**Inga Kamp**

# From Stars and Disks to Planetary Systems

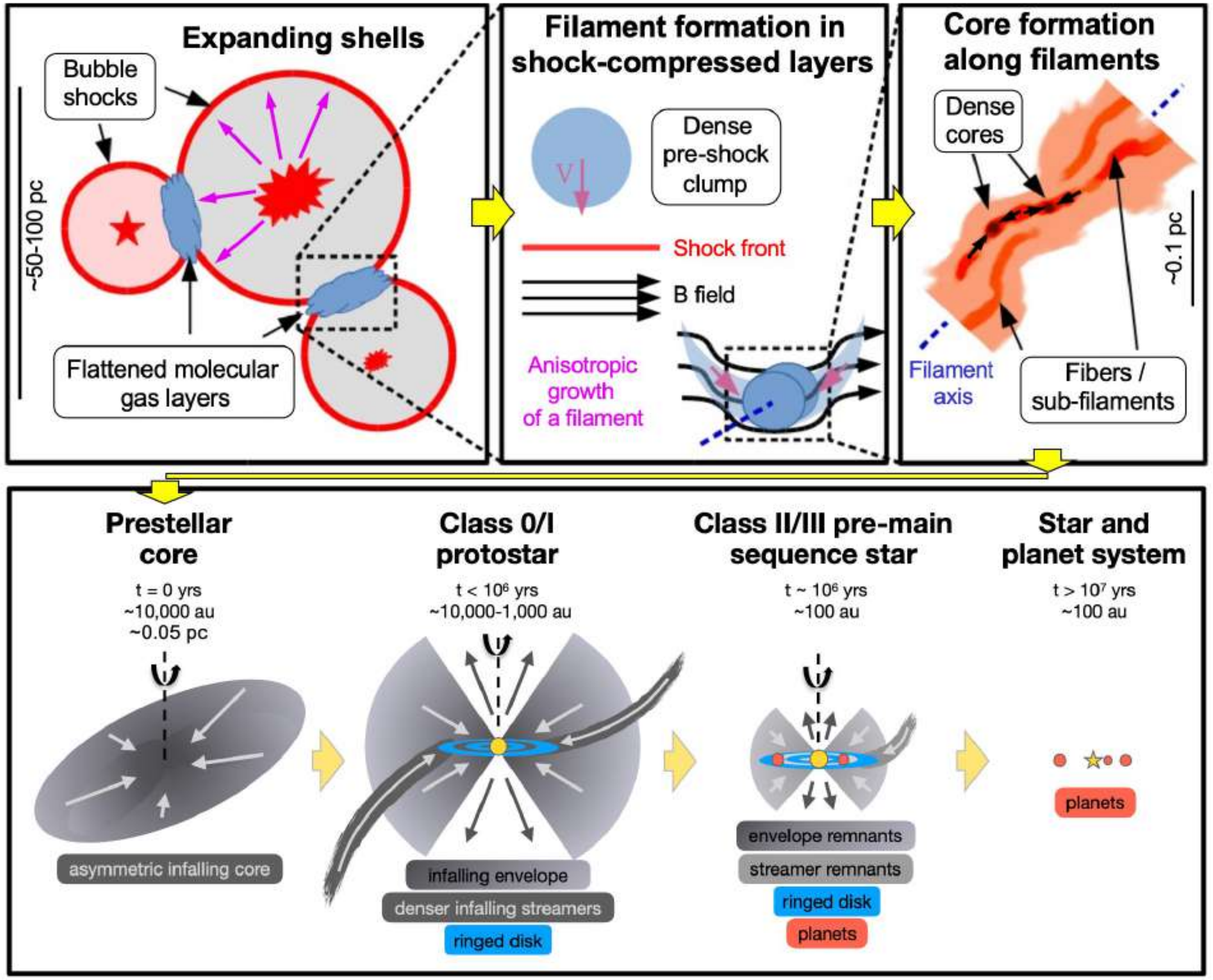
## the stuff planets are made of

# Outline

- Star formation and why disks form around protostars
- How chemistry traces the processes of star and disk formation
- Basic facts about planet forming disks
- Observing molecules in disks
- Forming molecules in disks

**Star formation is accompanied by forming a flat disk of gas and dust …**

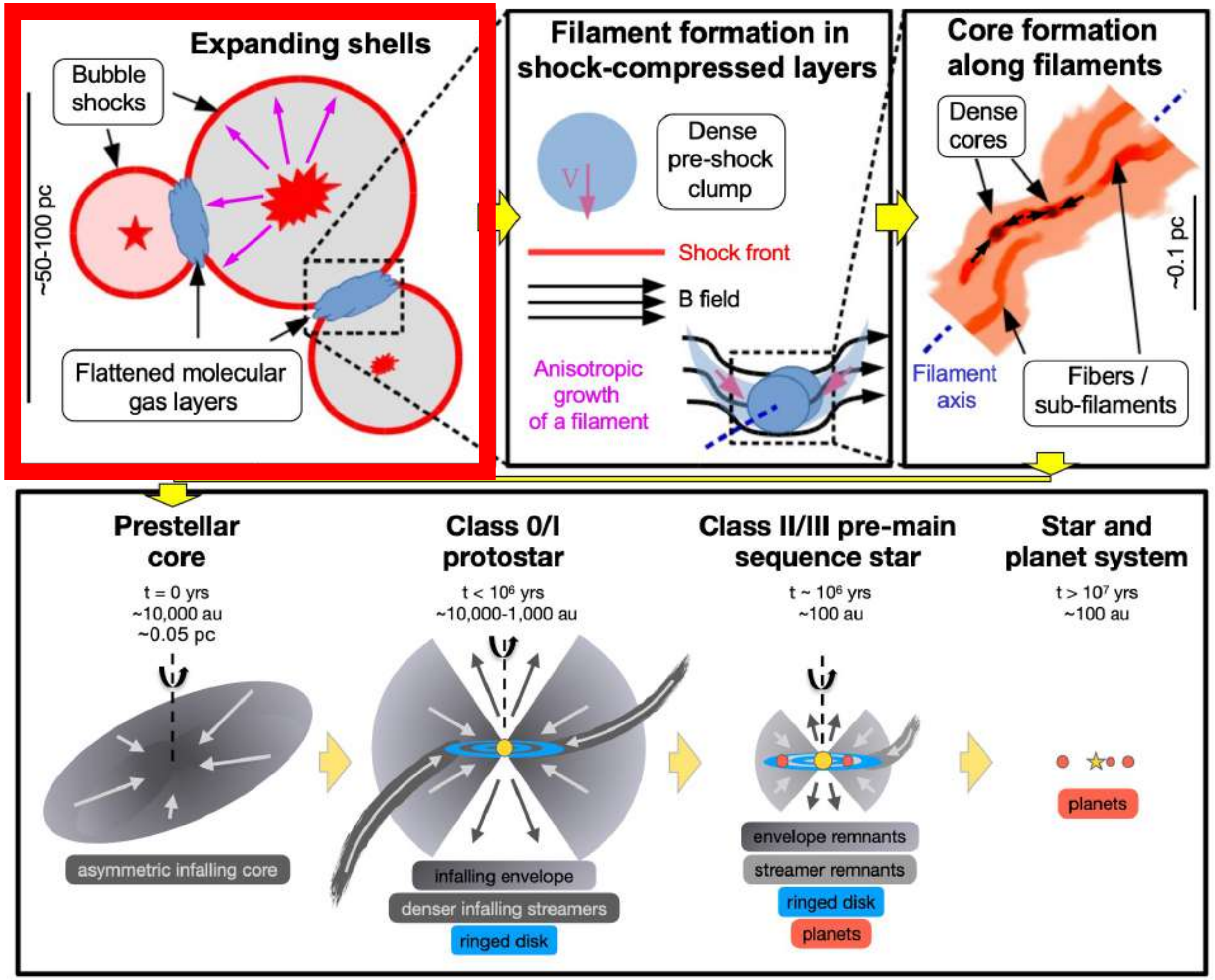
## From dense clouds to protostars, disks, and planetary systems



[Pineda+2022]

# From dense clouds to protostars, disks, and planetary systems

Floris van der Tak



[Pineda+2022]

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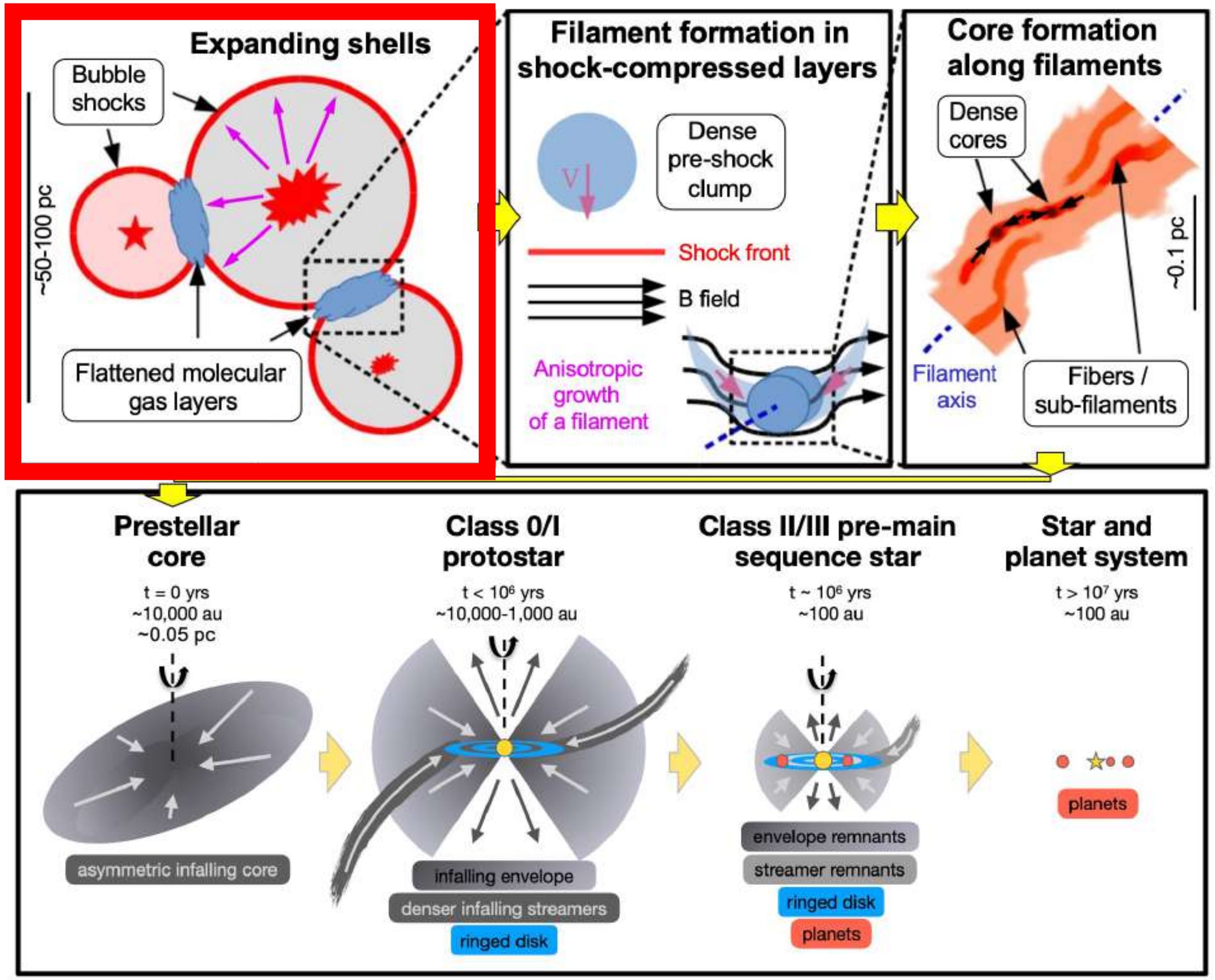
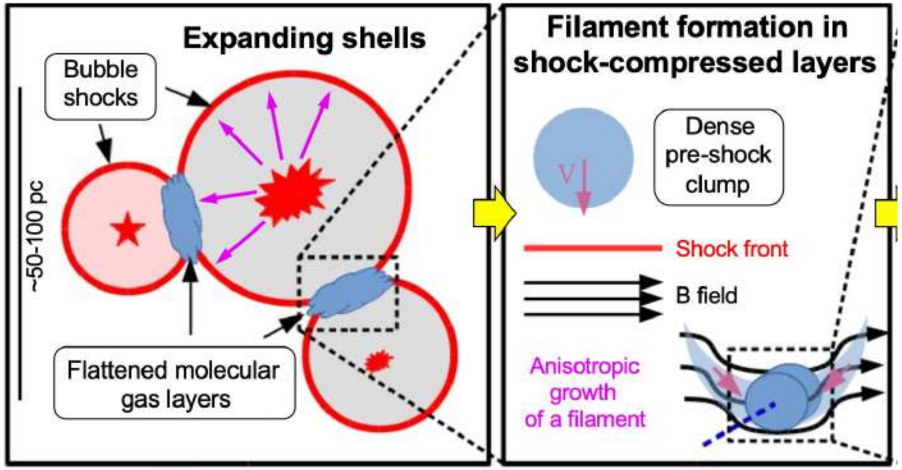


[Pineda+2022]

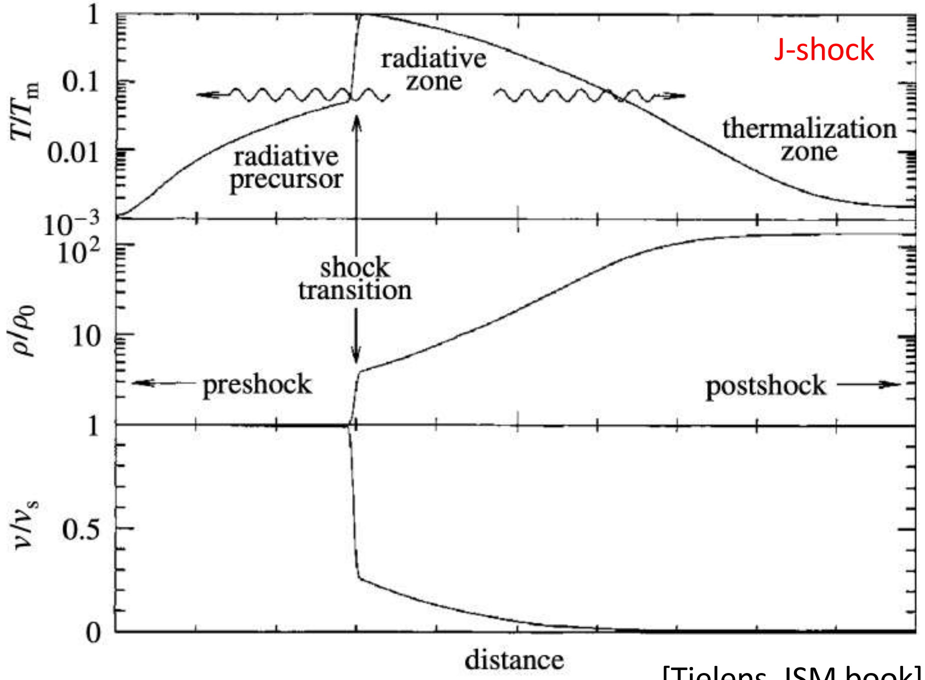
From dense clouds to protostars, disks, and planetary systems

- Shocks
- Gravitational collapse
- Angular momentum conservation

# Shocks



[Pineda+2022]

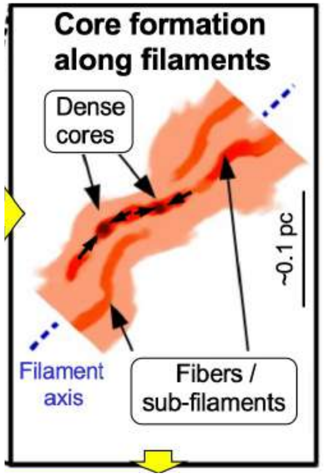


[Tielens, ISM book]

Two types:

- Fast (≳50 km/s) discontinuous shocks (J-shocks) → jumps in density, temperature, velocity → molecules get destroyed, re-form in post-shock gas
- Slow (≲50 km/s, strong B-fields) weak shocks (C-shocks) → smooth gradients

# Gravitational collapse



[Pineda+2022]

Collapse starts when the internal kinetic energy is smaller than the gravitational potential of a spherical cloud

$$\frac{3M_c kT}{\mu m_H} < \frac{3}{5}\frac{GM_c^2}{r_c}$$

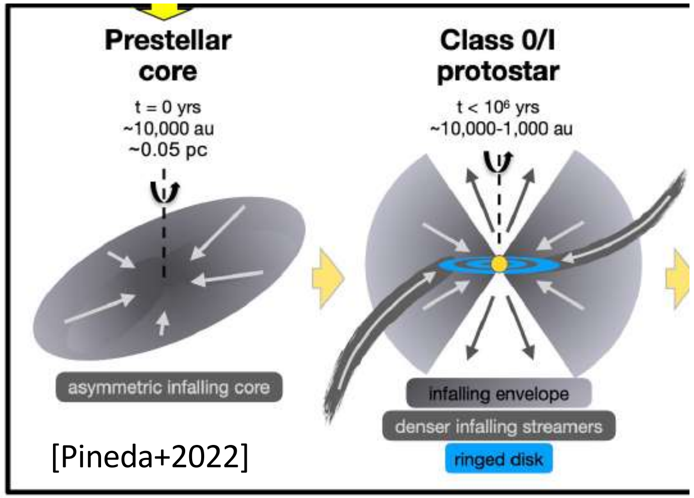
$r_c$ , $\rho_c$ – cloud radius, density
$M_c$ – cloud mass
T – temperature
G – gravitational constant
k – Boltzmann constant
$\mu$ – mean molecular weight of gas
$m_H$ – mass of H atom

- The Jeans criterium (critical length scale): $M_c > M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_c}\right)^{1/2}$

$M_J$ ~1 $M_{sun}$ (for typical conditions), $R_J$~0.5 pc

- The free-fall timescale: $t_{ff} = \sqrt{\frac{3\pi}{32}\frac{1}{G\rho_c}}$ ~ few thousand years, fast!!!

# Angular momentum conservation



[Pineda+2022]

Angular momentum enters via accretion of surrounding material and is removed from the system via jets, winds and outflows

https://www.youtube.com/watch?v=FmnkQ2ytlO8&t=7s

# Concept test

If the material in the primordial Solar System retained its angular momentum as it collapsed to form the Sun, the Sun’s rotation rate should be

A) fast (less than a week).

B) moderate (a week or a month).

C) slow (more than a month).

D) zero (non-rotating).

