Disk-ionization properties as revealed by molecular emission

Ilse Cleeves

Hubble Fellow, SAO/CfA/ITC

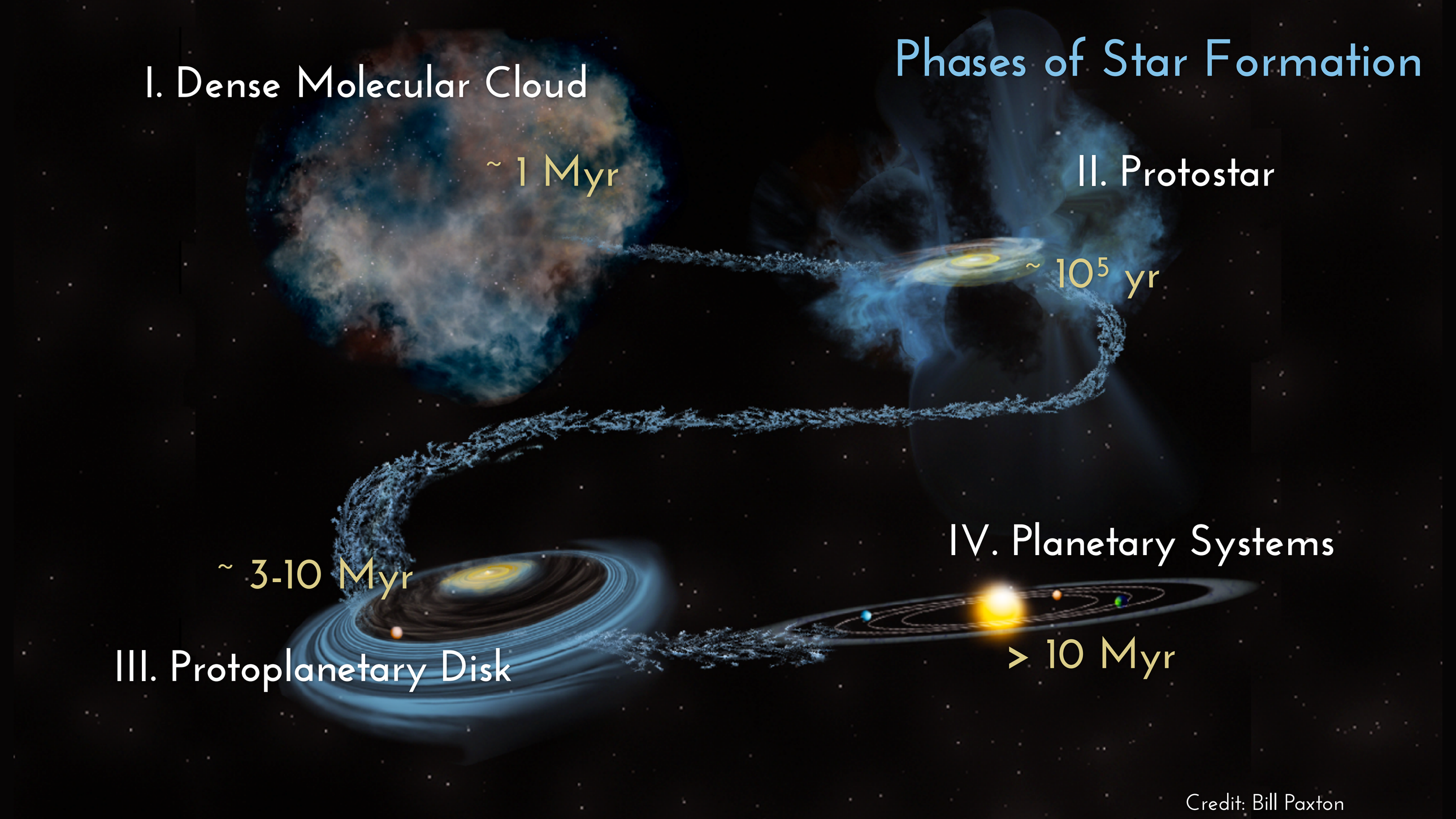
With many thanks to my colleagues at **Michigan:** *Ted Bergin, Fred Adams,* **CfA:** *Karin Öberg, David Wilner, Charlie Qi, Sean Andrews, Ryan Loomis, Jane Huang*

KITP: Confronting MHD Theories of Accretion Disks with Observations

February 6th, 2017

Image Credit: University of Copenhagen/Lars Buchhave

Phases of Star Formation



Credit: Bill Paxton

The Key Role of Ionizing Processes

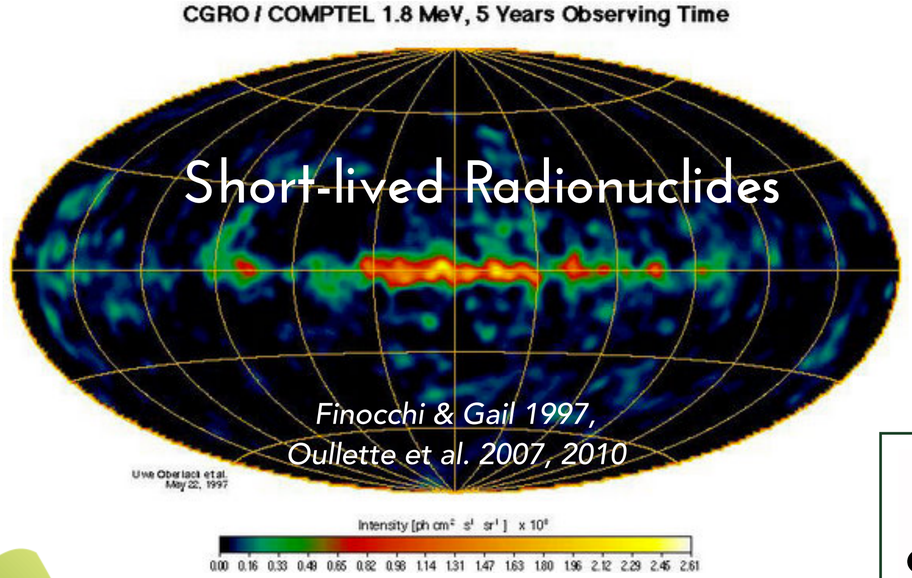
- The ionization regulates the *active chemistry (both gas and ice!)* and *environmental conditions (temperature, coupling to B-fields)* during planet formation.

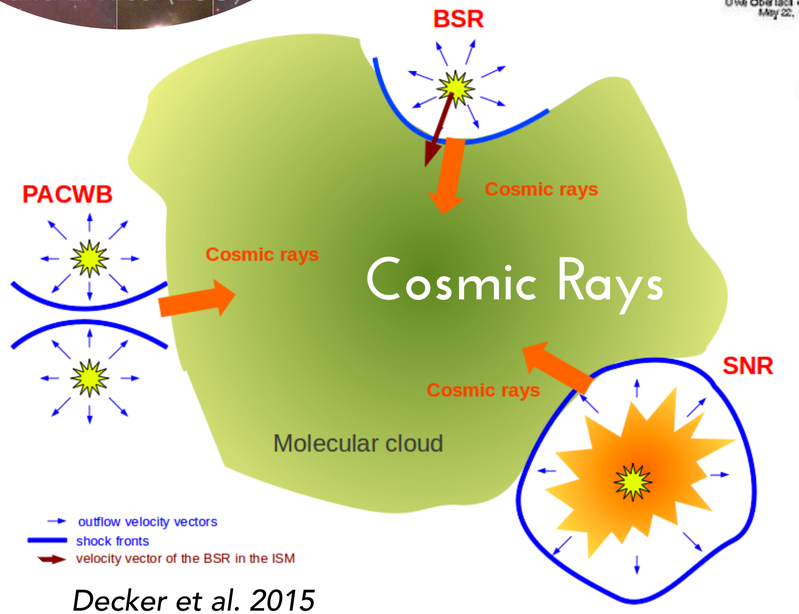
- "High energy" ionization: H_2 and He Ionization sources include X-rays, cosmic rays (CRs) and radionuclides (SLRs).

- Large gradients in overall ionization rates and a high degree of spatial variation.

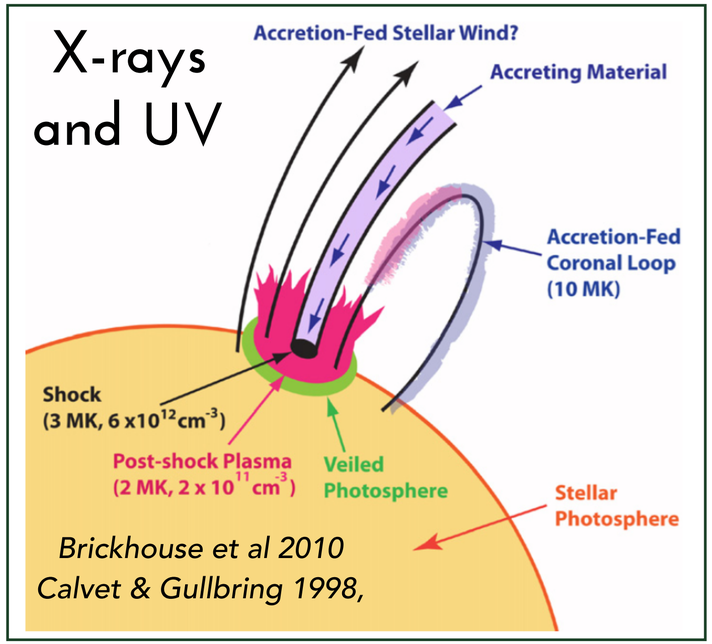
(e.g., Carballido+2008, Johansen+2007, Matsumoro & Pudritz 2005, 2007, Charnoz+2012, Gressel+2012)

