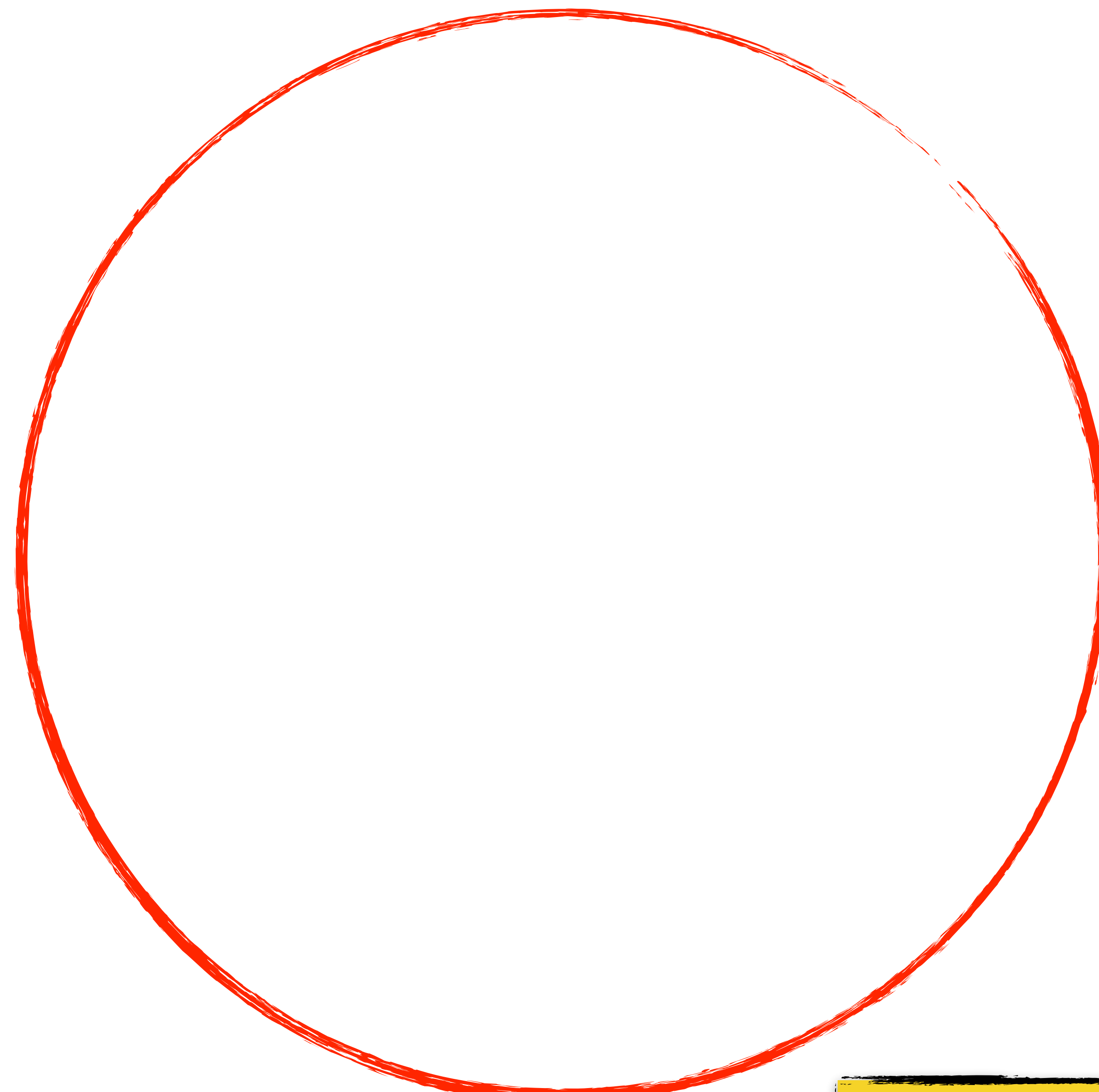
Cosmic rays & gamma rays: from supernova remnants (SNRs) to clusters of galaxies (GCs)

Stefano Gabici
APC, Paris

Why it is difficult to talk about SNRs and GCs in the same talk

not visible!



SuperNova Remnant

$R \approx 10$ pc

$R \approx 1$ Mpc

Galaxy Cluster

Why it is difficult to talk about SNRs and GCs in the same talk

because the reason why these objects are bound by a spherical non-relativistic shock is completely different…

massive star

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supernova explosion

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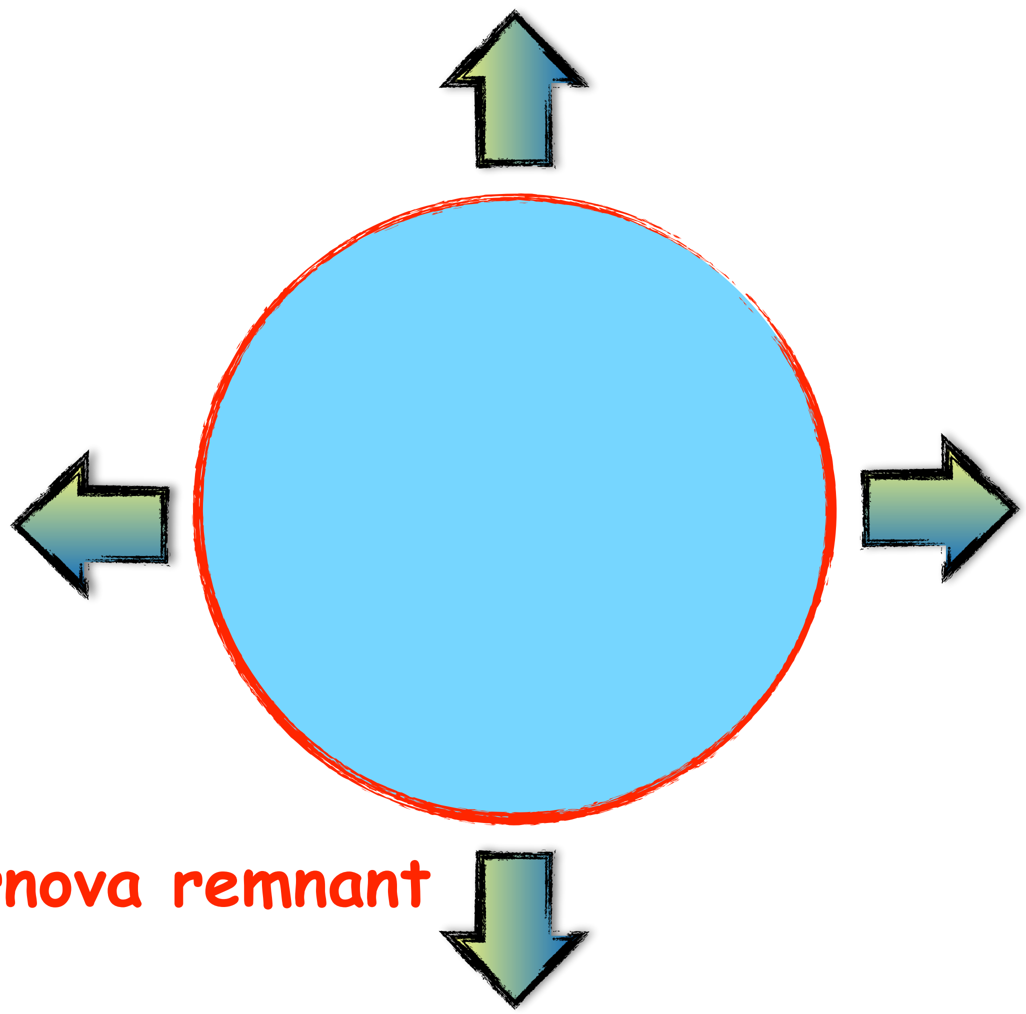

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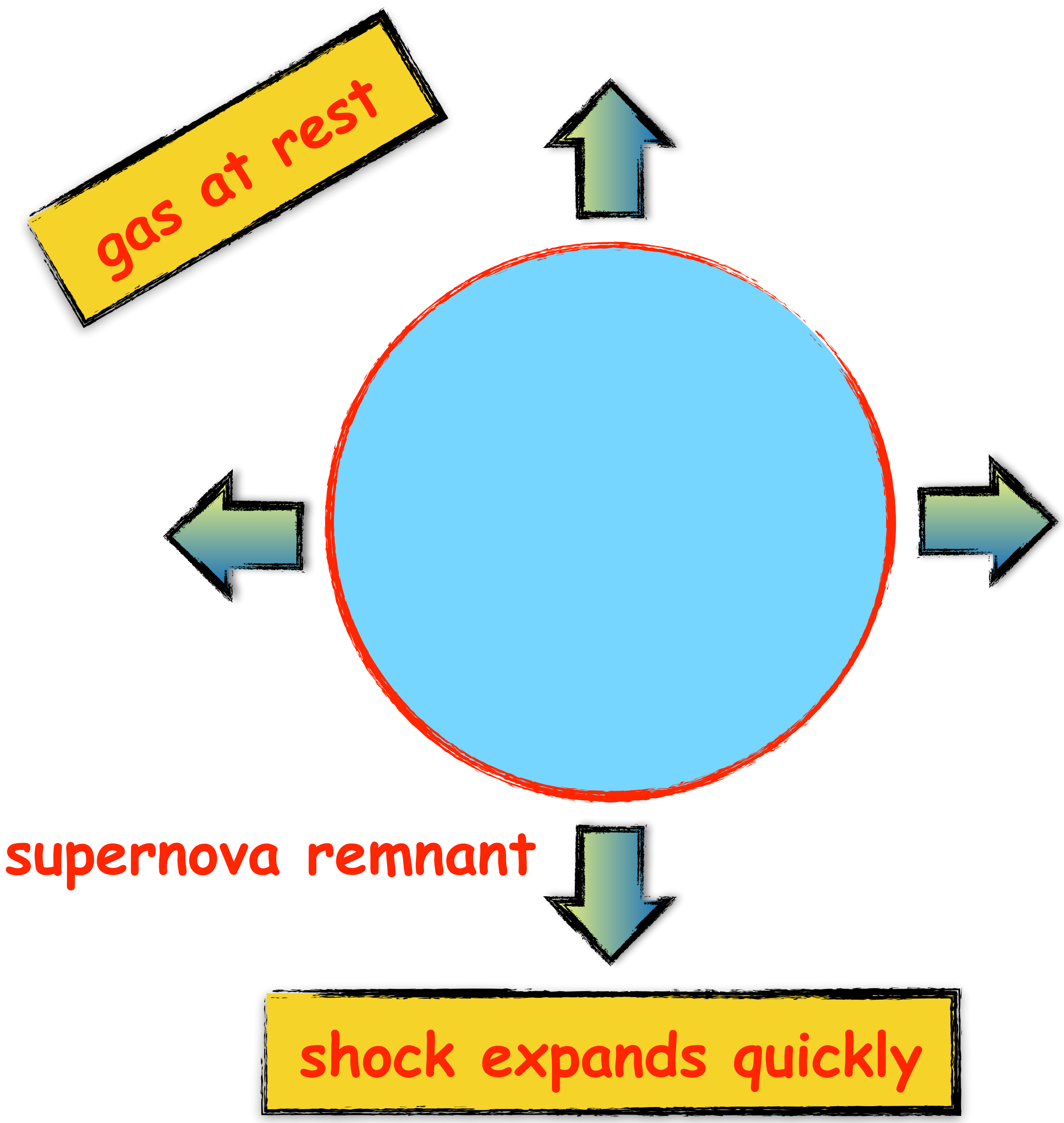

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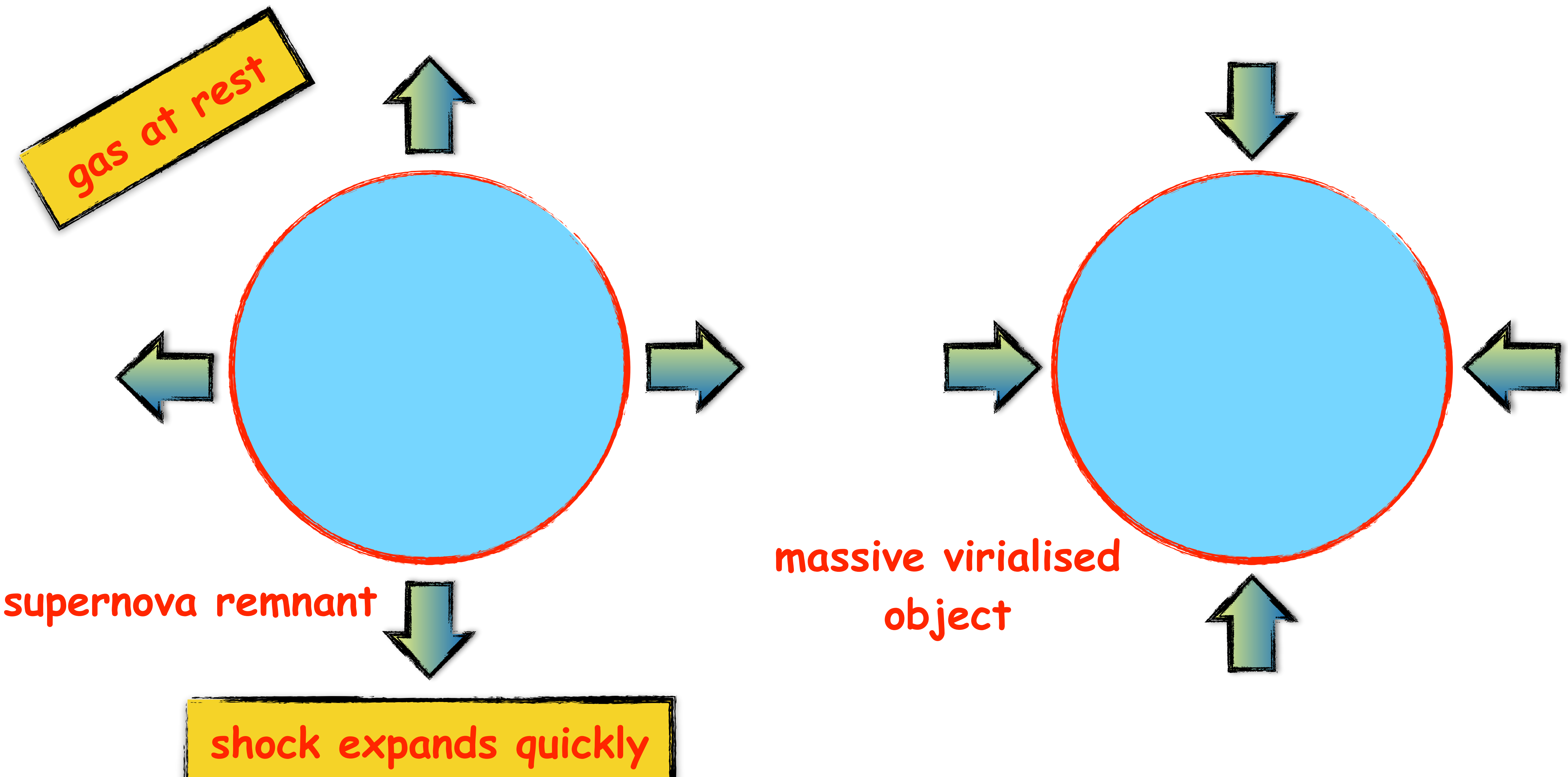

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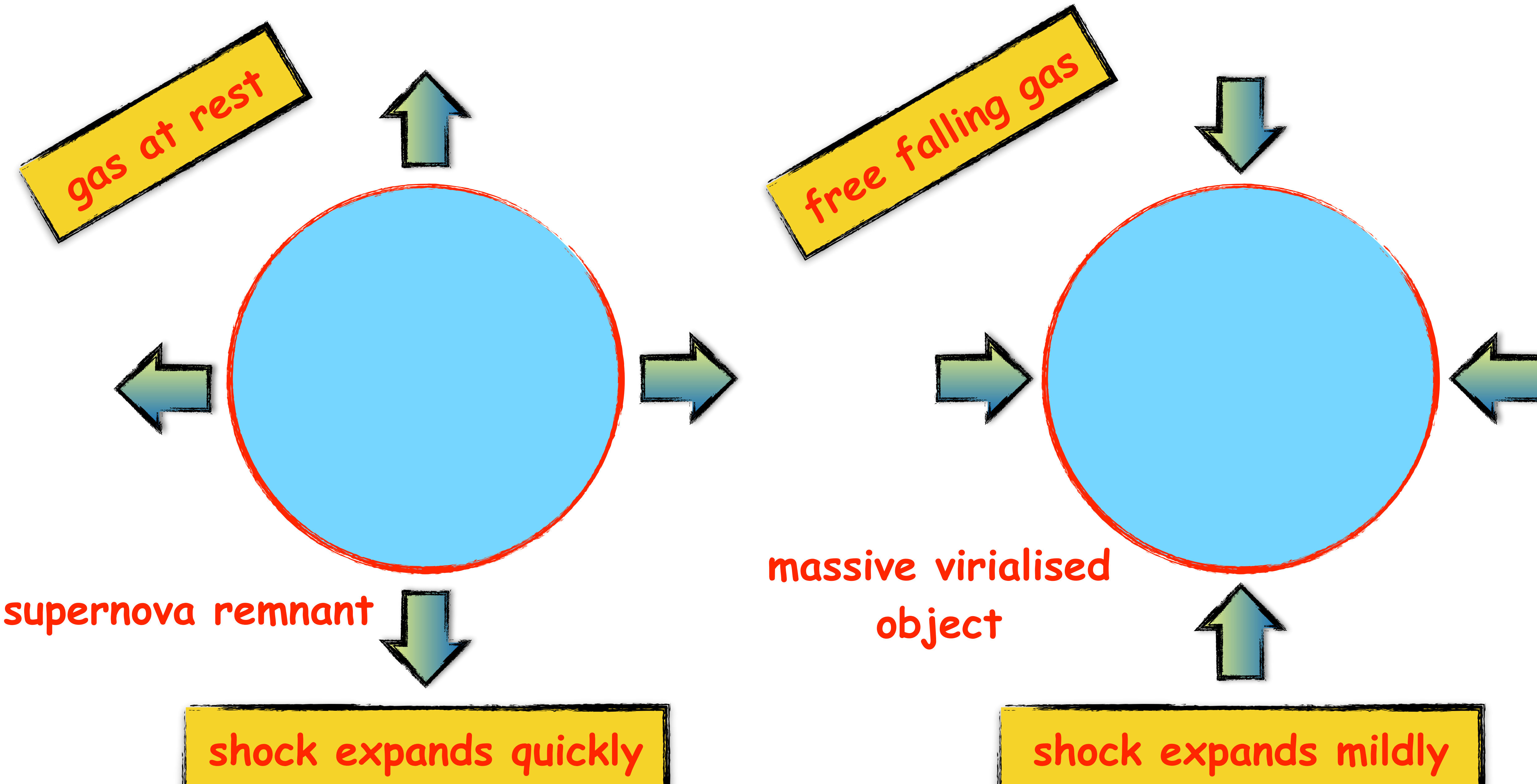

Why it does make sense to talk about SNRs and GCs in the same talk

Both are cosmic ray (CR) accelerators and, in both cases, particles can be accelerated at non-relativistic shock waves —> same acceleration mechanism

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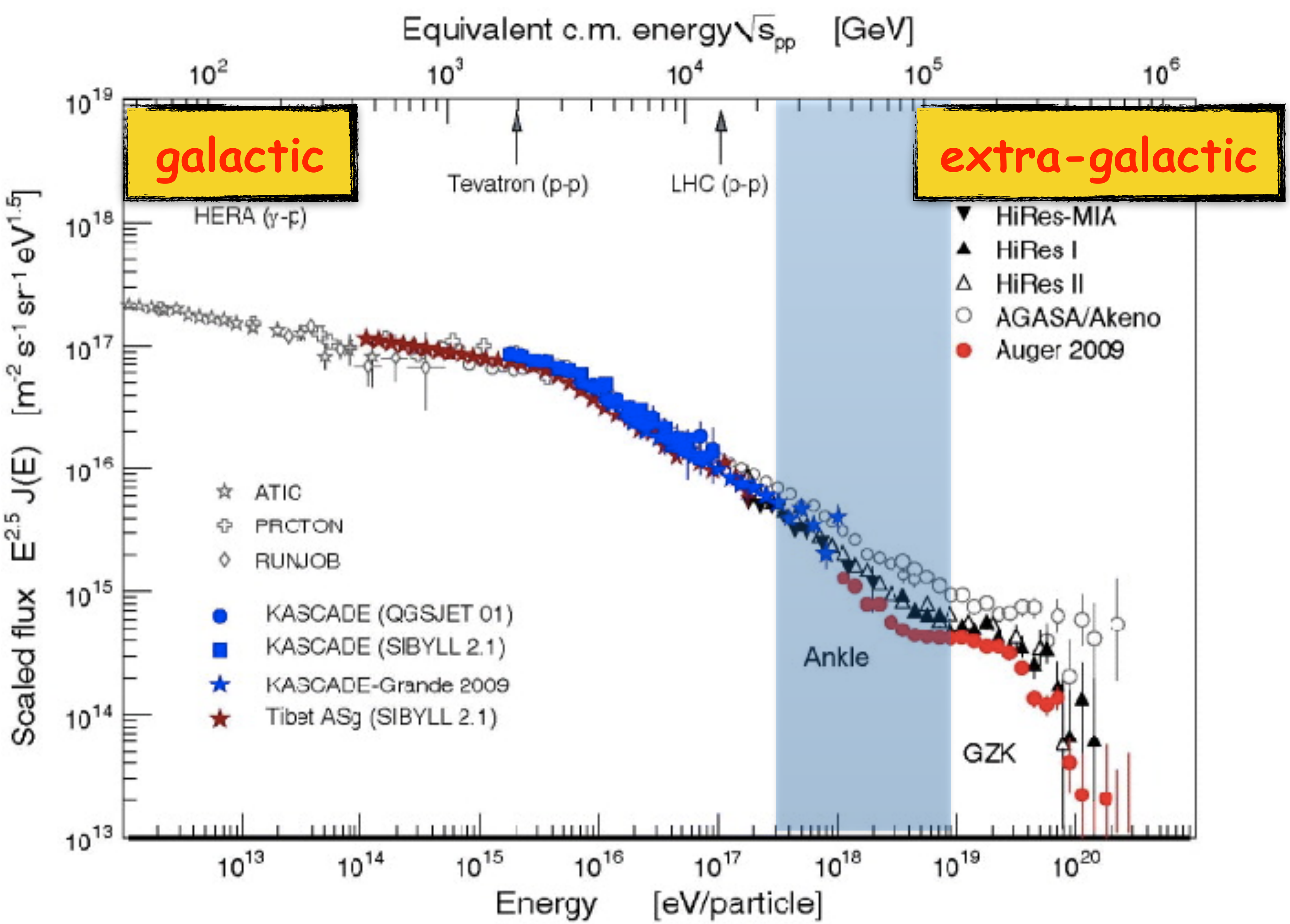

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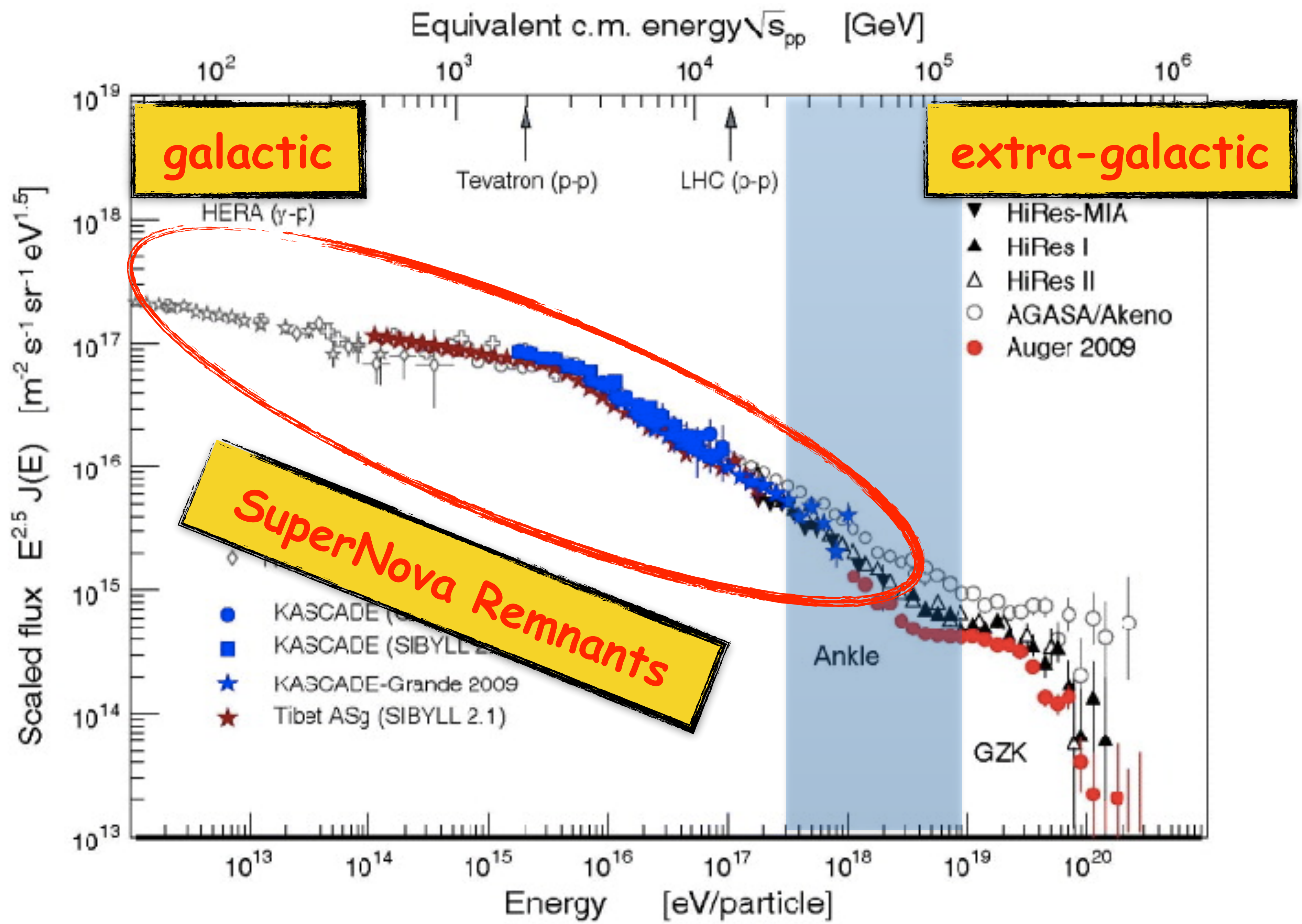

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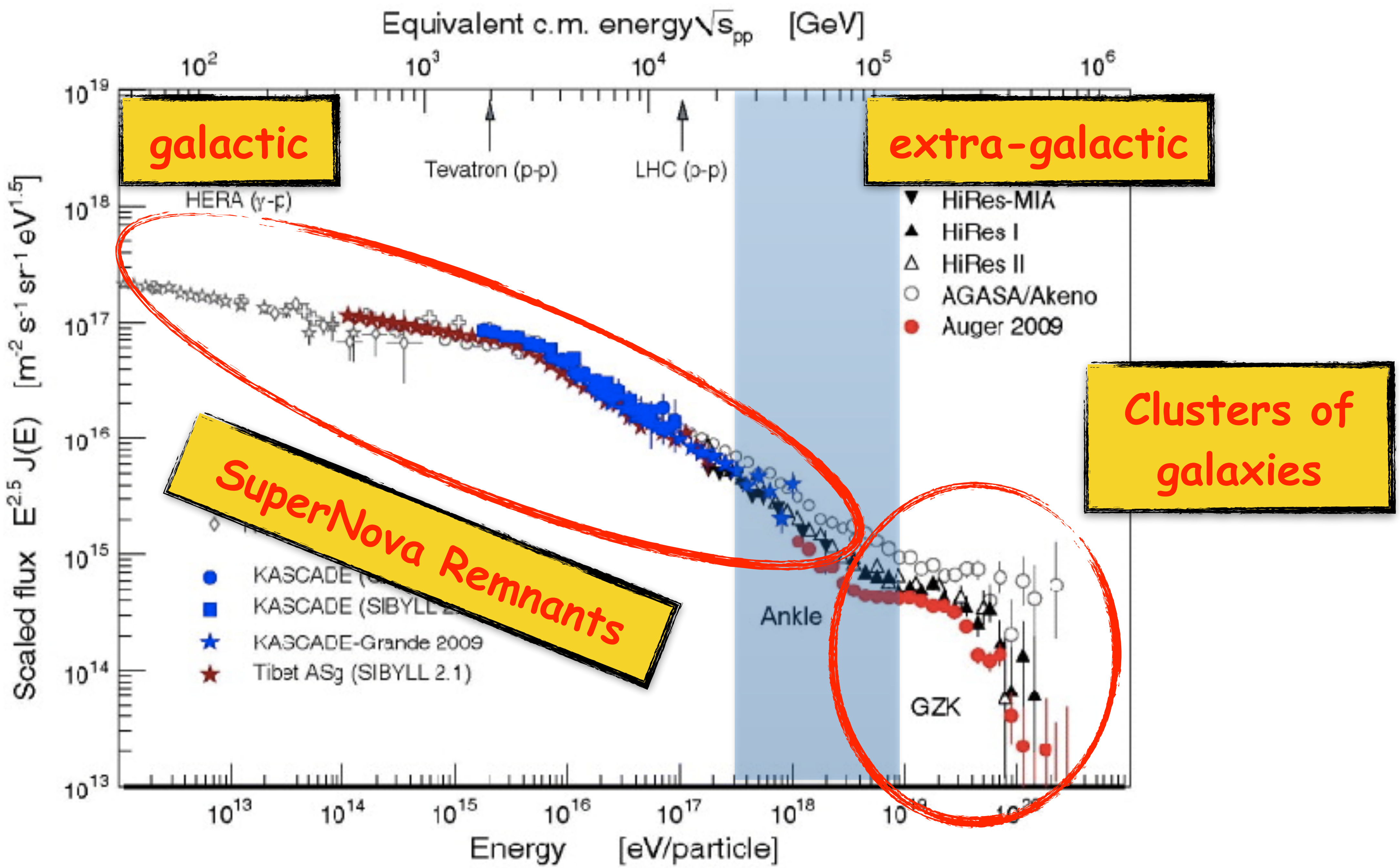

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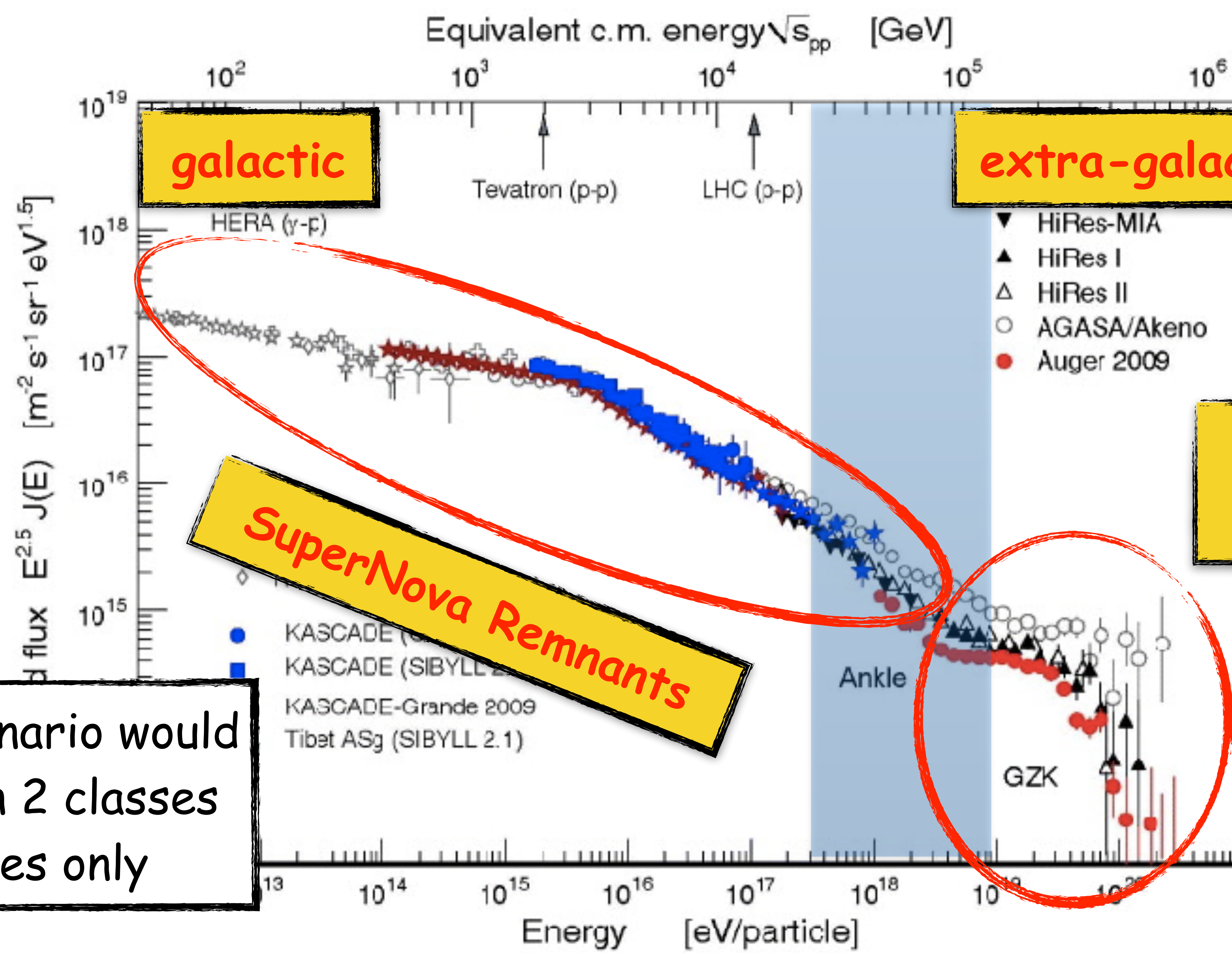
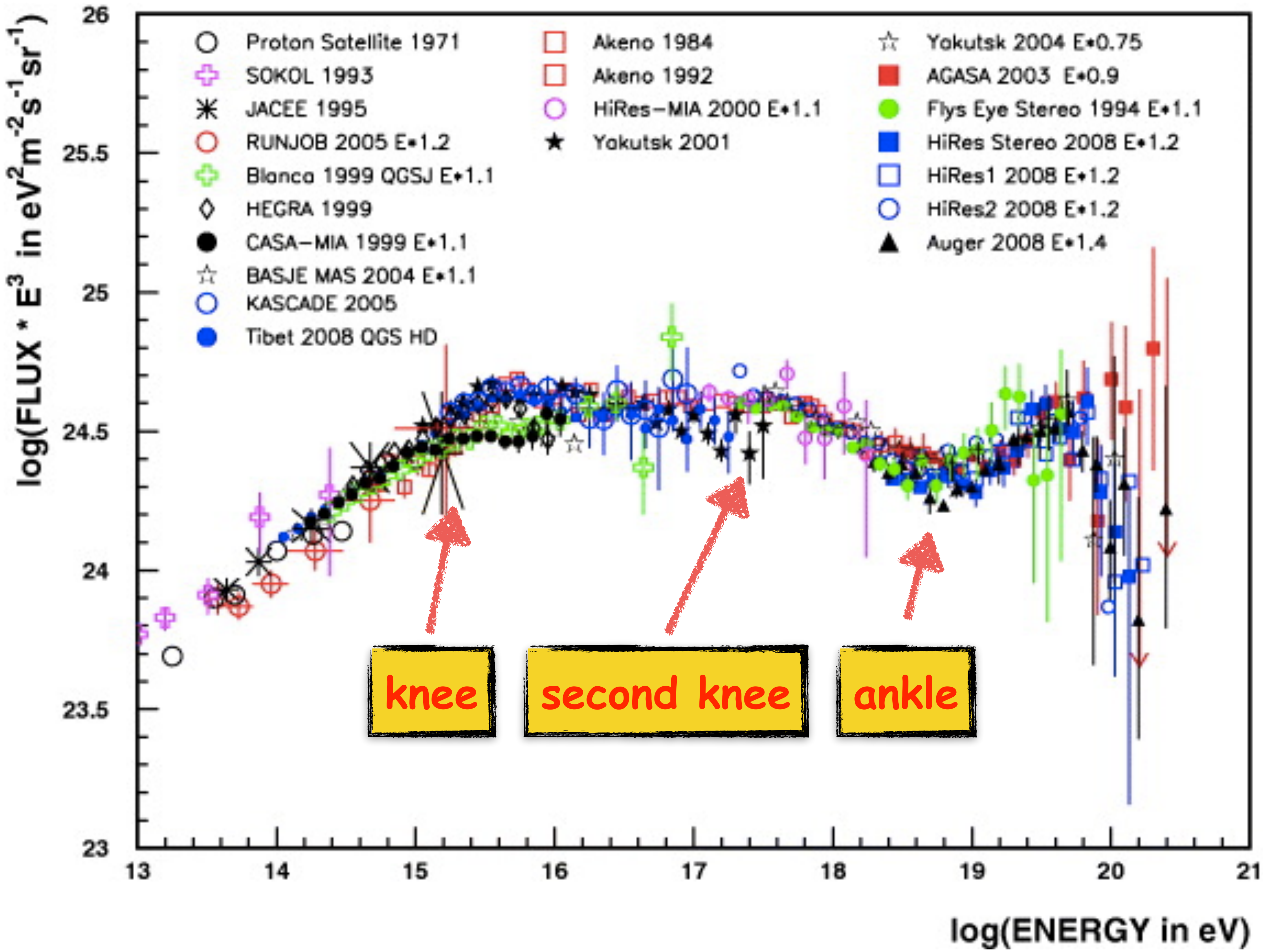


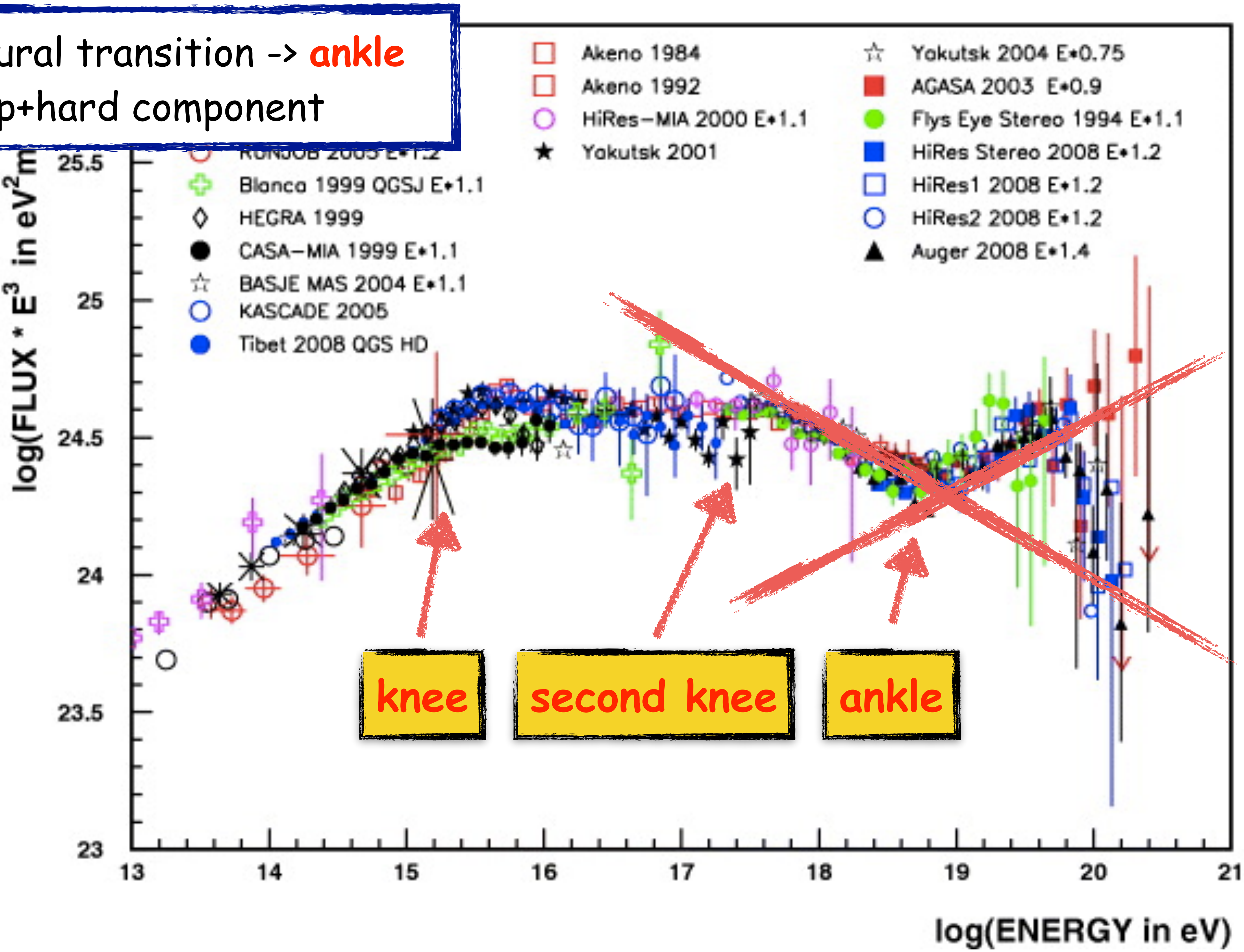
simplest scenario would be based on 2 classes of sources only

