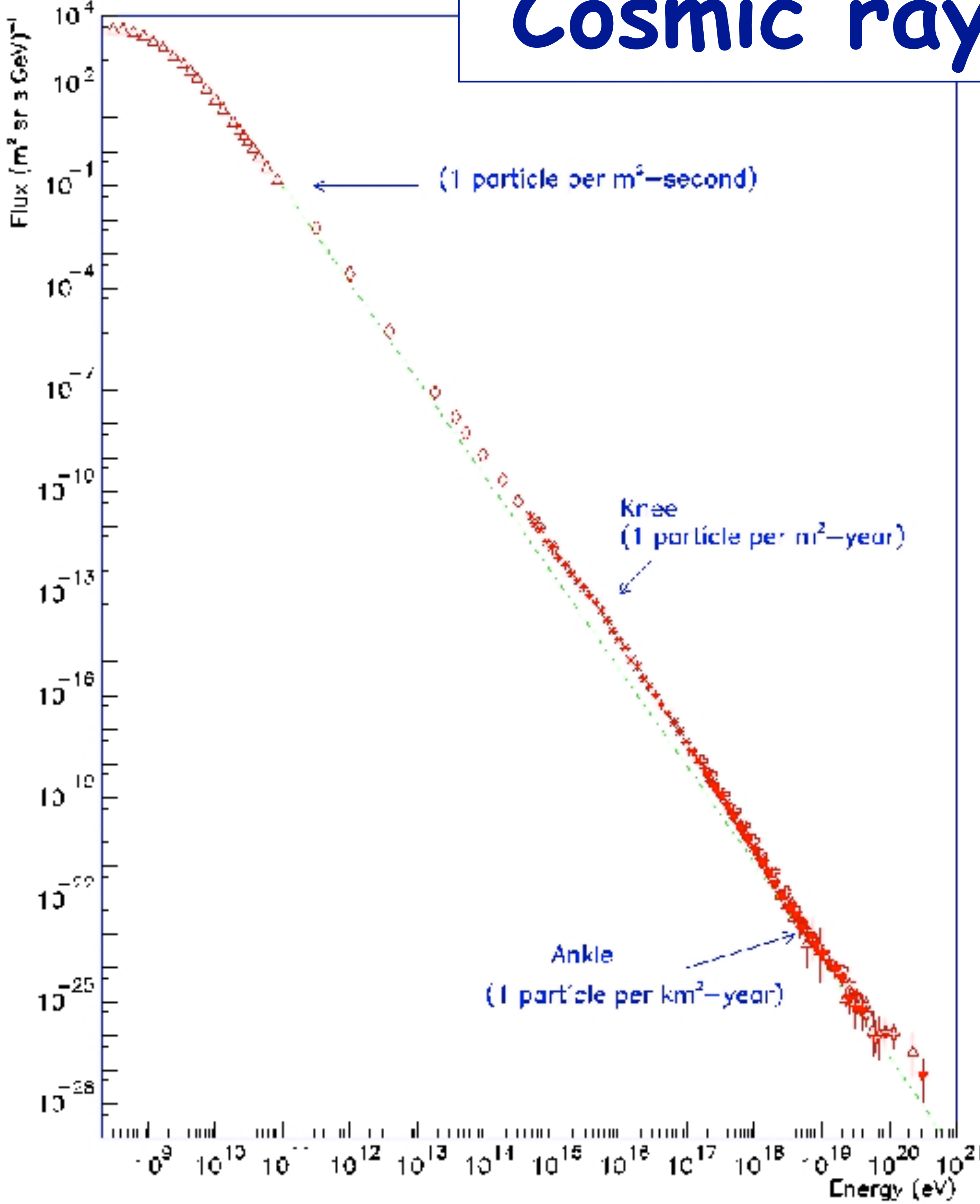
Cosmic ray penetration in (diffuse?) clouds

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

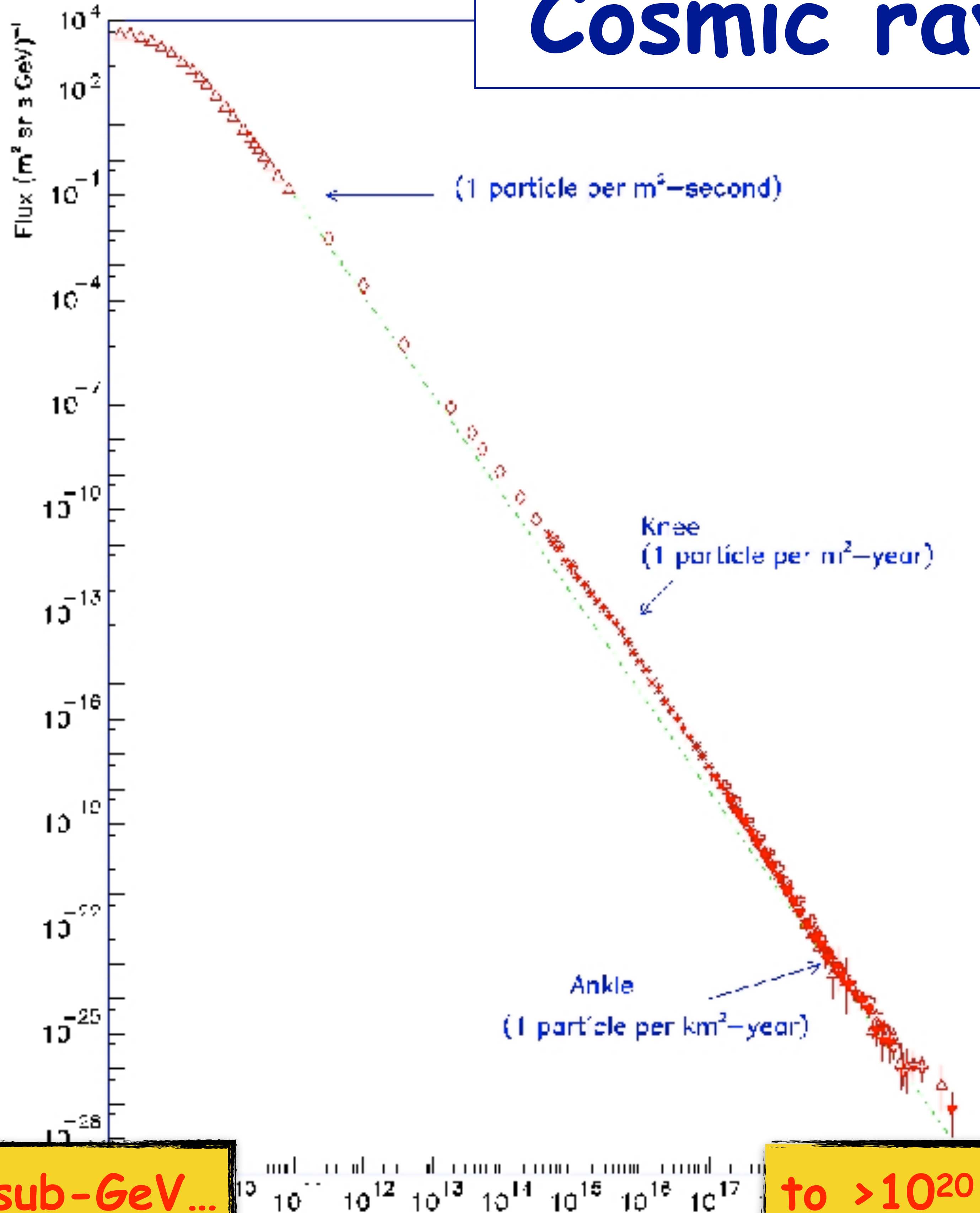
www.cnrs.fr

Cosmic rays



(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Flux (m² sr s GeV)⁻¹
Energy (eV)

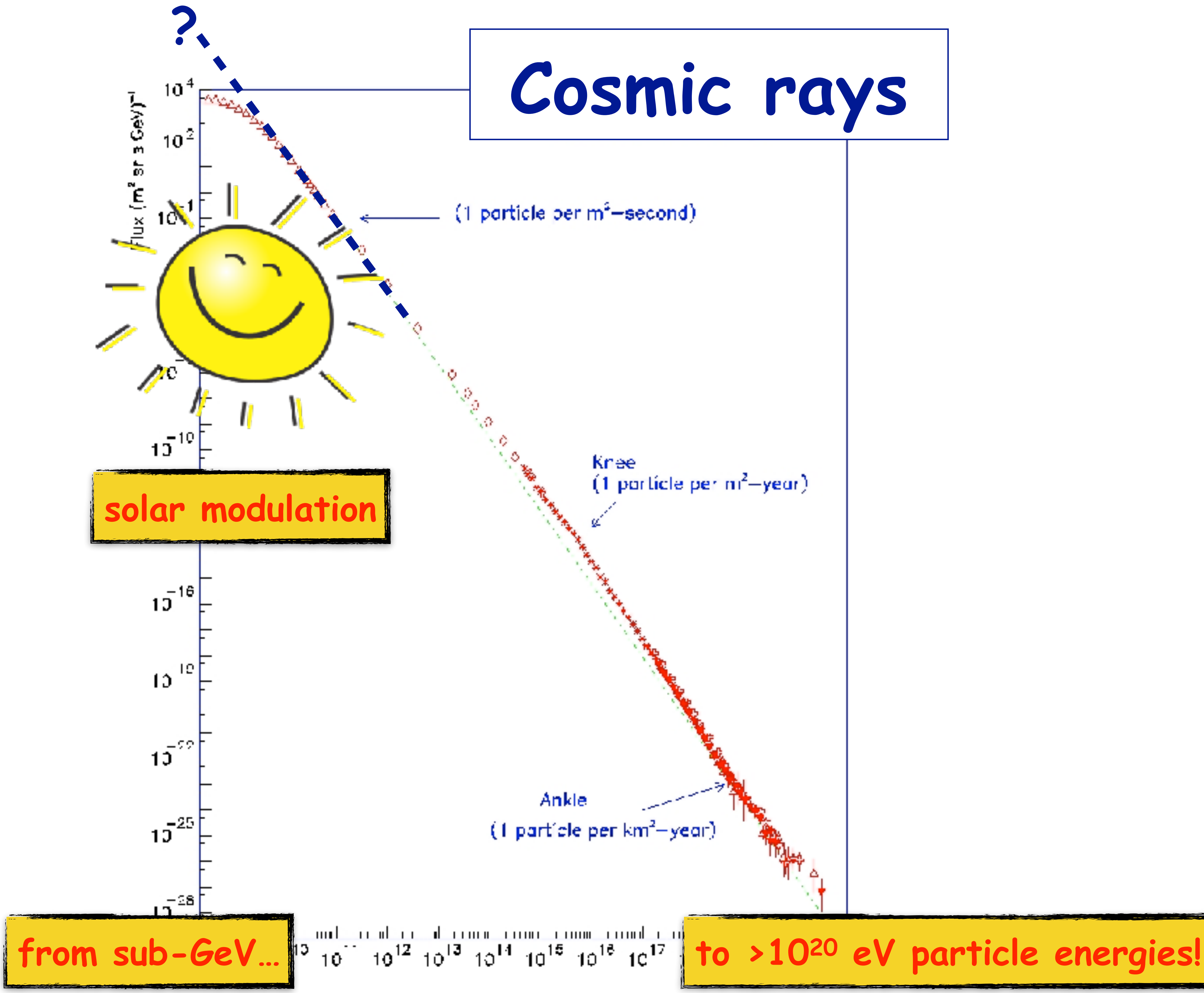
Cosmic rays



from sub-GeV…

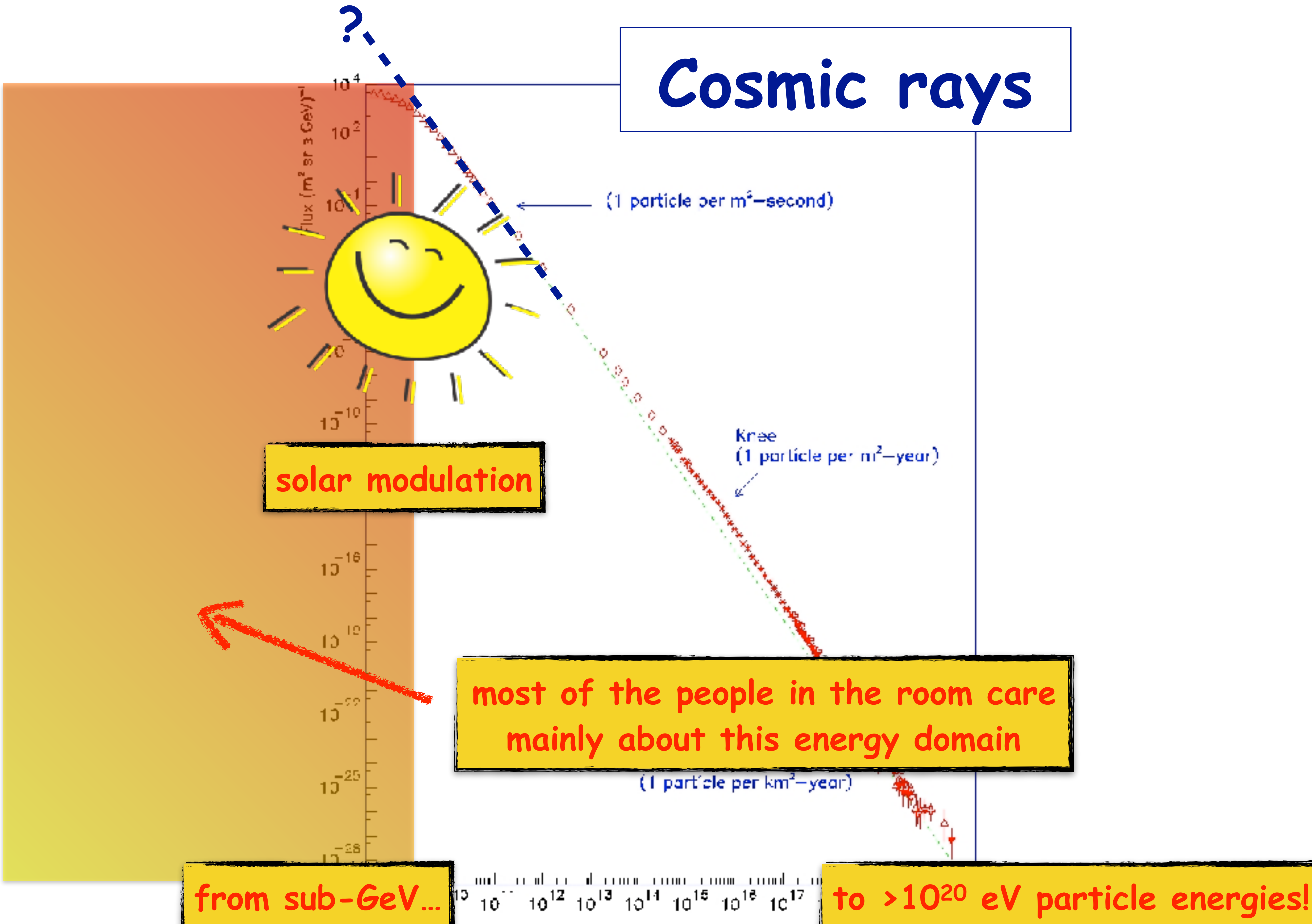
to >10^{20} eV particle energies!

Cosmic rays



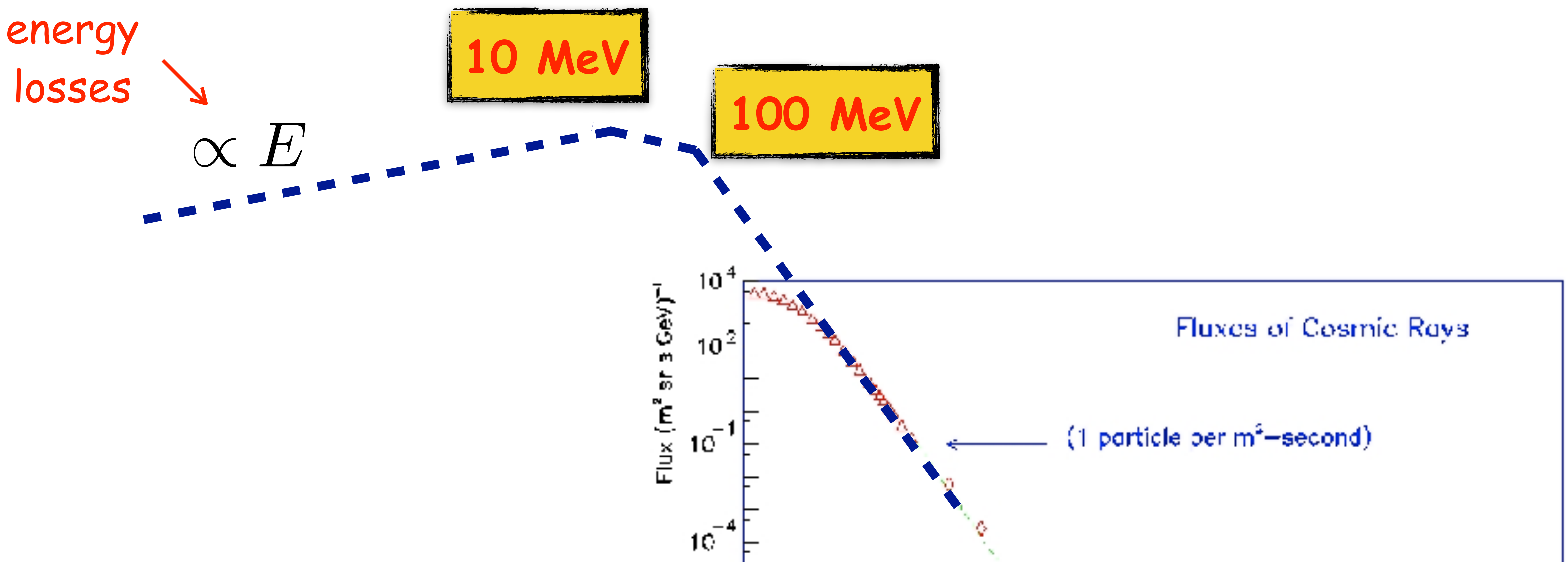
Intro | ballistic? | diffusive! | theory... | ...versus data | So?

Cosmic rays



(1 particle per m²–second)
Knee
(1 particle per m²–year)
(1 particle per km²–year)
solar modulation
most of the people in the room care mainly about this energy domain
from sub-GeV...
to >10²⁰ eV particle energies!

The cosmic ray ionisation rate



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

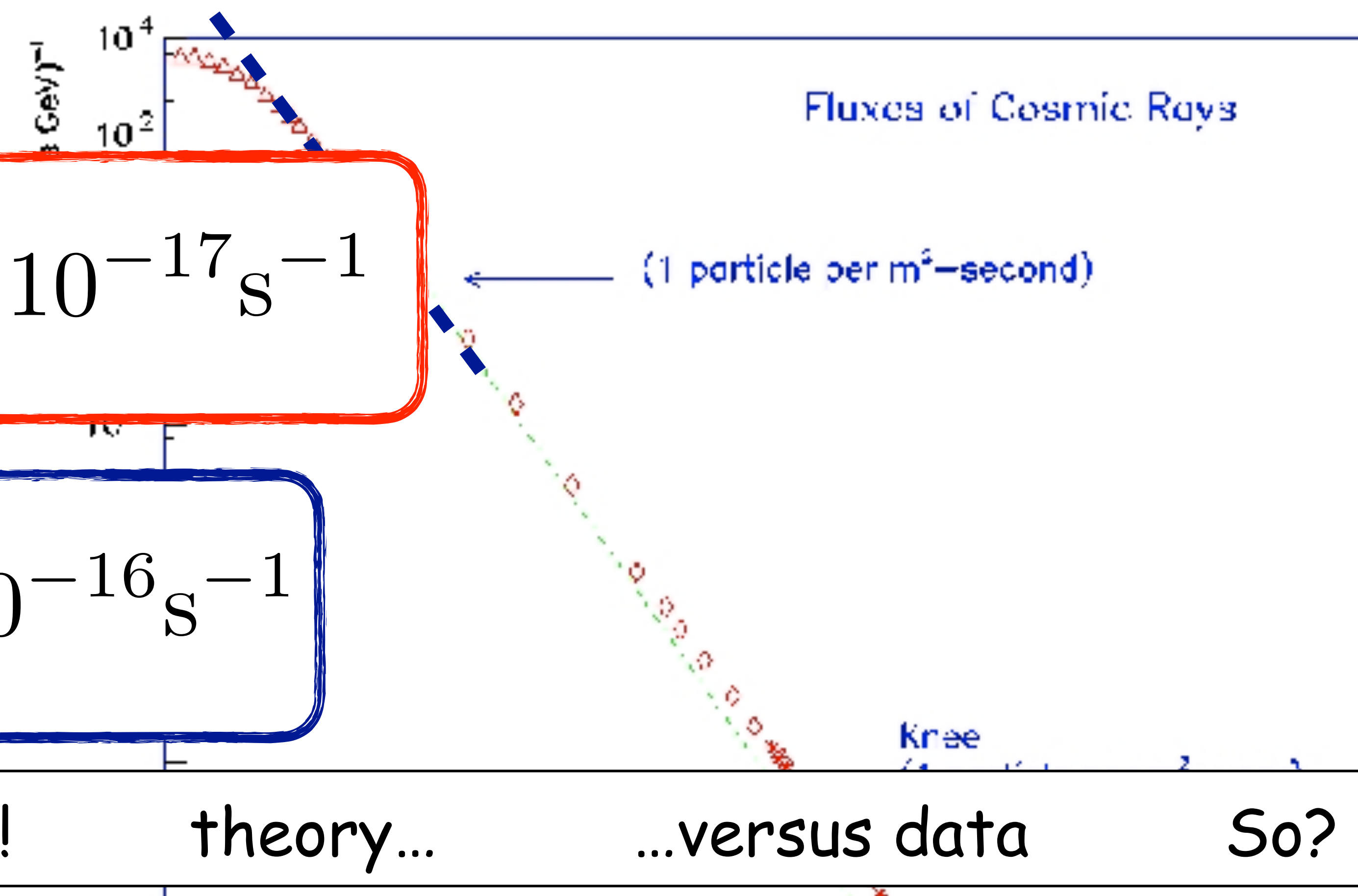
The cosmic ray ionisation rate

energy losses ↘

$\propto E$

10 MeV

0.85 GeV



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

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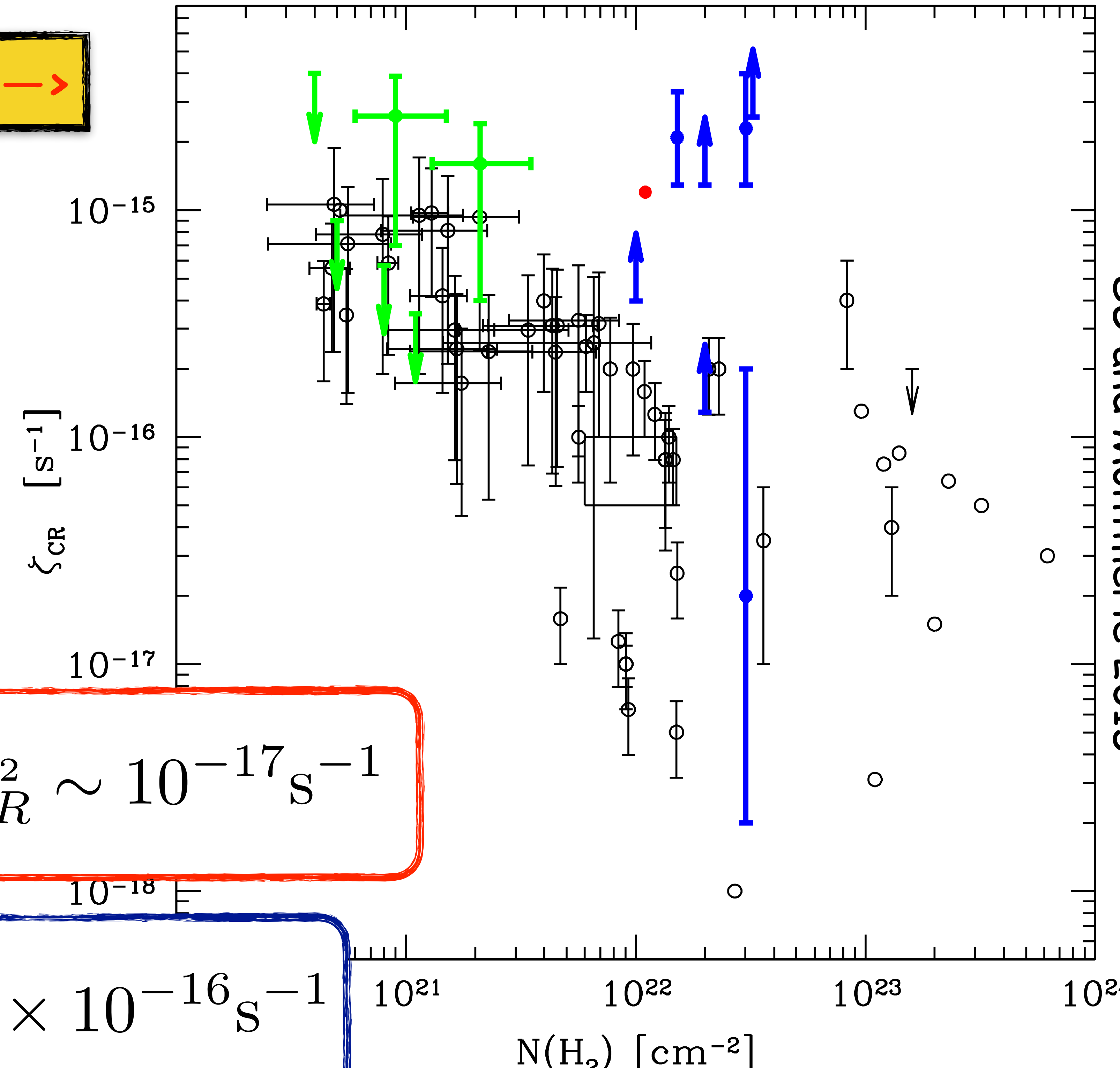
The cosmic ray ionisation rate

ion. rates observed in MCs —>



SG and Montmerle 2015

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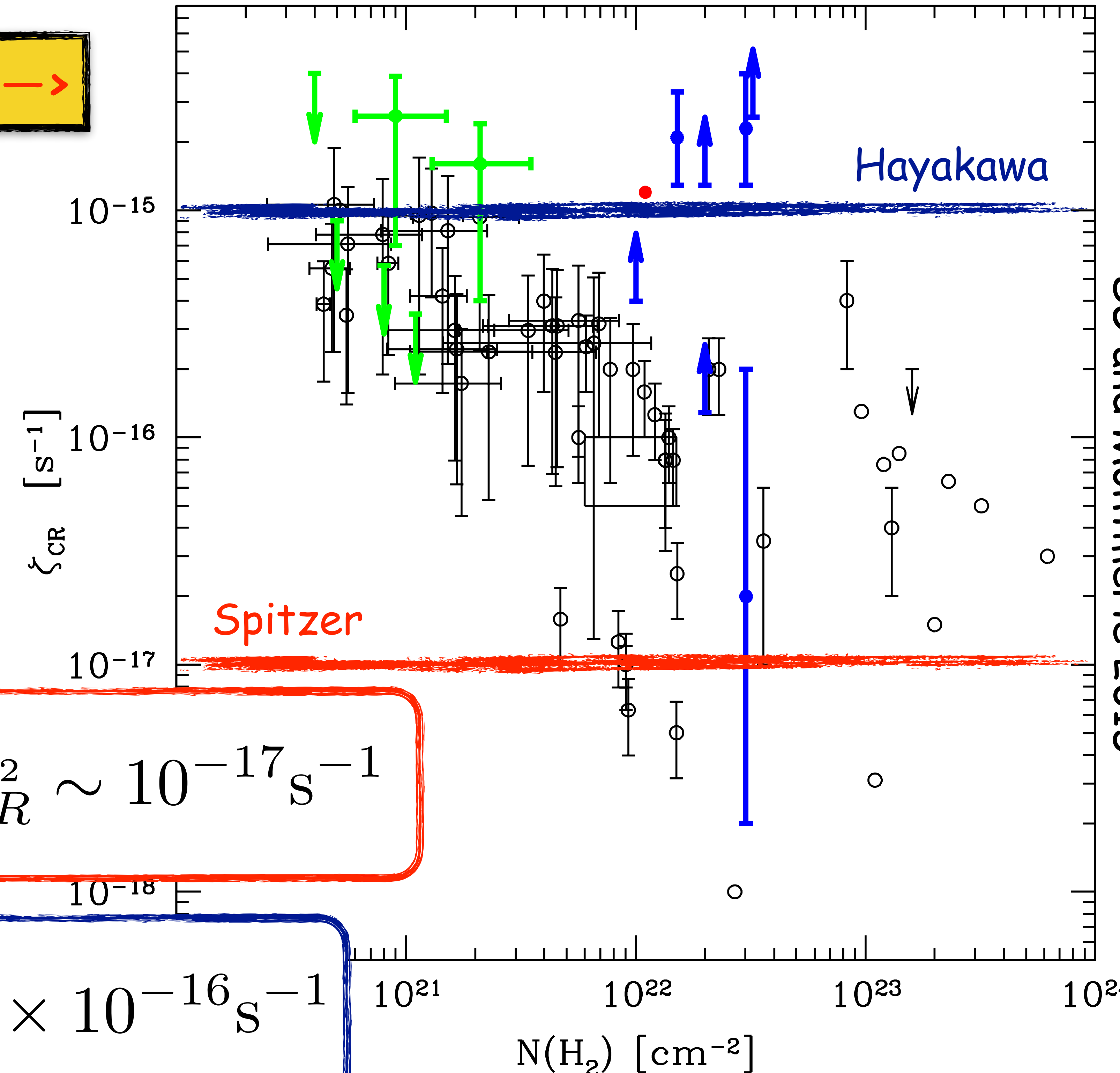

