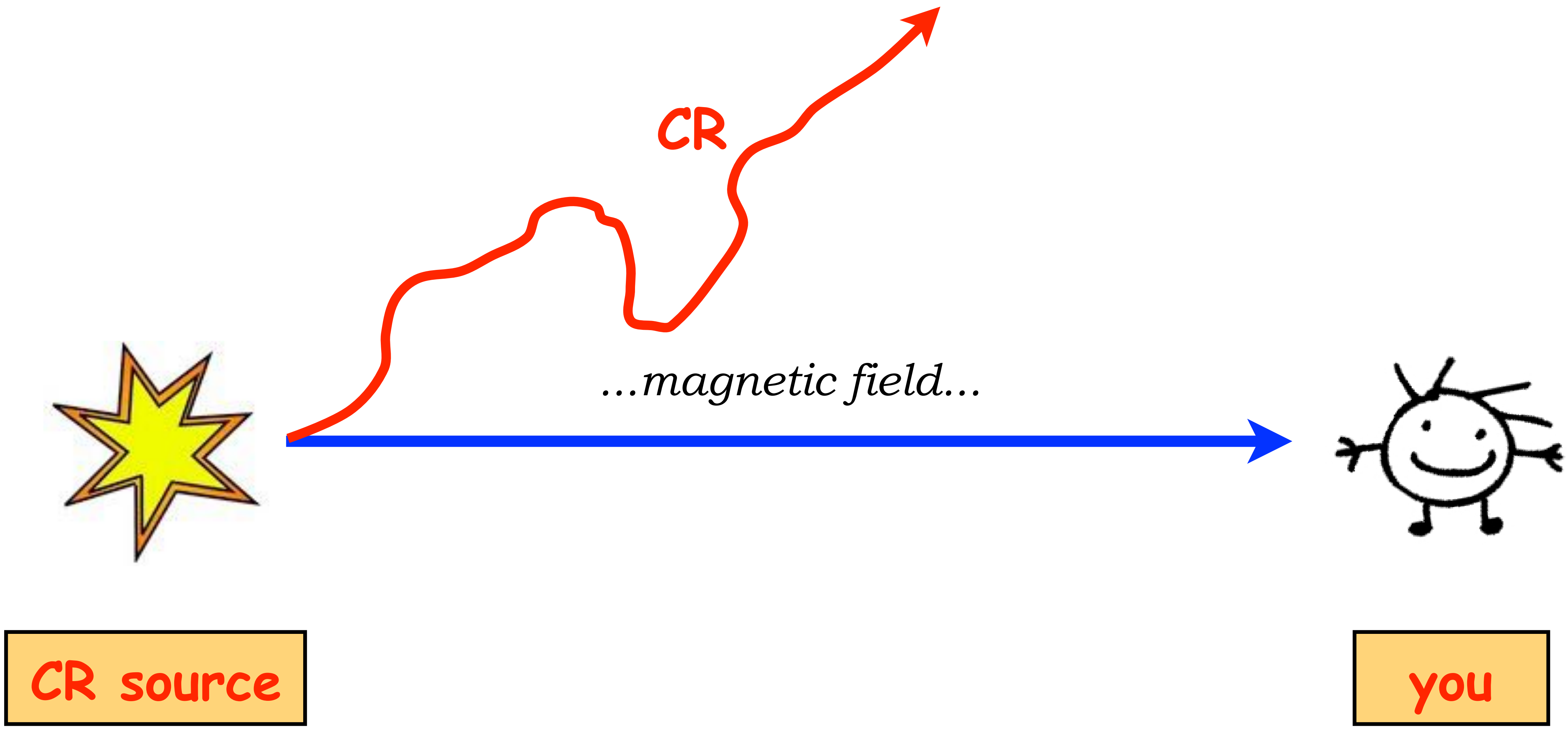
Low energy cosmic rays

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

www.cnrs.fr

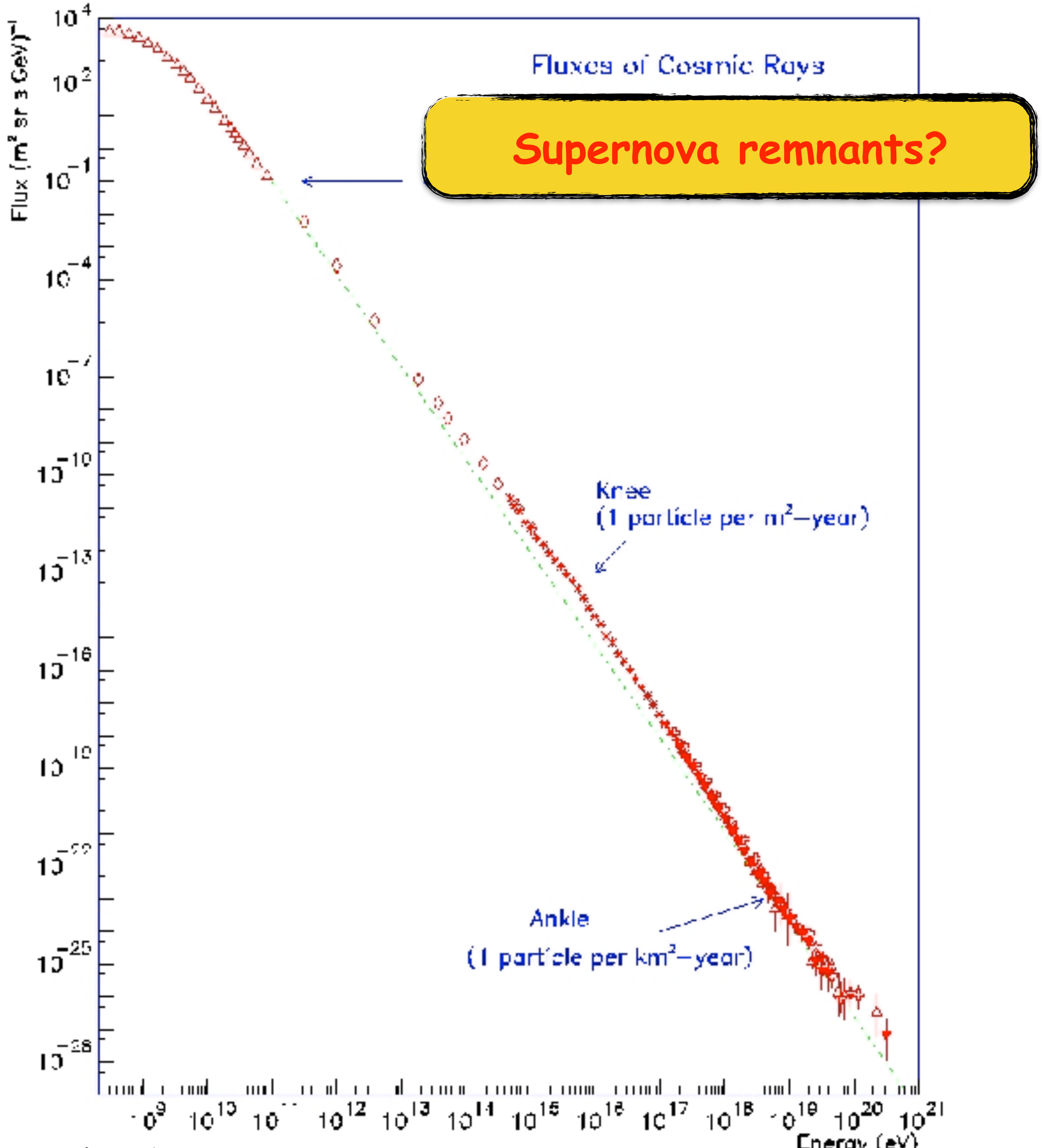
Cosmic ray sources: why is it so difficult?



We cannot do CR Astronomy.

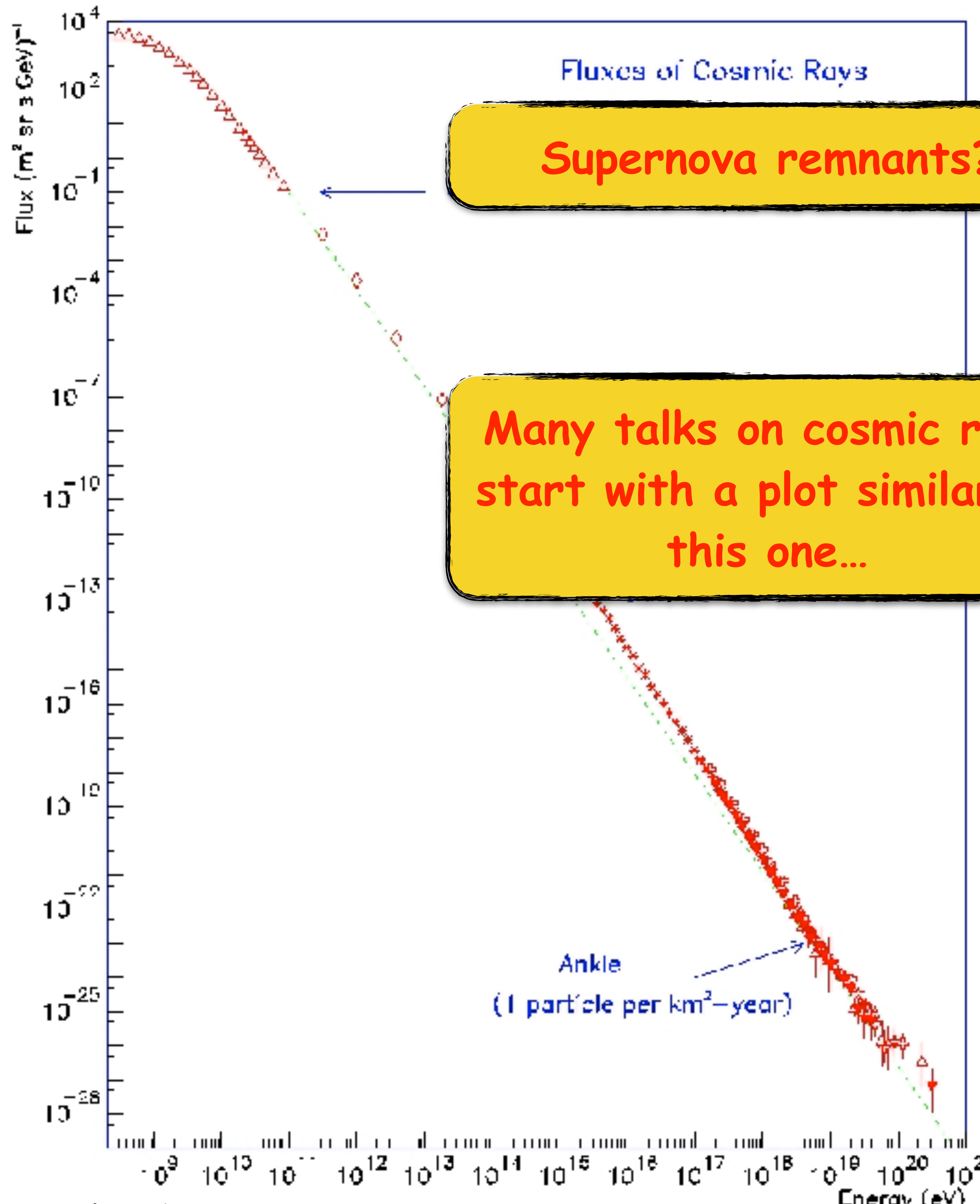
Need for indirect identification of CR sources.

Cosmic rays



Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD, 2019

Cosmic rays

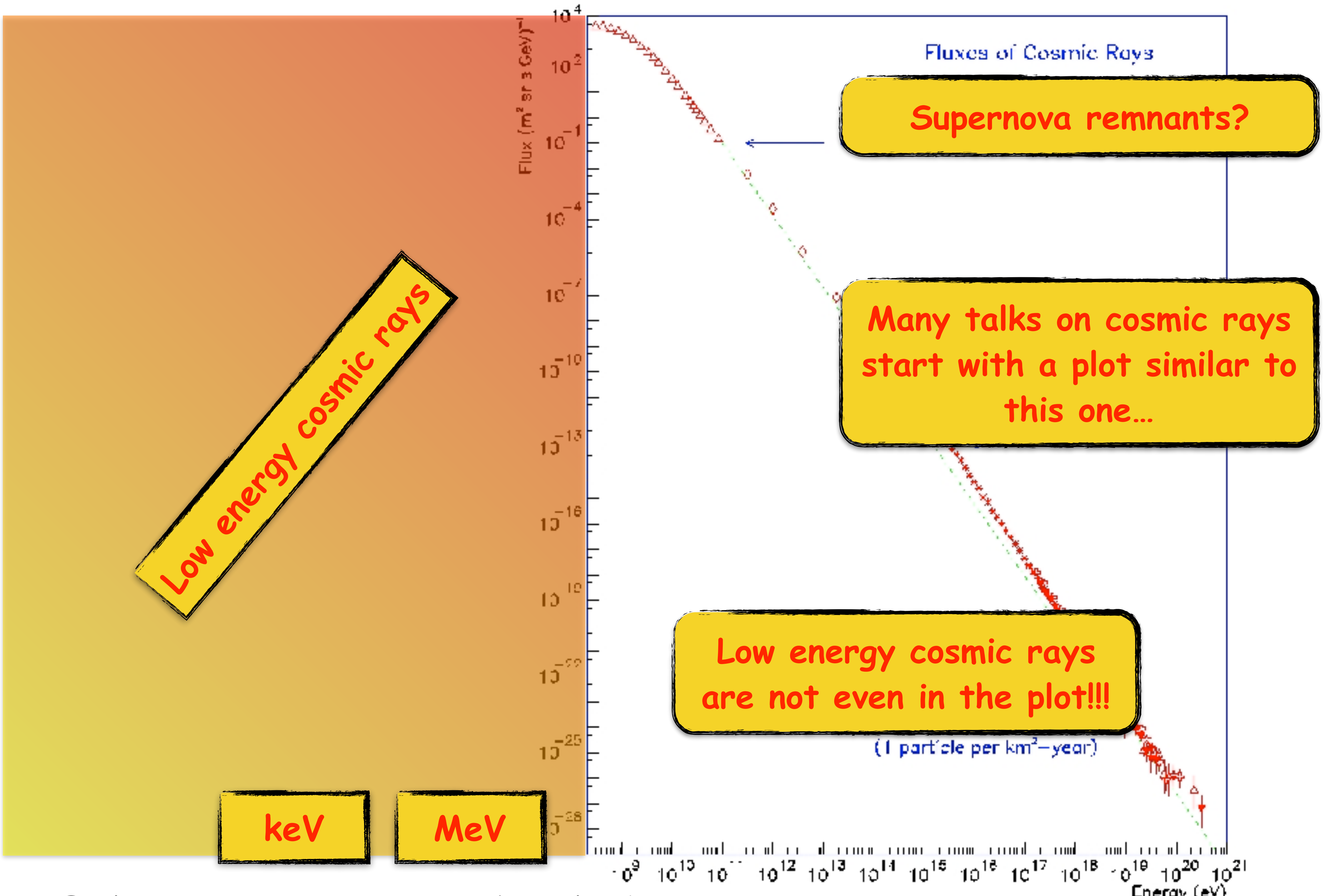


Supernova remnants?

Many talks on cosmic rays start with a plot similar to this one…

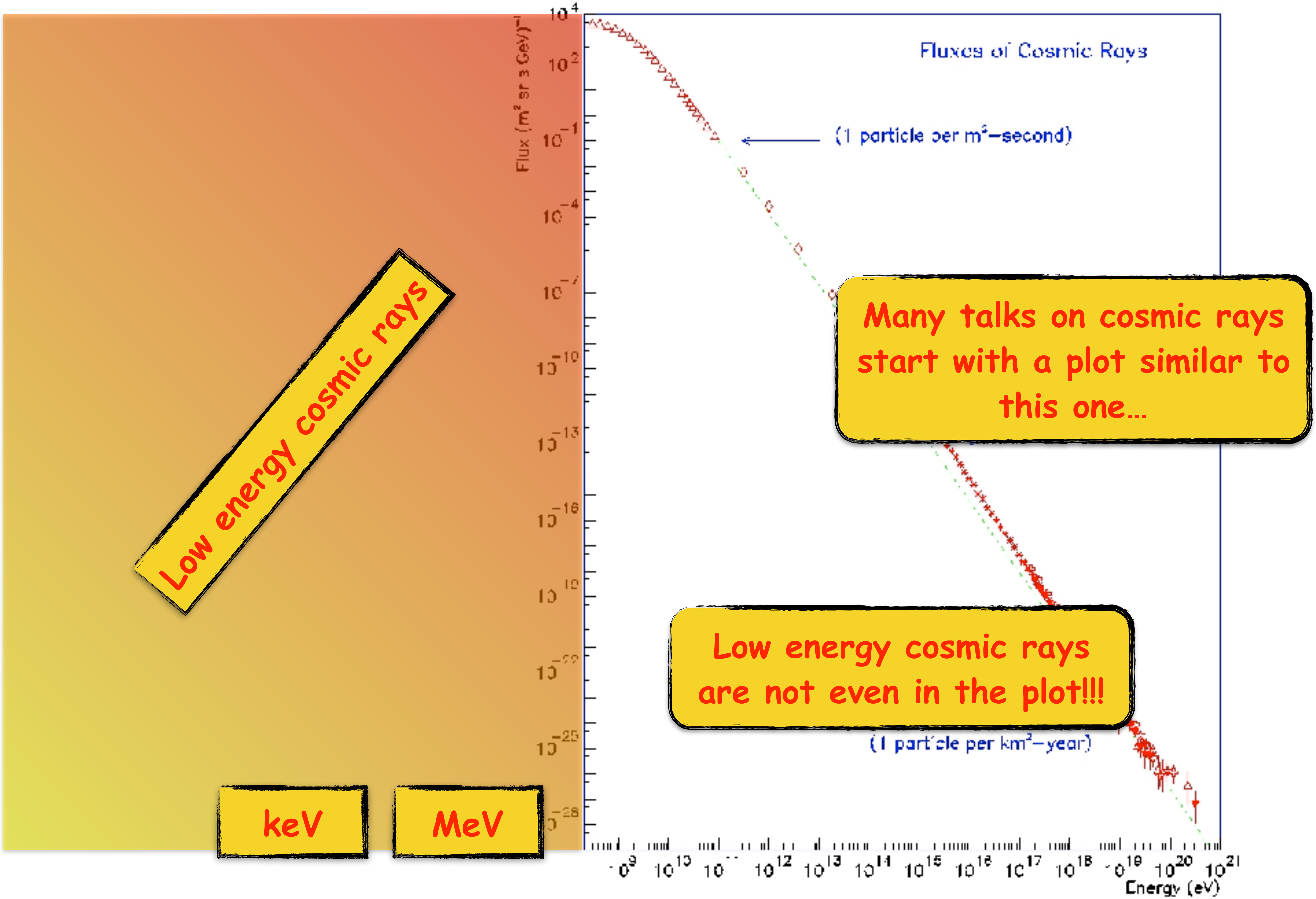
Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD, 2019

Cosmic rays

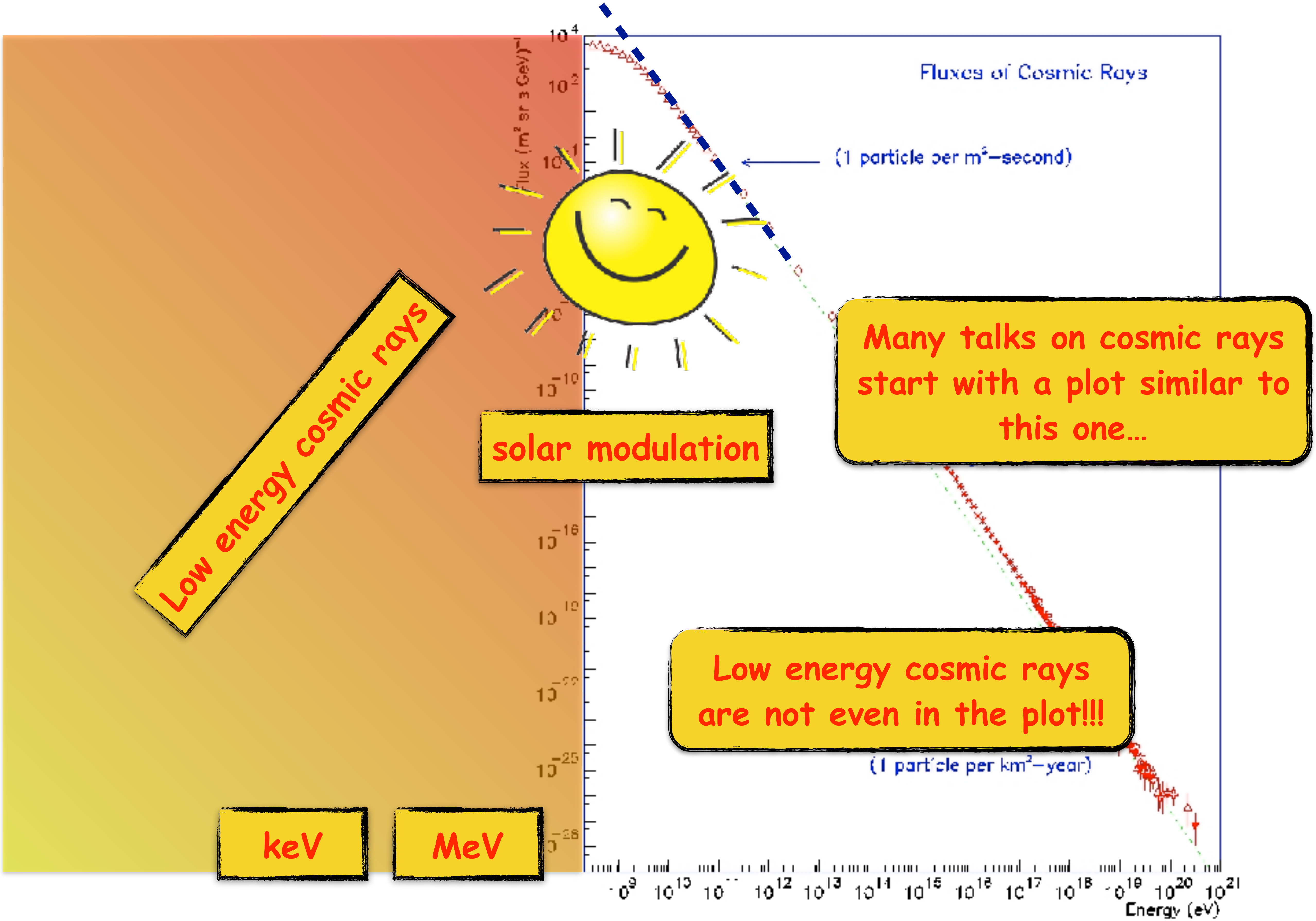


Gabici, Evoli, Gaggero, Lipari, Mertsch, Orlando, Strong, Vittino, IJMPD, 2019

Why so difficult?



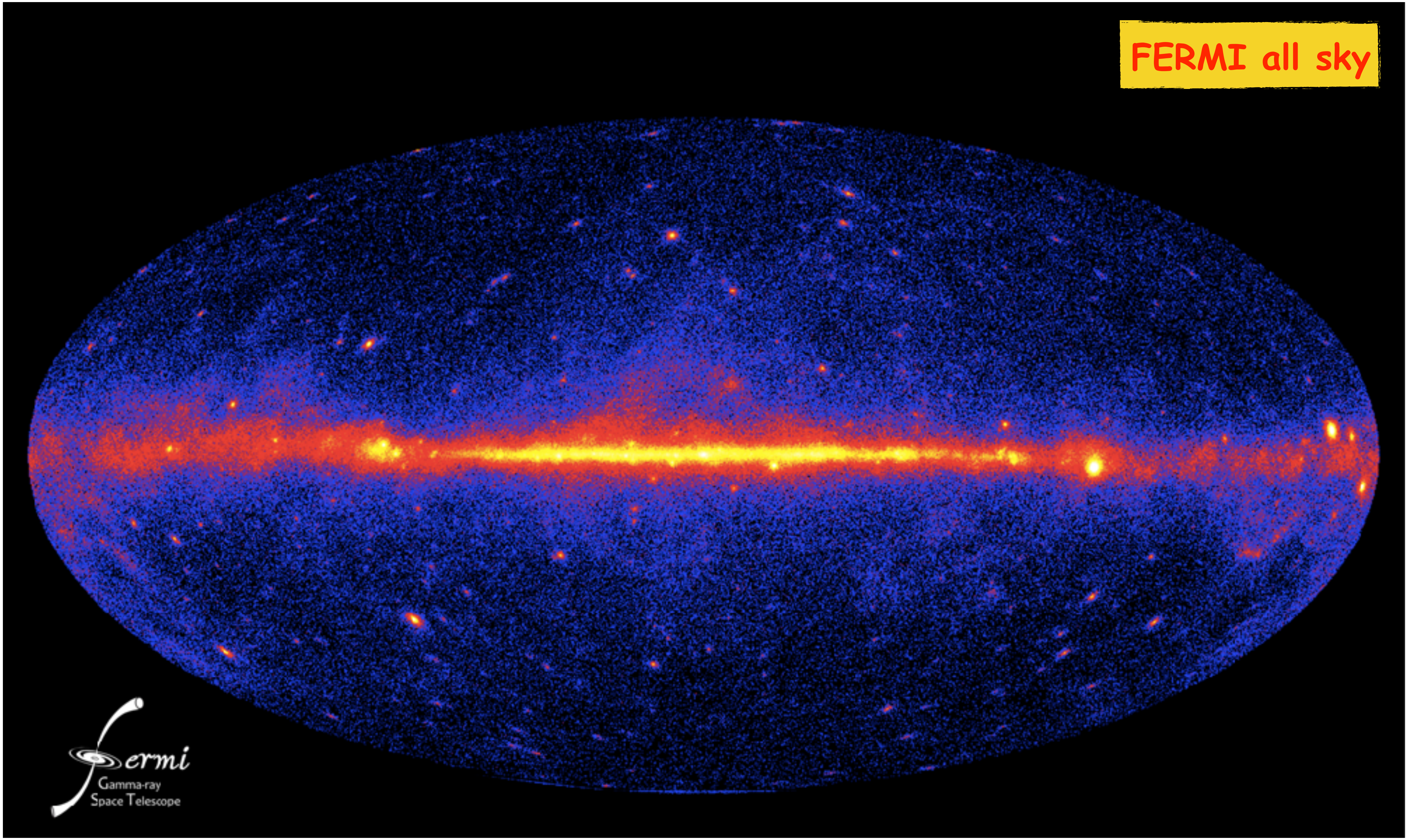
Why so difficult?



Far away cosmic rays

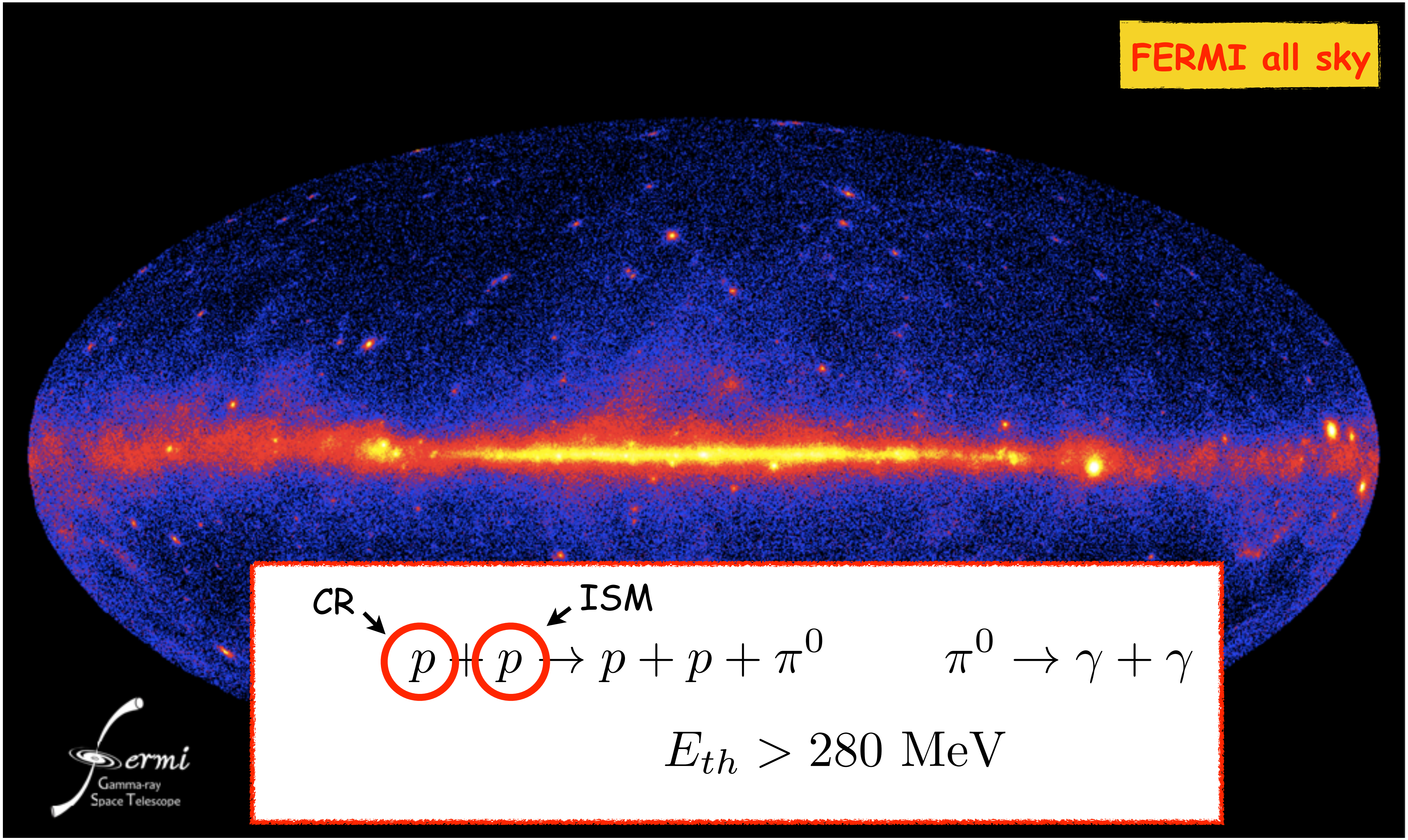
Predicted by Hayakawa in 1952 …….. the gamma-ray sky seen by Fermi/LAT now

Far away cosmic rays



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

Far away cosmic rays



$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma$$

$$E_{th} > 280 \text{ MeV}$$

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

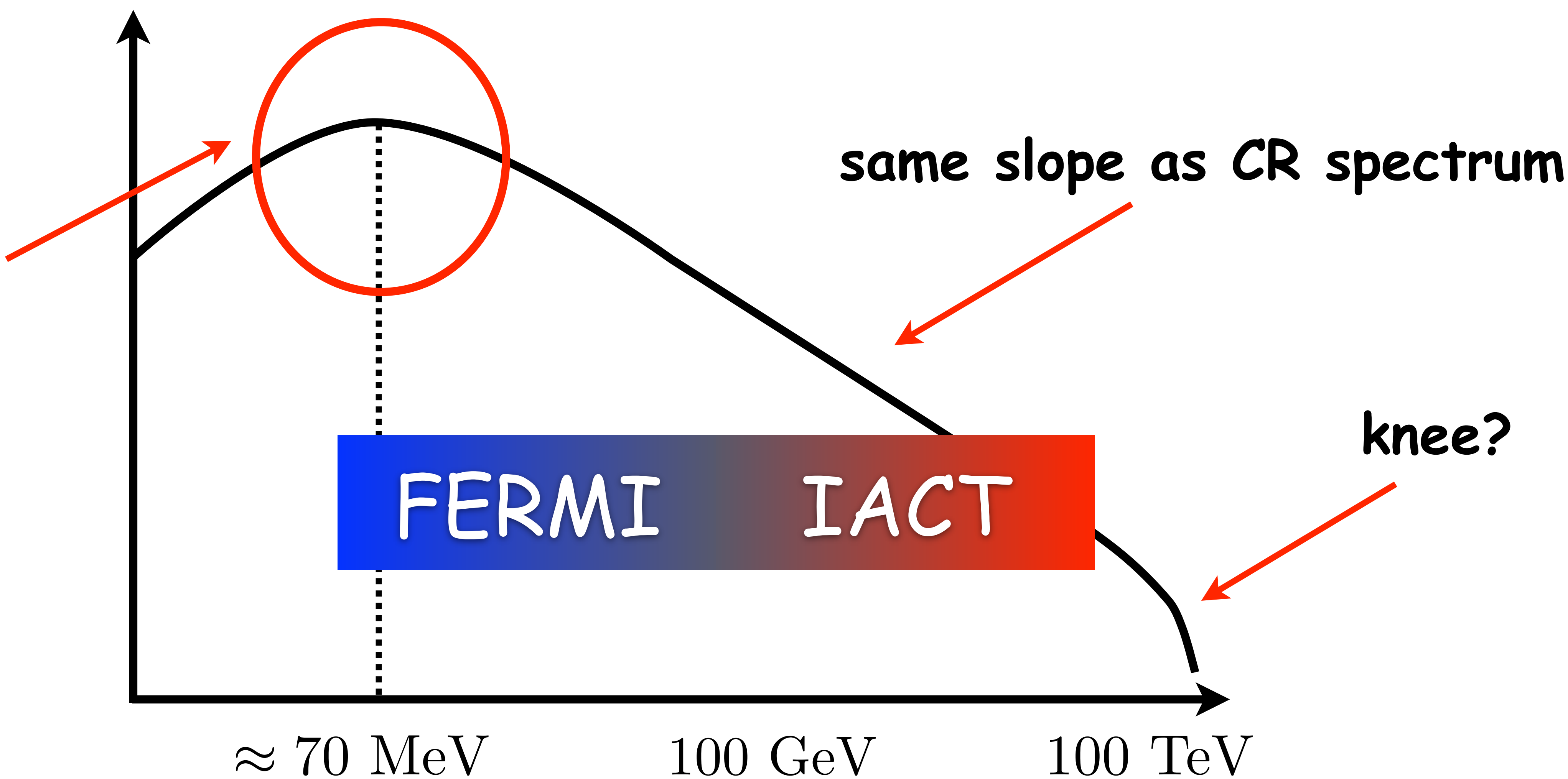
Gamma-ray astronomy

$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma$$

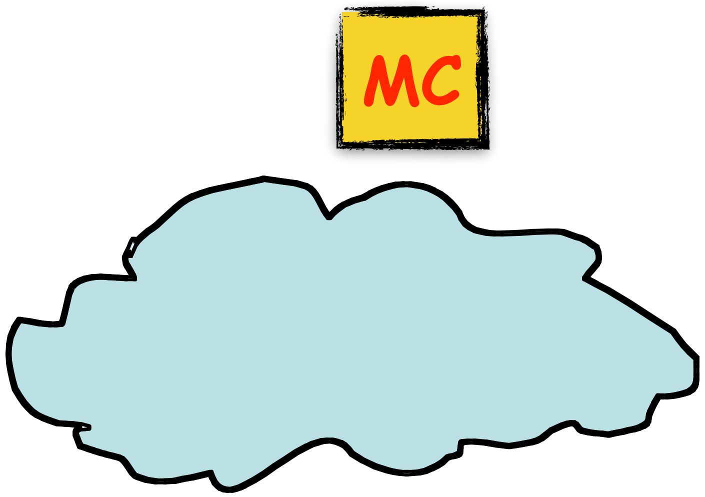
CR ISM

$$\langle E_\gamma \rangle \approx E_{CR}/10$$

$$E_{peak} = \frac{m_{\pi^0}}{2}$$



Molecular clouds as cosmic ray probes



see e.g.

Black&Fazio1973

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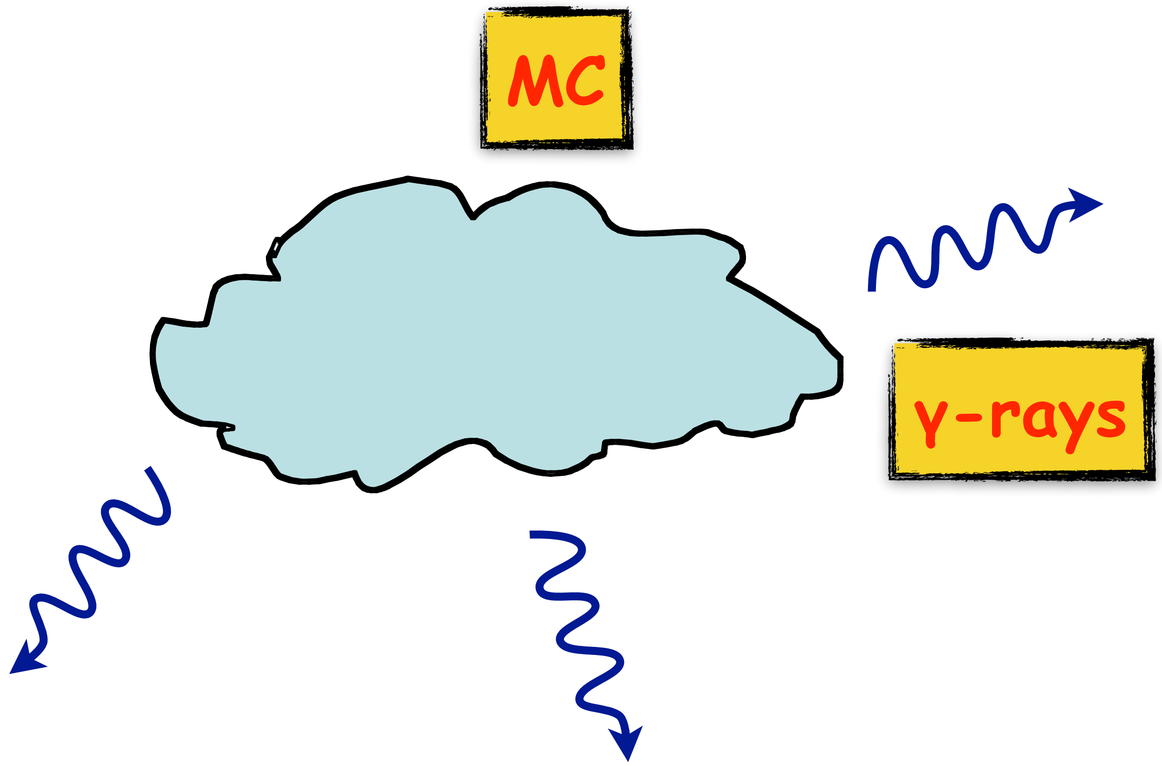

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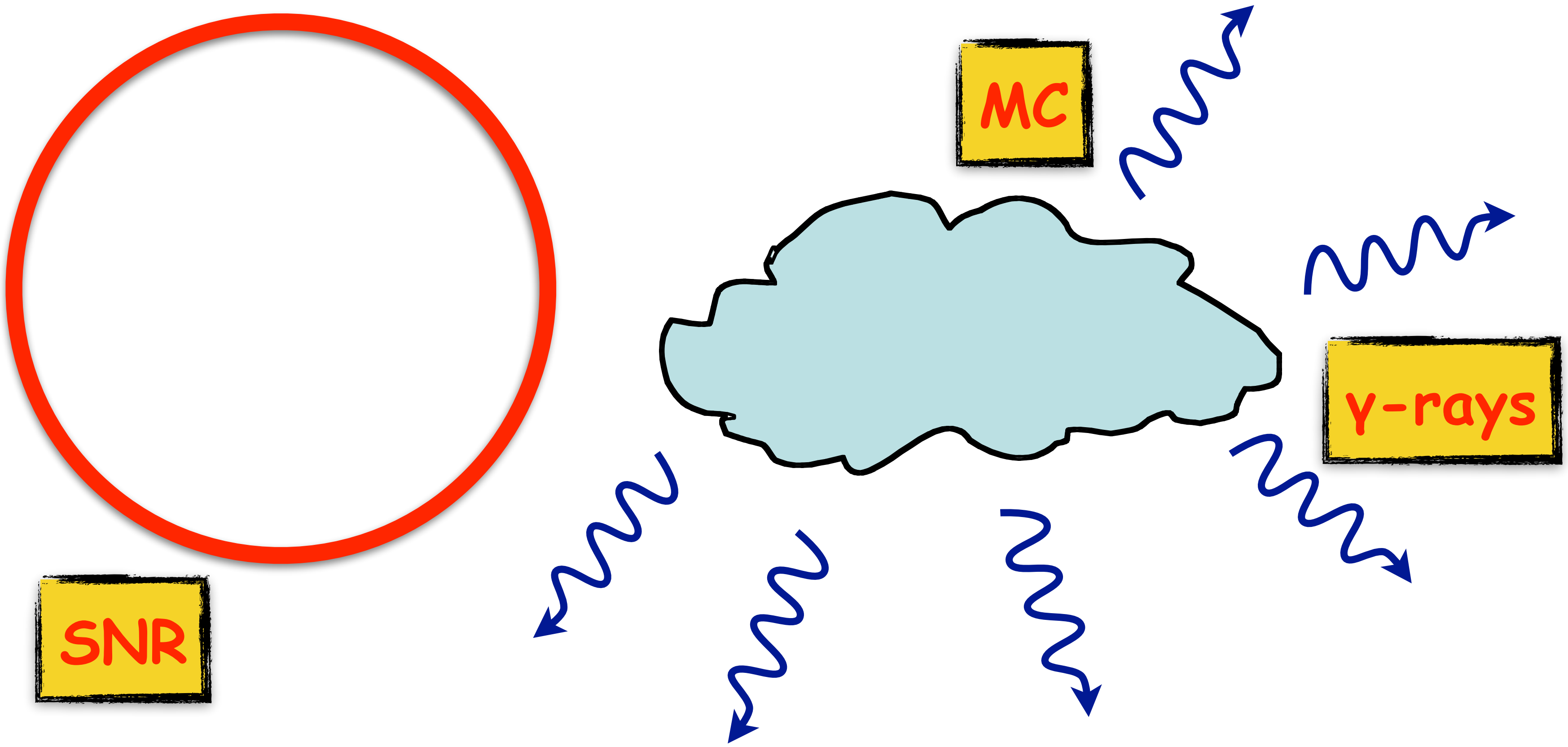
a MC immersed in the CR sea emits γ-rays

Molecular clouds as cosmic ray probes



see e.g.

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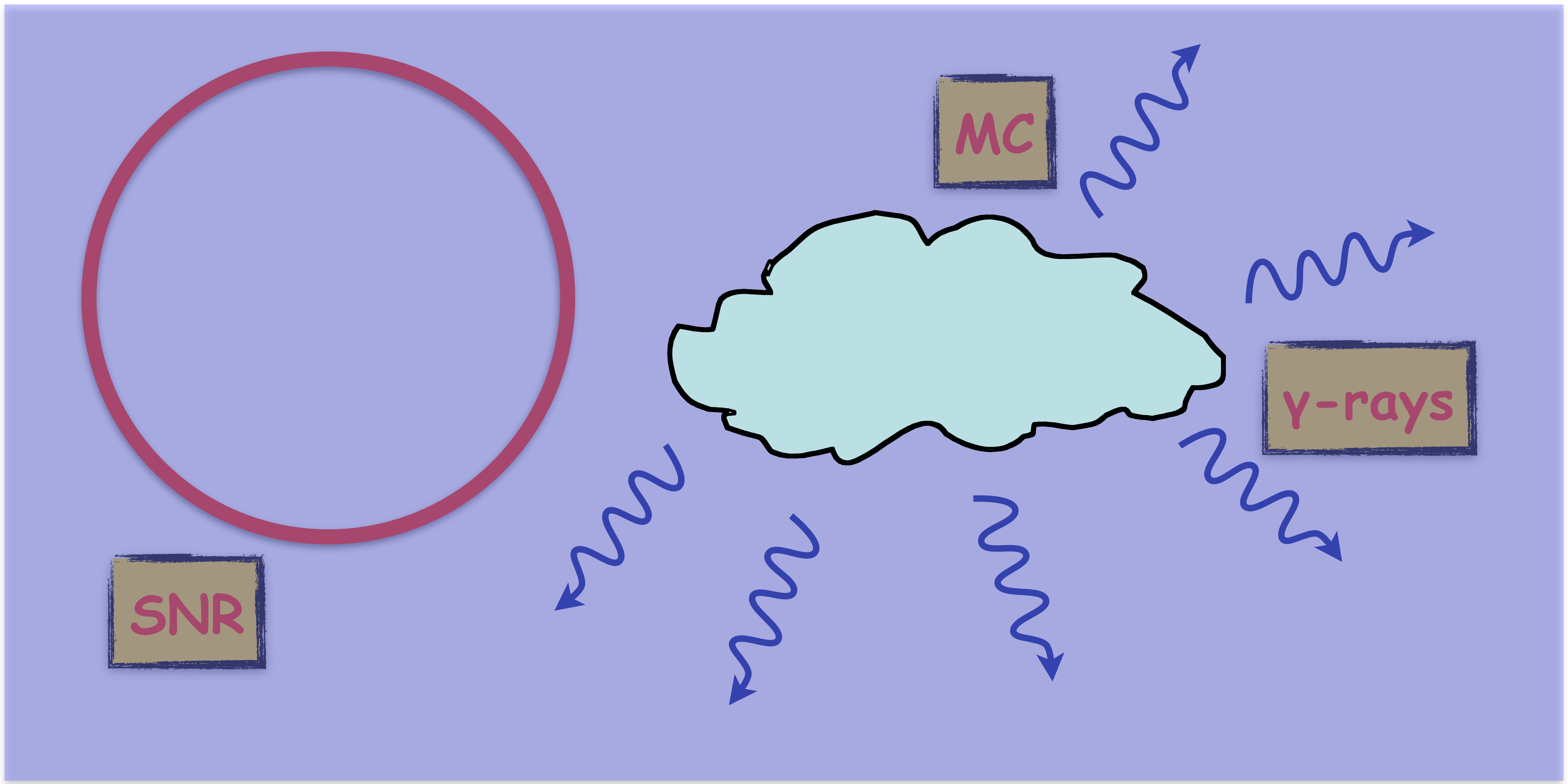
Aharonian&Atoyan1996

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

Molecular clouds as cosmic ray probes



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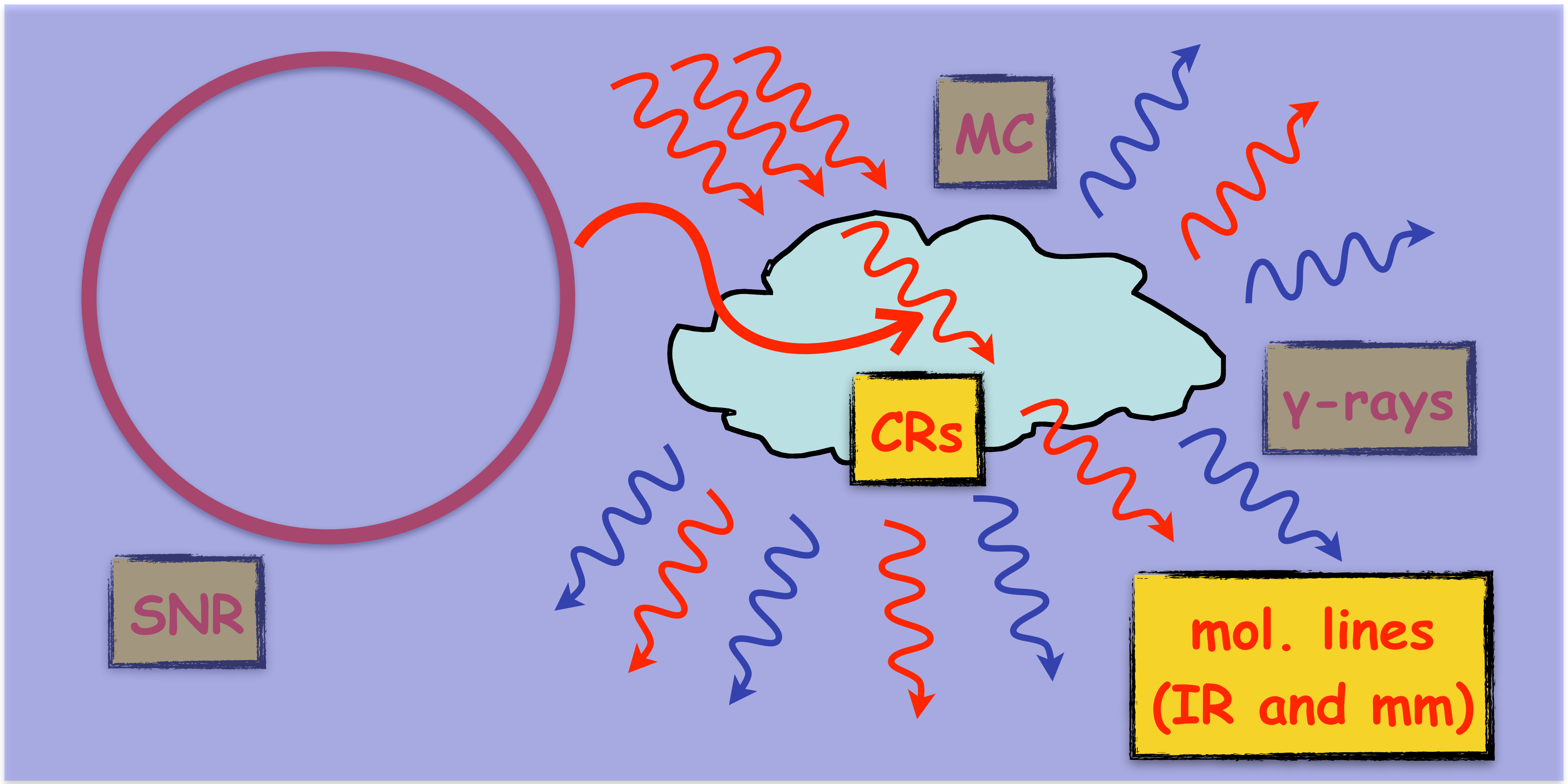
Aharonian&Atoyan1996

McKee 1989

ionizing UV photons do not penetrate molecular clouds

Molecular clouds as cosmic ray probes



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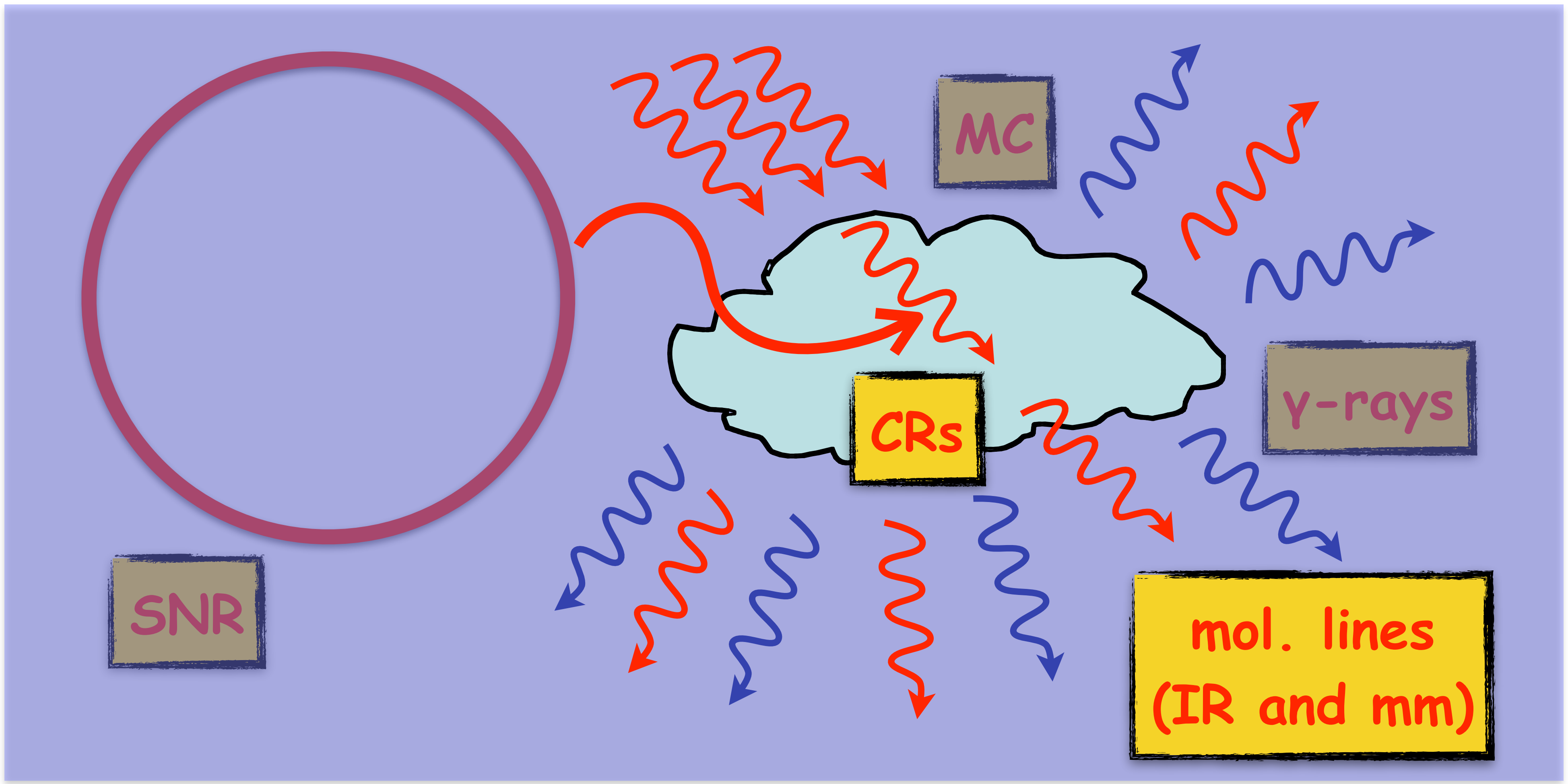
only cosmic rays can penetrate and drive the chemistry in the cloud

Molecular clouds as cosmic ray probes



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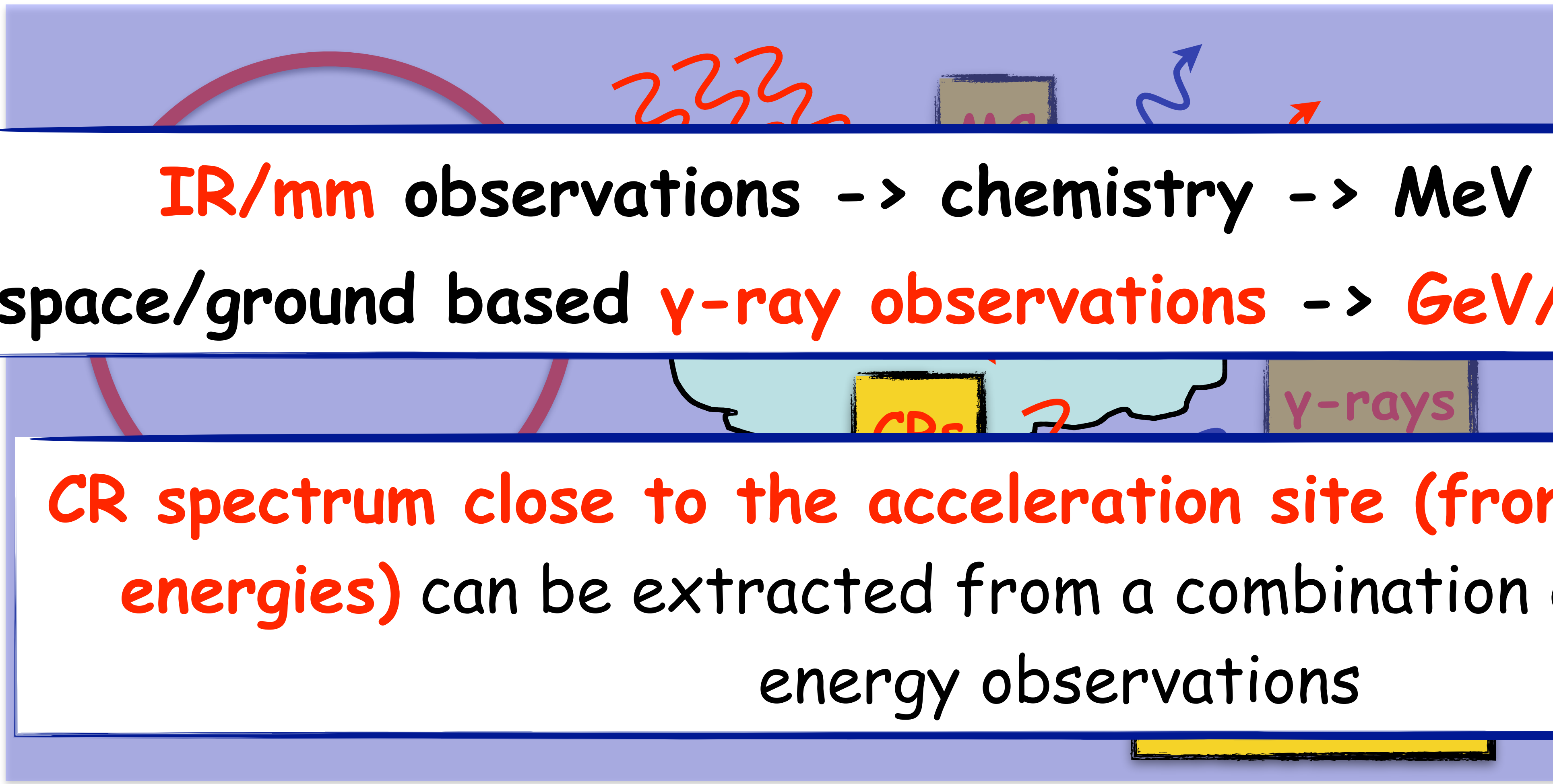
Molecular clouds

-> amplify the γ-ray emission from CR interactions

-> filter all ionizing agents but (MeV) CRs

Molecular clouds as cosmic ray probes



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

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

CR spectrum close to the acceleration site (from ~MeV to >TeV energies) can be extracted from a combination of low and high energy observations

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

Molecular clouds

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diffuse clouds

CRs and interstellar chemistry: H_3^+

for reviews see e.g. Oka (2006), Dalgarno (2006)

-> CR ionization

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

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-> CR ionization

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

CR spectrum (MeV)

$$\zeta_{\mathrm{CR}} = 4\pi \int_{I(\mathrm{H_2})}^{E_{max}} \mathrm{d}E \; j_{\mathrm{CR}}(E) \; \sigma_{ion}(E)$$