Transition from galactic to extra-galactic CRs



Transition from galactic to extra-galactic CRs

most natural transition -> ankle
steep+hard component



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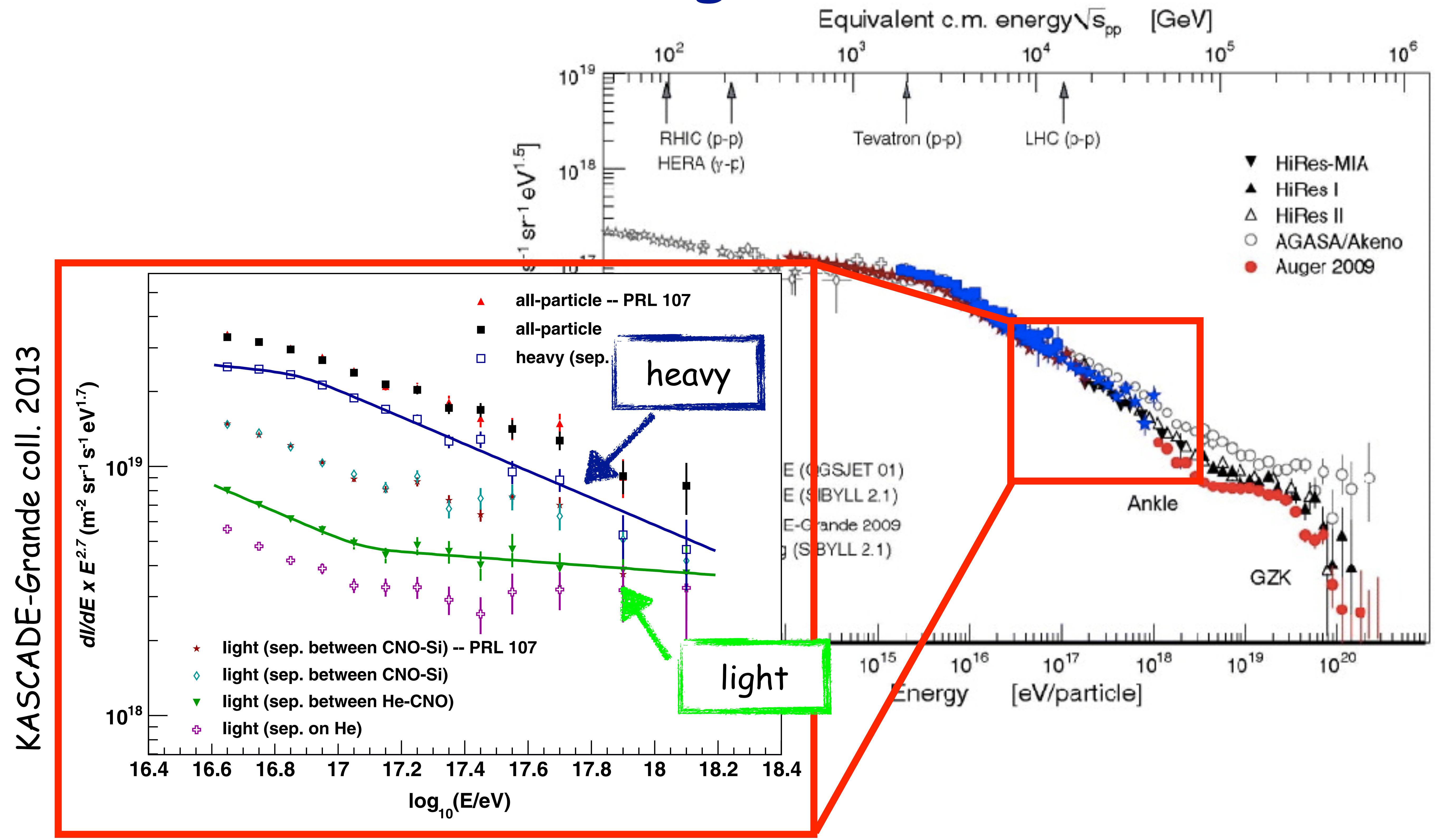

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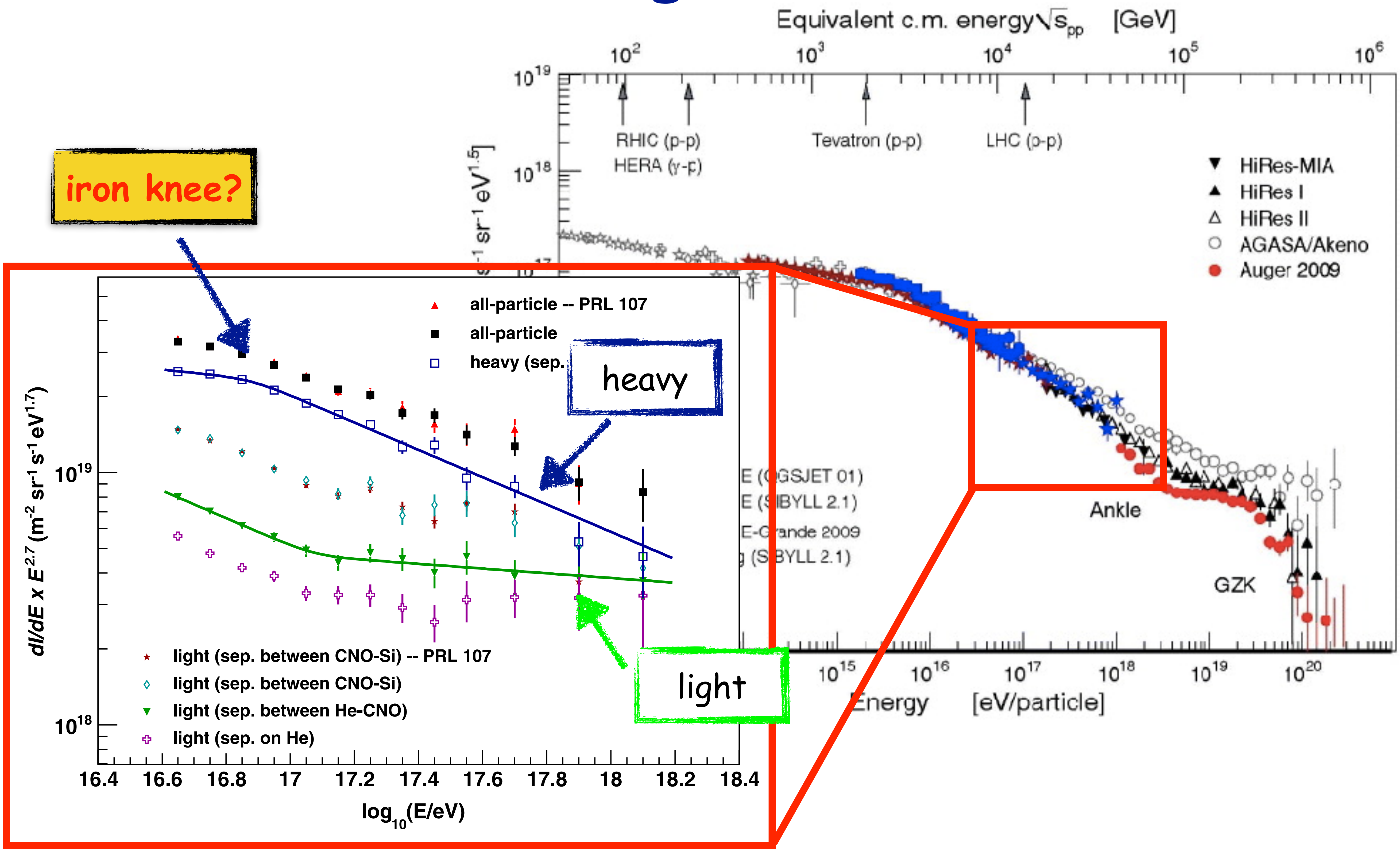

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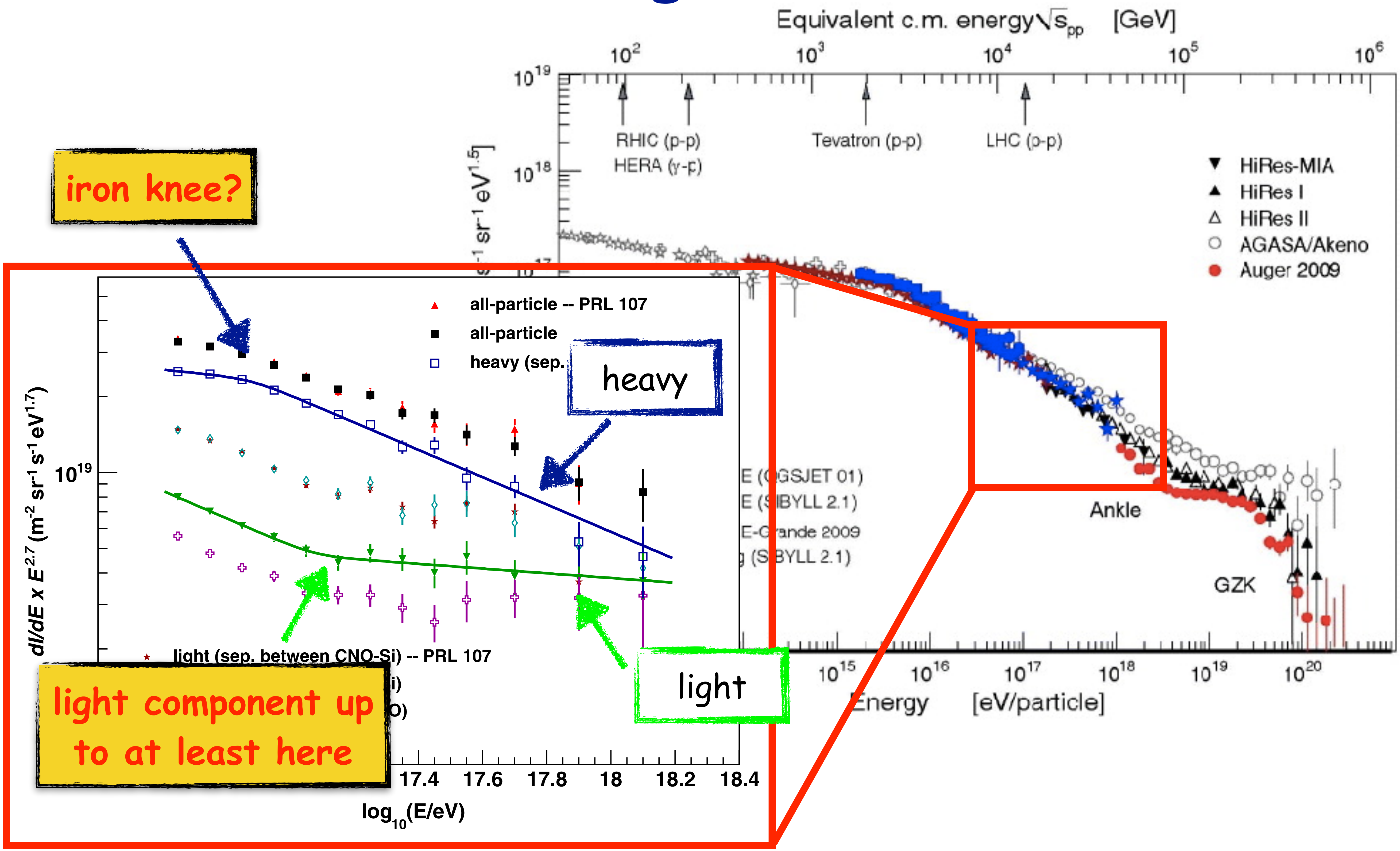

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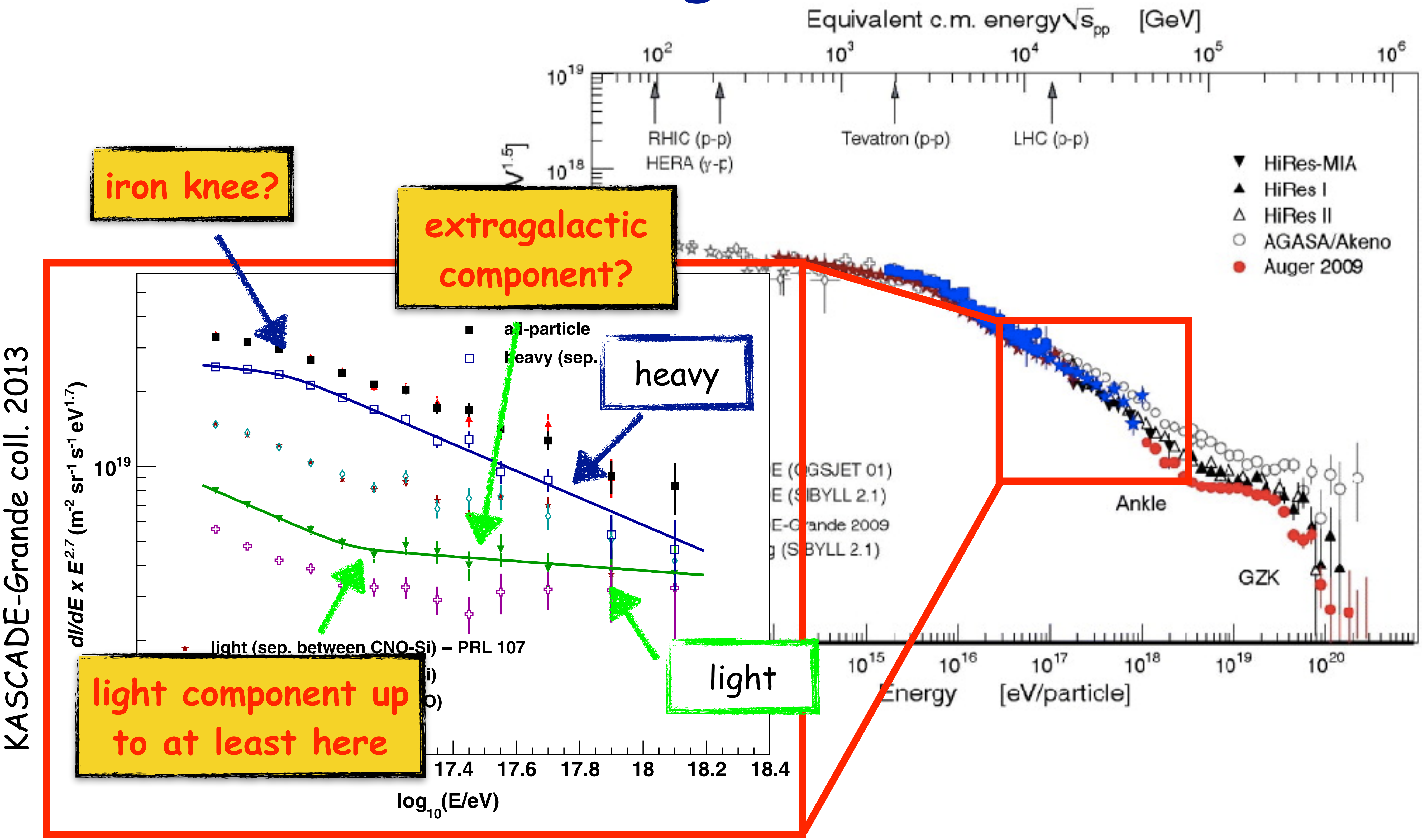

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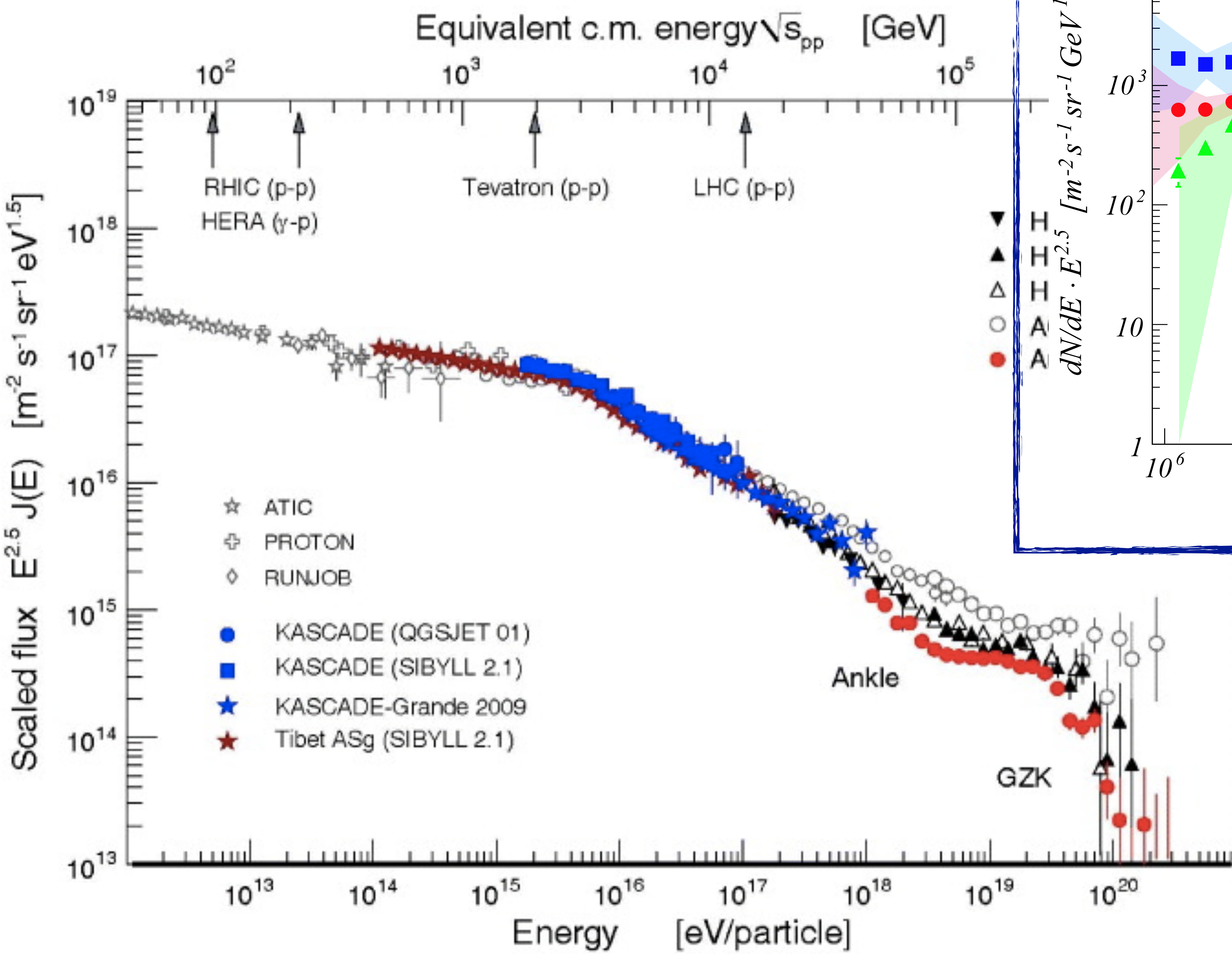

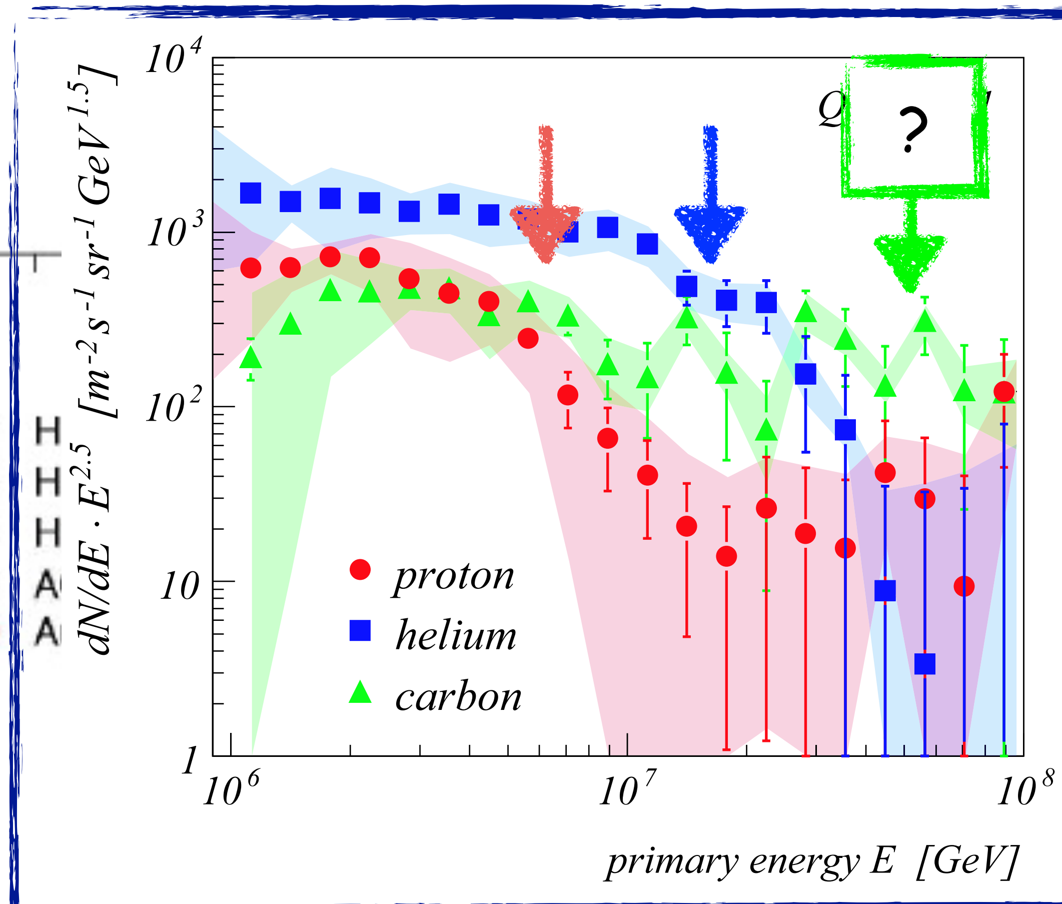

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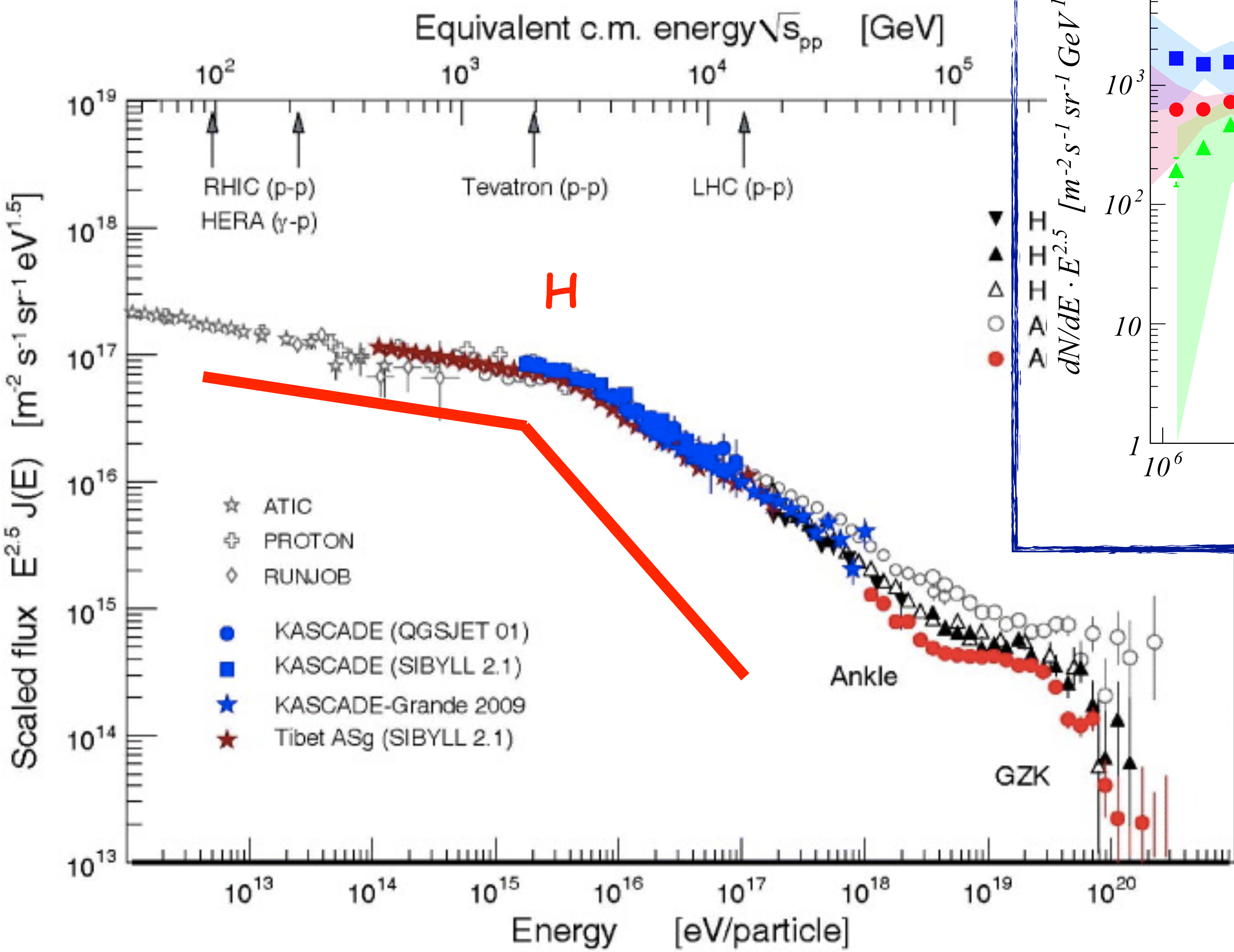
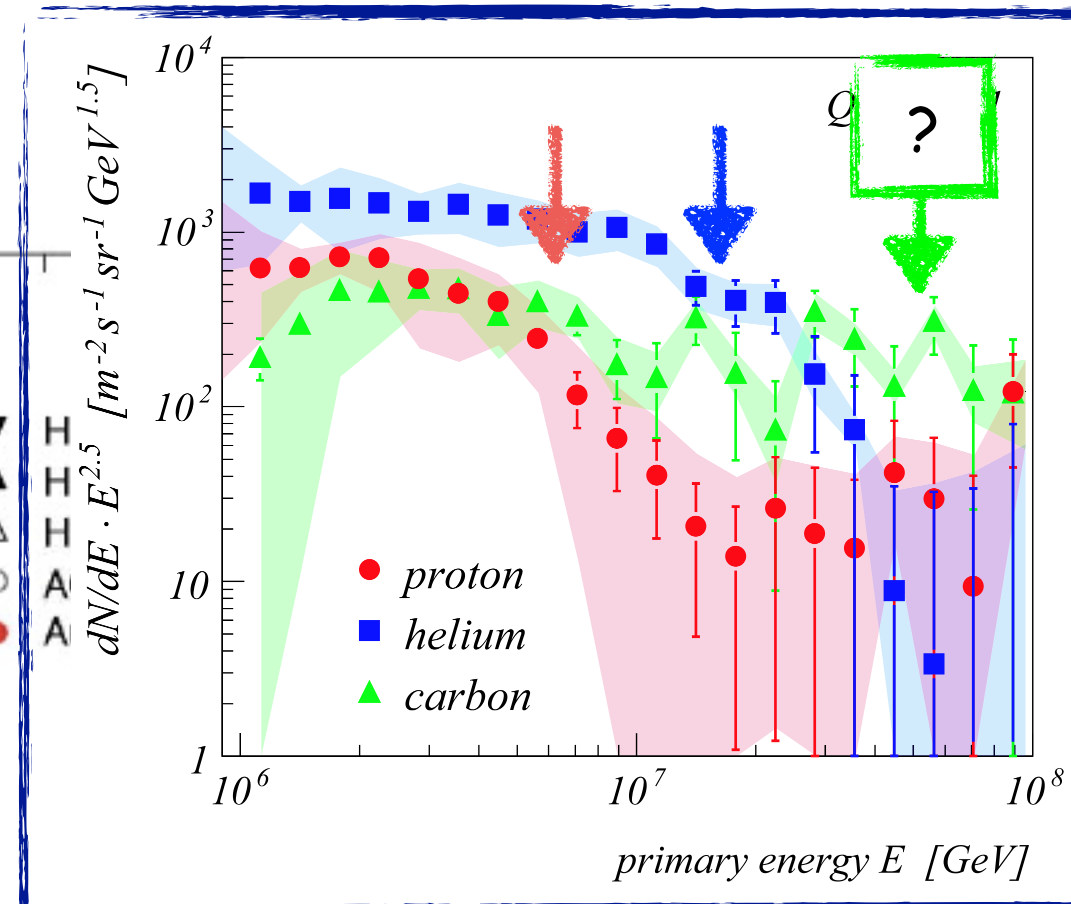
Z-dependent knee

Transition from galactic to extra-galactic CRs





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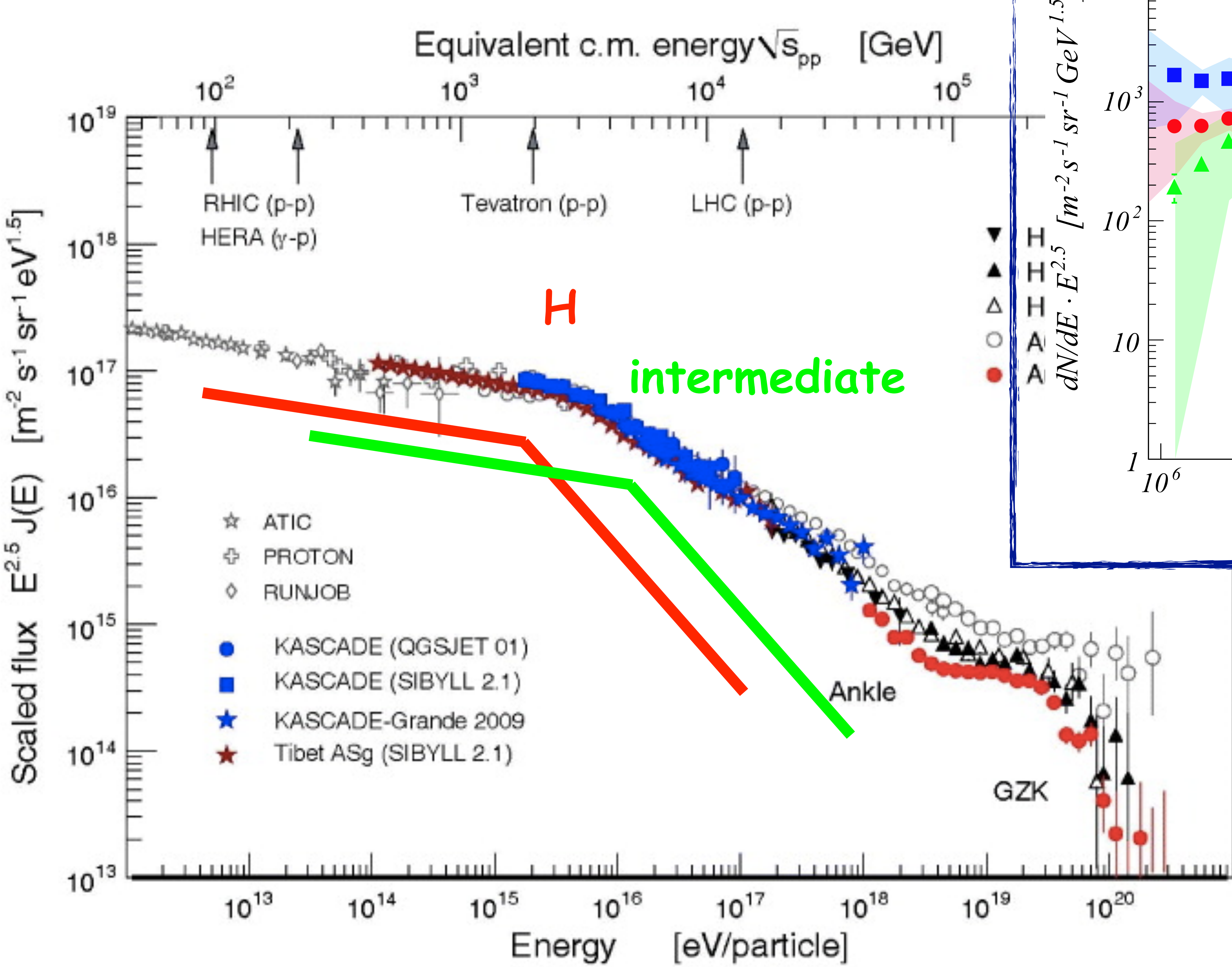

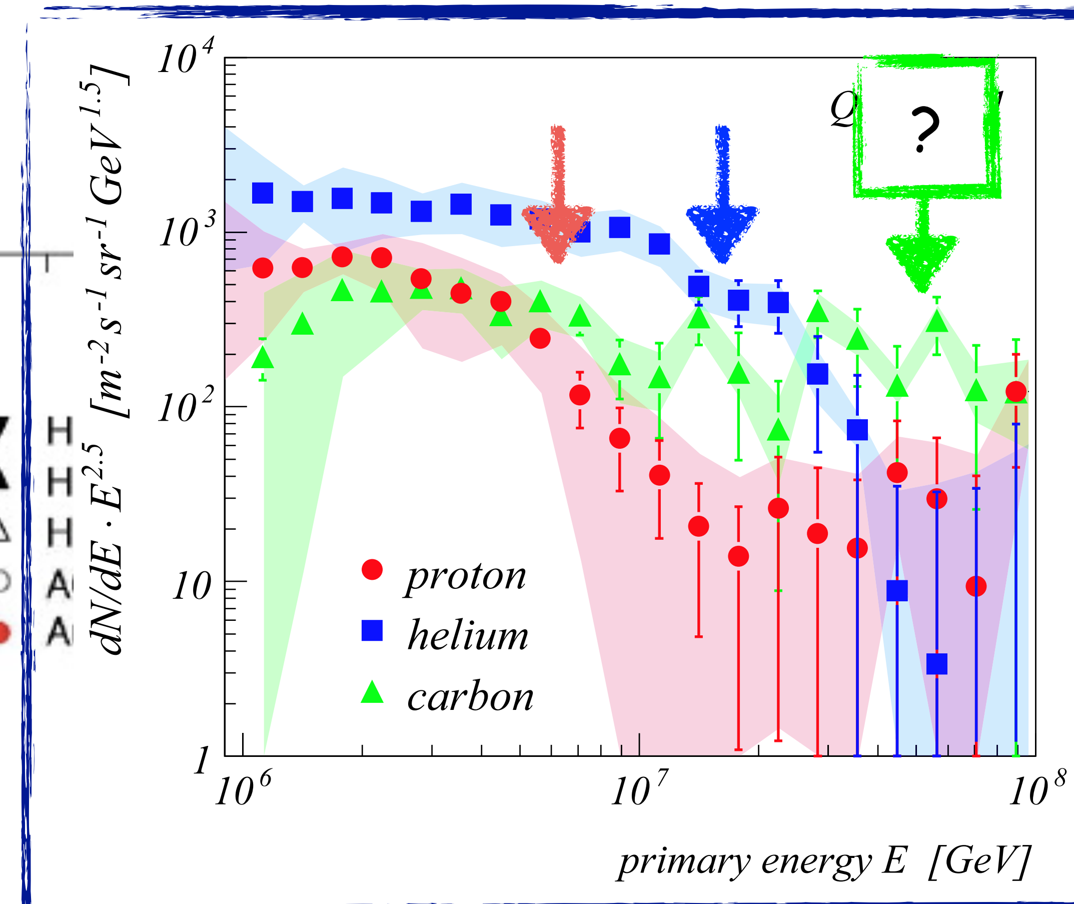

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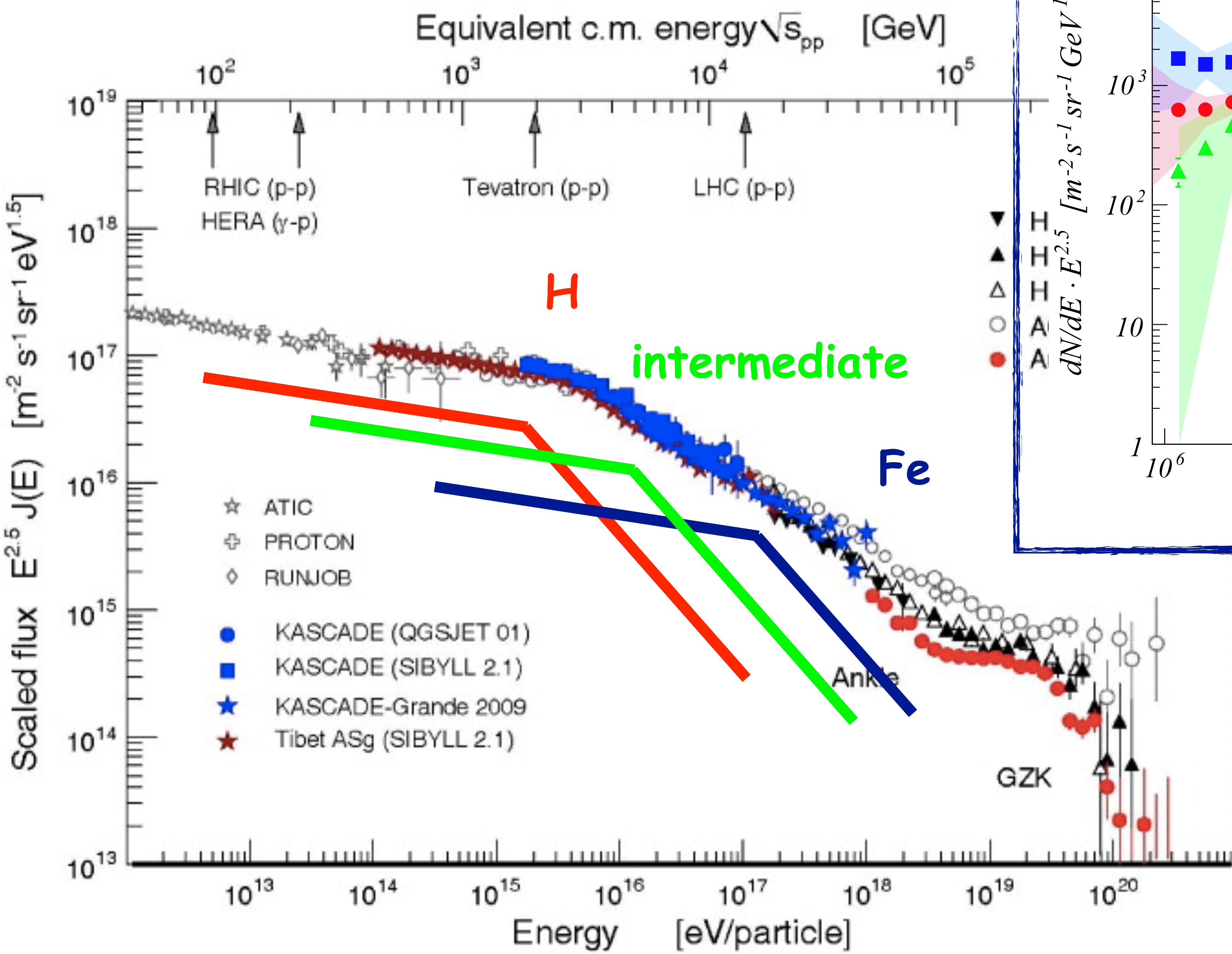

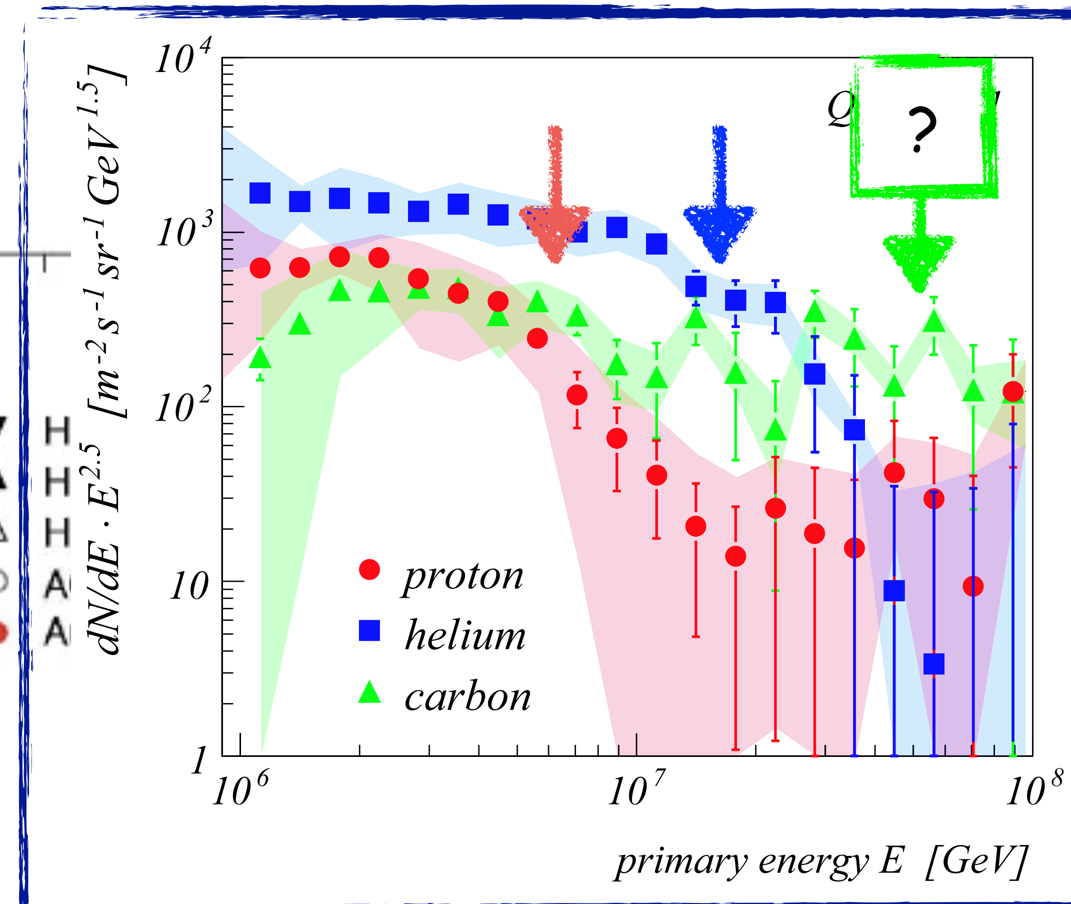

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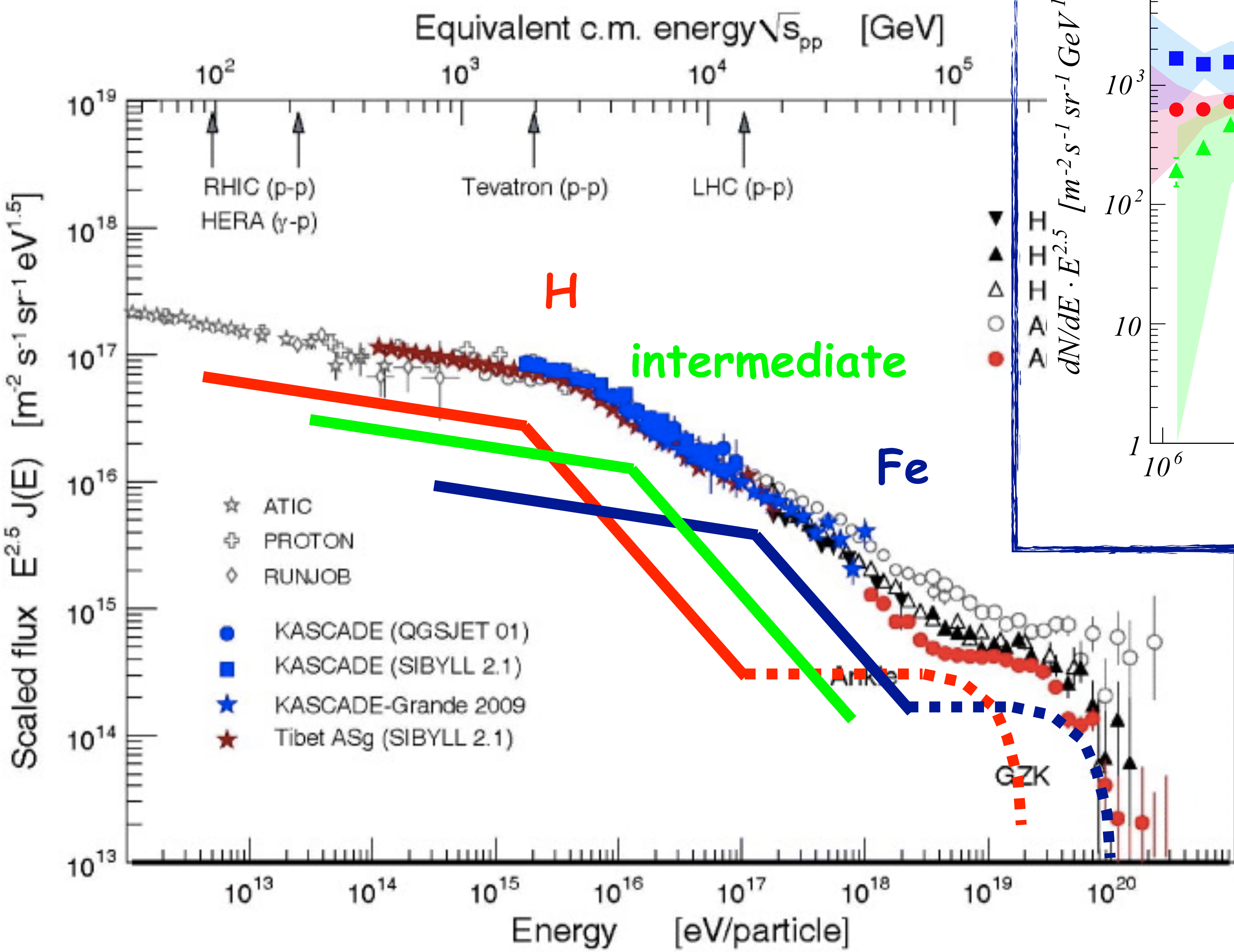

