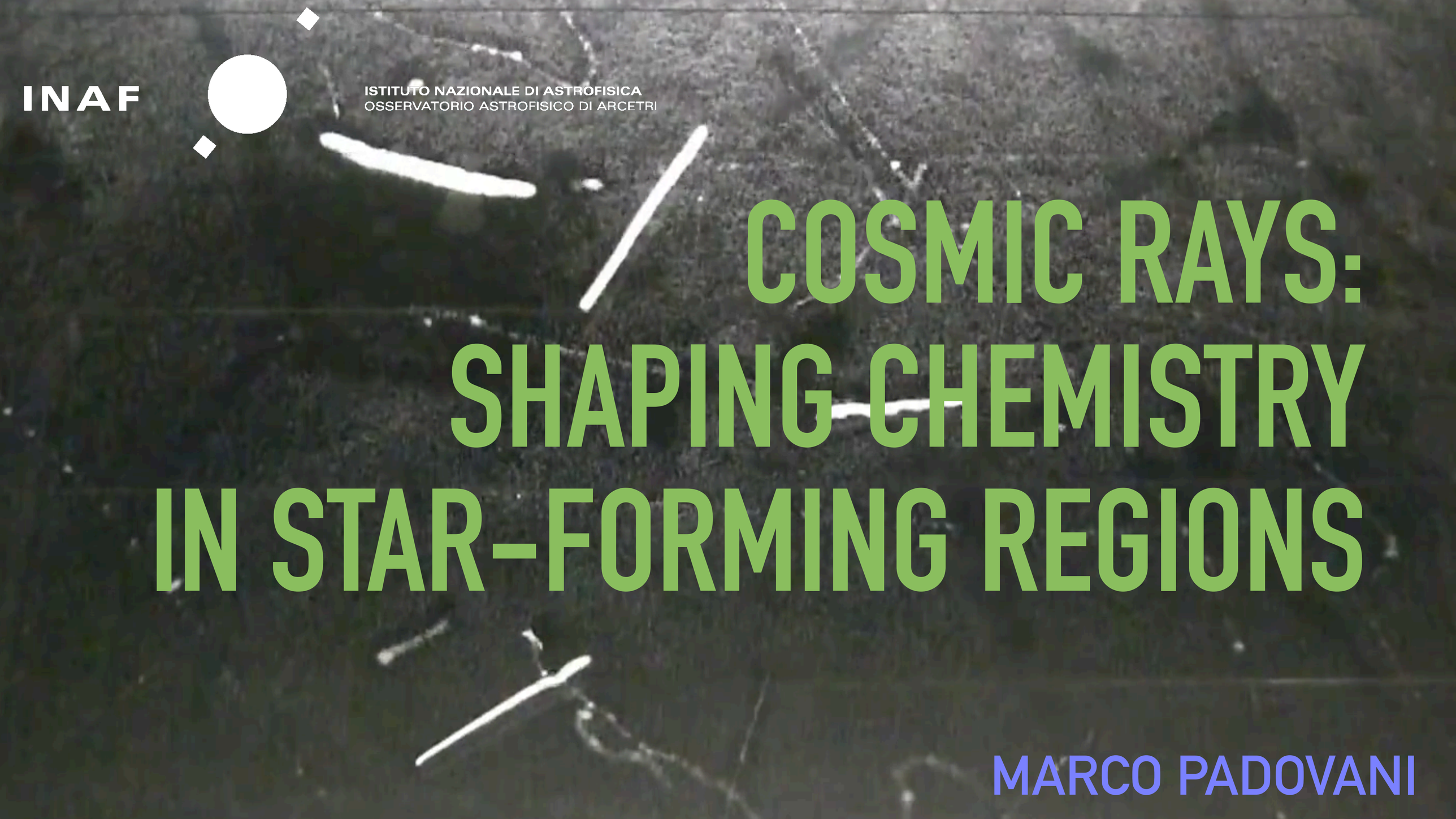


INAF
ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI ARCETRI

COSMIC RAYS: SHAPING CHEMISTRY IN STAR-FORMING REGIONS

MARCO PADOVANI

Space Sci Rev (2020) 216:29
https://doi.org/10.1007/s11214-020-00654-1

Impact of Low-Energy Cosmic Rays on Star Formation

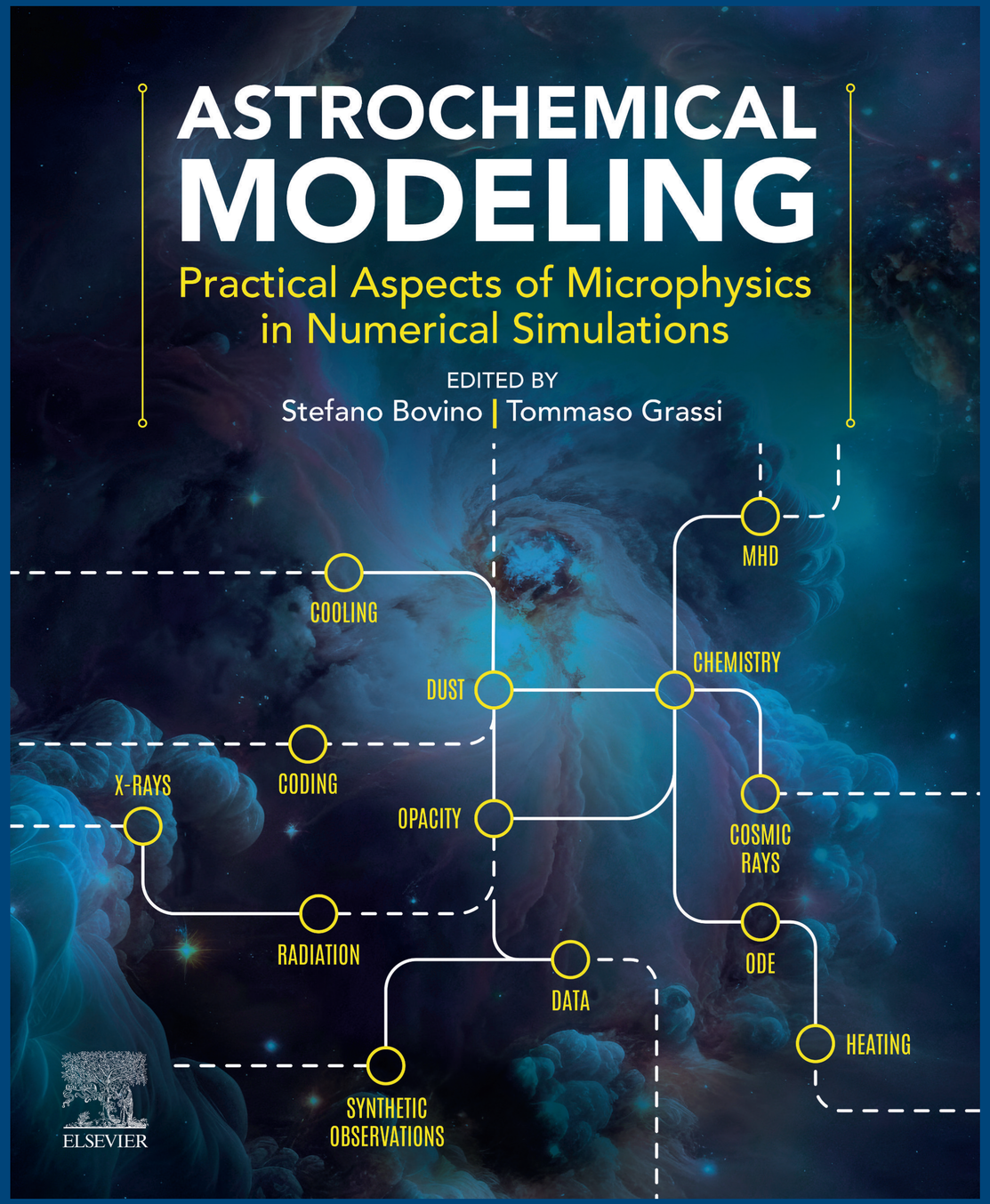
Marco Padovani[1] · Alexei V. Ivlev[2] · Daniele Galli[1] · Stella S.R. Offner[3] · Nick Indriolo[4] · Donna Rodgers-Lee[5] · Alexandre Marcowith[6] · Philipp Girichidis[7] · Andrei M. Bykov[8] · J.M. Diederik Kruijssen[9]

Received: 17 January 2020 / Accepted: 27 February 2020

Abstract In recent years, exciting developments have taken place in the identification of the role of cosmic rays in star-forming environments. Observations from radio to infrared wavelengths and theoretical modelling have shown that low-energy cosmic rays (< 1 TeV) play a fundamental role in shaping the chemical richness of the interstellar medium, determining the dynamical evolution of molecular clouds. In this review we summarise in a coherent picture the main results obtained by observations and by theoretical models of propagation and generation of cosmic rays, from the smallest scales of protostars and circumstellar discs, to young stellar clusters, up to Galactic and extragalactic scales. We also discuss the new fields that will be explored in the near future thanks to new generation instruments, such as: CTA, for the γ-ray emission from high-mass protostars; SKA and precursors, for the synchrotron emission at different scales; and ELT/HIRES, JWST, and ARIEL, for the impact of cosmic rays on exoplanetary atmospheres and habitability.

Other reviews

- Grenier et al. (2015) - *The nine lives of cosmic rays in galaxies*
- Gabici (2022) - *Low-energy cosmic rays: regulators of the dense interstellar medium*
- Owen et al. (2023) - *Cosmic-ray processes in galactic ecosystems*



CHAPTER

Cosmic rays: physics, chemistry, and computational challenges

8

Marco Padovani[a] **and Brandt Gaches**[b,c,d]

[a] *INAF Osservatorio Astrofisico di Arcetri, Firenze, Italy*
[b] *I. Physikalisches Institut, Universität zu Köln, Köln, Germany*
[c] *Department of Space, Earth and Environment, Chalmers University of Technology, Gothenburg, Sweden*
[d] *Center of Planetary Systems Habitability, The University of Texas at Austin, Austin, TX, United States*

The interstellar medium is immersed in a bath of cosmic rays: energetic charged particles with a non-thermal velocity distribution that exist in rough equipartition with the thermal and magnetic energies. Observations have shown that cosmic rays follow power-law distributions in energy from 1 GeV to 10 EeV with a turnover around 1 GeV. Cosmic rays are thought to have a wide range of effects on the interstellar medium and galaxies, such as ionization and heating of gas, pressure which aids in lifting gas out of galaxies, producing turbulence through instabilities in magneto-hydrodynamic turbulence. In this chapter, we will focus on the first of these and refer the reader to the many excellent reviews of the later effects (e.g., Strong et al., 2007; Zweibel, 2013; Grenier et al., 2015; Schlickeiser, 2015). We also refer the reader to Schlickeiser (2002) and Longair (2011) for more thorough monographs on cosmic-ray transport and high-energy phenomenon.

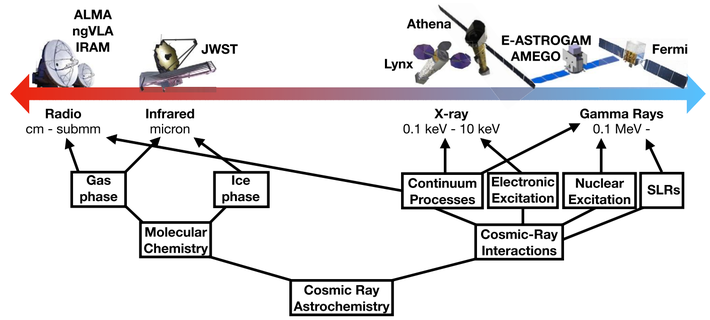
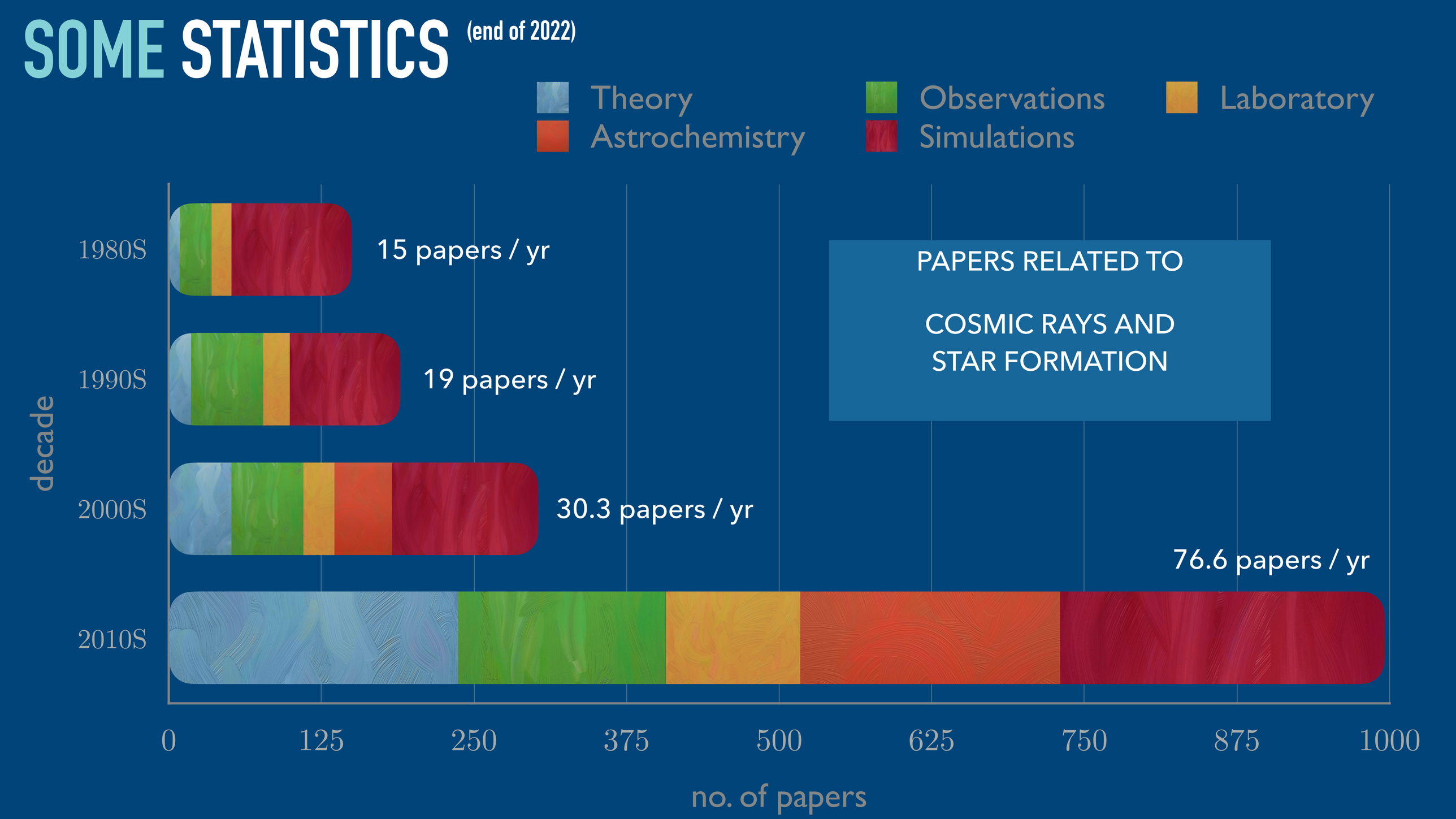


FIGURE 8.1

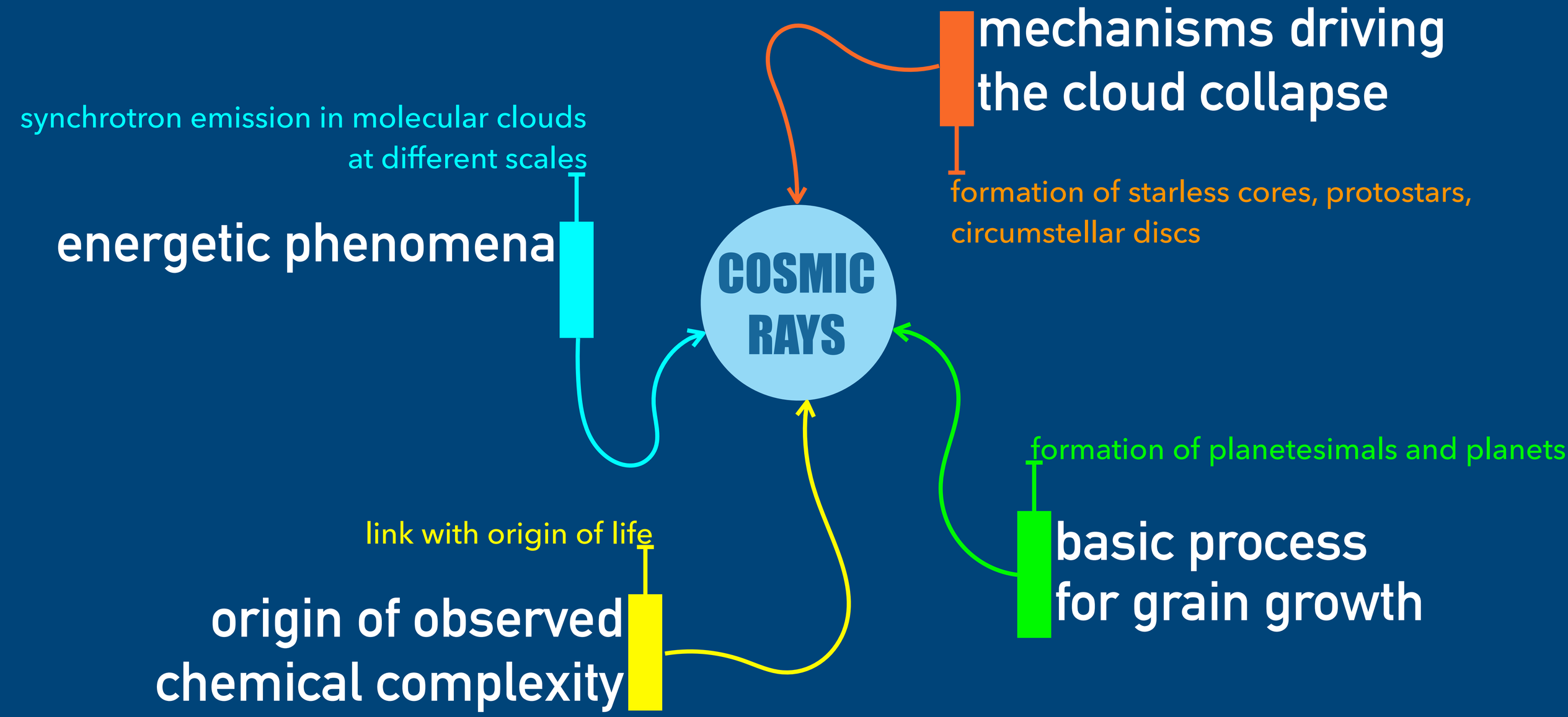
Emission processes diagnostics of cosmic-ray astrochemistry, with key current and proposed/future telescopes denoted at their respective wavelength regimes.

Astrochemical Modeling. https://doi.org/10.1016/B978-0-32-391746-9.00016-X

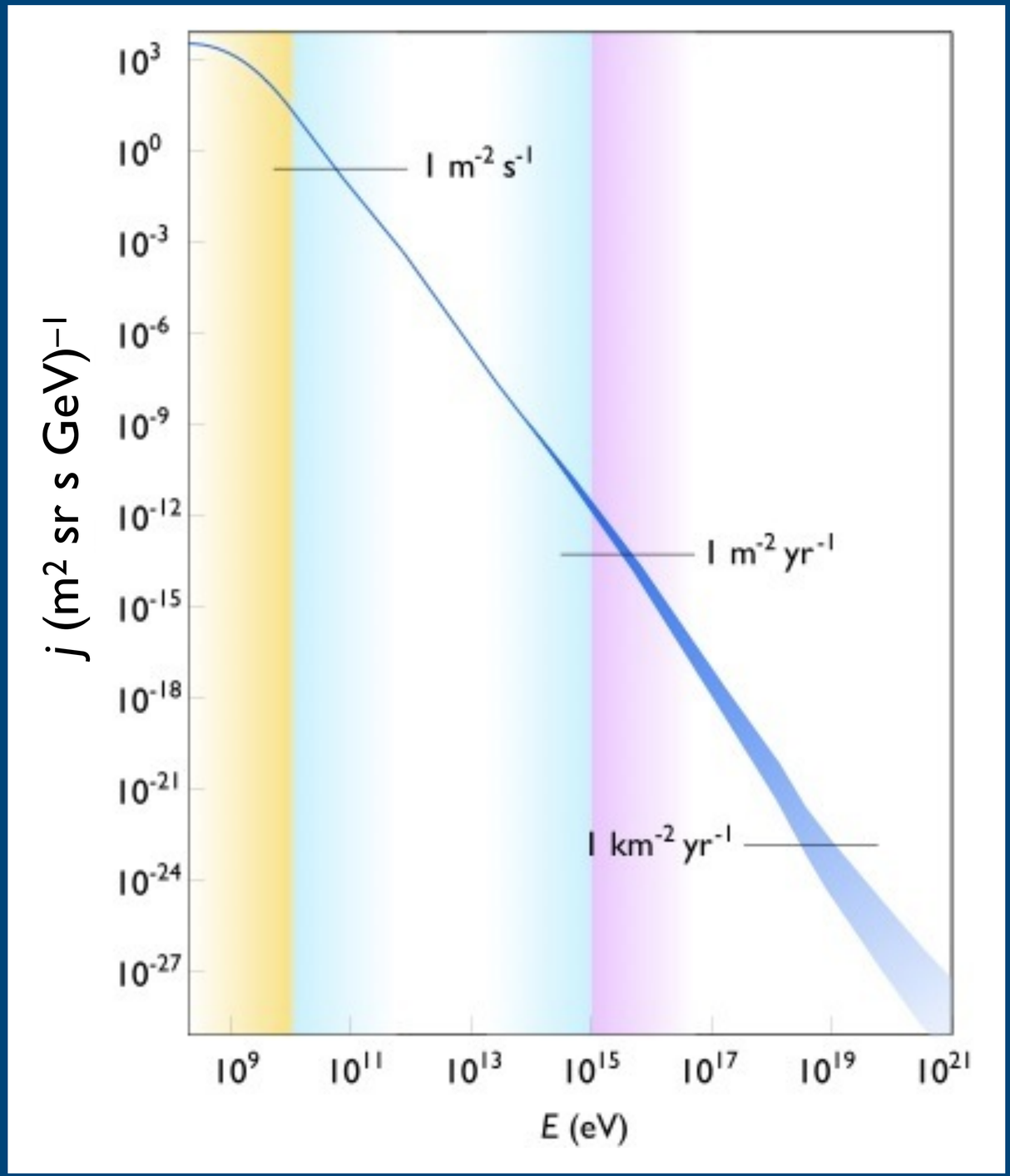
SOME STATISTICS (end of 2022)



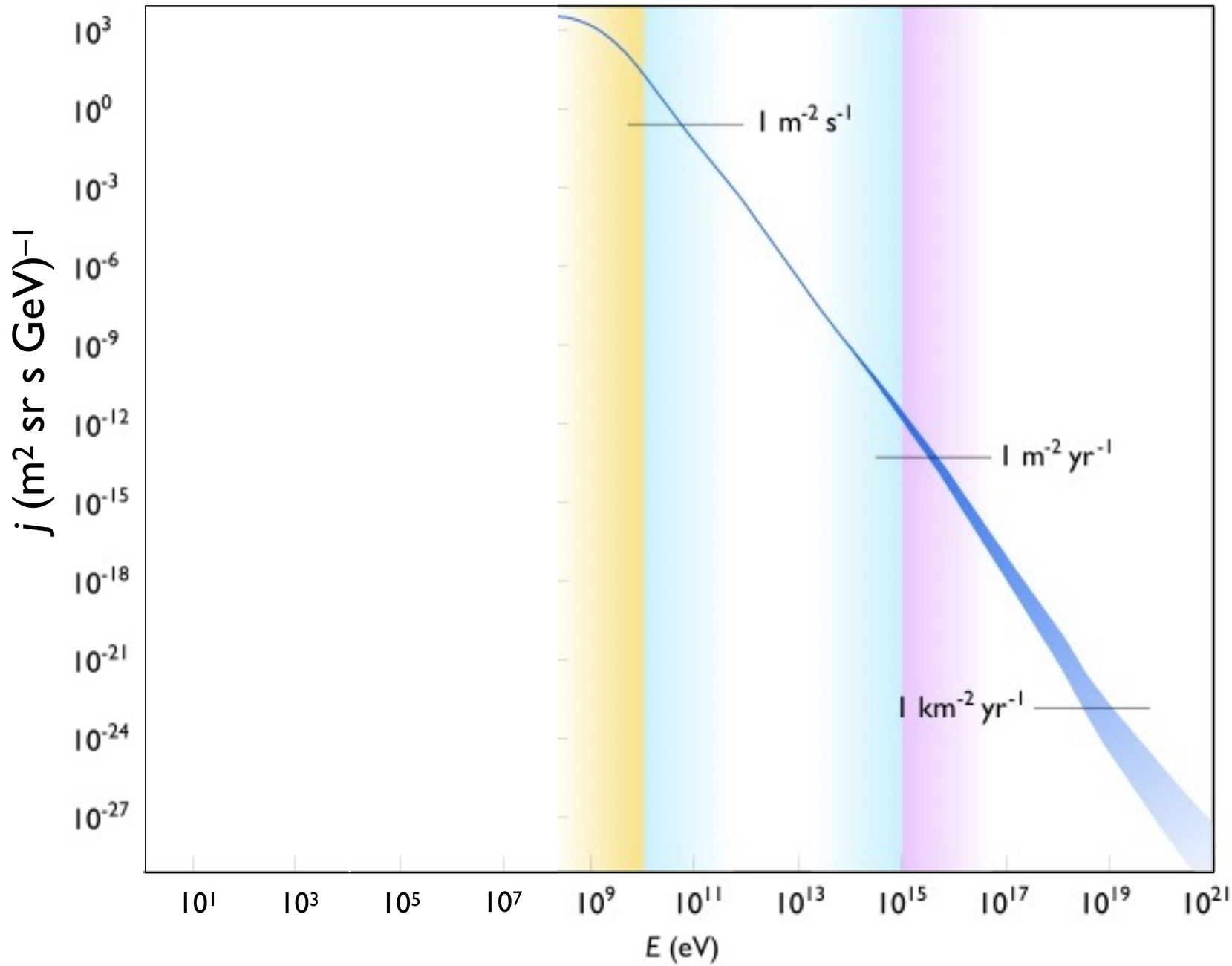
SOME KEY ASPECTS IN GALACTIC STAR FORMATION



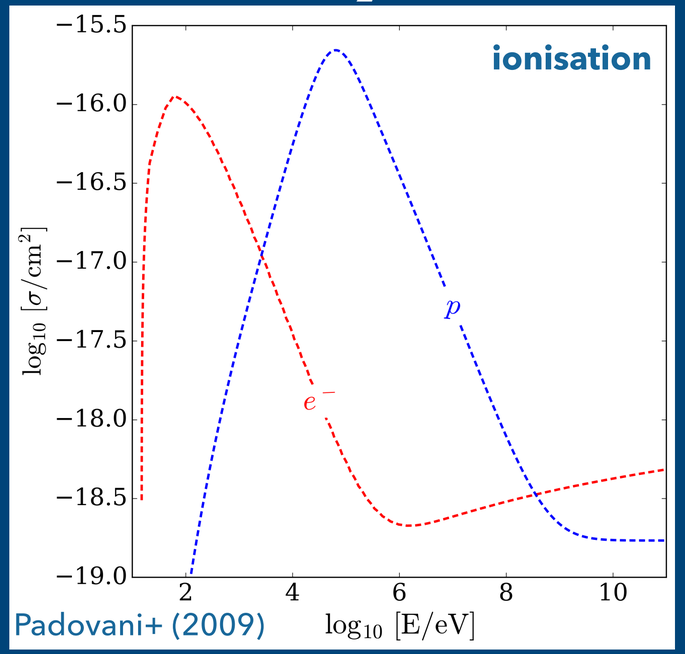
COSMIC-RAY FLUX



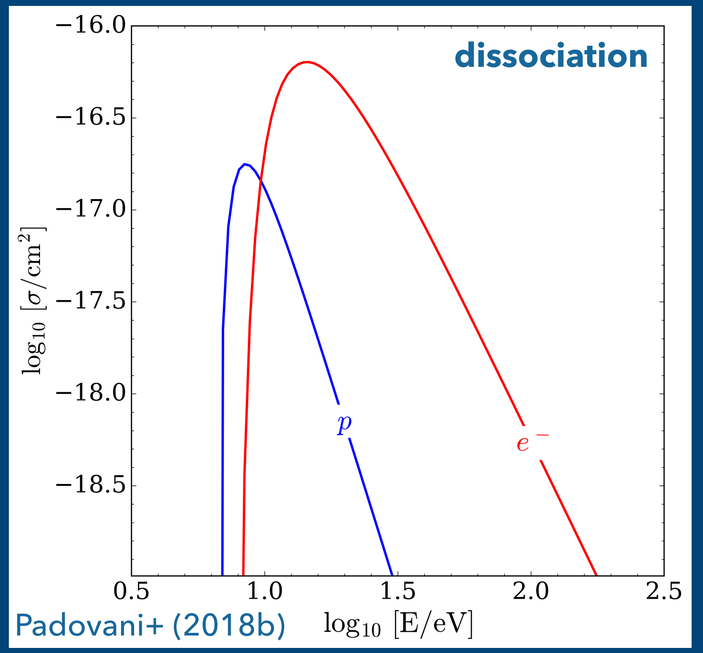
COSMIC-RAY FLUX

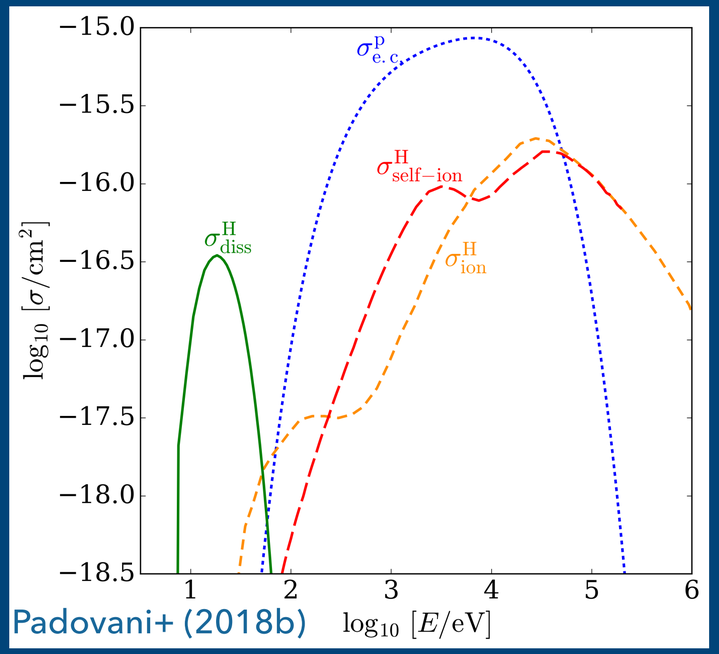


$$(p, e) + \mathrm{H}_2 \rightarrow \mathrm{H}_2^+ + e'' + (p', e')$$



$$(p, e) + \mathrm{H}_2 \rightarrow \mathrm{H} + \mathrm{H} + (p', e')$$



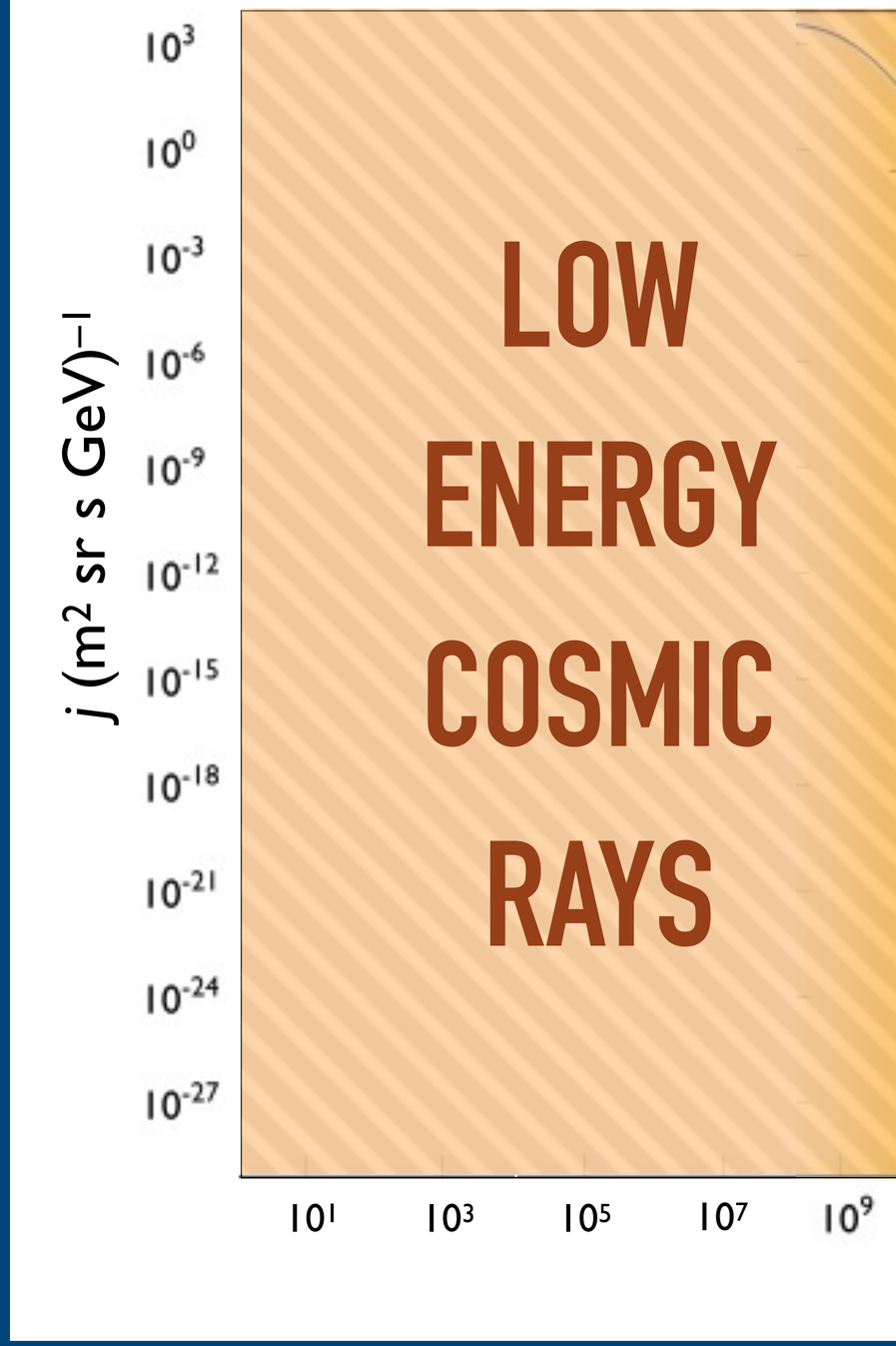


$$p + \mathrm{H}_2 \rightarrow \mathrm{H}_2^+ + \mathrm{H}_{\mathrm{fast}} \qquad (\sigma^p_{\mathrm{e.c.}})$$

$$\mathrm{H}_{\mathrm{fast}} + \mathrm{H}_2 \rightarrow \mathrm{H}_{\mathrm{fast}} + \mathrm{H}_2^+ + e \qquad (\sigma^{\mathrm{H}}_{\mathrm{ion}})$$

