Protoplanetary Disks – JEDI

Osservatorio Astronomico di Roma - *June, 25th 2018*

Protostars: Forges of cosmic rays?

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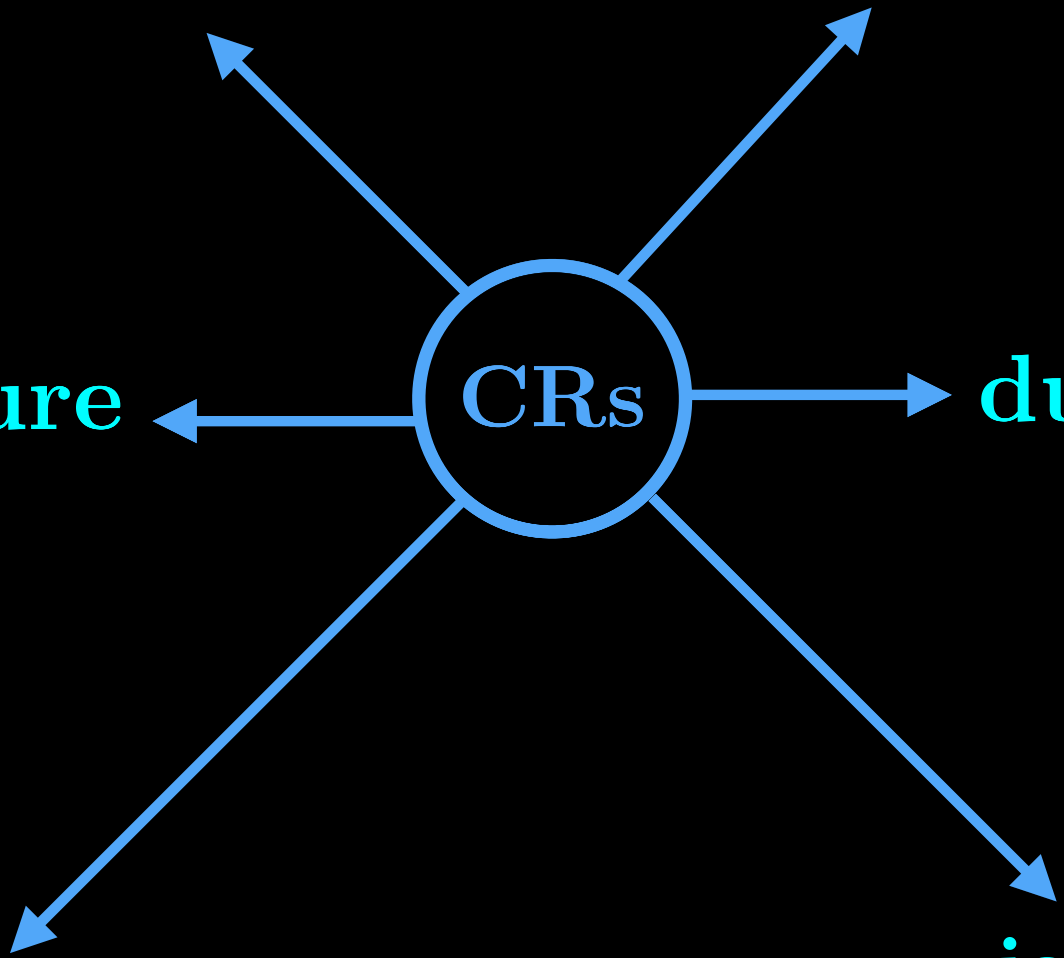
Alexei Ivlev, Paola Caselli (MPE - Garching)

Alexandre Marcowith (LUPM - Montpellier)
Patrick Hennebelle (CEA - Saclay)
Katia Ferrière (IRAP - Toulouse)

Cosmic rays and interstellar medium in one slide



chemistry of molecular clouds

Caselli+ (1998)
Padovani+ (2009,2011)
Indriolo+ (2012)
Padovani & Galli (2013)

collapse timescale

Nakano+ (2002)
Padovani+ (2013,2014)

gas temperature

Glassgold & Langer (1973)
Cravens & Dalgarno (1978)
Dalgarno+ (1999)
Glassgold+ (2012)
Galli & **Padovani** (2015)

dust grain charge

Prasad & Tarafdar (1983)
Cecchi-Pestellini & Aiello (1992)
Shen+ (2004)
Ivlev, **Padovani**, Galli+ (2015)

protostars as cosmic-ray sources

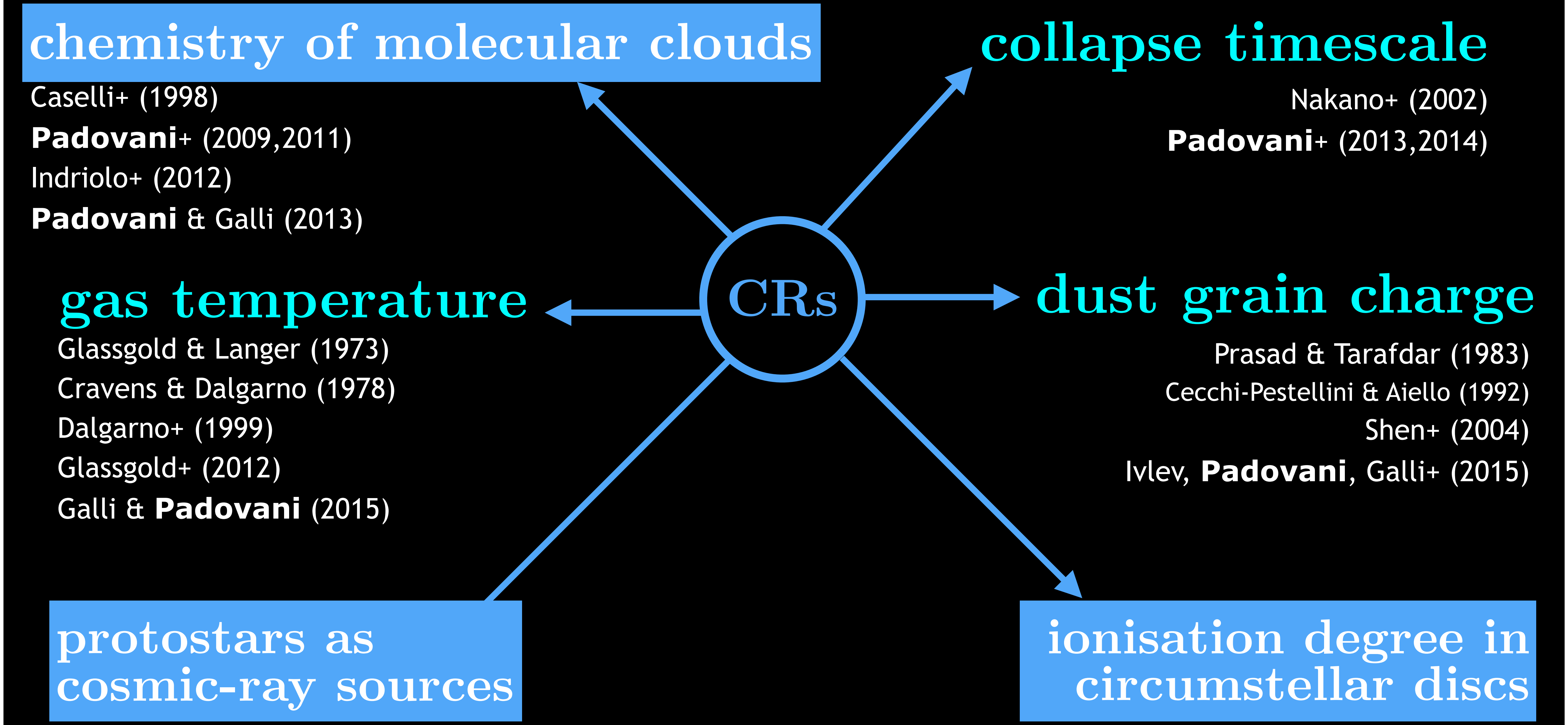
Padovani+ (2015,2016,2017)

ionisation degree in circumstellar discs

Padovani+ (2018)

(production of light elements, γ-ray emission through π^0 decay...)

Cosmic rays and interstellar medium in one slide



CRs

chemistry of molecular clouds

Caselli+ (1998)
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collapse timescale

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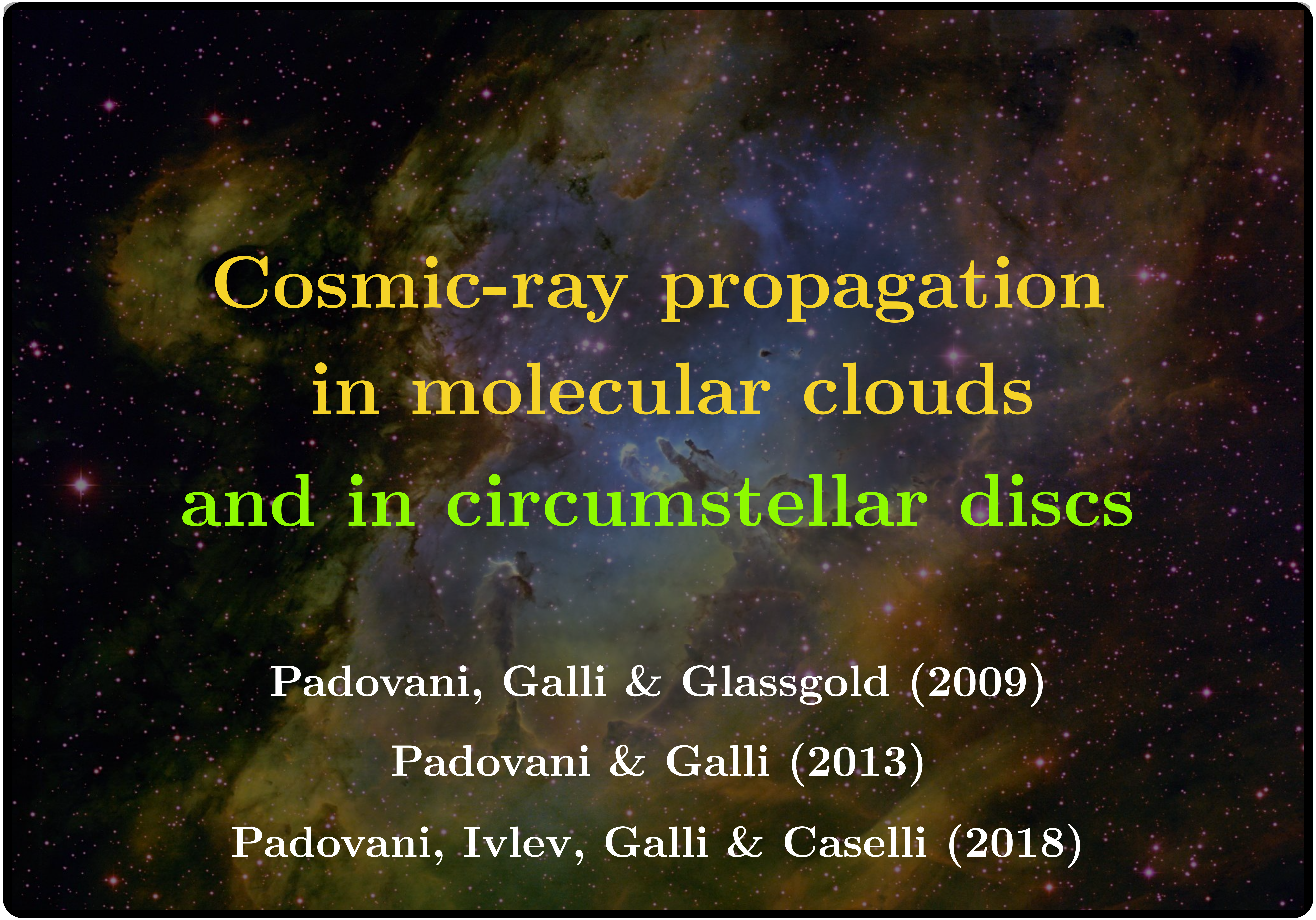


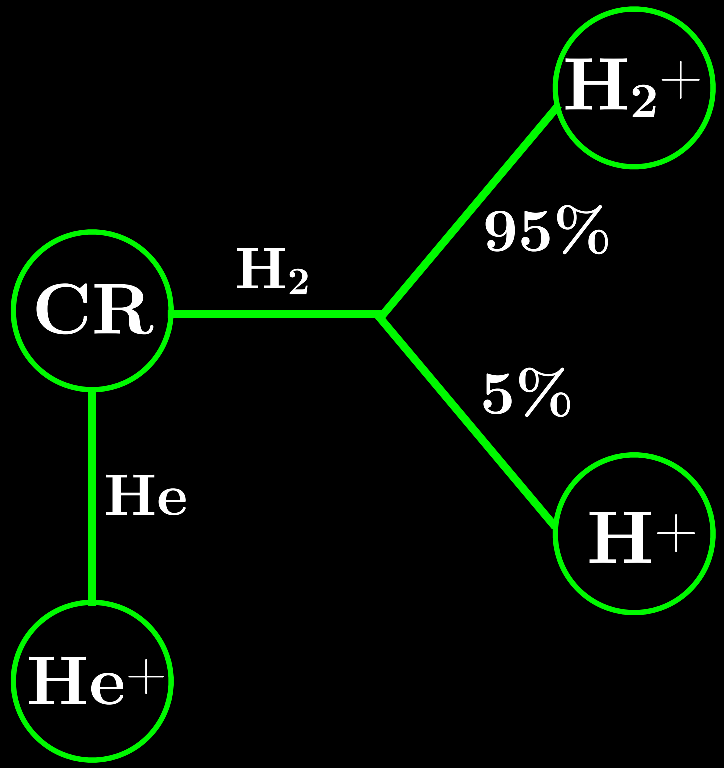
Cosmic-ray propagation in molecular clouds and in circumstellar discs

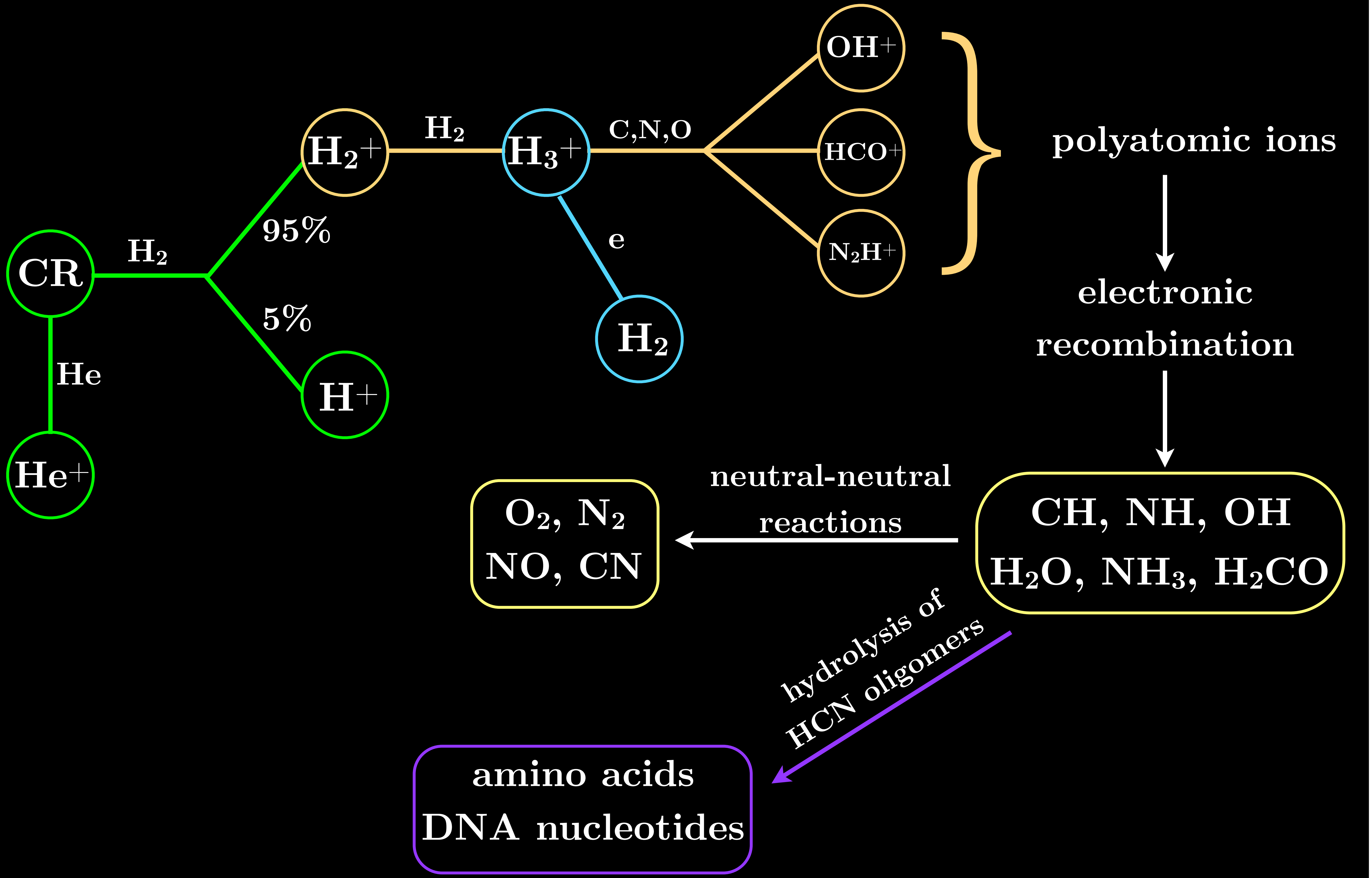
Padovani, Galli & Glassgold (2009)

Padovani & Galli (2013)

Padovani, Ivlev, Galli & Caselli (2018)

- Diffuse clouds ($A_v \sim 1$ mag) → the UV radiation field is the principal ionising agent (photodissociation regions);
- Dense clouds ($A_v \gtrsim 5$ mag) → the ionisation is due to low-energy CRs ($E < 100$ MeV) and, if close to young stars, to soft X–rays ($E < 10$ keV).





CR

H_2

He

He^+

95%

5%

H_2^+

H^+

H_2

H_3^+

e

H_2

C,N,O

OH^+

HCO^+

N_2H^+

polyatomic ions

electronic recombination

CH, NH, OH

H_2O, NH_3, H_2CO

neutral-neutral reactions

O_2, N_2

NO, CN

hydrolysis of HCN oligomers

amino acids

DNA nucleotides

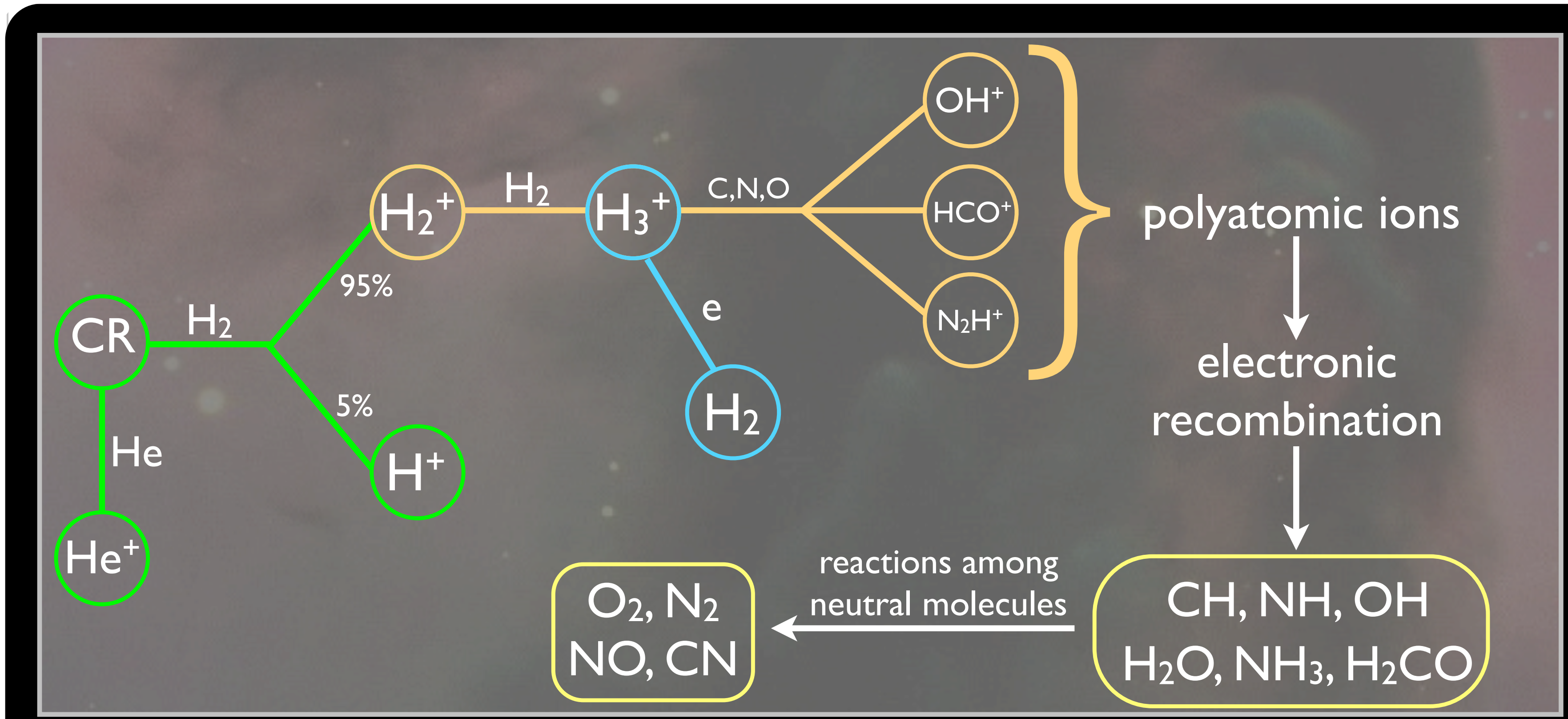
Cosmic-ray ionisation rate

(number of ionisation per second)

$\zeta\ [\mathrm{s}^{-1}]$ ⟶ *key-brick parameter:*

— chemical models (interpretation of observed abundances);

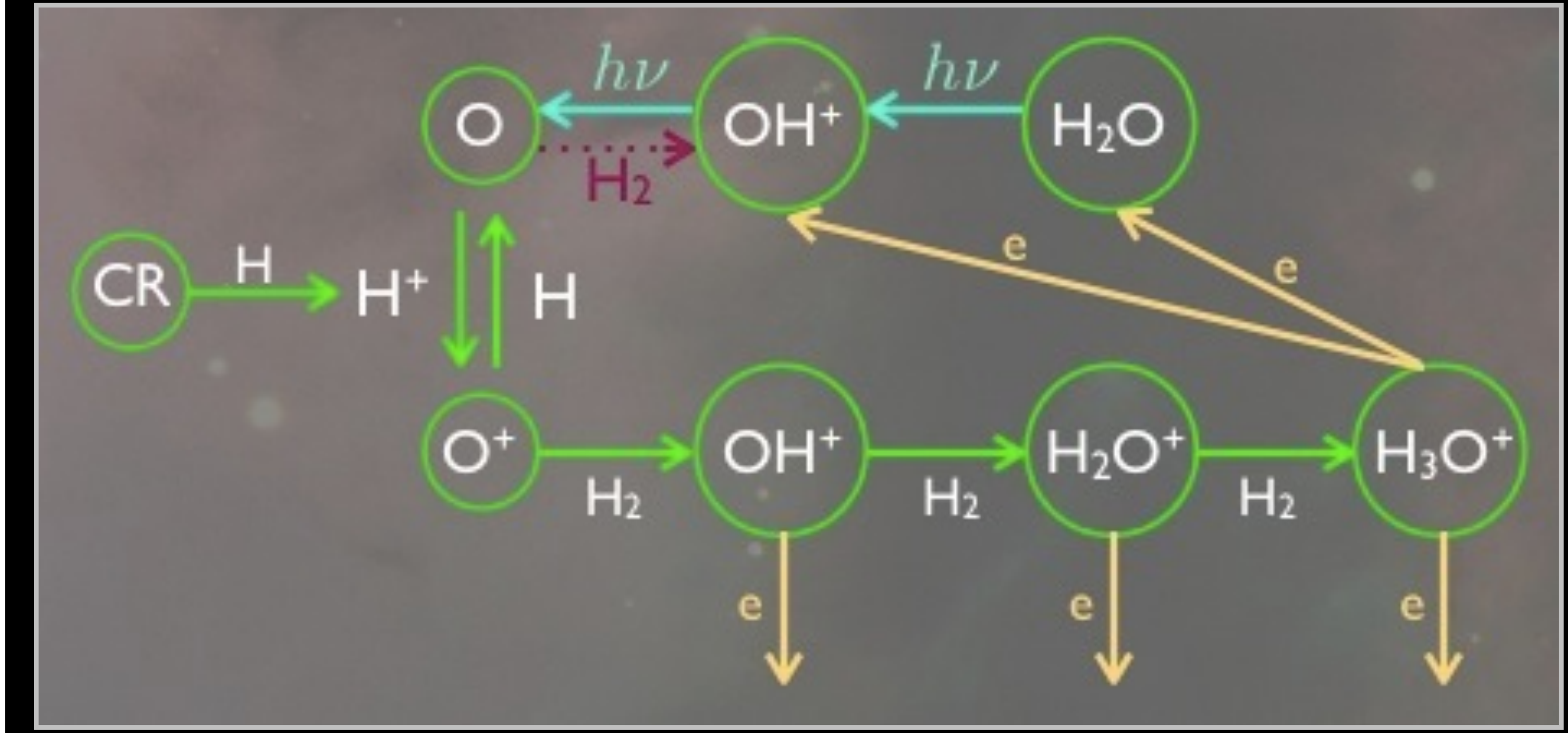
— non-ideal MHD simulations (study of the collapse of a molecular cloud core and the formation of a protostellar disc);