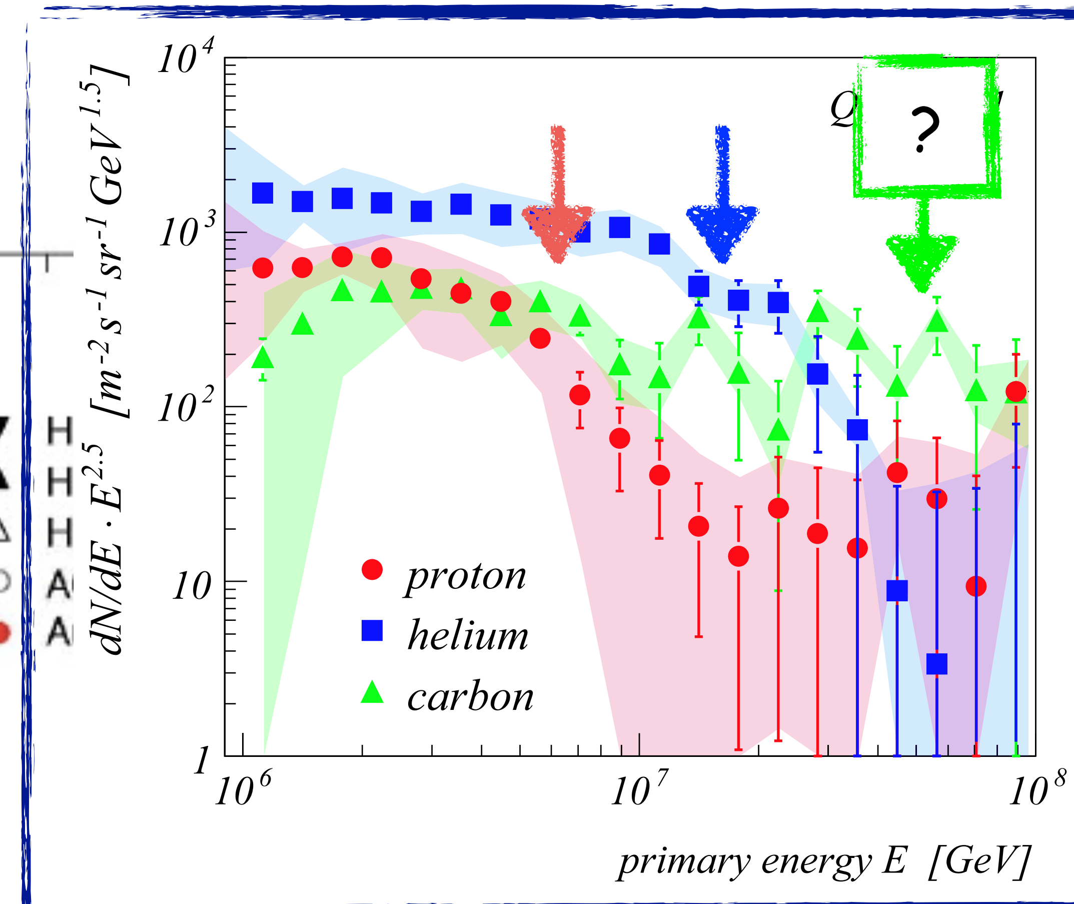

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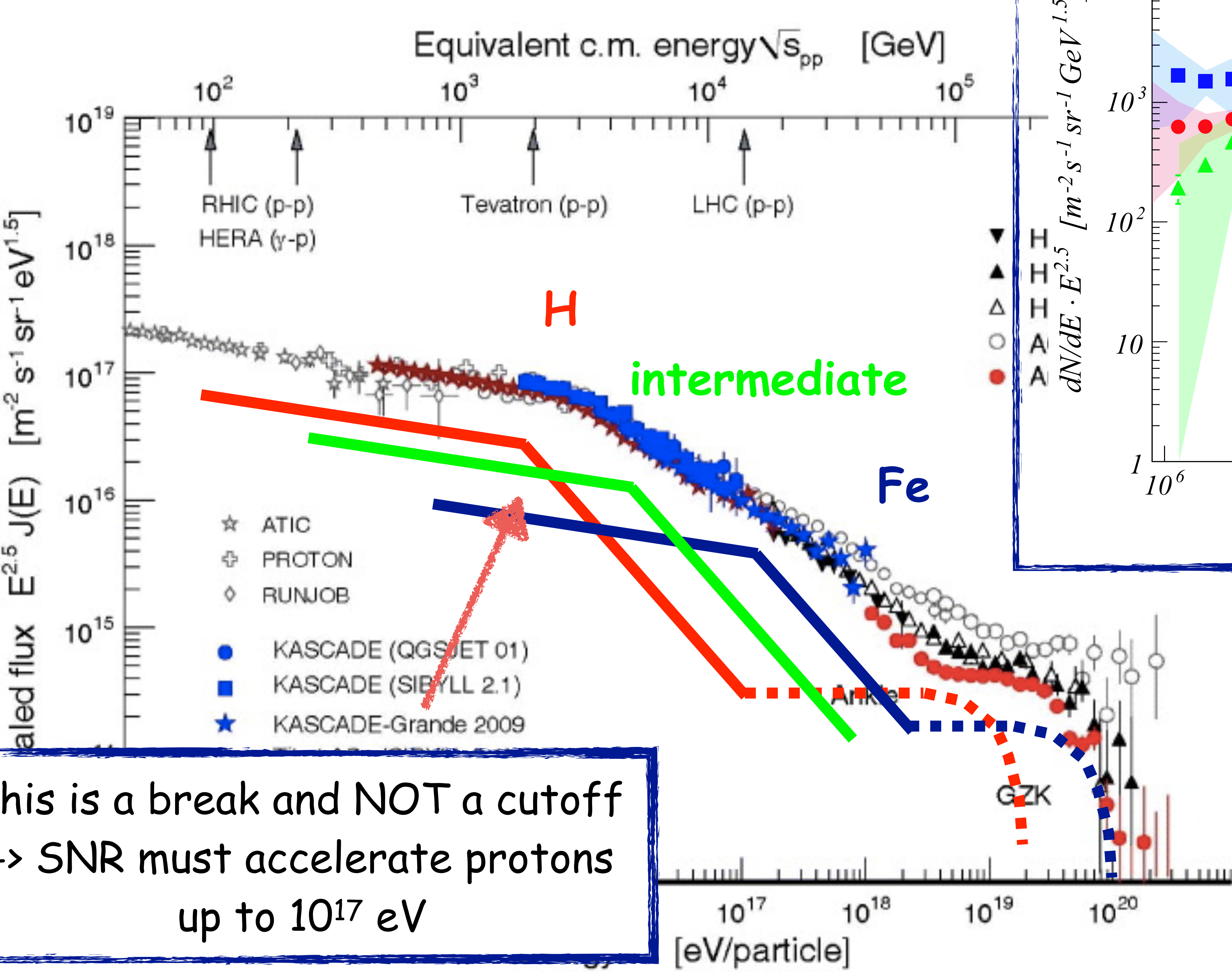
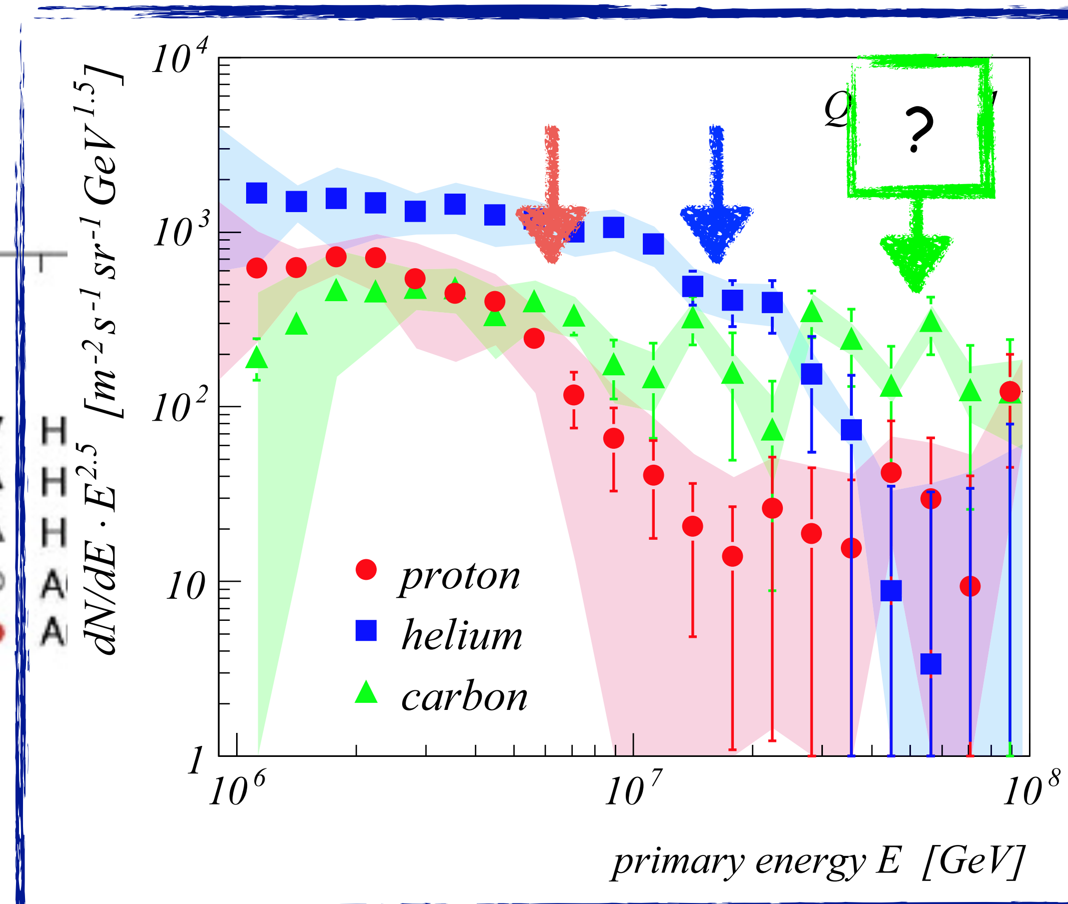


this is a break and NOT a cutoff
-> SNR must accelerate protons
up to 10^{17} eV



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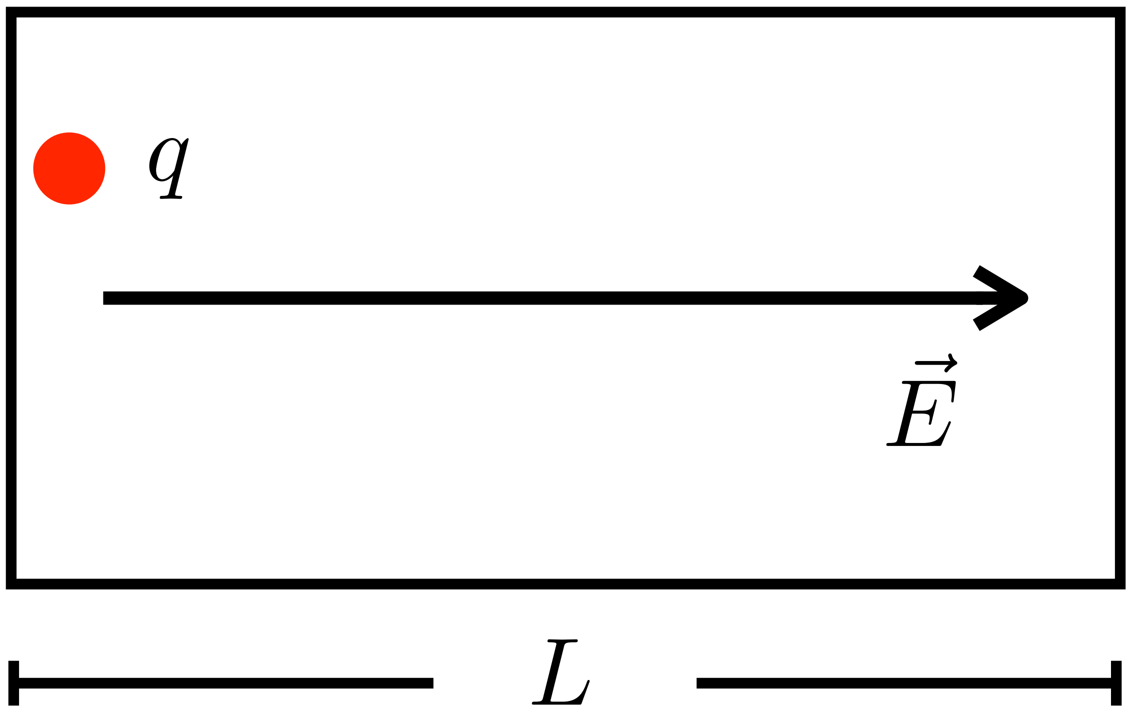
Z-dependent knee

The Hillas criterion

this is the best possible accelerator



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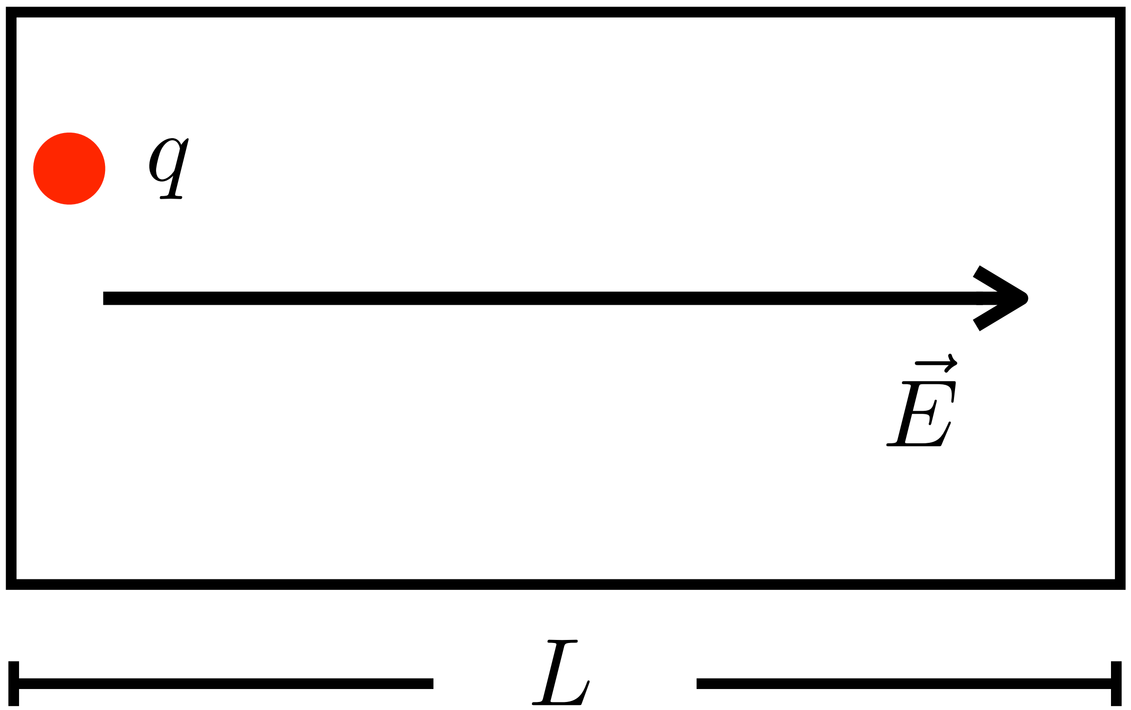

$$E_{max} = q\,|\,\overrightarrow{E}\,|\,L$$

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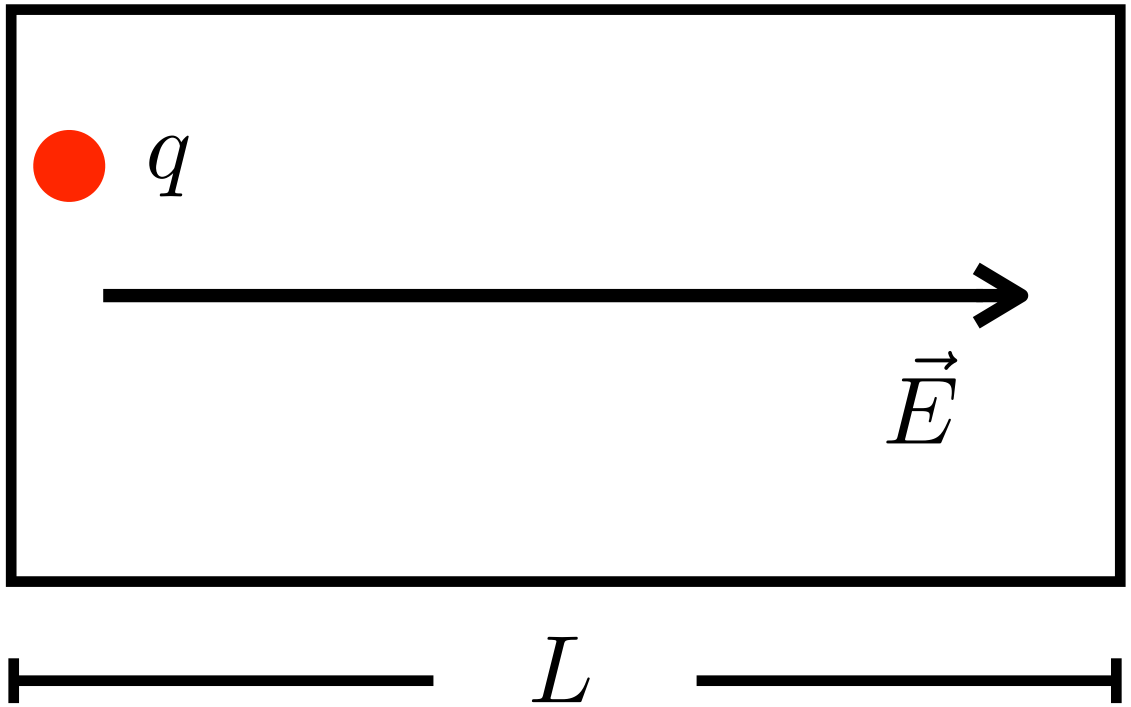

large charge

strong E field

$$E_{max} = q\,|\,\vec{E}\,|\,L$$

large accelerator

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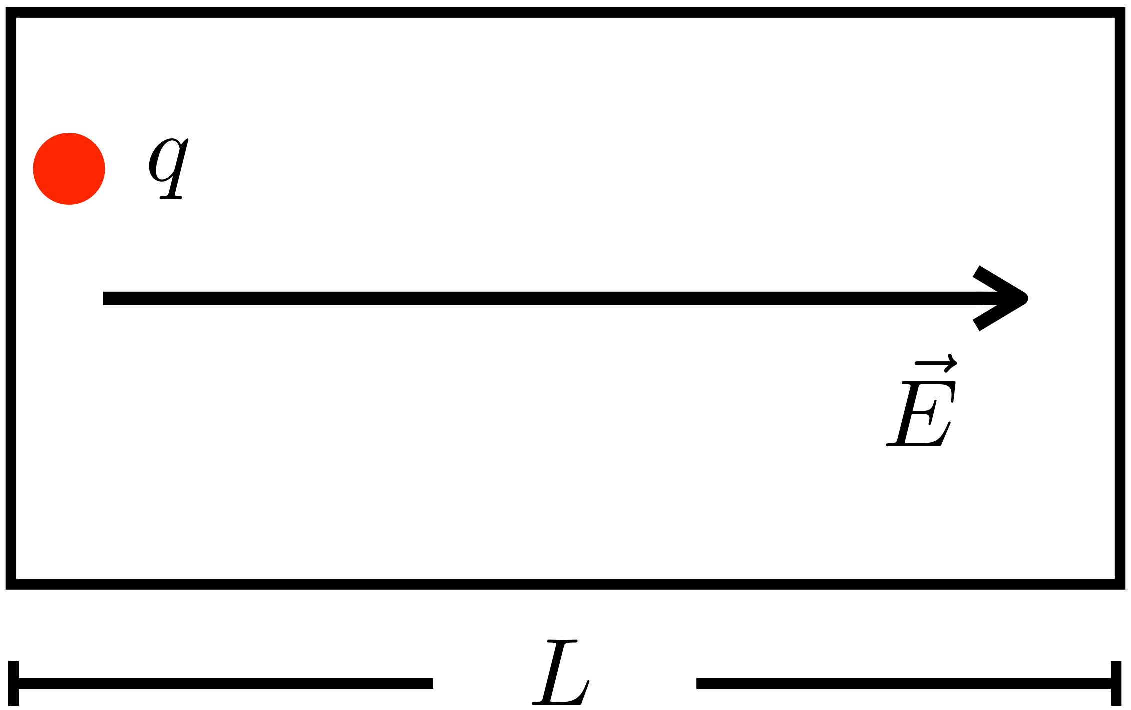

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"...a basic property of plasma, its **tendency towards electrical neutrality**. If over a large volume the number of electrons per cubic centimeter deviates appreciably from the corresponding number of positive ions, the electrostatic forces resulting 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."

(Lyman Spitzer "Physics of fully ionised gases")

The Hillas criterion

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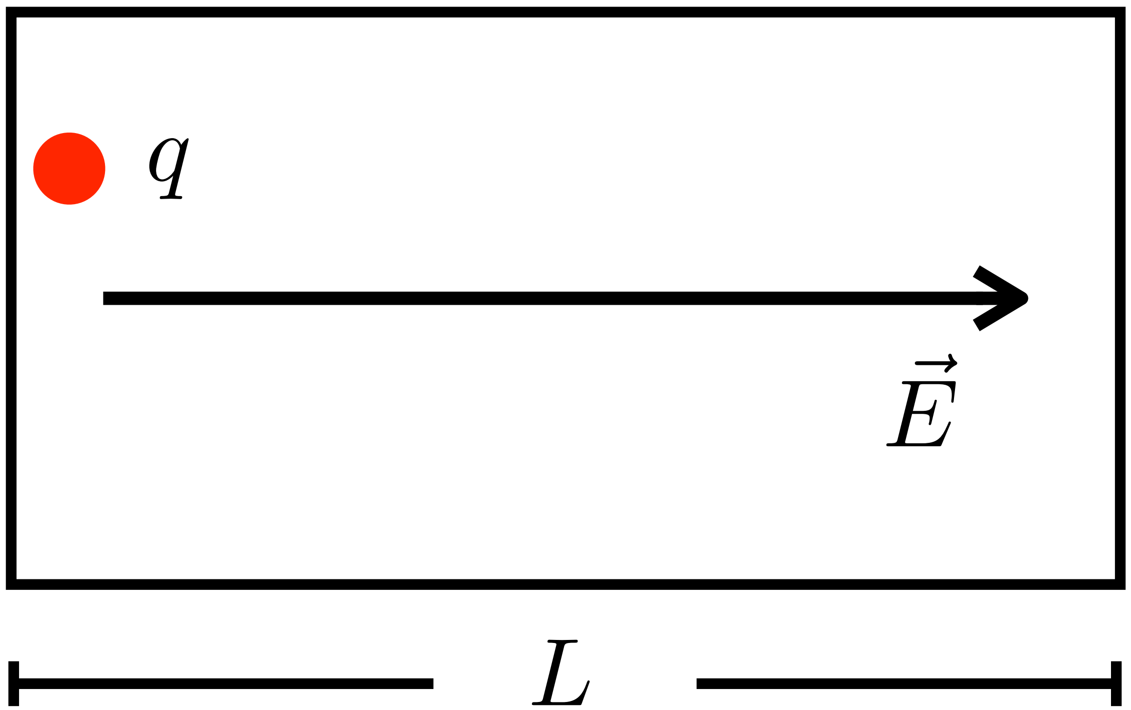

large charge

strong E field

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large accelerator

$$|\,\vec{E}\,| \sim 0$$

"...a basic property of plasma, its **tendency towards el**[illegible]**cal neutrality**. If over a large volume the number of electrons per cubic centimeter d[illegible]ciably from the corresponding number of positive ions, the electrostati[illegible]d a potential energy per particle that is enormously greater than th[illegible] Unless very special mechanisms are involved to support such large poten[illegible]ged particles will rapidly move in such a way as to reduce these potential difference[illegible]restore electrical neutrality."

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The Hillas criterion

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Faraday law

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$ —> a time-varying B is a source of E !

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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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characteristic time

characteristic velocity

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

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electric charge

velocity

$$\boxed{E_t^{max} \approx \left(\frac{q}{c}\right) B \; U \; L}$$

B-field

size

The Hillas criterion applied to SNRs

$$E^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}} \right) \left(\frac{U}{1000\ \mathrm{km/s}} \right) \left(\frac{L}{\underbrace{\mathrm{pc}}_{1\text{-}10}} \right)\ \mathrm{eV}$$

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how fast are SNR shock?

1-10

SNR shocks in one slide

stellar explosion of energy $E_{SN} = 10^{51}$ erg ejecting M_{ej} solar masses

early times —> $\boxed{M_{ej} \gg M_{sw}}$ mass of the ISM swept up by the shock

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SNR shocks in one slide

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late times —> $\boxed{M_{ej} \ll M_{sw}}$

solution must depend on ρ (ISM density) and not M_{ej}!

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

SNR shocks in one slide

stellar explosion of energy $E_{SN} = 10^{51}$ erg ejecting M_{ej} solar masses

early times —> $\boxed{M_{ej} \gg M_{sw}}$

mass of the ISM swept up by the shock

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

$$u_s \sim 2 \times 10^3 \left(\frac{E_{SN}}{10^{51}\ \mathrm{erg}} \right)^{1/5} \left(\frac{n_{ISM}}{\mathrm{cm}^{-3}} \right)^{-1/5} \left(\frac{t}{\mathrm{kyr}} \right)^{-3/5} \mathrm{km/s}$$

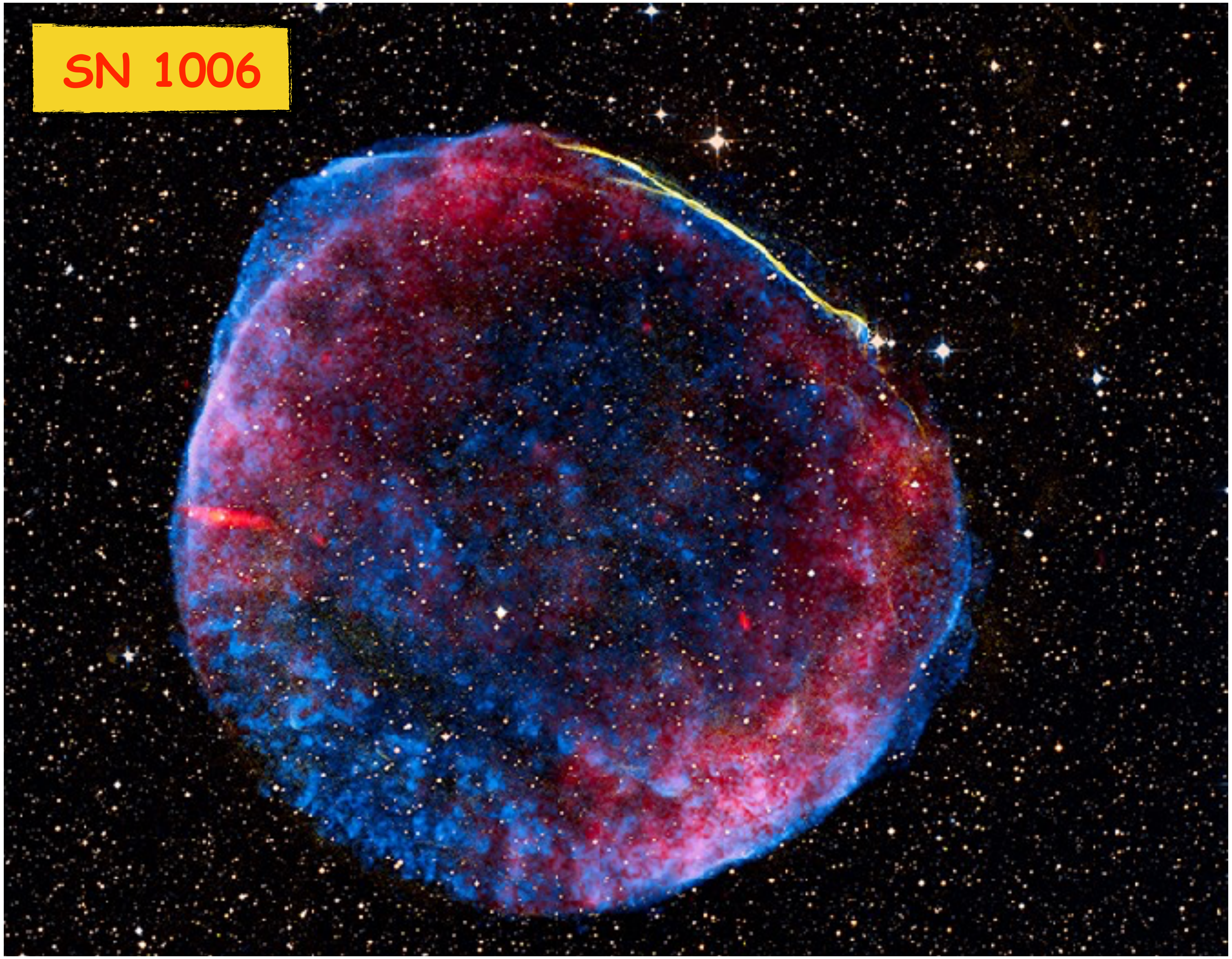
The Hillas criterion applied to SNRs

$$E^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{U}{1000\ \mathrm{km/s}}\right) \left(\frac{L}{\mathrm{pc}}\right)\ \mathrm{eV}$$

1-10

1-10

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



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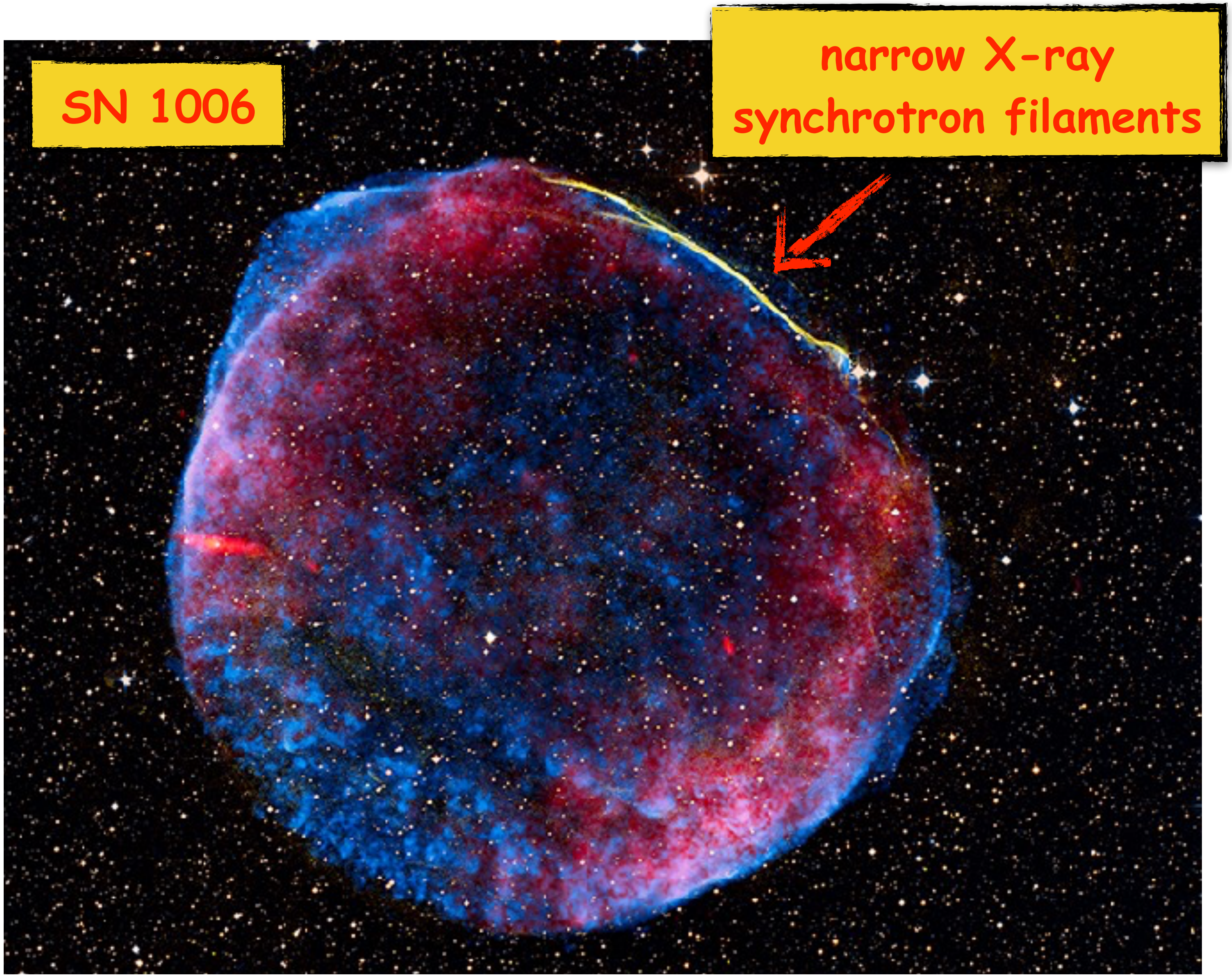

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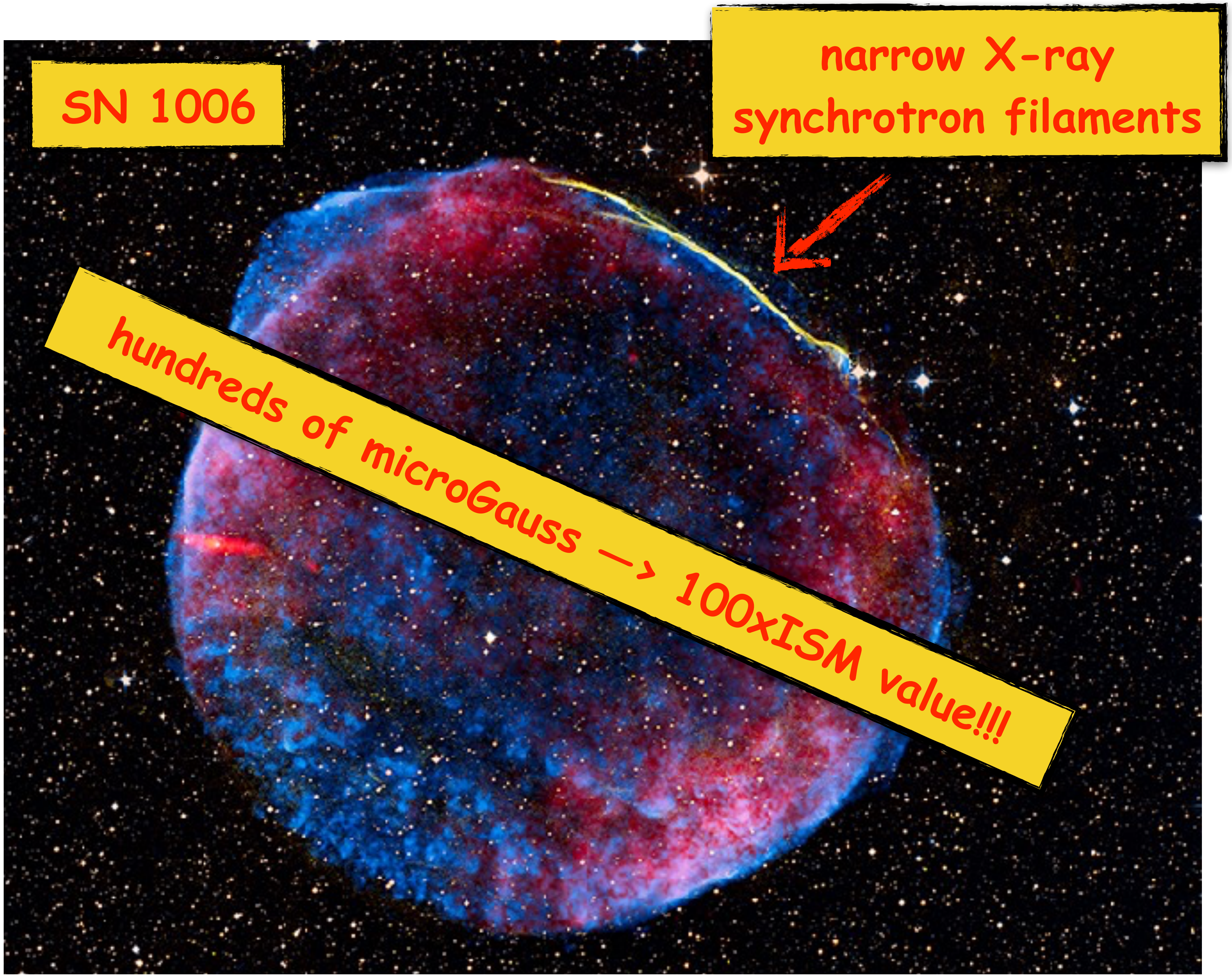

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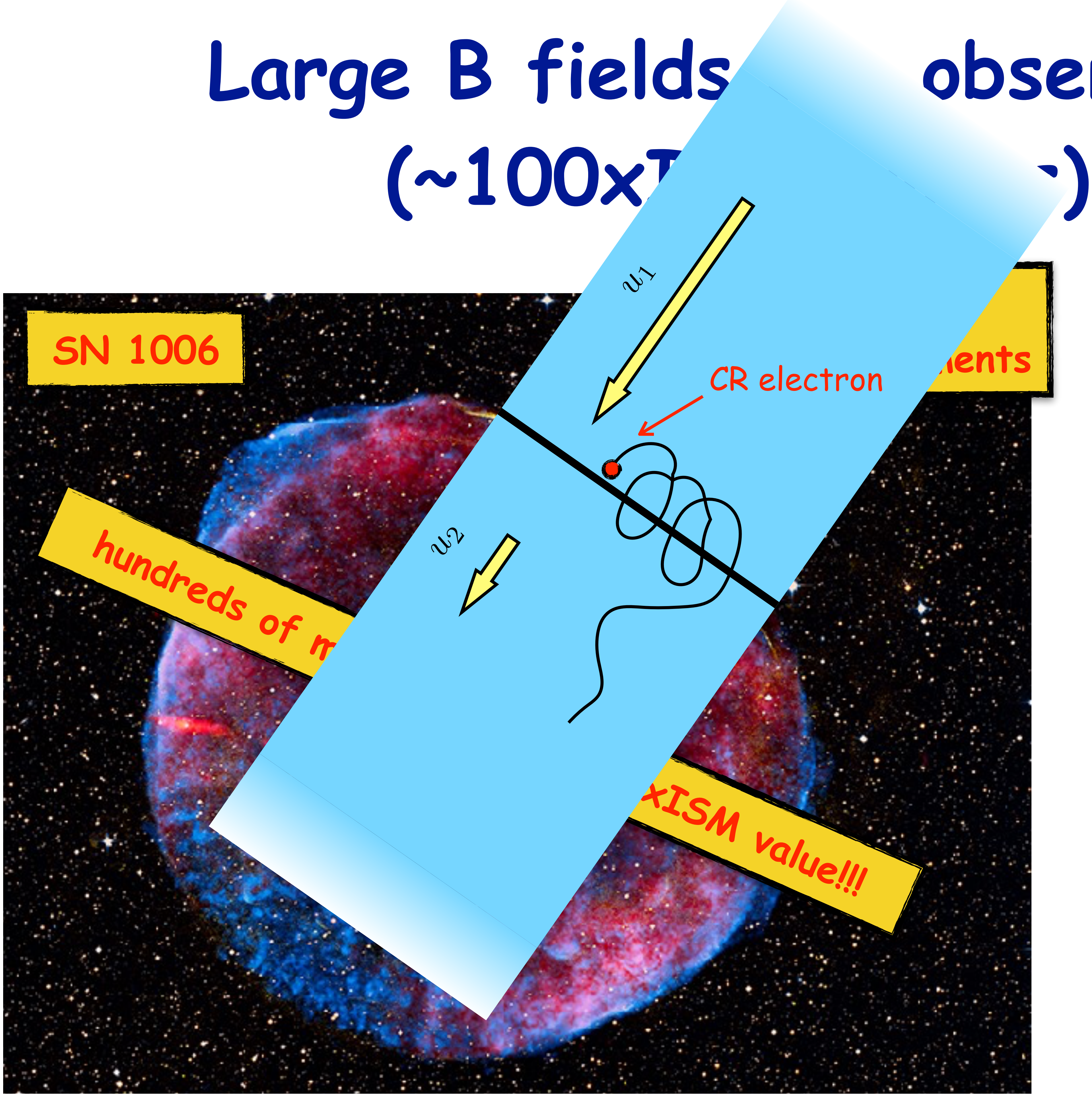

