ALMA observations of planet-forming disks

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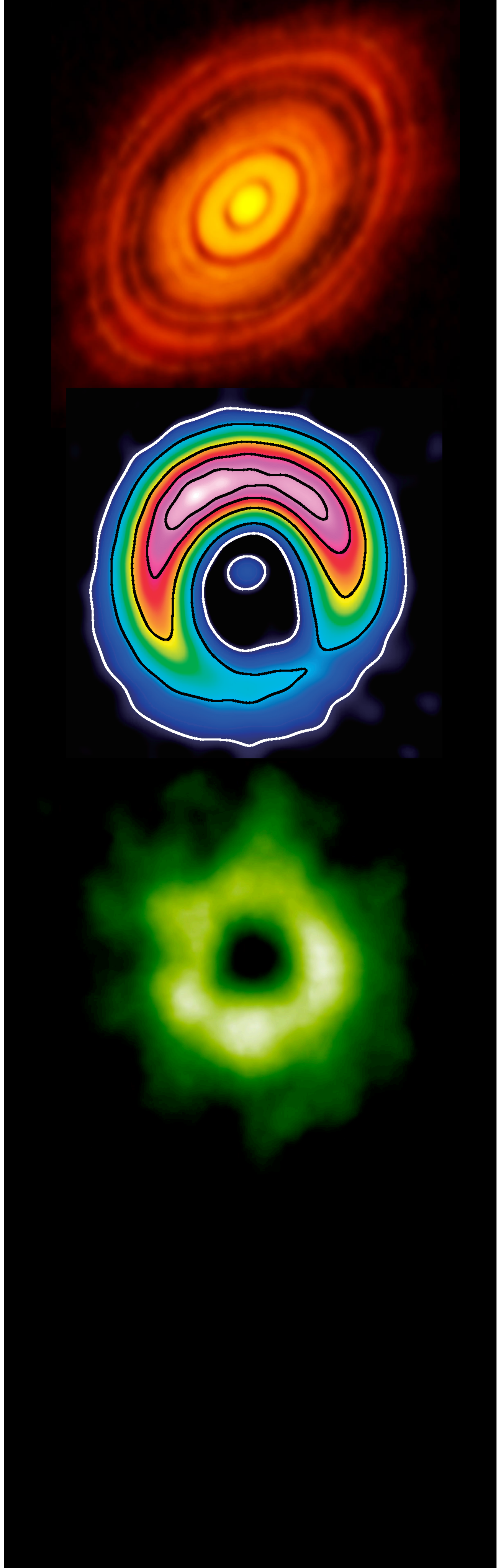
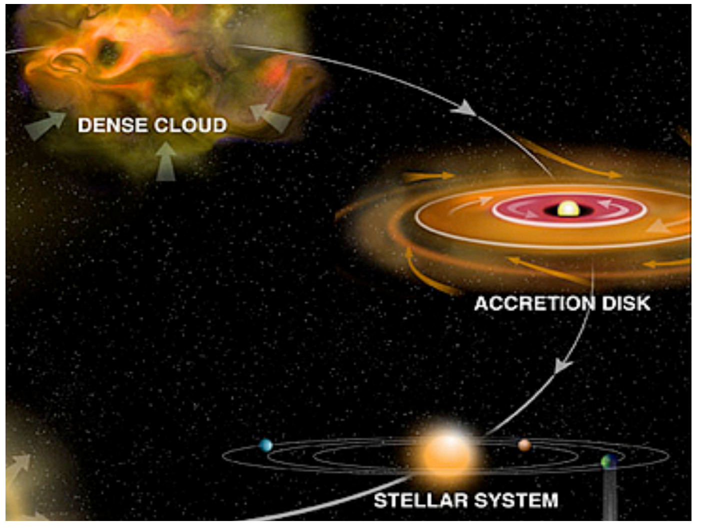
50+ papers on planet-forming disks
containing ALMA data.

Outline

- Introduction:
    - what we know about the structure, composition and evolution of disks
- ALMA results:
    - on dust
    - on molecular gas:
        - structure, kinematics, composition
- Conclusions and outlook

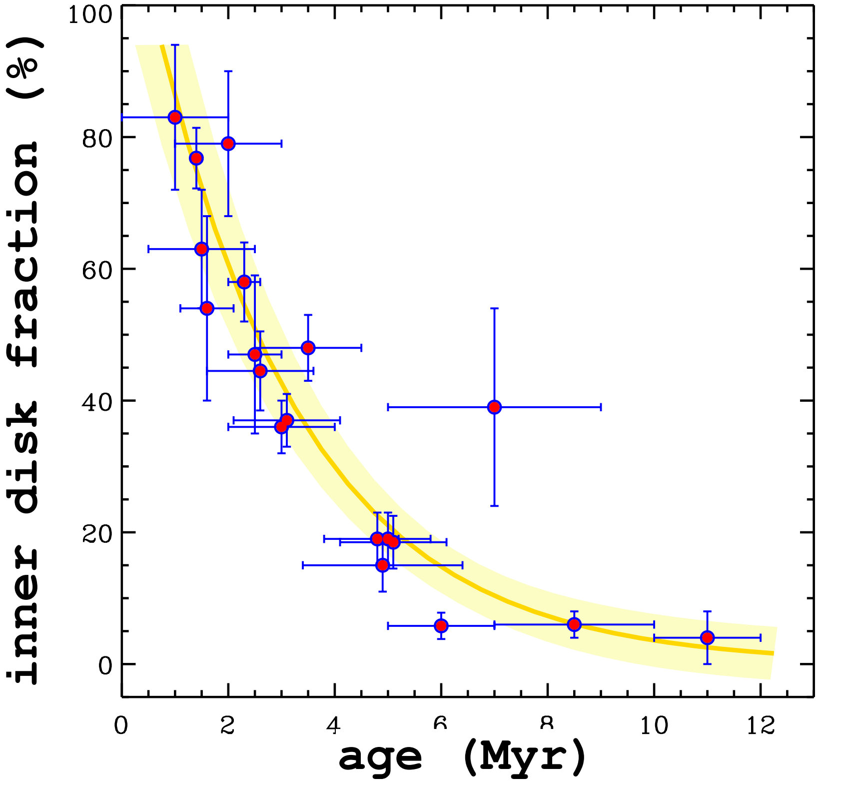


Introduction (1)



Most young stars have disks

- T Tauri stars (≲2 $M_\odot$)
- Herbig Ae/Be stars (2-8 $M_\odot$)
- [contradictory evidence for stars >10 $M_\odot$]

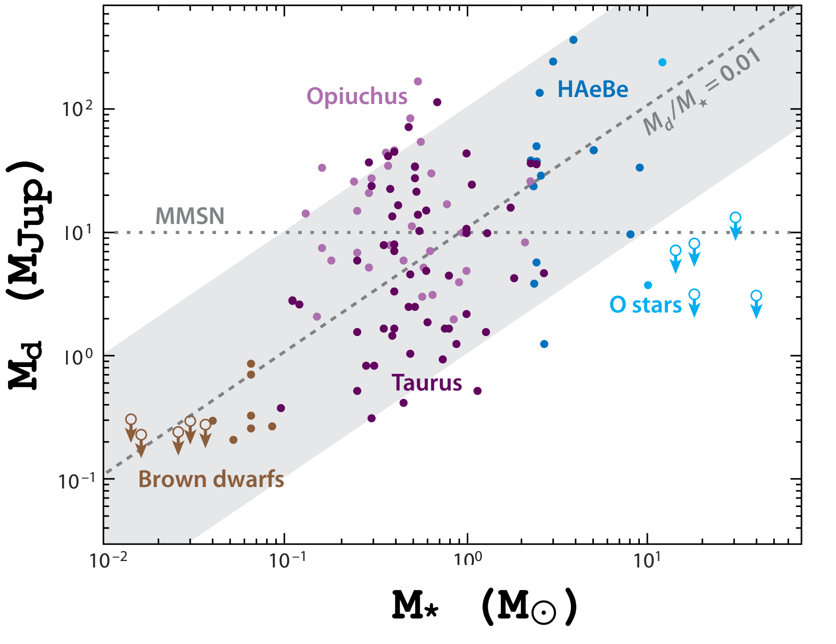


Disks last several Myr

- Inside-out clearing is rapid

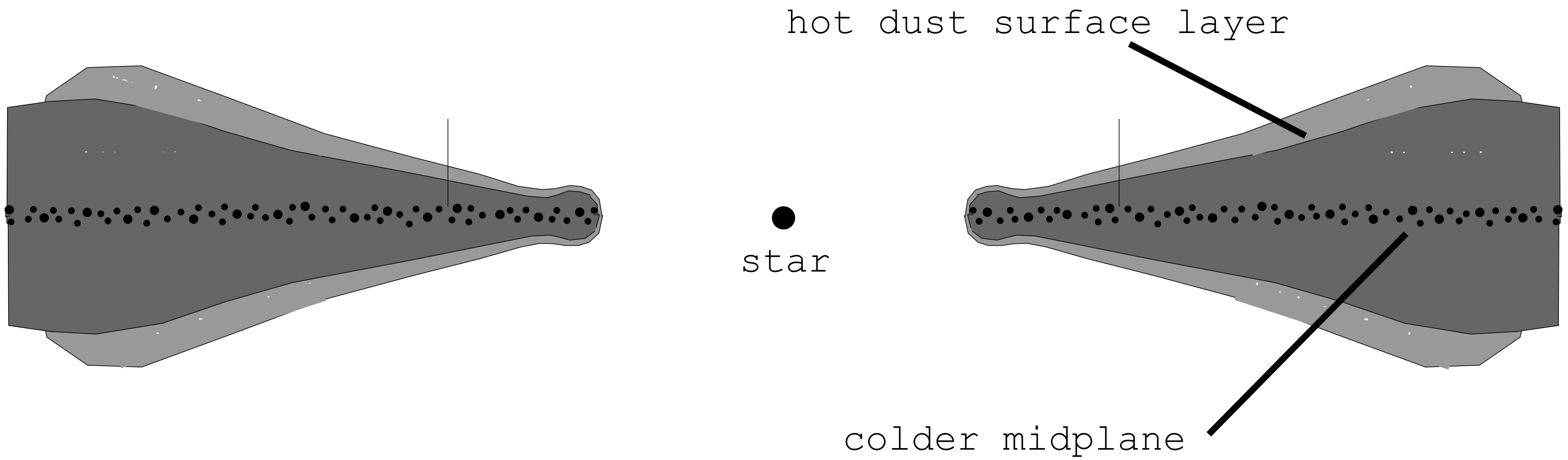
$M_{disk(gas+dust)}$ ~ 10^{-3}–10^{-1} $M_\odot$