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present-day rotation perion 24.5 days

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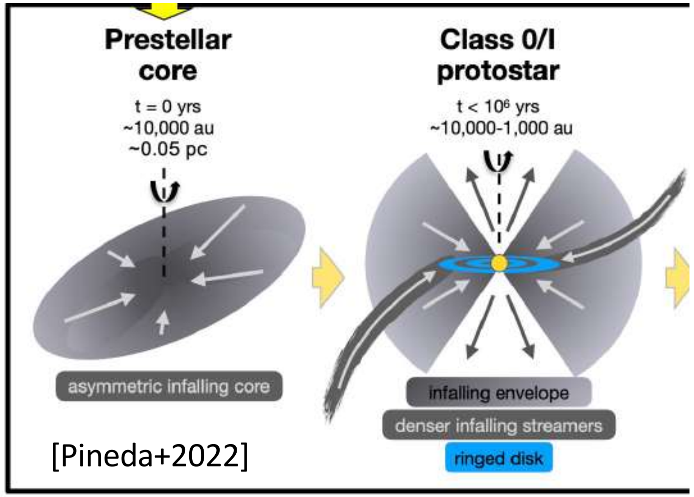
**Star formation is accompanied by forming a flat disk of gas and dust …**

**… and chemistry helps us to understand this process**

# Angular momentum conservation



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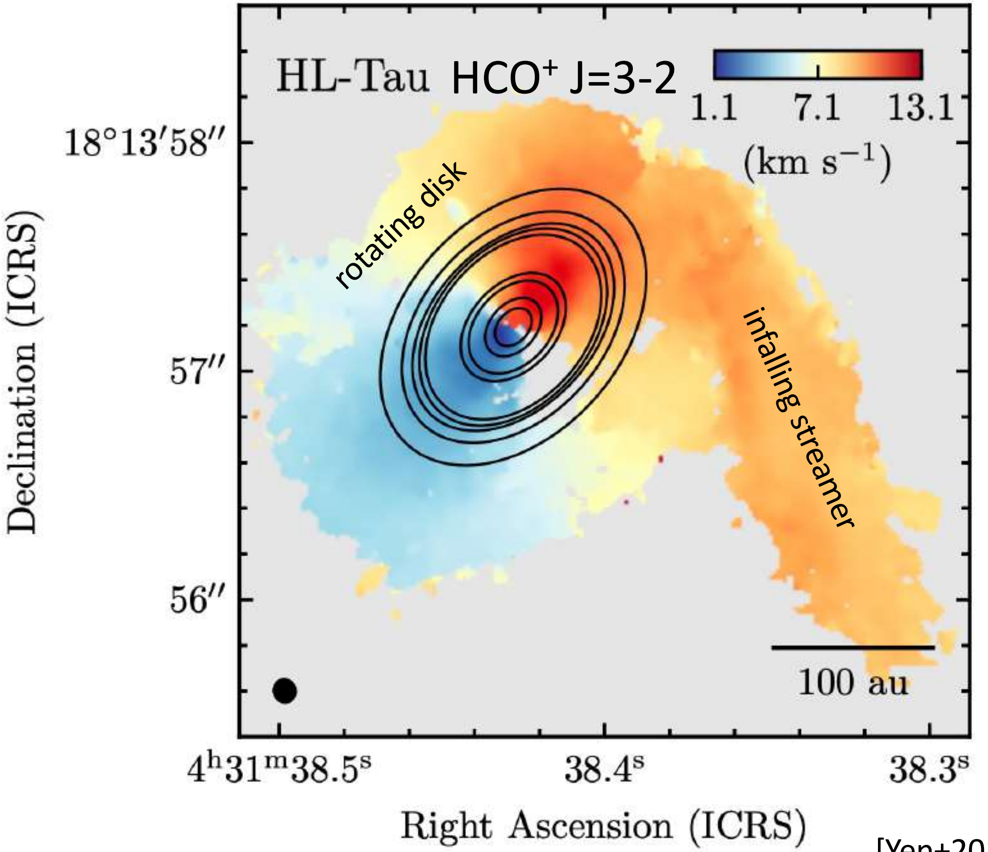
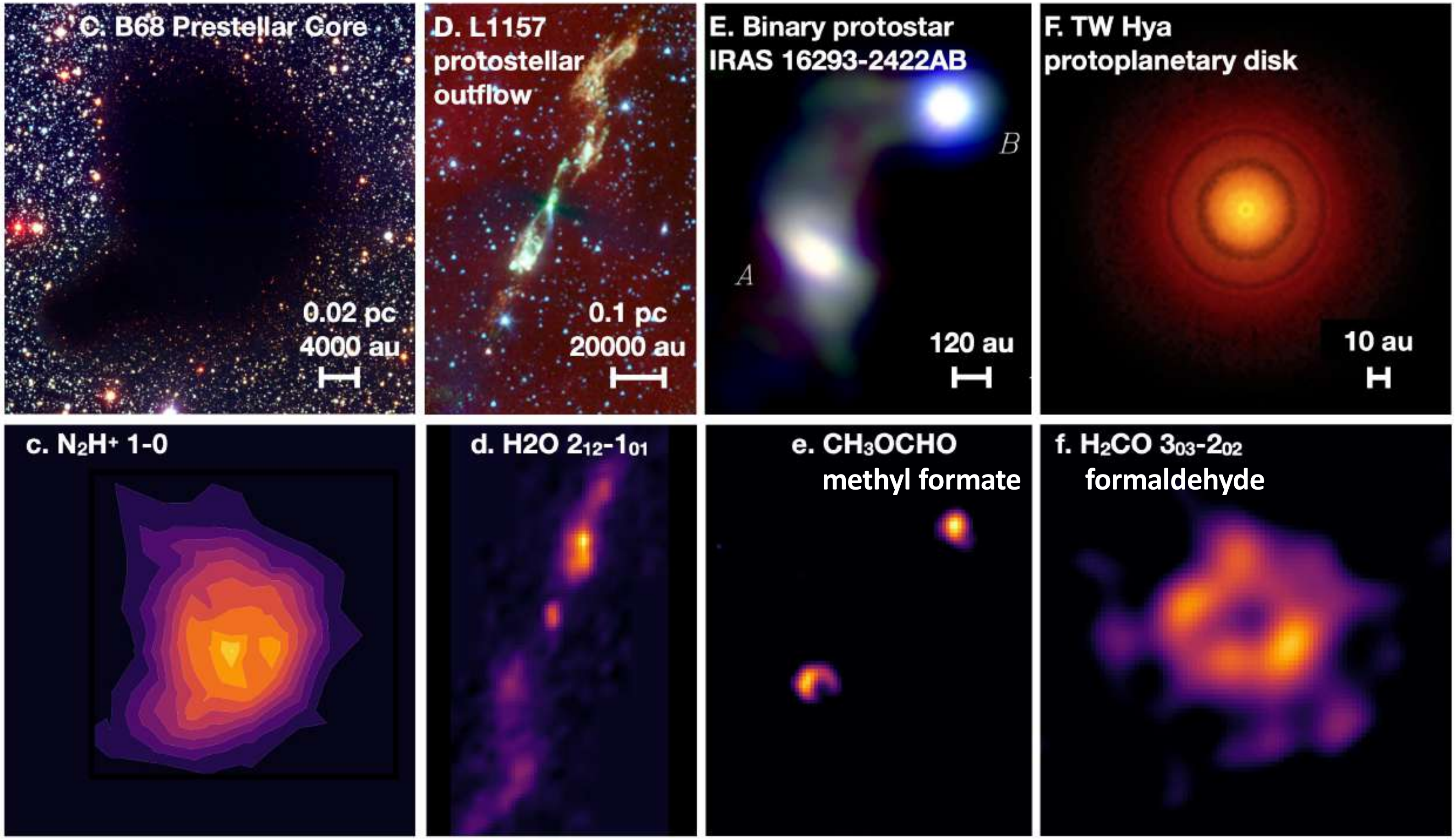


[Yen+2019]

# Chemistry of star formation and disks



[Physics Review: Oeberg & Bergin 2020]

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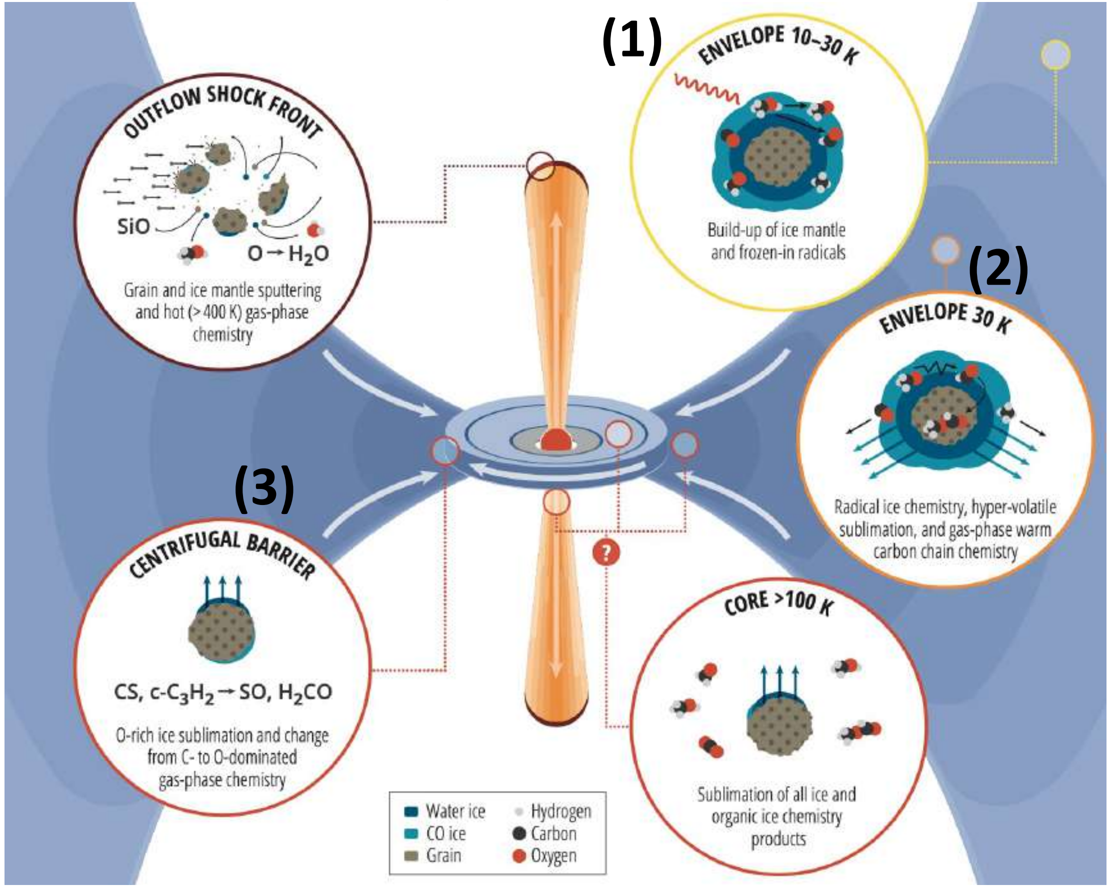

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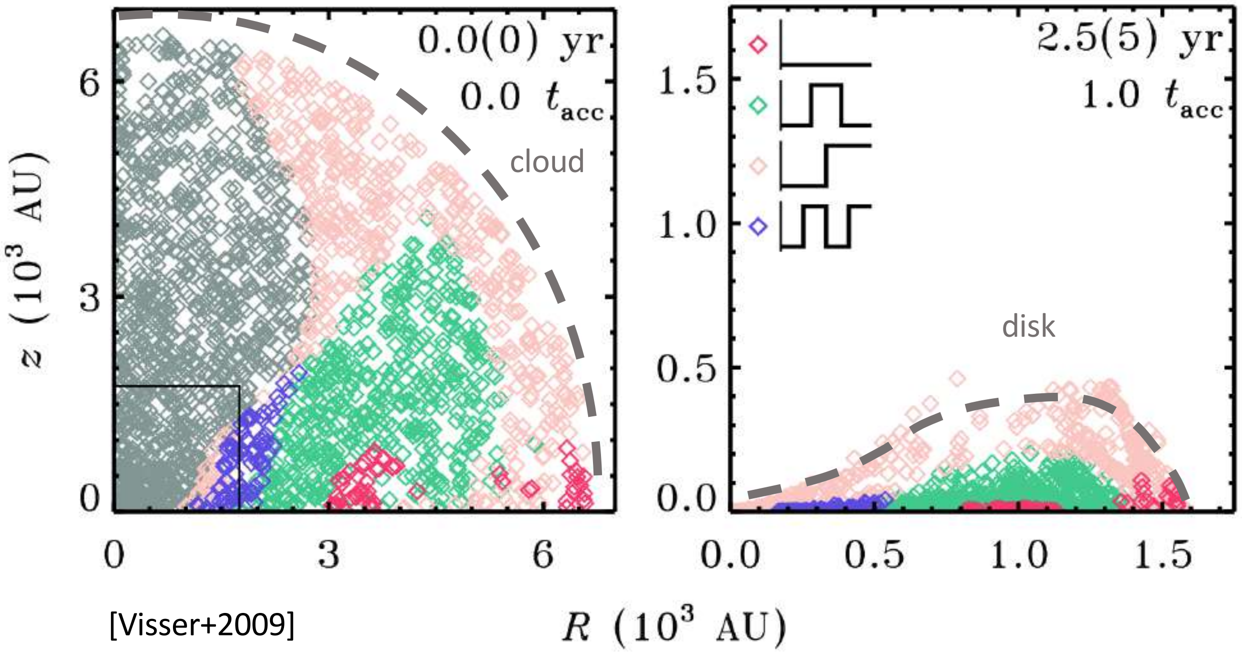
ices can sublimate and recondense – multiple times – during the star and disk formation process

recall lecture of Thanja Lamberts

# Chemistry of star formation and disks



[Visser+2009]

ices can sublimate and recondense – multiple times – during the star and disk formation process

CO ice history from cloud to disk
iceline at ~20 K (inside ~500 au, T>20 K)

red: CO remains adsorbed
green: CO desorbs and re-adsorbs
pink: CO desorbs and remains desorbed
blue: CO desorbs, re-adsorbs and desorbs once more

# Planet forming disks and some basic facts to start with …

Every young star is surrounded by a protoplanetary (planet forming) disk.

distance ~1300 light years (~400 pc); youngest stars < 1 million years old

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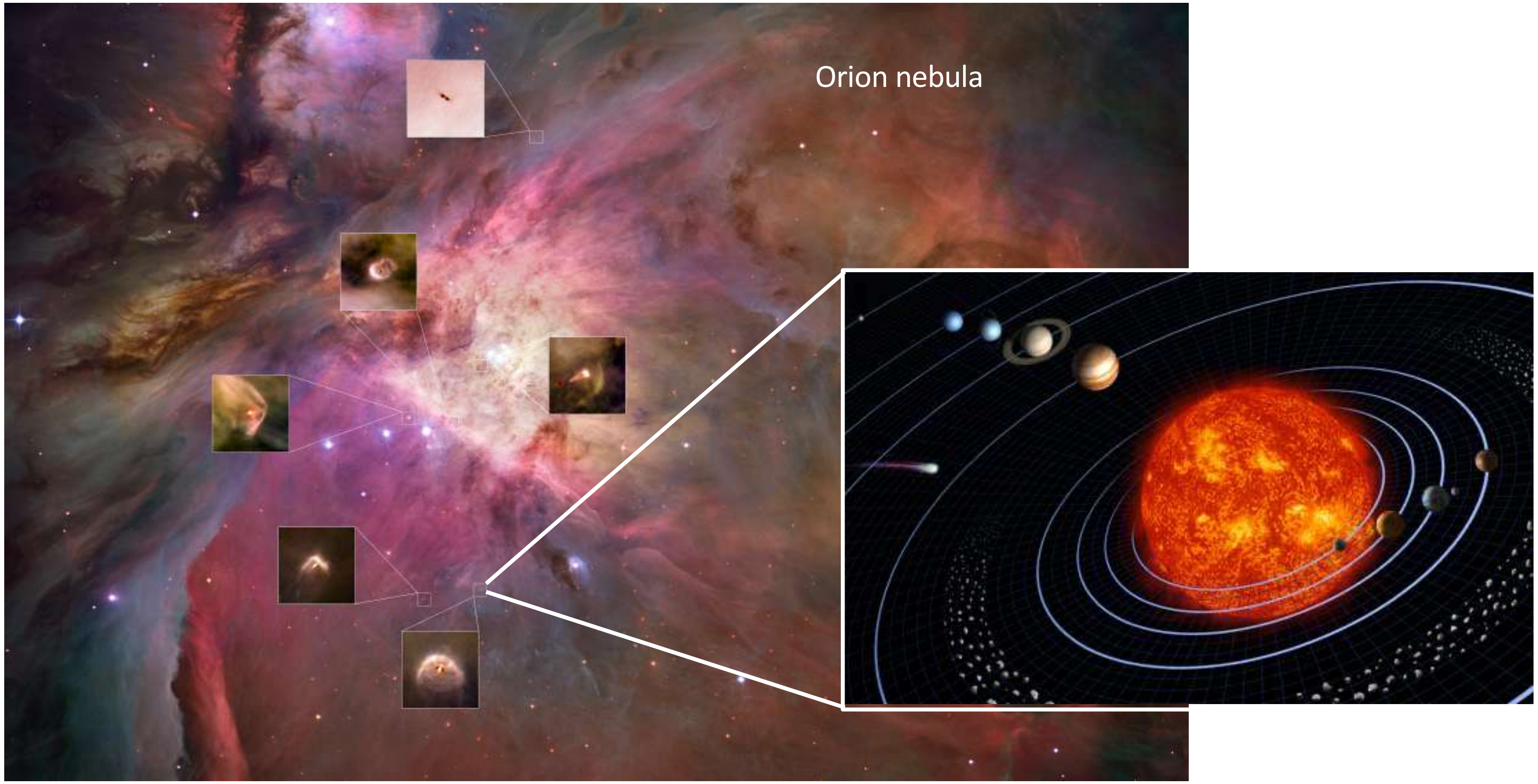
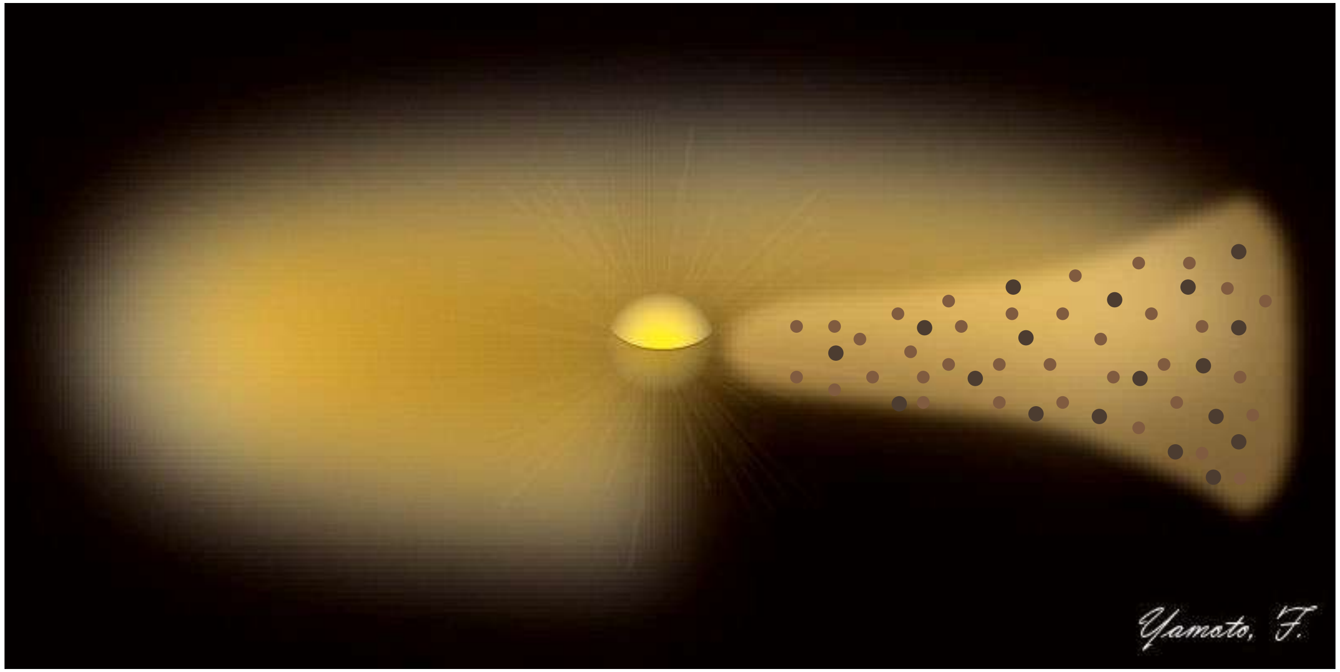


distance ~1300 light years (~400 pc); youngest stars < 1 million years old

# How does a disk look like?

Gas and minuscule dust particles mixed



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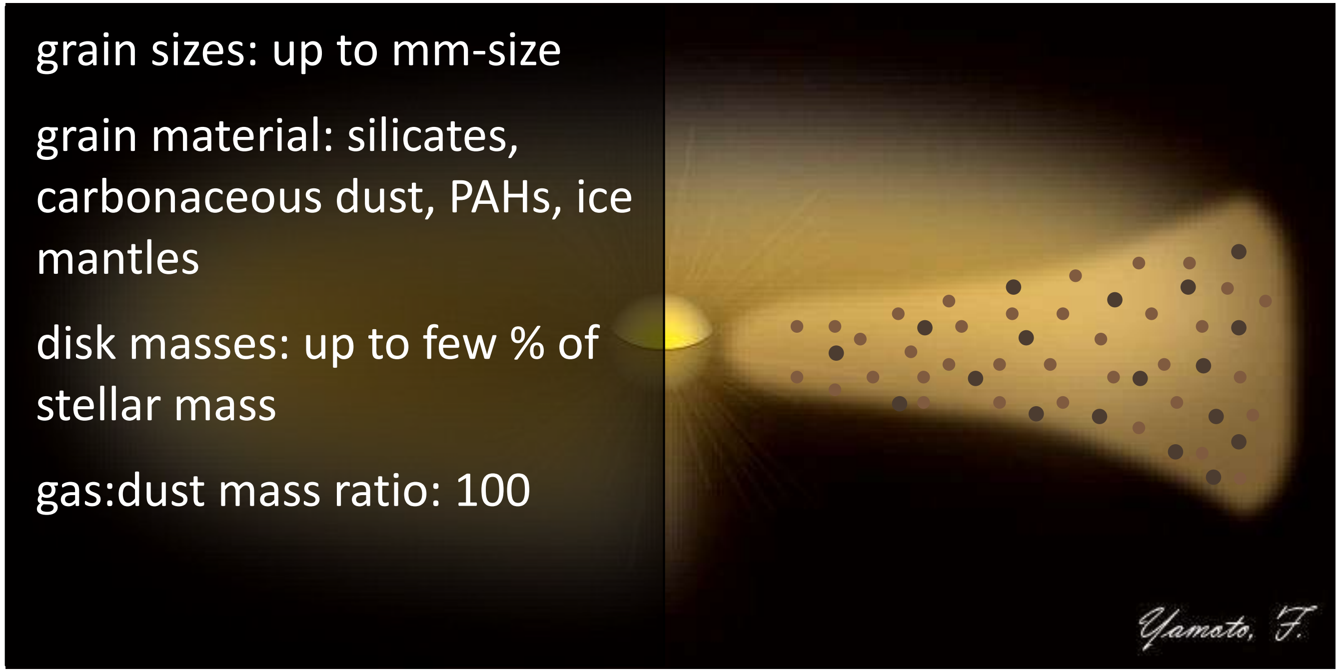

