Cosmic Roller Coaster

Tracing the highs and lows of cosmic ray ionization in protoplanetary disks

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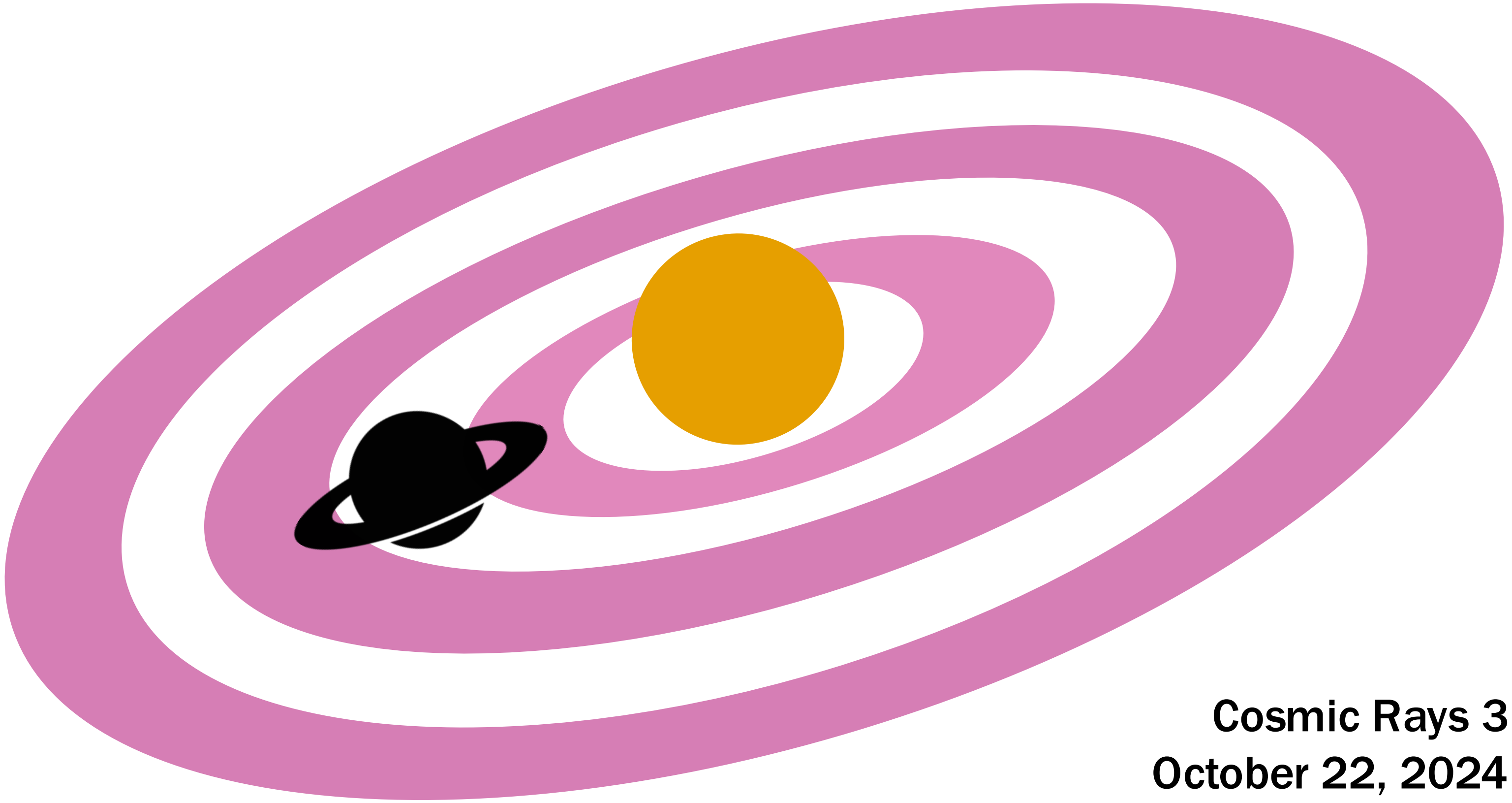
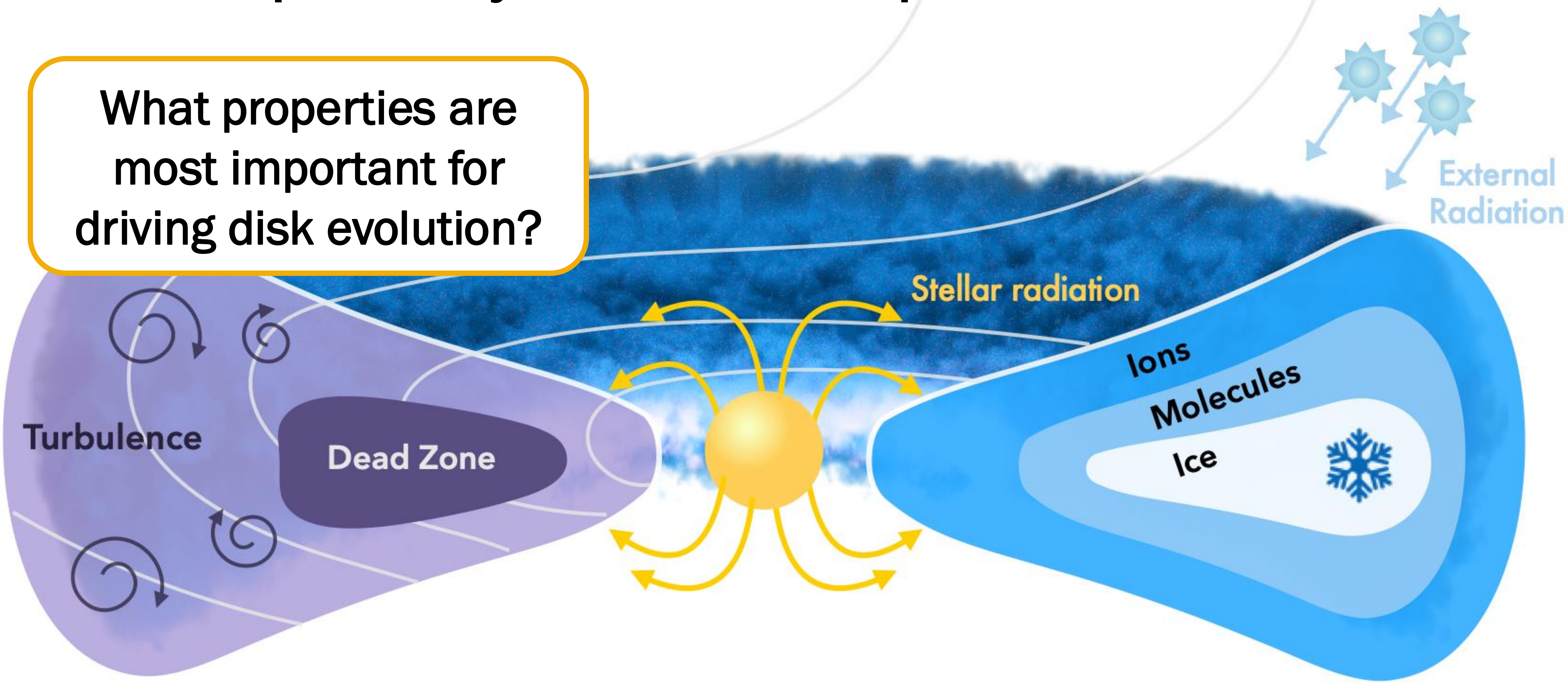


Cosmic Rays 3
October 22, 2024

Protoplanetary disks are complex environments...

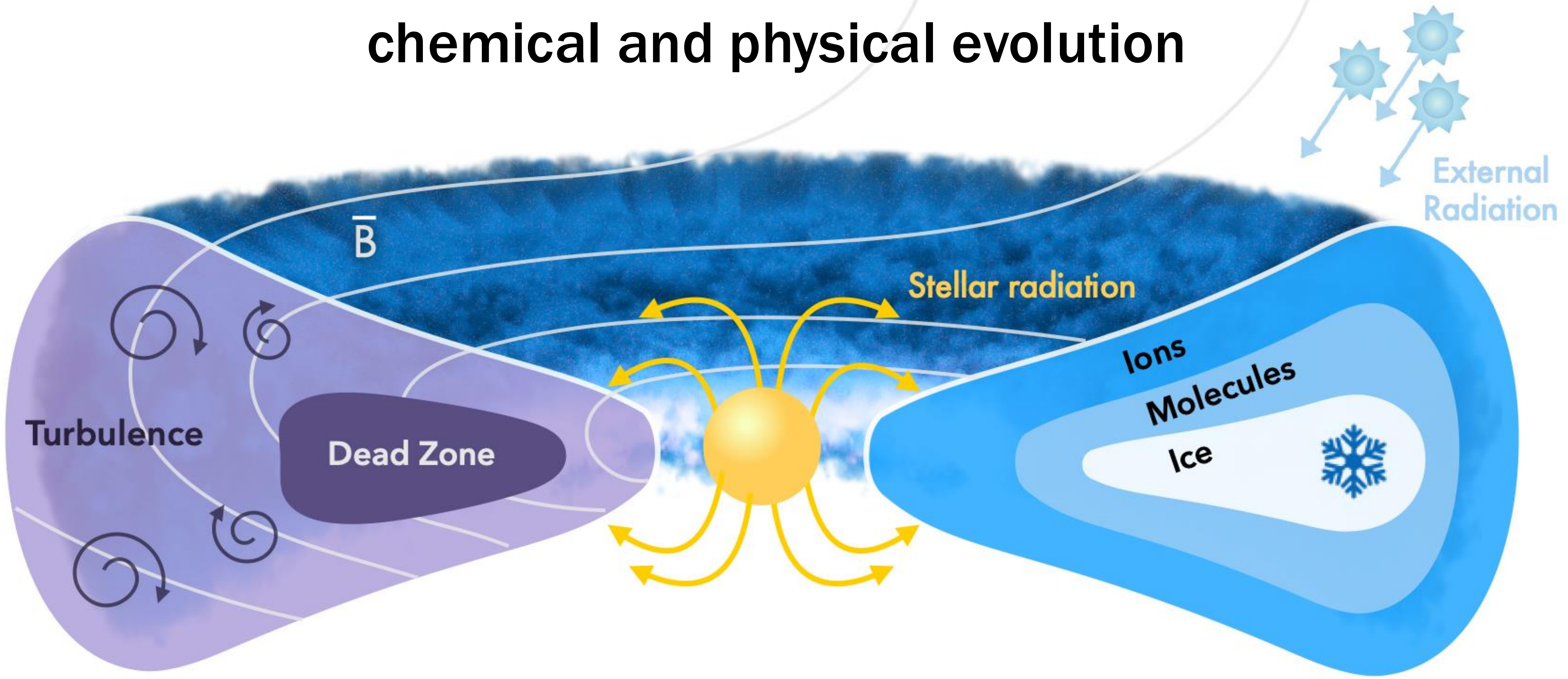
What properties are most important for driving disk evolution?



