Cosmic rays in the interstellar medium

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REVIEW ARTICLE

Low-energy cosmic rays: regulators of the dense interstellar medium

Stefano Gabici[1]

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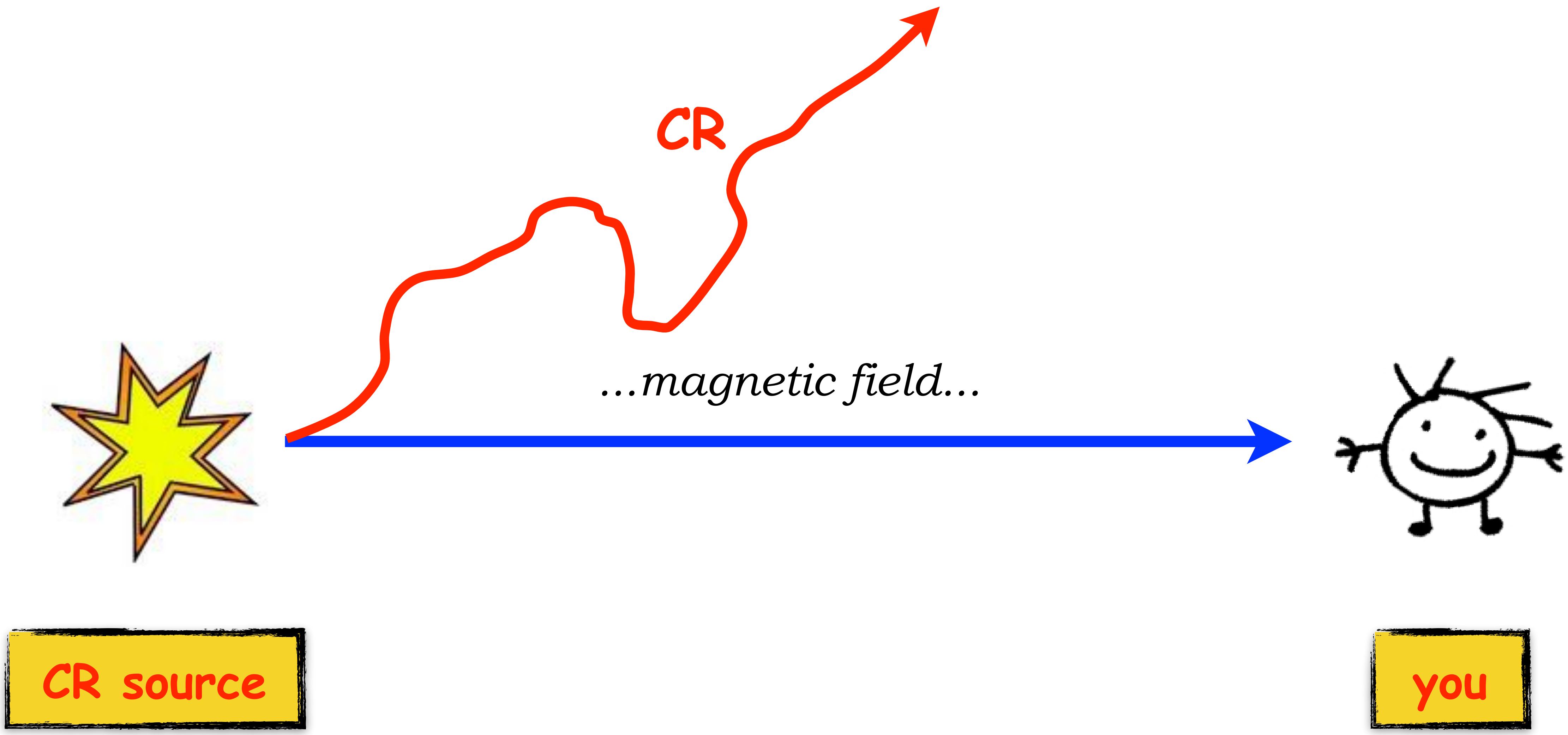
—> Cosmic rays are energetic particles hitting the Earth's atmosphere from outer space.

—> Most of them (90%) are protons.

—> Most people believe they are accelerated at supernova remnant shocks.

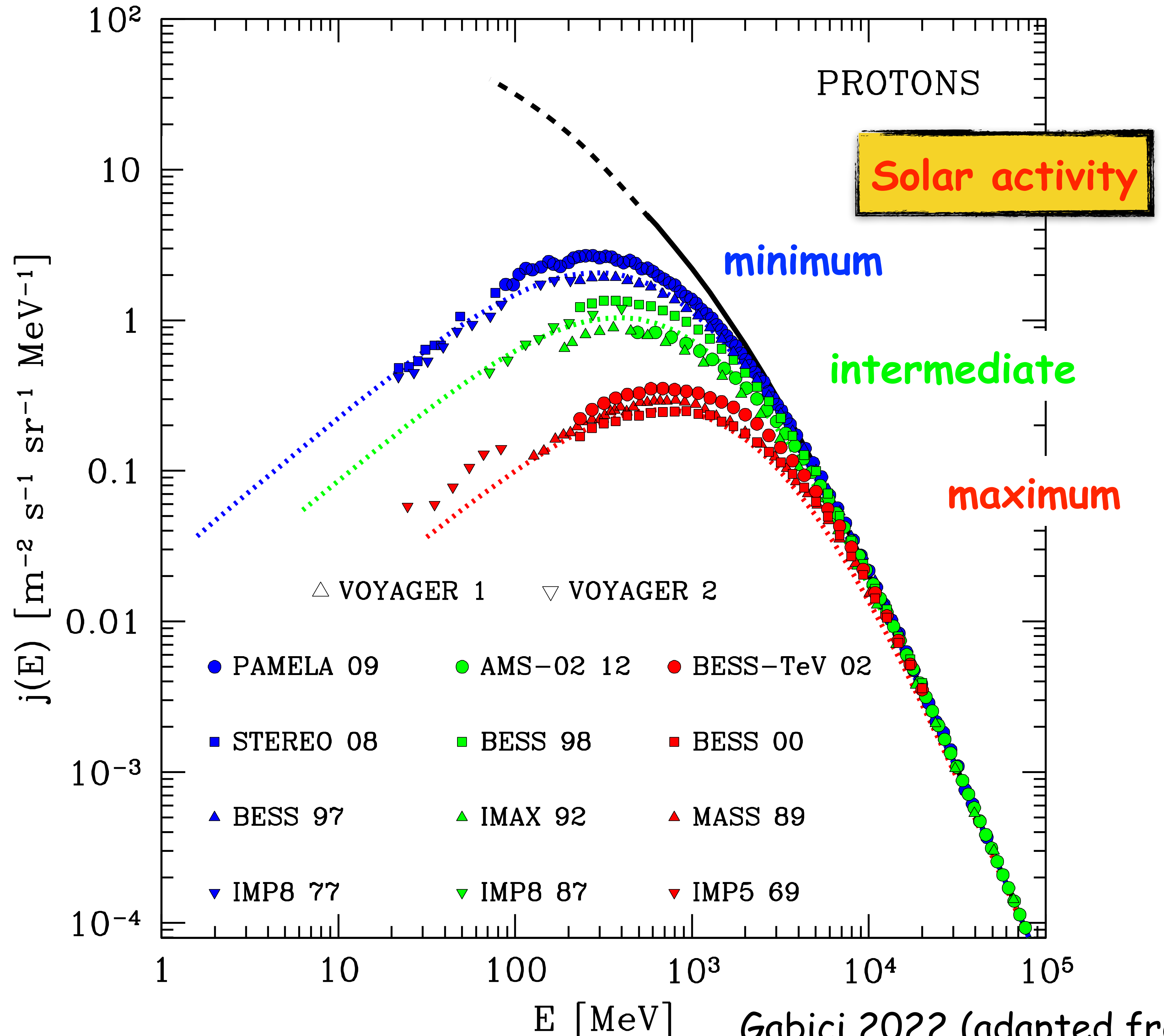
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

Need for indirect identification of CR sources.

Solar modulation



Gabici 2022 (adapted from Vos & Potgieter 2015)

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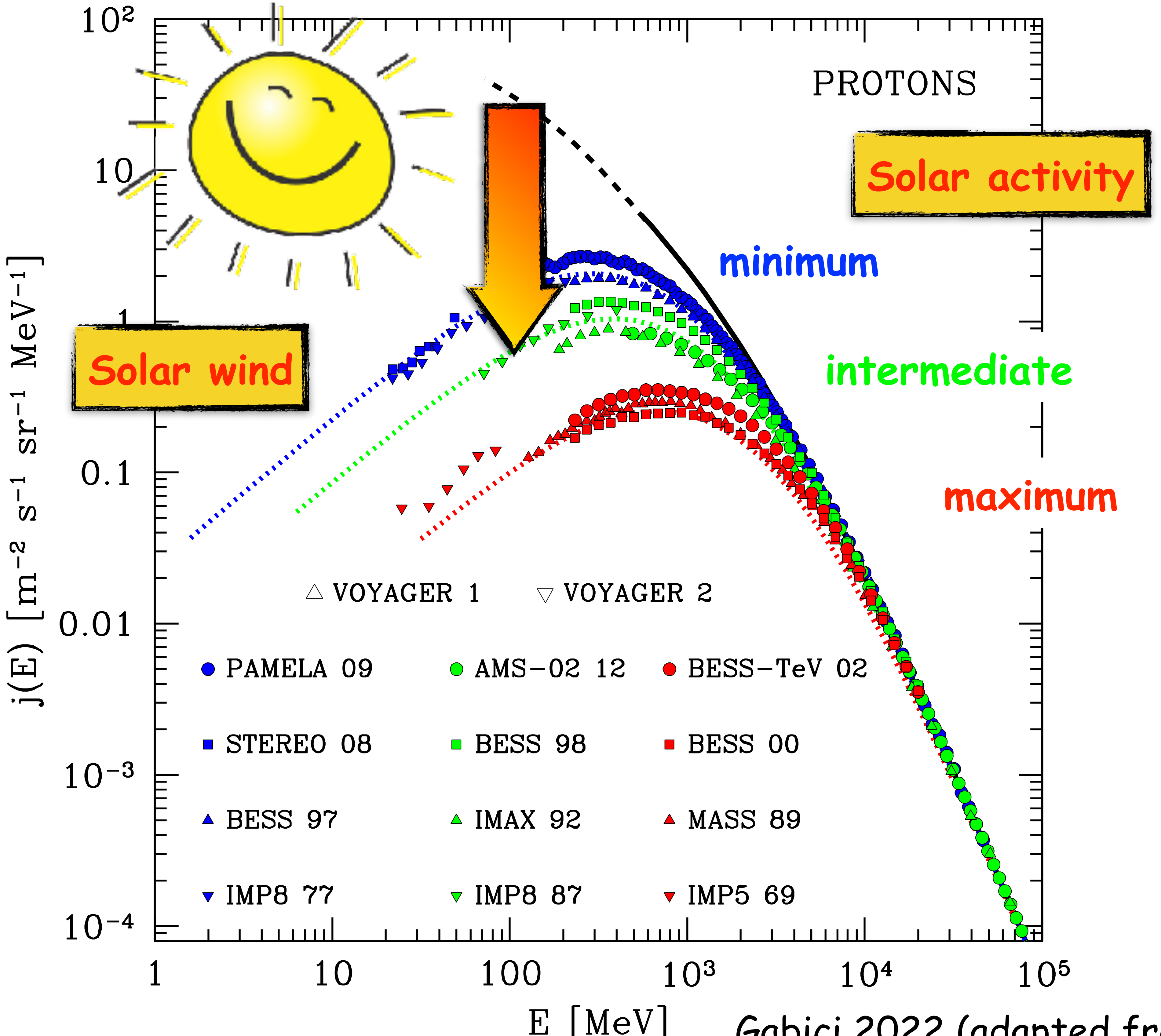

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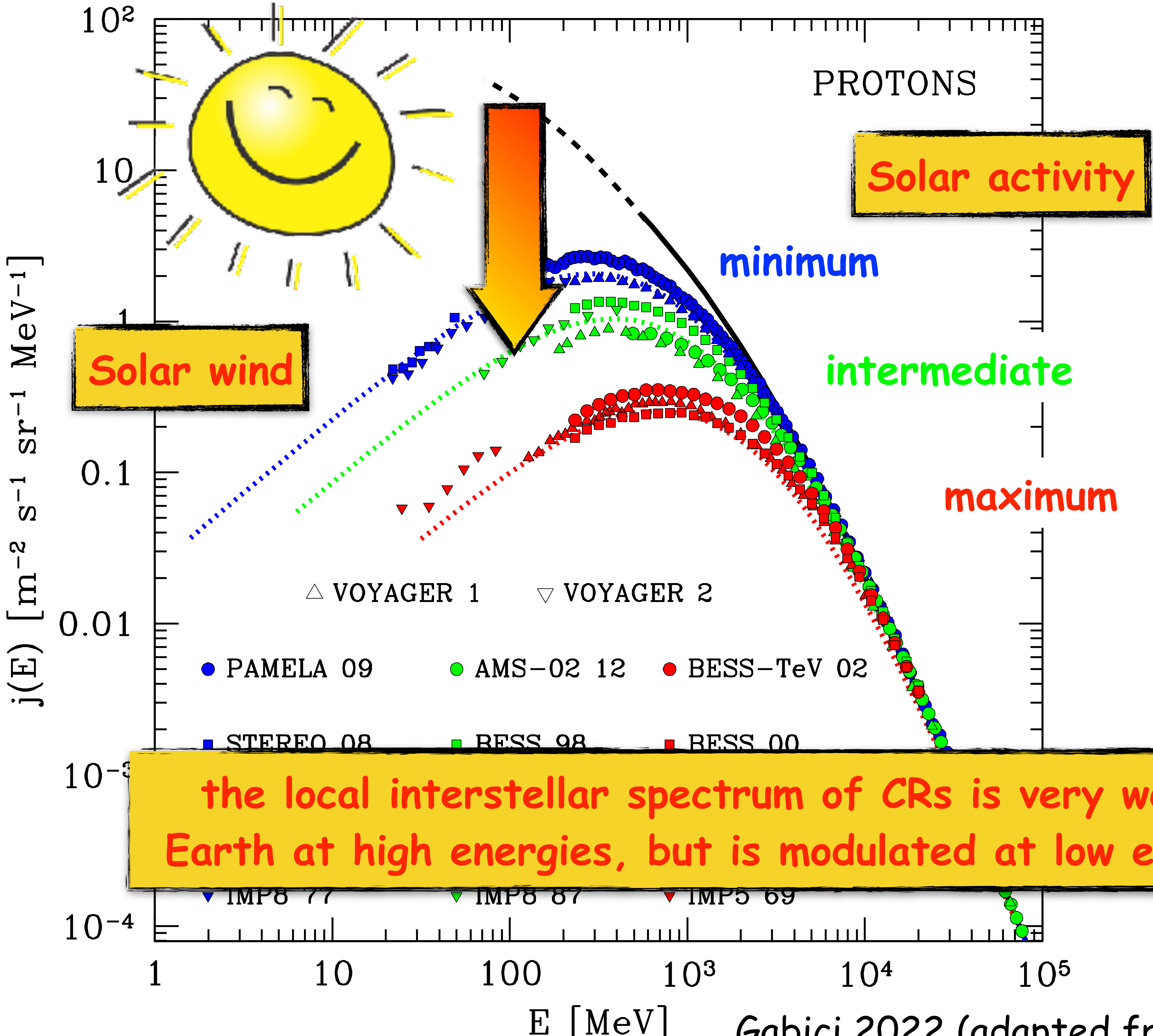


the local interstellar spectrum of CRs is very well measured from Earth at high energies, but is modulated at low energyes (< 20 GeV)

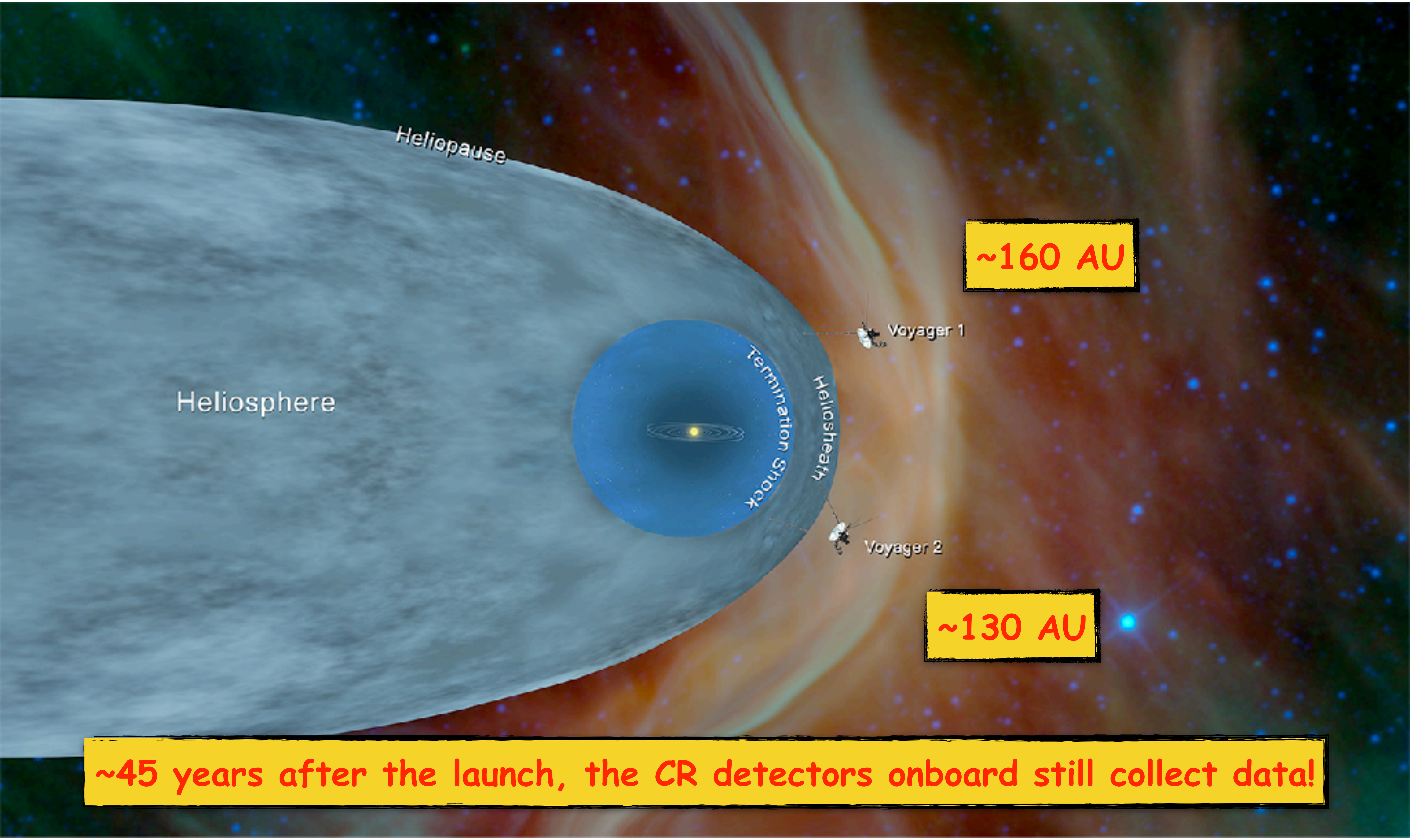
Gabici 2022 (adapted from Vos & Potgieter 2015)

Voyager probes

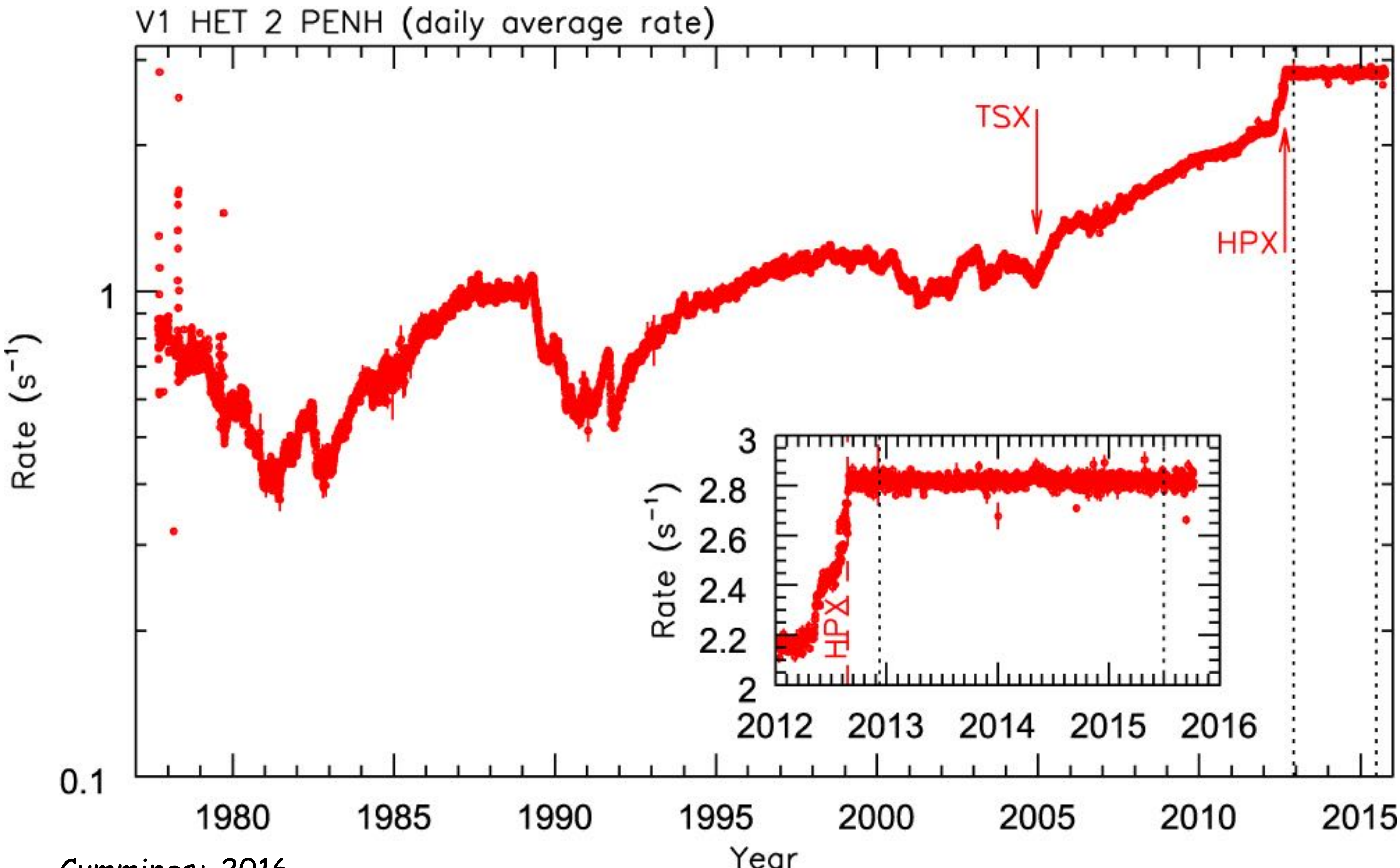
September 5 1977
the launch of Voyager 1

August 20 1977 launch of the twin probe Voyager 2

Voyager probes crossed the heliopause



An epic journey



Cummings+ 2016

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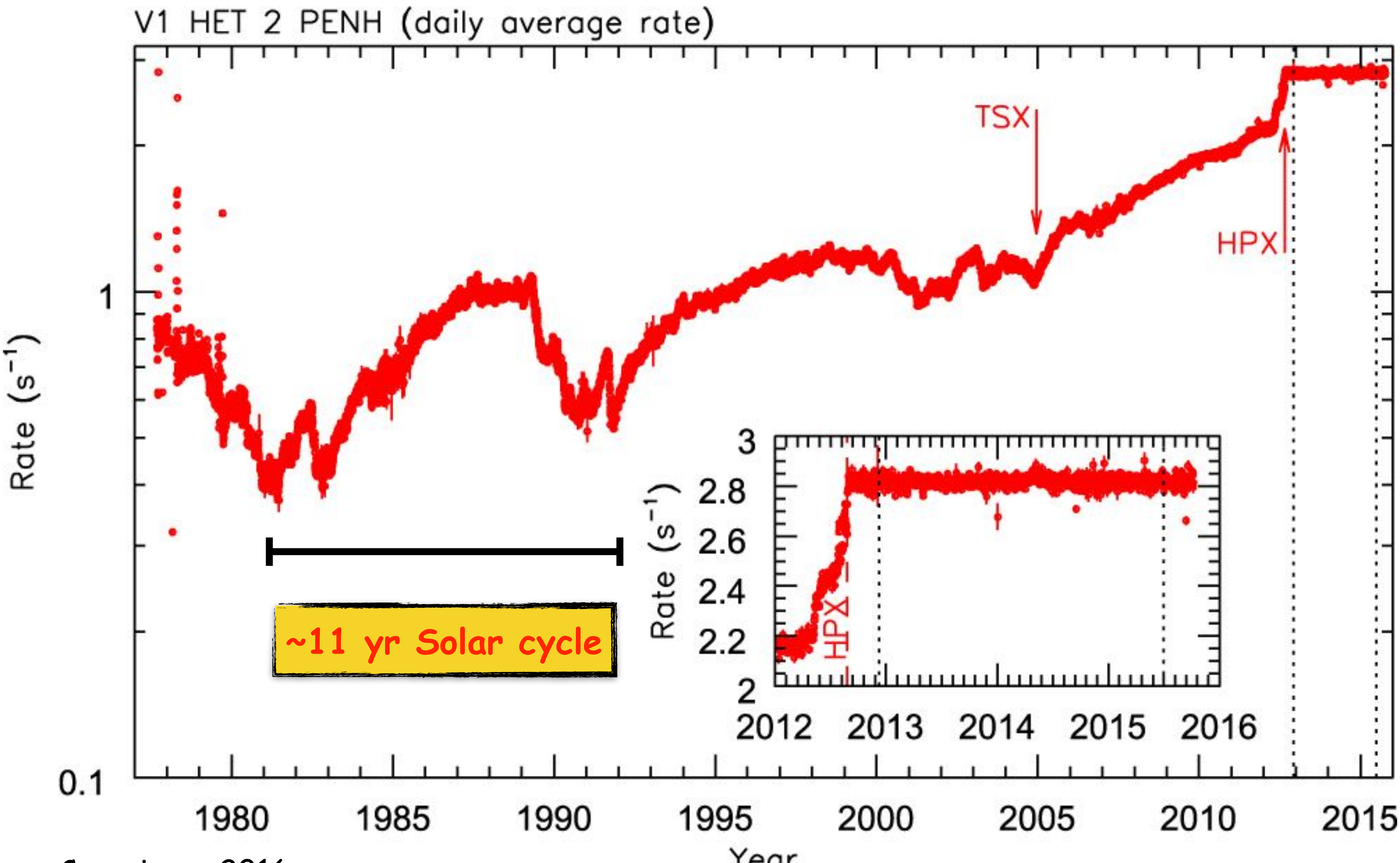

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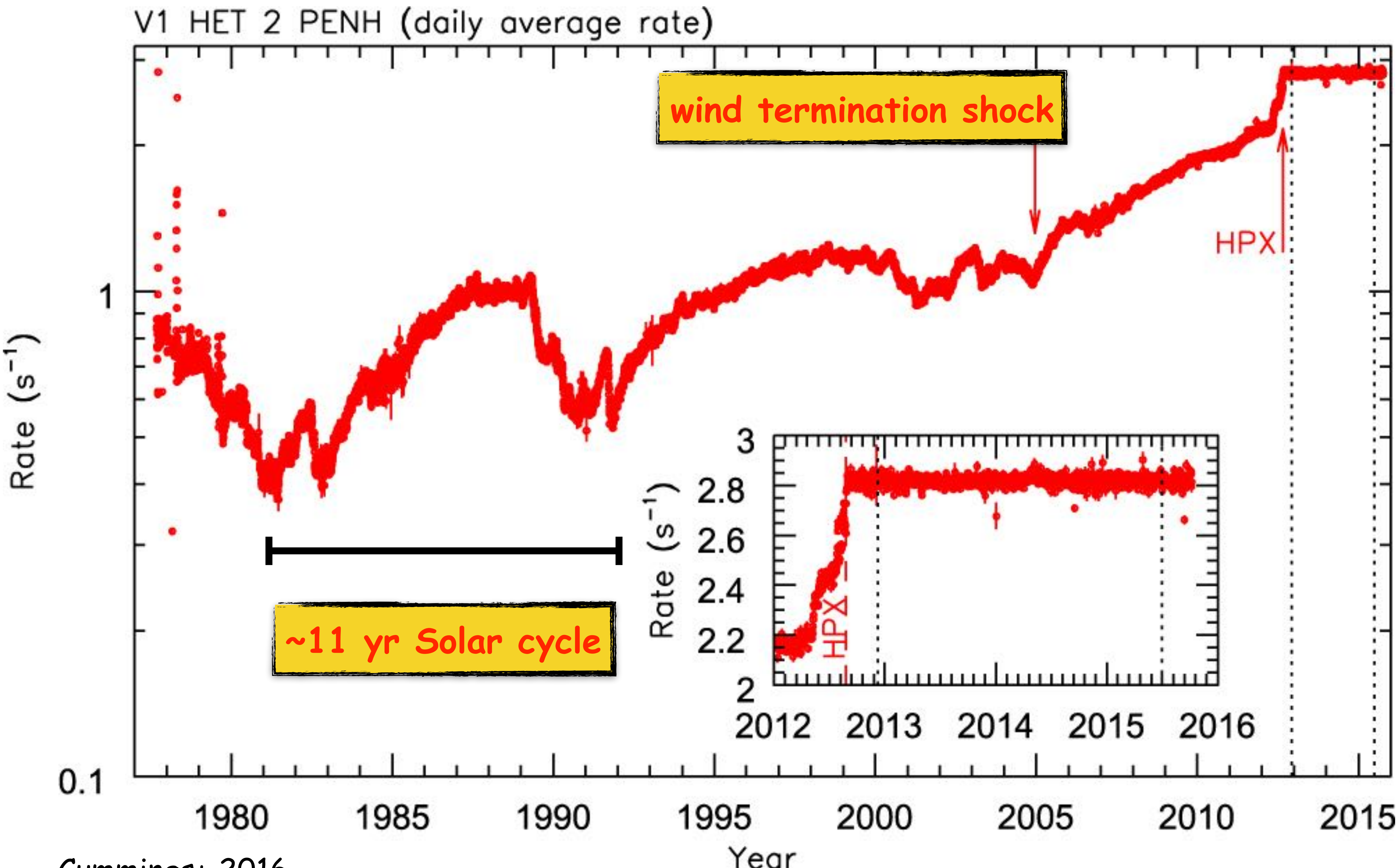

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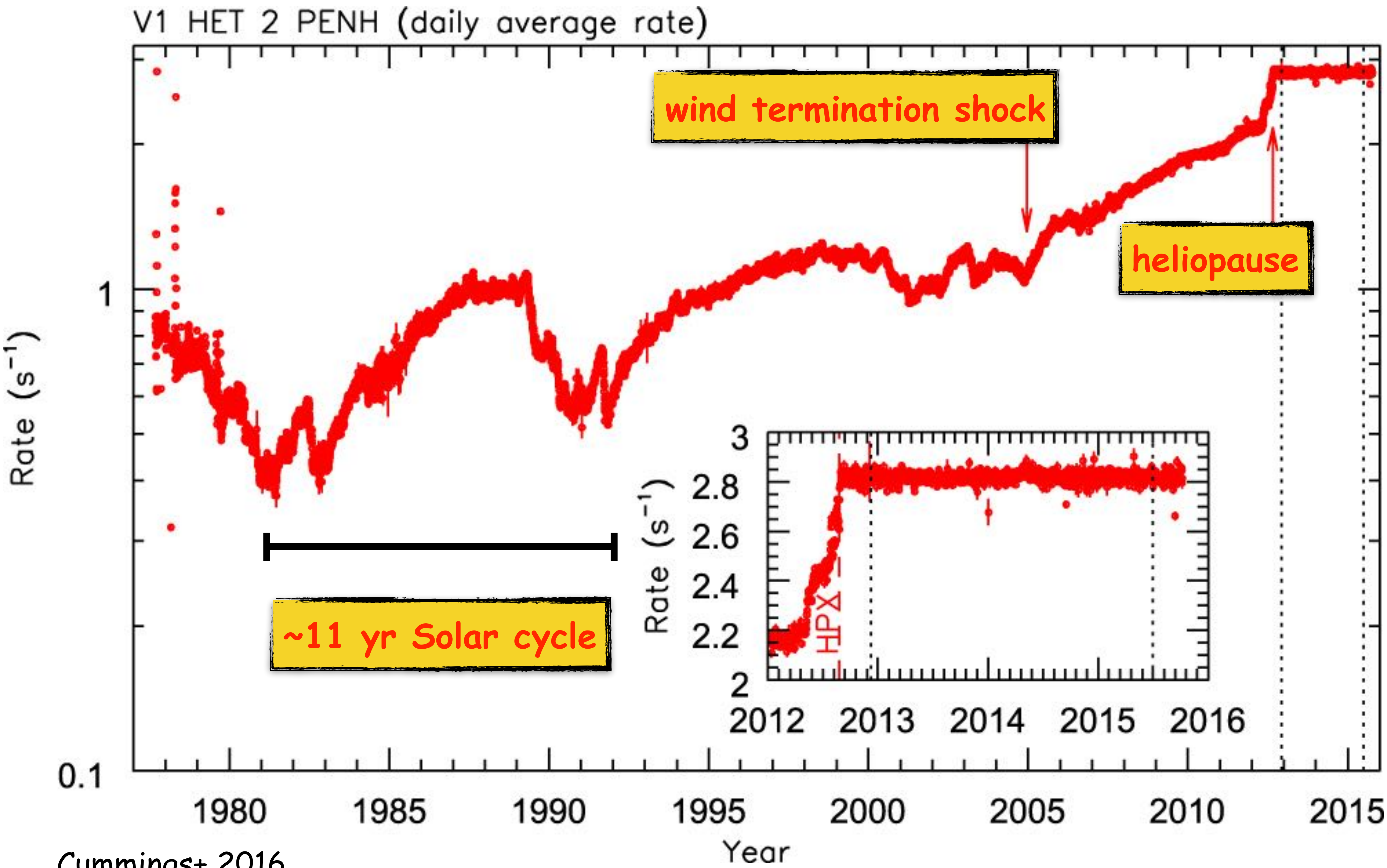

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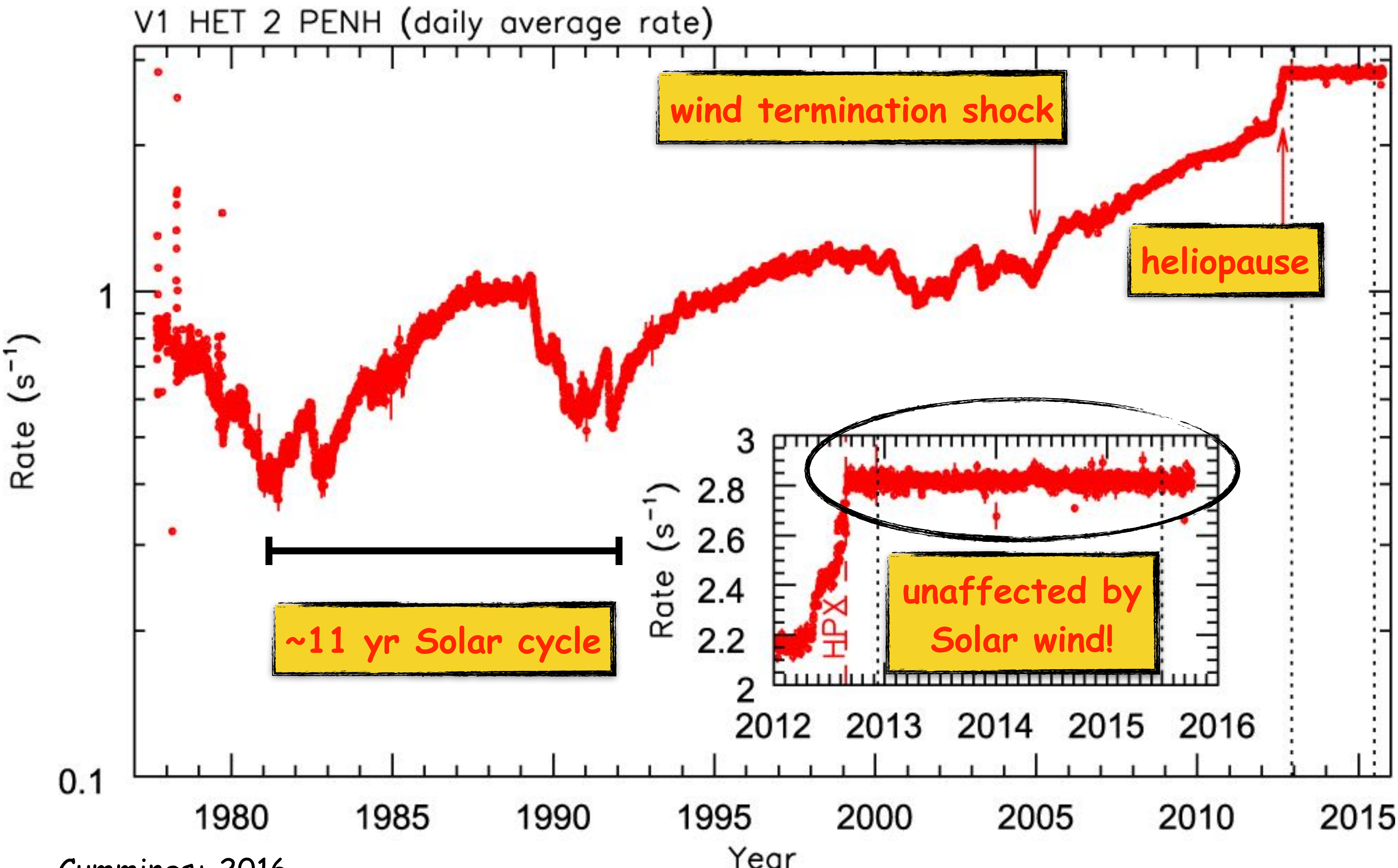

Cummings+ 2016

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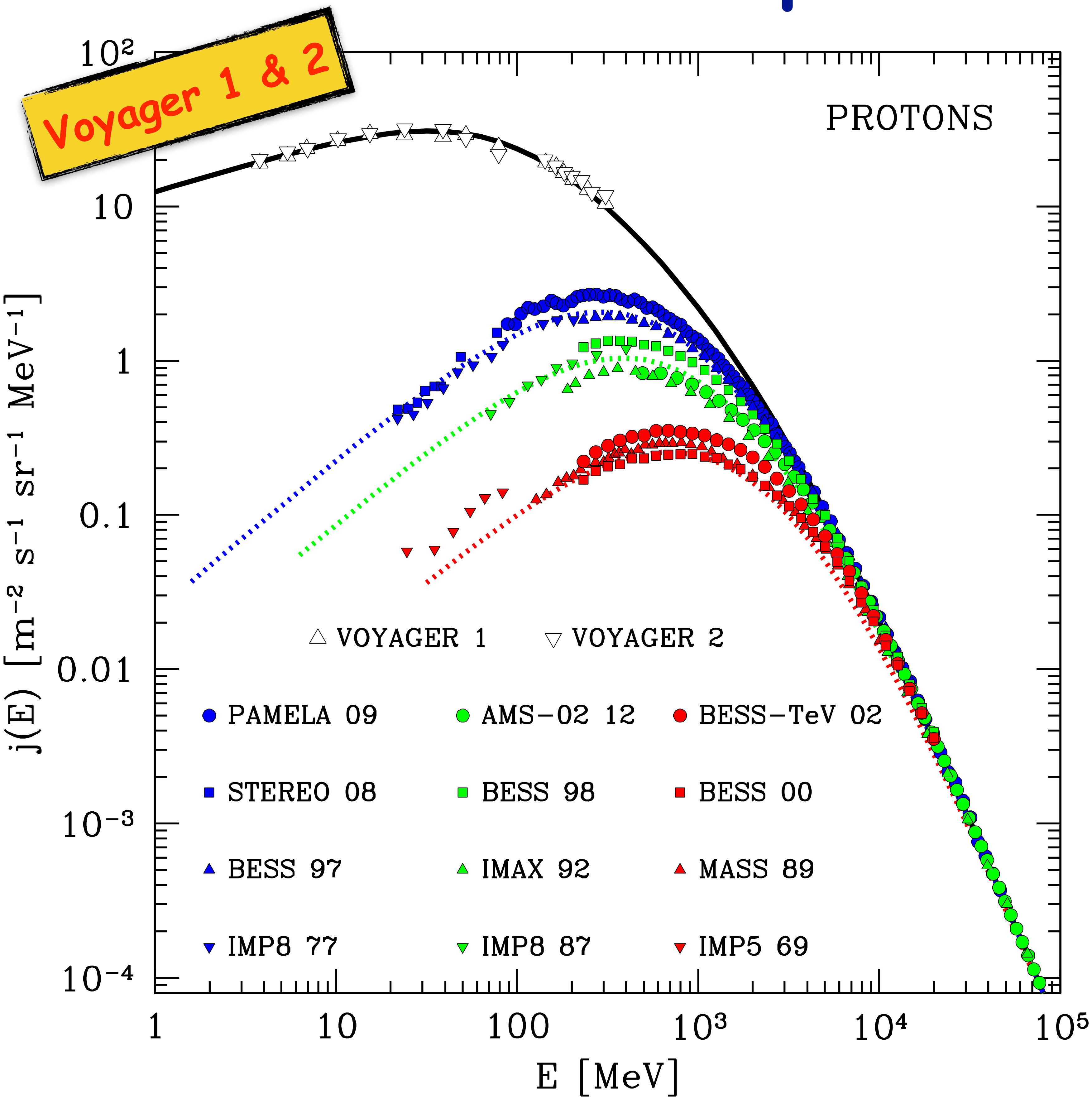

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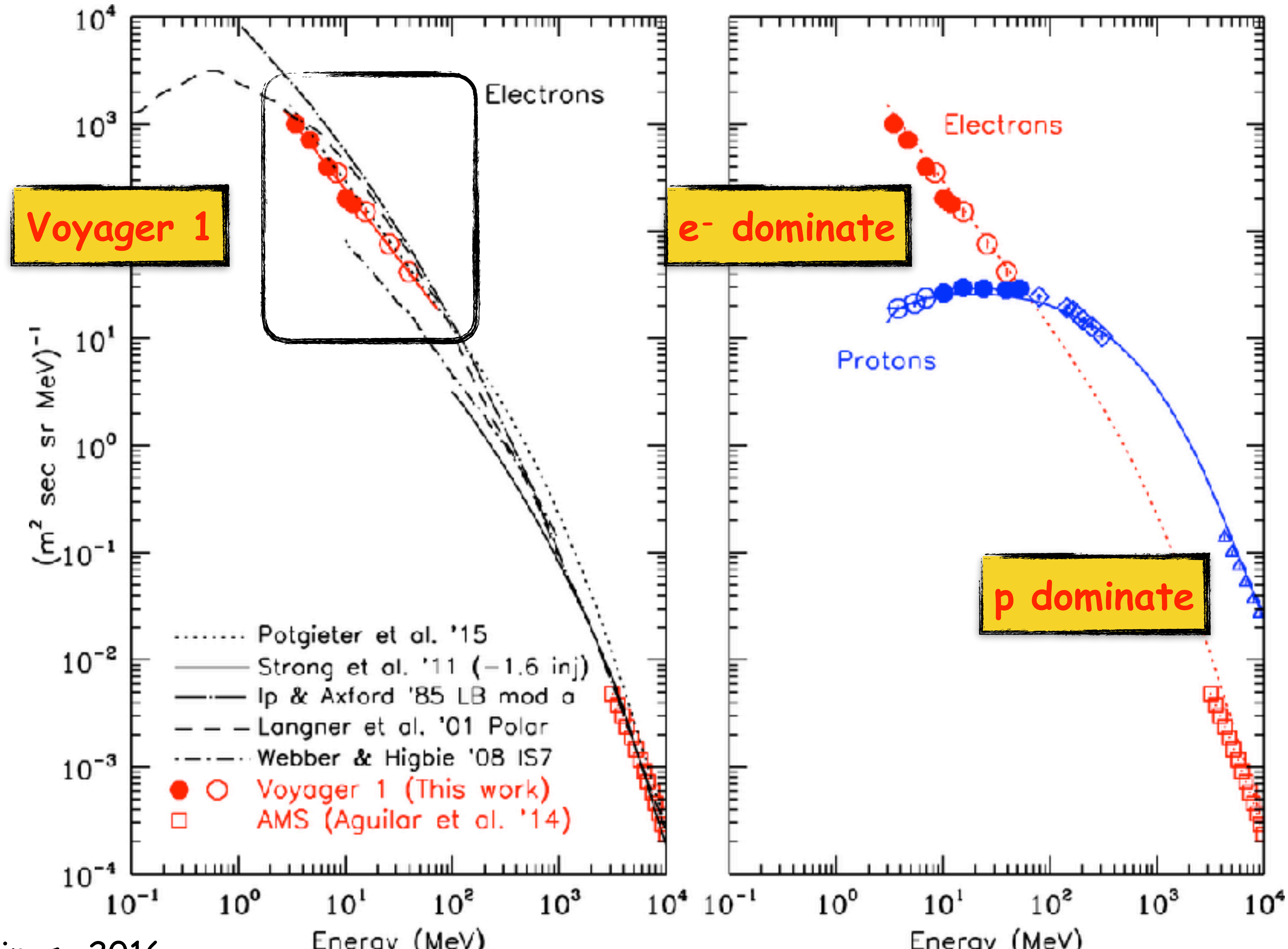
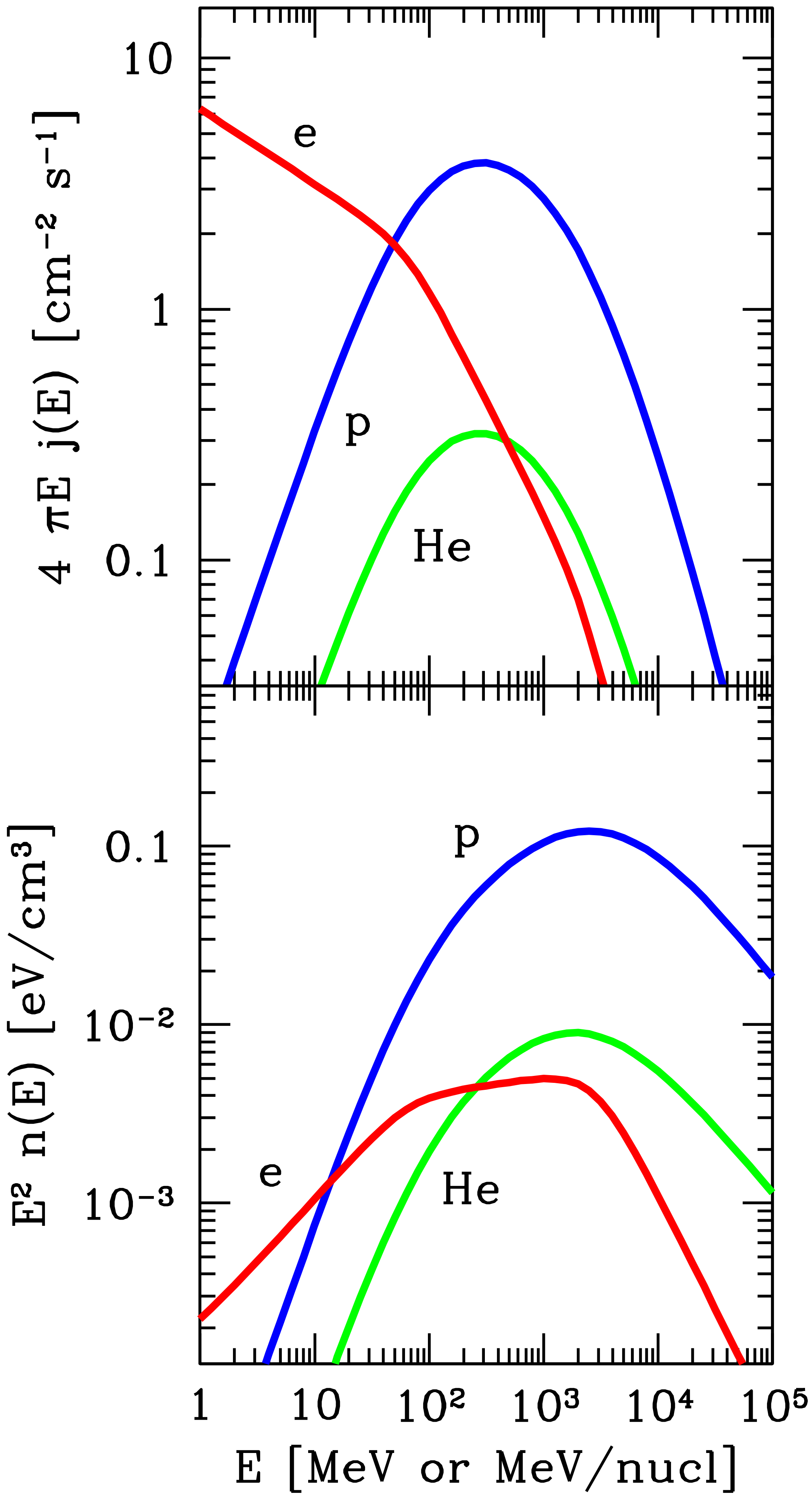
Electron spectrum in the local ISM



Cummings+ 2016

flux of particles

spectral energy distribution

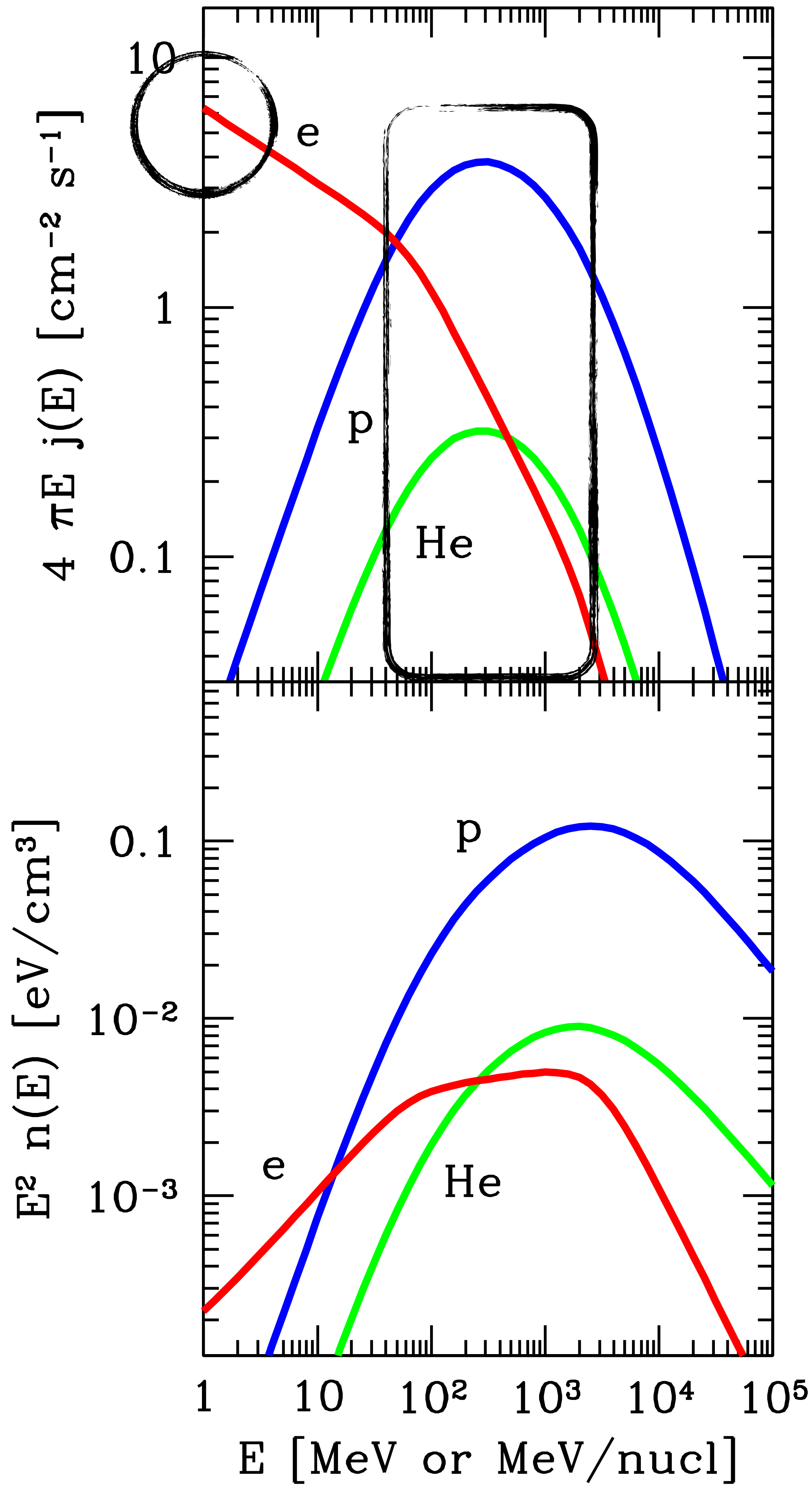


flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution



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$\approx 10^{-9} - 10^{-10}\ \mathrm{cm}^{-3}$

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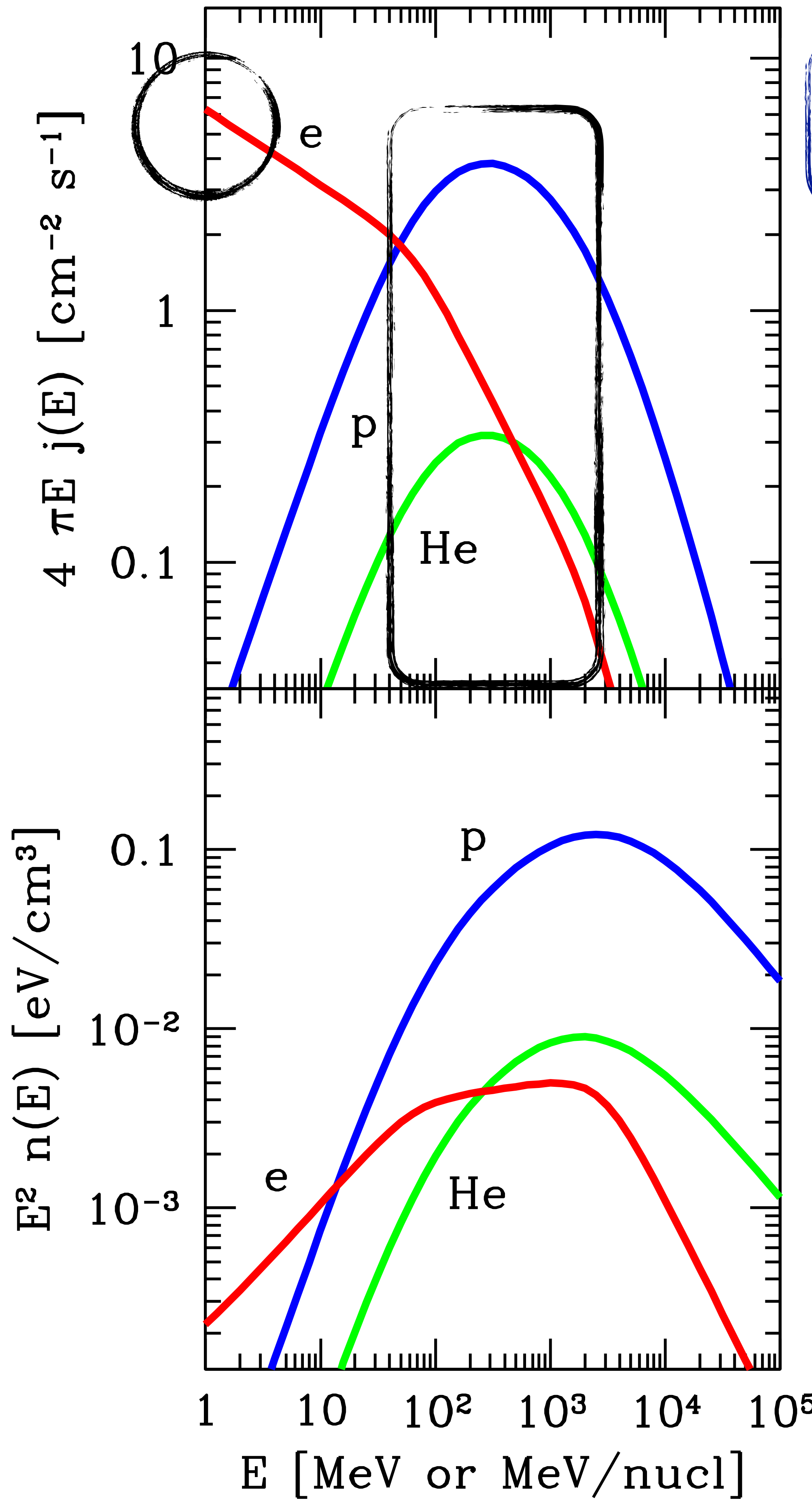

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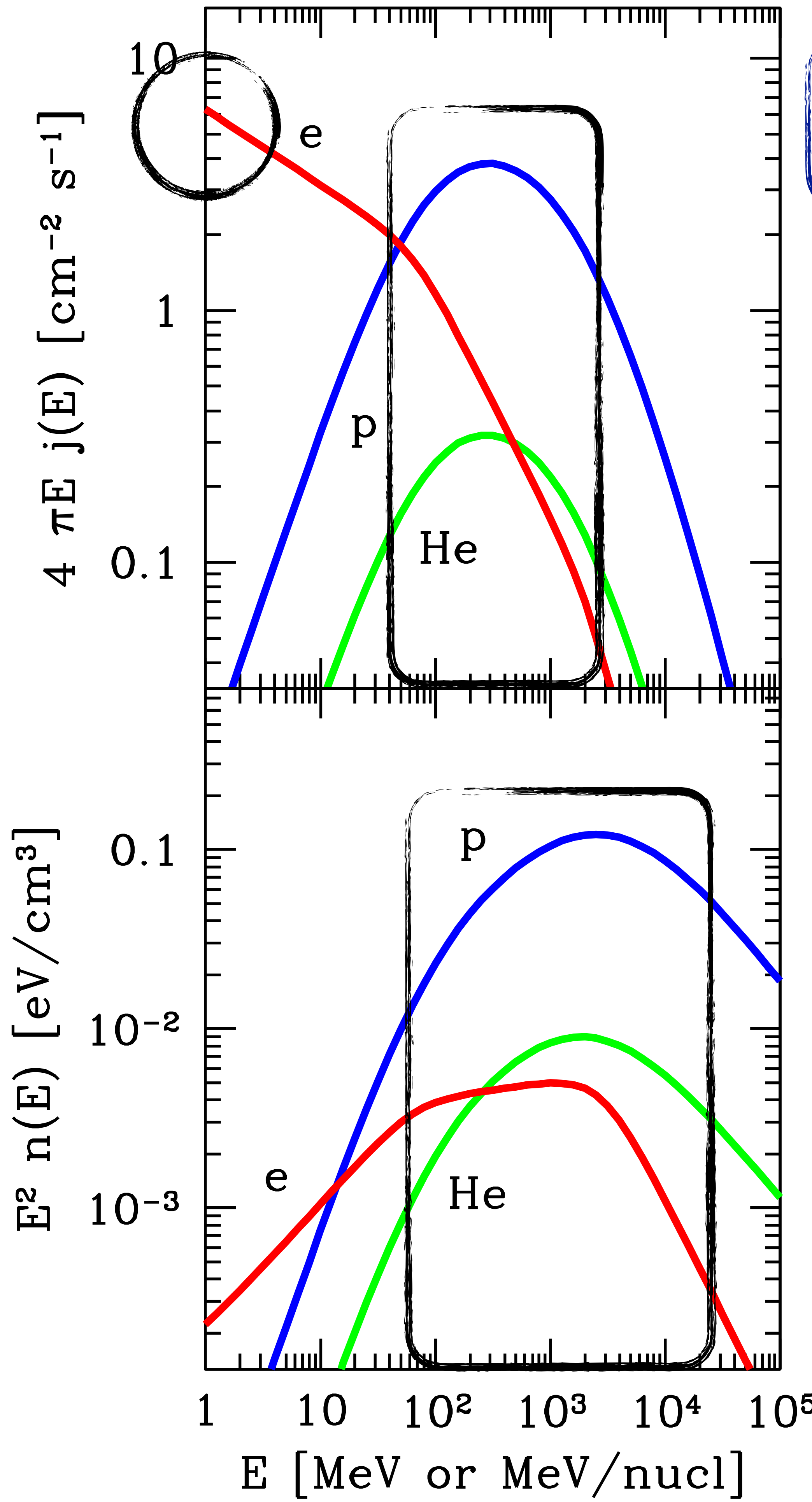

spectral energy distribution

energy is carried mainly by particles of energy 100 MeV-10 GeV

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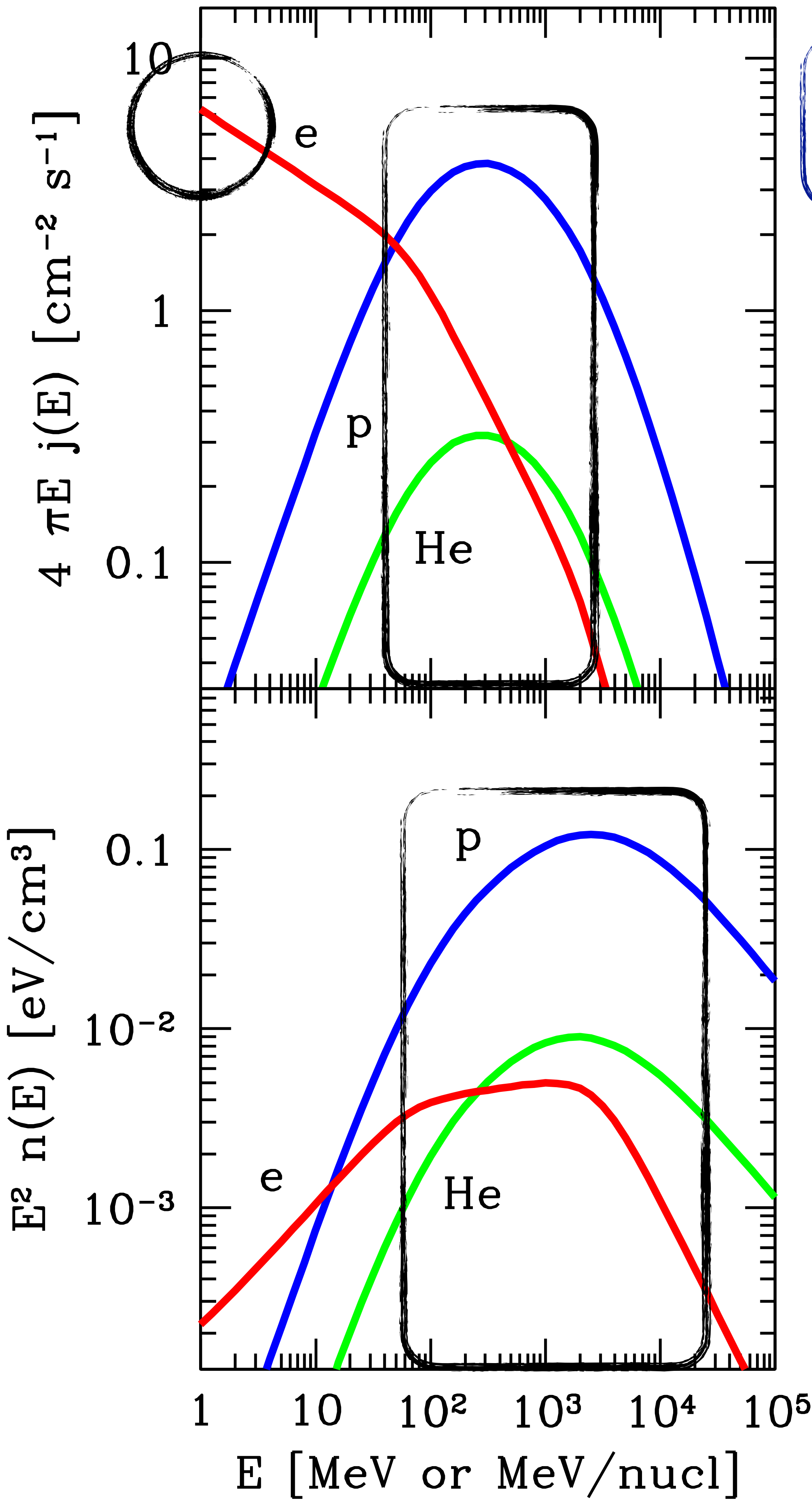

$\approx 10^{-9} - 10^{-10}\ cm^{-3}$

spectral energy distribution

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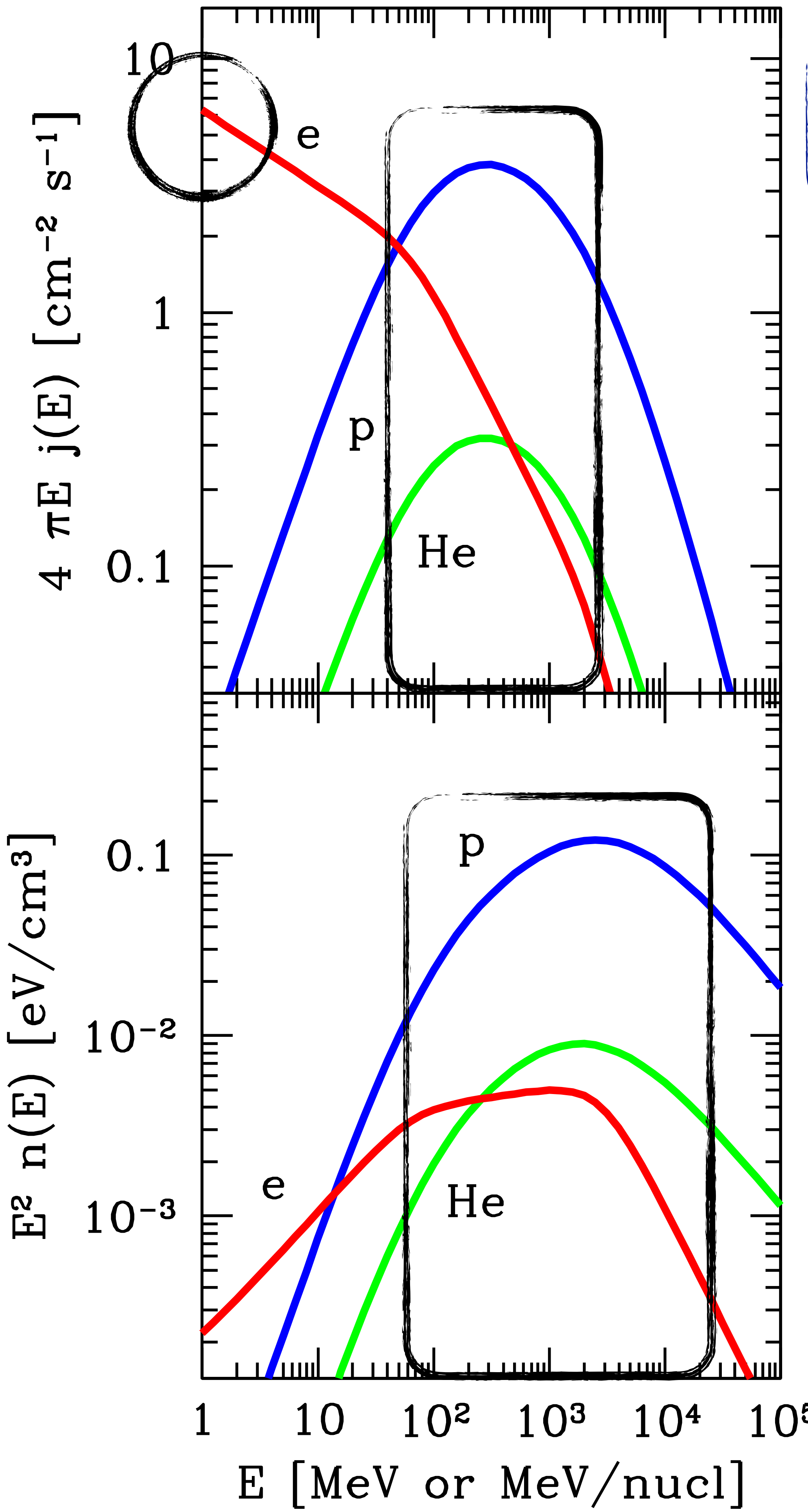

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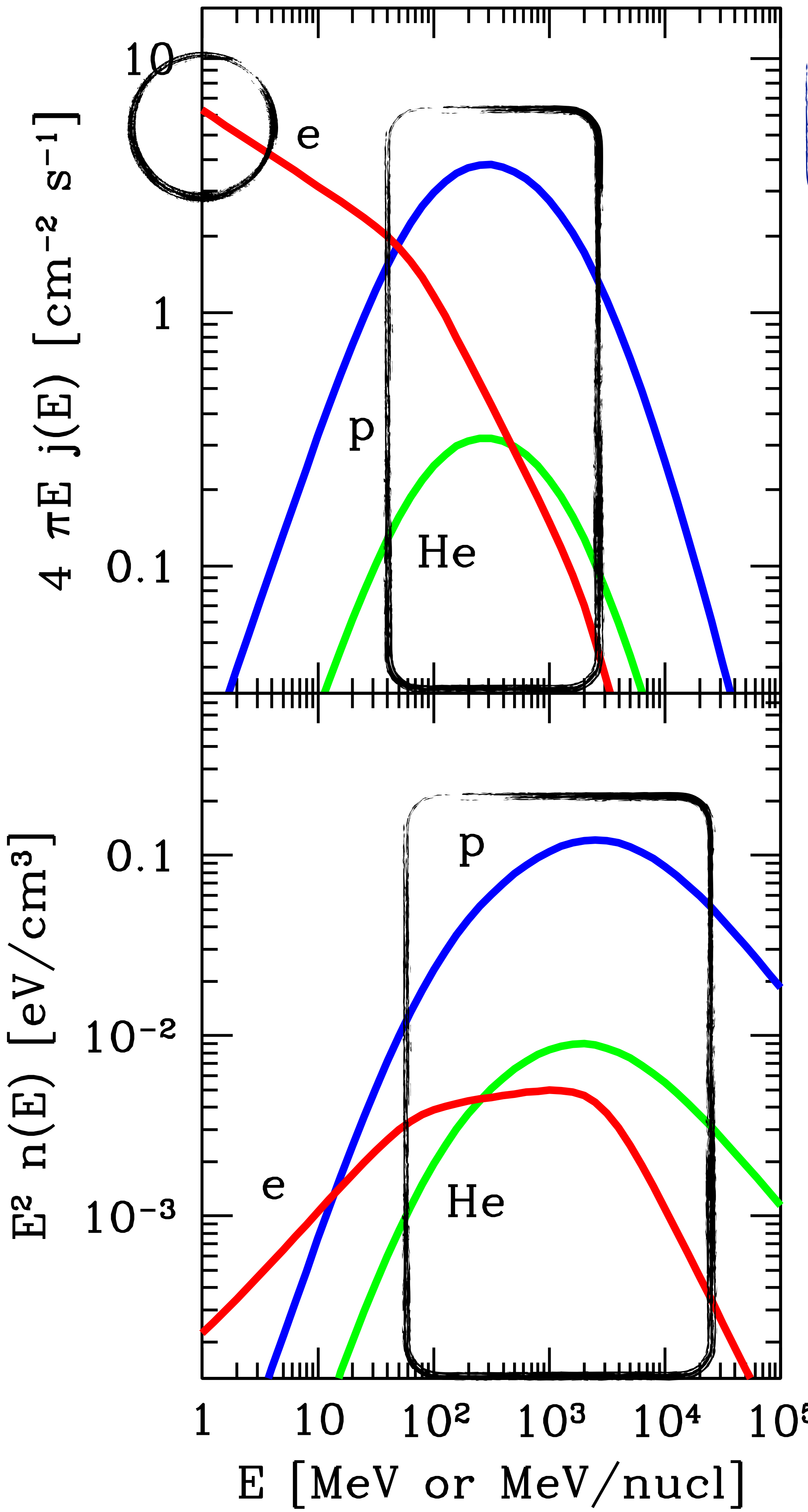