-> CR ionization rate

Spitzer&Tomasko 68…Padovani+ 09, Krause+15

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

$$\mathrm{H_2^+} + \mathrm{H_2} \longrightarrow \mathrm{H_3^+} + \mathrm{H}$$

very fast

H_3^+ production rate

$$\zeta_{\mathrm{CR}}\; n(\mathrm{H_2})$$

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$$H_2 + CR \longrightarrow H_2^+ + e^- + CR$$

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-> dissociative recombination

$$H_3^+ + e^- \longrightarrow H_2 + H \text{ or } H + H + H$$

H_3^+ production rate

$$\zeta_{CR}\ n(H_2)$$

H_3^+ destruction rate

$$k_e\ n(e^-)\ n(H_3^+)$$

CR spectrum (MeV)

$$\zeta_{CR} = 4\pi \int_{I(H_2)}^{E_{max}} dE\ j_{CR}(E)\ \sigma_{ion}(E)$$

-> CR ionization rate

Spitzer&Tomasko 68…Padovani+ 09, Krause+15

k_e -> from lab measurements under near interstellar conditions McCall+ 2003

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H_3^+ production rate

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H_3^+ destruction rate

$$k_e\ n(e^-)\ n(H_3^+)$$

in equilibrium

$$n(H_3^+) = \left(\frac{\zeta_{CR}}{k_e}\right)\frac{n(H_2)}{n(e^-)}$$

diffuse clouds

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H_3^+ destruction rate

$$k_e \, n(e^-) \, n(H_3^+)$$

in equilibrium

from densities to column densities N = n x L

$$n(H_3^+) = \left(\frac{\zeta_{\mathrm{CR}}}{k_e}\right) \frac{n(H_2)}{n(e^-)} \Longrightarrow \zeta_{\mathrm{CR}} L = k_e \frac{N(e^-)}{N(H_2)} N(H_3^+)$$

H_3^+ in space: InfraRed absorption line

Geballe&Oka 1996, McCall+ 2003, Indriolo+ 2012 (UKIRT, Keck, KPNO, Gemini South, VLT)

ζ-Persei diffuse cloud

size of the cloud

UV lines from H_2 and C^+

$$\zeta_{\rm CR} L = k_e \, \frac{N(e^-)}{N({\rm H_2})} \, N({\rm H_3^+})$$

measured in the lab

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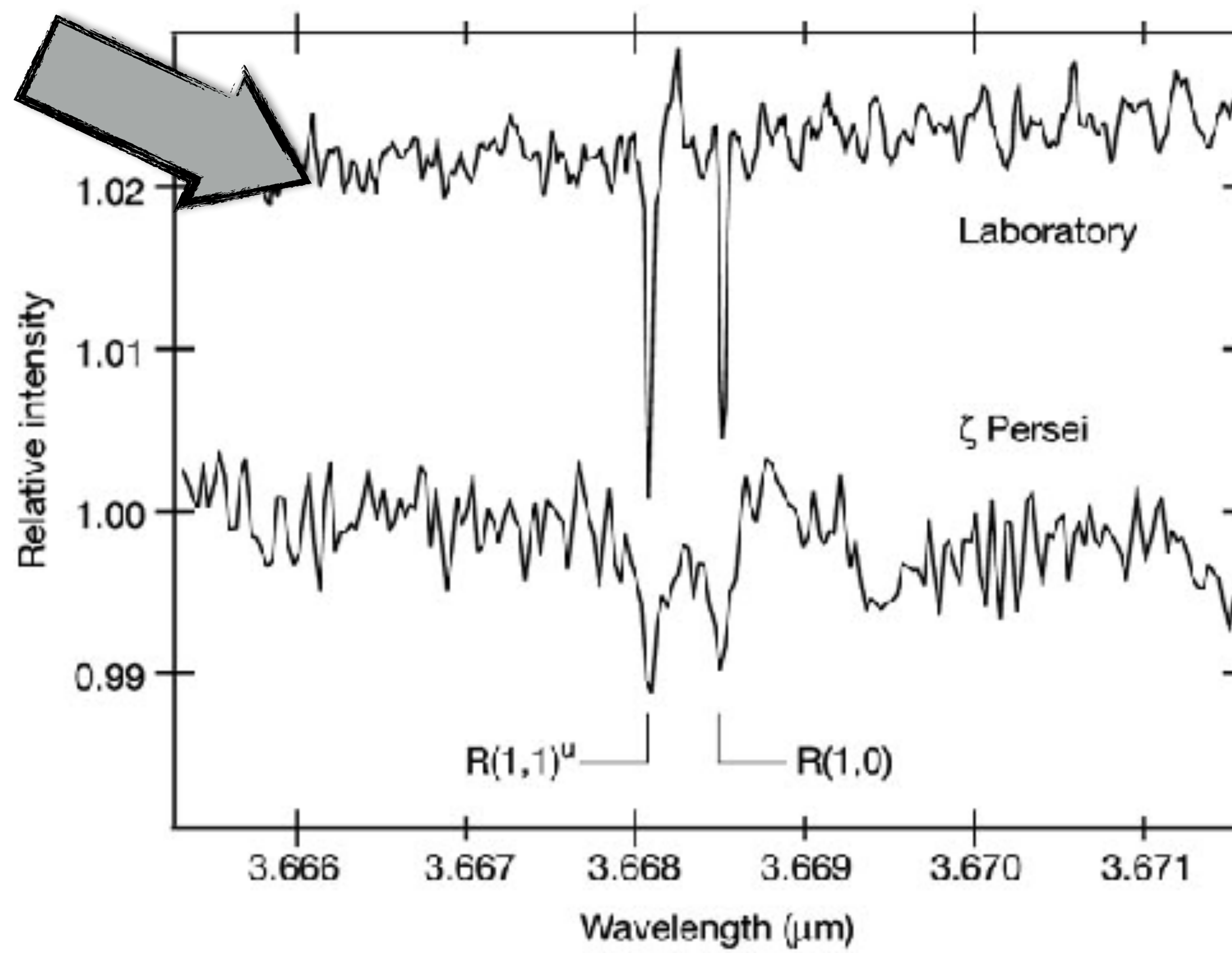

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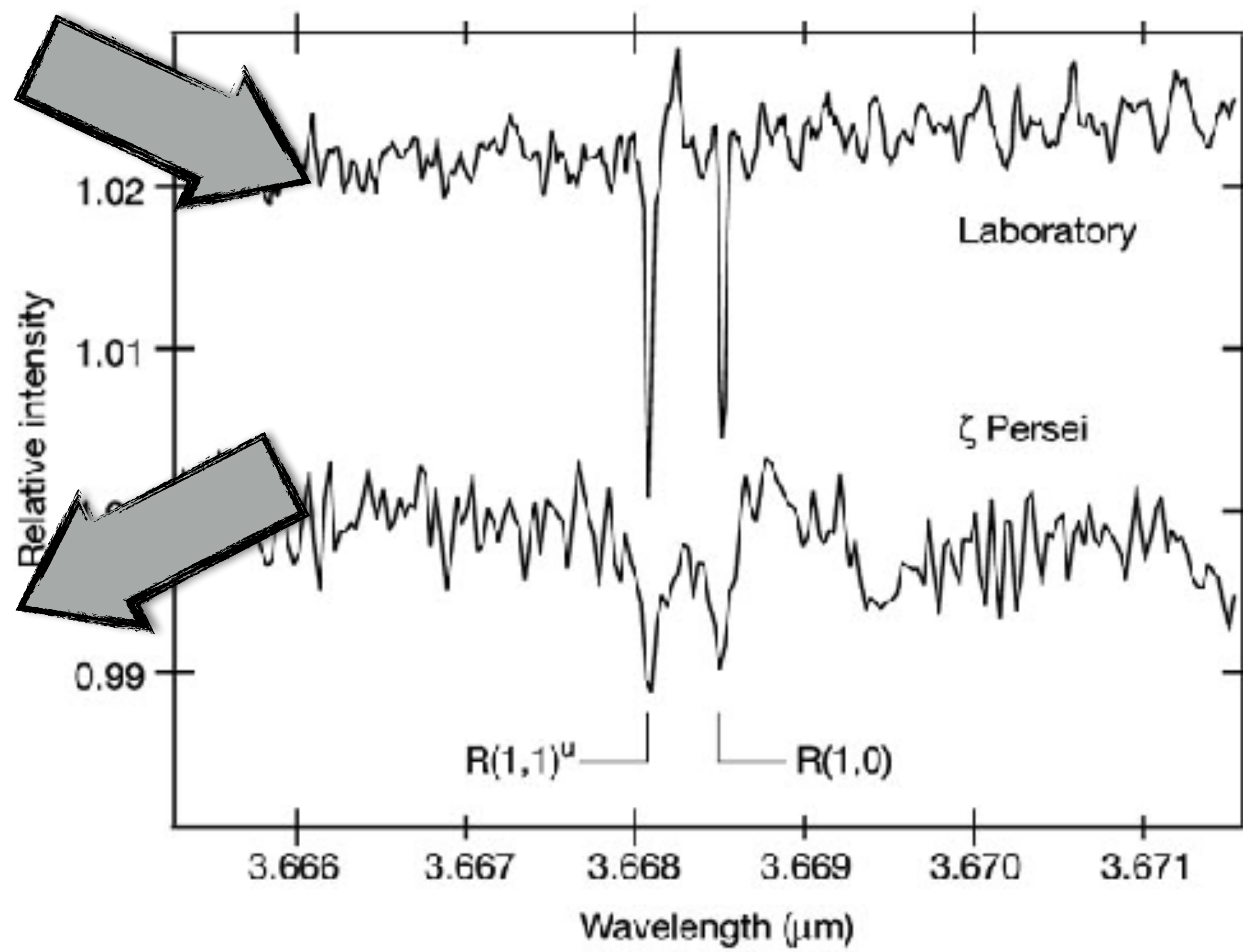
much larger than the Spitzer value!

$$\zeta_{\rm CR} \approx 10^{-17}\ \mathrm{s}^{-1}$$



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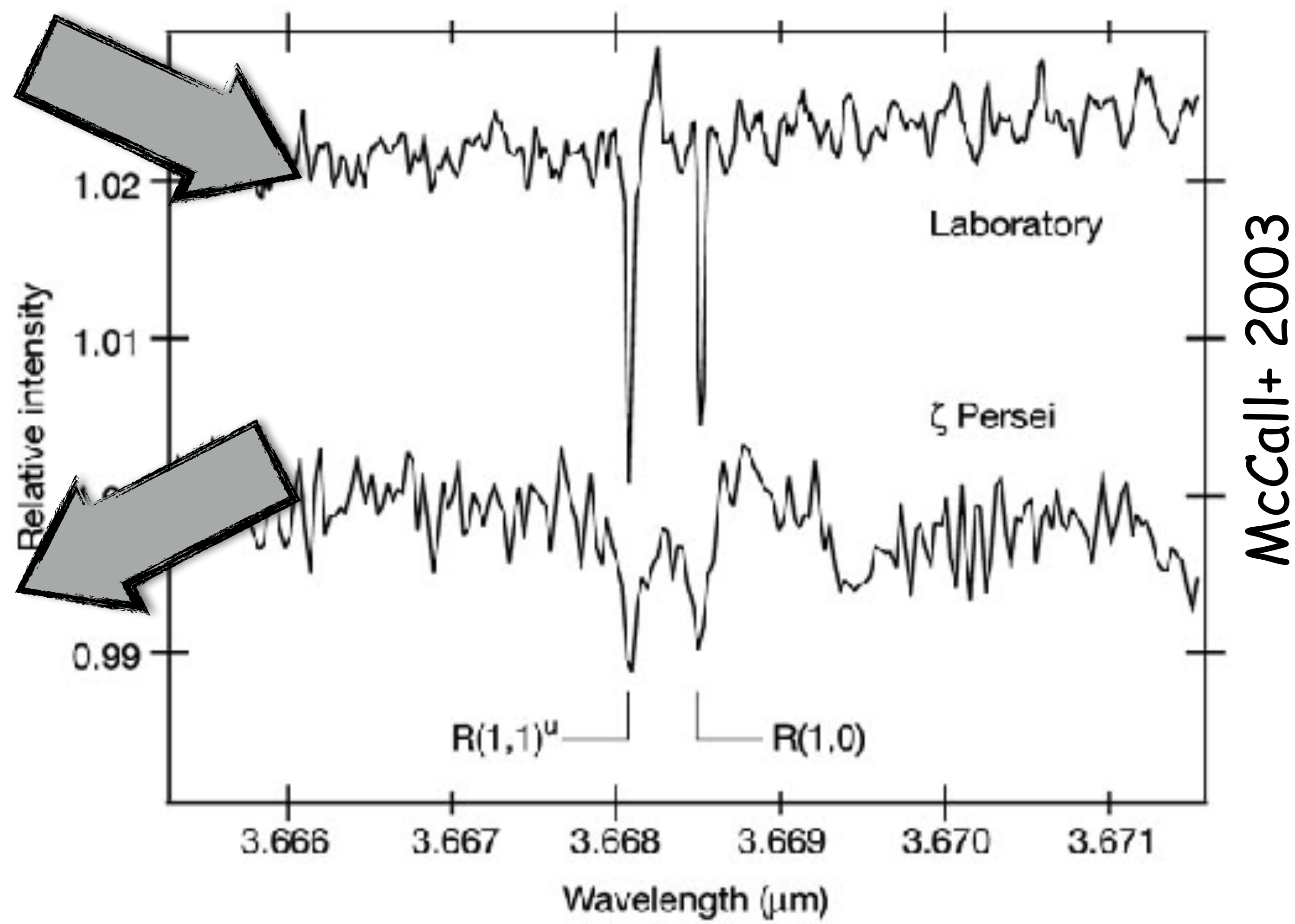
Herschel -> OH^+ H_2O^+ H_3O^+

Gerin+2010,Neufeld+2010,Indriolo+2015

Most direct probe -> H_2^+

Becker+ 2011



dense clouds

More chemistry: HCO^+ and DCO^+

Guelin+ 1977, Caselli+ 1998

issues:

-> N_H too large to see foreground stars

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$$H_3^+ + CO \longrightarrow HCO^+ + H_2$$

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similarly, a chain of reactions initiated by

H_3^+ and HD leads to the formation

of DCO^+

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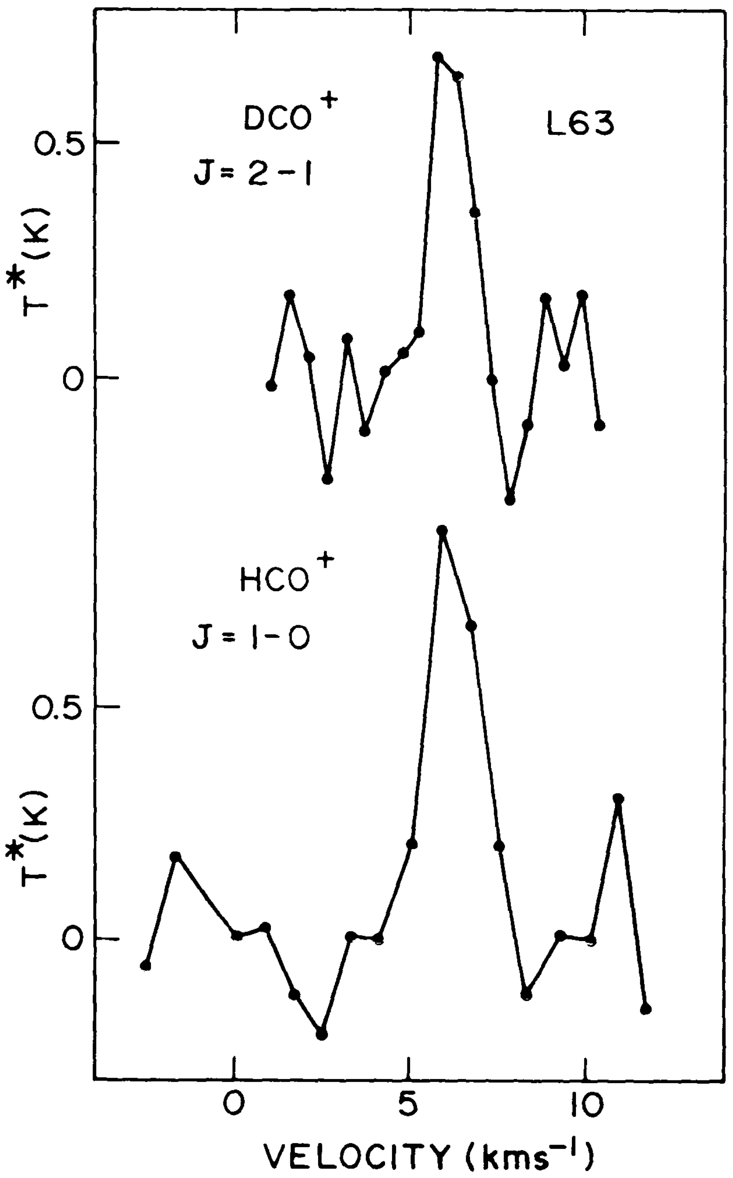
	Reaction			Reaction rate [$cm^3\ s^{-1}$]
No. 1	$CR + H_2$	$\xrightarrow{\zeta}$	$H_2^+ + e^-$	ζ [s^{-1}]
No. 2	$H_2^+ + H_2$	$\xrightarrow{k_{H_2^+}}$	$H_3^+ + H$	$k_{H_2^+} = 2.1\ 10^{-9}$
No. 3	$H_3^+ + CO$	$\xrightarrow{k_H}$	$HCO^+ + H_2$	$k_H = 1.61\ 10^{-9}$
No. 4	$HCO^+ + e^-$	$\xrightarrow{\beta'}$	$CO + H$	$\beta' = 2.8\ 10^{-7} \left(\frac{T}{300}\right)^{-0.69}$
No. 5	$H_3^+ + e^-$	$\xrightarrow{\beta}$	$H + H + H$	$\beta = 4.36\ 10^{-8} \left(\frac{T}{300}\right)^{-0.52}$
			$H_2 + H$	$+2.34\ 10^{-8} \left(\frac{T}{300}\right)^{-0.52}$
No. 6	$H + H$	$\xrightarrow{k'}$	H_2	$k' = 4.95\ 10^{-17} \left(\frac{T}{300}\right)^{0.50}$
No. 7	$H_3^+ + HD$	$\underset{k_f^{-1}}{\overset{k_f}{\rightleftharpoons}}$	$H_2D^+ + H_2$	$k_f = 1.7\ 10^{-9}$
				$k_f^{-1} = k_f\ e^{-220/T}$
No. 8	$H_2D^+ + CO$	$\xrightarrow{k_D}$	$DCO^+ + H_2$	$k_D = 5.37\ 10^{-10}$
No. 9	$DCO^+ + e^-$	$\xrightarrow{\beta'}$	$CO + D$	$\beta' = 2.8\ 10^{-7} \left(\frac{T}{300}\right)^{-0.69}$
No. 10	$H_2D^+ + e^-$	$\xrightarrow{k_e}$	$H + H + D$	$k_e = 4.38\ 10^{-8} \left(\frac{T}{300}\right)^{-0.50}$
			$H_2 + D$	$+1.20\ 10^{-8} \left(\frac{T}{300}\right)^{-0.50}$
			$HD + H$	$+4.20\ 10^{-9} \left(\frac{T}{300}\right)^{-0.50}$
No. 11	$H + D$	$\xrightarrow{k''}$	HD	$k'' = \sqrt{2}k'$
No. 12	$H_2D^+ + CO$	$\xrightarrow{k'_D}$	$HCO^+ + H_2$	$k'_D = 1.1\ 10^{-9}$
No. 13	$H_3^+ + D$	$\underset{k_f'^{-1}}{\overset{k'_f}{\rightleftharpoons}}$	$H_2D^+ + H$	$k'_f = 1.0\ 10^{-9}$
				$k_f'^{-1} = k'_f\ e^{-632/T}$
No. 14	$CO^+ + HD$	$\xrightarrow{k_{CO^+}}$	$DCO^+ + H$	$k_{CO^+} = 7.5\ 10^{-10}$

HCO^+/DCO^+:emission lines (mm -> IRAM)

emission lines -> no need of a foreground star



Guelin+ 1977

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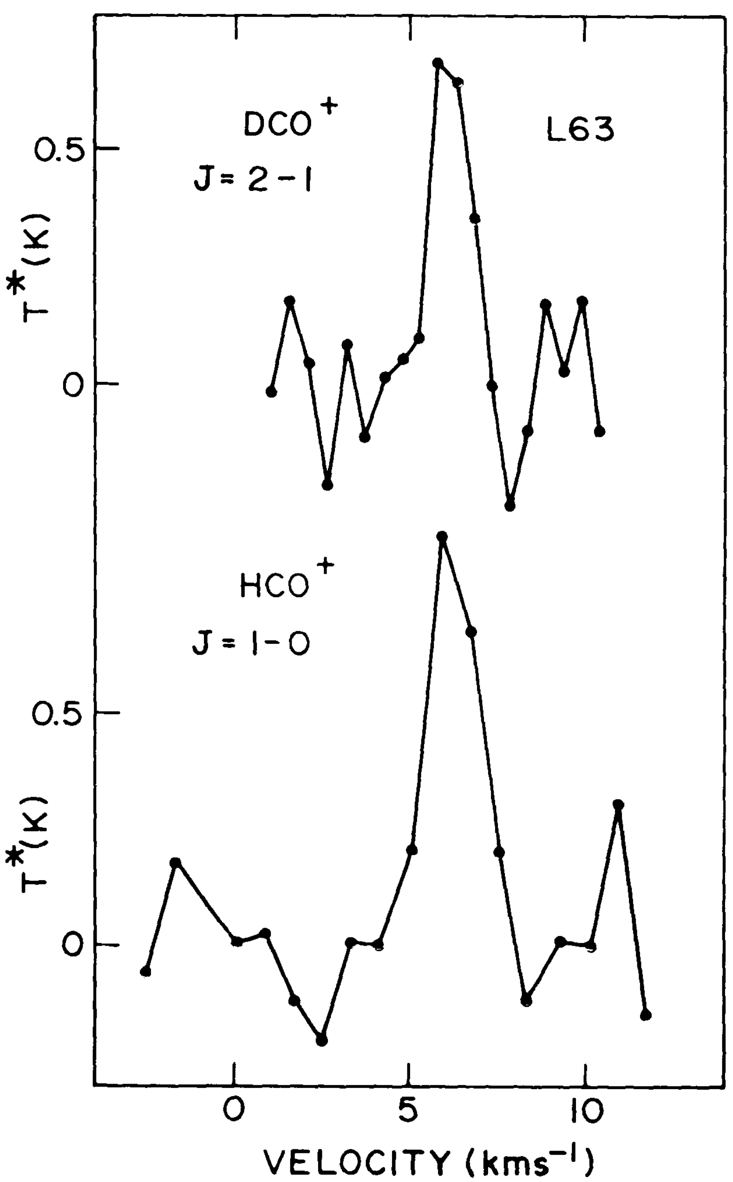
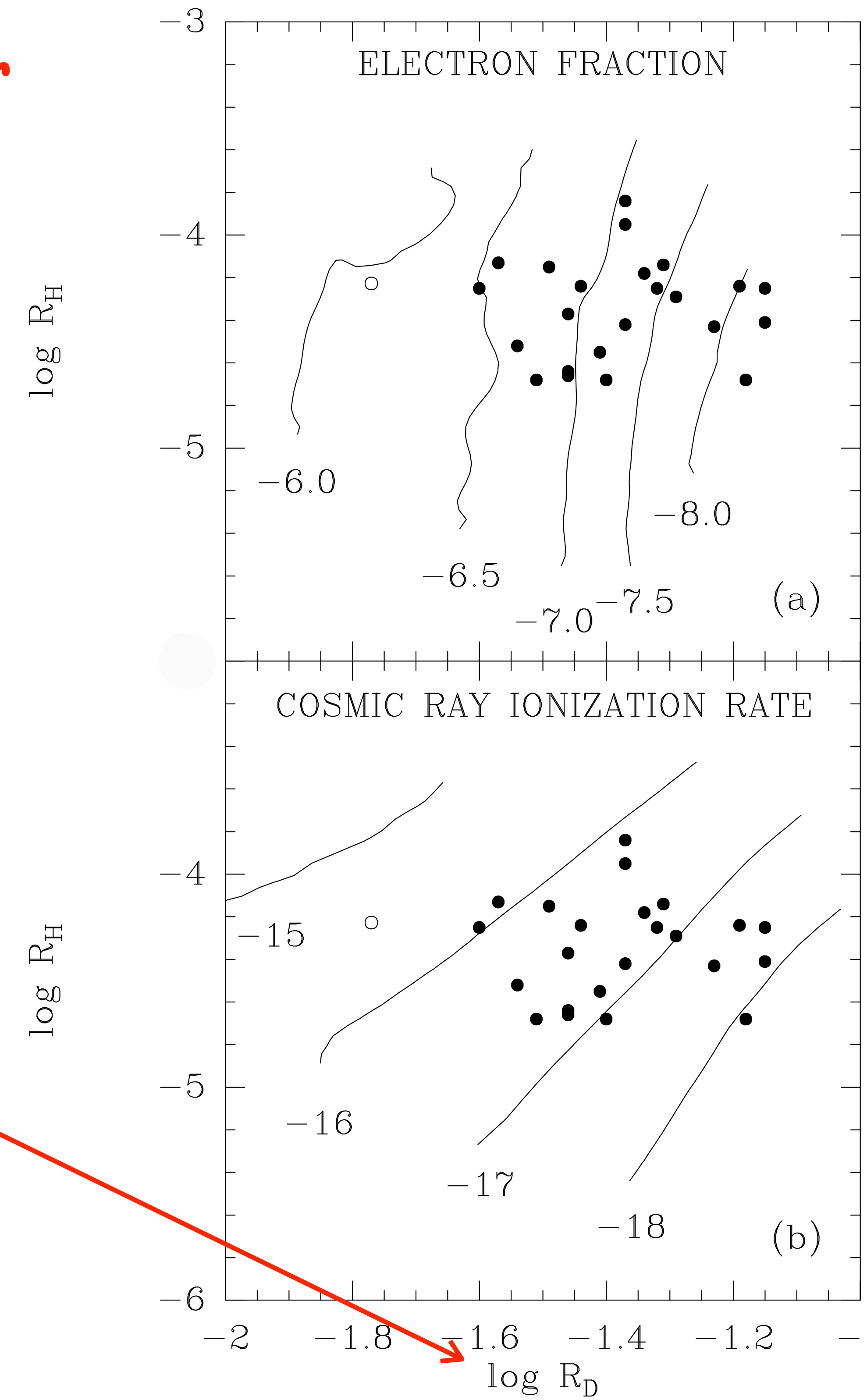


Guelin+ 1977

$$R_{\rm H} = \frac{[{\rm HCO^+}]}{[{\rm CO}]}$$

$$R_{\rm D} = \frac{[{\rm DCO^+}]}{[{\rm HCO^+}]}$$



Caselli+ 1998

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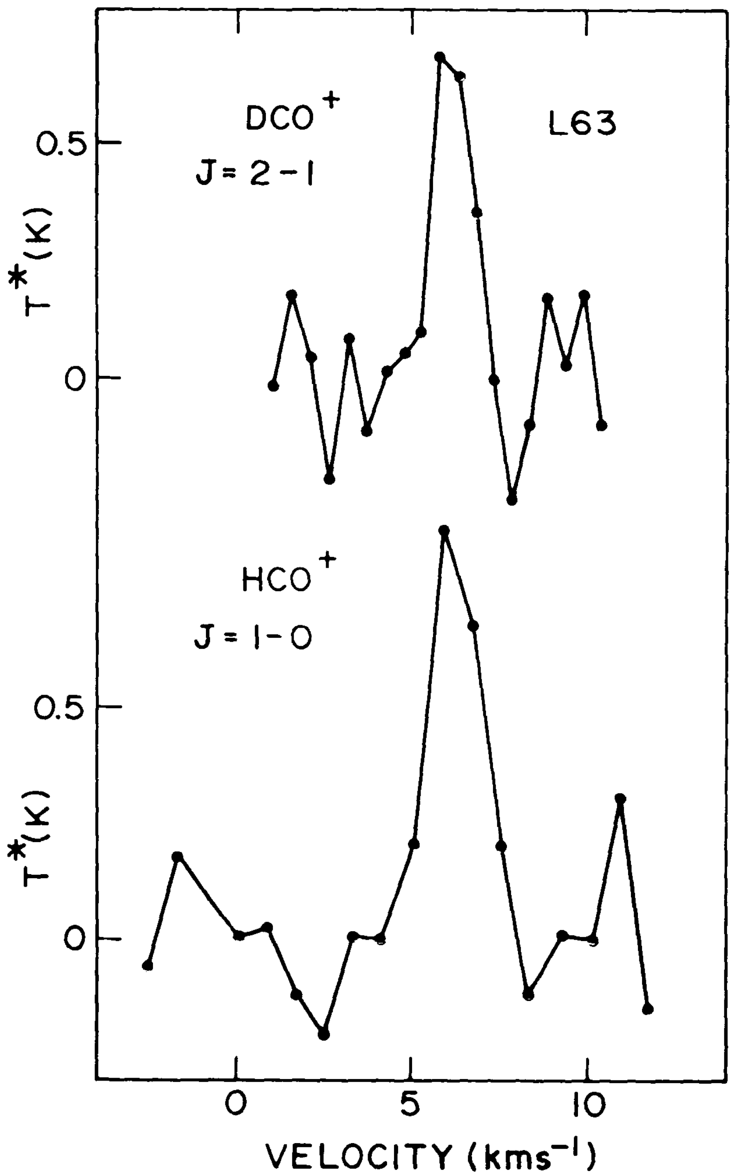

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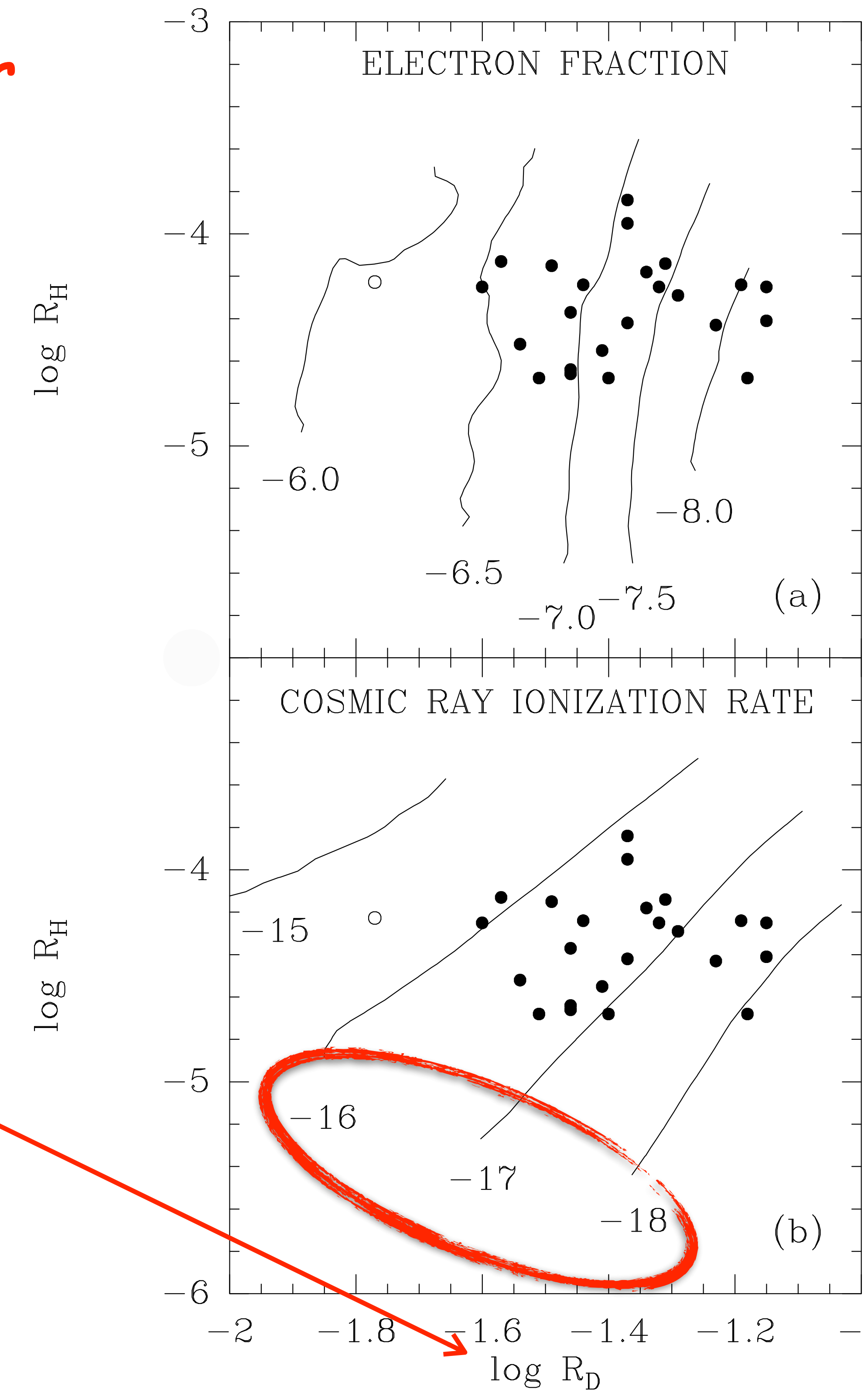
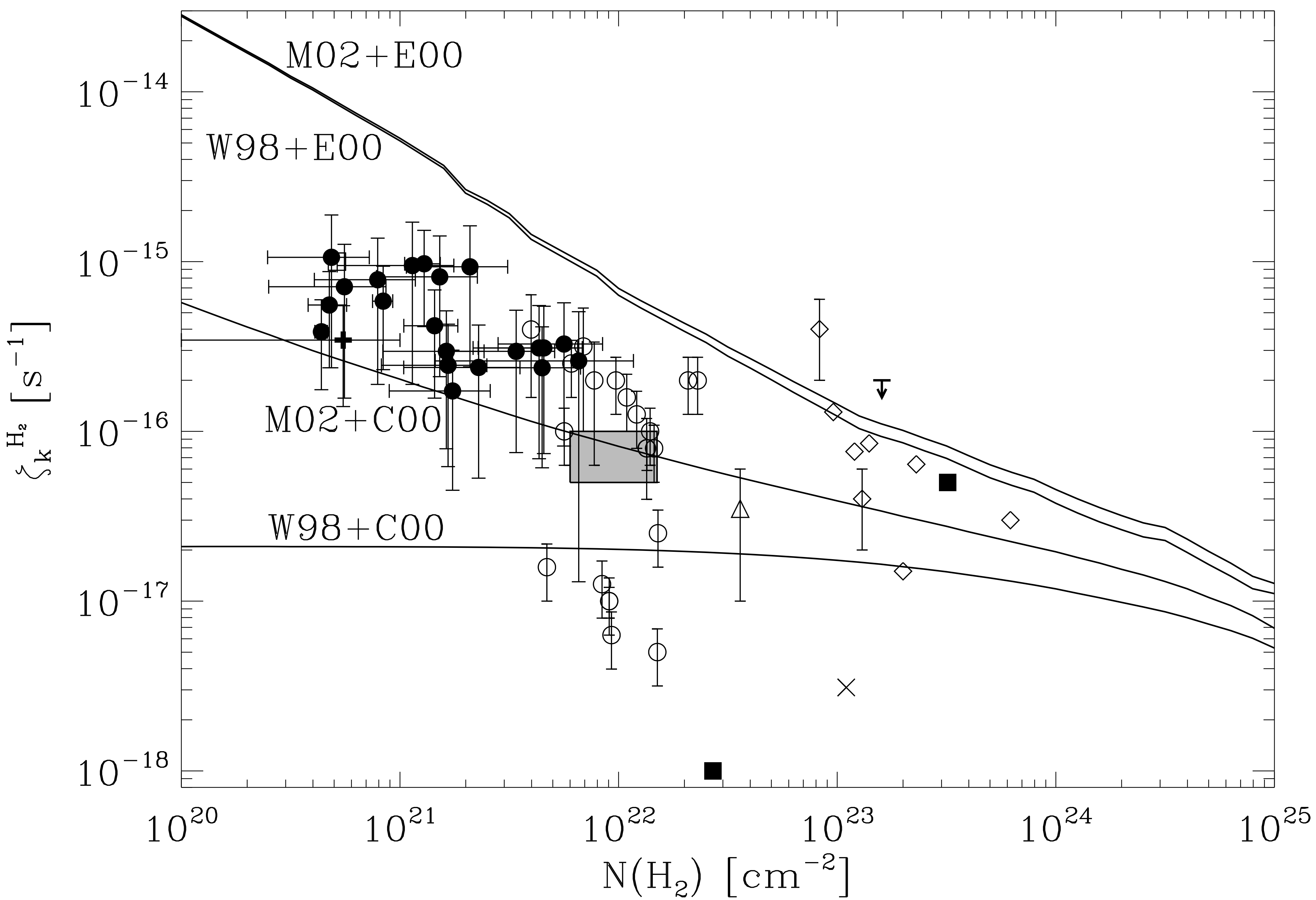


Caselli+ 1998

CR ionization rate in isolated MCs

compilation of data from Padovani+ 2009



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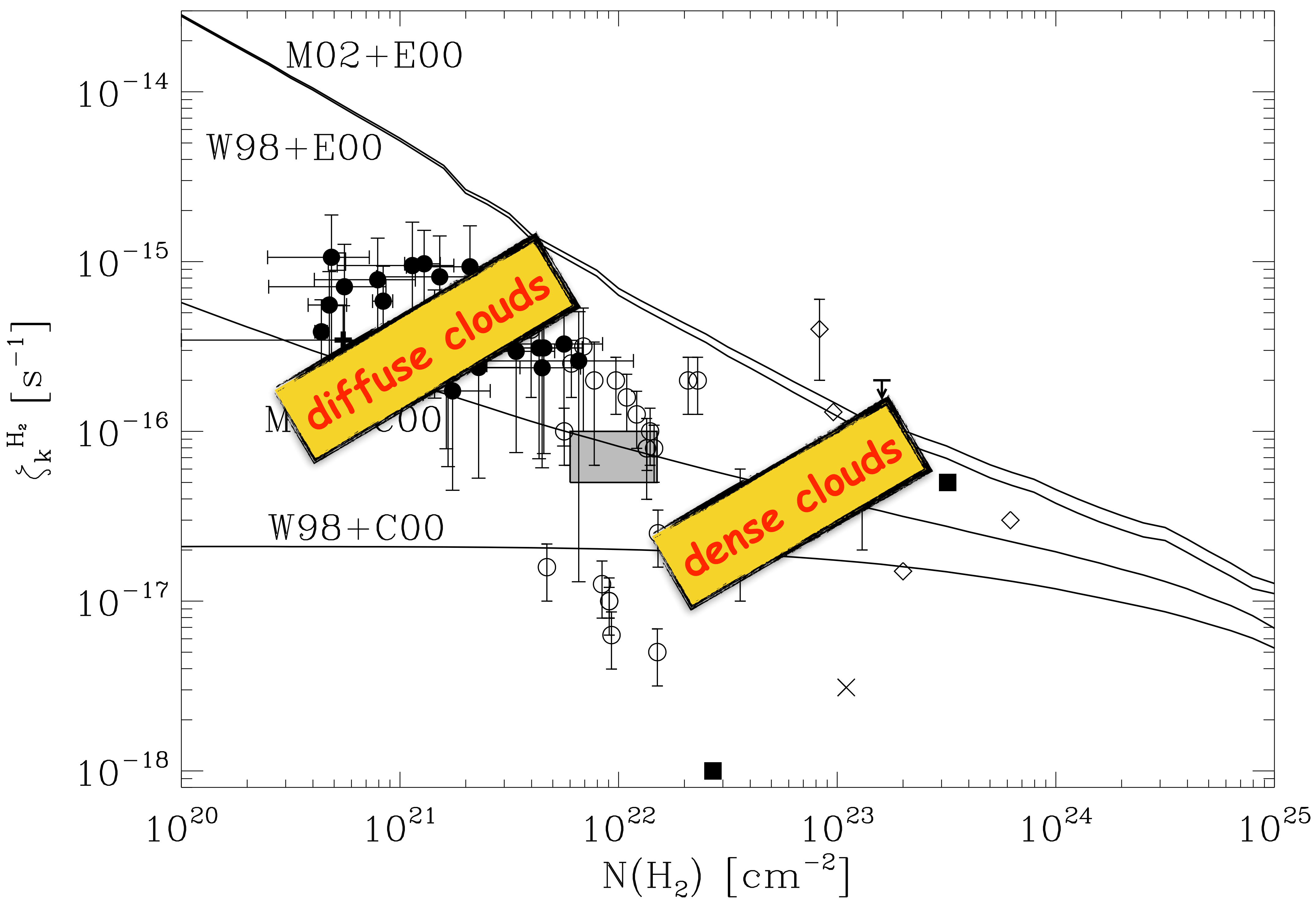
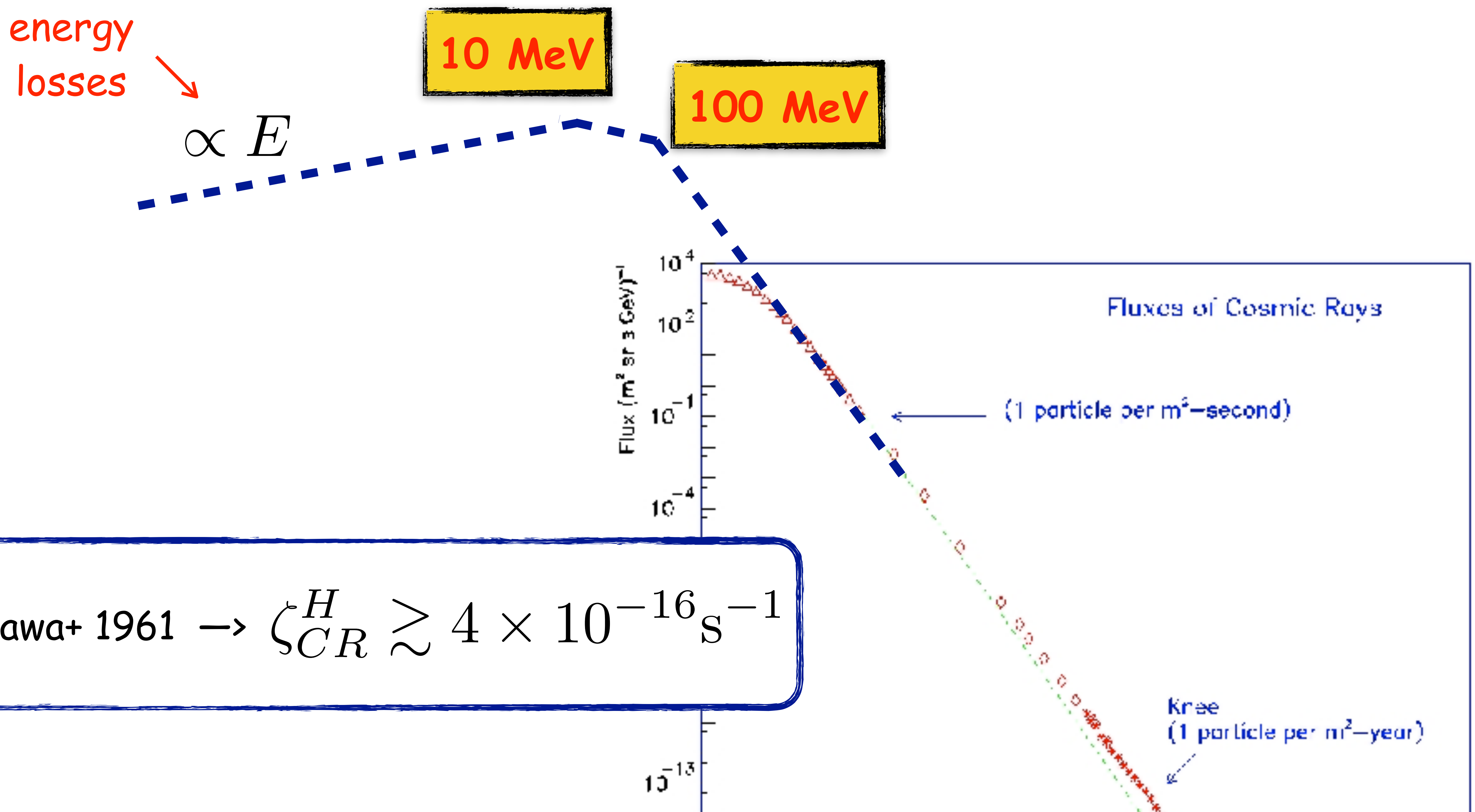
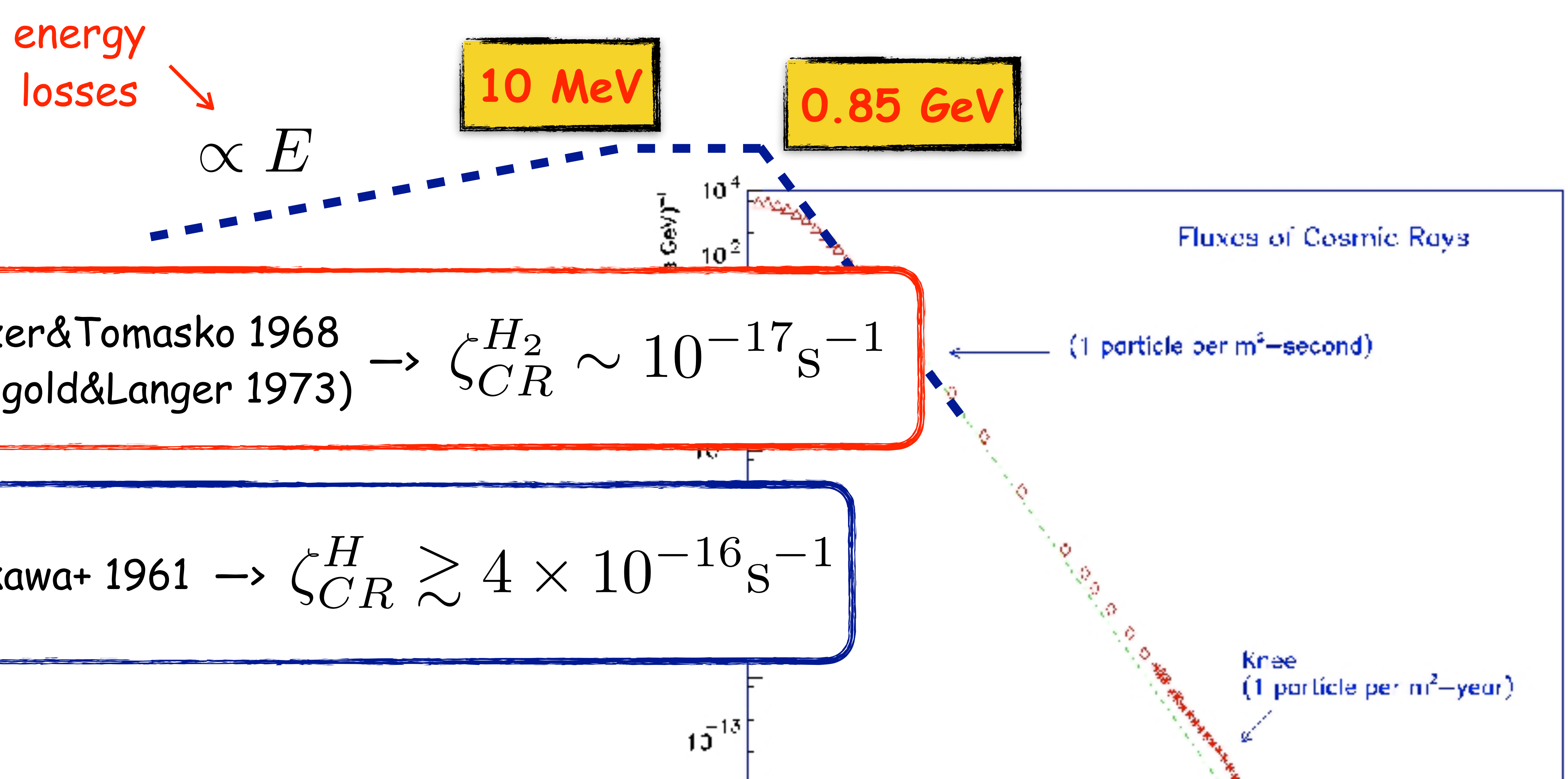


Pioneering studies



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

Pioneering studies



Spitzer&Tomasko 1968
(Glassgold&Langer 1973) $\longrightarrow$ $\zeta_{CR}^{H_2} \sim 10^{-17}\mathrm{s}^{-1}$

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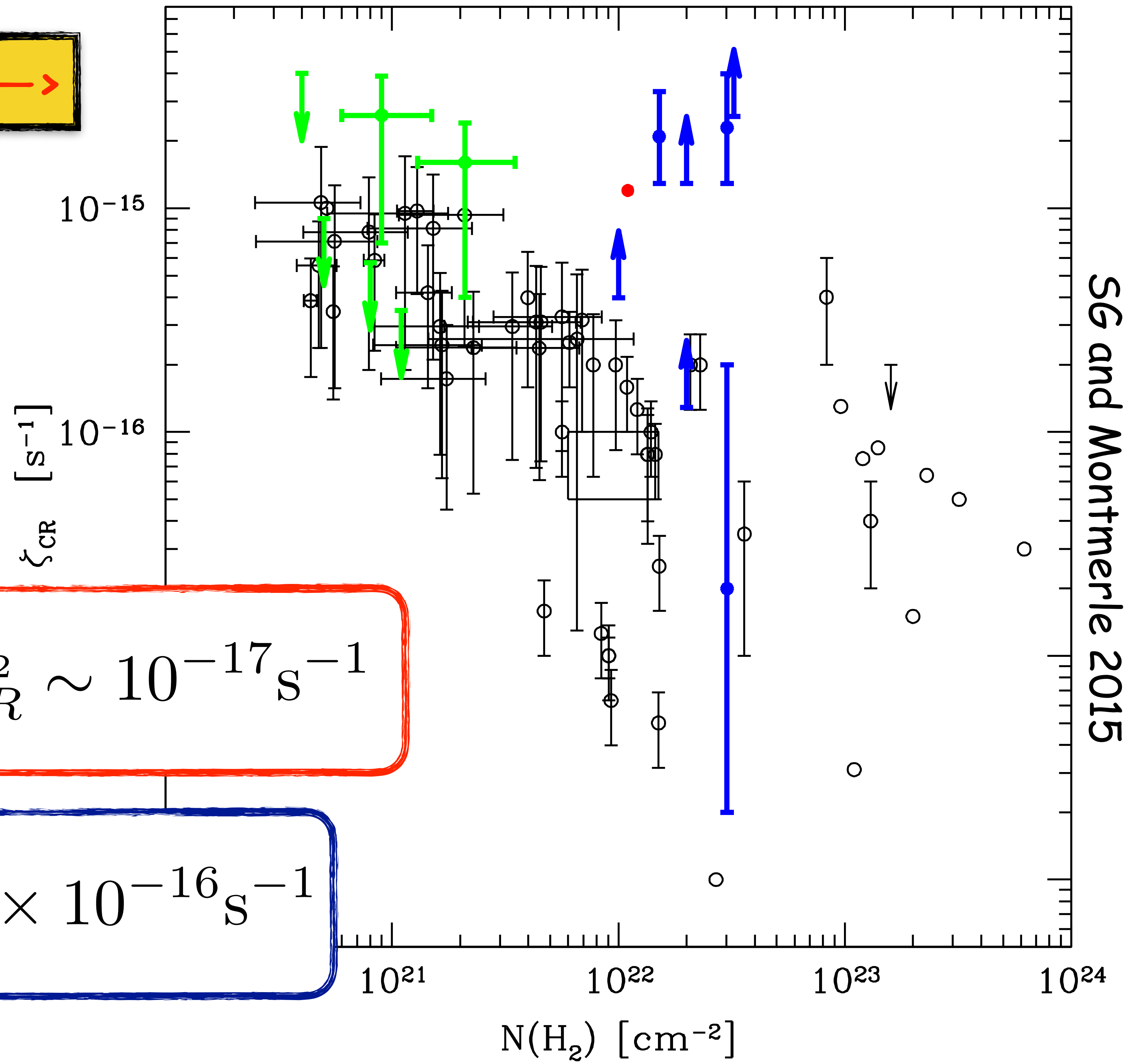
The cosmic ray ionisation rate

ion. rates observed in MCs —>



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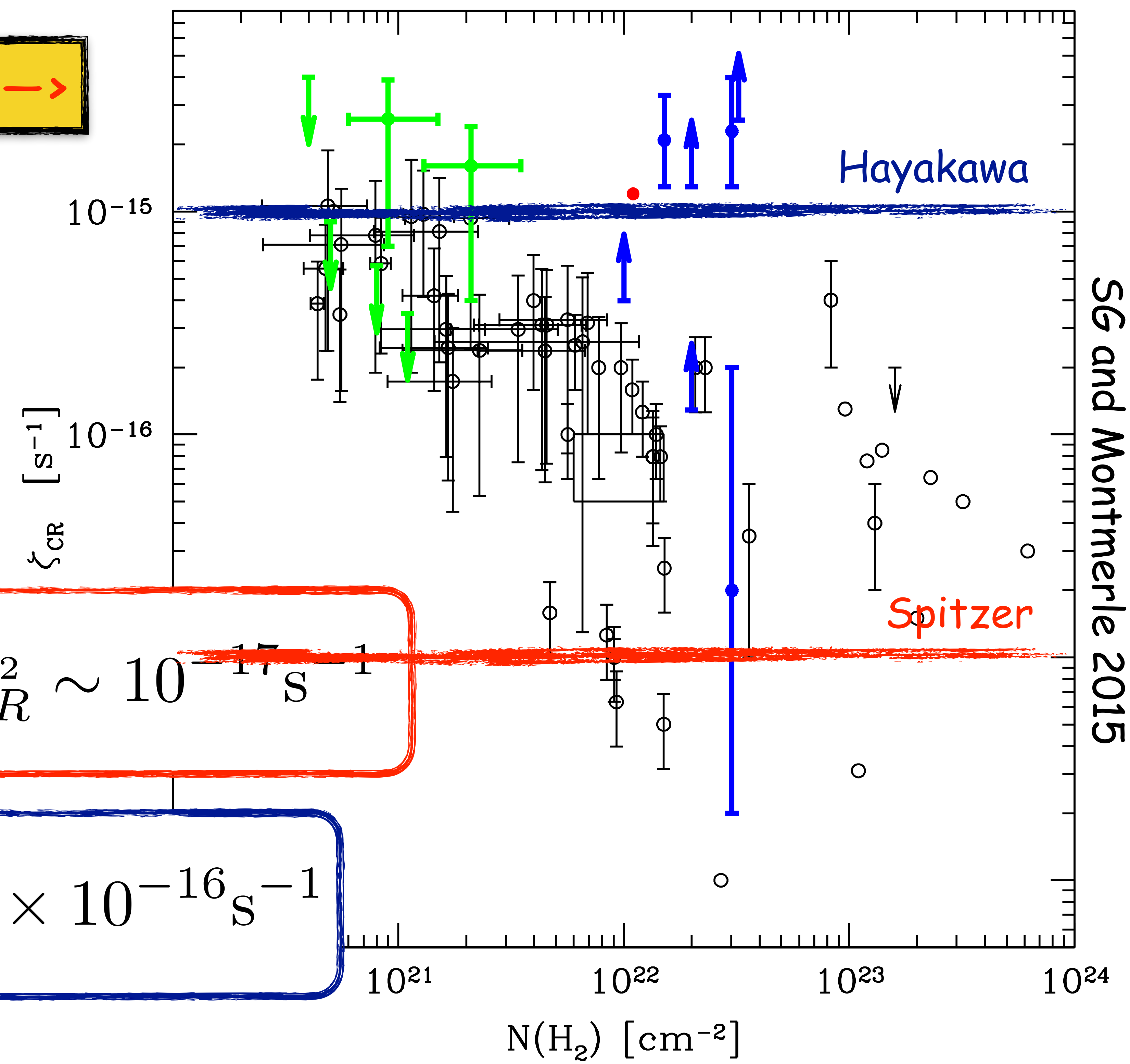

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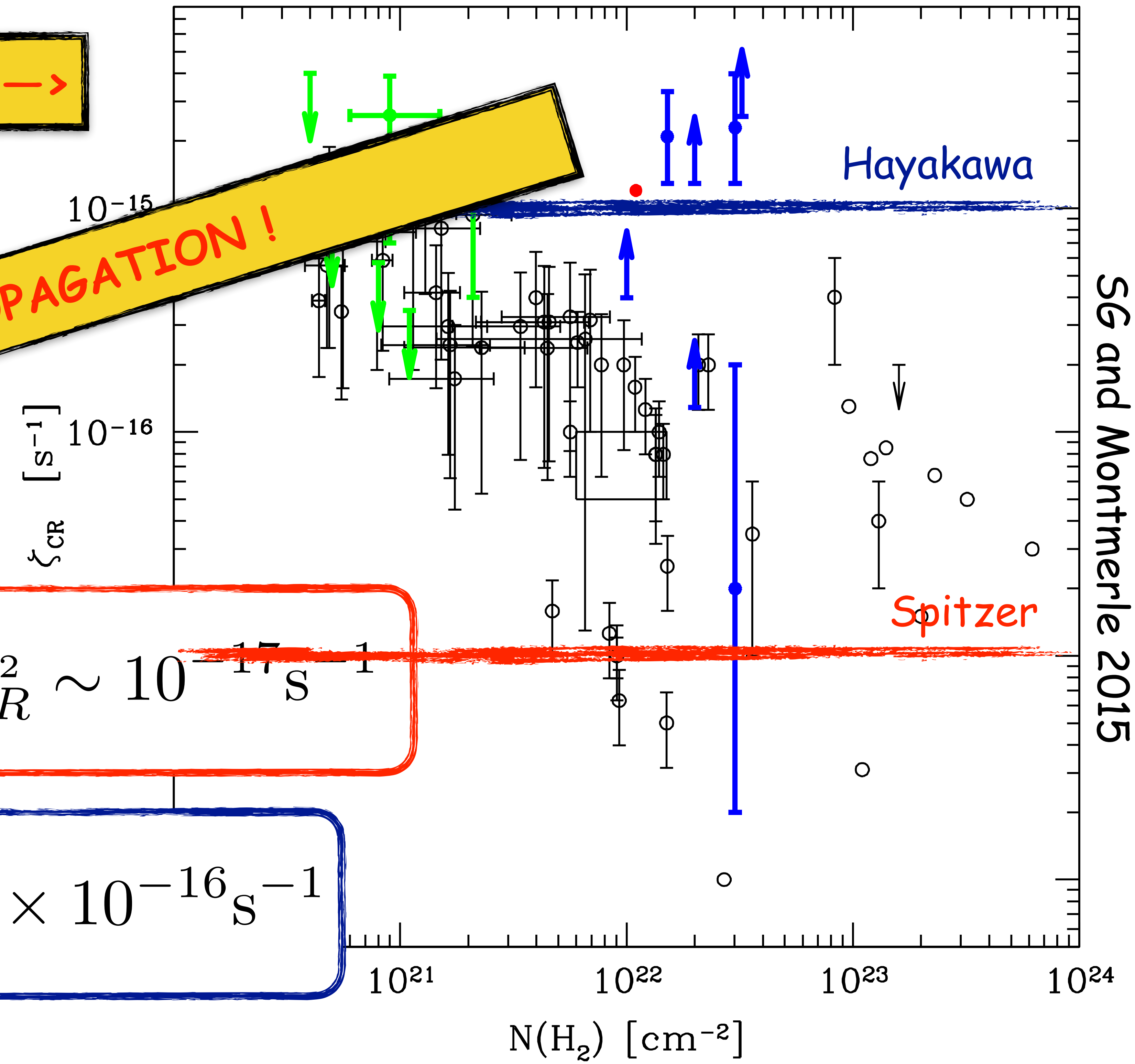

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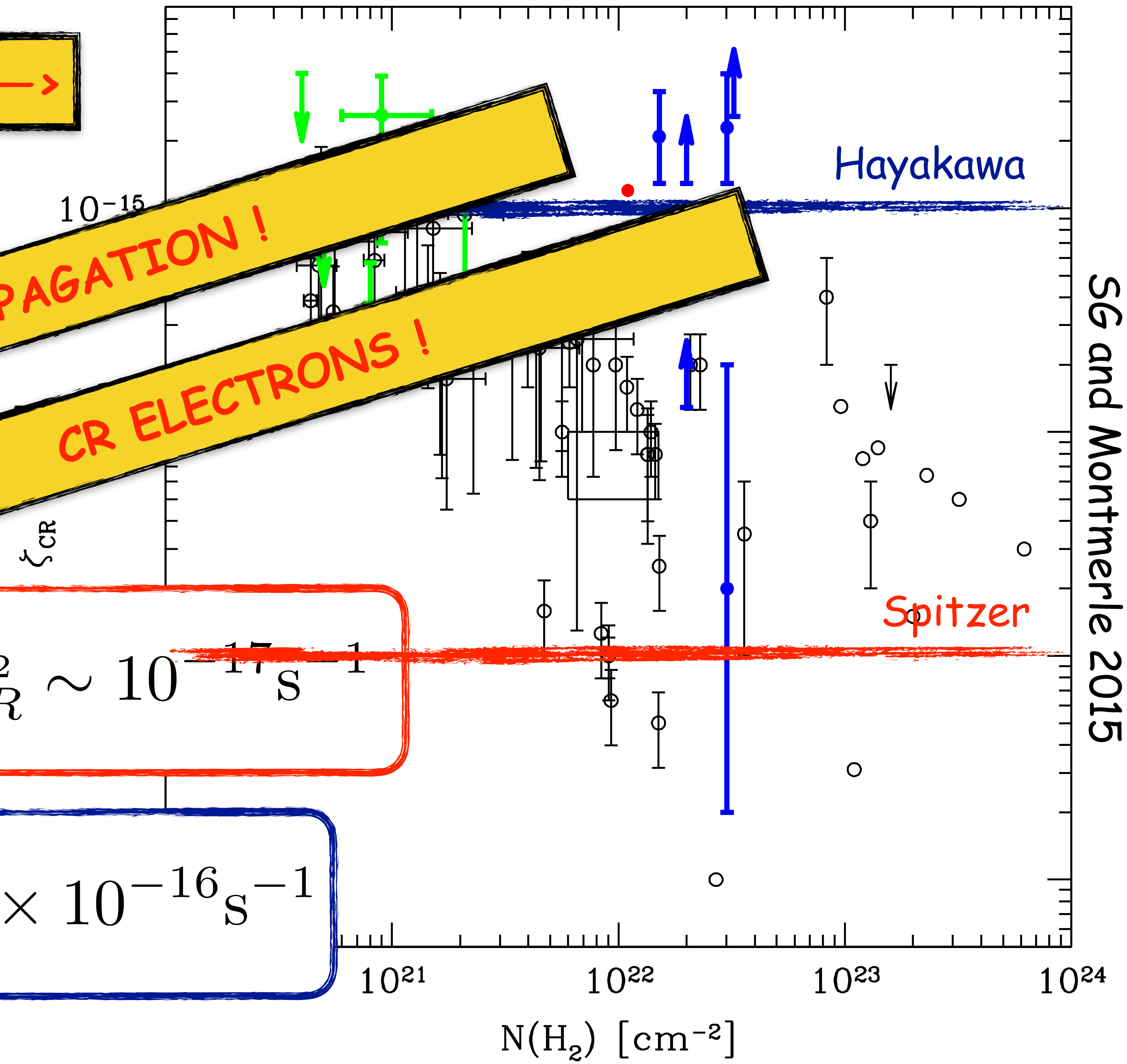

CR PROPAGATION !