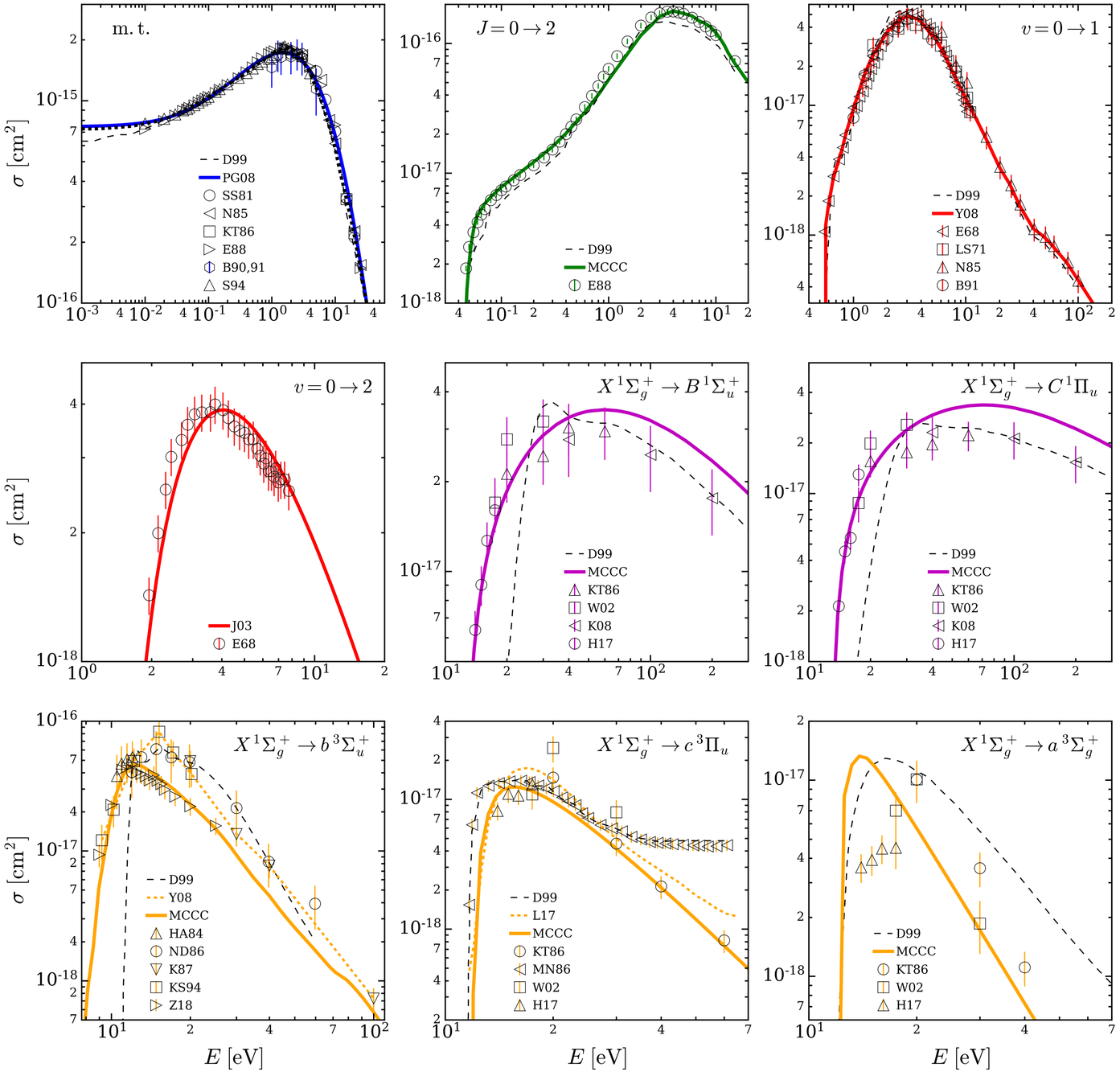
$$\rightarrow p + \mathrm{H}_2 + e \qquad (\sigma^{\mathrm{H}}_{\mathrm{self-ion}})$$

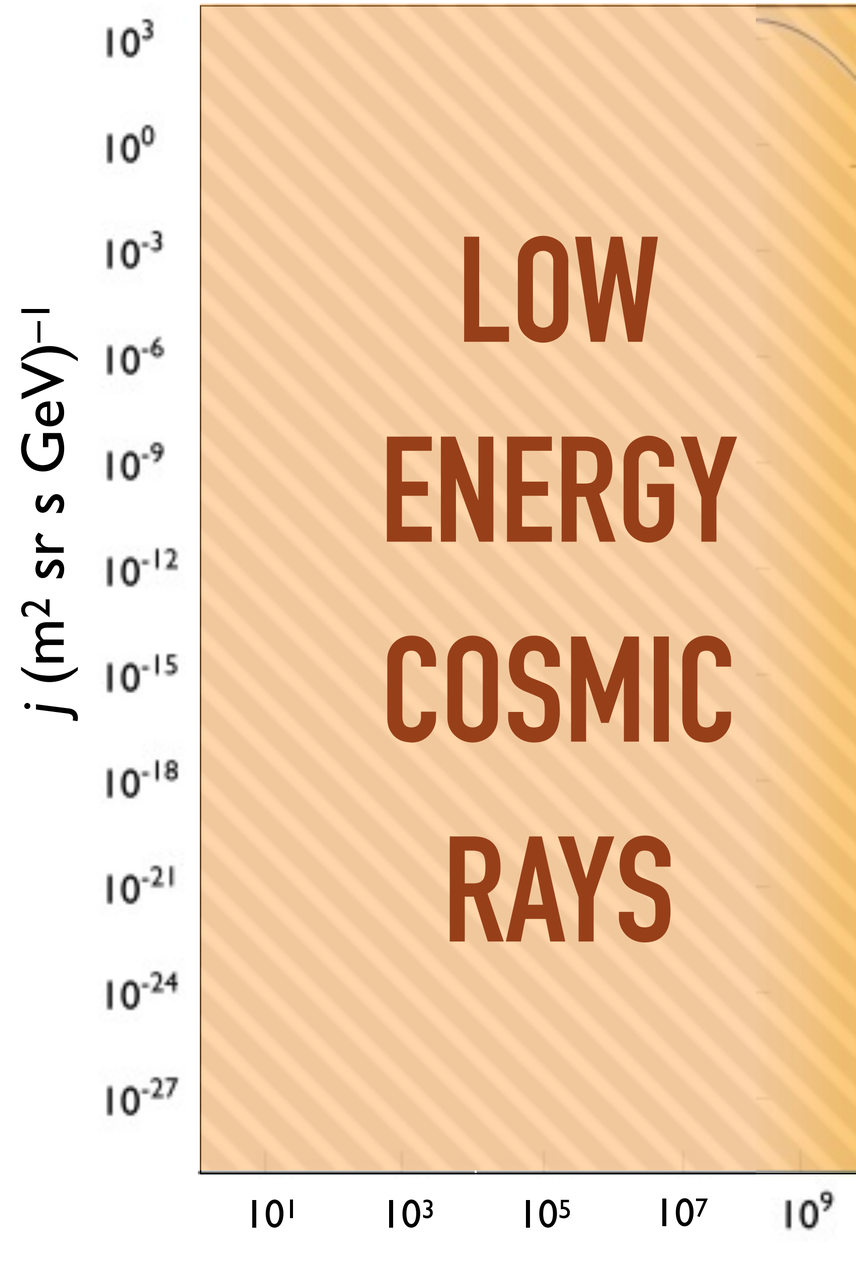
$$\rightarrow \mathrm{H}_{\mathrm{fast}} + \mathrm{H} + \mathrm{H} \qquad (\sigma^{\mathrm{H}}_{\mathrm{diss}})$$



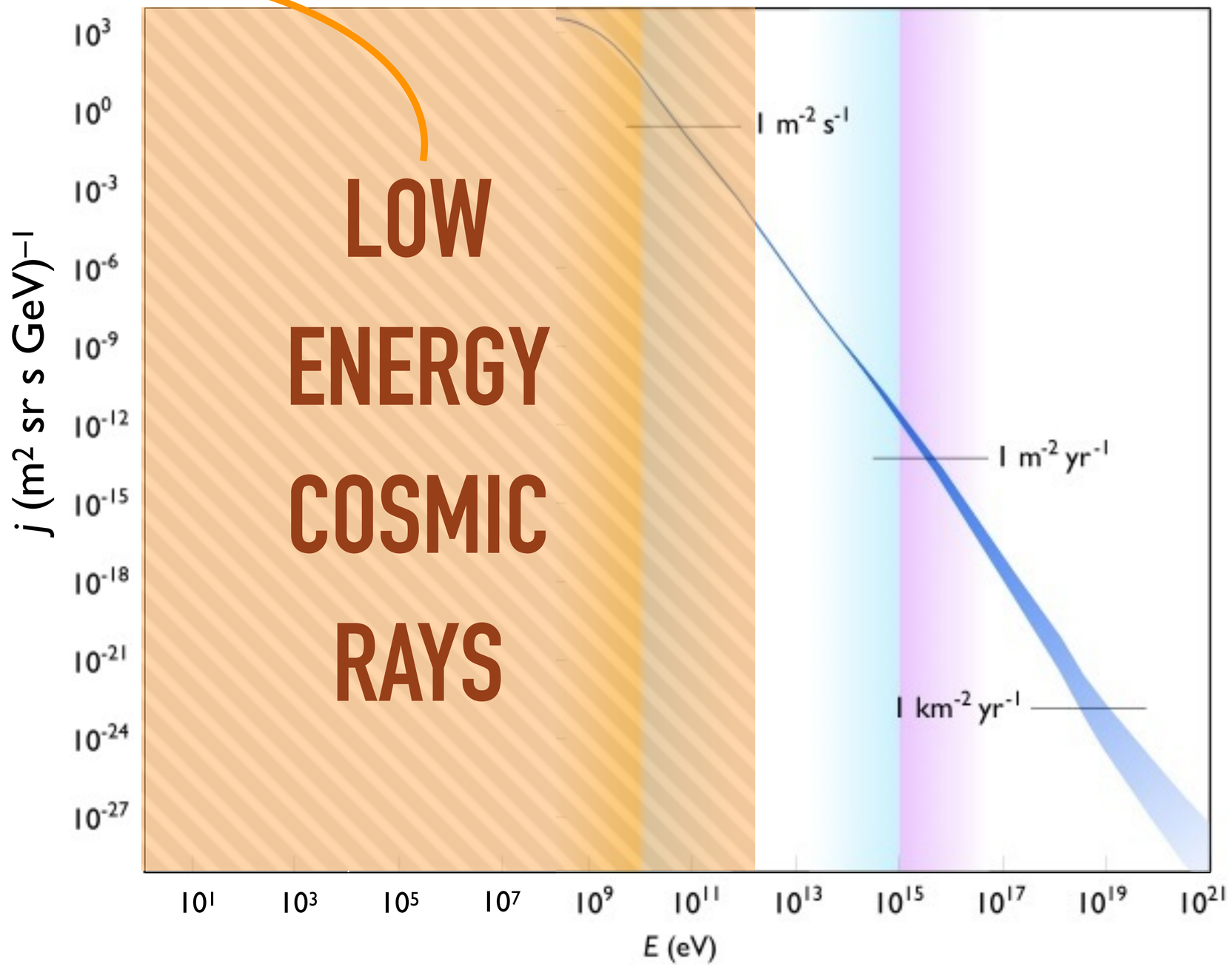
$e + H_2 \rightarrow H_2^* + e'$

Padovani+ (2022)

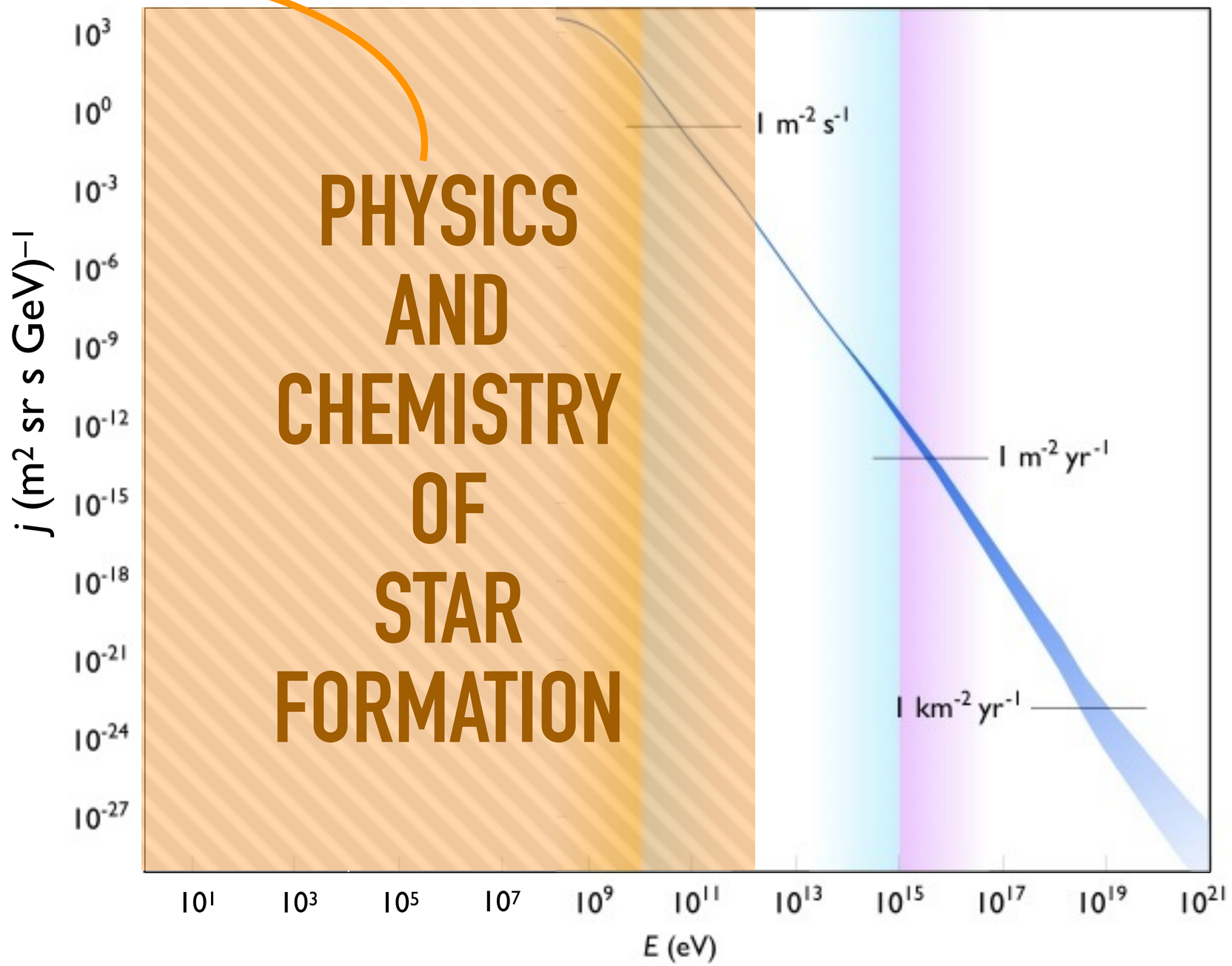




- CHEMISTRY;
- DYNAMICS OF STAR FORMATION;
- HEATING;
- DUST GRAIN CHARGE;
- SYNCHROTRON EMISSION;
- ATOMIC HYDROGEN FRACTION;
- SPALLATION;
- GAMMA-RAY EMISSION;
- . . .



- CHEMISTRY;
- DYNAMICS OF STAR FORMATION;
- HEATING;
- DUST GRAIN CHARGE;
- SYNCHROTRON EMISSION;
- ATOMIC HYDROGEN FRACTION;
- SPALLATION;
- GAMMA-RAY EMISSION;
- . . .



COSMIC-RAY SIGNATURES

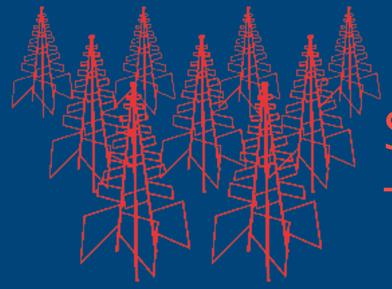
how can we reassemble the cosmic-ray spectrum from observations?

we have information on different energy ranges of the cosmic-ray flux

using different observational techniques

COSMIC-RAY SIGNATURES

* for $B_\perp \approx 2 - 20\ \mu$G and $\nu \approx 0.1 - 10$ GHz

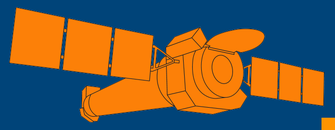


SKA
+precursors

synchrotron emission

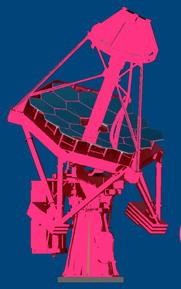
$\approx$ 200 MeV – 40 GeV *

Chandra+



spallation

$\gtrsim$ 30 MeV

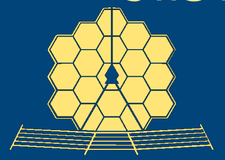


CTA
+precursors

γ-ray emission

$\gtrsim$ 280 MeV

JWST



secondary-electron
excitation/dissociation

$\approx$ 1 – 20 eV

ALMA
NOEMA+

proton ionisation

$\approx$ 1 – 100 MeV

secondary-electron
ionisation

$\approx$ 10 – 100 eV

electron ionisation

$\approx$ 10 keV – 10 MeV

COSMIC RAYS: CHARGED PARTICLES OUT OF THE THERMAL DISTRIBUTION

- protons
- electrons
- bare nuclei

Maxwell-Boltzmann distribution

$$j_{\mathrm{M}} = \frac{c\ n_{\mathrm{H}_2} x\ E\ \ \exp[-E/(k_{\mathrm{B}}T)]}{\sqrt{2m(\pi k_{\mathrm{B}}T)^3}}$$

$$[j_{\mathrm{M}}] = \frac{\text{particles}}{\text{energy} \times \text{area} \times \text{time} \times \text{solid angle}}$$

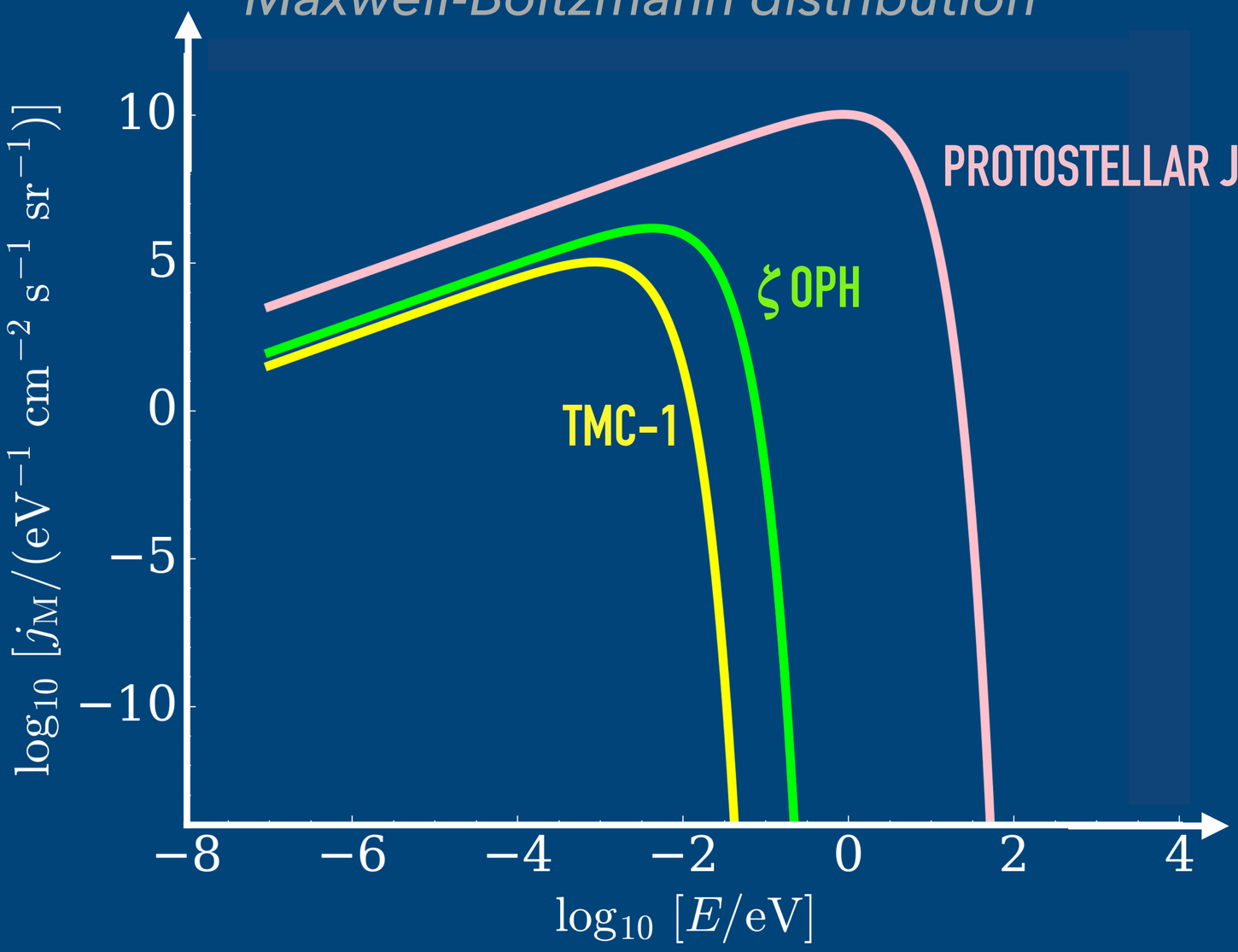
COSMIC RAYS: CHARGED PARTICLES OUT OF THE THERMAL DISTRIBUTION

$$j_{\mathrm{M}} = \frac{c\, n_{\mathrm{H_2}} x\, E\, \exp[-E/(k_{\mathrm{B}}T)]}{\sqrt{2m(\pi k_{\mathrm{B}}T)^3}}$$

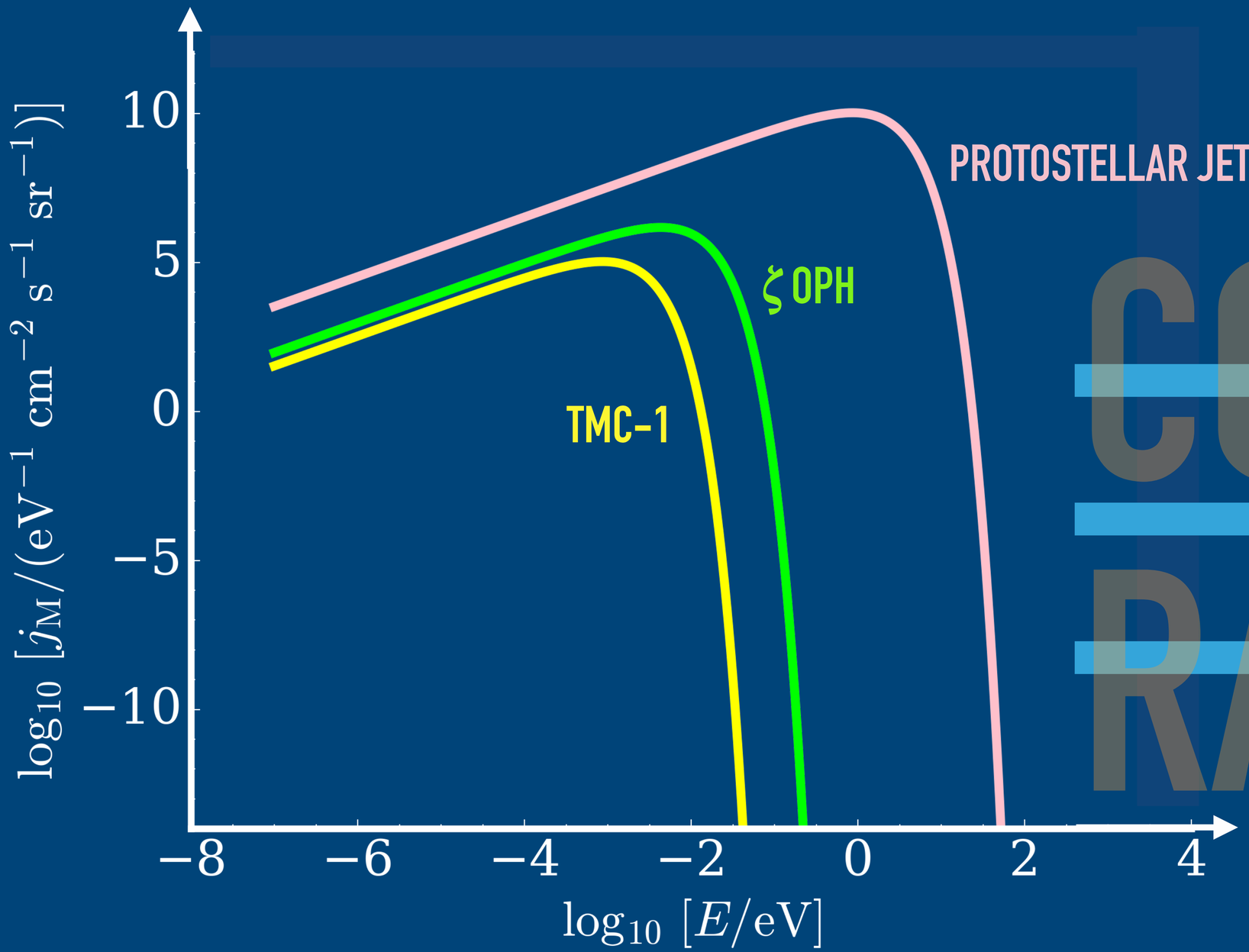
ζ OPH
$n(\mathrm{H_2}) = 500\ \mathrm{cm^{-3}}$
$x = 10^{-4}$
$T = 50\ \mathrm{K}$

TMC-1
$n(\mathrm{H_2}) = 10^4\ \mathrm{cm^{-3}}$
$x = 10^{-7}$
$T = 10\ \mathrm{K}$