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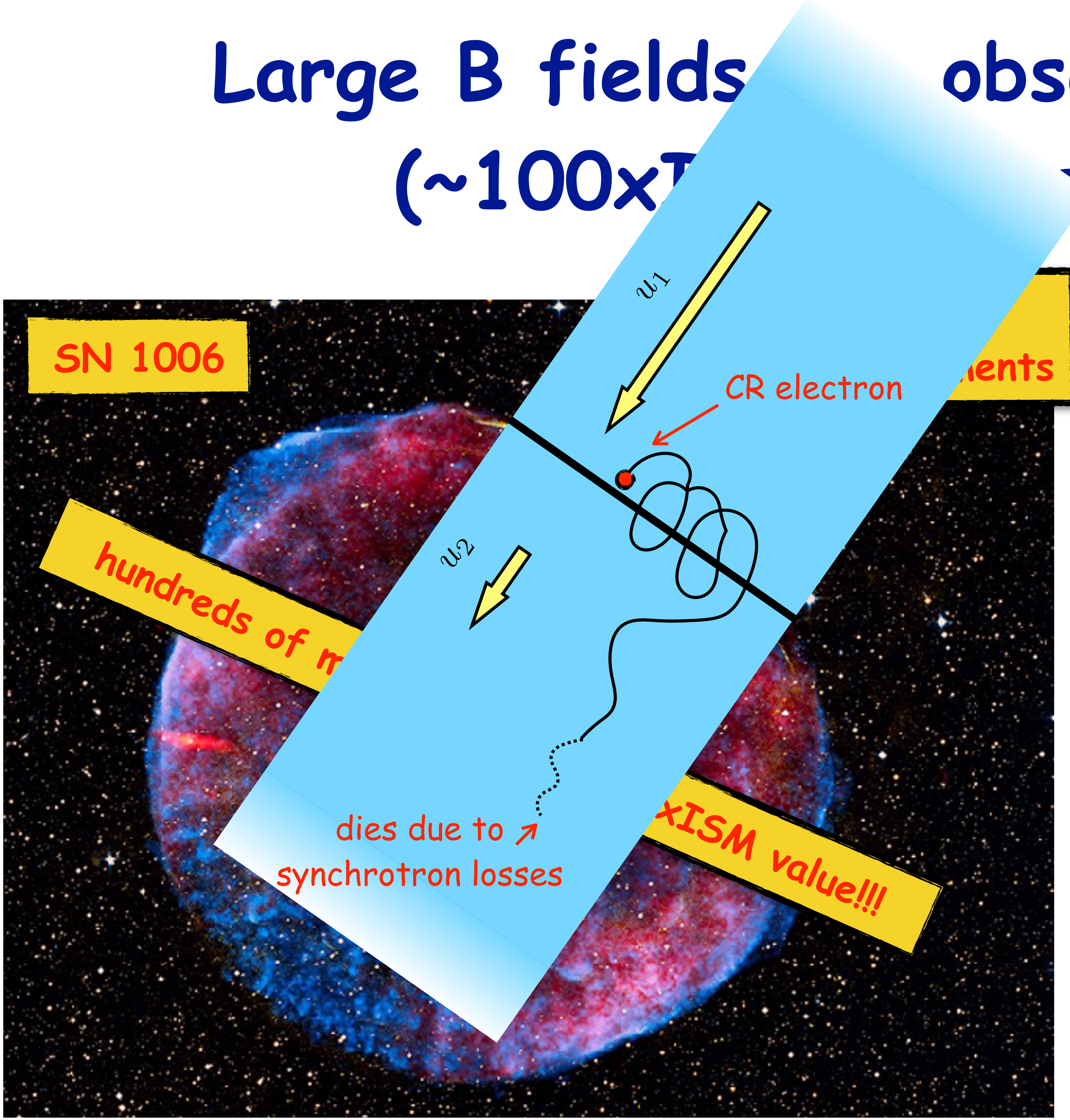

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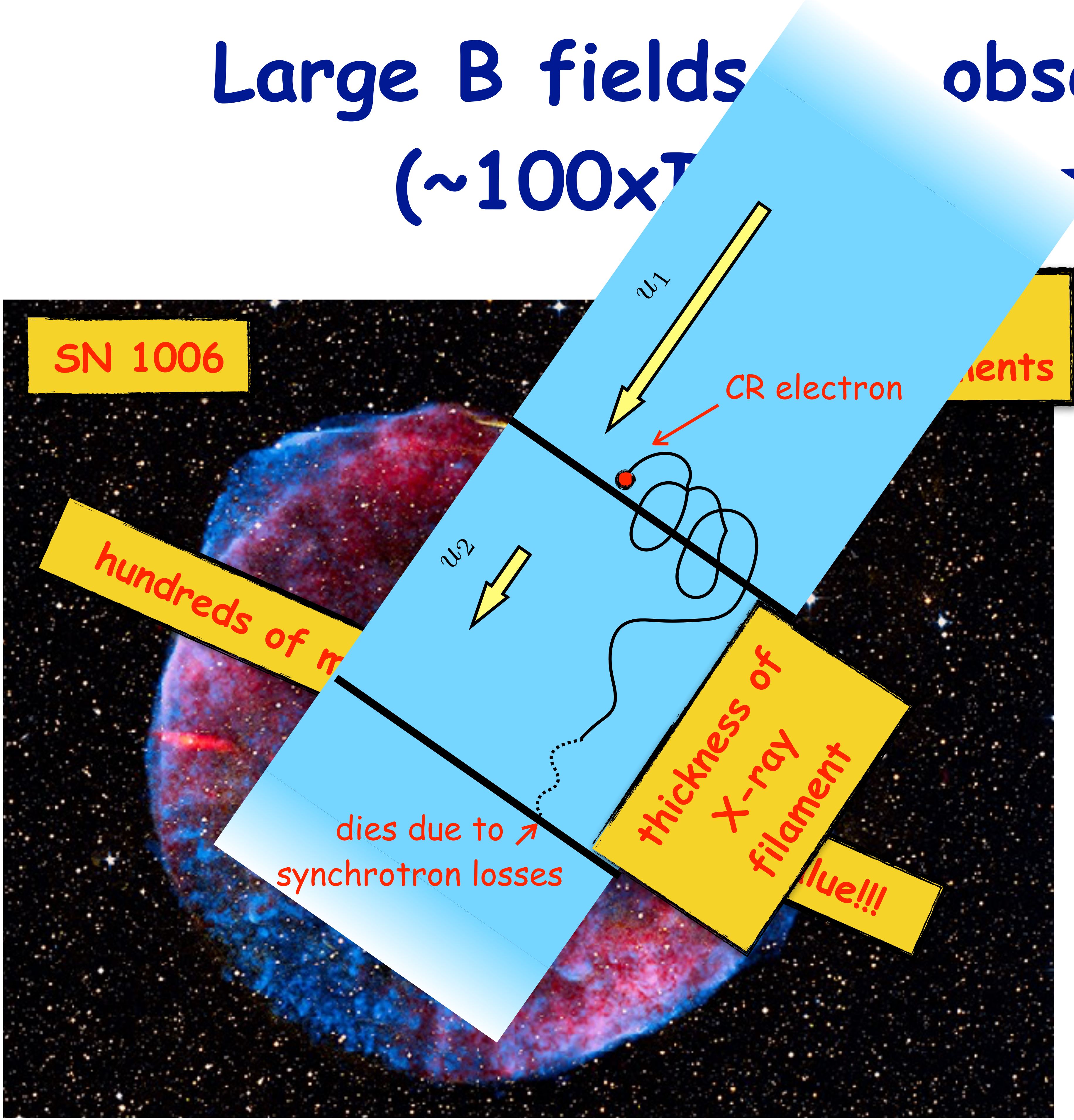
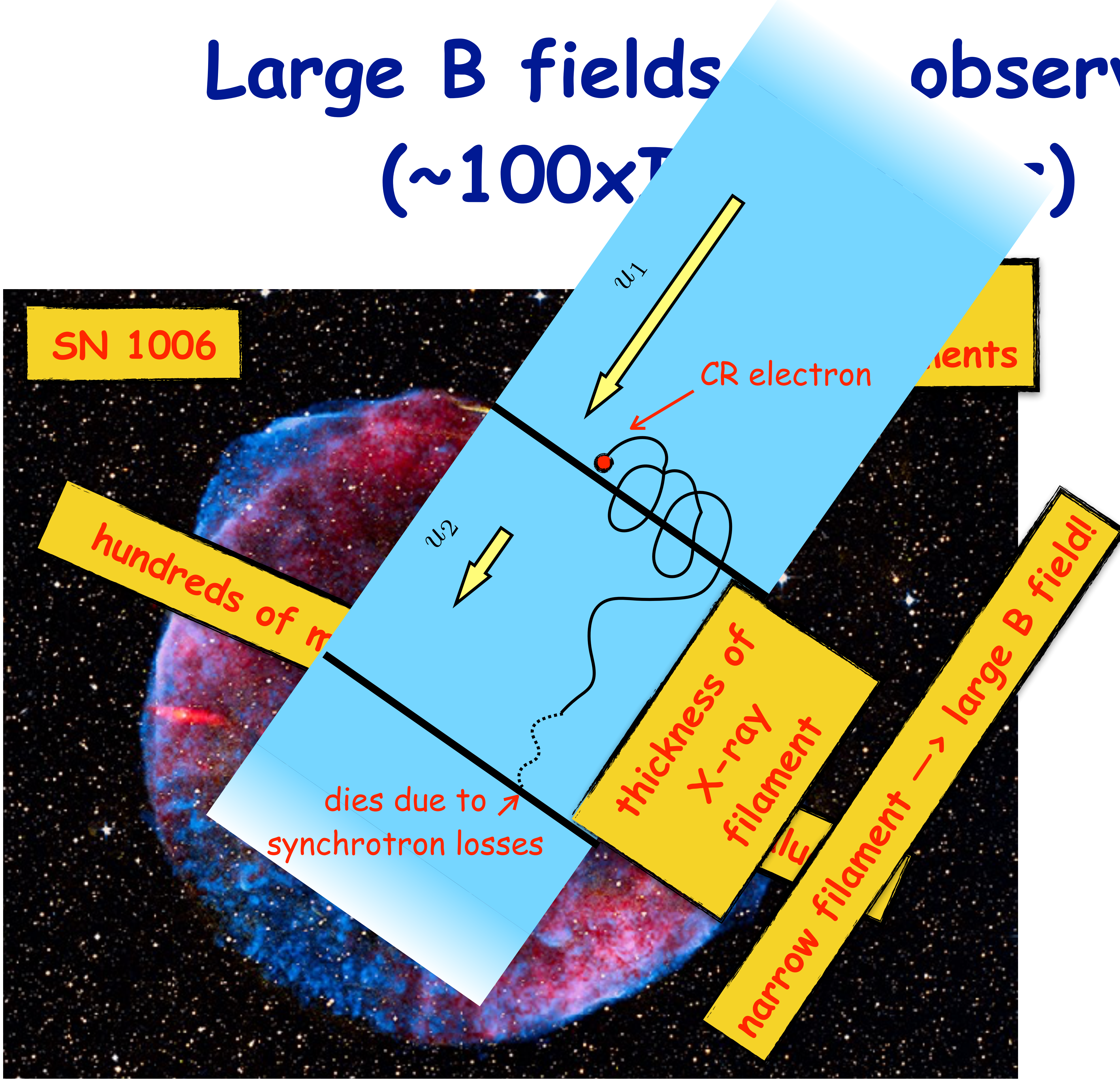


Large B fields ... observed!
(~100x...)



Large B fields ... observed!
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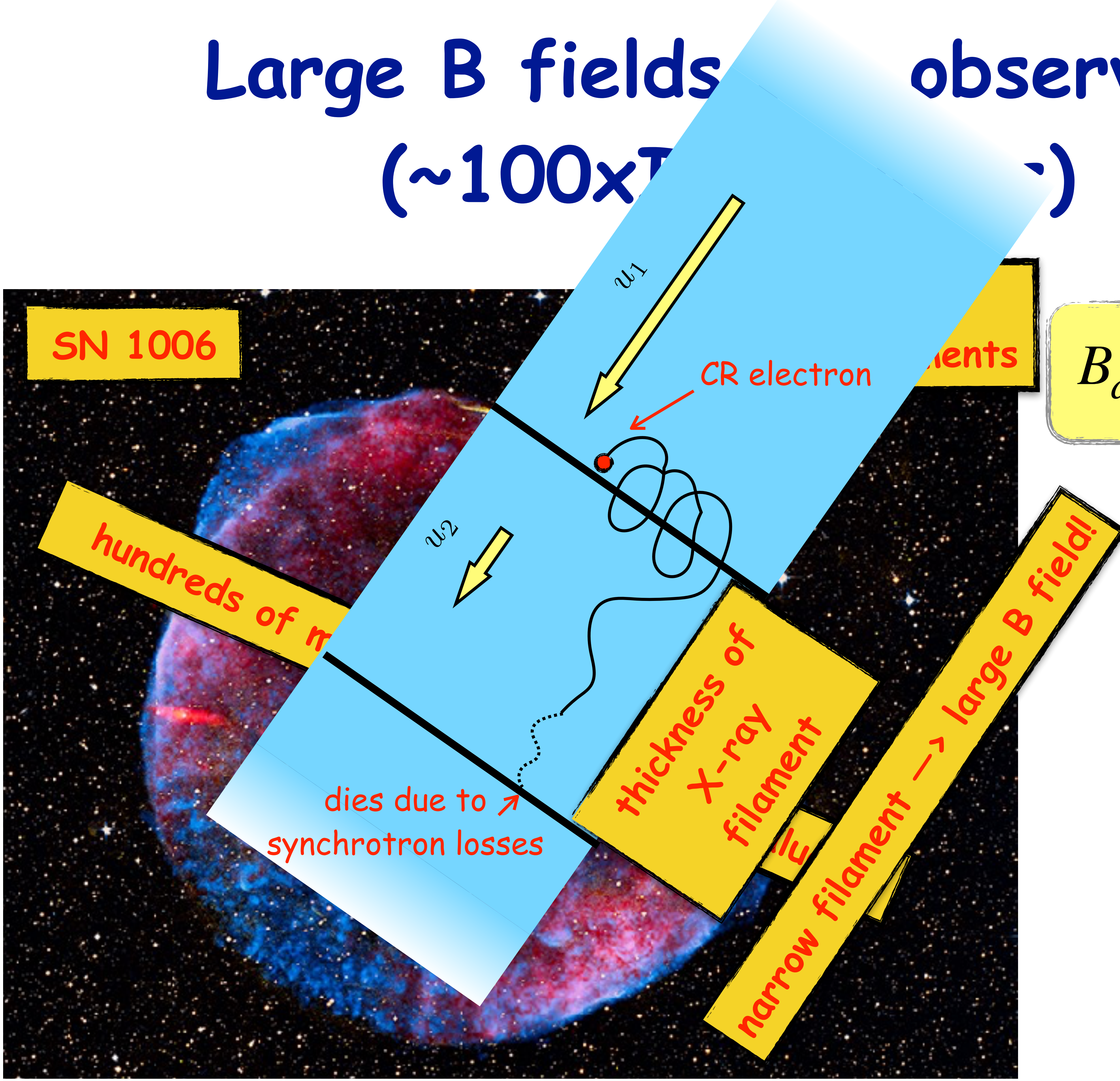

$$B_d \approx 100 \times B_{ISM}$$

Large B fields observed!

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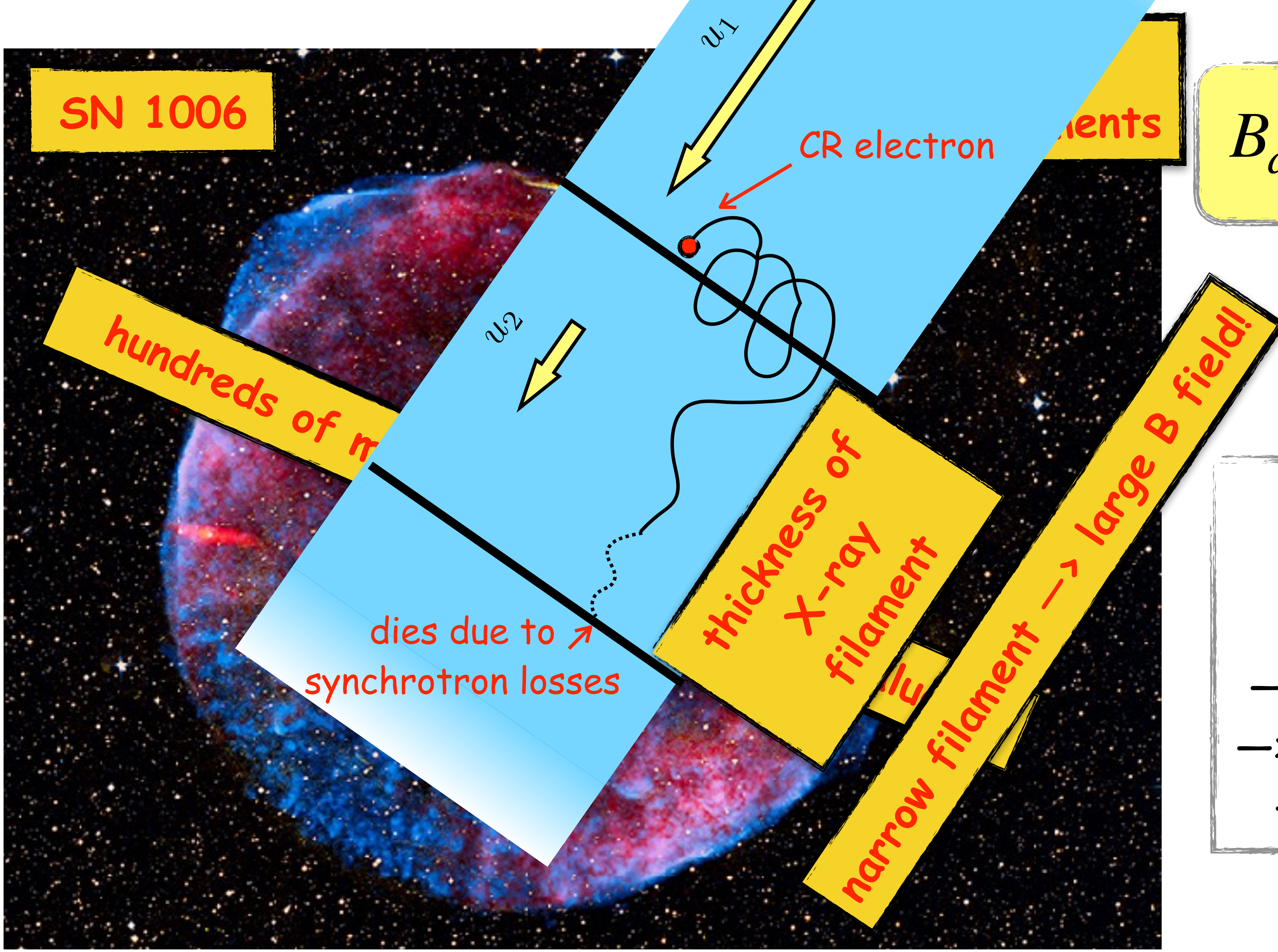

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NON LINEAR!

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

The Hillas criterion applied to SNRs

$$E^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{U}{1000\ \mathrm{km/s}}\right)\left(\frac{L}{\mathrm{pc}}\right)\ \mathrm{eV}$$

$3 \times 10^{14} - 3 \times 10^{16}$ eV

~100

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3×10^{14} — 3×10^{16} eV

~100

1-10

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can SNR shocks accelerate particles up the knee(s)? —> **most likely yes!**

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3 x 10^{14} — 3 x 10^{16} eV

~100

1-10

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can SNR shocks accelerate particles up the knee(s)? —> **most likely yes!**

can SNR shocks accelerate ENOUGH particles up the knee(s)? —>

The Hillas criterion applied to SNRs

$$E^{max} \approx 3 \times 10^{12} Z \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{U}{1000\ \mathrm{km/s}}\right) \left(\frac{L}{\mathrm{pc}}\right)\ \mathrm{eV}$$

3×10^{14} — 3×10^{16} eV

~100

1-10

1-10

can SNR shocks accelerate particles up the knee(s)? —> **most likely yes!**

can SNR shocks accelerate ENOUGH particles up the knee(s)? —>

—> Carmelo told us (based on CR data) that SNRs must inject steep spectra (~$E^{-2.4}$)

—> gamma-ray observations of individual SNRs suggests the same

The Hillas criterion applied to SNRs

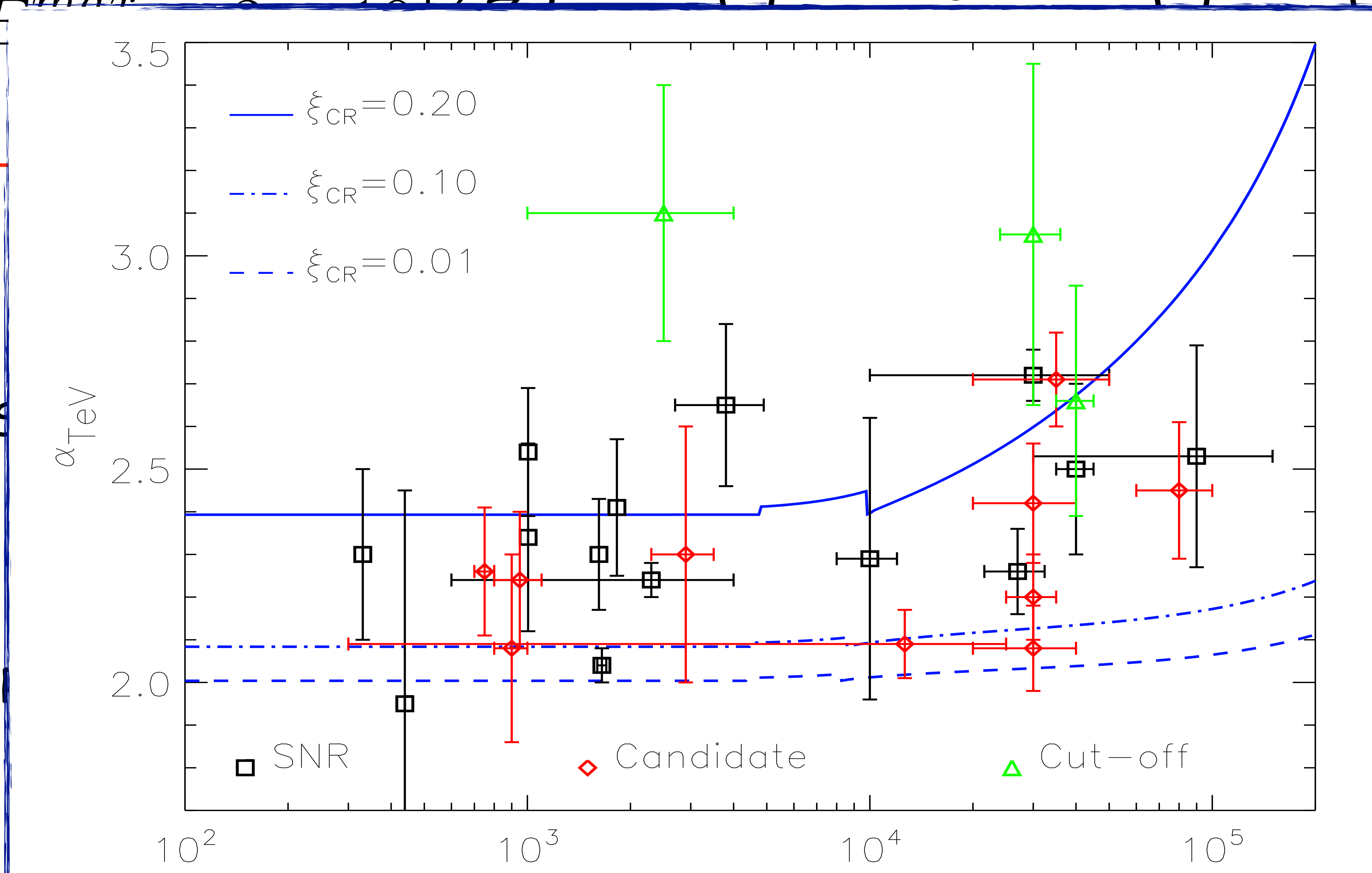
$E^{max} \ldots 10^{12} Z \left(\frac{B}{\ldots}\right)\left(\frac{U}{\ldots}\right)\left(\frac{L}{\ldots}\right)$ eV

3 x 10^14 – … 10

can S…

ely yes!

can SN…



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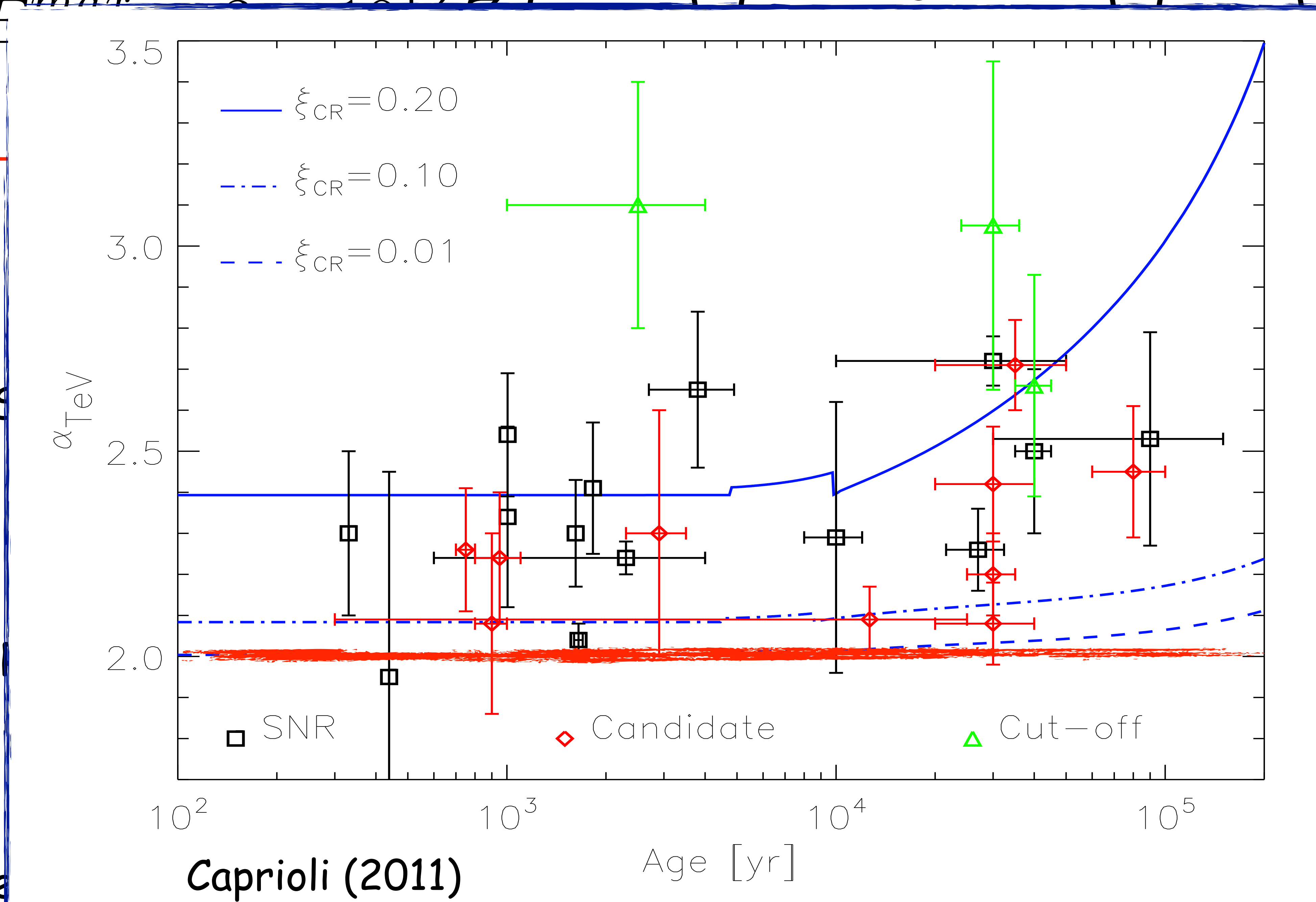

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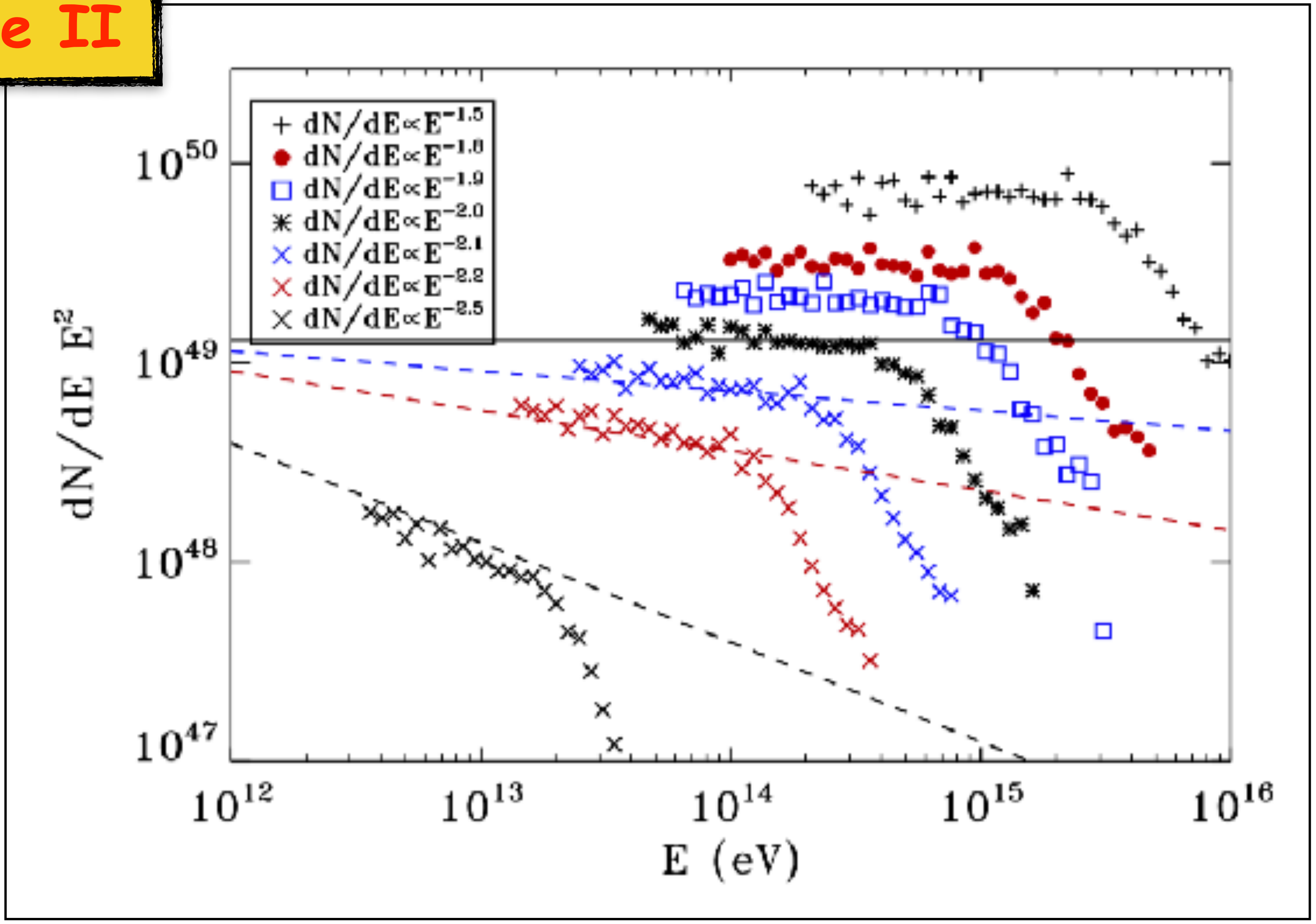
One can't have everything…

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

type II

Schure & Bell 2014



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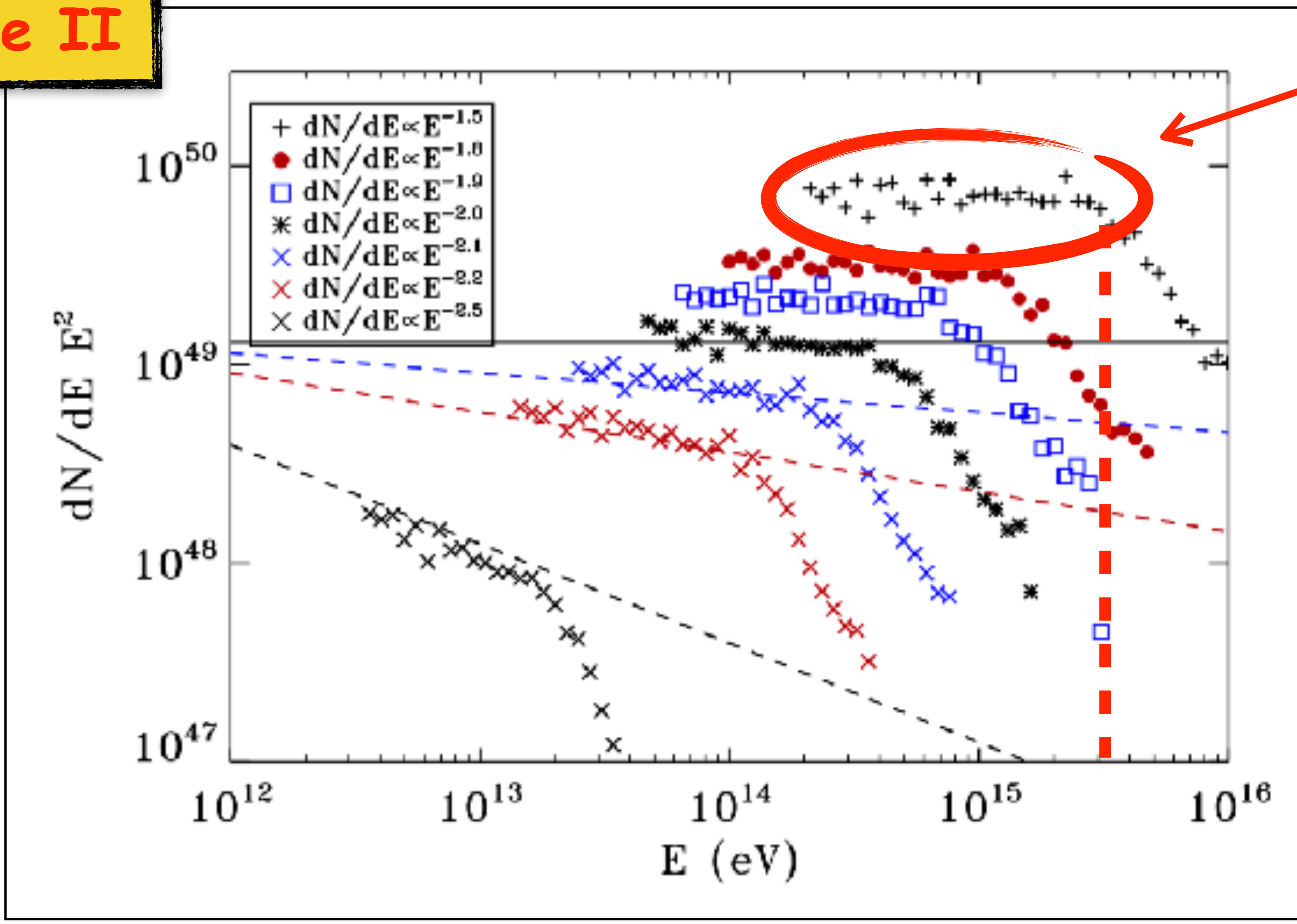

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—> injection too hard

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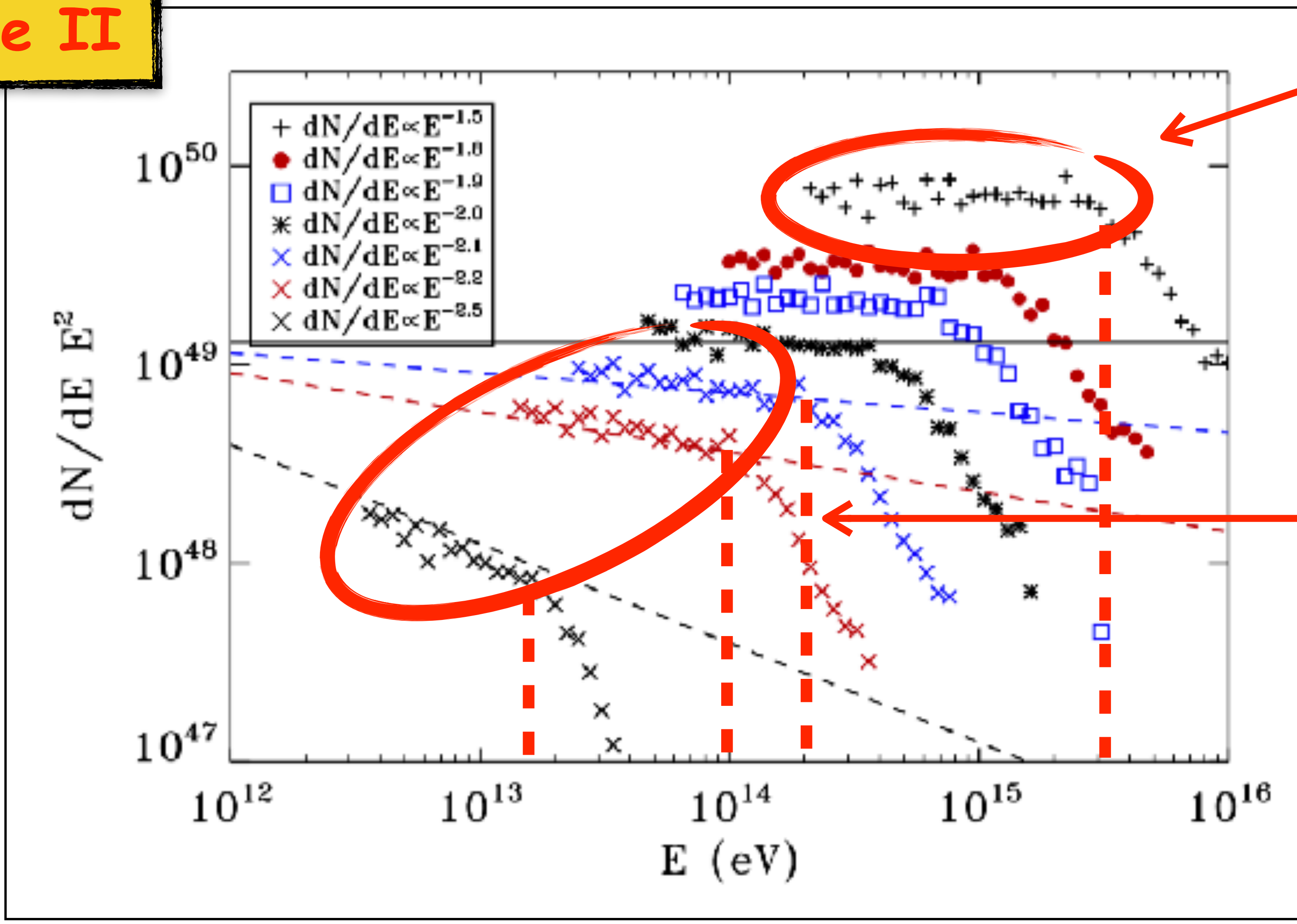

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steeper than 2

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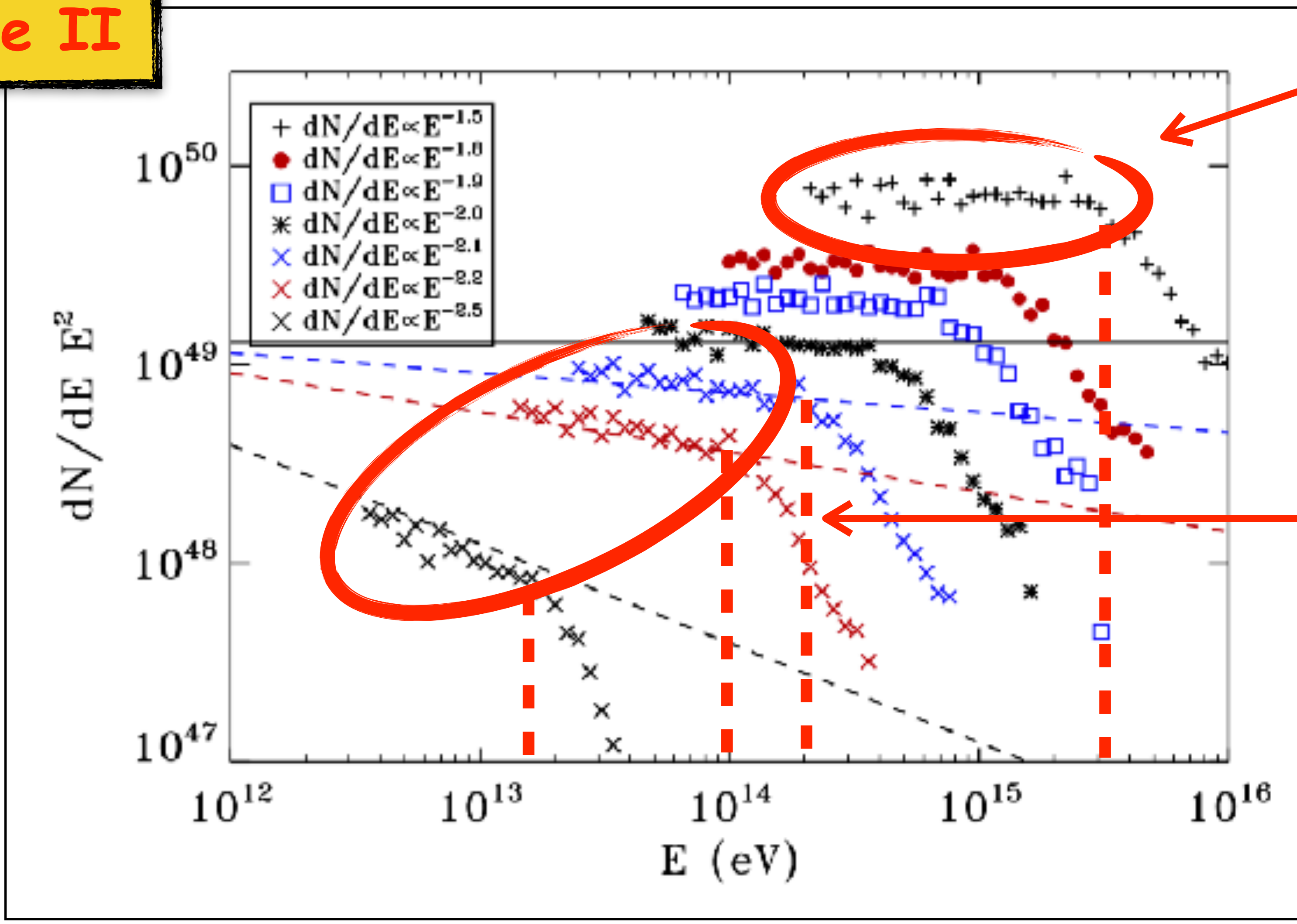

