In-situ accelerated energetic particles in the environment of young stellar objects

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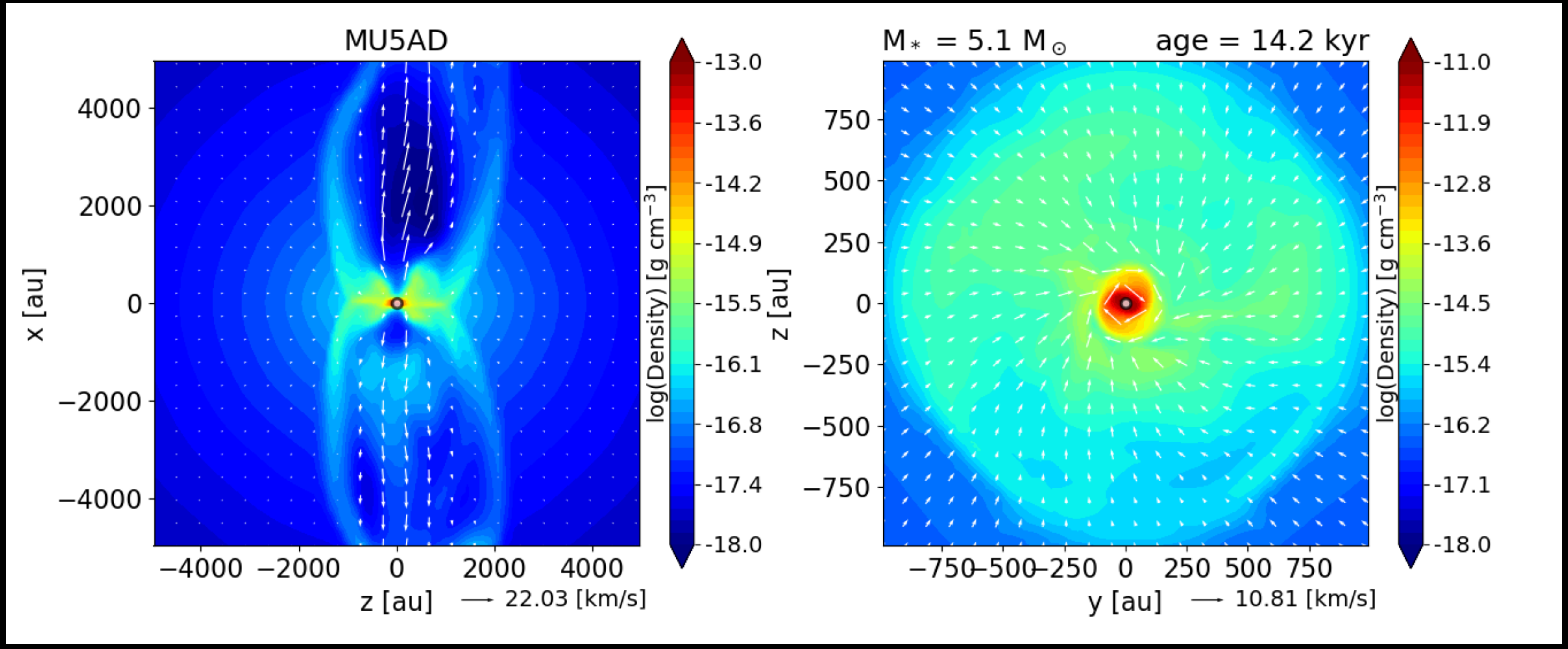
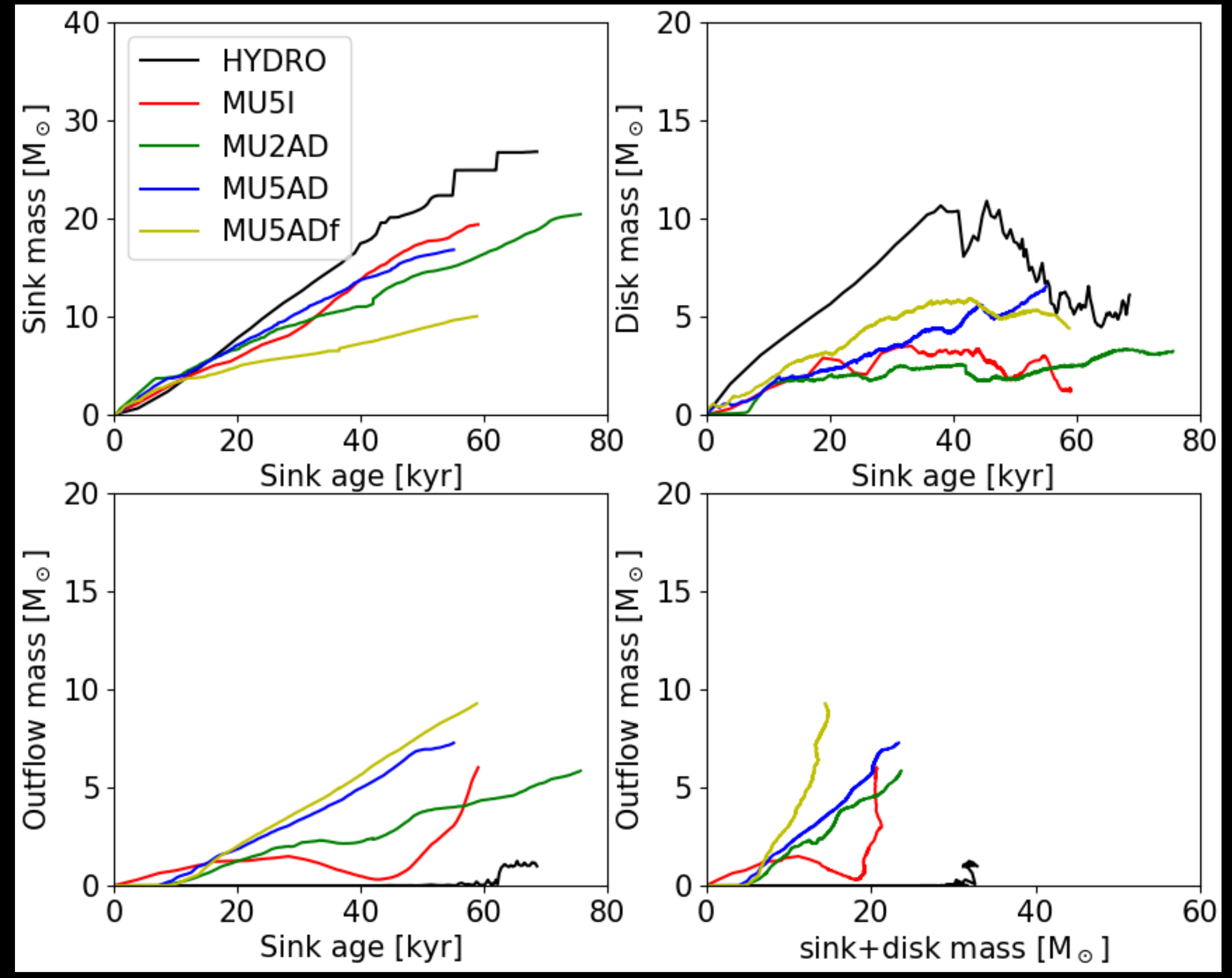
Scientific context

- Star formation / Accretion & ejection in YSO
  - Ambipolar diffusion, magnetic resistivity effects essential to fix disc properties
  - Magneto-centrifugal process essential for outflows

★ Ionisation rate controls magnetic field / matter coupling : Role of non-thermal particles ?

Commerçon et al 2022 non ideal MHD simulations





upleft : time evolution of the sink mass

upright : time evolution of the disk mass

lowleft : time evolution of the outflow mass

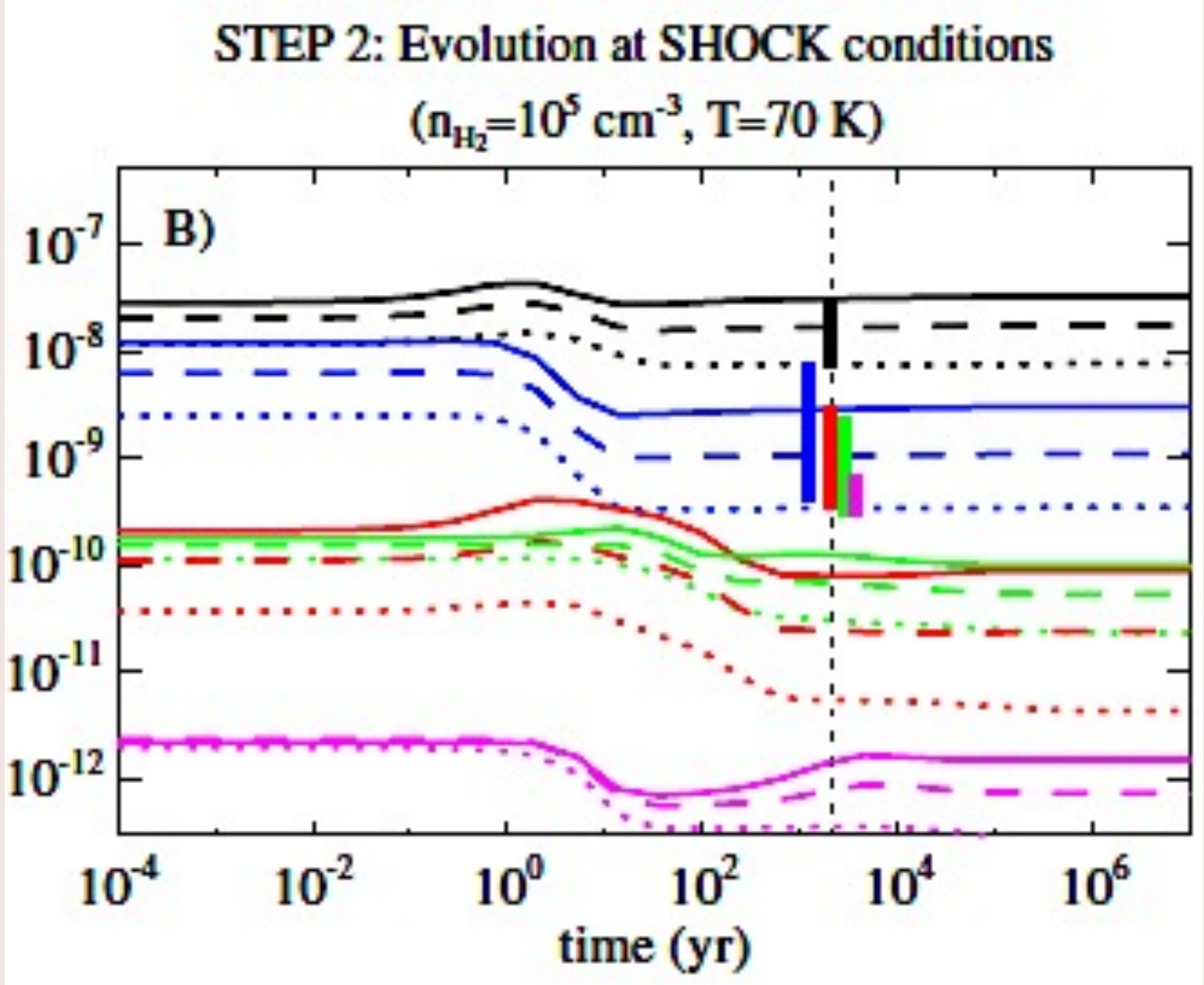
lowright : evolution of the outflow as function of the sink and disk mass

Non-thermal signatures in YSO

- Synchrotron radiation : growing number of objects do show non-thermal radio emission from their jets (both massive and solar mass stars)

- Purser et al 2017 : mean spectral index : -0.55 compatible with optically thin synchrotron emission

Herschel observations of HCO^+, N_2H^+ ion species show abundances explain by $\zeta \sim 3\ 10^{-16}$ s^{-1} (continuous line below)



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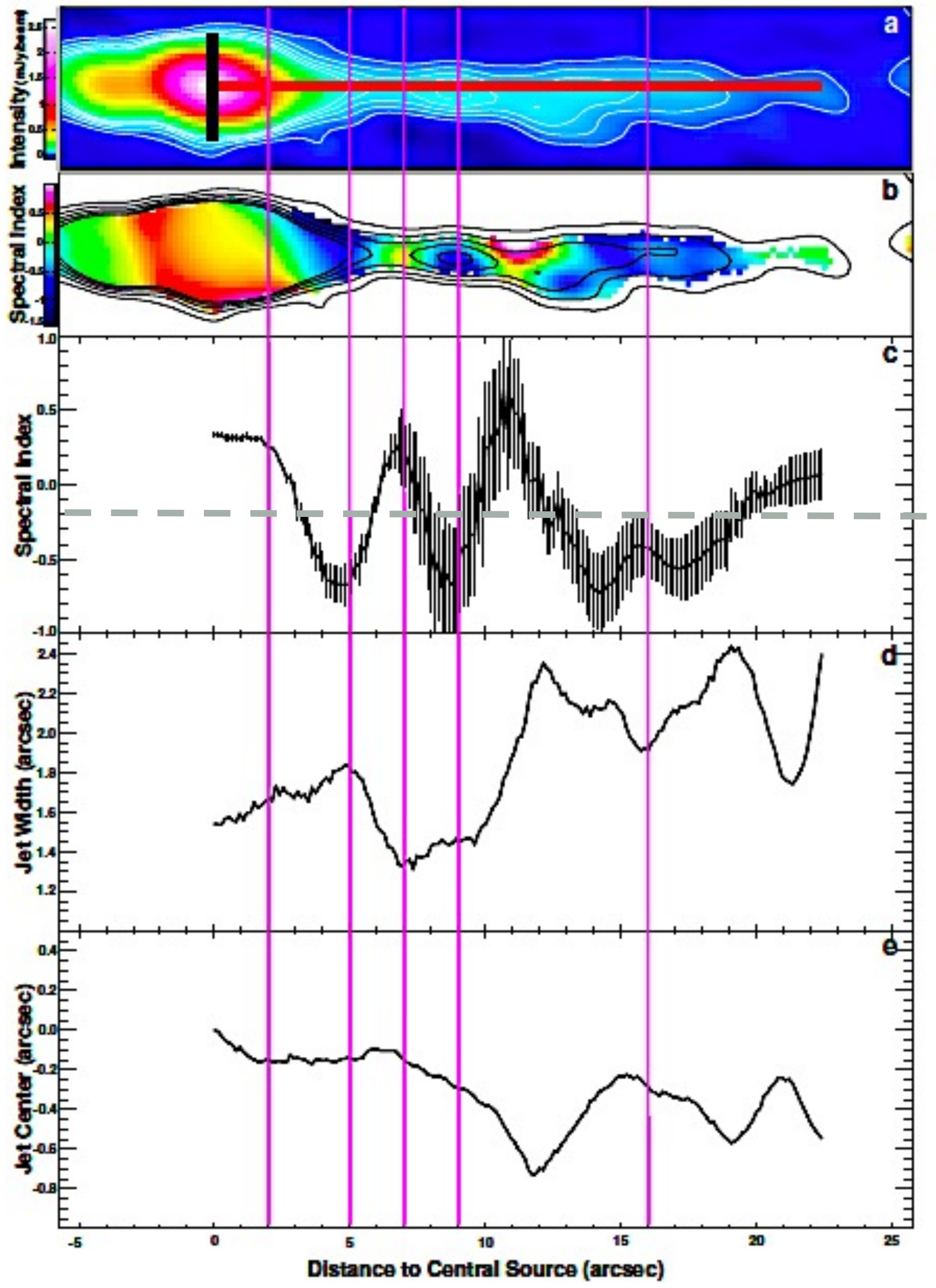
- Possibly related to non-thermal particles …

