EXCLUSION OF COSMIC RAYS WITHIN A "T-TAURIOSPHERE"

Image Credit: NASA/Goddard Space Flight Center Conceptual Image Lab

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2013 Rocks!
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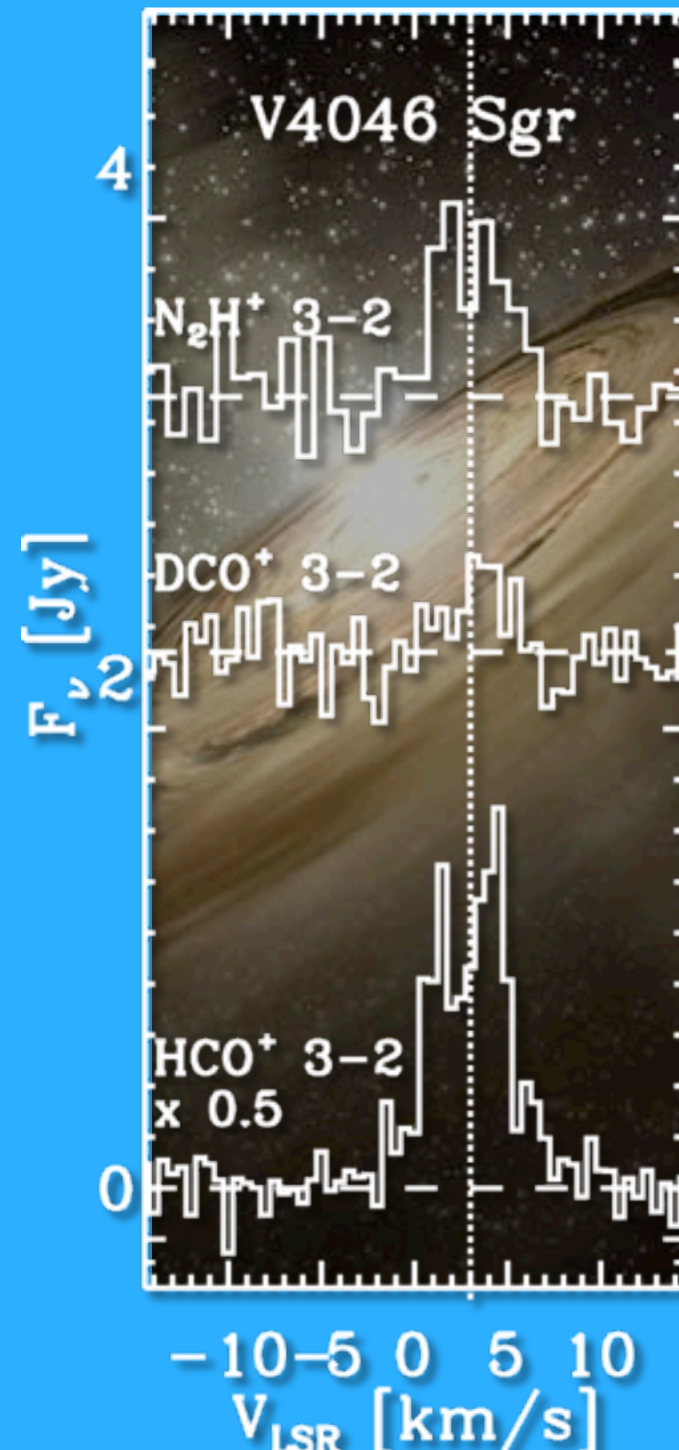
Ionization in Protoplanetary Disks

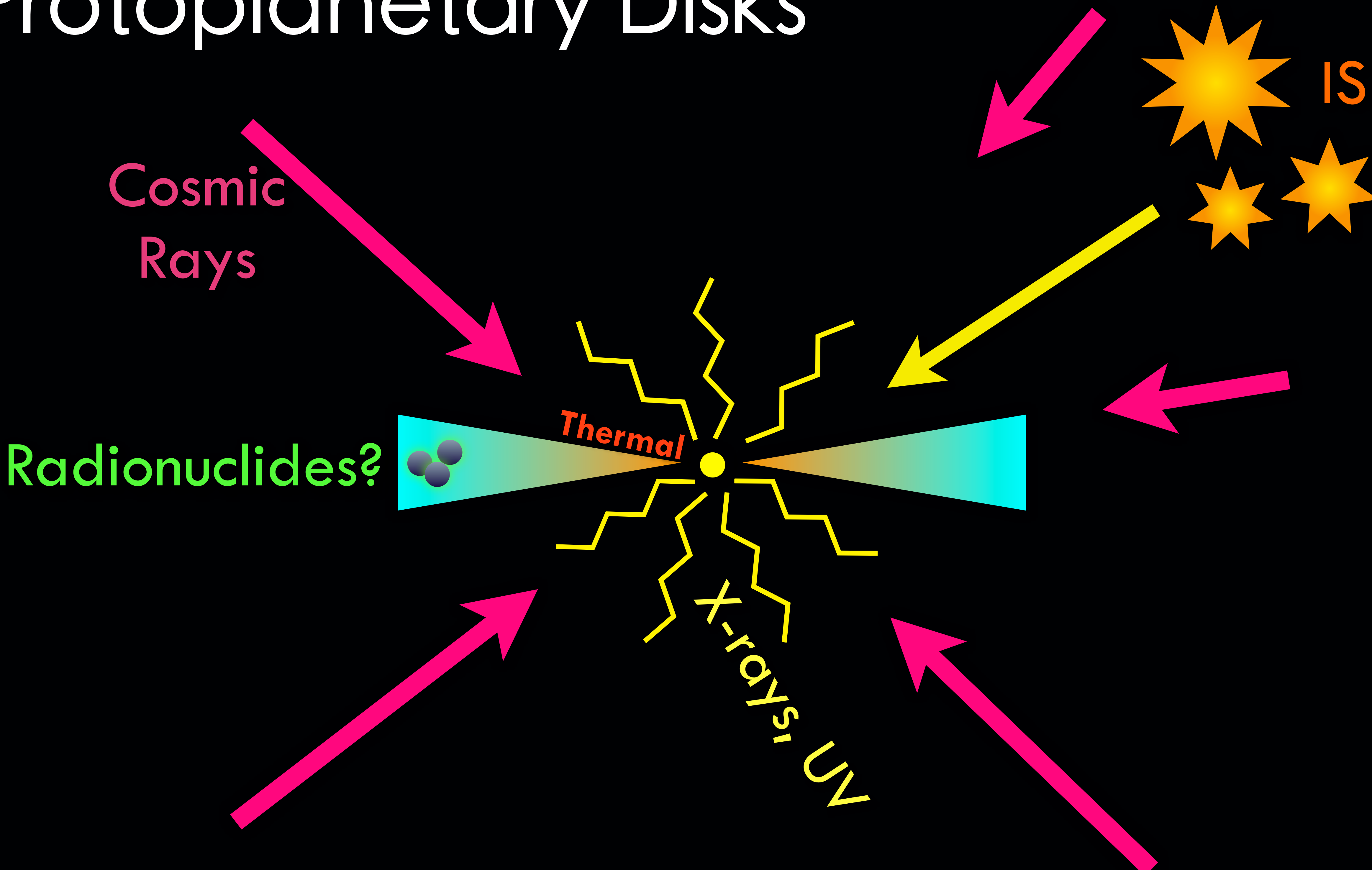
- Circumstellar disks around young stars set the chemistry & physics of planet formation.
- Ionization drives important physical & chemical processes in disks (Pnueman & Mitchell 1965, Umebayashi 1983, Glassgold et al. 1997, and *many* others), such as accretion.
- Only a handful of molecular ions detected, e.g., HCO^+, DCO^+, N_2H^+ (Dutrey et al. 1997, van Dishoeck et al. 2003, Qi et al. 2008, Öberg et al. 2010, 2011, and others).



Öberg et al. 2010

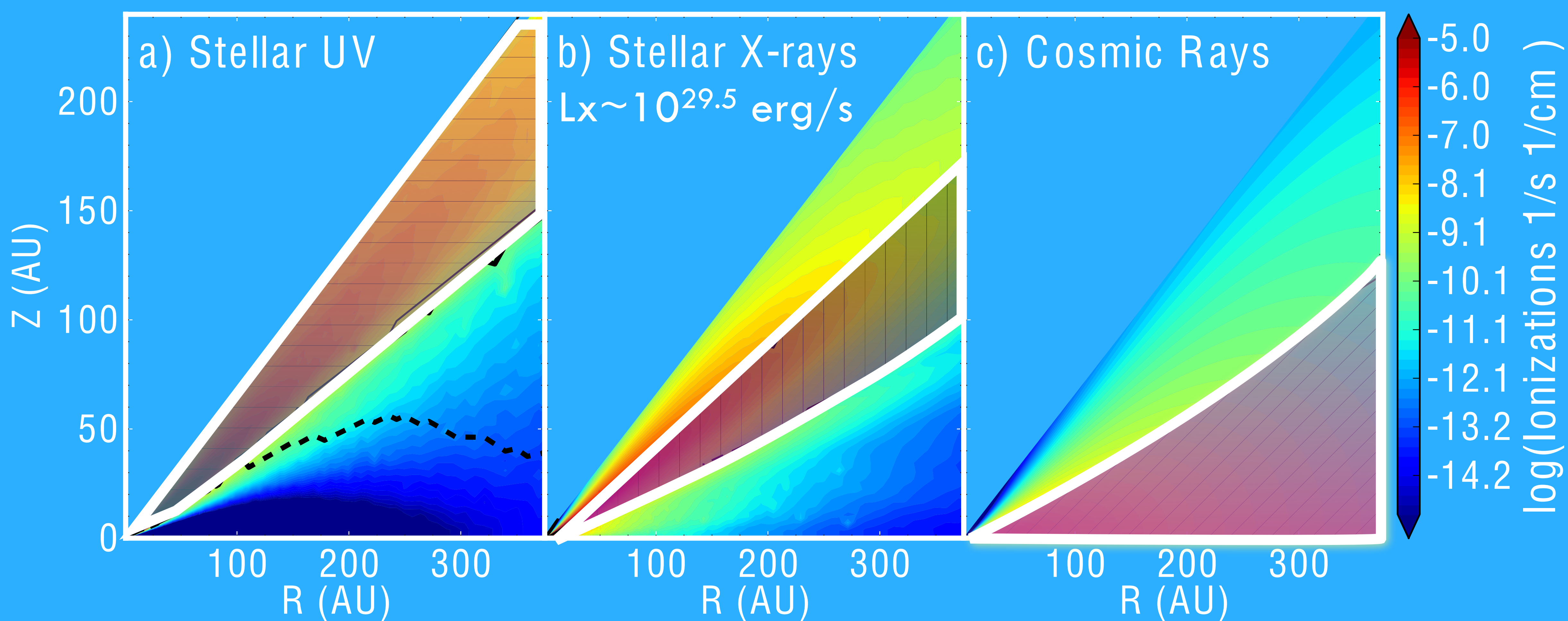
Courtesy NASA/JPL Caltech

Ionization in Protoplanetary Disks



Ionization in Protoplanetary Disks

- **Disk ionization has structure - set by opacity.**
  - **Of stellar UV and X-rays, cosmic rays dominate ionization in the deep disk midplane!**

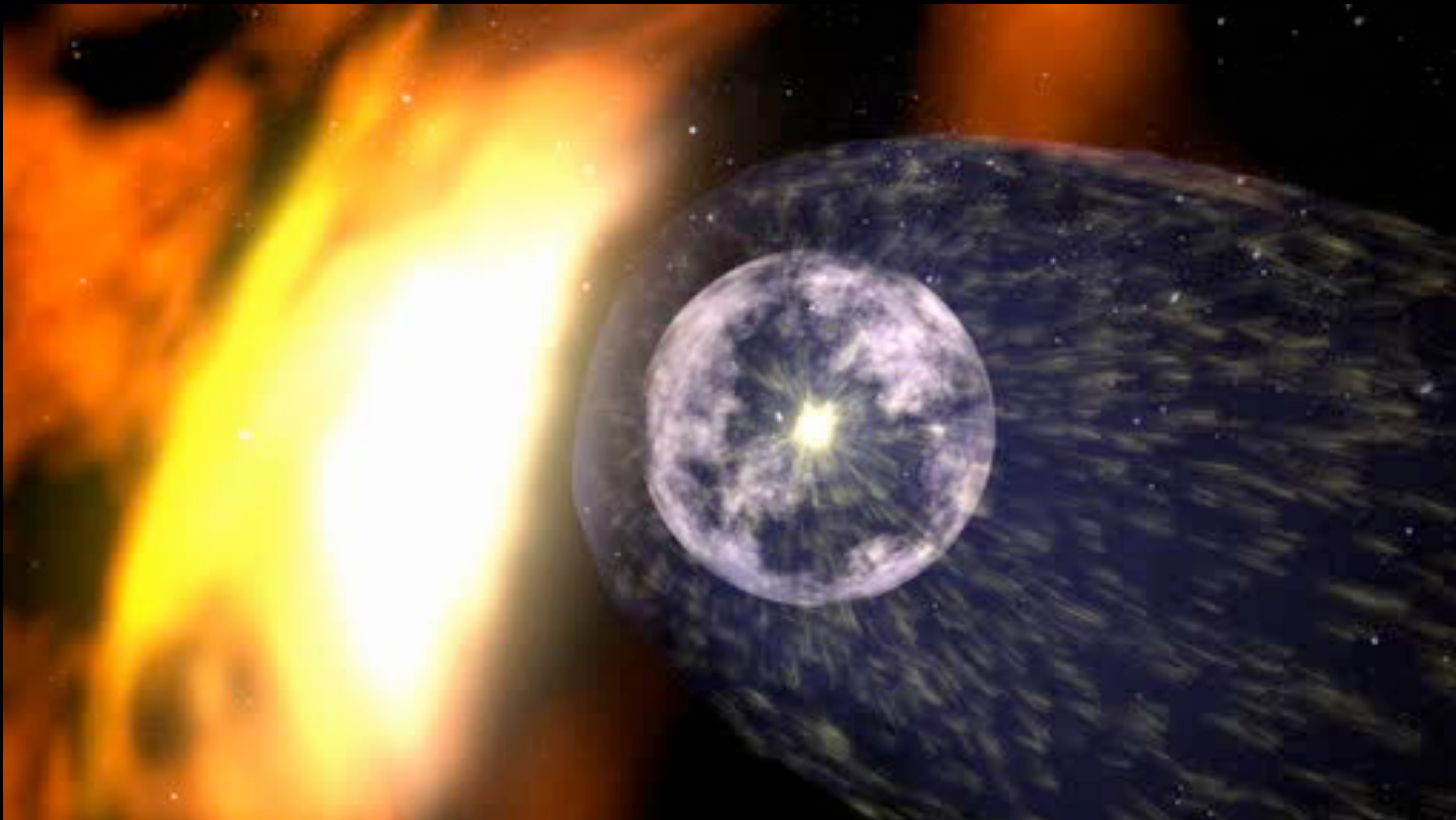


BUT ARE COSMIC RAYS PRESENT?

