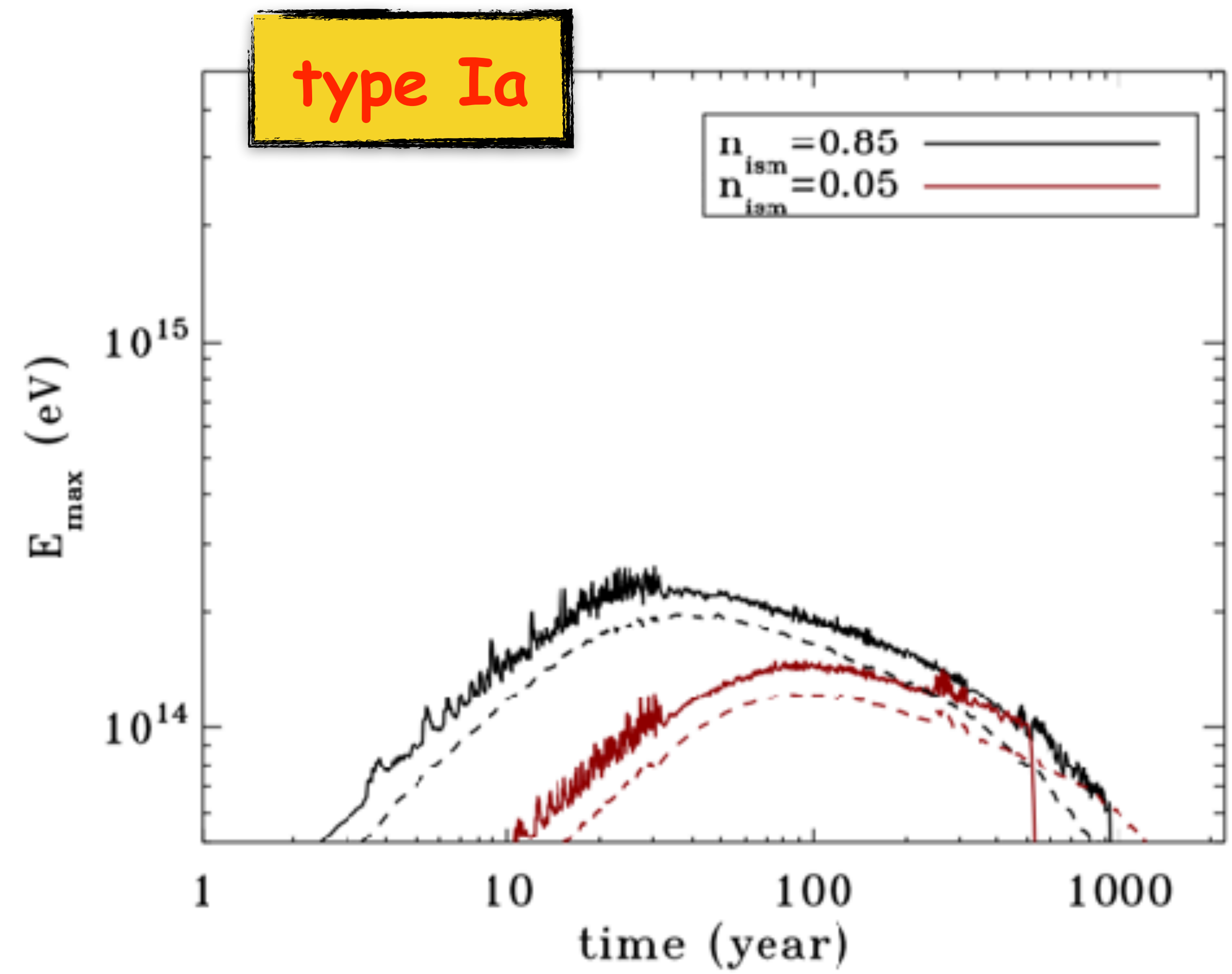
Drury 2011

Bell 1978

Only very young SNRs accelerate to PeV

Schure & Bell 2013





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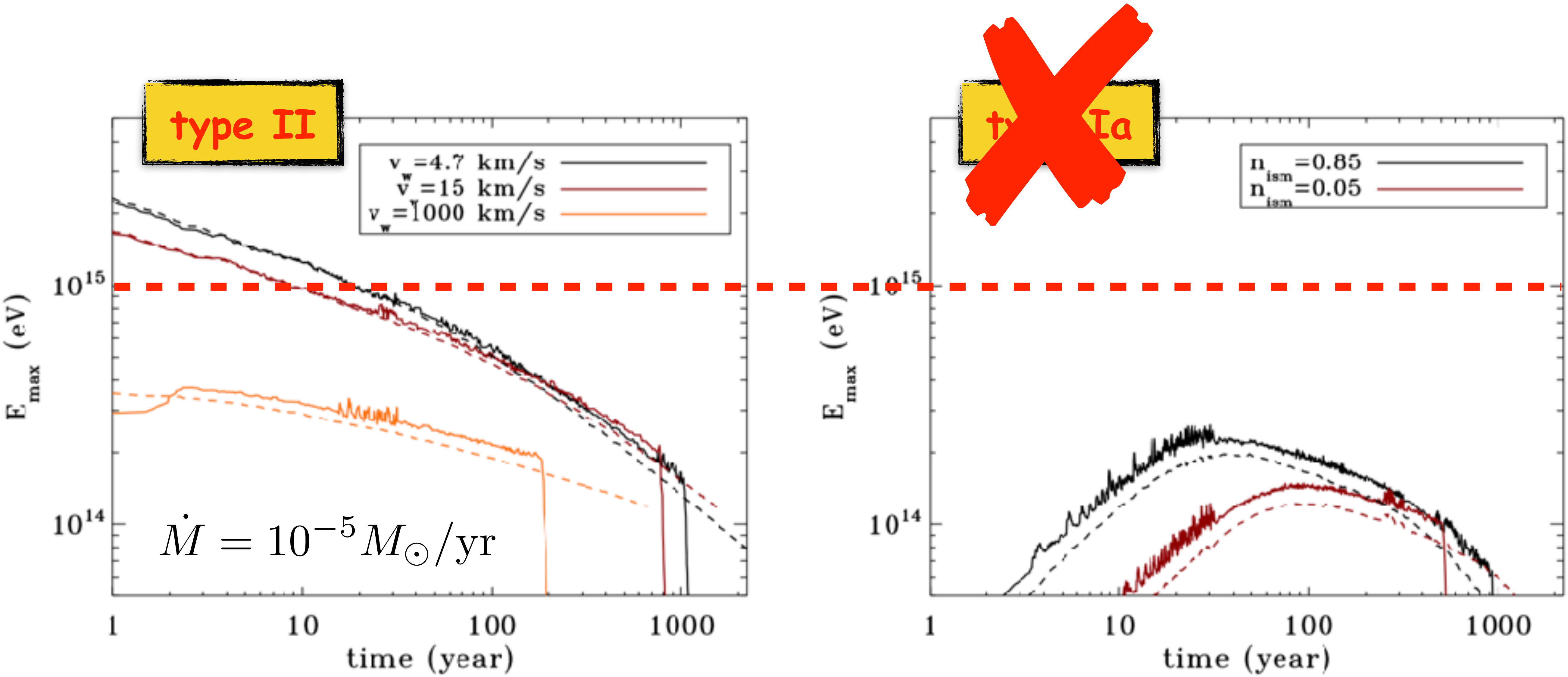