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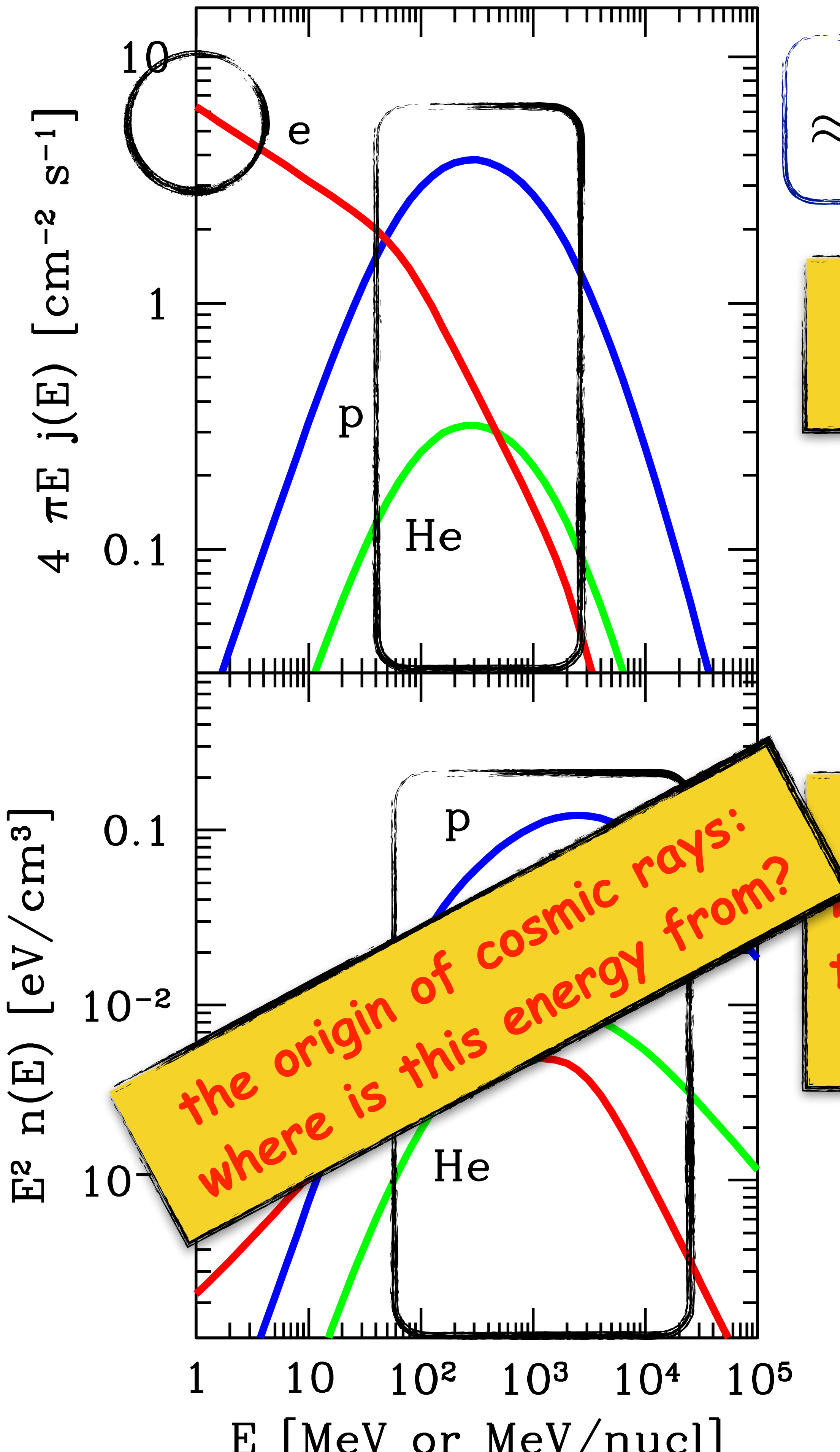

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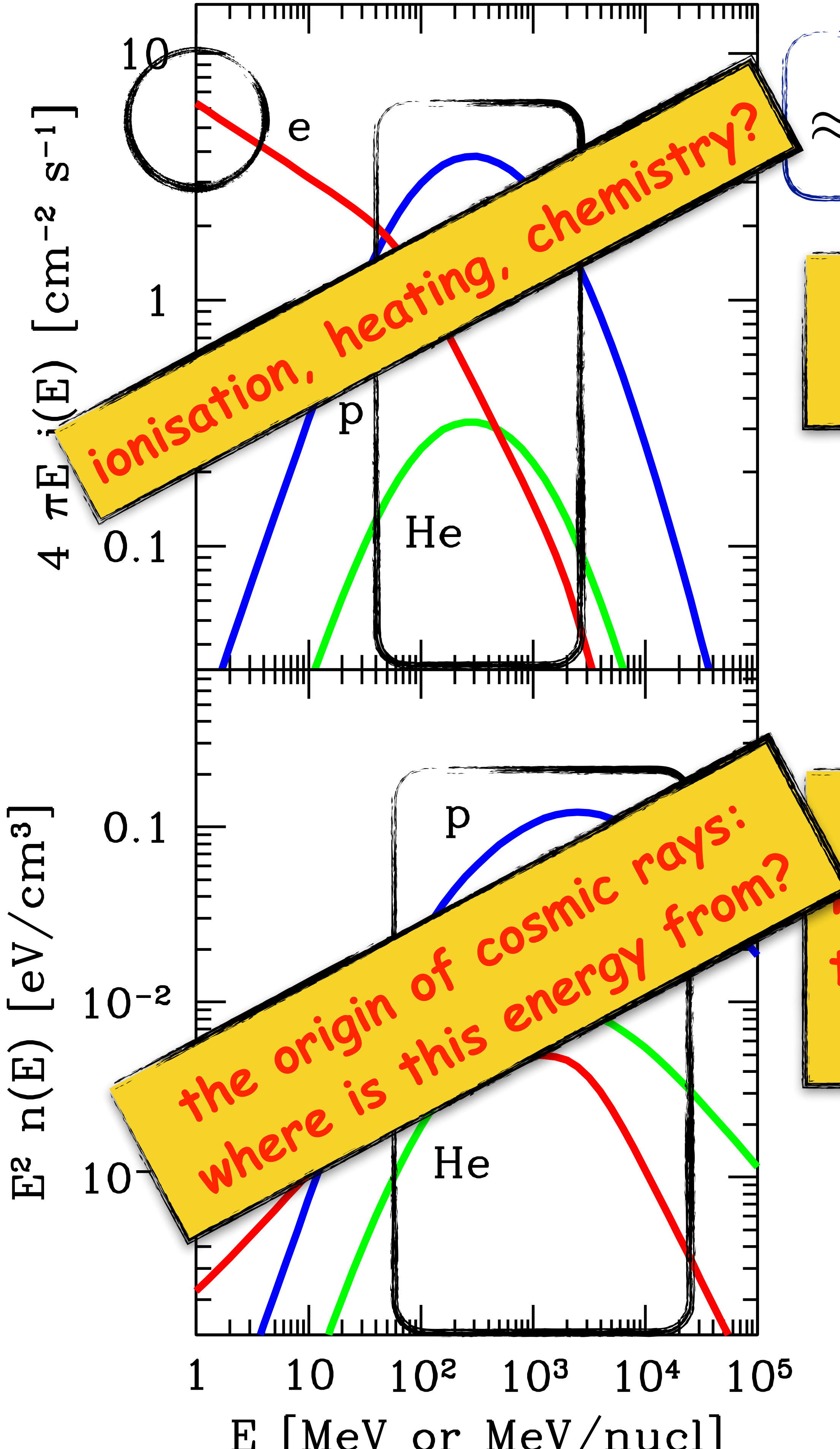

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Far away cosmic rays

Predicted by Hayakawa in 1952 …….. the gamma-ray sky seen by Fermi/LAT now

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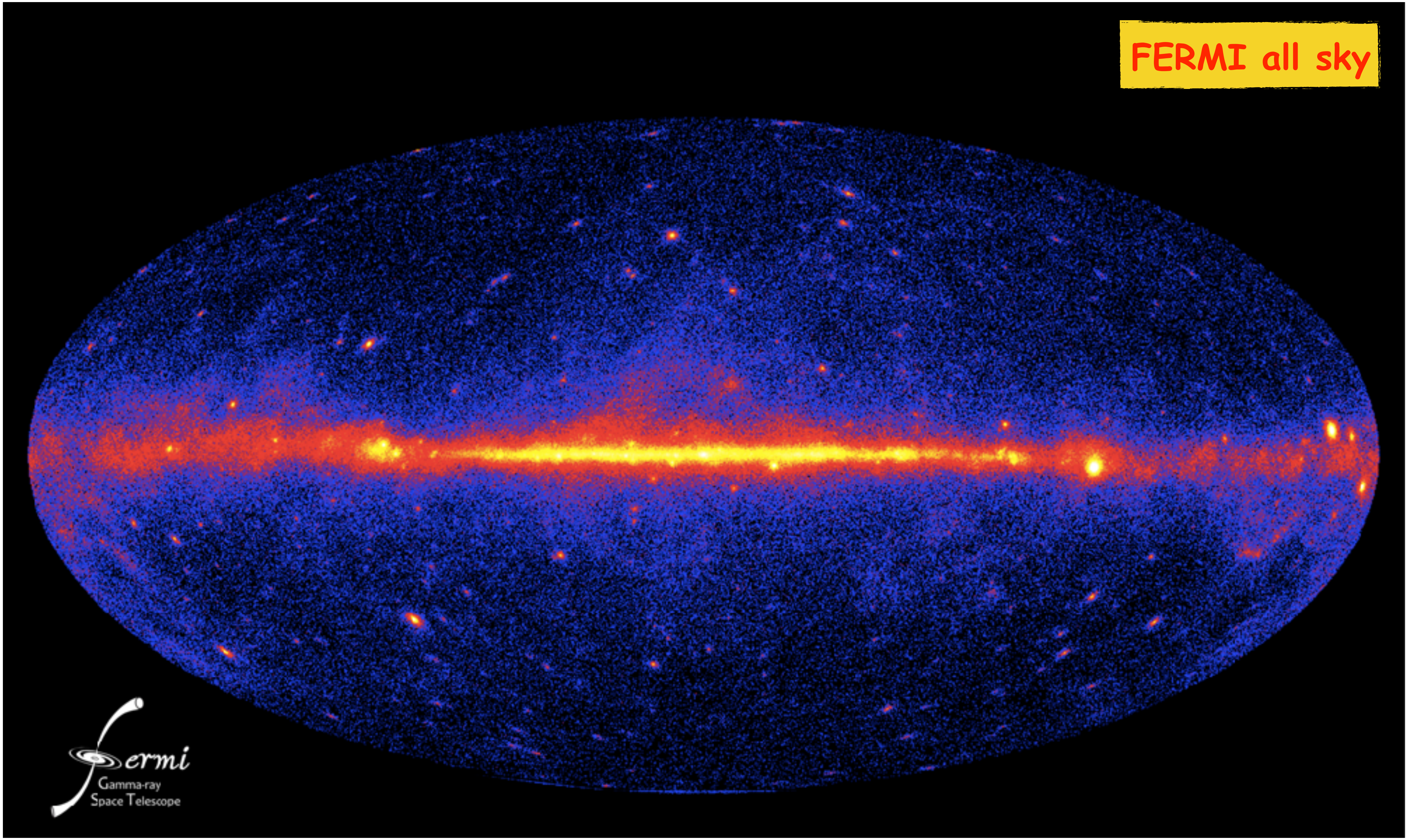

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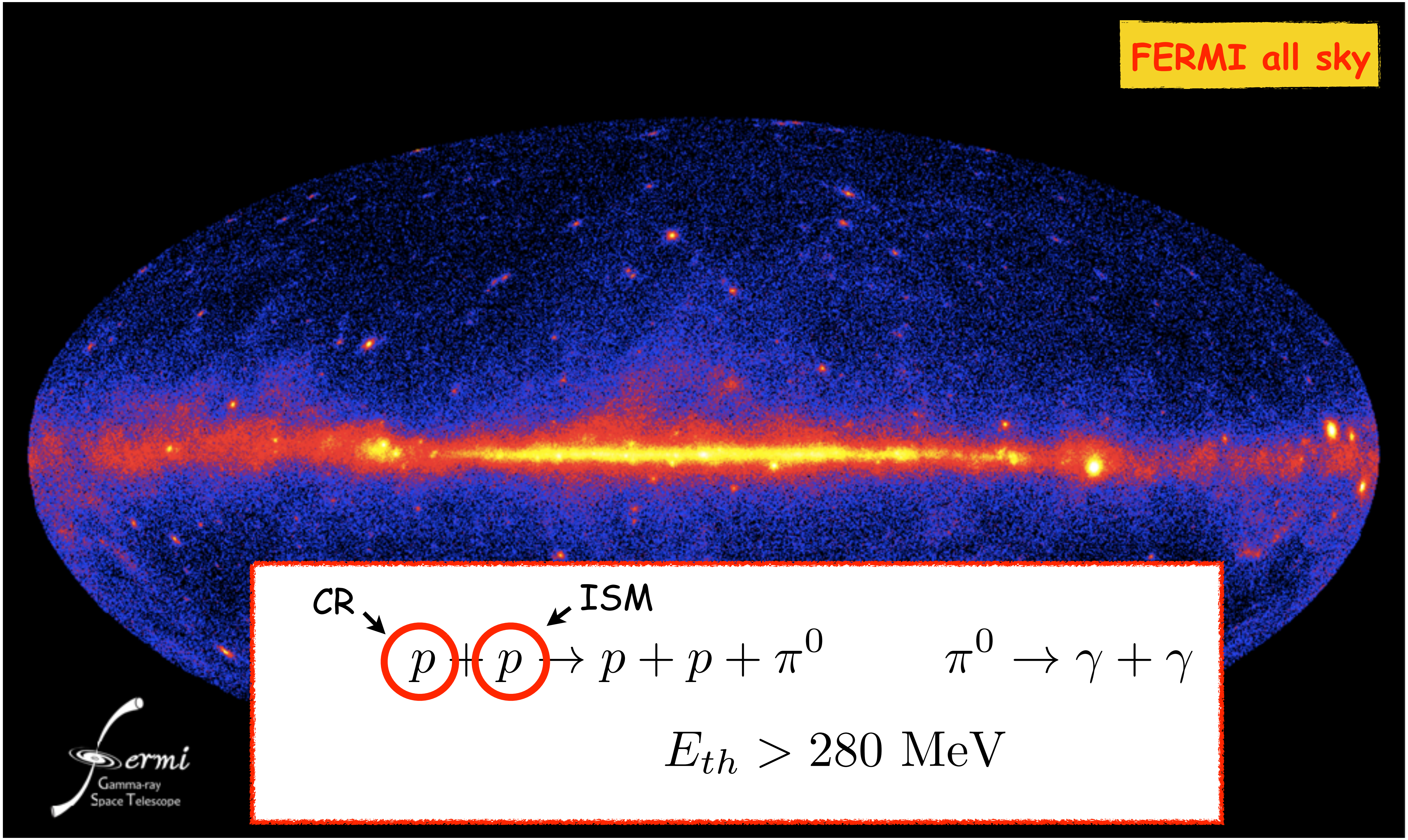

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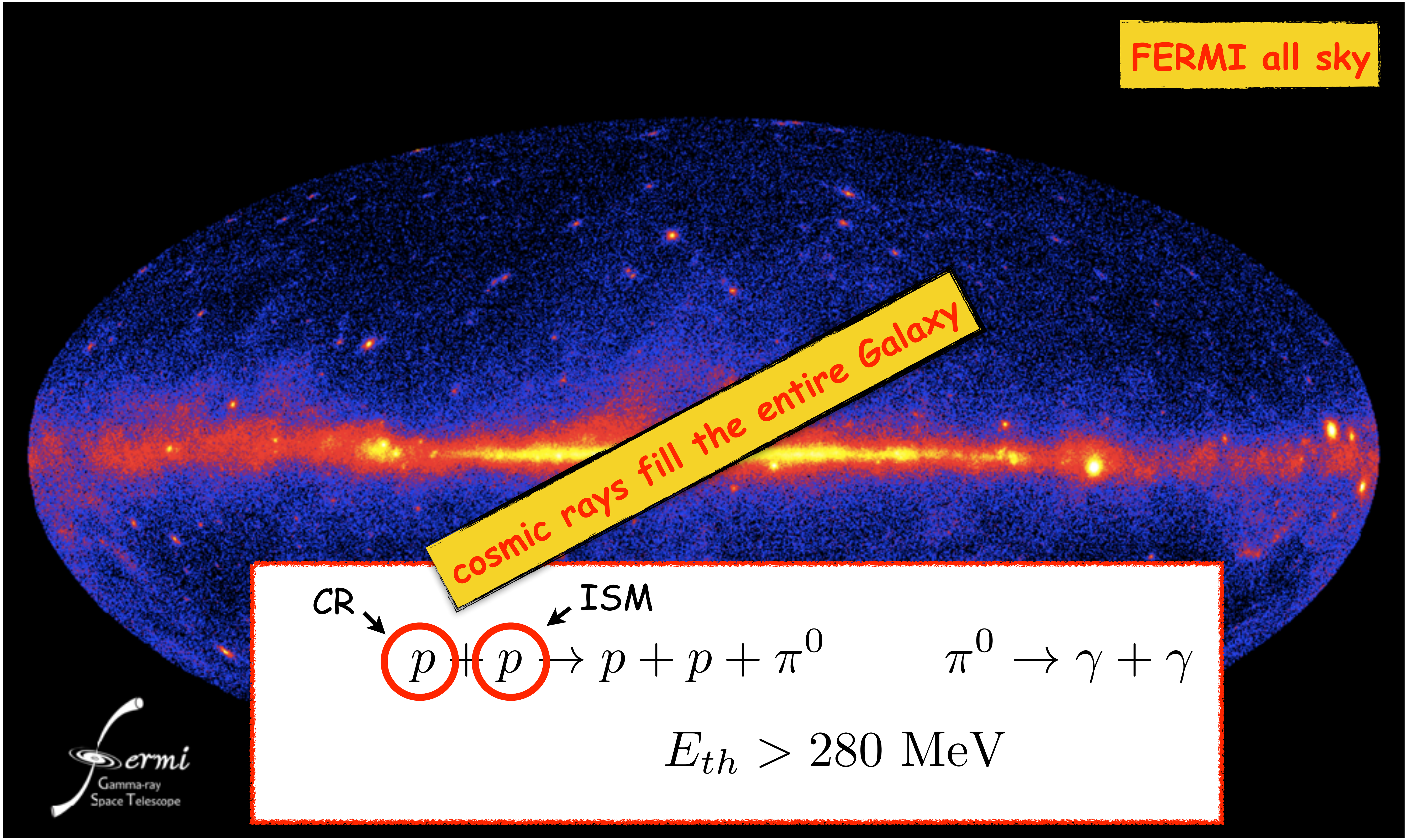

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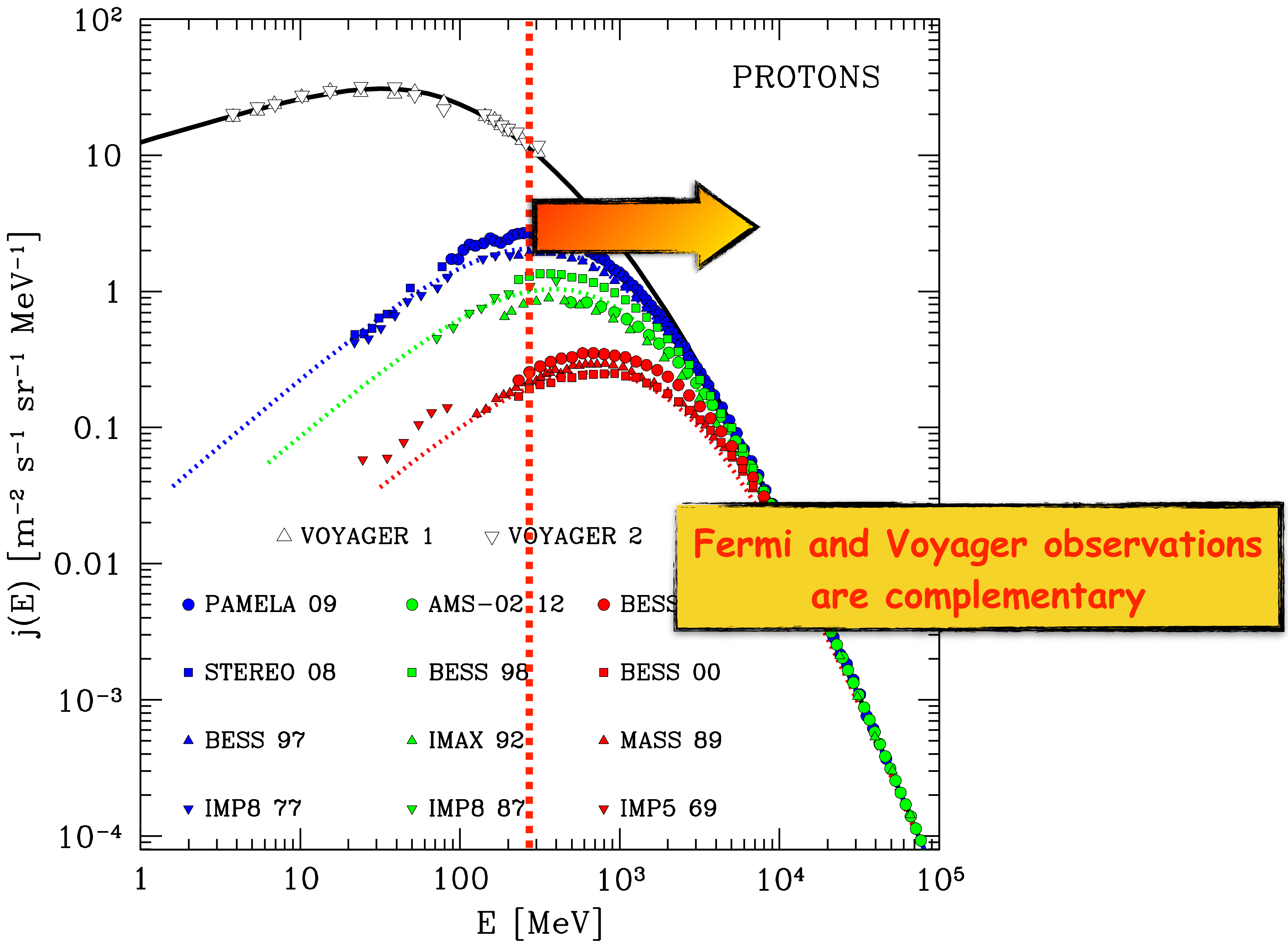
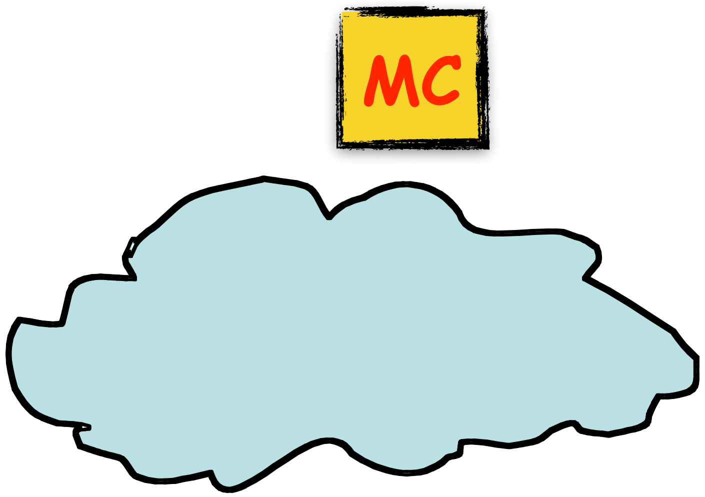
Gamma-rays from distant cosmic rays



How well we know the spatial distribution of cosmic rays throughout the Galactic disk?

Molecular clouds as cosmic ray probes



see e.g.

Black&Fazio1973

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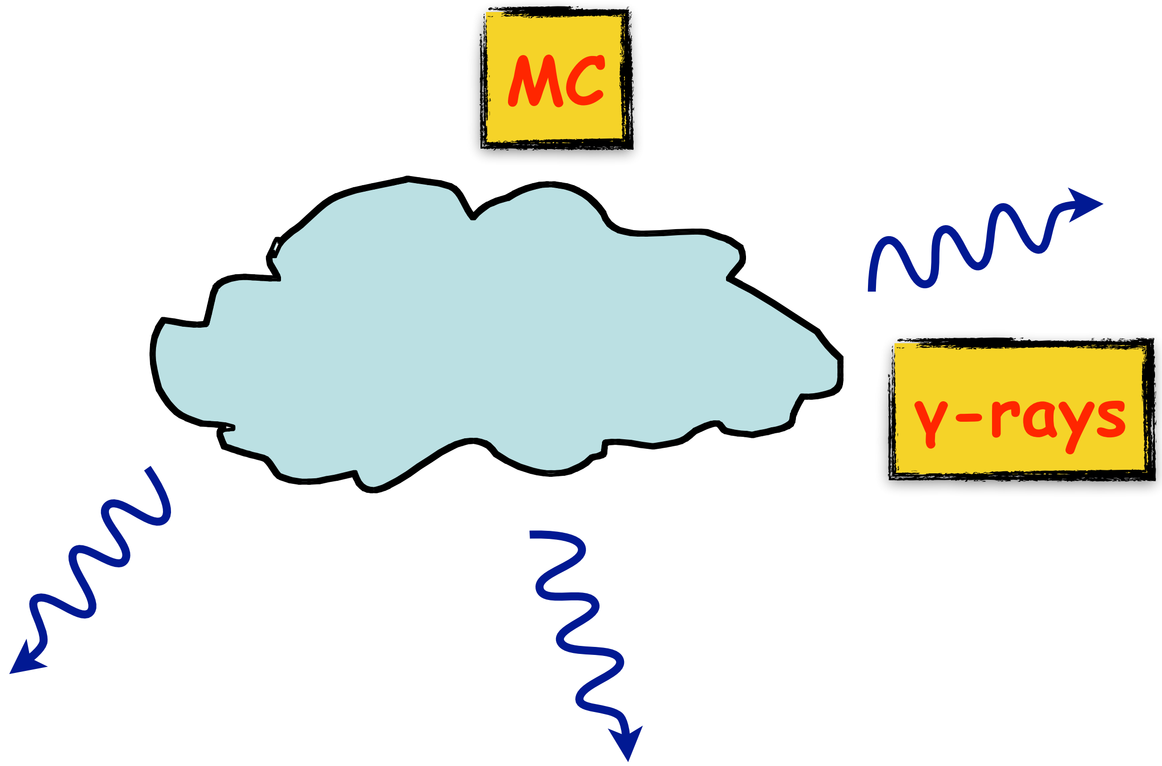

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a MC immersed in the CR sea emits γ-rays

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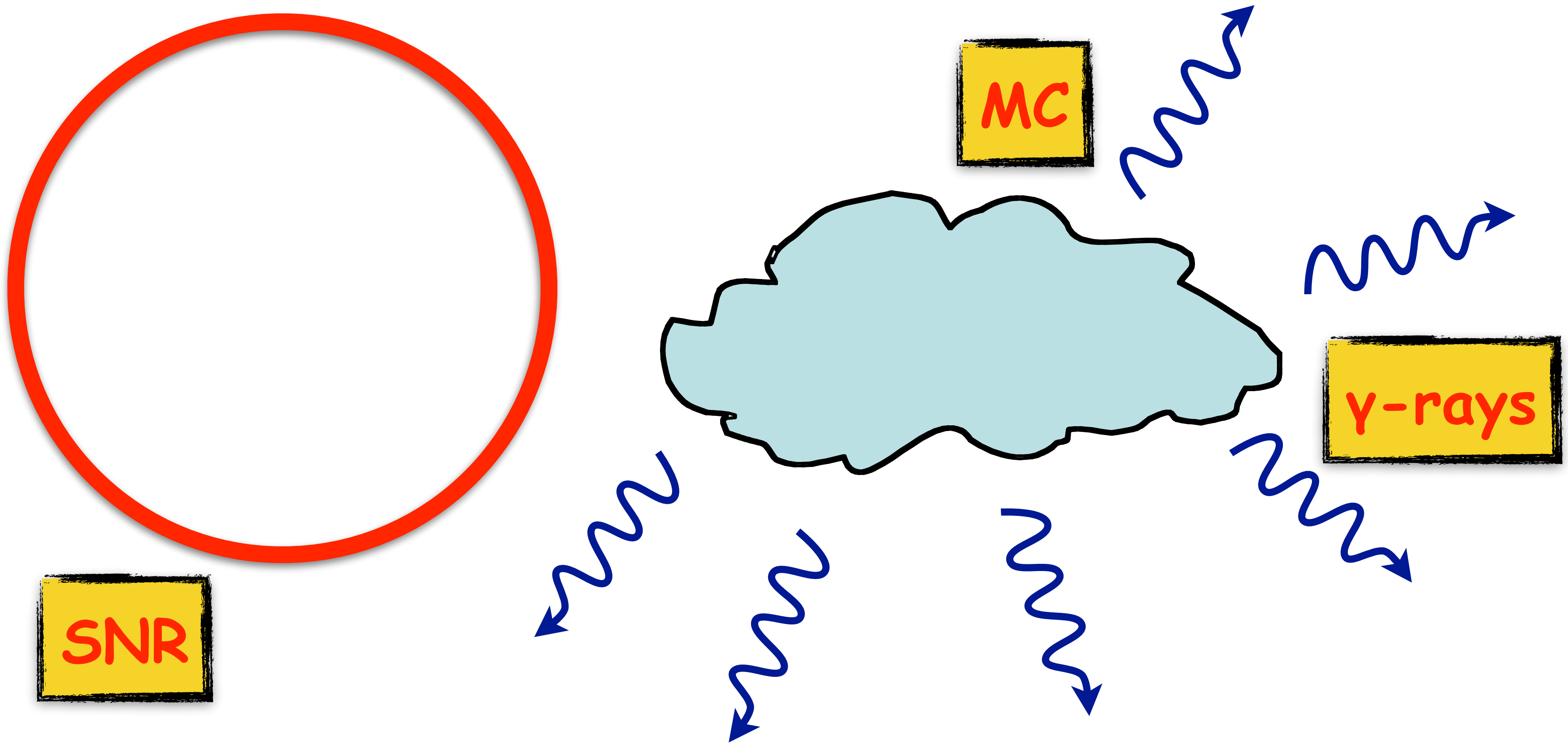

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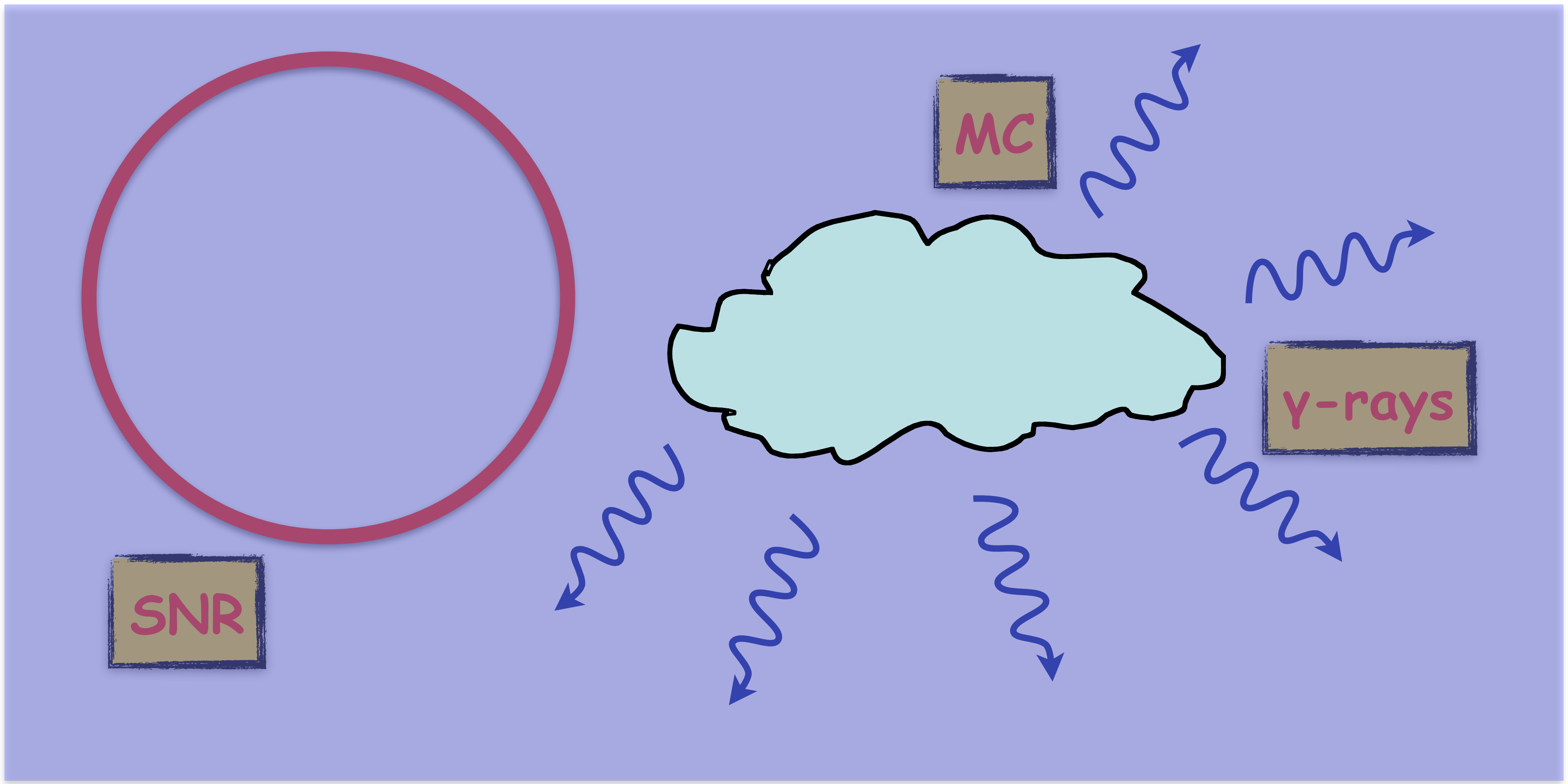
Aharonian&Atoyan1996

if a CR source is present, the MC emits more γ-rays

Molecular clouds as cosmic ray probes



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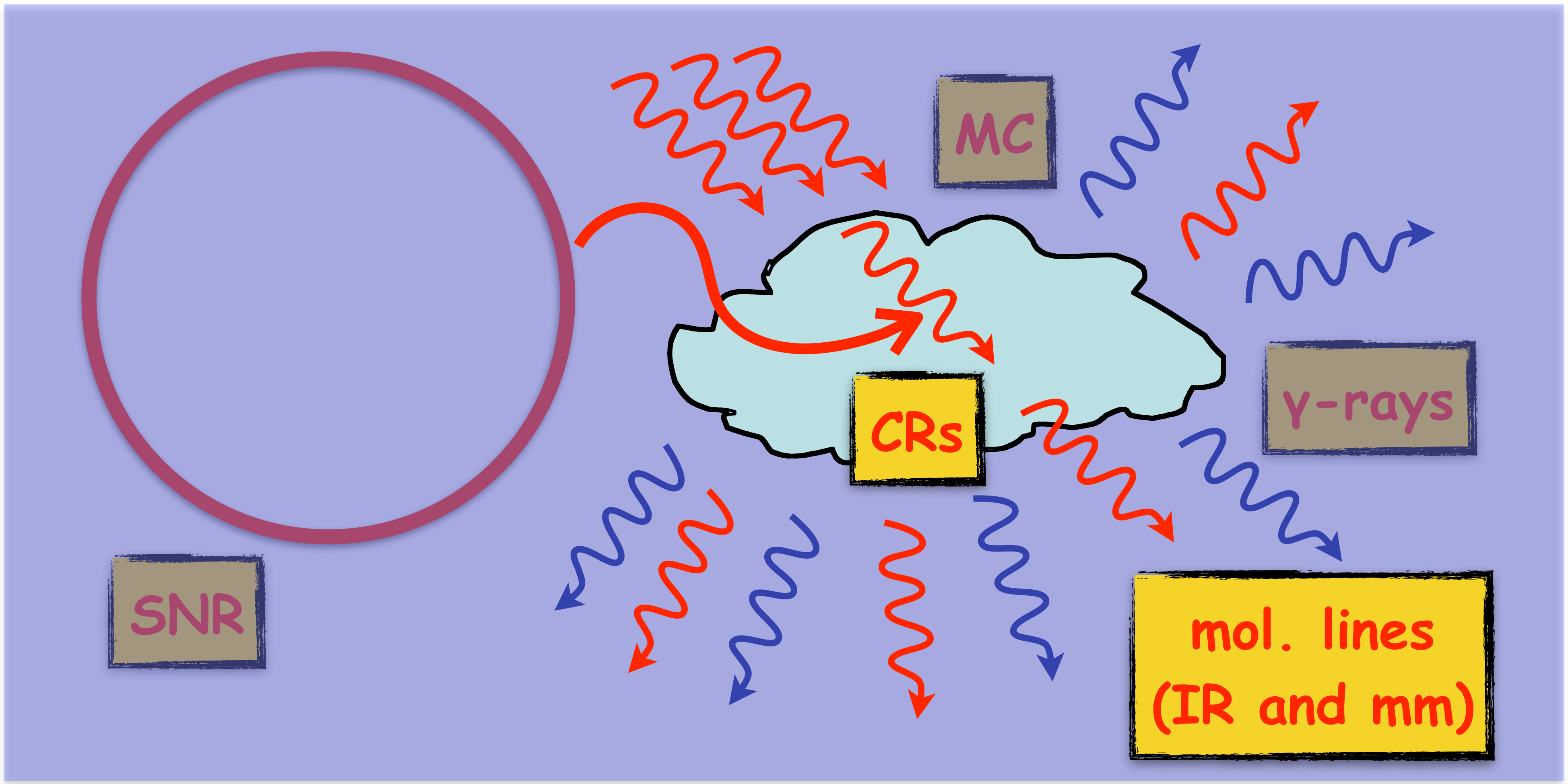
McKee 1989

ionizing UV photons do not penetrate molecular clouds

Molecular clouds as cosmic ray probes



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only cosmic rays can penetrate and drive the chemistry in the cloud

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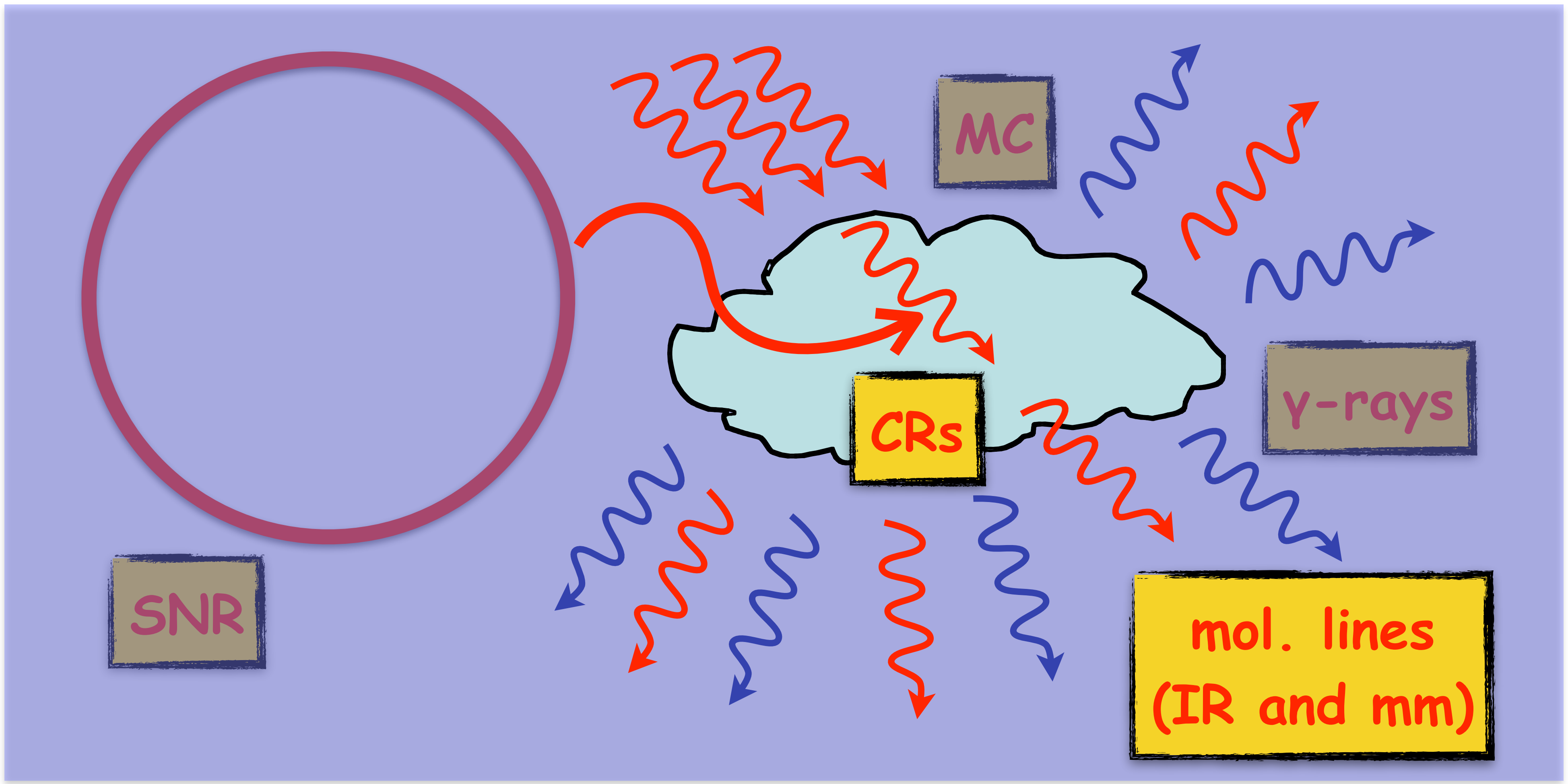

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Molecular clouds

-> amplify the γ-ray emission from CR interactions

-> filter all ionizing agents but (MeV) CRs

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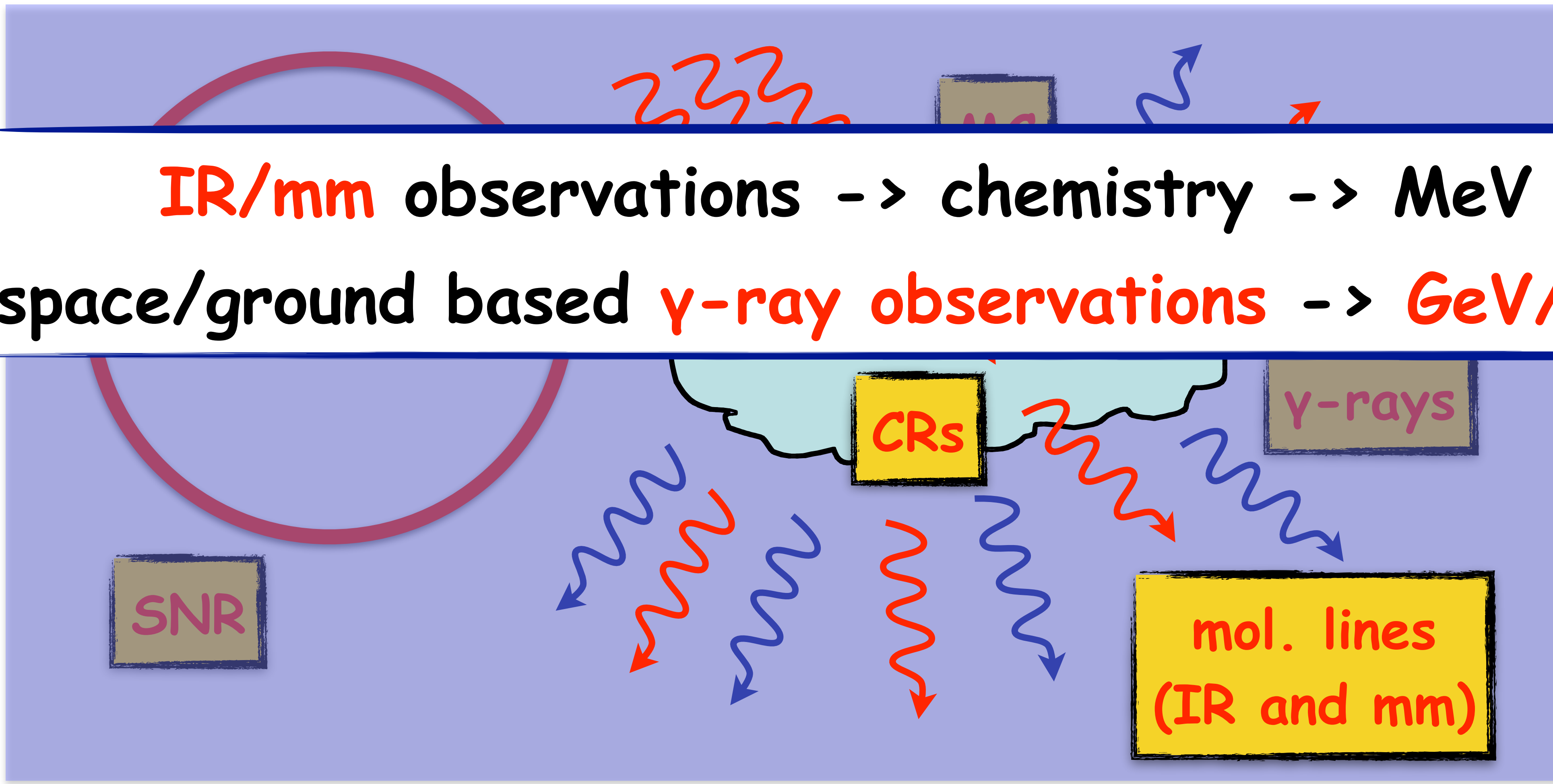

McKee 1989

Herbst&Klemperer1973

IR/mm observations -> chemistry -> MeV CR spectrum

space/ground based γ-ray observations -> GeV/TeV CR spectrum

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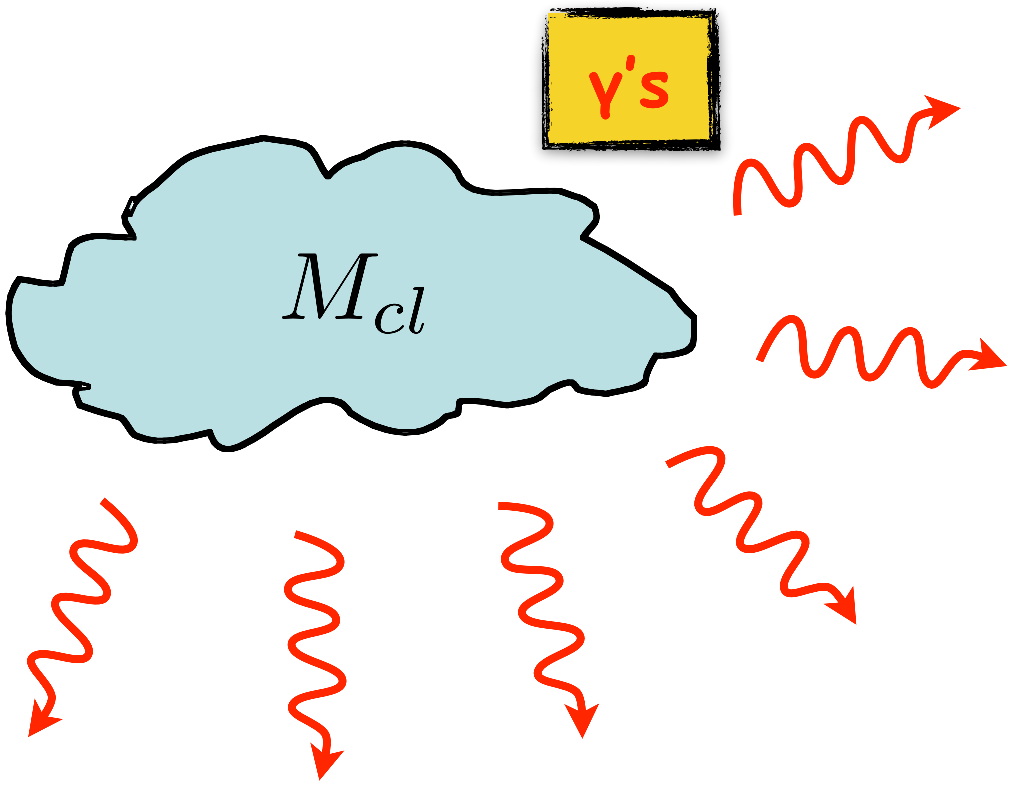
Gamma rays from molecular clouds



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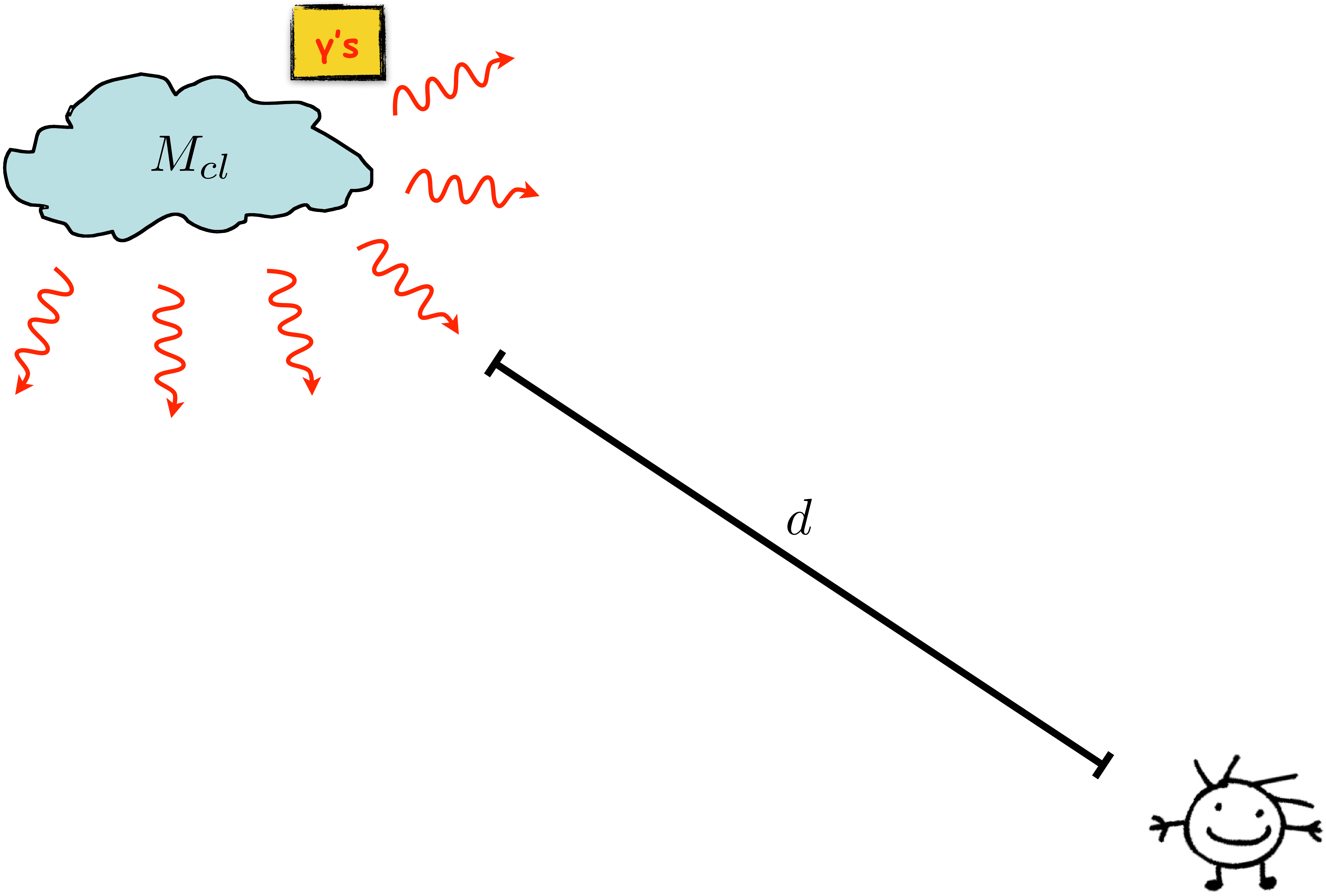

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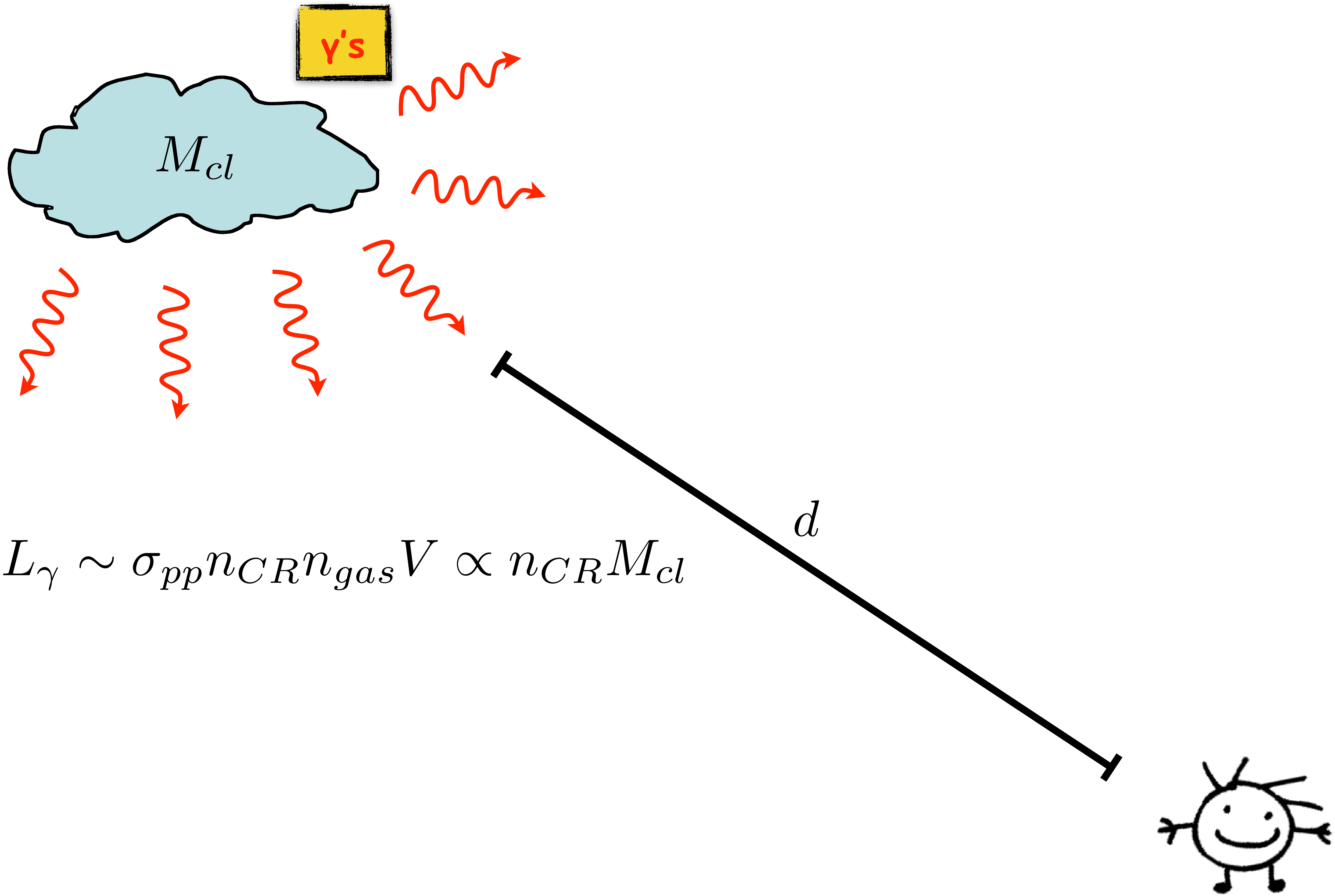
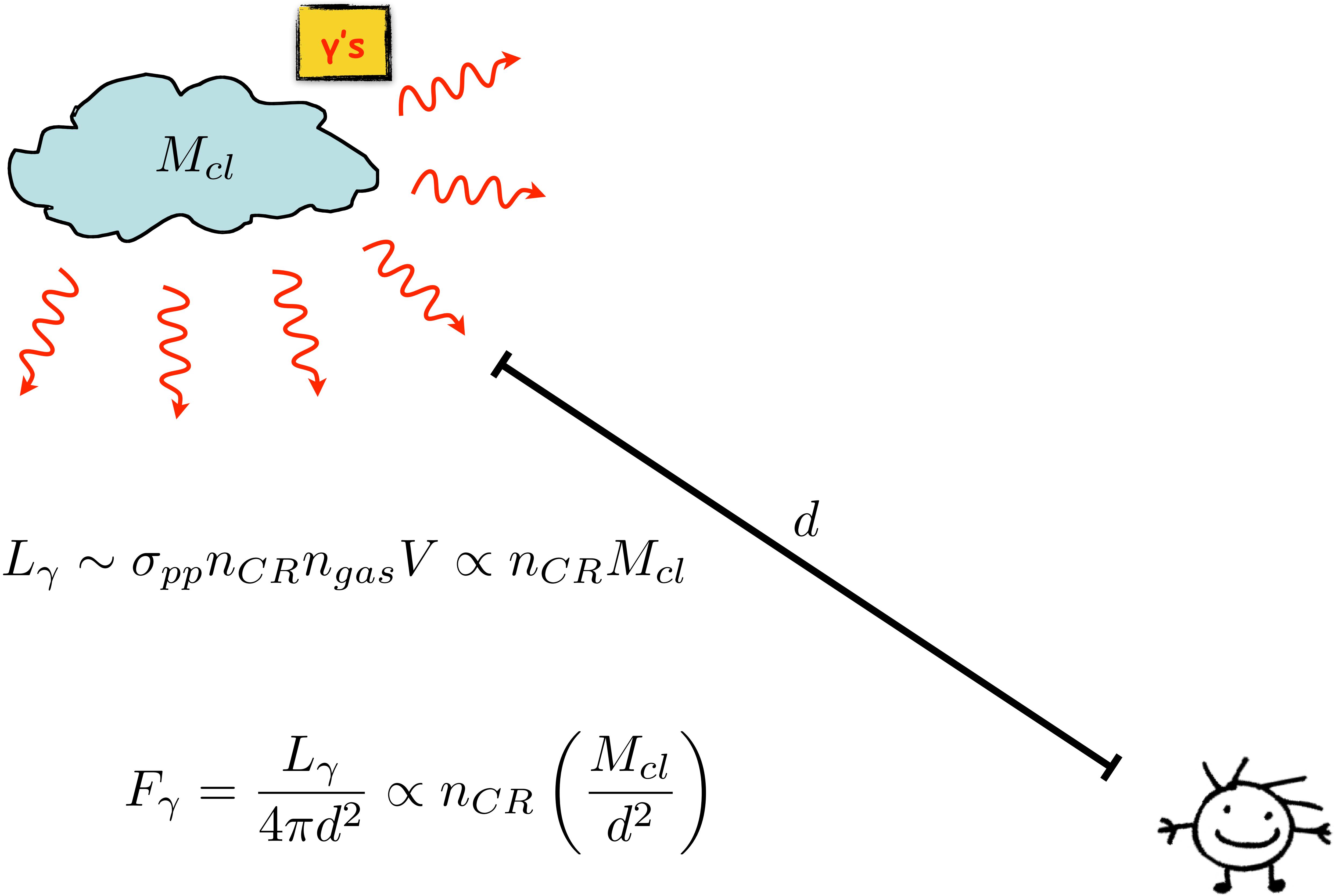


$$L_\gamma \sim \sigma_{pp} n_{CR} n_{gas} V \propto n_{CR} M_{cl}$$

Gamma rays from molecular clouds



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$$F_\gamma = \frac{L_\gamma}{4\pi d^2} \propto n_{CR} \left(\frac{M_{cl}}{d^2} \right)$$

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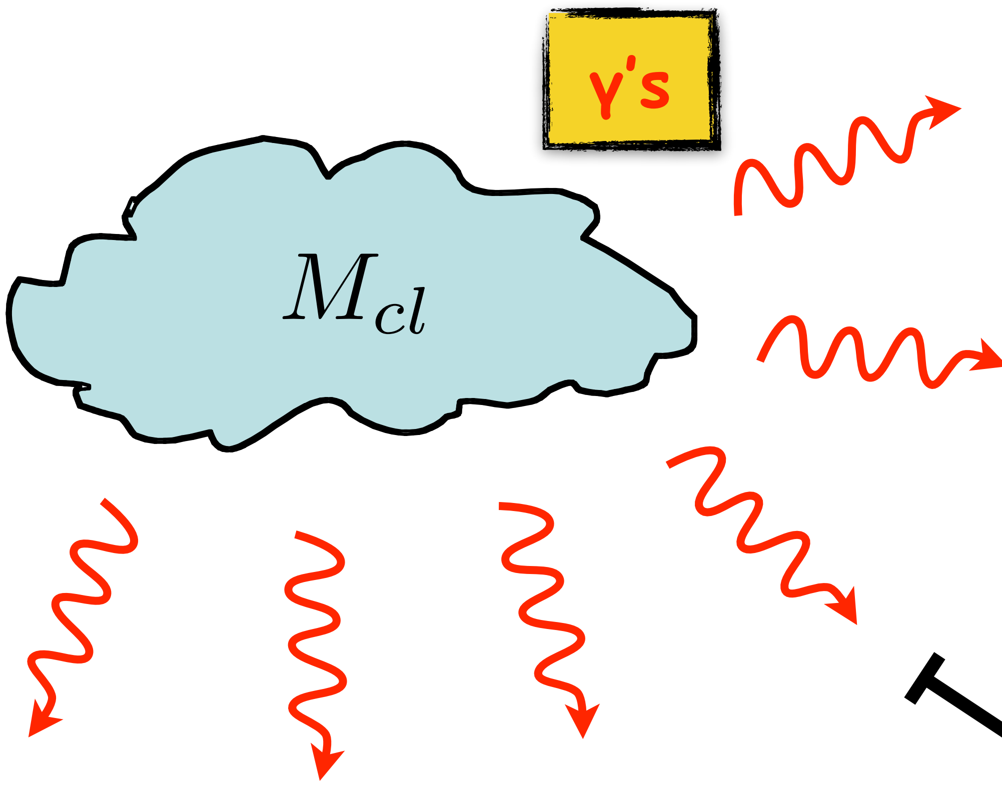