...with many ongoing processes that can alter the outcomes of planet formation

Adapted from Miotello et al. 2023

Ionization is central to the disk's chemical and physical evolution

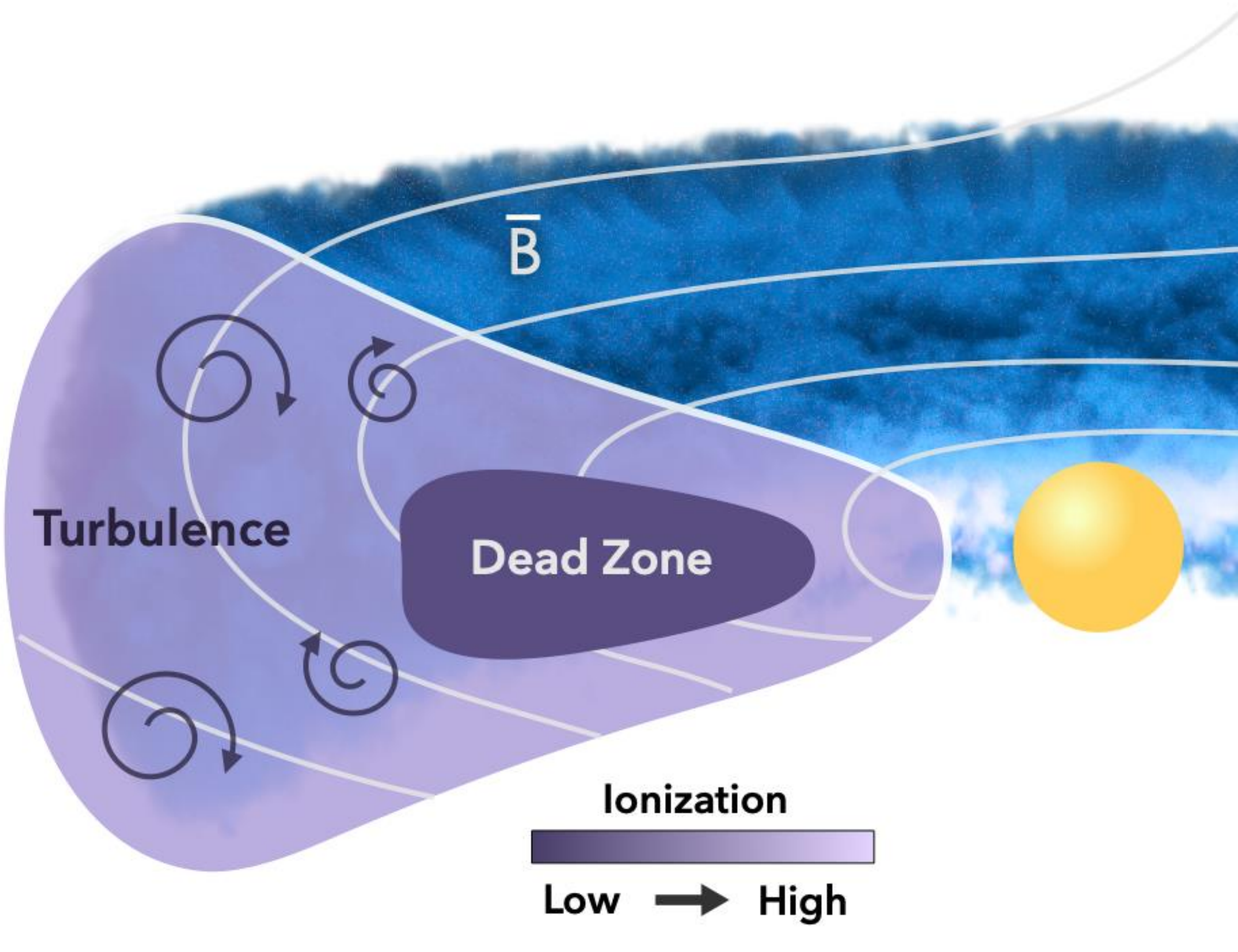


particularly when it comes to planet formation!

Adapted from
Miotello et al. 2023

Ionization sets the conditions for disk turbulence

High ionization	Low ionization
↓	↓
Gas coupled to B-field	Gas decoupled from B-field
↓	↓
Turbulence driven by magneto-rotational instability (MRI)	**Dead zones = safe havens for planet formation?**

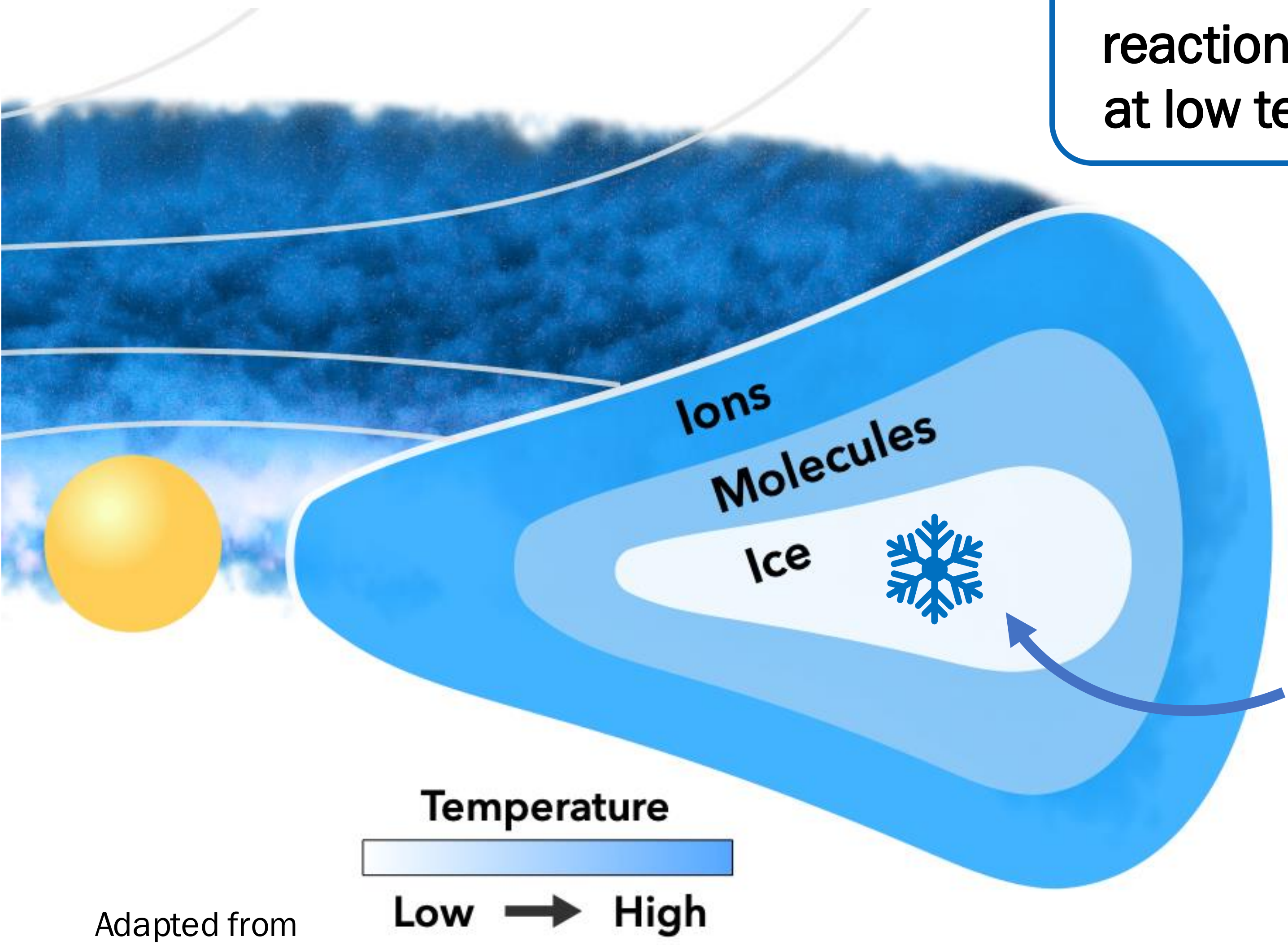


Adapted from Miotello et al. 2023

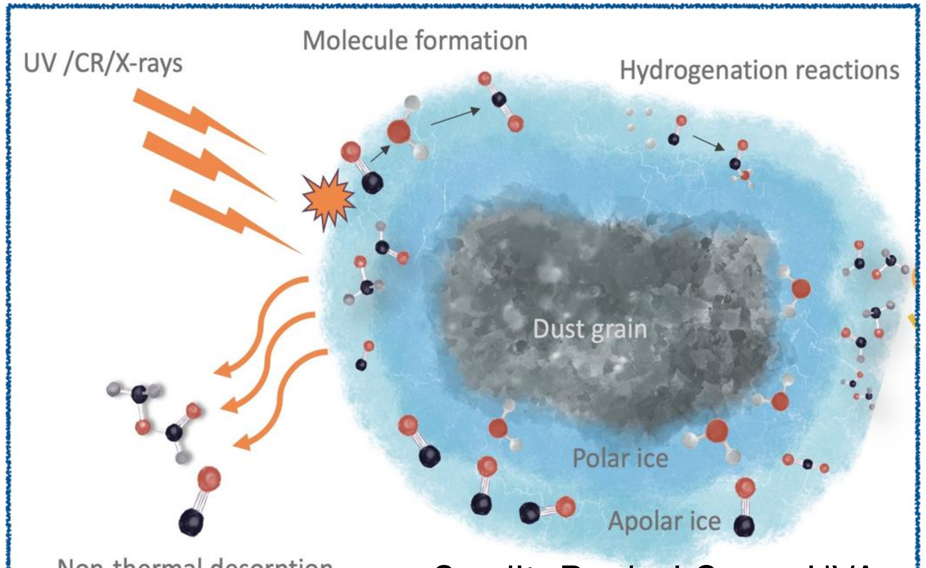
Ionization drives cold midplane chemistry