Dense cores

(HCO^+, DCO^+)

Guélin (1977)
Caselli+ (1998)
Maret & Bergin (2007)



Diffuse clouds

(OH, HD, NH)

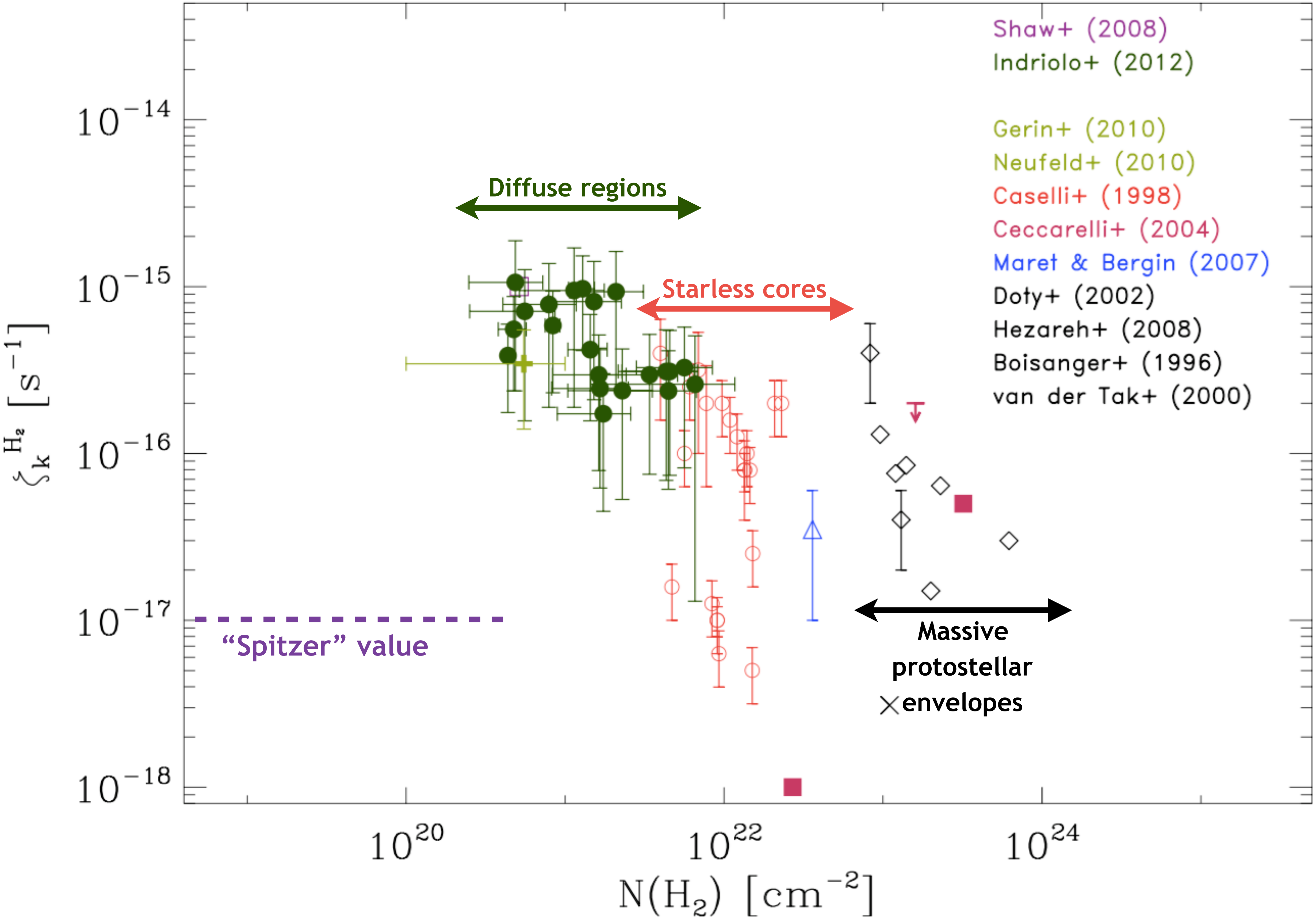
Black & Dalgarno (1977),
Hartquist+ (1978), Black+ (1978),
van Dishoeck & Black (1986),
Federman+ (1996)

(H_3^+)

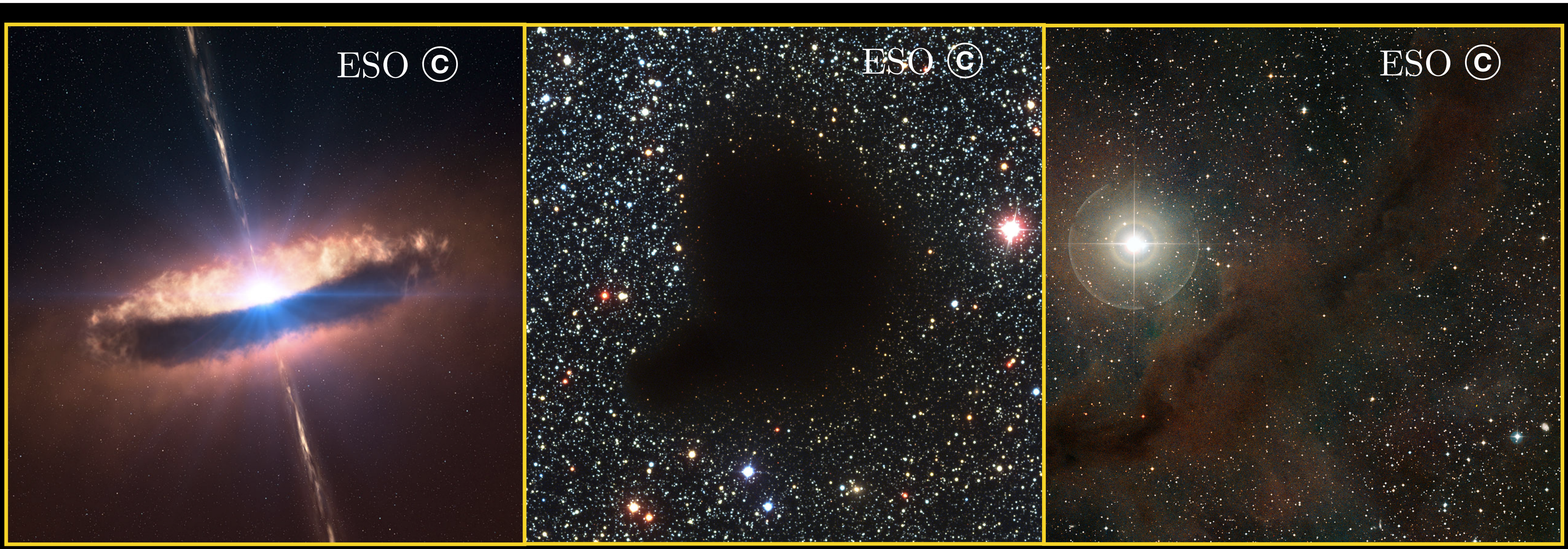
McCall+ (1993), Geballe+ (1999)
McCall+ (2003),
Indriolo+ (2009,2012,2015)

(OH^+, H_2O^+)

Neufeld+ (2010), Gerin+ (2010)



10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
$\zeta_k^{H_2}$ [s^{-1}]
10^{20}
10^{22}
10^{24}
N(H_2) [cm^{-2}]
Shaw+ (2008)
Indriolo+ (2012)
Gerin+ (2010)
Neufeld+ (2010)
Caselli+ (1998)
Ceccarelli+ (2004)
Maret & Bergin (2007)
Doty+ (2002)
Hezareh+ (2008)
Boisanger+ (1996)
van der Tak+ (2000)
Diffuse regions
Starless cores
Massive protostellar envelopes
"Spitzer" value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ESO ©
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$\approx 10^{-19}$ 10^{-17} 10^{-15}

10^{-22} 10^{-18} 10^{-16}

$\zeta\ [\mathrm{s}^{-1}]$

protostar

set by decay of short-lived radionuclei
Cleeves+ 2013; 2015

dense

$\mathrm{HCO^+}$, $\mathrm{DCO^+}$

Guélin+ 1977
Caselli+ 1998
Maret & Bergin 2007

diffuse

$\mathrm{H_3^+}$, $\mathrm{OH^+}$, $\mathrm{H_2O^+}$

McCall+ 1993; Geballe+ 1999;
McCall+ 2003; Indriolo+ 2009,2012,2015
Gerin+ 2010; Neufeld+ 2010

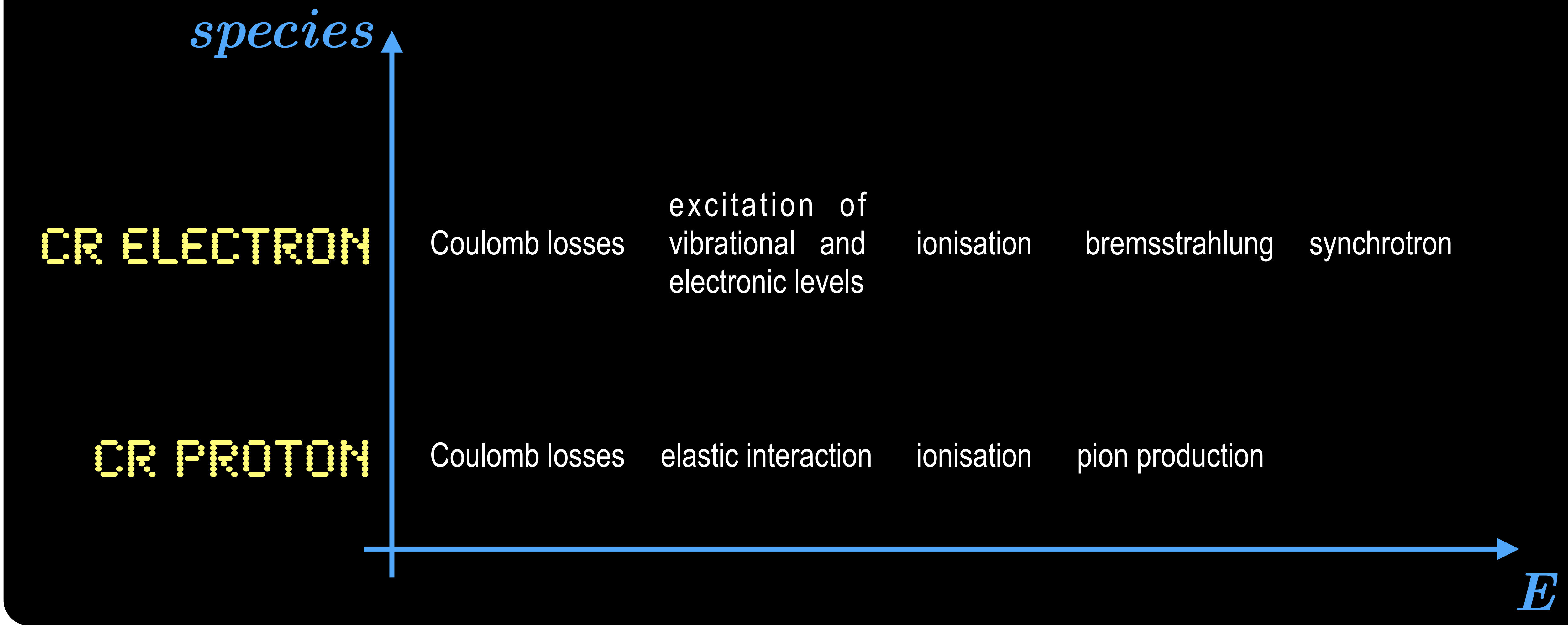
HOW TO RECONCILE THE HIGH VALUES OF ζ IN DIFFUSE CLOUDS WITH THE LOWER VALUES IN DENSER ENVIRONMENTS?

CR propagation inside a cloud

Theoretical model (Padovani, Galli & Glassgold 2009)

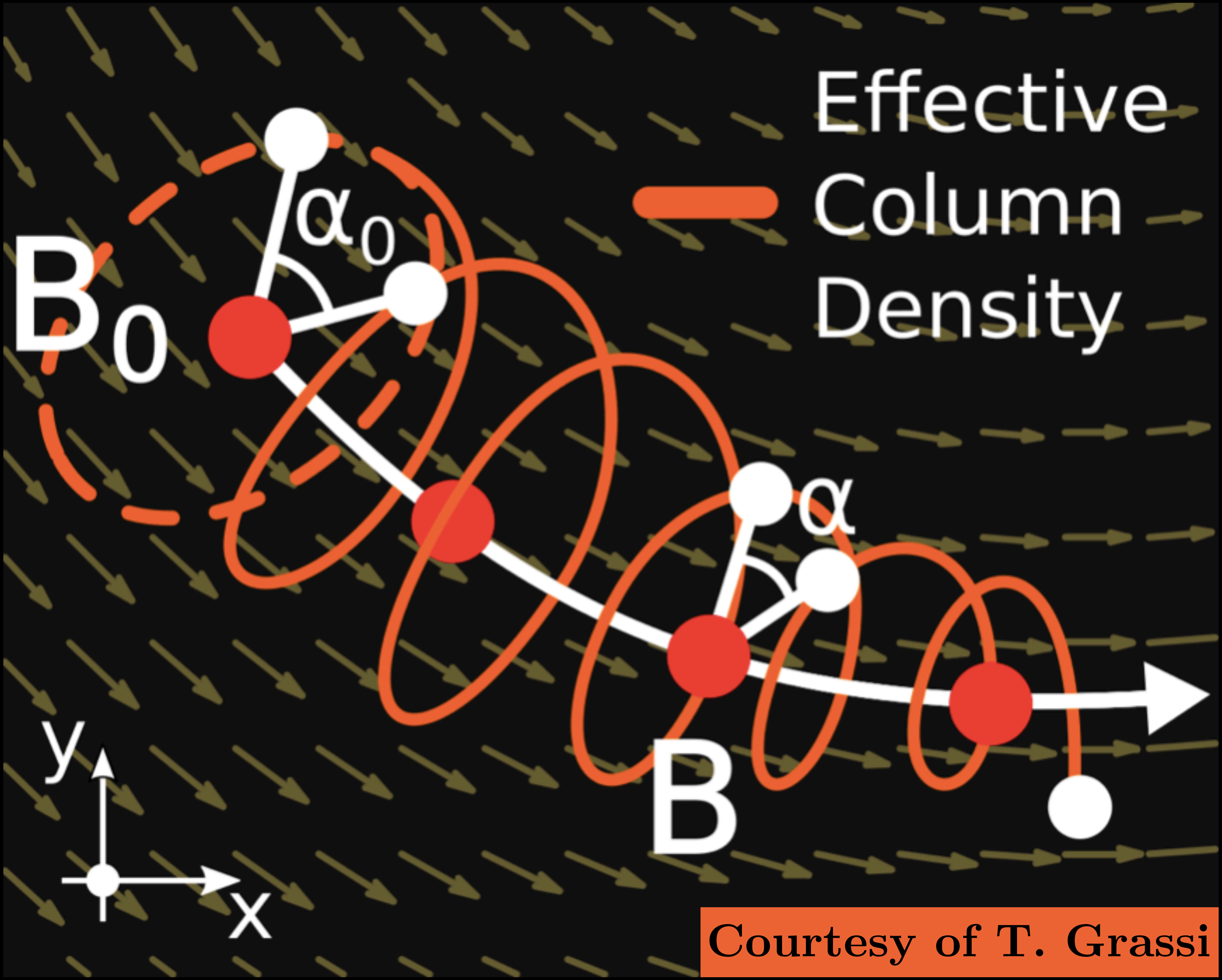
computing the variation of the ionisation rate due to cosmic rays, ζ_{CR} [s^{-1}], inside a molecular cloud, with the increasing of the column density, *N* [cm^{-2}], of the traversed interstellar matter.

$$\zeta_{CR}^{(\mathrm{H}_2)}(N) = 4\pi \int_0^\infty j(E,N)\sigma(E)\,\mathrm{d}E$$



CR ELECTRON: Coulomb losses; excitation of vibrational and electronic levels; ionisation; bremsstrahlung; synchrotron

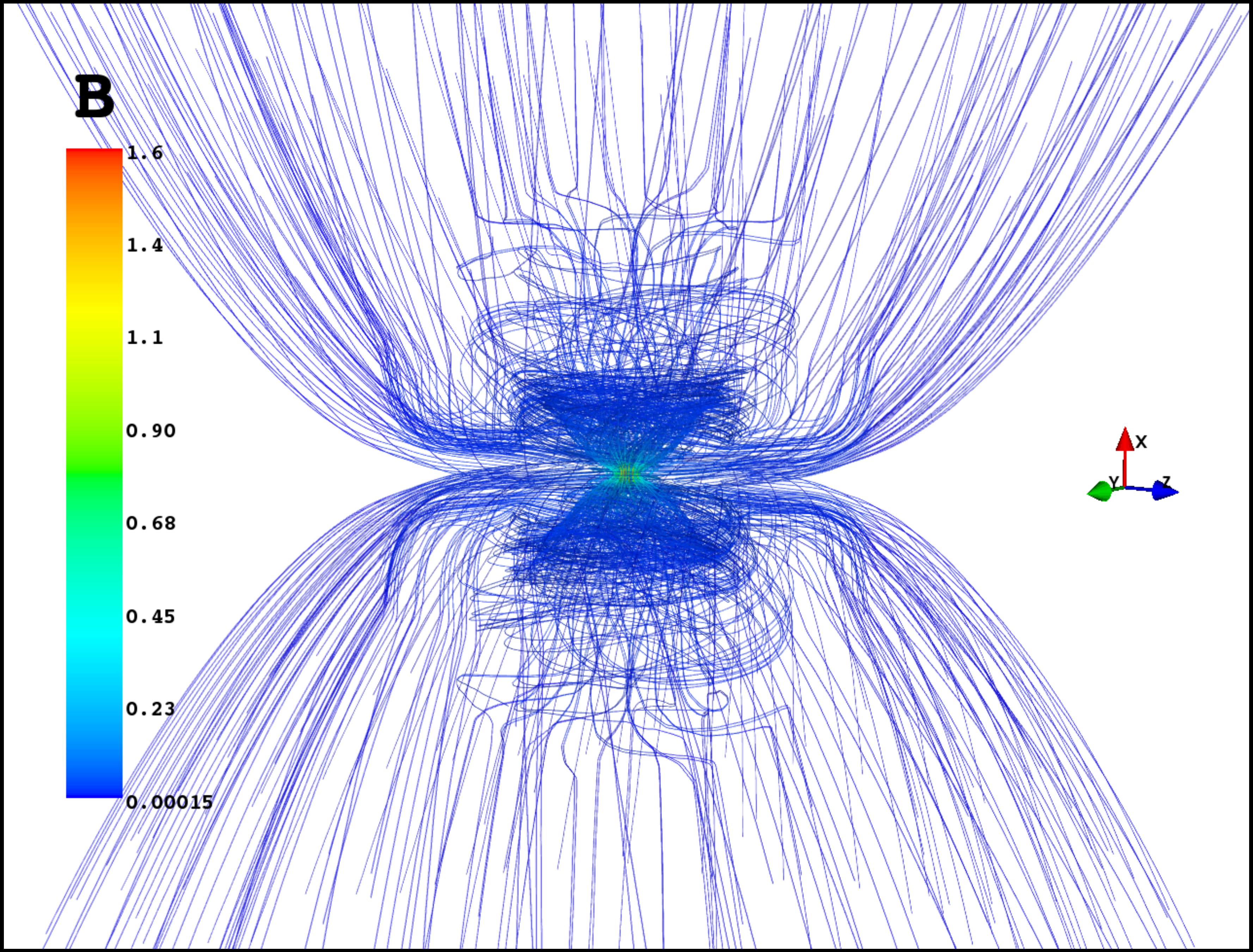
CR PROTON: Coulomb losses; elastic interaction; ionisation; pion production



Courtesy of T. Grassi

Numerical models : rotating collapsing core

Field lines in the inner 600 AU



PM, Hennebelle & Galli 2013a

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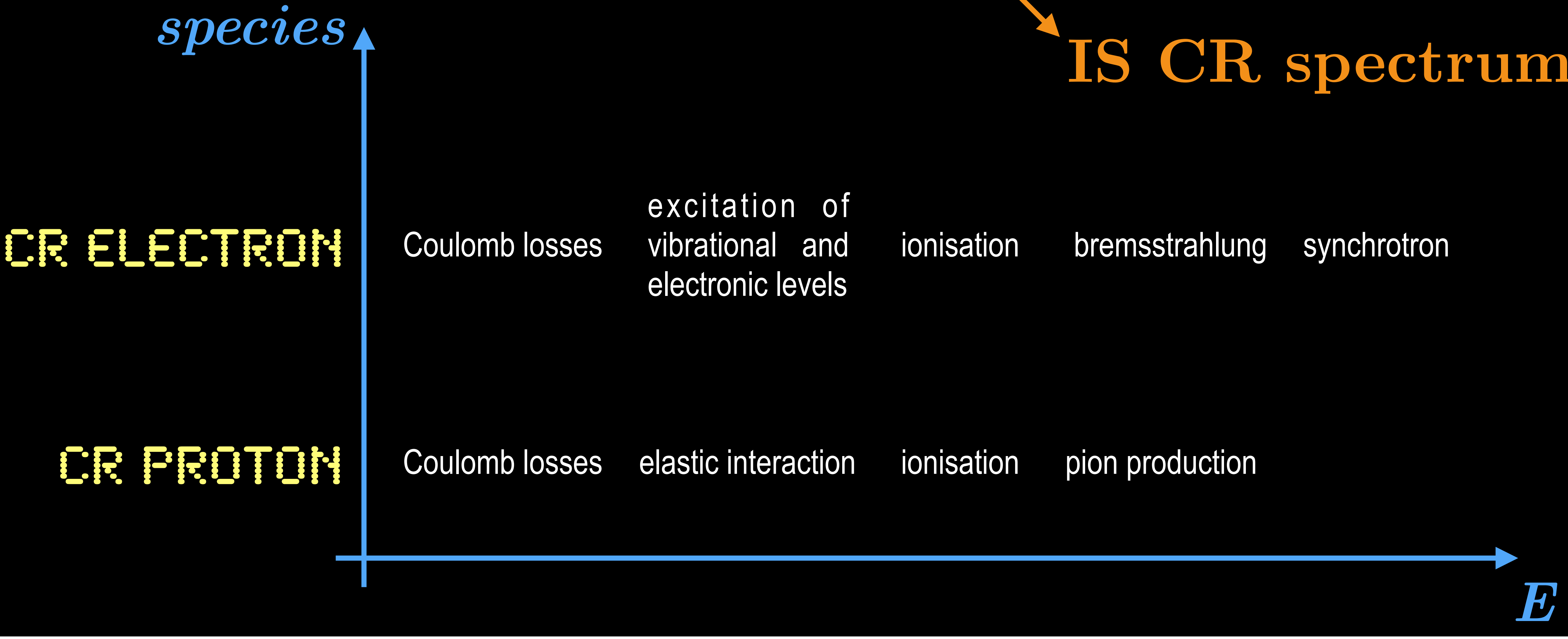
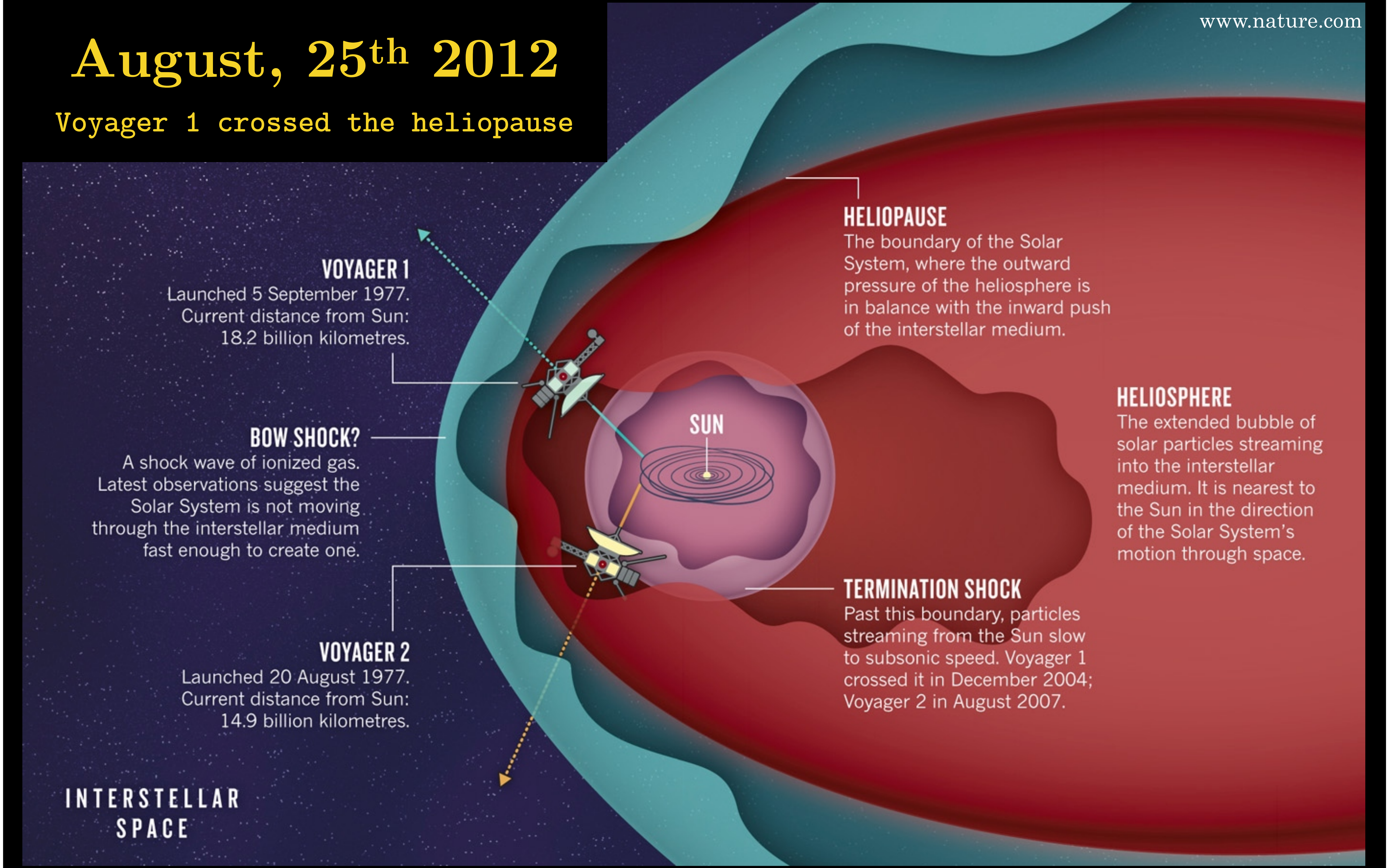
IS CR spectrum



CR ELECTRON	Coulomb losses	excitation of vibrational and electronic levels	ionisation	bremsstrahlung	synchrotron
CR PROTON	Coulomb losses	elastic interaction	ionisation	pion production	

August, 25th 2012

Voyager 1 crossed the heliopause



www.nature.com

HELIOPAUSE
The boundary of the Solar System, where the outward pressure of the heliosphere is in balance with the inward push of the interstellar medium.

