Wind-driven Exclusion of Cosmic Rays in the Protoplanetary Disk Environment

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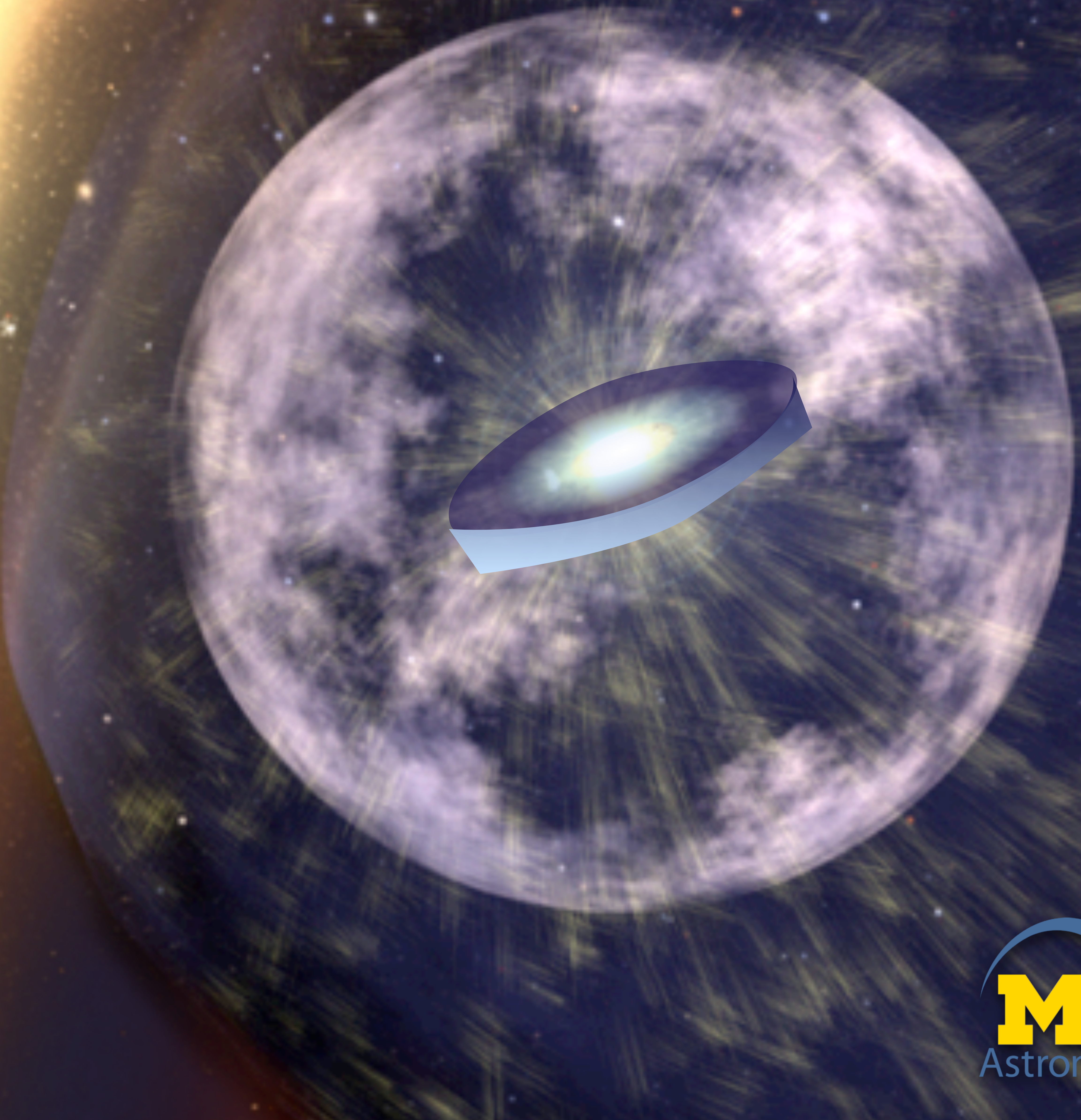

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Astronomy

PROTOPLANETARY DISKS: The Key Role of Ionization

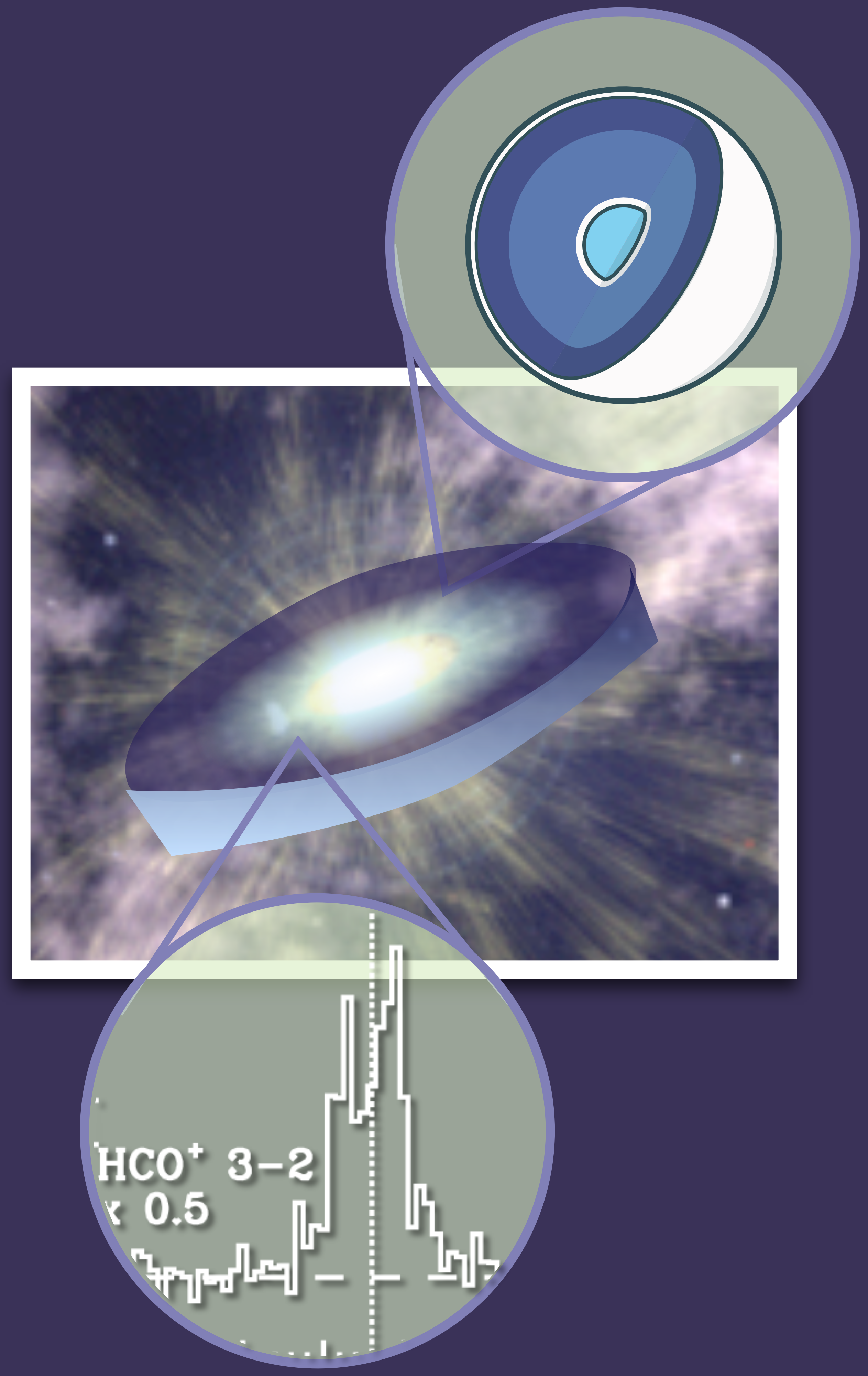
Disks around young stars are the birthsites of **planetary systems**.

Their **ionization** plays a particularly important role in the planet formation process.

Ionization sources include X-rays, UV, cosmic rays (CR) and radionuclides.

Total ionization rates span *ten orders of magnitude* over height at R = 1 AU.

Of these processes, CRs and potentially SLRs are thought to be the ***primary ionization sources*** in the midplanes of disks → the planet formation zone.



IONIZATION IN DISKS

Ionization plays a central role in the physics and chemistry of planet formation.

Regulates the efficiency by which planets form *and* their chemical make up.

MRI driven turbulence transfers angular momentum, enabling accretion (Velikhov 1959, B&H1991).

Turbulence-free zones posited as "save-havens" for planet formation (Gressel+2012).

PHYSICS

Activates gas turbulence by linking the magnetic fields with the primarily neutral gas.

IONIZATION

CHEMISTRY

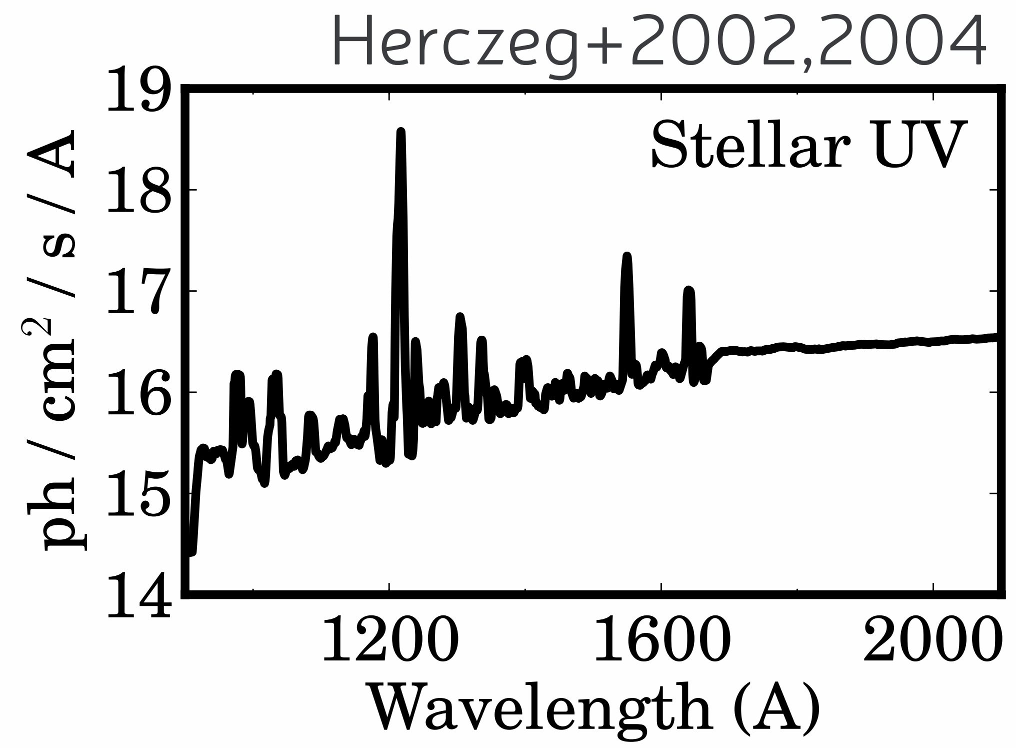
The most efficient molecular chemical processes occur in cold ($T_g < 100$ K) gas.

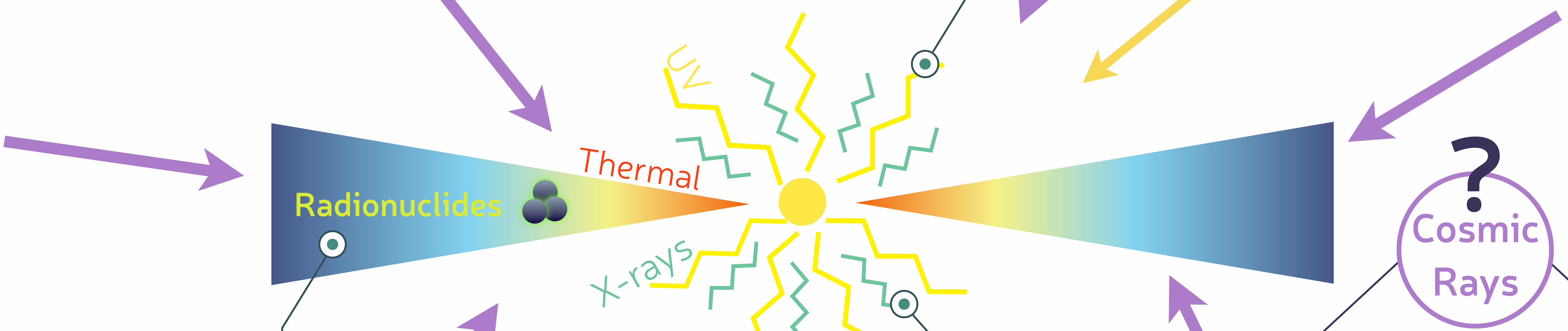
Ion-neutral reactions drive gas-phase chemistry.

Ice-formation by hydrogenation requires atoms (H) extracted from H_2.

Is a non-thermal desorption source!

SOURCES OF IONIZATION IN DISKS





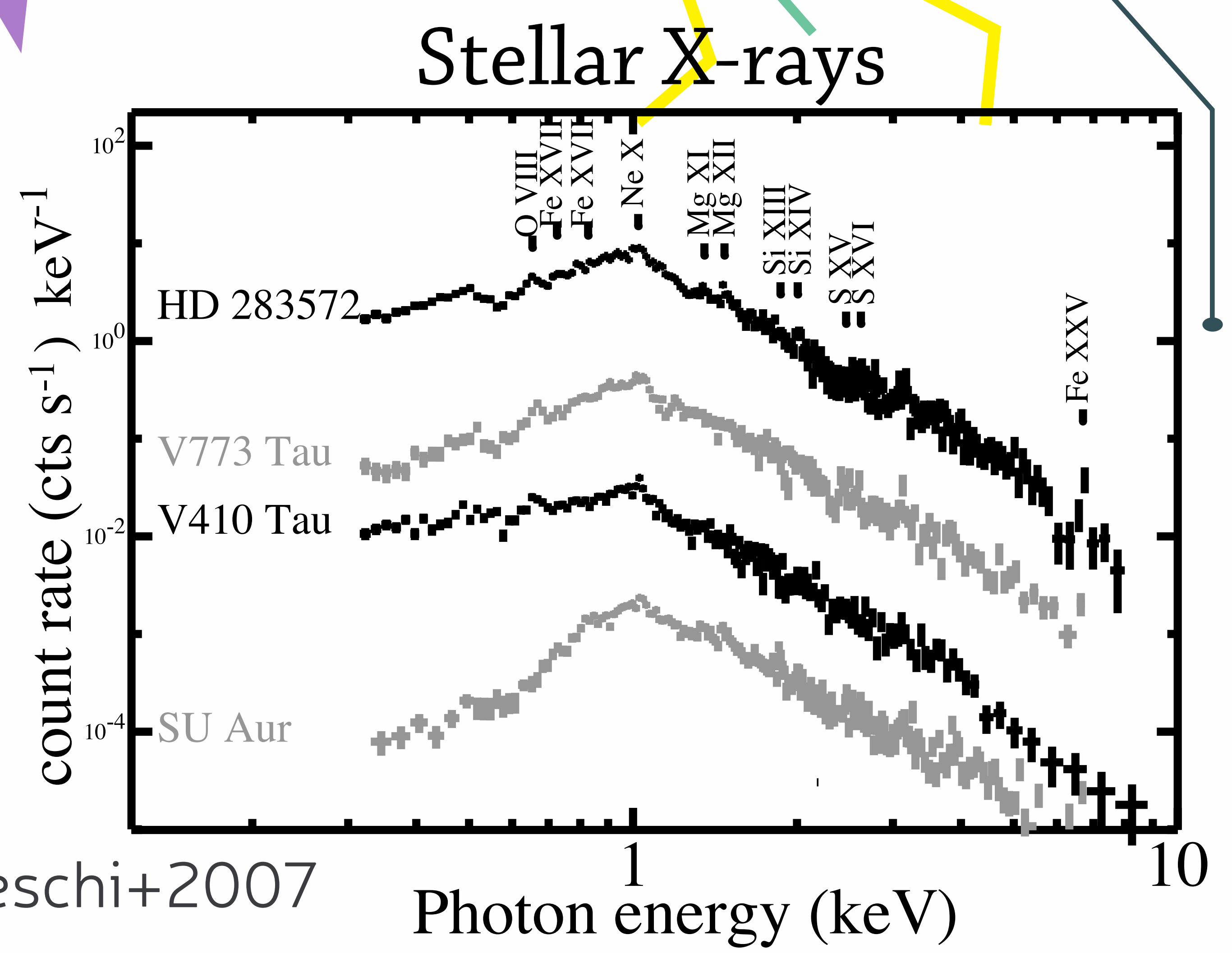
Meteoritic Record

Excess of ^{26}Mg points to large quantities of ^{26}Al.