IONIZATION STATE IS A KEY PHYSICAL PARAMETER OF THE DISK, AND THERE ARE BOTH INTERNAL AND EXTERNAL FACTORS

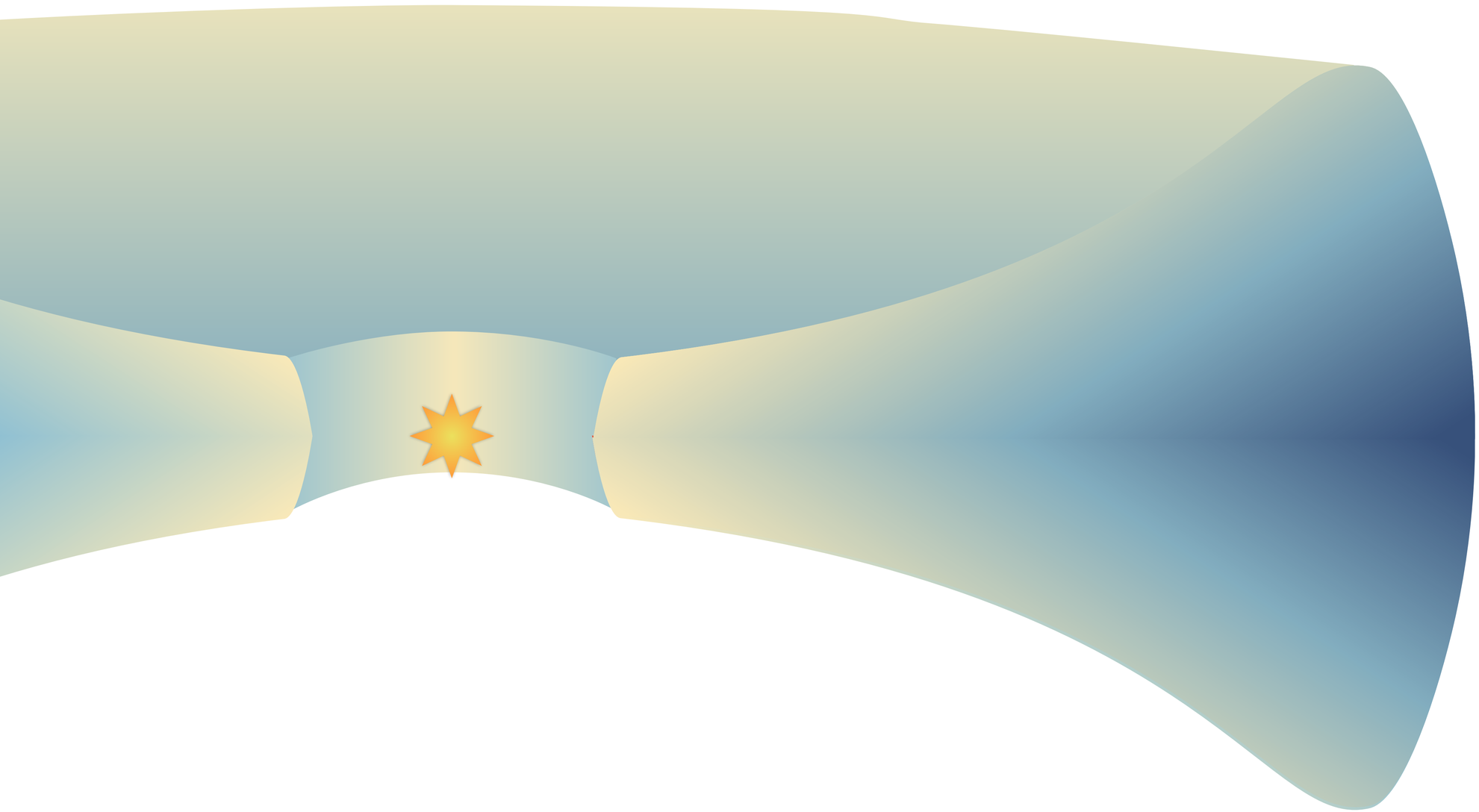




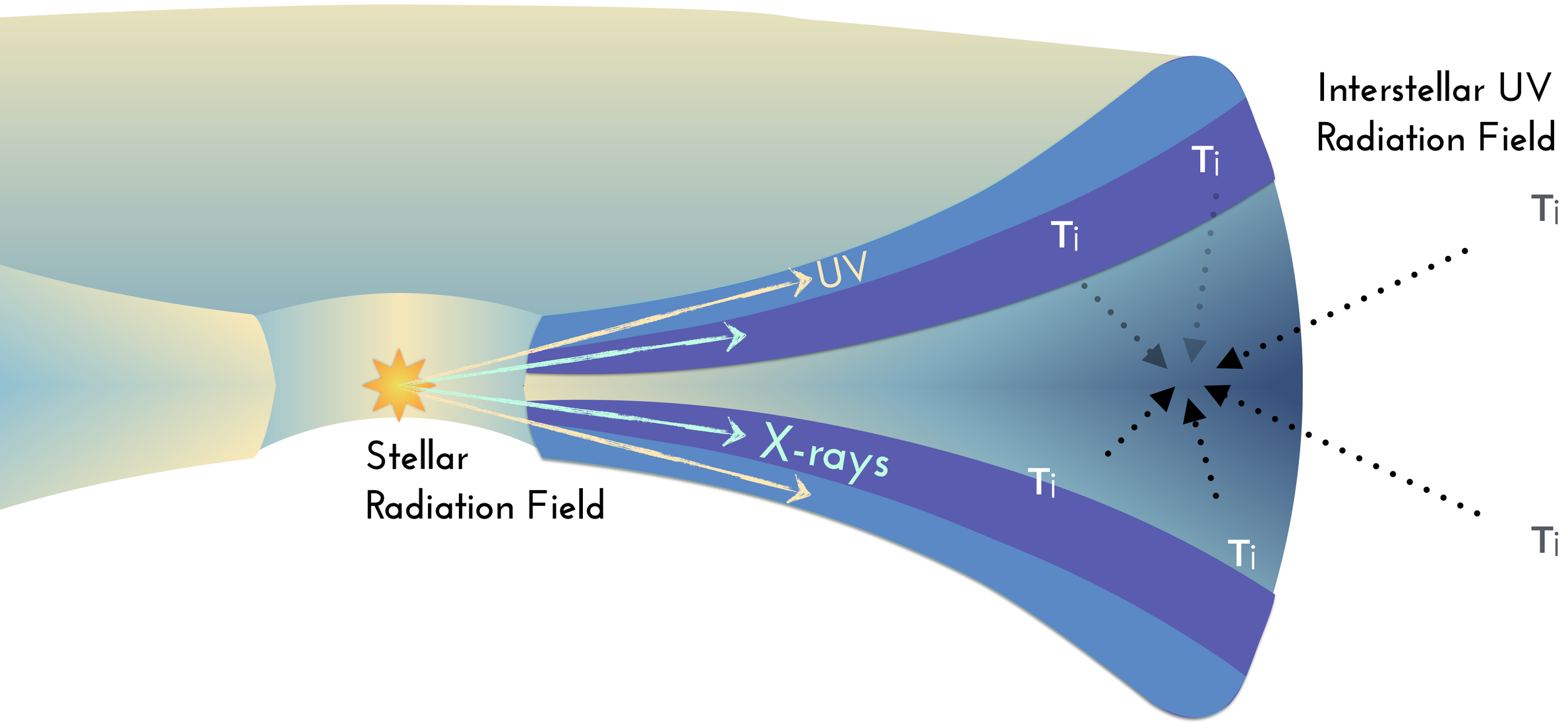
Decker et al. 2015



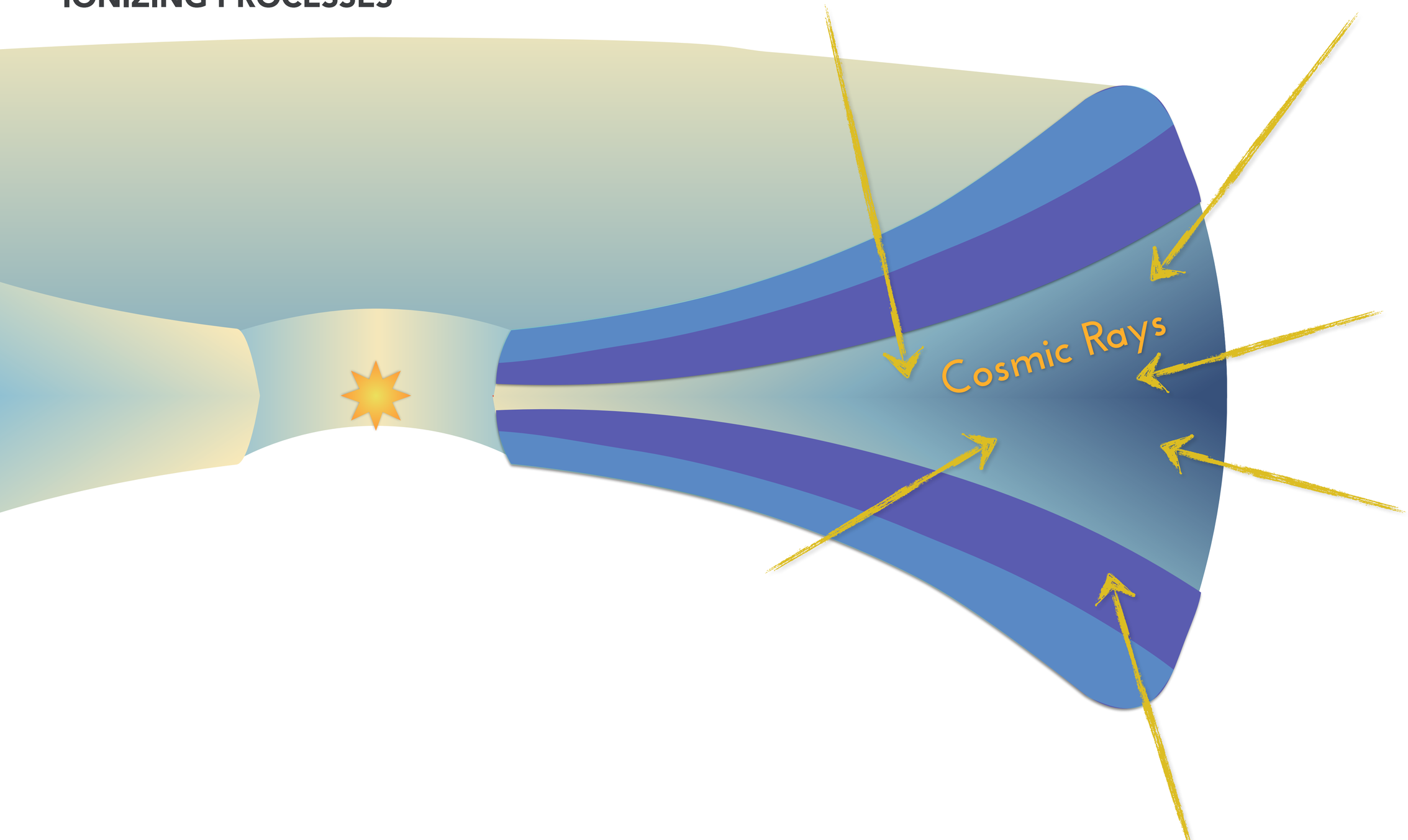
IONIZING PROCESSES



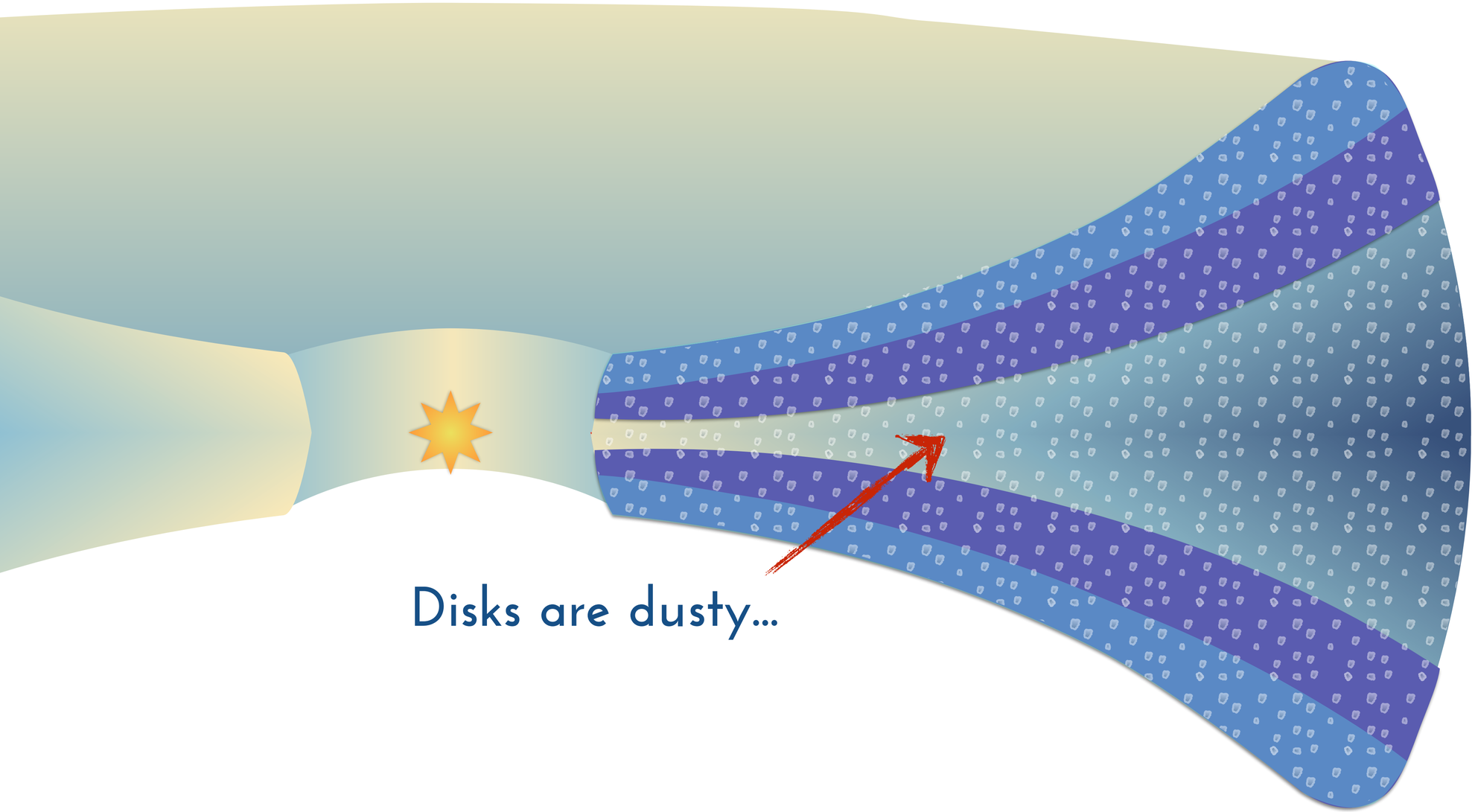
IONIZING PROCESSES



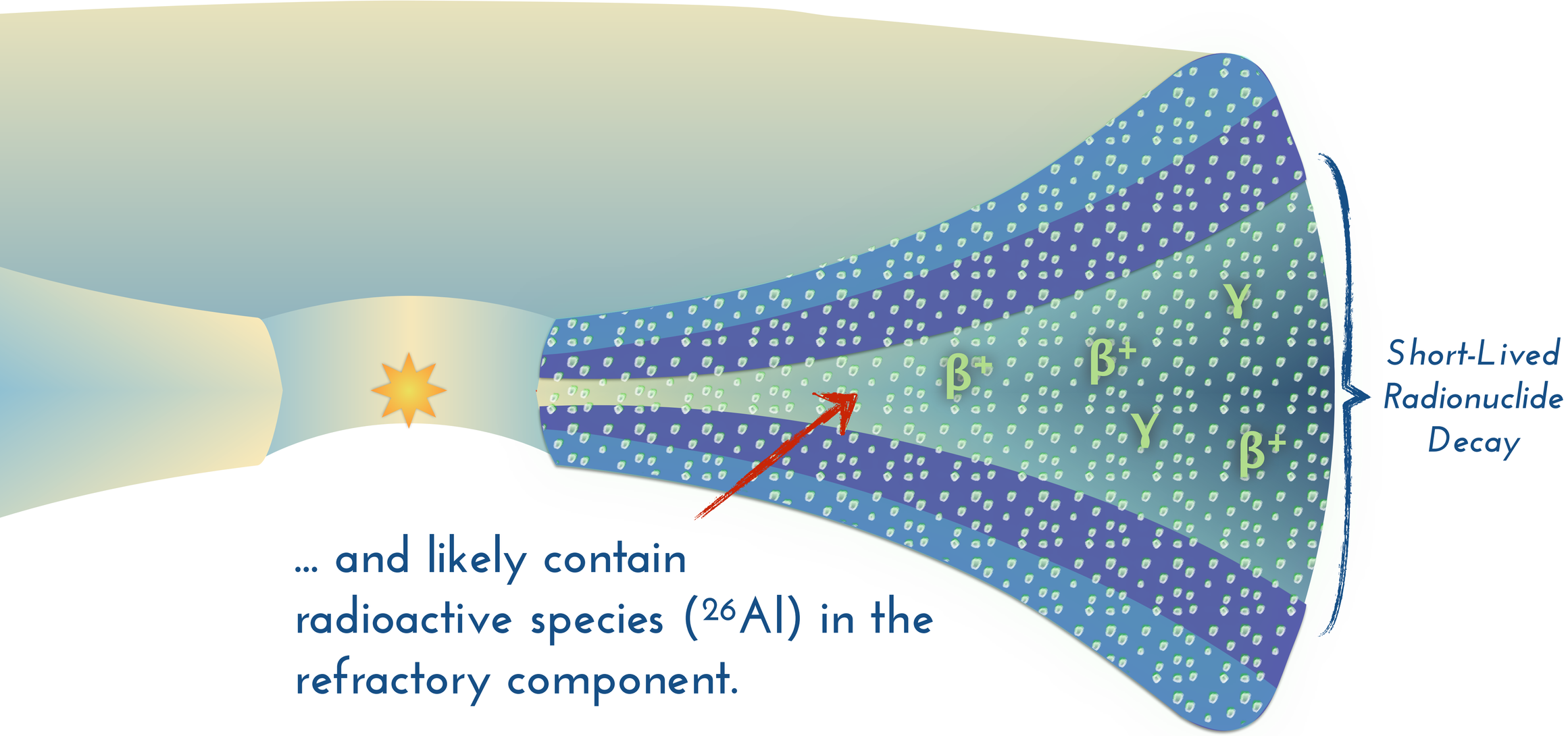
IONIZING PROCESSES



IONIZING PROCESSES

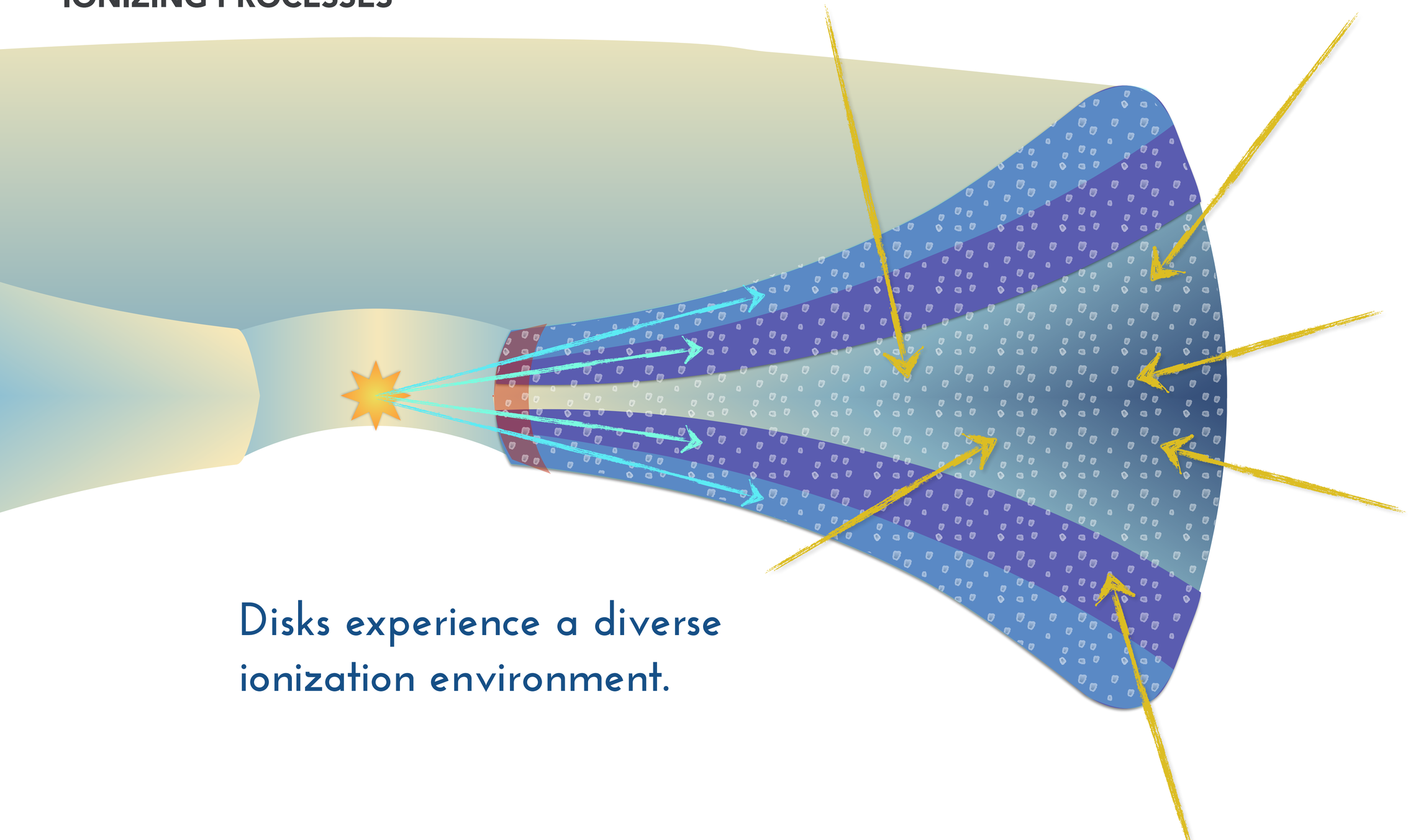


IONIZING PROCESSES



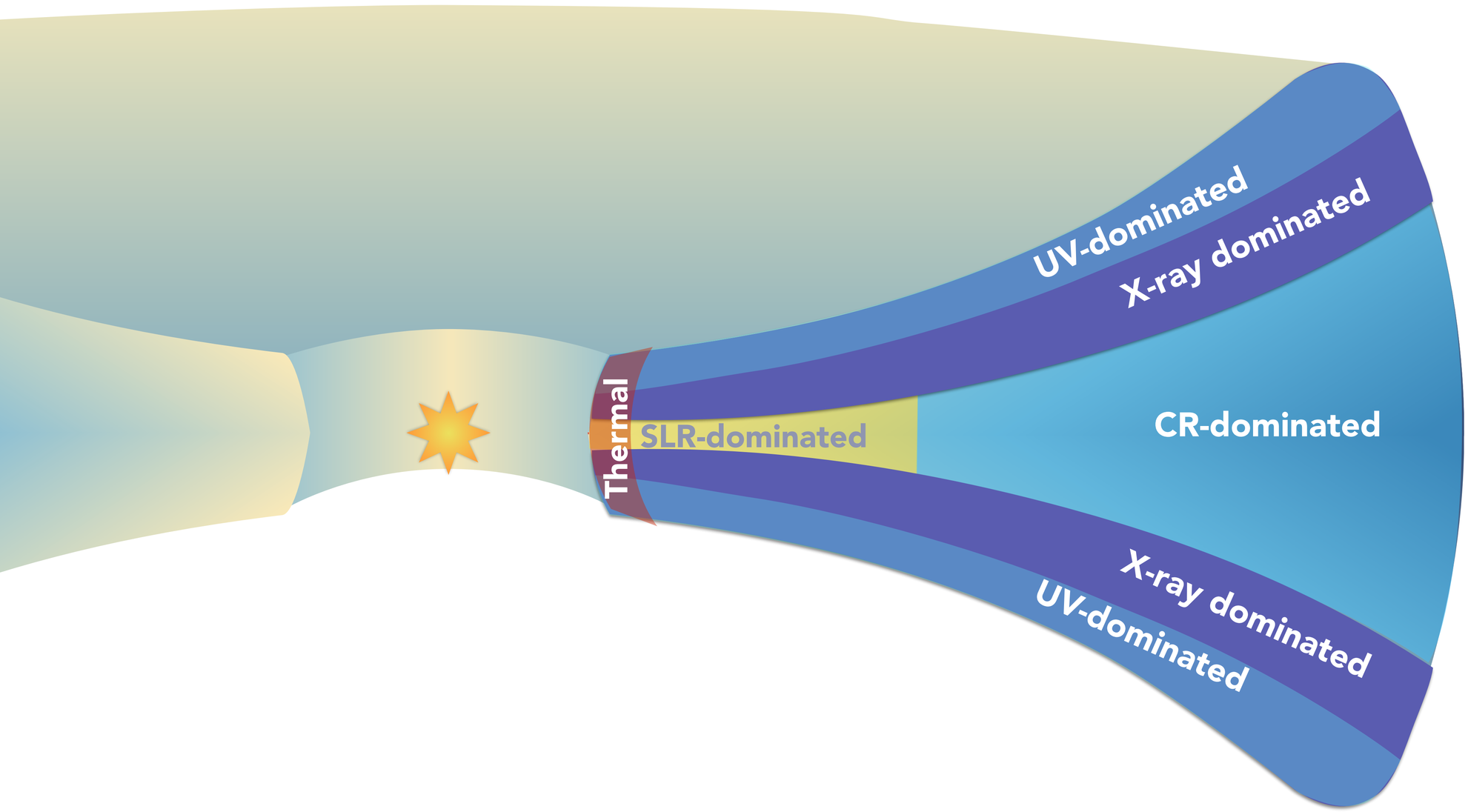
... and likely contain radioactive species (^{26}Al) in the refractory component.

IONIZING PROCESSES

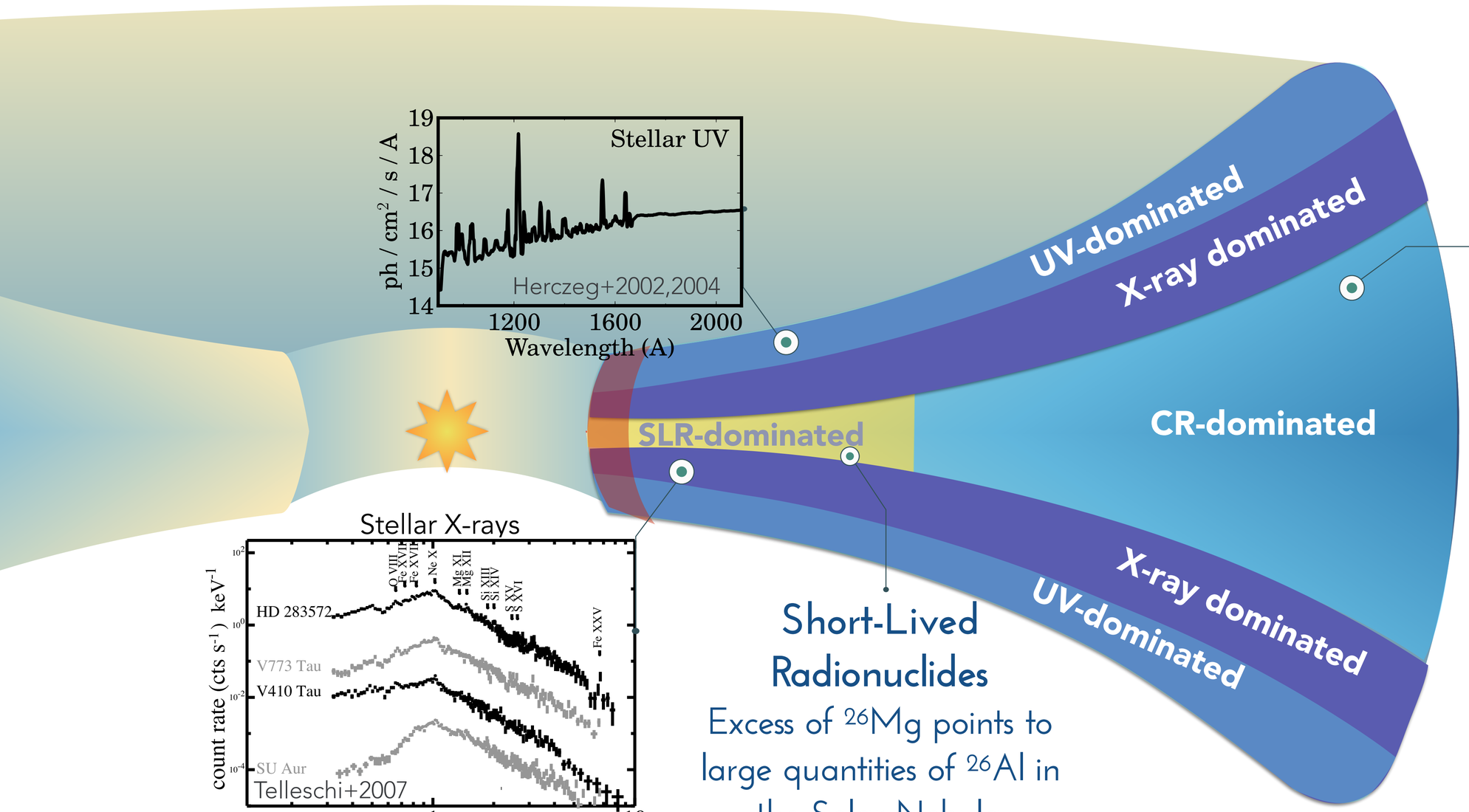


Disks experience a diverse ionization environment.

IONIZING PROCESSES



IONIZING PROCESSES



Cosmic Ray

Ionization in Disks:

Largely unconstrained

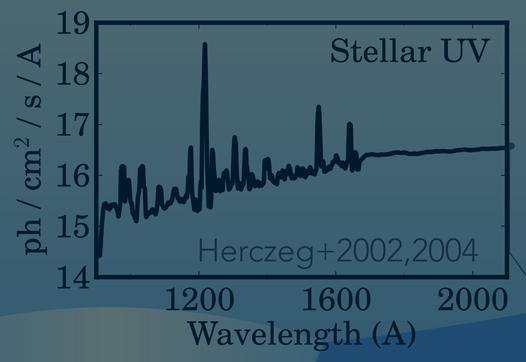
Short-Lived Radionuclides

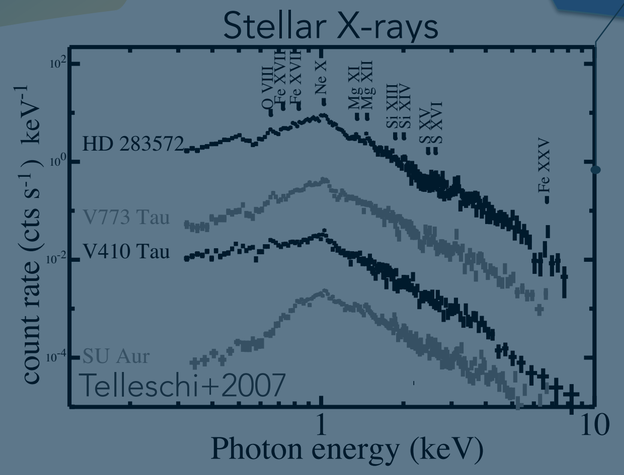
Excess of ^{26}Mg points to large quantities of ^{26}Al in the Solar Nebula.

But what is "typical?"

See also Jura & Young 2013.

IONIZING PROCESSES





UV-dominated

X-ray dominated

SLR-dominated

CR-dominated

X-ray dominated

UV-dominated

Cosmic Ray

Ionization in Disks:

Largely unconstrained

The main ionization sources in the disk midplane are highly uncertain.

Short-Lived Radionuclides

Excess of ^{26}Mg points to large quantities of ^{26}Al in the Solar Nebula.

But what is "typical?"

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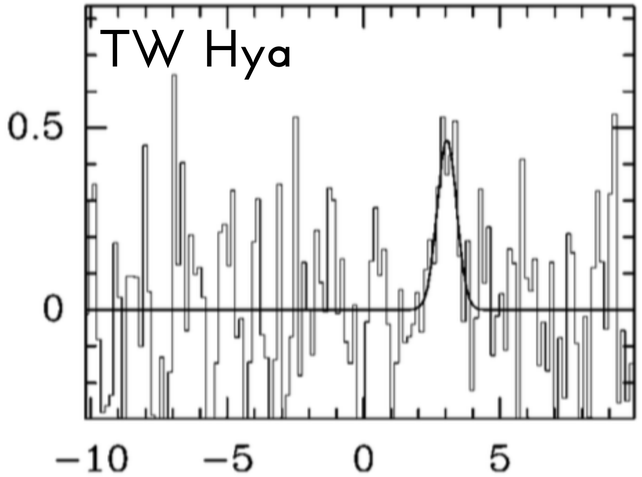
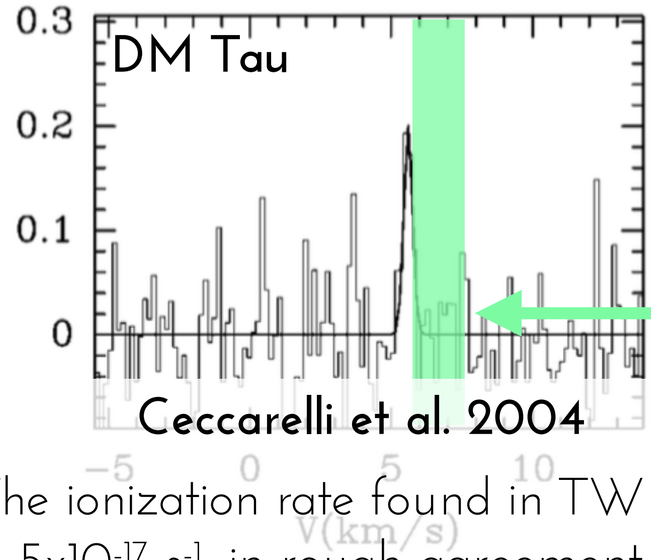
PREVIOUS OBSERVATIONAL STUDIES OF DISK IONIZATION



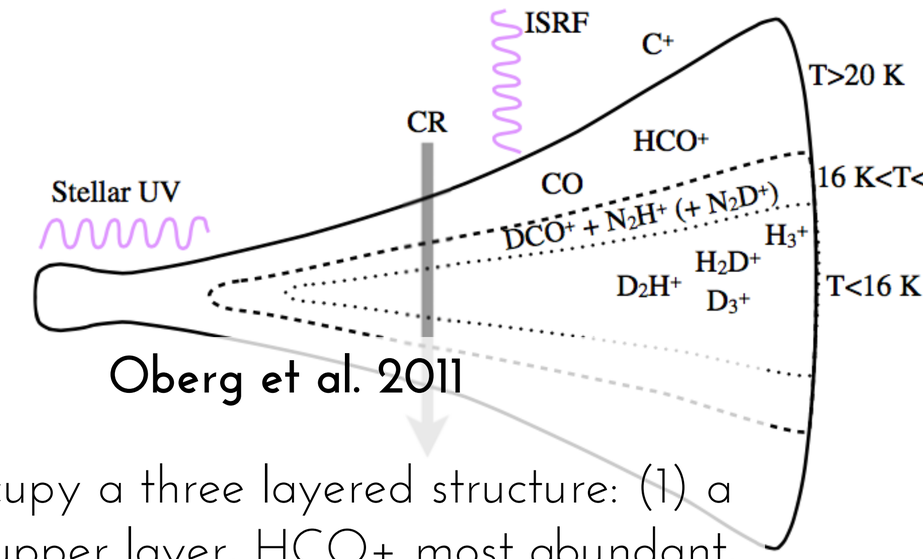


Ceccarelli et al. 2004

Guilloteau et al. 2006

The "line" is in the wrong place!

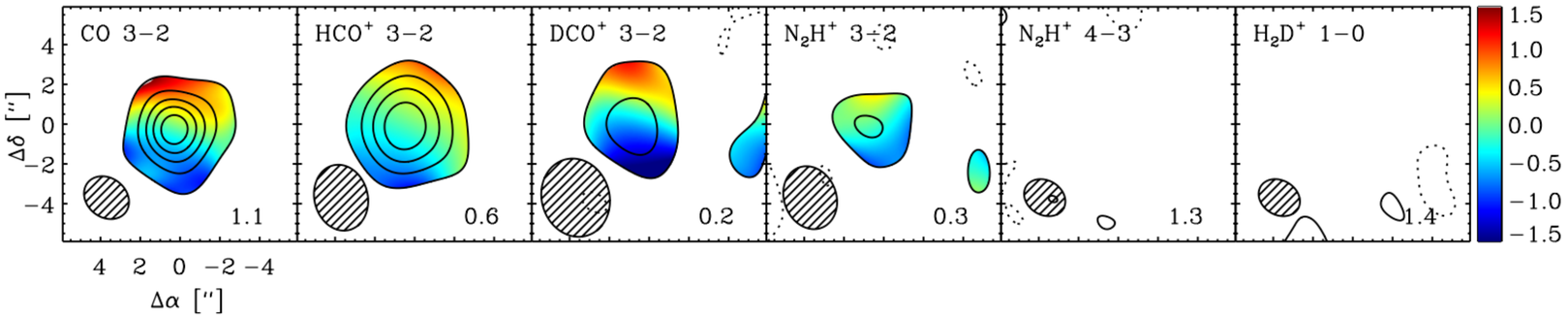
"We also show that the detection of H_2D^+ in DM Tau, previously reported by these authors, is only a 2-sigma detection when the proper velocity is adopted."



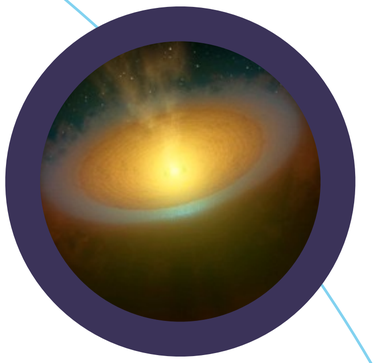
Oberg et al. 2011

Ions occupy a three layered structure: (1) a warm, upper layer, HCO+ most abundant, xi ≃ 4×10−10 ; (2) a cooler molecular layer with T = 16-20 K, N_2H^+ and DCO^+ abundant, with xi ≃ 3×10−11; and (3) the cold midplane (T<15 K) where H_3^+ abundant and xi < 3×10−10.

The ionization rate found in TW Hya is 5×10^{-17} s^{-1}, in rough agreement with the canonical value ~3×10^{-17} s^{-1} (e.g., Webber et al. 1998), whereas it is relatively low, 1×10^{-18} s^{-1}, in DM Tau.



