TIME-DOMAIN ASTROCHEMISTRY DURING PLANET FORMATION

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ALMA2019: Science Results and Cross-Facility Synergies
October 15, 2019

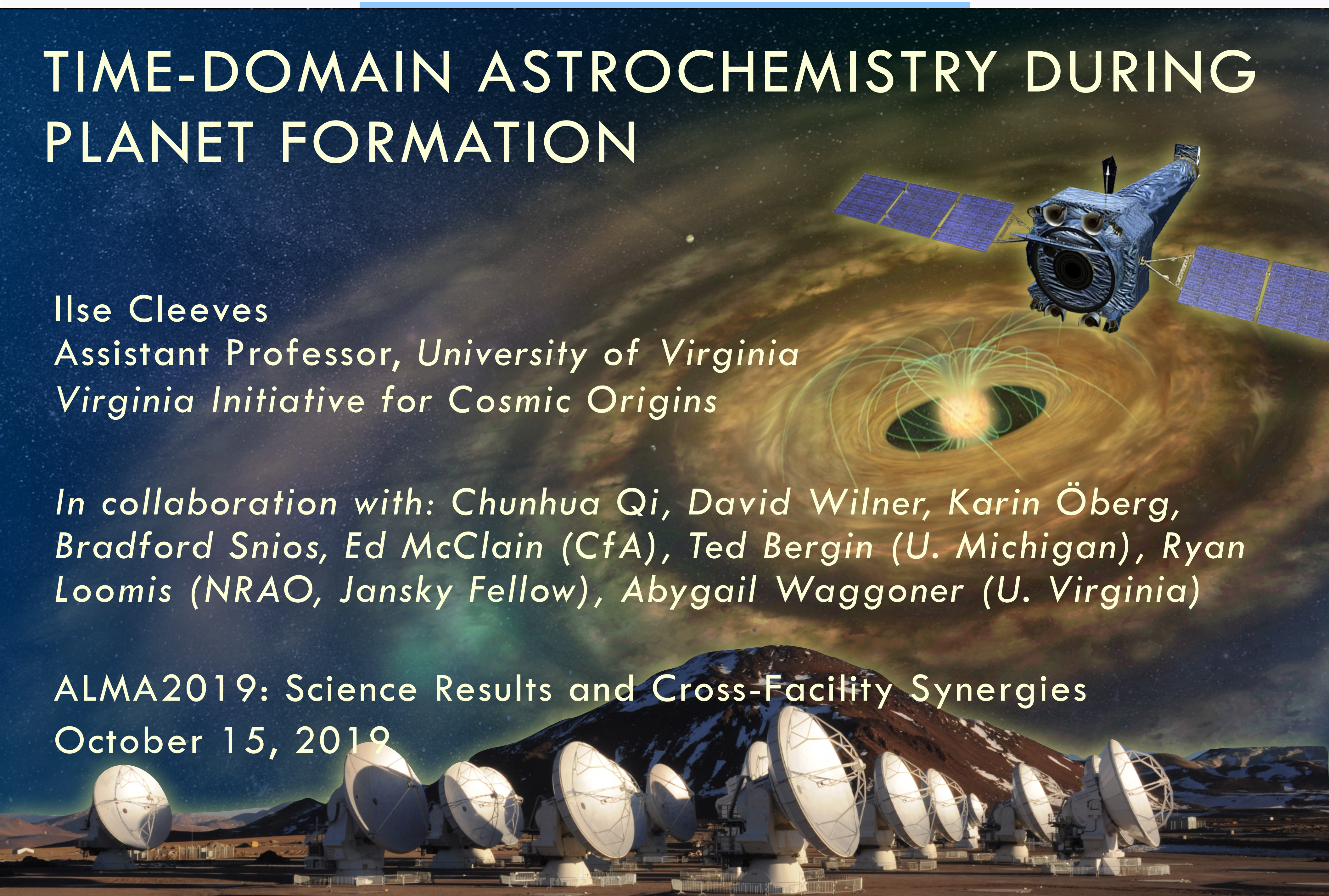
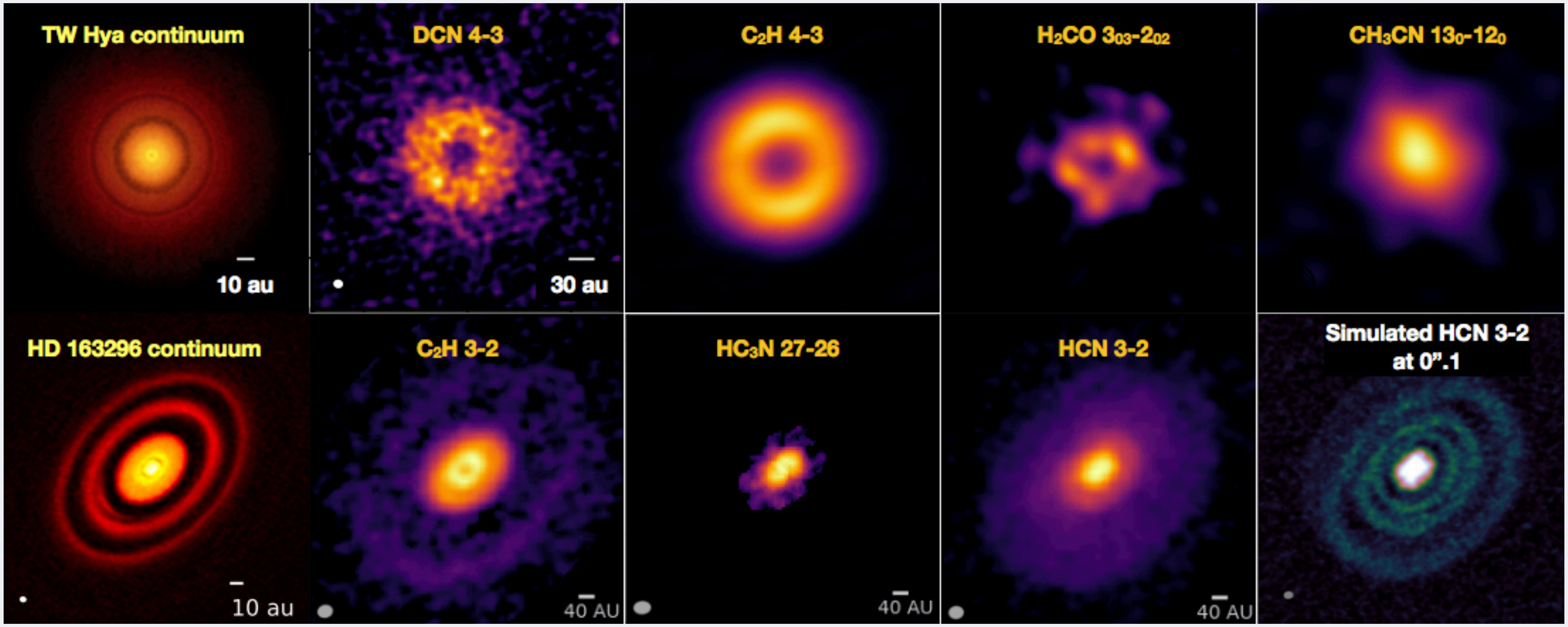
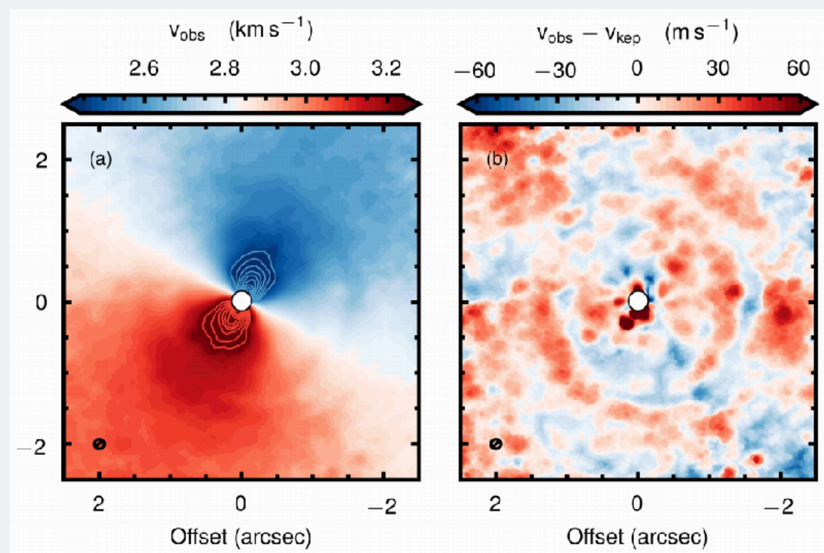


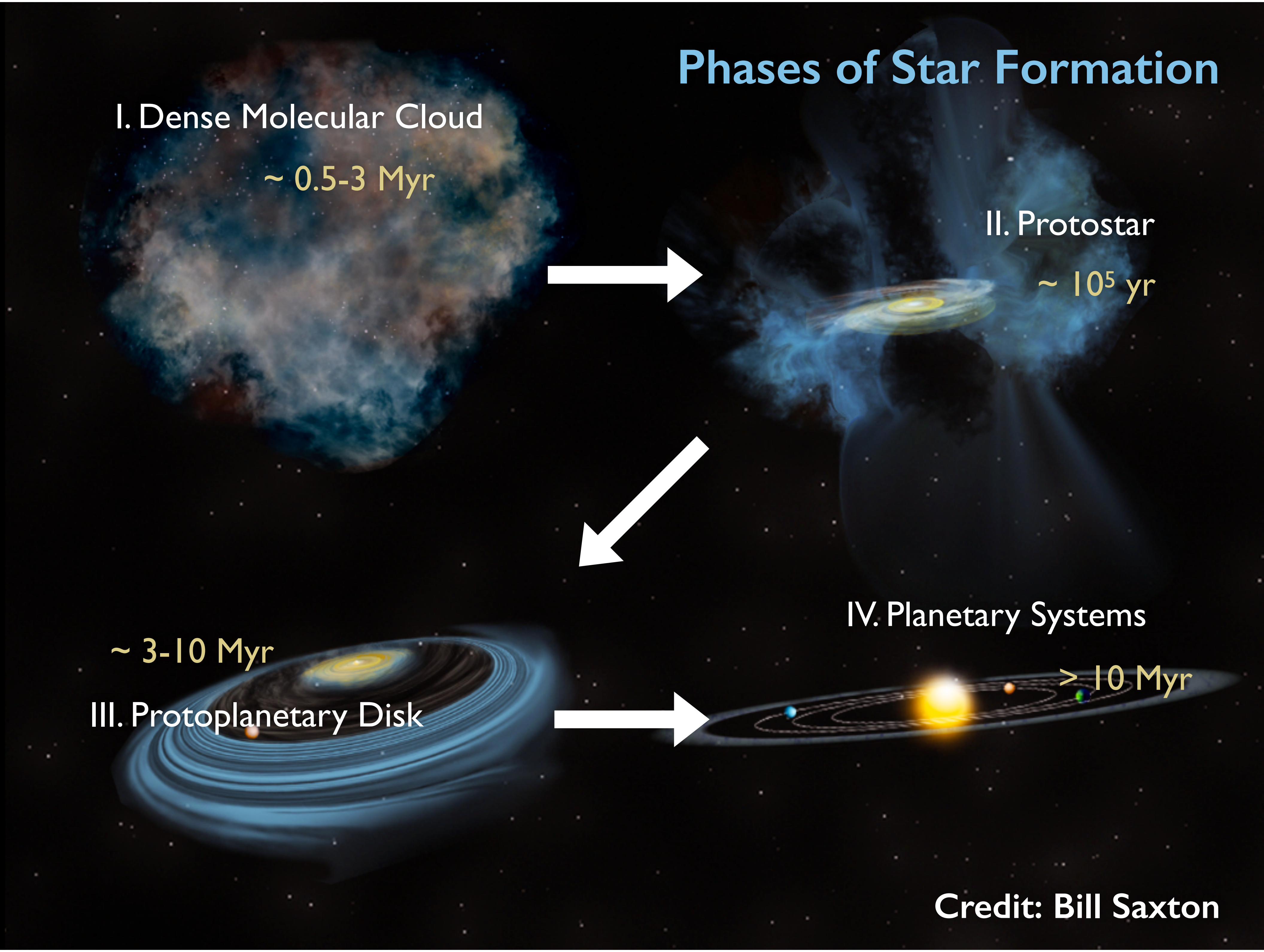
Image Credit: NASA/JPL-Caltech/R. Hurt (SSC), University of Copenhagen/Lars Buchhave, W. Garnier, ALMA (ESO/NAOJ/NRAO)