Limits on H_2D^+ hint that CR fluxes *are not interstellar*

$\zeta_{CR} < 3 \times 10^{-17}\ s^{-1}$

(Chapillon+2011)

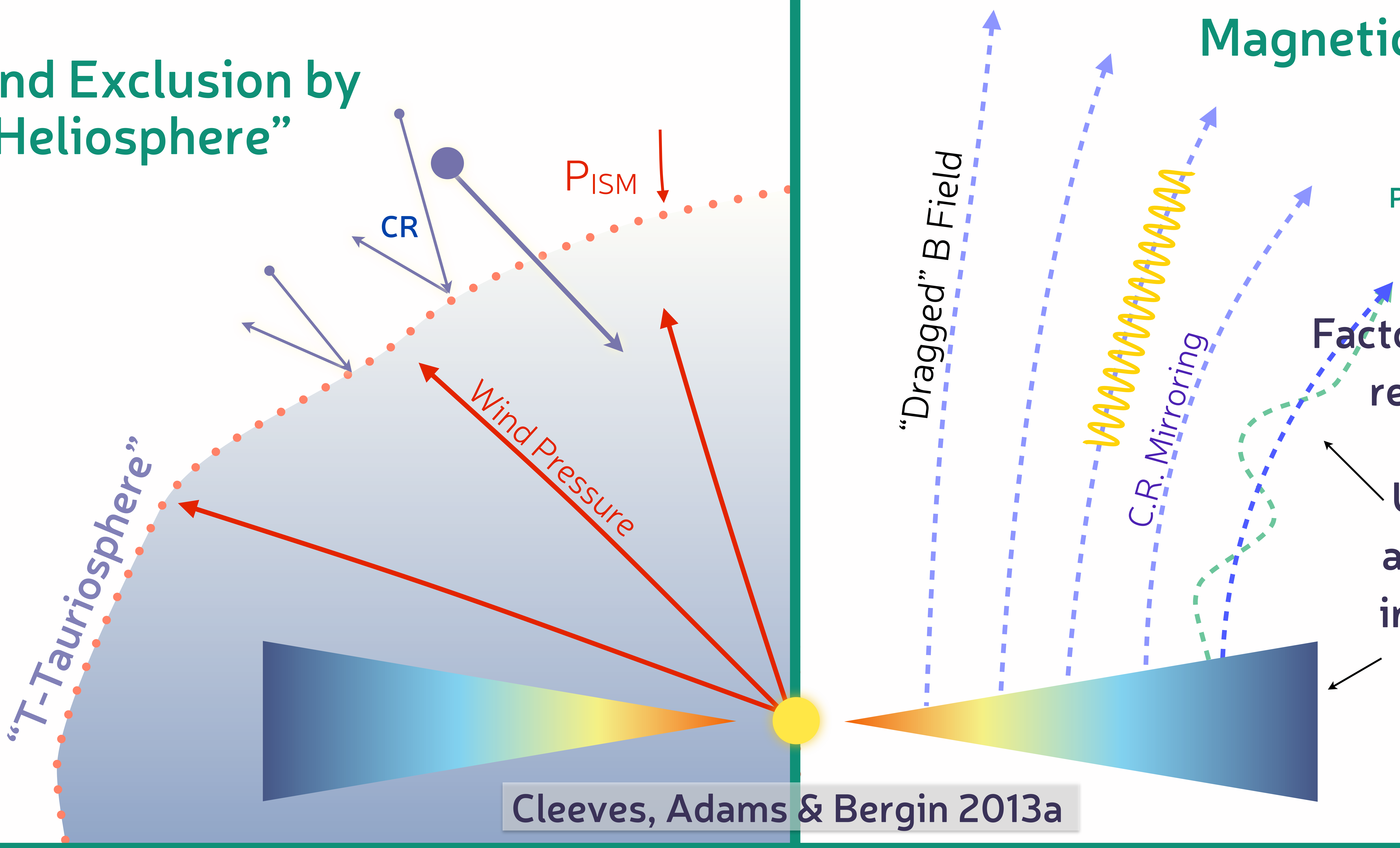


COSMIC RAY EXCLUSION MECHANISMS

Wind Exclusion by a "Heliosphere"

Magnetic Exclusion: "Mirroring"

(Li & Shu 1996, Padovani & Galli 2011)



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Factor of ≤ 2 reduction

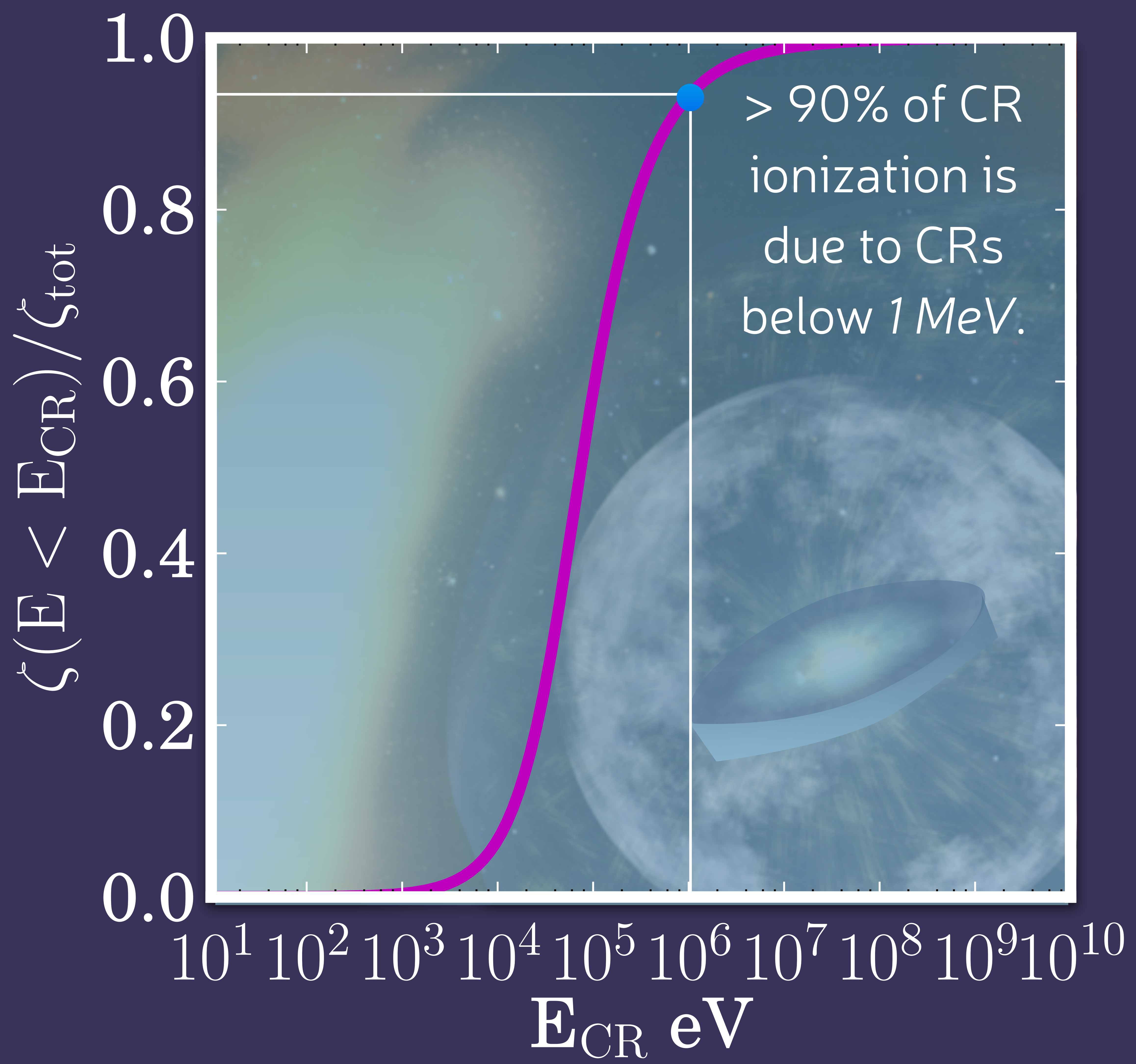
Unless there are magnetic irregularities

(Dolginov+94, Padovani+13, Fatuzzo+14)

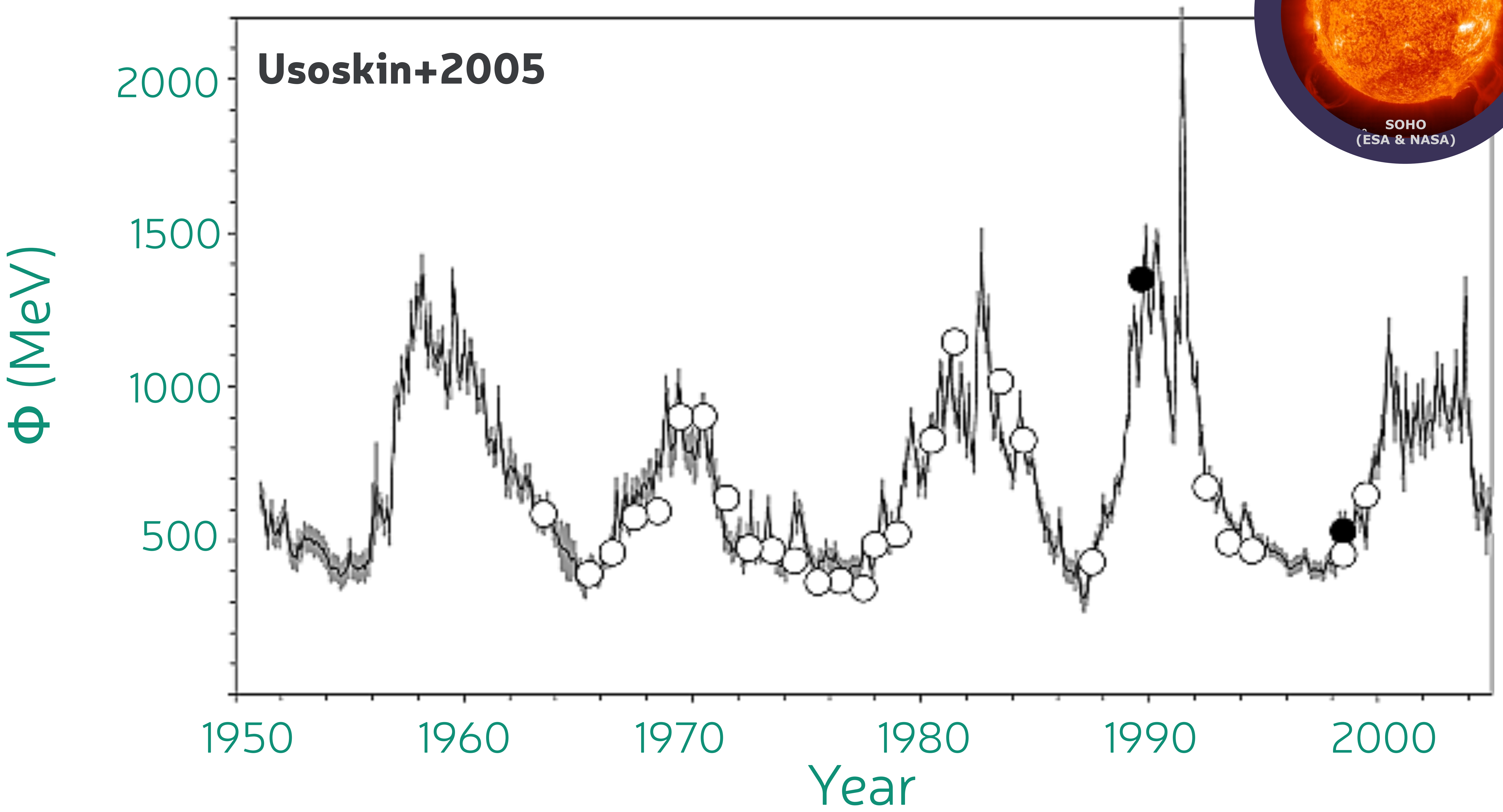
Wind Exclusion by a “Heliosphere”

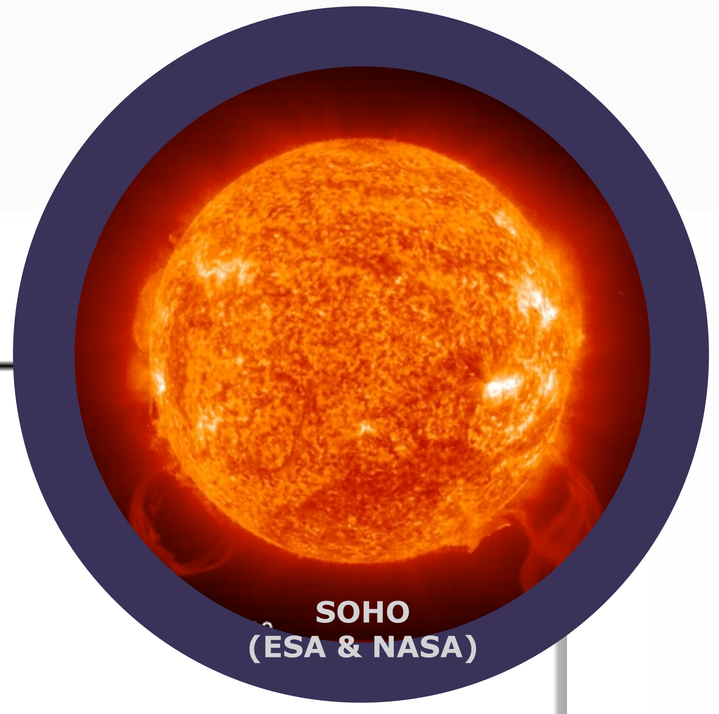
COSMIC RAY EXCLUSION BY WINDS: The Sun

- The modern day solar wind is an efficient modulator of CR particles, E_{CR} < 100 MeV.
- Young stars have 1) 10^2-10^3x higher surface B-fields, 2) 10^5-10^7x higher mass-loss rates (star and disk) and rotate more rapidly than the Sun.
- Young stars should be *as efficient* (if not more) at modulating the CR flux in the circumstellar environment.
- Major implications for the ionization (and chemistry) of protoplanetary disks.



