ALMA observations of protoplanetary disks: II

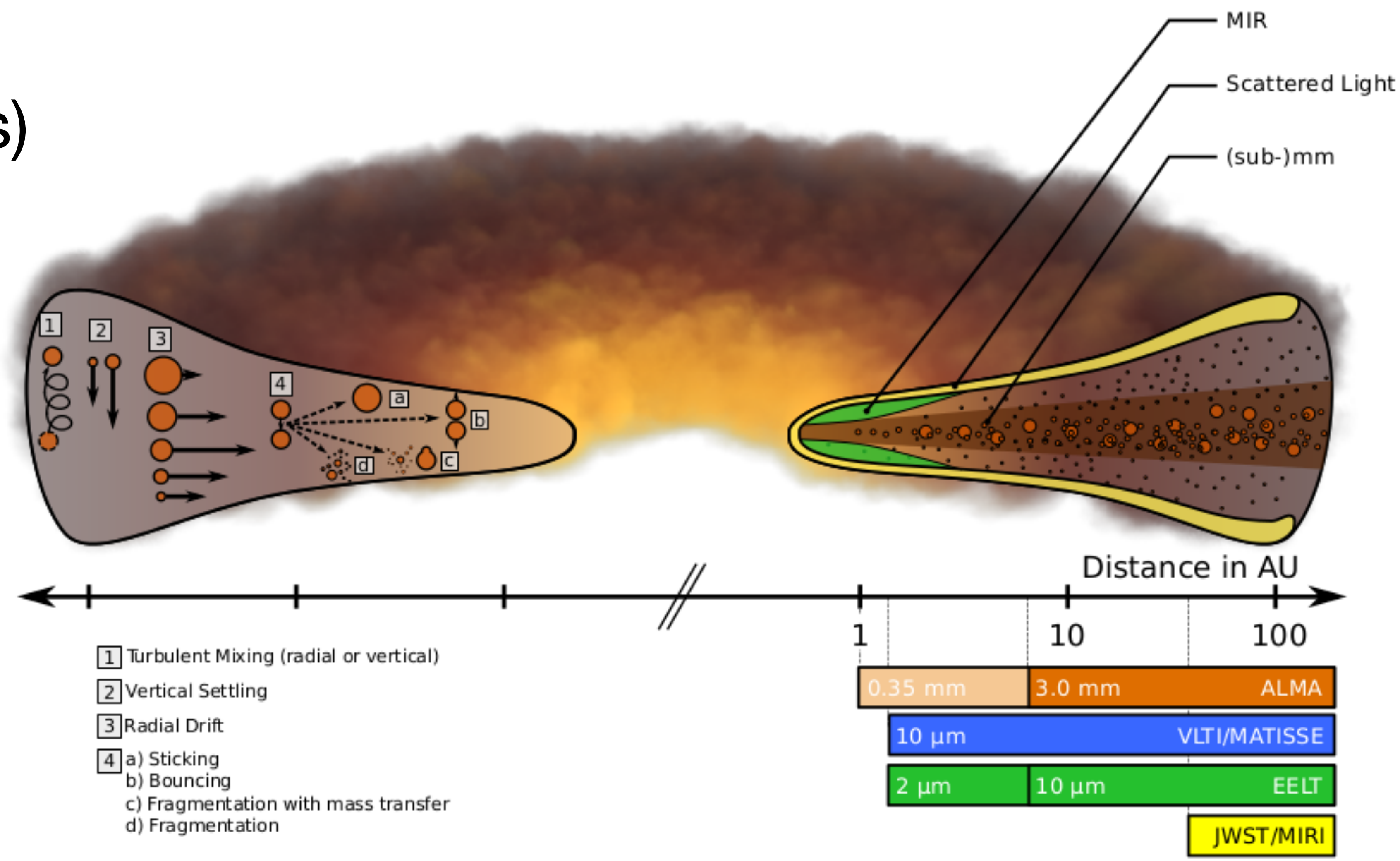
Dustbusters school 2024

Nienke van der Marel
Leiden Observatory
January 23rd

Sterrewacht Leiden

Recap dust observations

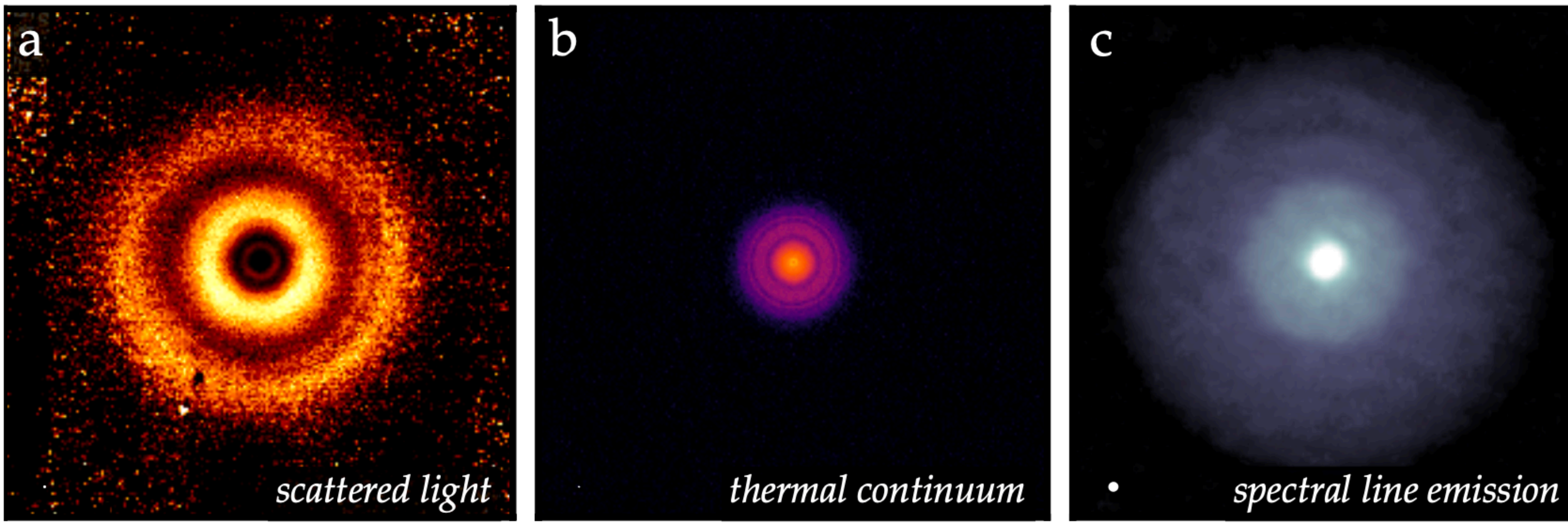
- Disk dust structure
- Dust mass (incl. trends)
- Dust substructures
- Analysis:
  - Multi-wavelength
  - Polarisation
  - Visibilities



Contents today (‘gas’)

1. Disk gas structure
2. Molecular line emission
3. CO in disks
    1. Observations
    2. Determining disk gas mass
    3. CO depletion
    4. Gas-to-dust size ratio
    5. Gas gaps
    6. Vertical structure
4. Other molecules
    1. Snowlines
    2. COMs
    3. Other tracers
5. Kinematics

Disk structure

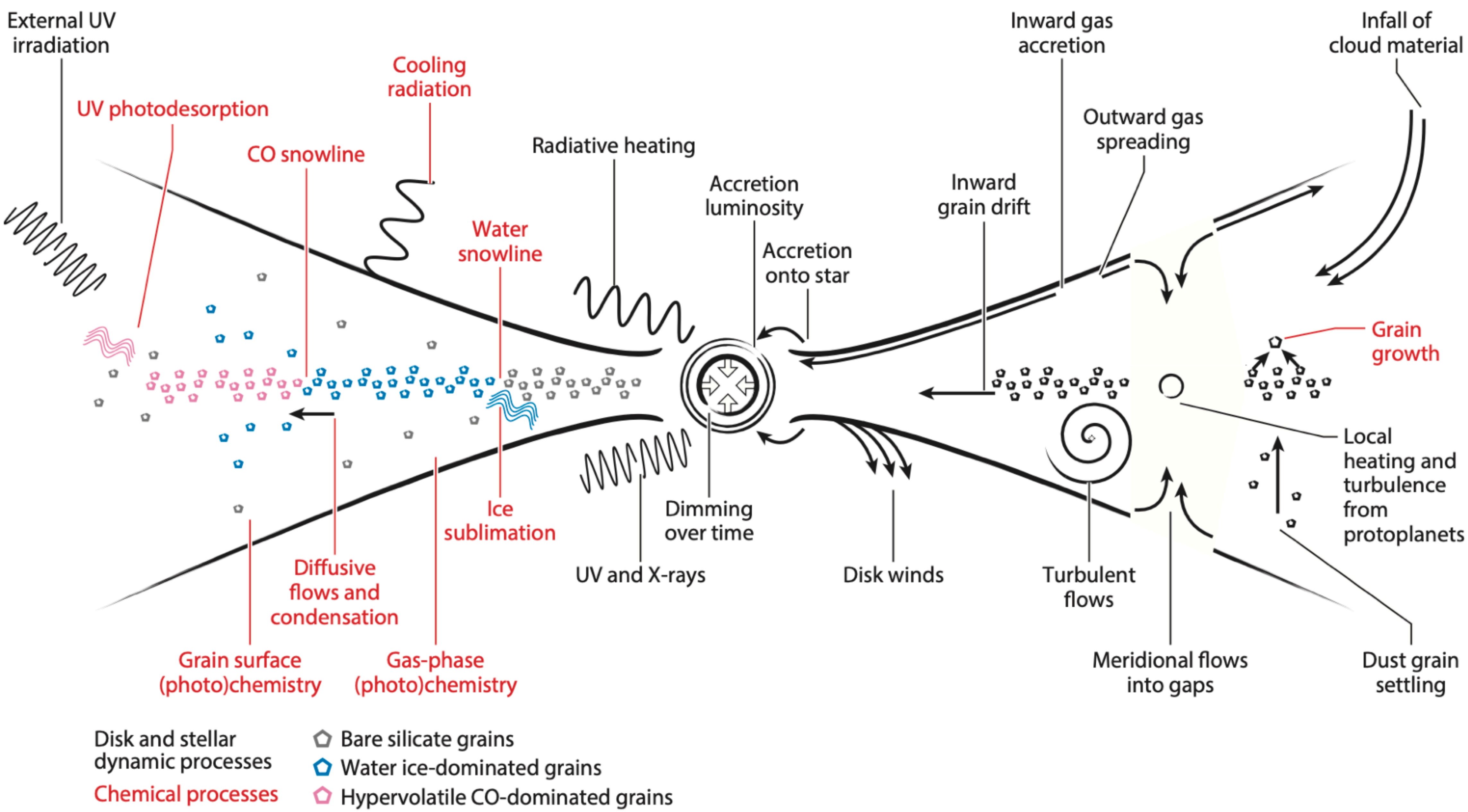


Gas and millimeter dust show very different distributions, and gas is the bulk component of the disk

Andrews 2020

Disk gas structure

More complex than dust

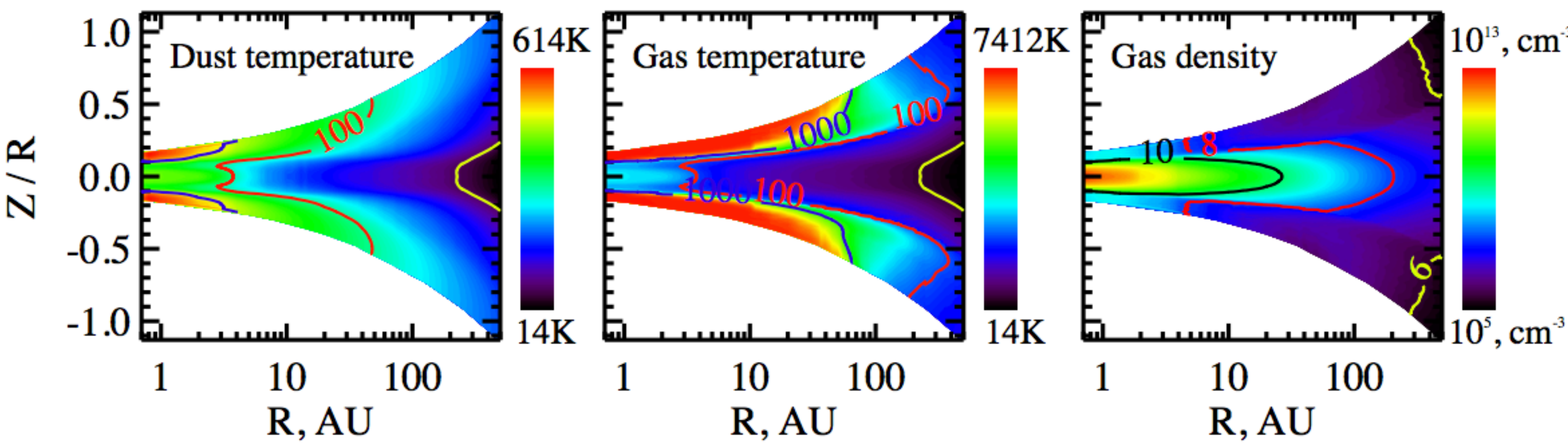


Many processes affecting the gas and the molecules

Oberg, Facchini & Anderson 2023 (ARAA)

Disk gas structure

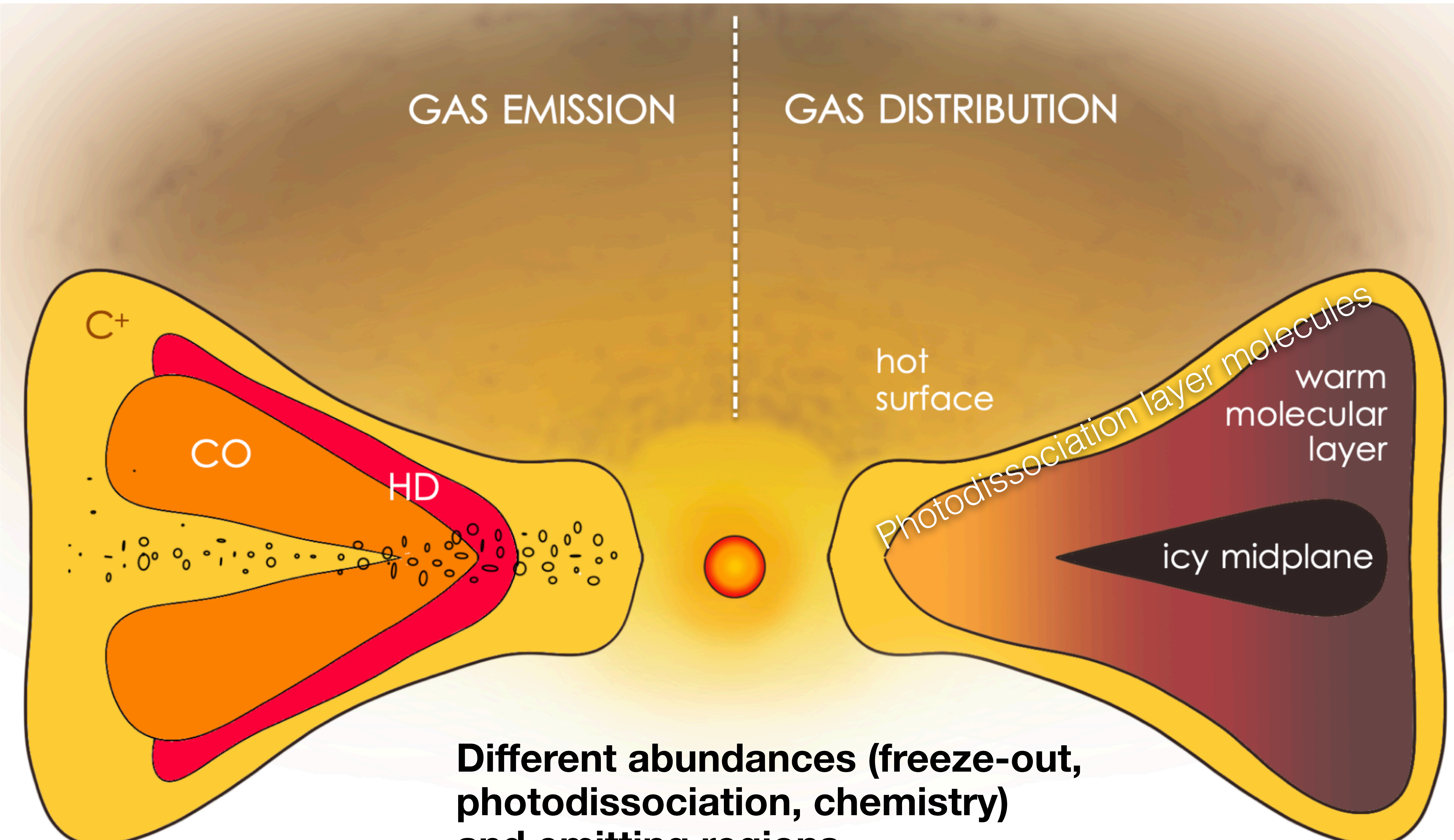
In order to use molecular line emission as a tracer of mass, we need to understand the density and temperature structure of the disk



T_{gas} decoupled from T_{dust} and large gradients in density and T impact the molecular emission

Disk gas structures

Molecular abundances



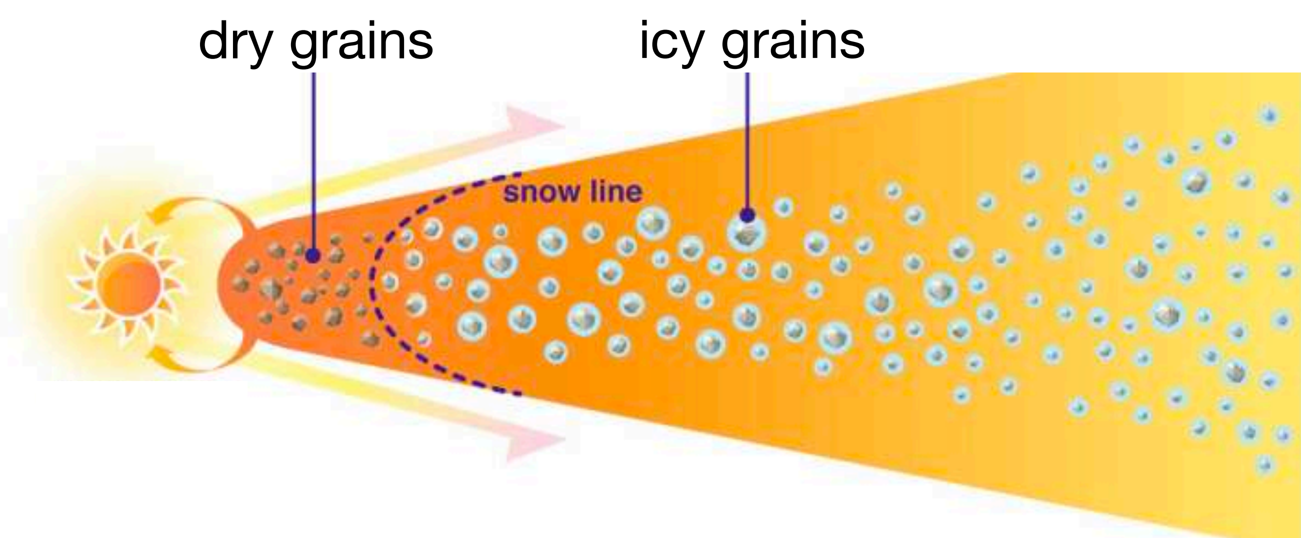
Different abundances (freeze-out, photodissociation, chemistry) and emitting regions

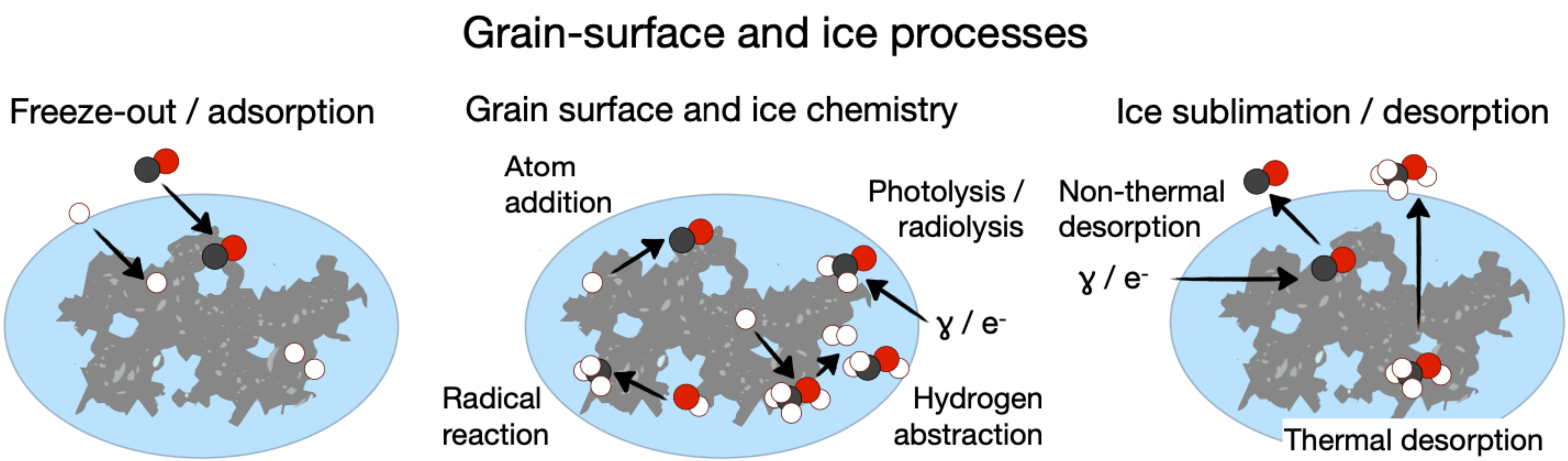
figure by Anna Miotello

Disk gas structure

Icy midplane

Freeze-out in disk when $T<T_{subl}$





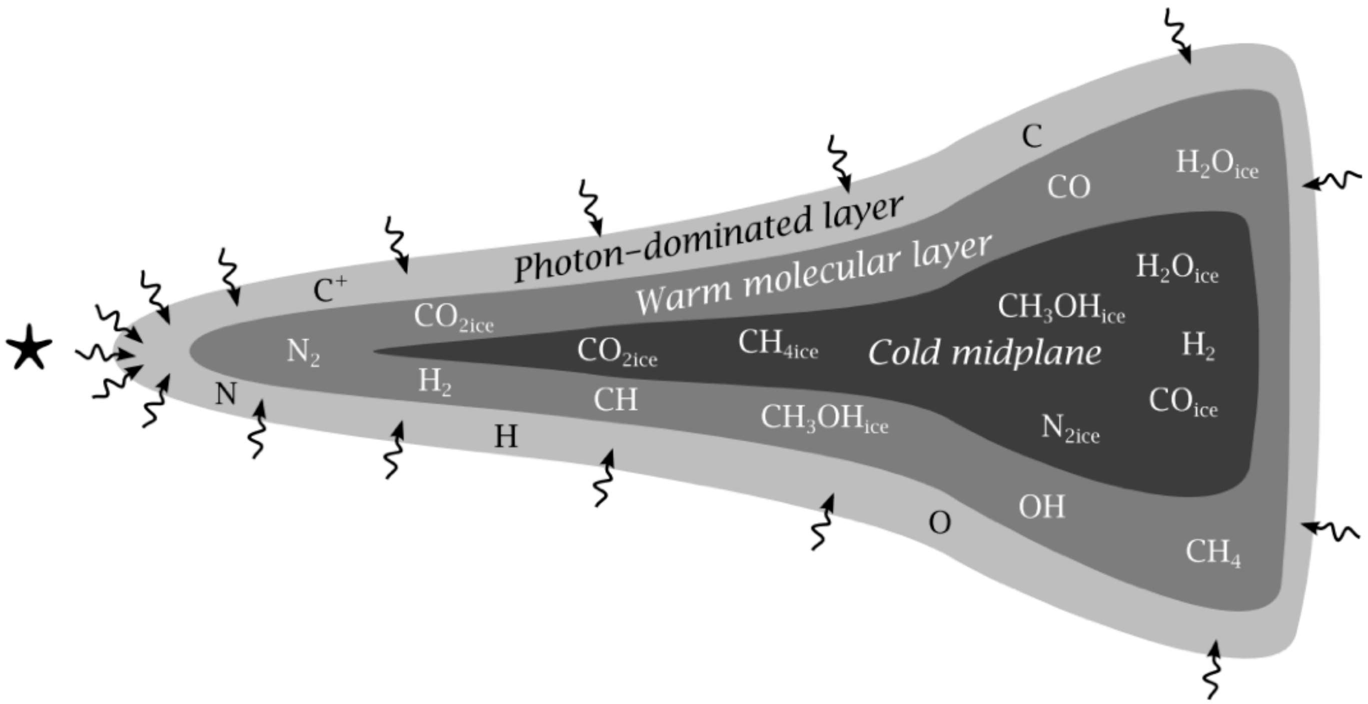
Many possible chemical reactions, followed by ice sublimation

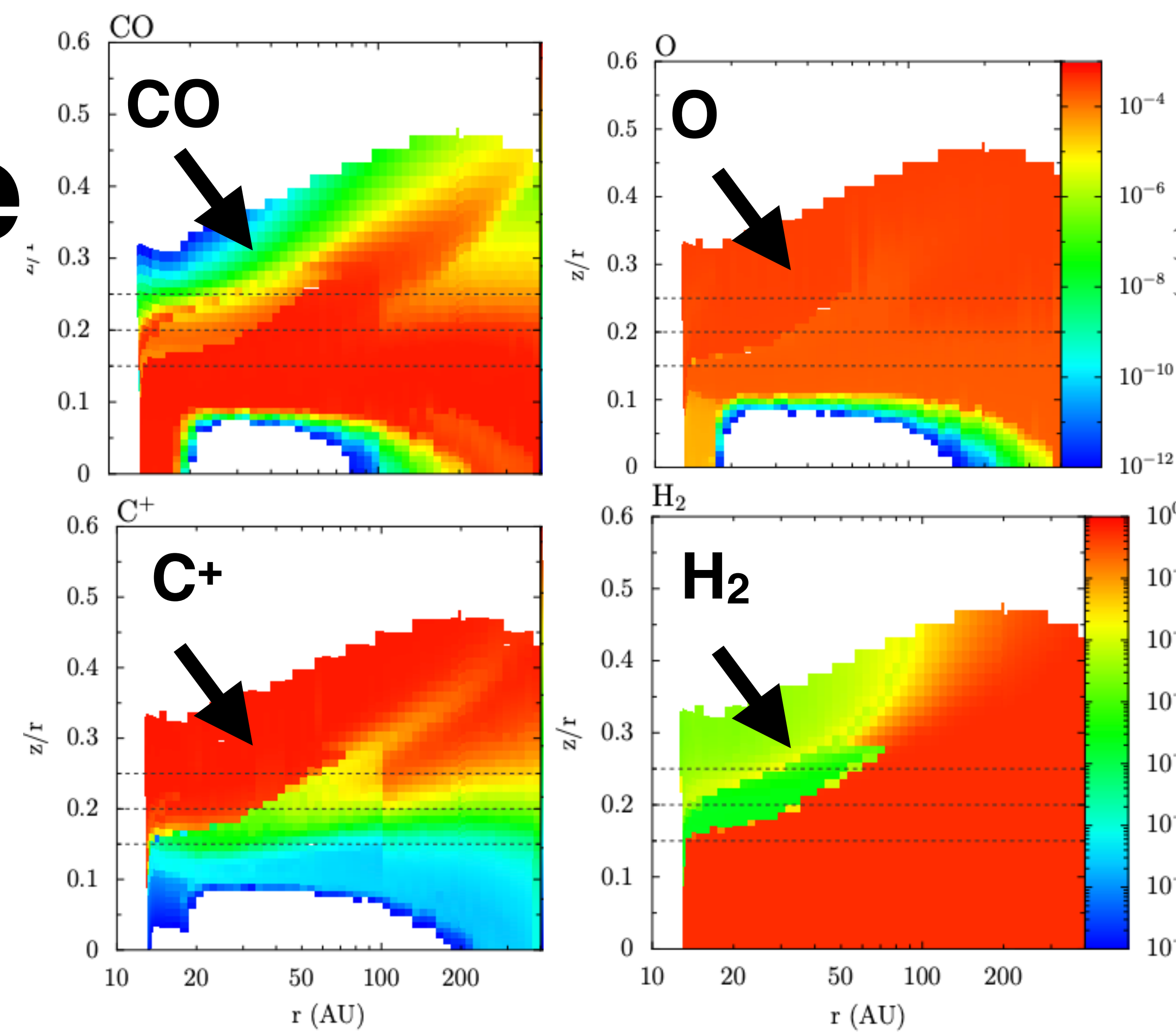
Oberg & Bergin 2020

Disk gas structure

Photodissociation

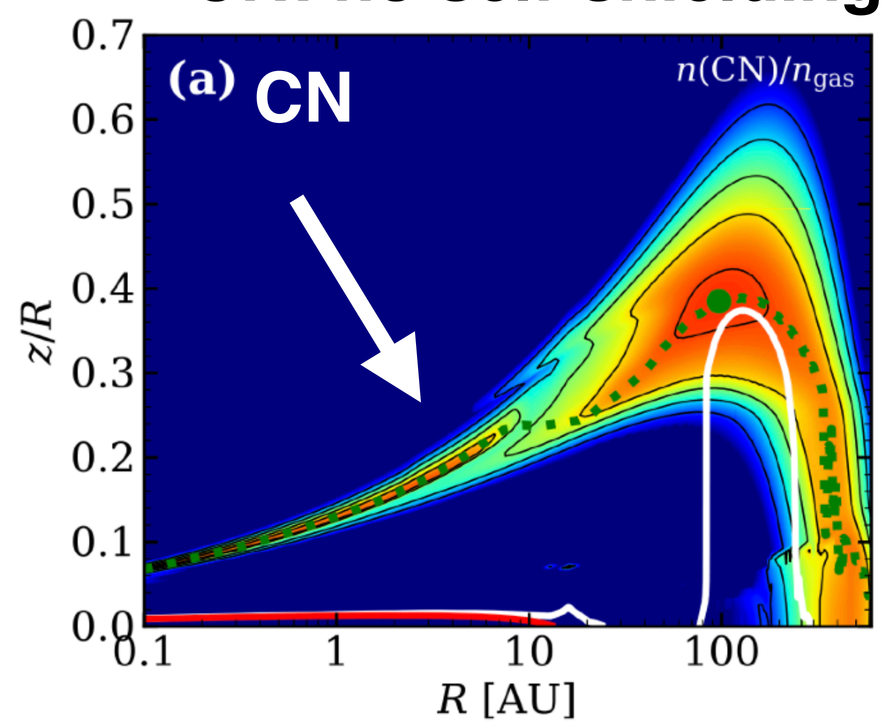
Radiation of molecules (e.g. CO, H_2):
photodissociation into atoms/ions ("PDR chemistry" in ISM/diffuse clouds**)**





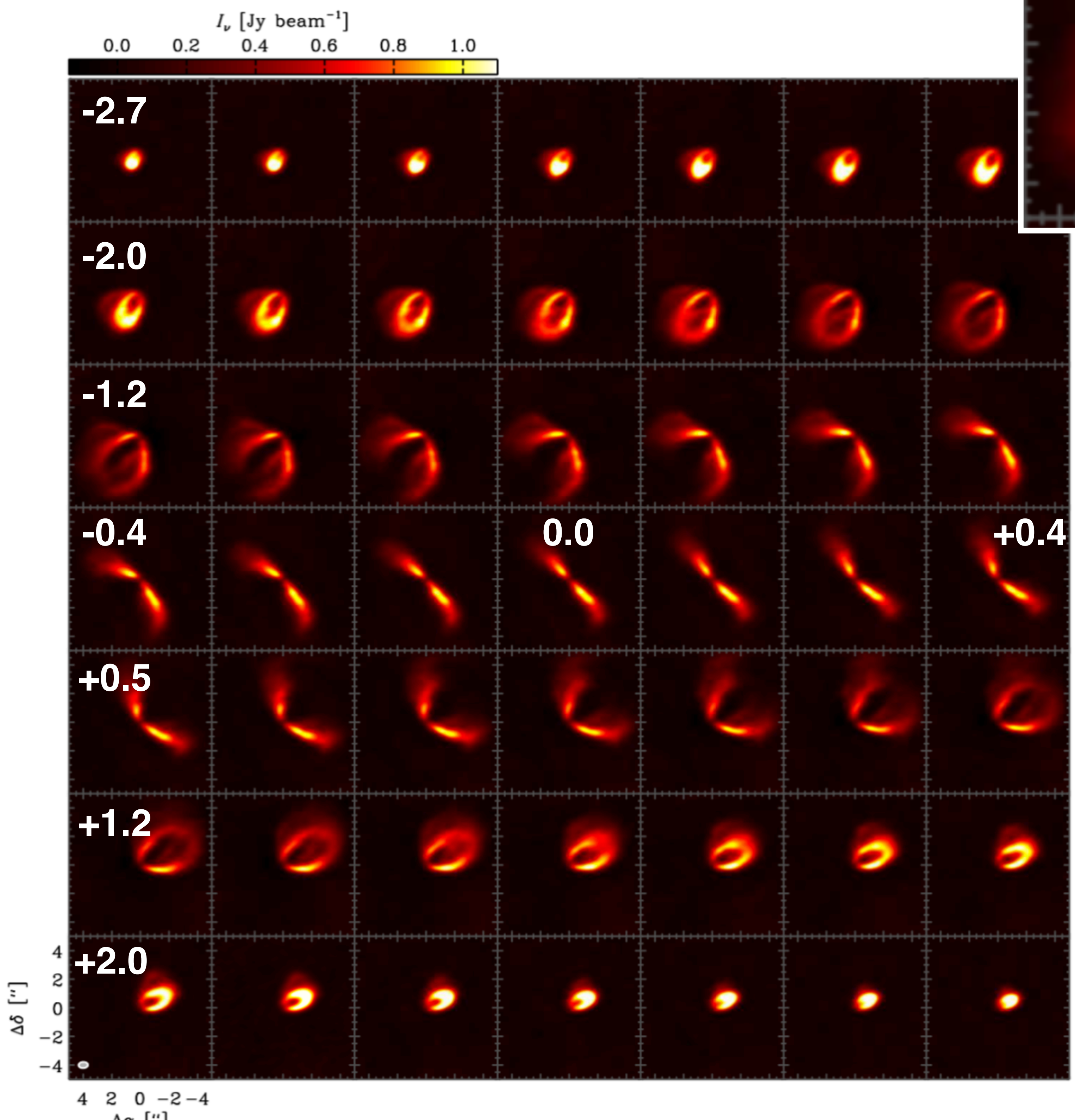
CO and H_2 also susceptible to **self-shielding: limited** range **photodissociating layer (some molecules**, e.g. CN, **no self-shielding** due to hyperfine-structure splitting of quantum levels**)**

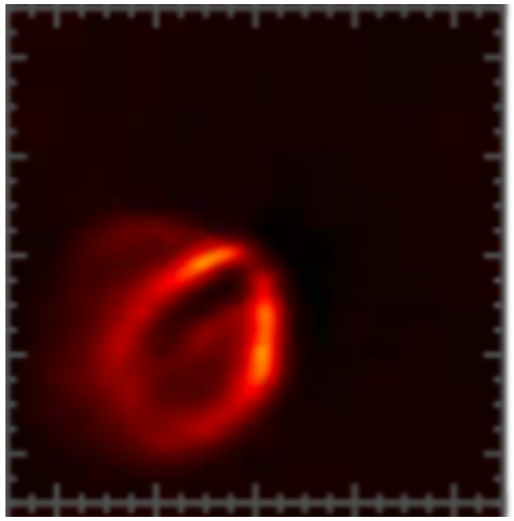
CN: no self-shielding



Visser et al. 2009
Bruderer et al. 2012
Cazzoletti et al. 2019

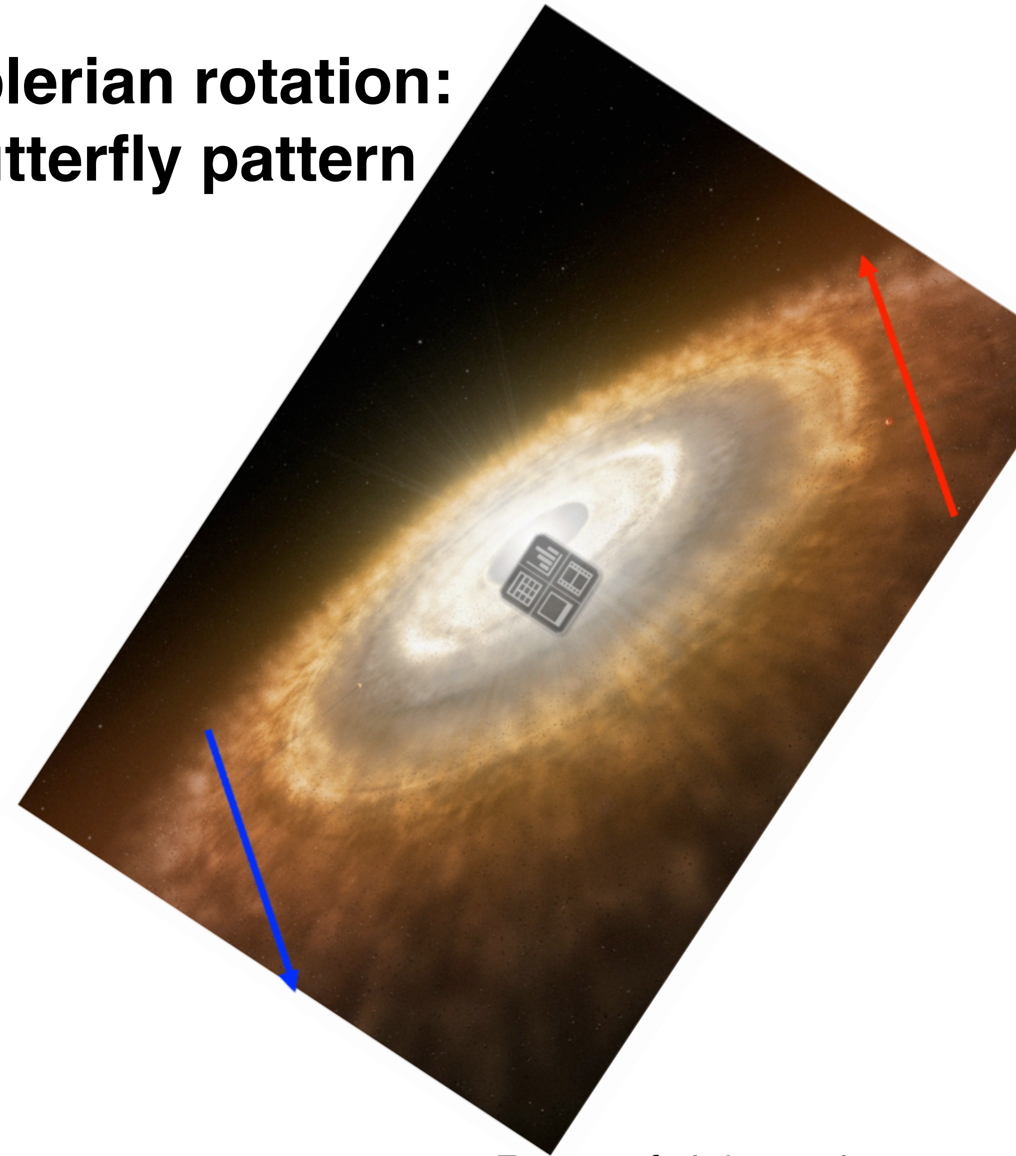
Molecular line emission with ALMA (CO)





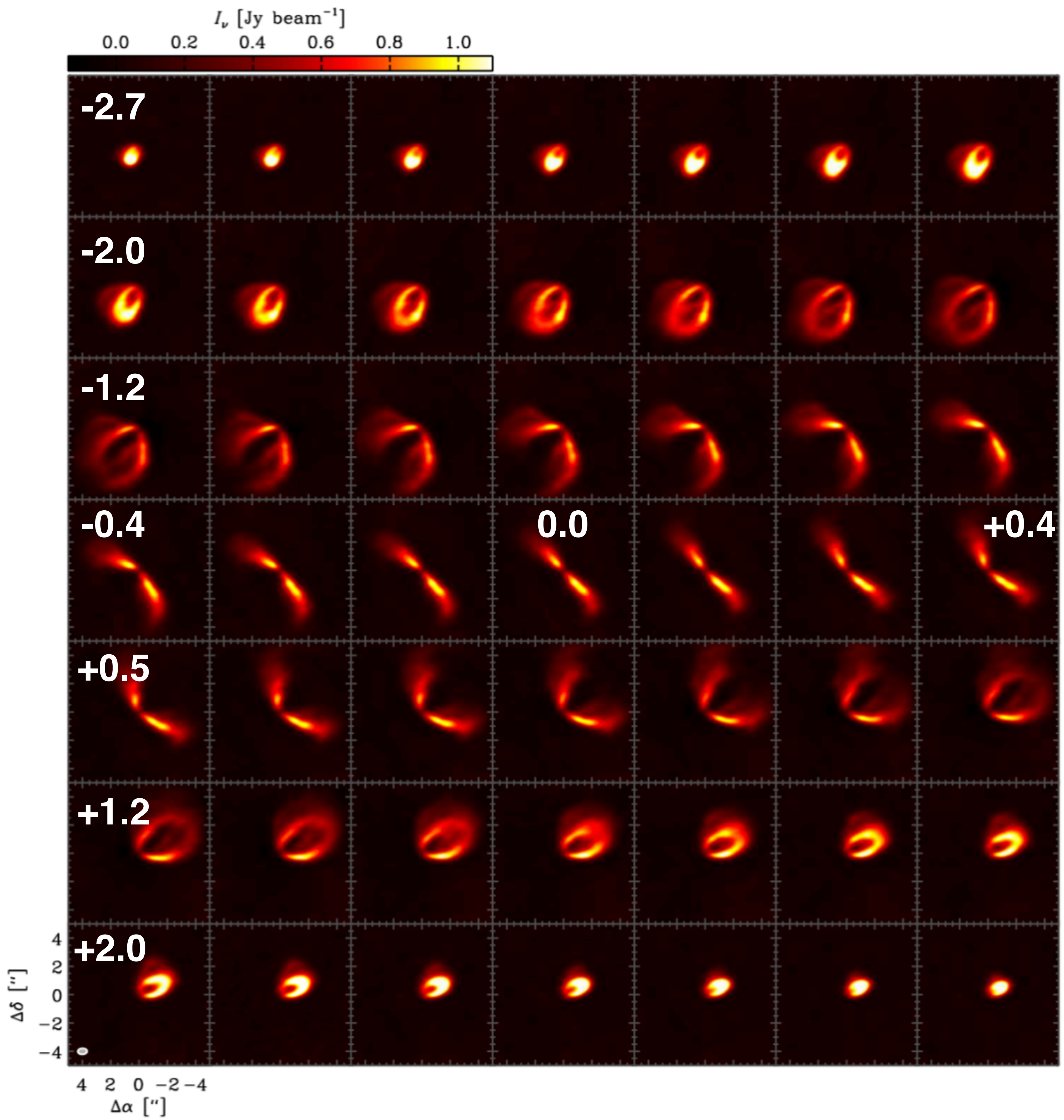
Notice front and backside of the disk!