THE SUN'S HELIOSPHERE

Movie Credit: NASA / Goddard Space Flight Center
Conceptual Image Lab

THE SUN'S HELIOSPHERE



Movie Credit: NASA/Goddard Space Flight Center
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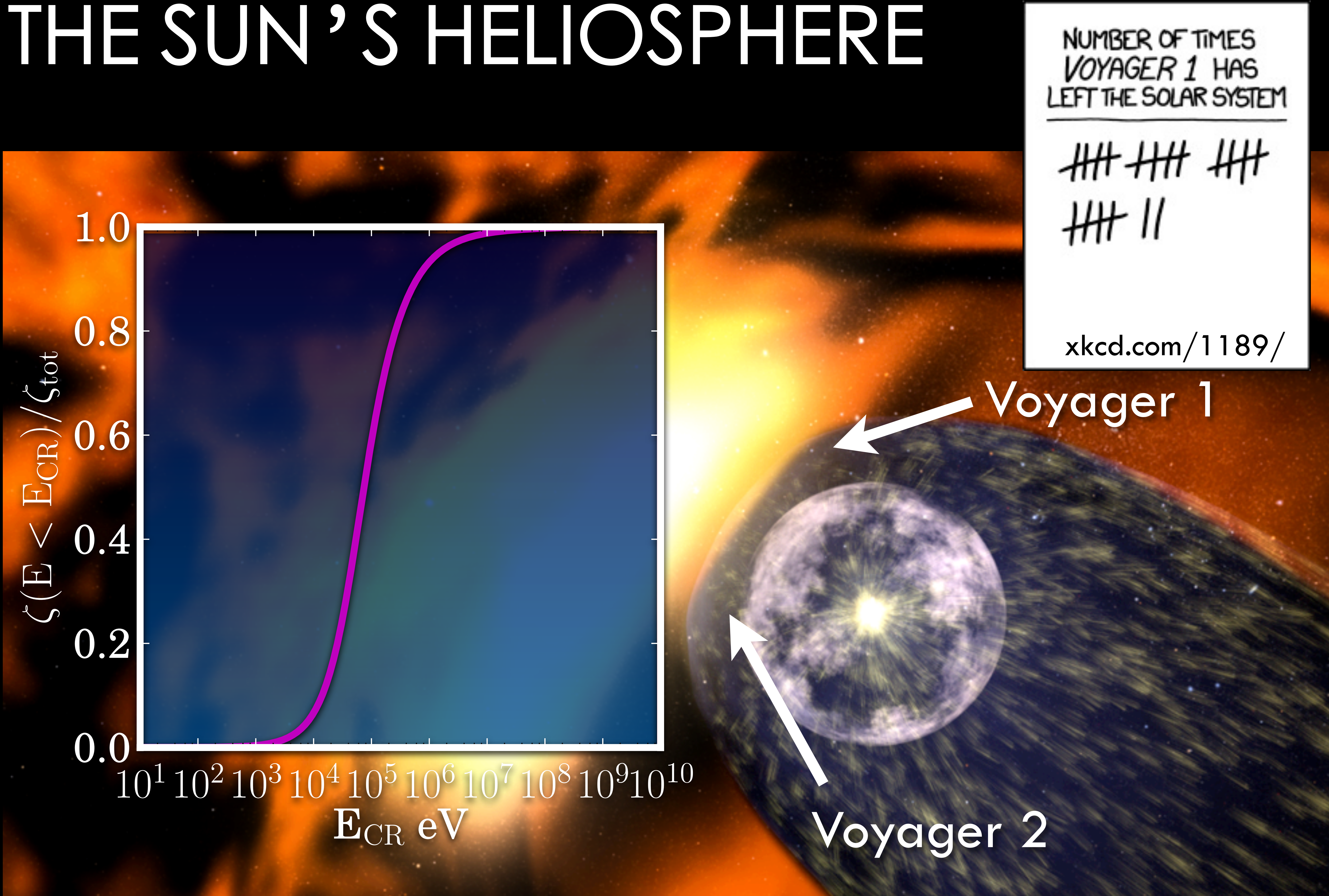

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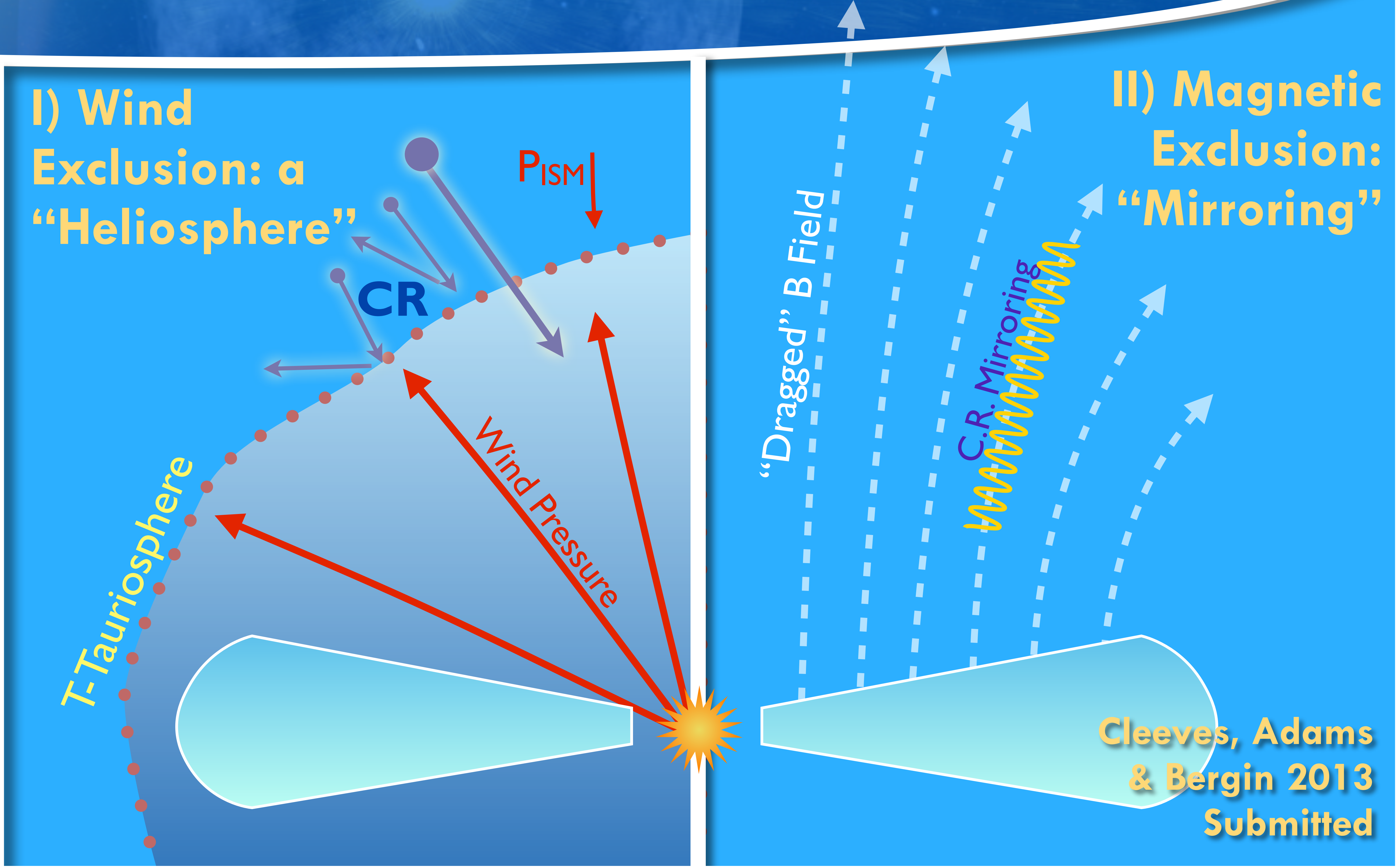
Cosmic Ray Exclusion Processes in Disks



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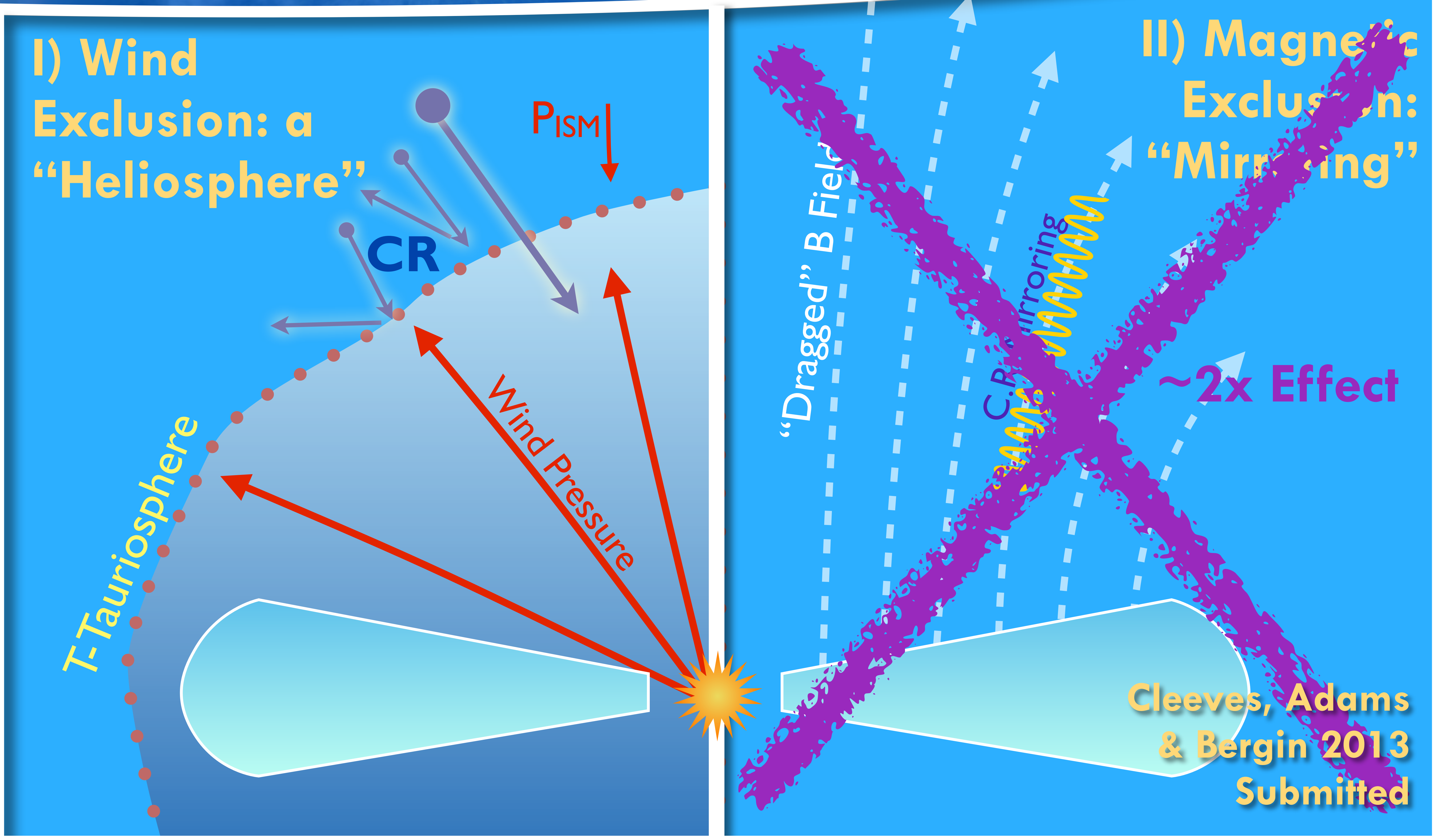
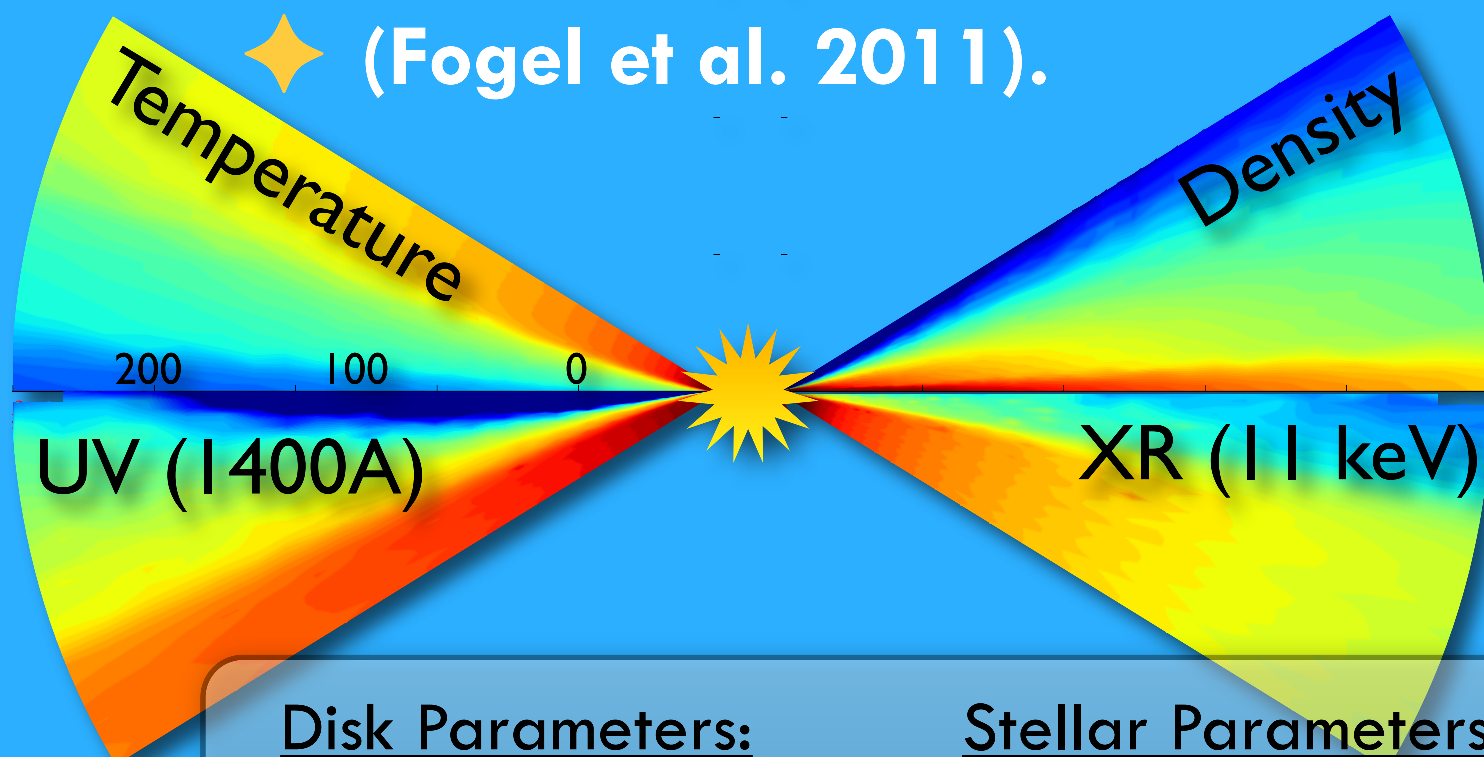
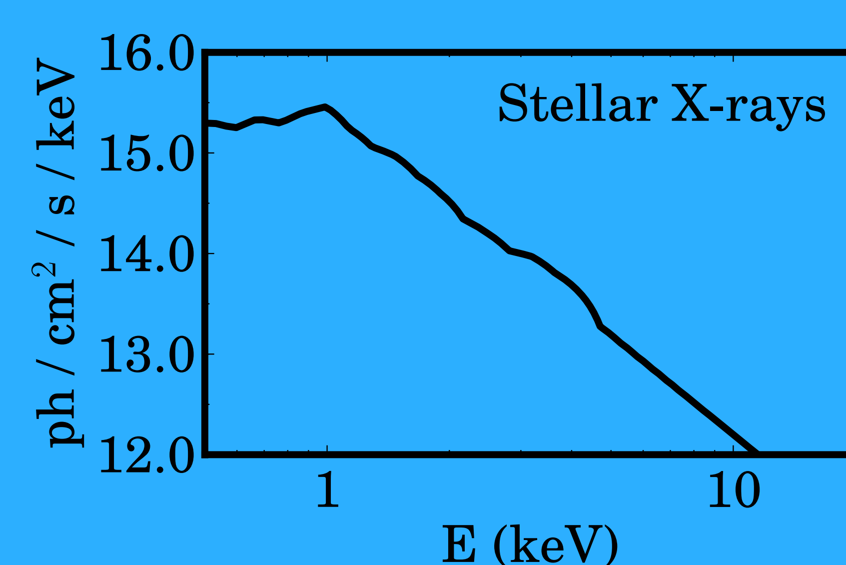