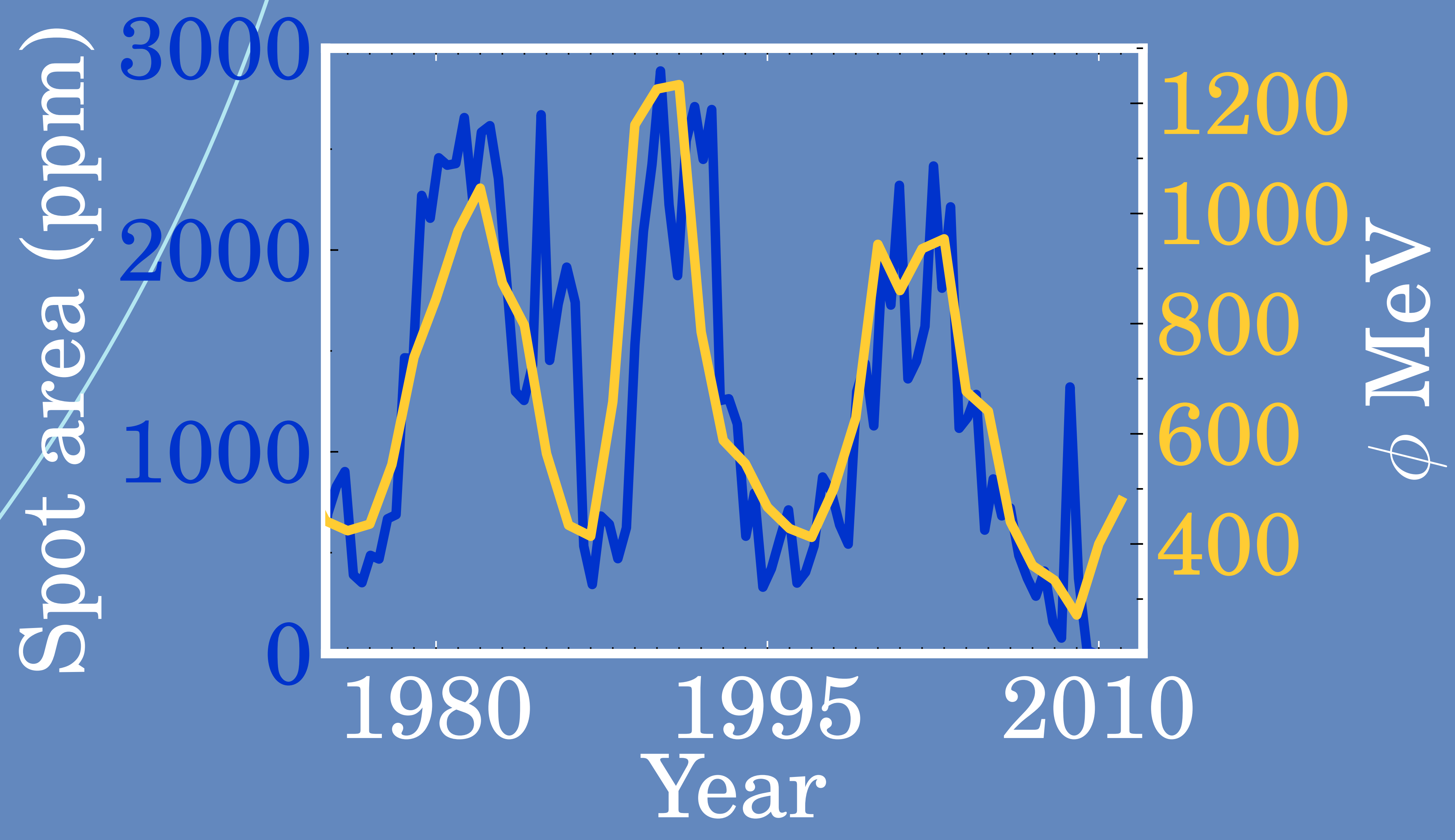
CR EXCLUSION BY WINDS: THE SOLAR WIND

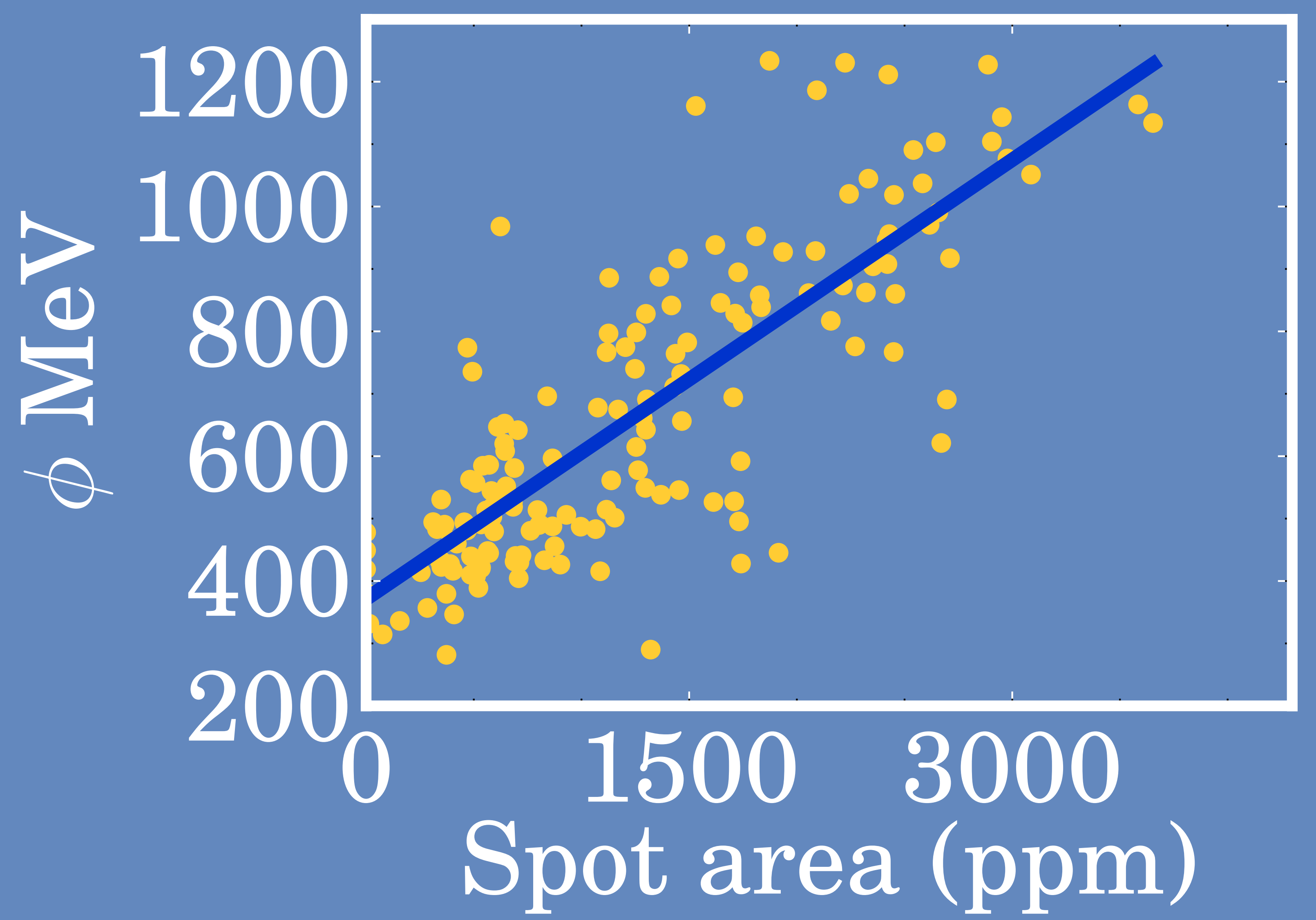




To empirically estimate the magnitude of young star CR-exclusion, we use properties of the Sun to relate CR modulation efficiency to the magnetic Solar Cycle along with the **force-field approximation** (Gleeson & Axeford 1968).

EXTENSION TO A YOUNG STAR





- We correlate magnitude of CR modulation (Usoskin et al. 2005) with various solar parameters potentially measurable on other stars: spot coverage, |B|, number of spots, coverage of coronal holes, etc.
- Spot coverage is readily measurable. Solar values range from 0-0.3%.
- Can estimate the modulation parameter by extrapolating solar values to TT coverage (<18%).

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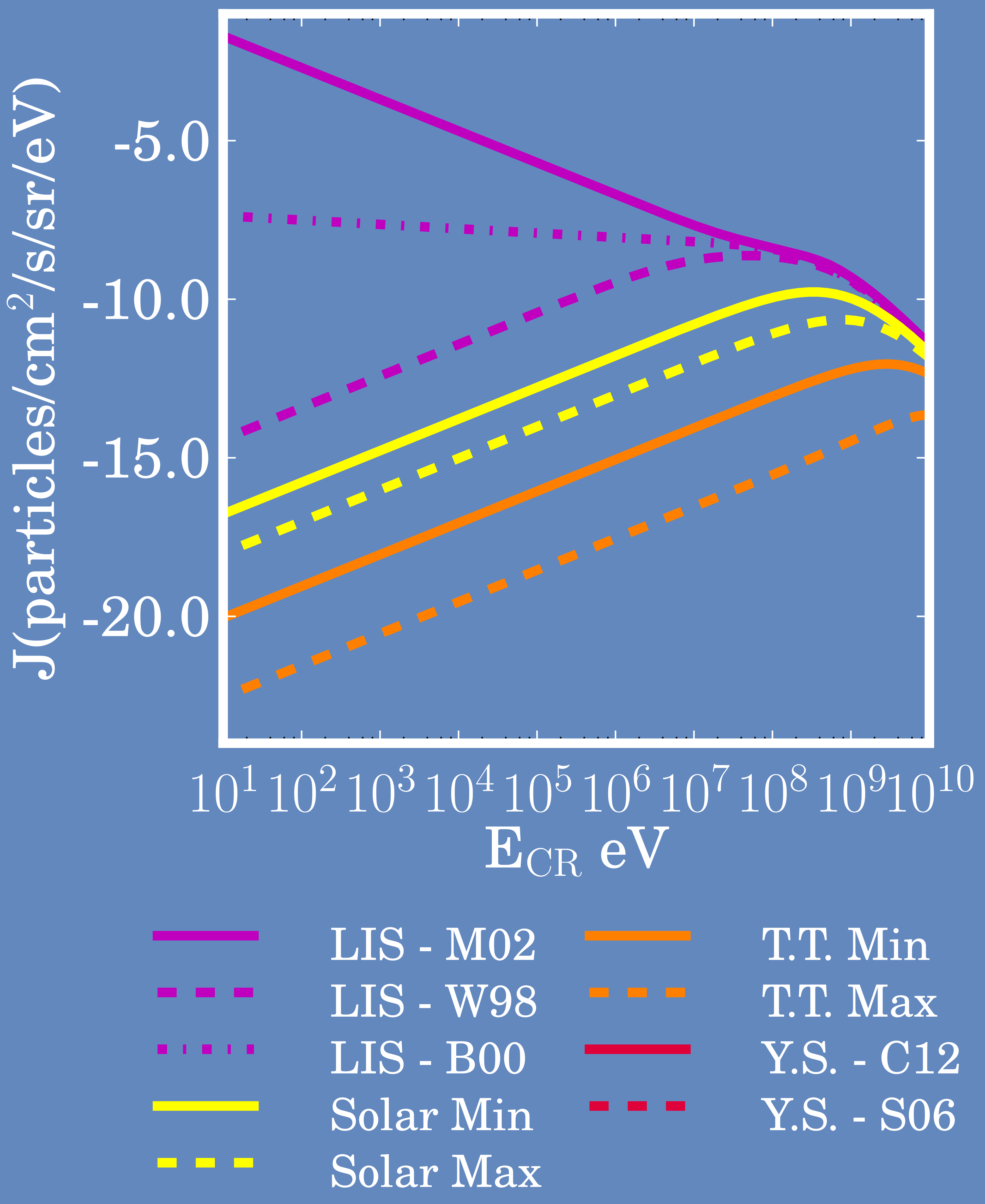
EXTENSION TO A YOUNG STAR: Spectra

- Relate solar magnetic activity (spots) to magnitude of CR exclusion.
- First-order approximation: treat a T Tauri star as an extreme Sun.
- Solar spot coverage is up to 0.4%
- T Tauri spot coverage is significantly higher, ranges from 3% - 17% (Bouvier et al. 1989).
- Corresponds to modulation strengths of Φ ~ 5 (5%) - 18(10%) GeV.



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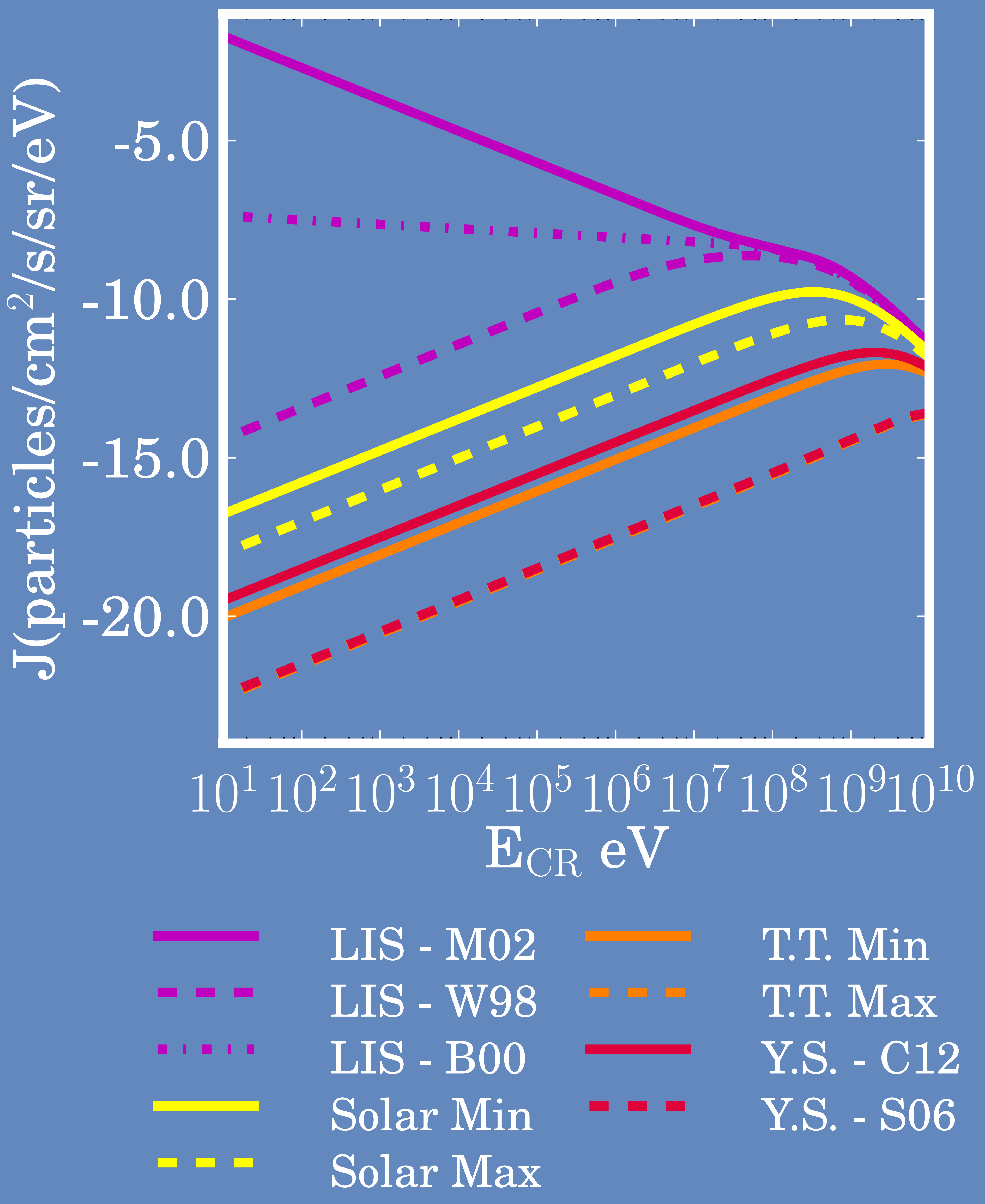
- Corresponds to modulation strengths of Φ ~ 5 (5%) - 18(10%) GeV.
- Our simple extrapolation (T.T.) agrees with models of the ~Gyr-old young sun, Y.S.

  (Svensmark et al. 2006, Cohen et al. 2012)



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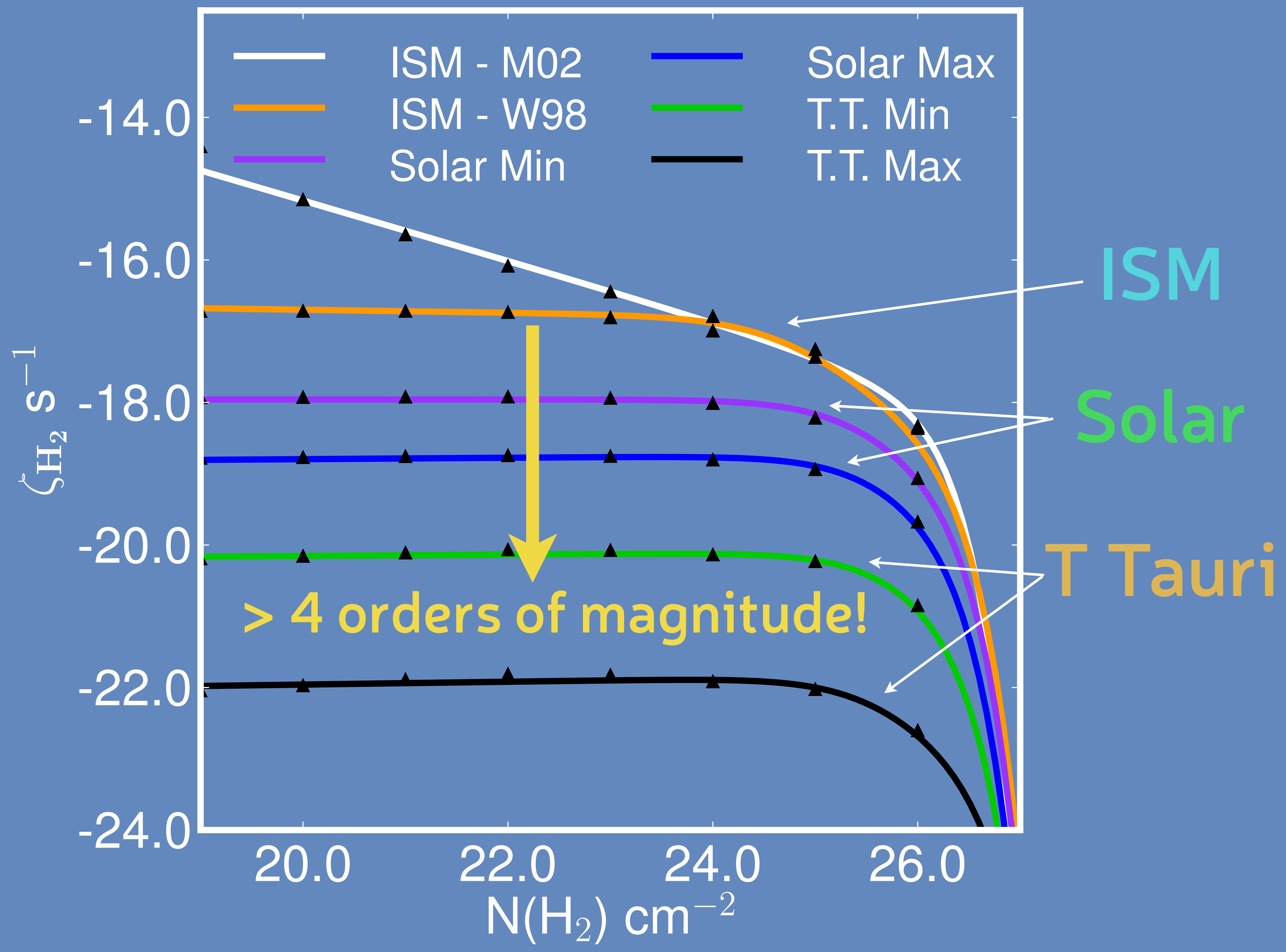
EXTENSION TO A YOUNG STAR: Ionization Rates

- 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 Tauriosphere solar-extrapolation models.
- In the simple model, for > 10% spot coverage CRs can be neglected.