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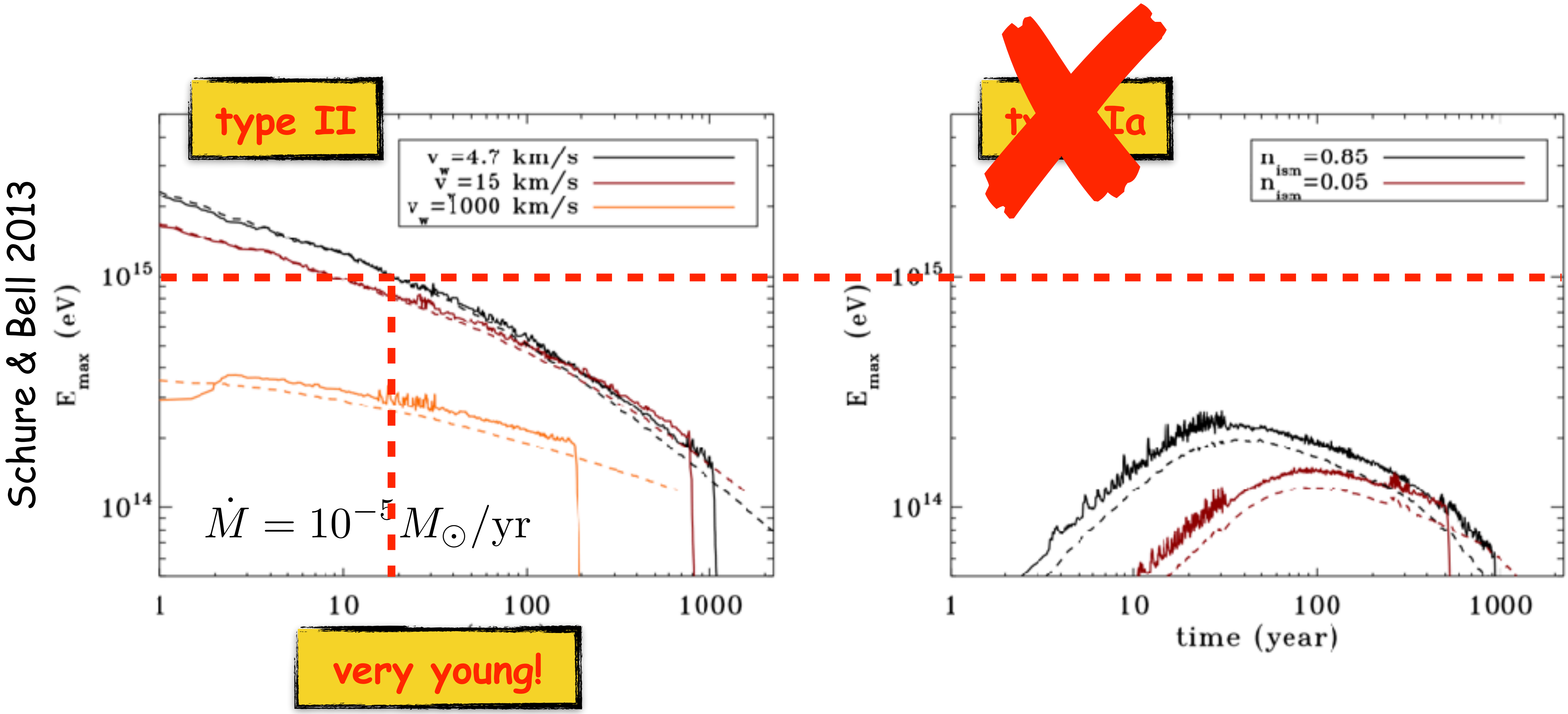

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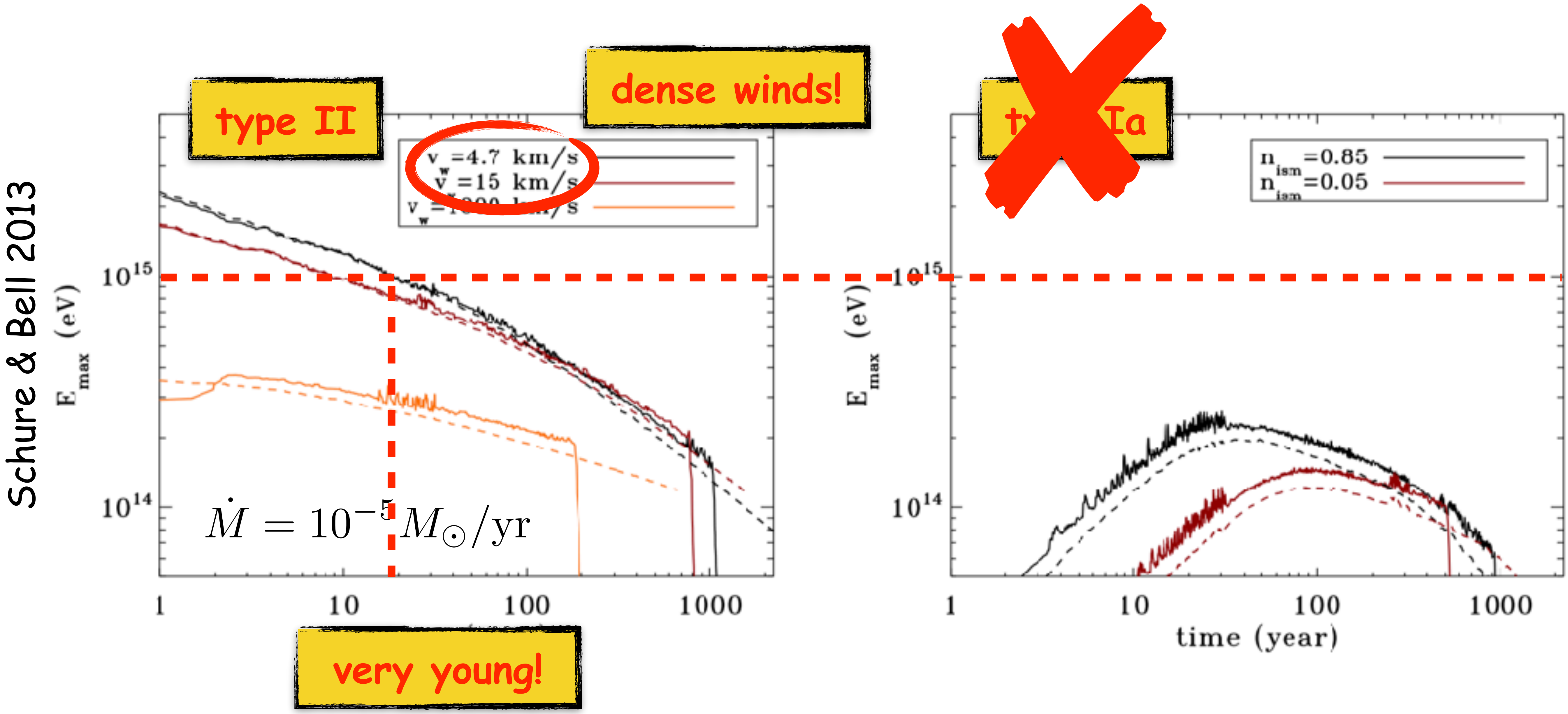

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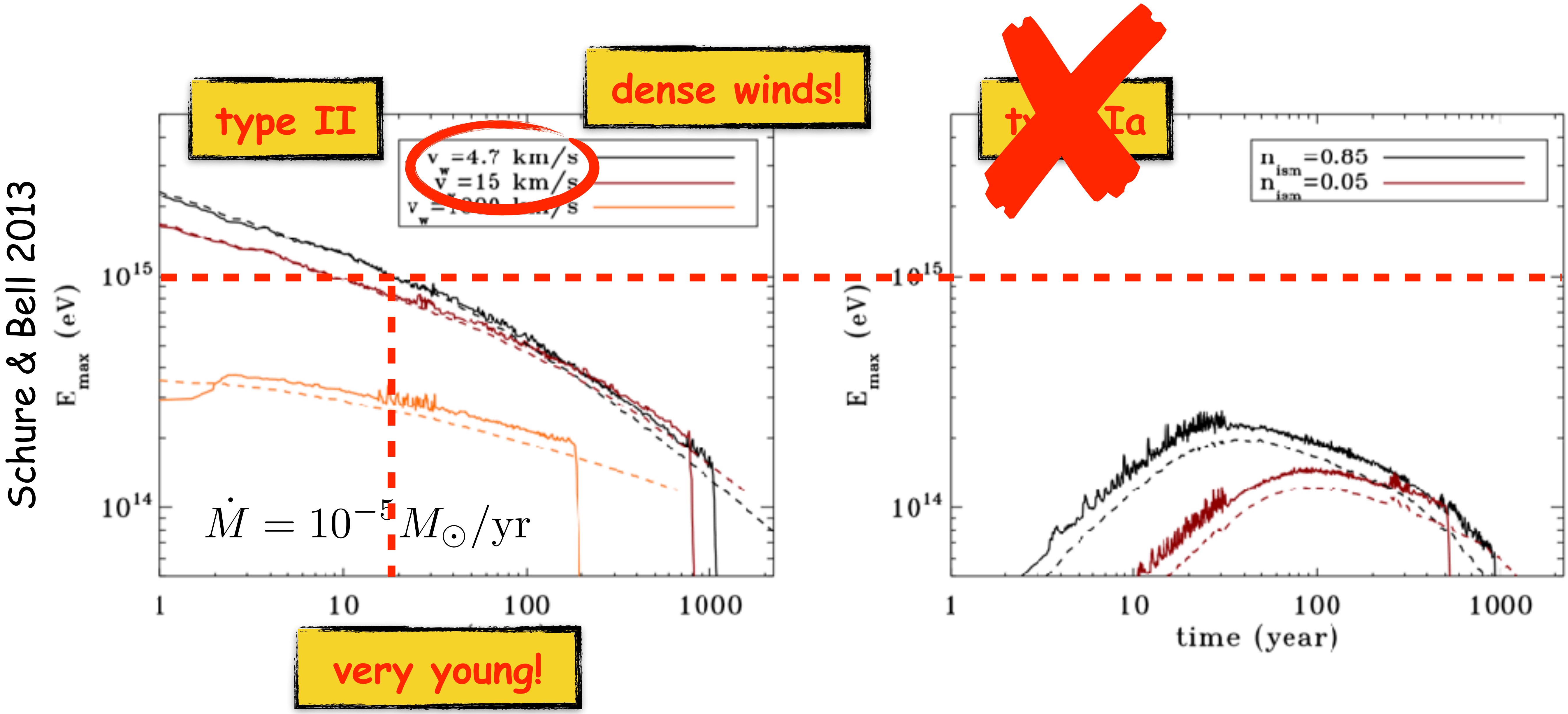