Neutral-neutral reactions slow down at low temperatures

Ions drive gas & ice chemistry in the midplane

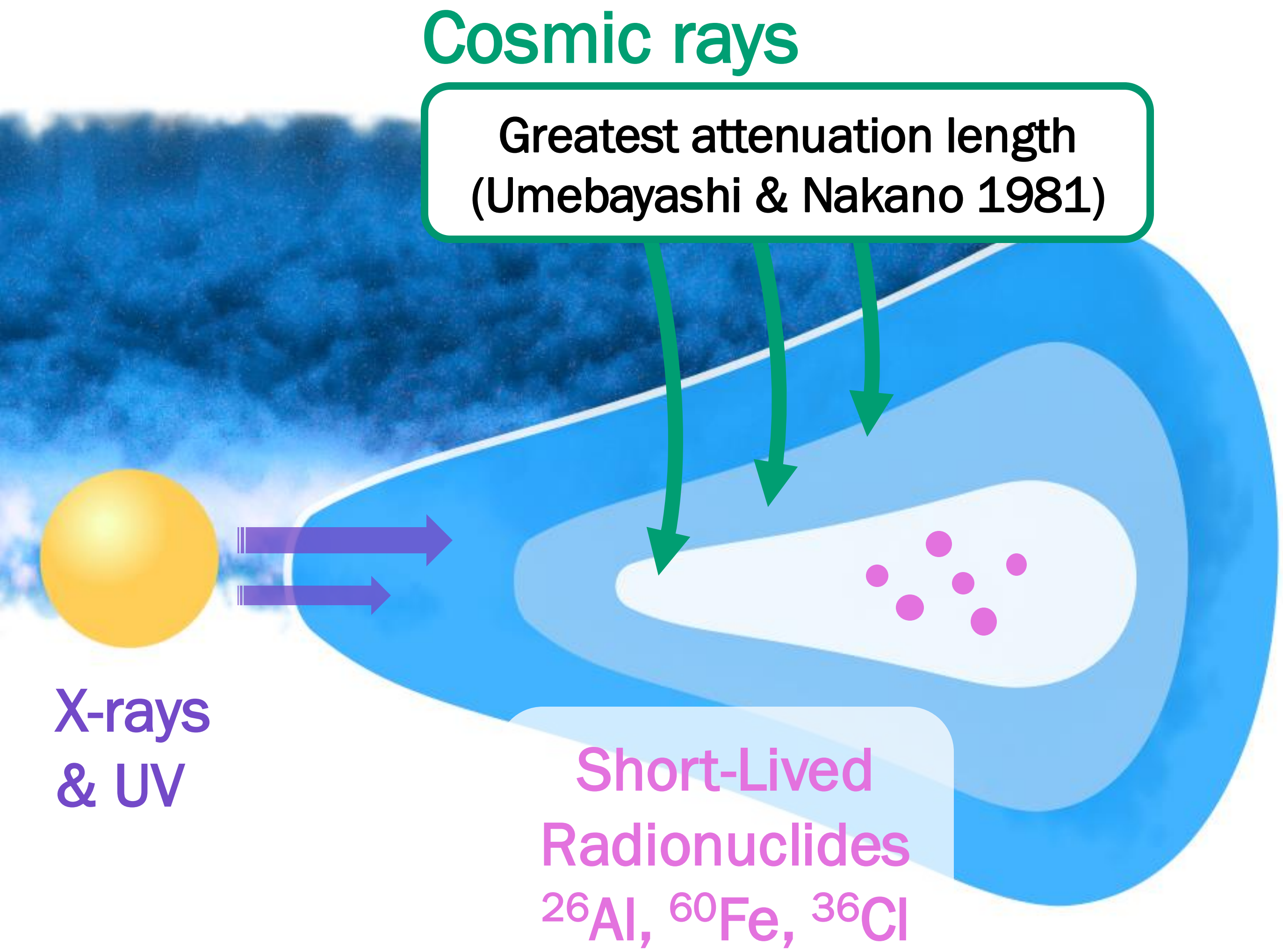


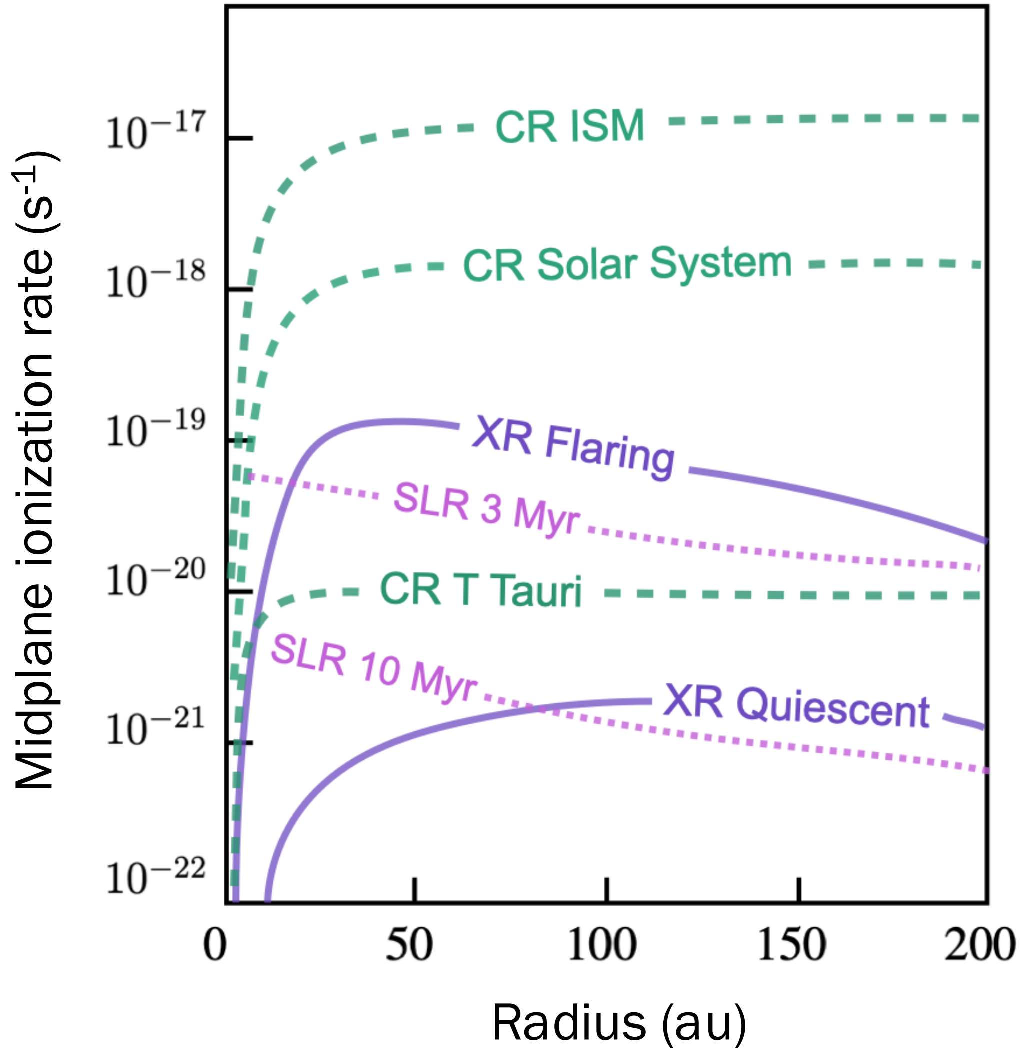
Adapted from Miotello et al. 2023



Credit: Rachel Gross UVA

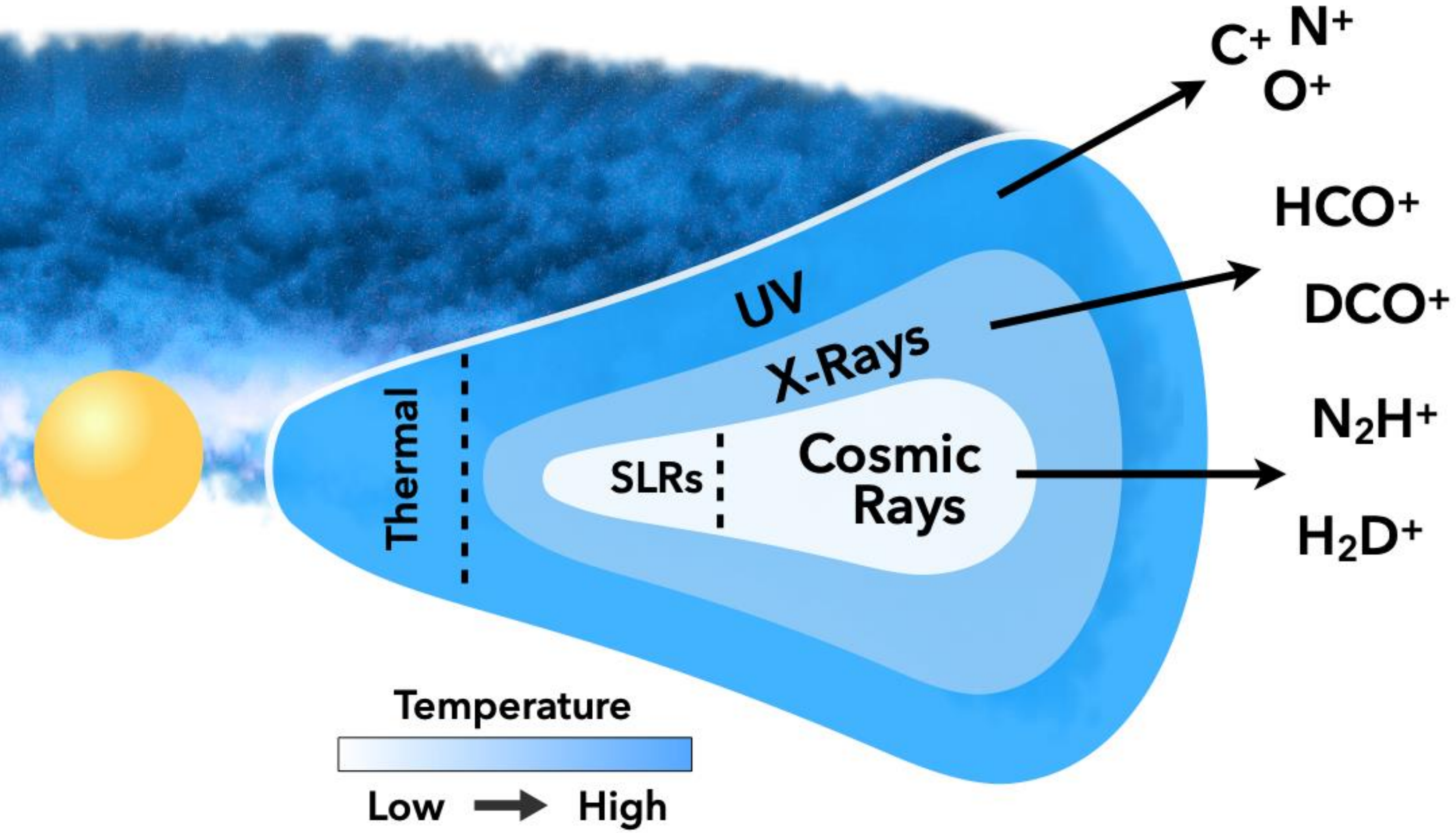
However, there is significant spatial variation in ionization, making it difficult to resolve and constrain





Adapted from Cleeves et al. 2015

Luckily we can trace different ionizing processes using radio-wavelength observations of molecular ions