- $M_d/M_\star$~0.01



Williams & Cieza (2011); Williams (2015), based on Hernandez et al. (2007)

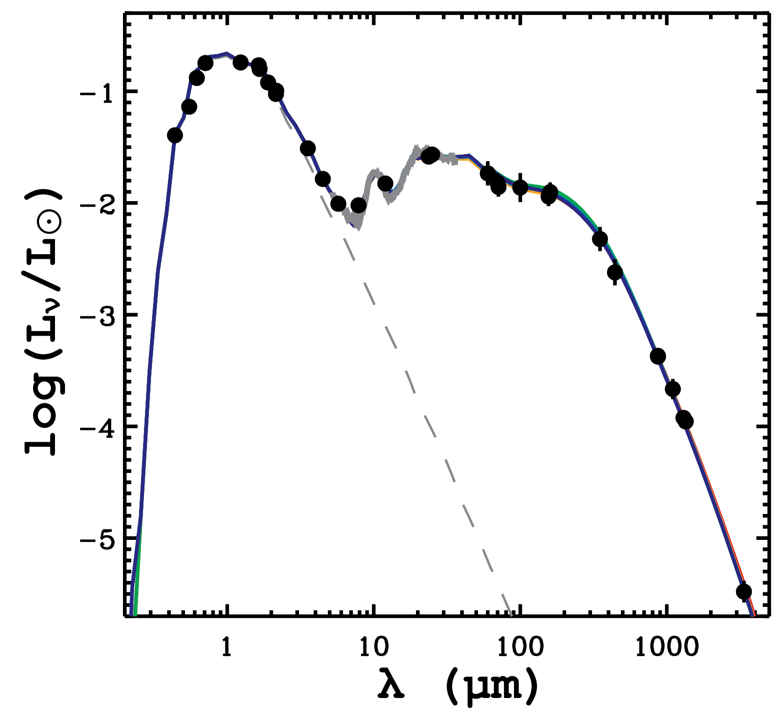
Introduction (2)



<u>Surface density ∝ $R^{-(0.5-1)}$,</u>
<u>temperature ∝ $R^{-(0.25-0.5)}$</u>

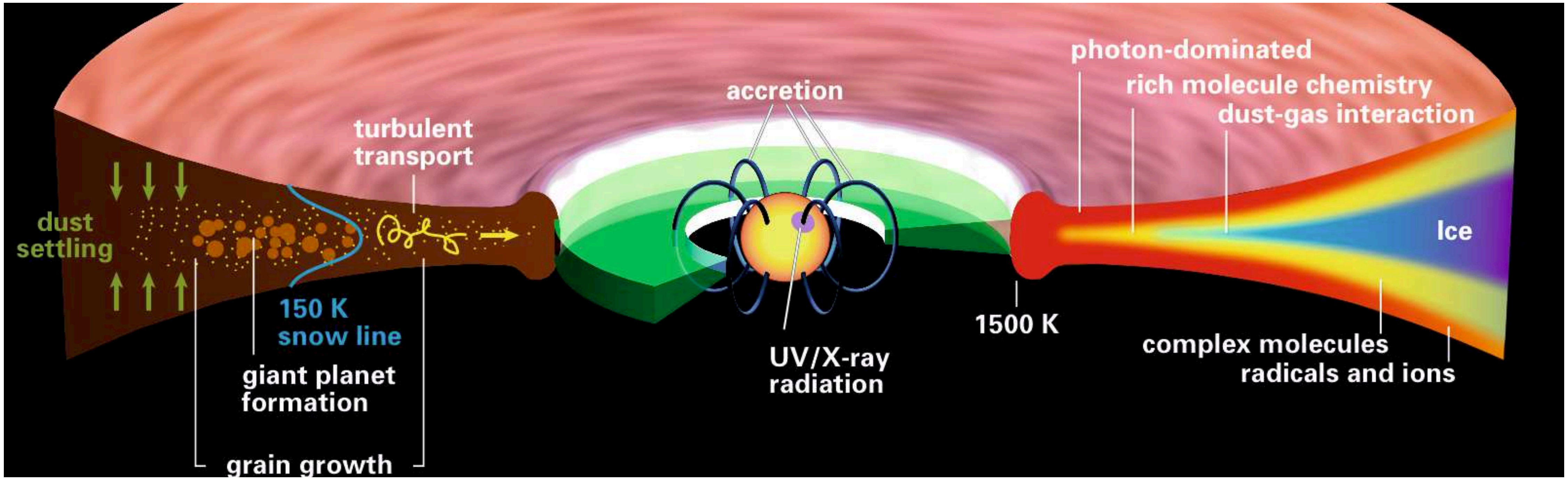
- vertical hydrostatic scale height increases with radius; flaring if raised surface intercepts more stellar light
- inner disk wall can shadow part of disk around Herbig stars

Spectral Energy Distribution (SED)



Dullemond et al. (2007); Andrews et al. (2012)

Introduction (3)



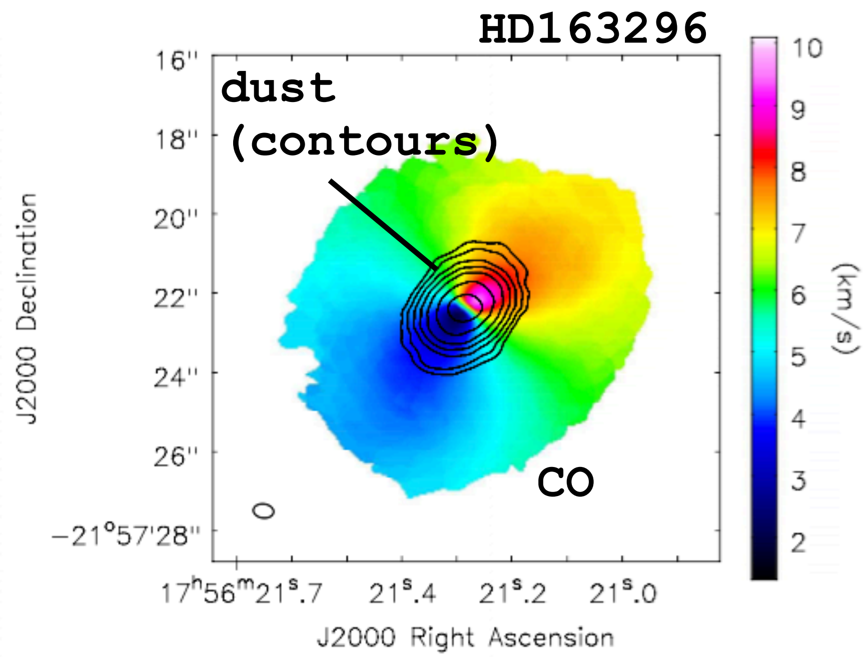
<u>Three chemical zones</u>

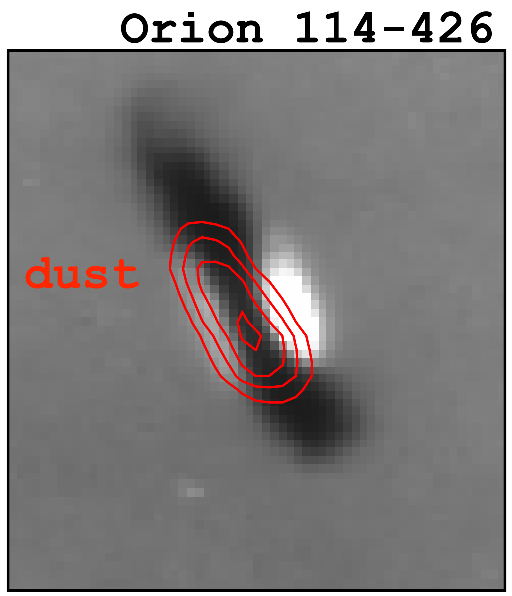
- **cold midplane:** most molecular species (ex. H_2) frozen out
- **intermediate height and inner disk:** rich in molecules
- **disk surface:** molecules photodissociated

Henning & Semenov (2013)

ALMA results

Radial drift of mm grains





HD163296
Orion 114-426

HD100546
MWC480
DM Tau
...

<u>Disk in mm continuum ≪ disk at μm, CO emission</u>

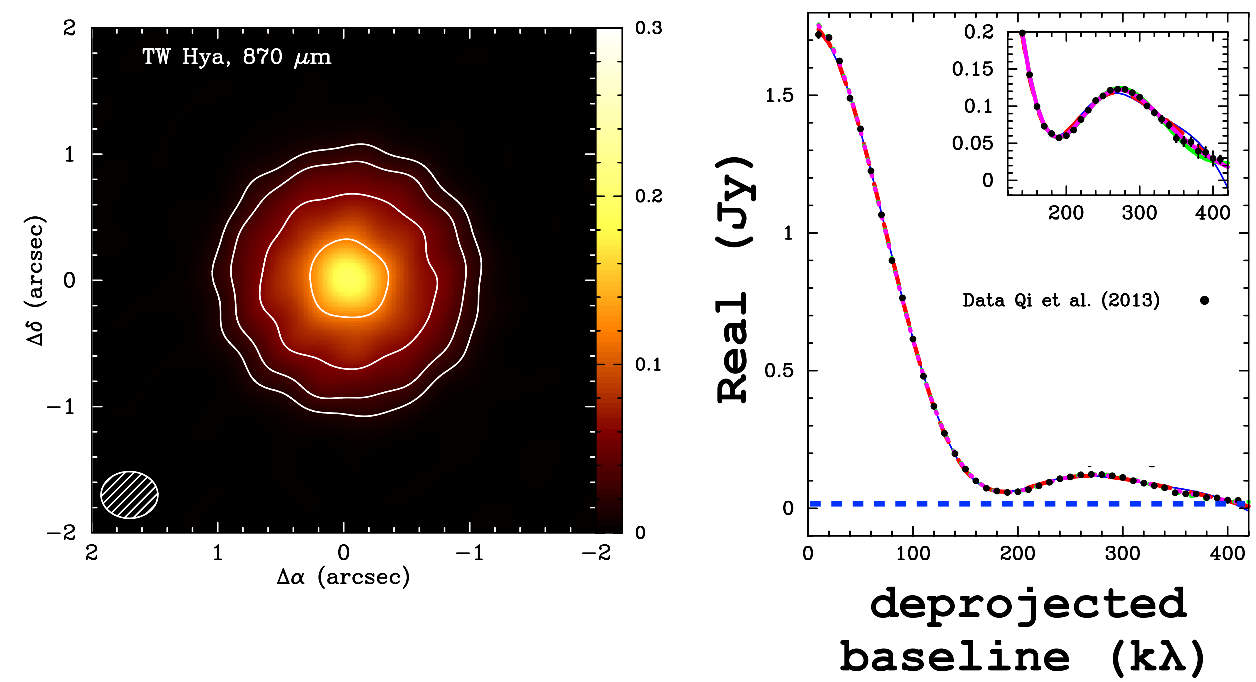
- radial drift of mm-sized grains (e.g., Birnstiel & Andrews 2014)
- already seen by SMA in IM Lup, Panić et al. (2009); TW Hya, Andrews et al. (2012)

de Gregorio-Monsalvo et al. (2013); Bally et al. (2015)