VOYAGER 1
Launched 5 September 1977.
Current distance from Sun:
18.2 billion kilometres.

HELIOSPHERE
The extended bubble of solar particles streaming into the interstellar medium. It is nearest to the Sun in the direction of the Solar System's motion through space.

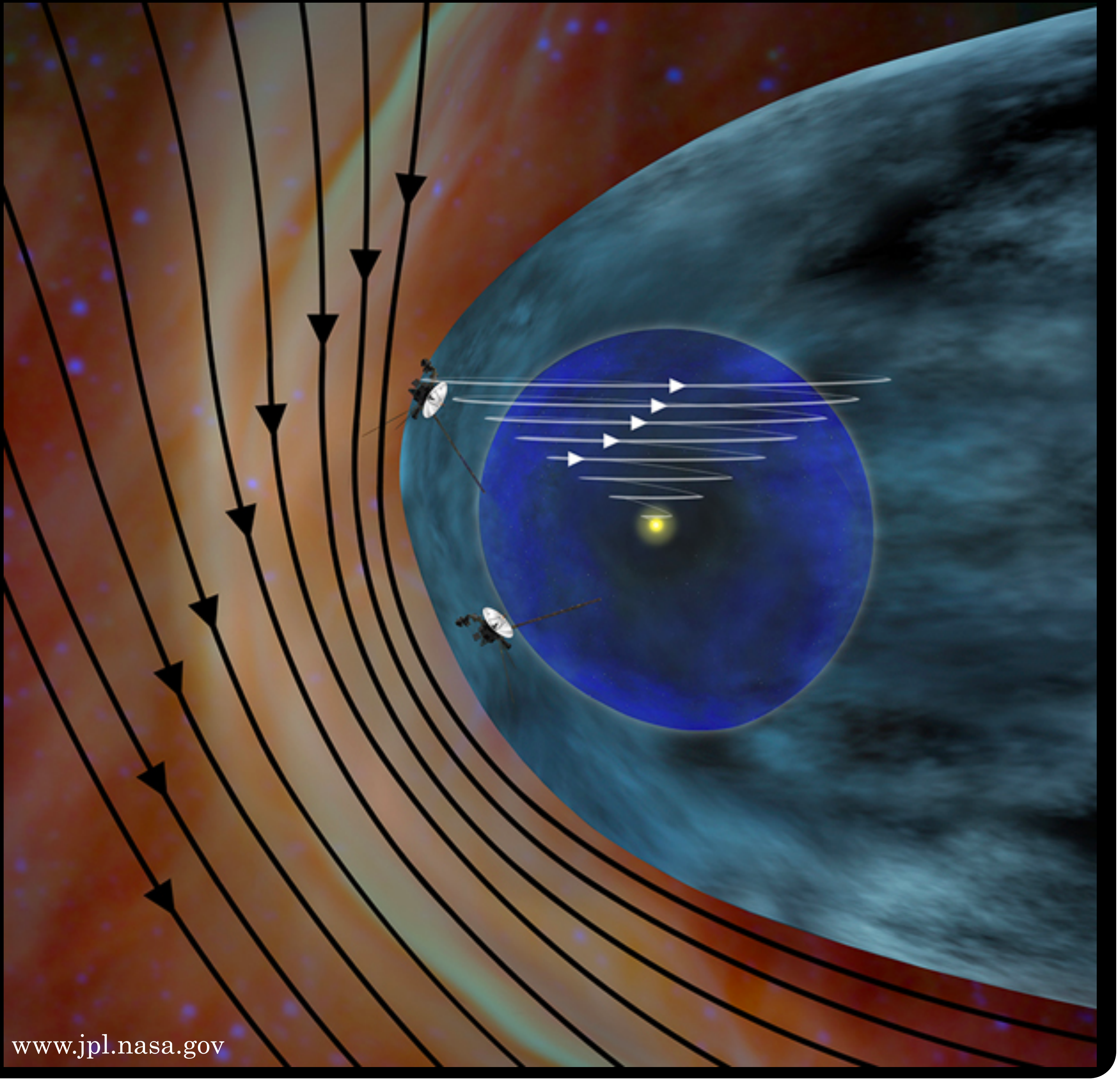
BOW SHOCK?
A shock wave of ionized gas. Latest observations suggest the Solar System is not moving through the interstellar medium fast enough to create one.

TERMINATION SHOCK
Past this boundary, particles streaming from the Sun slow to subsonic speed. Voyager 1 crossed it in December 2004; Voyager 2 in August 2007.

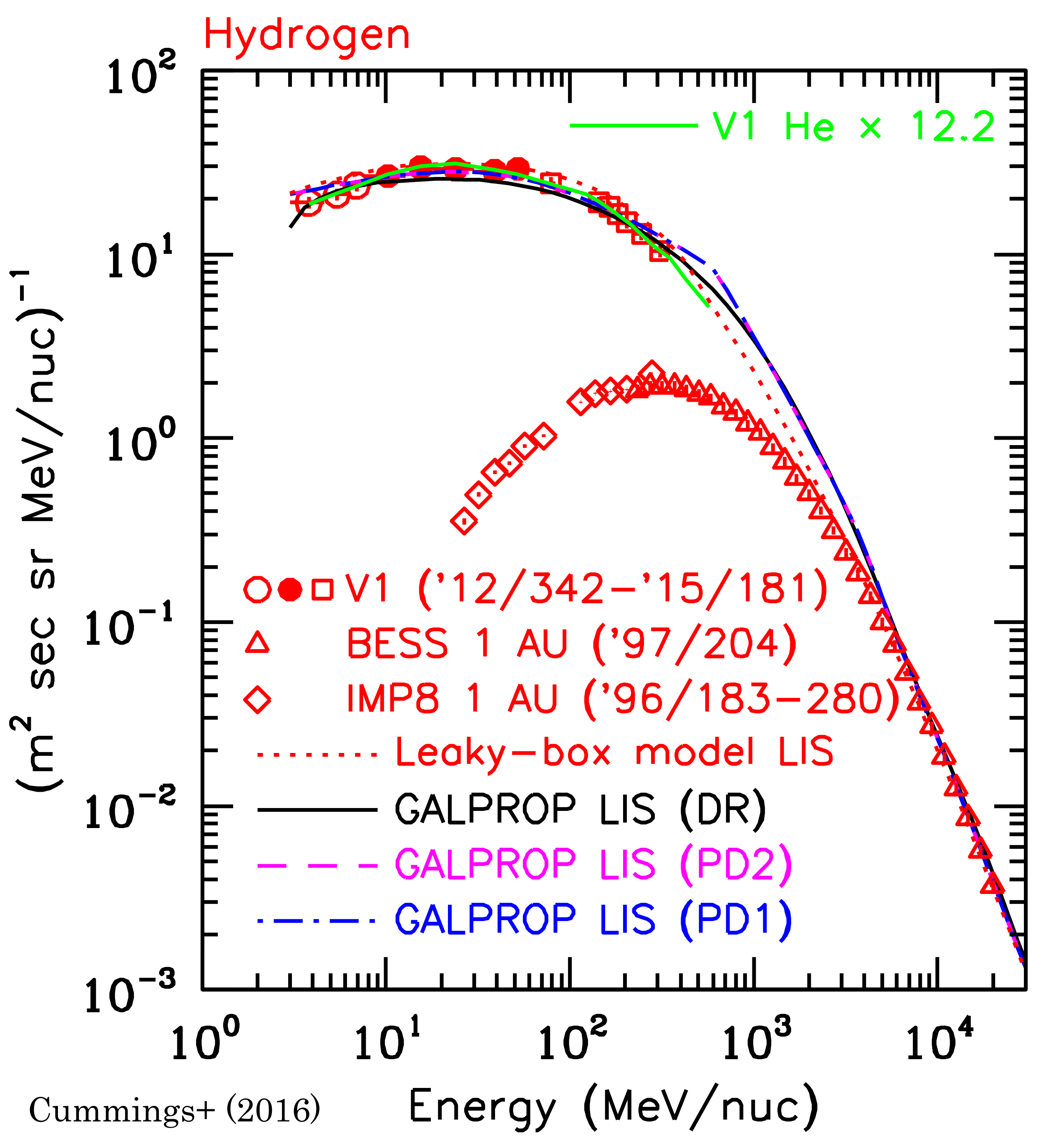
VOYAGER 2
Launched 20 August 1977.
Current distance from Sun:
14.9 billion kilometres.

Magnetic field:
- in the ISM (black lines);
- from the Sun (white lines).

Next expected signature:
variation in the magnetic field direction

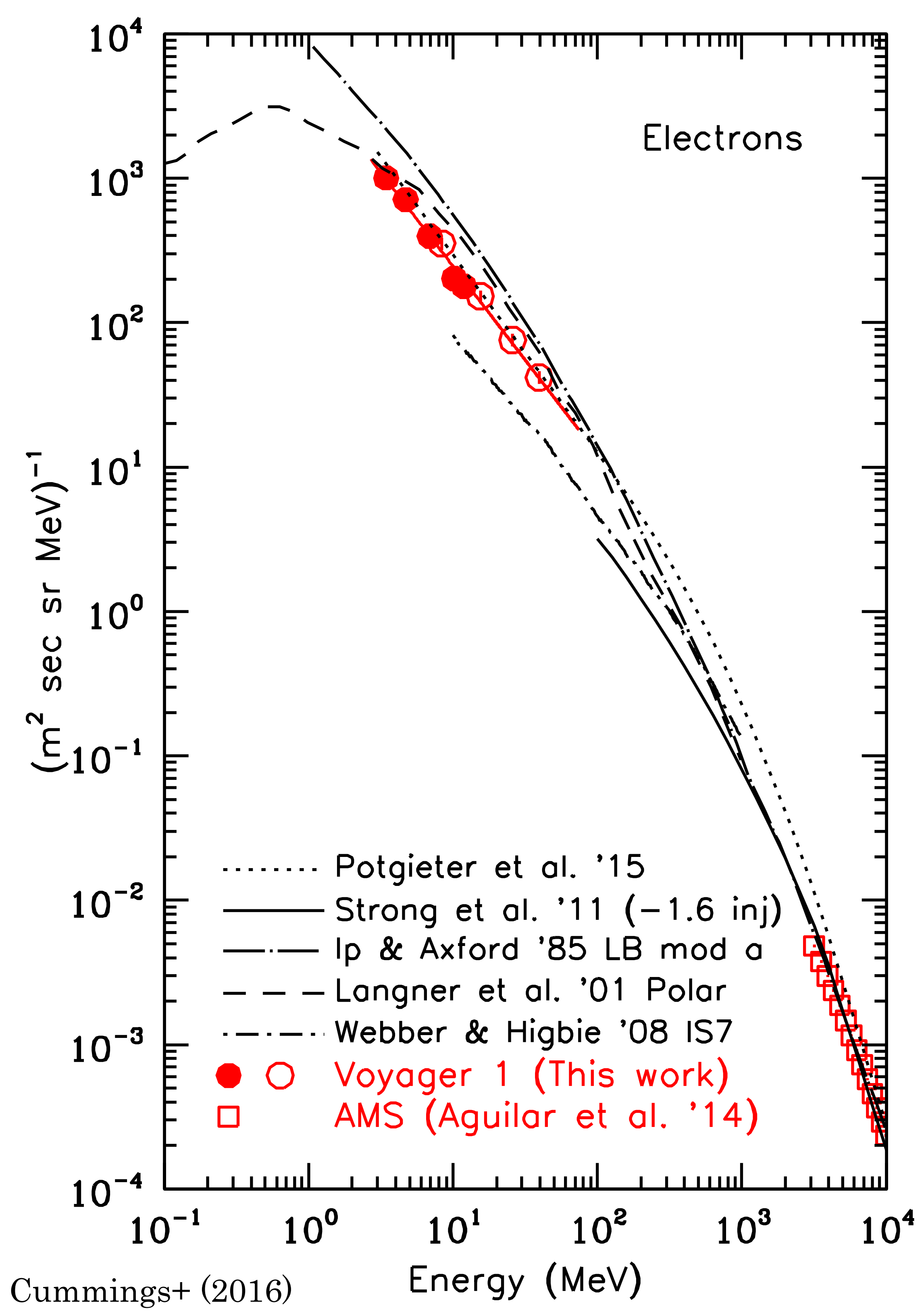

www.jpl.nasa.gov

CR protons

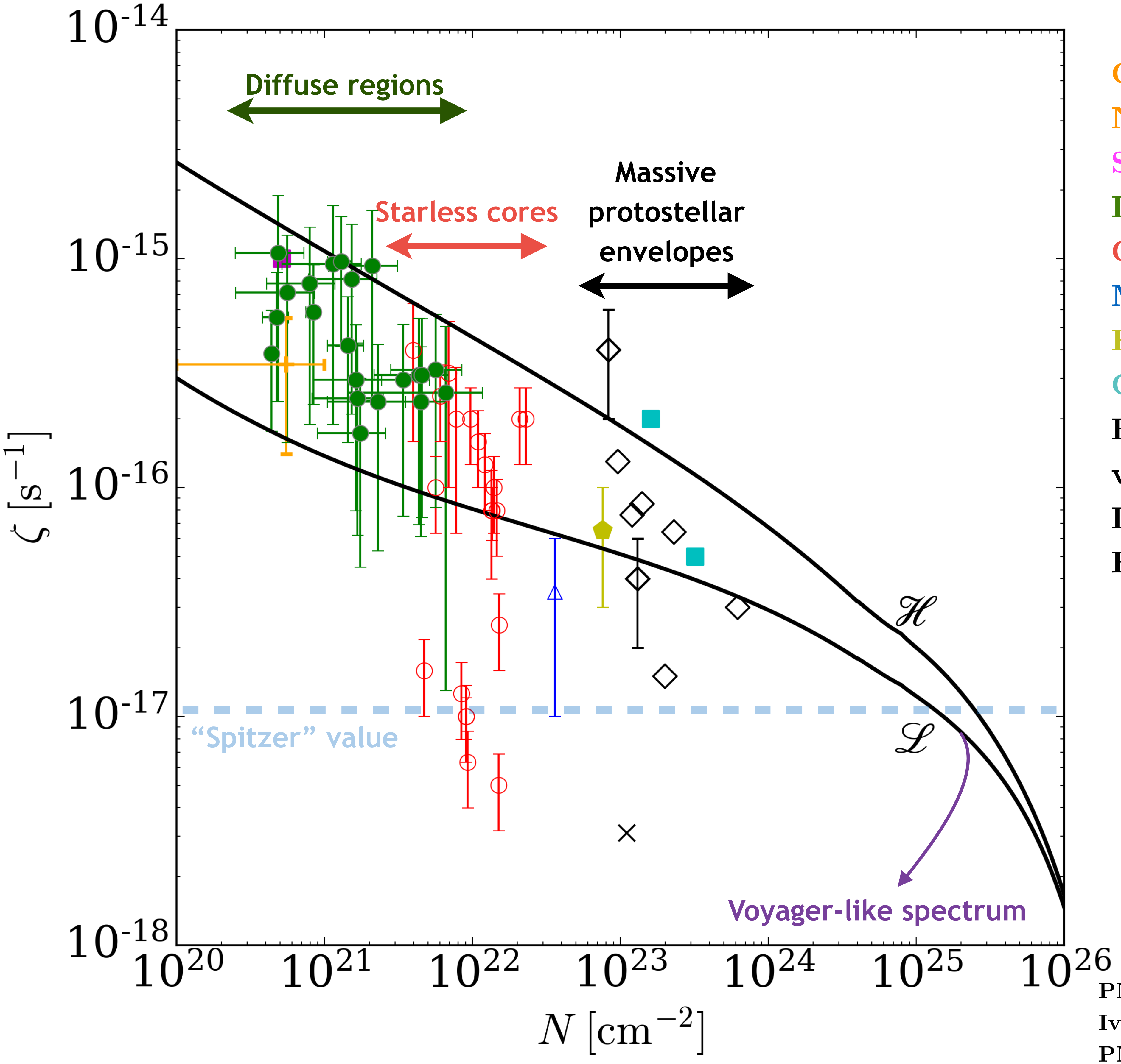


Cummings+ (2016)

CR electrons



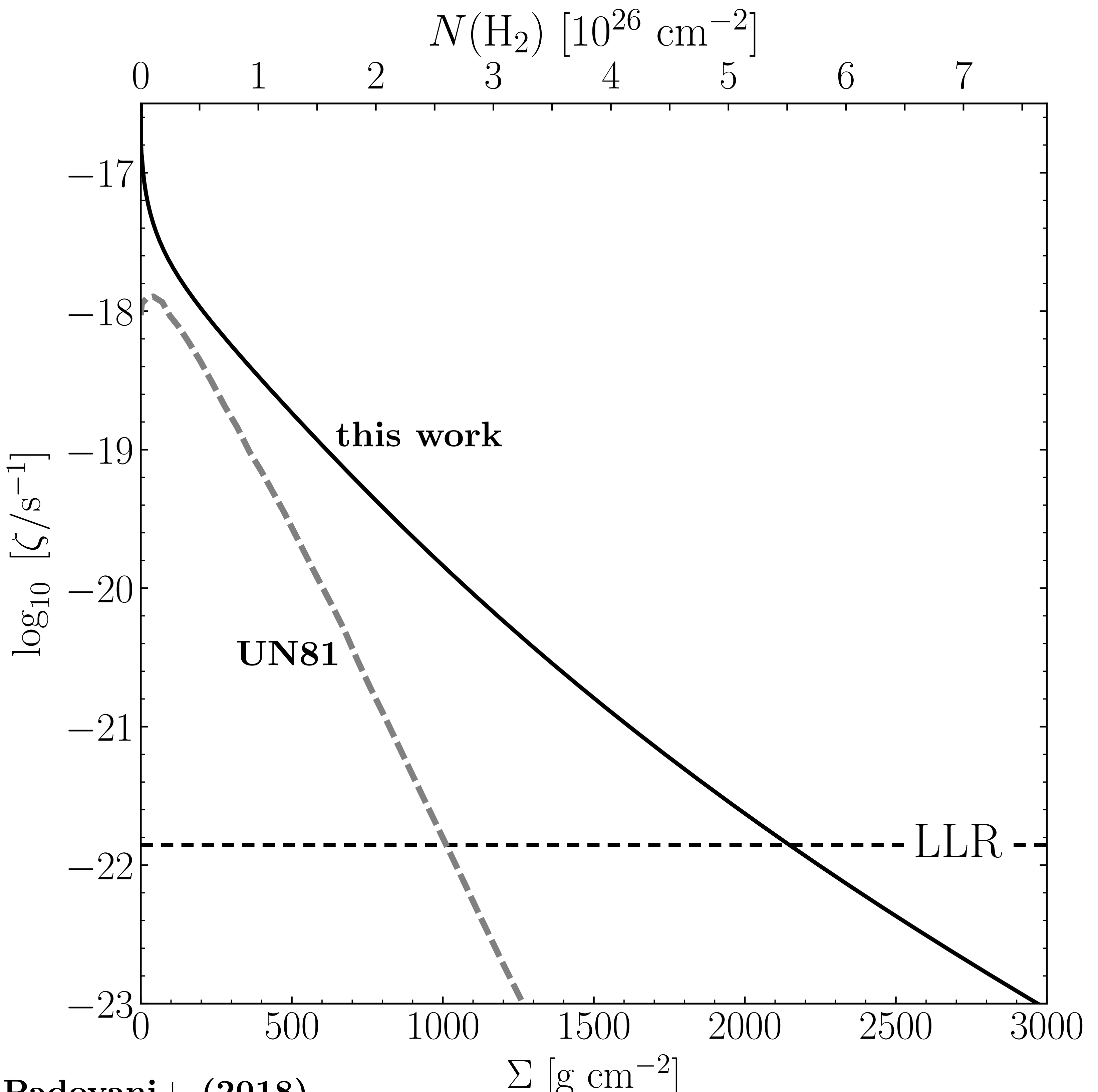
Cummings+ (2016)



Gerin+ (2010)
Neufeld+ (2010)
Shaw+ (2008)
Indriolo+ (2012)
Caselli+ (1998)
Maret & Bergin (2007)
Fuente+ (2016)
Ceccarelli+ (2004)
Boisanger+ (1996)
van der Tak+ (2000)
Doty+ (2002)
Hezareh+ (2008)

PM, Galli & Glassgold (2009)
Ivlev, PM, Galli & Caselli (2015)
PM, Ivlev, Galli & Caselli (2018)