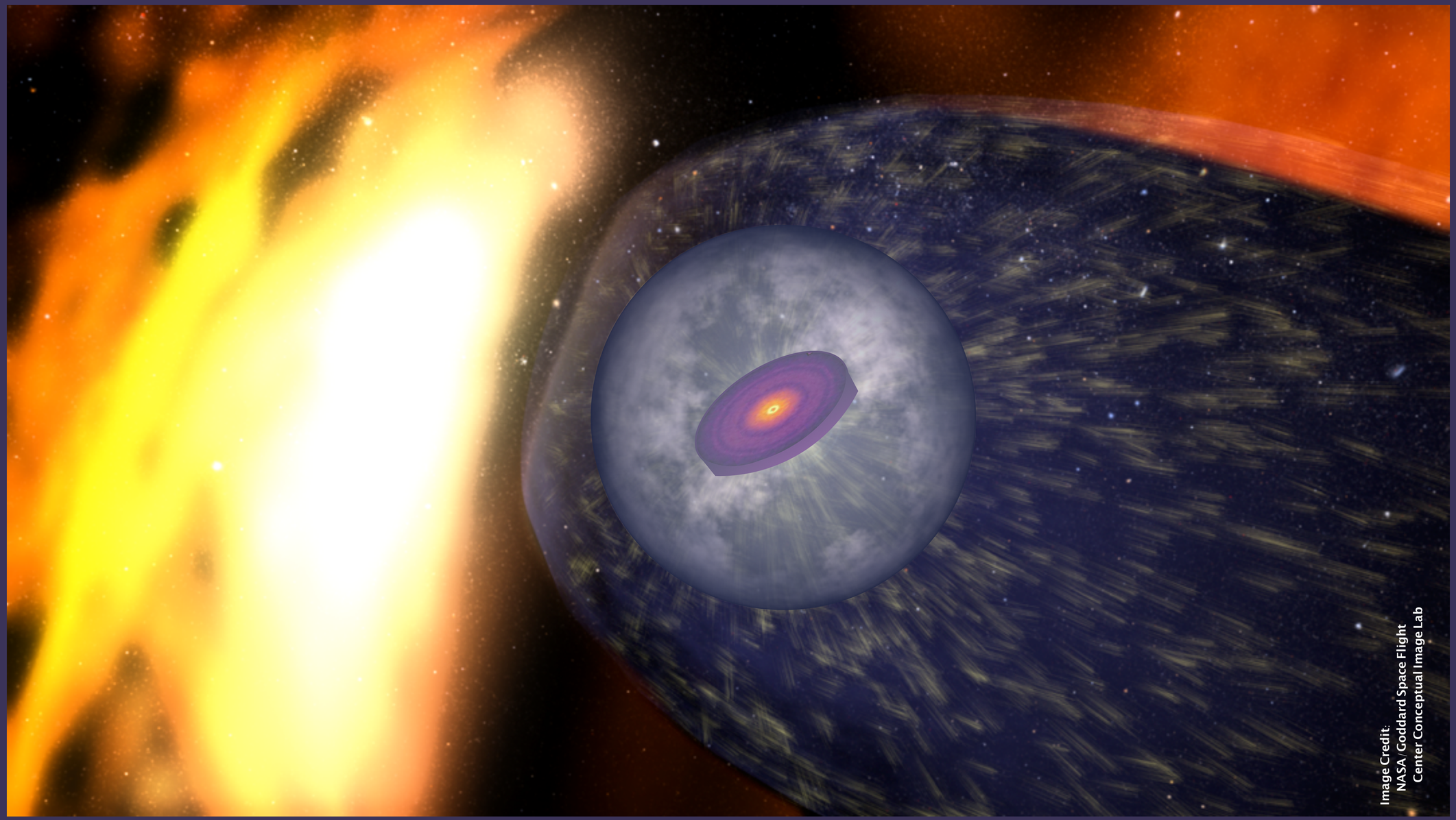
Fast forward to 2017: H_2D^+ still not detected! (Cleeves, Qi et al. in prep)



Disk Ionizing Mechanisms

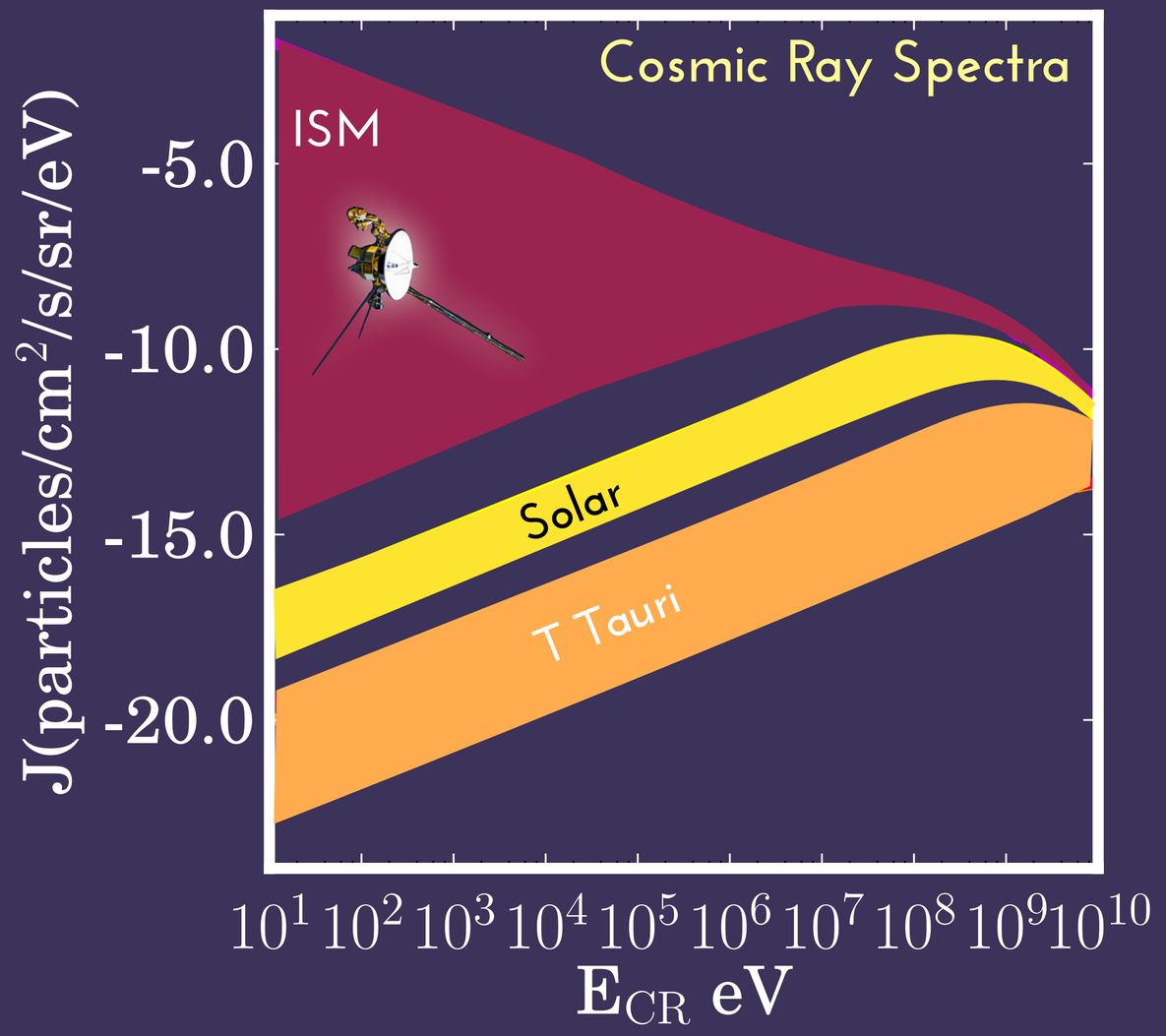
Cosmic Rays, Radionuclides, X-rays

WINDS AND THE COSMIC RAY IONIZATION RATE



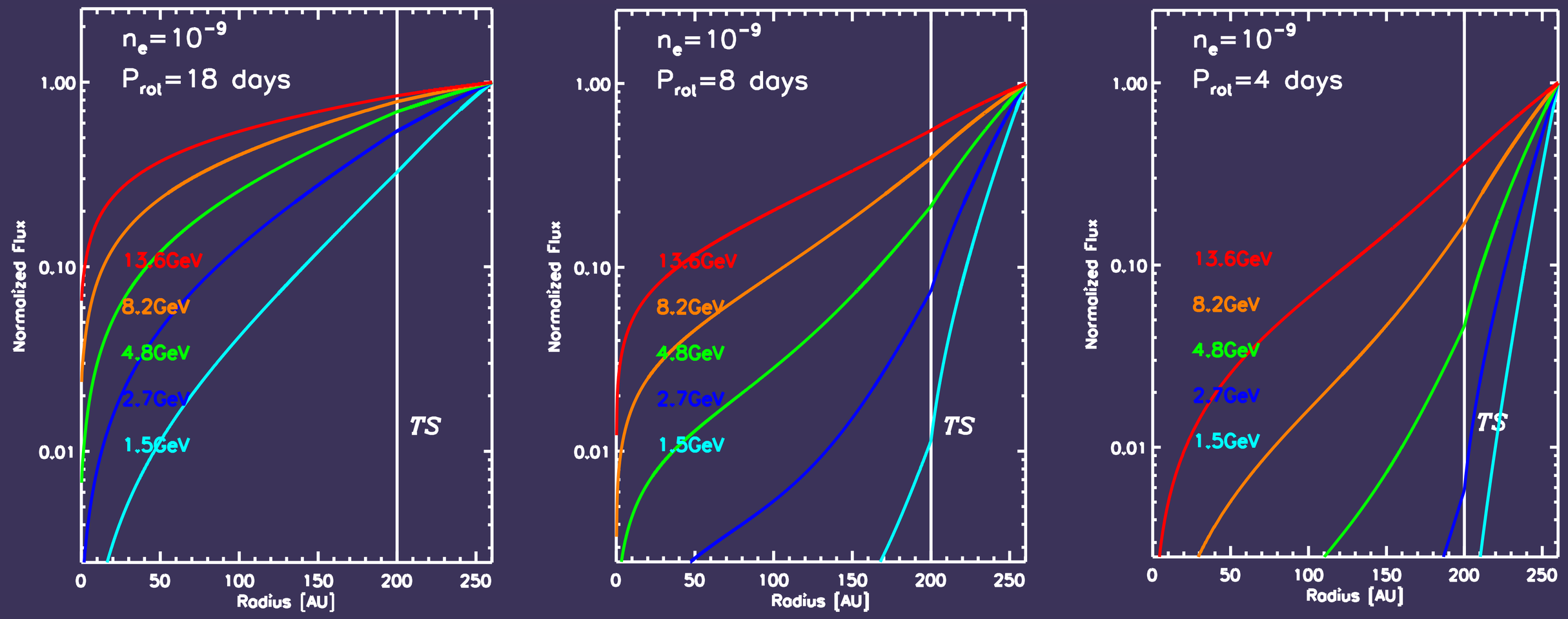
WINDS AND THE COSMIC RAY IONIZATION RATE

- The solar wind expels >99% of CRs, especially with < 100 MeV.
- T Tauri stars have winds, strong stellar and perhaps disk B-fields.
- Two sources of CR-deflection, winds and disk magnetic fields.
- Expected to substantially reduce the CR flux by OOM.



Cleeves, Adams & Bergin 2013a

WINDS AND THE COSMIC RAY IONIZATION RATE: RADIAL VARIATIONS



Calculations courtesy Jeremy Drake, CfA

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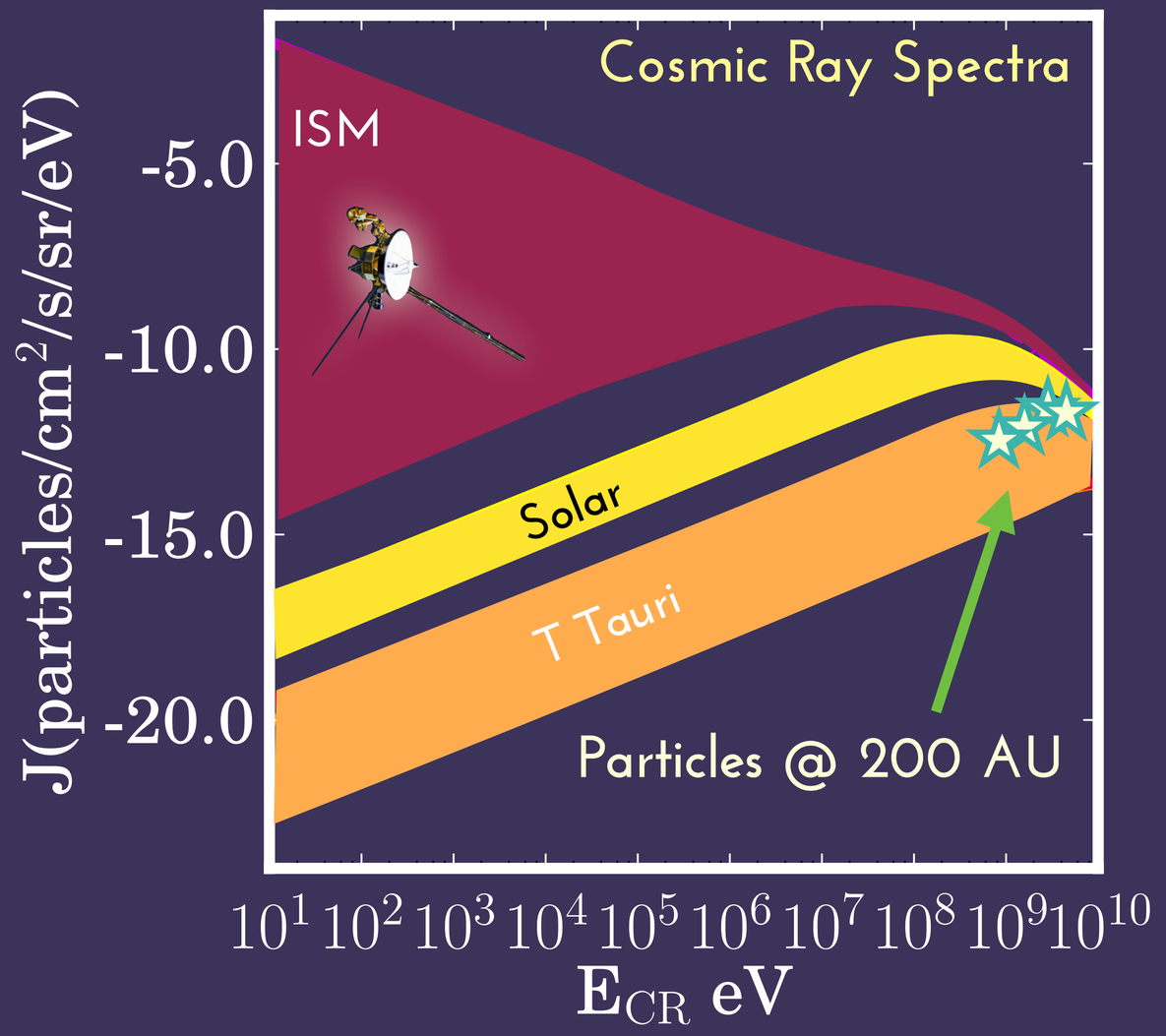
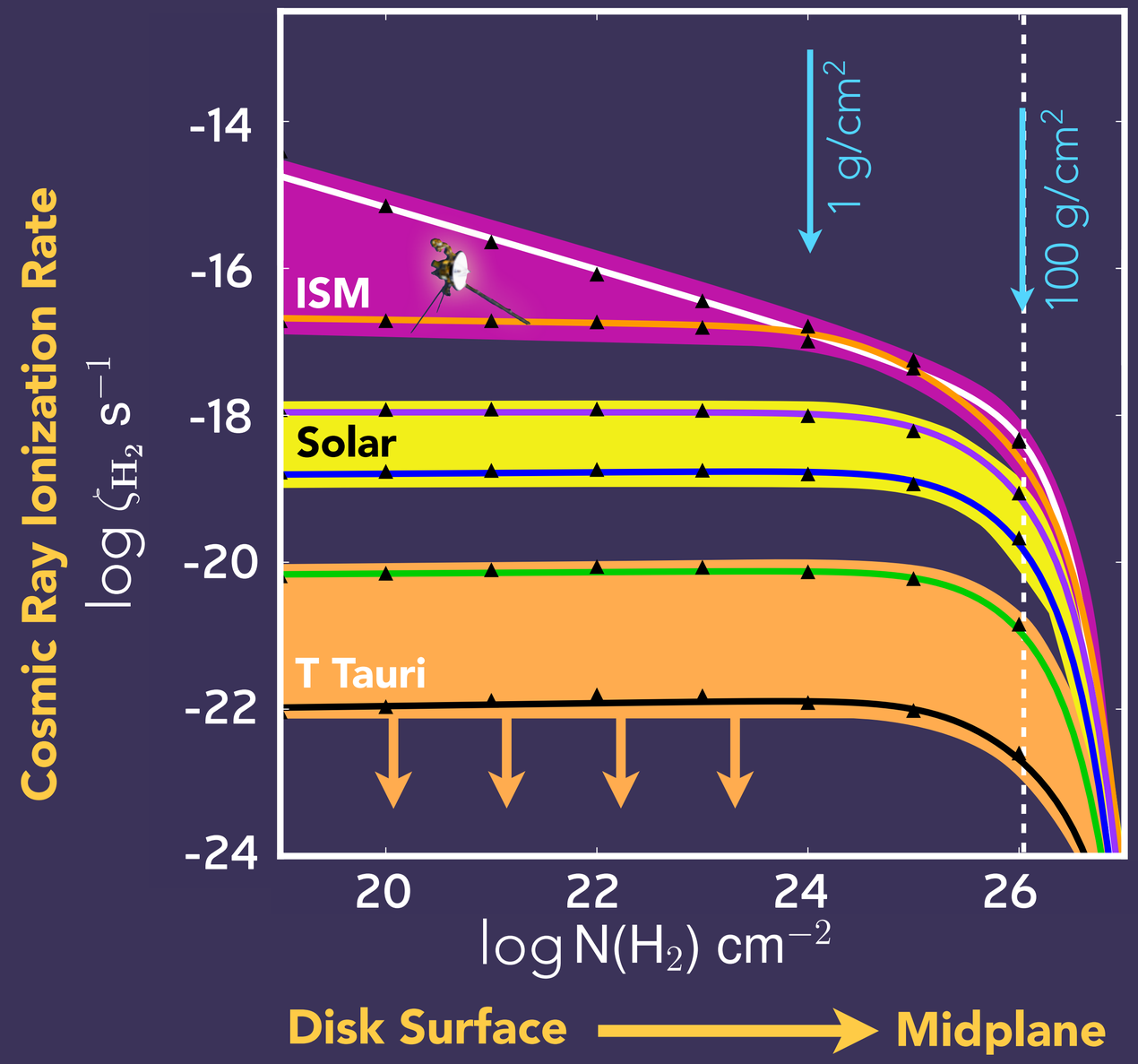


Cleeves, Adams & Bergin 2013a

WINDS AND THE COSMIC RAY *Ionization Rate*



Diffuse & Dense ISM

Webber 1998, Burger 2000, Moskalenko 2002

Solar Minimum to Maximum

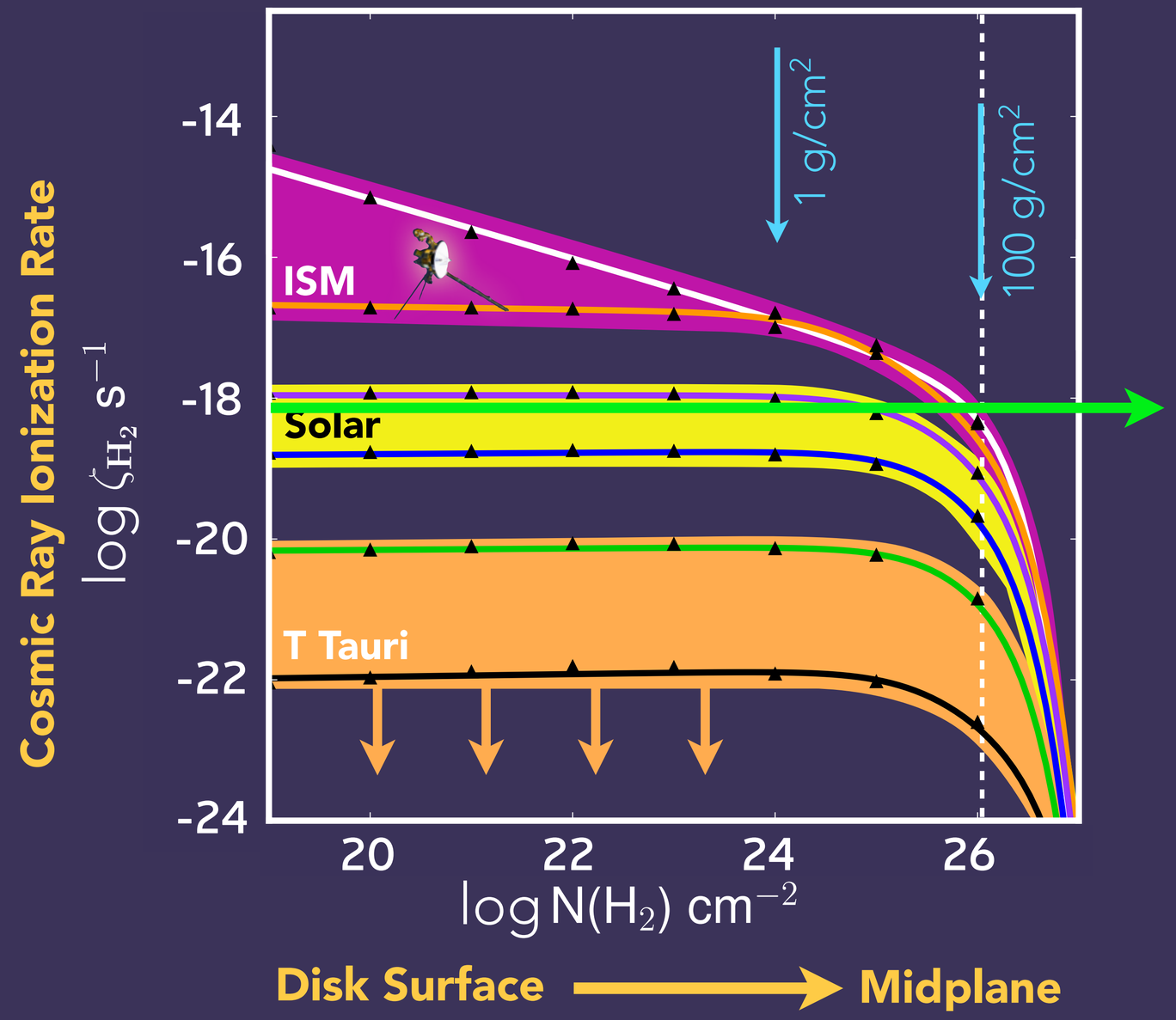
Usoskin 2005

"Extrapolated" Sun

Cleeves, Adams and Bergin 2013a

Cleeves, Adams & Bergin 2013a

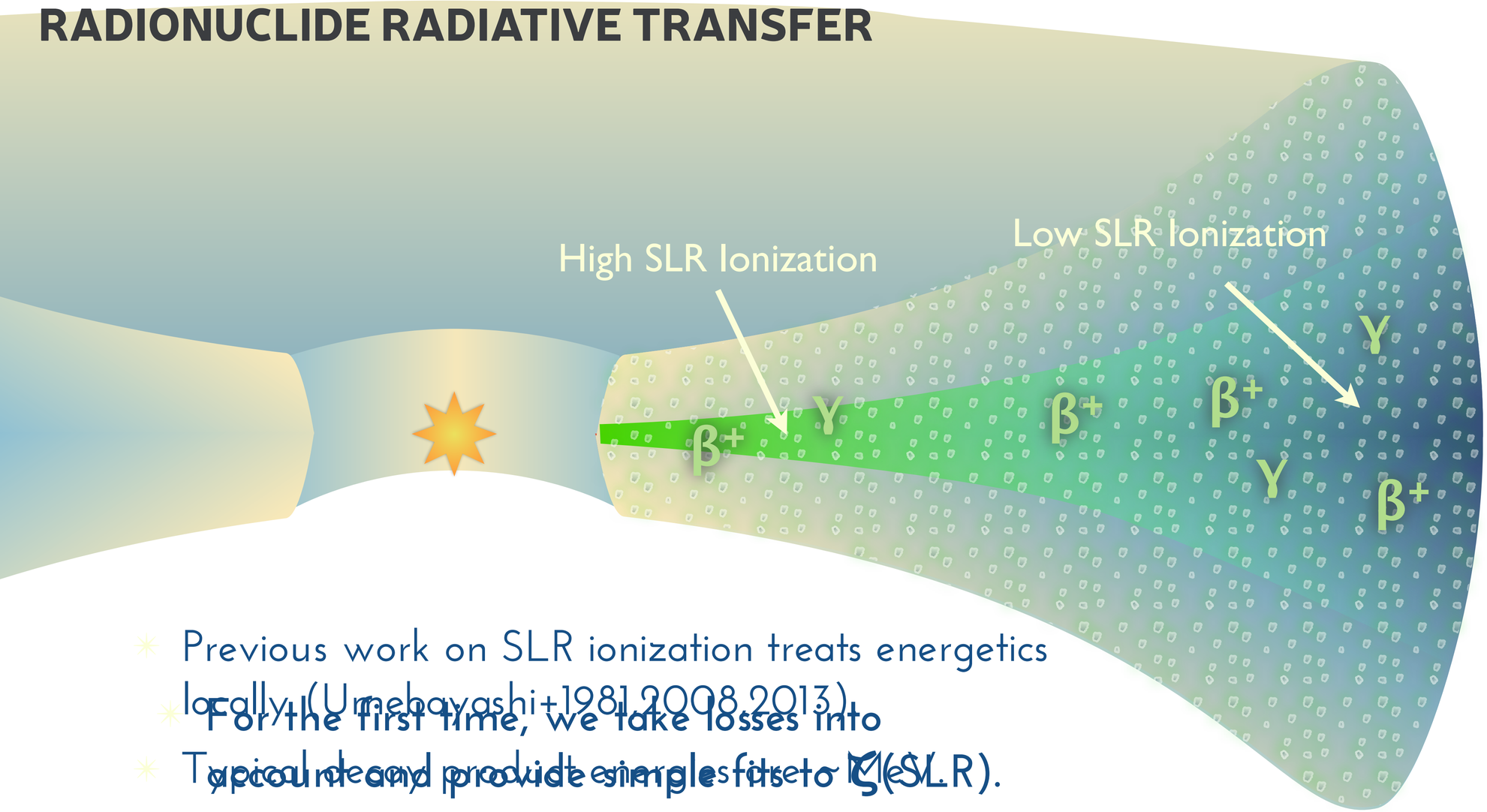
WINDS AND THE COSMIC RAY *Ionization Rate*



Ionization rate falls below that due to short-lived radionuclide decay for solar nebula ^{26}Al abundances (e.g., Umebayashi & Nakano 1981).

