Impacts of Energetic Particles from T Tauri flares on inner discs of protoplanetary discs

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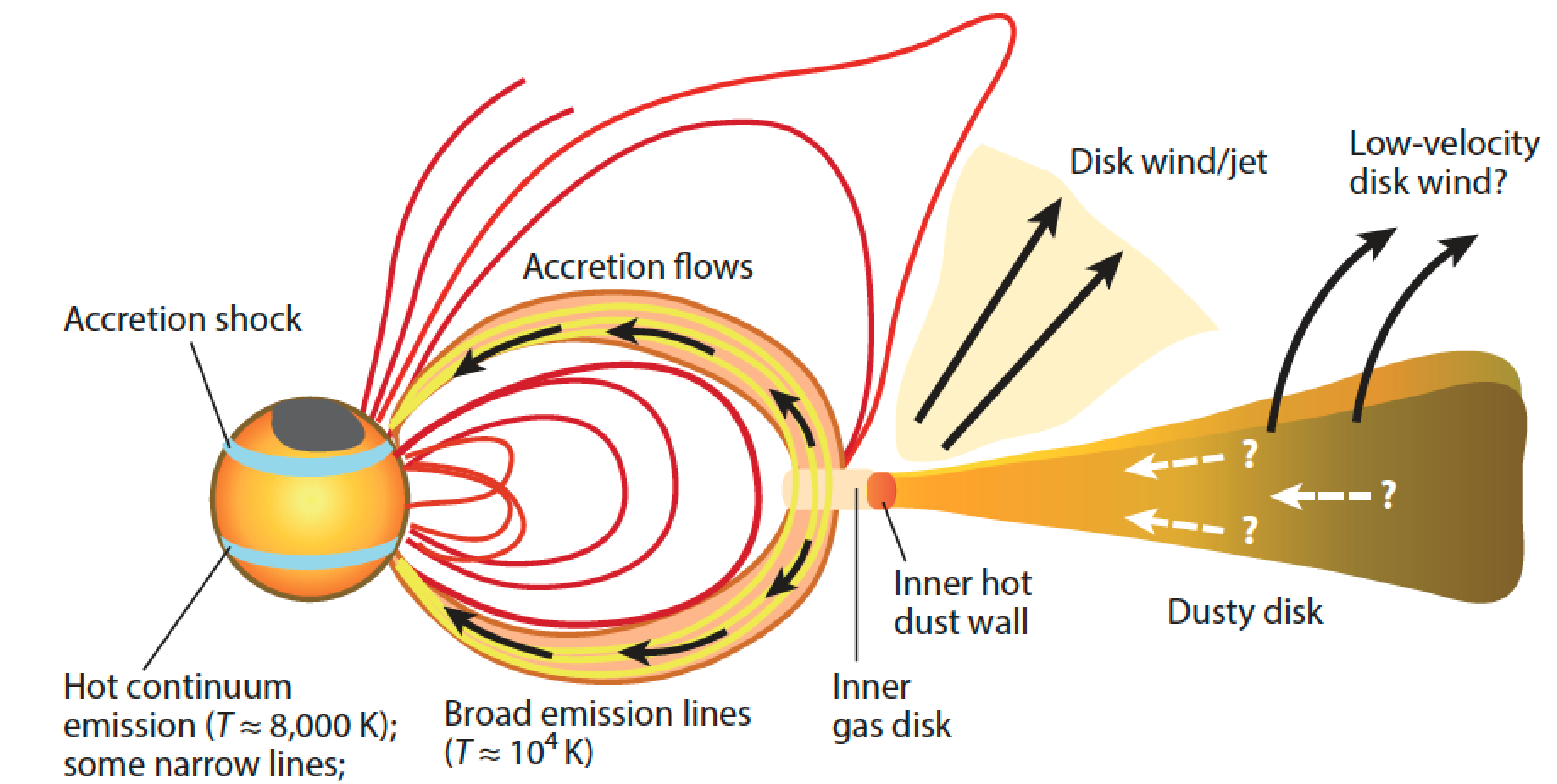
In collaboration with **A. Marcowith, C. Sauty, C. Rab, M. Padovani**

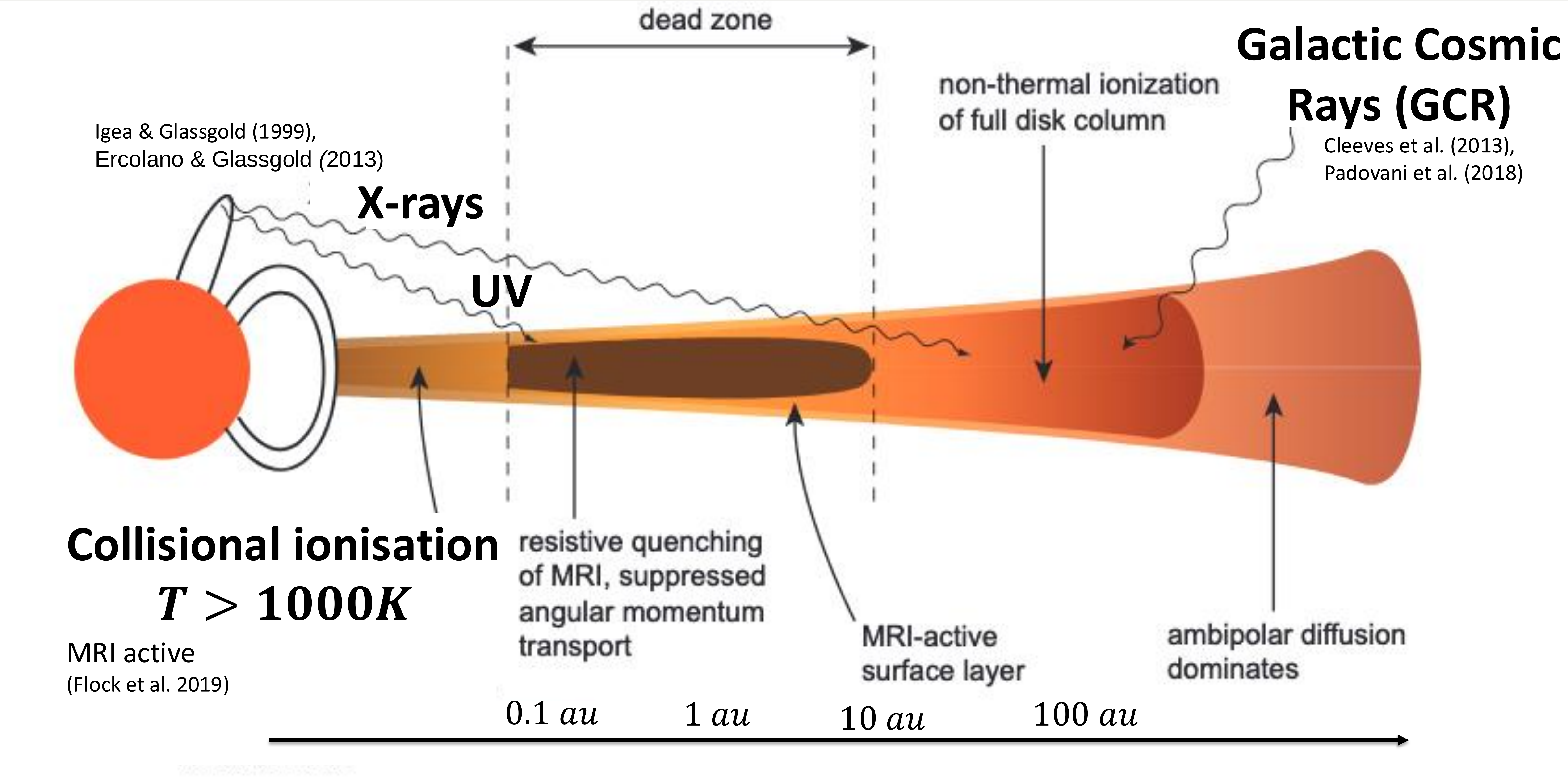
Young stellar objects (YSO) are complex systems with many open questions



Hartman et al. 2016

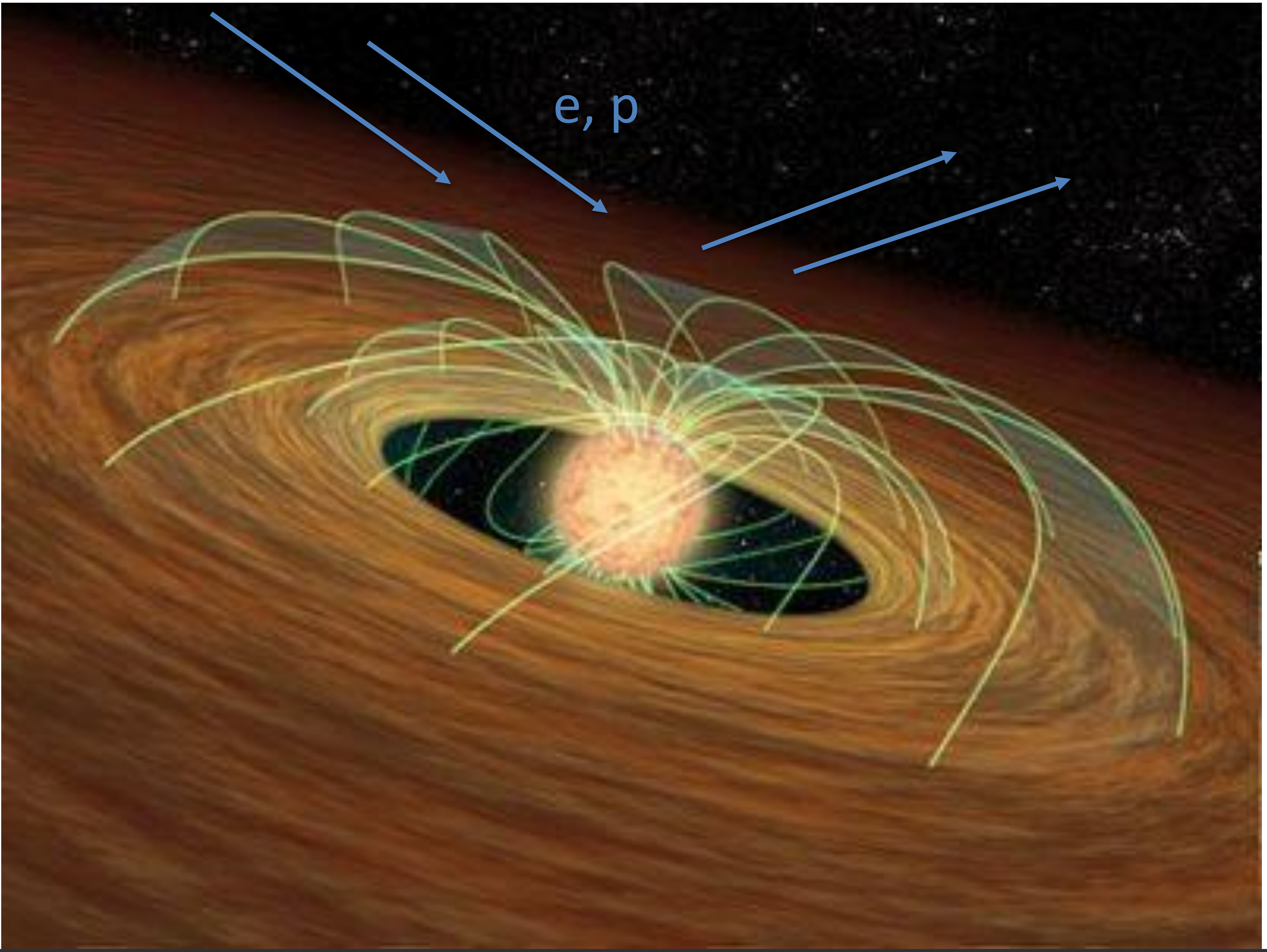
All related to ionisation

Ionisation sources for different disc regions



Igea, J., & Glassgold, A. E. (1999). X-ray ionization of the disks of young stellar objects. *The Astrophysical Journal*, *518*(2), 848.
Ercolano, B., & Glassgold, A. E. (2013). X-ray ionization rates in protoplanetary discs. *Monthly Notices of the Royal Astronomical Society*, *436*(4), 3446-3450.
Cleeves, L. I., Adams, F. C., & Bergin, E. A. (2013). Exclusion of cosmic rays in protoplanetary disks: stellar and magnetic effects. *The Astrophysical Journal*, *772*(1), 5.
Padovani, M., Ivlev, A. V., Galli, D., & Caselli, P. (2018). Cosmic-ray ionisation in circumstellar discs. *Astronomy & Astrophysics*, *614*, A111.
Flock, M., Turner, N. J., Mulders, G. D., Hasegawa, Y., Nelson, R. P., & Bitsch, B. (2019). Planet formation and migration near the silicate sublimation front in protoplanetary disks. *Astronomy & Astrophysics*, *630*, A147.

Galactic Cosmic Rays should dominate the ionization of the mid-plane, but...