Keplerian rotation: Butterfly pattern



Rosenfeld et al. 2013

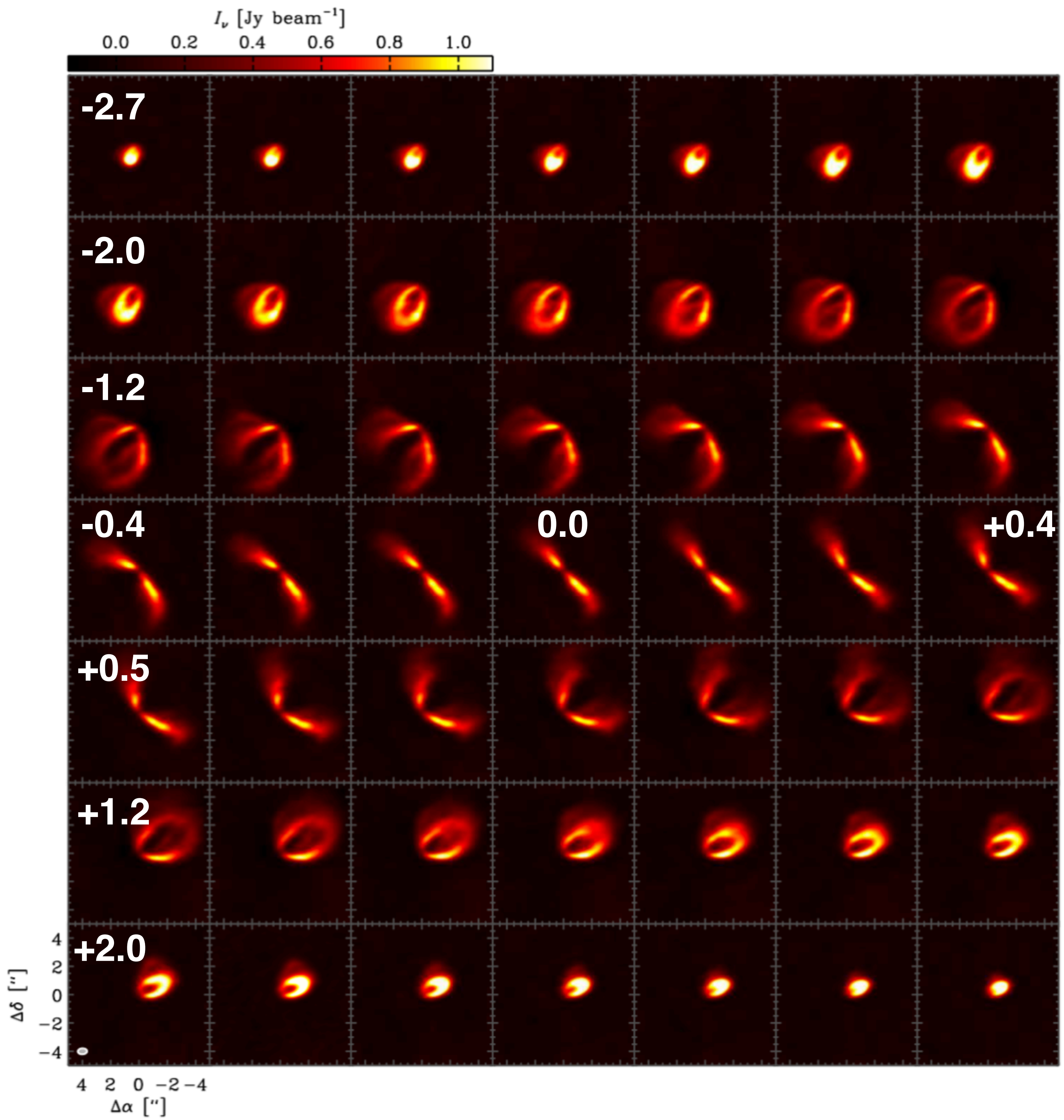
Molecular line emission with ALMA (CO)



What can we derive and compute with a channel map?

Rosenfeld et al. 2013

Molecular line emission with ALMA (CO)



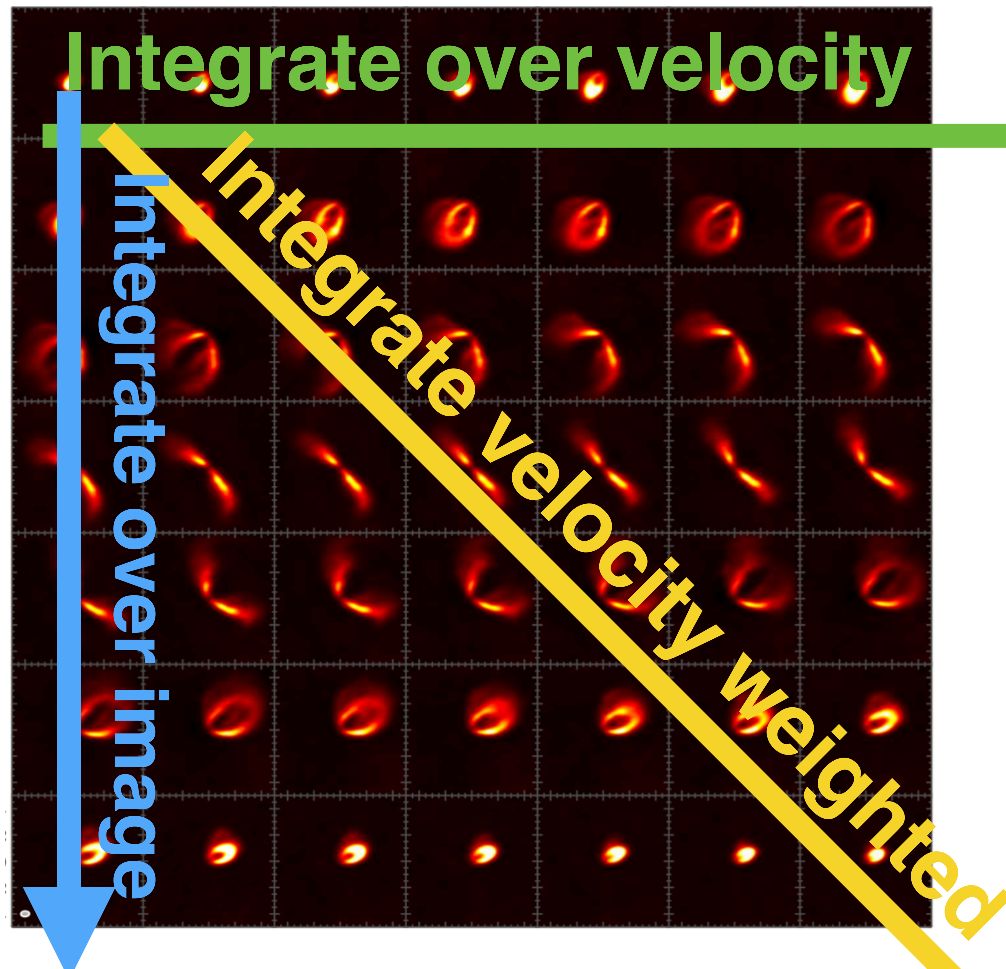
Direct:

1. Image properties (Peak flux, rms)
2. Moment maps and spectrum
3. Integrated flux
4. Brightness temperature

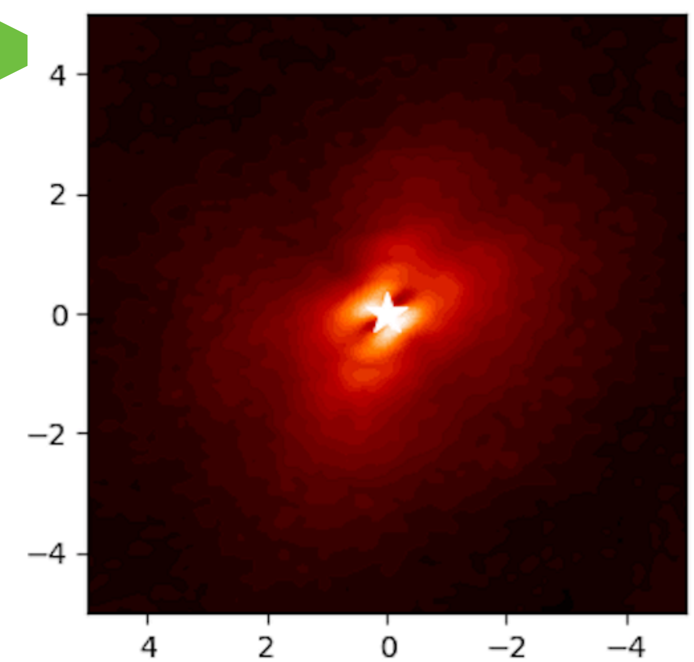
Indirect:

1. Disk orientation
2. Molecular surface density
3. Disk gas mass and size
4. Emitting height molecules
5. Keplerian motion: stellar mass
6. Deviations from Keplerian motion

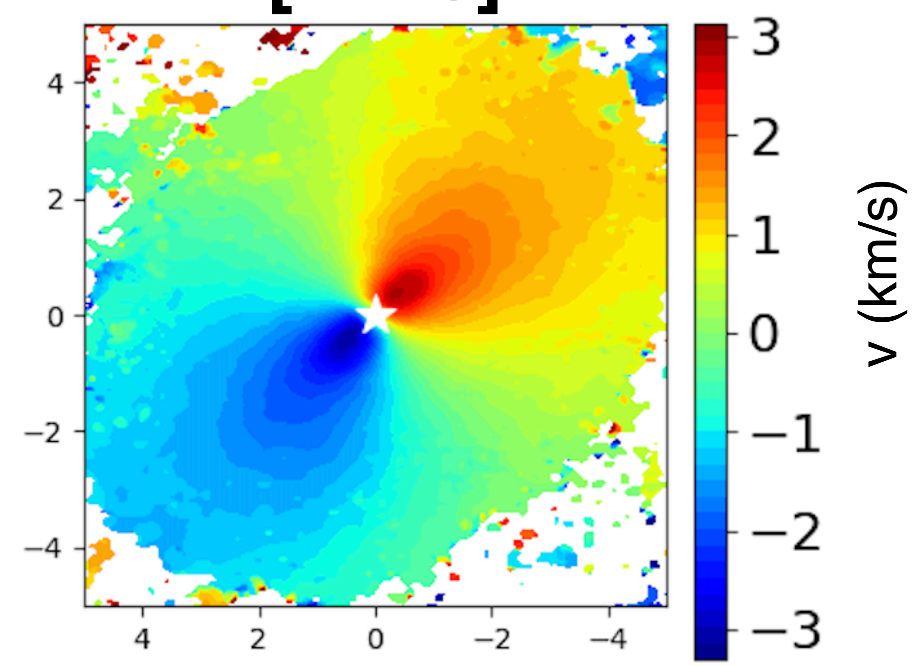
Molecular line emission with ALMA (CO)



Intensity map (moment 0) [Jy/beam km/s]

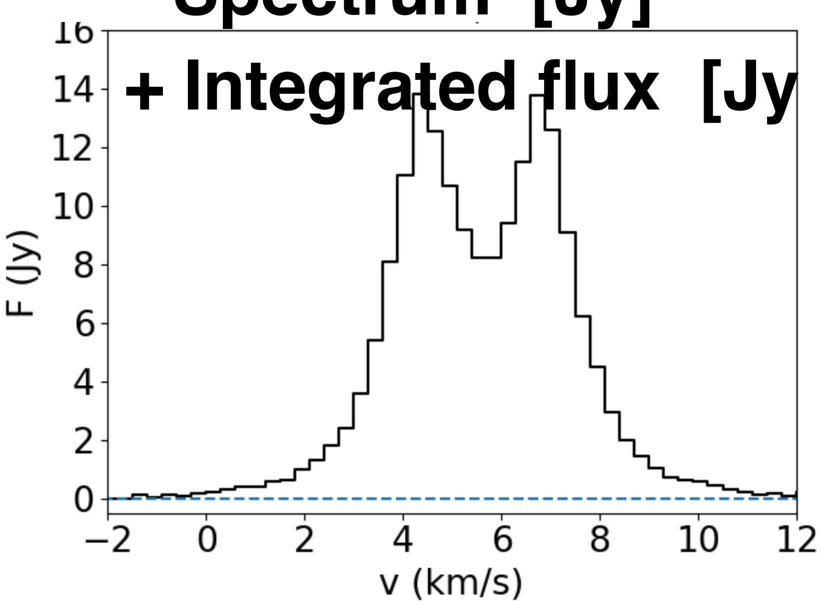


Velocity map (moment 1) [km/s]



Spectrum [Jy]

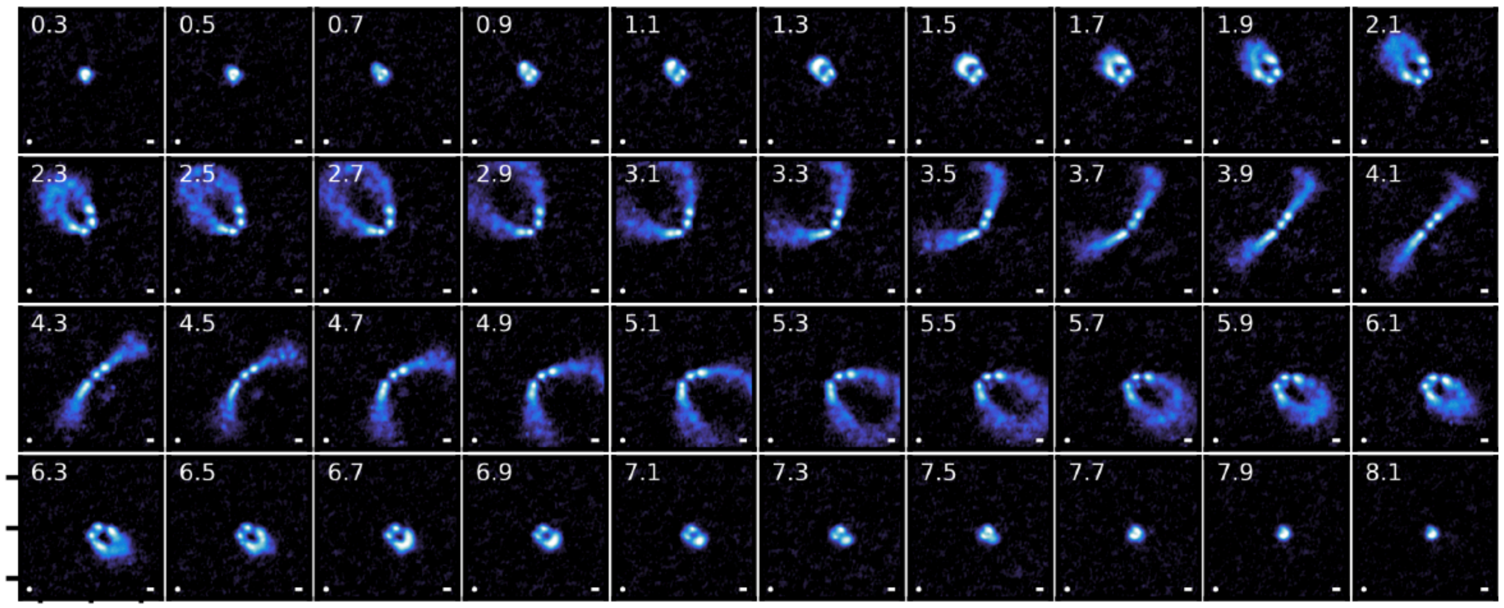
+ Integrated flux [Jy km/s]



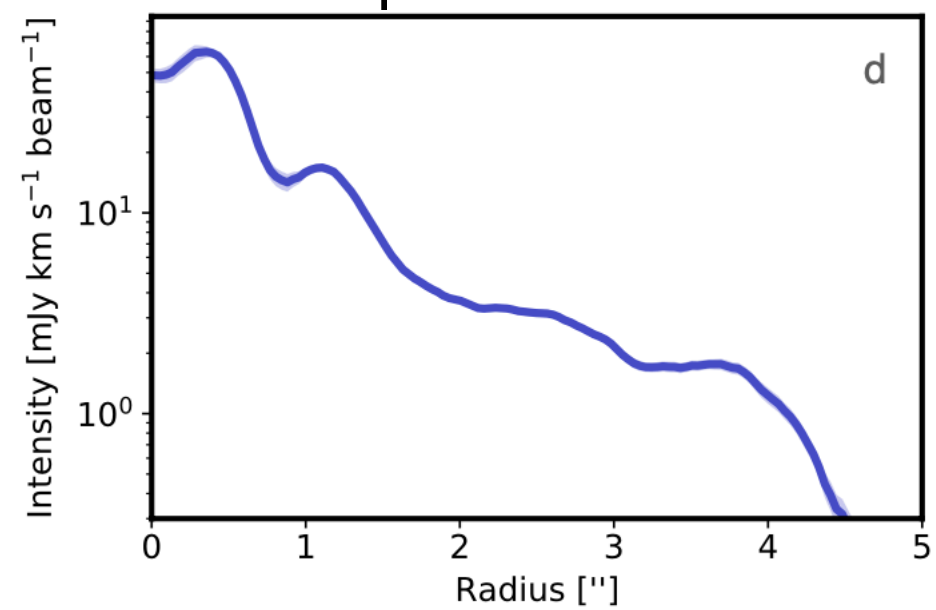
Molecular line emission with ALMA

MAPS approach

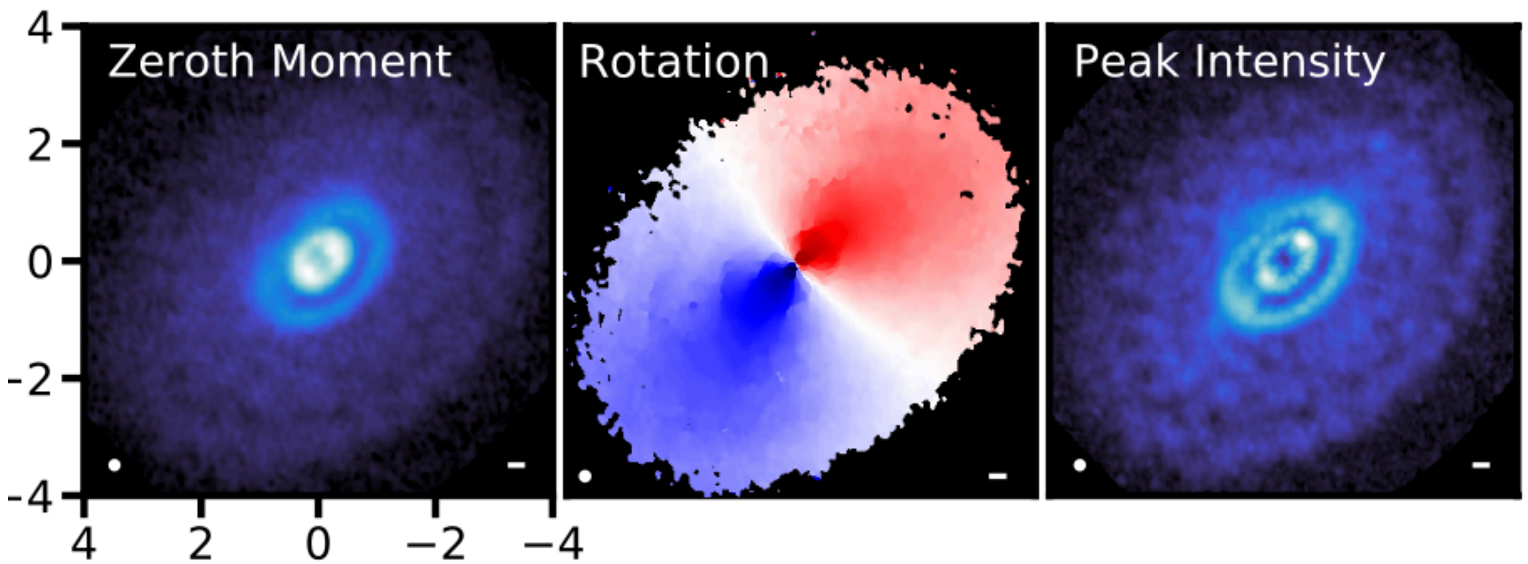
Channel cubes



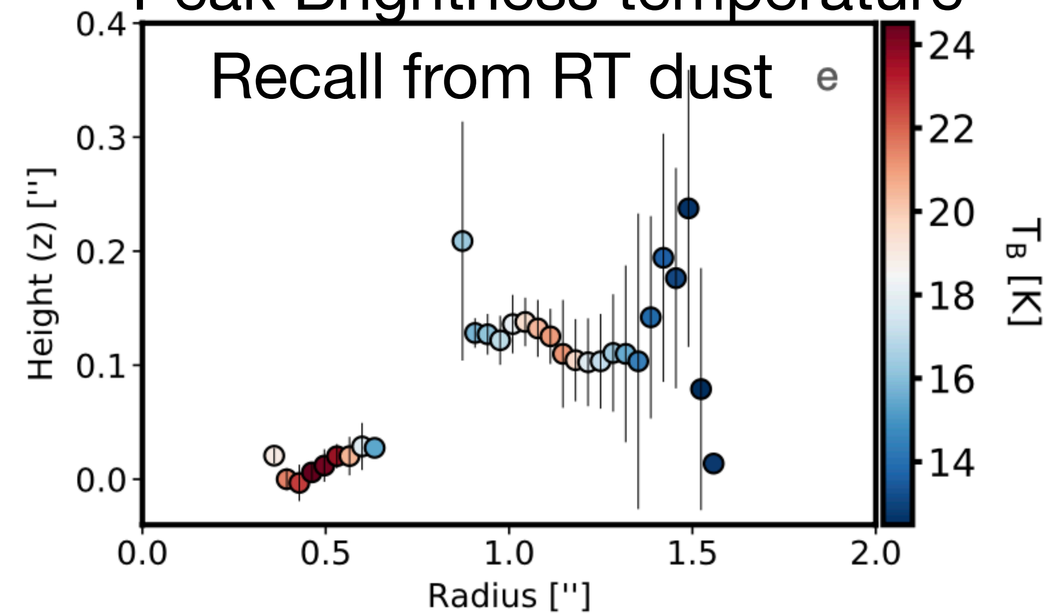
Radial profile Moment 0



Moment 0 Moment 1 Moment 8



Peak Brightness temperature



$$T_b = \frac{h\nu}{k_B}\left[\ln\left(\frac{2h\nu^3}{c^2 I_\nu} + 1\right)\right]^{-1}$$

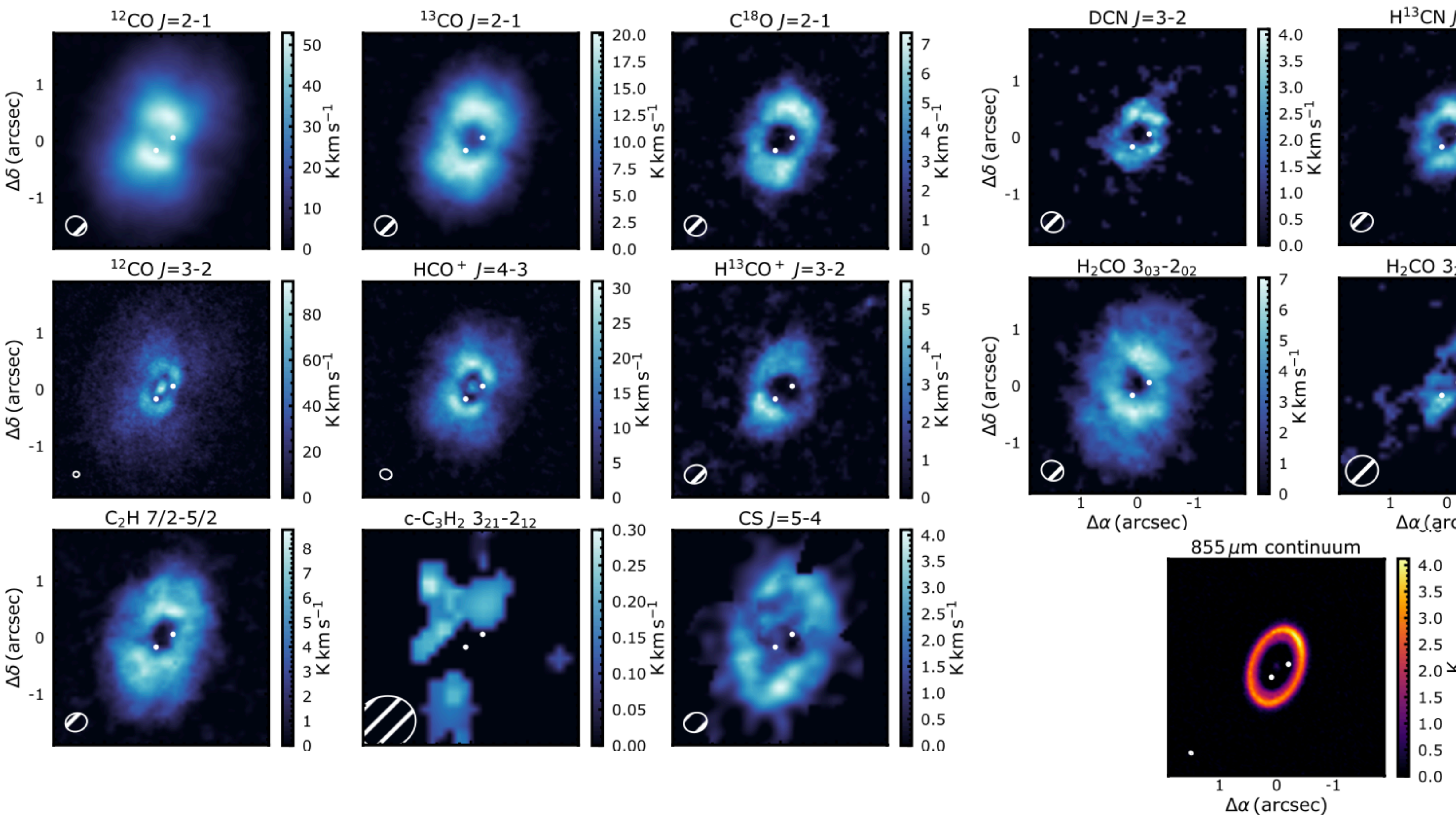
Tools: CASA immoments or bettermoments (GitHub, Teague+2018)

Oberg et al. 2021 (MAPS), Law et al. 2021 (MAPS)

Molecular line emission with ALMA

Example: PDS70

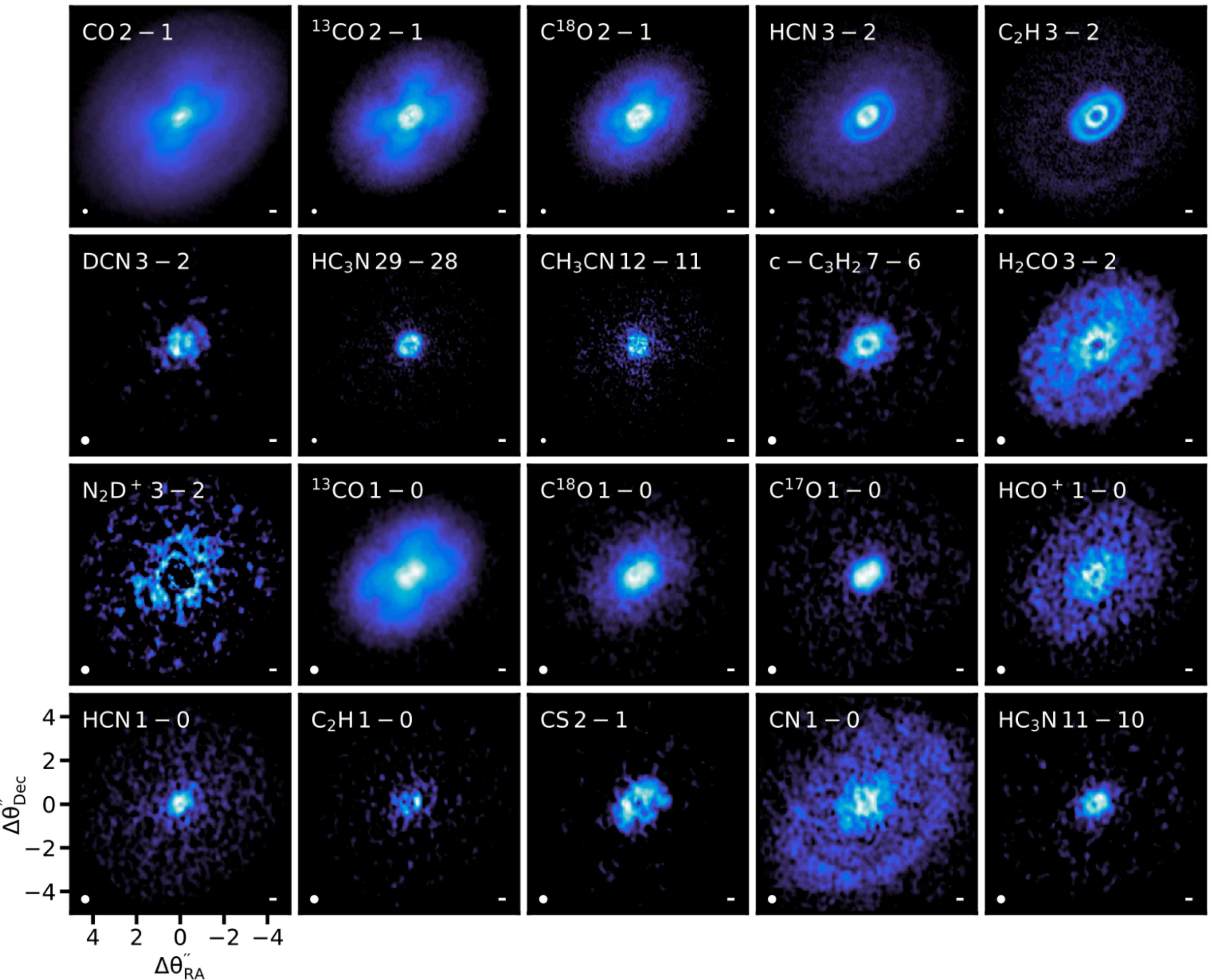
Different molecules show different radial extents in their intensity map

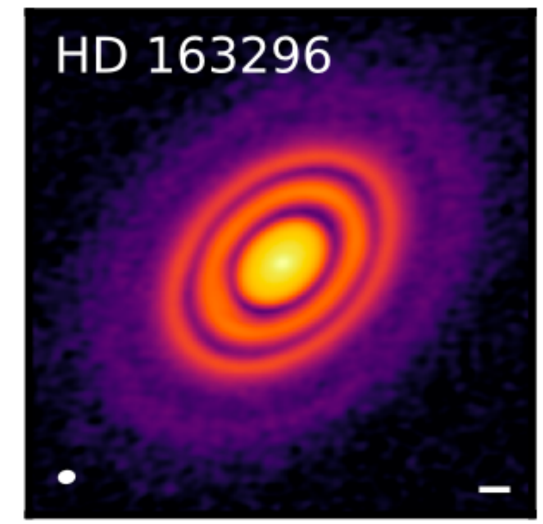


Facchini et al. 2021

Molecular line emission with ALMA

Example: HD163296 (MAPS)





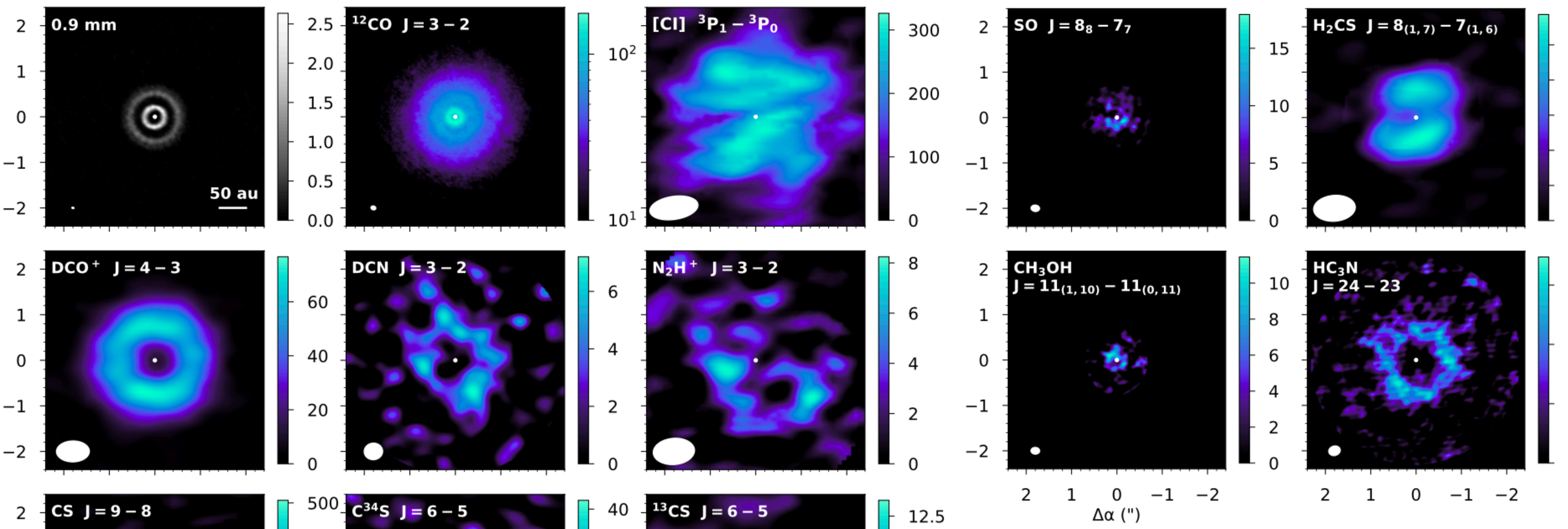
Some disks actually show much larger diversity between molecules and dust

Oberg et al. 2021 (MAPS)

Molecular line emission with ALMA

Example: HD169142

Some disks actually show much larger diversity between molecules



What properties set the molecular line emission?

Booth et al. 2022

Molecular line emission

Origin

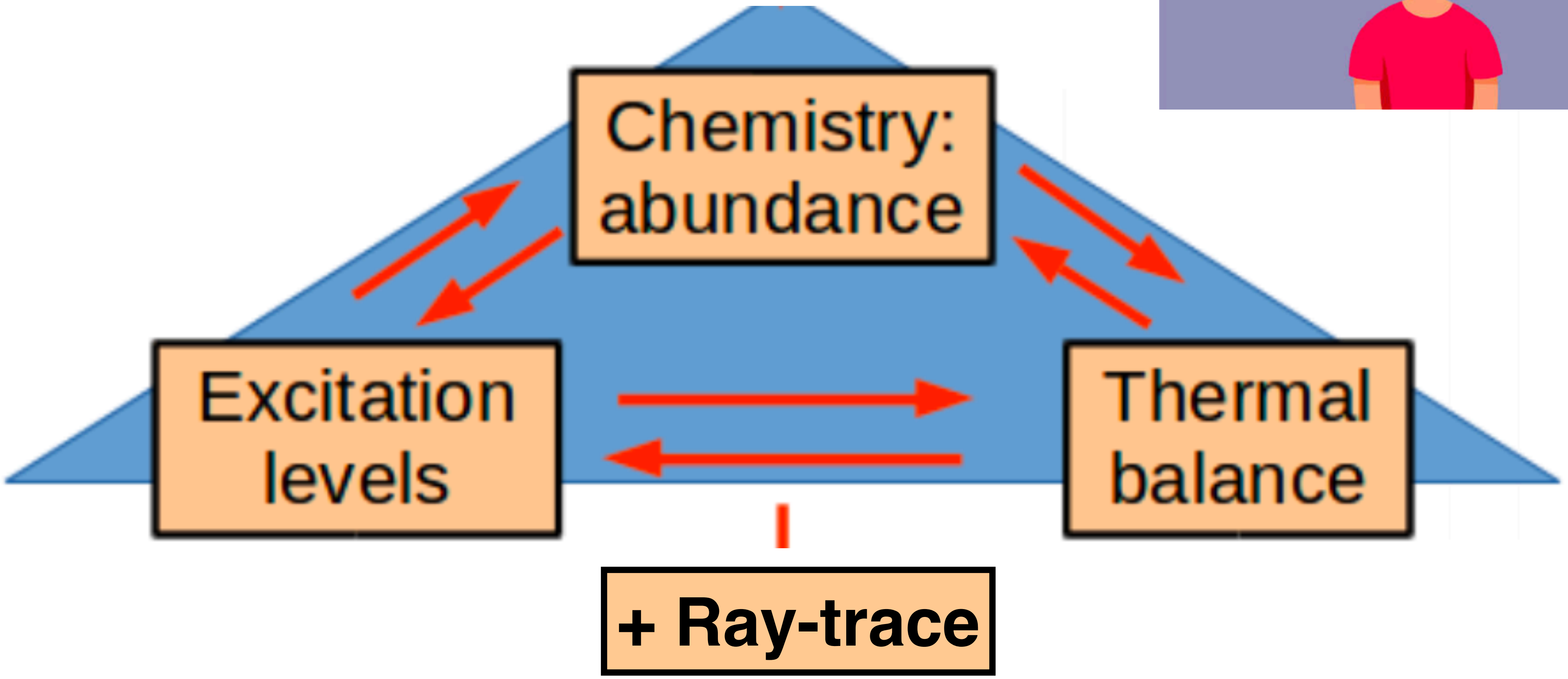
<u>**Factors in molecular line intensity**</u>:

- **Abundances**
  - Chemical reactions (destruction + formation)
  - Physical reactions (freeze-out, photodissociation, self-shielding, gas-grain heating/cooling, ionisation, radiation)
  - Ice chemistry + desorption
- **Gas temperature** (various heating/cooling mechanisms)
- **Gas density** ← **Usual parameter of interest, but requires knowledge of others**
- **Excitation**
- **Optical depth and orientation (ray-trace)**

Molecular line emission

Origin

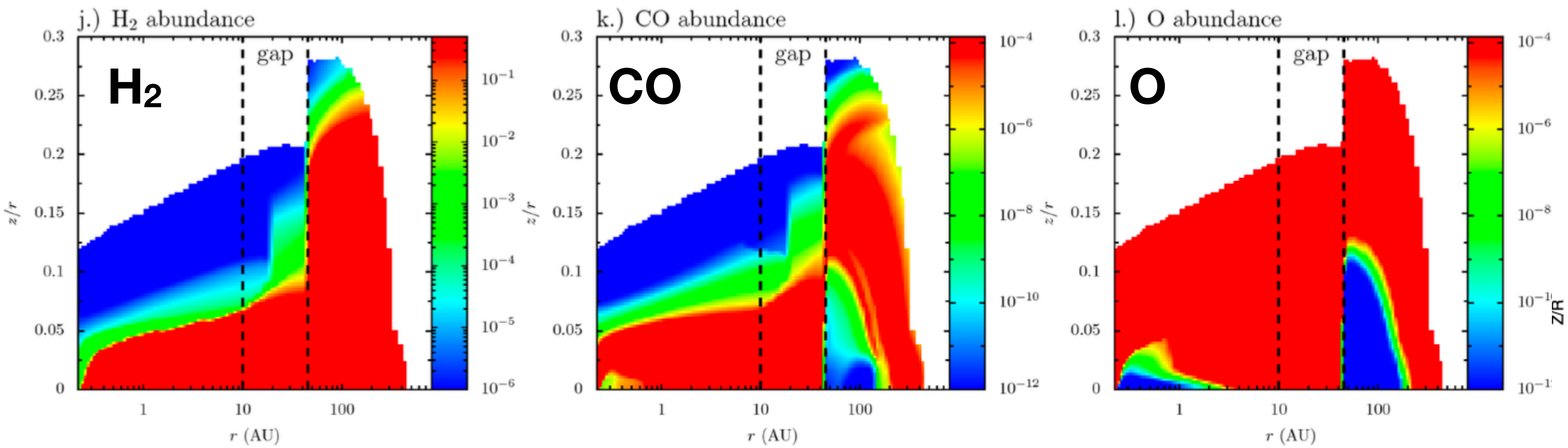
And processes in triangle all impact each other!