JET
$n(\mathrm{H_2}) = 10^4\ \mathrm{cm^{-3}}$
$x = 0.5$
$T = 10^4\ \mathrm{K}$



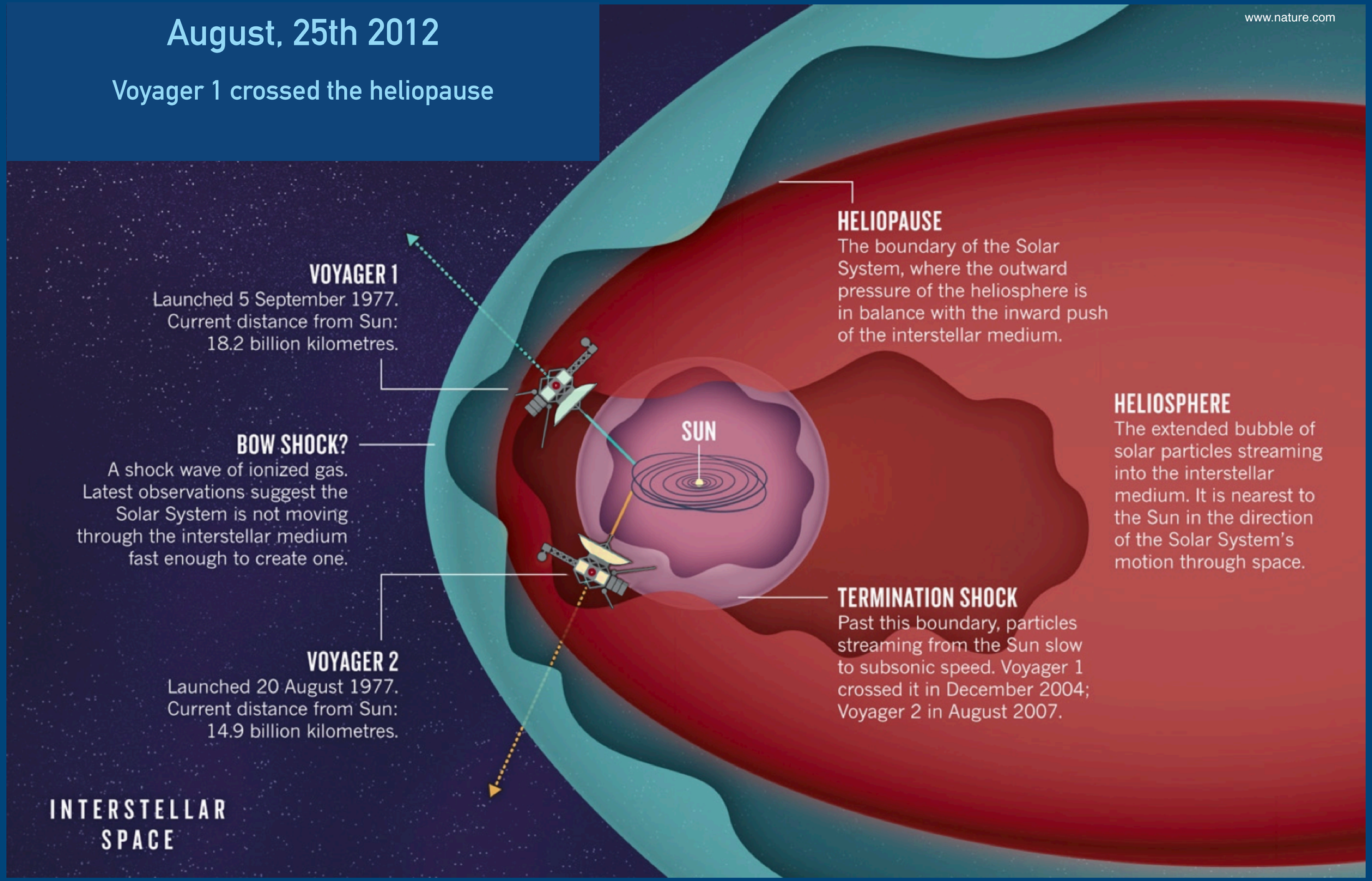
COSMIC RAY: CHARGED PARTICLE OUT OF THE THERMAL DISTRIBUTION



COSMIC RAYS

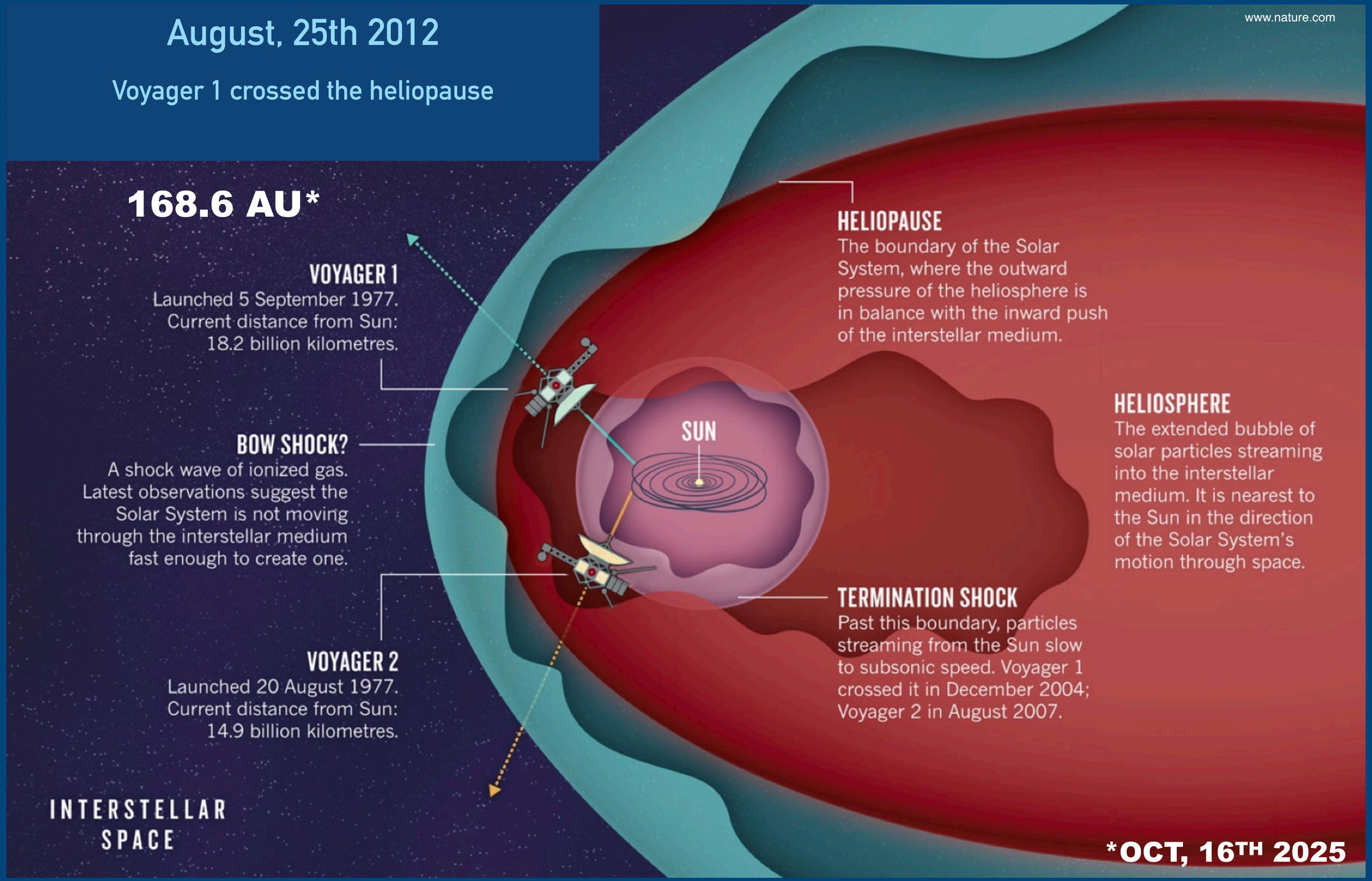
August, 25th 2012

Voyager 1 crossed the heliopause

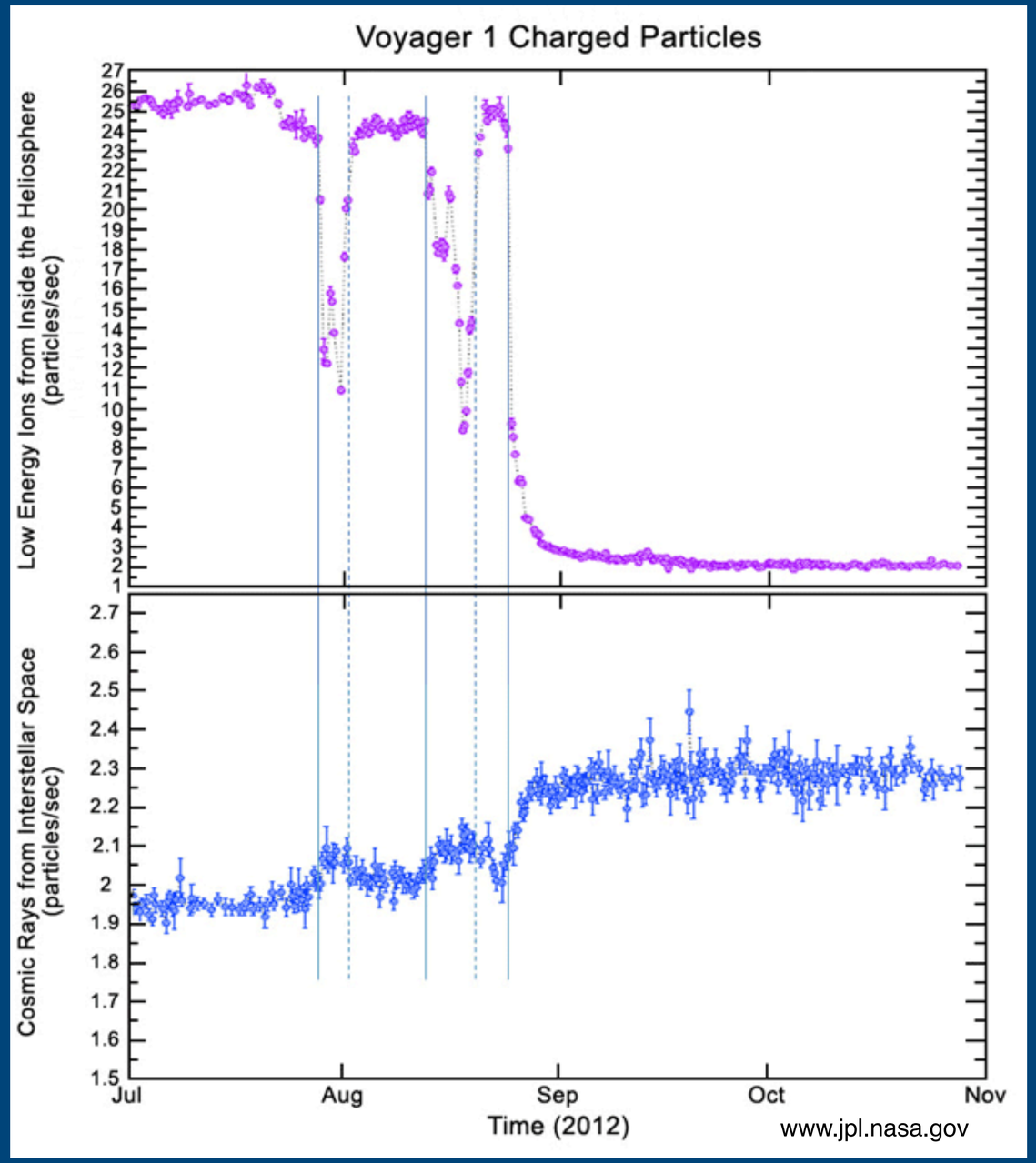


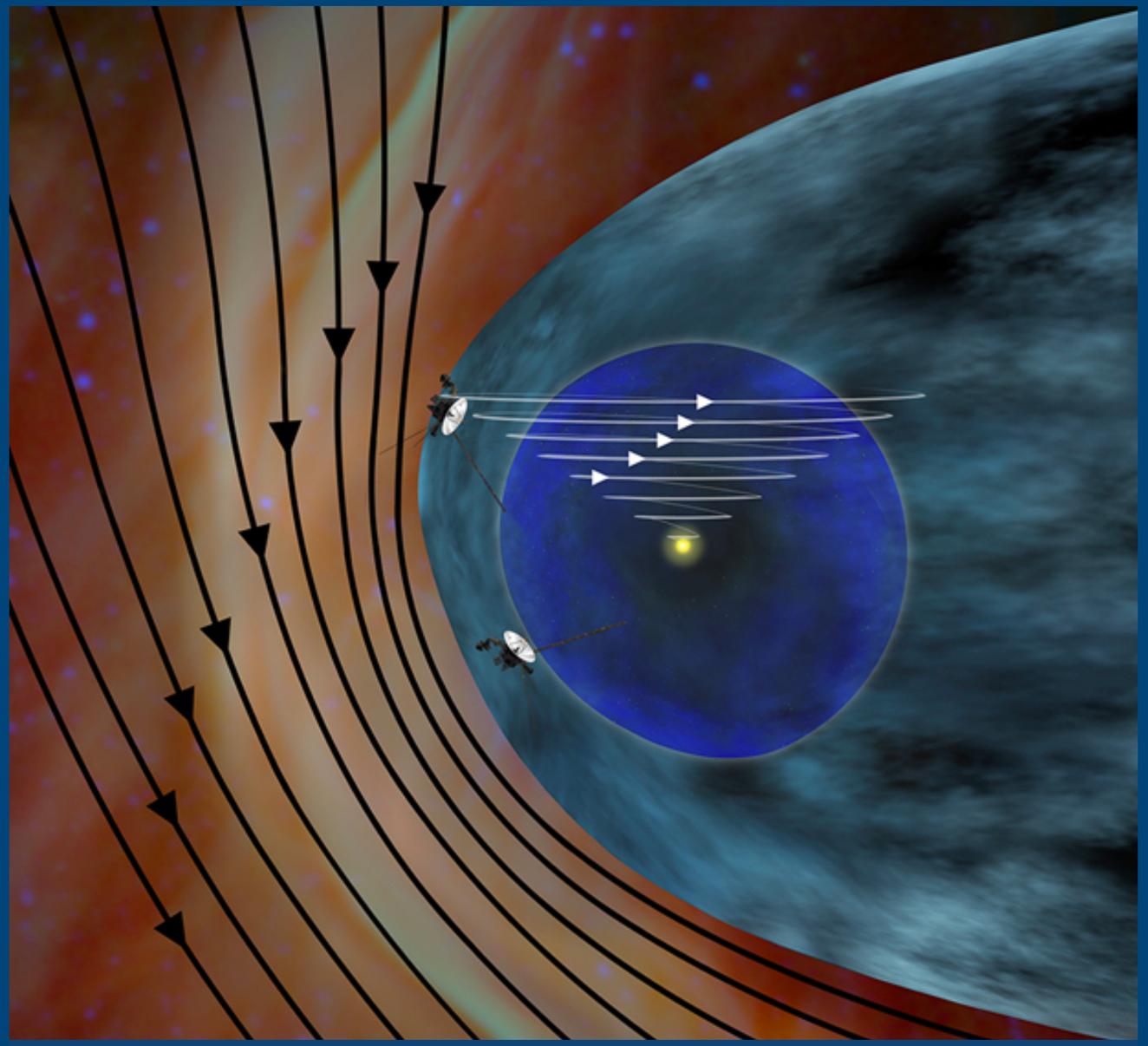
August, 25th 2012

Voyager 1 crossed the heliopause

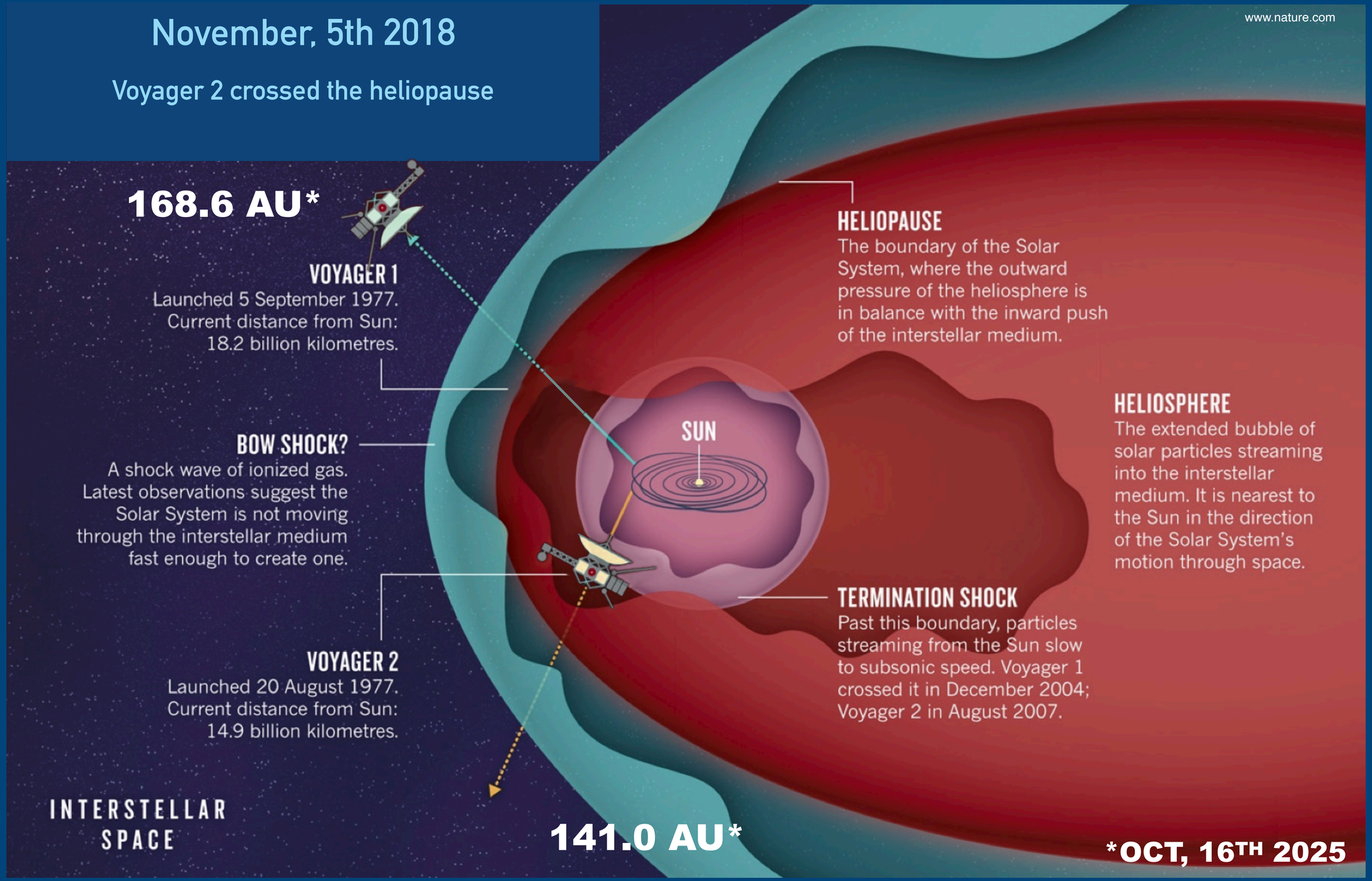


AUGUST, 25TH 2012: VOYAGER 1 CROSSED THE HELIOPAUSE



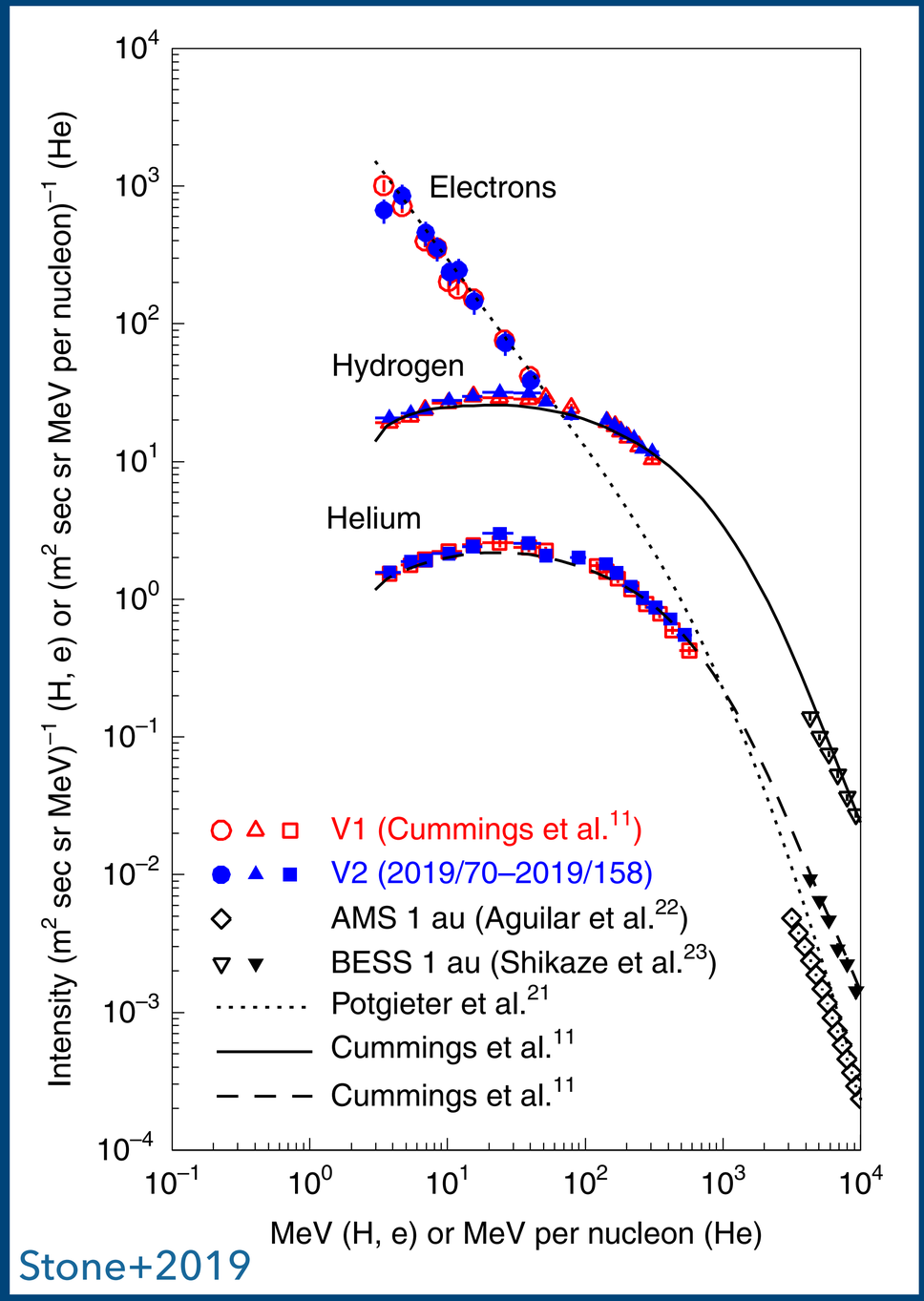


still… variation in the magnetic field direction not seen so far

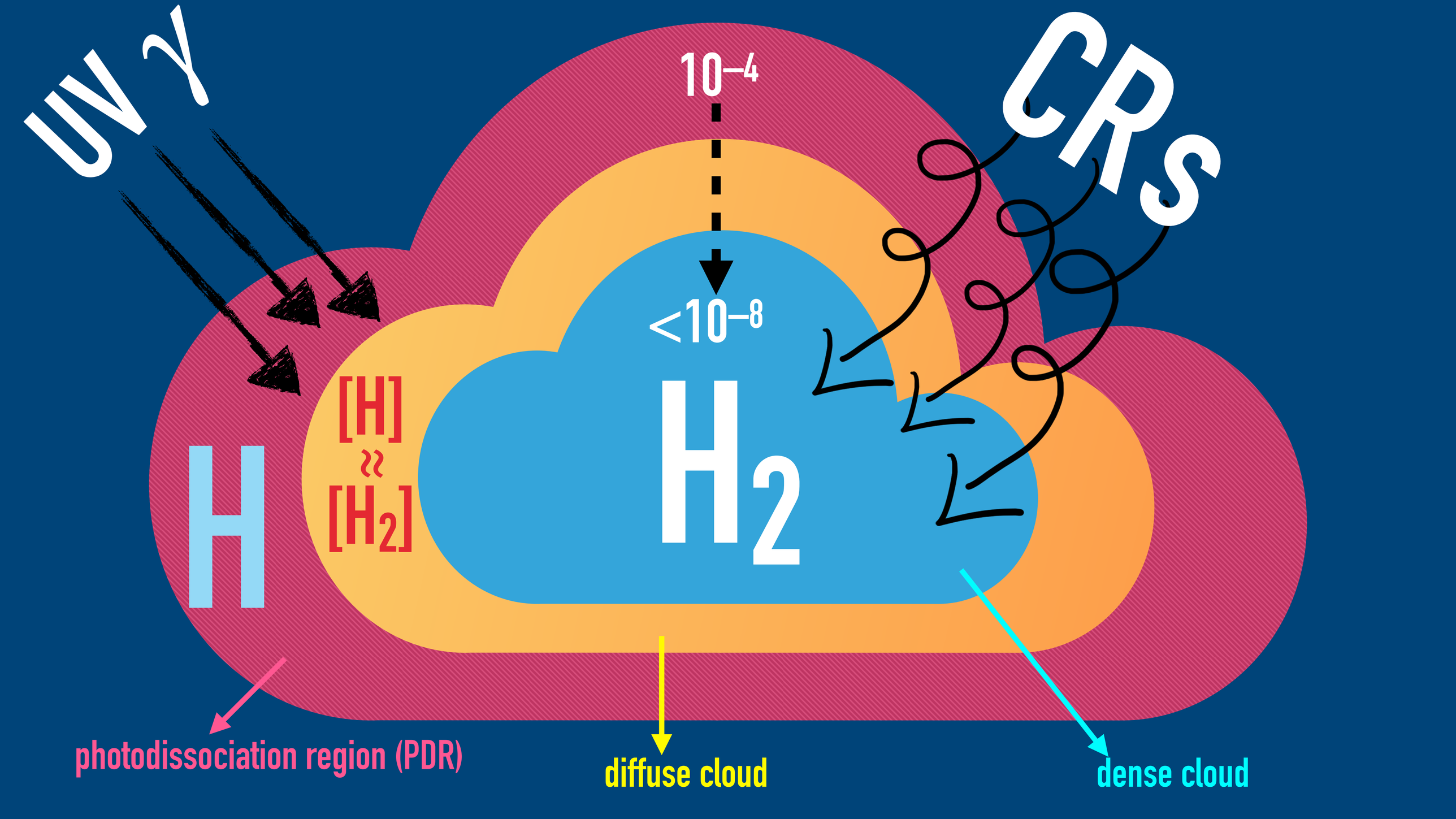

November, 5th 2018
Voyager 2 crossed the heliopause
www.nature.com
168.6 AU*
VOYAGER 1
Launched 5 September 1977.
Current distance from Sun:
18.2 billion kilometres.
BOW SHOCK?
A shock wave of ionized gas.
Latest observations suggest the
Solar System is not moving
through the interstellar medium
fast enough to create one.
VOYAGER 2
Launched 20 August 1977.
Current distance from Sun:
14.9 billion kilometres.
INTERSTELLAR
SPACE
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.
SUN
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.
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.
141.0 AU*
*OCT, 16TH 2025

WHAT VOYAGER SPACECRAFTS ARE TELLING US

The two spacecraft share comparable cosmic-ray fluxes (90% agreement) in spite of the different crossing points of the heliopause.



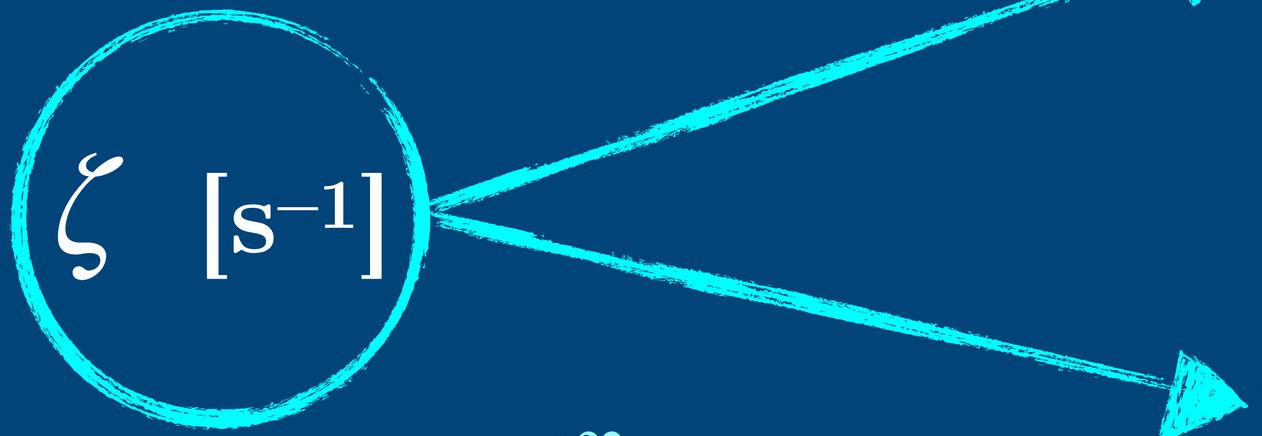
Stone+2019


UV γ
CRs
10−4
<10−8
H
[H] ≈ [H2]
H2
photodissociation region (PDR)
diffuse cloud
dense cloud

COSMIC-RAY IONISATION RATE

number of H_2 ionisation per unit time

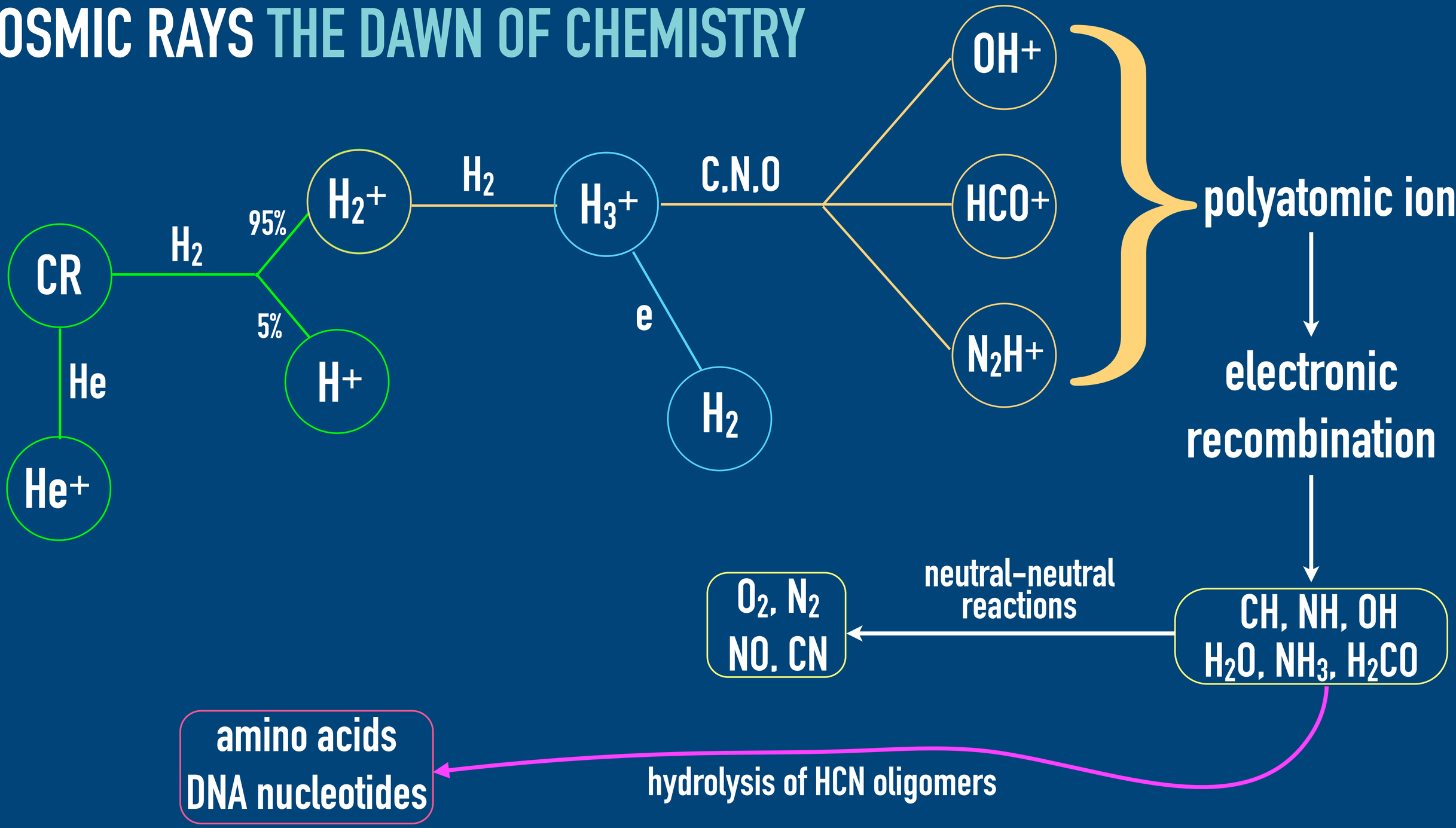
key-brick parameter



$$\zeta = 4\pi \int_I^\infty j(E)\sigma_{\rm ion}(E)\ \mathrm{d}E$$

- astrochemical models
  (interpretation of the observed abundances);
- non-ideal MHD simulations
  (study of the collapse of a molecular cloud,
  protostar and circumstellar disc formation…);

COSMIC RAYS THE DAWN OF CHEMISTRY



COSMIC-RAY IONISATION TRACERS

diffuse clouds

OH , HD , NH

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

H_3^+ , OH^+ , H_2O^+

Geballe+ (1999),
McCall+ (2003),
Indriolo+ (2009,2012,2015),
Neufeld+ (2010), Gerin+ (2010)

ArH^+

Neufeld & Wolfire (2017)

CO, OH, CH, HCO^+

Luo+ (2023a,b)

dense clouds

HCO^+ , DCO^+

Guélin+ (1977), Caselli+ (1998)
Maret & Bergin (2007), Cabedo+ (2023)
Pineda+ (2024)

$N_2H^+, HCO^+, N_2D^+, DCO^+$

Redaelli+ (2021)

sulfur chemistry

Fuente+ (2016)

PO^+

Rivilla+ (2022b)

oH_2D^+

Bovino+ (2020)
Sabatini+ (2023)
Redaelli+ (2024)

H_2

Bialy (2020)
Padovani+ (2022)
Bialy, Belli, Padovani (2022)
Bialy+ (2025)

circumstellar discs

HCO^+ , N_2H^+

oH_2D^+

Ceccarelli+(2004)
Cleeves+ (2014)

protostellar jets (shocks)

HCO^+ , N_2H^+

Podio+ (2014),
Ceccarelli+ (2014)
Rab+ (2017)

HC_3N , HC_5N

Fontani+ (2017)

$c-C_3H_2$

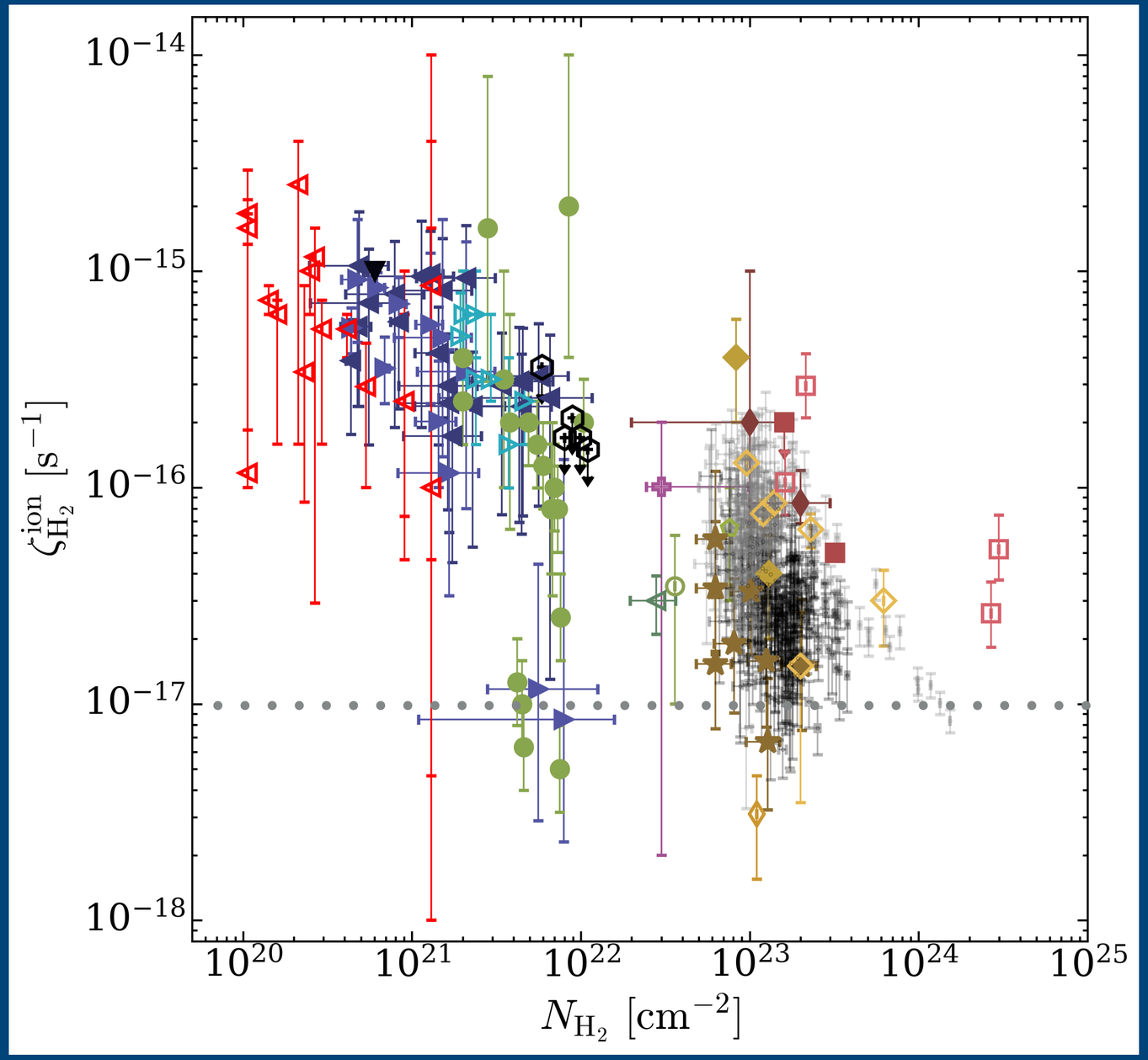
Favre+ (2018)

ESTIMATES OF ζ FROM OBSERVATIONS

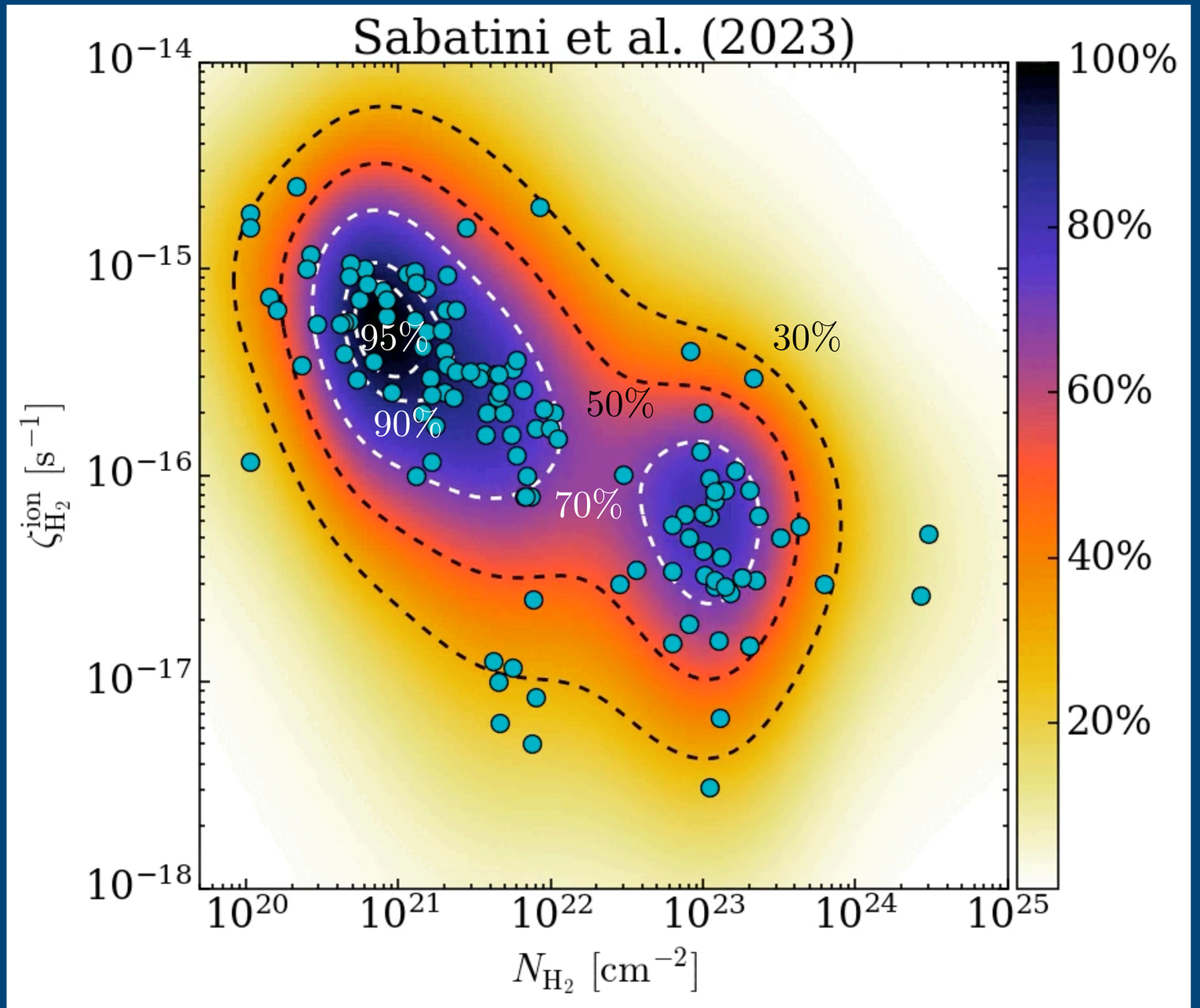
Sabatini+ 2023

HM SFRs

oH_2D^+



KERNEL DENSITY ESTIMATE OF THE AVAILABLE ζ VALUES



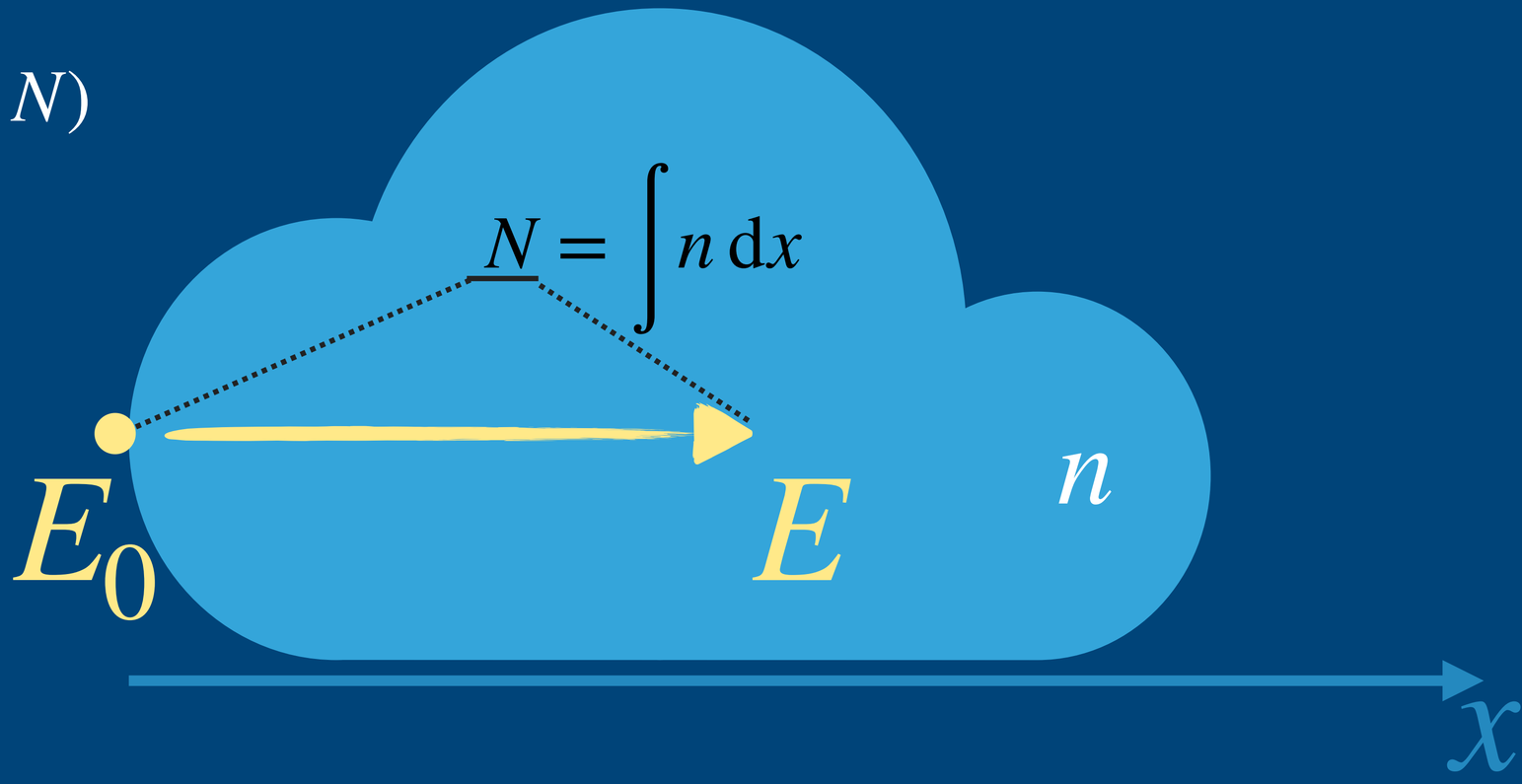
COSMIC-RAY PROPAGATION INSIDE A MOLECULAR CLOUD

$$j(E_0, N = 0) = j^{\mathrm{IS}}(E_0) \longrightarrow j(E, N)$$

Continuous Slowing-Down Approximation

1. straight-line propagation;
2. ΔE≪E.