CR ELECTRONS !

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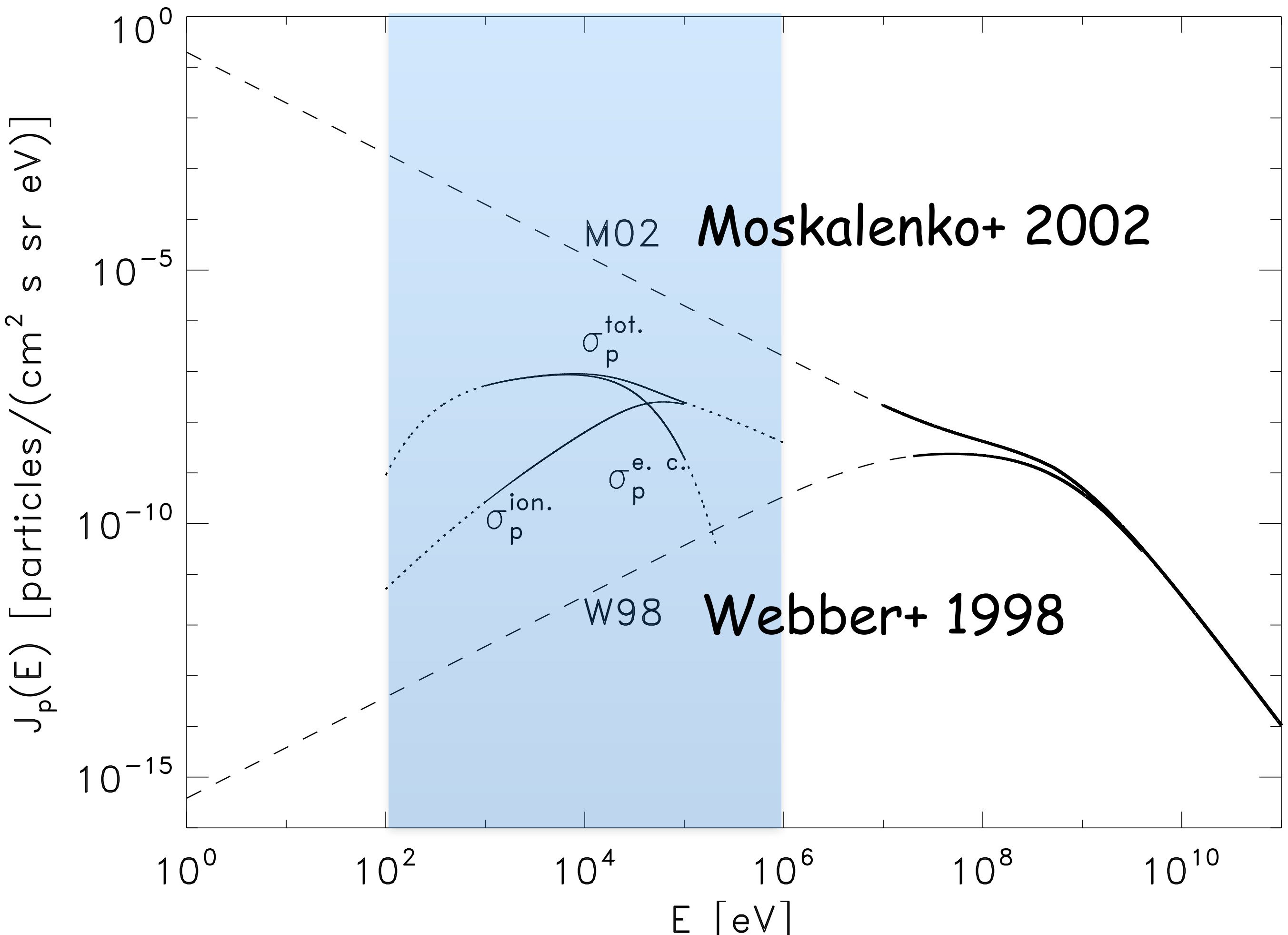
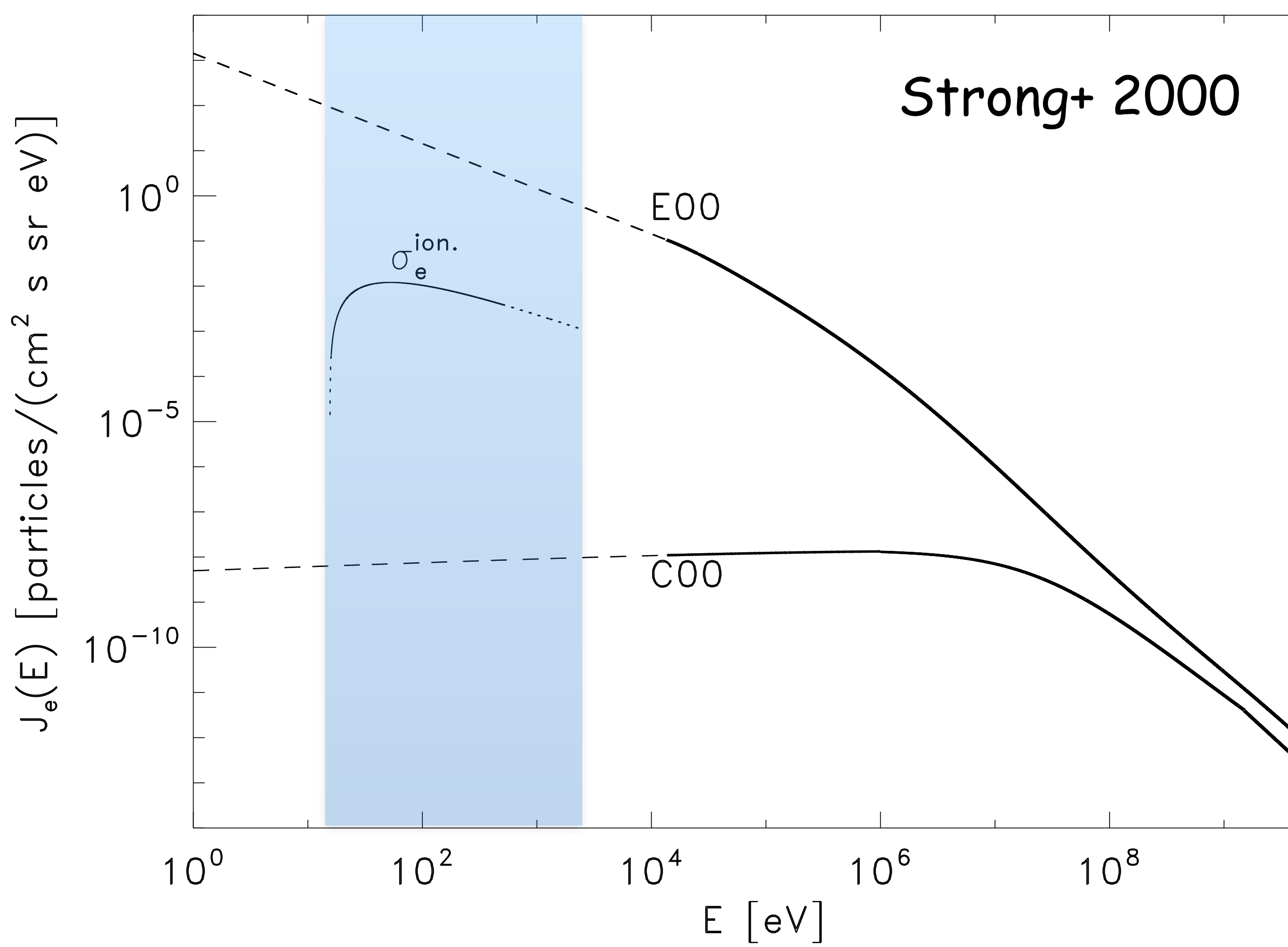
CR spectrum in the ISM

uncertainties in the background CR spectrum



Padovani+ 2009



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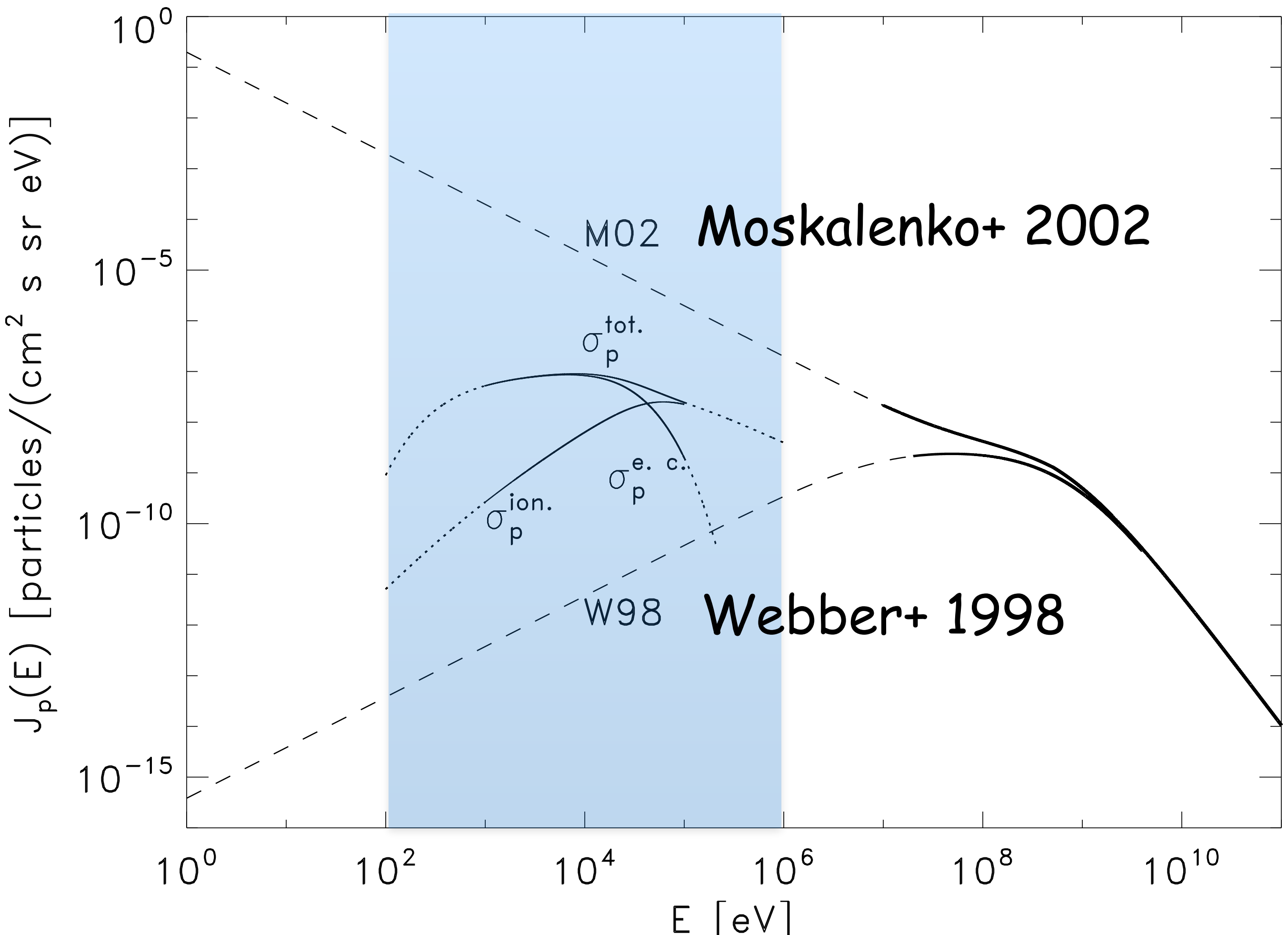

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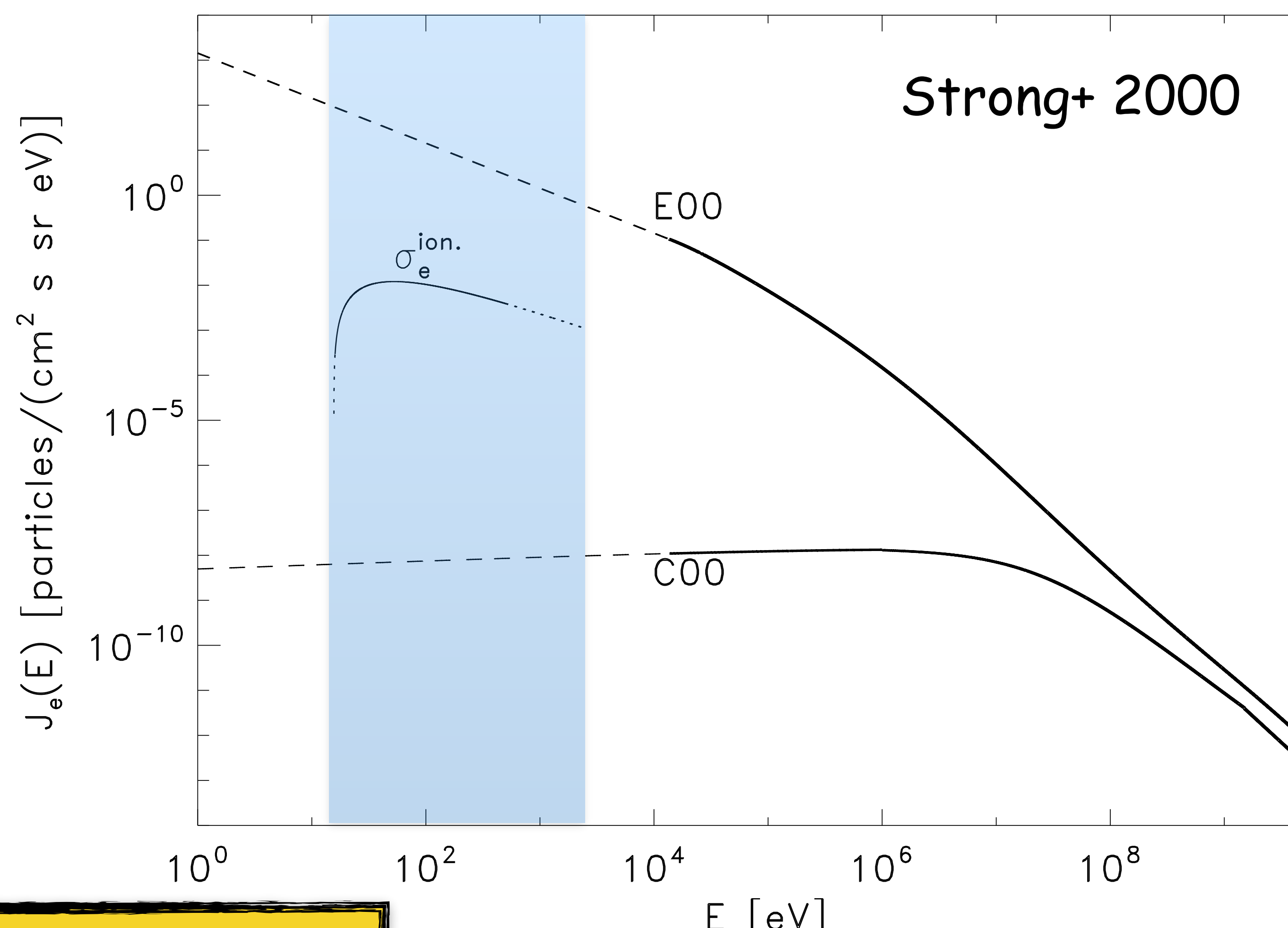
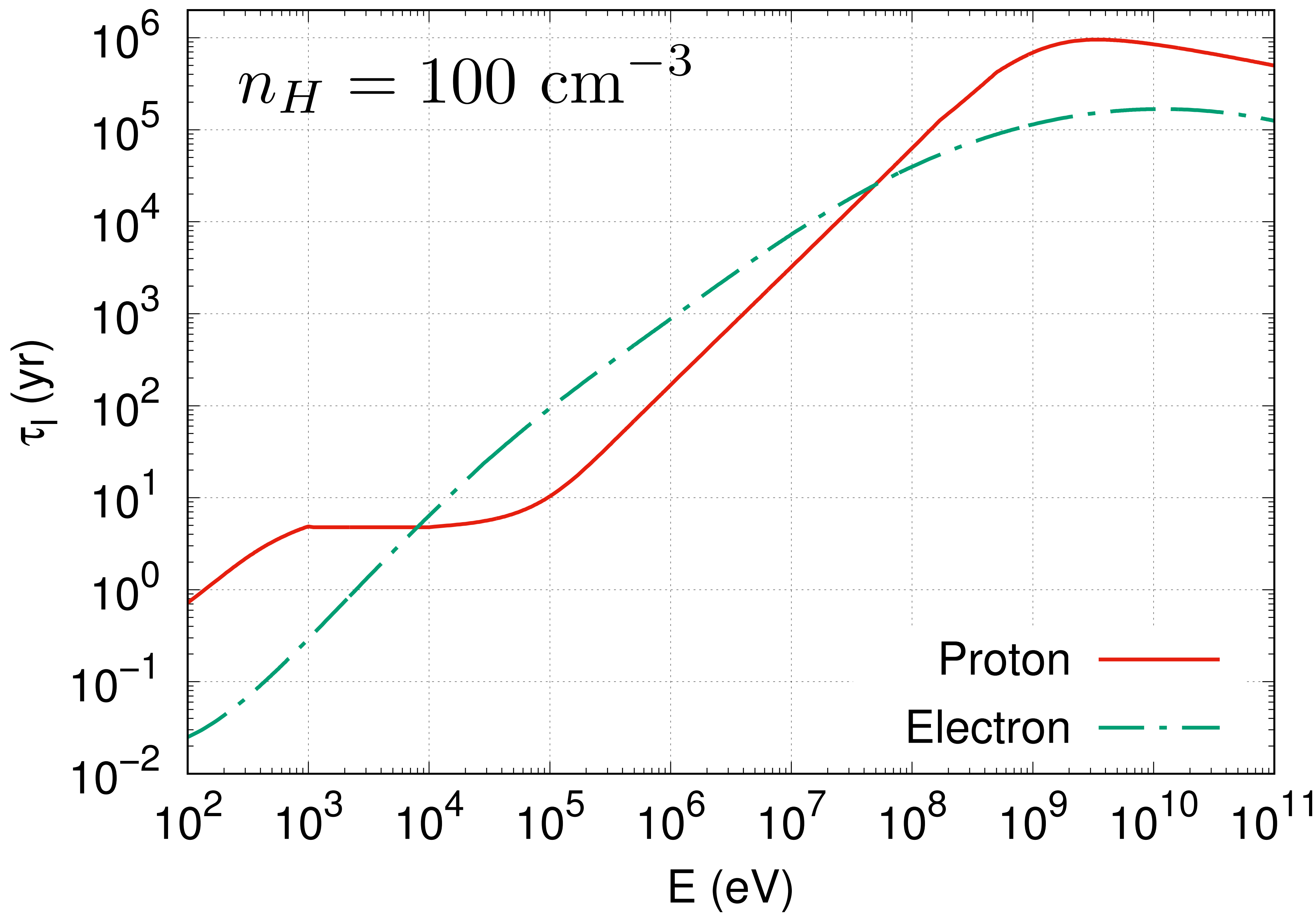


+ uncertainties in the penetration of CRs into clouds

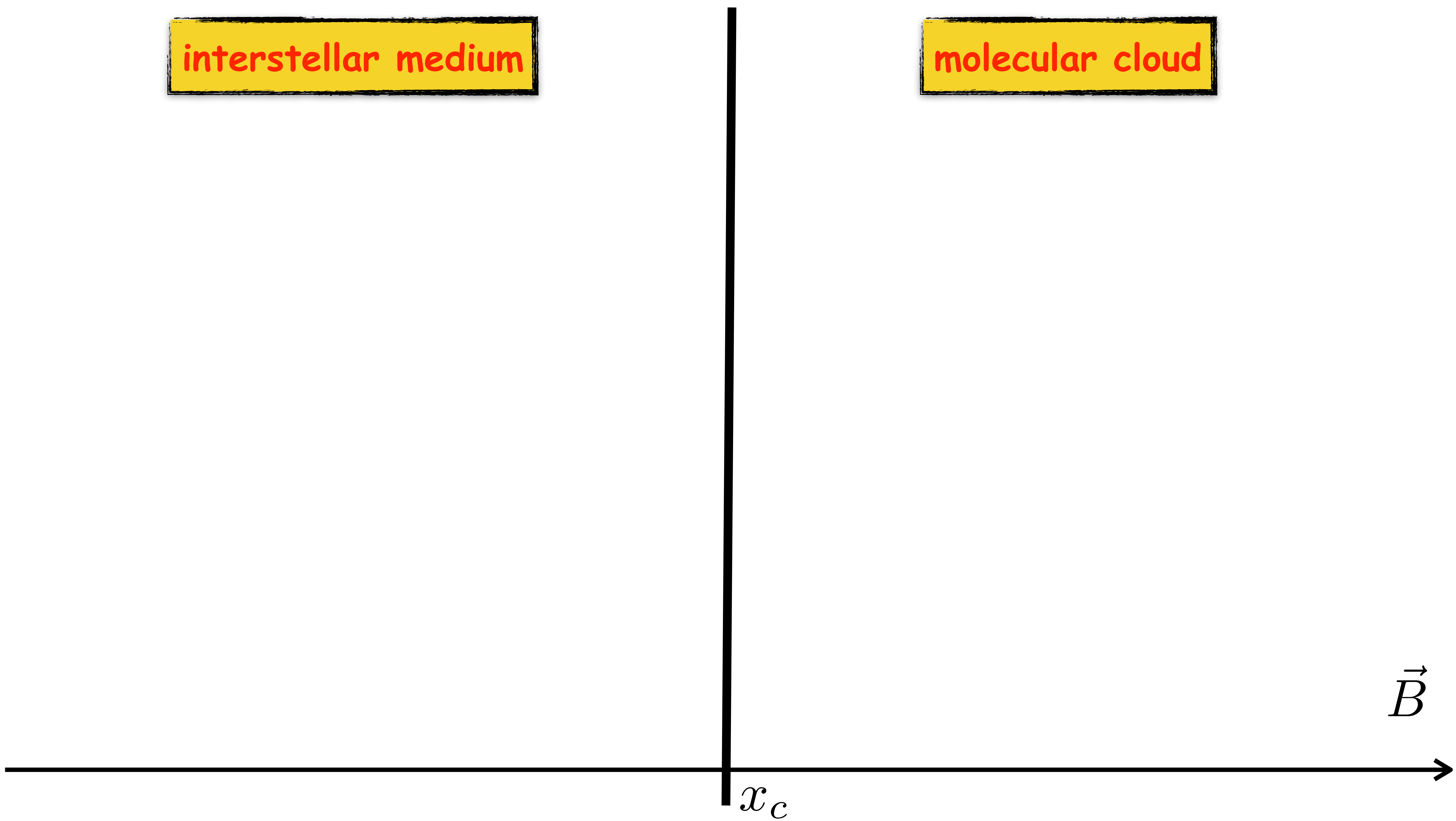
Energy losses

mainly ionization losses



Padovani+ 2009, Phan+ 2018

CR penetration into MCs (II)



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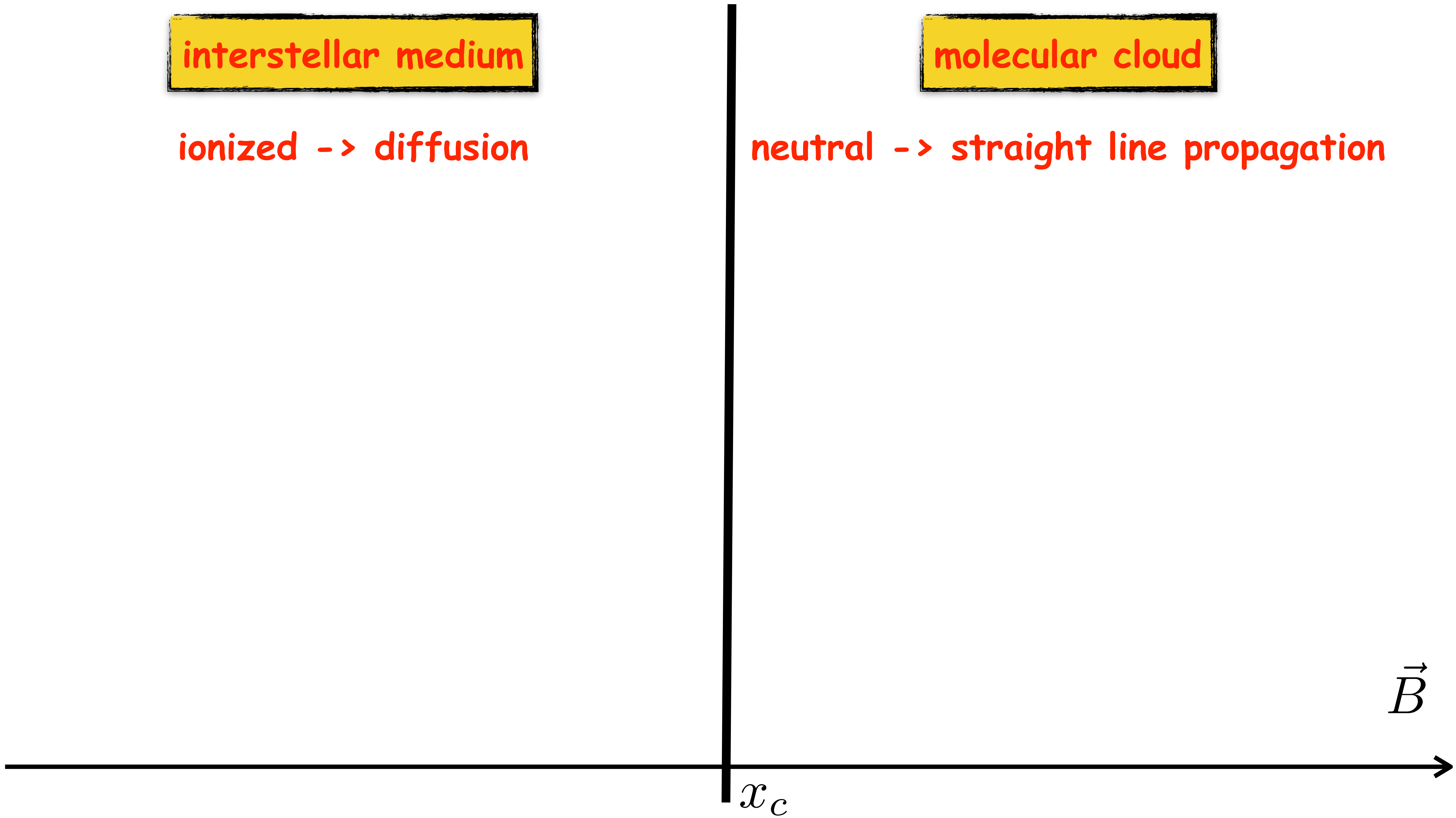

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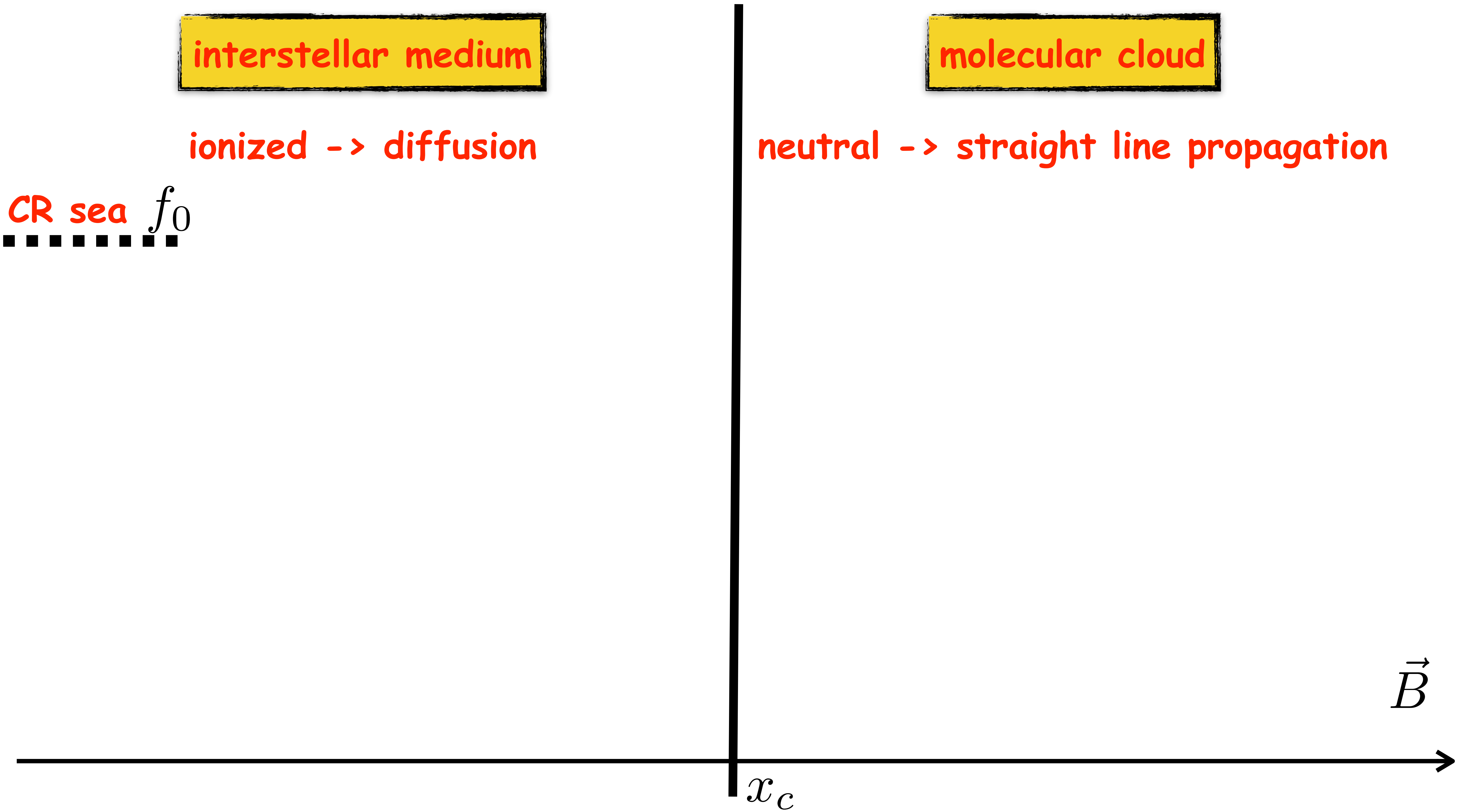

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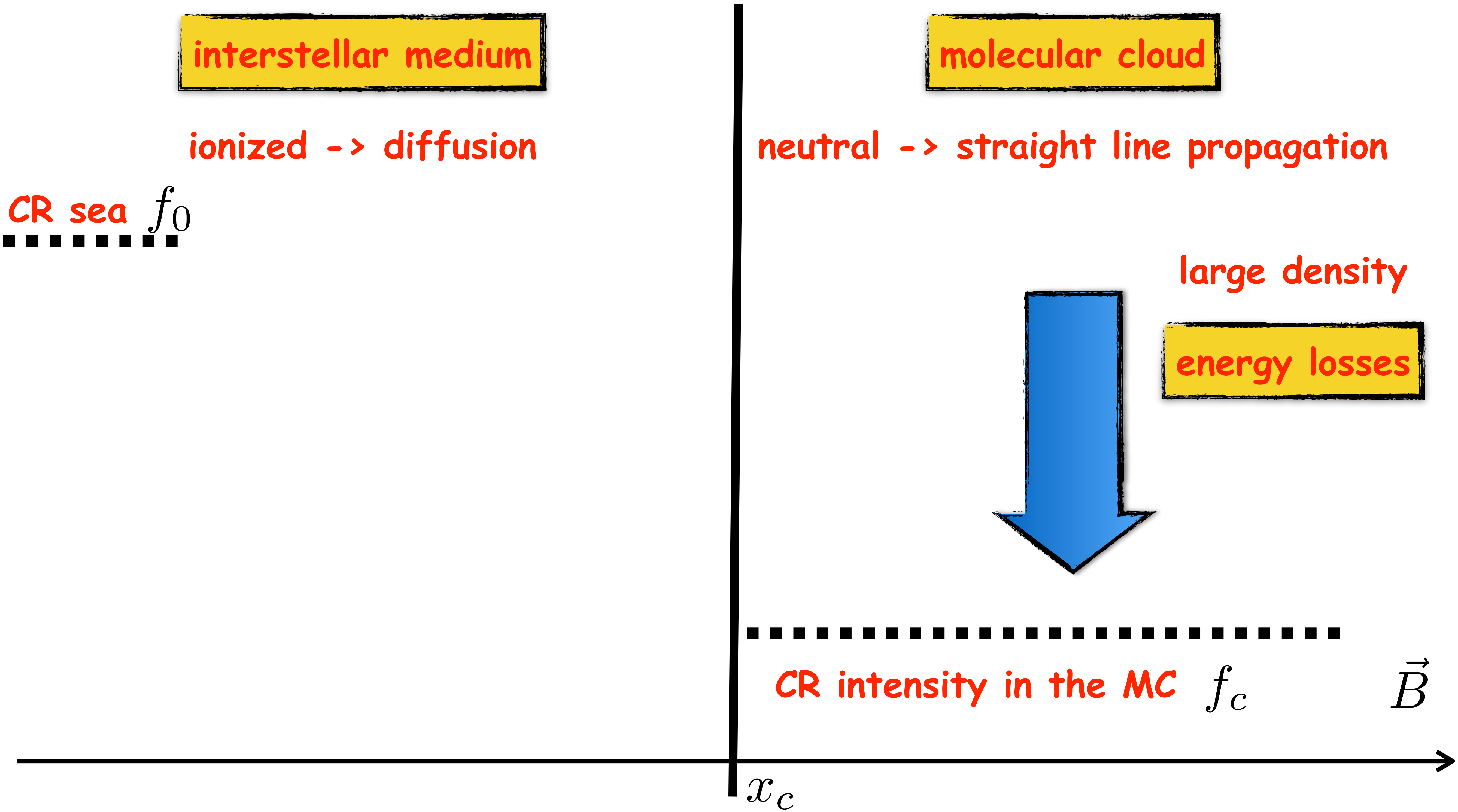

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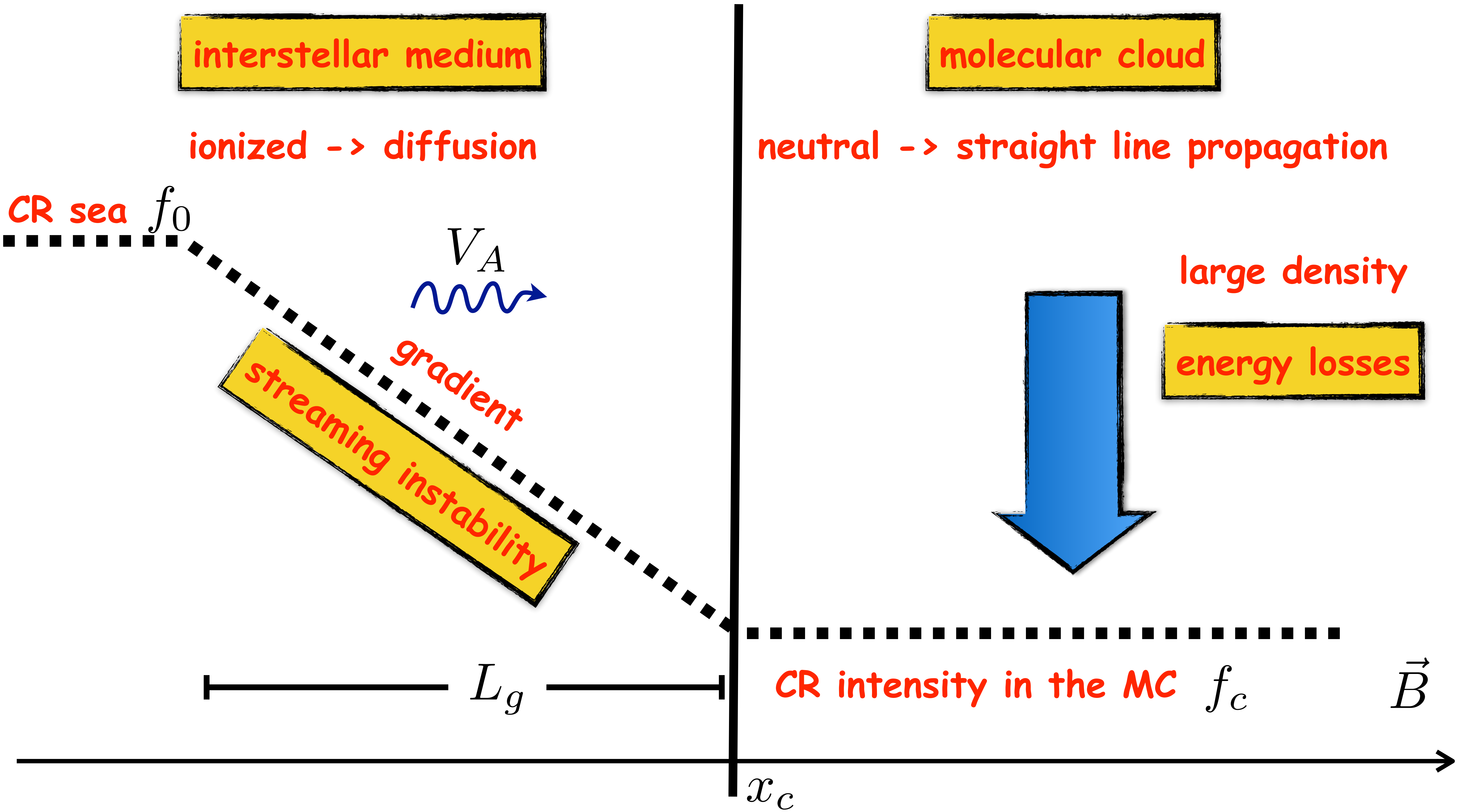

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CRs into MCs: incoming flux

what is the role of streaming instability?

Skilling&Strong1976
Morlino&Gabici 2015

CR flux into the cloud ->

$$D \frac{\partial f}{\partial x}|_{x_c} + V_A f(x_c)$$

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does NOT depend on streaming instability

determined by streaming instability

condition: L_g < field coherence length

CRs into MCs: universal spectrum

solution -> flux into both sides of the cloud $2 f_0 V_A$

equal to the flux down-ward in momentum $\frac{L_c}{p^2} \frac{\partial}{\partial p} \left[\dot{p} \, p^2 f_c \right]$

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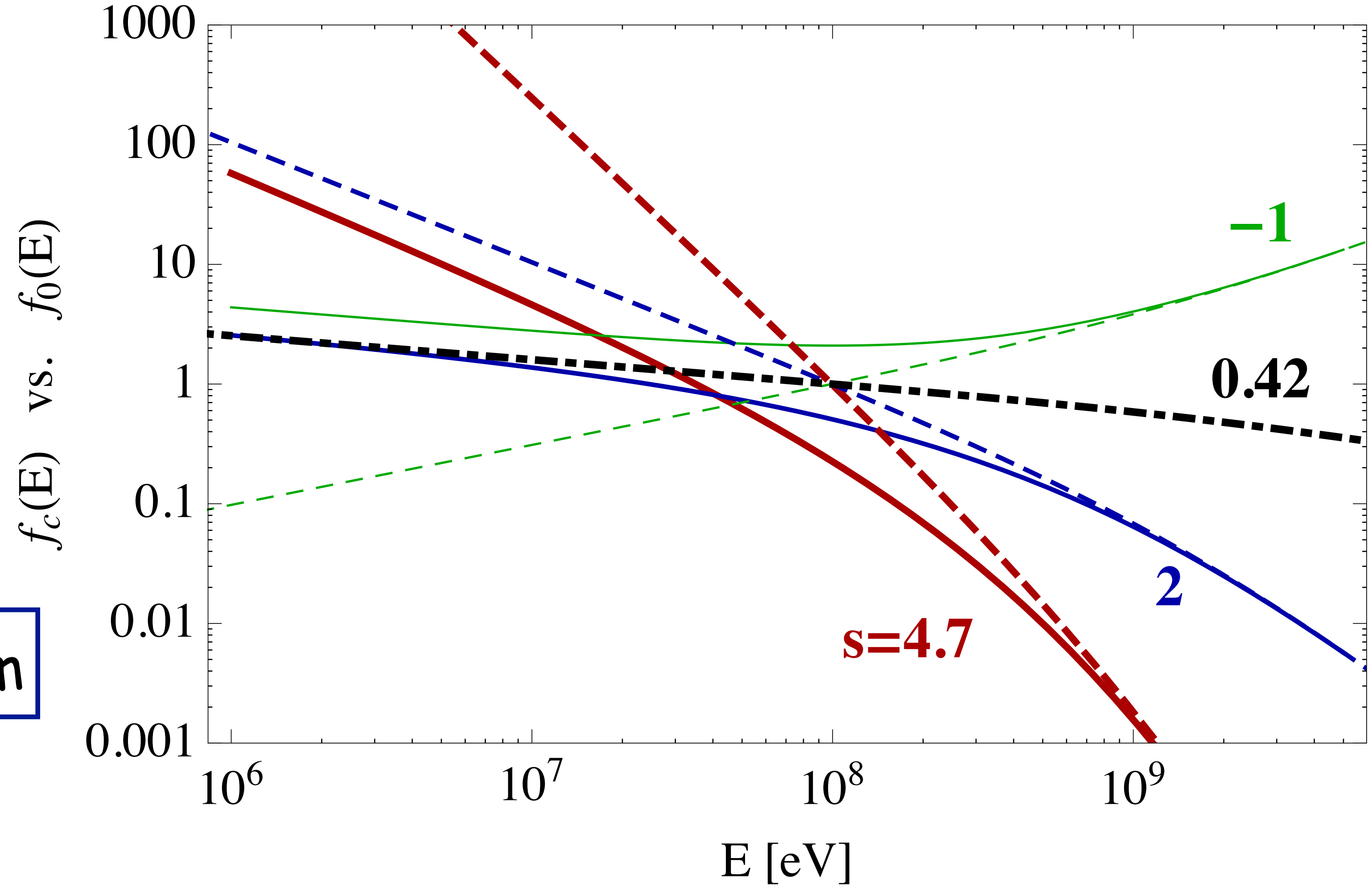
dashed -> outside of the MC
solid -> inside of the MC

~$p^{-0.42}$ eigenvalue of the problem



Morlino&Gabici 2015

CRs into MCs: universal spectrum

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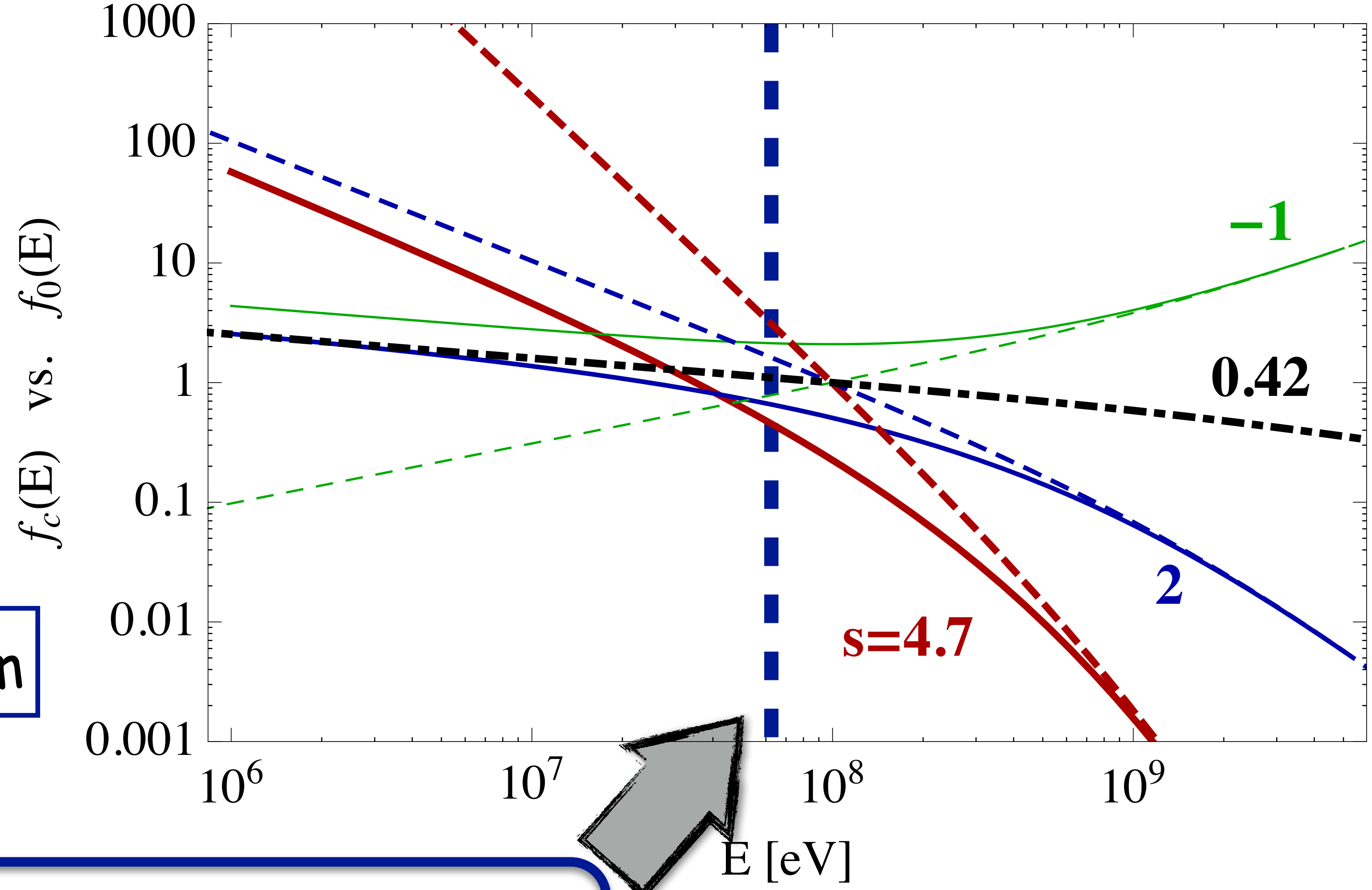


$$E_{br} \sim 70 \left(\frac{V_A}{100\ \mathrm{km/s}}\right)^{-0.78} \left(\frac{N_H}{3\times 10^{23}\ \mathrm{cm}^{-2}}\right)^{0.78} \mathrm{MeV}$$

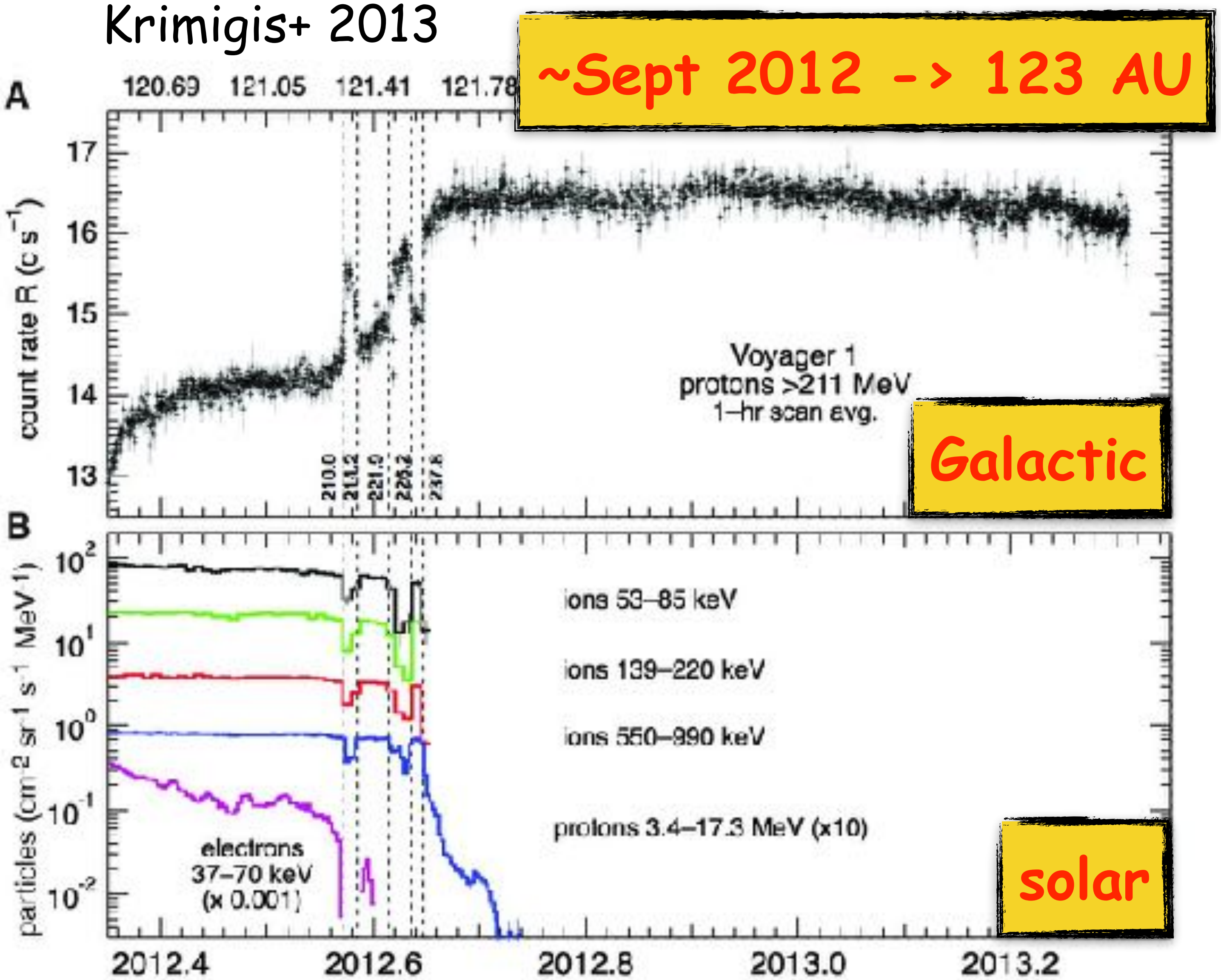
Morlino&Gabici 2015

Voyager probes

September 5 1977
the launch of Voyager 1

Voyager 1 at Heliosphere's border

Krimigis+ 2013



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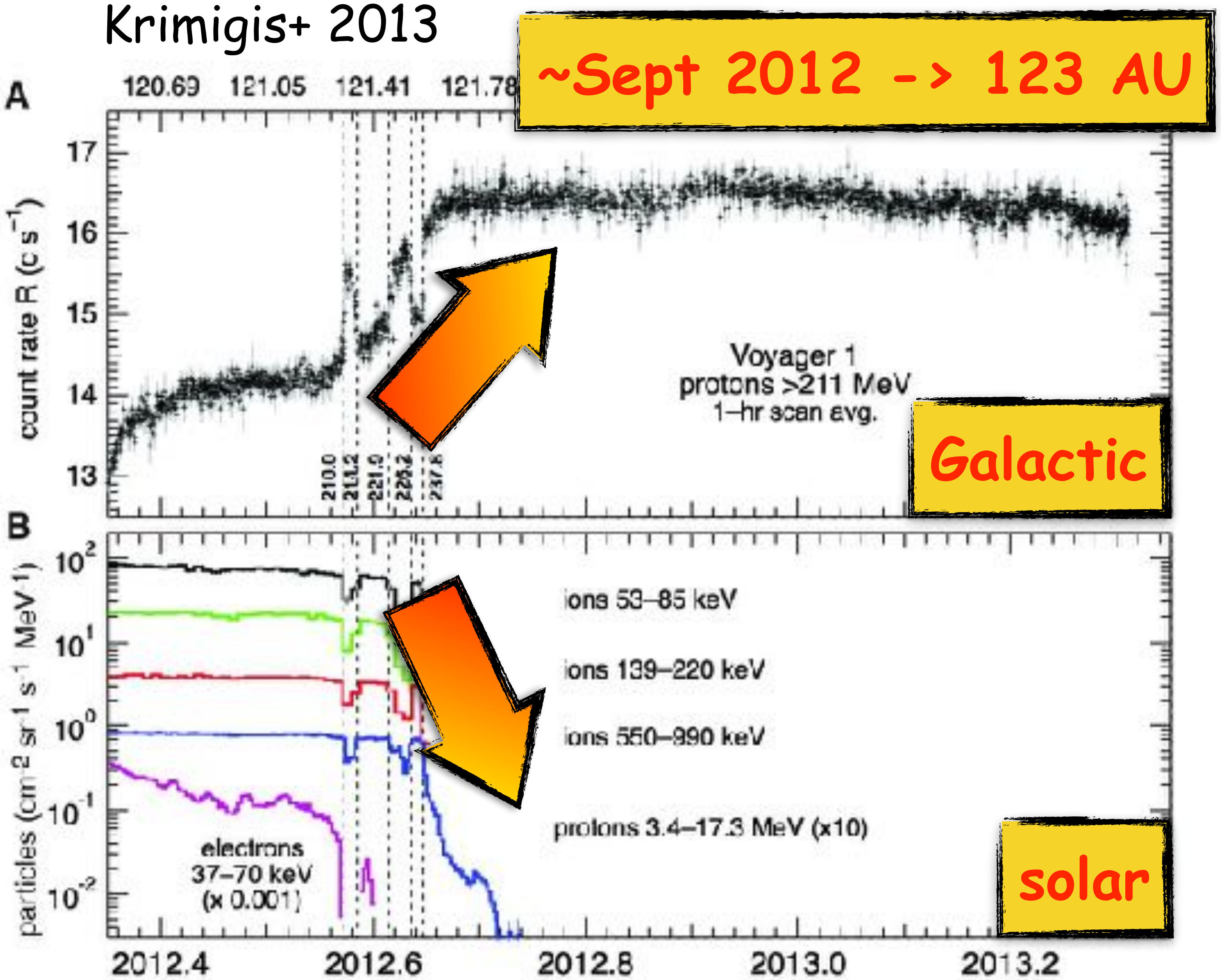