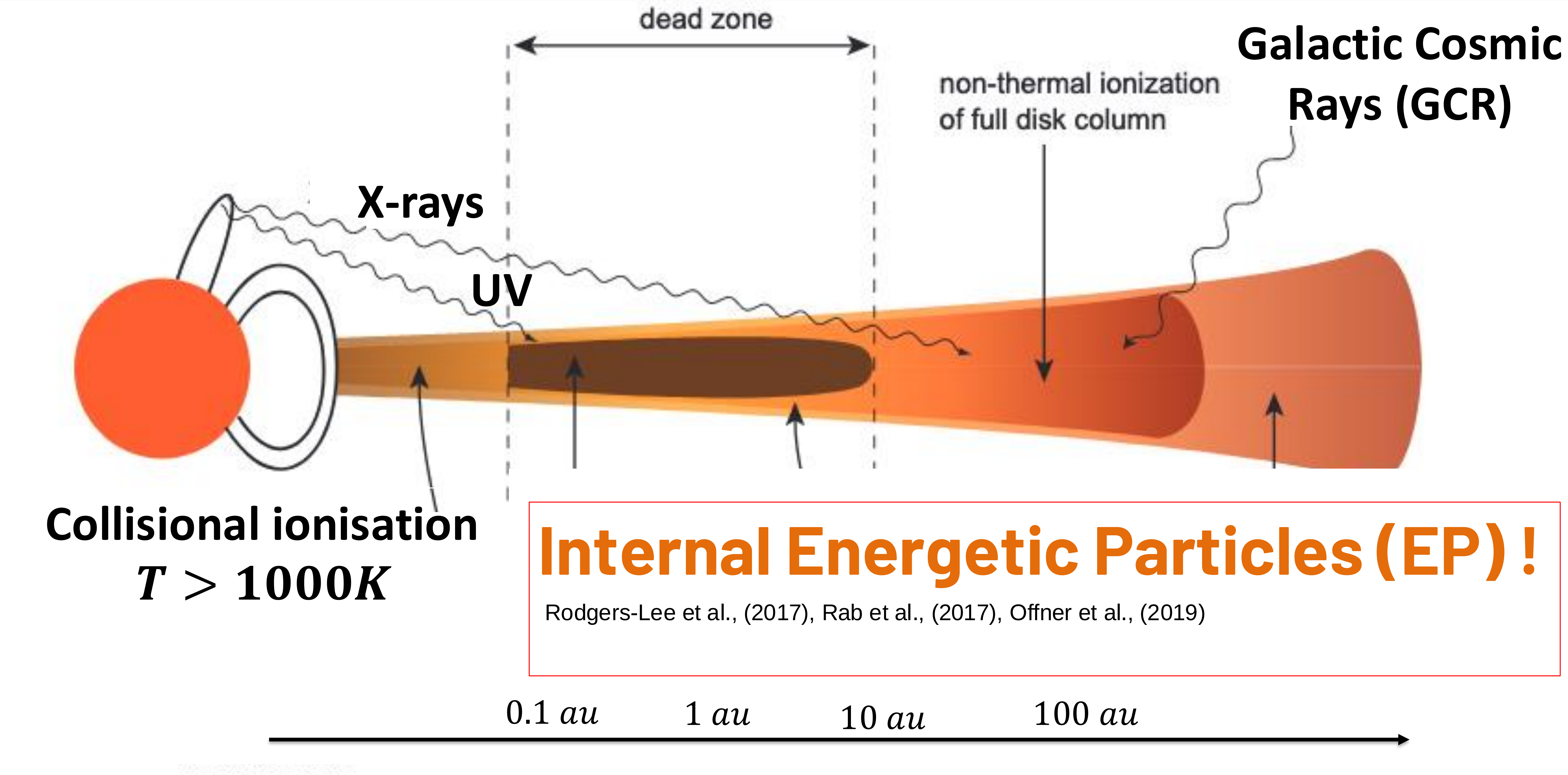


- Stellar winds and magnetic fields suppress the GCR flux.
- T Tauri winds are much stronger than solar winds.
- GCR are an inefficient ionisation sources within the inner 100 au

(Cleeves *et al.* 2013).

Low-energy GCR are suppressed by T Tauri winds

Ionisation sources for different disc regions

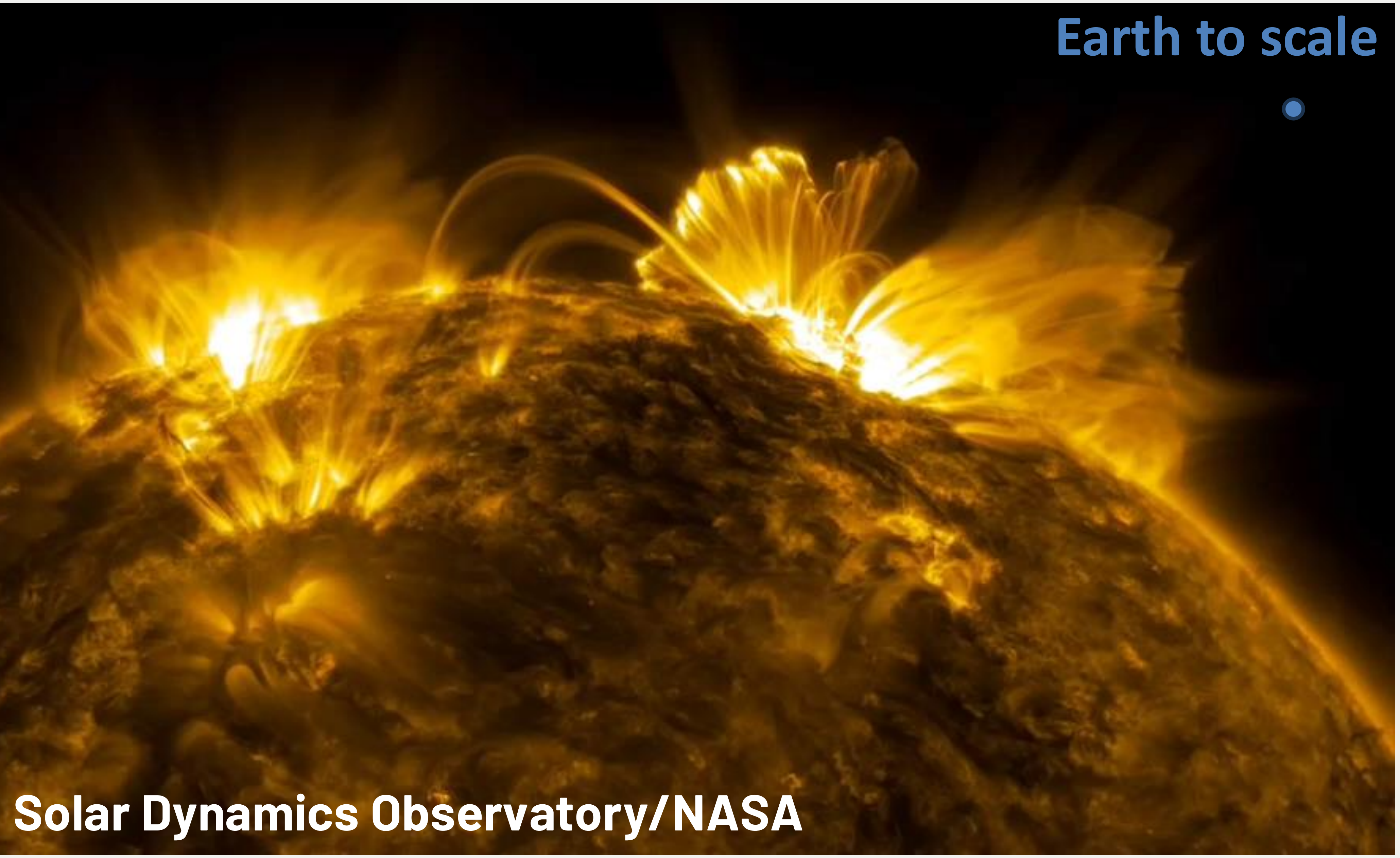


Rab, C., Güdel, M., Padovani, M., Kamp, I., Thi, W. F., Woitke, P., & Aresu, G. (2017). Stellar energetic particle ionization in protoplanetary disks around T Tauri stars. *Astronomy & Astrophysics*, *603*
Rodgers-Lee, D., Taylor, A. M., Ray, T. P., & Downes, T. P. (2017). The ionizing effect of low-energy cosmic rays from a class II object on its protoplanetary disc. *Monthly Notices of the Royal Astronomical Society*, *472*(1), 26-38.
Offner, S. S., Gaches, B. A., & Holdship, J. R. (2019). Impact of cosmic-ray feedback on accretion and chemistry in circumstellar disks. *The Astrophysical Journal*, *883*(2), 121.

Particle Acceleration in T Tauri Flares

How to model particles acceleration due to magnetic reconnection?

EP are produced by Flares in T Tauri stars



- **T Tauri flares are observed to be large scale versions of solar flares**

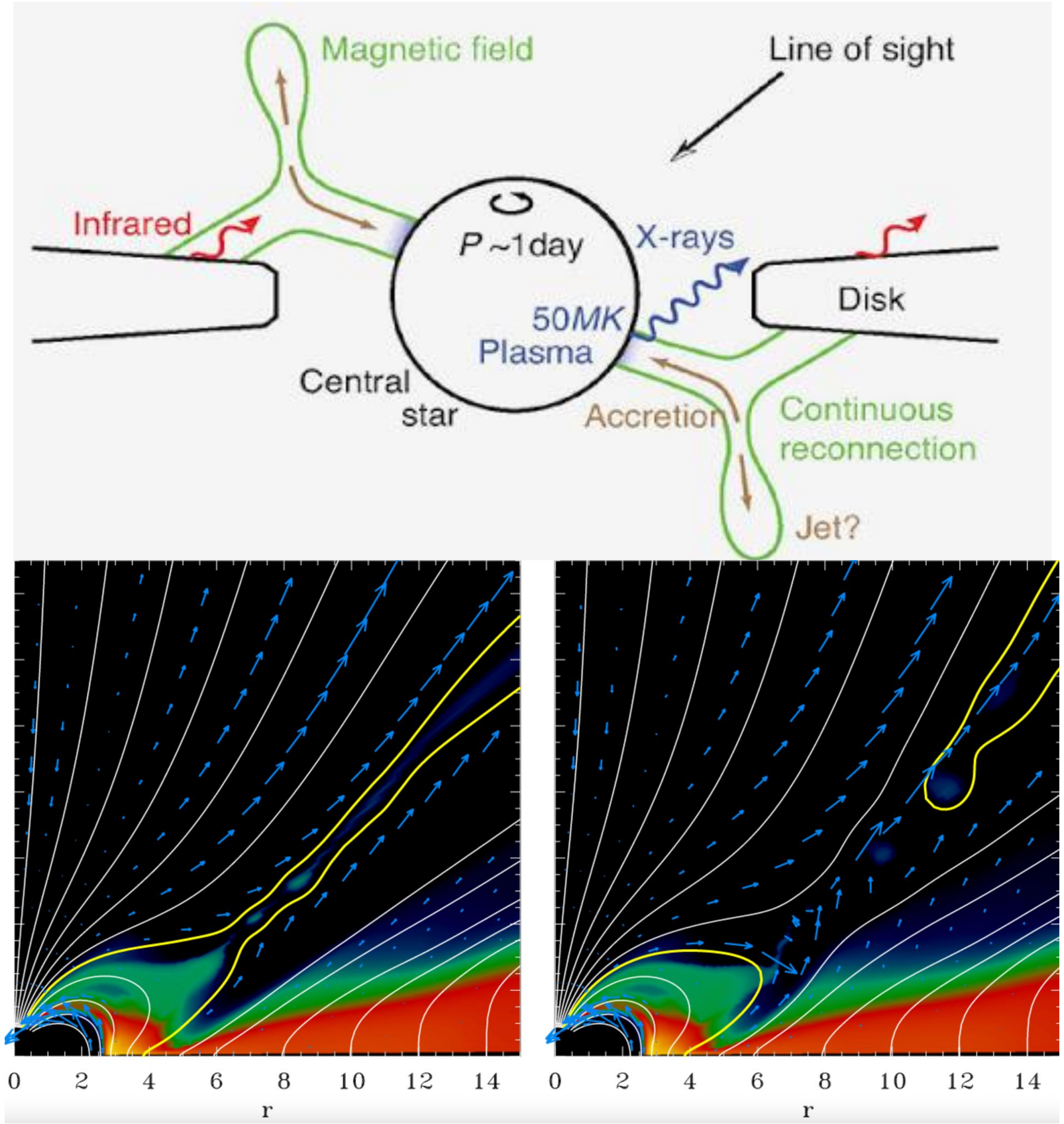
  Feigelson *et al.* (2002), Getman *et al.* (2008), Getman *et al.* (2021)

- **Previous way to estimate proton flux of T Tauri flares :**

  10^5 times higher than the solar one

  Feigelson *et al.* (2002), Rab *et al.* (2017)

Feigelson, E. D., Garmire, G. P., & Pravdo, S. H. (2002). Magnetic flaring in the pre-main-sequence Sun and implications for the early Solar System. *The Astrophysical Journal*, *572*(1), 335.
Getman, K. V., Feigelson, E. D., Broos, P. S., Micela, G., & Garmire, G. P. (2008). X-ray flares in Orion young stars. I. Flare characteristics. *The Astrophysical Journal*, *688*(1), 418.
Getman, K. V., & Feigelson, E. D. (2021). X-ray superflares from pre-main-sequence Stars: Flare energetics and frequency. *The Astrophysical Journal*, *916*(1), 32.
Rab, C., Güdel, M., Padovani, M., Kamp, I., Thi, W. F., Woitke, P., & Aresu, G. (2017). Stellar energetic particle ionization in protoplanetary disks around T Tauri stars. *Astronomy & Astrophysics*, *603*, A96.