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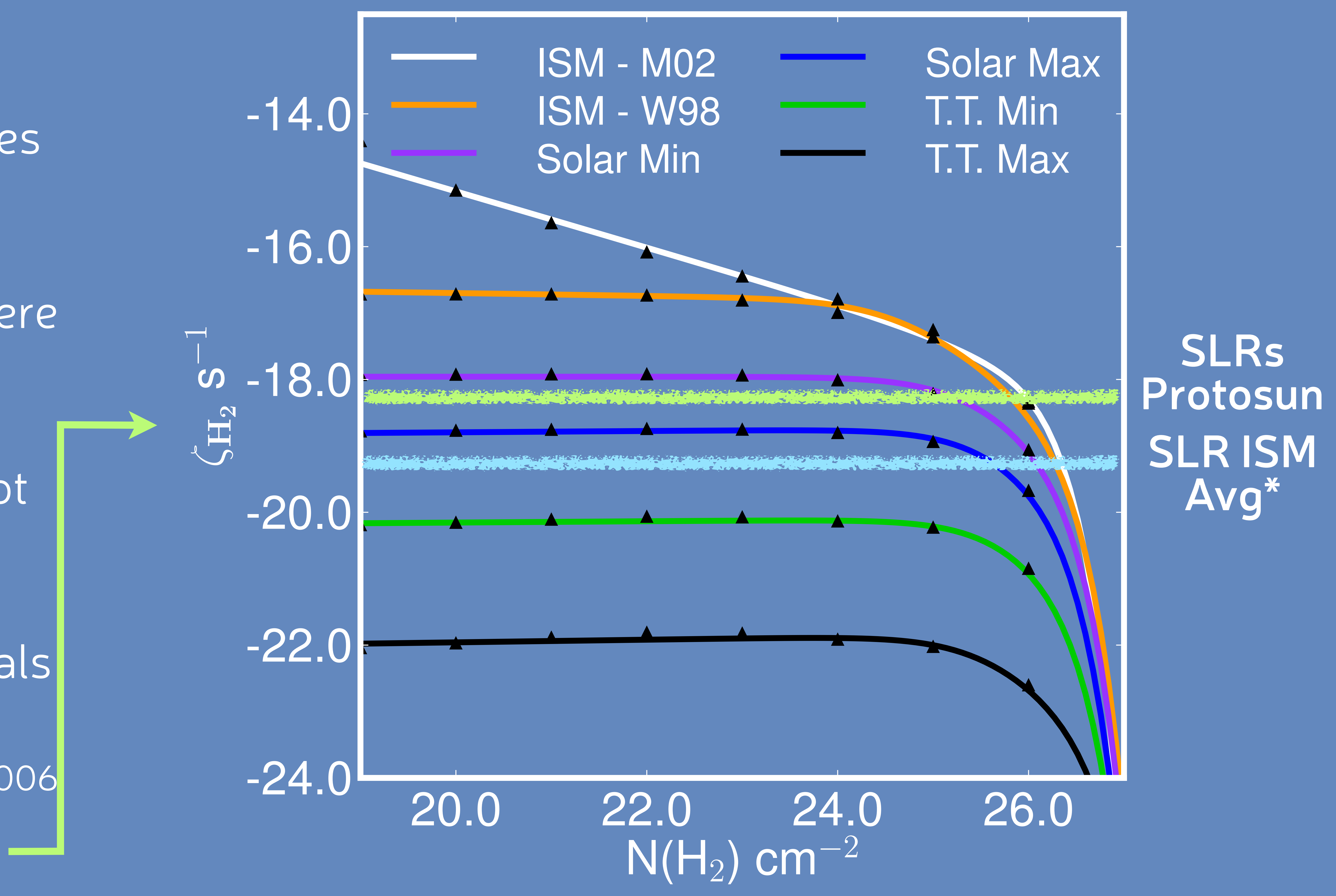
- $\zeta_{CR} < 10^{-20}$ s^{-1} for the T Tauriosphere solar-extrapolation models.
- In the simple model, for > 10% spot coverage CRs can be neglected.
- For $\zeta_{CR} < 10^{-19}$ s^{-1} radioactivity rivals or exceeds CR ionization.

*Umebayashi & Nakano 2008, Diehl et al. 2006



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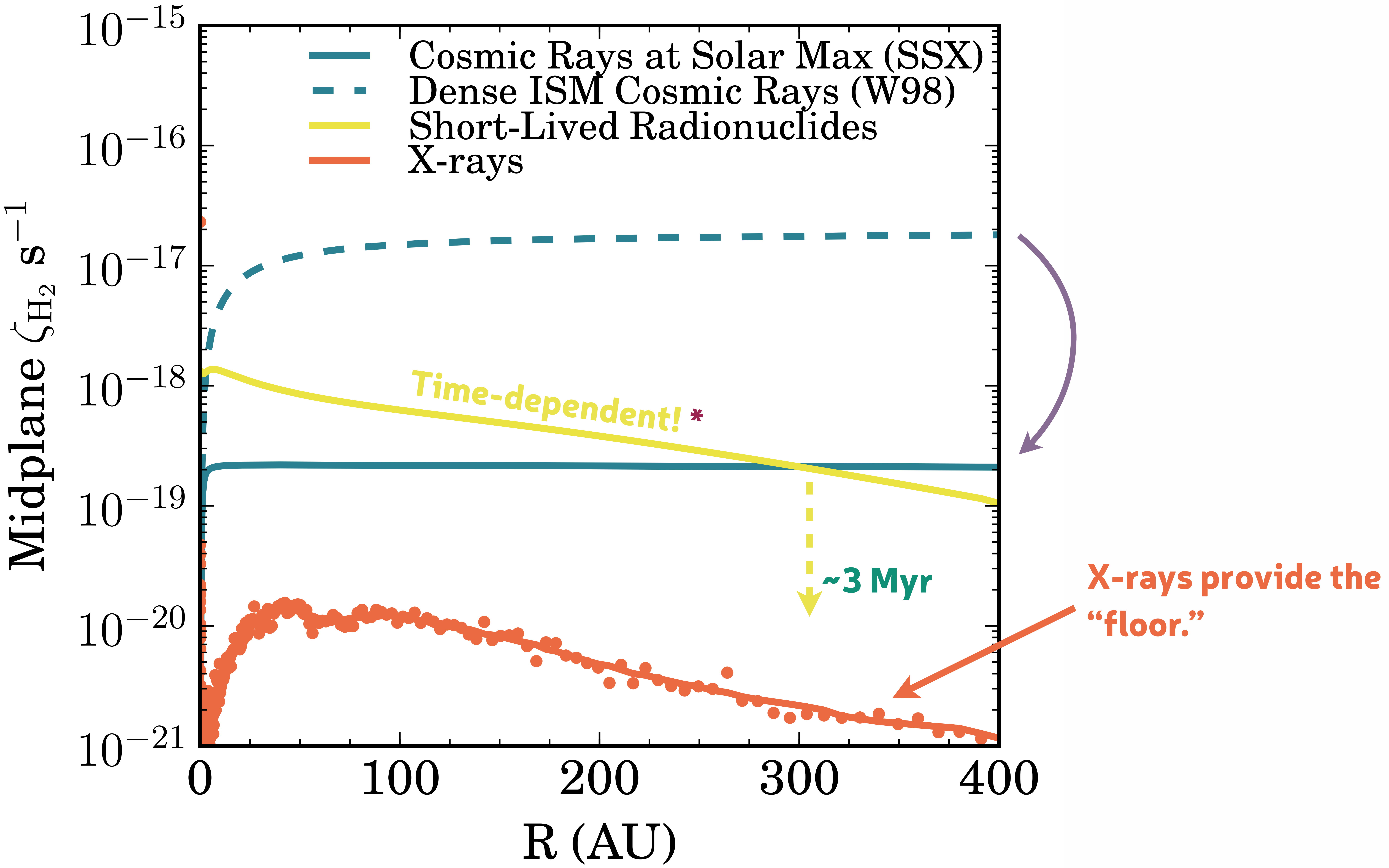
A NEW PICTURE OF DISK IONIZING PROCESSES



*Cleeves, Adams, Bergin, Visser 2013b

Implications

1

TURBULENCE

Dead-zones

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2

CHEMISTRY

and Observable Effects

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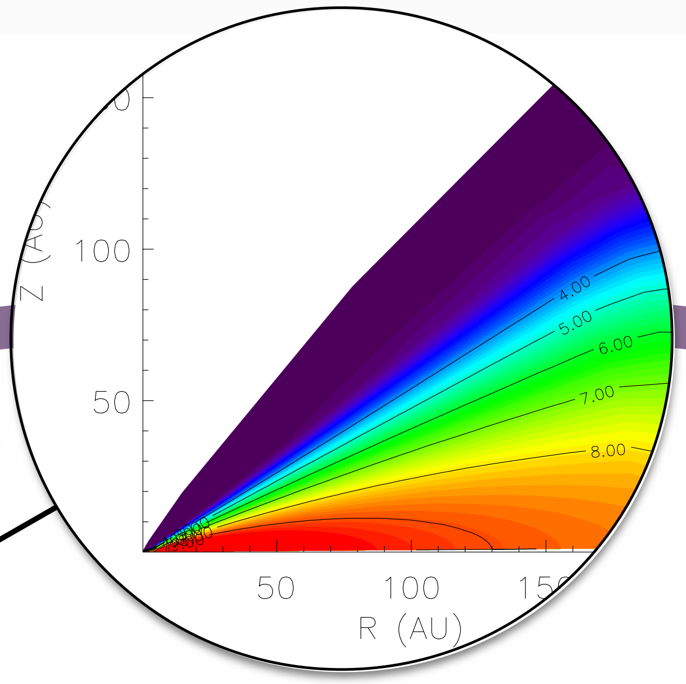
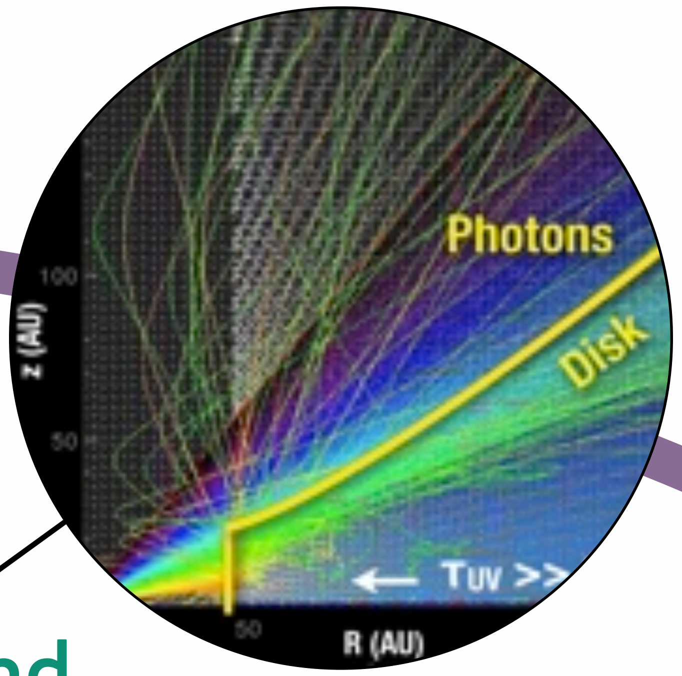
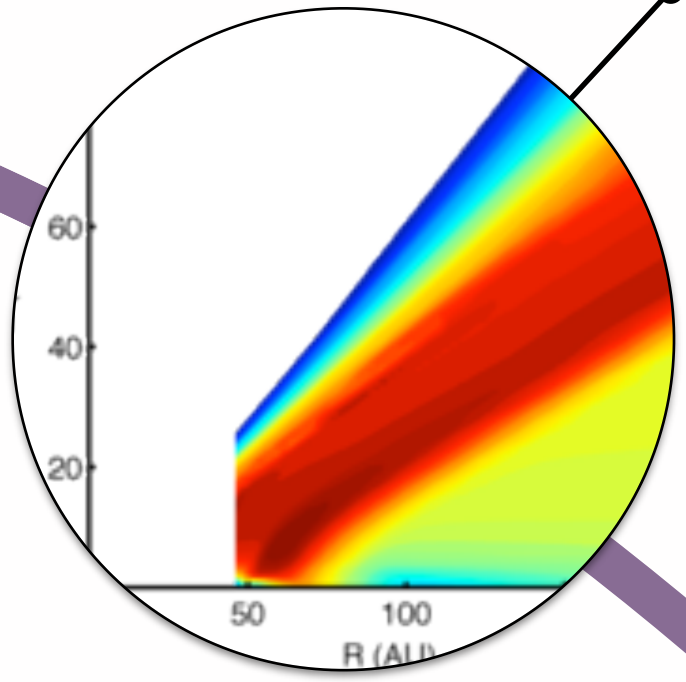
MODELING TOOLS



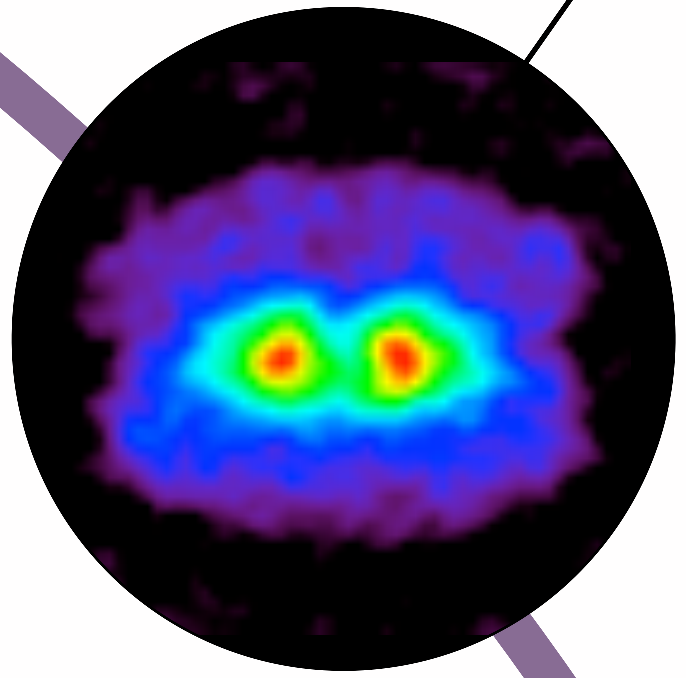
1. A physical model: density, temperature, settling.



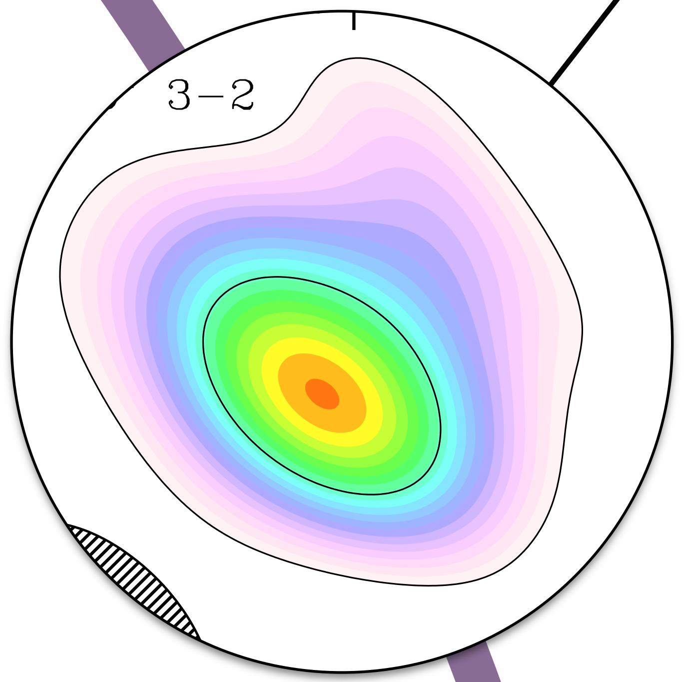
2. UV (Lyα and continuum) & X-ray rad. transfer.



3. Chemical model calculation: photo-chemistry, grain-surface chemistry, ion-chemistry, self-shielding (Fogel et al. 2011).



4. Model resultant line emission, LTE and non-LTE.



5. Compare to observed line emission.

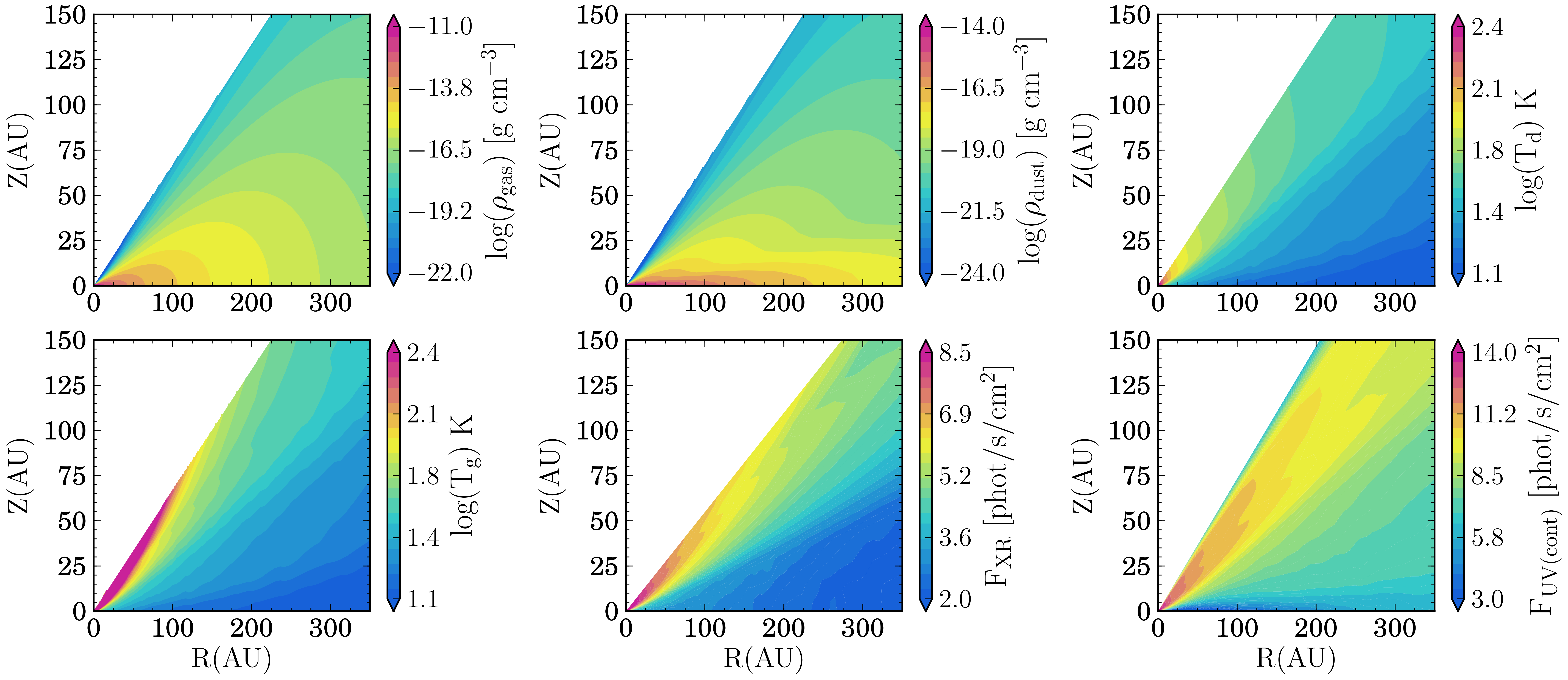
STRUCTURE

- Disk model (ρ_g, ρ_d, T_g, T_d): TORUS (T. Harries), Bruderer
- UV field: continuum and Ly-α (Bethell and Bergin 2011a).
- X-ray from 1-20 keV (Bethell and Bergin 2011b).
- Settled disk with respect to gas.