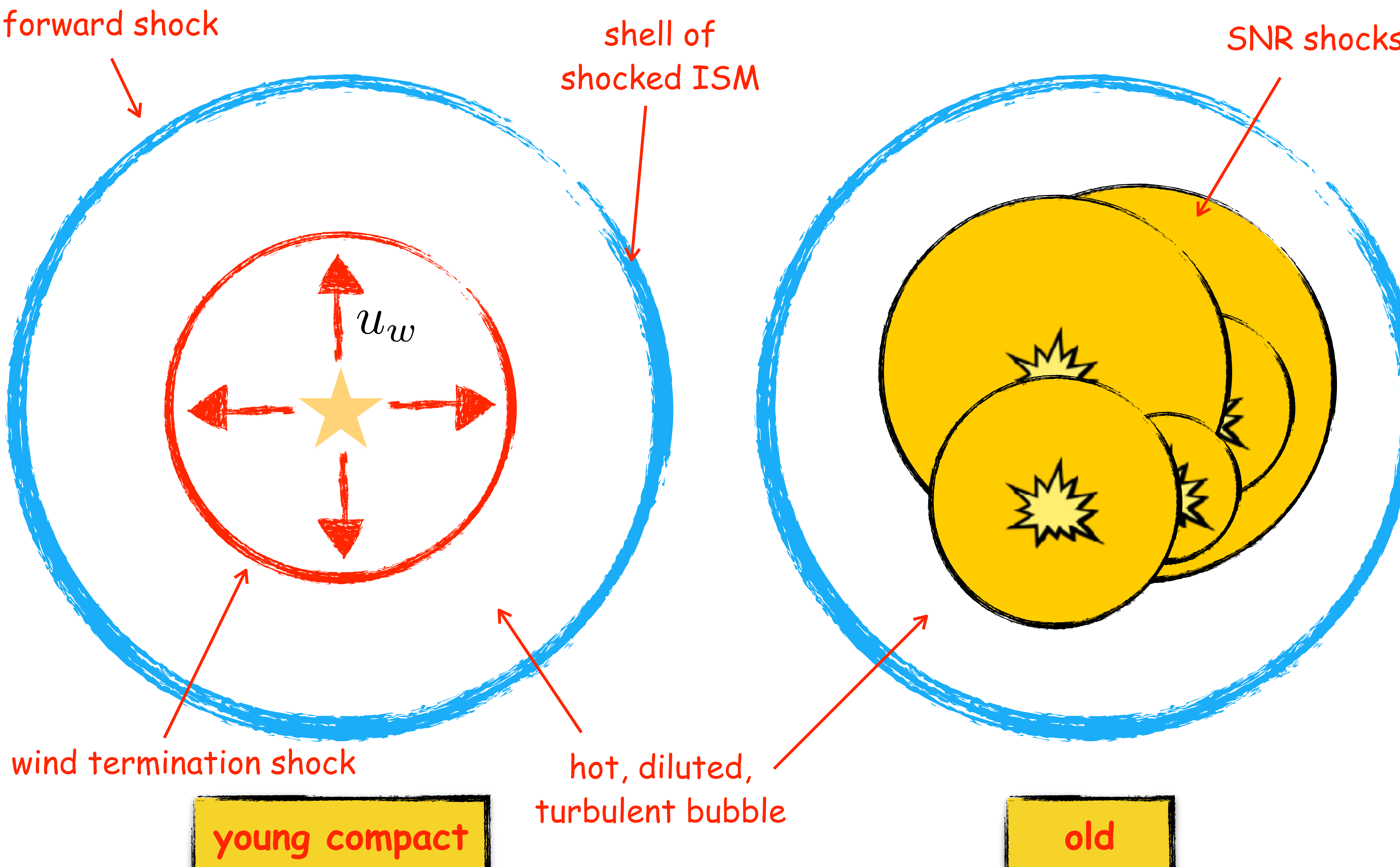
3 consequences:

- very dense winds (type IIb?) —> go to PeV or beyond! (Ptuskin+ 2010)
- very rare events —> # of active PeV SNRs = 0 (Cristofari+ 2020)
- "knee" in the spectrum from one SNR at transition to Sedov (Cardillo+ 2015)

Star clusters

Interstellar bubbles around star clusters

Castor+ 75, Weaver+ 77, McCray&Kafatos 87, Mac Low&McCray 88, Koo&McKee 92...



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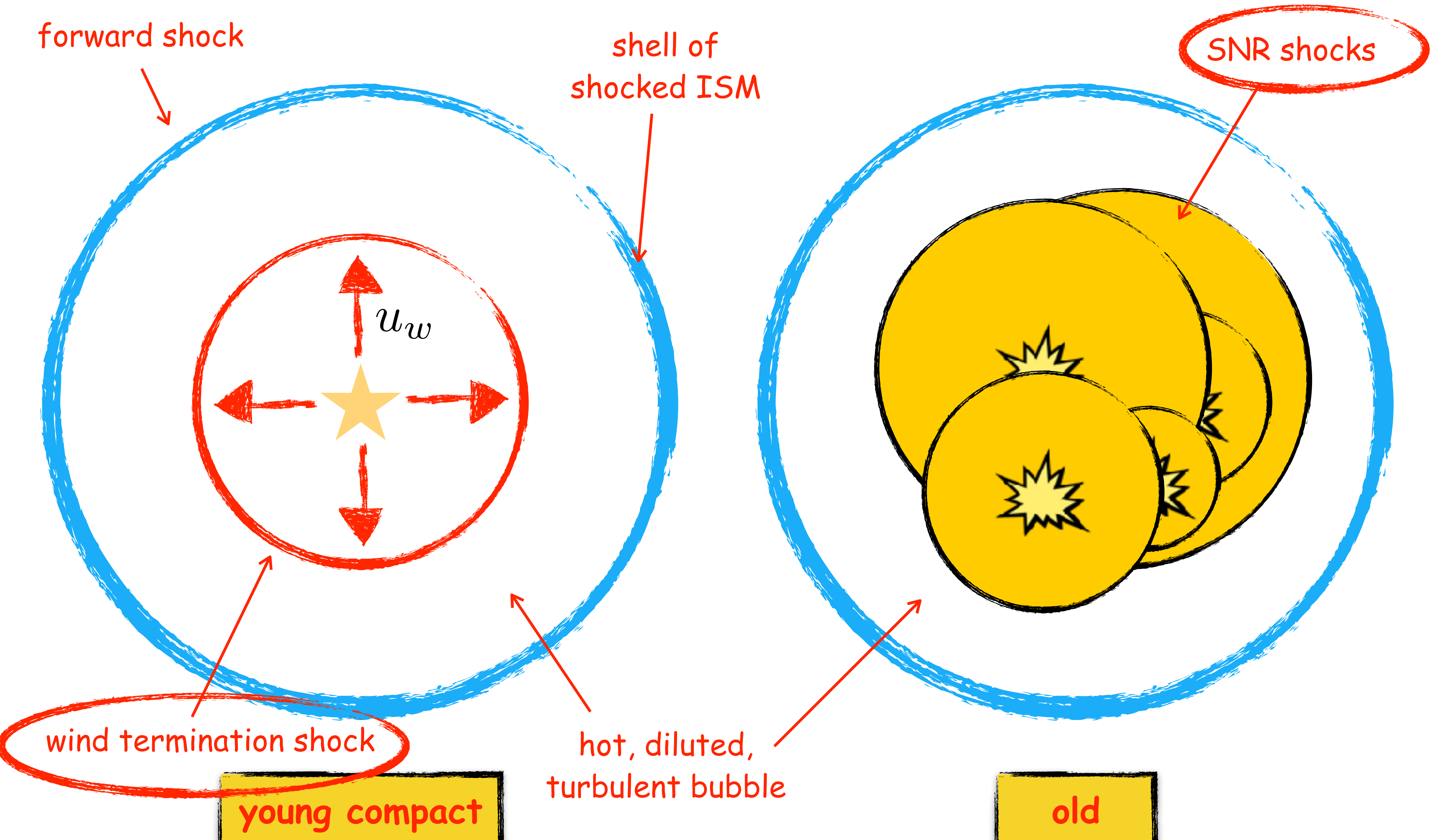