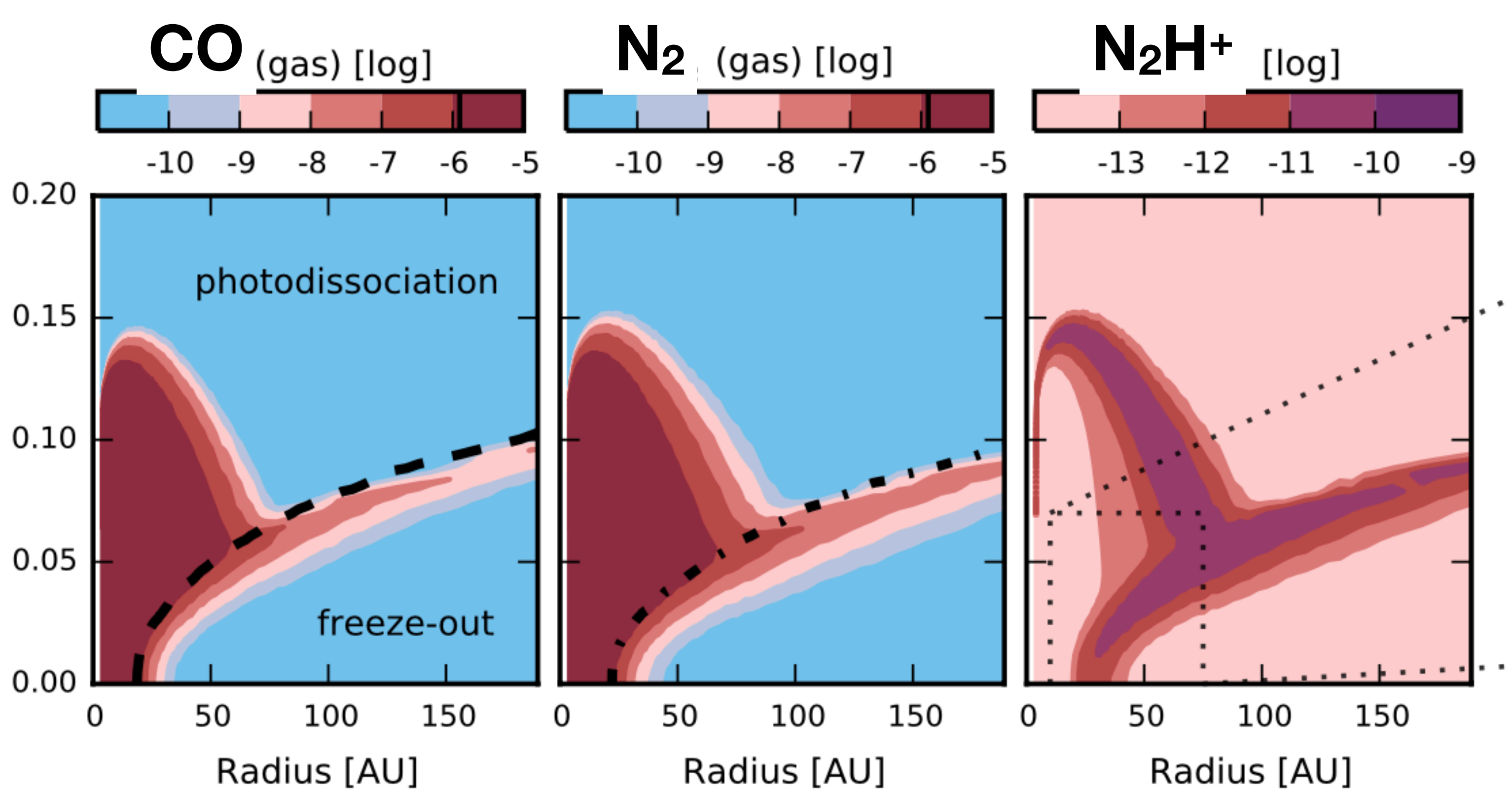


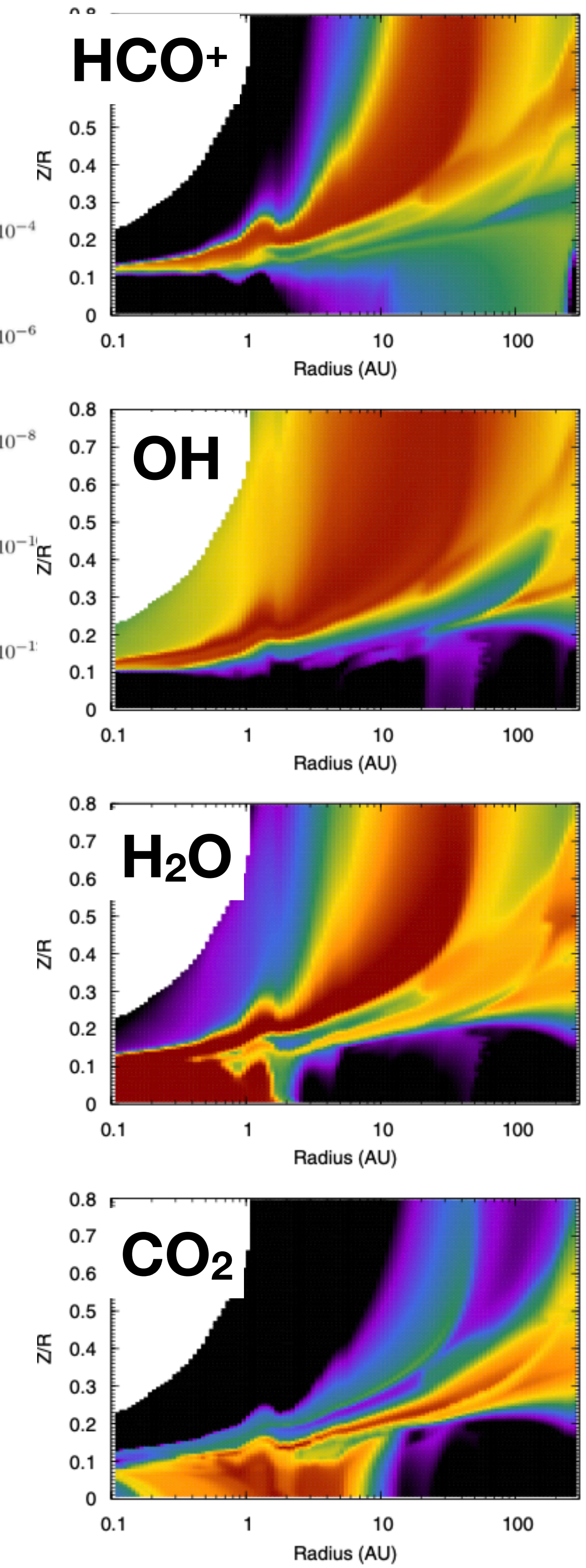
=> usually physical-chemical modeling needed to interpret line data

Molecular abundances in disk models

Disk physical chemistry





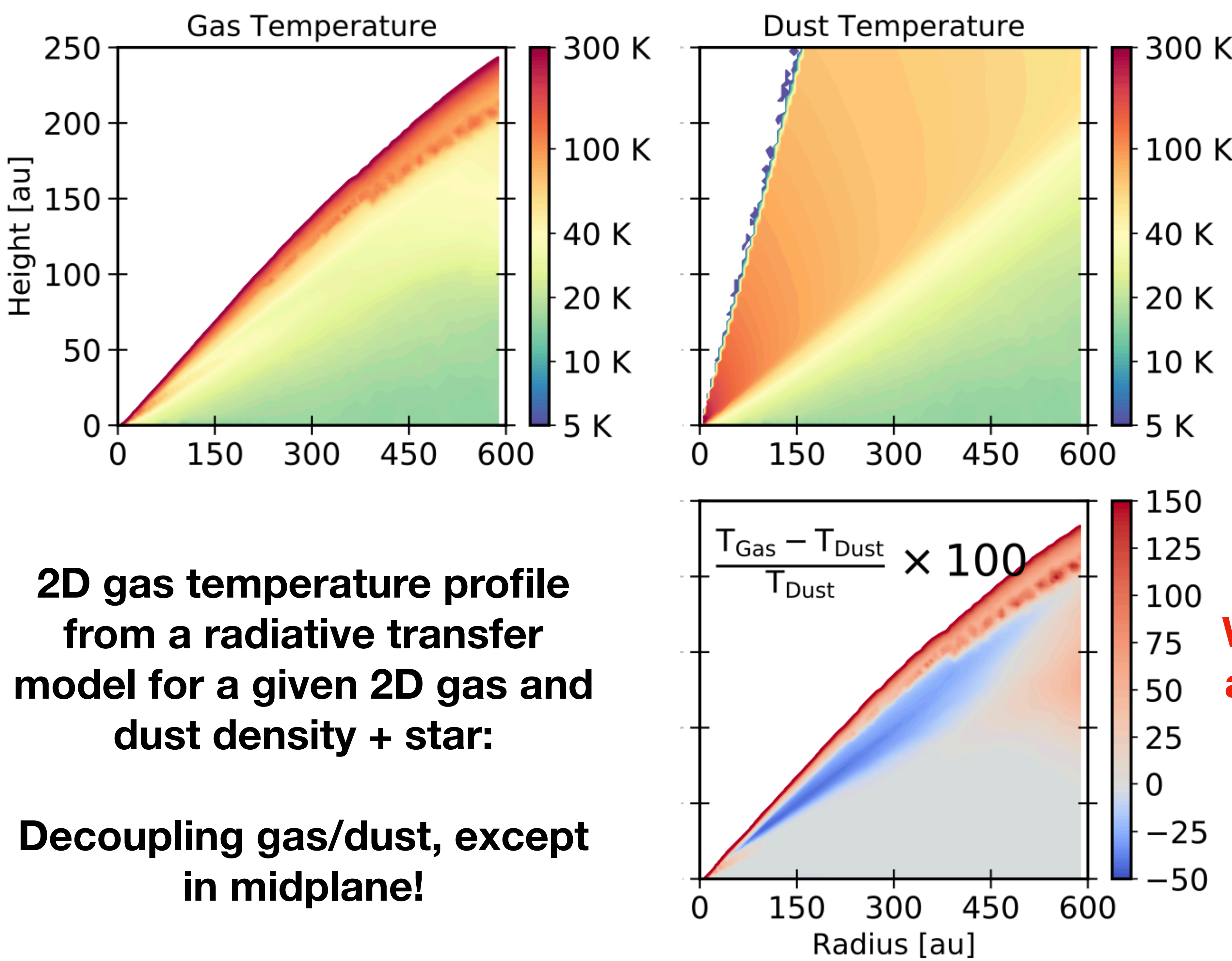


Examples physical-chemical models: DALI, ProDiMo, RAC2D, …

Walsh et al. 2012, Bruderer 2013, van 't Hoff et al. 2017

Gas temperature

Radiative transfer including gas heating/cooling effects



2D gas temperature profile from a radiative transfer model for a given 2D gas and dust density + star:

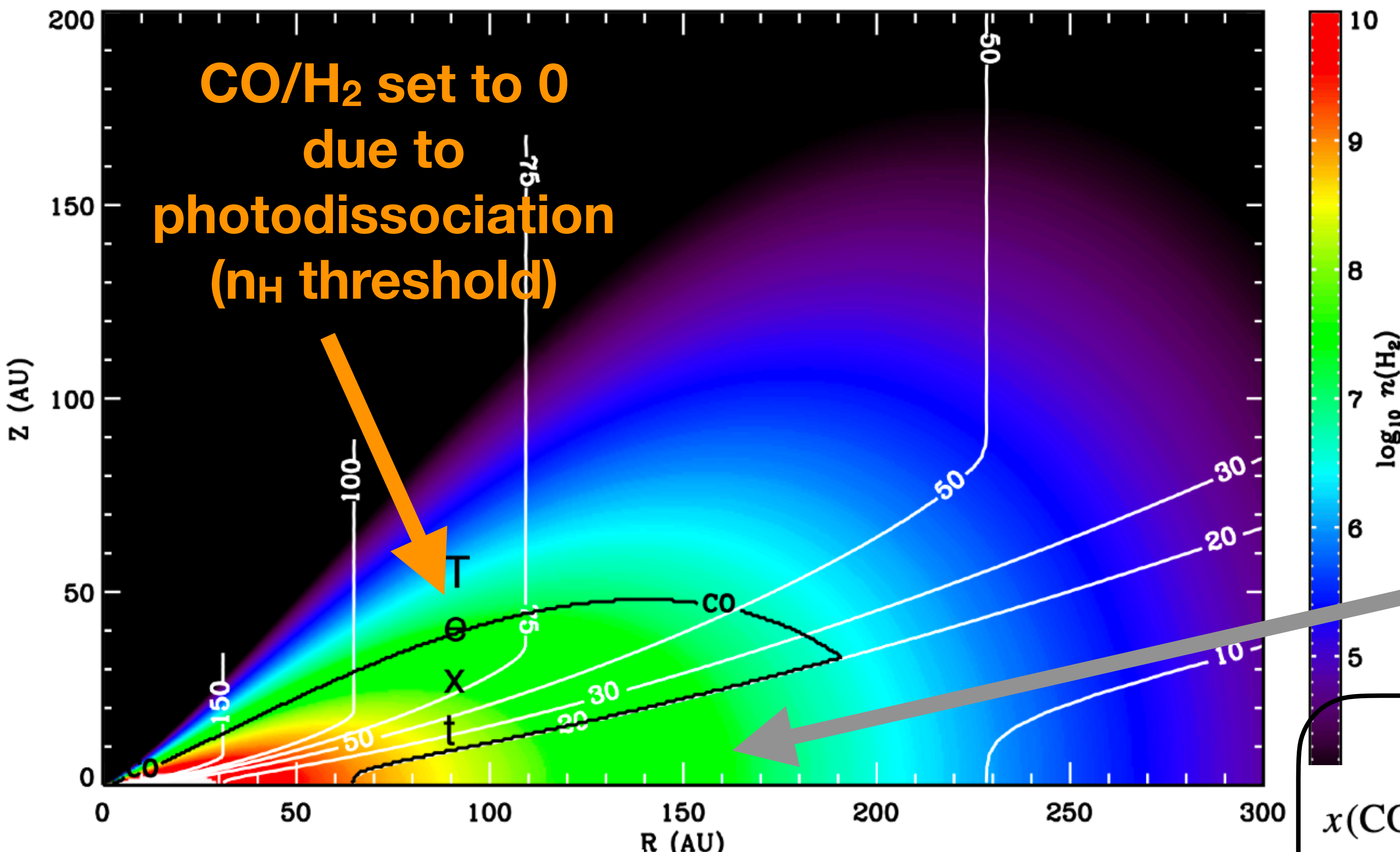
Decoupling gas/dust, except in midplane!

What if you don't have access to (or time for) a fancy chemical disk model?

Calahan et al. 2021 (MAPS)

Parametrized disk model

Alternative without physical-chemical model



Gas density

$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_c}\right)^{-\gamma} \exp\left[-\left(\frac{r}{r_c}\right)^{2-\gamma}\right]$$

$$\frac{\partial \ln \rho}{\partial z} = -\left[\left(\frac{G M_{\rm star} z}{(r^2+z^2)^{3/2}}\right)\left(\frac{\mu m_{\rm H}}{kT}\right) + \frac{\partial \ln T}{\partial z}\right]$$

Molecular abundance (CO)

$$x(\mathrm{CO}) = [\mathrm{CO}]/[\mathrm{H_2}] = \begin{cases} 1\times 10^{-4} & \text{where } T > 20\,\mathrm{K} \text{ and } N_{\rm H_2} > N_{\rm dissoc} \\ 0 & \text{elsewhere.} \end{cases}$$

Gas temperature

$$T_{\rm mid}(r) = T_{\rm mid,1}\left(\frac{r}{1\,\mathrm{AU}}\right)^{-q}$$

$$T_{\rm atm}(r) = T_{\rm atm,1}\left(\frac{r}{1\,\mathrm{AU}}\right)^{-q}$$

$$T(r,z) = \begin{cases} T_{\rm mid} + (T_{\rm atm} - T_{\rm mid})\left[\sin\left(\frac{\pi z}{2 z_q}\right)\right]^{2\delta} & \text{if } z < z_q \\ T_{\rm atm} & \text{if } z \geqslant z_q \end{cases}$$

=> Remaining steps: excitation + ray-trace! (e.g. RADMC-3D)

Williams & Best 2014

Molecular excitation

Usual assumption: LTE

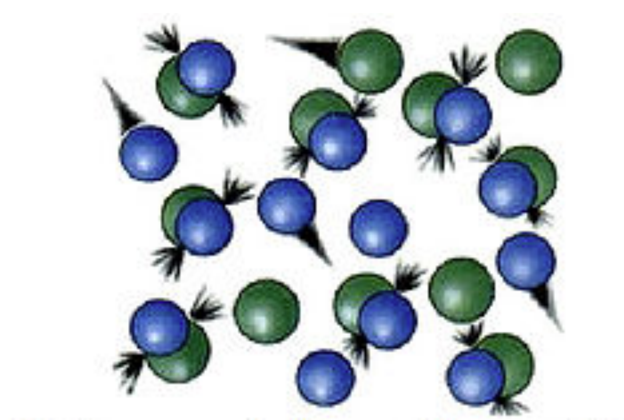
When density > n_{crit} of the molecule, Local Thermodynamic Equilibrium (LTE):
collisions lead to excitation and spontaneous emission photon: **Boltzmann distribution**

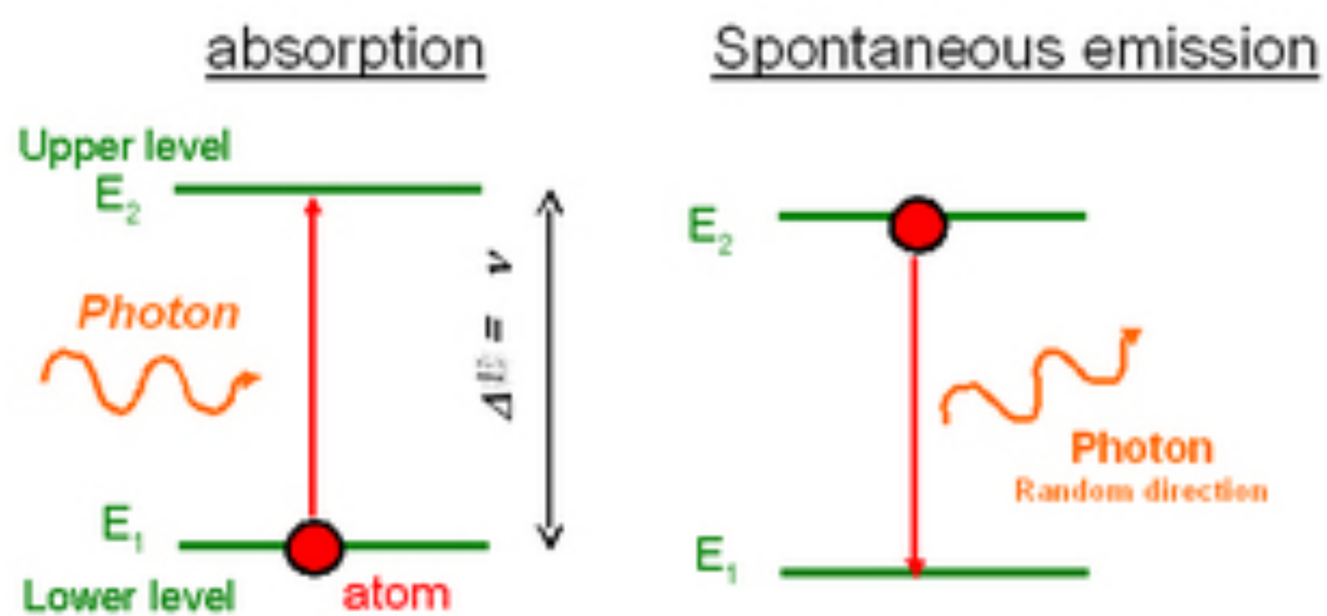
$$\frac{n_u}{n_l} = \frac{g_u}{g_l}\exp\left(-h\nu / kT_{ex}\right)$$

$$= \frac{g_u}{g_l}\exp\left(-(E_u - E_l)/kT_{ex}\right)$$

g = degeneracy of energy level

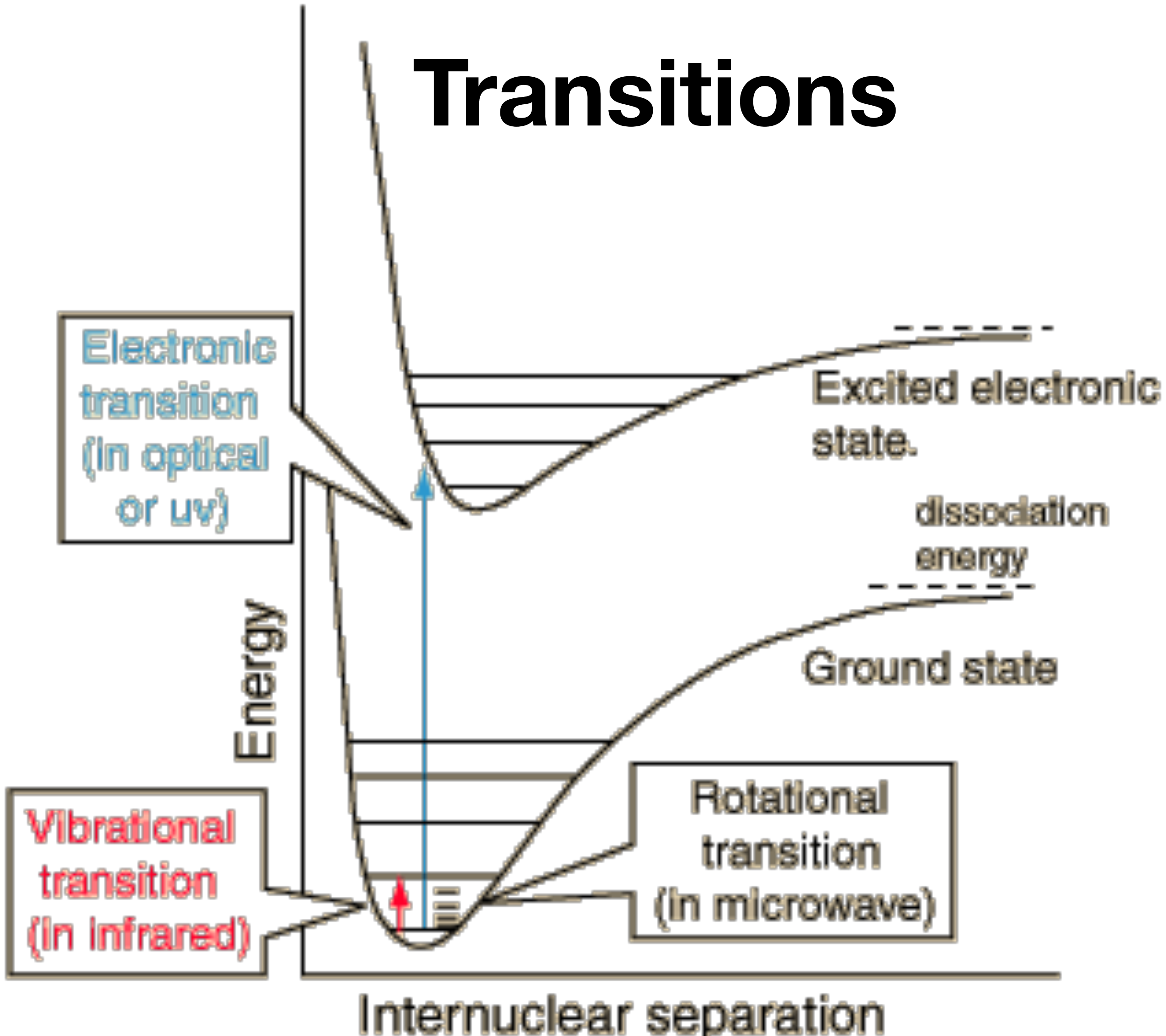
Example ^{12}CO:
J=1-0: 115.271 GHz, E_u=5.5 K
J=2-1: 230.538 GHz, E_u=17 K
J=3-2: 345.596 GHz, E_u=33 K
..
J=6-5: 691.473 GHz, E_u=116 K





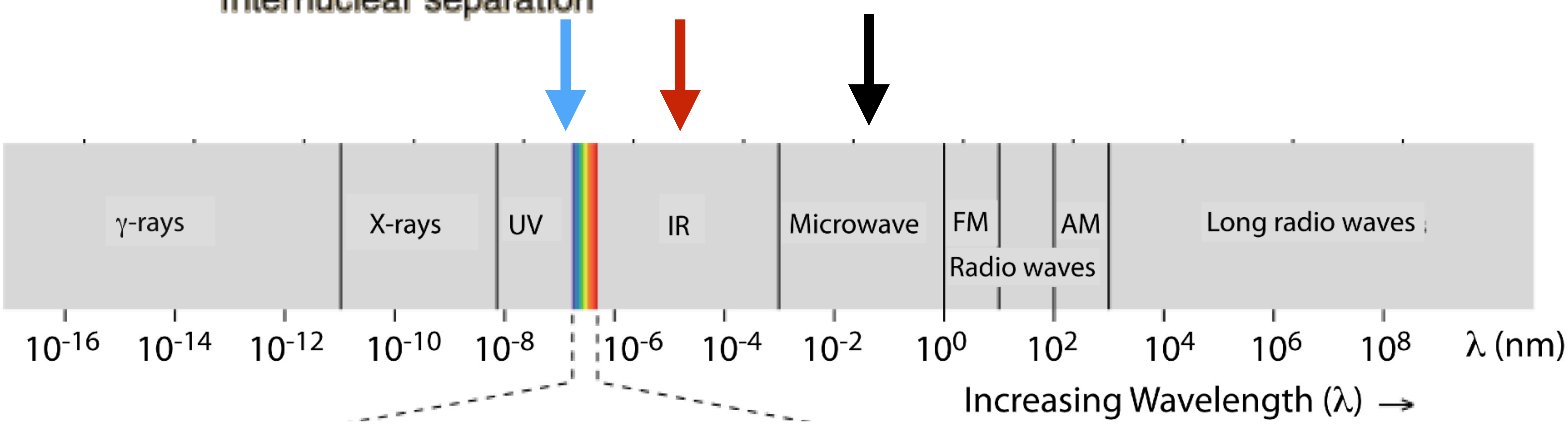
Find transitions + frequencies:
http://www.splatalogue.net

Molecular excitation



ALMA sub-mm/mm:
=> rotational transitions
(often low-T, <500K)

Infrared (e.g. JWST, Spitzer, CRIRES)
=> vibrational and rovibrational
(often high-T, >1000K)



Molecular excitation

Computing column from flux

1. Calculate N_u (column density of the upper energy population level), using the **integrated line flux**

Flux linewidth

$$N_u^{\text{thin}} = \frac{4\pi S_\nu \Delta v}{A_{ul}\Omega hc}$$

Emitting area

The rate of spontaneous emission is set by the Einstein coefficient A_{ul} (property of transition)

2. Calculate N_T (total column density of a molecule) using the energy level **E_u**, the partition function **Q(T)** (summing over all N_u/N_l combinations) and an **assumed temperature T_{rot}**

$$\frac{N_u}{g_u} = \frac{N_T}{Q(T_{\text{rot}})} e^{-E_u/kT_{\text{rot}}}$$

Q(T) is a property of the molecule

Constant T

=> only works for a small disk region

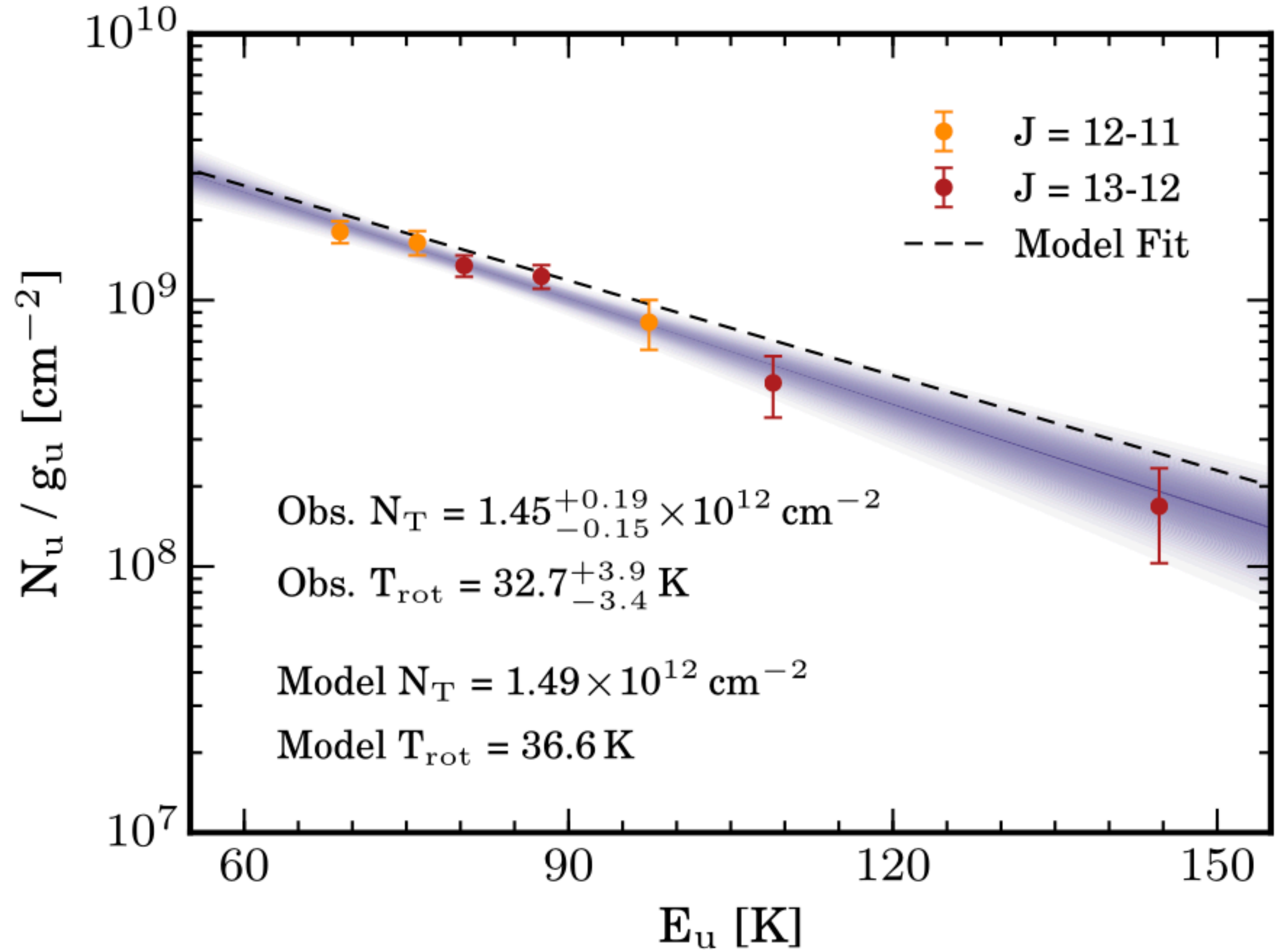
Find E_u, A_{ul}, $Q(T_{rot})$ for each molecular transition on
http://www.splatalogue.net

See Loomis et al. 2018

Molecular excitation

Rotational diagram

If you have **multiple transitions** of a **slab of material** (single T and n)**:**
Compute N_T and T_{rot} using a
linear fitting procedure
<u>a rotational diagram</u>
(Technique from clouds)



$$\frac{N_u}{g_u} = \frac{N_T}{Q(T_{\rm rot})} e^{-E_u/kT_{\rm rot}}$$

Take logarithm:

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N}{Q(T)}\right) - \frac{E_u}{kT} = -\frac{1}{T}\frac{E_u[\mathrm{erg}]}{k} + ln\left(\frac{N}{Q(T)}\right)$$

$$\underbrace{\ln\left(\frac{N_u}{g_u}\right)}_{y} = \underbrace{-\frac{1}{T}}_{a}\ \underbrace{E_u[\mathrm{K}]}_{x} + \underbrace{\ln\left(\frac{N}{Q(T)}\right)}_{b}$$

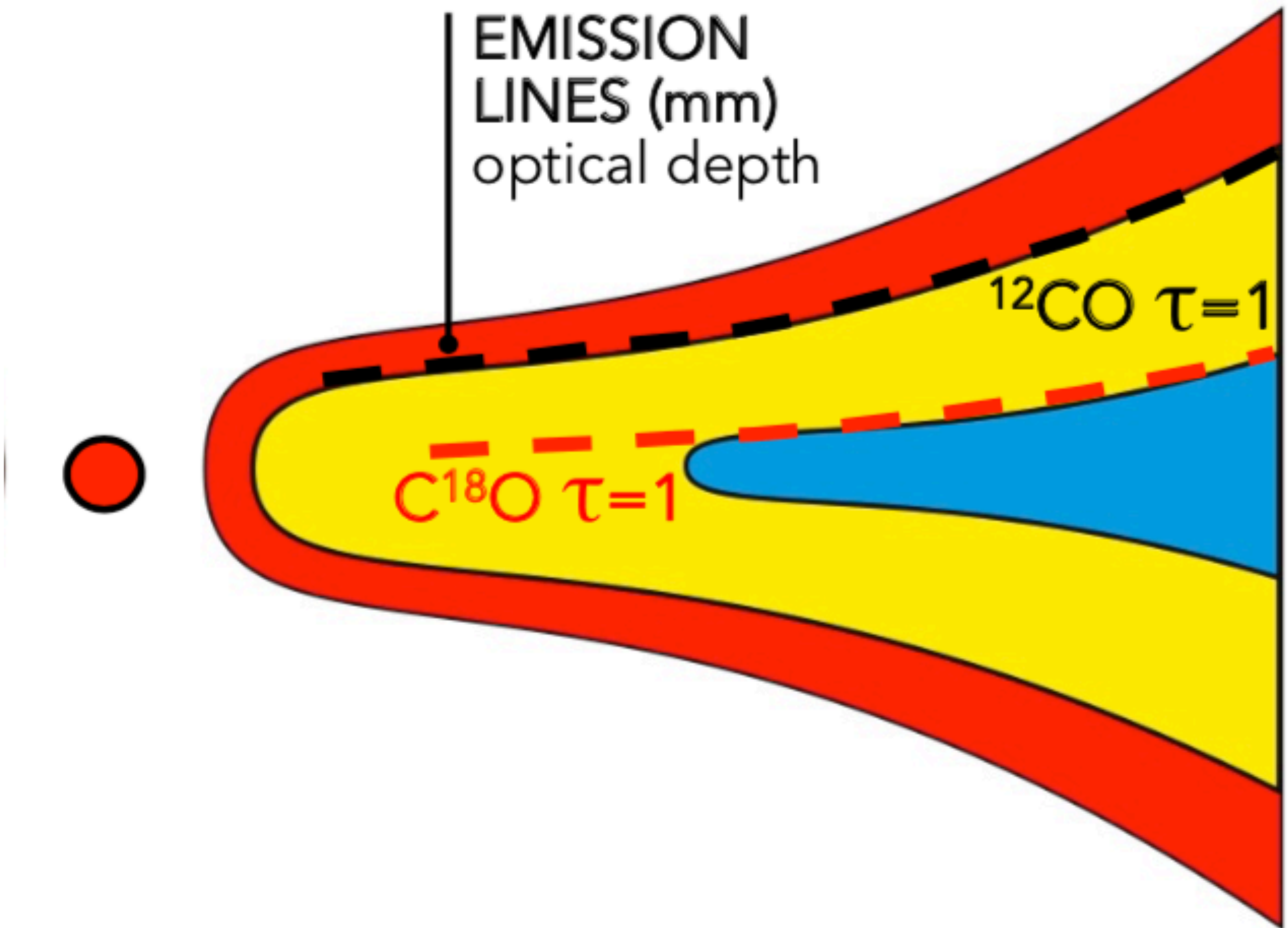
From obs. line flux

Fit: column density *N* and temperature *T*
=> only works for a small disk region

See Loomis et al. 2018

Optical depth

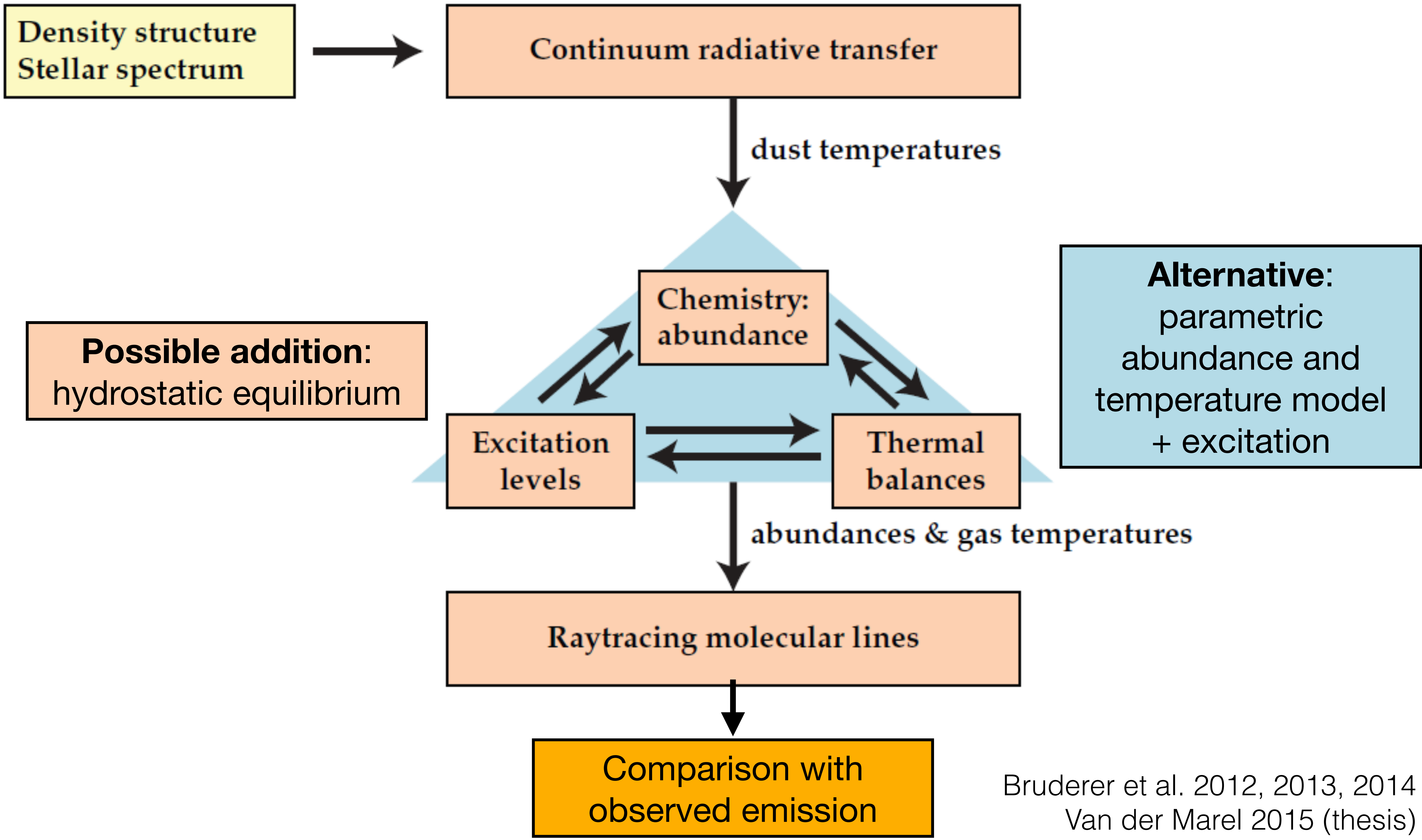
Example: CO isotopologues



- ^{12}CO 1
- ^{13}CO 1/68
- $C^{18}O$ 1/560

Full procedure molecular line emission

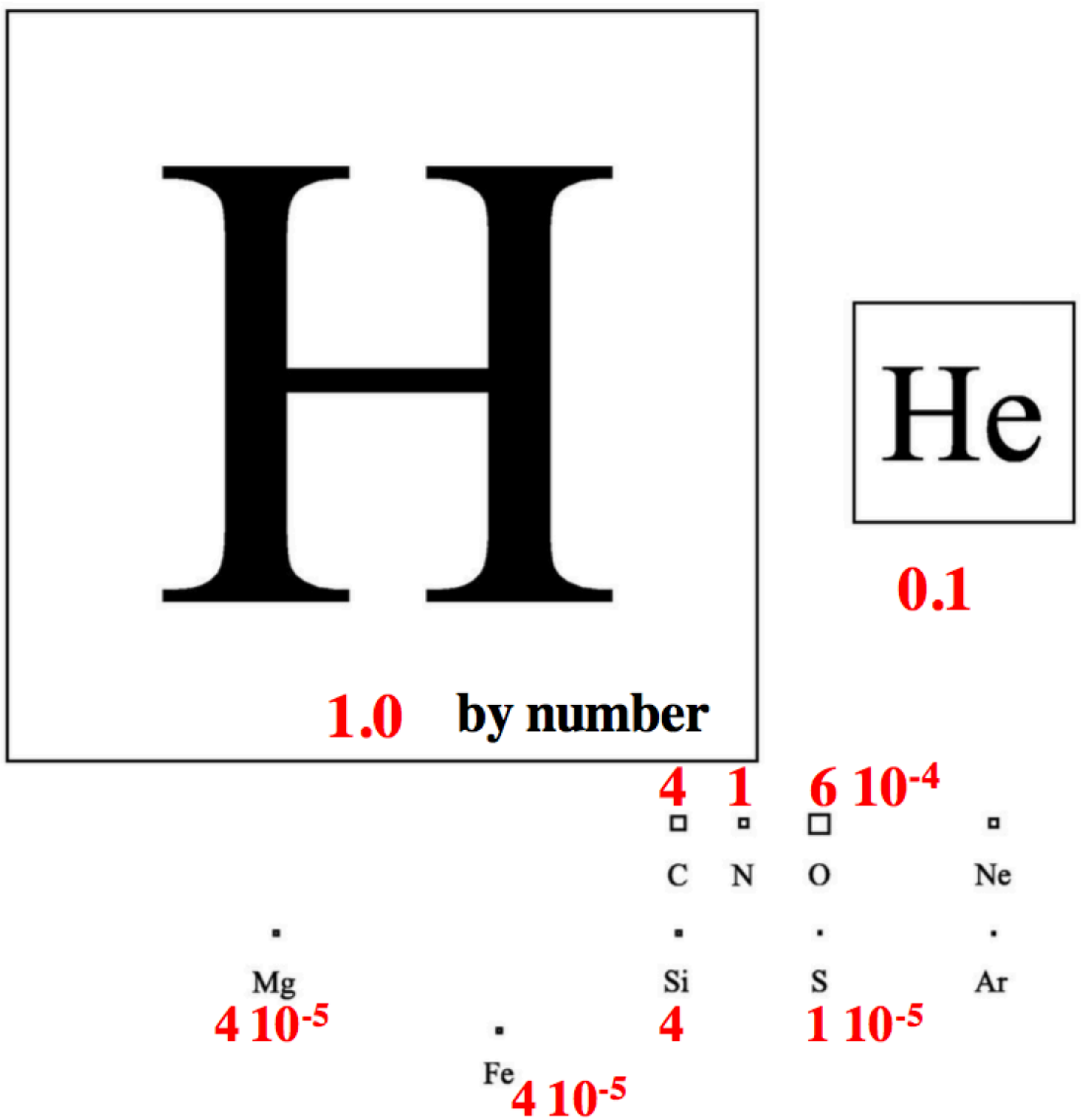
Example: DALI (ProDiMo/RAC2D)



Bruderer et al. 2012, 2013, 2014
Van der Marel 2015 (thesis)

Molecules

Periodical table of the Universe:



Simple molecules:
- H_2

- CO
- CO_2
- H_2O
- CN
- OH
- CH^+
- HCO^+
- H_2CO
- …

Molecules in disks

Observed so far (infrared + (sub-)mm)

Table 6
List of Molecules, Including Rare Isotopic Species, Detected in Protoplanetary Disks, with References to Representative Detections

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	
Species	Ref.	Species	Ref.	Species	Ref.	Species	Ref.	Species	Ref.
CN	1, 2	H_2O	3, 4, 5	NH_3	6	HC_3N	7	CH_3OH	8
$C^{15}N$	9	HCO^+	1, 2	H_2CO	2	HCOOH	10	CH_3CN	11
CH^+	12	DCO^+	13	H_2CS	14, 15	c-C_3H_2	16		
OH	17, 5	$H^{13}CO^+$	18, 13	C_2H_2	19	CH_4	20		
CO	21	HCN	1, 2						
^{13}CO	22	DCN	23						
$C^{18}O$	24	$H^{13}CN$	25						
$C^{17}O$	26, 27	$H^{15}CN$	25						
$^{13}C^{18}O$	39								
$^{13}C^{17}O$	40								
H_2	28	HNC	2						
HD	29	DNC	14						
CS	30, 31, 32	H_2S	33						
$C^{34}S$	14, 15	N_2H^+	34, 35						
^{13}CS	14, 15	N_2D^+	36						
SO	37	C_2H	2						
		C_2D	14						
		CO_2	38						

Why do we target CO so often in ALMA observations?