DISK CHEMISTRY/EMISSION

- Chemical reaction network (Fogel et al. 2011).
- Observables. Line emission, dust continuum (LIME, Brinch+2010).

DISK MODEL



K7 Star
M_{disk} = 0.04 M_{sun}
R_{out} = 400 AU
gas-to-dust = 100

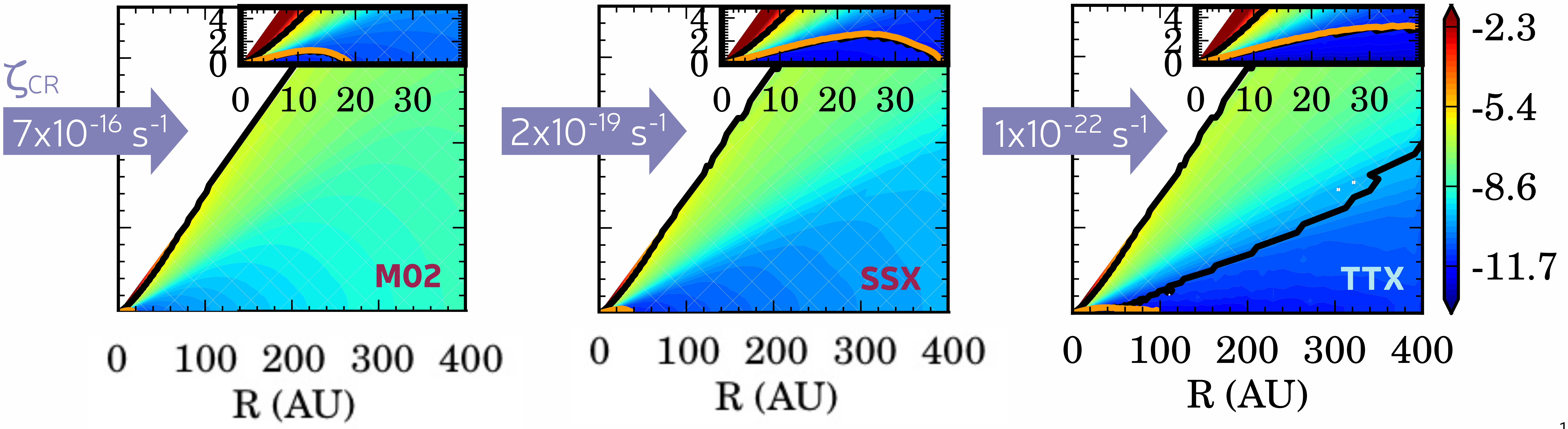
Monte Carlo wavelength dependent UV (TW Hya spectrum) and X-rays ($L_x=10^{29.5}$ erg/s).

T_{gas} from S. Bruderer prescription (in private communication) from the UV calculations.

T_{dust} in Radiative Equilbrium (passively heated by the star, no accretion)

1. RESULTS: Disk Turbulence

- Estimates in the literature for minimum ionization fraction to be MRI turbulent (Perez-Becker and Chiang 2010, also Turner et al. 2007).
  - Re = B-field to plasma
  - Am = Ion-neutral collision time
  - Elsasser (Lundquist) #:
    - ~Re with v_{alfven}.
- Re > 3300 (orange), Am > 0.1 (black). **Hatched region = Active.**
- Without CRs, MRI unsustainable at midplane → large "deadzones."



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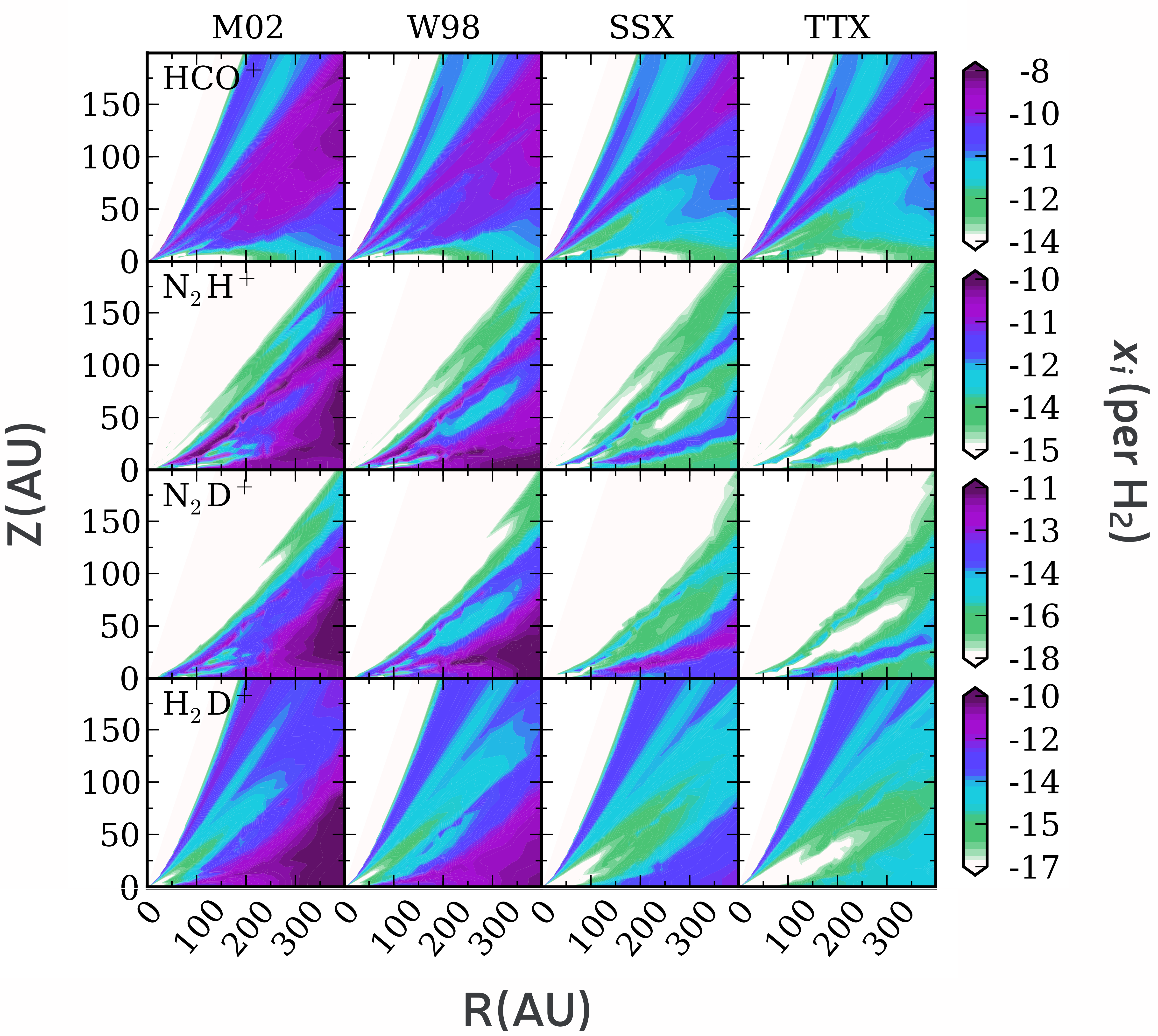
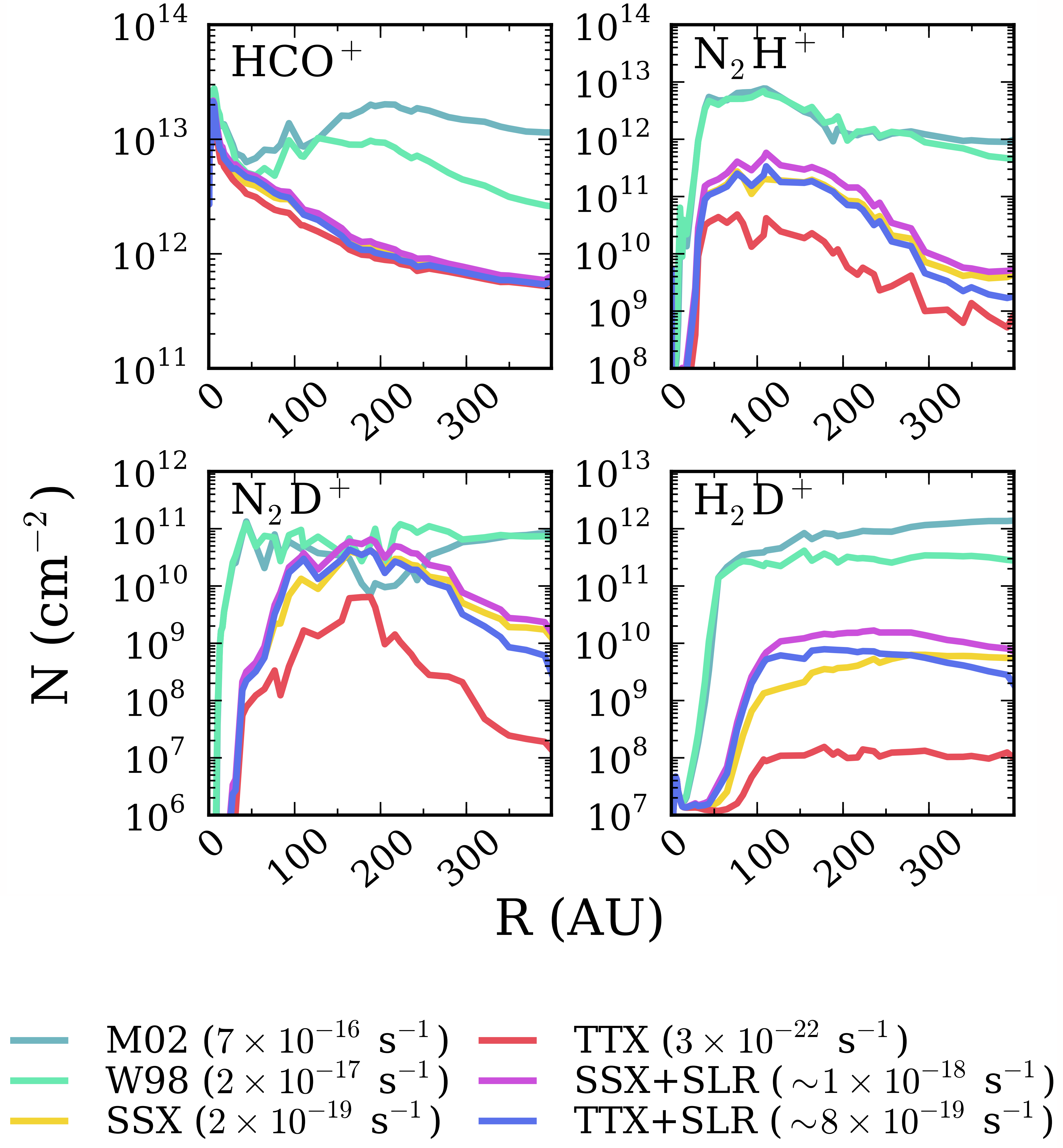
2. RESULTS: Chemical Signatures

Abundances



Column Densities



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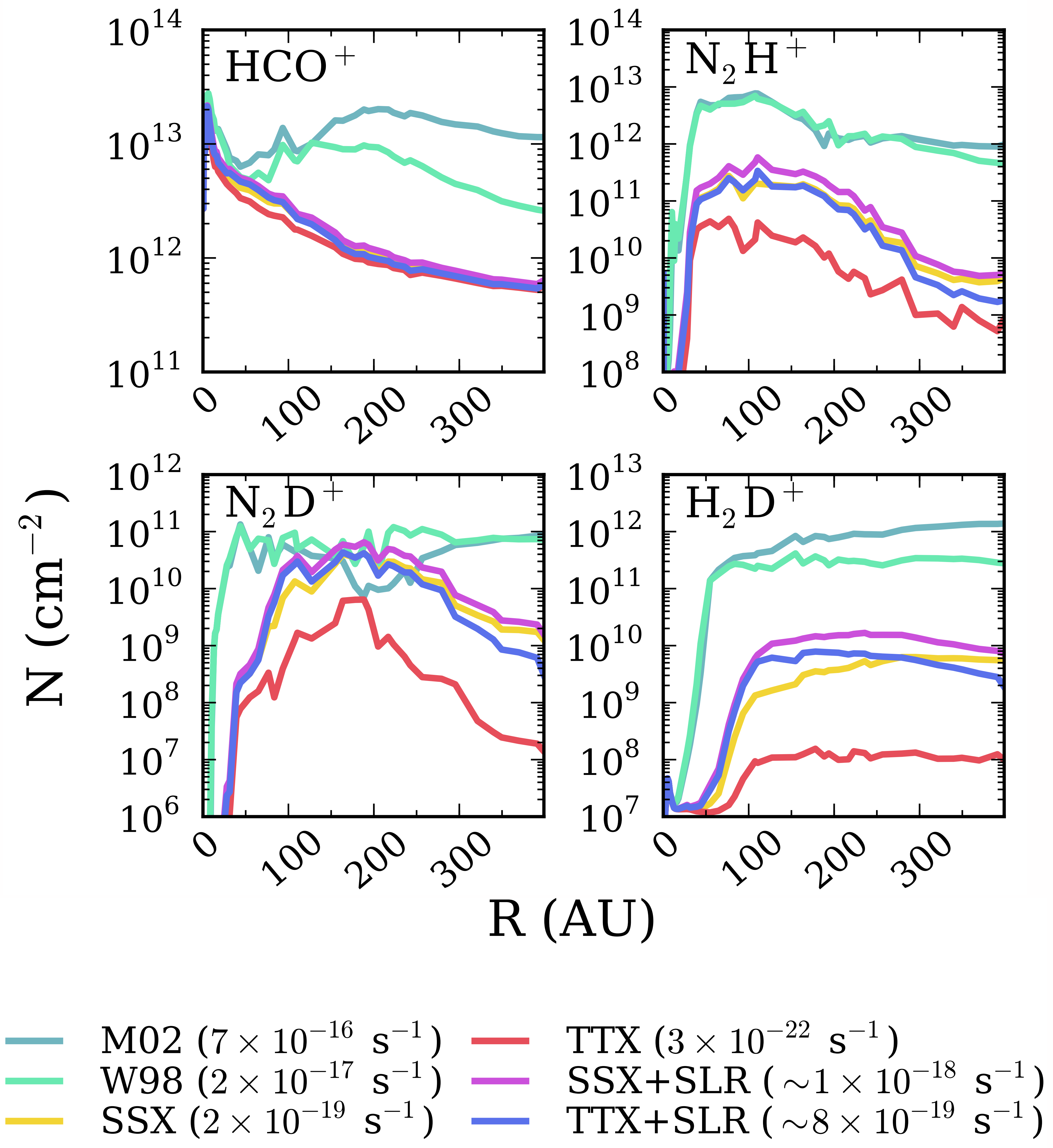
2. RESULTS: Chemical Signatures

- Changes in the incident CR rate cause a significant amount of **chemical structure**!
- Wealth of submillimeter **detectable transitions** of HCO^+, N_2H^+, and N_2D^+.
- **N_2D^+** is particularly sensitive to changes in the CR ionization rate.
- HCO^+ only sensitive to high levels of CR ionization in this model ($\zeta_{CR} > 10^{-17}$ s^{-1}) and is limited by X-rays.
- Canonical H_2D^+ will be difficult to detect and interpret.