Particle acceleration at WTSs: E_{max}

Hillas criterium —>

$$E_{max} \sim \left(\frac{q}{c}\right) B_s u_s R_s$$

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Morlino+ 2021, Vieu+ 2022

$$L_w = 3 \times 10^{38} \mathrm{erg/s}$$

$$u_w = 3000 \ \mathrm{km/s}$$

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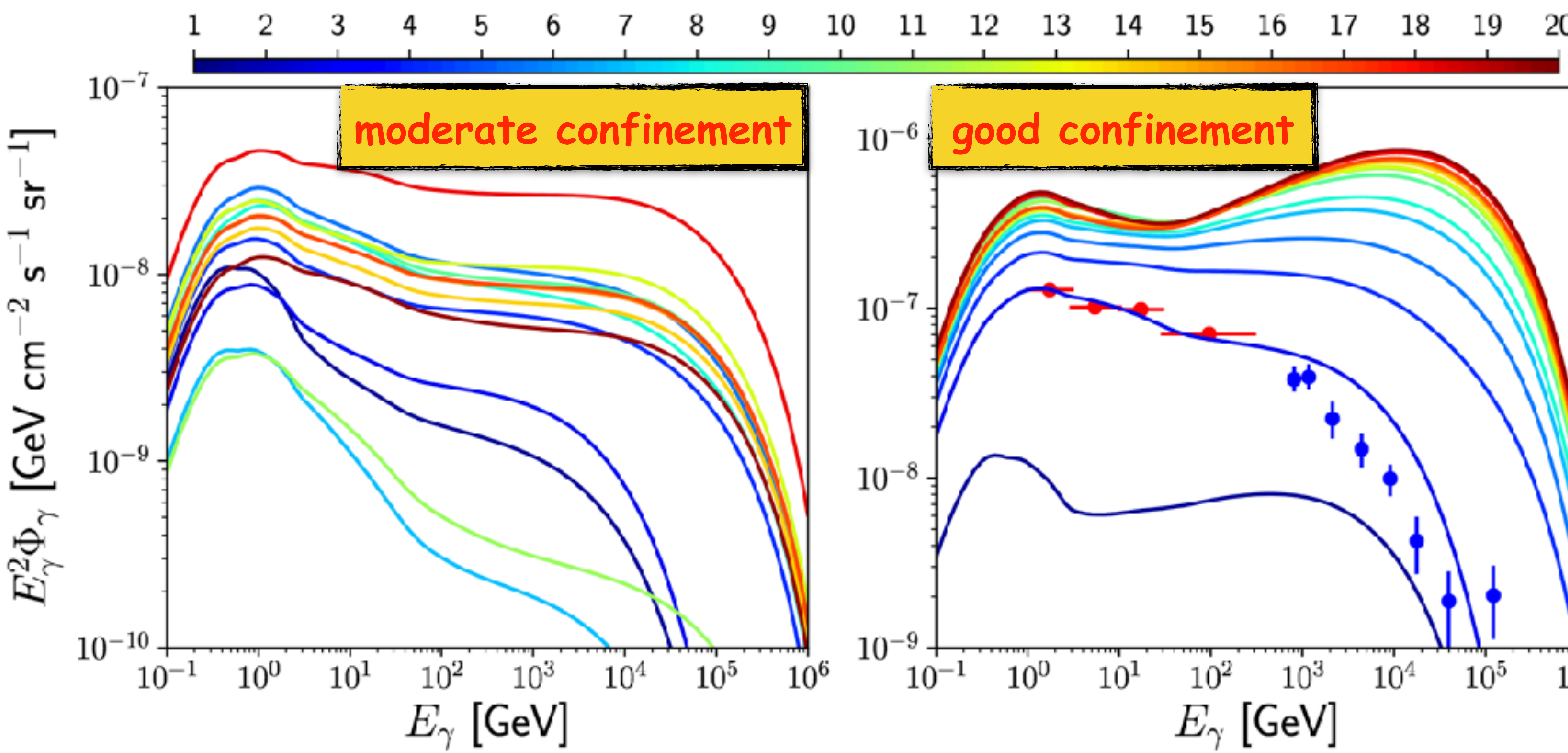
possible for powerful clusters ONLY

Particle acceleration in superbubbles: implications for observations

Vieu+ 2022

gamma ray observations

$N_* = 100$ - d = 1,5 kpc



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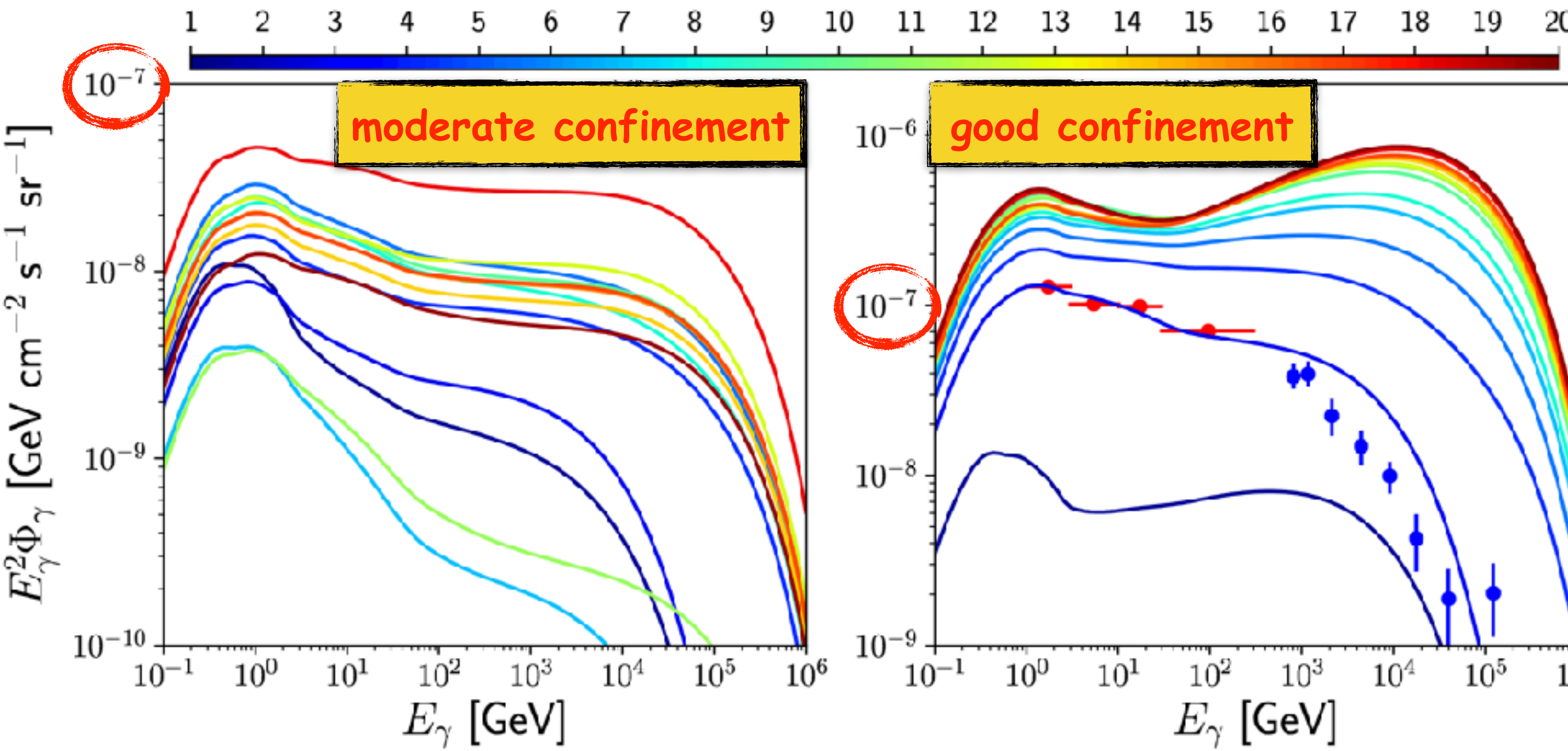