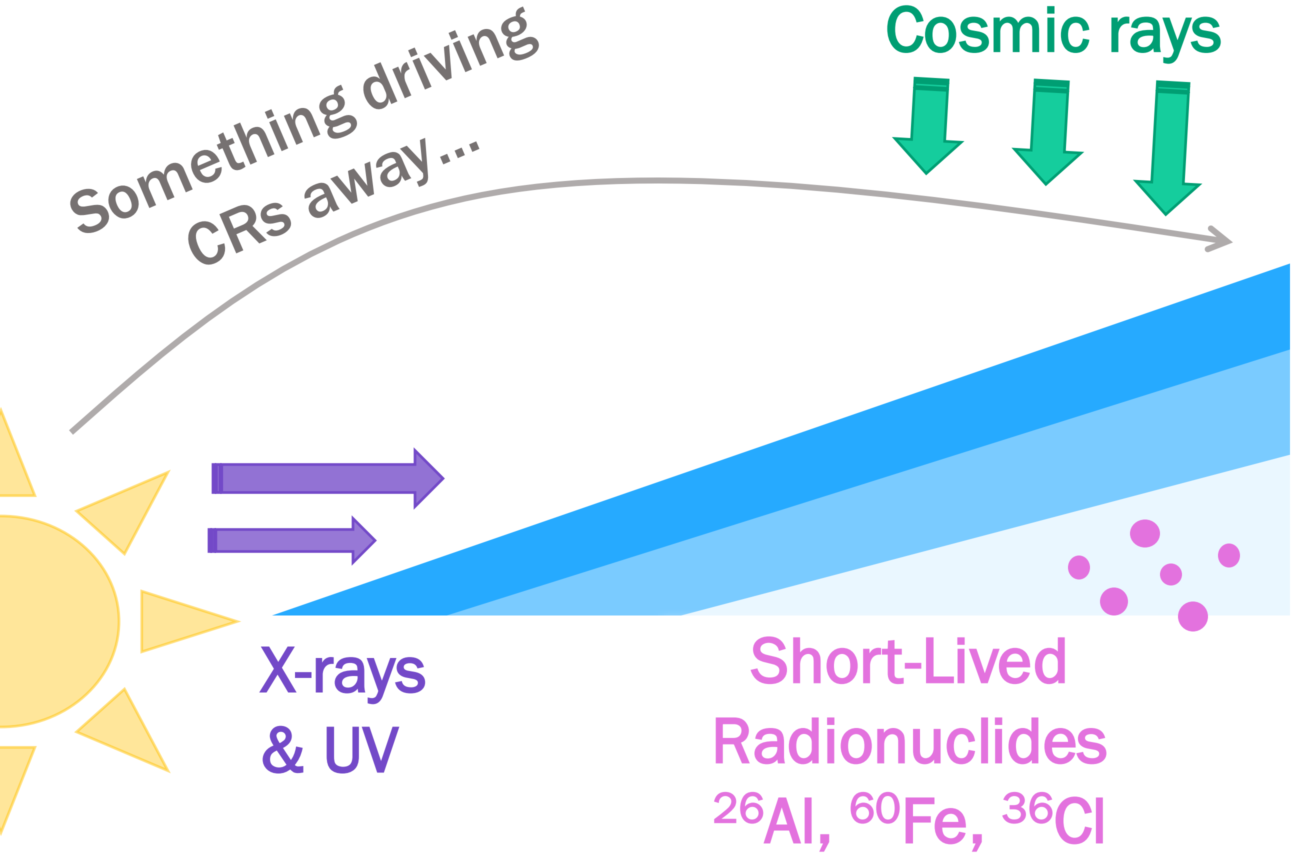


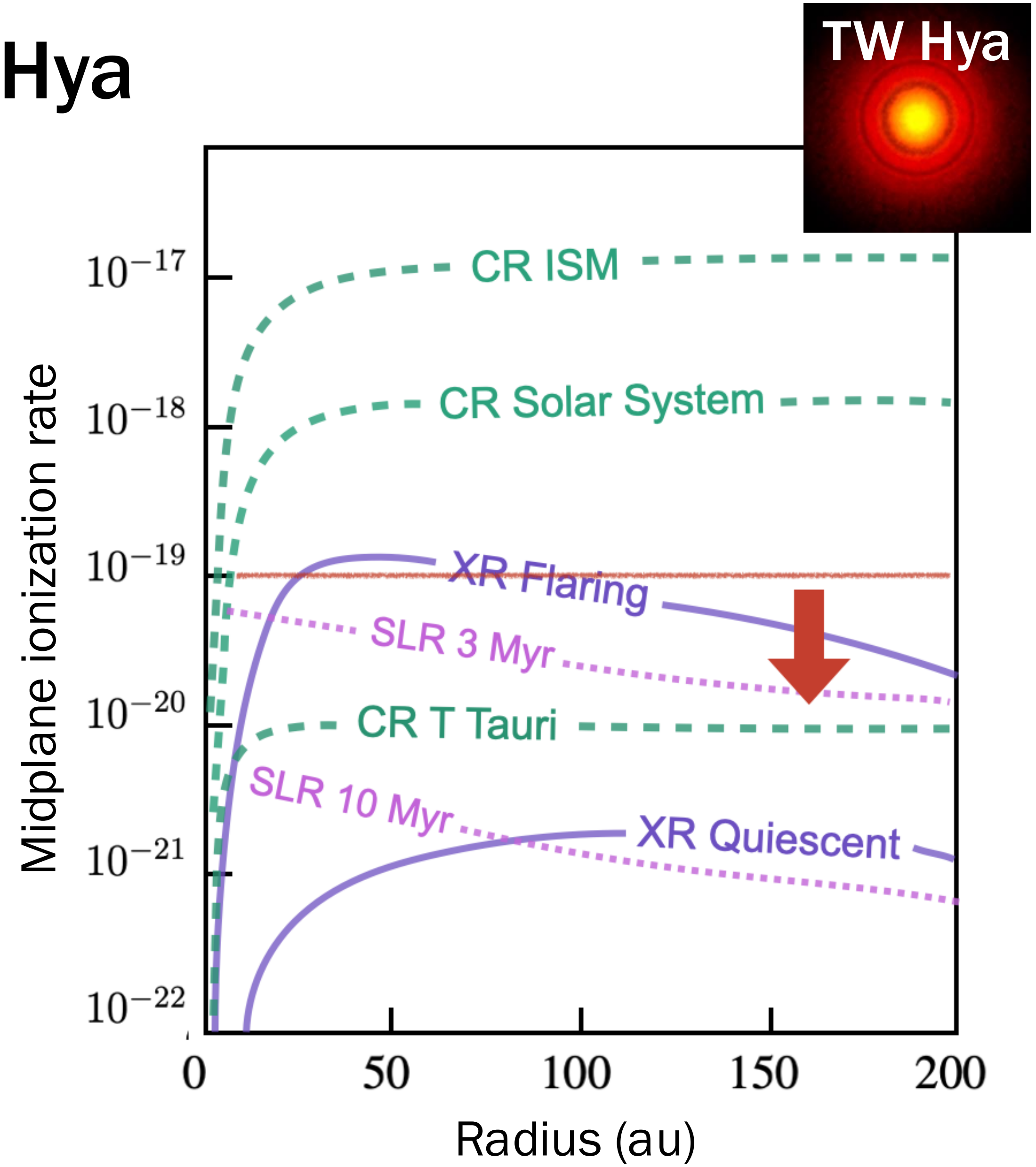
Surface Tracers

Midplane Tracers

Ionization in the closest disk: TW Hya

Observations of N_2H^+ and upper limits on H_2D^+ point to flaring XR conditions and **sub-interstellar CRs** (Cleeves et al. 2015)

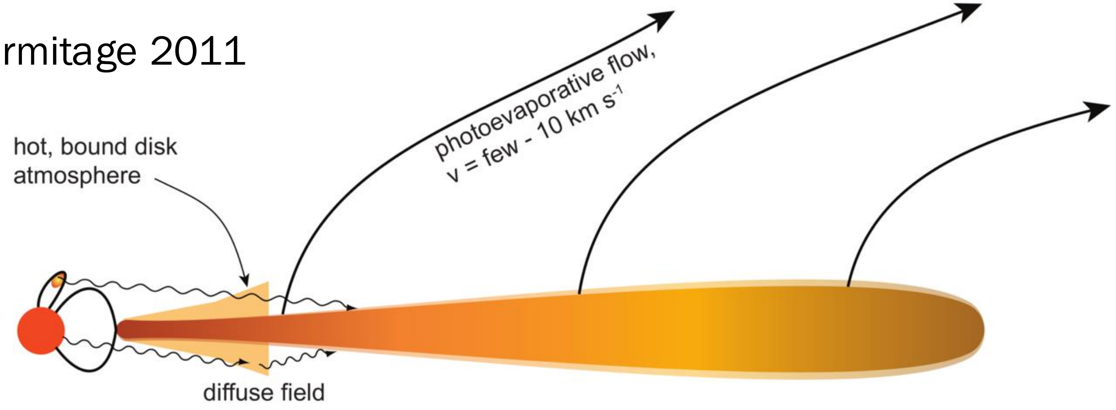




Adapted from Cleeves et al. 2015

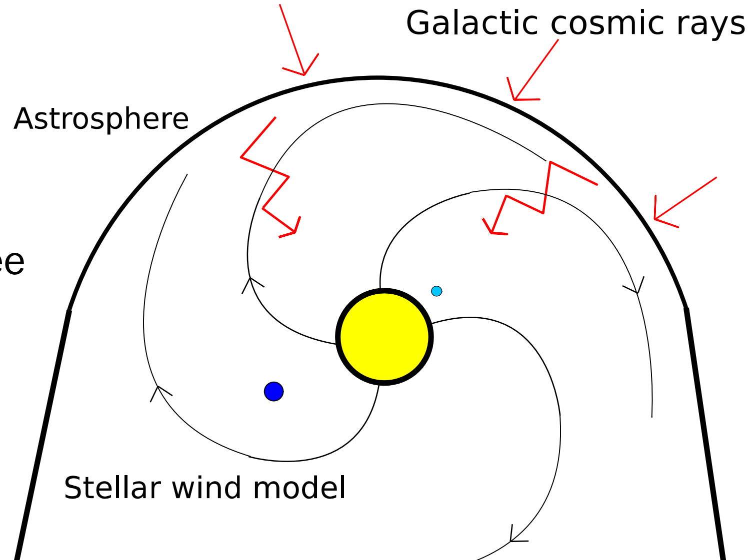
Many processes that may suppress CRs in disks

Armitage 2011



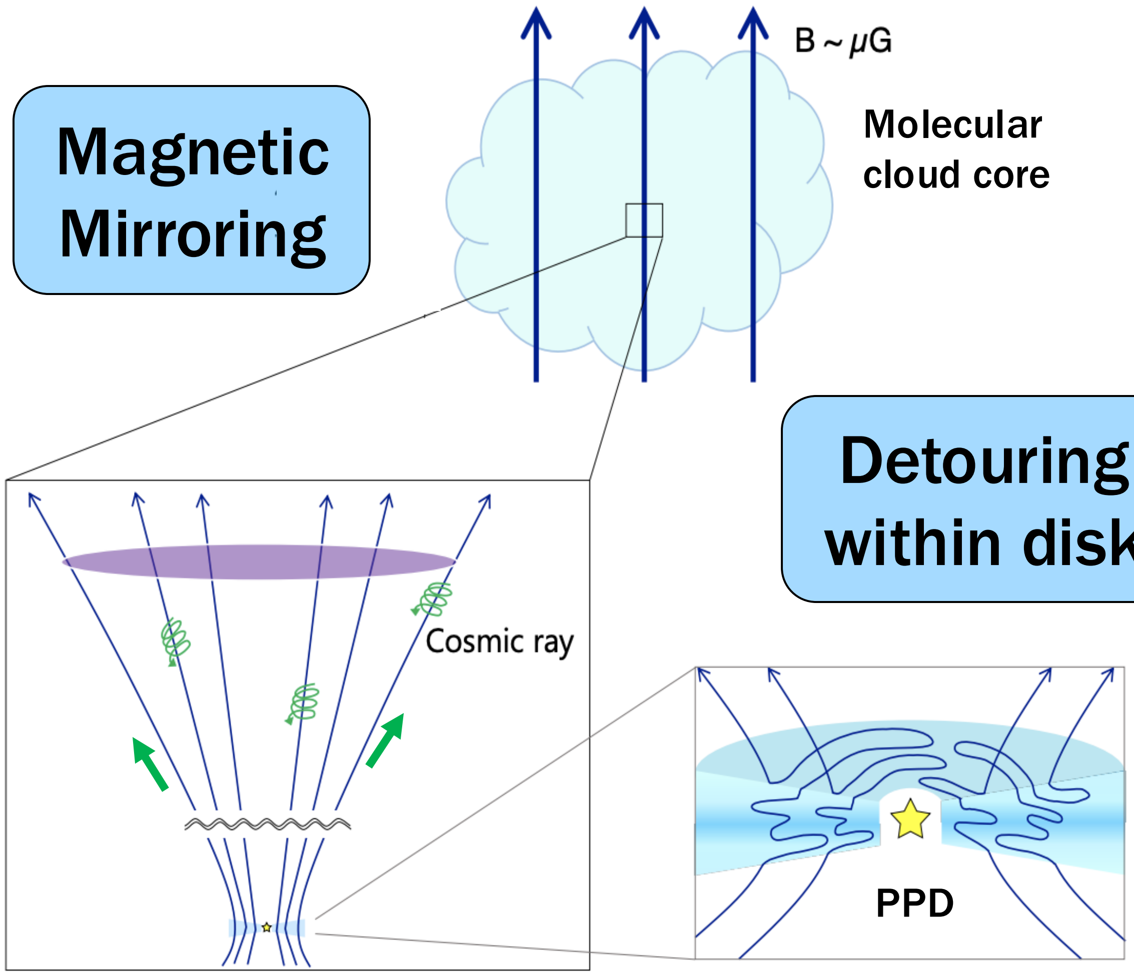
Winds/astrosphere

Rodgers-Lee et al. 2020



Magnetic Mirroring

Detouring within disk

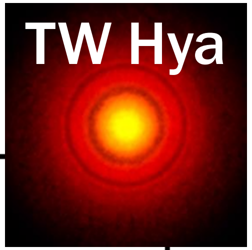


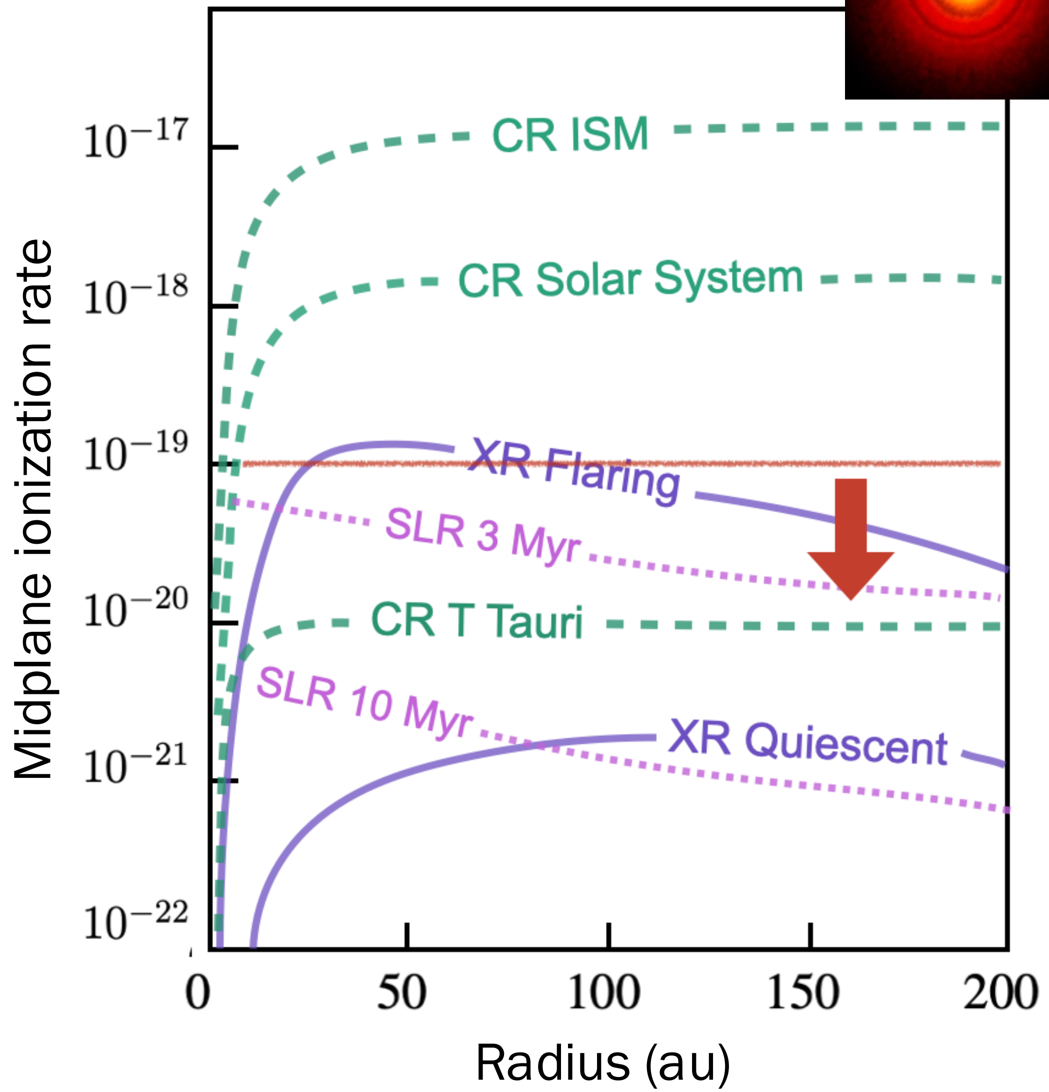
Adapted from Fuiji & Kimura 2022

Ionization in the closest disk: TW Hya

Observations of N_2H^+ and upper limits on H_2D^+ point to **sub-interstellar CRs** (Cleeves et al. 2015)

Are most disks "cosmic ray poor" like TW Hya?