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It is also worth noticing that none of the types of SNRs considered here is able alone to describe the relatively smooth CR spectrum that we measure over many decades in energy. In a way, rather than being surprised by the appearance of features, one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

(Cristofari+ 2020)

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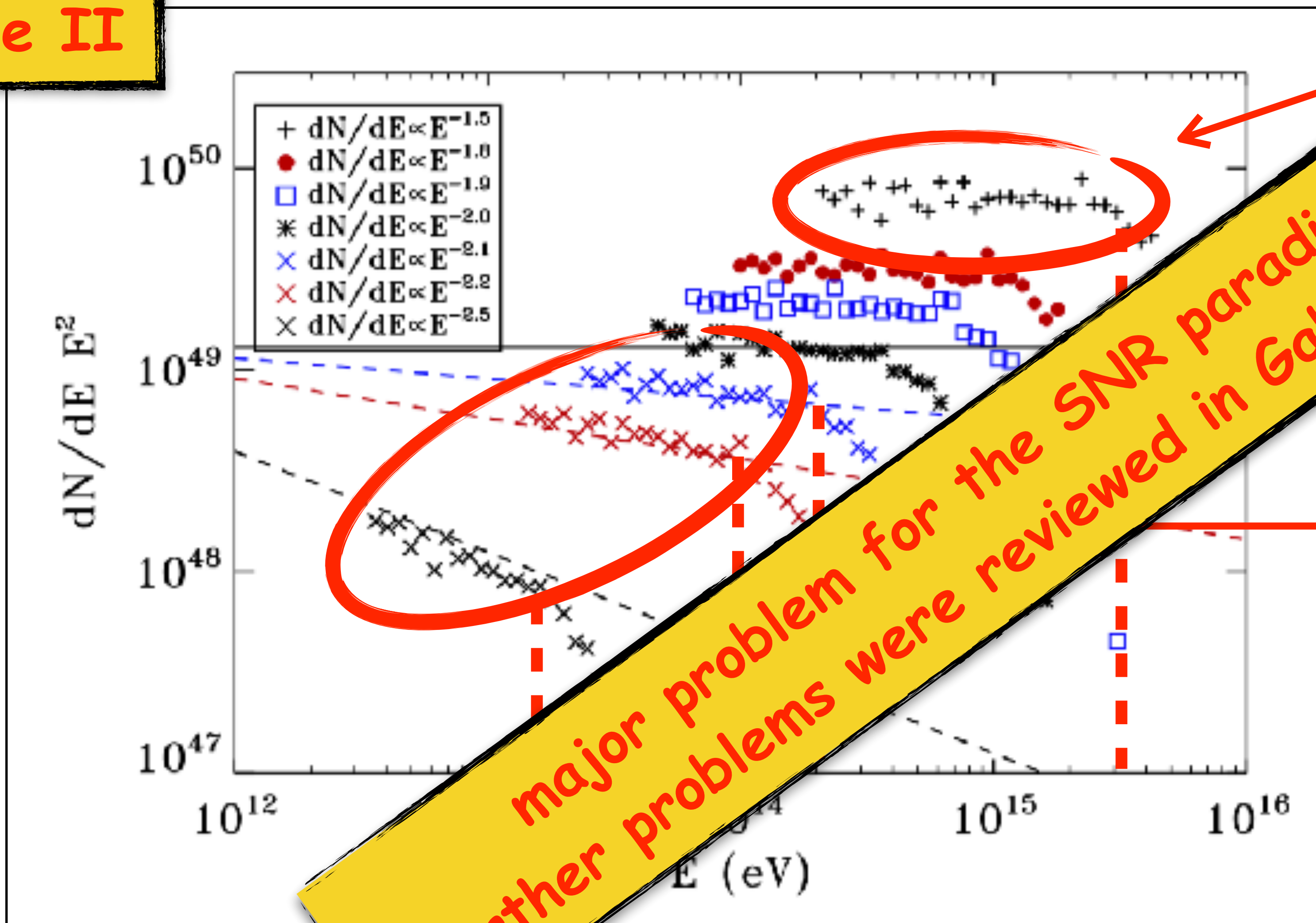

major problem for the SNR paradigm
(further problems were reviewed in Gabici+ 2019)

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ction too hard

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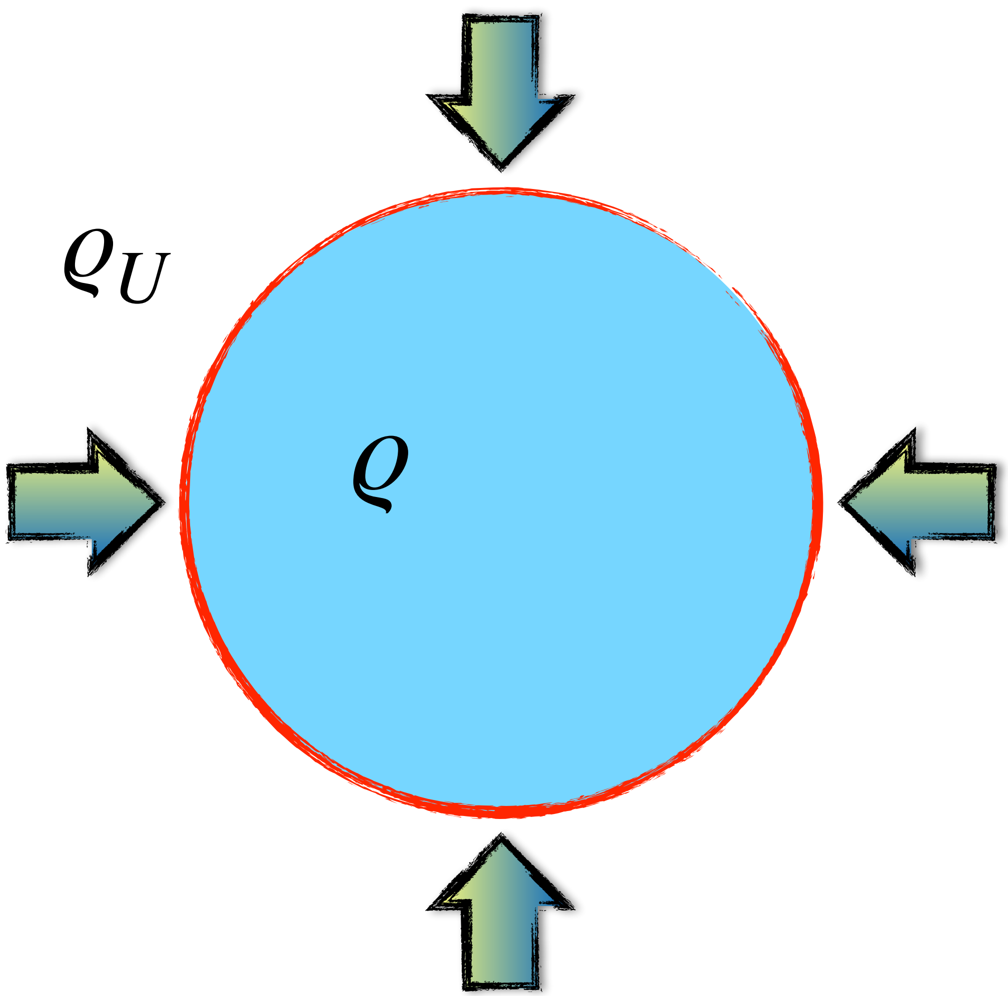
few 10^6

GCs shocks in one slide



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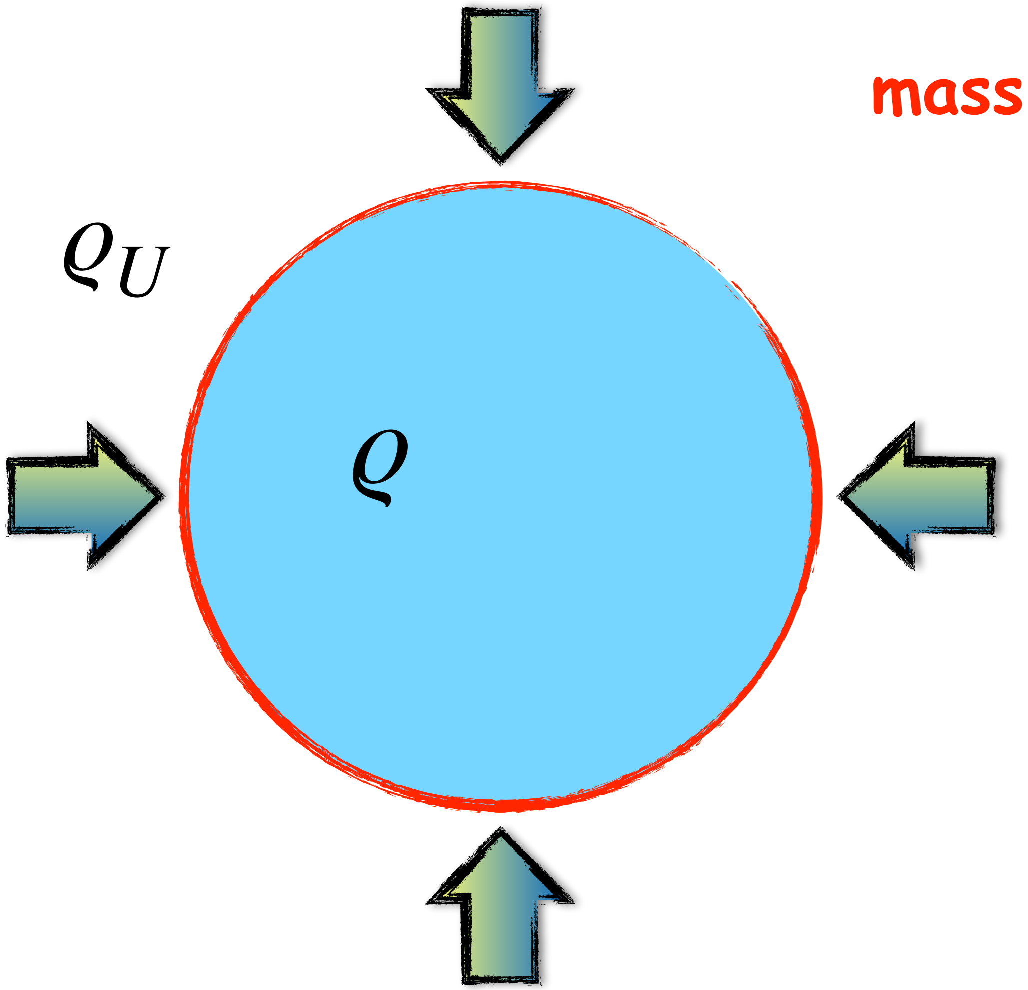

massive virialised object —> $\varrho \sim 200 \times \varrho_U$

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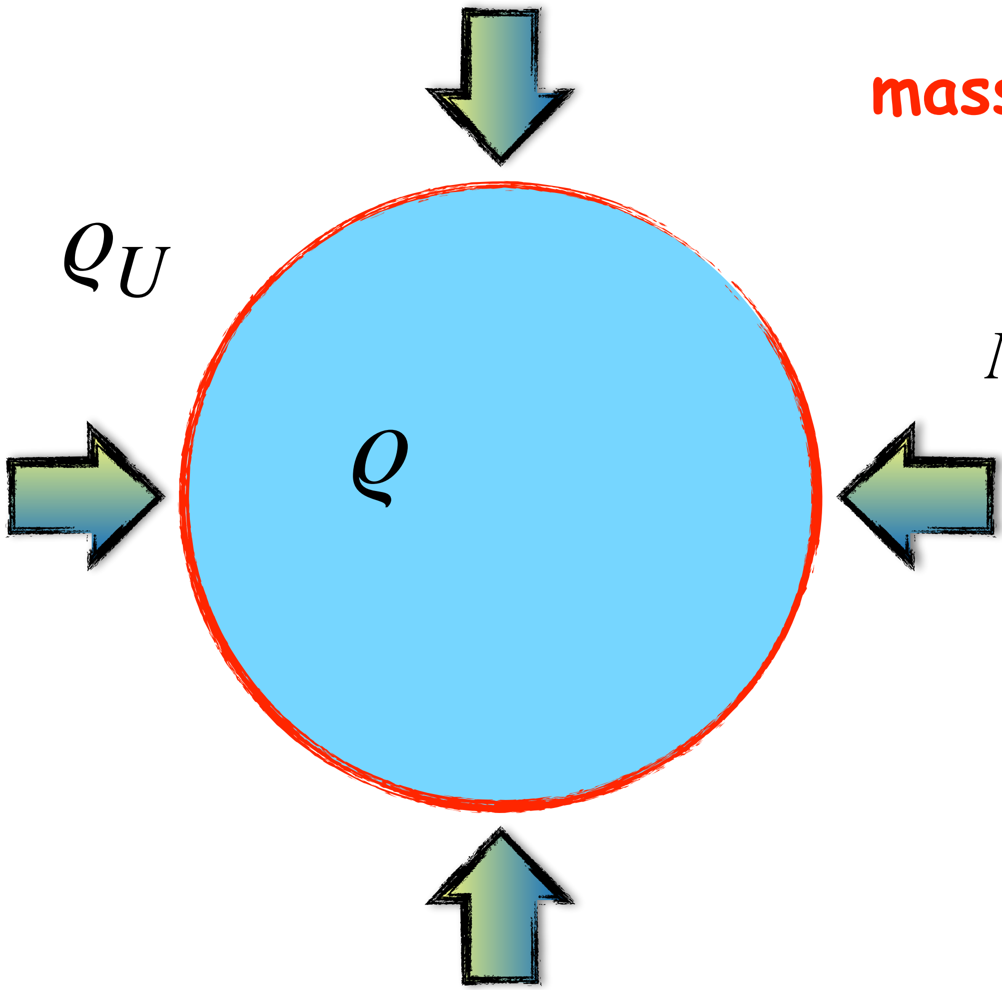

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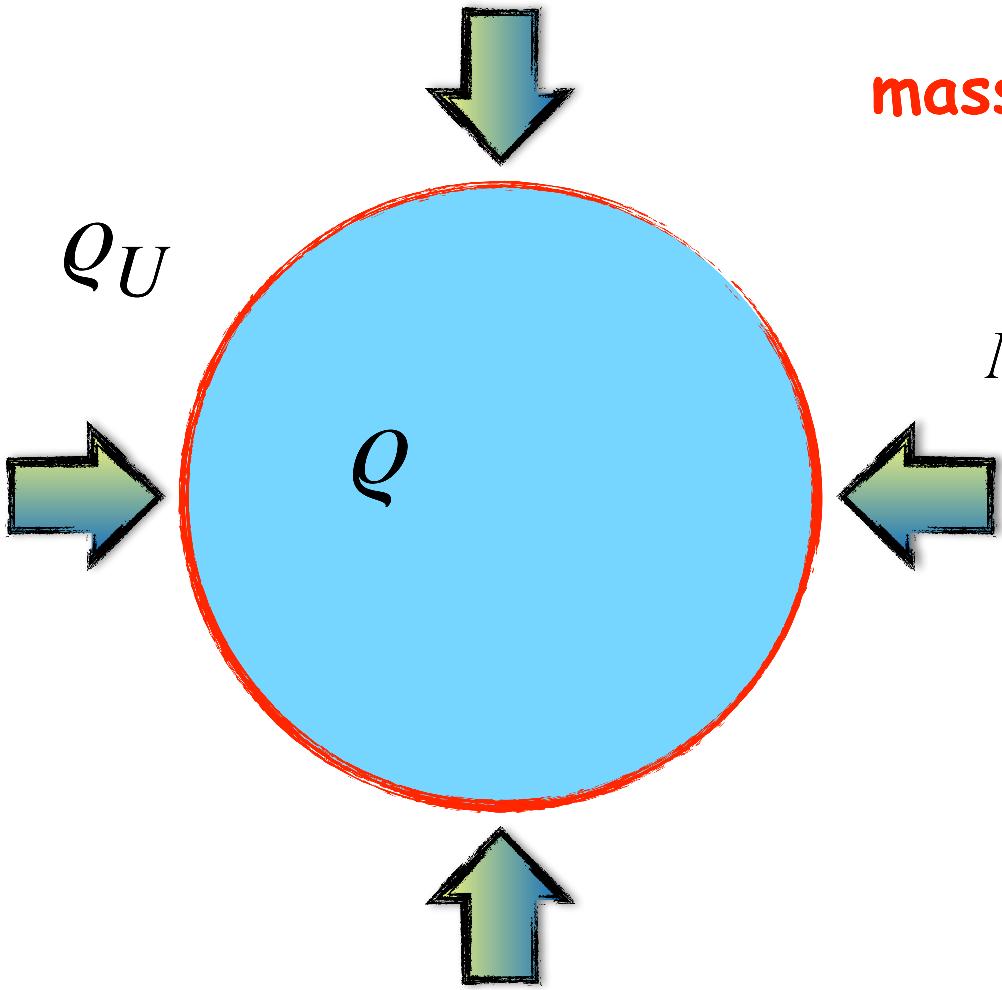

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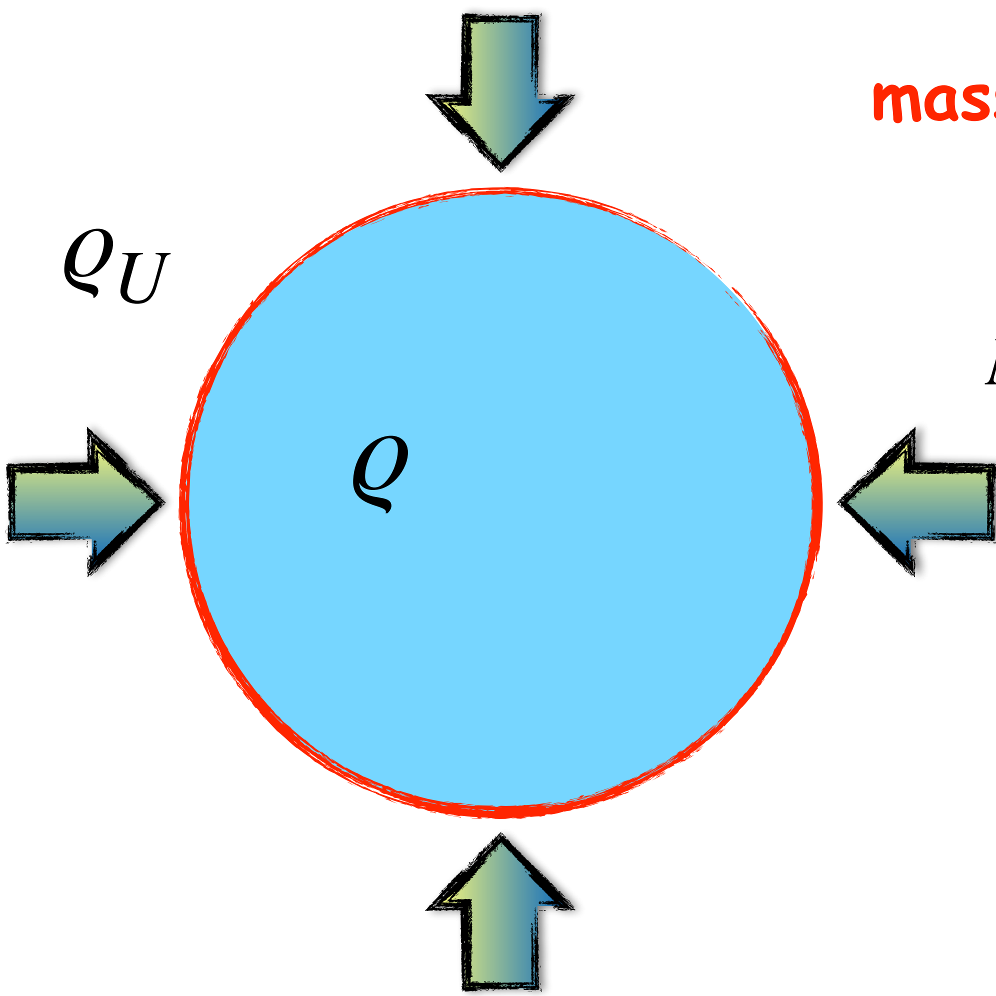

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same order as SNR shocks!
(of course this is just a
coincidence)

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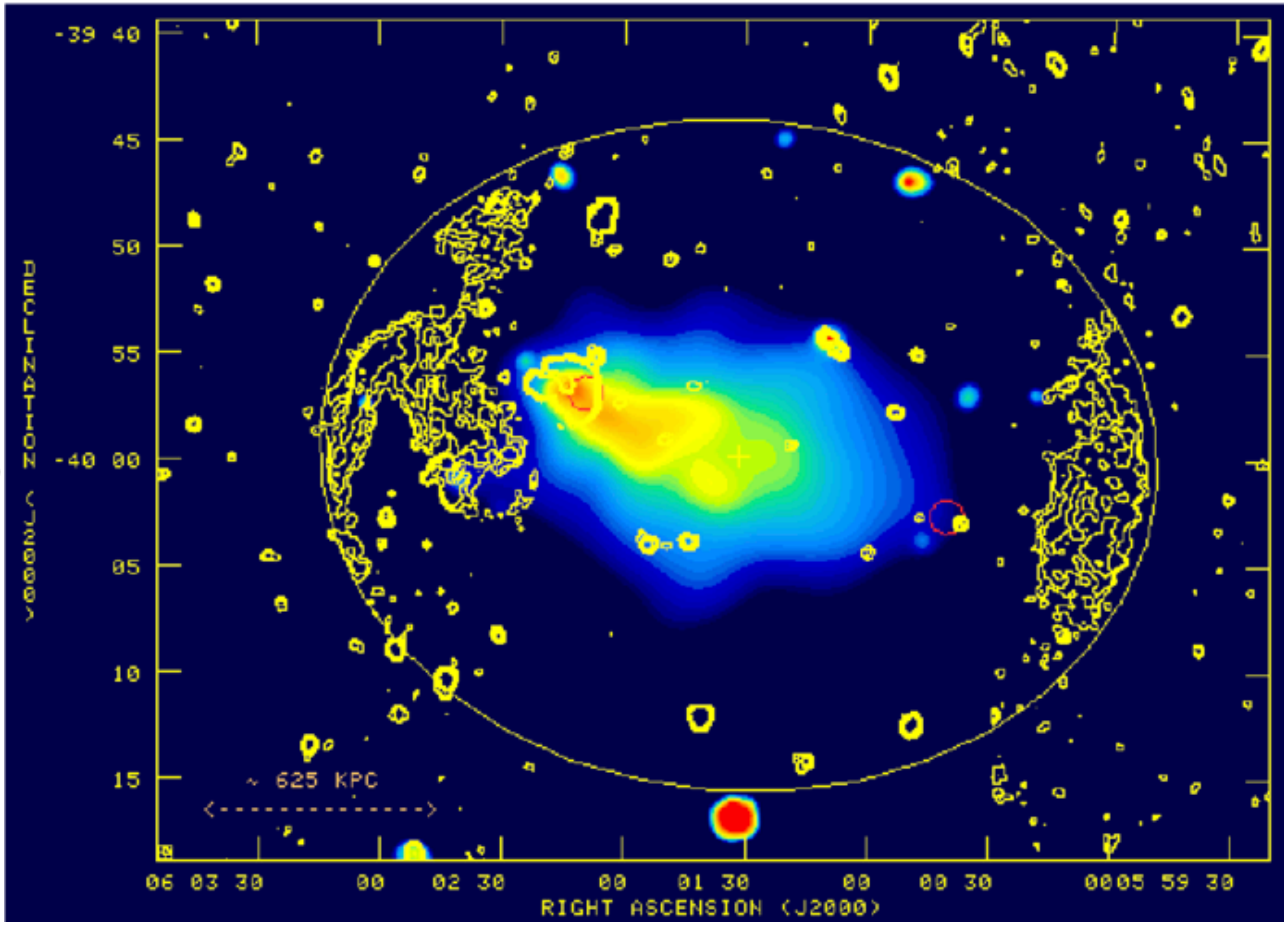
~2

few 10^6

B fields at the outskirts of GCs

Bagchi+ 2006



radio synchrotron emission from shocks around the GC A3376
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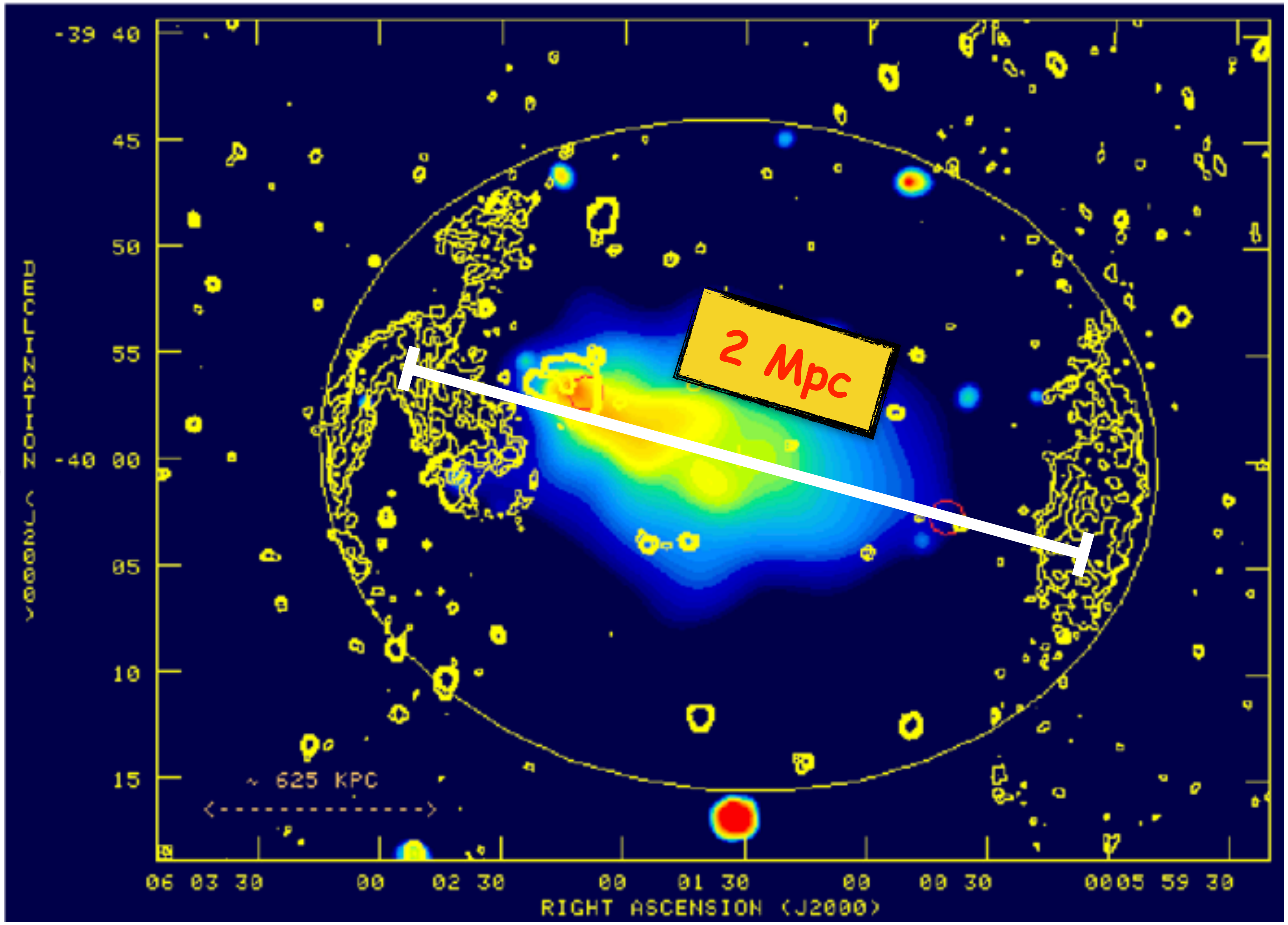

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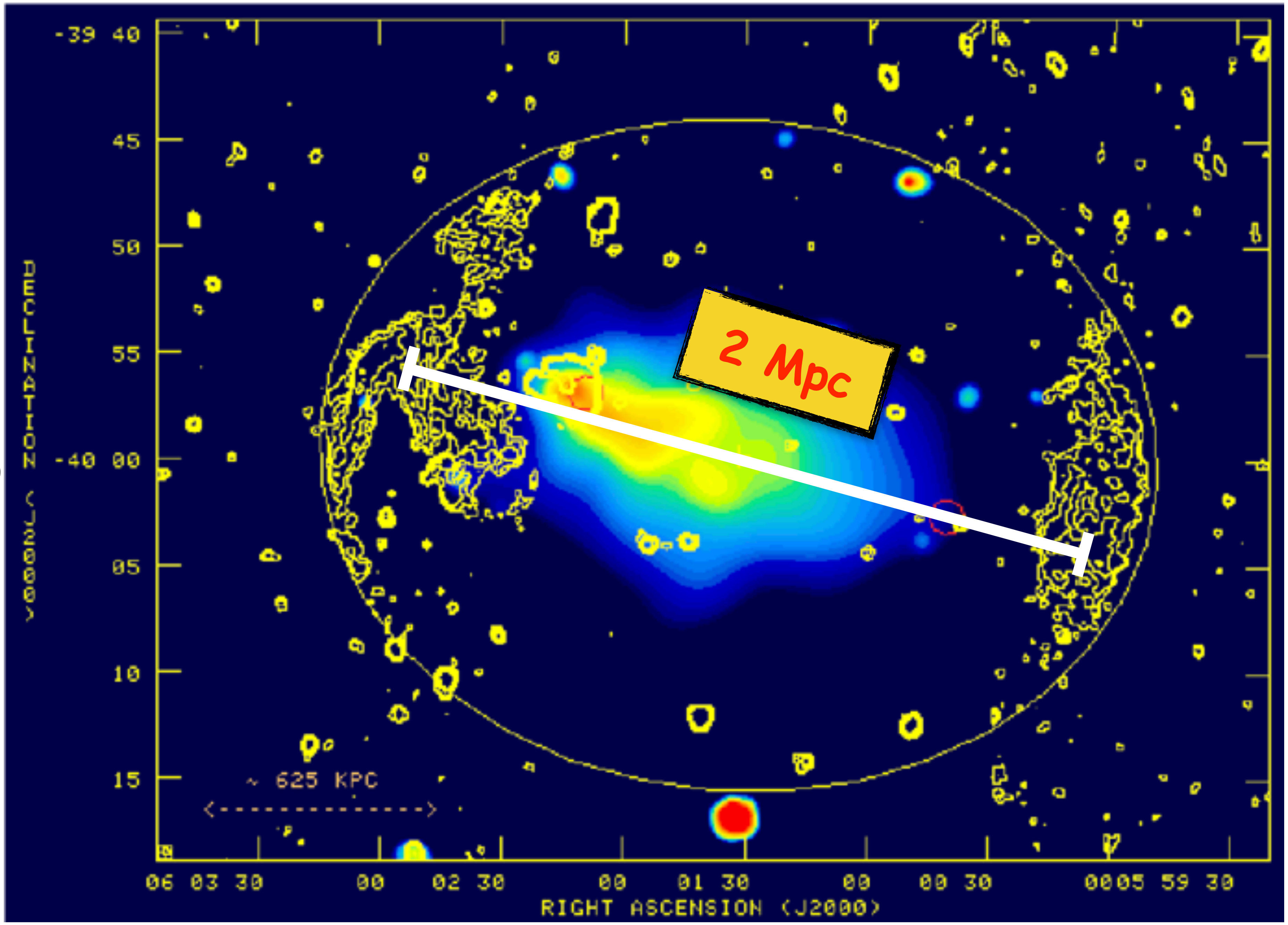

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equipartition B (U_{e^-} ~ U_B) —>

$B_{eq} \approx 0.5 - 3\ \mu\mathrm{G}$

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3×10^{20} eV

26 (Fe)

~1

~2

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3×10^{20} eV   26 (Fe)   ~1   ~2   few 10^{6}

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(Norman, Melrose & Achterberg 1995 … Allard & Protheroe 2009 … Vannoni+ 2011)

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possible to accelerate UHECRs! —> GZK cutoff or Emax of the accelerator?

other possible sources of UHECRs (AGN, GRBs...)

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26 (Fe)

few 10^6

recent claims of a detection in GeV of Coma

(Remi+ 2021, Baghmanyan+2022)

GeV particles CANNOT escape clusters —> they will NEVER reach us

ss rate

TeV band —> might probe CRs that will reach us!

(Norman, Melrose & Achterberg 1995 … Allard & Protheroe 2009 … Vannoni+ 2011)

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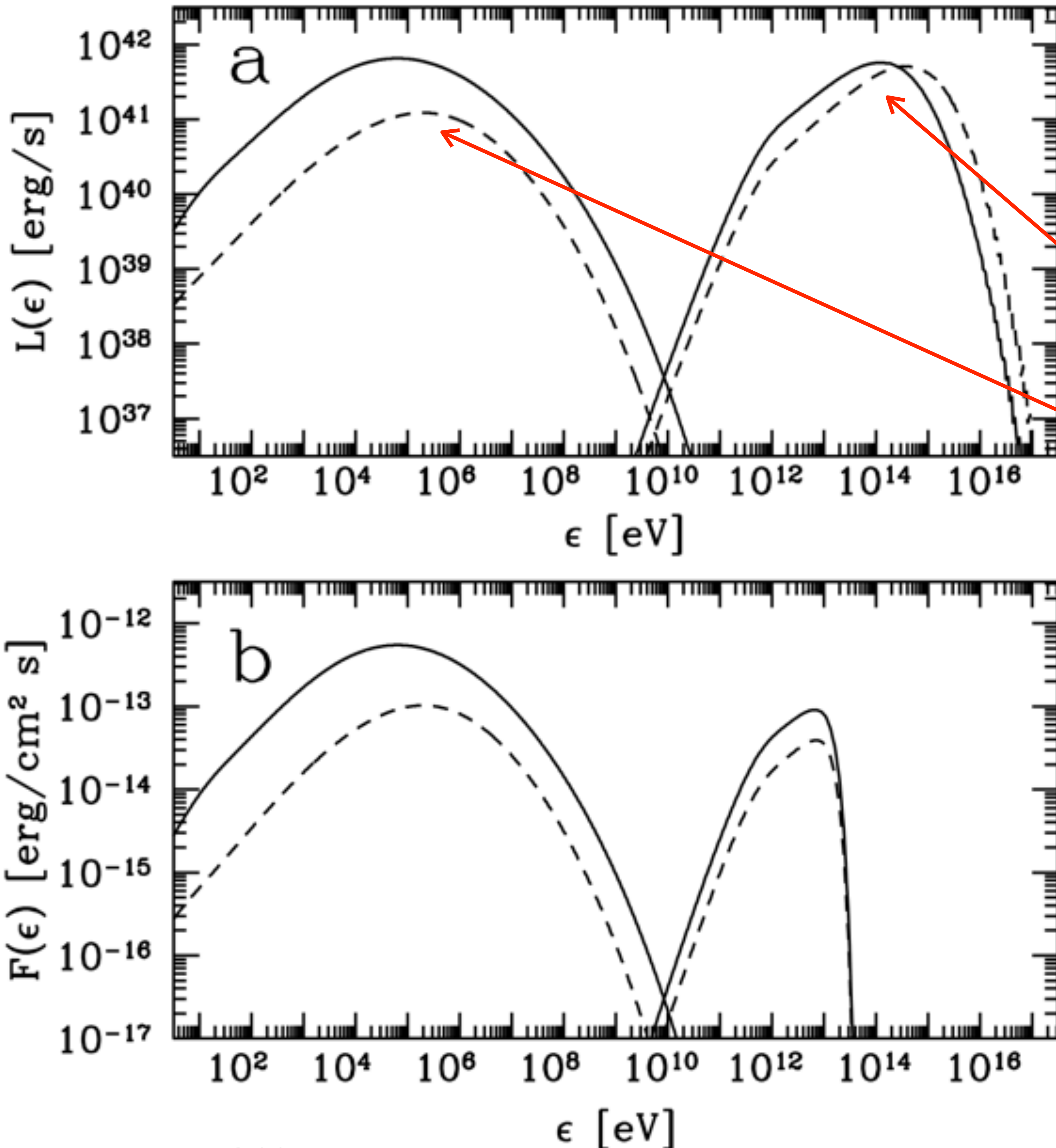
A possible test: gamma rays from GCs



photopion production

$$p + \gamma \longrightarrow p + e^{+} + e^{-}$$

they cool quickly due to
inverse Compton scattering
and
synchrotron radiation

Vannoni+ 2011

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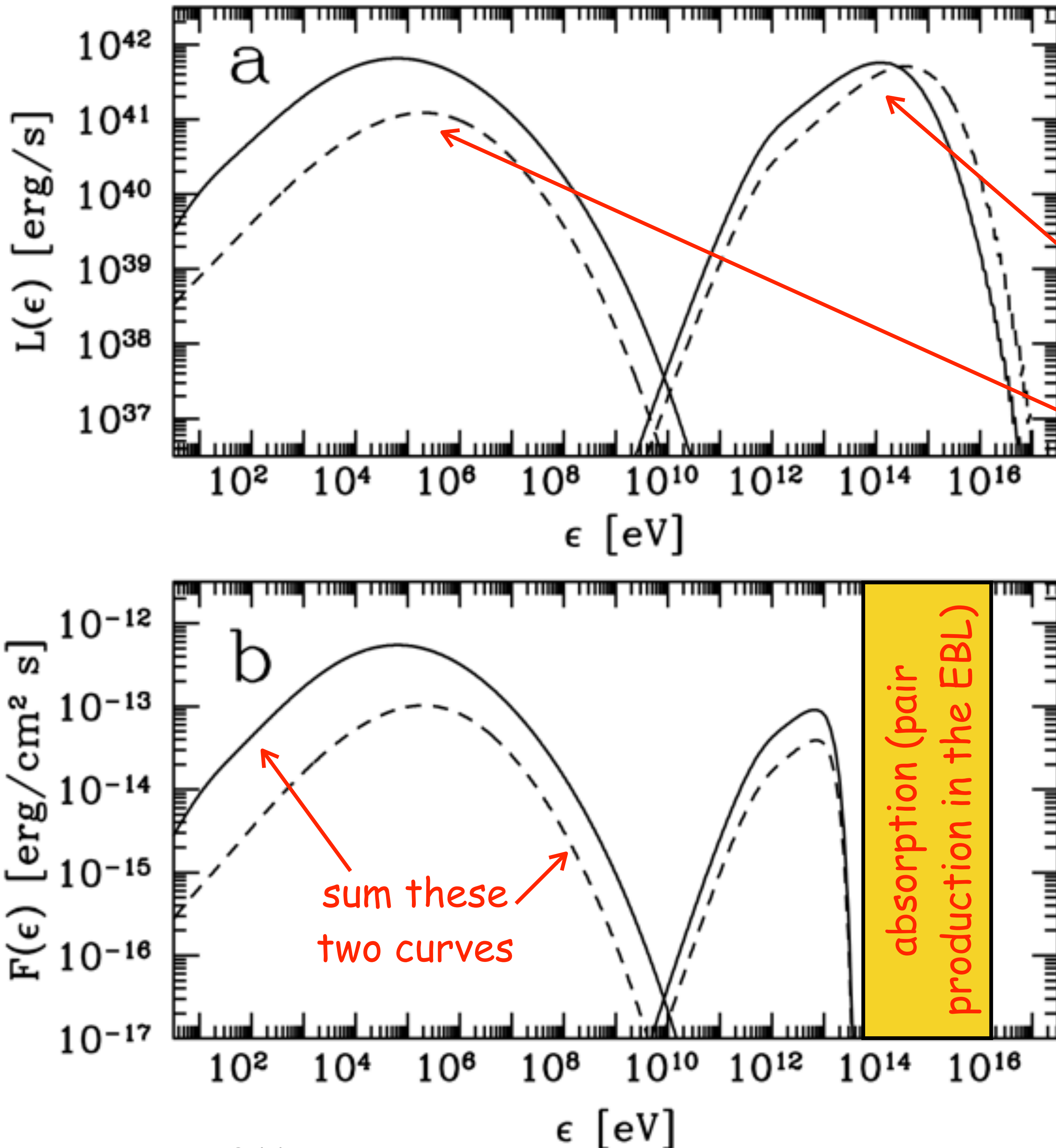