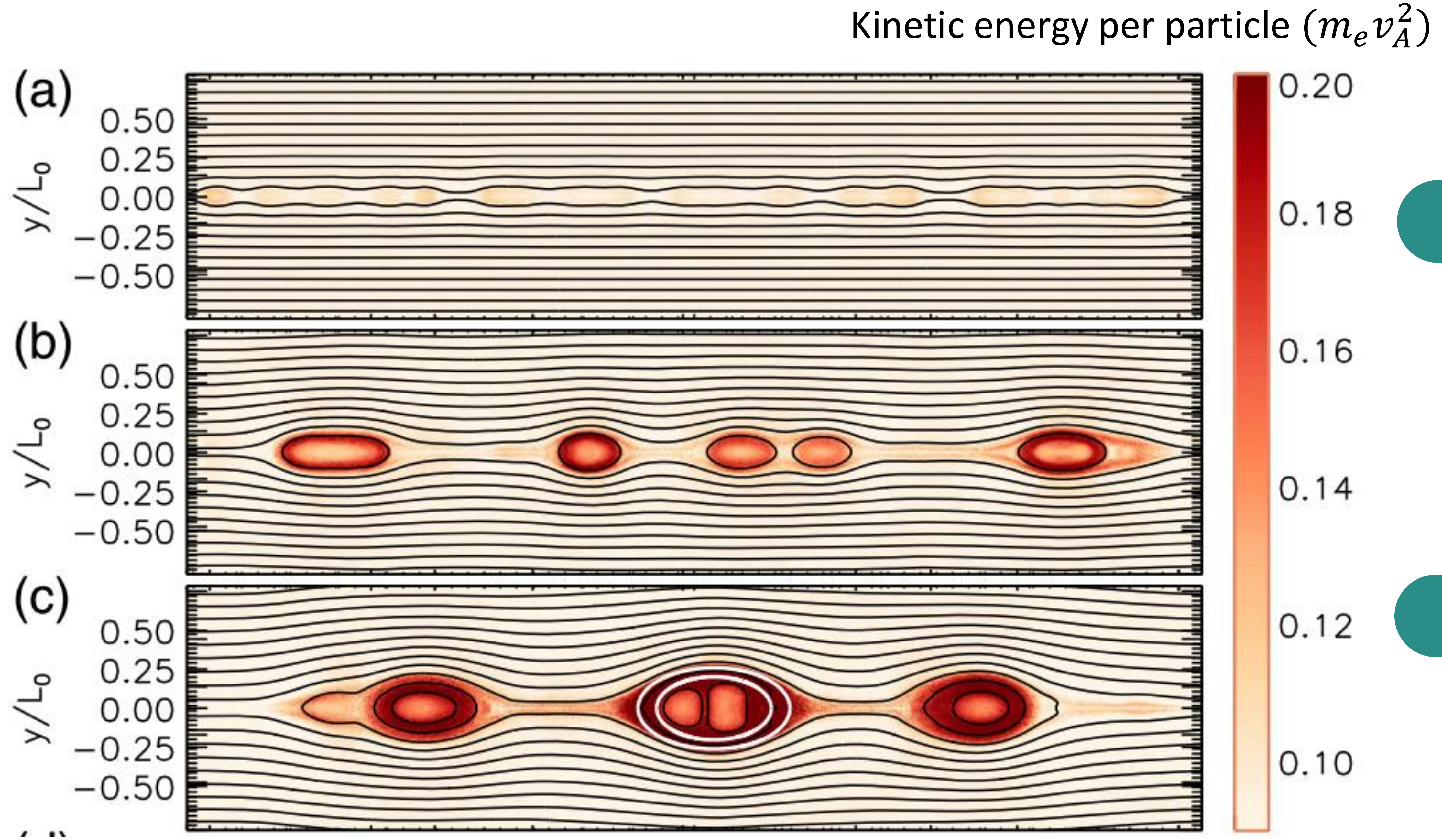


Magnetic Reconnection is expected in the Star-Disc interaction region

- The reconnection regime determine the EP acceleration efficiency.
- Assuming the plasma properties (T, n_e, L) of T Tauri flares: Collisional reconnection unstable to plasmoids

Zanni and Ferreira (2013)

Collisional magnetic reconnection unstable to plasmoids

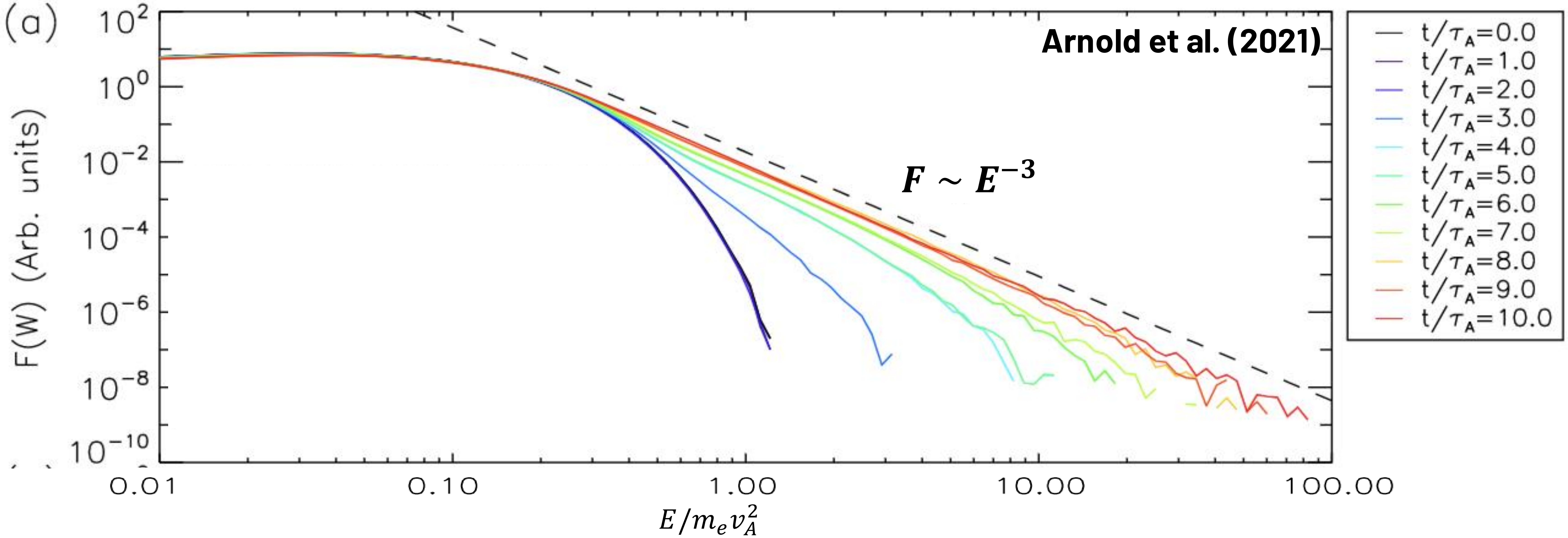


Arnold et al. (2021)

- **The reconnection regime determine the EP acceleration efficiency.**
- **Acceleration is efficient in plasmoids**

Arnold, H., Drake, J. F., Swisdak, M., Guo, F., Dahlin, J. T., Chen, B., ... & Shen, C. (2021). Electron acceleration during macroscale magnetic reconnection. *Physical review letters*, *126*(13), 135101.

The supra-thermal energy distribution in "Multi X-line Collisional" simulations

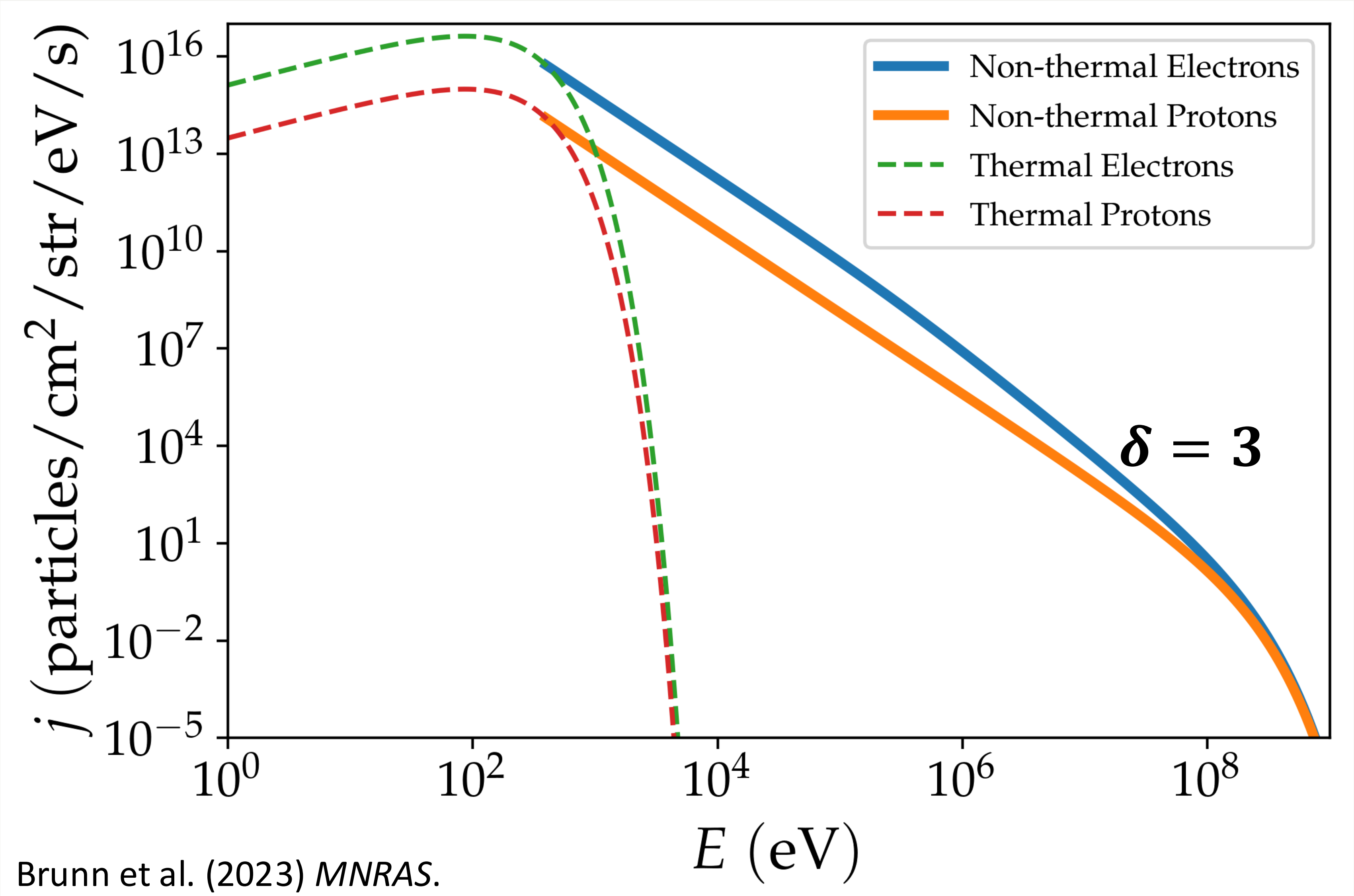


The energy distribution function of electron is a power-law :

$$F(E) \propto E^{-\delta}\ , \ \delta = 3$$

Arnold, H., Drake, J. F., Swisdak, M., Guo, F., Dahlin, J. T., Chen, B., ... & Shen, C. (2021). Electron acceleration during macroscale magnetic reconnection. *Physical review letters*, *126*(13), 135101.

The particle fluxes produced by a 10 MK flare



Brunn et al. (2023) *MNRAS*.