McGuire 2022

Molecules in disks

Why is CO so often targeted?

- Most abundant w.r.t. H_2 (ISM: factor 10^{-4})
- Low critical density
- Brightest observed lines in disks in sub-mm
- Tracer of gas surface density and disk gas mass (kinda…)
- Chemical network relatively well-understood
- Photodissociation and self-shielding well-understood
- Low-temperature freeze-out (22-30 K): abundant in gas-phase
- Low-T excitation levels: E_{up} = 5,17,33,116 K for J=1-0,2-1,3-2,..,6-5
- Frequency transitions accessible in ALMA bands
- Isotopologues can be combined in single ALMA spectral setting: trace optical depth

Zhang et al. 2021 (MAPS)

CO observations

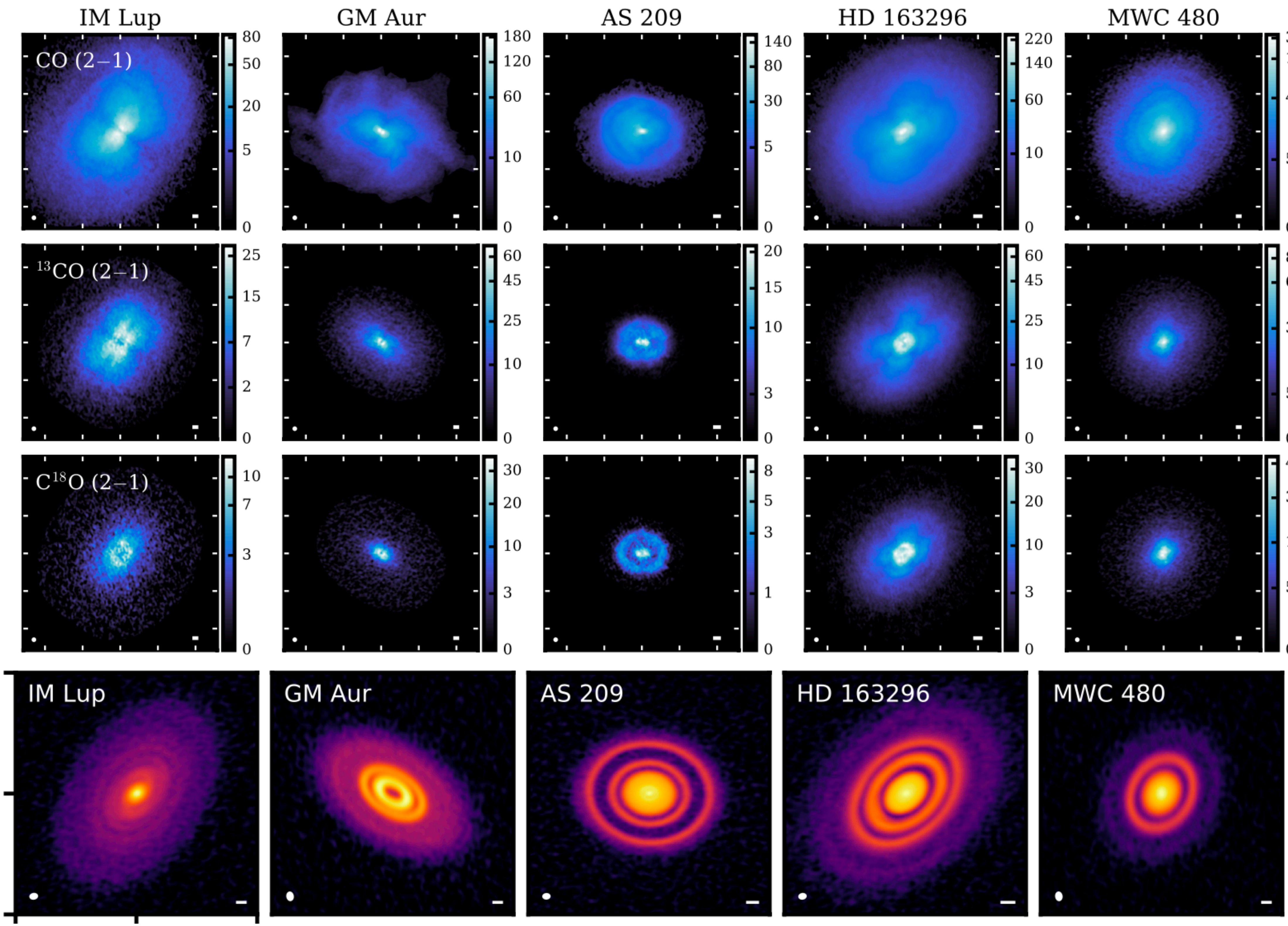
Examples full disks (MAPS)

^{12}CO 2-1

^{13}CO 2-1

$C^{18}O$ 2-1

Continuum



Zhang et al. 2021 (MAPS)

CO observations

What do you notice?

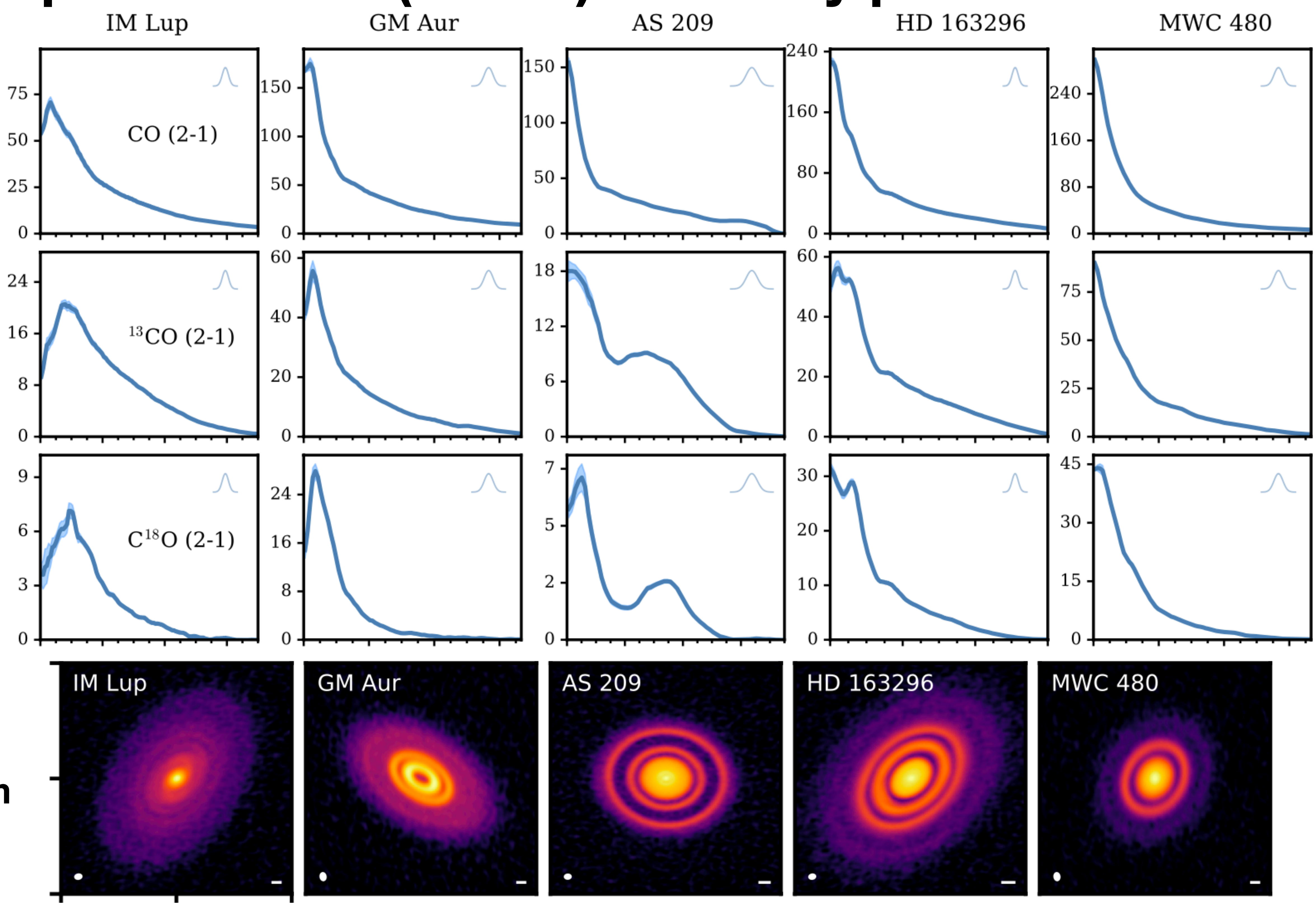
Example full disks (MAPS): intensity profiles

^{12}CO 2-1

^{13}CO 2-1

C^{18}O 2-1

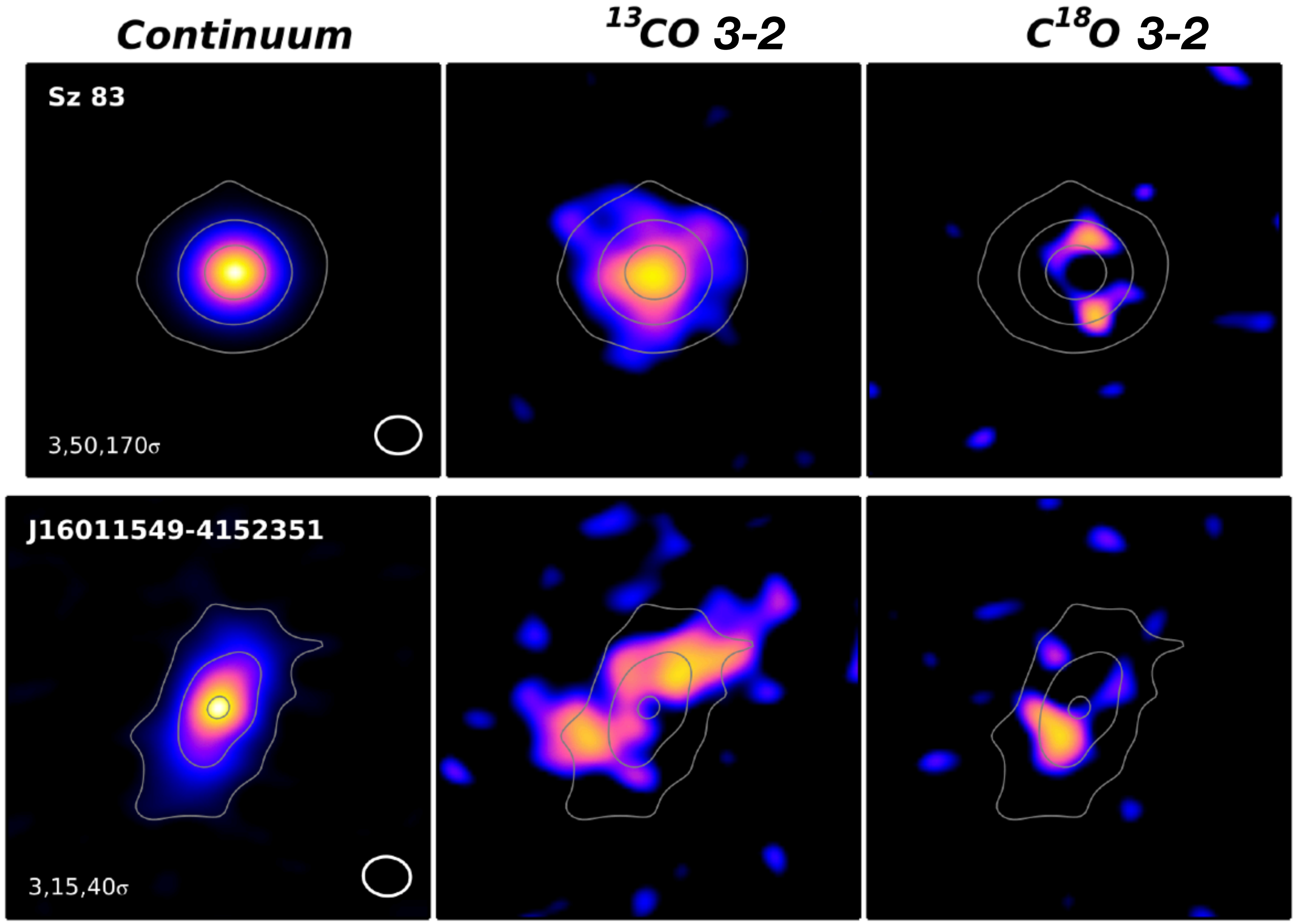
Continuum

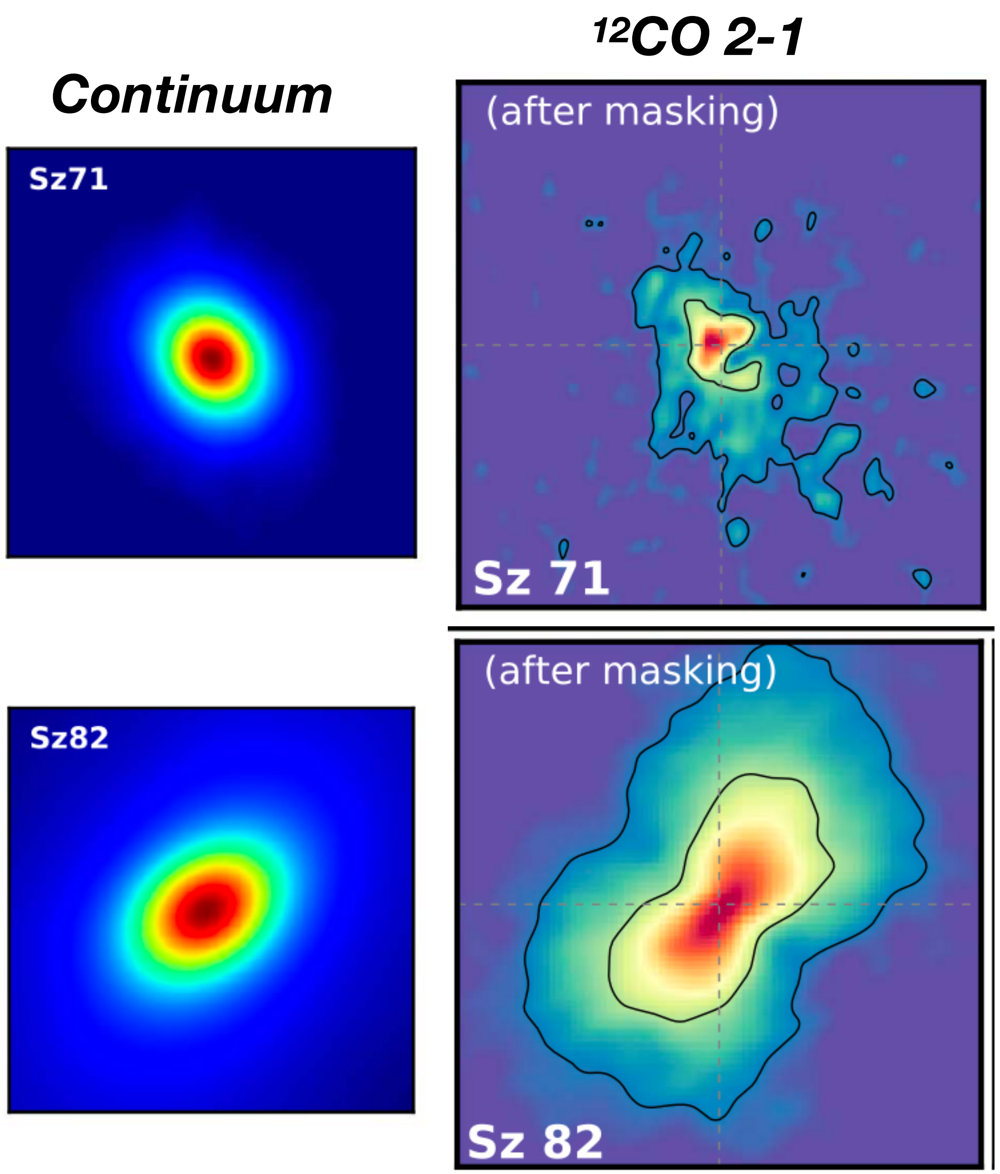


What do you notice?

CO observations

Example: full disks Lupus (shallow observations)





Difficult to detect emission in map, in particular the rarer isotopologues => often only disk integrated flux used for analysis

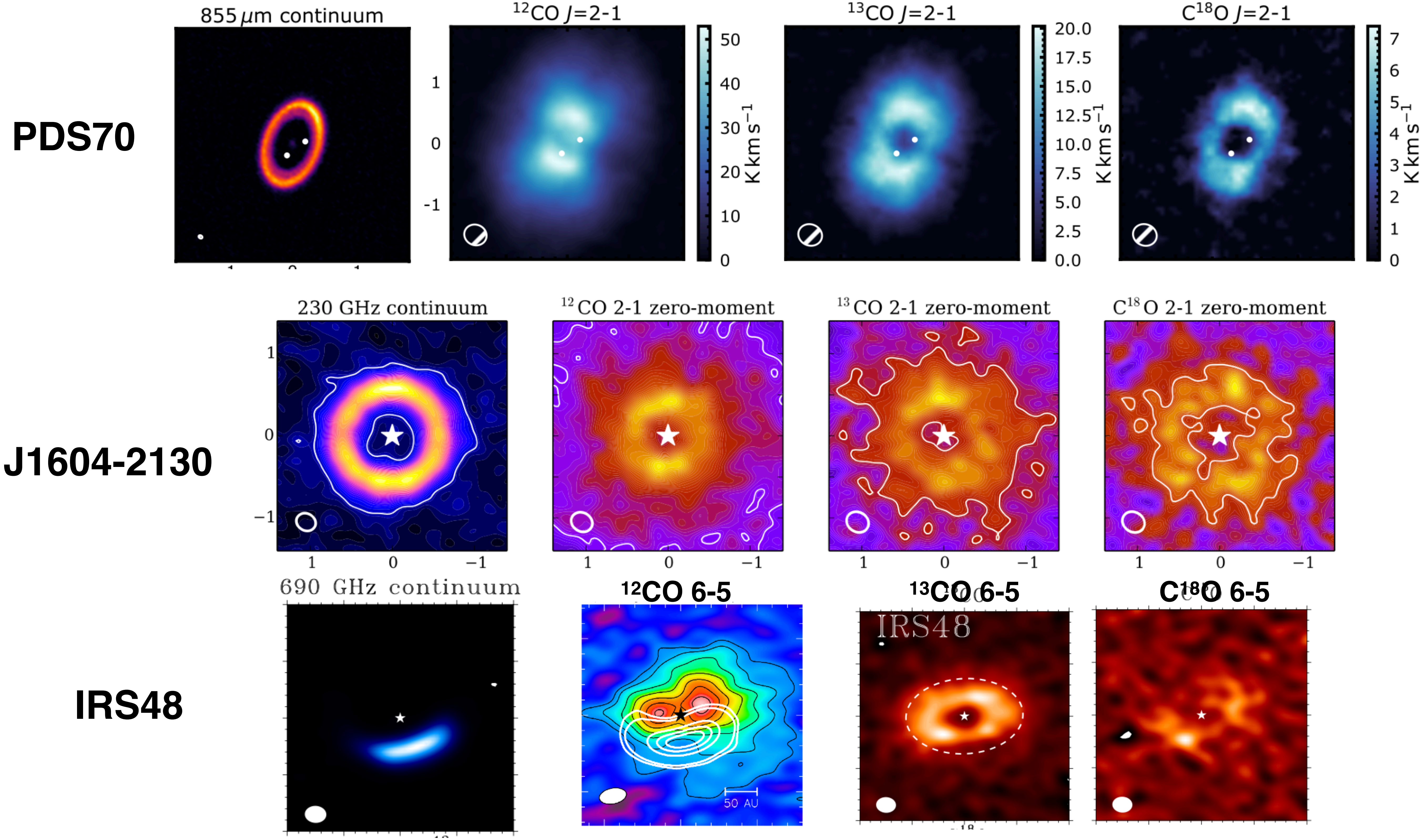
Ansdell et al. 2016, 2018

Facchini et al. 2021
Dong et al. 2017
van der Marel et al. 2016
Bruderer et al. 2014

CO observations

Example: transition disks

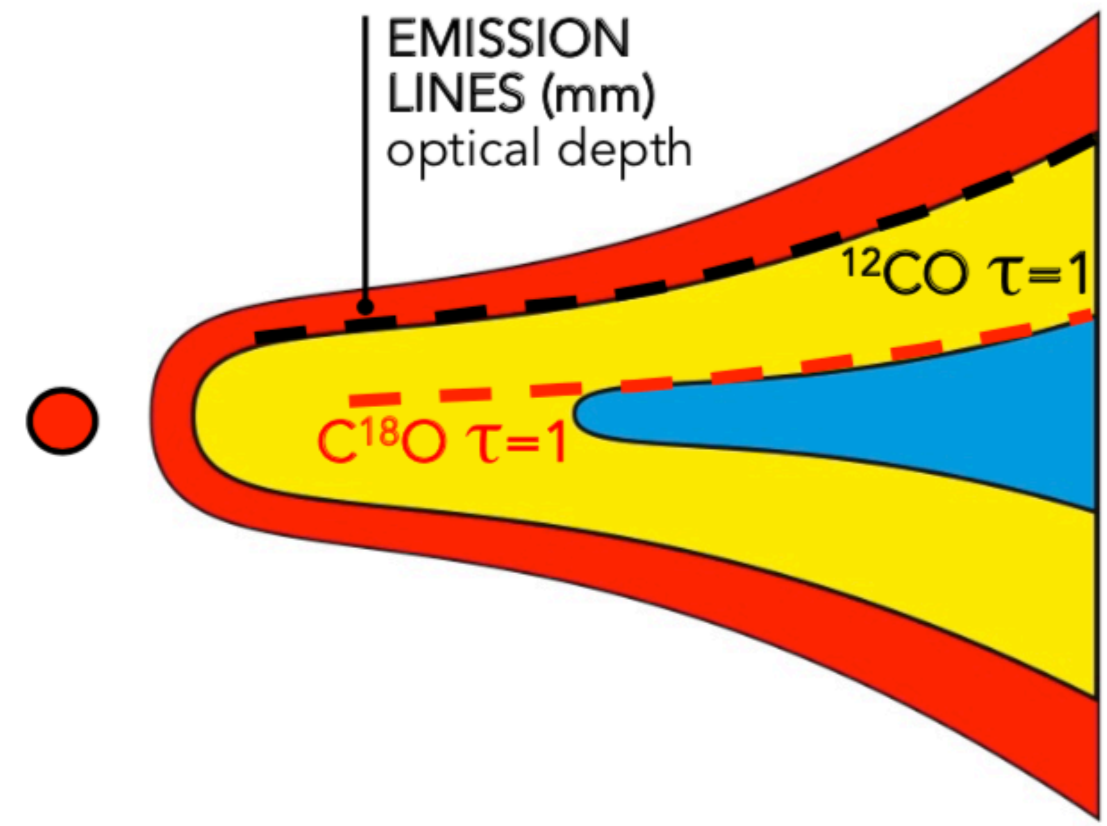
What do you notice?



CO observations

Evidence optical depth!

- The ^{12}CO emission is more radially extended than the other CO isotopologues
- Overall, emission decreases from ^{12}CO => ^{13}CO => $C^{18}O$
- Optical depth: $C^{18}O$ traces close to the midplane (‘optically thin’)
- Transition disks show an inner cavity in CO, smaller than dust cavity
- In transition disks, the CO gap size increases from ^{12}CO => ^{13}CO => $C^{18}O$
- CO emission is sometimes decreased at continuum peak (`continuum oversubtraction’)



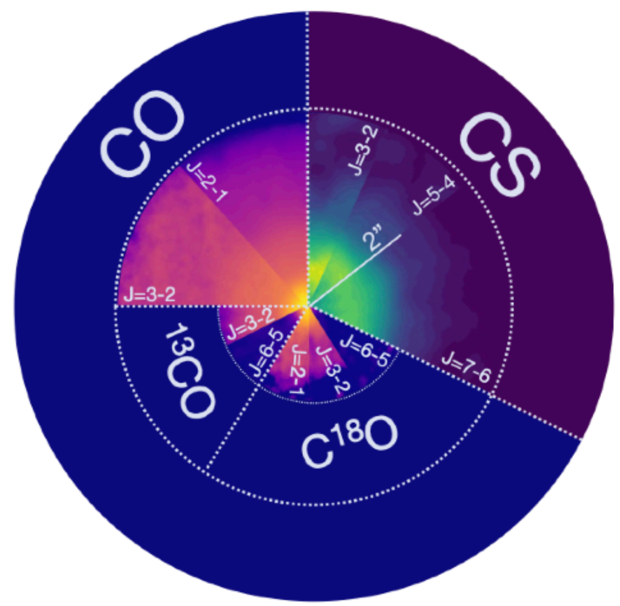
Disk gas mass

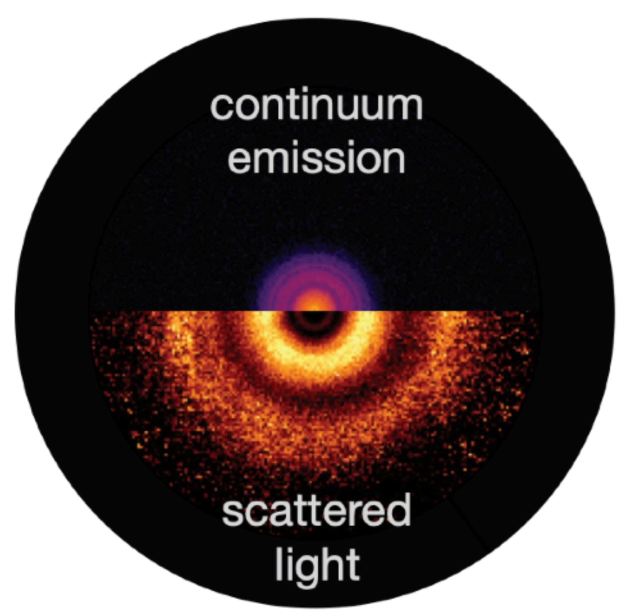
Motivation

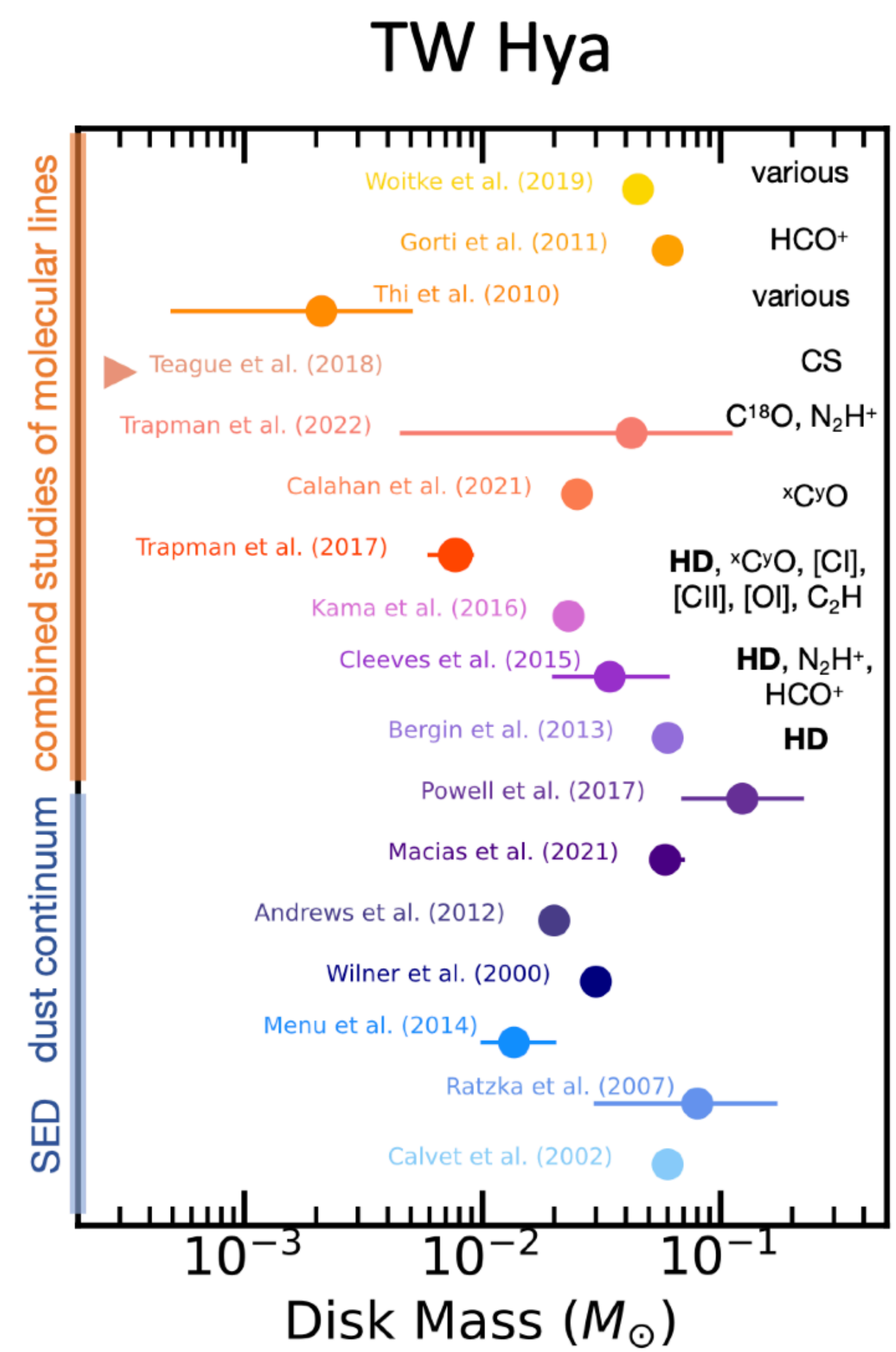
- Fundamental disk property: disk evolution, disk lifetime, planet formation processes

- Challenging to determine from line observations: wide range of outcomes

- Often used: **dust mass x 100** (ISM gas-to-dust-ratio)





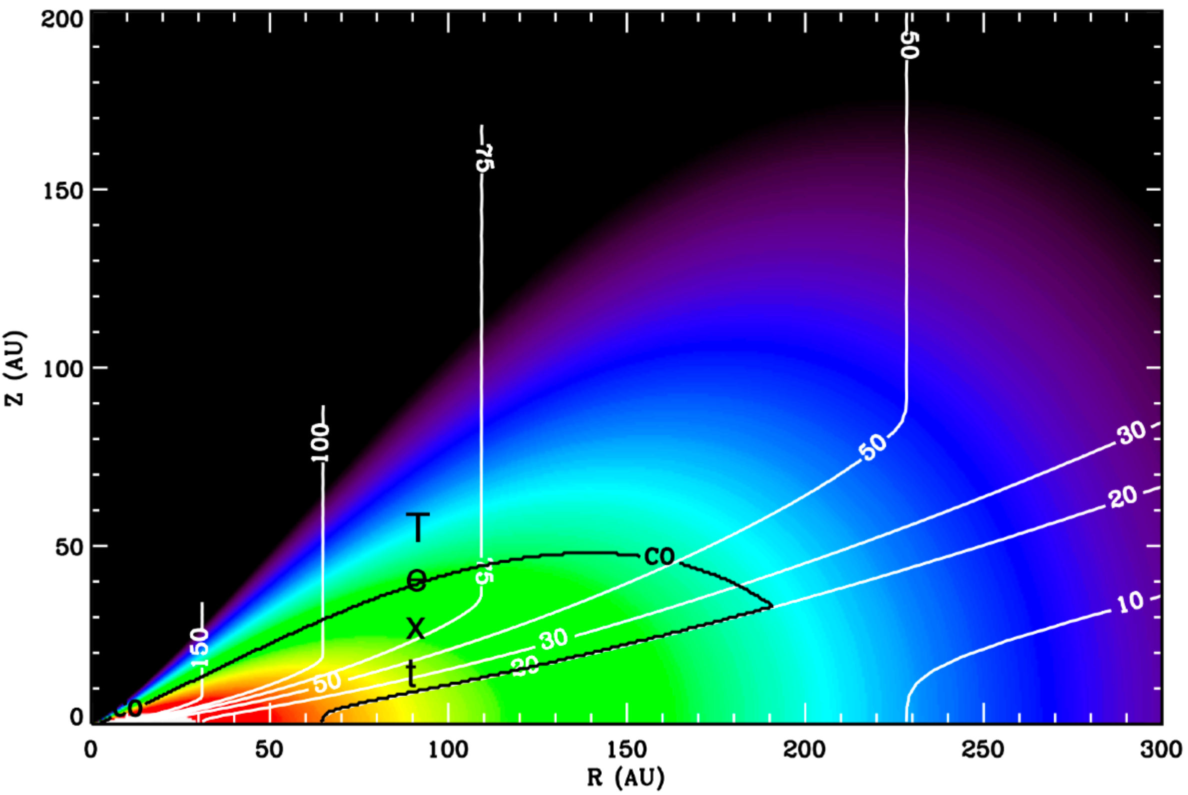


Why is this approach problematic?

Disk gas mass

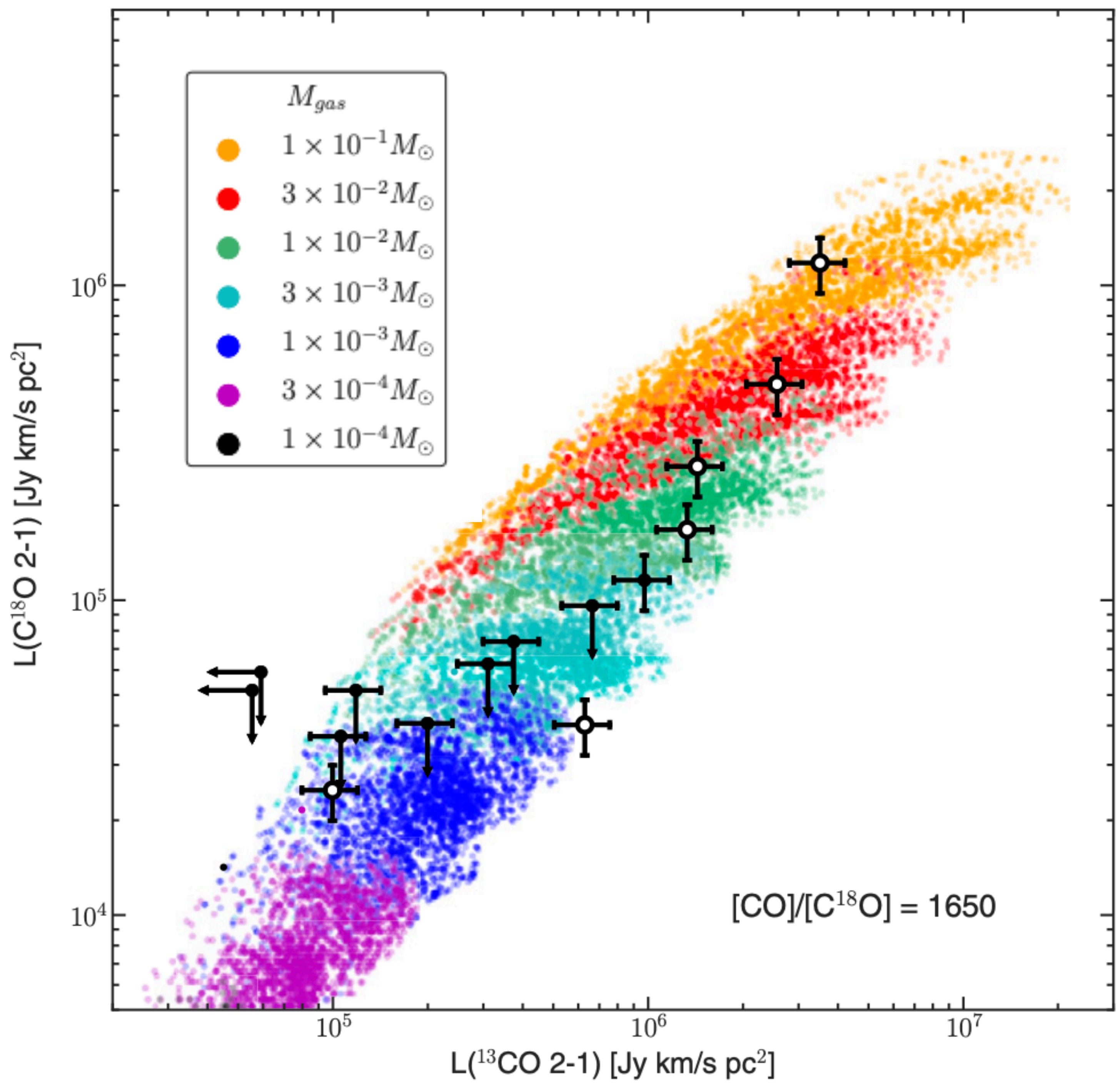
Using CO isotopologues

Recall parametric CO model:



Combination of integrated ^{13}CO and C^{18}O 2-1 flux gives estimate disk gas mass

Modeling grid

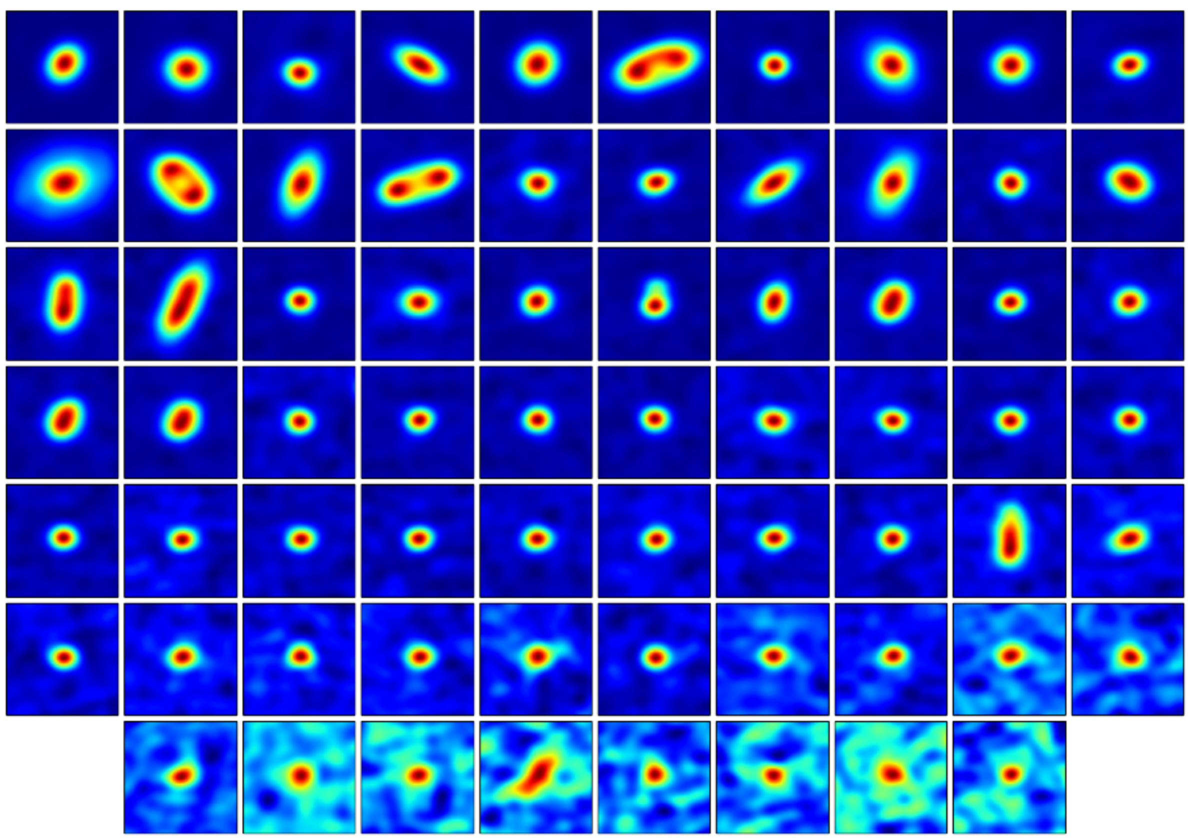


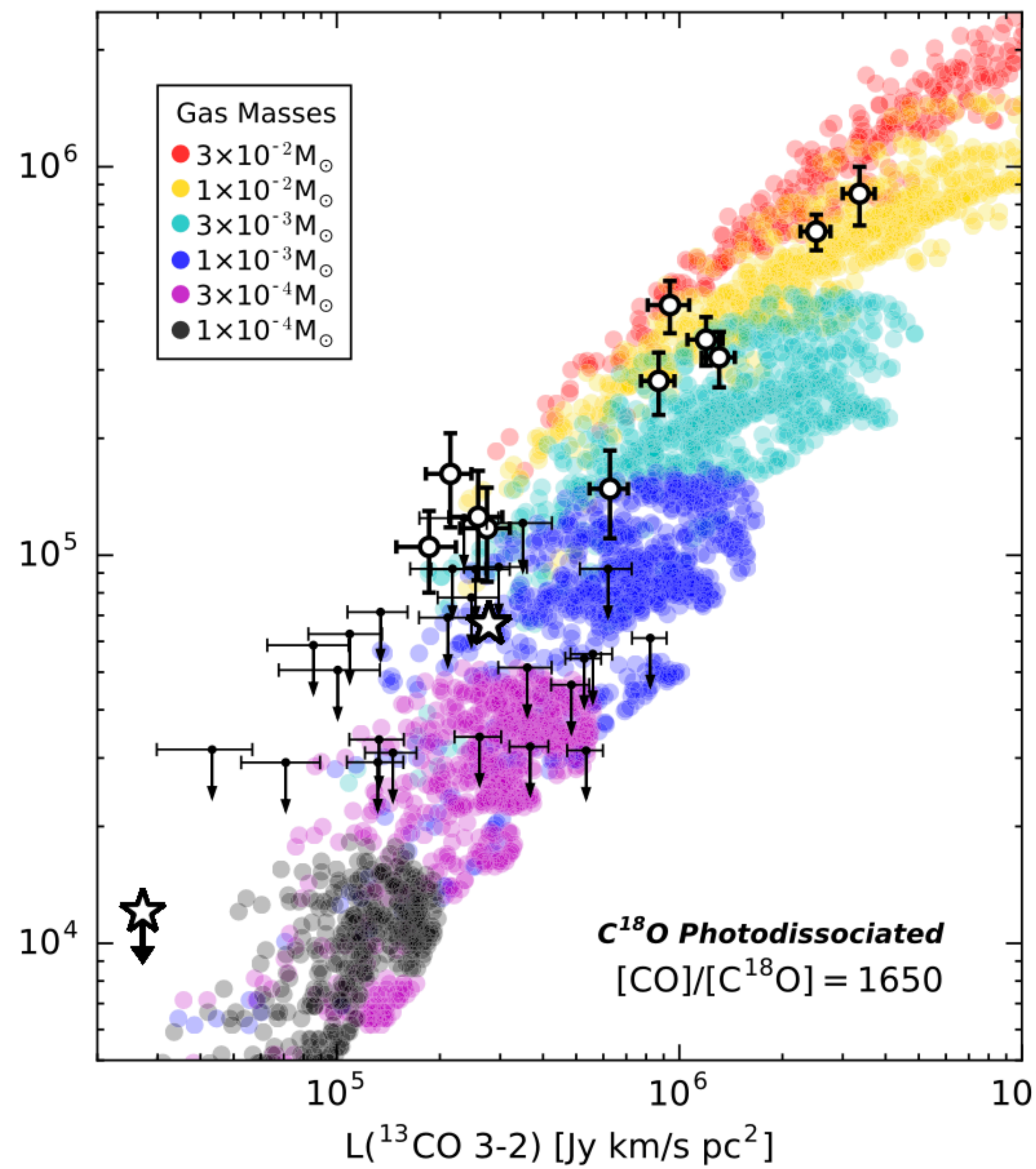
Williams & Best 2014

Disk gas mass

Using CO isotopologues (Lupus)