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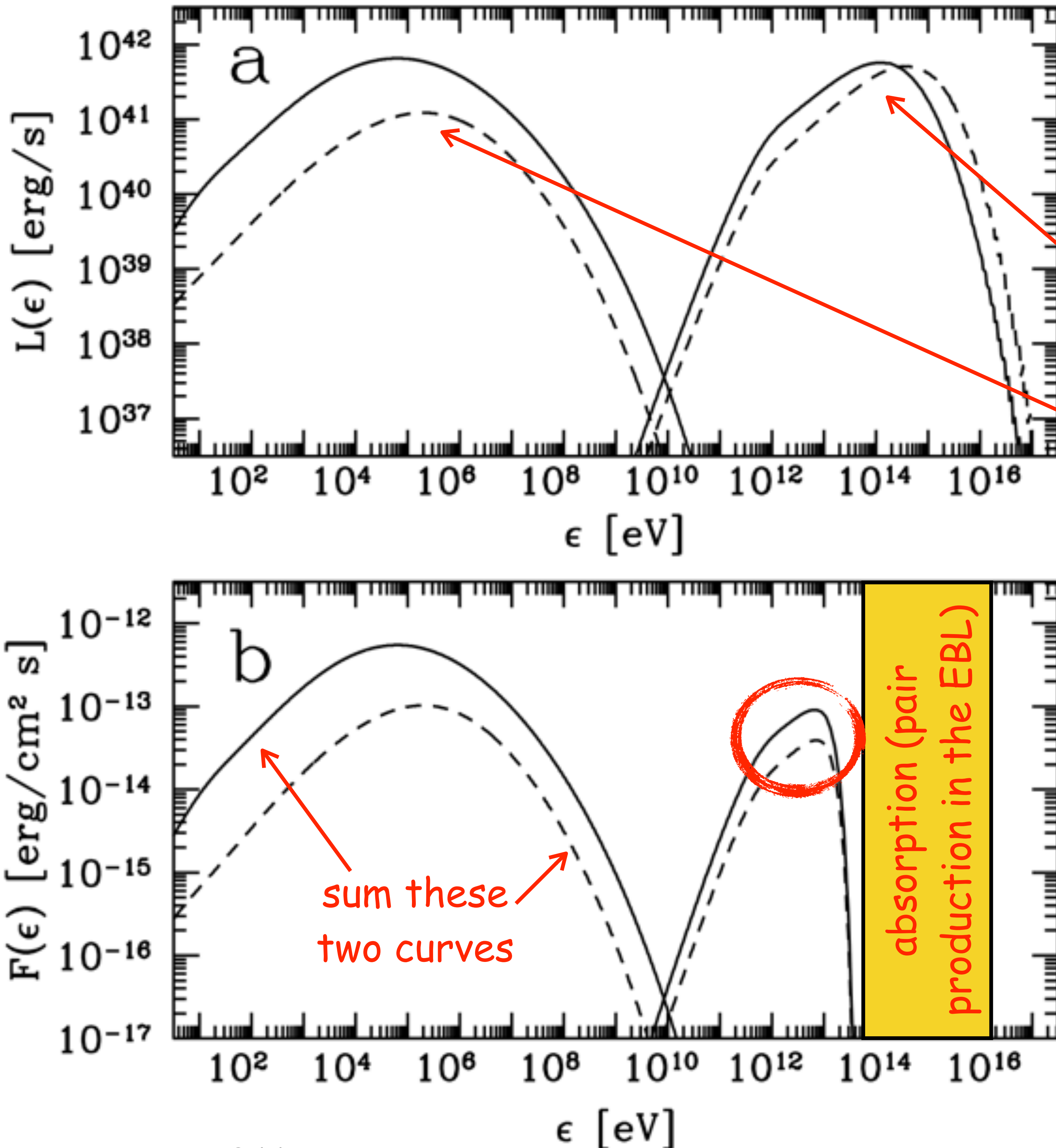

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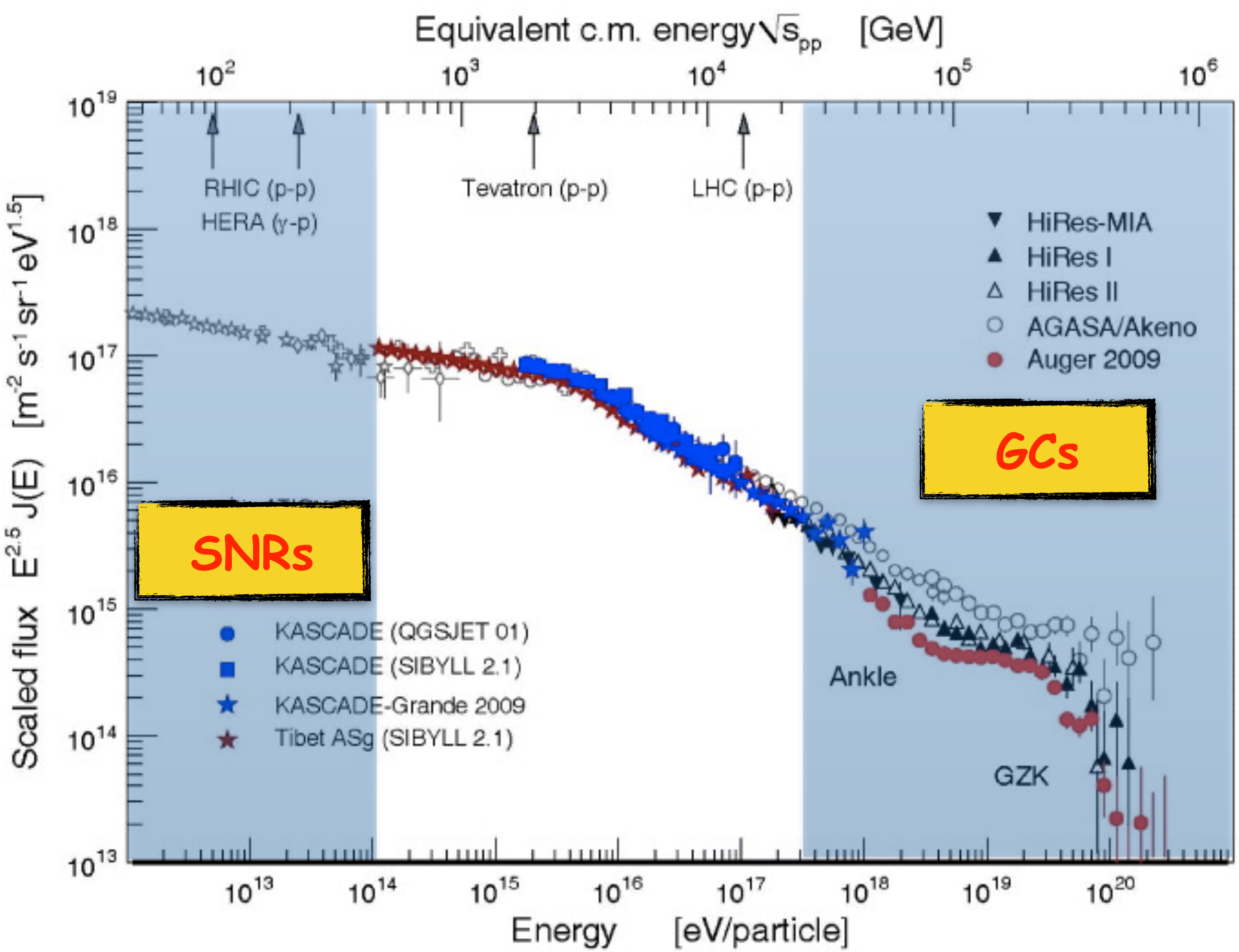
search for TeV gamma-rays!
optimistic case: 1% gravitational energy into CRs, Coma-like cluster @100 Mpc

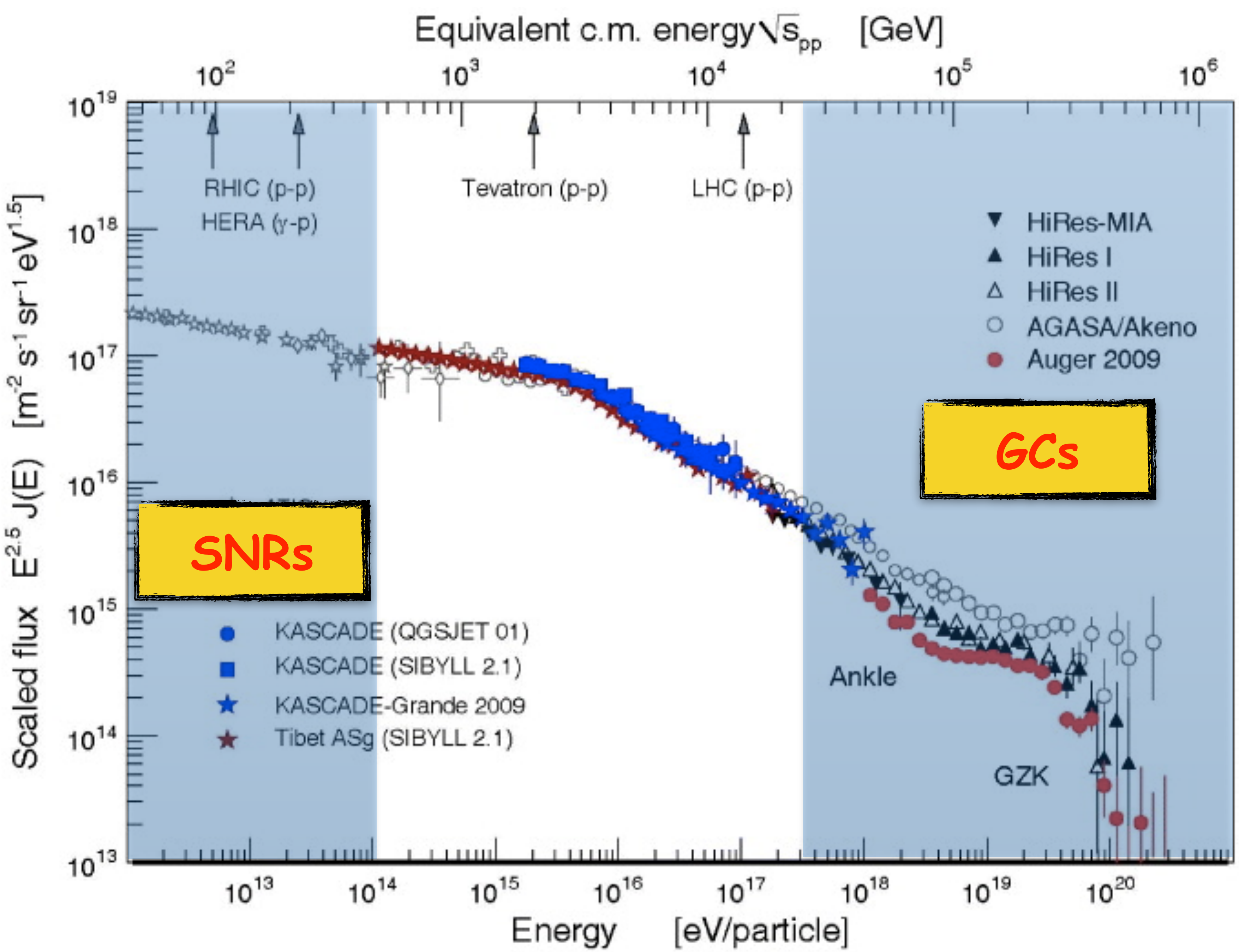
Vannoni+ 2011

So what?



Equivalent c.m. energy $\sqrt{s_{pp}}$ [GeV]
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
AGASA/Akeno
Auger 2009
GCs
SNRs
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2009
Tibet ASg (SIBYLL 2.1)
Ankle
GZK
Scaled flux $E^{2.5}$ J(E) [m^{-2} s^{-1} sr^{-1} $eV^{1.5}$]
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
Energy [eV/particle]

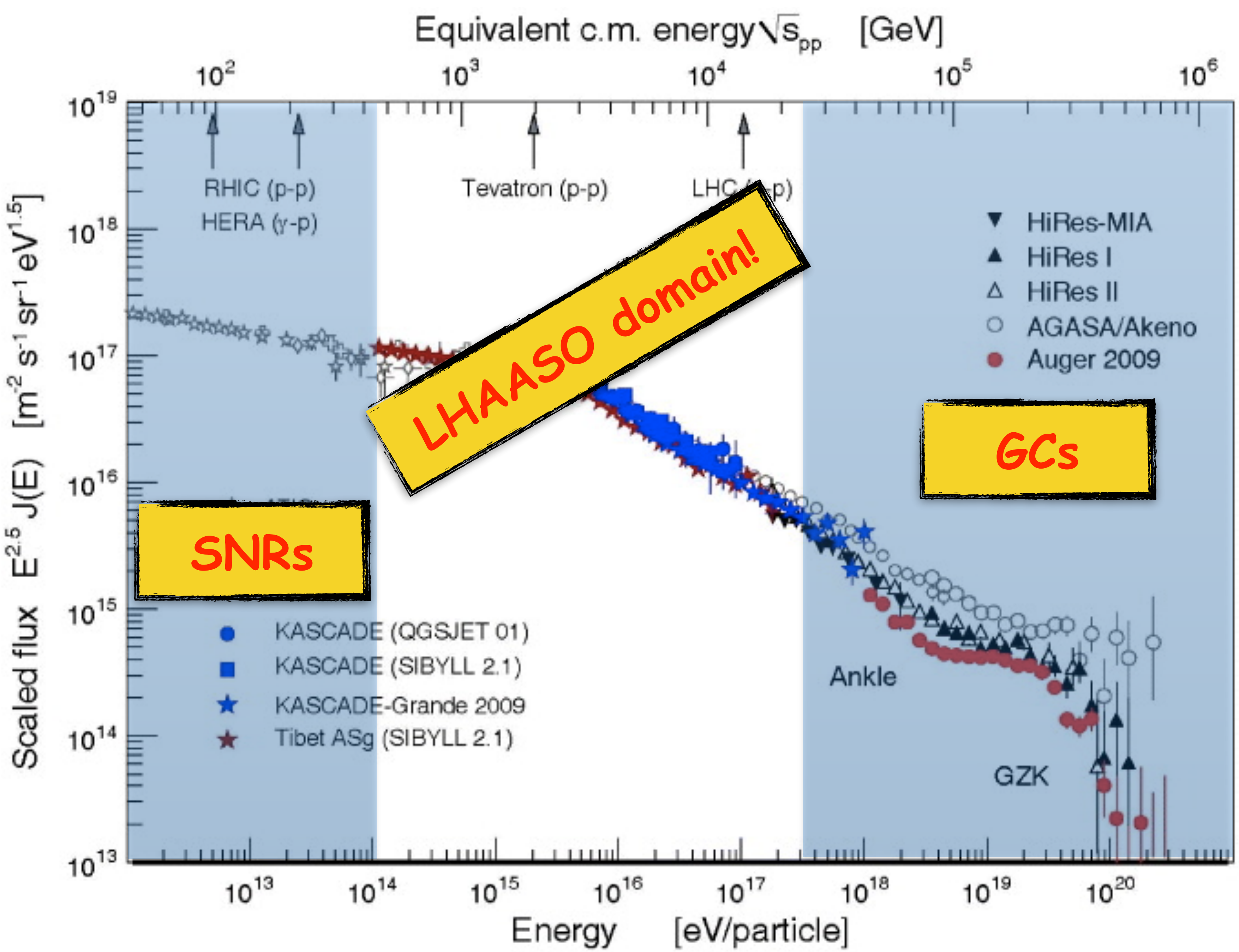
So what?



need for a third component?

—> Hillas' "B" component proposed long ago, needed even if SNRs could accelerate up to the knee!

So what?



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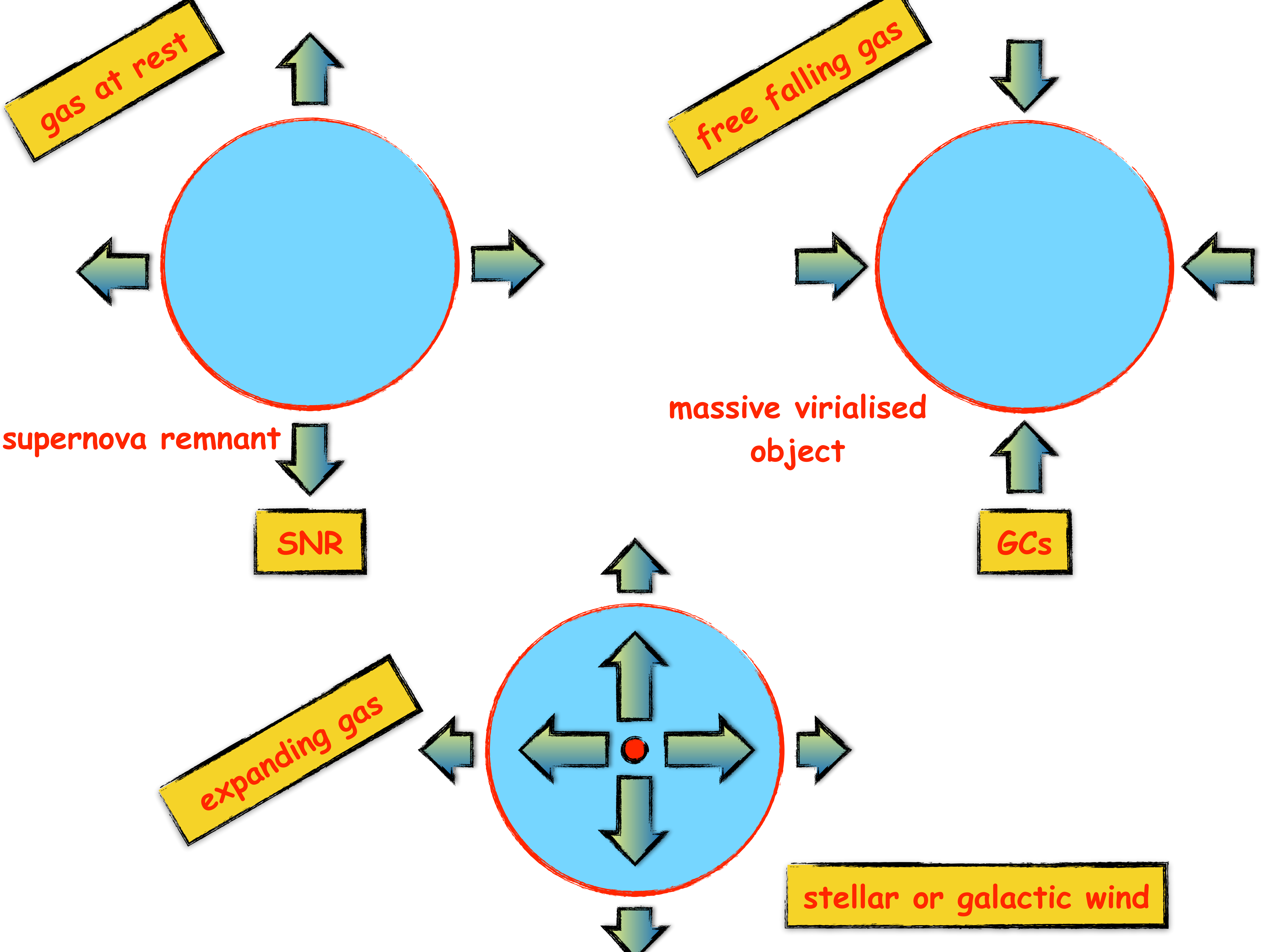
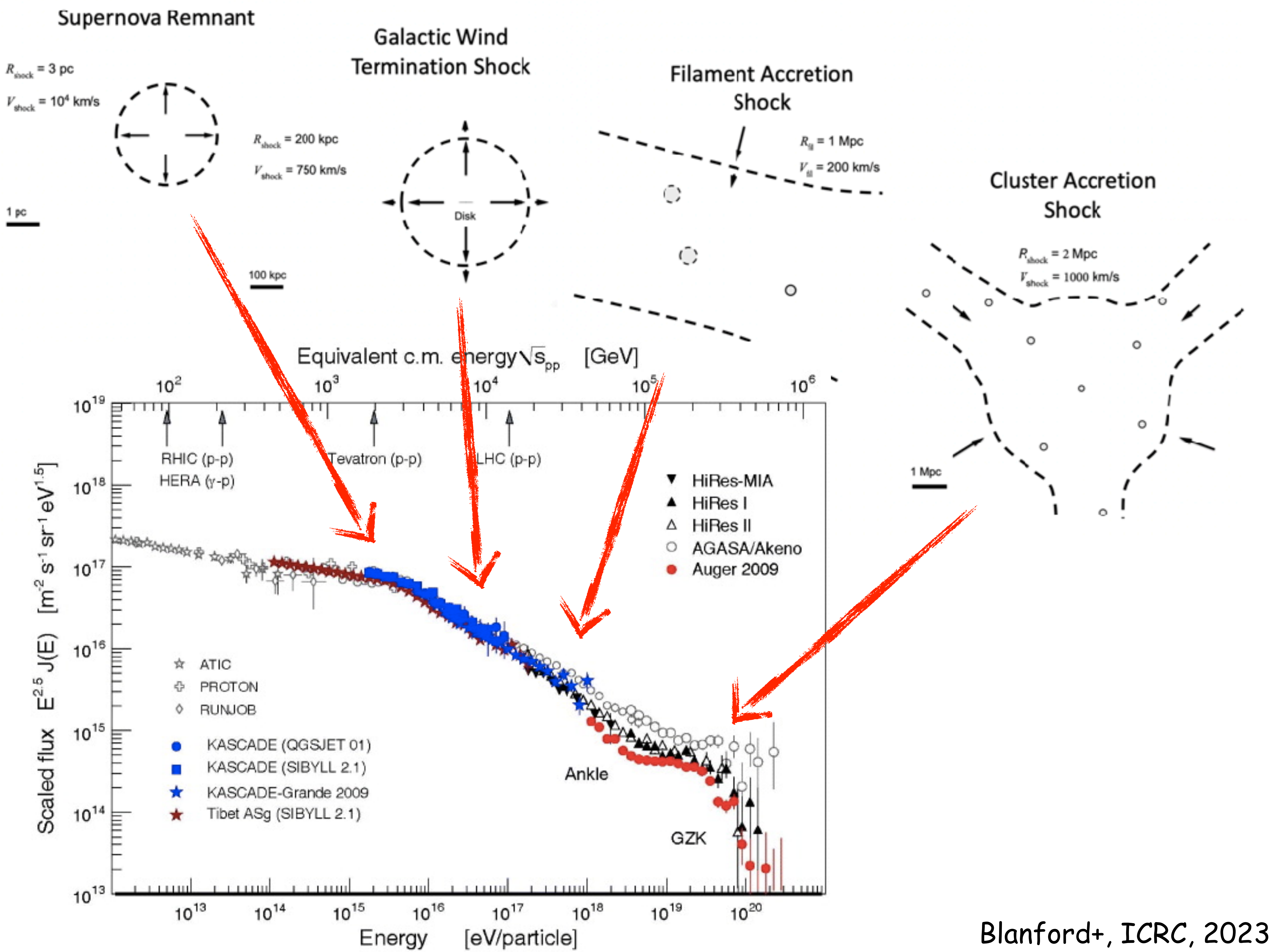
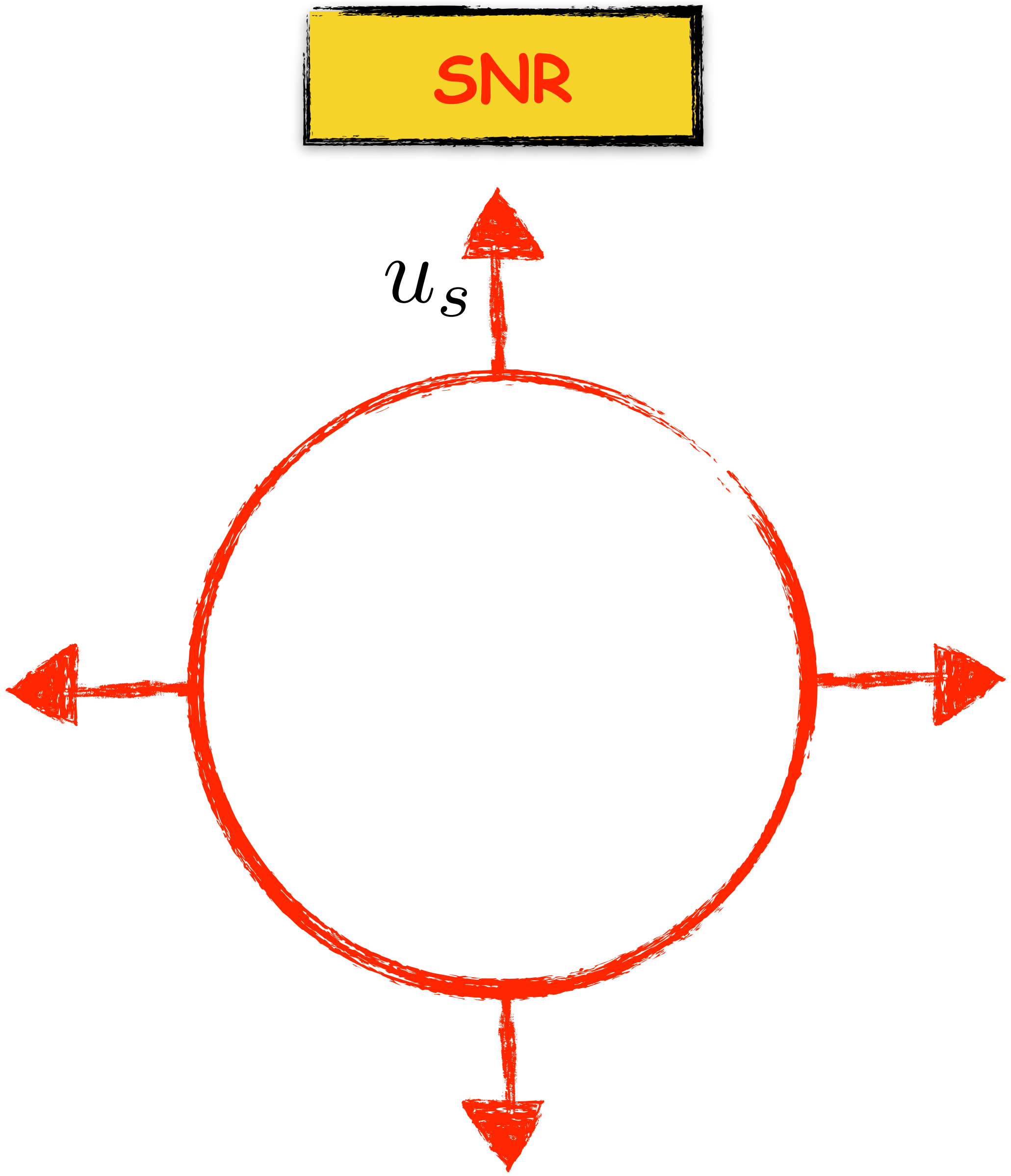

gas at rest
free falling gas
supernova remnant
massive virialised object
SNR
GCs
expanding gas
stellar or galactic wind



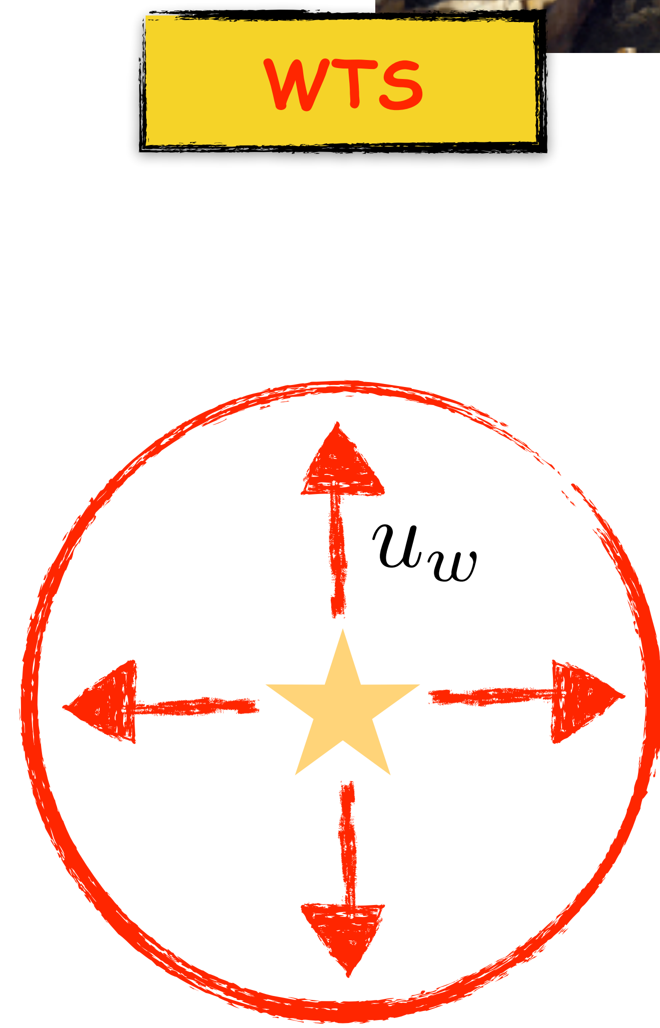
Blanford+, ICRC, 2023

Stellar wind termination shocks

Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983



$u_s \approx u_w$



analogy with solar WTS (Parker, Jokipii…) + DSA (BOBALSKy…)

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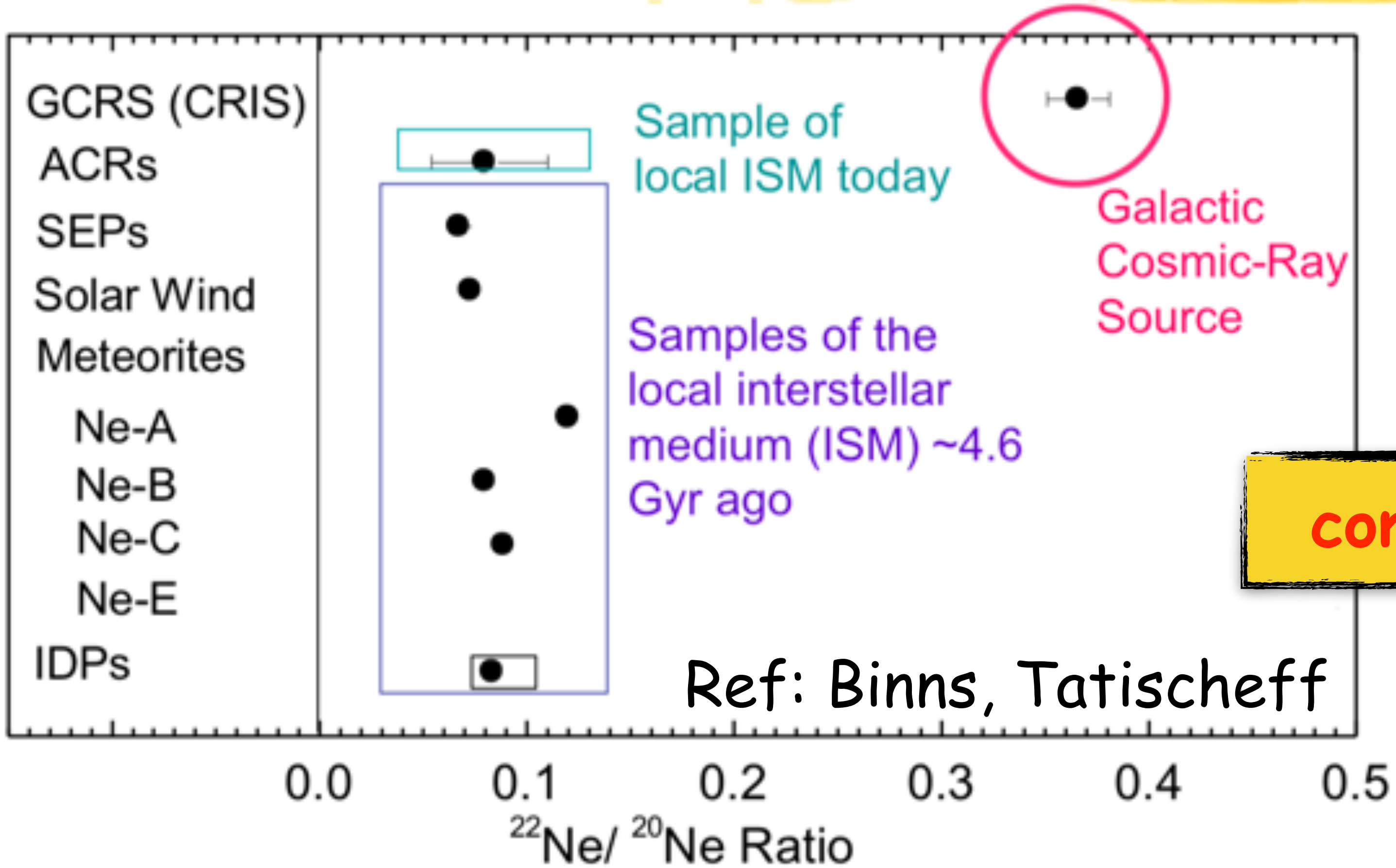
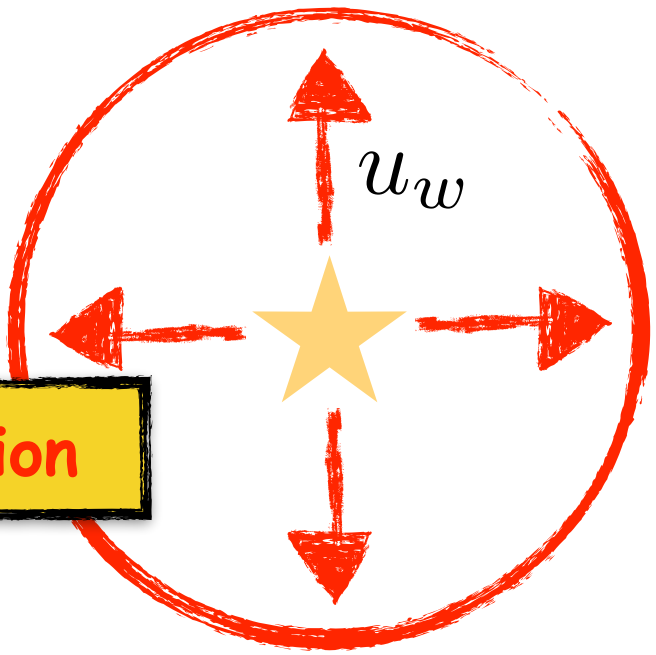
Cassé & Paul 1980, 1982 — Cesarsky & Montmerle 1983

SNR

WTS





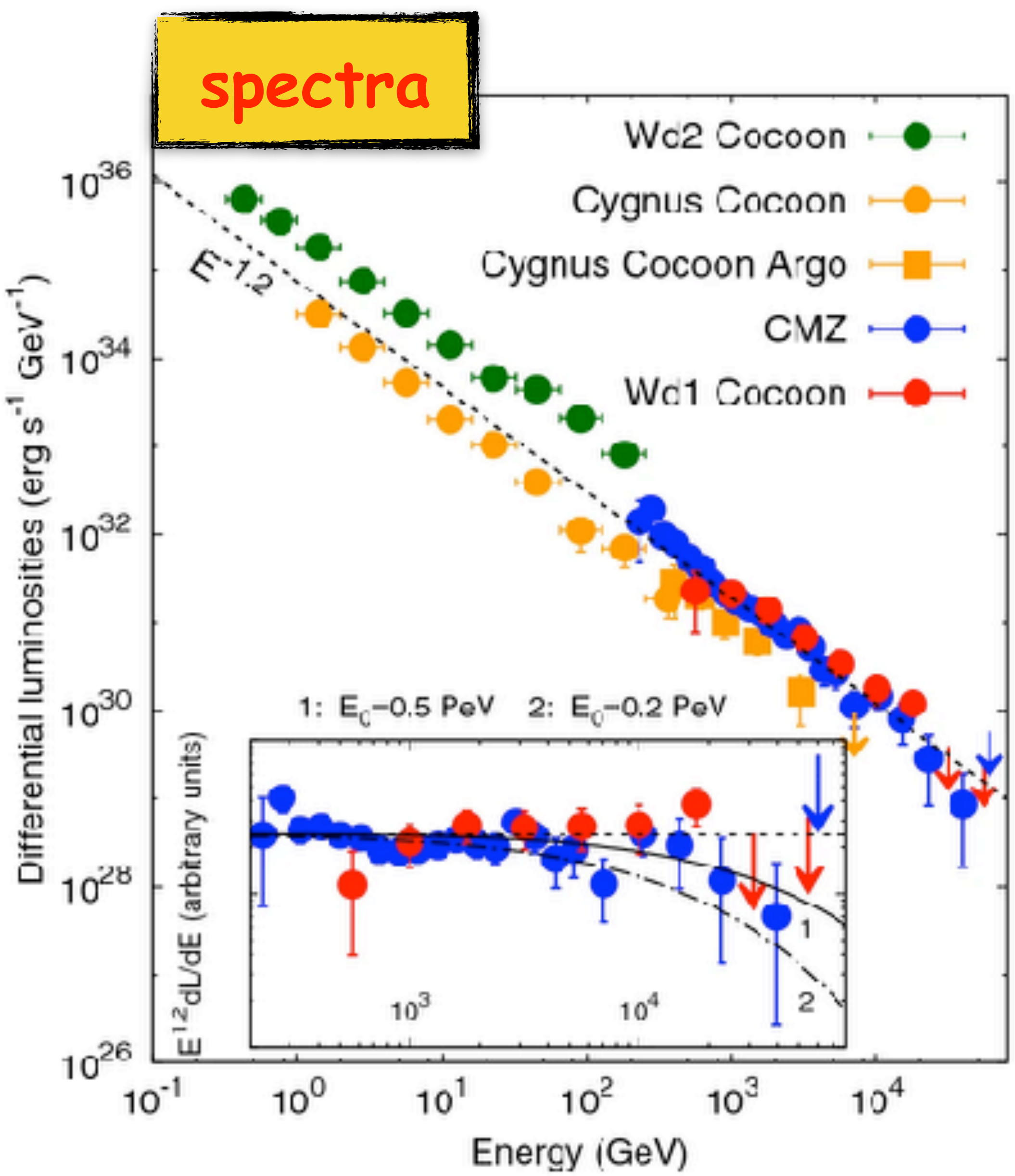
composition

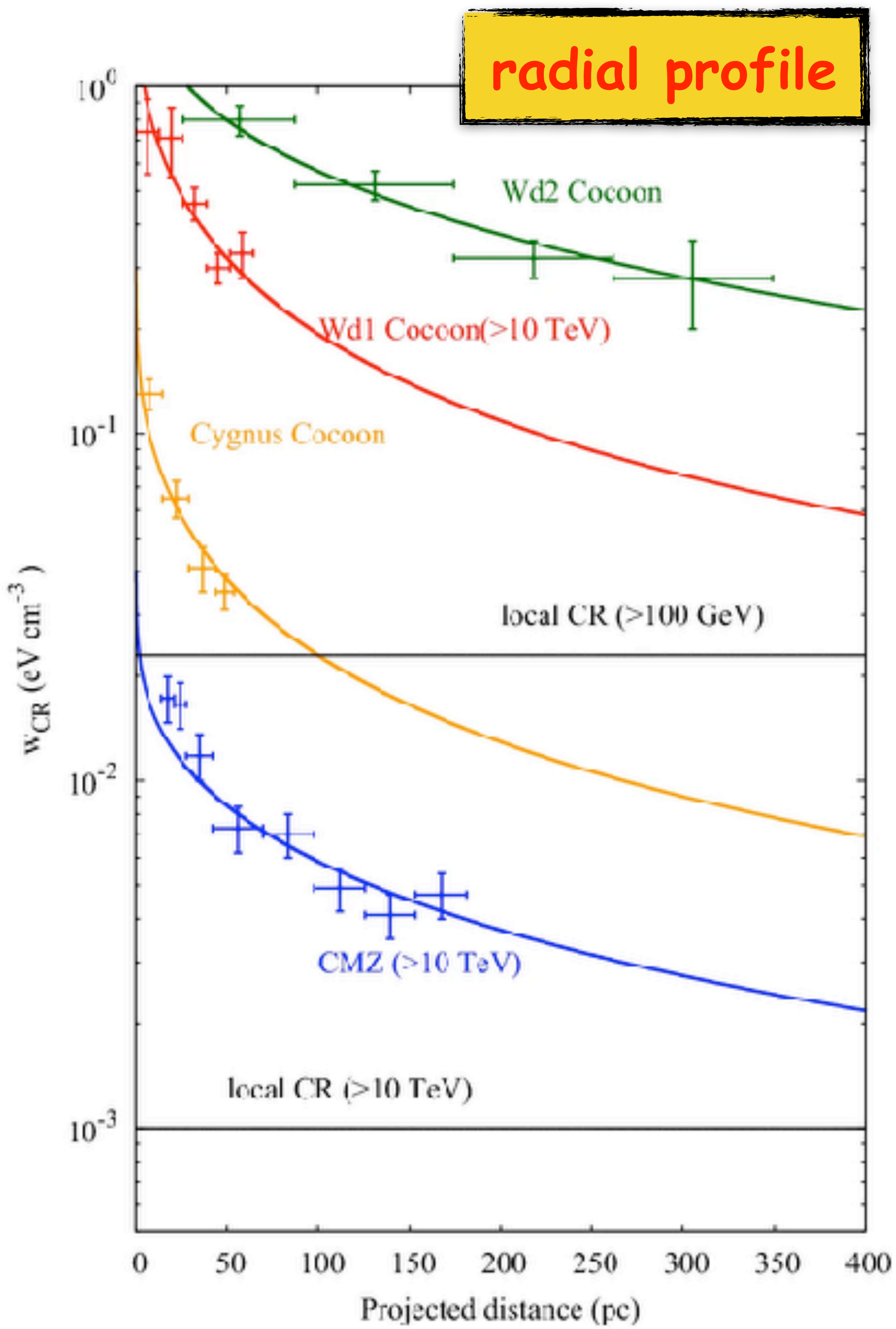
analogy with solar WTS (Parker, Jokipii…) + DSA (BOBALSKy…)

Bonus: Wolf-Rayet wind material enriched in ^{22}Ne —> composition (with dilution)

Stars or star clusters? Gamma rays...