Adapted from Cleeves et al. 2015

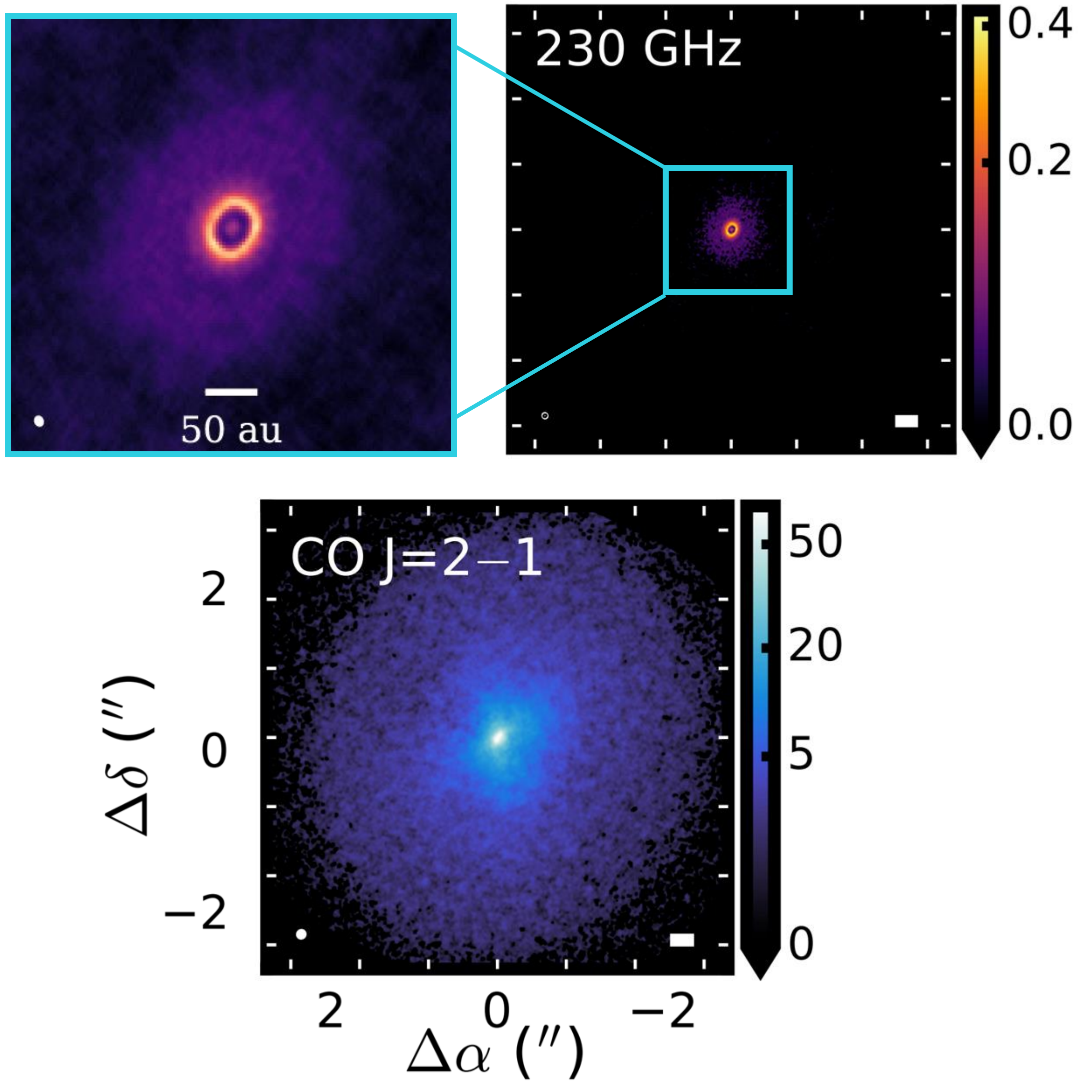
Will DM Tau tell a different story?

Large inner gap and the only disk with evidence of turbulence … at the time (Flaherty et al. 2020)

→ Is DM Tau uniquely turbulent because of high ionization?

→ Does the gap impact ionization environment?

→ How does it compare to TW Hya?

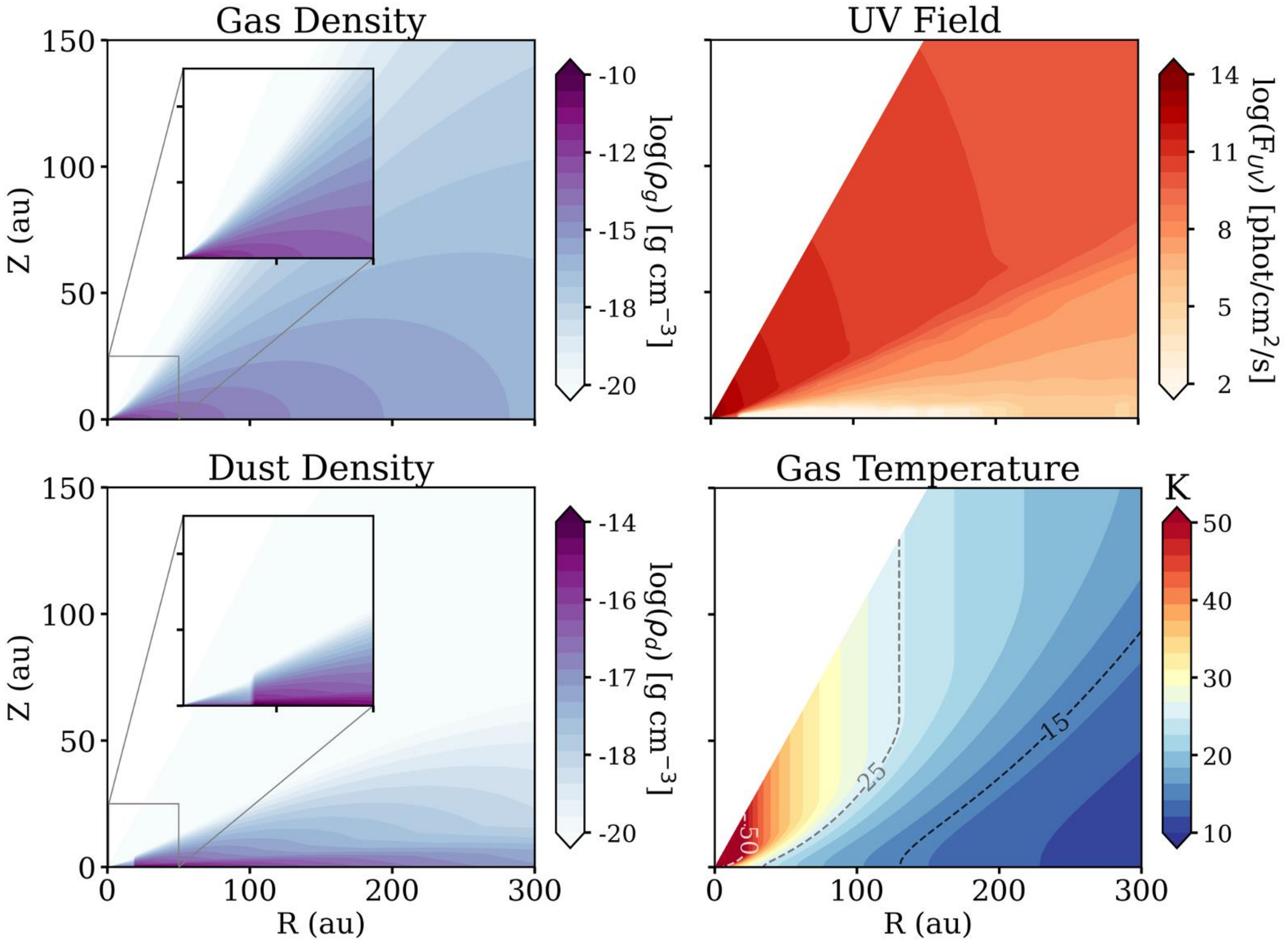


Adapted from Francis et al. 2022 and Law et al. 2023

Forward Modeling DM Tau

Physical model

Well-known temperature and density structure

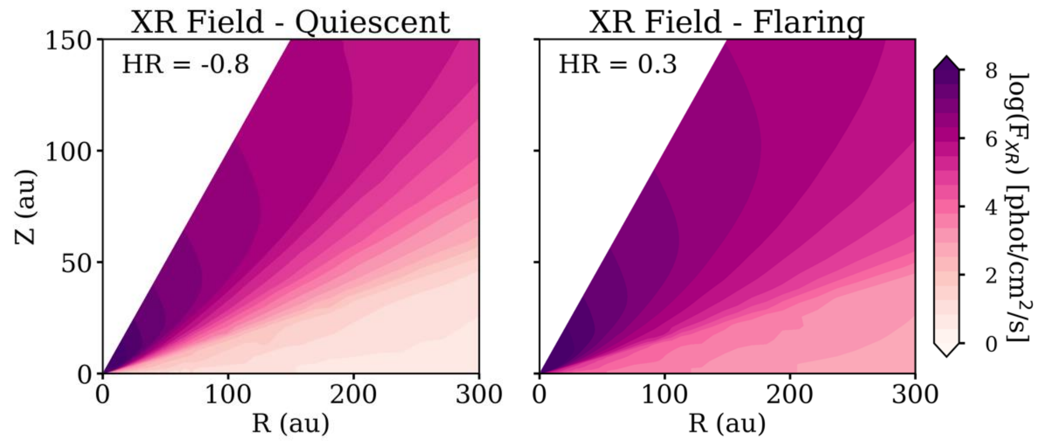


Forward Modeling DM Tau

Applied under a range of ionizing conditions

Physical model + **2D Chemical Code**

Abundances & distribution of molecules in disk



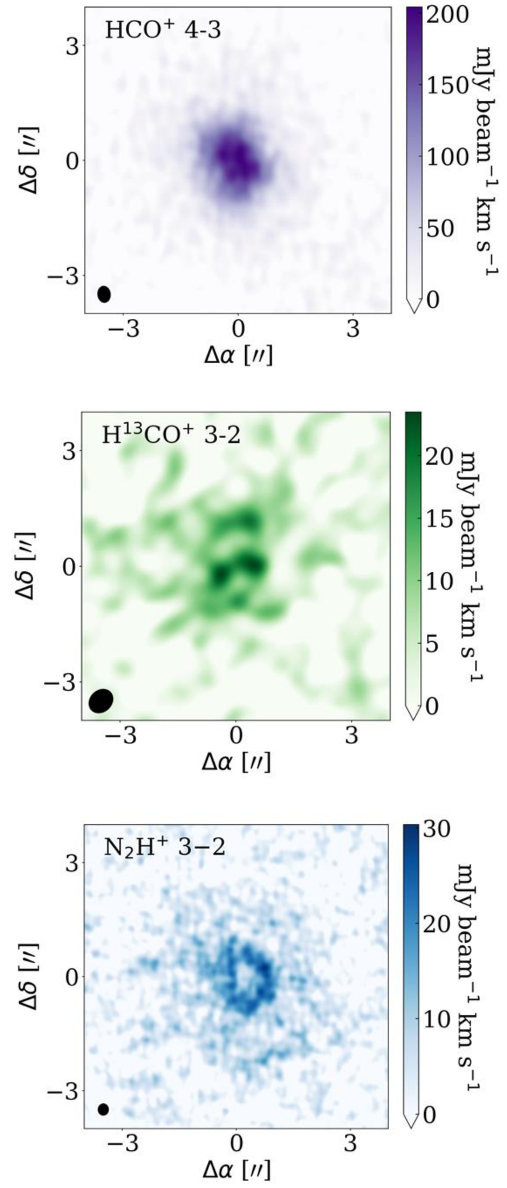
Cosmic Ray Model	Label	ζ_{CR}
Moskalenko et al. (2002)	M02	6.8×10^{-16}
Webber (1998)	W98	2.0×10^{-17}
Solar System Min Mod	SSM	1.1×10^{-18}
Solar System Max Mod	SSX	1.6×10^{-19}
T Tauri Max Mod	TTX	1.0×10^{-21}