Continuous disks and disk with gaps

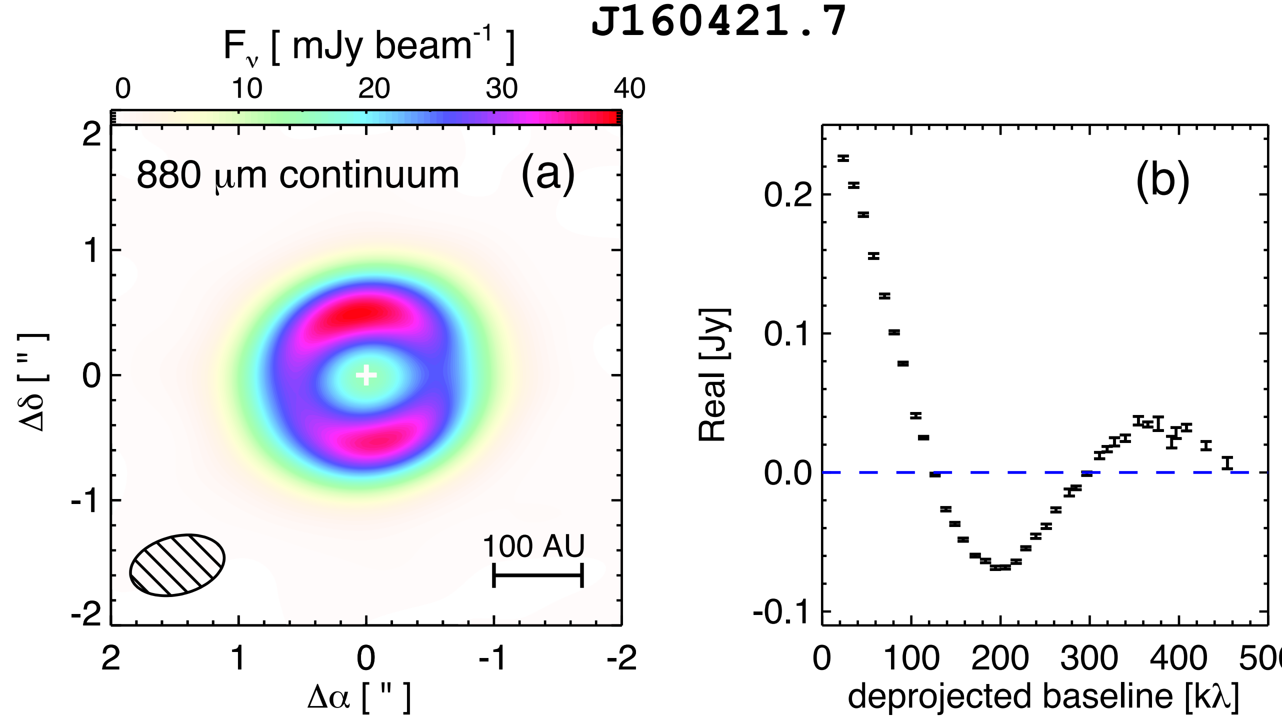
Some disks show <u>continuous disk structure</u>, well fit by one (or two) radial power laws

TW Hya



Other disks show clear <u>gaps in mm continuum</u> (often already known to be 'transitional disks')

J160421.7

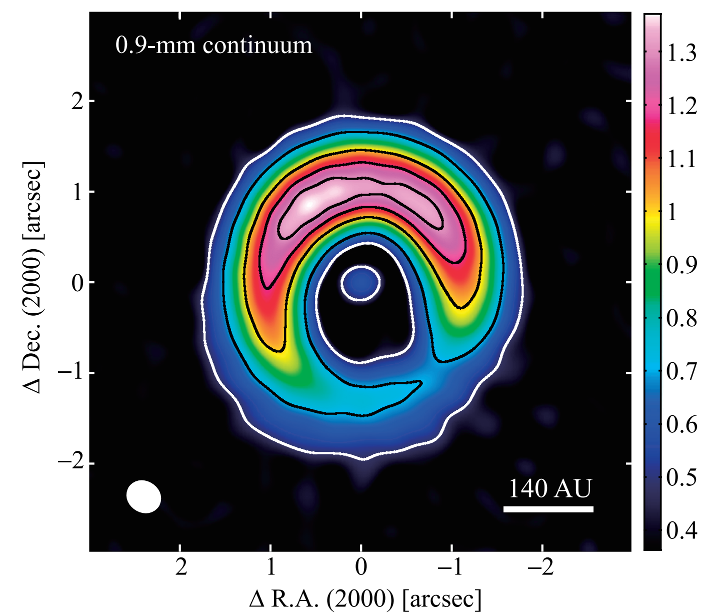


Zhang et al. (2014); Hogerheijde et al. (in prep.)

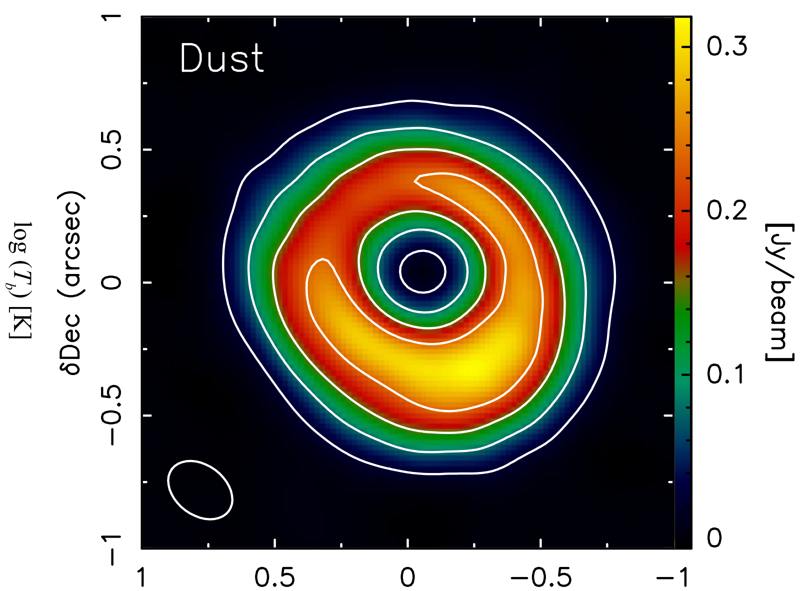
mm-dust 'traps'

mm-dust concentrated on one side of gap: <u>trapped</u> in a vortex?