THE MODEL

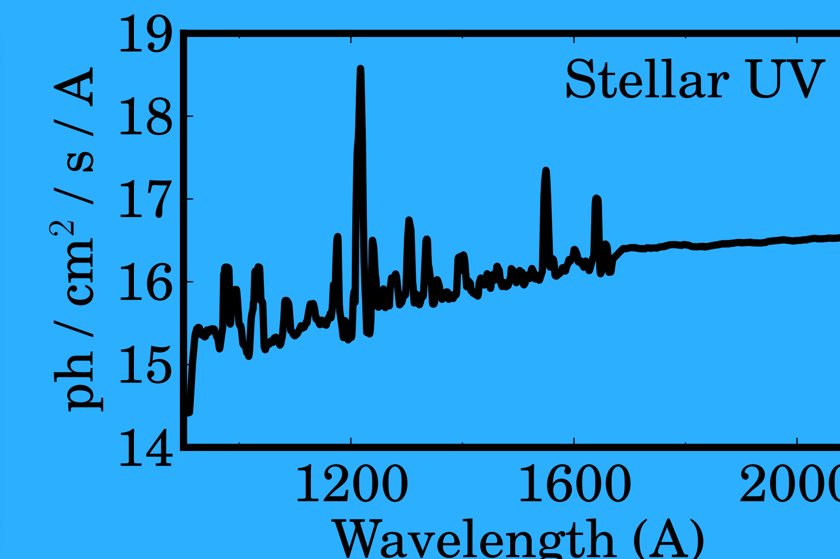
Disk Model

- Physical Structure from TORUS (Harries et al. 2000), passively irradiated disk model.
- FUV and X-ray Monte Carlo RT (Bethell & Bergin 2011a, 2011b).
- Explore both simple analytic chemistry and full chemical models:
  - (Fogel et al. 2011).





Telleschi et al. 2007



Herczeg et al. 2002, 2004

Disk Parameters:

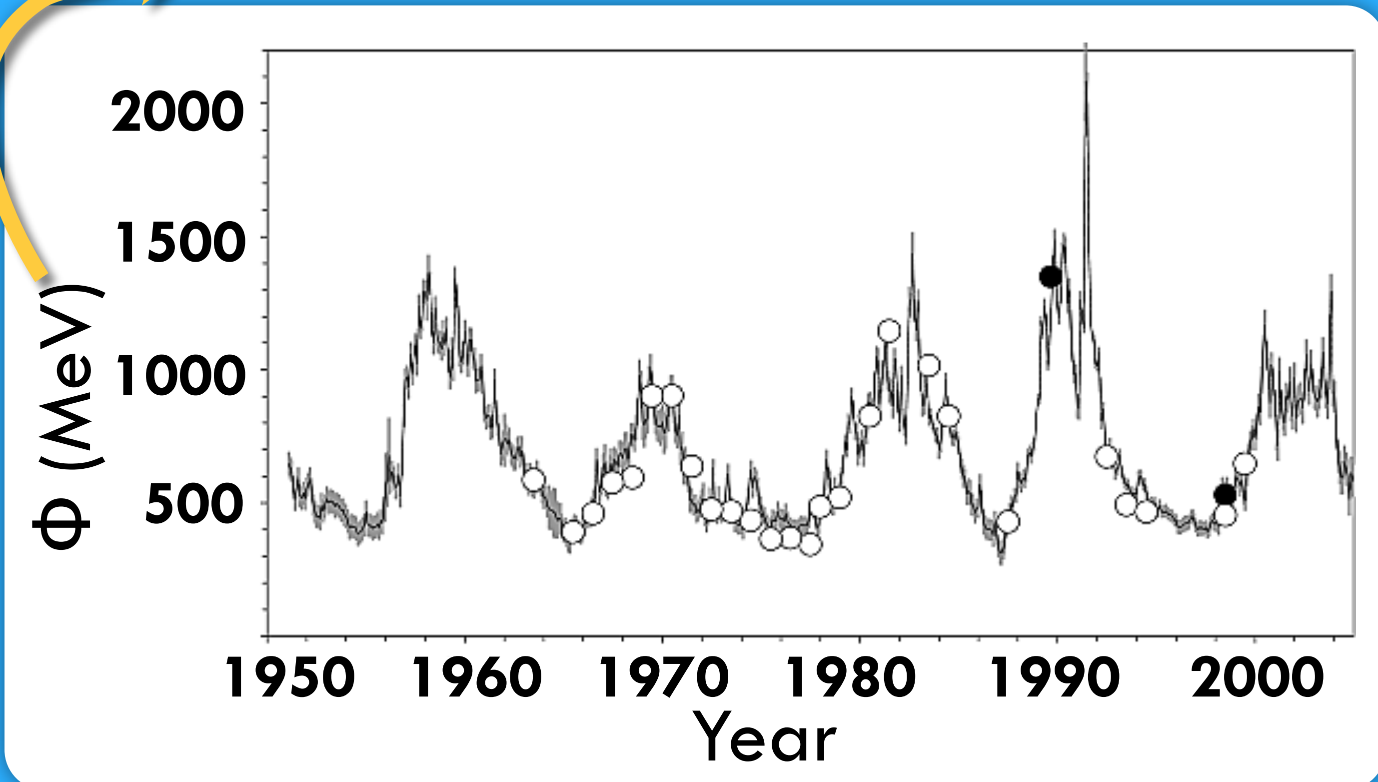
M_{gas} = 0.076 M_{sun},
f_g = 100,
R_i = 0.1 AU, R_d = 400 AU; 85% of mass in "big" grains

Stellar Parameters:

$M_\star$ = 1.06 M_{sun}
$R_\star$ = 1.8 R_{sun}
T_{eff} = 4300 K
L_{UV} = 0.01 L_{sun}
L_{XR} = 10^{-4} L_{sun}

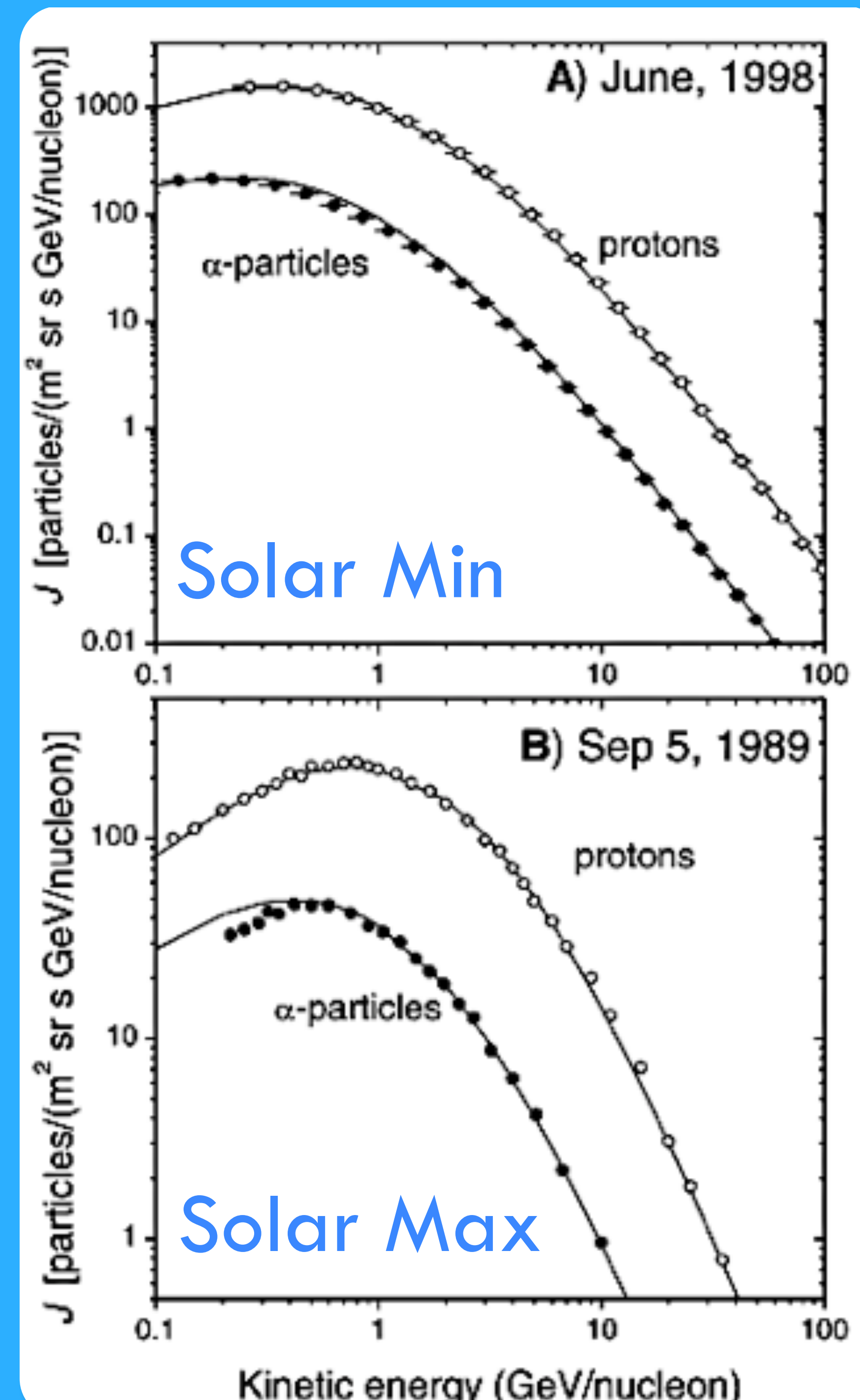
I. CR Exclusion by Winds: The Solar Wind

$$\mathbf{J}_{\mathrm{CR}}(\mathbf{E},\phi) = \mathbf{J}_{\mathrm{LIS,CR}}(\mathbf{E}+\phi)\frac{\mathbf{E}(\mathbf{E}+2\mathbf{E}_{\mathbf{r}})}{(\mathbf{E}+\phi)(\mathbf{E}+\phi+2\mathbf{E}_{\mathbf{r}})}$$



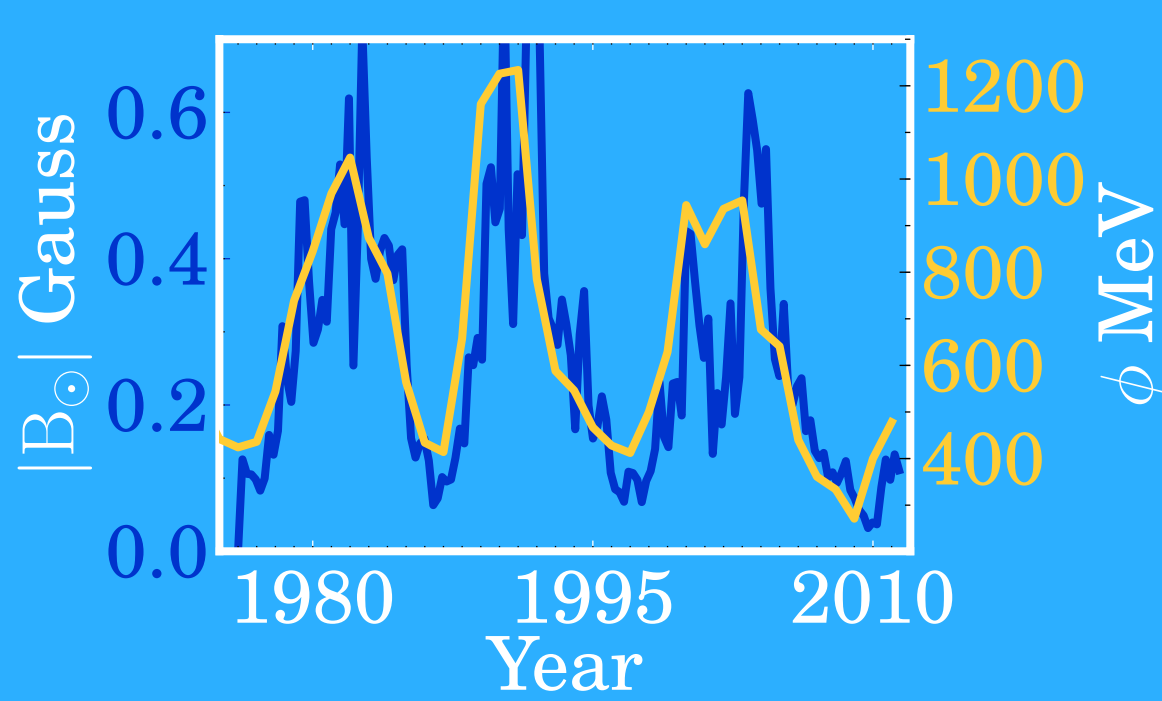
"ENERGY BARRIER"