Column Densities



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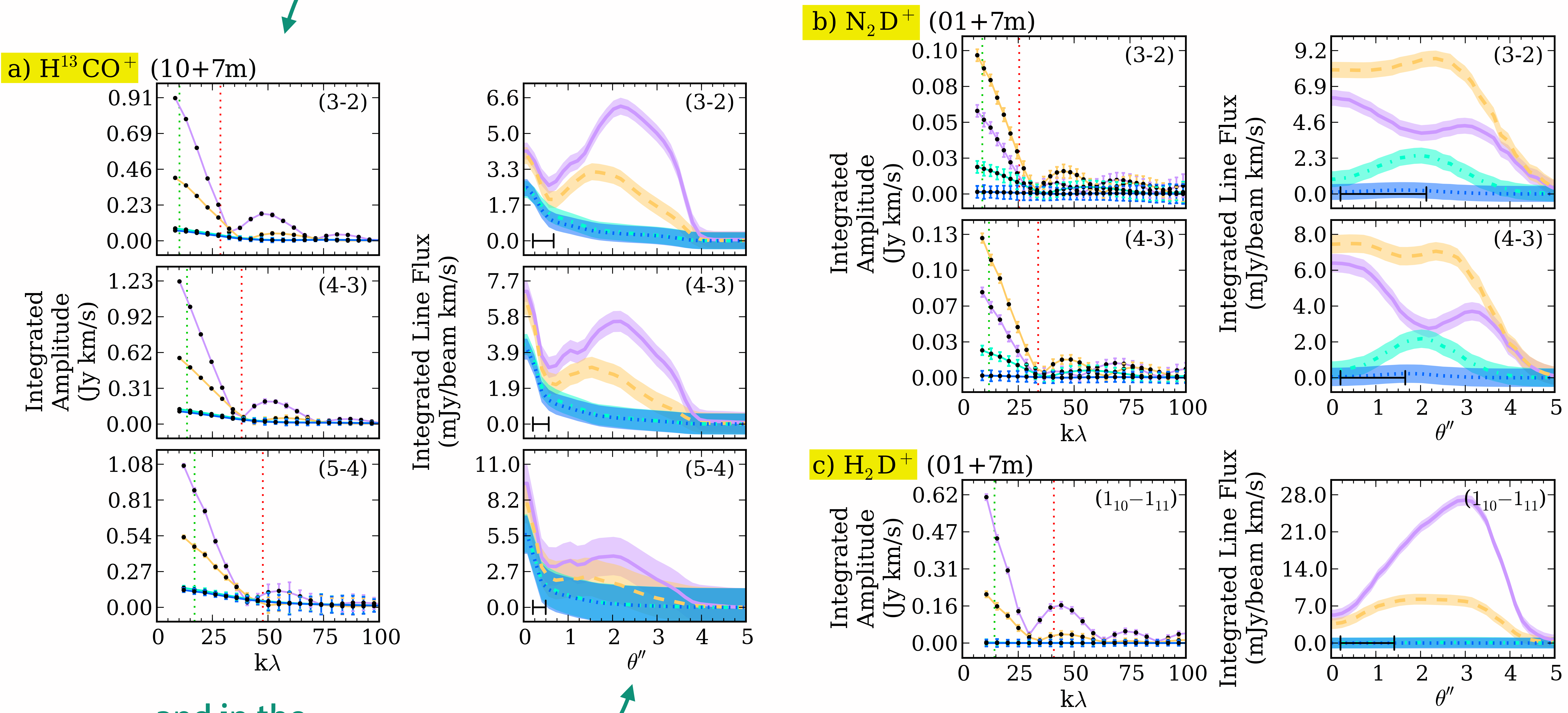
2. RESULTS: ALMA Simulations

Signatures in the Visibilities



... and in the image plane!

Key: M02 W98 SSX TTX

Cleeves, Bergin and Adams 2014 (sub.)

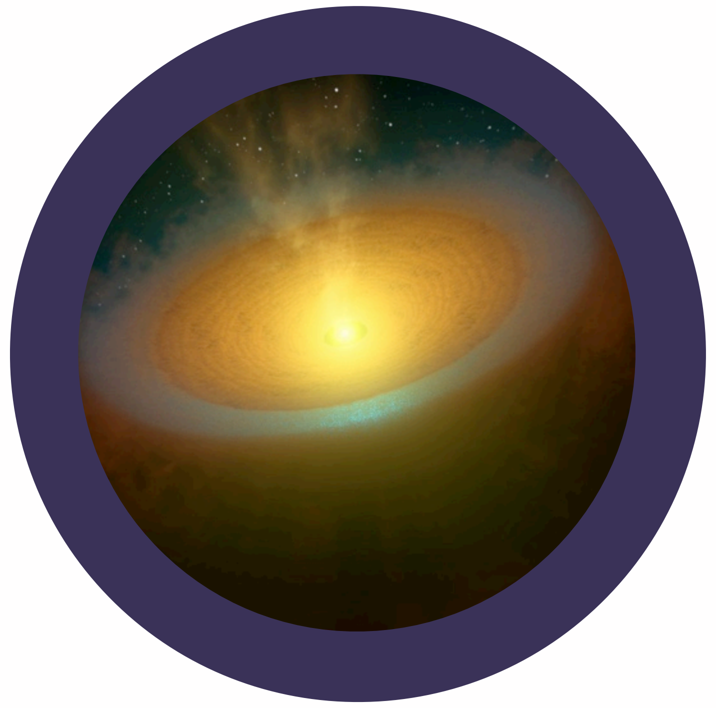
A Targeted

Case-study of

TW Hya

Cleeves et al. 2014 (in prep)

MAPPING IONIZATION IN THE TW HYA DISK



TW Hya
Our nearest planetary nursery

TW Hya is the closest (*d*=55pc) and most extensively studied protoplanetary disk.

Old (10 Myr) for its gas mass (0.03-0.05 M_{sun}), it nonetheless provides the closest and clearest (face-on, $i \sim 7^\circ$) view of planet-formation in situ.

We have constructed a highly calibrated model that matches the dust SED, gas mass, CO and HCN (Cleeves et al. 2014b in prep).

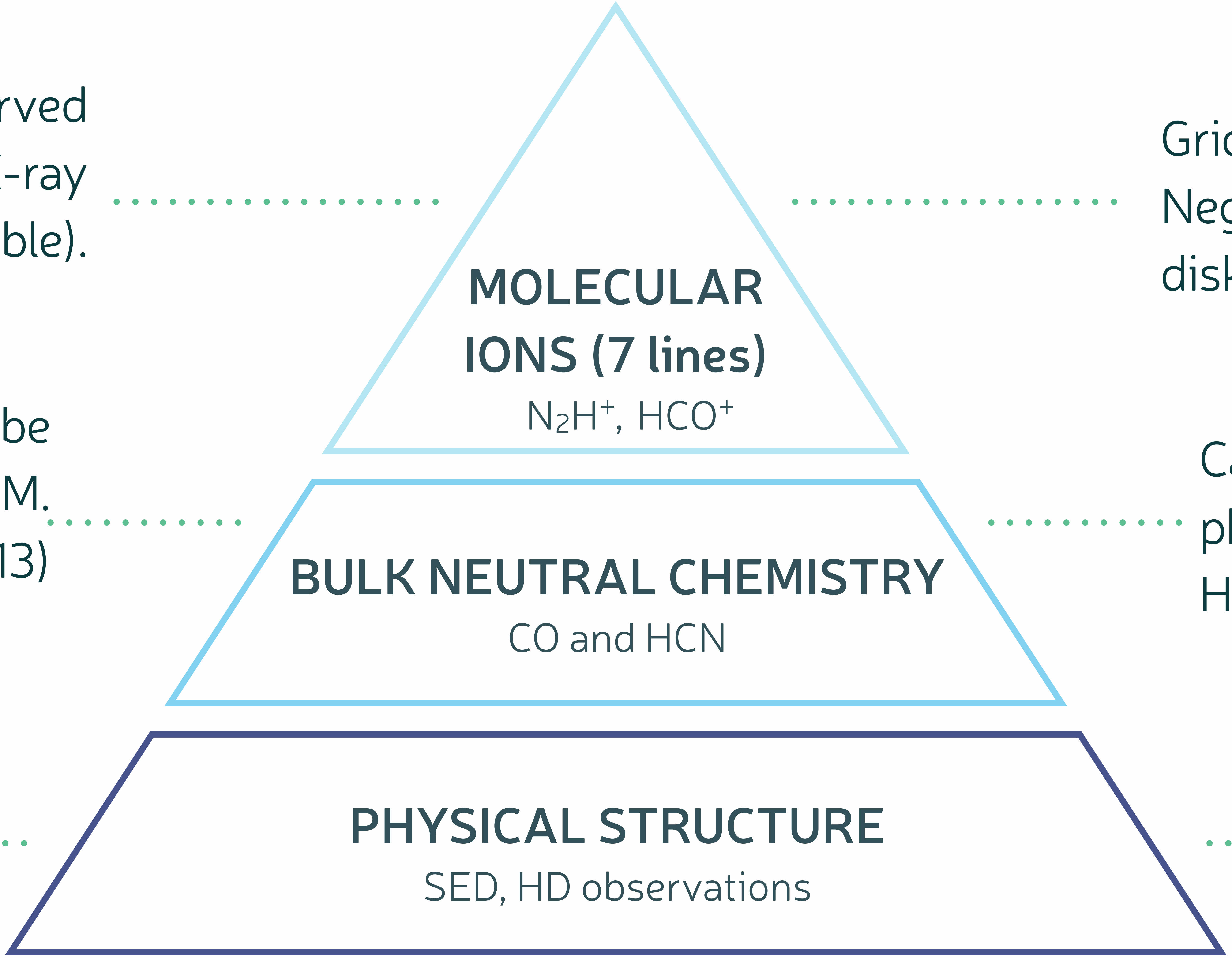
We use this framework to "map out" ionization sources and magnitudes in the gas disk.

Cleeves, Bergin, Qi, Adams+ 2014b (in prep.)

OBSERVATIONAL CONSTRAINTS

Grid of X-ray models (observed TWH spectrum is X-ray variable).

Grid of cosmic ray models. Neglect radionuclides (old disk).



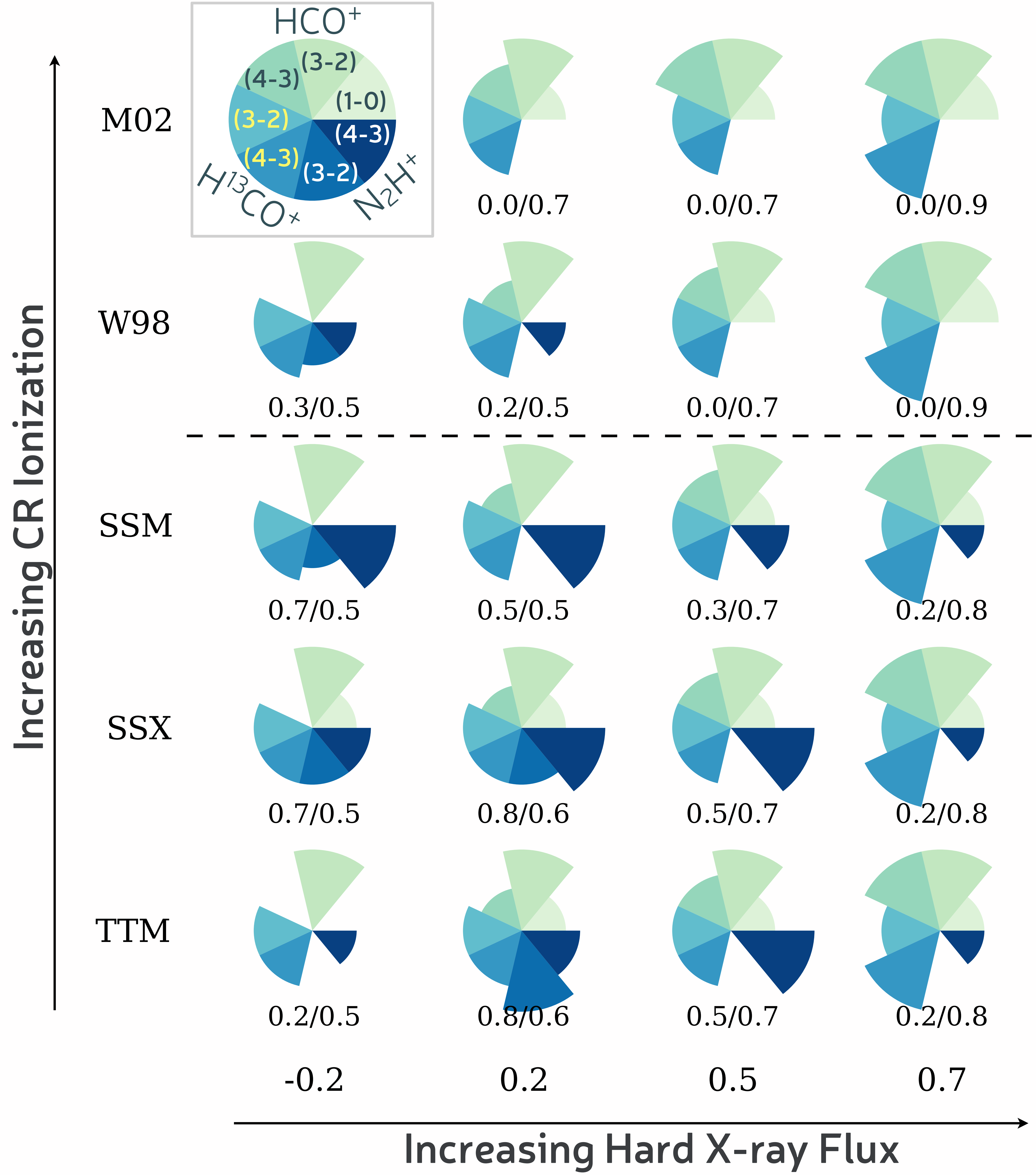
CO well known to be depleted by 1-2 O.O.M. (Favre, Cleeves, et al. 2013)

Calibrate nitrogen gas phase abundances using HCN.

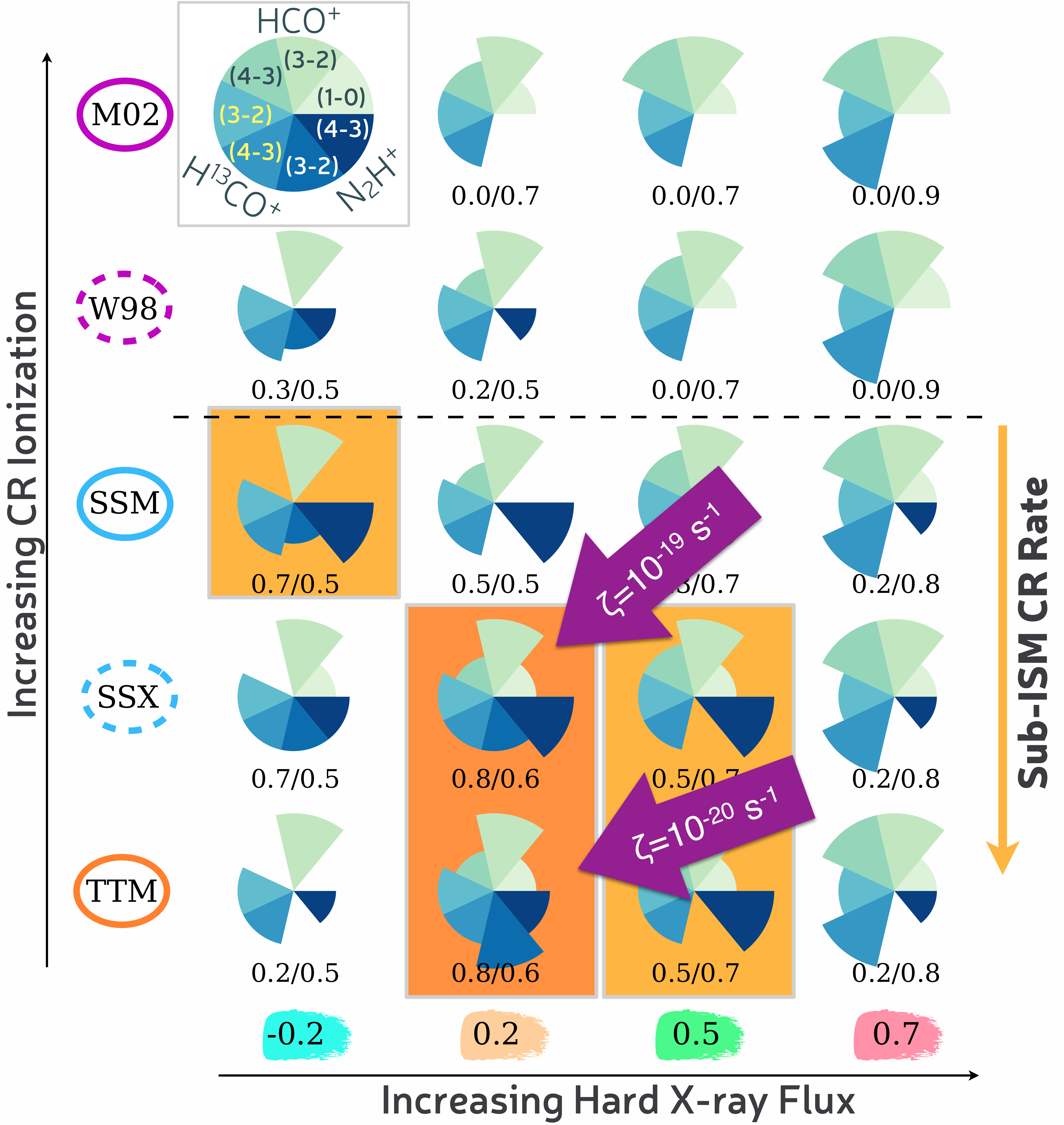
SED puts constraints on the dust disk mass and thermal structure.