Forward Modeling DM Tau

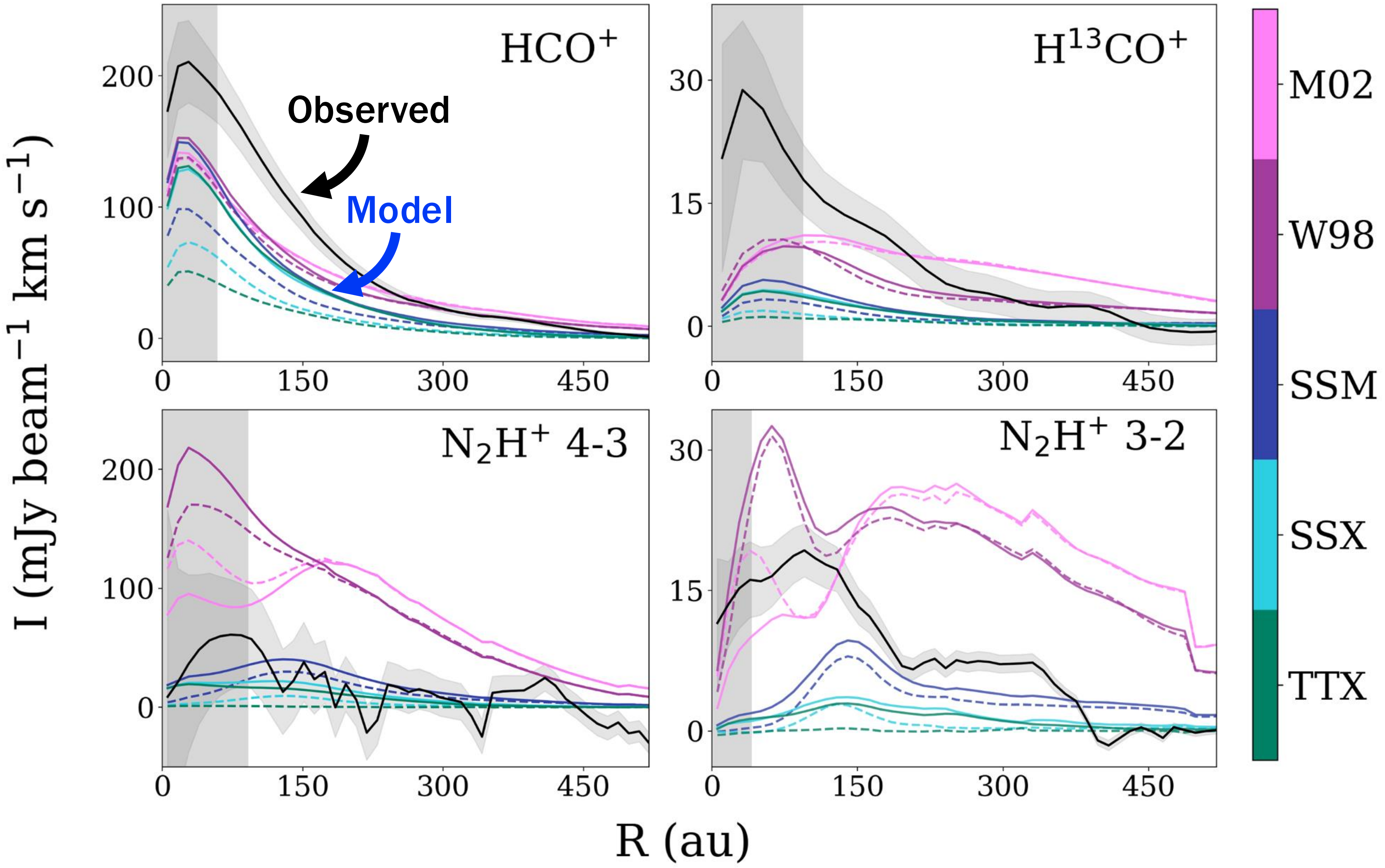
Applied under a range of ionizing conditions

Physical model + **2D Chemical Code** + **ALMA Observations**

Ionization-tracing molecules



Emission profiles reveal an ionization gradient in DM Tau

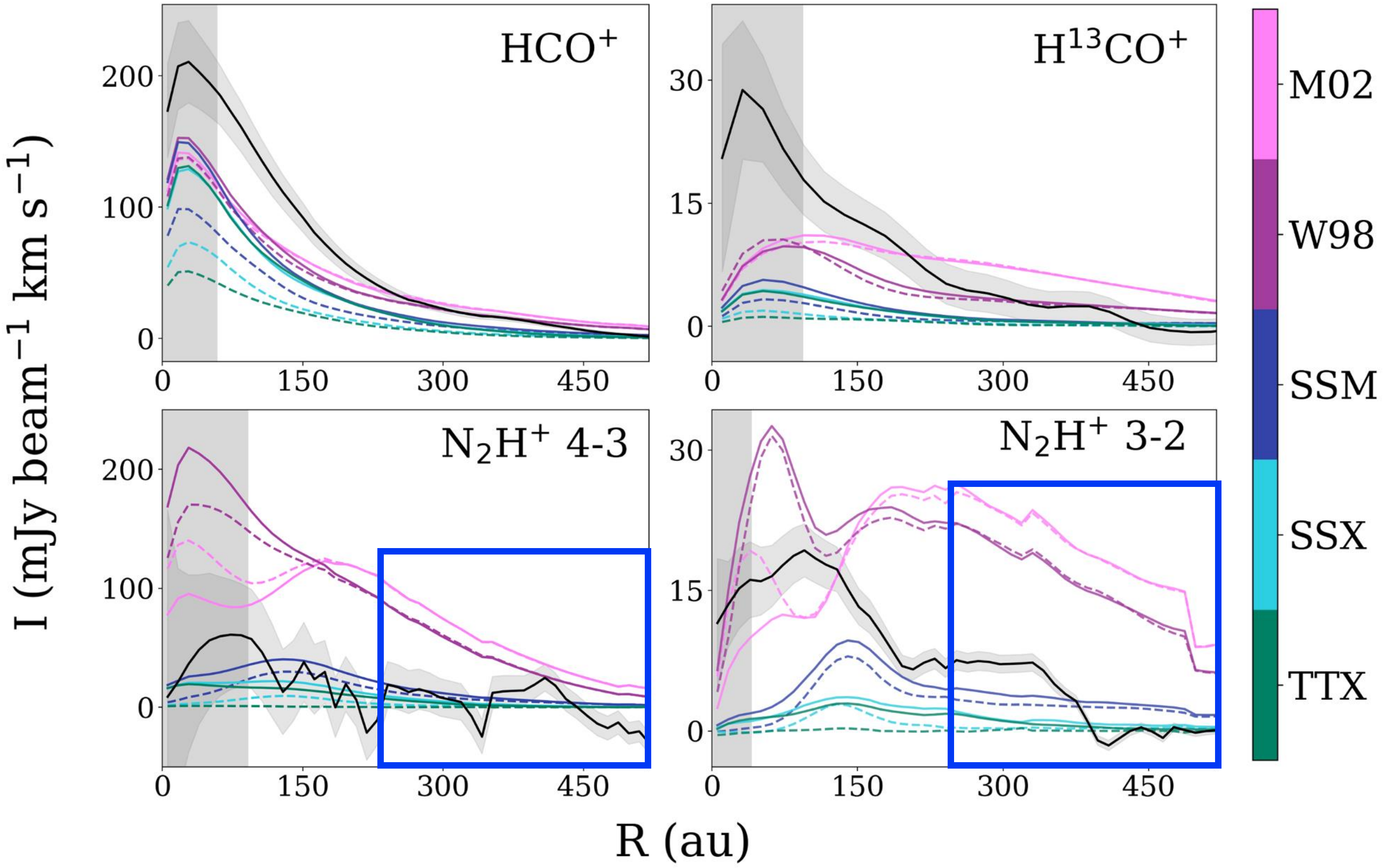


Dashed – Quiescent XR
Solid – Flaring XR

Difficult to reproduce observed emission profiles with a single CR ionization rate

Long et al. 2024

Outer disk N_2H^+ requires reduced cosmic rays

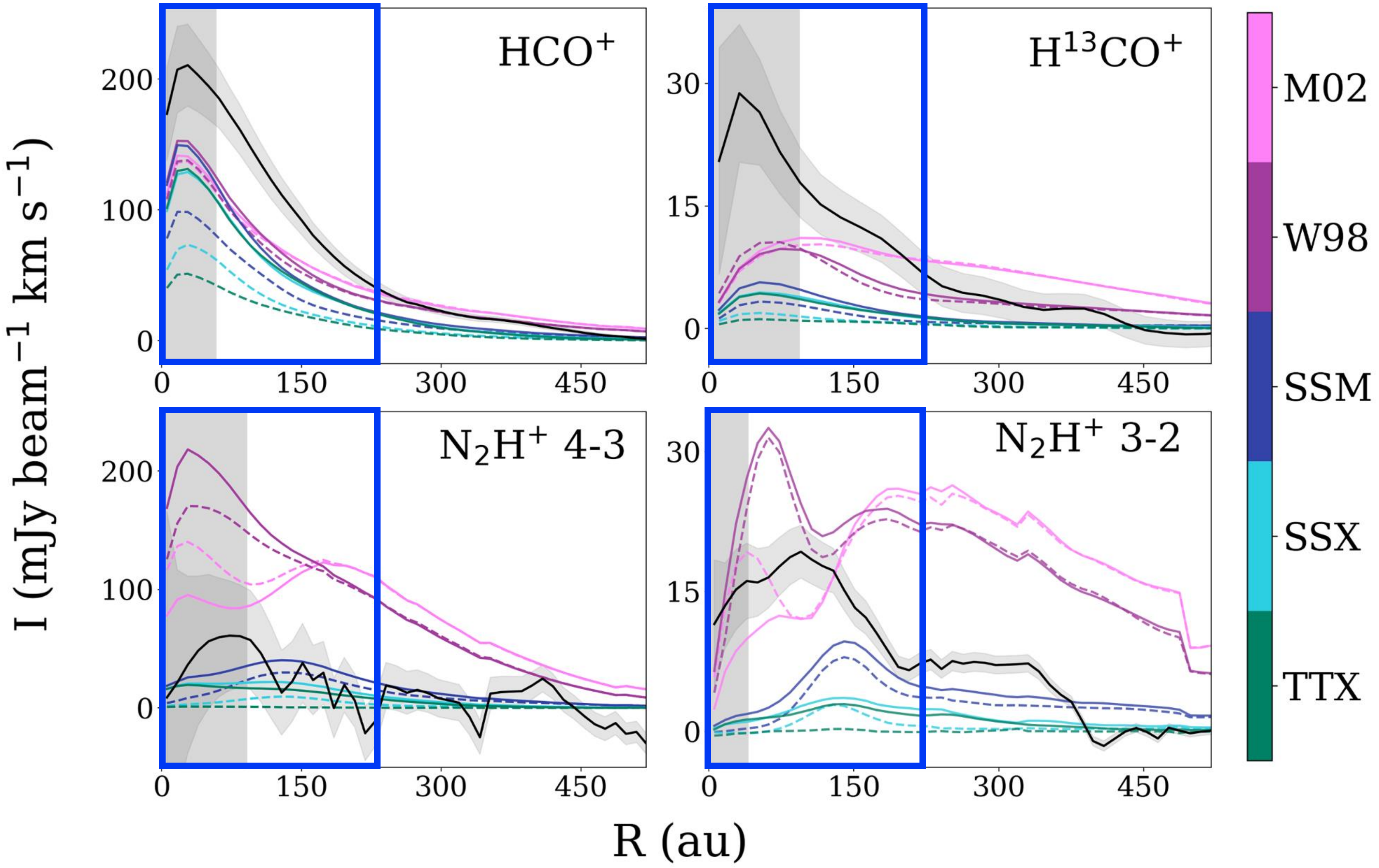


→ CR exclusion or modulation across or within the disk

Winds? CR detouring?