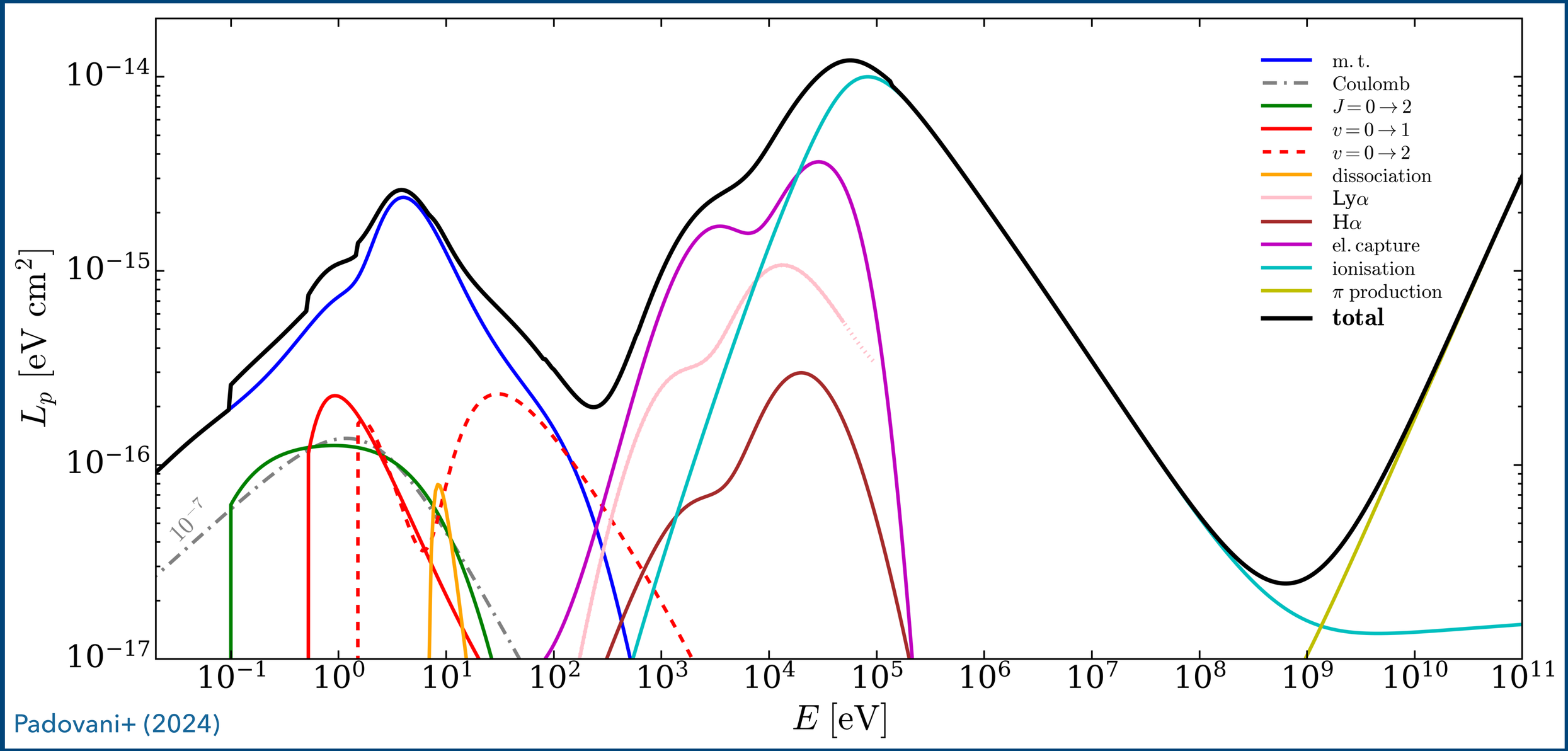
$$L(E) = -\frac{1}{n}\frac{\mathrm{d}E}{\mathrm{d}x} = -\frac{\mathrm{d}E}{\mathrm{d}N}$$



$$N = \int_E^{E_0} \frac{\mathrm{d}E}{L(E)} \qquad \frac{\mathrm{d}E}{L(E)} = \frac{\mathrm{d}E_0}{L(E_0)} \qquad j(E, N)\,\mathrm{d}E = j^{\mathrm{IS}}(E_0)\,\mathrm{d}E_0$$

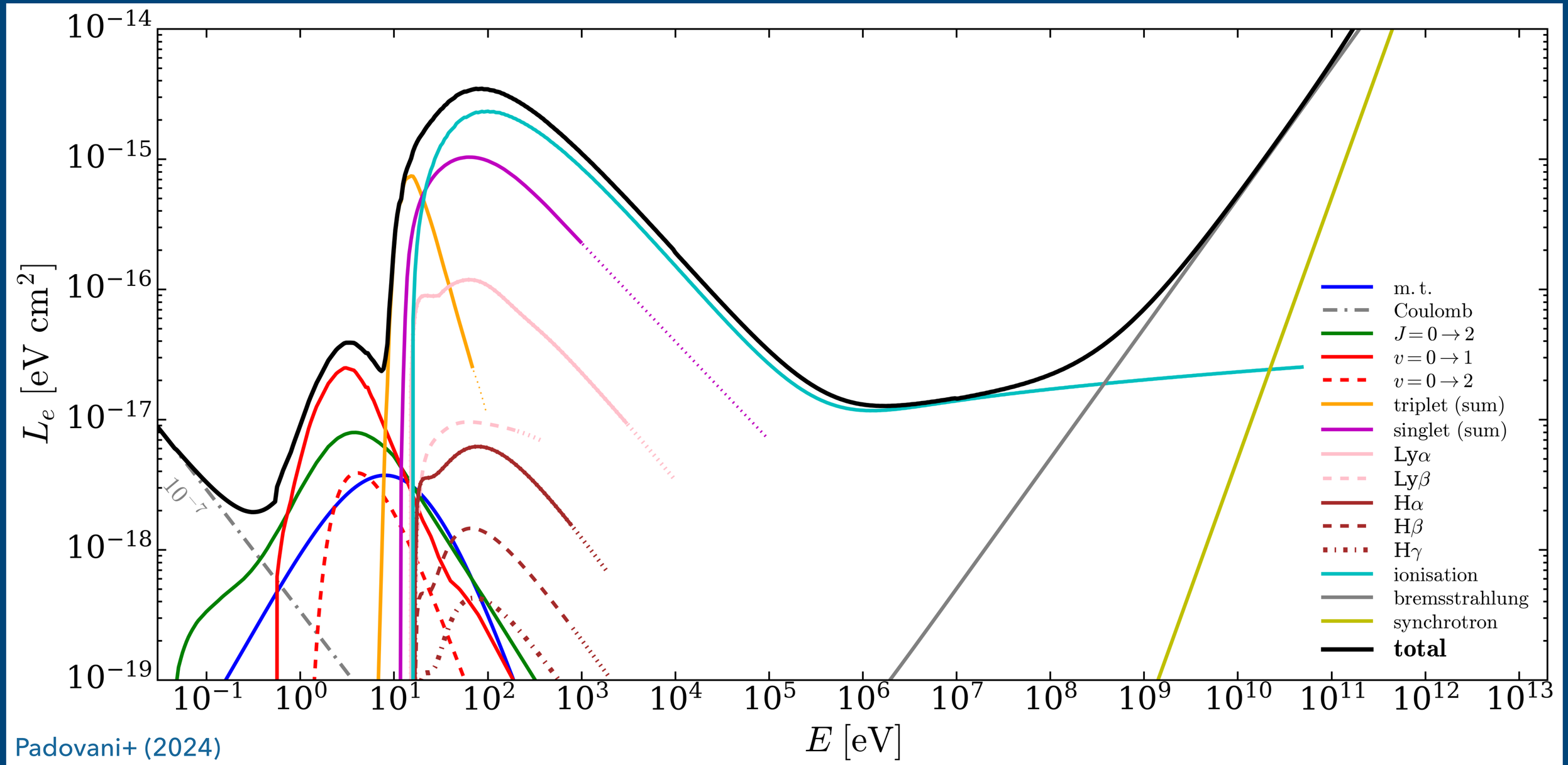
$$j(E, N) = j^{\mathrm{IS}}(E_0)\frac{\mathrm{d}E}{\mathrm{d}E_0} = j^{\mathrm{IS}}(E_0)\frac{L(E_0)}{L(E)} \longrightarrow \zeta(N) \propto \int j(E, N)\sigma(E)\,\mathrm{d}E$$

ENERGY LOSS FUNCTION PROTON + H_2



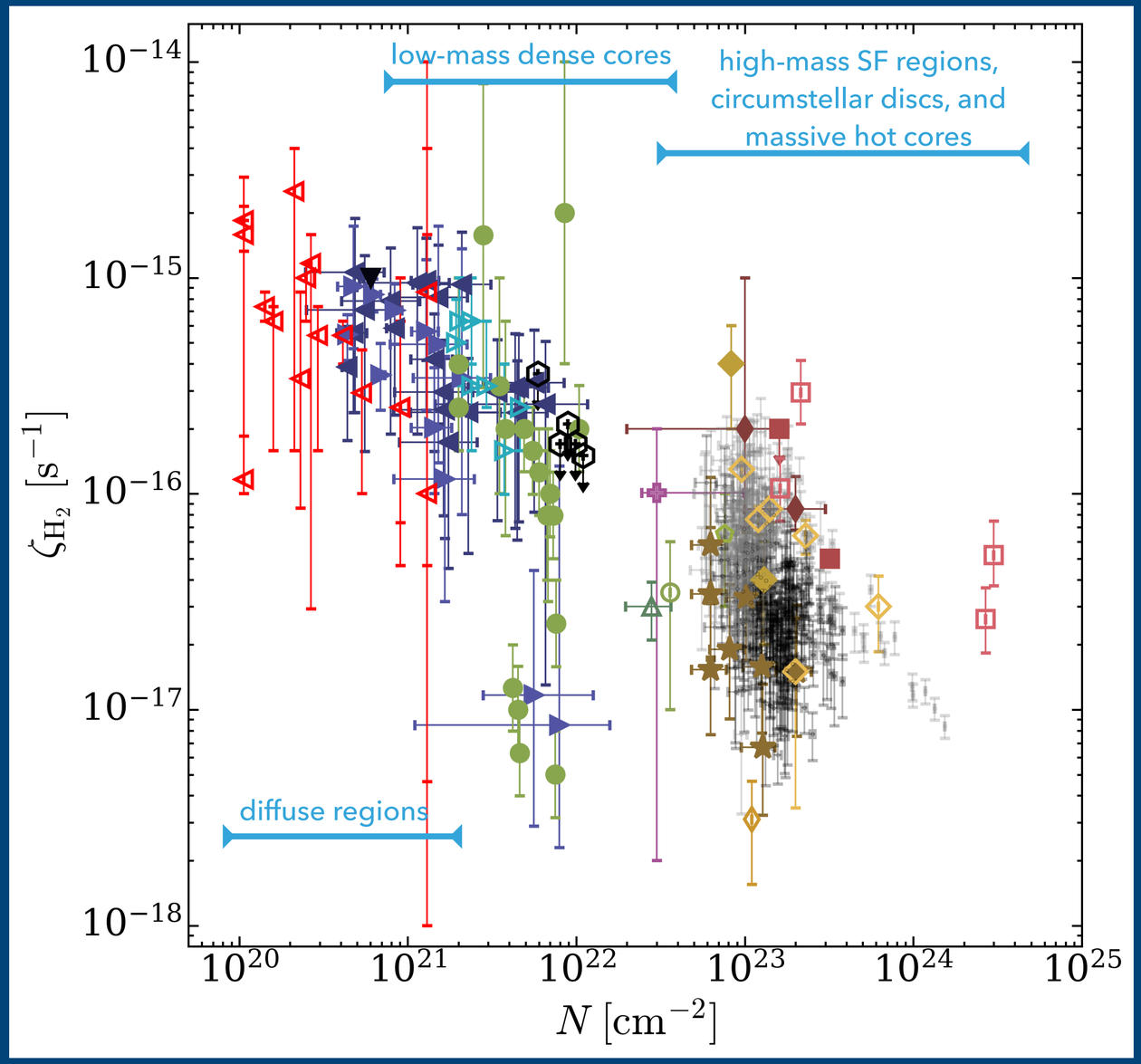
Padovani+ (2024)

ENERGY LOSS FUNCTION ELECTRON + H_2

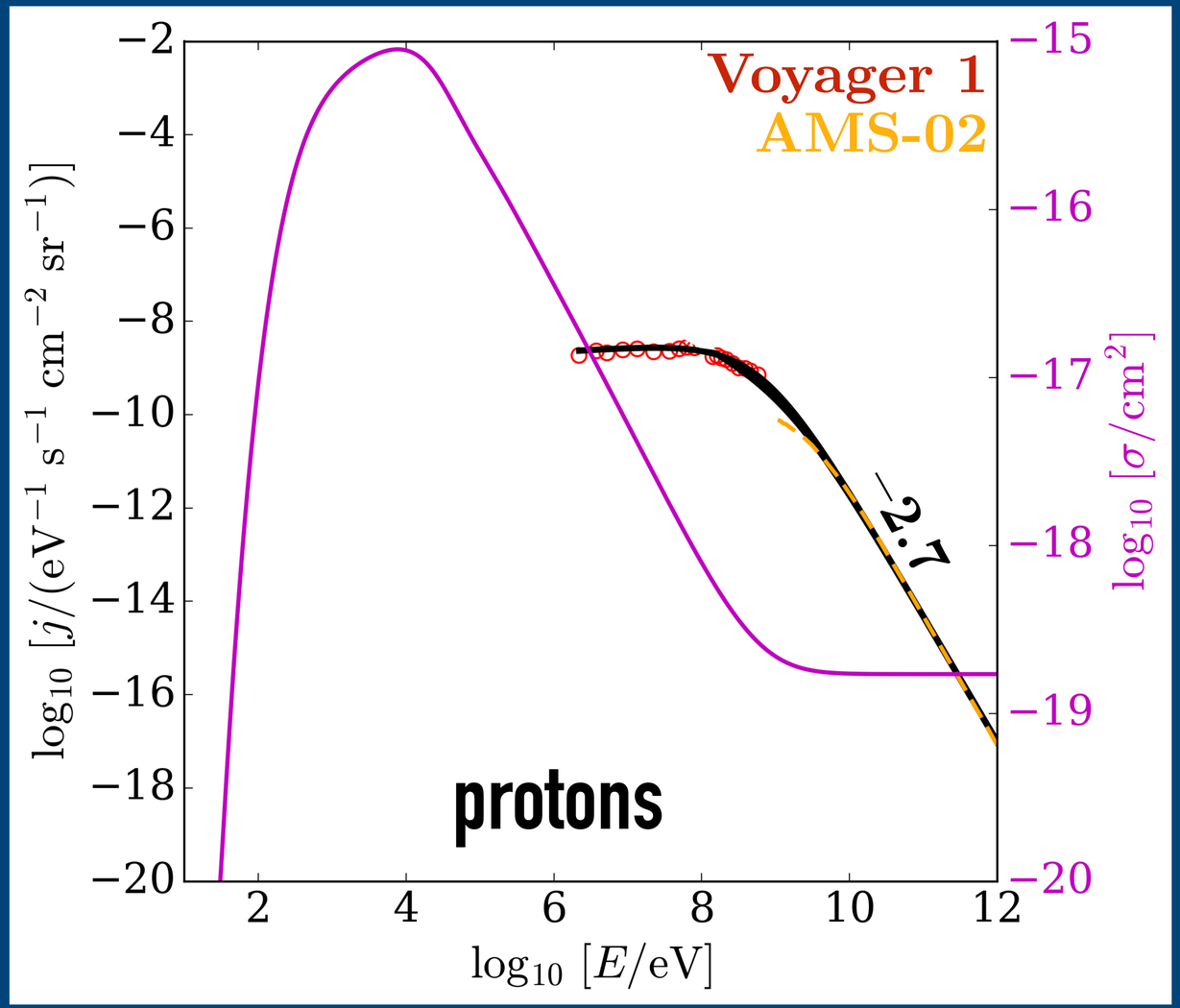


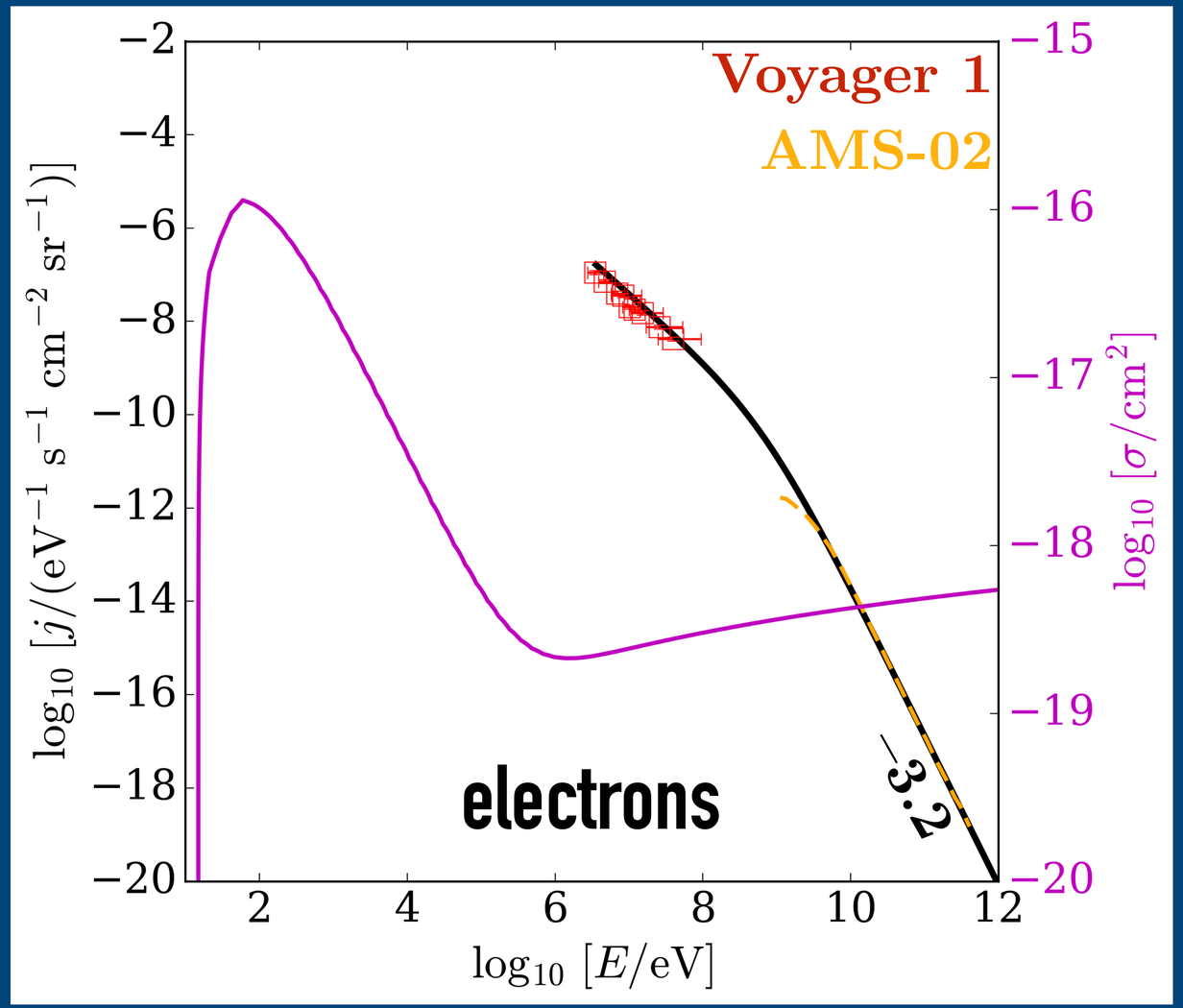
Padovani+ (2024)

ESTIMATES OF ζ COMPARING MODELS AND OBSERVATIONS

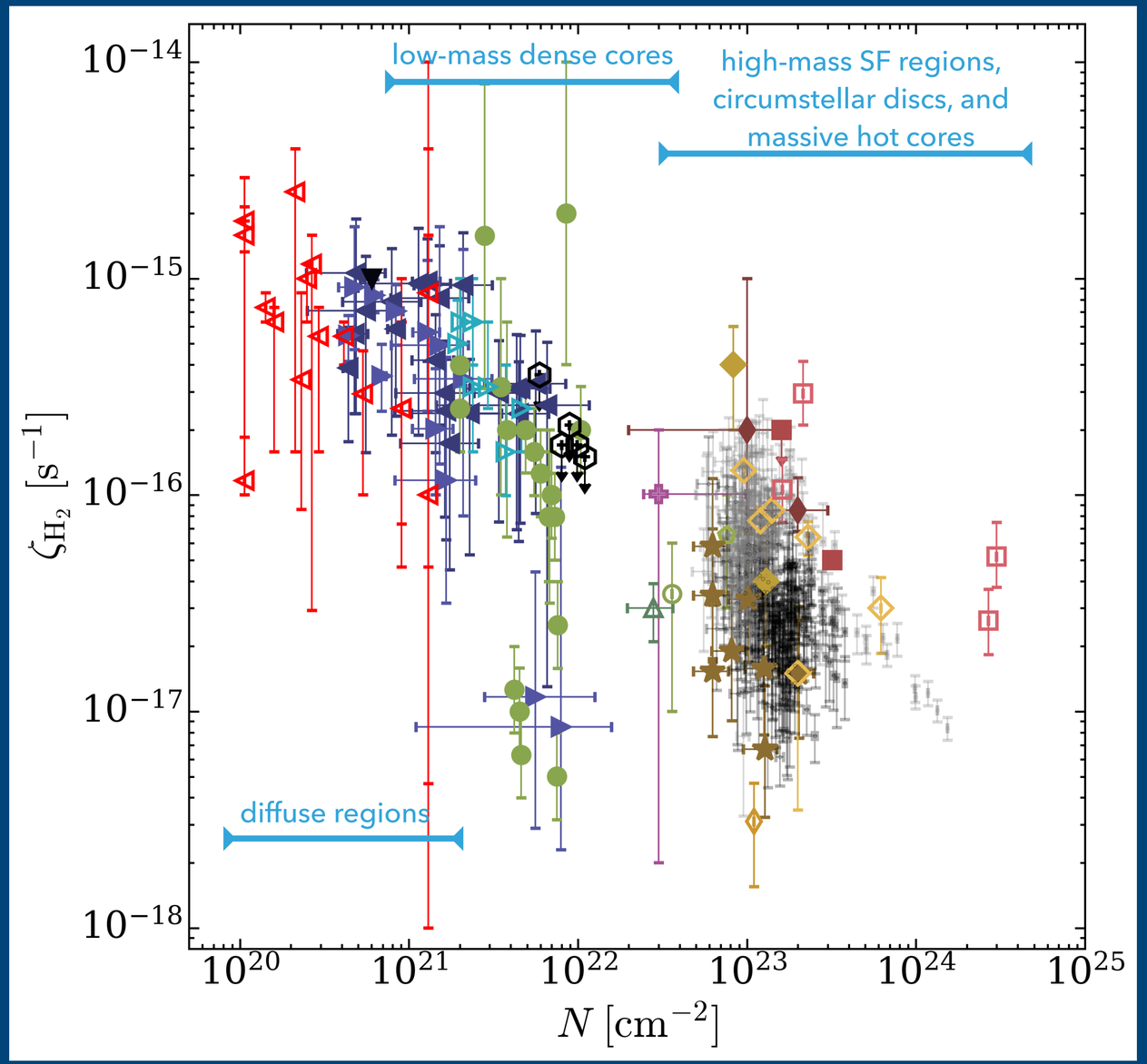


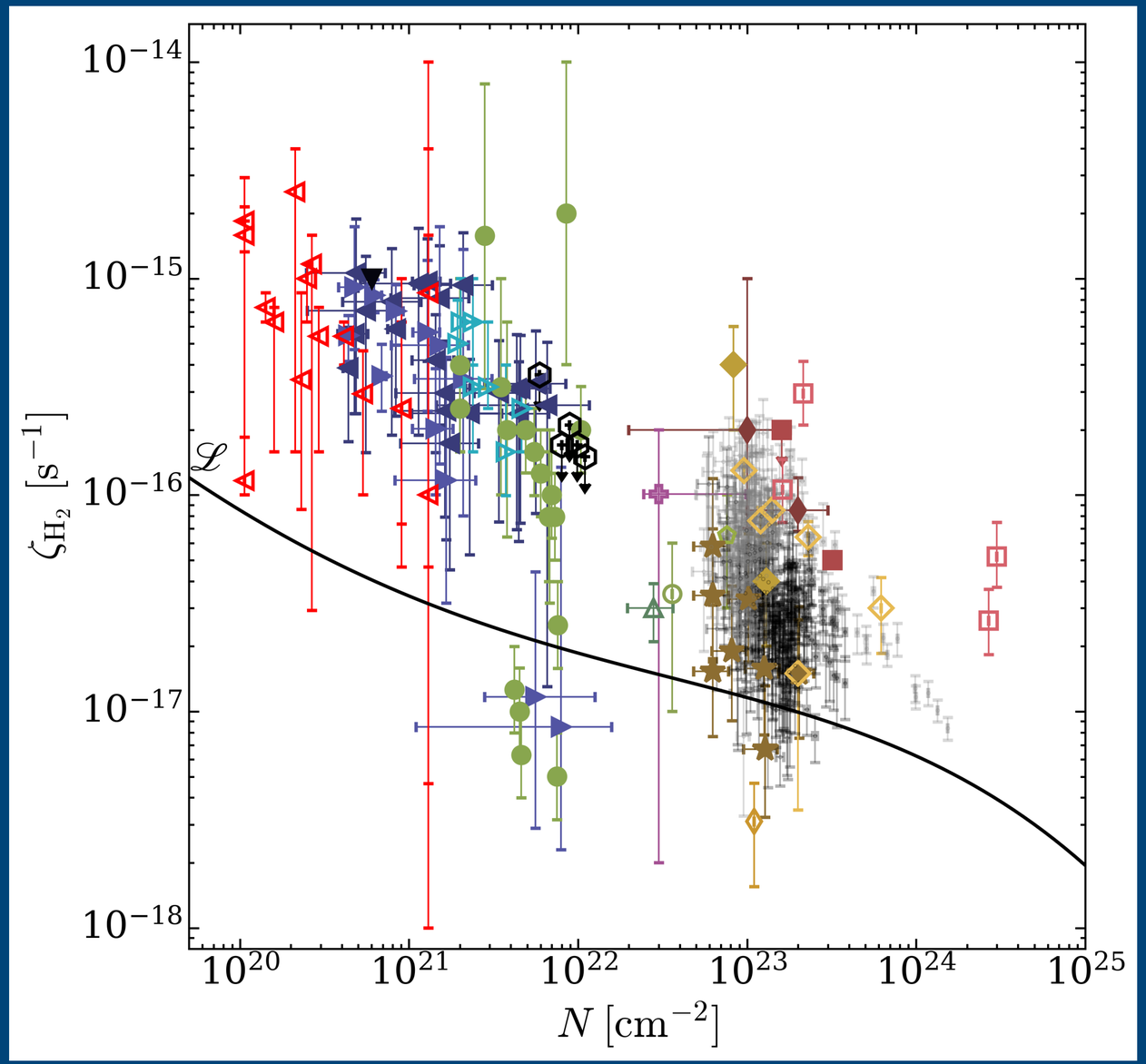
COSMIC-RAY FLUX BASED ON VOYAGER DATA



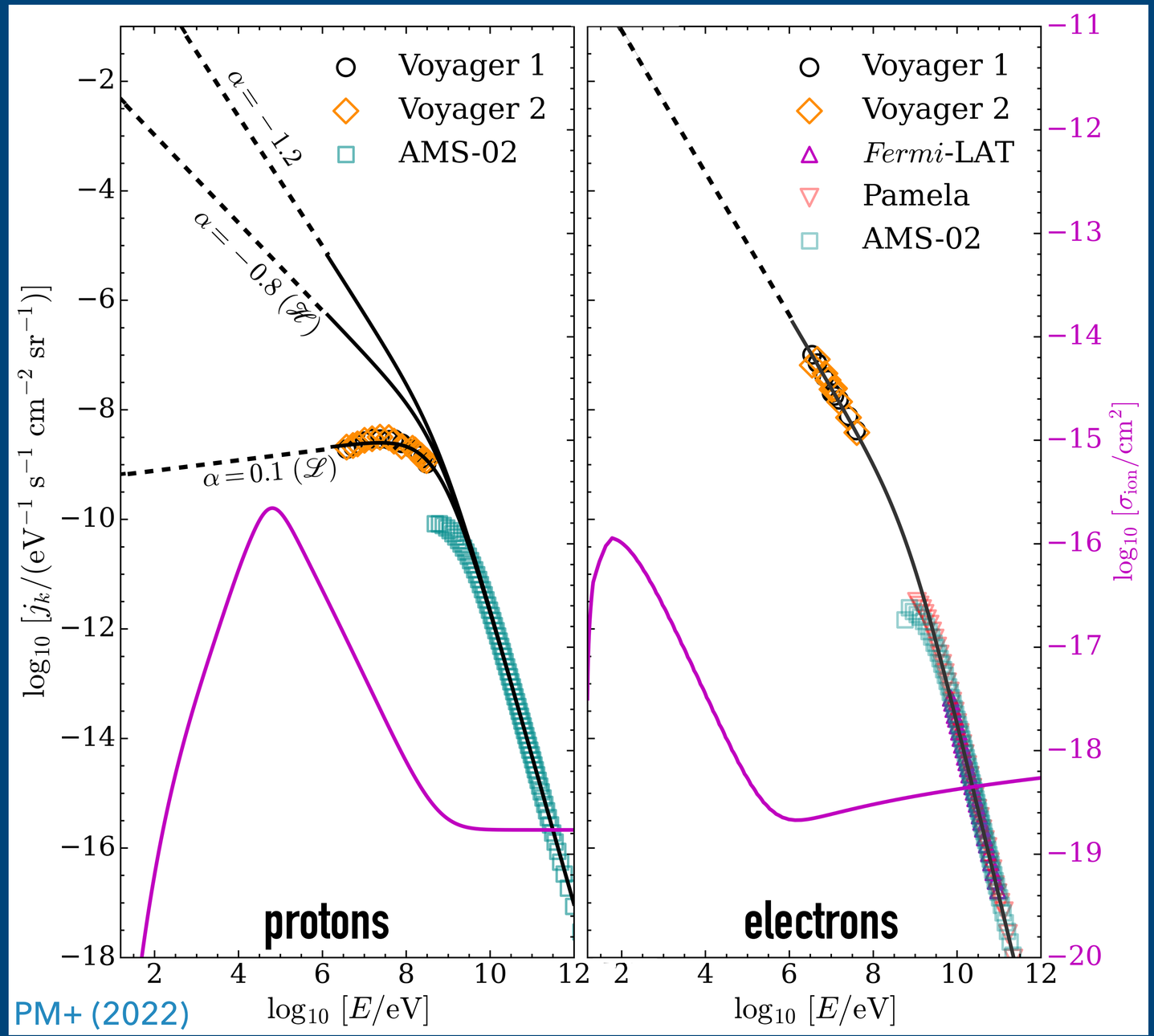


ESTIMATES OF ζ COMPARING MODELS AND OBSERVATIONS





PARAMETERISATION OF THE COSMIC-RAY SPECTRUM



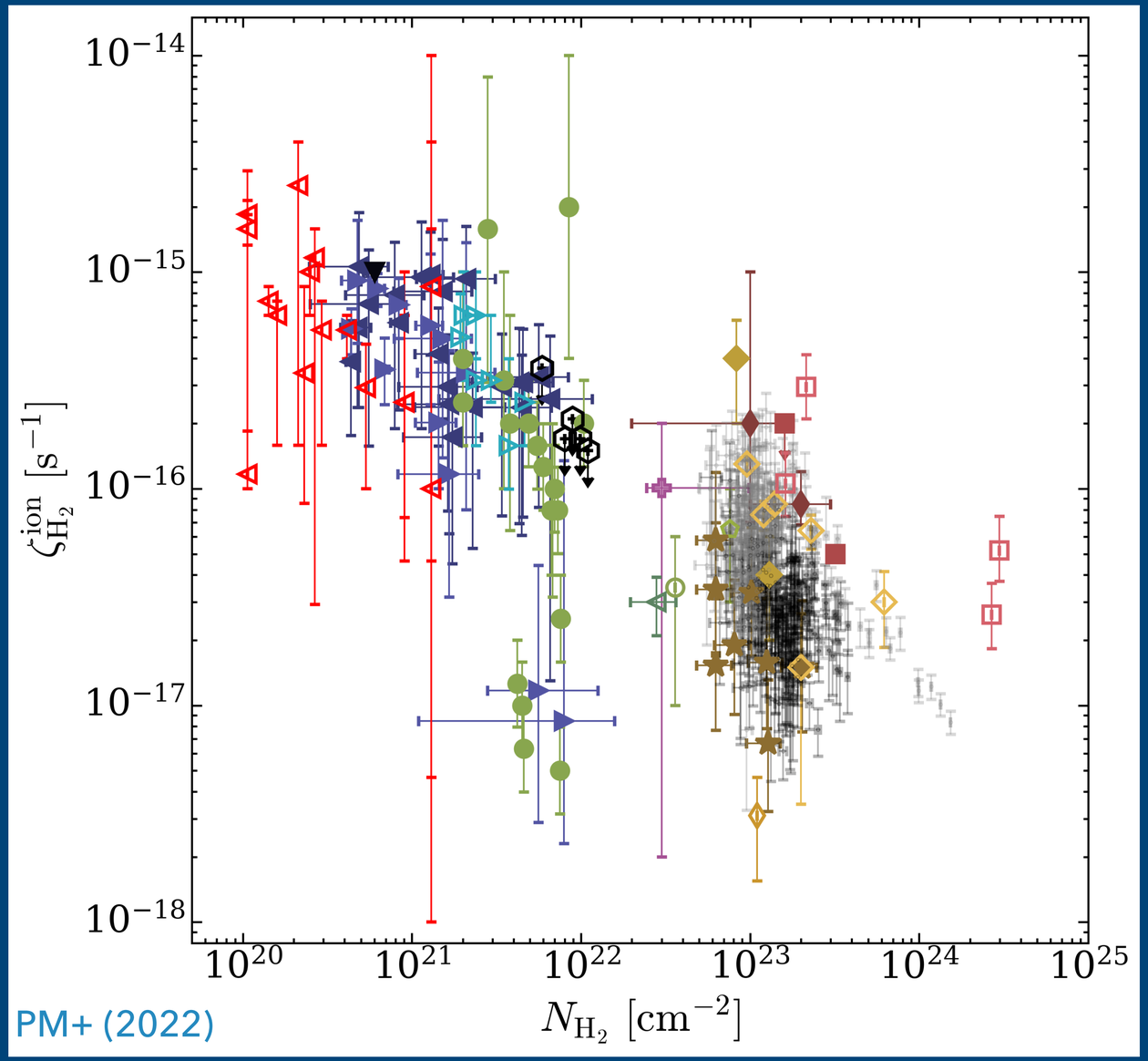
PM+ (2022)

$$j_k^{\mathrm{IS}}(E) = C\frac{E^\alpha}{(E+E_0)^\beta}\ \mathrm{eV}^{-1}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}$$

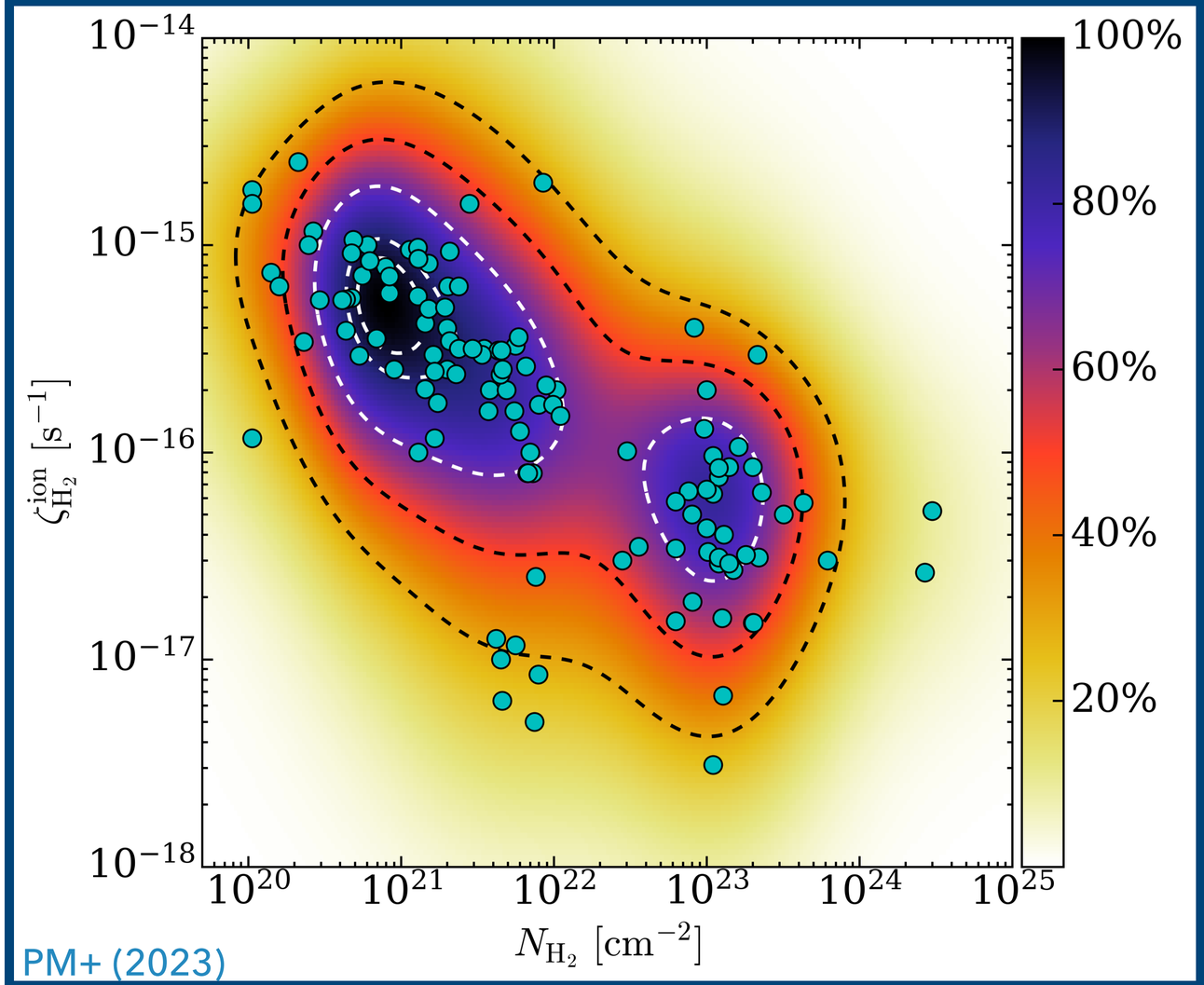
Species k	C	E_0 [MeV]	α	$\beta-\alpha$
e	2.1×10^{18}	710	−1.3	3.2
p (model $\mathscr{L}$)	2.4×10^{15}	650	0.1	2.7
p (model $\mathscr{H}$)	2.4×10^{15}	650	−0.8	2.7

Most of the parameter space is dominated by the ionisation of CR protons and by the excitation of secondary electrons. For this reason we consider a single parameterisation for primary CR electrons.