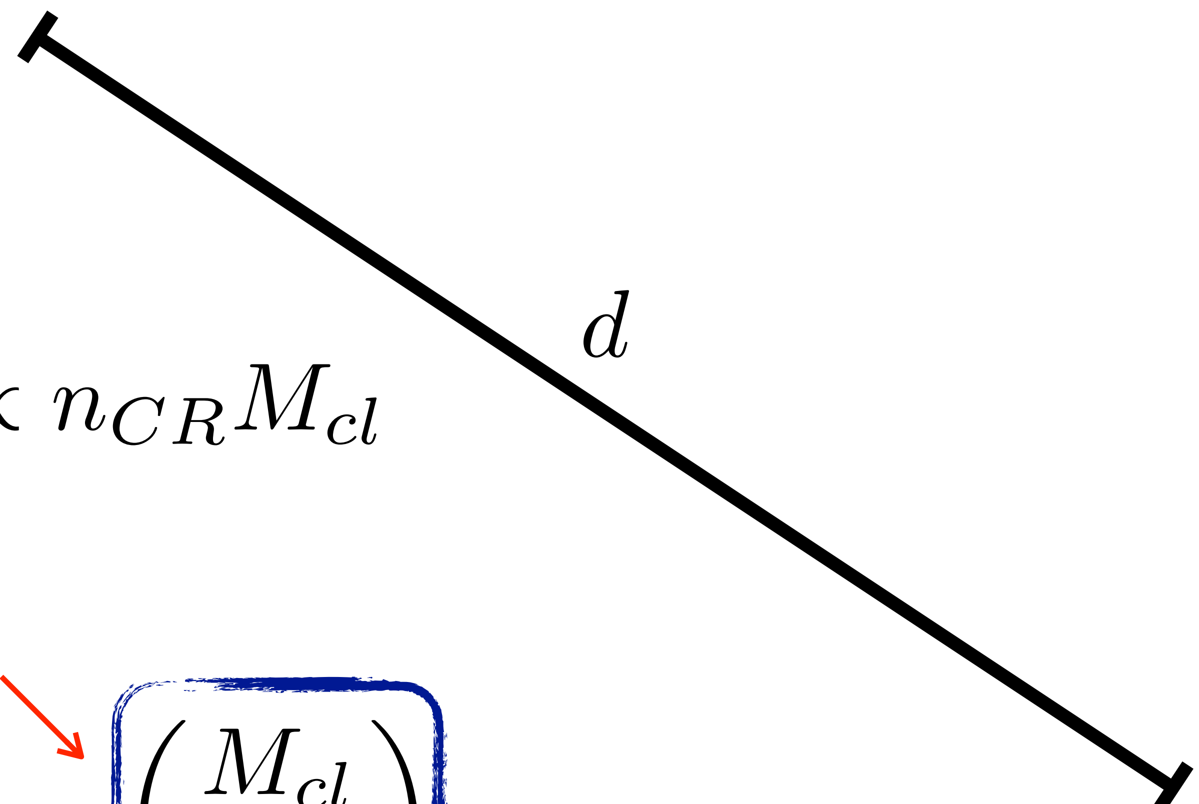

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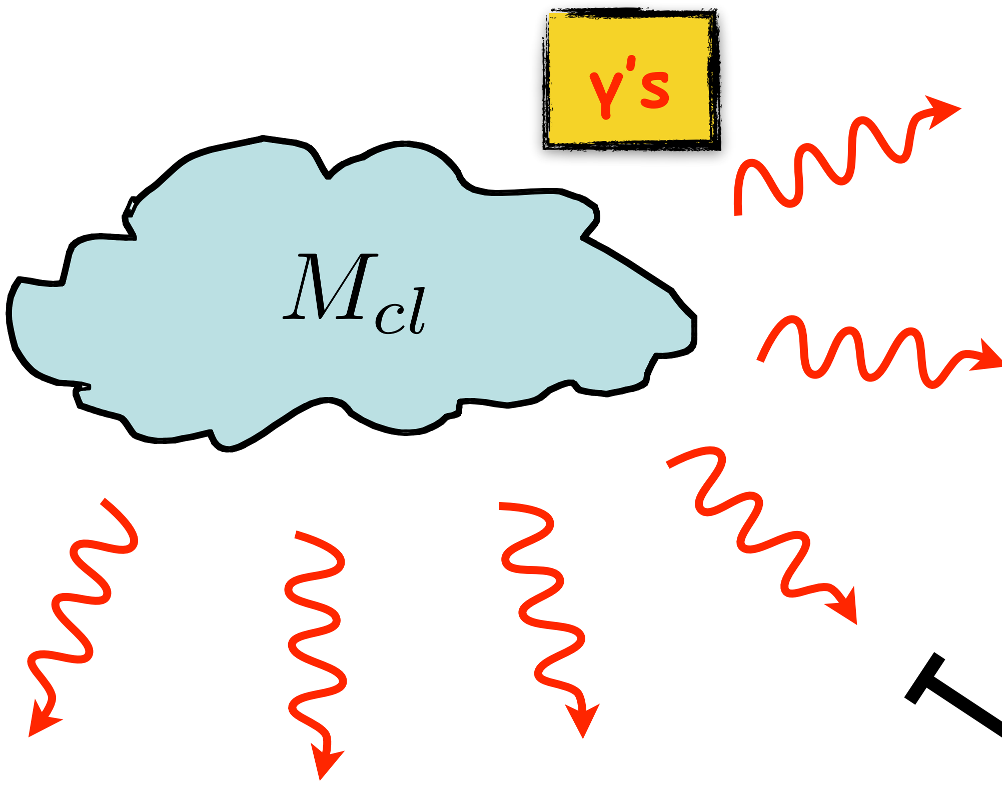
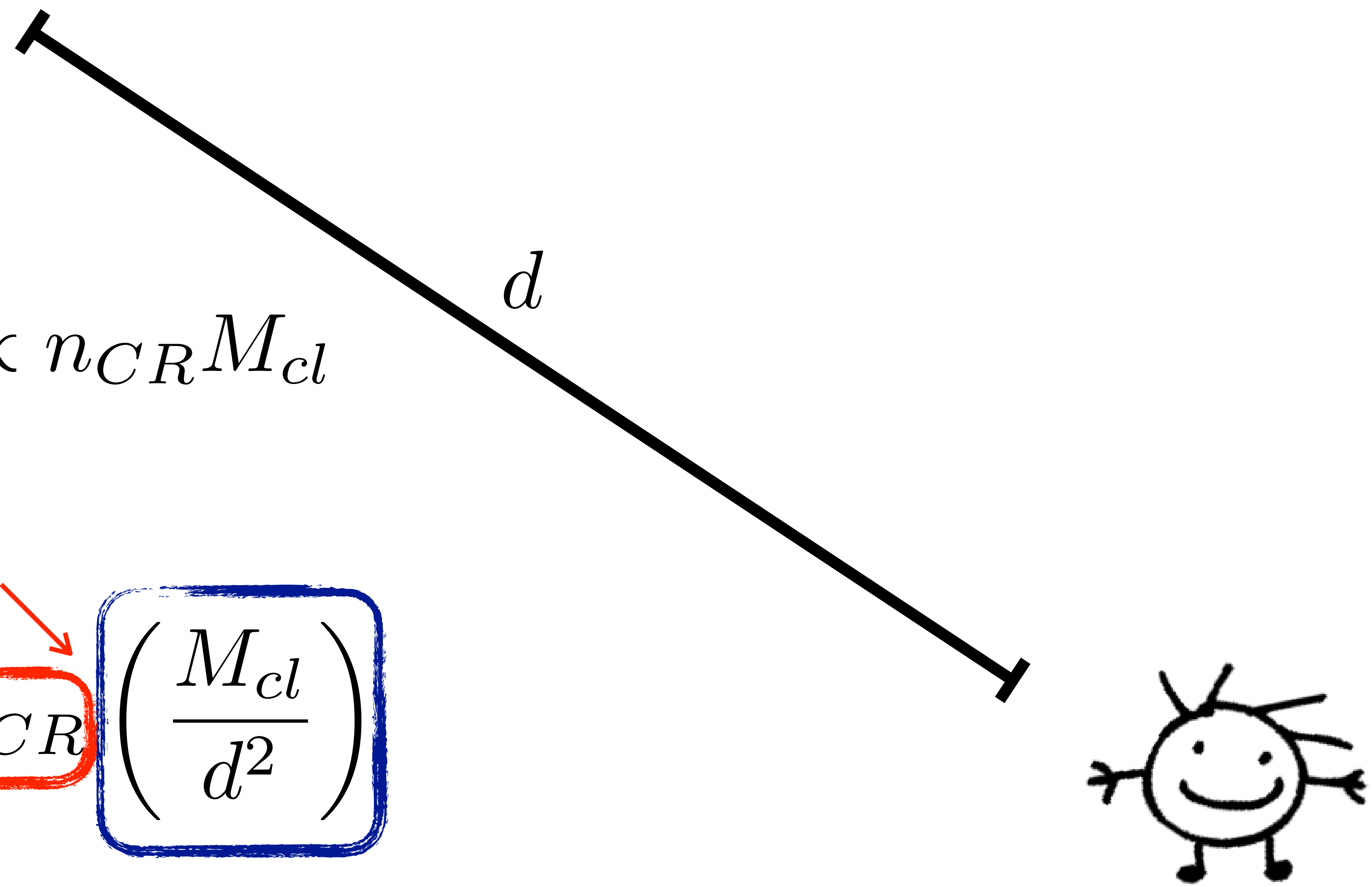
Gamma rays from molecular clouds



gamma-ray bright molecular clouds are cosmic ray barometers



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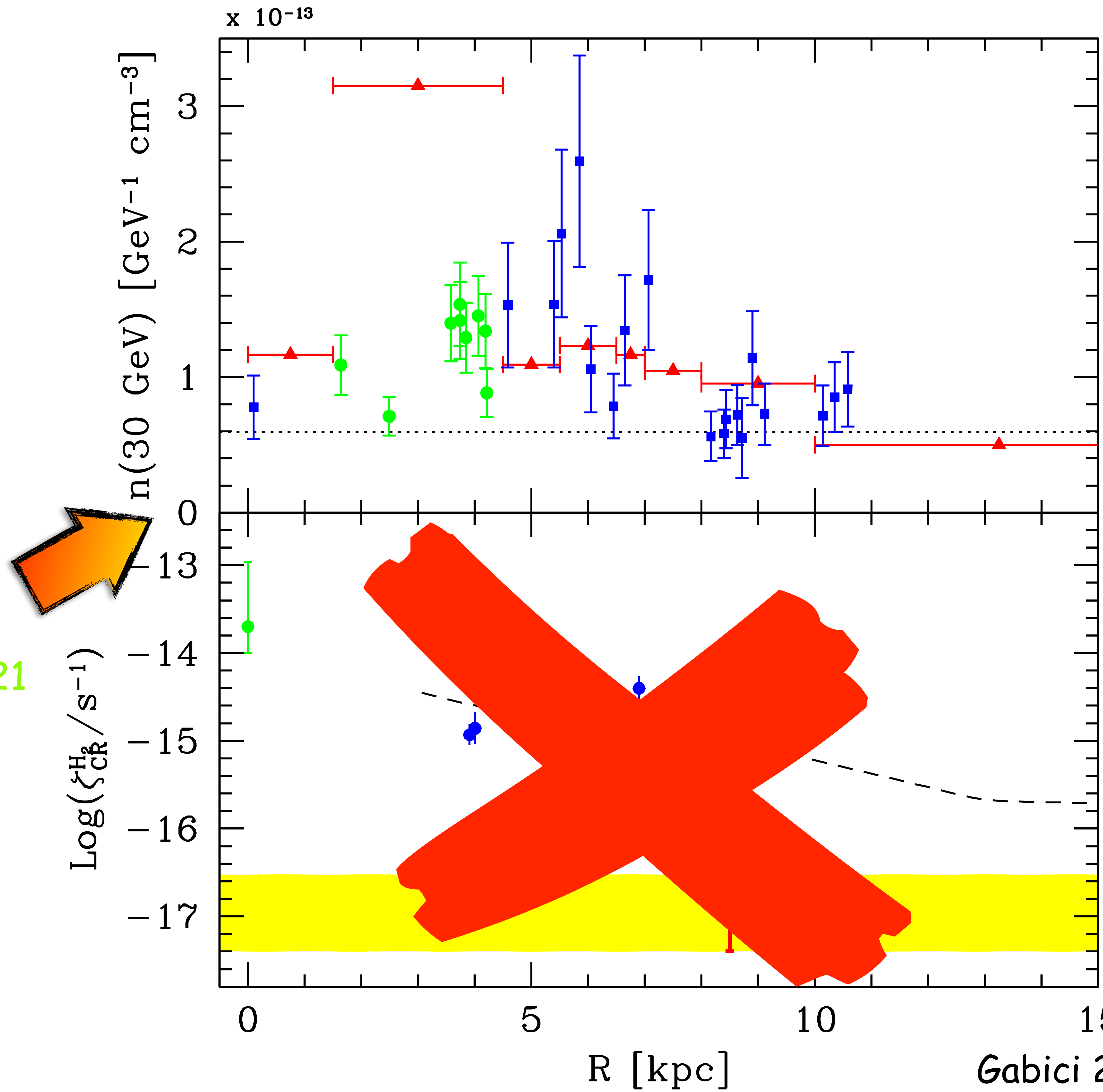
Spatial distribution of cosmic rays



data from Acero+ 16, Aharonian+ 20, Peron+ 21

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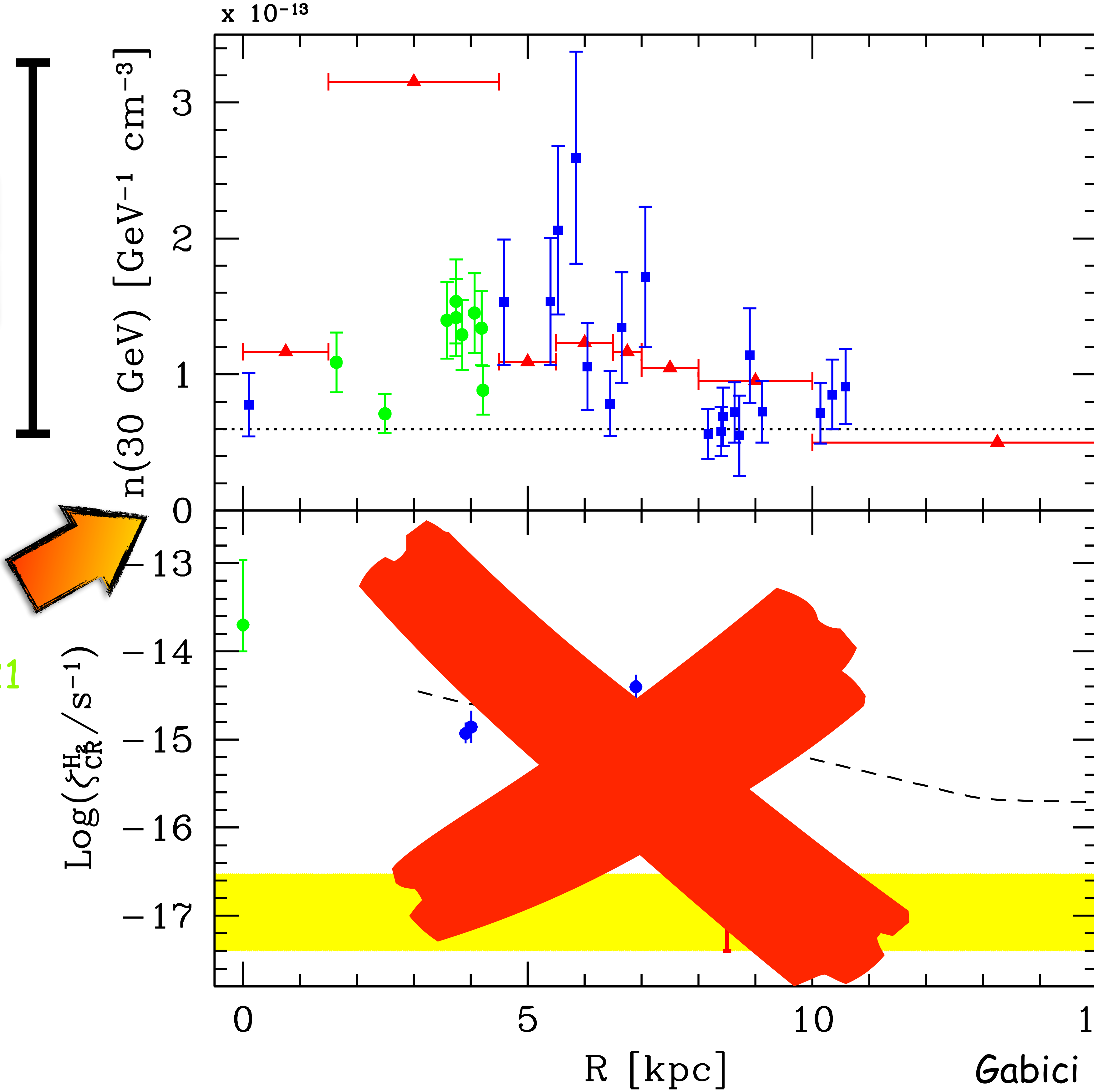
Spatial distribution of cosmic rays

factor of few over the entire disk



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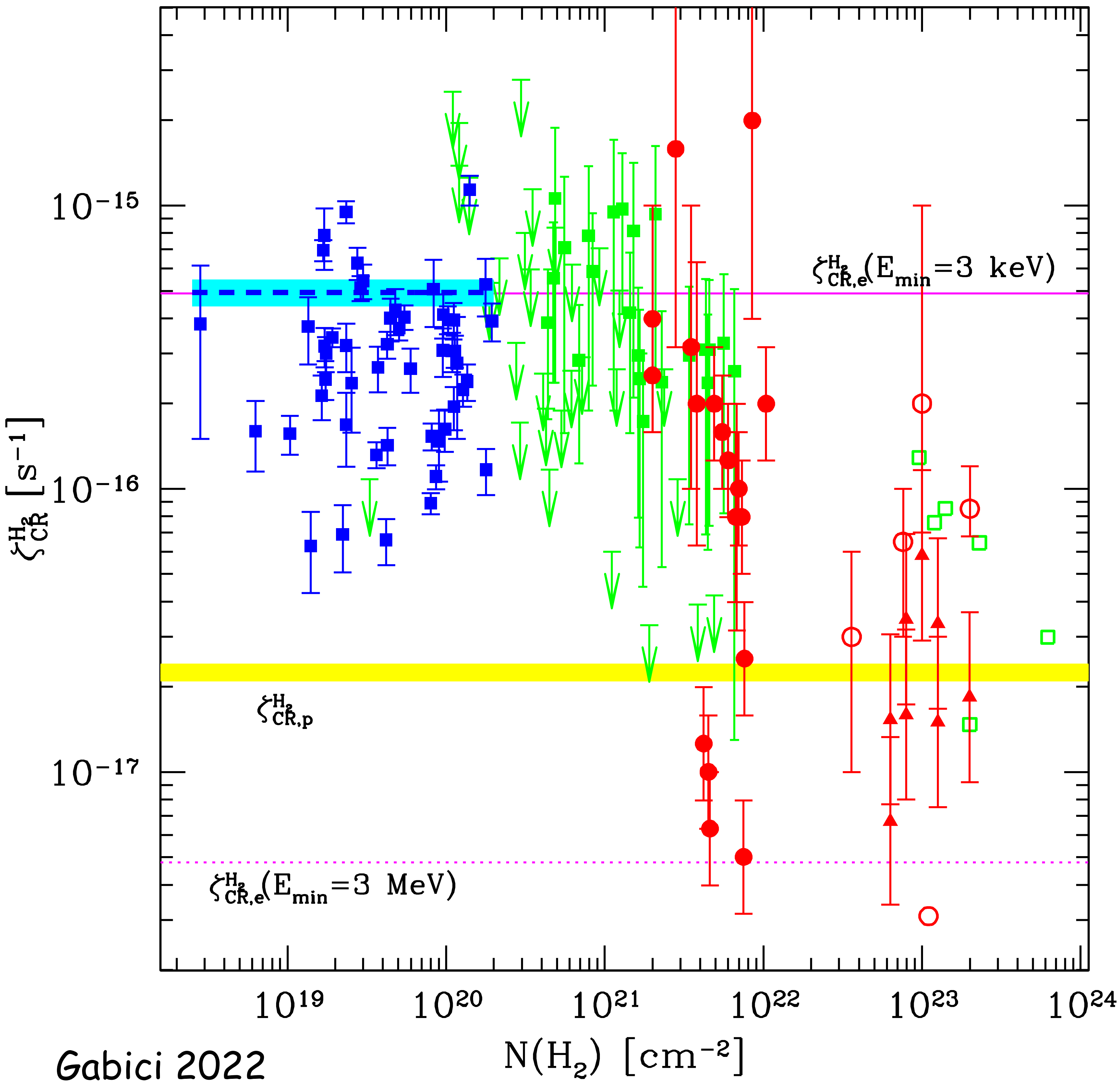
CR ionization rate in isolated MCs



H_3^+, HCO^+, DCO^+, OH^+, H_2O^+ H_3O^+ ...

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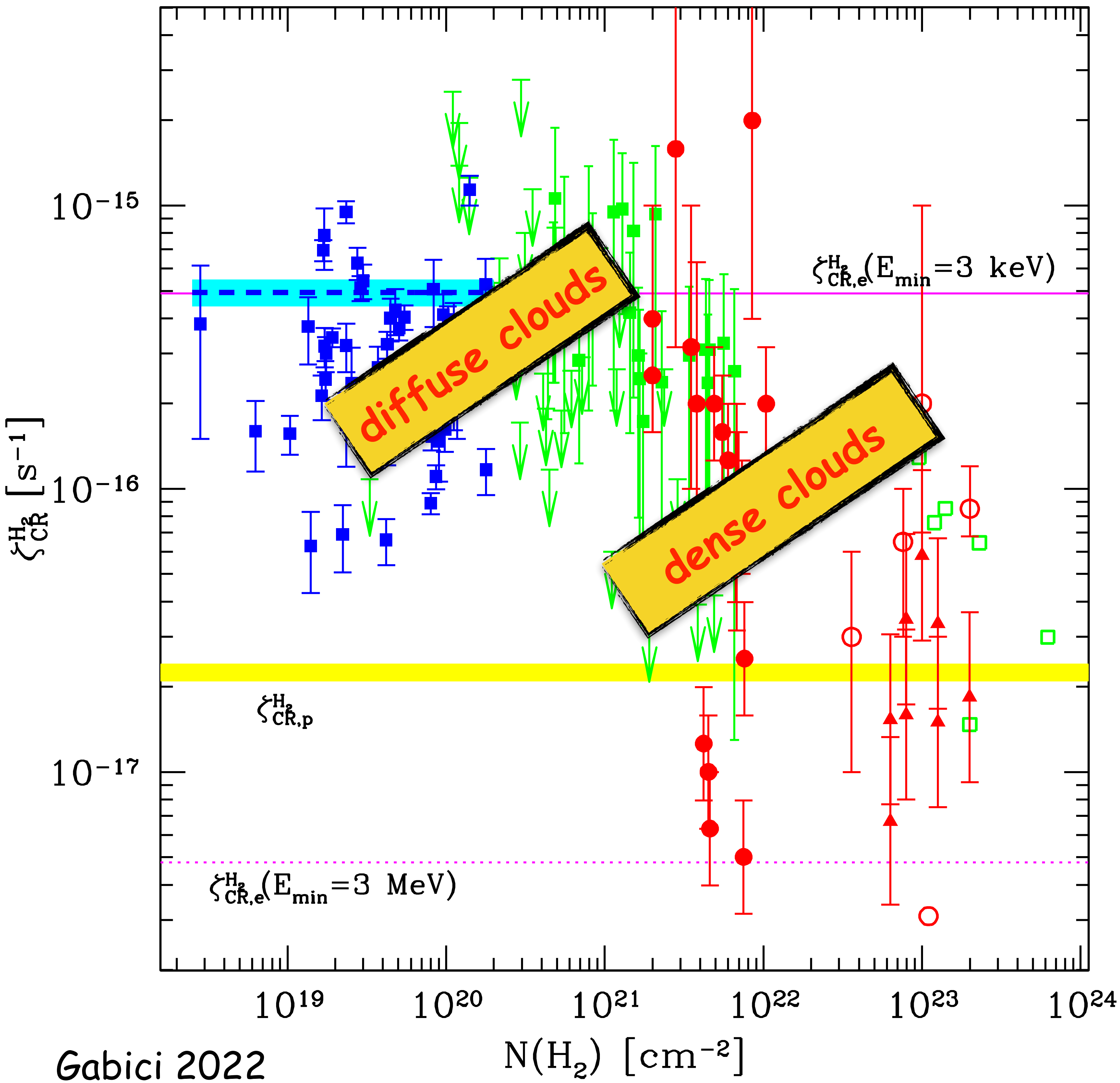

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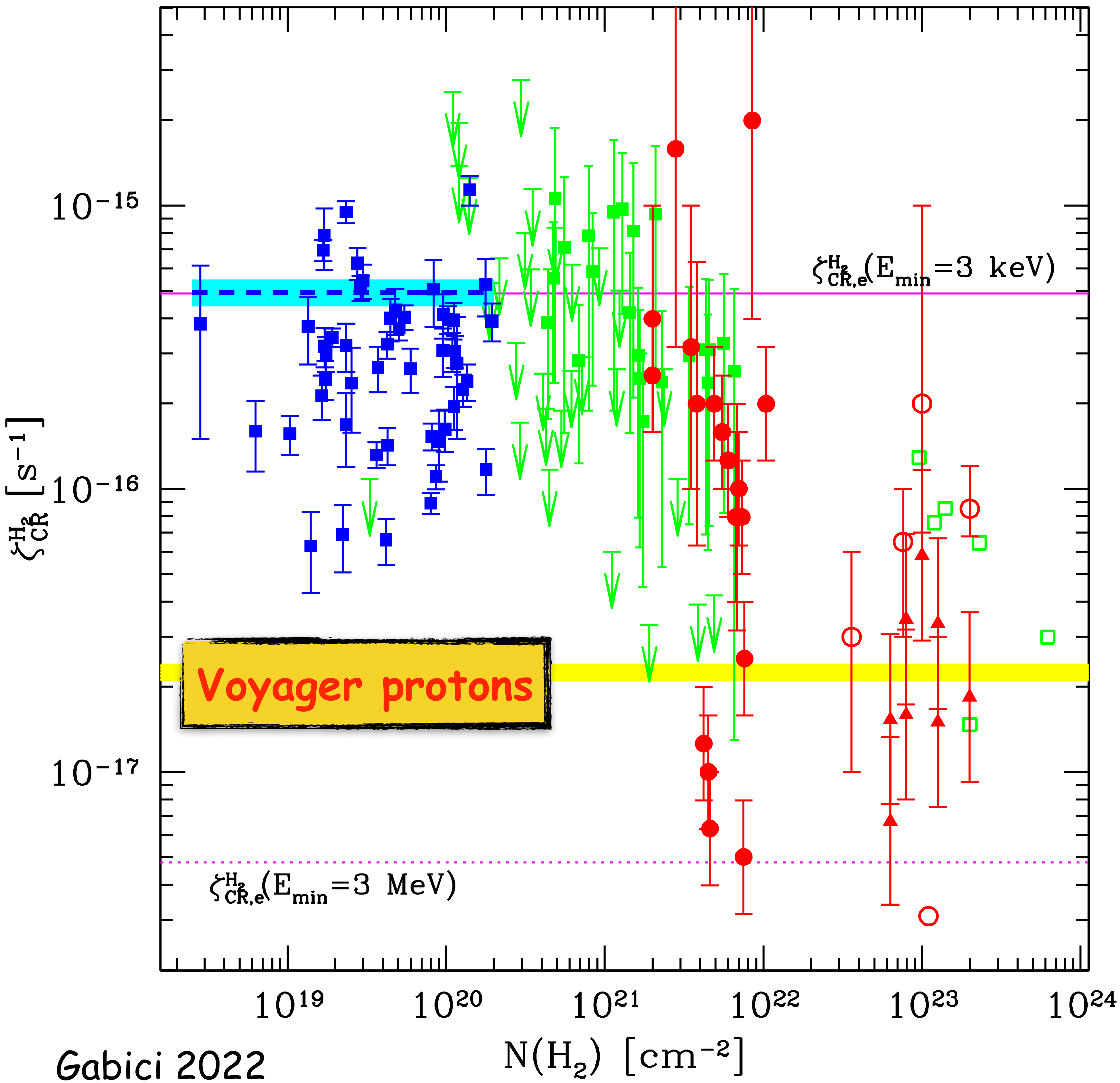

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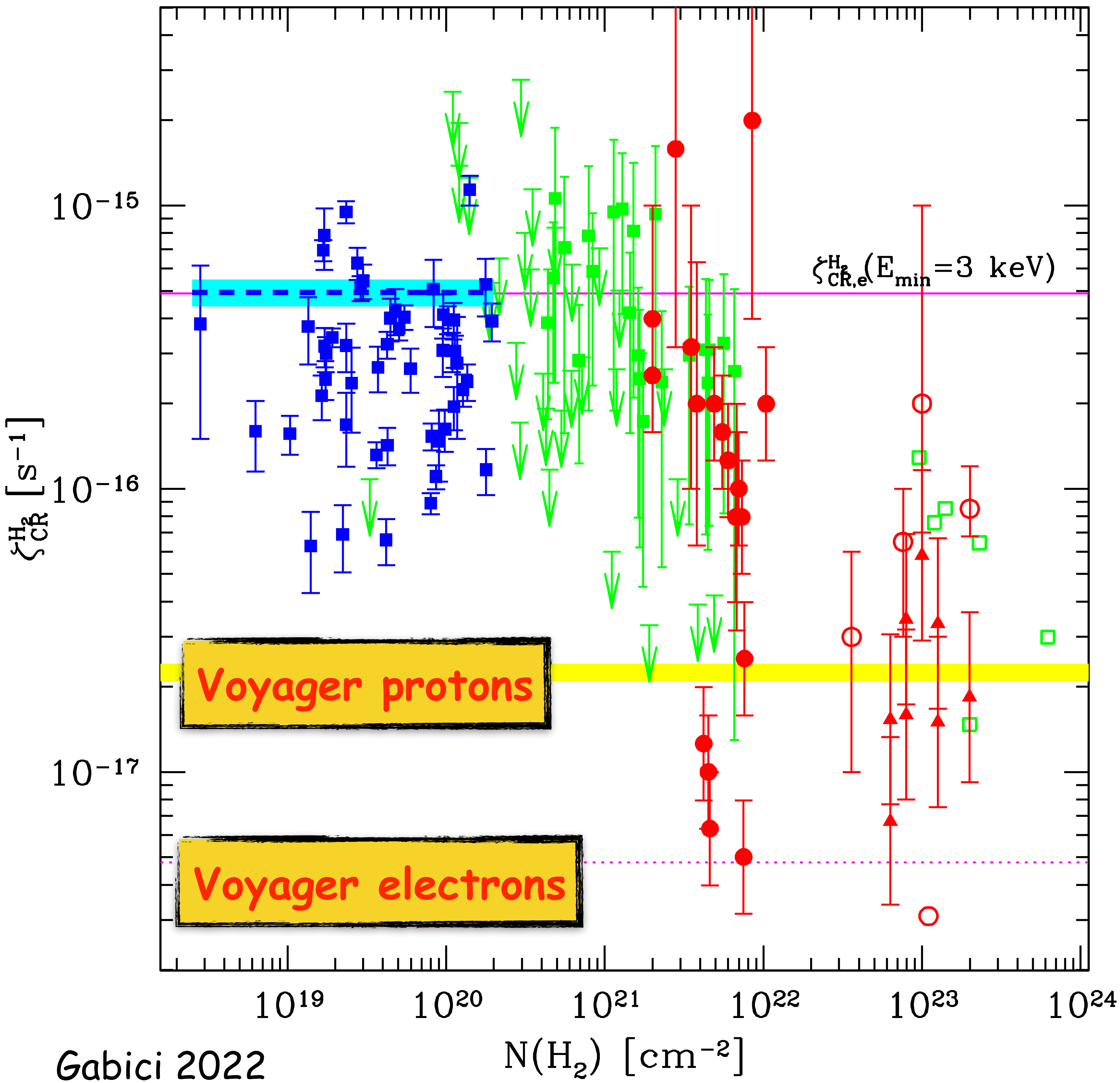

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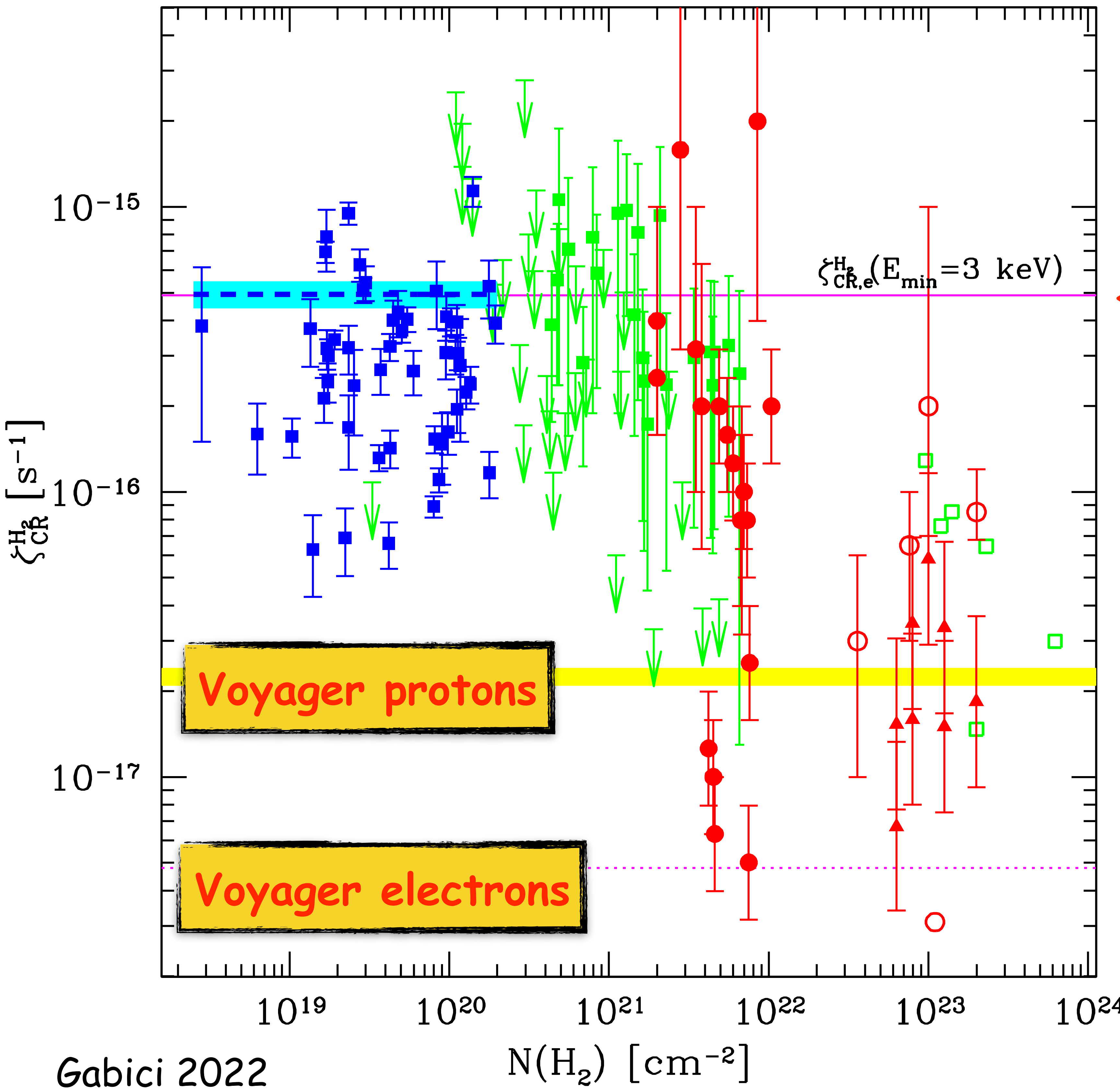

← Voyager electrons extrapolated down to 3 keV

Caselli+98, van der Tak&van Dischoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20

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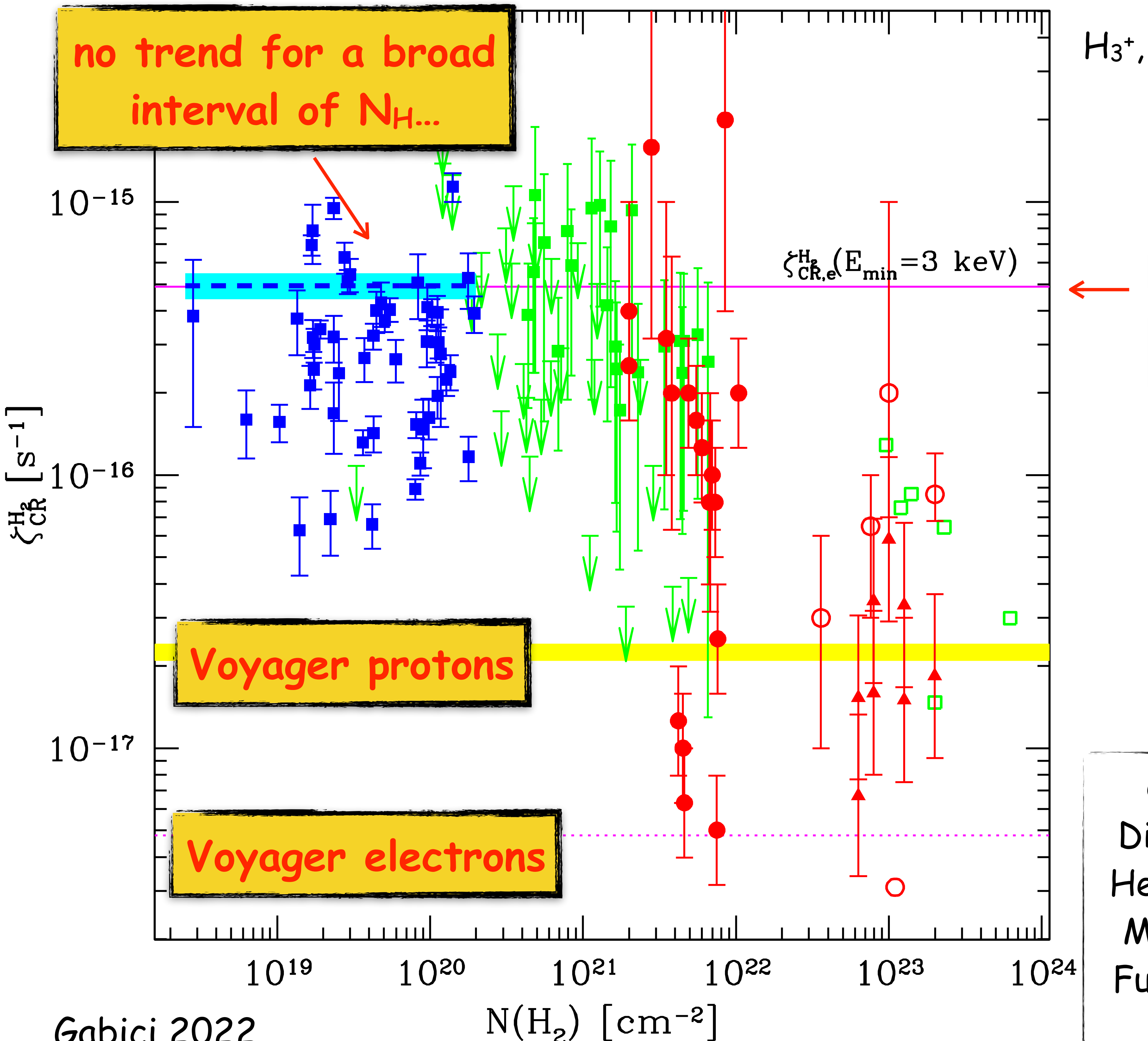

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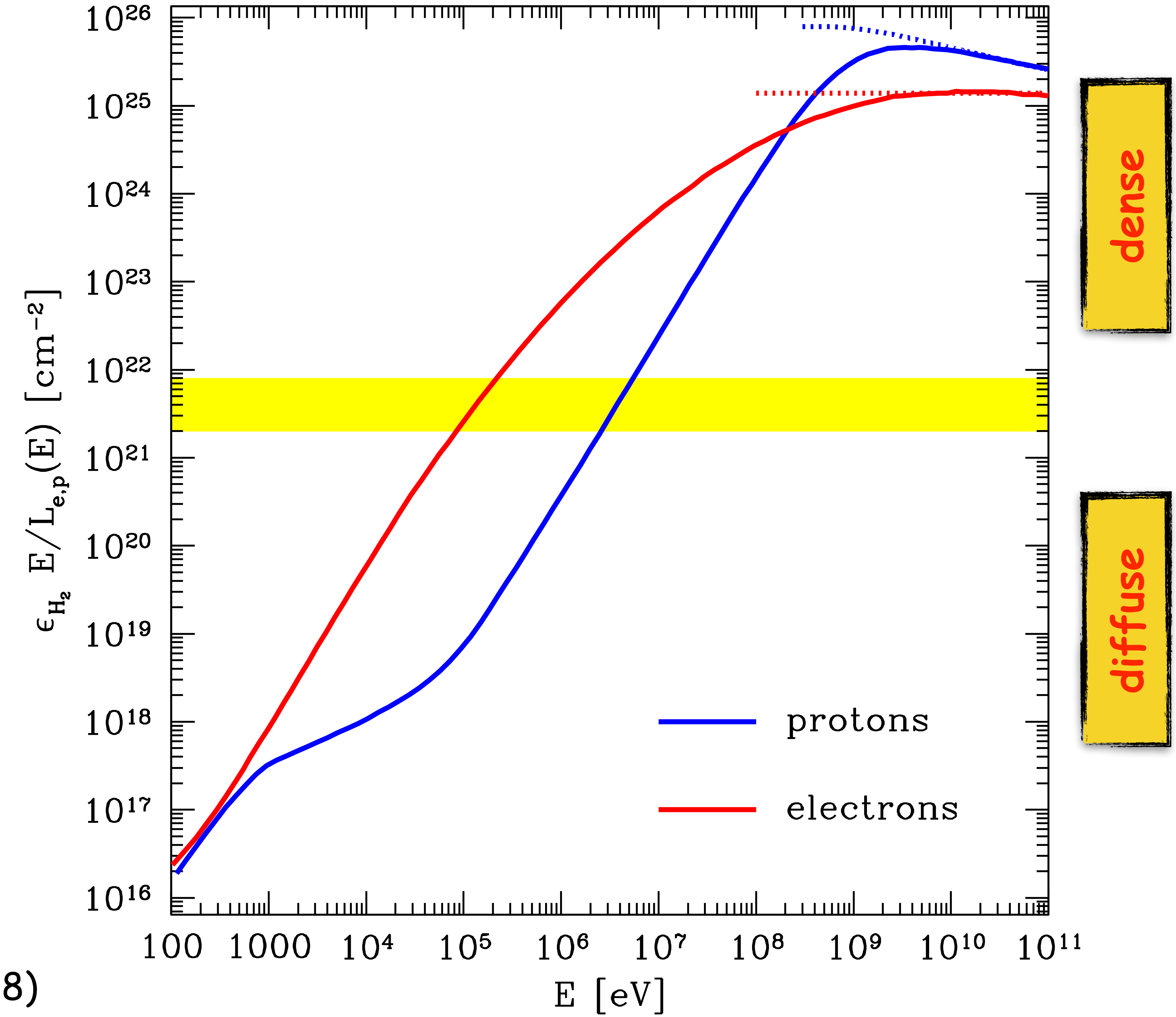

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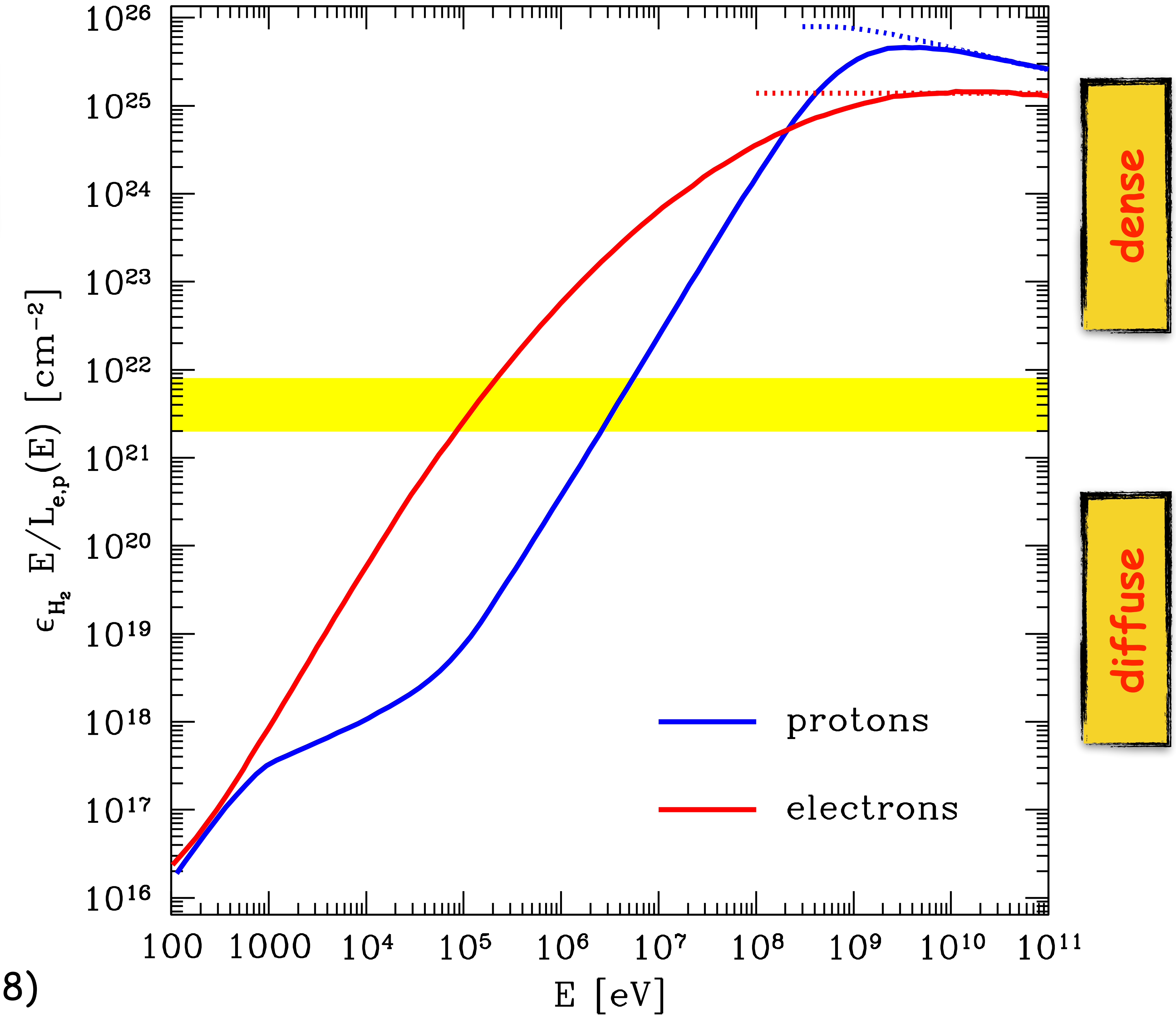
(adapted from Padovani+ 18)

Energy losses (mainly ionisation)

CRs cool after crossing this gas column density



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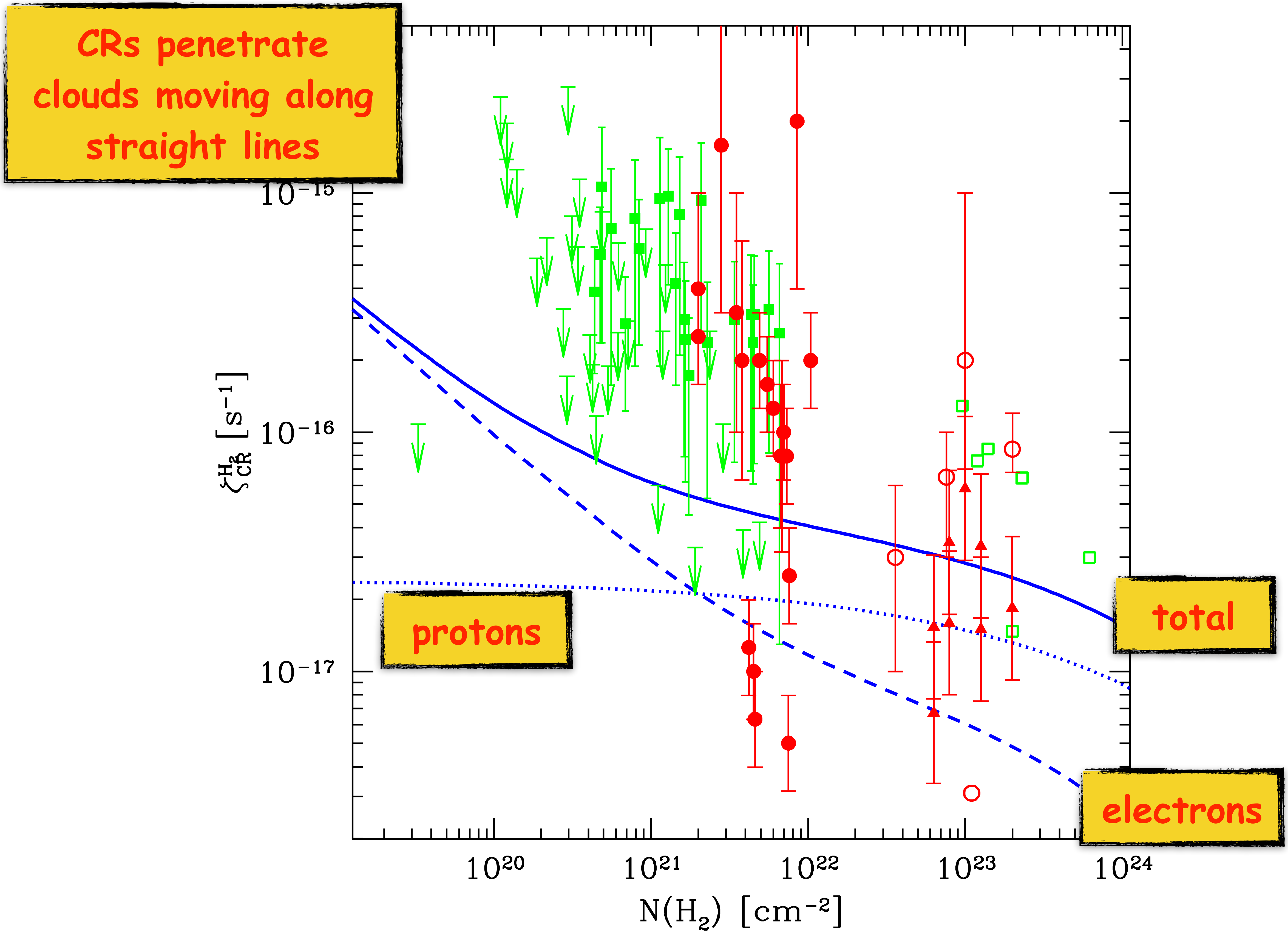
(adapted from Padovani+ 18)

Ballistic penetration into clouds



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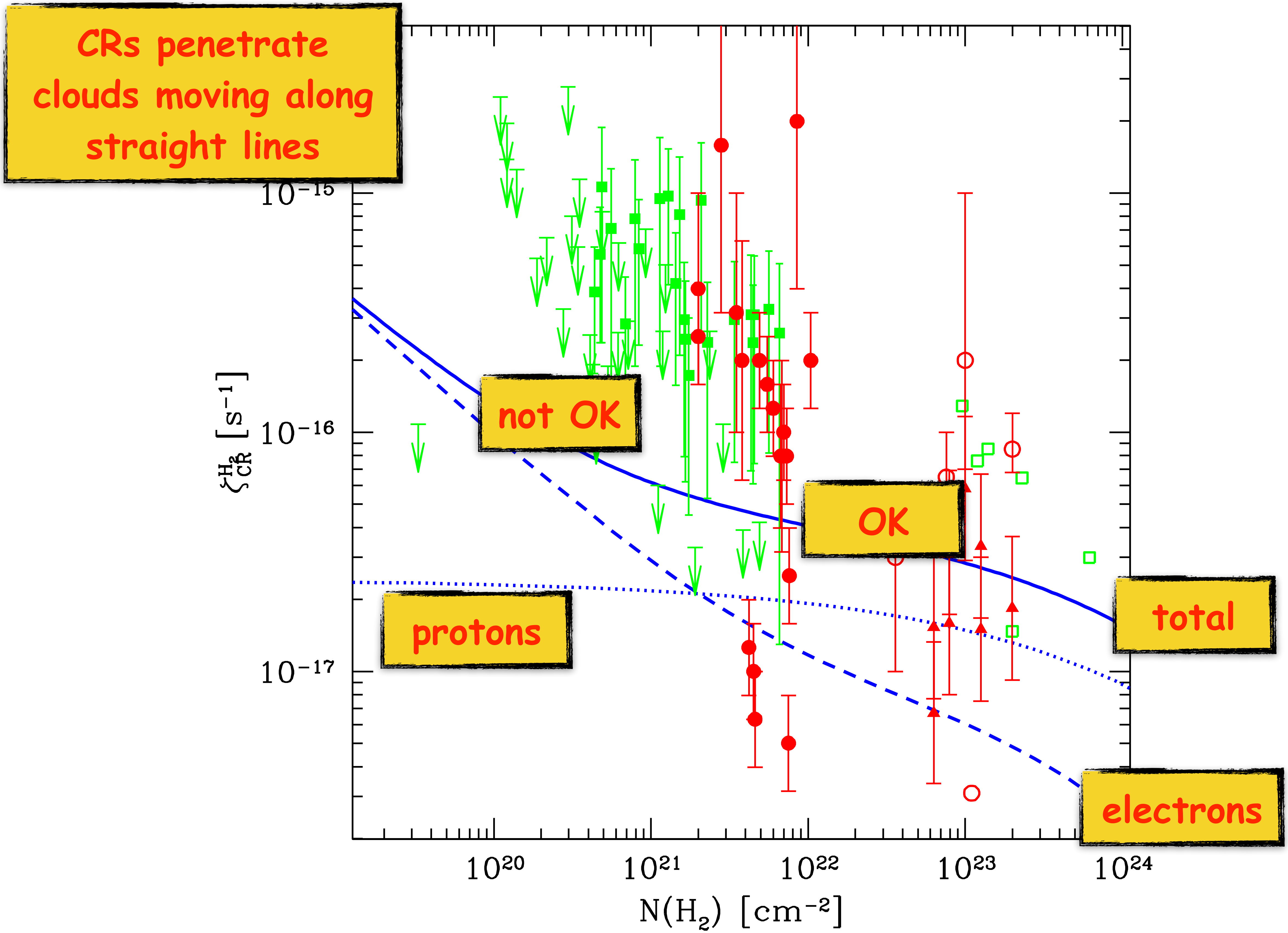

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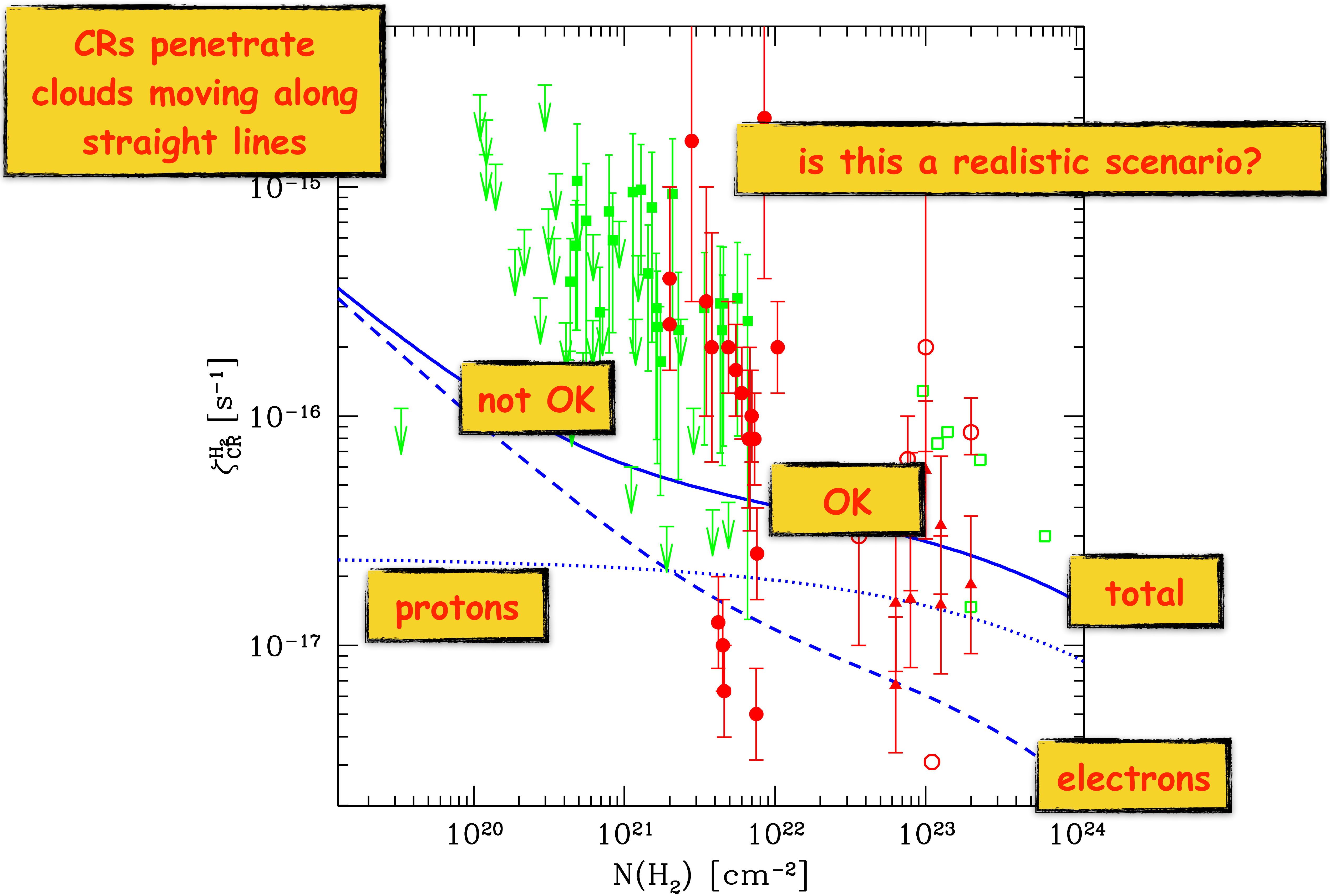
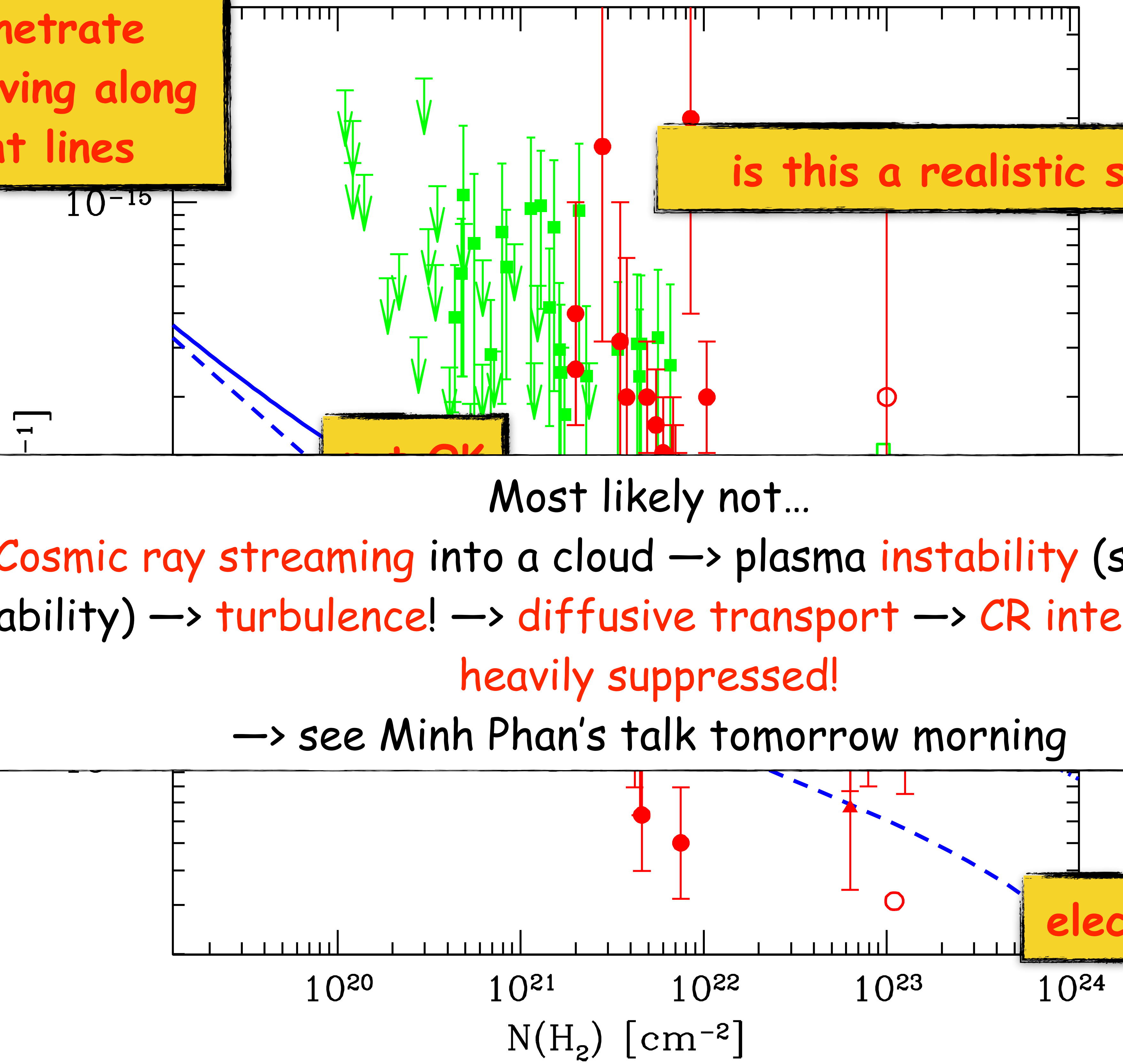


Ballistic penetration into clouds

CRs penetrate clouds moving along straight lines



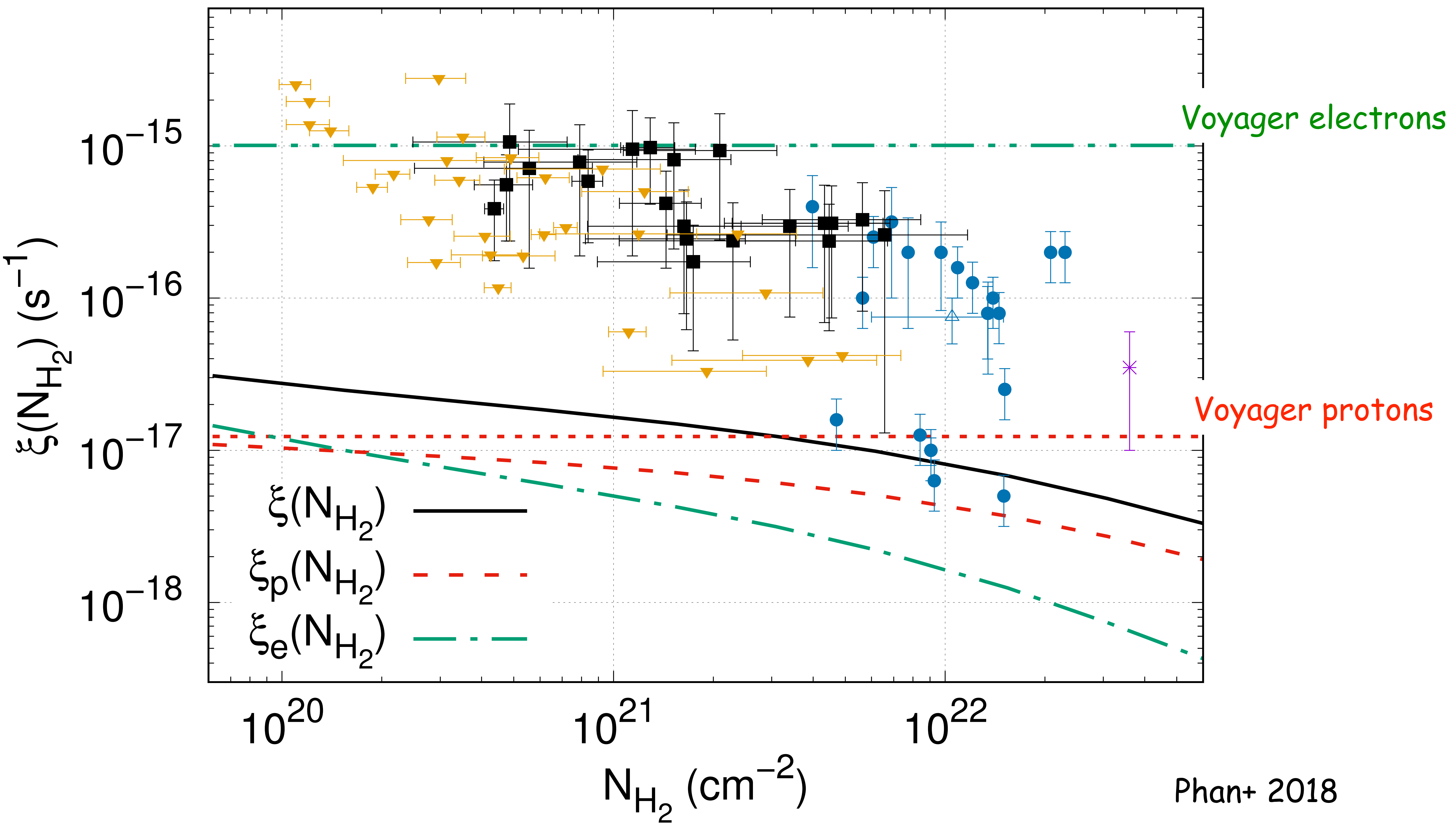
is this a realistic scenario?

Most likely not…

Cosmic ray streaming into a cloud —> plasma instability (streaming instability) —> turbulence! —> diffusive transport —> CR intensity is more heavily suppressed!

—> see Minh Phan's talk tomorrow morning

Comparison with data (???)



Phan+ 2018

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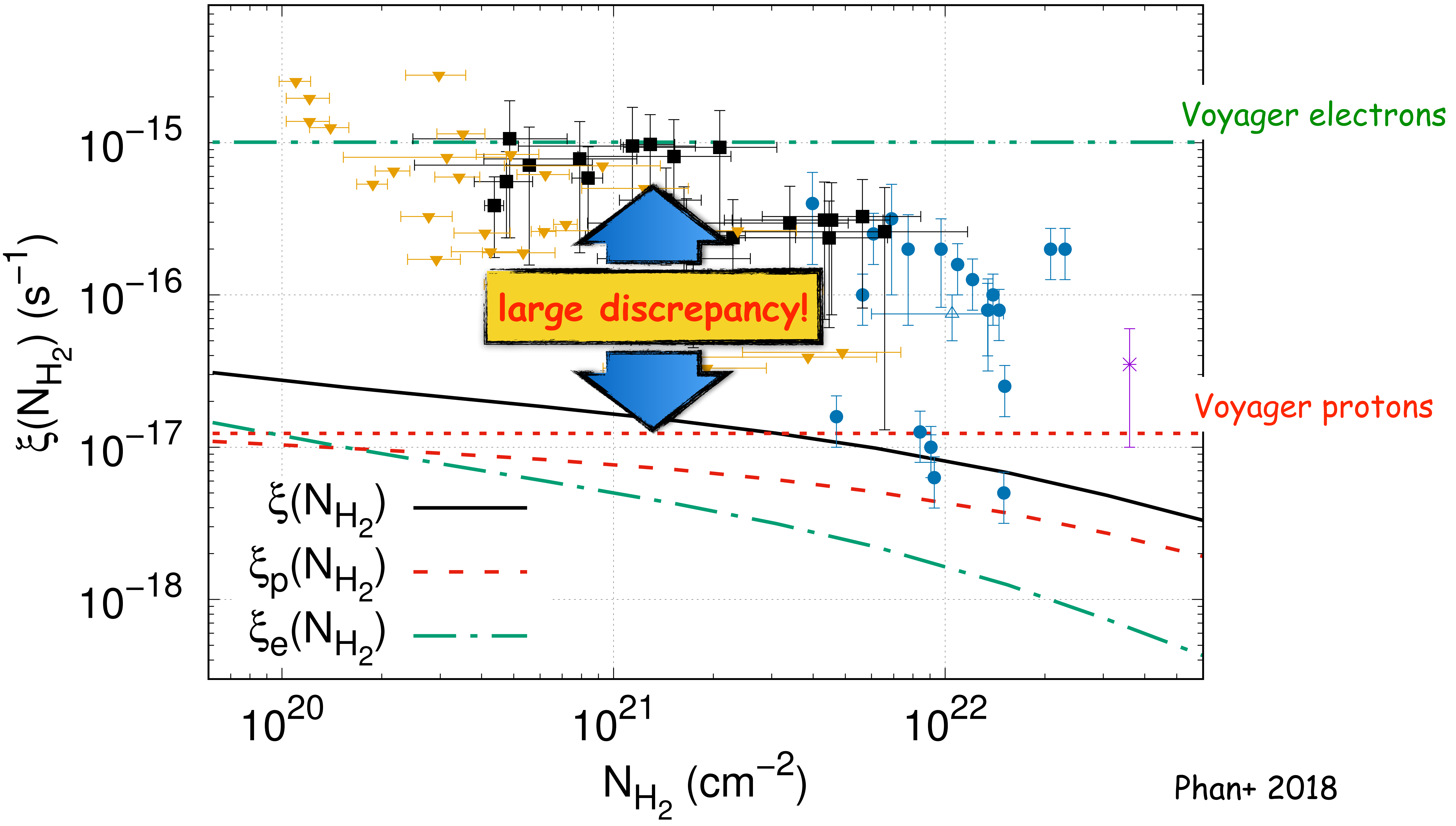
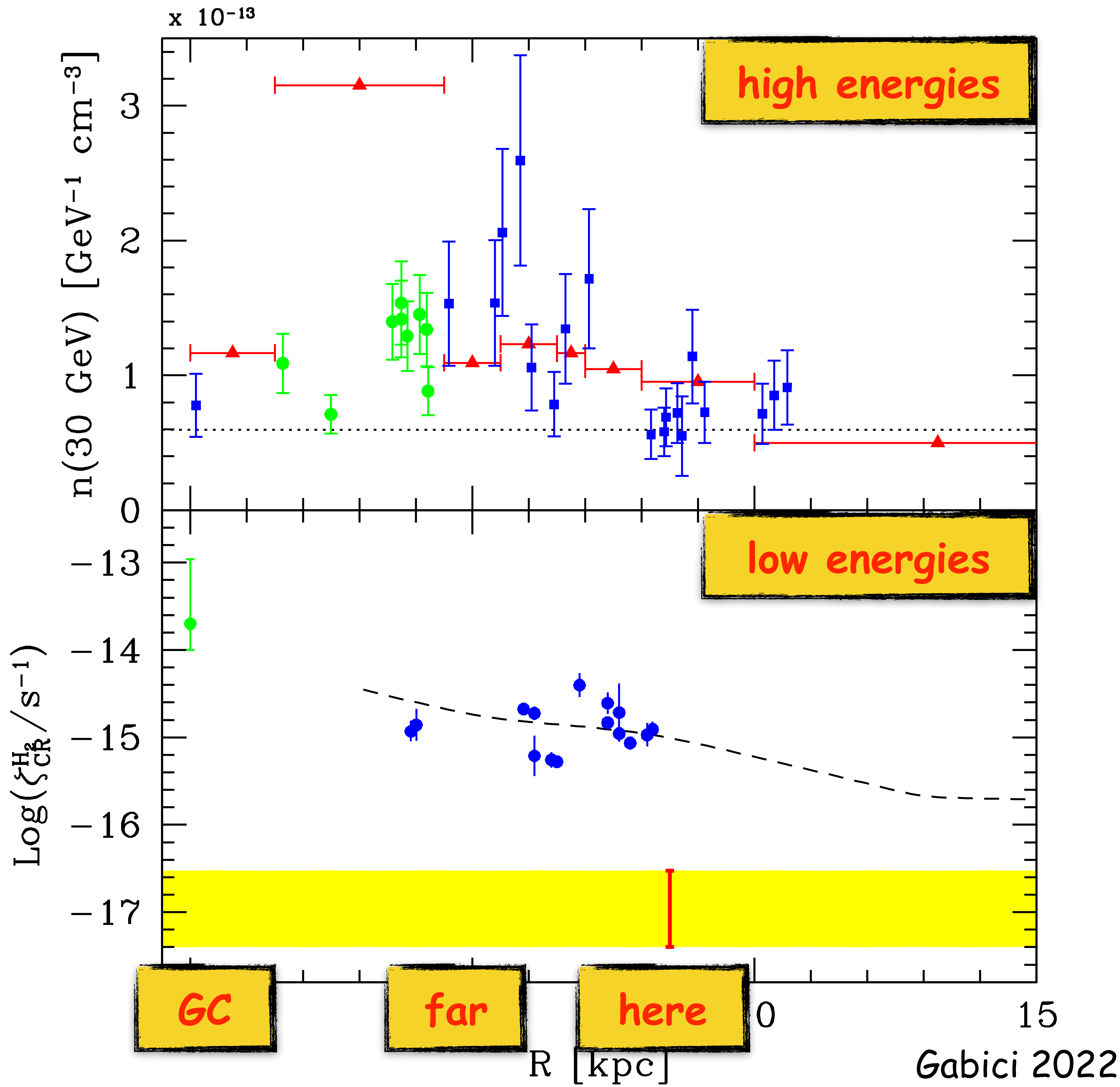