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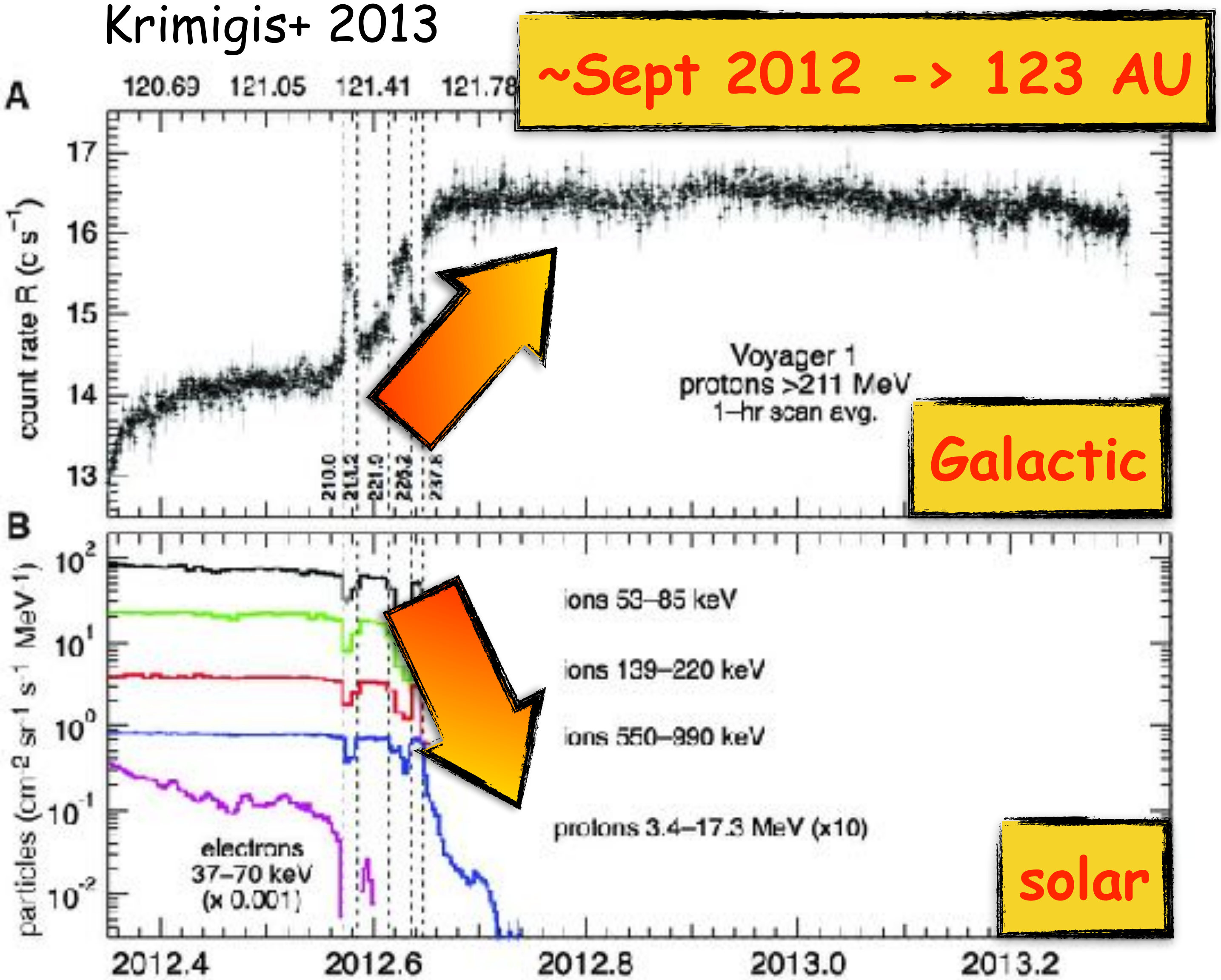

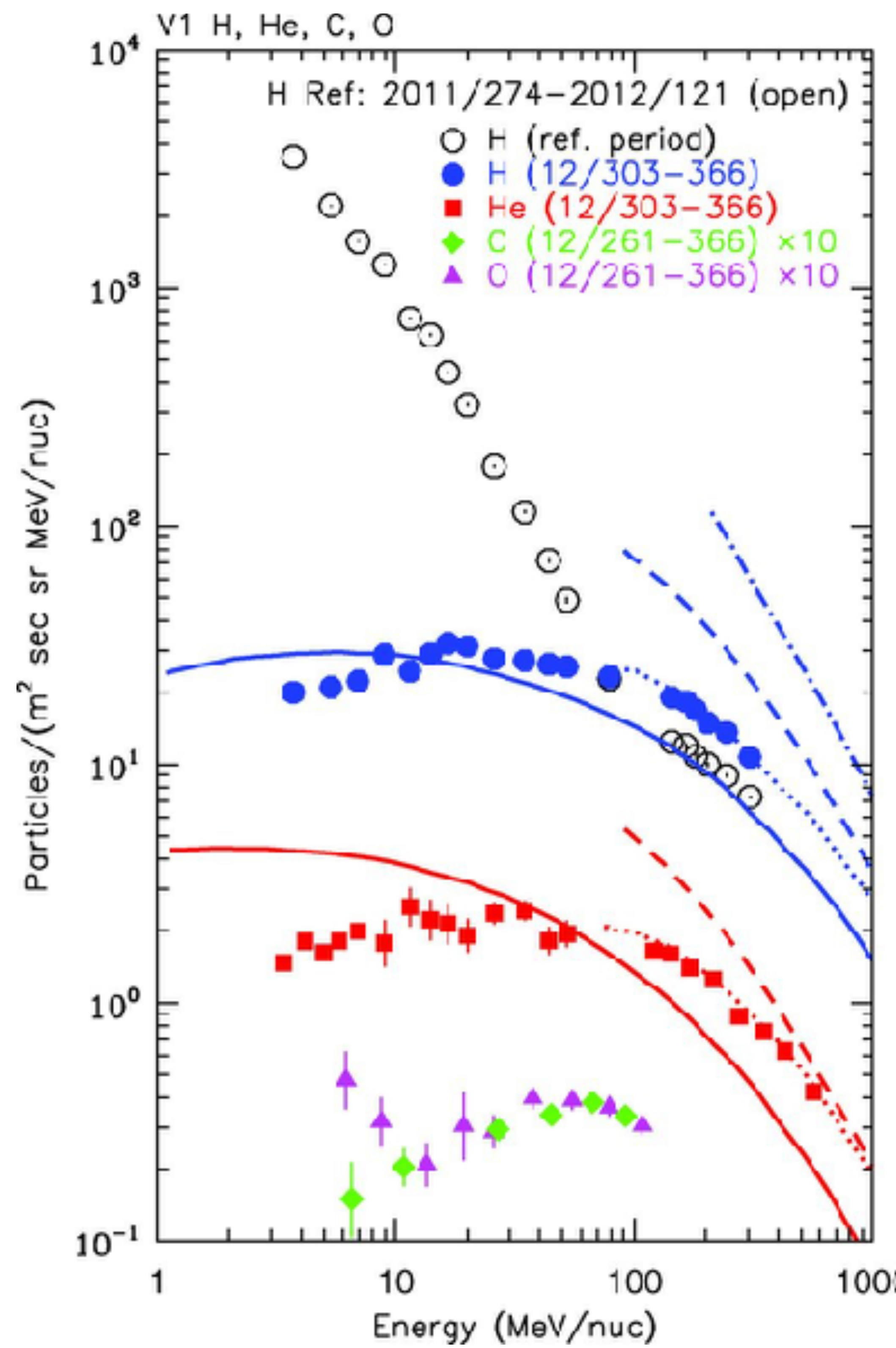

Stone+ 2013

Voyager 1 at Heliosphere's border

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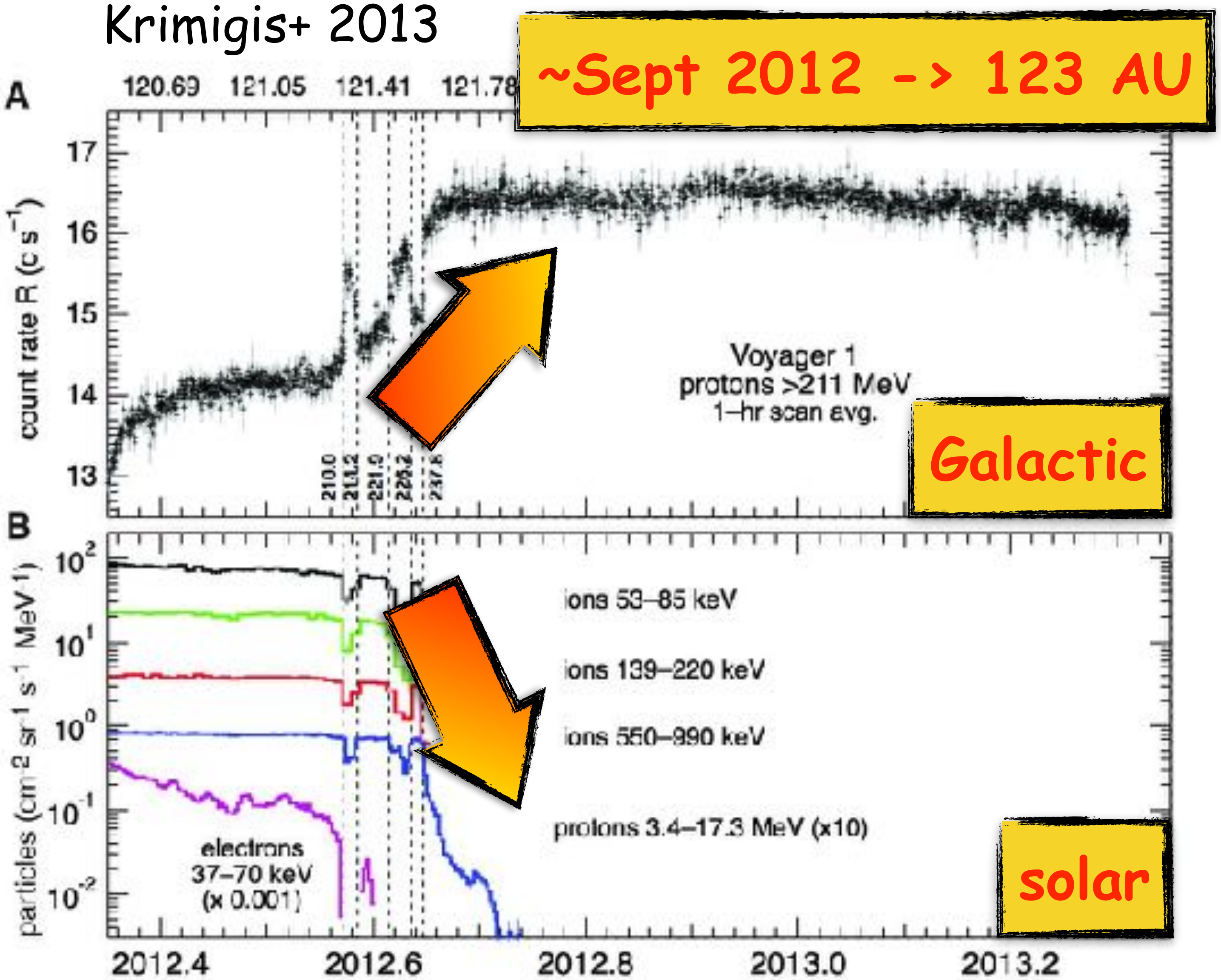

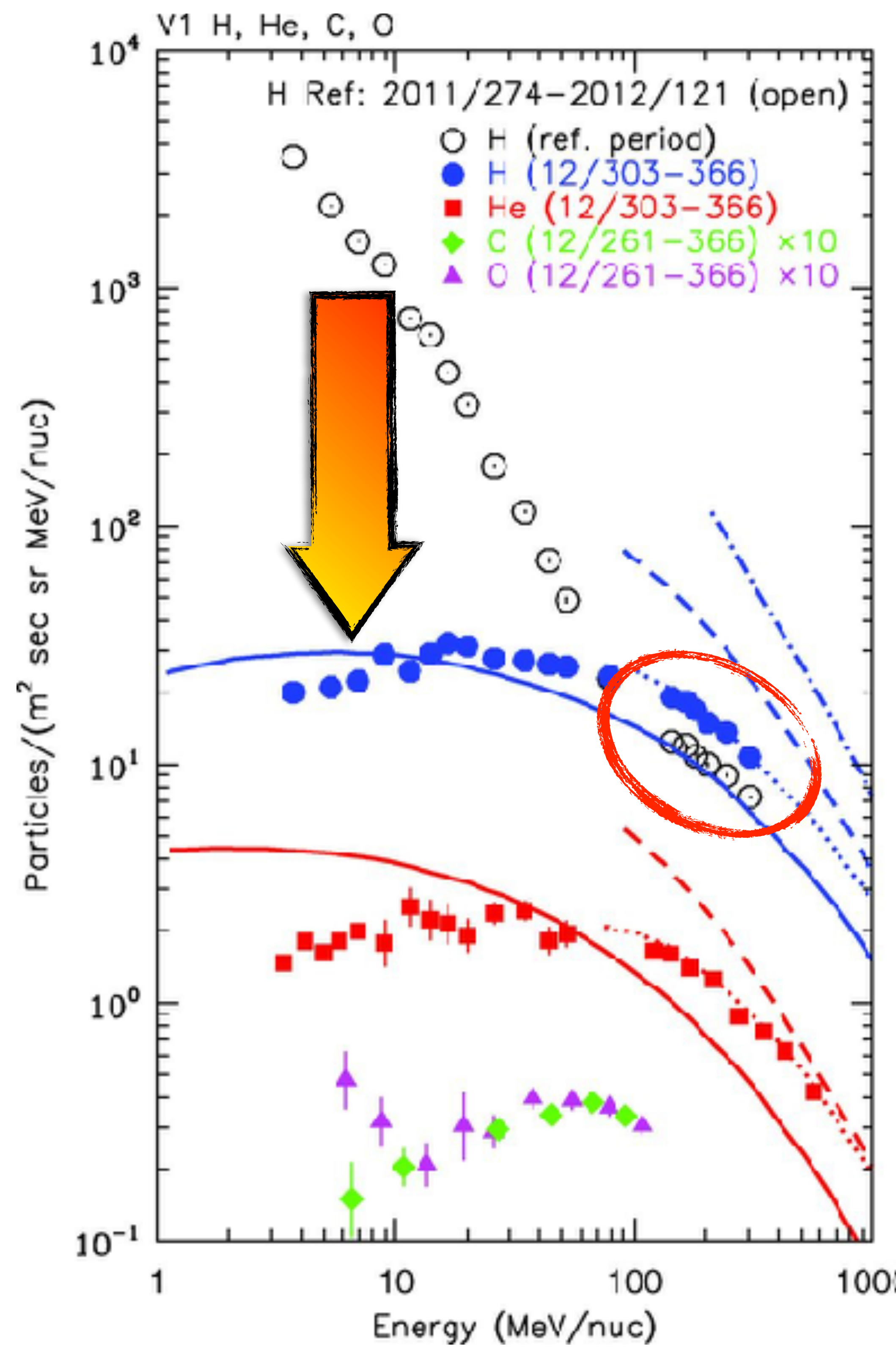

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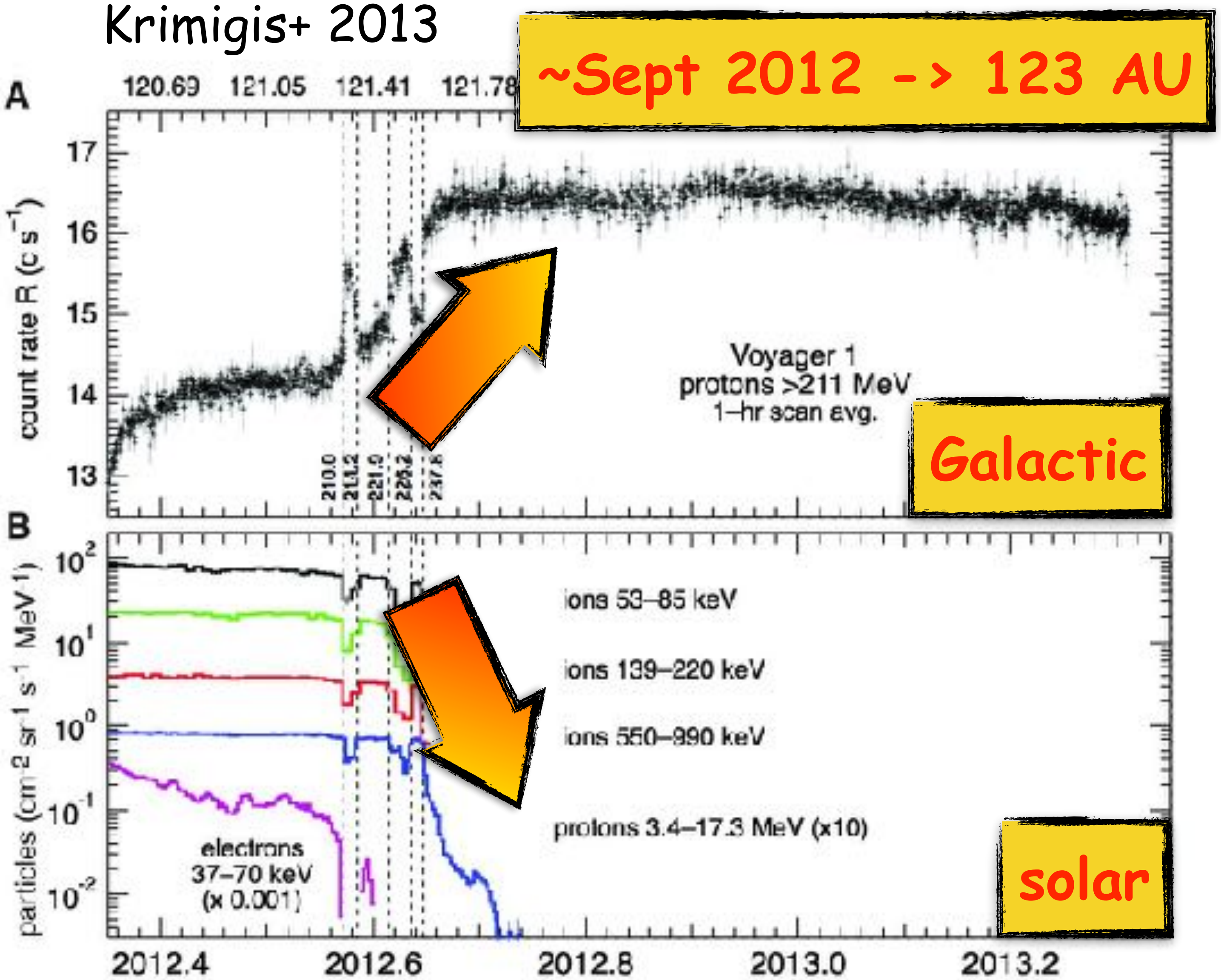
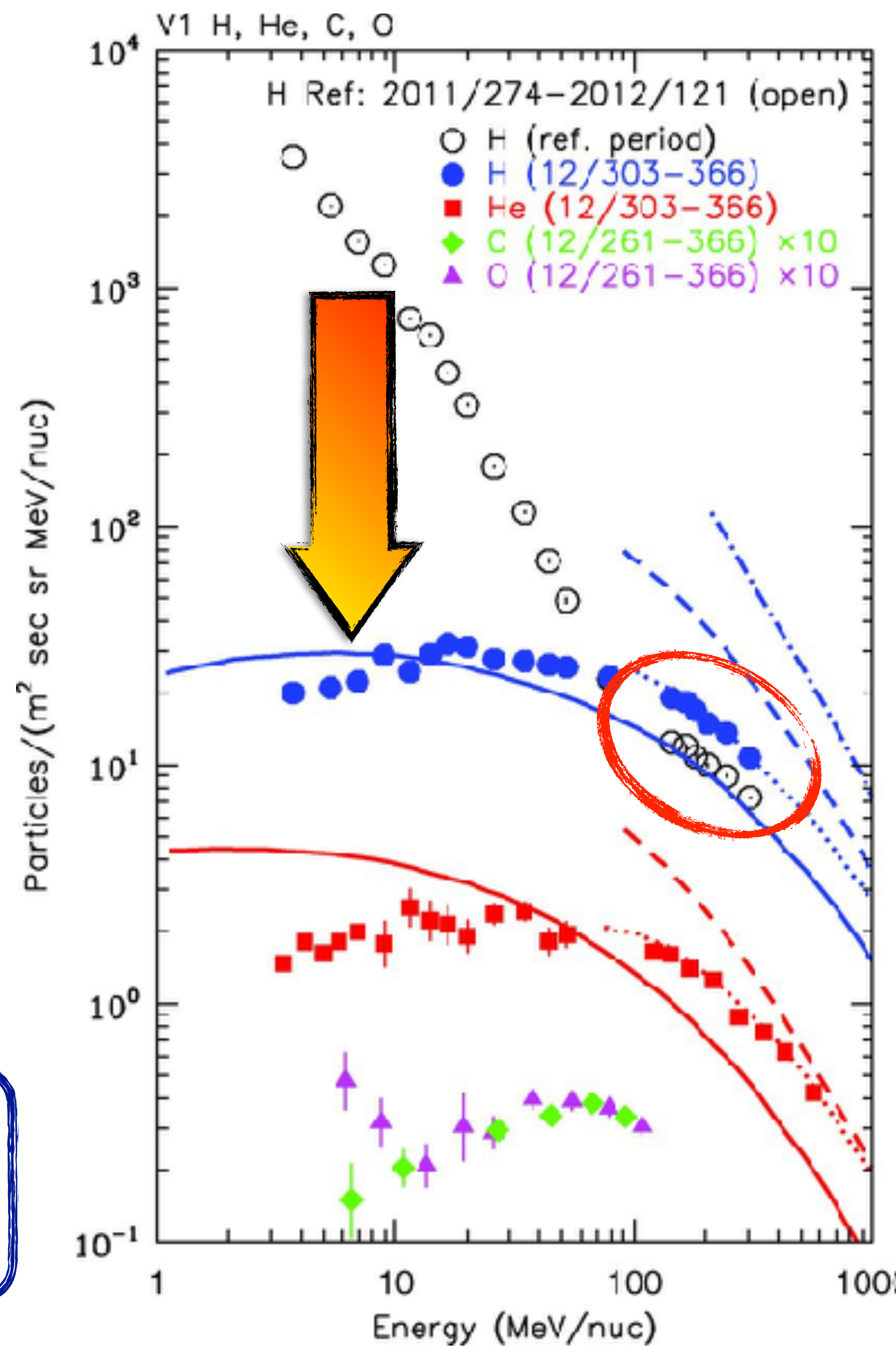
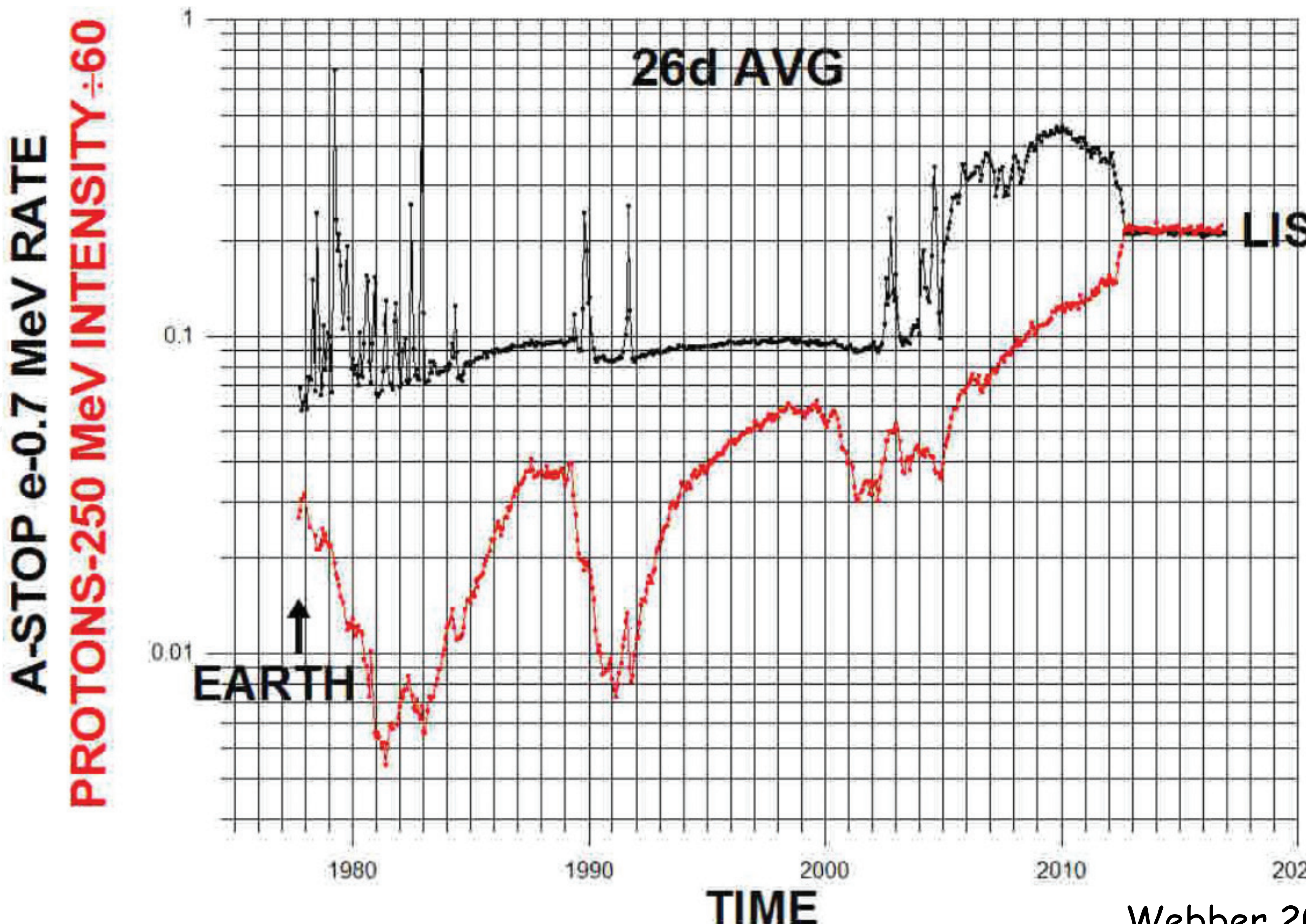




Stone+ 2013

Voyager data —> $\zeta_{CR}^{H_2} \sim 10^{-17}\mathrm{s}^{-1}$

An epic journey

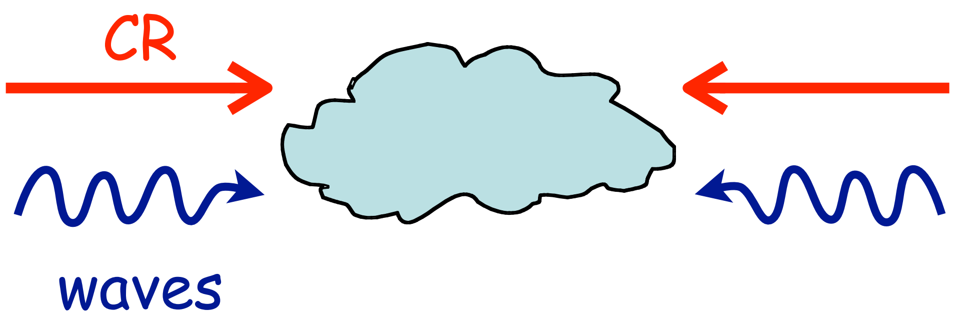


Webber 2018

Voyager 2 is also out since Nov 5th 2018

CRs into clouds: universal spectrum

flux into the cloud $2 f_0 V_A$ equal to the flux down in p $\frac{L_c}{p^2} \frac{\partial}{\partial p} \left[\dot{p} \; p^2 f_c \right]$



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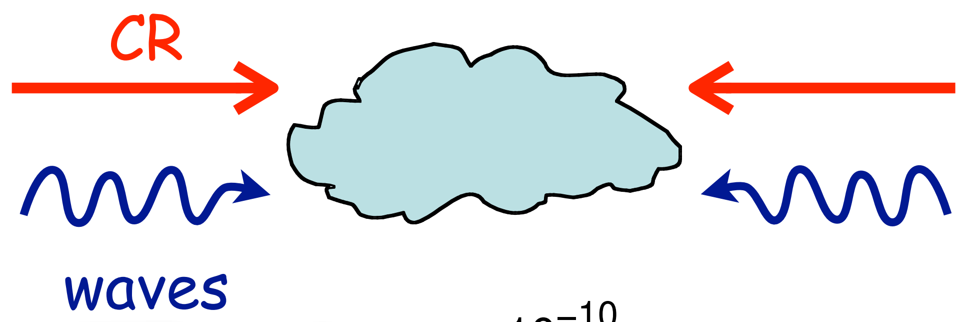

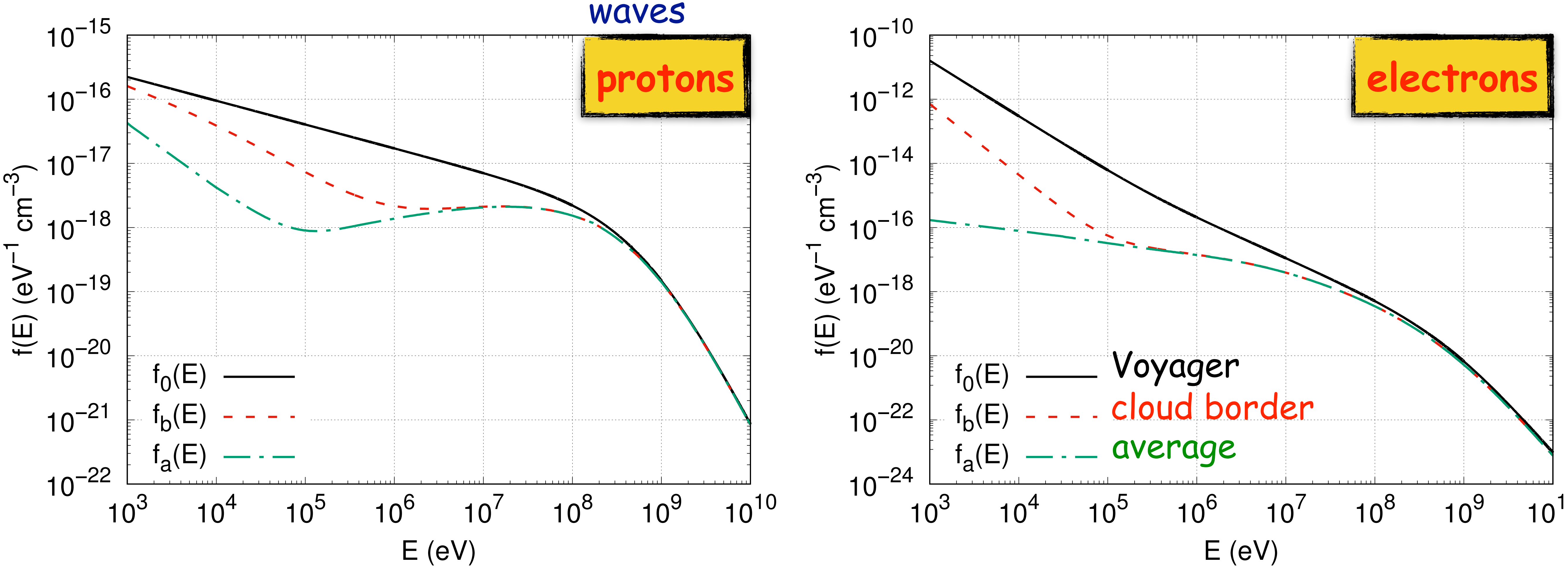

(a) CR protons

(b) CR electrons

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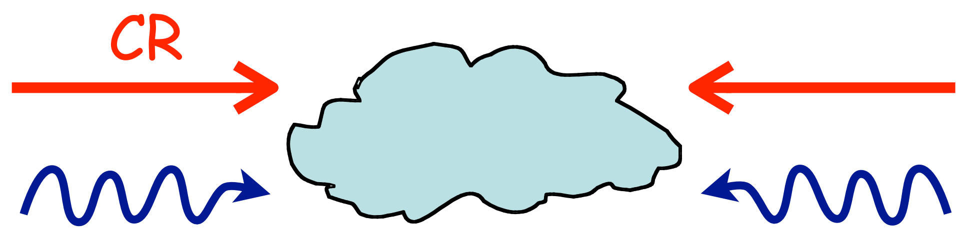

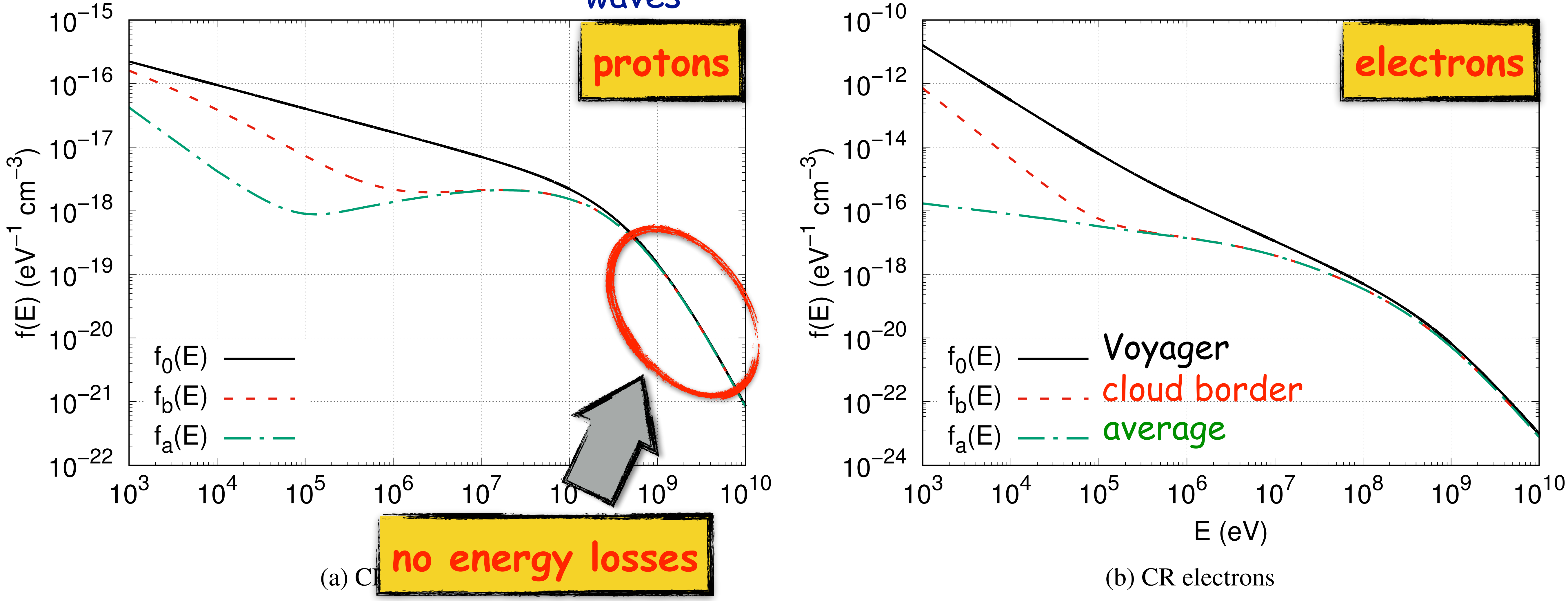

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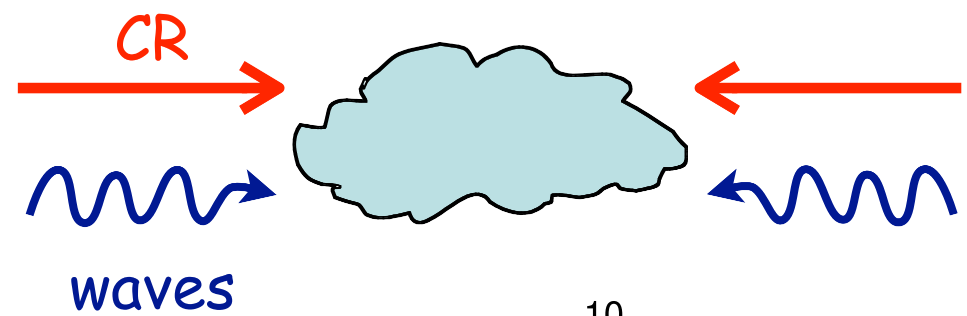

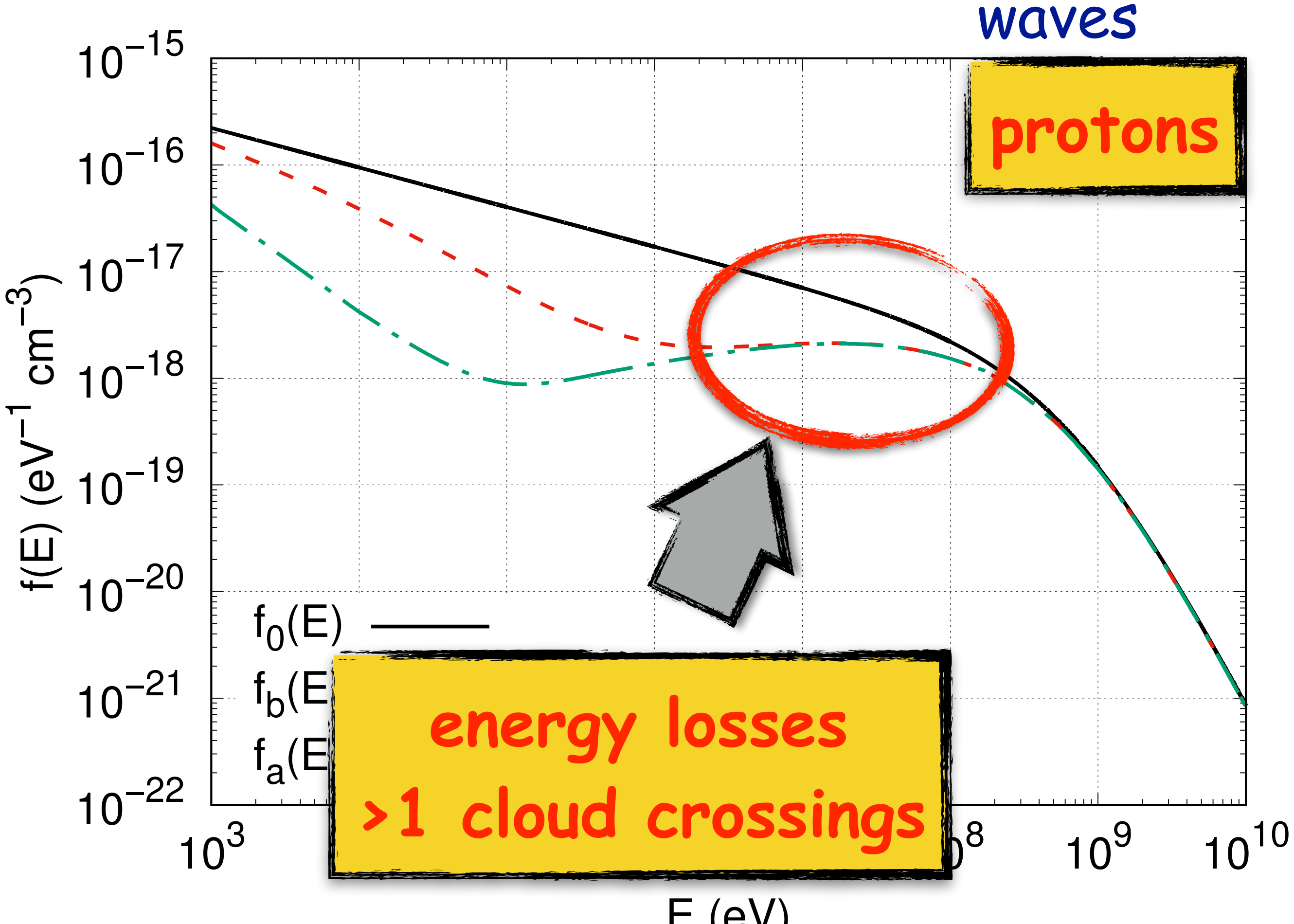

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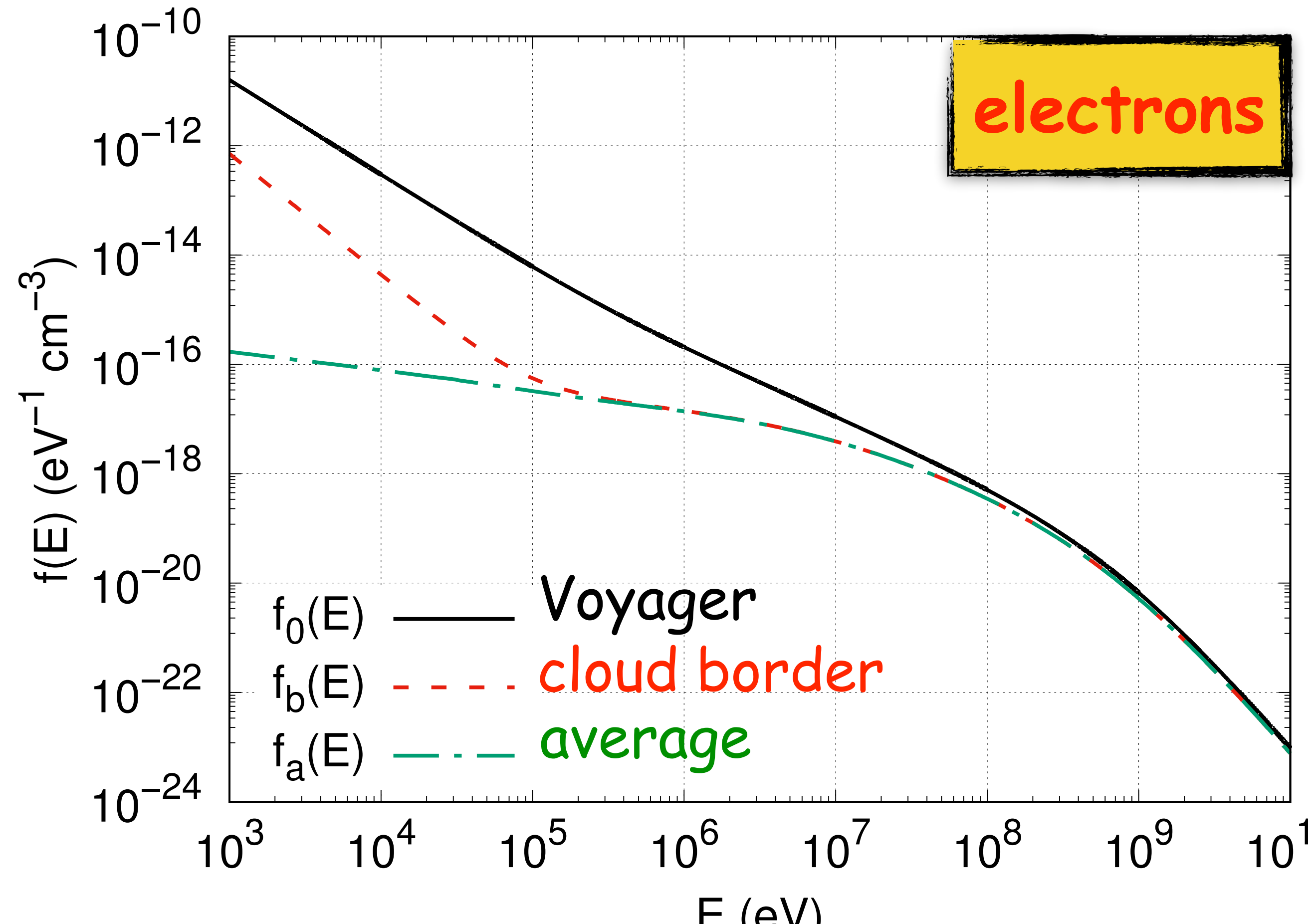

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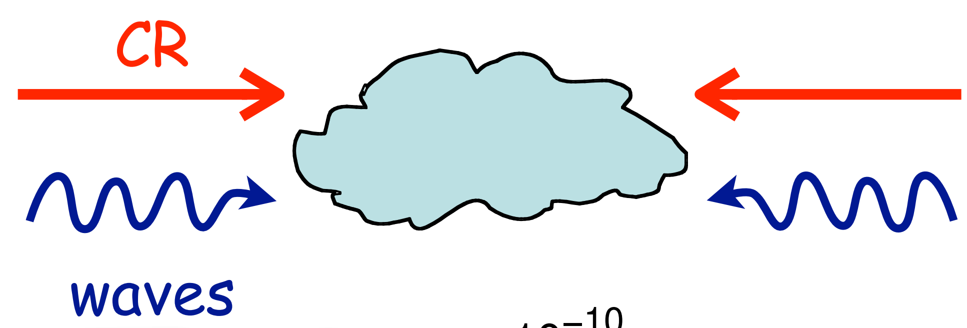

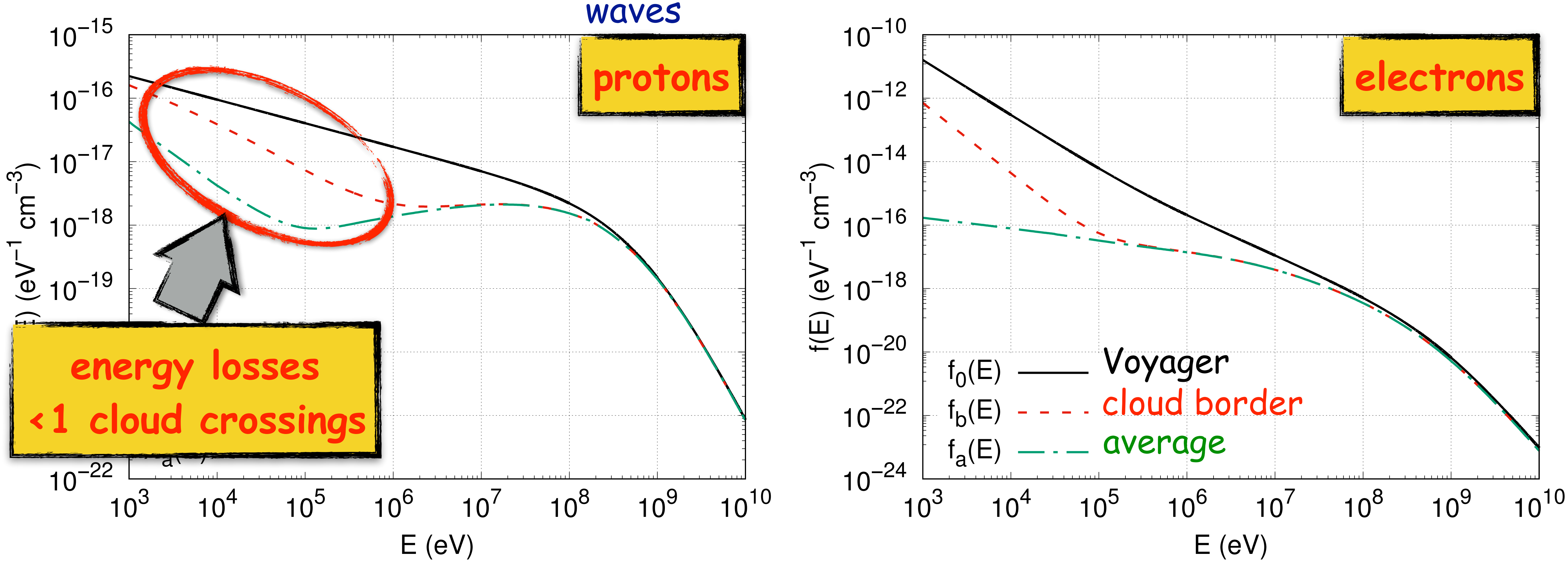

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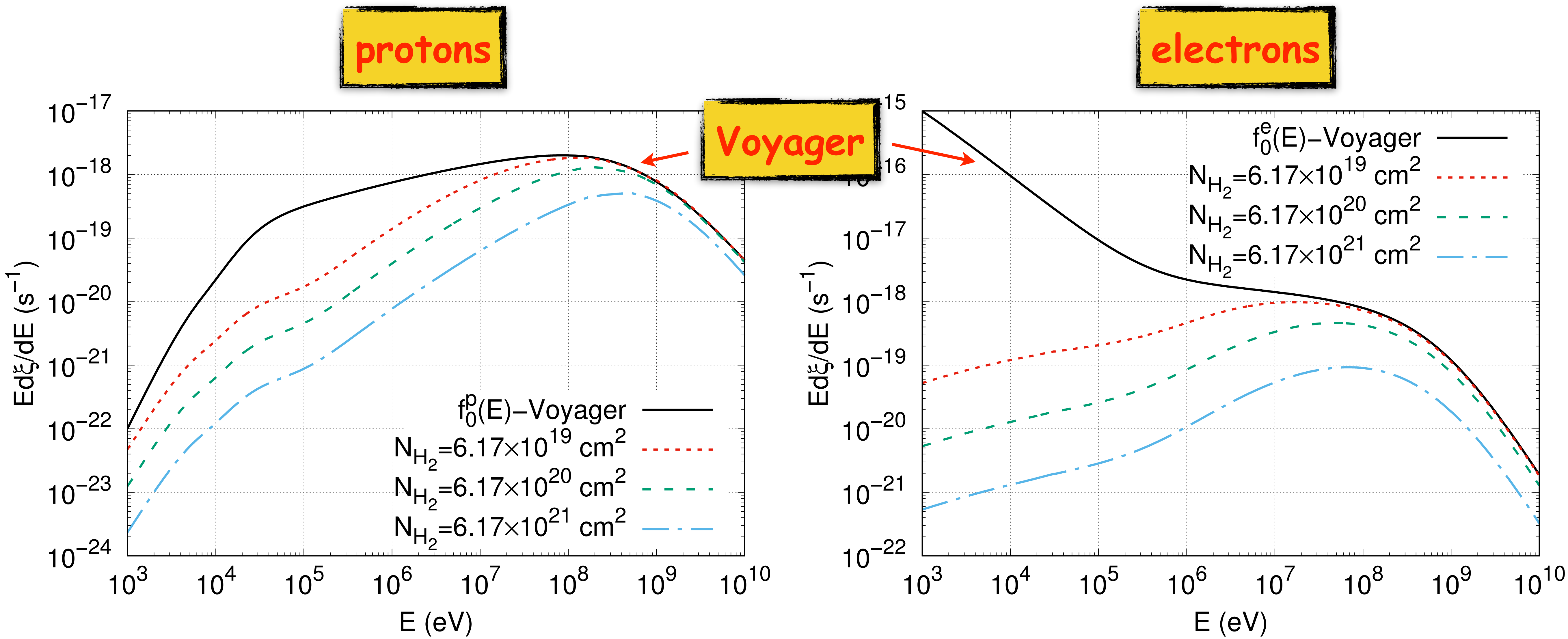
Phan+ 2018, Morlino&Gabici 2015

Differential ionisation rates



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Phan+ 2018

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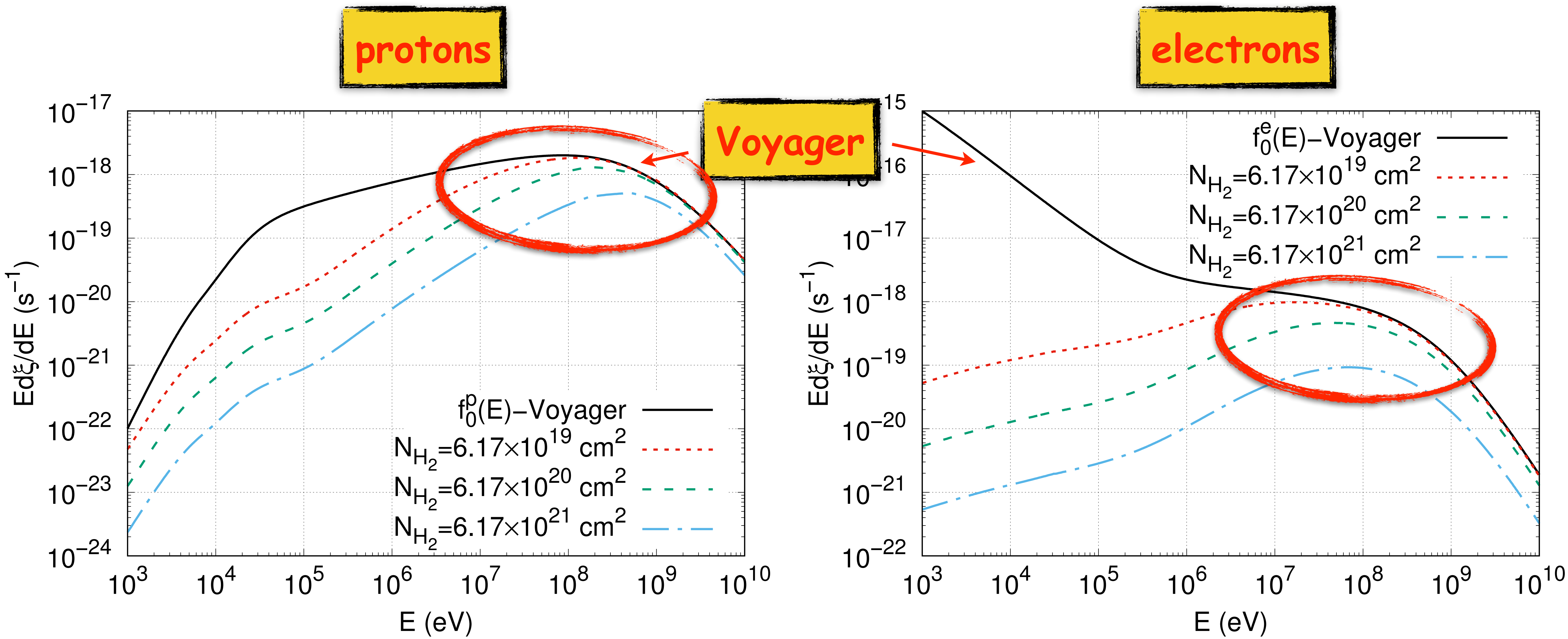


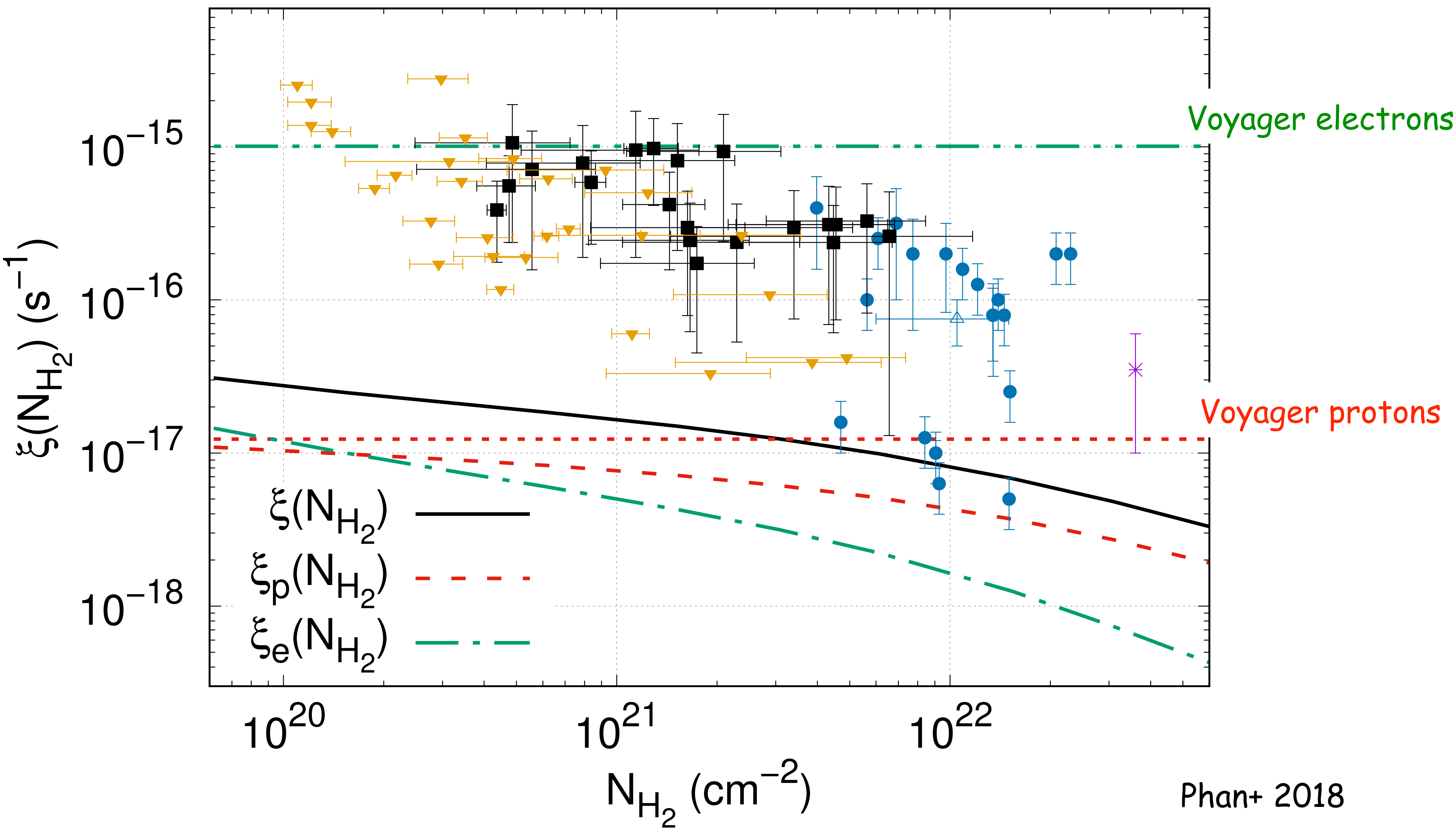
(a) CR protons

(b) CR electrons

most of the ionisation —> MeV < E < GeV

Phan+ 2018

Comparison with data (???)