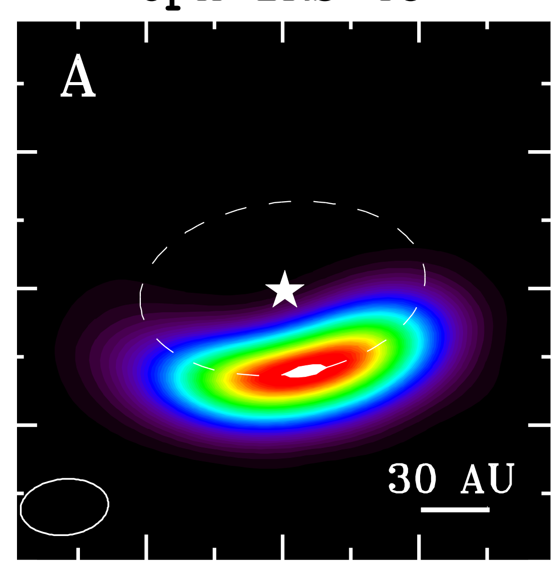
HD142527



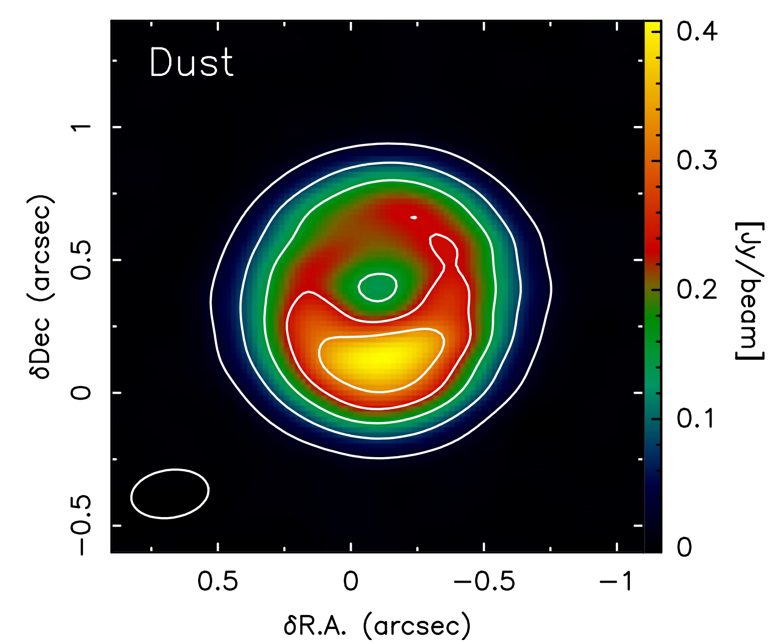
SAO 206462



Oph IRS 48



SR 21

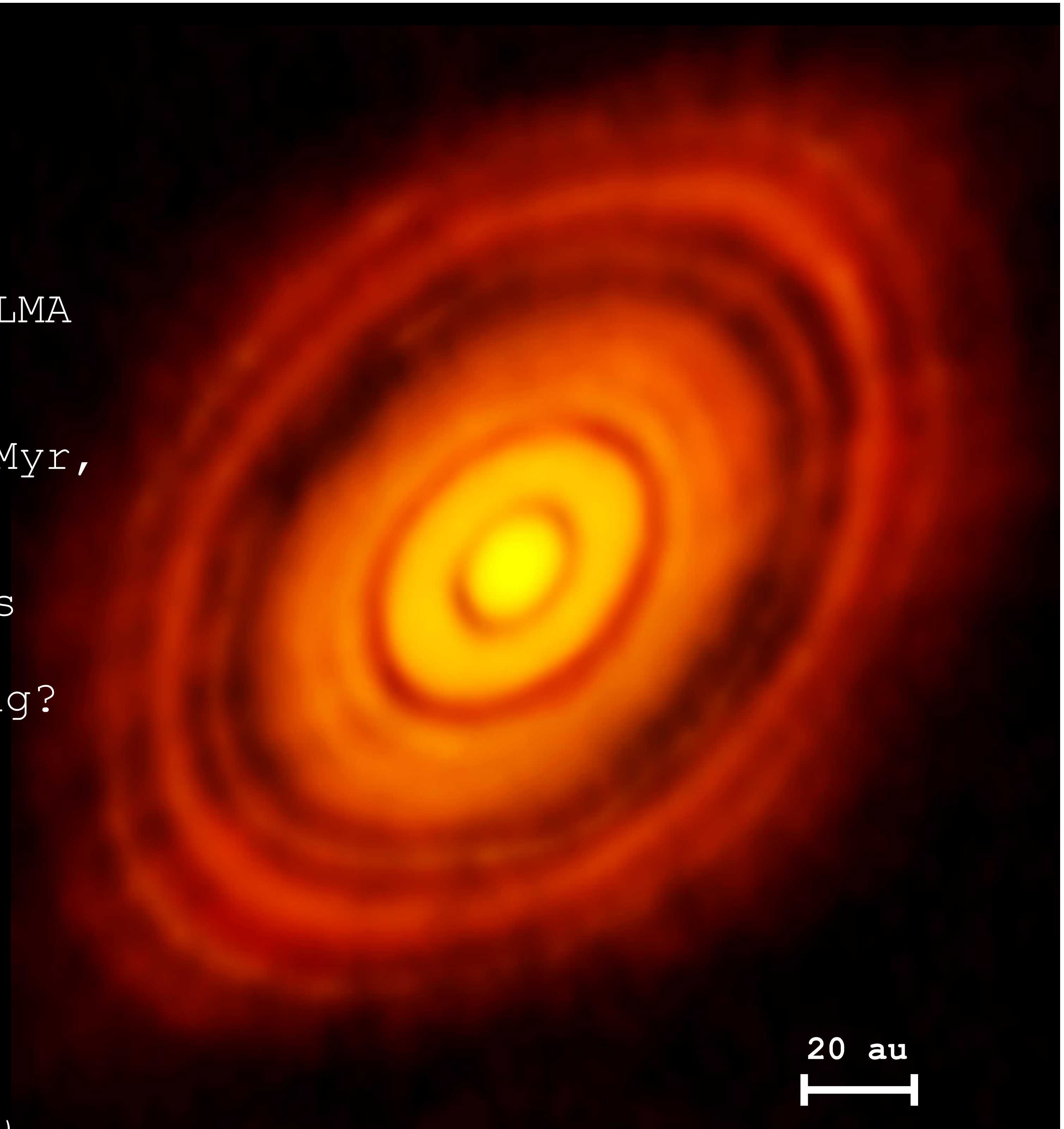


Pérez et al. (2014); Casassus et al. (2013); van der Marel et al. (2013); Fukagawa et al. (2013)

‘Gaps’ form early

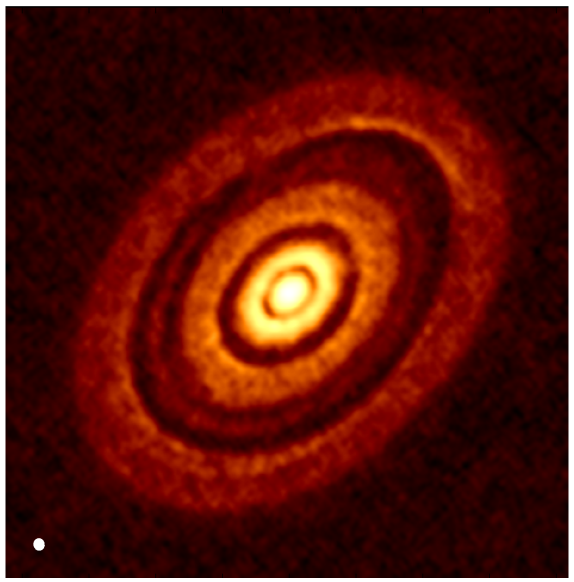
HL Tau:

- highest resolution ALMA data to-date
- very young disk (<1 Myr, still embedded)
- bright and dark rings
- planets ➛ gap opening?
- frost lines ➛ rapid grain growth?



ALMA Partnership, Brogan, et al. (2015)

‘Gaps’ form early

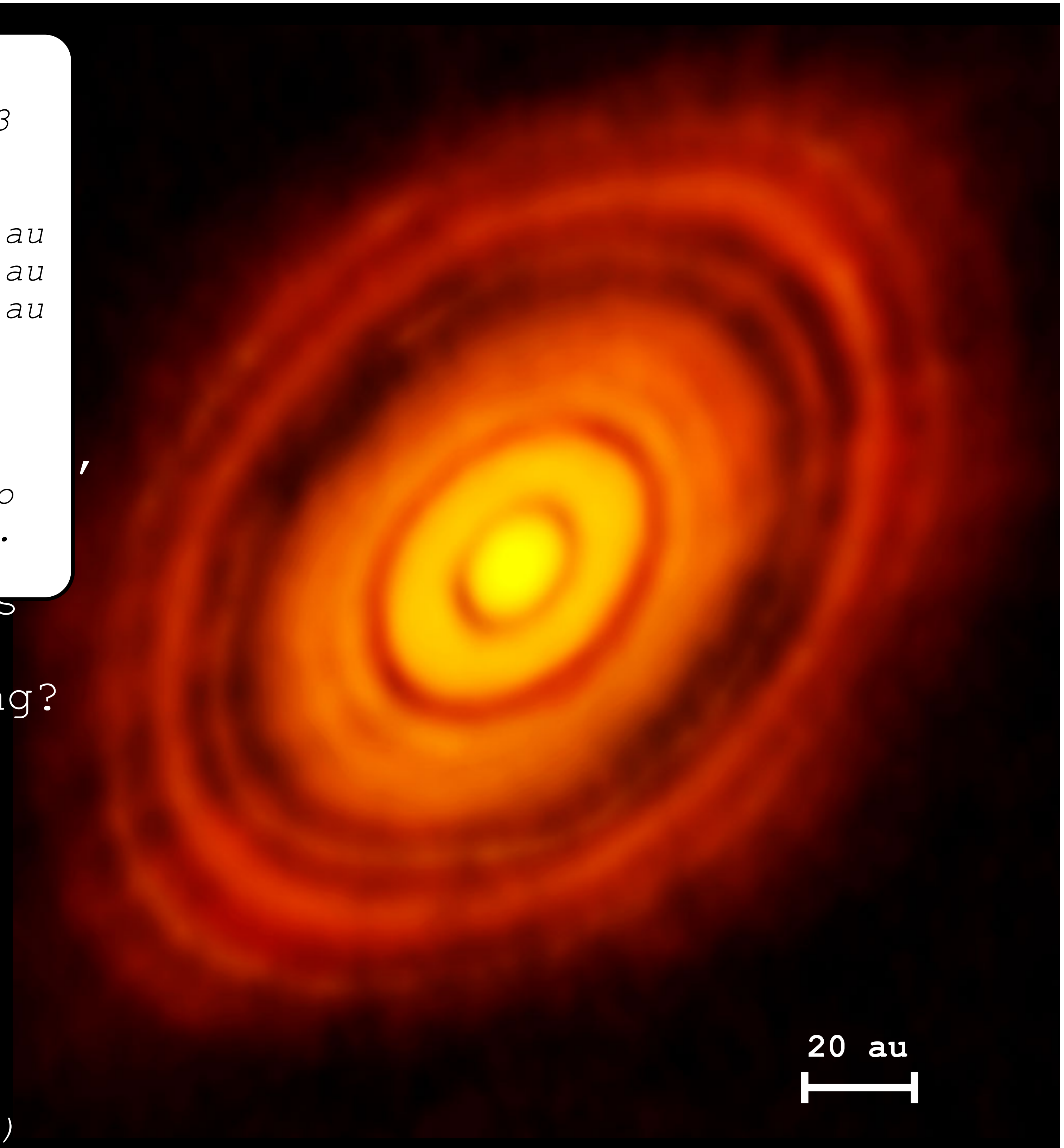


Model with 3 planets:

0.2 M_J @ 13 au
0.3 M_J @ 32 au
0.6 M_J @ 69 au

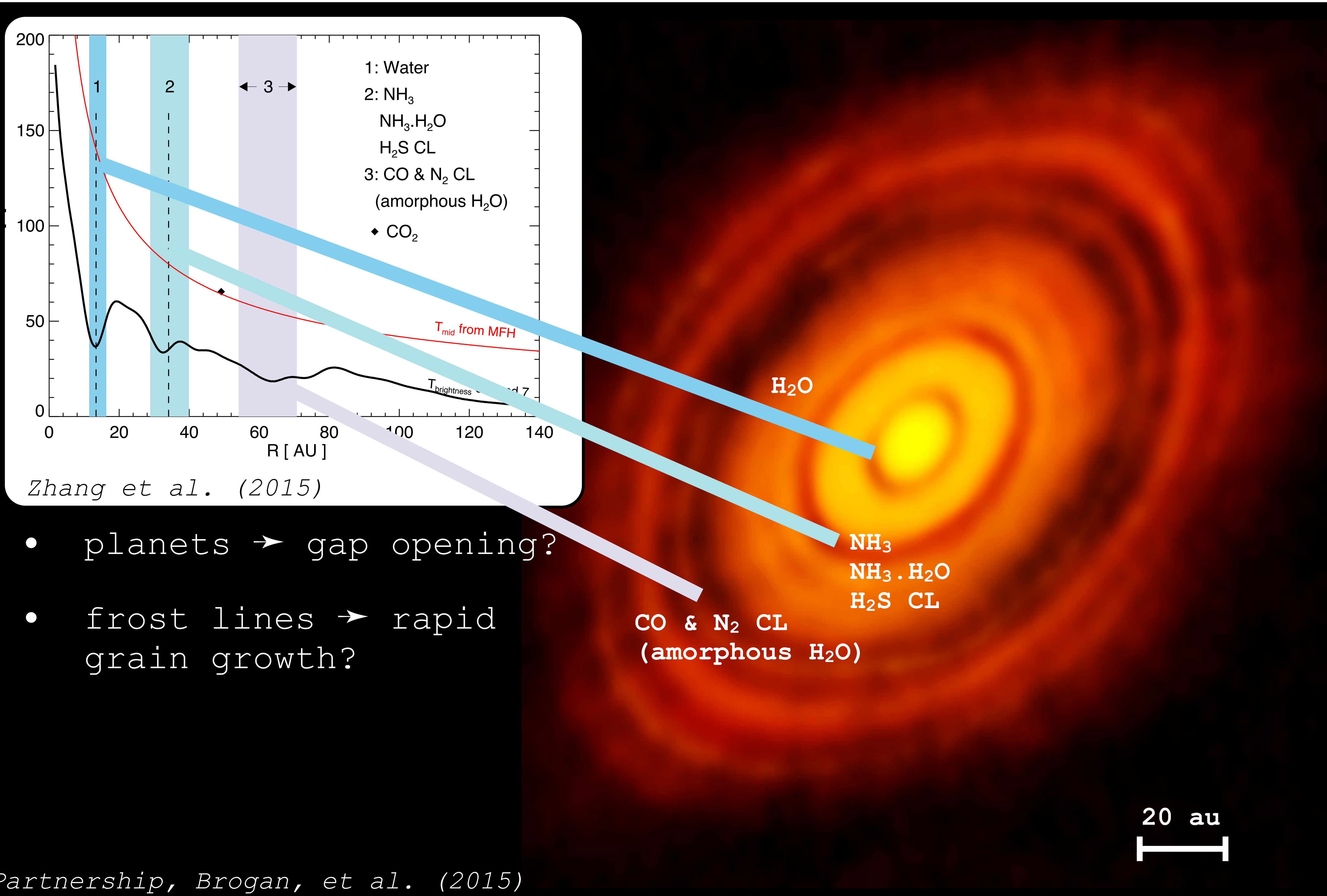
Dipierro et al. (2015); see also Dong et al. (2015), Pinte et al. (2015)

- bright and dark rings
- planets ➛ gap opening?
- frost lines ➛ rapid grain growth?



ALMA Partnership, Brogan, et al. (2015)

'Gaps' form early

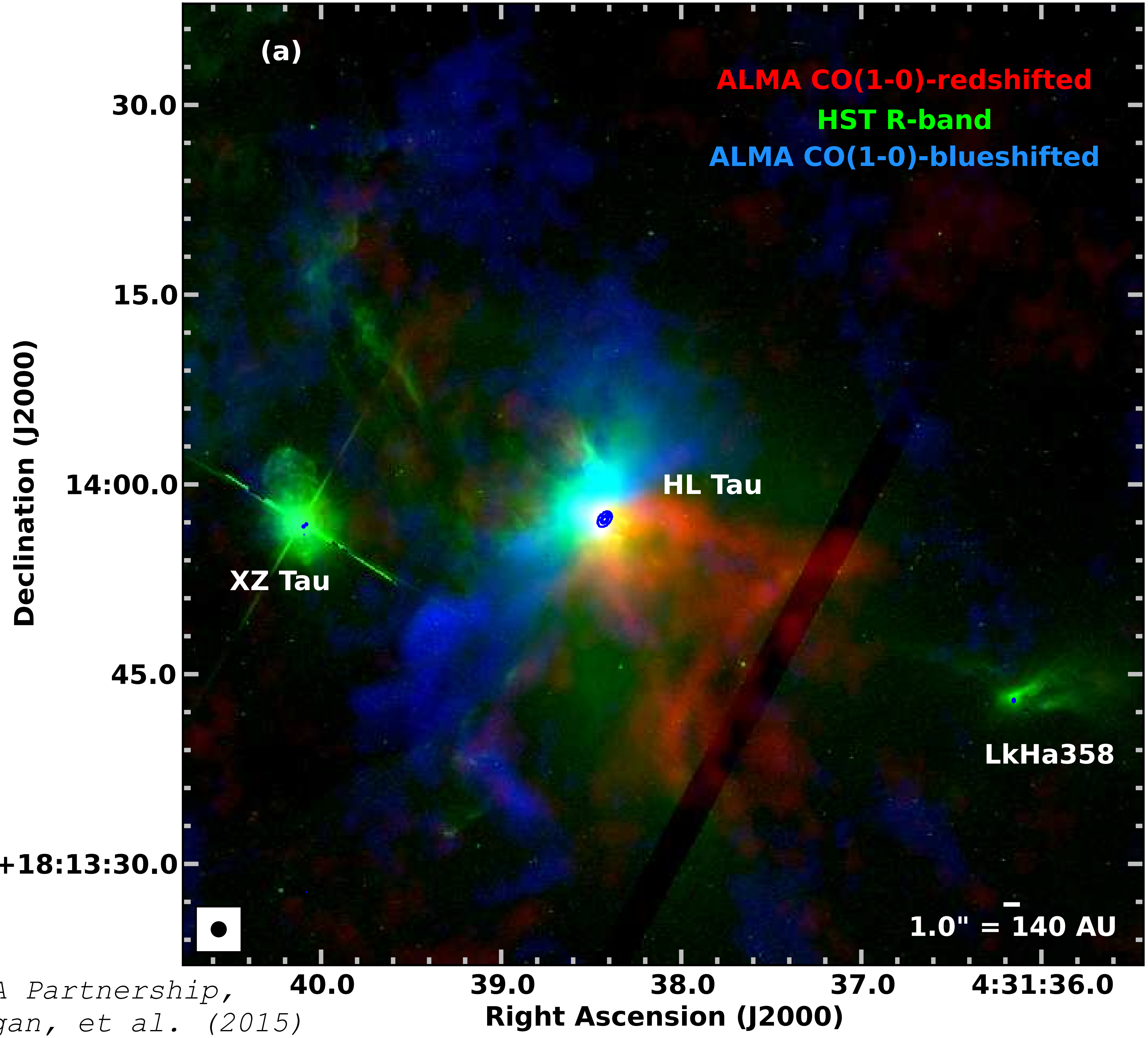


Zhang et al. (2015)

- planets ➛ gap opening?
- frost lines ➛ rapid grain growth?

ALMA Partnership, Brogan, et al. (2015)

The big picture

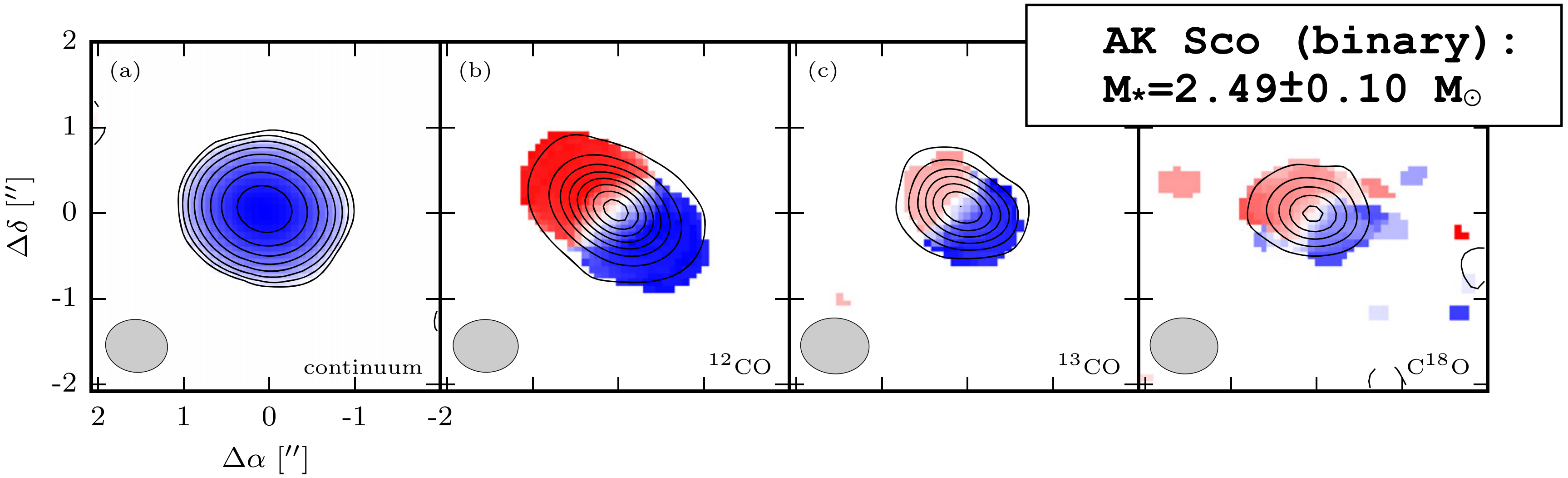


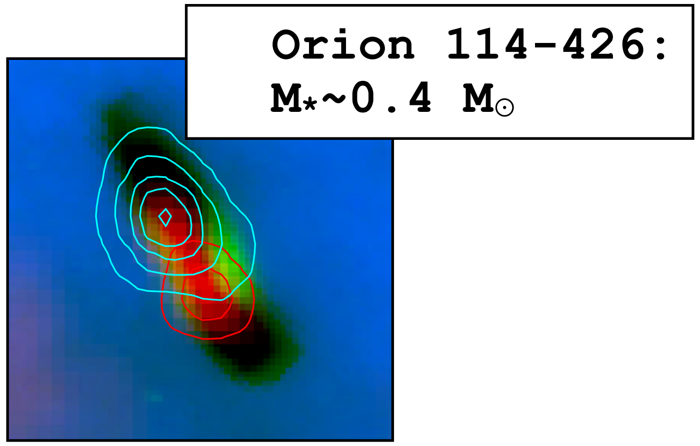
ALMA Partnership, Brogan, et al. (2015)