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grain material: silicates, carbonaceous dust, PAHs, ice mantles

disk masses: up to few % of stellar mass

gas:dust mass ratio: 100

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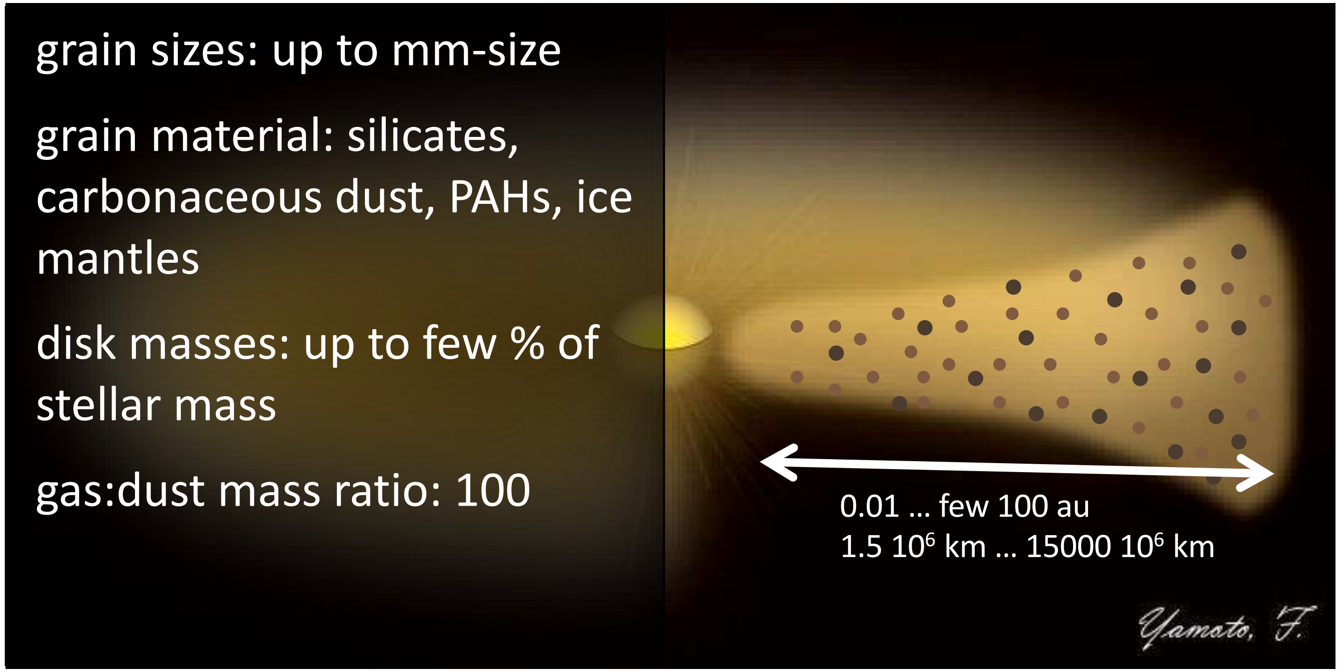

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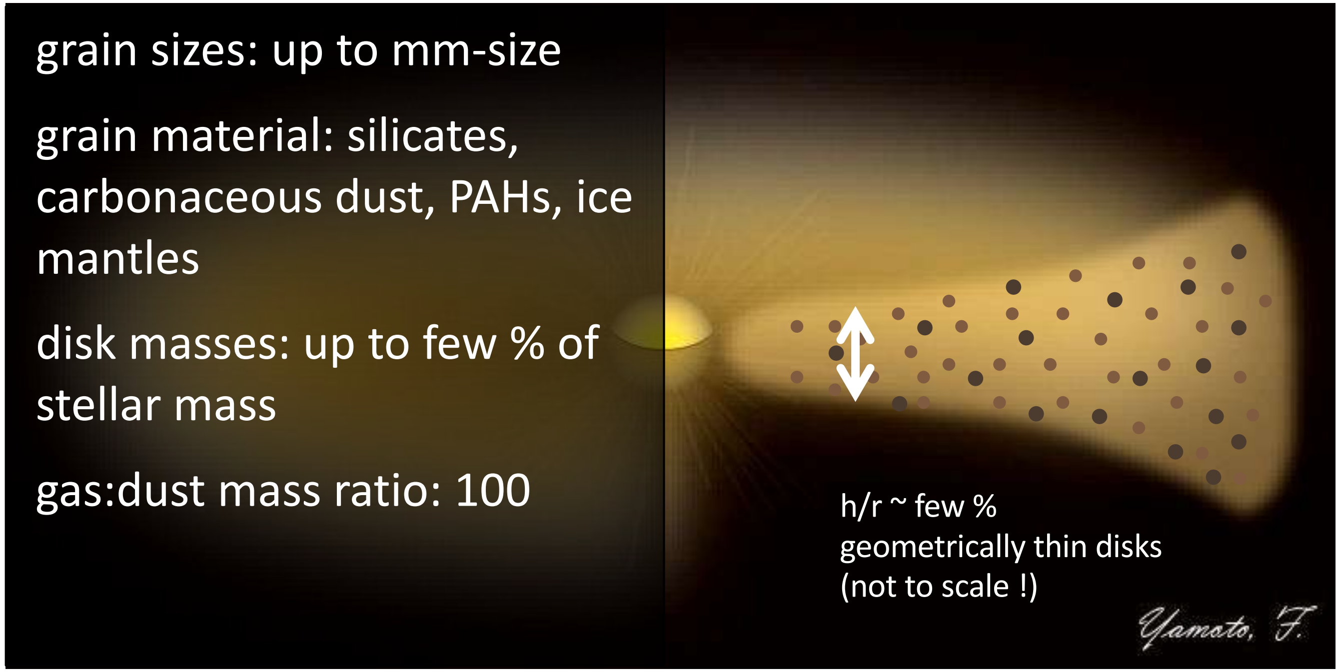

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h/r ~ few %
geometrically thin disks
(not to scale !)

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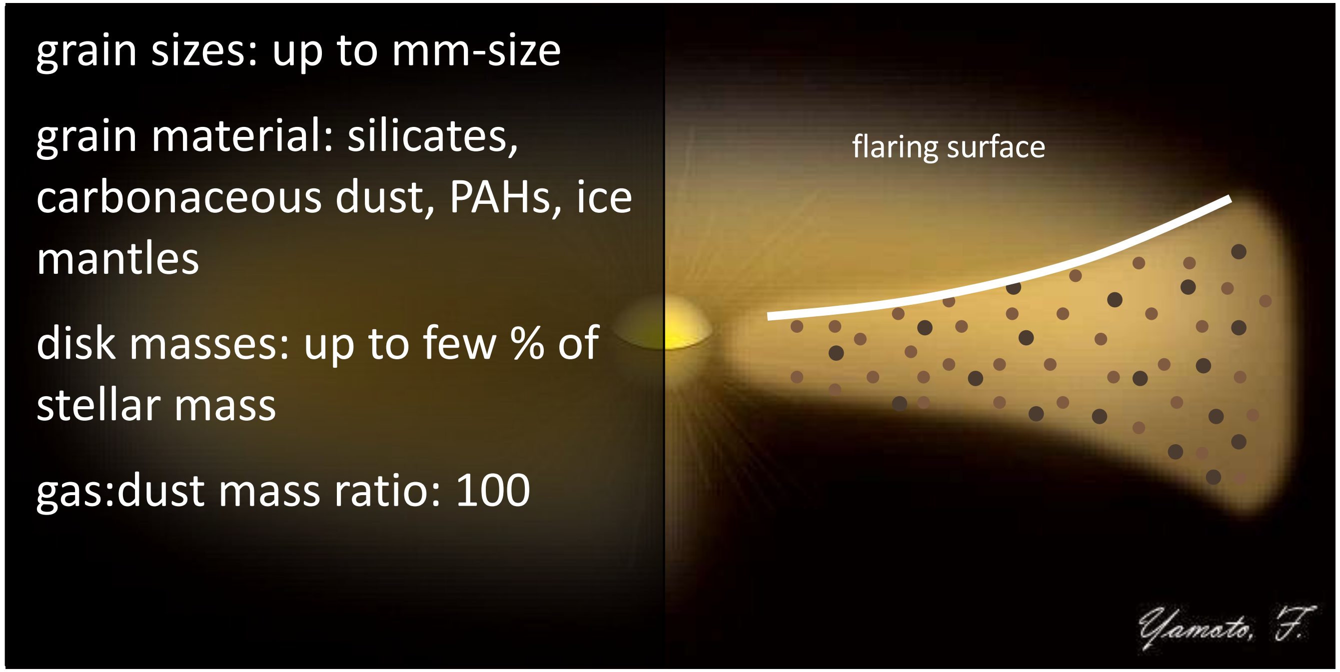

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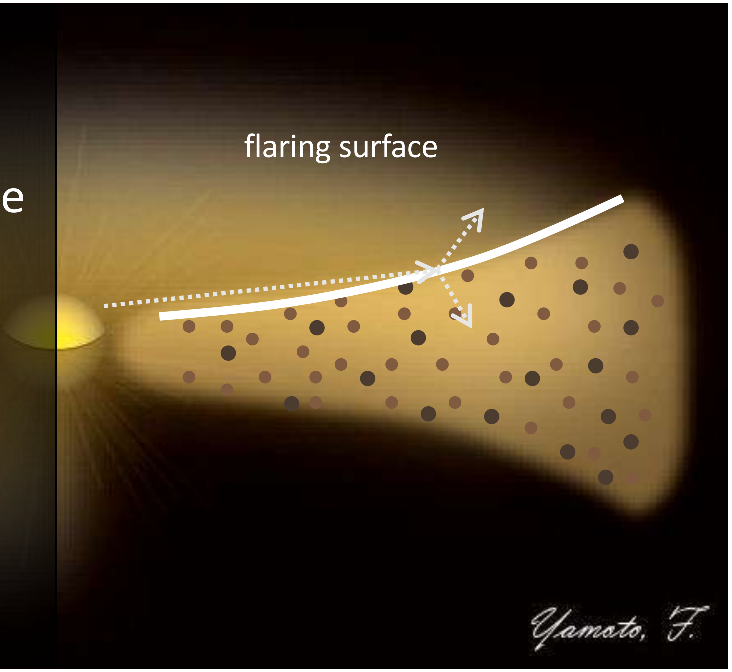

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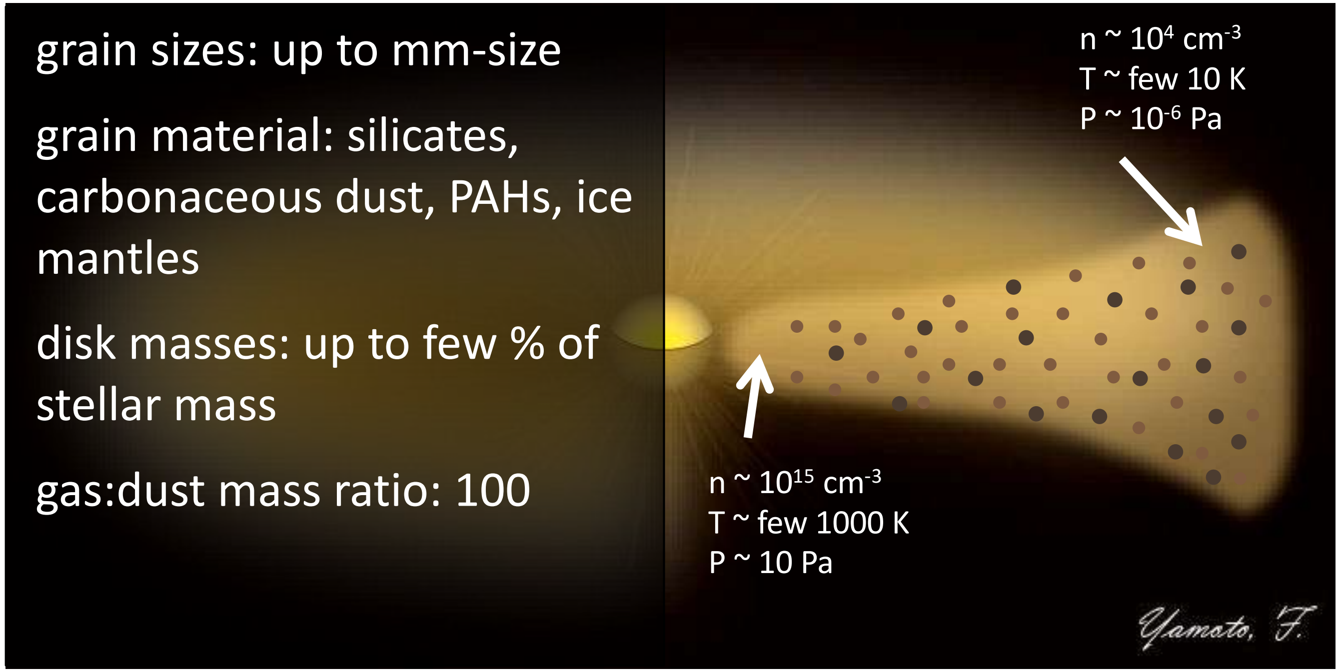

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$n \sim 10^{4}$ cm$^{-3}$
T ~ few 10 K
$P \sim 10^{-6}$ Pa

$n \sim 10^{15}$ cm$^{-3}$
T ~ few 1000 K
P ~ 10 Pa

Yamato, F.

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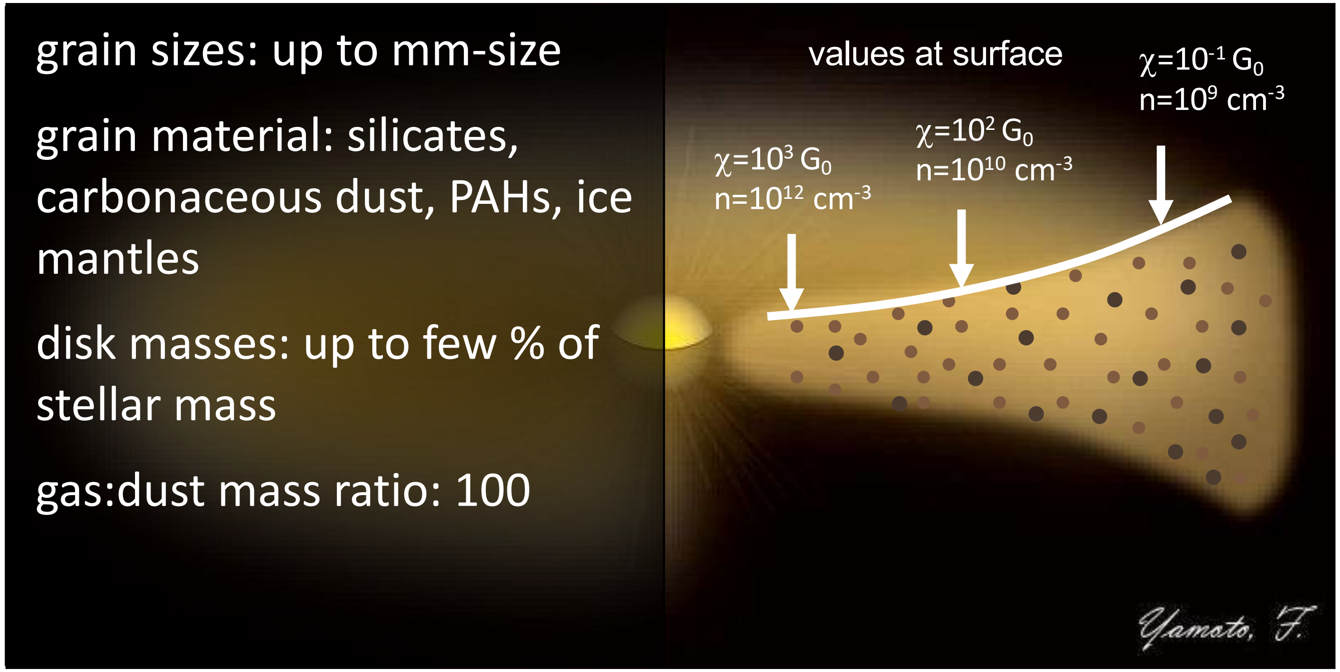