This model grid was applied to the line fluxes in the Lupus survey

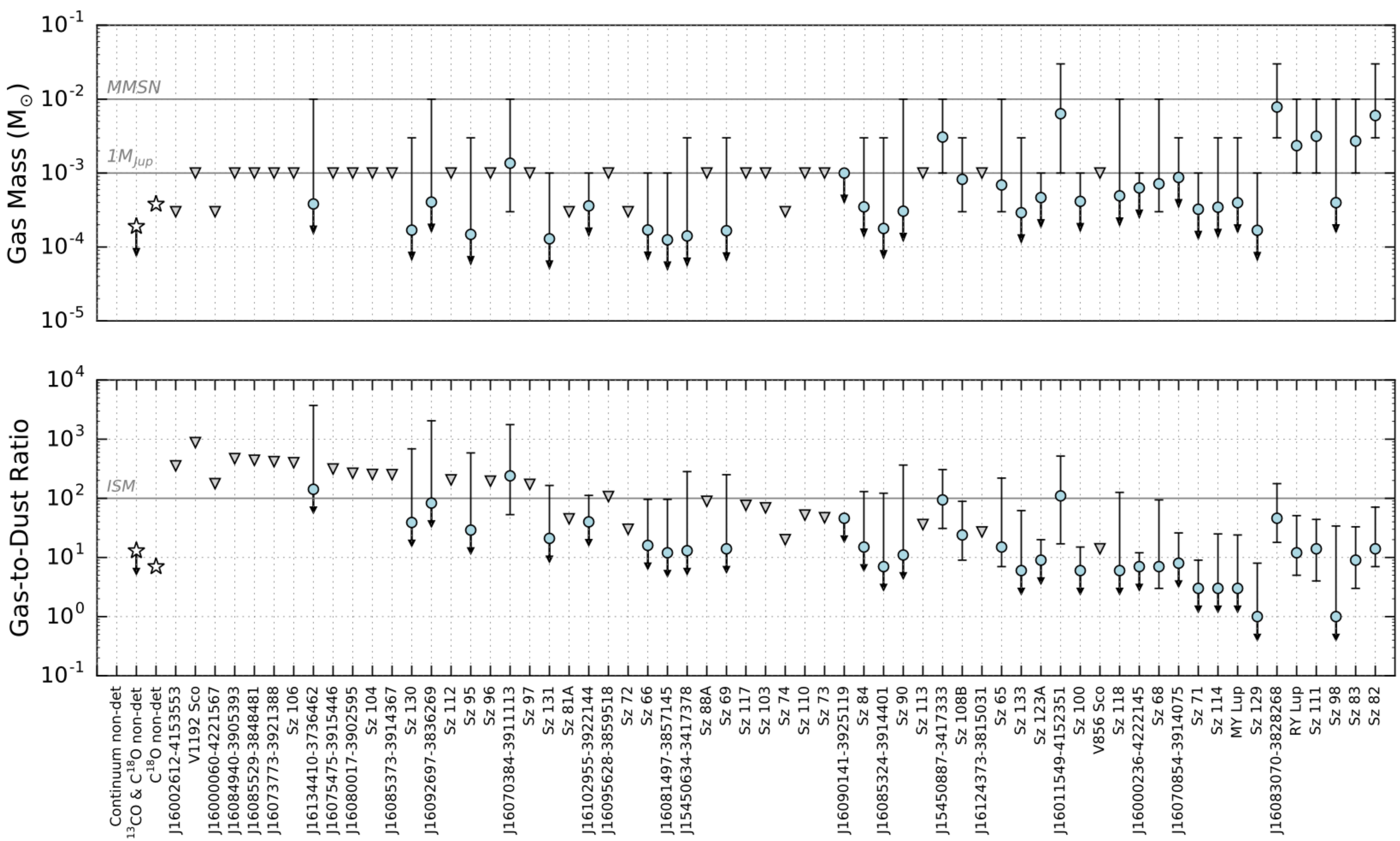




Ansdell et al. 2016

Disk gas mass

Using CO isotopologues (Lupus)

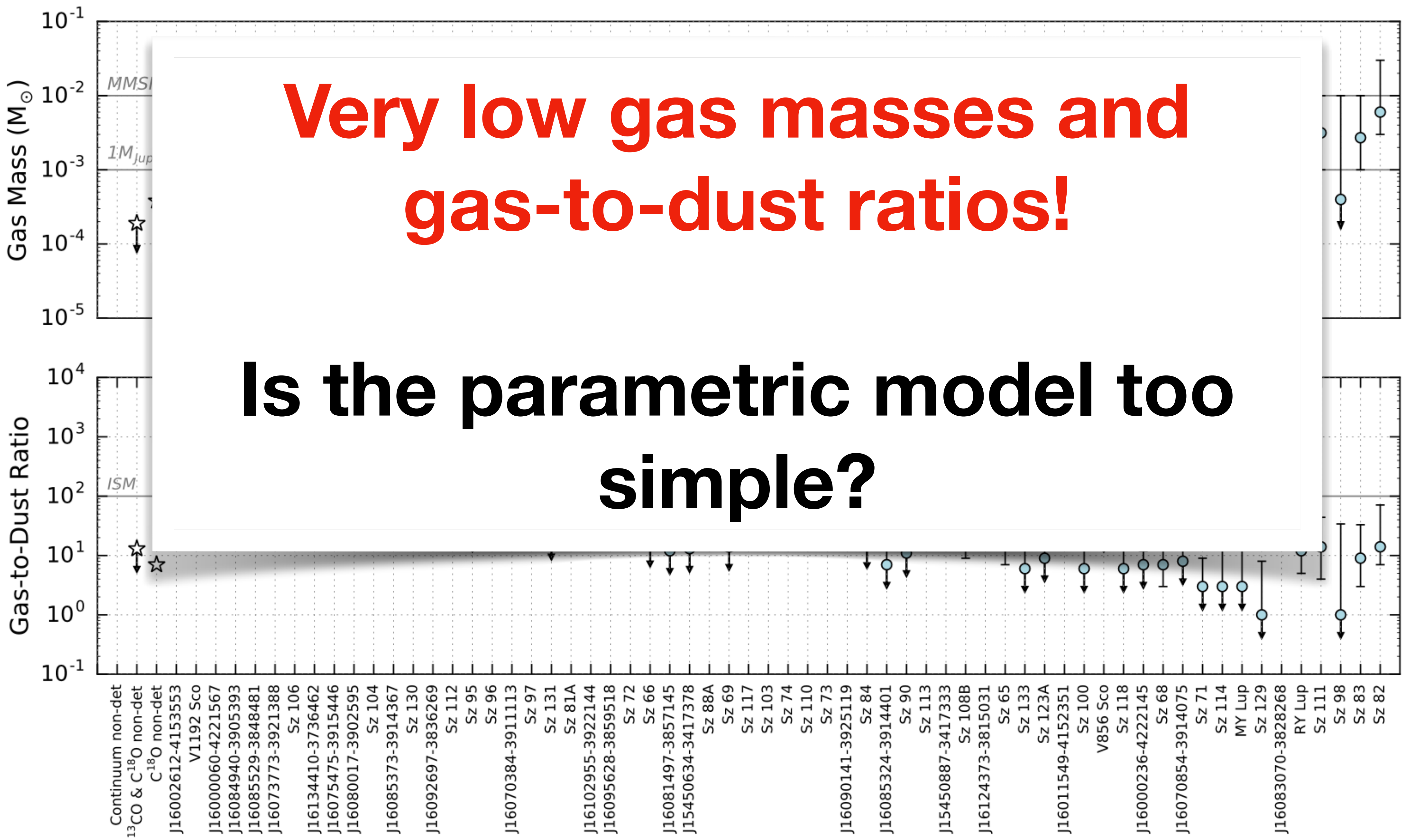


What do you notice?

Ansdell et al. 2016

Disk gas mass

Using CO isotopologues (Lupus)



Very low gas masses and gas-to-dust ratios!

Is the parametric model too simple?

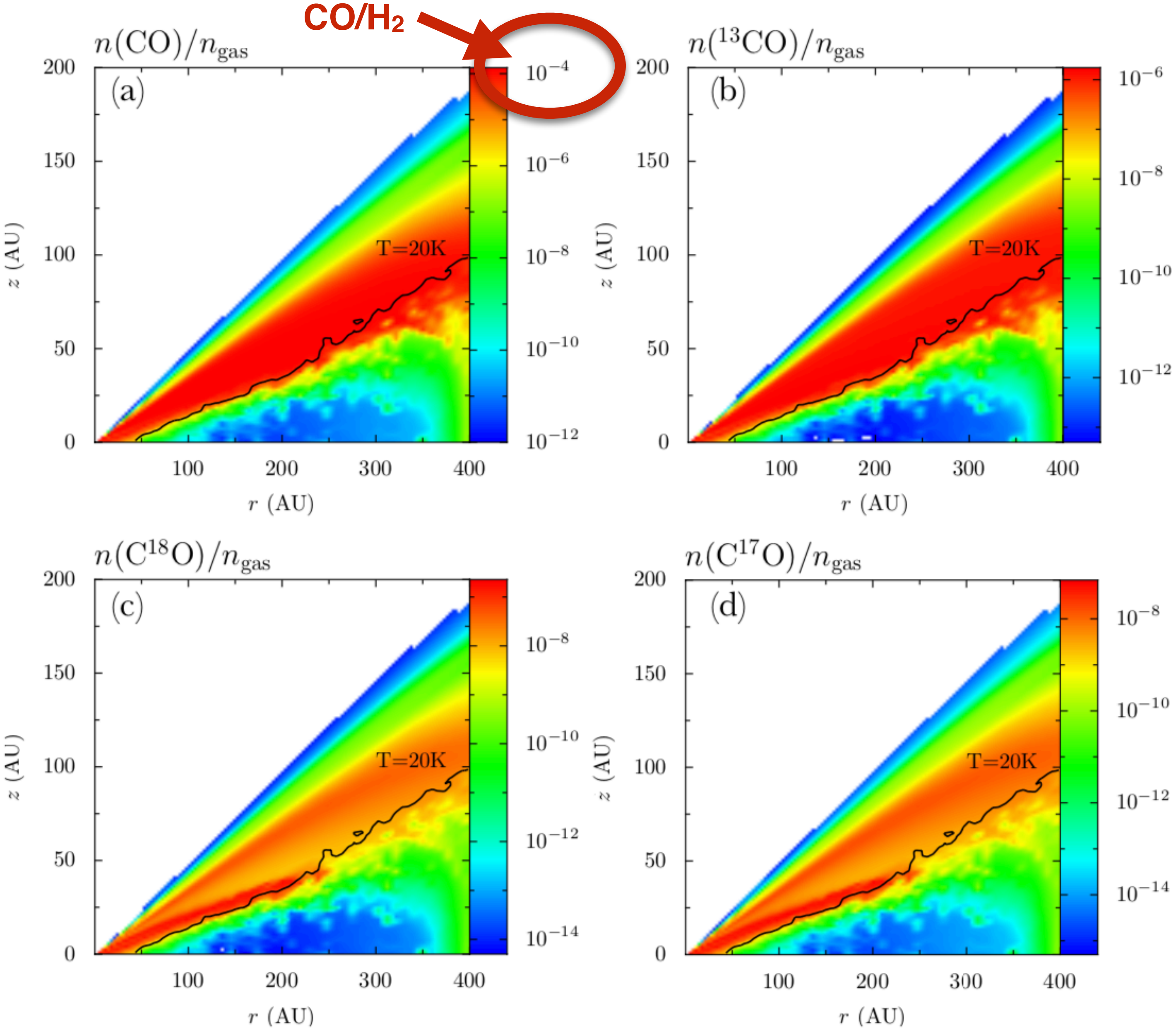
What do you notice?

Ansdell et al. 2016

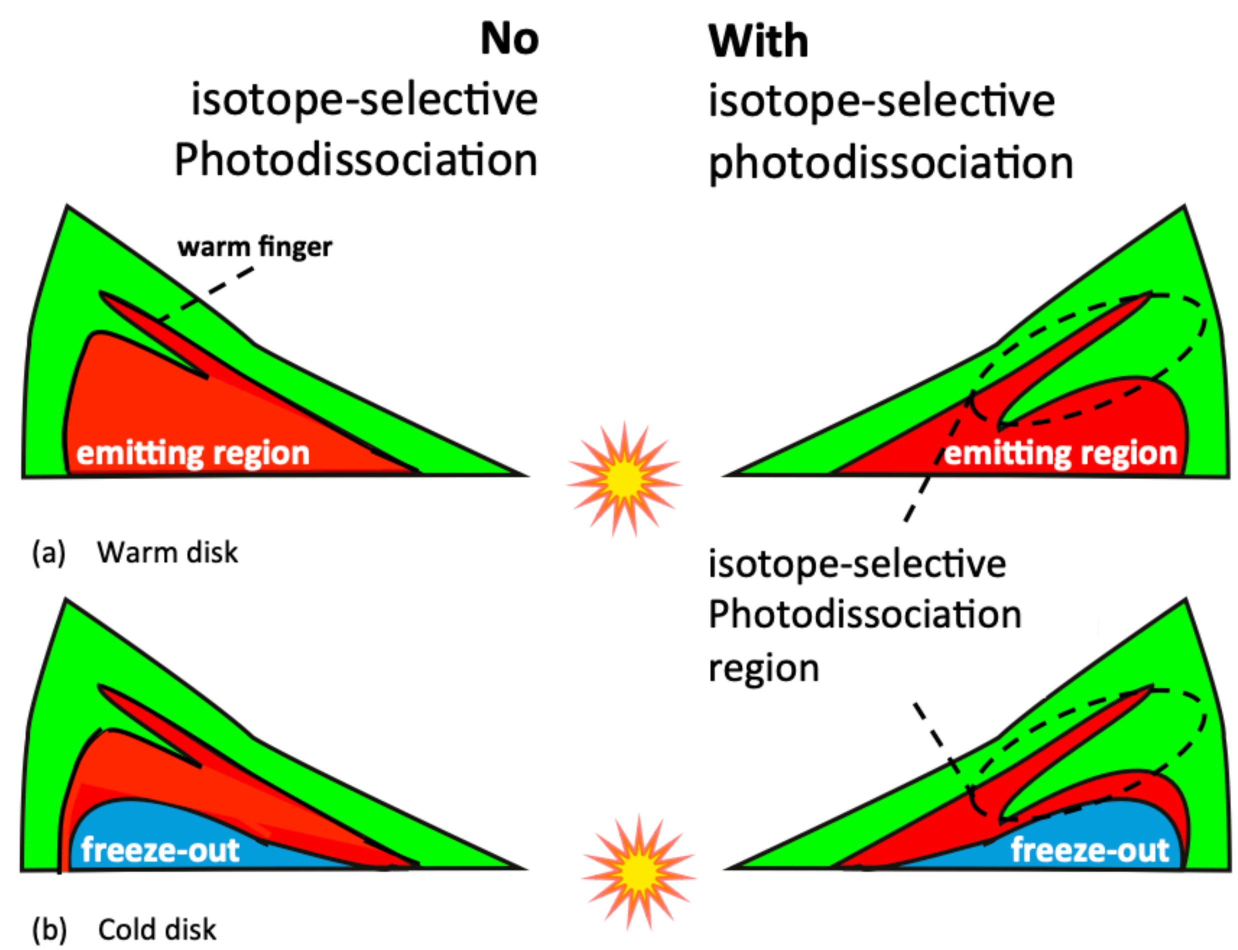
Disk gas mass

Using full physical-chemical modeling (DALI)

Typical value
CO/H_2



Additional effect:
Isotope-selective photodissociation:
photodissociation deeper into the disk surface for rarer isotopologues

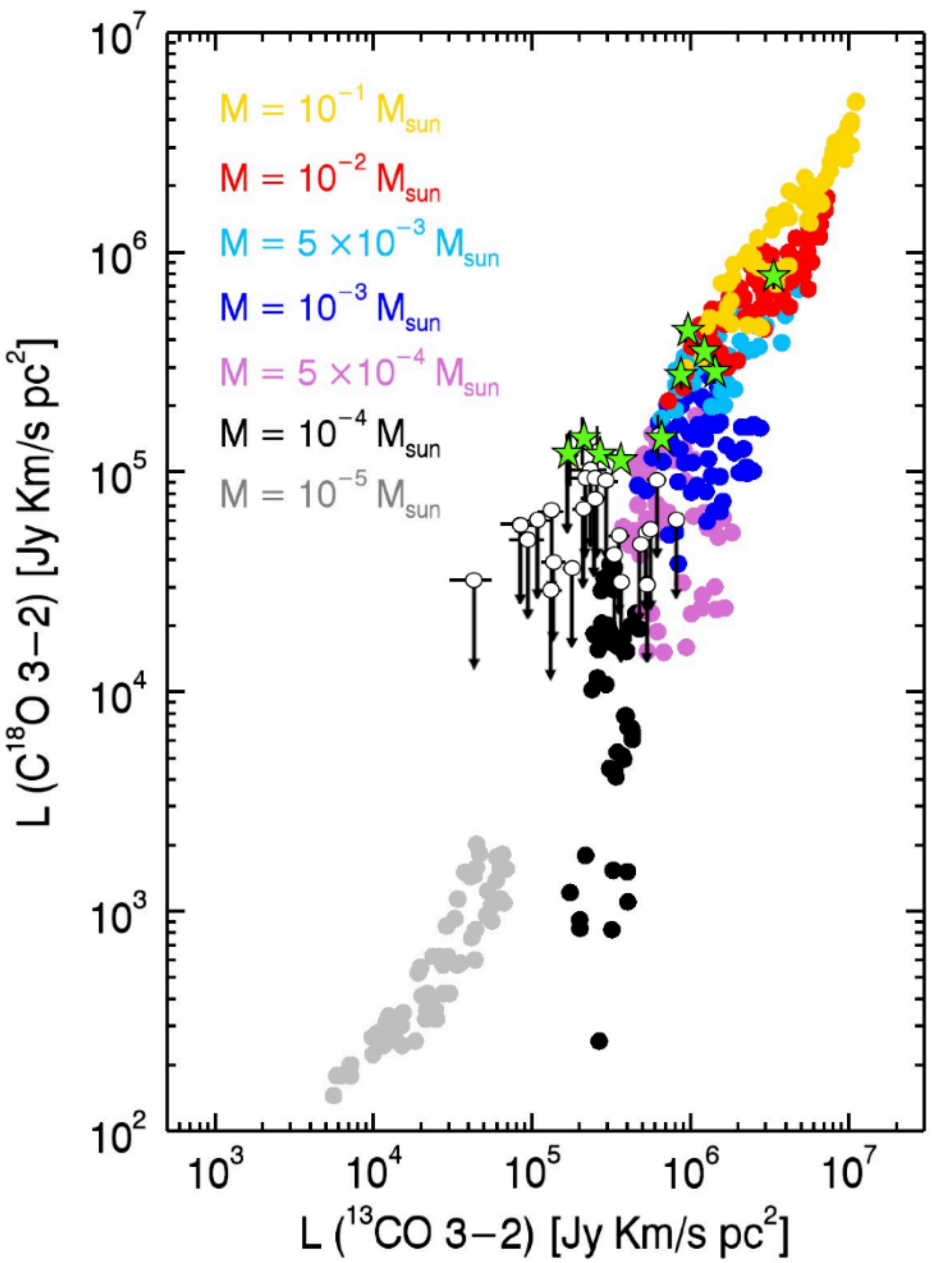


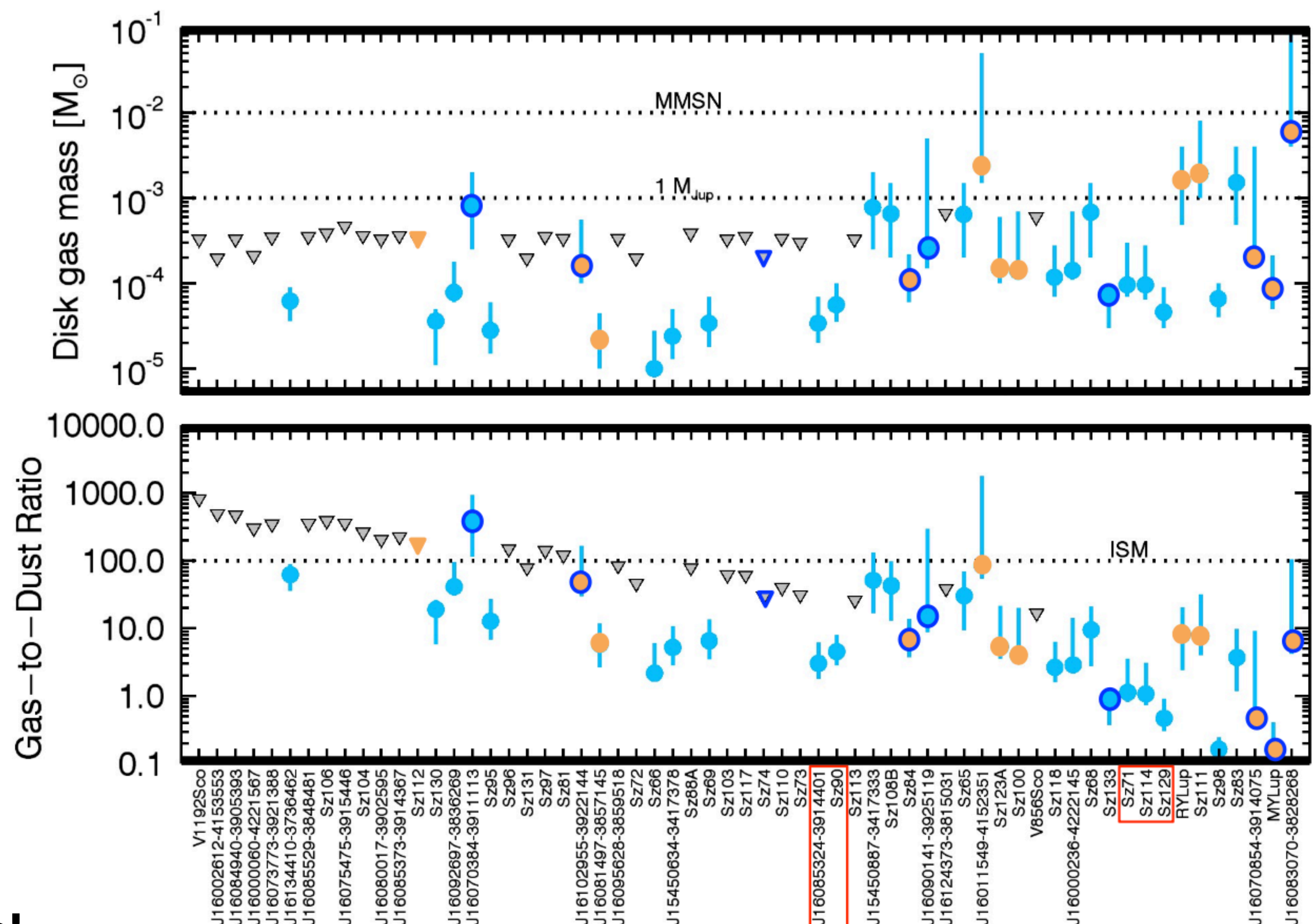
Again, grid of models to be compared with the Lupus data…

Miotello et al. 2014, 2016

Disk gas mass

Using full physical-chemical modeling (DALI)





Still low gas masses and GDRs!

Miotello et al. 2017

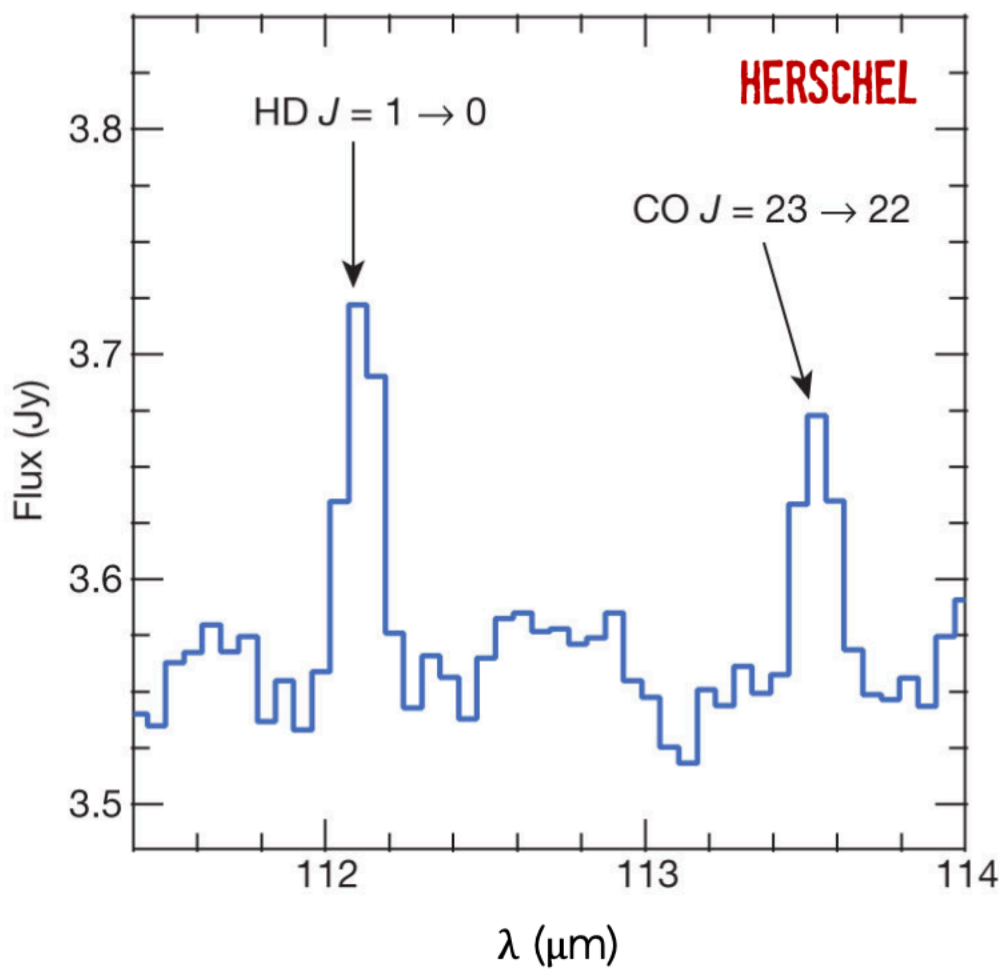
Is the gas already dissipated? Or is CO/H_2 ratio lower than ISM?

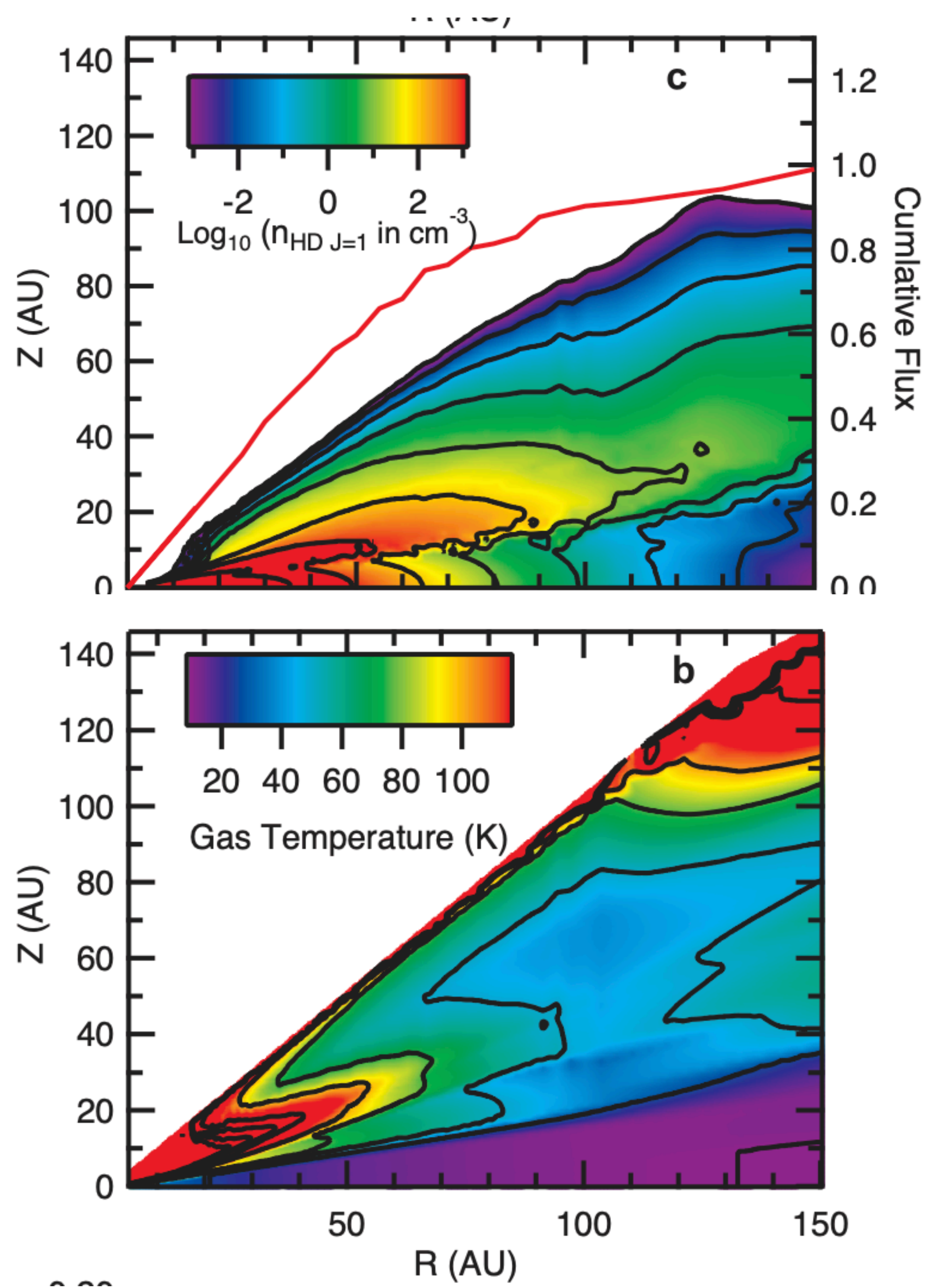
Disk gas mass

Using HD instead

HD/H$_2$ = 3.10^{-5}

FIR HD 1-0 line (Herschel-PACS) at 112 micron detected in TW Hya





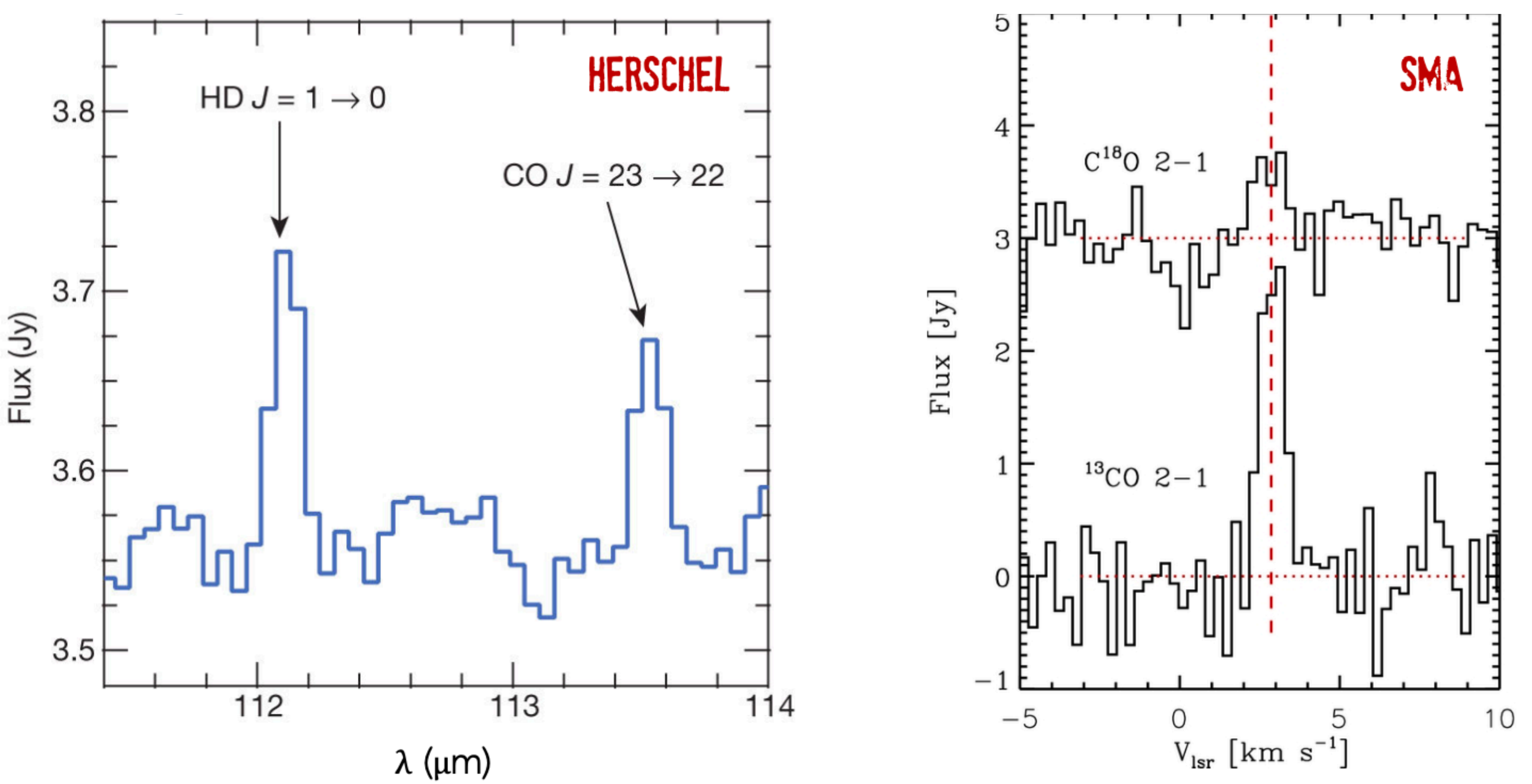
Using a thermo-chemical model:
gas mass of >0.05 M$_{sun}$ (MMSN)
And gas-to-dust ratio >100

Bergin et al. 2013

Disk gas mass

HD comparison with CO

Gas mass derived from $C^{18}O$ emission is only 0.005 M_{sun}!!

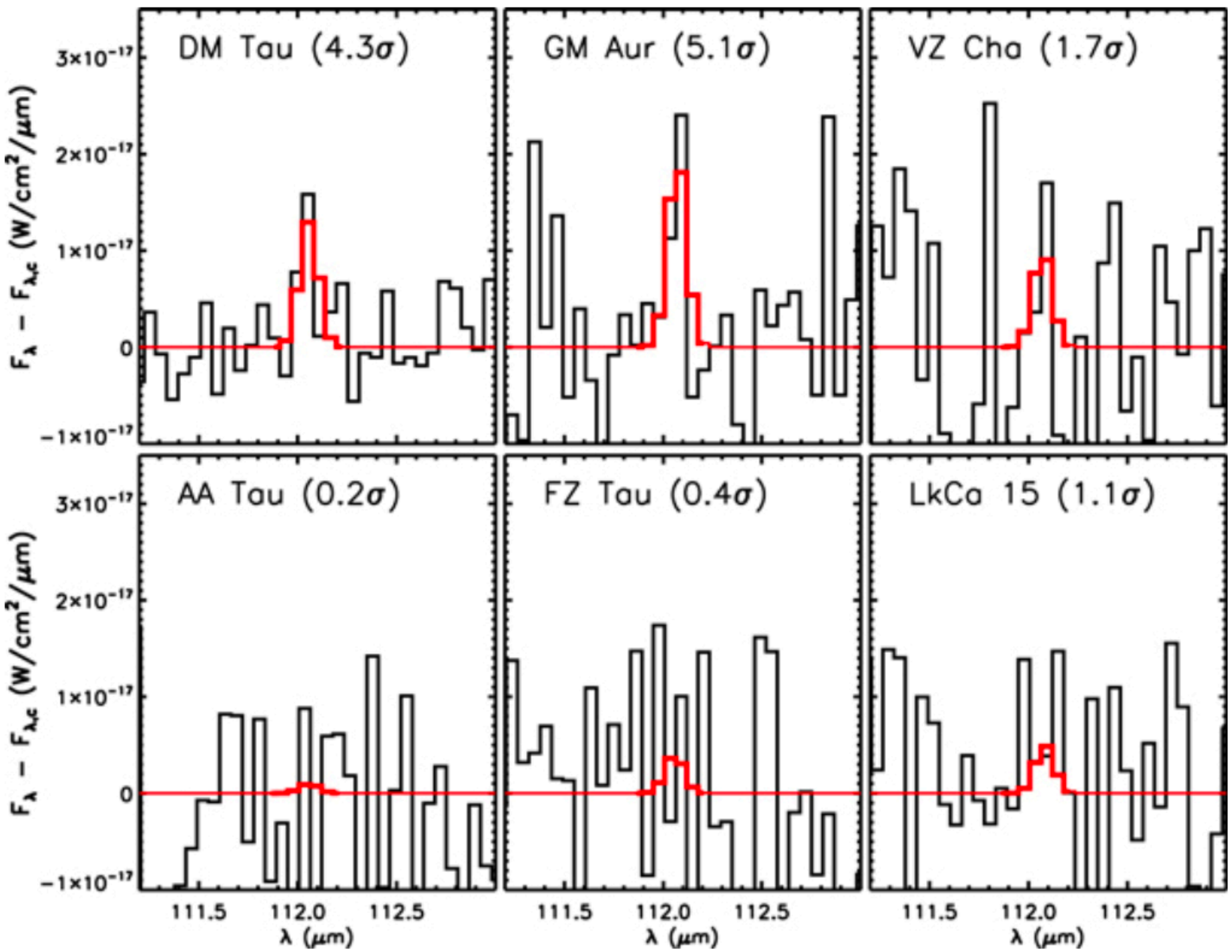


Implication: CO depleted by a factor >10?

Bergin et al. 2013
Favre et al. 2013

Disk gas mass

Other HD measurements



Only two more significant detections:

M_{gas} estimates suggest gas-to-dust ratios of ~100 are correct so **CO must be depleted (how?)**

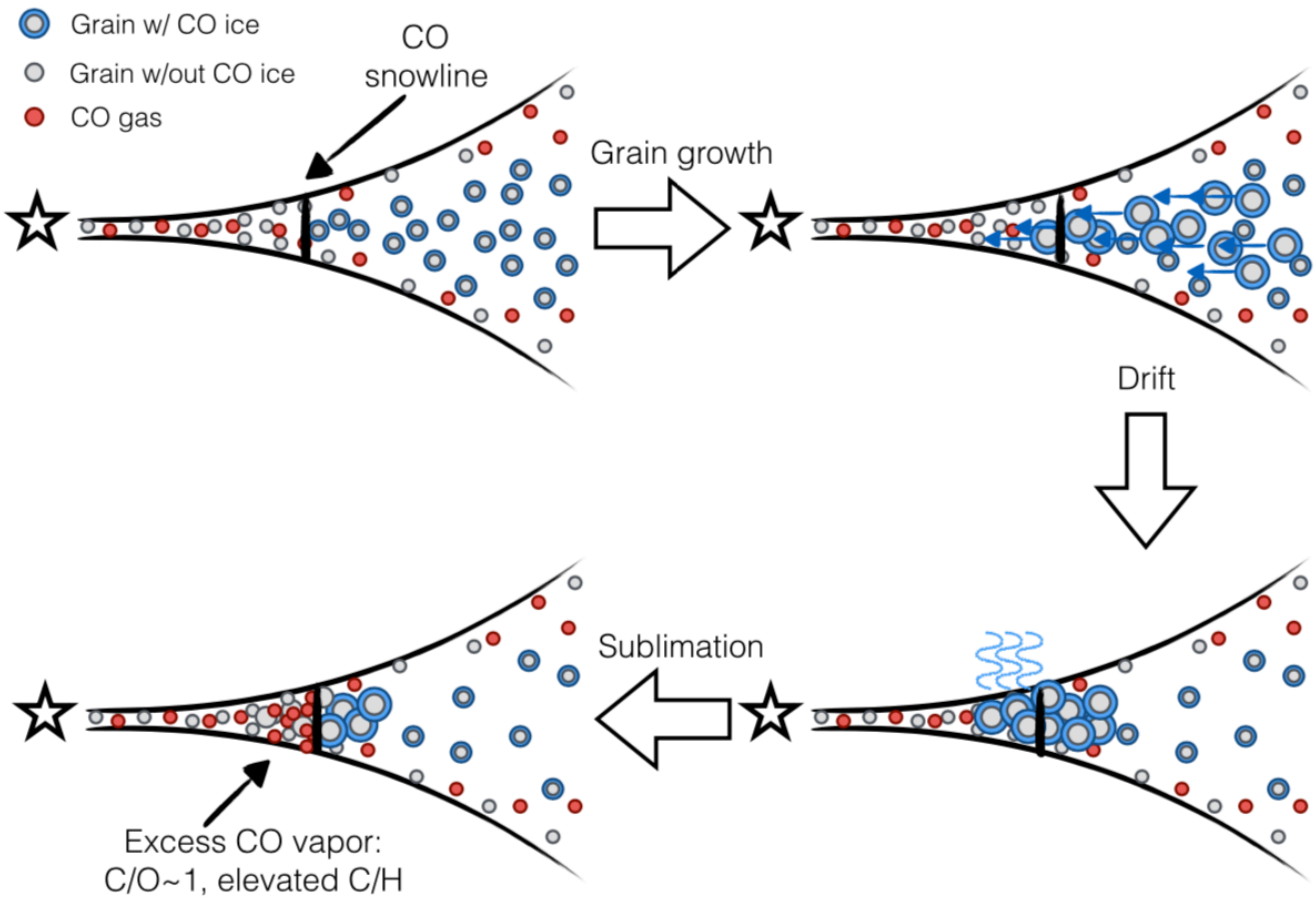
Note uncertainty:
HD depends on temperature (vertical) structure

Why are there no other HD observations since then?