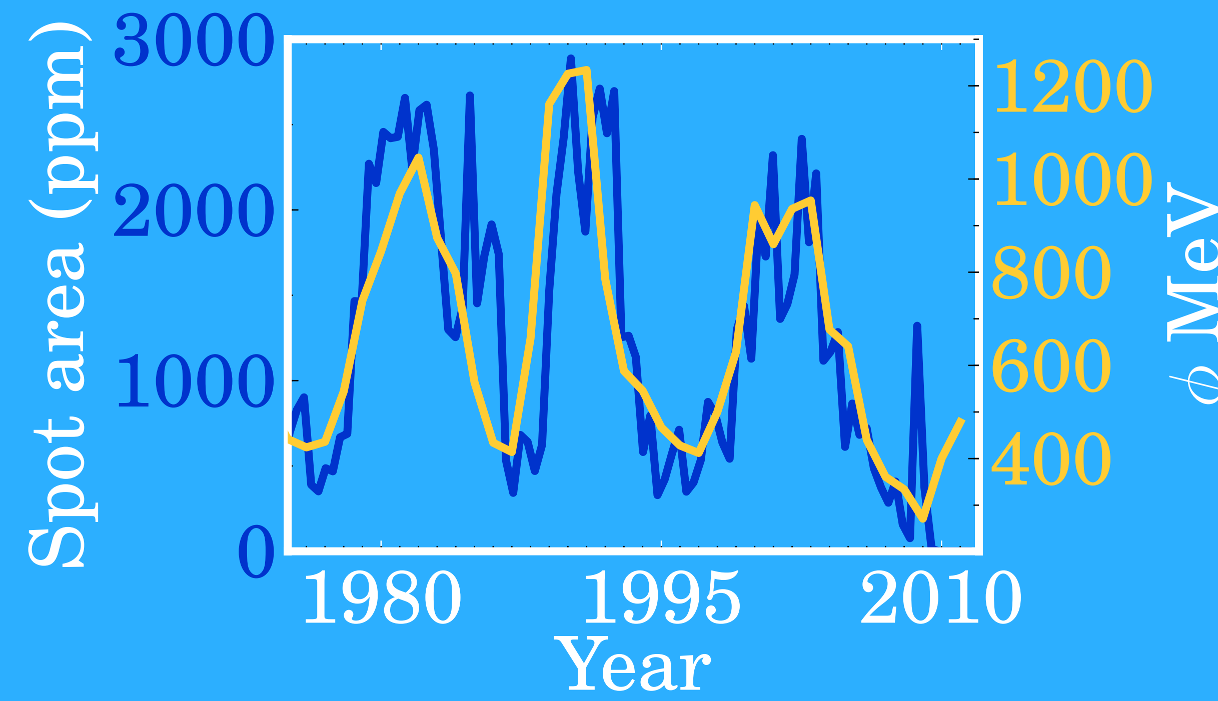
- The Sun variably modulates the CR flux:
  - Spectrum well described by the "force-field approximation," (Gleeson & Axeford 1968).

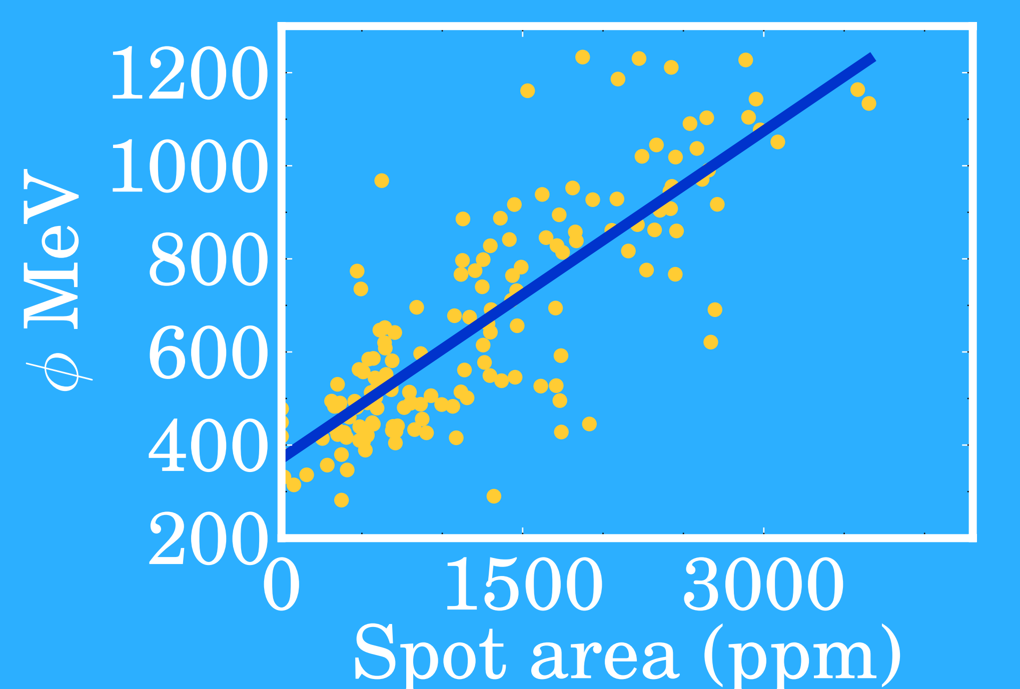


Usoskin et al. 2005

I. Variability of CR Modulation





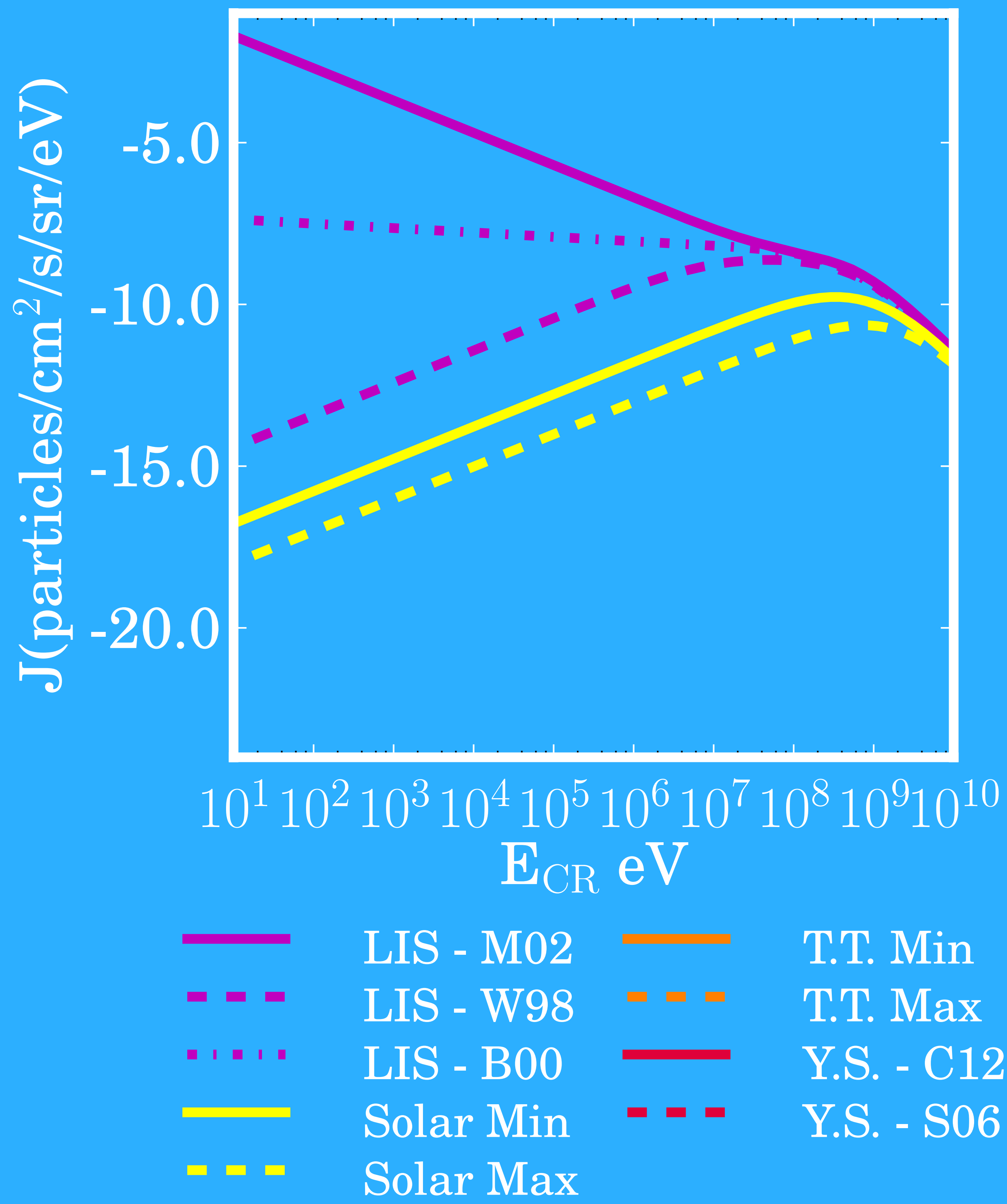


"magnetic activity"

- **Correlate magnitude of CR modulation (Usoskin et al. 2005) with various solar parameters potentially measurable on other stars.**
- **Such as spot coverage, |*B*|, number of spots, coverage of coronal holes, etc.**

I. CR Modulation by a T.T. Star?

- **Relate solar magnetic activity (spots) to magnitude of CR exclusion.**
- **First-order approximation: treat a T Tauri star as a "souped-up" Sun.**
- **T Tauri spot coverage ranges from 3% - 17% (Bouvier et al. 1989).**
- **Corresponds to modulation strengths of Φ ~ 5 (5%) - 18(10%) GeV.**



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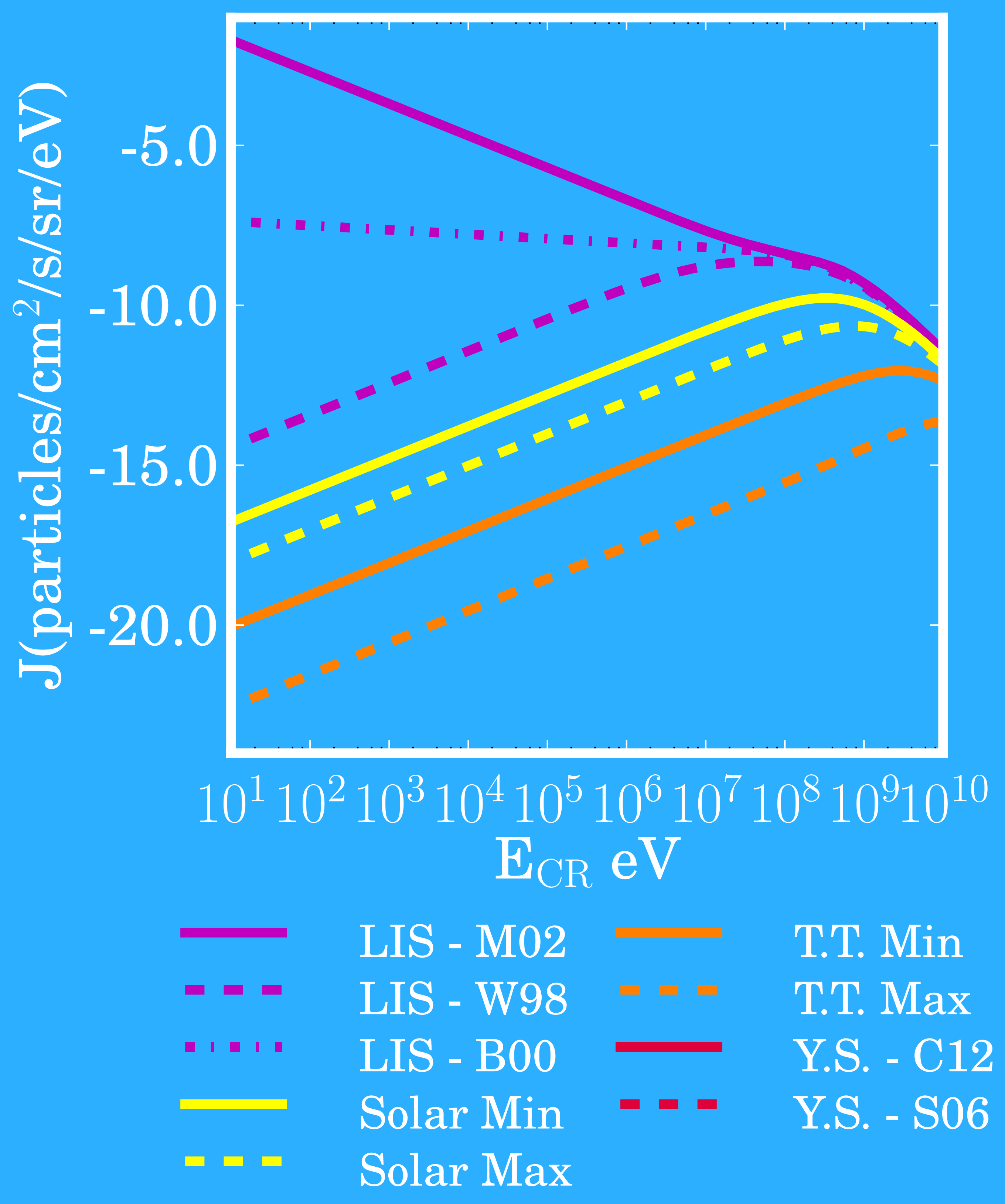