ESTIMATES OF ζ COMPARING MODELS AND OBSERVATIONS

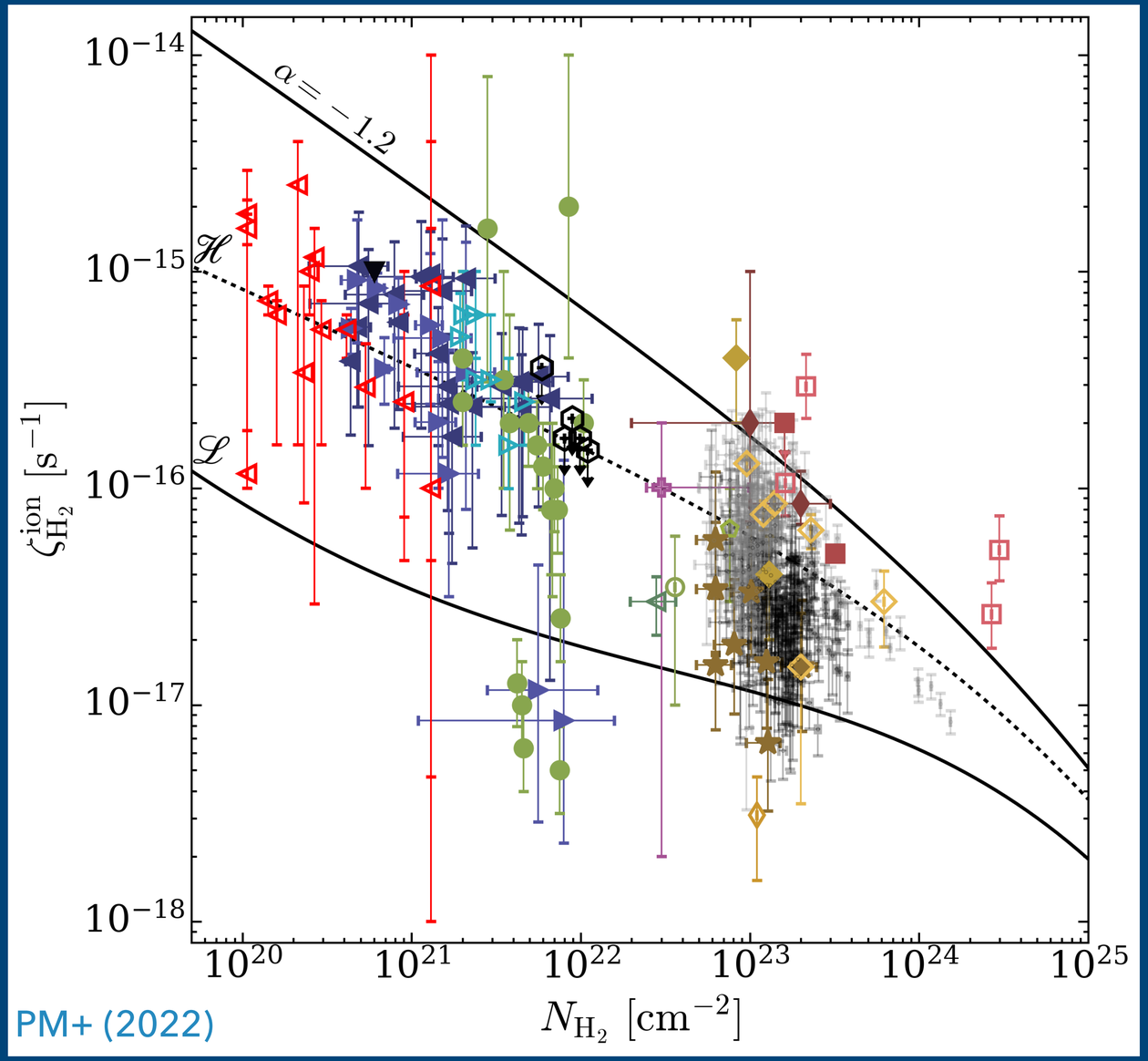


PM+ (2022)

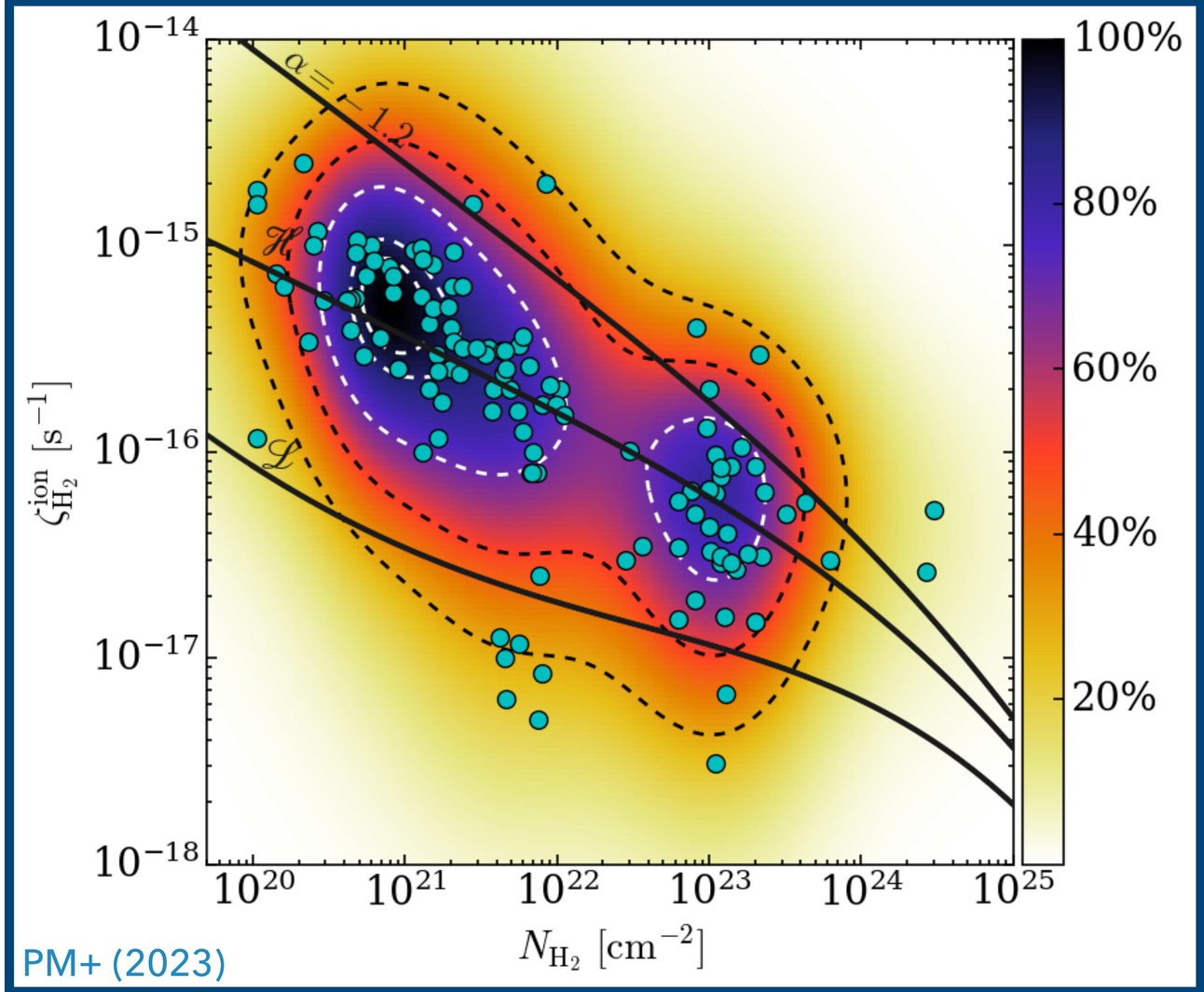


PM+ (2023)

ESTIMATES OF ζ COMPARING MODELS AND OBSERVATIONS



PM+ (2022)



PM+ (2023)

LIMITATIONS OF CURRENT METHODS TO ESTIMATE ζ

diffuse clouds

- absorption line studies of H_3^+, OH^+, H_2O^+ and ArH^+

downsides

- need to have an early-type star in the background;
- ζ obtained from this method is proportional to $n(H_2)$;
- uncertainties in the local x_e that in turn depends on details of the IS UV attenuation in the cloud;

dense clouds

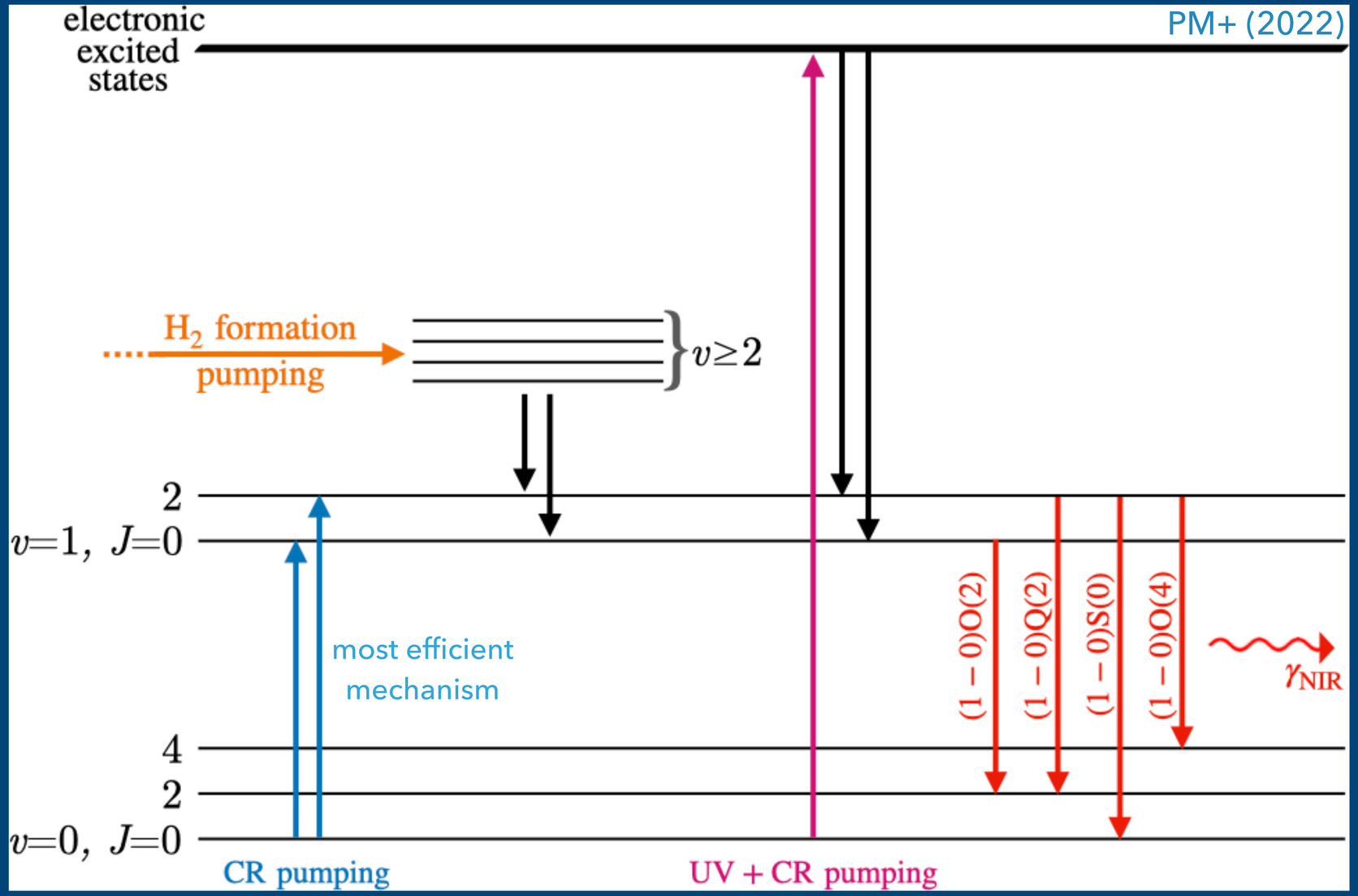
- $HCO^+, DCO^+, CO, oH_2D^+$ and more and more complex species

downsides

- require comprehensive and updated reaction networks;
- main source of uncertainty comes from the formation and destruction rates of some species;
- poorly constrained amount of carbon and oxygen depletion on dust grains;

A NEW METHOD TO ESTIMATE ζ IN MOLECULAR DENSE CLOUDS

First introduced by Bialy (2020), refined in PM+ (2022), and applied in Bialy+ (2022)

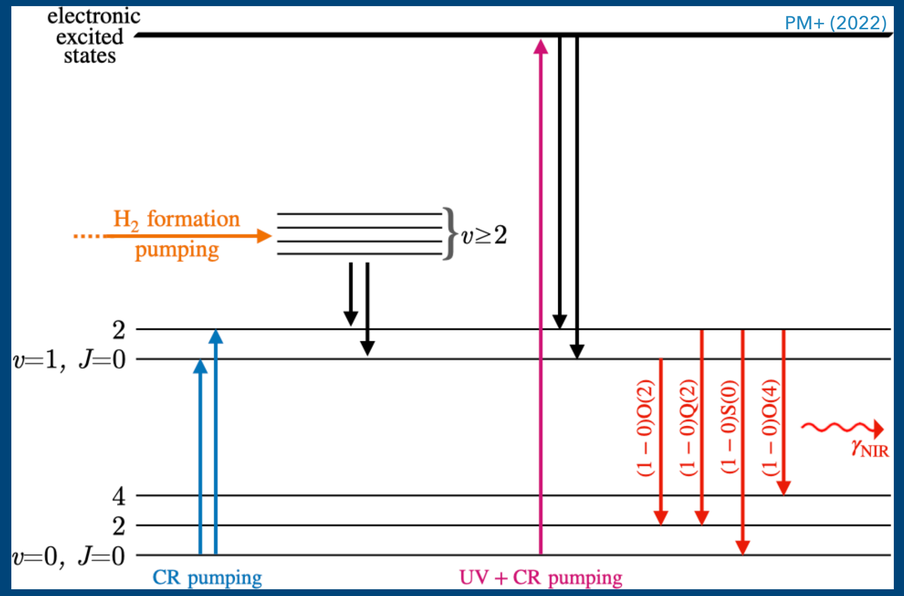


$$e + H_2 \rightarrow H_2^{*} + e'$$

lower degree of uncertainty

neither chemical networks nor abundances of other secondary species are involved

A NEW METHOD TO ESTIMATE ζ IN MOLECULAR DENSE CLOUDS



most efficient mechanism

$$I_{ul}^{\rm dir}(N) = \alpha_{ul}\frac{E_{ul}}{4\pi}\int_0^N \zeta_{{\rm exc},u}(N')e^{-\tau_d(N')}x_{\rm H_2}(N')\ {\rm d}N'$$

$\alpha_{ul} = A_{ul}/\Sigma_l A_{ul}$: probability to decay to state l given state u is excited

E_{ul} : transition energy

$\tau_d = \sigma_d N$: optical depth for dust extinction

$\sigma_d \approx 4.5\times10^{-23}$ cm^2 per H nucleus (averaged over 2-3 μm)

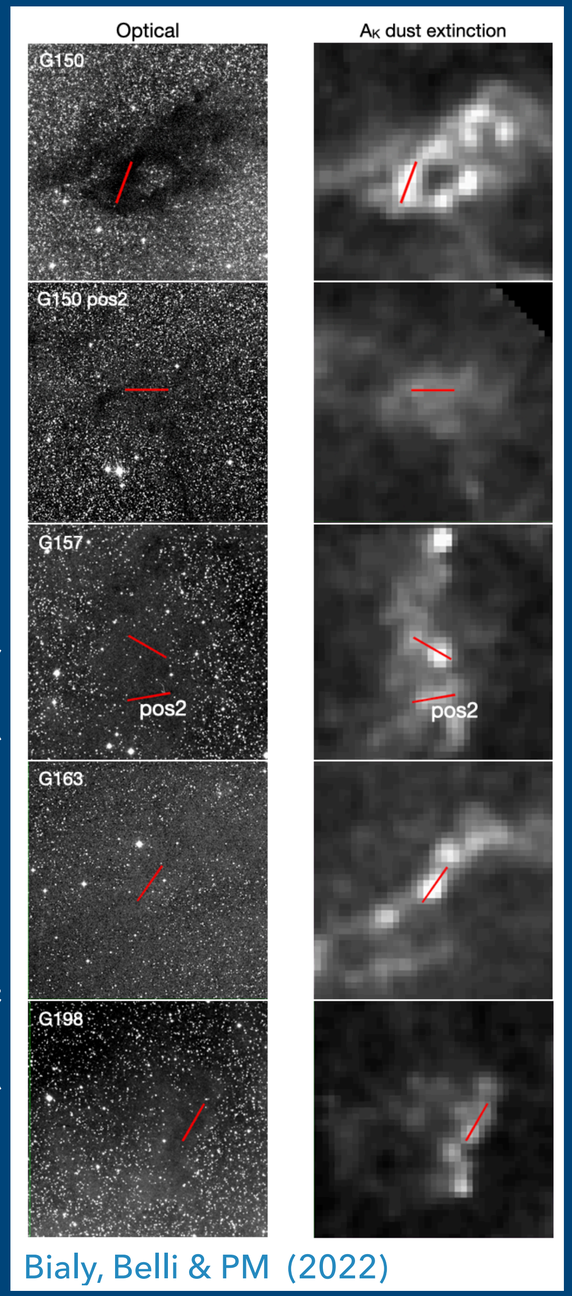
$x_{\rm H_2} = n_{\rm H_2}/(n_{\rm H} + 2n_{\rm H_2})$: molecular hydrogen fraction

Transition	Upper level (v, J)	Lower level (v', J')	λ [μm]
(1−0)O(2)	(1,0)	(0,2)	2.63
(1−0)Q(2)	(1,2)	(0,2)	2.41
(1−0)S(0)	(1,2)	(0,0)	2.22
(1−0)O(4)	(1,2)	(0,4)	3.00

$$\zeta_{{\rm exc},u}(N_{\rm H_2}) = 2\pi\ell\int j_k(E, N_{\rm H_2})\sigma_{{\rm exc},u}(E)\ {\rm d}E$$

$\ell = 1$ for primary CRs and $\ell = 2$ for secondary electrons

A NEW METHOD TO ESTIMATE ζ IN MOLECULAR DENSE CLOUDS



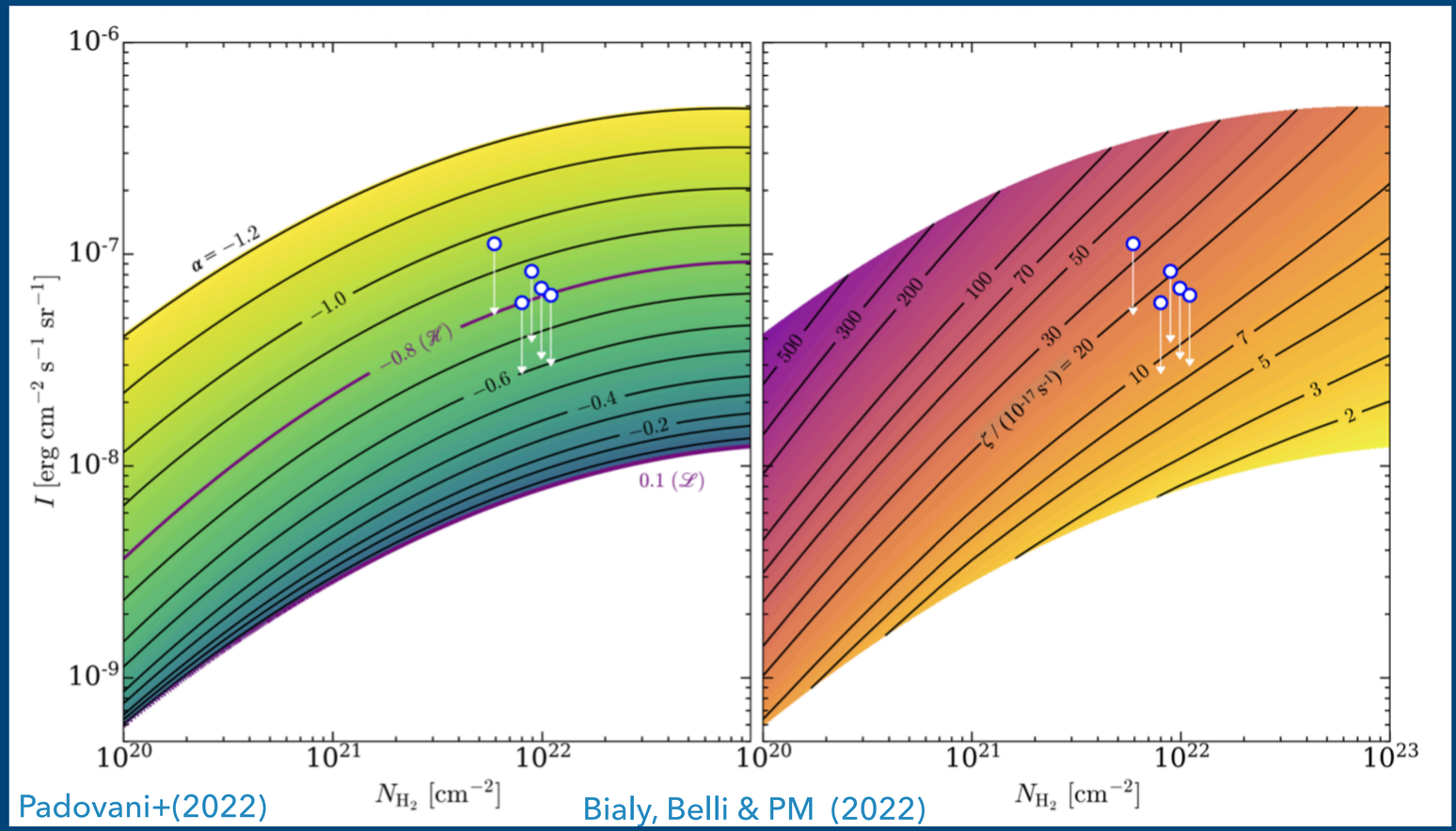
Baines et al. (2017); Skrutskie et al. (2006)

Bialy, Belli & PM (2022)

(1-0)S(0) line at 2.22 μm

Magellan Infrared Spectrograph (MMIRS), mounted on the Multiple Mirror Telescope (MMT)

Each field of view is 40' x 40' – the 7' slit is shown in red



Padovani+(2022)

Bialy, Belli & PM (2022)

THE JWST REVOLUTION

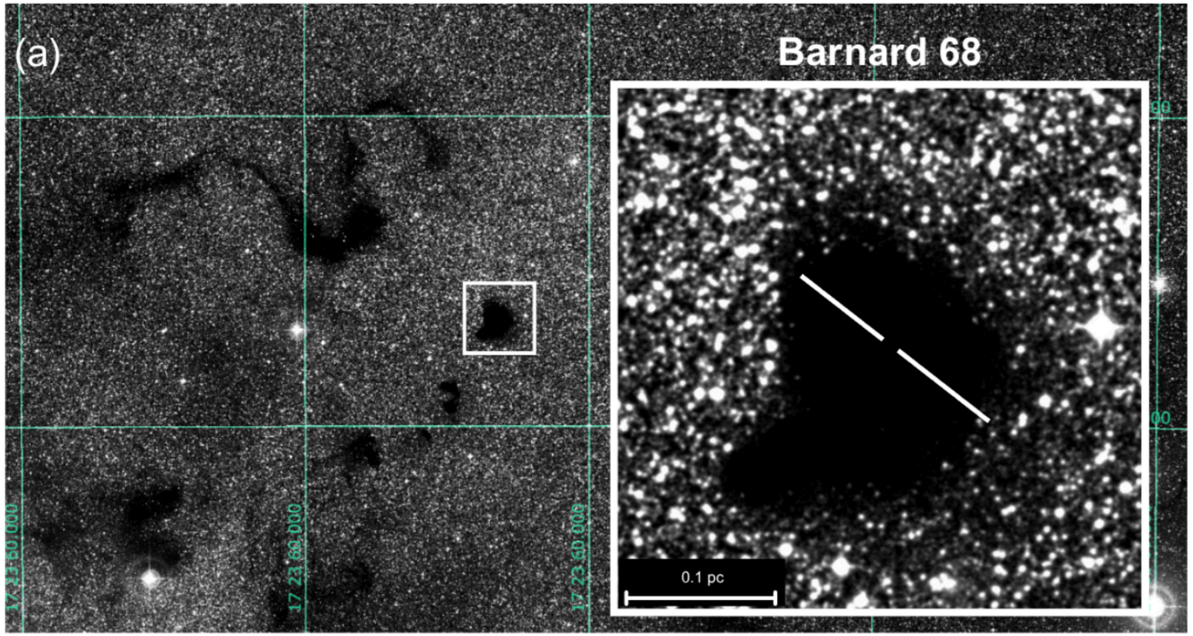
	MMIRS @MMT	X-shooter @VLT	NIRSpec @JWST
transitions	(1-0)S(0)	(1-0)S(0) – (1-0)Q(2)	(1-0)O(2) – (1-0)Q(2) (1-0)S(0) – (1-0)O(4)
slit size	7'	11"x0.4"	3.4' x 0.27"
obs. time (3σ)	3 h (upper limits)	8 h	1.25 h

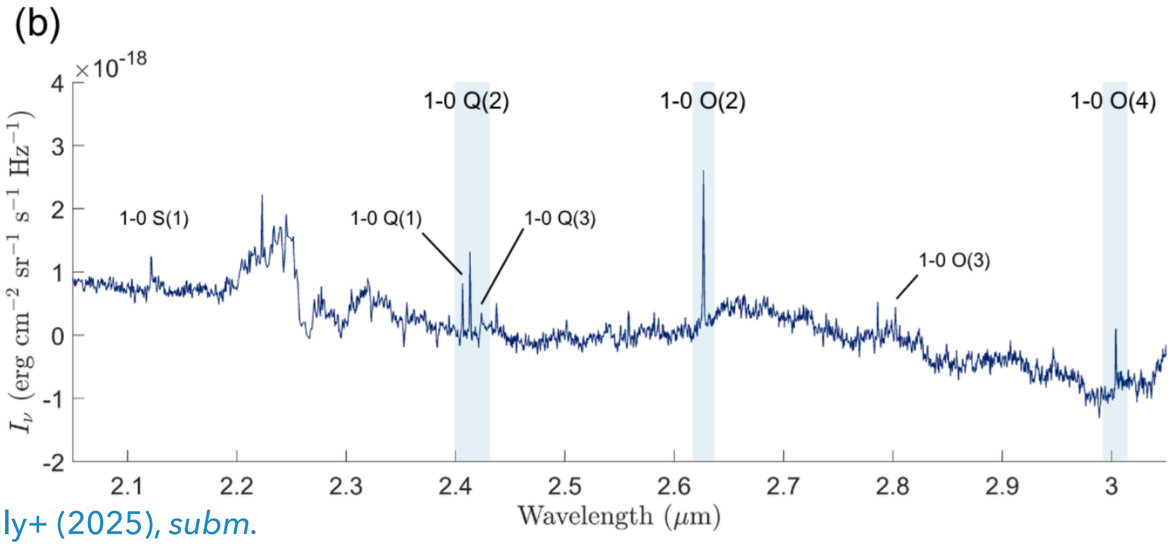
adding up the signal of e.g. 50 shutters (each shutter has a size of ~ 0.53"x0.27")
it is possible to obtain *a few independent estimates* of I_ν and then of ζ.

E.g.: for Barnard 68 (distance of 125 pc) it is possible to obtain about 10 independent estimates of ζ.

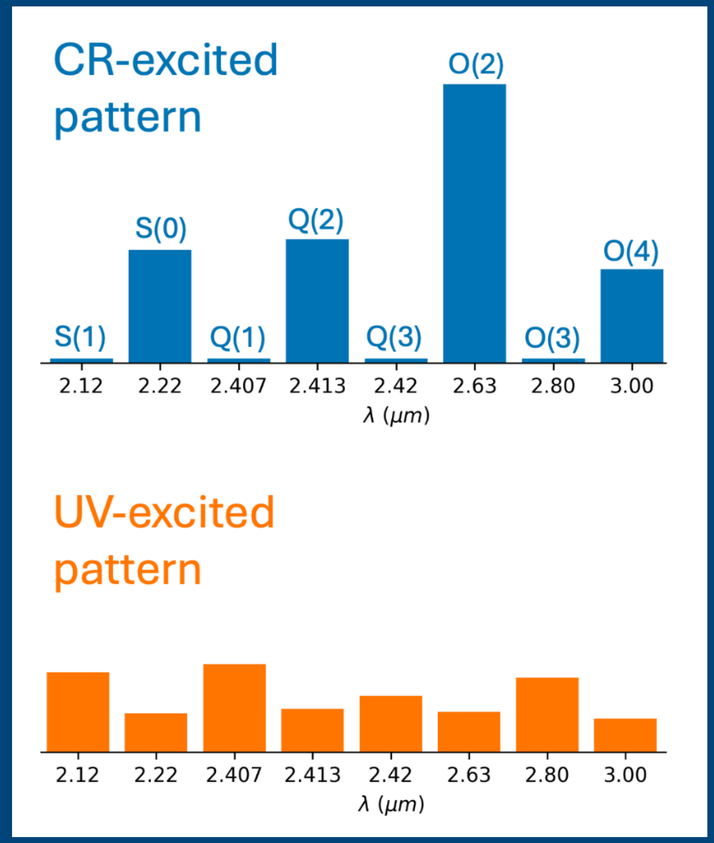
Testing the presence of a gradient of ζ as predicted by models of attenuation of the interstellar CR spectrum