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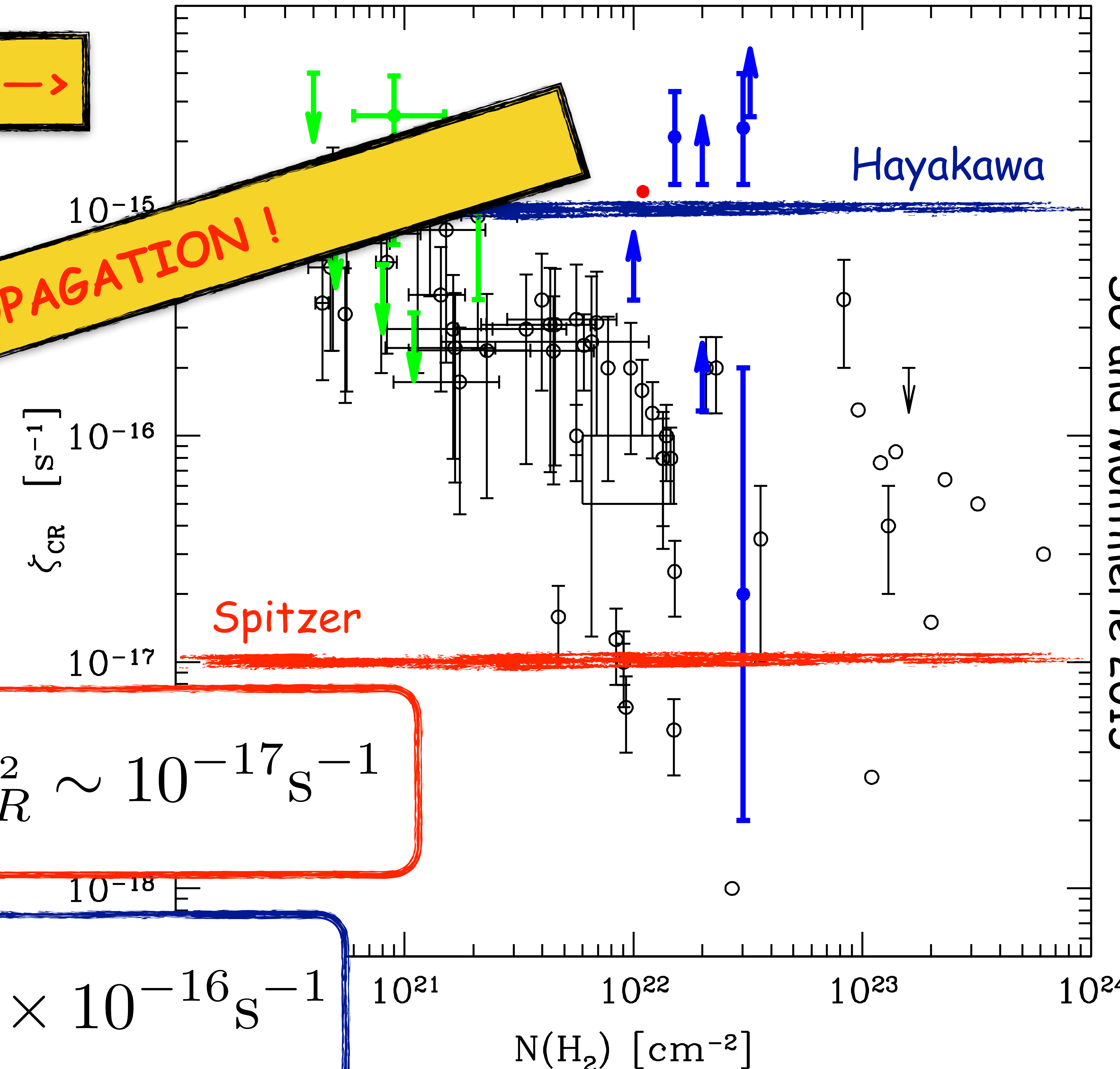

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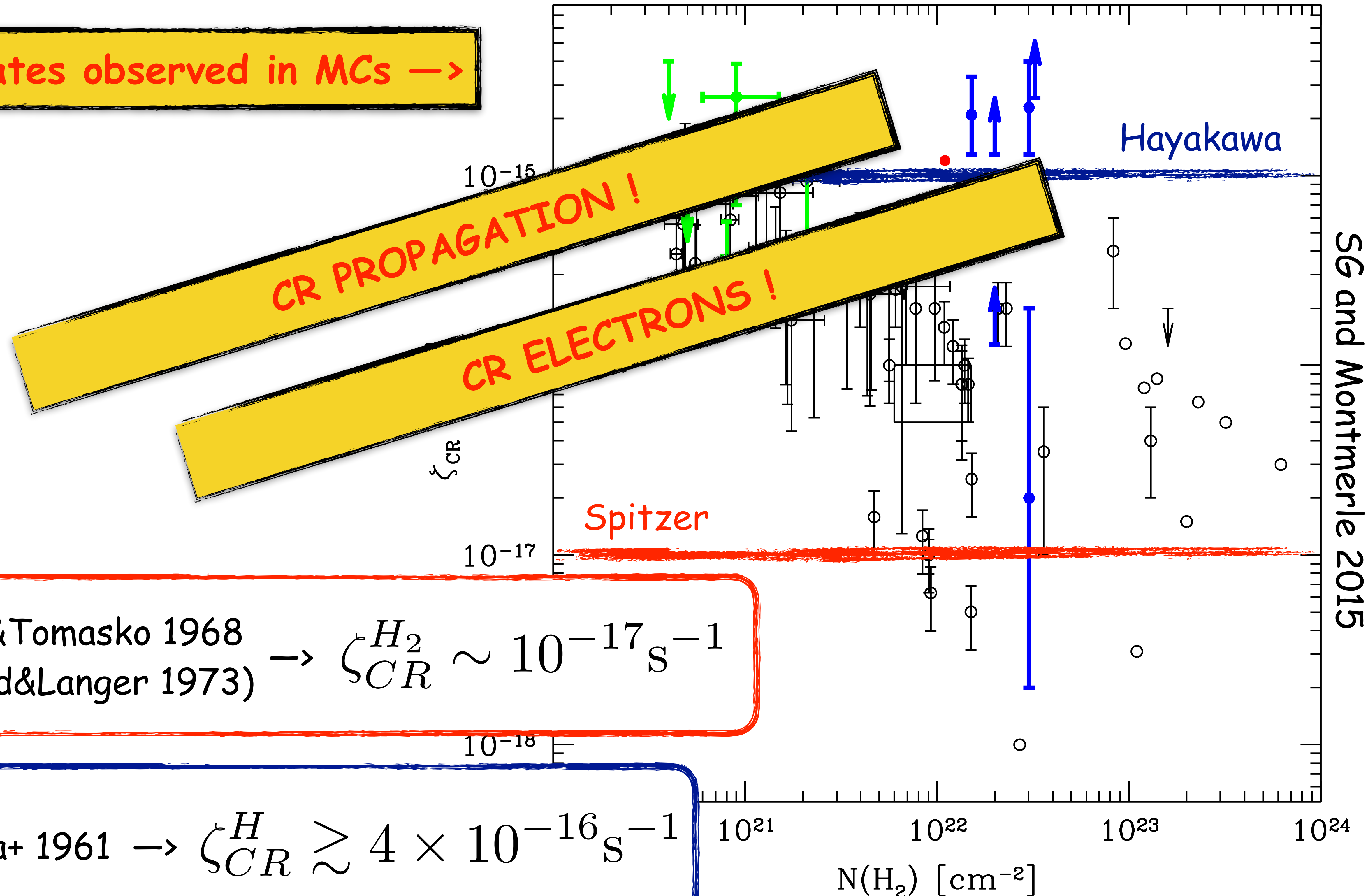

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The (horribly simplified) setup of the problem

interstellar magnetic field

The (horribly simplified) setup of the problem

hot ISM | cloud | hot ISM

fully ionised H

neutral H_2

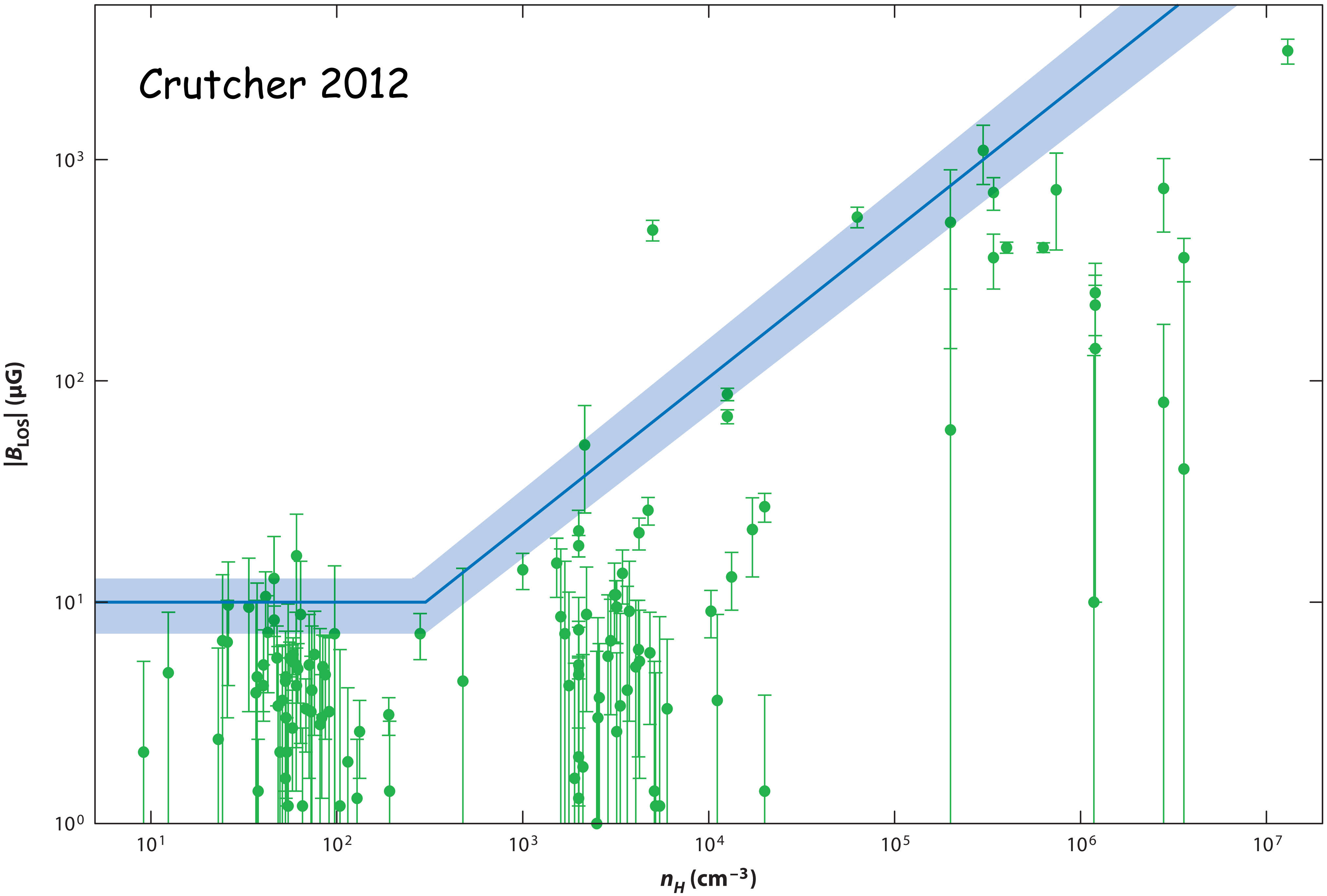
$$n_i \sim 0.01 \text{ cm}^{-3}$$

$$n_n \sim 100 \text{ cm}^{-3}$$

$\vec{B}$

interstellar magnetic field

The (horribly simplified) setup of the problem



ot ISM

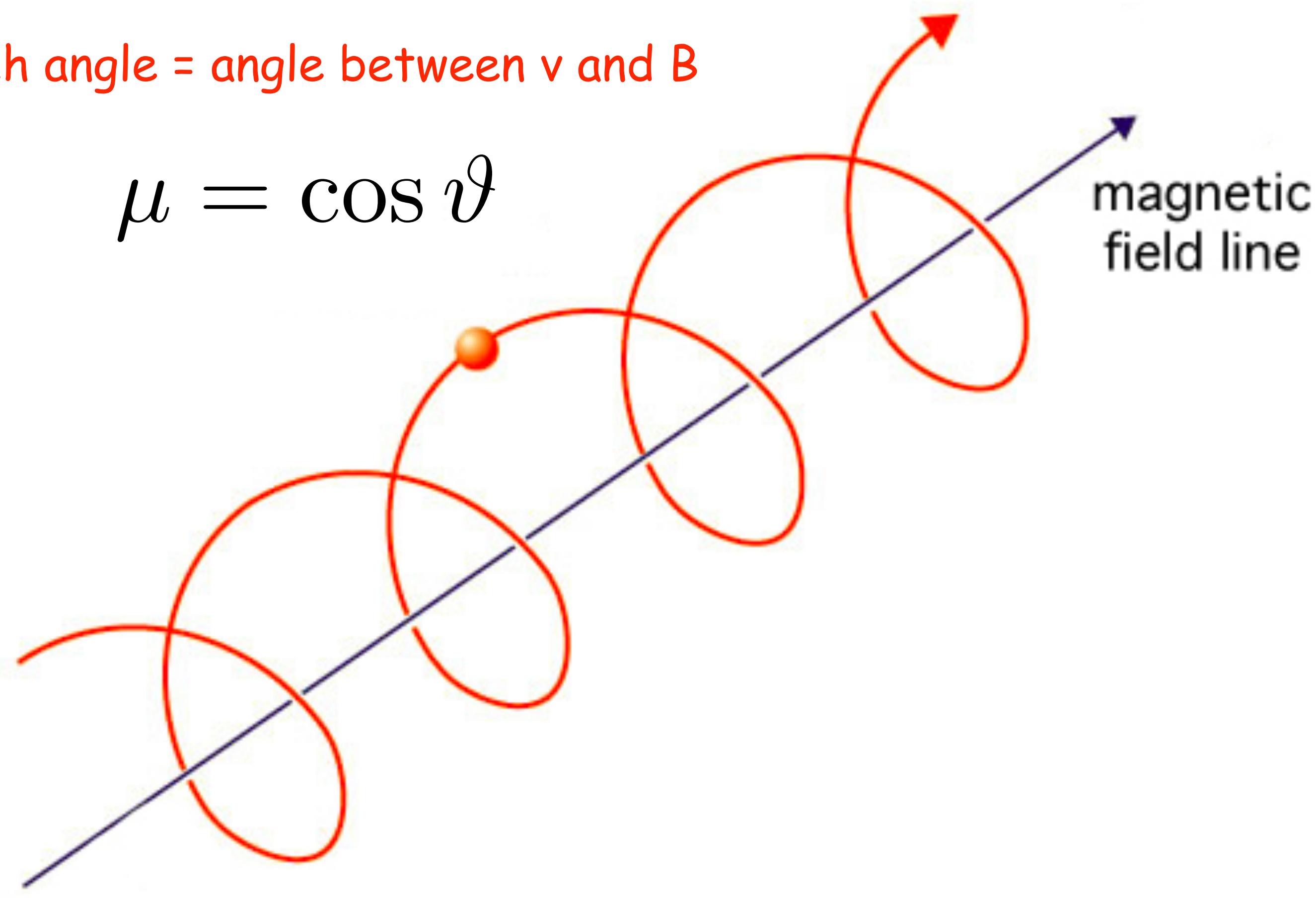
$\vec{B}$

interstellar magnetic field

CR motion in an ordered B field

pitch angle = angle between v and B

$$\mu = \cos\vartheta$$



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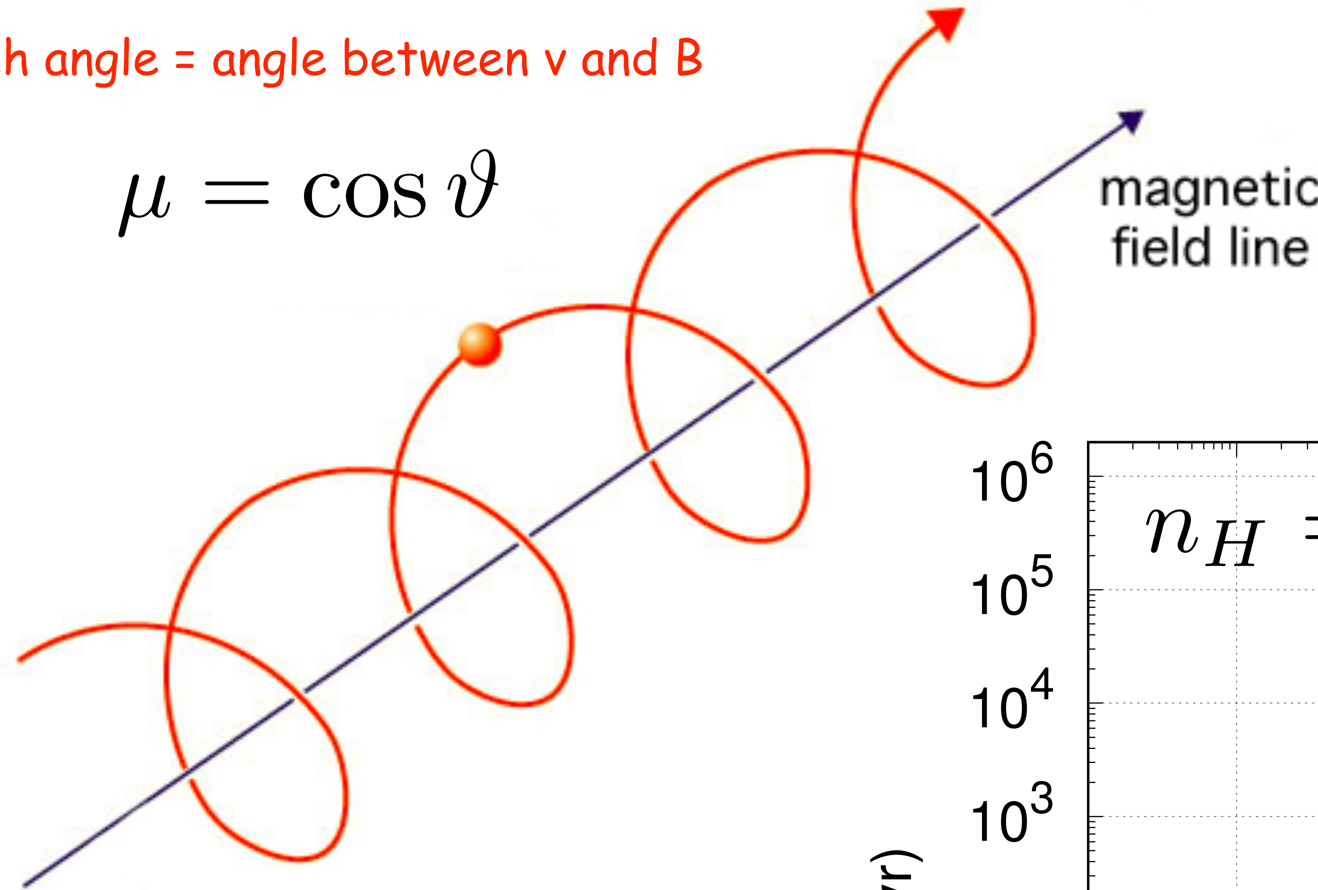
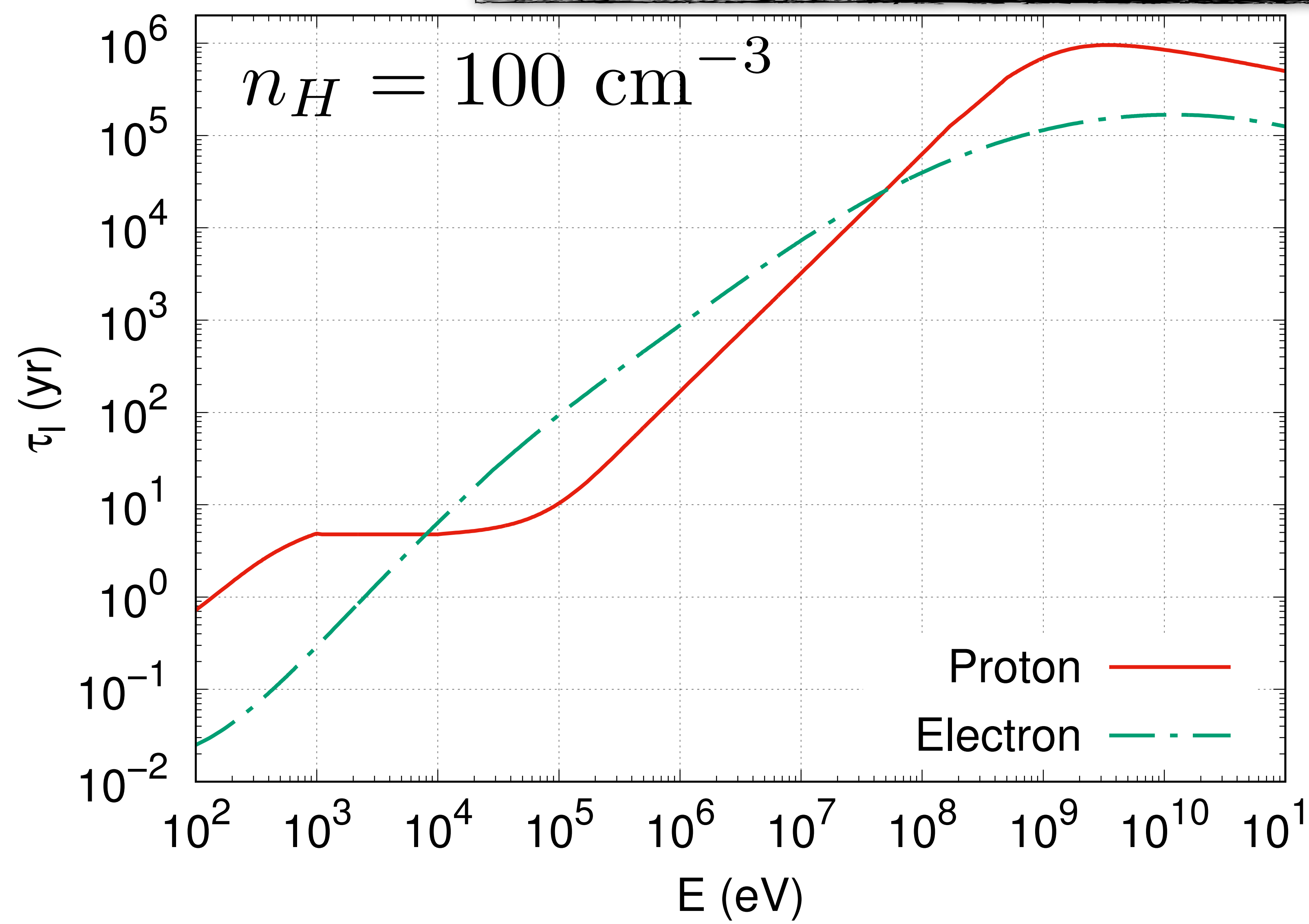
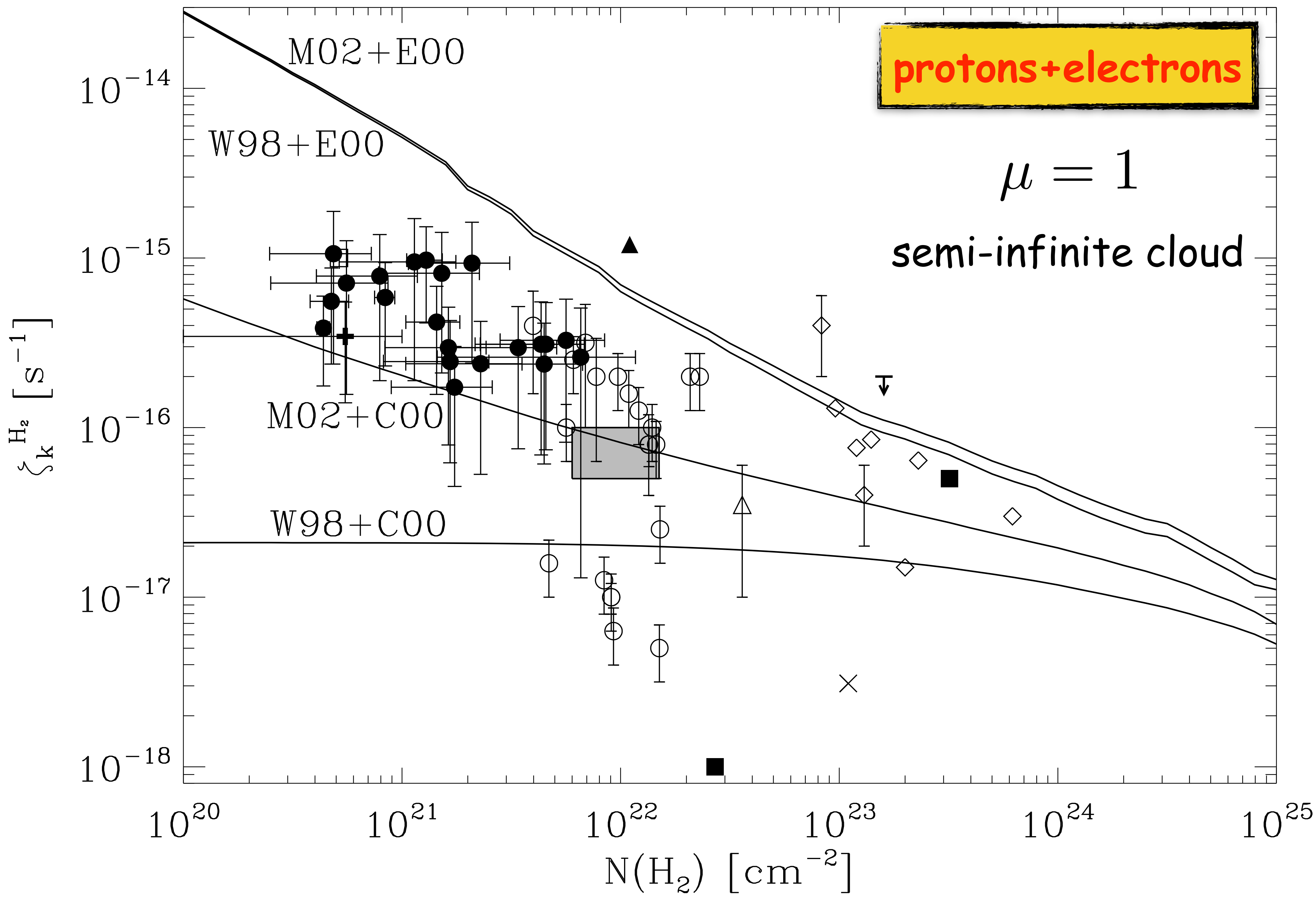


energy losses (mainly ionisation)