Cleeves, Adams & Bergin 2013a

ANALYTIC CALCULATIONS OF RADIONUCLIDE RADIATIVE TRANSFER



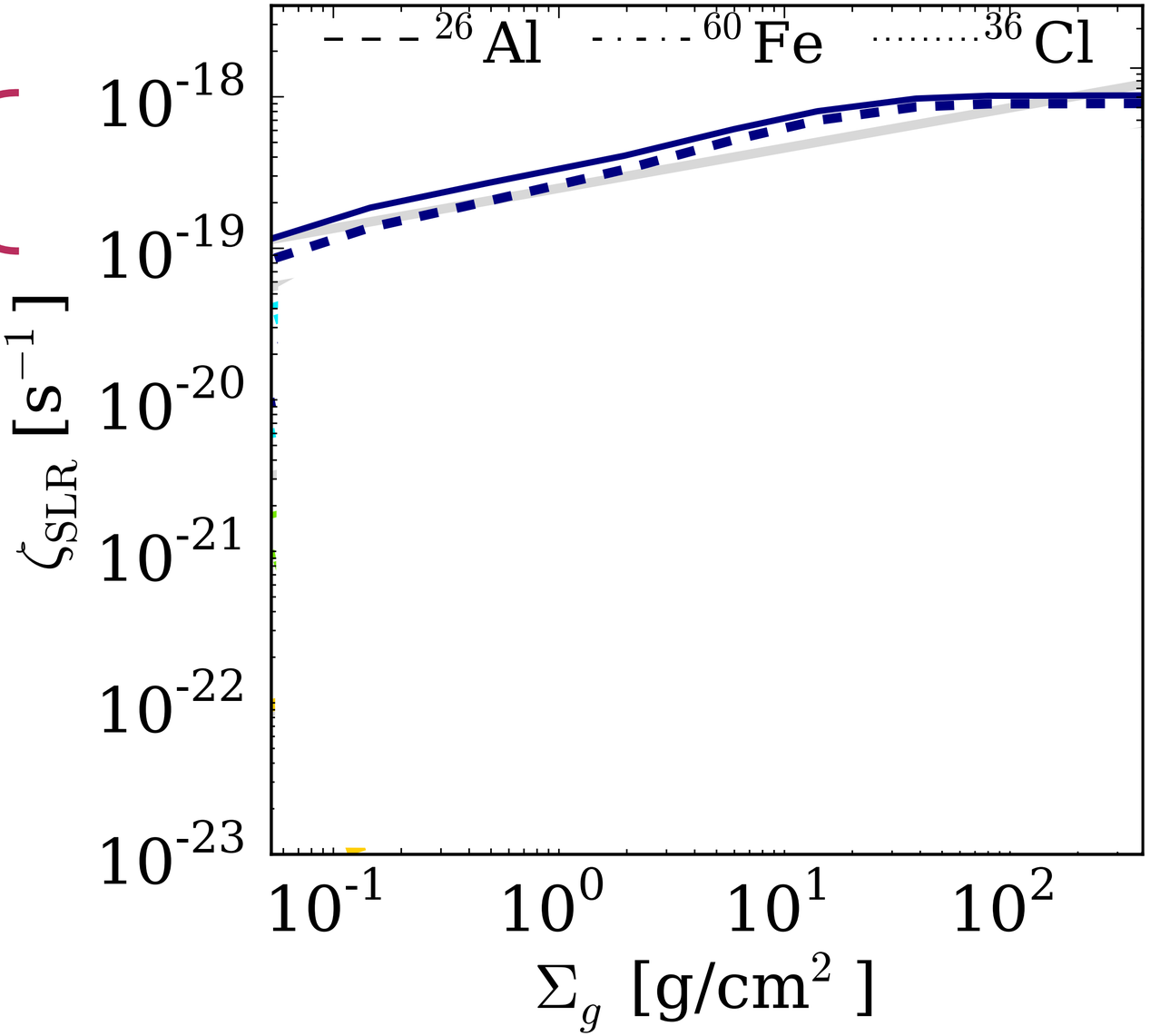
- Previous work on SLR ionization treats energetics locally (Umebayashi+1981,2008,2013).
- **For the first time, we take losses into account and provide simple fits to ζ(SLR).**
- Typical decay product energies fit to MeV.
- Stopping column ~0.1-13 g cm^{-2}.

Cleeves, Adams, Bergin & Visser 2013b
Cleeves, Bergin & Adams 2014b (Appendix A)

SHORT-LIVED RADIONUCLIDES: THE OUTER DISK

Outer Disk ← Inner Disk

Losses from escaping β^+, γ.



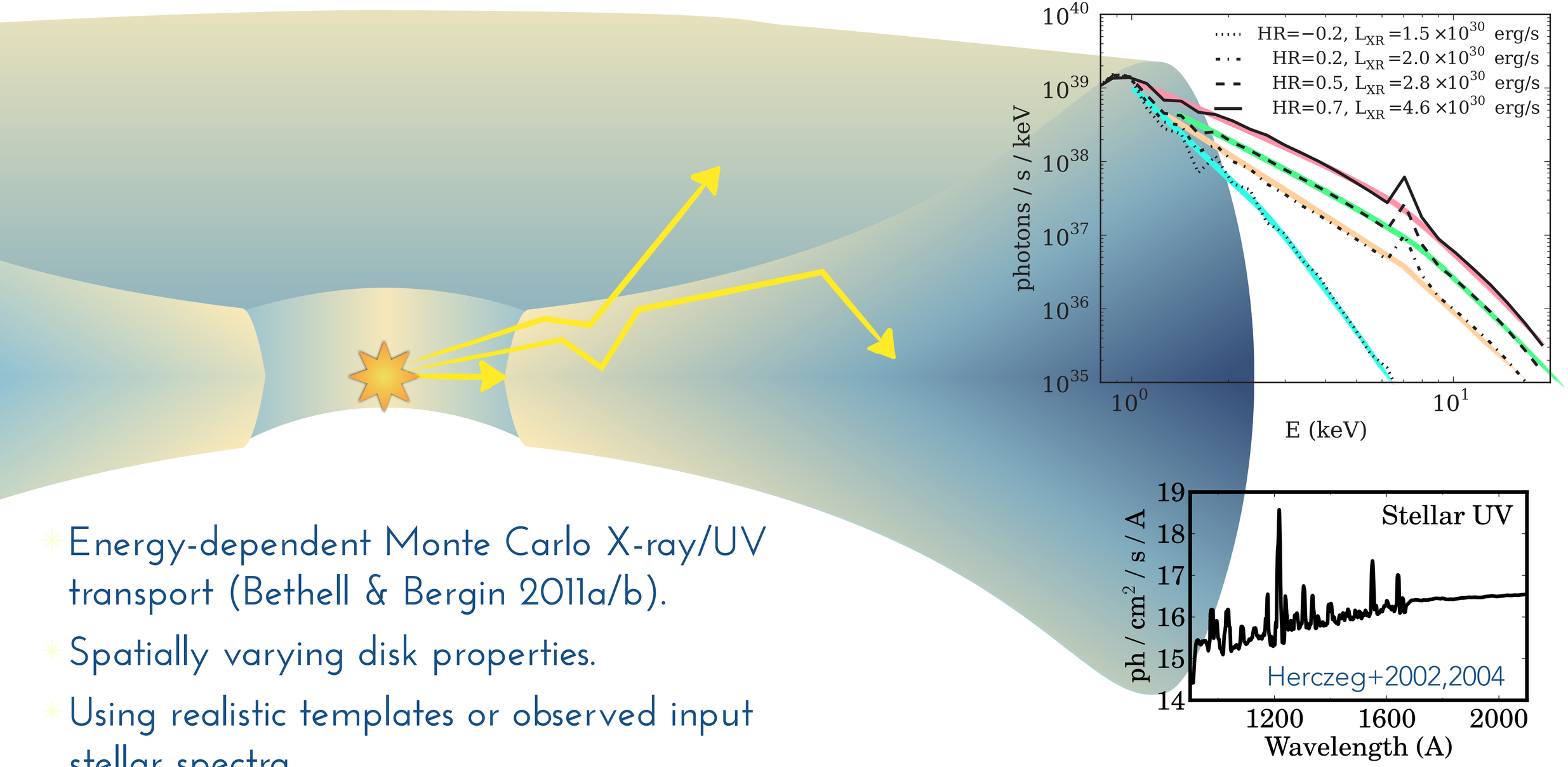
Grey = fit

0 Myr

Decays with time.

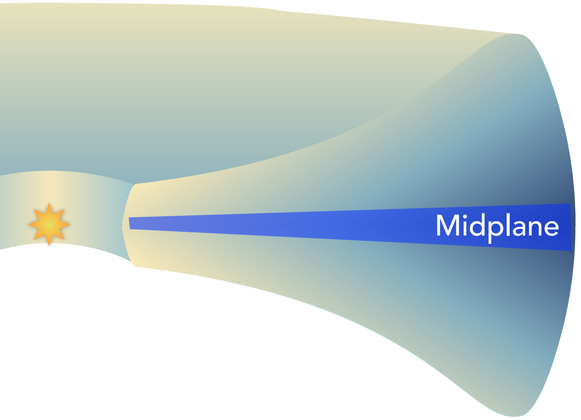
Cleeves, Adams, Bergin & Visser 2013b and Cleeves, Bergin & Adams 2014b (Appendix A)

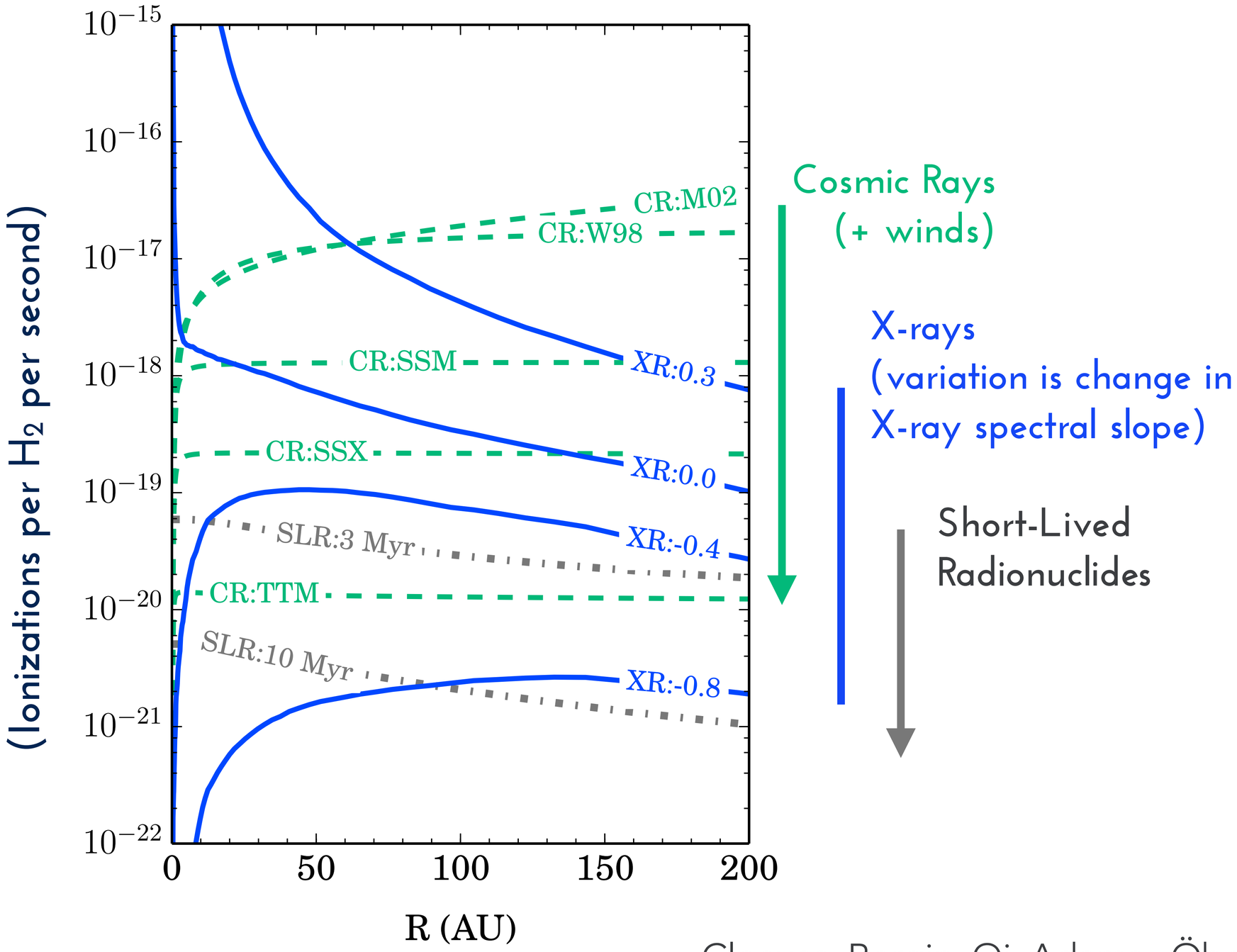
STELLAR RADIATION FIELD



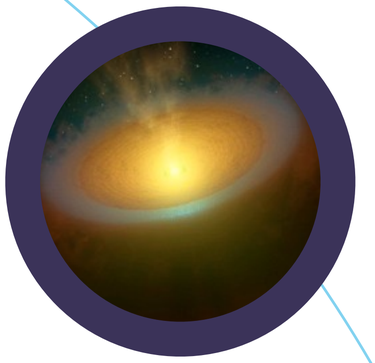
- Energy-dependent Monte Carlo X-ray/UV transport (Bethell & Bergin 2011a/b).
- Spatially varying disk properties.
- Using realistic templates or observed input stellar spectra.

DIVERSITY OF DISK IONIZATION IN THE MIDPLANE





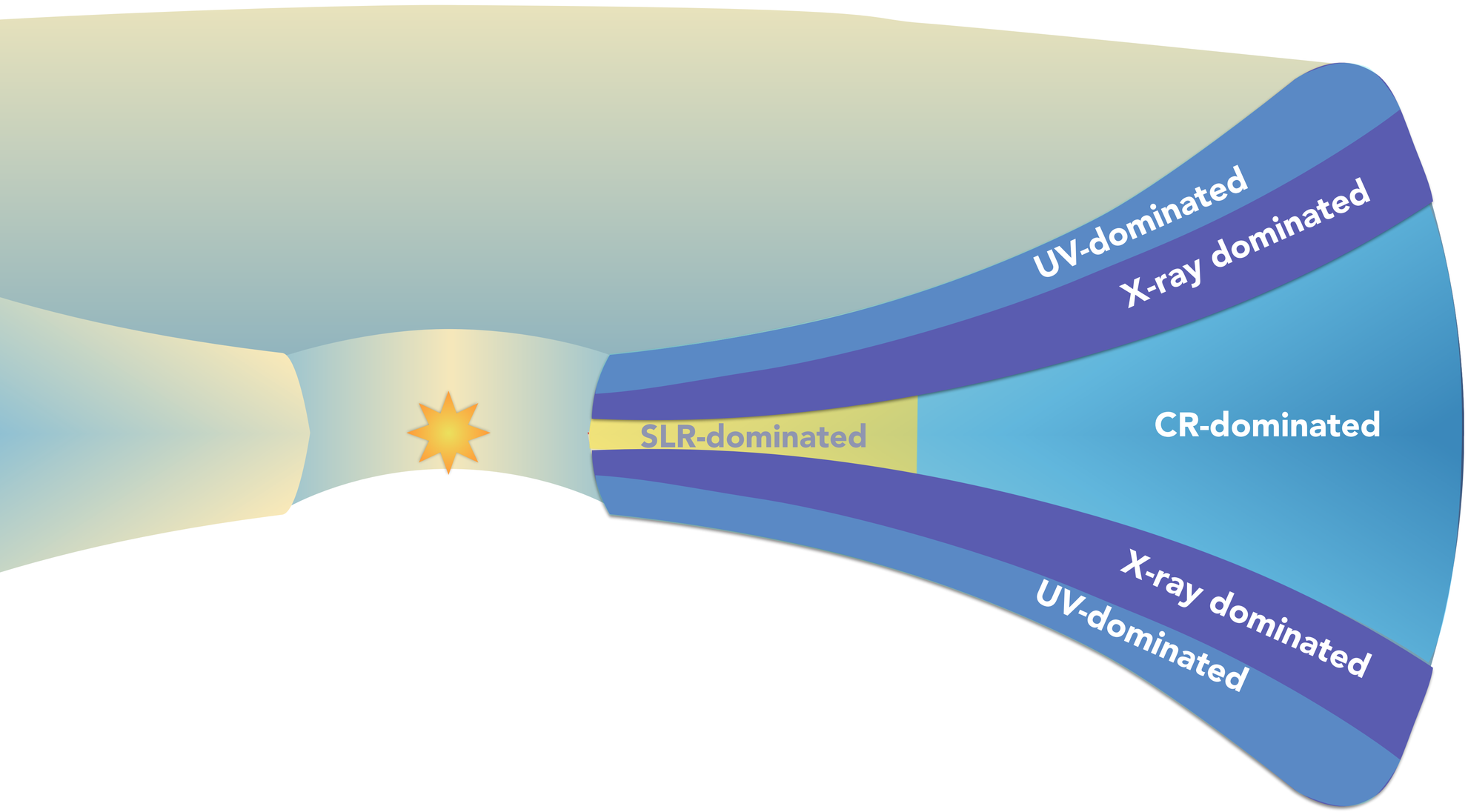
Cleeves, Bergin, Qi, Adams, Öberg 2015



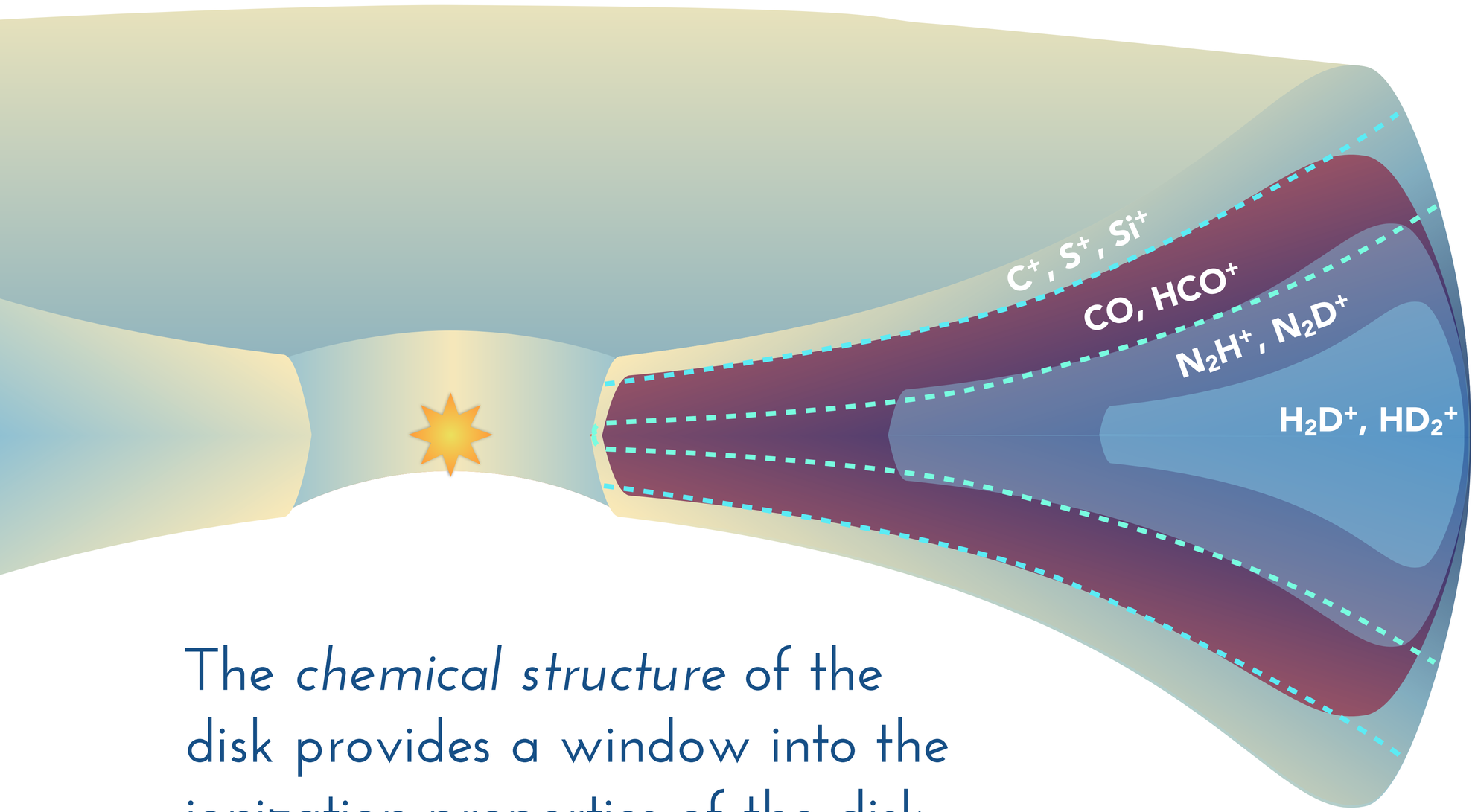
Chemical Signatures

Submillimeter Ionization Diagnostics

IONIZING PROCESSES



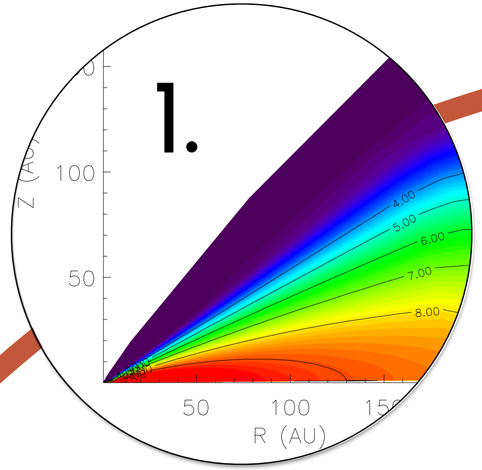
IONIZATION CHEMISTRY



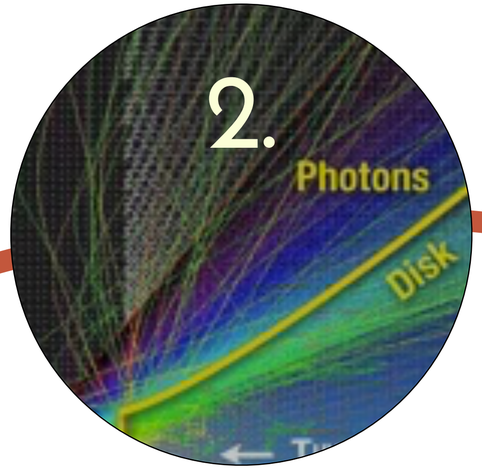
The *chemical structure* of the disk provides a window into the ionization properties of the disk.

Cleeves, Bergin and Adams 2014b

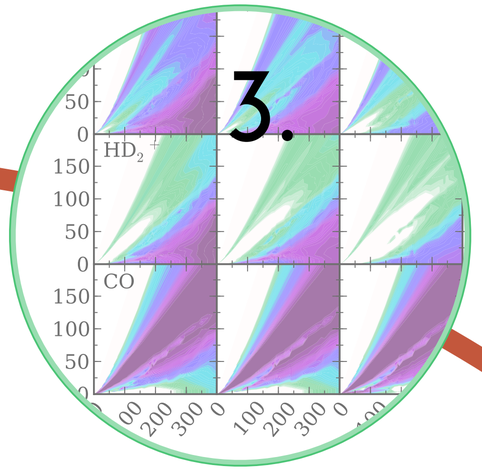
DISK MODELING TOOLS



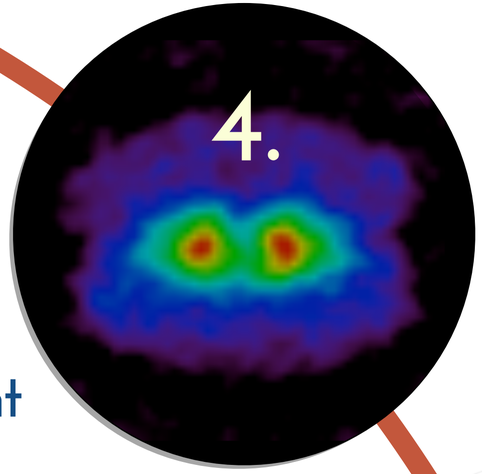
A physical model, ρg, ρd, Tg, Td: TORUS (T. Harries). + CR, SLR and external radiation field.