CR ionisation in circumstellar discs



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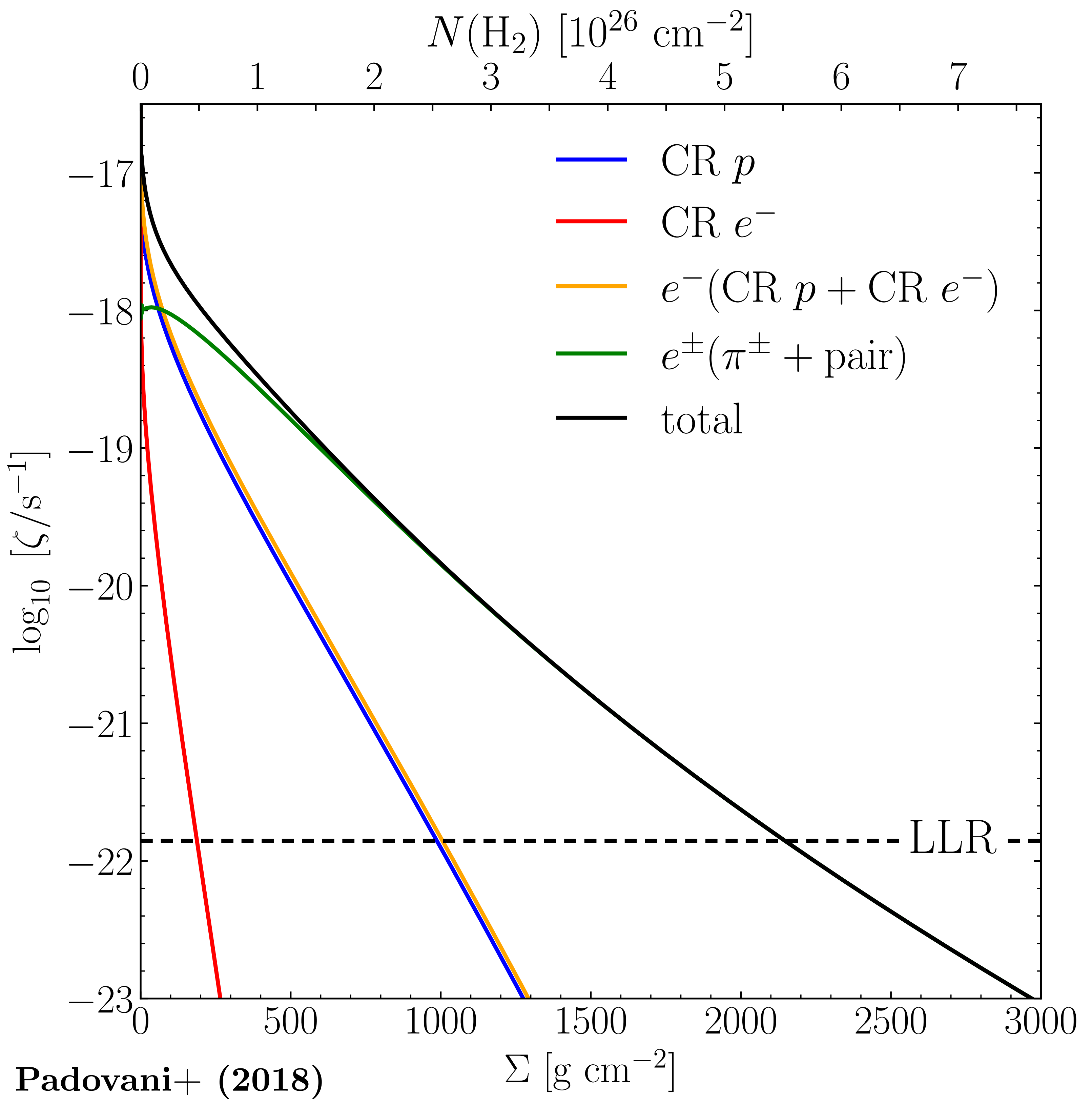
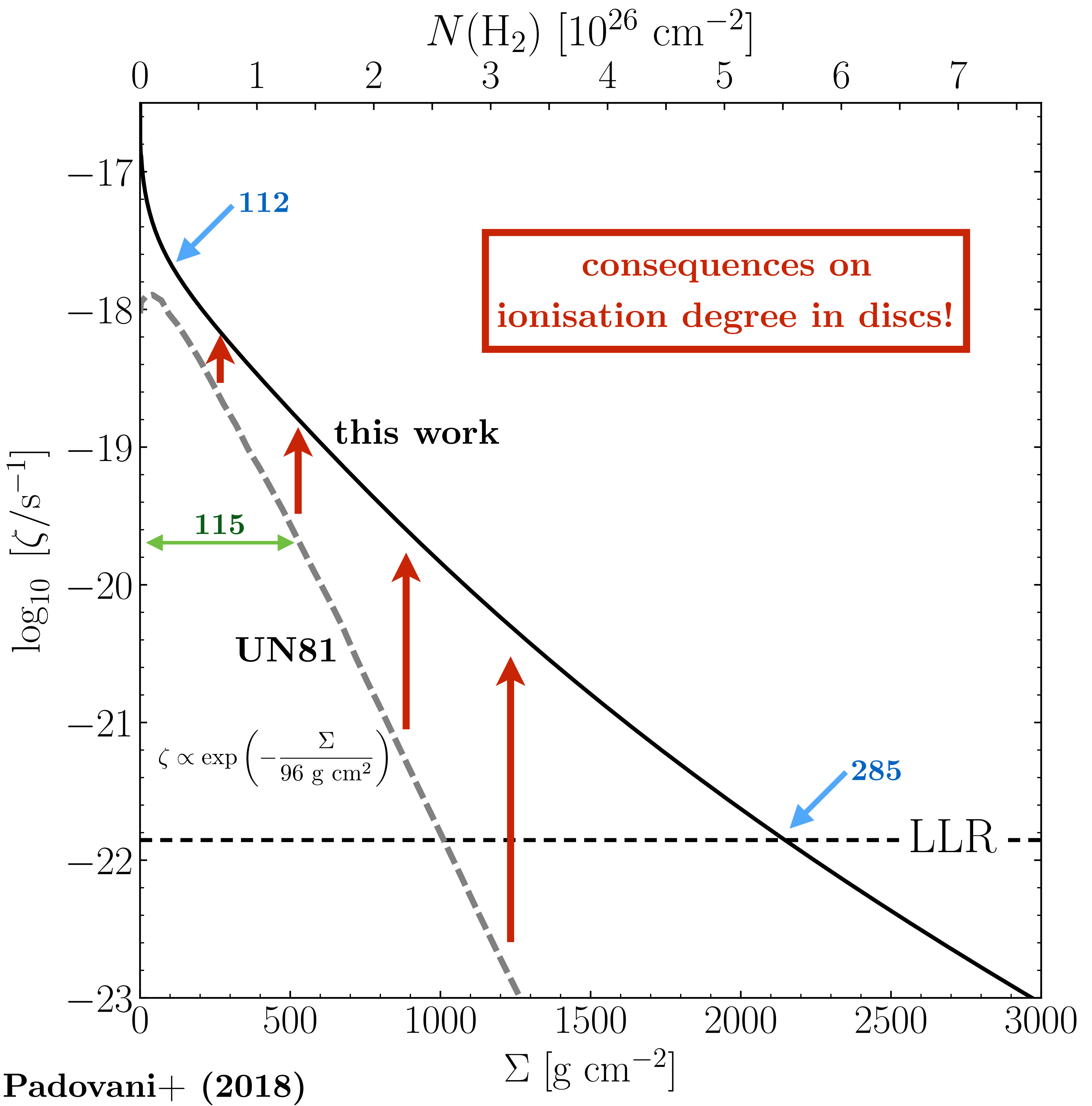


Padovani+ (2018)

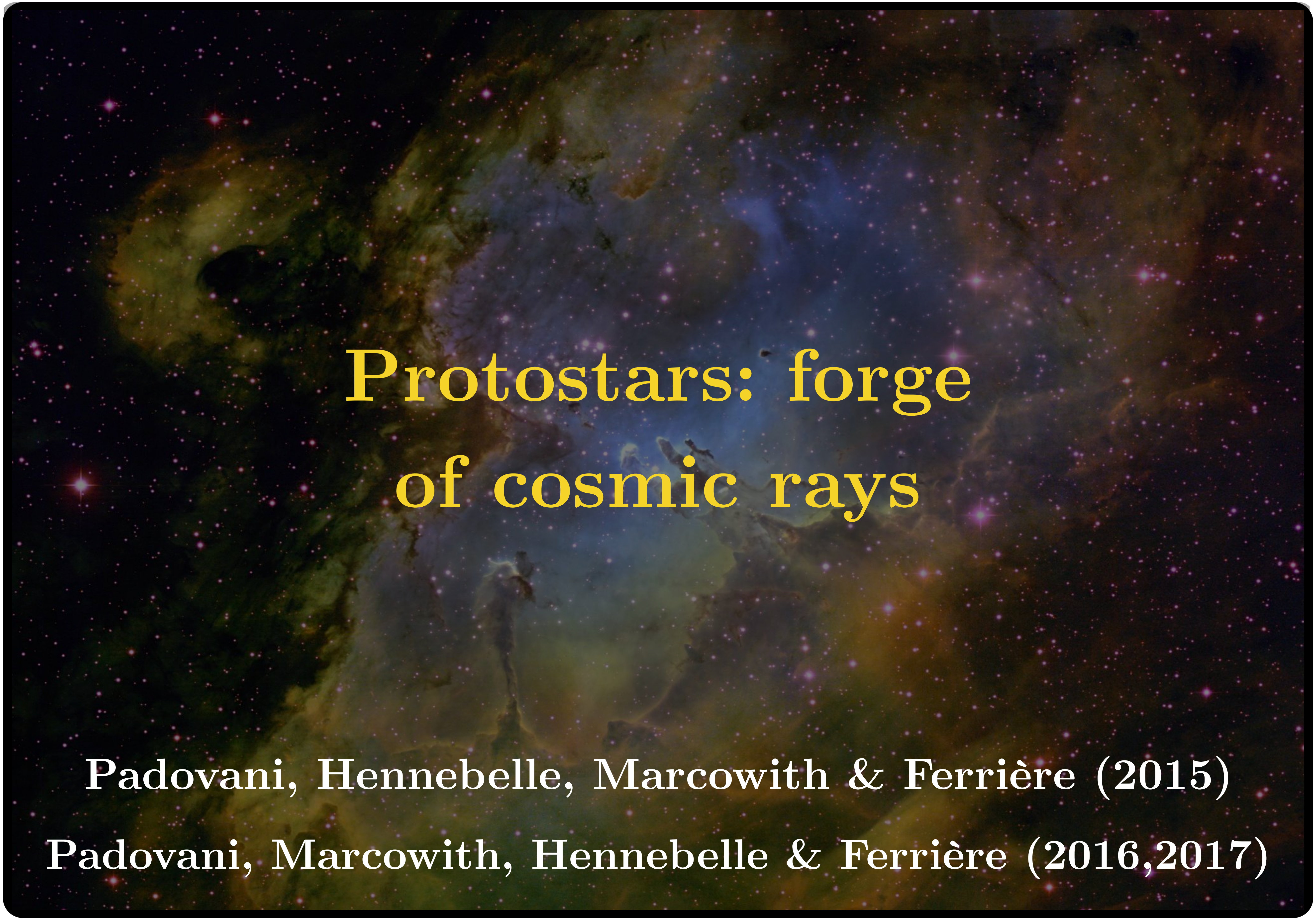
$$p_{\mathrm{CR}} + \mathrm{H_2} \to \pi^0, \pi^\pm$$

$$\begin{tikzcd}
\pi^0 \arrow[r] & 2\gamma \arrow[r, shift right, "\text{pair}"'] \arrow[dr, shift left, "\text{pair}"'] & e^\pm \arrow[l, shift right, "\text{BR}"'] \\
\pi^\pm \arrow[r] & \mu^\pm \arrow[r] & e^\pm \arrow[ul, shift right, "\text{BR}"']
\end{tikzcd}$$

CR ionisation in circumstellar discs



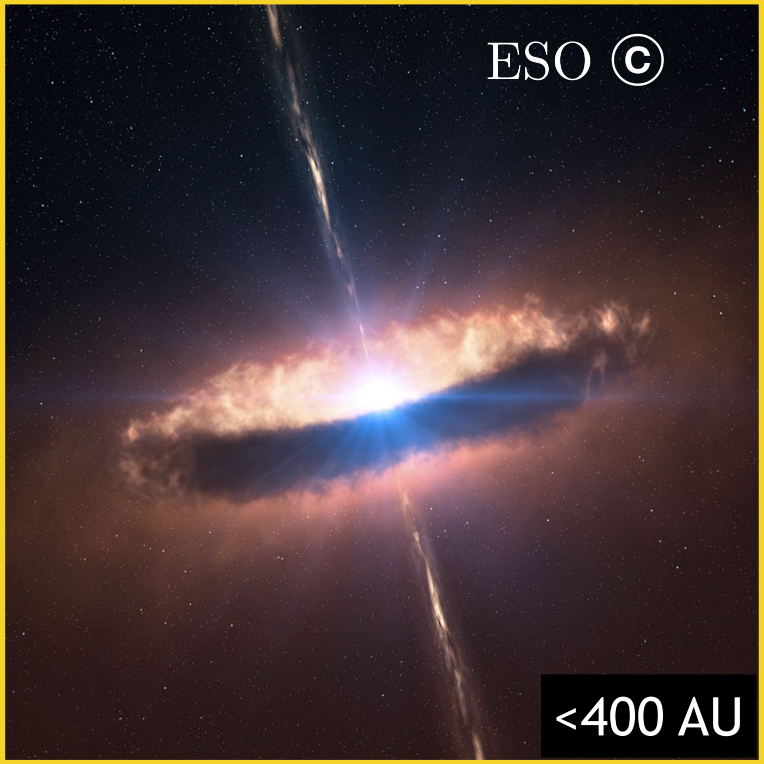
Padovani+ (2018)

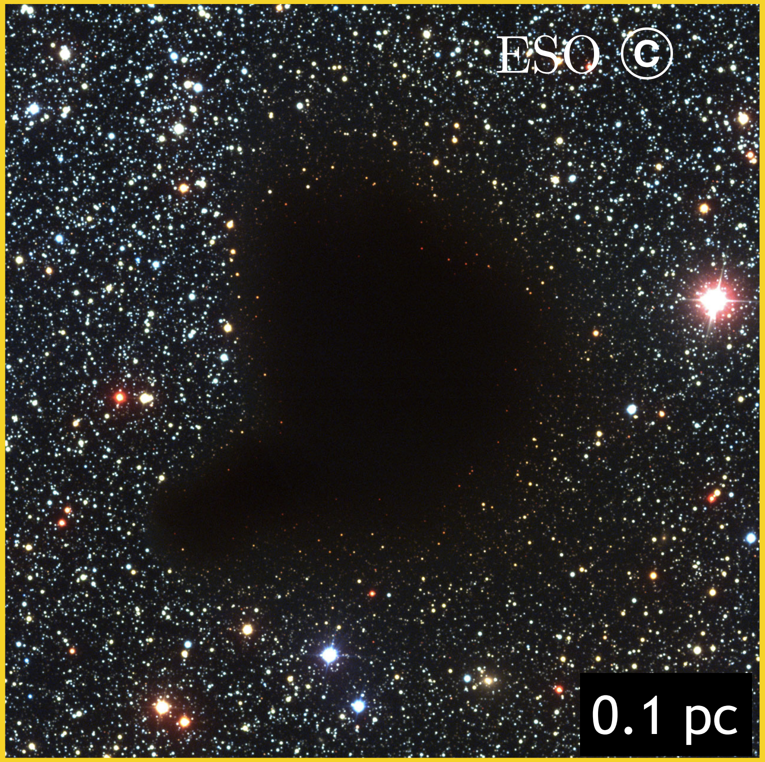


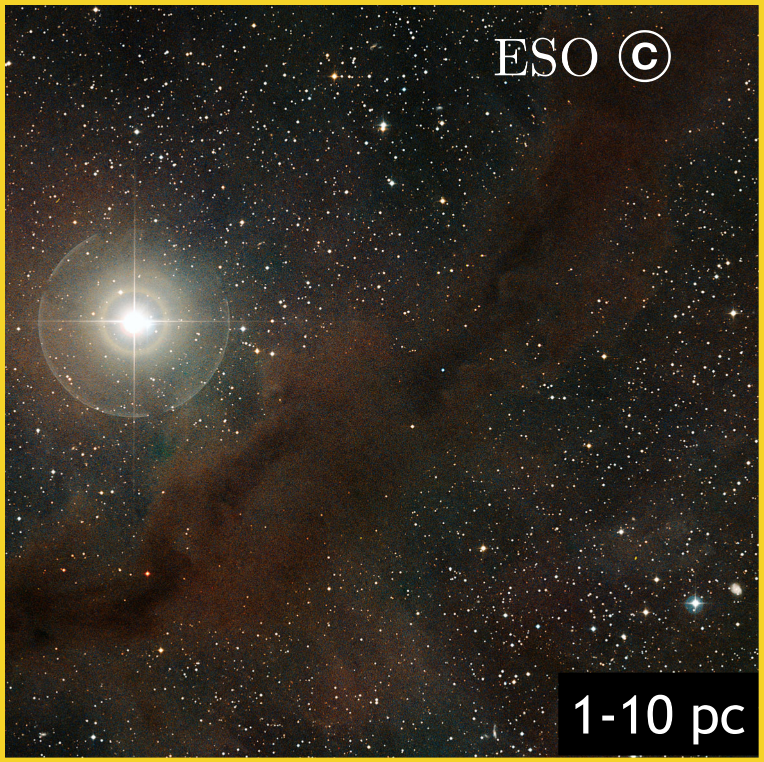
Protostars: forge of cosmic rays

Padovani, Hennebelle, Marcowith & Ferrière (2015)

Padovani, Marcowith, Hennebelle & Ferrière (2016,2017)







$\approx 10^{-19}$ 10^{-17} 10^{-15}

10^{-22} 10^{-18} 10^{-16}

protostar dense diffuse $\zeta\ [\mathrm{s}^{-1}]$

- $\zeta \sim 3\times10^{-16}\ \mathrm{s}^{-1}$ in L1157-B1 (Podio+ 2014)
- $\zeta \sim 4\times10^{-14}\ \mathrm{s}^{-1}$ and $8\times10^{-12}\ \mathrm{s}^{-1}$ in OMC-2 FIR 4 (Ceccarelli+ 2014)
- $S_\nu \propto \nu^{-0.89\pm0.07}$ in the bow shock of DG Tau (Ainsworth+ 2014)

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$\approx 10^{-19}$

10^{-22}

protostar

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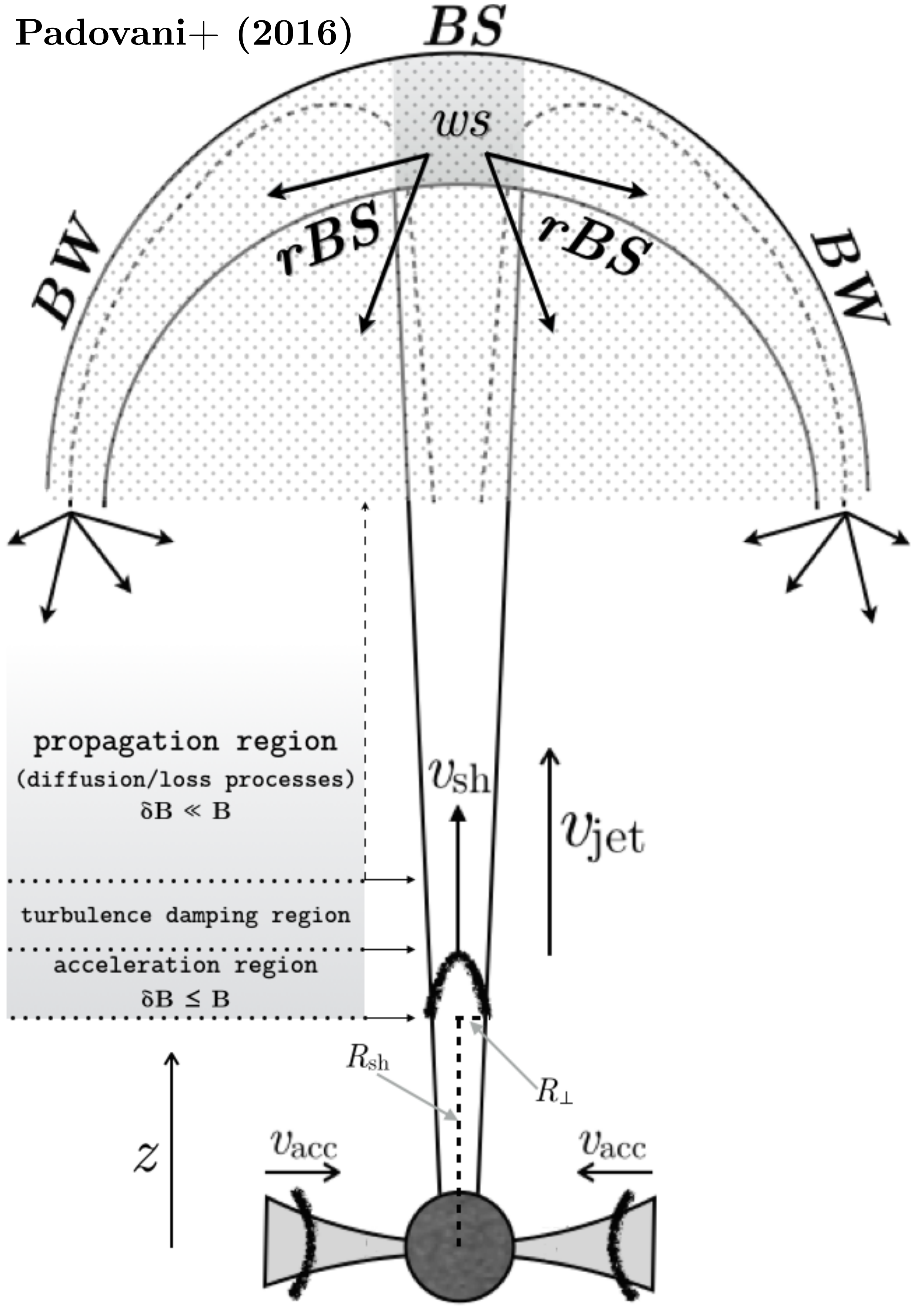
$\zeta \sim 4\times10^{-14}$ s^{-1} and 8×10^{-12} s^{-1} in OMC-2 FIR 4 (Ceccarelli+ 2014)

$S_\nu \propto \nu^{-0.89\pm0.07}$ in the bow shock of DG Tau (Ainsworth+ 2014)

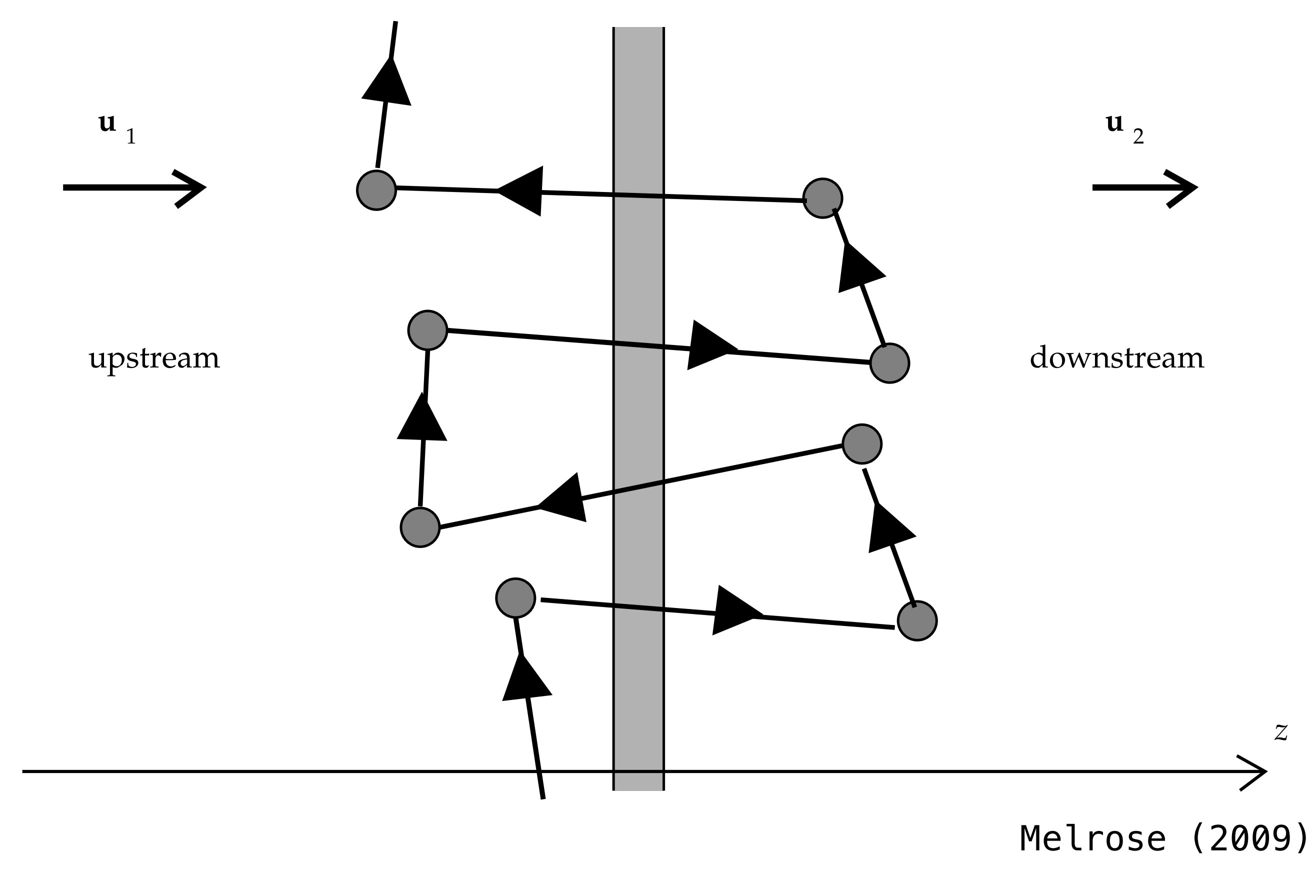
What are the possible sources of energetic particles?