Padovani+ 2009 —>
Phan+ 2018

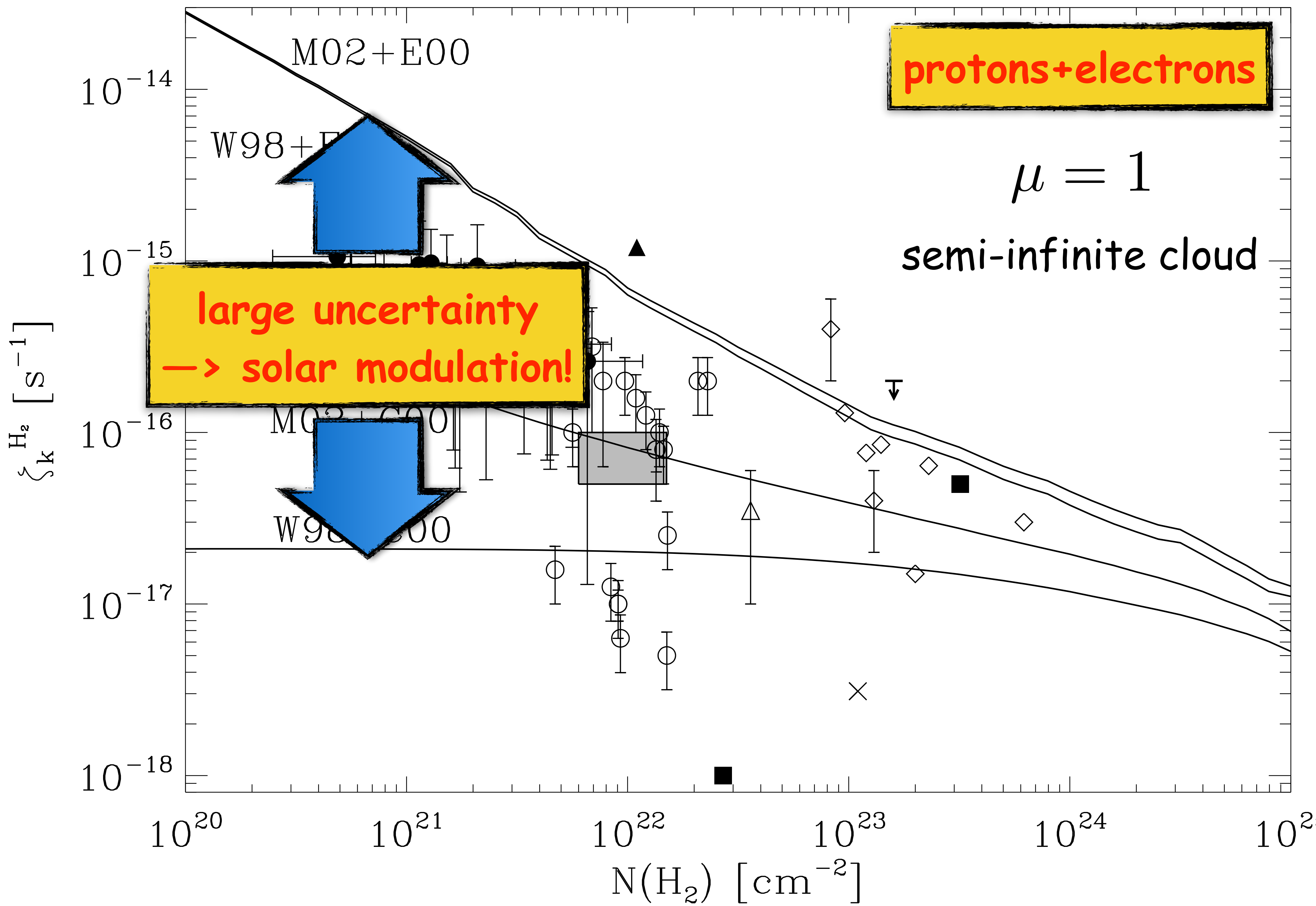


Most optimistic scenario



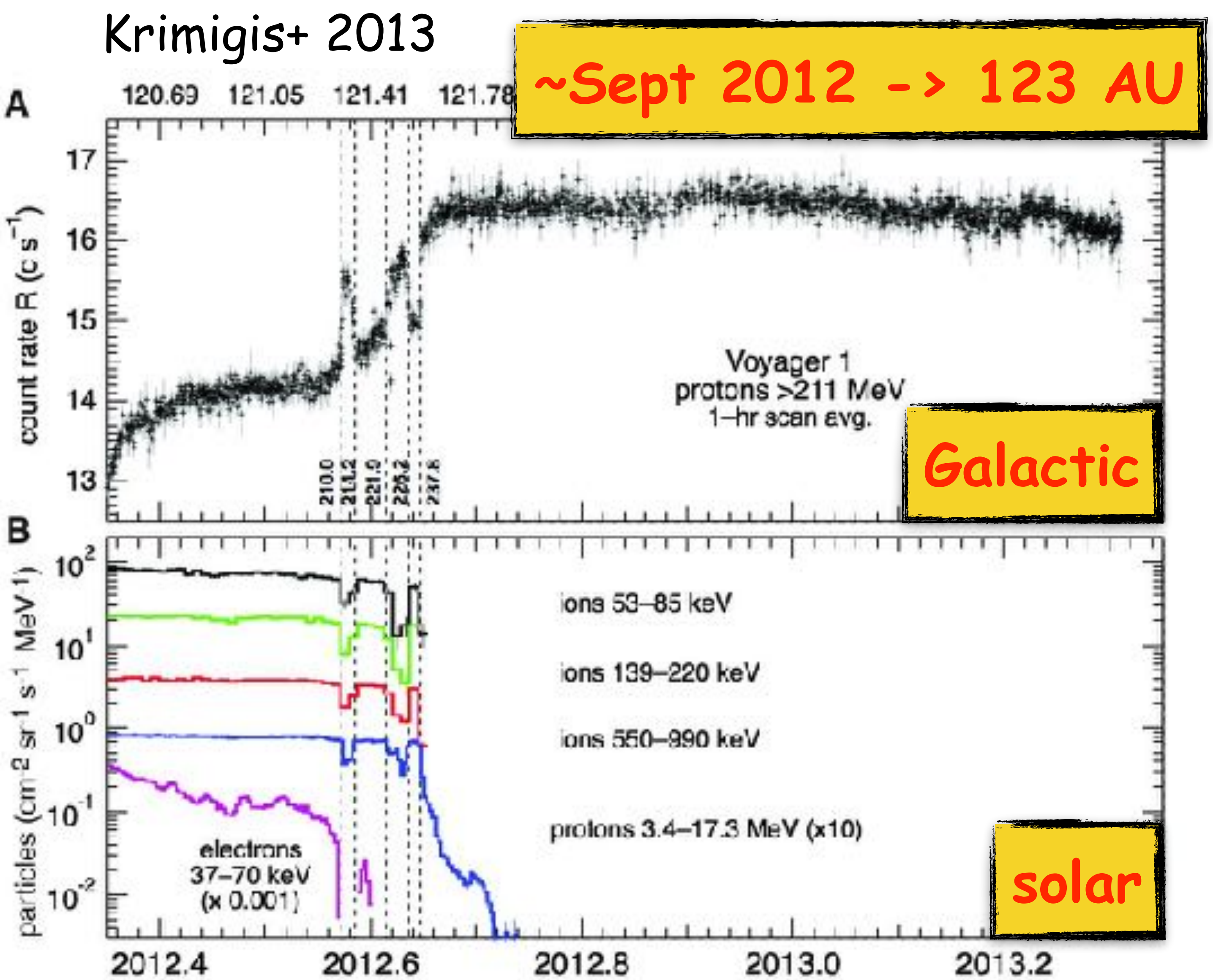
Padovani+ 2009

Most optimistic scenario



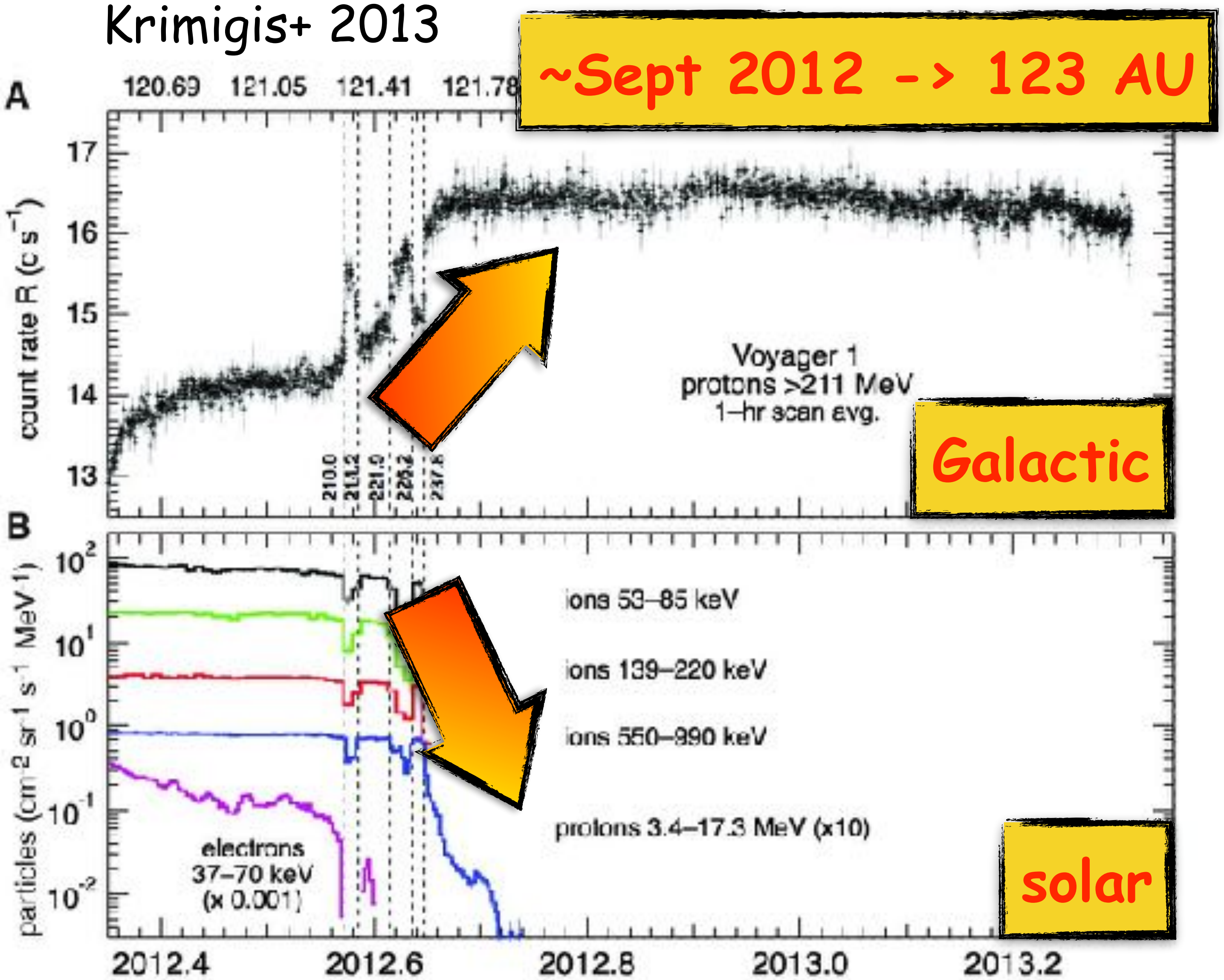
Padovani+ 2009

Voyager enters the interstellar medium



Voyager enters the interstellar medium

Krimigis+ 2013



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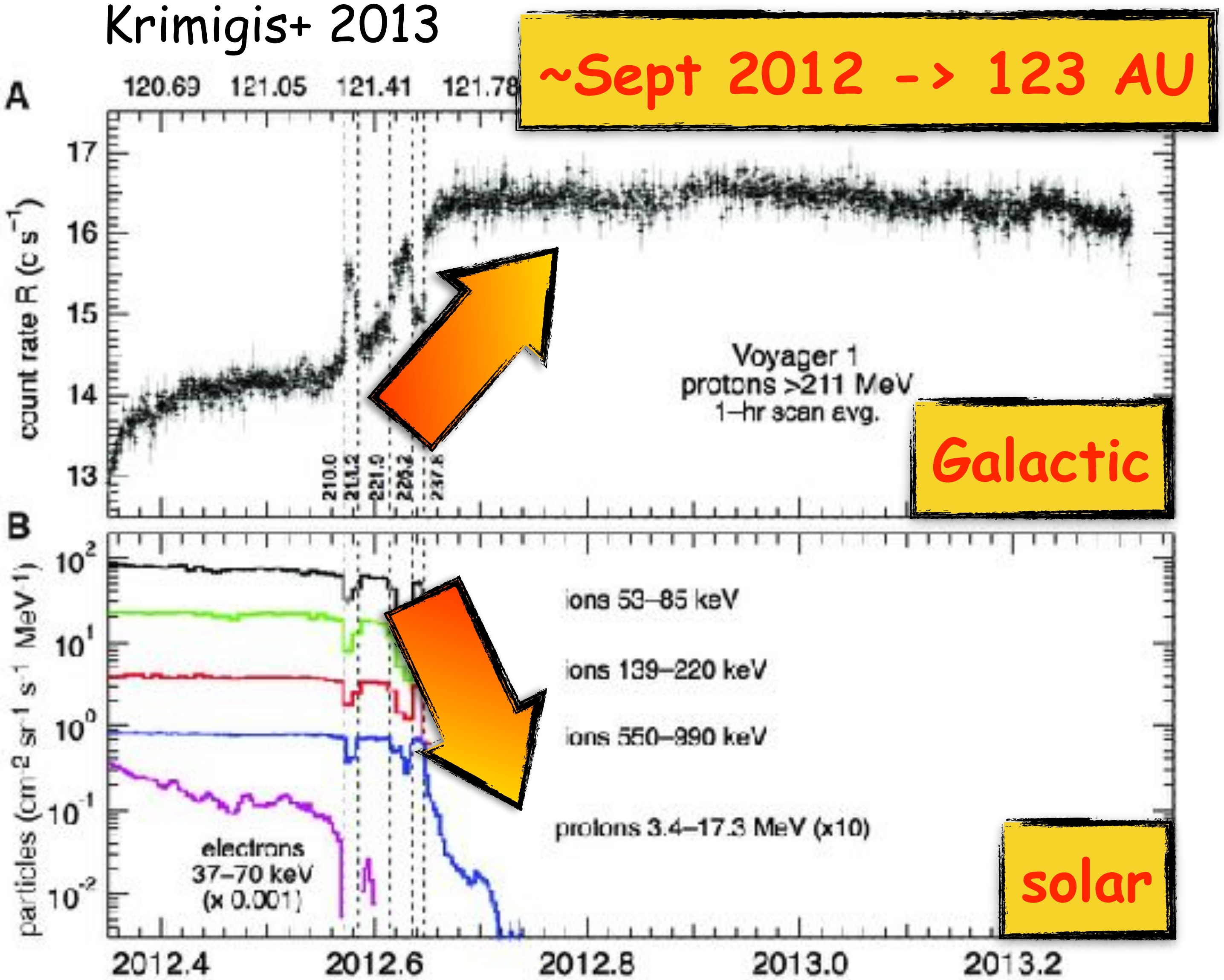
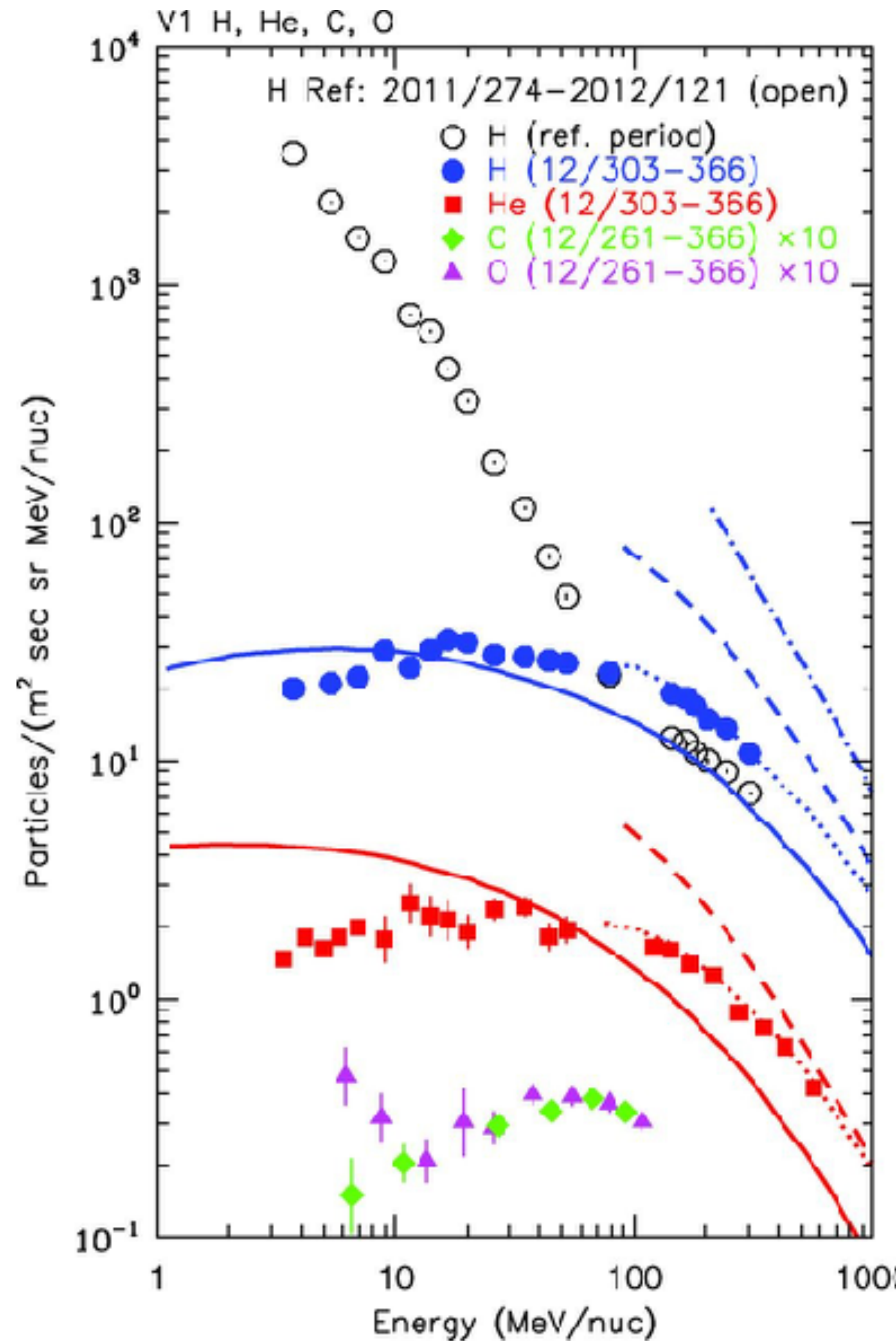
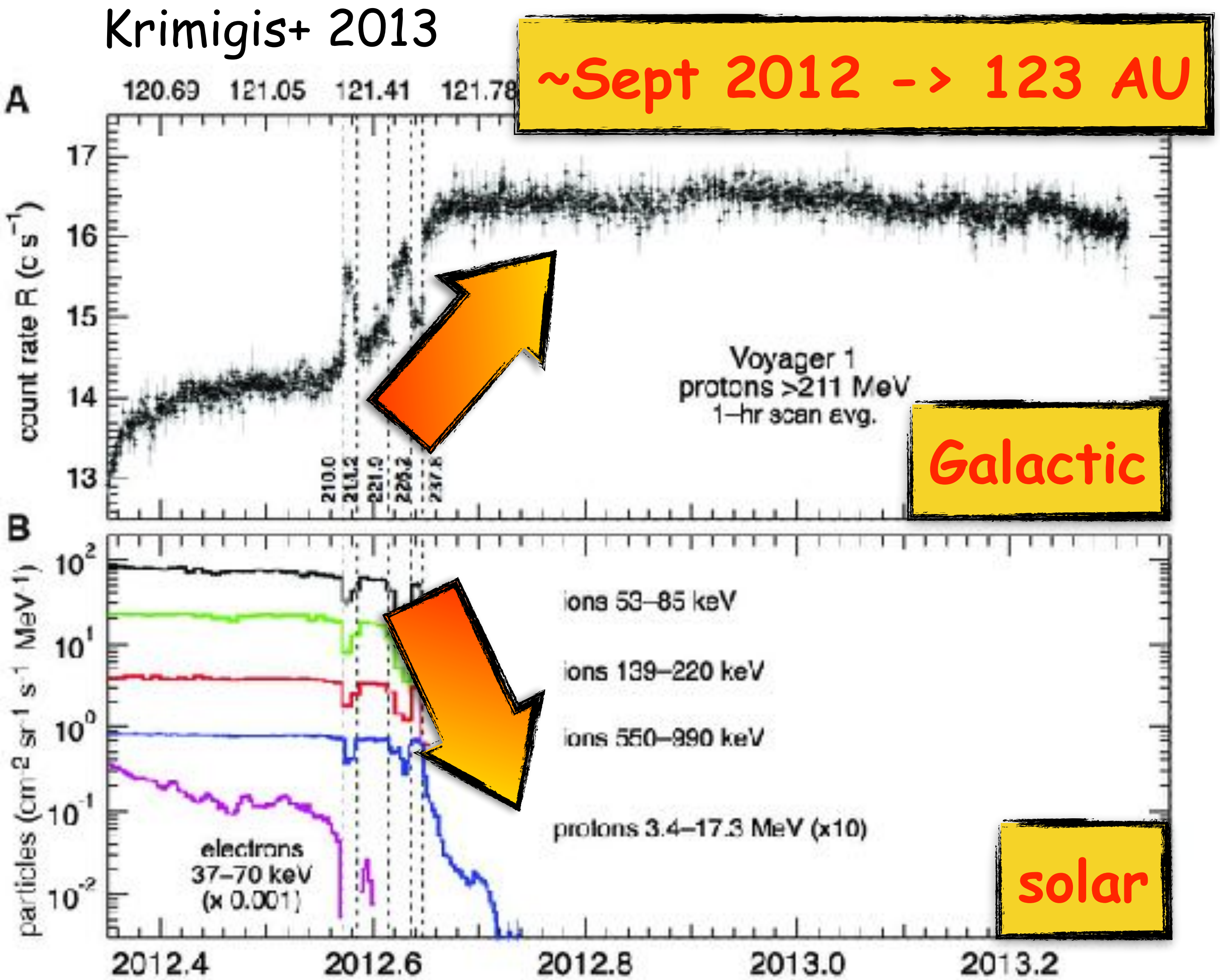
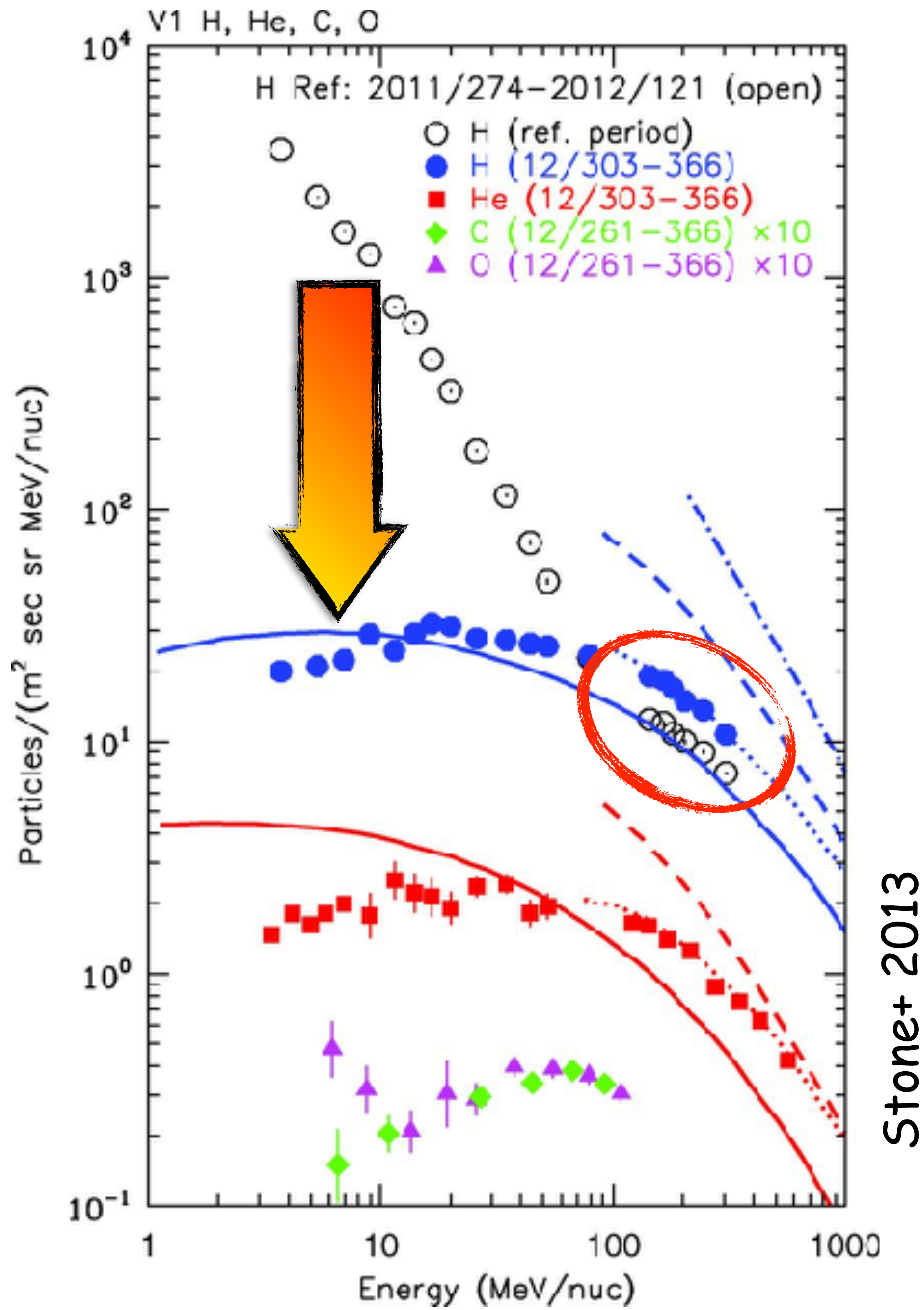




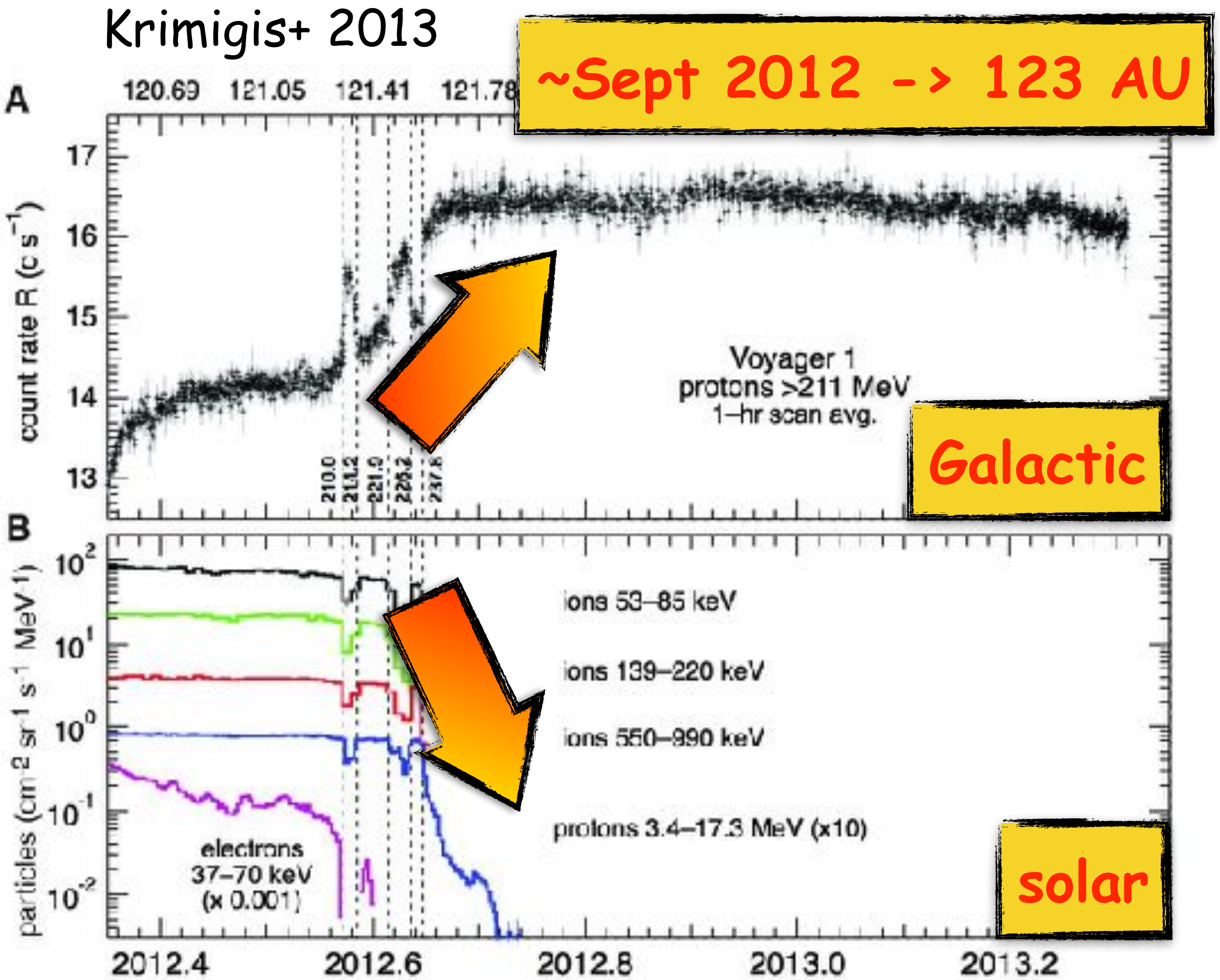
Stone+ 2013

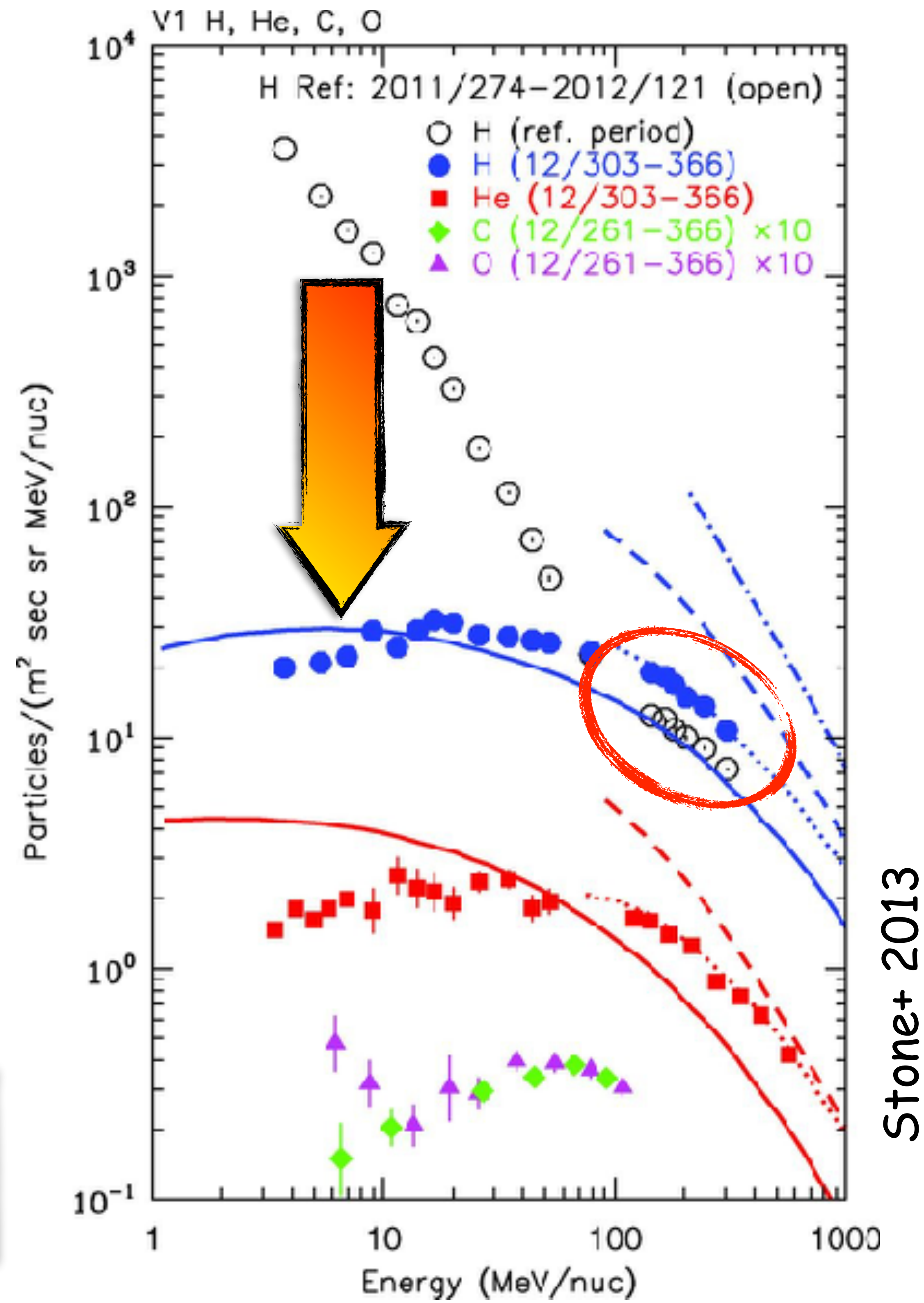
Voyager enters the interstellar medium





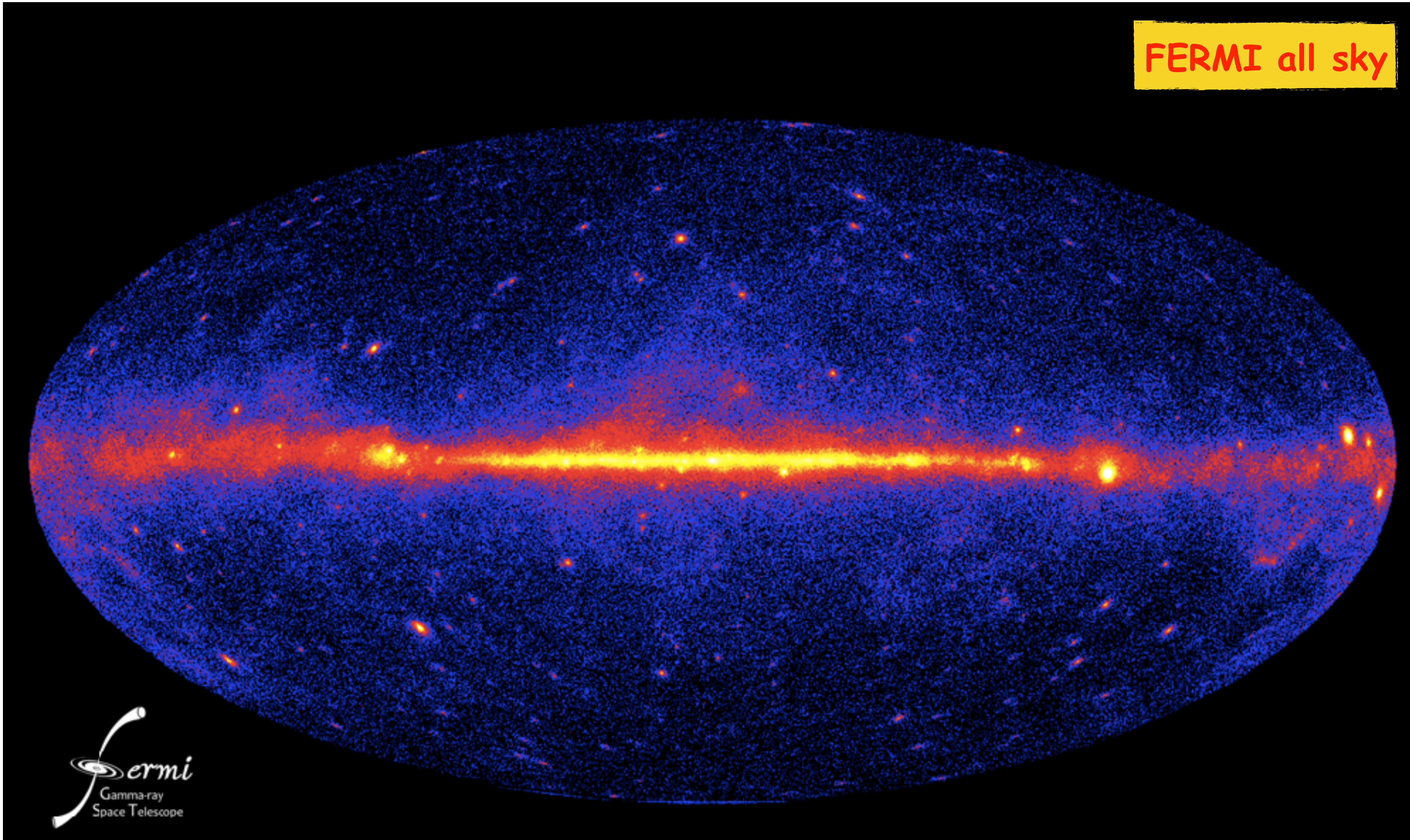
Voyager enters the interstellar medium





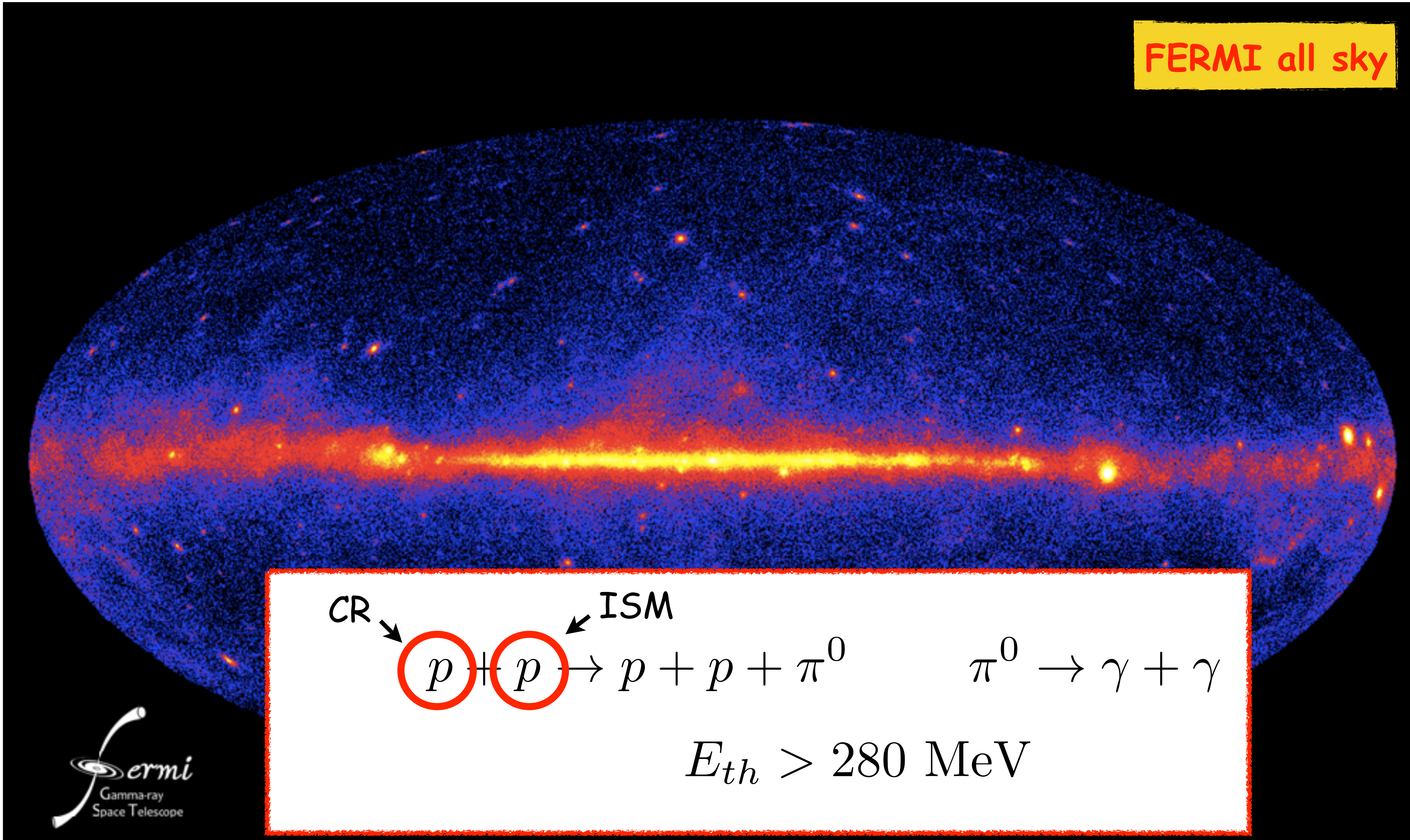
Zero order assumption: these spectra are representative for the entire ISM

Voyager enters the interstellar medium



Intro	ballistic?	diffusive!	theory…	…versus data	So?