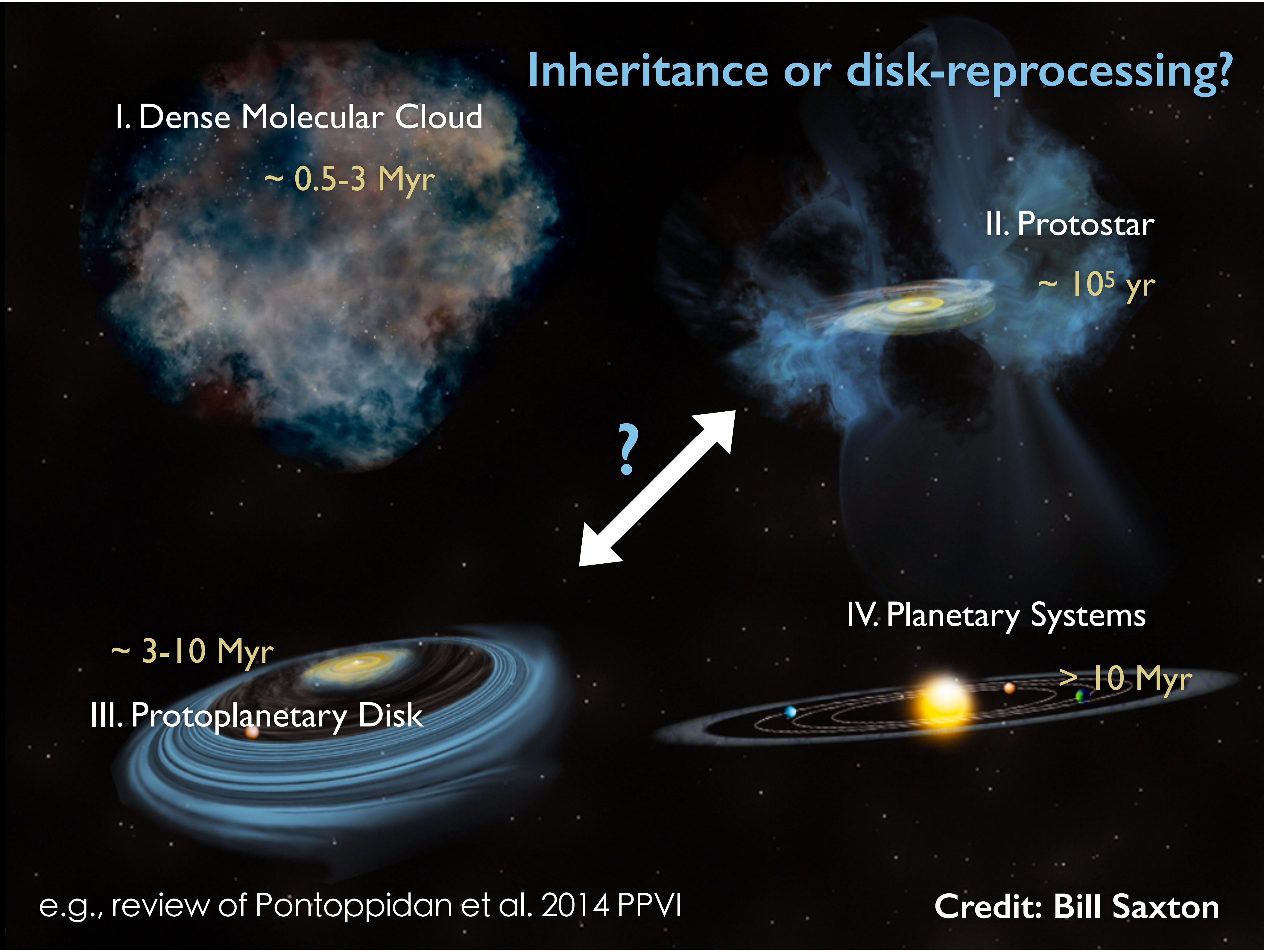
ALMA REVOLUTION IN DISK PHYSICS & CHEMISTRY





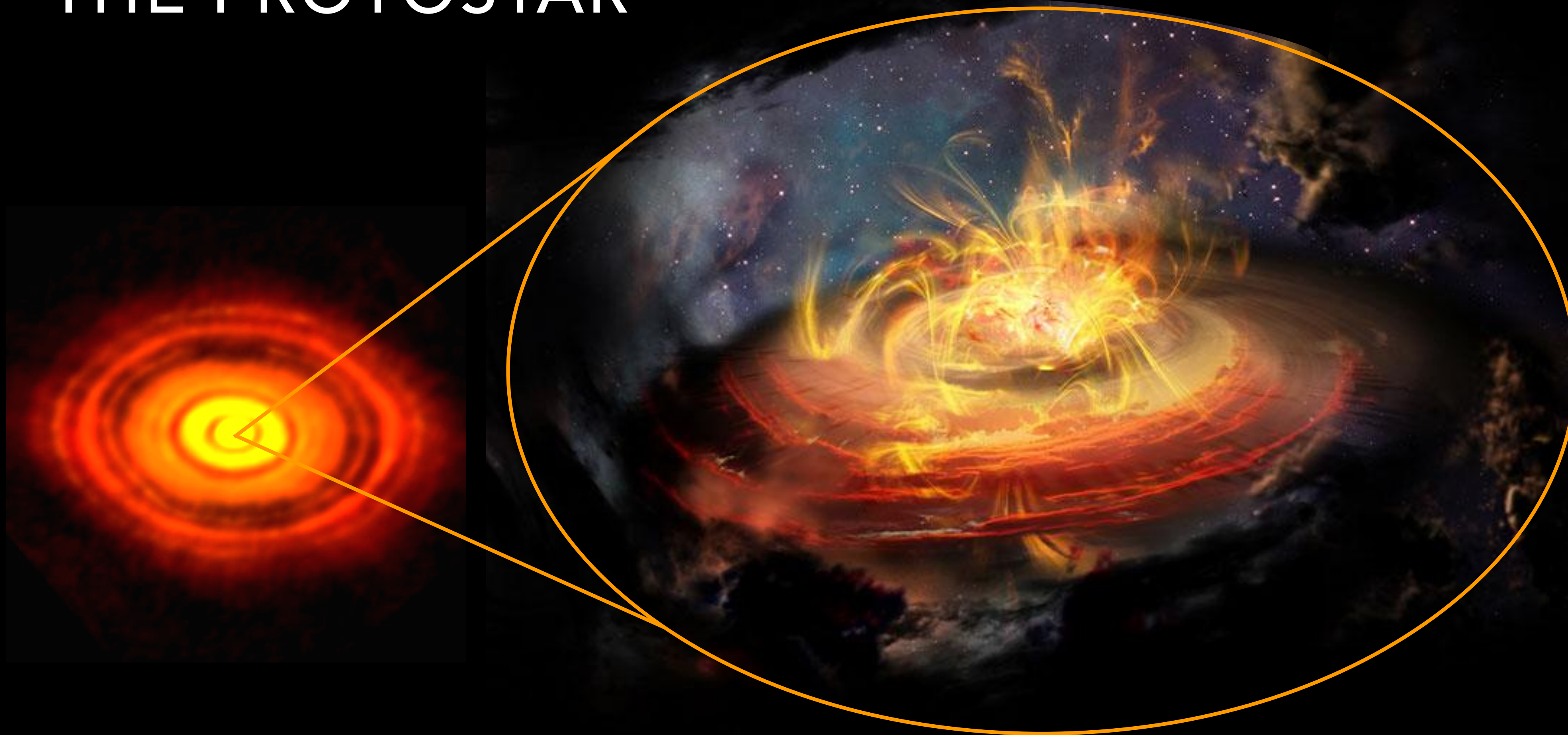
Oberg+2019, Cleeves+2019 Decadal WPs and ref therein, Teague+2019


Phases of Star Formation
I. Dense Molecular Cloud
~ 0.5-3 Myr
II. Protostar
~ 10⁵ yr
~ 3-10 Myr
III. Protoplanetary Disk
IV. Planetary Systems
> 10 Myr
Credit: Bill Saxton



Inheritance or disk-reprocessing?
I. Dense Molecular Cloud
~ 0.5-3 Myr
II. Protostar
~ 10^5 yr
?
~ 3-10 Myr
III. Protoplanetary Disk
IV. Planetary Systems
> 10 Myr
e.g., review of Pontoppidan et al. 2014 PPVI
Credit: Bill Saxton

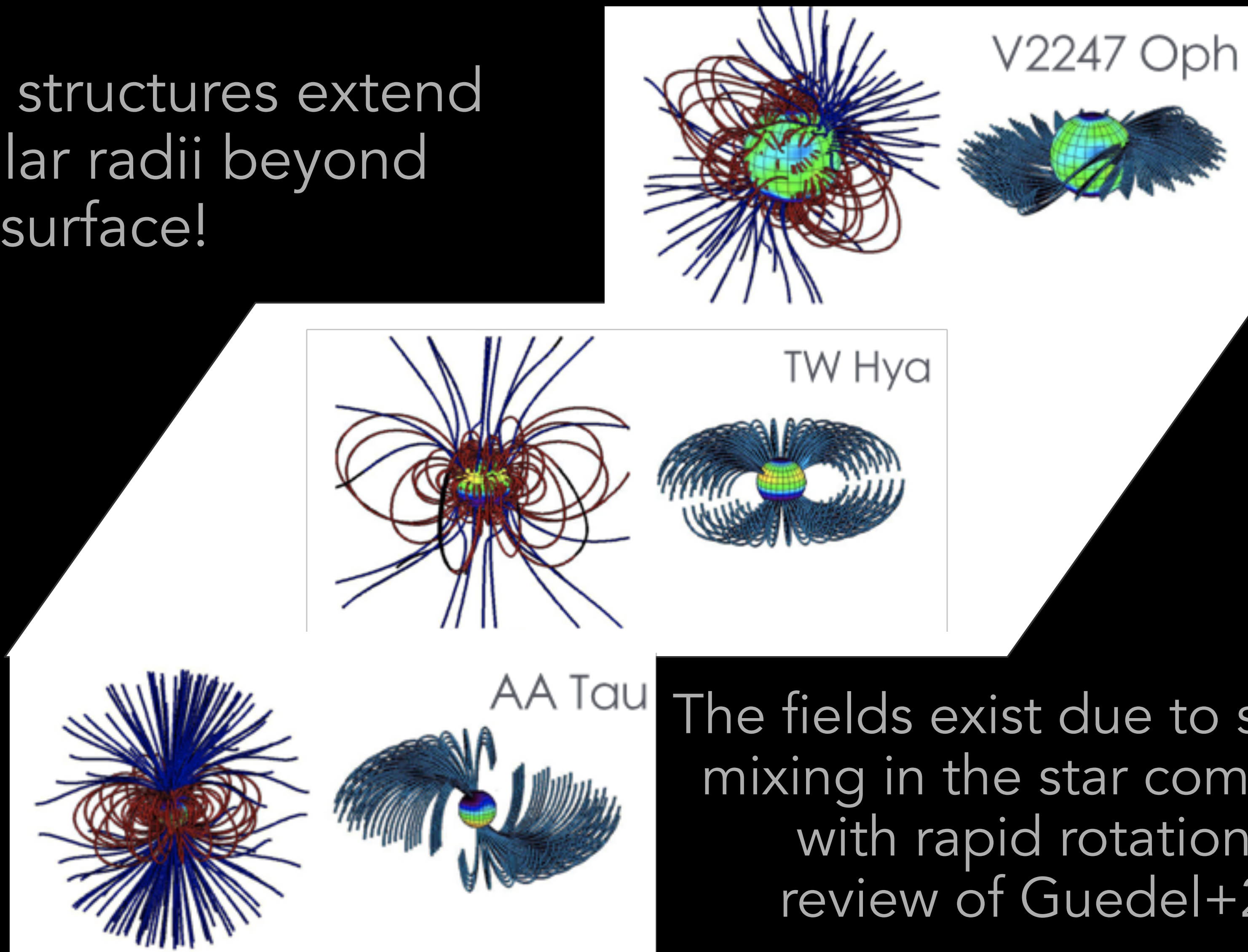
A LURKING "MONSTER": THE PROTOSTAR



Credit: Brogan, ALMA Partnership, NRAO/
AUI/NSF; D. Berry

Young Stars Tangled Magnetic Webs

Magnetic structures extend many stellar radii beyond the star's surface!



Credit: Johnstone et al. 2013

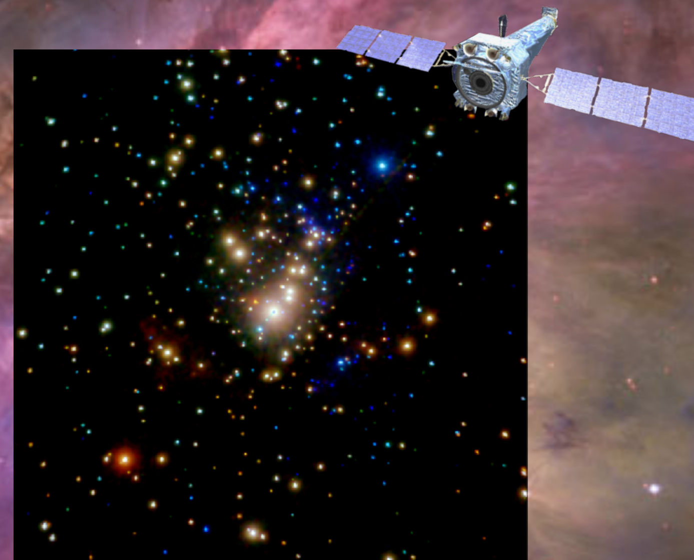
The fields exist due to strong mixing in the star combined with rapid rotation (e.g., review of Guedel+2004).

Trap hot x-ray emitting gas!