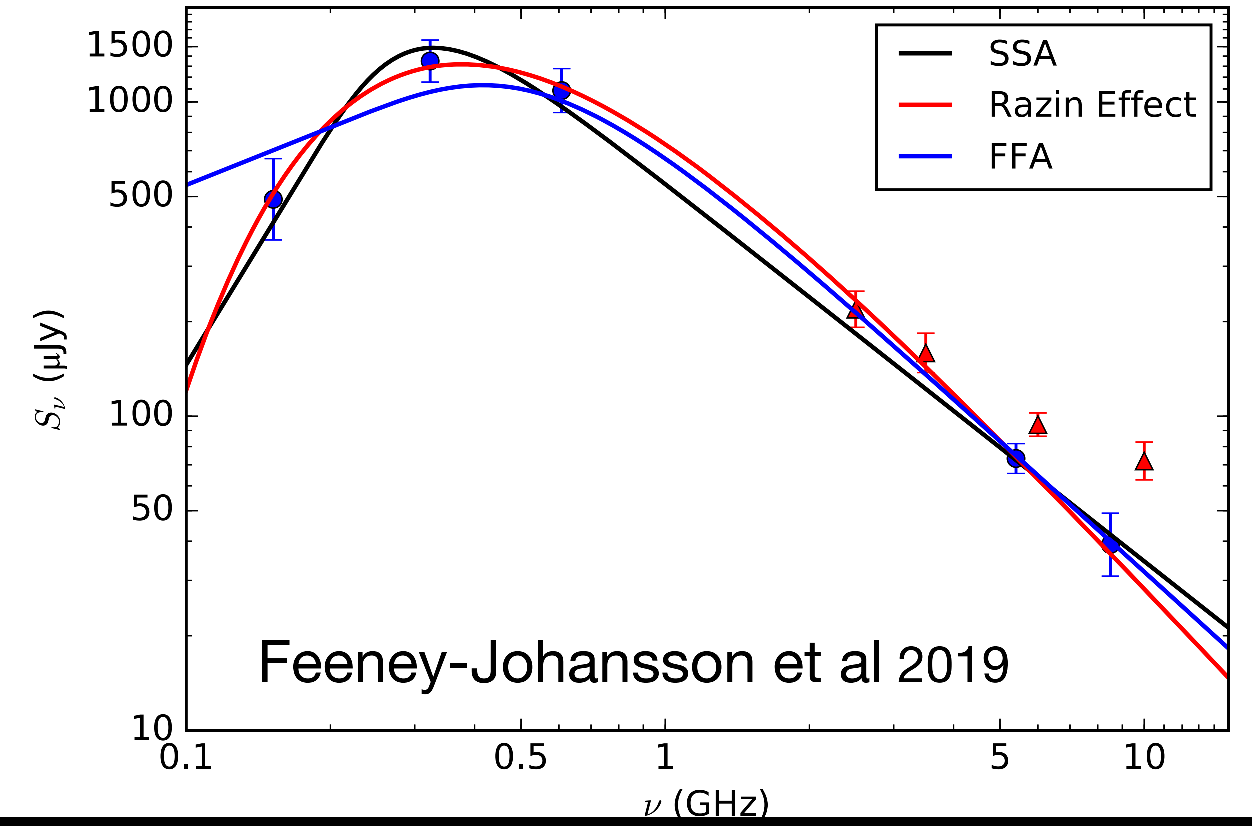
- ionization with <u>main parameter</u> ζ = CR ionization per H atom per unit time.

- Enhanced ionisation rates deduced from HCO^+ / N_2H^+ abundances (eg Podio et al 2014)

Rodriguez-Kamenetzky + 2017



HH80-81



Feeney-Johansson et al 2019

DG Tau hotspot C

Galactic Cosmic Ray contribution

- Likely restricted to outer enveloppes using simple energetic arguments (Padovani et al 2015)

Full gravitational luminosity

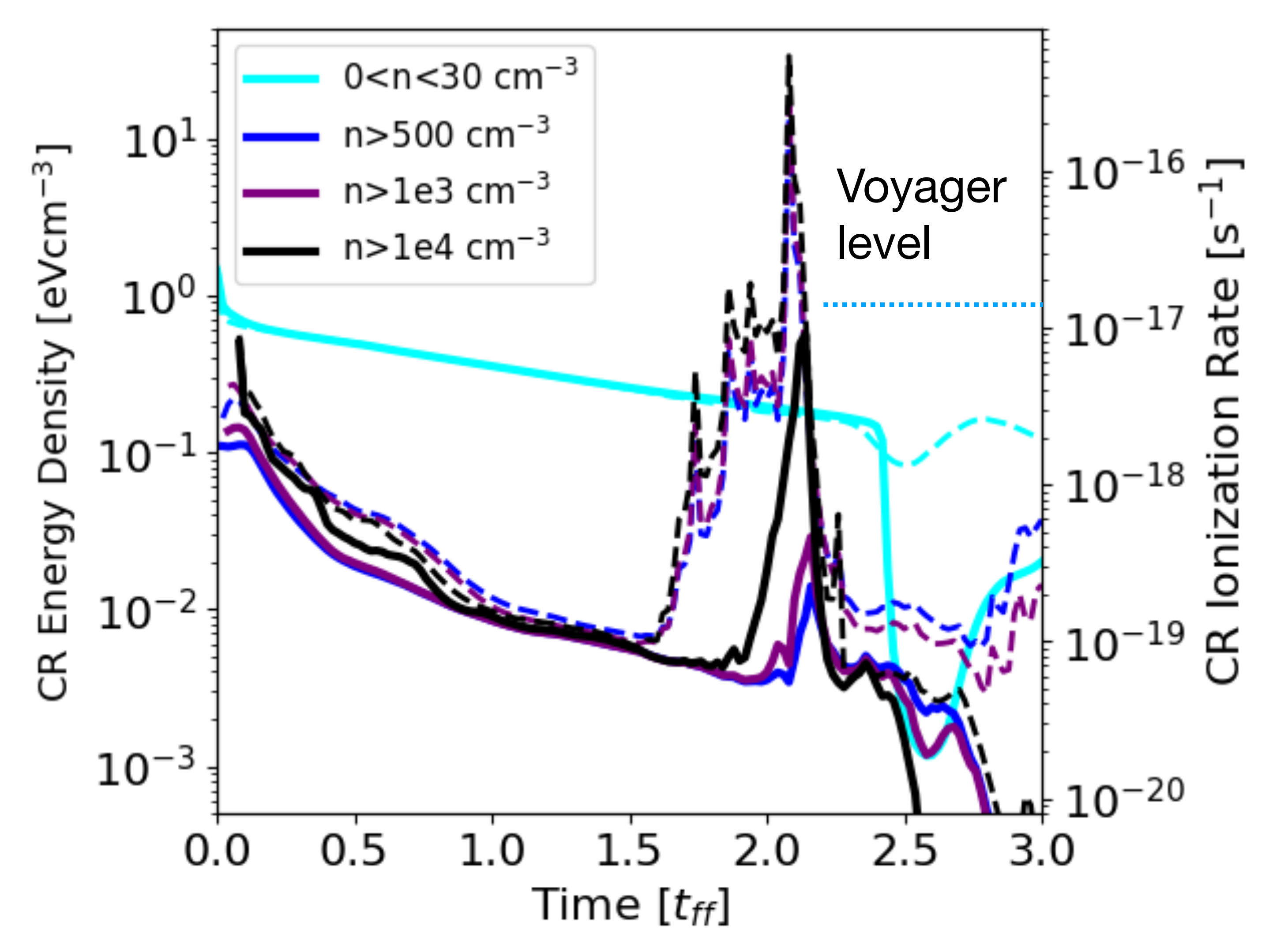
$$L_{\mathrm{grav}} = \frac{G\dot{M}M}{R_{\mathrm{sh}}} \sim 3\times10^{34}\,\mathrm{erg/s}$$ Class 0 low mass protostar

Cosmic Ray luminosity reaching the stellar core

$$L_{\mathrm{CR}} \sim R^{2}_{\mathrm{core}} V_{\mathrm{a}} e_{\mathrm{CR}} \sim 1.2\times10^{29}\,\mathrm{erg/s}$$ e_{CR} CR energy density

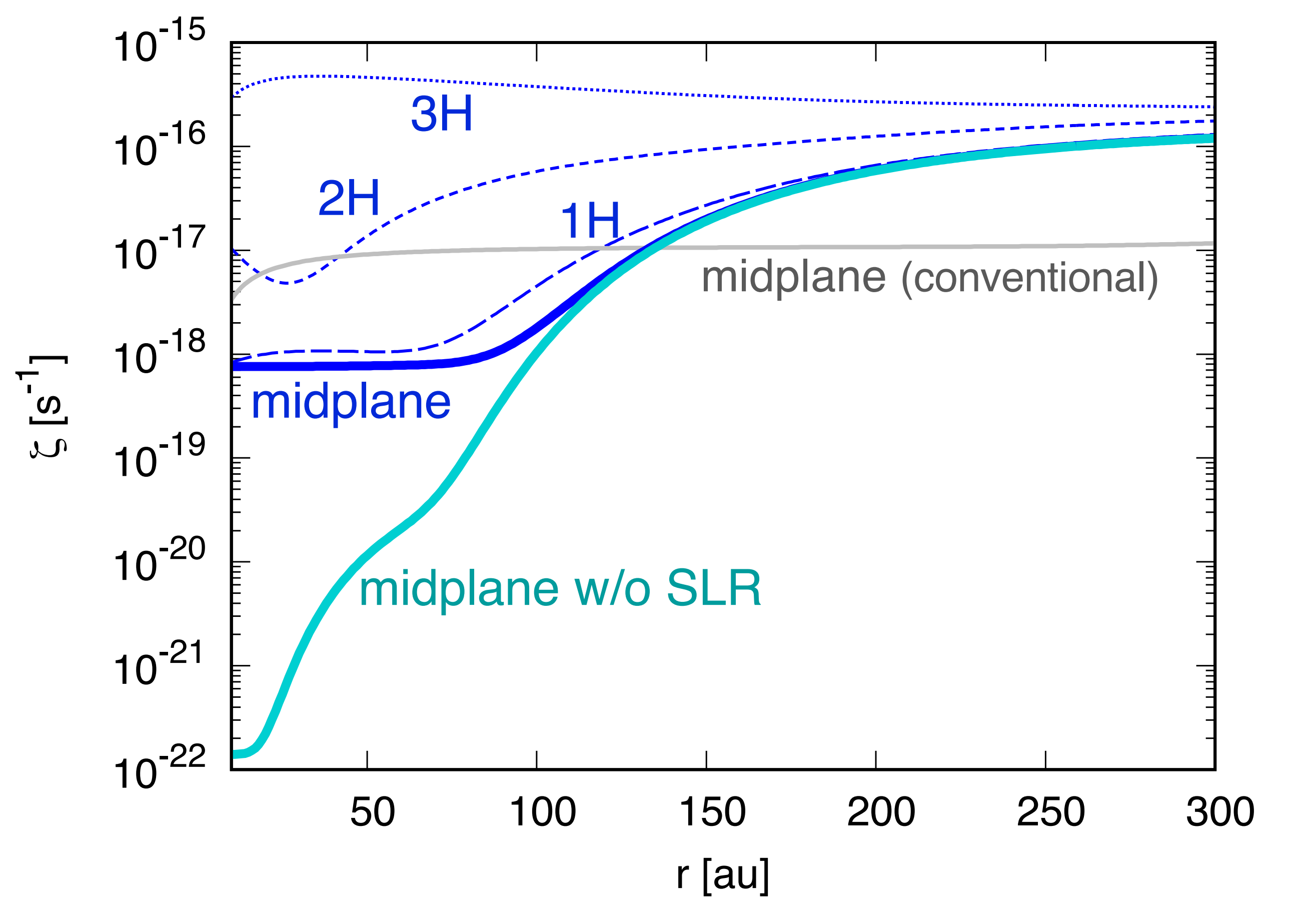
$>$ even a fraction of % of L_{grav} converted into in-situ accelerated EPs takes over L_{CR}

Molecular cloud to cloud core scales



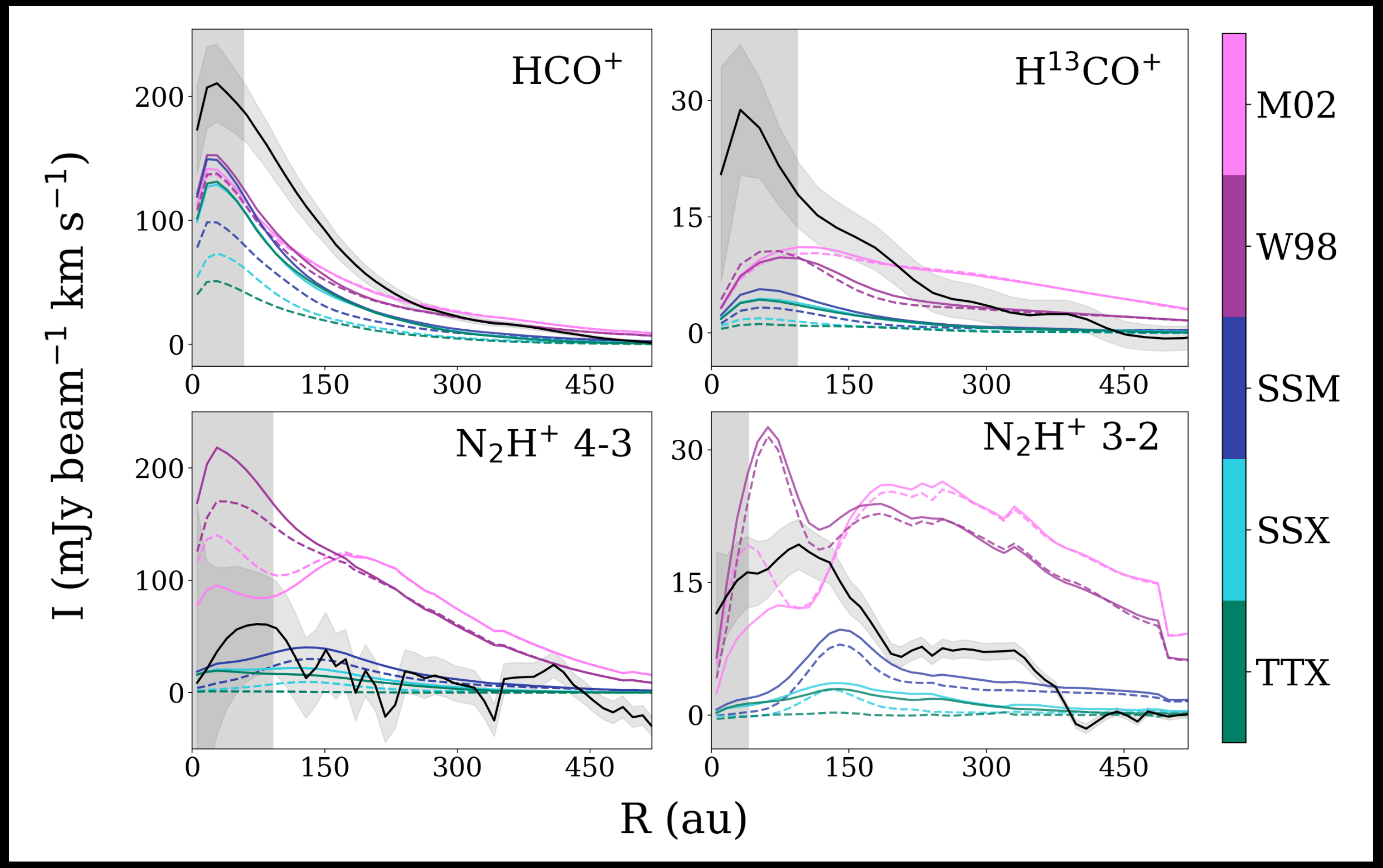
Fitz-Axen et al 2024 : bi-fluid MHD simulations