McClure et al. 2016
Trapman et al. 2017

CO depletion

Removal of CO in outer disk by pebble drift?



Dust pebble drift can cause
CO depletion as the CO-icy pebbles drift inwards,
depleting the outer disk of molecular CO

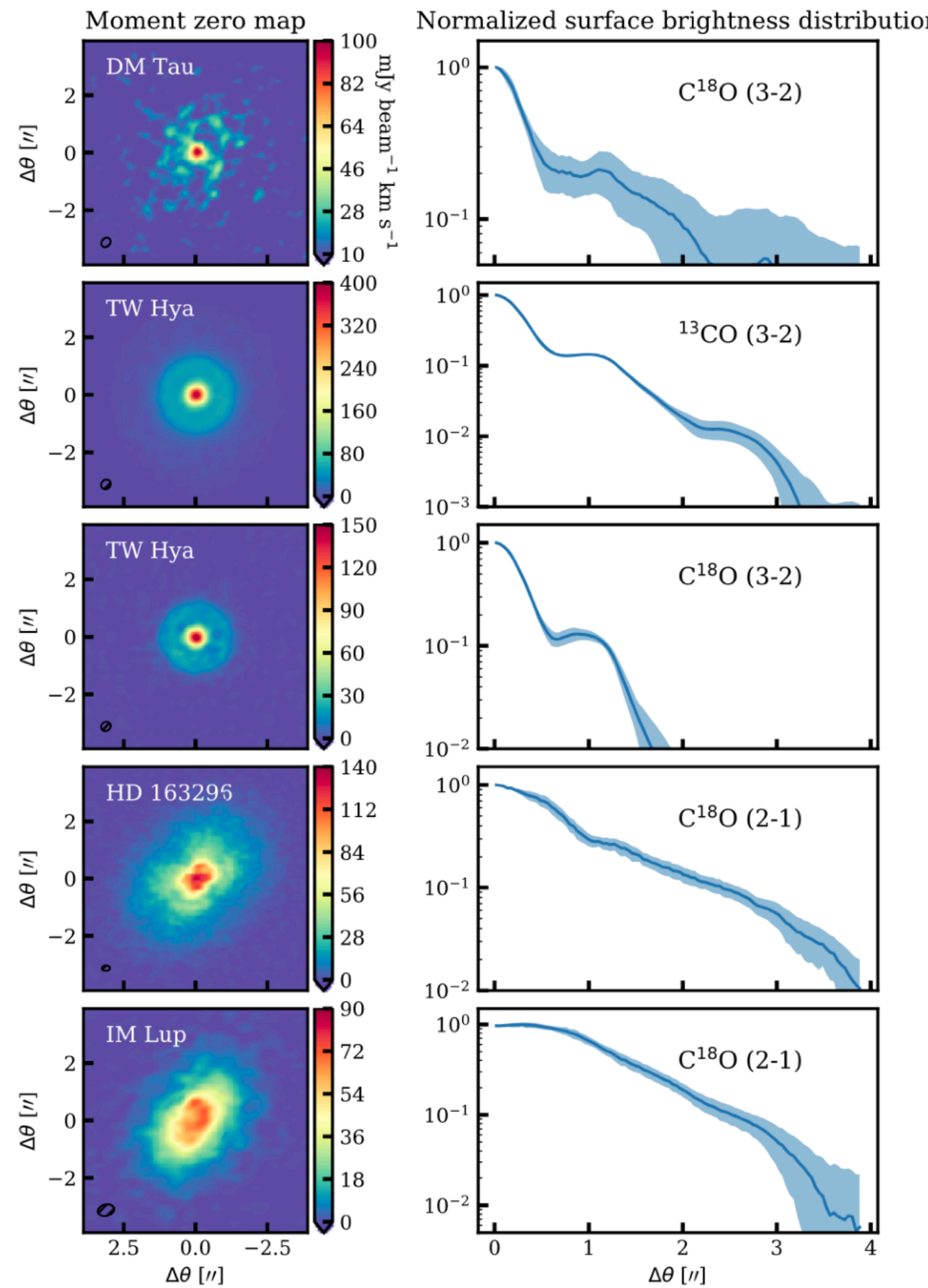
Oberg et al. 2016
Booth & Ilee 2019
Krijt et al. 2018, 2020

CO depletion

Testing with observations

Assume M_{gas} =100x M_{dust}, and derive the CO depletion w.r.t. the ISM $CO/H_2 \sim 10^{-4}$ from $C^{18}O$ observations

1. Derive the intensity profiles of the integrated (^{13}CO and) $C^{18}O$ line

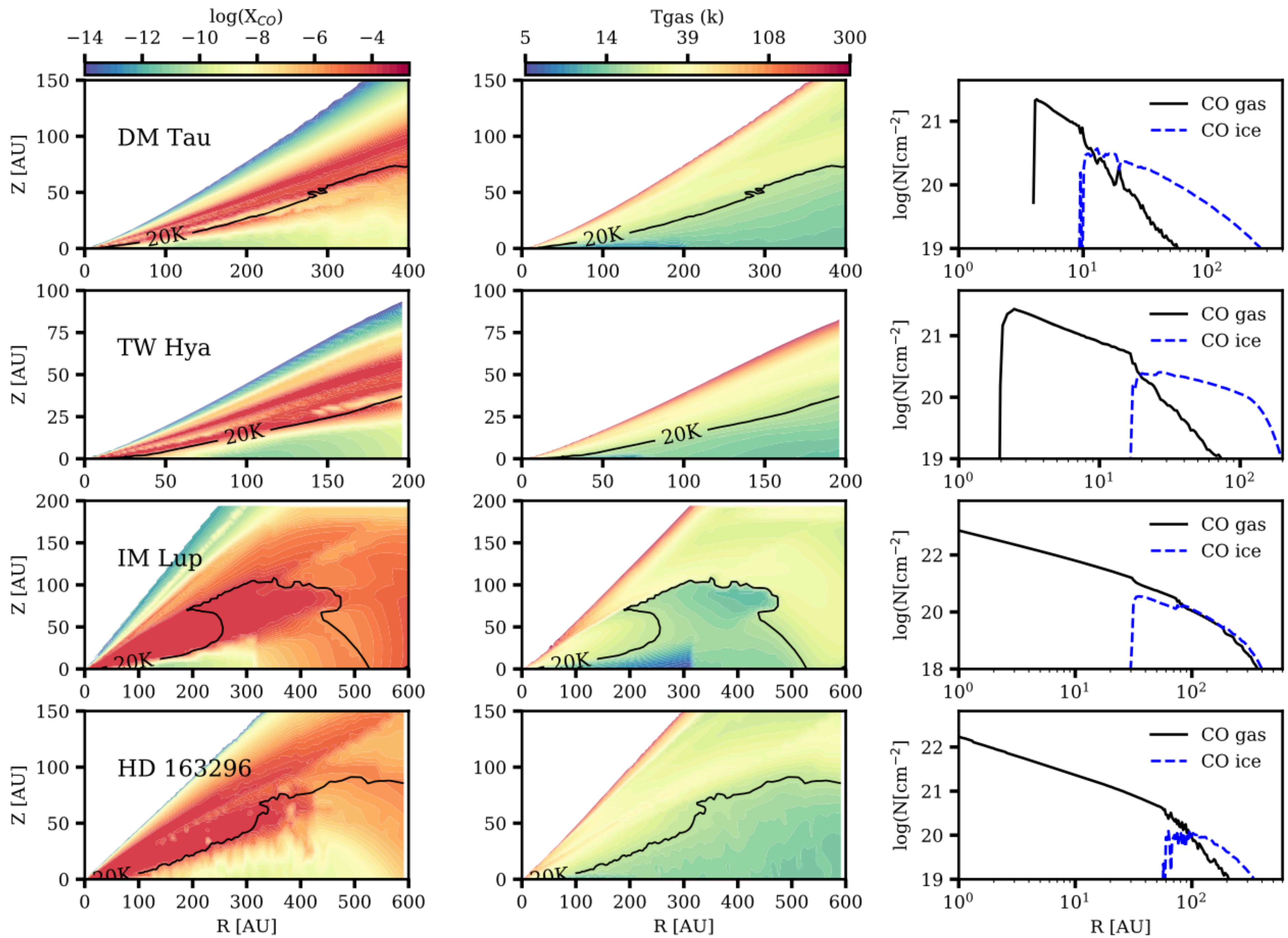


Zhang et al. 2020a

CO depletion

Testing with observations

2. Run a thermal-chemical model and compute the CO abundances and resulting ^{13}CO and $C^{18}O$ emission, for a number of depletion factors in CO

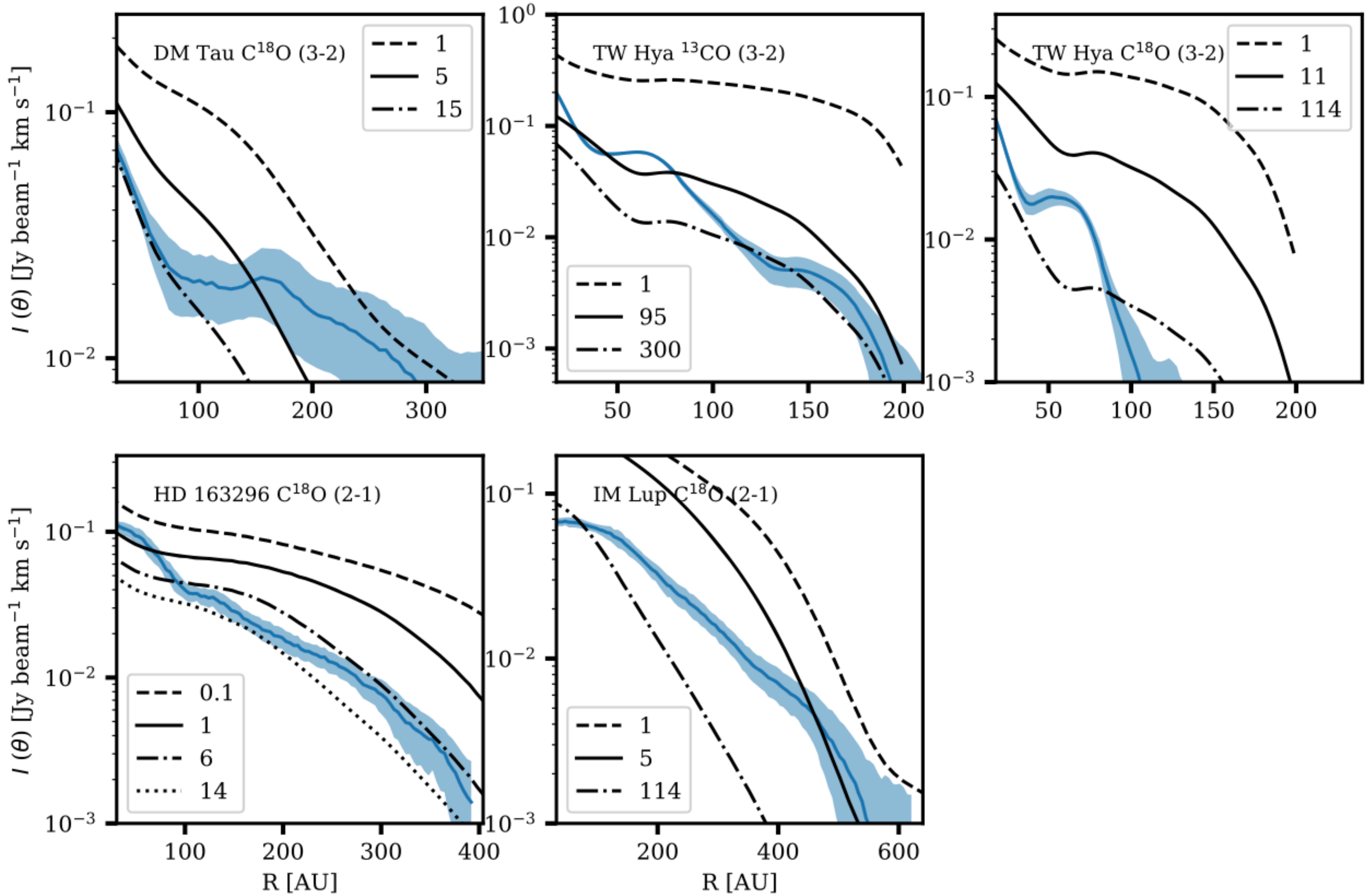


Zhang et al. 2020a

CO depletion

Testing with observations

3. Compare the resulting integrated ^{13}CO and $C^{18}O$ radial profiles with the data for different depletions



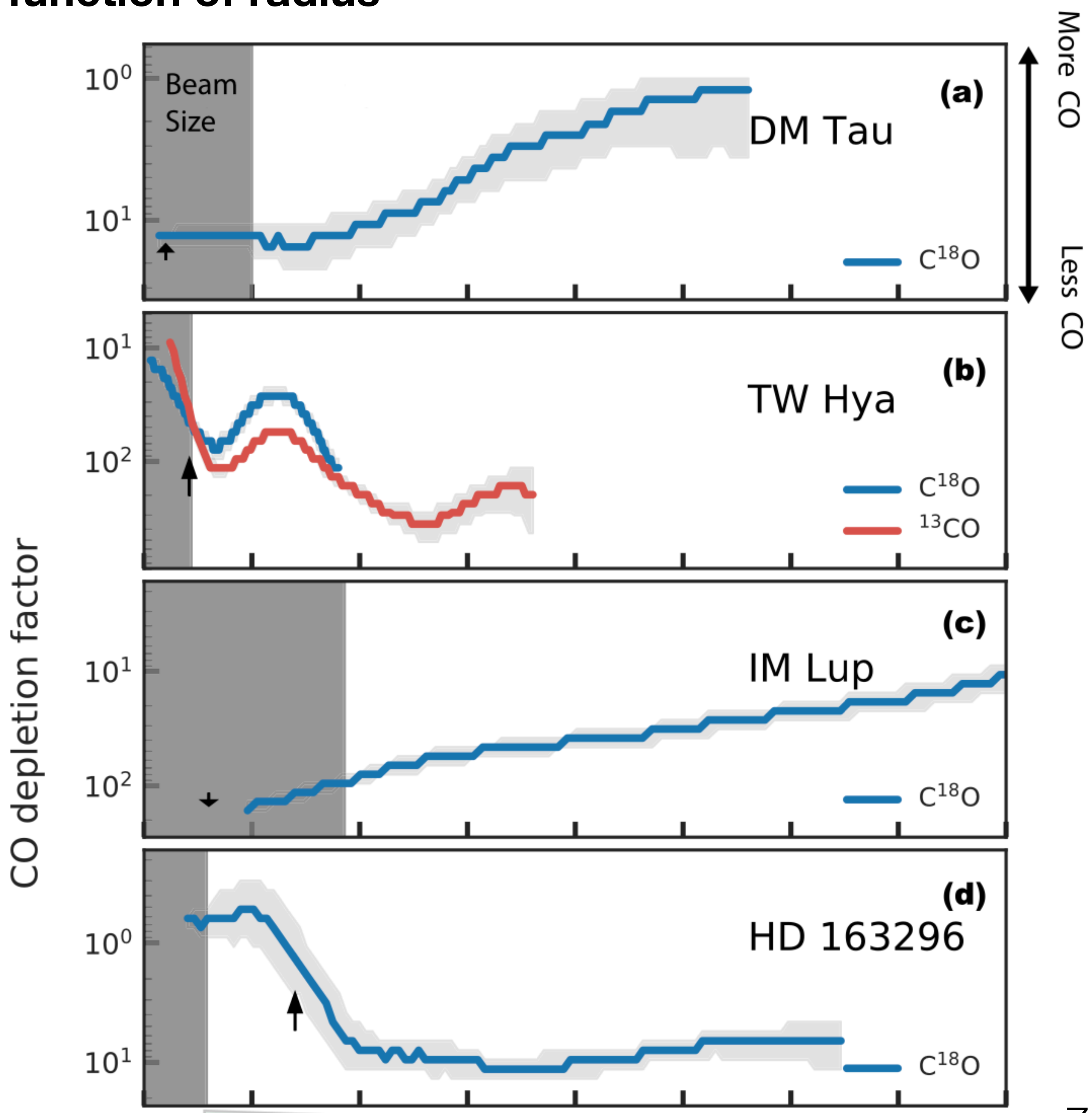
Zhang et al. 2020a

CO depletion

Testing with observations

4. Compute the depletion as a function of radius

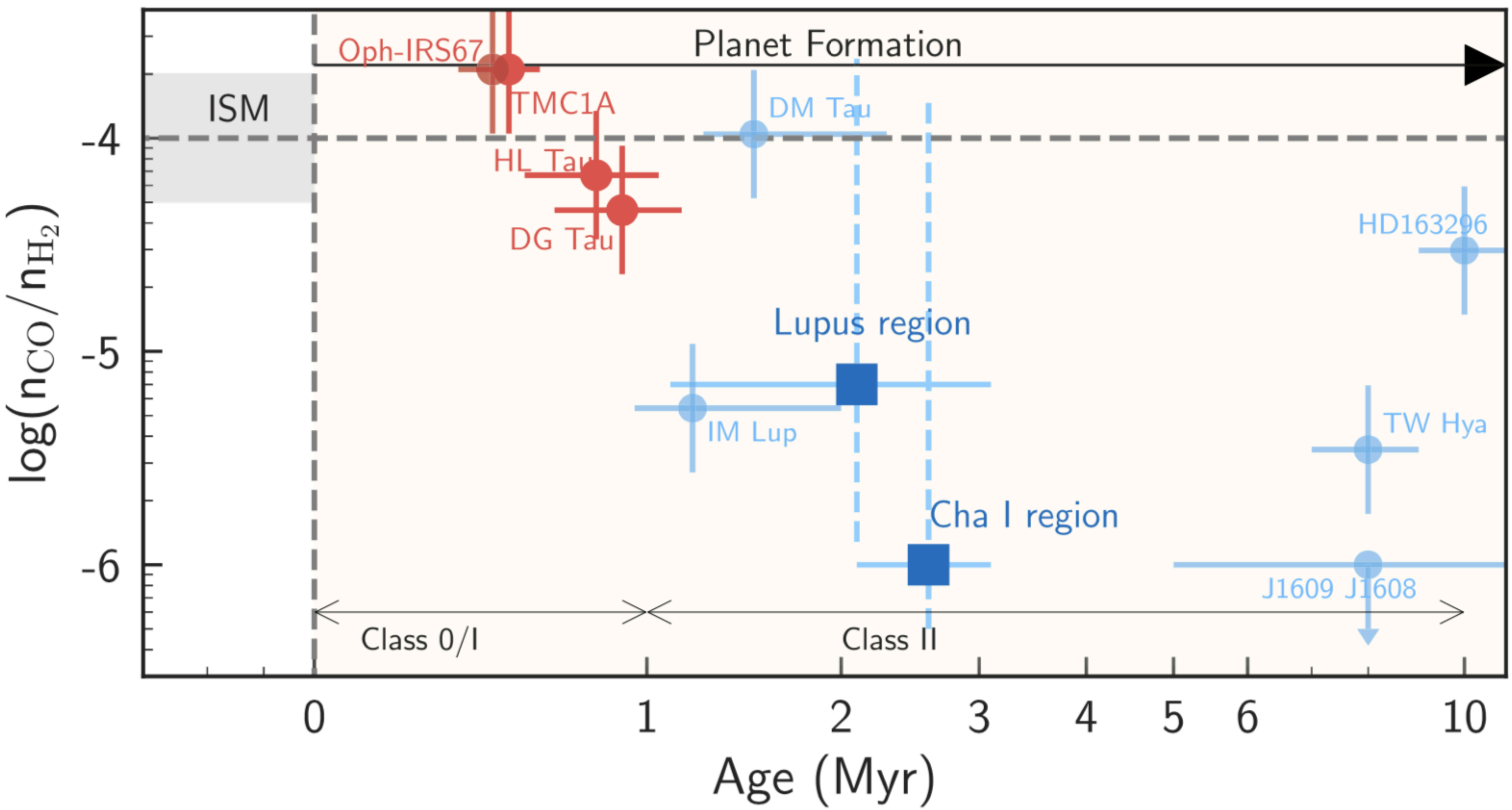
Depletion factor is a factor 10-100 for all four disks!



Zhang et al. 2020a

CO depletion

Similar study now as function of age



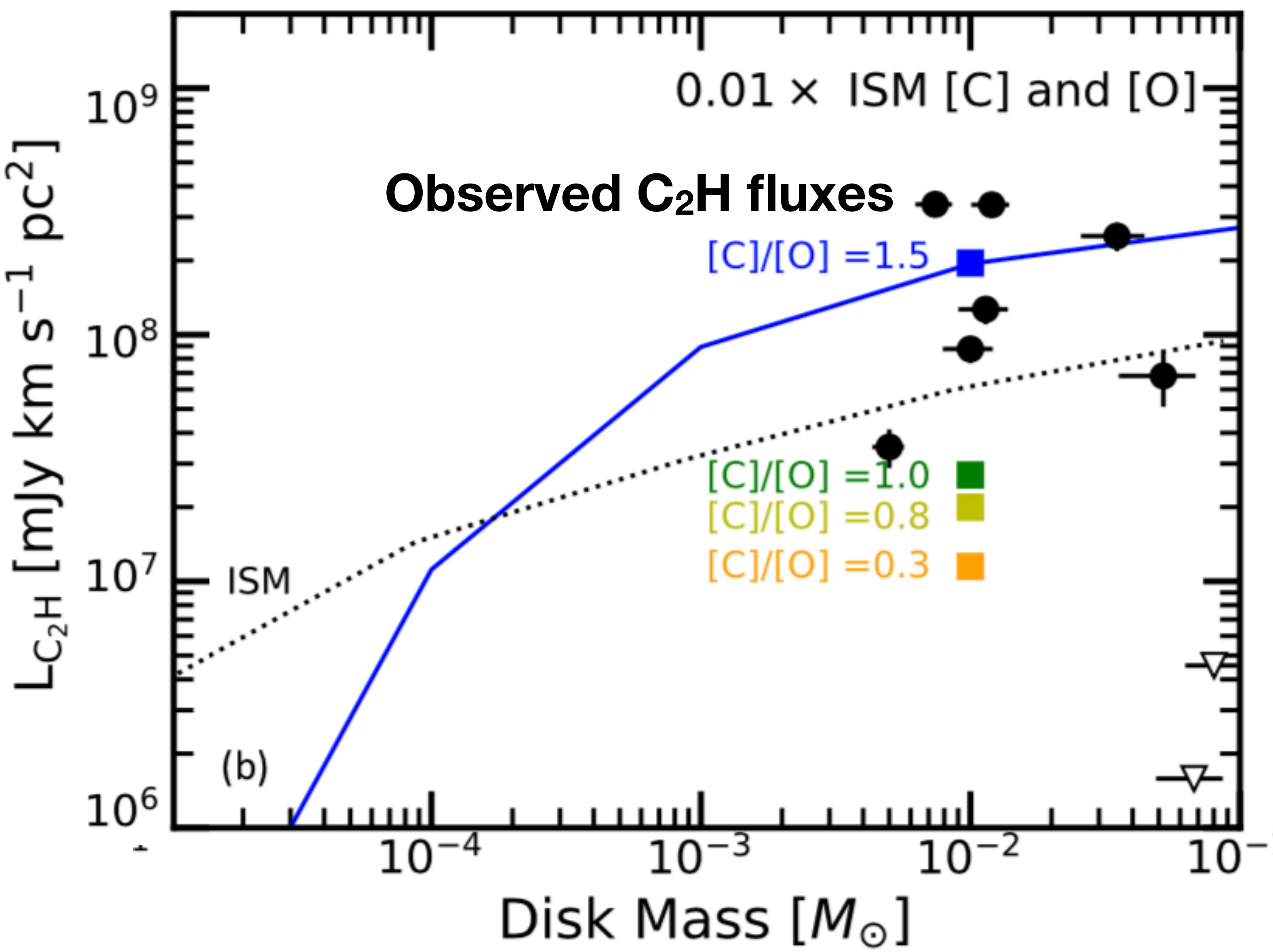
CO depletion is an evolutionary effect: ~ 1 Myr

Zhang et al. 2020
Bergner et al. 2020
Miotello et al. 2023 (PPVII)

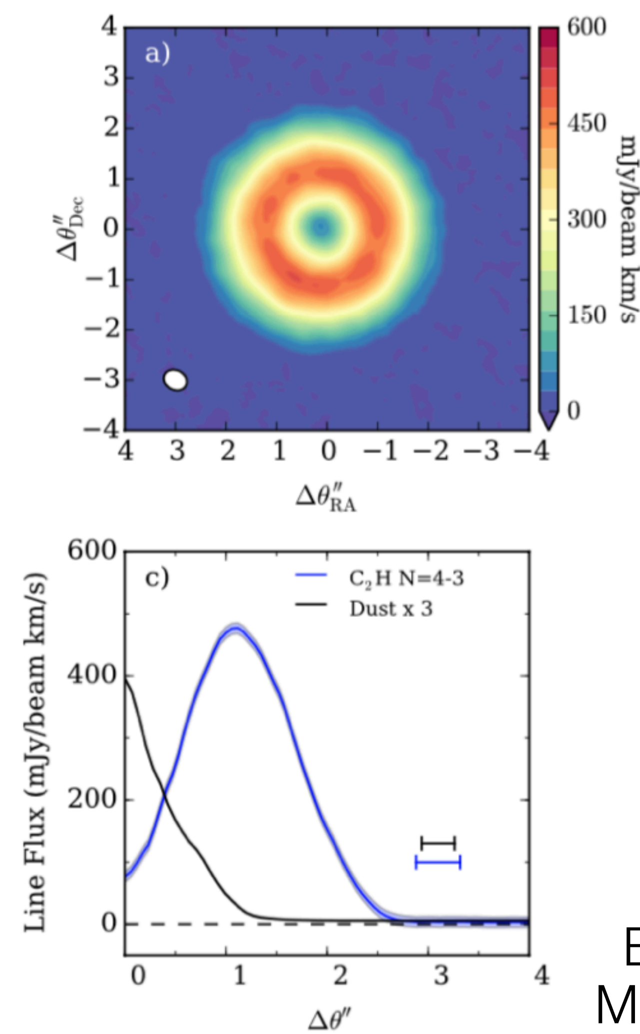
CO depletion

Tracing through other molecules?

CO depletion => depletion carbon and oxygen and **C/O>1**
(CO is important oxygen carrier, other molecules carry carbon too)
=> result: **strong C_2H emission**!



Example TW Hya C_2H ring



Bergin et al. 2016
Miotello et al. 2019
Krijt et al. 2020
Bosman et al. 2021

Mystery CO depletion and disk mass

Two ALMA Large Programs

AGE-PRO

ALMA survey of Gas Evolution in PROtoplanetary disks
(PI: Ke Zhang)

Survey of 30 disks of 1-10 Myr in CO isotopologues and N_2H^+ emission (CO snowline tracer) to derive better estimates on CO depletion mechanisms

DECO

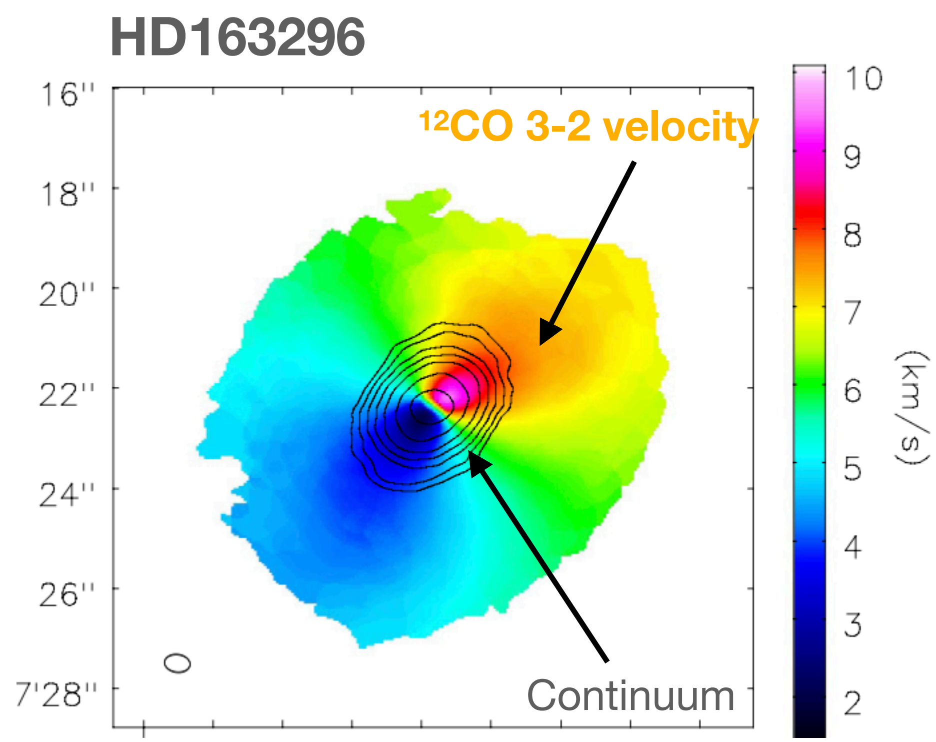
Disk-Exoplanet C/Onnection
(PI: I. Cleeves)

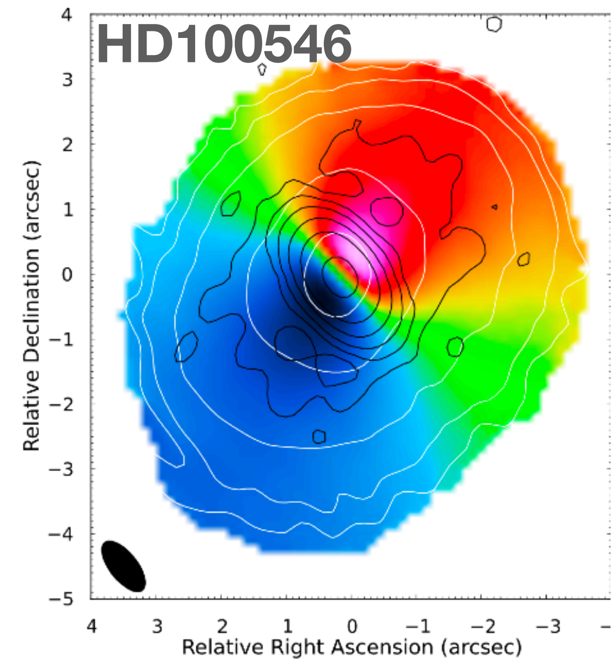
Survey of 80 disks in CO isotopologues, C_2H and N_2H^+ emission to derive C/O and C/H (+ additional chemistry)

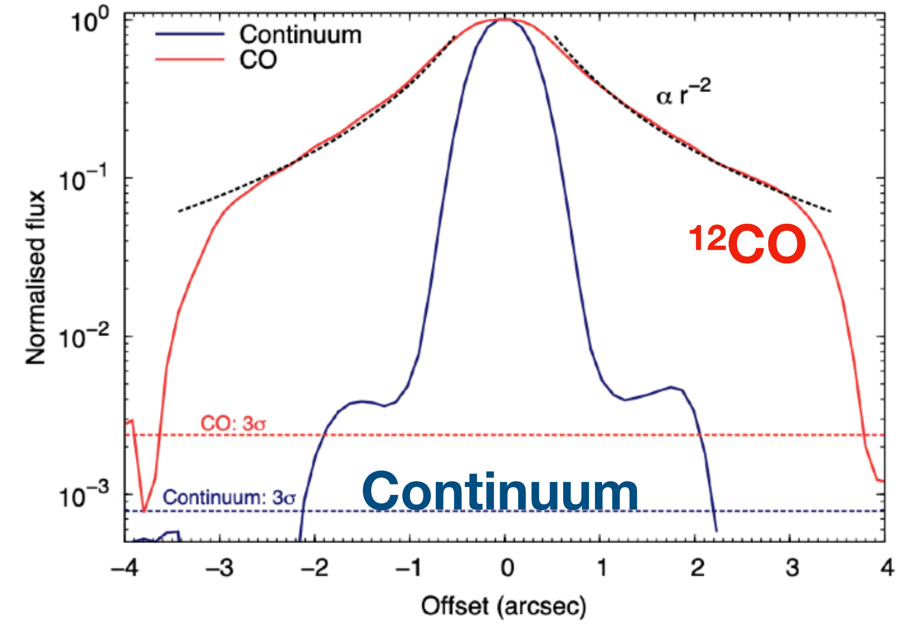
Keep an eye out for the outcome of these programs!

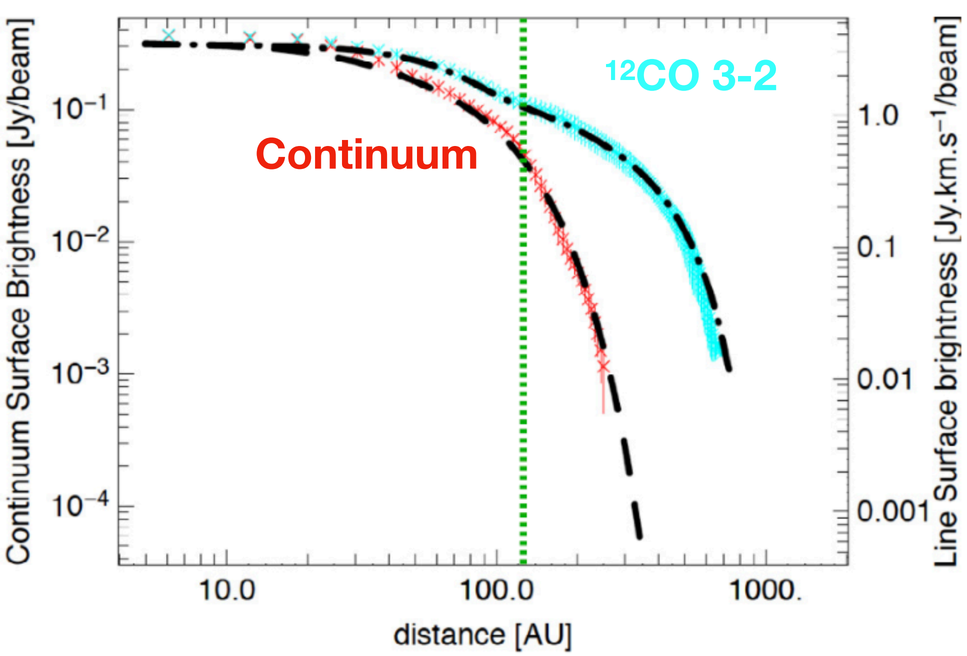
Gas-to-dust size ratios

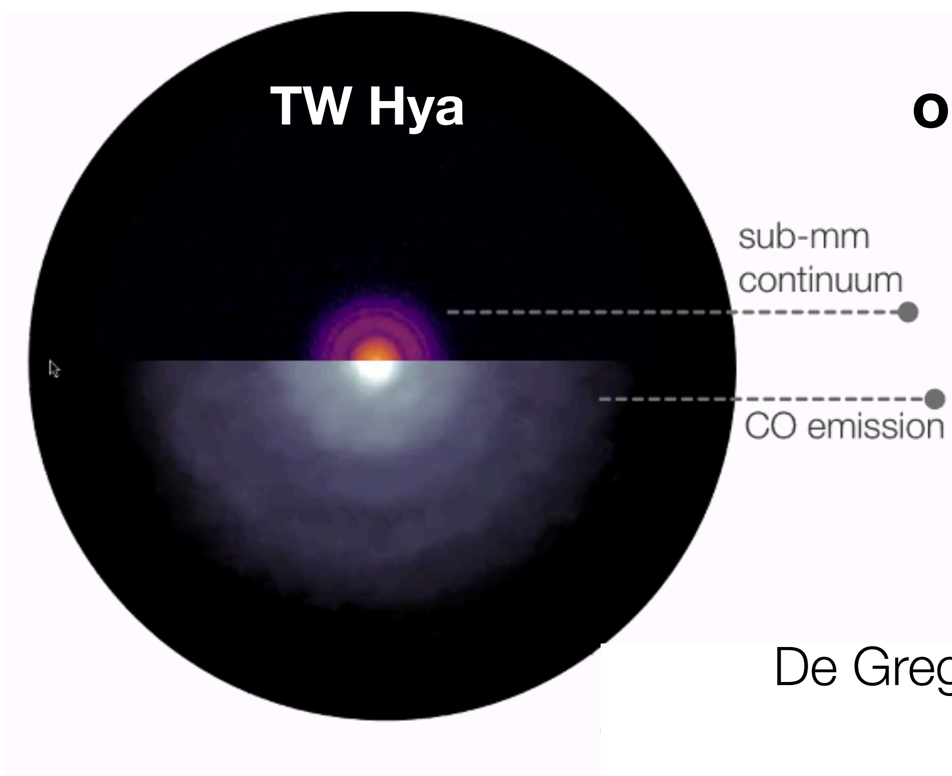
^{12}CO disk size >> dust disk size











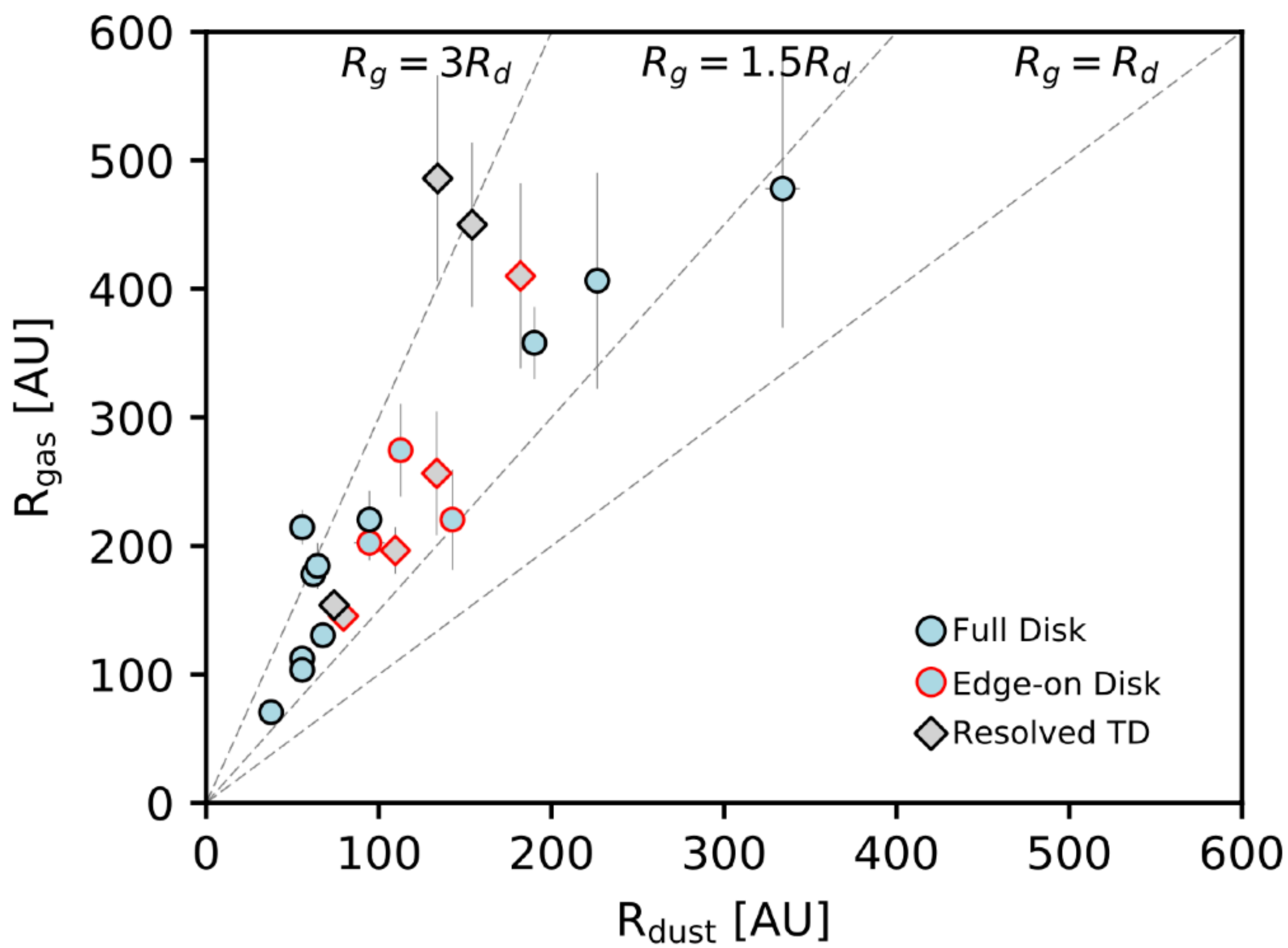
Not a sensitivity or optical depth effect! => radial drift

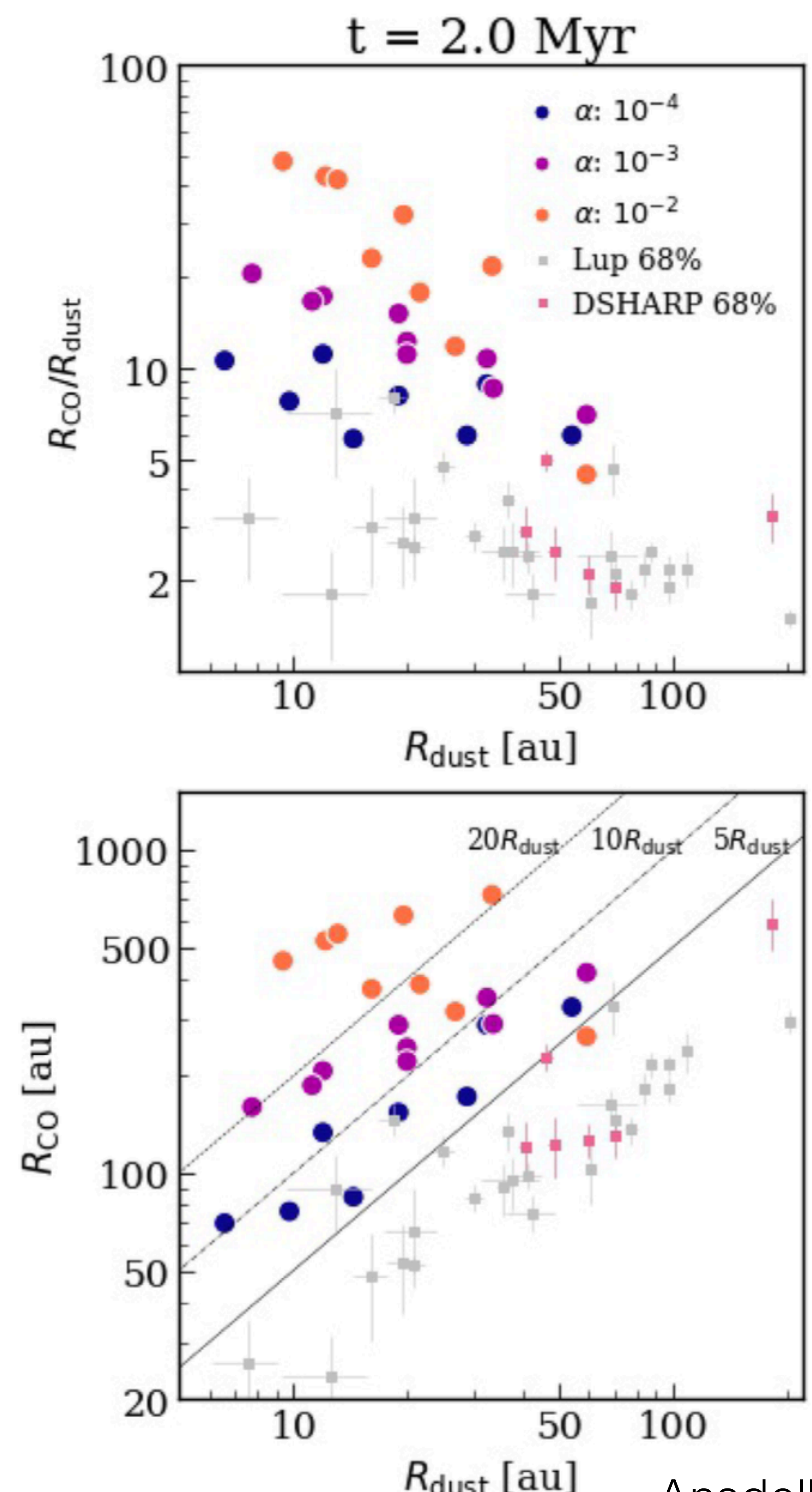
De Gregorio-Monsalvo et al. 2013
Walsh et al. 2014
Andrews et al. 2016

Gas-to-dust size ratios

Larger samples

Lupus disks: typically 2-3





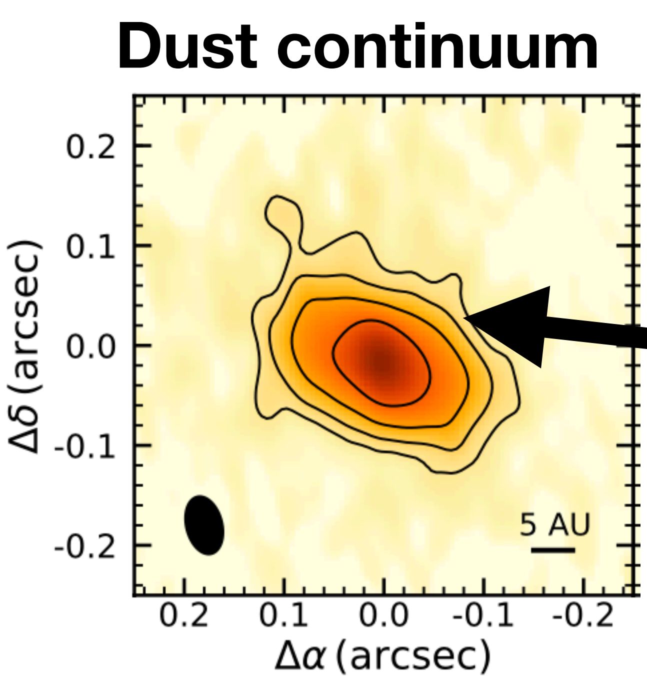
Typical dust evolution models of **drift-dominated** disks **much higher ratios: dust traps** must be present in these disks!