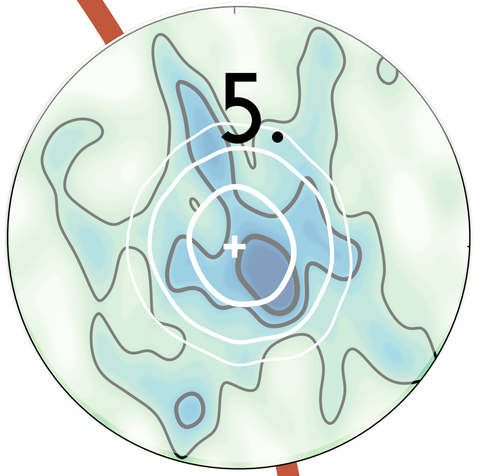
UV (Ly-α and continuum) & X-ray monte carlo radiation transport (Bethell & Bergin 2011a).



Time-dependent chemical model: photo-chemistry, grain-surface chemistry, ion-chemistry, self-shielding… (Fogel et al. 2011).



Model resultant line emission, (LIME, Brinch +2010).



Compare to observations.

CHEMICAL SIGNATURES

HCO^+

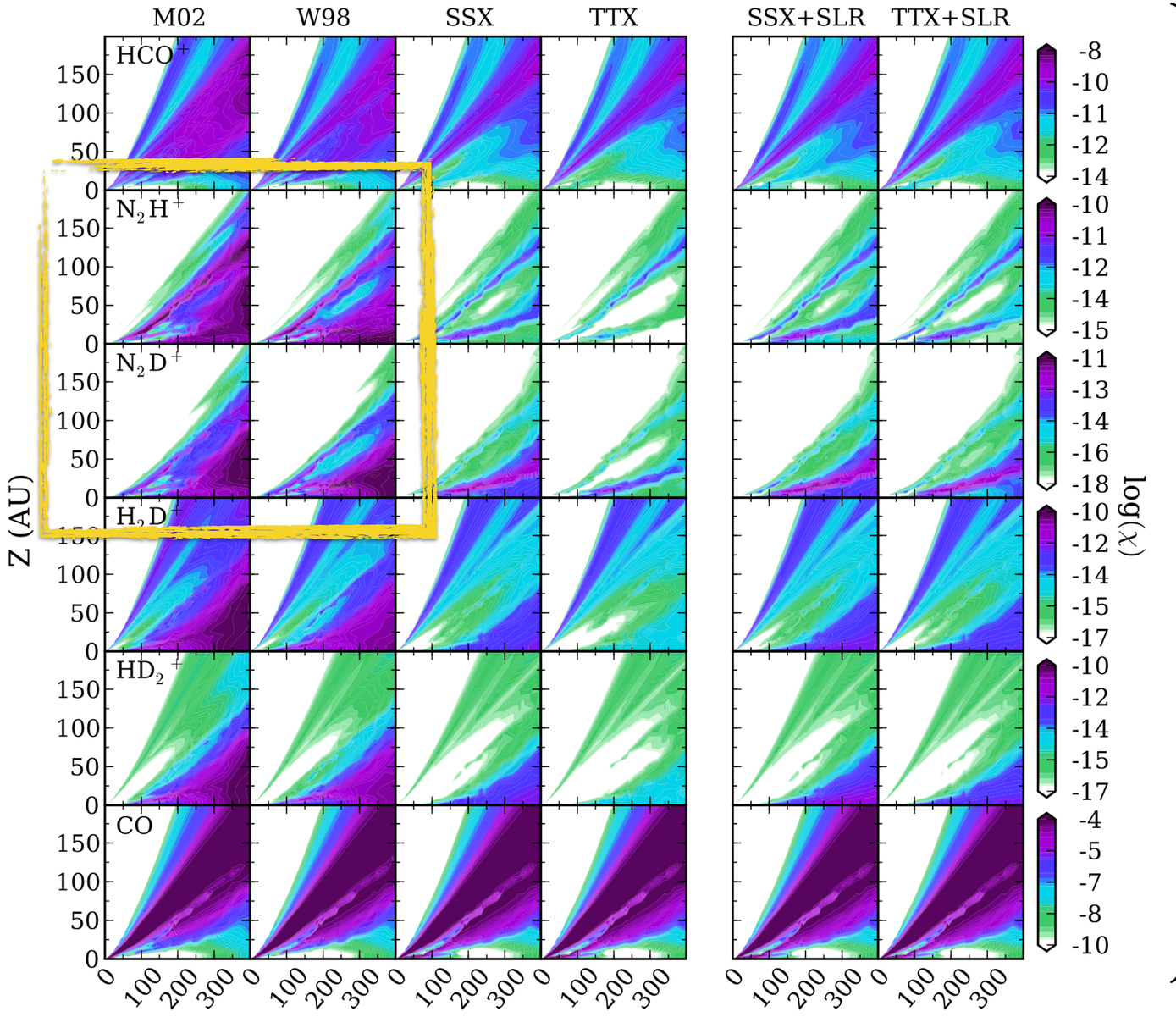
N_2H^+

N_2D^+

H_2D^+

HD_2^+

CO



Diffuse ISM CR

Dense ISM CR

Solar Max CR

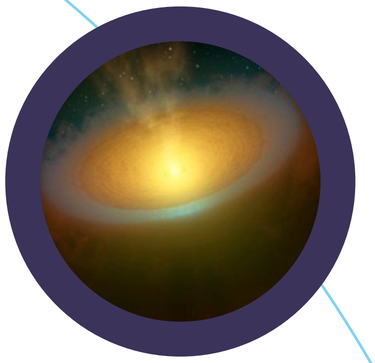
"T Tauri" CR

+Radionuclides

Changes in the incident CR rate cause a significant amount of chemical structure in molecular ion abundances.

These are *detectable effects.*

Cleeves, Bergin and Adams 2014b



A Targeted Case-study of TW Hya

Cleeves, Bergin, Qi, Adams, and Öberg 2015

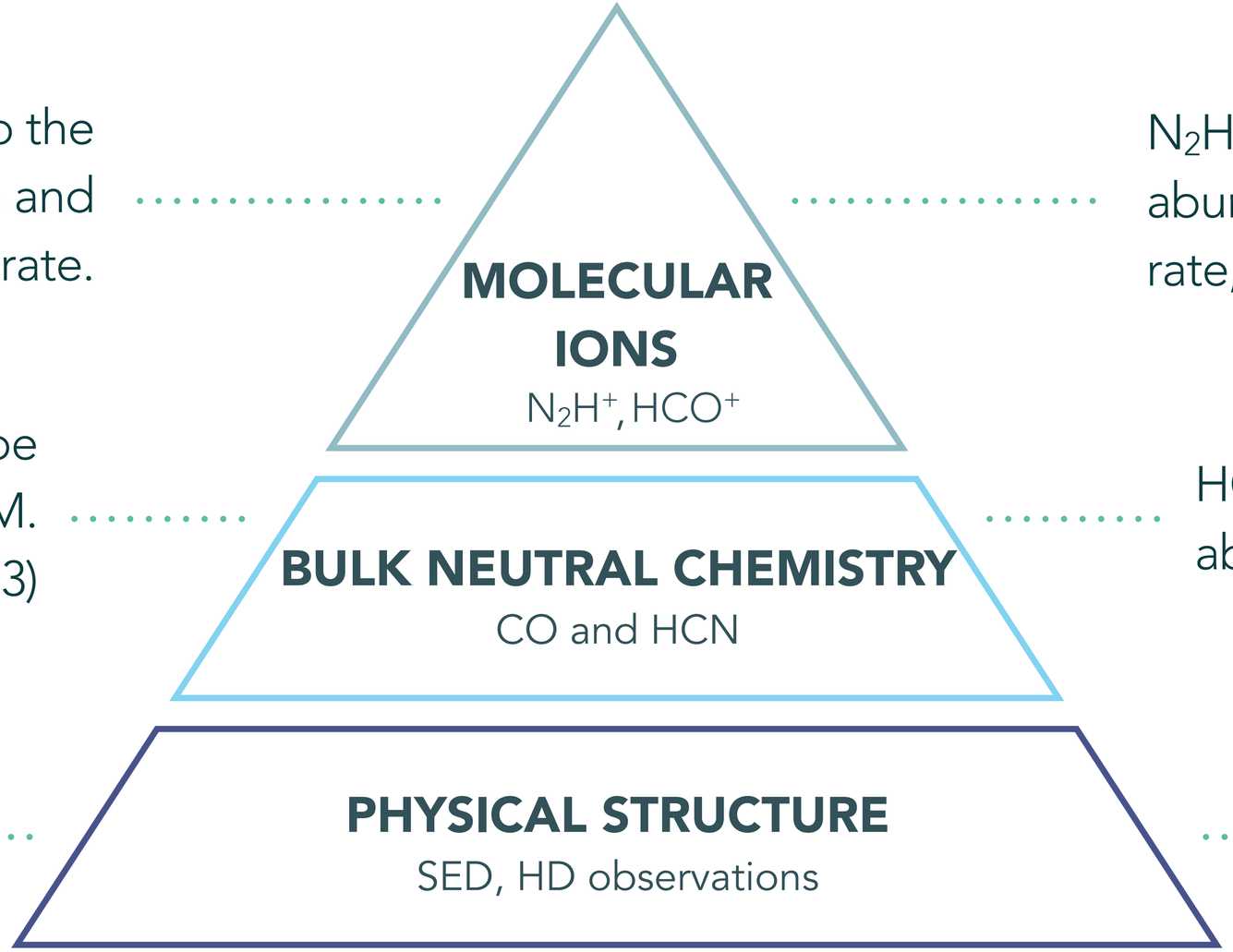
IONIZATION CONSTRAINTS: THE CASE OF TW HYA

Nearest (61 pc, Gaia) young star (3-10 Myr-old, Webb+1999, Song+2003, Weinberger+2013) with a gas rich circumstellar disk, $M_{disk} \sim 0.02\text{-}0.06\ M_\odot$ (Bergin et al. 2013).

MAPPING IONIZATION IN THE TW HYA DISK: MODELS

HCO^+ sensitive to the CO abundance and X-ray ionization rate.

N_2H^+ is sensitive to the CO abundance, X-ray ionization rate, and CR ionization rate.



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

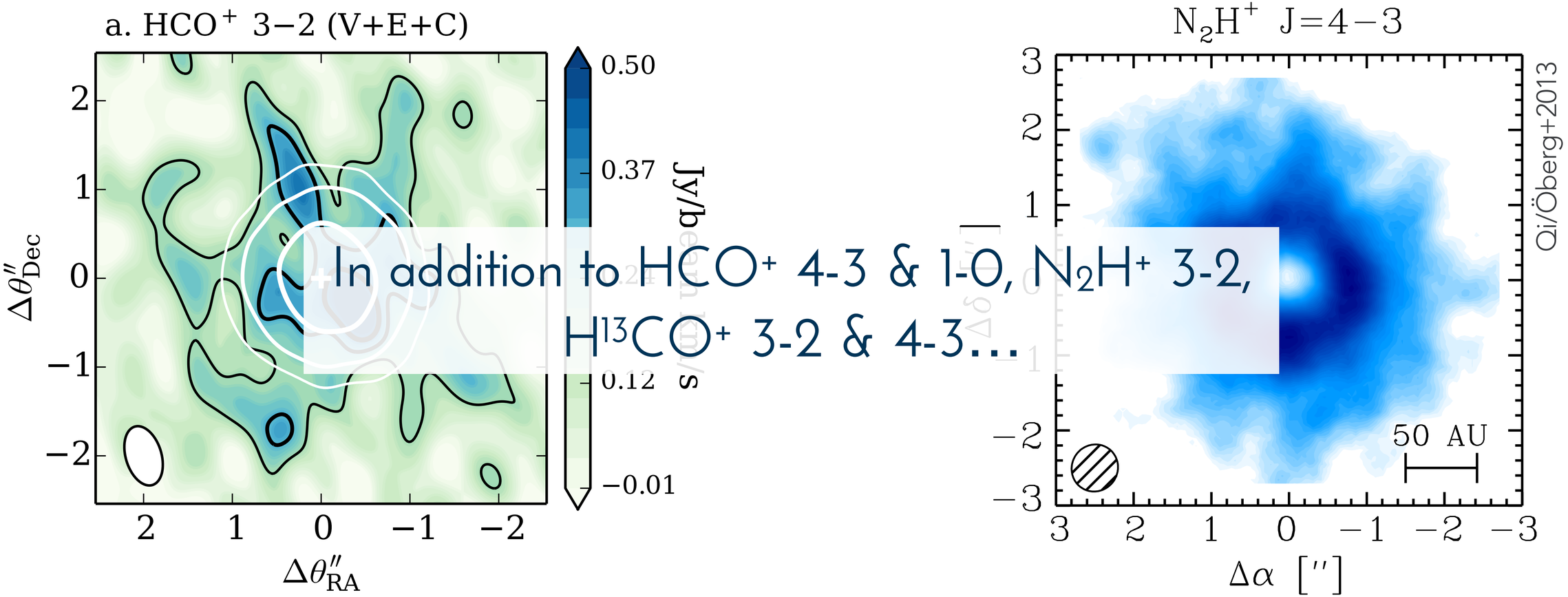
HCN calibrates nitrogen abundances.

SED puts constraints on disk density and thermal structure.

HD traces the otherwise invisible H_2 reservoir

Cleeves, Bergin, Qi, Adams, and Öberg 2015

MAPPING IONIZATION IN THE TW HYA DISK: OBSERVATIONS

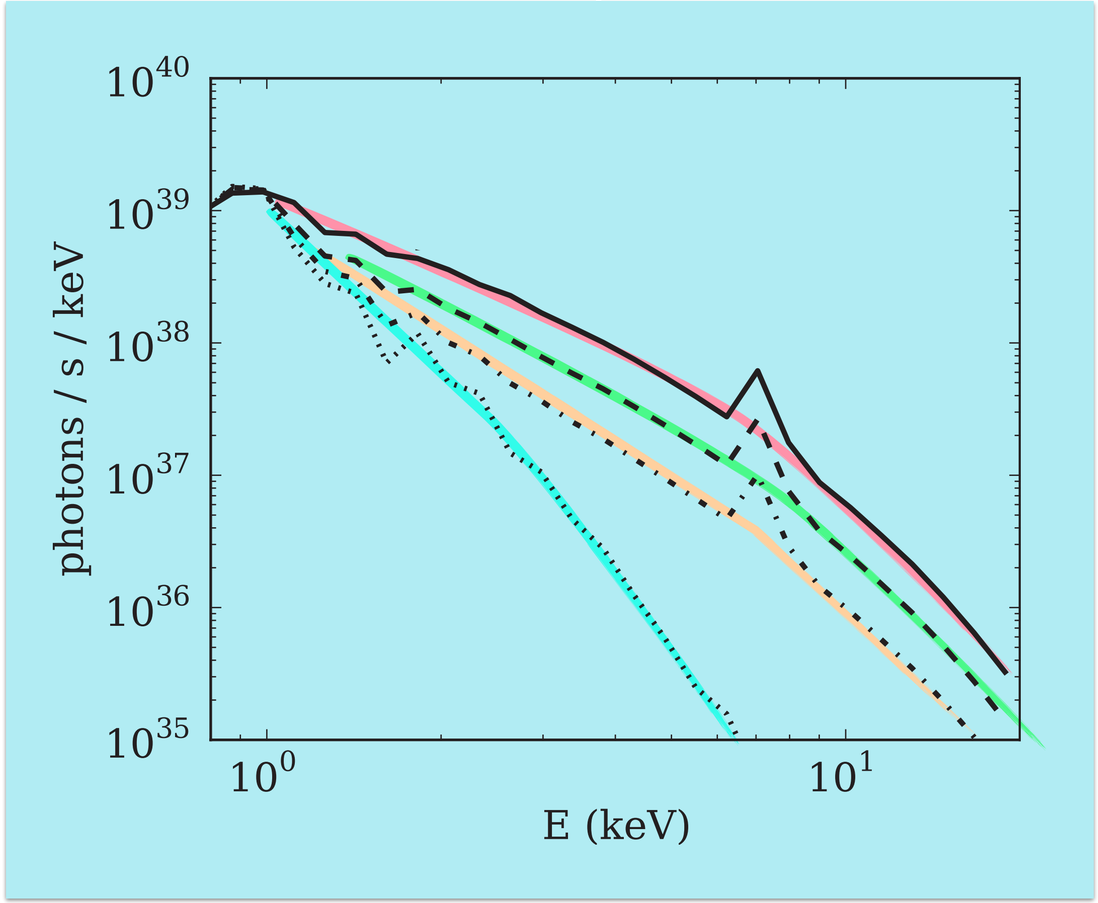


In addition to HCO^+ 4-3 & 1-0, N_2H^+ 3-2, $H^{13}CO^+$ 3-2 & 4-3…

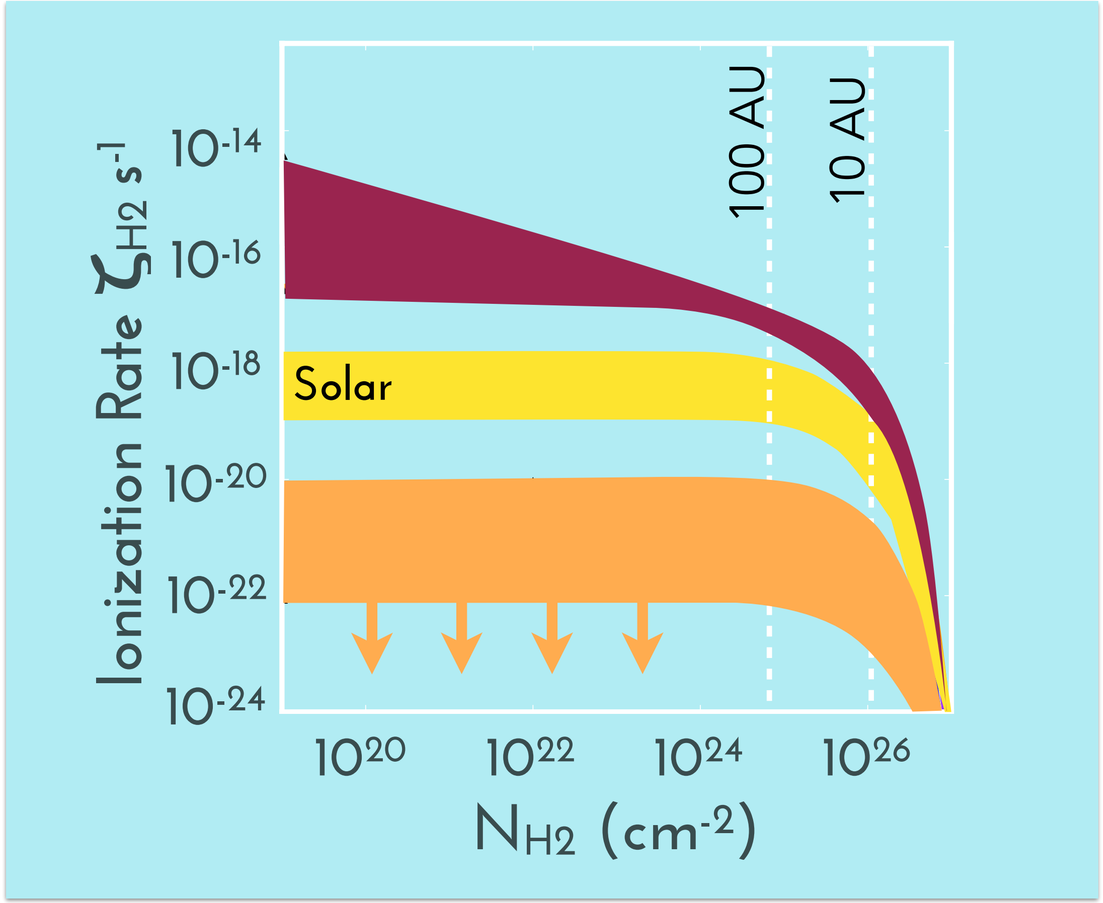
Cleeves, Bergin, Qi, Adams, and Öberg 2015