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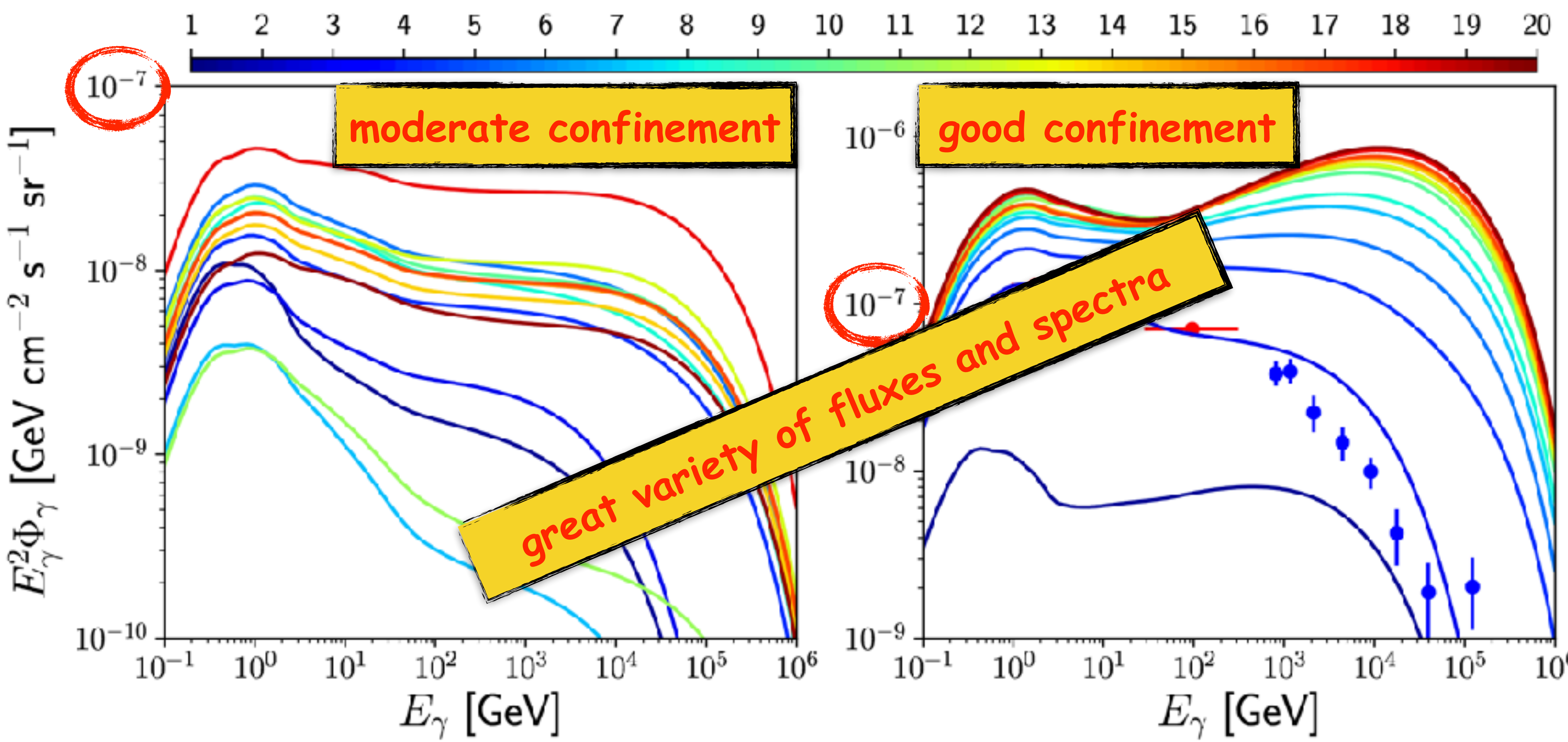

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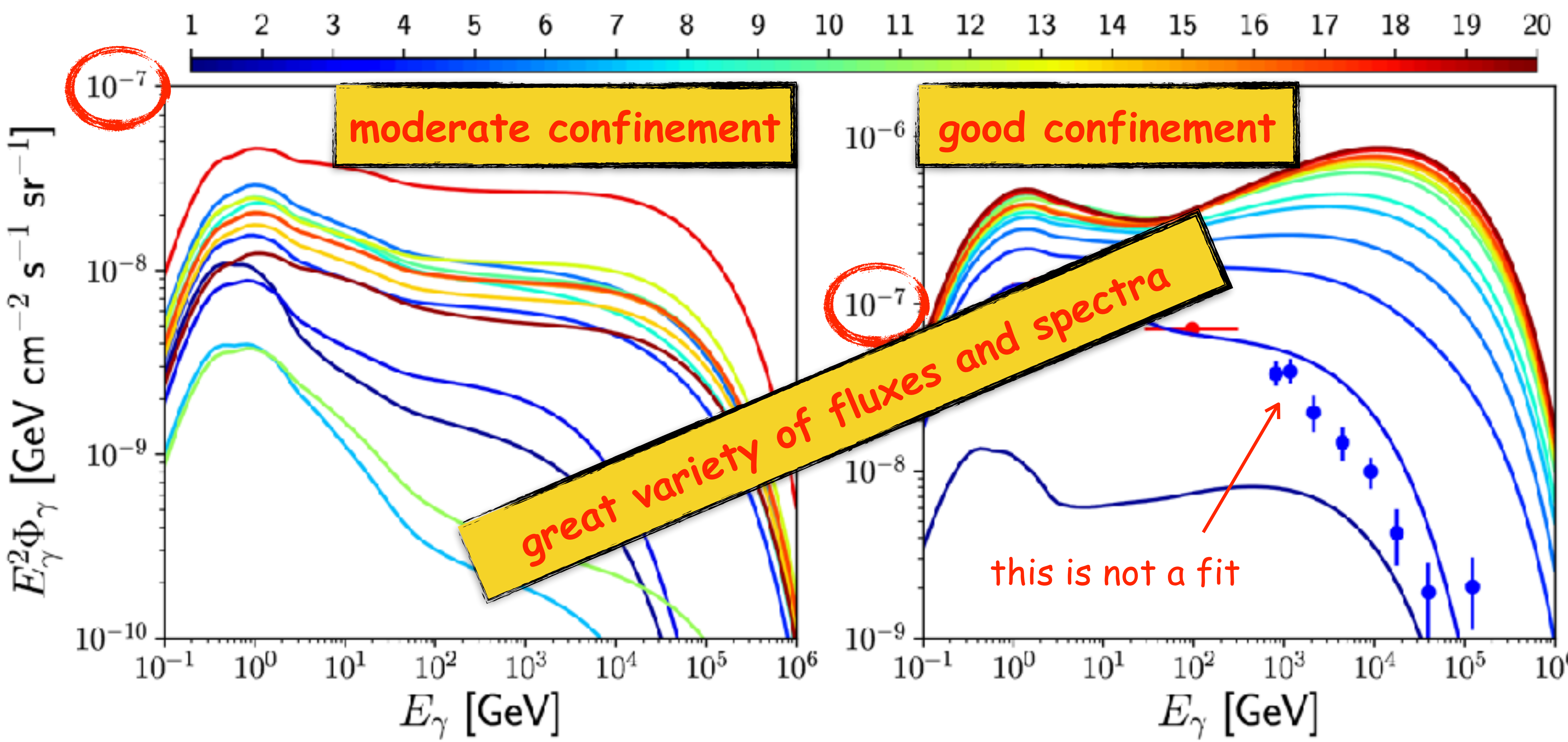