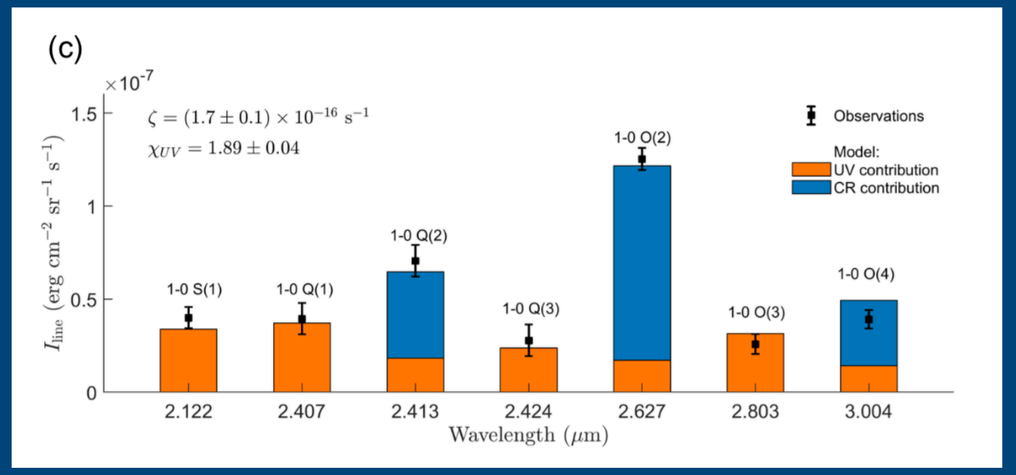
THE JWST REVOLUTION



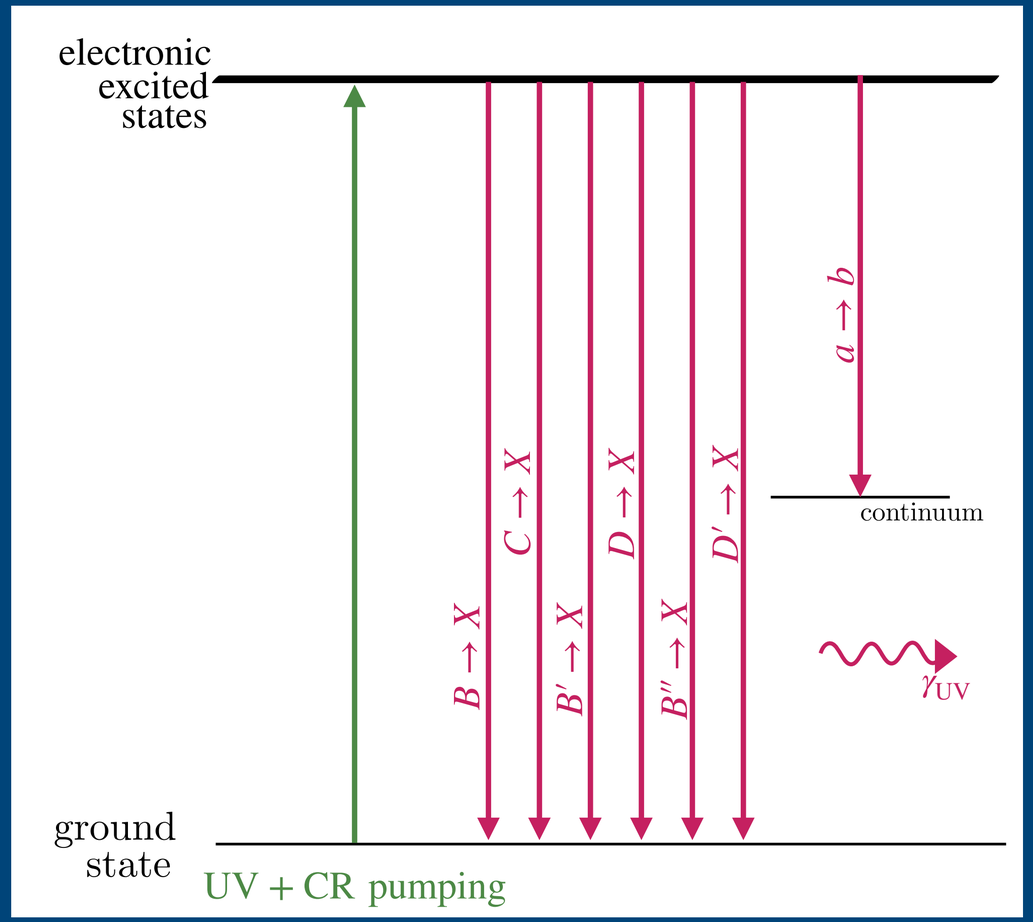


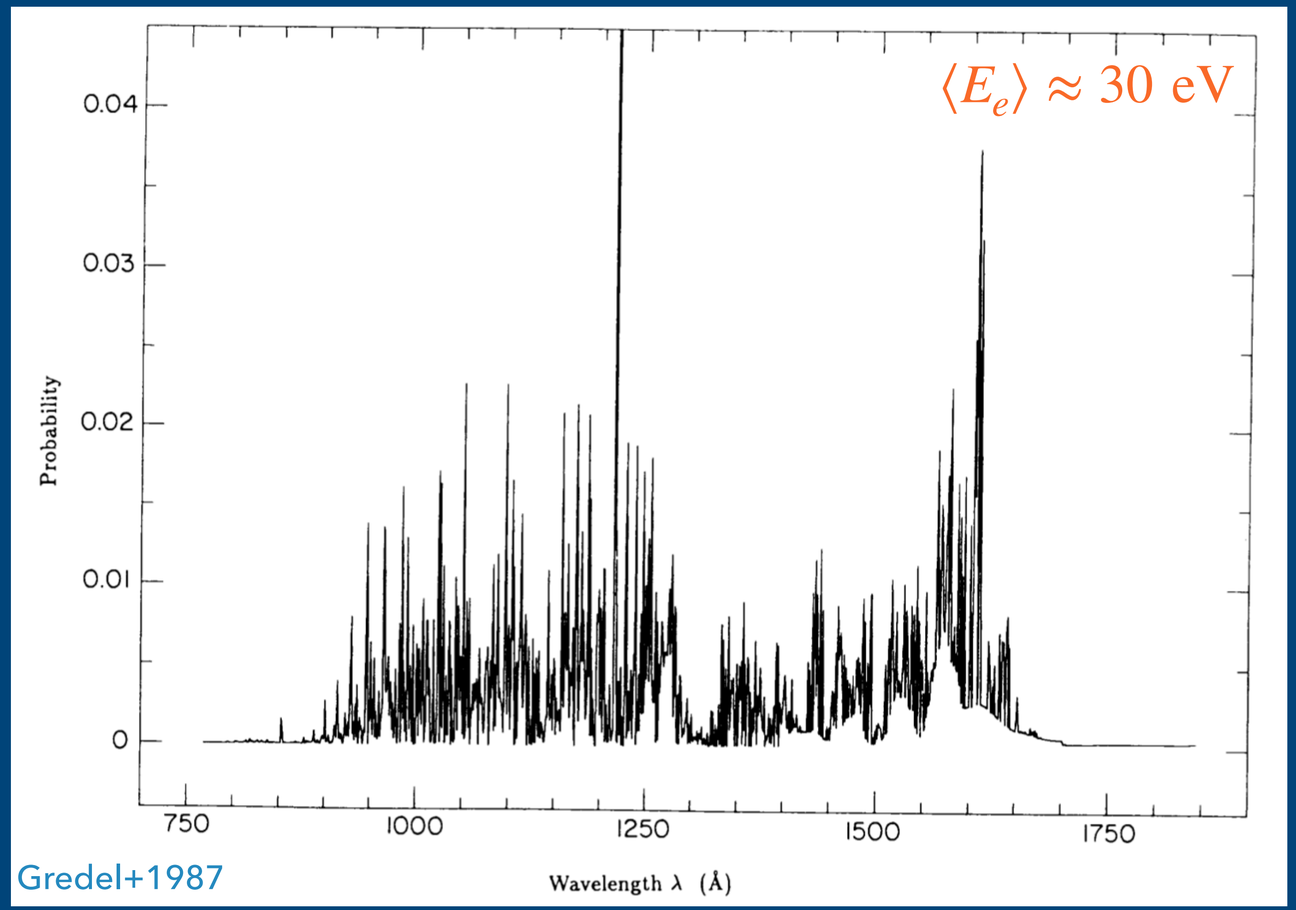
Bialy+ (2025), *subm.*





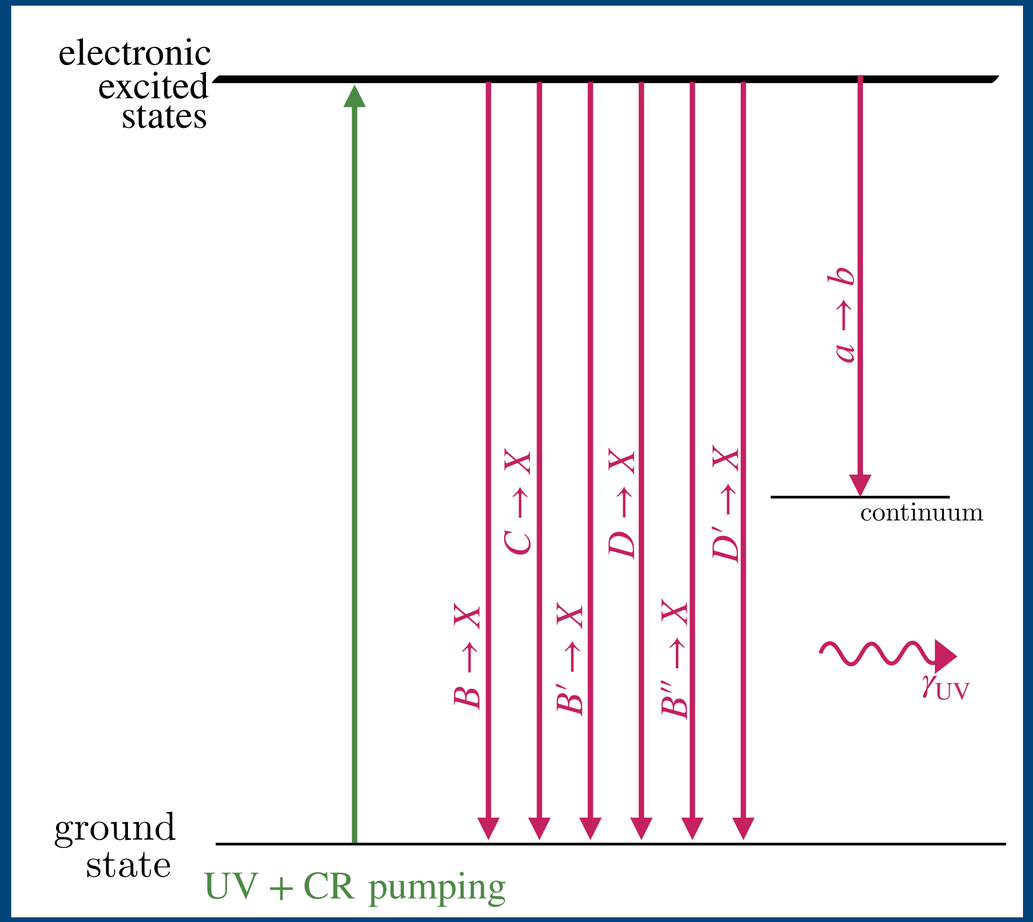
UV H_2 LUMINESCENCE IN MOLECULAR CLOUDS INDUCED BY COSMIC RAYS

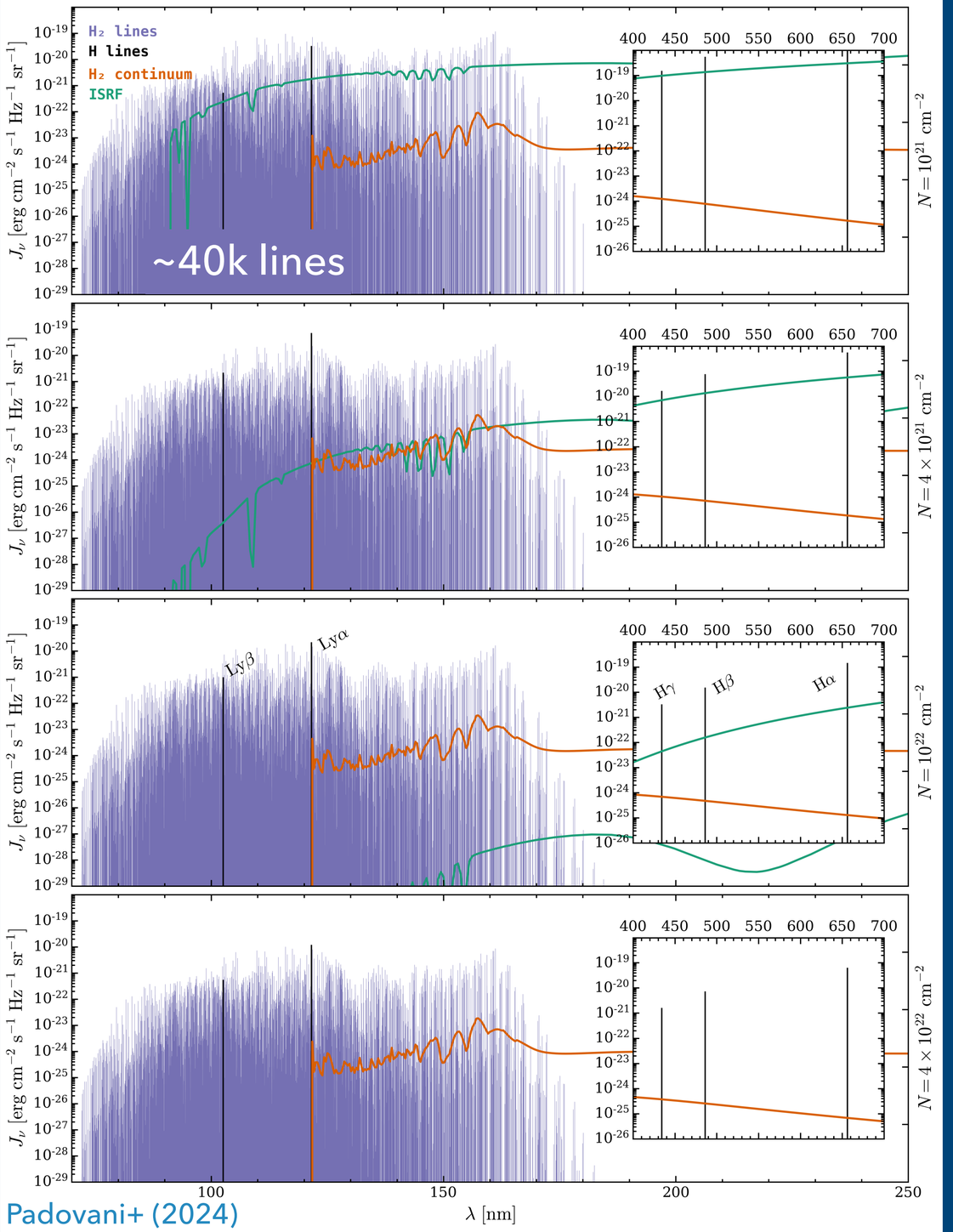




Gredel+1987

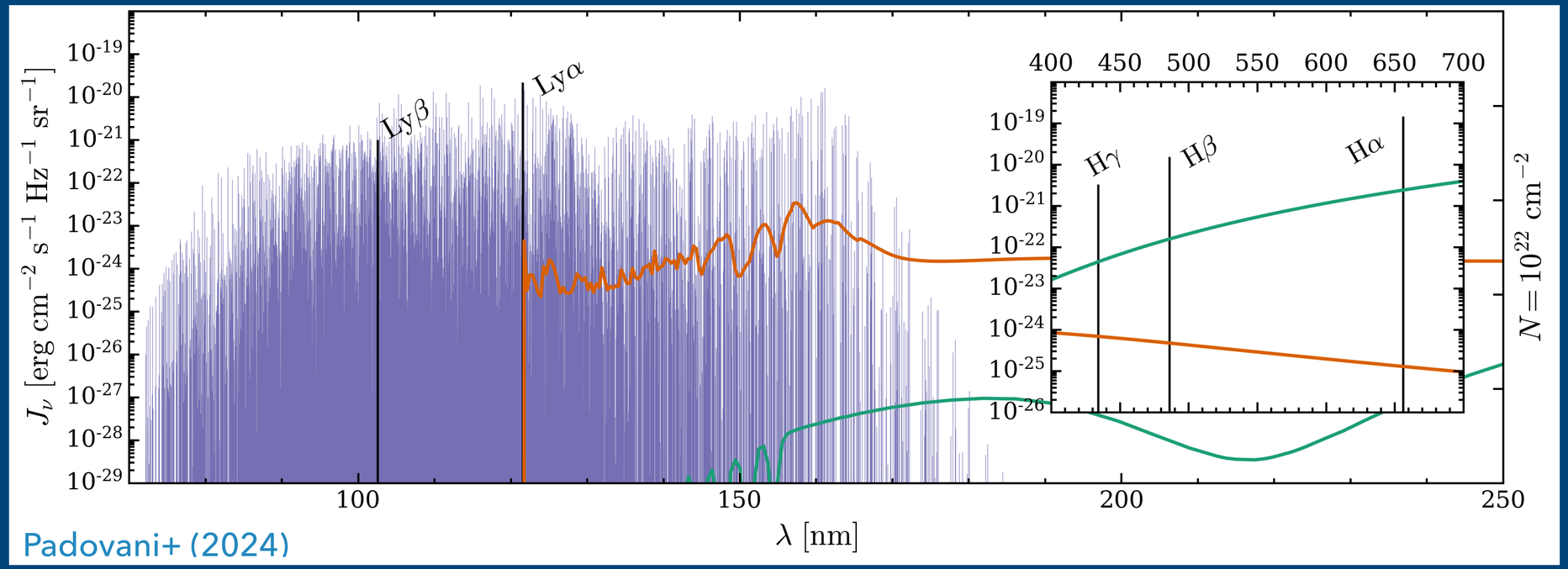
UV H_2 LUMINESCENCE IN MOLECULAR CLOUDS INDUCED BY COSMIC RAYS





Padovani+ (2024)

UV H_2 LUMINESCENCE IN MOLECULAR CLOUDS INDUCED BY COSMIC RAYS



Padovani+ (2024)

Photorates (dissociation and ionisation)

$$k_s^{\rm ph}(N) = 4\pi \int \frac{J_\nu(N)\sigma_s^{\rm ph}(\nu)}{h\nu} {\rm d}\nu$$

$\sigma_s^{\rm ph}$ from the Leiden Observatory Database

$$k_s^{\rm ph}(N) = k_{0,s}^{\rm ph} \zeta_{\rm H_2}(N)$$

parameterisation as a function of:

- interstellar CR spectrum;
- H_2 ortho-to-para ratio;
- dust composition (R_V: slope of extinction at visible wavelenths);
- ISRF

UV H_2 LUMINESCENCE IN MOLECULAR CLOUDS INDUCED BY COSMIC RAYS

$R_V = 3.1$

Species s	$k^{pd}_{0,s}$ o:p=0:1	$k^{pd}_{0,s}$ o:p=1:0	Species s	$k^{pd}_{0,s}$ o:p=0:1	$k^{pd}_{0,s}$ o:p=1:0	Species s	$k^{pd}_{0,s}$ o:p=0:1	$k^{pd}_{0,s}$ o:p=1:0
Al	–	–	Ca^+	–	–	NH_2CHO	1.292(3)	1.294(3)
AlH	1.641(1)	1.644(1)	Cl	–	–	NH_3	6.266(2)	6.093(2)
C	–	–	Cr	–	–	NO	1.715(2)	1.673(2)
C_2	1.368(2)	1.368(2)	Fe	–	–	NO_2	6.022(2)	6.046(2)
C_2H	8.184(2)	9.006(2)	H	–	–	Na	–	–
C_2H^-	–	–	H^-	–	–	NaCl	5.030(1)	5.036(1)
C_2H_2	1.086(3)	8.684(2)	H_2	4.048(2)	3.912(2)	NaH	2.323(2)	2.368(2)
C_2H_3	1.567(2)	1.566(2)	H_2^+	3.238(2)	3.290(2)	Ni	–	–
C_2H_4	1.450(3)	1.450(3)	H_2CO	6.247(2)	6.054(2)	O	–	–
C_2H_5	2.278(2)	2.262(2)	H_2CS	9.744(2)	9.734(2)	O_2	3.077(2)	3.106(2)
C_2H_5OH	1.466(3)	1.479(3)	H_2O	4.715(2)	4.670(2)	O_2^+	1.380(1)	1.420(1)
C_2H_6	1.264(3)	1.284(3)	H_2O_2	3.846(2)	3.893(2)	O_3	5.534(2)	5.633(2)
C_3	2.642(3)	2.600(3)	H_2S	1.387(3)	1.407(3)	OCS	2.319(3)	2.260(3)
C_3H_3	2.762(1)	2.765(1)	H_3^+	2.295(−1)	1.746(−1)	OH	2.646(2)	2.681(2)
C_3H_7OH	2.434(3)	2.470(3)	HC_3H	3.659(2)	3.708(2)	OH^+	8.375	8.063
C_4H^-	–	–	HC_3N	2.909(3)	2.901(3)	P	–	–
C_6H^-	–	–	HCN	1.052(3)	1.069(3)	PH	3.450(2)	3.318(2)
CH	4.598(2)	4.468(2)	HCO	2.211(2)	2.110(2)	PH^+	5.632(1)	5.736(1)
CH^+	2.045(2)	1.927(2)	HCO^+	3.049	3.770	Rb	–	–
CH_2	1.398(2)	1.383(2)	HCOOH	9.896(2)	1.006(3)	S	–	–
CH_2^+	7.252(1)	7.117(1)	HCl	1.090(3)	9.841(2)	S_2	3.176(1)	3.168(1)
CH_3	9.999(1)	1.058(2)	HCl^+	6.558(1)	6.413(1)	SH	3.782(2)	3.720(2)
CH_3CHO	8.908(2)	8.989(2)	HF	1.022(2)	1.031(2)	SH^+	4.309(2)	4.220(2)
CH_3CN	1.955(3)	2.006(3)	HNC	9.632(2)	9.729(2)	SO	2.791(3)	2.827(3)
CH_3NH_2	1.777(2)	1.755(2)	HNCO	1.431(3)	1.449(3)	SO_2	1.528(3)	1.534(3)
CH_3OCH_3	9.651(2)	9.637(2)	HO_2	8.162(1)	8.122(1)	Si	–	–
CH_3OCHO	1.171(3)	1.177(3)	K	–	–	SiH	1.852(2)	1.867(2)
CH_3OH	8.862(2)	8.892(2)	Li	–	–	SiH^+	6.804(2)	6.981(2)
CH_3SH	1.197(3)	1.203(3)	LiH	1.522(2)	1.518(2)	SiO	5.673(2)	5.855(2)
CH_4	9.917(2)	9.972(2)	Mg	–	–	Ti	–	–
CH_4^+	1.852(2)	1.840(2)	MgH	8.085(1)	9.088(1)	Zn	–	–
CN	4.287(2)	4.350(2)	Mn	–	–	c-C_3H	1.668(2)	1.645(2)
CO	1.192(2)	6.450(1)	N	–	–	c-C_3H_2	2.523(2)	2.554(2)
CO^+	4.960(1)	5.239(1)	N_2	3.372(1)	4.319(1)	l-C_3H	1.326(3)	1.281(3)
CO_2	5.850(2)	6.443(2)	N_2O	9.807(2)	9.976(2)	l-C_3H_2	1.454(3)	1.432(3)
CS	6.416(2)	5.137(2)	NH	1.932(2)	1.860(2)	l-C_4	4.637(2)	4.654(2)
CS_2	2.868(3)	2.687(3)	NH^+	1.678(1)	1.647(1)	l-C_4H	2.321(3)	2.314(3)
Ca	–	–	NH_2	3.539(2)	3.559(2)	l-C_5H	4.787(1)	4.790(1)

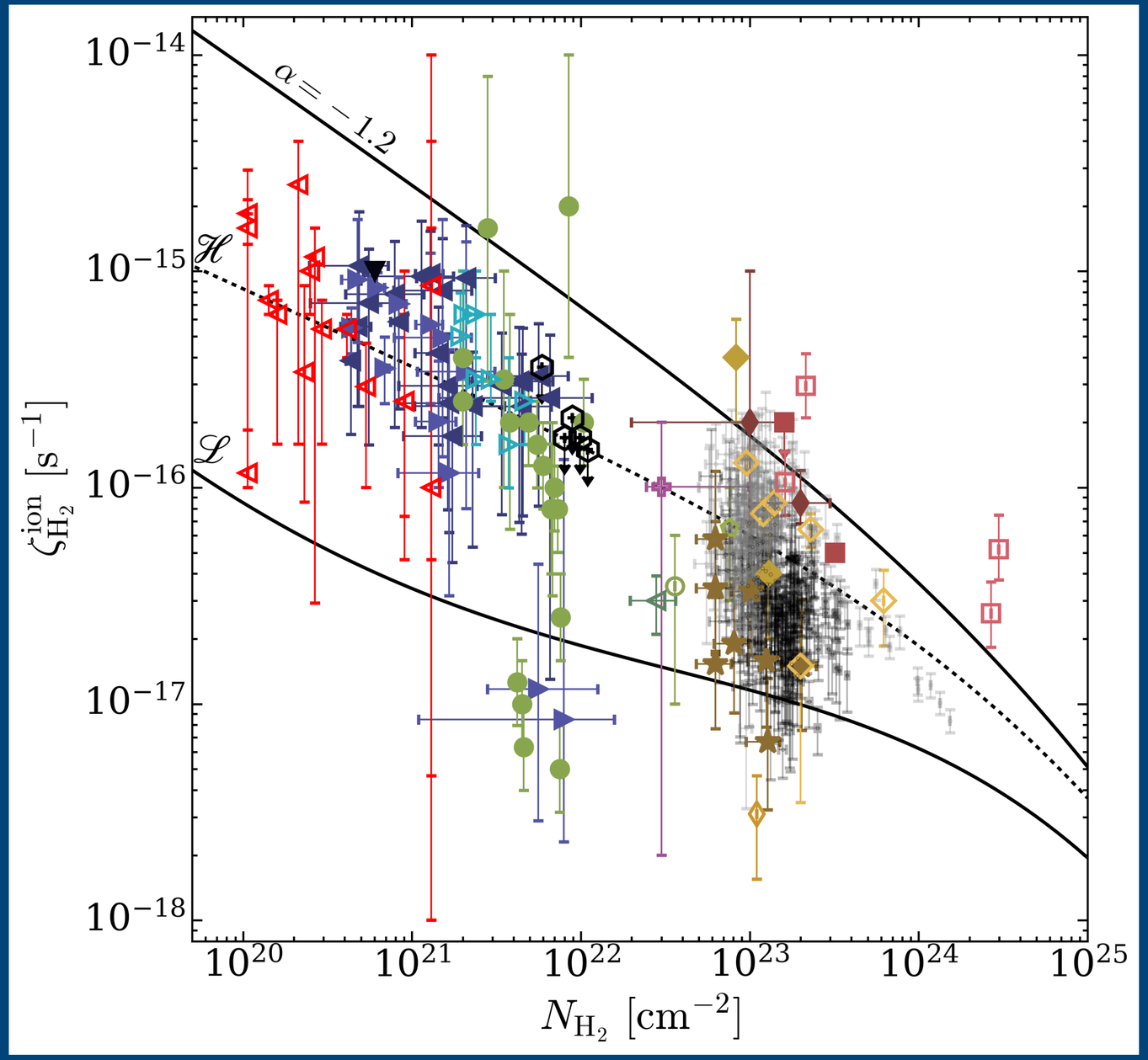
$R_V = 3.1$

Species s	$k^{pi}_{0,s}$ o:p=0:1	$k^{pi}_{0,s}$ o:p=1:0	Species s	$k^{pi}_{0,s}$ o:p=0:1	$k^{pi}_{0,s}$ o:p=1:0	Species s	$k^{pi}_{0,s}$ o:p=0:1	$k^{pi}_{0,s}$ o:p=1:0
Al	1.023(3)	9.708(2)	Ca^+	1.585	1.465	NH_2CHO	3.739(2)	3.681(2)
AlH	6.841(1)	6.918(1)	Cl	5.409(1)	5.322(1)	NH_3	1.887(2)	1.896(2)
C	2.333(2)	2.381(2)	Cr	4.909(2)	4.967(2)	NO	1.793(2)	1.791(2)
C_2	2.193(2)	2.055(2)	Fe	2.064(2)	2.093(2)	NO_2	1.032(2)	1.009(2)
C_2H	4.367(2)	4.197(2)	H	4.078	3.615	Na	6.693	6.704
C_2H^-	6.119(2)	6.107(2)	H^-	9.240(2)	9.247(2)	NaCl	–	–
C_2H_2	3.733(2)	3.603(2)	H_2	5.451(−2)	5.717(−2)	NaH	–	–
C_2H_3	1.335(3)	1.349(3)	H_2^+	–	–	Ni	4.789(1)	4.887(1)
C_2H_4	2.668(2)	2.617(2)	H_2CO	2.703(2)	2.683(2)	O	2.668	2.358
C_2H_5	2.401(2)	2.425(2)	H_2CS	1.066(3)	1.065(3)	O_2	3.338(1)	2.656(1)
C_2H_5OH	3.620(2)	3.484(2)	H_2O	2.289(1)	2.106(1)	O_2^+	–	–
C_2H_6	1.827(2)	1.687(2)	H_2O_2	1.804(2)	1.730(2)	O_3	3.324(1)	3.048(1)
C_3	9.367(1)	9.051(1)	H_2S	5.771(2)	5.735(2)	OCS	5.284(2)	5.053(2)
C_3H_3	1.022(3)	1.035(3)	H_3^+	–	–	OH	1.662(1)	1.569(1)
C_3H_7OH	5.667(2)	5.468(2)	HC_3H	1.290(3)	1.306(3)	OH^+	–	–
C_4H^-	5.022(2)	5.013(2)	HC_3N	1.696(2)	1.575(2)	P	1.330(3)	1.359(3)
C_6H^-	3.042(2)	3.036(2)	HCN	1.401(1)	1.136(1)	PH	–	–
CH	1.621(2)	1.624(2)	HCO	5.843(2)	5.904(2)	PH^+	–	–
CH^+	–	–	HCO^+	–	–	Rb	1.095(1)	1.102(1)
CH_2	–	–	HCOOH	2.035(2)	1.966(2)	S	7.989(2)	7.278(2)
CH_2^+	–	–	HCl	4.771(1)	4.243(1)	S_2	1.667(3)	1.699(3)
CH_3	2.433(2)	2.458(2)	HCl^+	–	–	SH	9.110(2)	9.244(2)
CH_3CHO	6.120(2)	6.256(2)	HF	1.026(−2)	9.336(−3)	SH^+	–	–
CH_3CN	9.682(1)	8.834(1)	HNC	1.518(2)	1.370(2)	SO	4.034(2)	4.298(2)
CH_3NH_2	1.157(3)	1.160(3)	HNCO	7.642(1)	7.172(1)	SO_2	1.056(2)	9.662(1)
CH_3OCH_3	8.670(2)	8.654(2)	HO_2	5.597(1)	5.442(1)	Si	2.030(3)	2.000(3)
CH_3OCHO	2.178(2)	2.114(2)	K	1.608(1)	1.606(1)	SiH	3.141(3)	3.146(3)
CH_3OH	2.314(2)	2.256(2)	Li	1.130(2)	1.126(2)	SiH^+	–	–
CH_3SH	1.354(3)	1.379(3)	LiH	–	–	SiO	–	–
CH_4	2.330(1)	2.039(1)	Mg	4.863(1)	4.797(1)	Ti	1.299(2)	1.312(2)
CH_4^+	–	–	MgH	–	–	Zn	4.198(2)	3.045(2)
CN	7.371	5.584	Mn	1.444(1)	1.453(1)	c-C_3H	9.757(2)	9.857(2)
CO	1.438(1)	1.029(1)	N	9.865(−1)	8.447(−1)	c-C_3H_2	1.227(3)	1.243(3)
CO^+	–	–	N_2	1.759(−1)	1.312(−1)	l-C_3H	9.998(2)	1.012(3)
CO_2	1.144(1)	9.550	N_2O	1.079(2)	1.061(2)	l-C_3H_2	–	–
CS	6.684(1)	6.861(1)	NH	7.819	6.735	l-C_4	–	–
CS_2	2.770(2)	2.782(2)	NH^+	–	–	l-C_4H	–	–
Ca	1.116(2)	1.110(2)	NH_2	6.265(1)	6.122(1)	l-C_5H	–	–

https://github.com/marcopadovani/UVfluorescence

ESTIMATES OF ζ COMPARING MODELS AND OBSERVATIONS

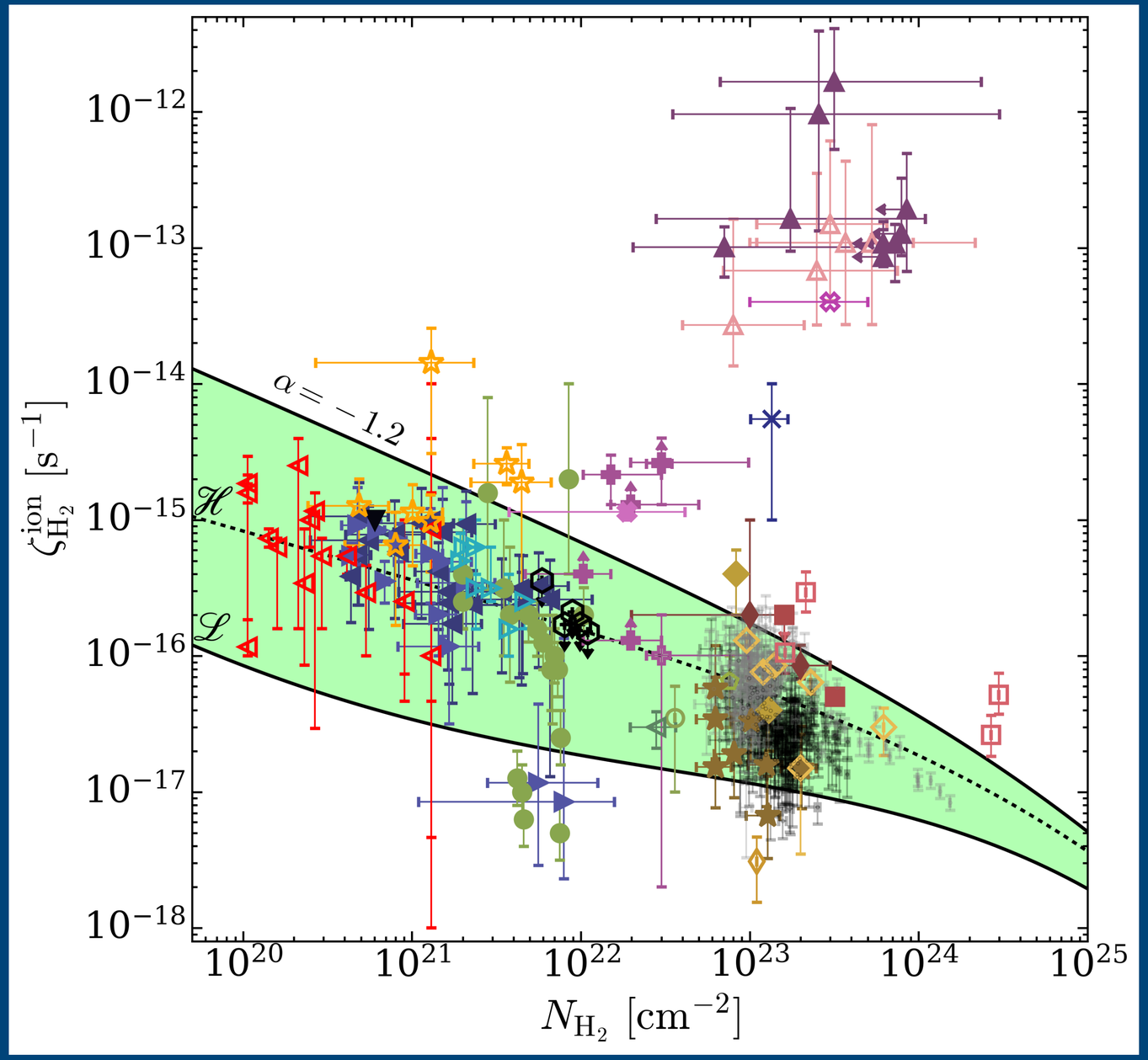
this is *not*
the end of the tale...



ESTIMATES OF ζ COMPARING MODELS AND OBSERVATIONS

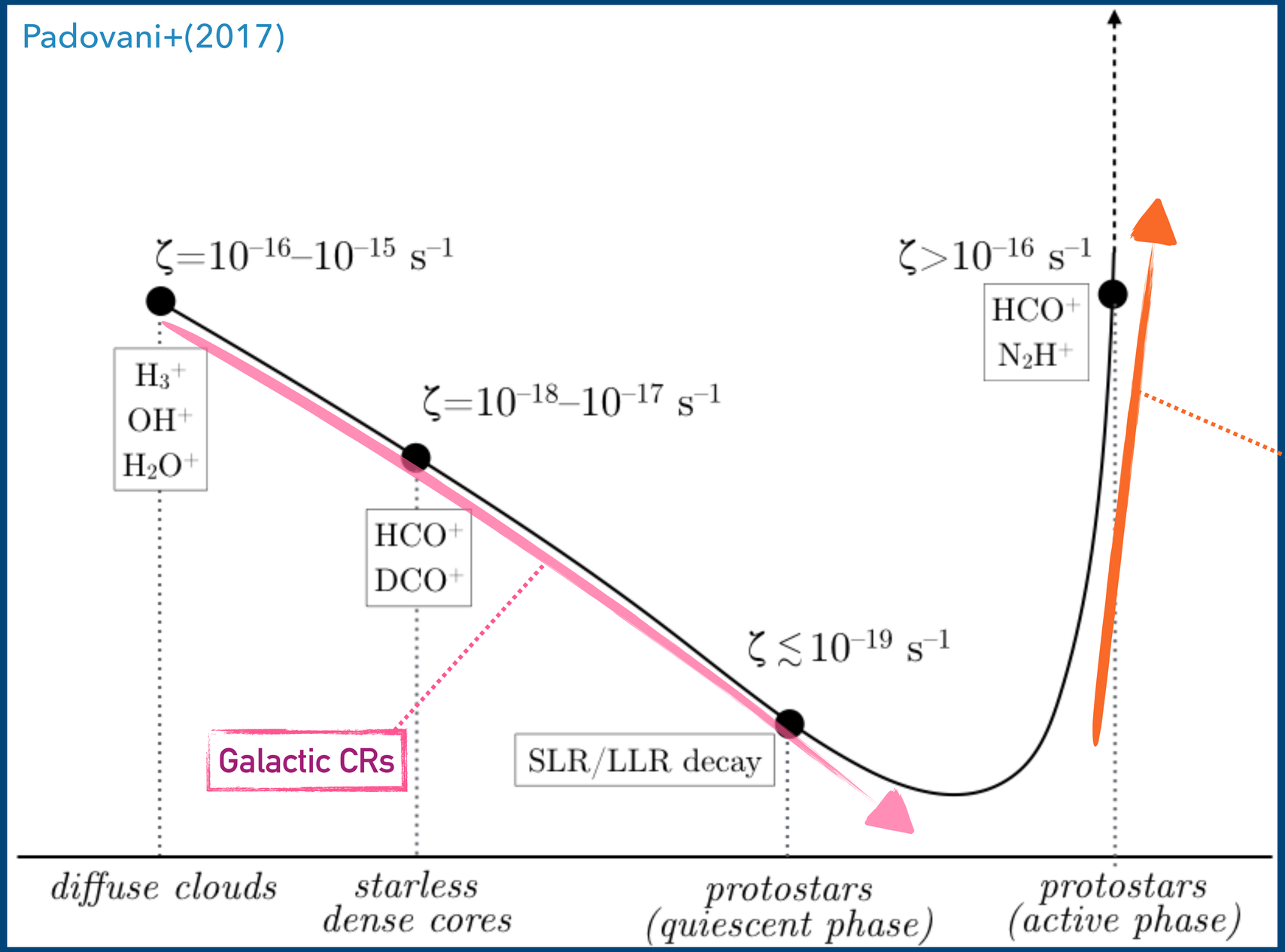
Values of ζ above the $\alpha = -1.2$ model cannot be explained by GCRs

an additional ***local*** CR source is needed



COSMIC-RAY IONISATION RATE INSIDE A MOLECULAR CLOUD

Padovani+(2017)

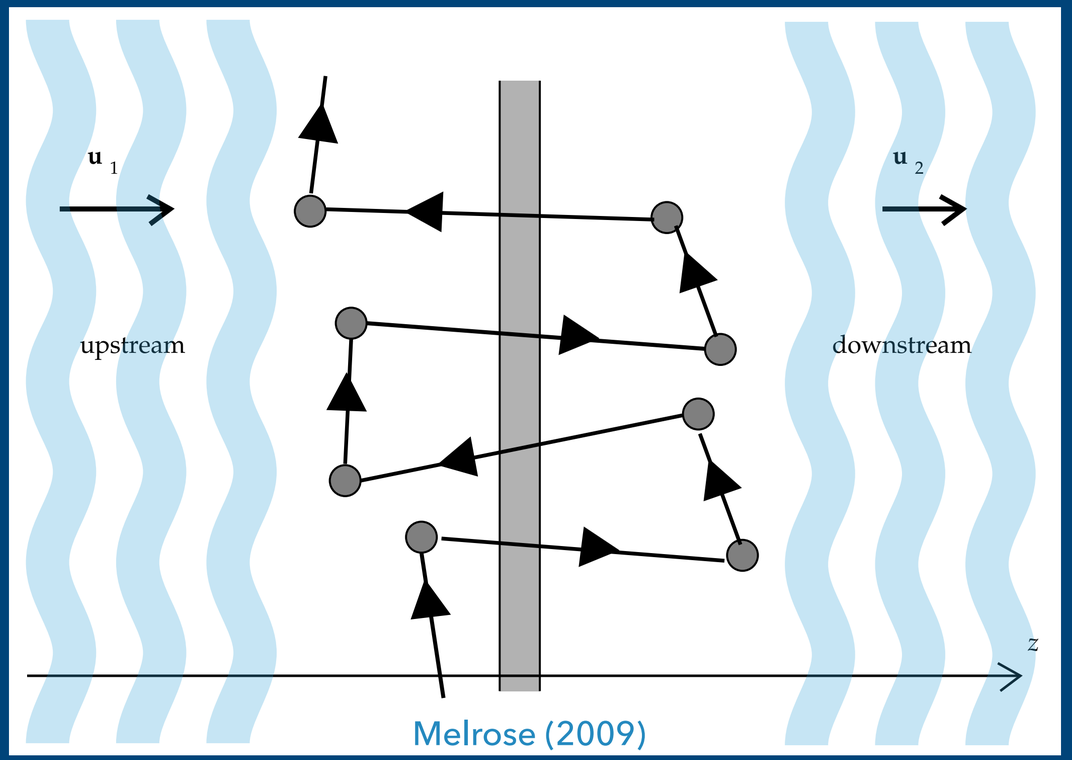


other sources of cosmic rays needed

COSMIC-RAY ACCELERATION SITES

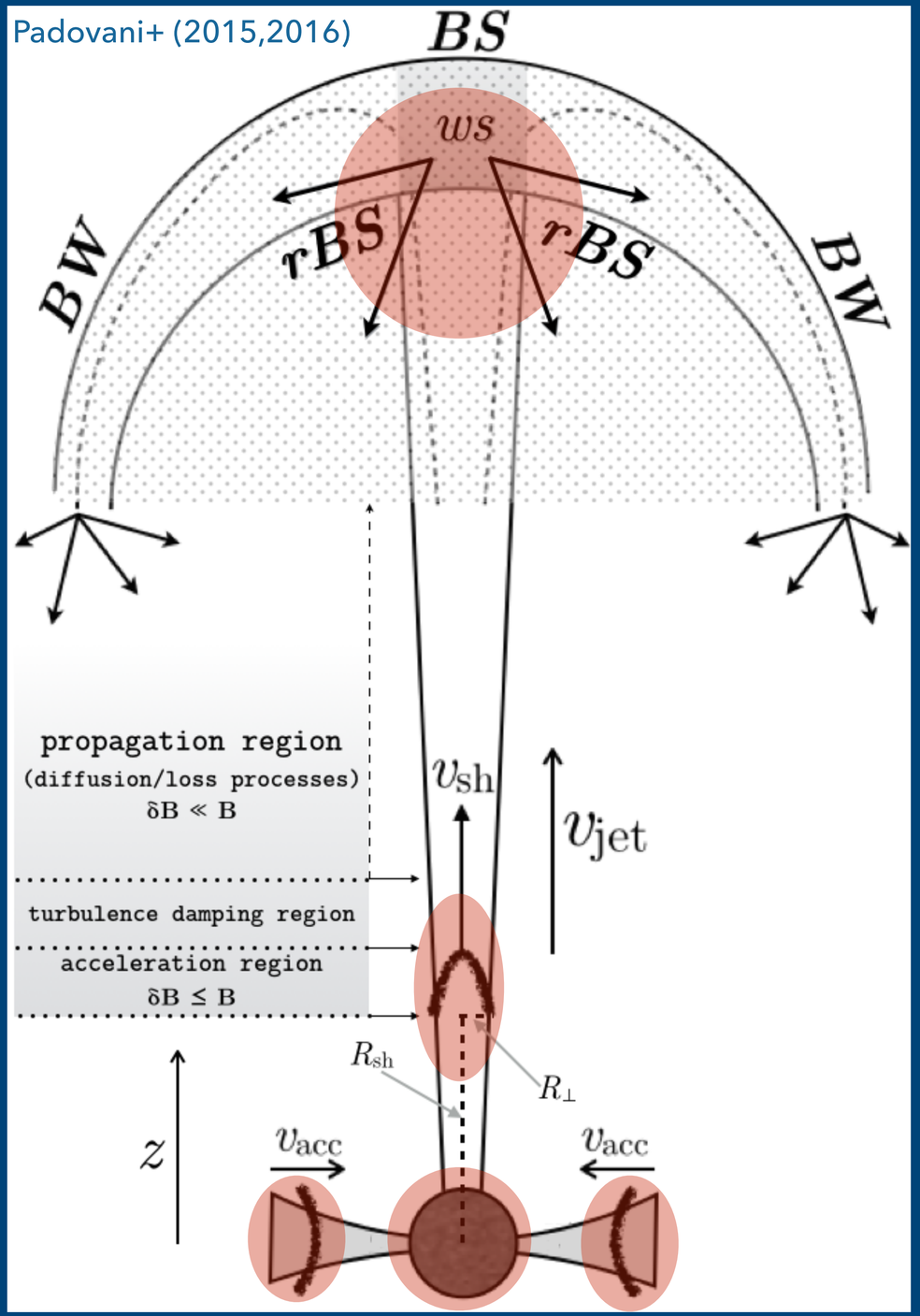
Looking for shocks in/on:
- accretion flows;
- protostellar surface;
- jet.