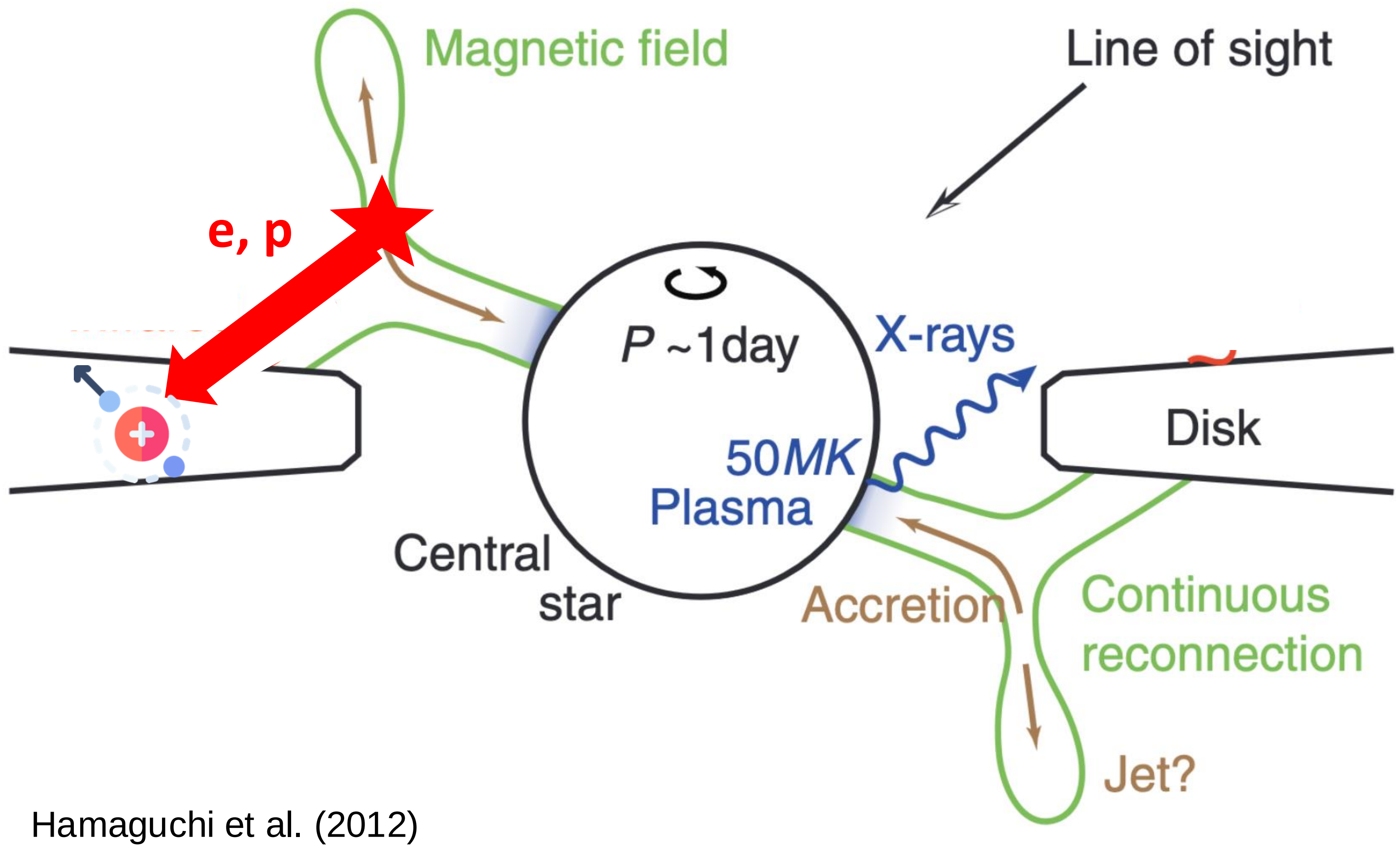
$$[j] = \frac{number\ of\ particle}{energy\ \times time\ \times area\ \times\ solid\ angle}$$

- **The power-law shape is based on MHD reconnection simulations.**
- **The normalisation is fixed by X-ray observations.**
- $j_{nt}(E) \sim n_{nt} \left(\frac{E}{E_{inj}}\right)^{-\delta} \exp\left(-\frac{E}{100\ MeV}\right)$

Ionisation produced by a single flare

How to estimate the propagated EP flux in the disc ?

Energetic particles produced by flares ionise the disc



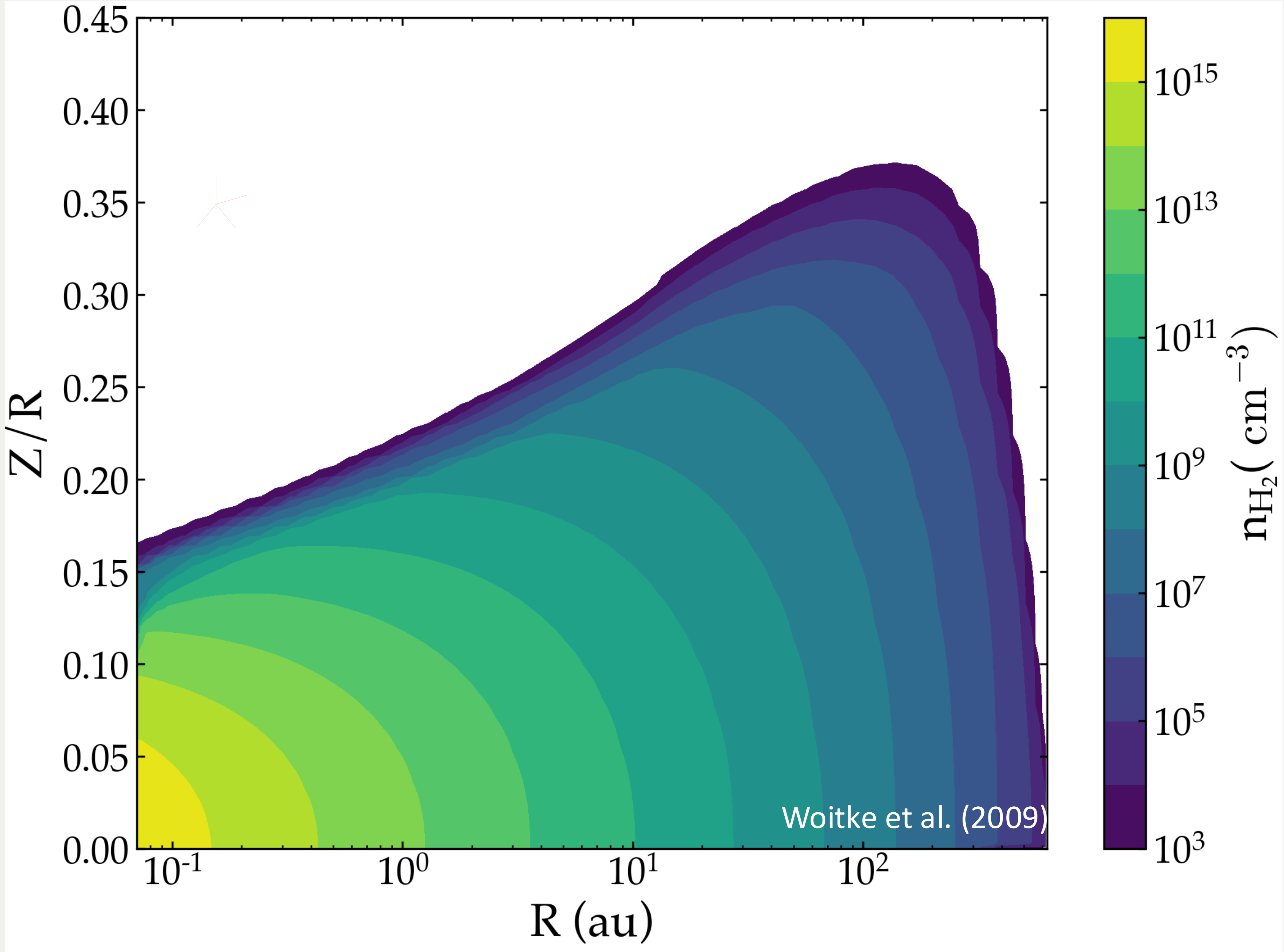
Hamaguchi et al. (2012)

- Particles are accelerated by magnetic reconnection.
- They propagate along magnetic field lines.
- They ionize the disc.

★ : Particle acceleration site

Hamaguchi, K., Grosso, N., Kastner, J. H., Weintraub, D. A., Richmond, M., Petre, R., ... & Principe, D. (2012). X-raying the Beating Heart of a Newborn Star: Rotational Modulation of High-energy Radiation from V1647 Ori. *The Astrophysical Journal*, *754*(1), 32.

ProDiMo to estimate the chemical abundances of a standard T Tauri disc



- **2D Thermochemical Code : PROtoplanetary DIsc MOdel**

  (ProDiMo; Woitke et al. 2009)

- **UV and X ray radiative transfer**

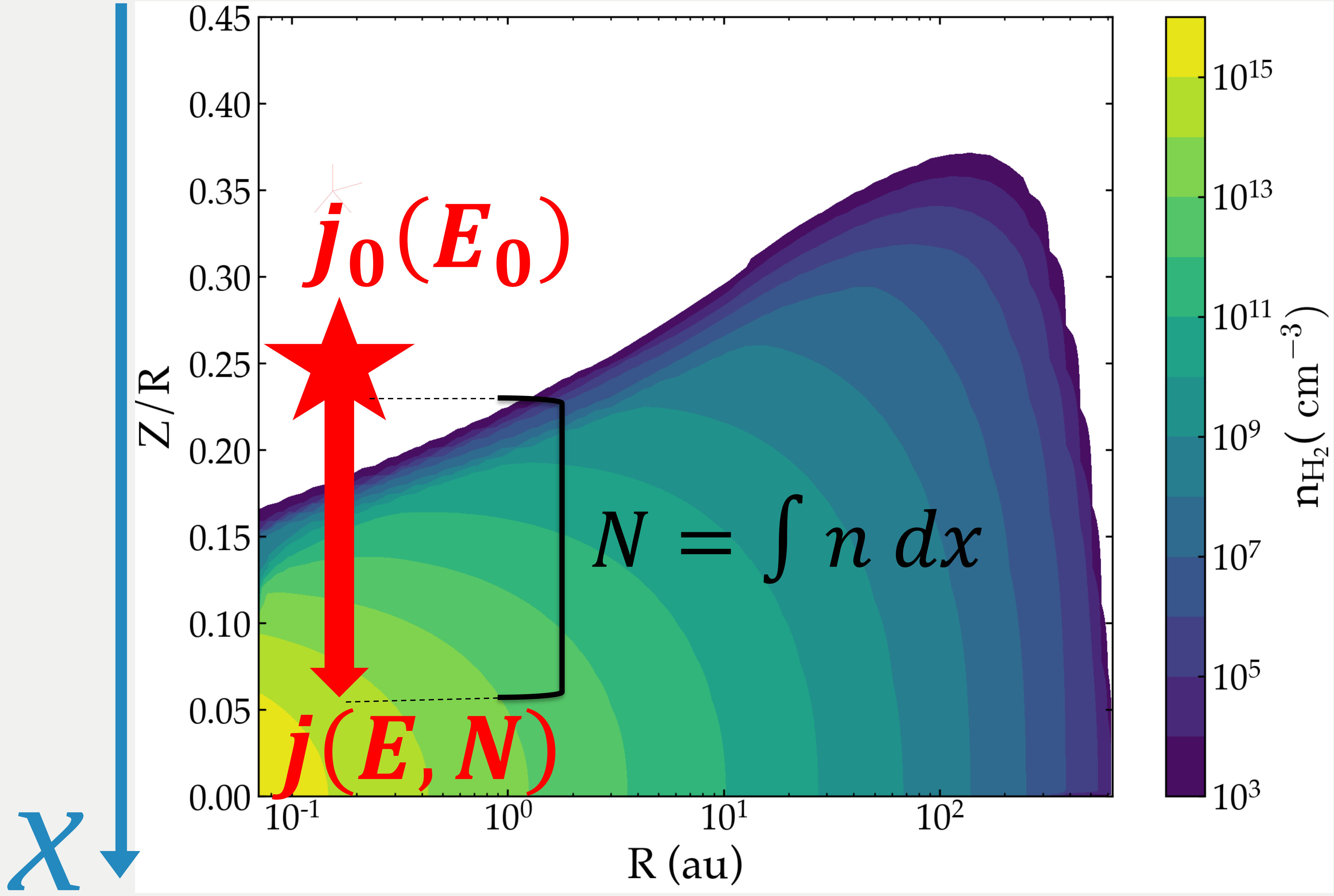
  (Kamp et al. 2010, Thi et al. 2011)

- **Hundreds of chemical species**

  (Woitke et al. 2016)

Woitke, P., Kamp, I., & Thi, W. F. (2009). Radiation thermo-chemical models of protoplanetary disks-I. Hydrostatic disk structure and inner rim. *Astronomy & Astrophysics*, *501*(1), 383-406.
Kamp, I., Tilling, I., Woitke, P., Thi, W. F., & Hogerheijde, M. (2010). Radiation thermo-chemical models of protoplanetary disks-II. Line diagnostics. *Astronomy & Astrophysics*, *510*, A18.
Thi, W. F., Woitke, P., & Kamp, I. (2011). Radiation thermo-chemical models of protoplanetary discs–III. Impact of inner rims on spectral energy distributions. *Monthly Notices of the Royal Astronomical Society*, *412*(2), 711-726.
Woitke, P., Min, M., Pinte, C., Thi, W. F., Kamp, I., Rab, C., ... & Spaans, M. (2016). Consistent dust and gas models for protoplanetary disks-I. Disk shape, dust settling, opacities, and PAHs. *Astronomy & Astrophysics*, *586*,