Orion-Eridani —> no gammas, Cygnus region —> gammas

Particle acceleration in superbubbles: maximum energy

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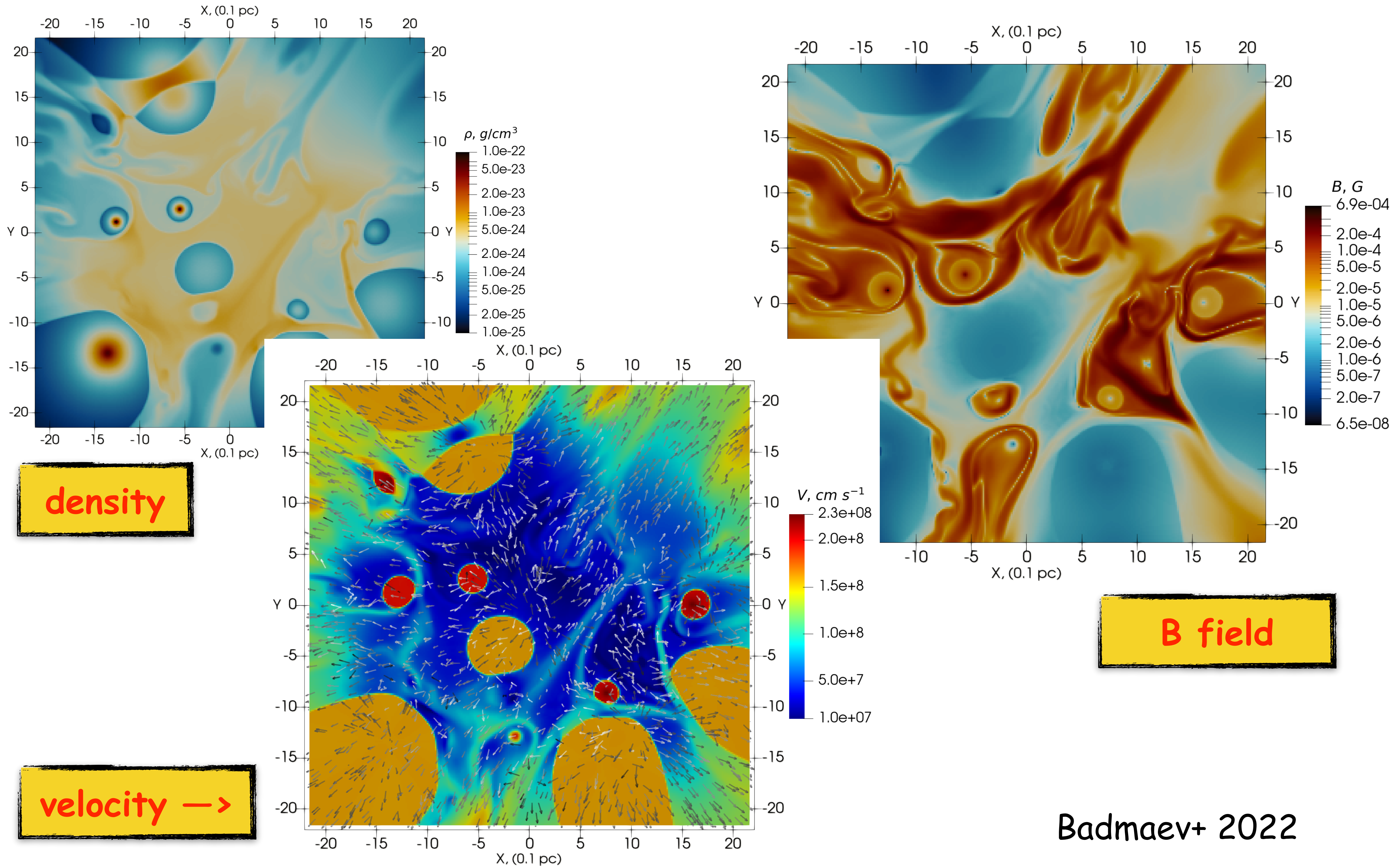
possible to go to PeV and possibly beyond