CO emission traces cloud + protostellar envelope + outflow

Image also covers XZ Tau binary and LkHα358 disks

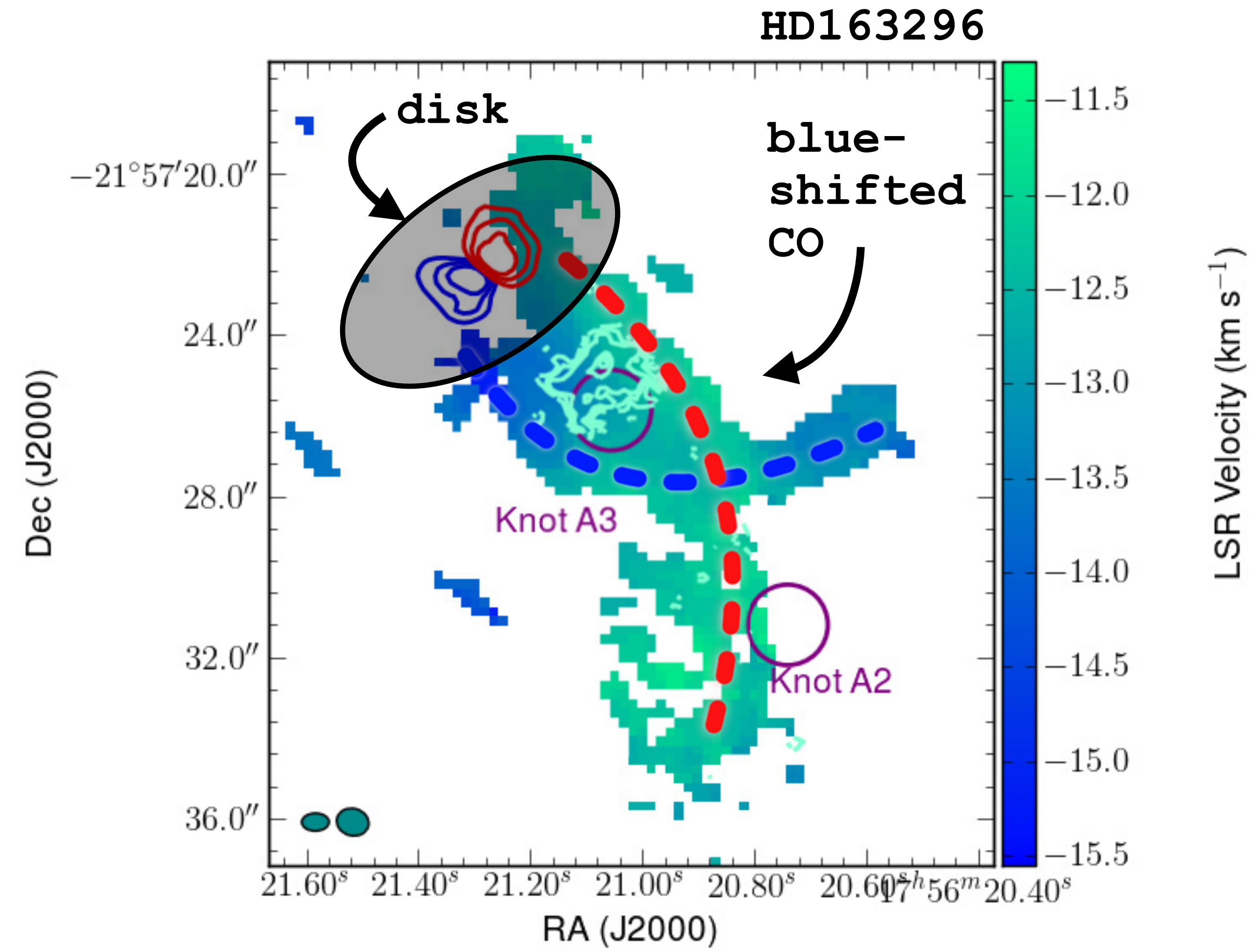
CO, ^{13}CO & C^{18}O → M_*, M_{CO}, R_{CO}





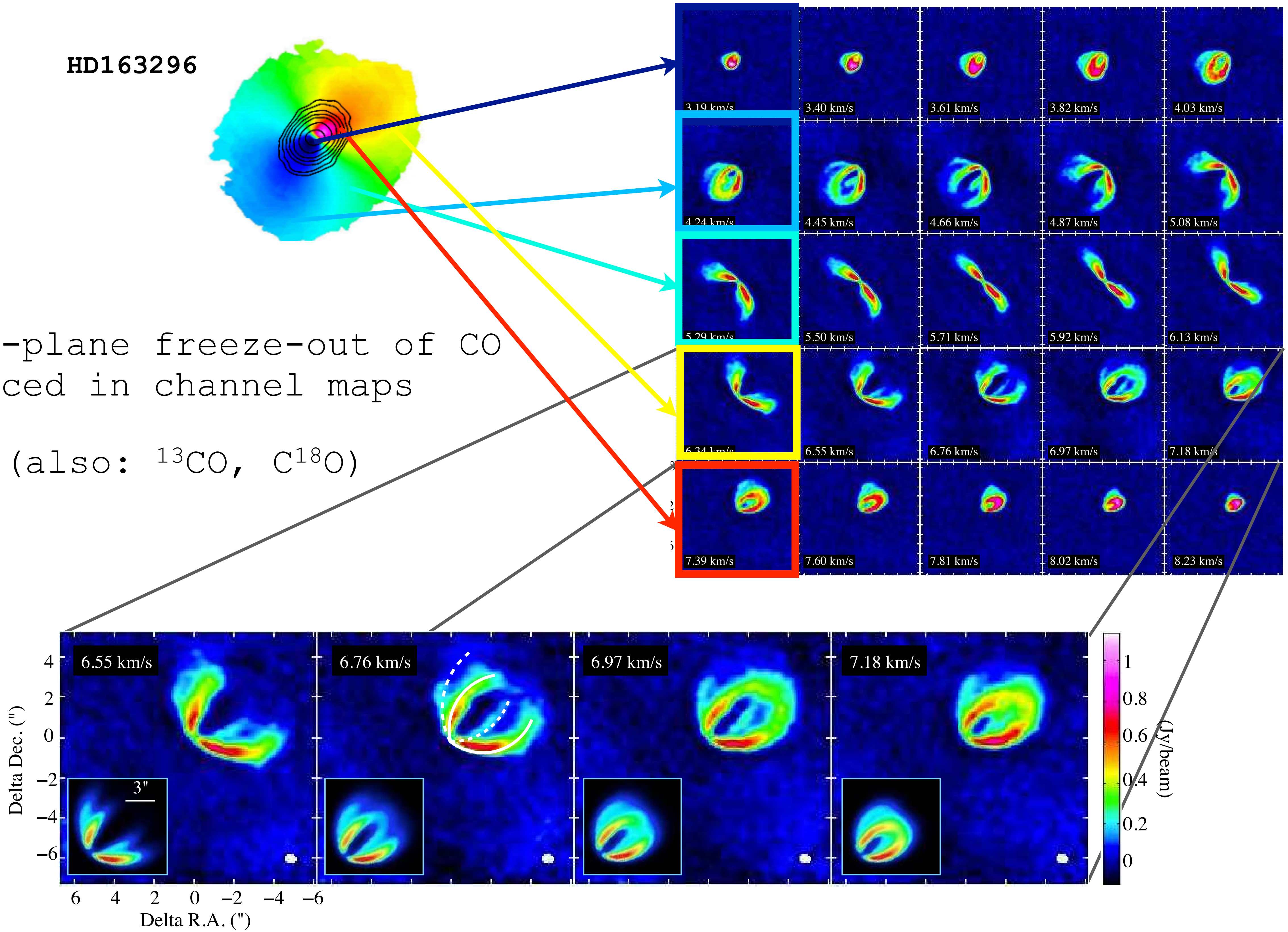
CO and its isotopes easily detected

- kinematics: M_*
- outer radius of (molecular) gas
- disk gas mass estimate (if we believe models; Williams & Best 2015; Miotello et al. 2014)
- look carefully: a molecular disk wind!



Czekala et al. (2015); Bally et al. (2015); Klaassen et al. (2013)