Acceleration sites


Padovani+ (2016)

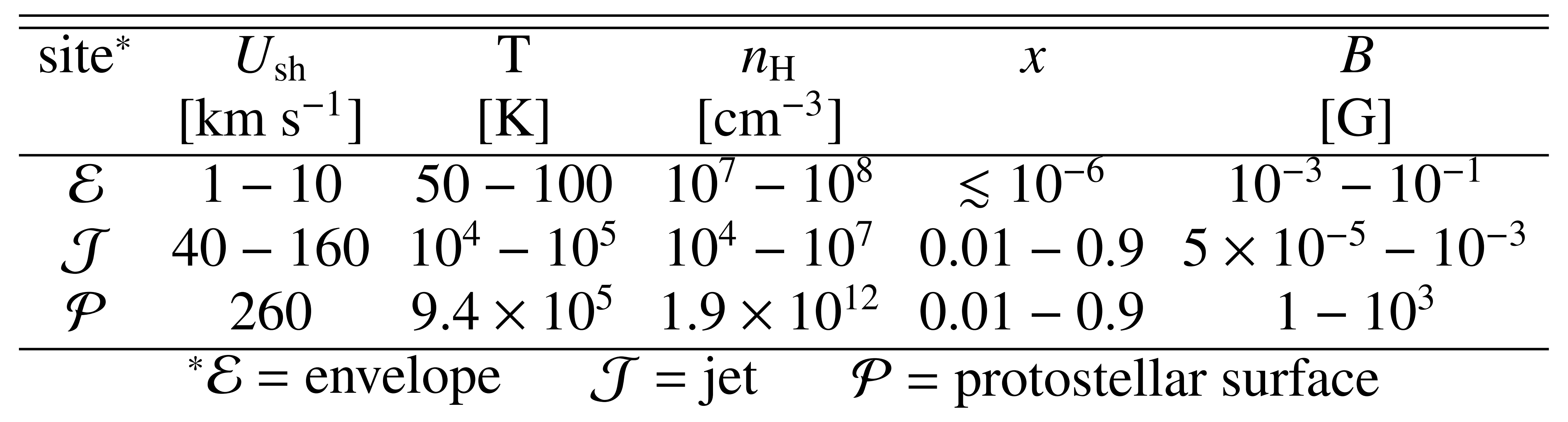
(1) accretion flows;
(2) protostellar surface;
(3) jet shock;

Diffusive Shock Acceleration (DSA) or First-order Fermi acceleration



Melrose (2009)

Parameters needed for the model



site*	$U_{\rm sh}$ [km s^{-1}]	T [K]	$n_{\rm H}$ [cm^{-3}]	x	B [G]
$\mathcal{E}$	$1-10$	$50-100$	10^7-10^8	$\lesssim 10^{-6}$	$10^{-3}-10^{-1}$
$\mathcal{J}$	$40-160$	10^4-10^5	10^4-10^7	$0.01-0.9$	$5\times10^{-5}-10^{-3}$
$\mathcal{P}$	260	9.4×10^5	1.9×10^{12}	$0.01-0.9$	$1-10^3$

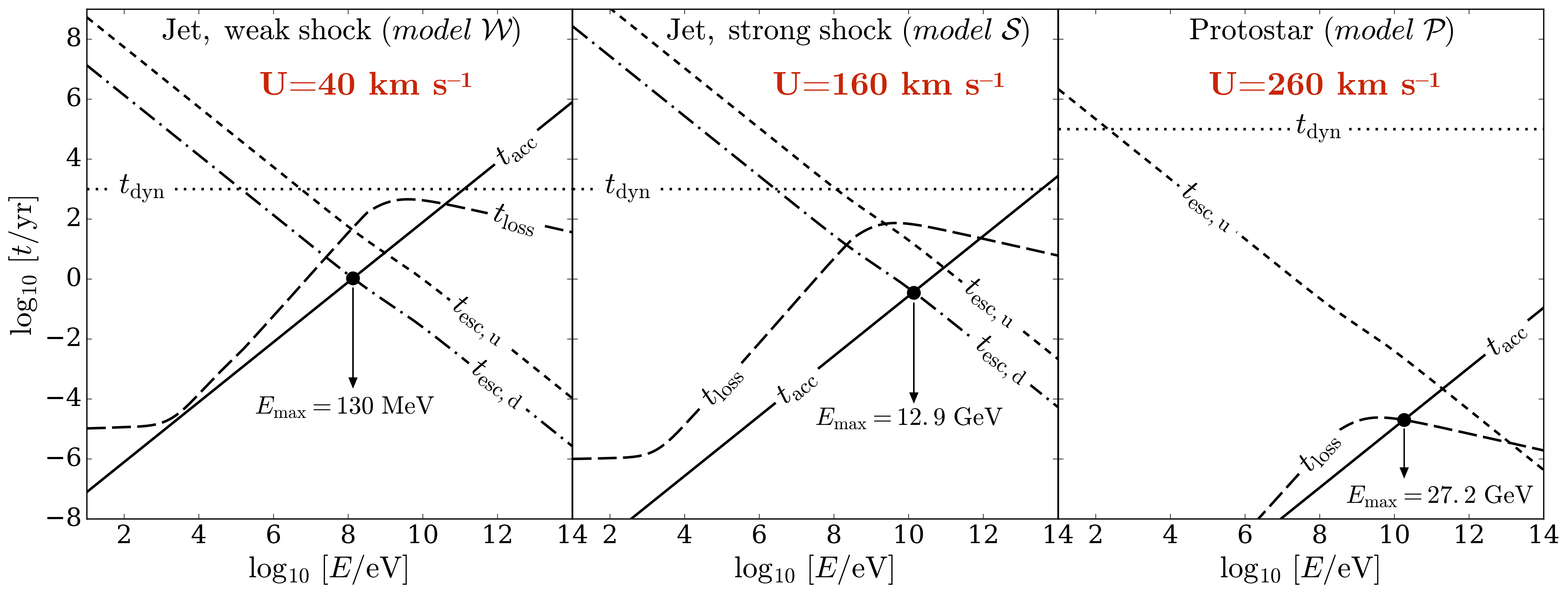
*$\mathcal{E}$ = envelope $\mathcal{J}$ = jet $\mathcal{P}$ = protostellar surface

Refs: $U_{\rm sh}$ (Raga+ 2002,2011; Hartigan & Morse 2007; Agra-Amboage+ 2011);
T (Frank+ 2014);
$n_{\rm H}$ (Lefloch+ 2012; Gómez-Ruiz+ 2012);
x (Nisini+ 2005; Podio+ 2006; Antoniucci+ 2008; Garcia López+ 2008; Dionatos+ 2010; Frank+ 2014; Maurri+ 2014);
B (Tesileanu+ 2009, 2012)
For protostellar surface shock, parameters from Masunaga & Inutsuka (2000)

- DSA works *only* for protons (electrons lose energy too fast, $E^{\rm max}(e)<300$ MeV);
- DSA is effective *only* in jet and protostellar surface shocks (in accretion flows, x and U_{sh} are too small, quenching the particle acceleration; B is as large as to produce a sub-Alfvénic shock).

Maximum Energy

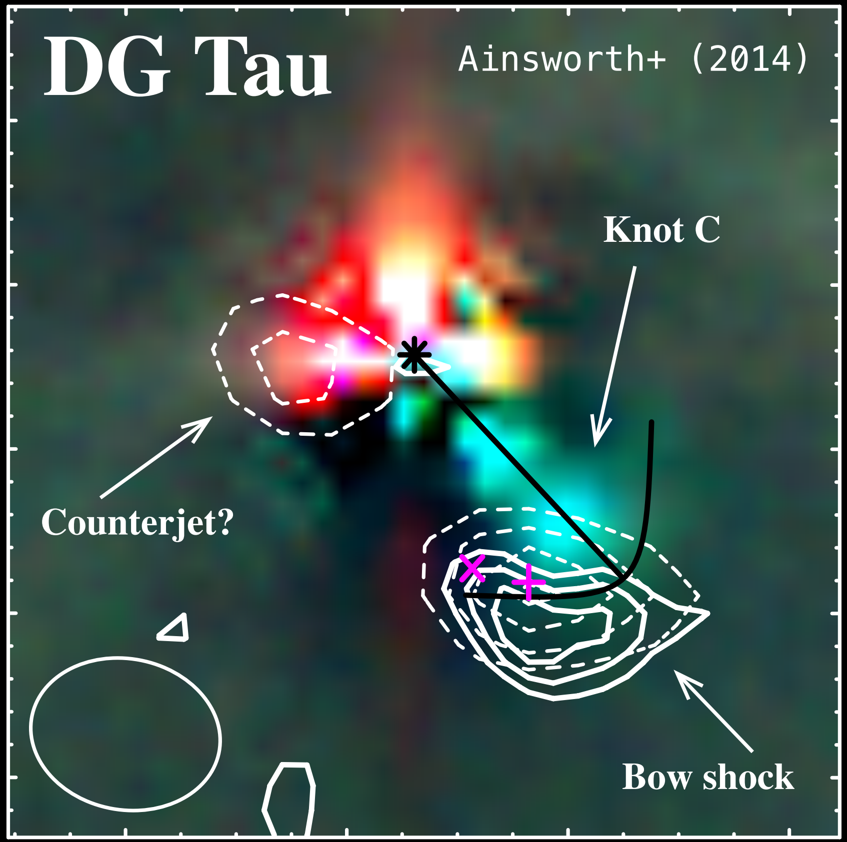
$$t_{\rm acc} = \min(t_{\rm loss}, t_{\rm esc,u}, t_{\rm esc,d}, t_{\rm dyn}) \rightarrow E_{\rm max}$$



PM, Marcowith, Hennebelle & Ferrière (2017)

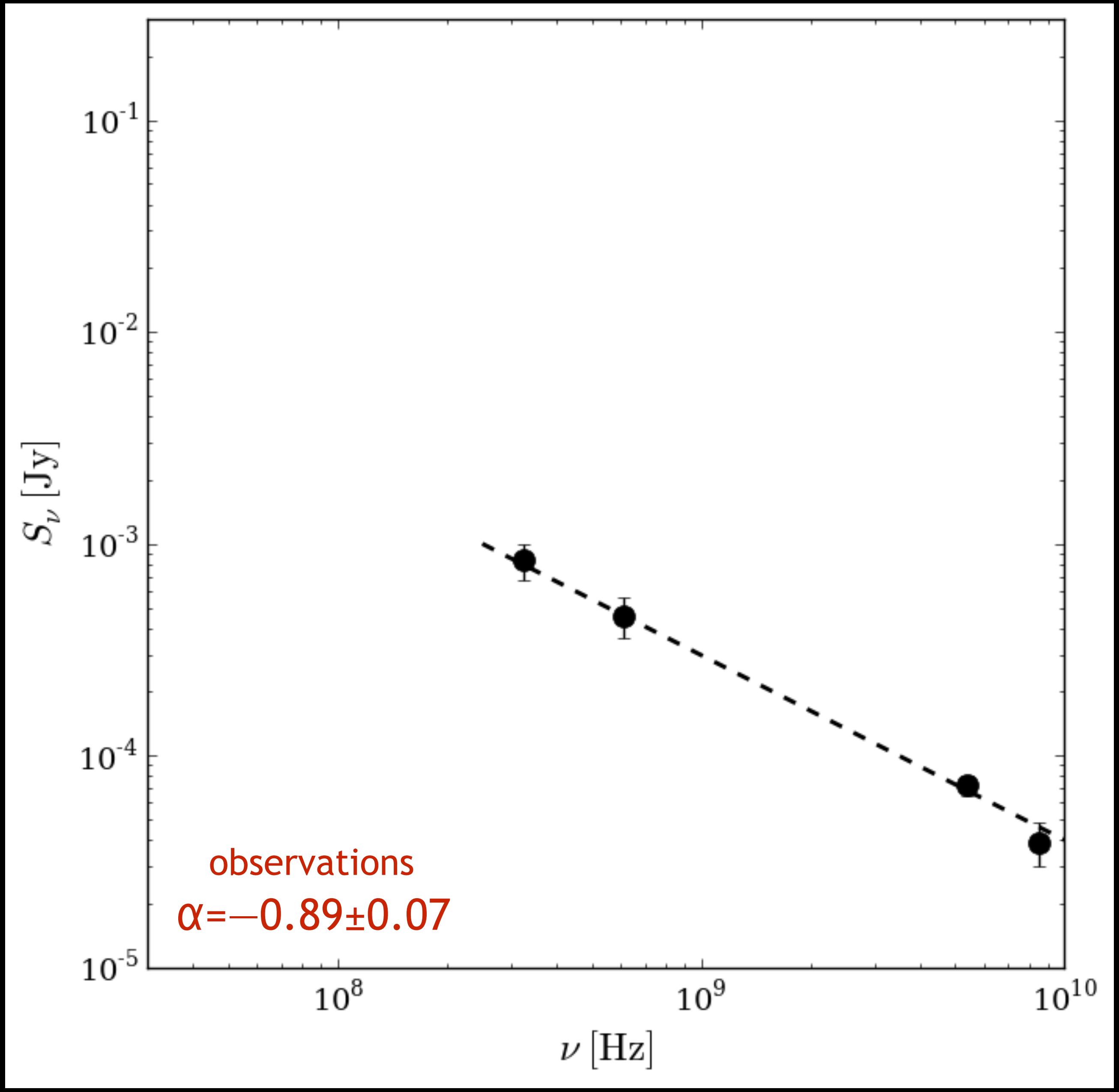
Application of the modelling: comparison with available observations

Ainsworth+ (2014) detected synchrotron emission (GMRT) towards the bow shock (knot C) of DG Tau, speculating that this could be due to relativistic electrons accelerated in the interaction between the jet and the ambient medium.



325 MHz (solid contours);
610 MHz (dashed contours).

Using results by Lynch+ (2013), EVLA obs.



observations
α=−0.89±0.07

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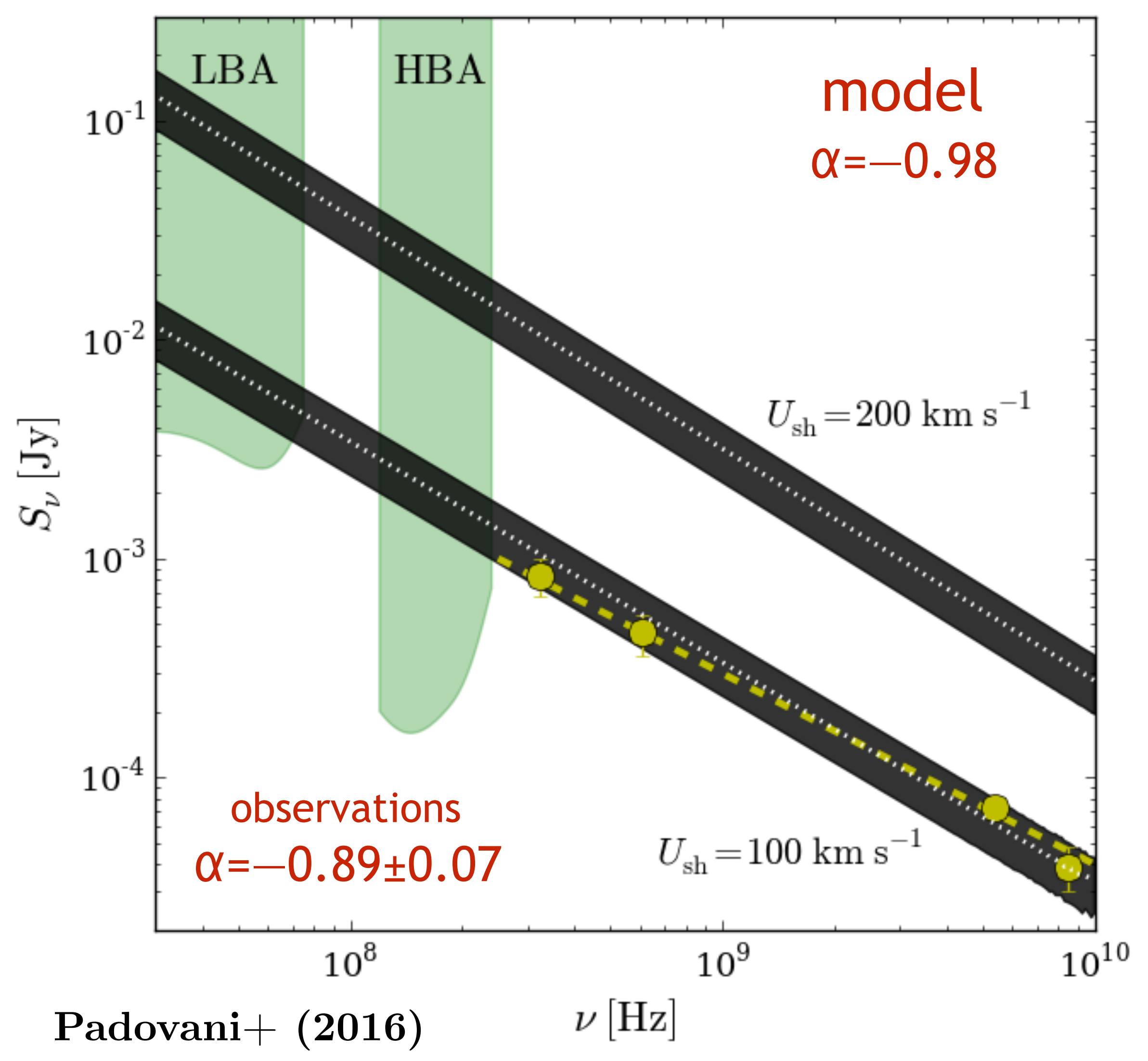


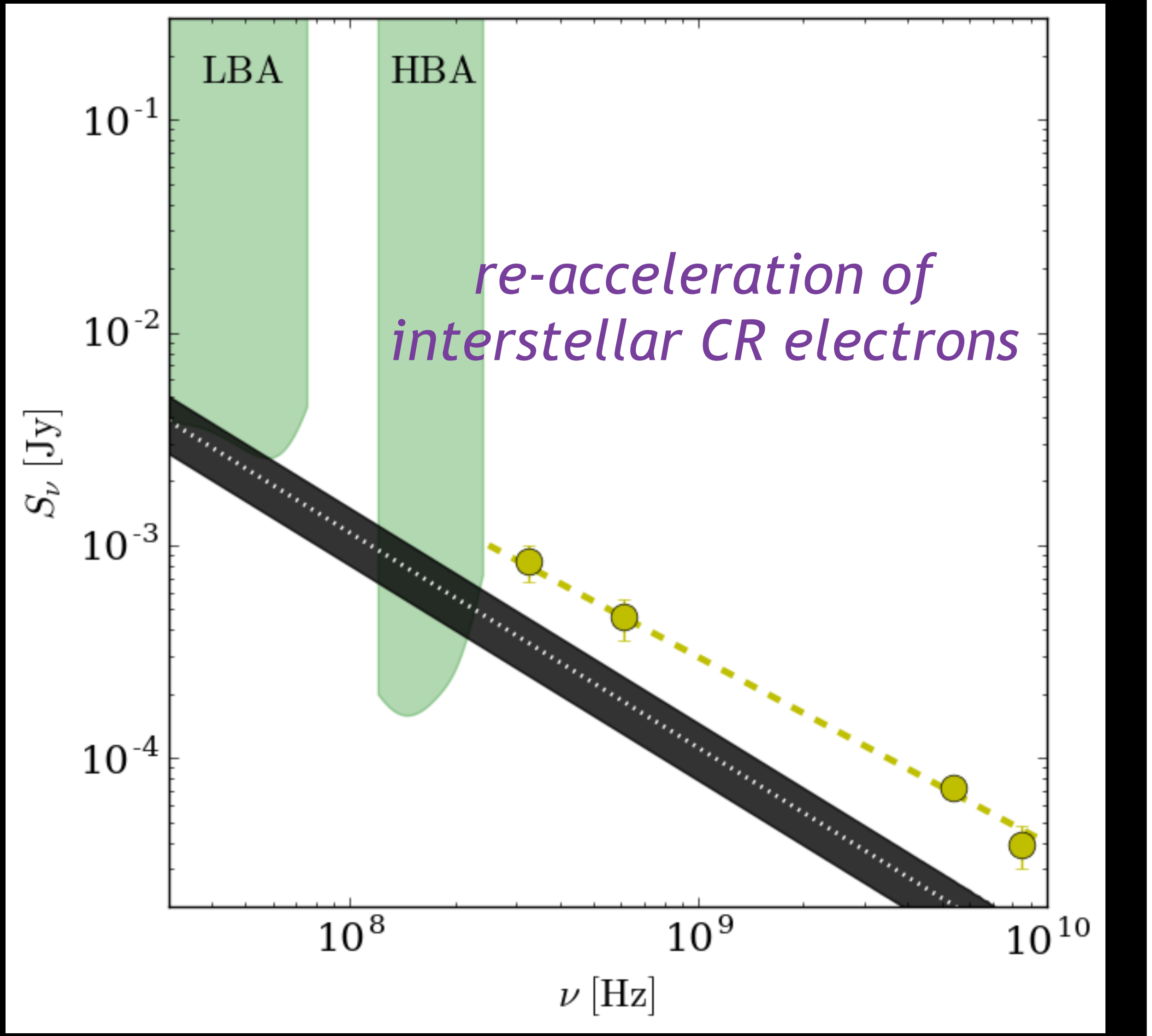
model

$\alpha=-0.98$

observations

$\alpha=-0.89\pm0.07$

Padovani+ (2016)