The Orion Star Forming Region

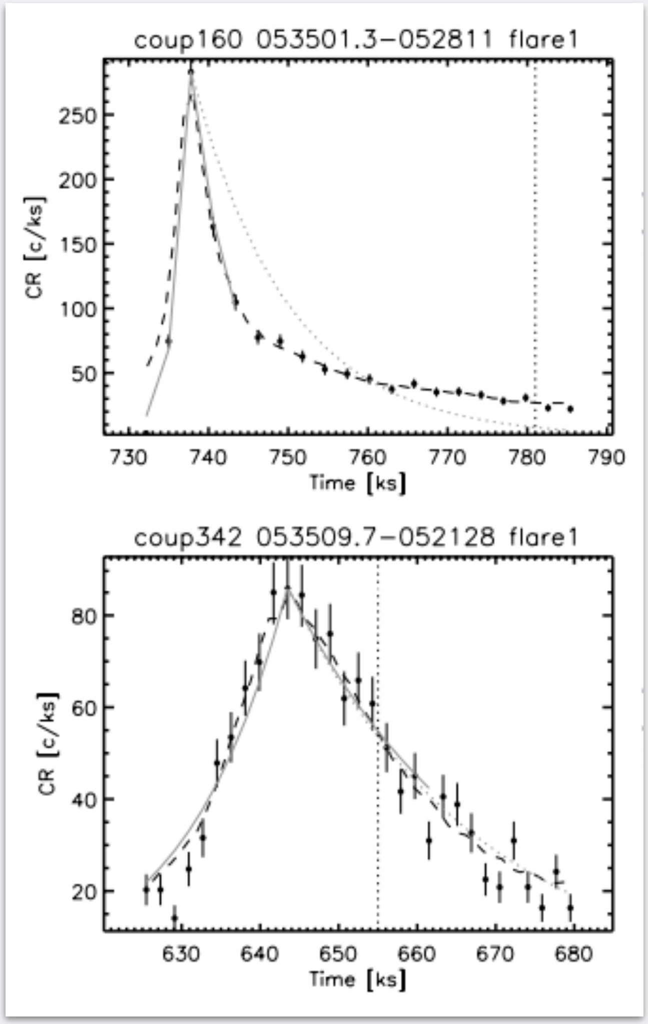
Optical/IR image from HST

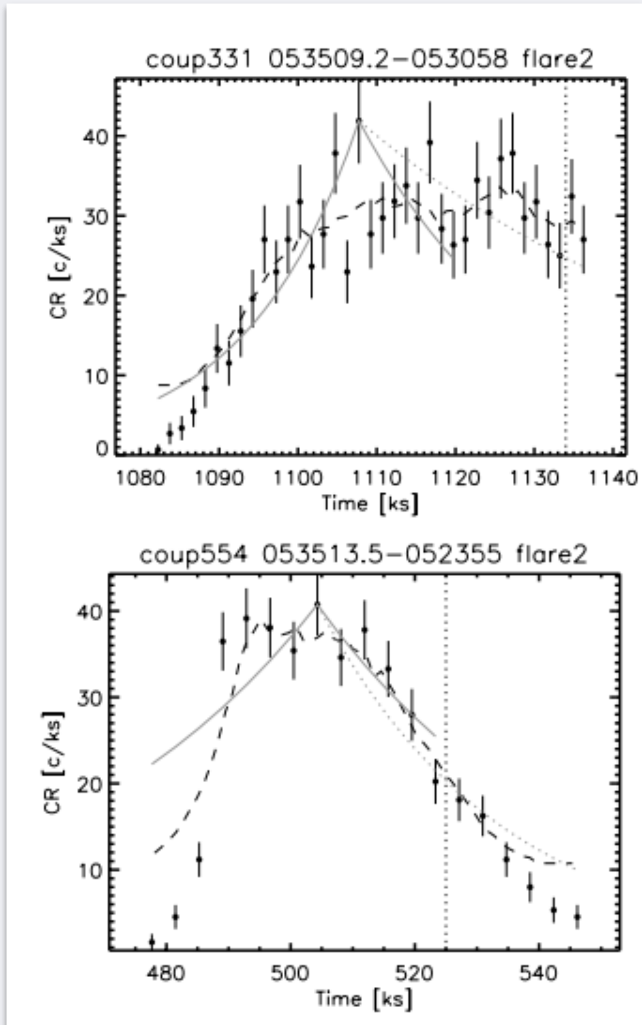
Chandra X-ray image from the *Chandra* Orion Ultradeep Project (COUP), e.g. Getman+2005

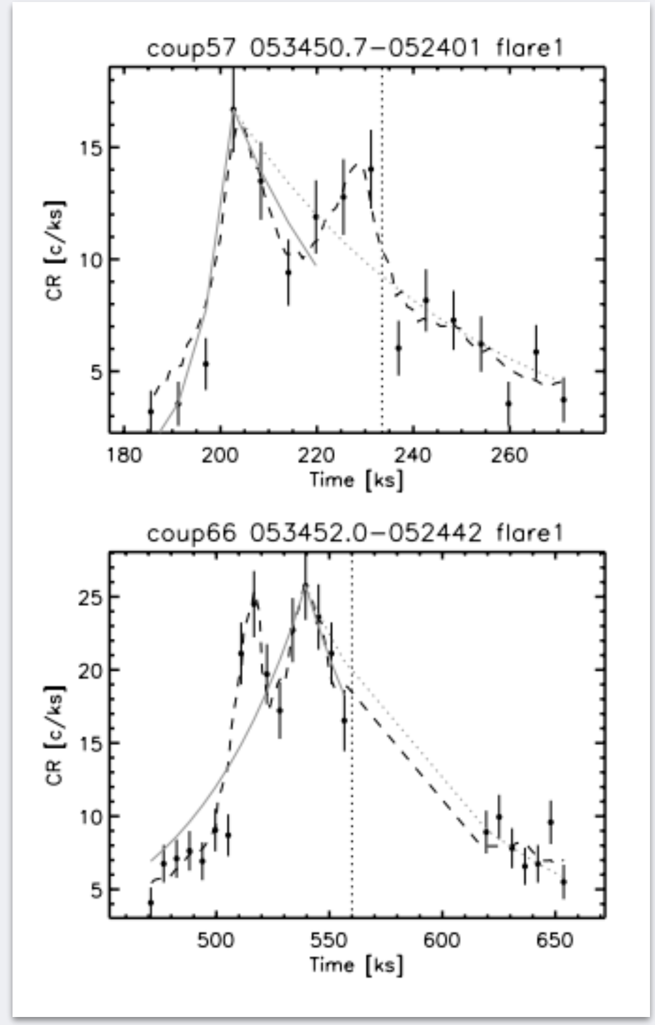


The young stars light up in X-rays!

X-RAYS: BRIGHT *AND* VARIABLE

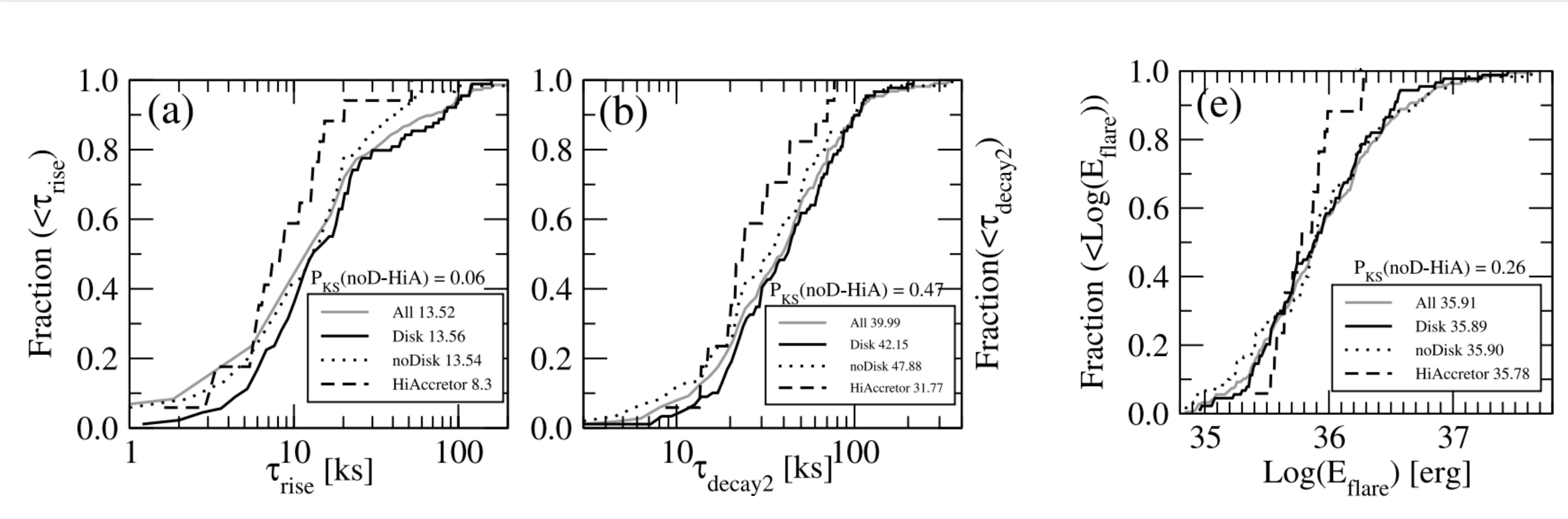






COUP Results on Flaring: Getman et al. 2008, Favata et al. 2005

YOUNG STARS' X-RAY FLARES



Typical rise time ~3-4^h

Typical decay time ~11-13^h

Typical energy ~10^{36} erg

COUP Results on Flaring: Getman et al. 2008, Favata et al. 2005

A HARSH ENVIRONMENT FOR PLANETS?

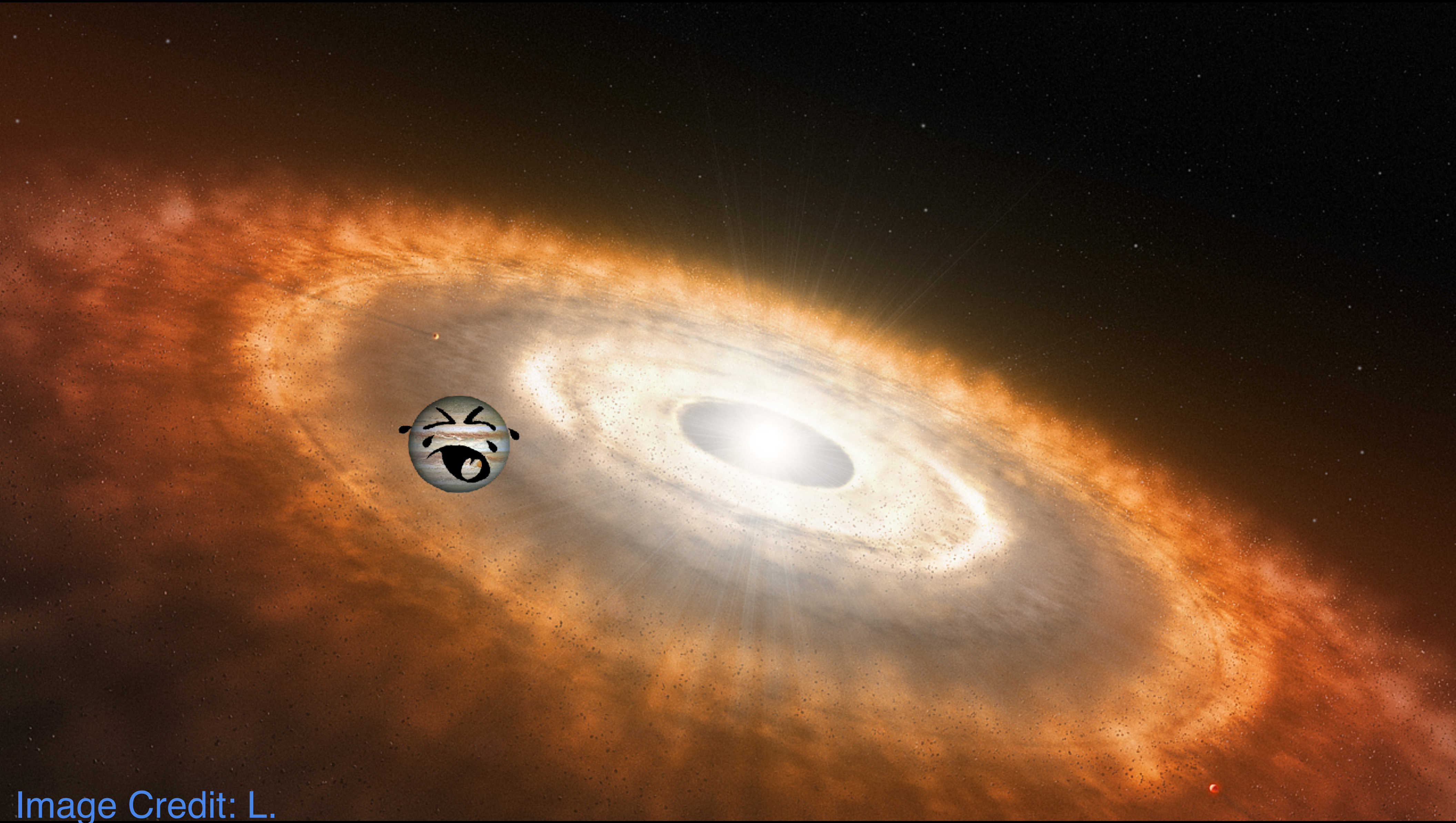
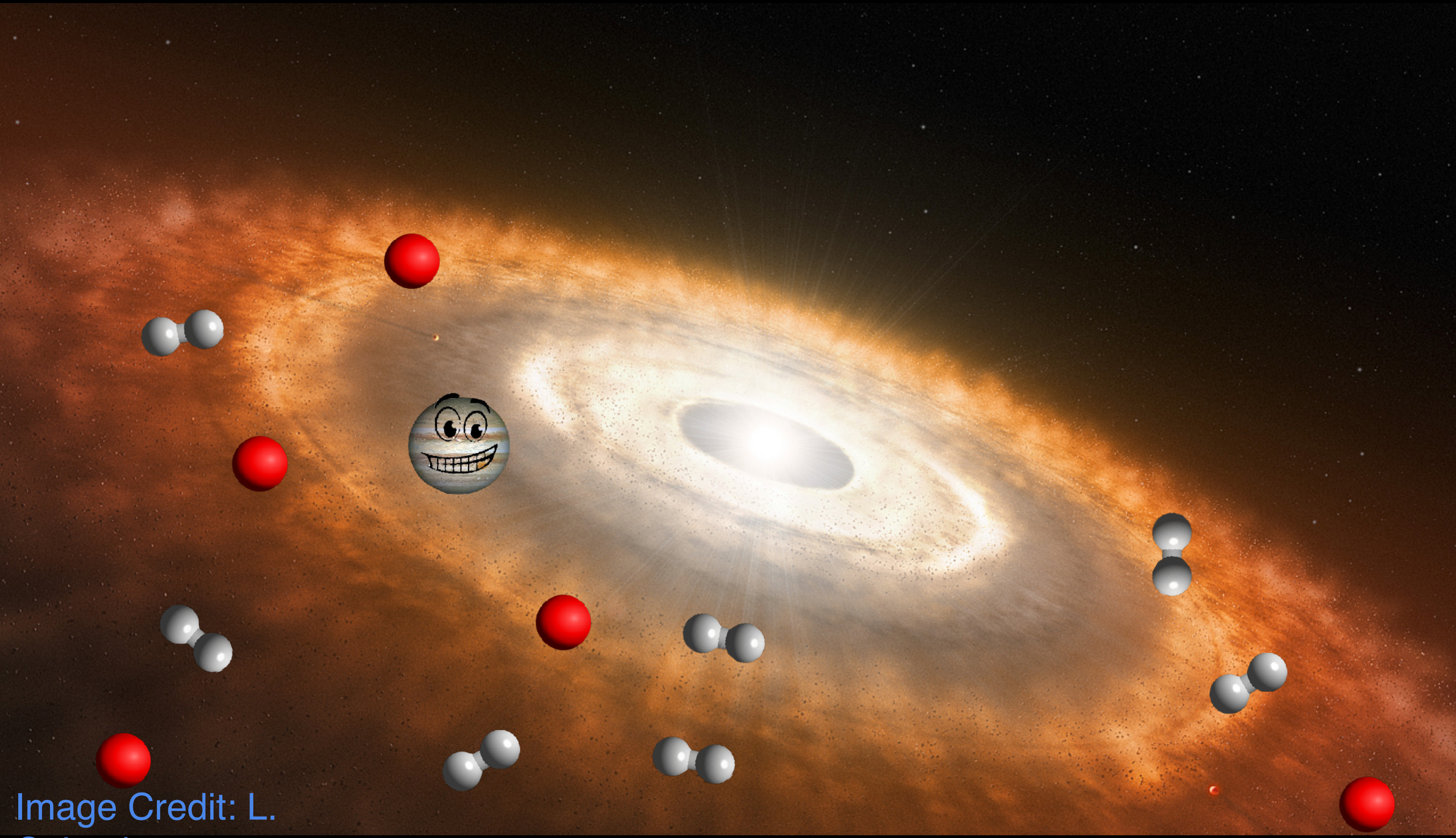