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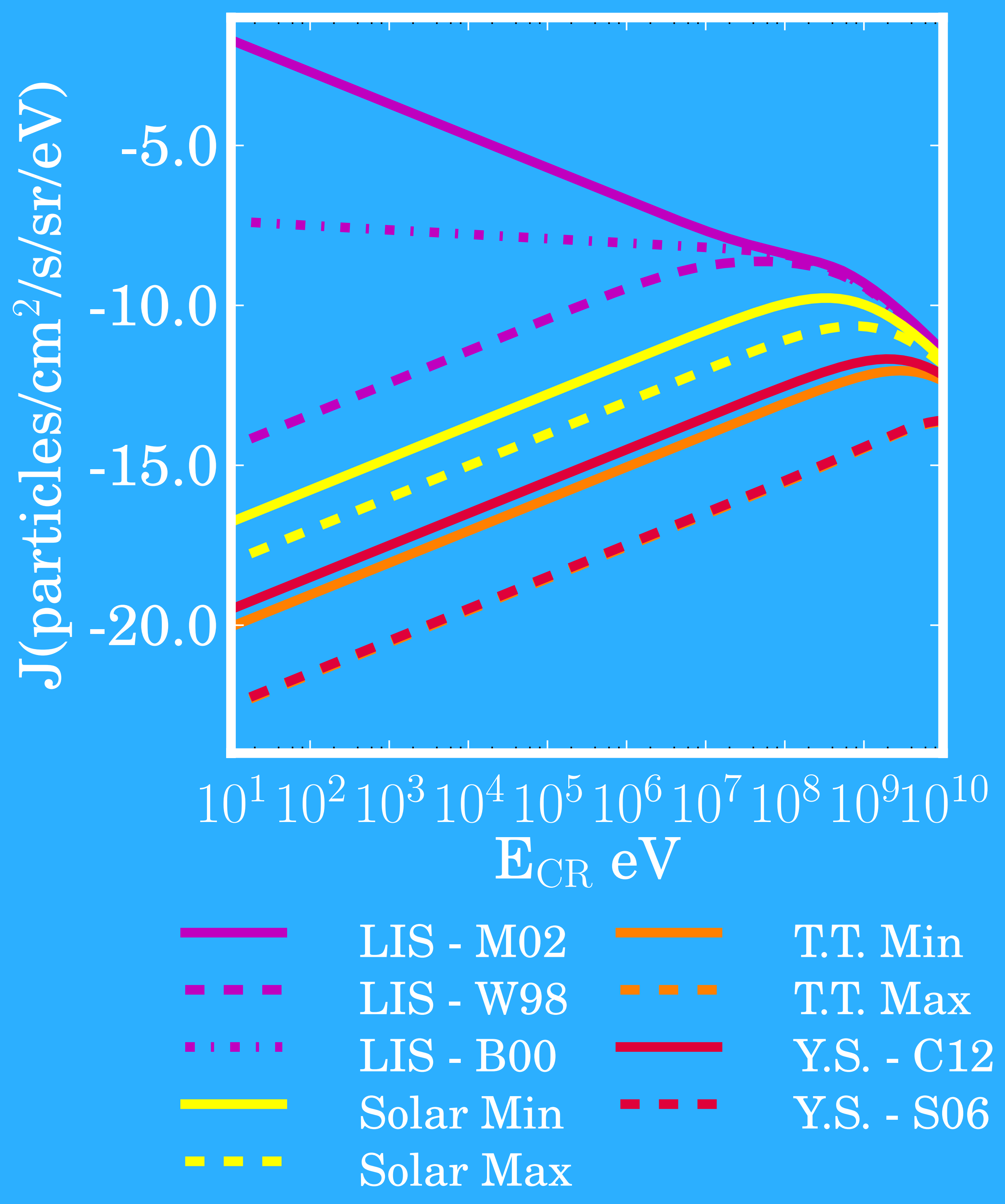
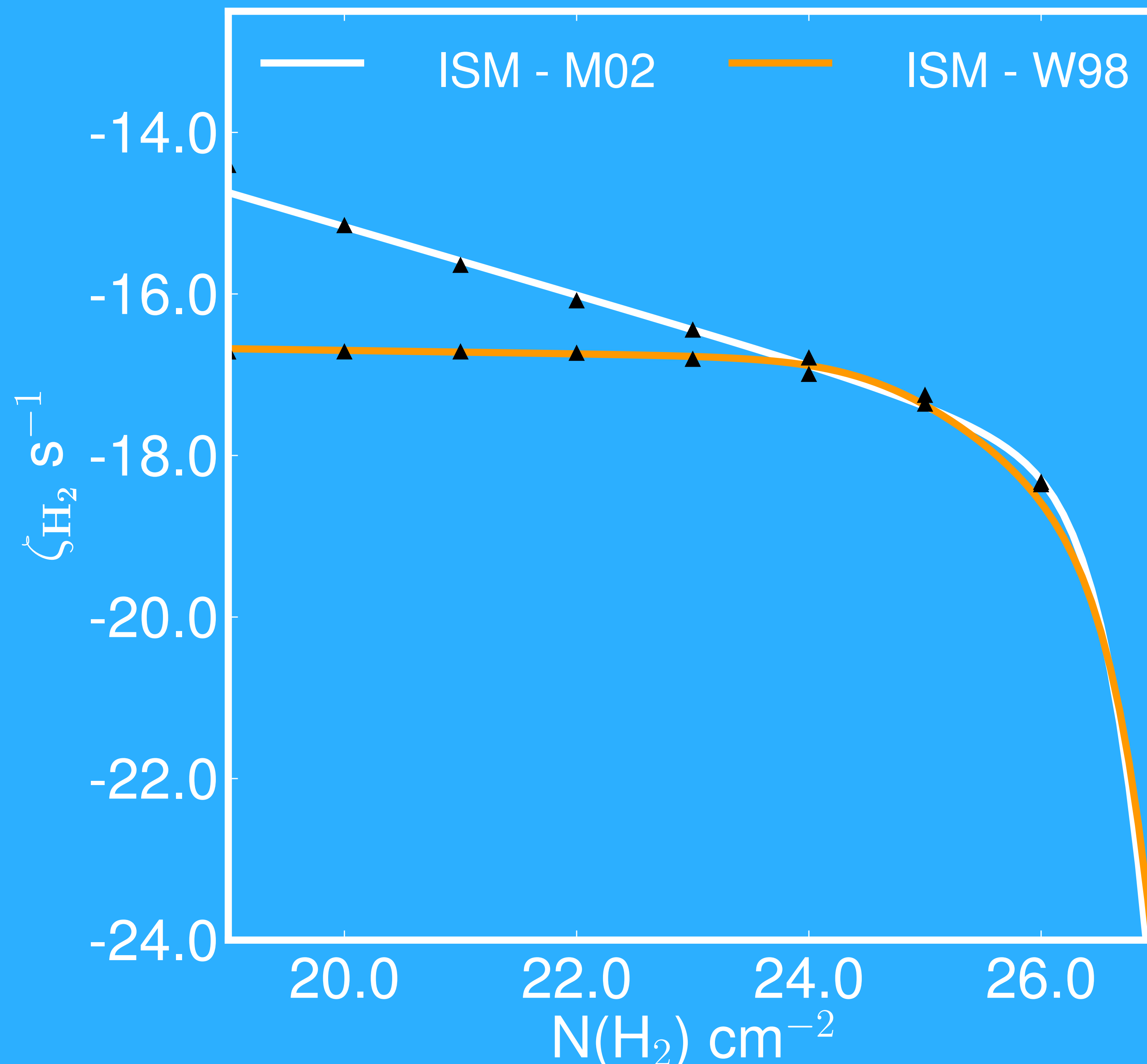


I. Result: Reduced ζ_{CR}

- From the CR fluxes and H_2 cross sections of Padovani et al. 2009, compute integrated ionization rates (ζ_{CR} s^{-1}).



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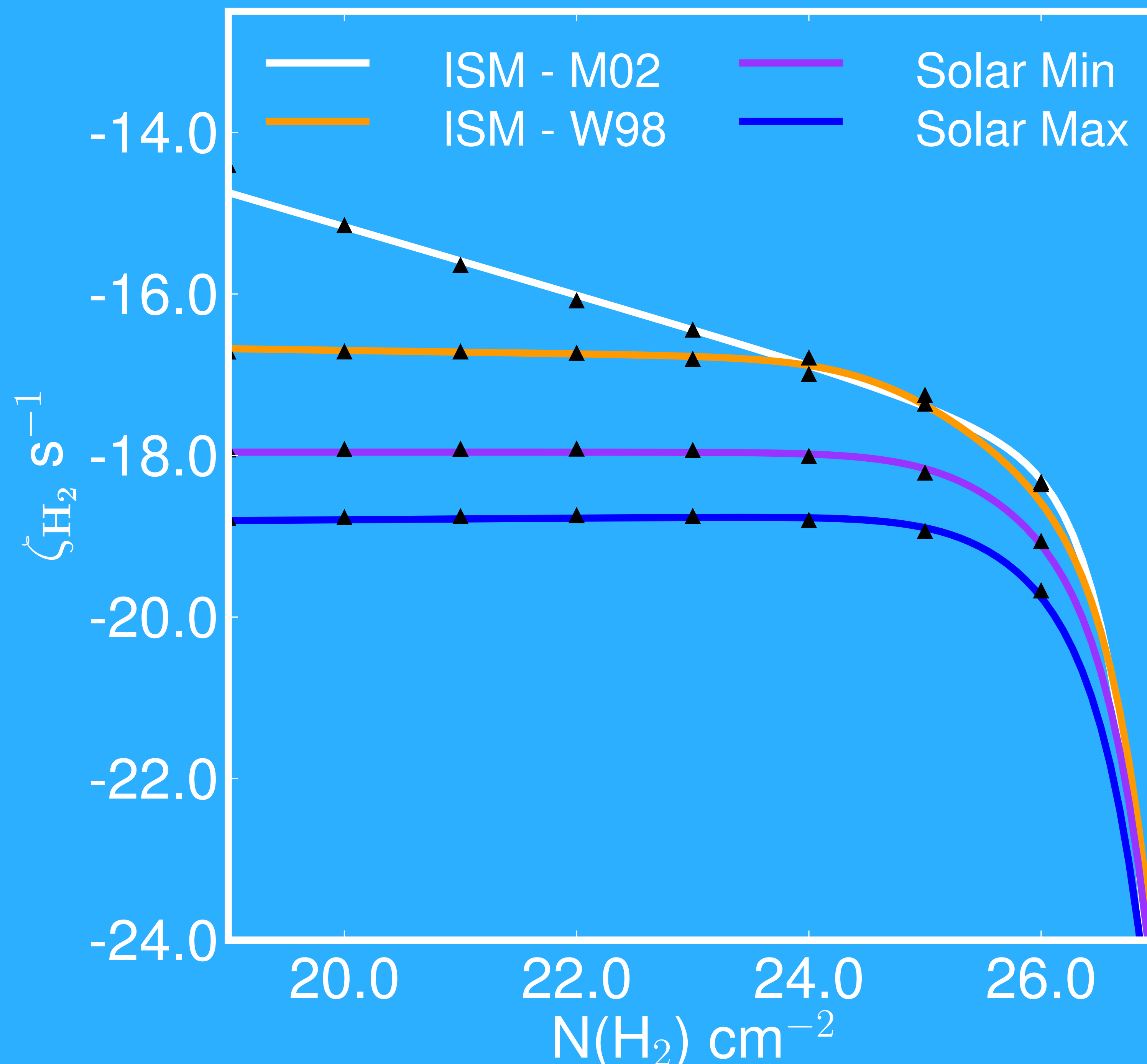
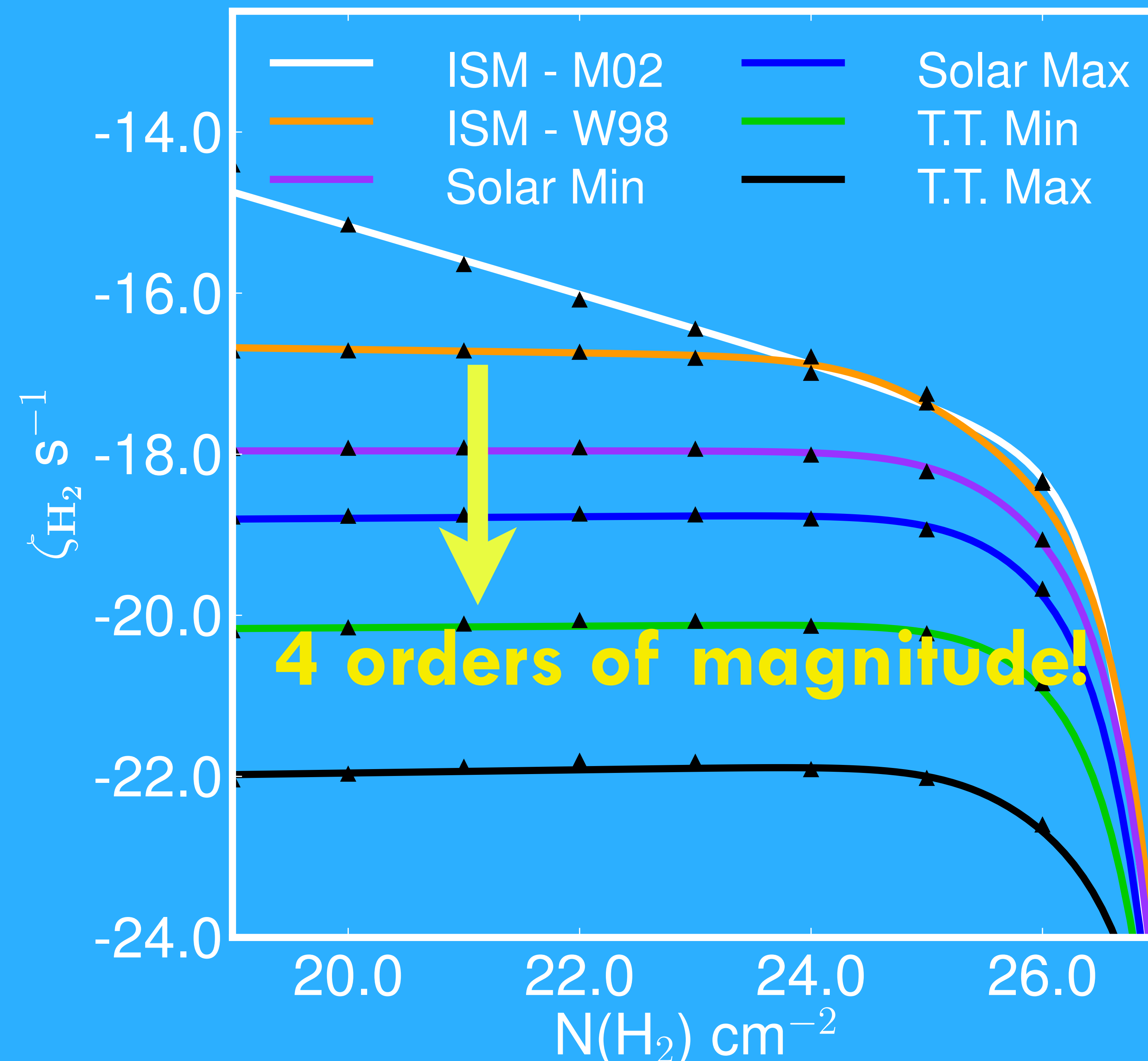