Propagation of EP produced by magnetic reconnection



★ : Particle acceleration site

N : Column density crossed by the particles

E_0 : Initial energy

E : Energy at column density N

L : Energy loss function

$$\boldsymbol{j(E, N)} = j_0(E_0) \frac{L(E_0)}{L(E)}$$

Ionisation rate, the key parameter

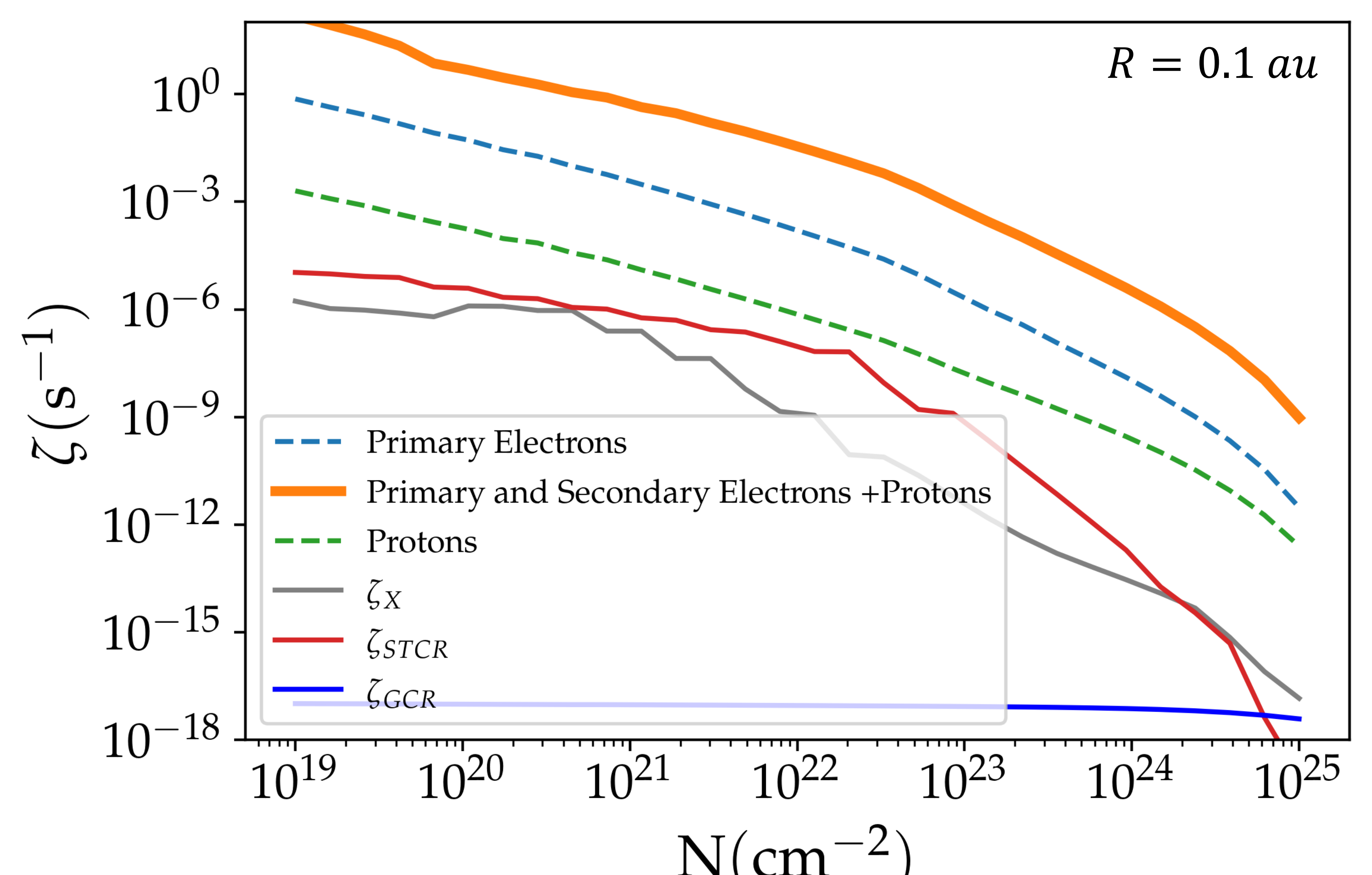
$$\zeta(N)[s^{-1}] = 2\pi \int \boldsymbol{j}(\boldsymbol{E},\boldsymbol{N})\big(1+\phi(E)\big)\,\sigma_{ion}(E)dE$$

(Padovani et al. 2009)

j (E,N) : propagated particle flux.
$\phi(E)$: secondary particles

- **The ionization rate is the number of H_2 ionisation per unit time.**
- **Fundamental parameter for chemical and non-ideal MHD simulations.**
- **We aim to compute the ionisation rate.**

The ionisation rate in a stationary configuration



Brunn et al. (2023) MNRAS

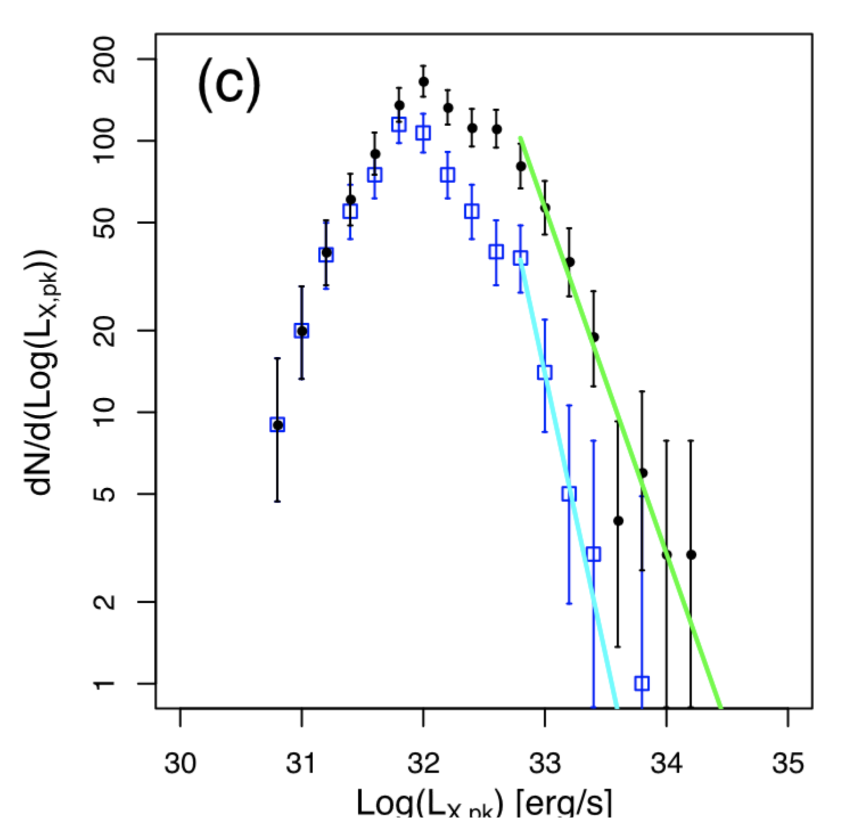
- 10 MK Flare (orange)
- Orders of magnitude higher than other ionisation sources
- We have a promising source of ionisation !

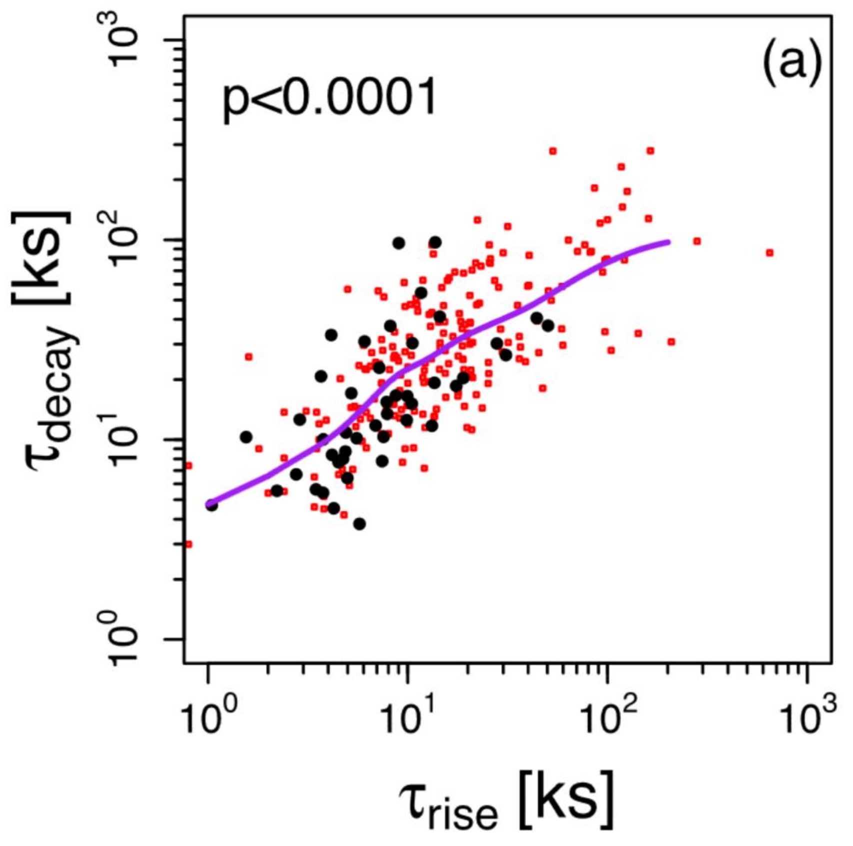
  … at the maximum flare luminosity.

Effects of EP produced by multiple flares on the inner discs of T Tauri stars

What effects have EP produced by magnetic reconnection events on the dynamics and chemistry of T Tauri discs and jets ?

X-Ray luminosity due to flares based on Observations

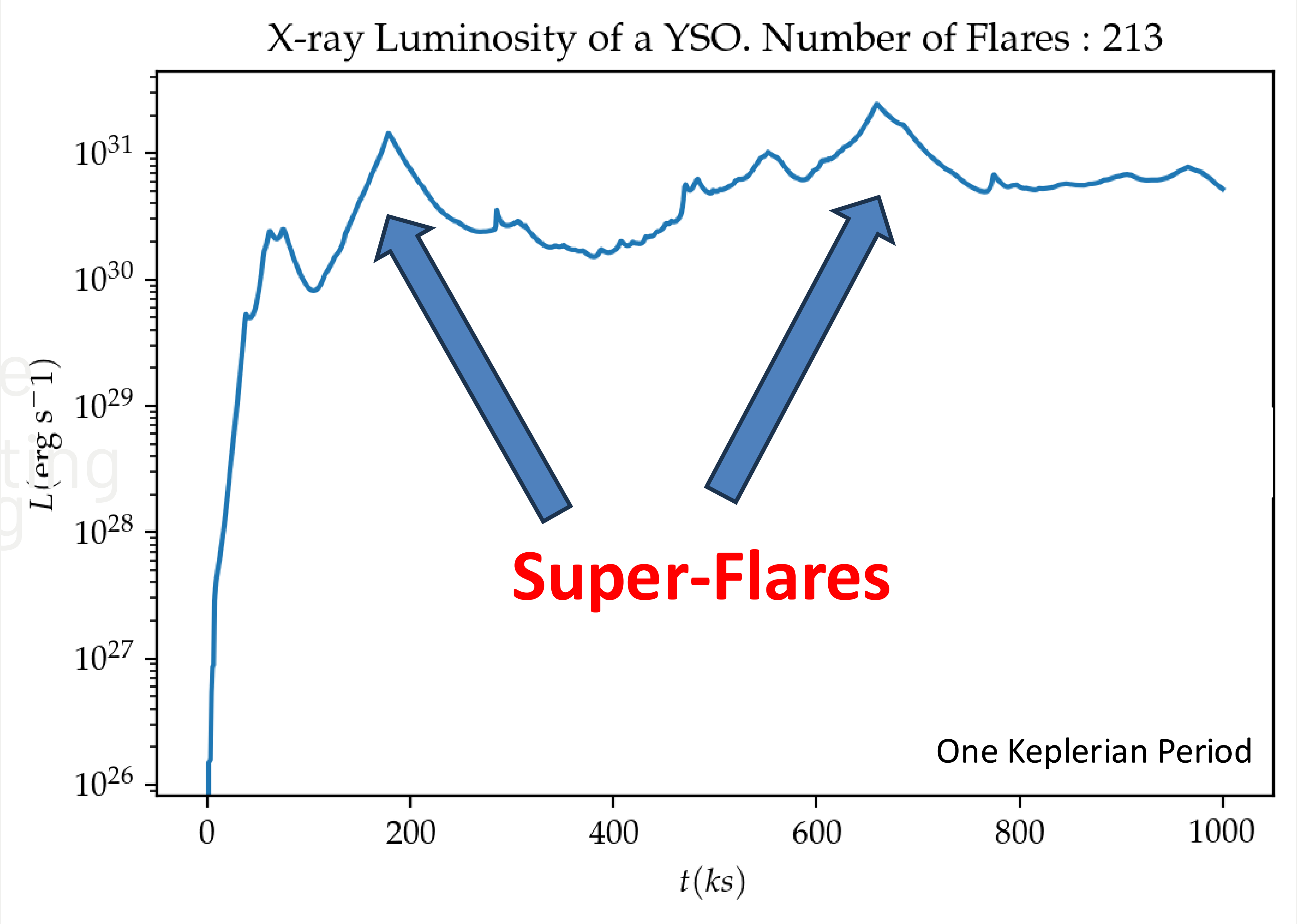




Luminosity distribution.