Image Credit: L. Calçada

NOT ENTIRELY... ENABLES CHEMISTRY



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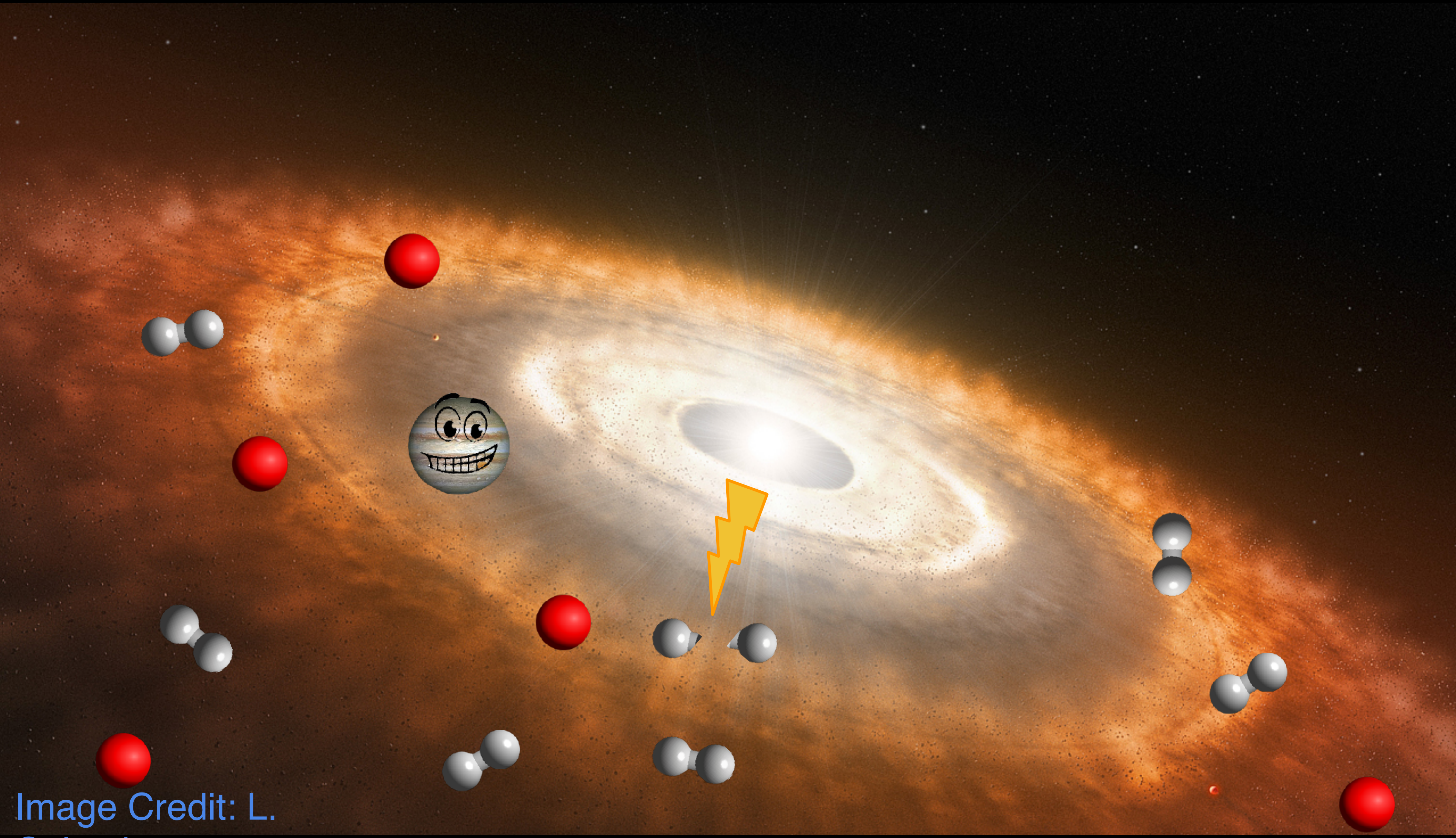

Image Credit: L. Calçada

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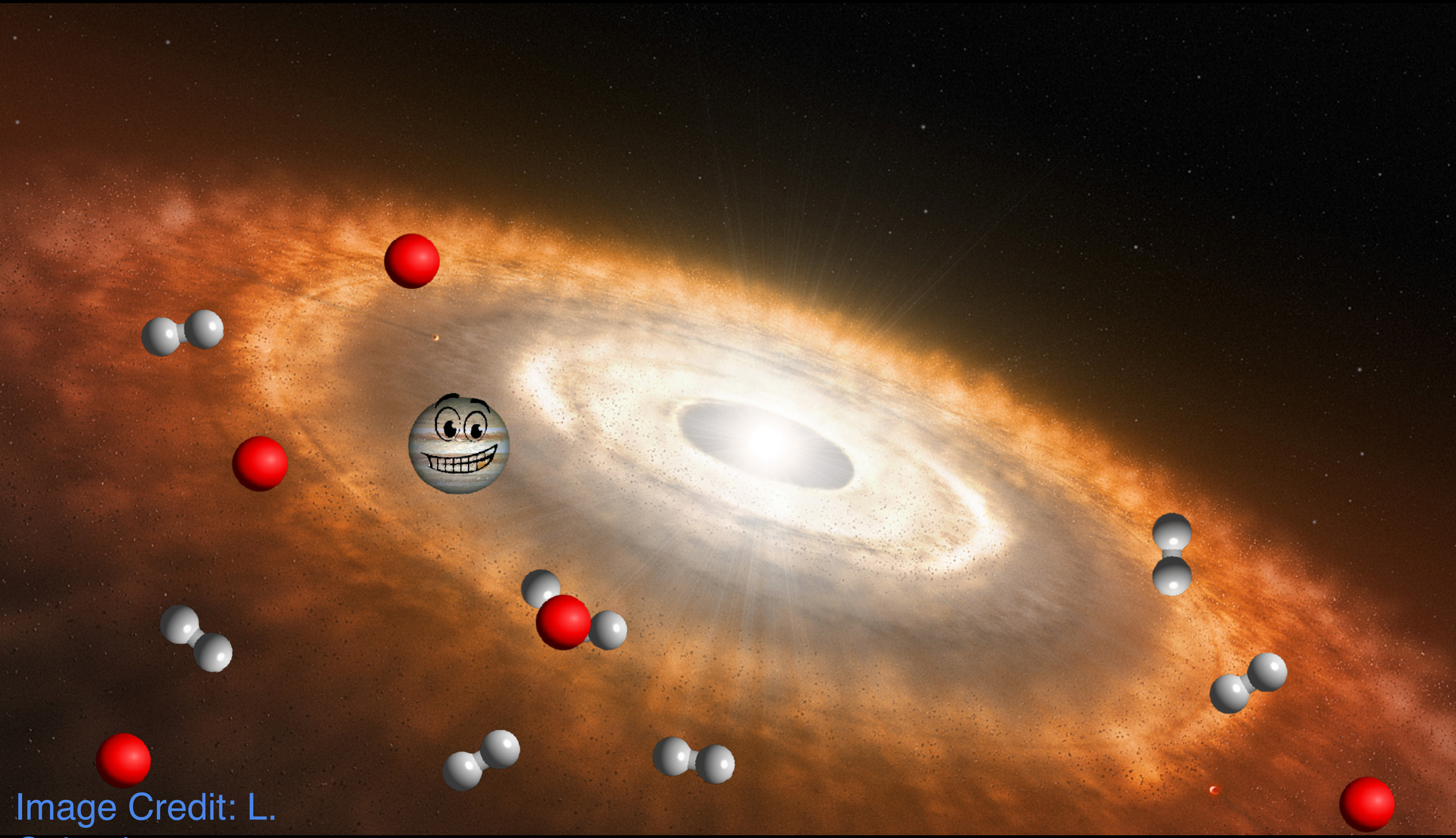
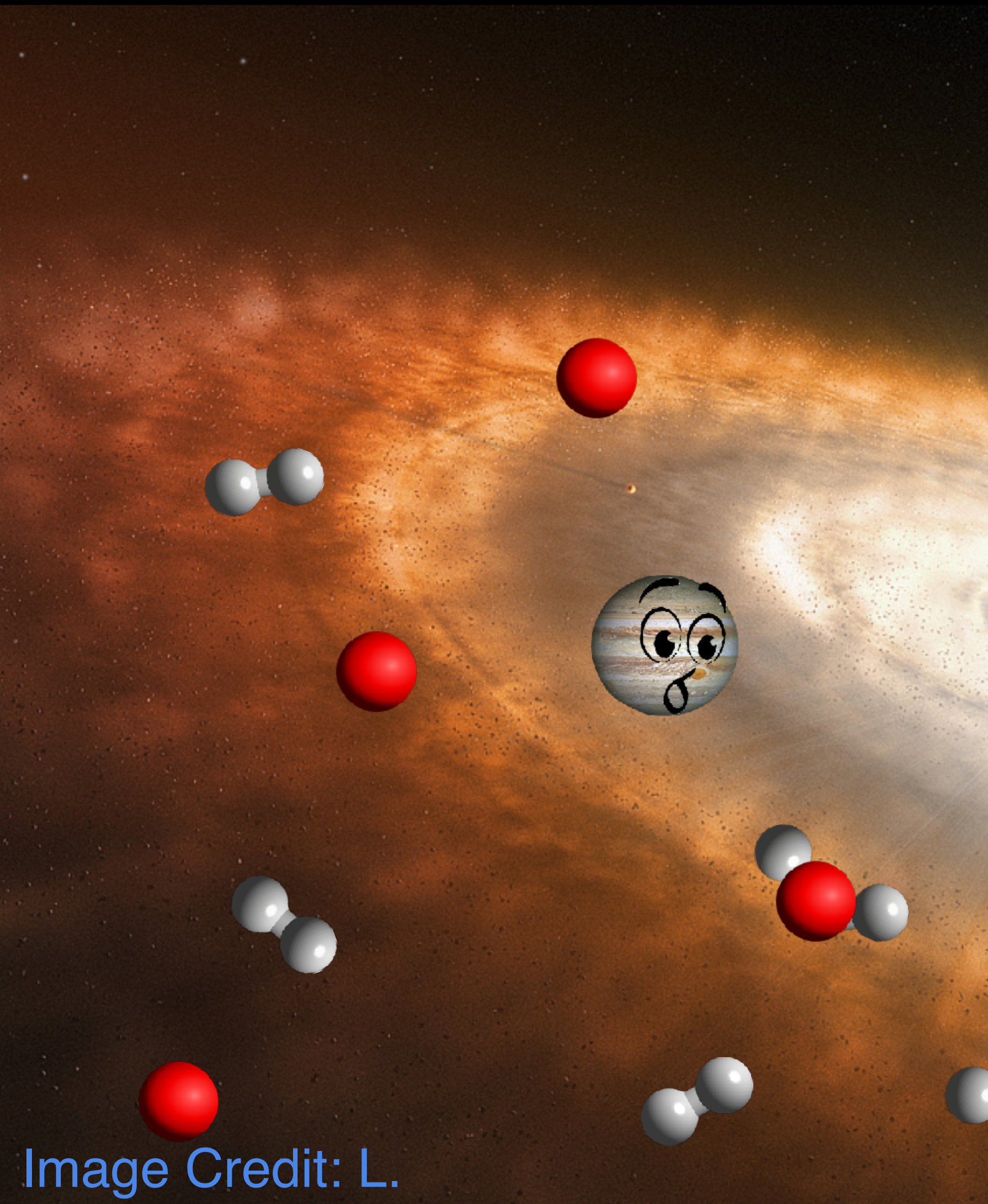


Image Credit: L. Calçada

NOT ENTIRELY... ENABLES CHEMISTRY



Or in slightly more detail….