Phan+ 2018

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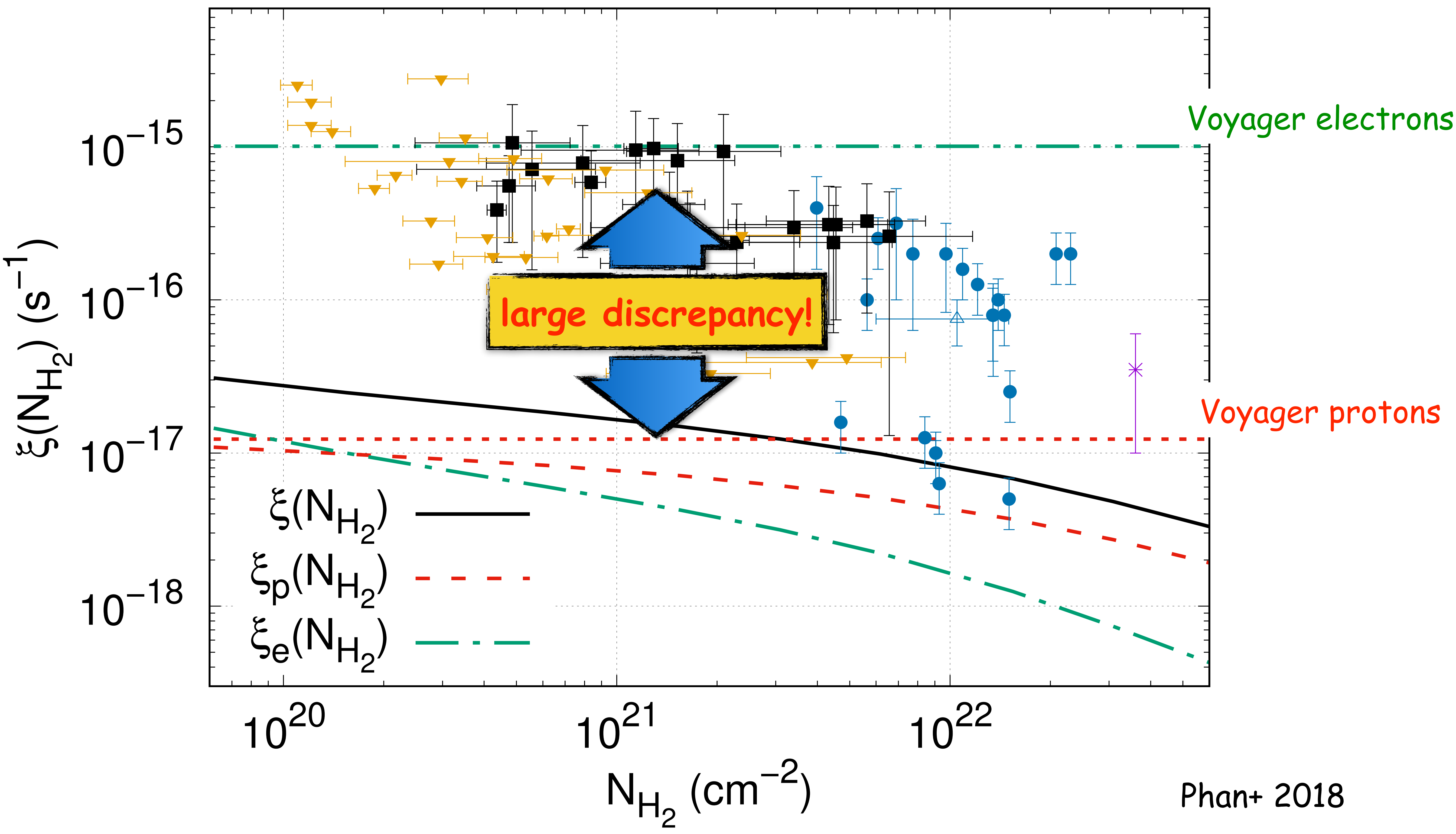

Phan+ 2018

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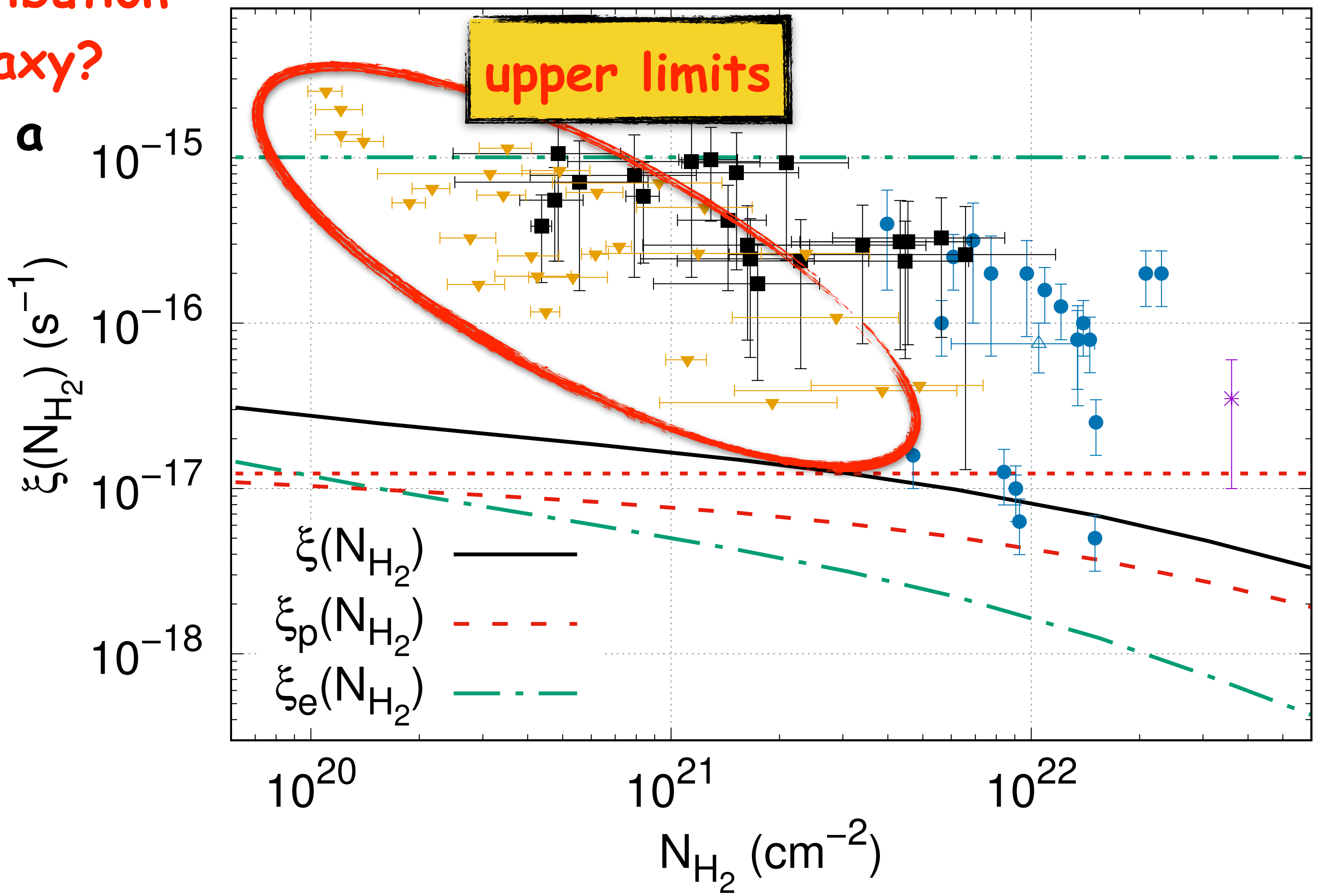

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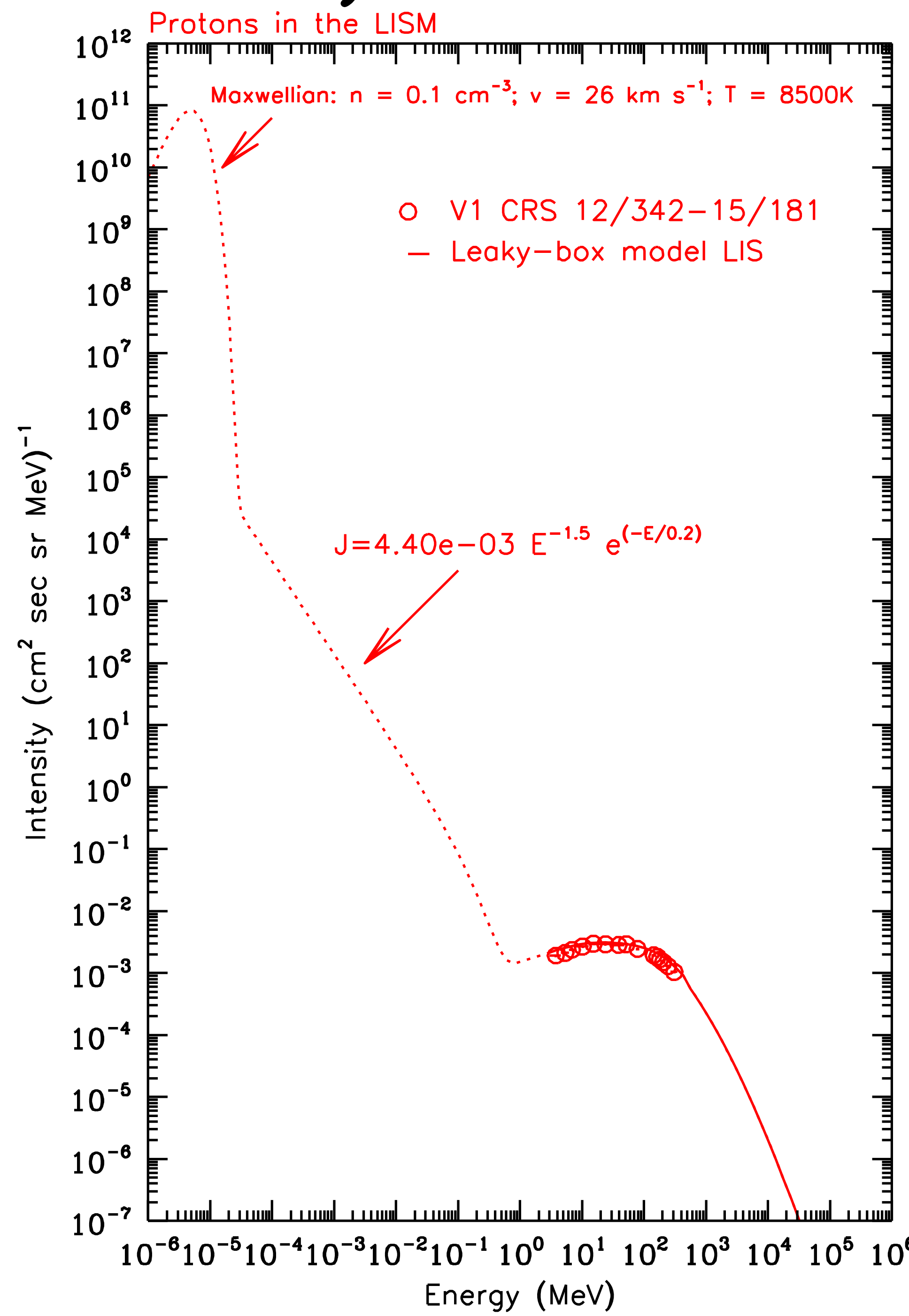
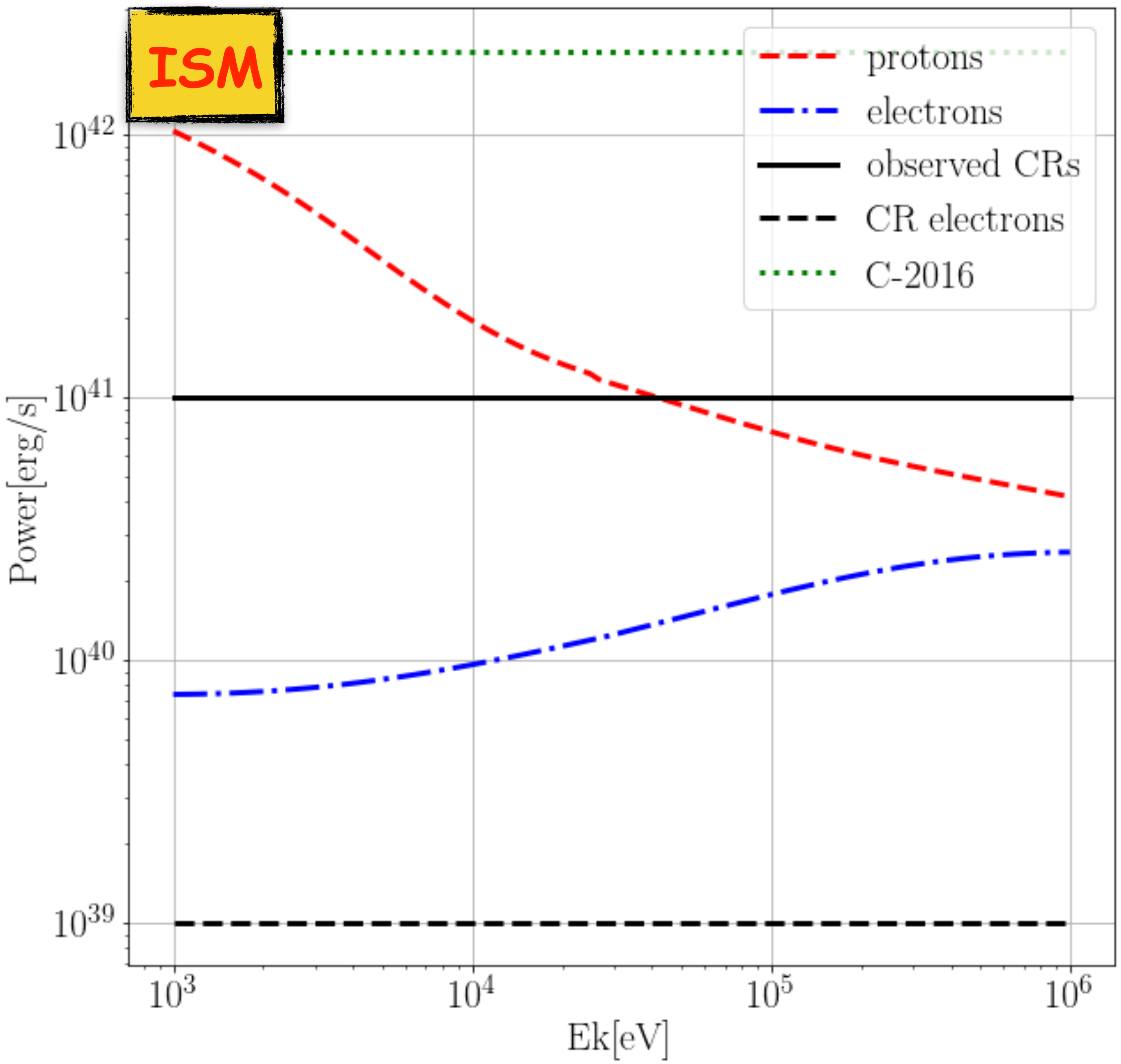


Cummings+ 2016

A cosmic ray carrot?



Cummings+ 2016

CRp luminosity of MW

CRe luminosity of MW

Recchia+ 2018

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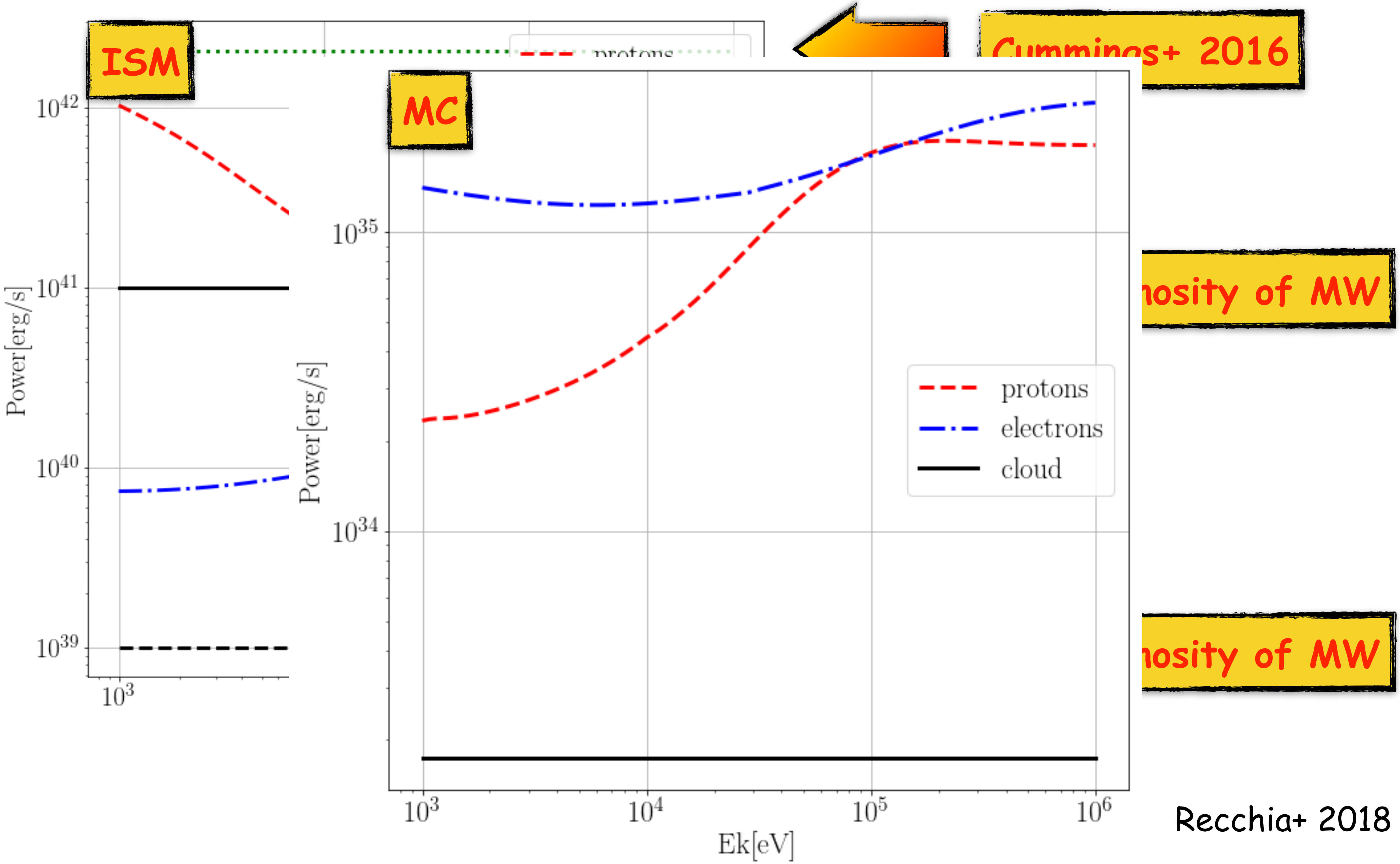

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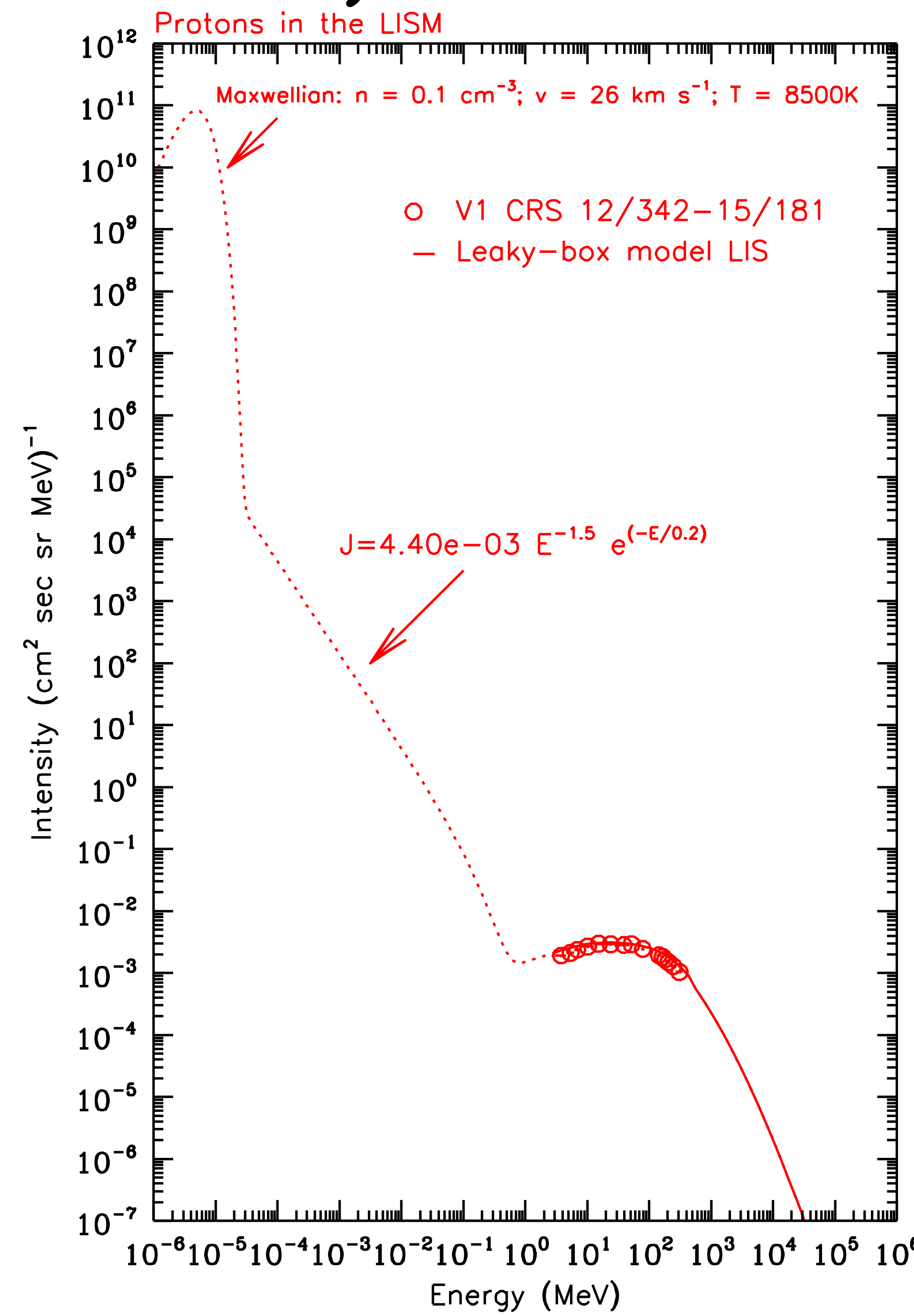


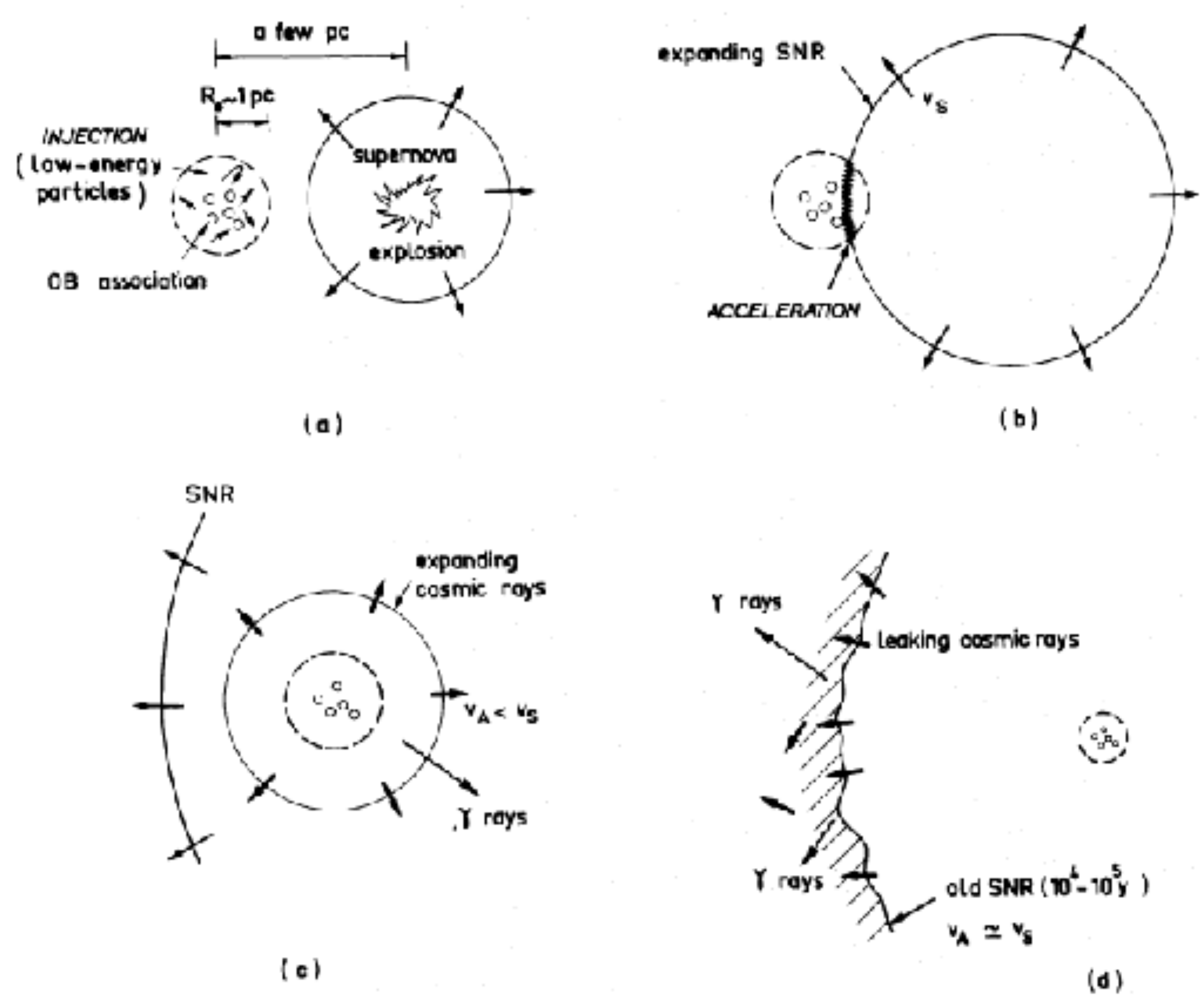
Cummings+ 2016

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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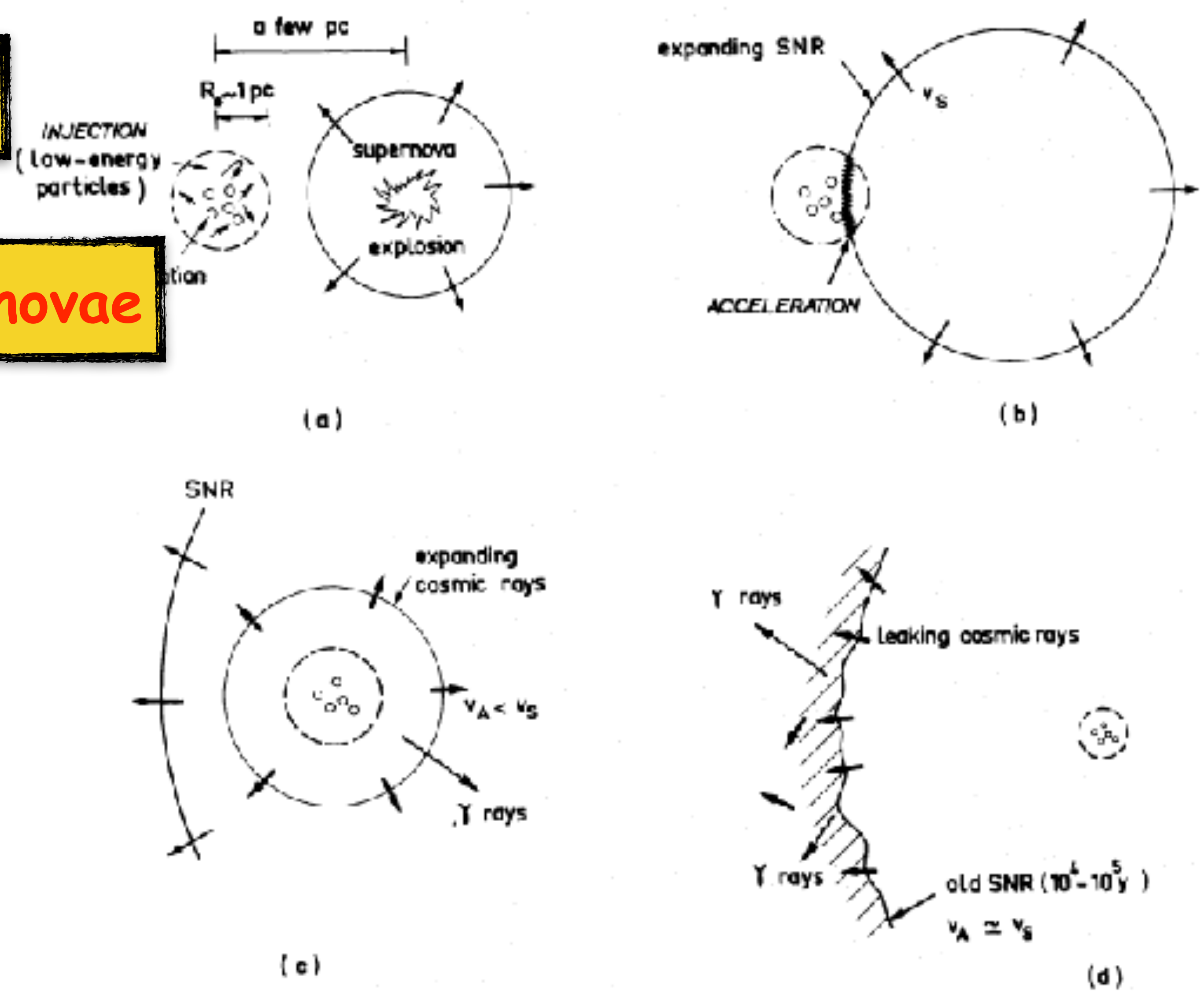

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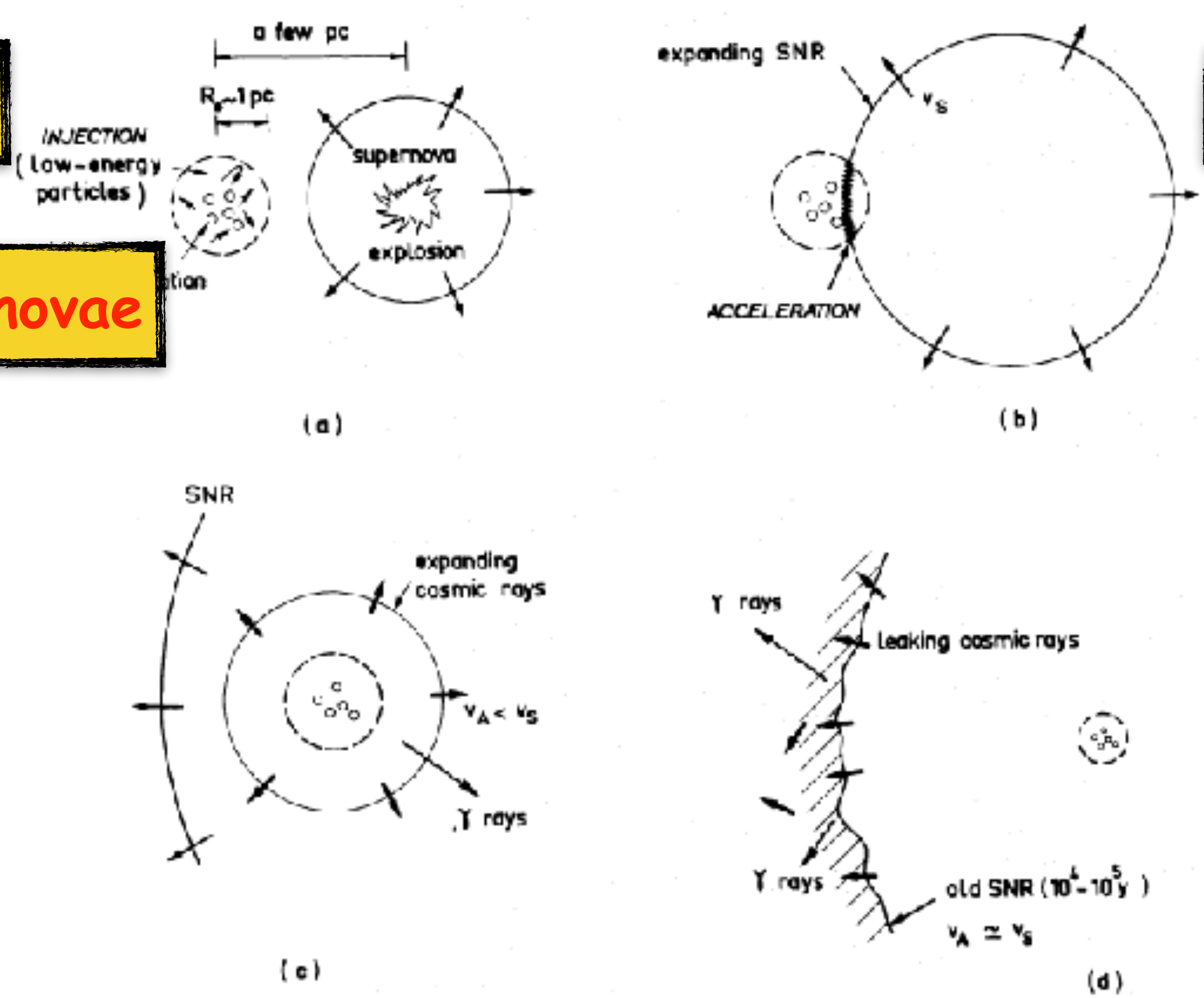
SNRs

CR acceleration



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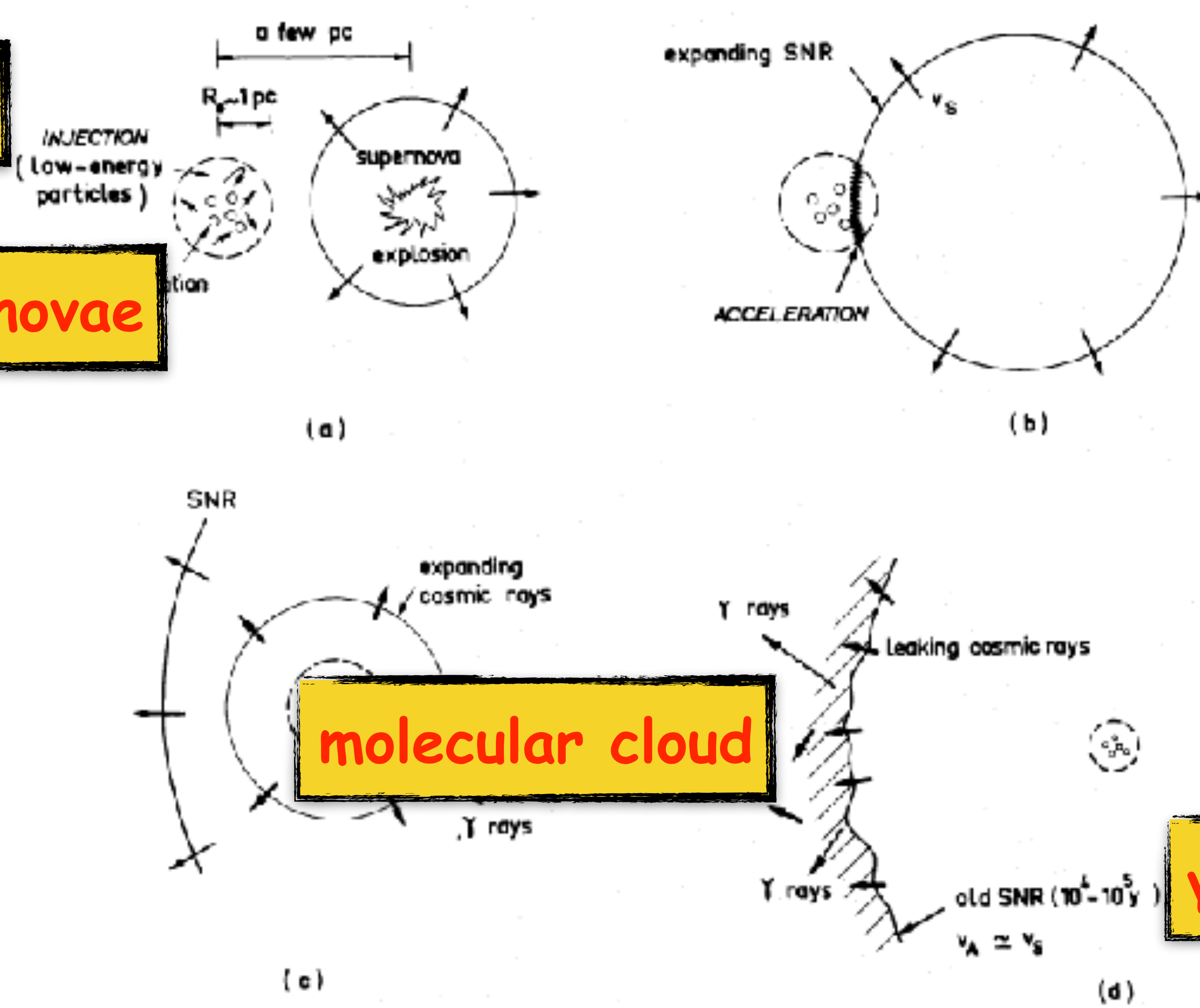

Black & Fazio 1973

The importance of being a SNOB

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SuperNovae OB …tions

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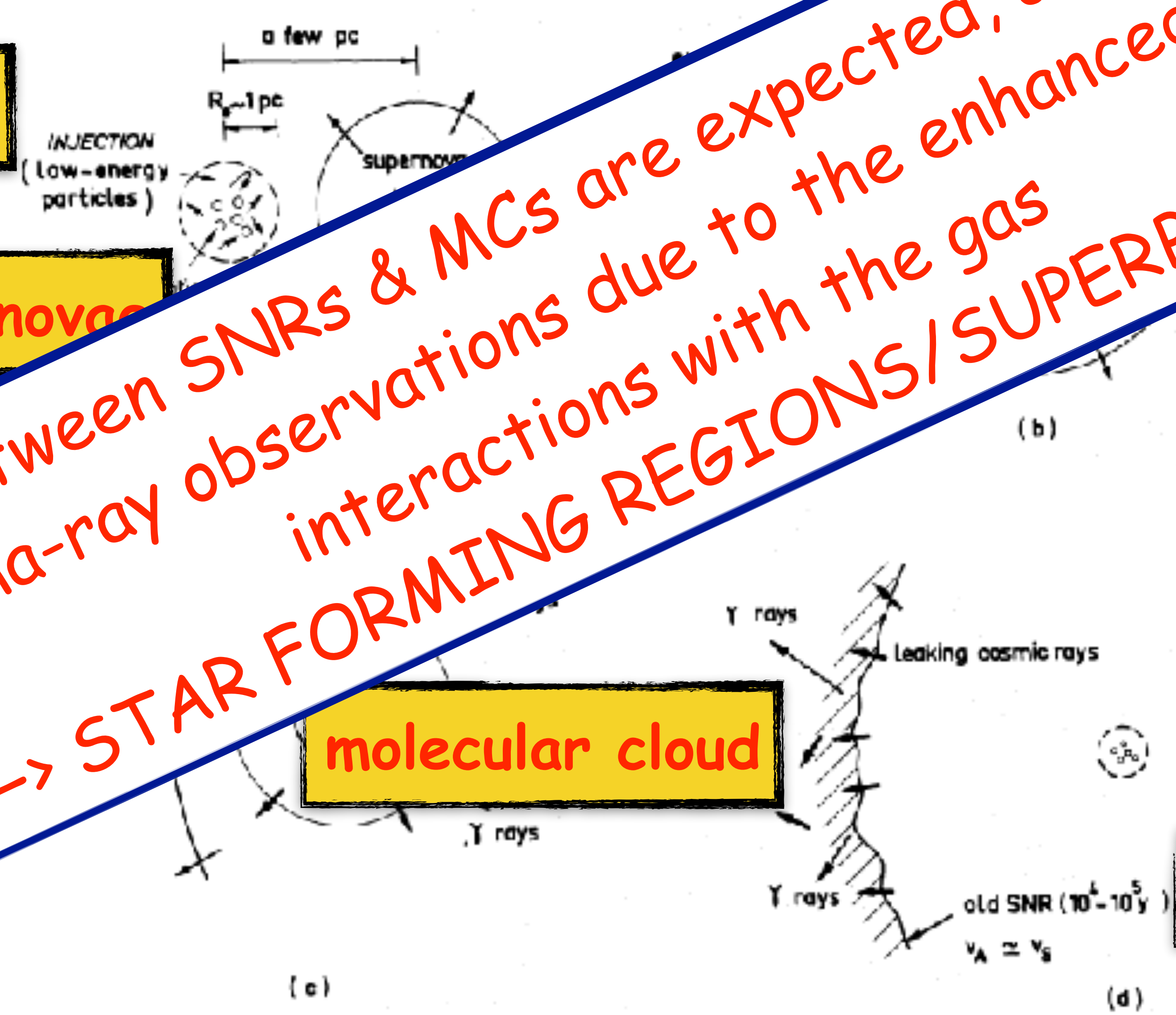


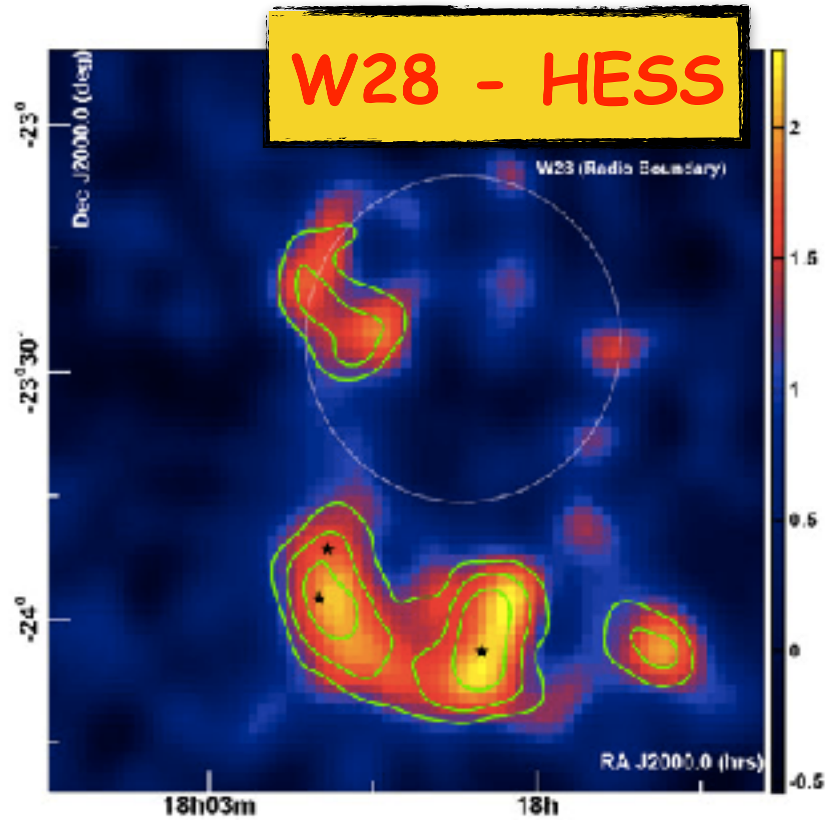
associations between SNRs & MCs are expected, and are ideal targets for gamma-ray observations due to the enhanced rate of CR interactions with the gas

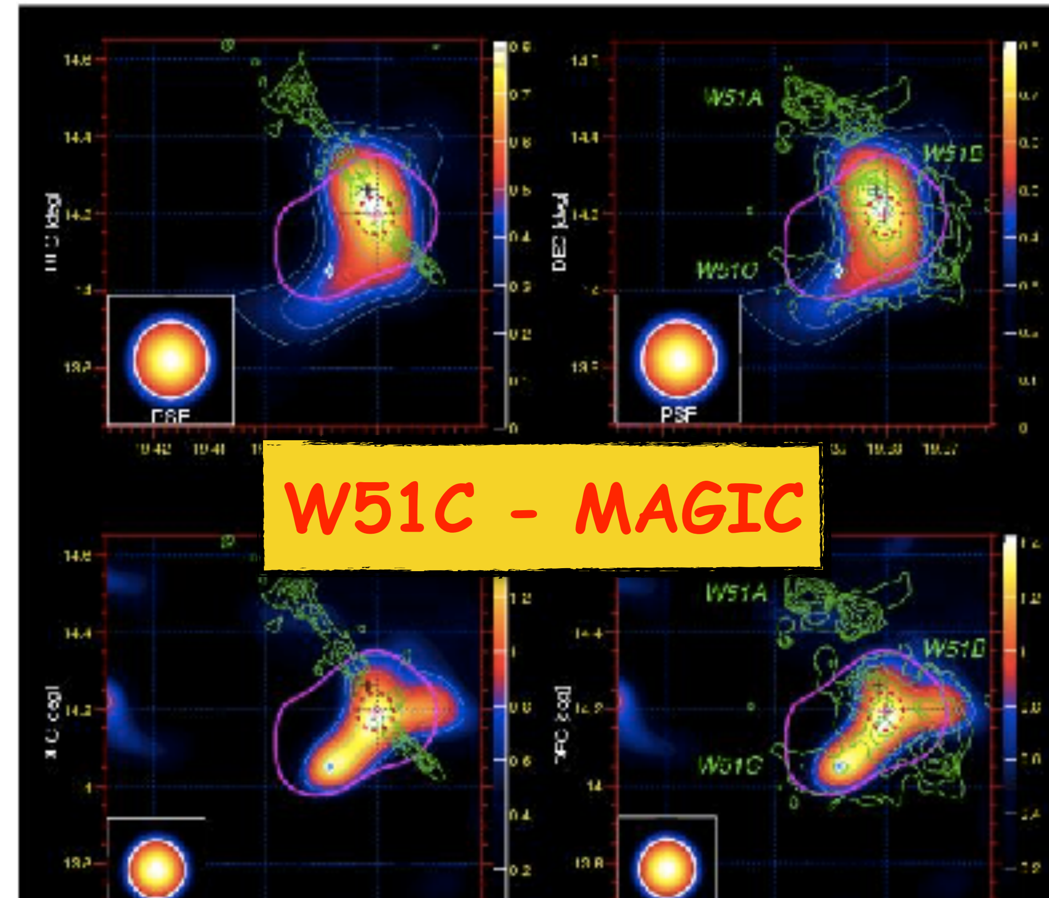
--> STAR FORMING REGIONS/SUPERBUBBLES

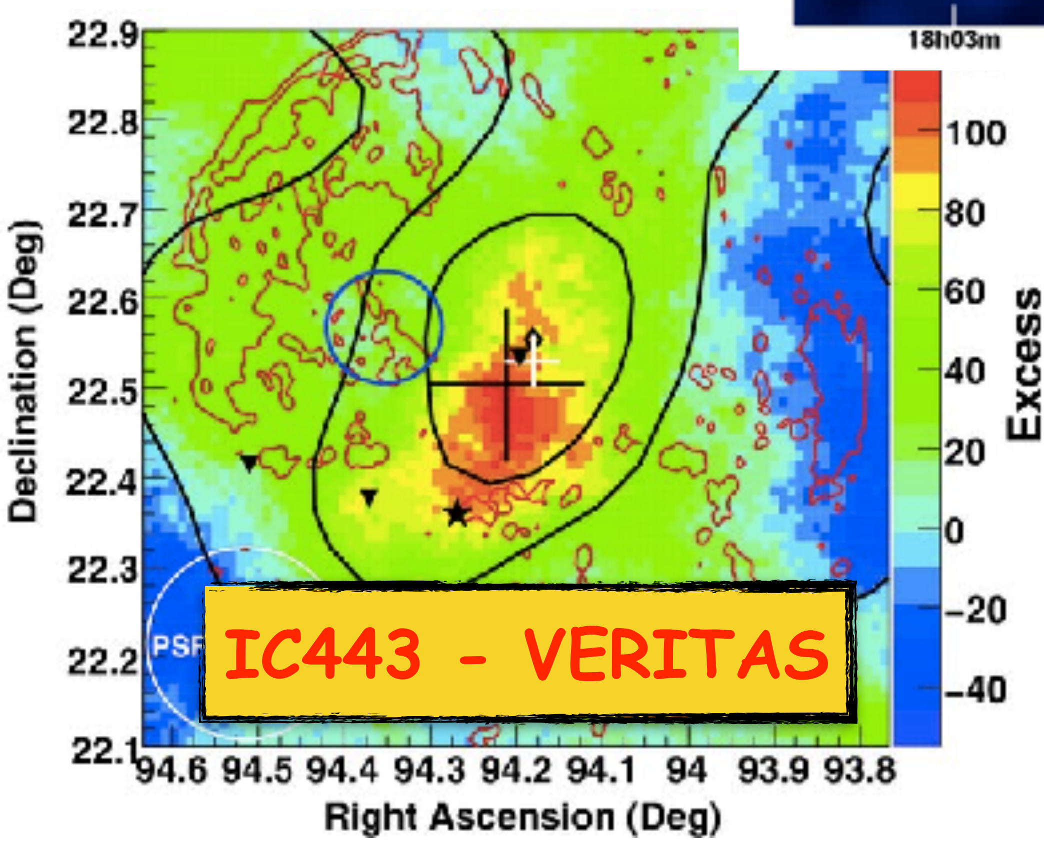
Black & Fazio 1973

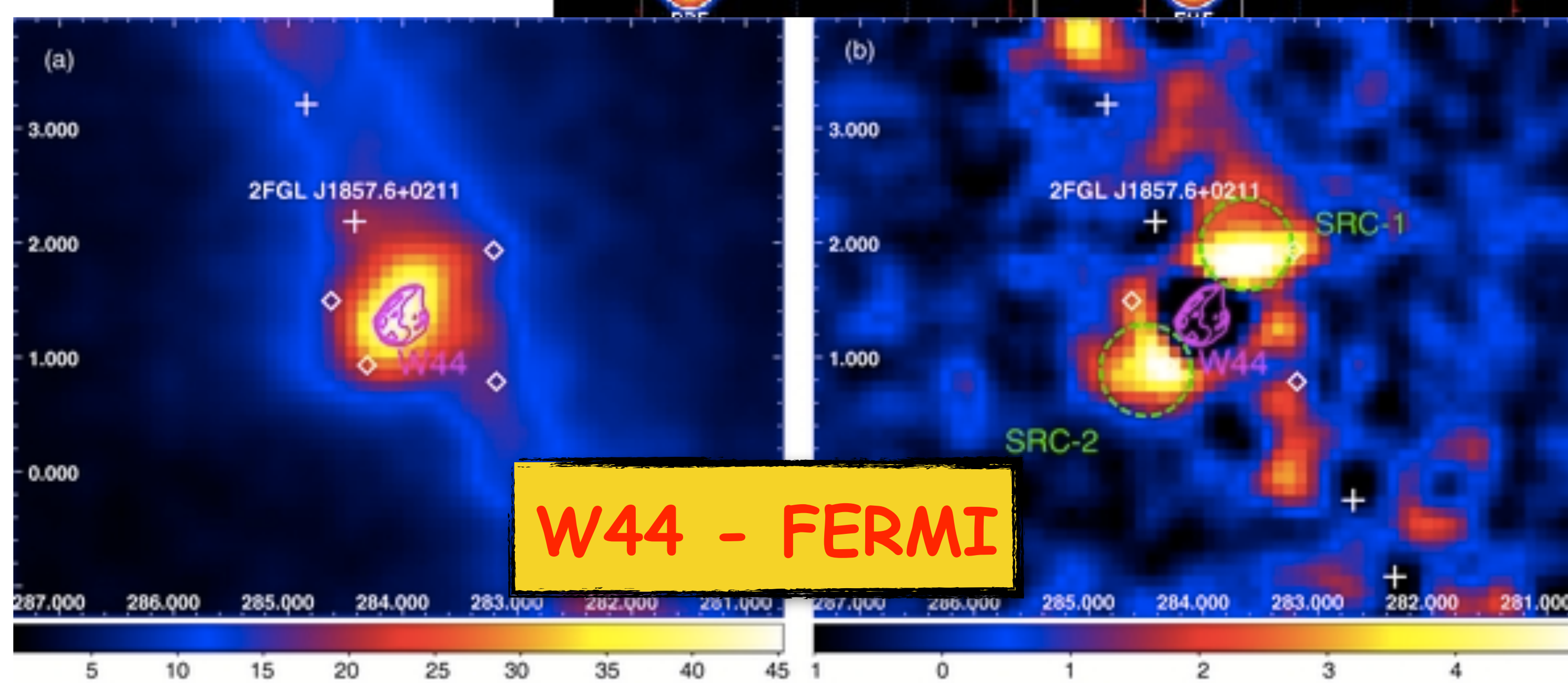
SNR/MC associations in γ-rays

spatial correlation between γ-ray and CO emission





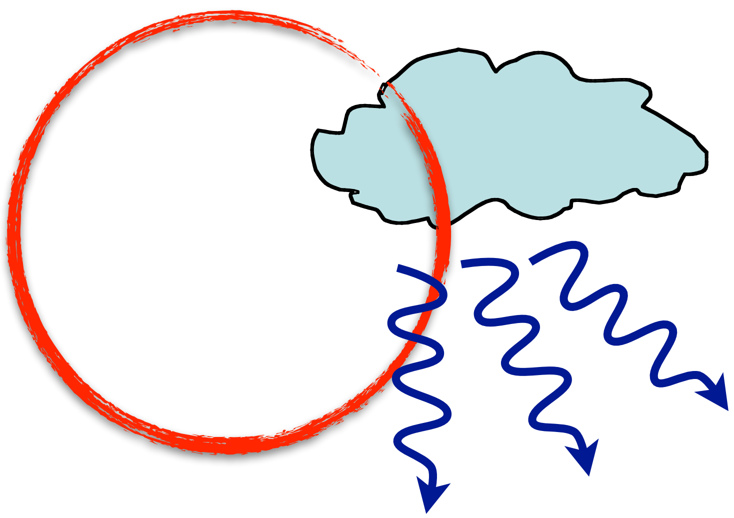




2 scenarios: interaction or runaway CRs?