MHD simulations of young massive star clusters



Badmaev+ 2022

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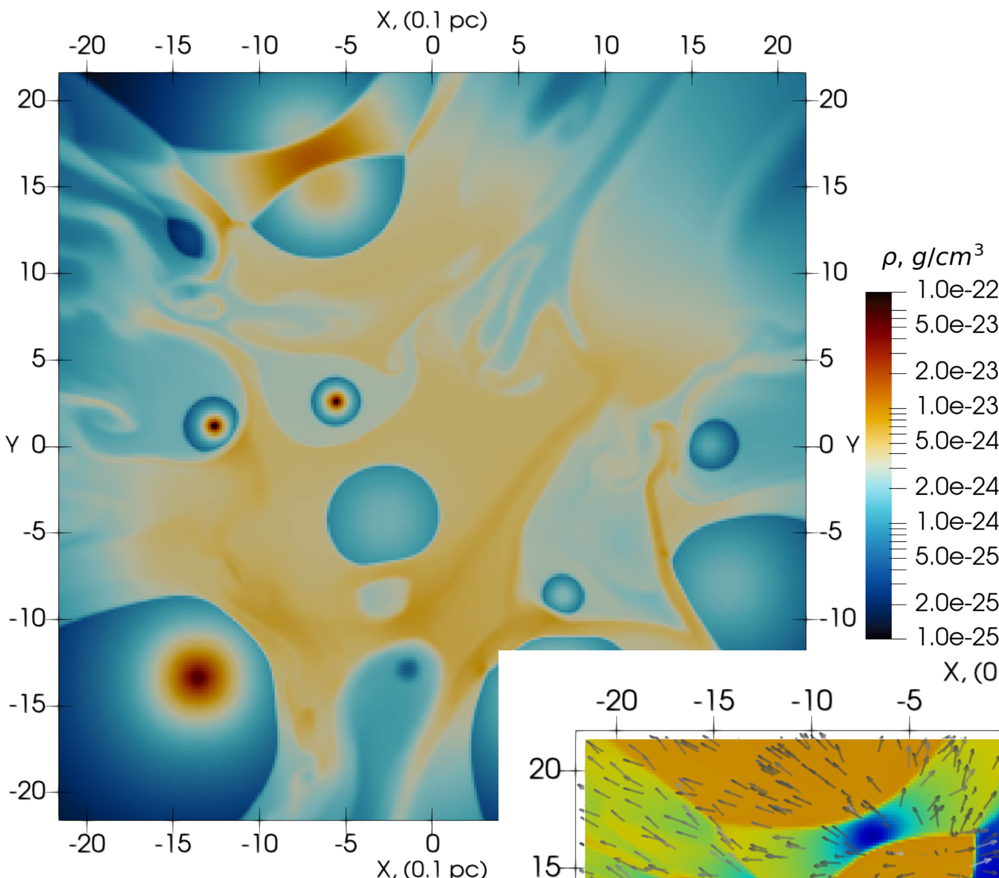
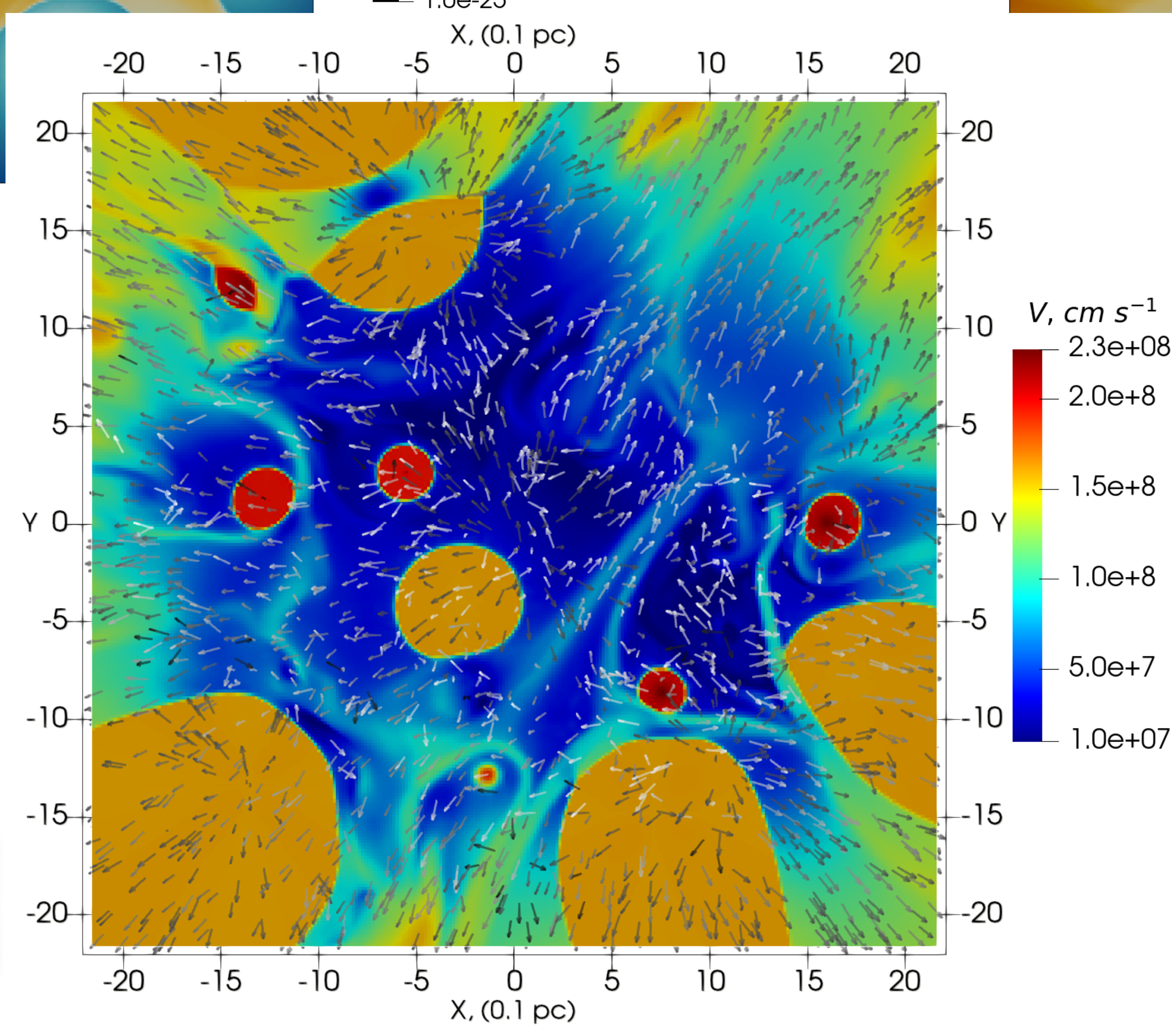
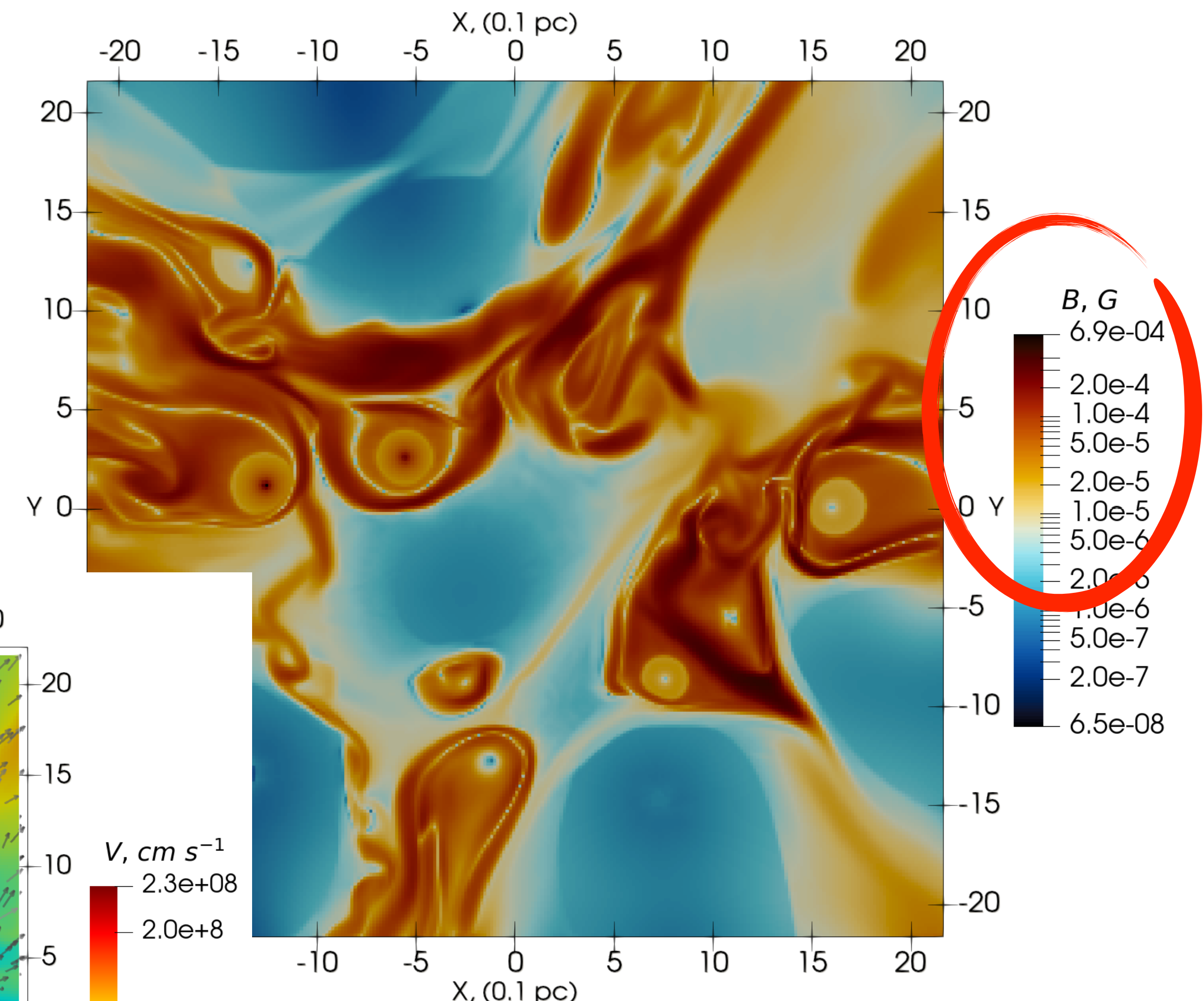


density



velocity —>



B field

Badmaev+ 2022

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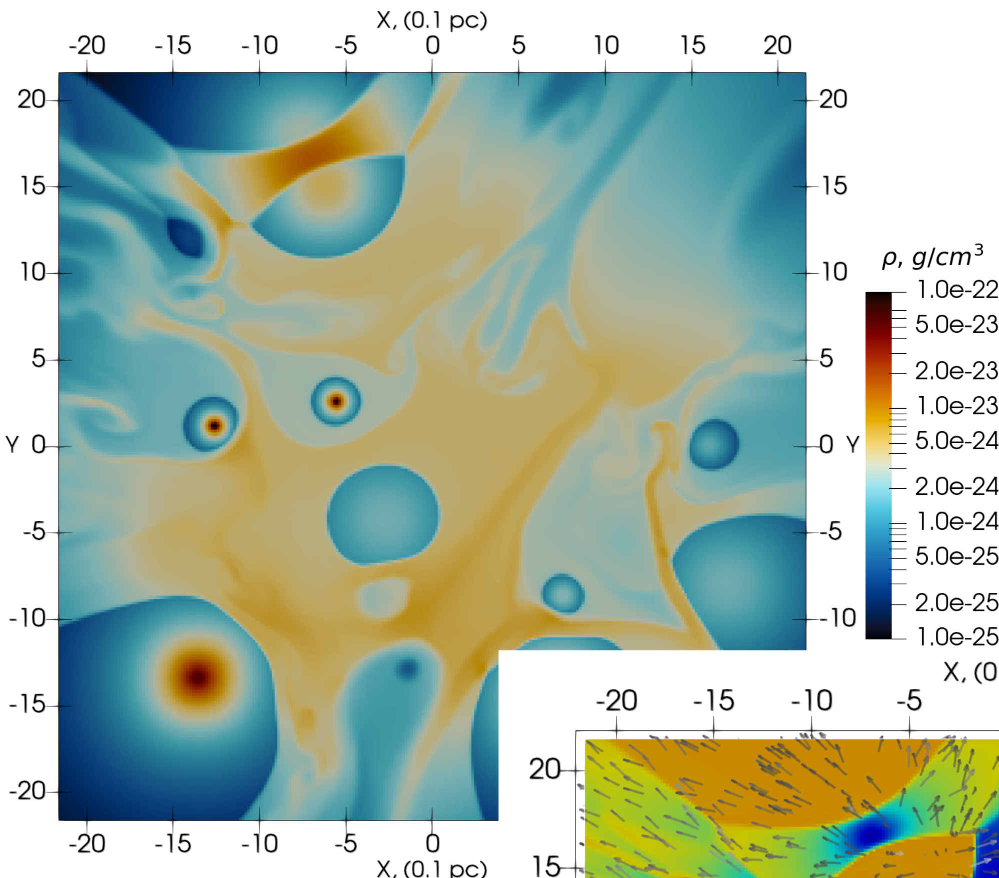