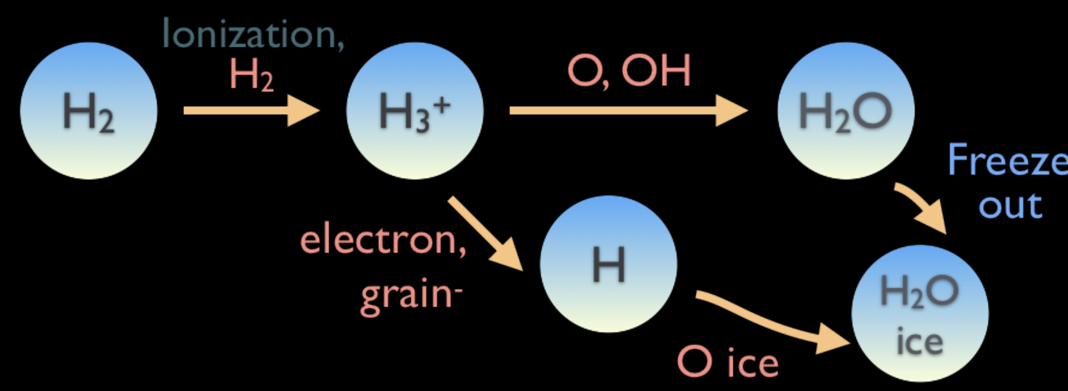
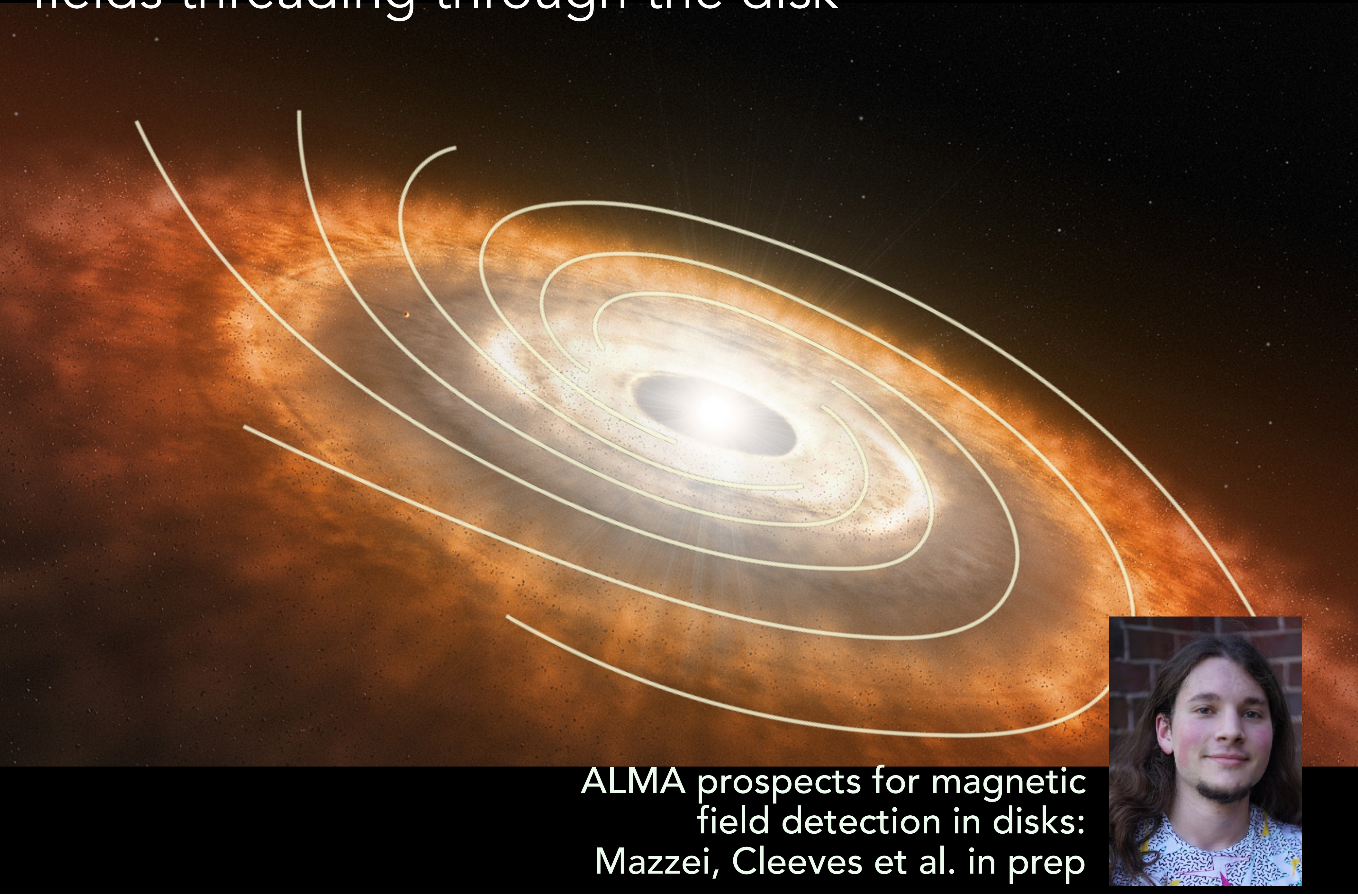


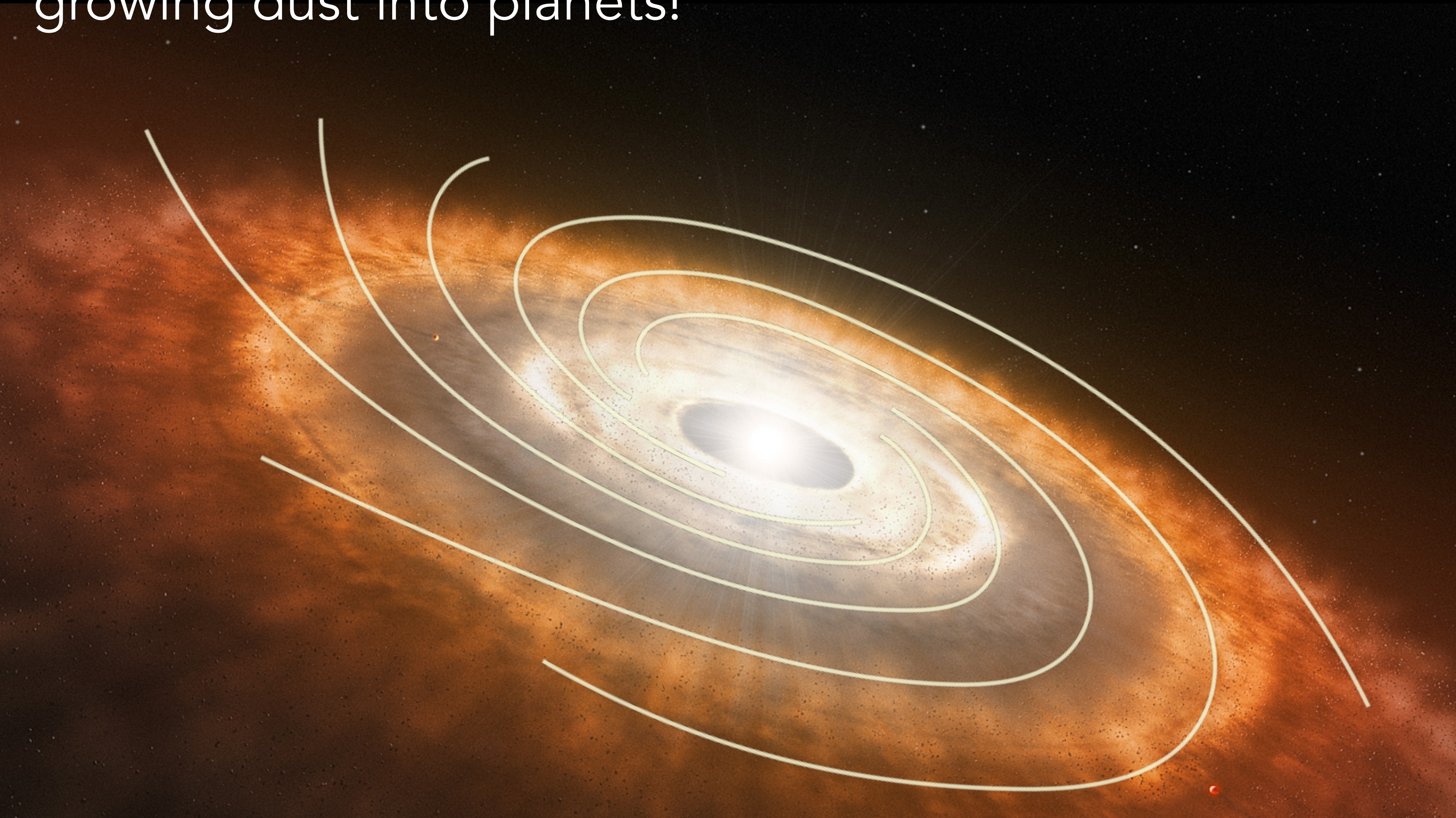
Image Credit: L. Calçada

X-rays create ions, which link the gas to magnetic fields threading through the disk



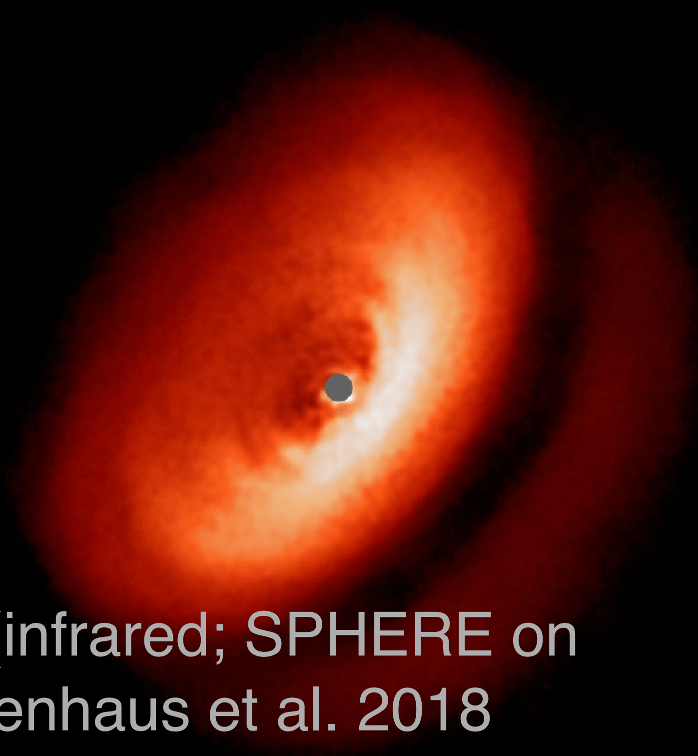
ALMA prospects for magnetic
field detection in disks:
Mazzei, Cleeves et al. in prep

Helps stir the disk… important for the process of growing dust into planets!



A little stirring (turbulence) helps grow dust, but too much and collisions fragment grains.

In 2014-2015, we asked ALMA to observe ionized molecules in a relatively nearby disk…



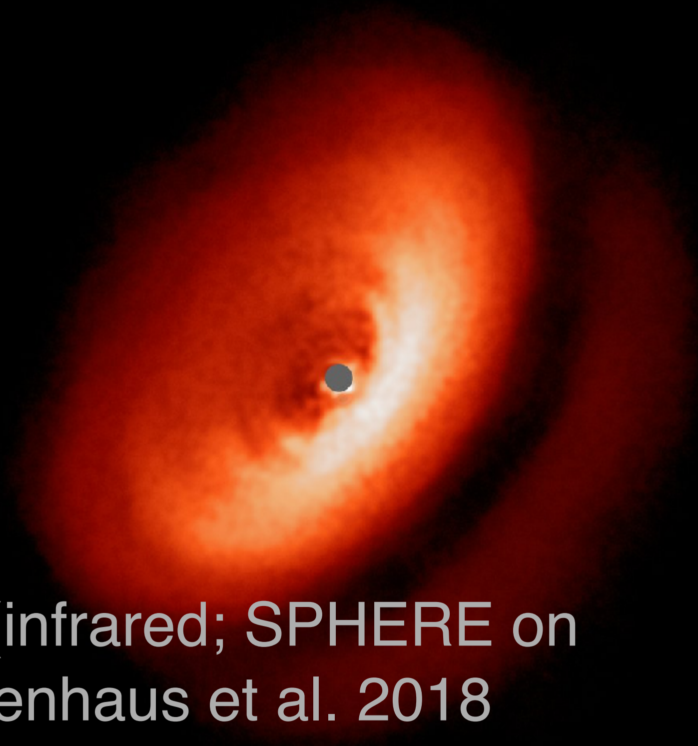
IM Lup (infrared; SPHERE on VLT) Avenhaus et al. 2018

IM Lup (ALMA; millimeter) Andrews et al. 2018

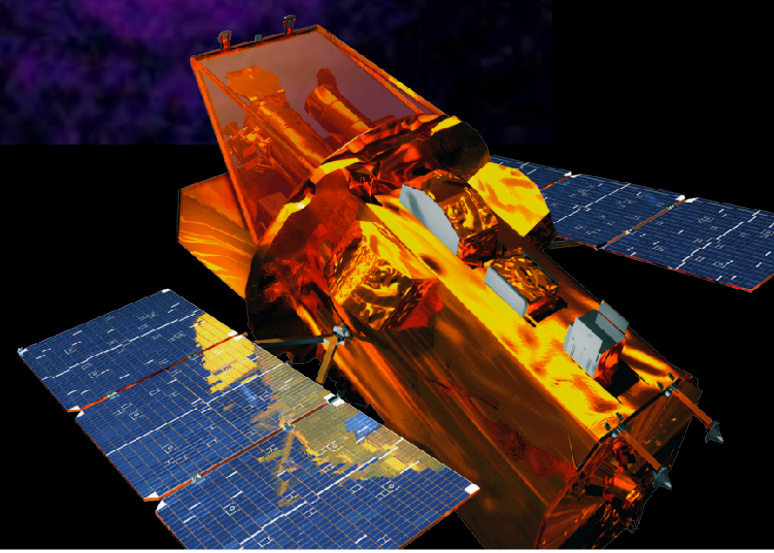
Stay tuned for work from Richard Seifert on mapping ionization in IM Lup