re-acceleration of interstellar CR electrons

Application of the modelling: comparison with available observations

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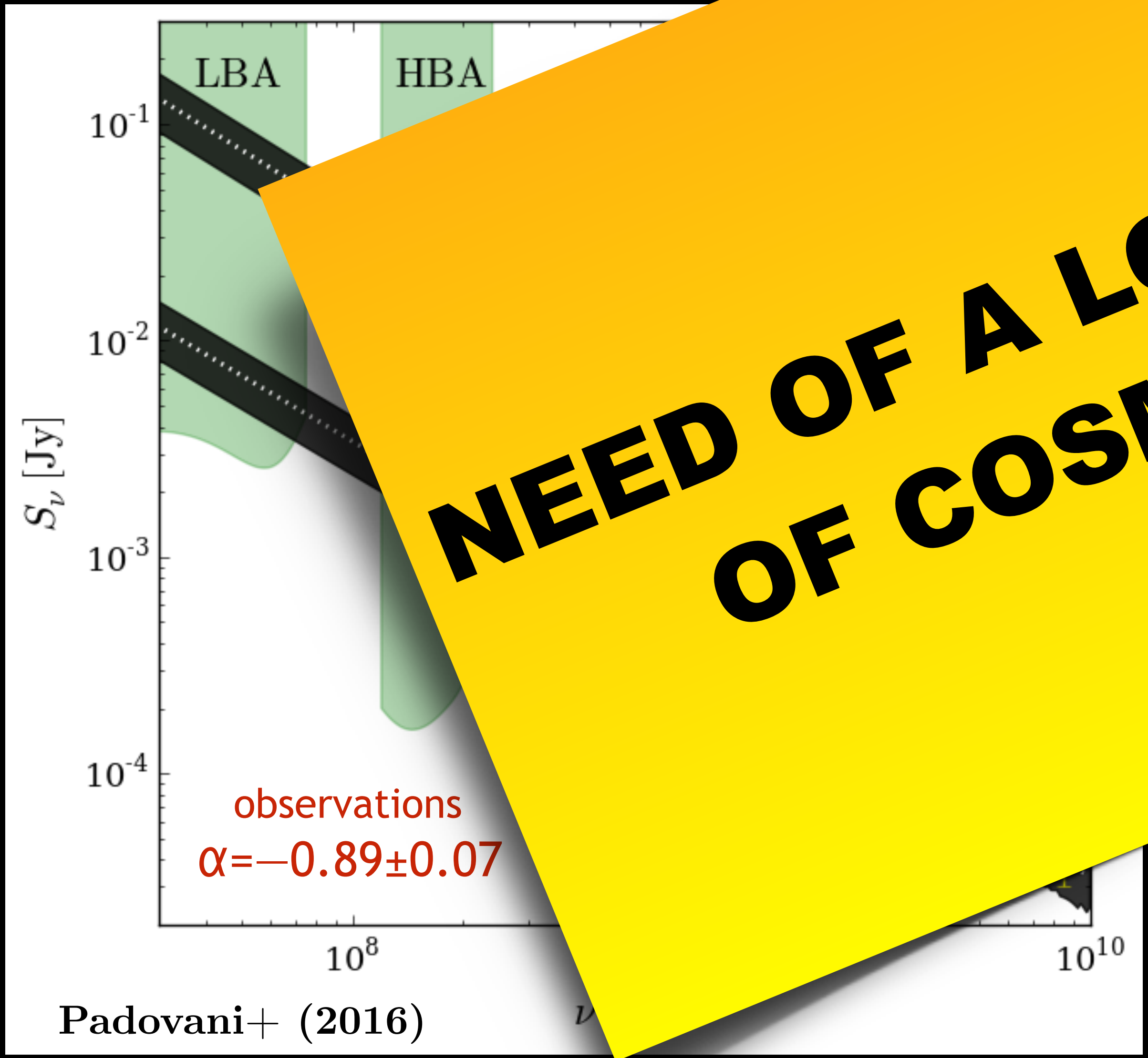
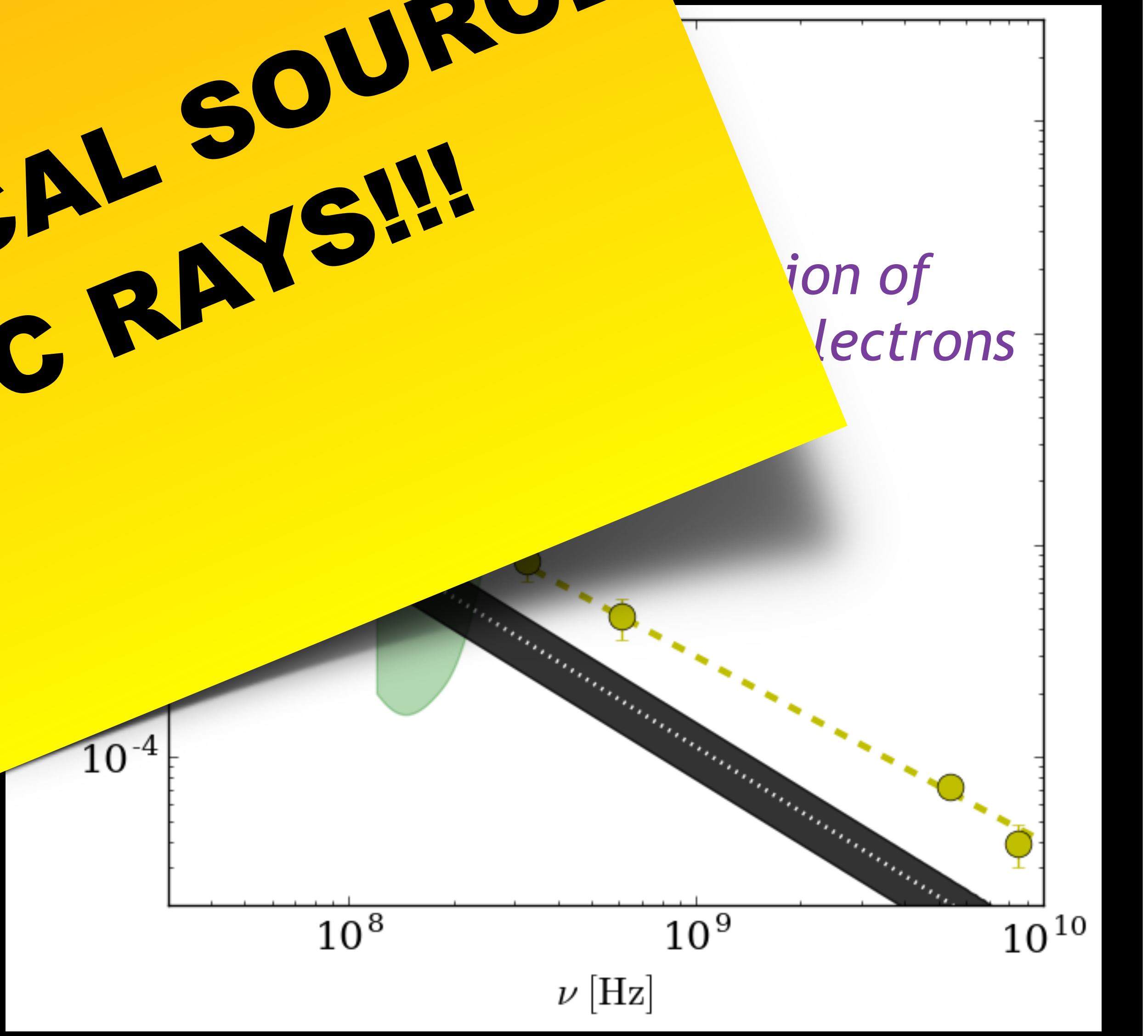
NEED OF A LOCAL SOURCE OF COSMIC RAYS!!!



observations
$\alpha = -0.89 \pm 0.07$

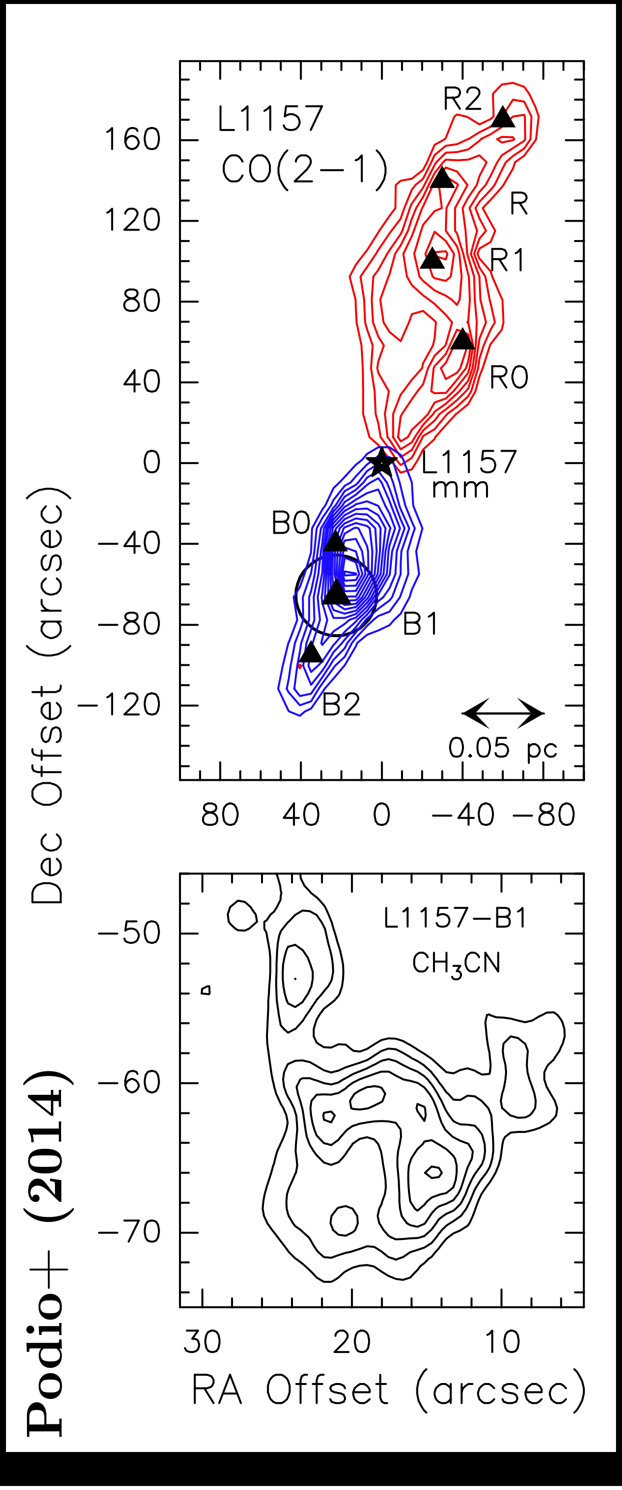
Padovani+ (2016)



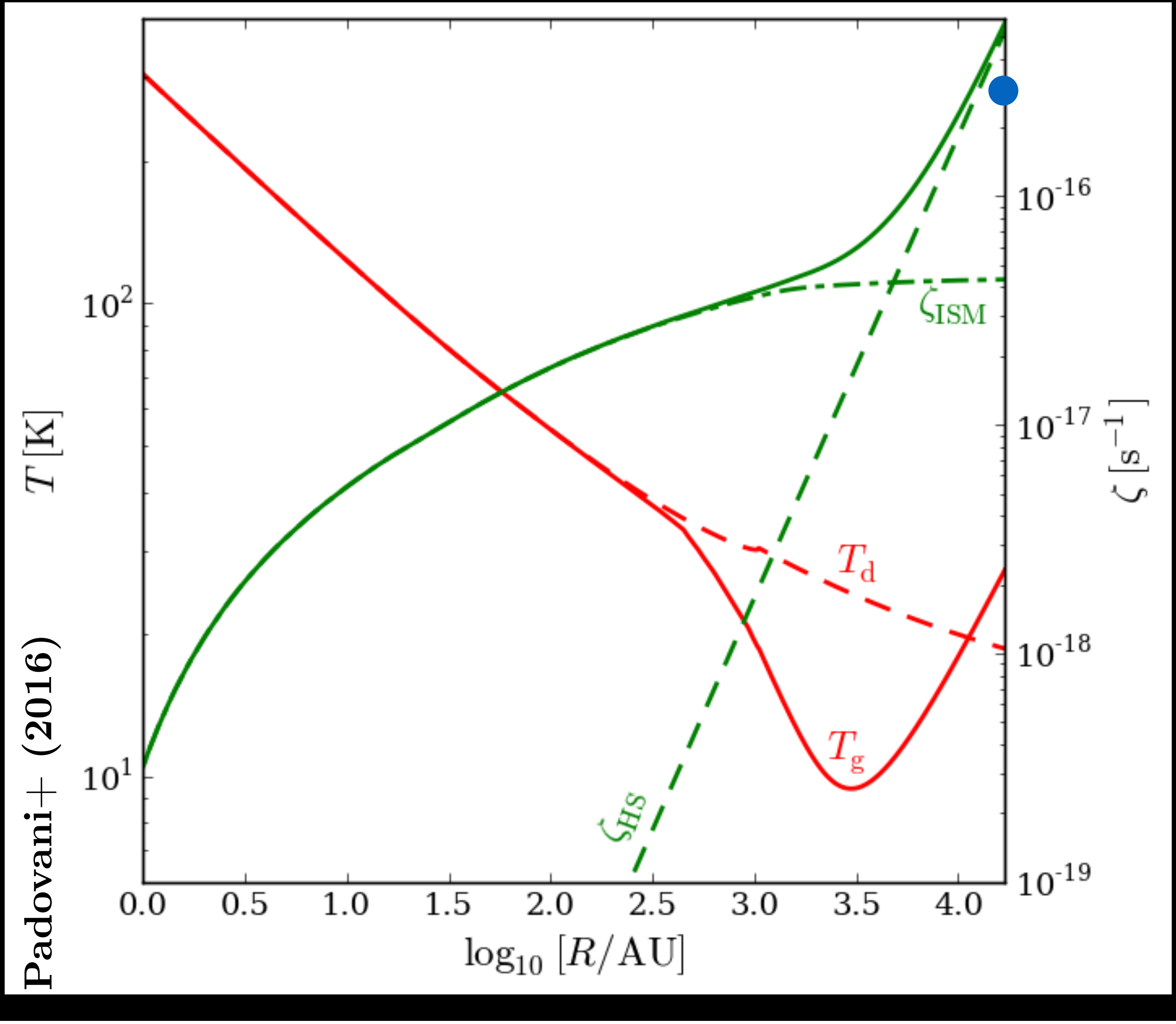
Application of the modelling: comparison with available observations

Podio+ (2014): $\zeta=3\times10^{-16}$ s^{-1} in the bow shock B1 in L1157 (HCO^+, N_2H^+).

OUR MODEL: $\zeta=6.1\times10^{-16}$ s^{-1}



Podio+ (2014)



Padovani+ (2016)

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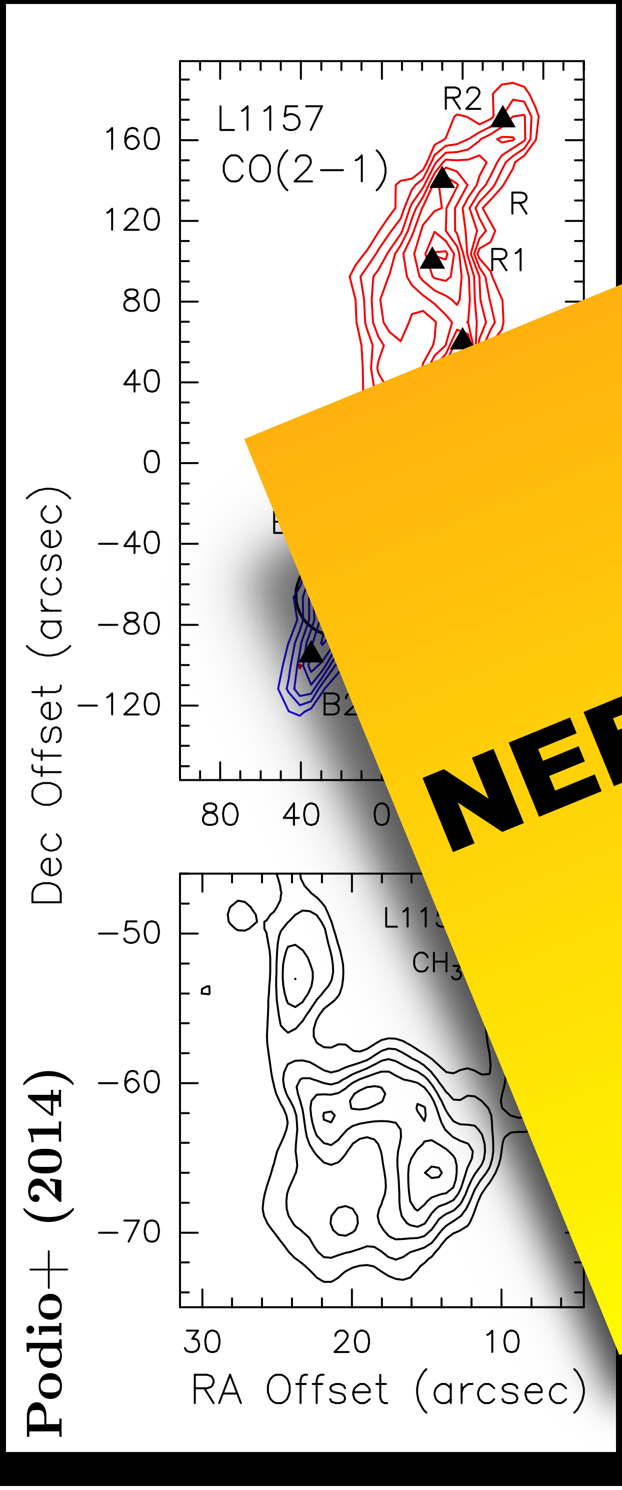
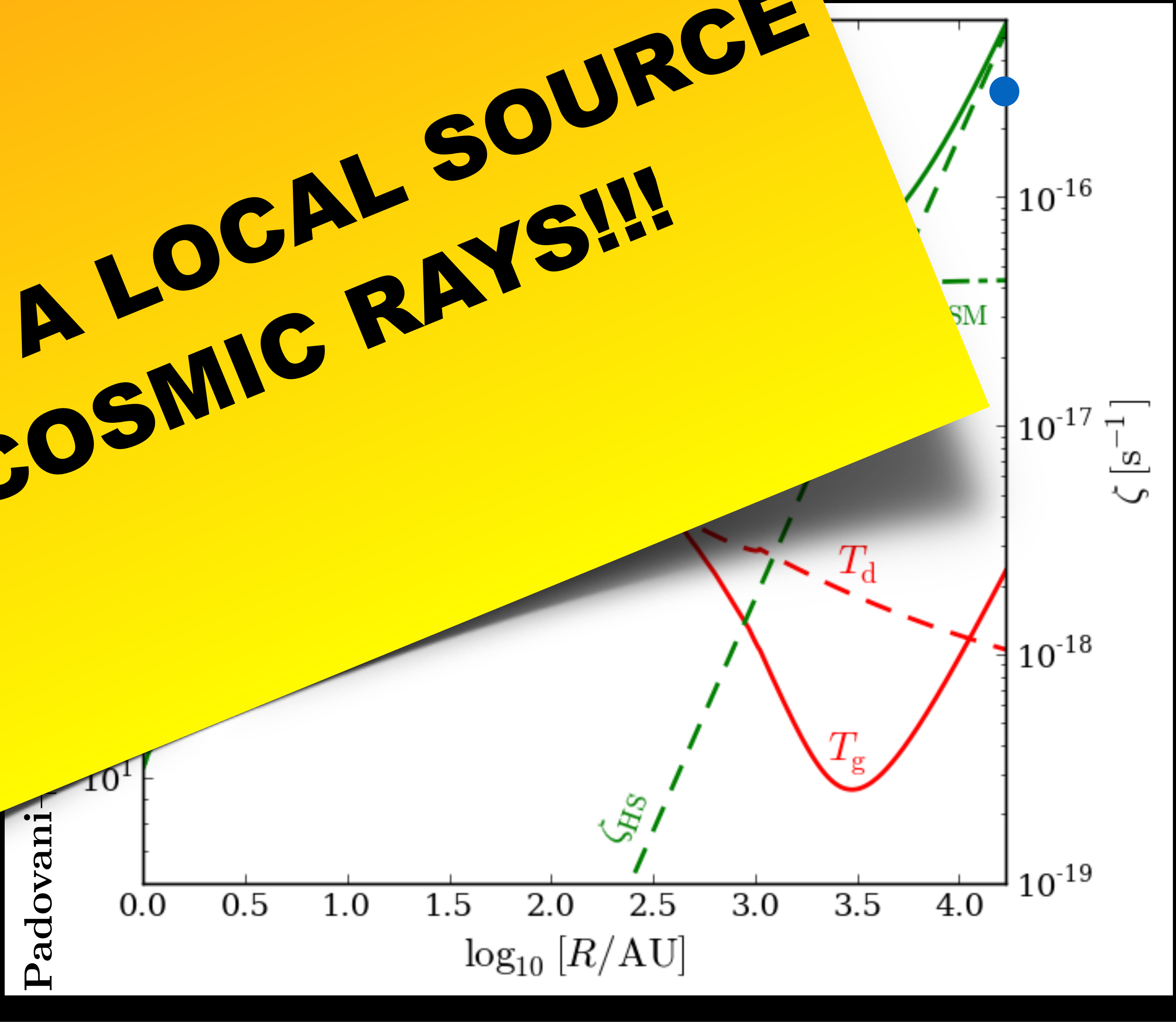
^{16} s^{-1}



Podio+ (2014)



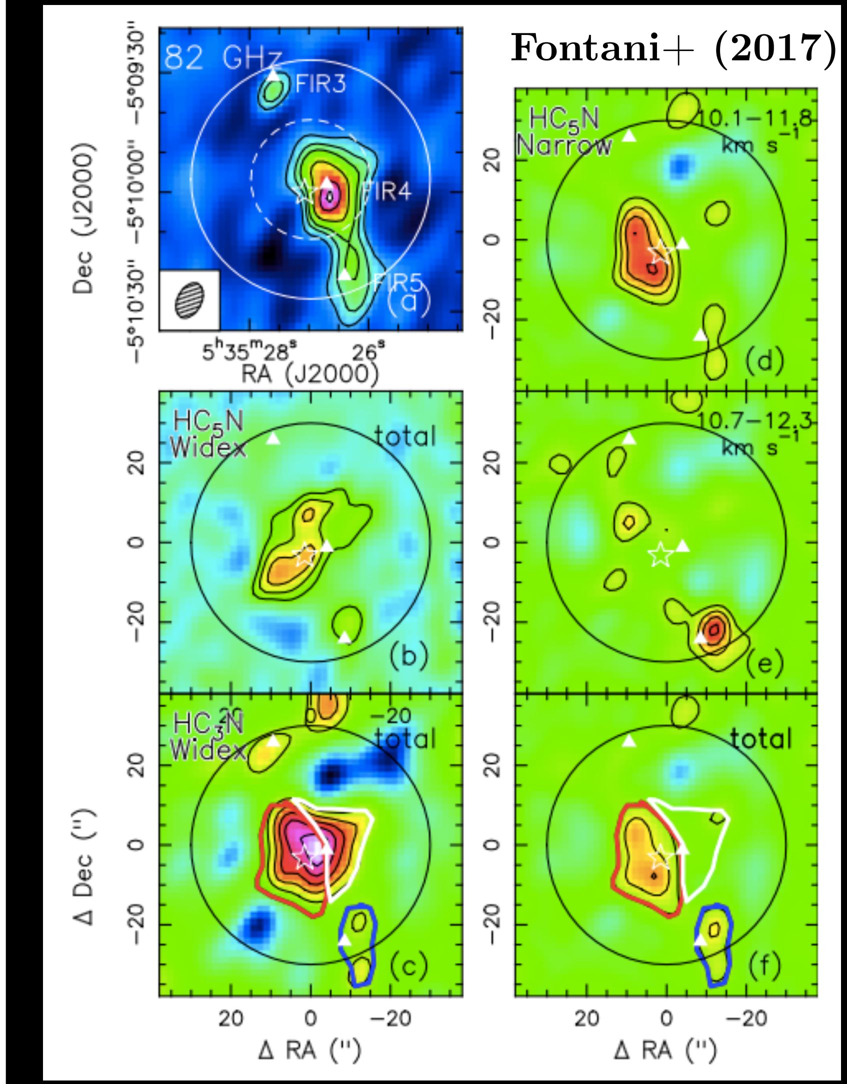
Padovani

NEED OF A LOCAL SOURCE OF COSMIC RAYS!!!

Application of the modelling: comparison with available observations

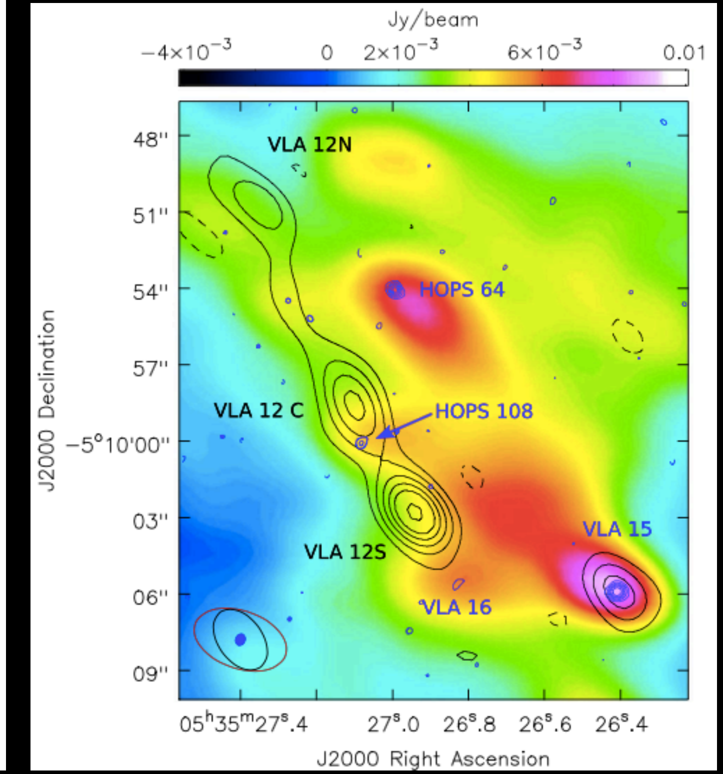
OMC-2 FIR 4 : $\zeta=4\times10^{-14}\ \mathrm{s}^{-1}$

(Ceccarelli+ 2014: HCO^+,N_2H^+ ; Fontani+ 2017: HC_3N,HC_5N; Favre+ 2018: c-C_3H_2)

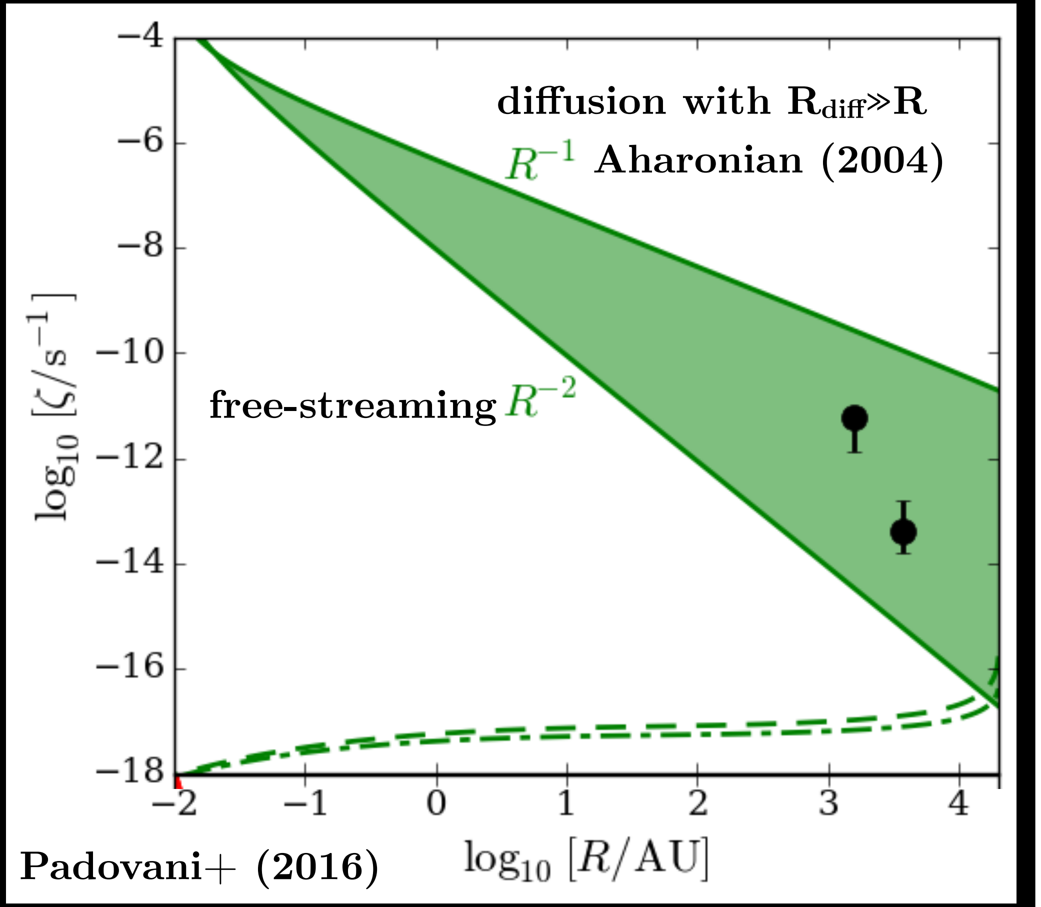


Fontani+ (2017)

Osorio+ (2017)



Protostellar surface acceleration model (parameters from Masunaga & Inutsuka 2000).