Protoplanetary discs scales



Fujii & Kimura 2023 (w/o T-Taurisphere)

ALMA data fitting of DM tau disc

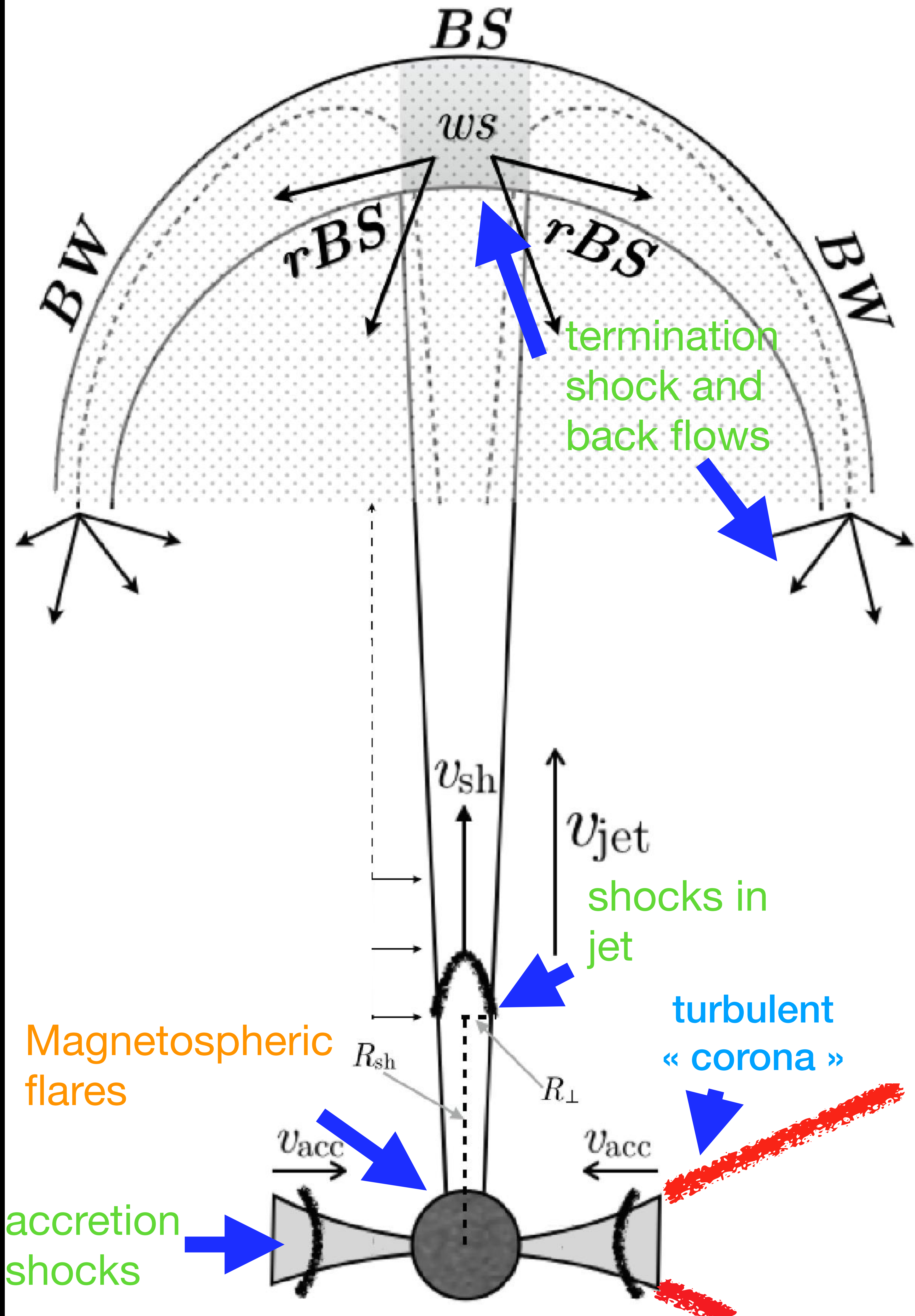


Long et al 2024 (w T-Taurisphere)

CR contribute to rates $10^{-19/-18}\mathrm{s}^{-1}$ at disc mid-plane, difficult to explain ion species abundances at inner discs

In-situ acceleration sites / mechanisms

- Shocks (part I, cf Padovani et al 2015, 2016, 2021, Araudo et al 2021) :
  - Accretion shocks
  - Shocks in jet
  - Termination shock & hot-spot/back flows (weak shocks + turbulence reacceleration) * back flows not treated yet.
- Stellar flares (magnetic reconnection) interacting with the accretion disc (part II, cf Brunn's talk, Brunn et al 2023, 2024).
- MRI-induced Turbulent « corona » (magnetic reconnection + Stochastic Fermi acceleration) (part III, Brunn et al 2025 in prep).



termination shock and back flows

shocks in jet

turbulent « corona »

Magnetospheric flares

accretion shocks

Part I shock acceleration

Main model parameters (W/S = jet, W = slow shock, S = fast shock, P=protostellar shock) and main results (see Padovani et al 2016)

shock speed

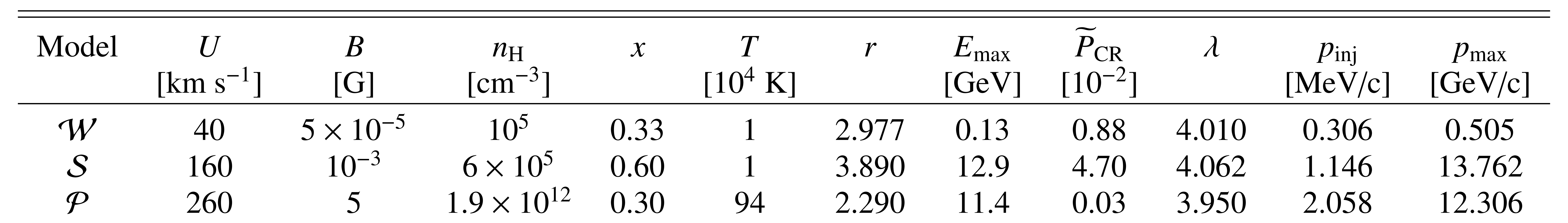
Magnetic field amplitude

gas density

ion fraction

Temperature

compression ratio



Model	U [km s^{-1}]	B [G]	n_H [cm^{-3}]	x	T [10^4 K]	r	E_max [GeV]	$\widetilde{P}_\mathrm{CR}$ [10^{-2}]	λ	p_inj [MeV/c]	p_max [GeV/c]
$\mathcal{W}$	40	5×10^{-5}	10^5	0.33	1	2.977	0.13	0.88	4.010	0.306	0.505
$\mathcal{S}$	160	10^{-3}	6×10^5	0.60	1	3.890	12.9	4.70	4.062	1.146	13.762
$\mathcal{P}$	260	5	1.9×10^{12}	0.30	94	2.290	11.4	0.03	3.950	2.058	12.306

proton max energy

fraction of shock kinetic energy into EP

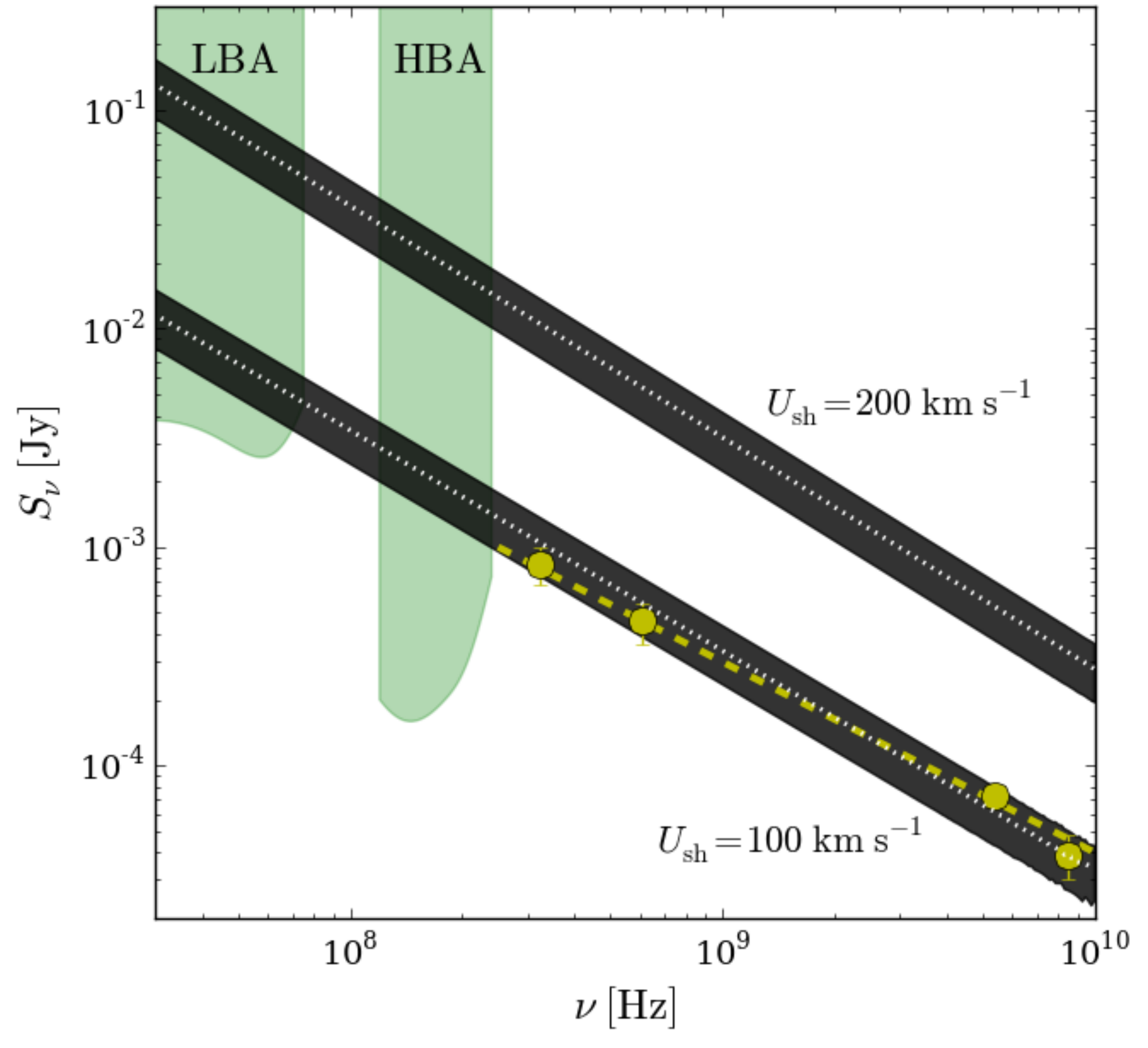
proton injection momentum to thermal momentum

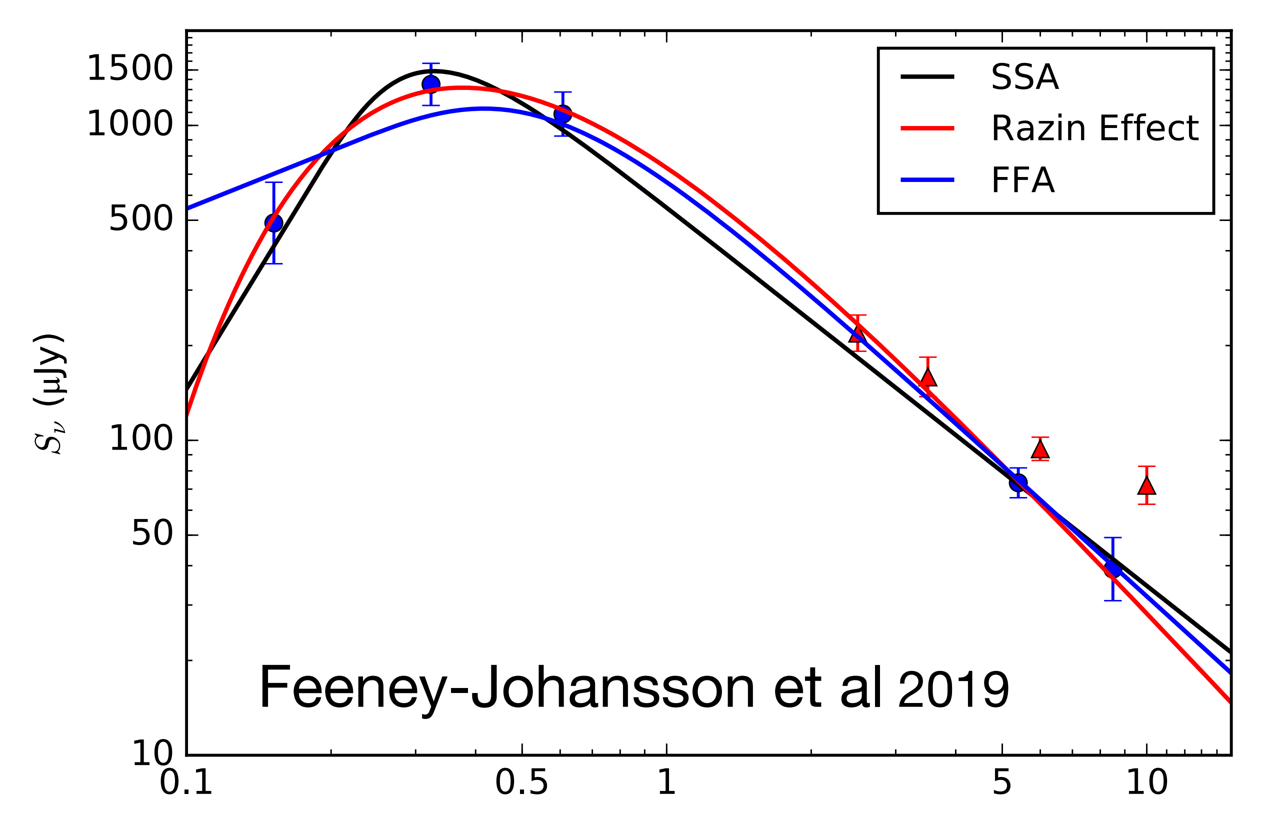
min/max proton momenta

EP pressure is low enough for shock to be unmodified, so EP distribution follows the test-particle solution.