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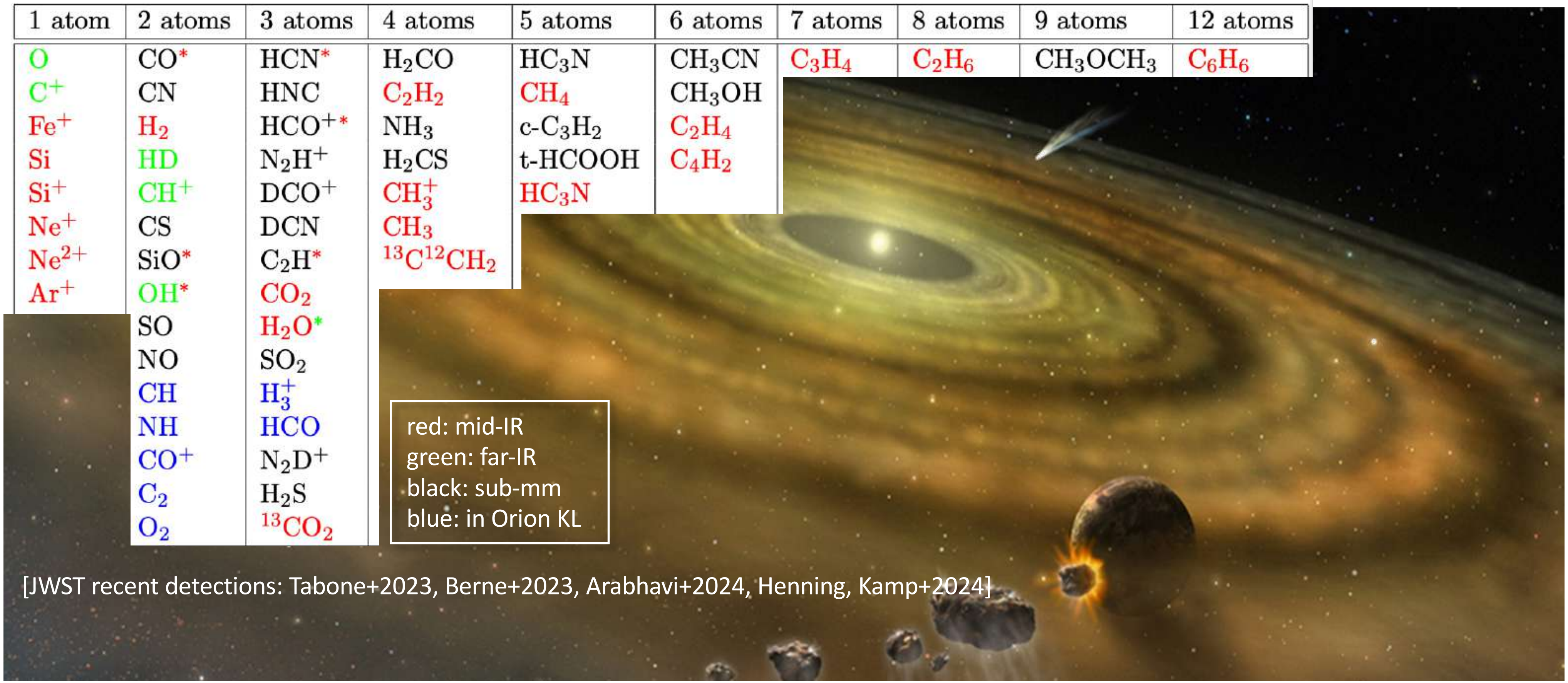
not the ‘typical’ Photon-dominated region (PDR)

# Observing molecules in disks …

# Molecules detected in disks

around 320 molecules in space, but only 44 in disks…



| 1 atom | 2 atoms | 3 atoms | 4 atoms | 5 atoms | 6 atoms | 7 atoms | 8 atoms | 9 atoms | 12 atoms |
|---|---|---|---|---|---|---|---|---|---|
| O | $CO^*$ | $HCN^*$ | $H_2CO$ | $HC_3N$ | $CH_3CN$ | $C_3H_4$ | $C_2H_6$ | $CH_3OCH_3$ | $C_6H_6$ |
| $C^+$ | CN | HNC | $C_2H_2$ | $CH_4$ | $CH_3OH$ | | | | |
| $Fe^+$ | $H_2$ | $HCO^{+*}$ | $NH_3$ | $c\text{-}C_3H_2$ | $C_2H_4$ | | | | |
| Si | HD | $N_2H^+$ | $H_2CS$ | t-HCOOH | $C_4H_2$ | | | | |
| $Si^+$ | $CH^+$ | $DCO^+$ | $CH_3^+$ | $HC_3N$ | | | | | |
| $Ne^+$ | CS | DCN | $CH_3$ | | | | | | |
| $Ne^{2+}$ | $SiO^*$ | $C_2H^*$ | $^{13}C^{12}CH_2$ | | | | | | |
| $Ar^+$ | $OH^*$ | $CO_2$ | | | | | | | |
| | SO | $H_2O^*$ | | | | | | | |
| | NO | $SO_2$ | | | | | | | |
| | CH | $H_3^+$ | | | | | | | |
| | NH | HCO | | | | | | | |
| | $CO^+$ | $N_2D^+$ | | | | | | | |
| | $C_2$ | $H_2S$ | | | | | | | |
| | $O_2$ | $^{13}CO_2$ | | | | | | | |

red: mid-IR
green: far-IR
black: sub-mm
blue: in Orion KL

[JWST recent detections: Tabone+2023, Berne+2023, Arabhavi+2024, Henning, Kamp+2024]

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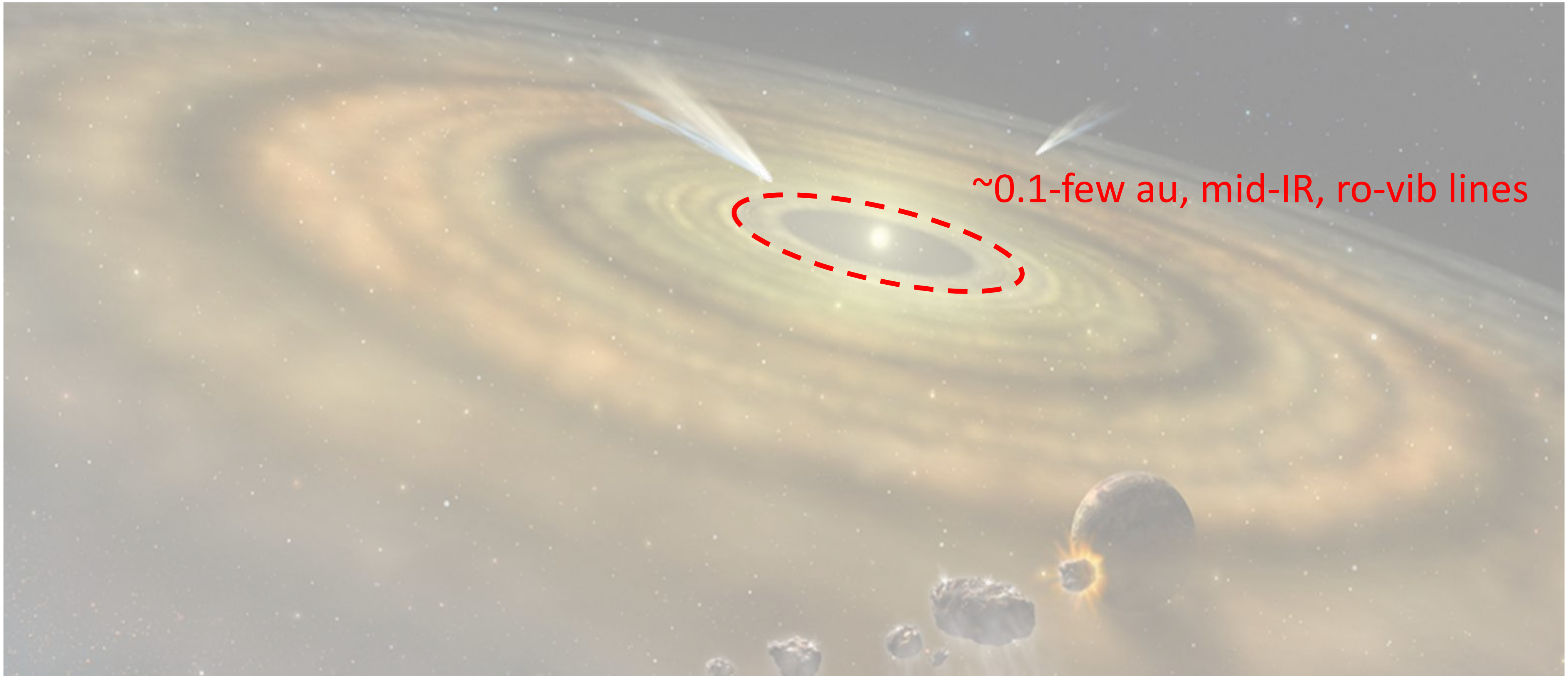

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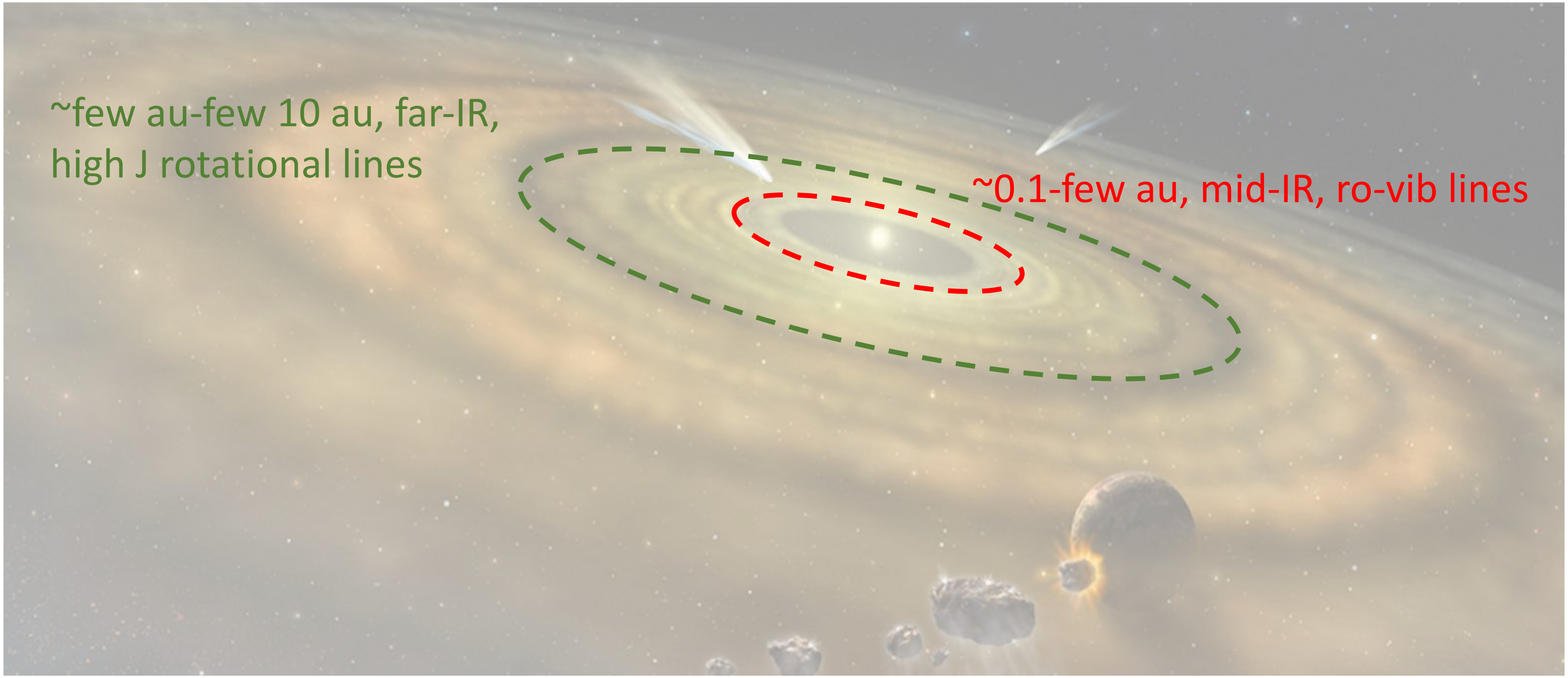

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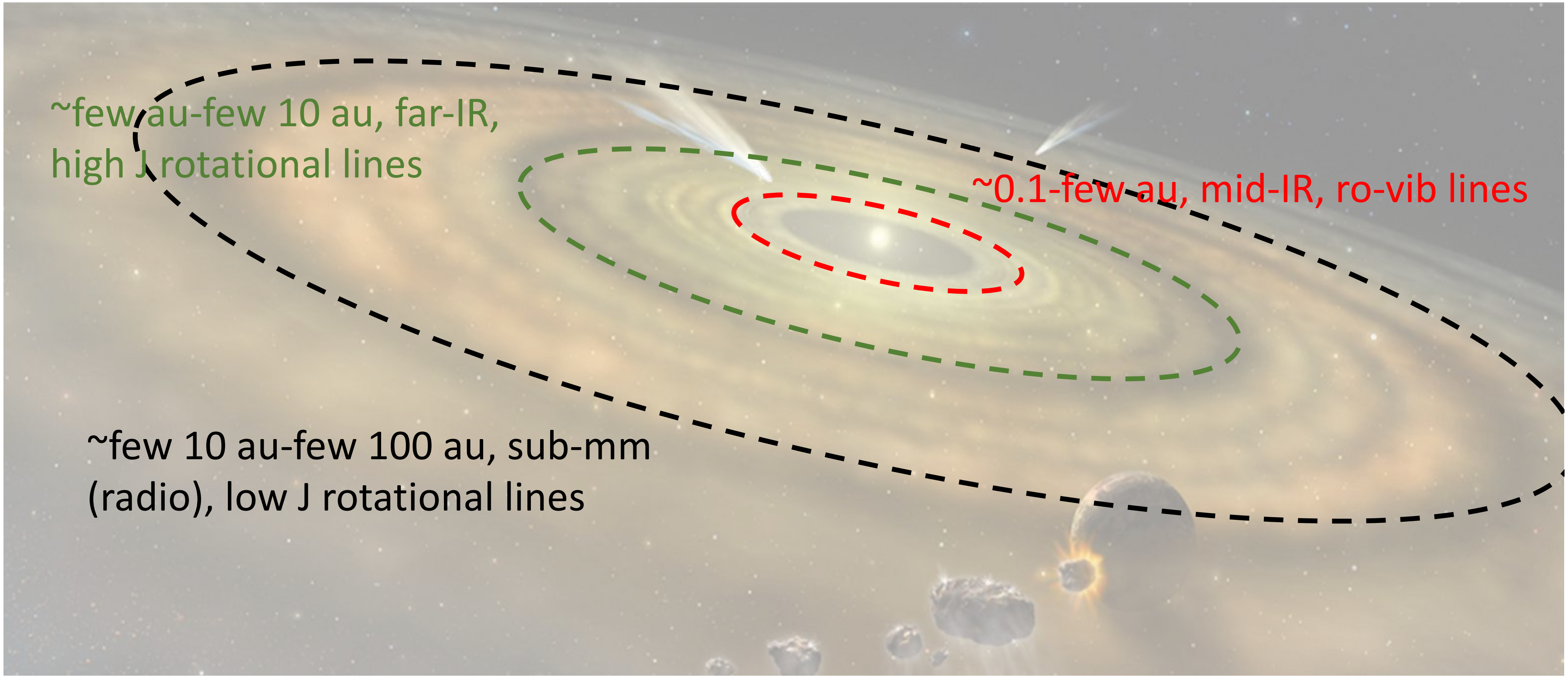
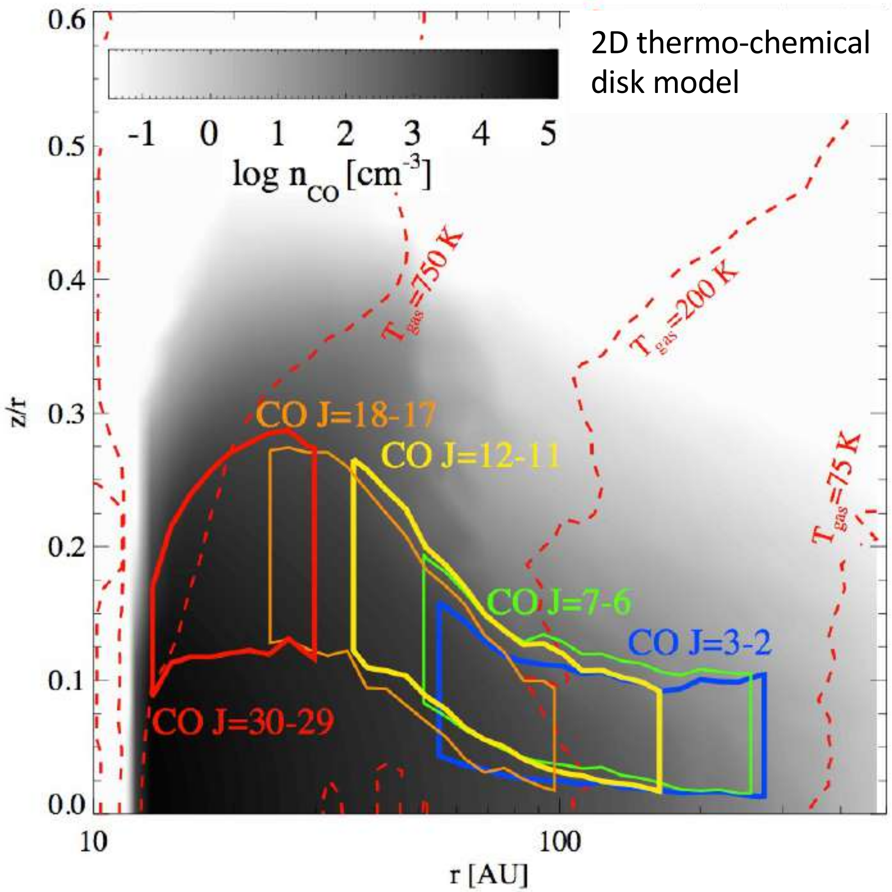
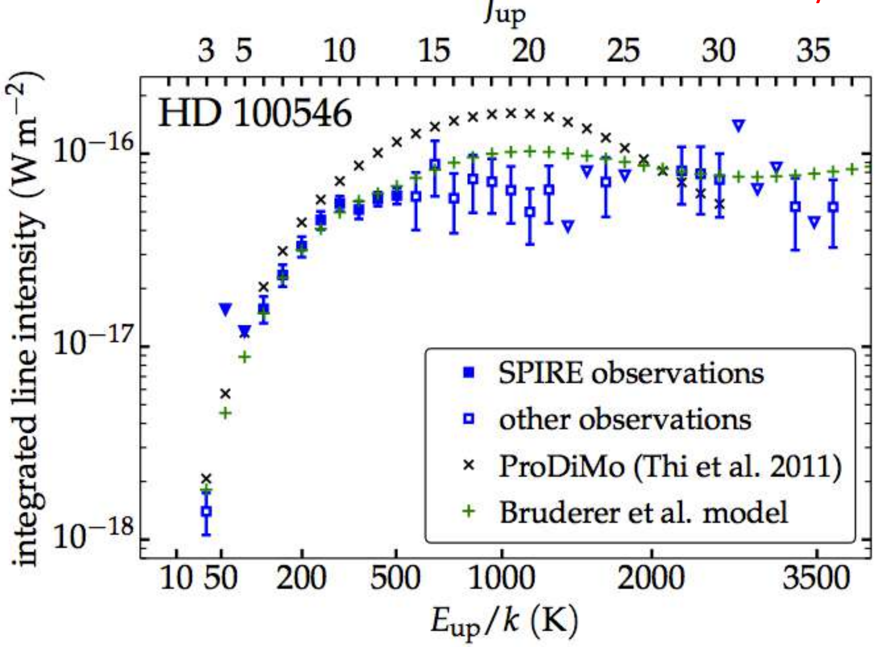


# Radial disk temperature gradients

Lecture of Maryvonne Gerin



2D thermo-chemical disk model



CO rotational lines ‘scan’ the disk surface radially, isotopologues probe vertical gradients

[van der Wiel+2014, Fedele+2016]