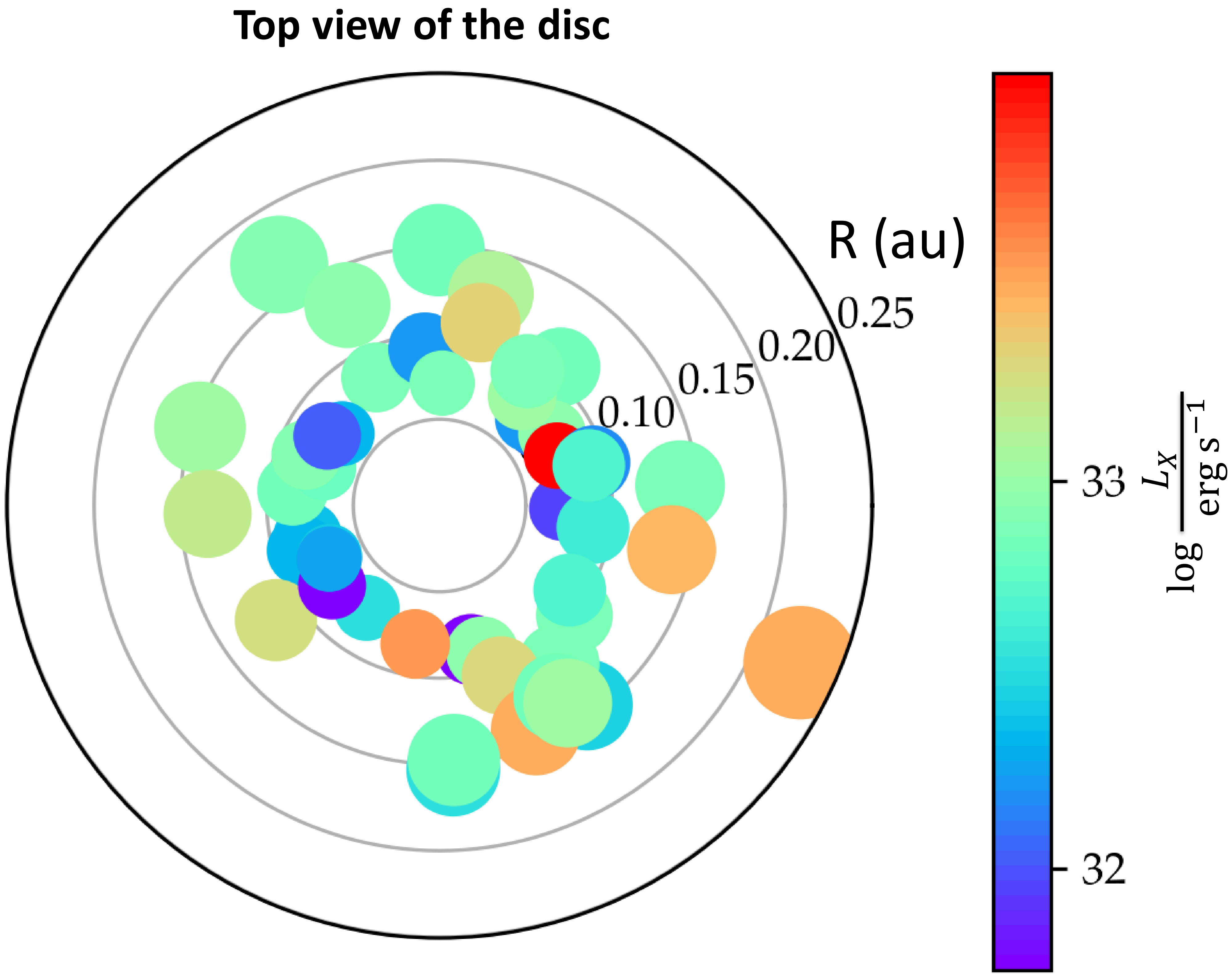
Frequency distribution.

Duration distribution.

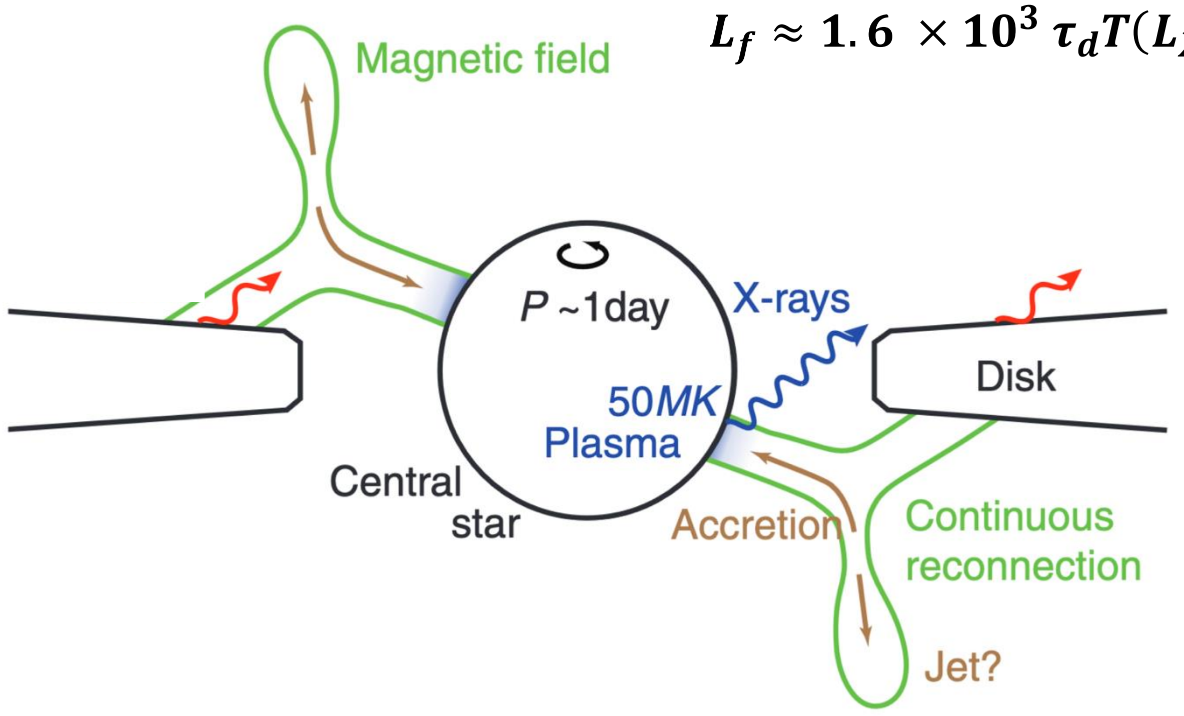


Getman et al. (2021)

Ten years Flaring activity

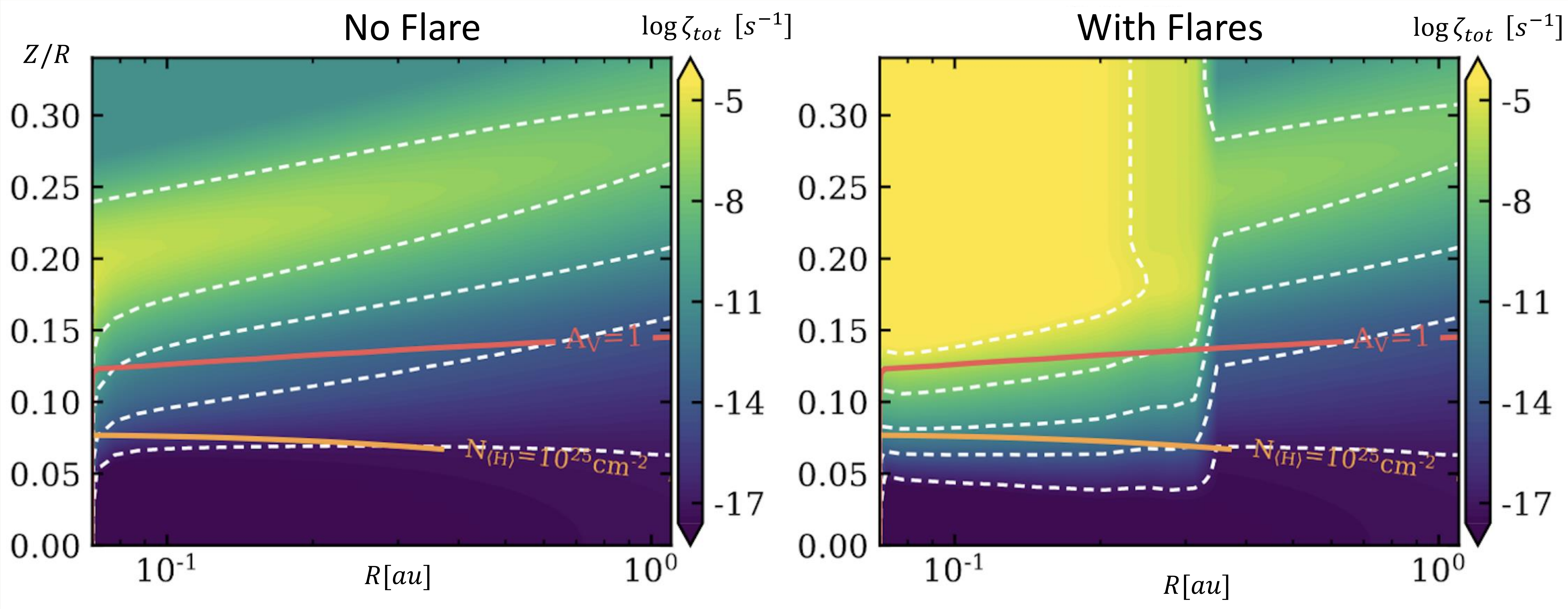


Solar flare loop half-length (Reale 2007) :
$L_f \approx 1.6 \times 10^3 \, \tau_d T (L_X)^{1/2} \approx R$



- **Cross sections of the flare loops with the disc are at scale**
- **Luminosity is given by the colour**

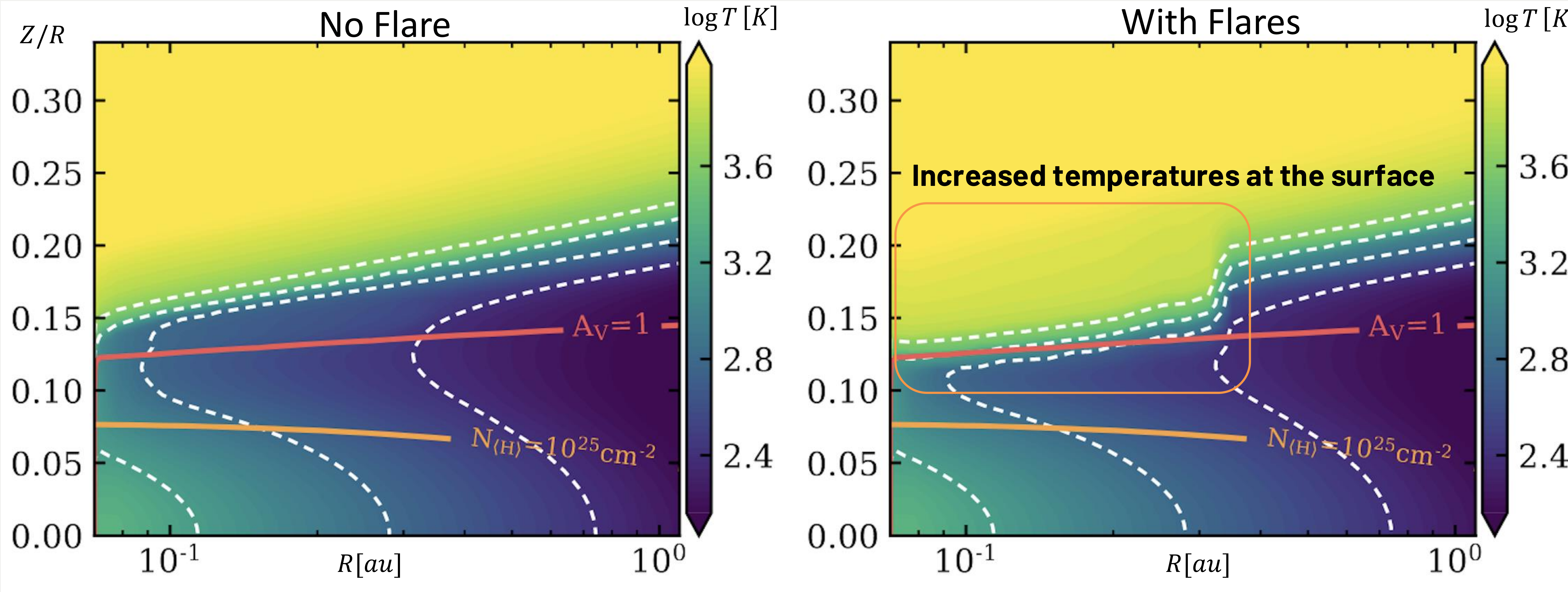
Energetic particles from flares are used as an input in ProDiMo



We recompute the thermochemical structure accounting for the additional EP ionisation source

Brunn, V., Rab, C., Marcowith, A., Sauty, C., Padovani, M., & Meskini, C. (2024). Impacts of energetic particles from T Tauri flares on inner protoplanetary discs. *Monthly Notices of the Royal Astronomical Society*, *530*(4), 3669-3687.