Voyager enters the interstellar medium



CR → p + p ← ISM

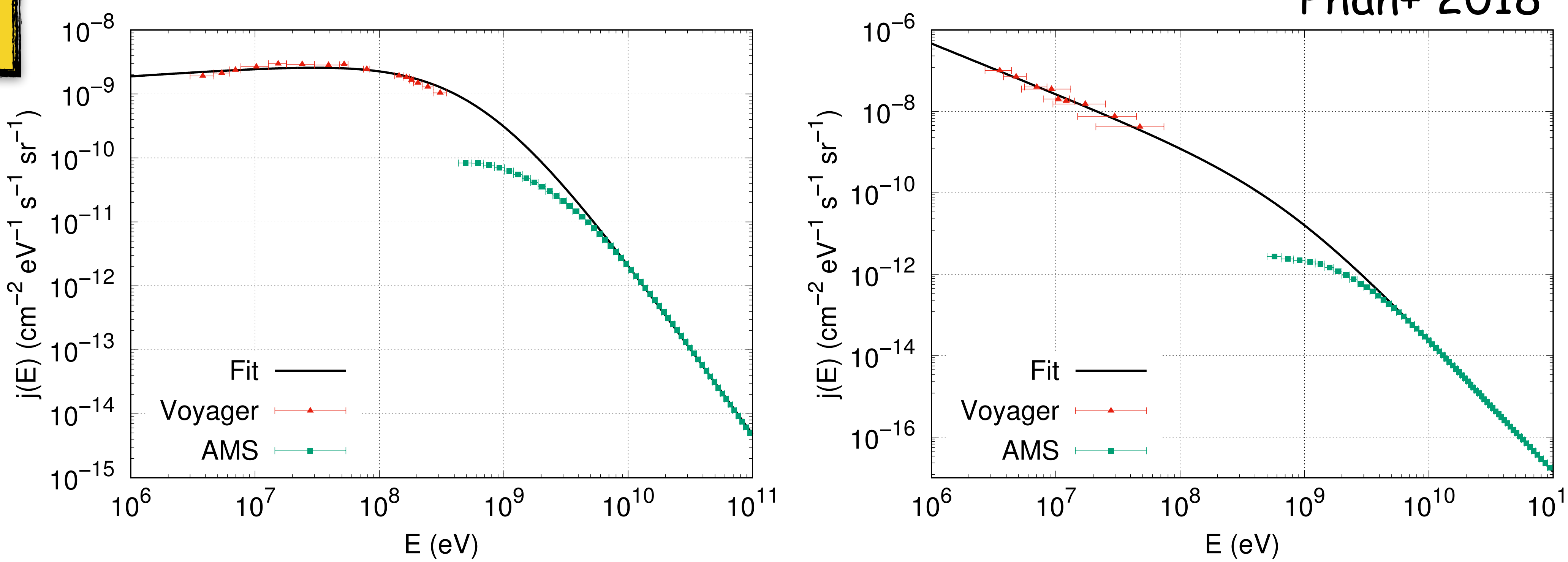
$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow \gamma + \gamma$$

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

Revised estimates…

Voyager spectra

Phan+ 2018



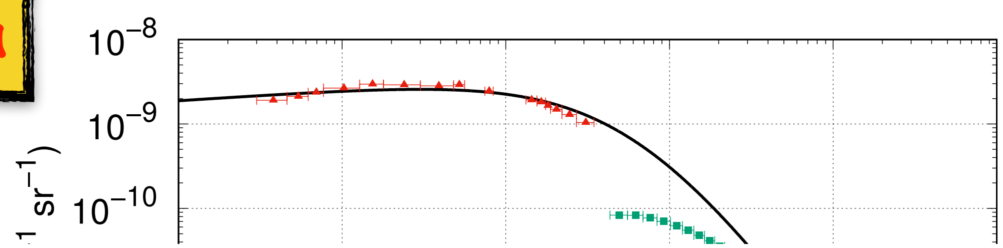
(a) CR protons

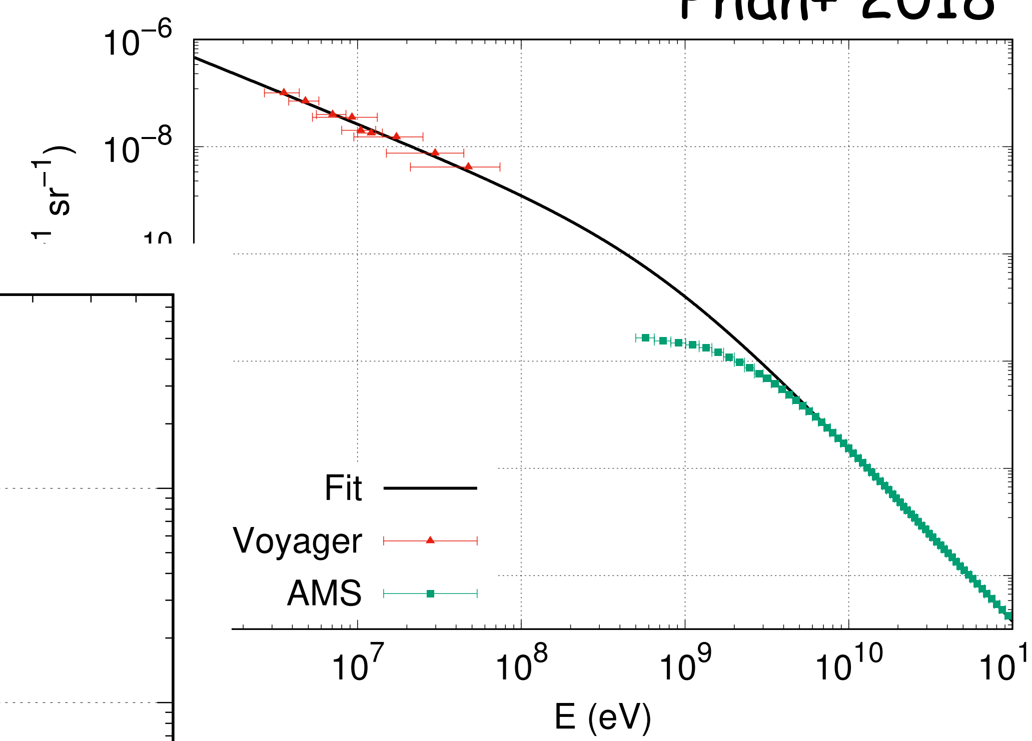
(b) CR electrons

Revised estimates…

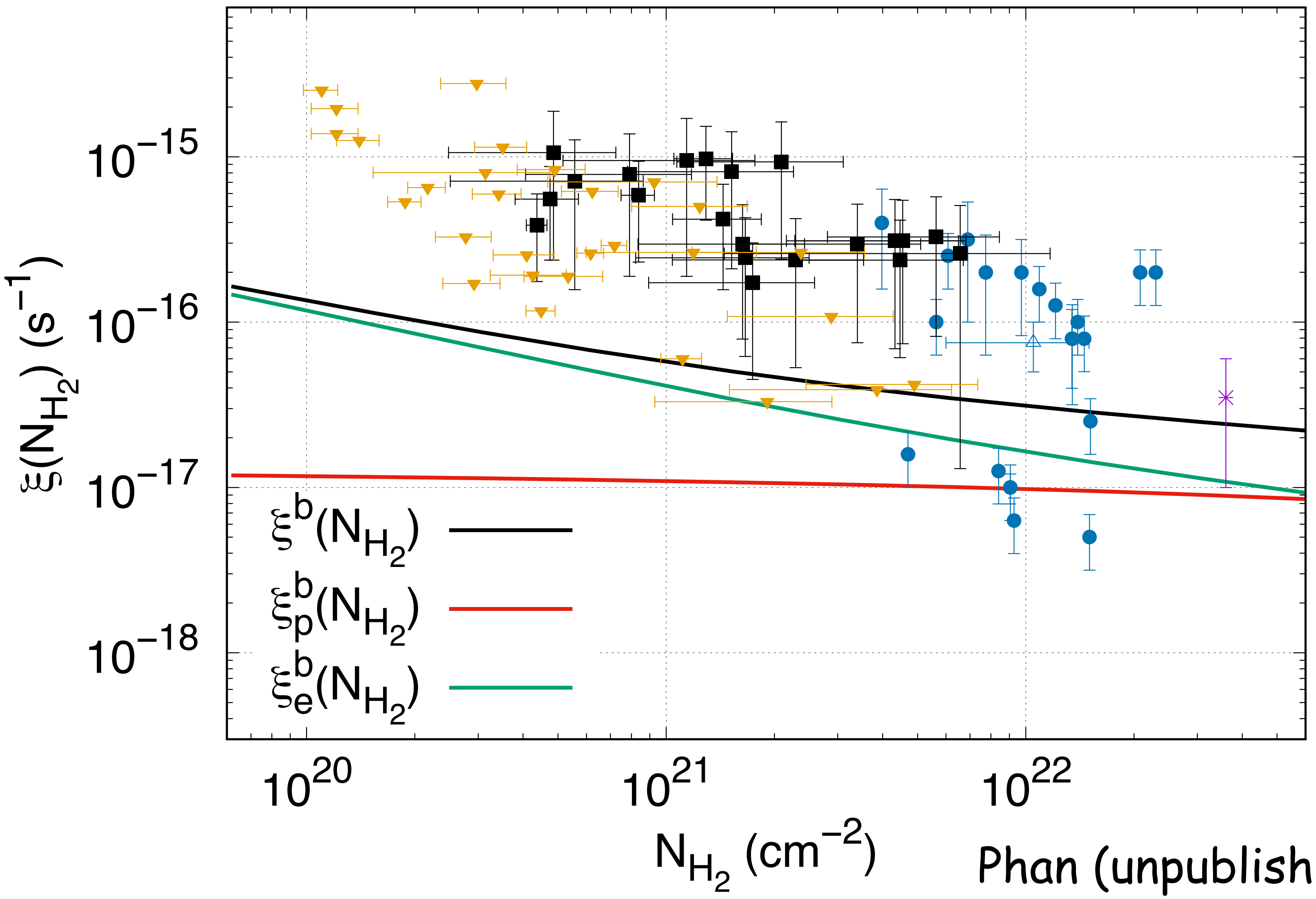
Voyager spectra

Phan+ 2018





(b) CR electrons



$$\mu = 1/2$$

finite cloud (2-sided)

Phan (unpublished), see also Ivlev+ 2015

The transport equation for cosmic rays

$$\frac{\partial f}{\partial t} = \quad ......?$$

$$f \equiv f(z, p, t)$$

particle distribution function → f

momentum → p

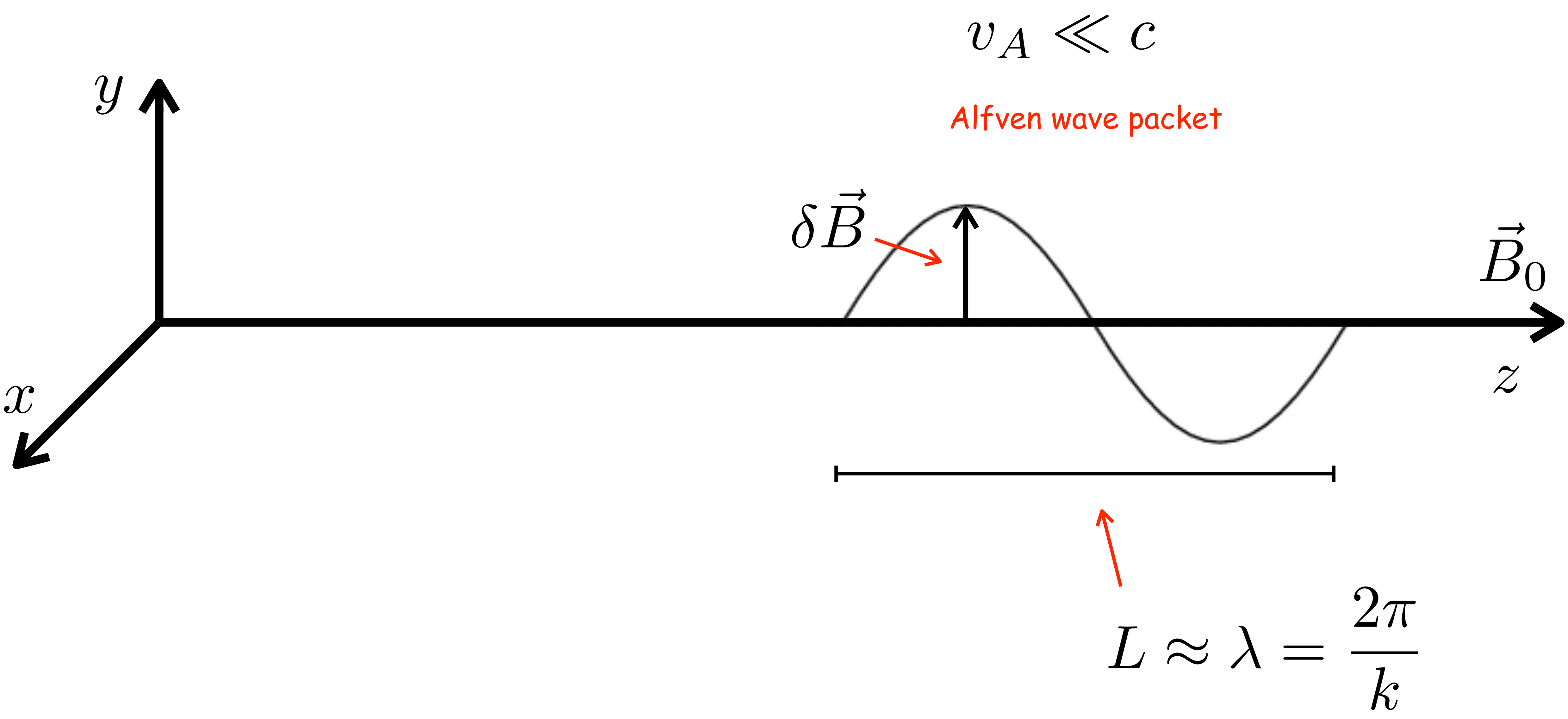
space → z

time → t

Pitch angle scattering off Alfven waves

Wentzel 1972, Kulsrud's book, ...

Pitch angle scattering off Alfven waves



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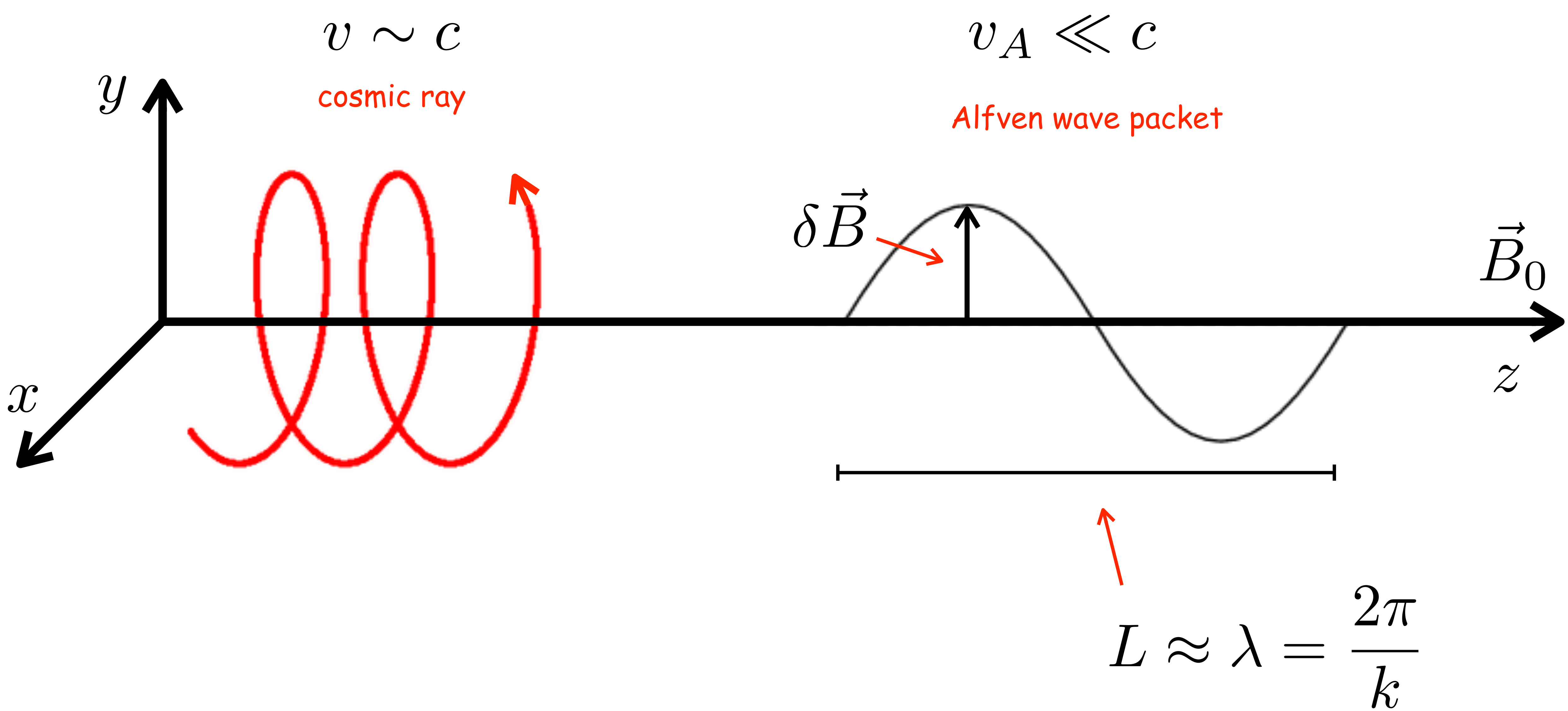

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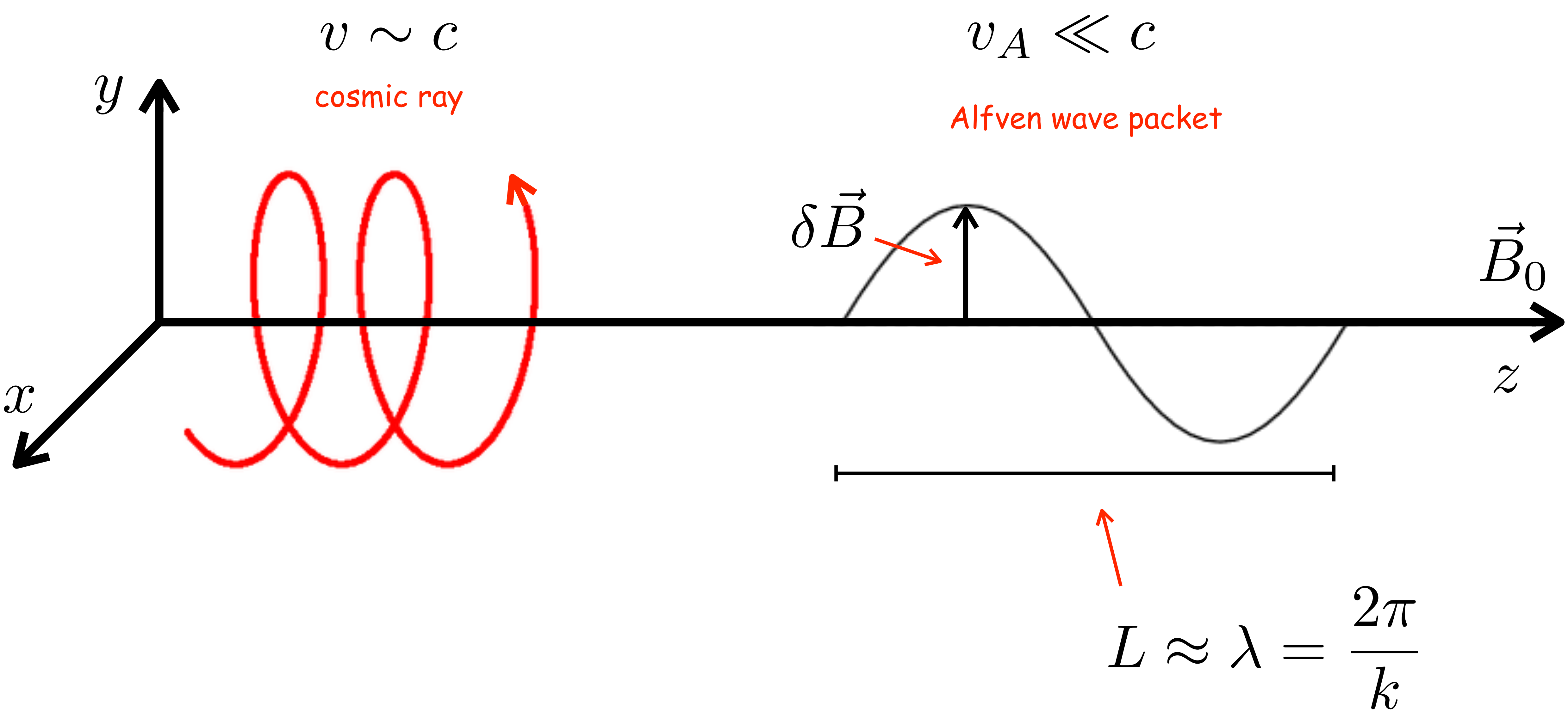
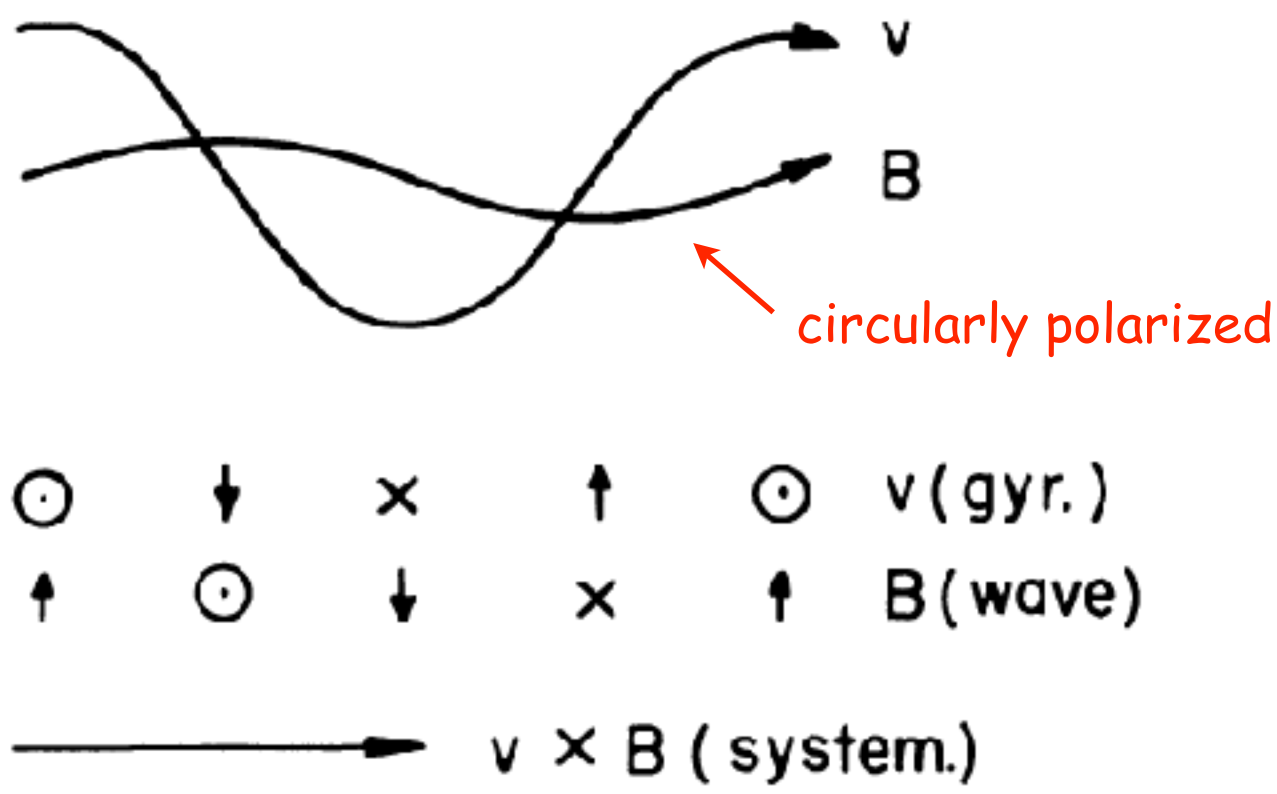


—> wave at rest -> Lorentz force -> energy of the particle is conserved

-> change of the pitch angle

Wentzel 1972, Kulsrud's book, ...

Resonant pitch angle scattering

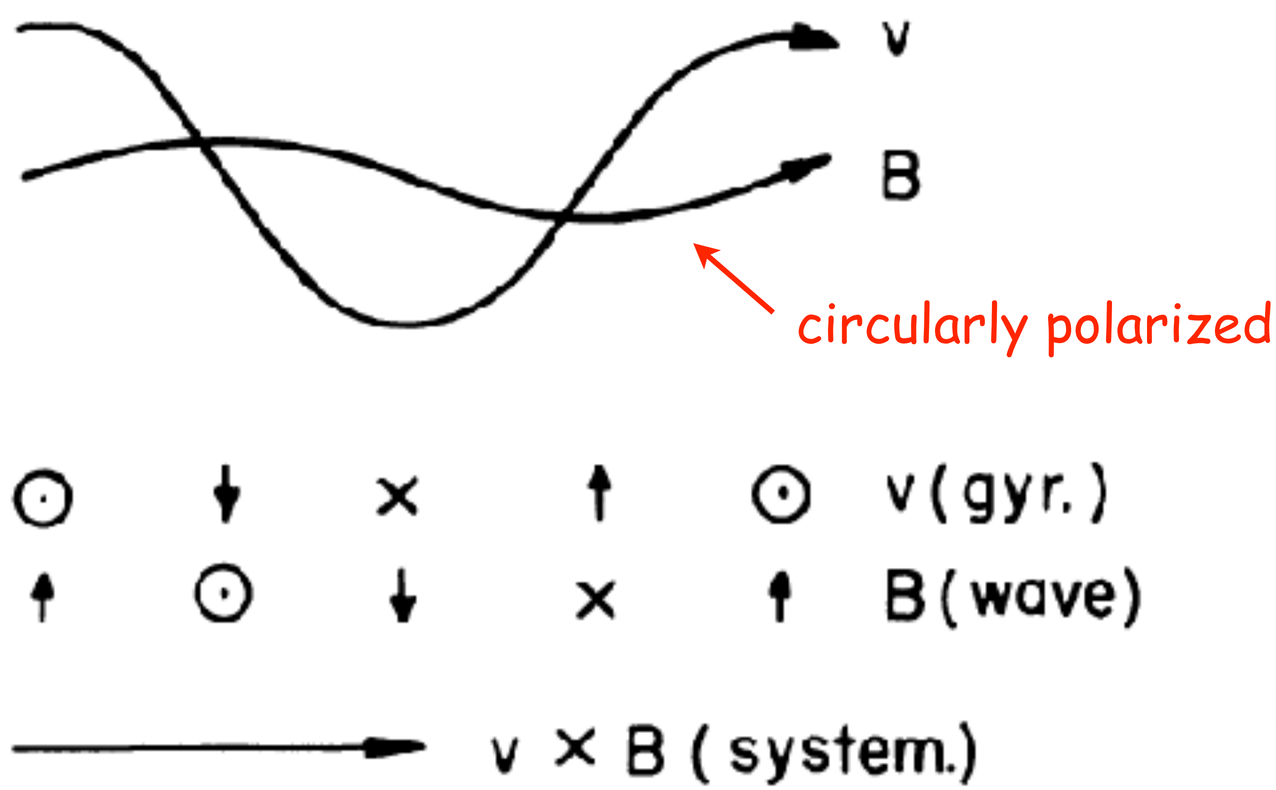


Lorentz force

$$F_L = \frac{q}{c}\, \vec{v} \times \vec{B}$$

Wentzel 1972, Kulsrud's book, ...