Confront theory and observations

DG Tau hot spot





Feeney-Johansson et al 2019

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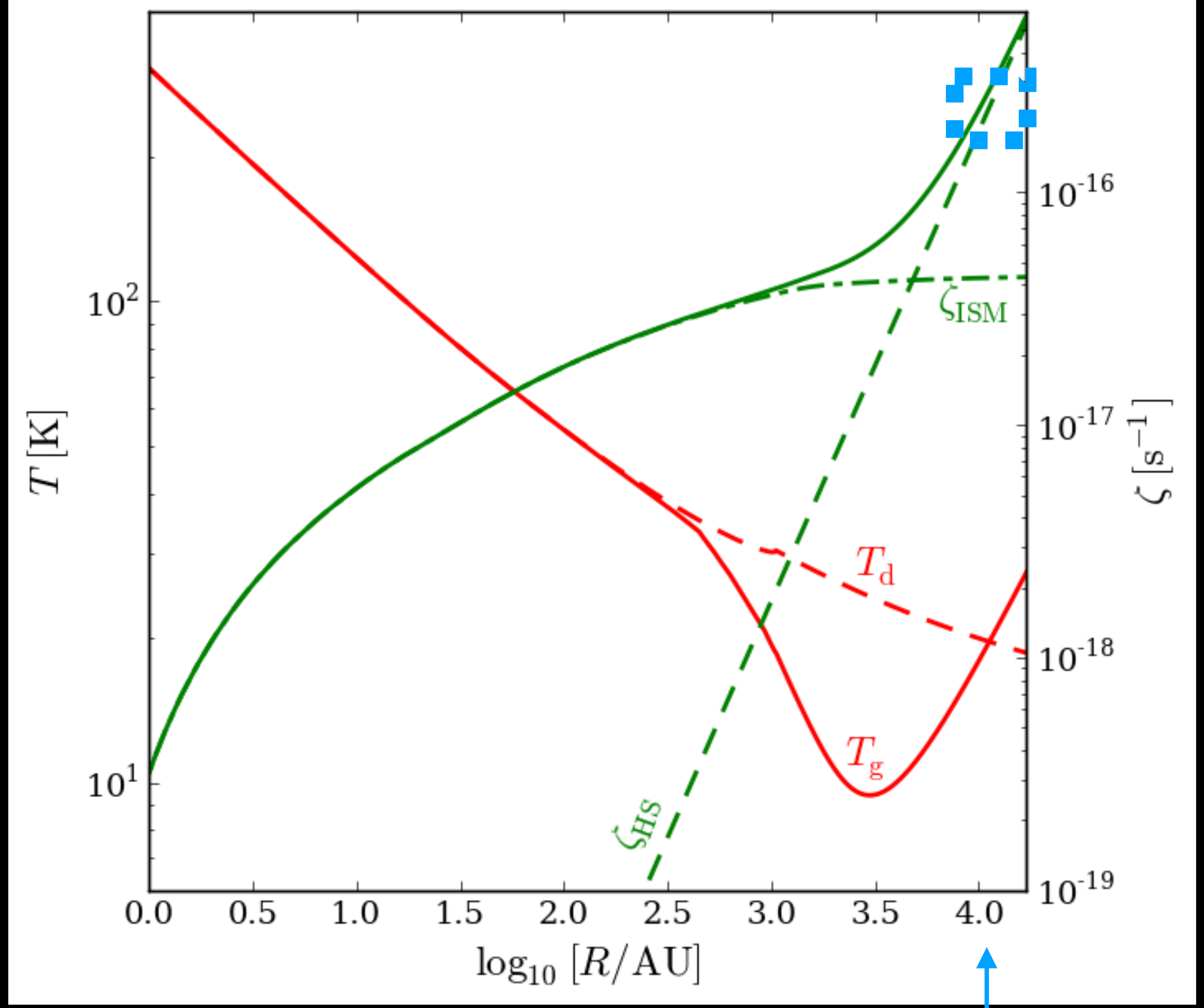
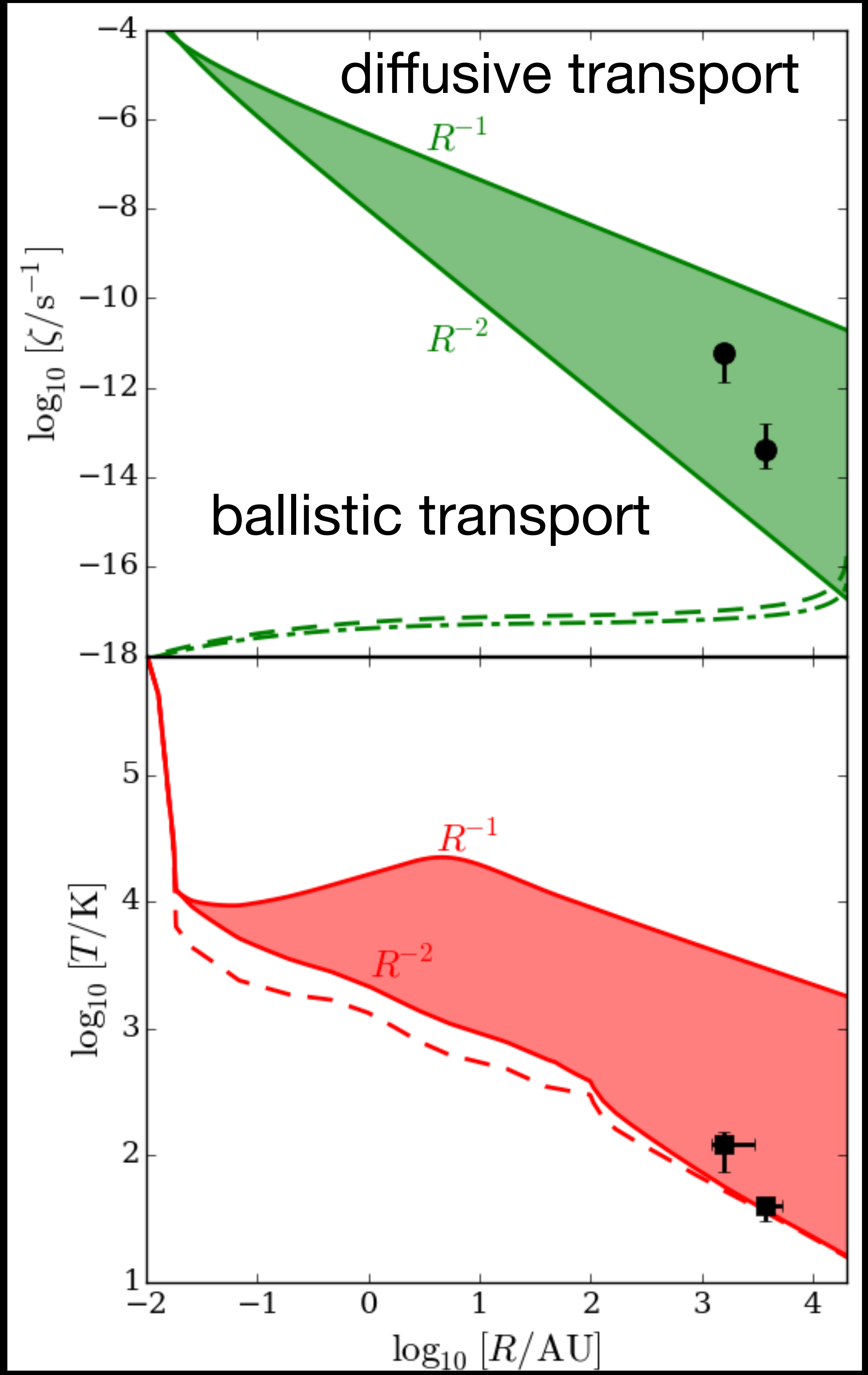


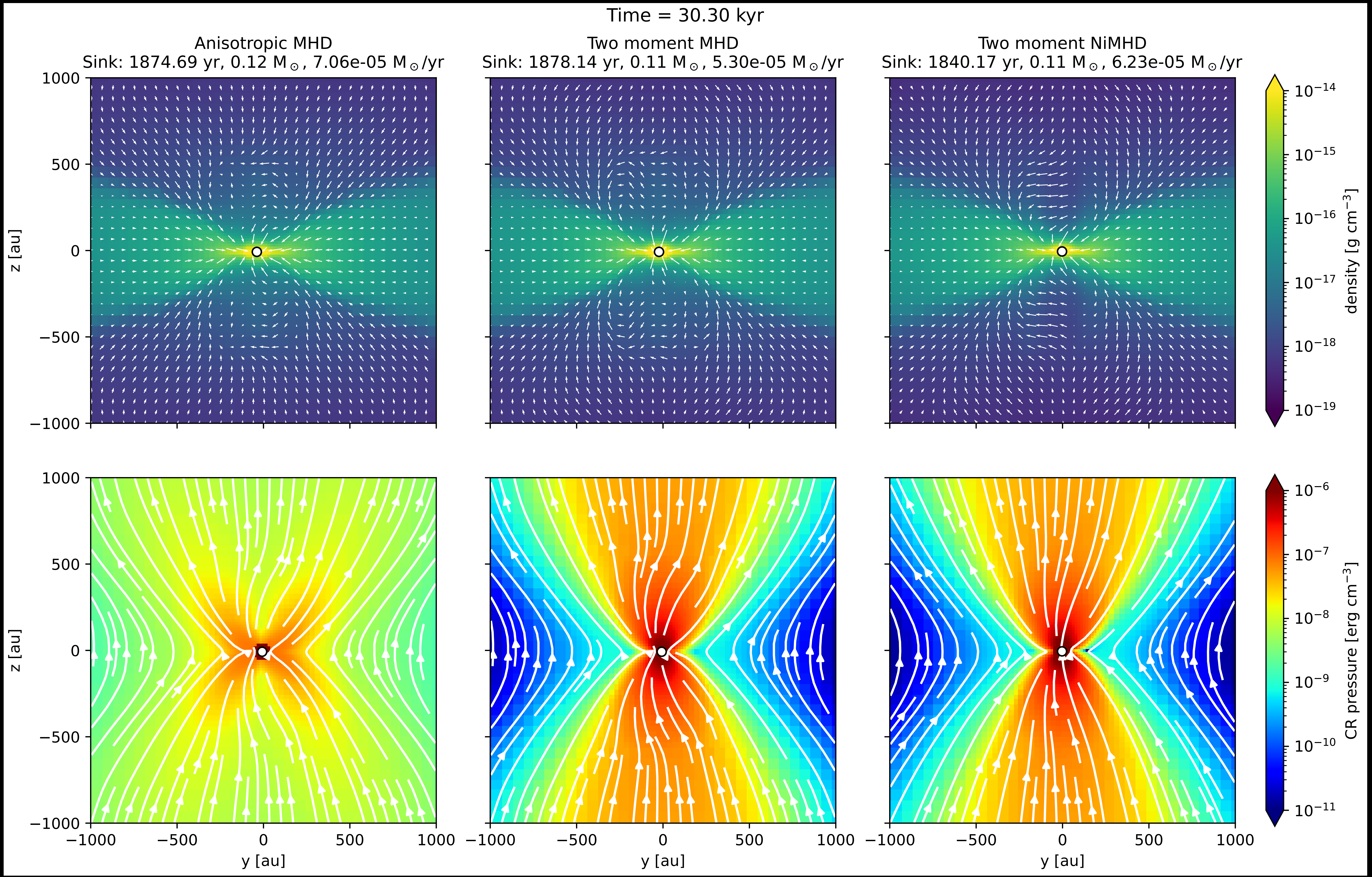
LH spots distance where ionization rates have been inferred, in dashed derived ionization rate.

OMC2-FIR4



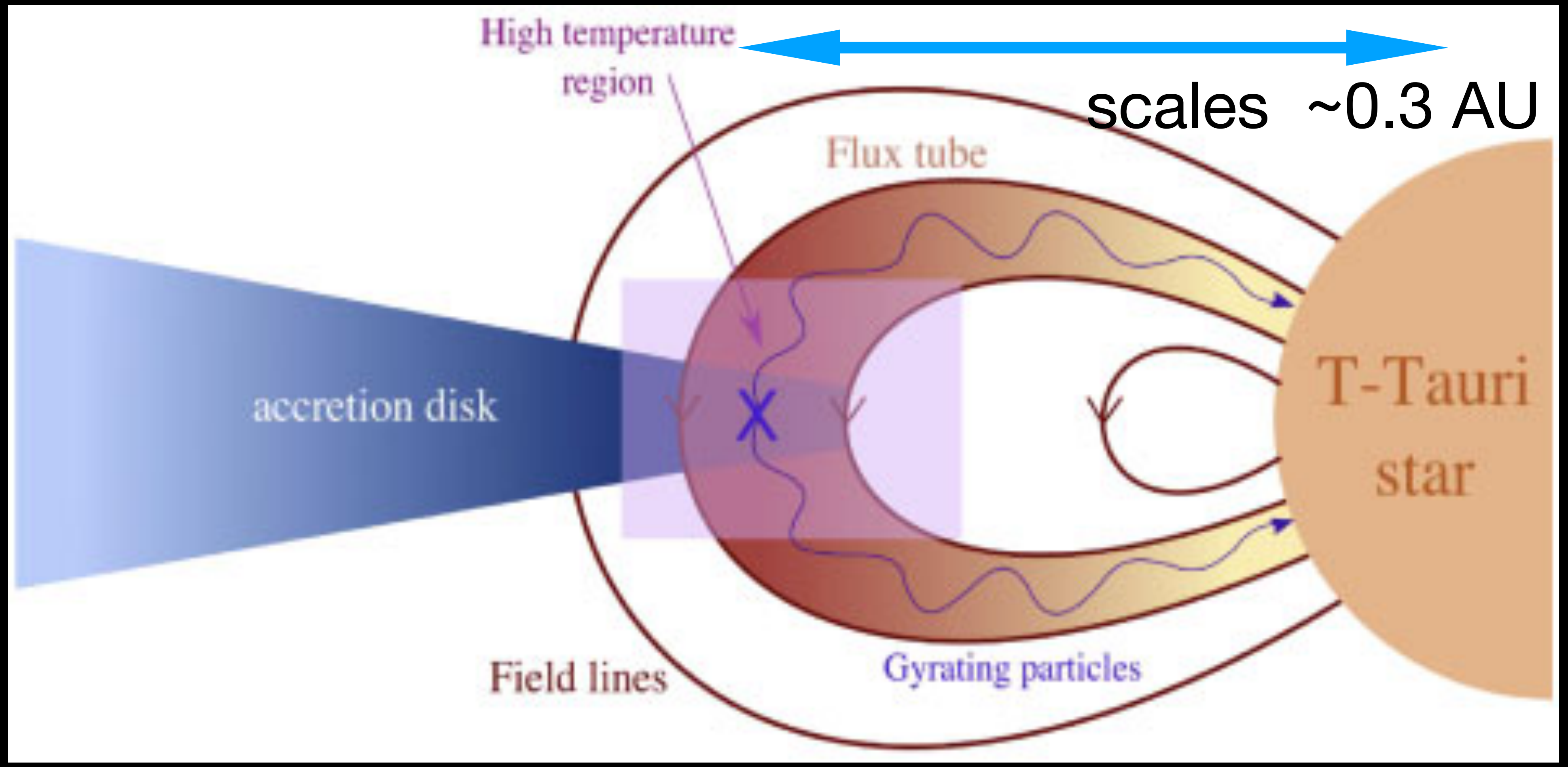
YSO as source EPs: ionization and dynamical effects

- See poster by Nai Chieh Lin
- Bi-fluid (gas+CR) simulations using RAMSES
- Only use model P (CR injection from protostellar shock)
- Default diffusion coefficient : $10^{24} \mathrm{cm}^2/\mathrm{s}$
- For now one CR component, but soon multi components (see Girichidis et al 2020)