Aharonian+ 2019, plus several papers especially by Yang and collaborators





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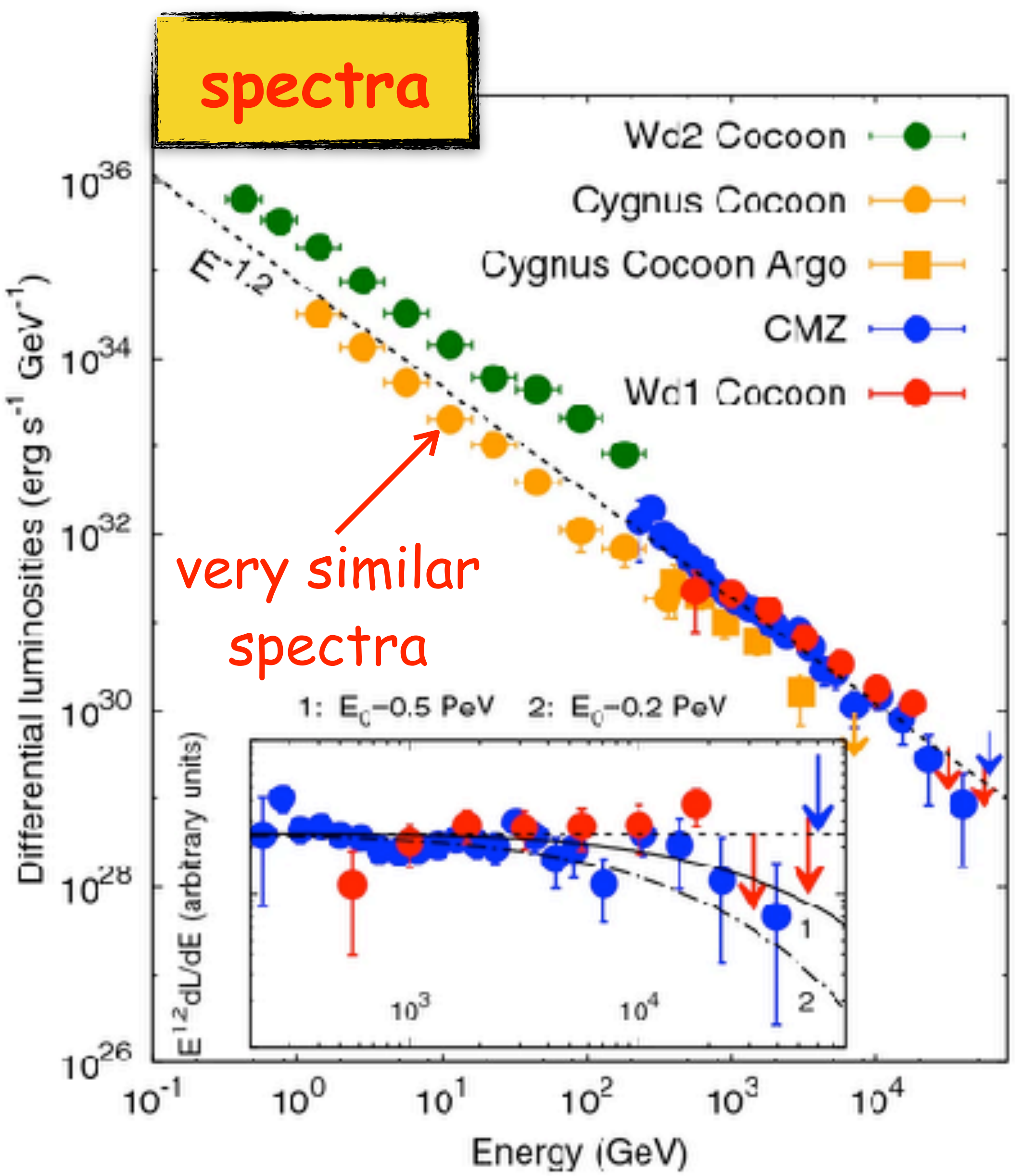

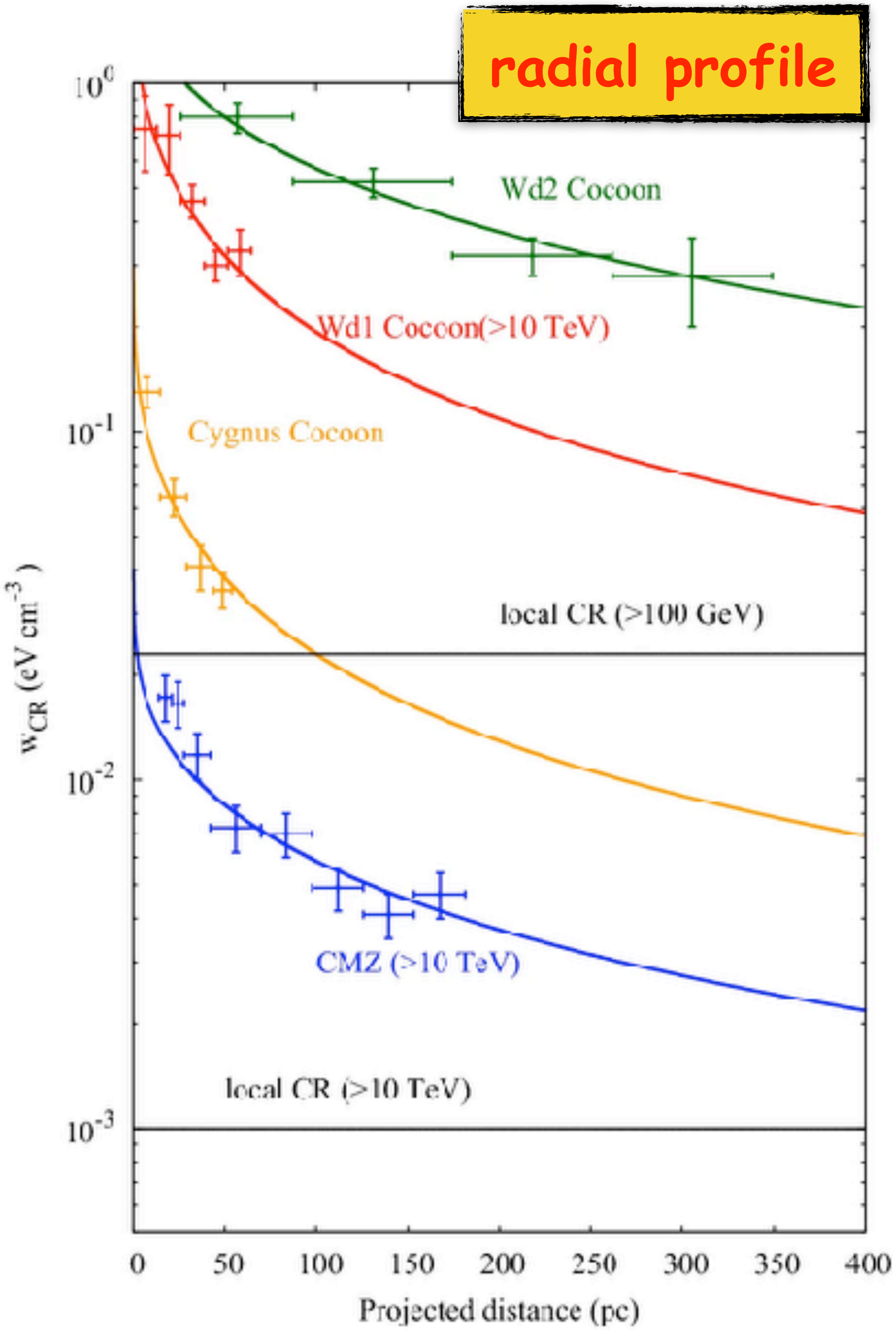

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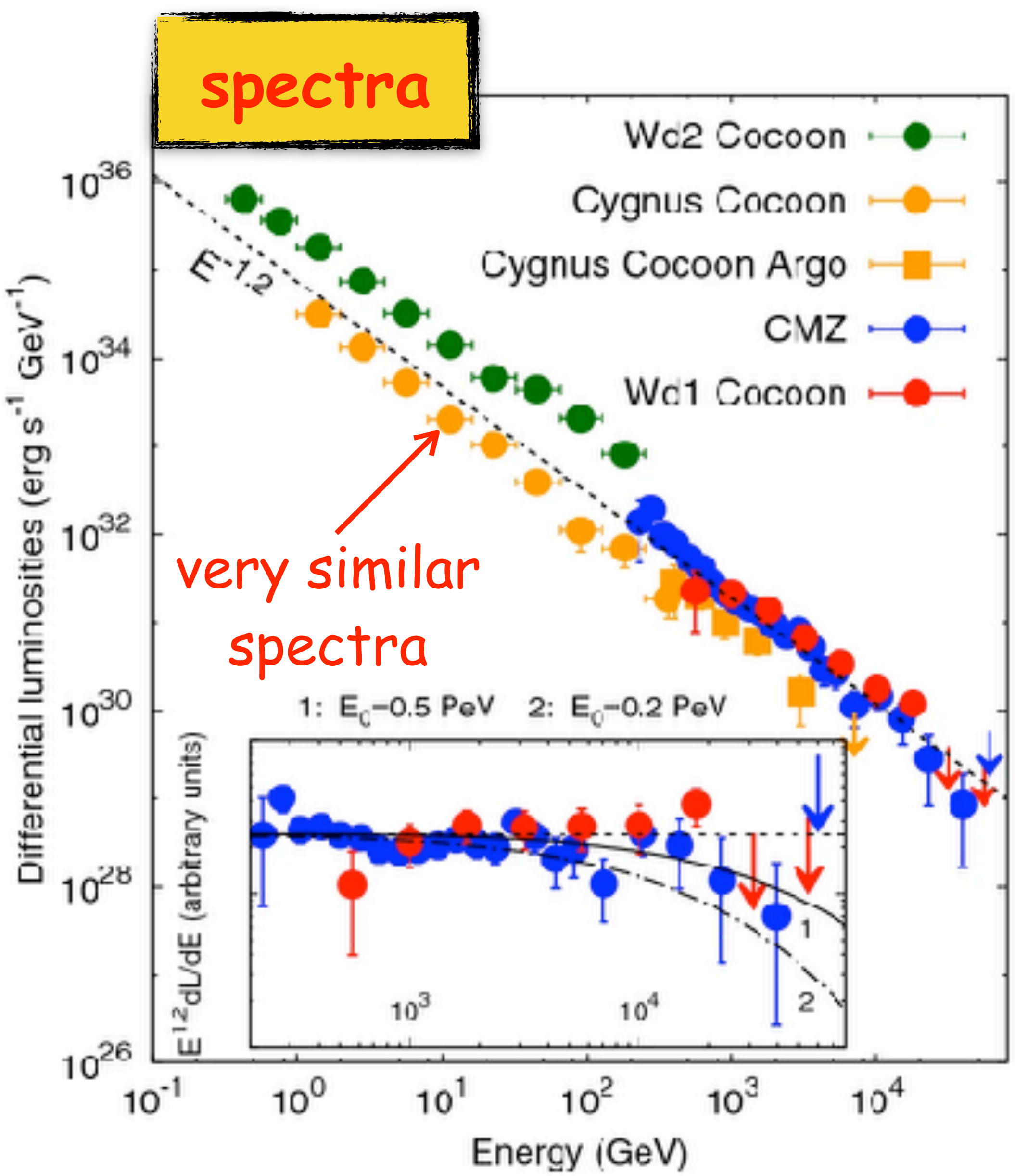

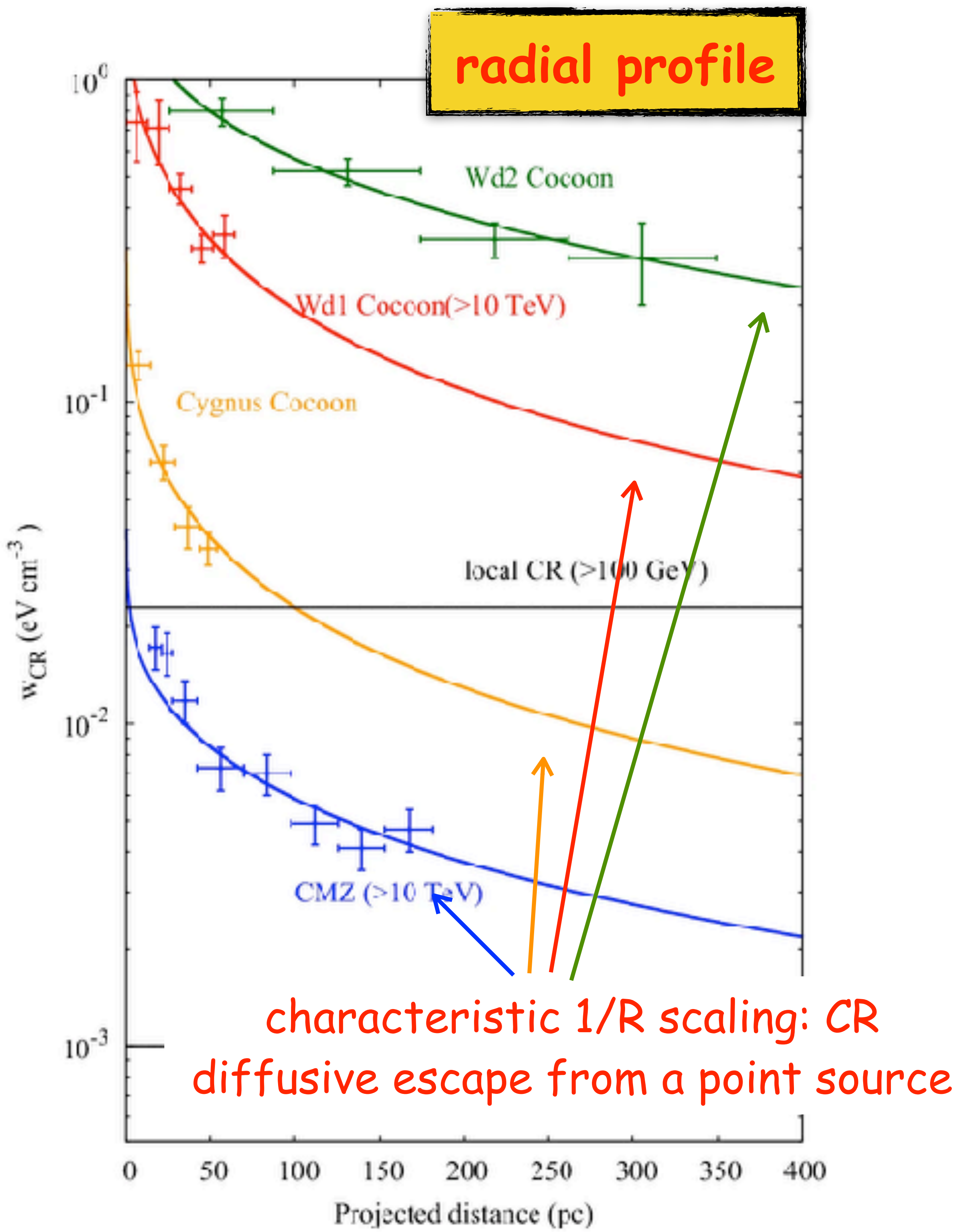

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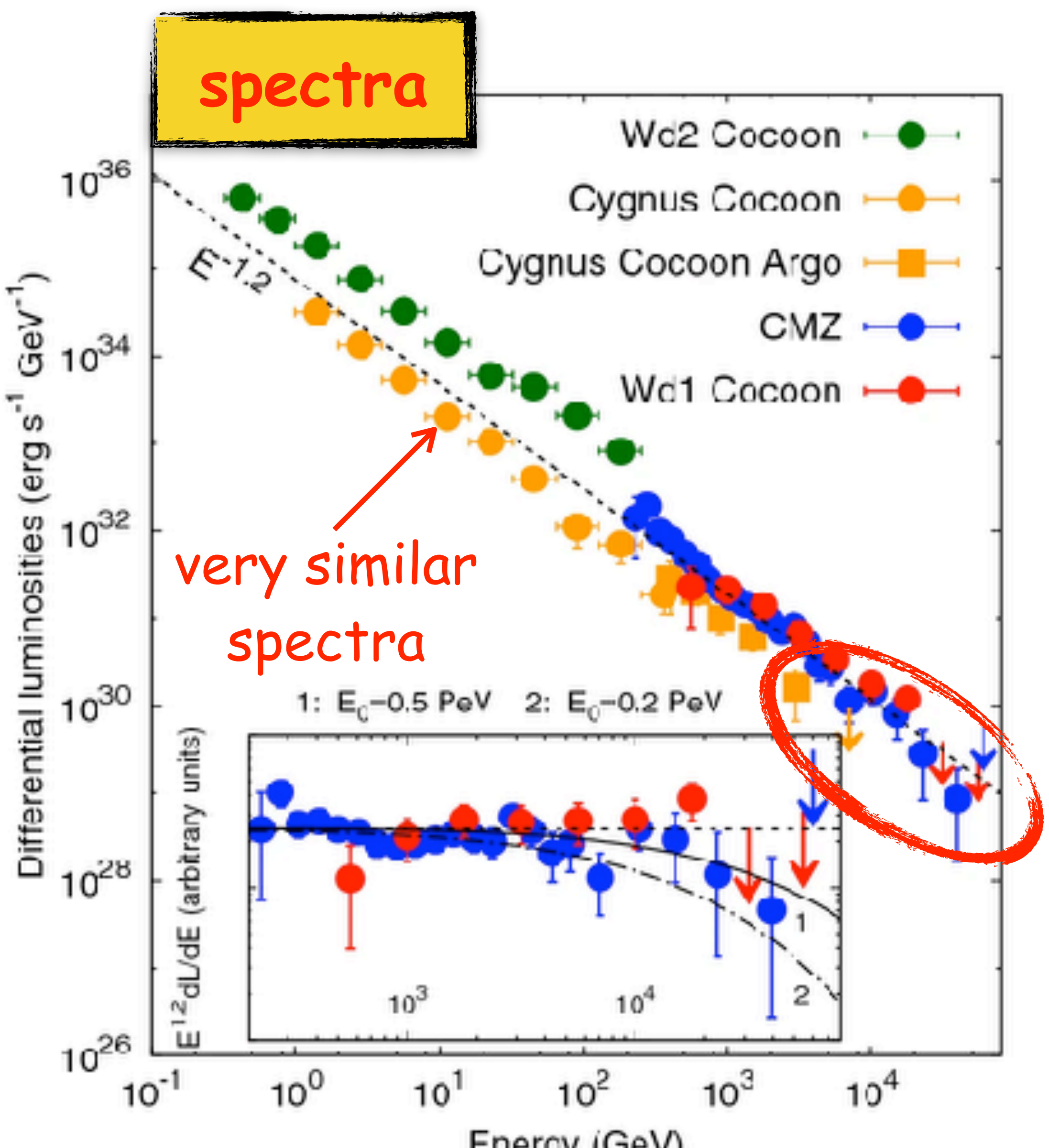

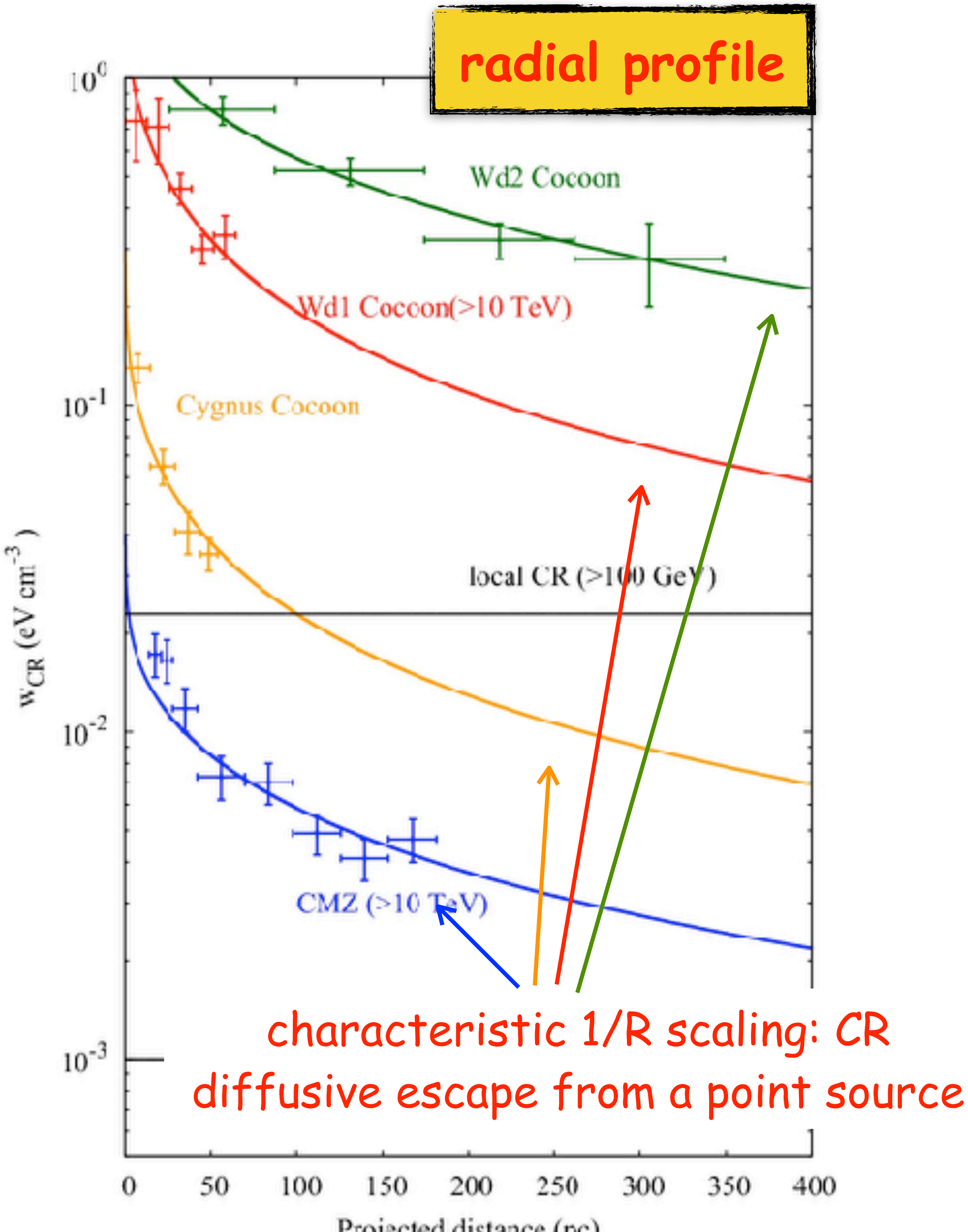

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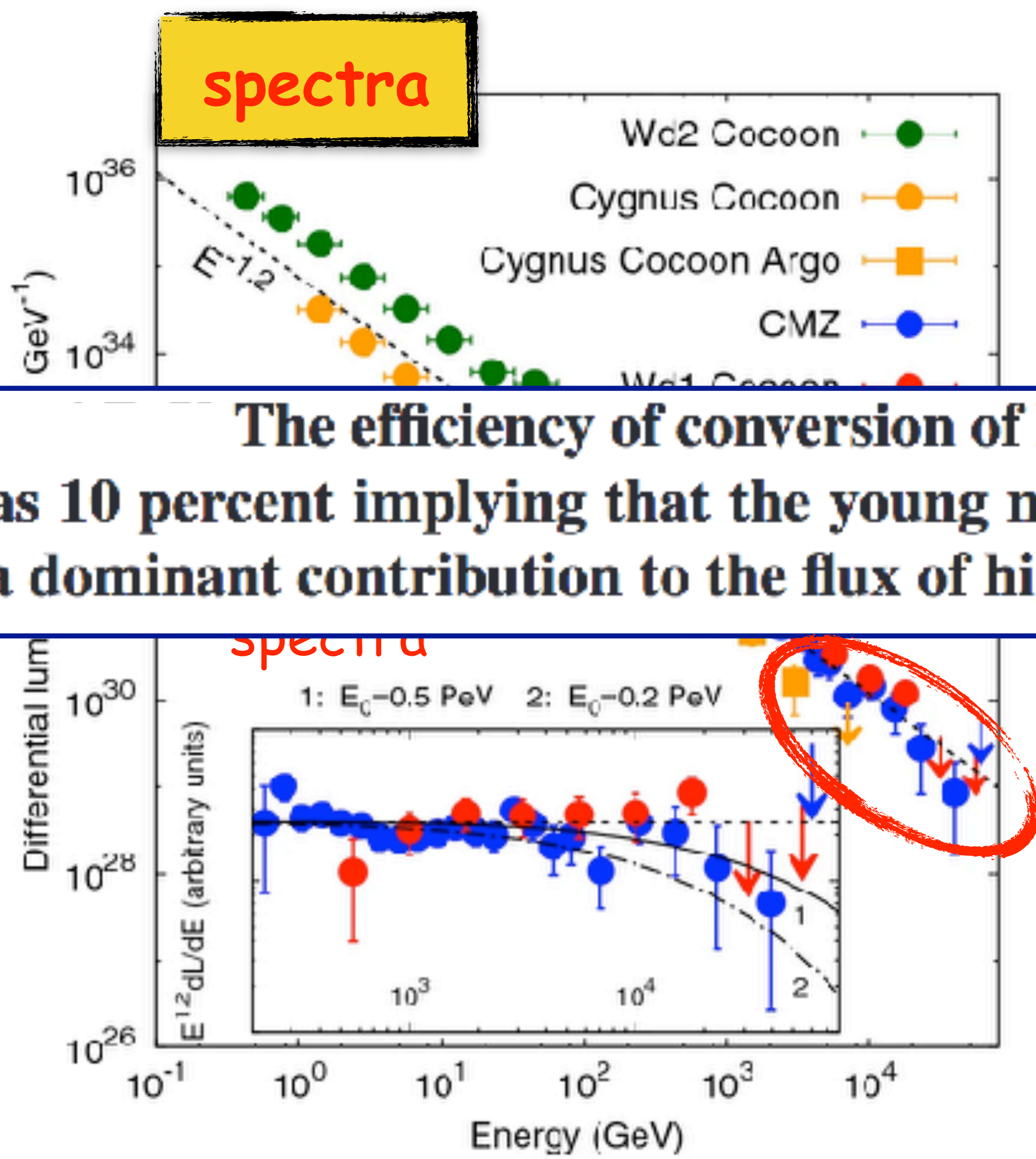

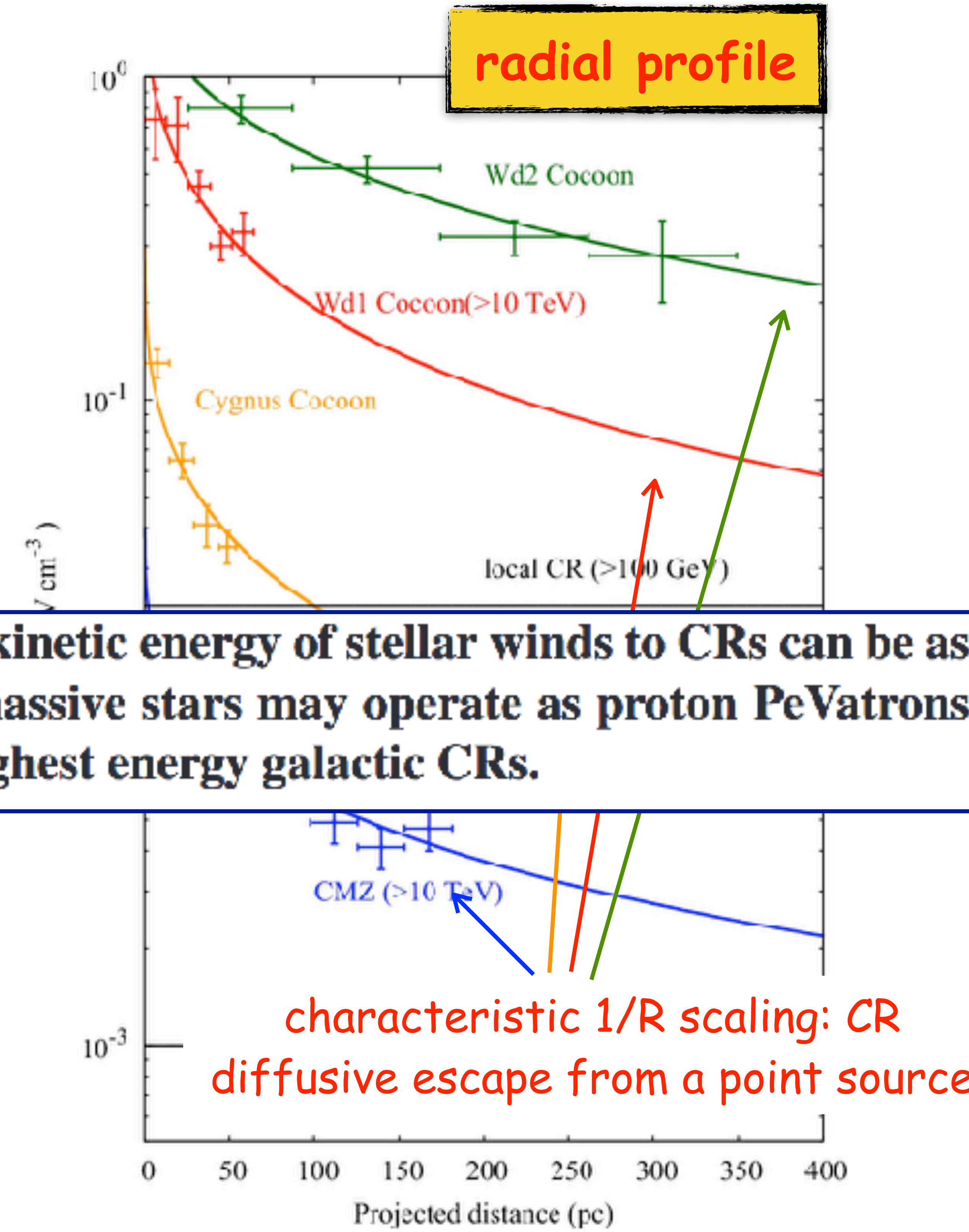

The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

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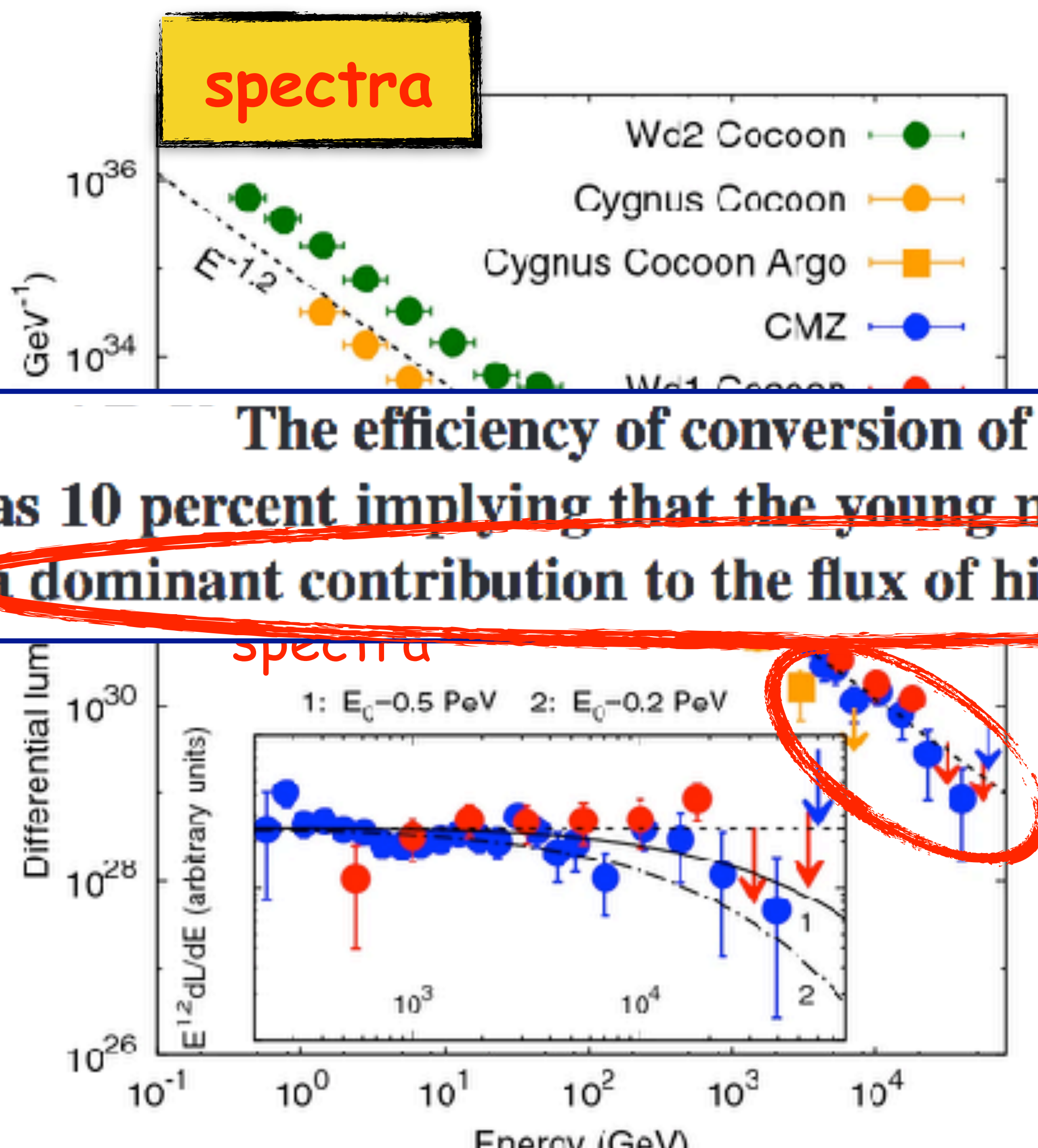

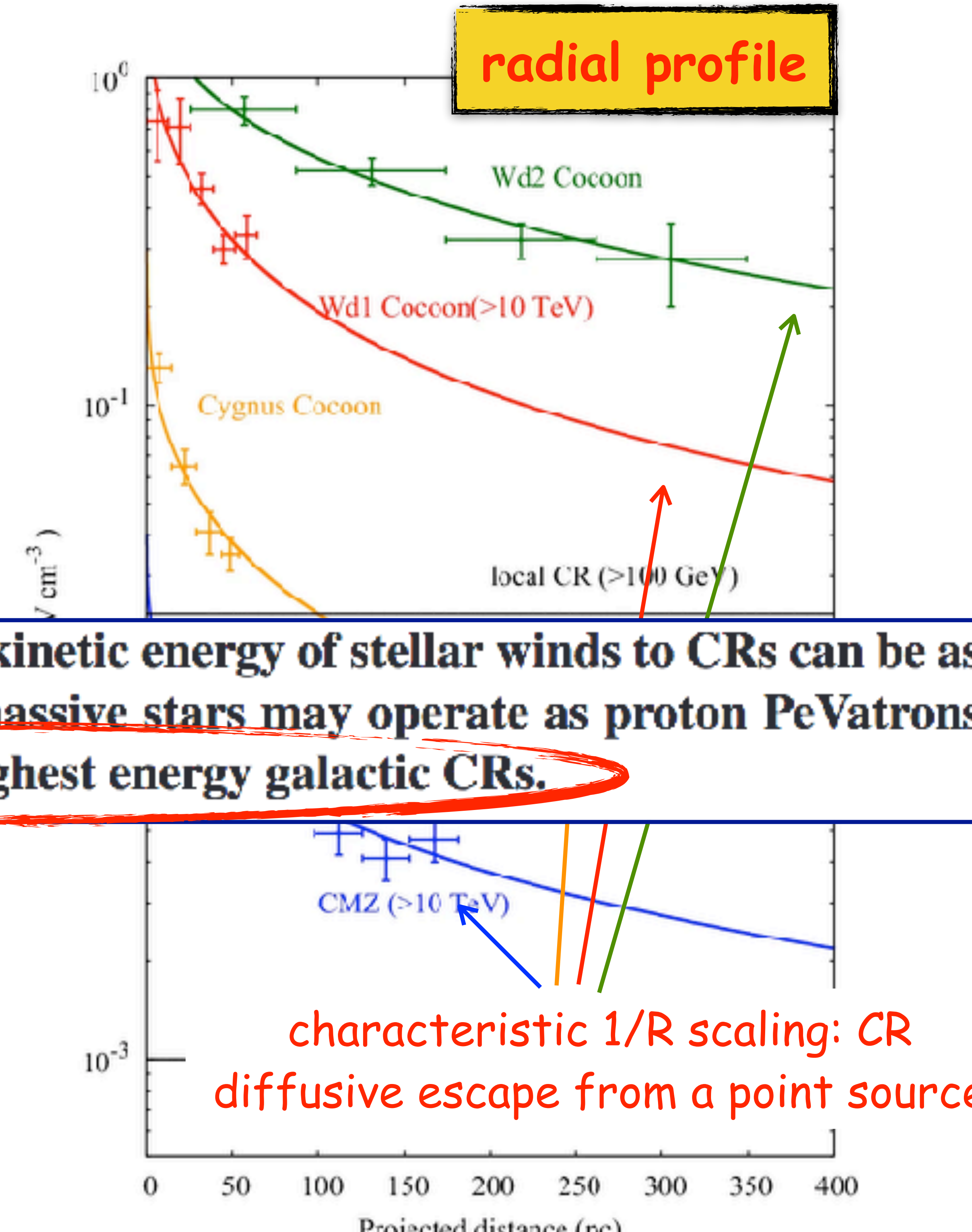

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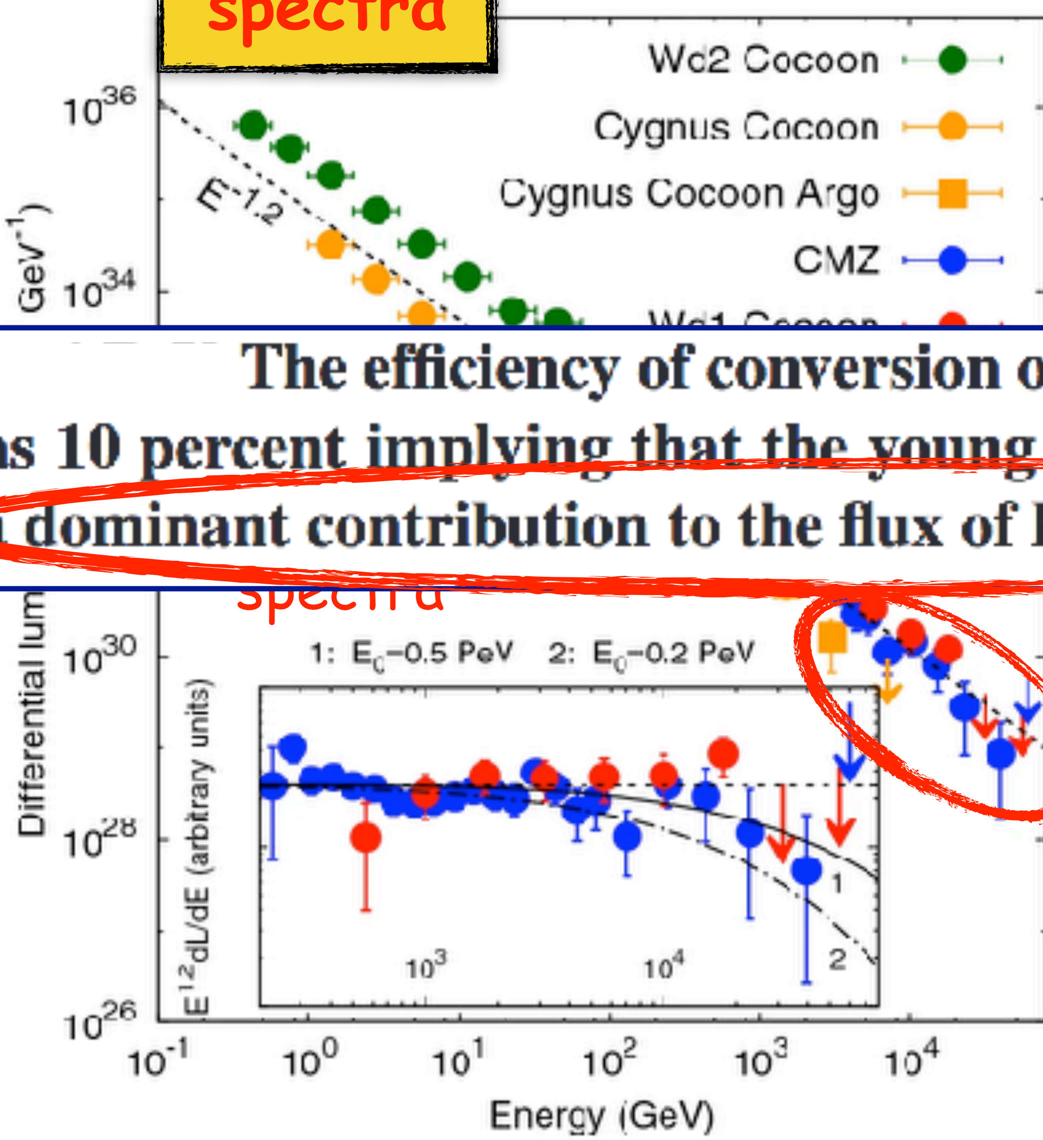
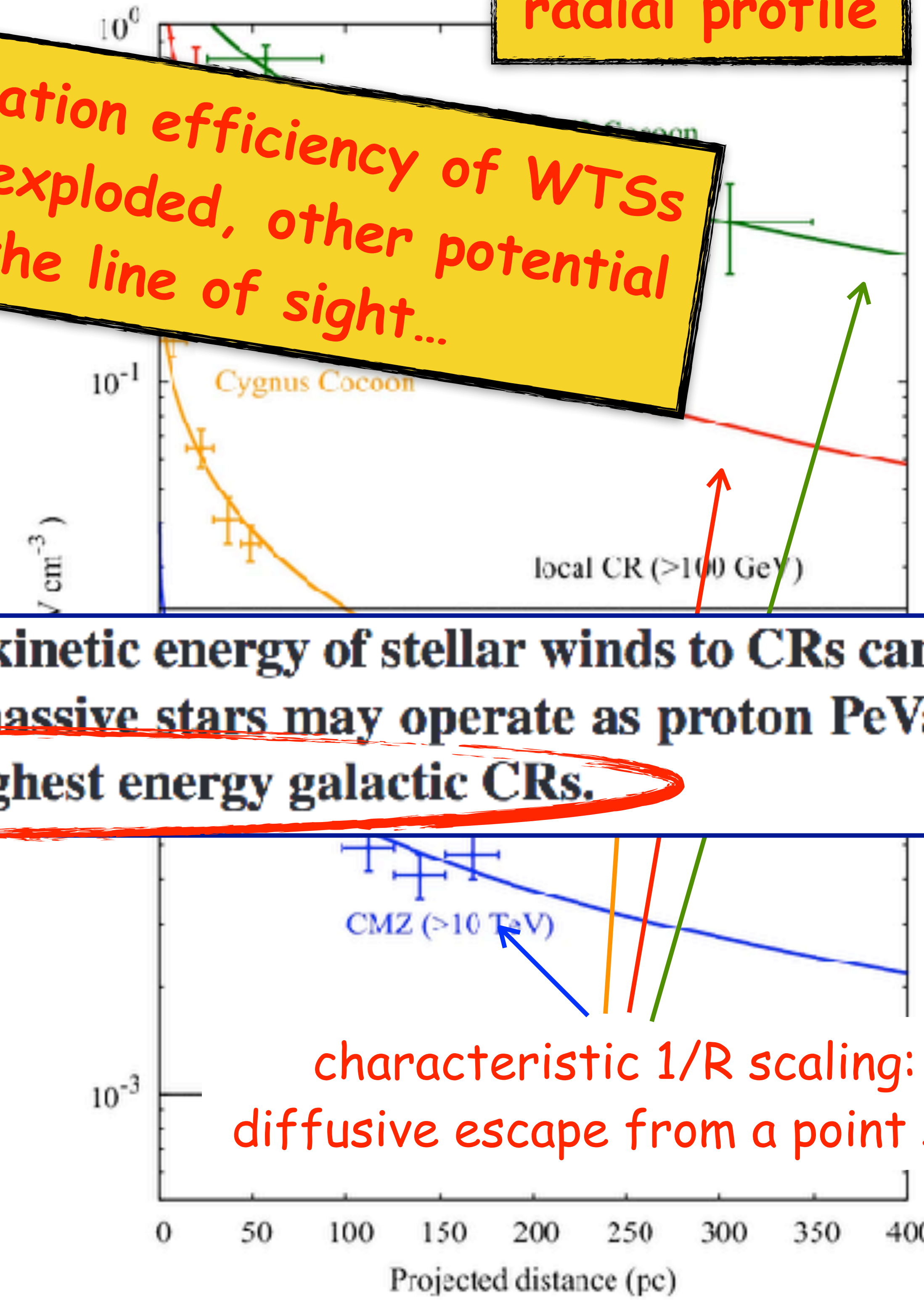
cannot constrain acceleration efficiency of WTSs
—> some SNae already exploded, other potential CR source along the line of sight…

radial profile

spectra



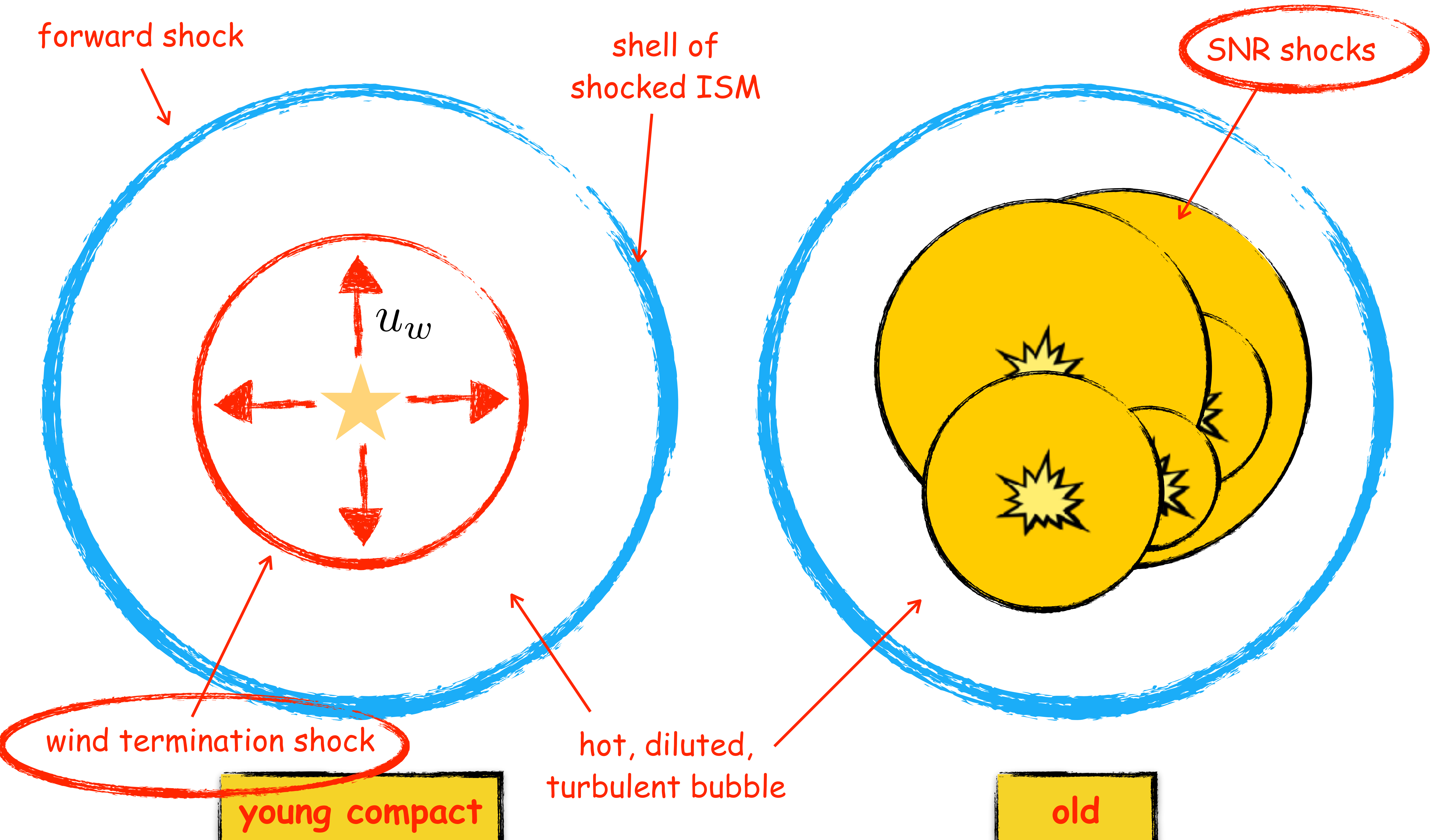


The efficiency of conversion of kinetic energy of stellar winds to CRs can be as high as 10 percent implying that the young massive stars may operate as proton PeVatrons with a dominant contribution to the flux of highest energy galactic CRs.