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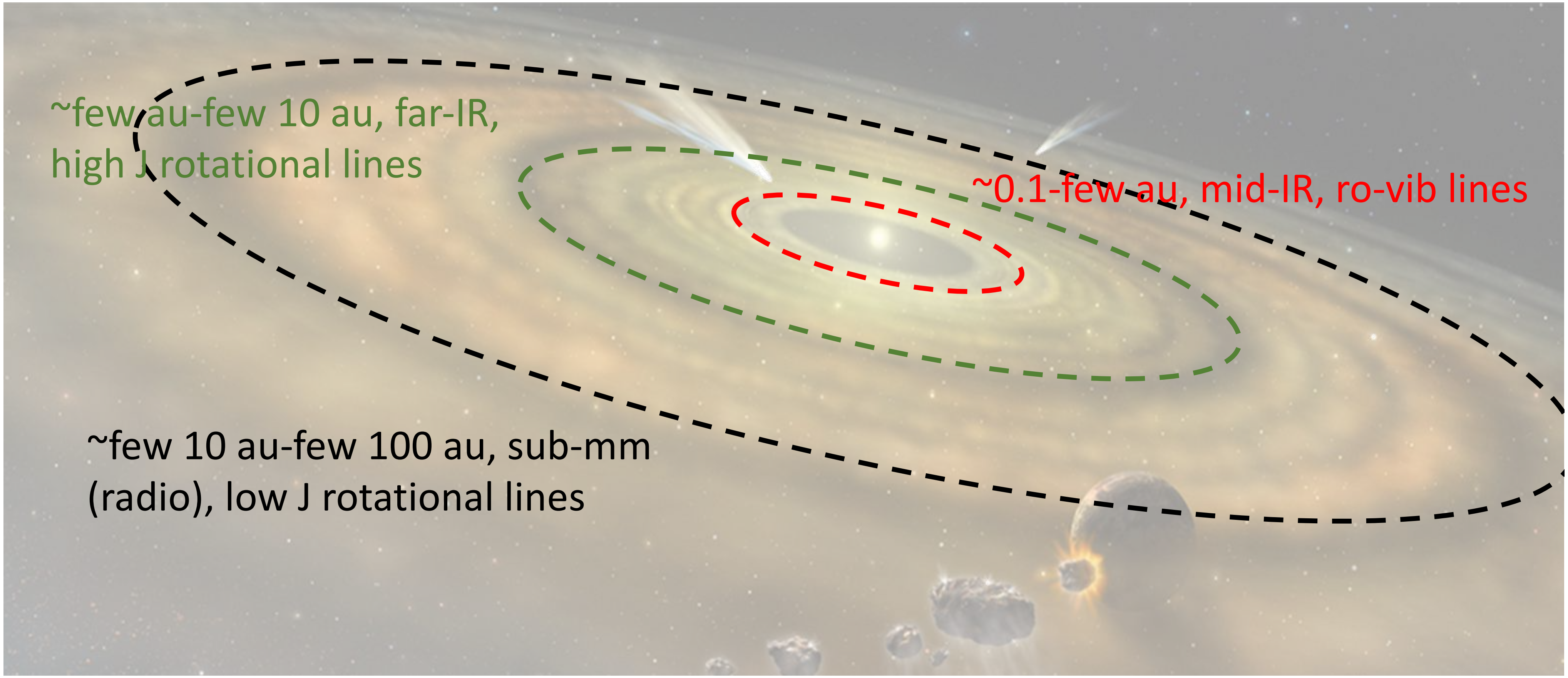
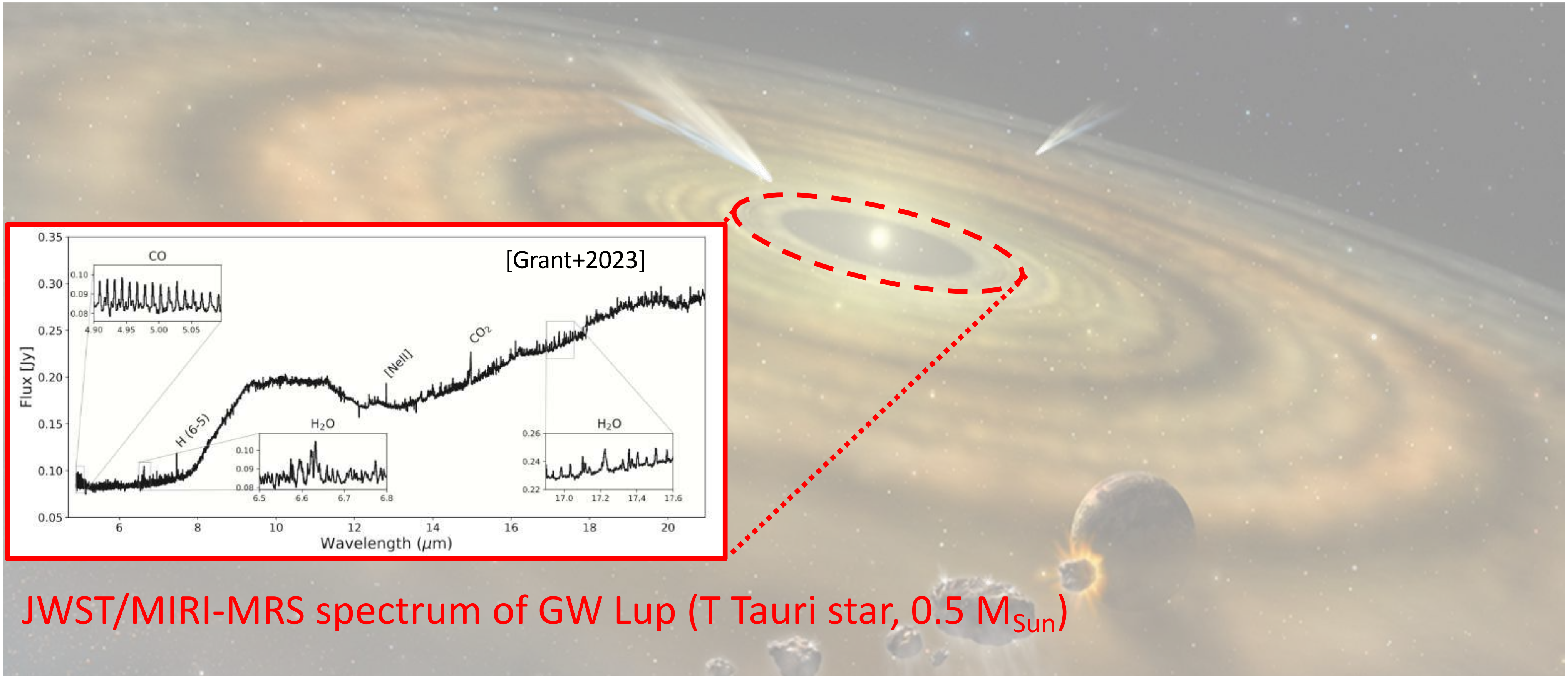


# Molecules in rocky planet forming region

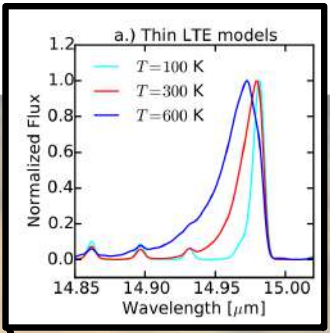


[Grant+2023]

JWST/MIRI-MRS spectrum of GW Lup (T Tauri star, 0.5 $M_{Sun}$)

# Molecules in rocky planet forming region

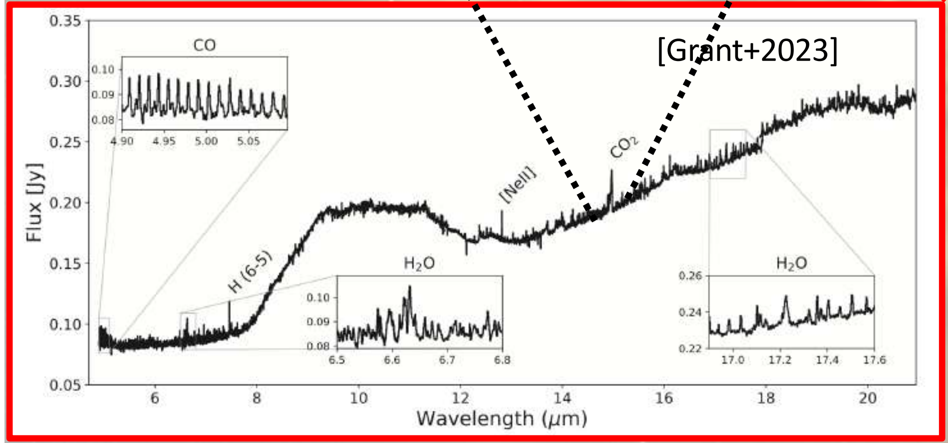
[Bosman+2017]



ro-vibrational emission of $CO_2$ depends on gas temperature, $CO_2$ column density

Lecture Jacques Le Bourlot

Blue exercise



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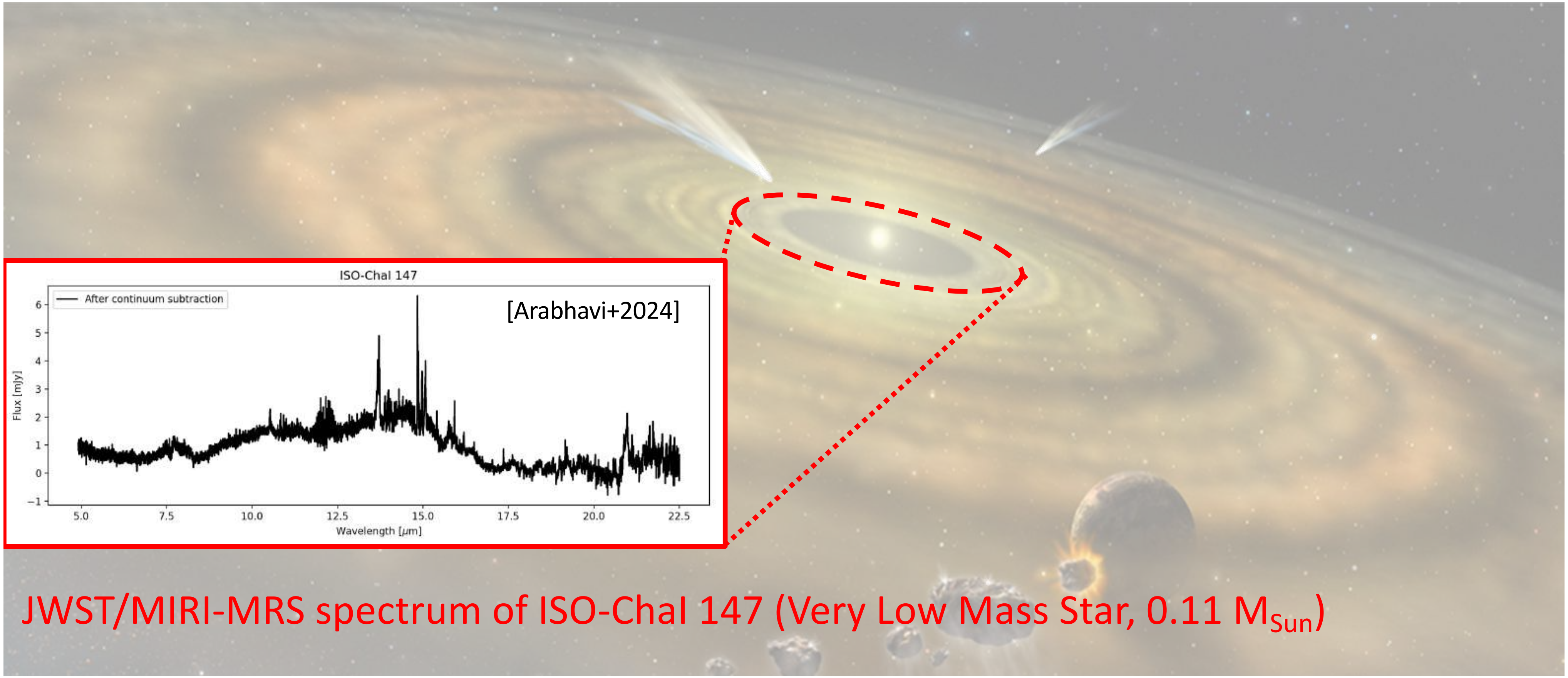

[Arabhavi+2024]

JWST/MIRI-MRS spectrum of ISO-ChaI 147 (Very Low Mass Star, 0.11 $M_{Sun}$)

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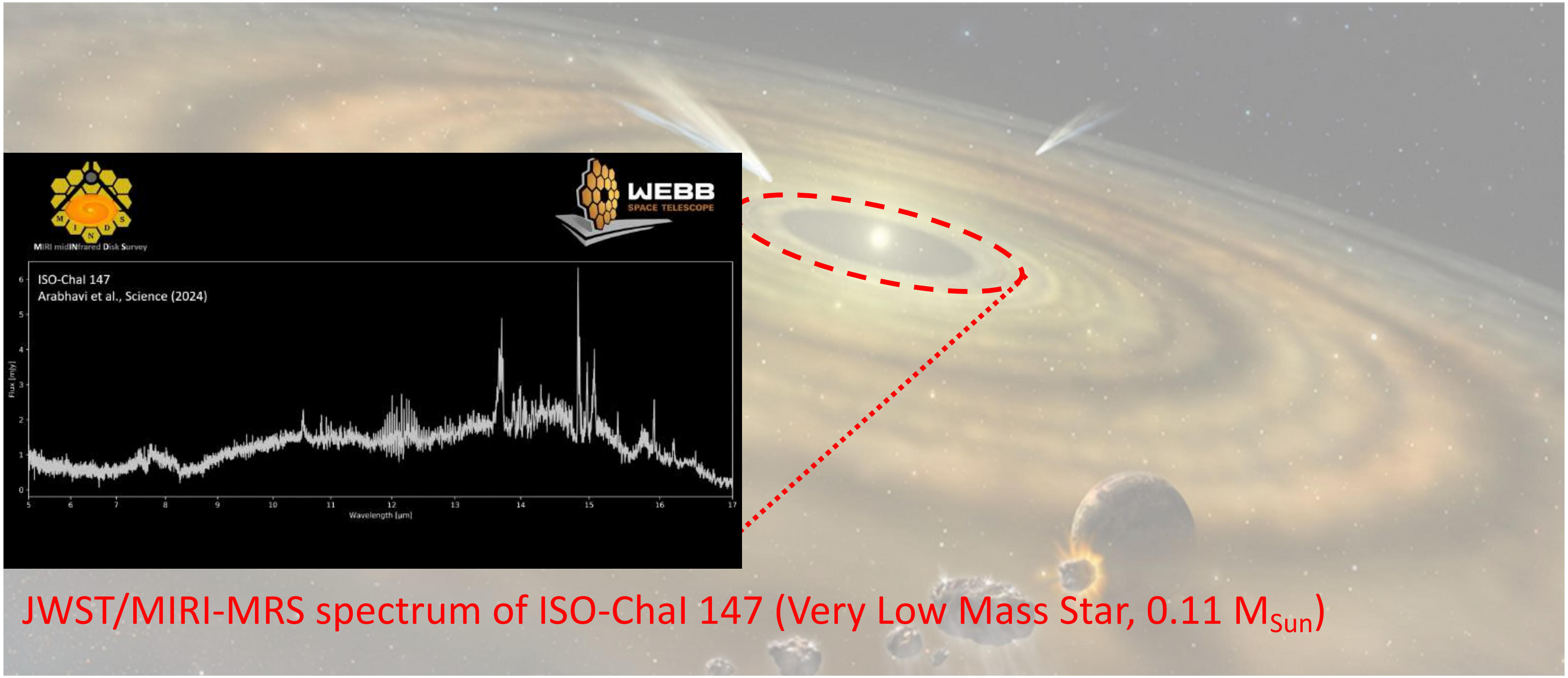

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# Concept test

The inner few au of a disk can be best observed at

A) optical wavelengths
B) mid-IR wavelengths
C) far-IR wavelengths
D) sub-mm (radio) wavelengths

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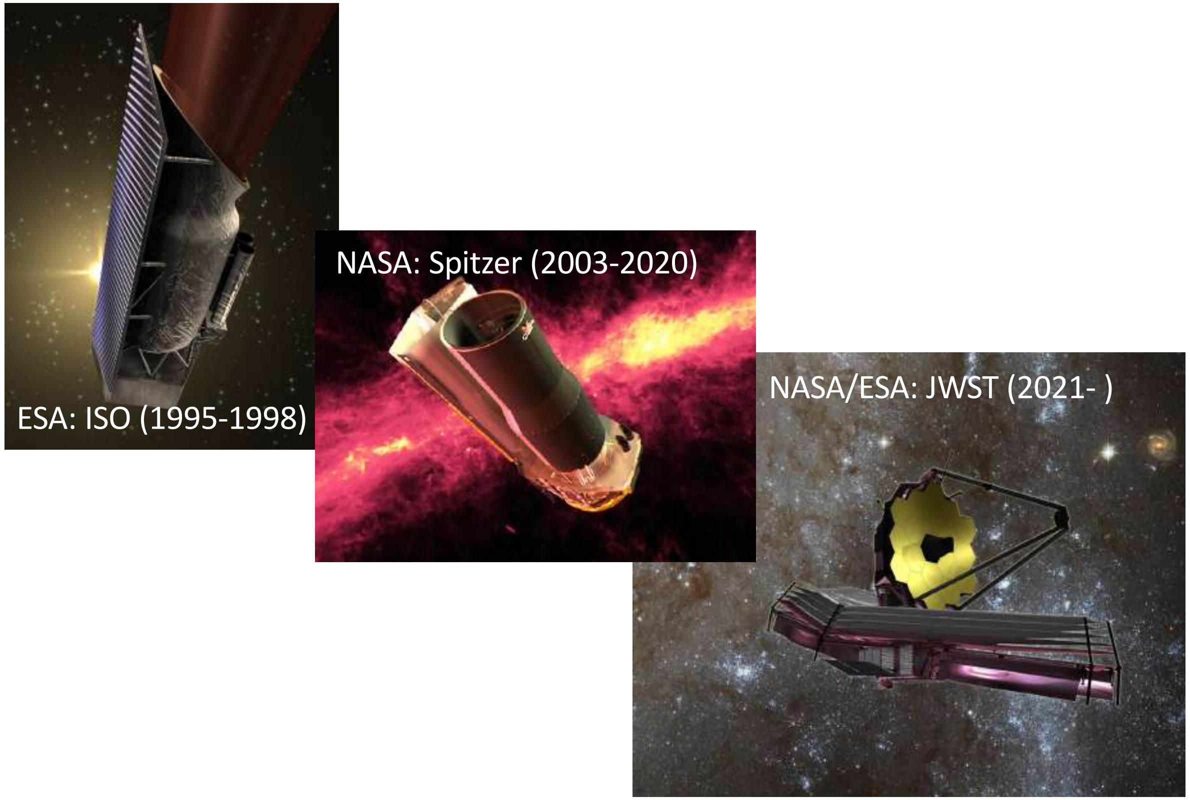


ESA: ISO (1995-1998)