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

shock/MC interaction



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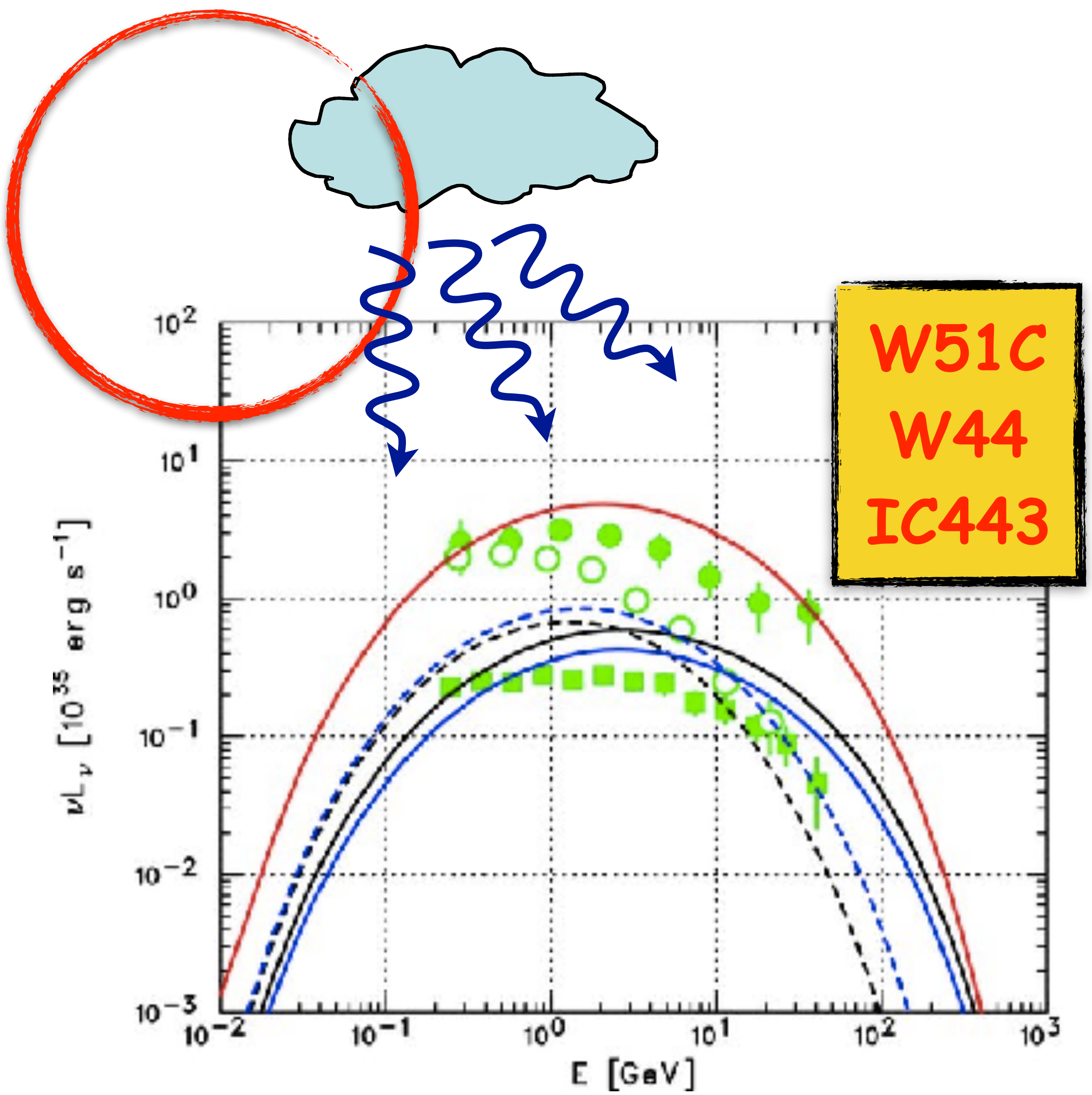
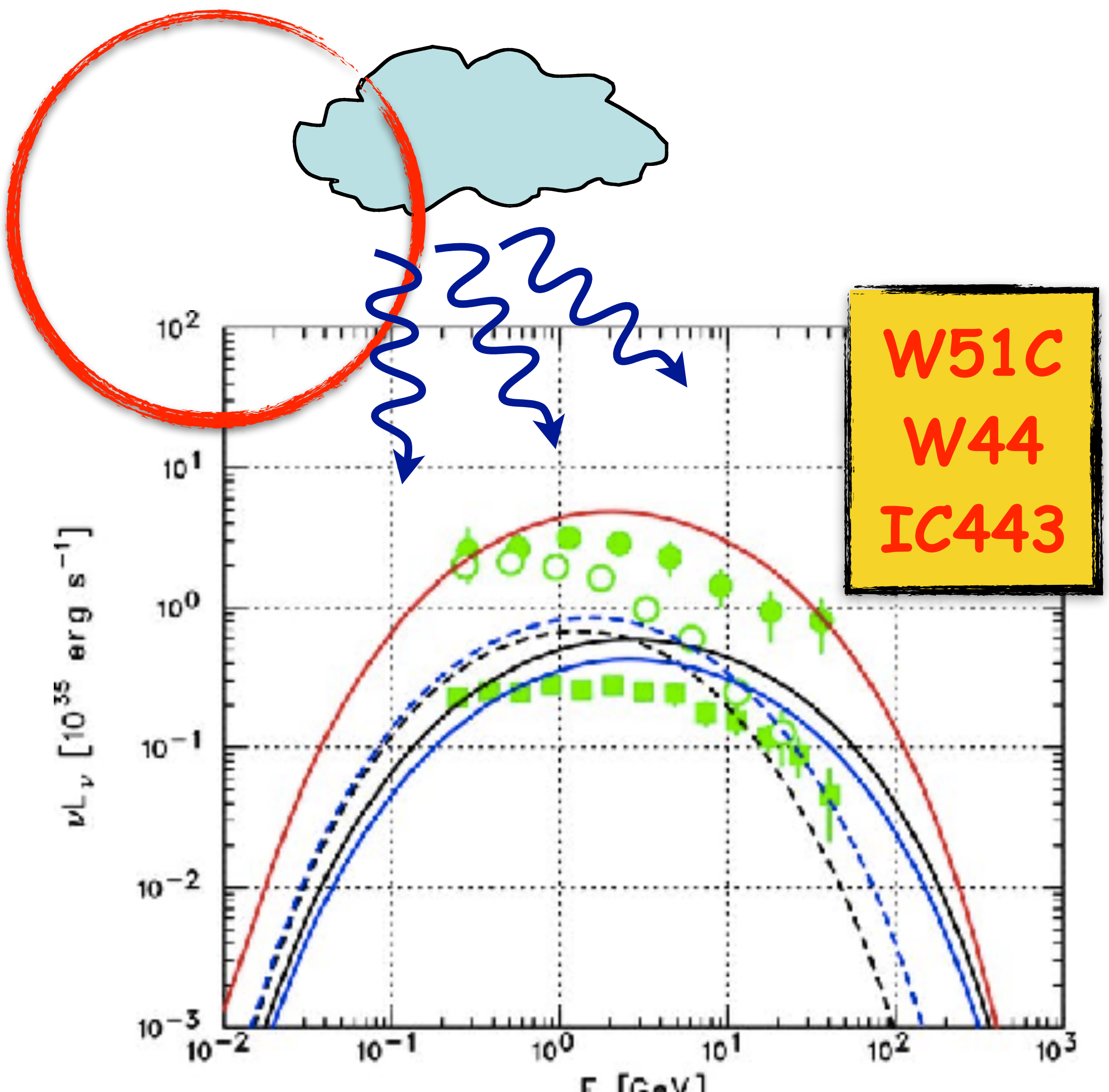


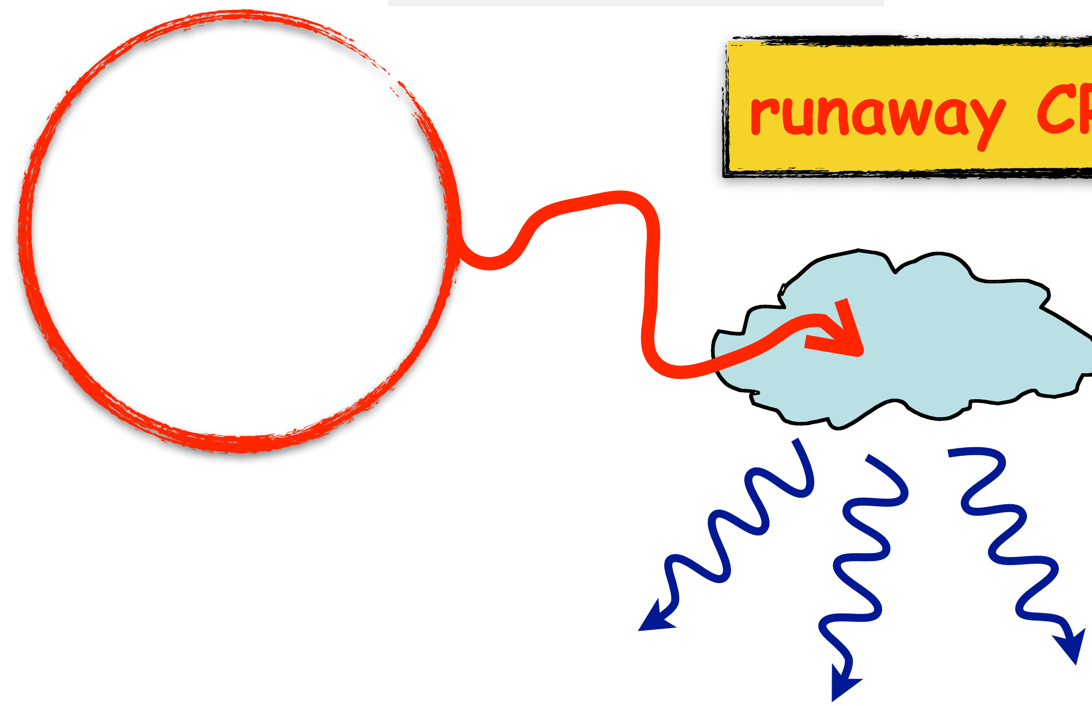
2 scenarios: interaction or runaway CRs?

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

shock/MC interaction

runaway CRs





Aharonian&Atoyan 1996, SG&Aharonian 2007, SG+ 2009,2010, Nava&SG 2013

2 scenarios: interaction or runaway CRs?

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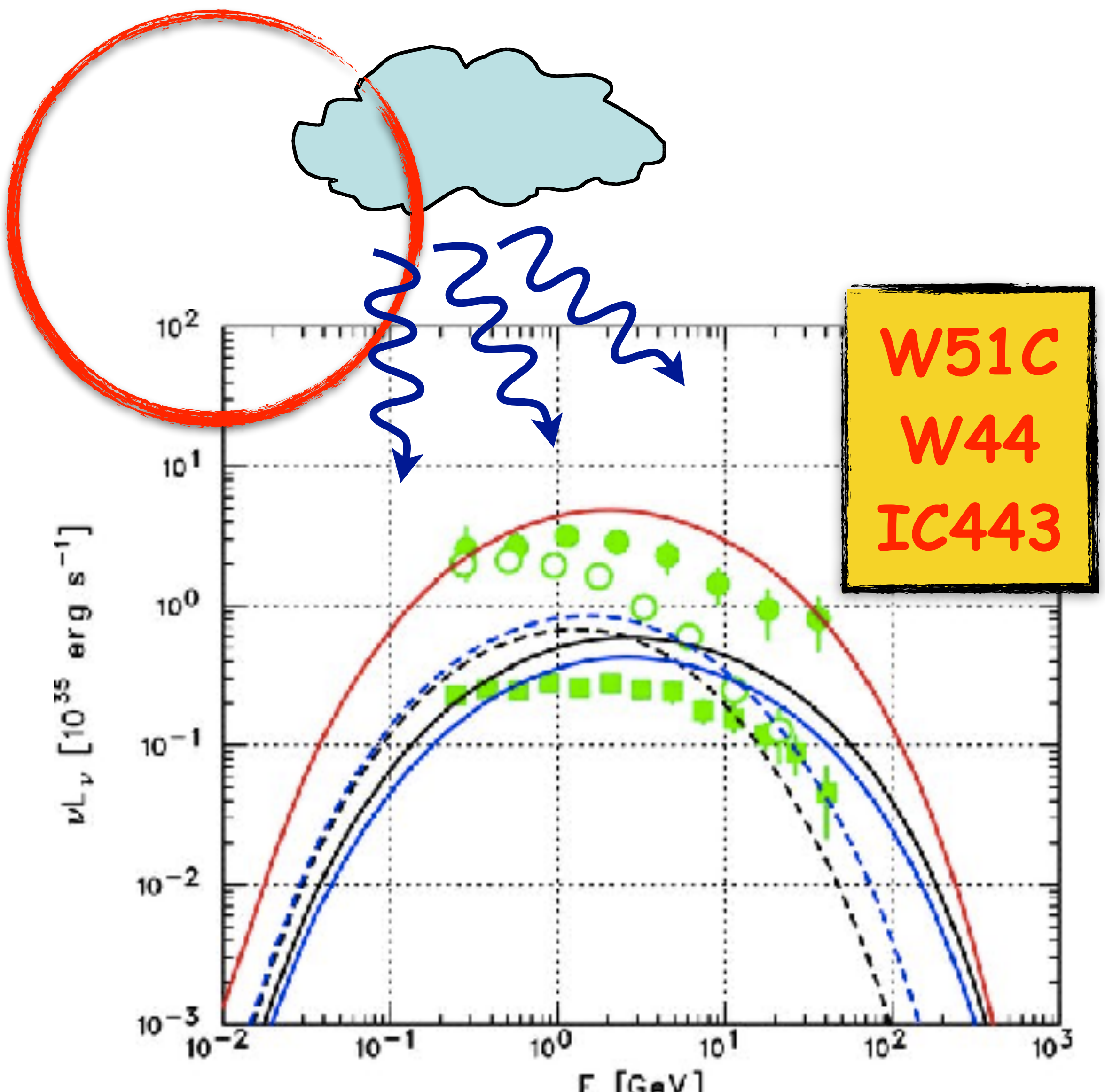
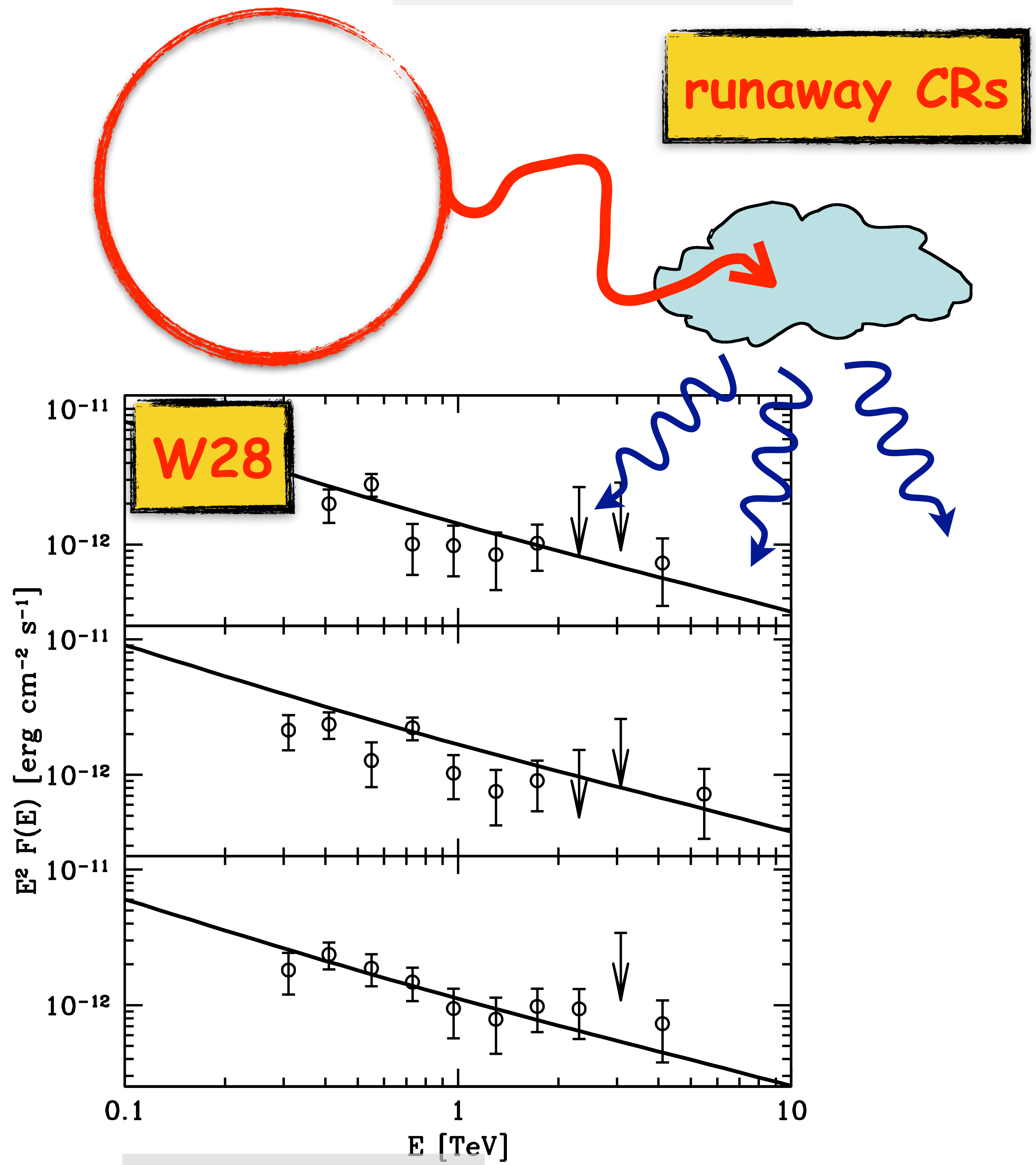


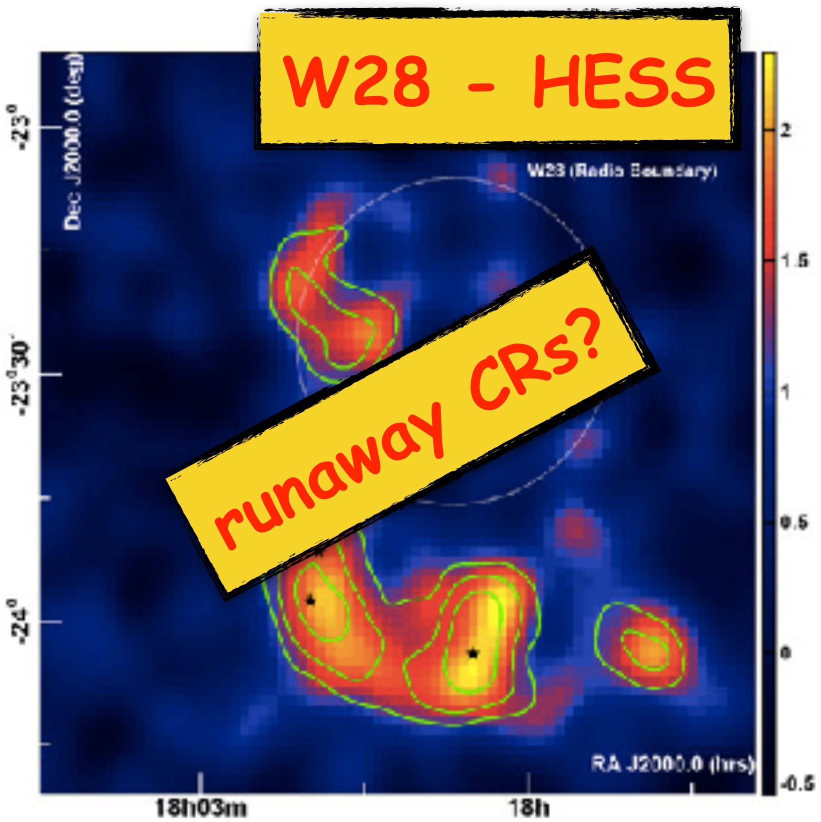
runaway CRs

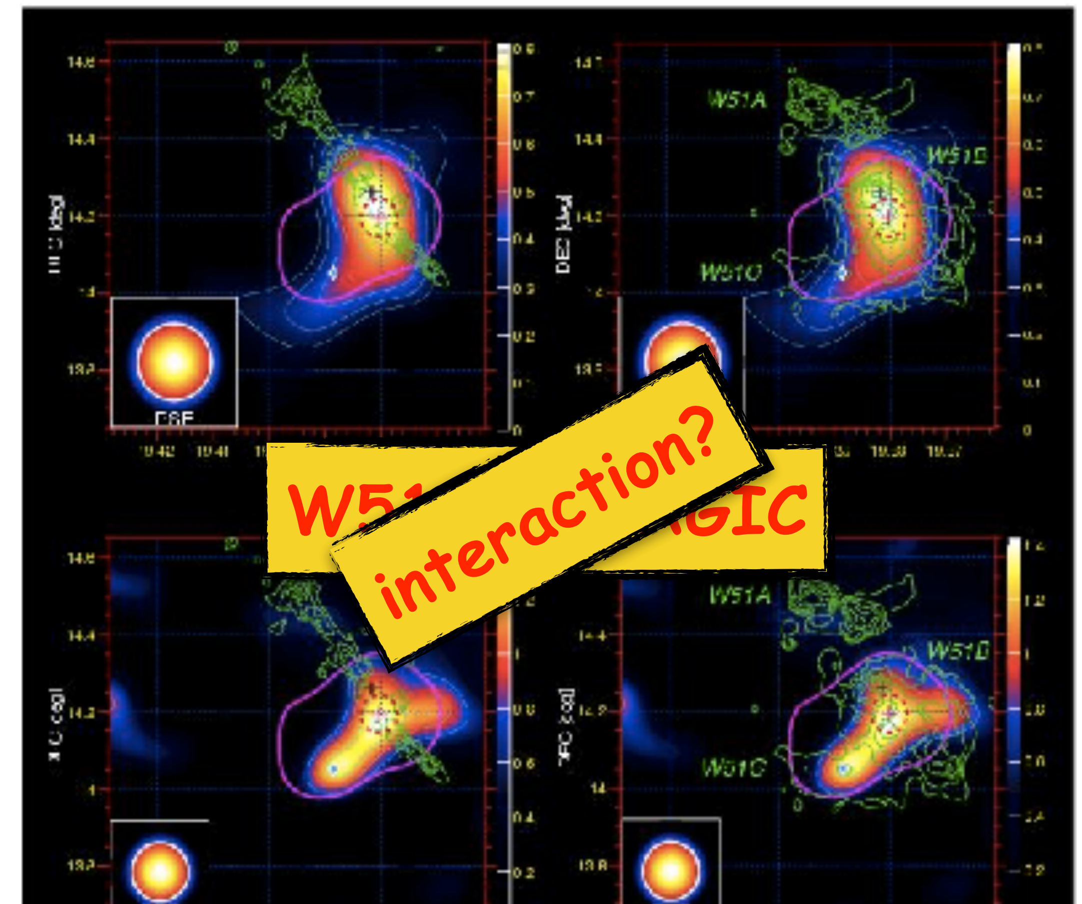


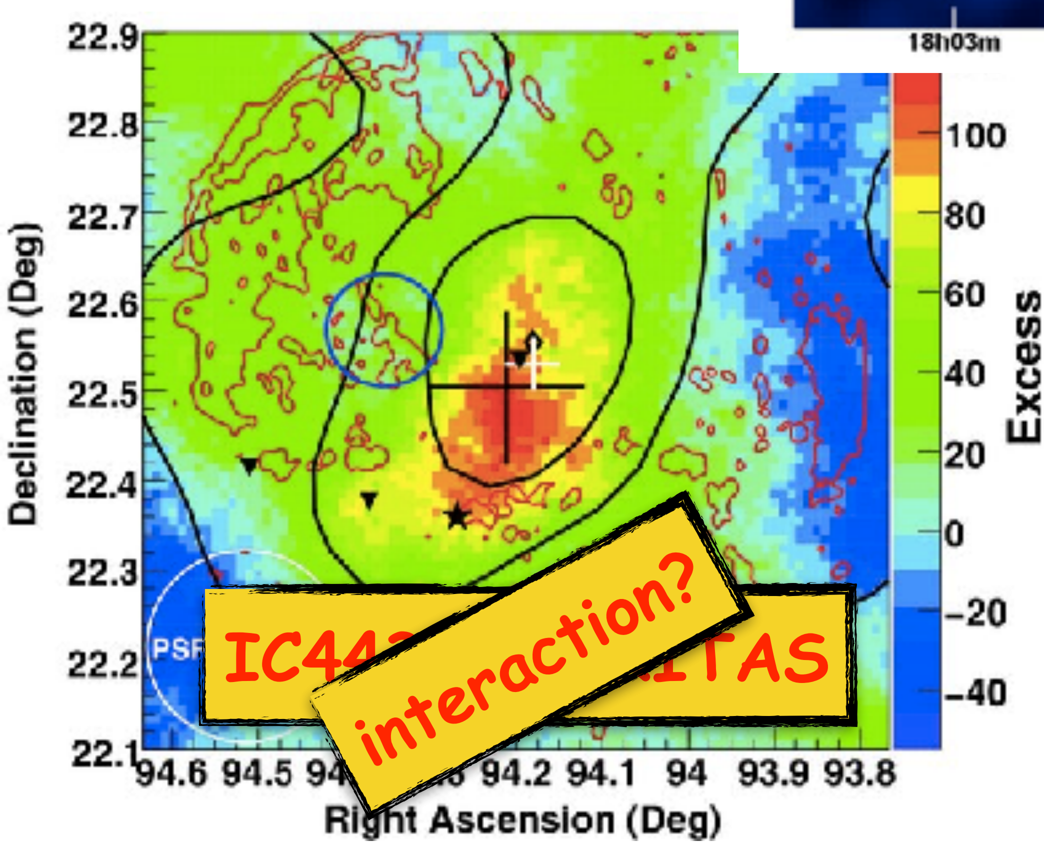
Aharonian&Atoyan 1996, SG&Aharonian 2007, SG+ 2009,2010, Nava&SG 2013

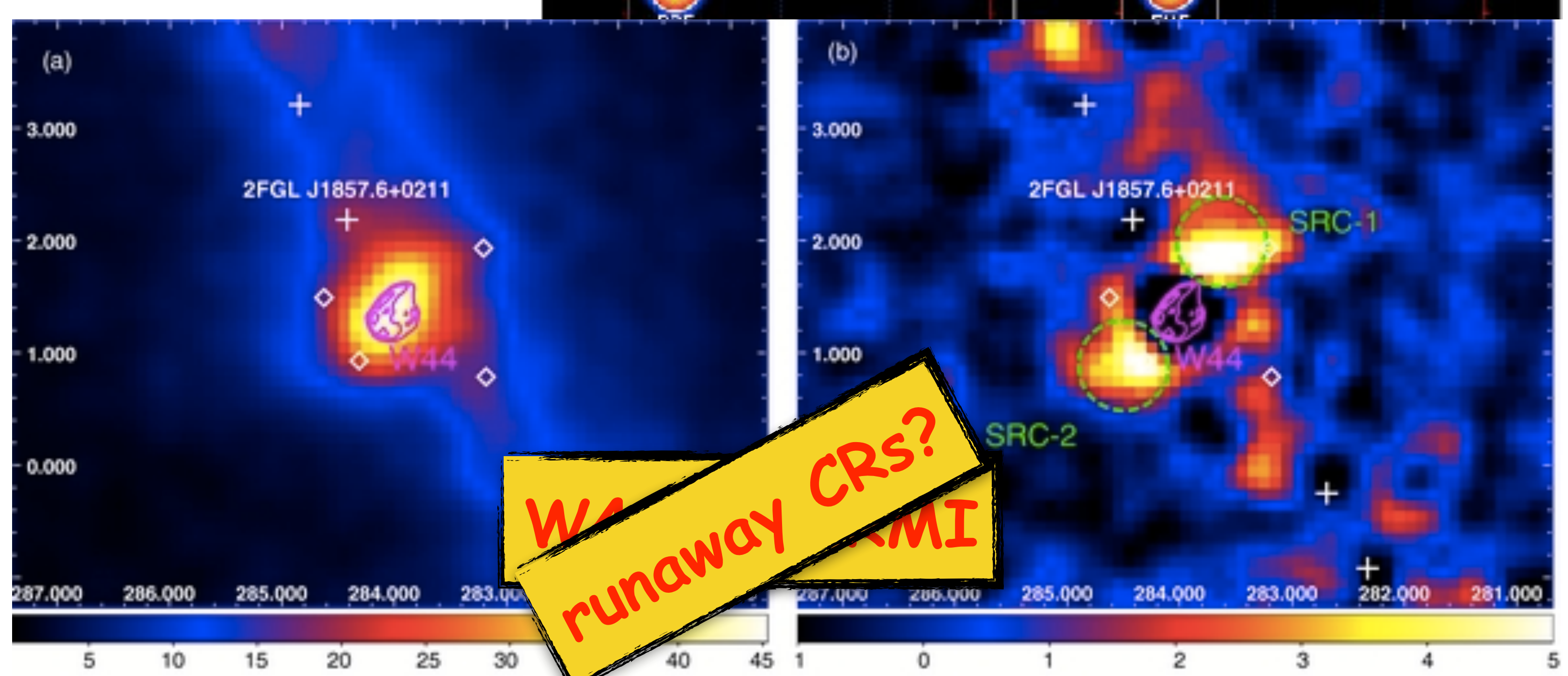
Interaction versus escape: who's who?

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



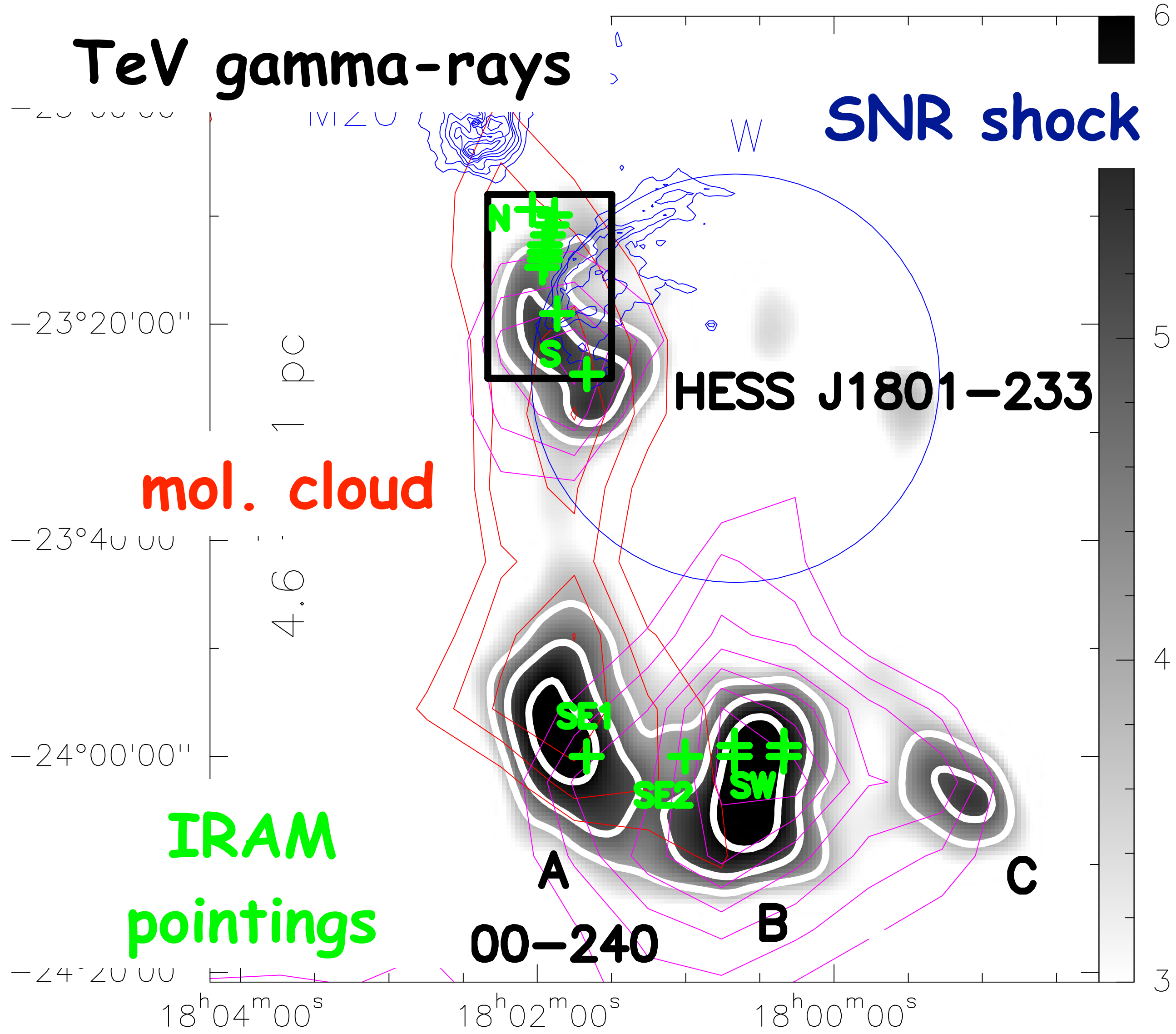






W28

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



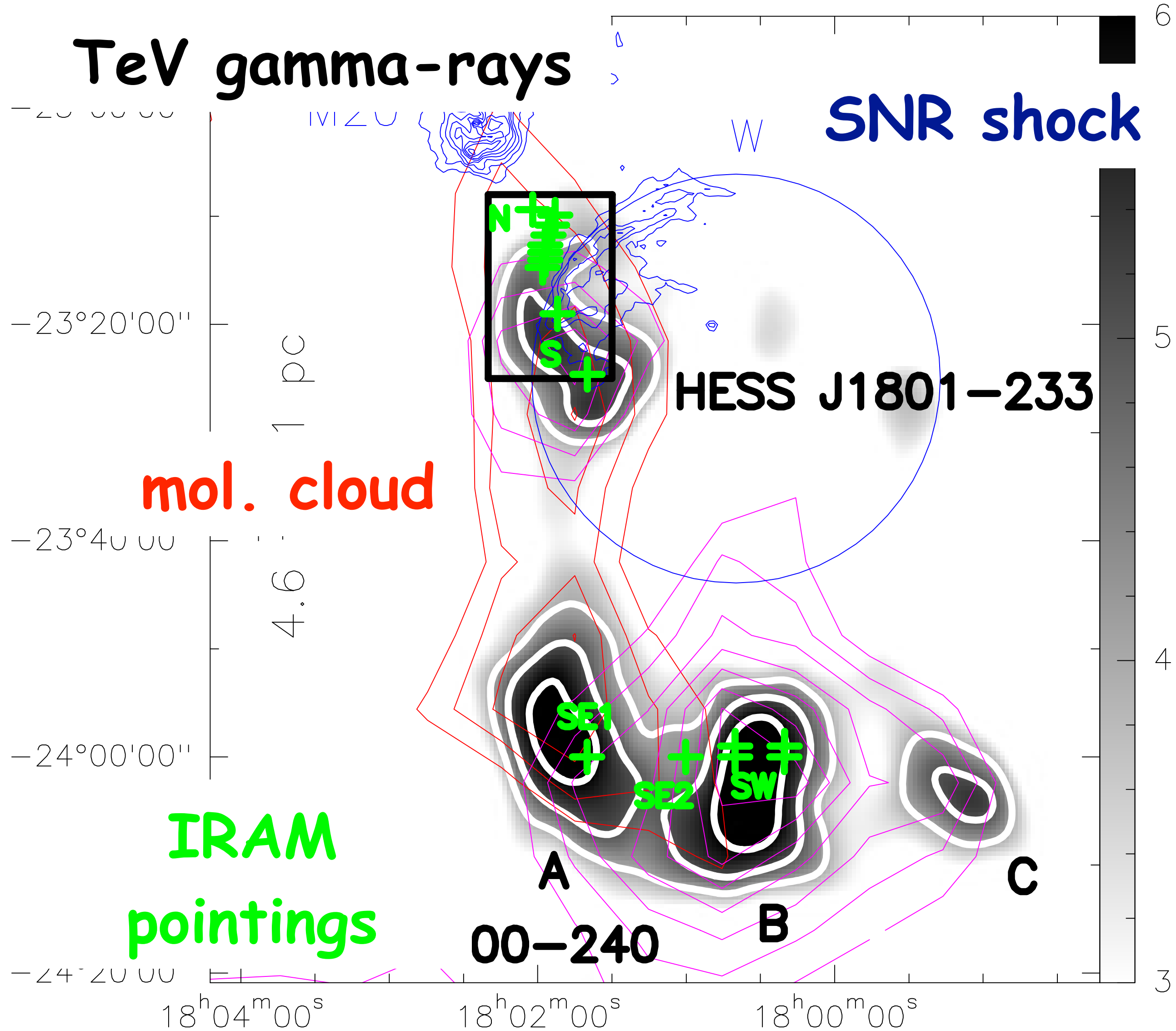
TeV + gas -> multi-TeV CR protons

DCO+/HCO+

W28

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

TeV gamma-rays



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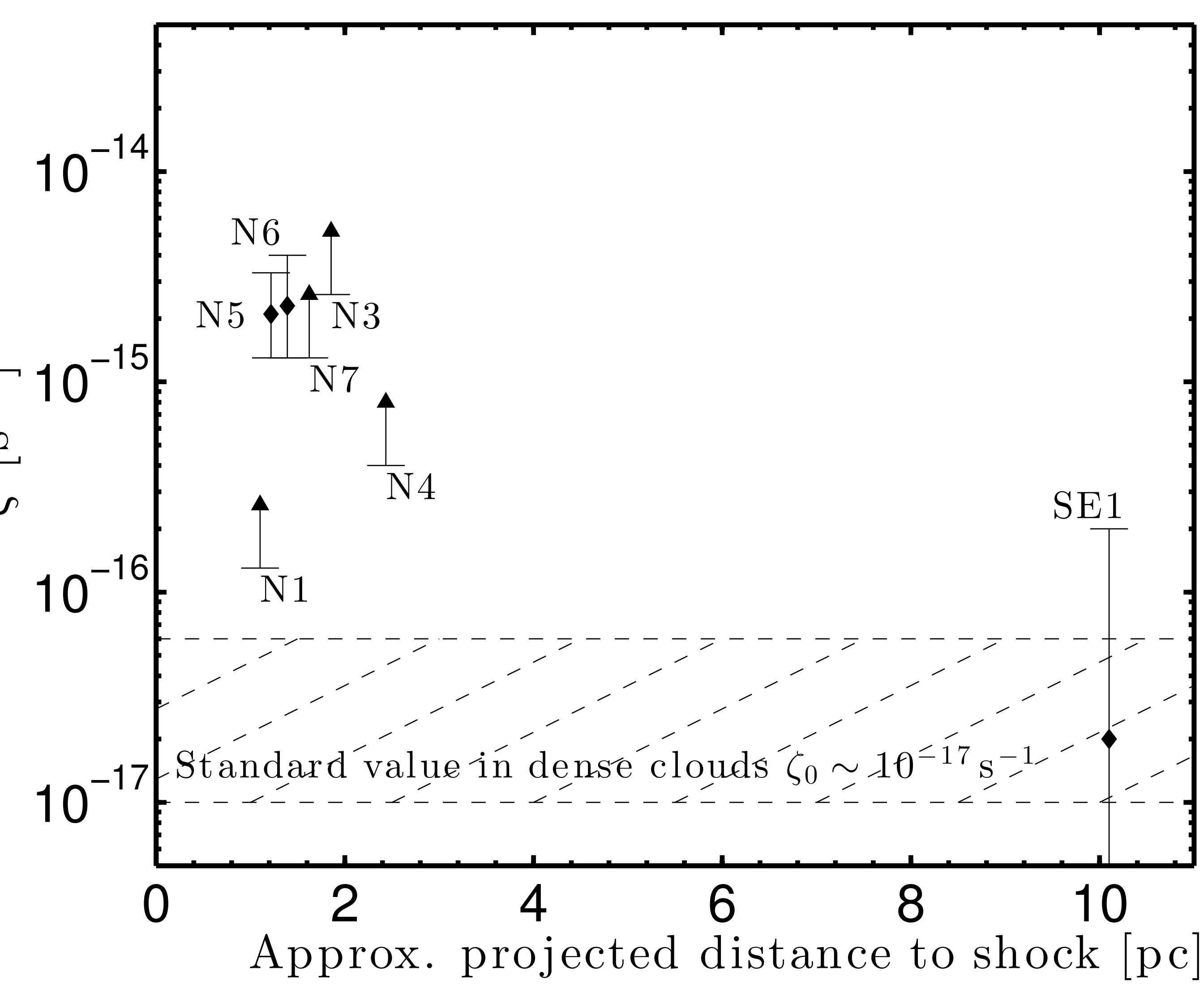
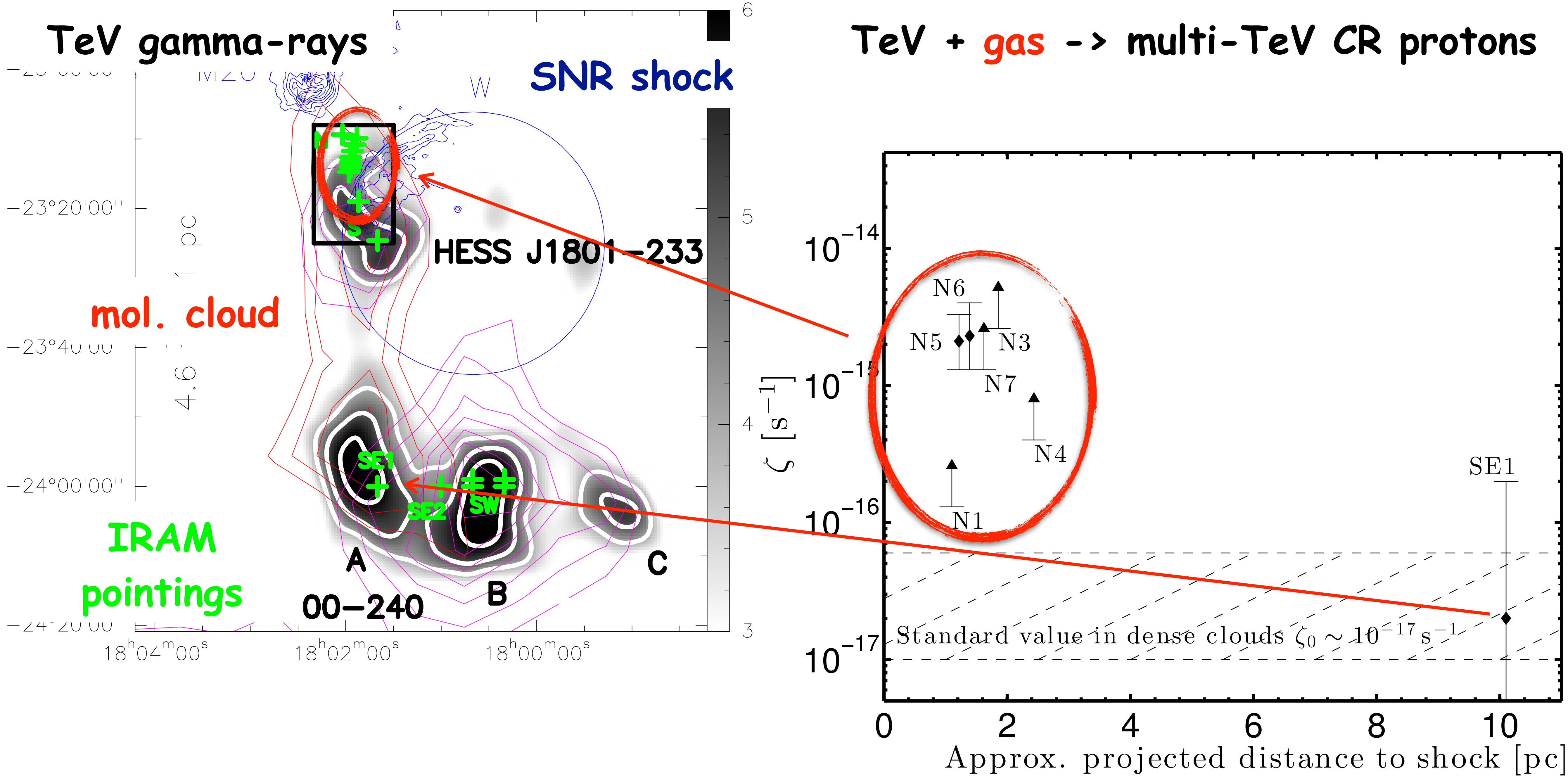


W28

DCO+/HCO+

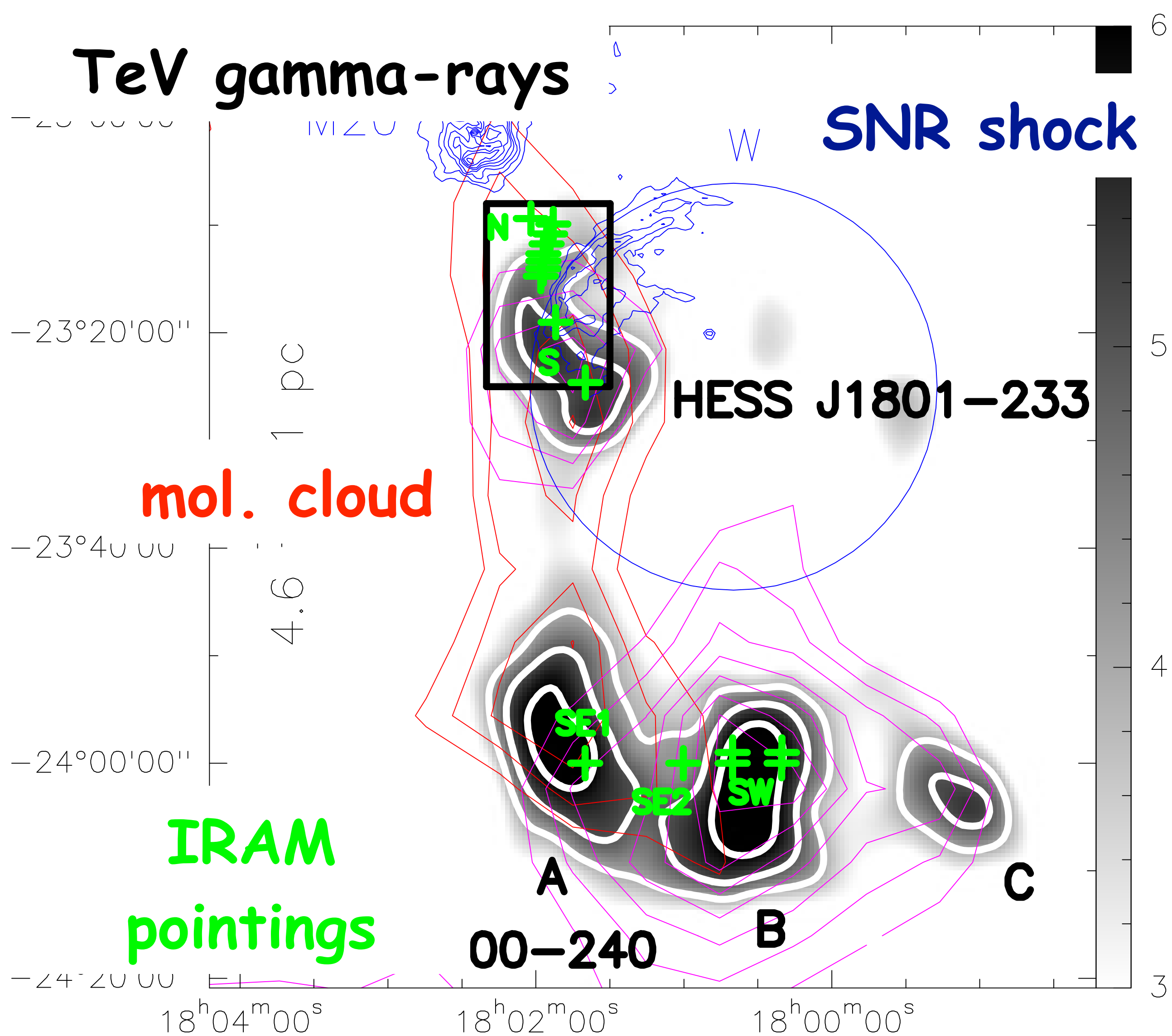
Vaupré, Hily-Blant, Ceccarelli, Dubus, SG, Montmerle (2014)



DCO^+/HCO^+

W28

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



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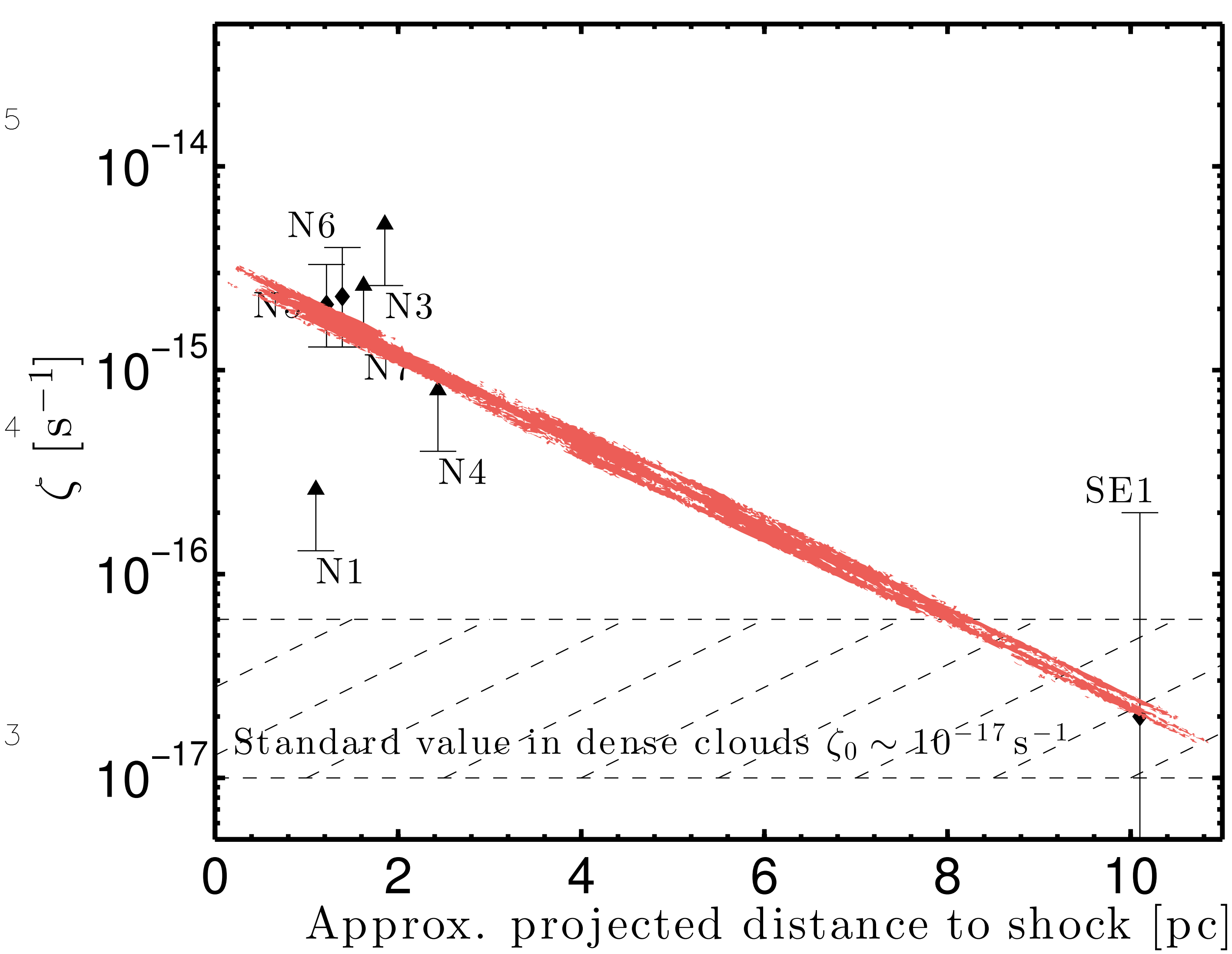

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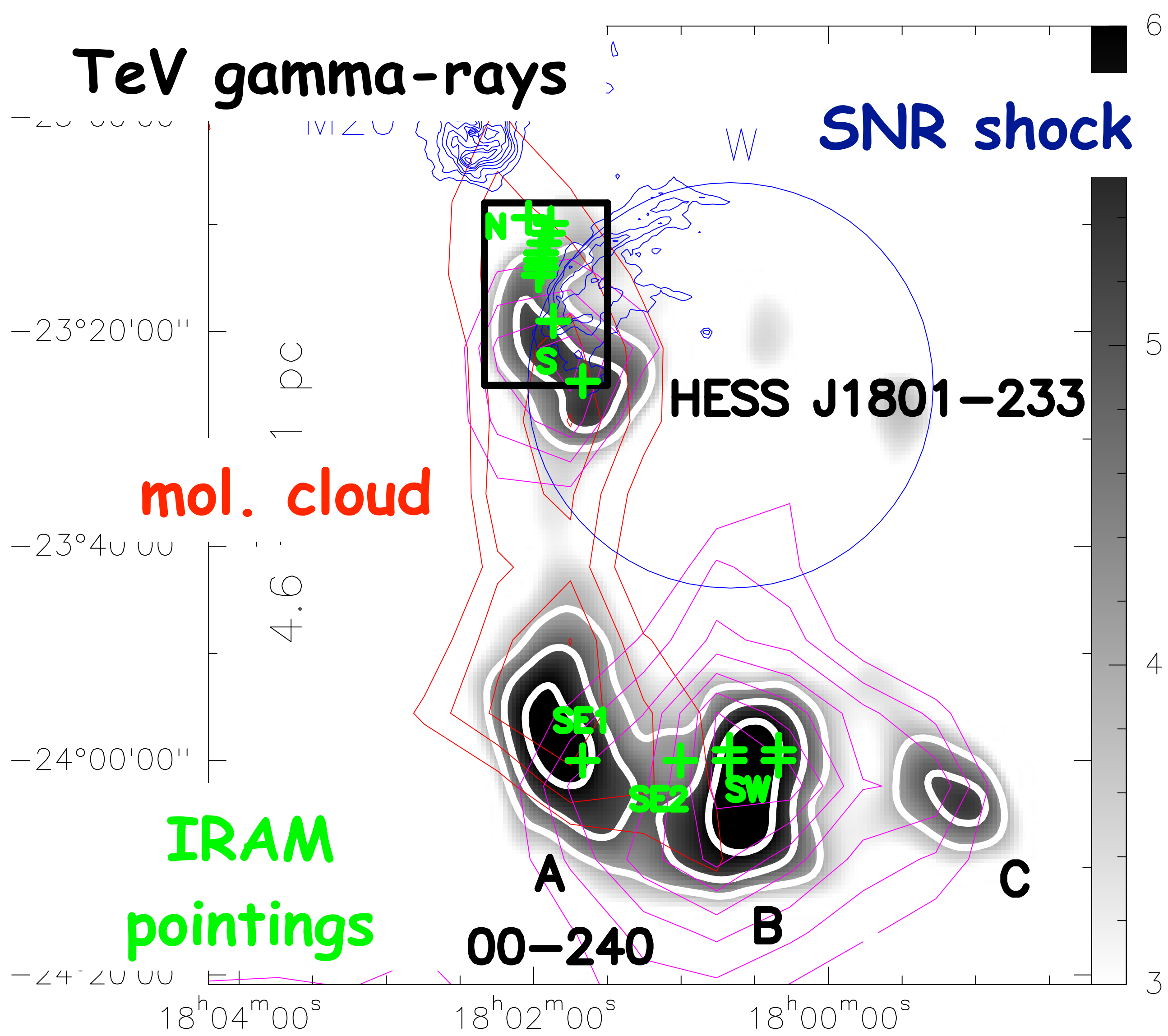
TeV gamma-rays



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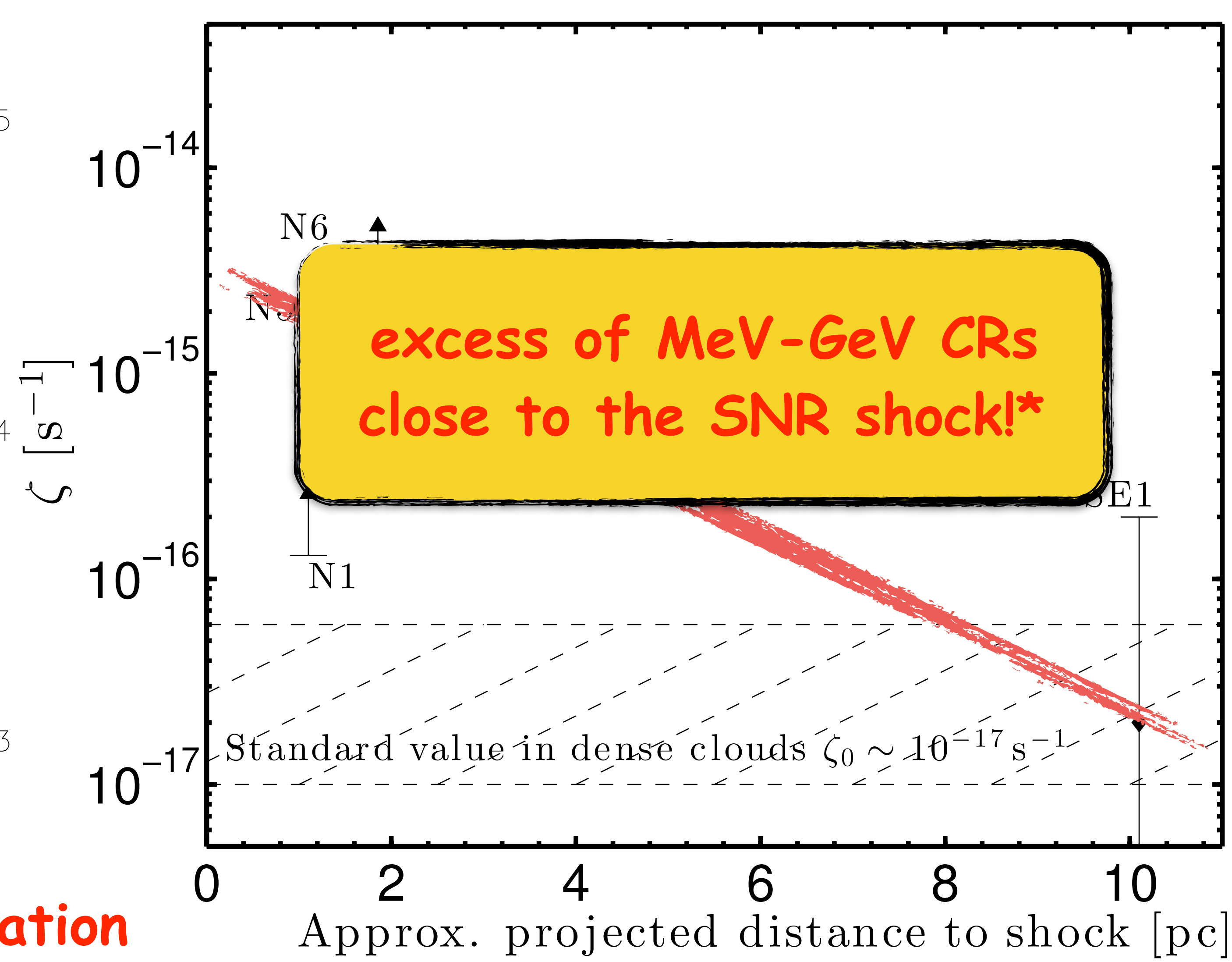