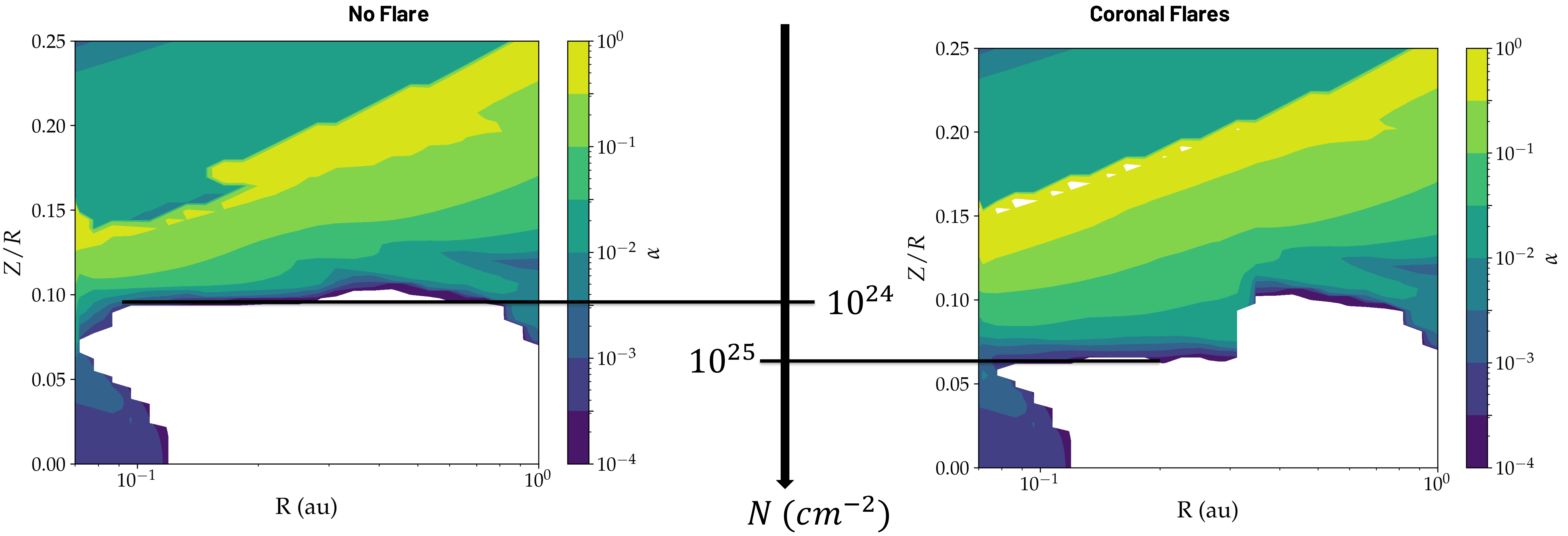
Energetic particles affect the thermal structure of discs



EP from flares is an additional source of heat : driver of winds and jets

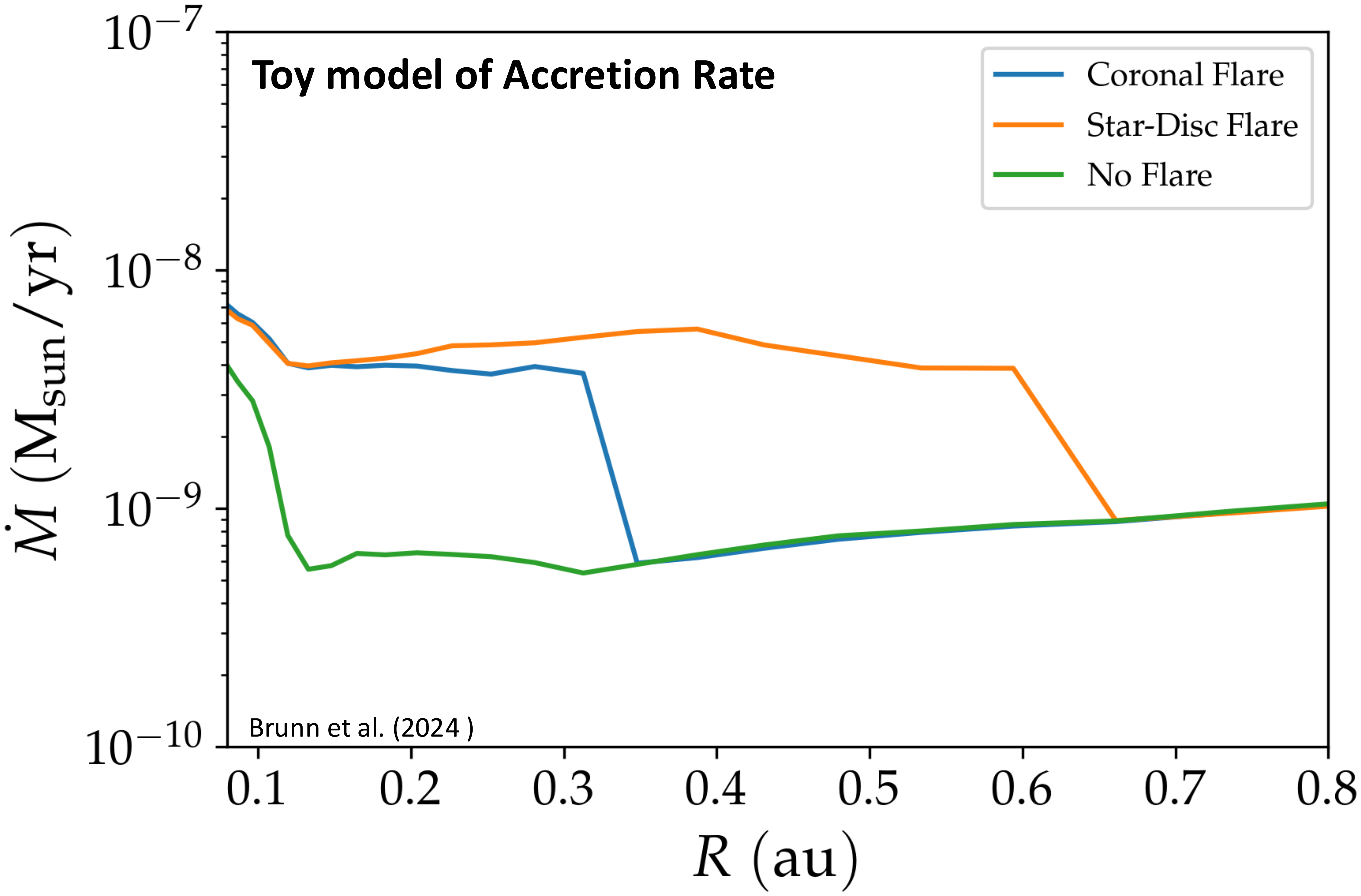
Energetic particles affect the accretion processes in discs

$$\dot{M}_{acc} \sim 10^{-8} \left(\frac{\alpha(T, n_e, n_n)}{0.01}\right)\left(\frac{R}{10\ au}\right)^{1/2}\left(\frac{M_*}{M_\odot}\right)^{1/2}\left(\frac{\mathrm{N}}{10^{24}\ cm^{-2}}\right)\ M_\odot\ yr^{-1}$$



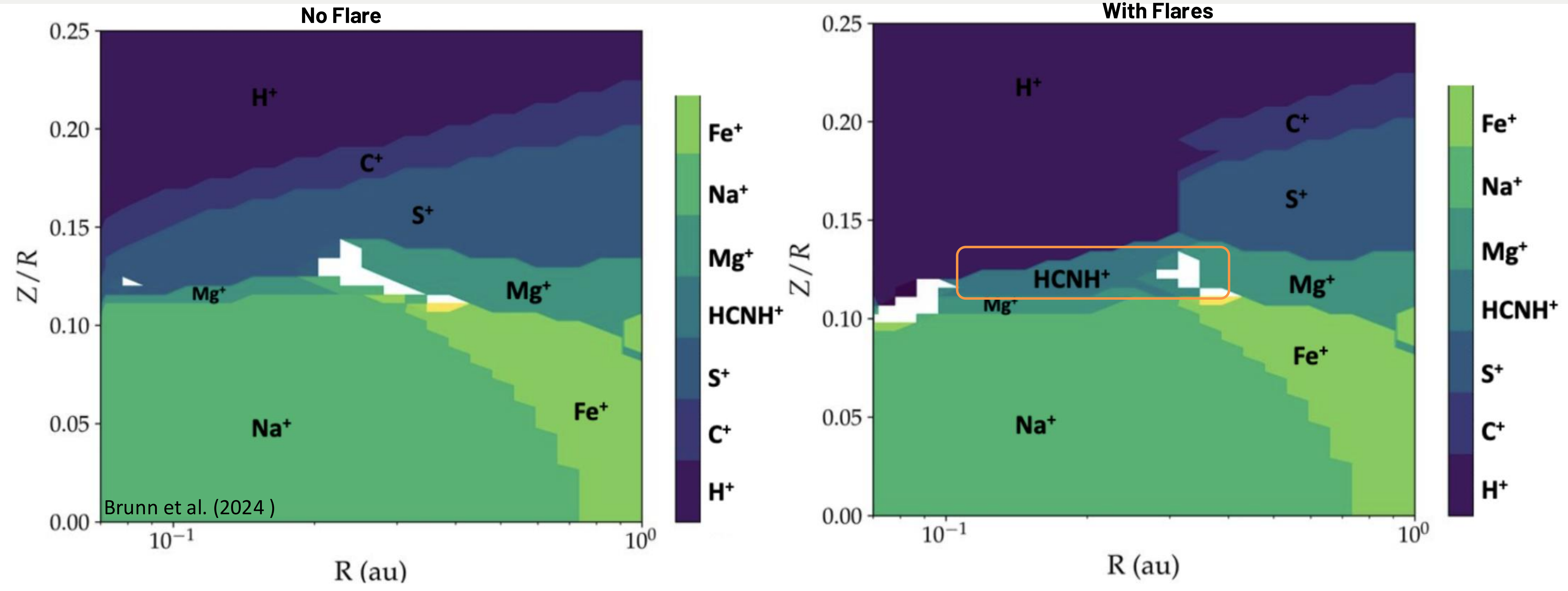
Accounting for flares reduces the size of the dead-zone in the inner disc