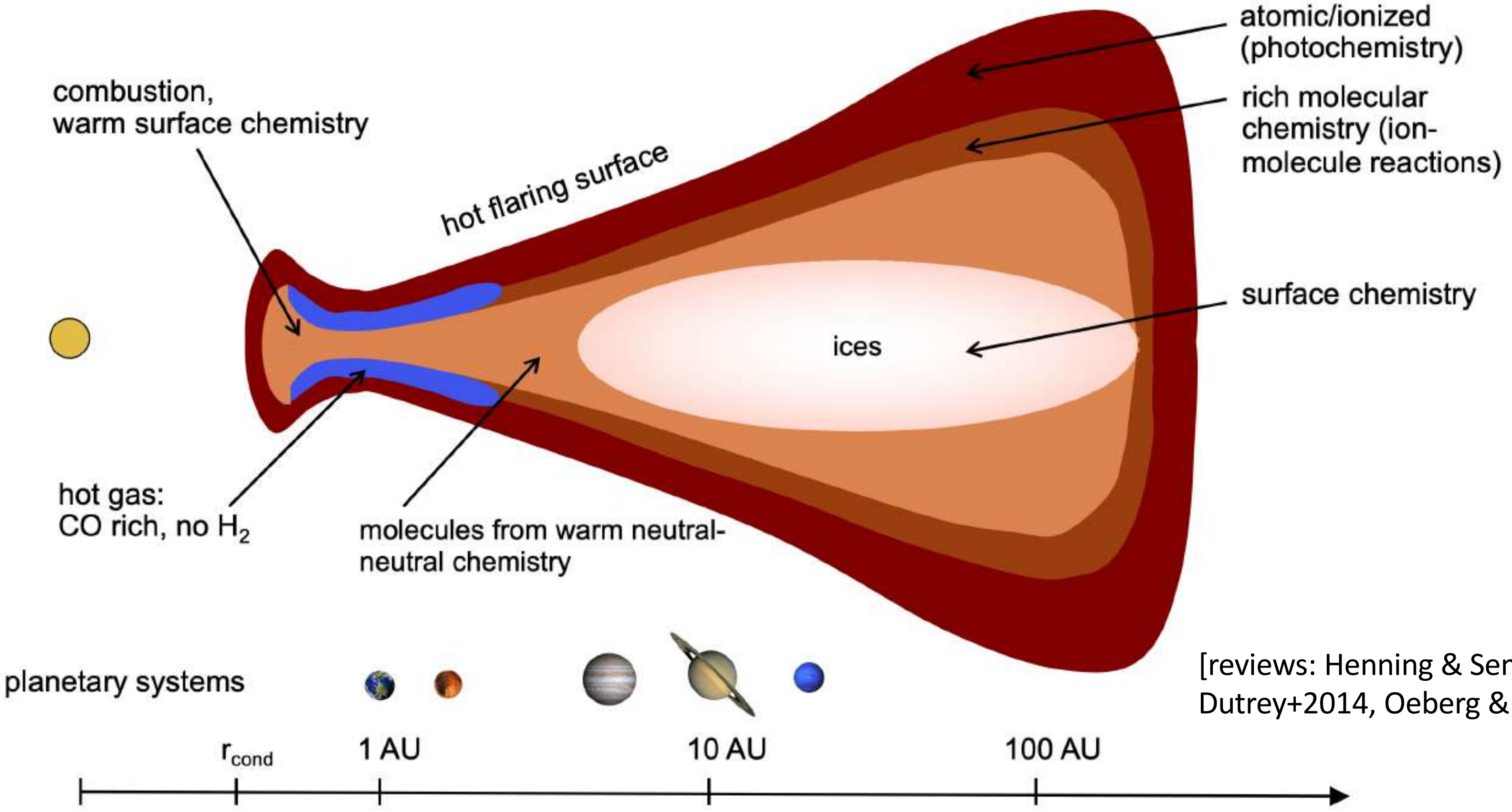
NASA: Spitzer (2003-2020)

NASA/ESA: JWST (2021- )

# Forming molecules in disks …

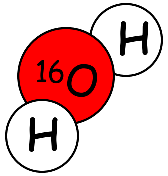
Two examples: water and hydrocarbons

# Which types of chemistry occur in disks?



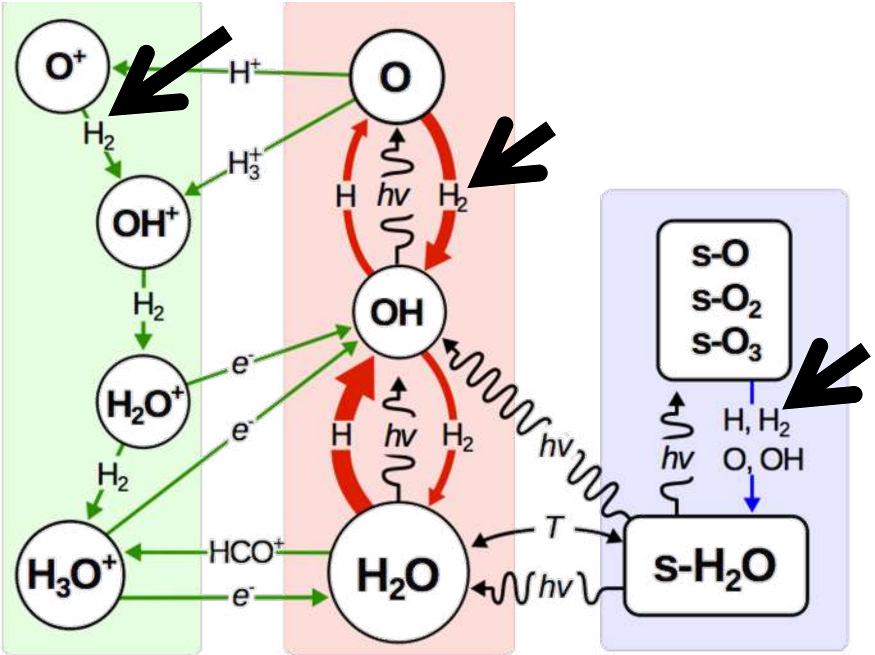
[reviews: Henning & Semenov 2013,
Dutrey+2014, Oeberg & Bergin 2020]

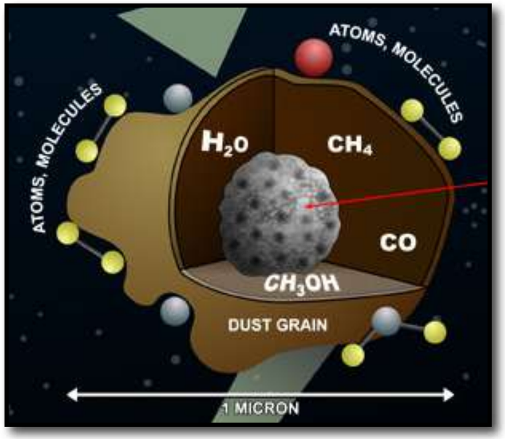
# How does water form in disks?



It also starts with molecular hydrogen…

cold gas warm gas (~20°C = 300 K)





gas chemistry

chemistry on dust grain surfaces

[van Dishoeck+2014]

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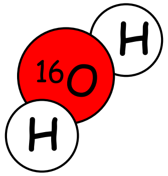
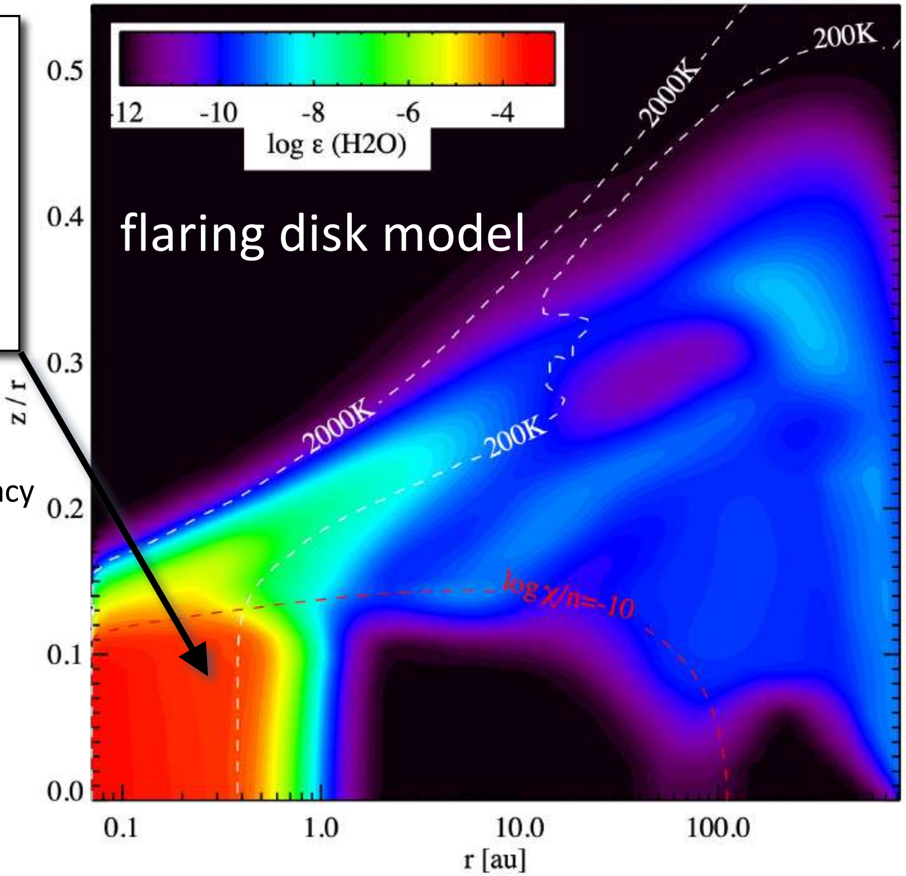


high densities ($n_{<H>} > 10^{13}$ cm$^{-3}$): all oxygen locked in gas phase water, neutral-neutral reactions

=> carbon rich chemistry ($CH_4$),
water formation not in
thermodynamic equilibrium

long timescales !



flaring disk model

[Aikawa et al., Bergin et al., Willacy et al., Kamp et al., Thi et al., Glassgold et al., Meijerink et al., Najita et al., Semenov et al., …]

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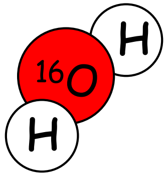

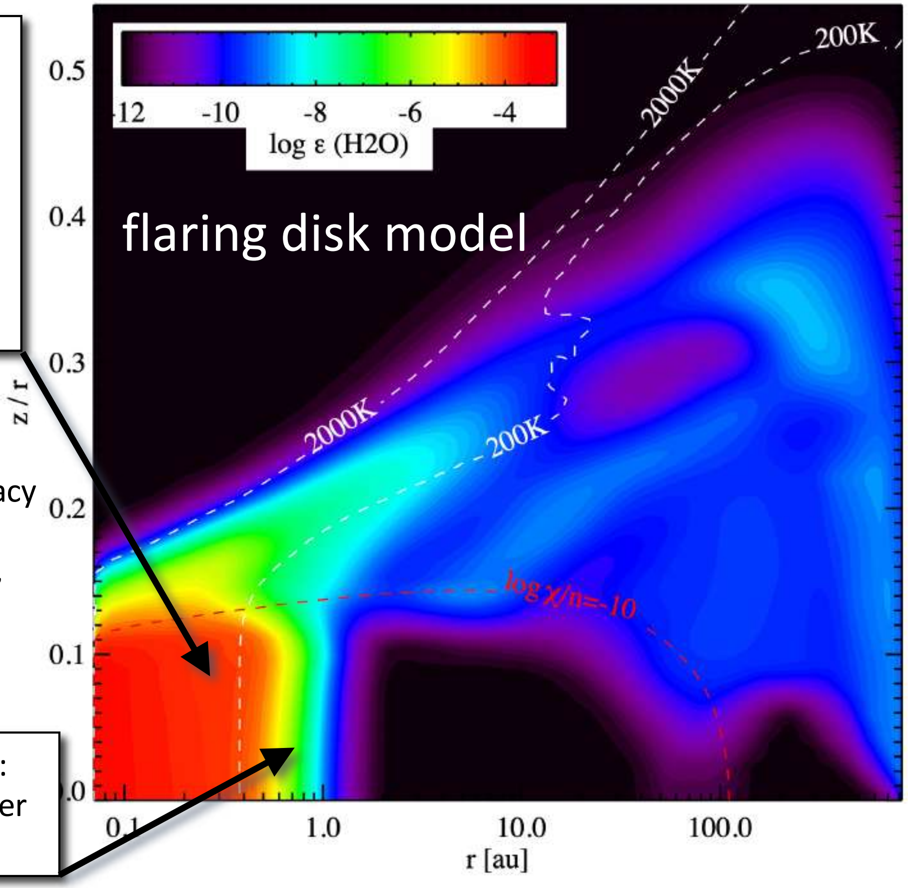

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warm temperatures (T > 150 K): oxygen locked in gas phase water <u>and</u> CO (also $CO_2$ ring ~ 0.3 AU)

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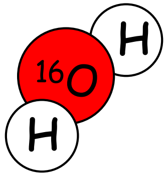

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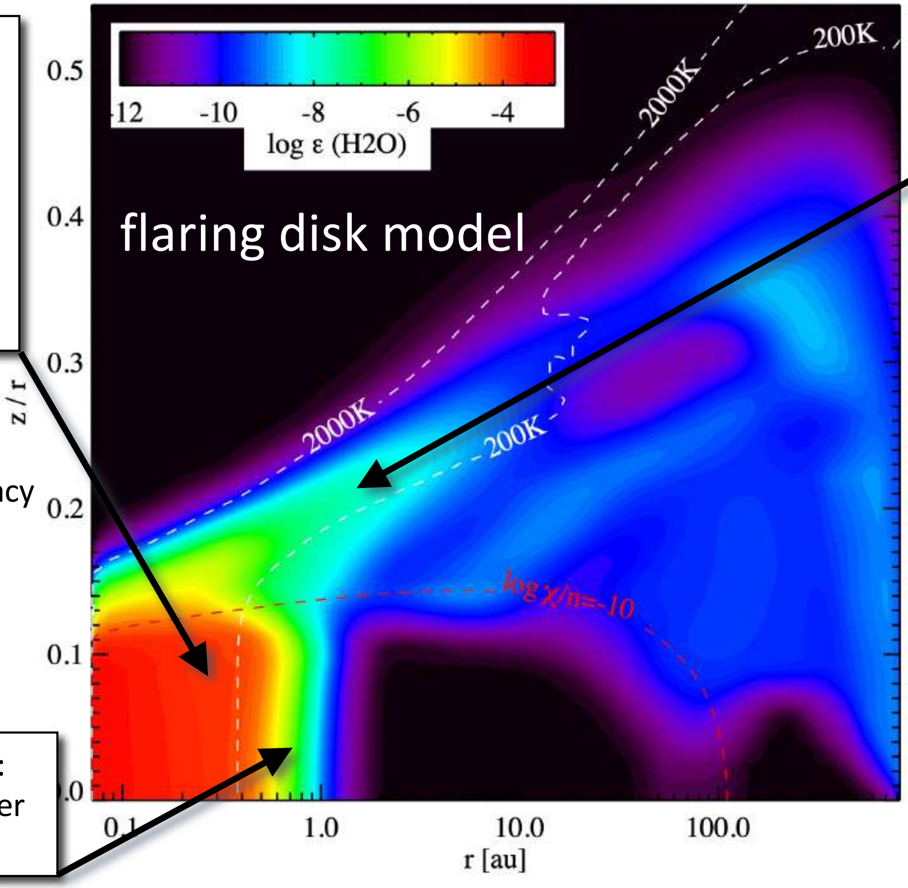
long timescales !

warm temperatures (T > 150 K):
water forms through neutral-neutral reactions



[Aikawa et al., Bergin et al., Willacy et al., Kamp et al., Thi et al., Glassgold et al., Meijerink et al., Najita et al., Semenov et al., …]

warm temperatures (T > 150 K):
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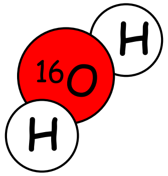
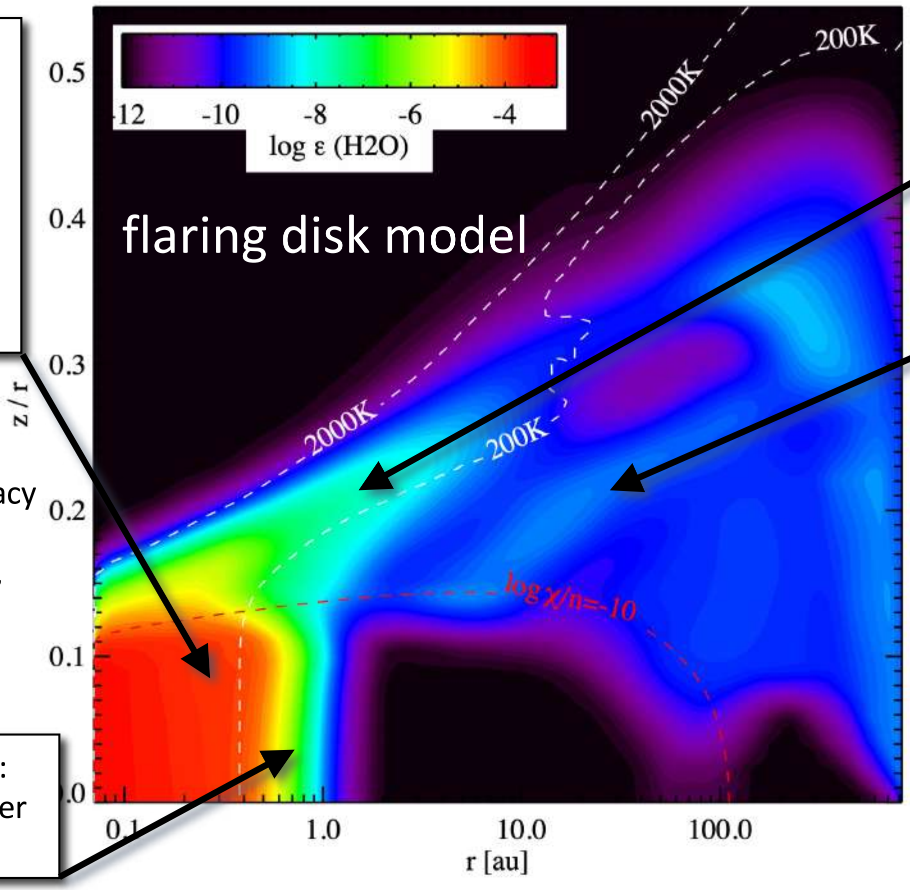
# How does water form in disks?





high densities ($n_{<H>} > 10^{13}$ $cm^{-3}$): all oxygen locked in gas phase water, neutral-neutral reactions
=> carbon rich chemistry ($CH_4$),
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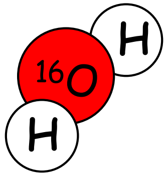

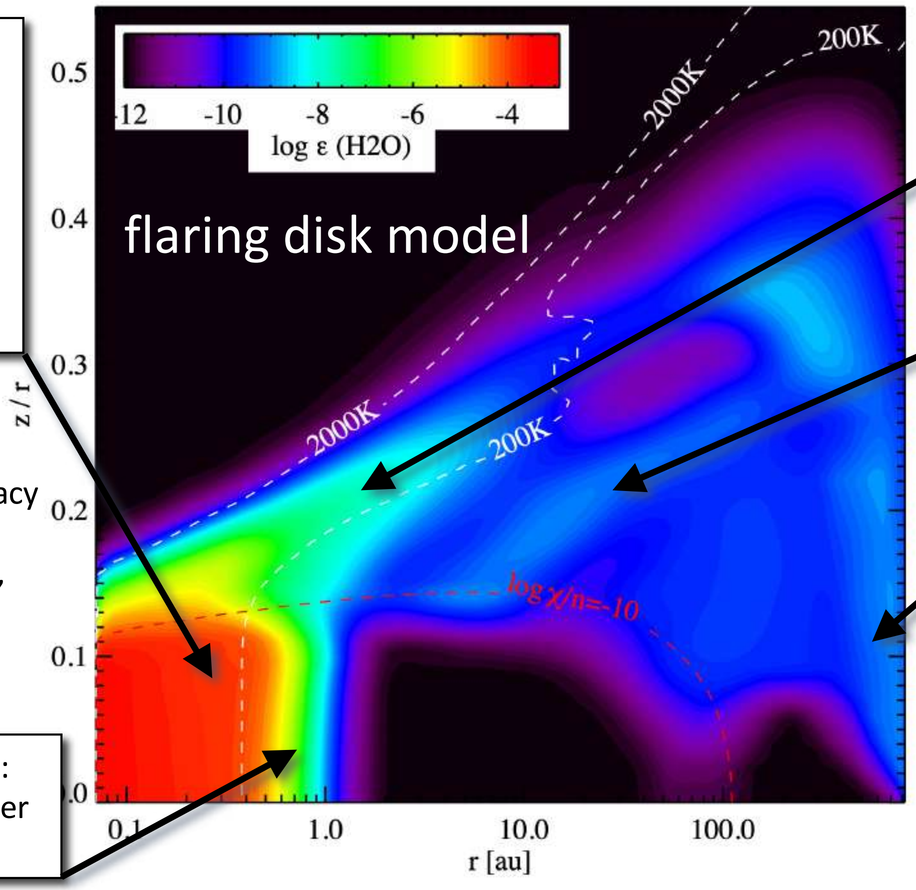

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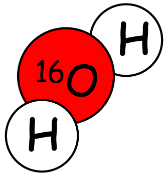