CO freeze out



Mid-plane freeze-out of CO traced in channel maps

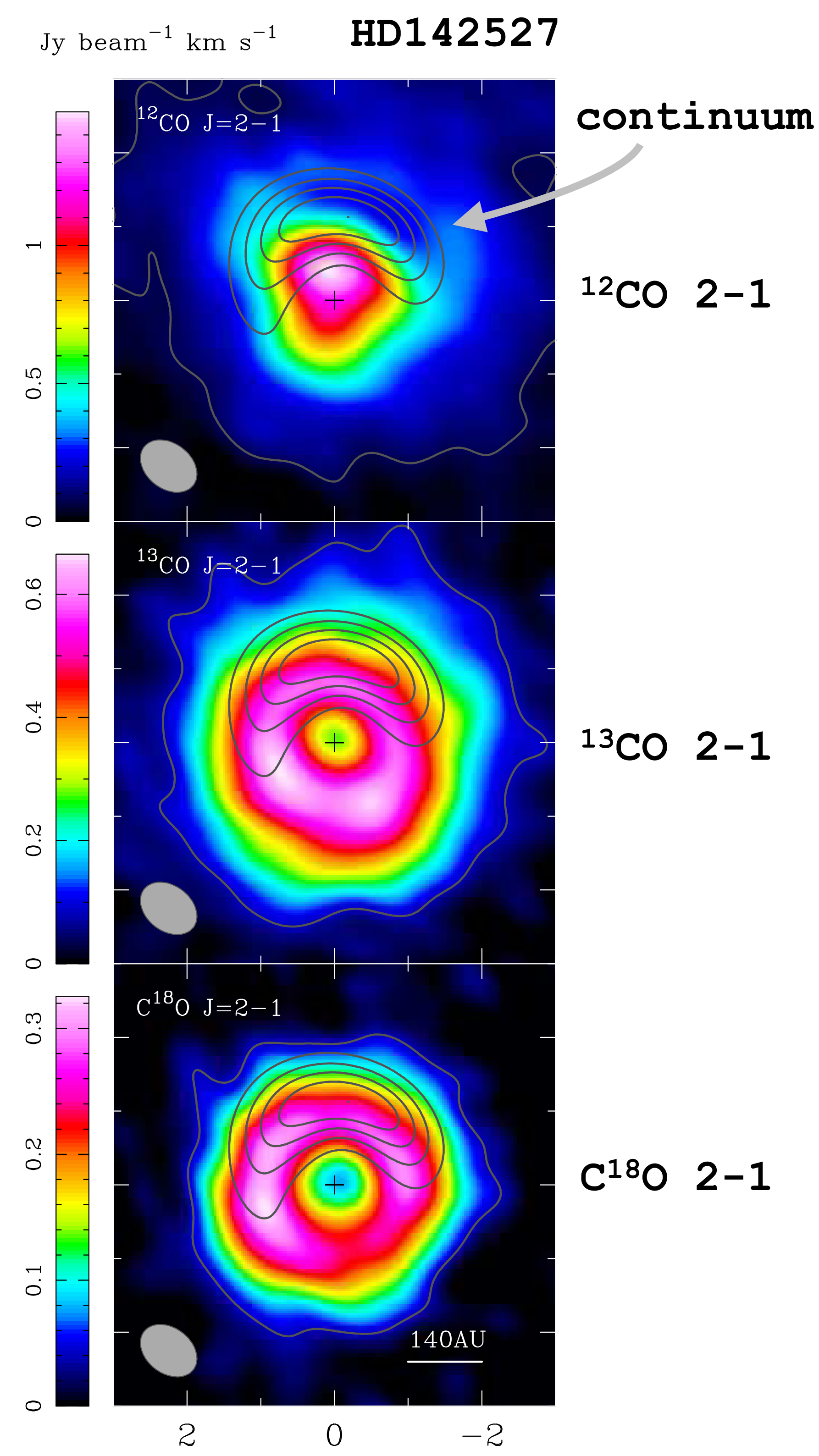
- (also: ^{13}CO, $C^{18}O$)

de Gregorio-Monsalvo et al. (2013)

'Gaps' contain gas

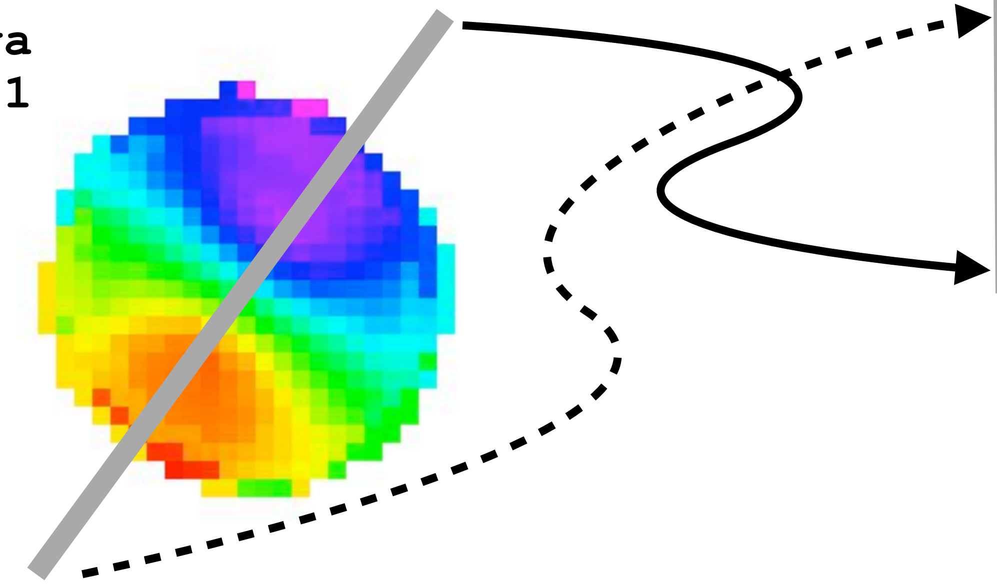
<u>Gaps seen in mm-continuum are not devoid of gas</u>

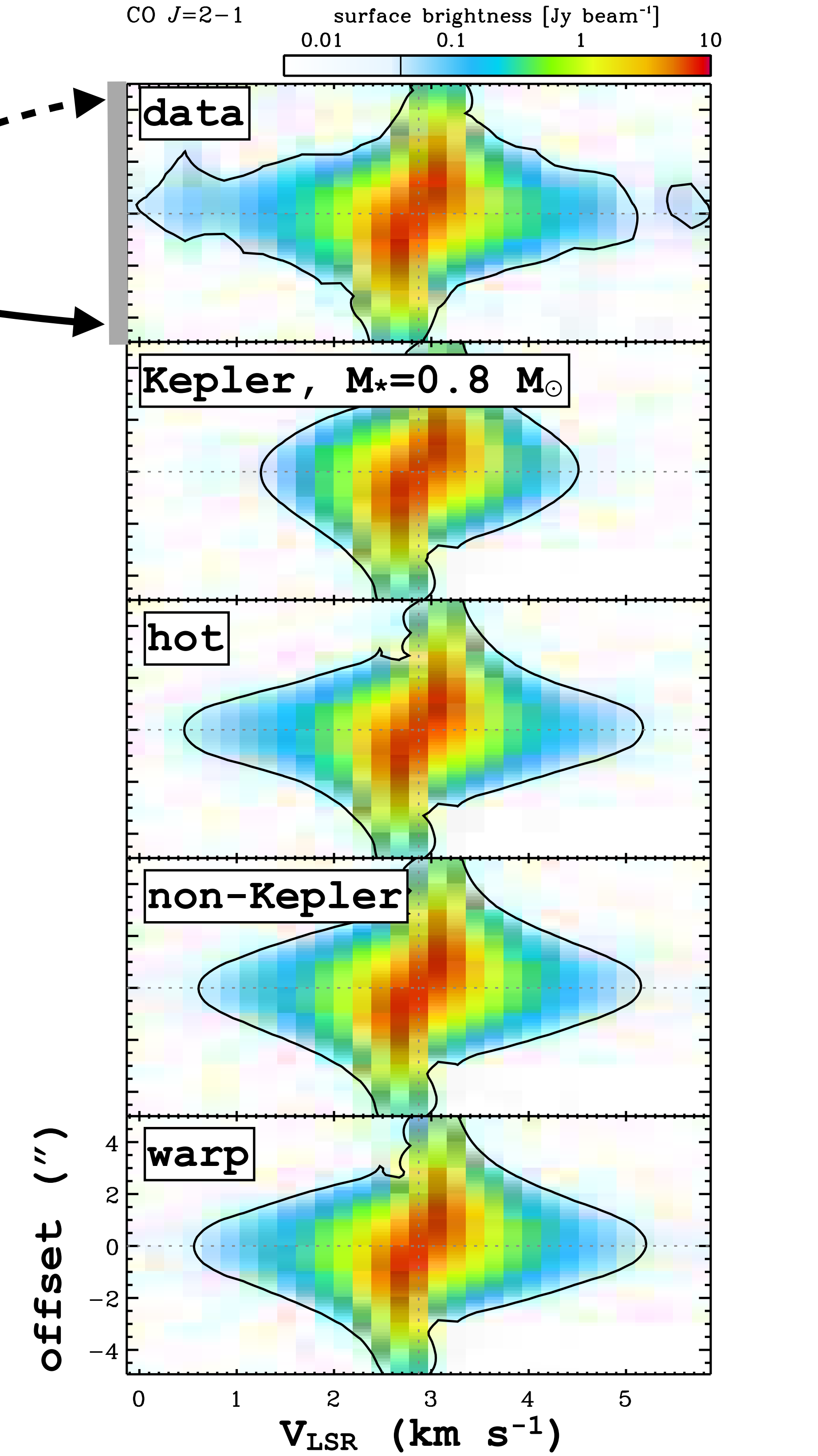
- reduced gas surface density
- fits with continued accretion
- fits with models of gap opening and trapping of mm grains



Pérez et al. (2015); see also van der Marel et al. (2015)

Disk kinematics





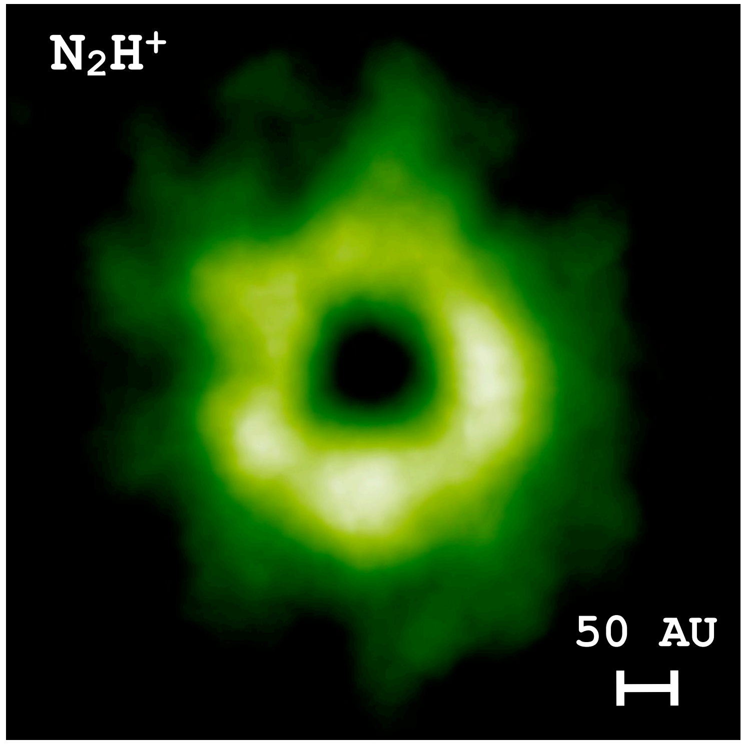
<u>Deviations hint at:</u>

- Local surface density or temperature enhancements?
- Warp in inner disk?