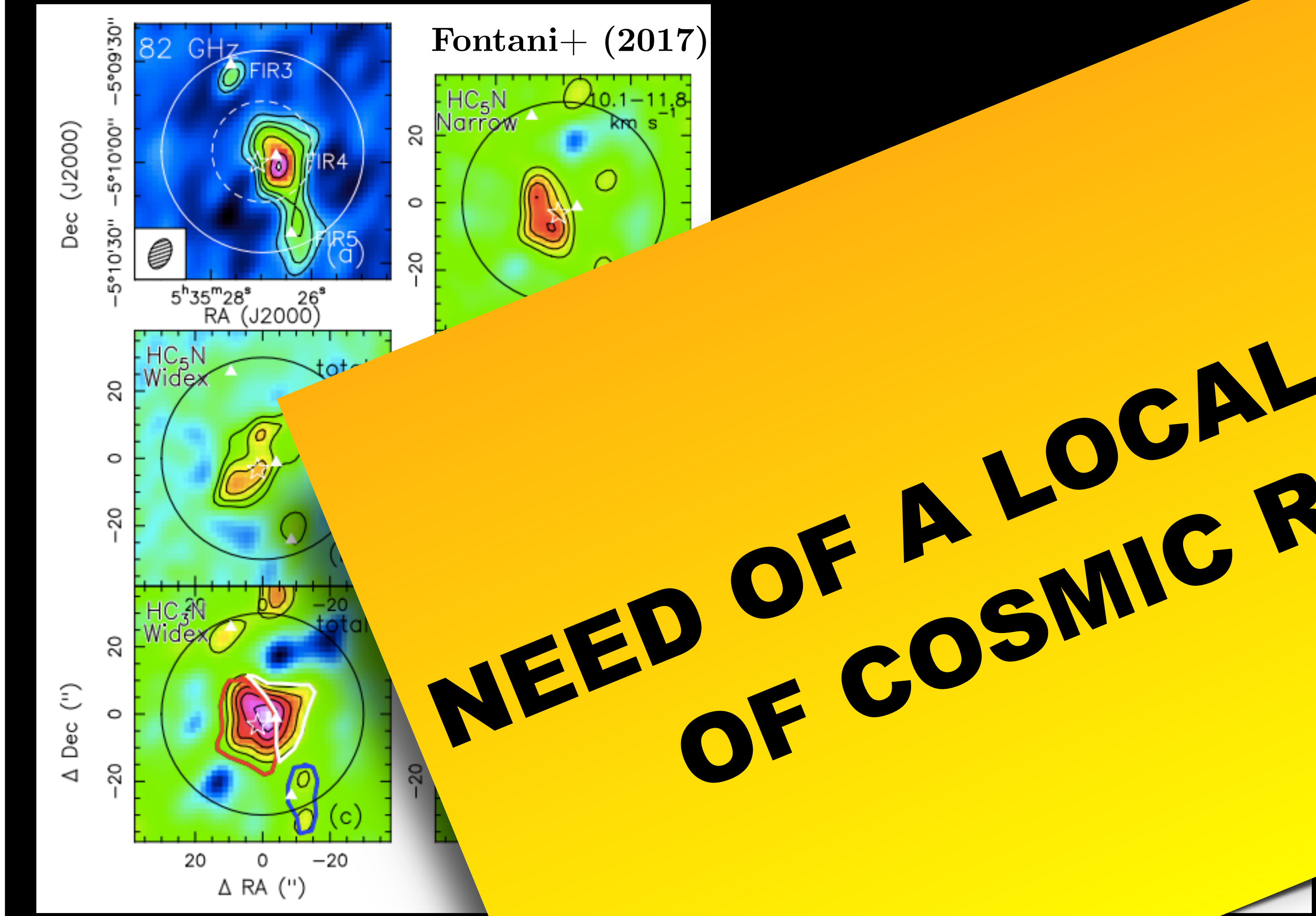


Padovani+ (2016)

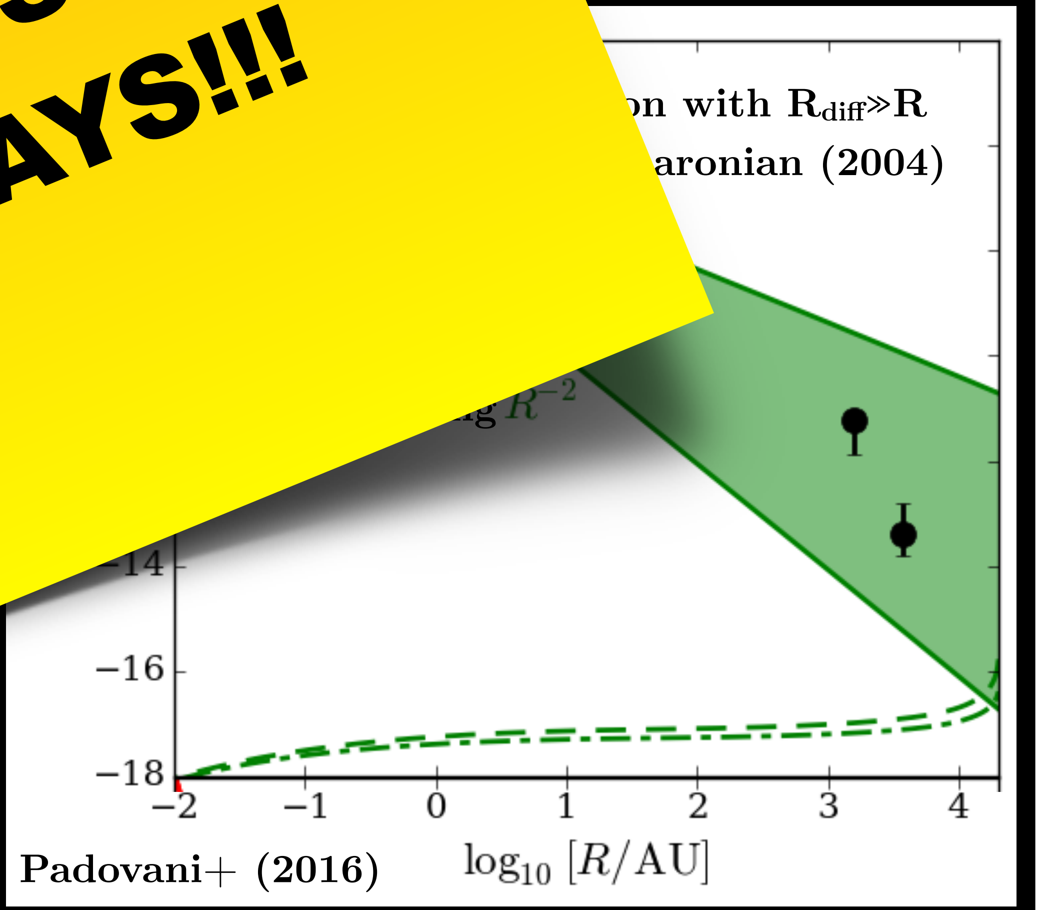
→ The propagation mechanism is probably neither purely diffusive nor free streaming.

Application of the modelling: comparison with available observations

OMC-2 FIR 4 : $\zeta=4\times10^{-14}\ s^{-1}$
(Ceccarelli+ 2014: HCO^+,N_2H^+ ; Fontani+ 2017: HC_3N,HC_5N 2018: c-C_3H_2)



face acceleration
s from Masunaga



NEED OF A LOCAL SOURCE OF COSMIC RAYS!!!

→ The propagation mechanism is probably neither purely diffusive nor free streaming.

Application of the modelling: comparison with available observations

$[^{10}\mathrm{Be}]_{\mathrm{meteorites}} \gg [^{10}\mathrm{Be}]_{\mathrm{ISM}}$

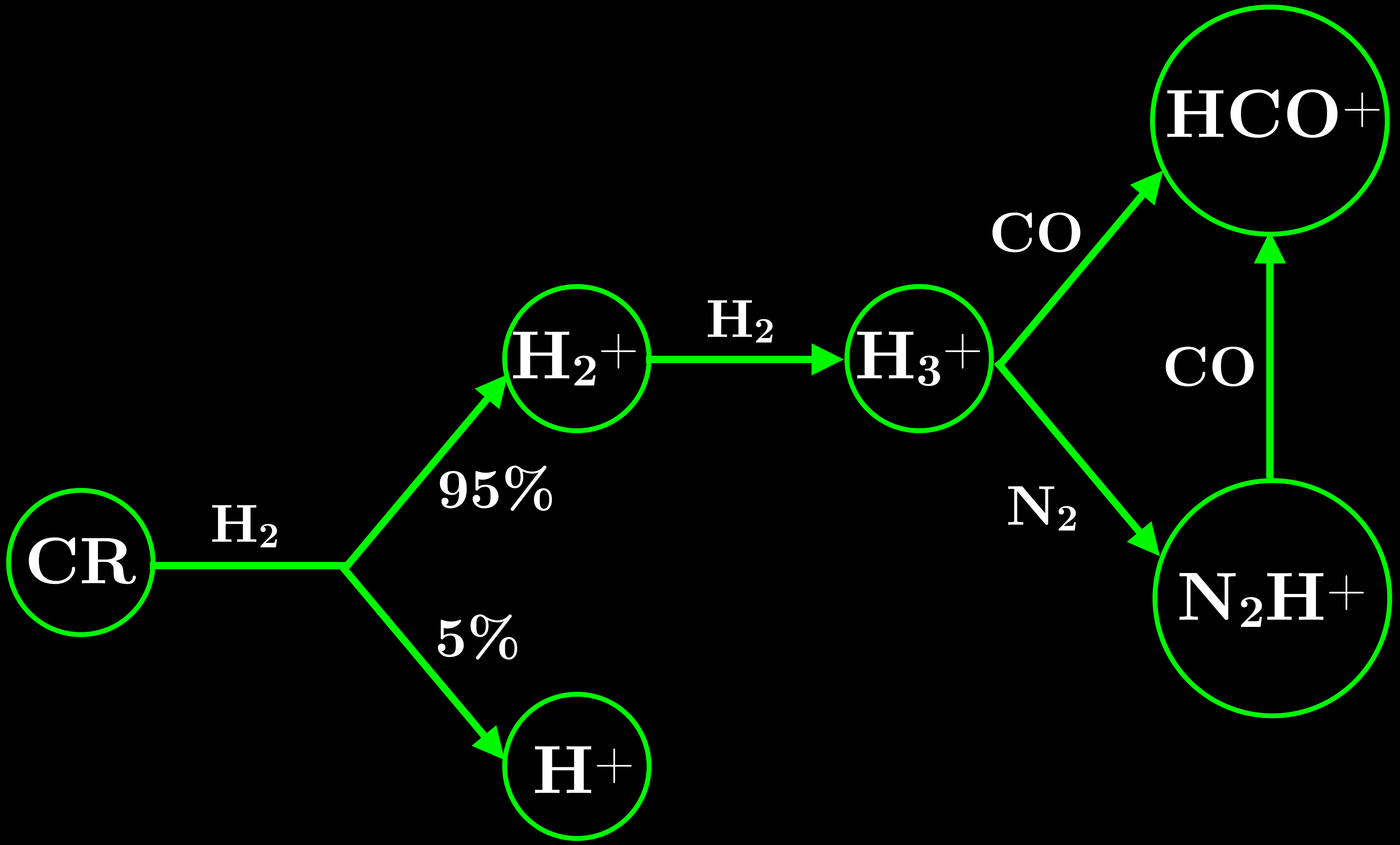
$$\mathcal{F}_t(E_{\min}) = 2\pi \int_{E_{\min}}^{E_{\max}} j(E)\mathrm{d}E$$

LOCAL CRS could be responsible for the formation of short-lived radionuclei (^{10}Be) contained in calcium-aluminium-inclusions of carbonaceous meteorites.

spallation reactions during the earliest phases of the protosolar nebula

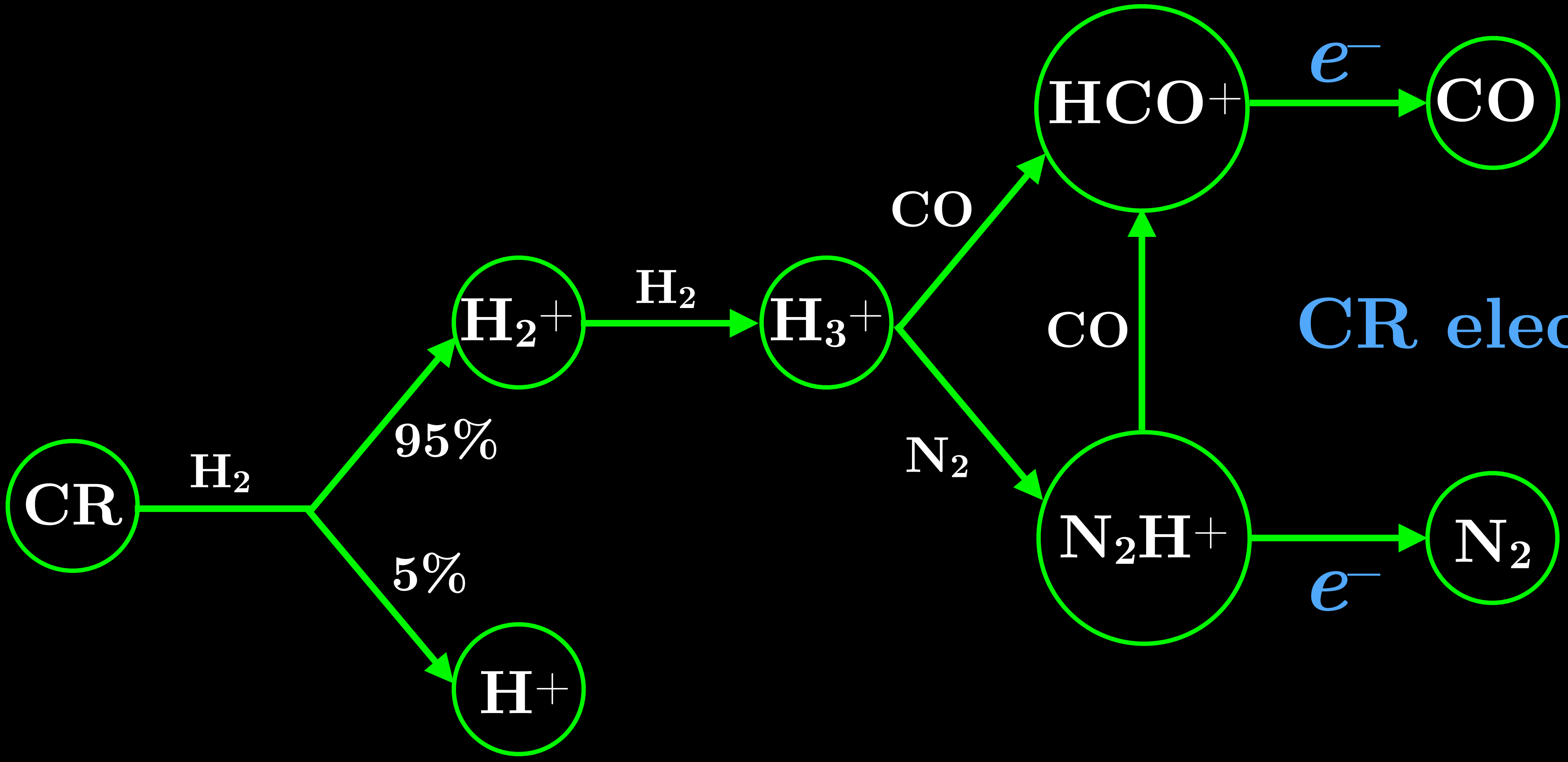
$$p +^{16}\mathrm{O} \rightarrow^{10}\mathrm{Be} + \ldots$$

HCO^+ and N_2H^+ as CR ionisation tracers



usually $[HCO^+]/[N_2H^+] \gg 1$

HCO^+ and N_2H^+ as CR ionisation tracers

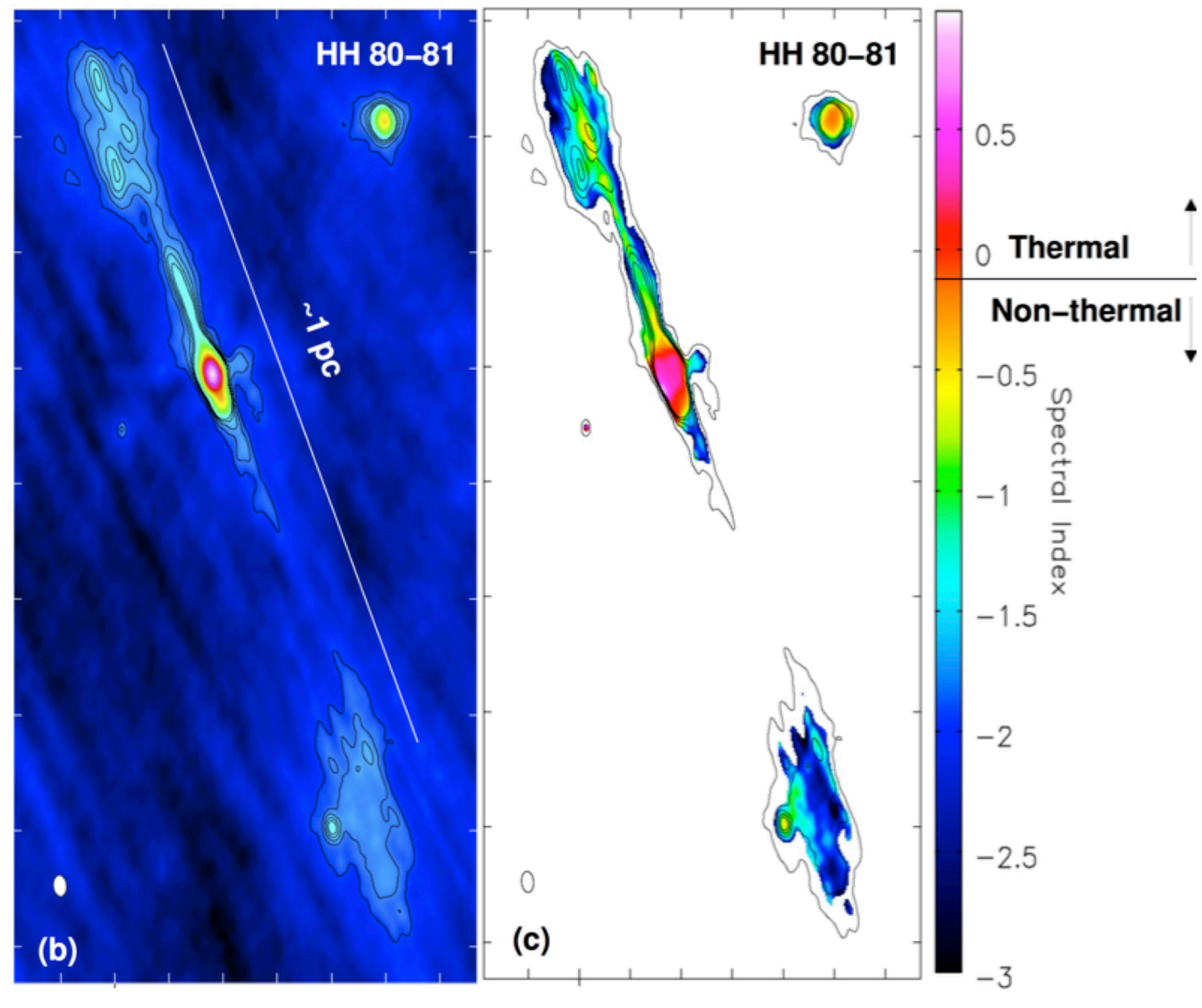


CR electrons!

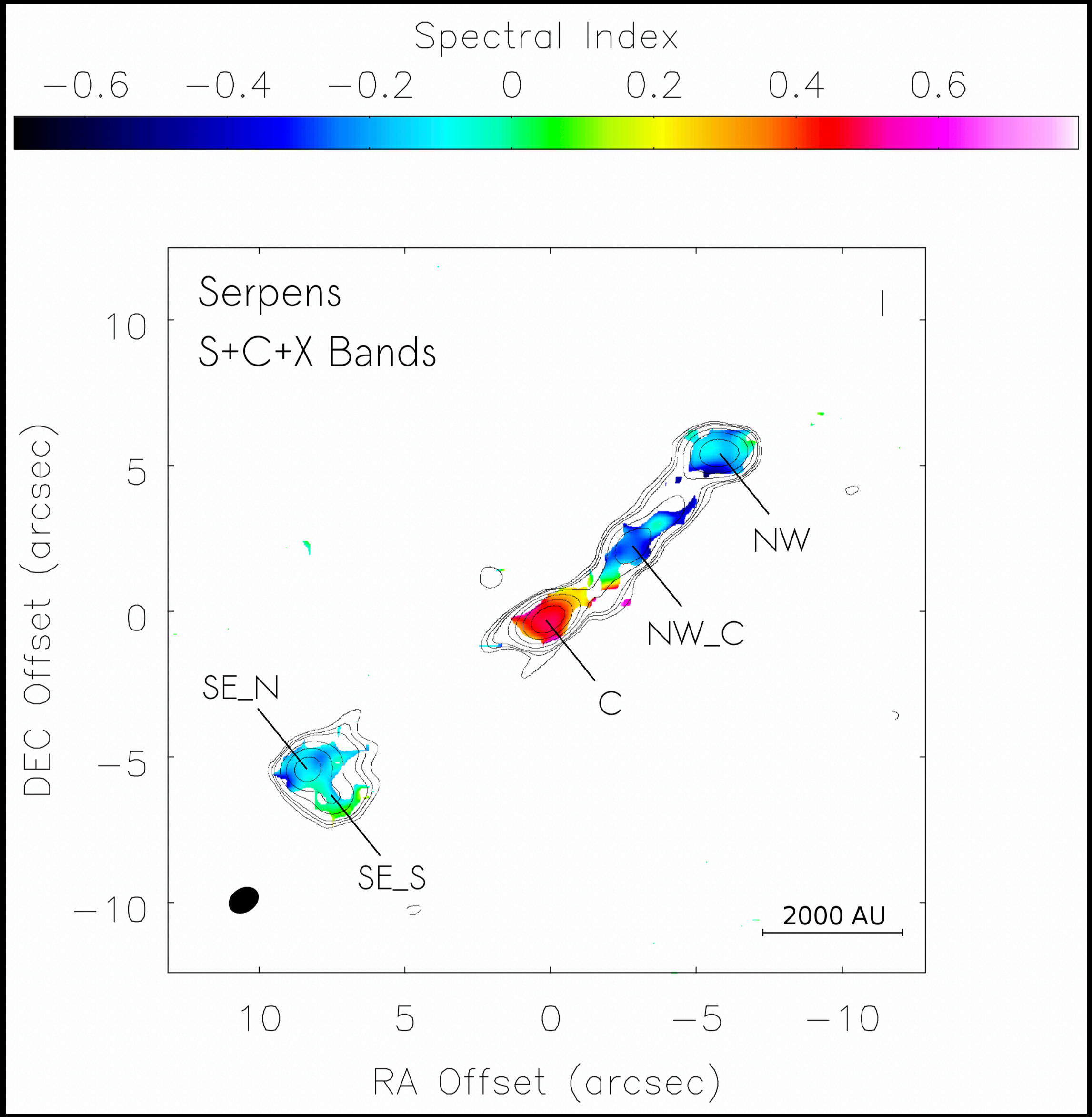
usually $[HCO^+]/[N_2H^+] \gg 1$

in presence of CRs $[HCO^+]/[N_2H^+] \approx 1$

In high-mass YSOs it is even easier to accelerate CRs!