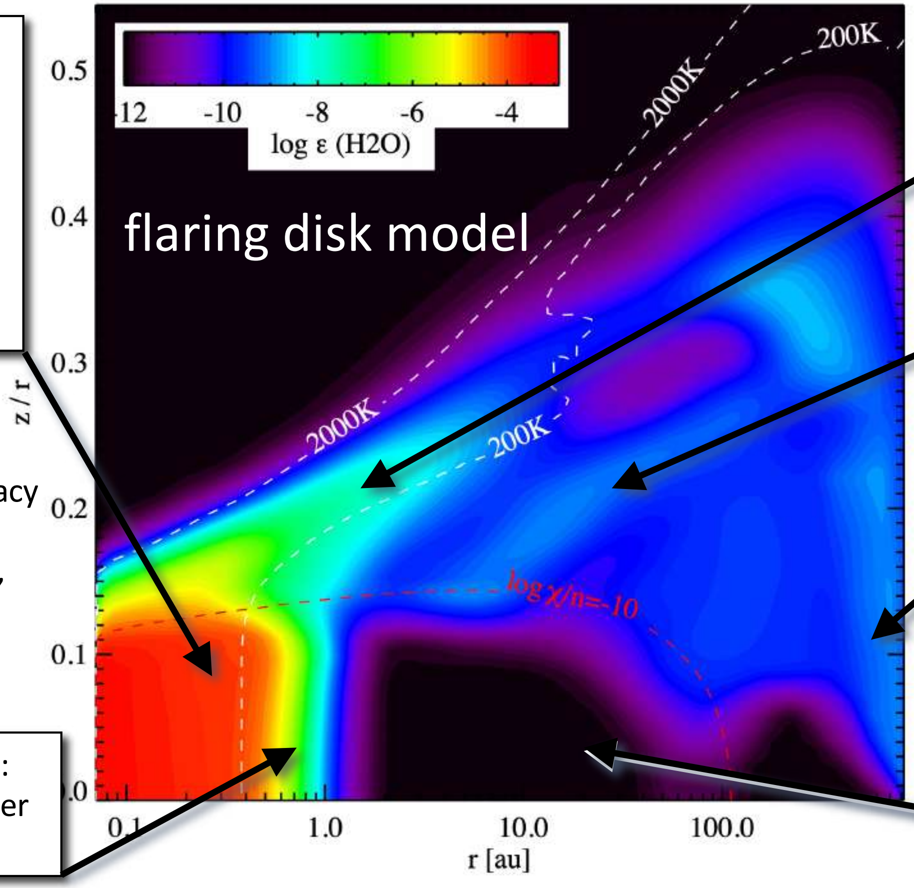

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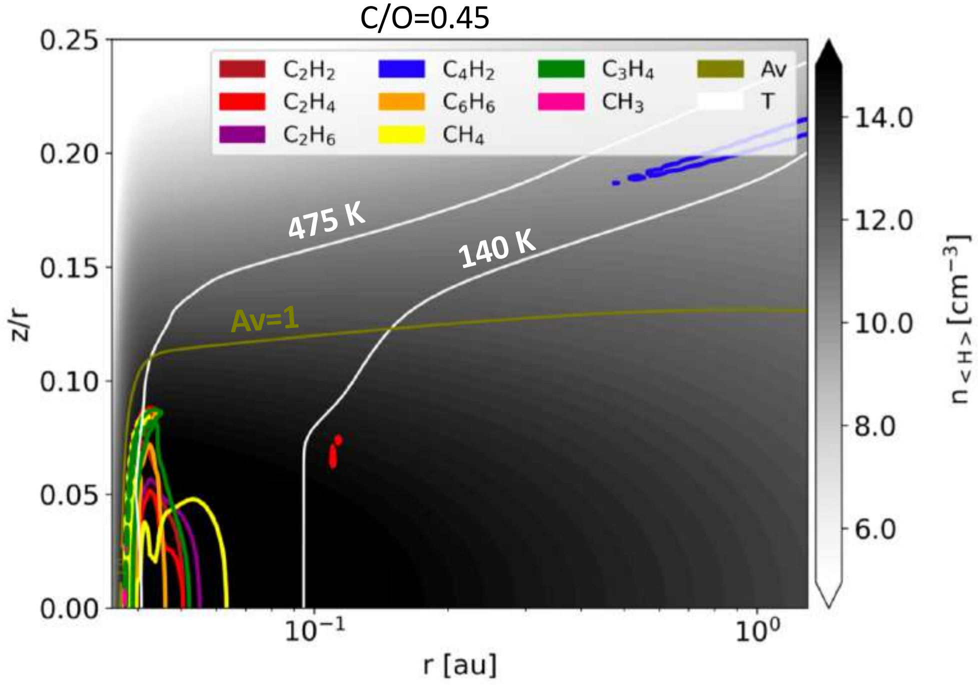
low temperatures (T<20 K): most oxygen locked in CO ice (r > 100 AU), gas phase water from photo-desorption

moderate temperatures (150 K <T< 20 K): all oxygen locked in water ice, long timescales !
=> carbon in $CH_4$/$CH_4$ ice (40 K)

# Chemistry in gas with different C/O ratio

2D thermo-chemical disk model for a protoplanetary disk [Greenwood+ 2017]



[extended hydrocarbon chemical network: Kanwar+2024a,b]

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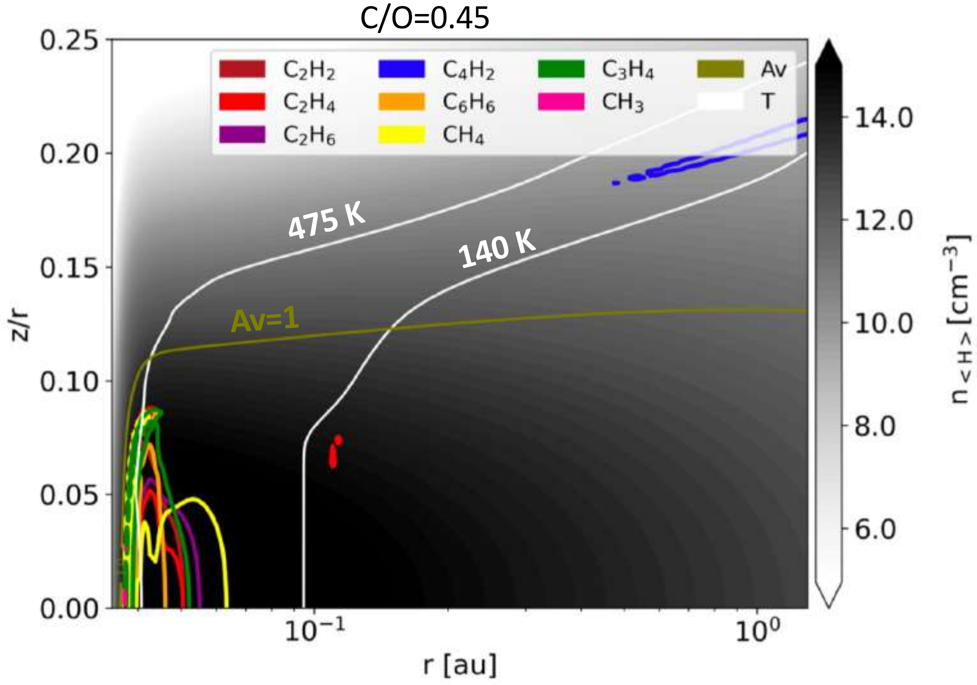

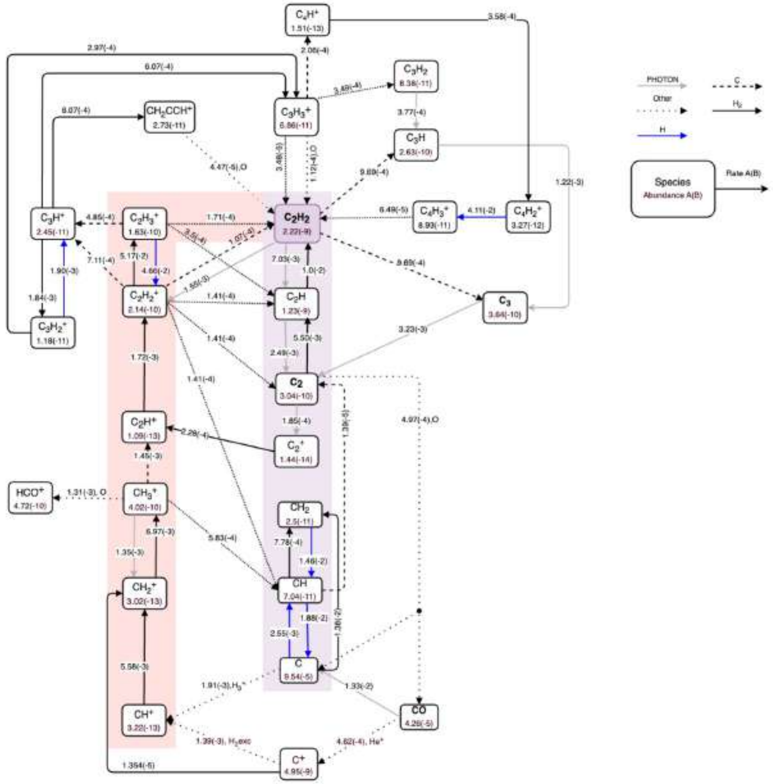

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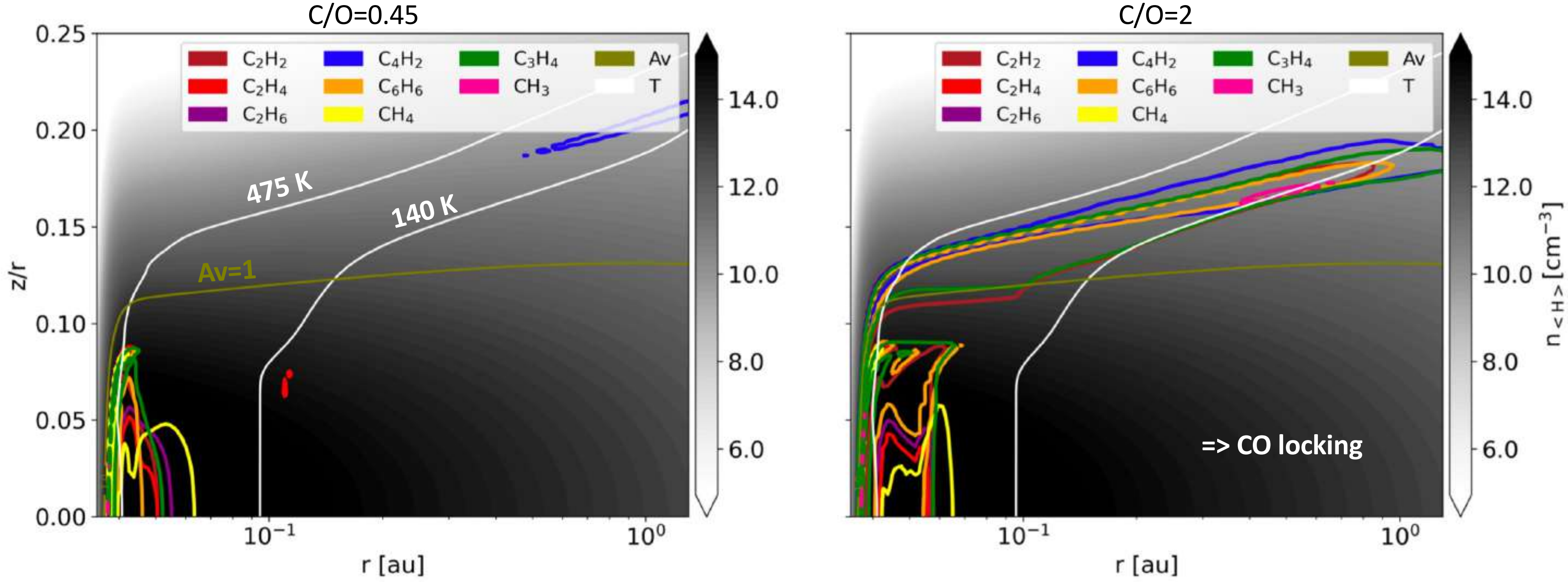

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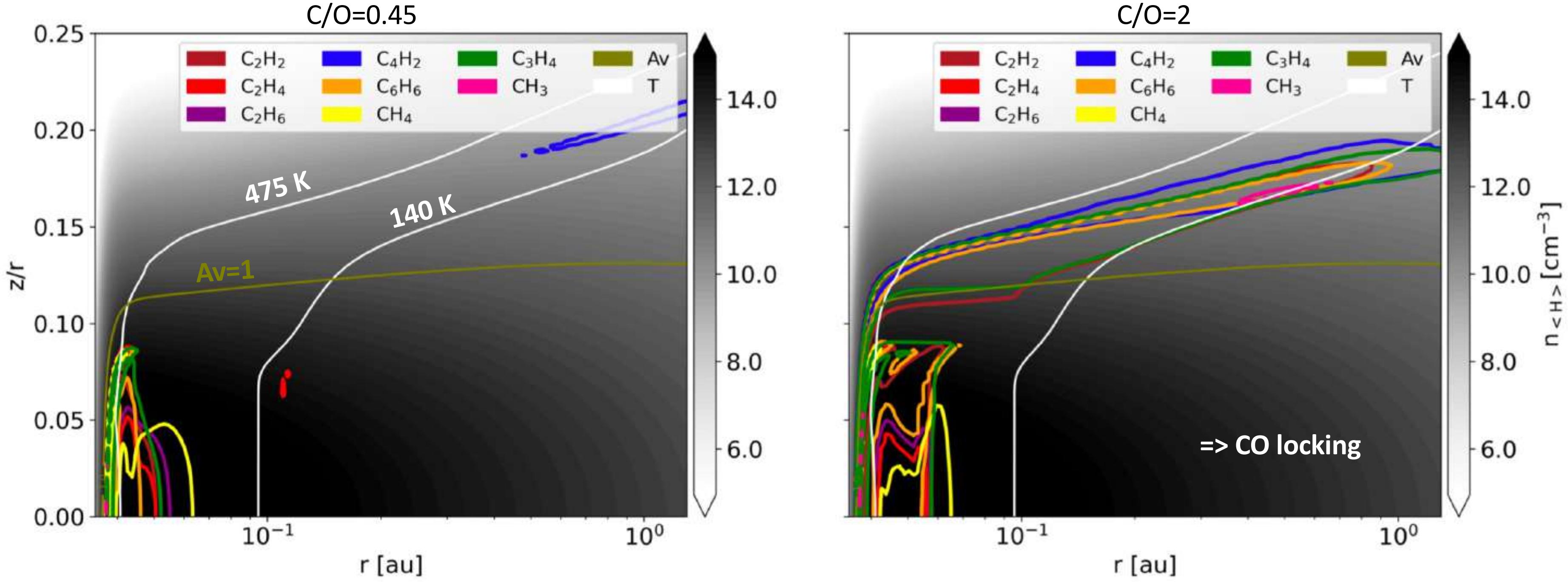

With a C/O>1, we form abundant hydrocarbons in the disk surface layer

[extended hydrocarbon chemical network: Kanwar+2024a,b]

# Concept test

What happens in a planet forming disk if the temperature drops below ~150 K?

A) Water molecules stay in the gas phase – supersaturated vapor.

B) Water molecules become very immobile and locally cluster together to form ices.

C) Water molecules adsorb on the surfaces of small dust grains and form ices.

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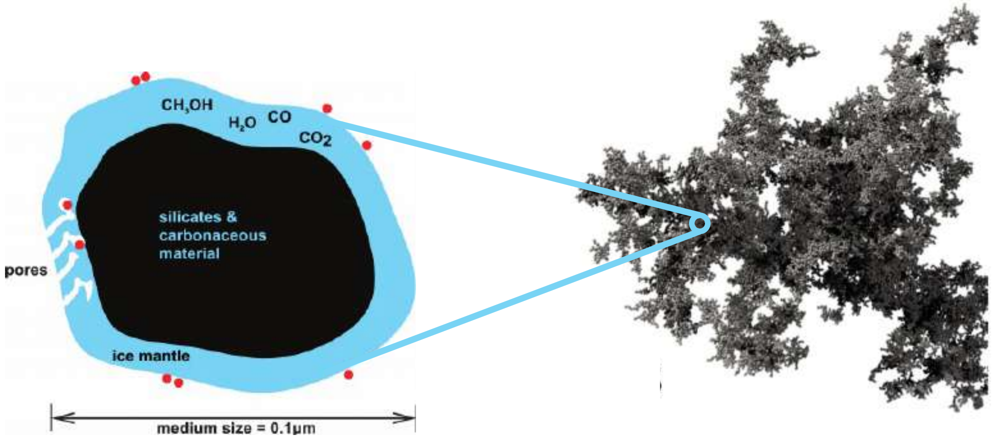


classical grain/ice model

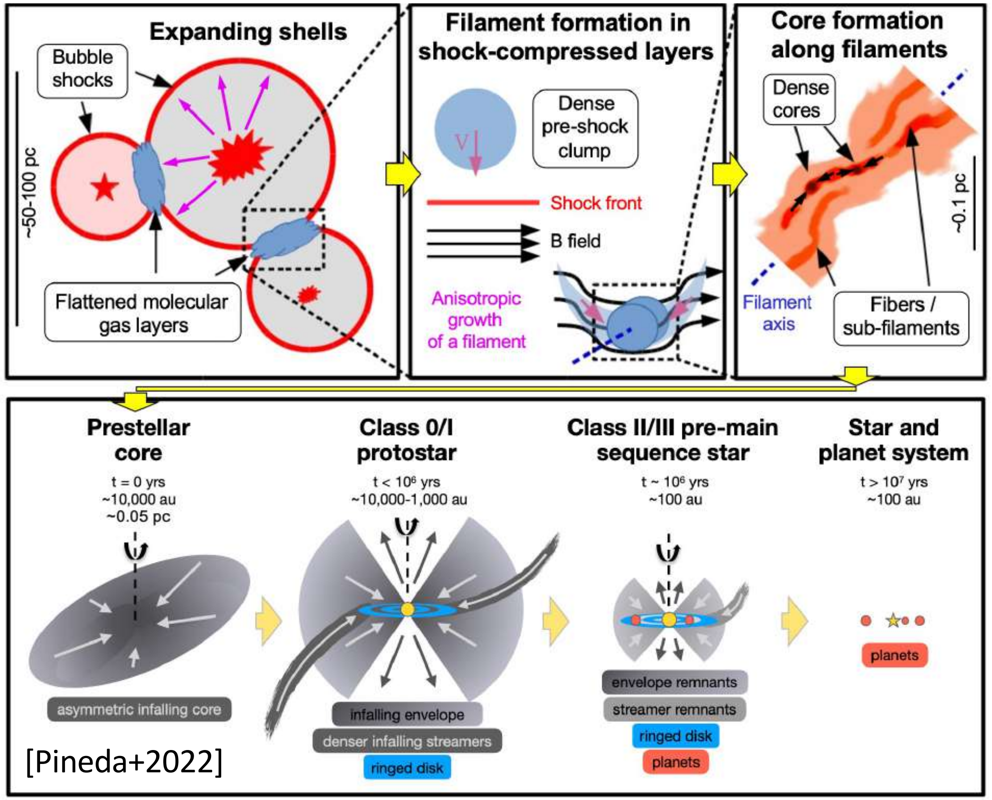
stochastic grain/ice model

Grains grow from clouds to disks by a factor $10^3$-$10^4$ in size.