MAPPING IONIZATION IN THE TW HYA DISK: MODELS

X-rays

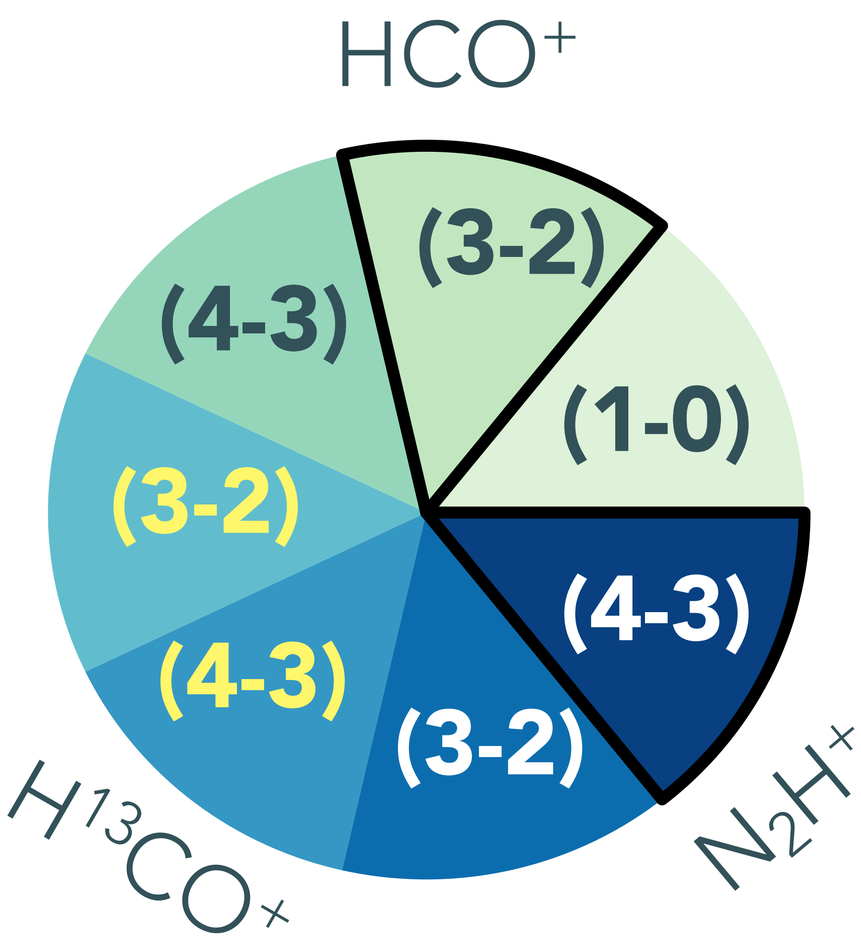


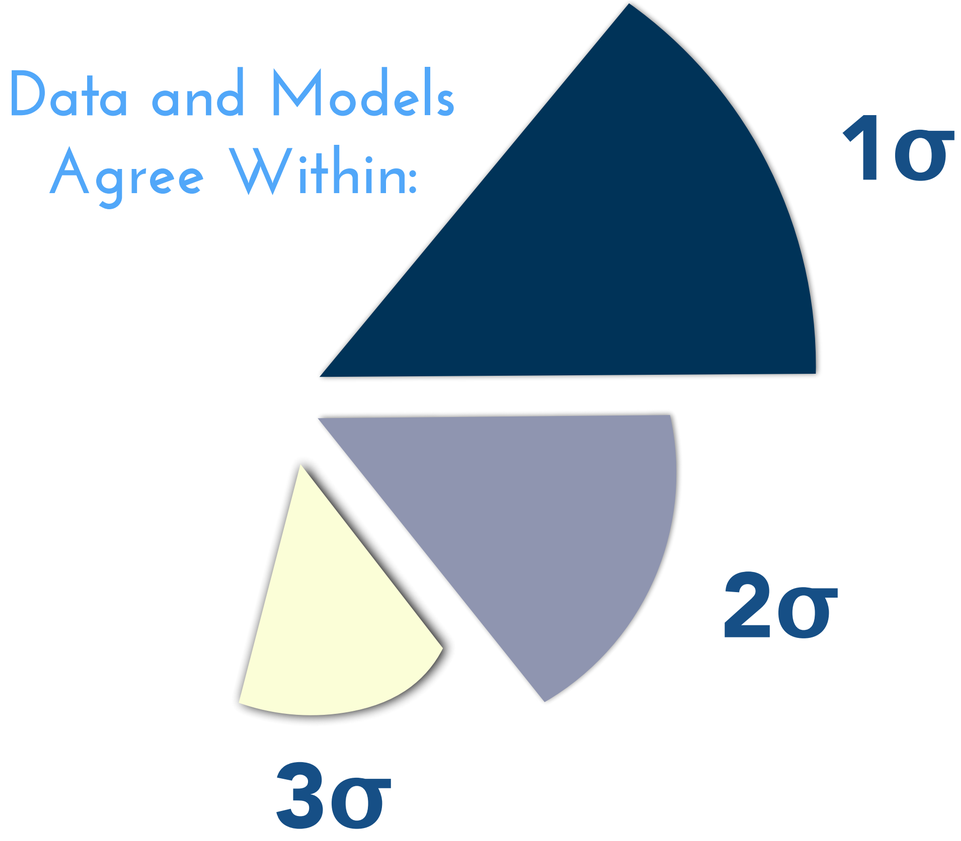
CRs

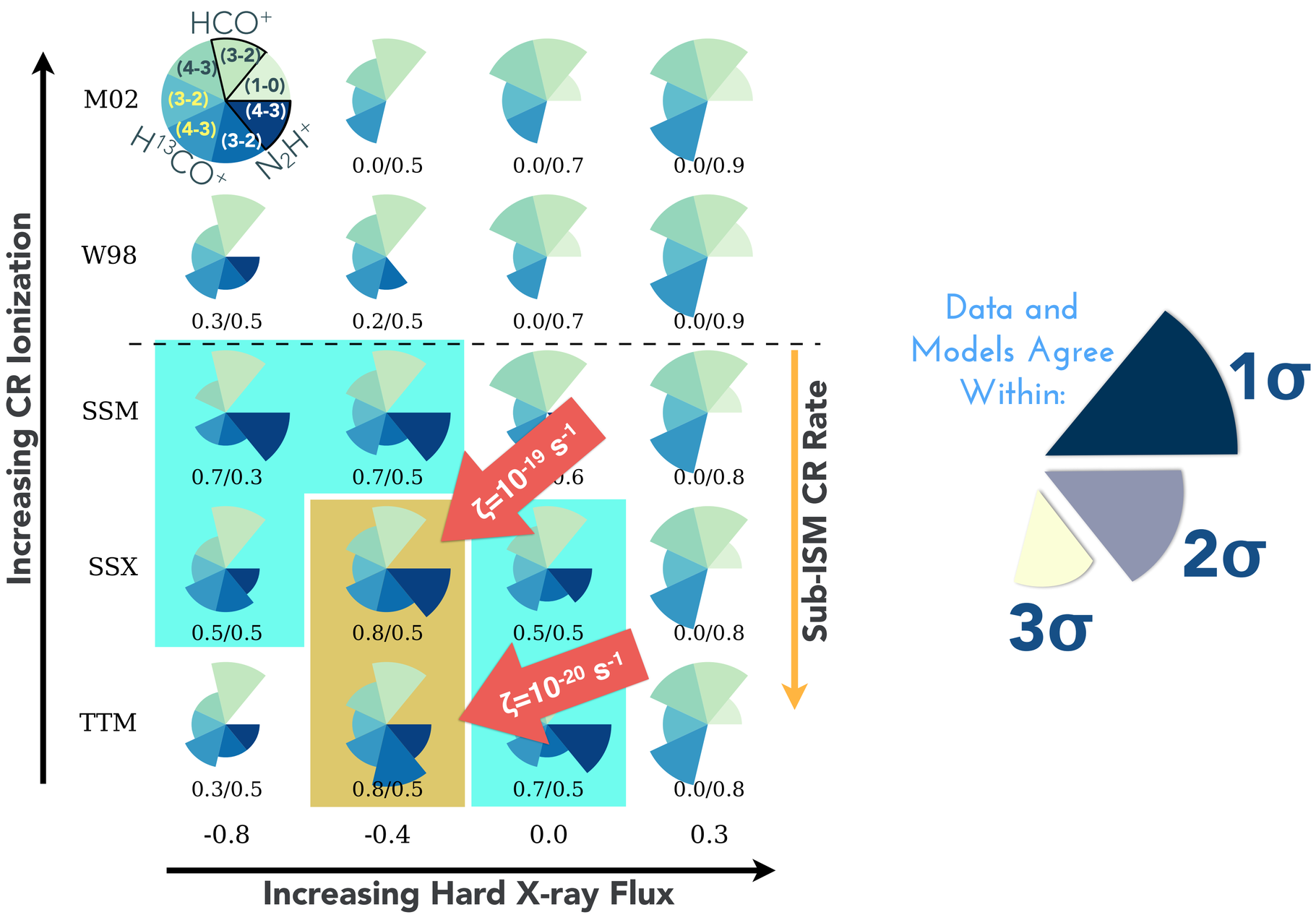


Cleeves, Bergin, Qi, Adams, and Öberg 2015

MAPPING IONIZATION IN THE TW HYA DISK: MODELS



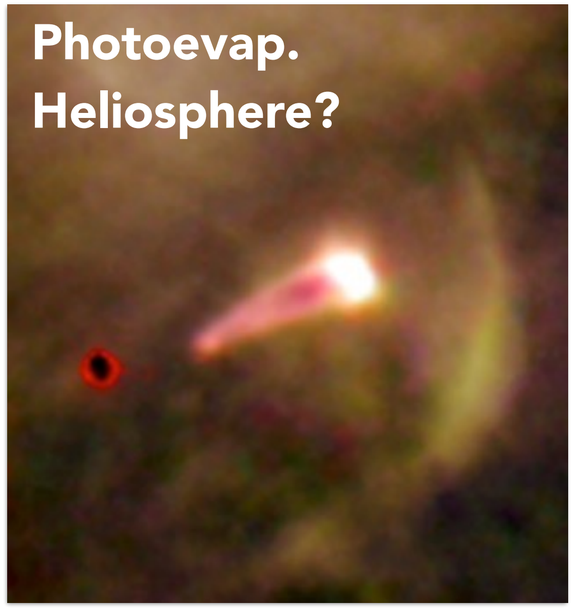



HCO+
(3-2)
(4-3)
(1-0)
(3-2)
(4-3)
(4-3)
(3-2)
H13CO+
N2H+
M02
W98
SSM
SSX
TTM
0.0/0.5
0.0/0.7
0.0/0.9
0.3/0.5
0.2/0.5
0.0/0.7
0.0/0.9
0.7/0.3
0.7/0.5
0.0/0.8
0.5/0.5
0.8/0.5
0.5/0.5
0.0/0.8
0.3/0.5
0.8/0.5
0.7/0.5
0.0/0.8
-0.8
-0.4
0.0
0.3
ζ=10-19 s-1
ζ=10-20 s-1
Increasing CR Ionization
Sub-ISM CR Rate
Increasing Hard X-ray Flux
Data and Models Agree Within:
1σ
2σ
3σ

POSSIBLE SCENARIOS FOR LOW IONIZATION

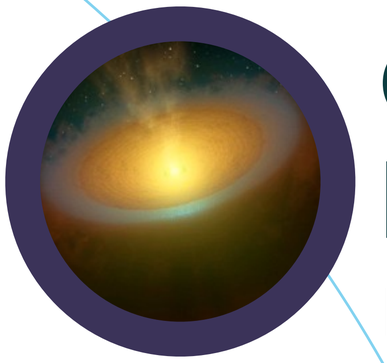
TW Hya

A lab for CR exclusion mechanisms



$$\zeta_{H2} \lesssim 10^{-19}\ s^{-1}\ ?$$

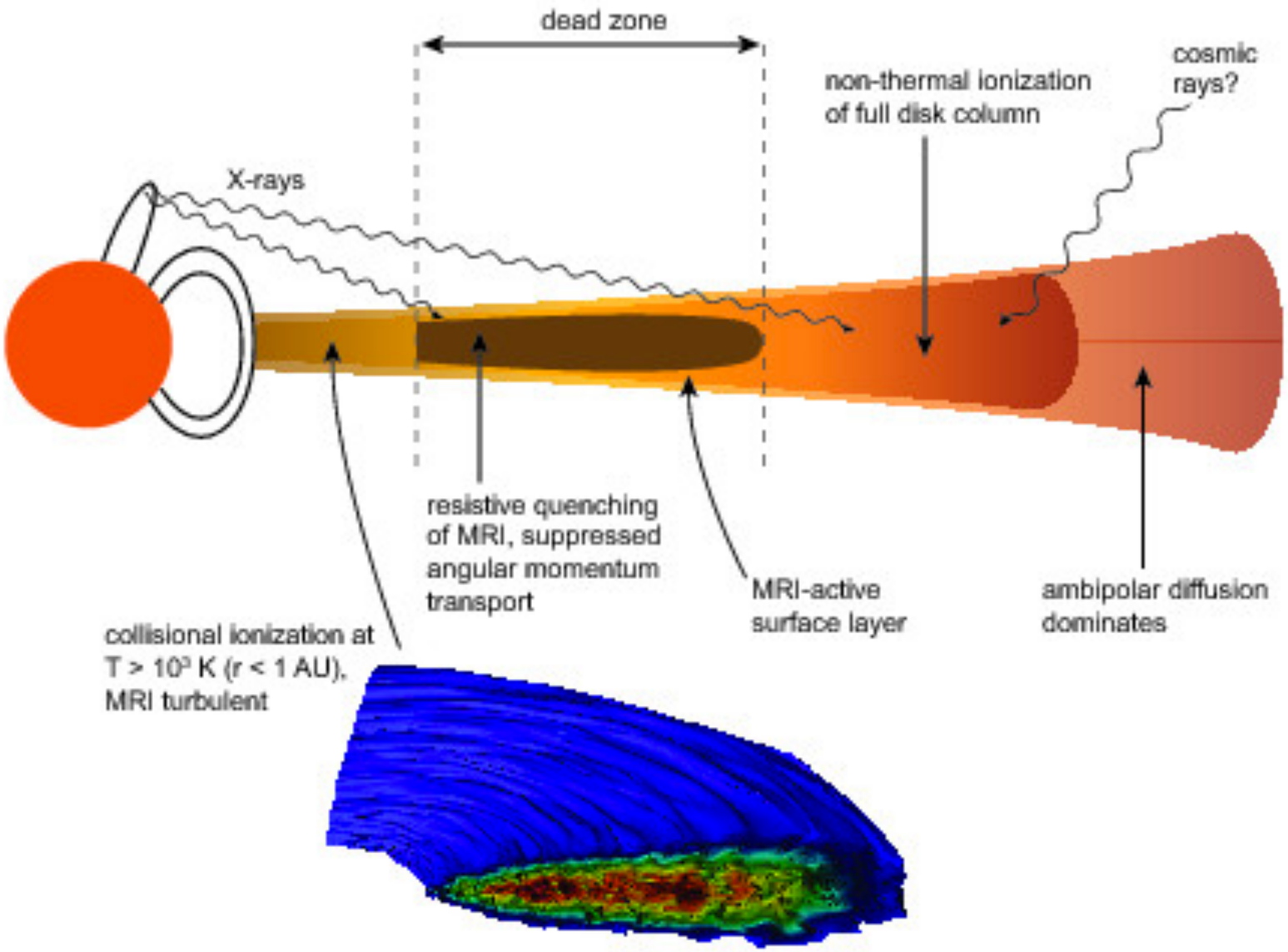
1. **Stellar, disk, or photoevaporative winds** block CRs across the entire disk. Would have to extend well beyond R > 200 AU.
   - Wind ram pressure > ambient interstellar pressure.
   - Collimation?
2. **Magnetic irregularities** in the disk as a source of local "opacity" to CRs (Dolginov & Stepinski).
   - 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.



Consequences of a Low Ionization Environment

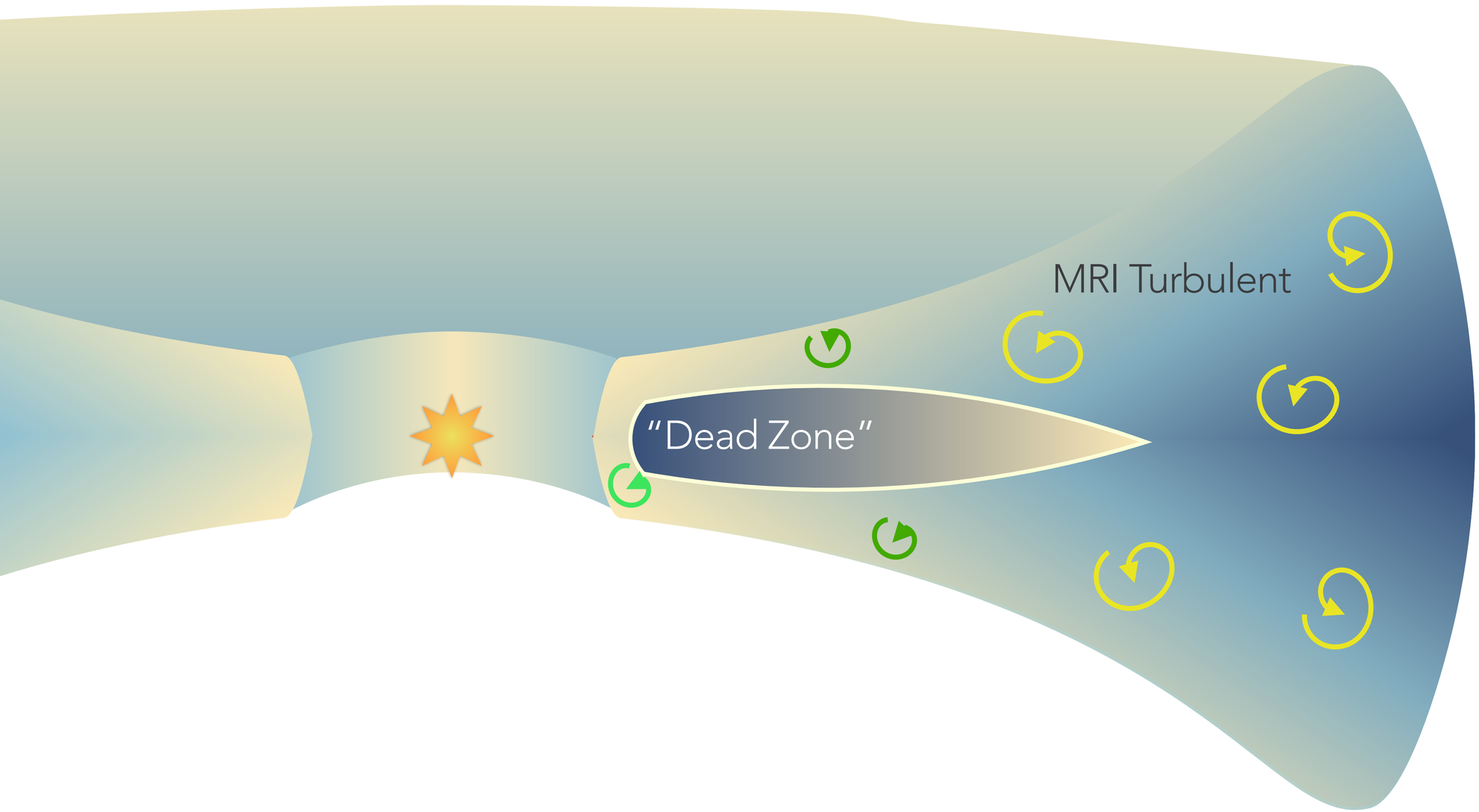
Dead zones + dust growth

IONIZATION AND DEAD ZONES



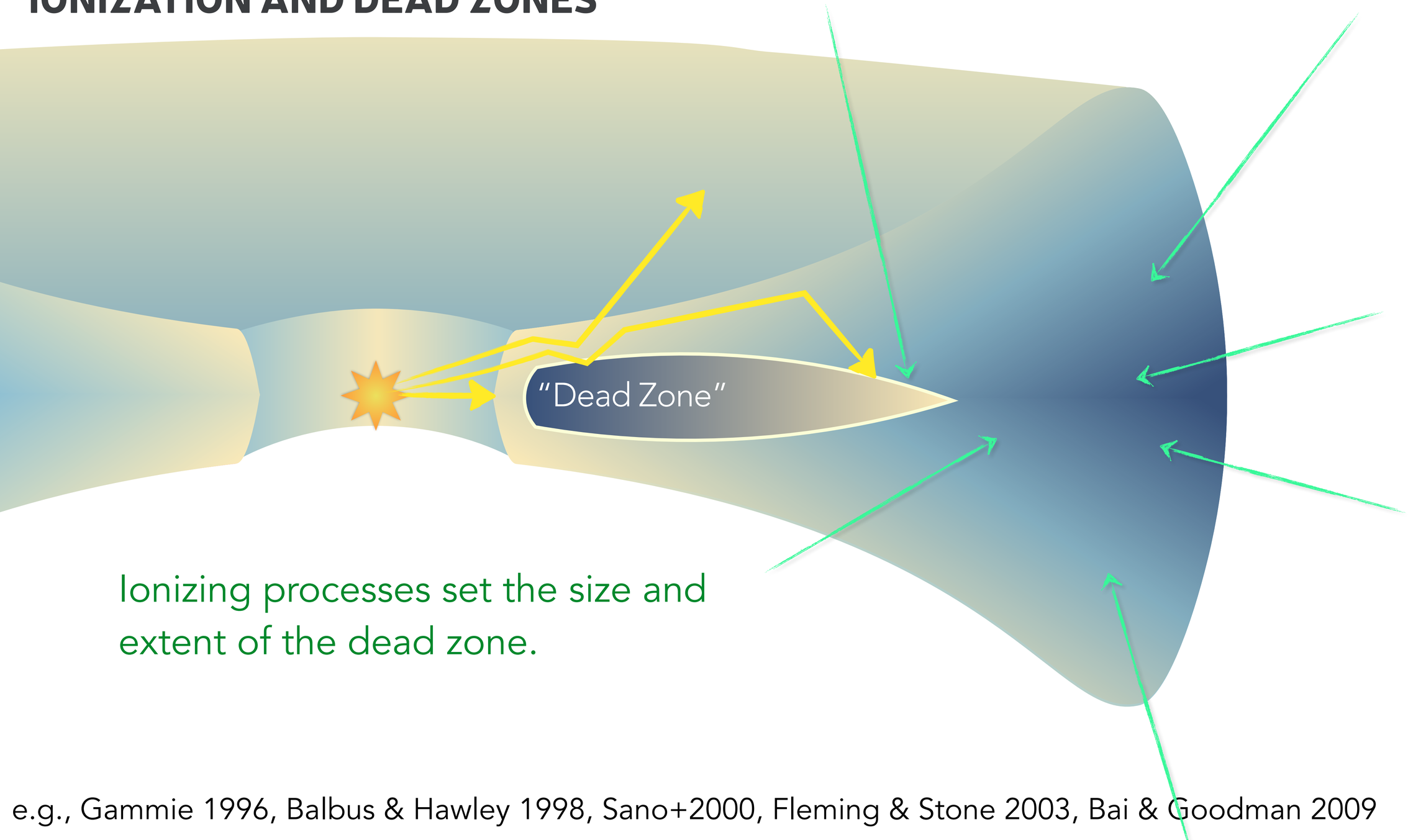
Credit: P. Armitage

IONIZATION AND DEAD ZONES



e.g., Gammie 1996, Balbus & Hawley 1998, Sano+2000, Fleming & Stone 2003, Bai & Goodman 2009

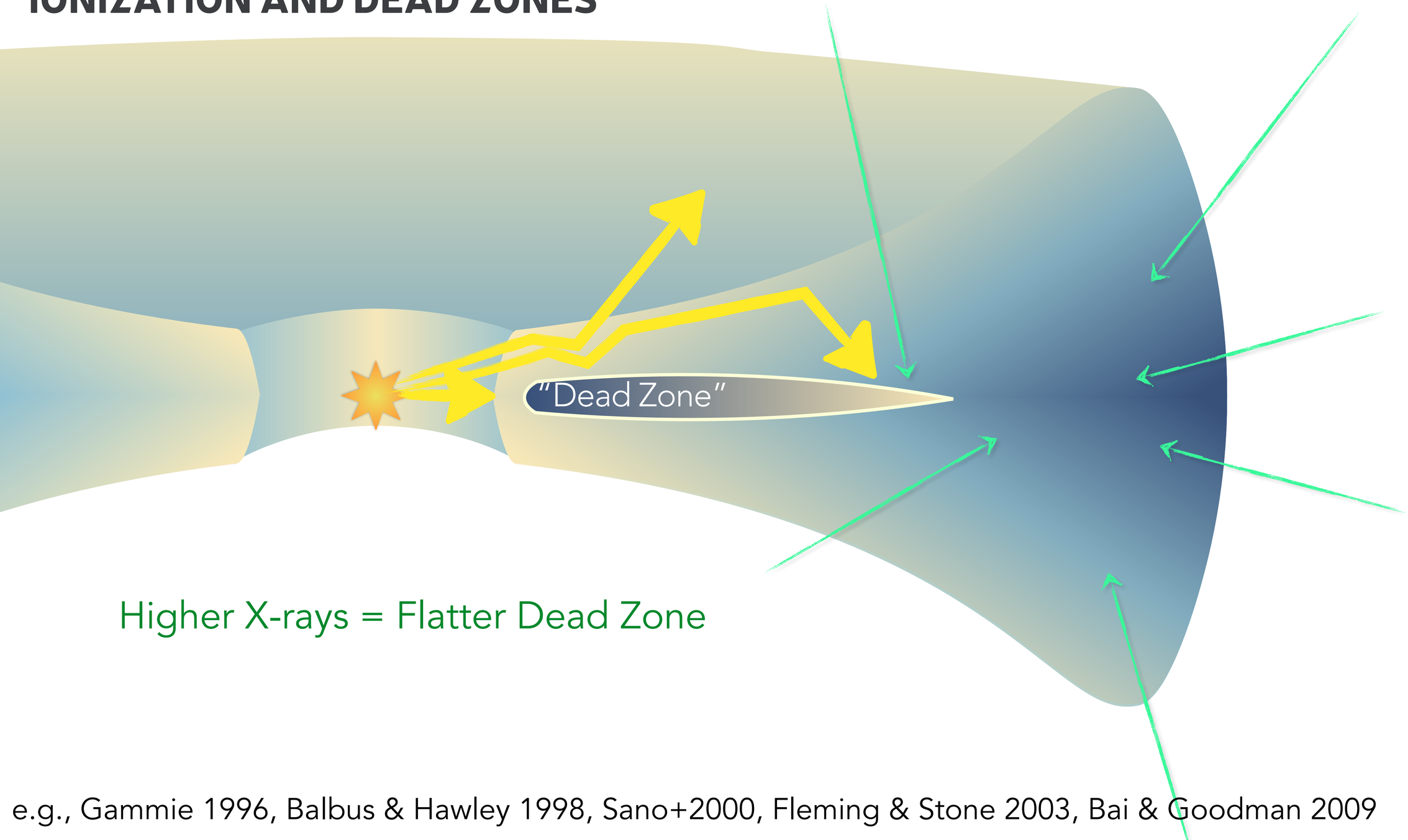
IONIZATION AND DEAD ZONES



Ionizing processes set the size and extent of the dead zone.

e.g., Gammie 1996, Balbus & Hawley 1998, Sano+2000, Fleming & Stone 2003, Bai & Goodman 2009

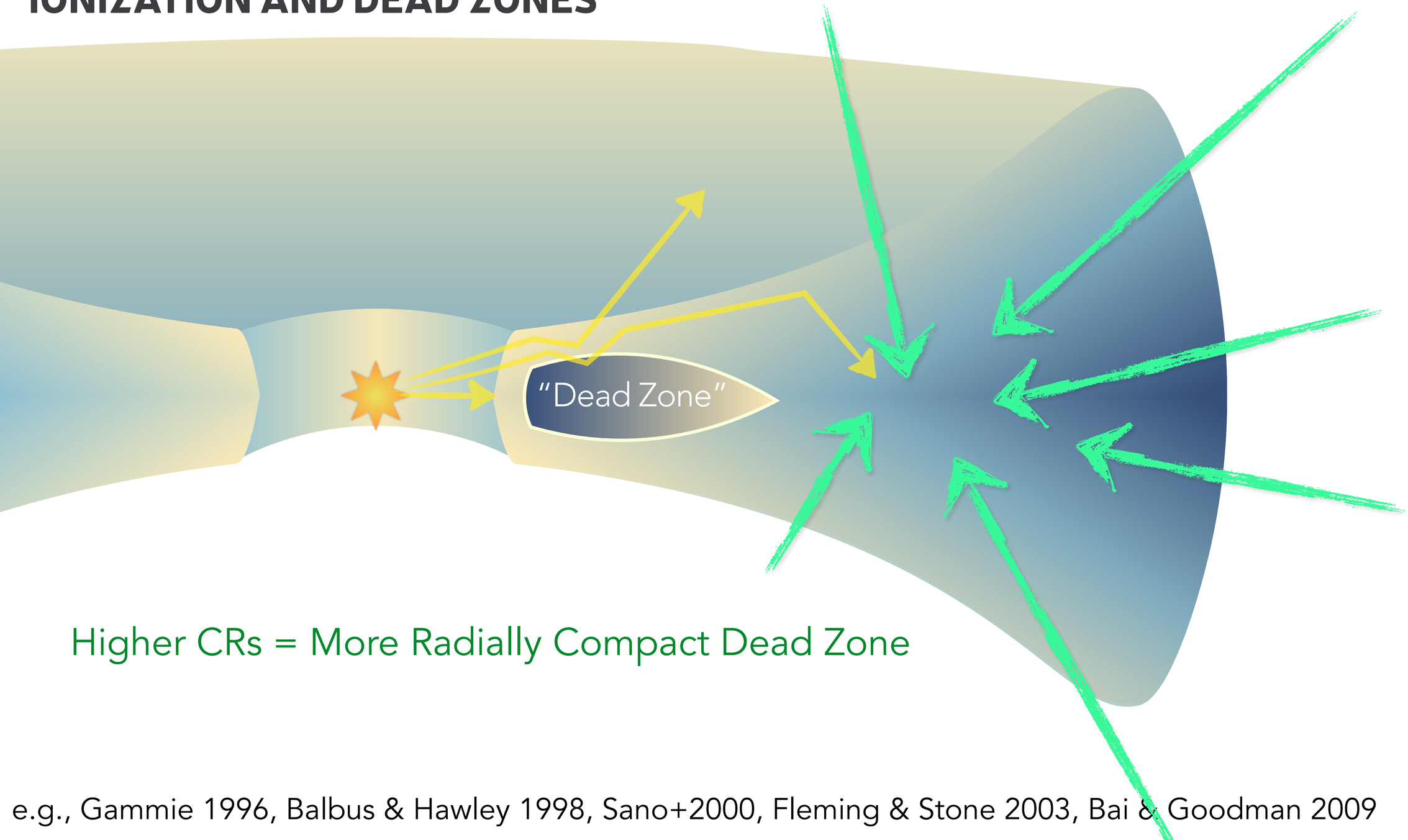
IONIZATION AND DEAD ZONES



Higher X-rays = Flatter Dead Zone

e.g., Gammie 1996, Balbus & Hawley 1998, Sano+2000, Fleming & Stone 2003, Bai & Goodman 2009