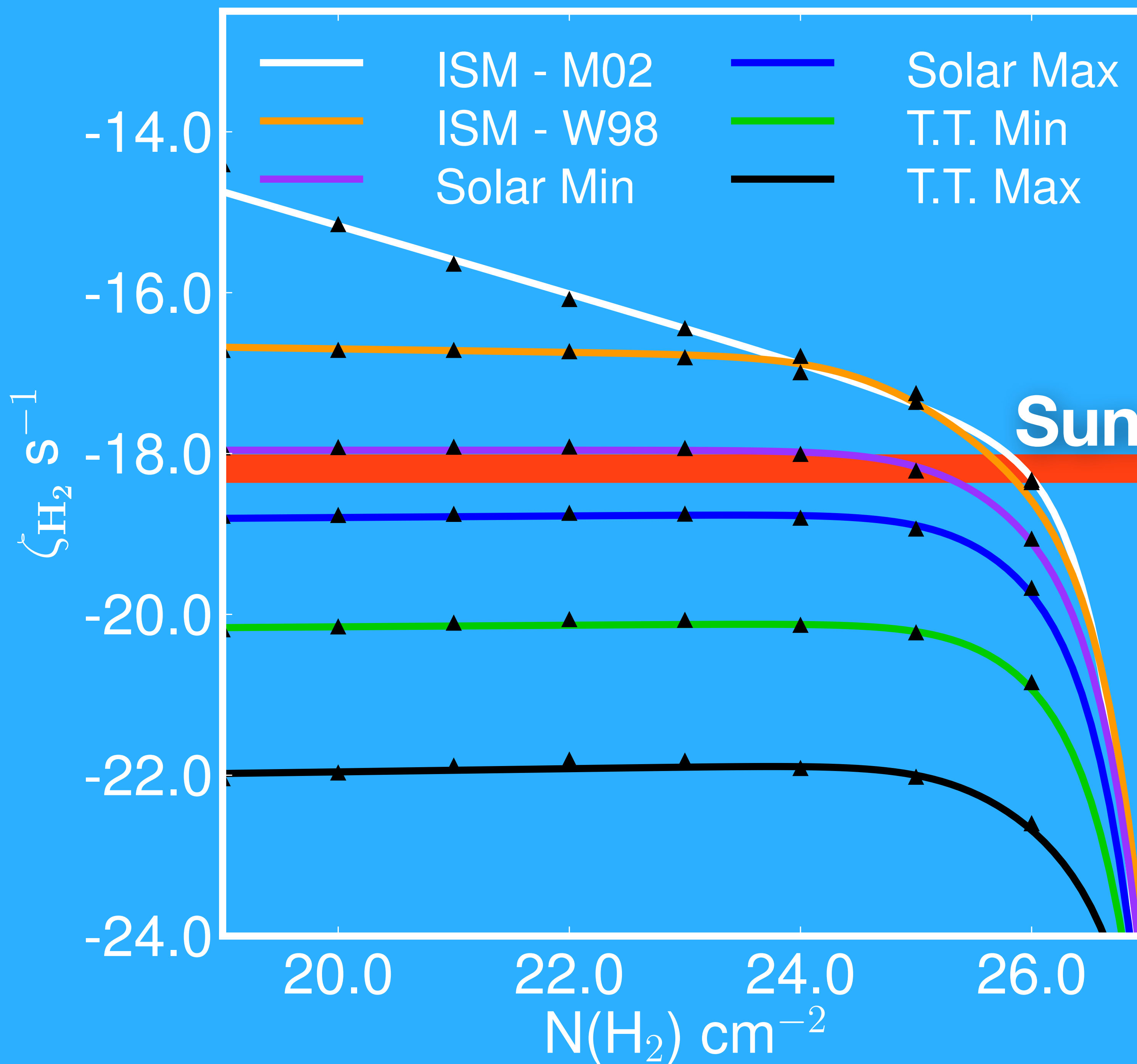
I. Result: Reduced ζ_{CR}

- **From the CR fluxes and H_2 cross sections of Padovani et al. 2009, compute integrated ionization rates (ζ_{CR} s^{-1}).**
- **$\zeta_{CR} < 10^{-20}$ s^{-1} for the T Tauri models.**
- **For > 10% spot coverage CRs can be neglected.**



Radionuclide Ionization

- **Inferred short-lived RN rates of $\zeta_{RN} \sim 7 \times 10^{-19}$ s^{-1} (Umebayashi et al. 2009).**
  - **If correct, $\zeta_{RN} > \zeta_{CR}$ for the entire disk.**
- **However, "normal" RN ionization rates completely unknown!**
  - **Enriched solar history?**



***Umebayashi & Nakano 2008, Diehl et al. 2006**

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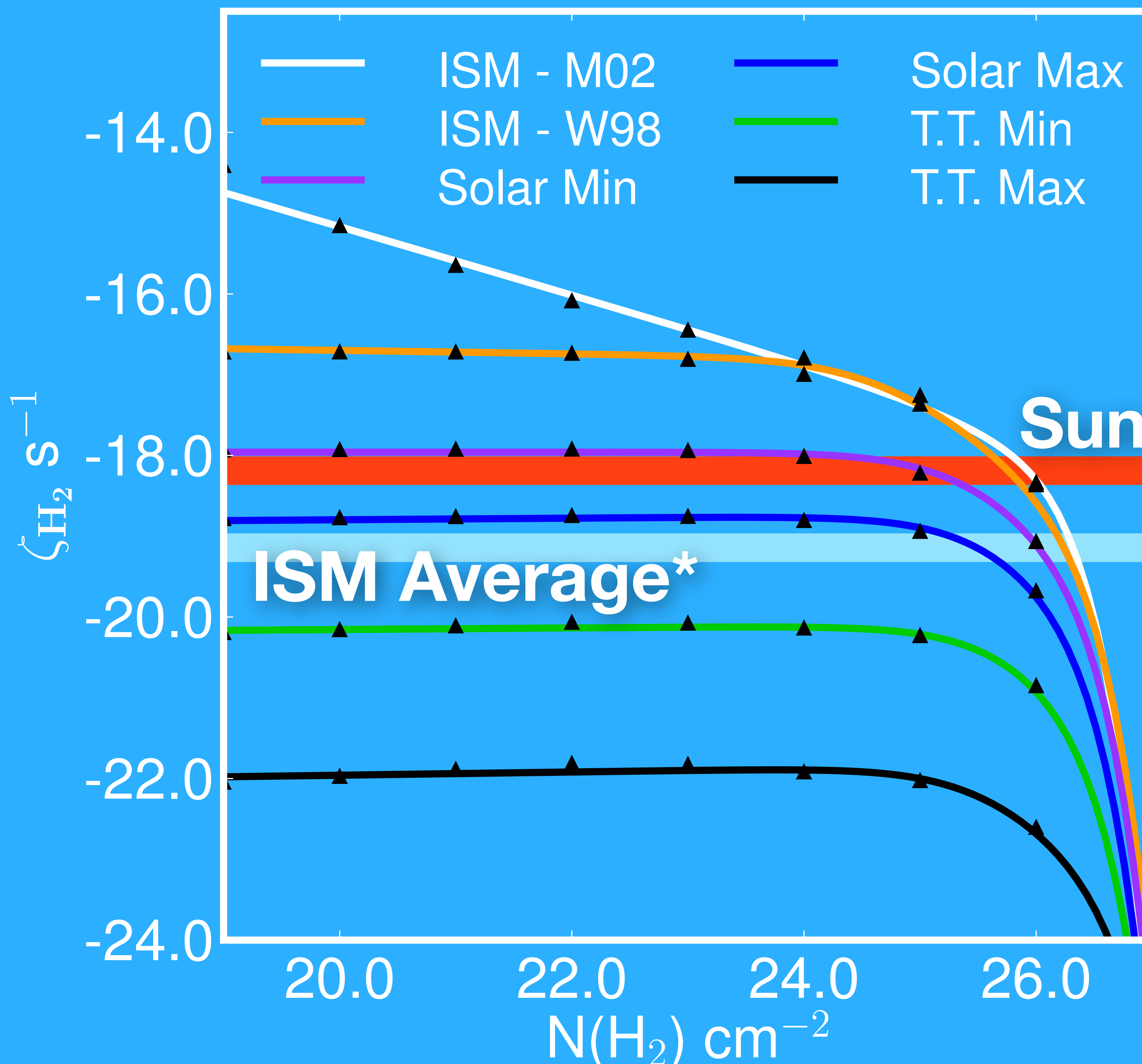


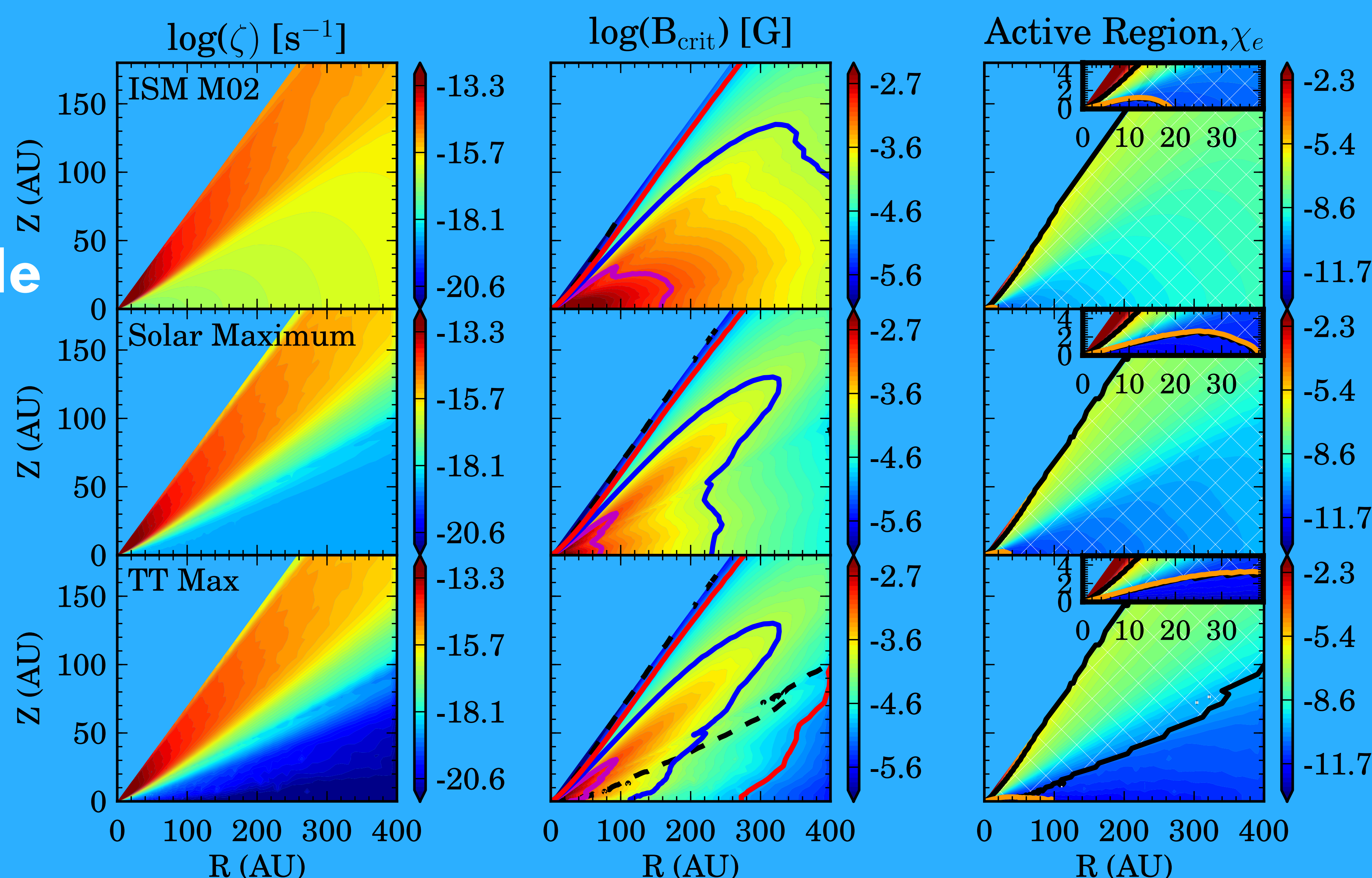
*Umebayashi & Nakano 2008, Diehl et al. 2006

IMPLICATIONS

I. Turbulence in Disks

- Estimates in the literature for minimum ionization fraction to be MRI turbulent. (*Re* and *Am* criteria, Perez-Becker and Chiang 2010).

- Without cosmic rays (or RN), MRI unsustainable throughout most of the disk.



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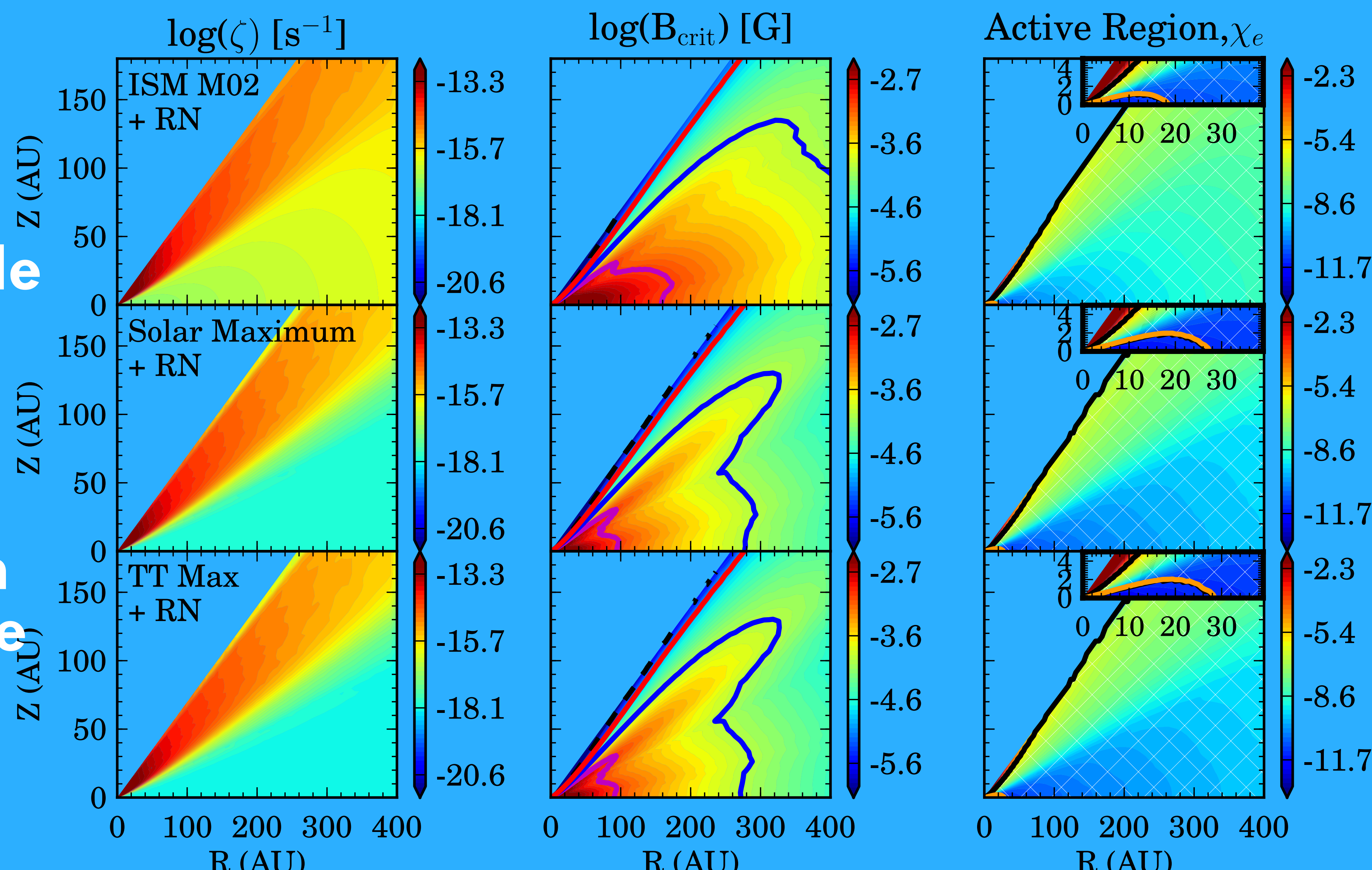
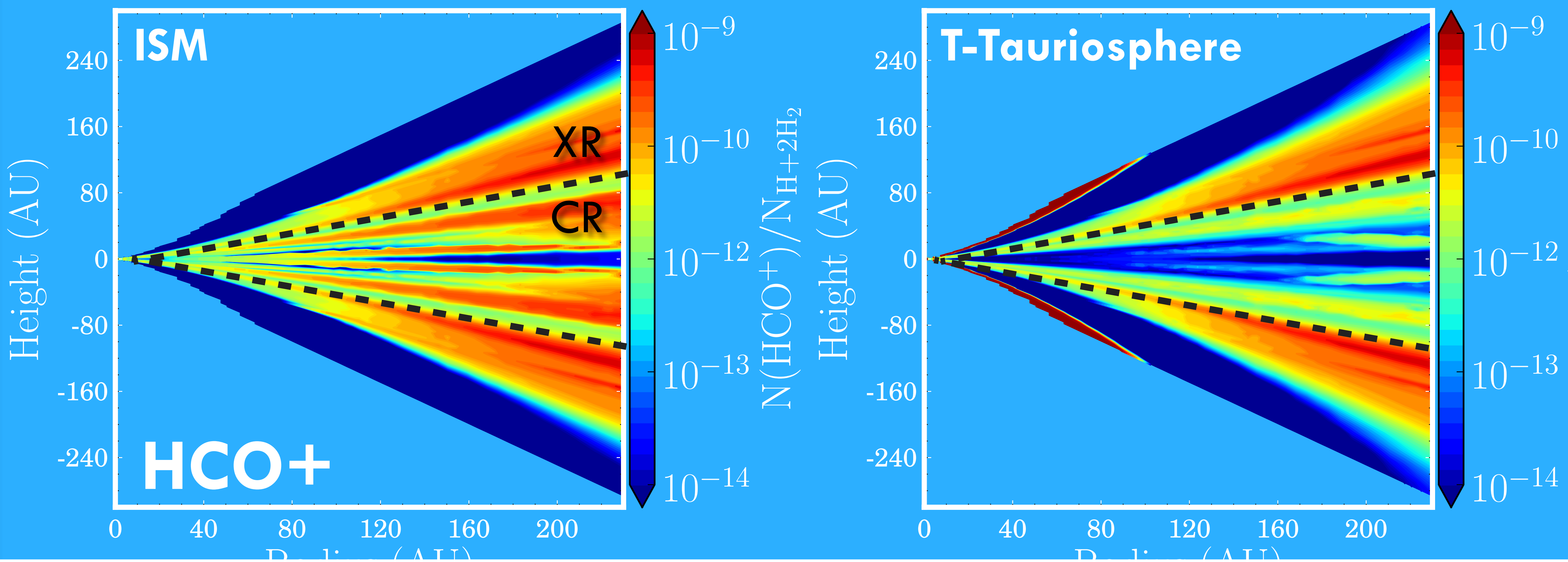
- Without cosmic rays (or RN), MRI unsustainable throughout most of the disk.
- But... RN can reactivate the midplane (R≳30 AU)!