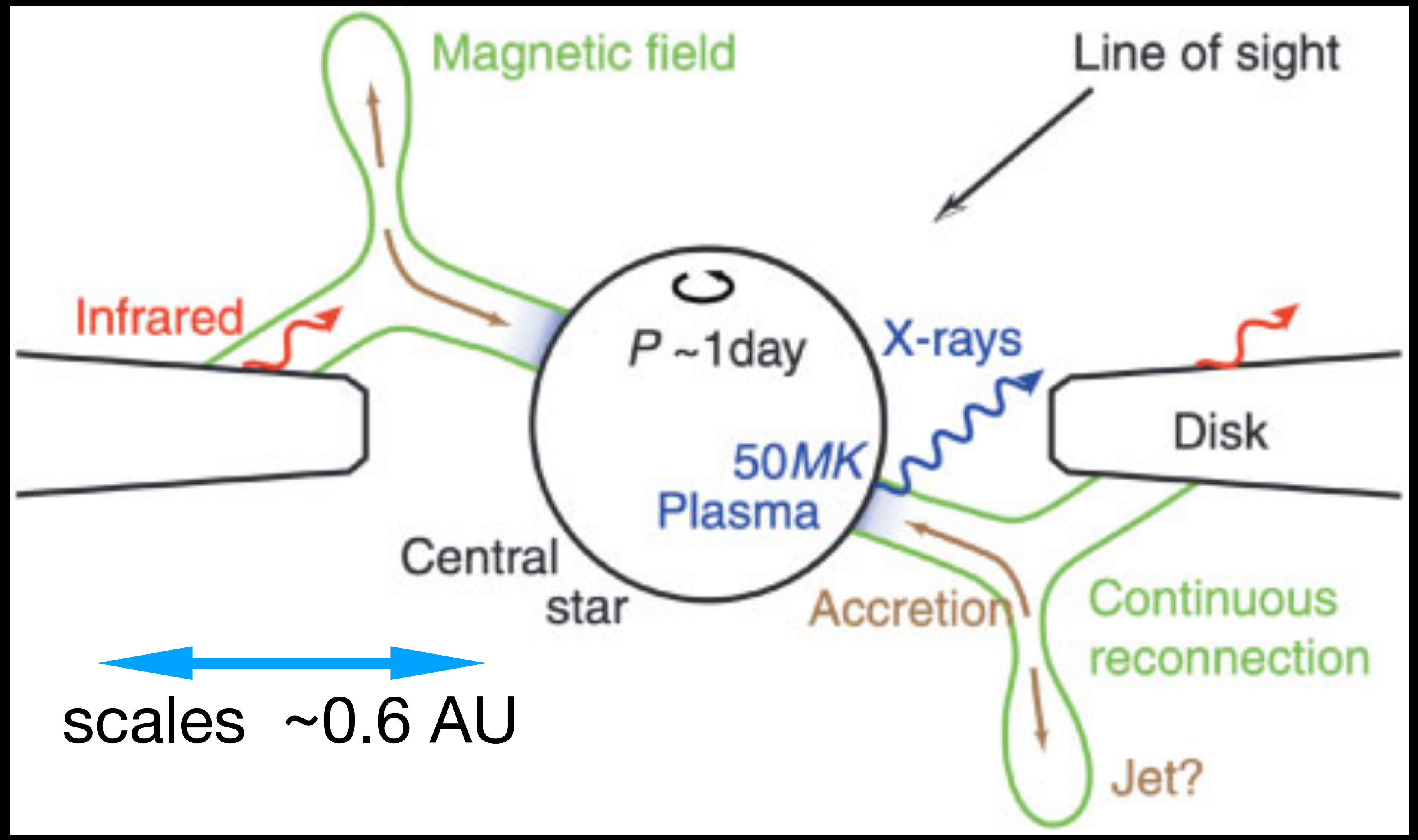


Part II : stellar flares and magnetosphere - accretion disc interaction

star-disc interaction configurations



from Waterfall et al 2020



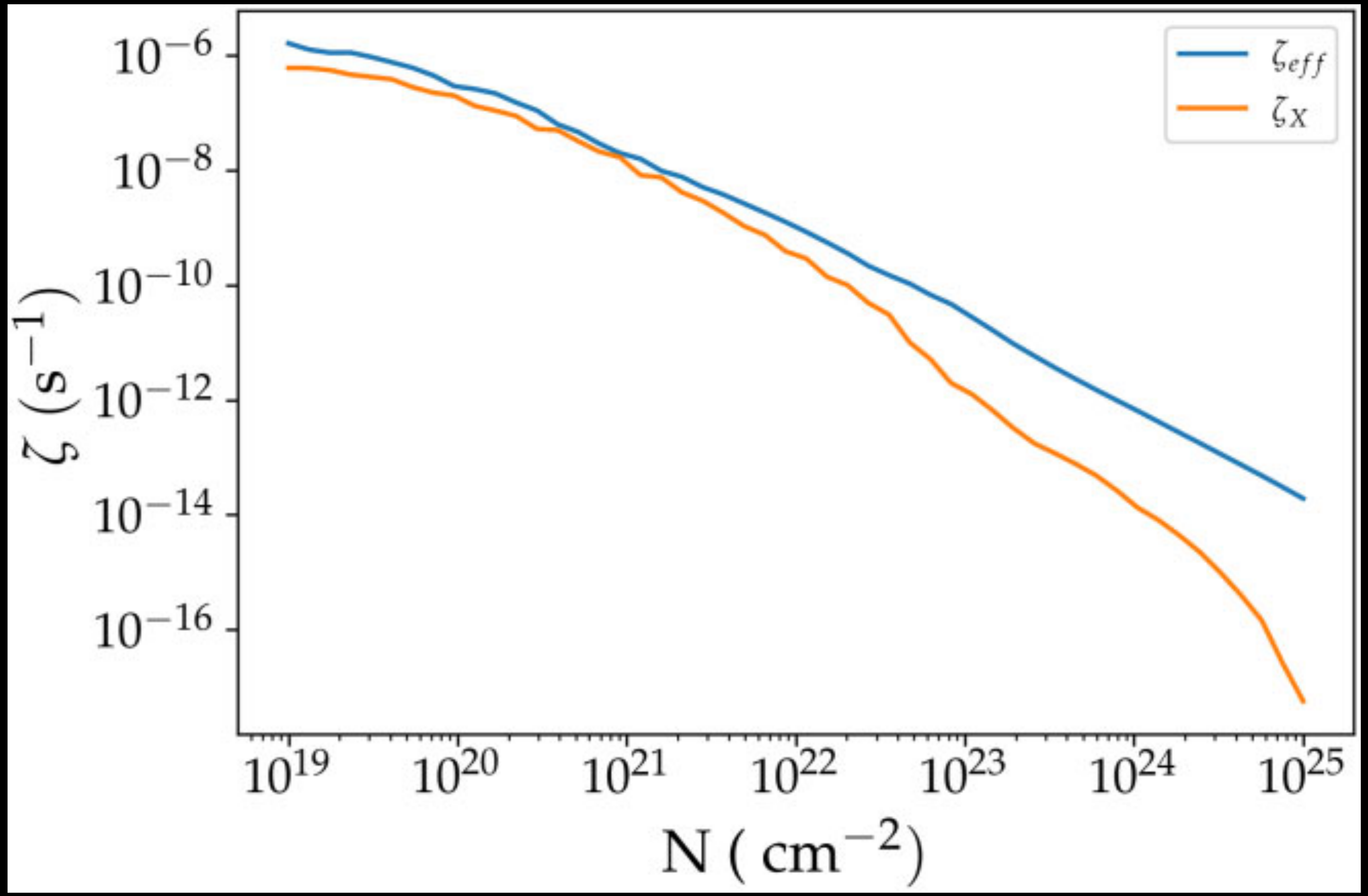
from Hamaguchi et al 2012

> EPs are injected during episodic magnetic reconnection events, with energetics sampled from Chandra data (COUP) and solar flare observations.