In 2014-2015, we asked ALMA to observe ionized molecules in a relatively nearby disk…

IM Lup (ALMA; millimeter)
Andrews et al. 2018



IM Lup (infrared; SPHERE on VLT) Avenhaus et al. 2018

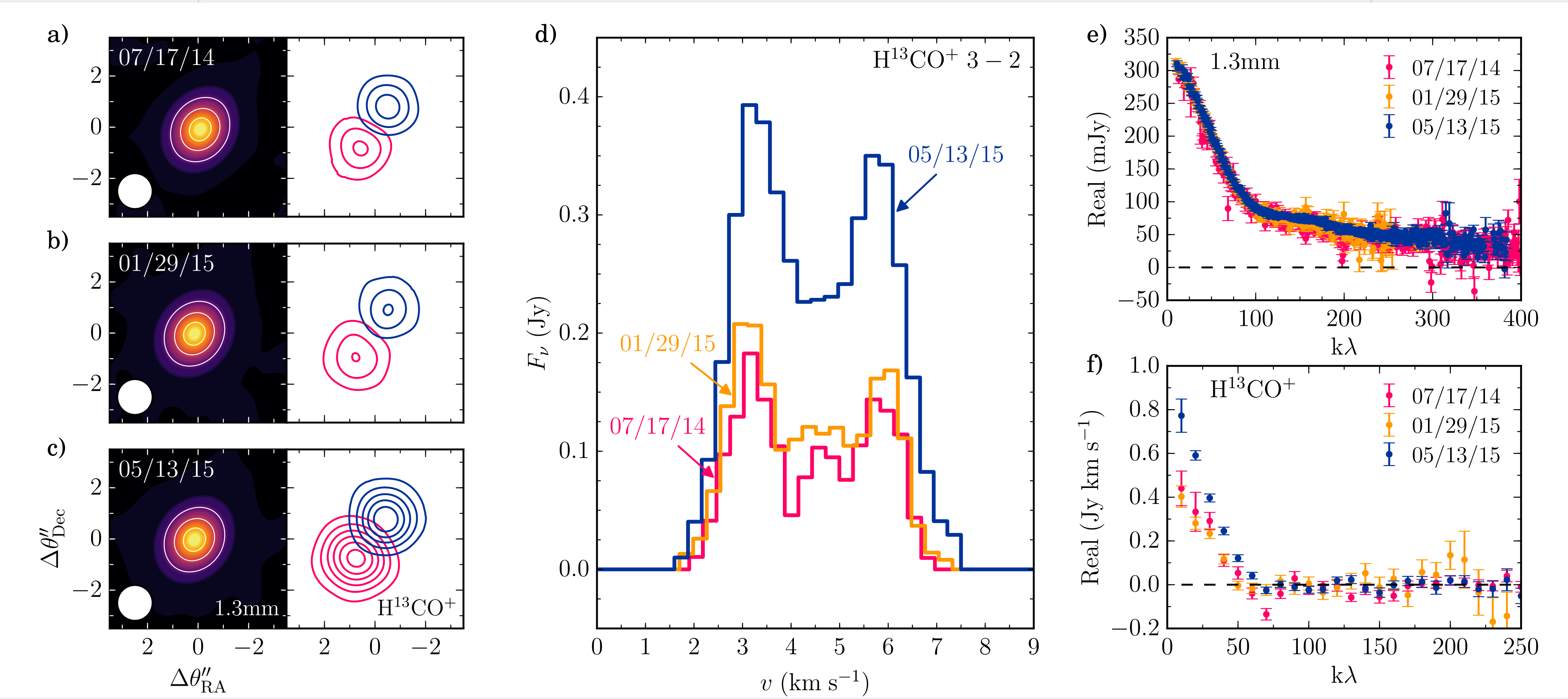


... and asked for *Swift* X-ray time to "keep an eye on" the star

A SERENDIPITOUS DISCOVERY: CHEMICAL VARIABILITY

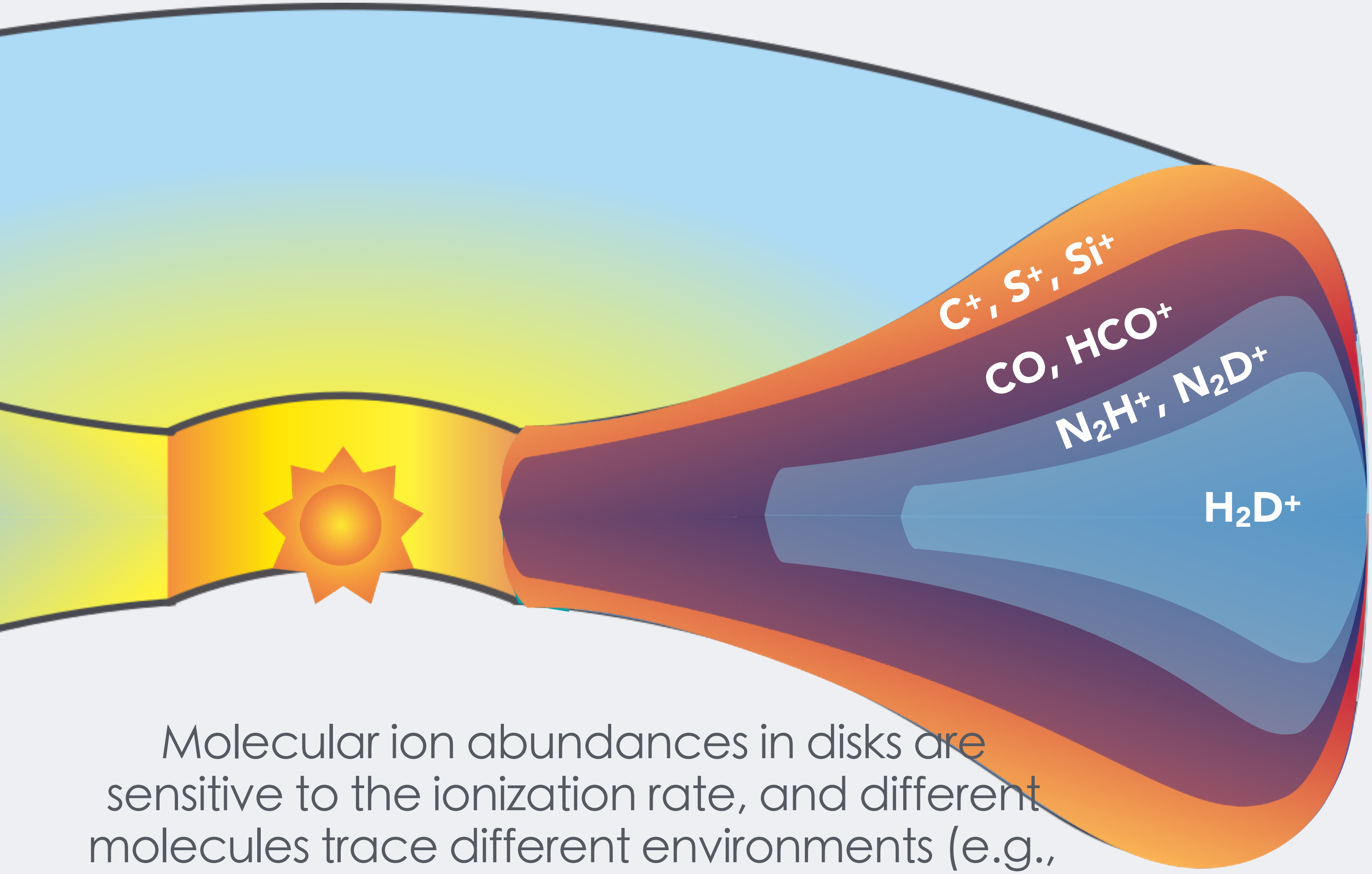
IM Lup Protoplanetary Disk with ALMA and Swift

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



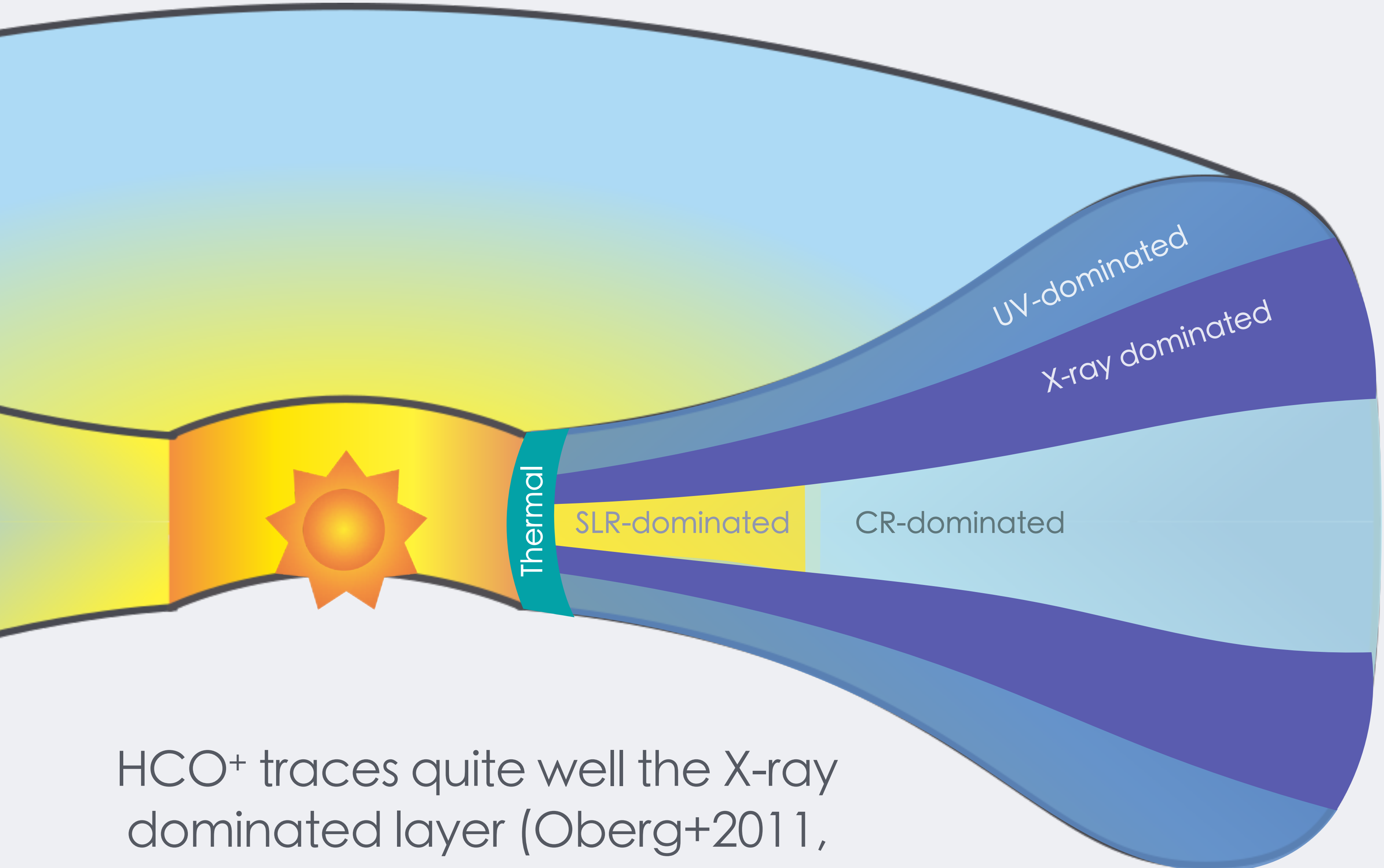
Cleeves et al. 2017

CHEMICAL TRACERS OF IONIZATION



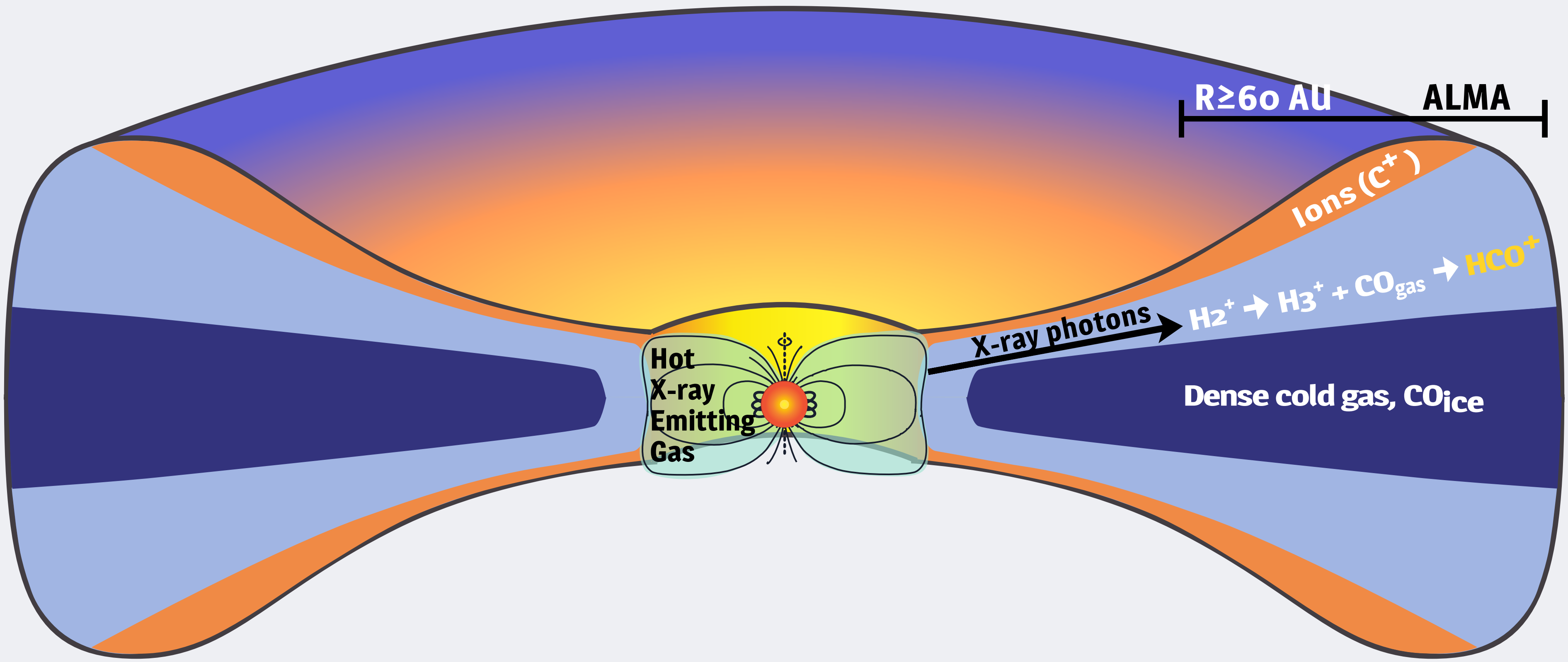
Molecular ion abundances in disks are sensitive to the ionization rate, and different molecules trace different environments (e.g., Semenov+2004, Oberg+2011, Cleeves+2014).