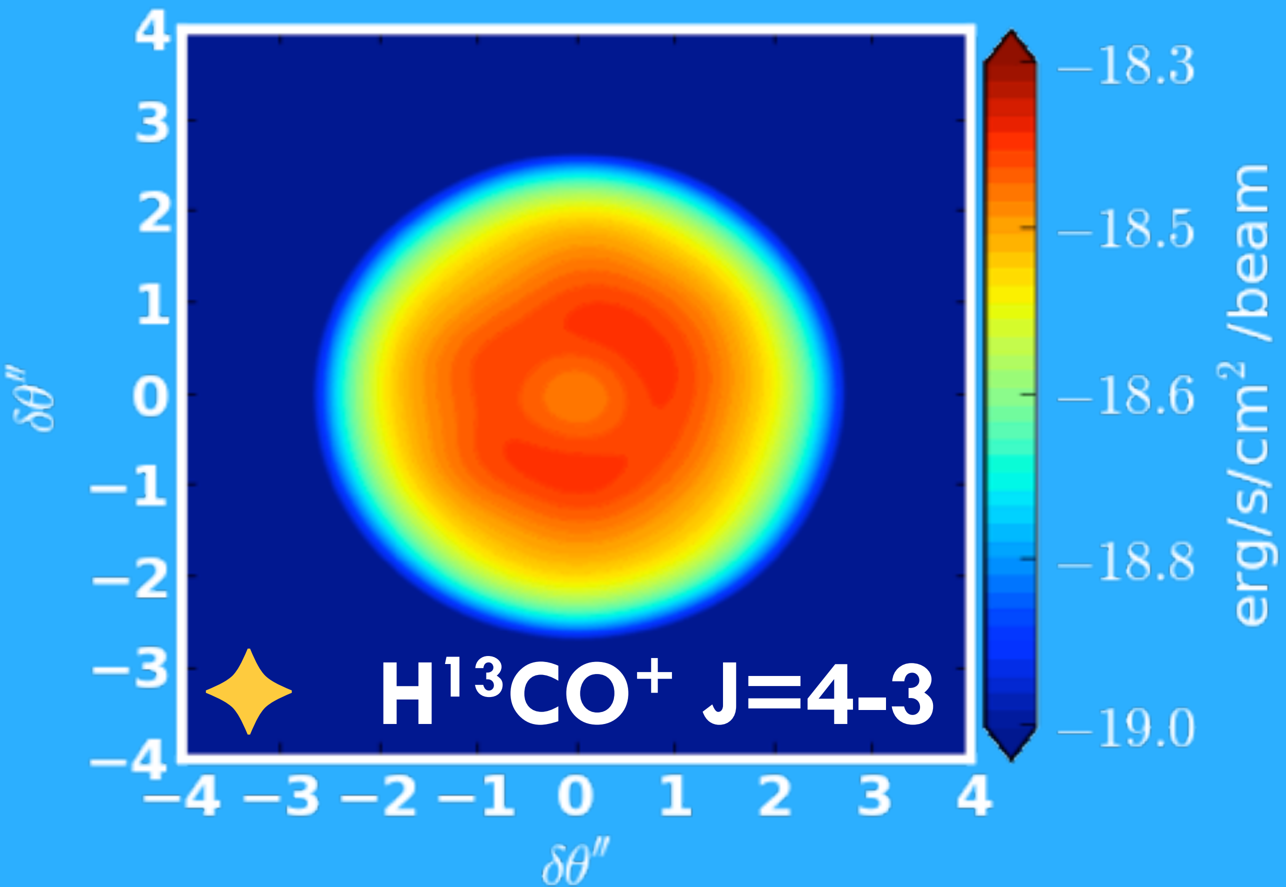
II. Chemistry in Disks

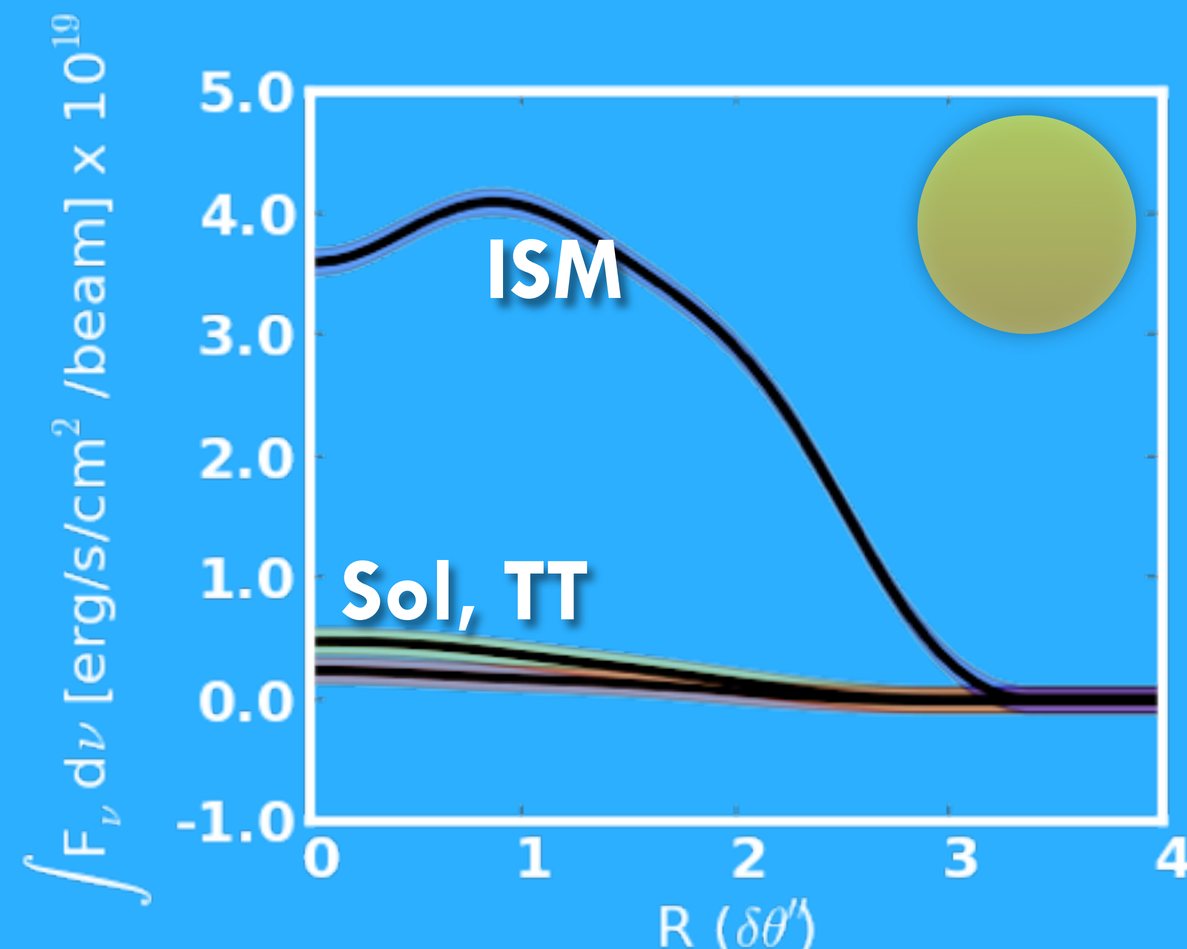
- **Can we infer the presence of an extrasolar Heliosphere?**
  - **"Usual suspects:" HCO^+, N_2H^+, & H_2D^+.**
  - **H_2D^+ would be great, but there can be issues (Walmsley et al. 2004).**
    - **But! Limits on H_2D^+ towards DM Tau consistent with below ISM (Chapillon et al. 2012).**
- **Implications for grain chemistry via hydrogenation.**



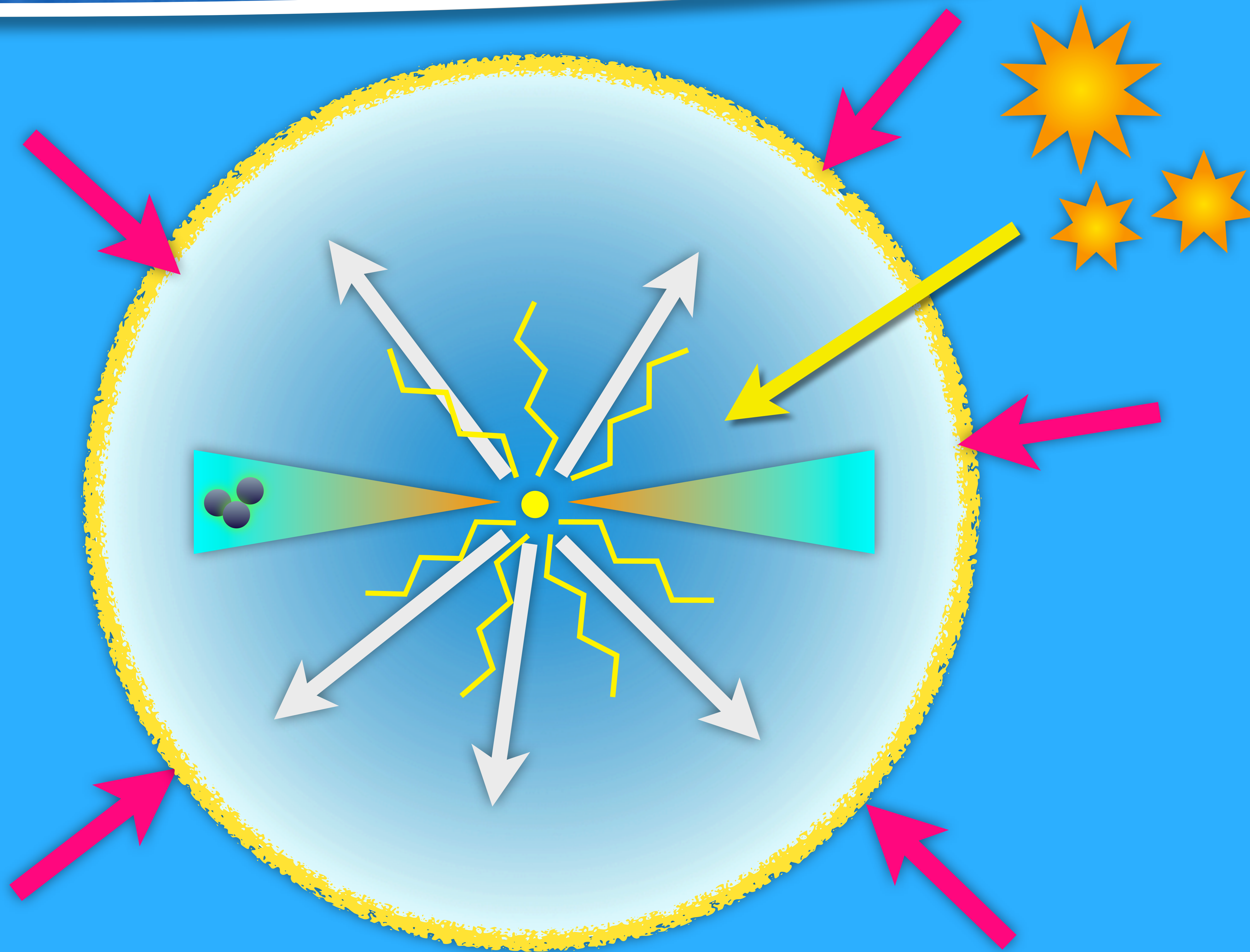
III. (Preliminary) ALMA Predictions

- Creating non-LTE line emission models for ALMA-observable transitions using LIME (Brinch & Hogerheijde 2010).
- ALMA Simulations with CASA, *D* = 140 pc. *i* = 0°, 60°.
- Extract line emission brightness profiles for comparison to observed profiles.