First-order Fermi acceleration
(or Diffusive Shock Acceleration)



Melrose (2009)

Padovani+ (2015,2016)



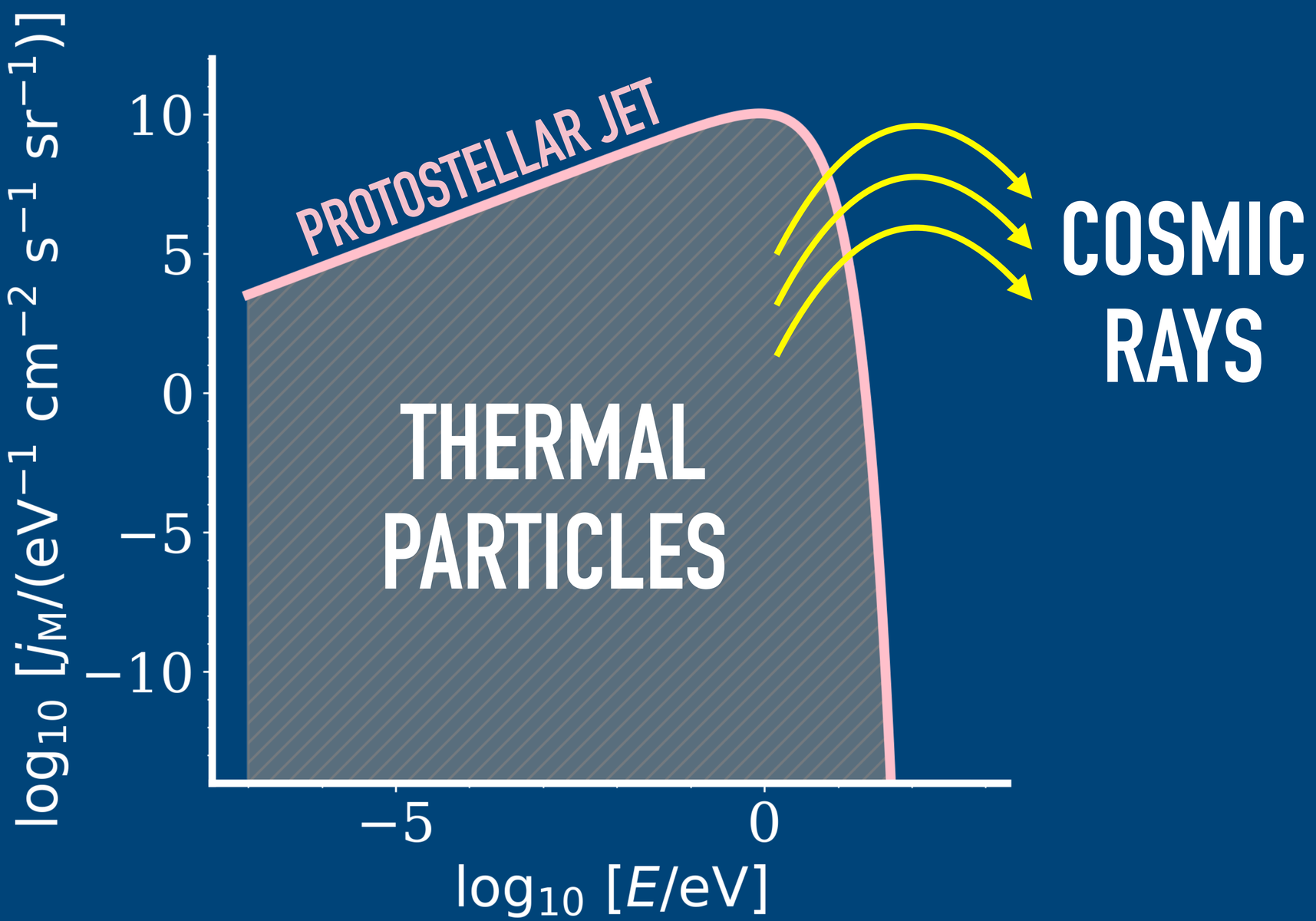
COSMIC-RAY ACCELERATION SITES

JET

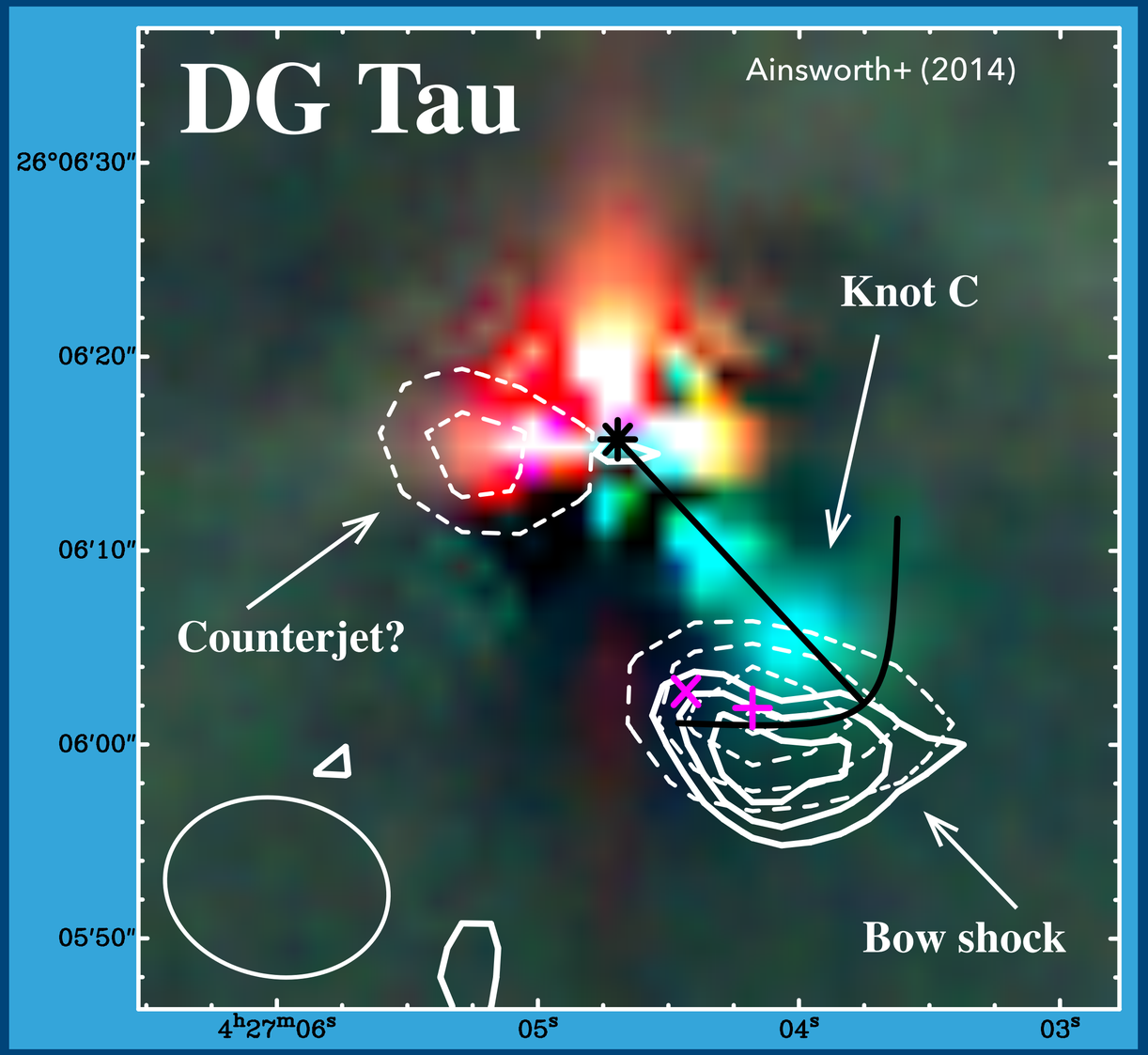
$n(\mathrm{H_2}) = 10^4\ \mathrm{cm^{-3}}$

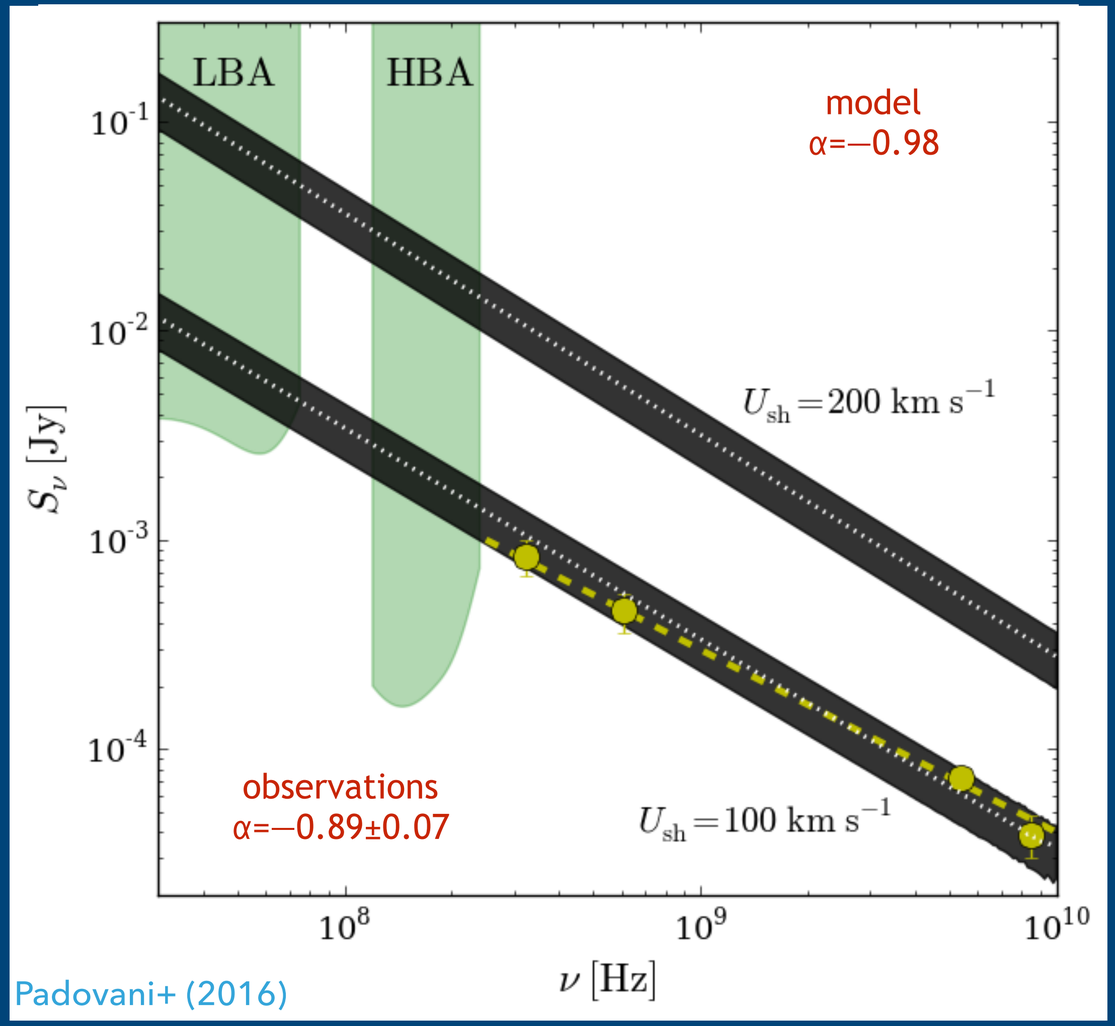
$x = 0.5$

$T = 10^4\ \mathrm{K}$



PROTOSTELLAR JETS AS PARTICLE ACCELERATORS

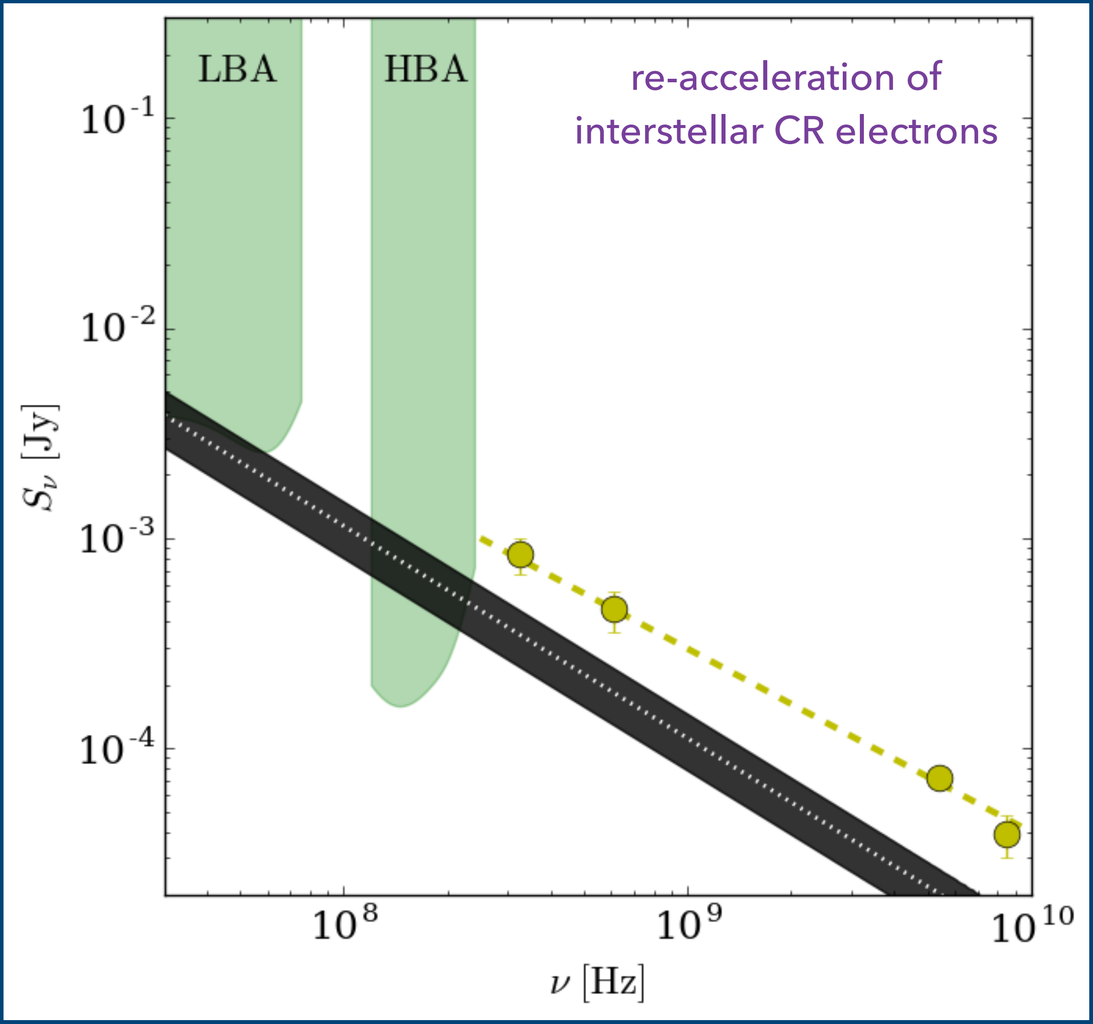


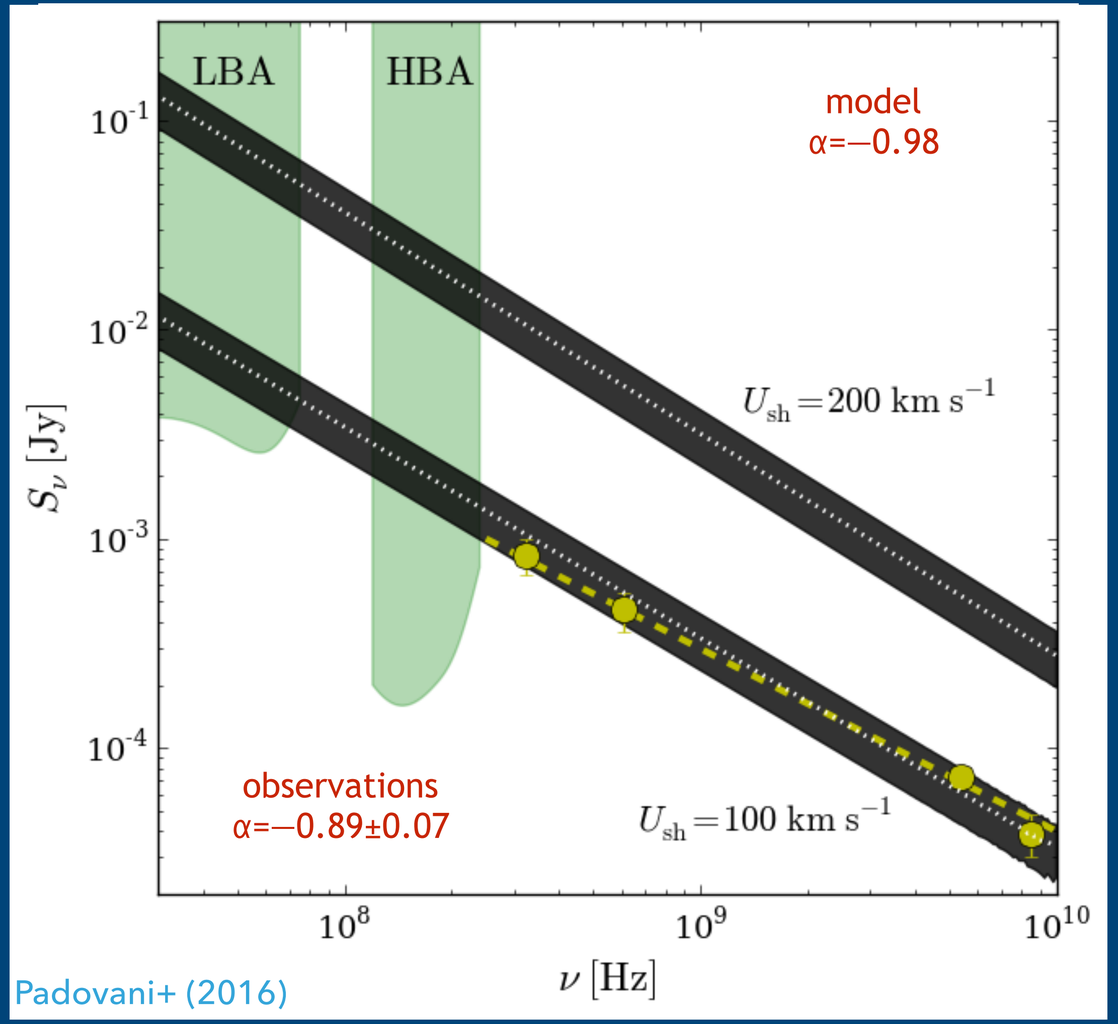


Padovani+ (2016)

PROTOSTELLAR JETS AS PARTICLE ACCELERATORS

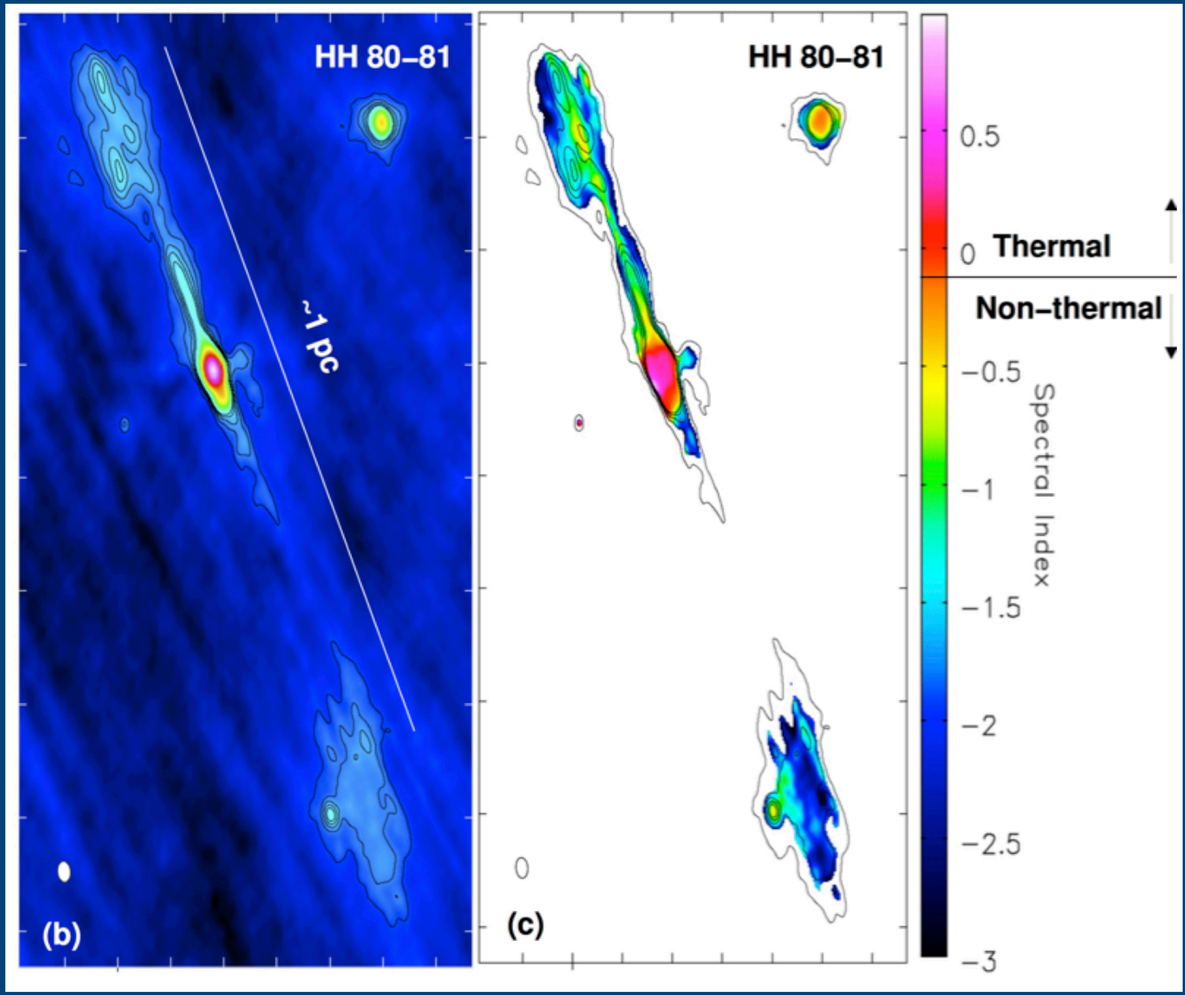
Other examples of synchrotron emission in protostellar jets ⇒ acceleration of local cosmic-ray electrons



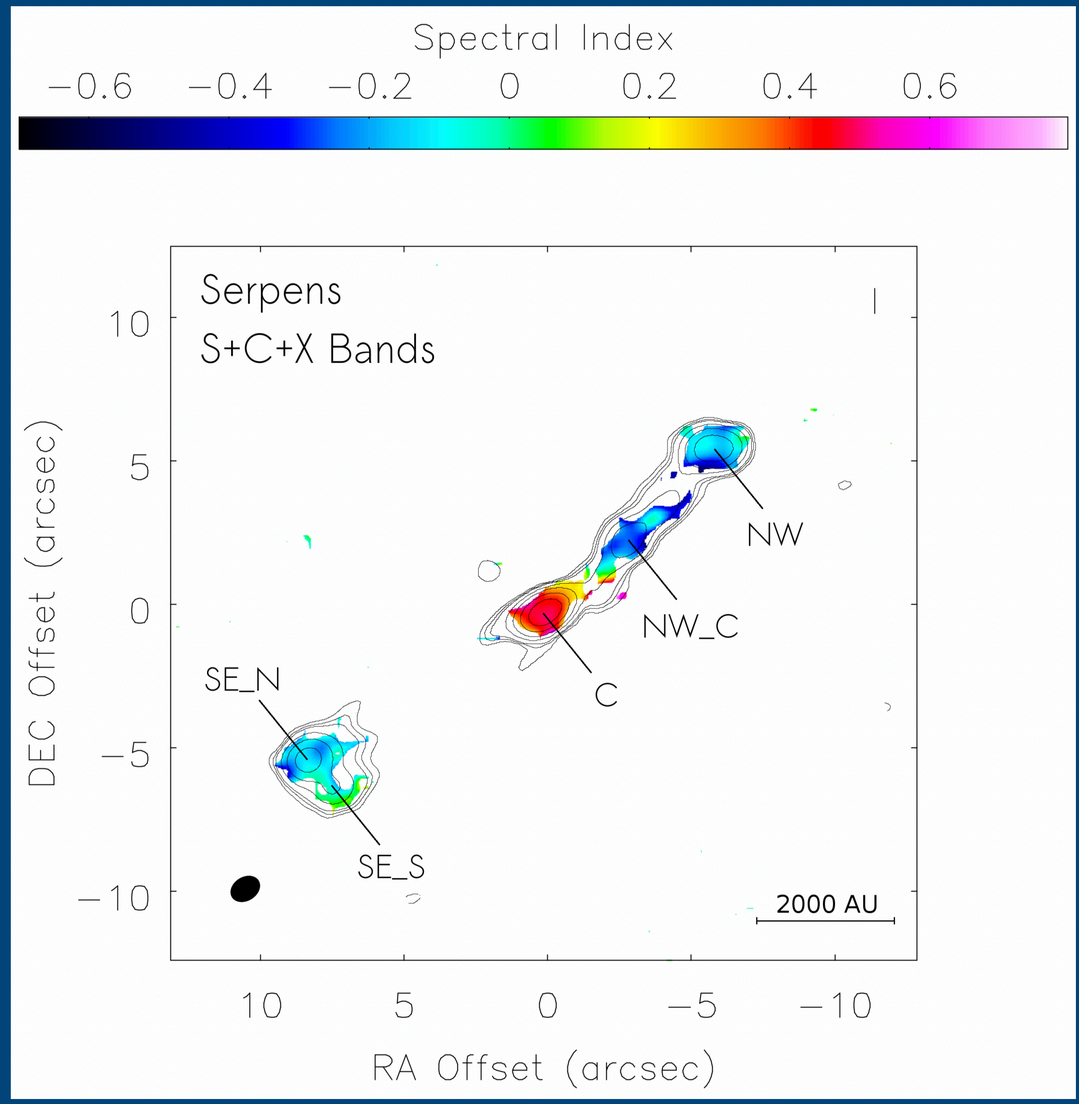


Padovani+ (2016)

PROTOSTELLAR JETS AS PARTICLE ACCELERATORS



Carrasco-González+ (2013)
Rodríguez-Kamenetzky+ (2017)

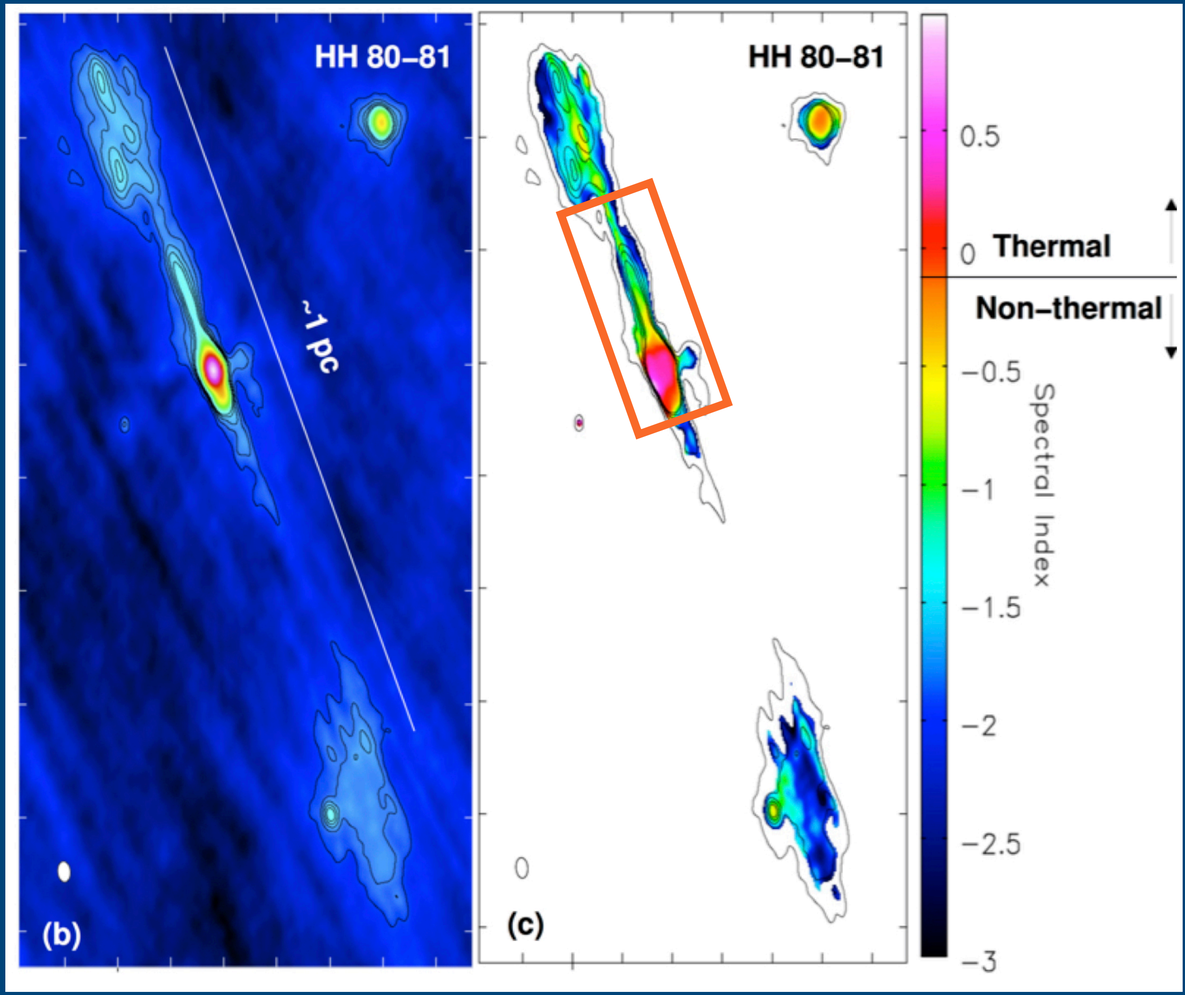


Rodríguez-Kamenetzky+ (2016)

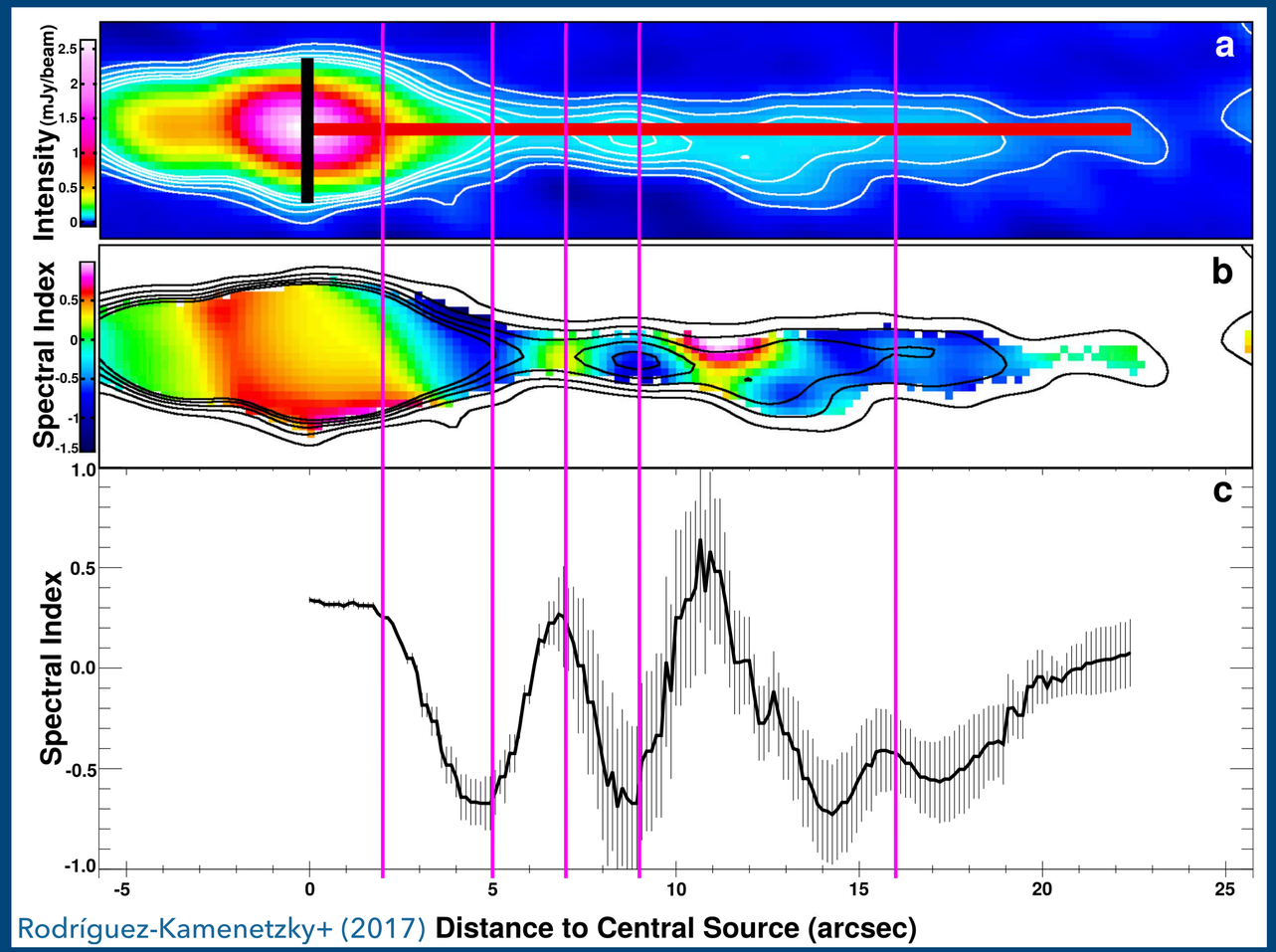
For high-mass protostellar jets see e.g.
Araudo+ (2007), Bosch-Ramon+ (2010), Munar-Adrover+ (2011)