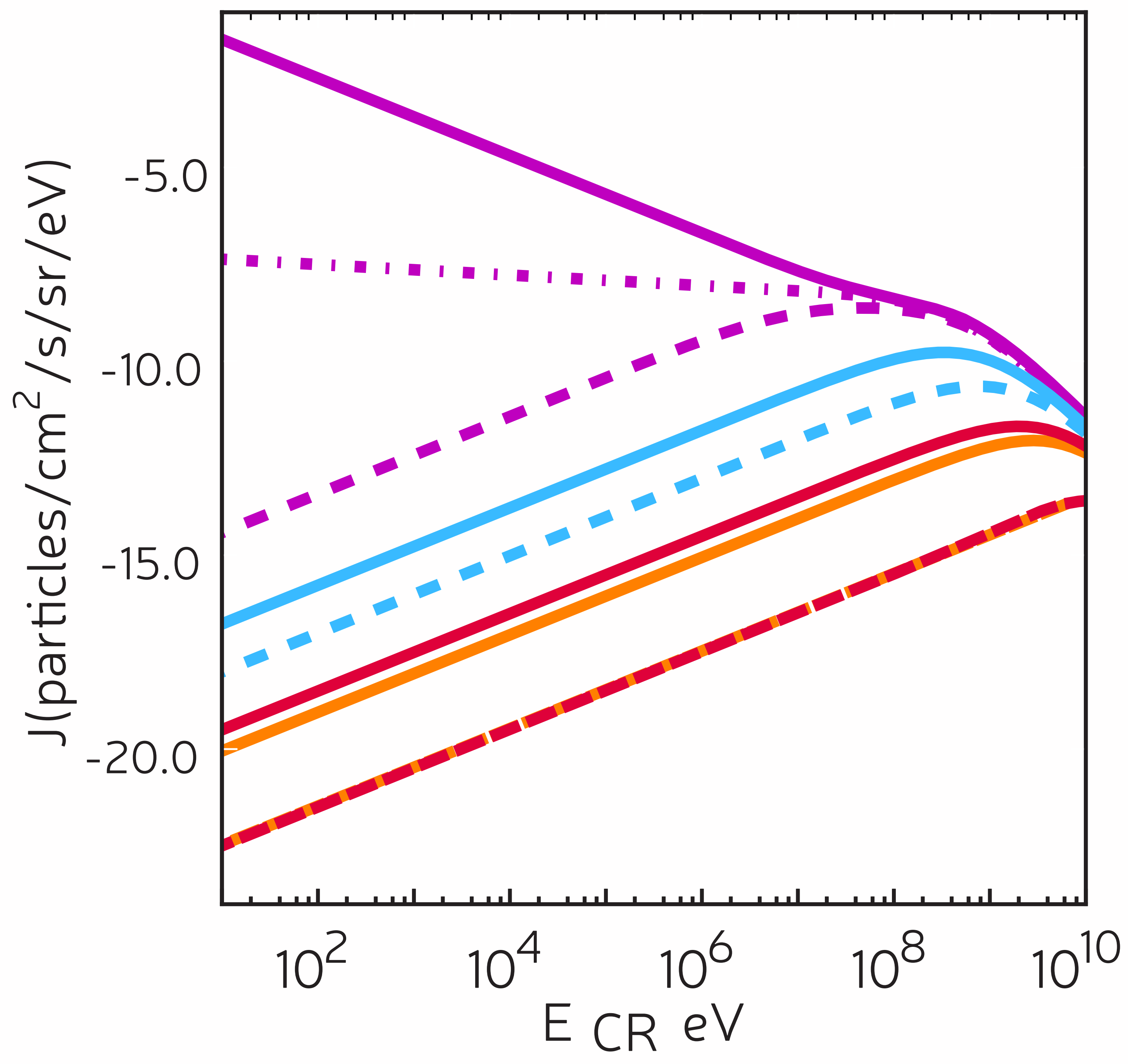
HD traces the otherwise invisible H_2 reservoir, best gas mass tracer available.

Cleeves, Bergin, Qi, Adams+ 2014b (in prep.)

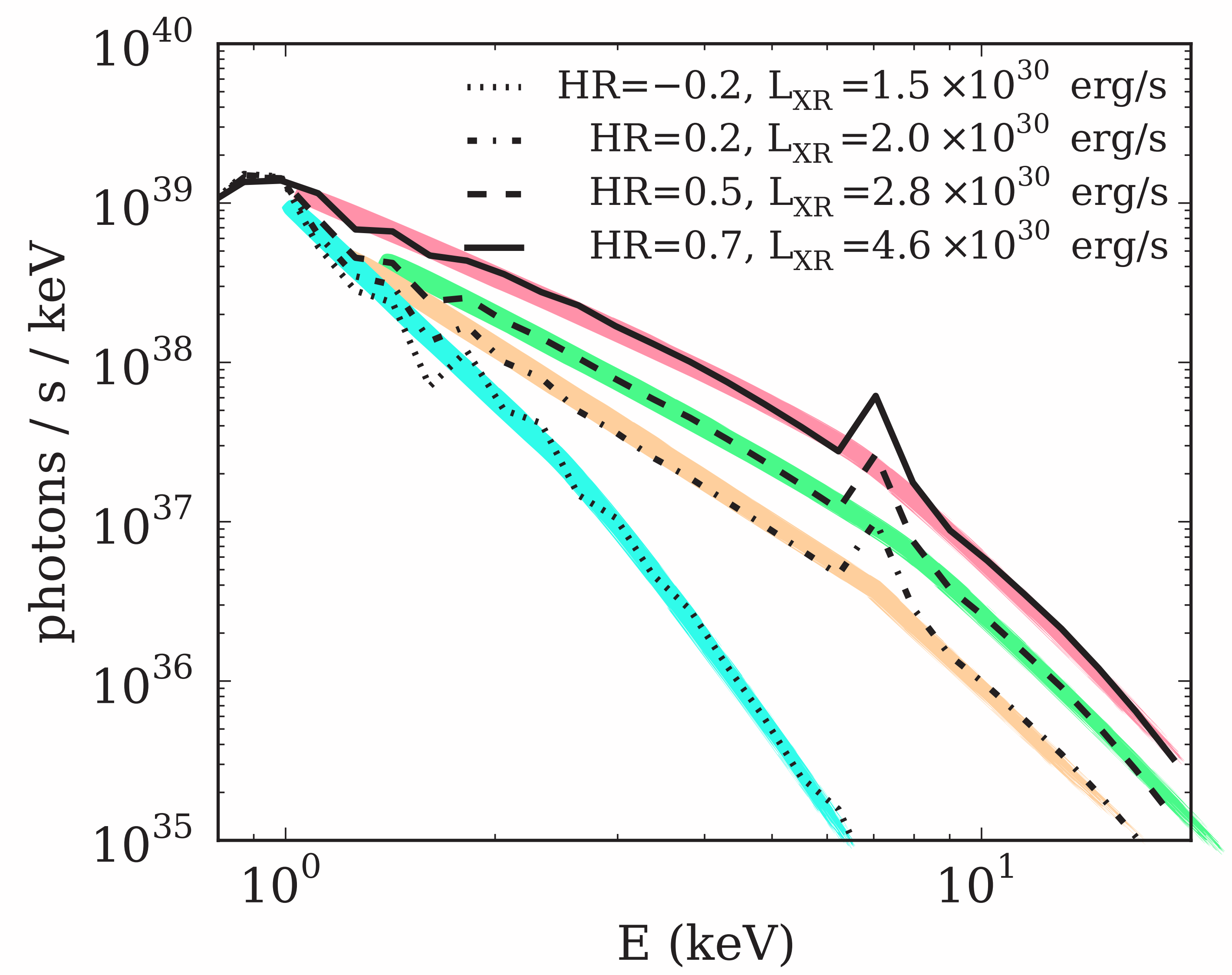


Increasing CR Ionization
HCO+
(4-3)
(3-2)
(1-0)
(3-2)
(4-3)
(4-3)
(3-2)
H13CO+
N2H+
M02
0.0/0.7
0.0/0.7
0.0/0.9
W98
0.3/0.5
0.2/0.5
0.0/0.7
0.0/0.9
SSM
0.7/0.5
0.5/0.5
0.3/0.7
0.2/0.8
SSX
0.7/0.5
0.8/0.6
0.5/0.7
0.2/0.8
TTM
0.2/0.5
0.8/0.6
0.5/0.7
0.2/0.8
-0.2
0.2
0.5
0.7
Increasing Hard X-ray Flux

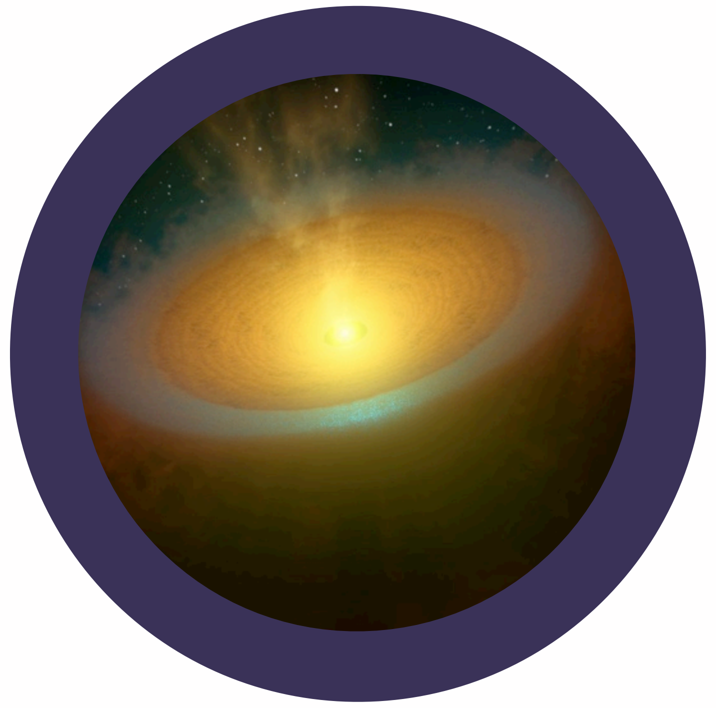




CR Models from Cleeves +2013a.



XSPEC Models Based on Kastner+ 1999, 2003. Cleeves (in prep).

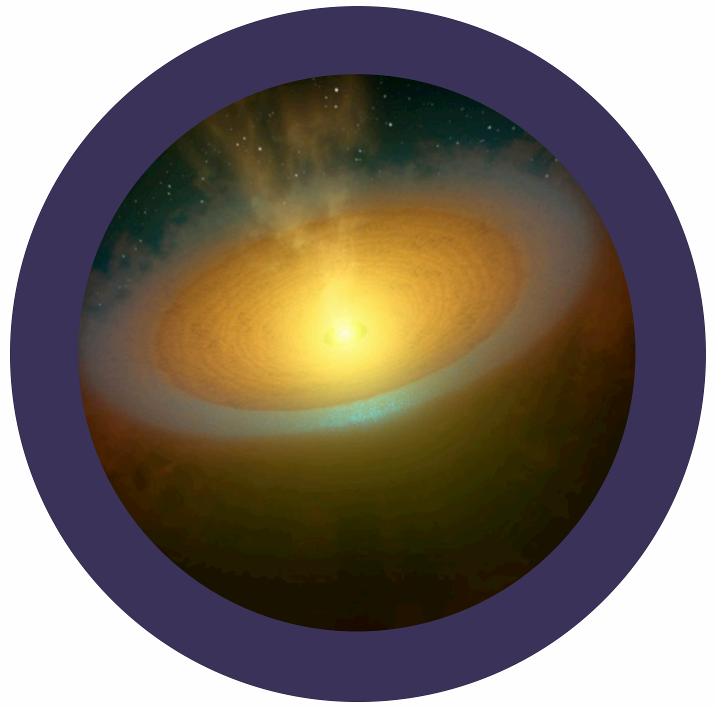


TW Hya

A lab for CR exclusion mechanisms

With careful modeling of the joint ionization contribution due to X-rays and cosmic rays with a well-calibrated physical model, the CR ionization rate from N_2H^+ in TW Hya is **very low**:

$$\zeta_{CR} \lesssim 10^{-19}\ s^{-1}.$$

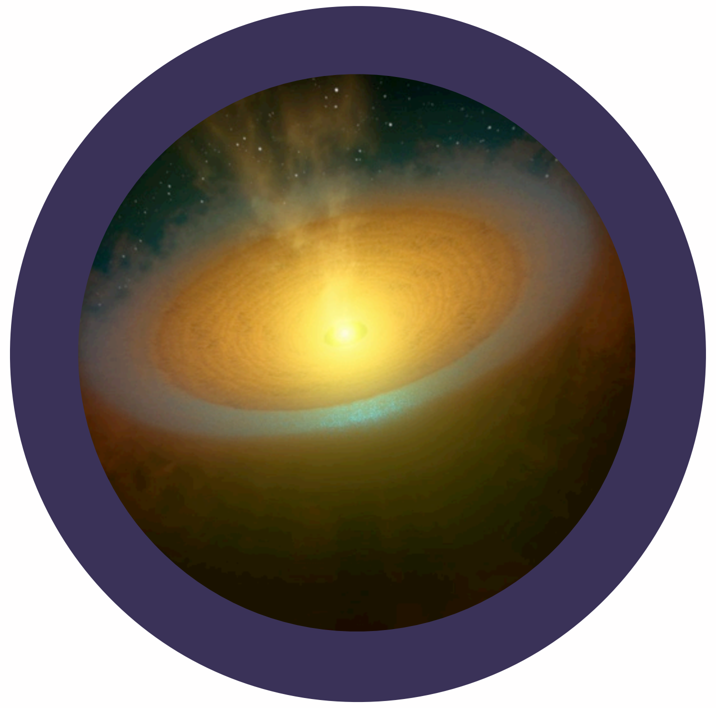


TW Hya

A lab for CR exclusion mechanisms

Possible Scenarios, $\zeta_{H2} \lesssim 10^{-19}$ s^{-1}

1. **Stellar winds** block CRs across the entire disk. The T-Tauriosphere would have to extend well beyond R>200 AU.
   - Ram pressure is enough to exceed the ambient interstellar pressure.
   - But what if winds are collimated by stellar or disk B fields?
2. **Magnetic irregularities** in the disk as a source of local "opacity" to CRs (Dolginov & Stepinski 1994, Padovani+2013).
   - Irregularities are generated by turbulence (requiring ionization). Are they the chicken or the egg?
3. **Short-Lived Radionuclides** have the right order of magnitude.
   - Disk is too old (10 Myr) ➠ no SLRs left. No massive stars nearby to replenish.



TW Hya

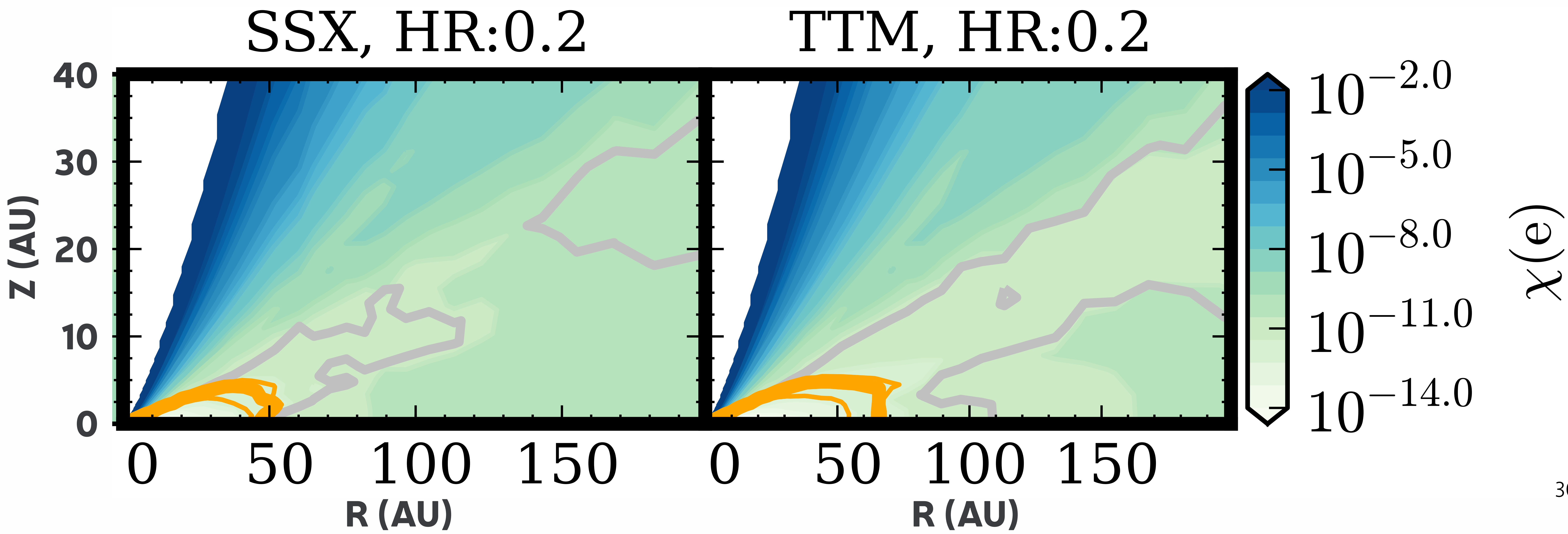
Turbulence and/or dead zones?