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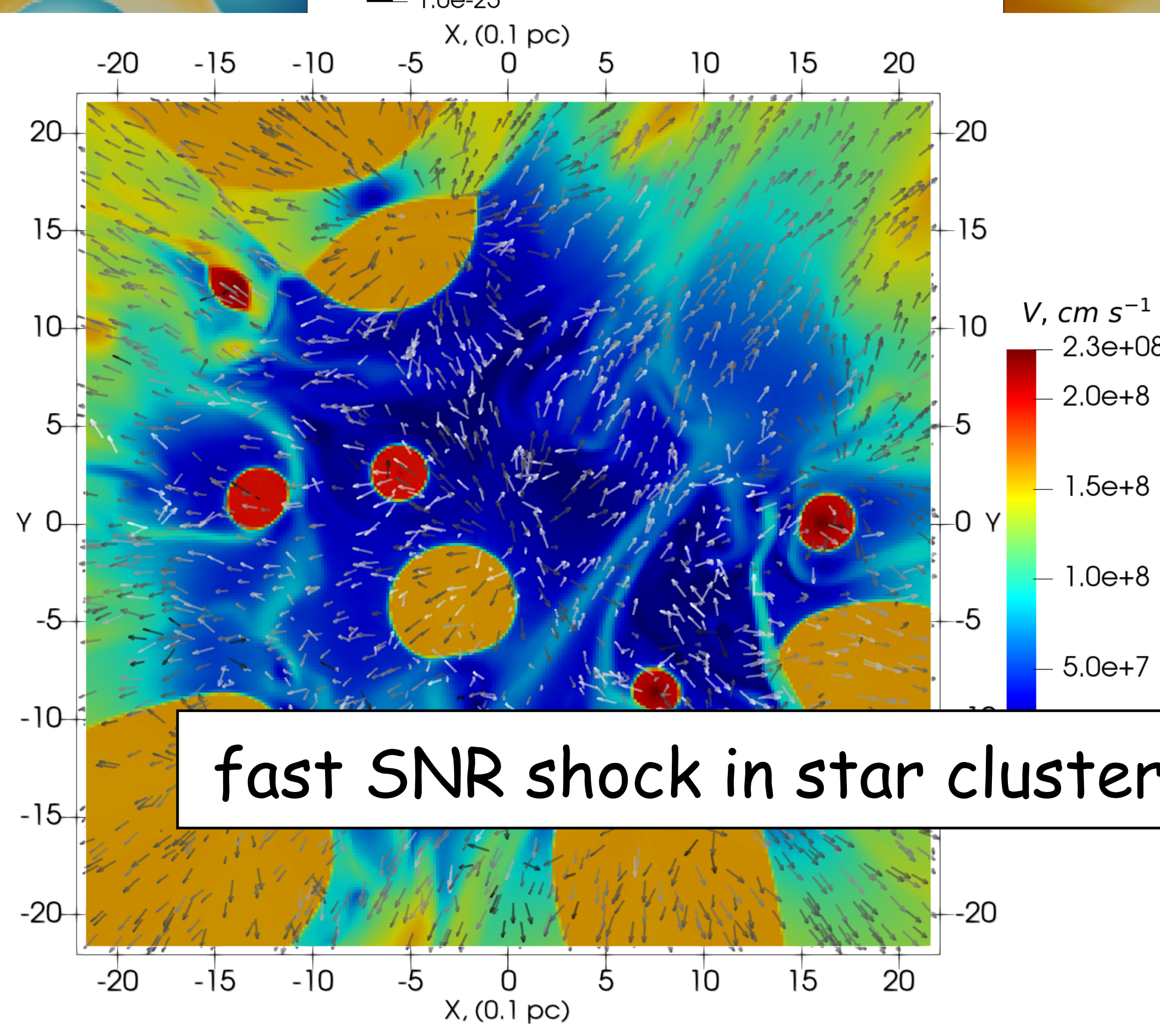

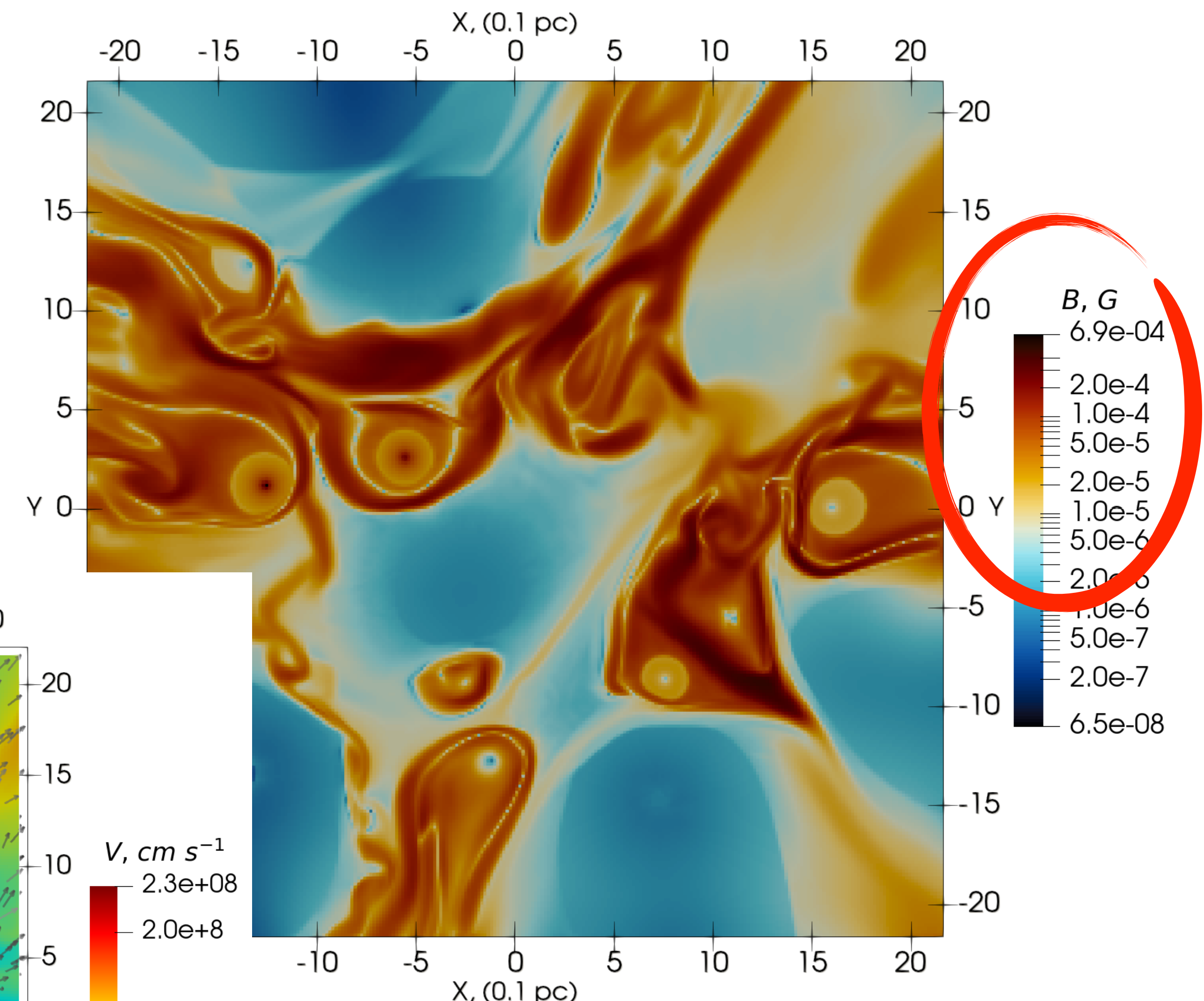

B field

fast SNR shock in star clusters might accelerate >> PeV!

velocity —>

Badmaev+ 2022

Conclusions, open questions, perspectives

- Direct measurements
  - Where is the knee? (KASCADE —> few PeV, ARGO —> 0.7 PeV)
  - Both values are a challenge for theoreticians
  - To answer this questions we need a detector able to obtain high statistics and good energy resolution (we need to measure accurately the spectrum) and able to measure CR composition
  - Who can do that? —> LHAASO ... ? (complementary to other space and ground based instruments to connect to lower energies)

Conclusions, open questions, perspectives

- Indirect measurements: gamma rays
  - Where are PeVatrons?
  - TIBET/LHAASO diffuse —> PeV CRs everywhere
  - To answer this question we need detectors with superior collecting surface in the multi TeV (100 TeV and beyond) domain
    - LHAASO: + best sensitivity at 100 TeV, broad energy domain, wide field of view; - northern hemisphere (no MW)
    - CTA: + southern site, excellent angular resolution; - capabilities beyond 100 TeV?
    - SWGO: + southern site, wide field of view (complementary to CTA), MW diffuse emission; - capabilities beyond 100 TeV?