Rosenfeld et al. (2012)

CO snow line

TW Hya



HD163296

100 AU

- <u>N_2H^+ traces the CO snow line</u>
  - formation: $N_2 + H_3^+ \rightarrow N_2H^+ + H_2$
    - competes with $CO + H_3^+ \rightarrow HCO^+ + H_2$
  - destruction: $N_2H^+ + CO \rightarrow HCO^+ + N_2$
- bottom line: N_2H^+ avoids regions with abundant CO

Qi et al. (2013, in prep.)

Two paths for deuteration (1)

Two deuteration path ways

- ≲21 K: $H_3^+ + HD \rightleftarrows H_2D^+ + H_2 + \Delta E$
  - competes with $H_3^+ + CO \rightarrow HCO^+ + H_2$
  - $H_2D^+ + CO \rightarrow \mathbf{DCO^+} + H_2$
- up to ~70 K: $CH_3^+ + HD \rightleftarrows CH_2D^+ + H_2 + \Delta E$
  - $CH_2D^+ + O \rightarrow \mathbf{DCO^+} + H_2$
  - $CH_2D^+ + \ldots \rightarrow CH_4D^+ + CO \rightarrow \mathbf{DCO^+} + CH_4$
  - $CH_2D^+ + \ldots \rightarrow \ldots \rightarrow$ **DCN**

DCO^+ enhanced below ~20 K

DCO^+ and DCN enhanced up to ~70 K

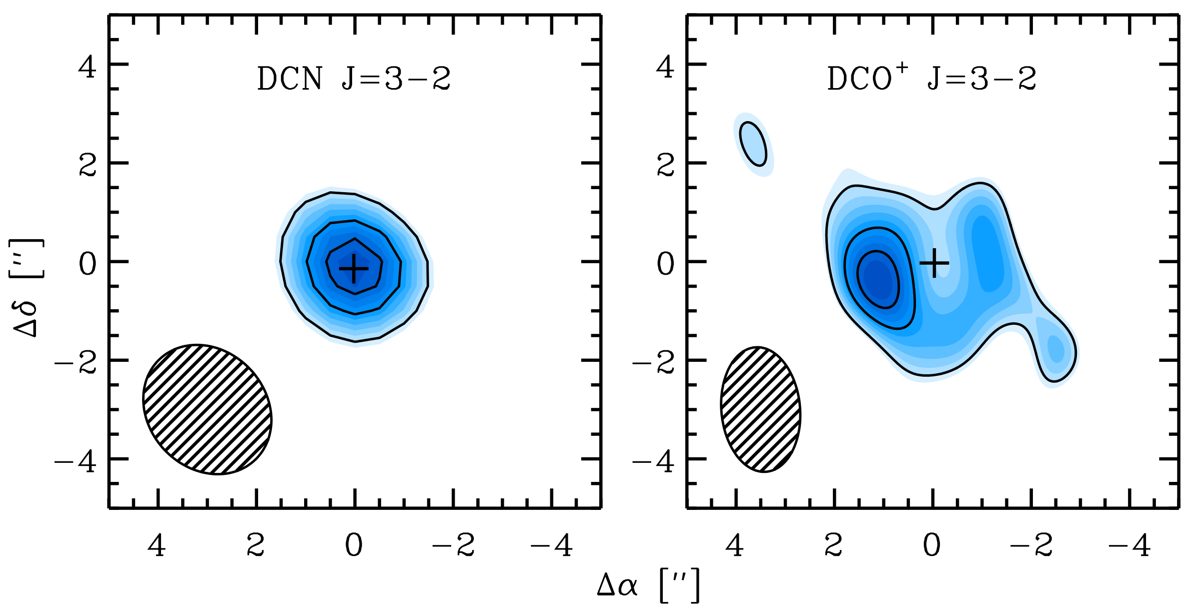
Parise et al. (200(); Öberg et al. (2012); Favre et al. (2015)

Two paths for deuteration (2)

HD163296

DCN

TW Hya



DCO^+

N_2D^+

- DCN forms via warm deuteration
- N_2D^+ only traces cold deuteration
- DCO^+ forms via both paths

Öberg et al. (2012); Mathews et al. (2013); Salinas, Hogerheijde et al. (in prep.)

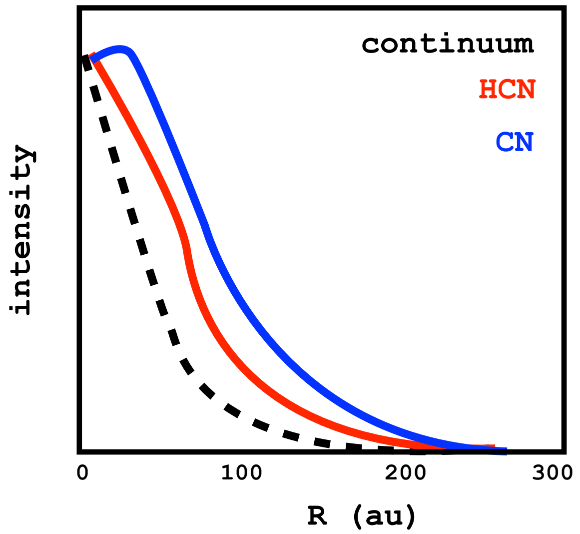
The influence of radiation

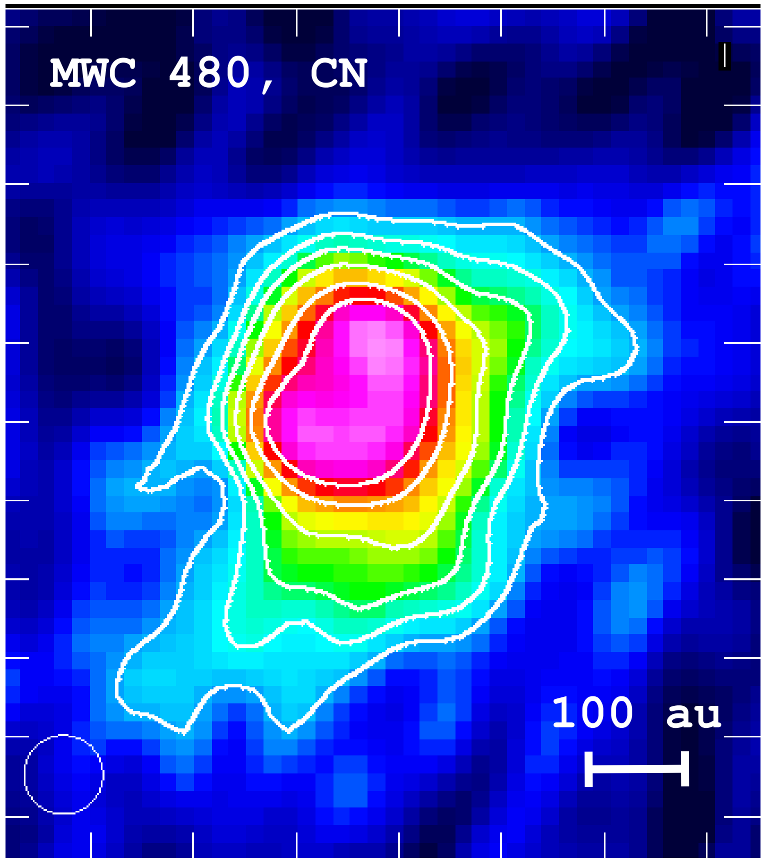
IM Lup shows a double ring in DCO^+

- traces CO in outer disk re-appearing in the gas-phase: heating by ISRF

MWC 480 has extended CN vs HCN

- photodissociation of HCN by (inter)stellar UV

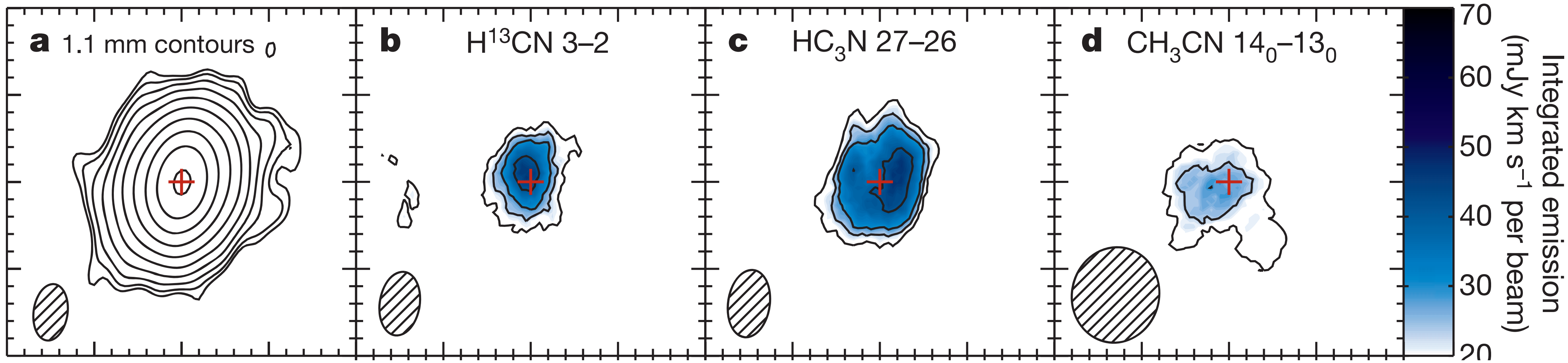




Öberg et al. (submitted)

Organic molecules

MWC 480



HD163296

Detection of cyanides in MWC480:
CH_3CN, HC_3N, (and HCN)

H_2CO ubiquitous (HD163296, DM Tau)

- no trace yet of CH_3OH. Where did the methanol go?

Öberg et al. (2015); Loomis et al. (in prep.); Carney, Hogerheijde et al. (in prep.)

Conclusions and outlook

ALMA offers high sensitivity and high resolution for disk studies

- grains grow and drift inward; gaps open
- molecular emission understood in terms of freeze out, photodissociation ⇔ formation of trace species
- gas motions combine with asymmetries in density / abundance / temperature ➛ kinematic signatures
- earliest disk stages finally accessible

☛ **Detailed understanding of individual objects**

☛ **Population studies of selected aspects**