Ansdell et al. 2018
Toci et al. 2021

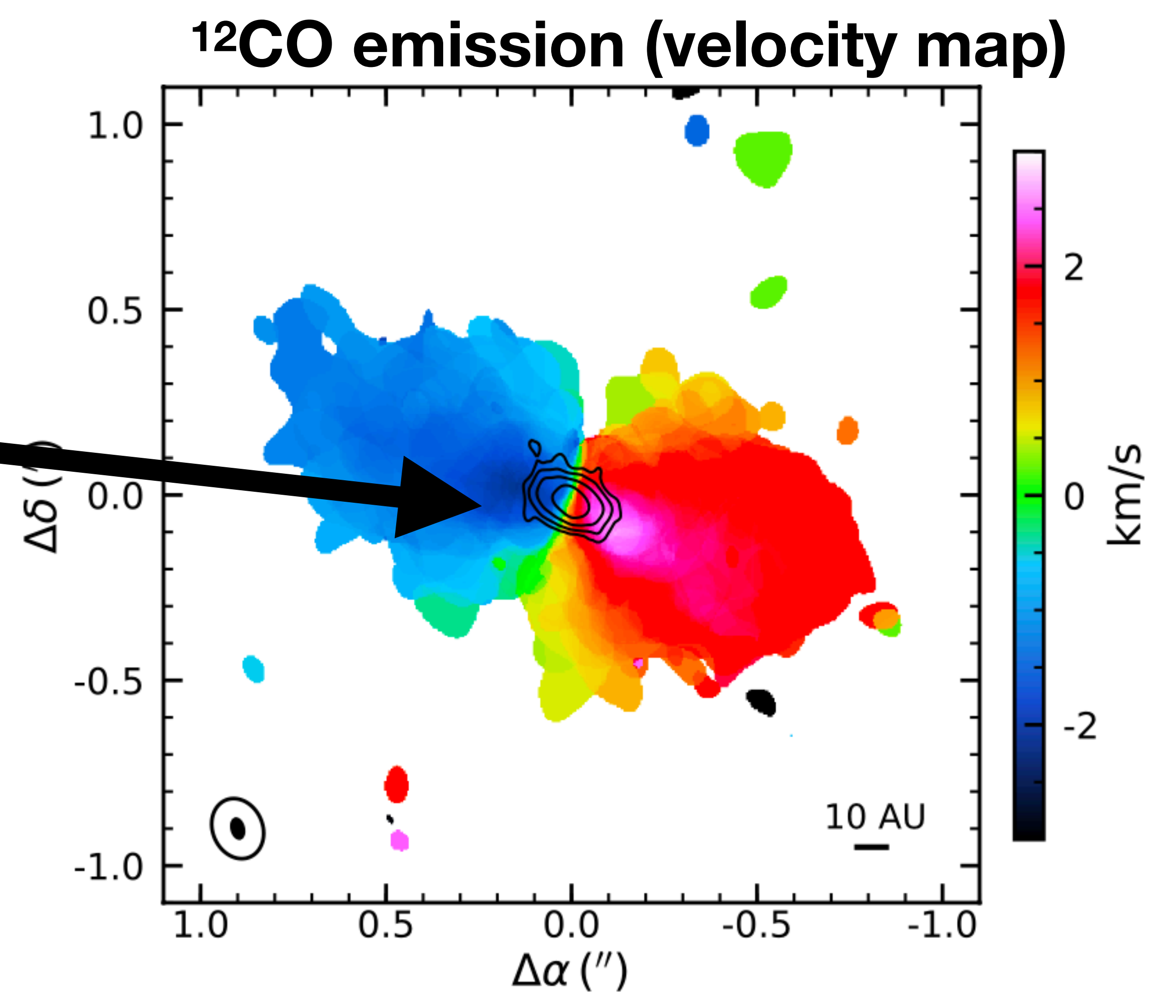
Gas-to-dust size ratios

An extreme example

CX Tau (at high resolution of 0.04”!) has a ratio of >6:



(No gaps seen)

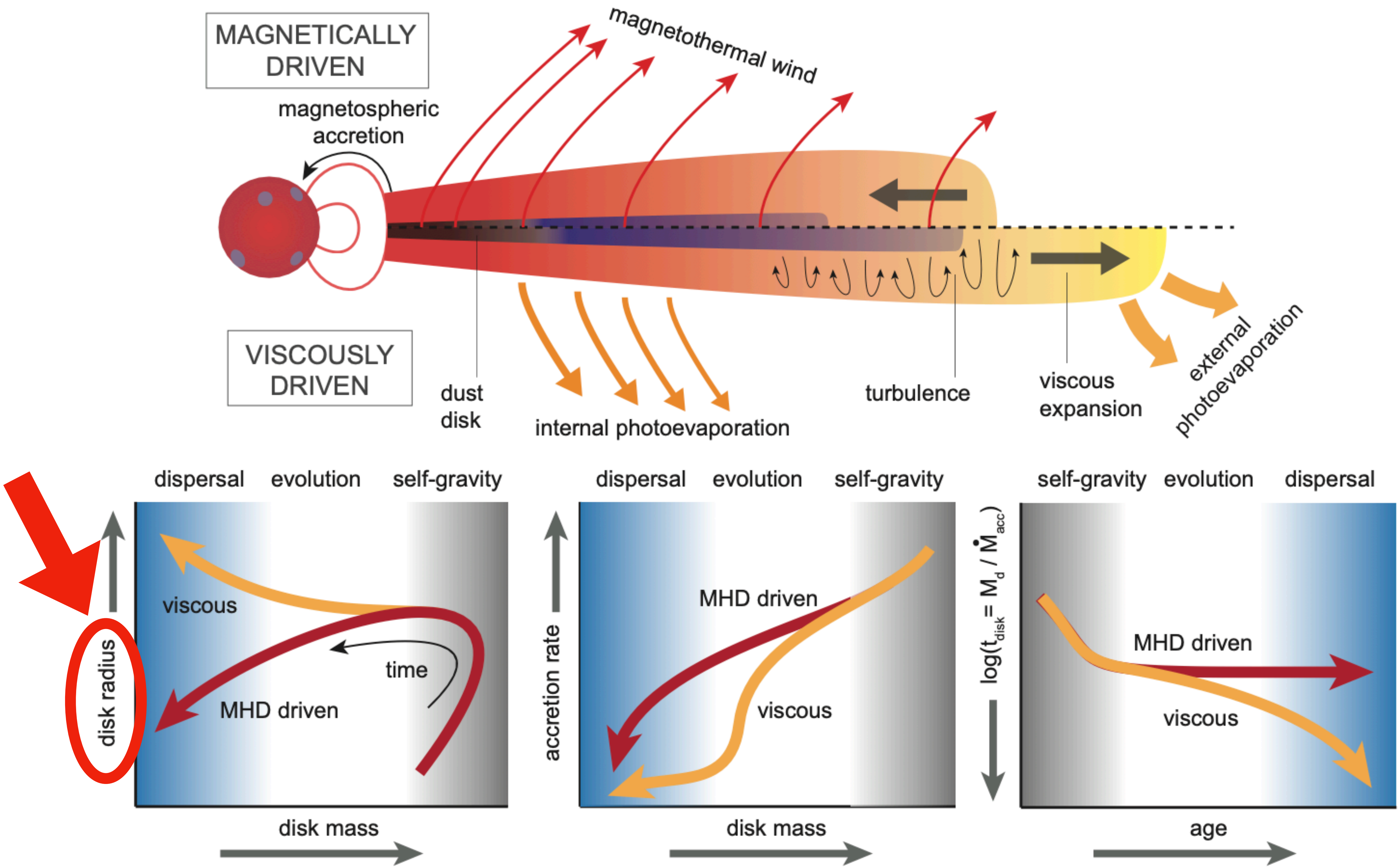


This may be a true case of a **drift-dominated disk!**

Facchini et al. 2019

Gas disk size

Constraining disk evolution?

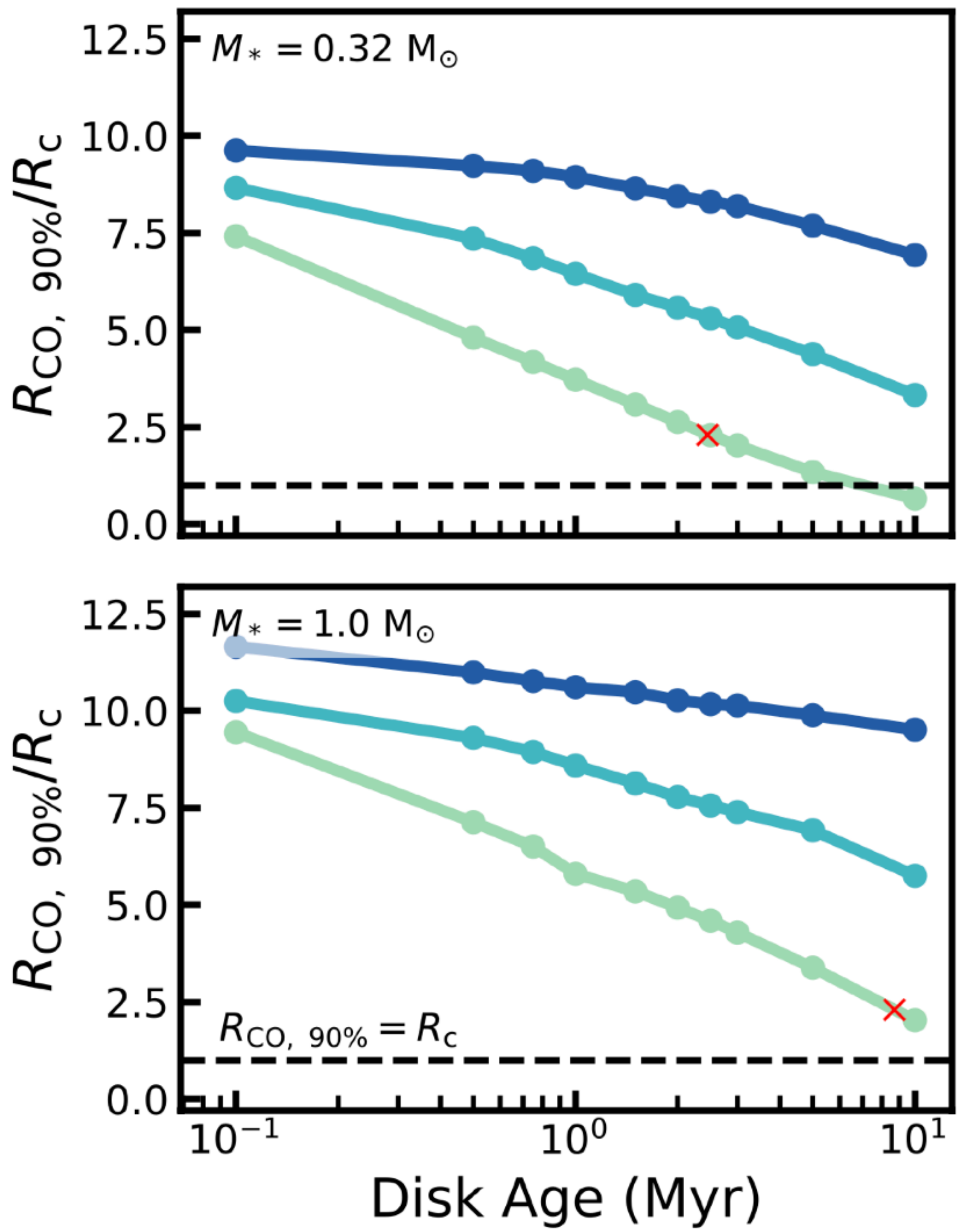


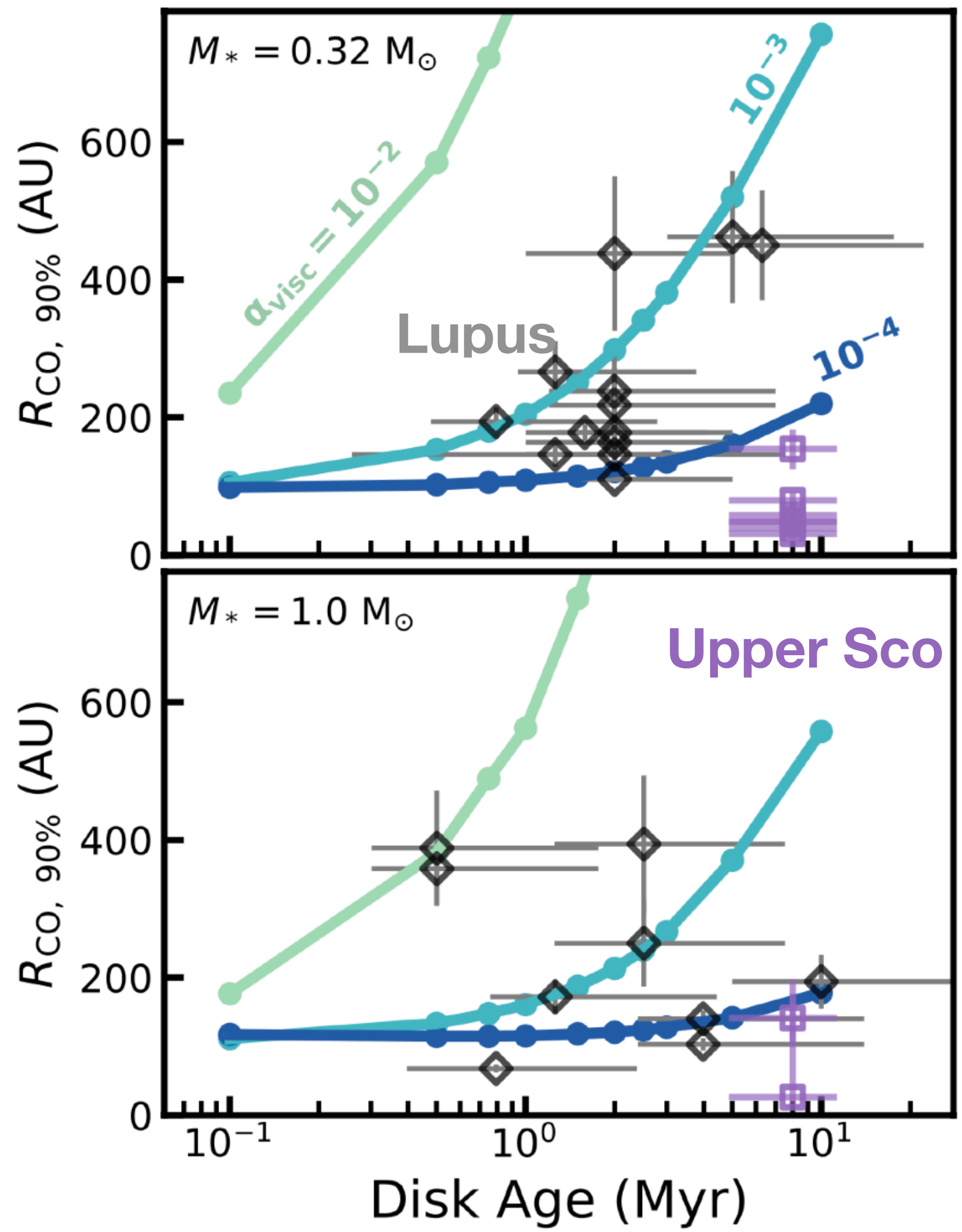
Manara et al. 2023 (PPVII)

Gas disk size

Constraining disk evolution?

Predictions viscous disk model ^{12}CO disk size



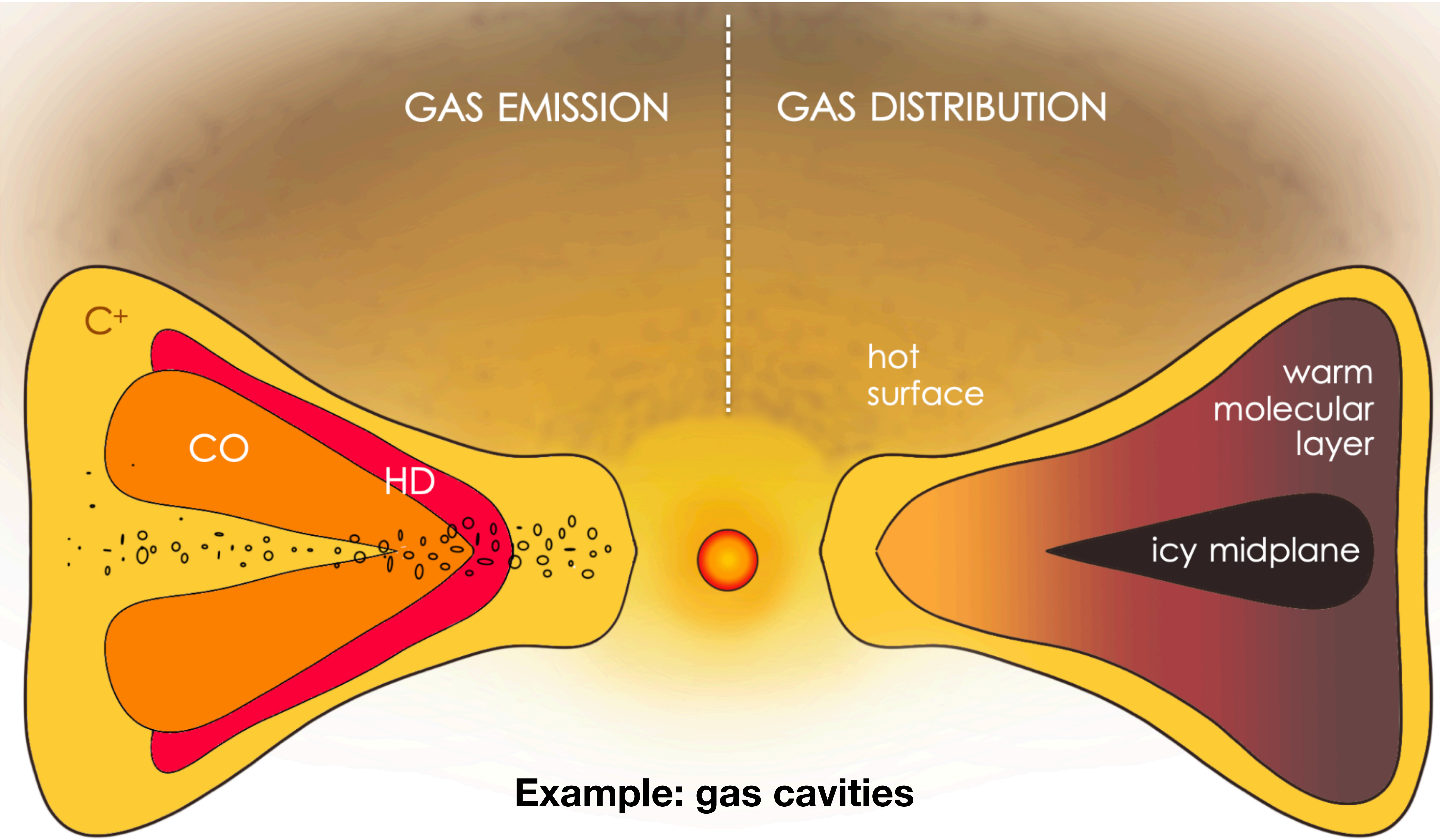


CO observations somewhat consistent with low alpha <~10^{-3}

Trapman et al. 2020

Resolved gas substructure

What if the disk is not continuous?

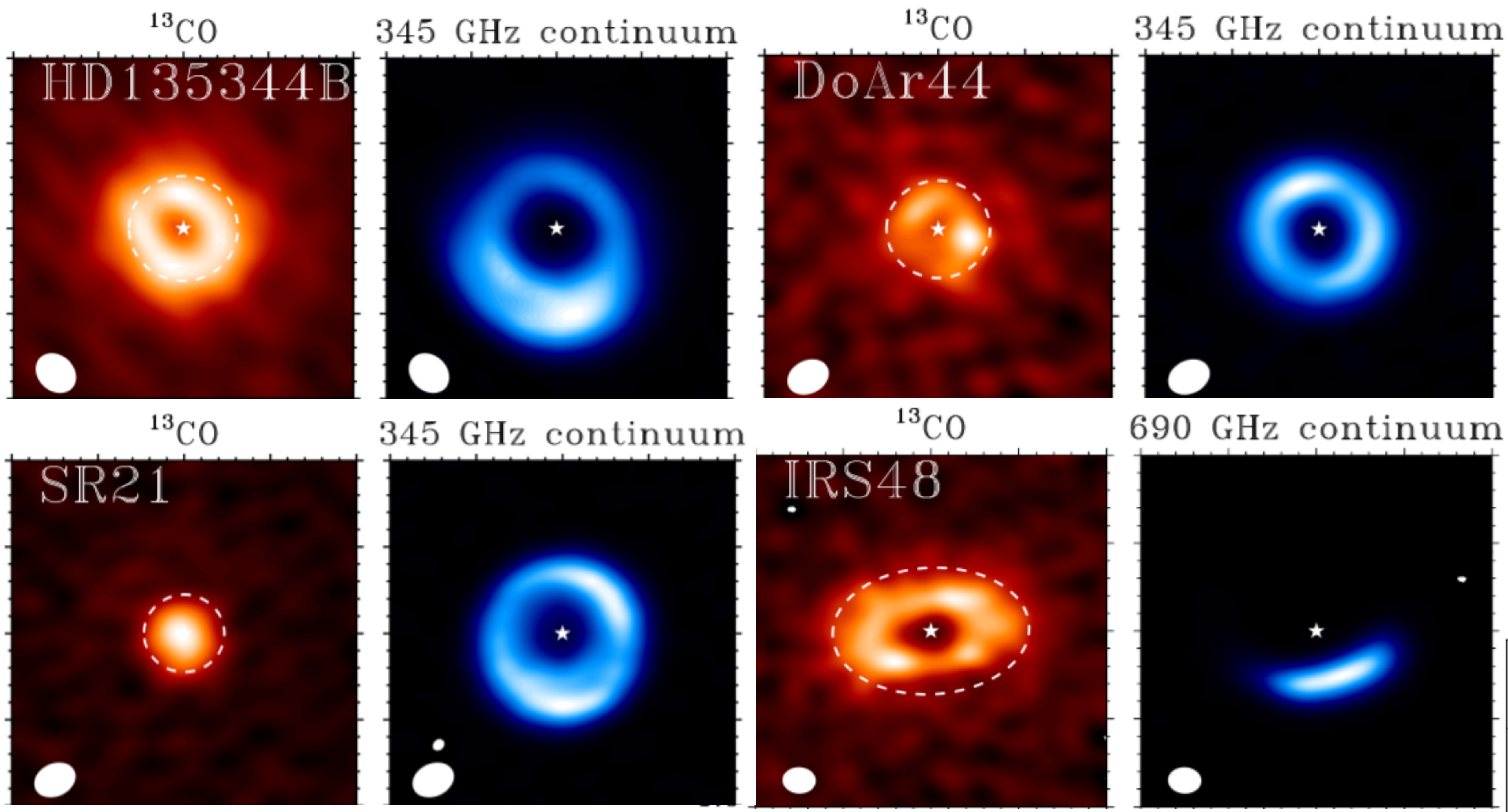


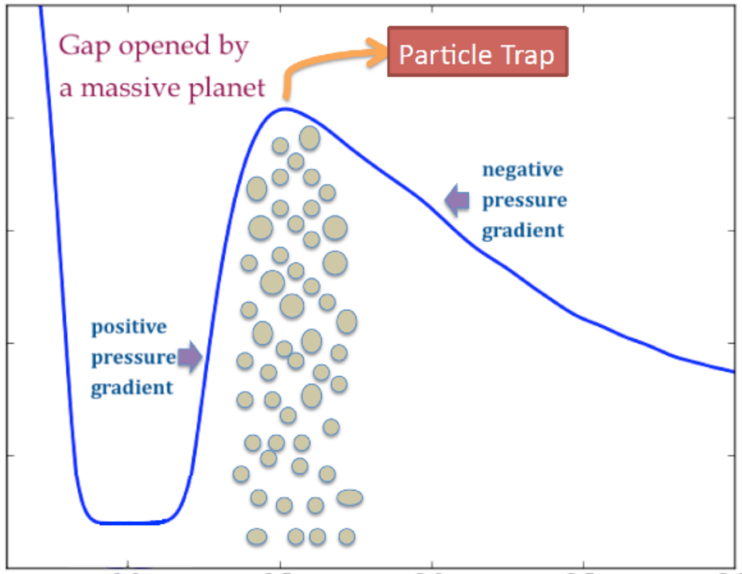
Example: gas cavities

figure by Anna Miotello

Gas gaps in transition disks

Spatially resolved CO isotopologue images of transition disks



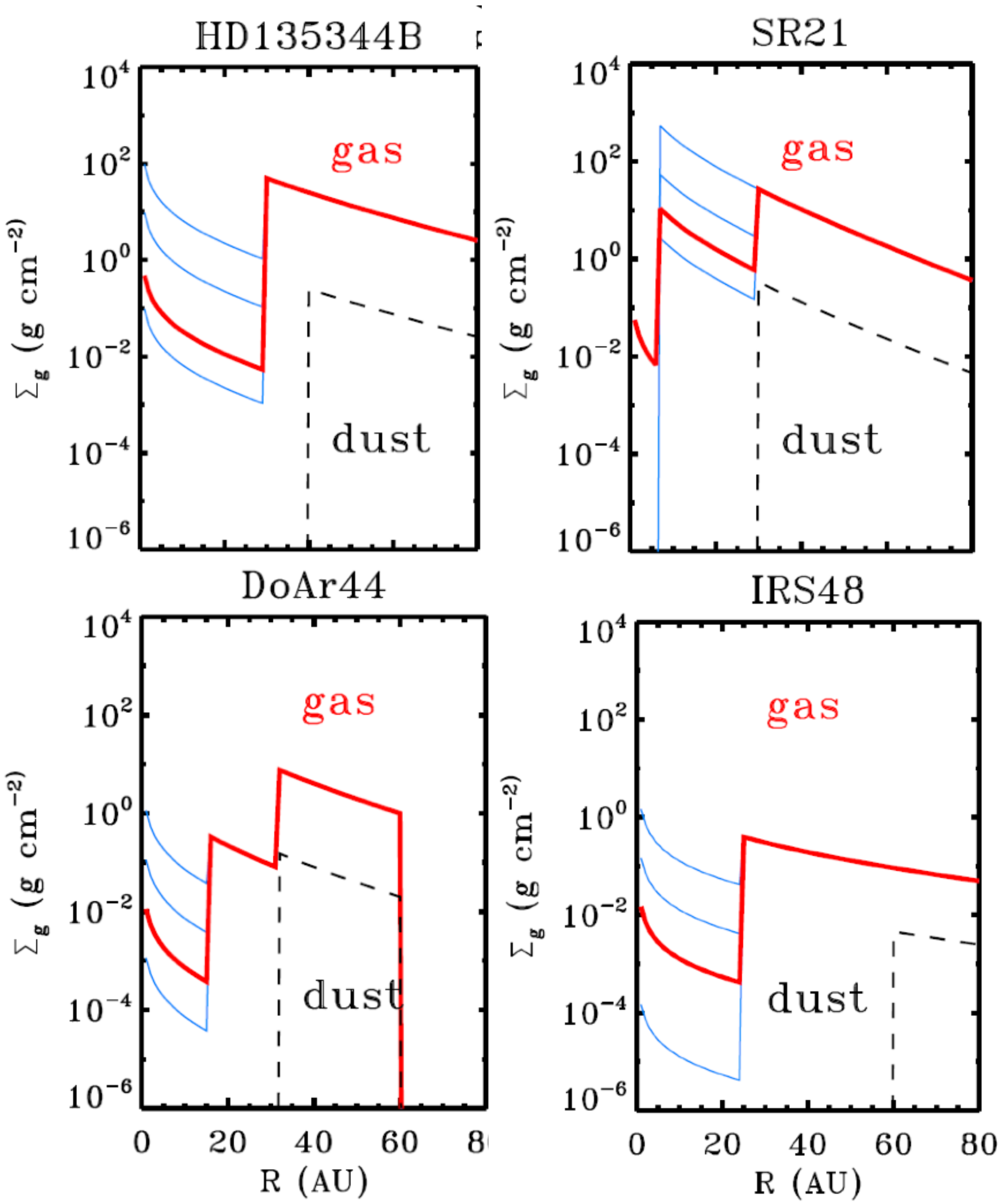


Gas cavities inside dust cavities:
Pressure bump and signature for planets!

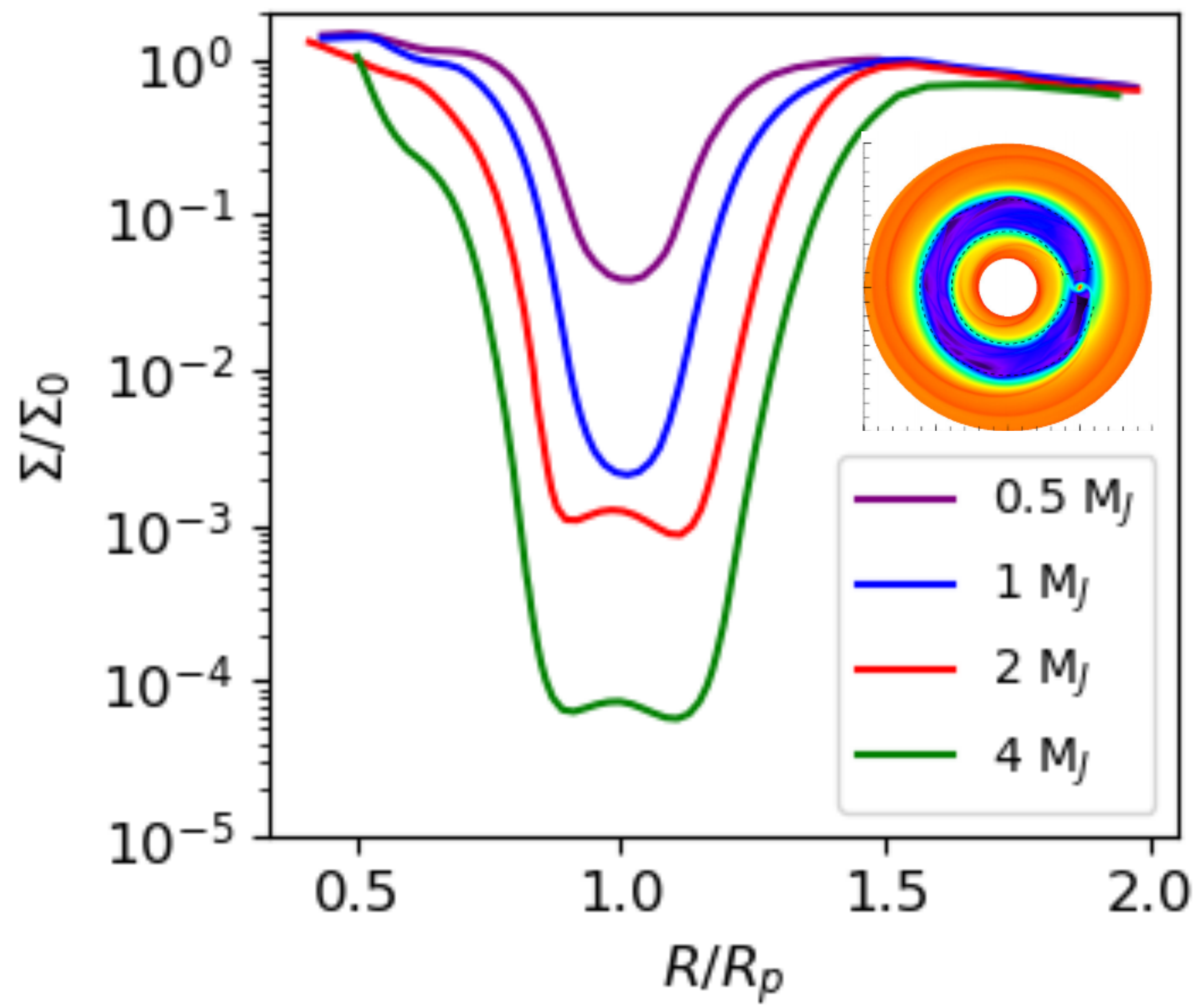
Van der Marel et al. 2016a

Gas gaps in transition disks

Physical-chemical modeling to derive depth



Compare with planet-disk interaction simulations

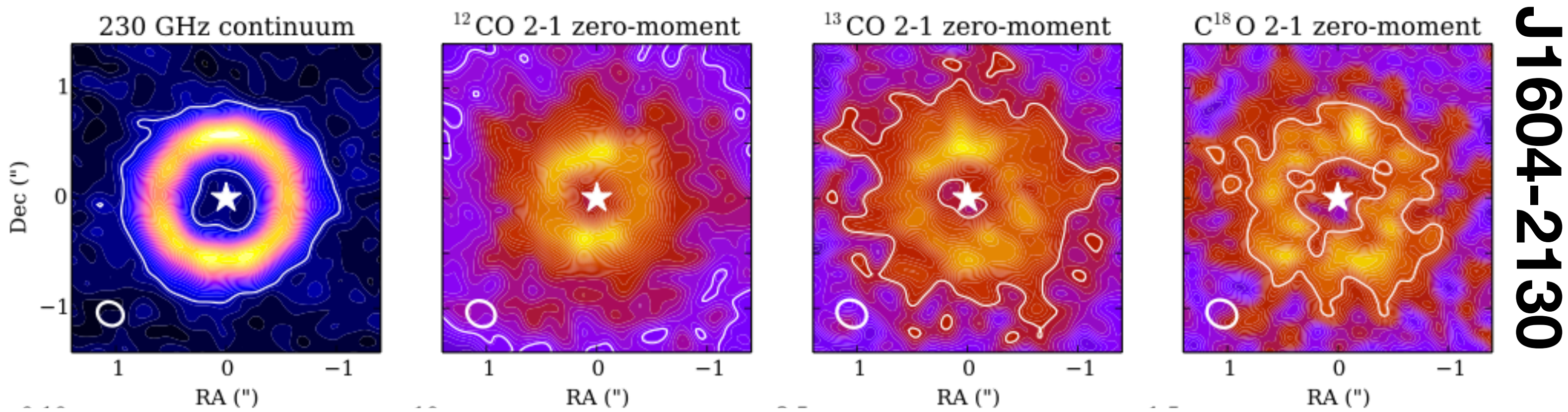


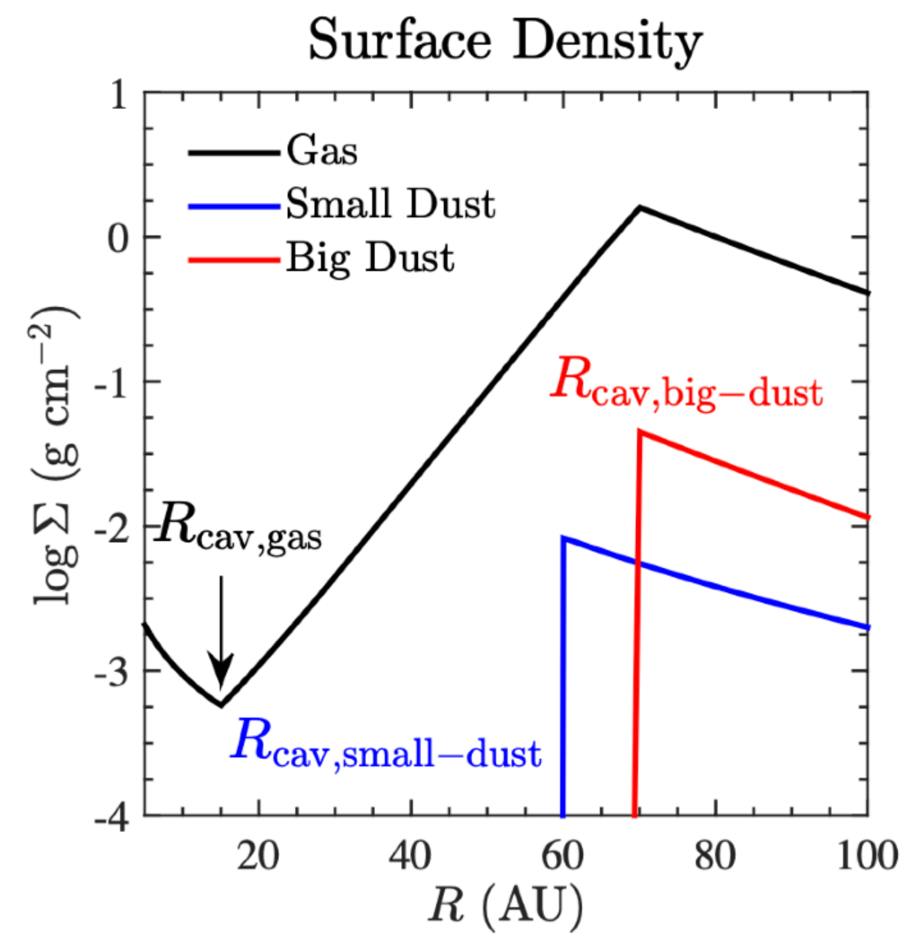
Deep wide gas gap
=> <u>massive planets</u> (~few M_{Jup}) at <u>tens of AU</u>