For a recent review, see Anglada+ (2018)

PROTOSTELLAR JETS AS PARTICLE ACCELERATORS



Carrasco-González+ (2013)
Rodríguez-Kamenetzky+ (2017)

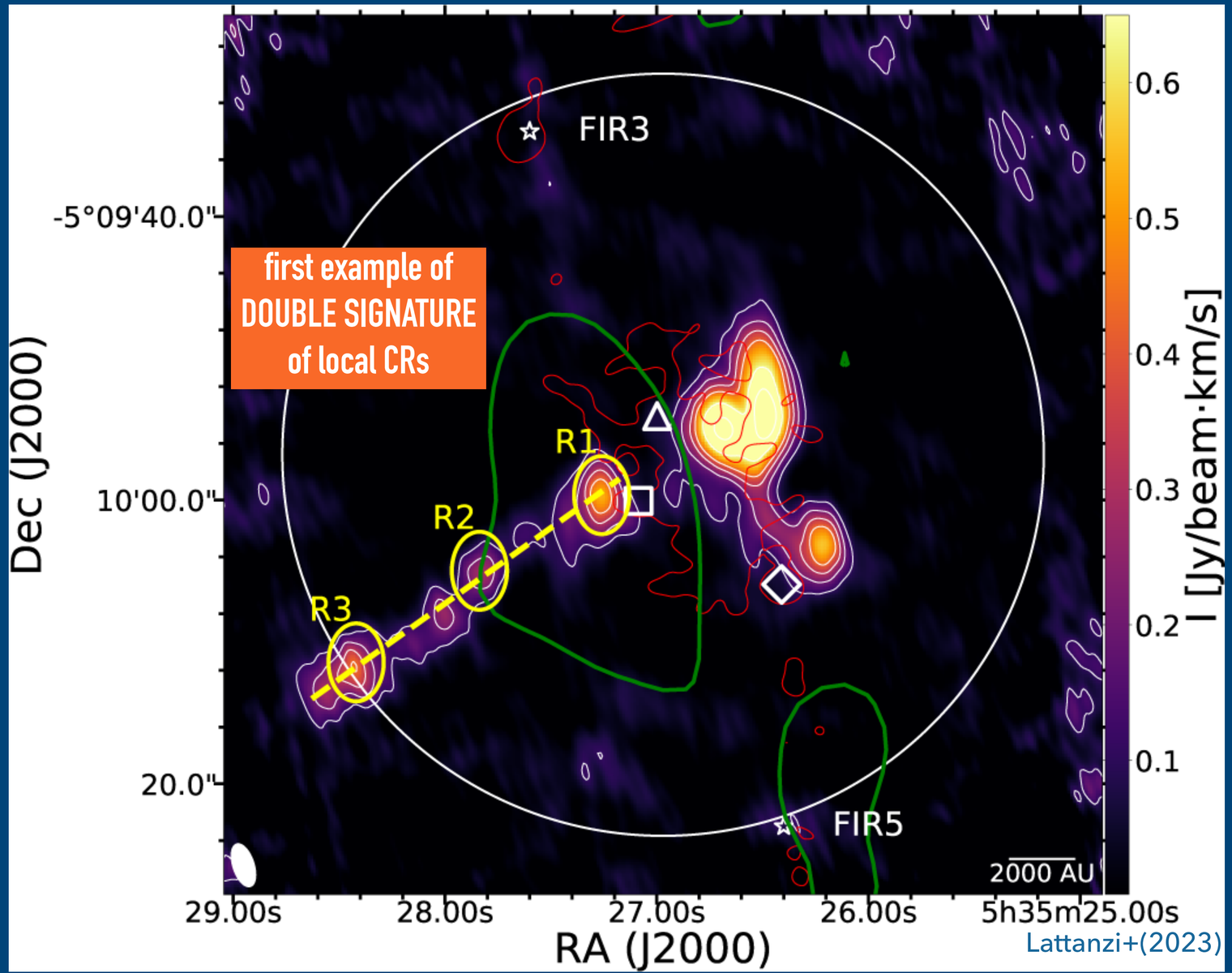


Rodríguez-Kamenetzky+ (2017)

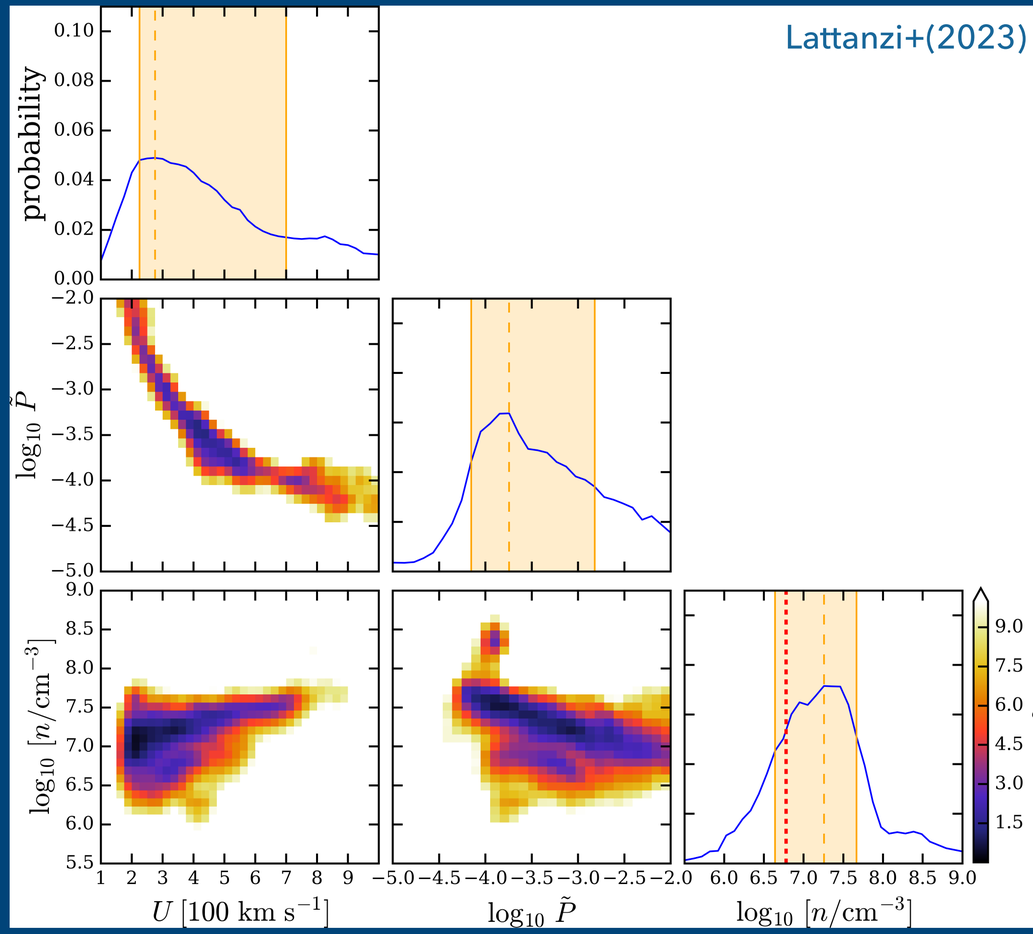
For high-mass protostellar jets see e.g.
Araudo+ (2007), Bosch-Ramon+ (2010), Munar-Adrover+ (2011)

For a recent review, see Anglada+ (2018)

LOCALLY ACCELERATED
COSMIC RAYS



Lattanzi+(2023)



Lattanzi+(2023)

$$U = 275^{+425}_{-50}\ \mathrm{km\ s^{-1}}$$

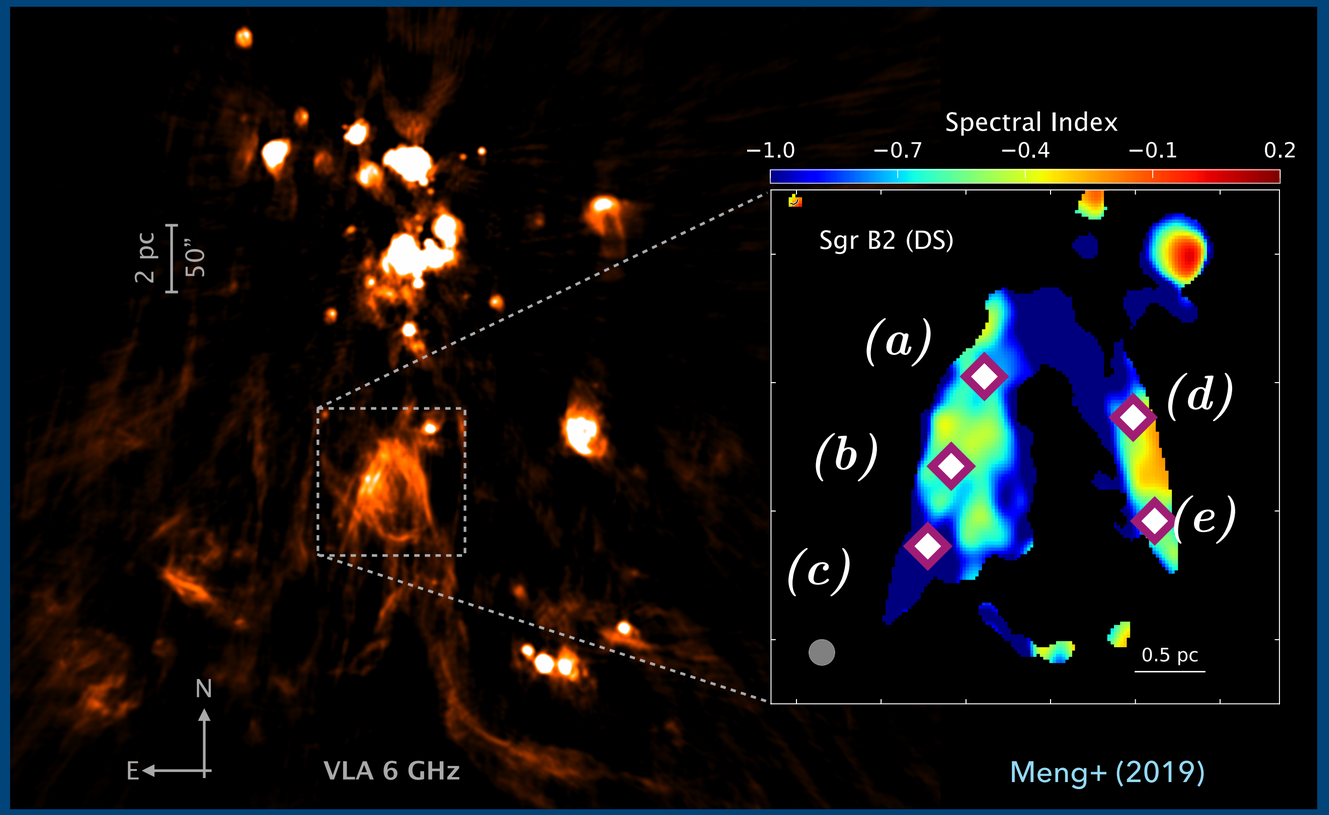
$$n/(10^6\ \mathrm{cm^{-3}}) = 18.05^{+28.37}_{-13.67}$$

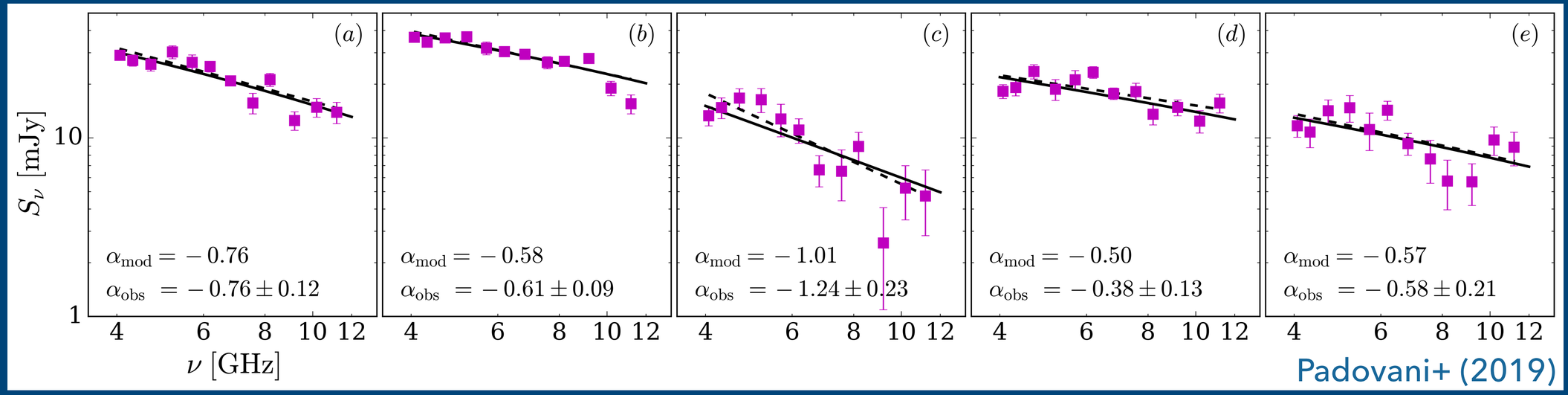
$$\tilde{P}/10^4 = 1.80^{+13.31}_{-1.10}$$

LOCALLY ACCELERATED COSMIC RAYS

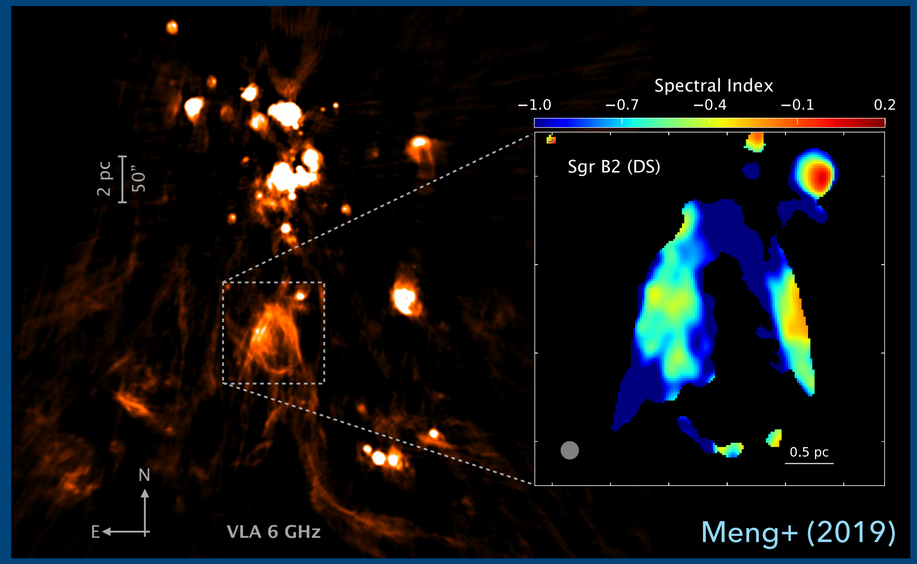
fit to observations
Meng+ (2019)

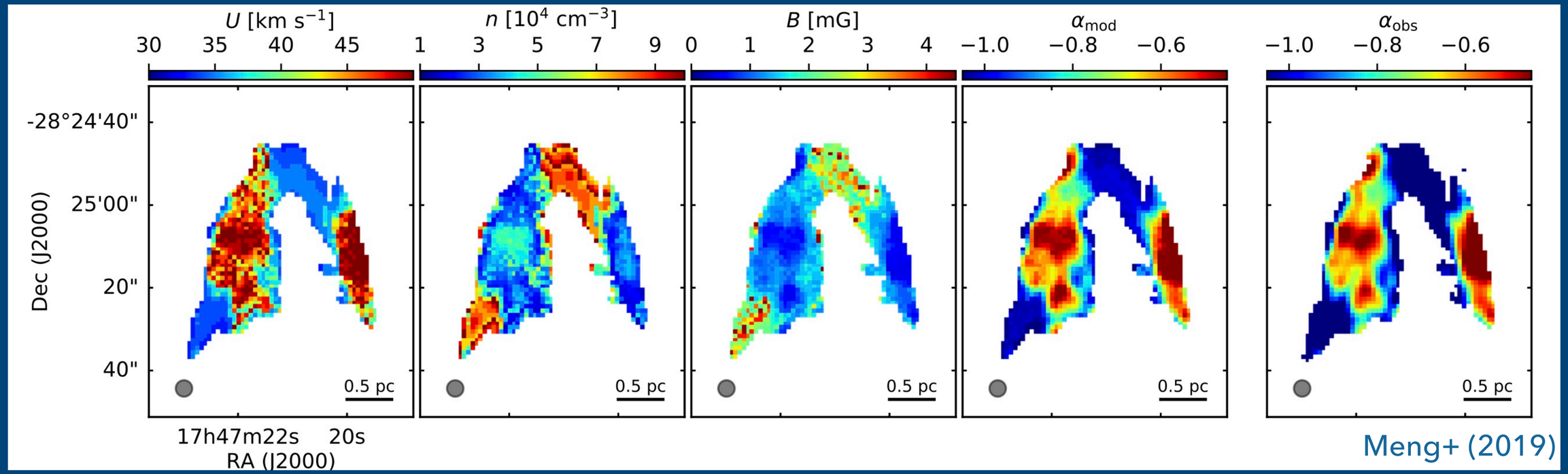
model
Padovani+ (2019)





COSMIC-RAY ACCELERATION SITES





COSMIC-RAY ACCELERATION IN HII REGIONS

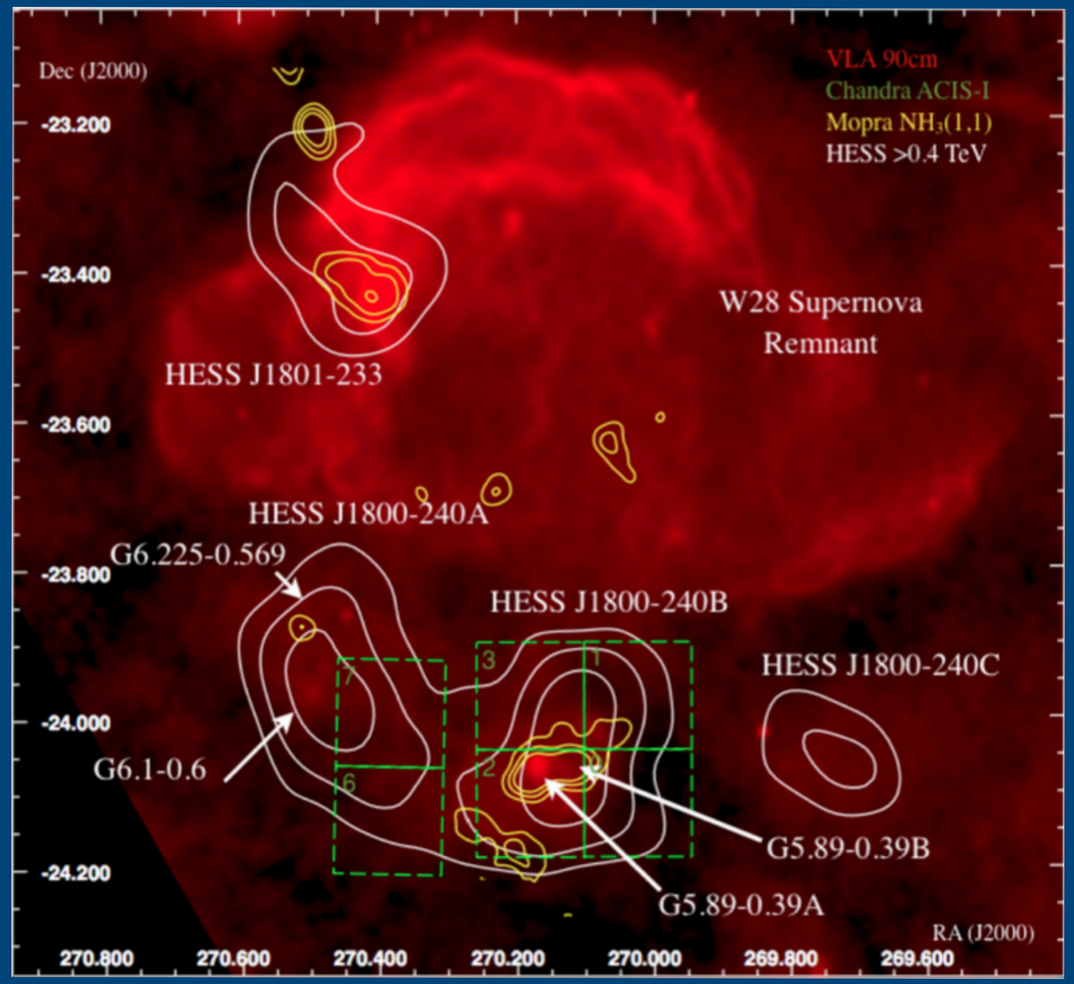
Chandra observations of the HII complex G5.89-0.39 and TeV γ-ray source HESS J1800-240B

- VLA 90 cm - background red map
- Mopra $NH_3(1,1)$ - yellow contours
- HESS >0.4 TeV - white contours
- Chandra FOV - green boxes

γ-rays as a TRIPLE SIGNATURE of local CRs?

10 out of 75 X-ray sources observed by Chandra could provide sufficient energy to account for a part of the GeV to TeV γ-ray emission in the source HESS J1800-240B. However, *future arc-minute angular resolution γ-ray imaging will be needed to disentangle the potential γ-ray components powered by G5.89-0.39 from those powered by the W28 SNR.*

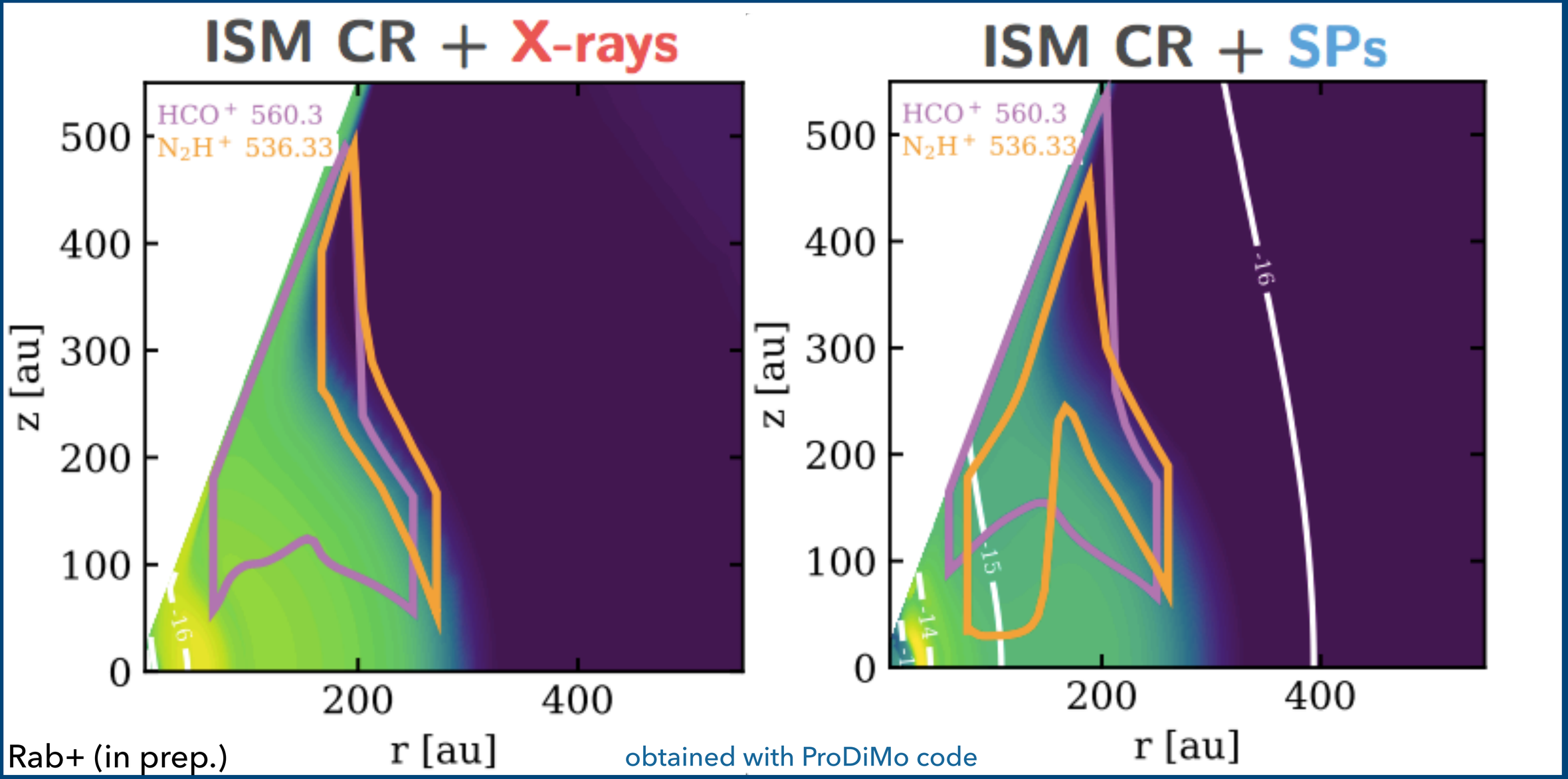
Hampton+ (2016)



in-situ CR acceleration already proposed by Gusdorf, Marcowith et al. (2015)

EFFECT OF STELLAR PARTICLES ON CIRCUMSTELLAR DISC CHEMISTRY

origin of the emission of HCO^+(6-5) and N_2H^+(6-5)

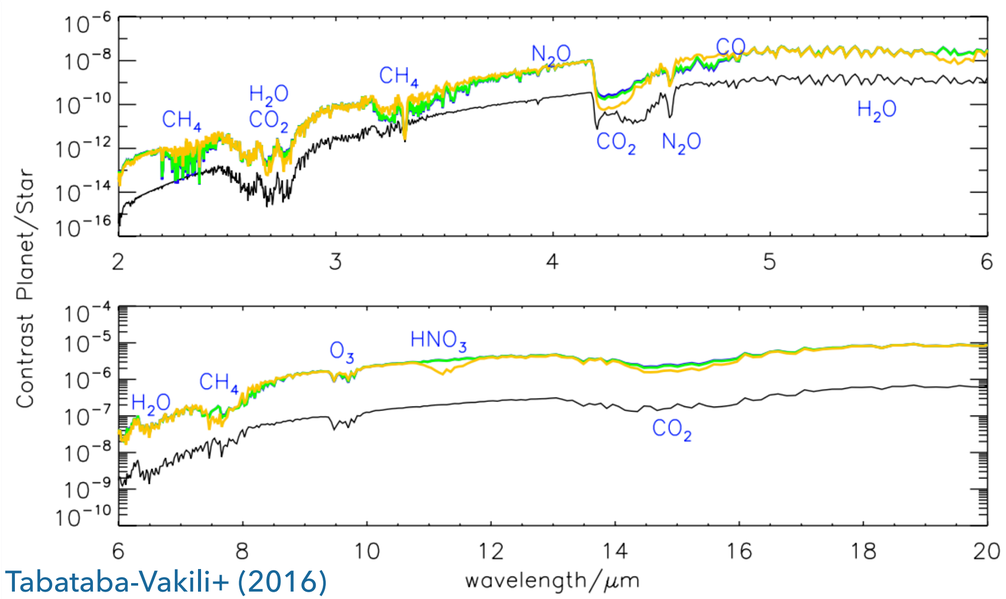


Rab+ (in prep.)

obtained with ProDiMo code

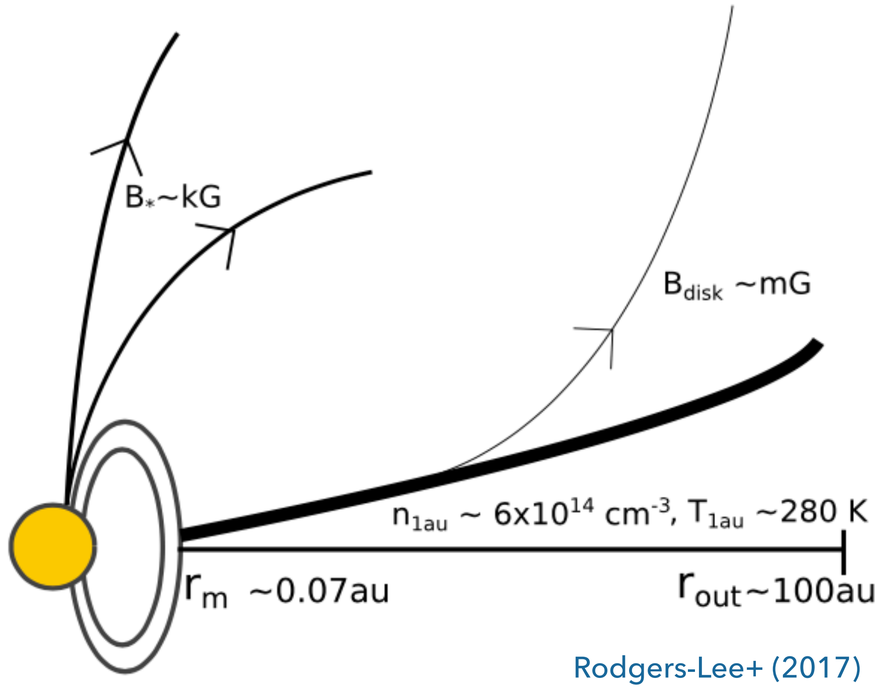
STELLAR PARTICLES : A NEW RESEARCH FIELD

Effect of Stellar CRs from M-dwarfs on Earth-like exoplanetary atmospheres



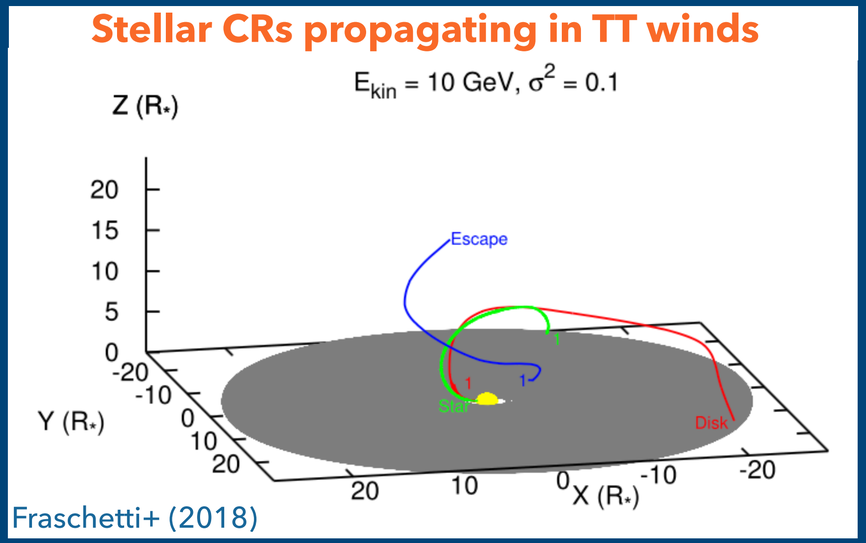
Tabataba-Vakili+ (2016)

Effect of stellar CRs from TT stars on PPDs

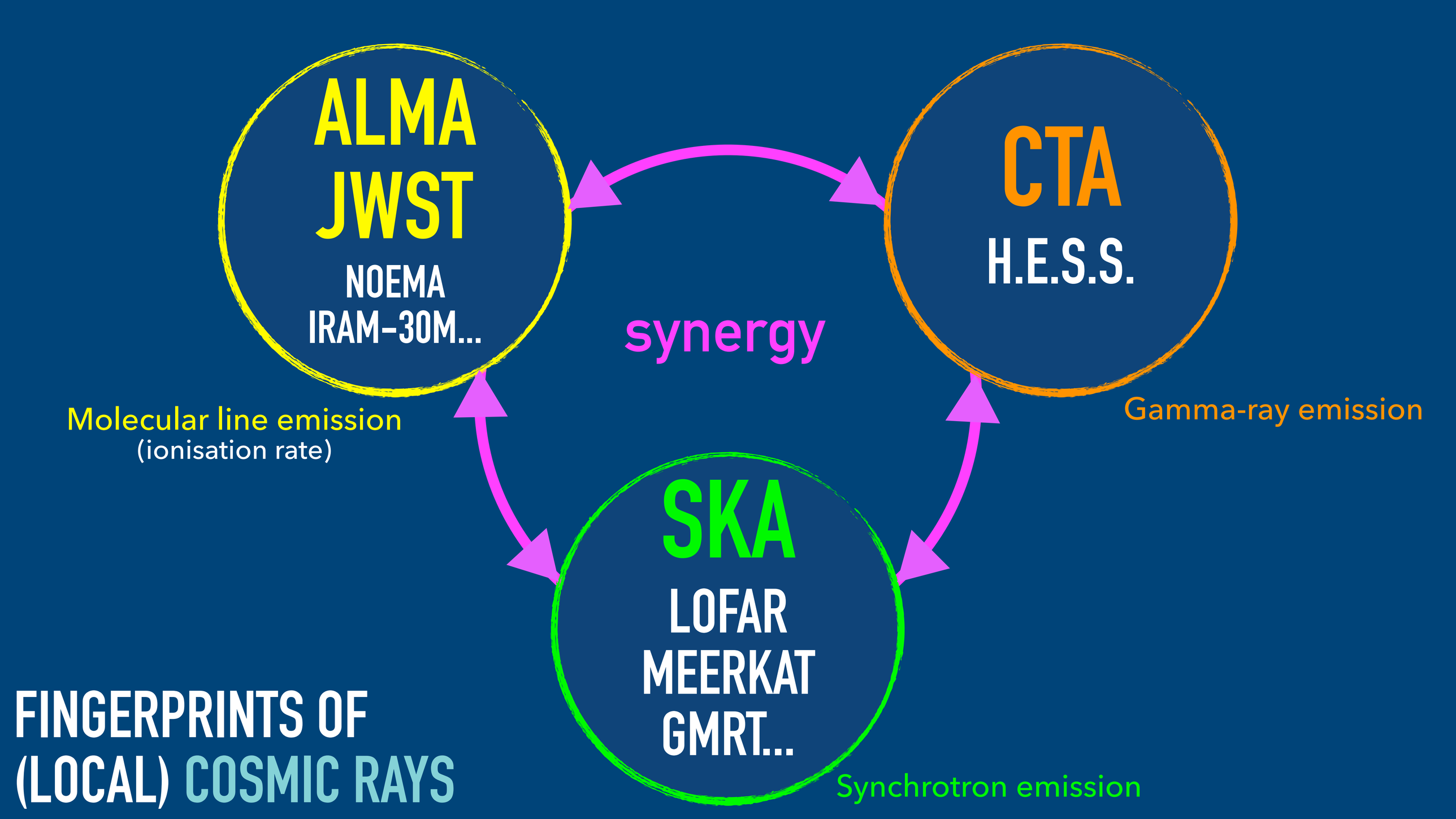


Rodgers-Lee+ (2017)

Stellar CRs propagating in TT winds



Fraschetti+ (2018)


ALMA
JWST
NOEMA
IRAM-30M...
CTA
H.E.S.S.
synergy
SKA
LOFAR
MEERKAT
GMRT...
Molecular line emission
(ionisation rate)
Gamma-ray emission
Synchrotron emission
FINGERPRINTS OF
(LOCAL) COSMIC RAYS