Resonant pitch angle scattering



Lorentz force

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neglecting factors of order unity:

Larmor radius

resonance condition: $R_L(p) \approx \frac{1}{k}$

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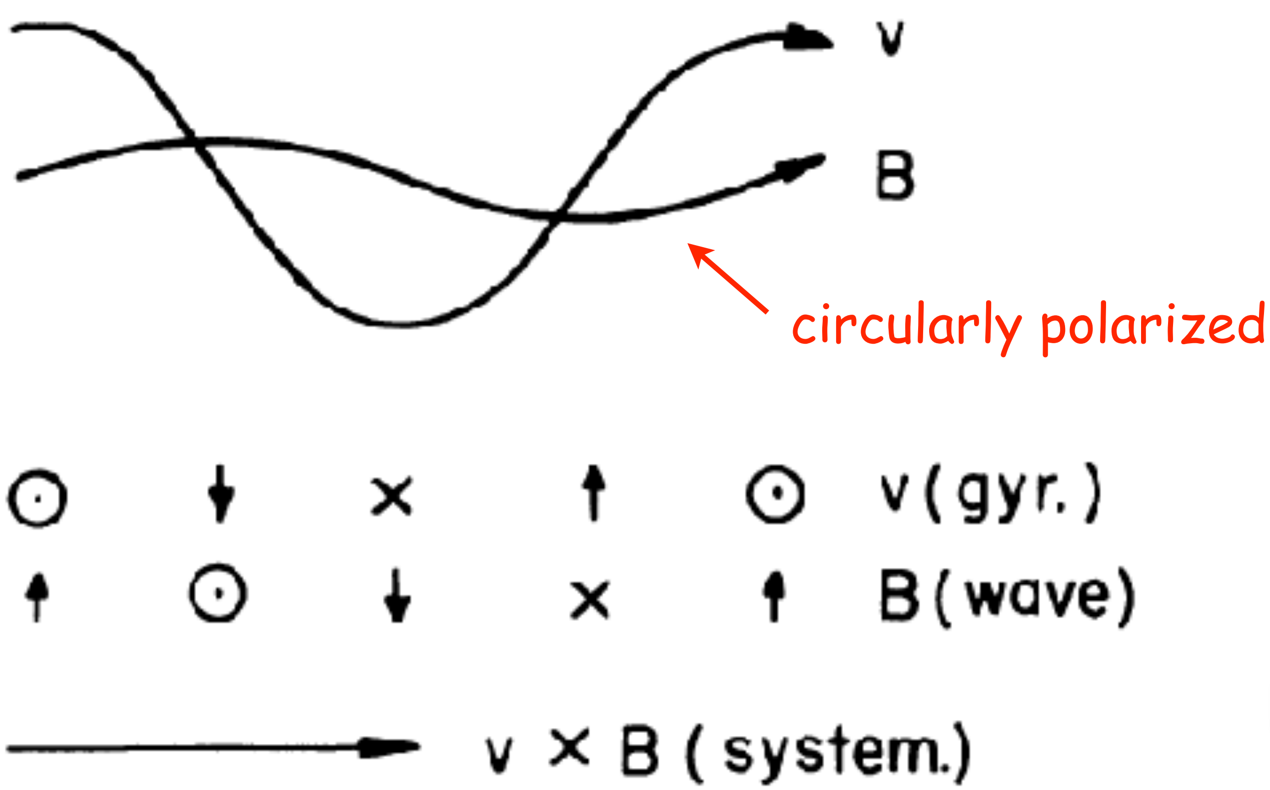
Resonant pitch angle scattering



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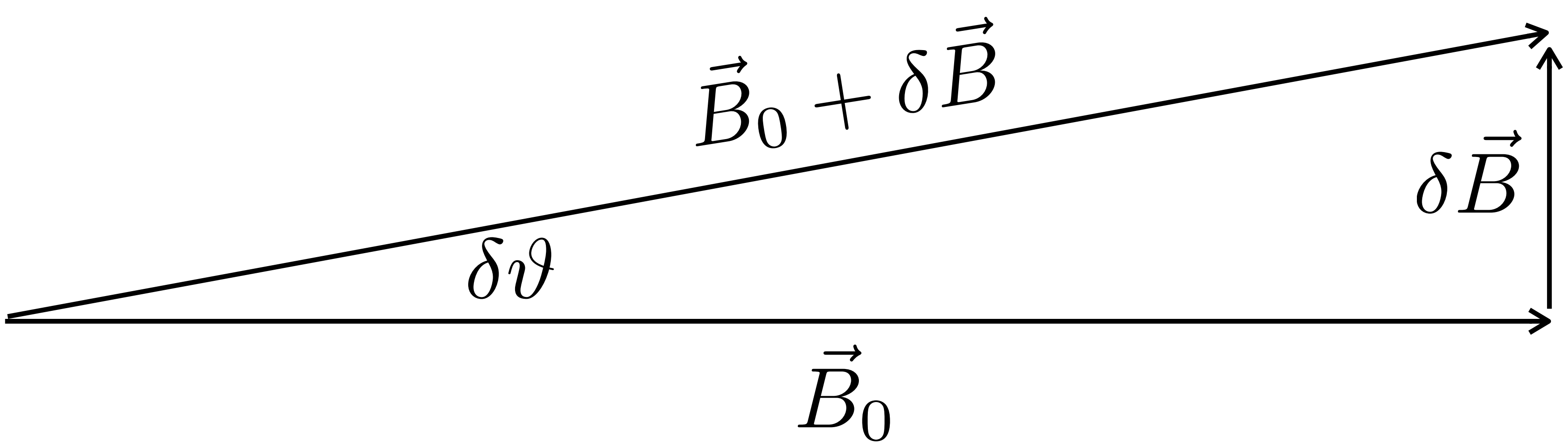
variation of pitch angle = deflection of B due to the wave

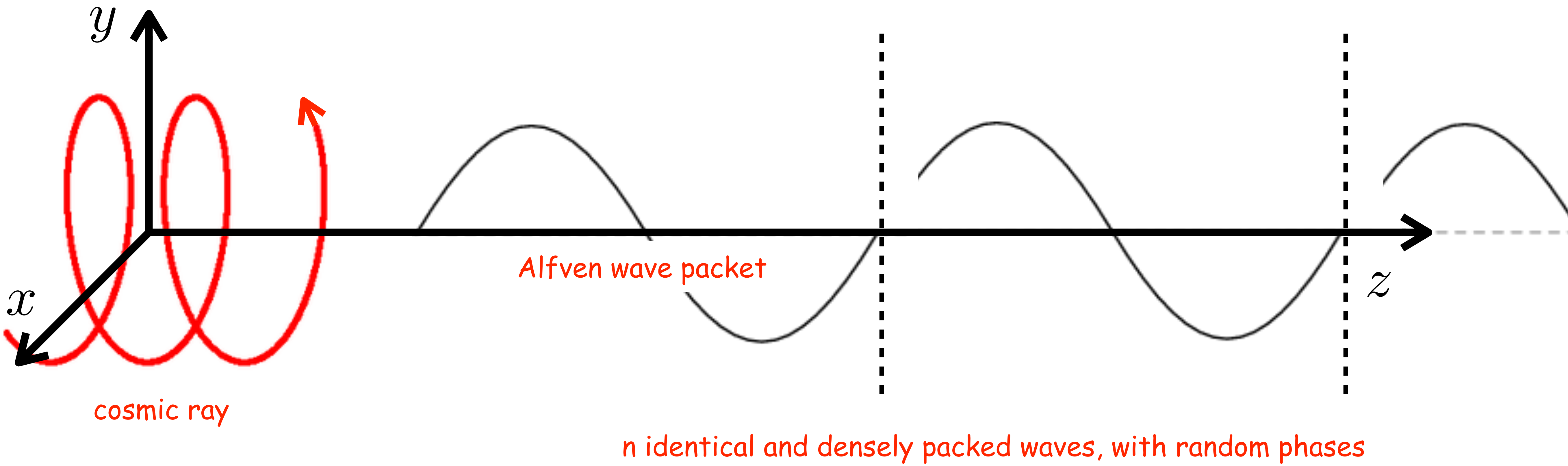


relative phase

$$\delta\vartheta \sim \pm\frac{\delta B}{B_0}$$

Wentzel 1972, Kulsrud's book, ...

Pitch angle diffusion

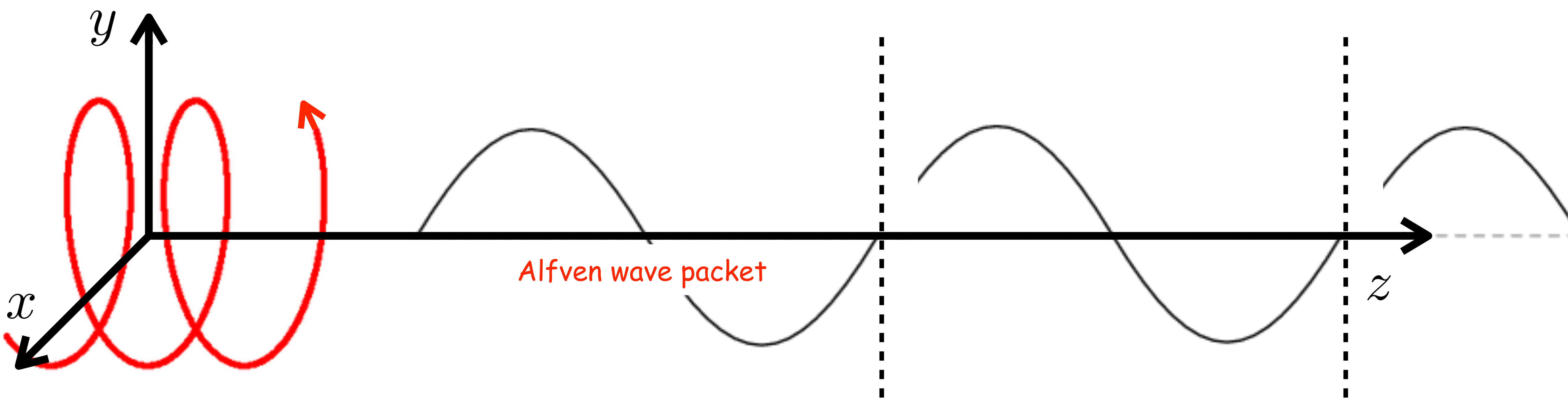


$$\langle (\delta\vartheta)^2 \rangle$$

single scattering

Wentzel 1972, Kulsrud's book, …

Pitch angle diffusion



n identical and densely packed waves, with random phases

random walk

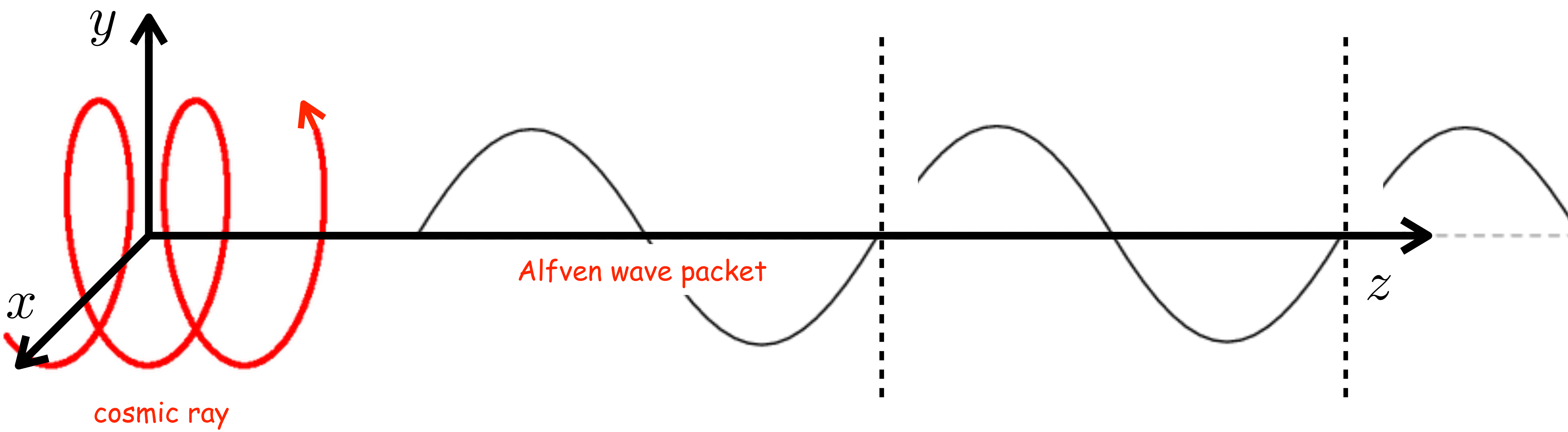
$$\langle (\Delta\vartheta)^2 \rangle = n \, \langle (\delta\vartheta)^2 \rangle$$

total variation of pitch angle

single scattering

Wentzel 1972, Kulsrud's book, ...

Pitch angle diffusion



n identical and densely packed waves, with random phases

random walk

$$\langle (\Delta\vartheta)^2 \rangle = n \, \langle (\delta\vartheta)^2 \rangle = \frac{t}{\tau_c} \, \langle (\delta\vartheta)^2 \rangle$$

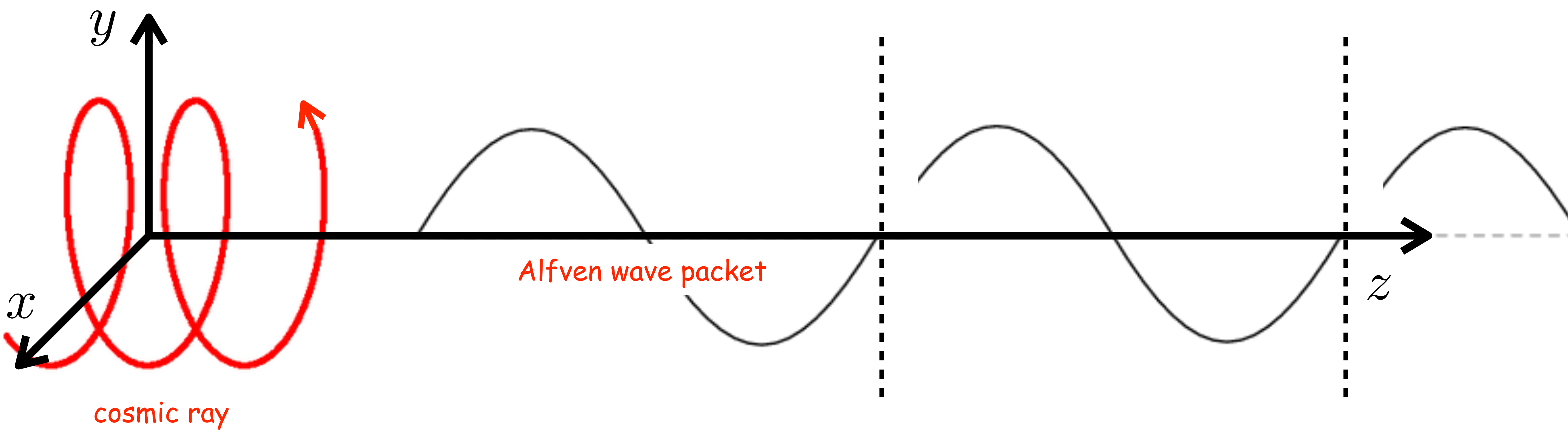
total variation of pitch angle

single scattering

crossing time

Wentzel 1972, Kulsrud's book, …

Pitch angle diffusion



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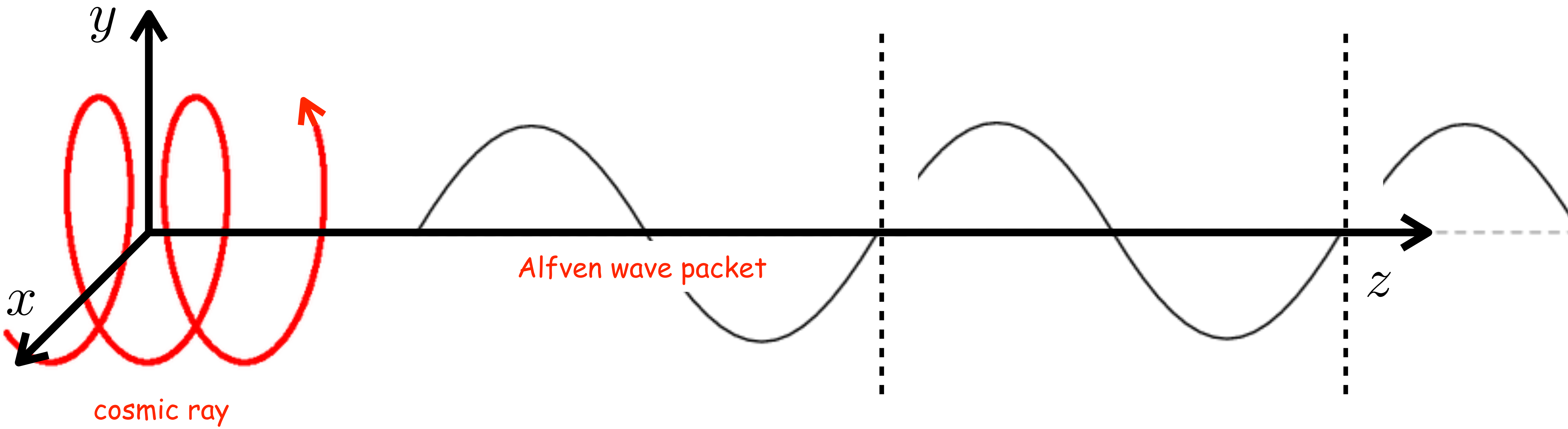
total variation of pitch angle — single scattering — crossing time — gyration frequency

Wentzel 1972, Kulsrud's book, ...

Pitch angle diffusion



n identical and densely packed waves, with random phases

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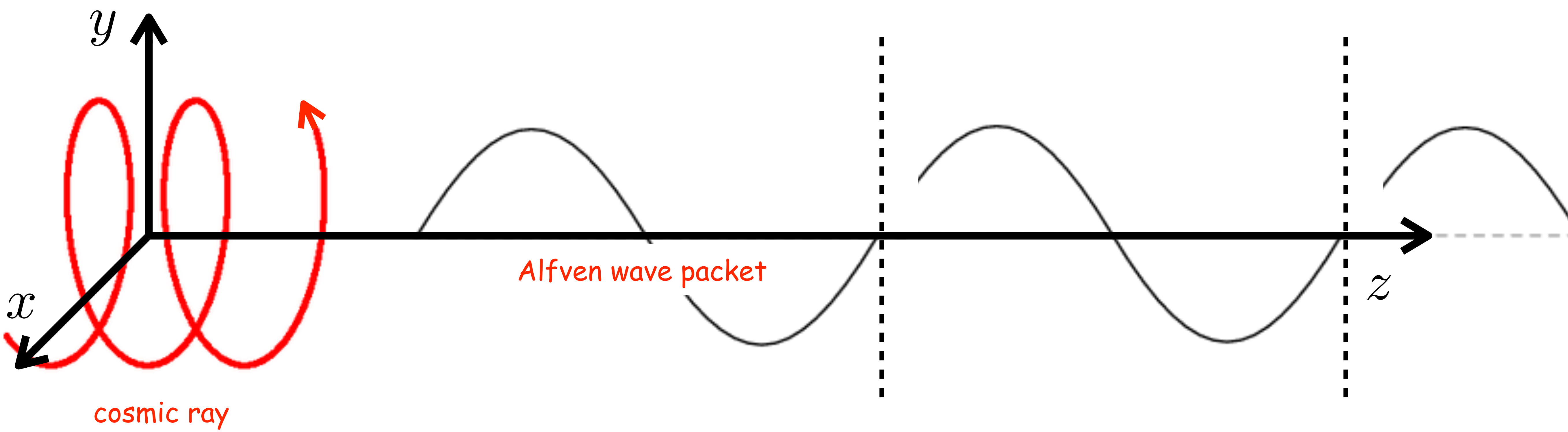
total variation of pitch angle — single scattering — crossing time — gyration frequency

Wentzel 1972, Kulsrud's book, ...

Pitch angle diffusion



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total variation of pitch angle — single scattering — crossing time — gyration frequency

diffusion in pitch angle!

Wentzel 1972, Kulsrud's book, ...

Spatial diffusion

diffusion coefficient (pitch angle)

$$D_\vartheta \sim \frac{\langle (\Delta\vartheta)^2 \rangle}{t} \sim \Omega_g \langle \left(\frac{\delta B}{B} \right)^2 \rangle$$

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time to diffuse over a radian ↘

isotropisation time

$$\tau_{iso} \sim \frac{1}{D_\vartheta}$$

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after this time the cosmic ray "forgets" its initial pitch angle

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time to diffuse over a radian

isotropisation time

$$\tau_{iso} \sim \frac{1}{D_\vartheta}$$

after this time the cosmic ray "forgets" its initial pitch angle

particle velocity

mean free path for SPATIAL diffusion

$$\lambda_{mfp} \sim \tau_{iso} v$$

The transport equation for cosmic rays

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right]$$ + ...?

spatial diffusion coefficient

$$D \sim \lambda_{mfp} v \sim R_L v / \langle \left(\frac{\delta B_k}{B}\right)^2 \rangle$$

The transport equation for cosmic rays

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] + \ldots\ldots?$$

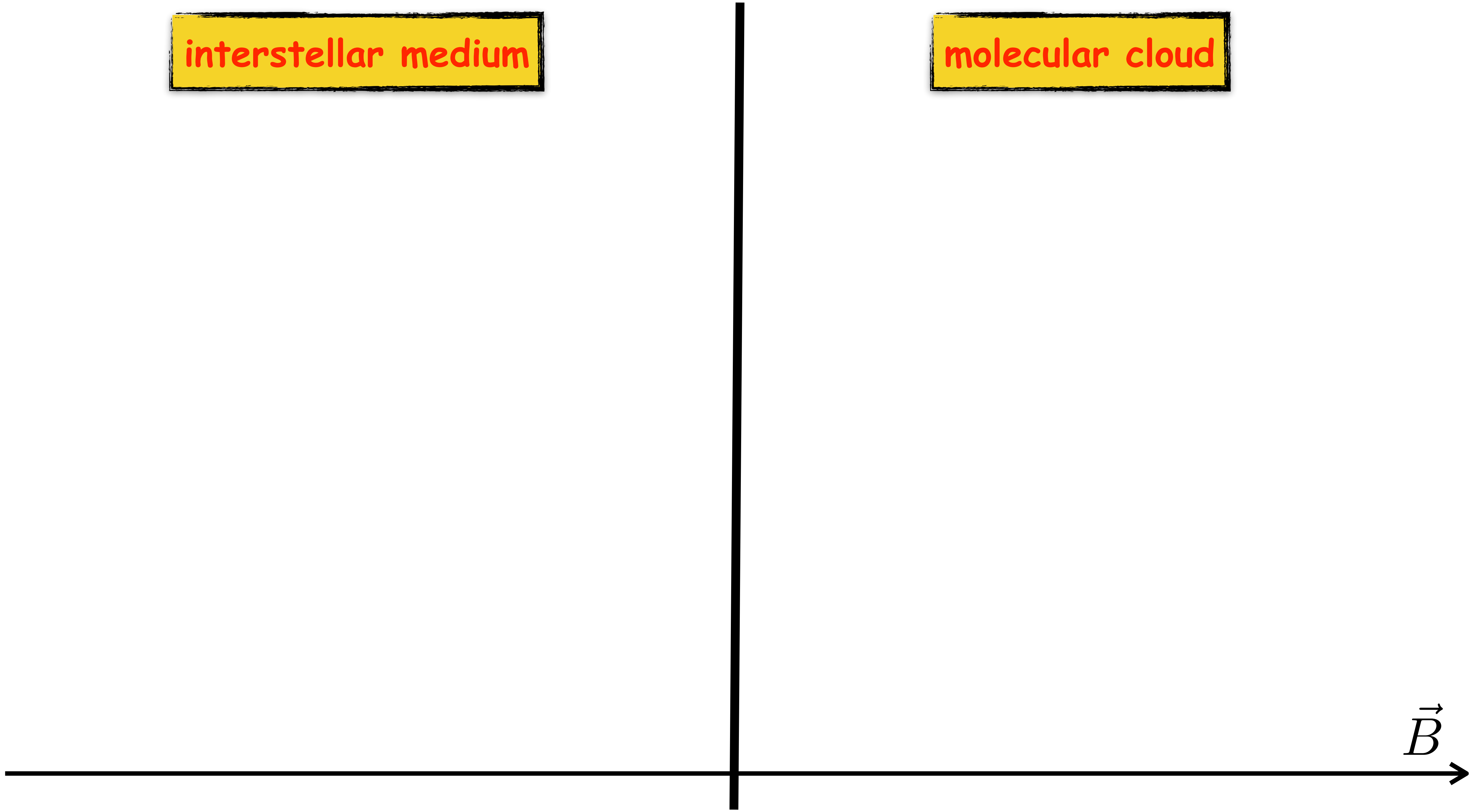
spatial diffusion coefficient

resonant scale

$$D \sim \lambda_{mfp} v \sim R_L v / \langle \left(\frac{\delta B_k}{B} \right)^2 \rangle$$

the power spectrum of turbulence determines the diffusion coefficient

The effect of energy losses



Skilling&Strong 1976, Cesarsky&Völk 1978, Morfill 1982, Everett&Zweibel 2010, Morlino&Gabici 2015

The effect of energy losses

interstellar medium

ionized -> diffusion

molecular cloud

neutral -> straight line propagation

"we" call this ion-neutral damping
"you" call this ambipolar diffusion

$\vec{B}$

Skilling&Strong 1976, Cesarsky&Völk 1978, Morfill 1982, Everett&Zweibel 2010, Morlino&Gabici 2015

The effect of energy losses

interstellar medium

ionized -> diffusion

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CR sea f_0

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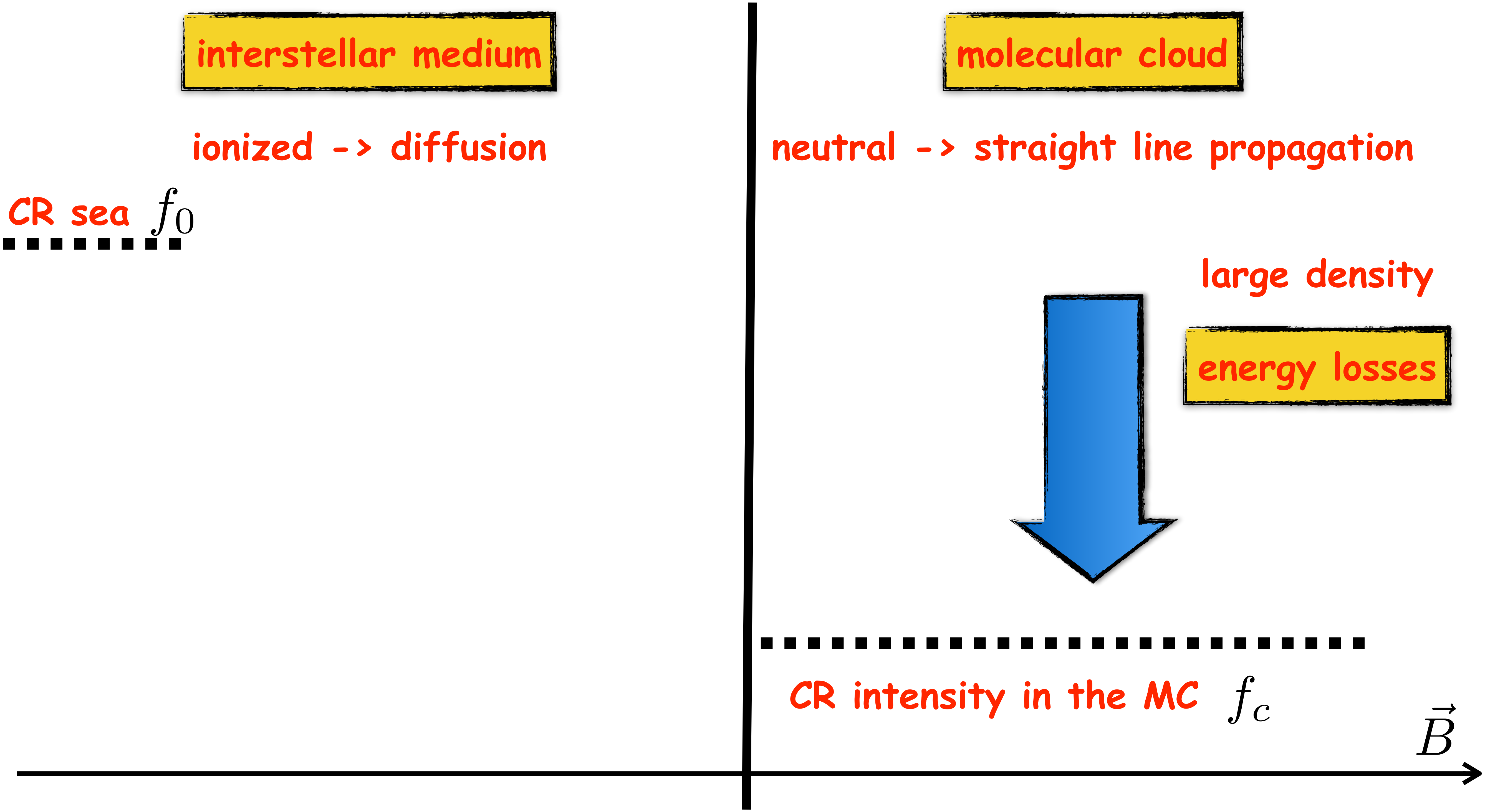
The effect of energy losses



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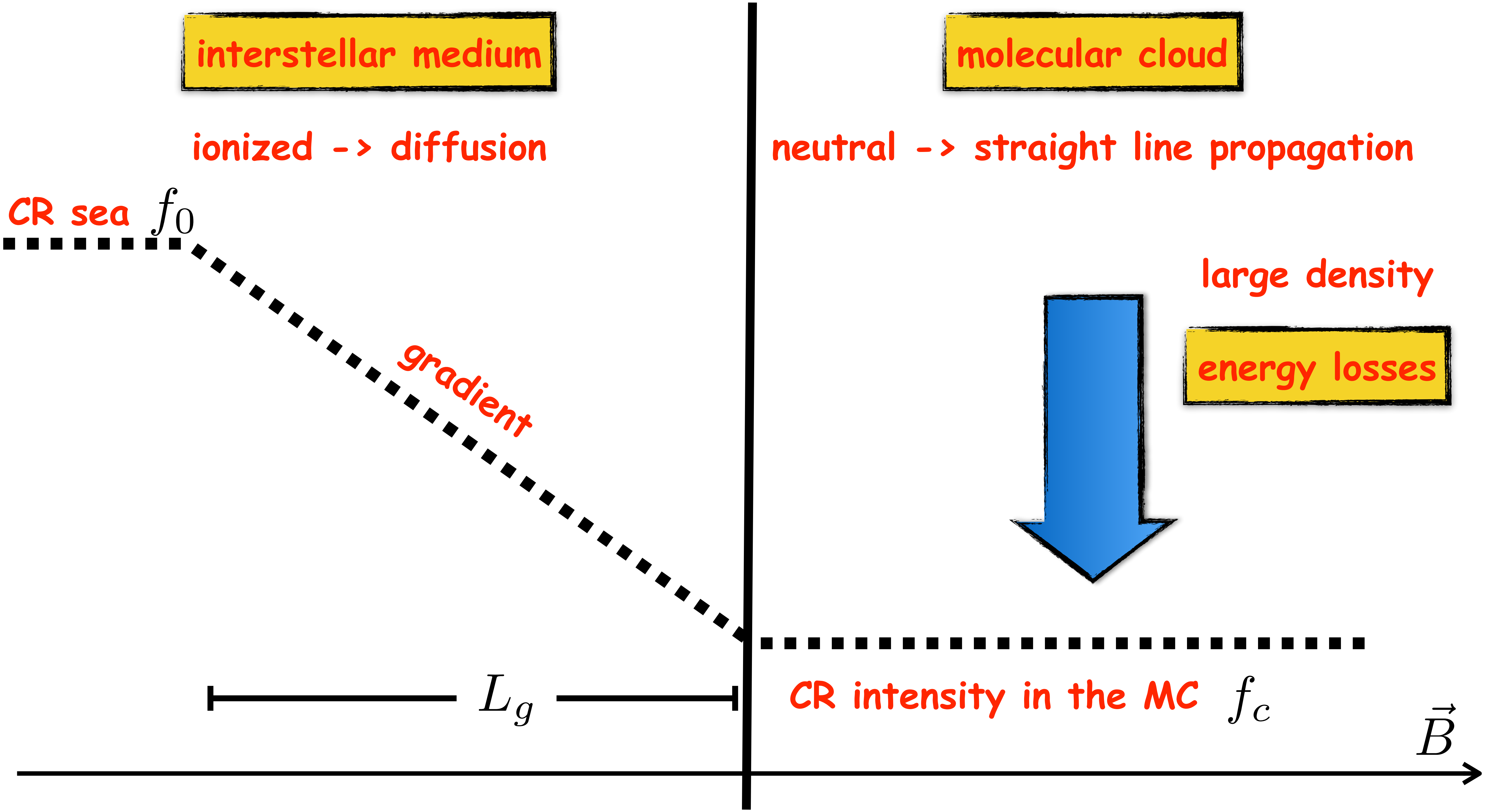