IONIZATION AND DEAD ZONES

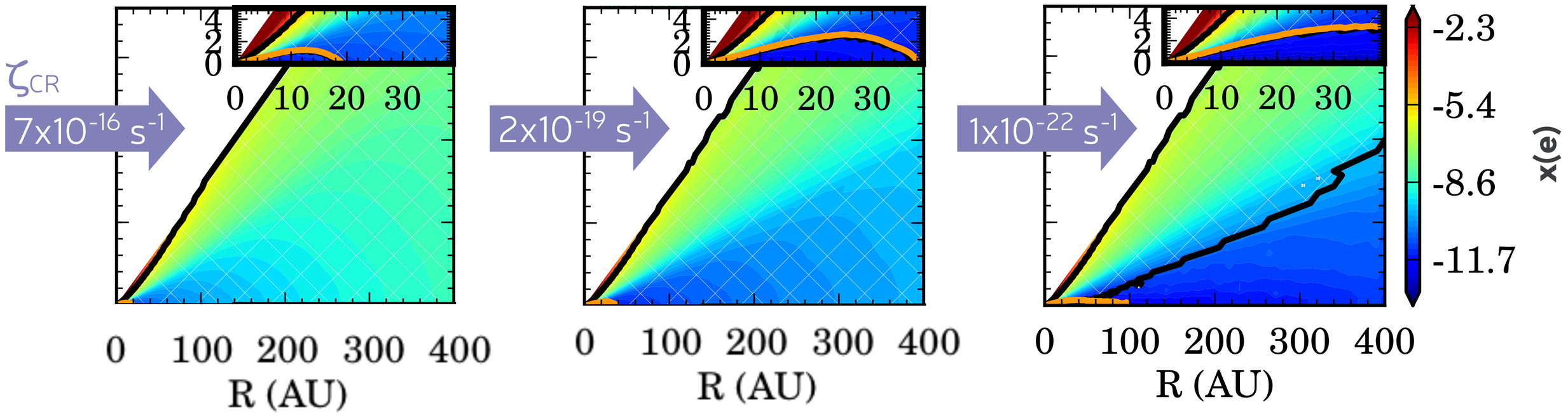


Higher CRs = More Radially Compact Dead Zone

e.g., Gammie 1996, Balbus & Hawley 1998, Sano+2000, Fleming & Stone 2003, Bai & Goodman 2009

IONIZATION AND DEAD ZONES

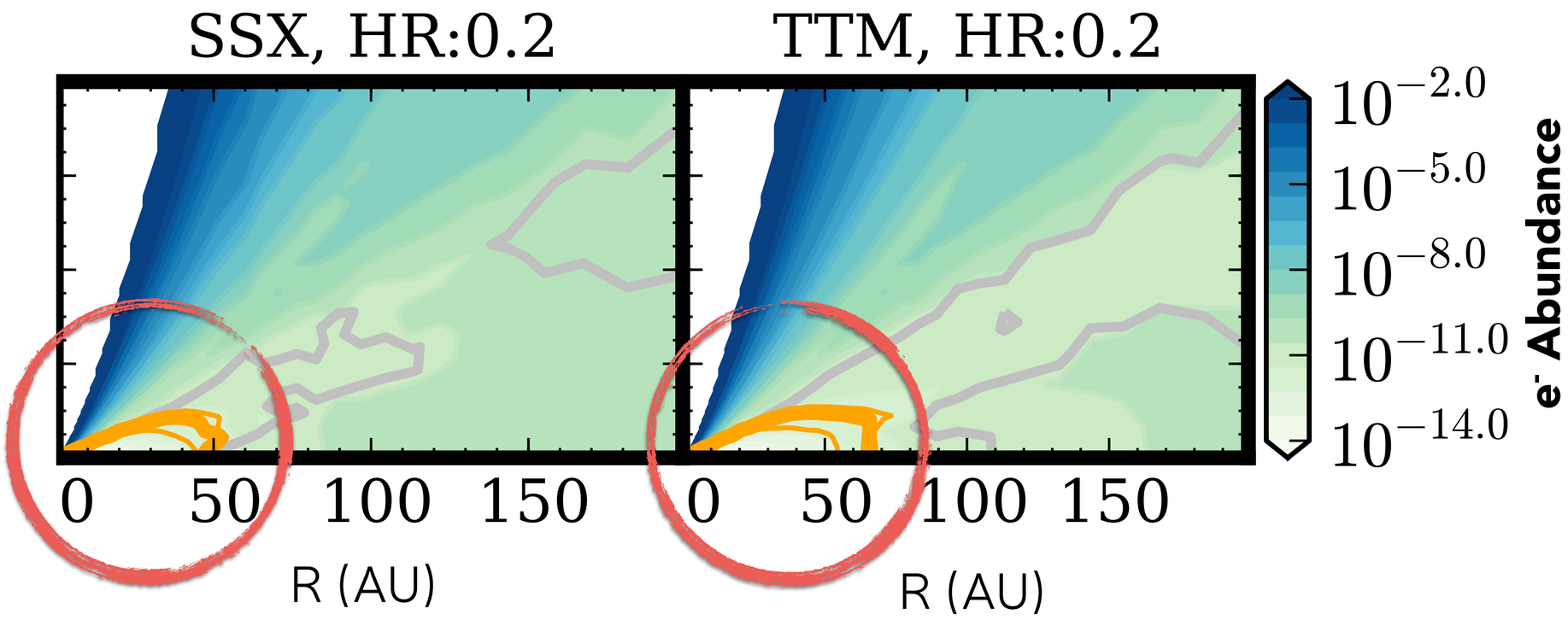
- Can estimate where the disk is MRI "dead" (Perez-Becker and Chiang 2010, Turner et al. 2007).
  - Re = B-field to plasma
  - Am = Ion-neutral collision time
- Re > 3300 (orange), Am > 0.1 (black). **Hatched region = Active.**
- Without CRs, MRI unsustainable at midplane → **large MRI "dead zones."**



Cleeves, Adams, and Bergin 2013a

IONIZATION AND DEAD ZONES: TW HYA

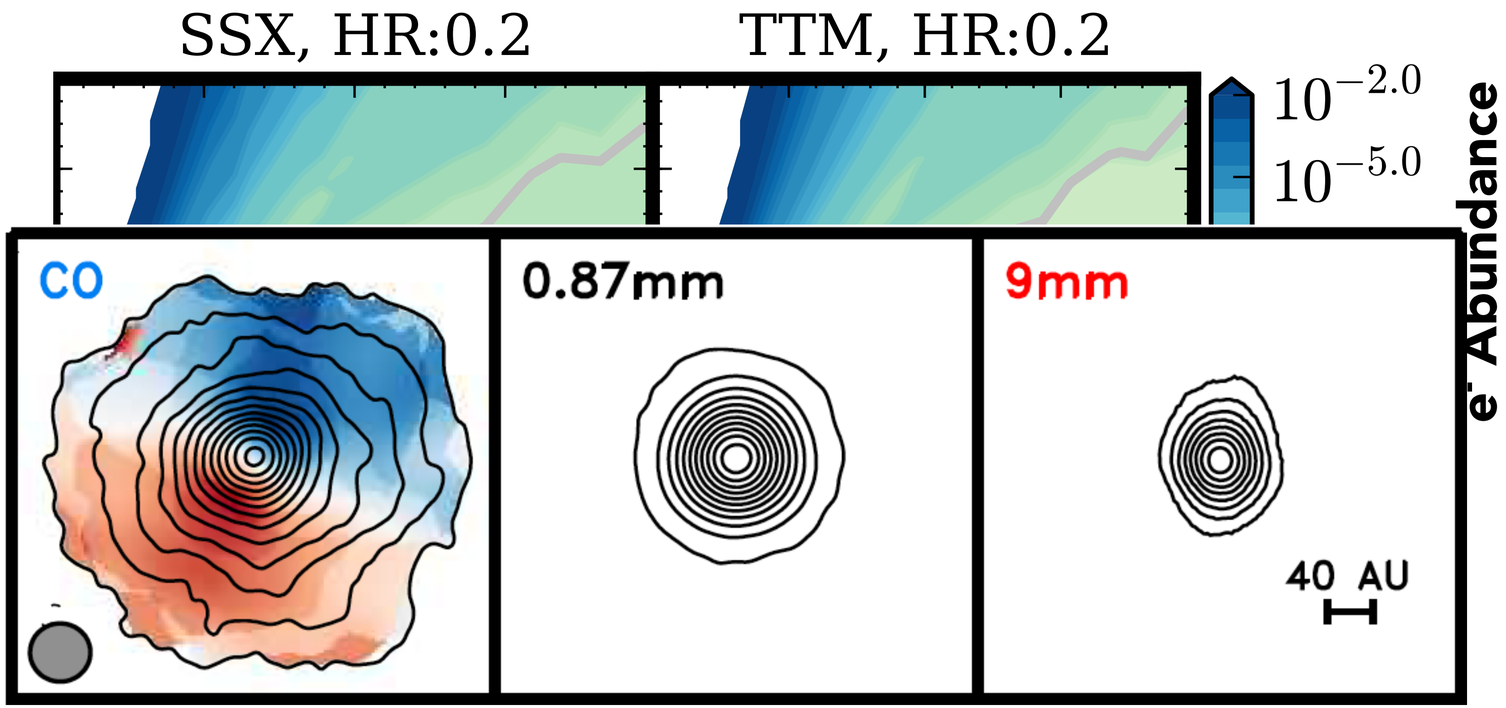
- Low ionization regions of the disk are quiescent against MRI (low turbulence).
  - **Predicted TW Hya dead zone of R~50-65 AU.**



Cleeves, Bergin, Qi, Adams, and Öberg 2015

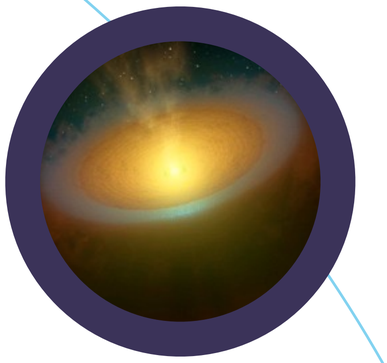
LOW IONIZATION IN THE TW HYA DISK: DEAD ZONES

- Low ionization regions of the disk are quiescent against MRI (low turbulence).
  - **Estimated TW Hya dead zone out to R~50-65 AU.**
- Coincides with region of mm-dust concentration.
  - **Perhaps dust coaguation is being facilitated by a dead zone out to ~65 AU?**



(Wilner+2000, Andrews+2012, Andrews 2015, Menu+2014)

Cleeves, Bergin, Qi, Adams, and Öberg 2015



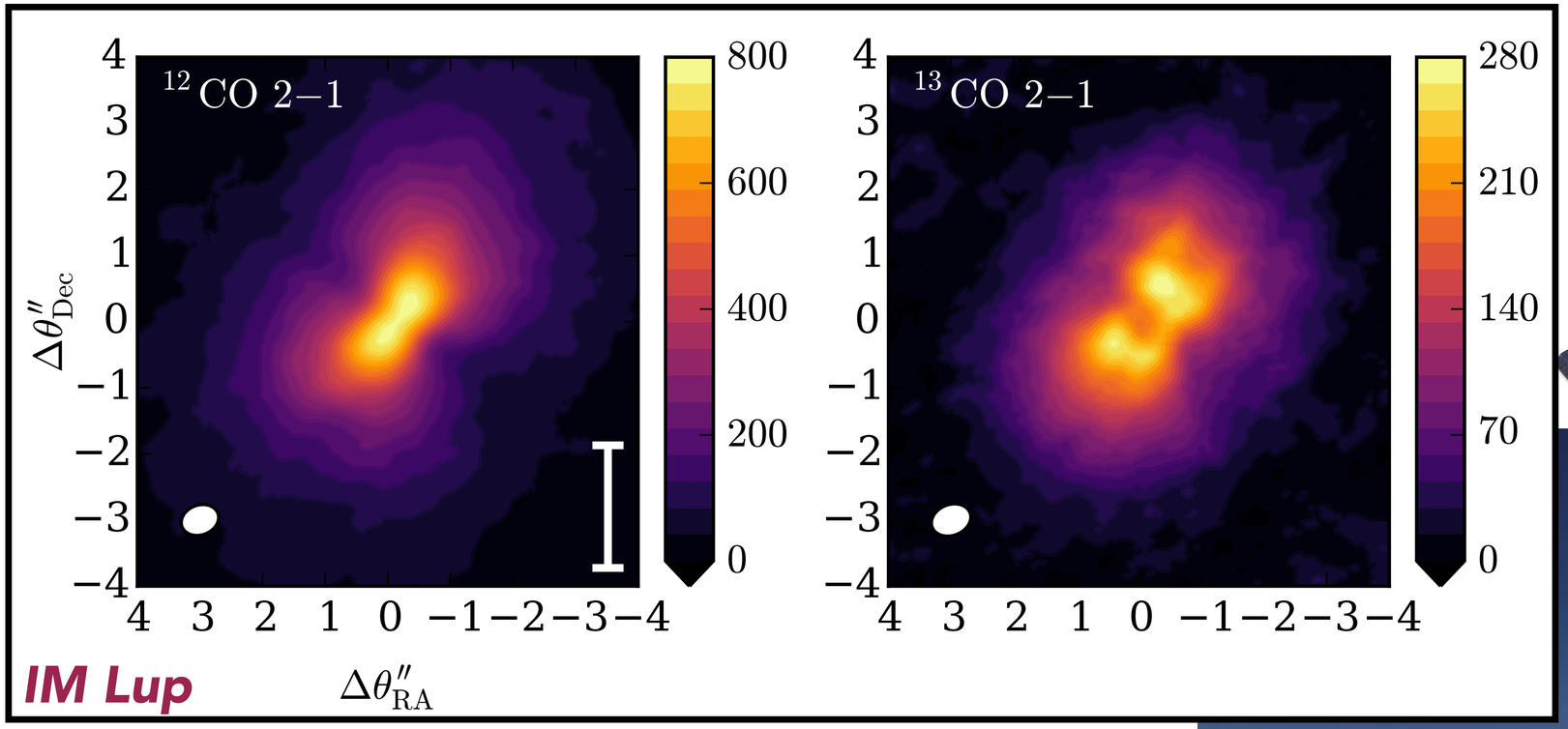
On-going Work and Future Directions

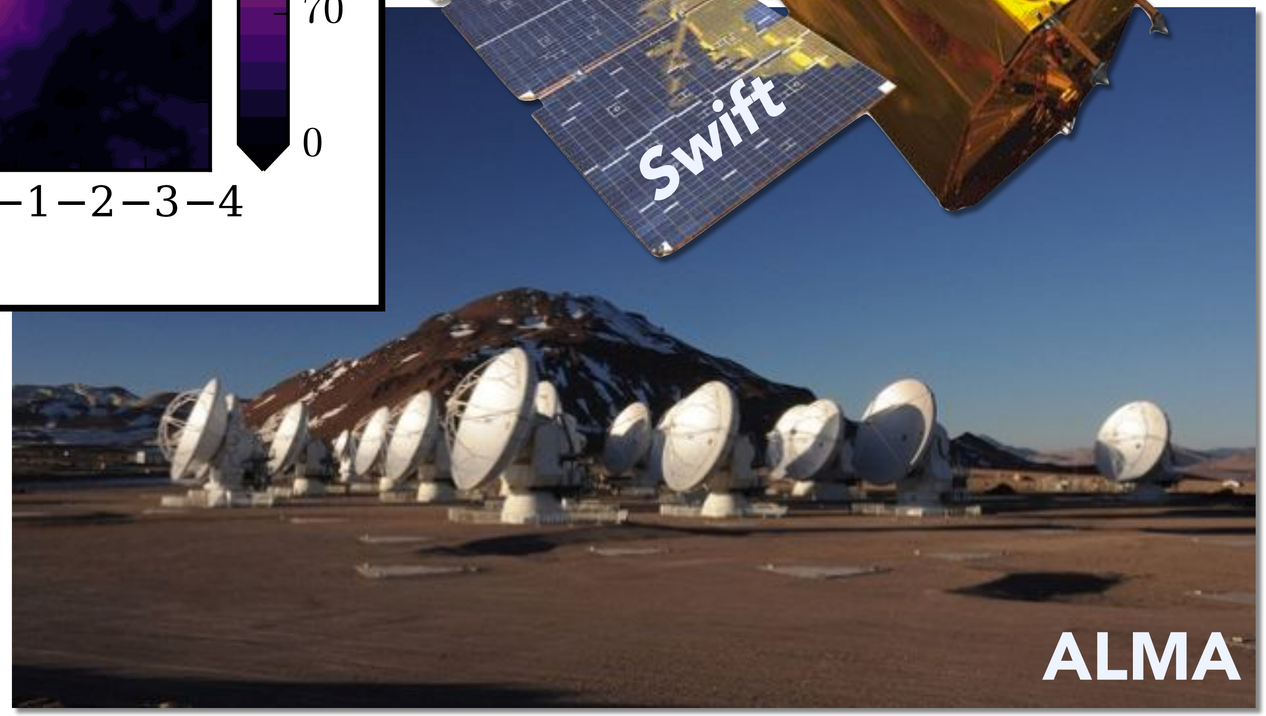
ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY (ALMA)

Chajnantor plateau, Atacama Desert, Chile (5000 meters)

Credit: ESO/B. Tafreshi (twanight.org)

FUTURE DIRECTIONS: MAPPING IONIZATION

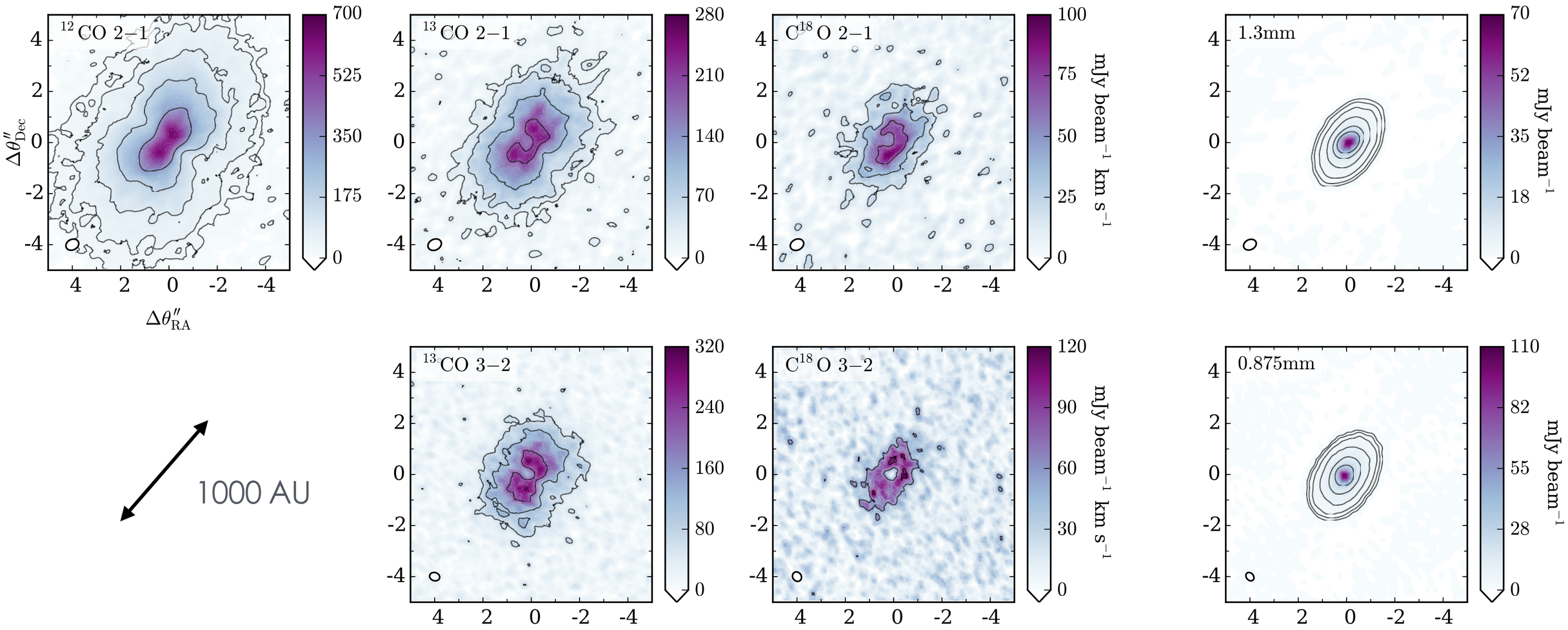




ALMA Cycle 2, mapping ionization in IM Lup at high resolution. ~25 beams across the diameter combined with *Swift* X-ray and UV observations of the star during the observations.

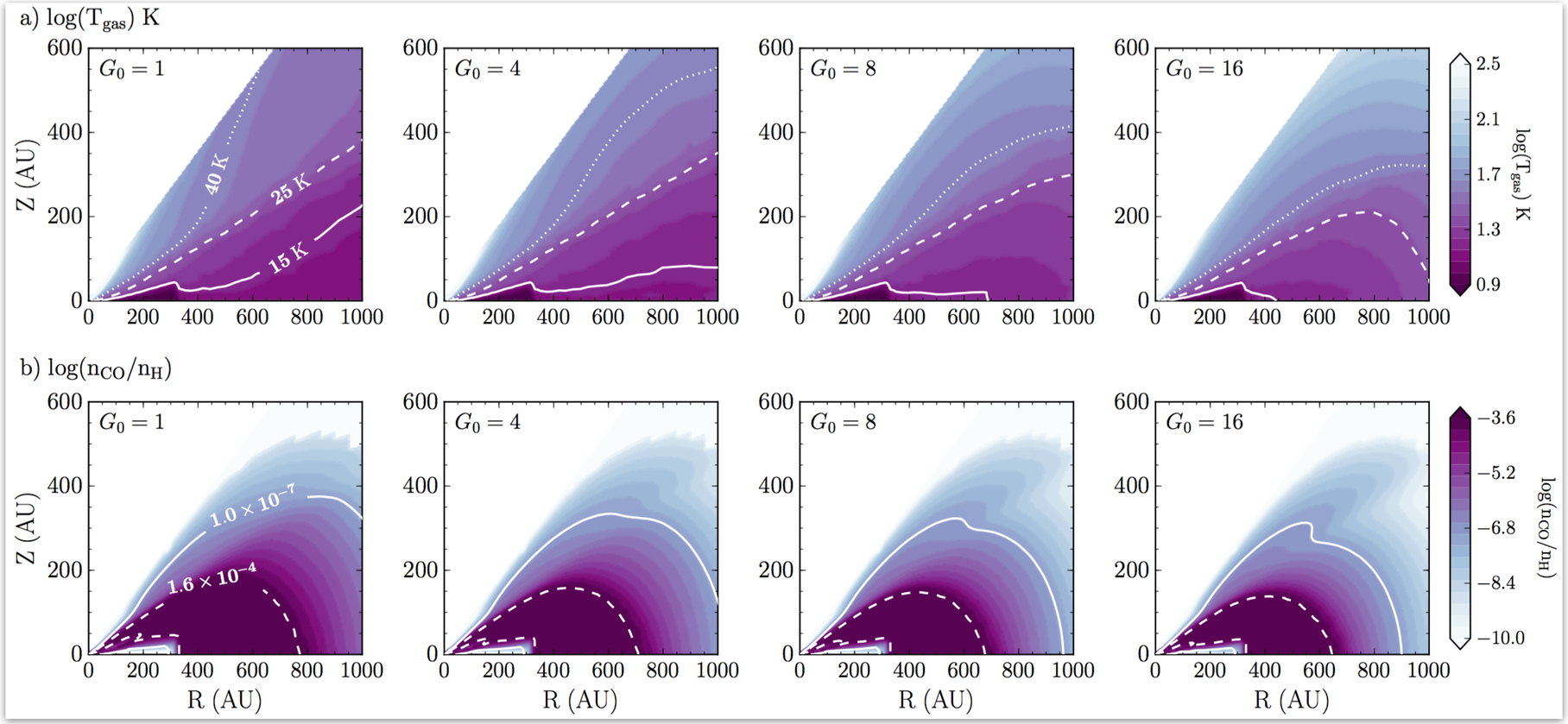
CO-EVOLVING DUST AND UV CHEMISTRY

IM Lup Protoplanetary Disk with ALMA, 161pc (Gaia)



Cleeves et al. 2016c

CO-EVOLVING DUST AND UV CHEMISTRY

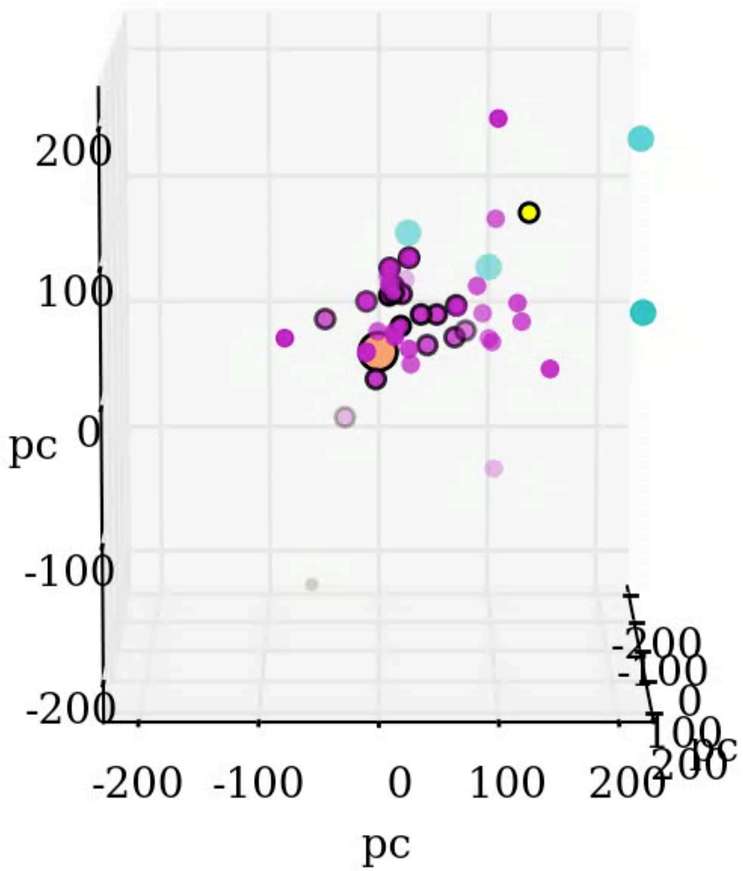


Result: Full suite of CO and continuum data consistent with UV exposed cold chemistry, with mild external UV, $G_0 \leqslant 4$.