> EPs produced above/close to the disc propagate along disc magnetic fields

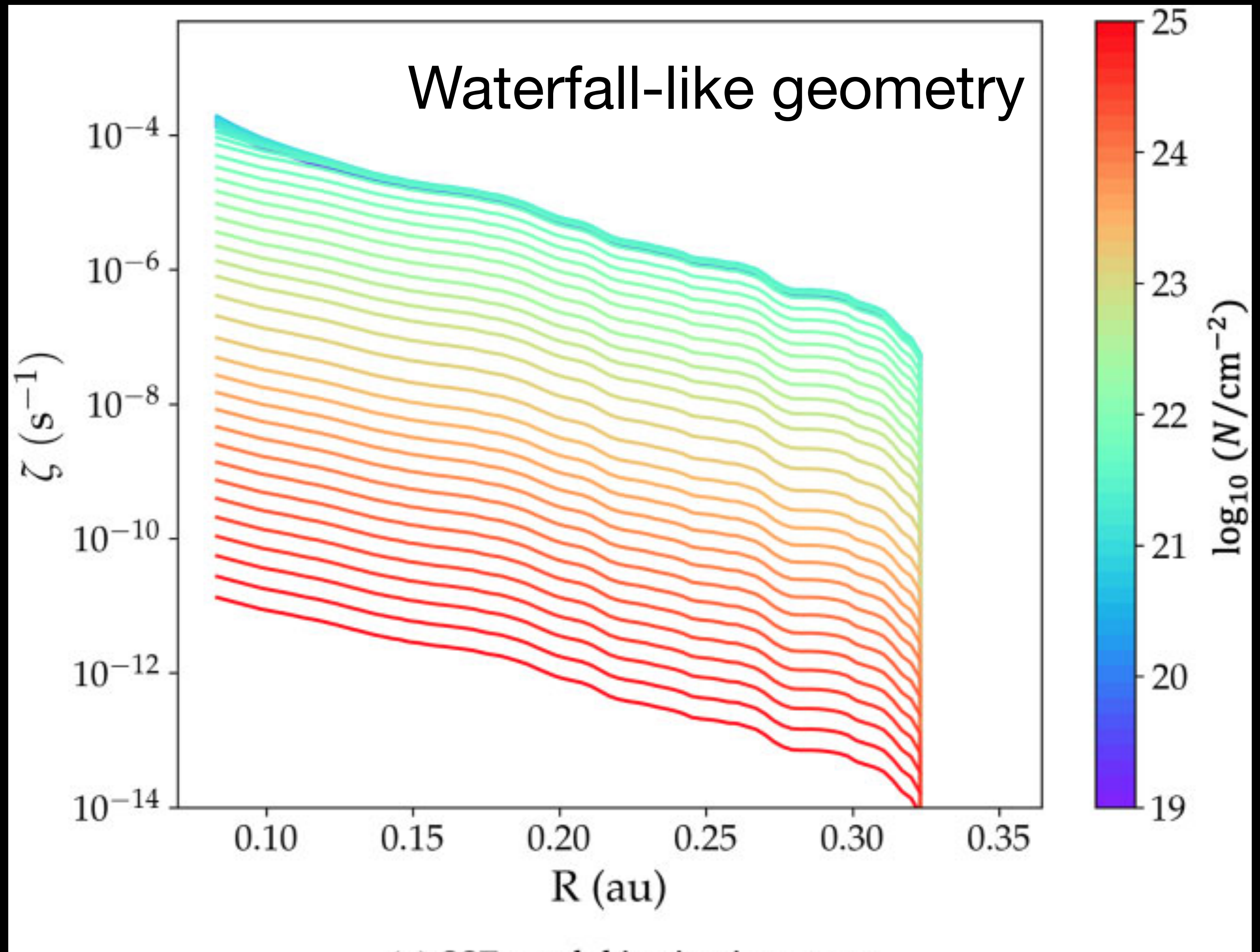
Ionisation rates

single 10 MK (luminous) flare ionisation rate

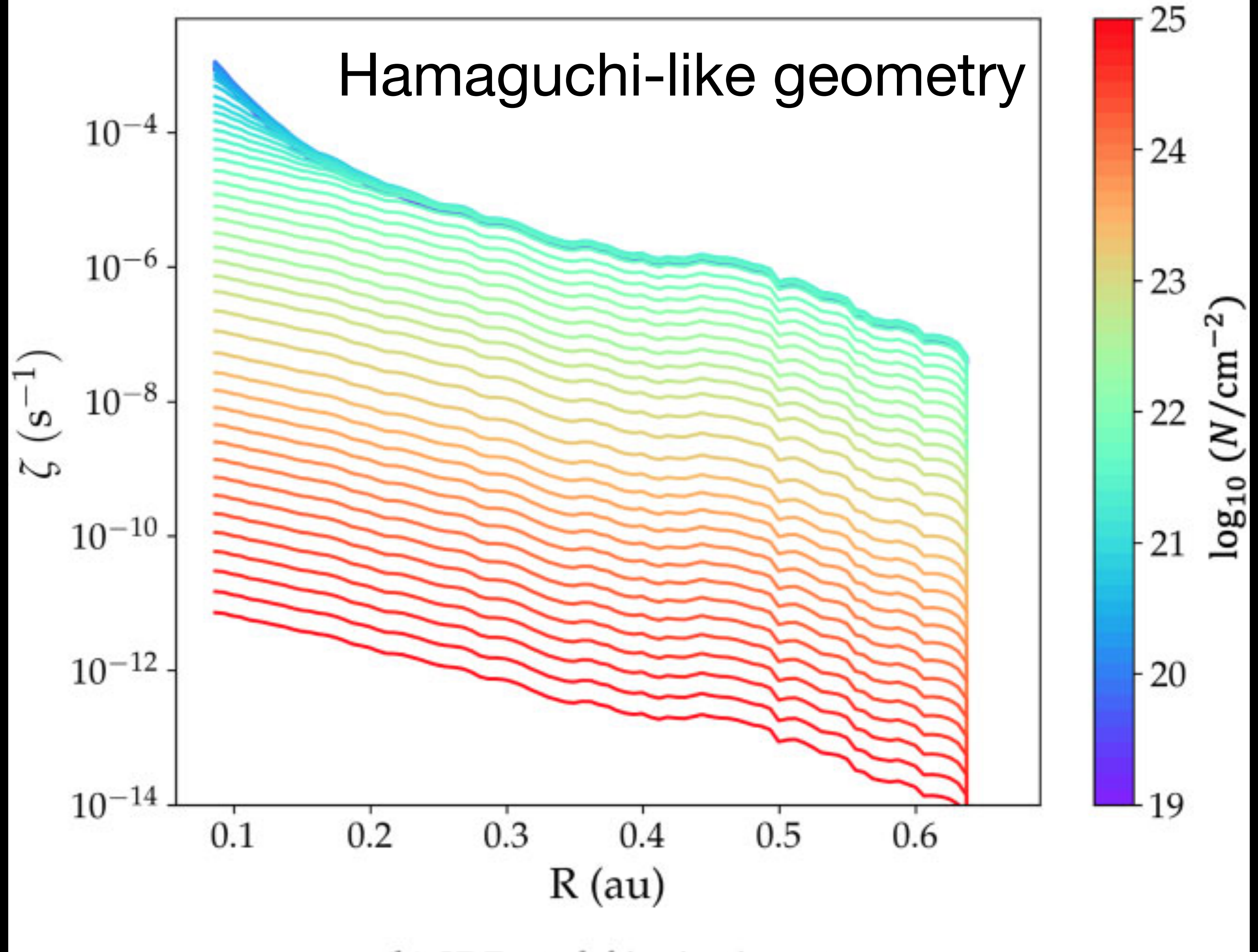


versus effect of stellar X-rays

Multiple flares ionisation rates



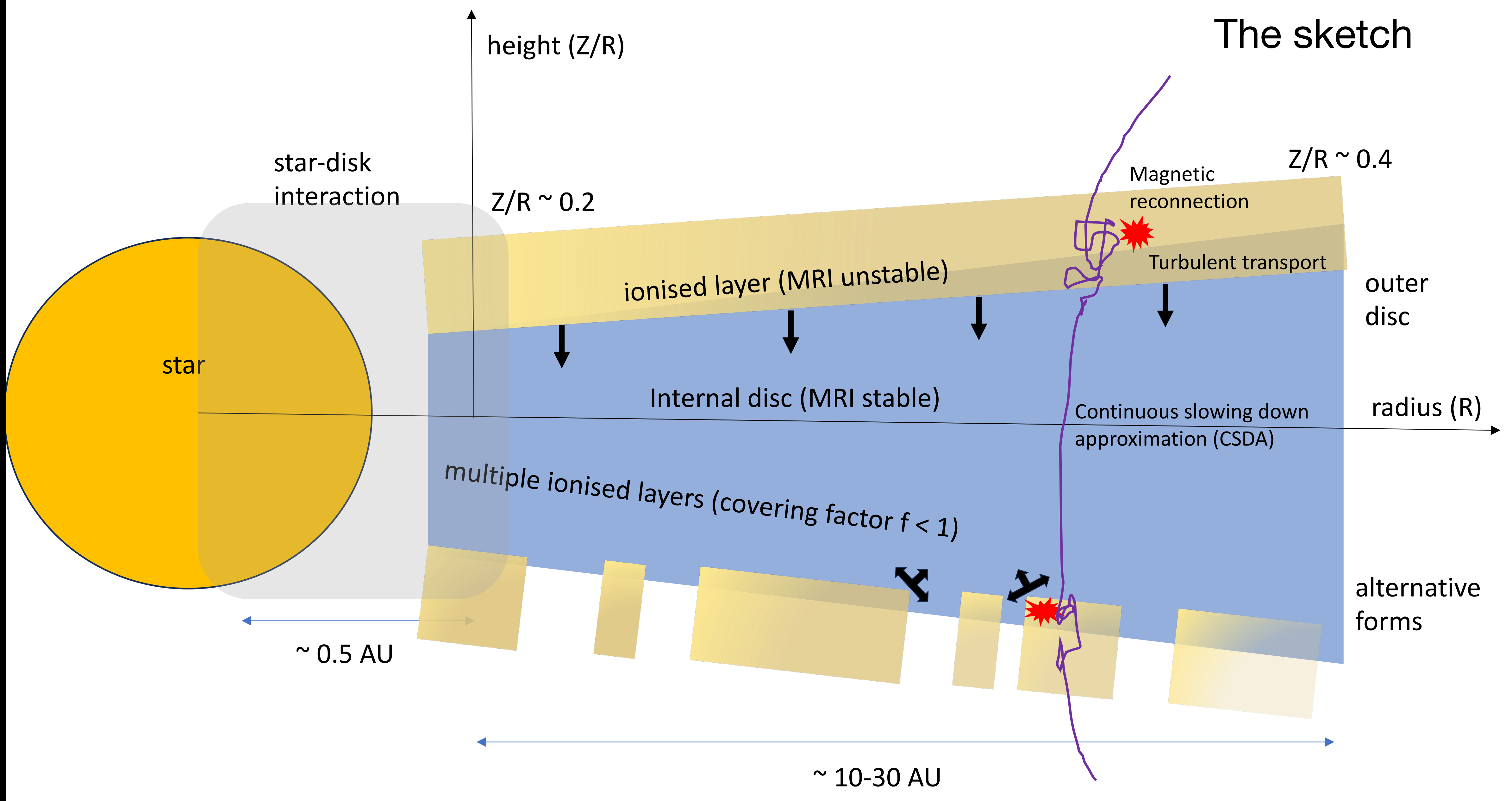
(a) SSF model ionisation rates



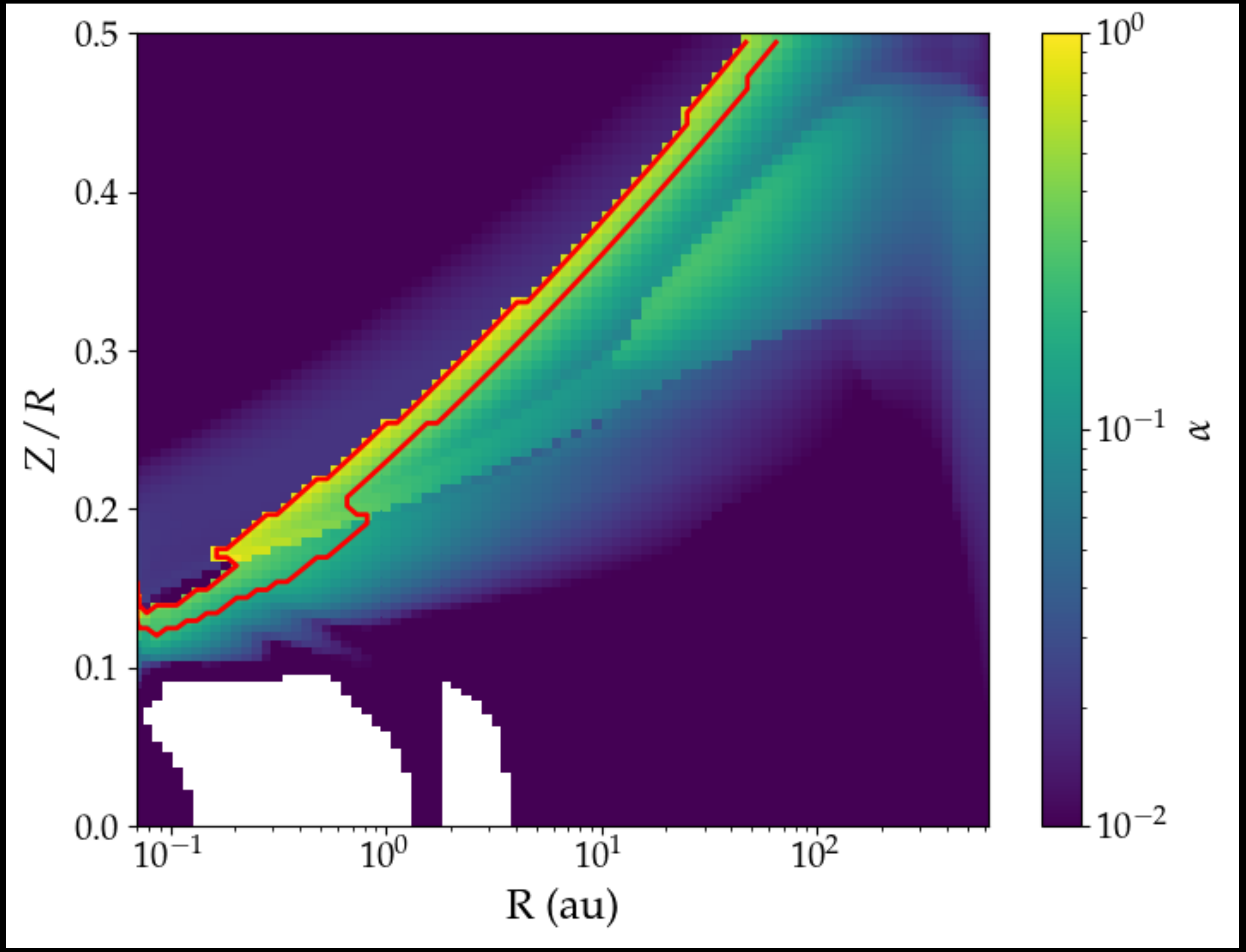
(b) SDF model ionisation rates

see talk by V. Brunn

Part III : turbulently-driven magnetic reconnection in accretion discs



Prodimo profiles : alpha parameter



the red curve delimits regions with $\alpha = \alpha_{max}$ where MRI is saturated (Bai & Stone 2011), based on a condition over plasma beta parameter.

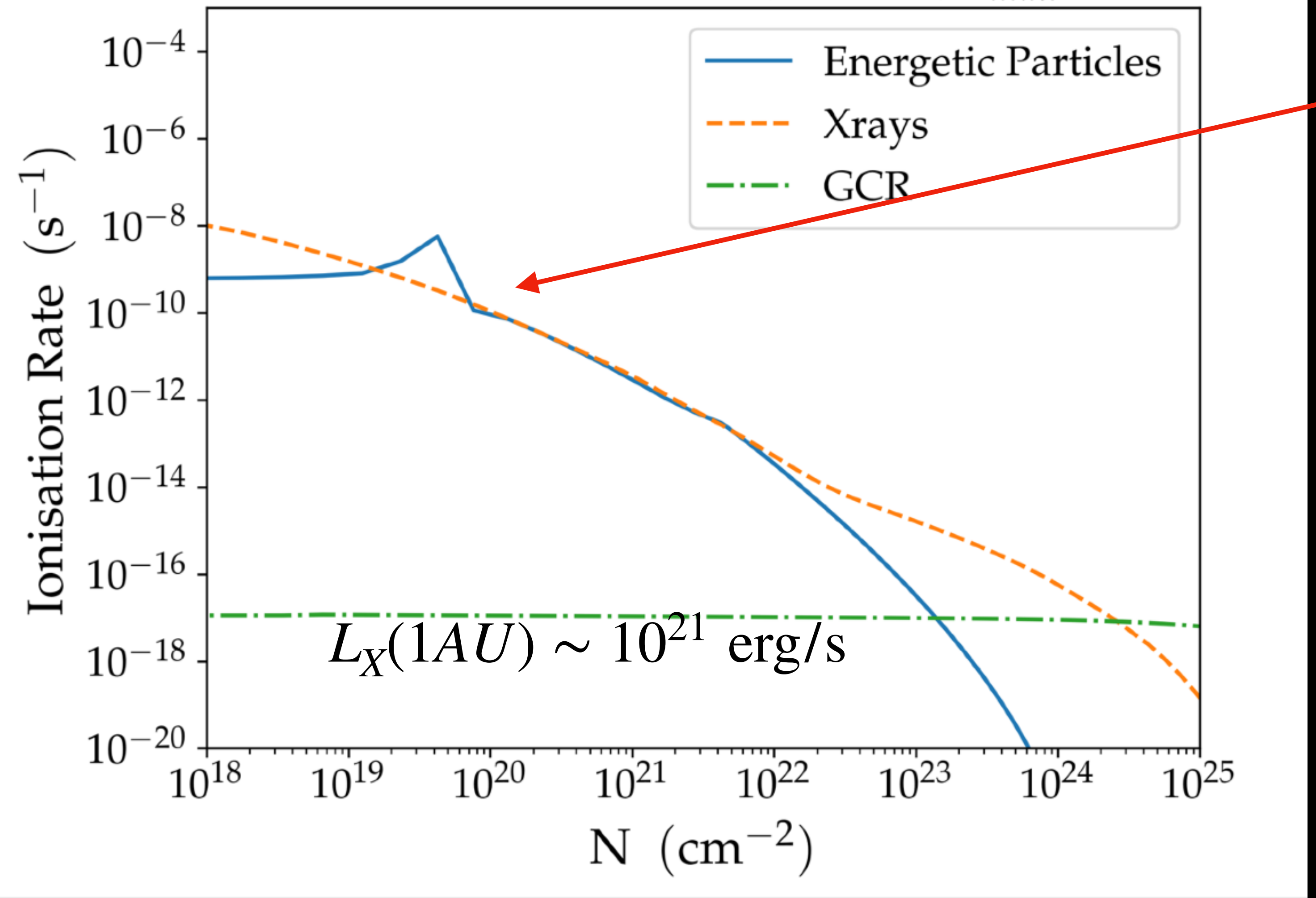
First estimations : ionisation rates

Injection $N_{EP}(E) = N_0 \left(\frac{E}{E_c}\right)^a \exp(-E/E_{\max})$ in the MRI saturated zone at a given radius, N_0 deduced from free electron density,

$E_c = 3k_BT$ (see Brunn et al 2023), $E_{\max}$ fixed by the size of reconnection regions L fixed by the scale at which MRI grows the fastest.

Hence the parameters are : $N_e, T, a, E_{\max}$, continuous slowing down approximation is used for EP transport.

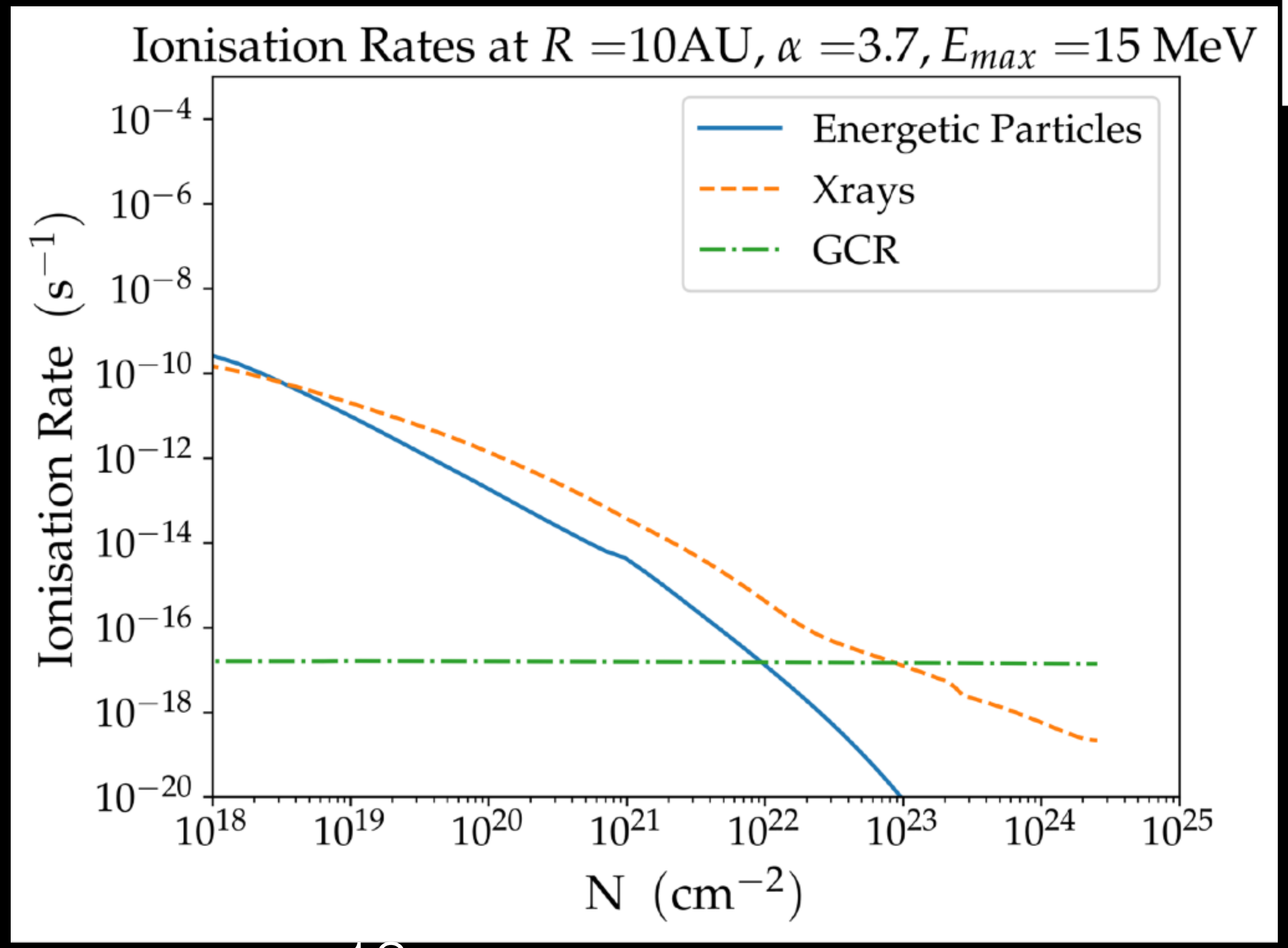
Case $a = 3.7, E_{\max} = 15MeV$, X-ray luminosity $L_X = 10^{30}\mathrm{erg/s}$