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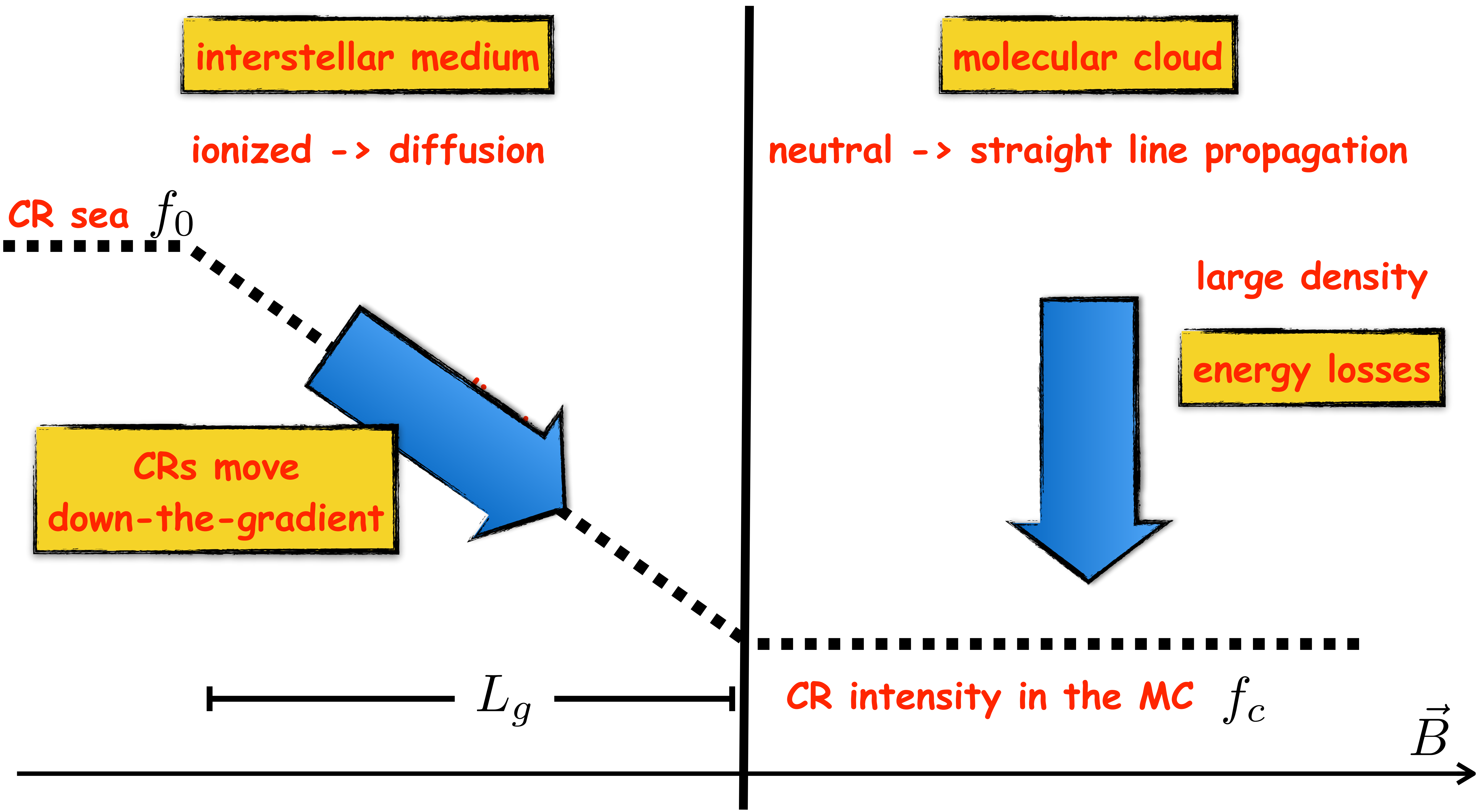
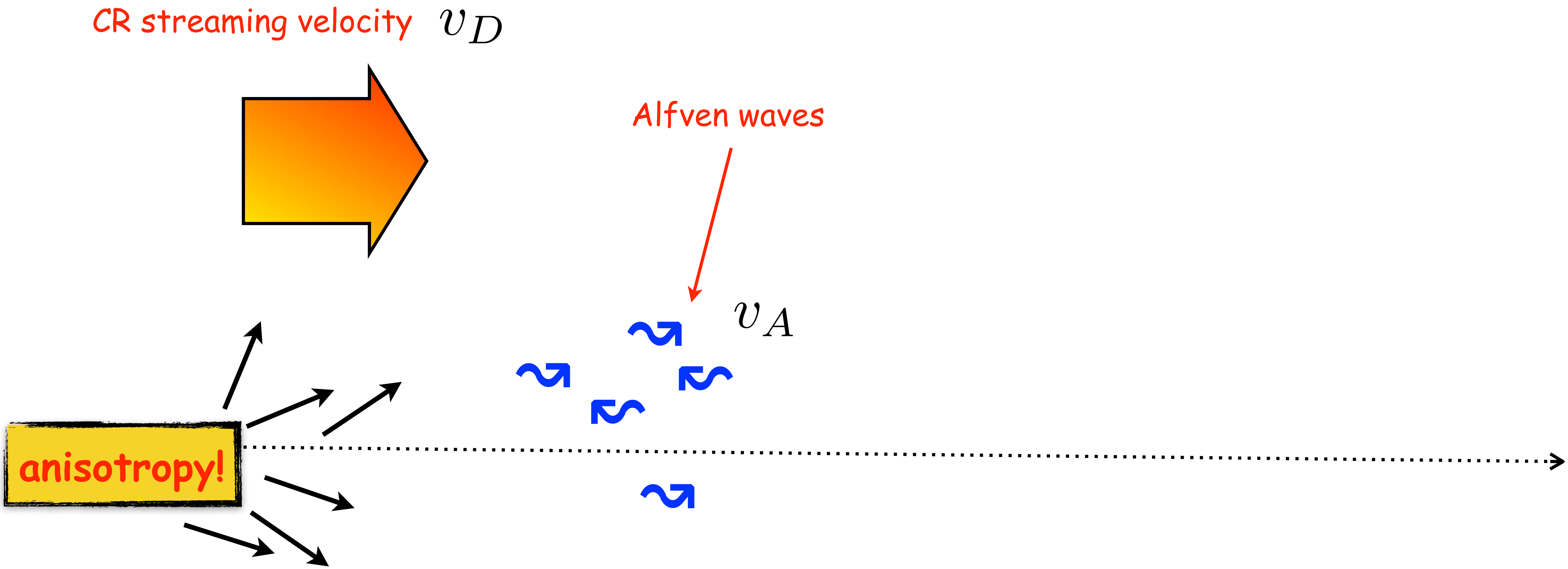
The effect of energy losses



Skilling&Strong 1976, Cesarsky&Völk 1978, Morfill 1982, Everett&Zweibel 2010, Morlino&Gabici 2015

Streaming instability

Kulsrud's book



Streaming instability

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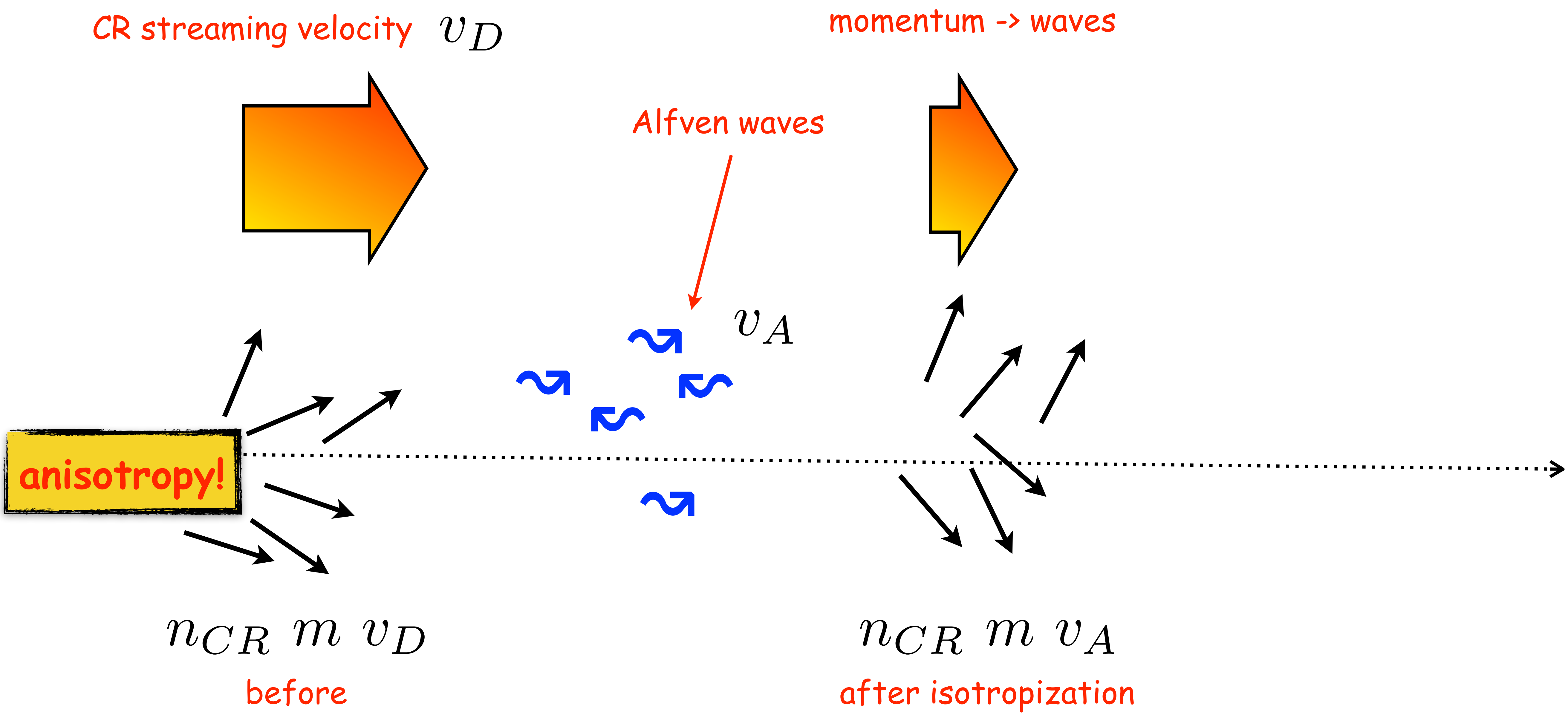
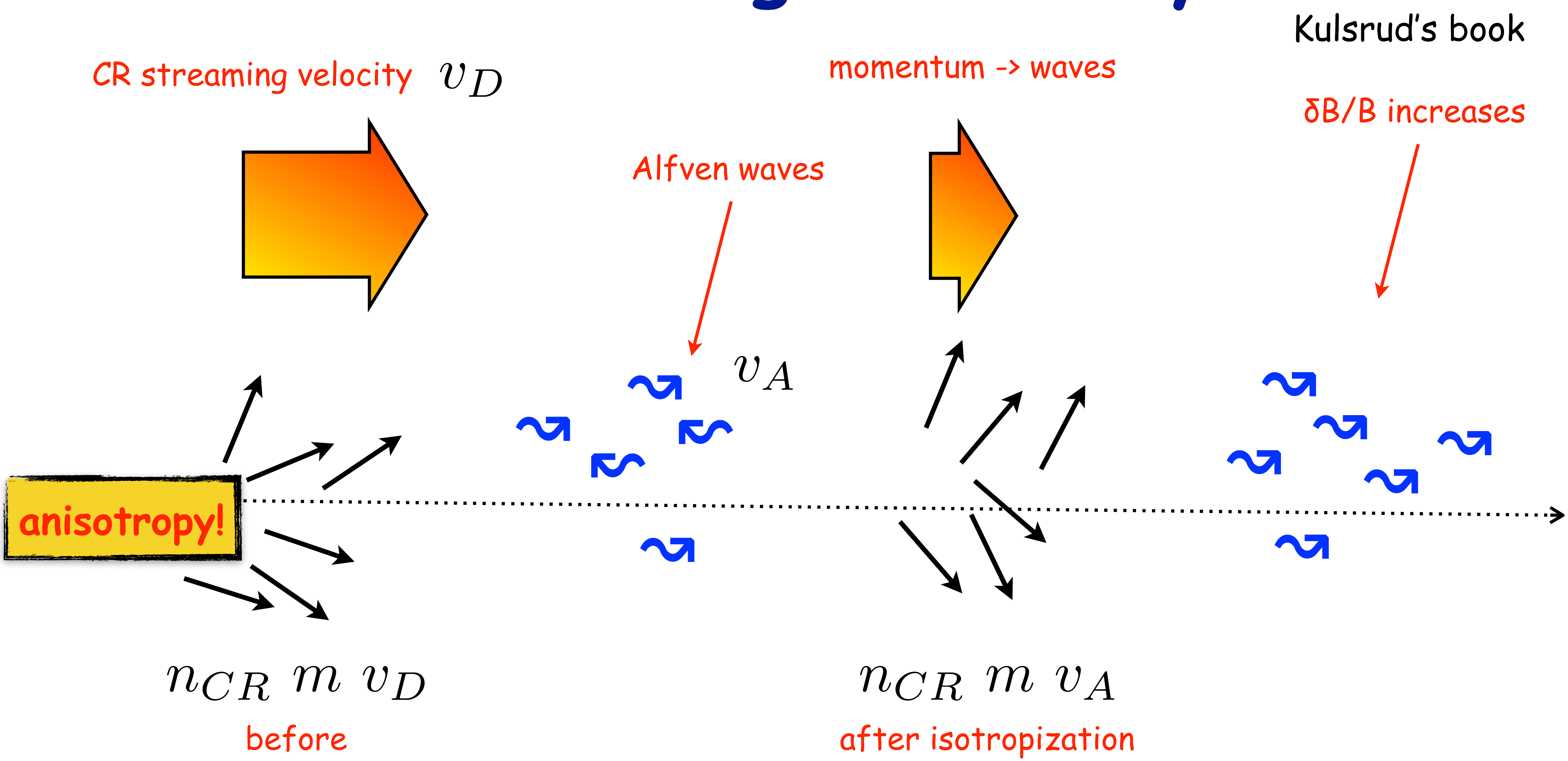


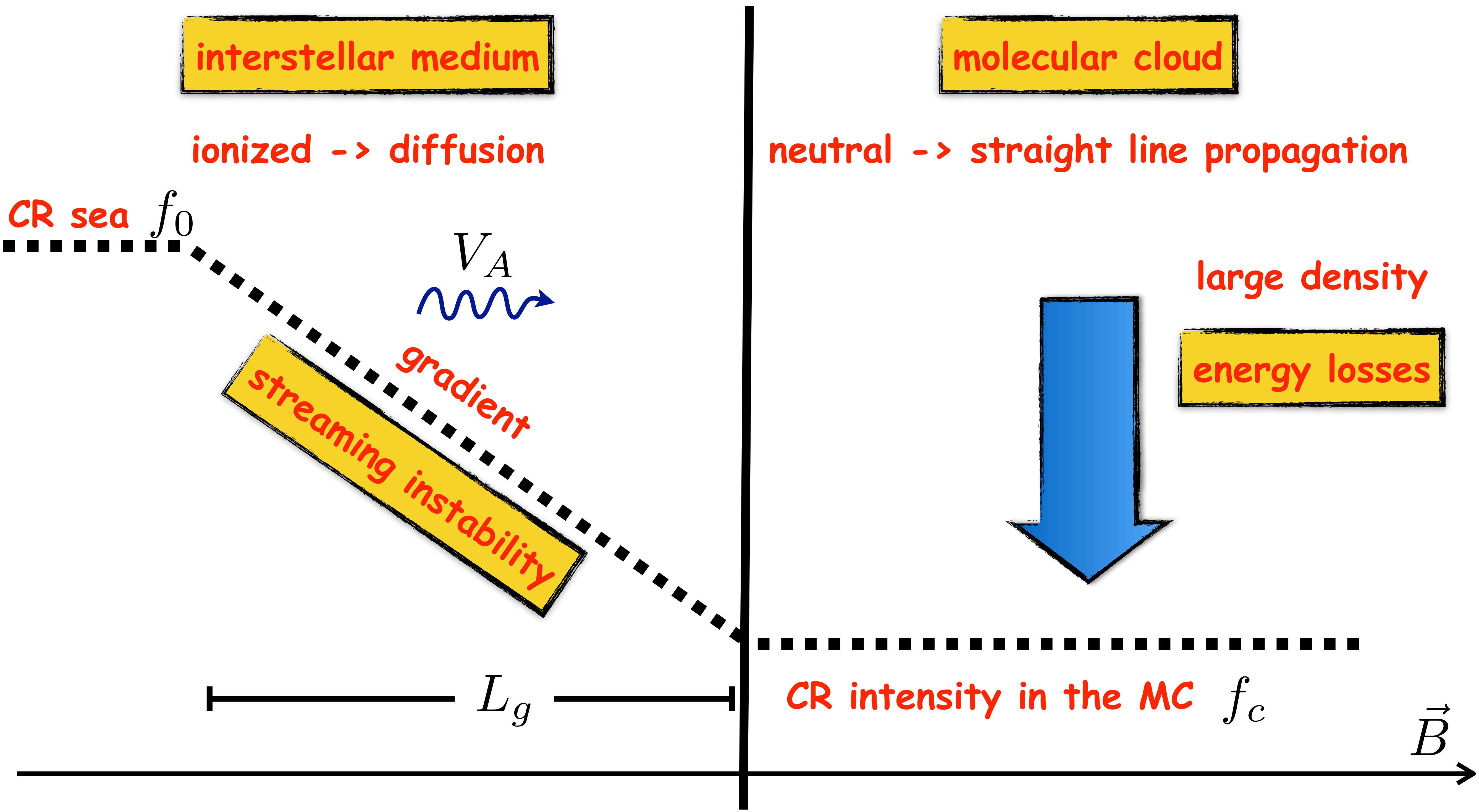
Streaming instability



CRs are isotropized in the frame of waves

$$\frac{dP_{CR}}{dt} = \frac{n_{CR}\ m\ (v_D - v_A)}{\tau} \qquad \tau \approx \frac{1}{D_\vartheta}$$

A converging flow of Alfven waves



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The transport equation for cosmic rays

outside of the cloud

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial z}\left[D\frac{\partial f}{\partial z}\right] - v_A\frac{\partial f}{\partial z} - \frac{1}{p^2}\frac{\partial}{\partial p}\left[\dot{p}p^2 f\right]$$

CR are advected with waves

energy losses

The transport equation for cosmic rays

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CR are advected with waves

energy losses

inside of the cloud

$$\langle\mu\rangle v\frac{\partial f}{\partial z} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[\dot{p}p^2 f\right] = 0$$

particle velocity

CR flux entering a cloud

rate of particle penetration into a cloud

Morlino&Gabici 2015

diffusive advective

CR flux into the cloud ->

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

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CR flux into the cloud ->

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

$$\approx D \; \frac{f_0 - f_c}{L_g} + V_A f_c$$

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CR flux into the cloud ->
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$$L_g \sim \frac{D}{V_A}$$

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diffusive — advective

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does NOT depend on the diffusion coefficient!!!

CR flux entering a cloud

rate of particle penetration into a cloud

Morlino&Gabici 2015

diffusive advective

CR flux into the cloud ->

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$$\approx D \frac{f_0 - f_c}{L_g} + V_A f_c \approx V_A f_0$$

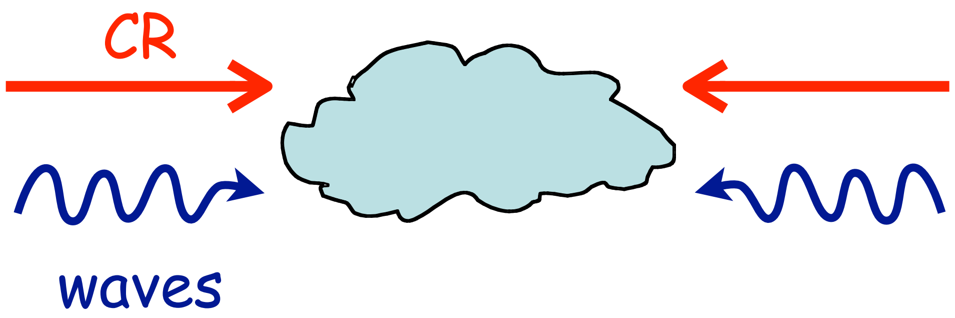
does NOT depend on the diffusion coefficient!!!

determined by streaming instability

condition: L_g < field coherence length

CRs into clouds: universal spectrum

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



Phan+ 2018, Morlino&Gabici 2015

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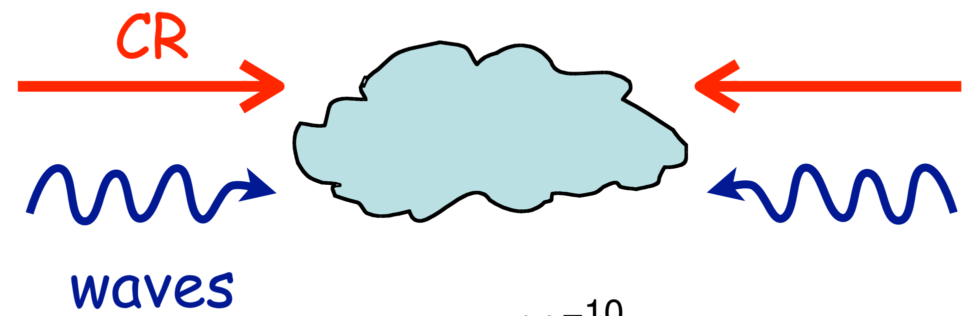

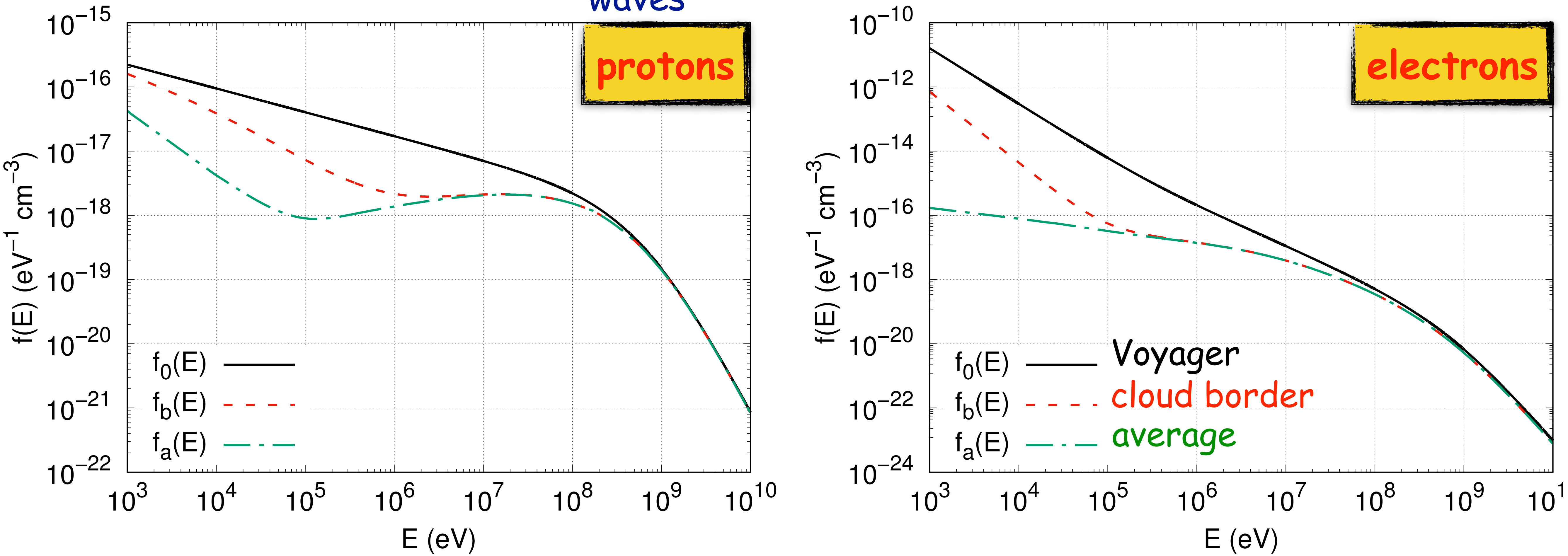

(a) CR protons

(b) CR electrons

Phan+ 2018, Morlino&Gabici 2015

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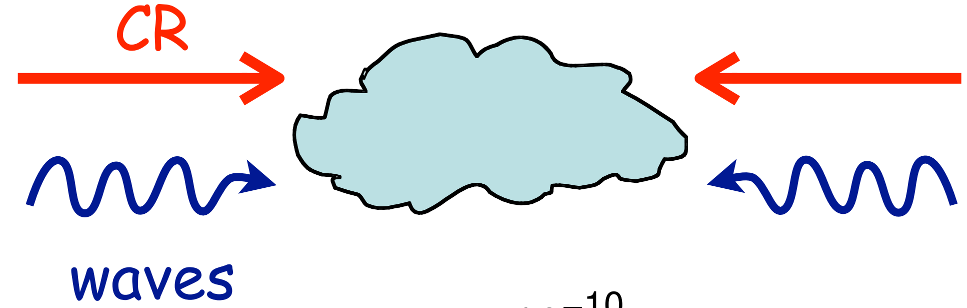
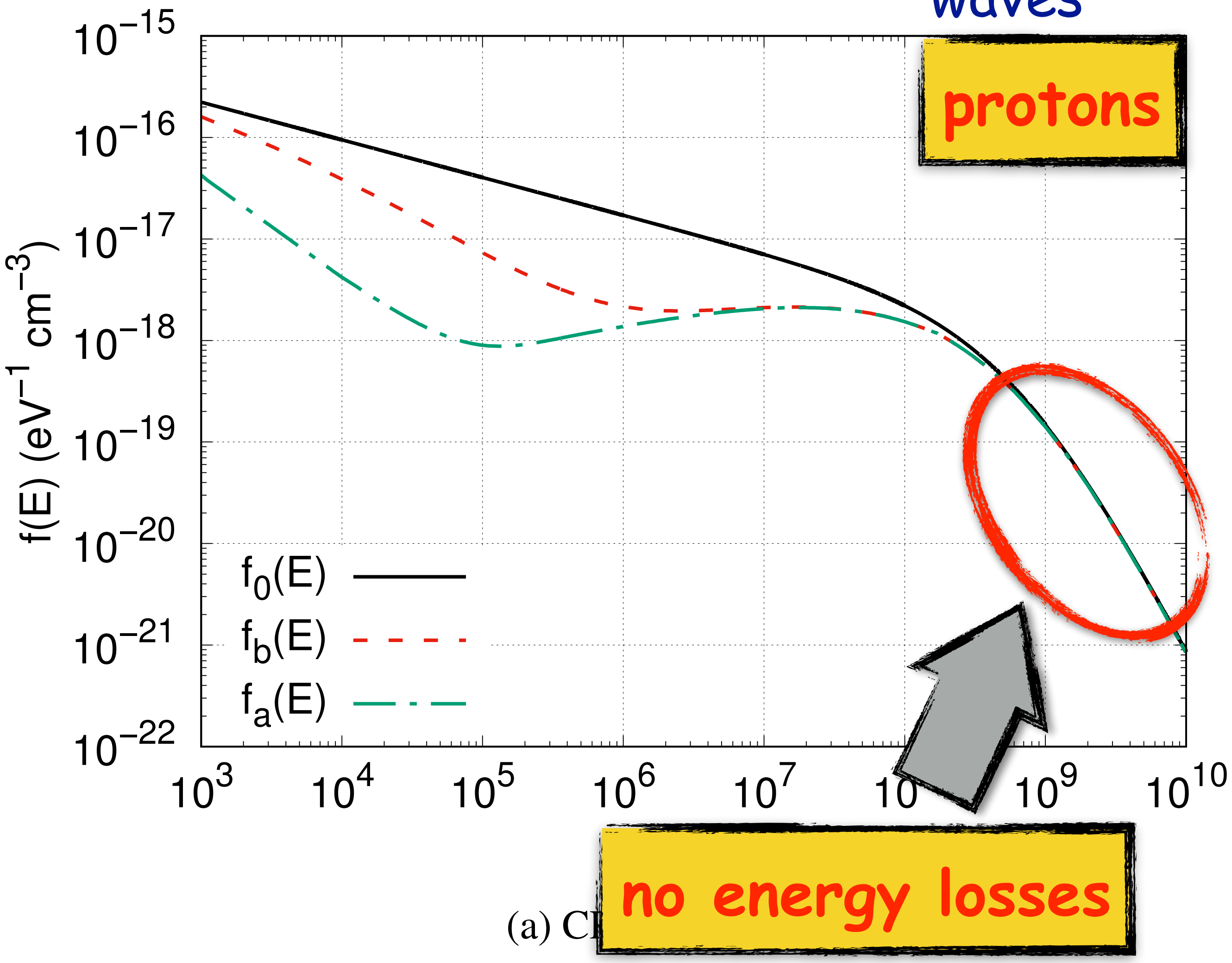
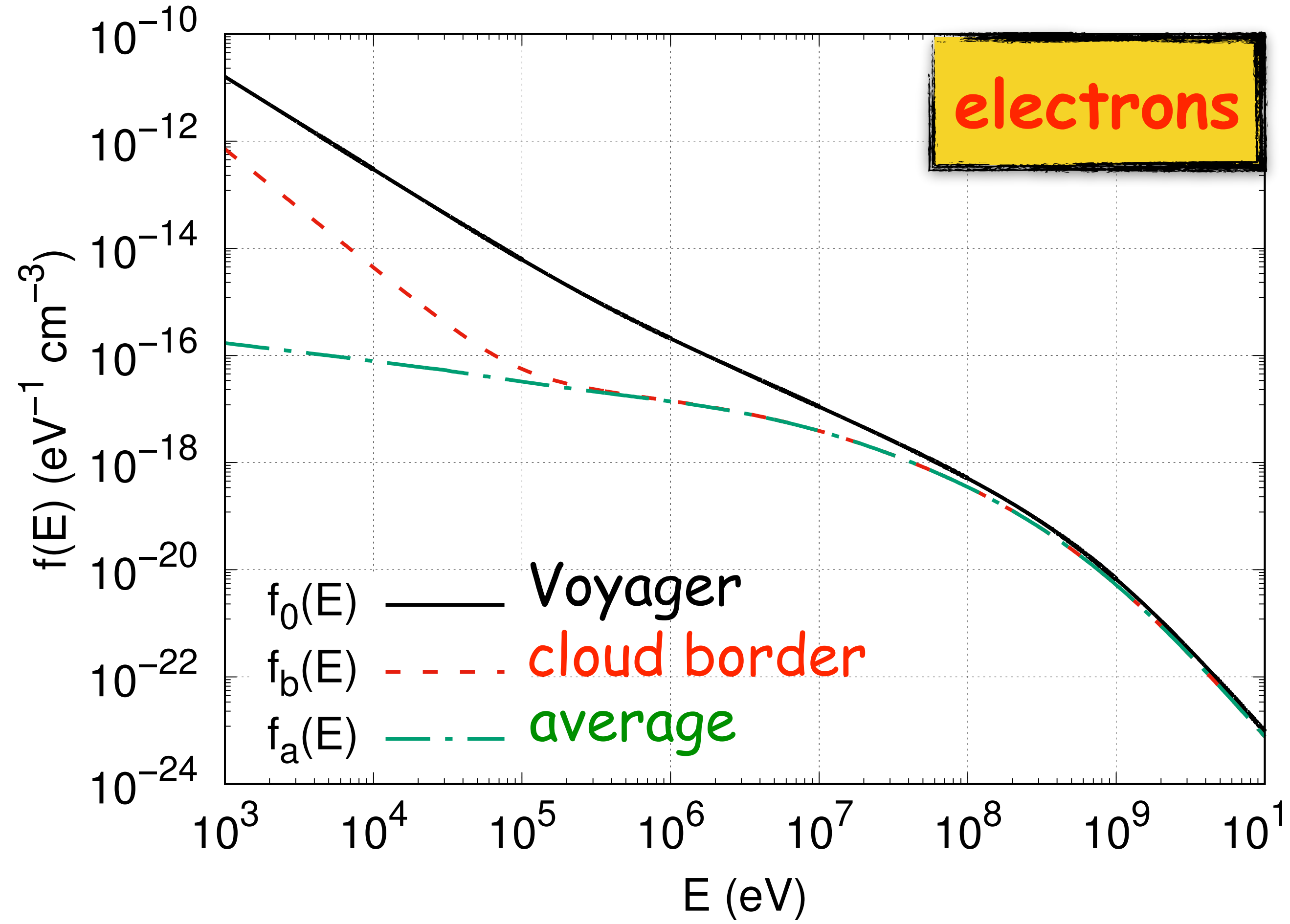