Cleeves et al. 2016c

CO-EVOLVING DUST AND UV CHEMISTRY

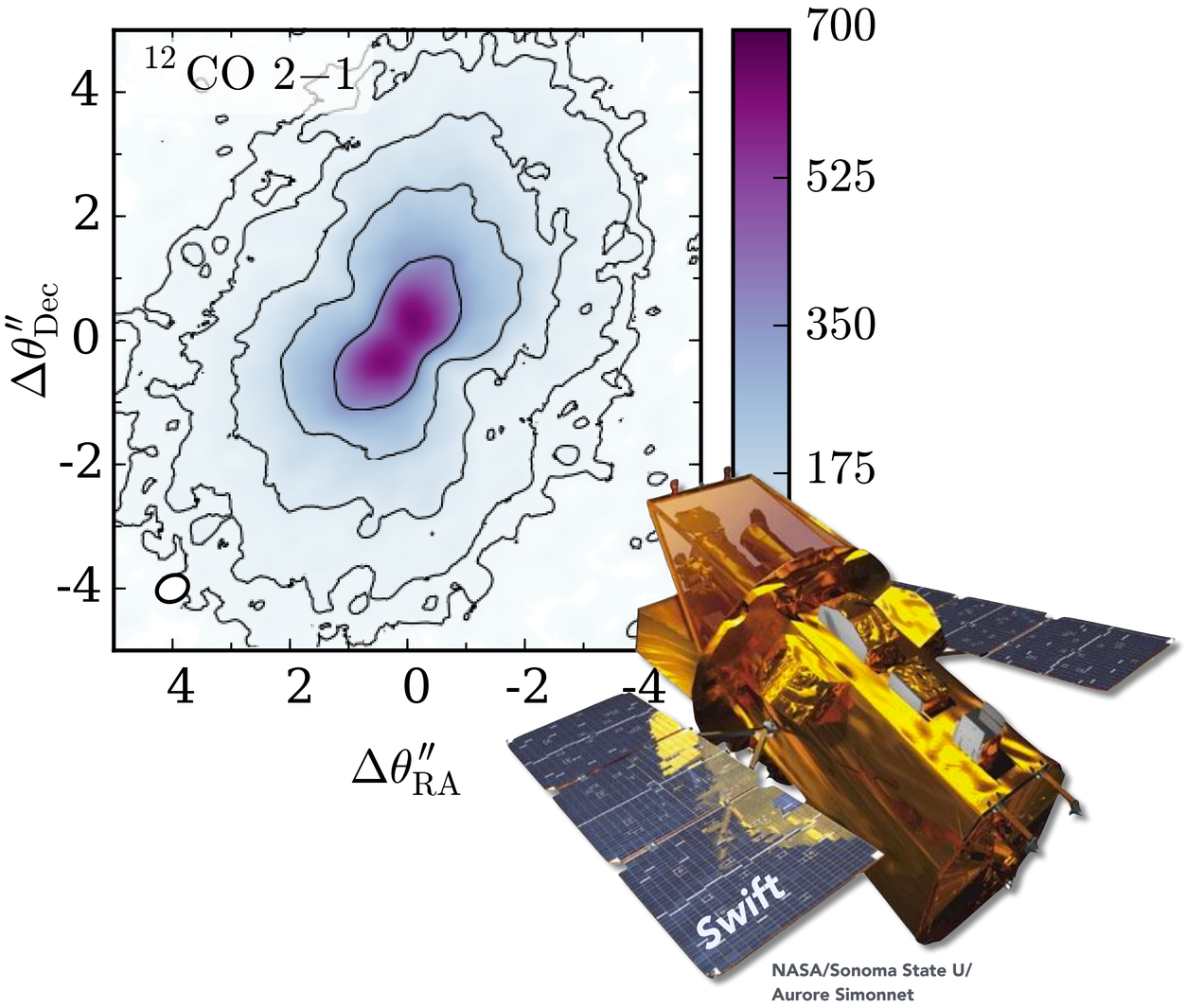
IM Lup Protoplanetary Disk with ALMA, 161pc (Gaia)



Result: External UV consistent with the local stellar population from Hipparcos population.

Cleeves et al. 2016c

IONIZATION IN THE IM LUP PROTOPLANETARY DISK WITH ALMA AND *SWIFT*



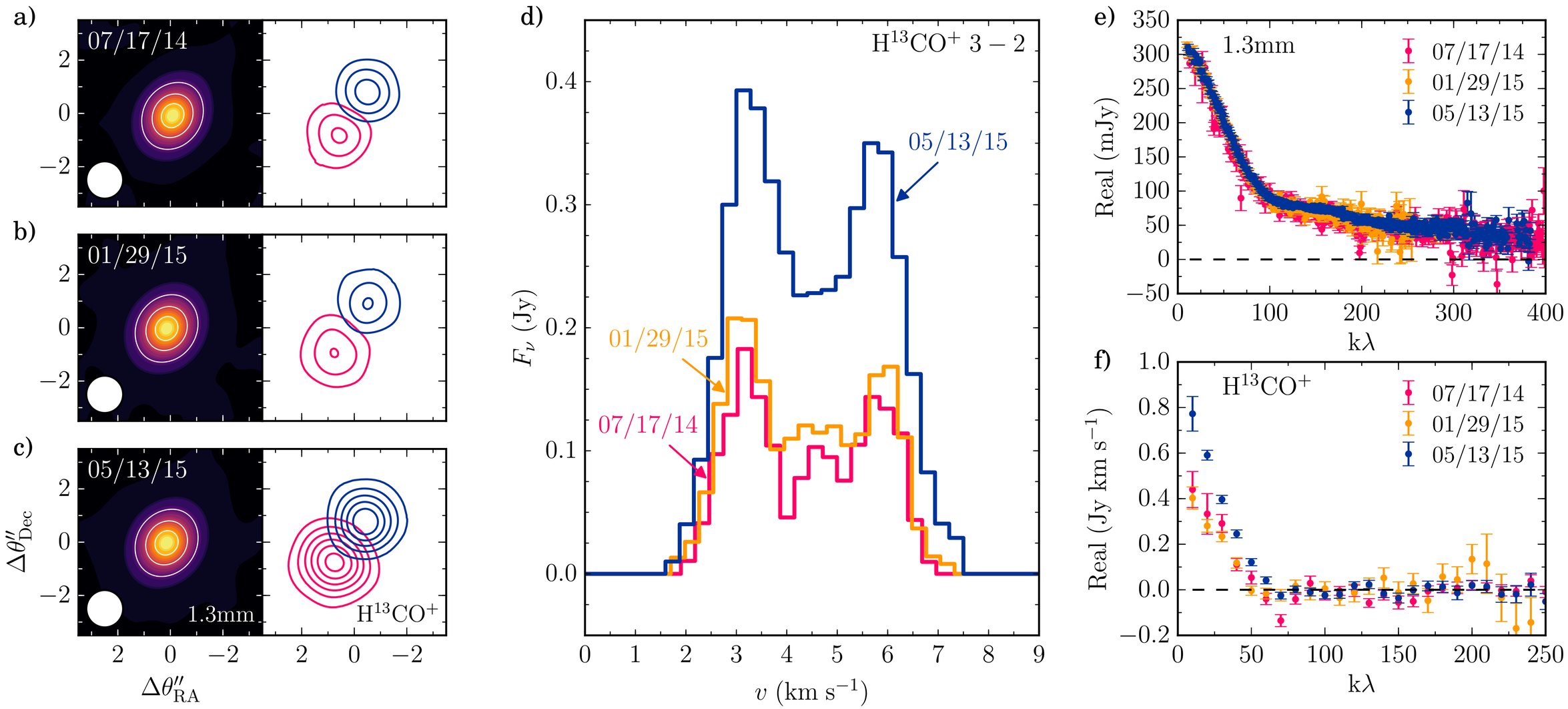
NASA/Sonoma State U/
Aurore Simonnet

Gas and dust constraints plus:

+ N_2H^+ 3-2,
+ DCO^+ 4-3, 3-2,
+ $H^{13}CO^+$, 3-2,
+ $HC^{18}O^+$ 4-3, 3-2 …

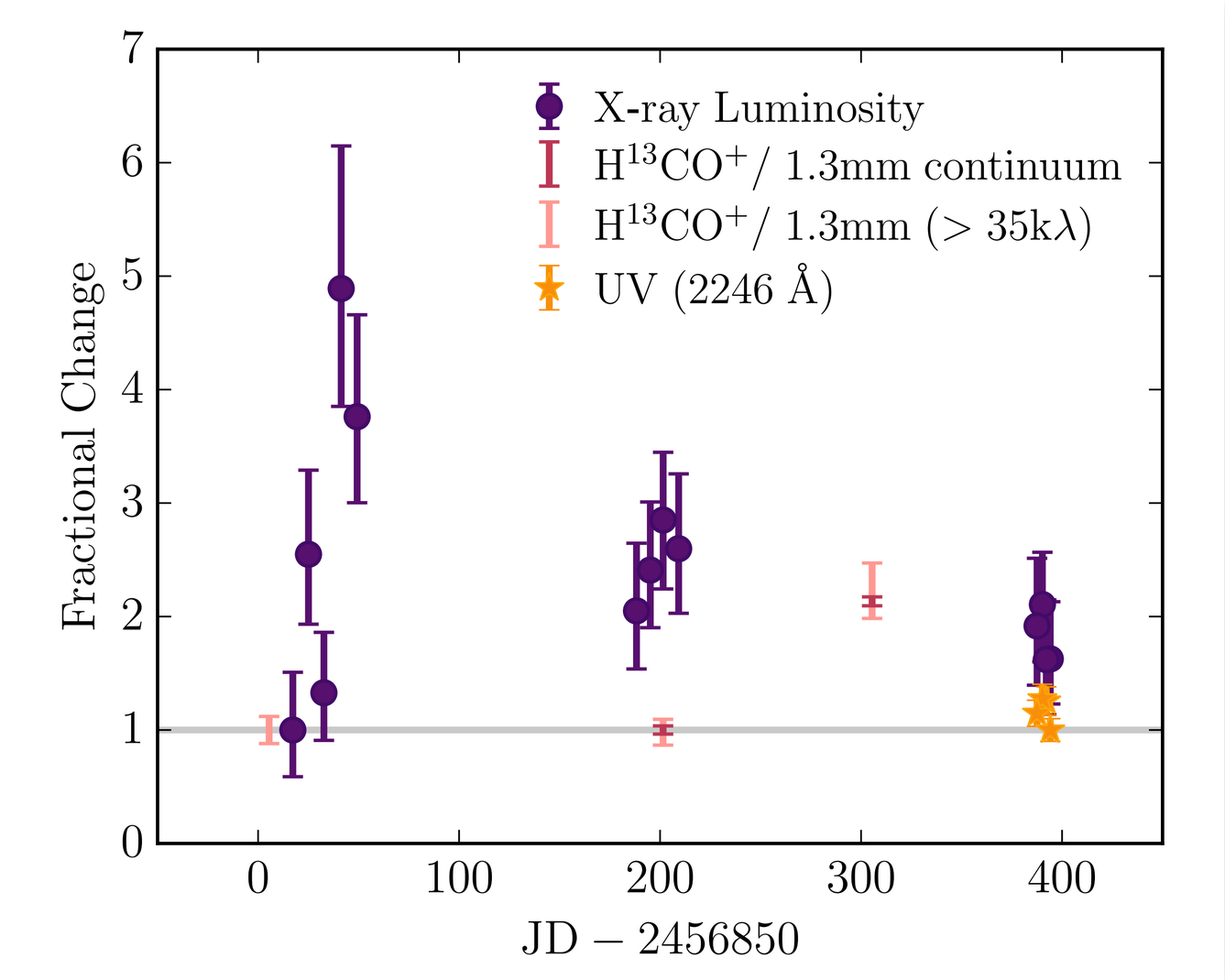
IONIZATION IN THE IM LUP PROTOPLANETARY DISK WITH ALMA AND *SWIFT*

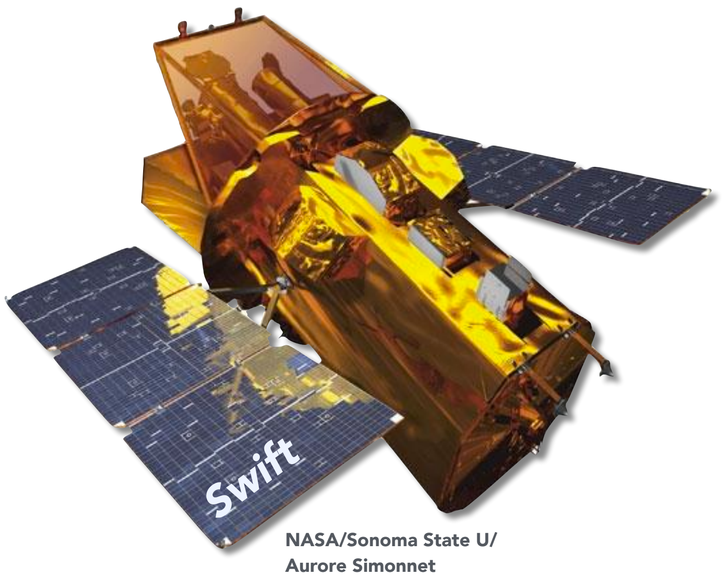
Variable Ion chemistry in $H^{13}CO^+$!



Cleeves et al. 2017, submitted

IONIZATION IN THE IM LUP PROTOPLANETARY DISK WITH ALMA AND *SWIFT*

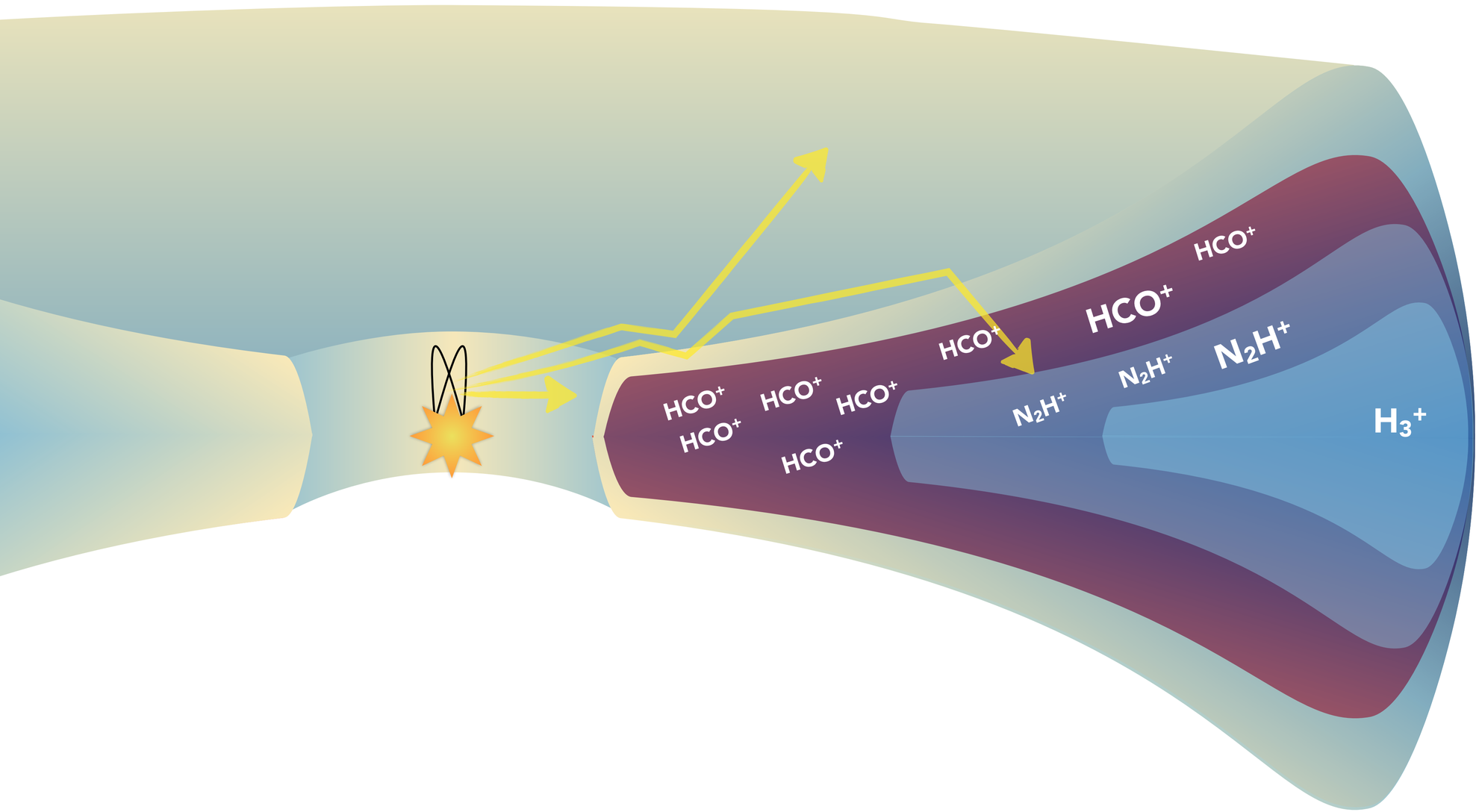




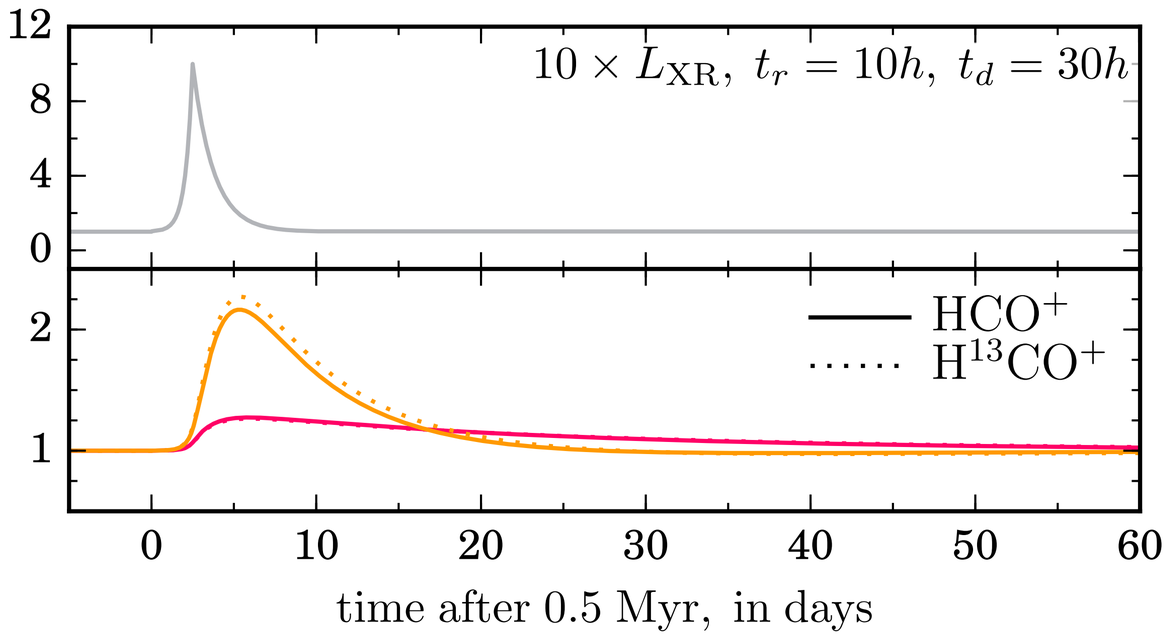
NASA/Sonoma State U/
Aurore Simonnet

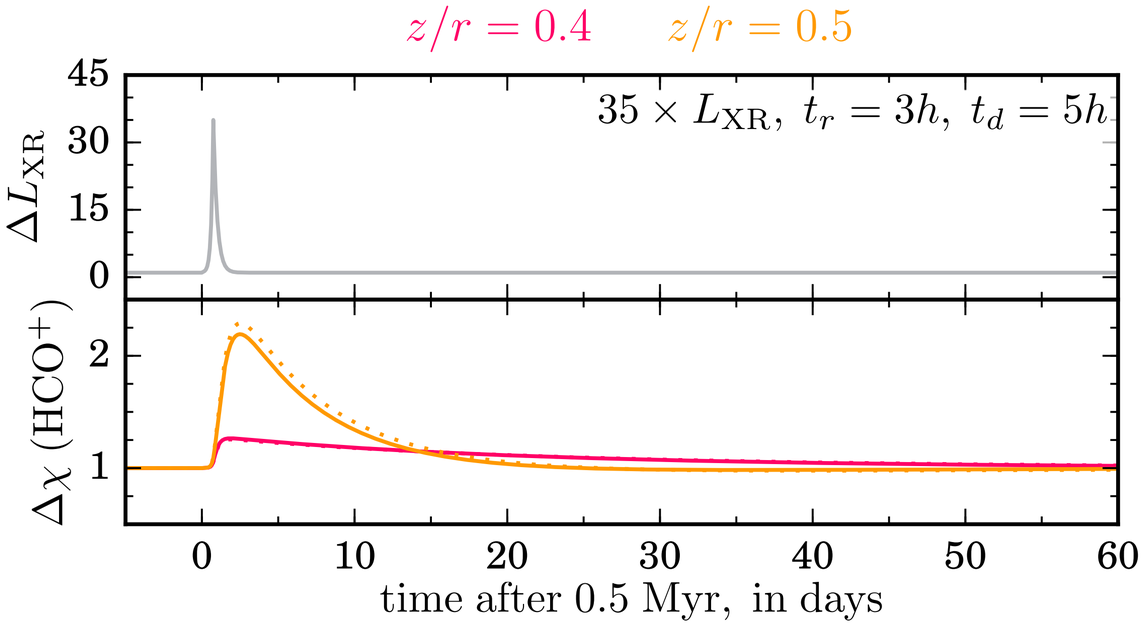
Cleeves et al. 2017, submitted

IONIZATION AND DEAD ZONES



IONIZATION IN THE IM LUP PROTOPLANETARY DISK WITH ALMA AND *SWIFT*





Consistent with model expectations for high energy X-ray flares!

CONCLUSIONS

1

External and internal ionizing processes, which impact MRI efficiency, thermal structure, dust growth, and disk chemistry.

2

X-rays, cosmic rays, short-lived radionuclides most important for setting the ionization in the molecular disk.

3

Detailed modeling of TW Hya's molecular ions already points to low global CR rate ($\zeta_{CR}<10^{-19}$ s^{-1}).

4

Preliminary modeling of IM Lup suggests similar low CR rates, but also variable, X-ray driven ion chemistry perhaps along with radioactivity.

Thank you!