Long et al. 2024

Surface & midplane tracers both point to high ionization in inner disk

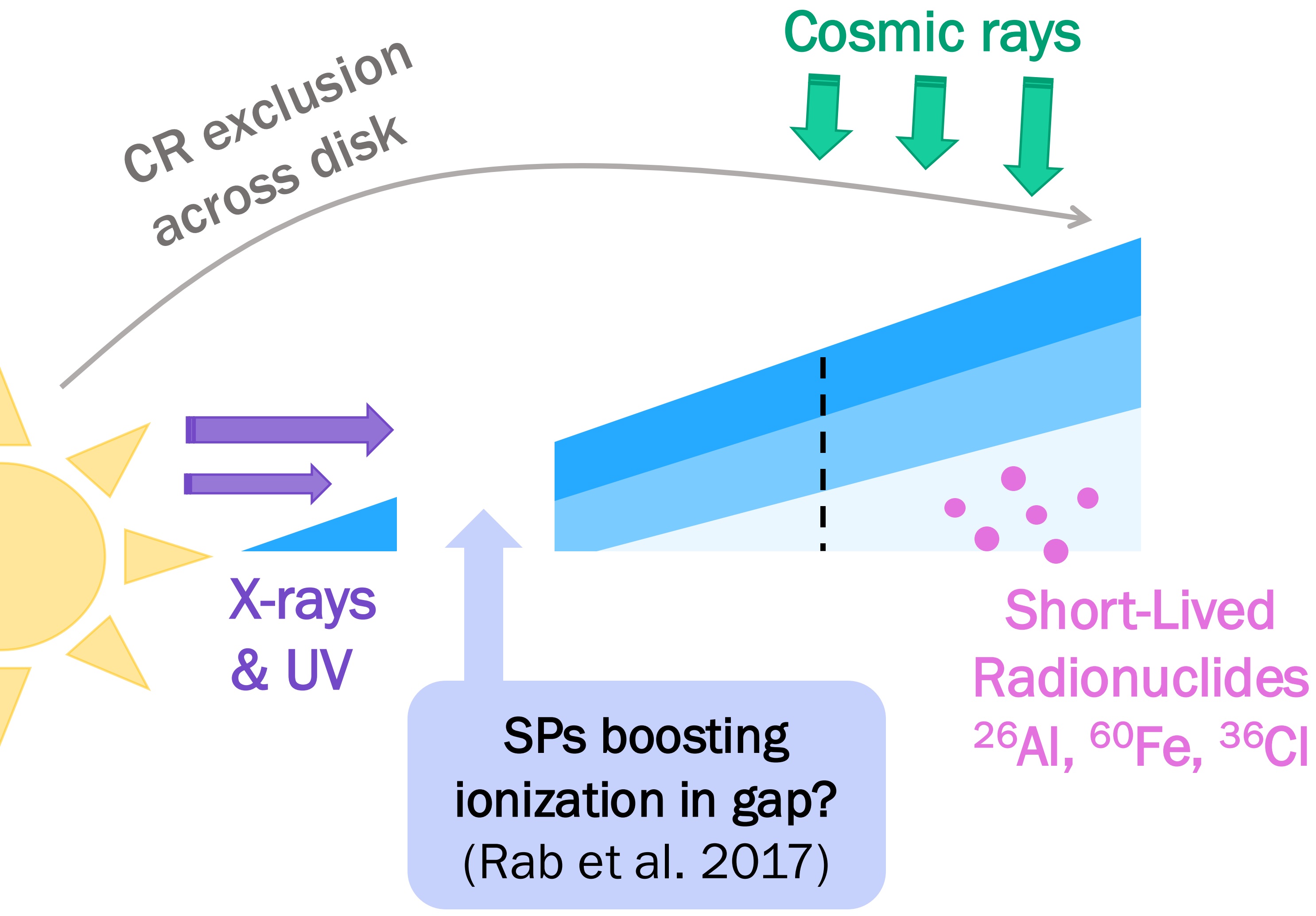


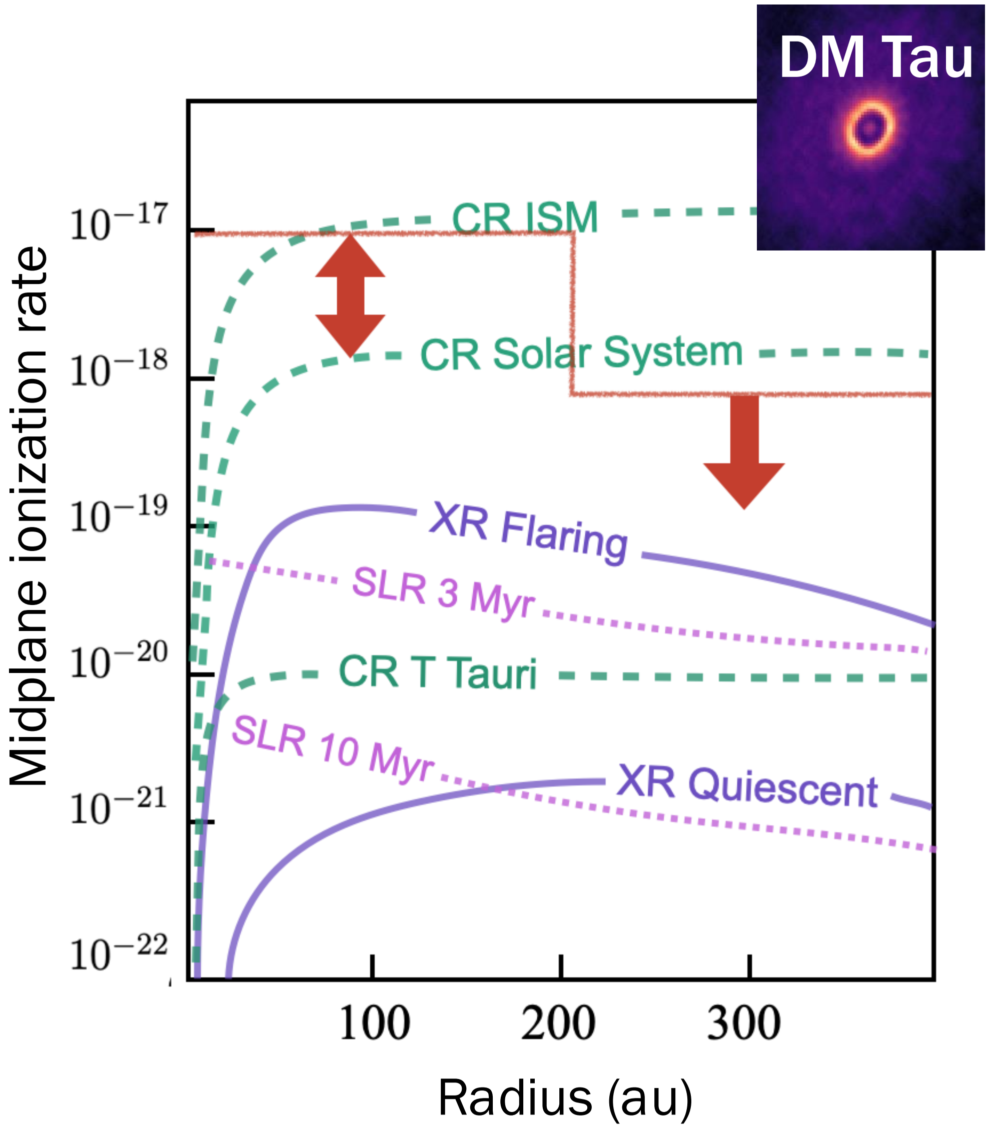
→ **Something "boosting" ionization in the inner disk!**

Possibly (1) stellar energetic particles and/or (2) substructure making the inner disk more permeable to CRs.

Long et al. 2024

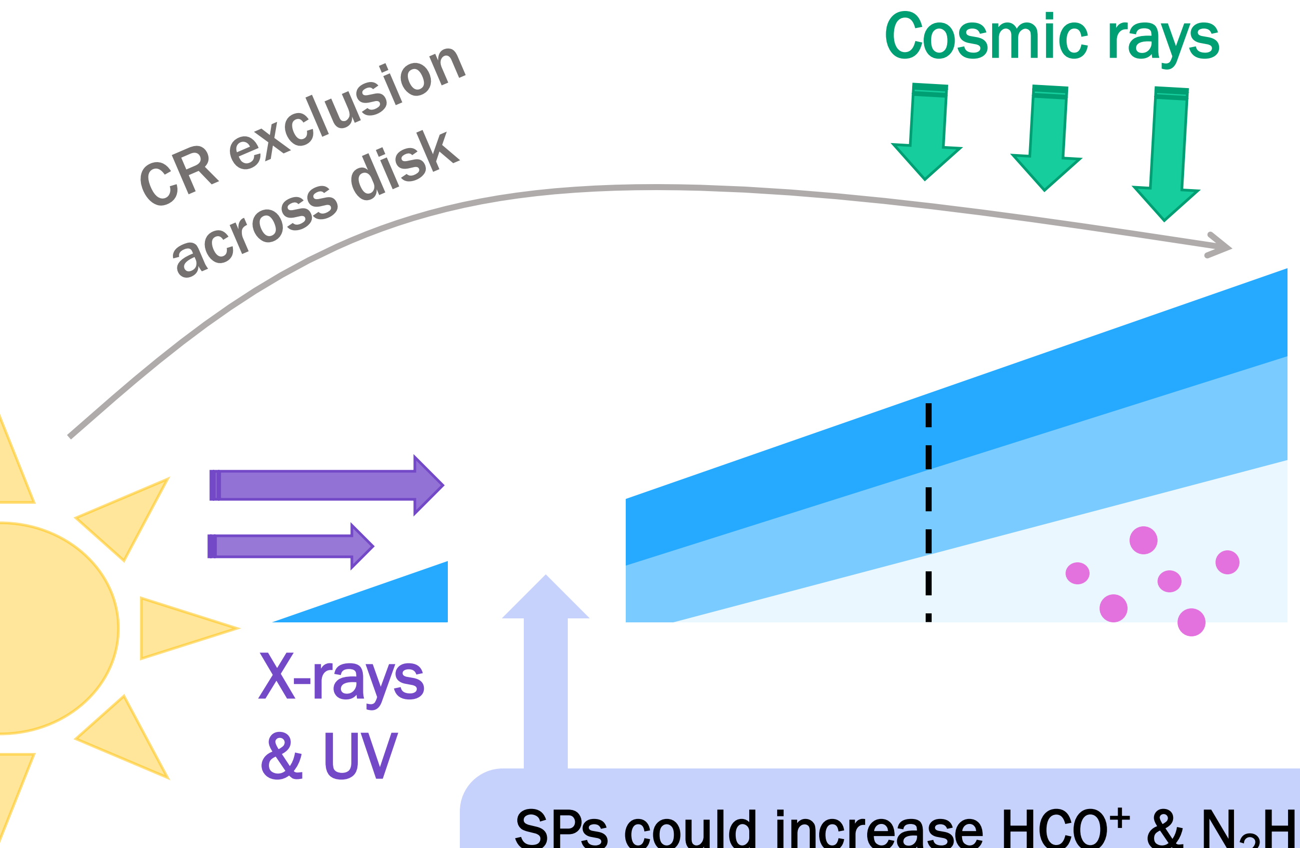
DM Tau exhibits evidence of CR exclusion and hints at the interplay between substructure and the central star



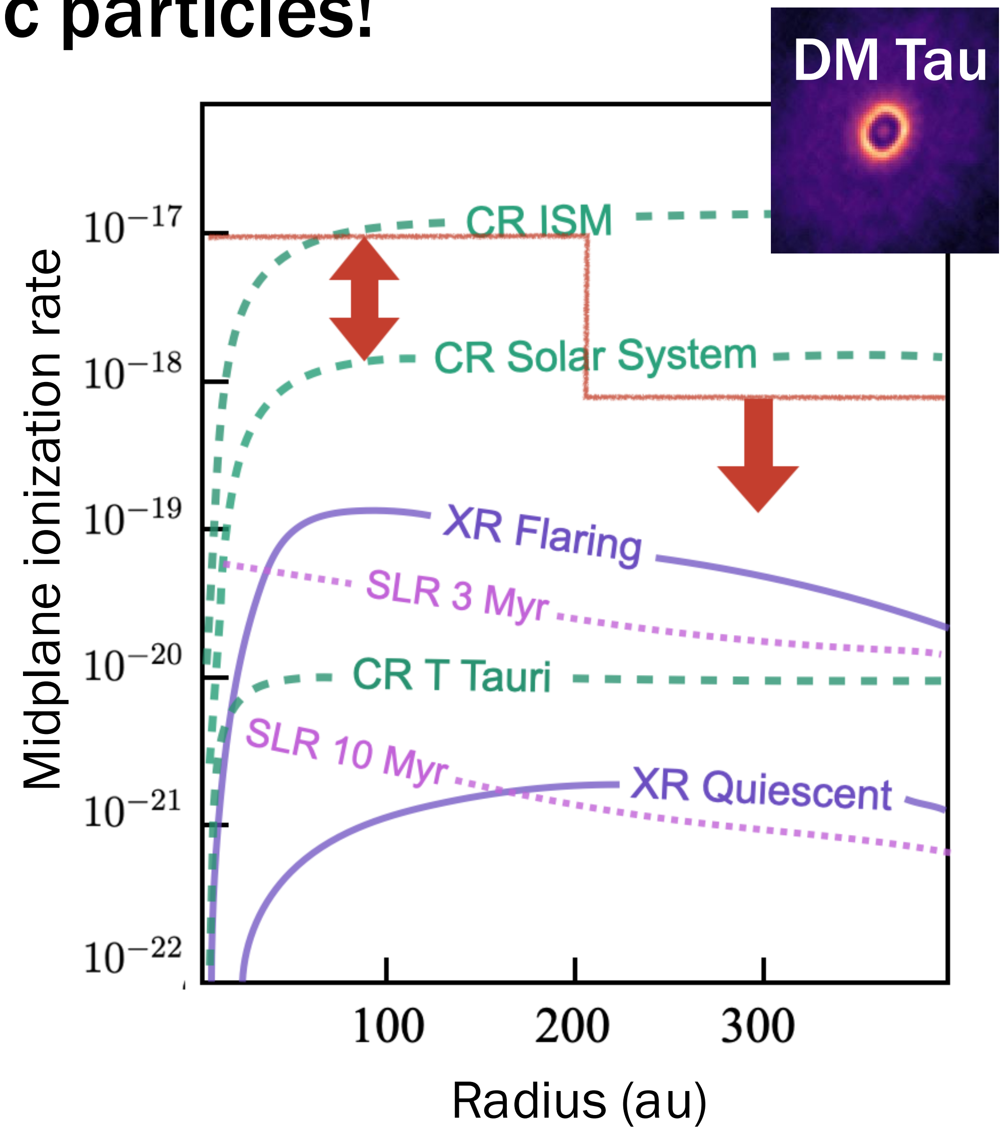


Adapted from Cleeves et al. (2015)

DM Tau exhibits evidence of CR exclusion and hints at the interplay between substructure and stellar energetic particles!