Phan+ 2018

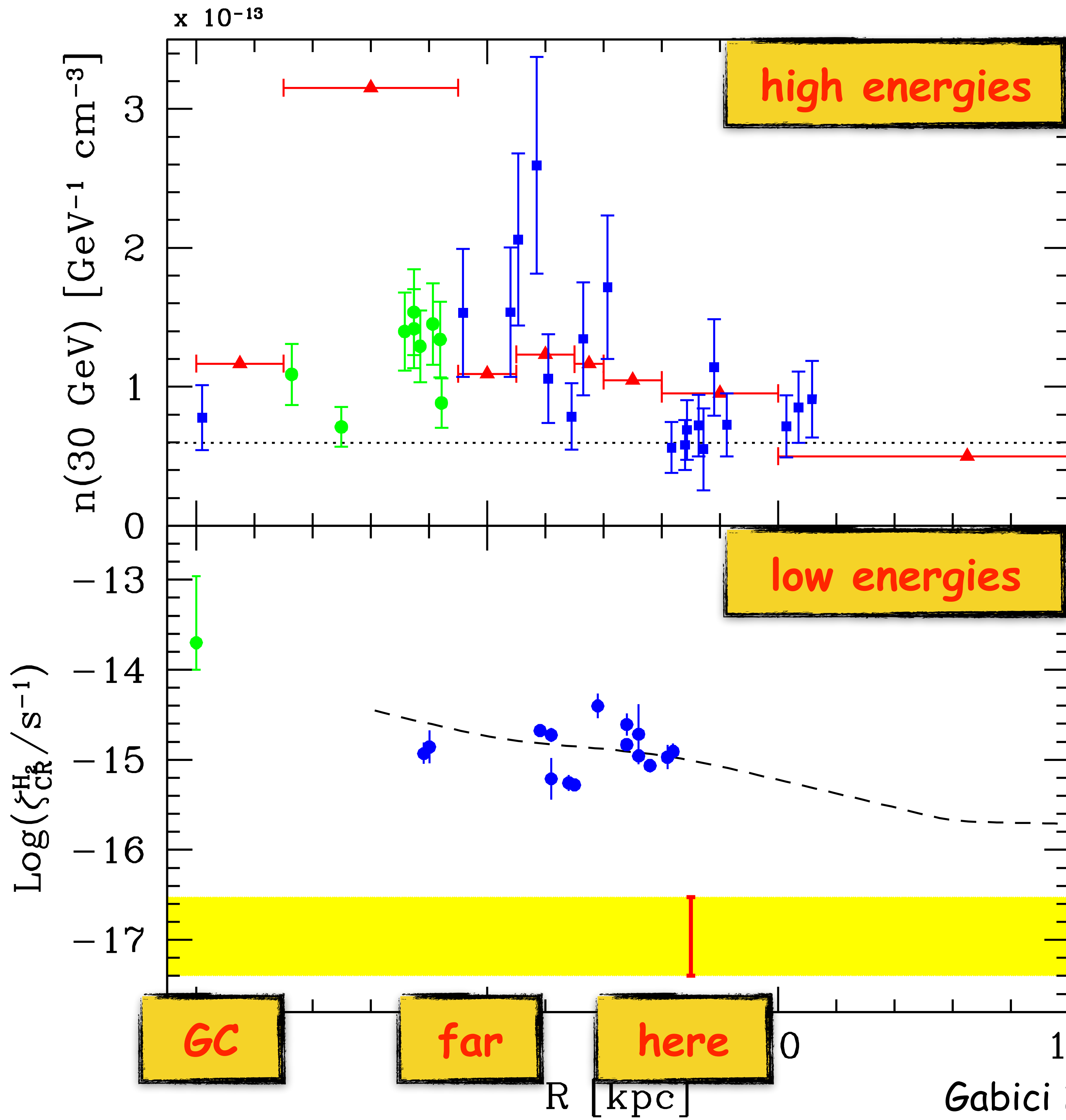
Spatial distribution of cosmic rays



GC: Oka+, LePetit+,
Far: Neufeld&Wolfire

Spatial distribution of cosmic rays

factor of few over
the entire disk



Gabici 2022

GC: Oka+, LePetit+,
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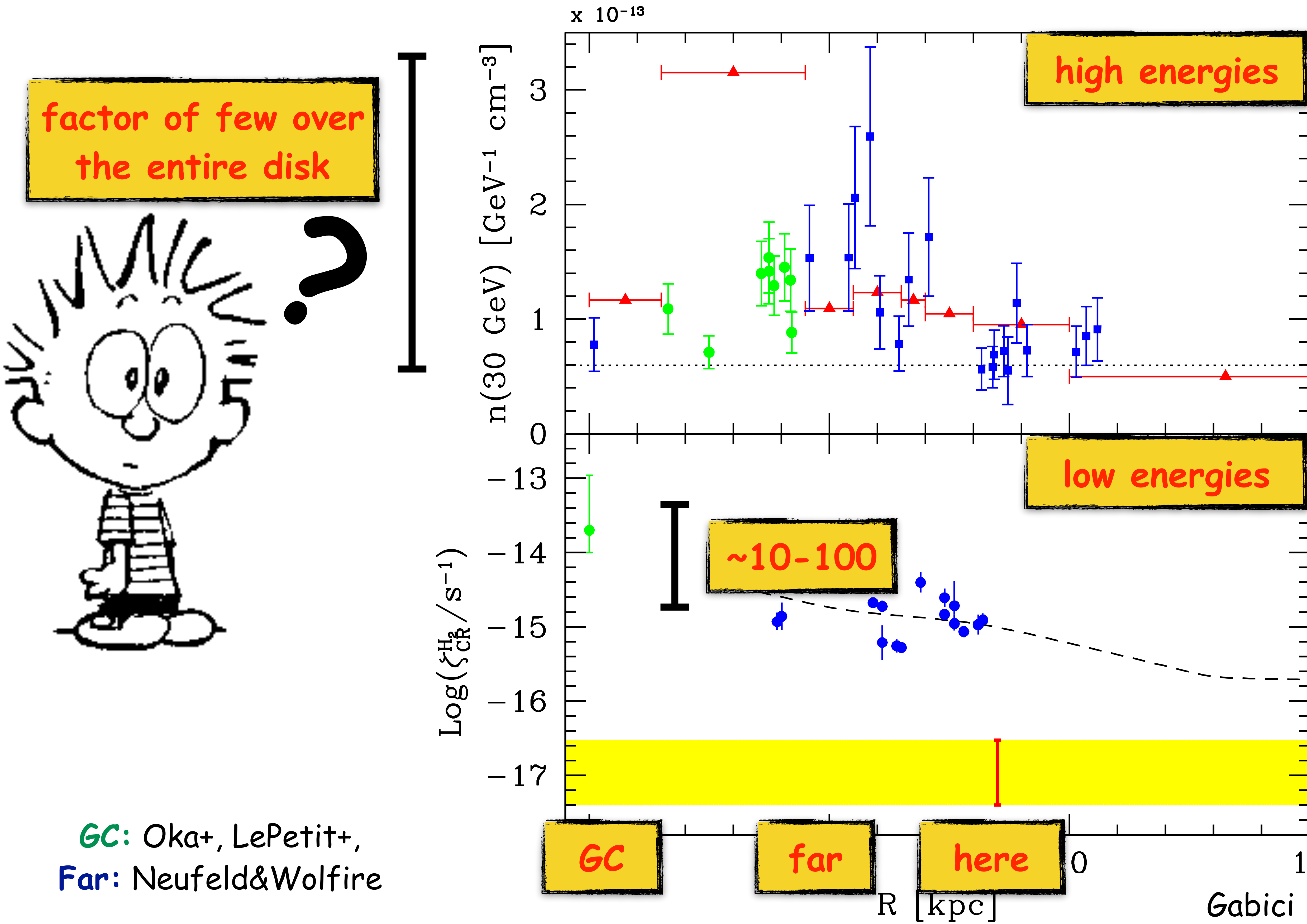

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Gabici 2022

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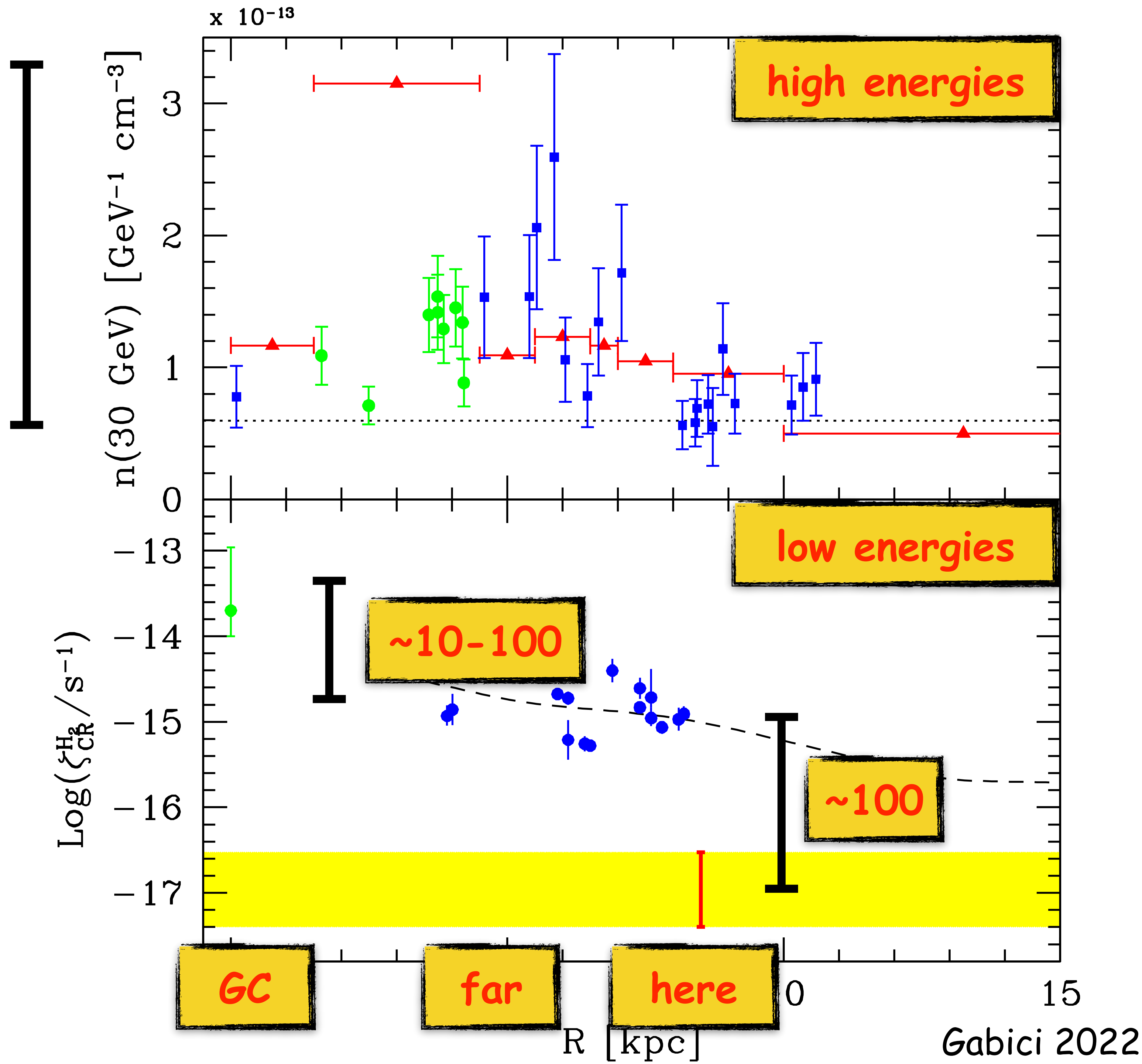

GC: Oka+, LePetit+,
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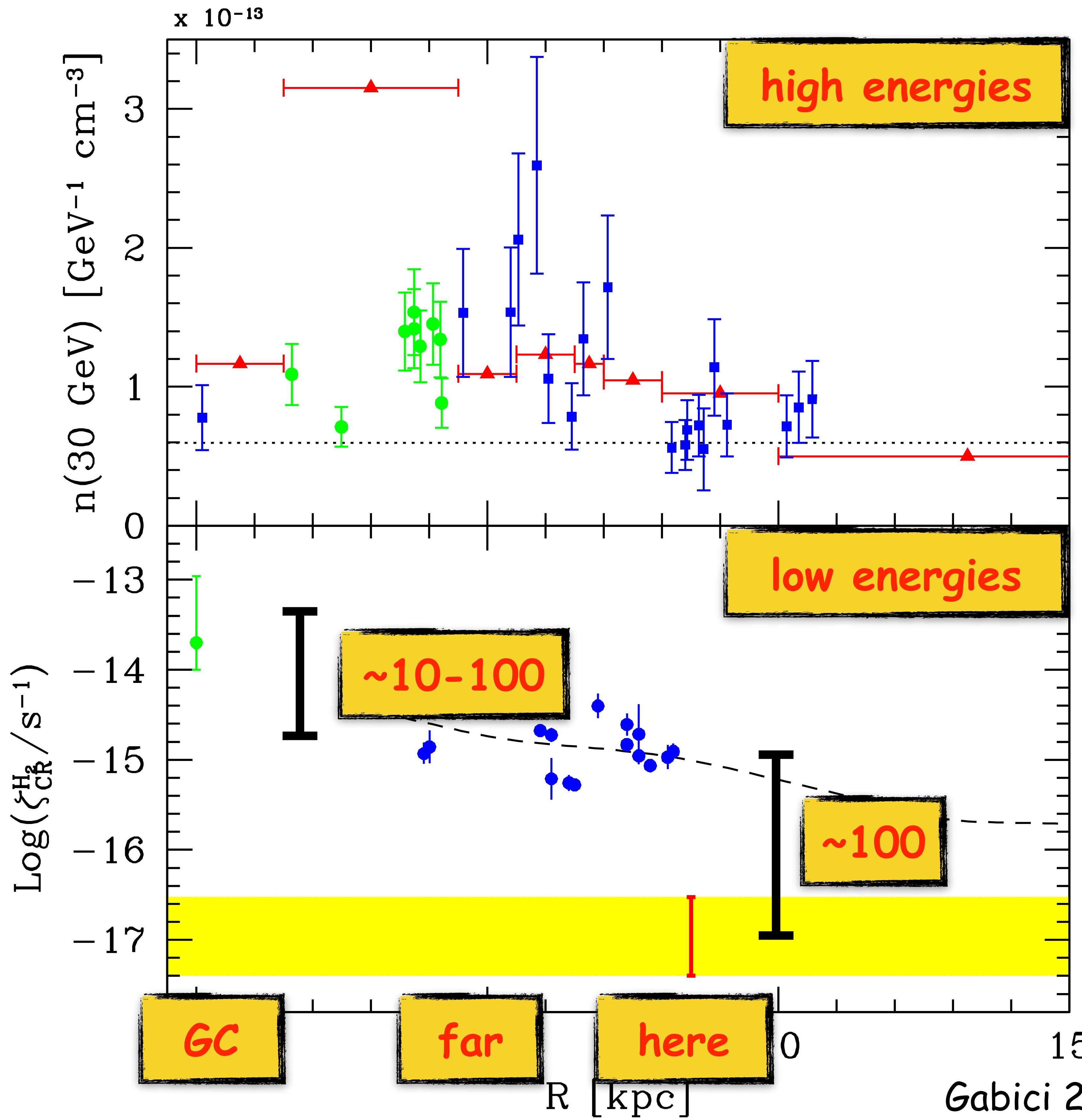
Spatial distribution of cosmic rays

factor of few over the entire disk

4 orders of magnitude



Gabici 2022

GC: Oka+, LePetit+,
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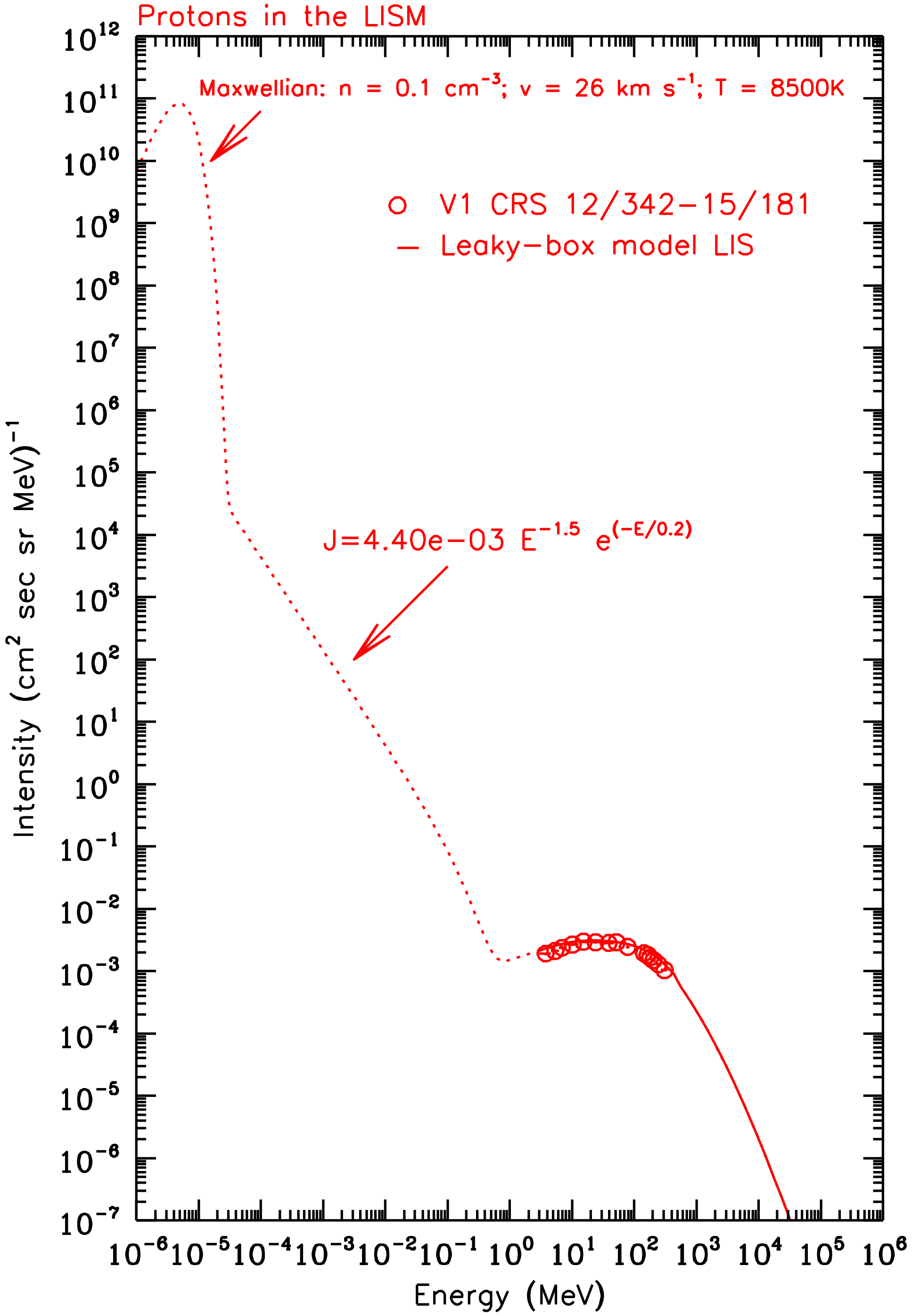
Possible solutions

a CR carrot?

Cummings+ 2016



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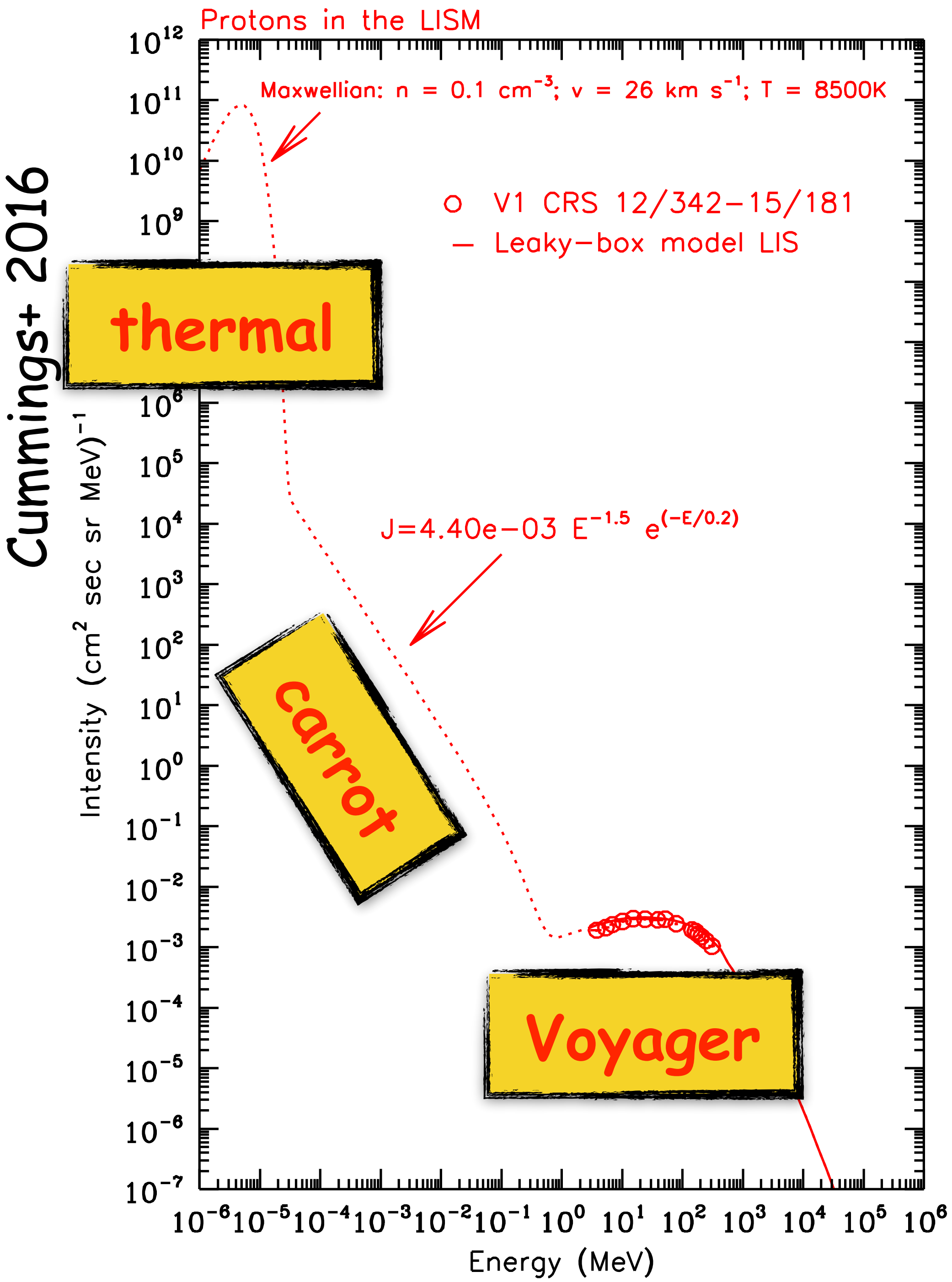

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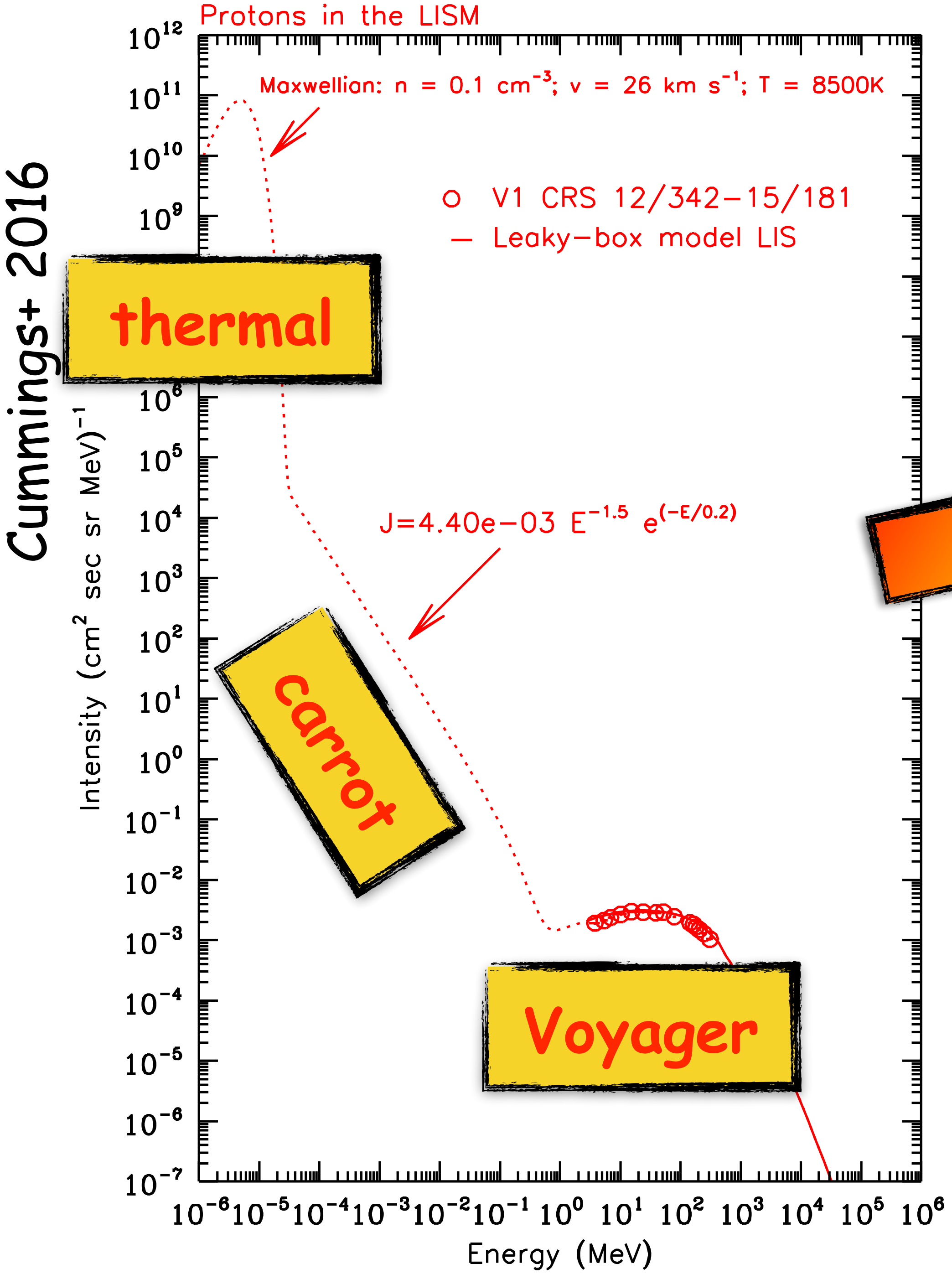
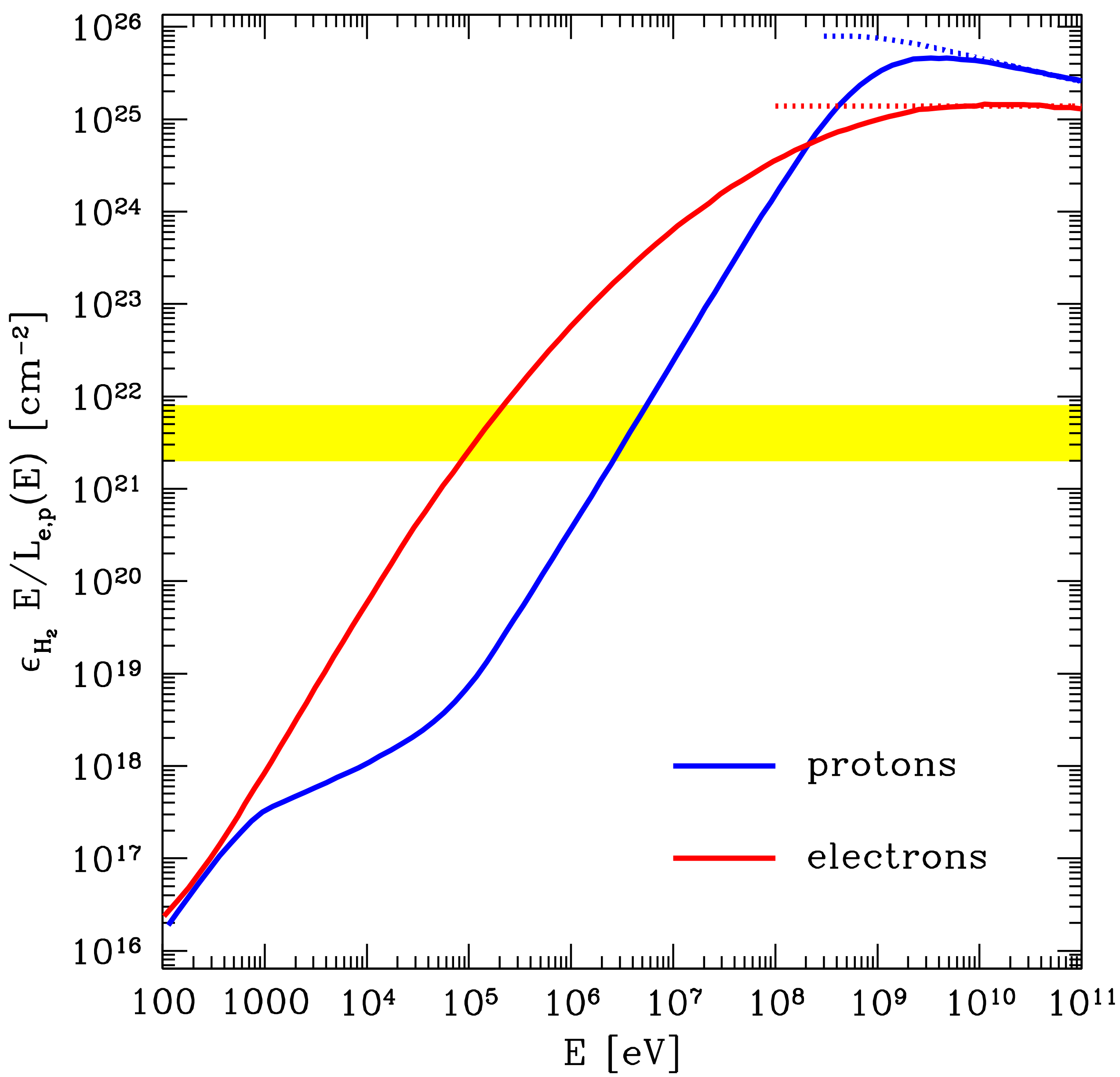
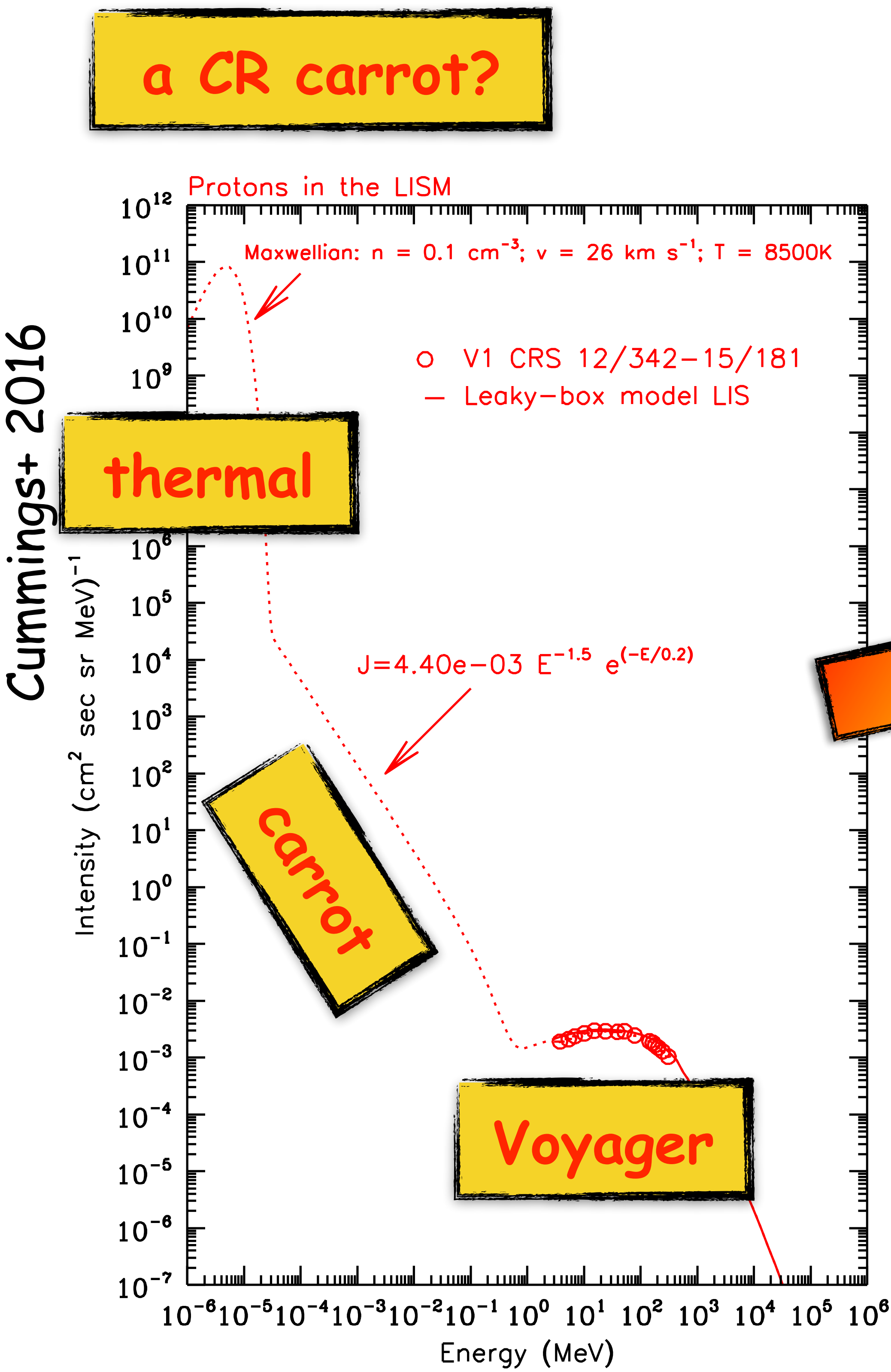
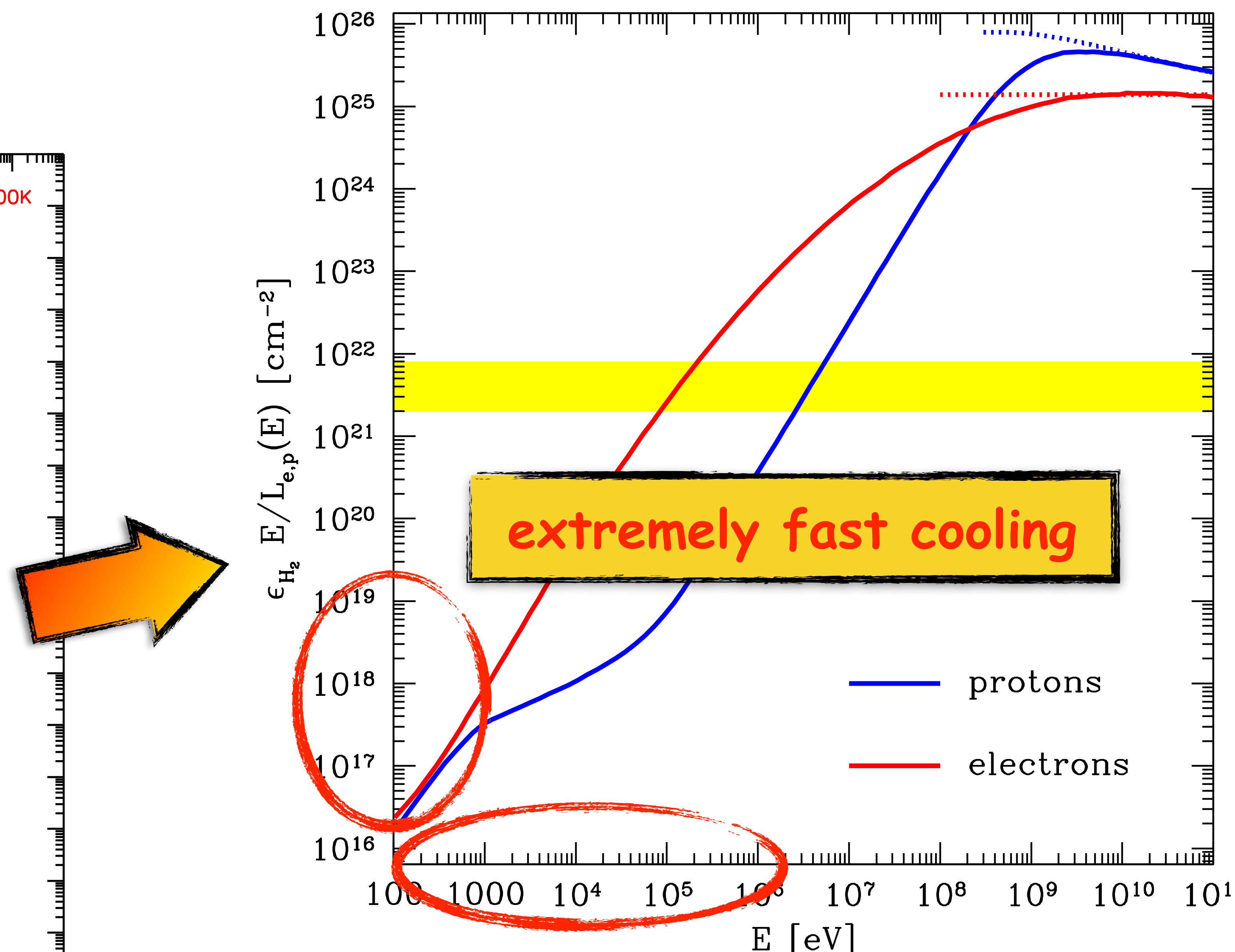




Possible solutions





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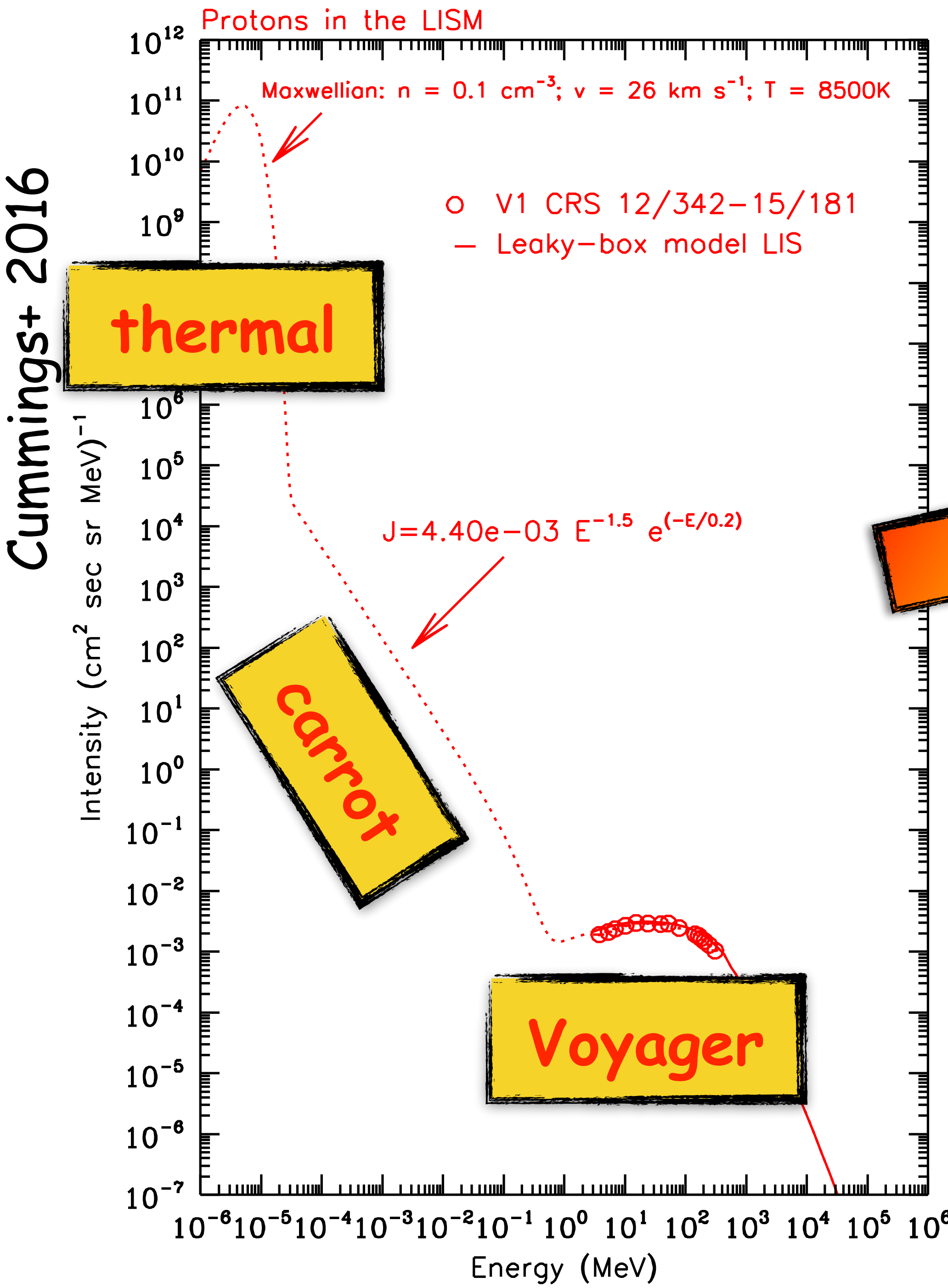
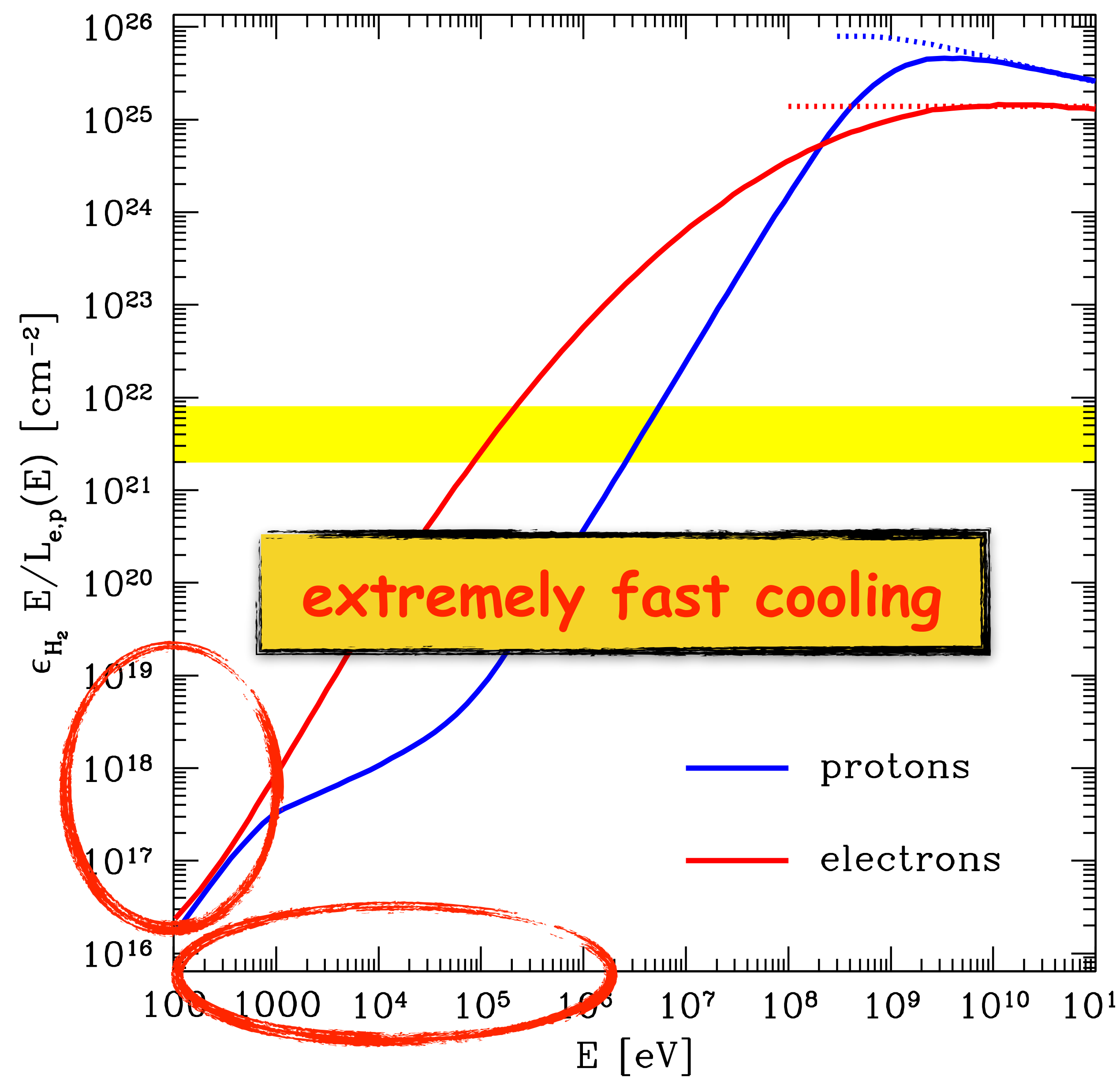


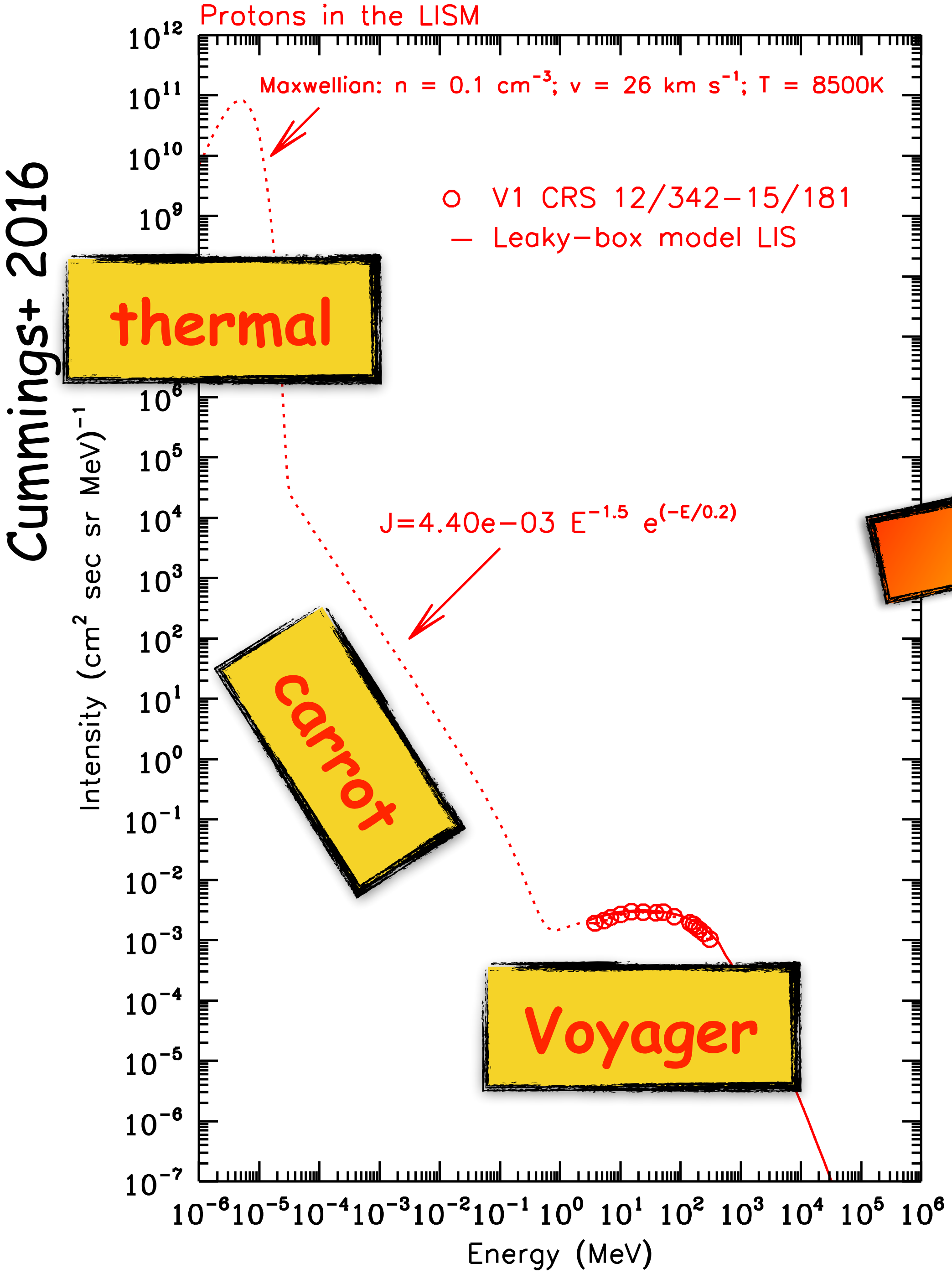


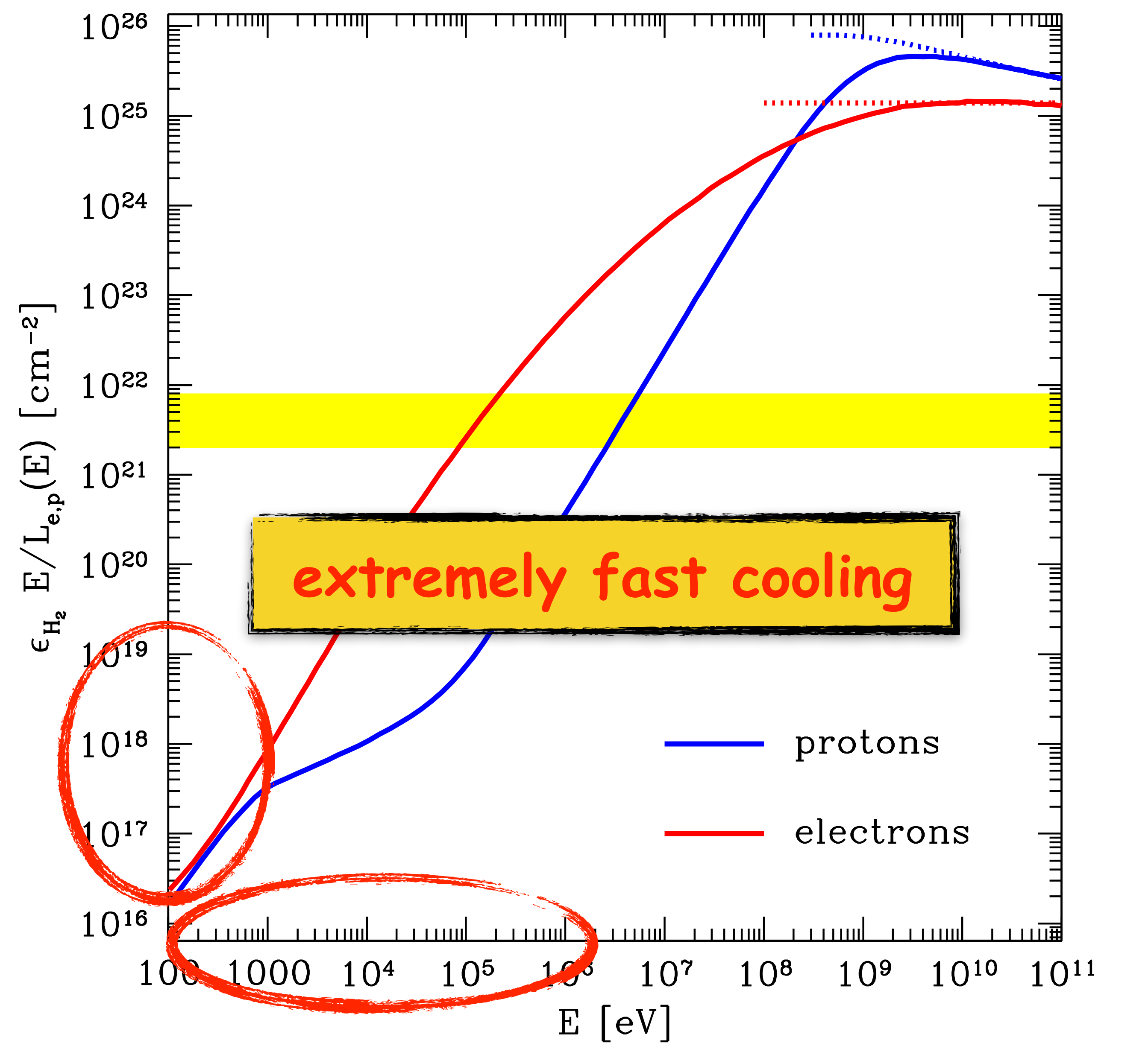
the carrot requires too much energy!

Recchia+ 2019

Possible solutions

a CR carrot?





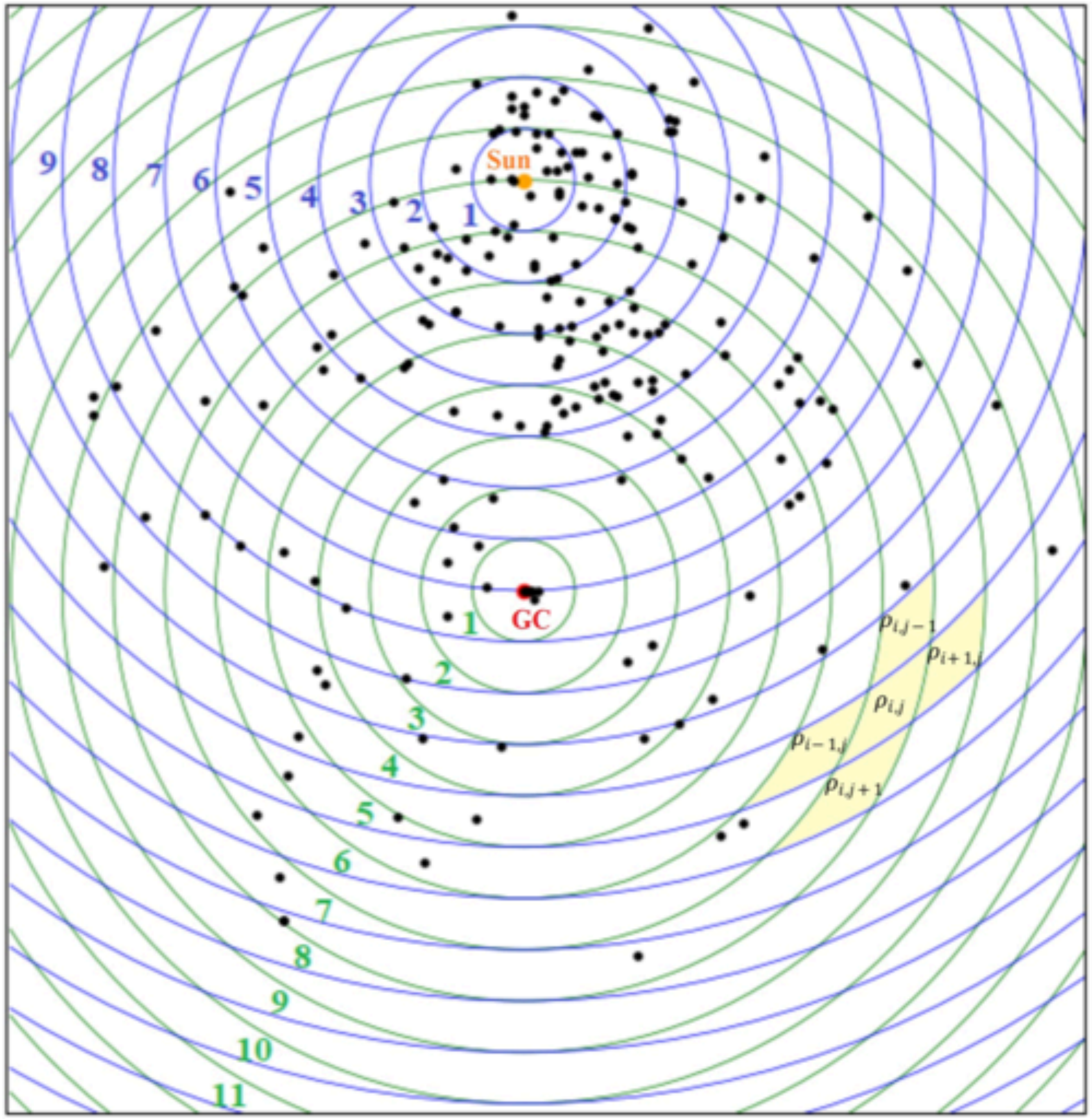
the carrot requires too much energy!

Recchia+ 2019

CR sources within clouds?

—> what about starless cores? (see works by Padovani+)

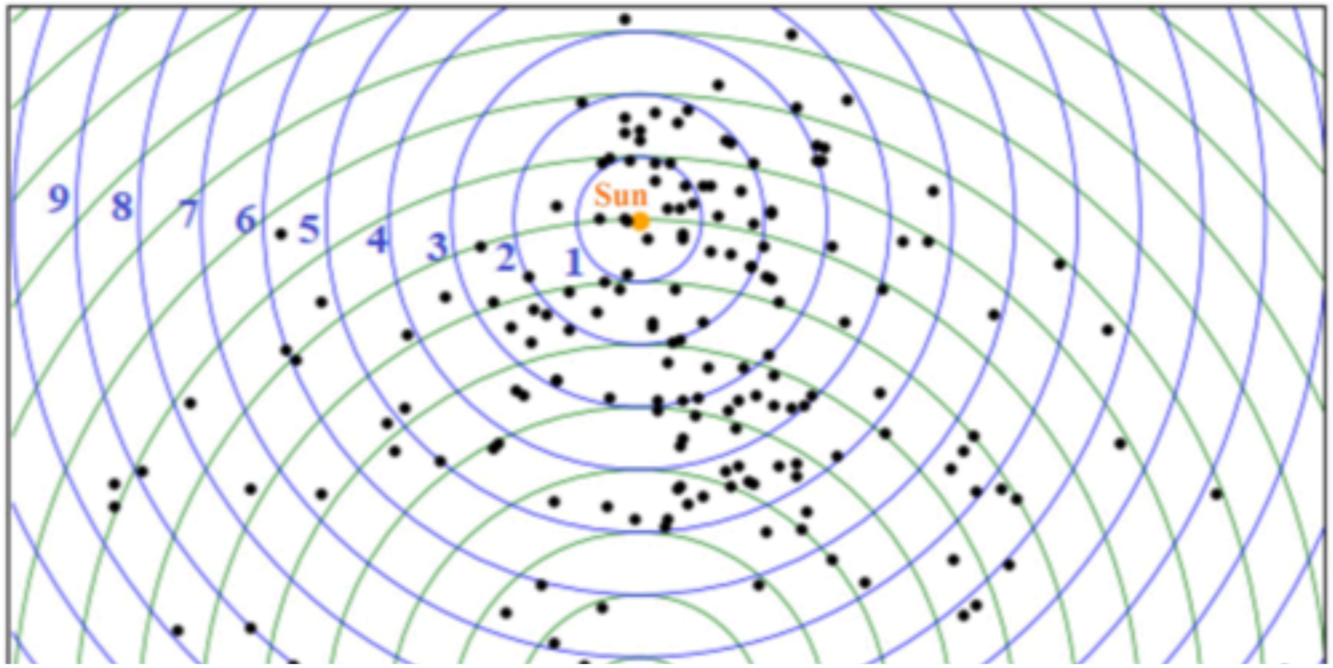
Stochasticity of sources



<— position of known SNR in the MW

Ranasinghe & Leahy 2022

Stochasticity of sources



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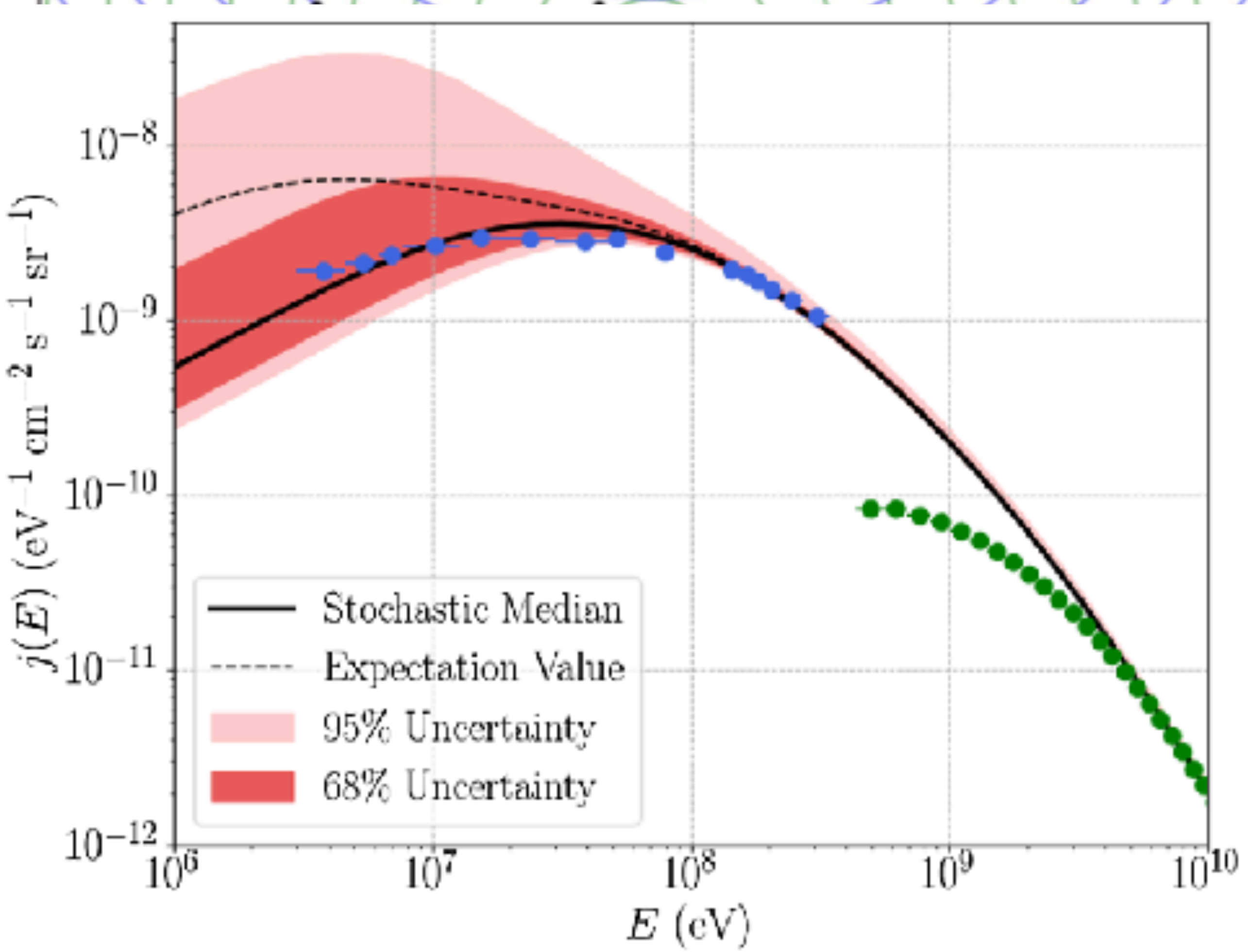
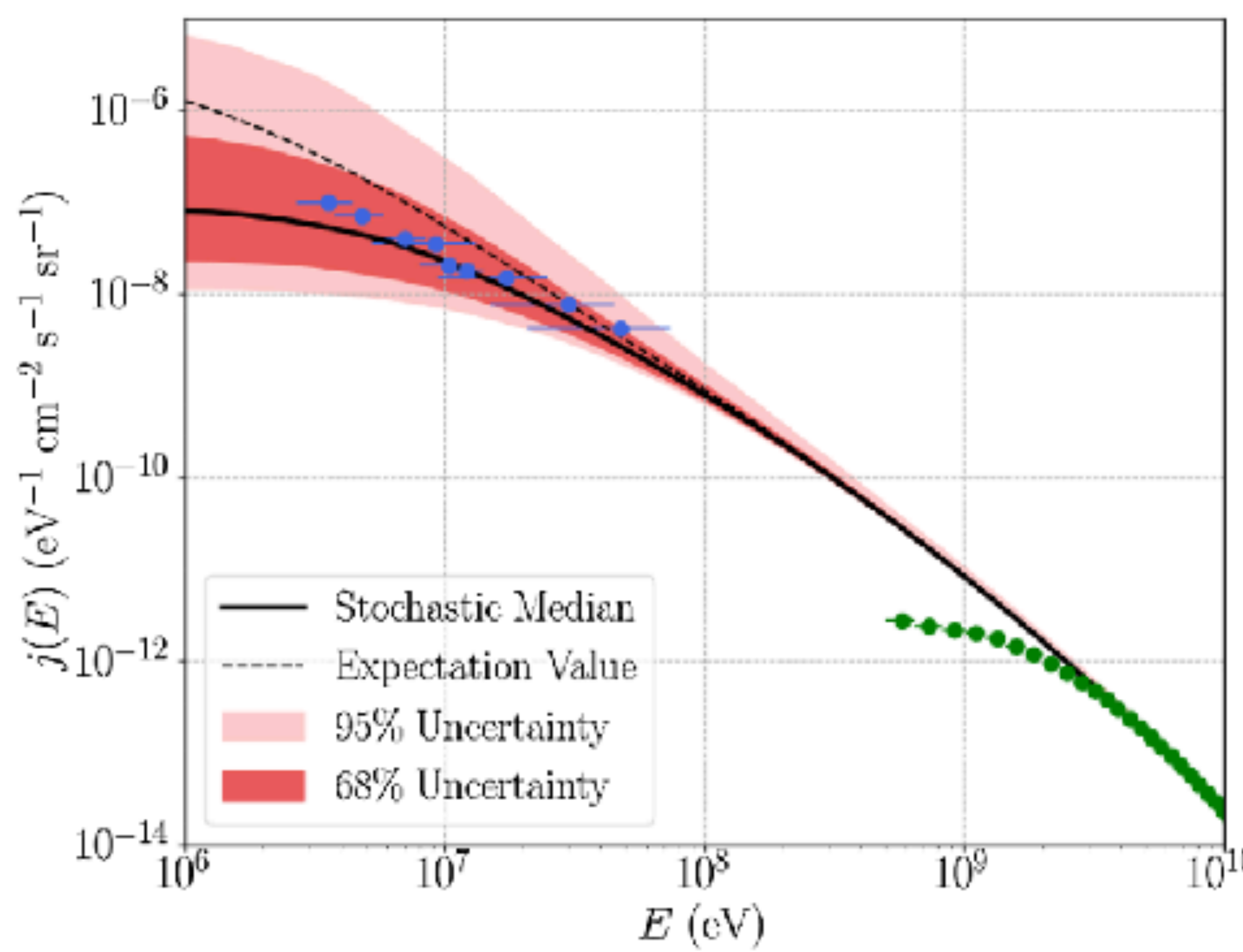
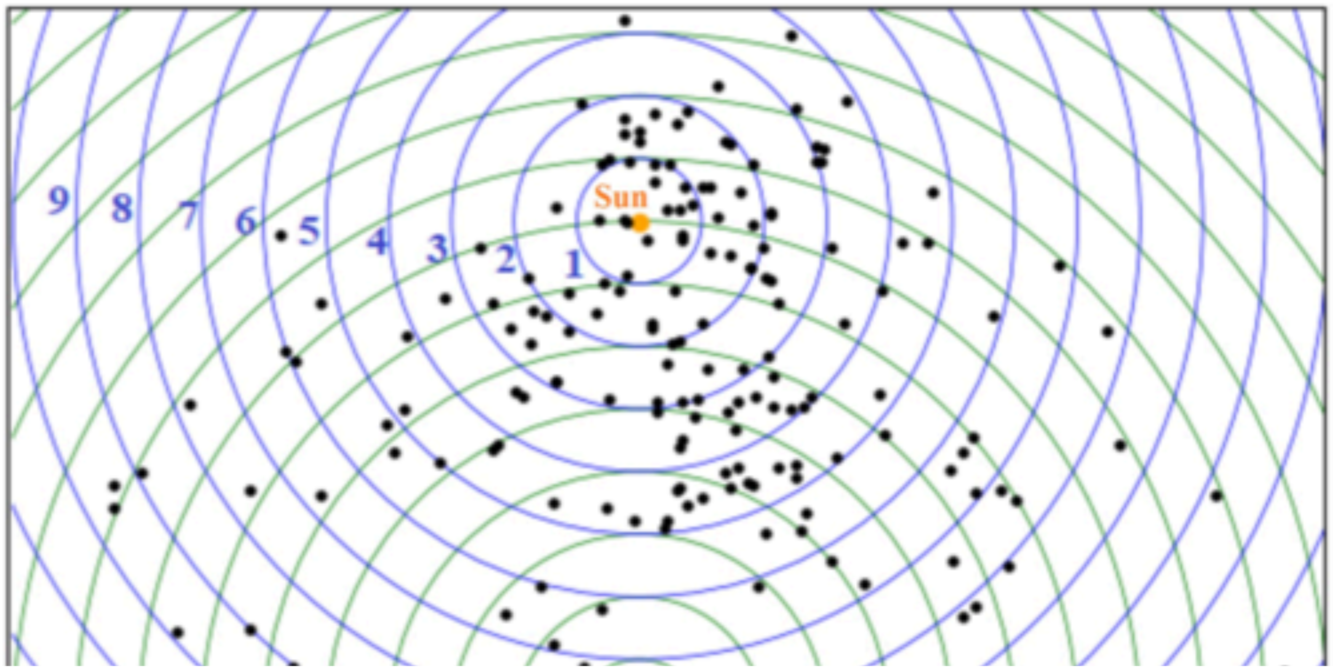