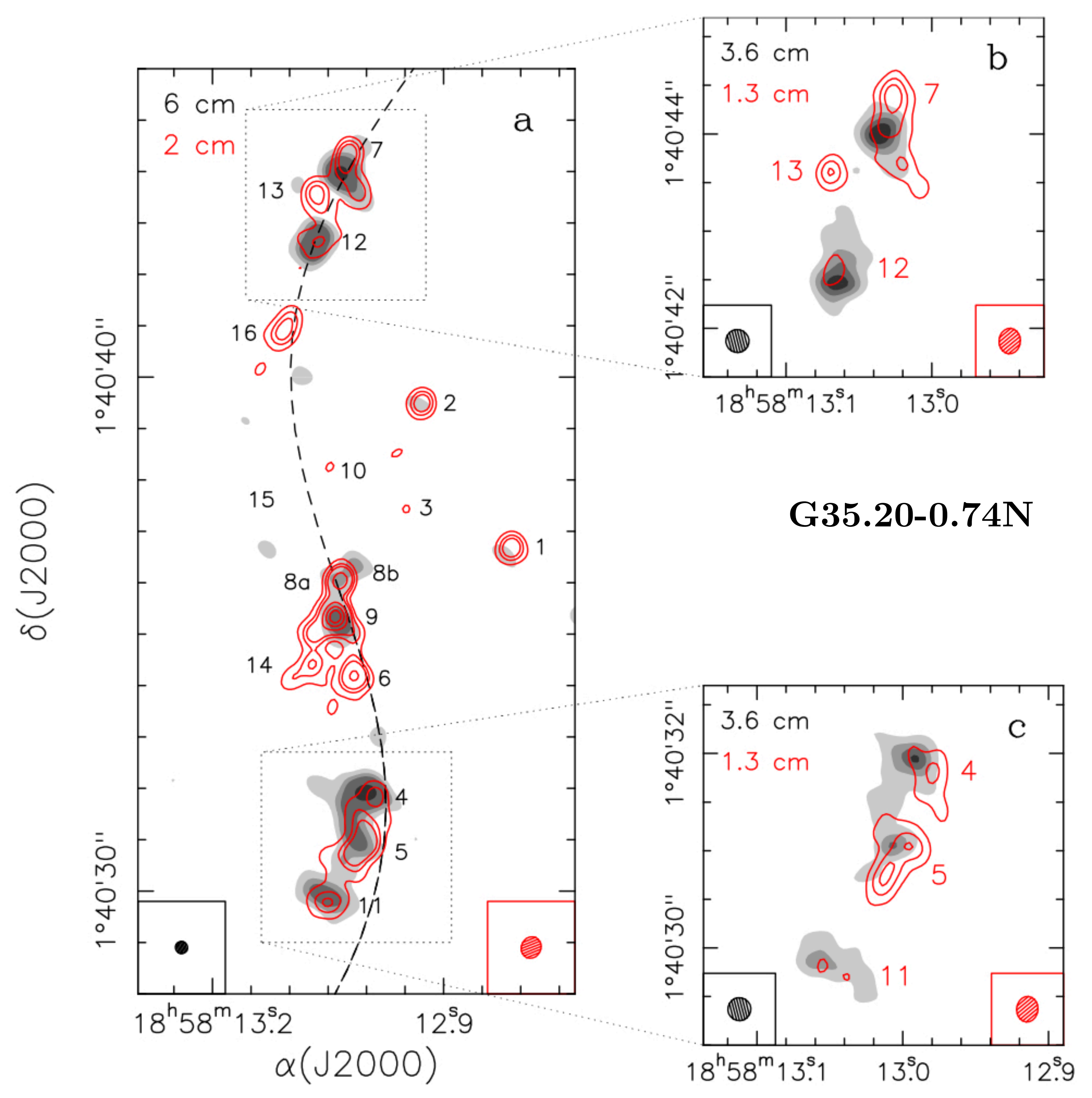


Carrasco-González+ (2013)



Rodríguez-Kamenetzky+ (2015)

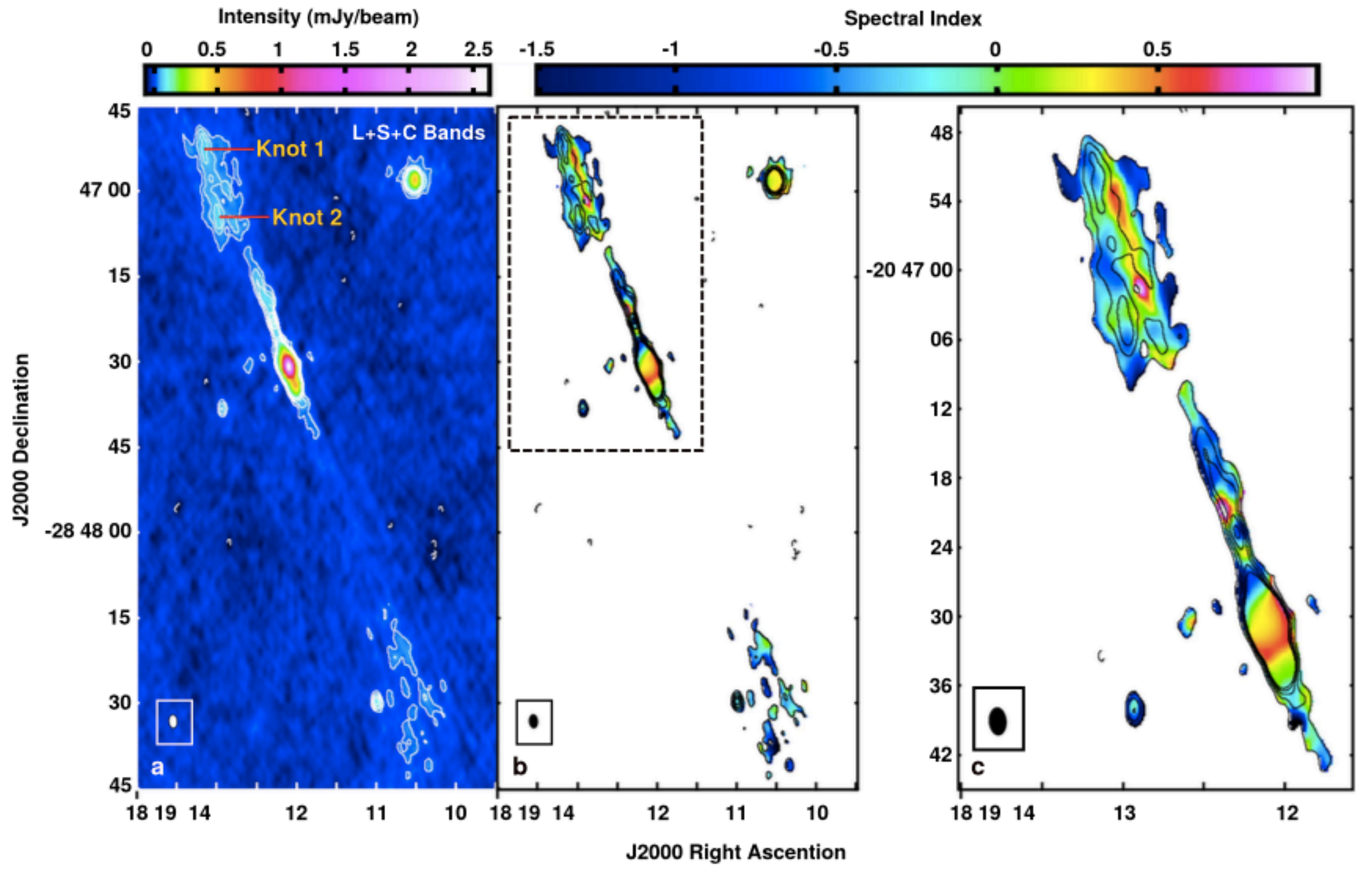
In high-mass YSOs it is even easier to accelerate CRs!



G35.20-0.74N

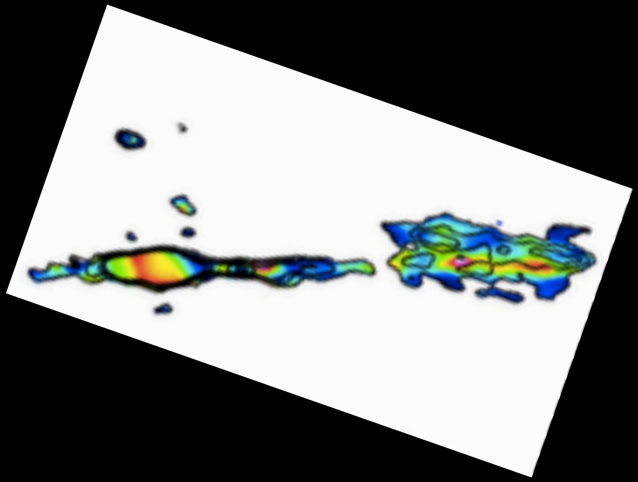
Beltrán+ (2016)

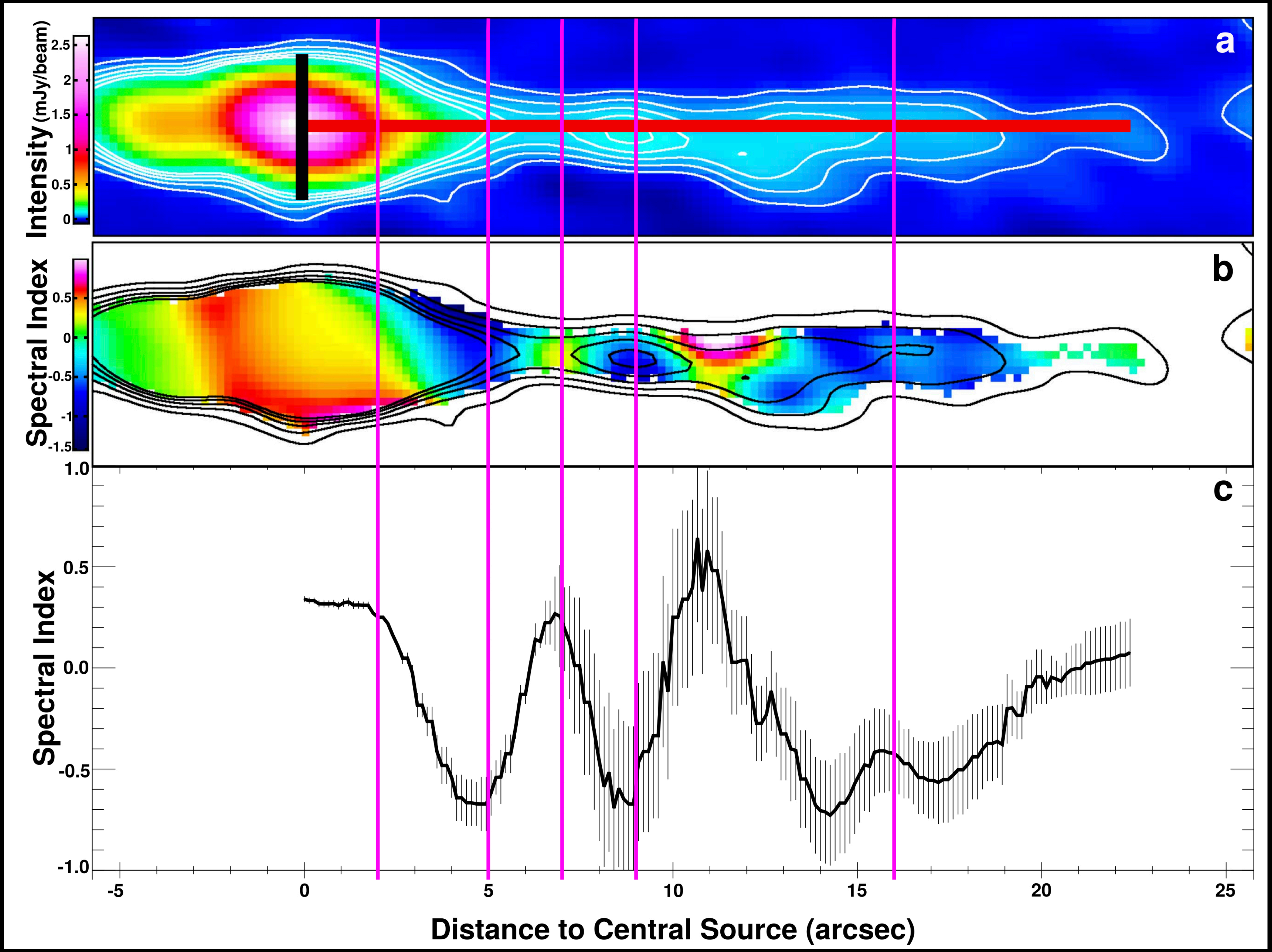
In high-mass YSOs it is even easier to accelerate CRs!



Rodríguez-Kamenetzky+ (2017)

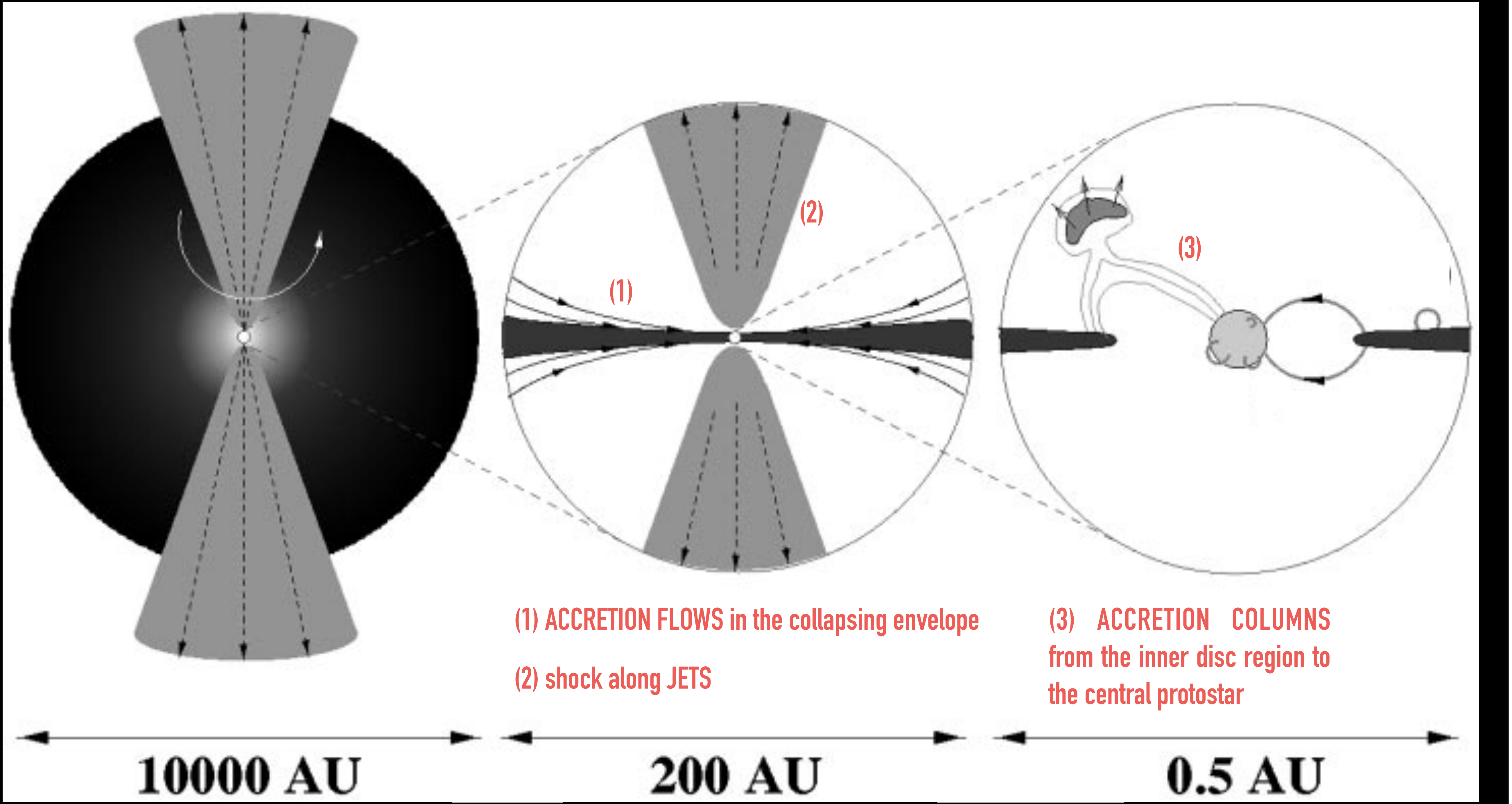
In high-mass YSOs it is even easier to accelerate CRs!





Rodríguez-Kamenetzky+ (2017)

Other acceleration mechanisms...



(1) ACCRETION FLOWS in the collapsing envelope

(2) shock along JETS

(3) ACCRETION COLUMNS from the inner disc region to the central protostar

Adapted from Feigelson & Montmerle (1999)

Conclusions and Perspectives

- We identified a new mechanism to accelerate CRs in protostellar shocks.
- A number of observations can be explained by our model: synchrotron emission in DG Tau, very high ionisation rate in L1157-B1 and OMC-2 FIR 4.

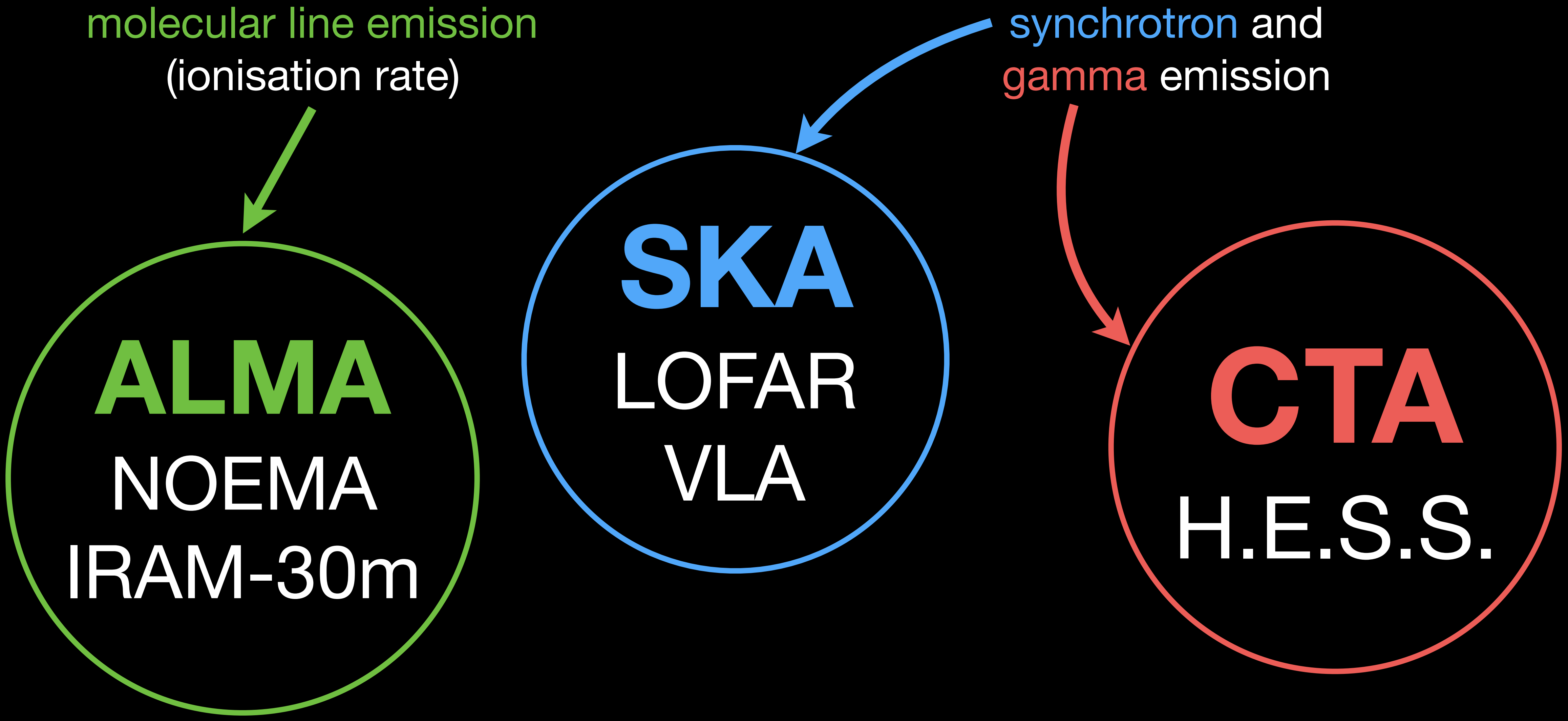
OUTCOMES

- the formation of meteoric ^{10}Be
- the creation of COMs on dust grains + release in the gas phase
- the extension of dead zone in discs

Conclusions and Perspectives

- We identified a new mechanism to accelerate CRs in protostellar shocks.
- A number of observations can be explained by our model: synchrotron emission in DG Tau, very high ionisation rate in L1157-B1 and OMC-2 FIR 4.

LOCAL CR acceleration is revealed by



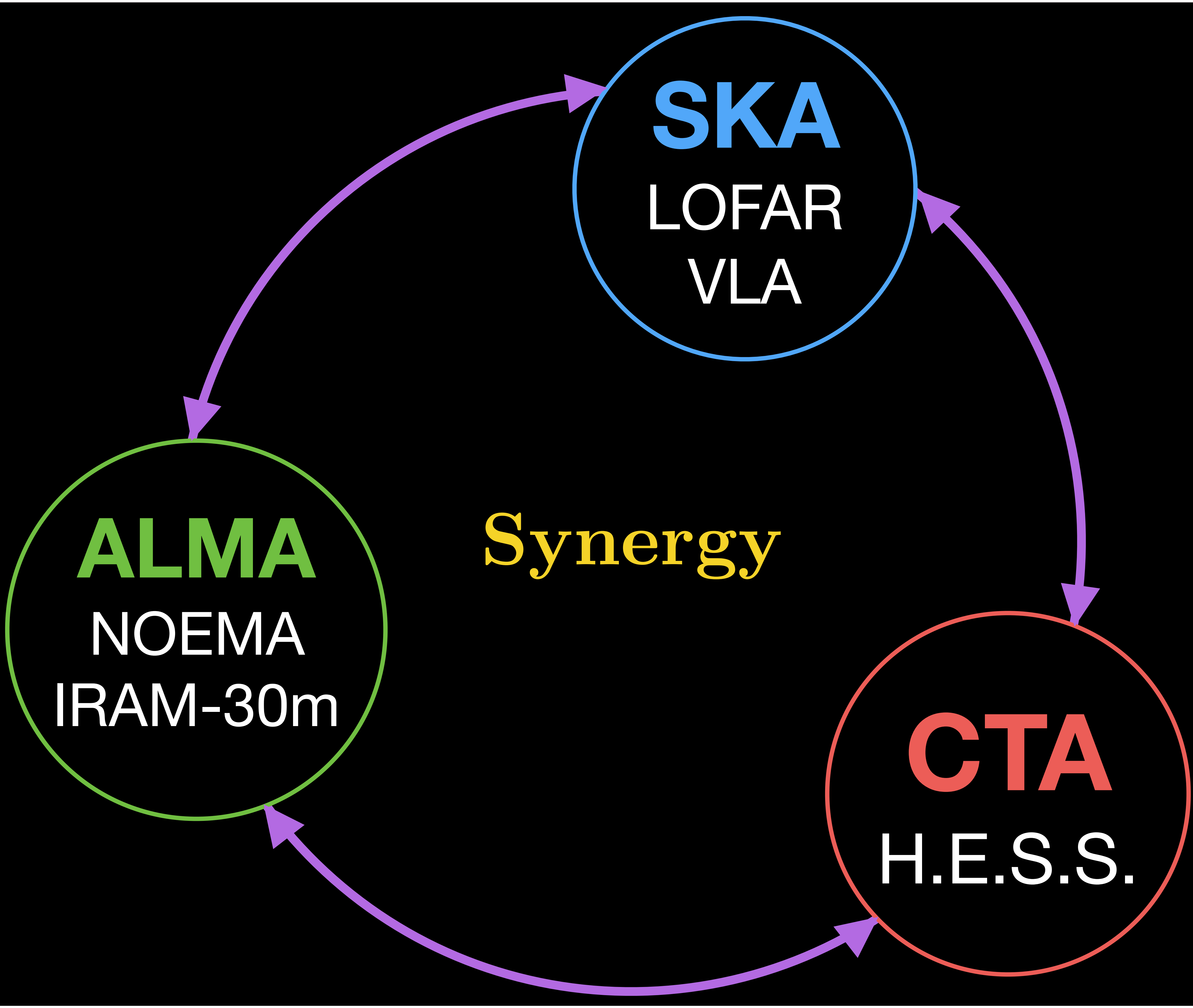
molecular line emission
(ionisation rate)

synchrotron and
gamma emission

ALMA
NOEMA
IRAM-30m

SKA
LOFAR
VLA

CTA
H.E.S.S.



SKA
LOFAR
VLA

ALMA
NOEMA
IRAM-30m

Synergy

CTA
H.E.S.S.