DISK IONIZING PROCESSES



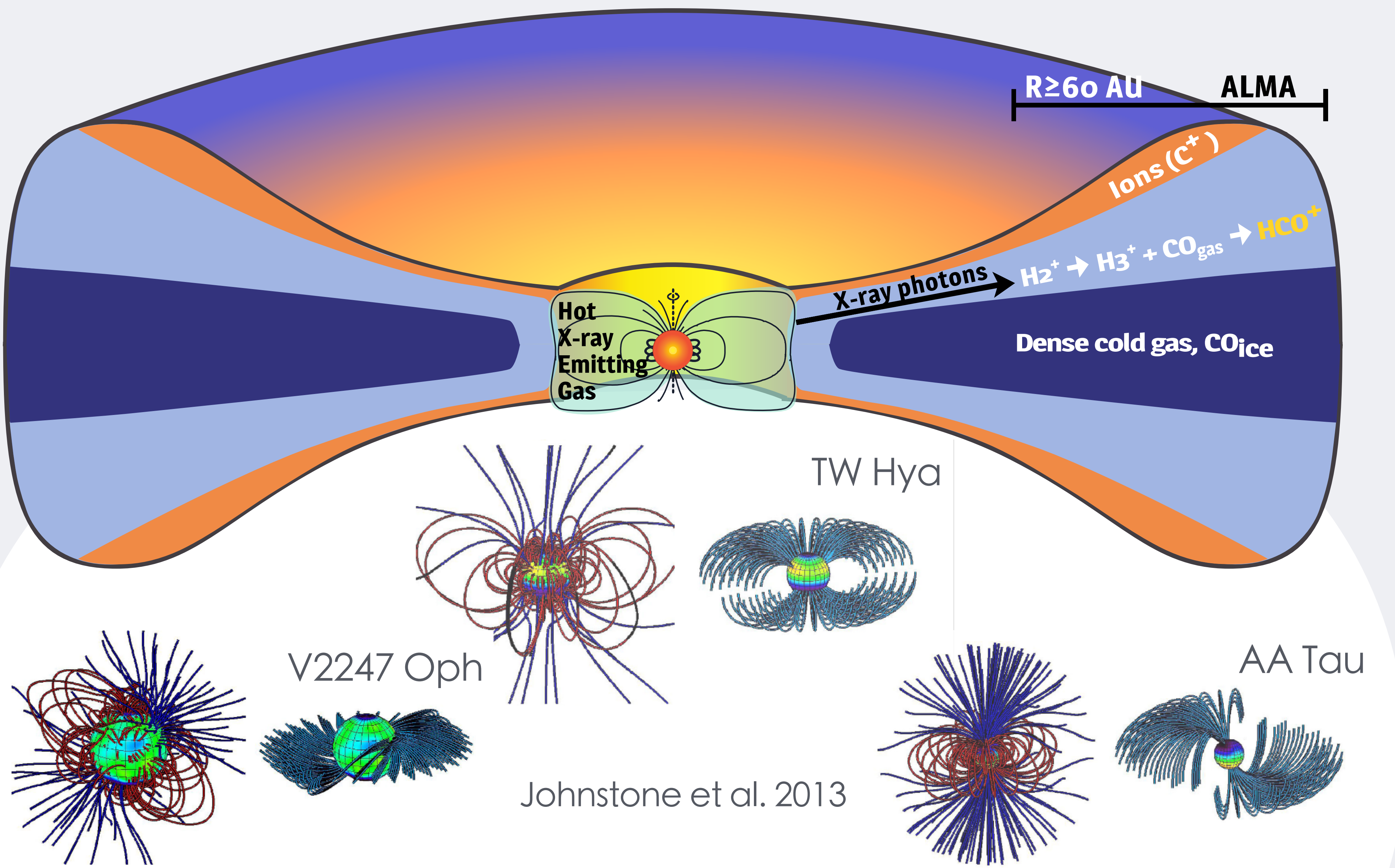
HCO^+ traces quite well the X-ray dominated layer (Oberg+2011, Cleeves+2014,2015)

X-RAYS AS THE CULPRIT?

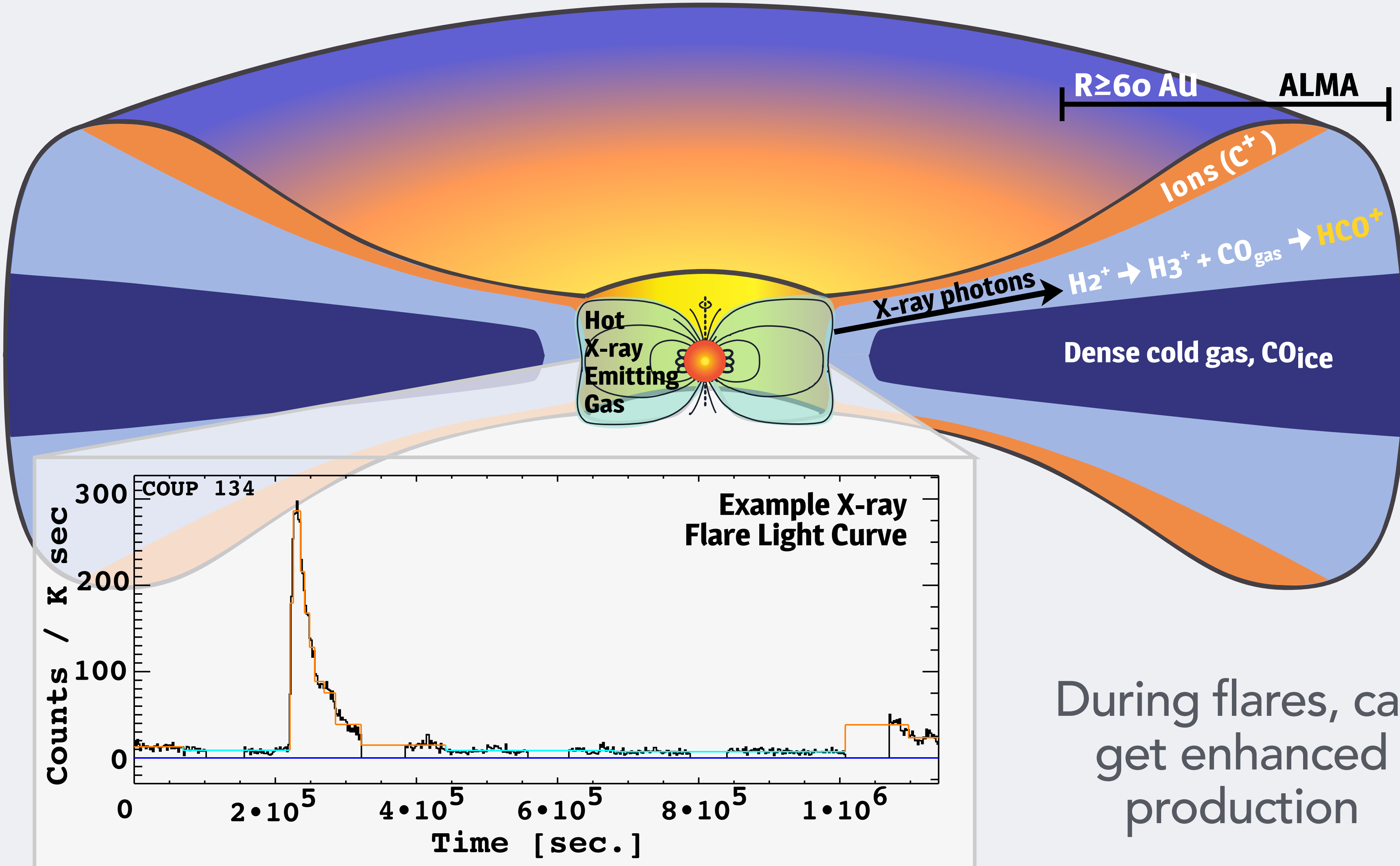


Hot X-ray emitting gas sustains a base level of HCO^+ in the disk "atmosphere".

X-RAYS AS THE CULPRIT?



X-RAYS AS THE CULPRIT?



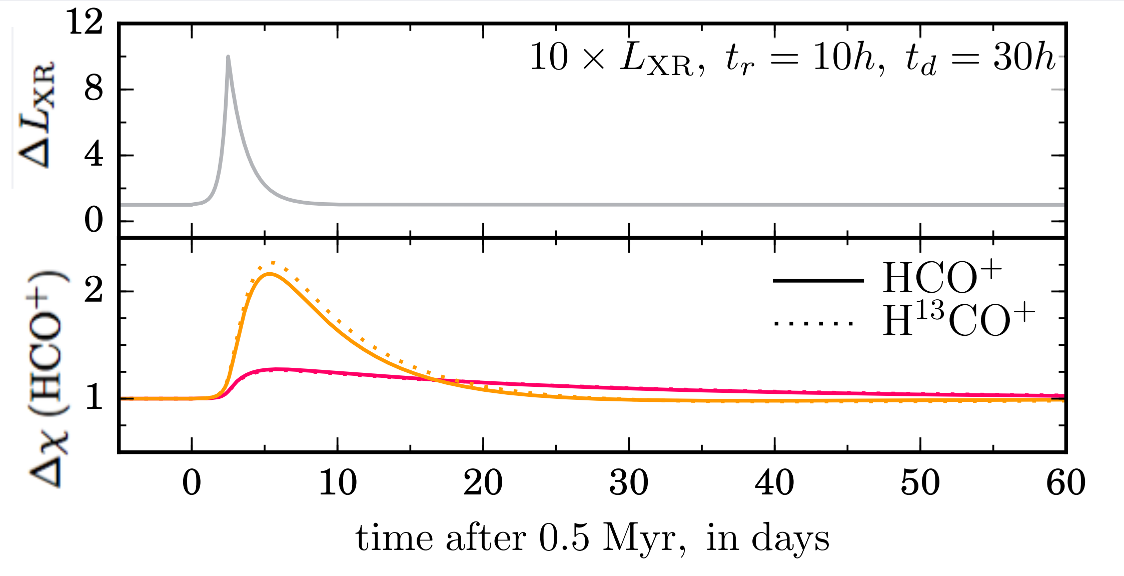
COUP Survey

Favata et al. 2005

During flares, can get enhanced production

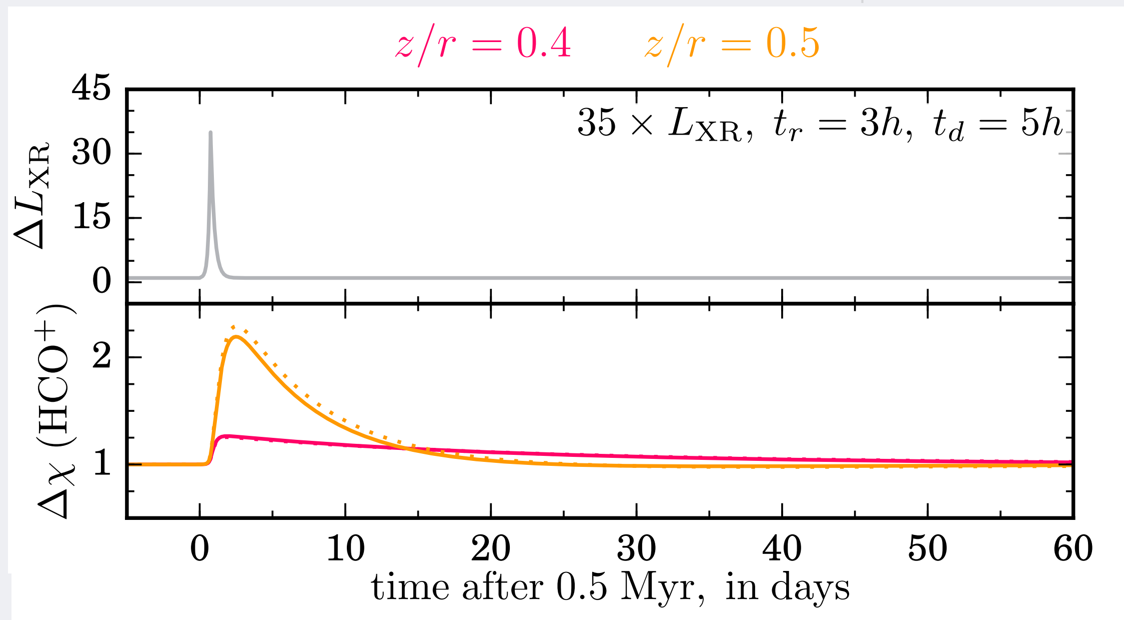
DISK IONIZATION "TOY" MODELS

TIME DEPENDENT CHEMISTRY?