(a) C



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Phan+ 2018, Morlino&Gabici 2015

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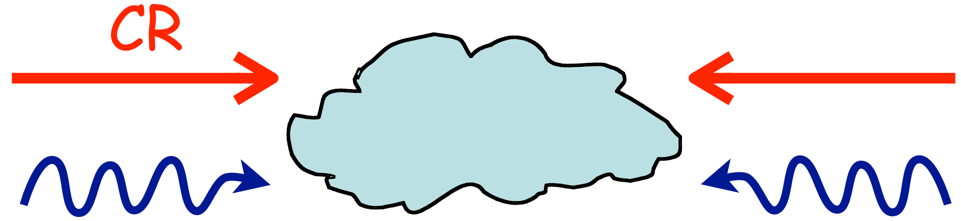

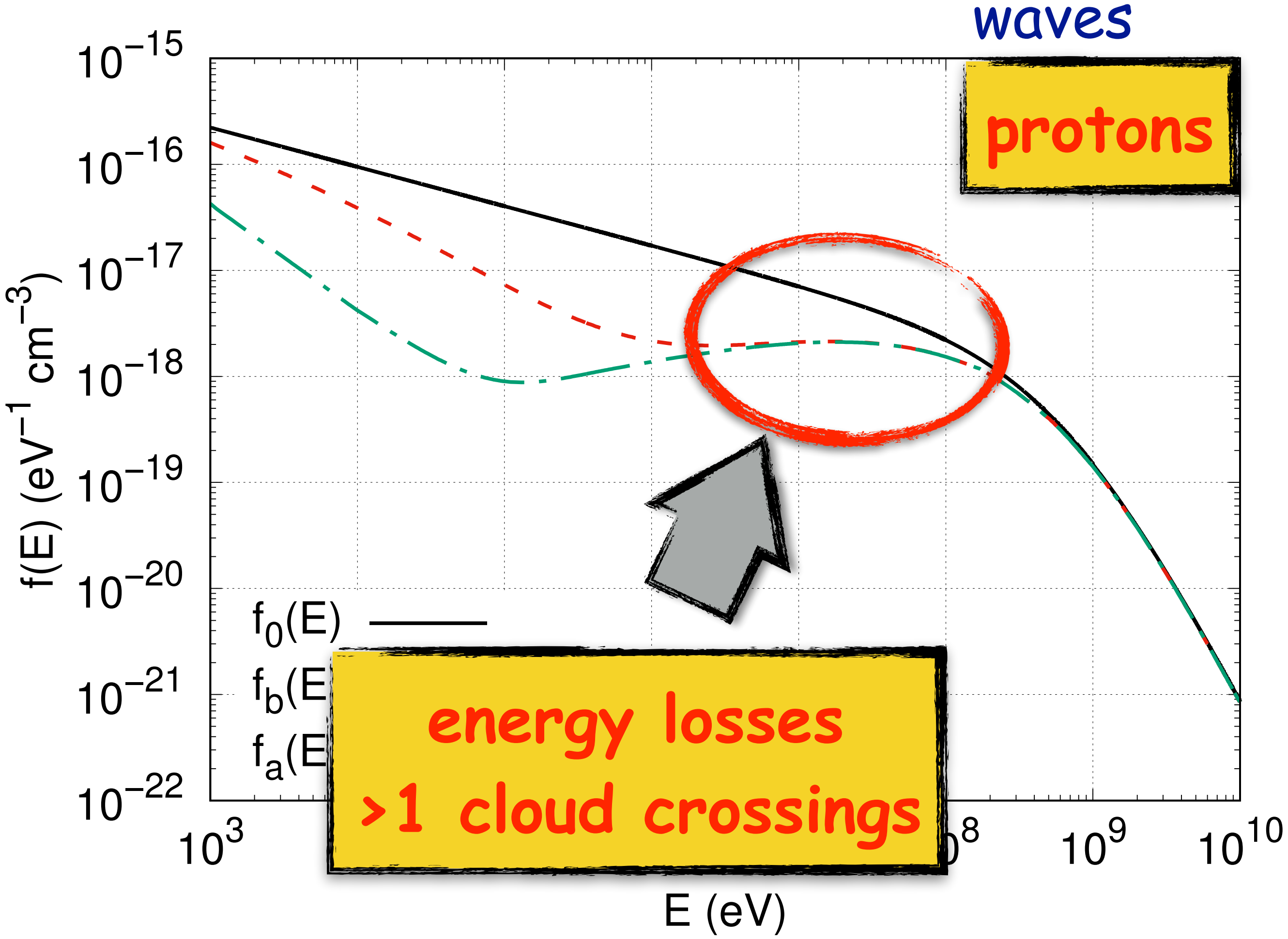

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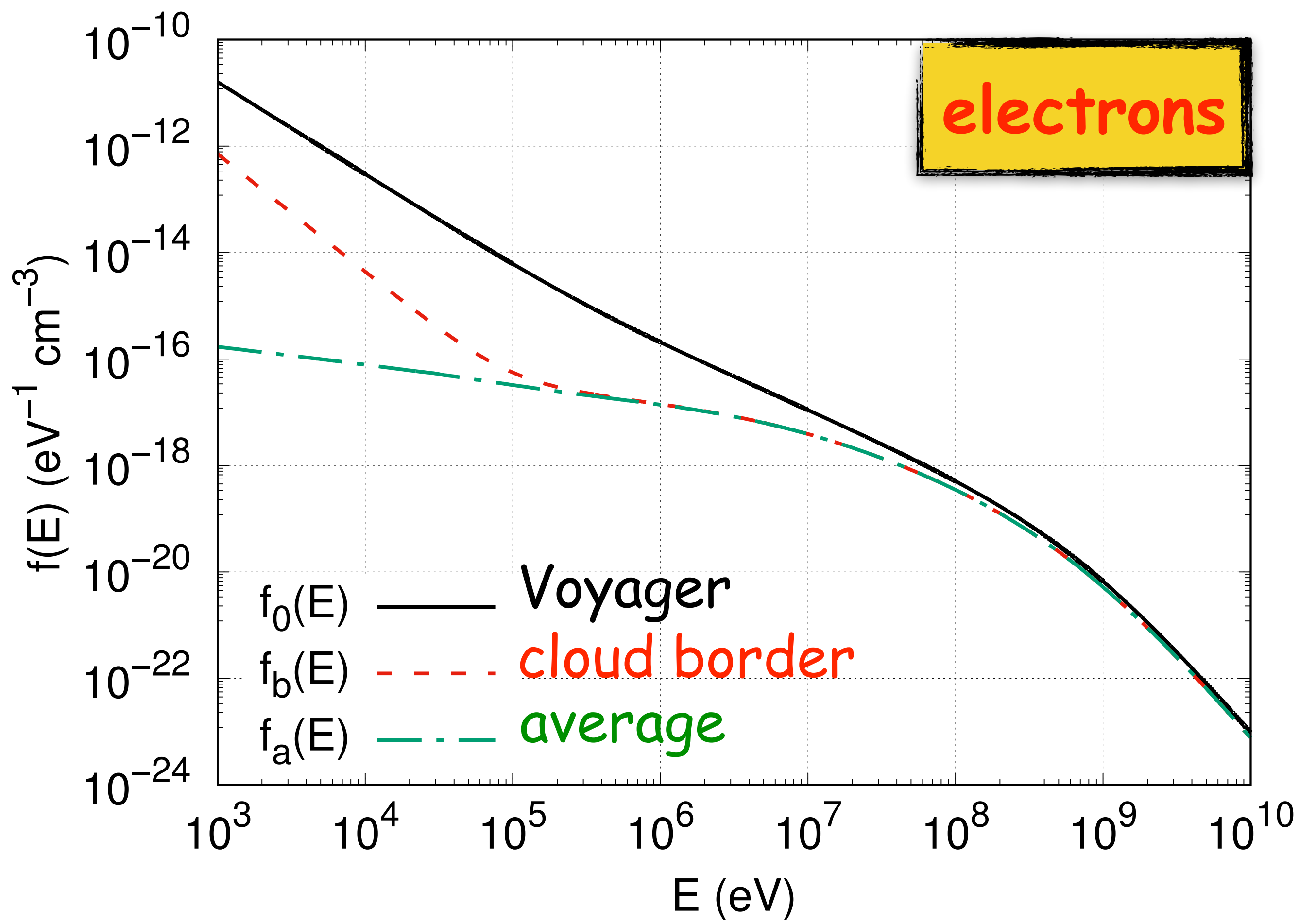

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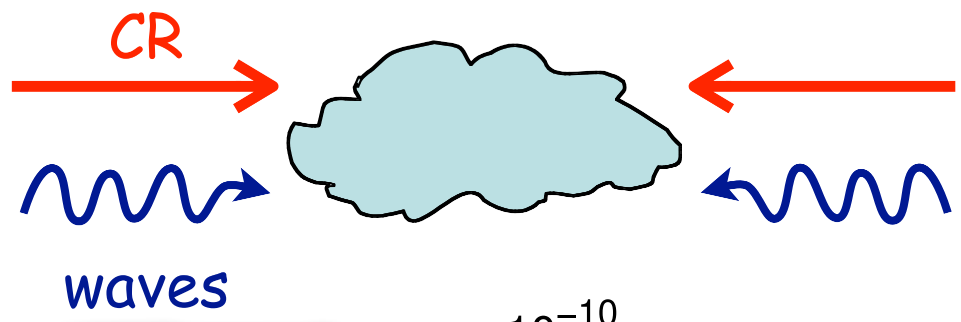

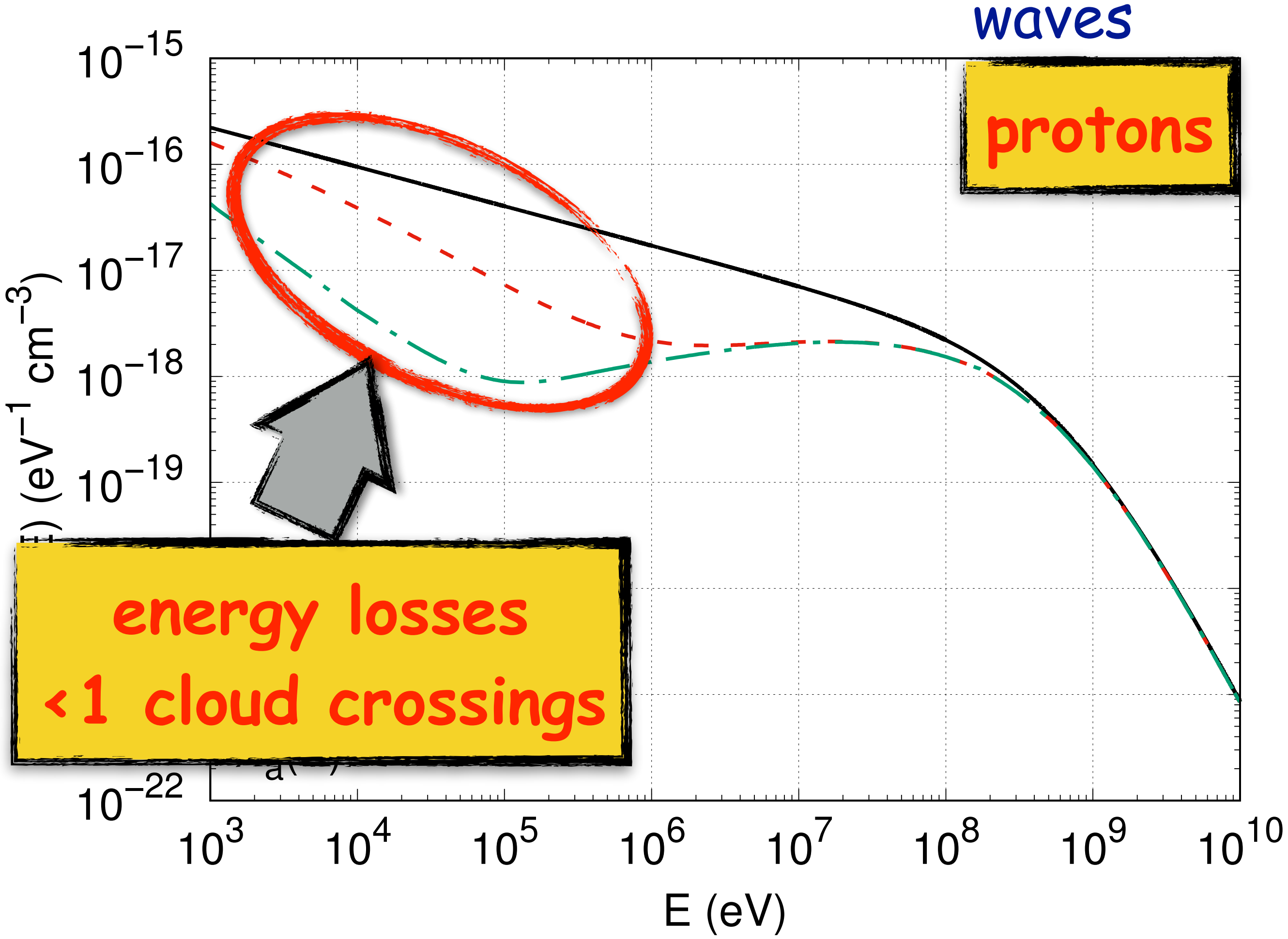

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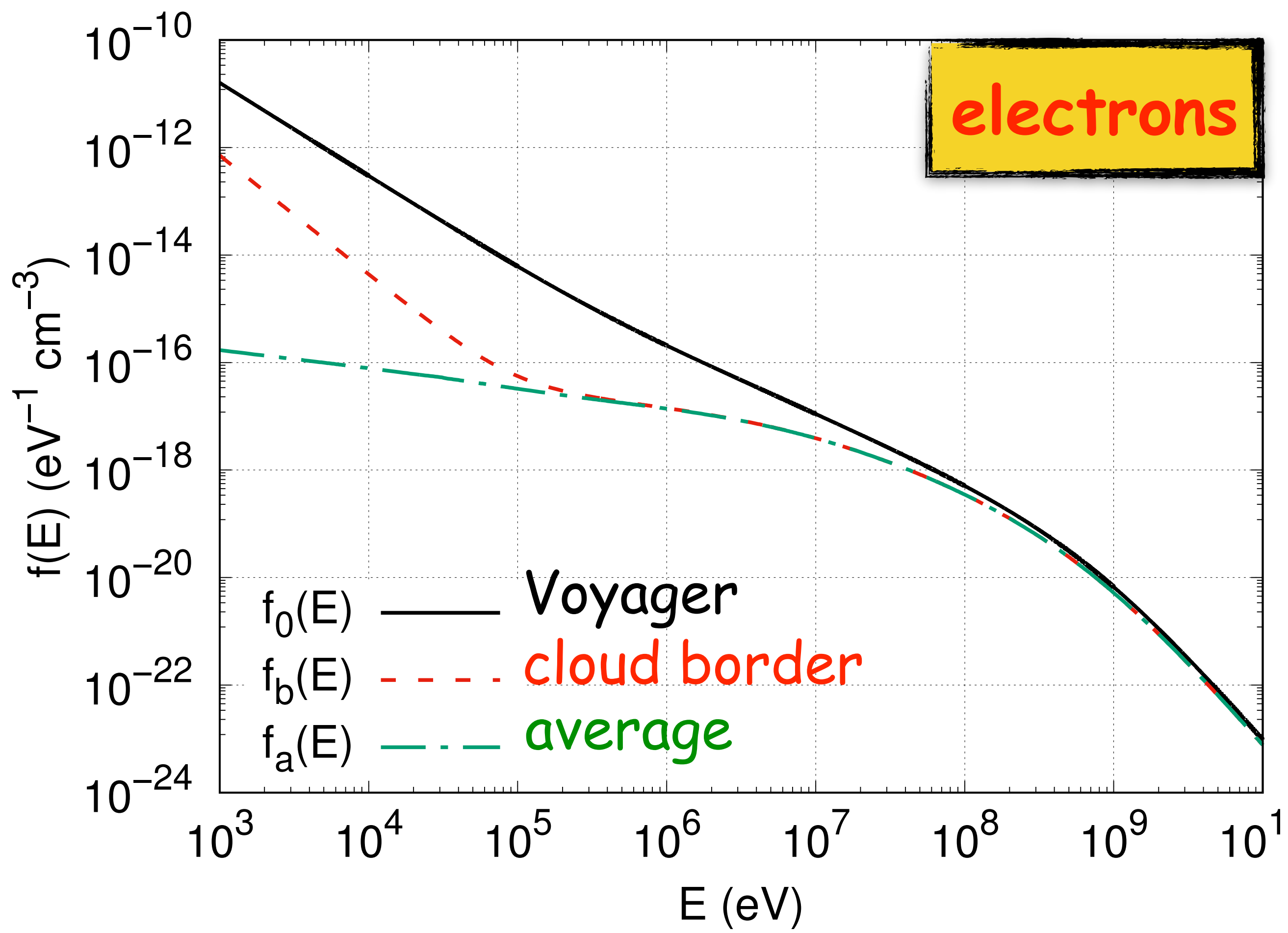

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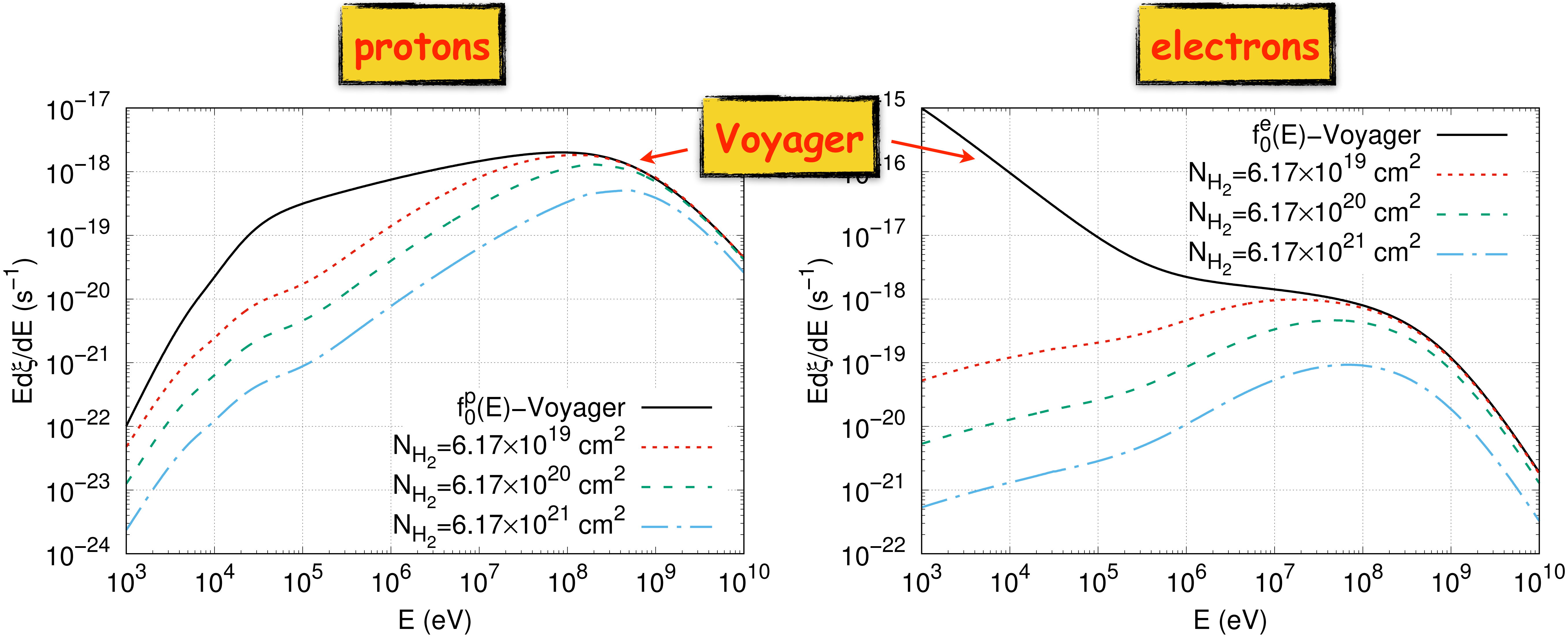
Phan+ 2018, Morlino&Gabici 2015

Differential ionisation rates



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Phan+ 2018

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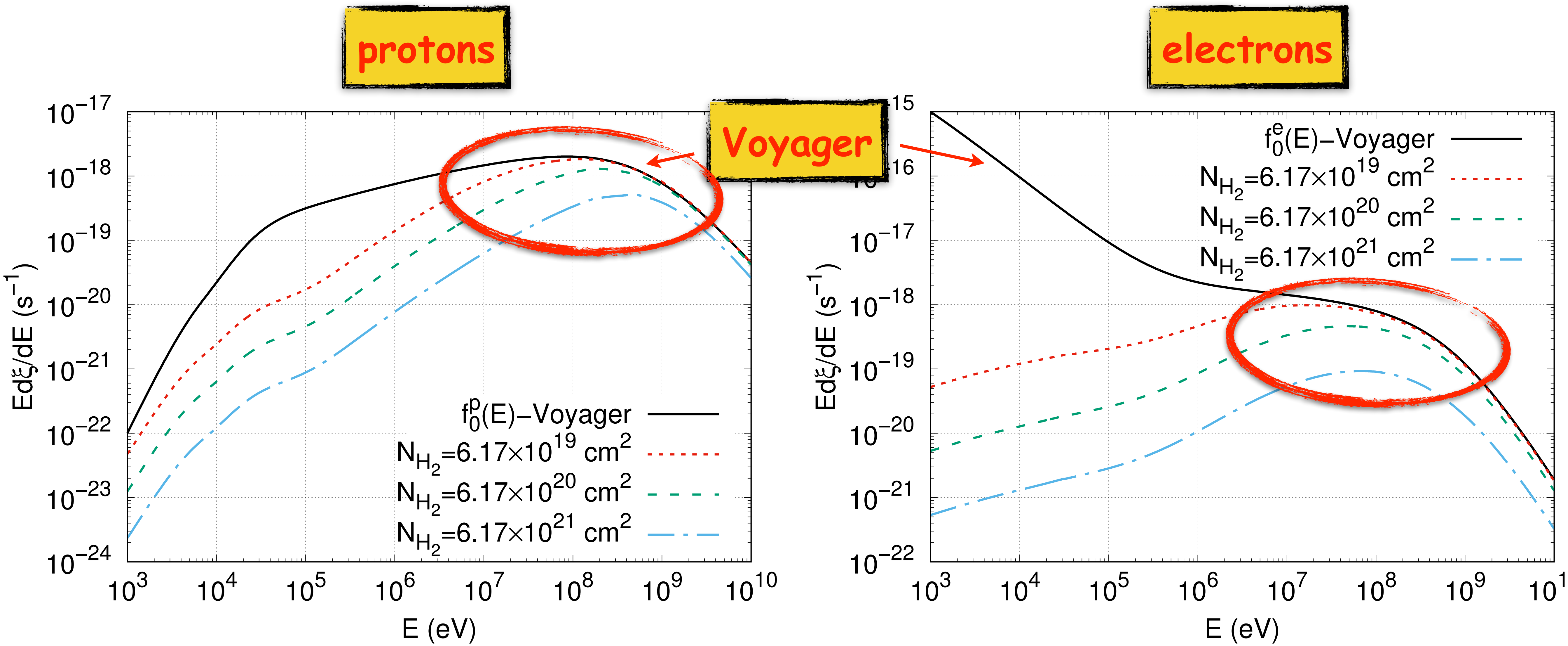


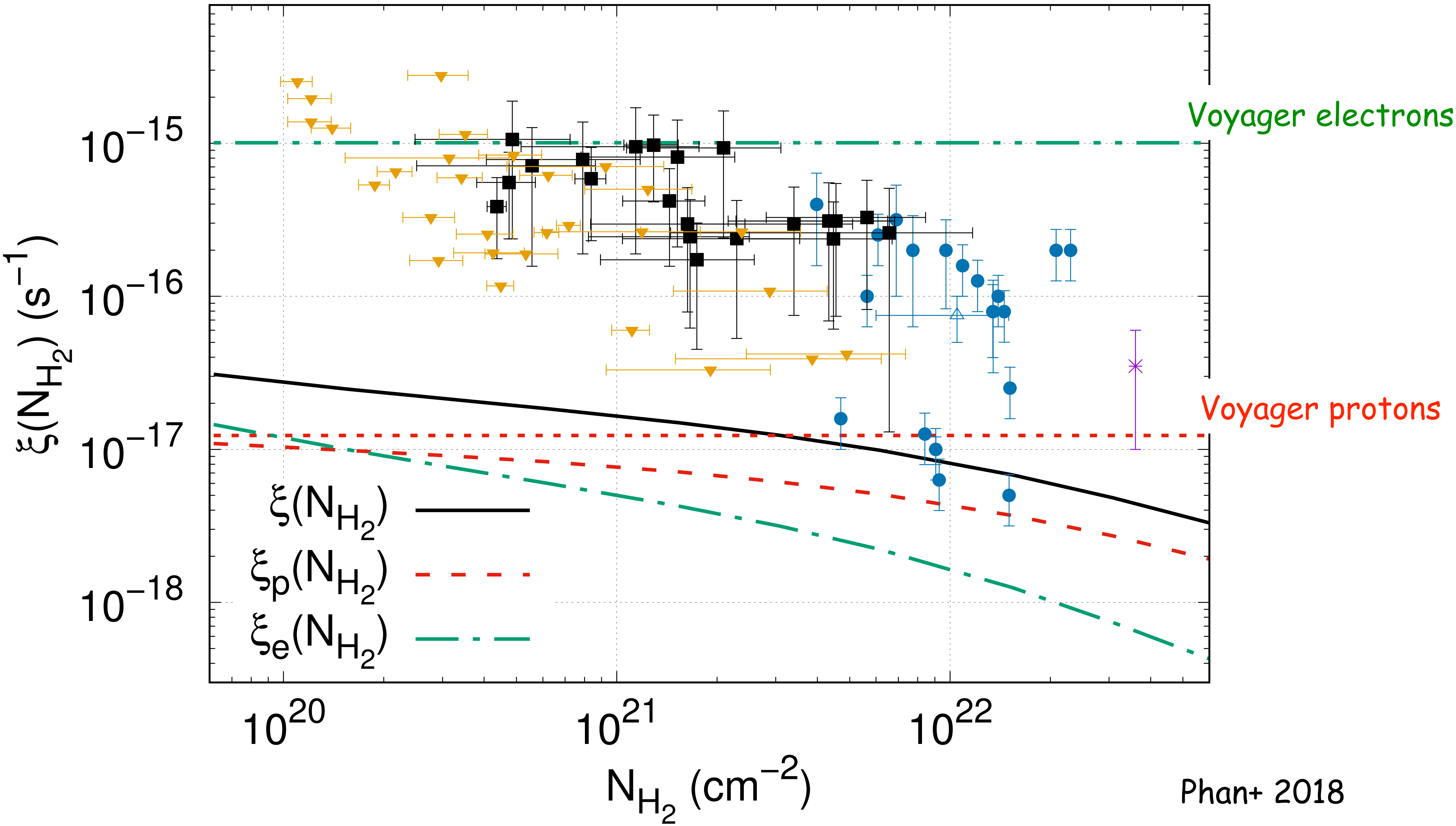
(a) CR protons

(b) CR electrons

most of the ionisation —> MeV < E < GeV

Phan+ 2018

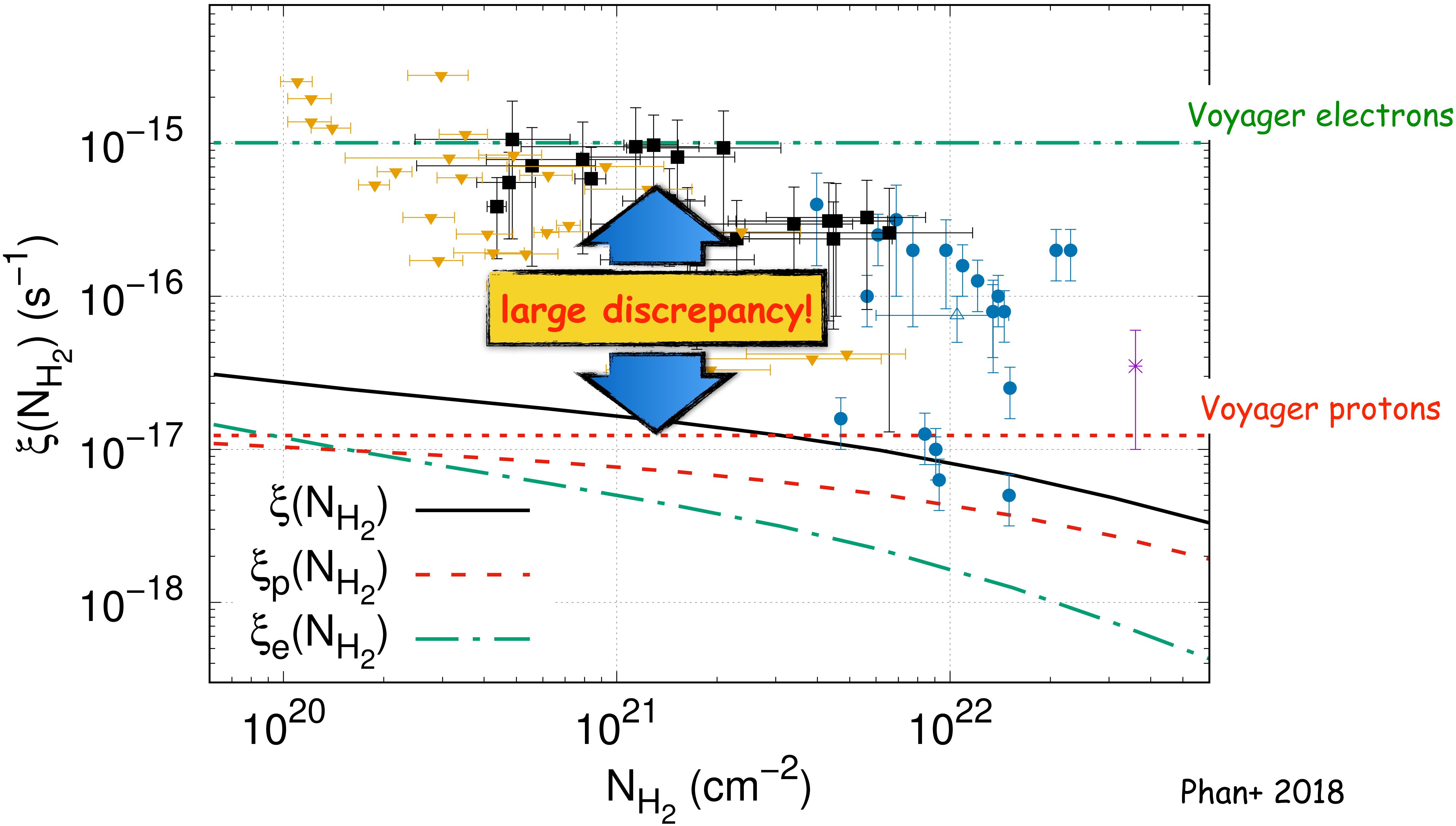
Comparison with data (???)