Are they porous? compact? Do they keep their ice mantles?

# From molecules to planets …

# From dense clouds to protostars, disks, and planetary systems

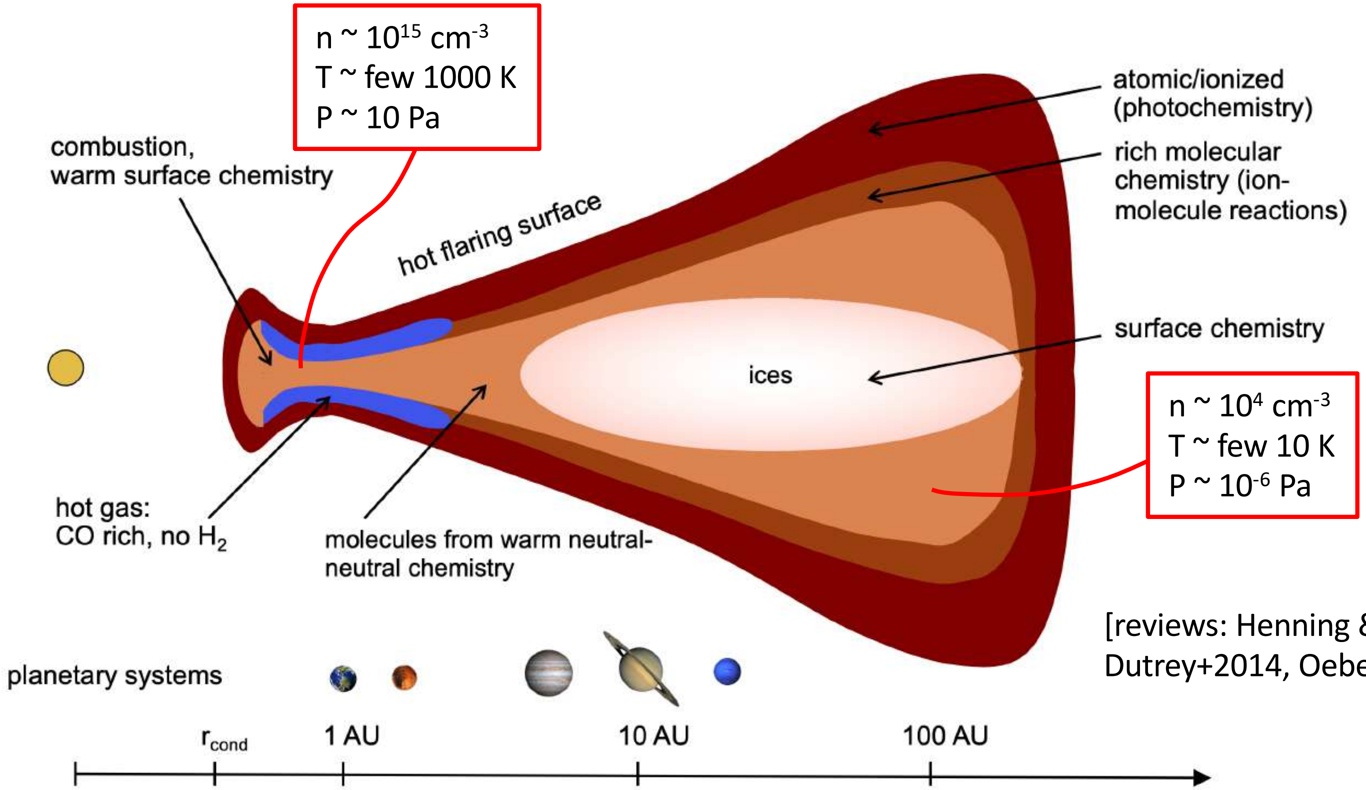


[Pineda+2022]

chemistry occurs at all stages
→ building up molecular complexity

we use molecules as tracers of physical conditions, time scales, transport processes (in-situ versus inheritance)

# Disks provide very diverse conditions – many types of chemistry occur

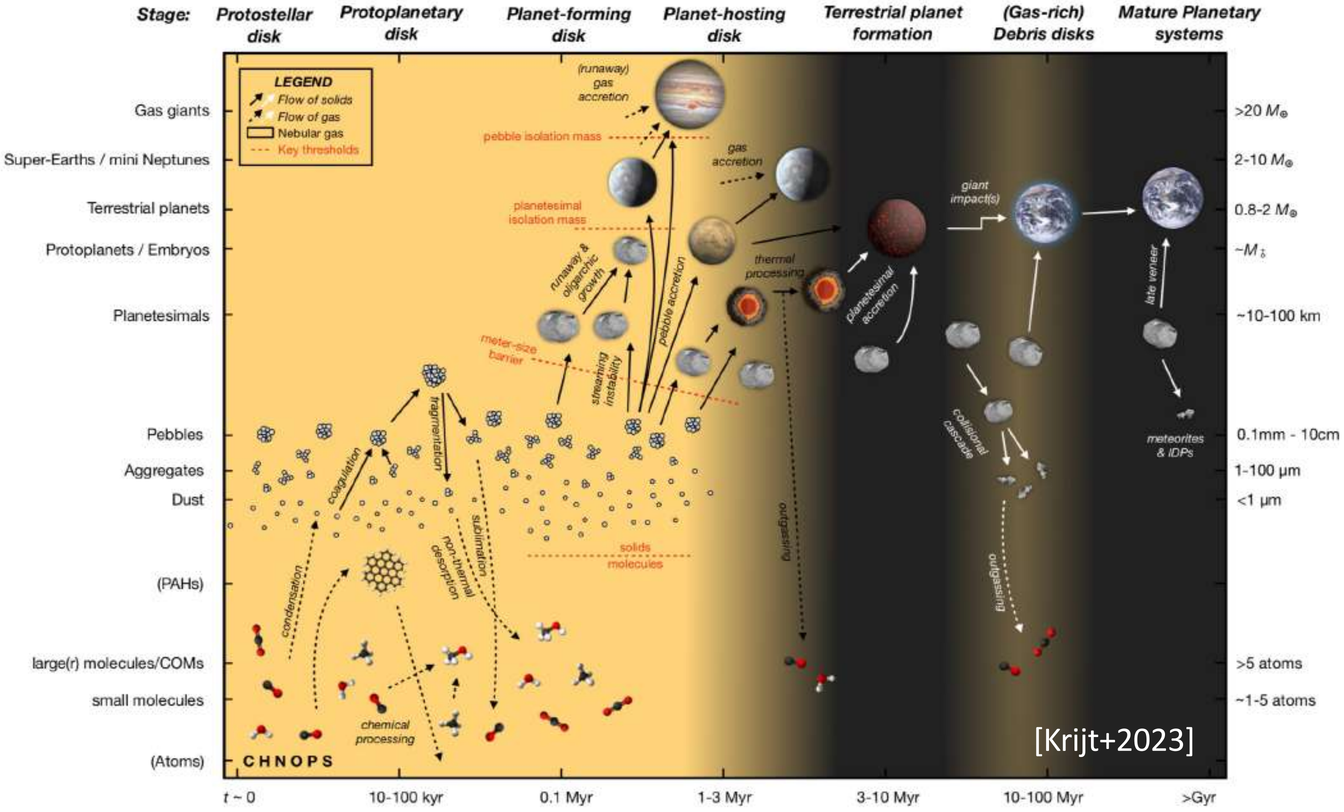


$n \sim 10^{15}$ cm$^{-3}$
T ~ few 1000 K
P ~ 10 Pa

$n \sim 10^{4}$ cm$^{-3}$
T ~ few 10 K
P ~ $10^{-6}$ Pa

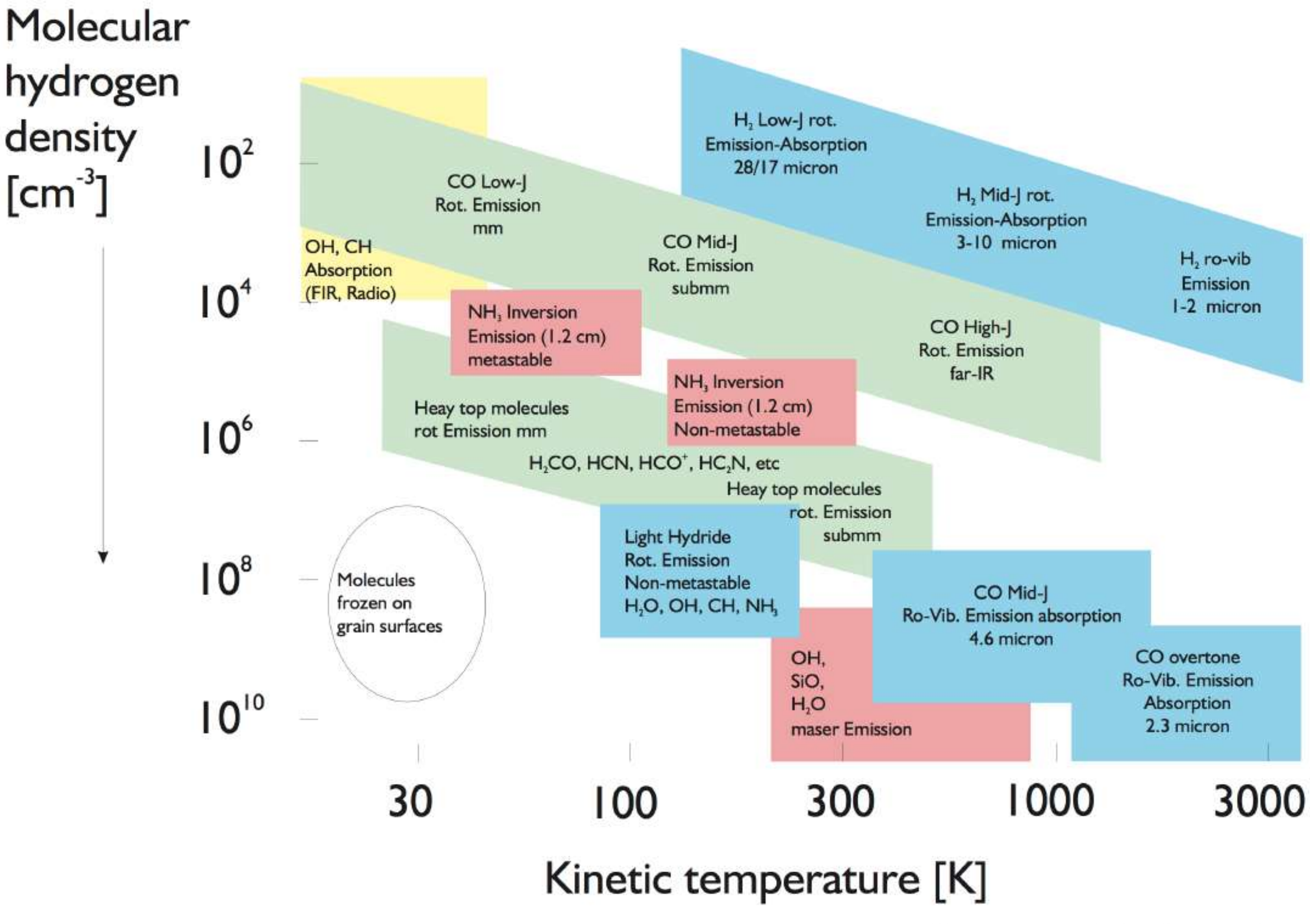
[reviews: Henning & Semenov 2013, Dutrey+2014, Oeberg & Bergin 2020]

# How planets inherit the disk composition is a complex puzzle



[Krijt+2023]

# The end…



After R. Genzel

[credit: Wing-Fai Thi]

# emission probes for protoplanetary disks

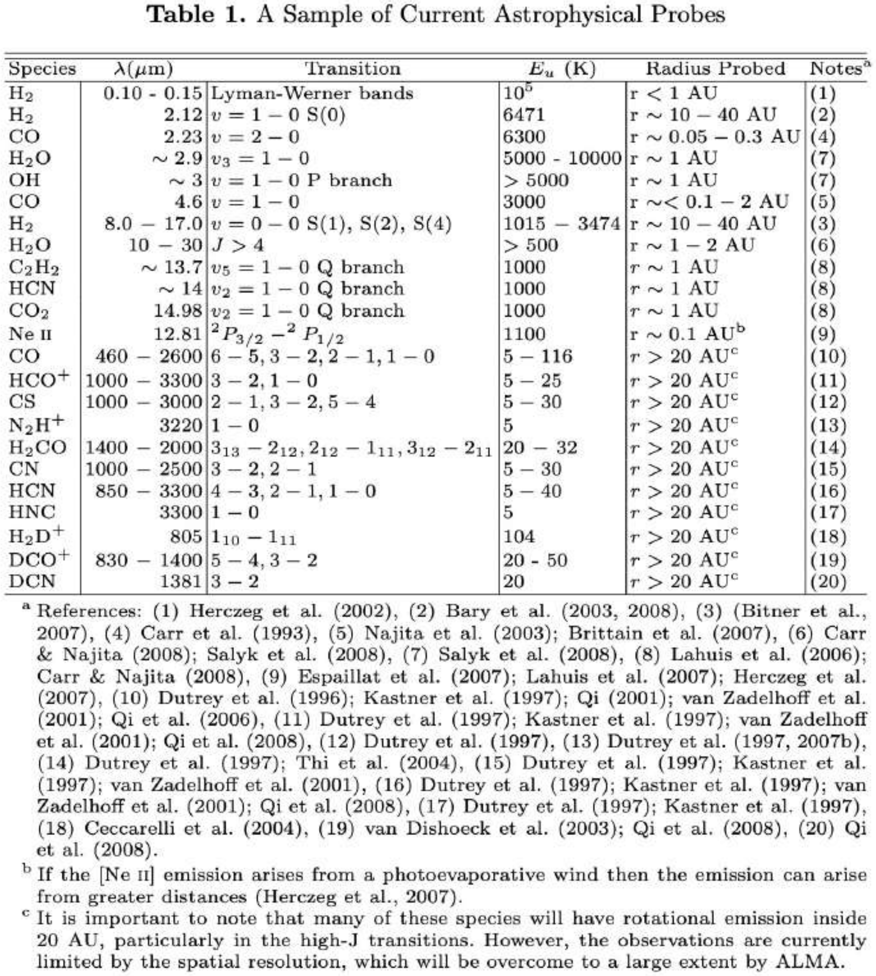


**Table 1.** A Sample of Current Astrophysical Probes

| Species | $\lambda(\mu m)$ | Transition | $E_u$ (K) | Radius Probed | Notes[a] |
|---|---|---|---|---|---|
| $H_2$ | 0.10 - 0.15 | Lyman-Werner bands | $10^5$ | r < 1 AU | (1) |
| $H_2$ | 2.12 | $v = 1 - 0$ S(0) | 6471 | $r \sim 10 - 40$ AU | (2) |
| CO | 2.23 | $v = 2 - 0$ | 6300 | $r \sim 0.05 - 0.3$ AU | (4) |
| $H_2O$ | $\sim 2.9$ | $v_3 = 1 - 0$ | 5000 - 10000 | $r \sim 1$ AU | (7) |
| OH | $\sim 3$ | $v = 1 - 0$ P branch | > 5000 | $r \sim 1$ AU | (7) |
| CO | 4.6 | $v = 1 - 0$ | 3000 | $r \sim< 0.1 - 2$ AU | (5) |
| $H_2$ | $8.0 - 17.0$ | $v = 0 - 0$ S(1), S(2), S(4) | $1015 - 3474$ | $r \sim 10 - 40$ AU | (3) |
| $H_2O$ | $10 - 30$ | $J > 4$ | > 500 | $r \sim 1 - 2$ AU | (6) |
| $C_2H_2$ | $\sim 13.7$ | $v_5 = 1 - 0$ Q branch | 1000 | $r \sim 1$ AU | (8) |
| HCN | $\sim 14$ | $v_2 = 1 - 0$ Q branch | 1000 | $r \sim 1$ AU | (8) |
| $CO_2$ | 14.98 | $v_2 = 1 - 0$ Q branch | 1000 | $r \sim 1$ AU | (8) |
| Ne II | 12.81 | $^2P_{3/2} -^2 P_{1/2}$ | 1100 | $r \sim 0.1$ AU[b] | (9) |
| CO | $460 - 2600$ | $6 - 5, 3 - 2, 2 - 1, 1 - 0$ | $5 - 116$ | $r > 20$ AU[c] | (10) |
| $HCO^+$ | $1000 - 3300$ | $3 - 2, 1 - 0$ | $5 - 25$ | $r > 20$ AU[c] | (11) |
| CS | $1000 - 3000$ | $2 - 1, 3 - 2, 5 - 4$ | $5 - 30$ | $r > 20$ AU[c] | (12) |
| $N_2H^+$ | 3220 | $1 - 0$ | 5 | $r > 20$ AU[c] | (13) |
| $H_2CO$ | $1400 - 2000$ | $3_{13} - 2_{12}, 2_{12} - 1_{11}, 3_{12} - 2_{11}$ | $20 - 32$ | $r > 20$ AU[c] | (14) |
| CN | $1000 - 2500$ | $3 - 2, 2 - 1$ | $5 - 30$ | $r > 20$ AU[c] | (15) |
| HCN | $850 - 3300$ | $4 - 3, 2 - 1, 1 - 0$ | $5 - 40$ | $r > 20$ AU[c] | (16) |
| HNC | 3300 | $1 - 0$ | 5 | $r > 20$ AU[c] | (17) |
| $H_2D^+$ | 805 | $1_{10} - 1_{11}$ | 104 | $r > 20$ AU[c] | (18) |
| $DCO^+$ | $830 - 1400$ | $5 - 4, 3 - 2$ | 20 - 50 | $r > 20$ AU[c] | (19) |
| DCN | 1381 | $3 - 2$ | 20 | $r > 20$ AU[c] | (20) |

[a] References: (1) Herczeg et al. (2002), (2) Bary et al. (2003, 2008), (3) (Bitner et al., 2007), (4) Carr et al. (1993), (5) Najita et al. (2003); Brittain et al. (2007), (6) Carr & Najita (2008); Salyk et al. (2008), (7) Salyk et al. (2008), (8) Lahuis et al. (2006); Carr & Najita (2008), (9) Espaillat et al. (2007); Lahuis et al. (2007); Herczeg et al. (2007), (10) Dutrey et al. (1996); Kastner et al. (1997); Qi (2001); van Zadelhoff et al. (2001); Qi et al. (2006), (11) Dutrey et al. (1997); Kastner et al. (1997); van Zadelhoff et al. (2001); Qi et al. (2008), (12) Dutrey et al. (1997), (13) Dutrey et al. (1997, 2007b), (14) Dutrey et al. (1997); Thi et al. (2004), (15) Dutrey et al. (1997); Kastner et al. (1997); van Zadelhoff et al. (2001), (16) Dutrey et al. (1997); Kastner et al. (1997); van Zadelhoff et al. (2001); Qi et al. (2008), (17) Dutrey et al. (1997); Kastner et al. (1997), (18) Ceccarelli et al. (2004), (19) van Dishoeck et al. (2003); Qi et al. (2008), (20) Qi et al. (2008).

[b] If the [Ne II] emission arises from a photoevaporative wind then the emission can arise from greater distances (Herczeg et al., 2007).

[c] It is important to note that many of these species will have rotational emission inside 20 AU, particularly in the high-J transitions. However, the observations are currently limited by the spatial resolution, which will be overcome to a large extent by ALMA.

[Bergin+2009]