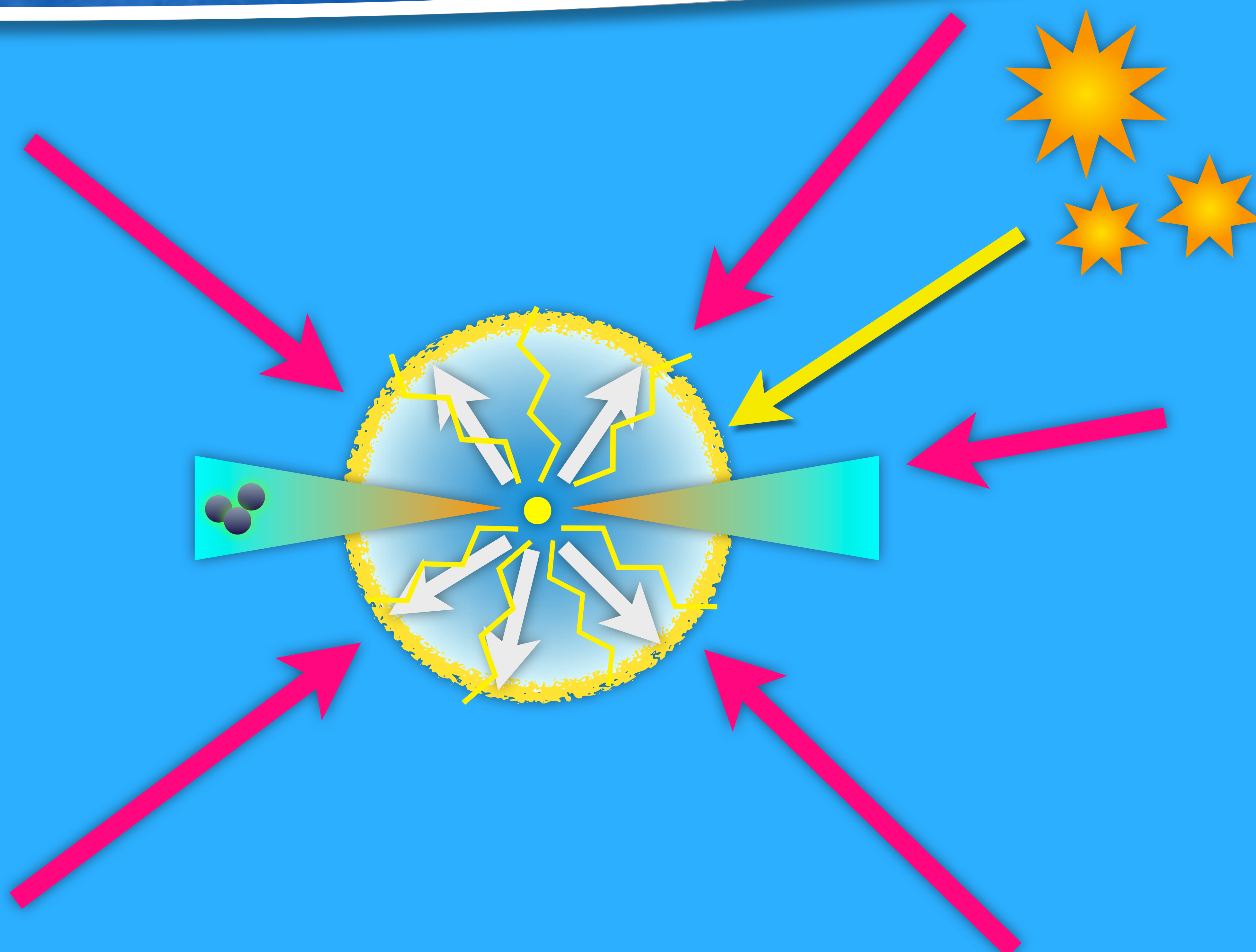


IV. Extent of a T Tauriosphere



Does it enclose the entire disk?

IV. Extent of a T Tauriosphere



Or some small inner region?

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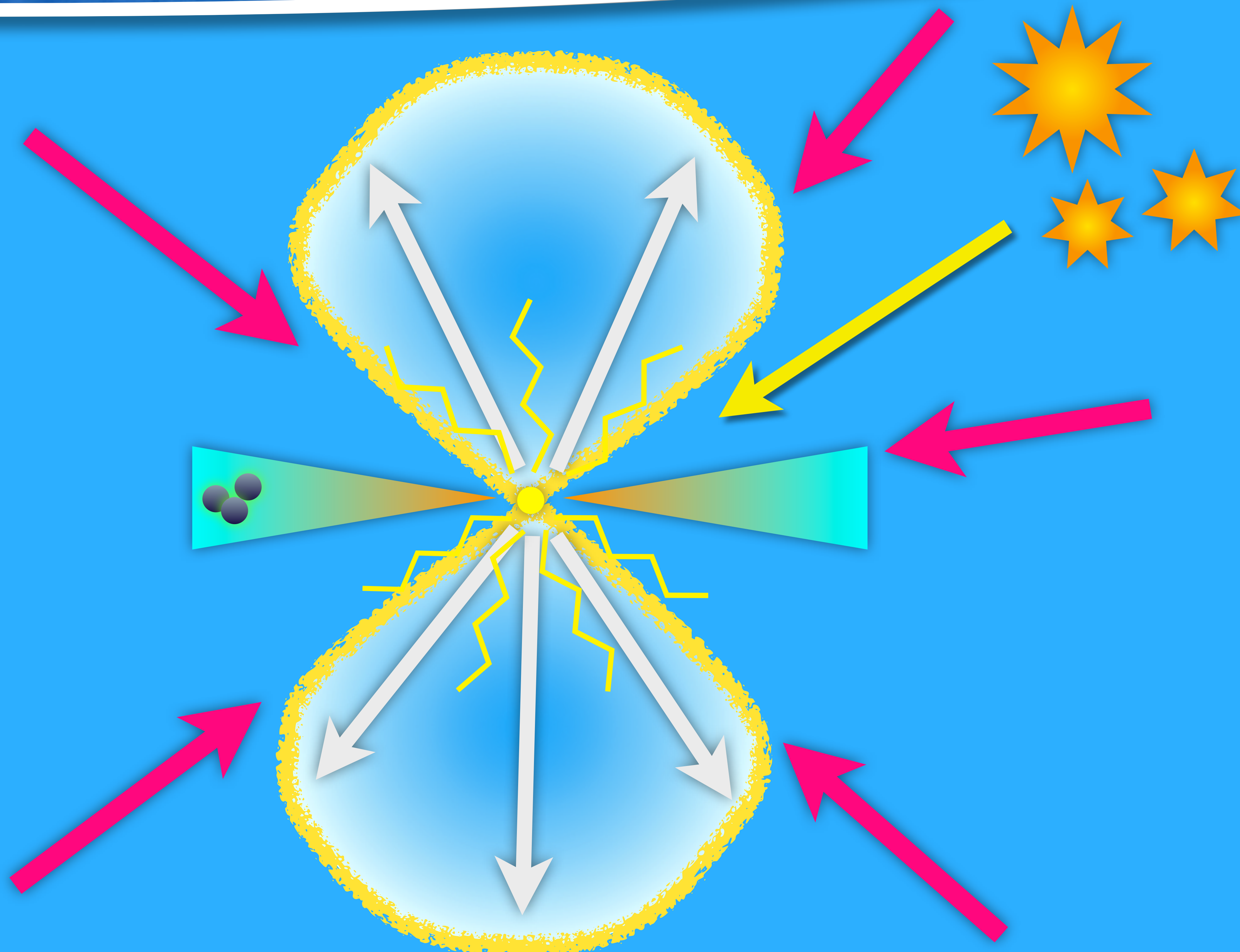


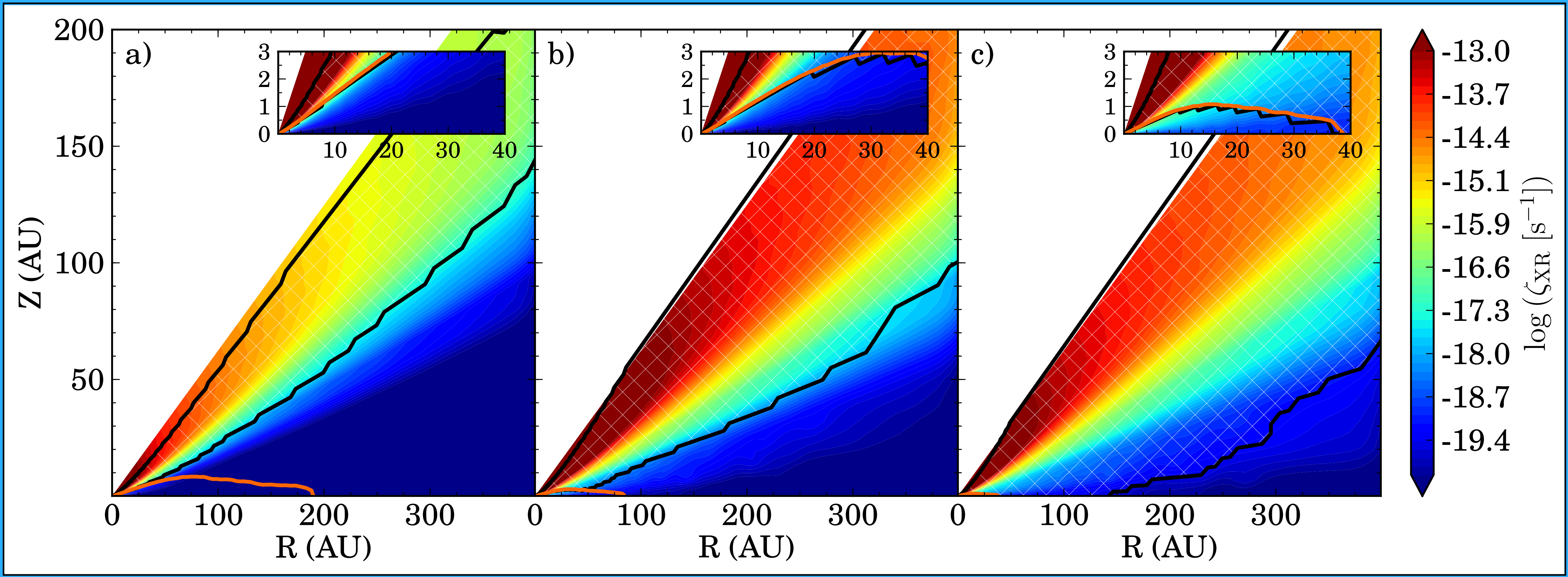
Or is it spherical at all?

Conclusions

- Wind modulation of the CR ionization rate can be > 4 orders of magnitude *lower* than an unshielded disk.
  - Can inhibit MRI, impact chemistry (e.g., grain surface, deuteration and ion-neutral chemical channels).
- In the absence of CR, RN can become the dominant source of H_2 ionization in the outermost regions and midplane of the disk.
- All of these ionization predictions can and will be readily tested by ALMA!

THANK YOU!

Importance of X-rays



- **Increasing X-ray flux can also substantially increase active region but CRs or RN still necessary in the outer disk.**
- **a) $L_{xr} = 10^{28}$ erg/s, b) $10^{29.5}$ erg/s, c) 10^{31} erg/s.**

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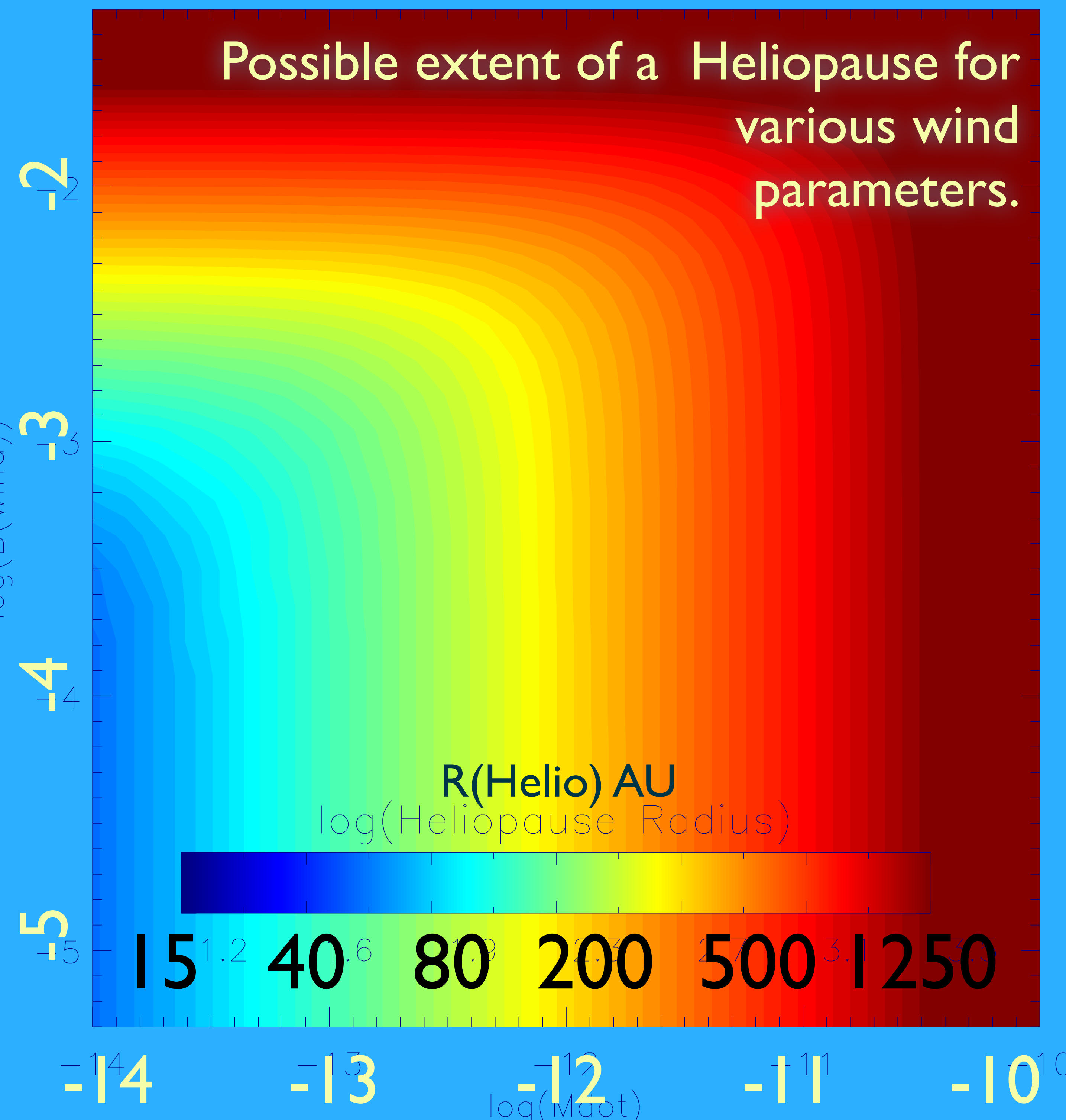

log(B_{wind}(1 AU)) Gauss

log(Mdot) M_{sun}/yr