Energetic particles affect the accretion processes in discs



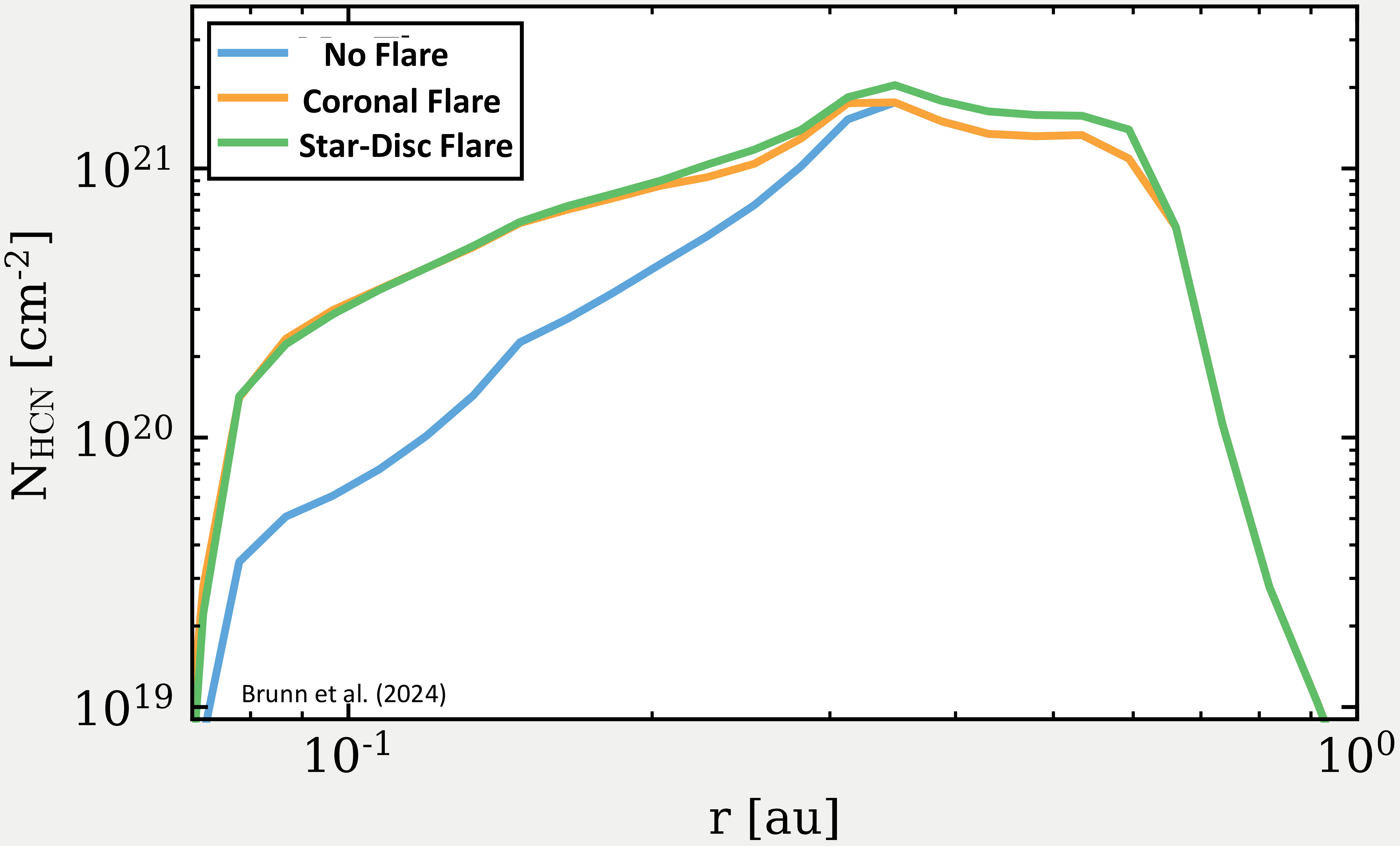
- **Accounting for flares reduce the dead-zone size in the inner disc.**
- **The reduction of the dead zone size leads to an increase of the accretion rate.**

Energetic particles affect the chemical complexity in discs



The interaction of EP with the disc creates a layer of $HCNH^+$

Energetic particles affect the chemical complexity in discs



- **HCN is fundamental in prebiotic chemistry**
- **EP affect the HCN vertical column density**

Conclusion

- **Locally produced EP are crucial to understand Young Stellar Objects**

  In recent years, numerous studies have shown the central role played by CRs in star forming region, dense clouds, protostars and planetary systems. Particularly locally produced CRs.

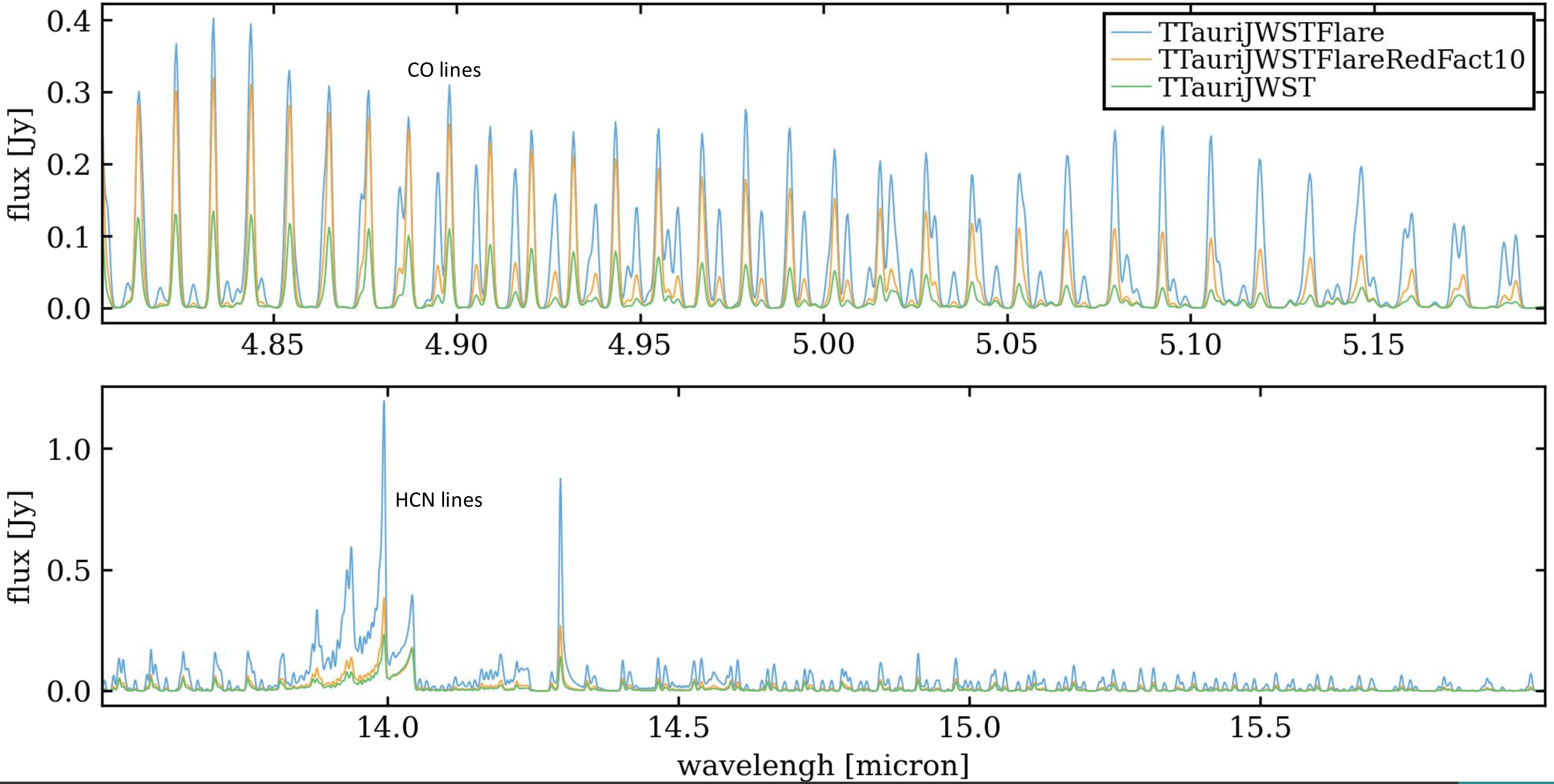
- **We identified and modelled a new local source of EP : magnetic reconnection.**

  X-ray emission and MHD simulations of the magnetic structure of YSOs suggest that magnetic reconnection events must take place in these objects. We have modelled the particle emission from these events.

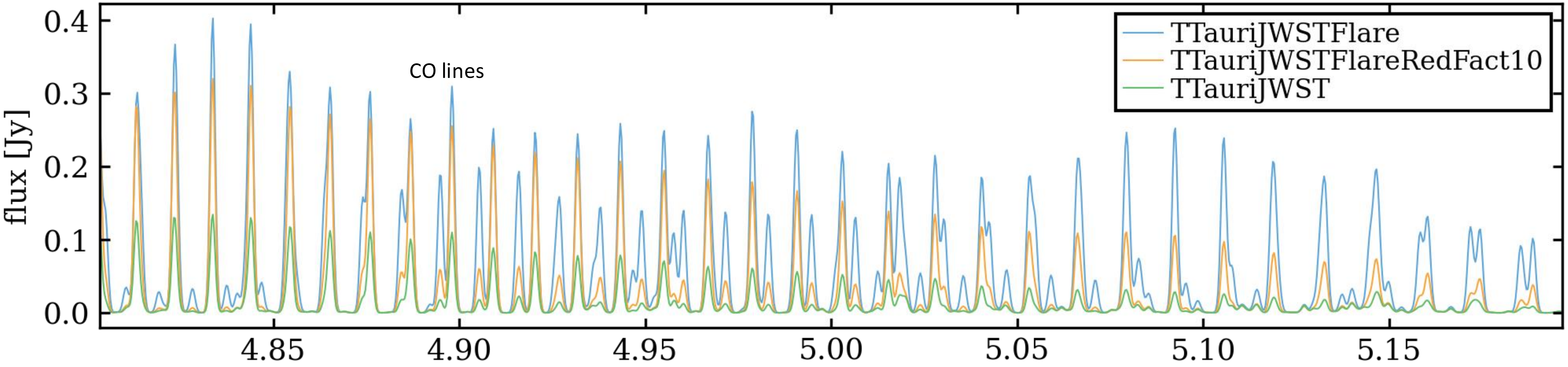
- **This additional source of EP has significant effects on the dynamics and chemistry of discs and jets of T Tauri stars.**

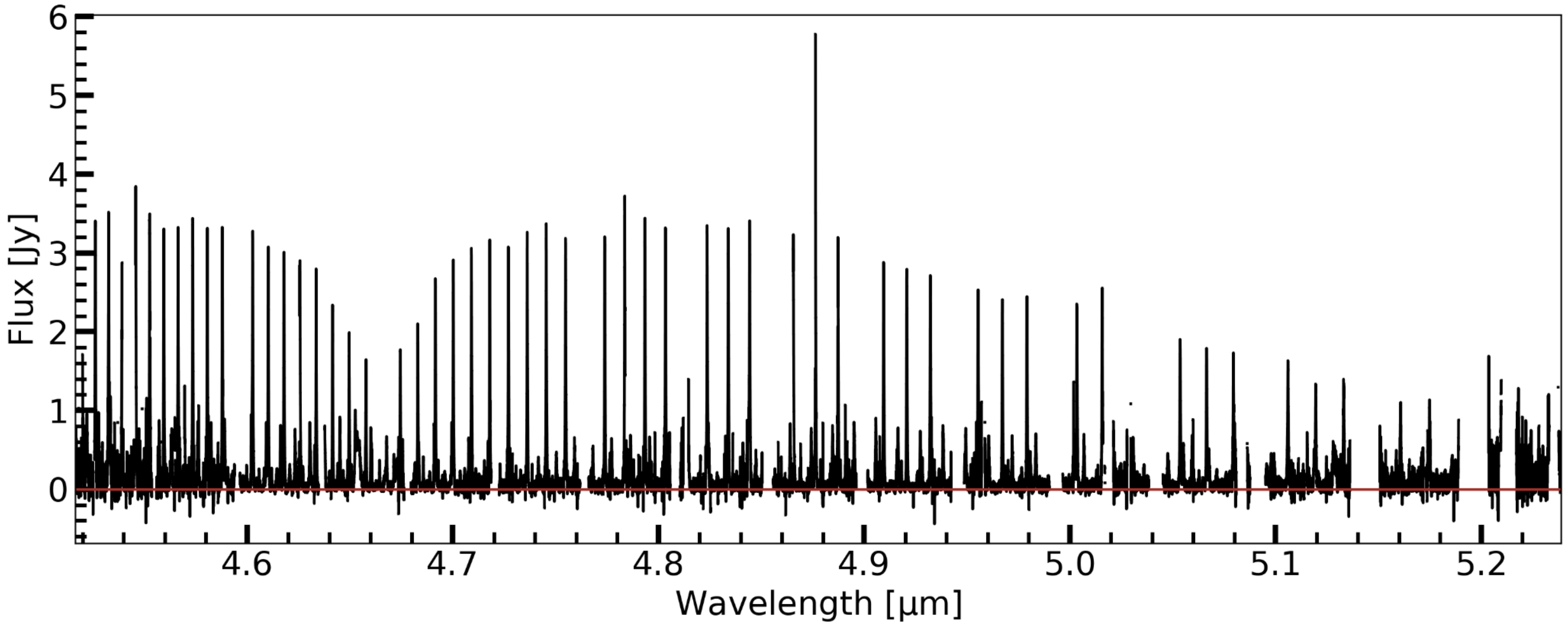
  The chemistry is more complex, the accretion and heating rates increase, modifying the thermal structure of the disc and supports the jet launch mechanisms.

Energetic particles affect the observational tracers in discs



Energetic particles affect the observational tracers in discs





Observed JWST Spectra of DR Tau.

Temmink, M., et al., A&A, 686, A117 (2024)

EP from magnetic reconnection must be considered and further studied for a better description of protoplanetary discs