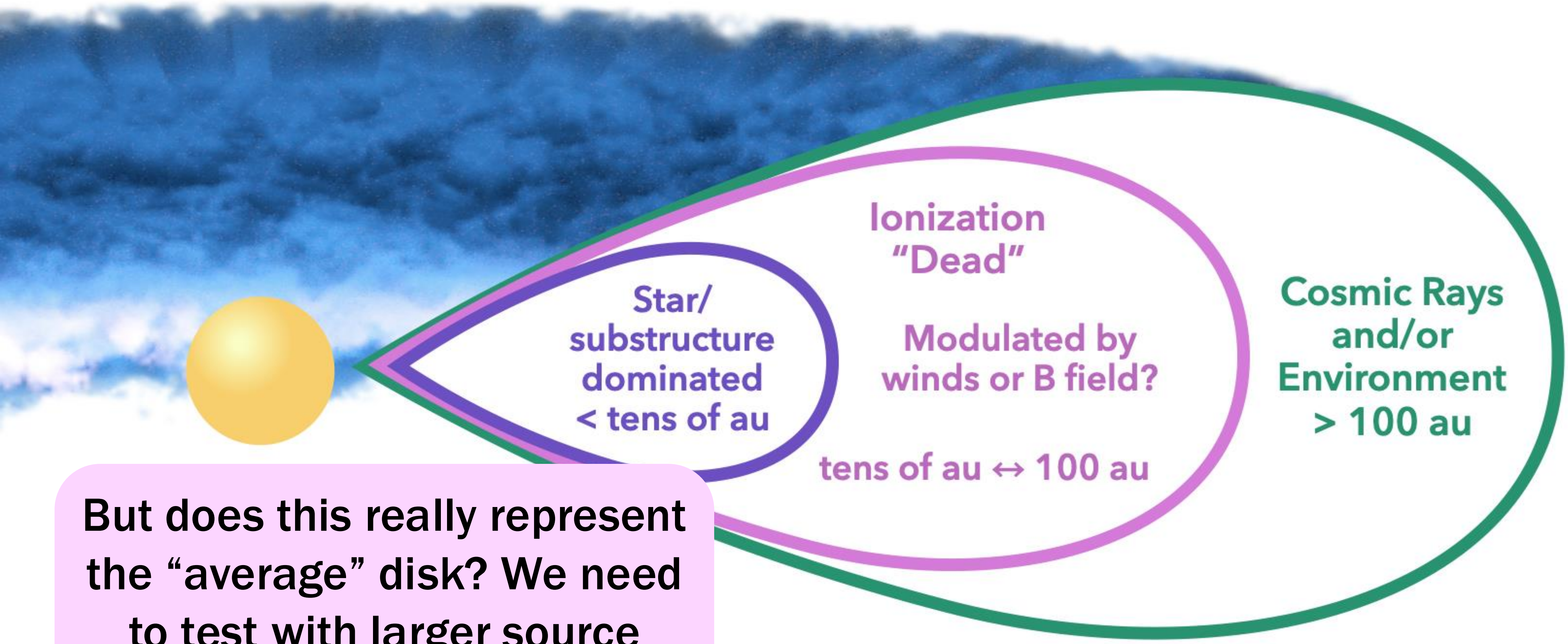


SPs could increase HCO^+ & N_2H^+ column densities by 3-10x in the inner disk (Rab et al. 2017)

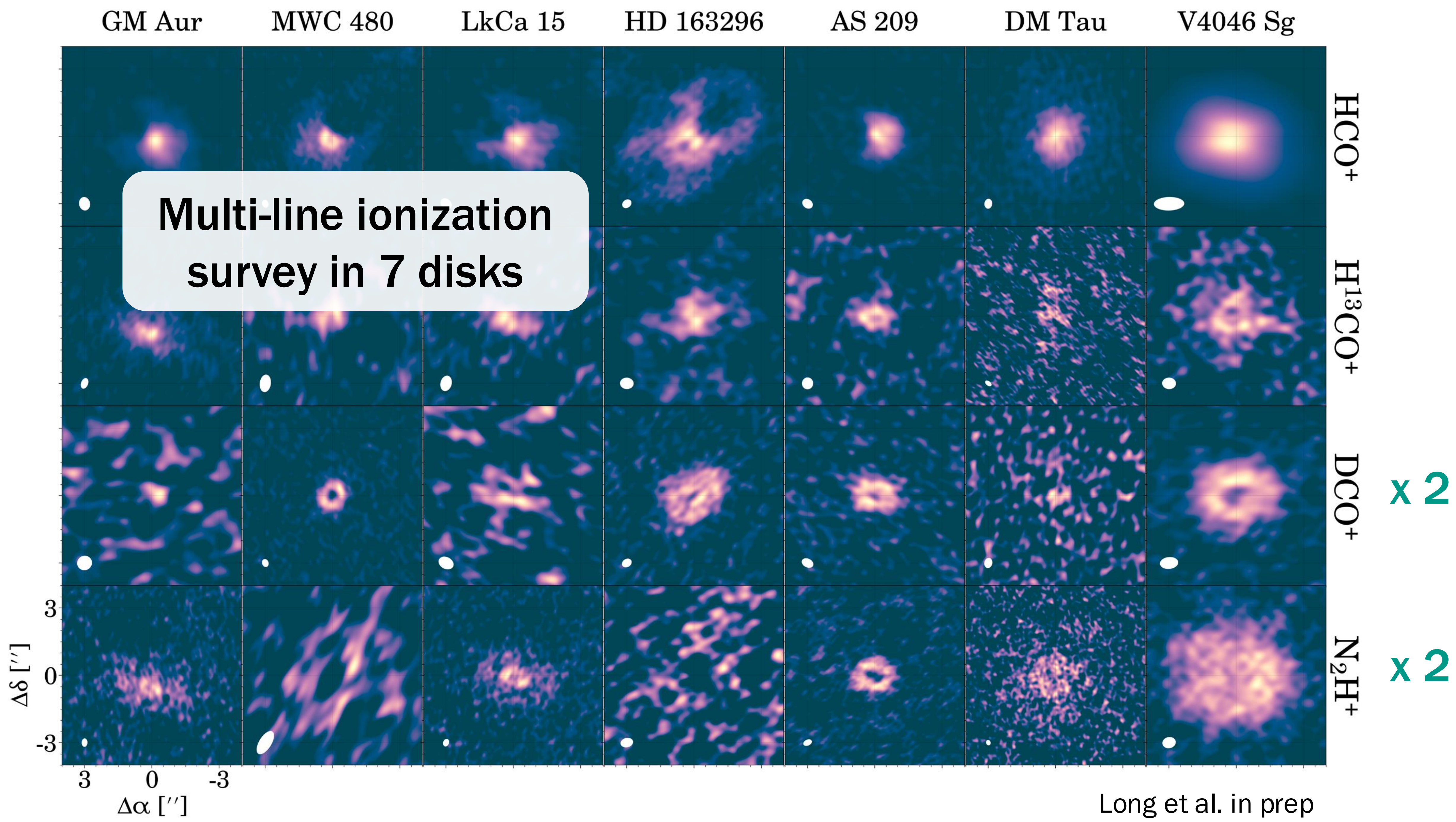


Adapted from Cleeves et al. (2015)

Unifying disk cosmic ray ionization

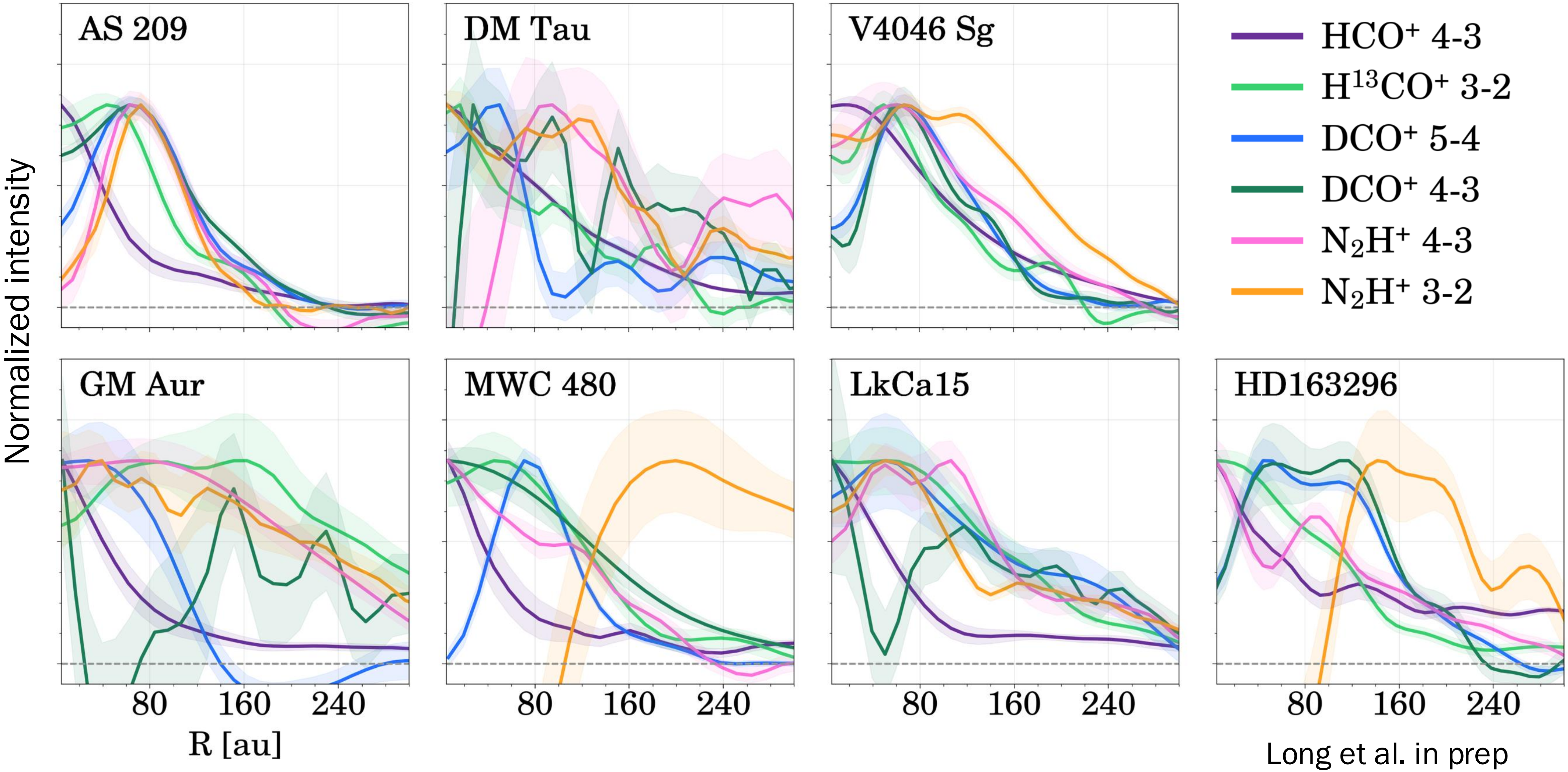


But does this really represent the "average" disk? We need to test with larger source samples!



Long et al. in prep

Preliminary radial profiles reveal diverse emission morphology & hint at complex ionization environments



Long et al. in prep

Takeaways

Cosmic rays are thought to be a crucial source of ionization in the planet-forming midplane, but observations of disks suggest modulation is common

Spatially resolved observations of molecular ions & detailed astrochemical models help us disentangle ionization sources – **multi-line studies are key**

DM Tau follows common thread of CR modulation, but results hint at complexities related to substructure and the central star… **Stay tuned for survey results ☺**

Questions?