Phan+ 2018

Intro	ballistic?	diffusive!	theory...	...versus data	So?

Comparison with data (???)



Phan+ 2018

So?

- **More refined model? (better description of transition from hot to neutral medium, time dependence induced by turbulence?) —> the flux balance argument seems quite solid…**

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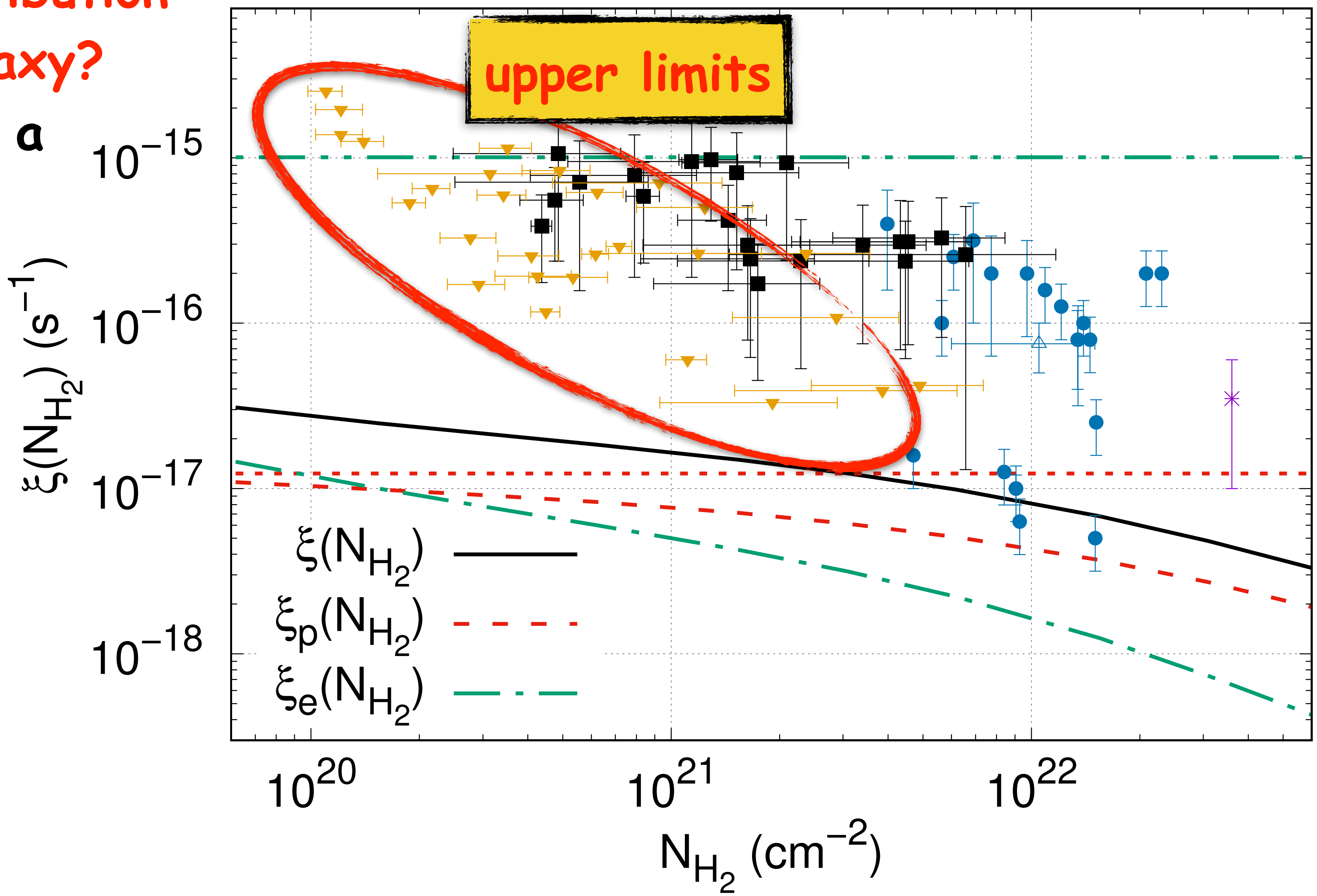

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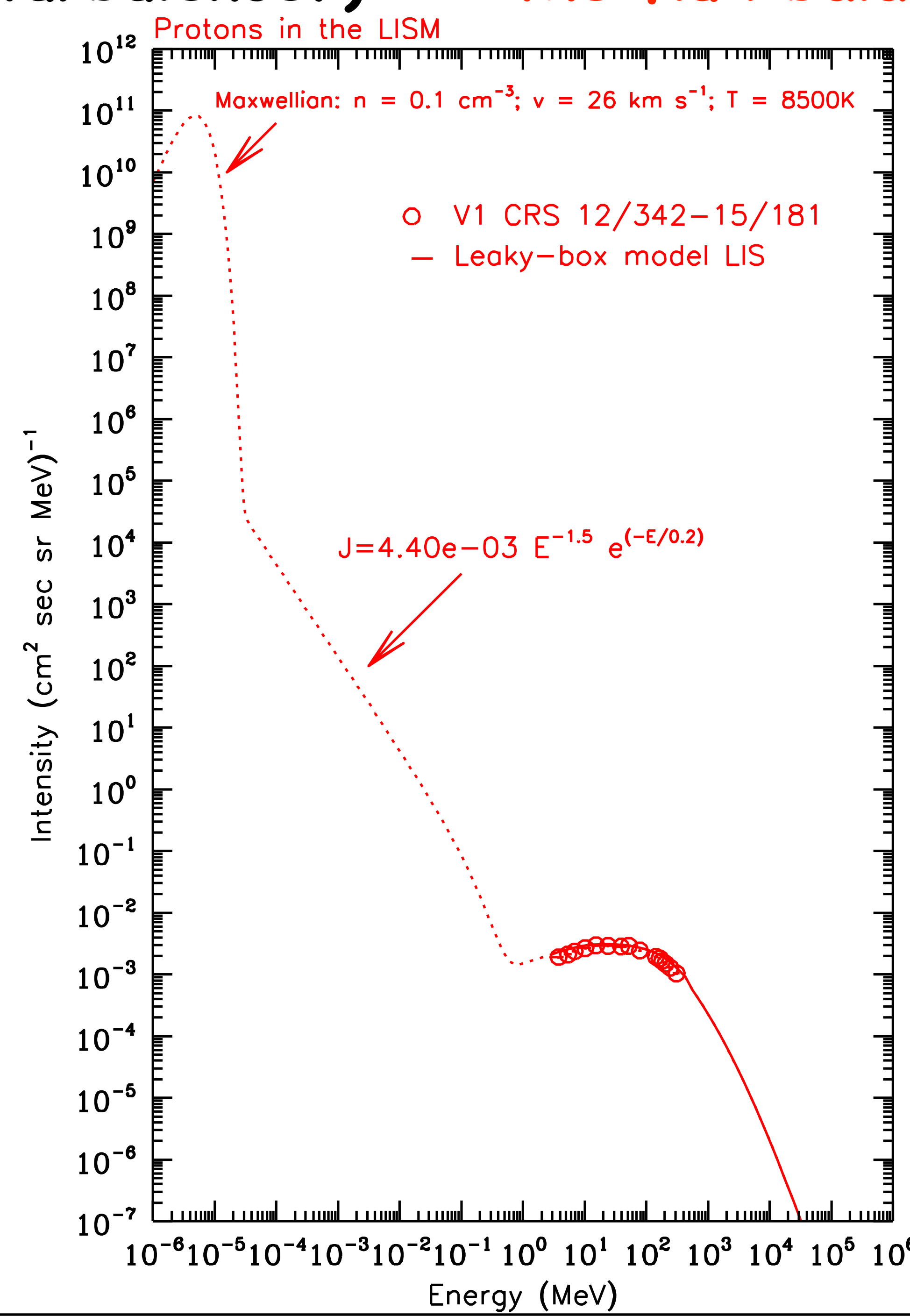

Cummings+ 2016

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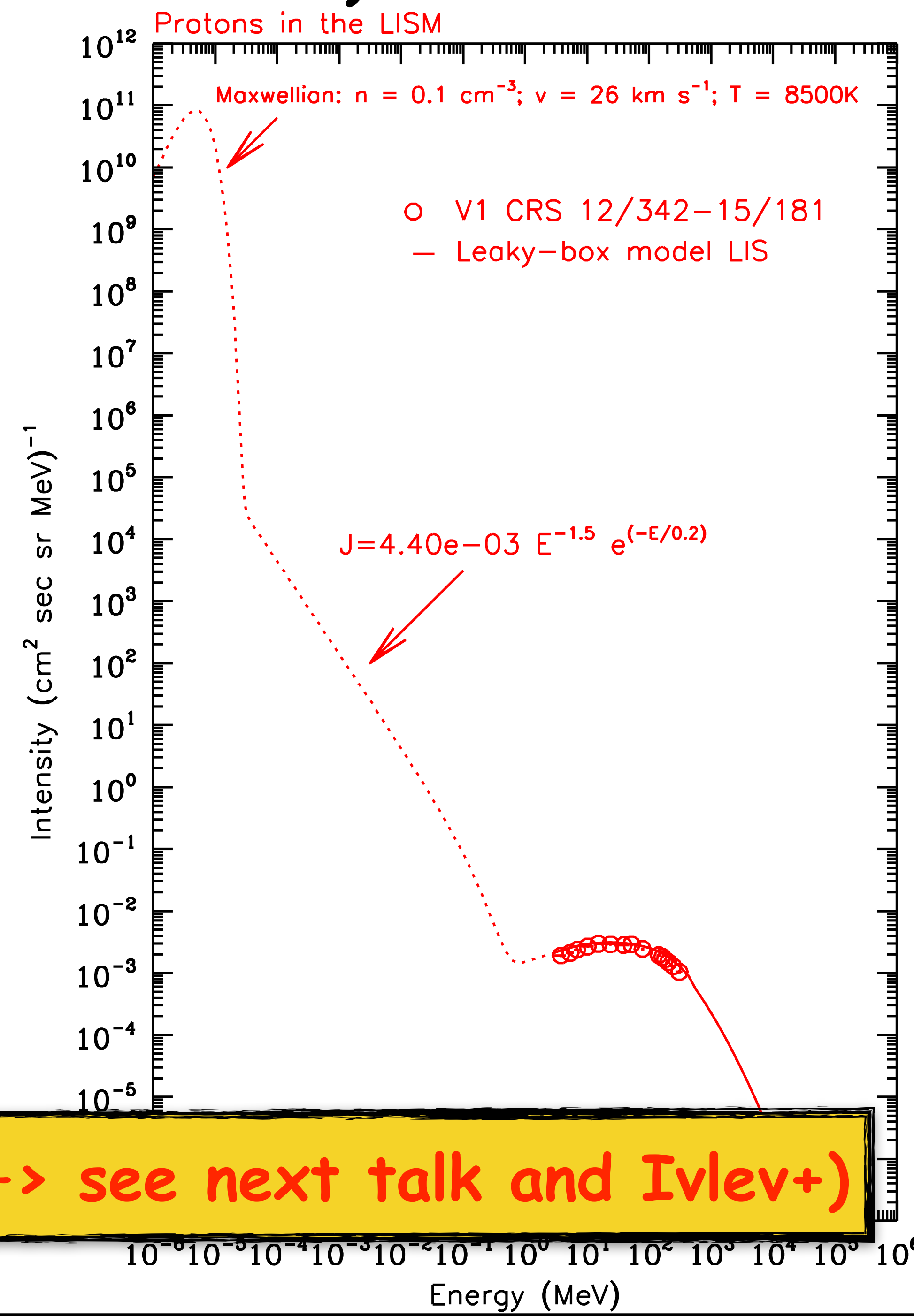
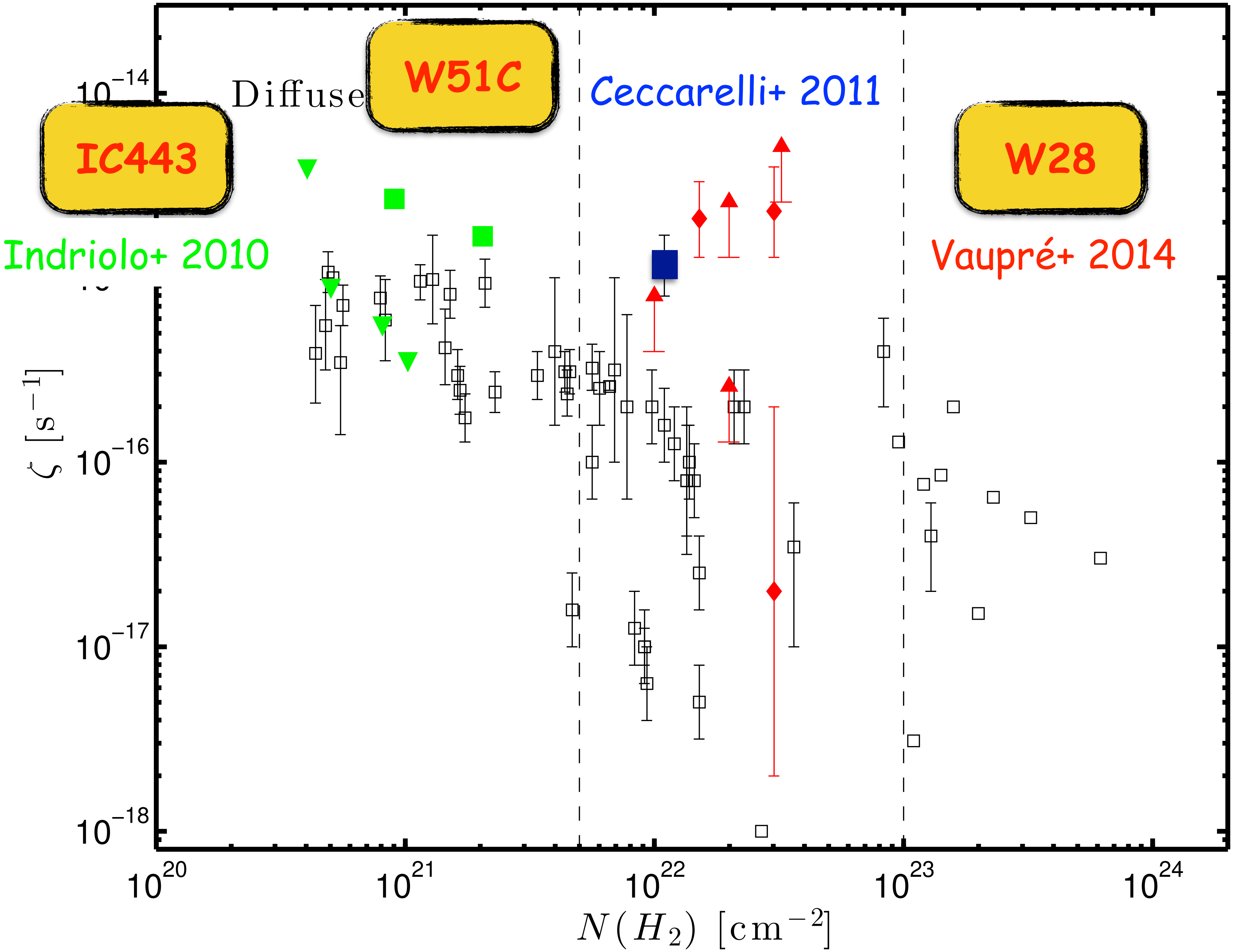


Cummings+ 2016

Dense clouds (with clumps) —> see next talk and Ivlev+)

SNR/MC associations…

SG & Montmerle 2015



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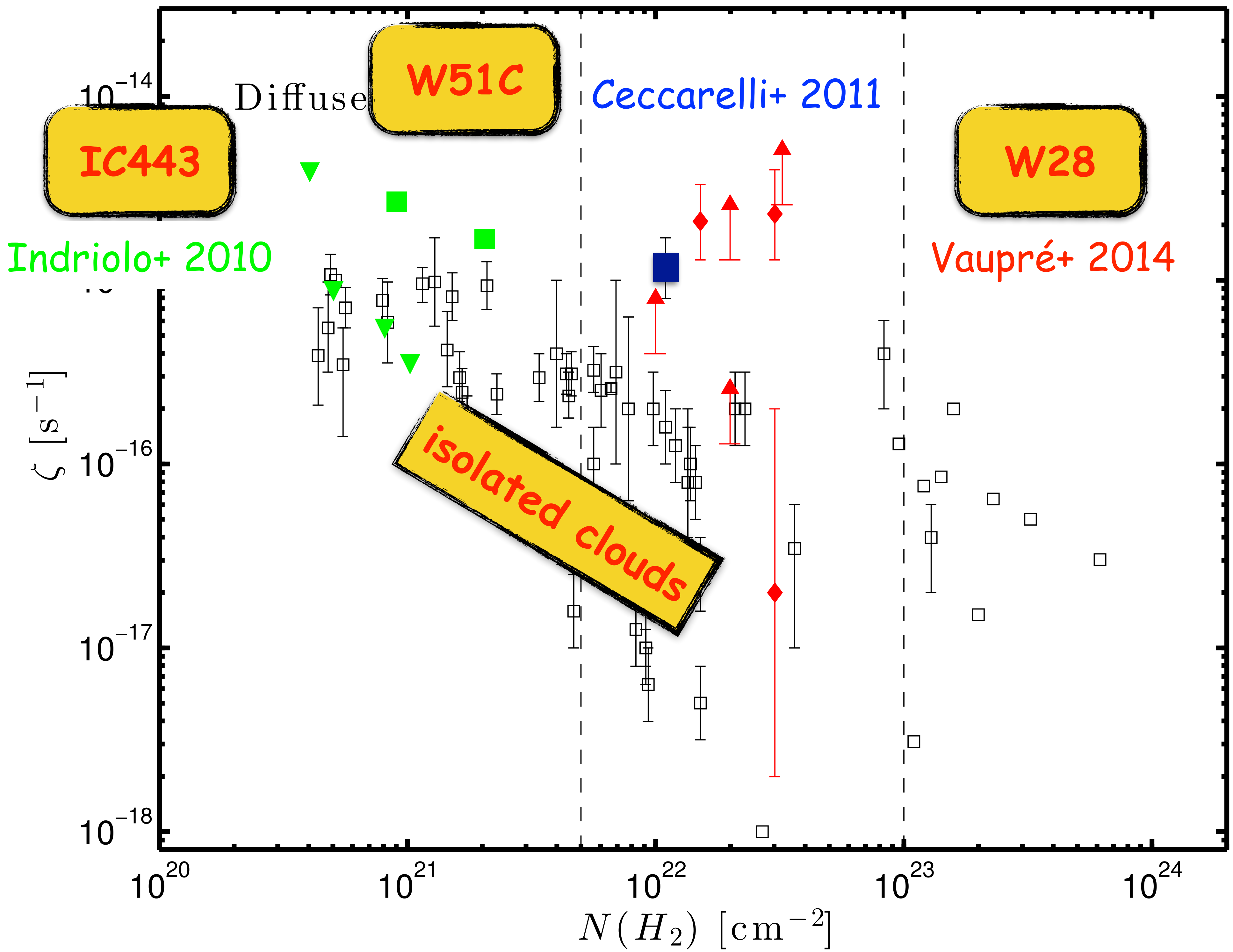

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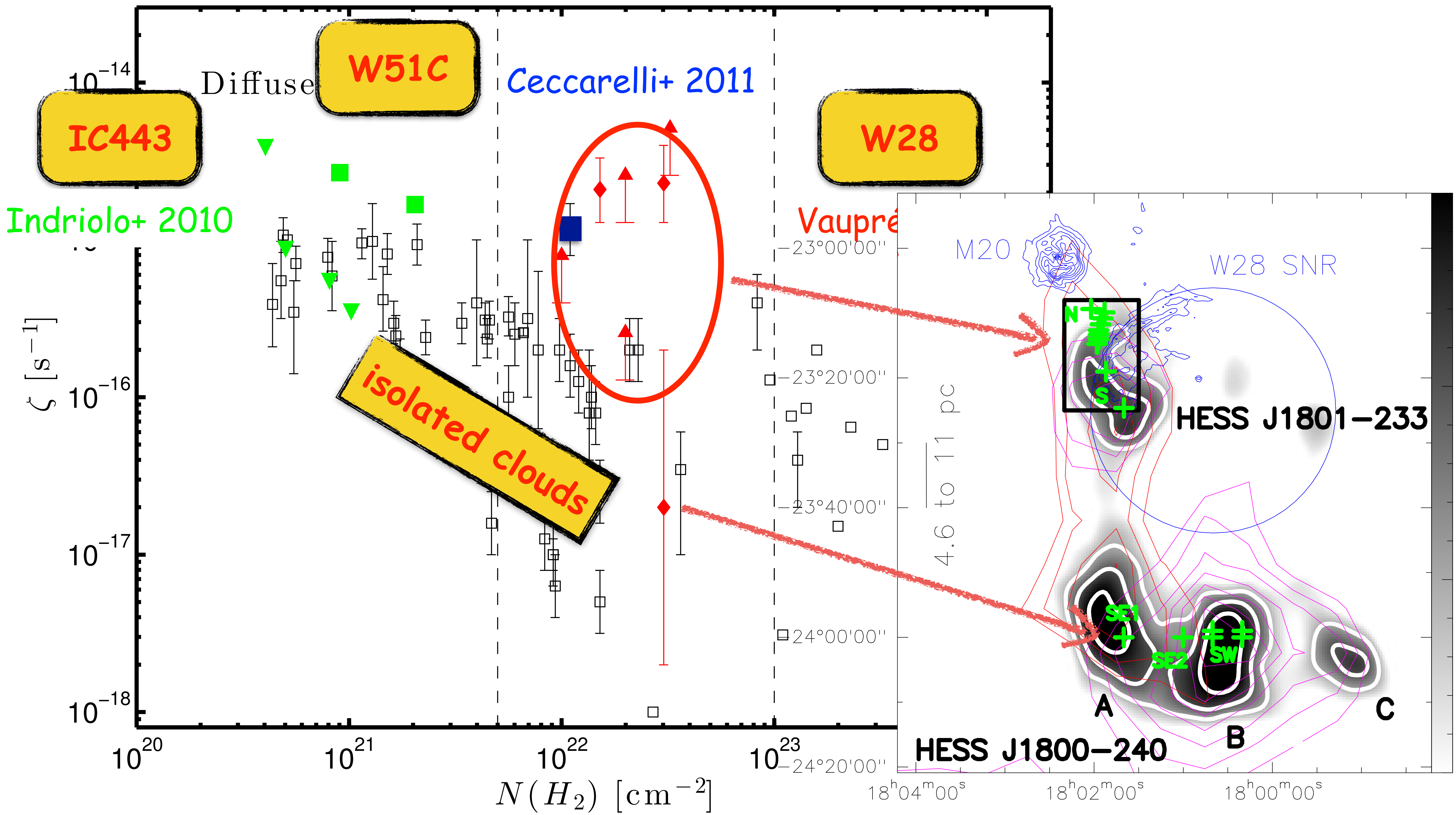

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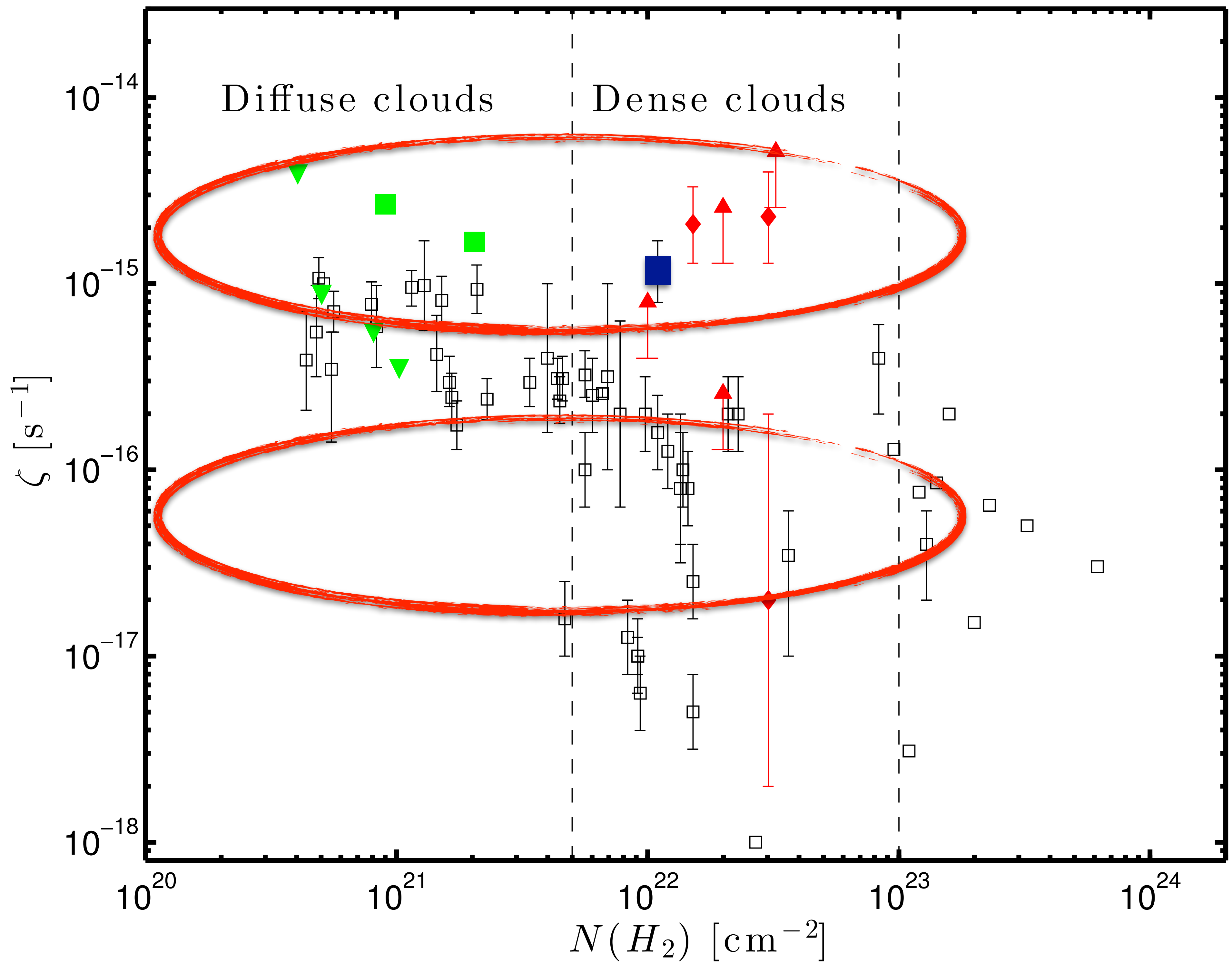

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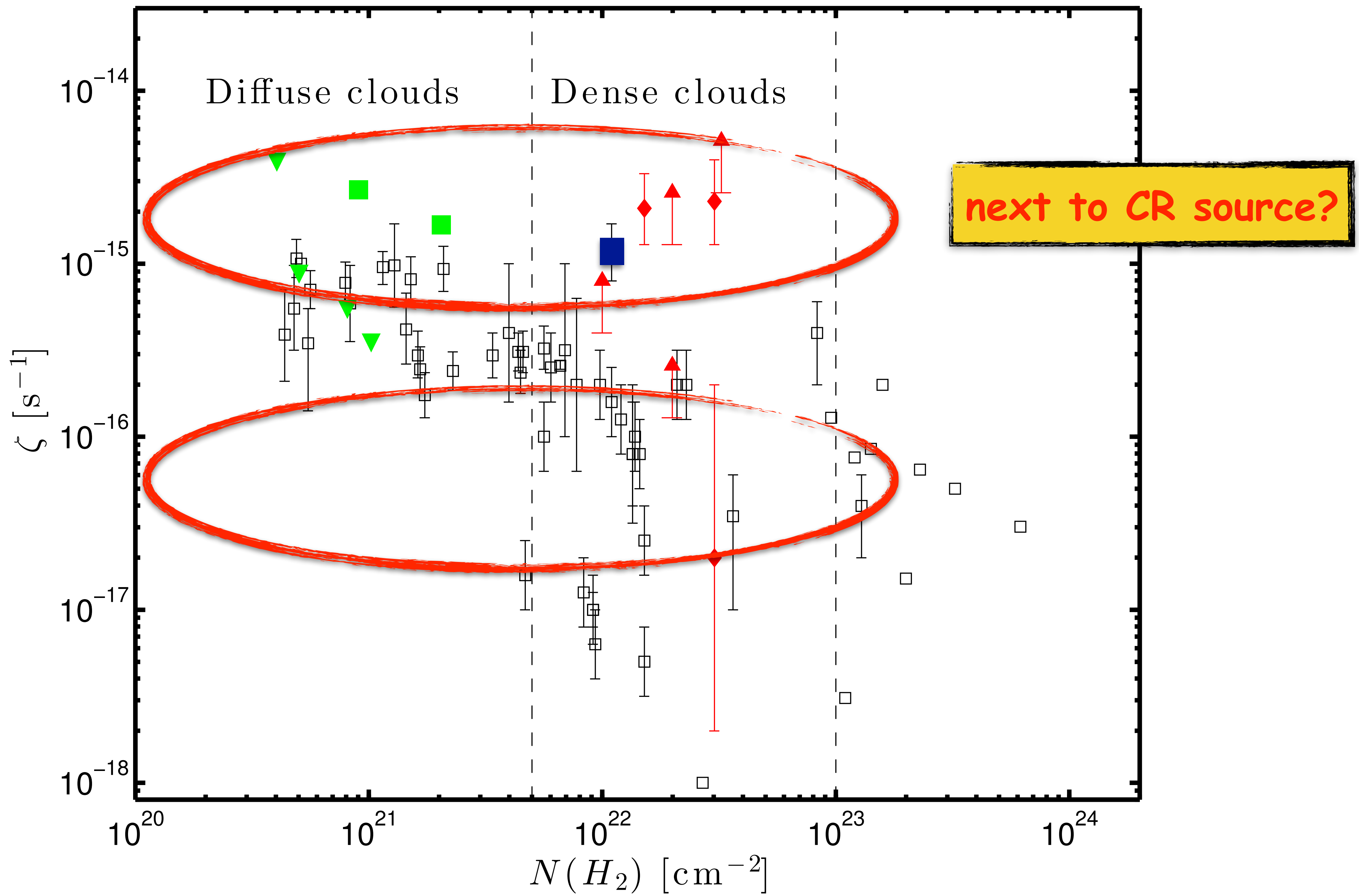

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