Conditions from physical structure of IM Lup (Cleeves et al. 2016).

Consistent with model expectations for high energy X-ray flares

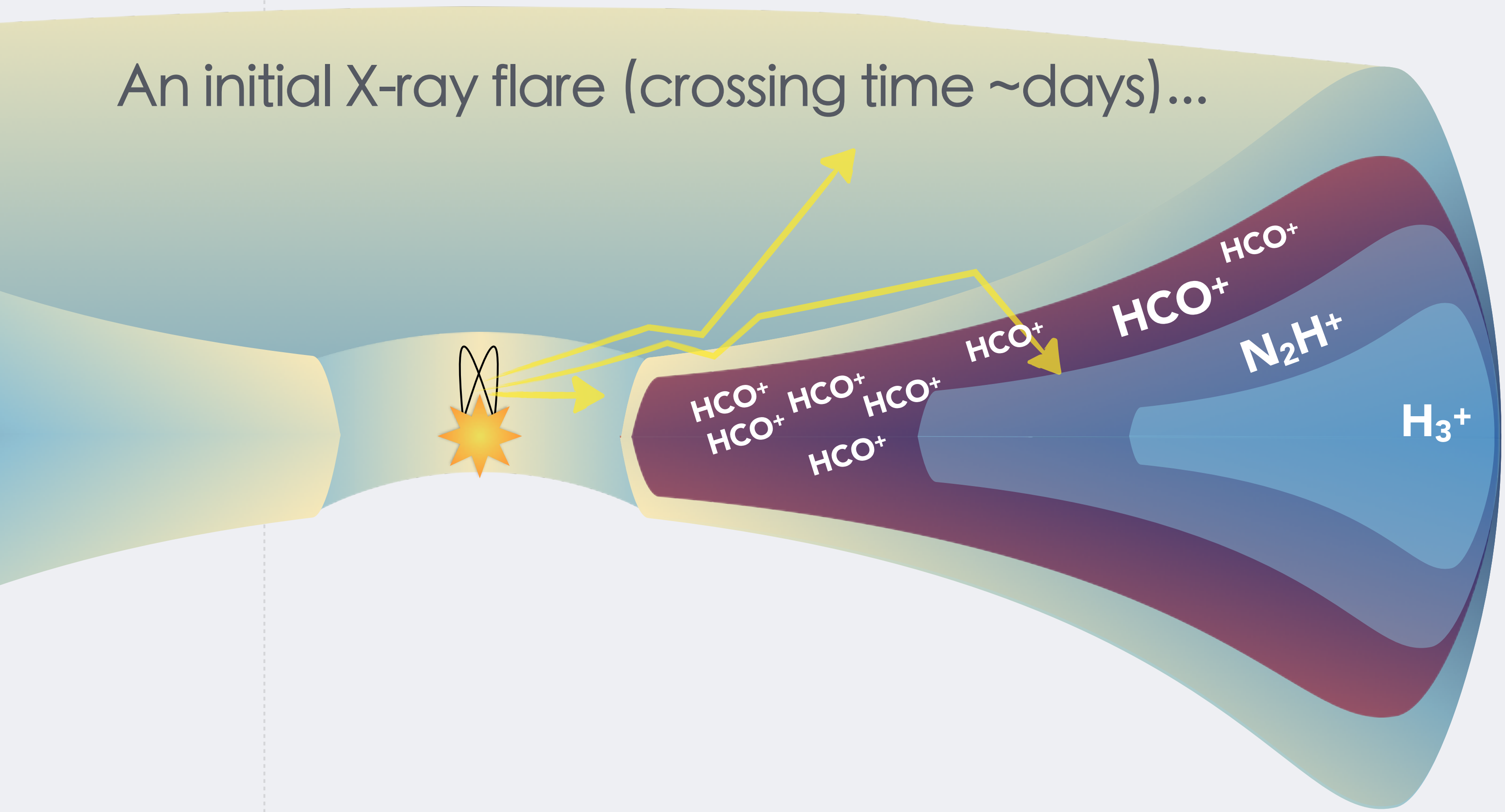


Cleeves et al. 2017

DISK IONIZATION

TIME DEPENDENT CHEMISTRY?

An initial X-ray flare (crossing time ~days)...



... Followed by electron recombination (1-3 weeks).

DECAY TIMESCALES

$$\frac{dn_{\mathrm{HCO^+}}}{dt} = \kappa n_{\mathrm{CO}} n_{\mathrm{H_3^+}} - \alpha n_e n_{\mathrm{HCO^+}}$$

$$n_{\mathrm{HCO^+}} = n_{\mathrm{HCO^+(peak)}} e^{-t/\alpha n_e}$$

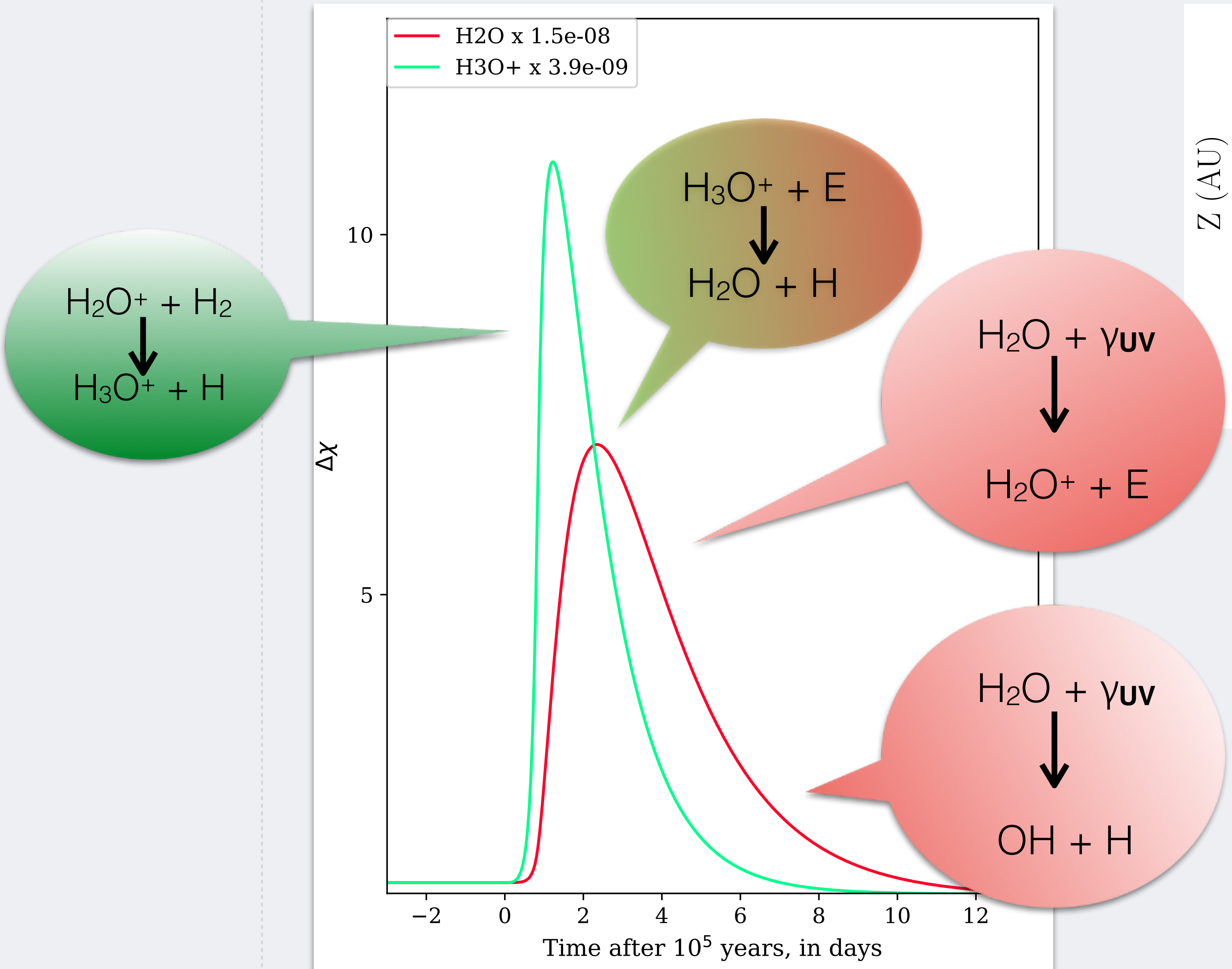
$$t_{\mathrm{half}} = \frac{-\ln(1/2)}{\alpha n_e}$$

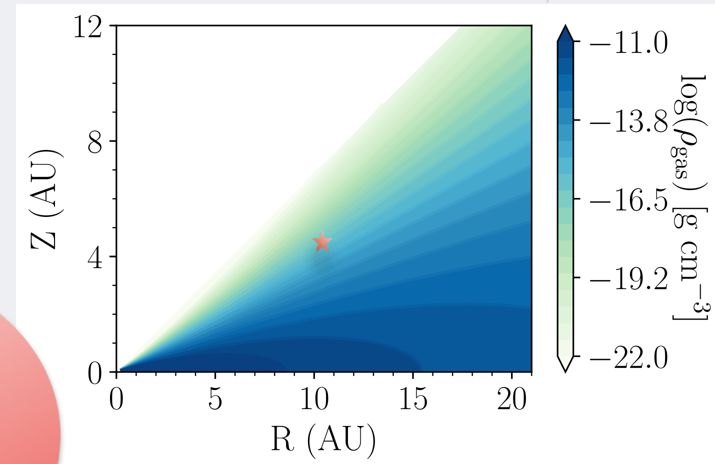
$$\alpha = 2.8 \times 10^{-7} (T_{\mathrm{gas}}/300\mathrm{K})^{-0.69} \mathrm{cm^3 s^{-1}}$$

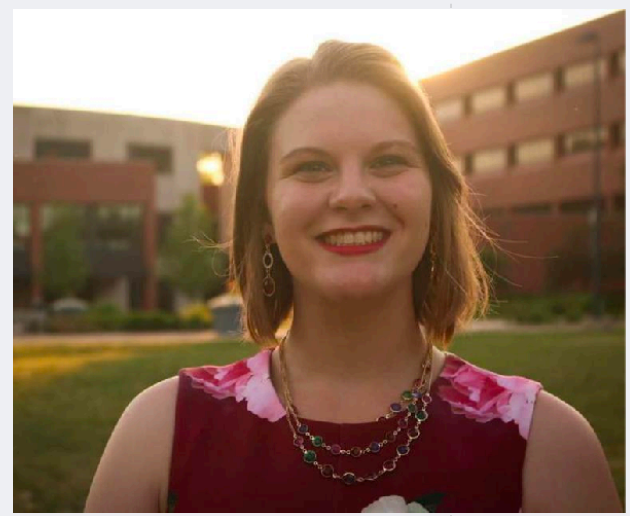
(Amano et al. 1990, JChPhys)

New means to measure n_e!

IONIZATION AND WATER CHEMISTRY







X-ray flares can create short-lived bursts of water formation (Waggoner and Cleeves 2019, ApJ)

IONIZATION AND WATER CHEMISTRY

We often think of how flaring stars negatively impact habitability on fully formed planets...

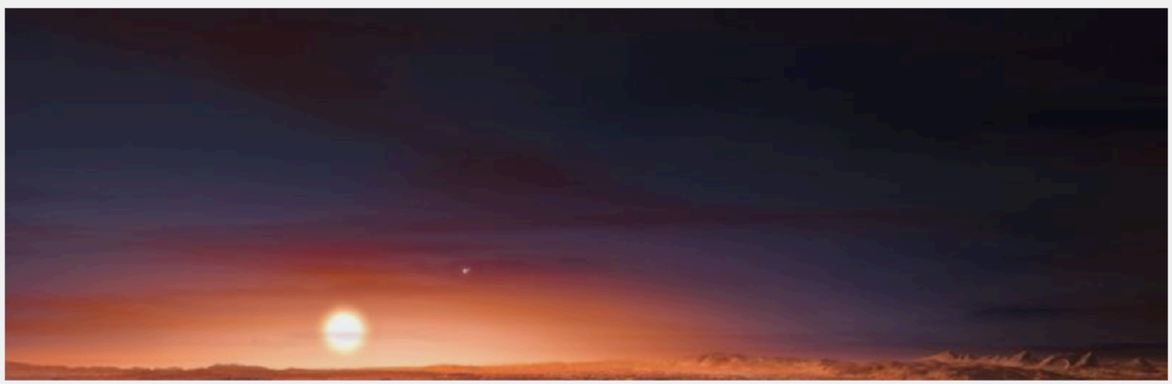
ars TECHNICA SUBSCRIPTIONS SIGN IN

SUNSCREEN NEEDED —

The closest exoplanet to Earth just got doused with deadly flares

"This suggests that life on Proxima b will have to undergo complex adaptations."

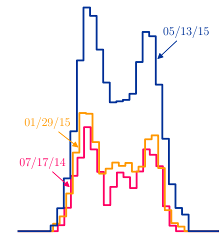
ERIC BERGER - 4/10/2018, 9:42 AM



But does the activity of the star also shape whether habitable planets form in the first place?

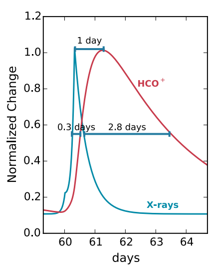
SUMMARY

$H^{13}CO^+$ variable in both systems where we've looked. Optically thick lines and deep ionization tracers aren't changing.



How much is the broader chemistry shaped by flares (e.g., H_2O; Abygail Waggoner)?

How much does disk and/or magnetic field geometry matter? CO abundance? Disk mass? Energetic stellar particles?



Now working on getting the "smoking gun" of a flare immediately preceding a $H^{13}CO^+$ change!