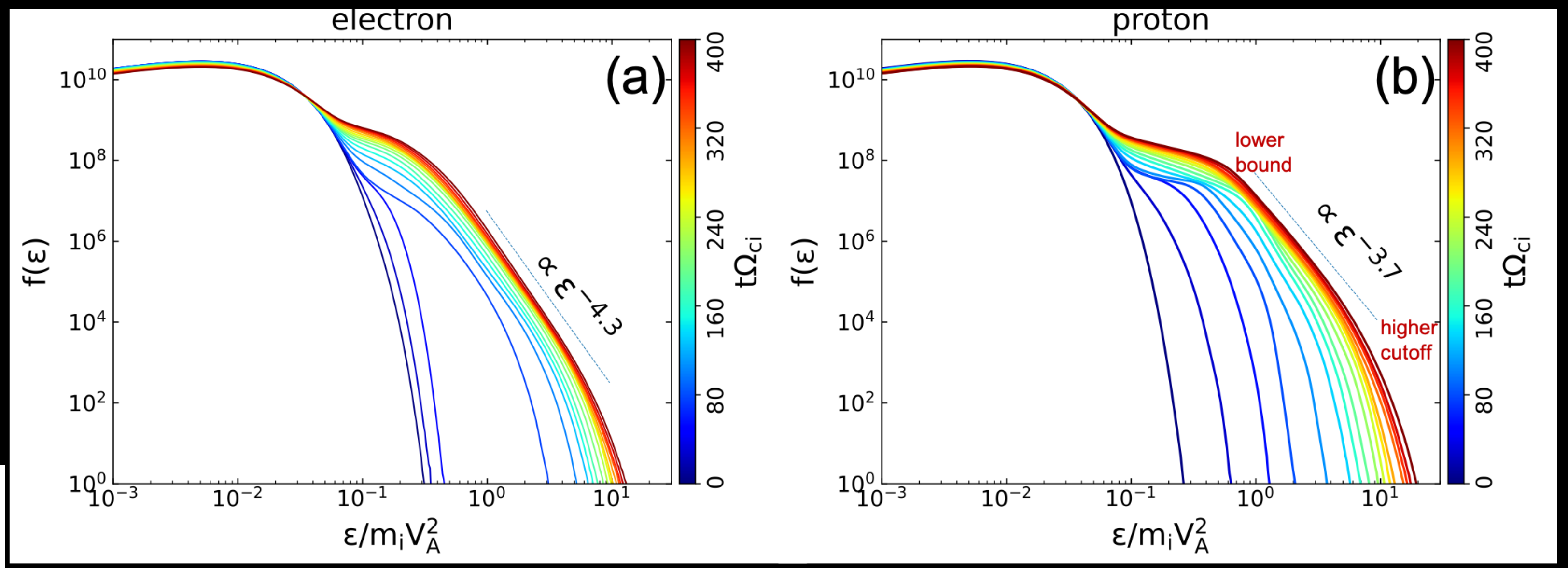


injection site

$a = 3.7$

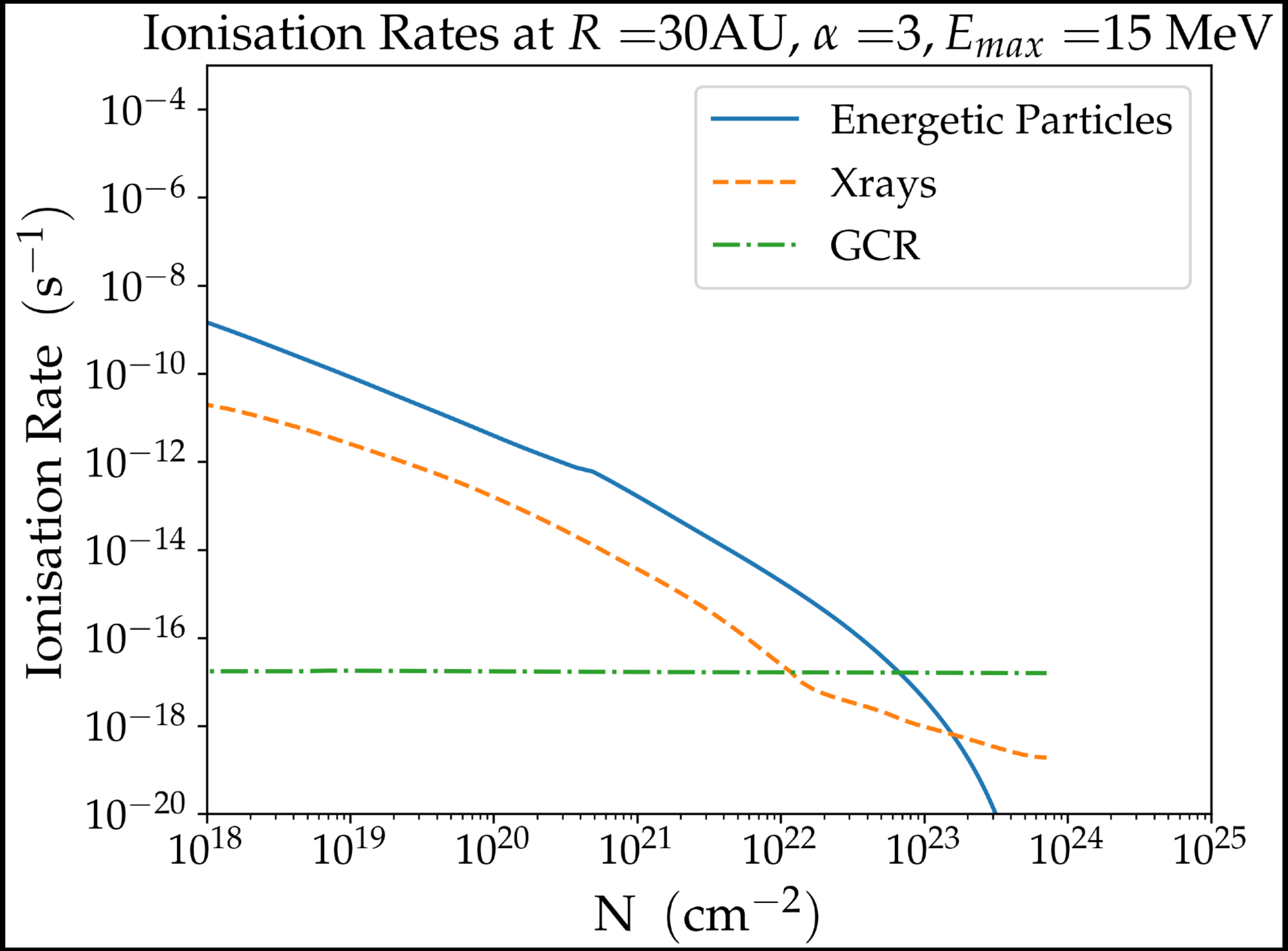
$E_{\max}$ <=> $t_{acc} = t_{dyn}$

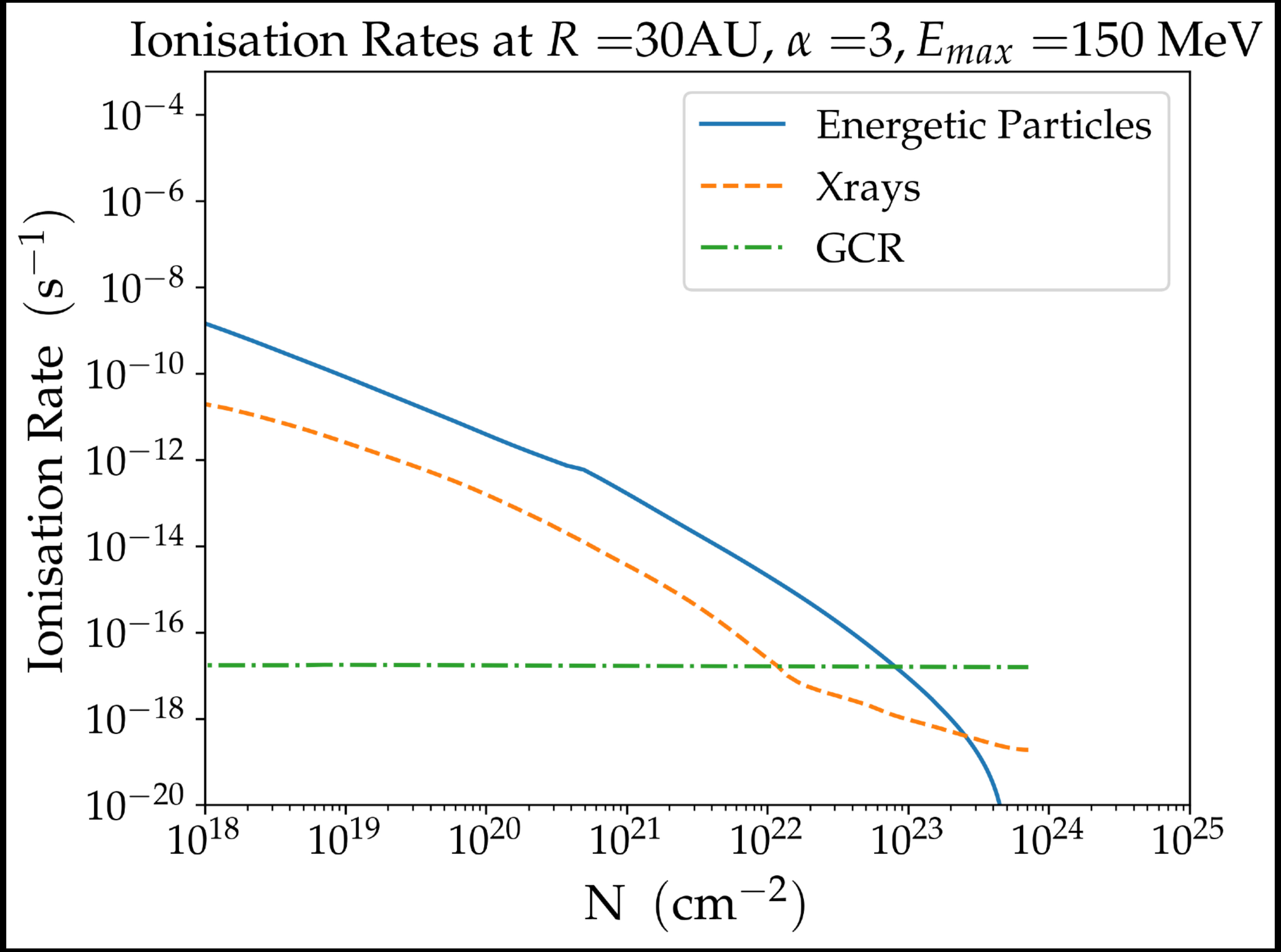




Zhang et al 2024 (3D PIC simulations)