* also CR electrons contribute to ionization

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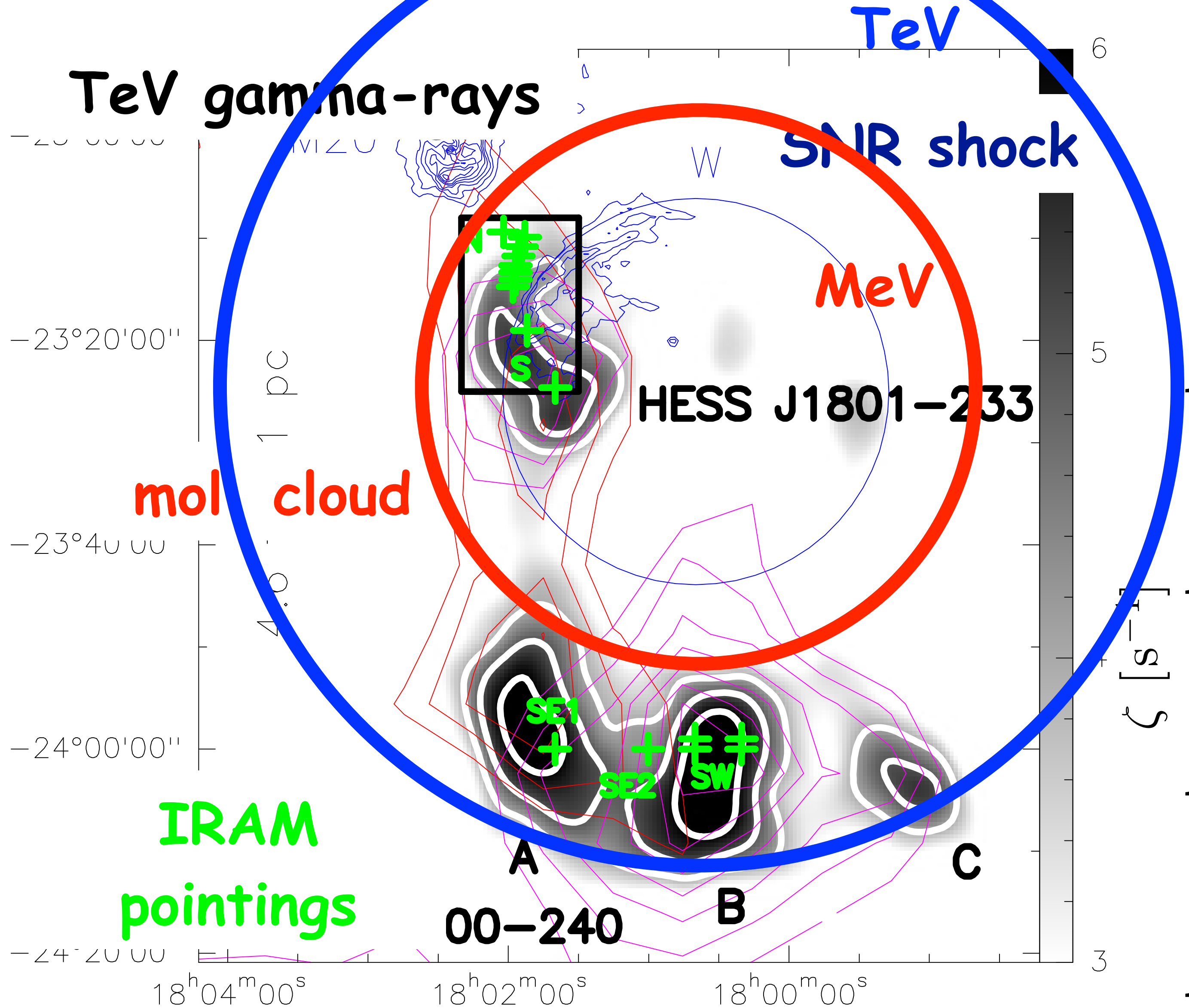
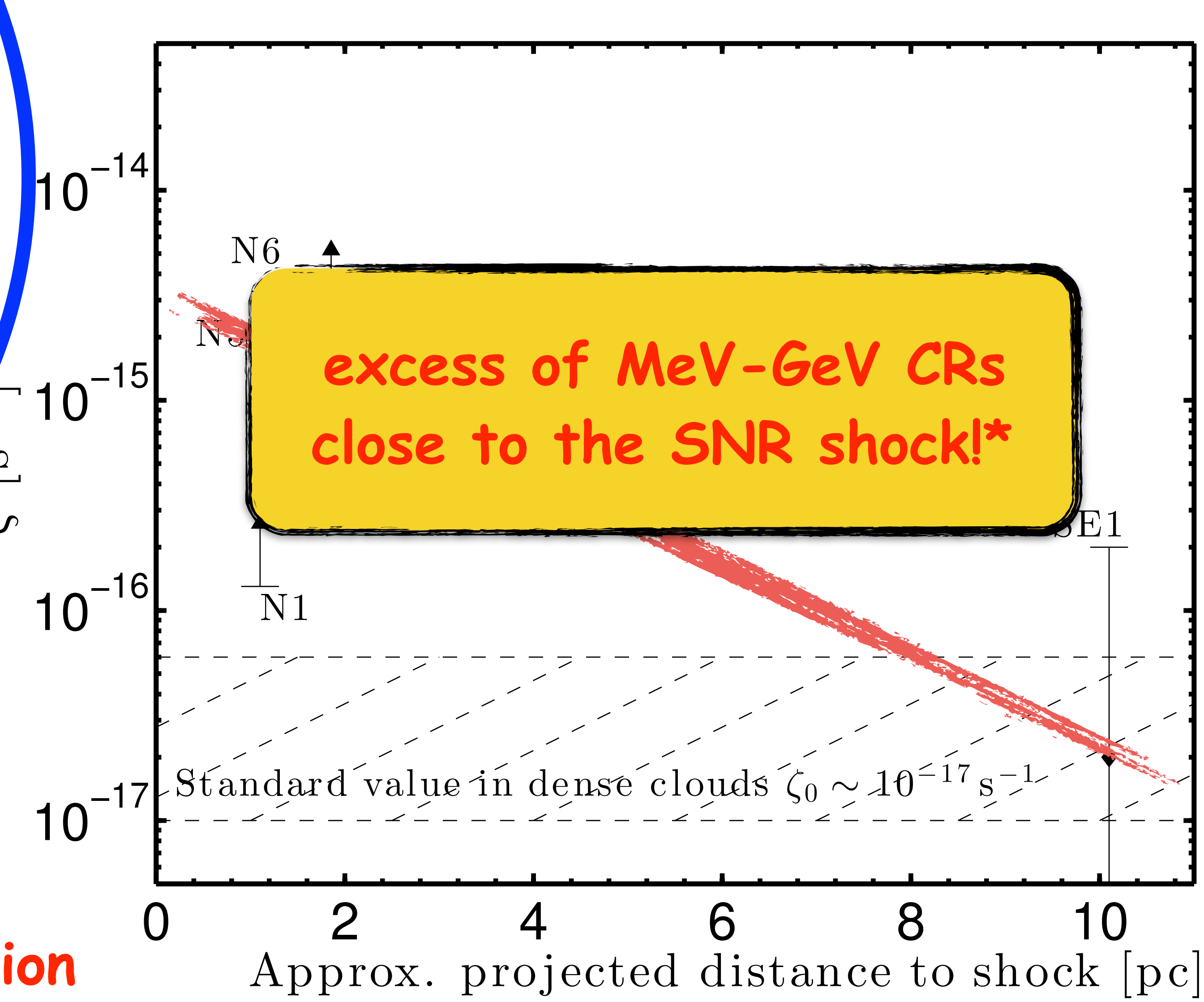
W28

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

TeV gamma-rays

TeV + gas -> multi-TeV CR protons





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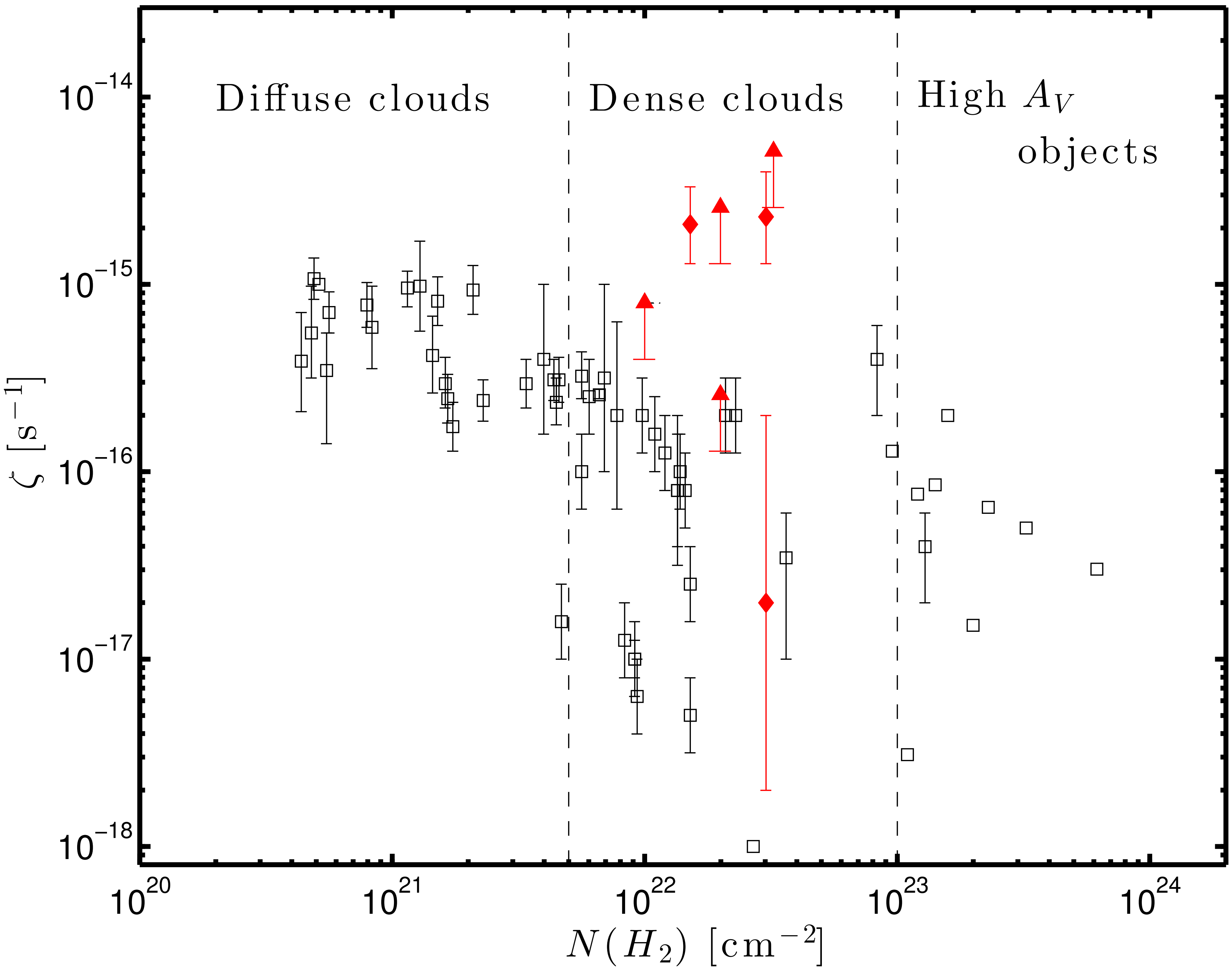
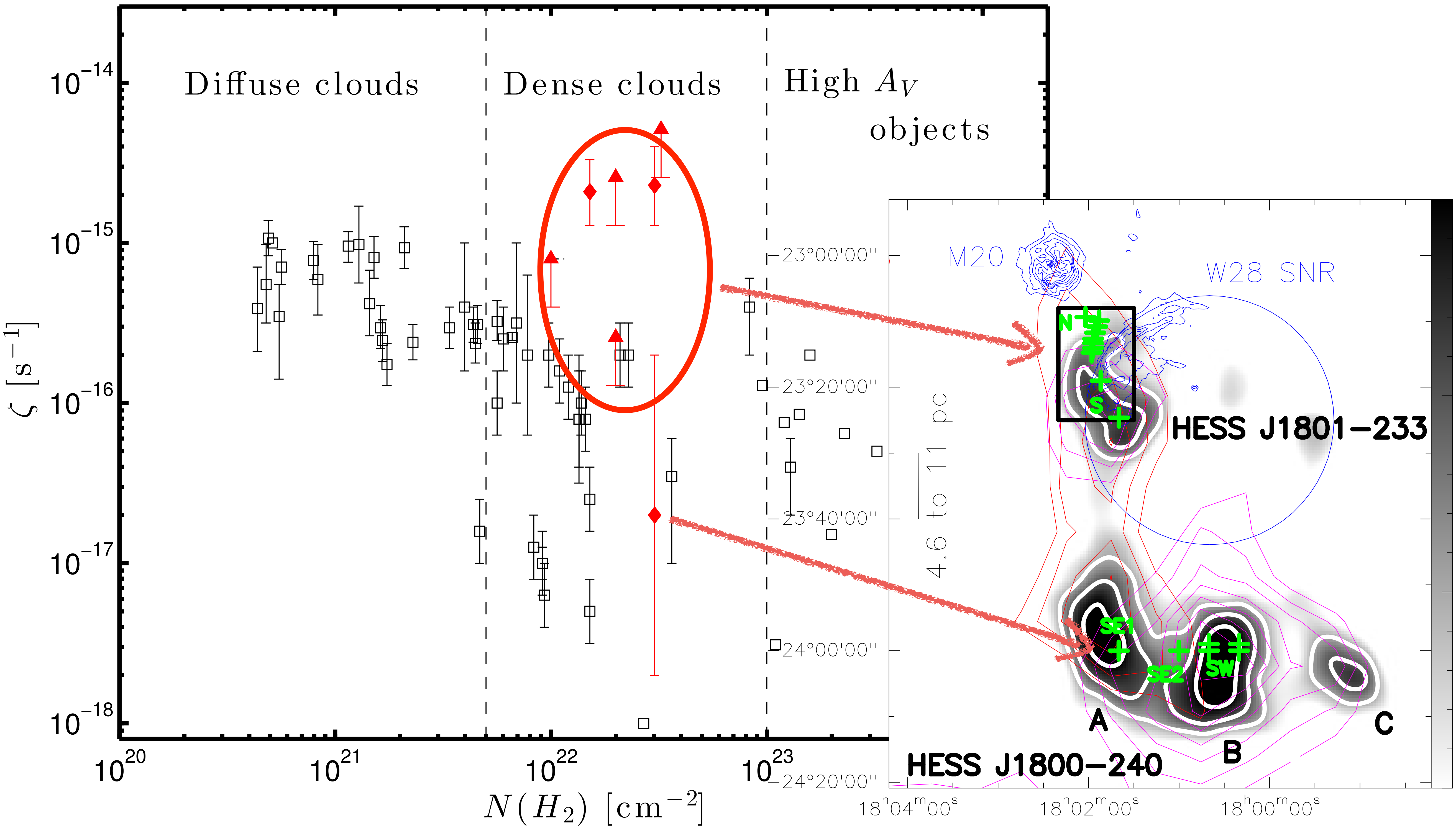
CR ionization rate in MCs next to SNRs

Vaupré et al 2014



CR ionization rate in MCs next to SNRs

Vaupré et al 2014



CR ionization rate in MCs next to SNRs

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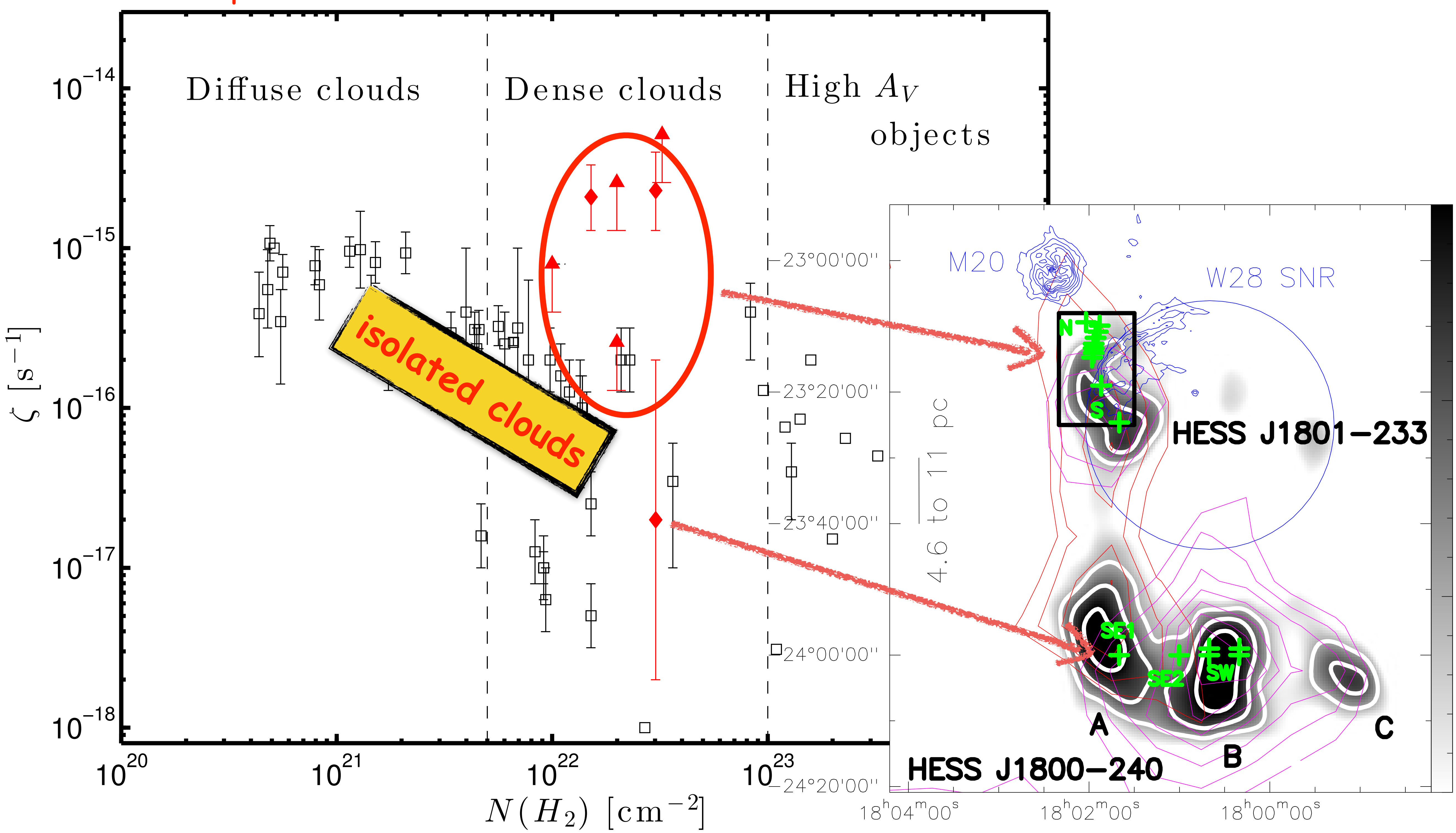
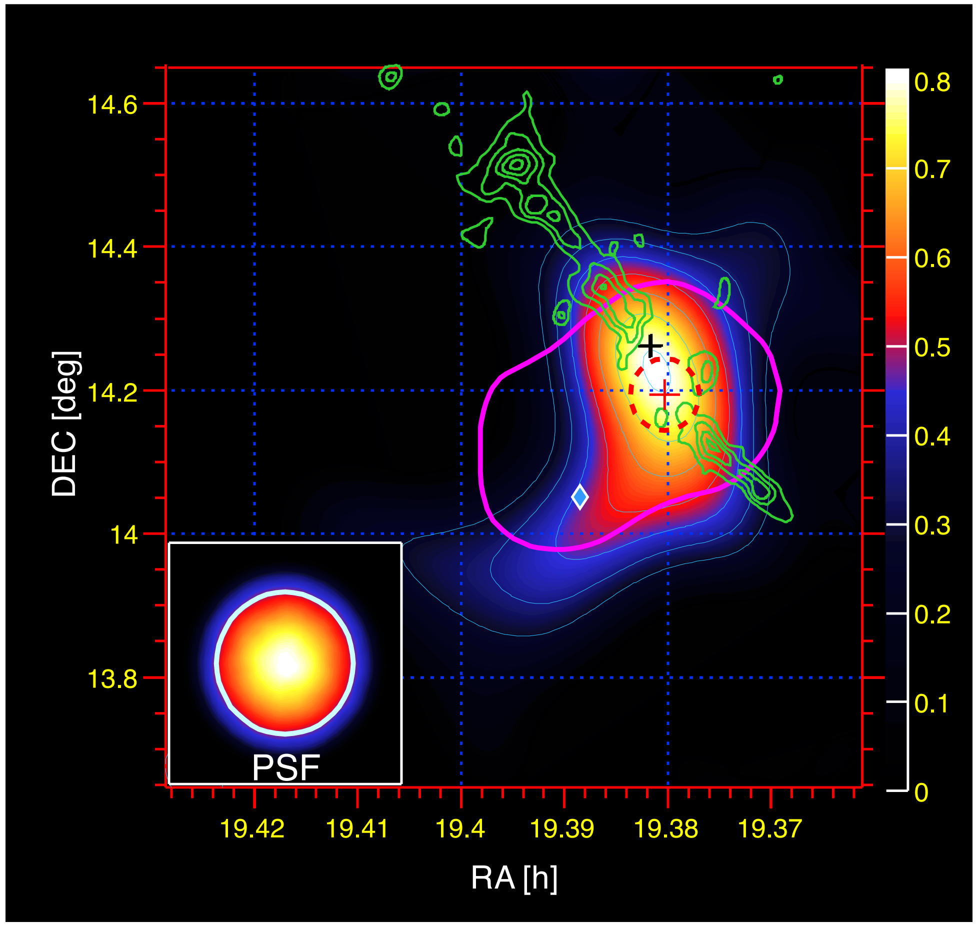


DCO+/HCO+

W51C

Aleksic+ 2012

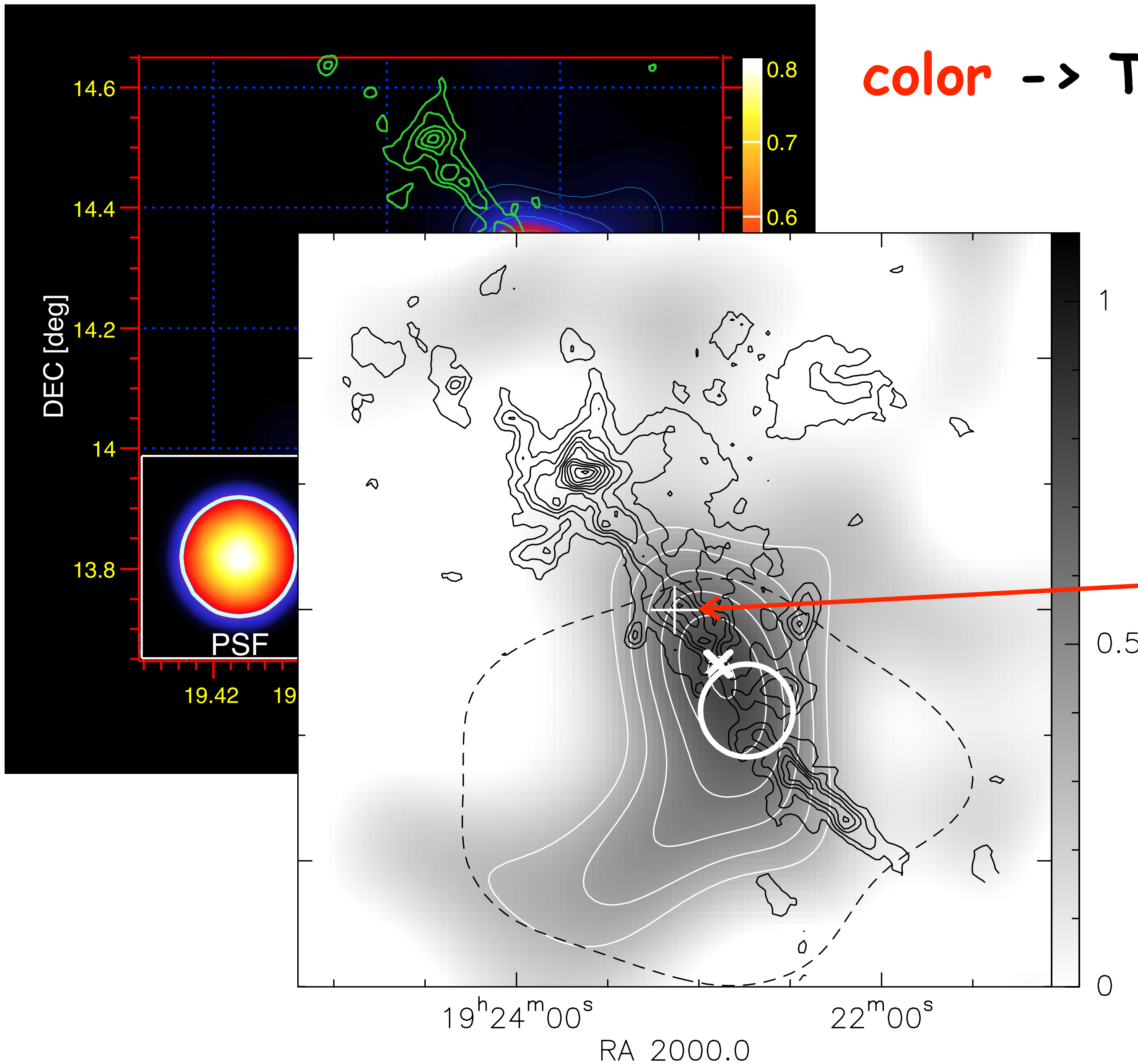


color -> TeV gamma-rays (MAGIC)
green -> CO

DCO+/HCO+

W51C

Aleksic+ 2012



color -> TeV gamma-rays (MAGIC)

green -> CO

white contours -> TeV gamma-rays

black contours -> CO

dashed -> Fermi

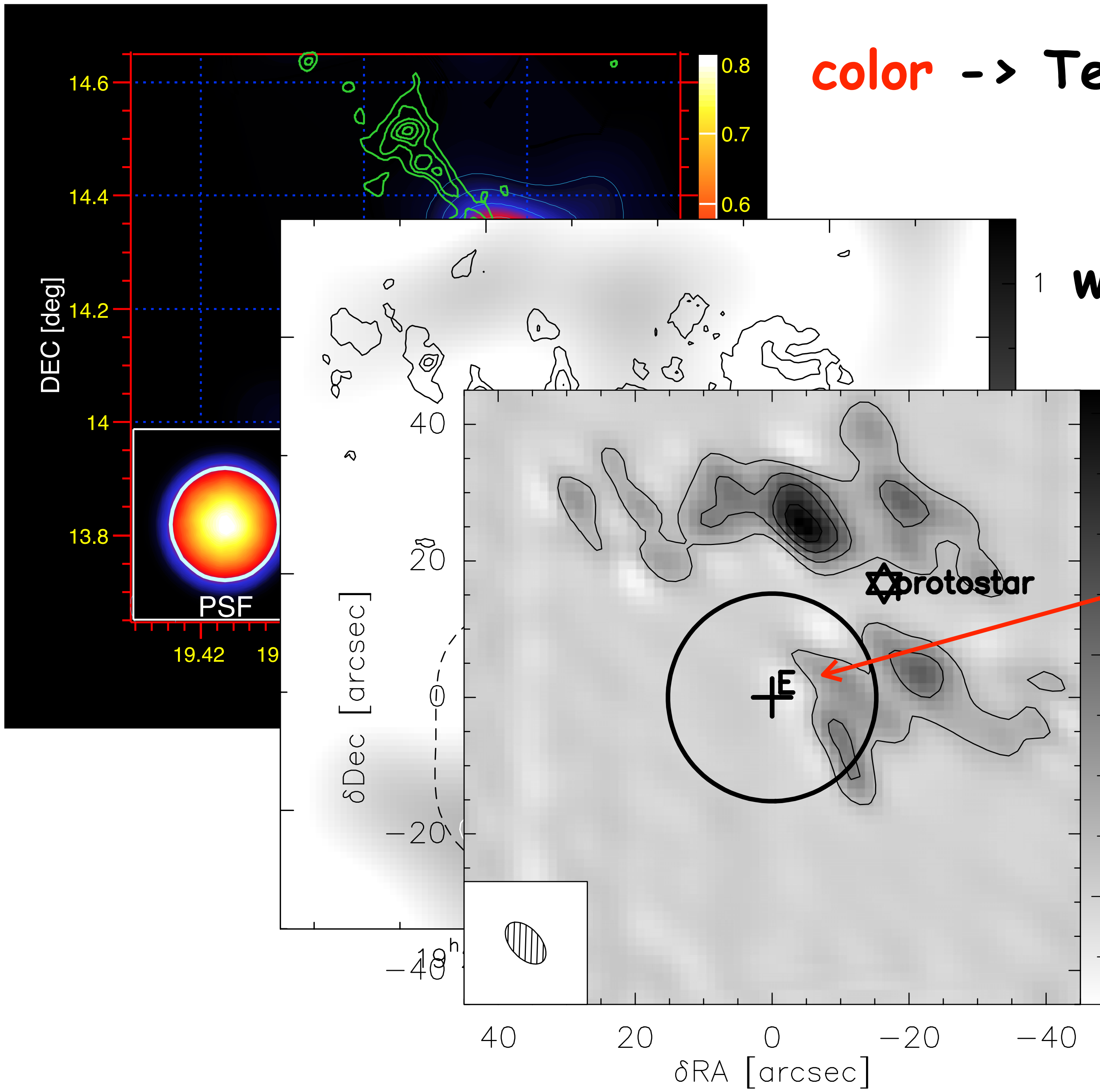
ζ_{CR} ~ few 10^{-15} s^{-1}

Ceccarelli+ 2011

DCO+/HCO+

W51C

Aleksic+ 2012



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ζ_{CR} ~ few 10^{-15} s^{-1}

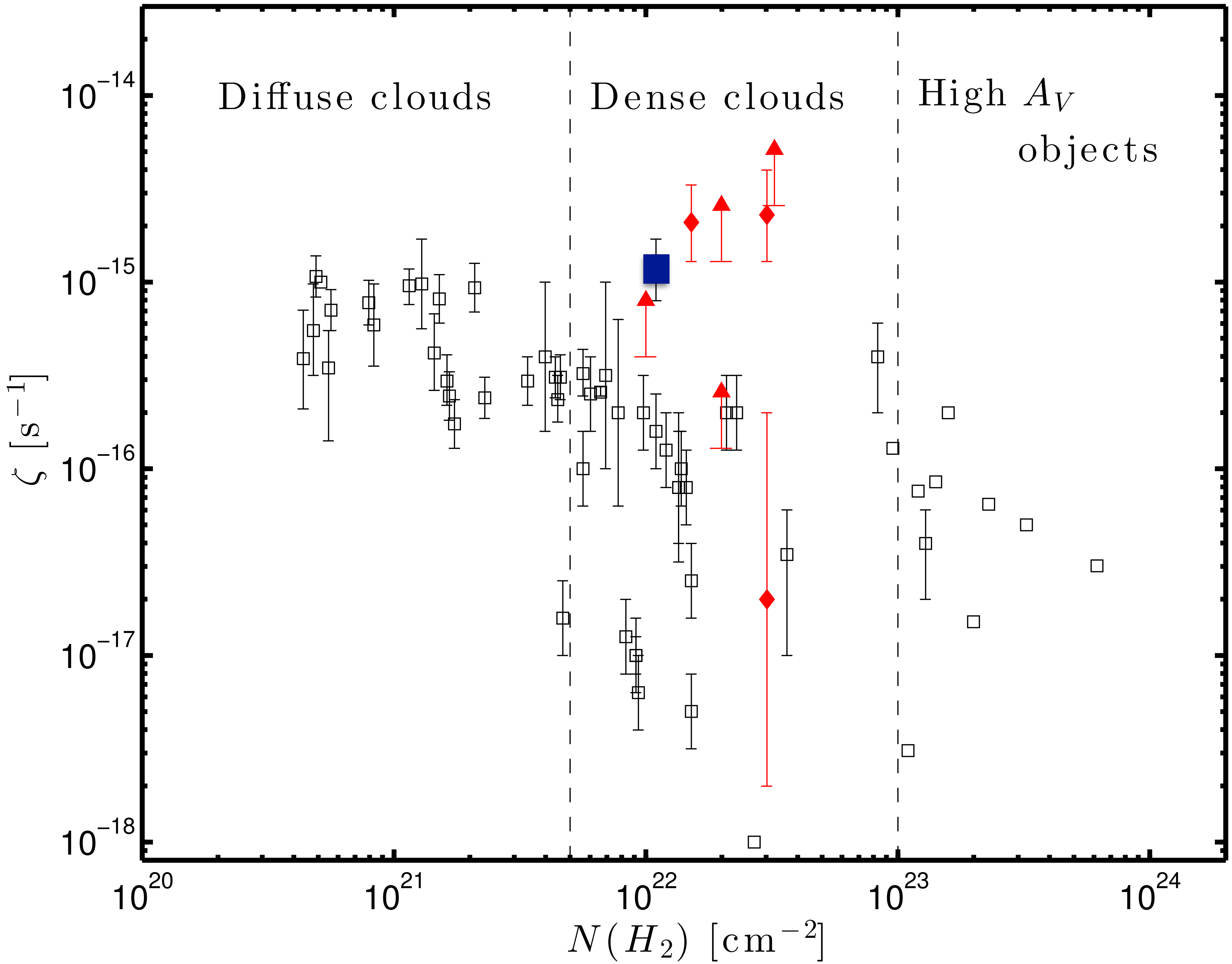
Ceccarelli+ 2011

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

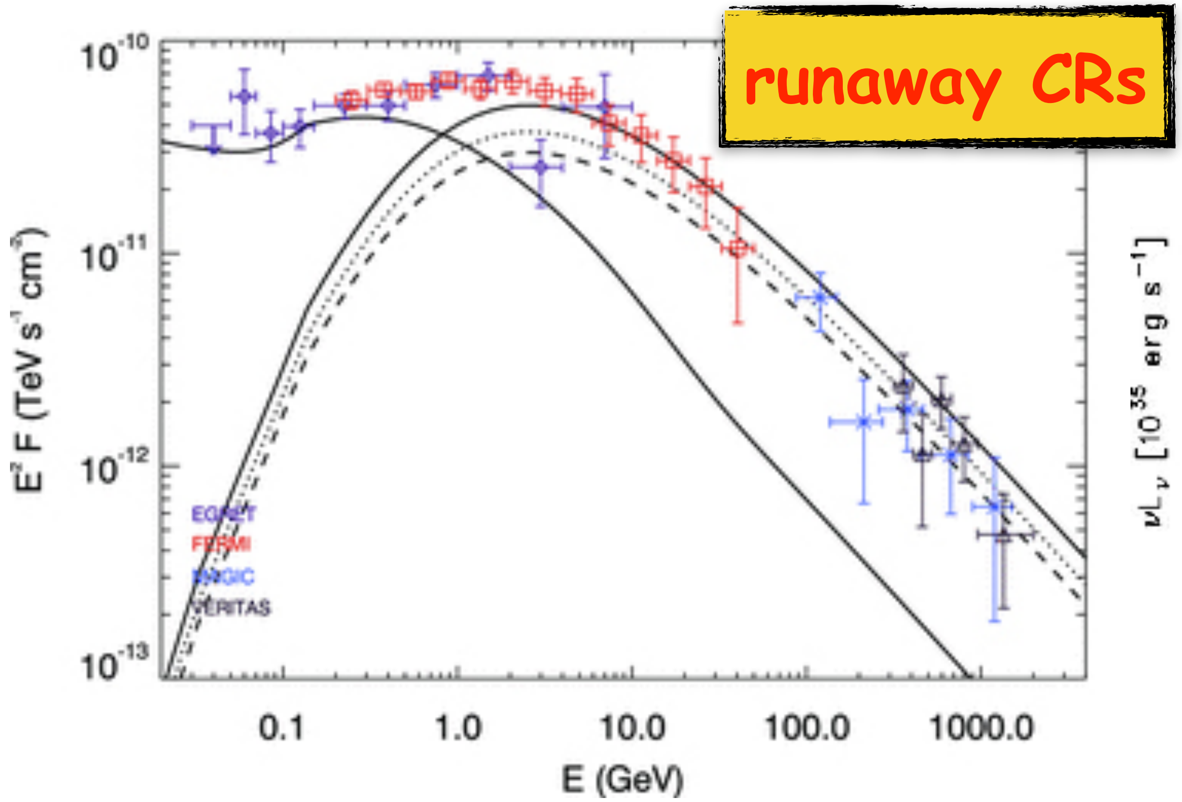


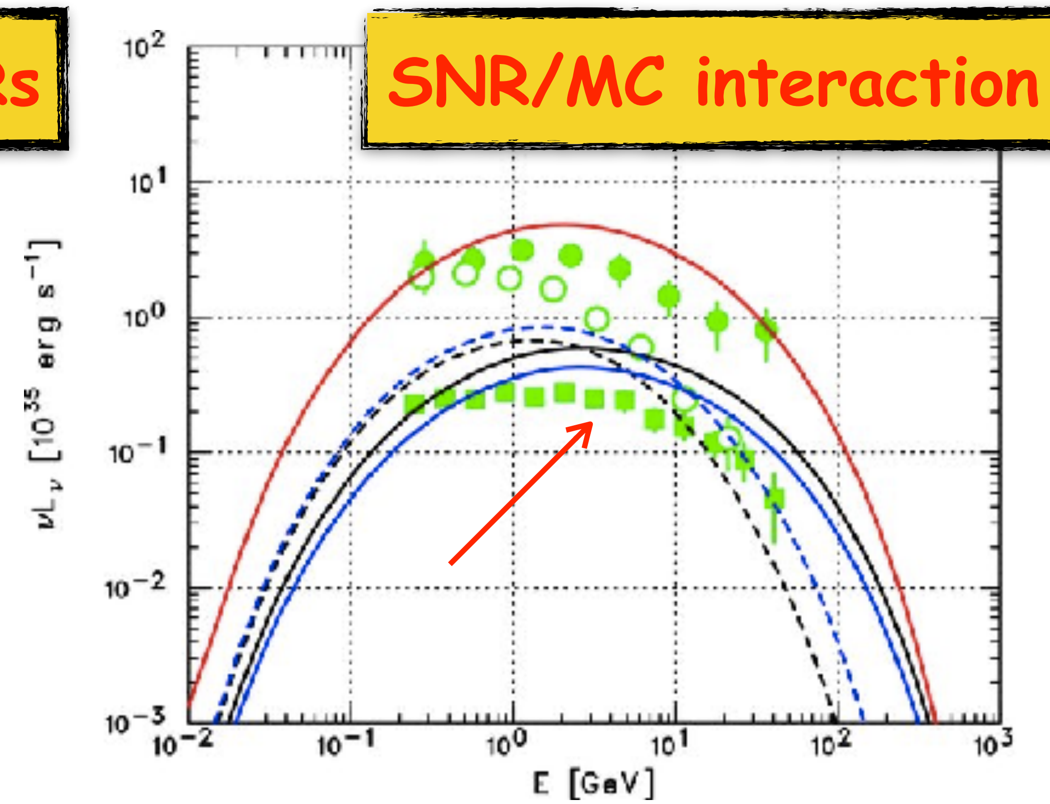
H_3^+

IC443

age ~ 3 x 10⁴ yr, evidence of shocked cloud material, clumps

Torres+ 2010





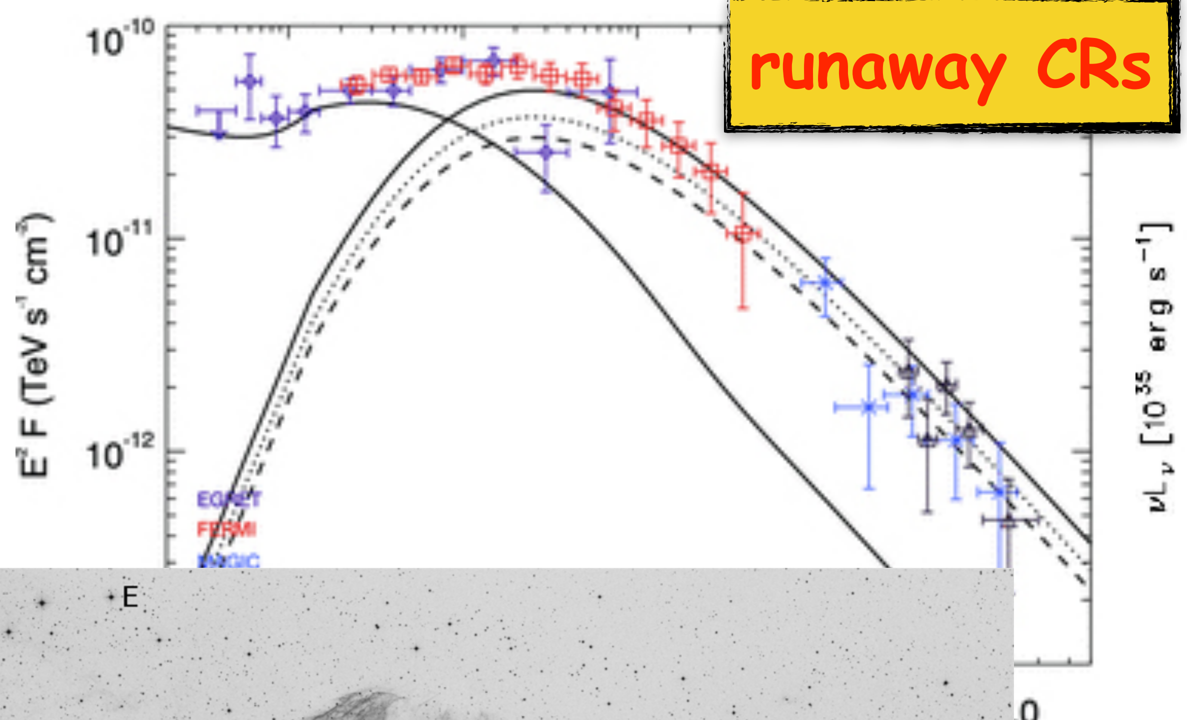
Uchiyama+ 2010

IC443

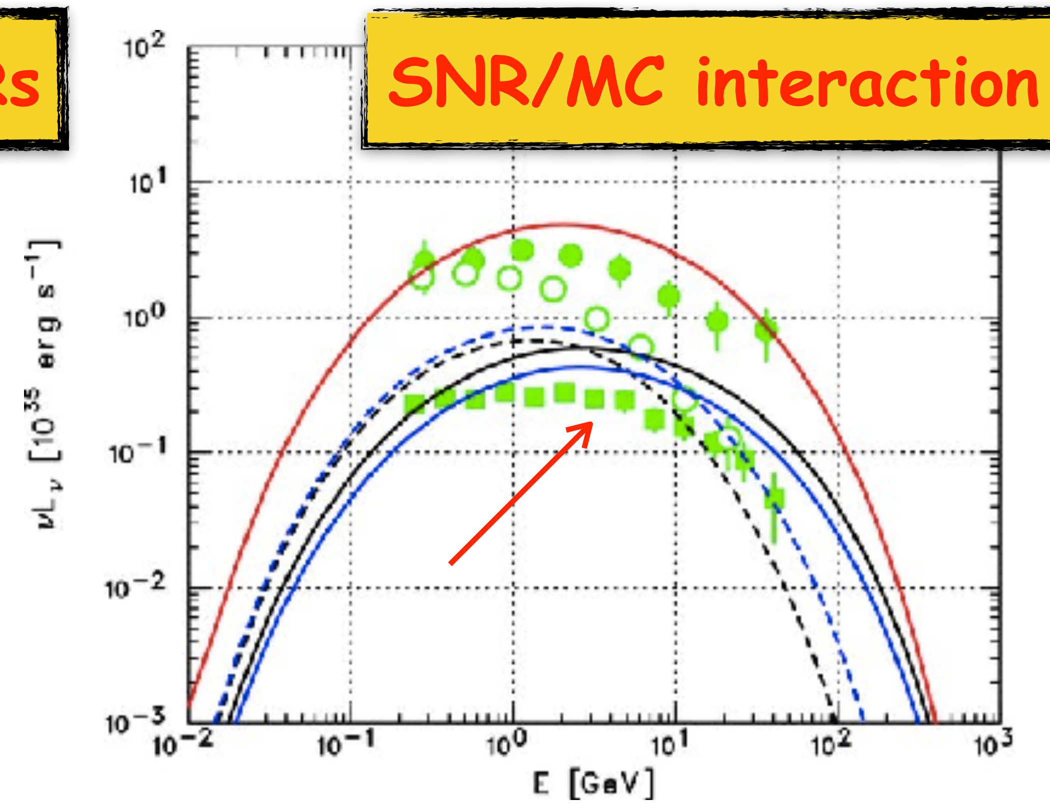
H_3^+

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

Torres+ 2010



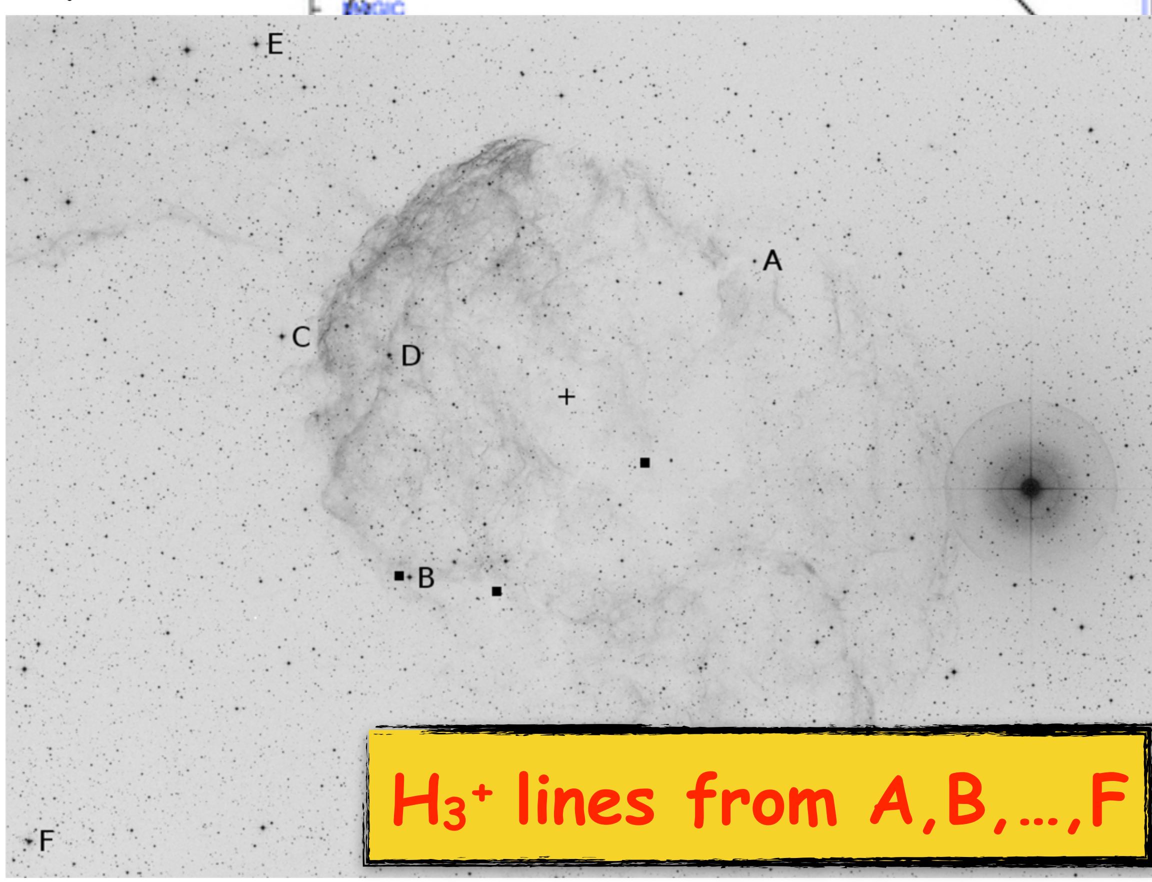
runaway CRs



SNR/MC interaction

Uchiyama+ 2010

Indriolo+ 2010 (Keck, Subaru)



H_3^+ lines from A,B,…,F

IC443

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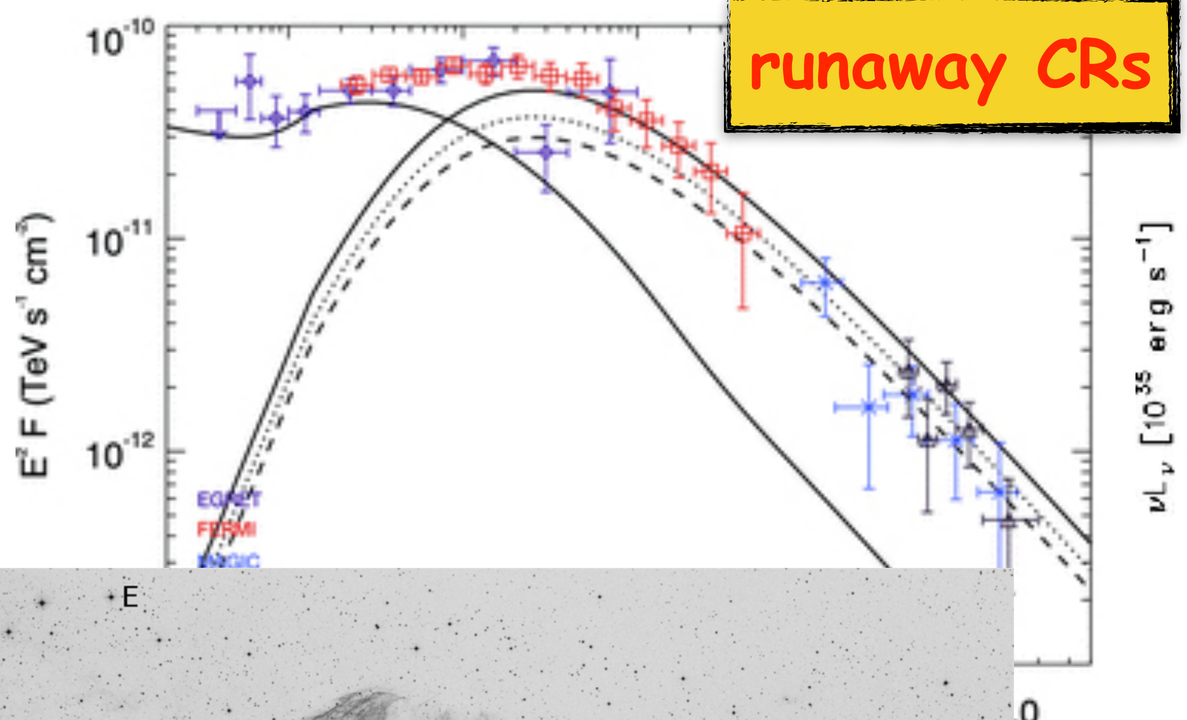

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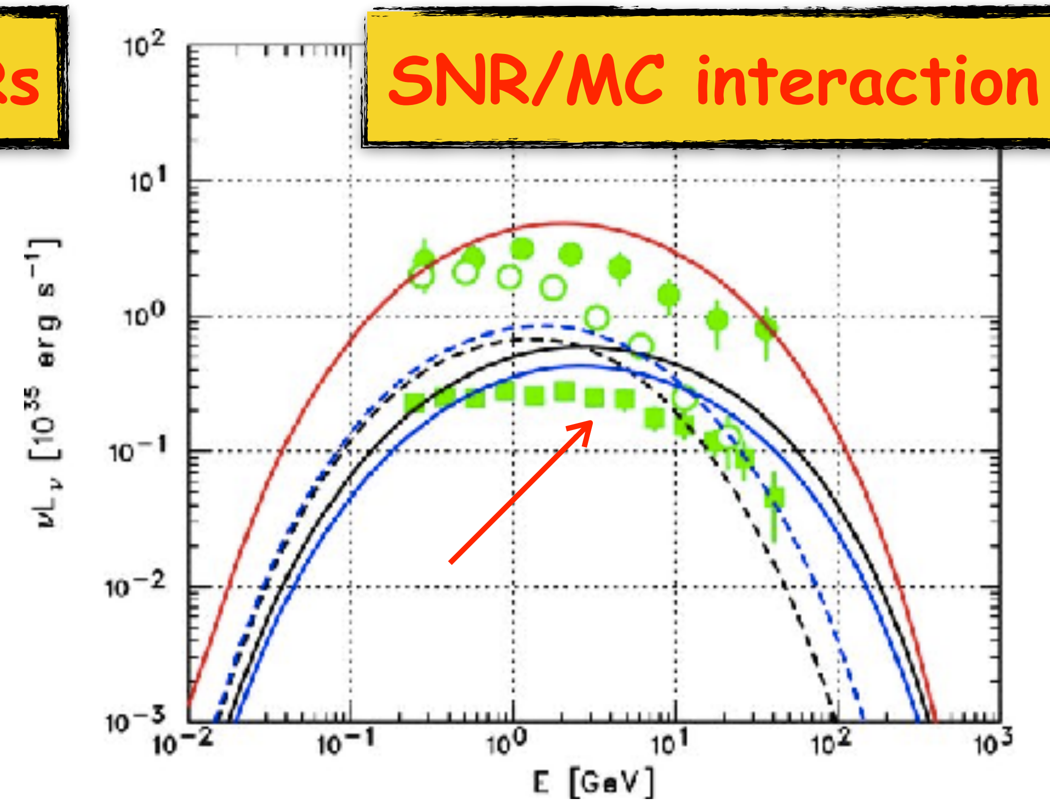

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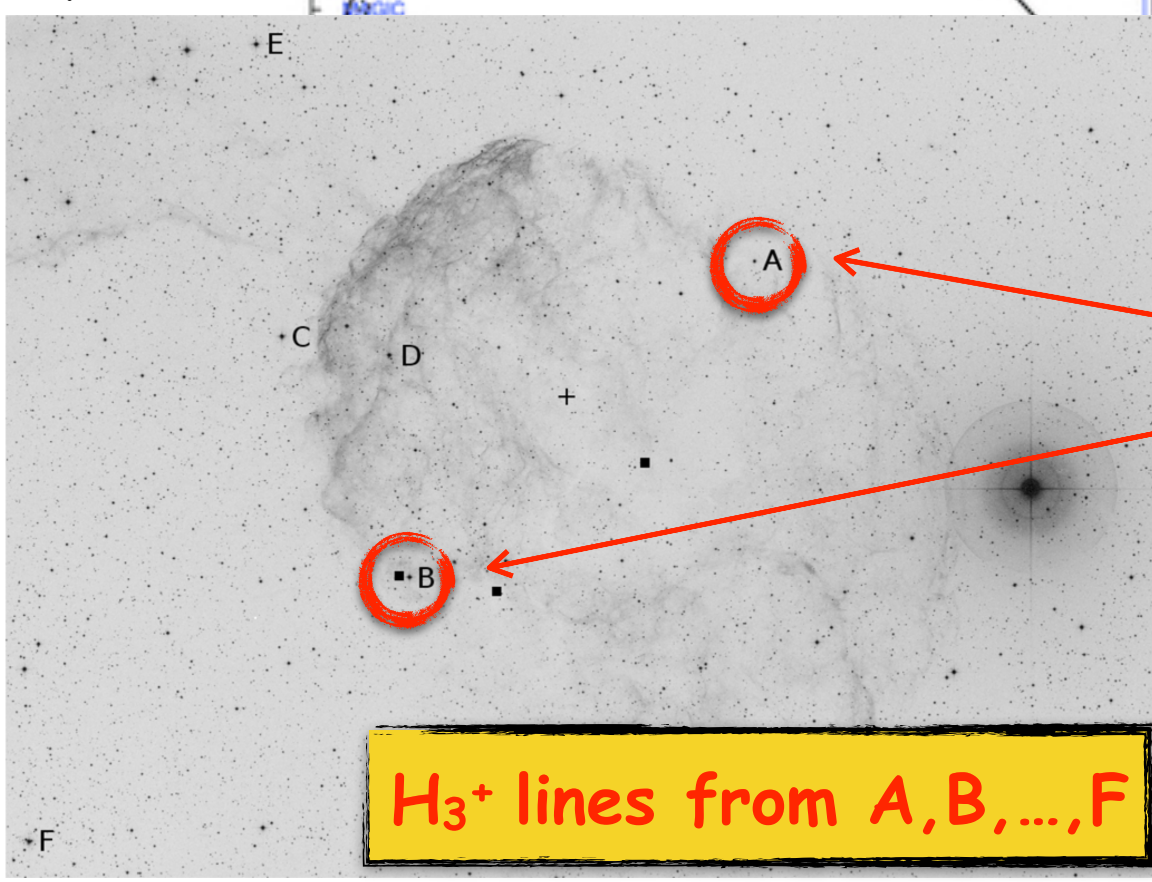


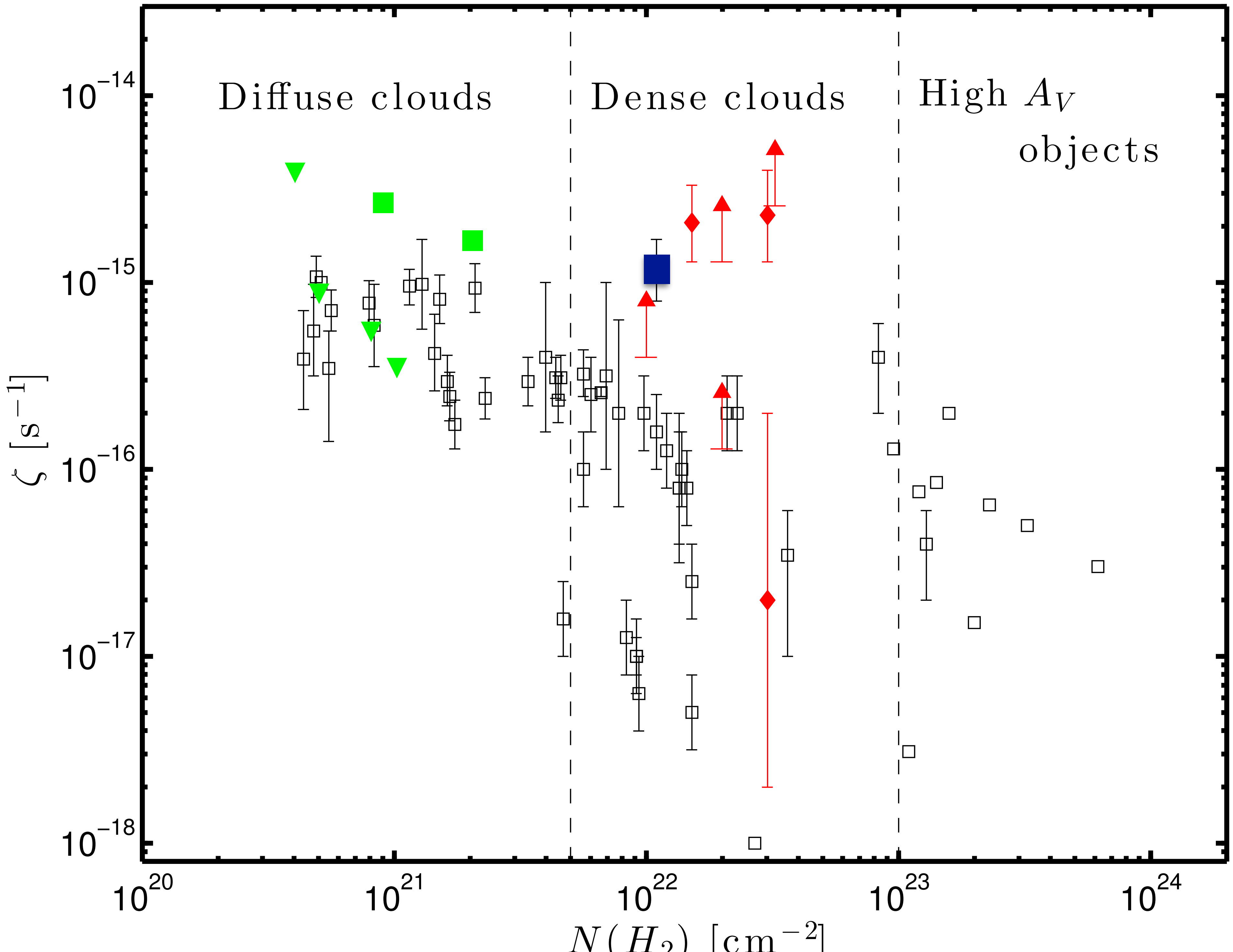
H_3^+ lines from A,B,…,F

ζ_{CR} ~ few 10^{-15} s^{-1}

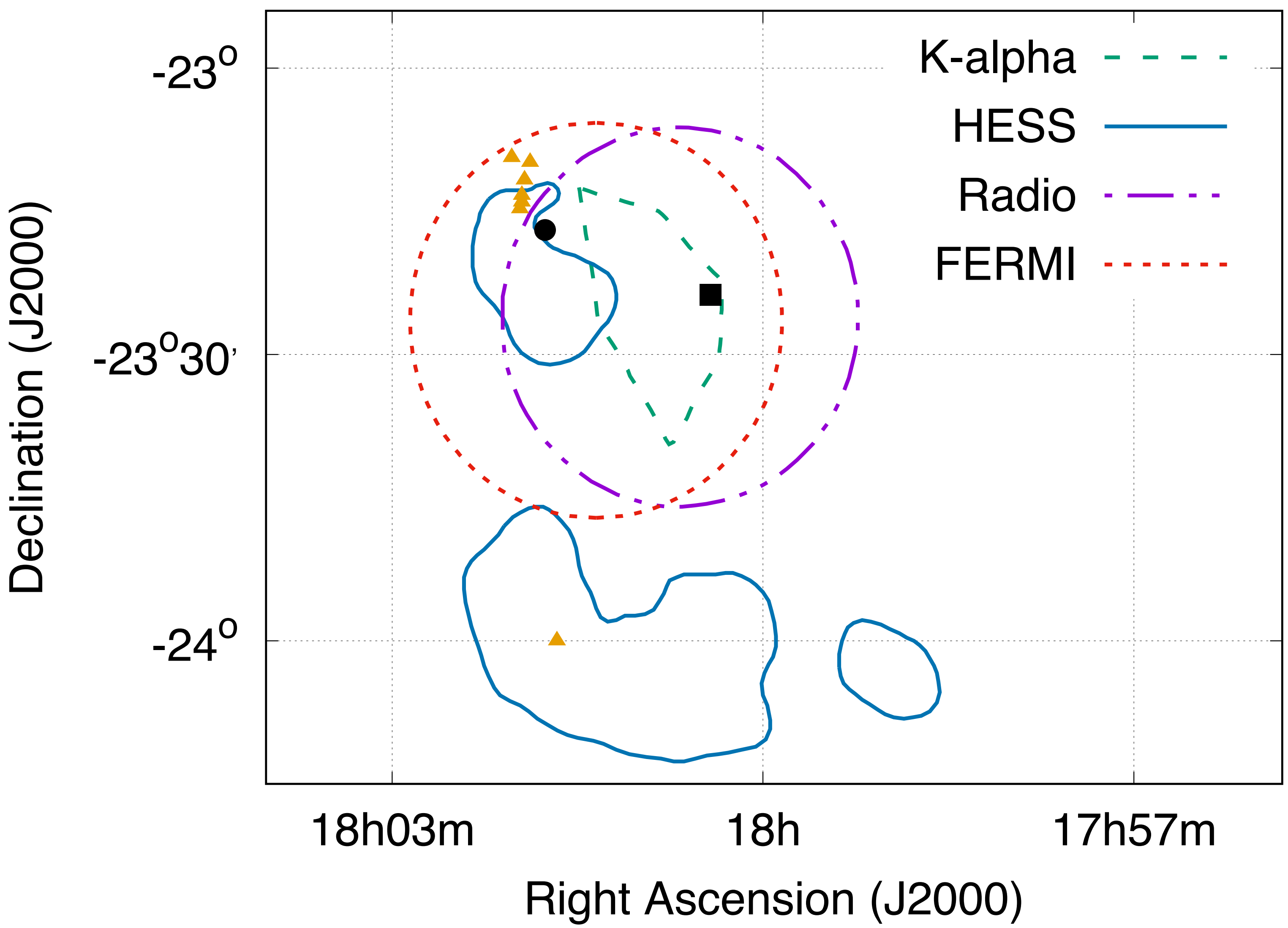
non detections: propagation effects? gas up-downstream of the shock?