characteristic 1/R scaling: CR diffusive escape from a point source

Interstellar bubbles around star clusters

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



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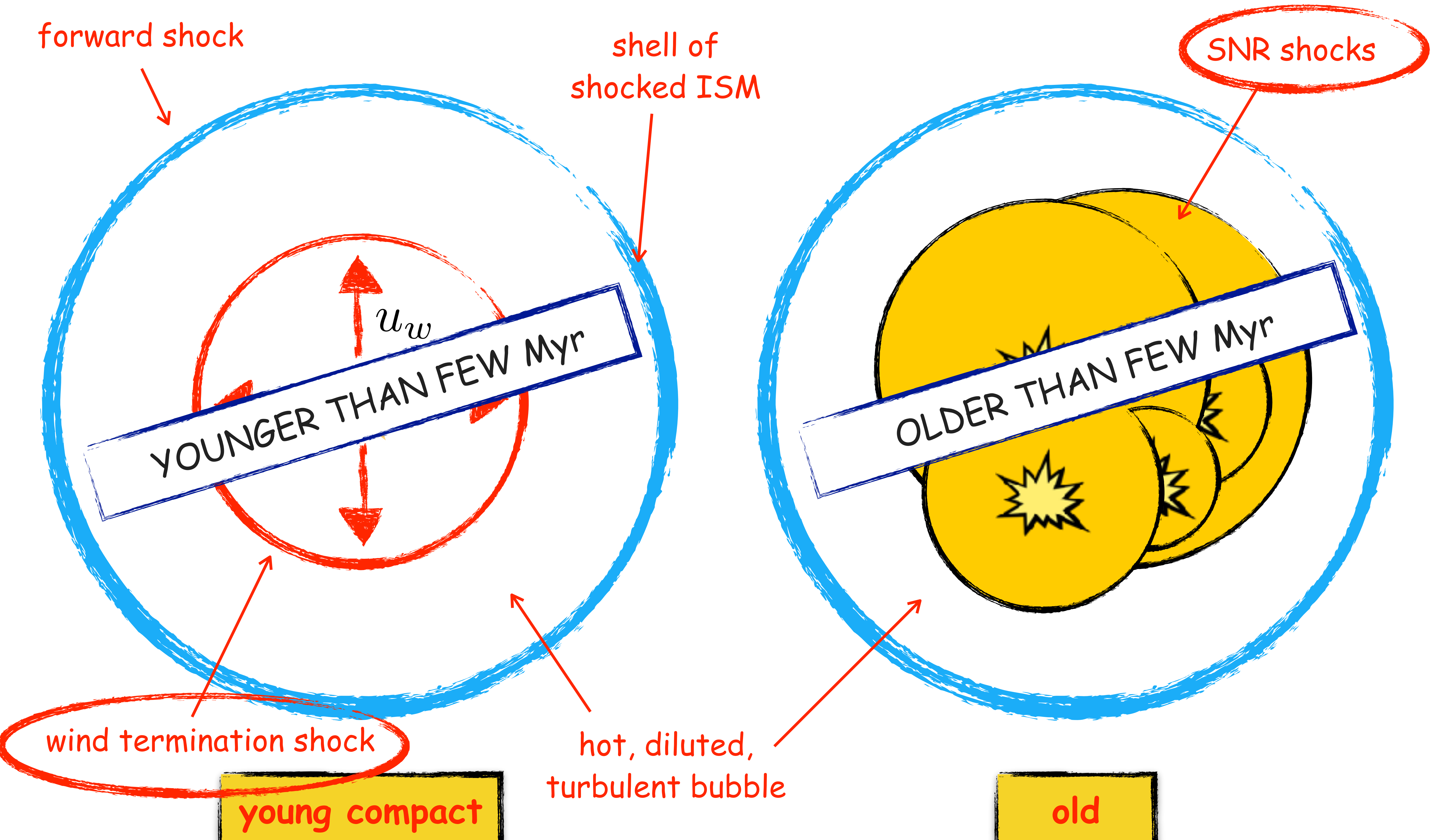
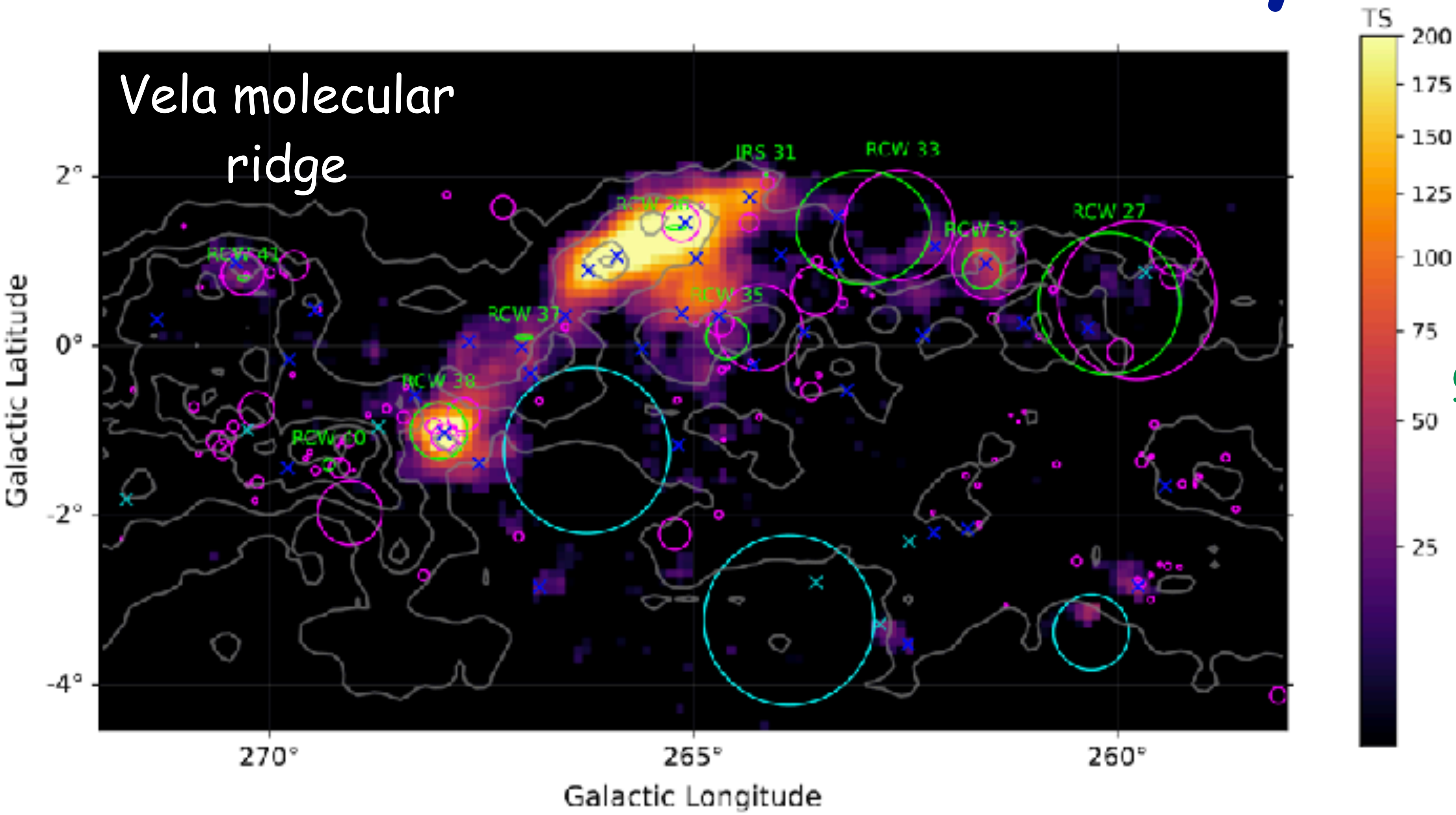


Wind termination shocks accelerate cosmic rays



grey —> gas

color —> gamma

green/purple —> HII regions

Peron+, Nature Astronomy, 2024

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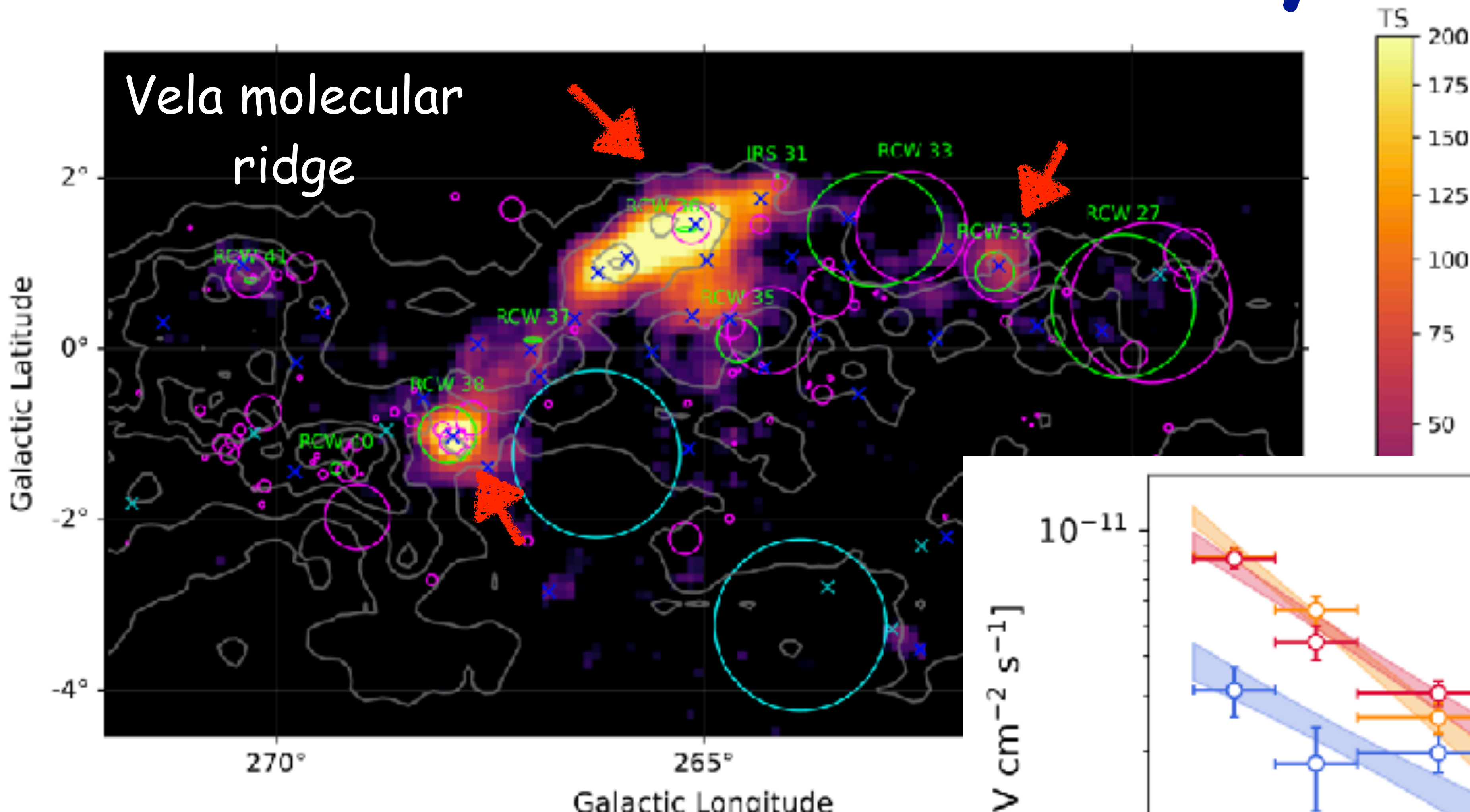

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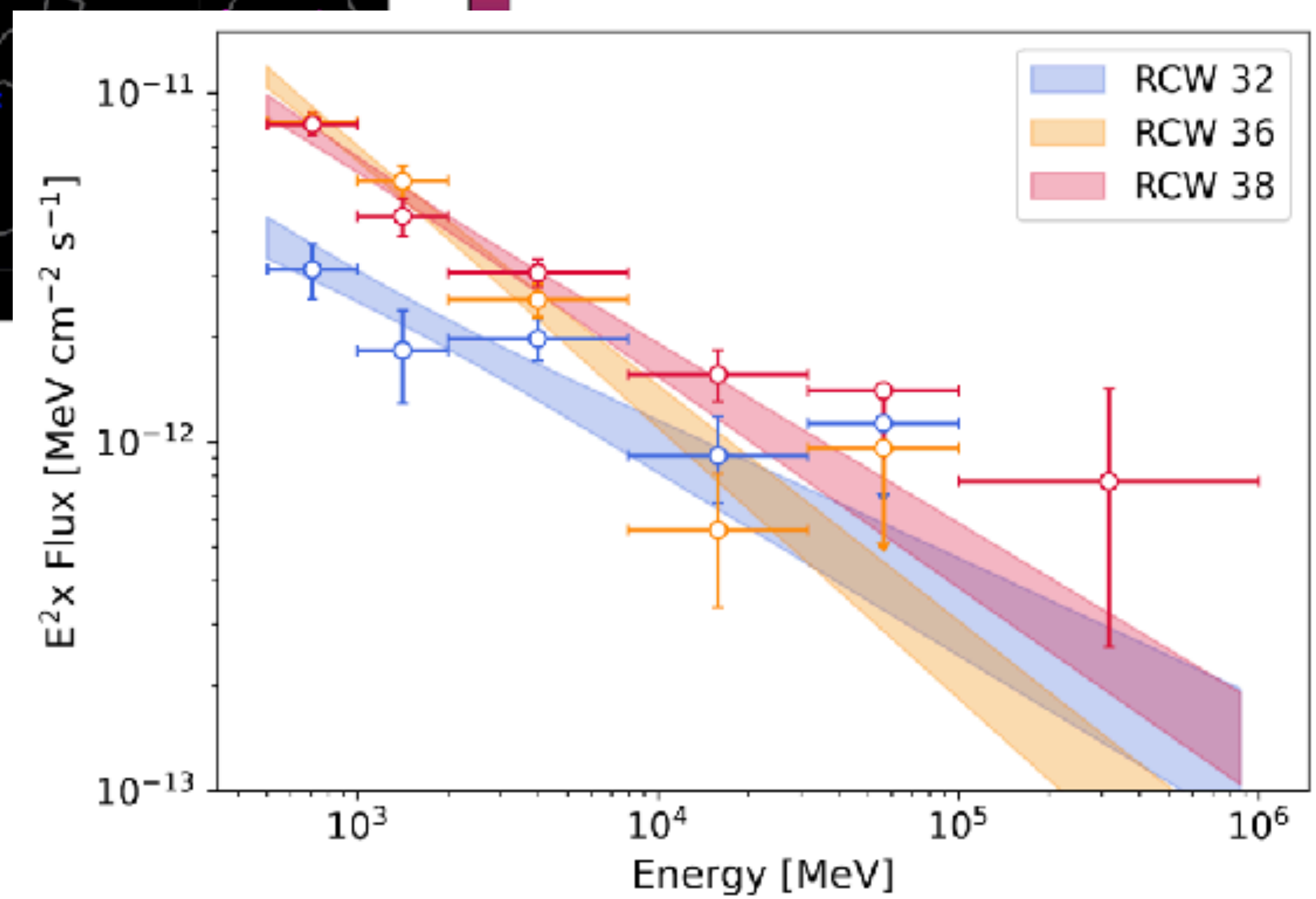

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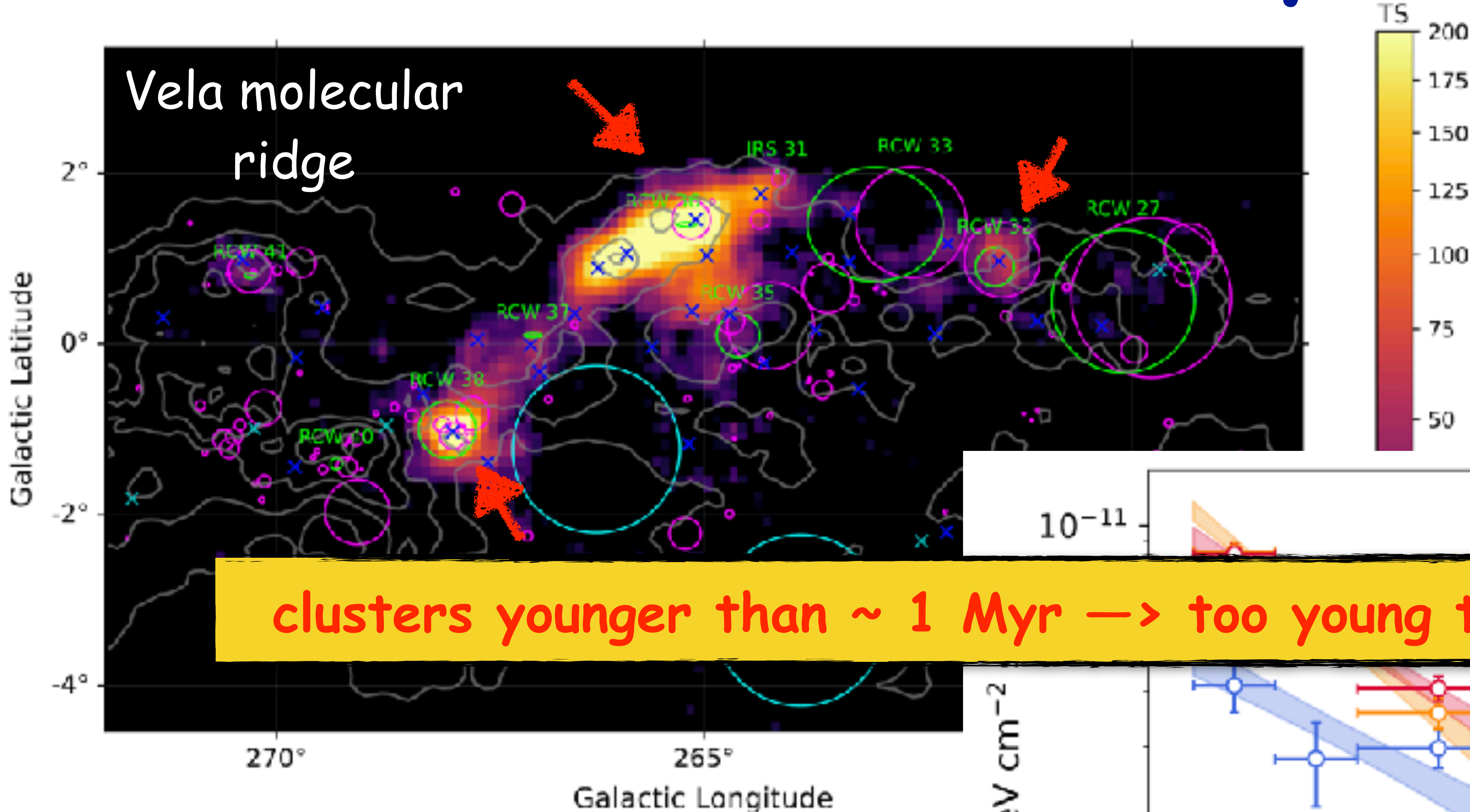

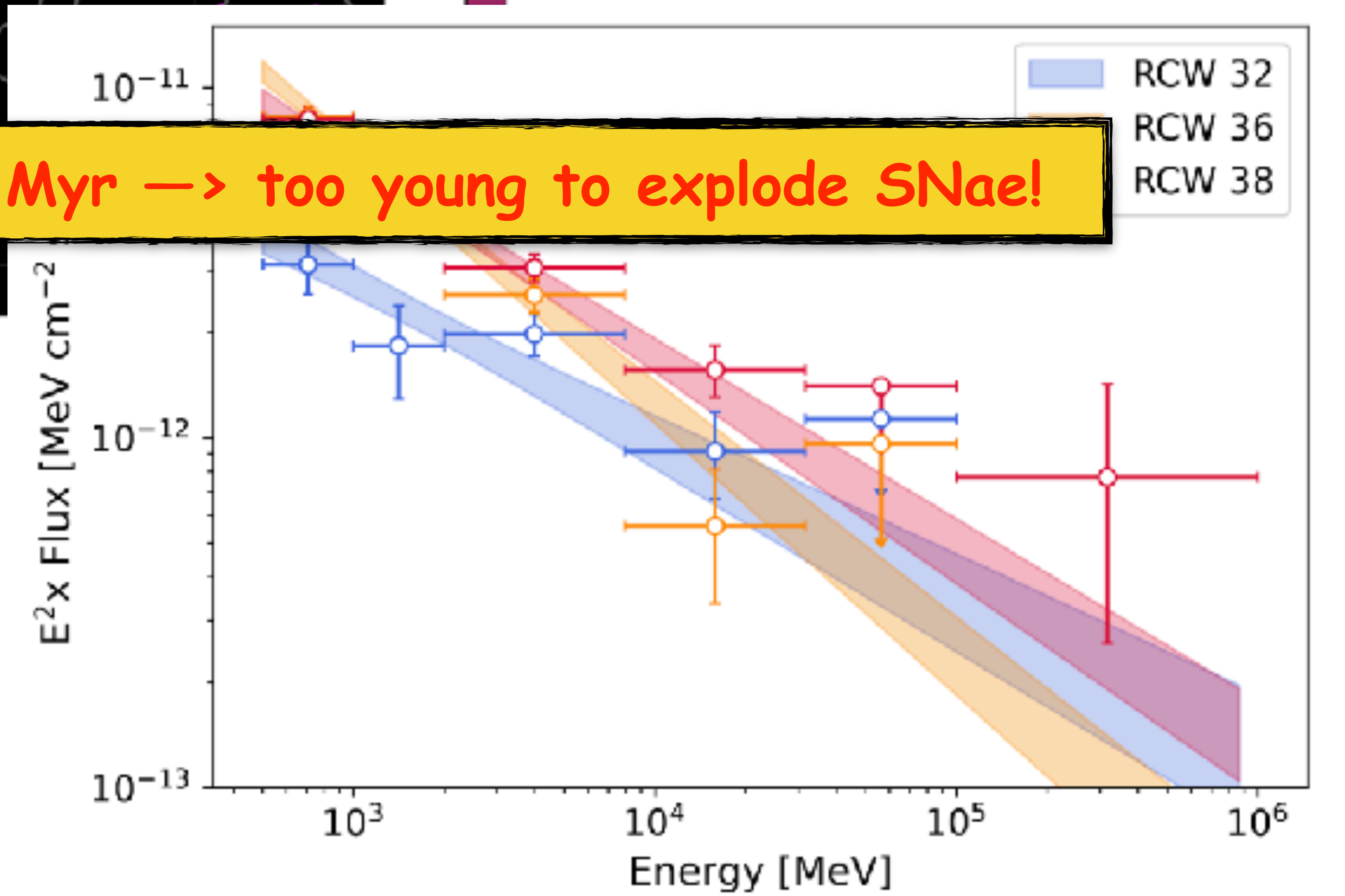

clusters younger than ~ 1 Myr —> too young to explode SNae!

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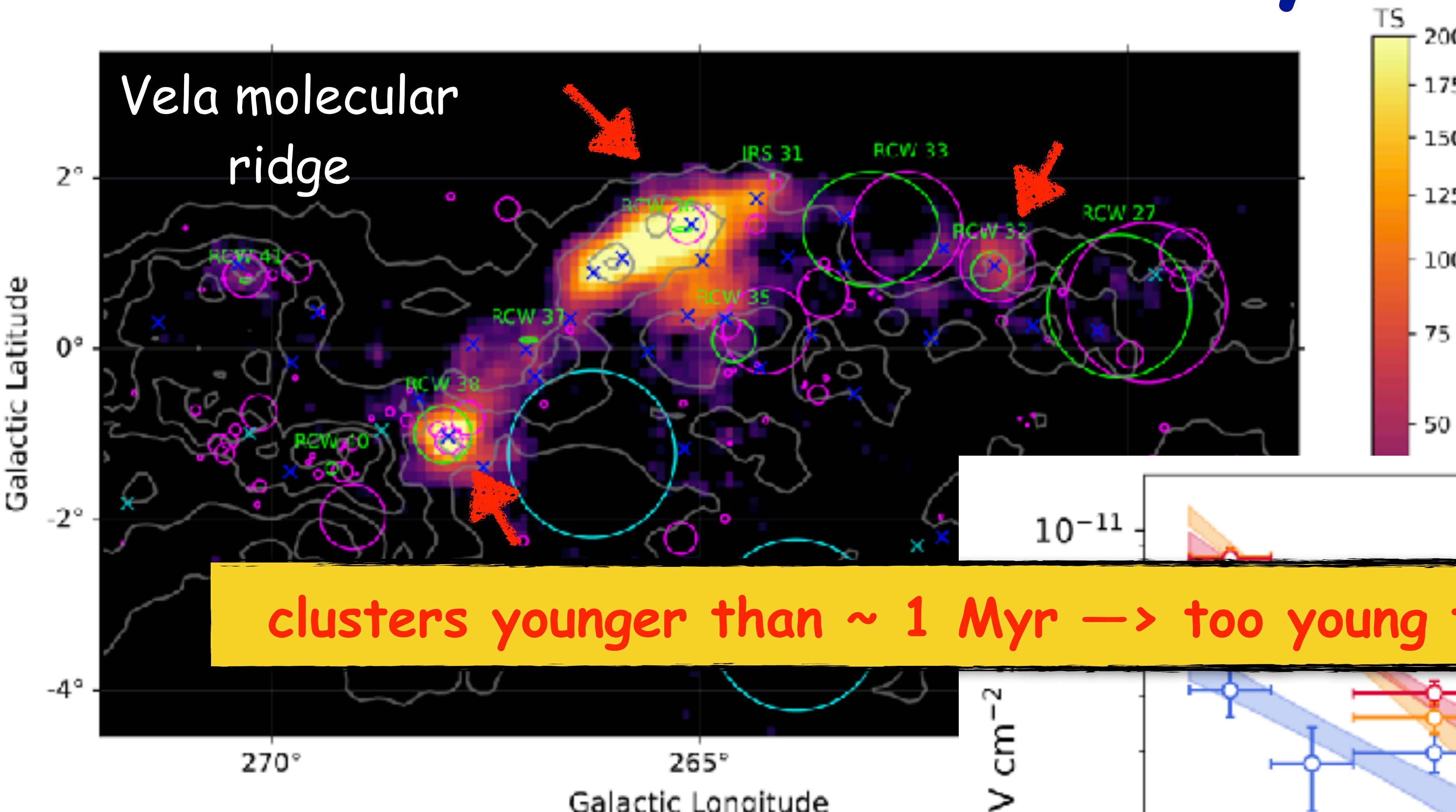
Wind termination shocks accelerate cosmic rays



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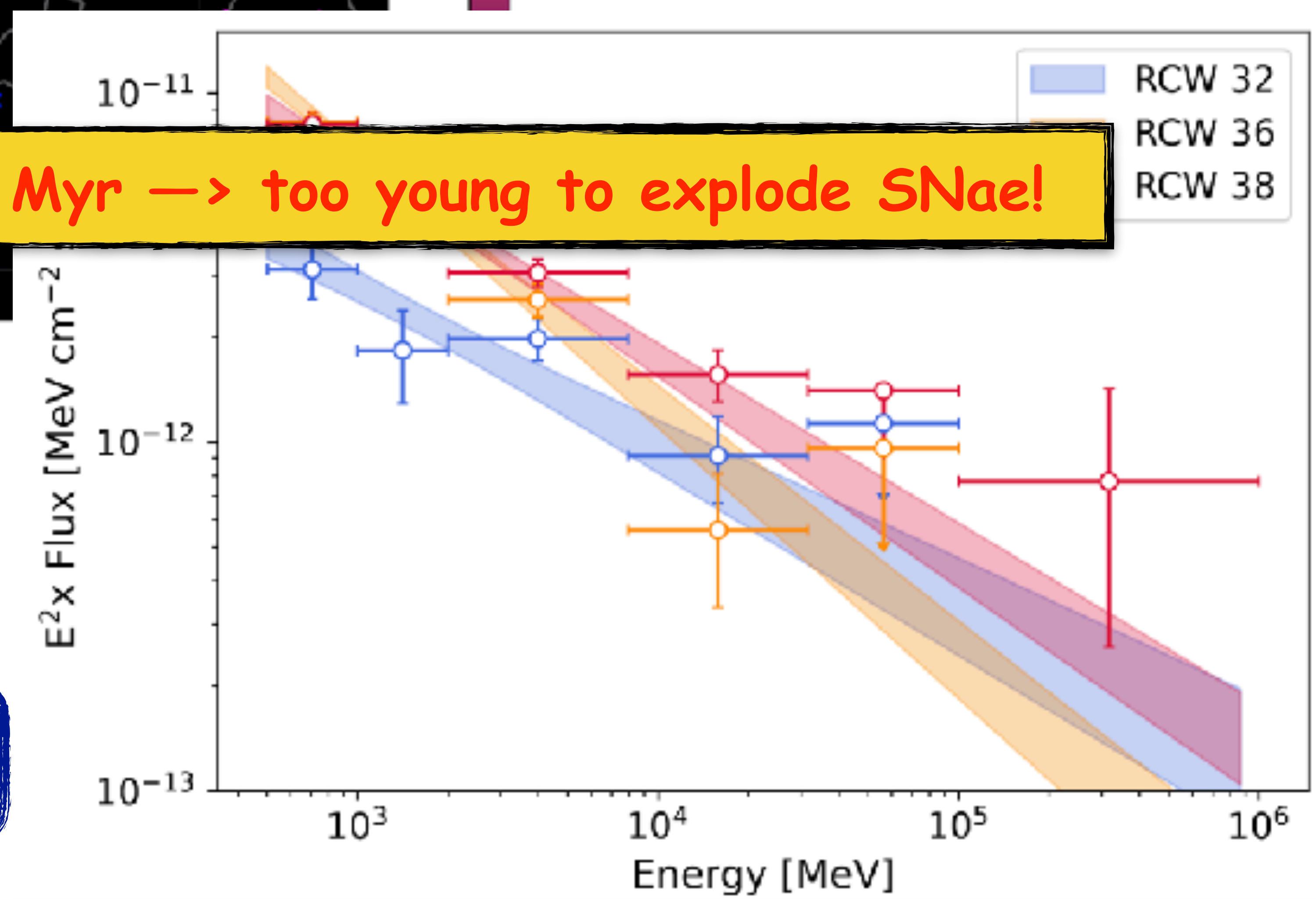

strict lower bound on the CR acceleration efficiency (energy)

$$\boxed{\eta_{CR} > 1\%}$$

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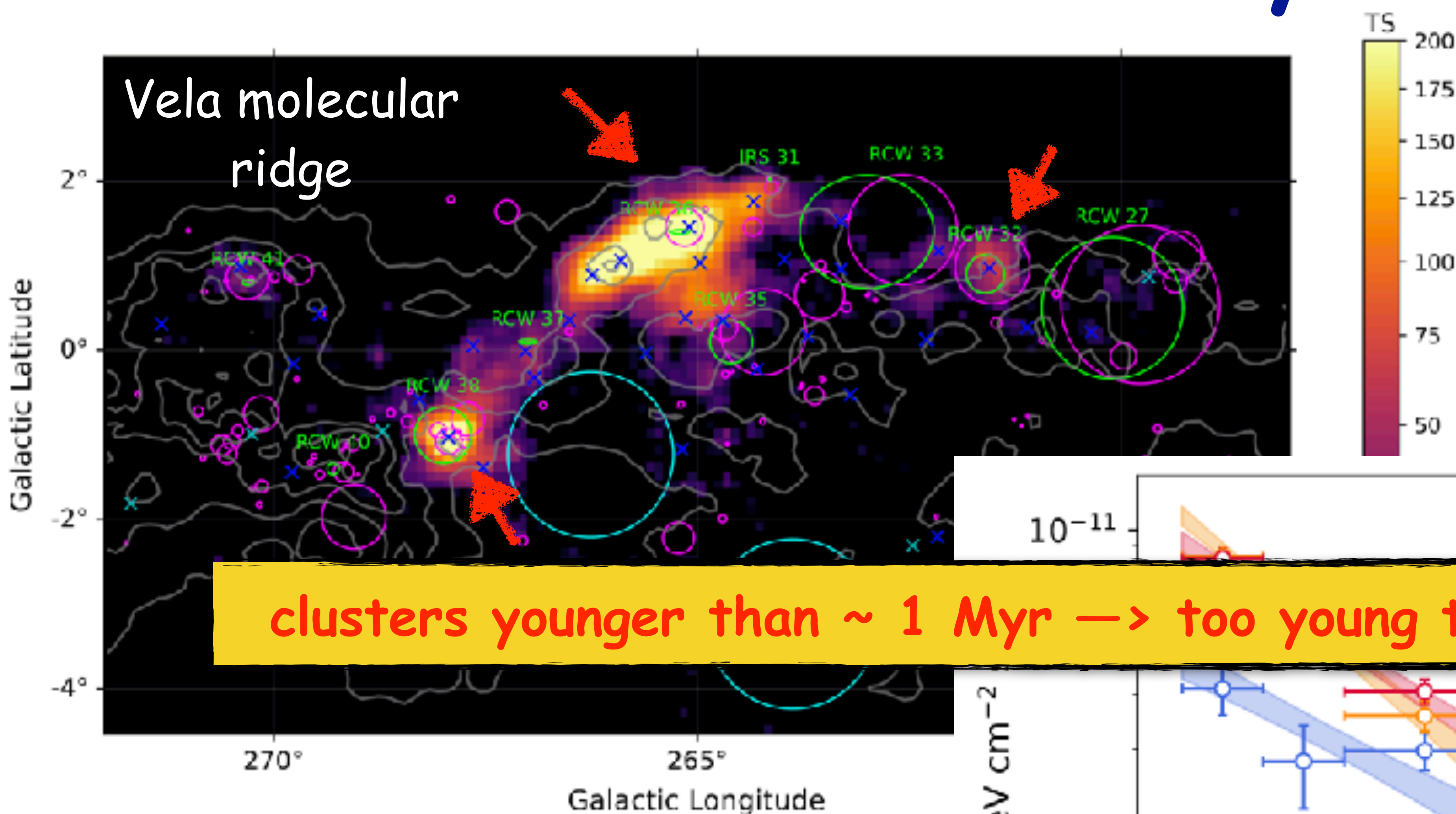
Wind termination shocks accelerate cosmic rays



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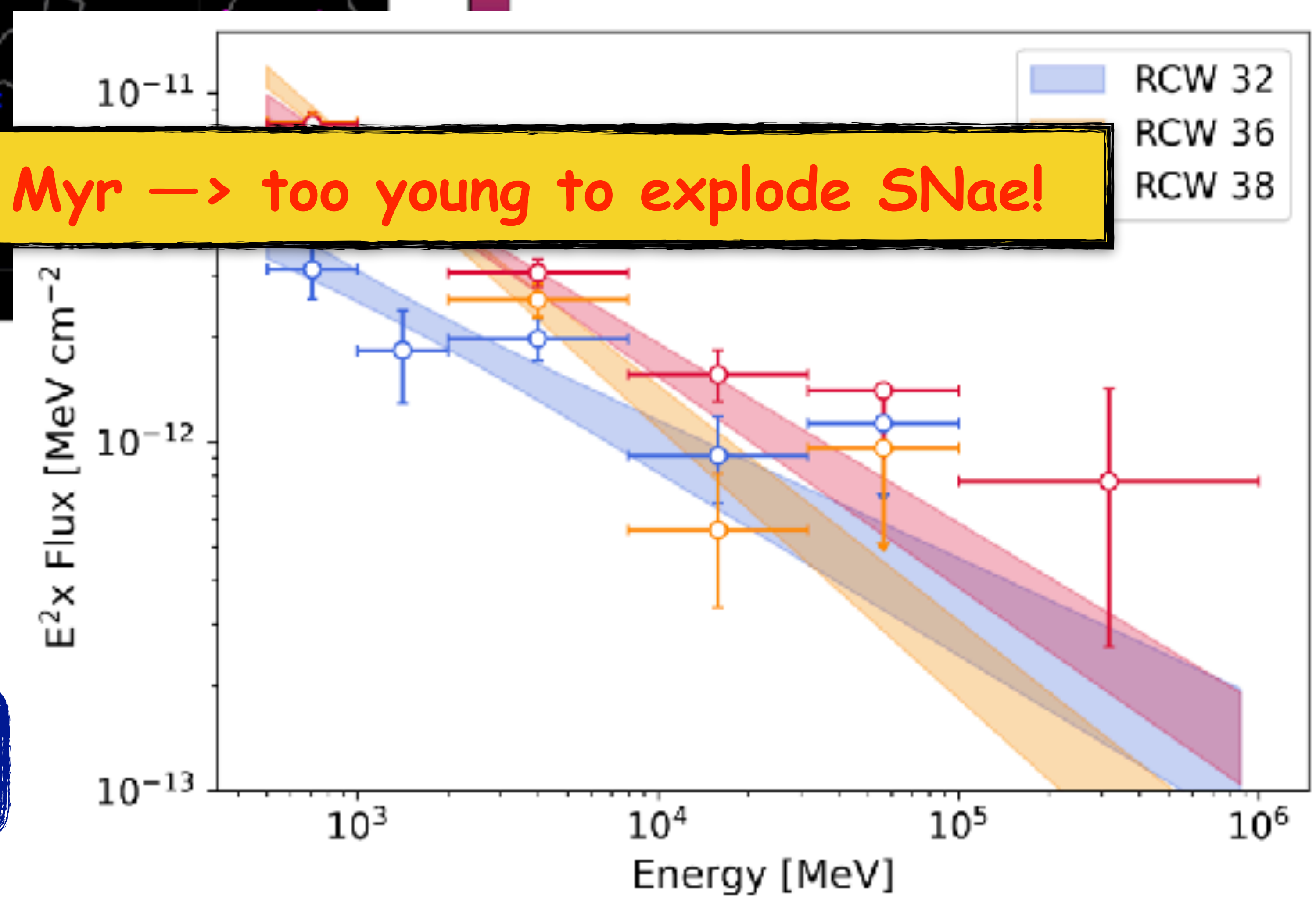

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strict lower bound on the CR acceleration efficiency (energy)

fraction of CRs coming from stellar winds

$$\boxed{\eta_{CR} > 1\%}$$

Conclusions

- The SNR paradigm for the origin of CRs suffers some major problems
  - Most notably, can they accelerate up to the knee (and beyond)?
- Galaxy cluster accretion shocks might accelerate up to the maximum energies observed
- Emerging (?) evidence —> need for a third component
- Wind termination shocks? Galactic wind? Stellar cluster winds?
- Stellar matter is needed to explain CRs! Stellar wind would fix the problem with $^{22}Ne/^{20}Ne$ ratio.
- All cosmic rays from non-relativistic shocks?