Ionisation as function of $(E_{\max}, \alpha)$



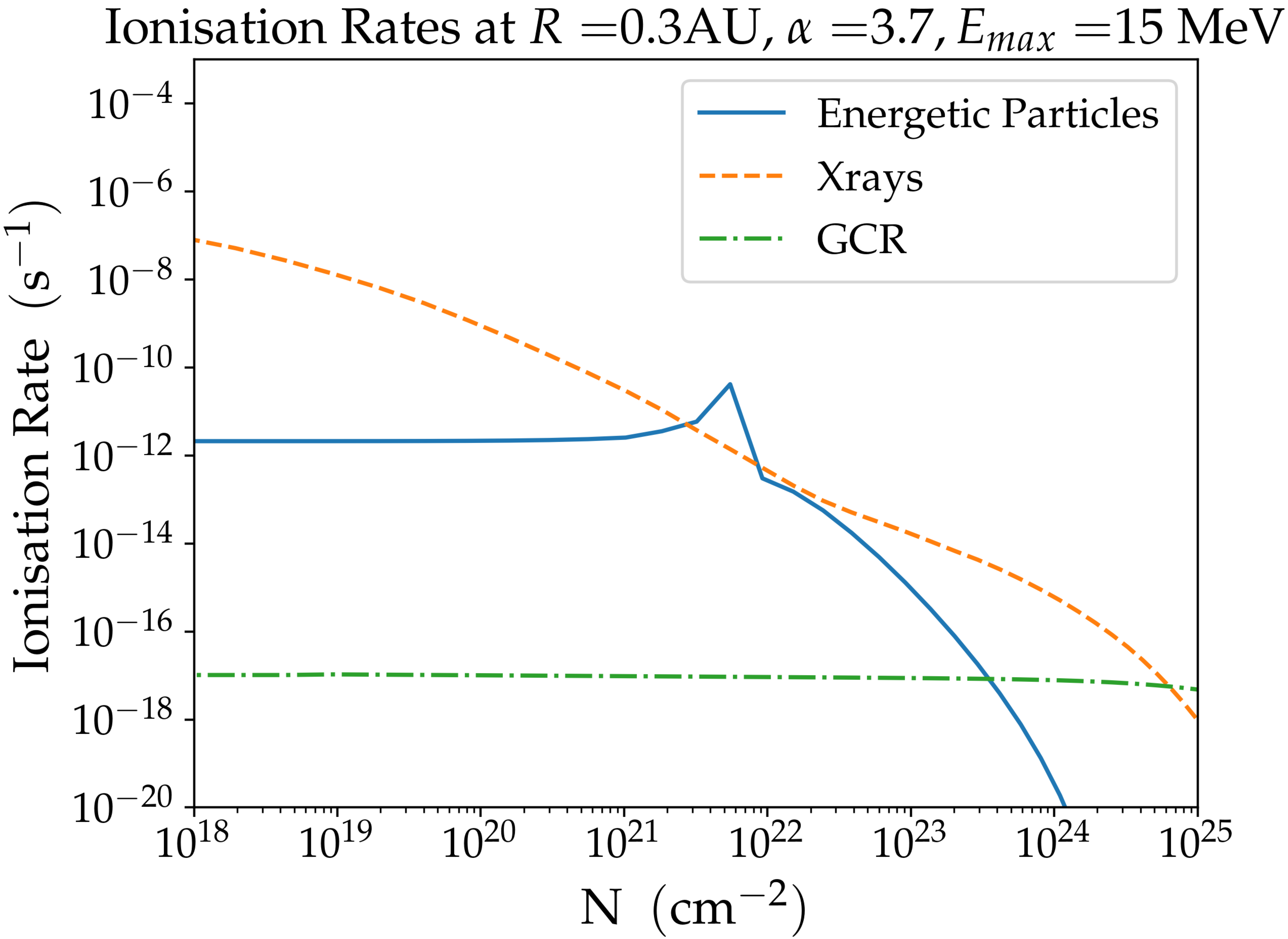


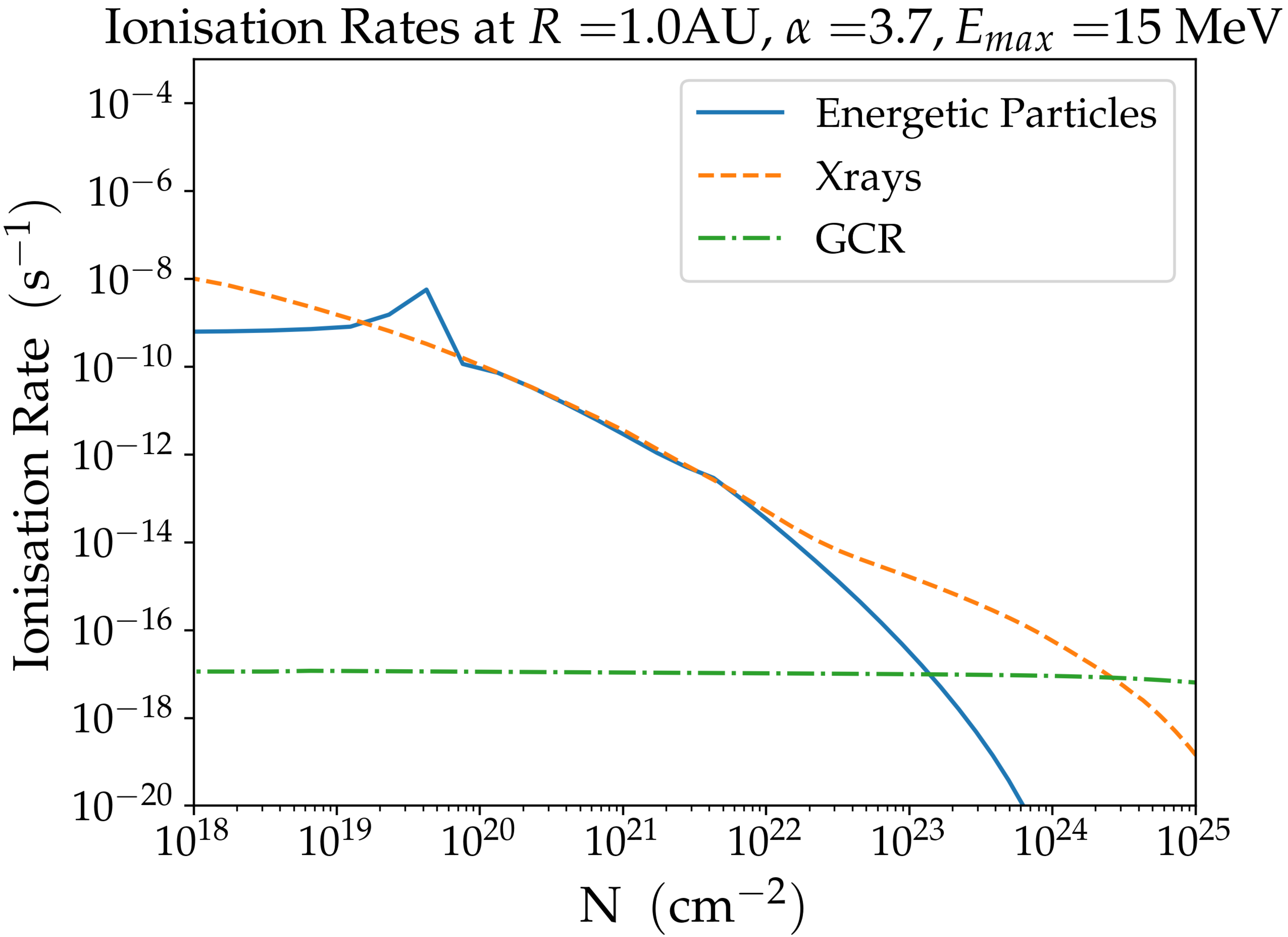
Conclusions

- In-situ EP should take over CR contribution at YSO inner disc and in jets.
- The model can help explaining non-thermal radio emission and high ionization rates @ 100-1000 AU

=>YSO should hence be proper sources of EPs and of local ionization (YSO clusters) of the parent molecular cloud (Padovani et al in prep)

- EP can contribute to dynamics because of ionization and pressure effects (see N.C. Lin)
- EP can potentially be a source of ionization @ 1-10 AU and explain some ALMA data.


Ionisation Rates at R =0.3AU, α =3.7, E_{max} =15 MeV
Energetic Particles
Xrays
GCR
Ionisation Rate (s^{-1})
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
N (cm^{-2})


Ionisation Rates at R =1.0AU, α =3.7, E_{max} =15 MeV
Energetic Particles
Xrays
GCR
Ionisation Rate (s^{-1})
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
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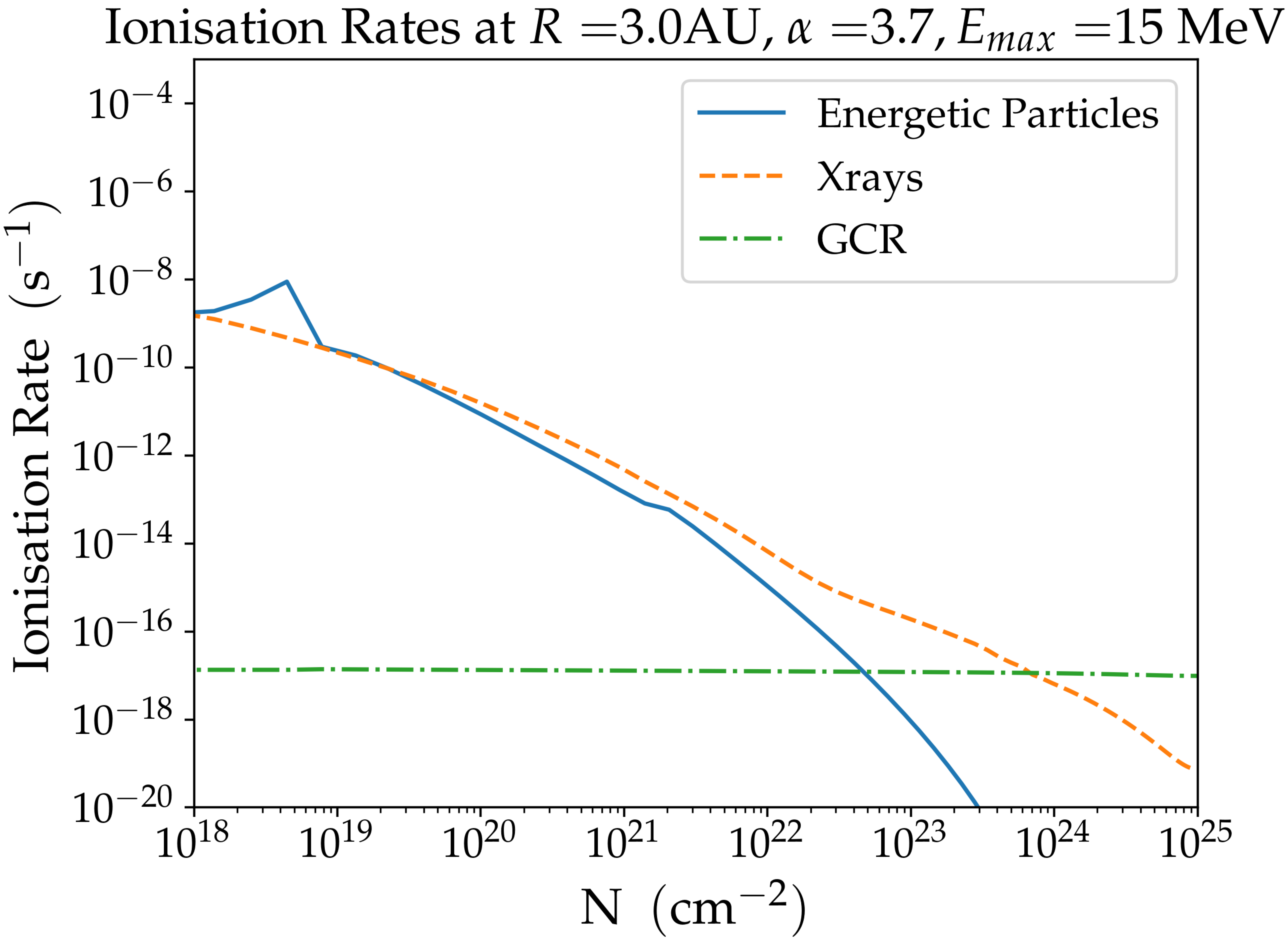
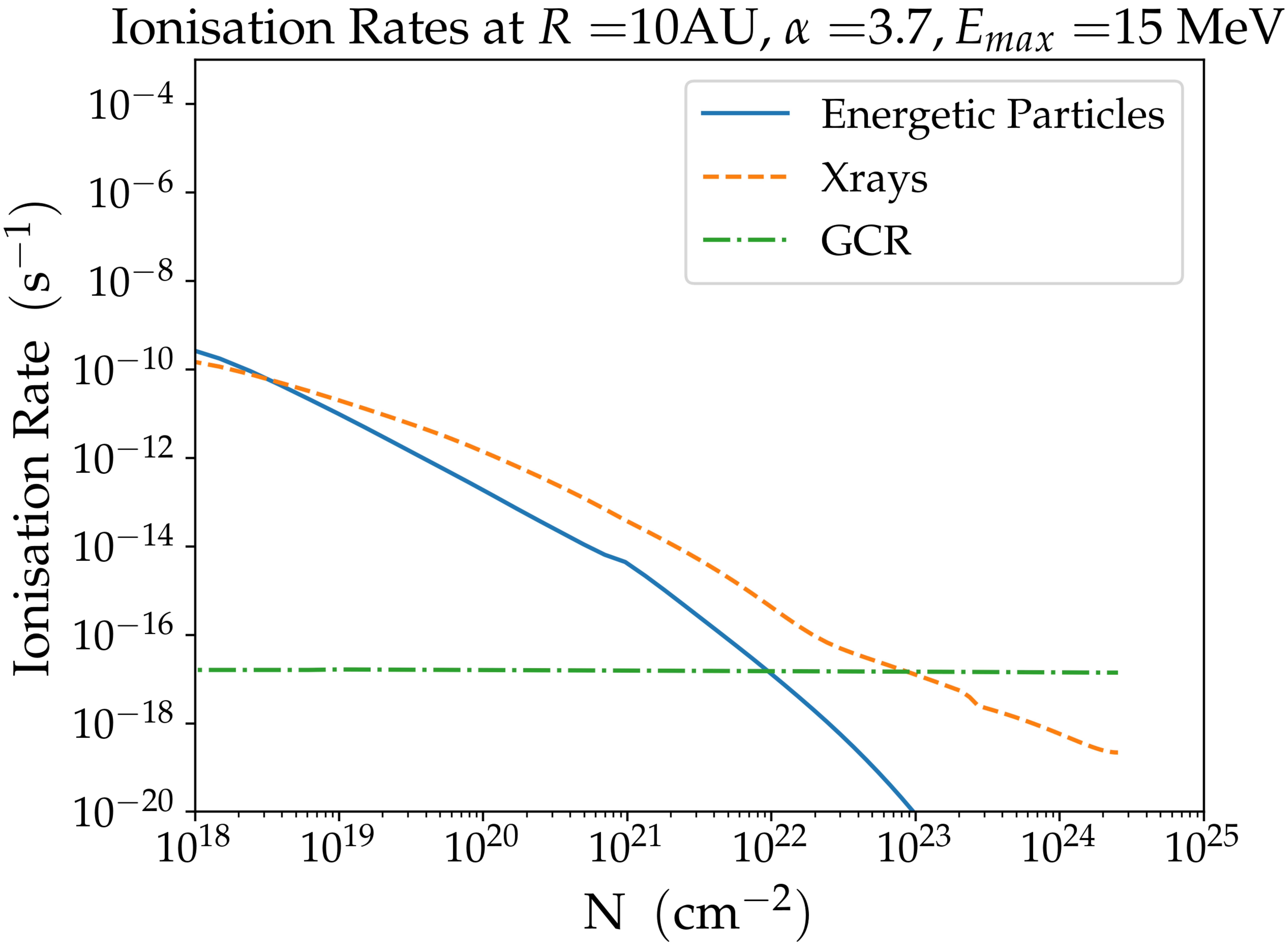
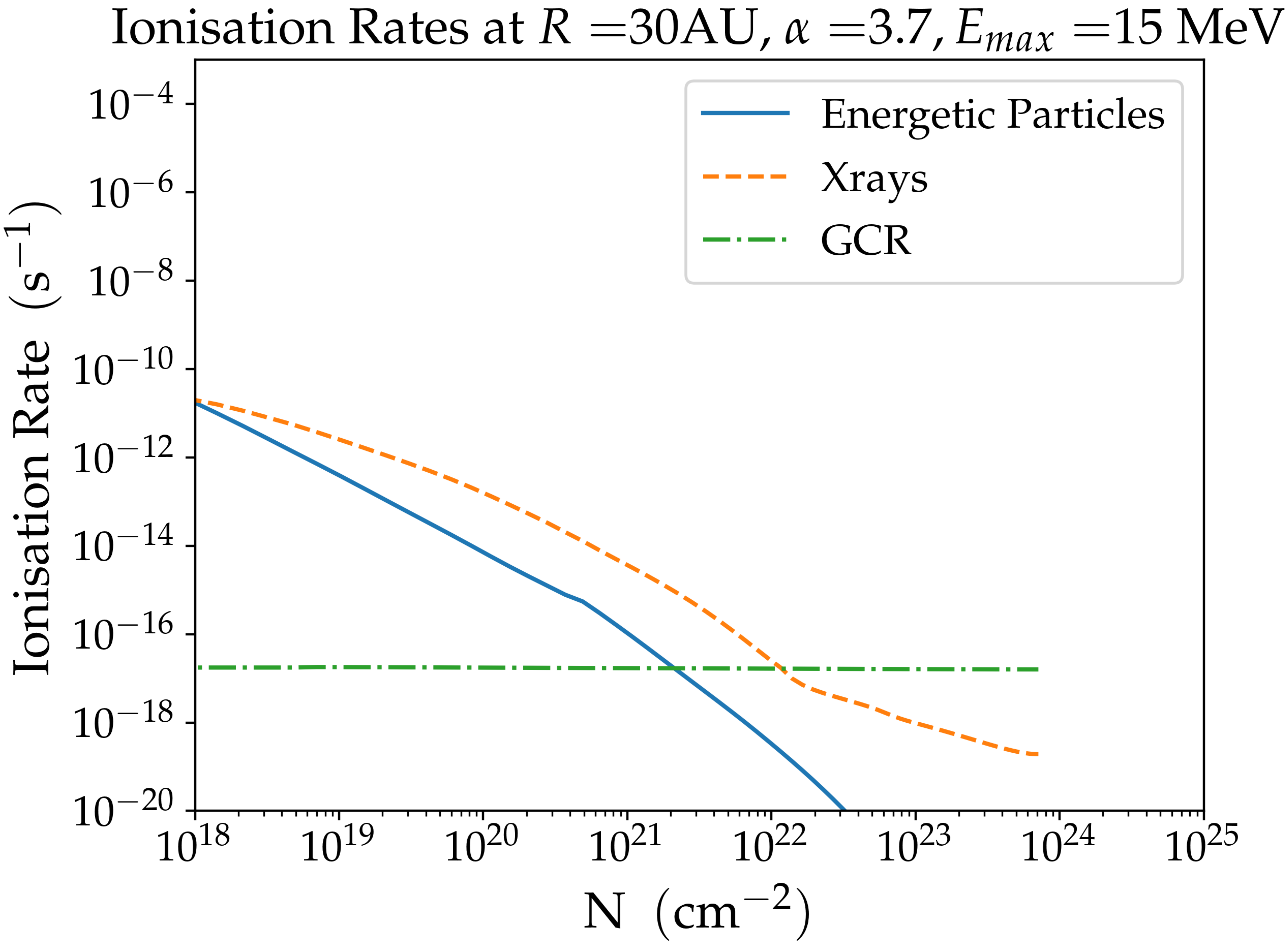
10^{22}
10^{23}
10^{24}
10^{25}
N (cm^{-2})



Ionisation Rates at $R = 3.0\text{AU}, \alpha = 3.7, E_{max} = 15$ MeV


Ionisation Rates at $R = 10$AU, $\alpha = 3.7$, $E_{max} = 15$ MeV
Energetic Particles
Xrays
GCR
Ionisation Rate (s^{-1})
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{18}
10^{19}
10^{20}
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
N (cm^{-2})


Ionisation Rates at R =30AU, α =3.7, E_{max} =15 MeV
Energetic Particles
Xrays
GCR
Ionisation Rate (s^{-1})
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
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10^{23}
10^{24}
10^{25}
N (cm^{-2})