Phan+ 2021

Stochasticity of sources



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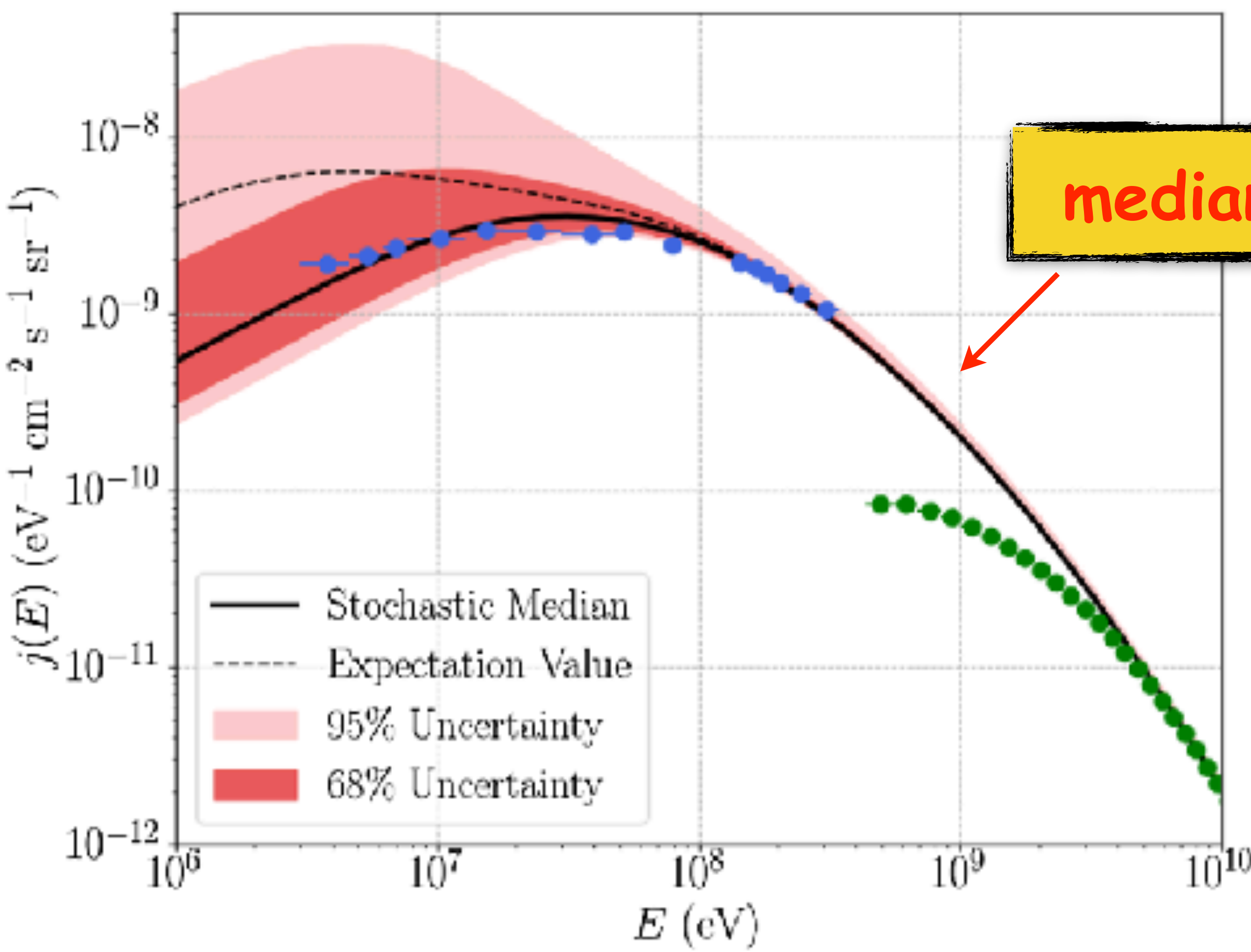
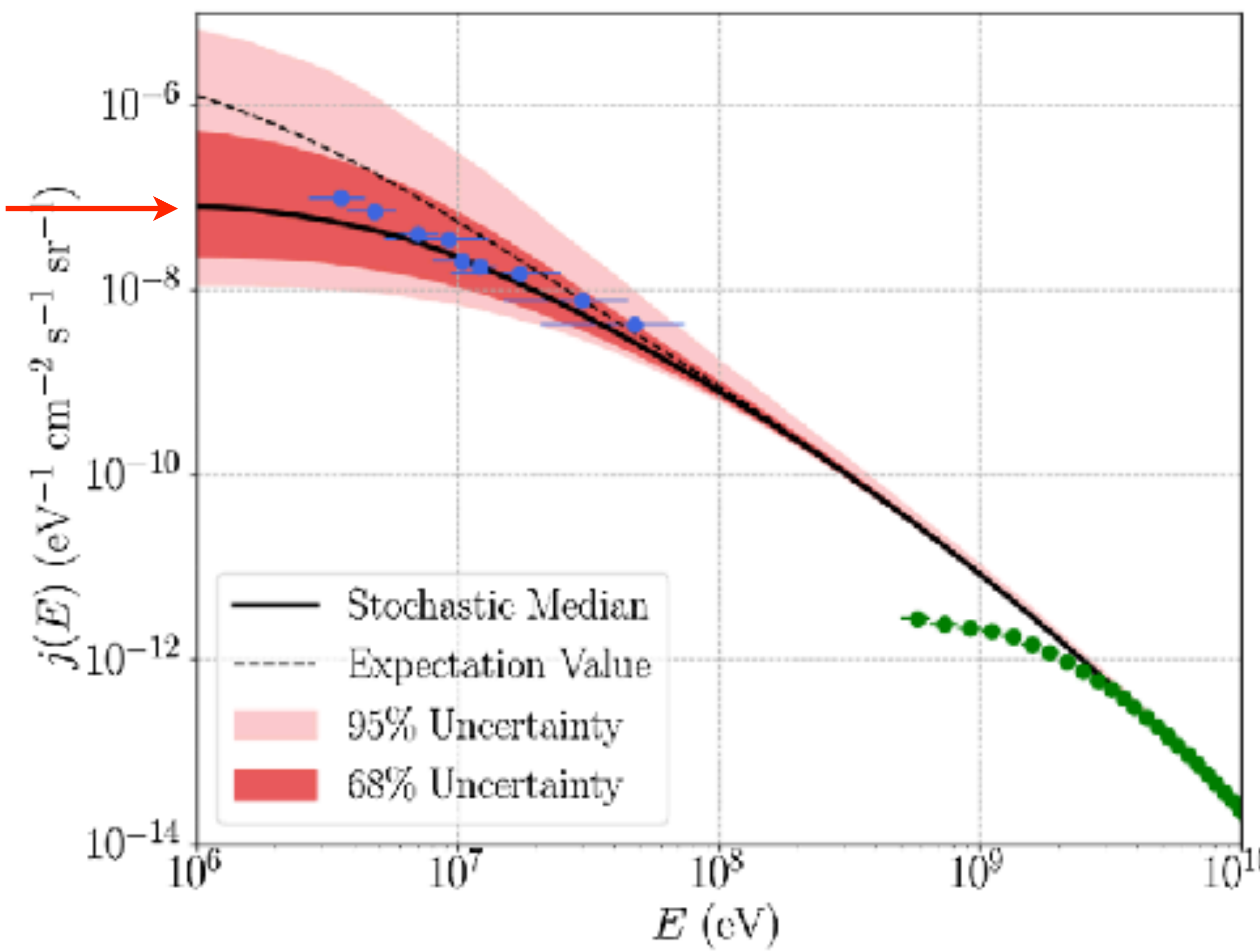
Ranasinghe & Leahy 2022

median





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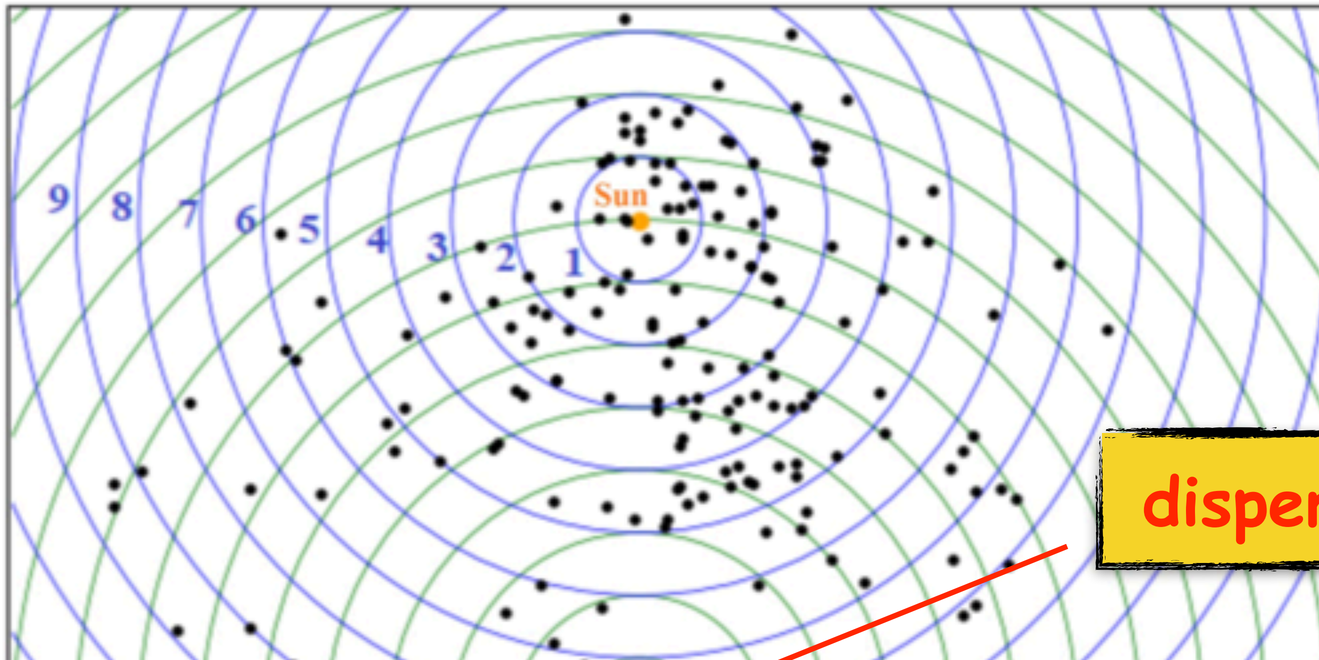

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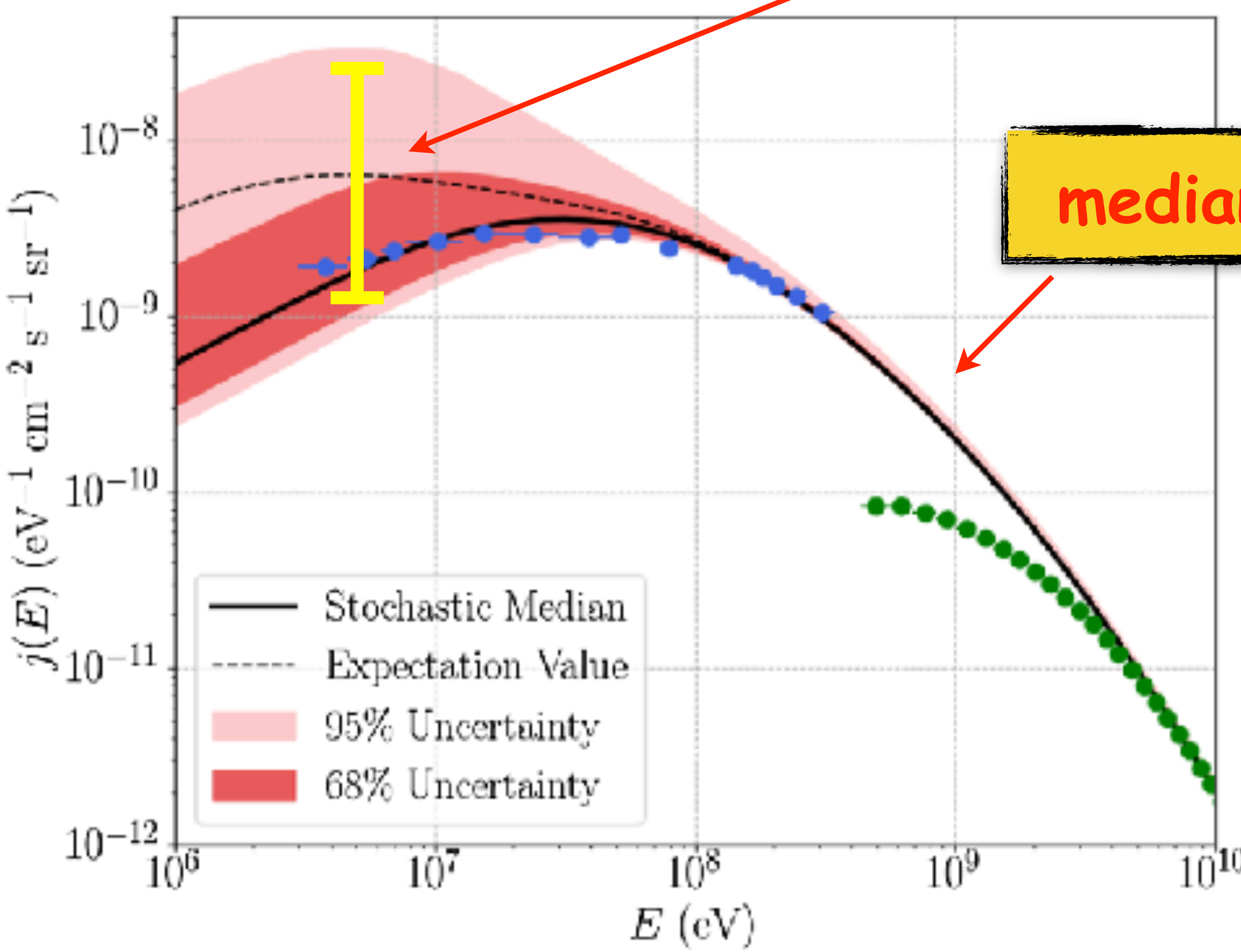
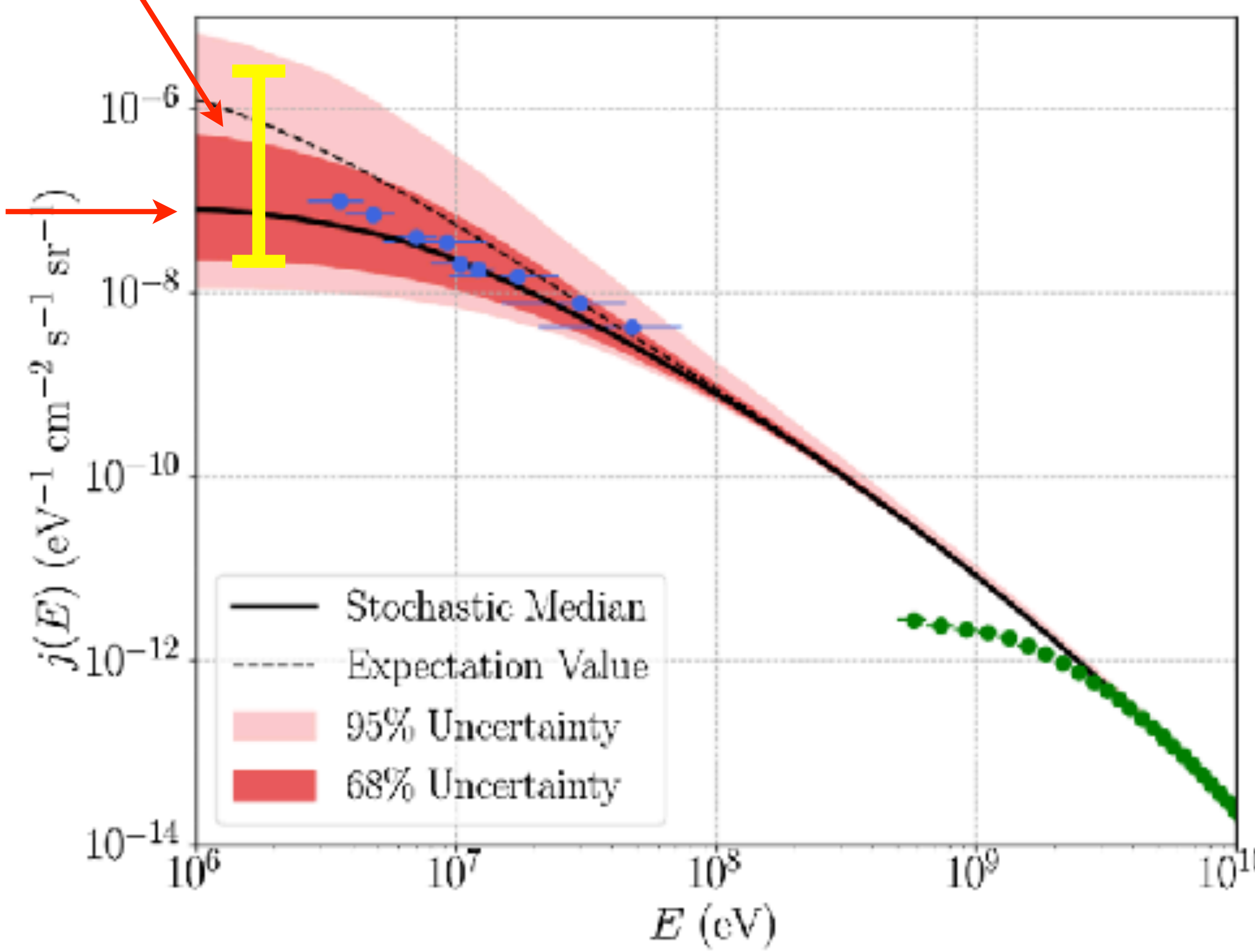
Ranasinghe & Leahy 2022

dispersion

median





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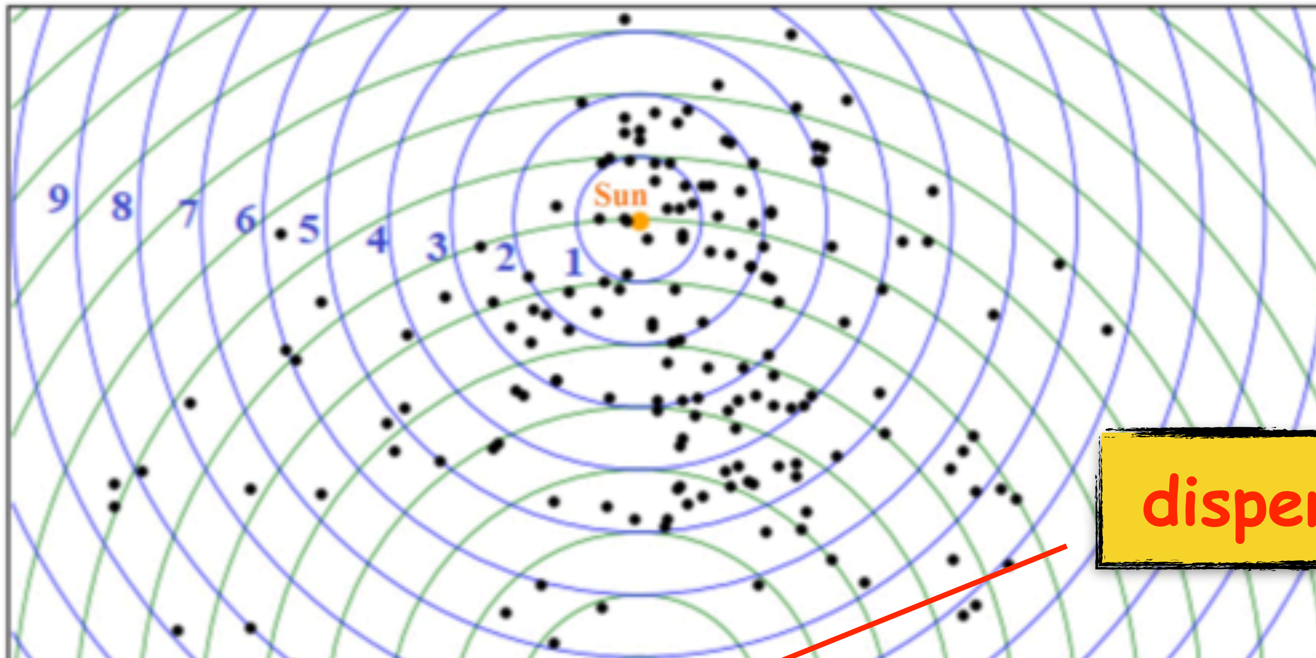
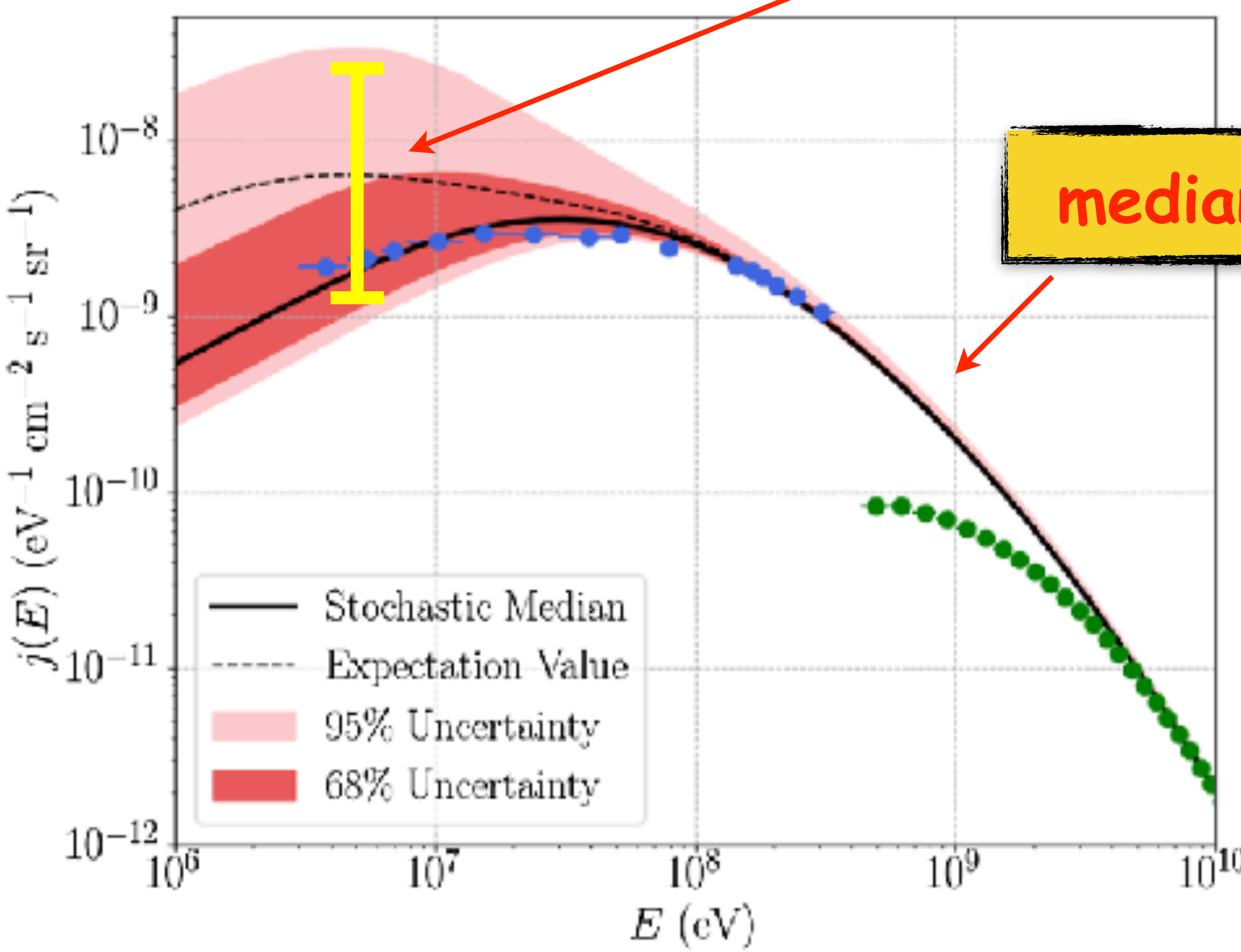


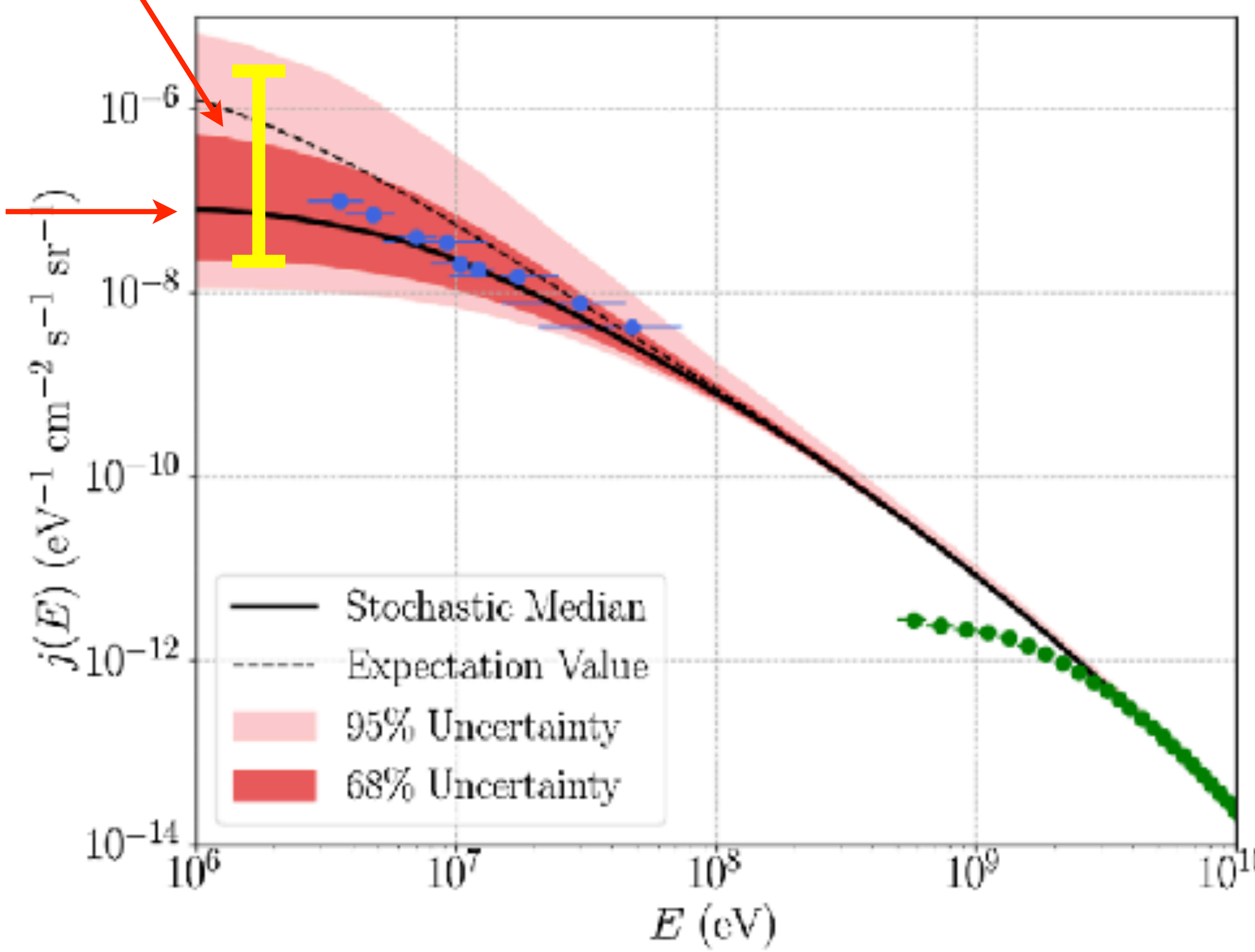
<— position of known SNR in the MW

enhancement of ionisation rate? Stay tuned! (Phan+ submitted —> HIS TALK TOMORROW!)

dispersion

median





Phan+ 2021

Open questions on low energy CRs

We do not understand the origin of the ionisation rates measured in clouds.

Several questions need then to be answered.

- What induces the **large ionisation rates** observed in clouds?
- Are the spectra of low energy CRs measured in the local ISM representative of the entire Galaxy? Or, what is the **spatial distribution** of low energy CRs throughout the Galactic disk?
- Why are diffuse **atomic and molecular** clouds, despite their different column density, characterised by the **same ionisation rate**?
- Why is the ionisation rate so large in the **Galactic centre region**?
- What are the **sites of acceleration** of the low energy CRs responsible for the ionisation of clouds? —> turbulent reaccelerating in clouds? (Gaches+)
- Does the observed intensity of LECRs in the local ISM reflects the fact that we live in a **special place in the Galaxy? —> Local Bubble?** (Silsbee & Ivlev 2019)

The future (I): JWST

$$\mathrm{CR} + \mathrm{H}_2 \rightarrow \mathrm{CR} + \mathrm{H}_2^+ + e^-$$

$$e^- + \mathrm{H}_2 \rightarrow \text{rovibrational line emission (IR)}$$

The future (I): JWST

$$\mathrm{CR} + \mathrm{H_2} \rightarrow \mathrm{CR} + \mathrm{H_2^+} + e^-$$

NO CHEMISTRY!!!

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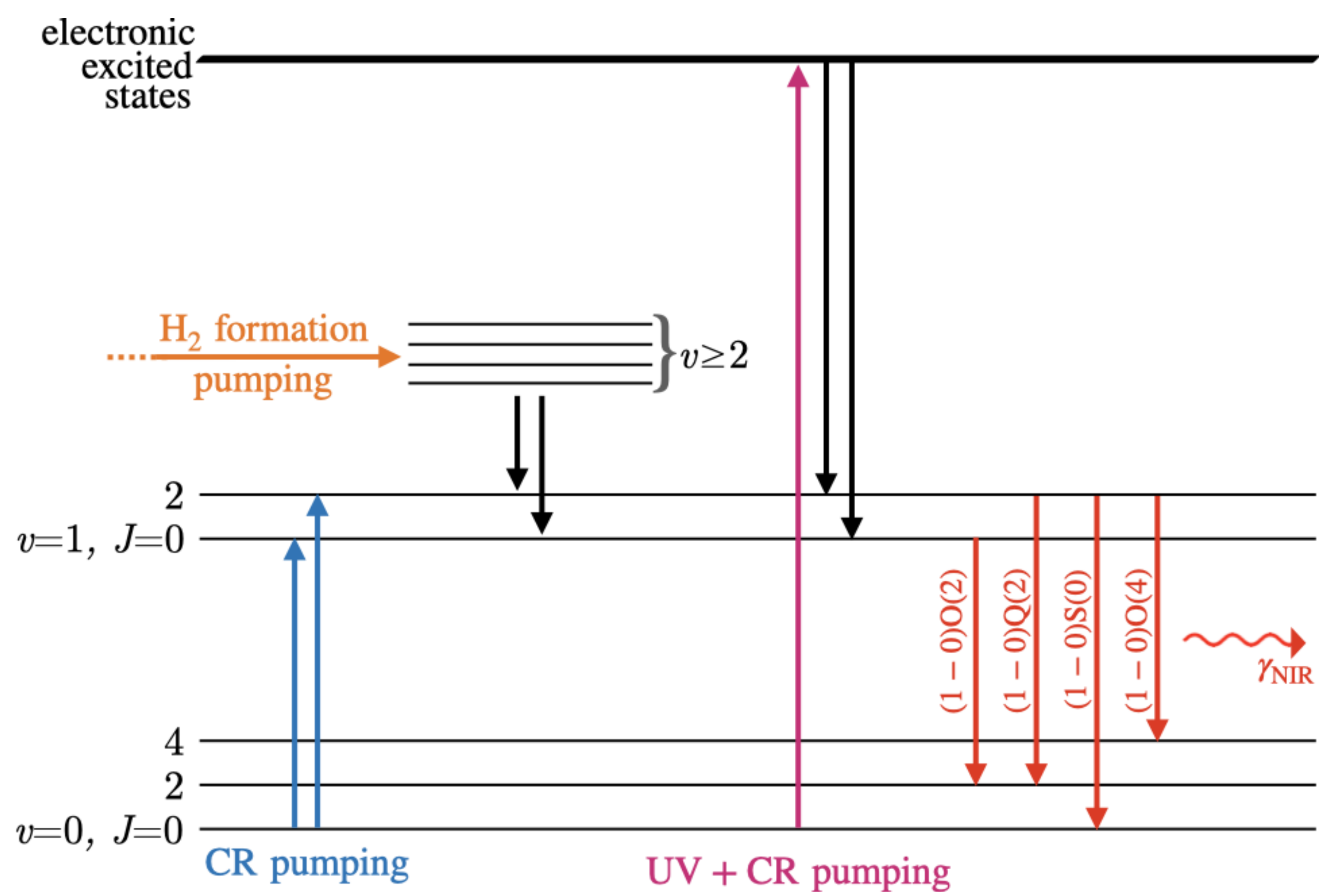
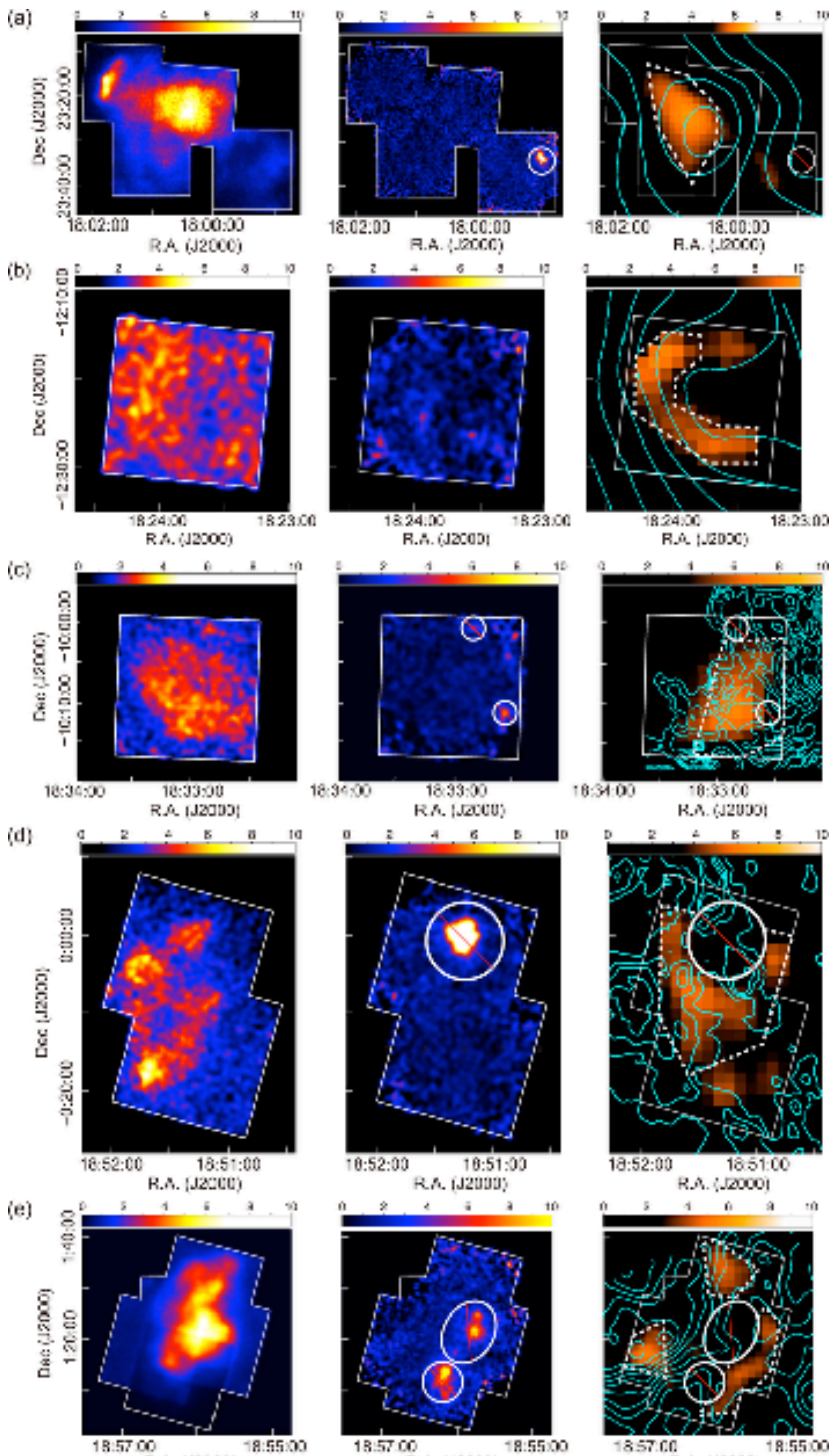
NO CHEMISTRY!!!

detectable by JWST



Padovani+ 2021

The future (II): Athena



cold gas irradiated by CRs
—> Fe Ka line @6.4 keV

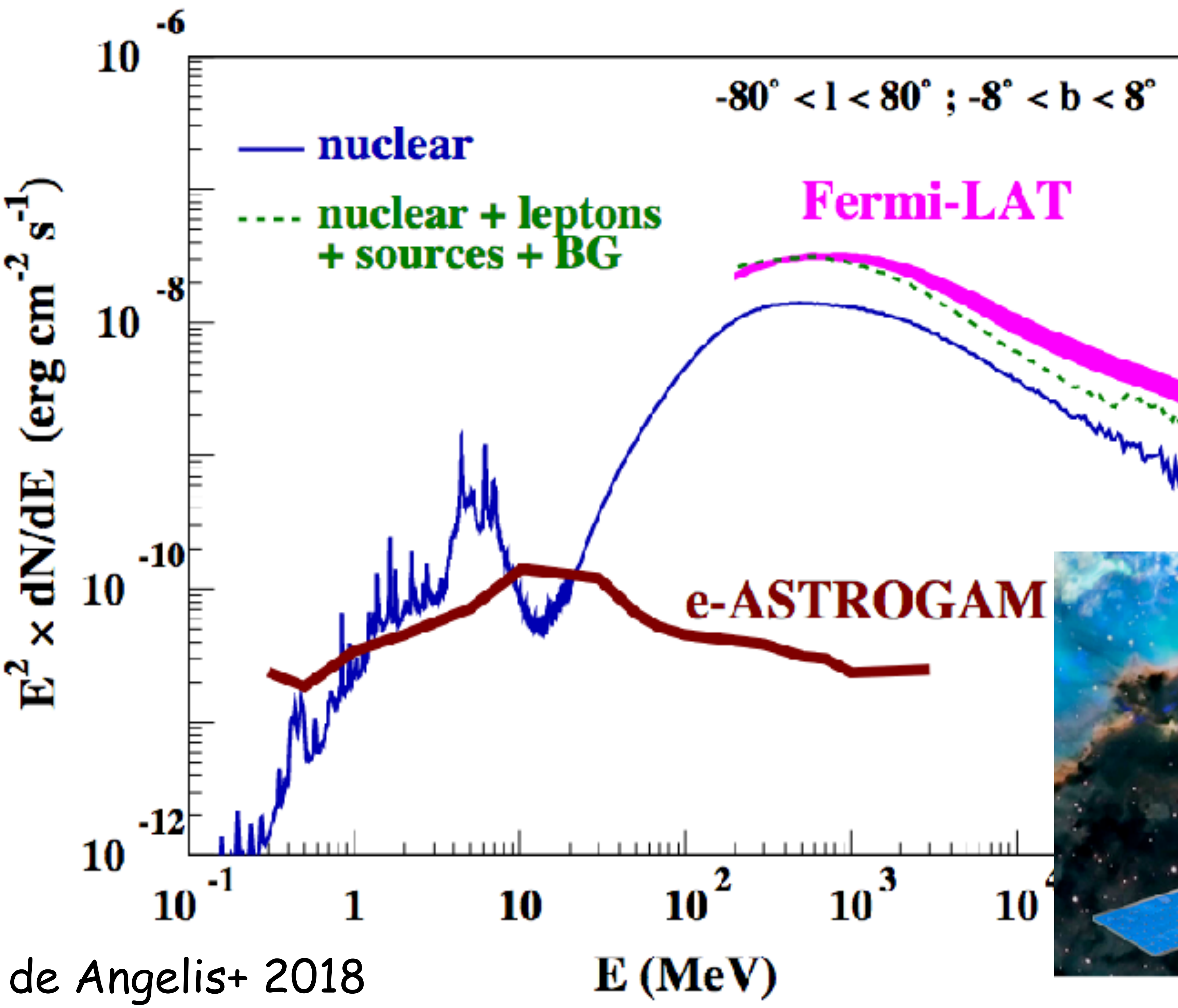
<— tentative evidence from a number of SNRs

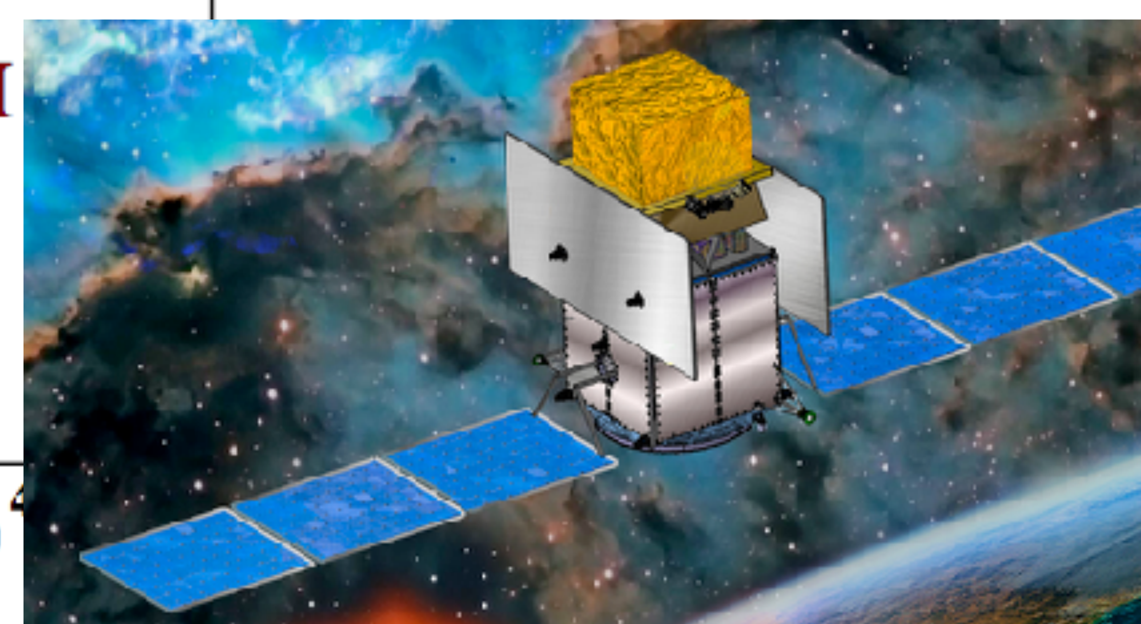
(Nobukawa+ 2018)

—> we need Athena

The future (III): MeV astronomy

De-excitation nuclear gamma-ray line emission (Ramaty+)

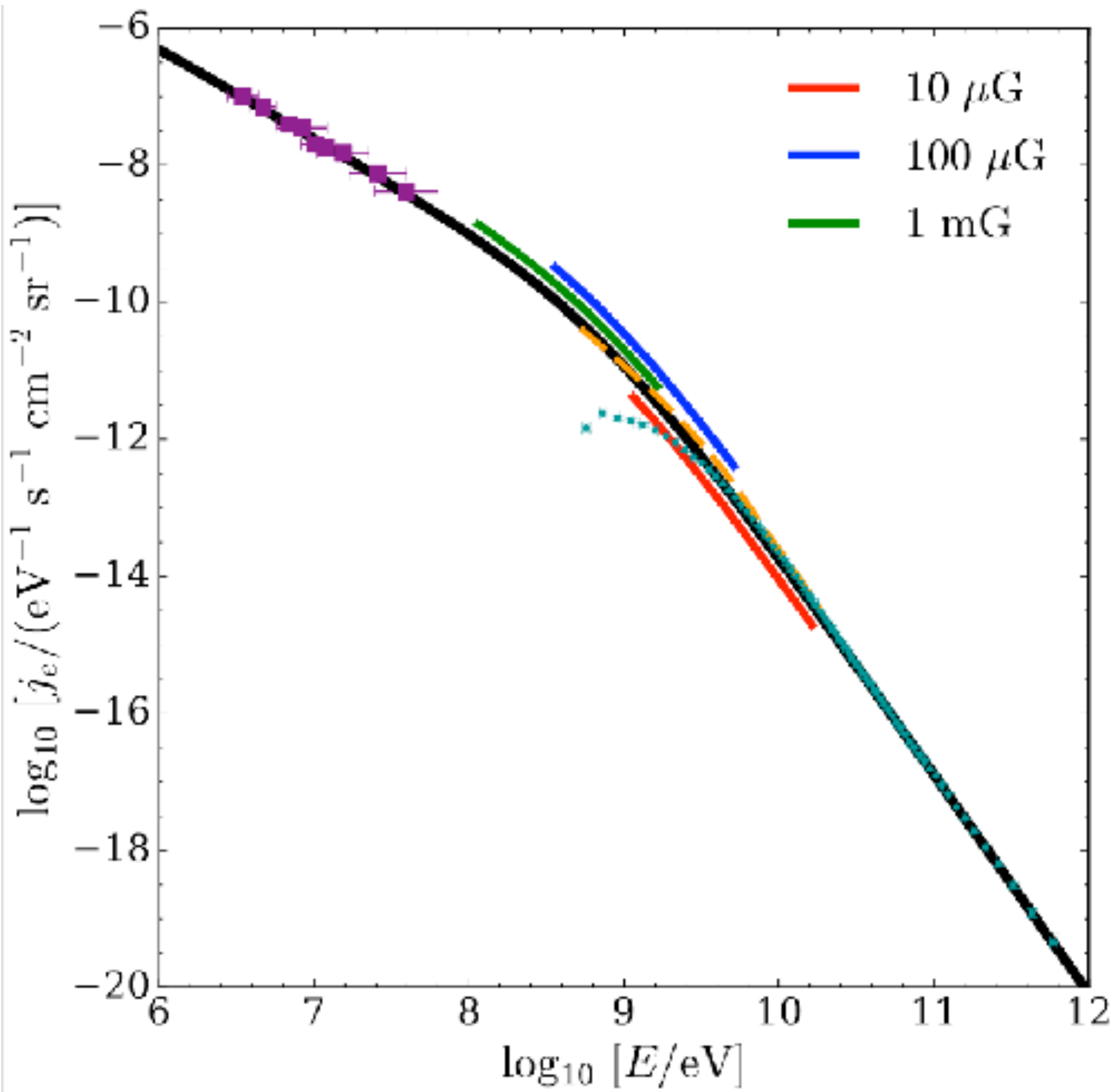




de Angelis+ 2018

The future (IV): SKA

Synchrotron radiation from low energy electrons

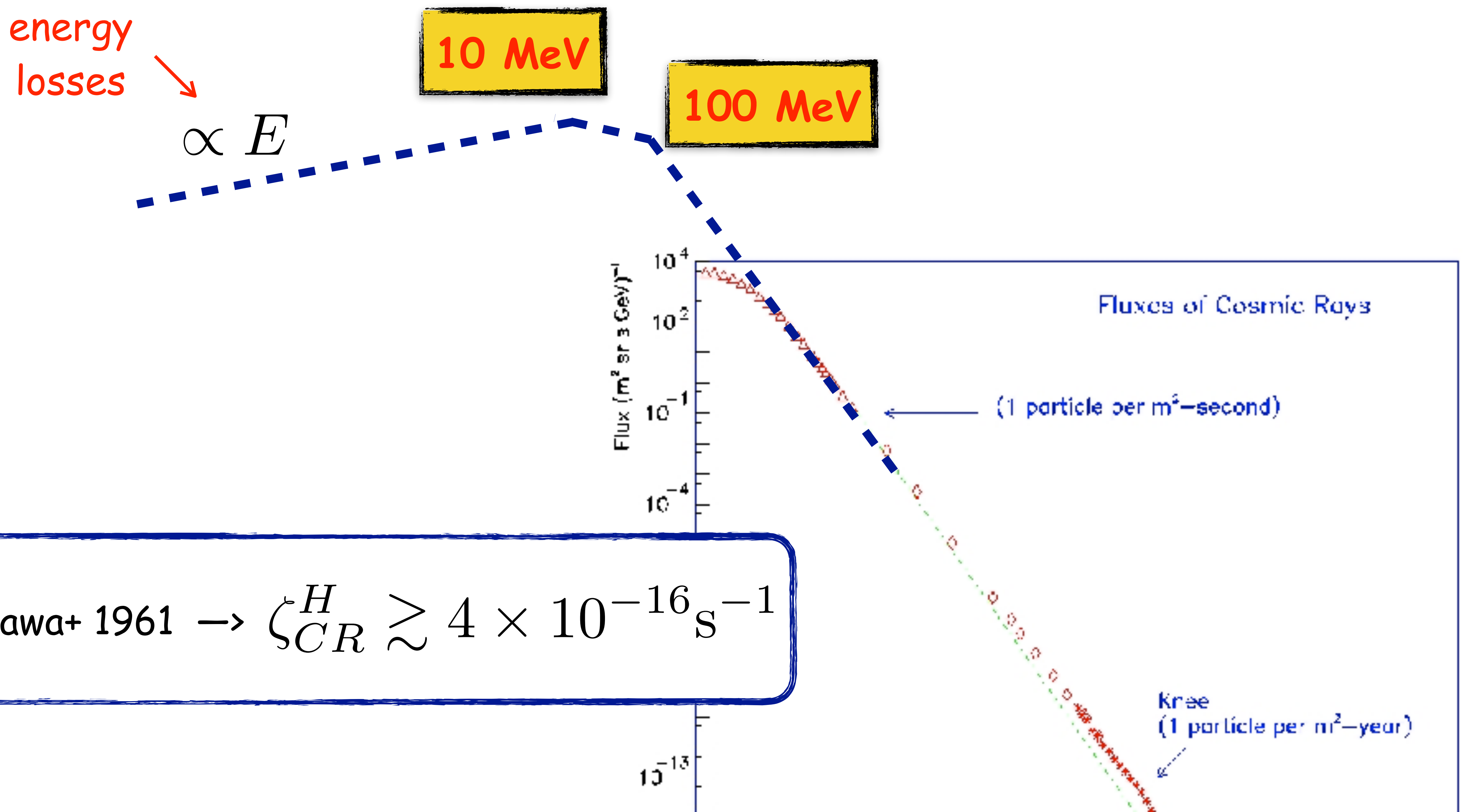


Padovani & Galli 2018

Merci!

Backup slides

Pioneering studies



Hayakawa+ 1961 → $\zeta_{CR}^{H} \gtrsim 4 \times 10^{-16} \mathrm{s}^{-1}$

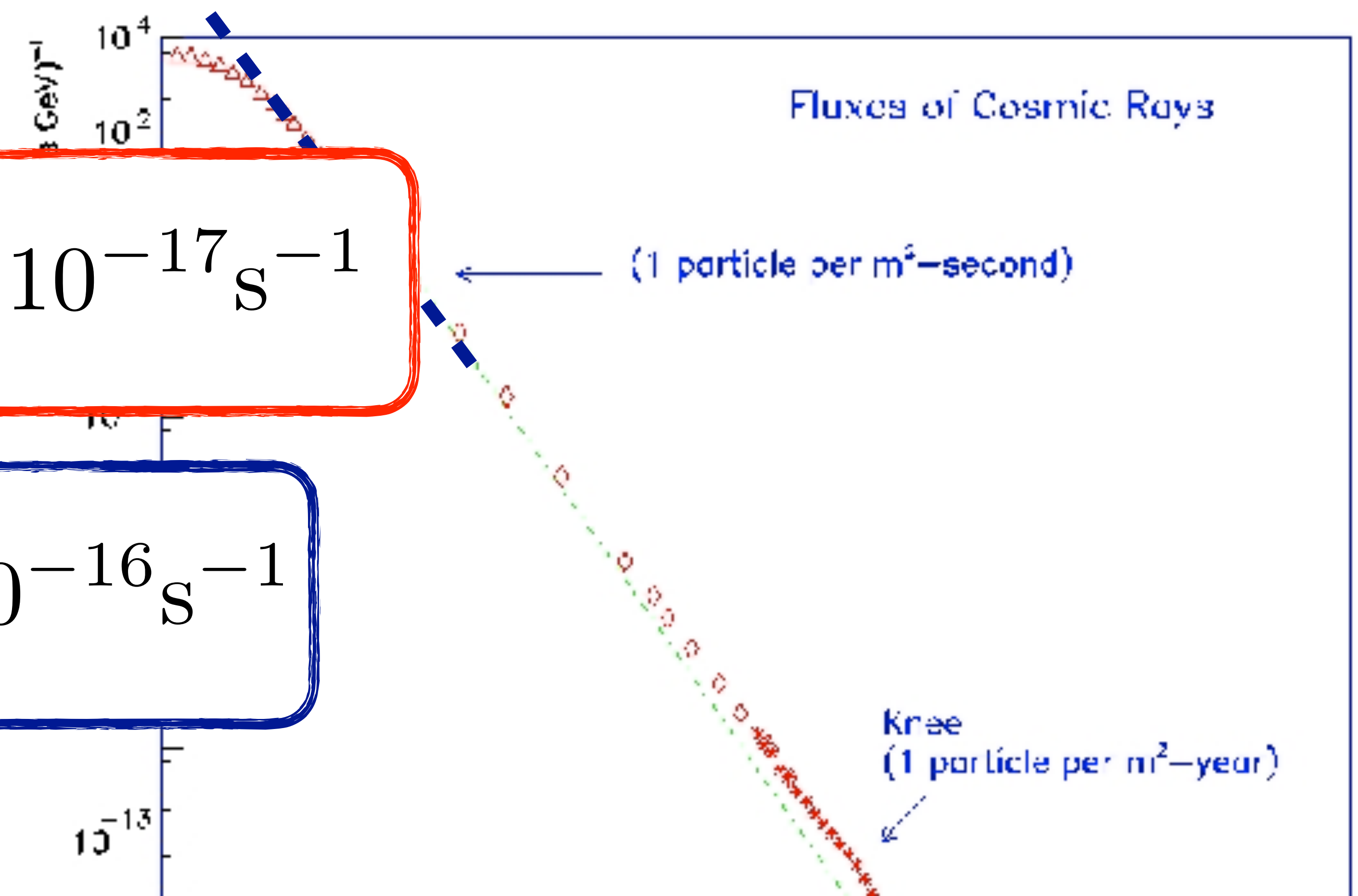
Pioneering studies

energy losses

$\propto E$

10 MeV

0.85 GeV



Spitzer&Tomasko 1968
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Pioneering studies

for some reason, the Spitzer value became the standard reference

energy losses ↘ $\propto E$

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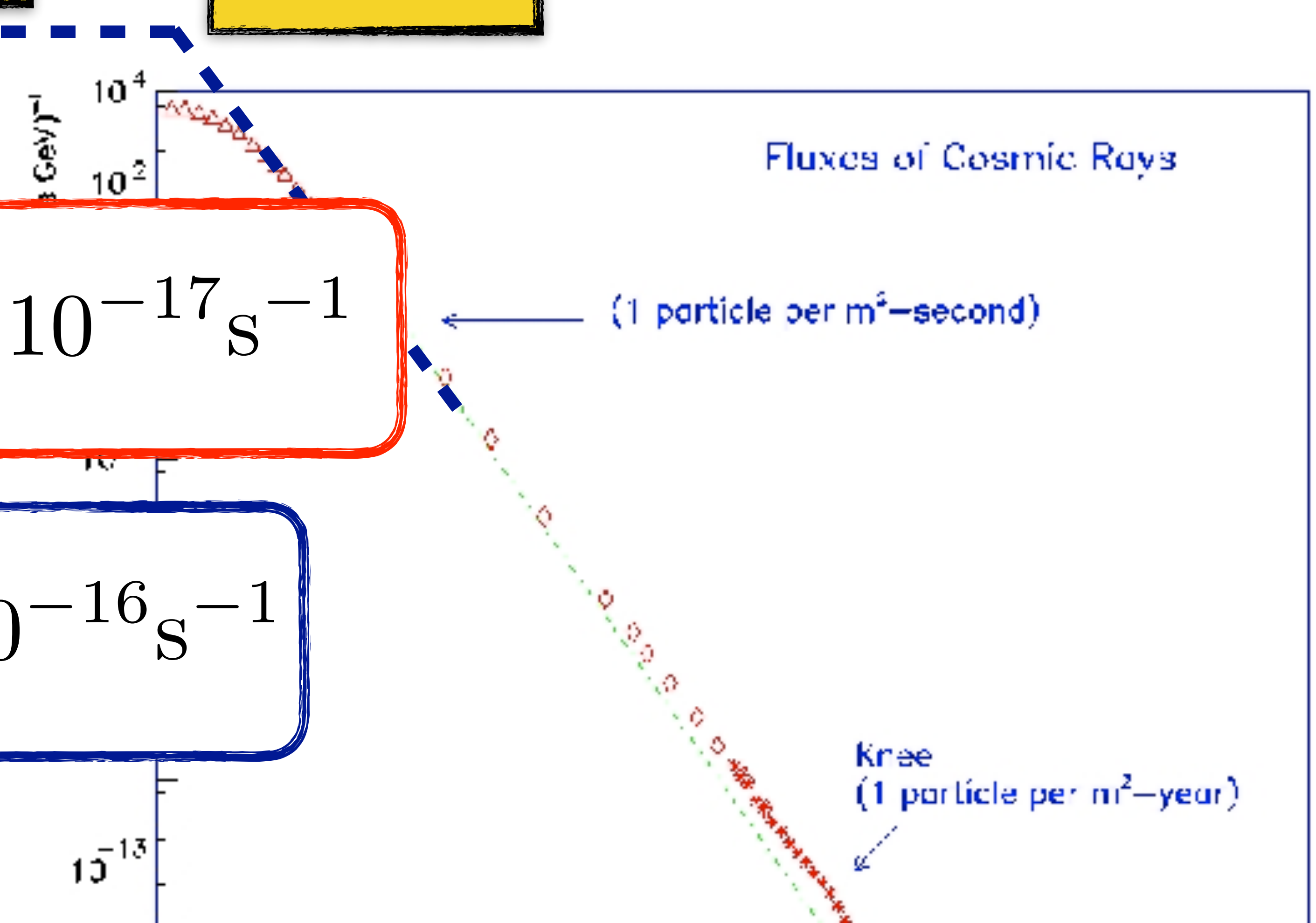

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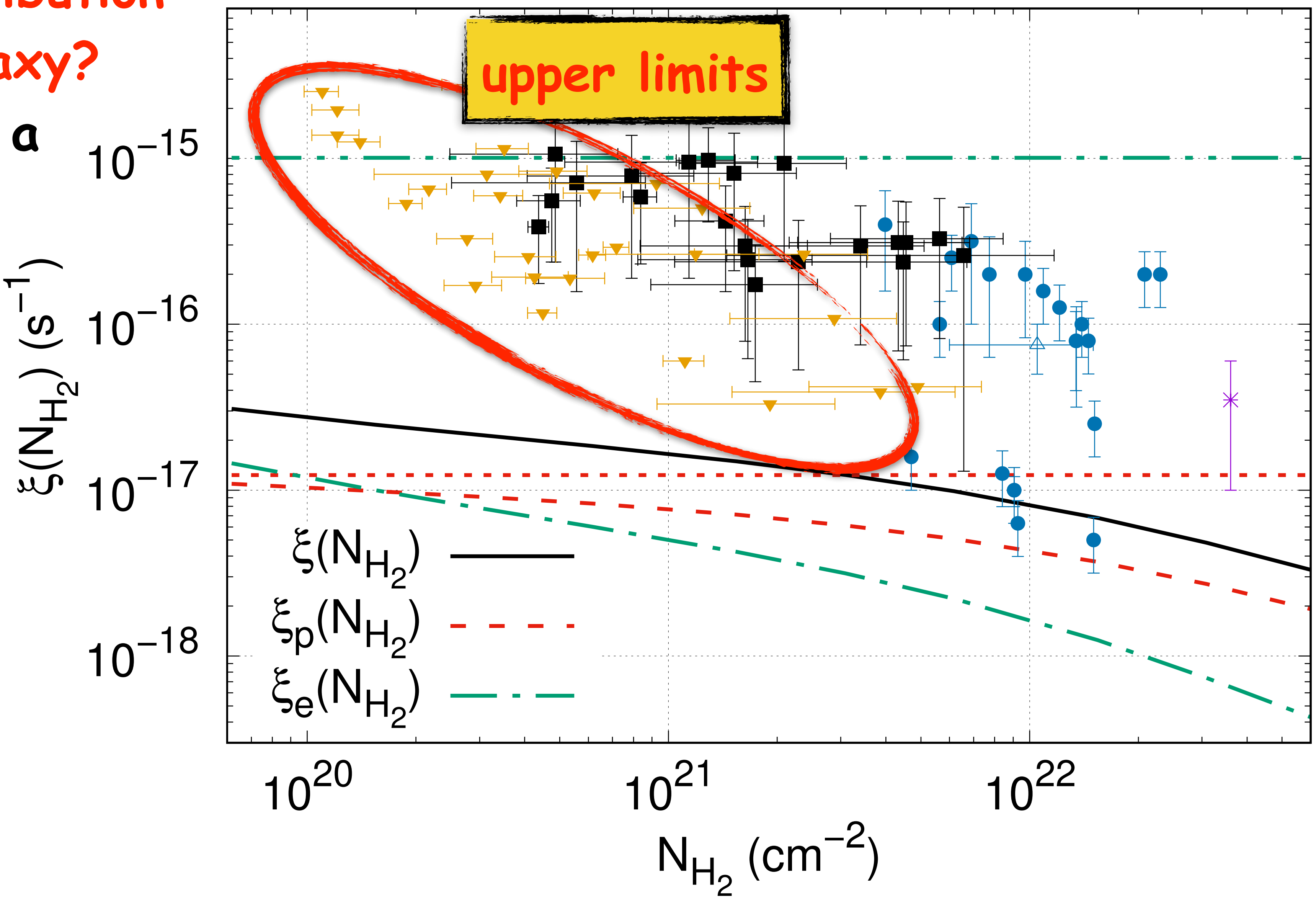
(see Cesarsky 1975 for a pioneering work)



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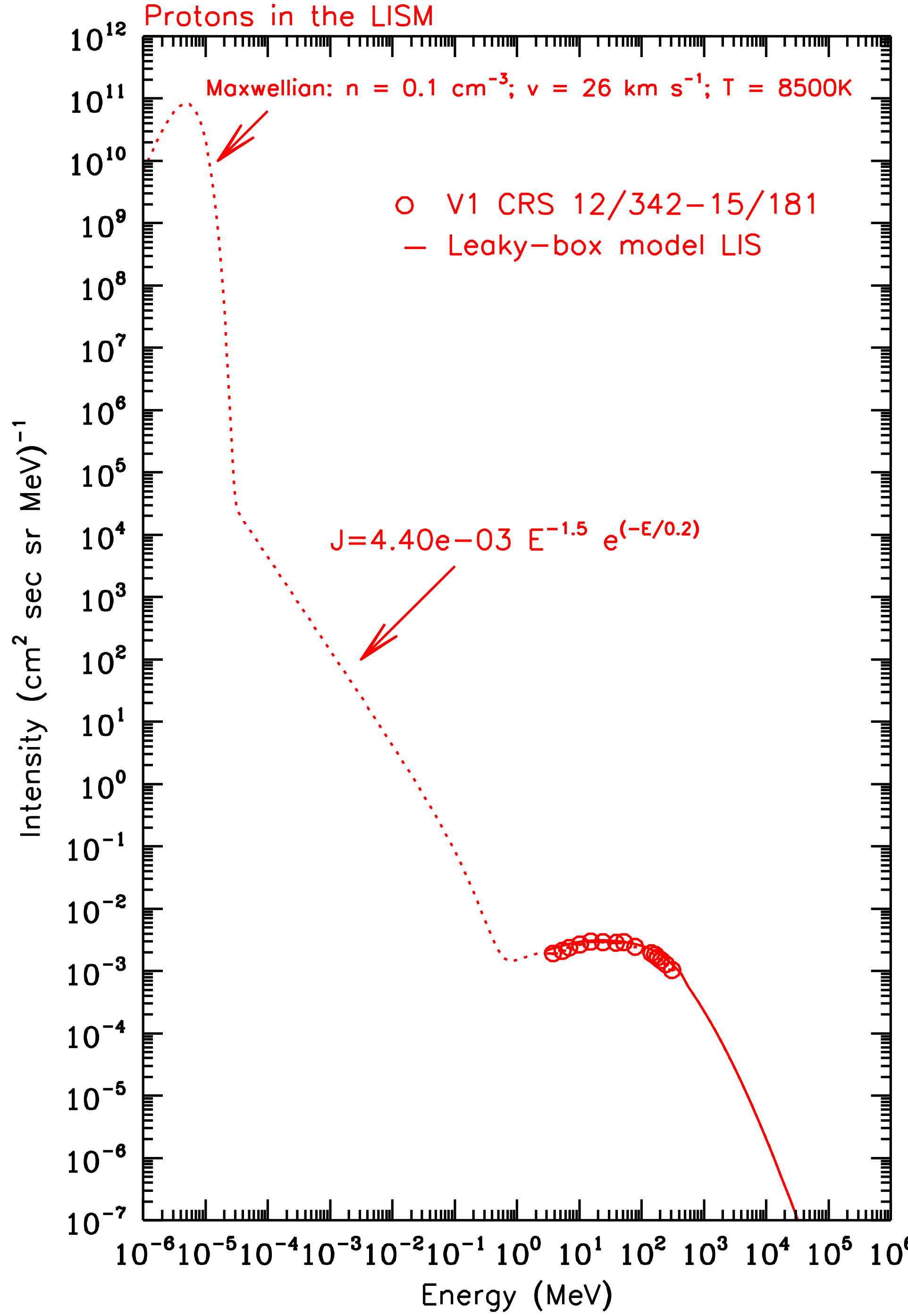

Cummings+ 2016

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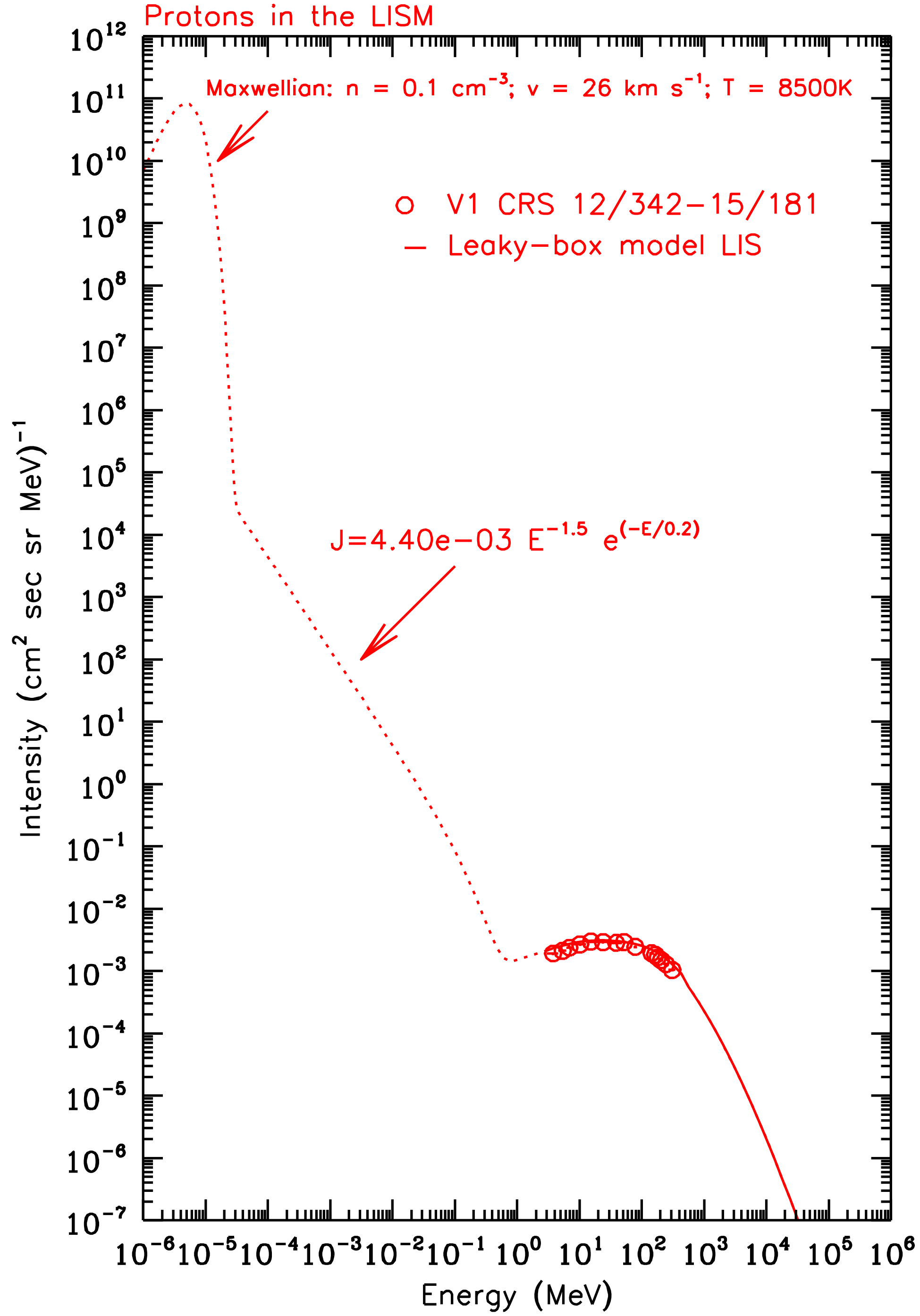
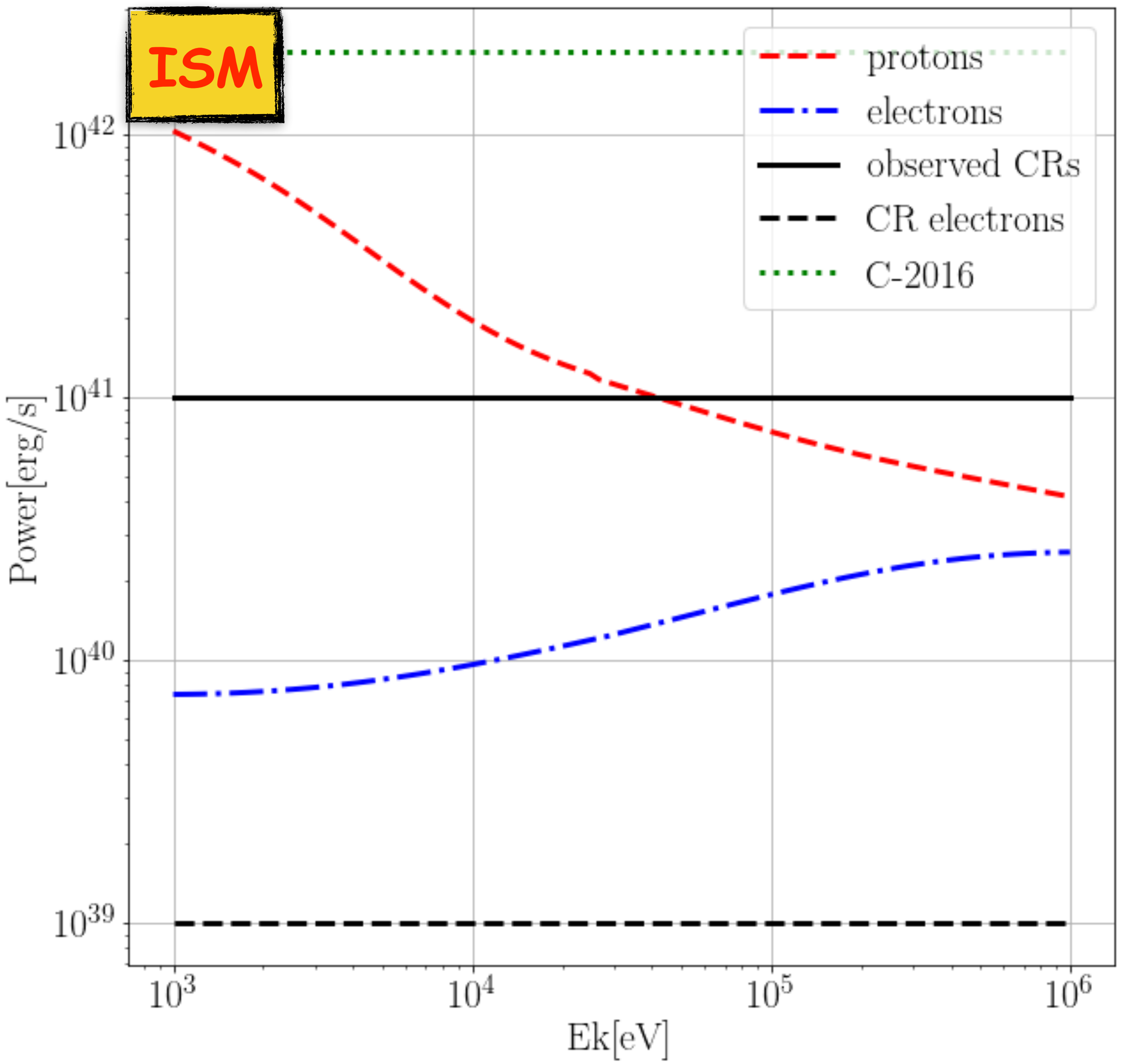


Cummings+ 2016

A cosmic ray carrot?