1. Regardless of one's favorite explanation, it is clear that CRs are *not present at the interstellar level*.

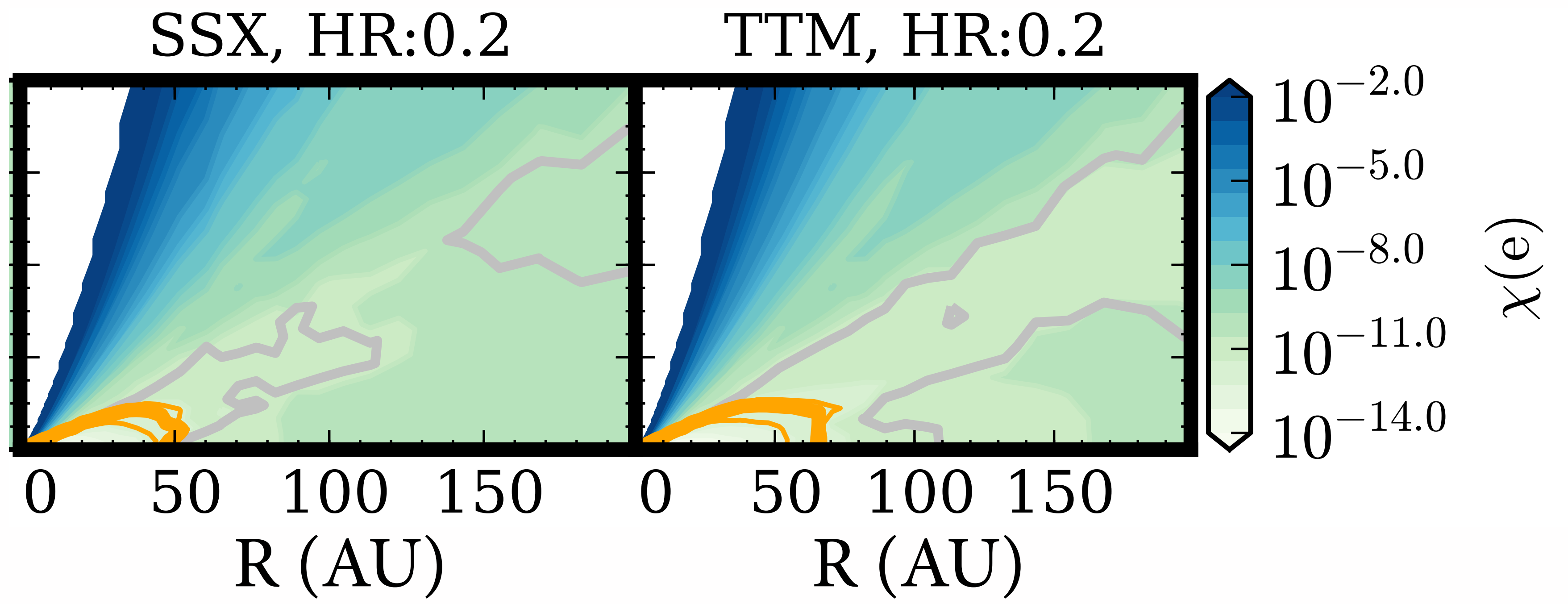
2. We can use the ion abundances (from the electron abundance) to estimate the approximate size of TW Hya's **dead-zone.**

MAPPING IONIZATION IN THE TW HYA DISK:
DEAD ZONES

1. **Orange:** Dead zone determined from the magnetic *Re* number.
   - Bold line is the "critical" value, 3300 (PBC2011).
   - Thin lines correspond to the range of reasonable values typically assumed (*Re*~1000-5000).
2. **Gray:** *Am*-criteria (depends on B-field).
3. *Re*-determined dead zone for the best fit ionization models encompasses the inner disk midplane out to **R~50-65 AU.**



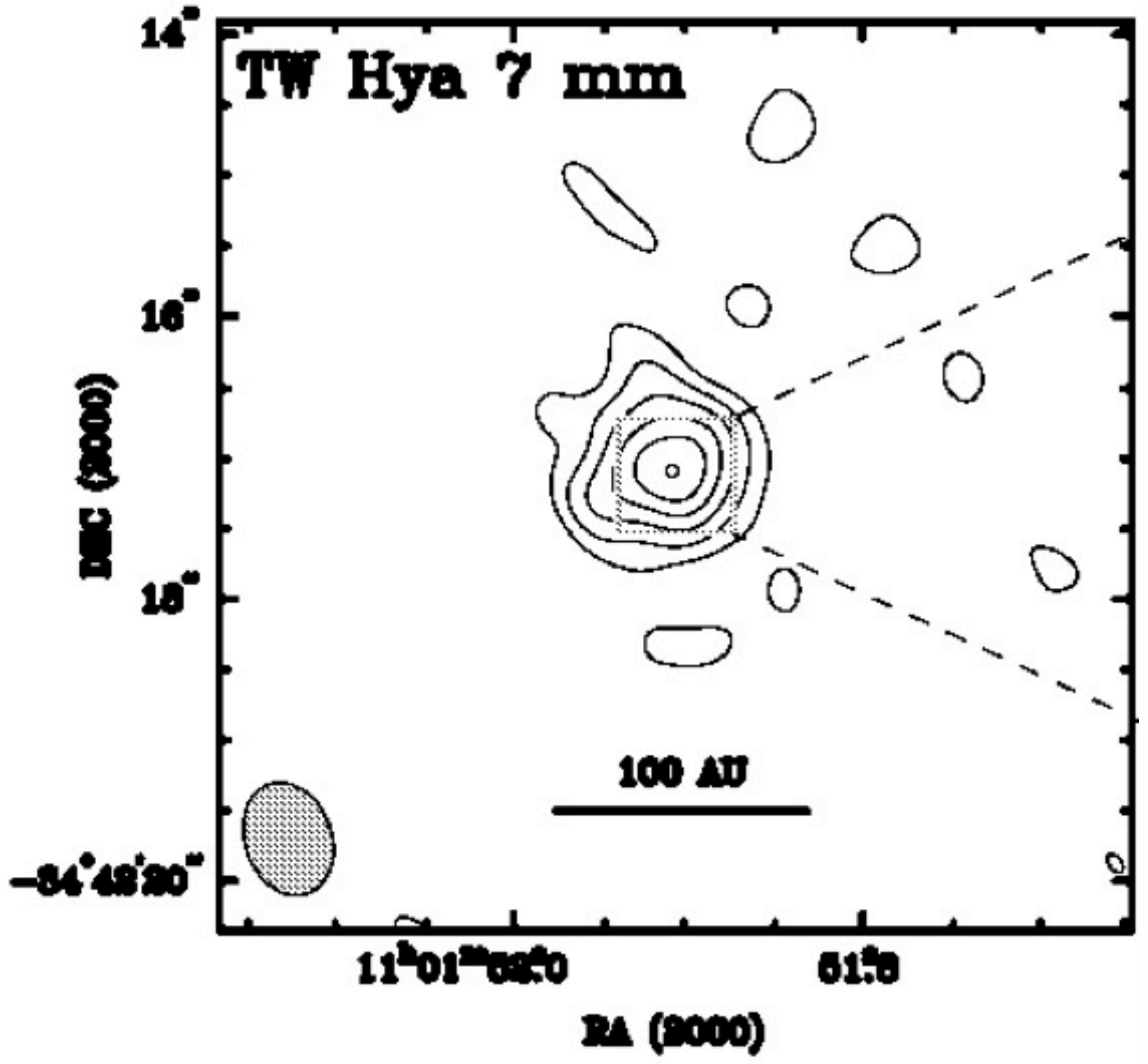
MAPPING IONIZATION IN THE TW HYA DISK



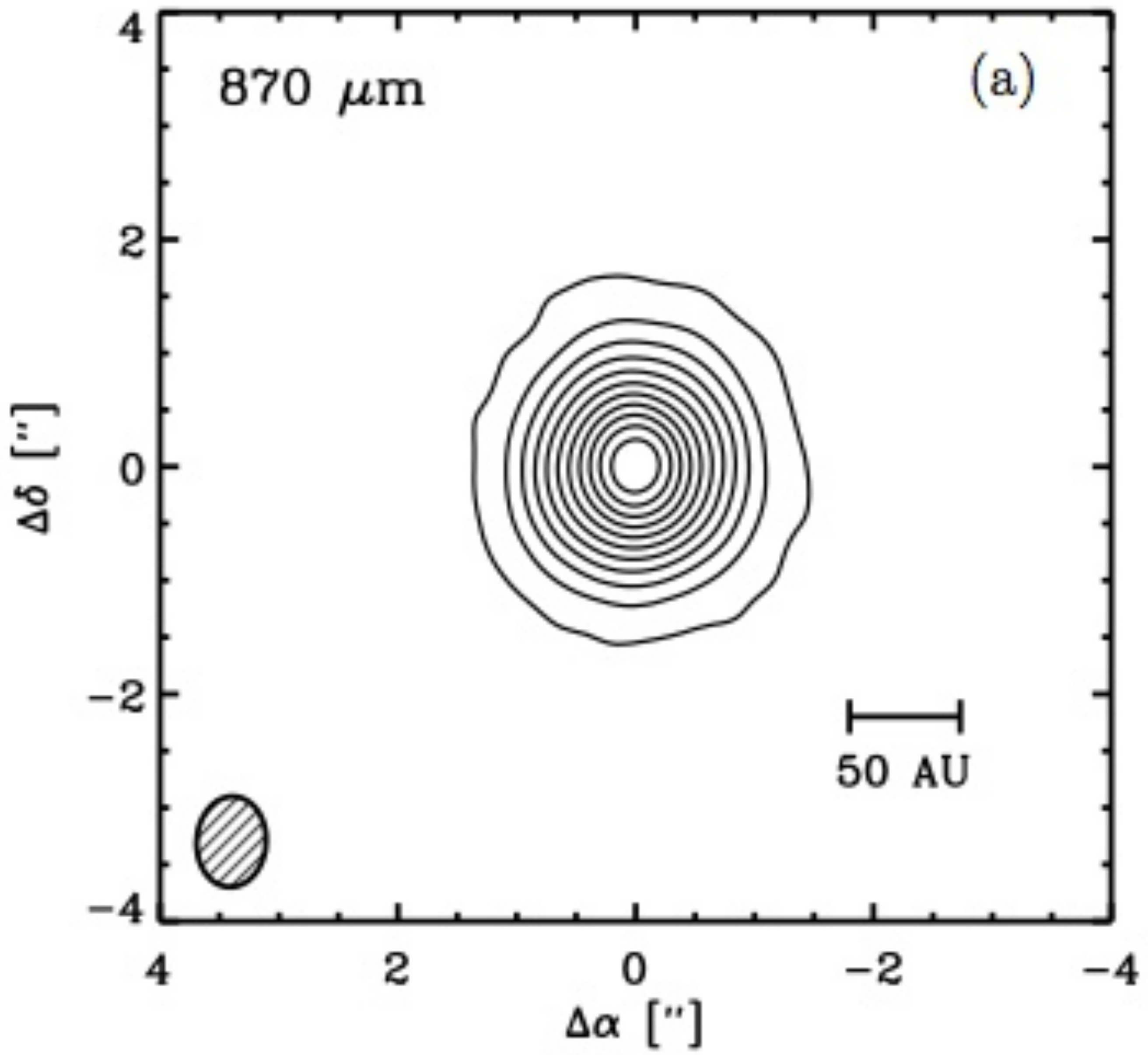
Large grains are known to be substantially concentrated relative to the gas and smaller micron sized-grains.

- 3.8 cm unresolved in a 1” beam (55 AU or *R*~27 AU) (Wilner+2000)
- Resolved images of 7 mm (Wilner +2000) and 0.87 mm (Andrew +2012) show large dust out to *R*=50-60 AU.
- **Perhaps dust coagulation is being facilitated by a dead zone out to 65 AU?**

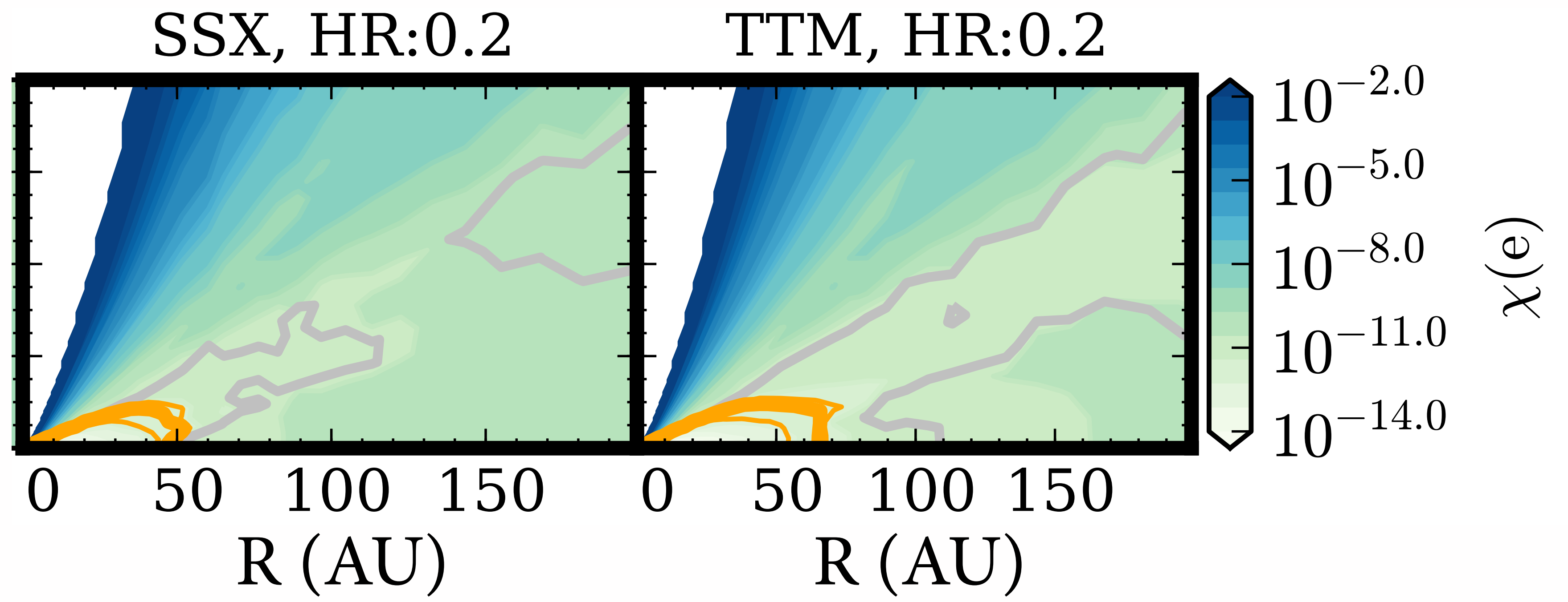
- (Wilner+2000)



- (Andrews+2012)



MAPPING IONIZATION IN THE TW HYA DISK



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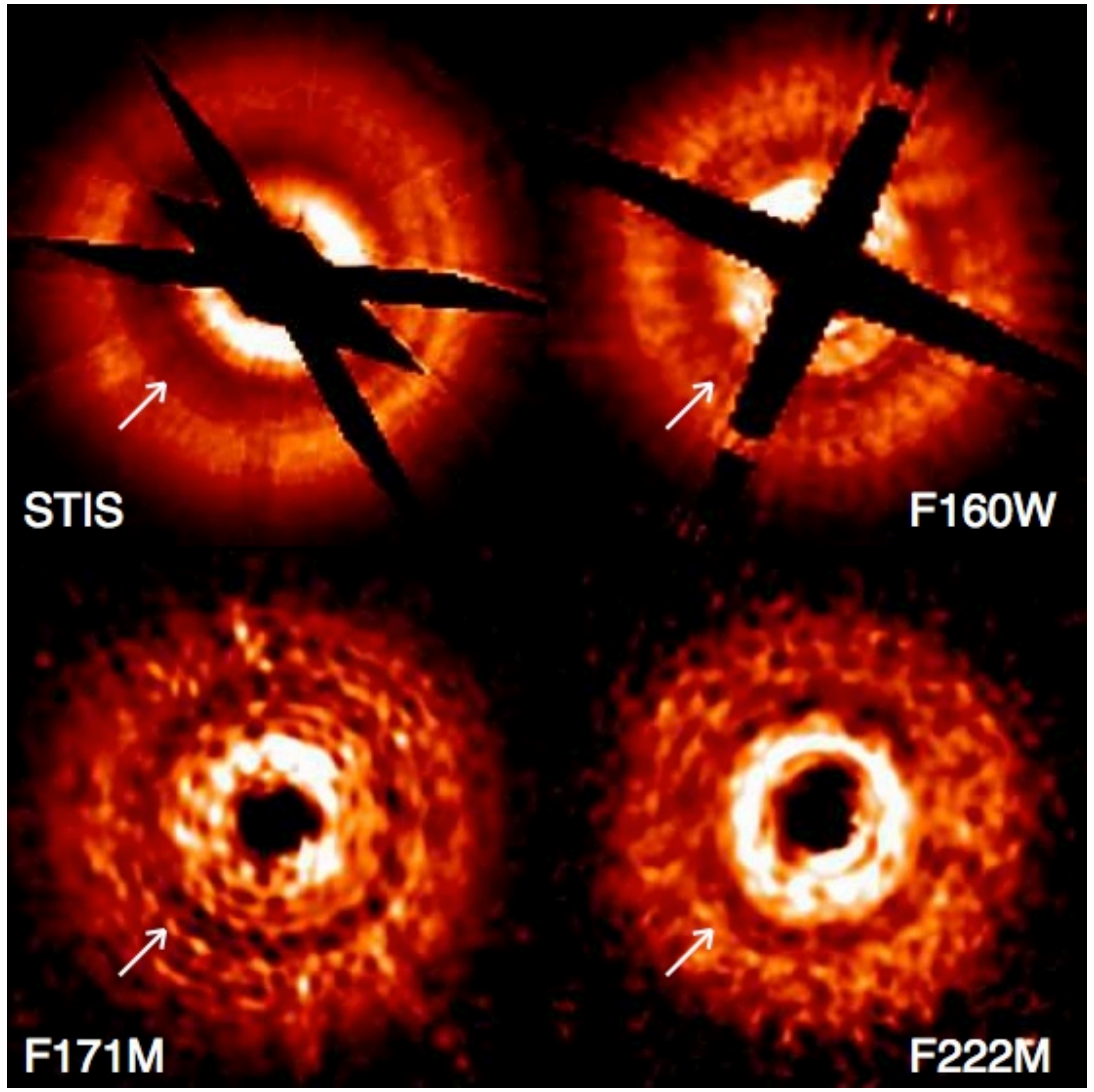

- (Debes+2013)

Gap or dust depression at R~80 AU.

Edges of dead zones may facilitate planet growth (Drazkowska +2013).

CONCLUSIONS

1

Understanding the ionization environment of PPD **is important** for informing models of disk physics and chemistry.

2

Winds and/or magnetic fields may actively **modulate the CR flux** in the disk.

Without CRs, SLRs or X-rays are the primary midplane ionizer.

3

CRs (and all types of ionization) imprint signatures on the chemistry **detectable in submillimeter emission.**

4

Detailed modeling of TW Hya already points to **low CR rates** ($\zeta_{CR} \lesssim 10^{-19}$ s^{-1}). Coincides with region of known dust growth.

Thanks for your attention!