CR ionization rate in MCs next to SNRs

Vaupré et al 2014 - Ceccarelli et al 2011 - Indriolo et al 2010



W28: cosmic rays or X-rays?



Phan+ 2020

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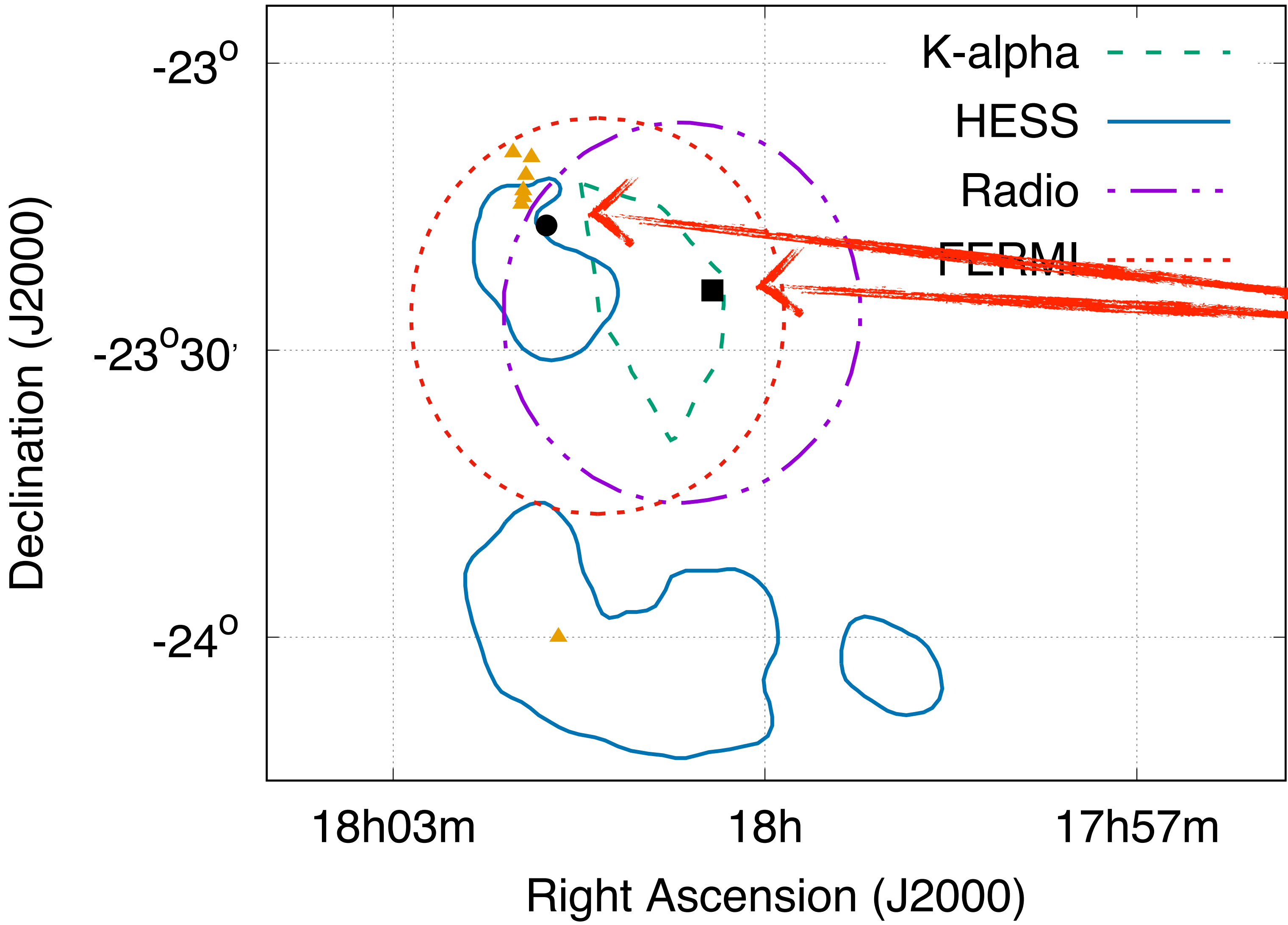

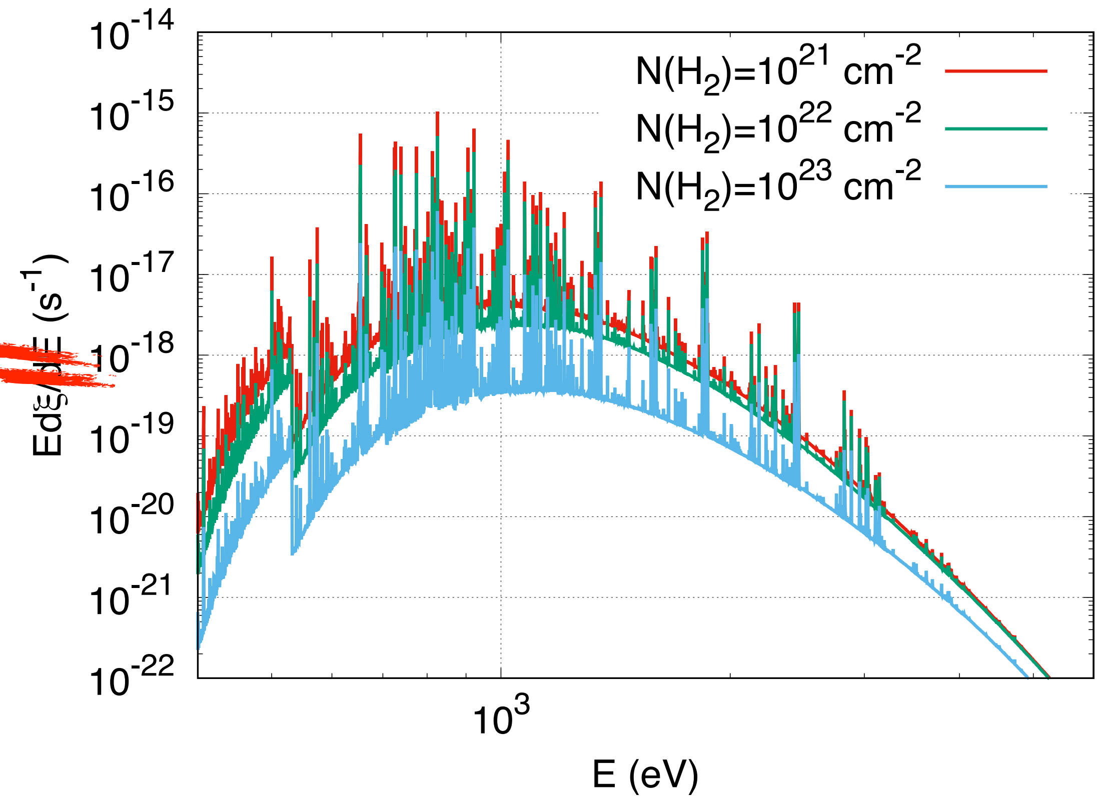

Phan+ 2020

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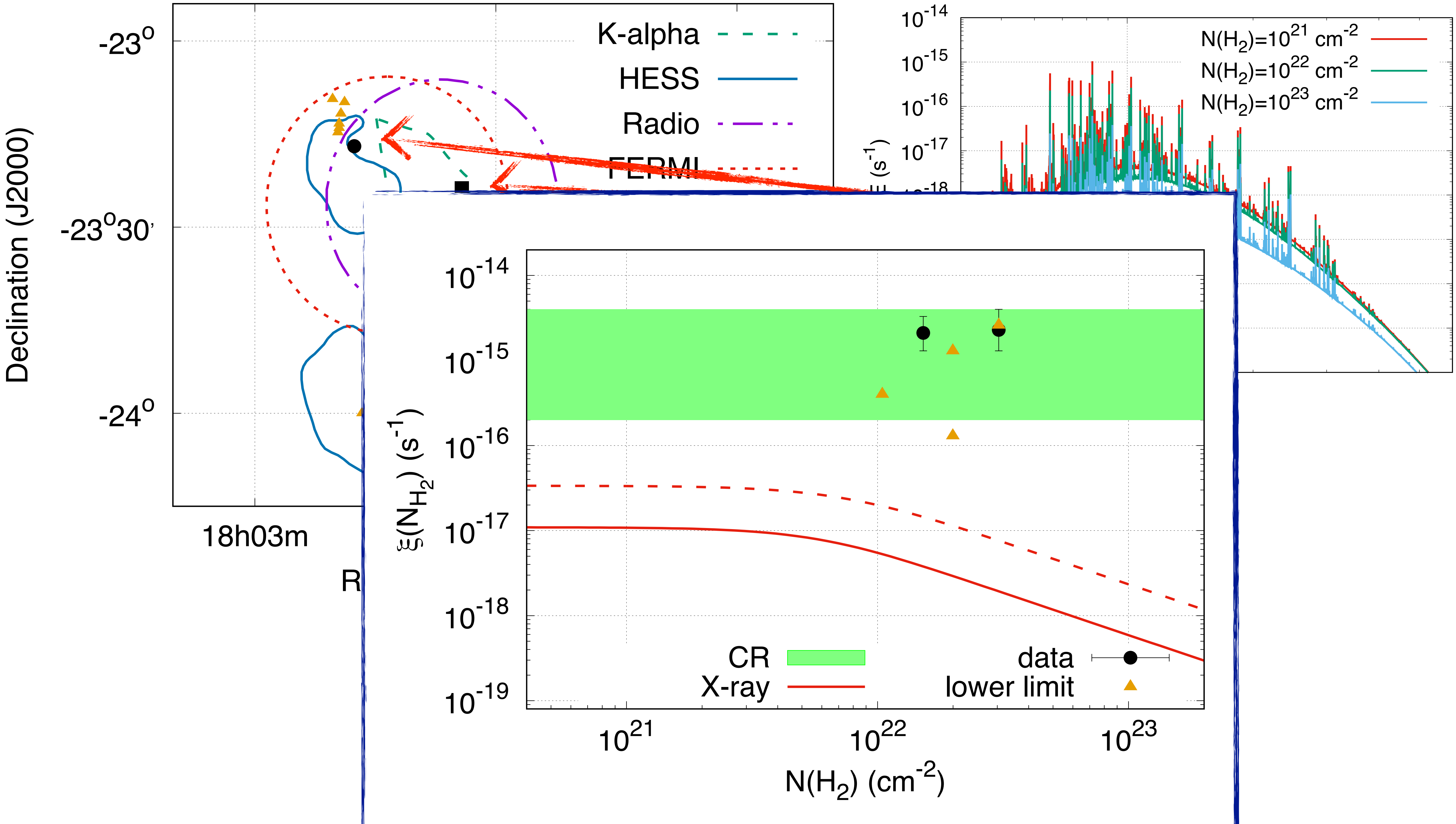

Phan+ 2020

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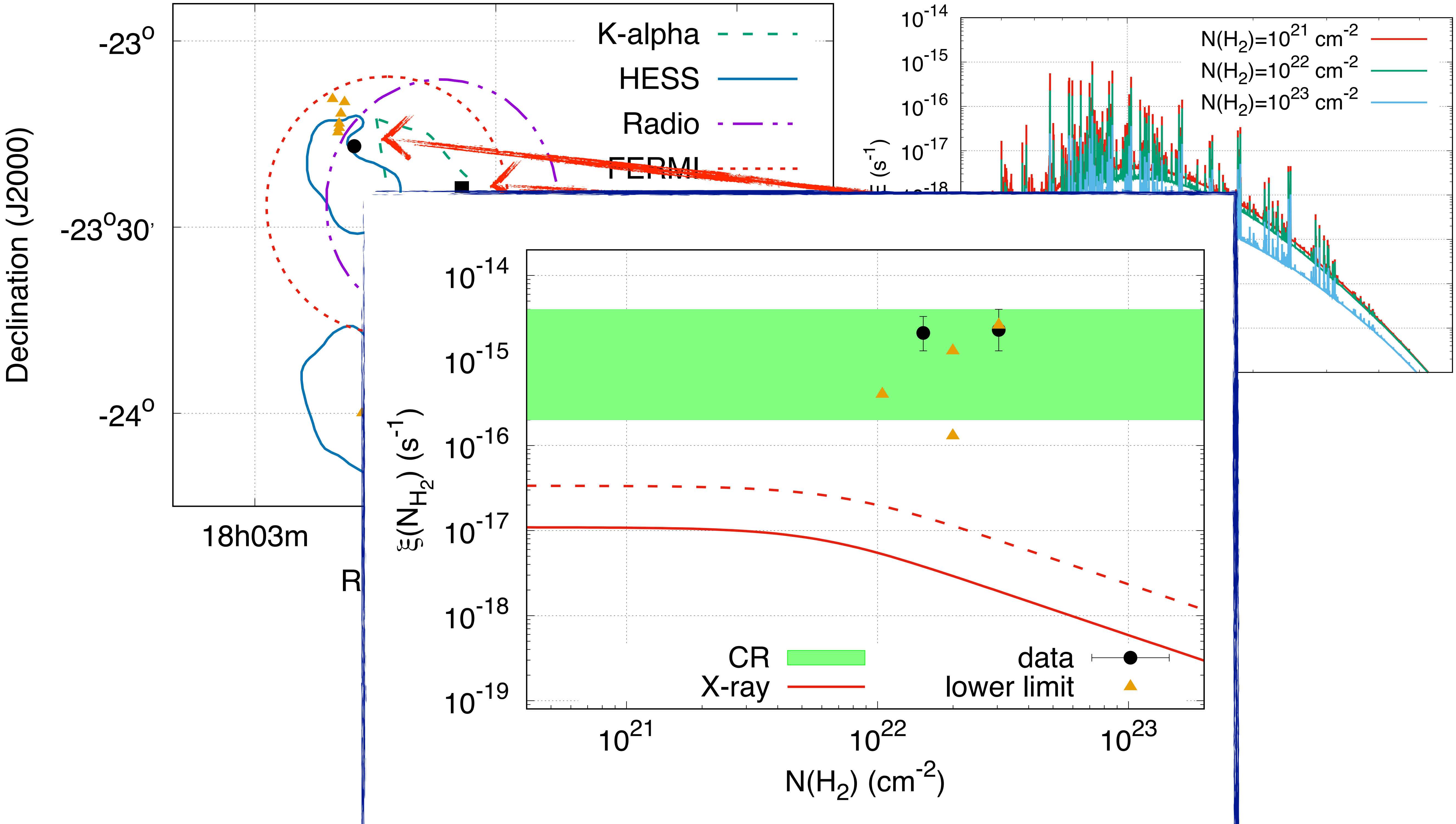
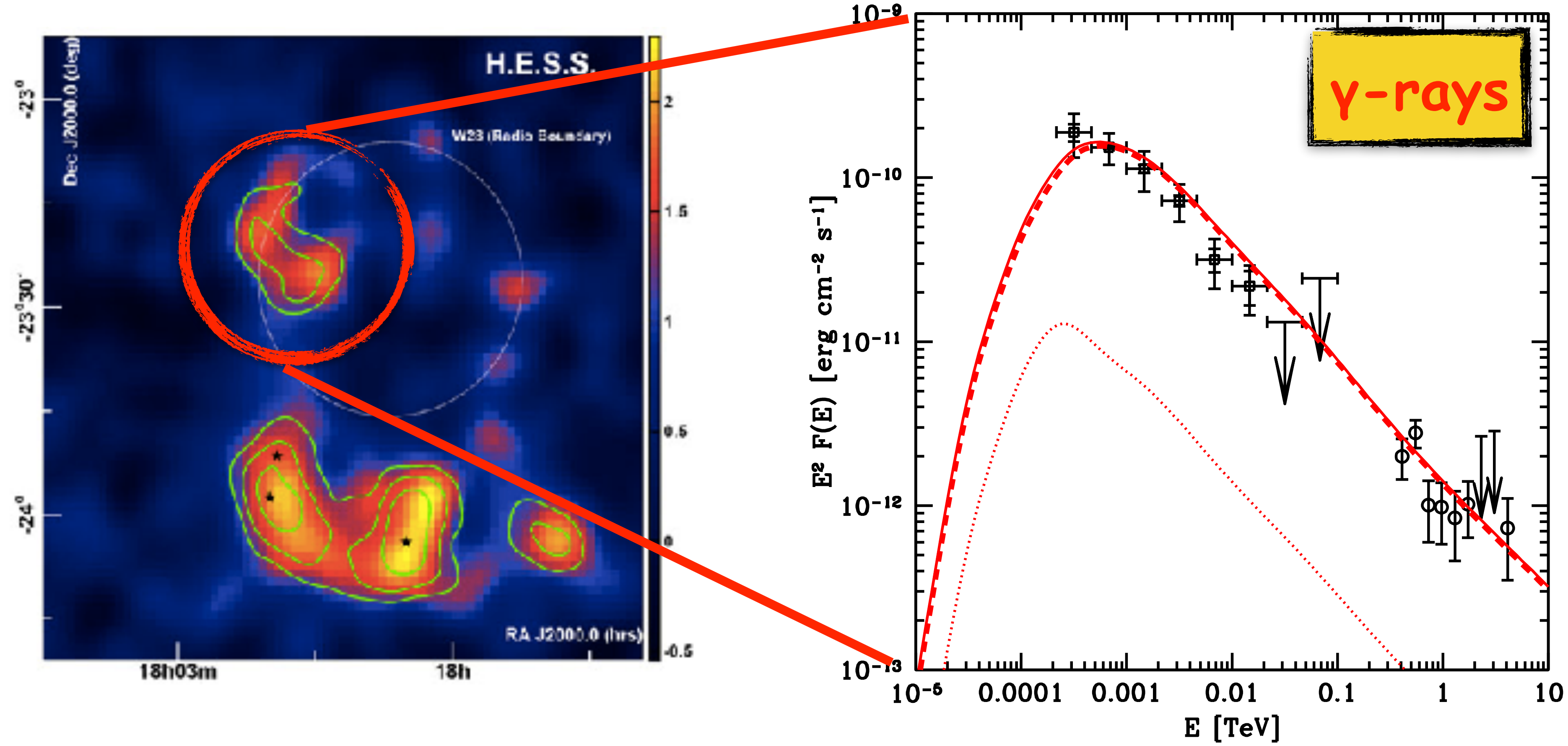


Phan+ 2020

W28: bridging high and low energy CRs



fit with a proton spectrum

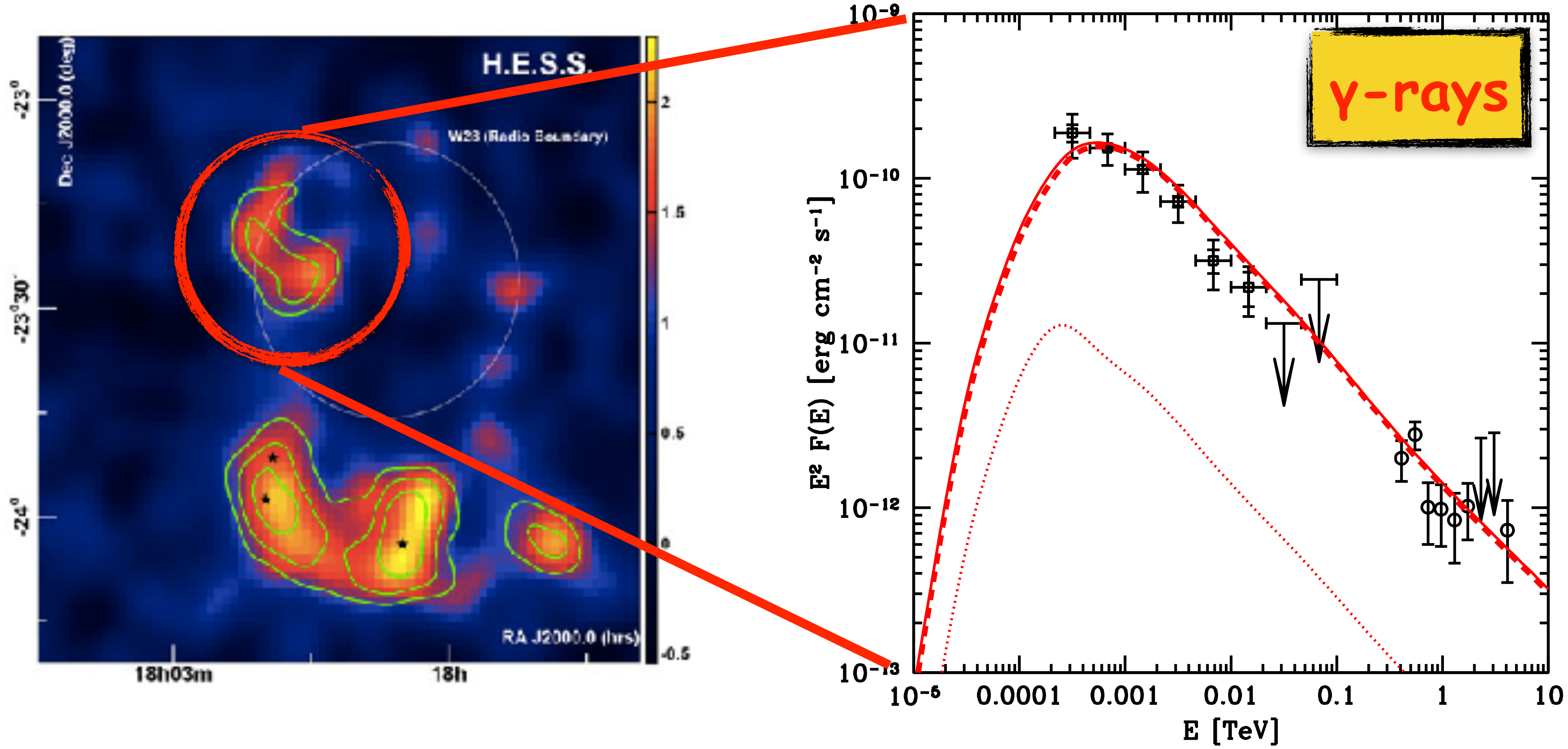
$$f_{\rm CR} \propto p^{-2.8}$$

gammas produced by protons of energy

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

Phan+ 2020

W28: bridging high and low energy CRs



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

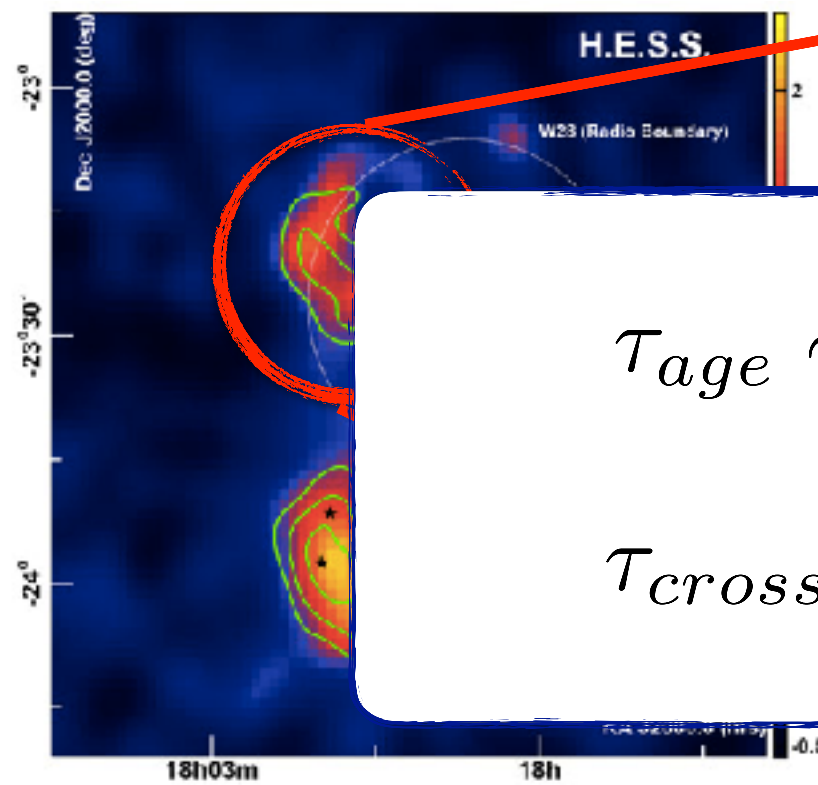
ionization rate

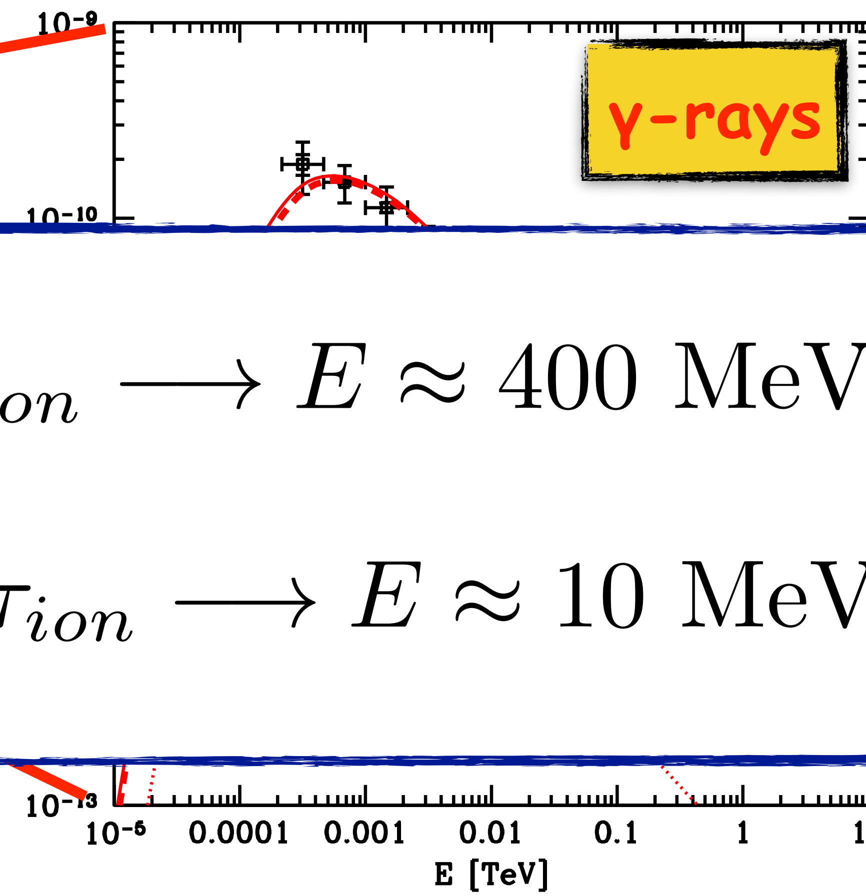
$$\zeta_{\rm CR} \gtrsim 2 \times 10^{-15} \ {\rm s}^{-1}$$

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

Phan+ 2020

W28: bridging high and low energy CRs





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

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

fit with a proton spectrum

$_R \propto p^{-2.8}$

s produced by
ns of energy

$\gtrsim 1$ GeV

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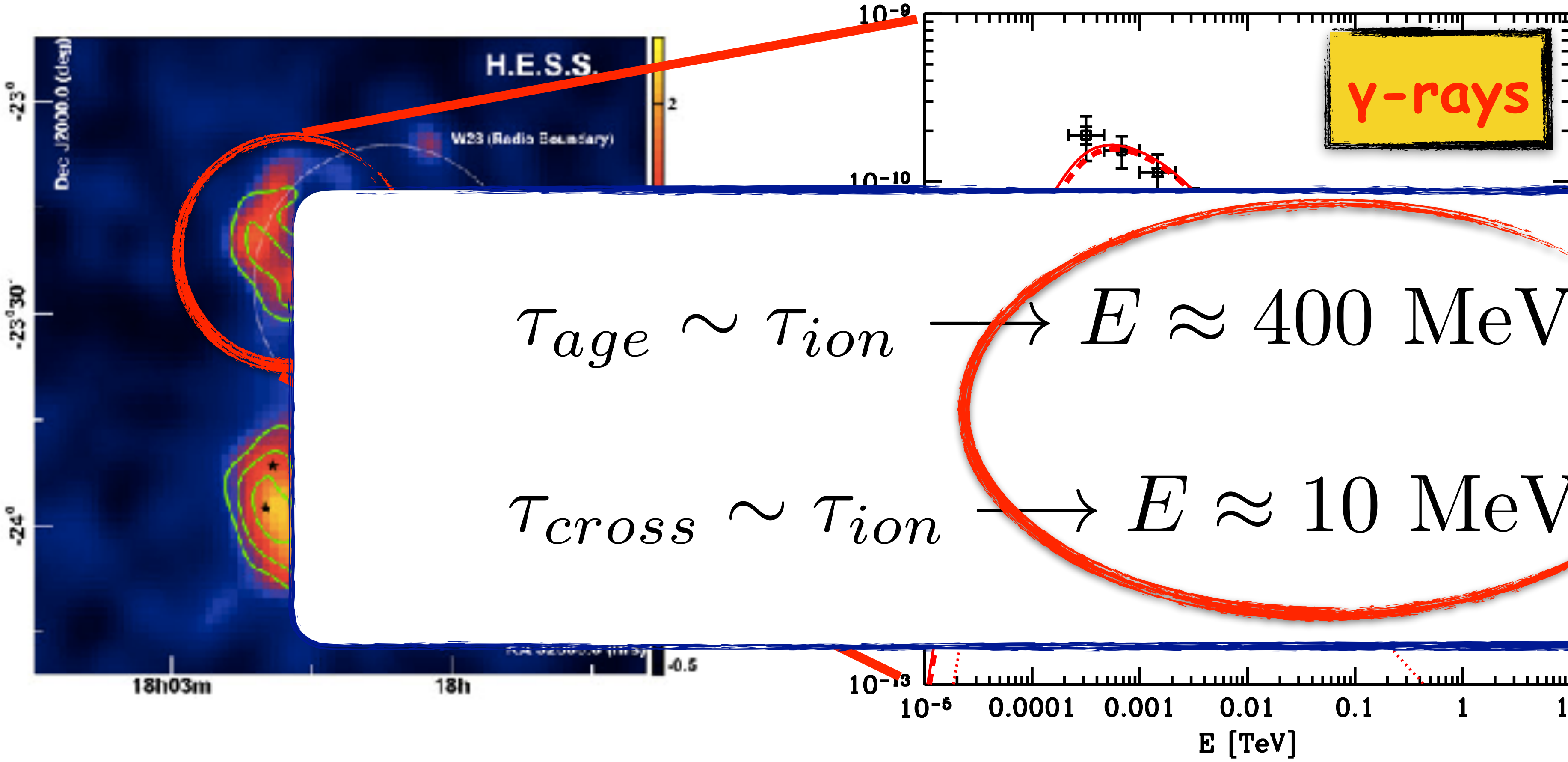
Phan+ 2020

W28: bridging high and low energy CRs



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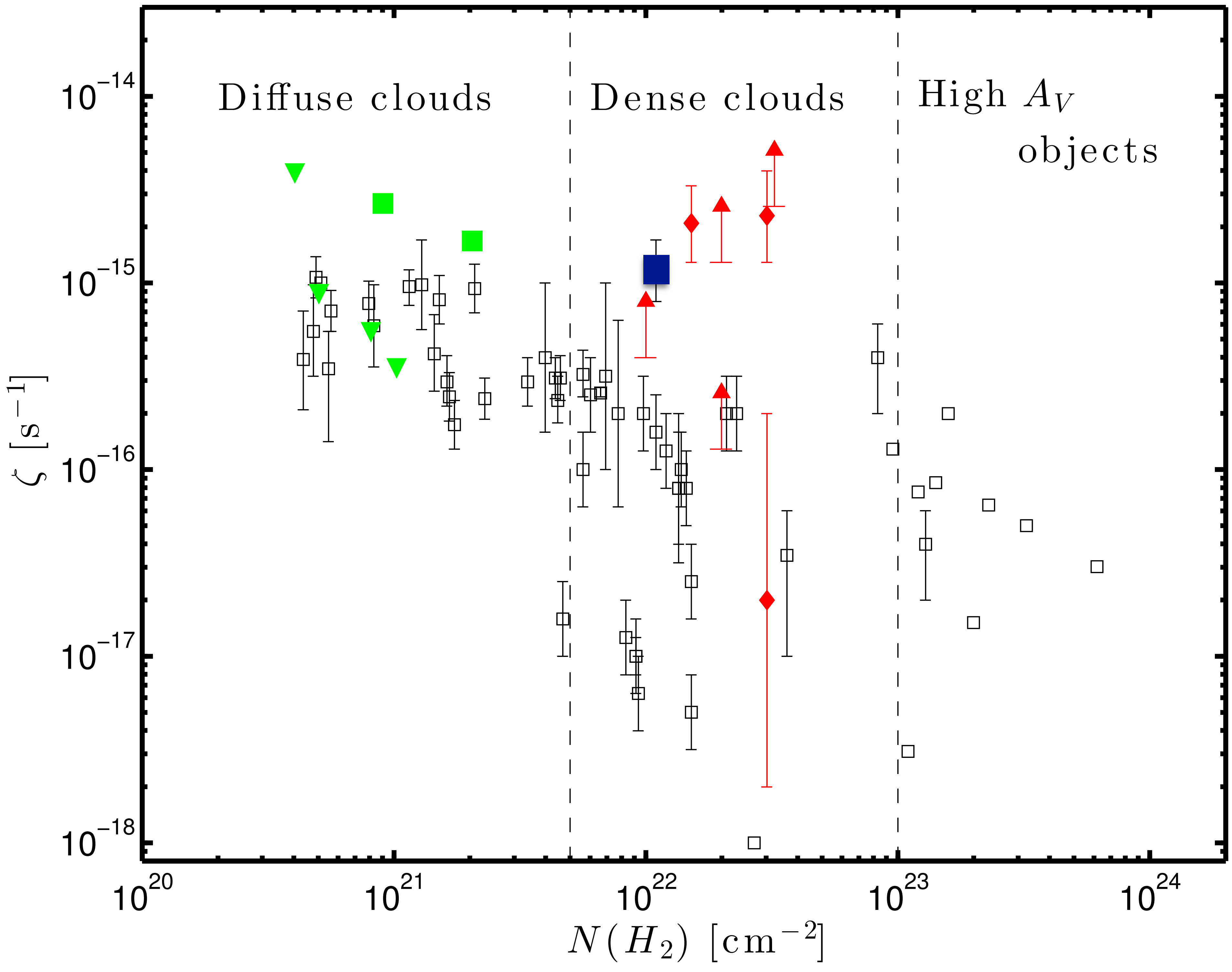
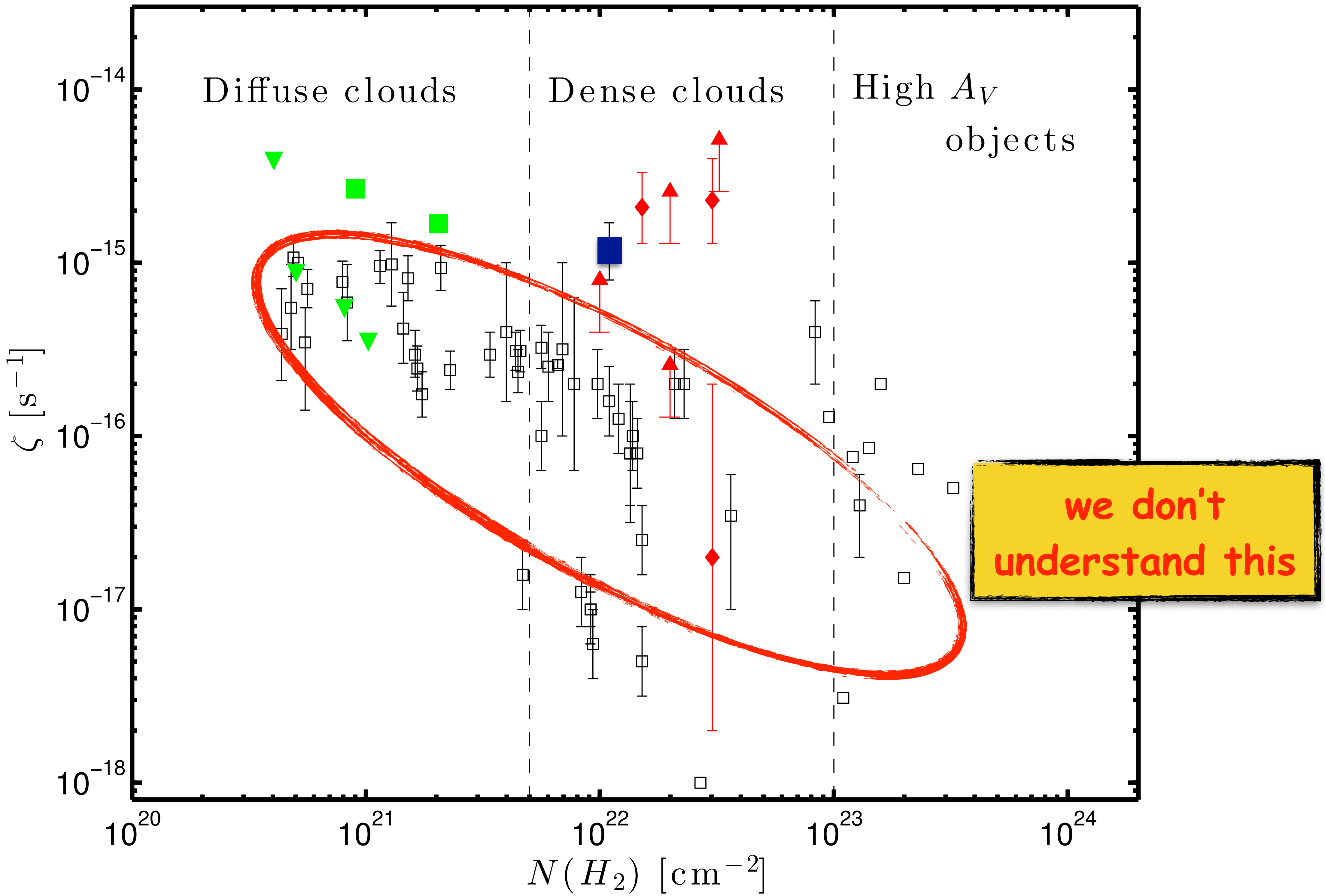
Phan+ 2020

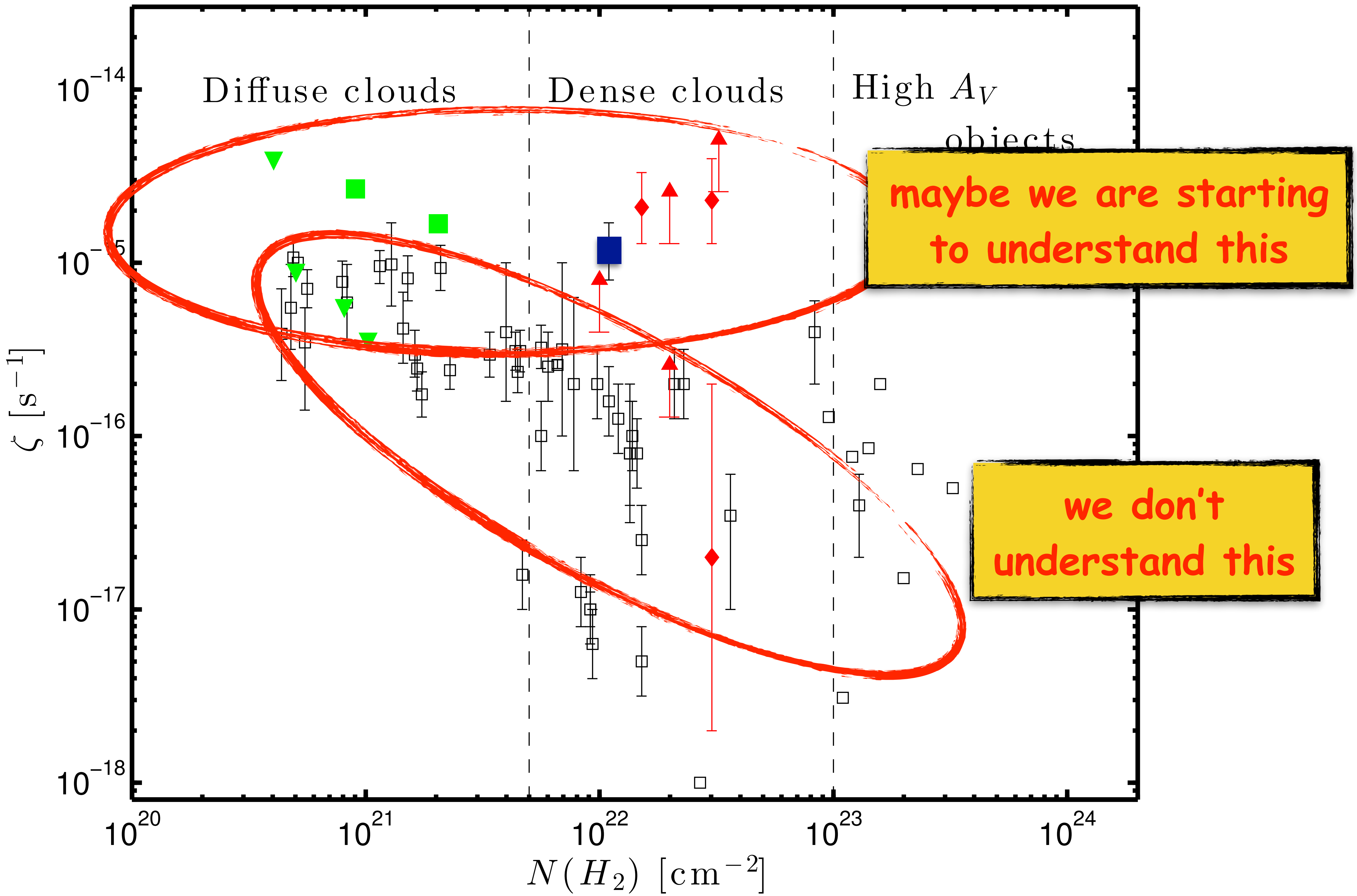
Conclusions (?)



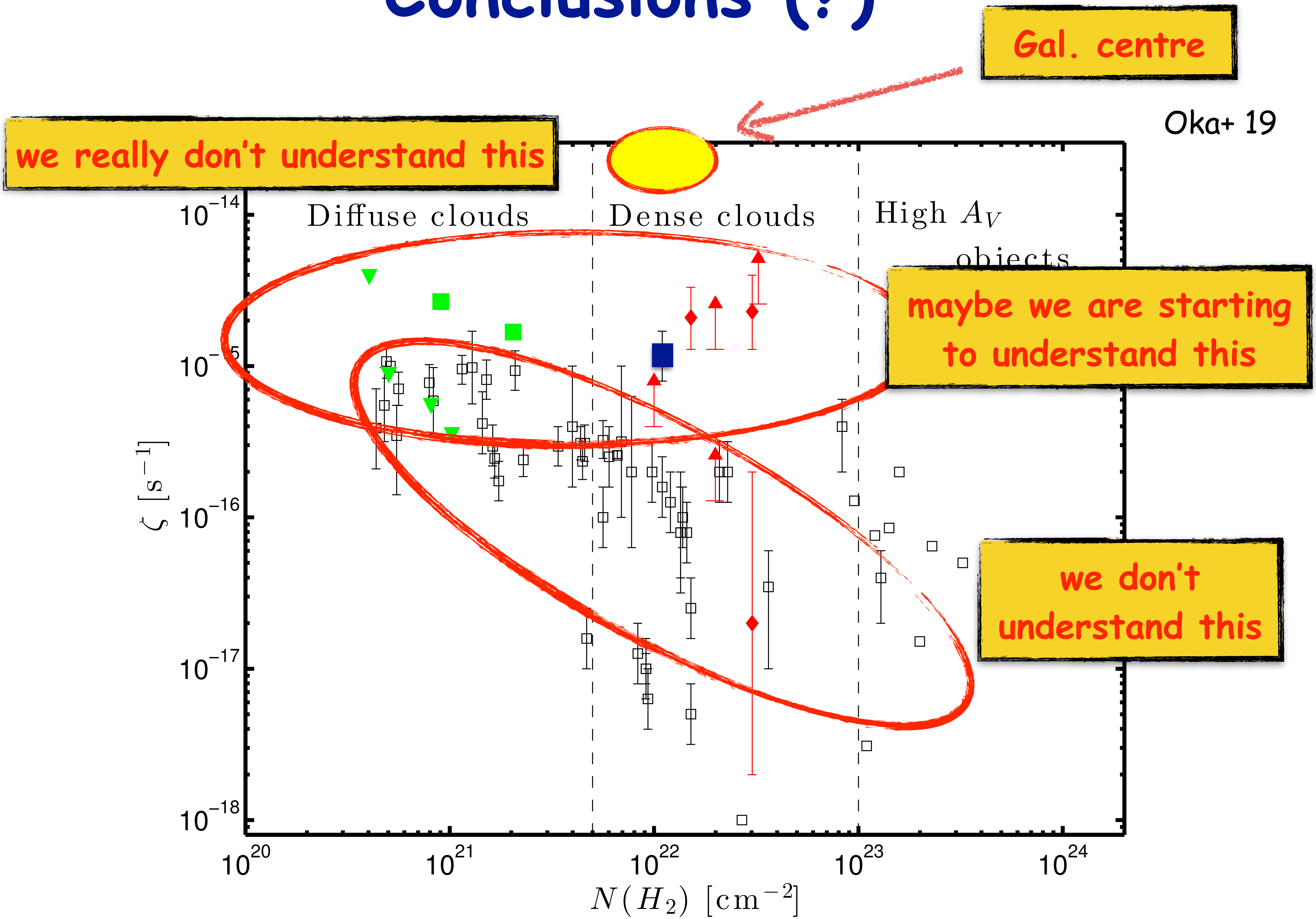
Conclusions (?)



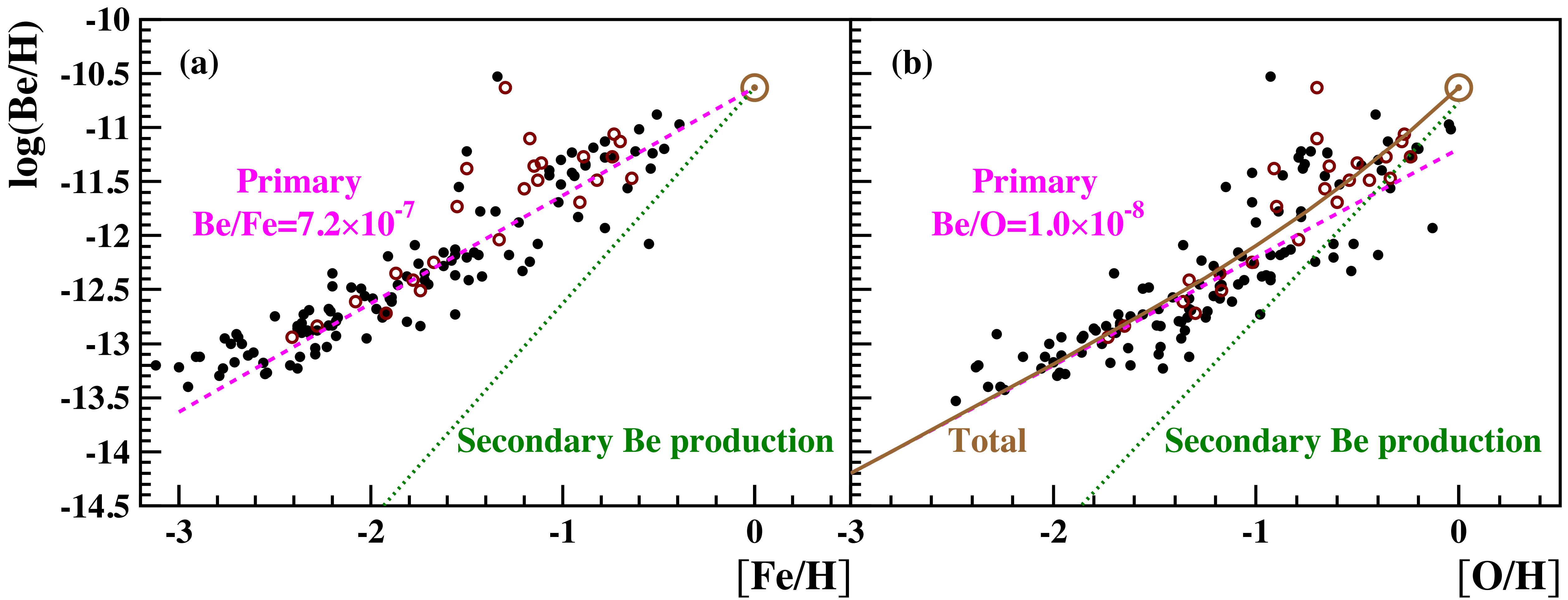
Conclusions (?)



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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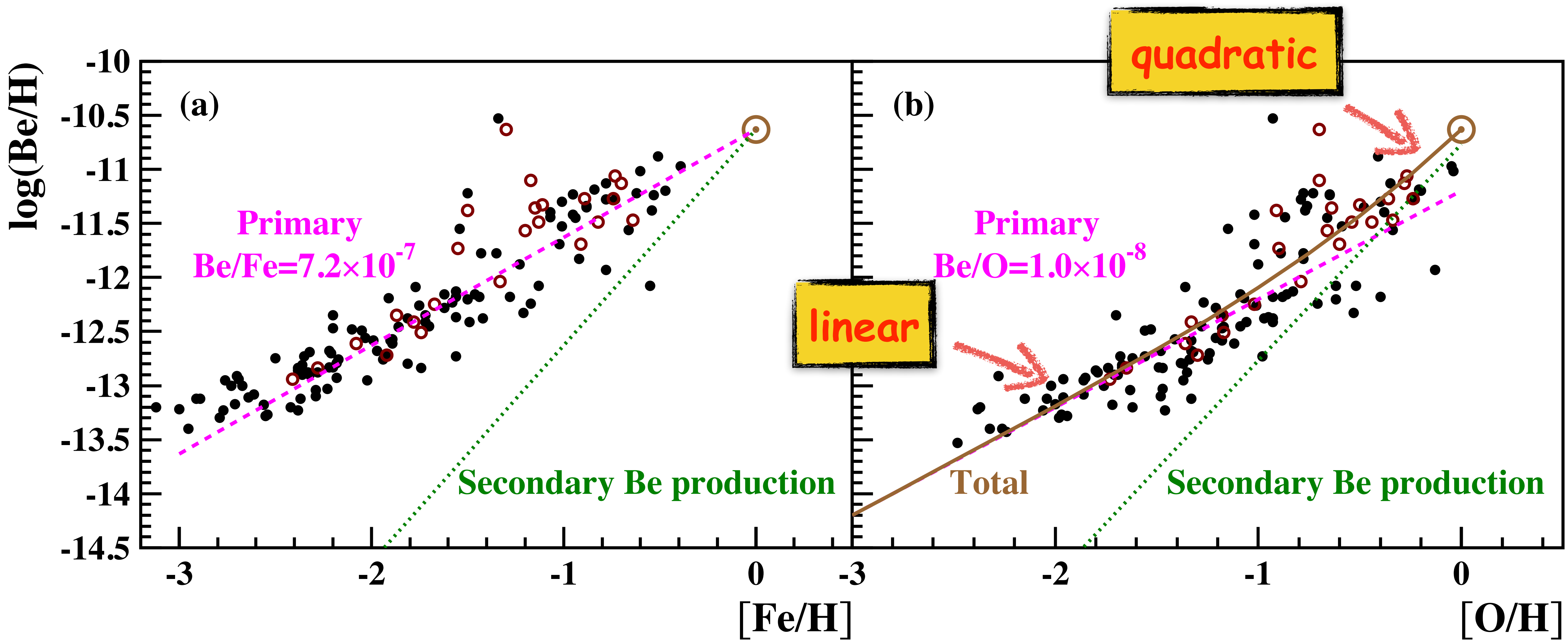

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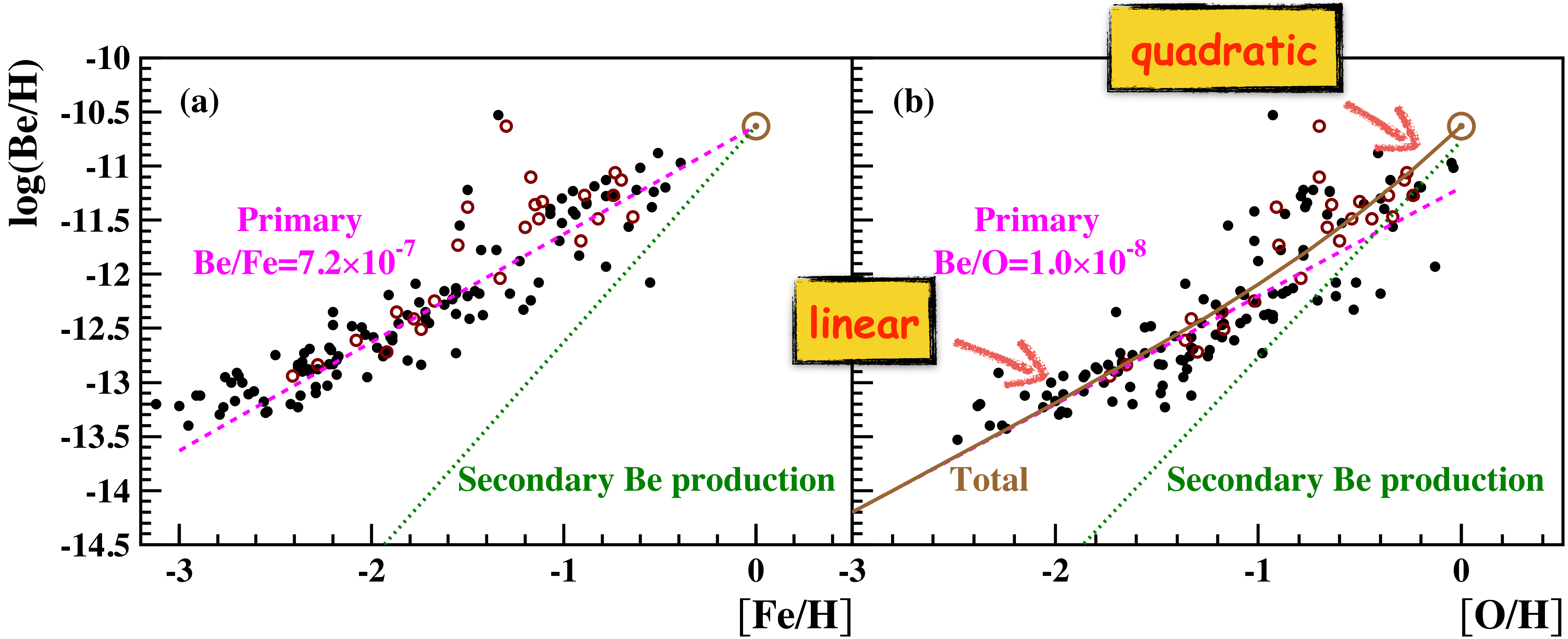

superbubbles -> CRs are accelerated from an enriched ISM (X_{CR} closer to constant rather than X_{ISM})

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

(Real) conclusions