Cummings+ 2016

CRp luminosity of MW

CRe luminosity of MW

Recchia+ 2018

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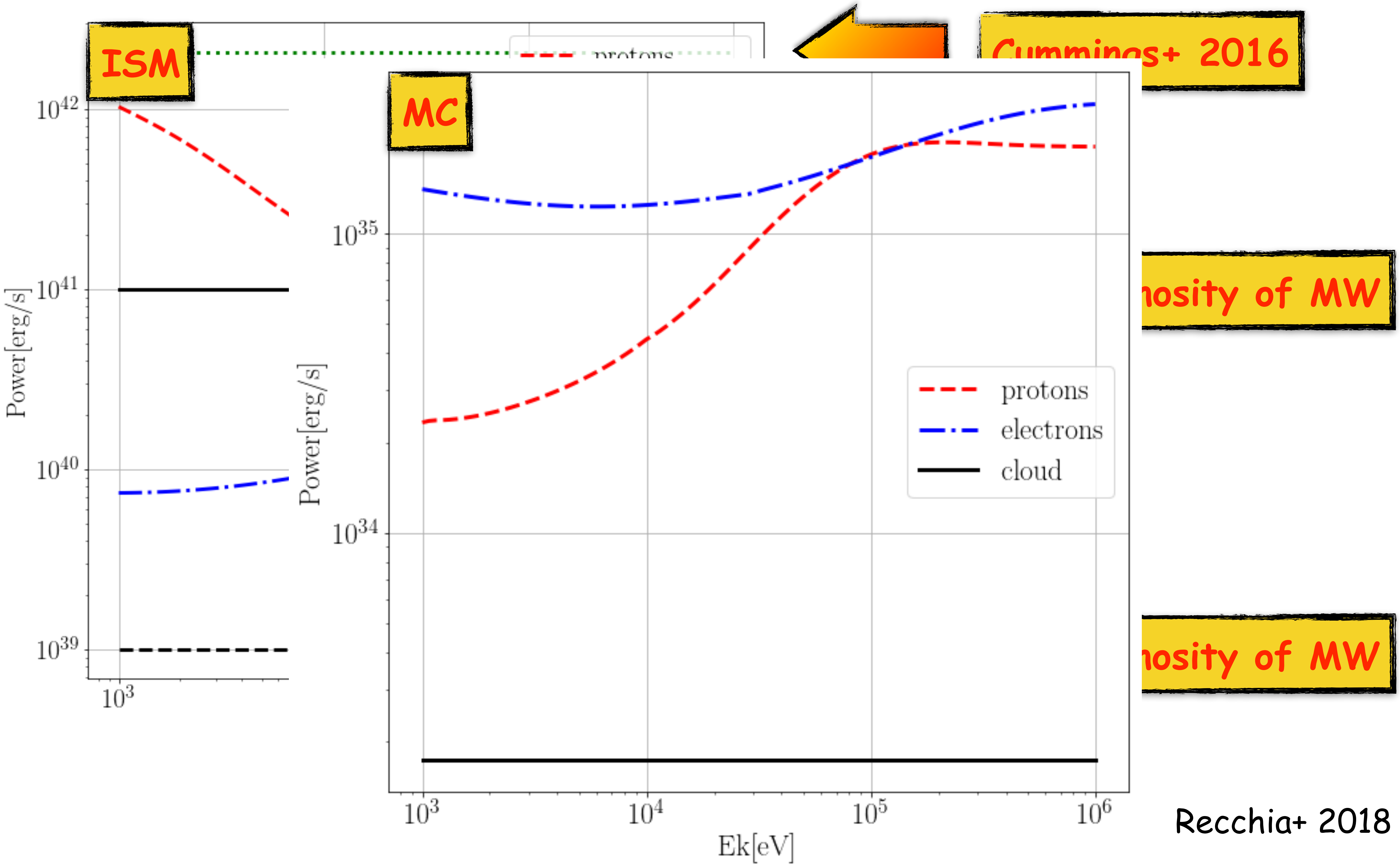

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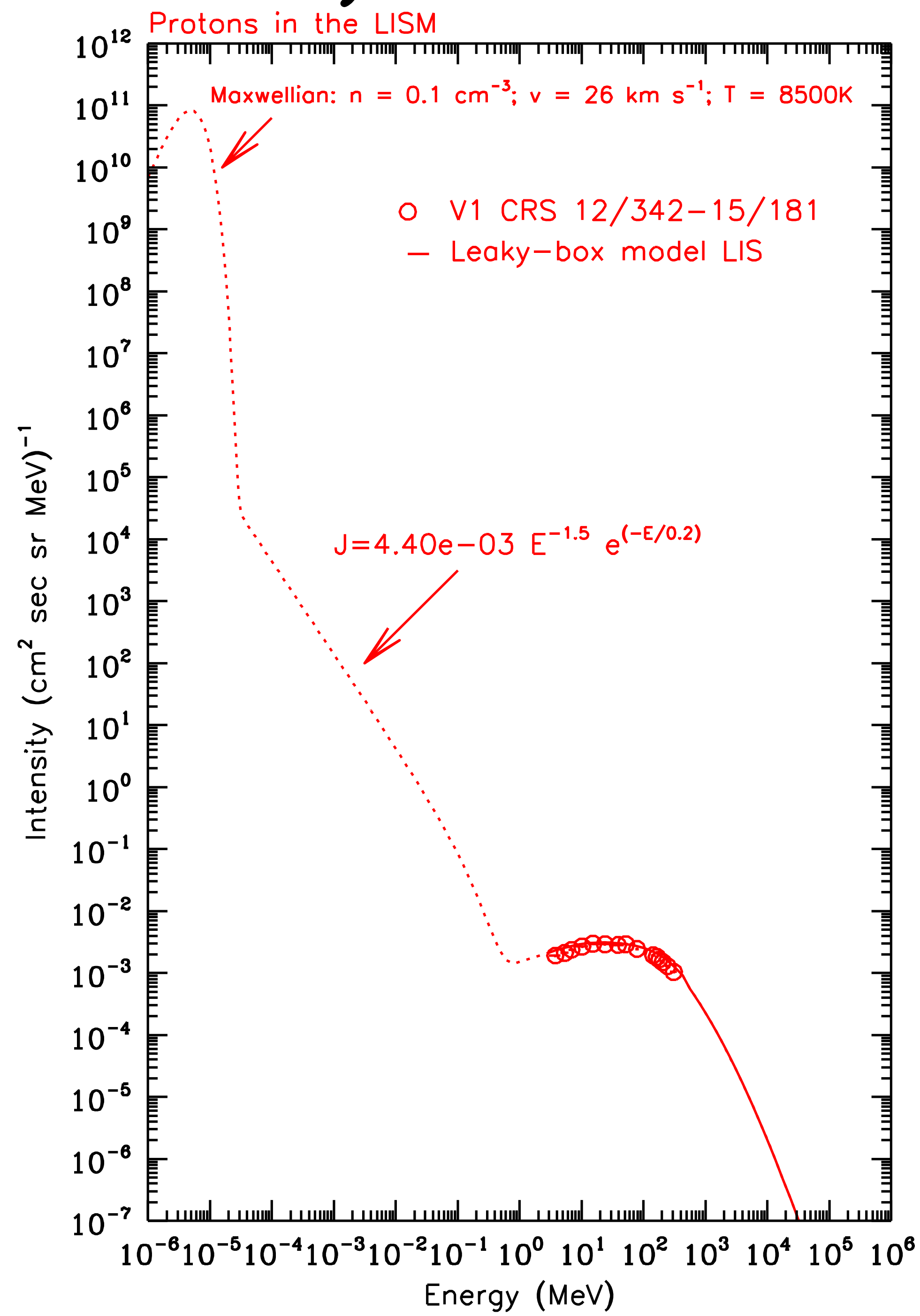


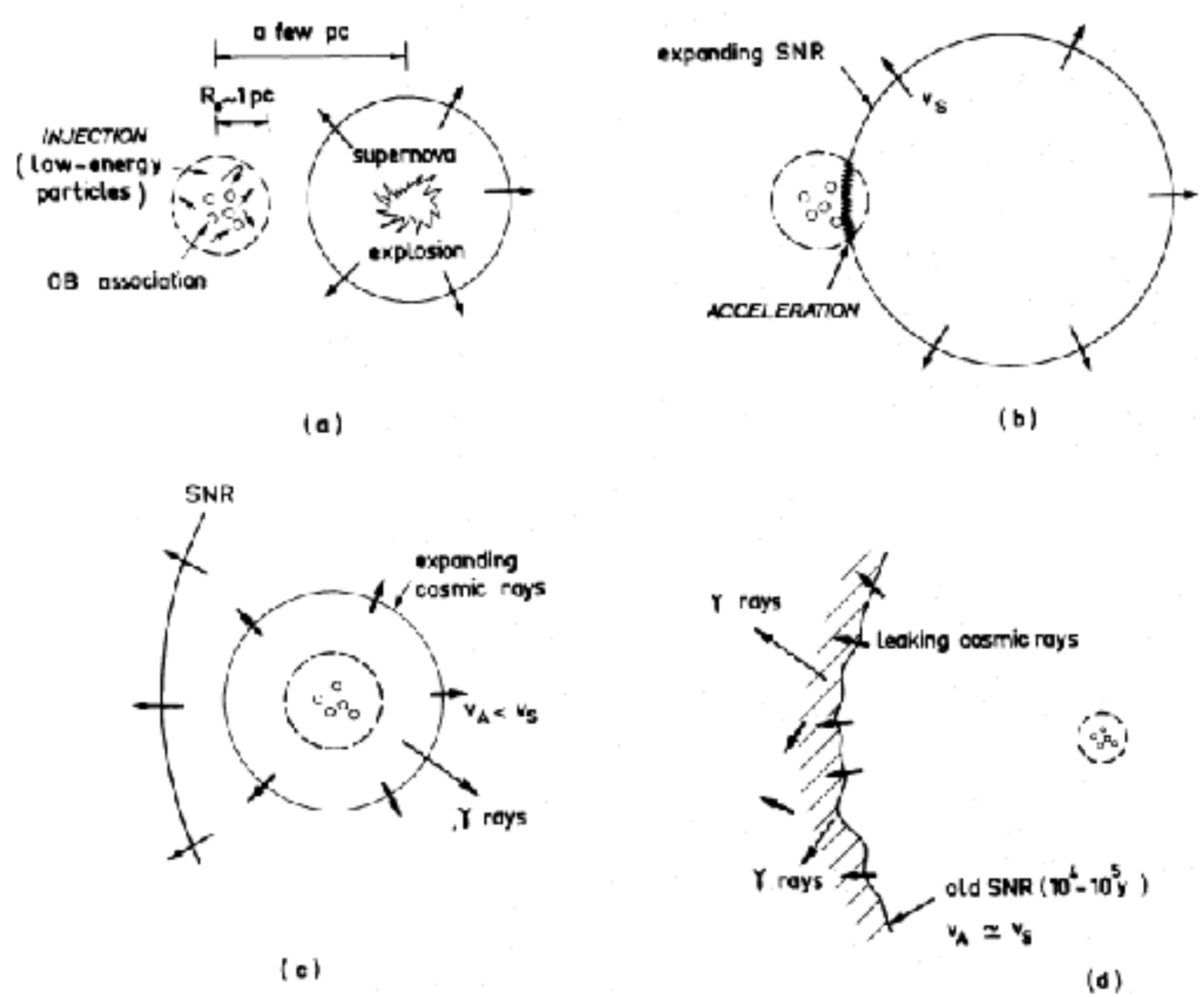
Cummings+ 2016

The importance of being a SNOB

Montmerle 1979

SuperNovae → SN; OB associations → OB

tentative spatial association between SNOBs and COS B hot spots



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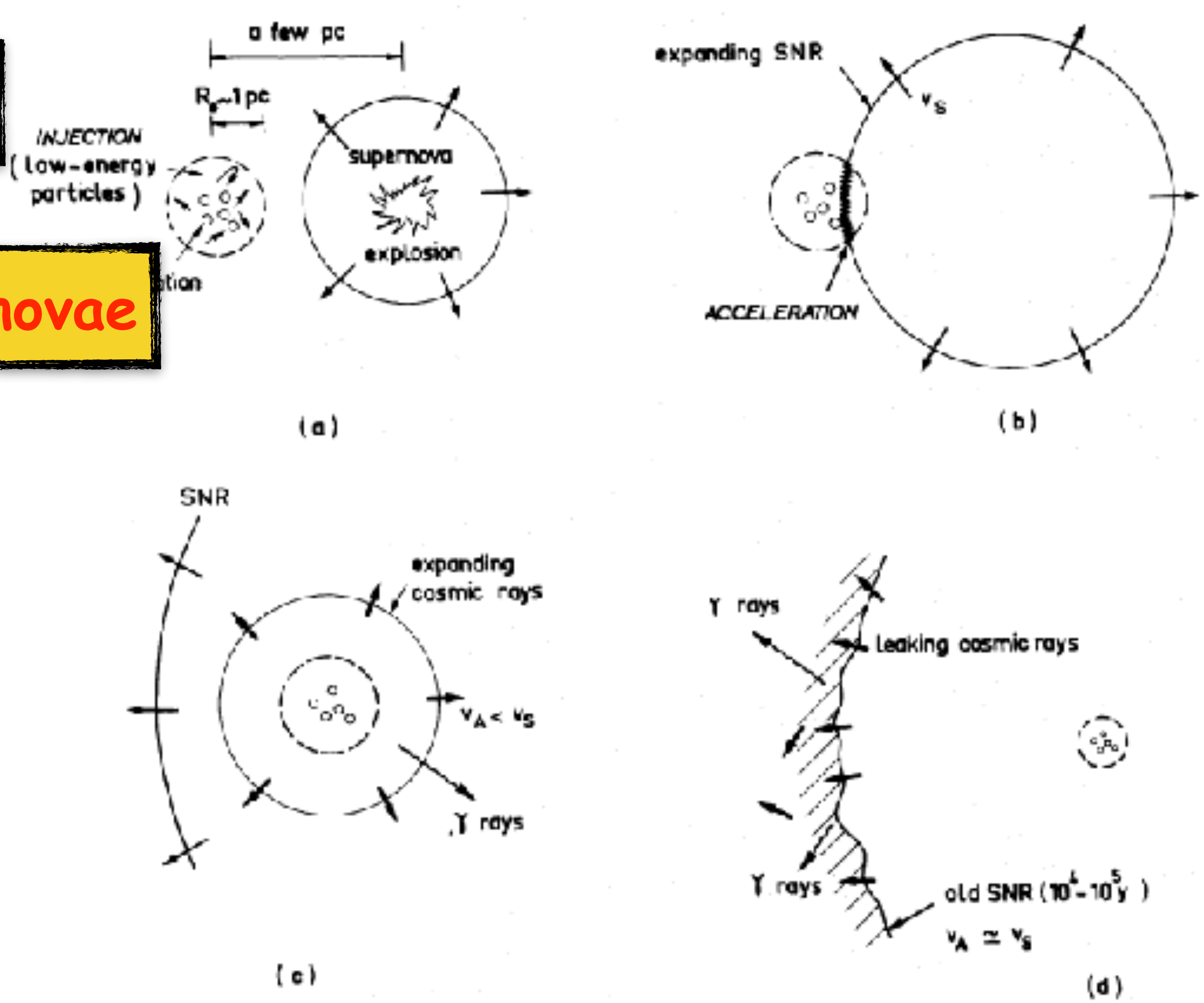
OB stars

supernovae



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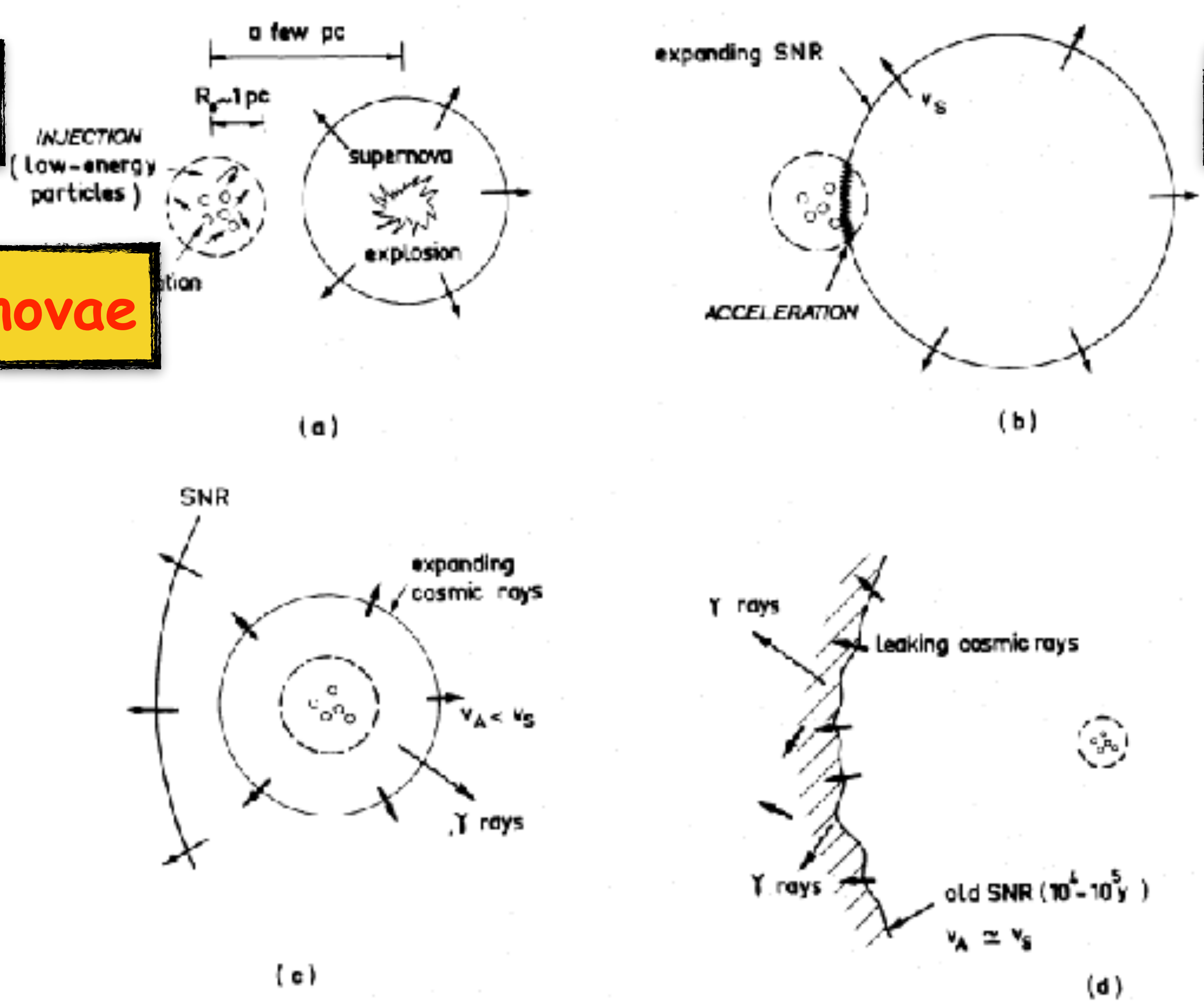
SNRs

CR acceleration



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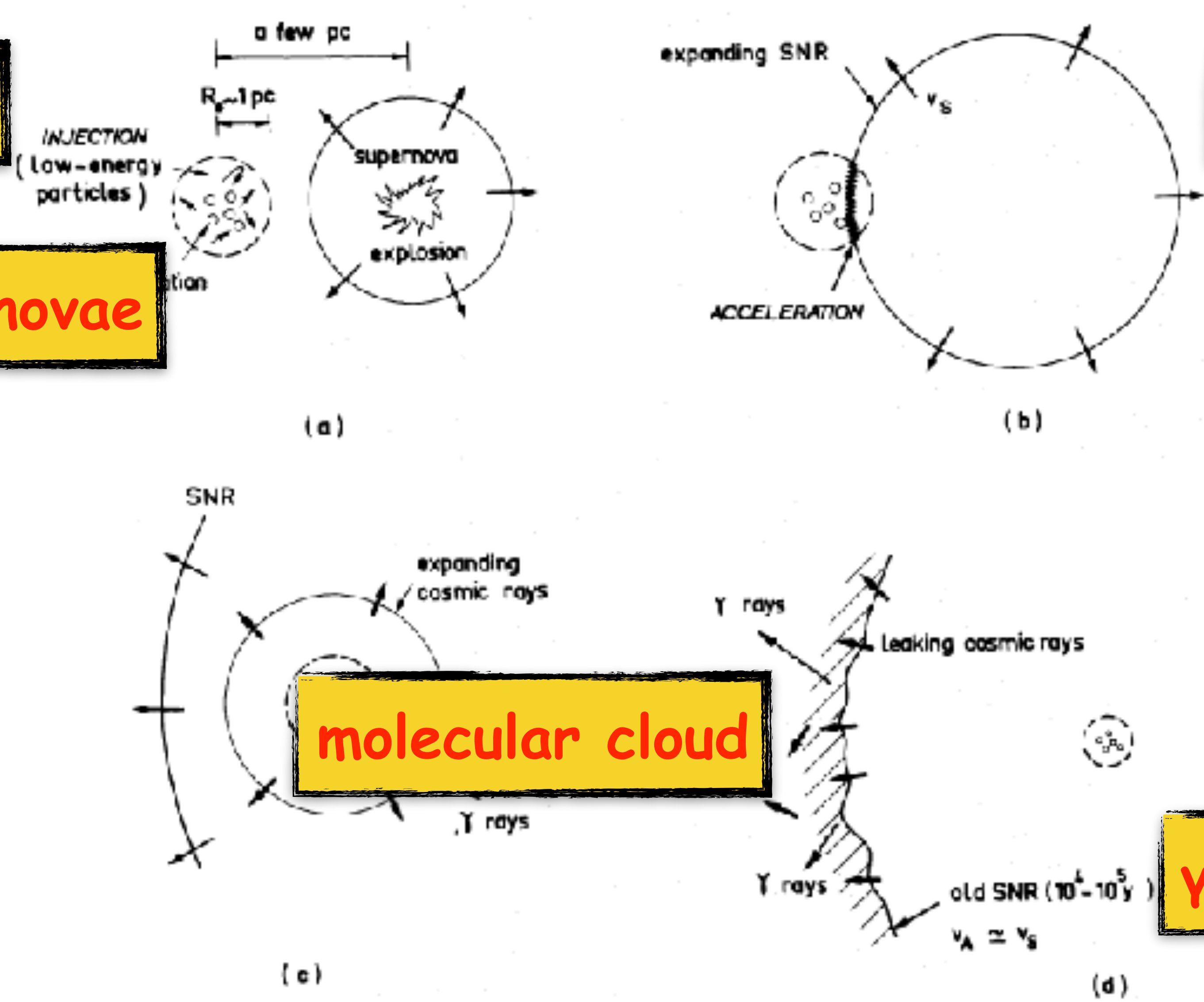


molecular cloud

γ-rays

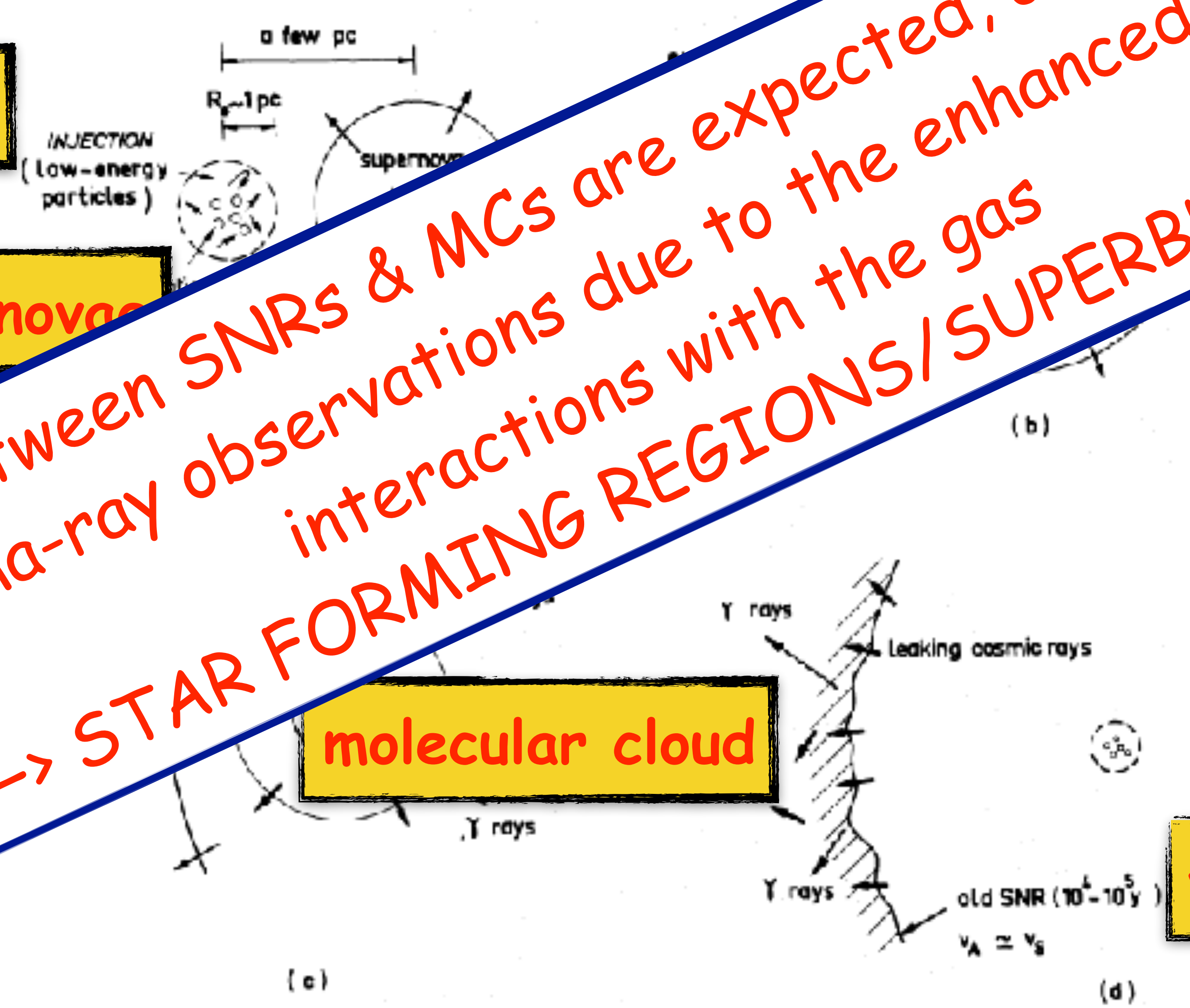
Black & Fazio 1973

The importance of being a SNOB

Montmerle 1979

SuperNovae OB tions

tentative spatial association between SNOBs



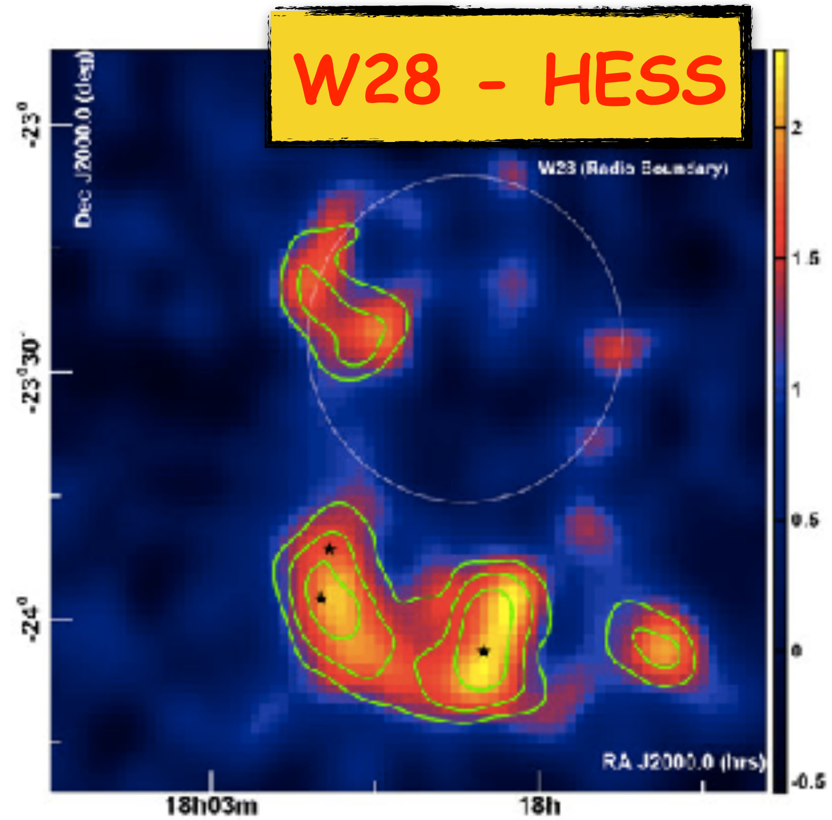
Black & Fazio 1973

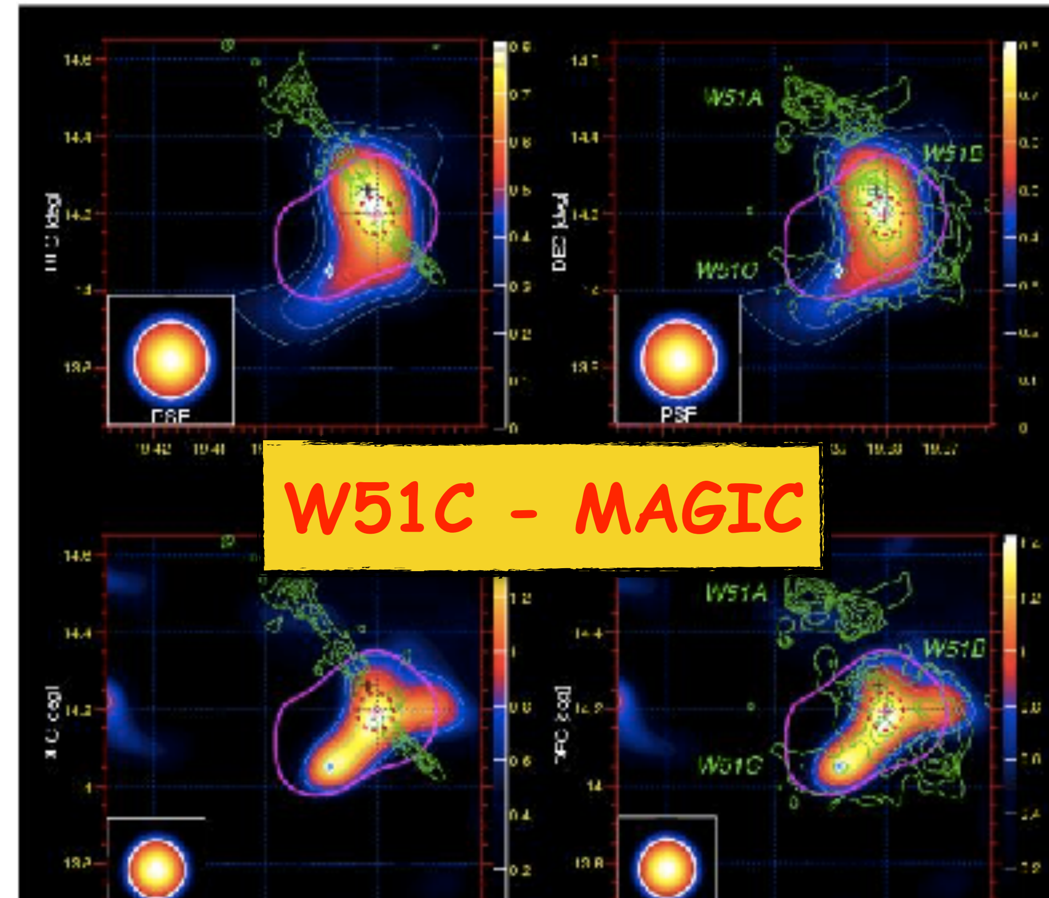
associations between SNRs & MCs are expected, and are ideal targets for gamma-ray observations due to the enhanced rate of CR interactions with the gas

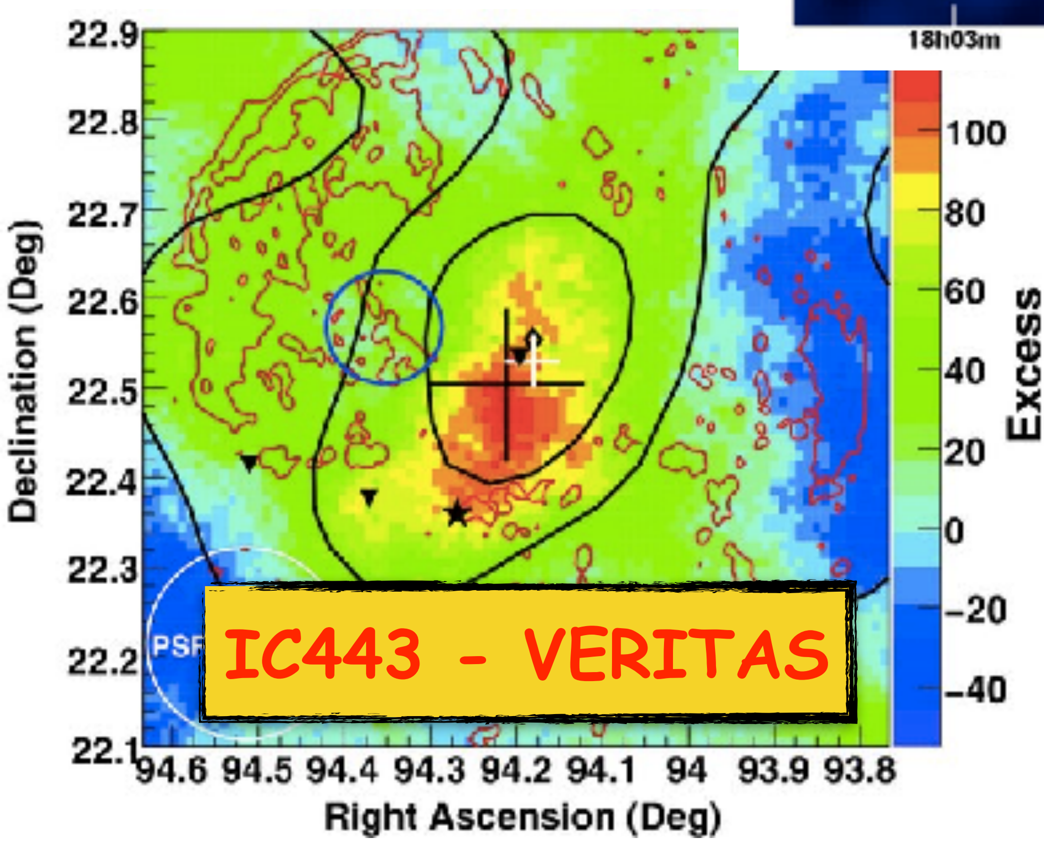
--> STAR FORMING REGIONS/SUPERBUBBLES

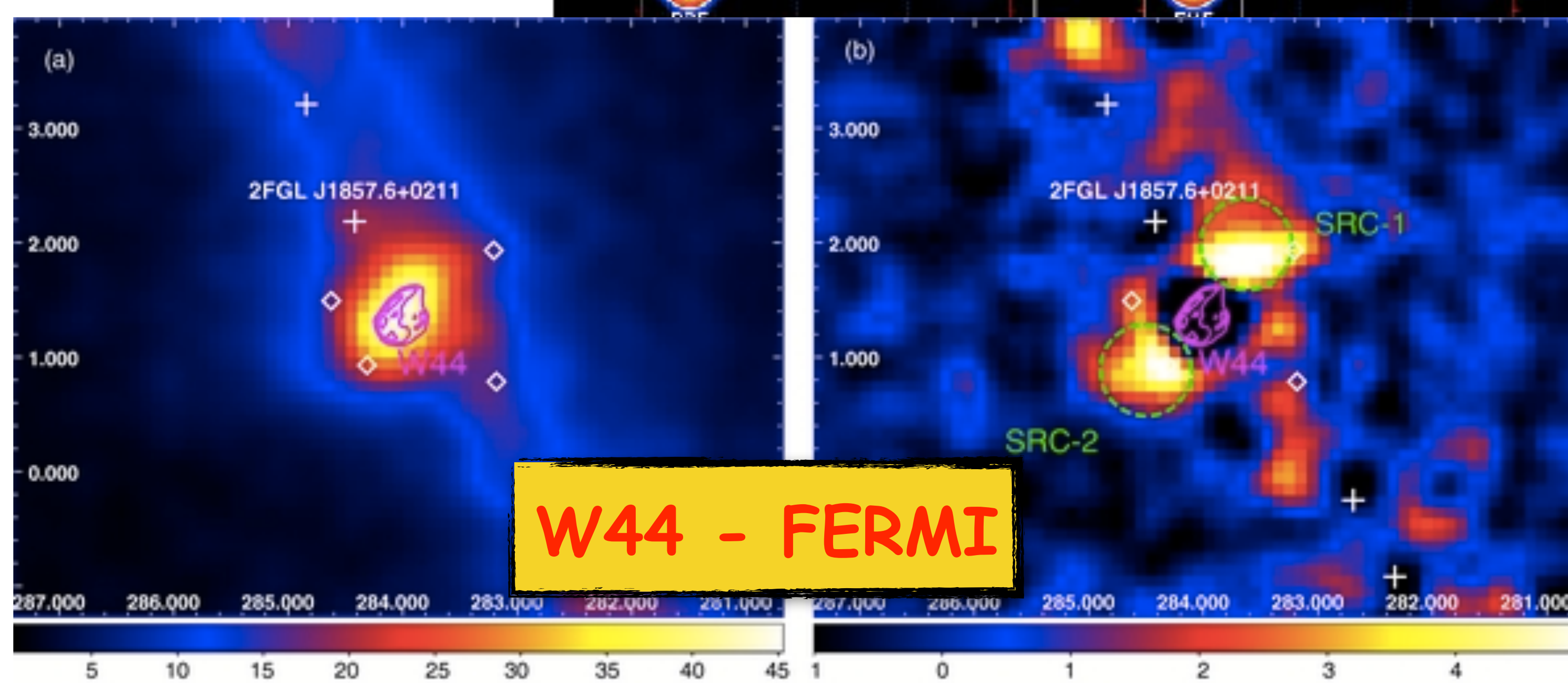
SNR/MC associations in γ-rays

spatial correlation between γ-ray and CO emission





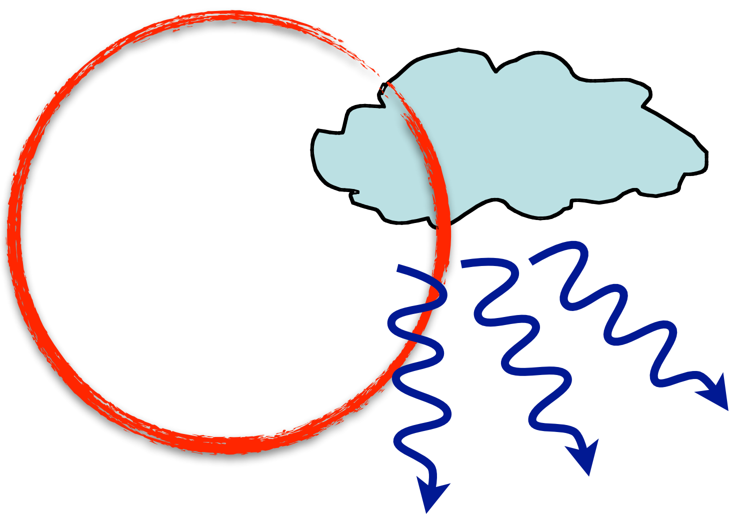




2 scenarios: interaction or runaway CRs?

Blandford&Cowie 1982, Aharonian+ 1994, Bykov+ 2000, Uchiyama+ 2010

shock/MC interaction



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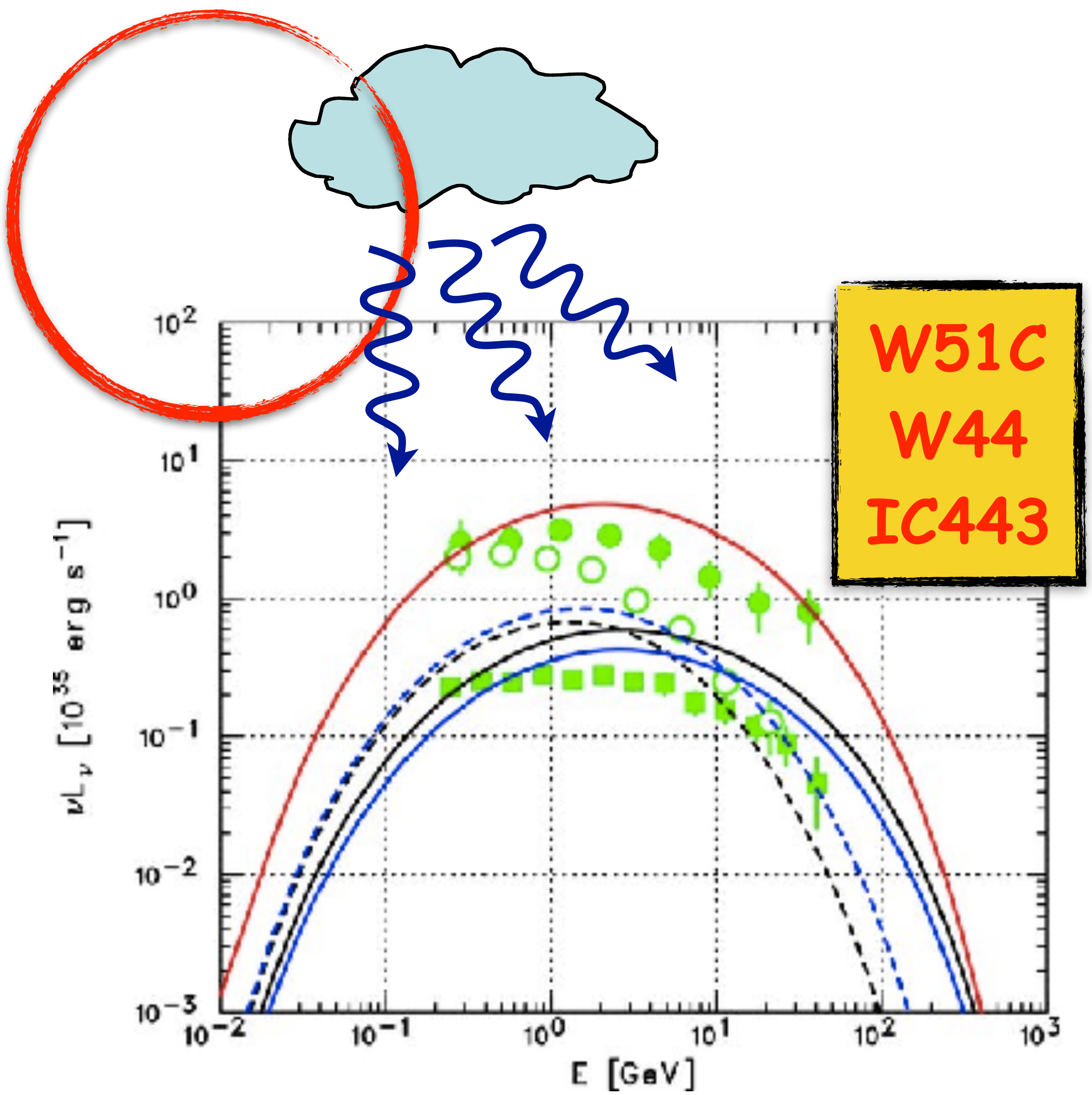

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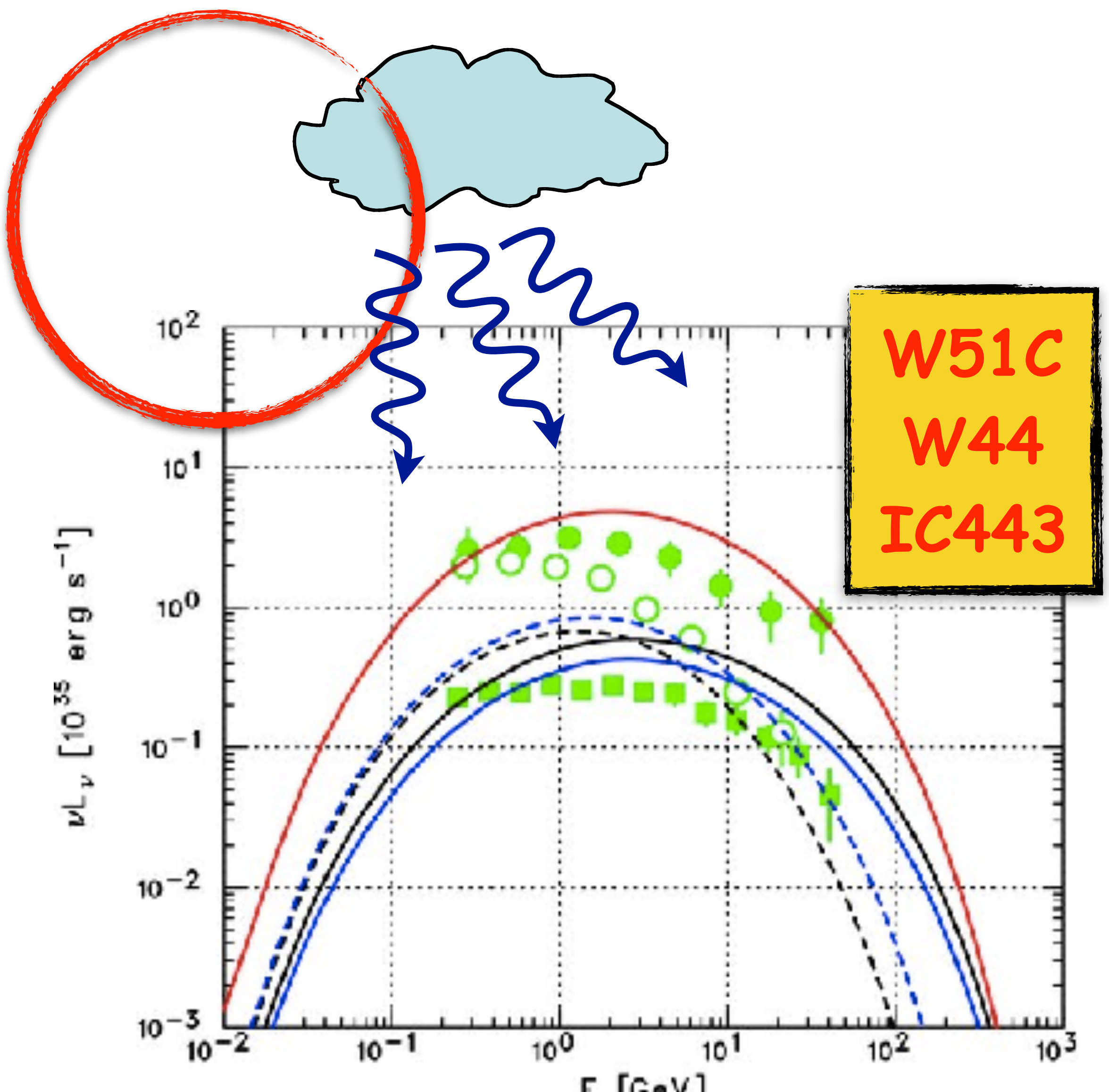

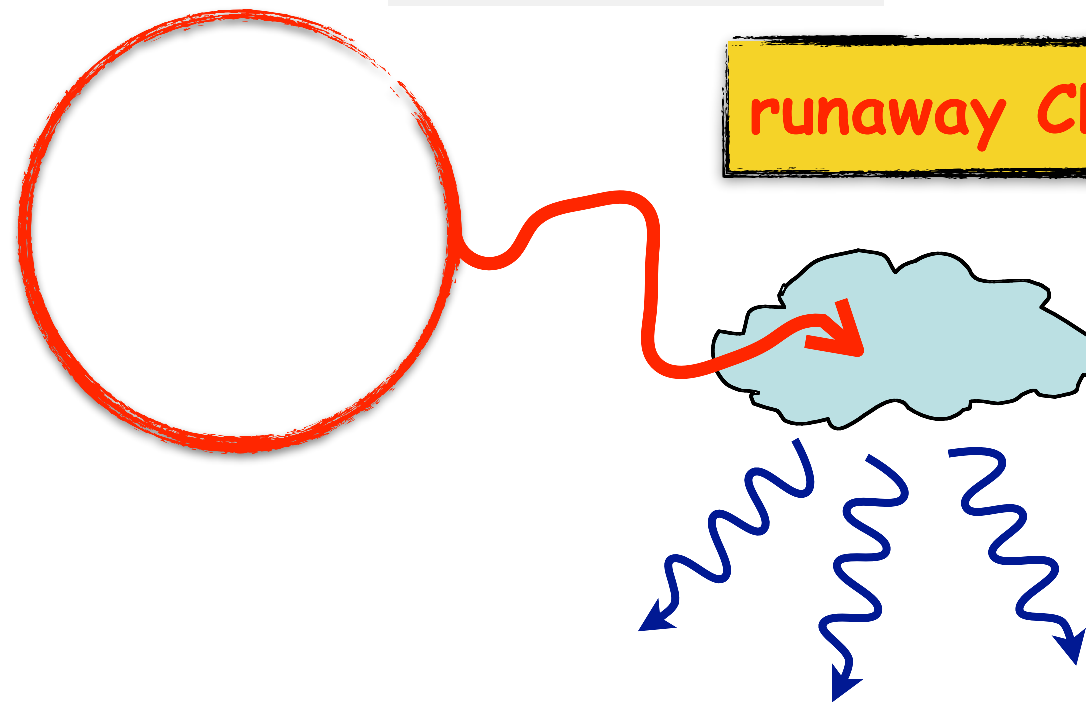

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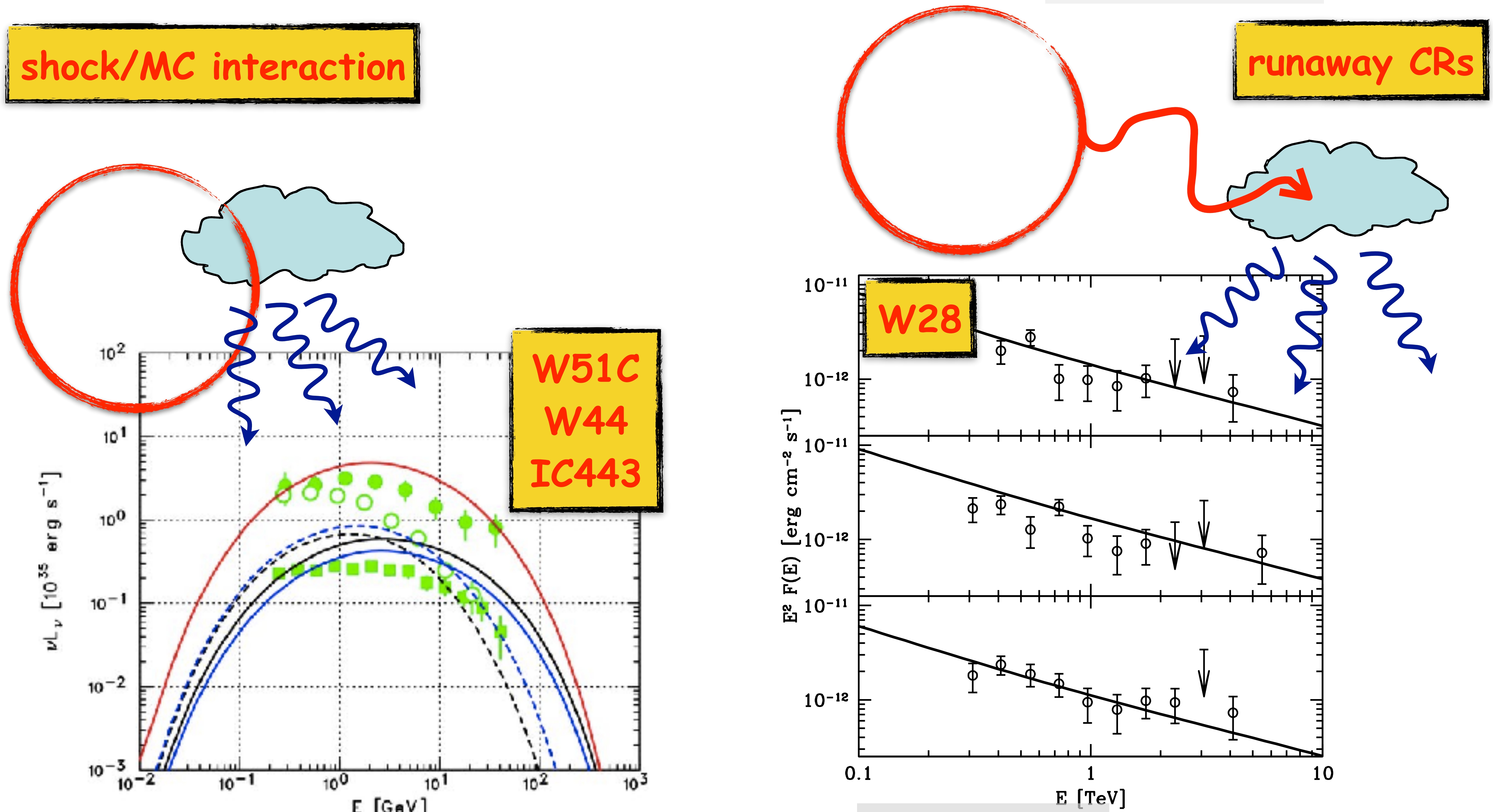

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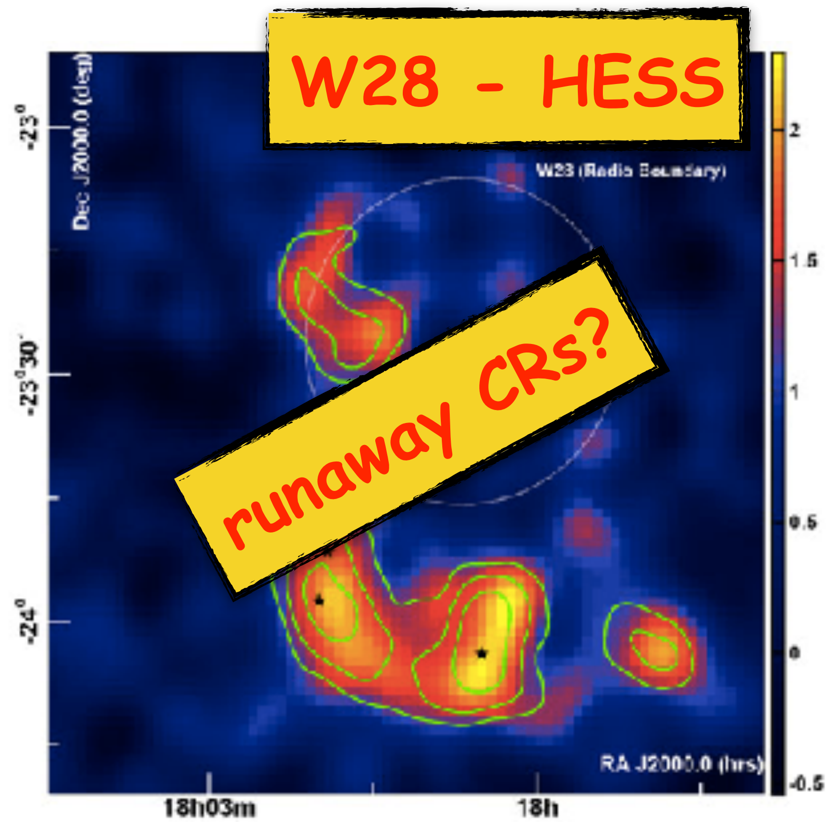
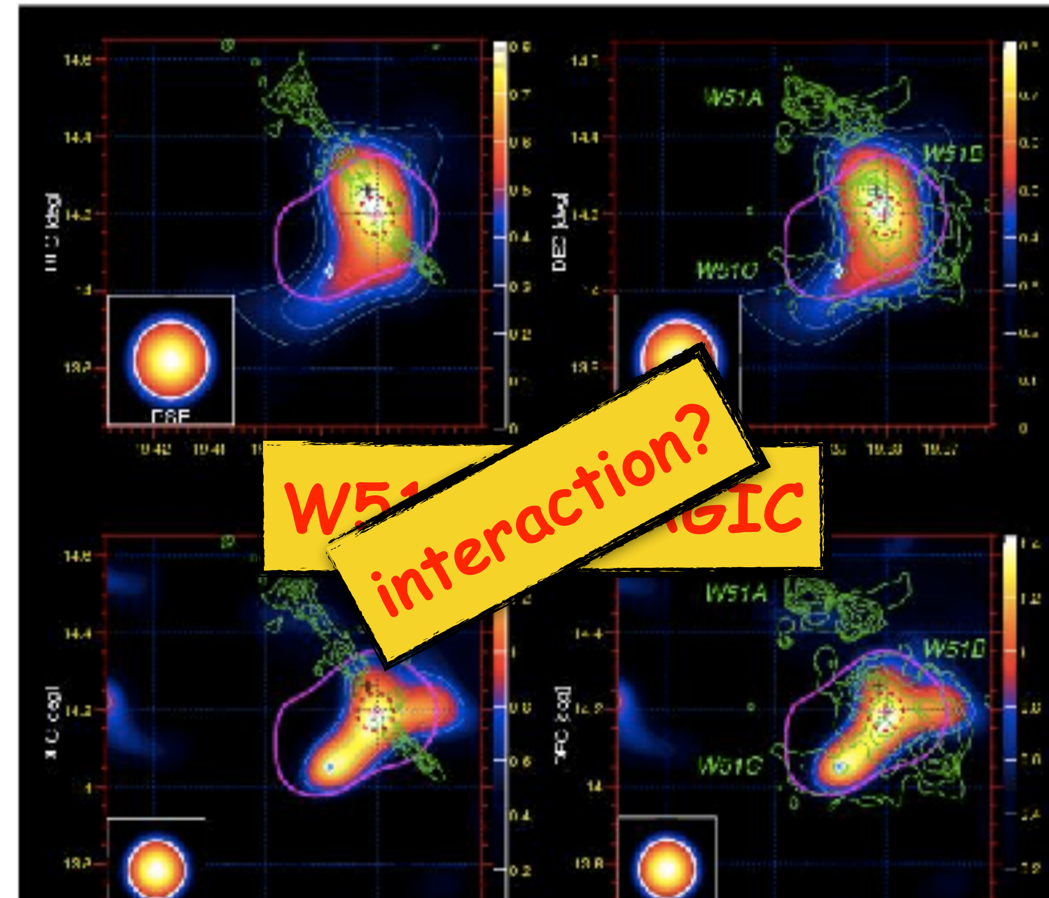
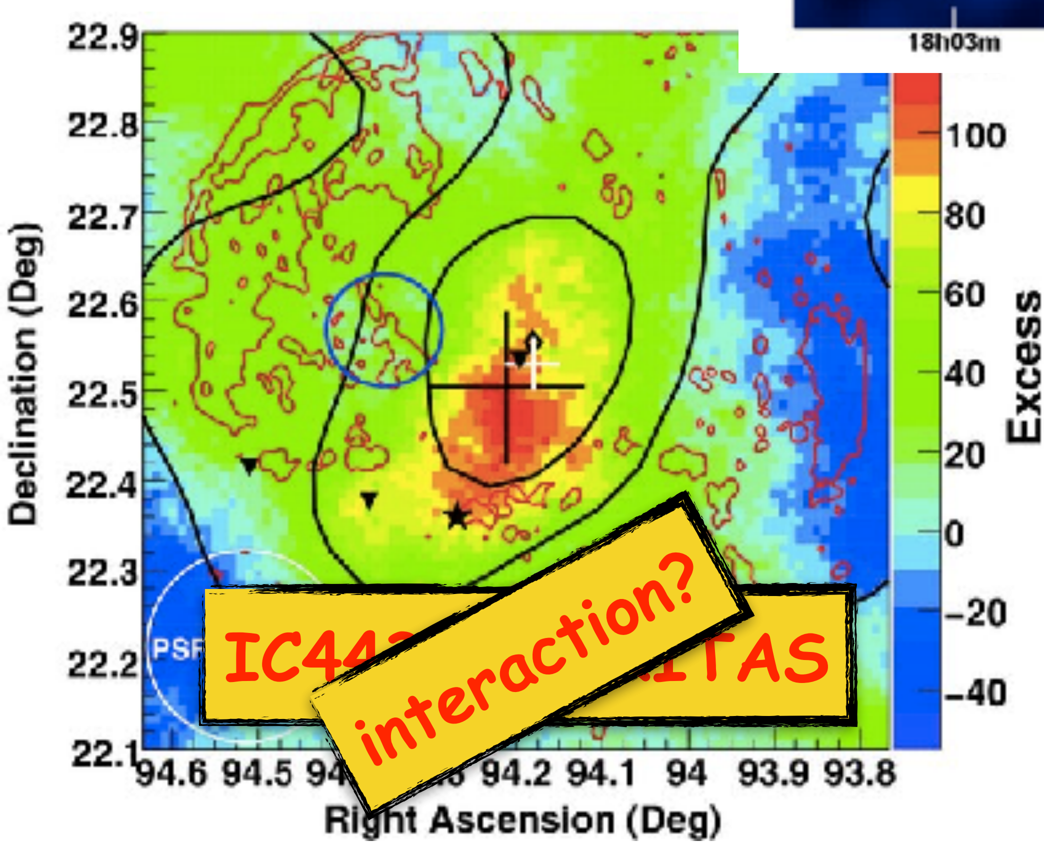
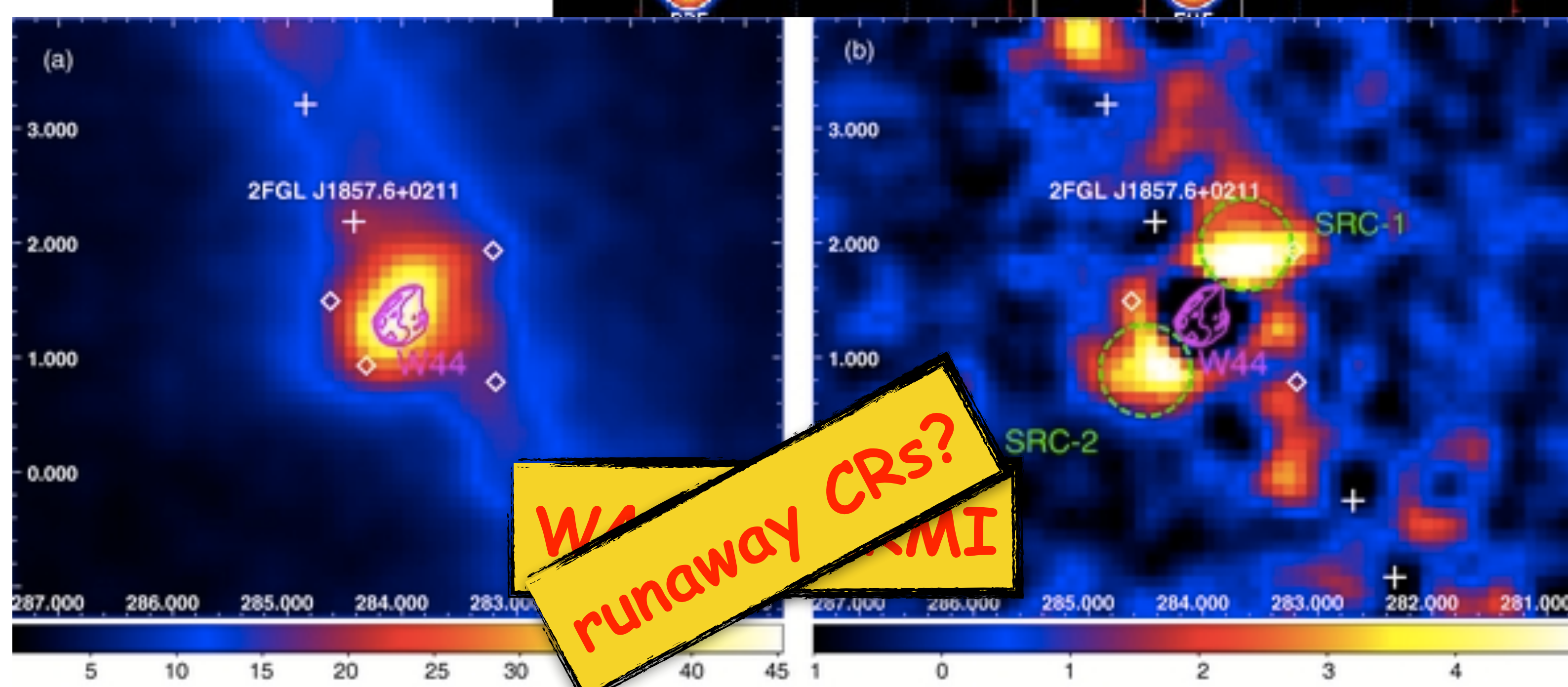
Interaction versus escape: who's who?

both scenarios require an **overdensity of GeV-TeV CRs** at the MC







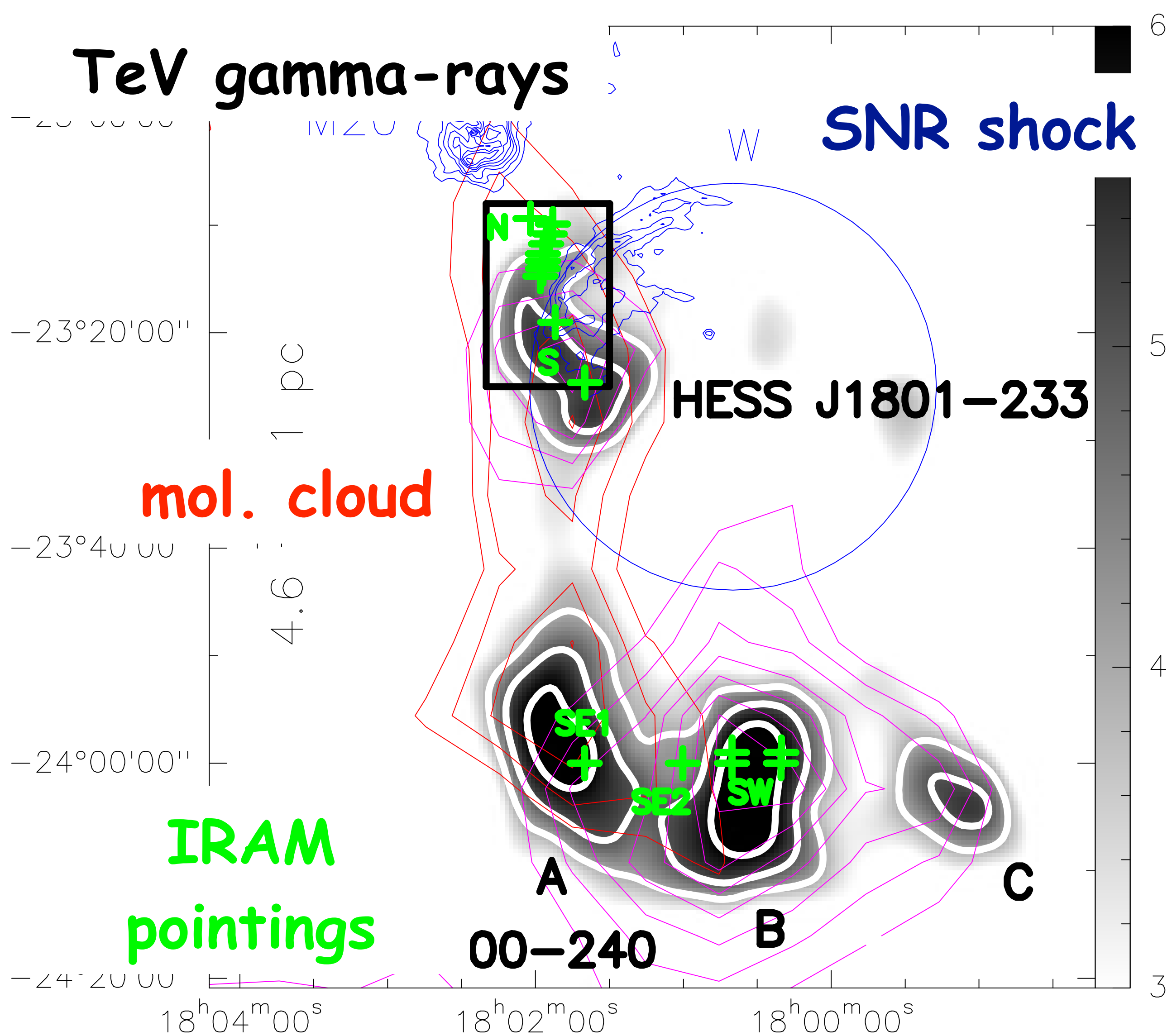


DCO+/HCO+

W28

Vaupré, Hily-Blant, Ceccarelli, Dubus, SG, Montmerle (2014)

TeV gamma-rays



TeV + gas -> multi-TeV CR protons

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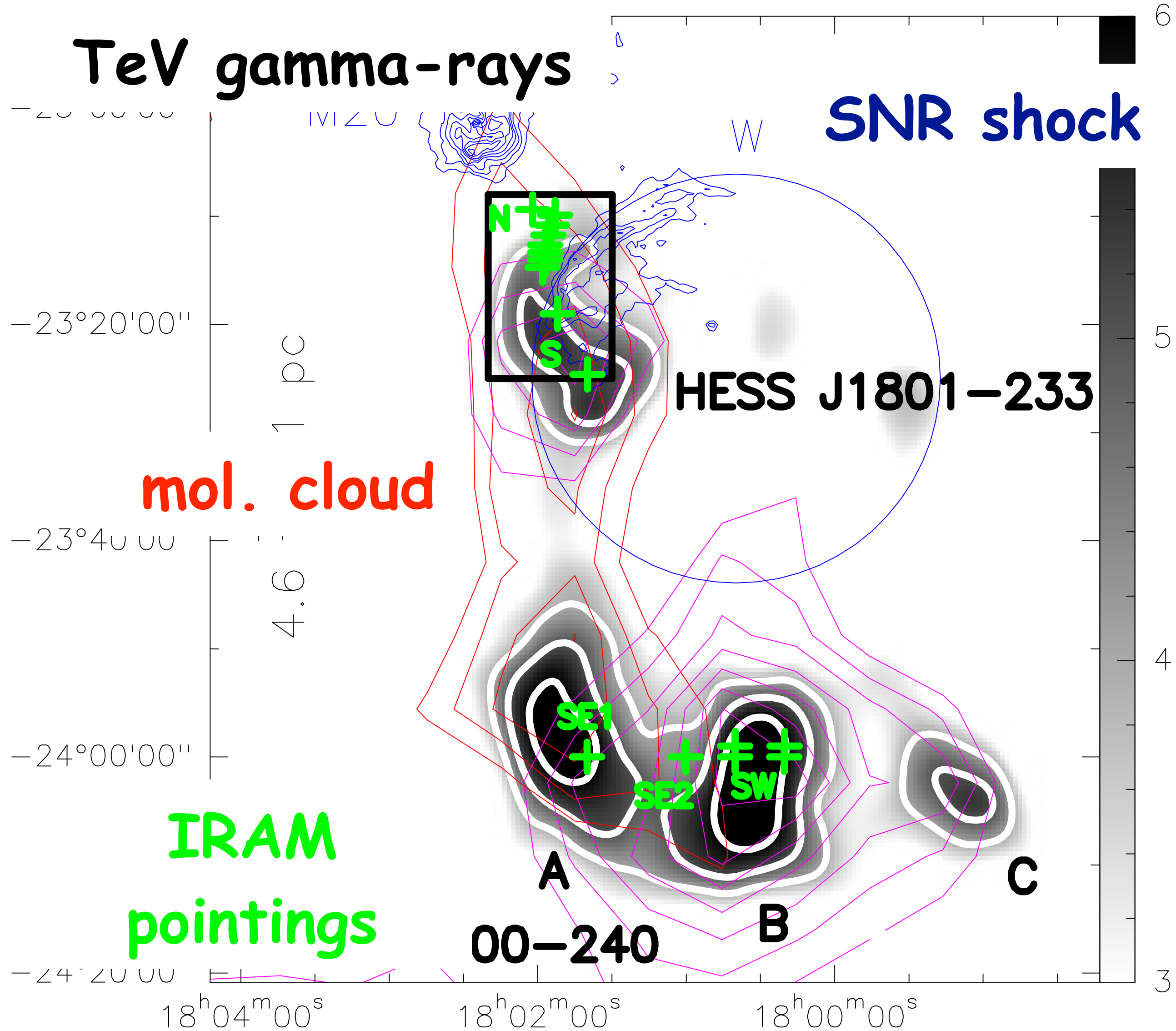

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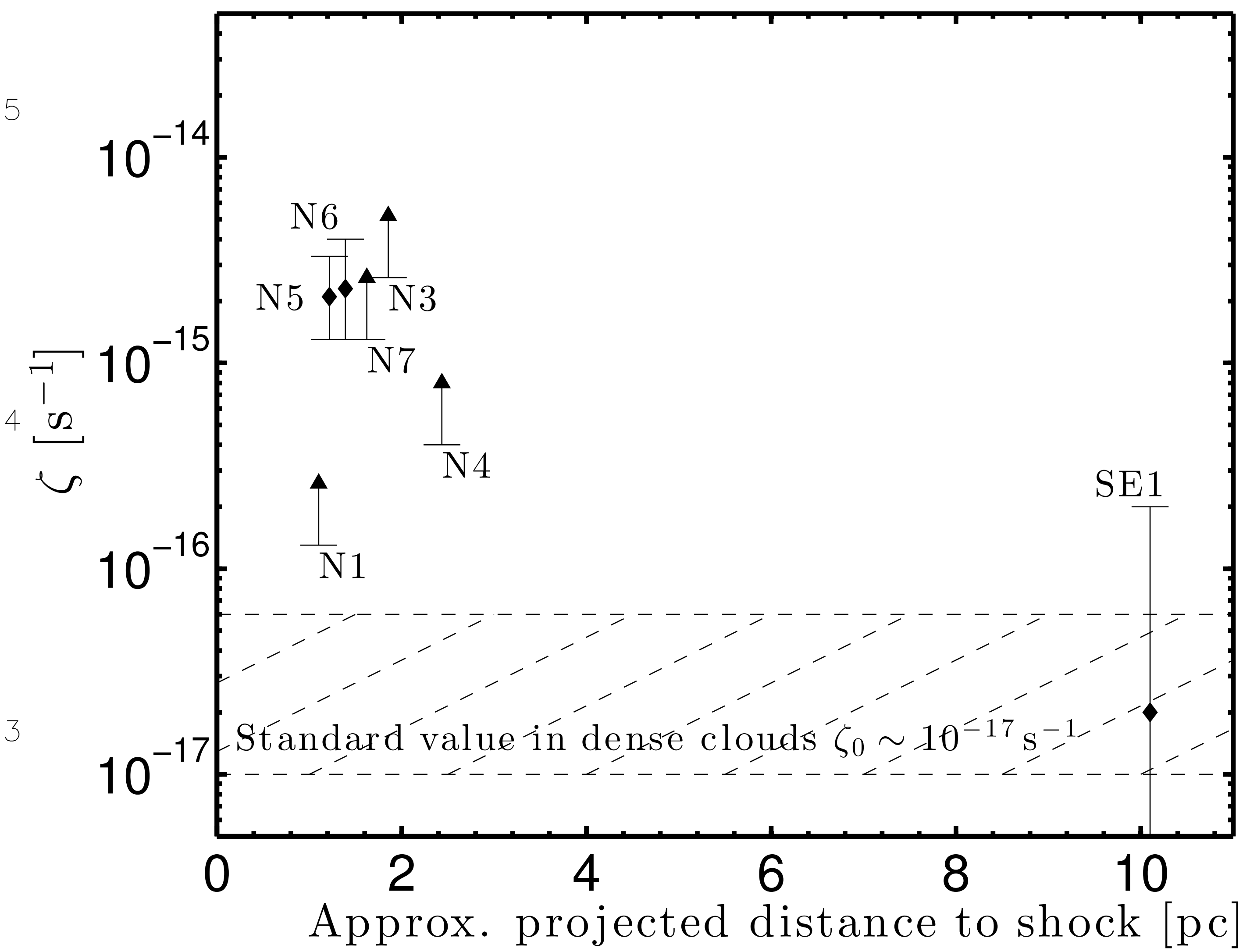

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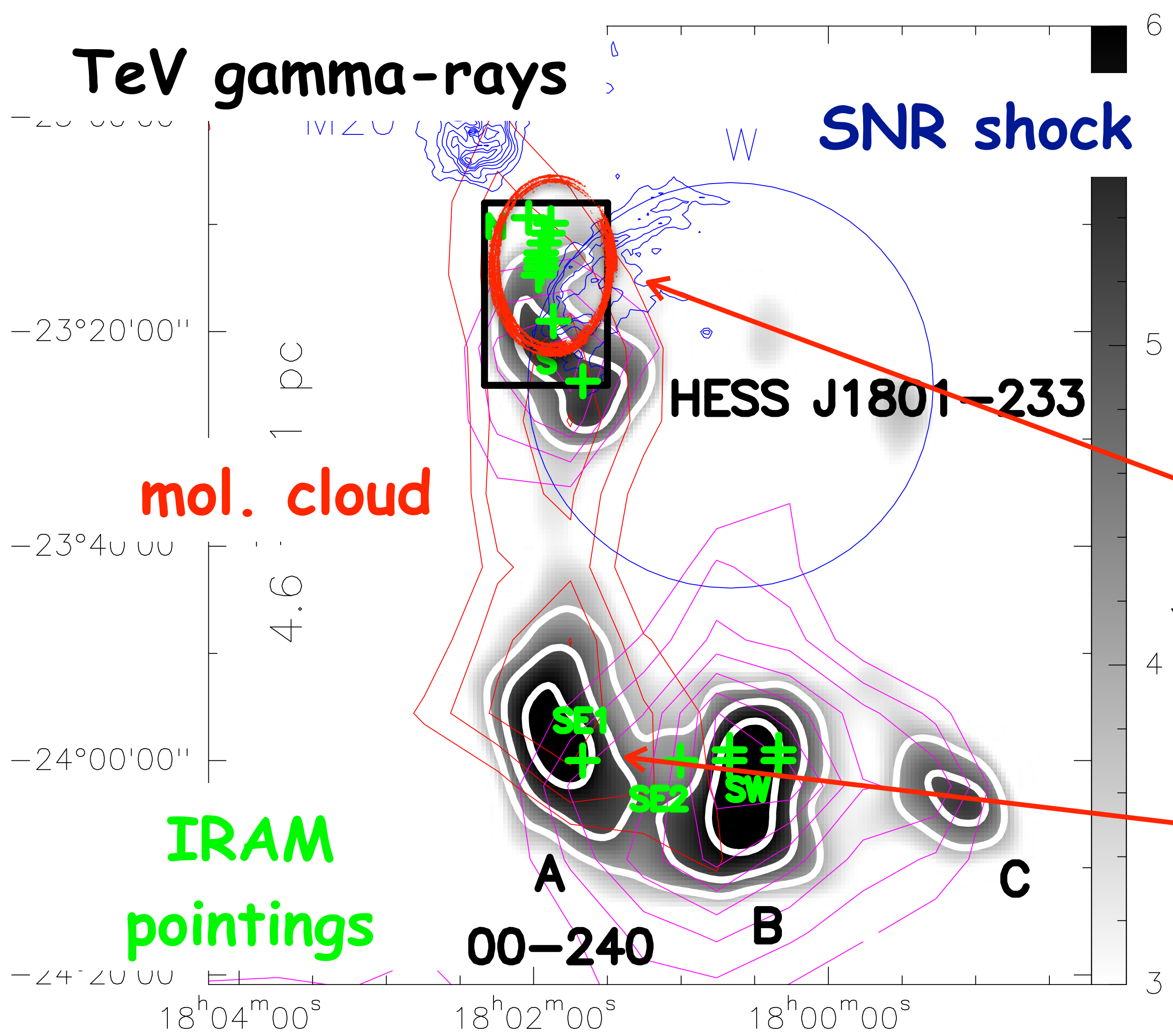

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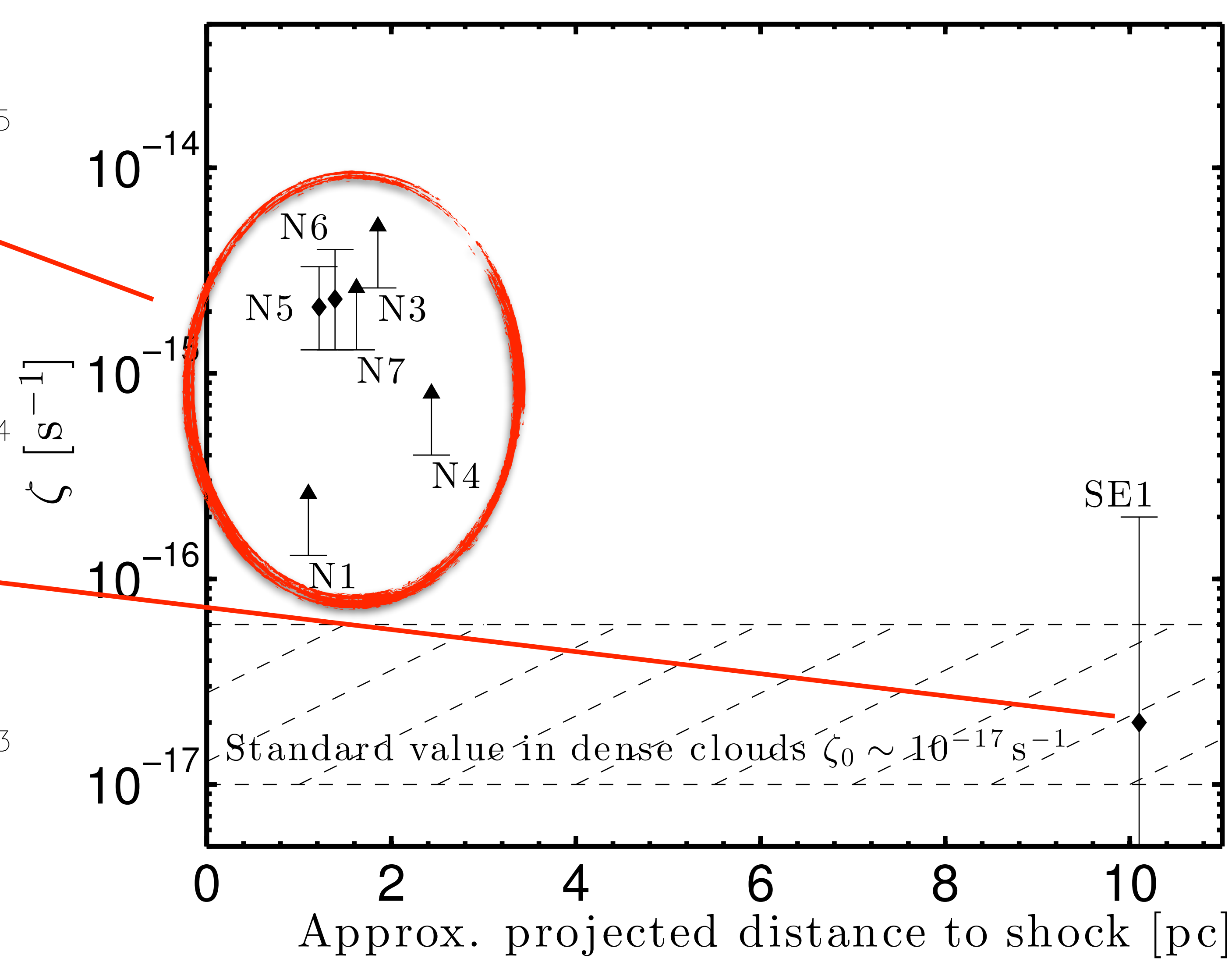

W28

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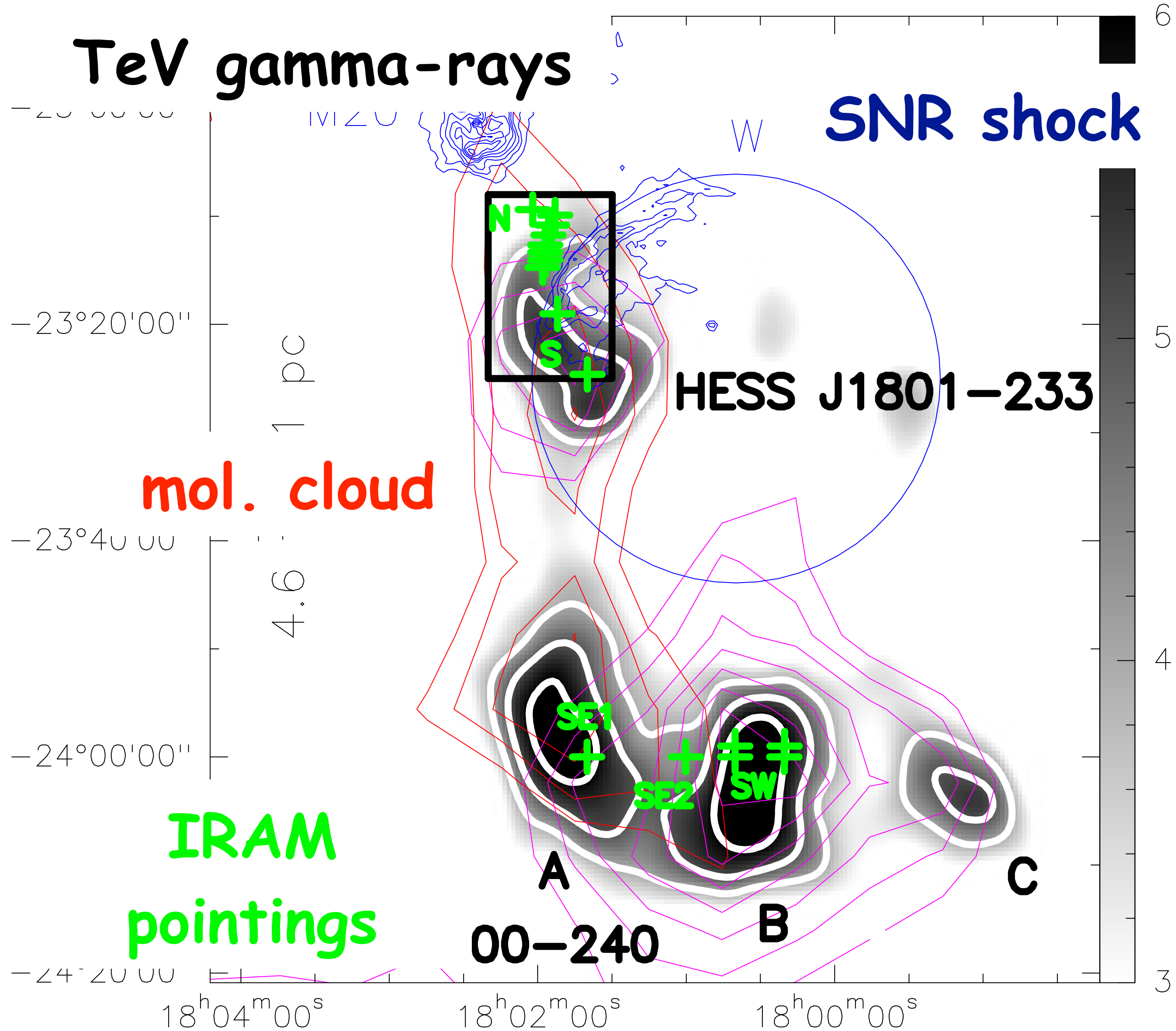

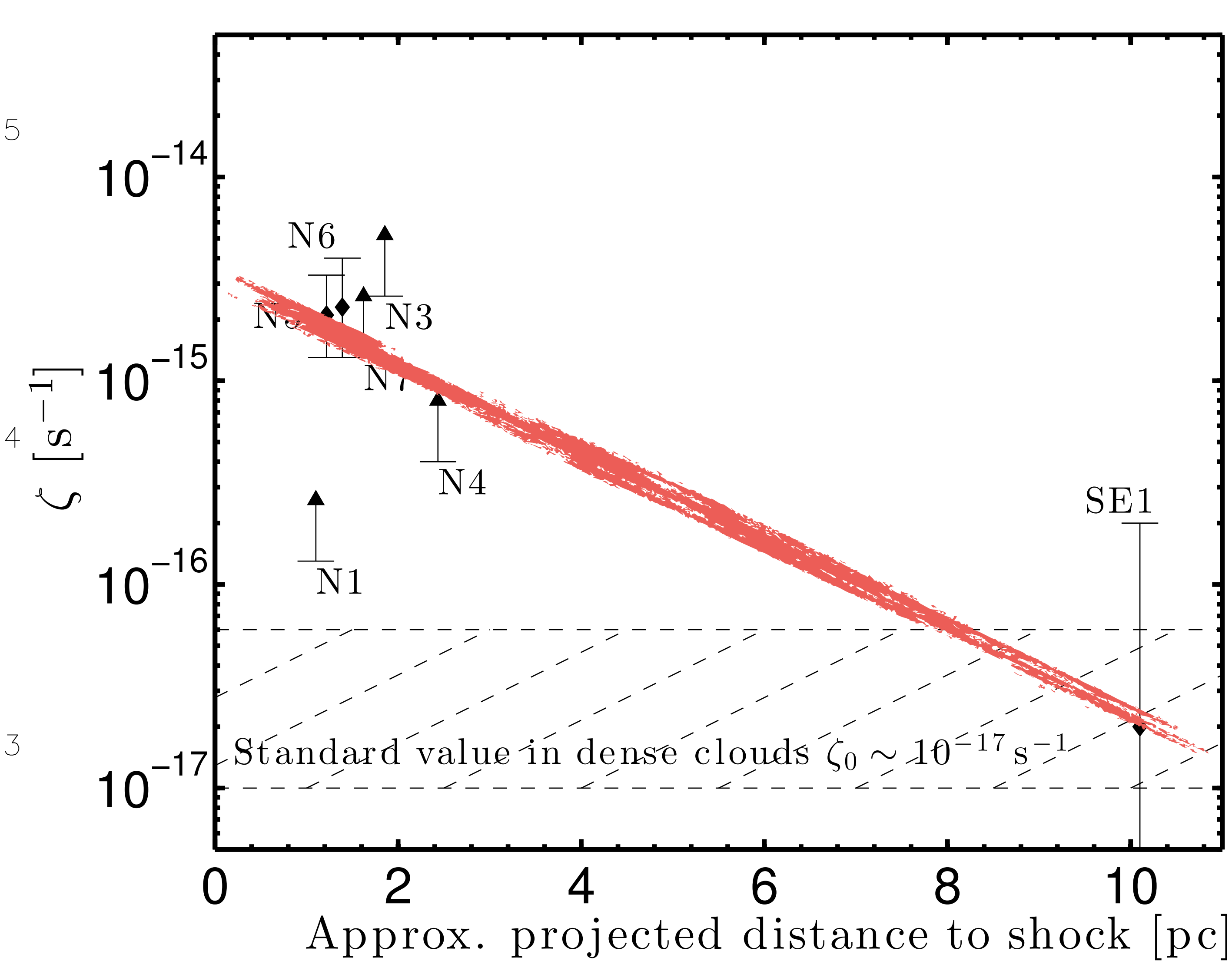

DCO^+/HCO^+

W28

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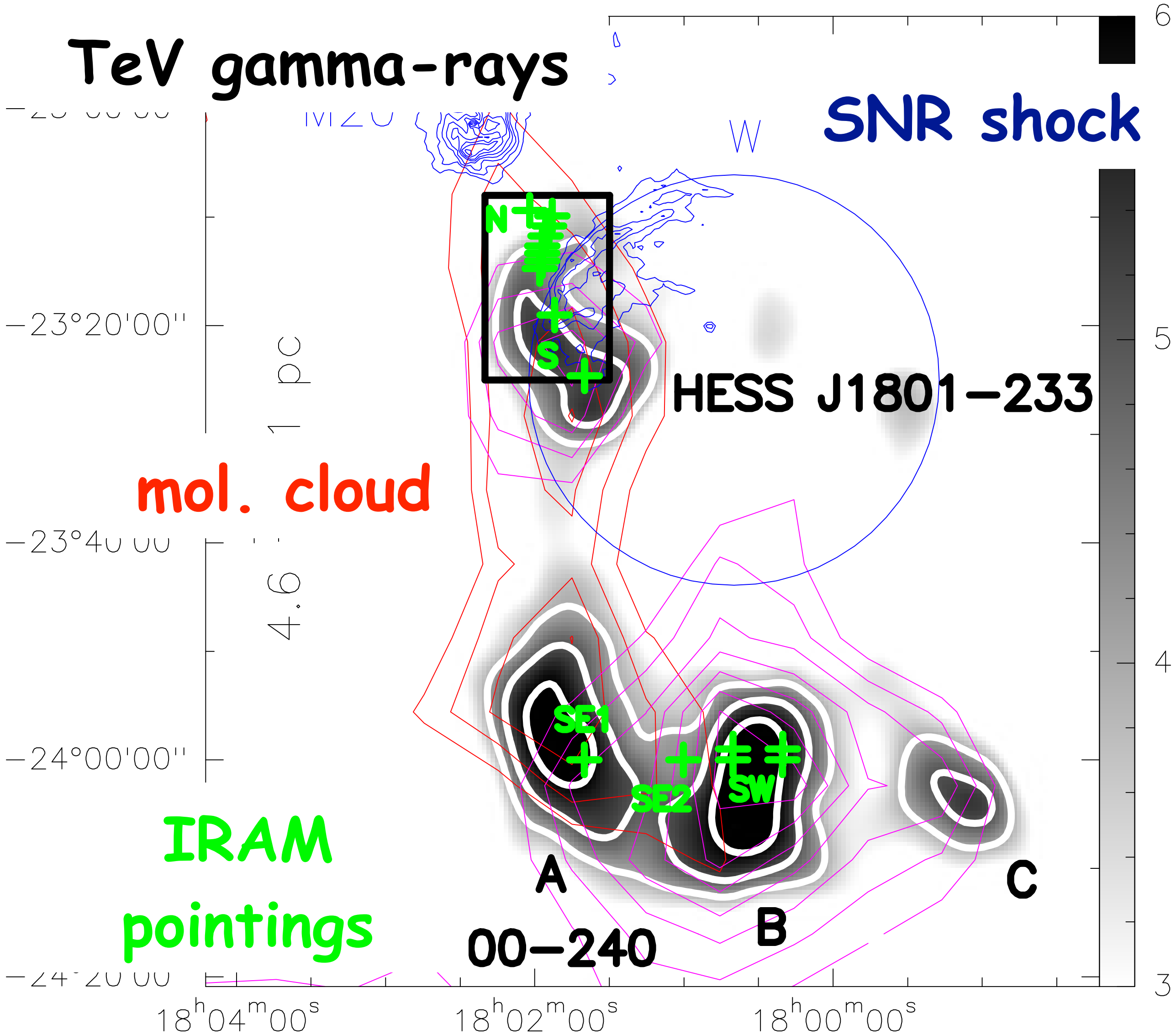

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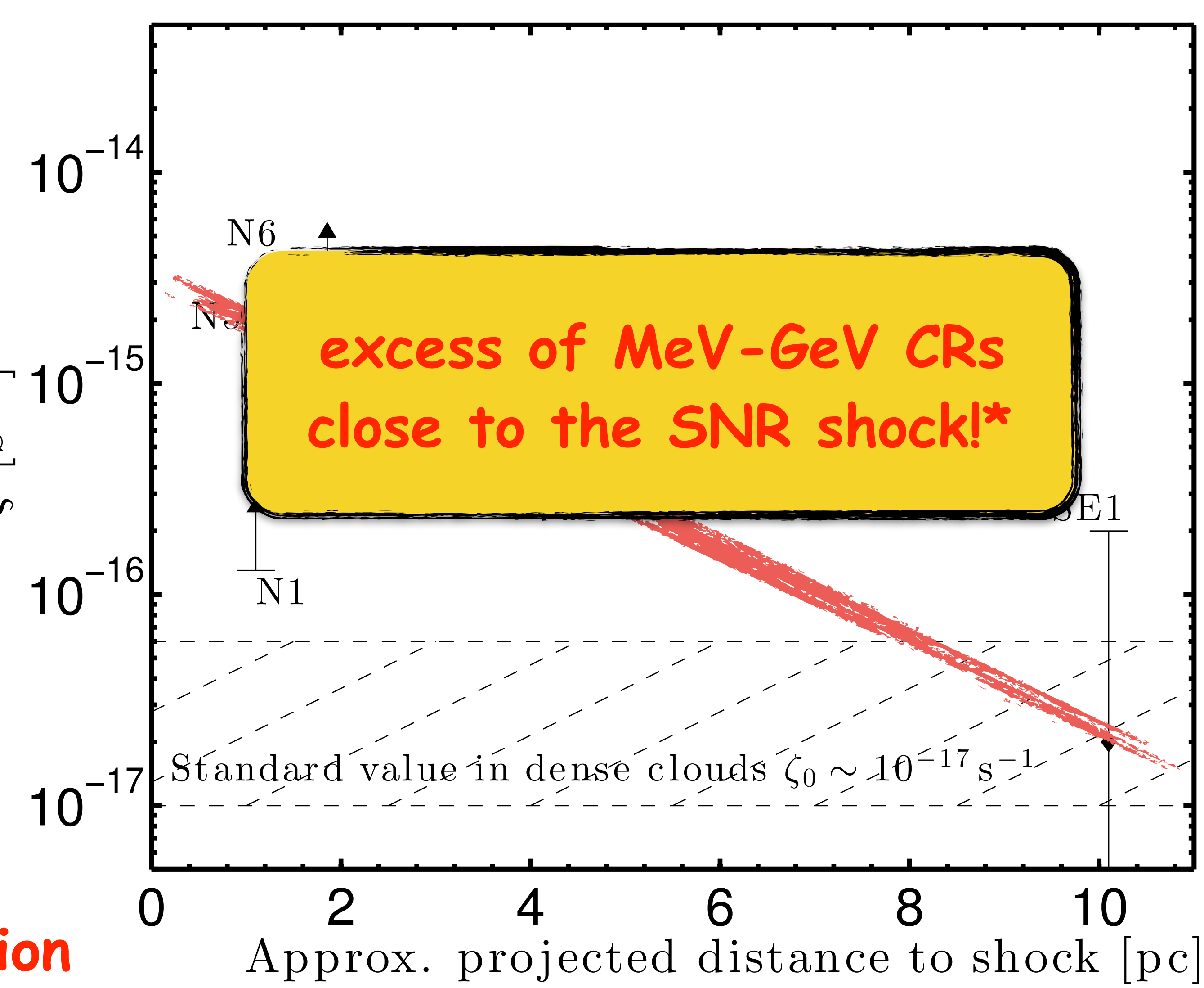

* also CR electrons contribute to ionization

W28

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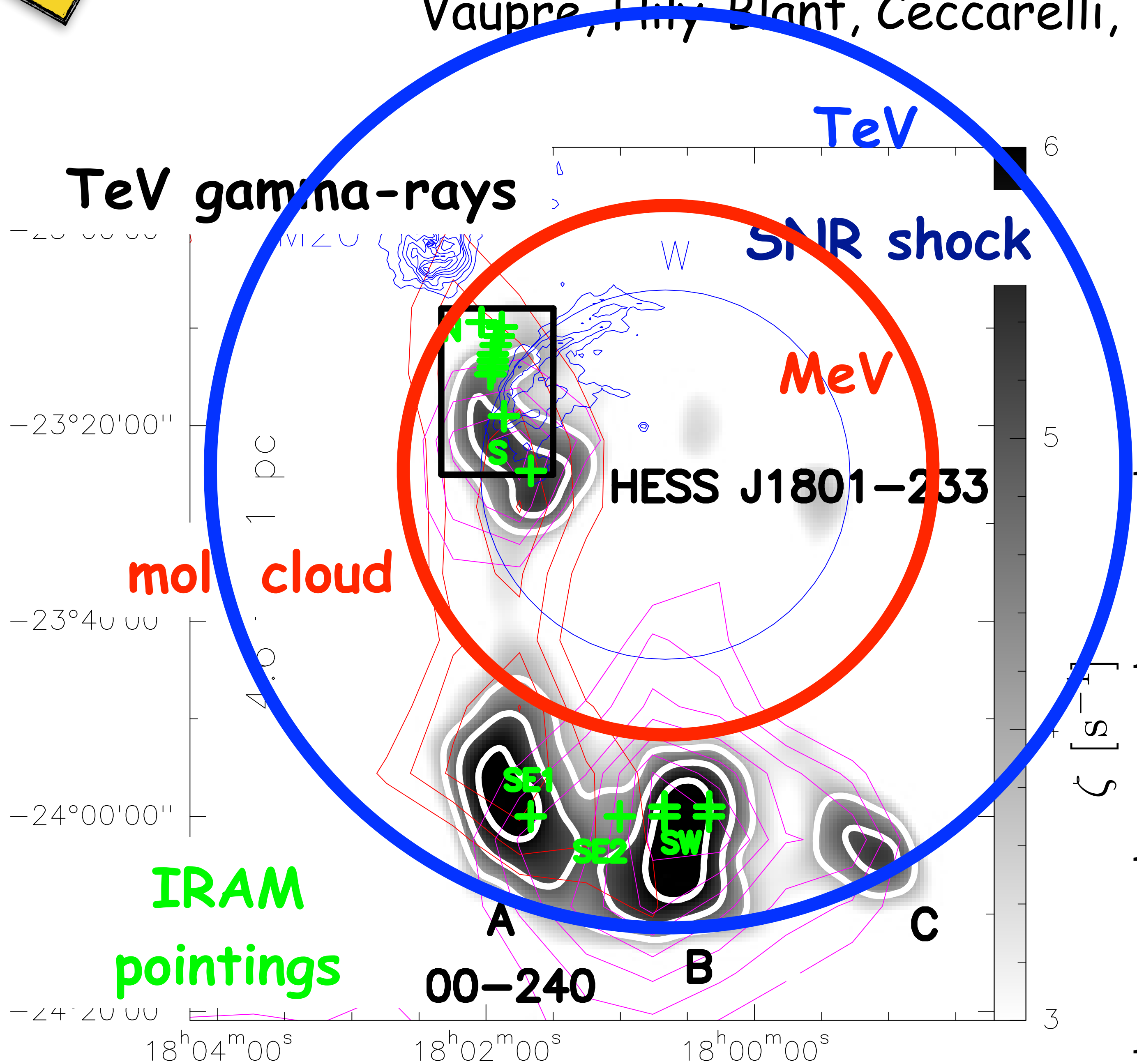

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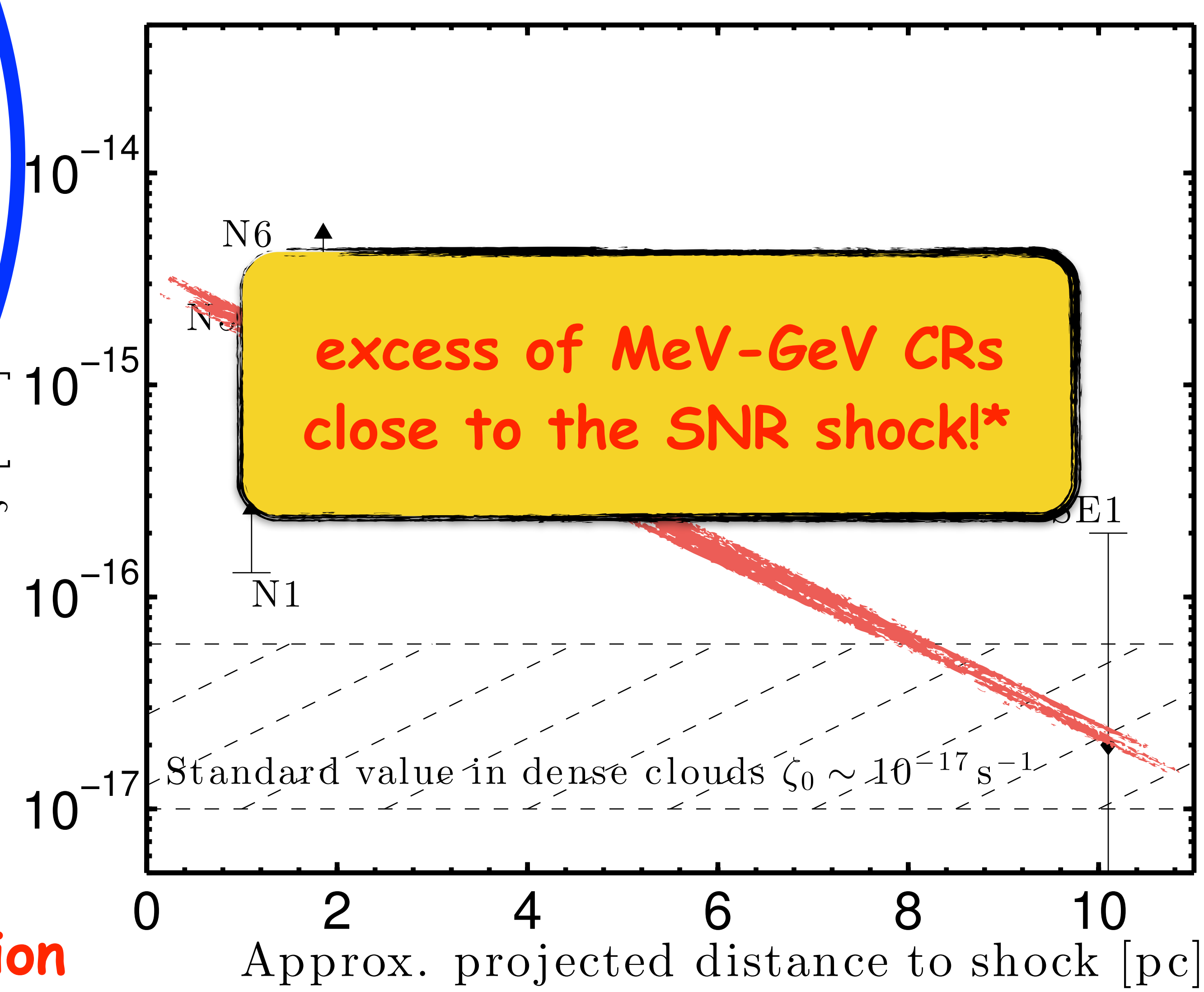

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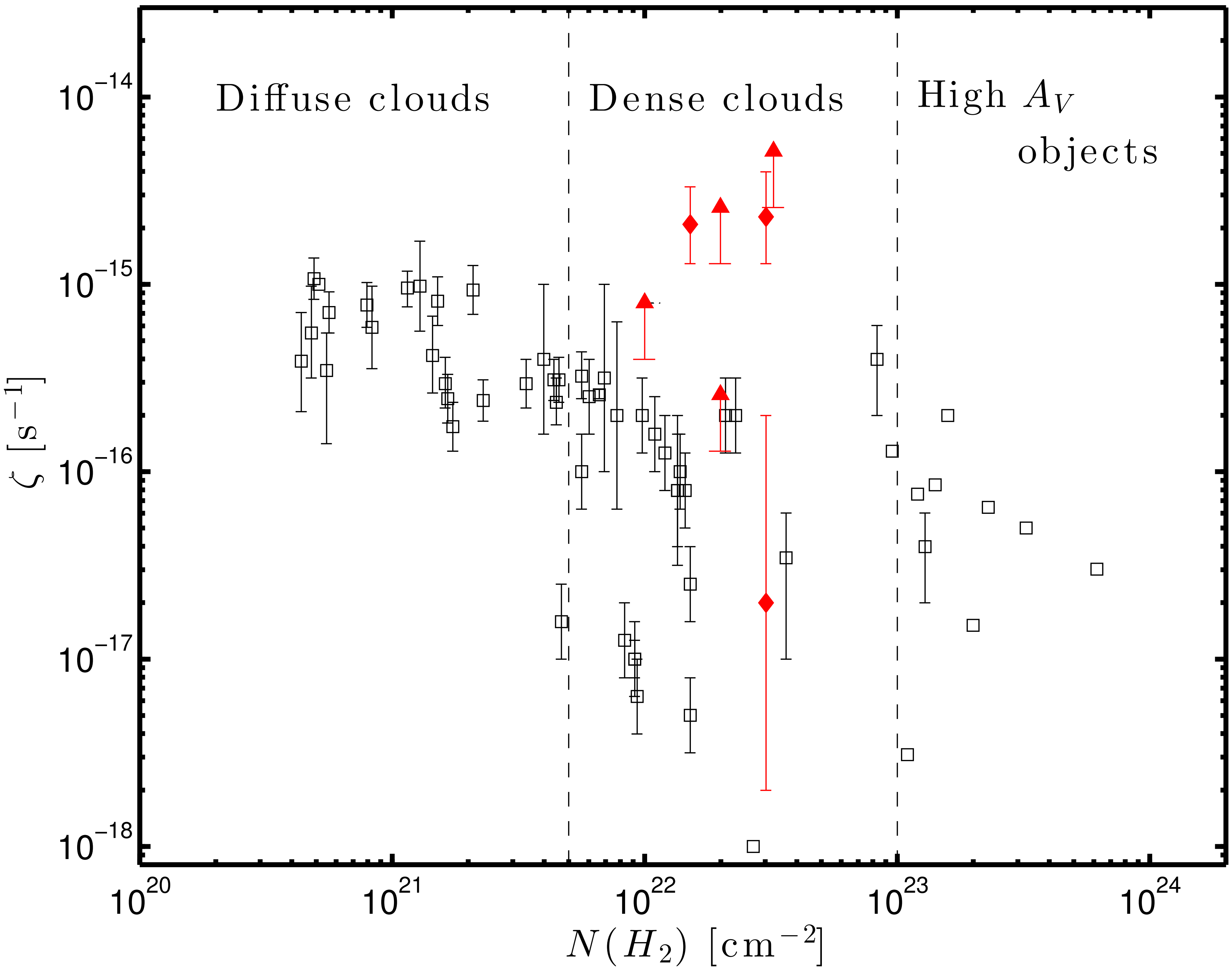
CR ionization rate in MCs next to SNRs

Vaupré et al 2014



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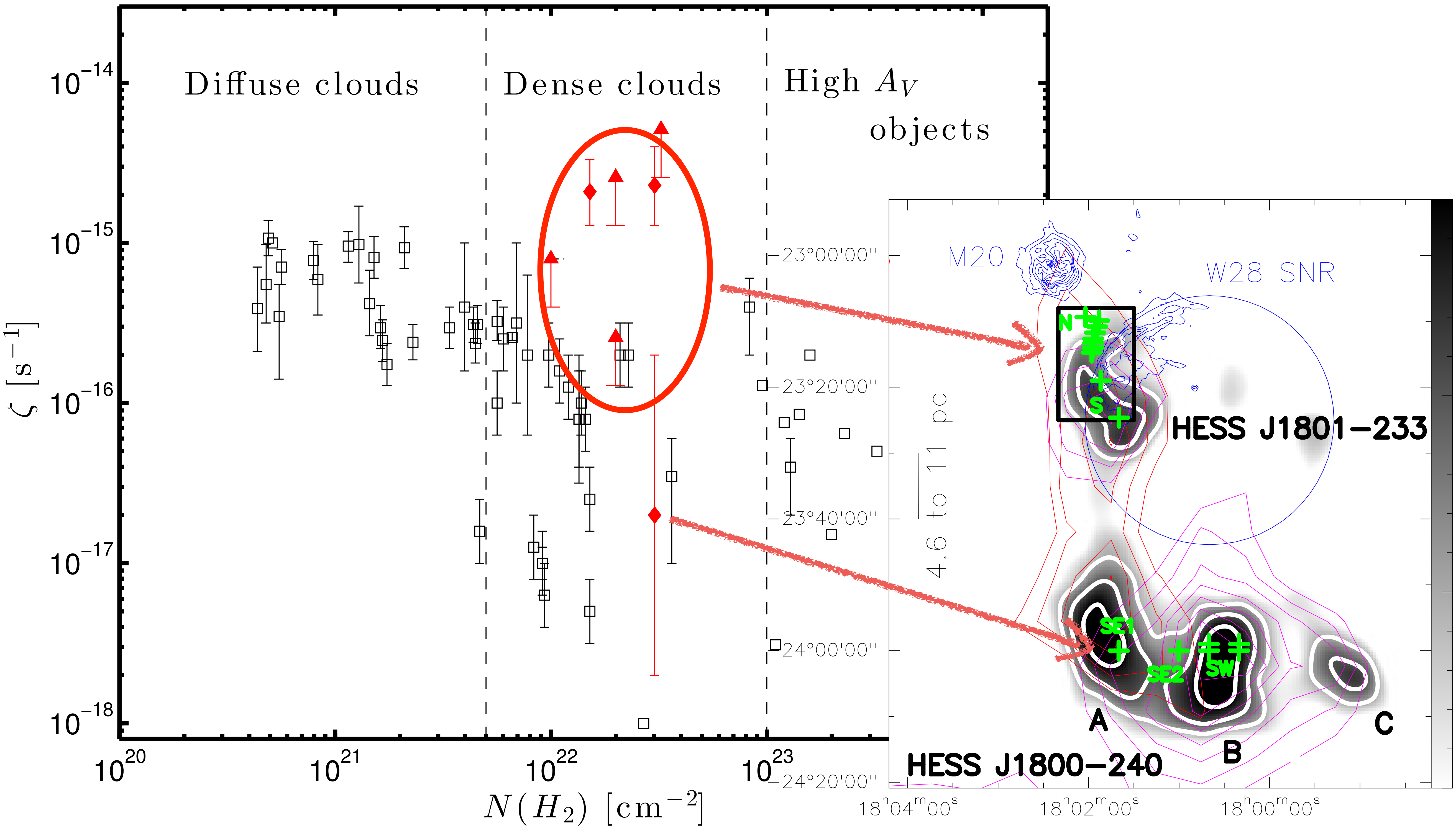

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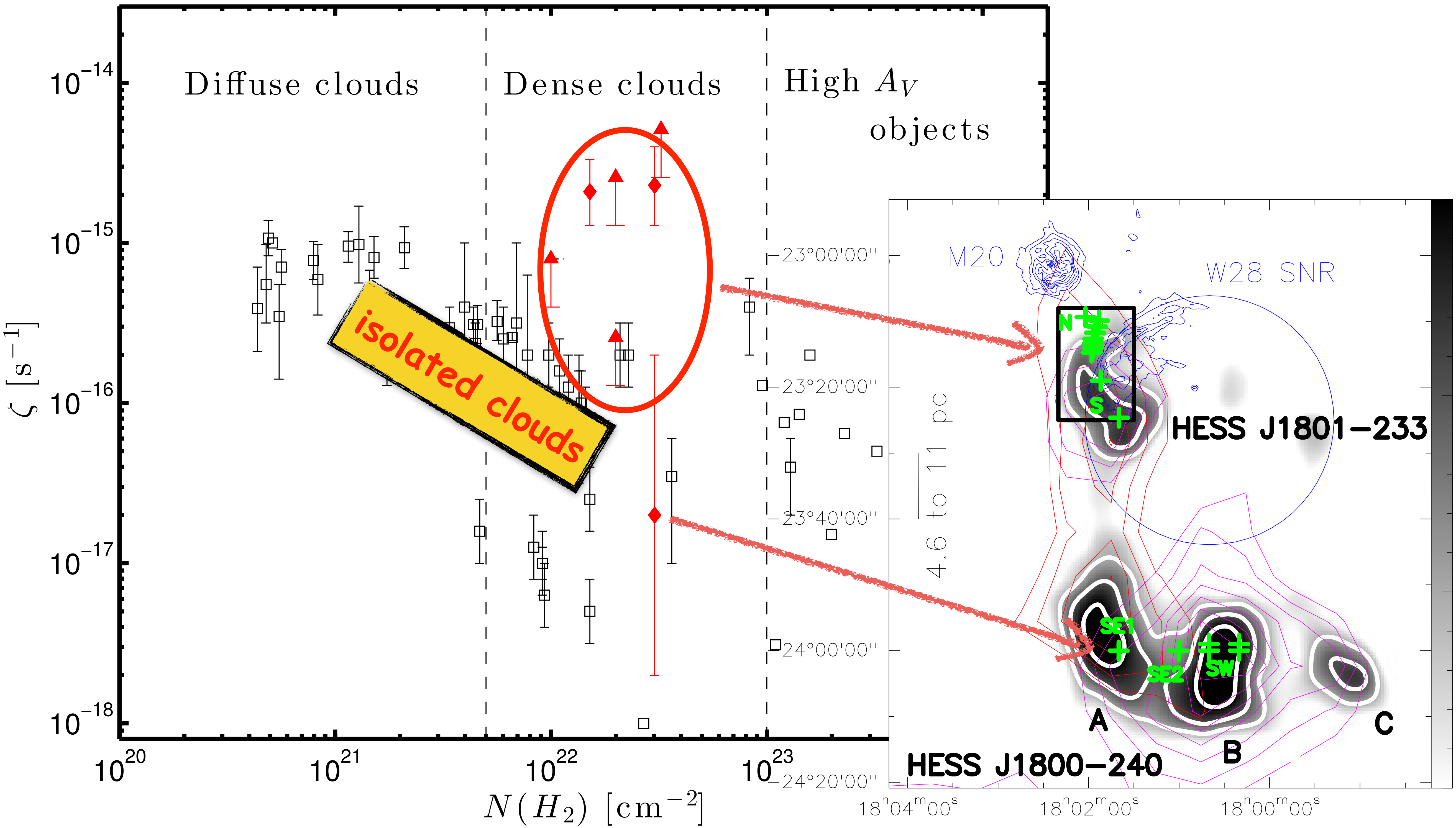
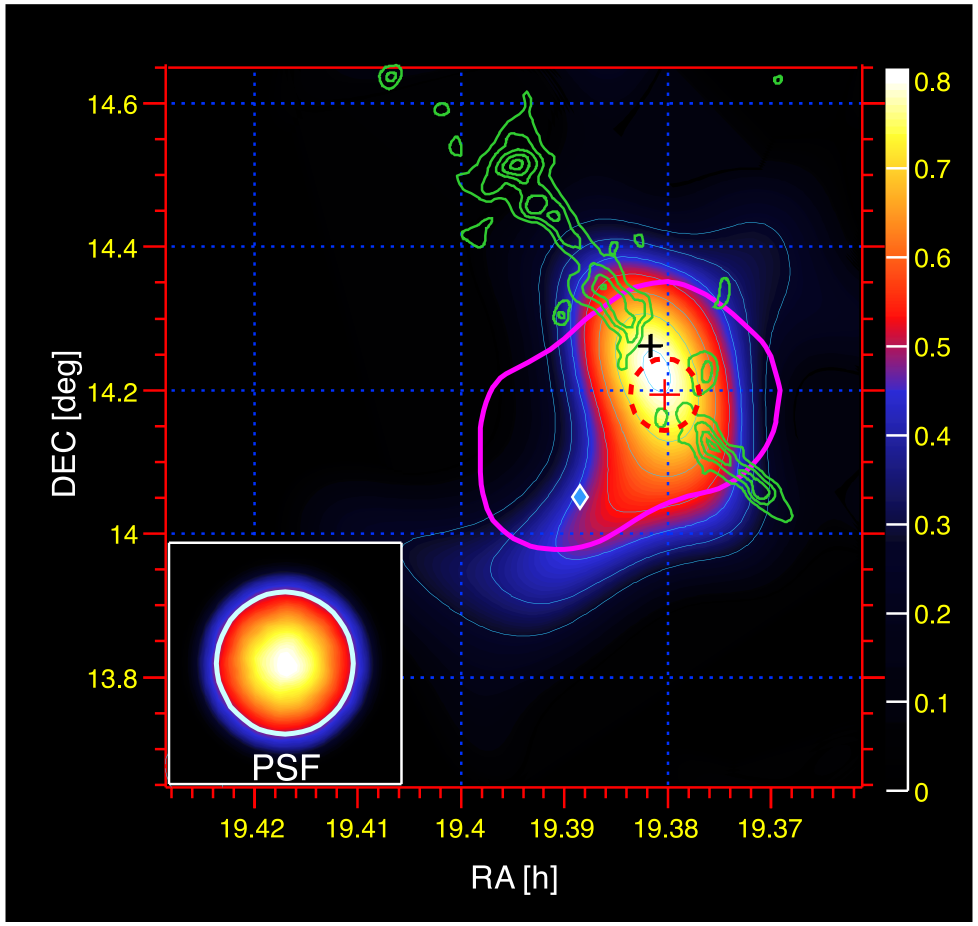


DCO+/HCO+

W51C

Aleksic+ 2012



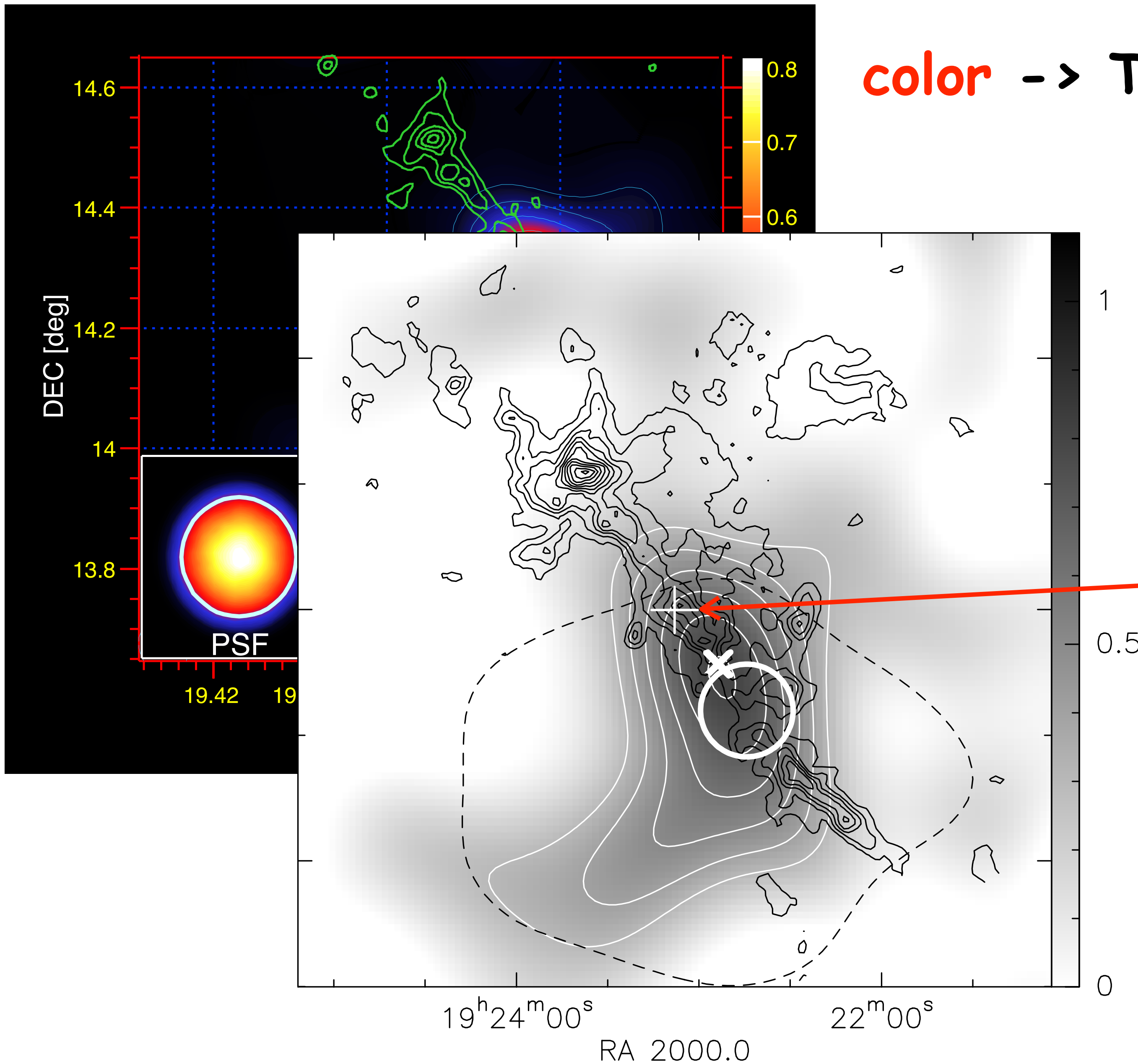
color -> TeV gamma-rays (MAGIC)

green -> CO

DCO^+/HCO^+

W51C

Aleksic+ 2012



color -> TeV gamma-rays (MAGIC)

green -> CO

white contours -> TeV gamma-rays

black contours -> CO

dashed -> Fermi

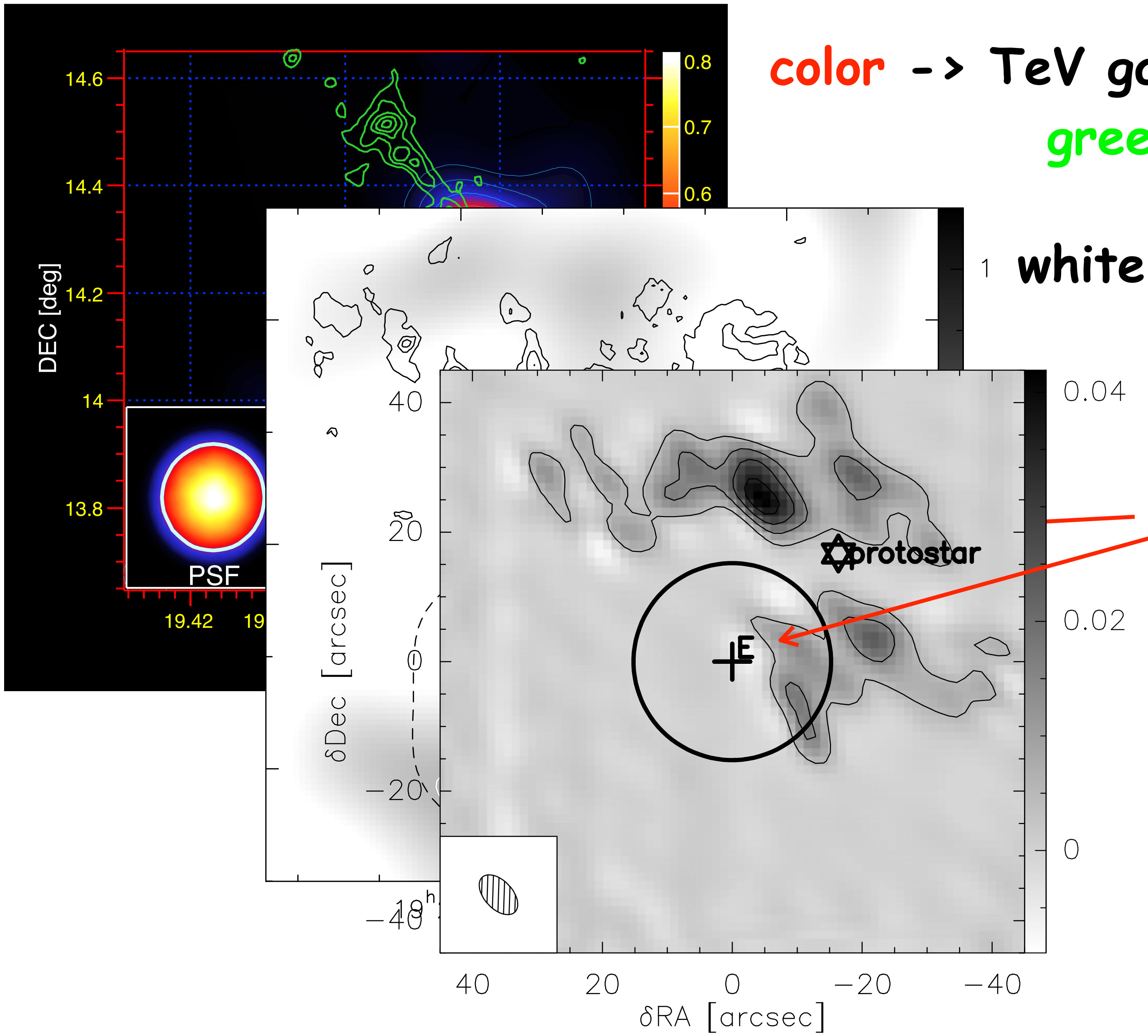
ζ_{CR} ~ few 10^{-15} s^{-1}

Ceccarelli+ 2011

DCO+/HCO+

W51C

Aleksic+ 2012



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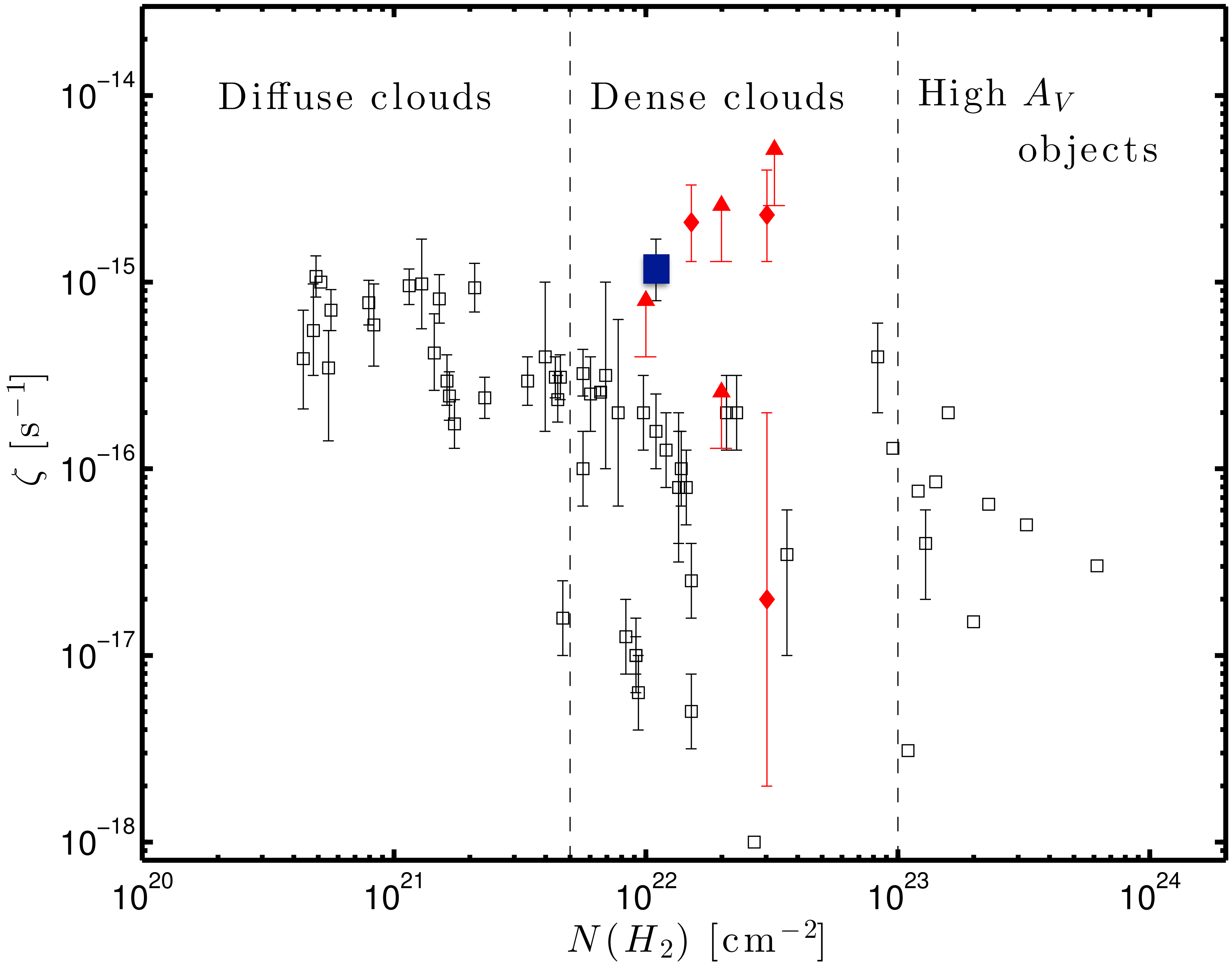
Ceccarelli+ 2011

Dumas+ 2014

SiO emission->slow shock->shock-clump interaction?->downstream of SNR shock

CR ionization rate in MCs next to SNRs

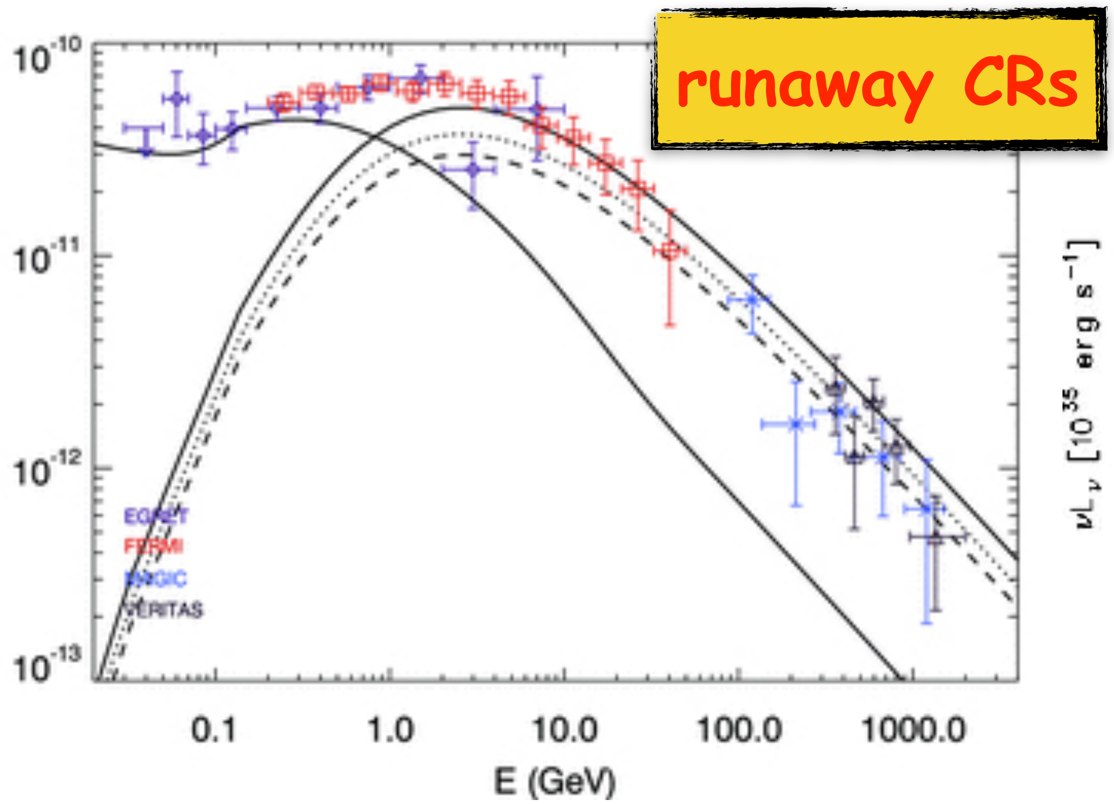
Vaupré et al 2014 - Ceccarelli et al 2011

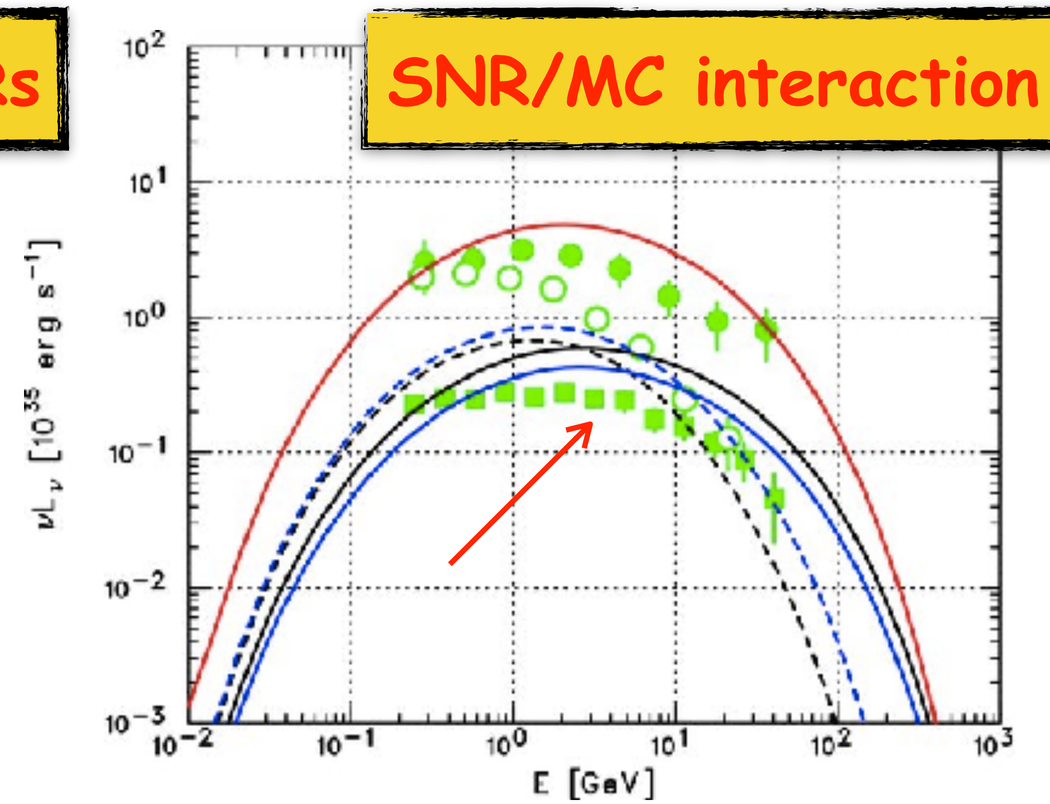


IC443

age ~ 3 x 10^4 yr, evidence of shocked cloud material, clumps

Torres+ 2010





Uchiyama+ 2010

H_3^+

IC443

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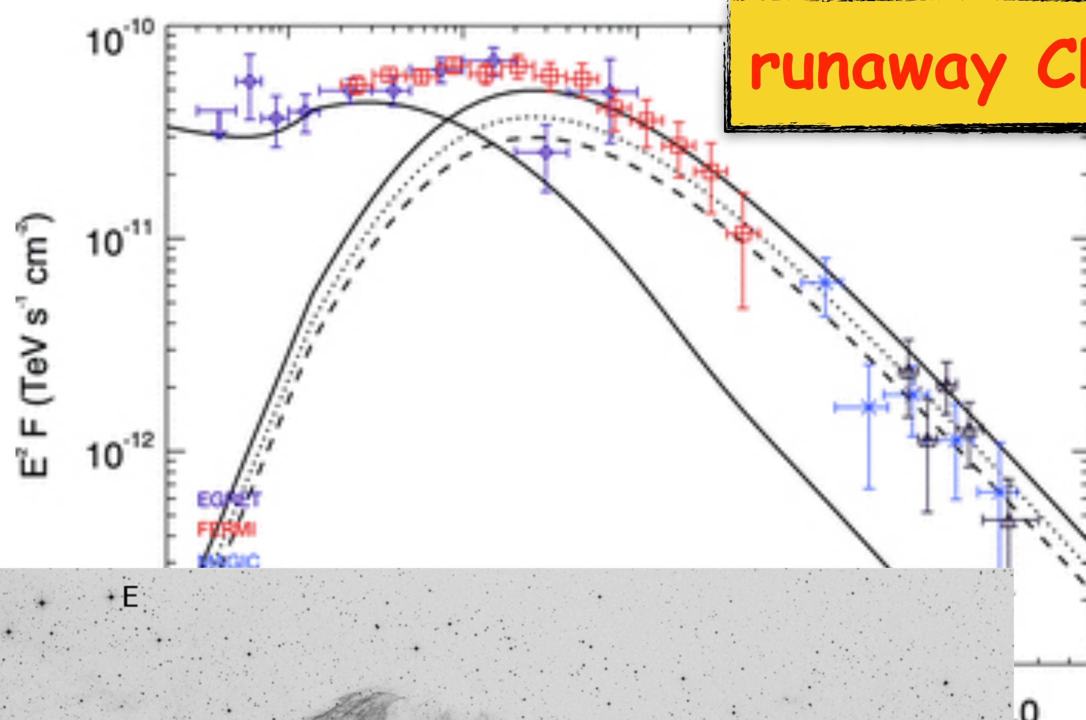
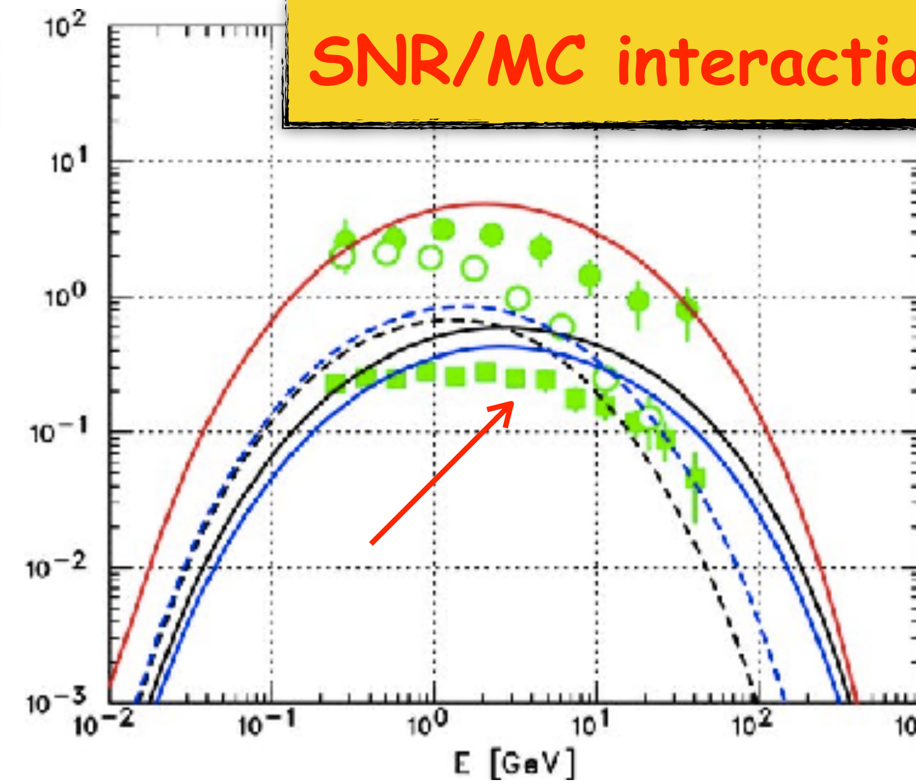


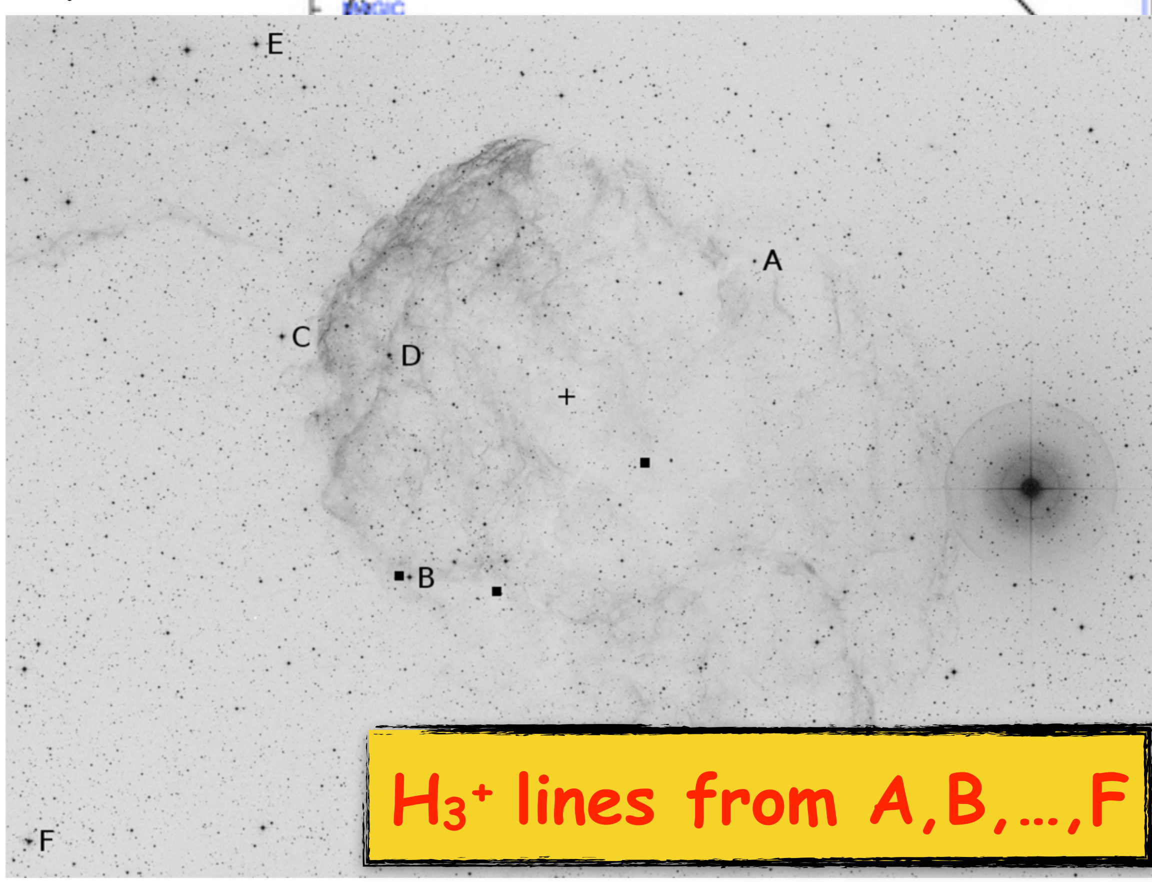
runaway CRs



SNR/MC interaction

Uchiyama+ 2010

Indriolo+ 2010 (Keck, Subaru)



H_3^+ lines from A,B,…,F

H_3^+

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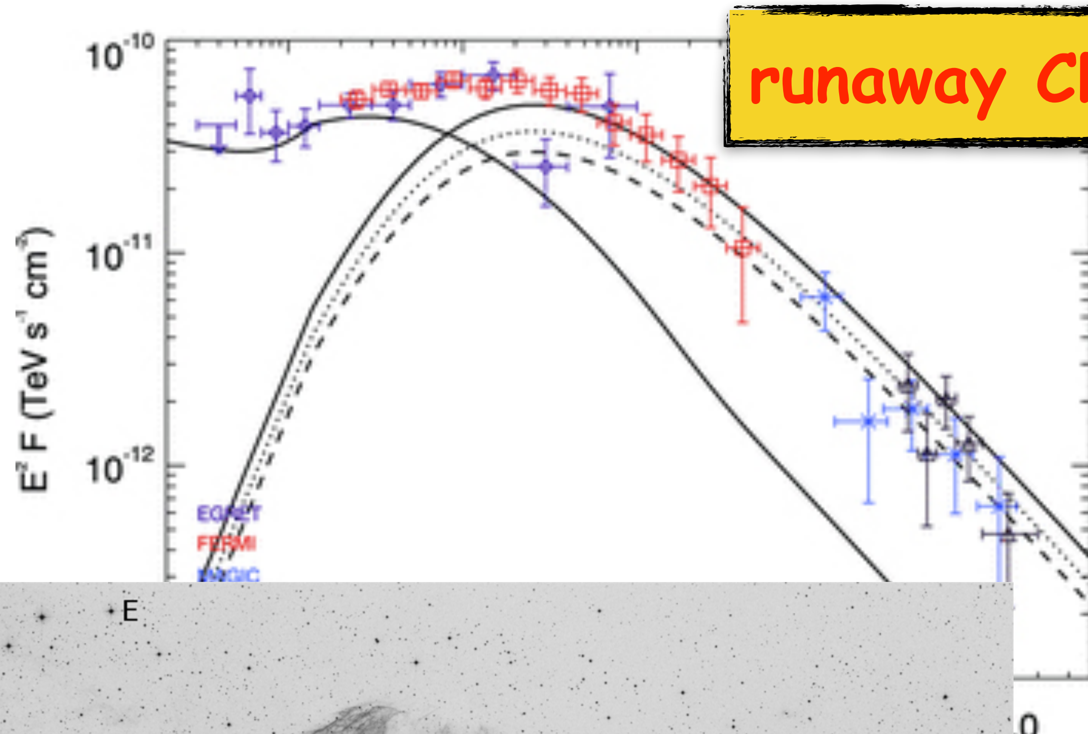

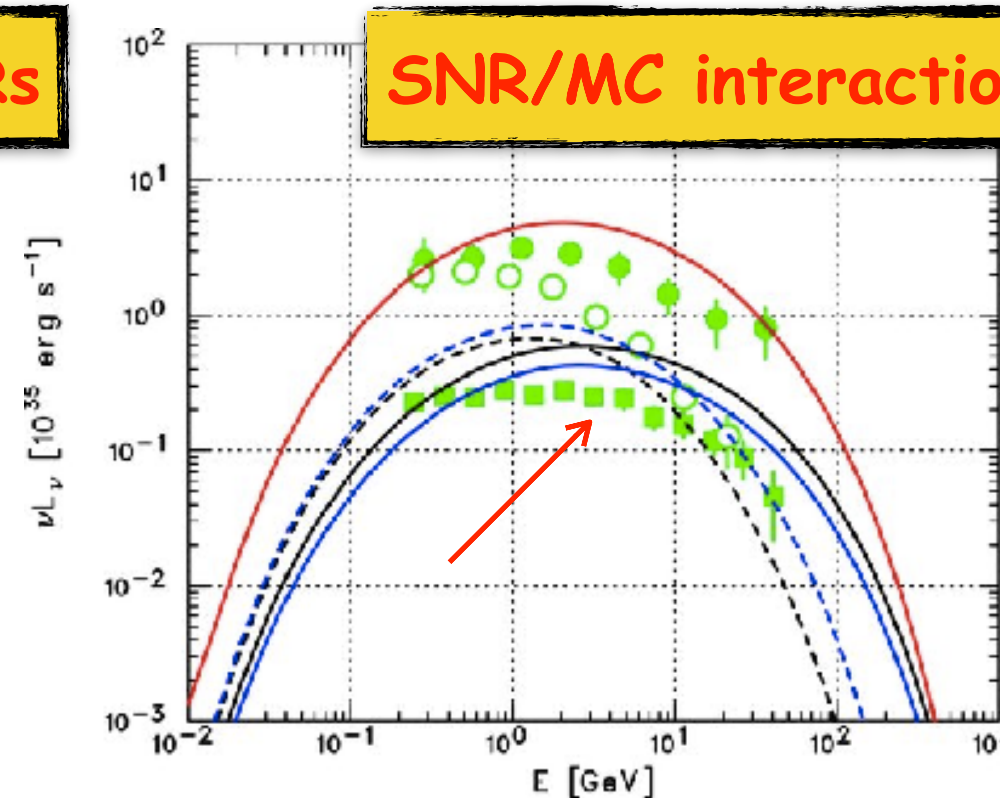

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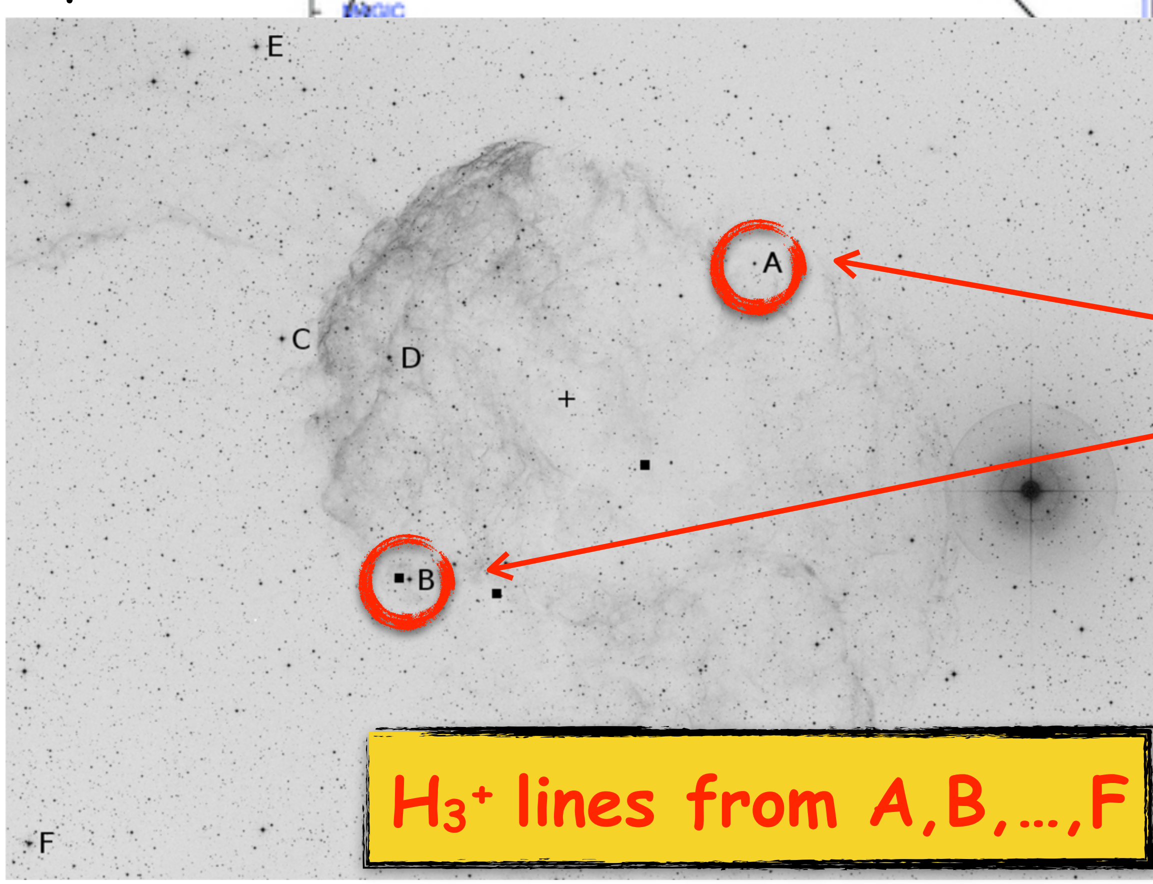
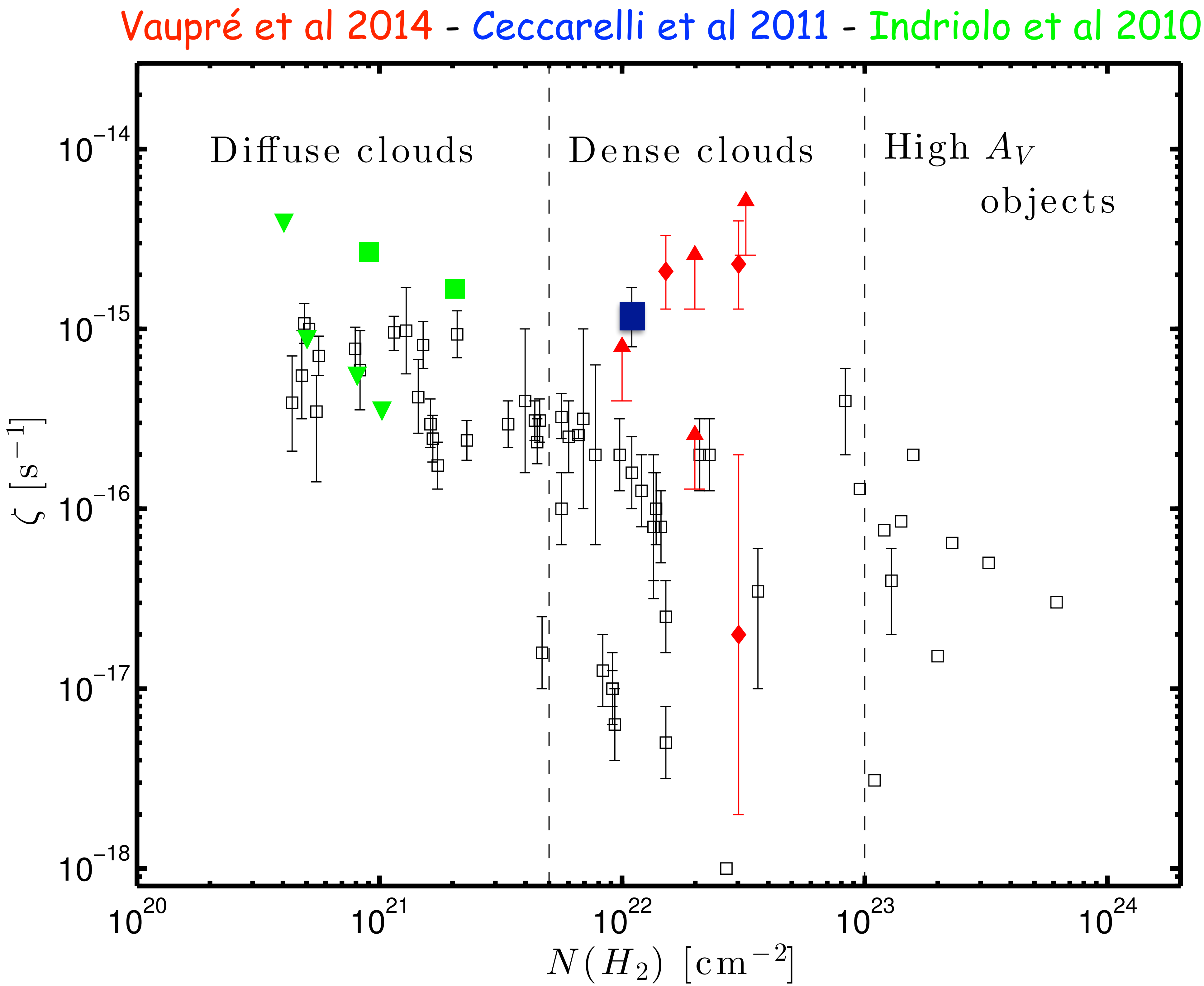


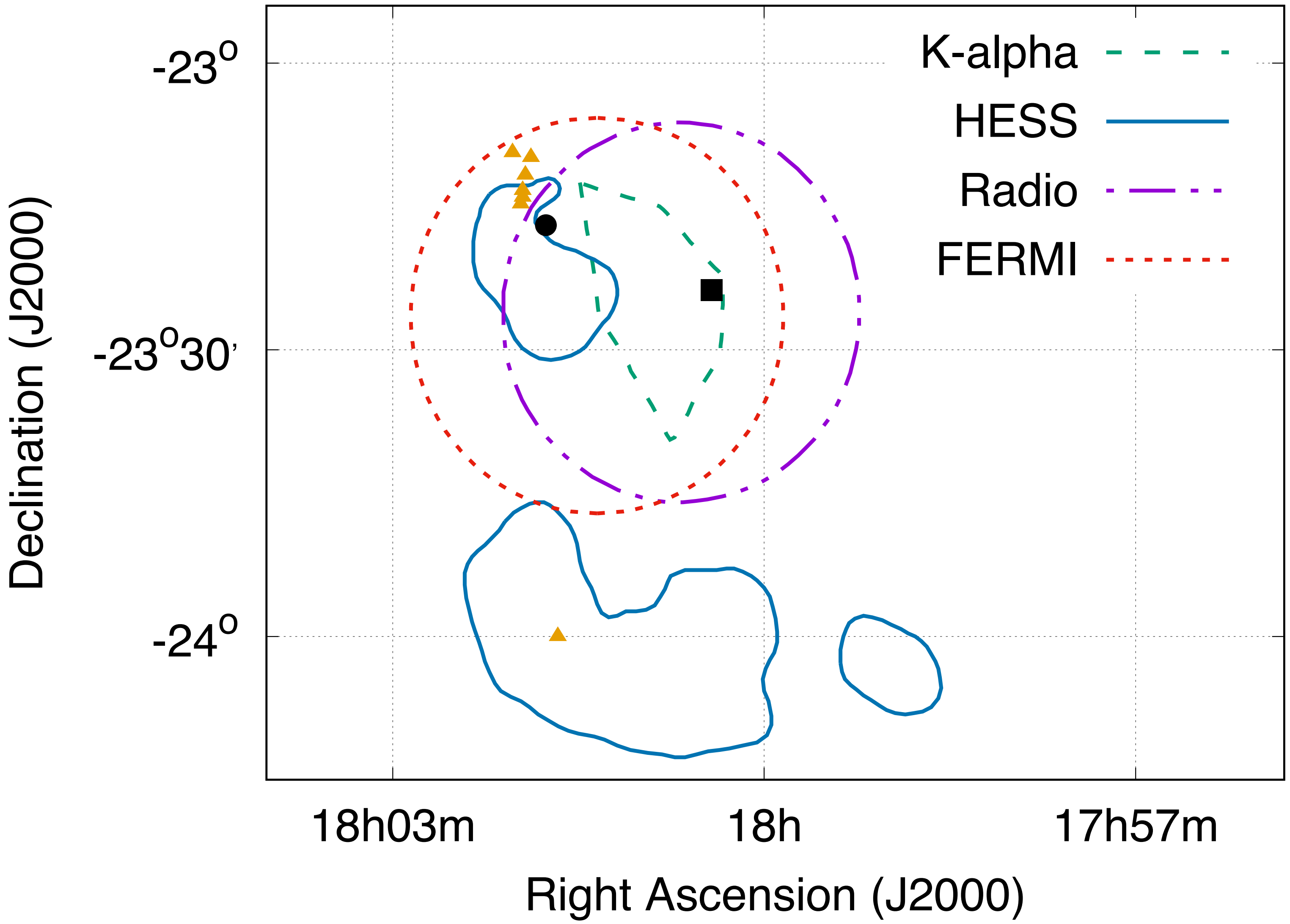
ζ_{CR} ~ few 10^{-15} s^{-1}

non detections: propagation effects? gas up-downstream of the shock?

CR ionization rate in MCs next to SNRs



W28: cosmic rays or X-rays?



Phan+ 2020

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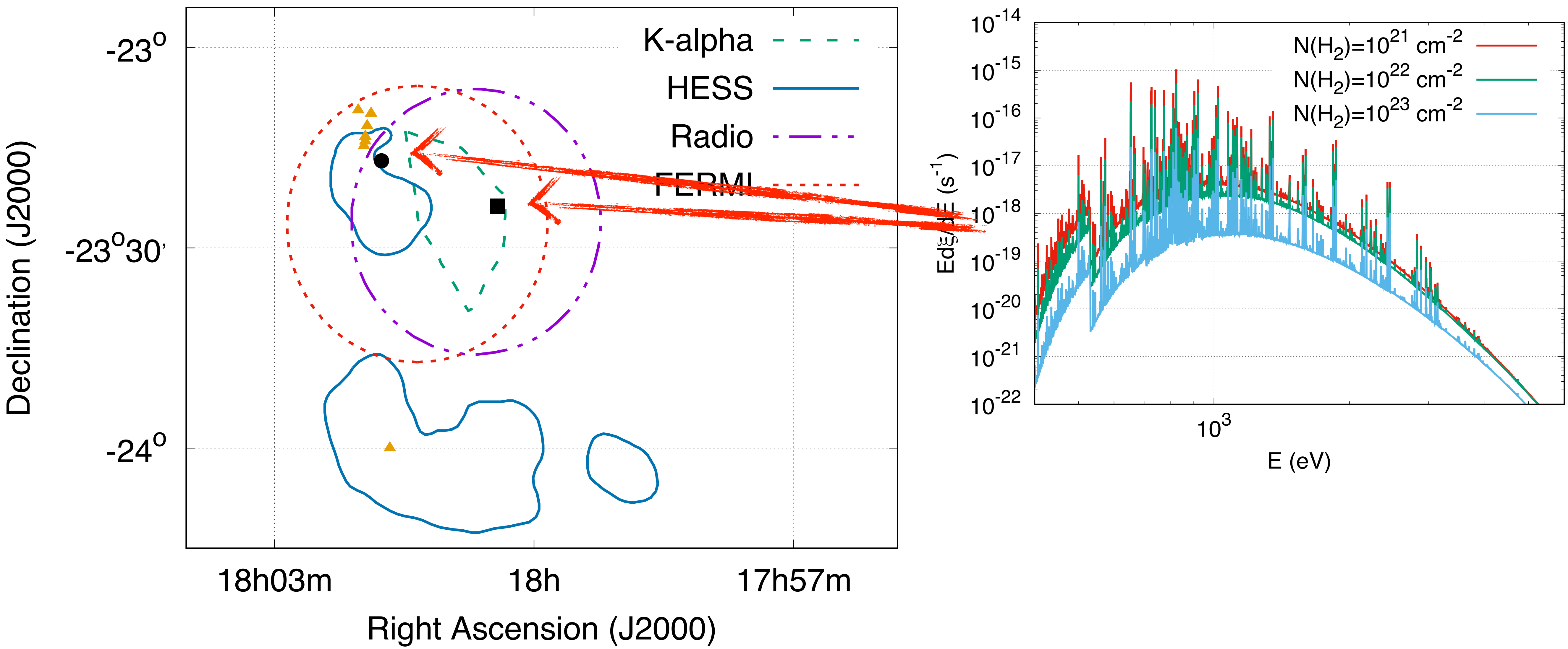

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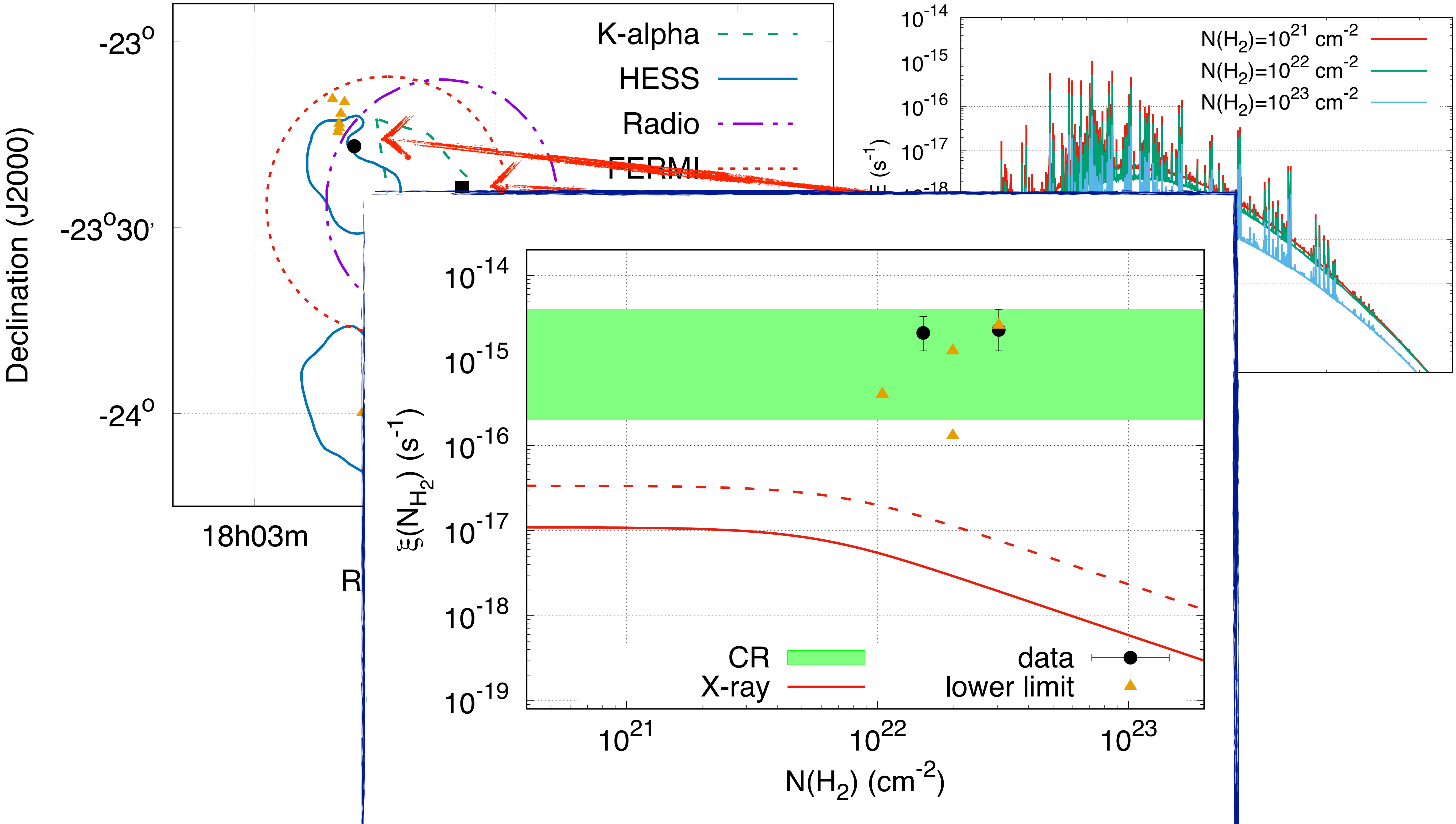

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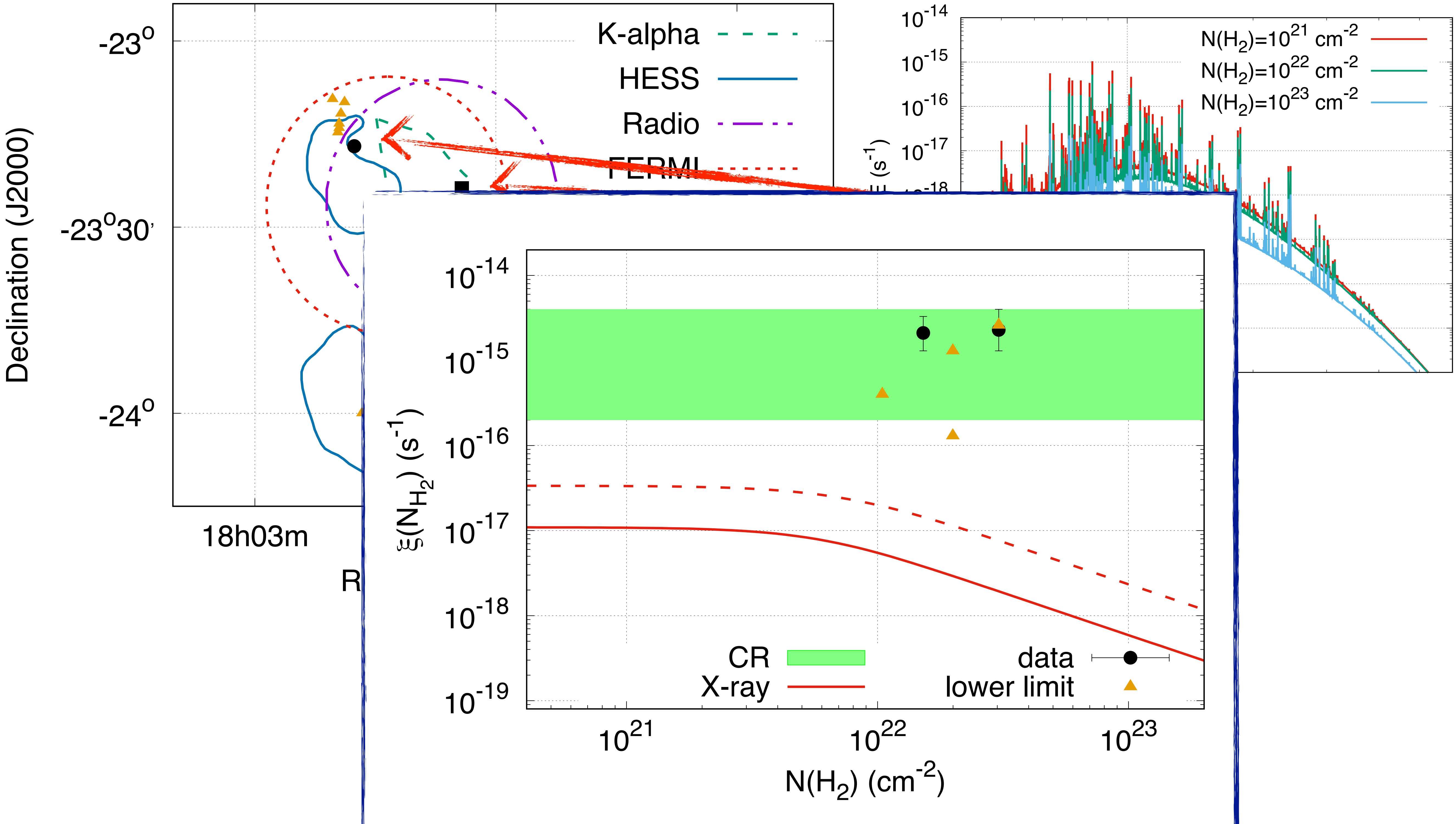
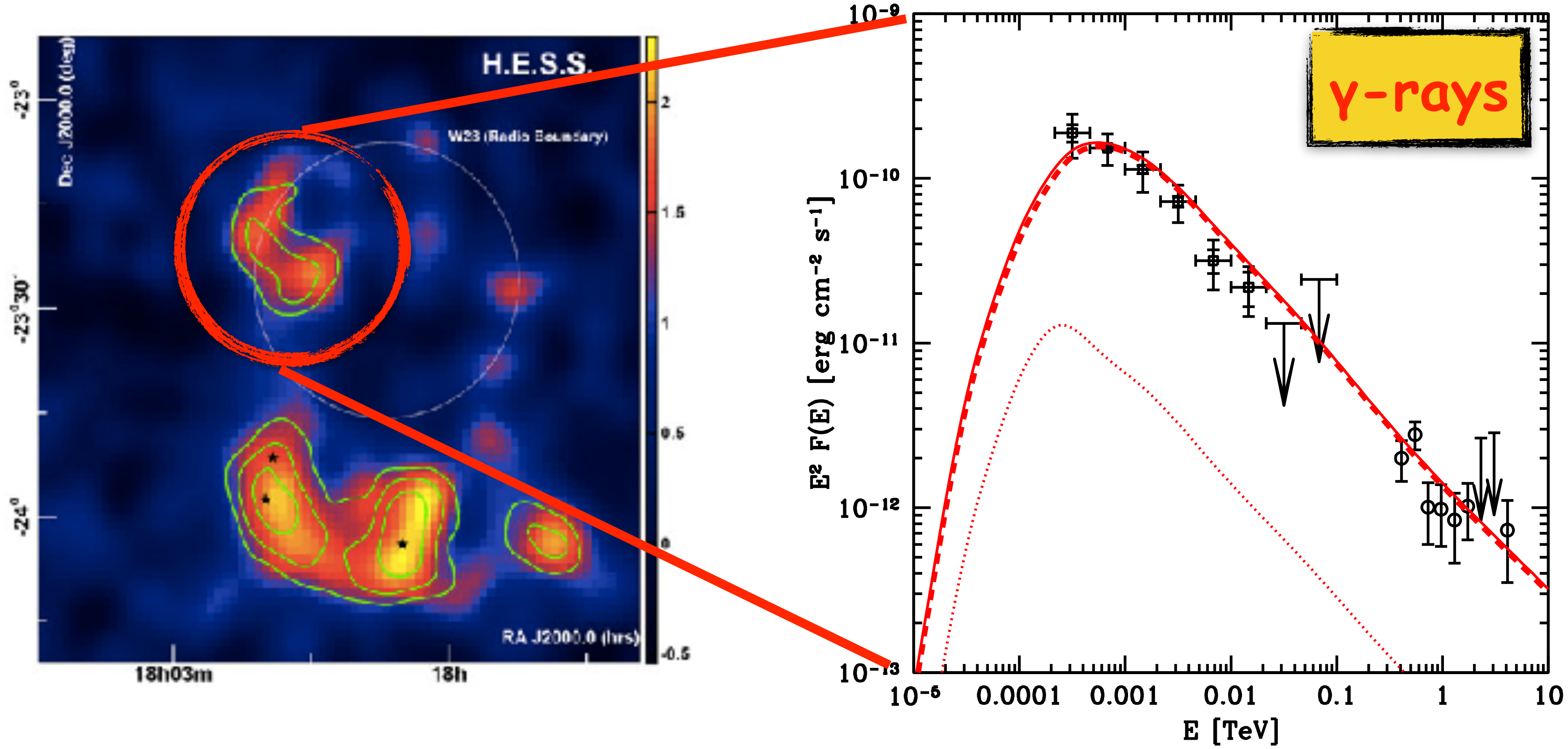


Phan+ 2020

W28: bridging high and low energy CRs



fit with a proton spectrum

$$f_{\rm CR} \propto p^{-2.8}$$

gammas produced by protons of energy

$$E \gtrsim 1 \text{ GeV}$$

Phan+ 2020

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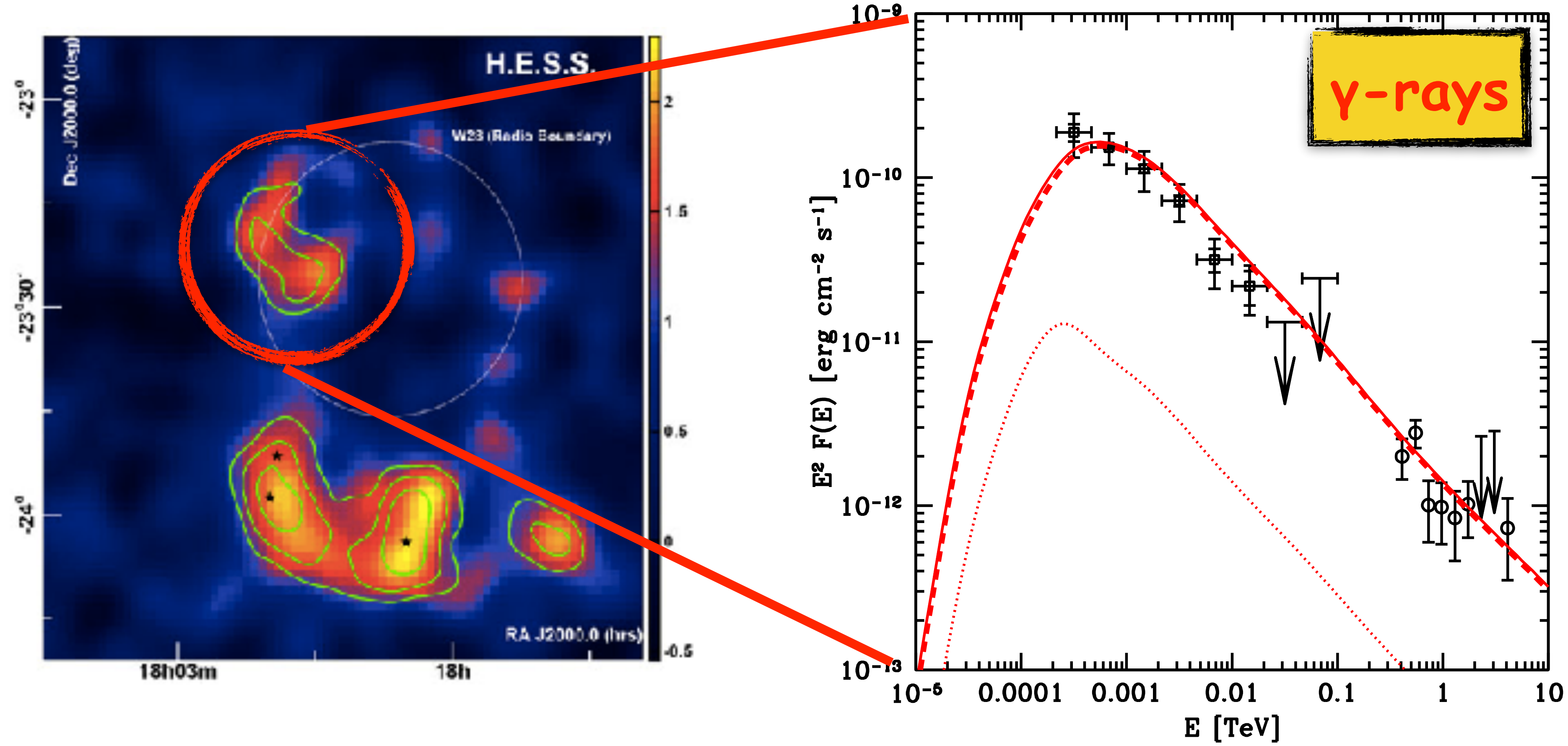

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$$\zeta_{\rm CR} \gtrsim 2 \times 10^{-15} \text{ s}^{-1}$$

$$E_{min} \approx 30 - 300 \text{ MeV}$$

Phan+ 2020

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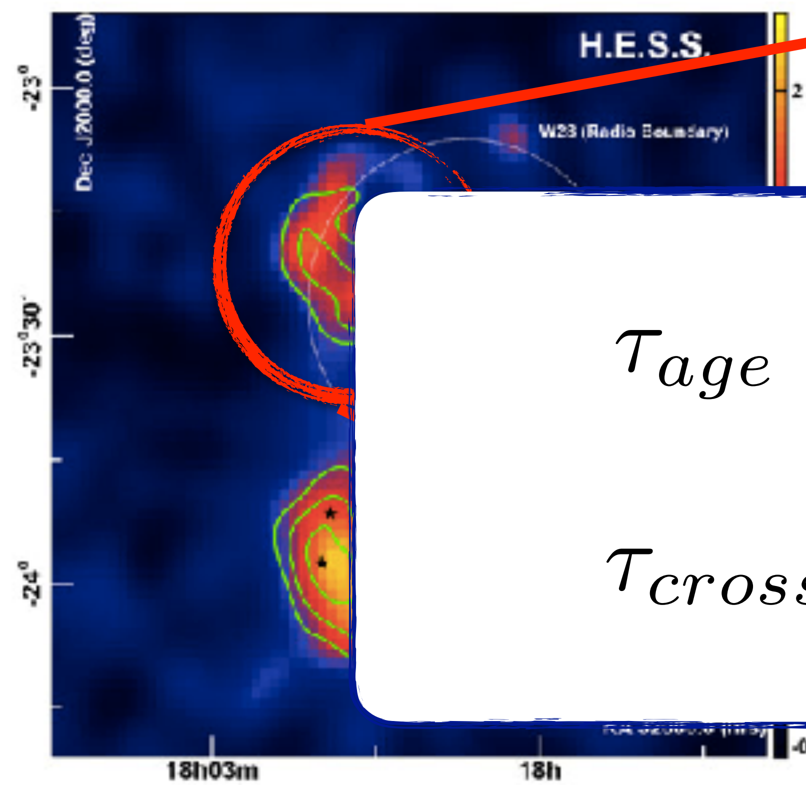

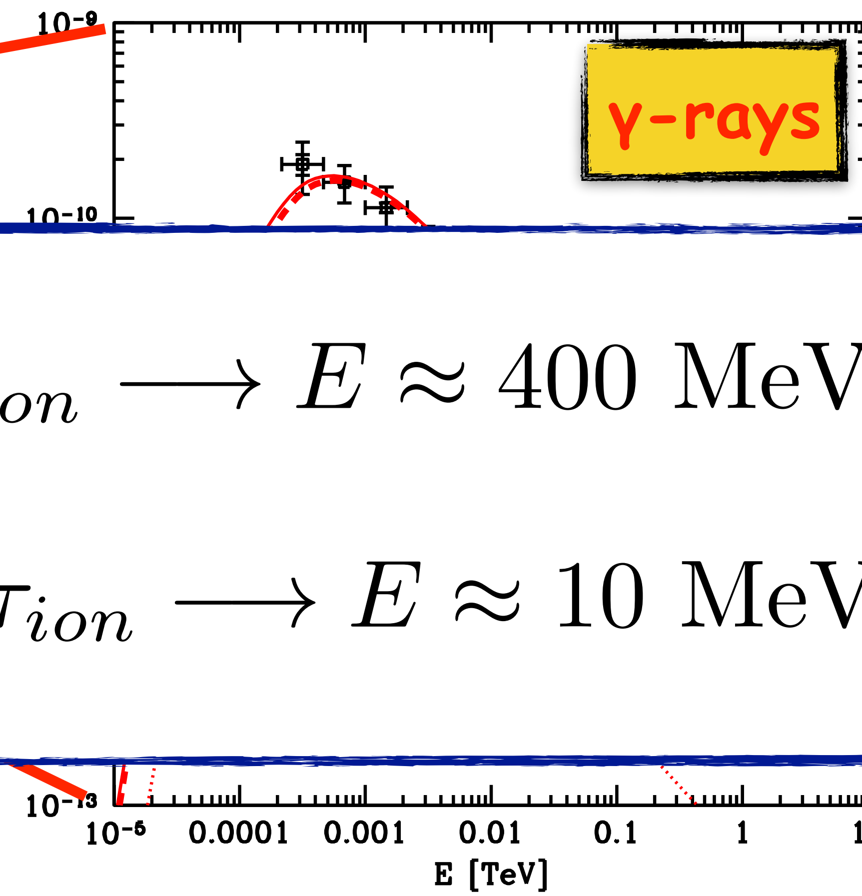

fit with a proton spectrum

$\mathrm{R} \propto p^{-2.8}$

s produced by

ns of energy

$\gtrsim 1\ \mathrm{GeV}$

$$\tau_{age} \sim \tau_{ion} \longrightarrow E \approx 400\ \mathrm{MeV}$$

$$\tau_{cross} \sim \tau_{ion} \longrightarrow E \approx 10\ \mathrm{MeV}$$

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Phan+ 2020

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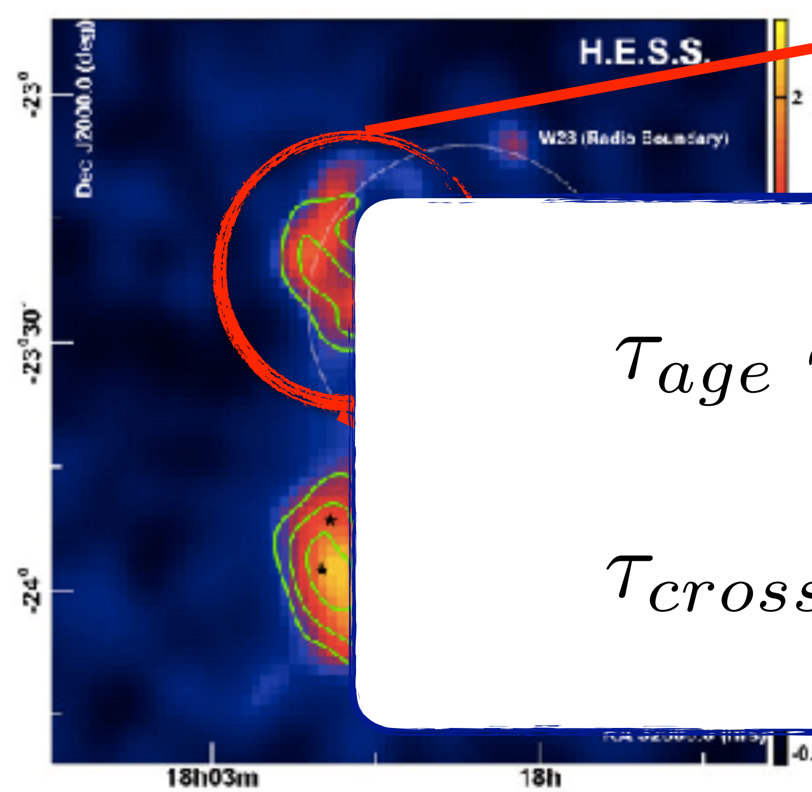

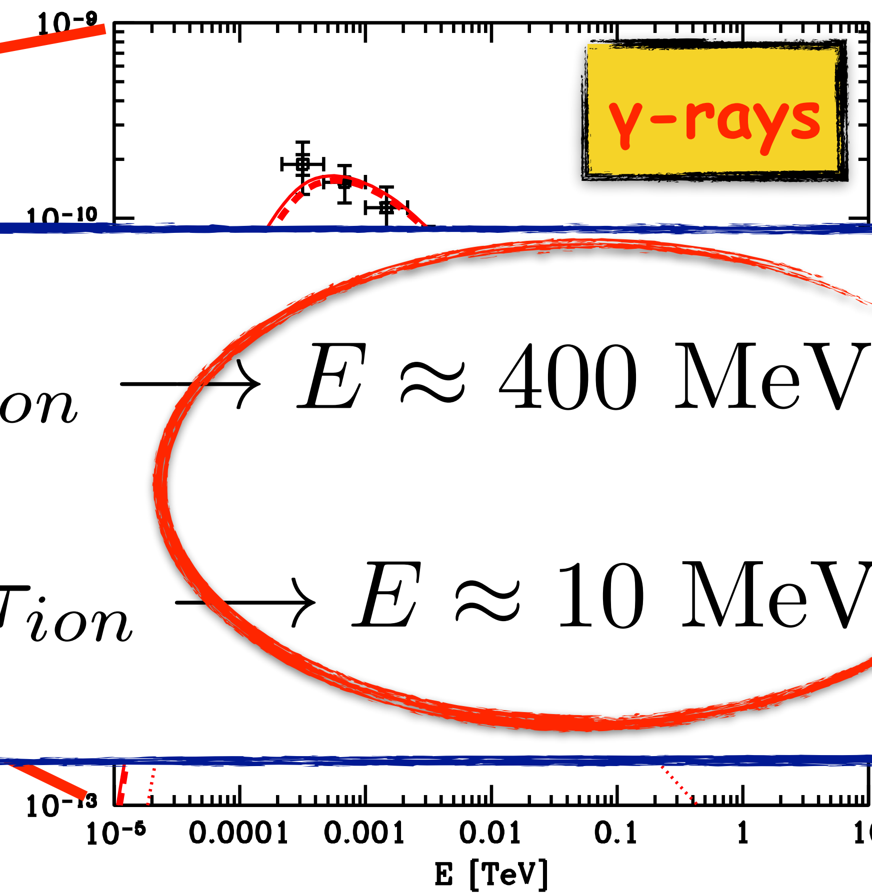

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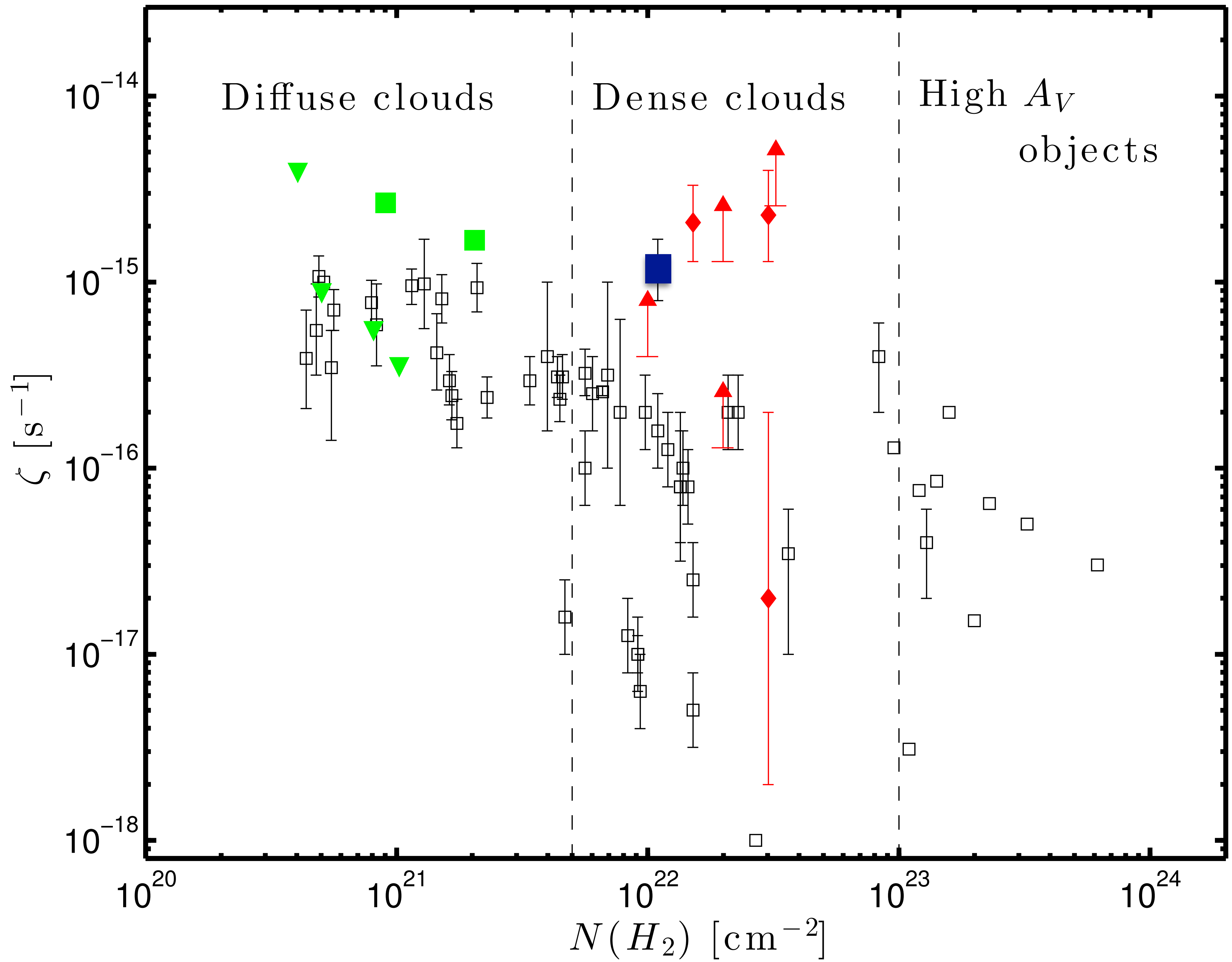
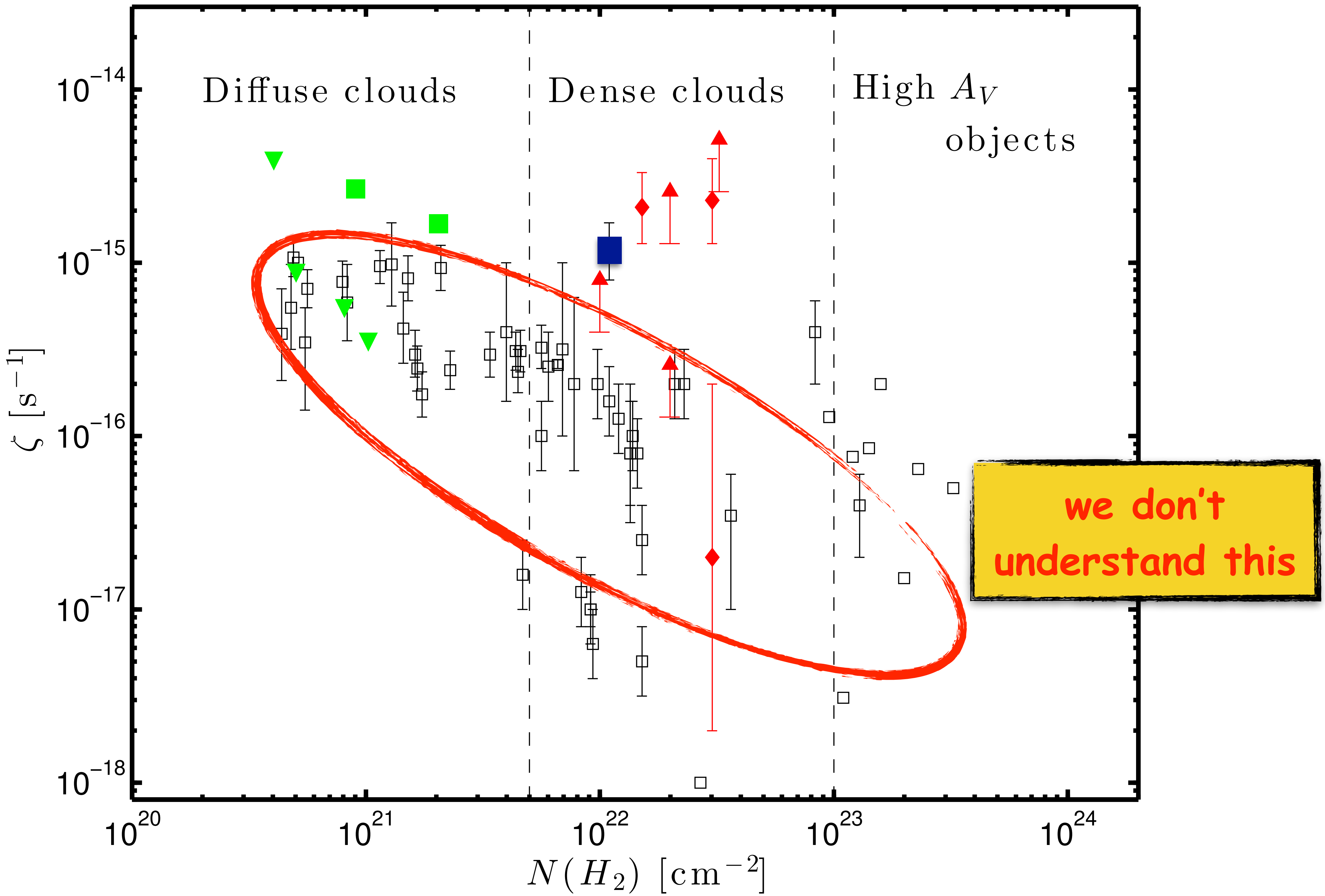
Phan+ 2020

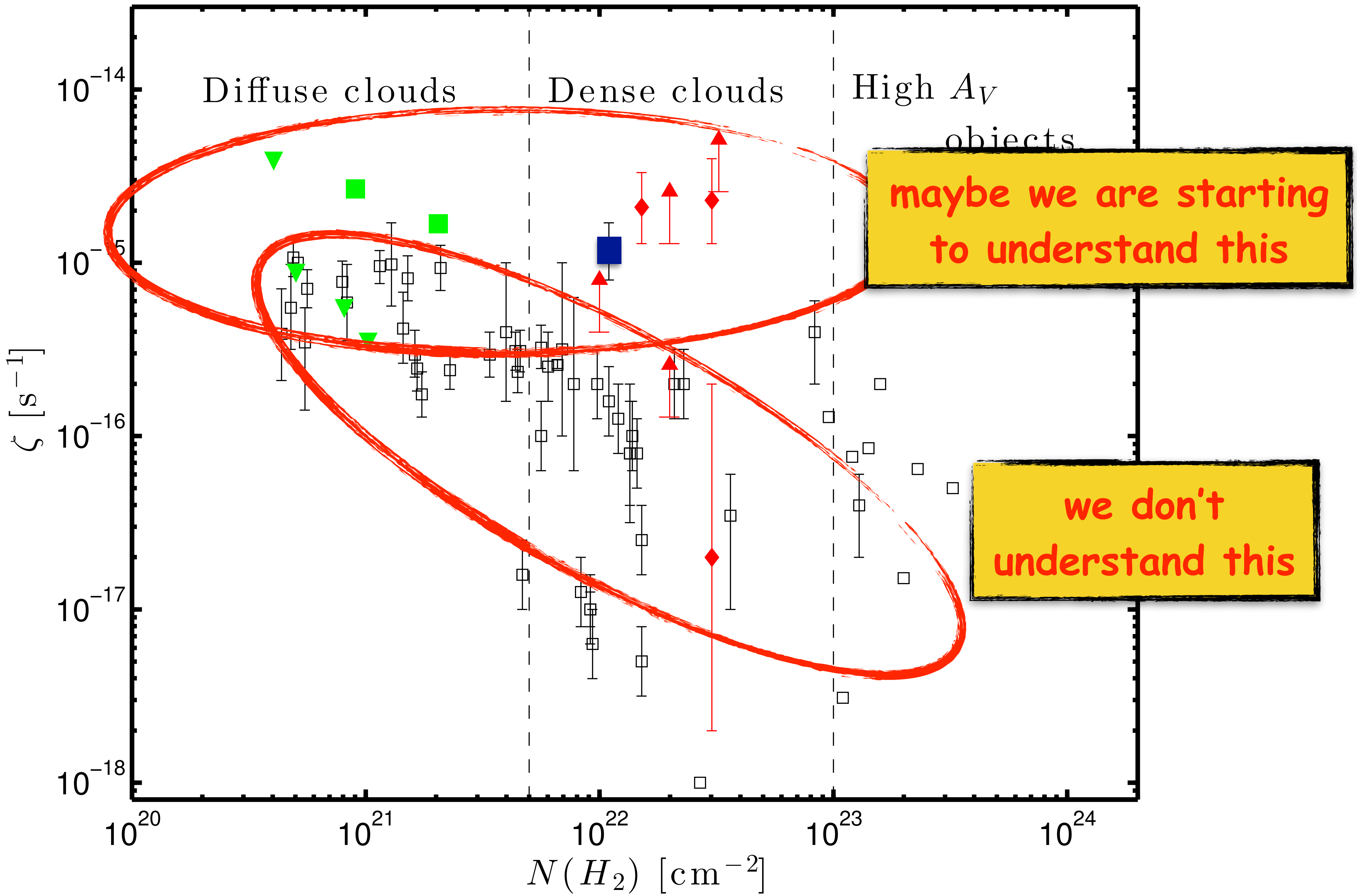
Conclusions (?)



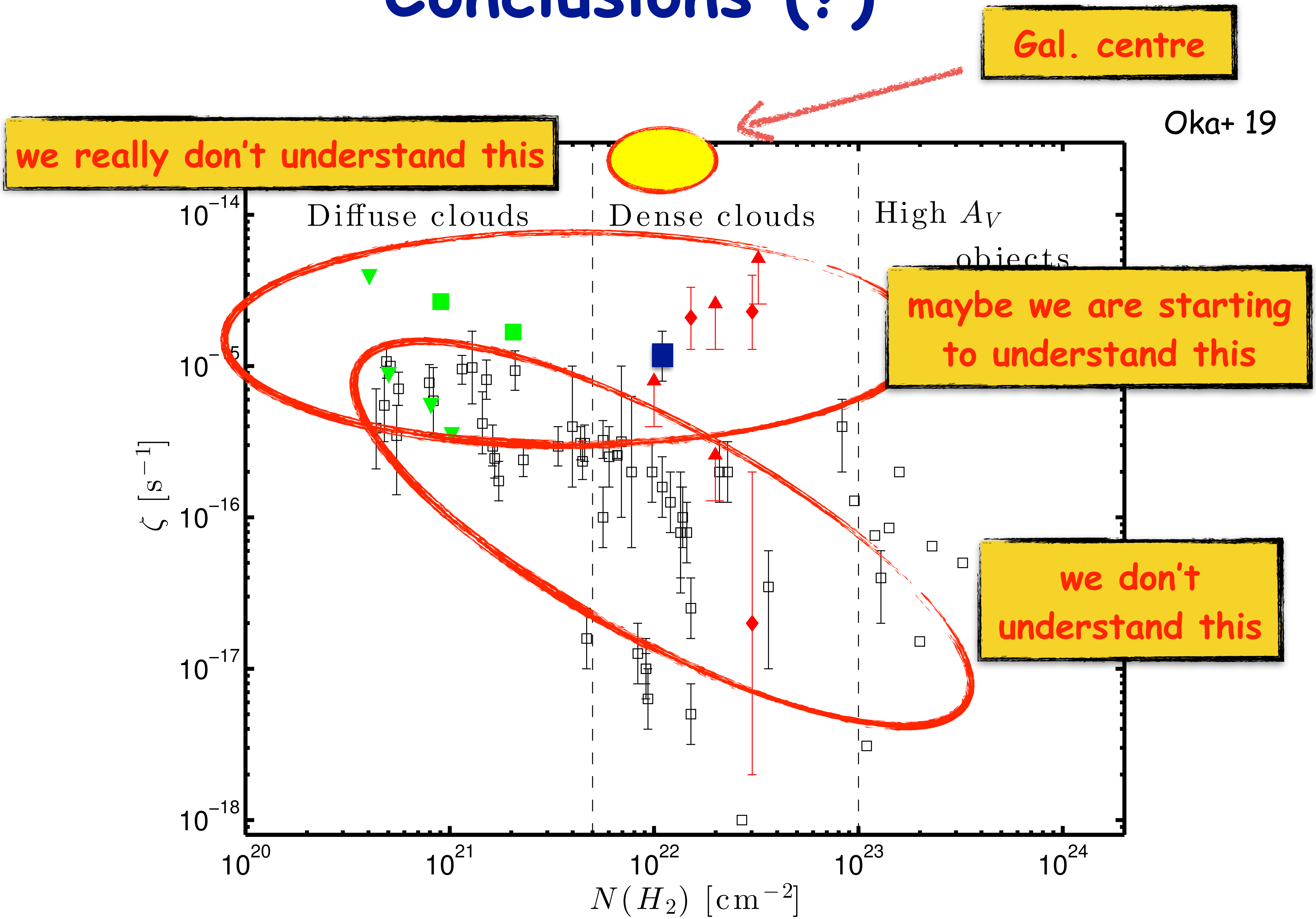
Conclusions (?)



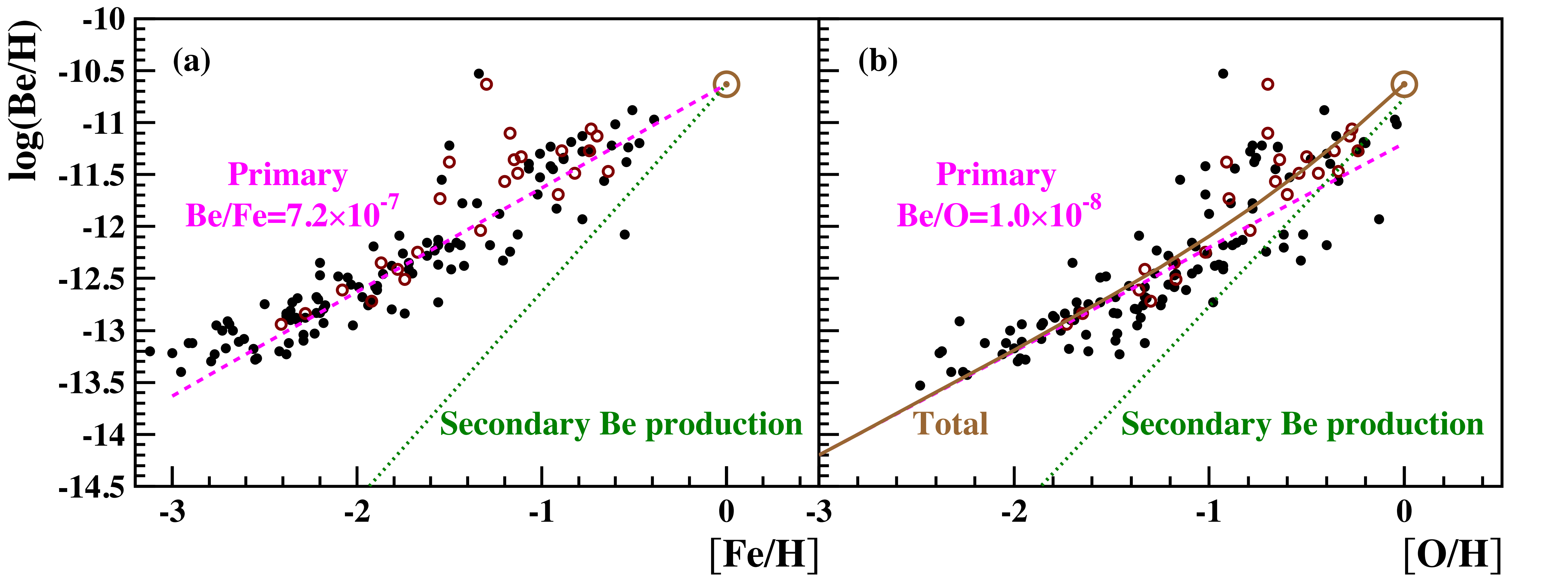
Conclusions (?)



Conclusions (?)



Another thing we don't understand: Spallogenic nucleosynthesis of Li-Be-B



e.g. Parizot 2000, for a review see Tatischeff&Gabici 2018

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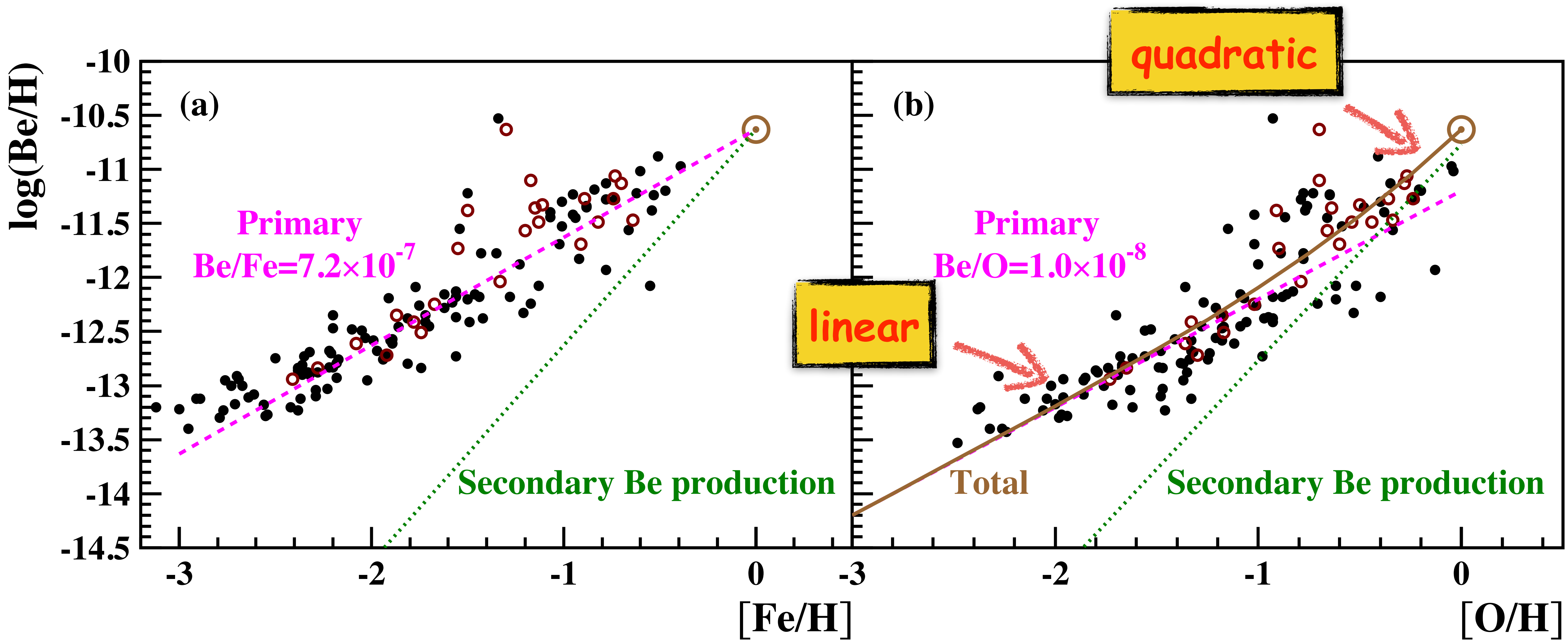

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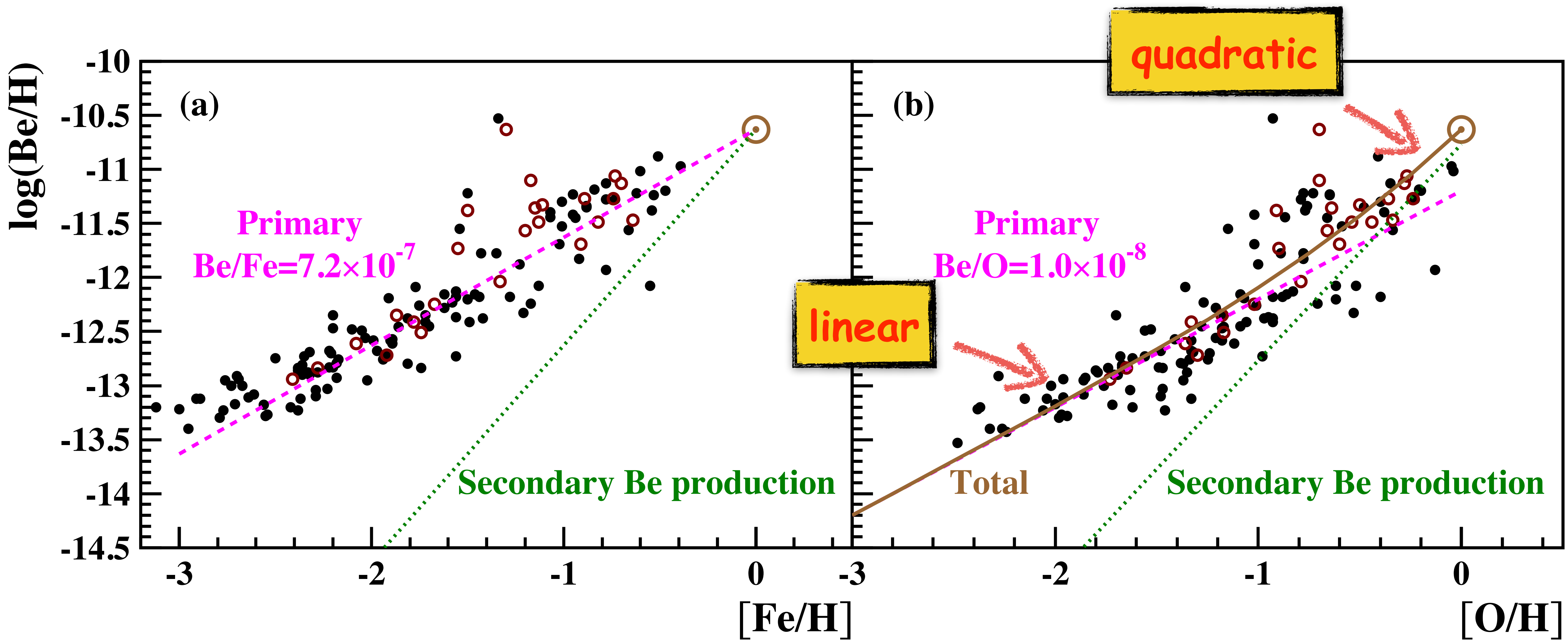

superbubbles -> CRs are accelerated from an enriched ISM
(X_{CR} closer to constant rather than X_{ISM})

e.g. Parizot 2000, for a review see Tatischeff&Gabici 2018

(Real) conclusions