van der Marel et al. 2016a
Fung & Chiang 2016

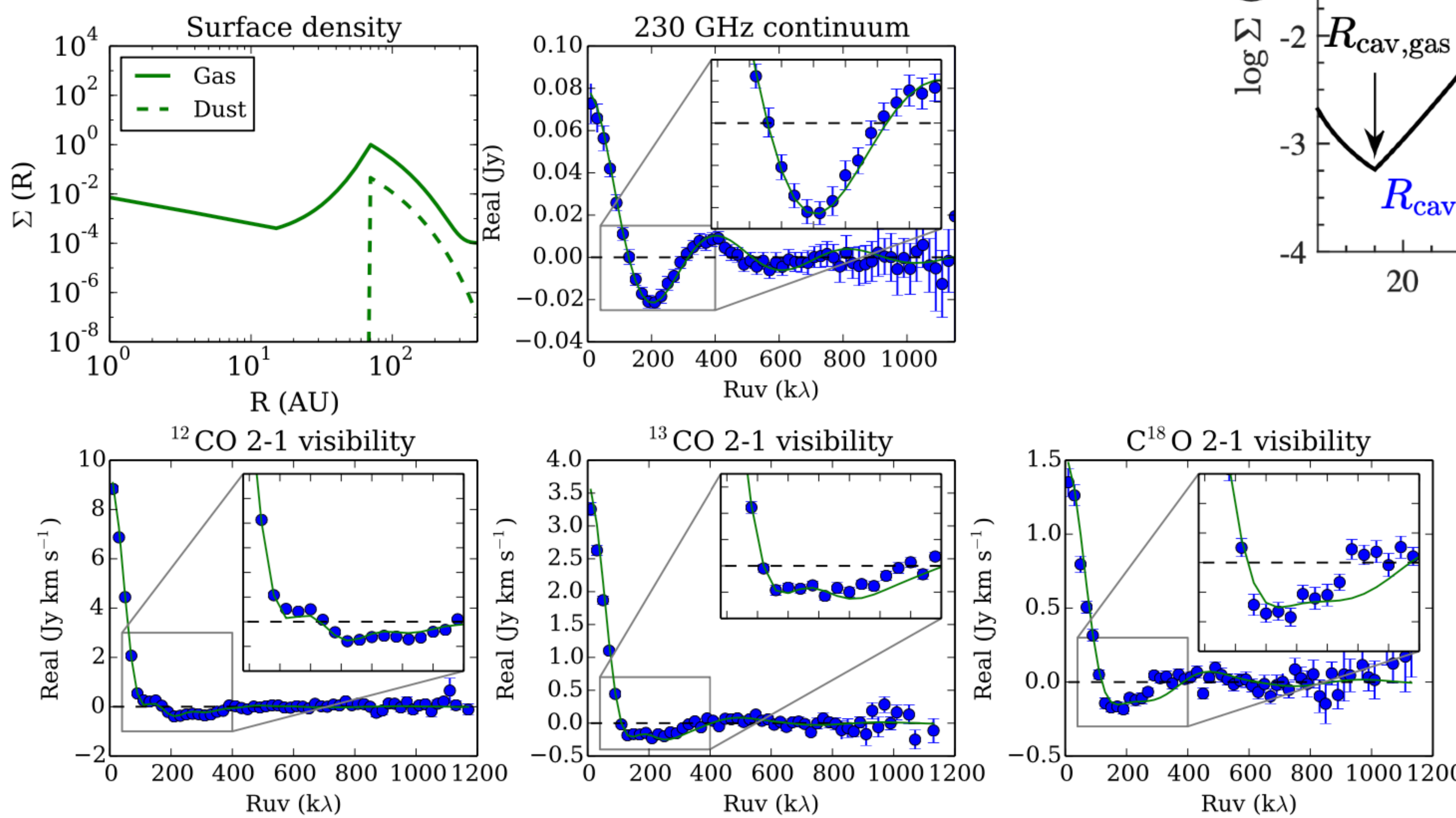
Gas gaps in transition disks

Physical-chemical modeling: gradual drop





Resolved CO isotopologues: evidence for gradual slope

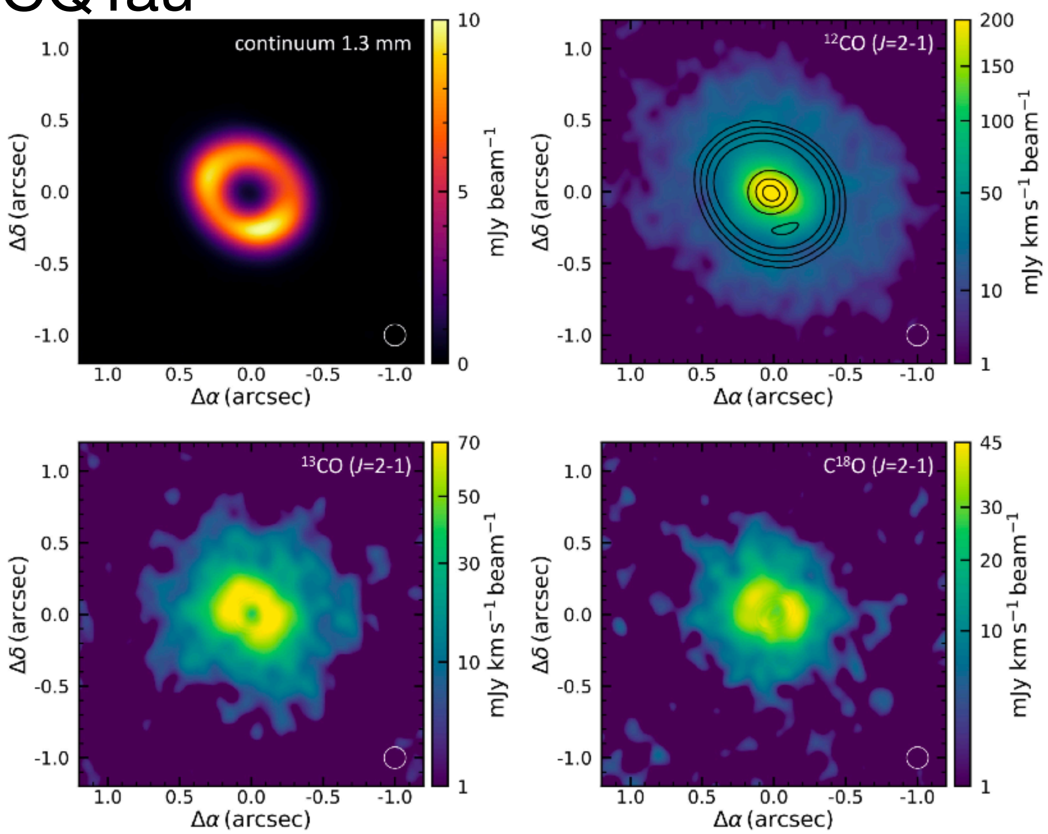


Dong et al. 2017

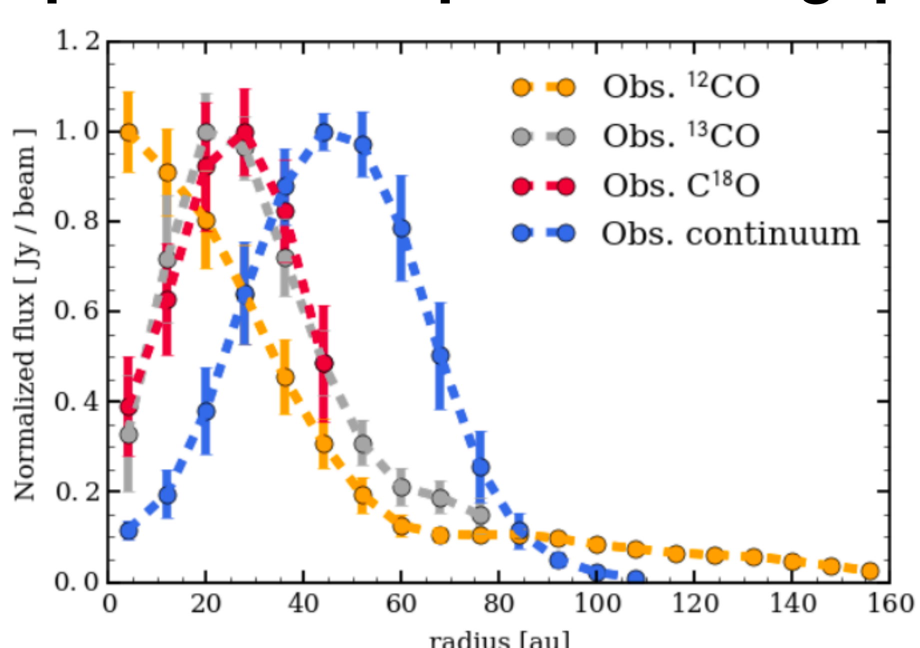
Gas gaps in transition disks

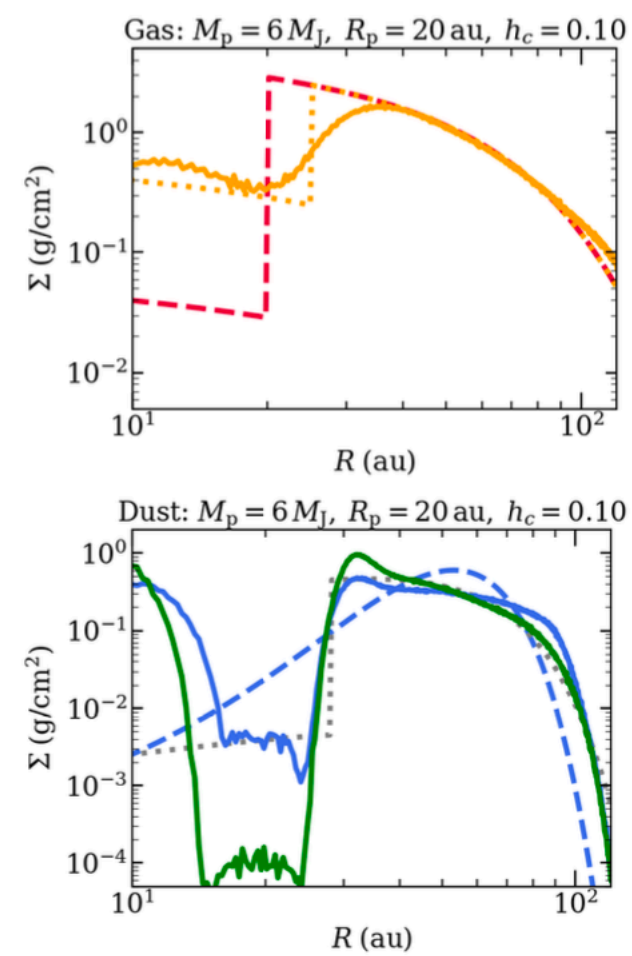
Physical-chemical modeling: gradual drop

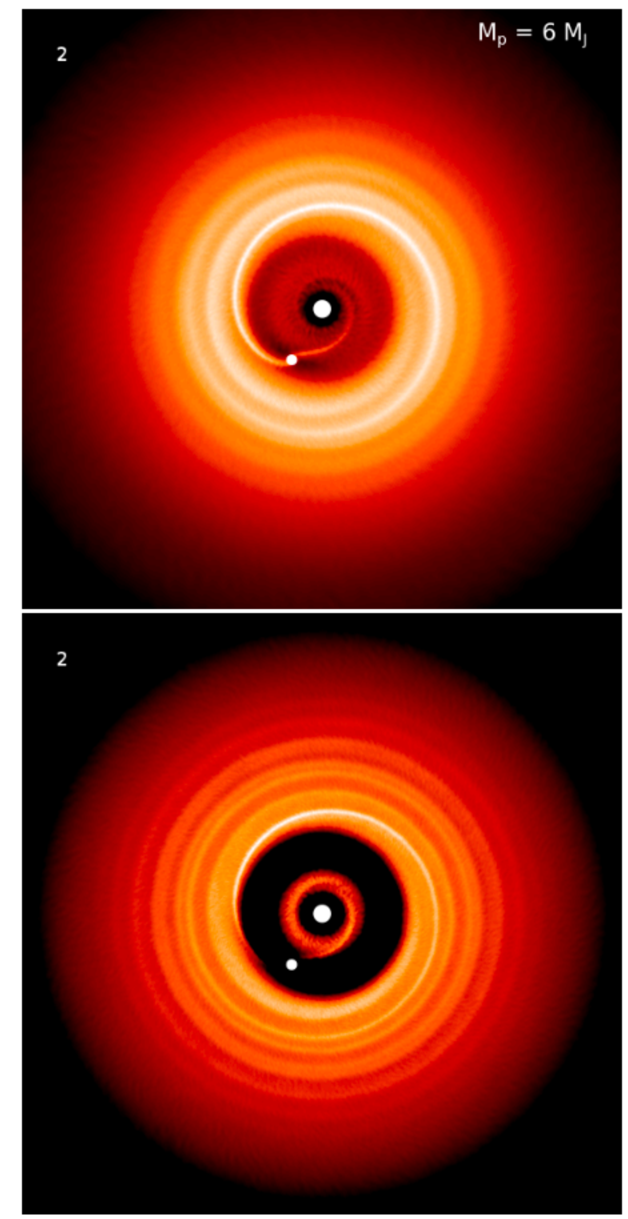
CQTau



Resolved CO isotopologues: comparison with planet-disk gap



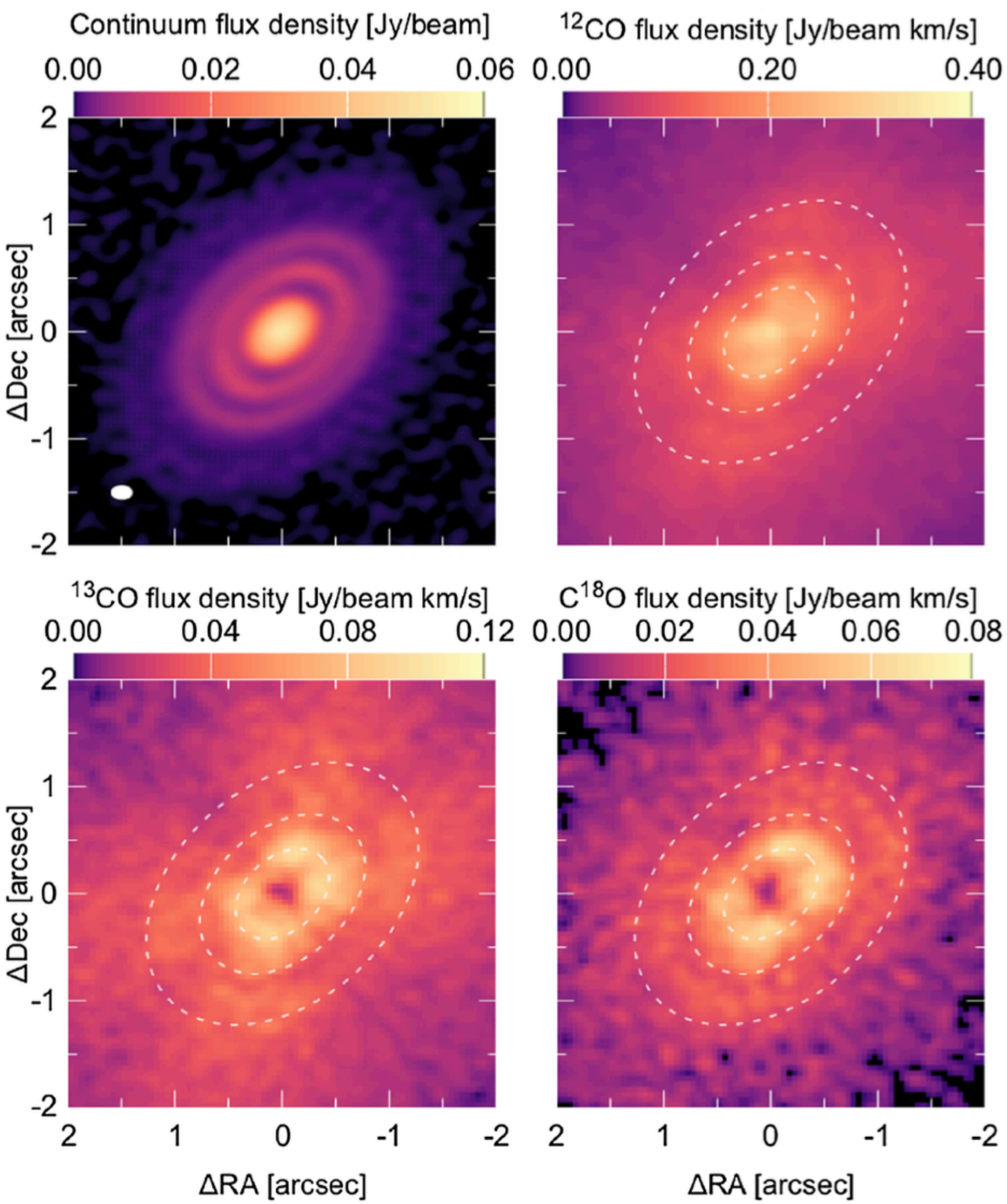




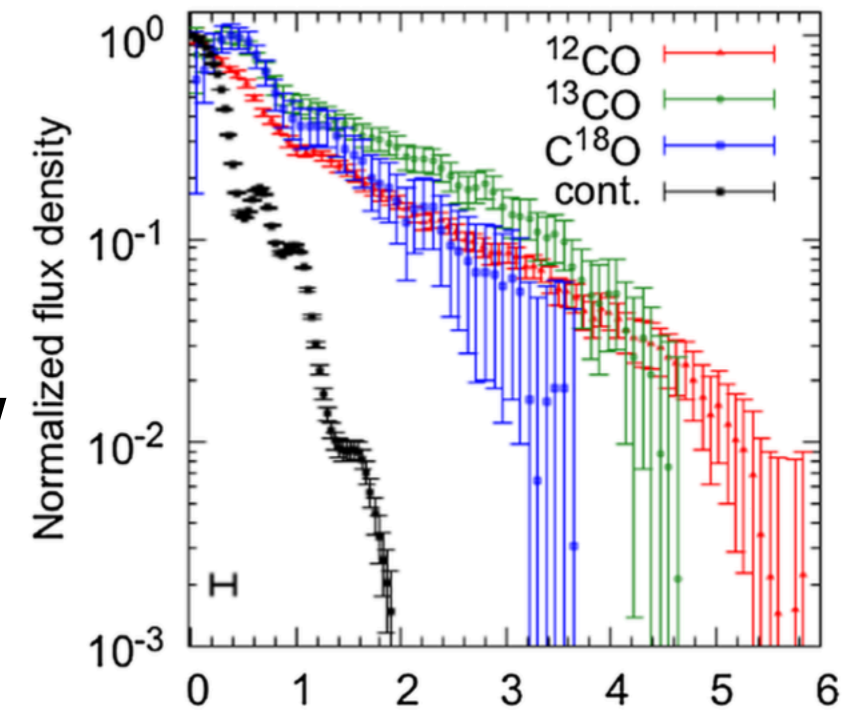
Gabellini et al. 2019

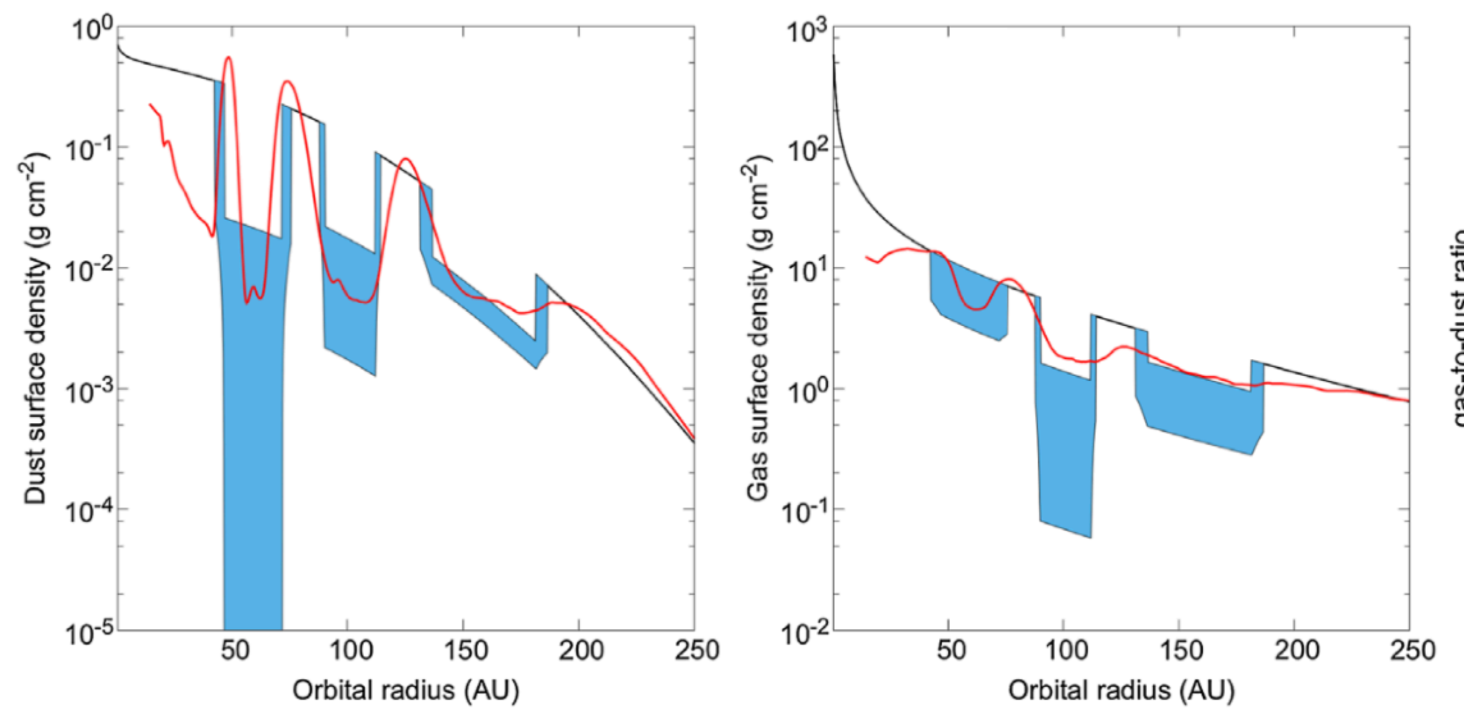
Gas gaps in ring disks?

HD163296



CO isotopologues in HD163296 show dips: gas gaps?

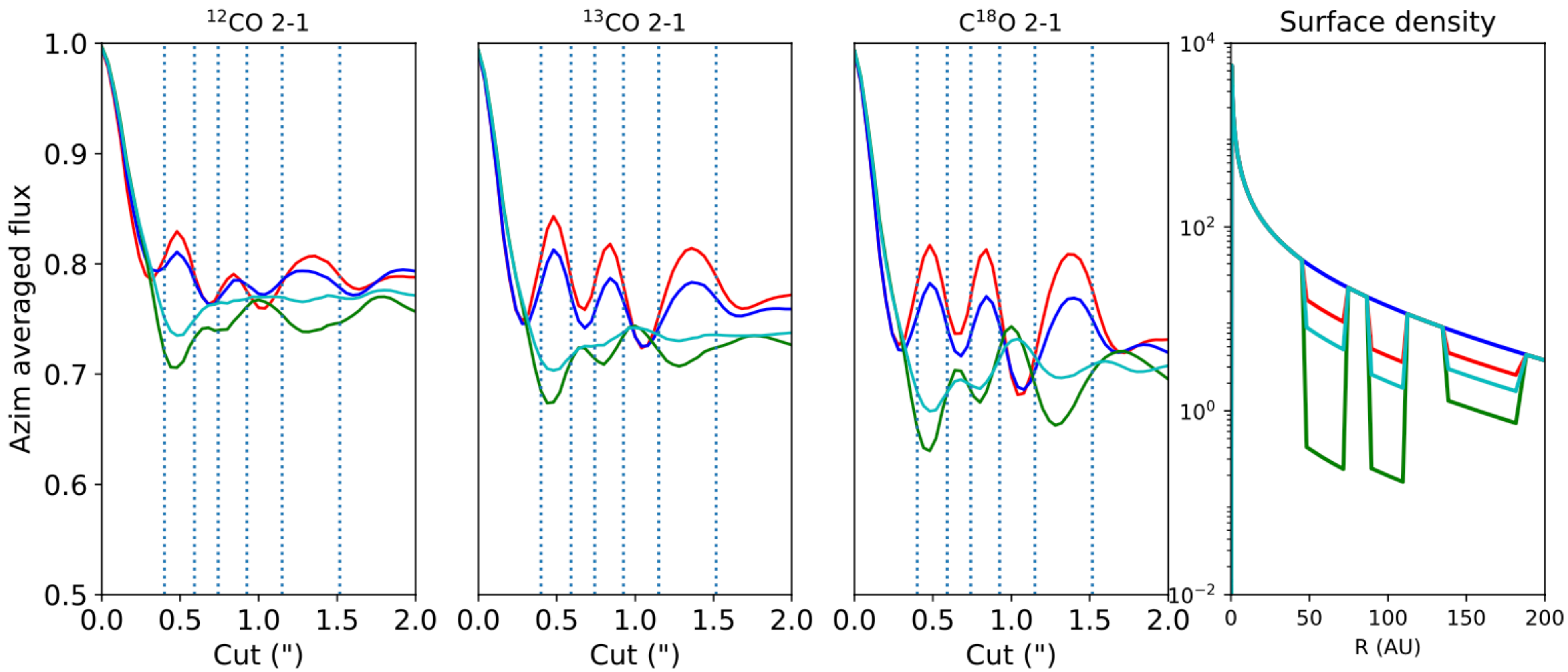




Isella et al. 2016

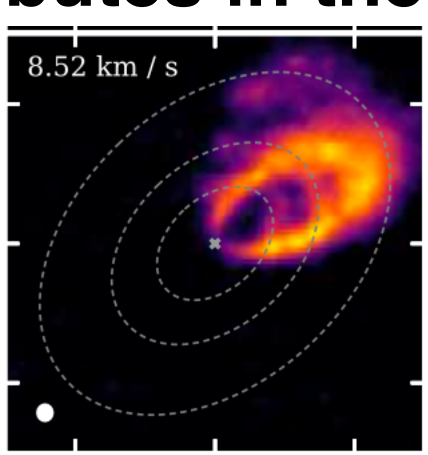
Gas gaps in ring disks?

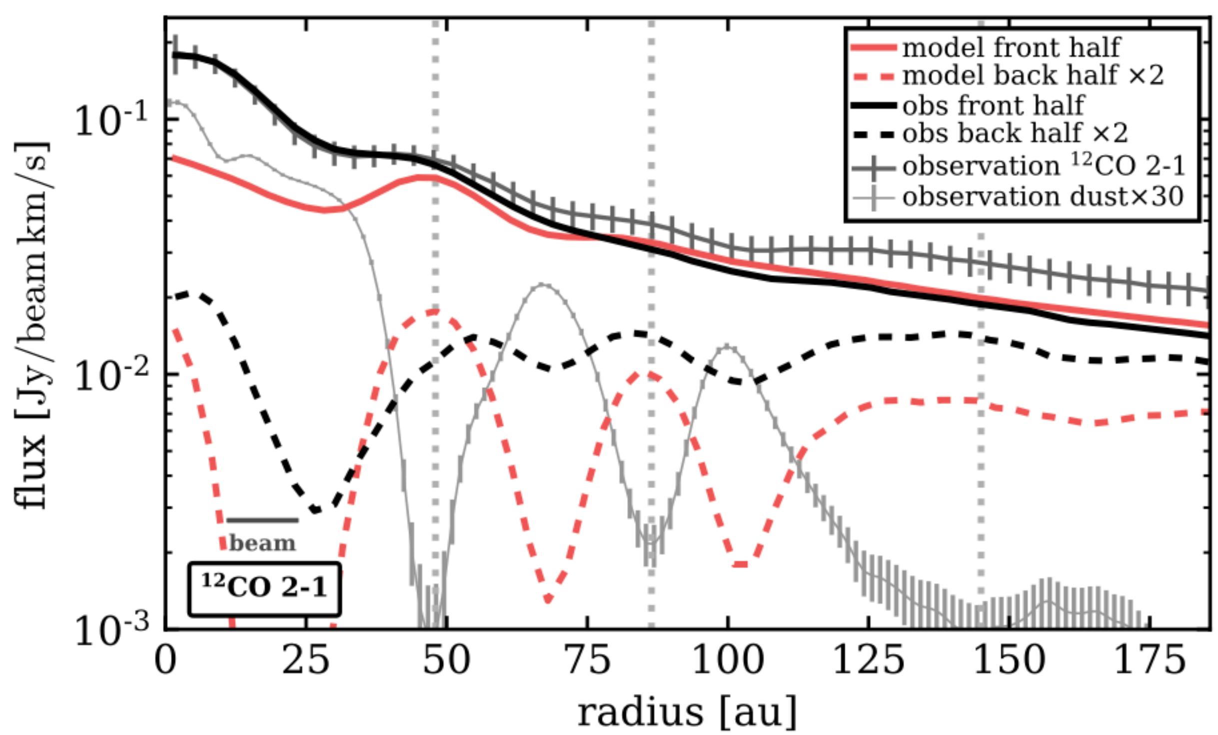
Not as easy as for transition disks



Gas temperature inside gaps changes due to gas-to-dust ratio

CO emission from the back side of the disk contributes in the gaps

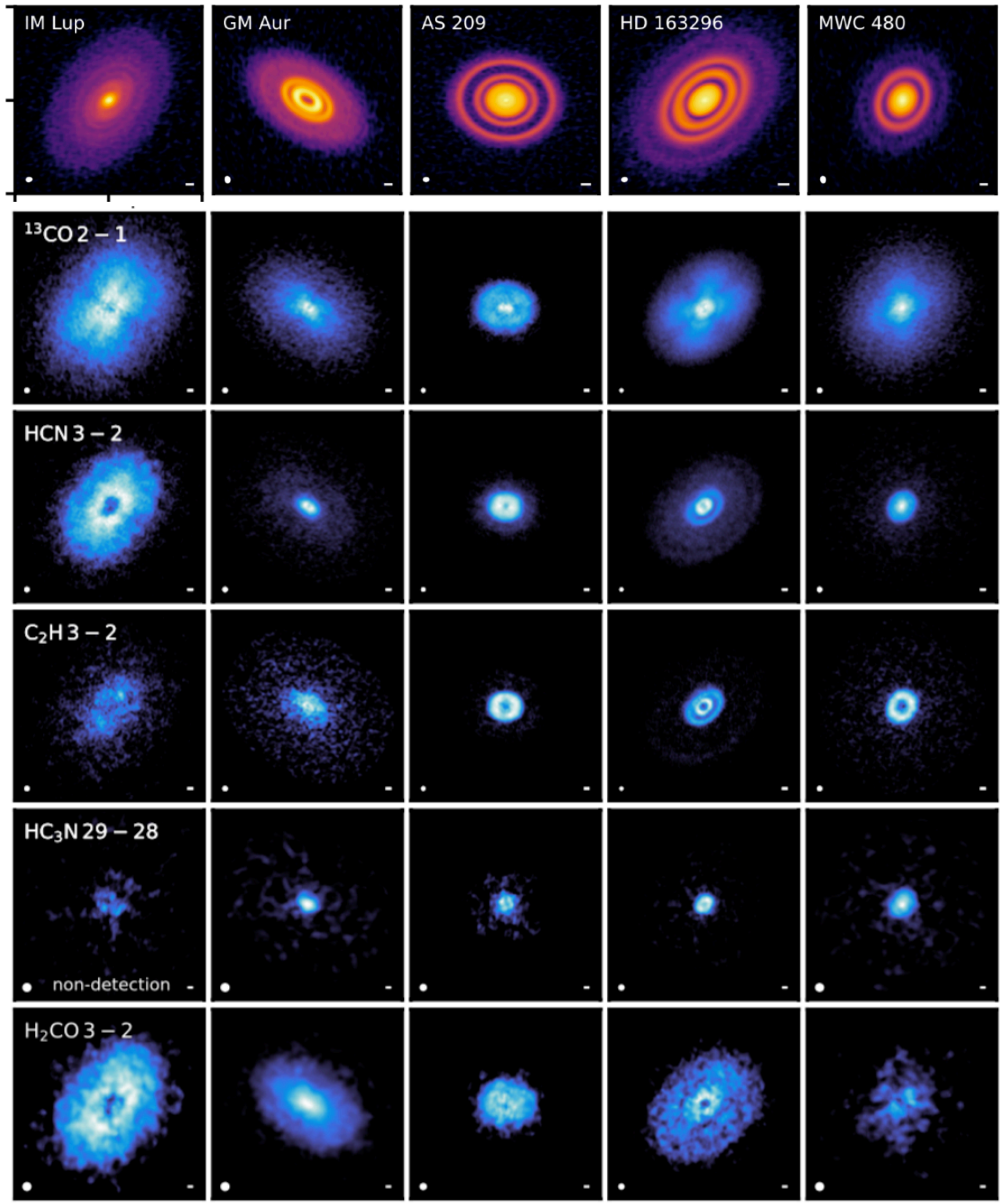




Van der Marel et al. 2019
Rab et al. 2020

Gas gaps in ring disks?

MAPS

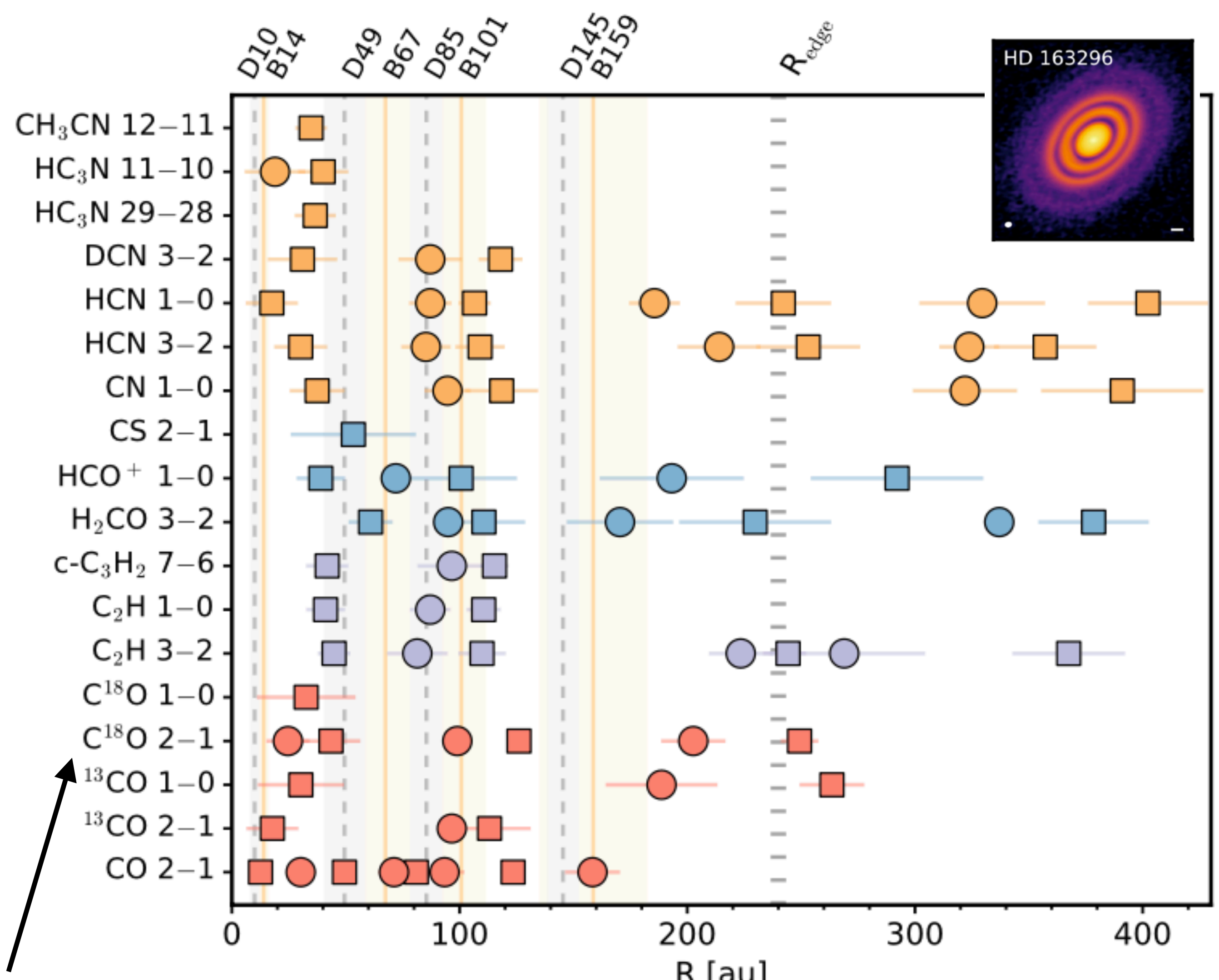


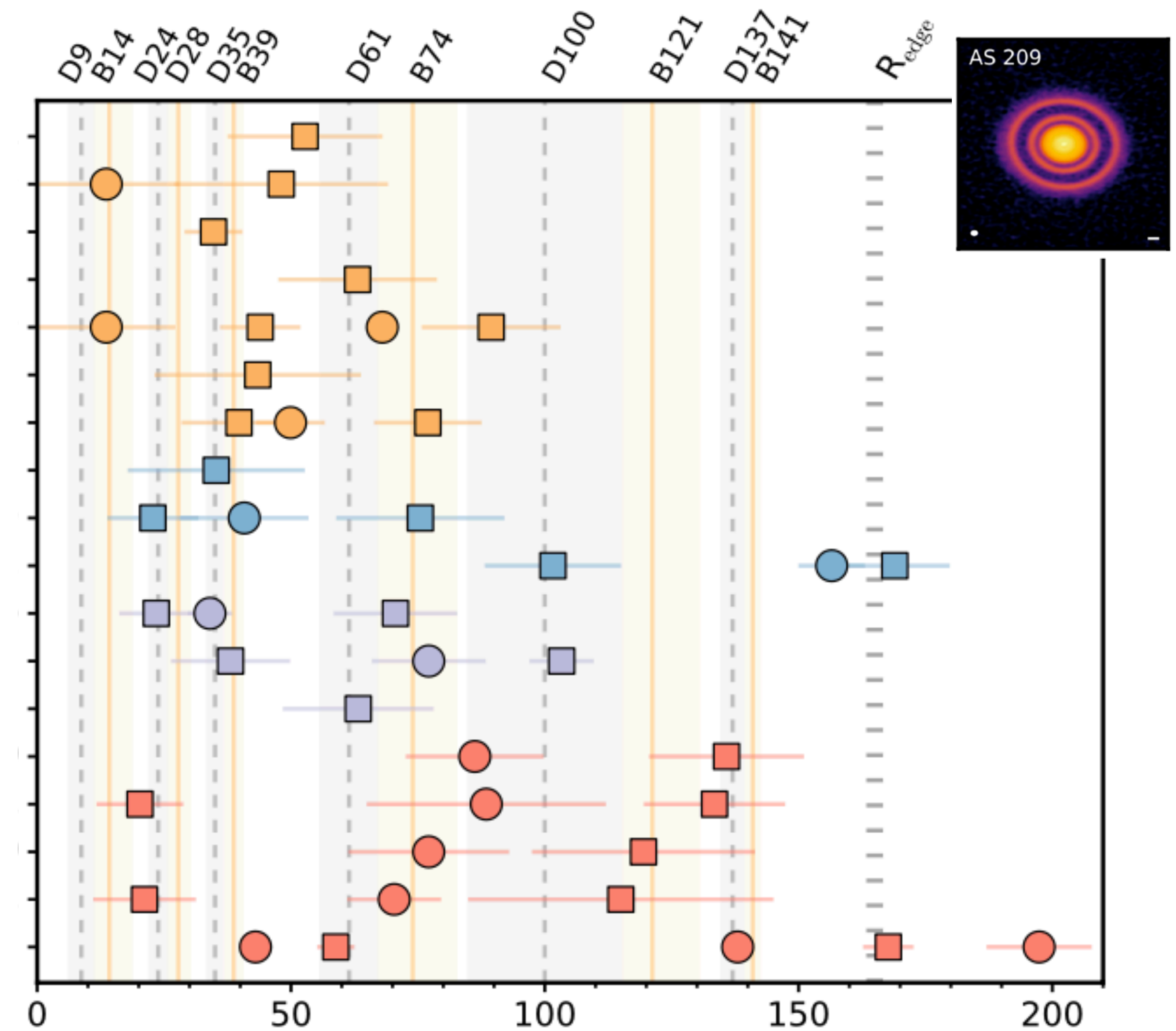
Large diversity in gaps in various molecules

Oberg et al. 2021 (MAPS)

Gas gaps in ring disks?

MAPS





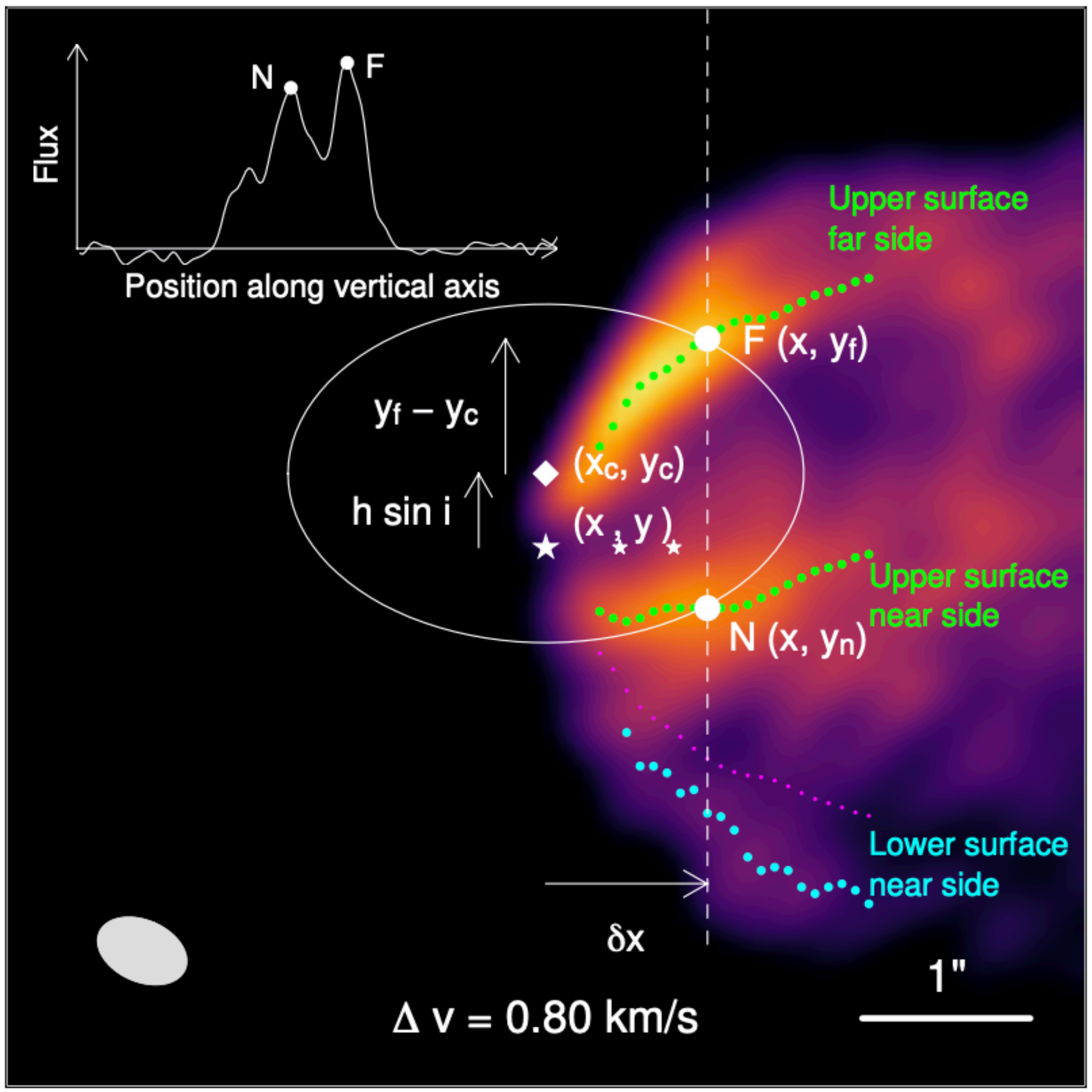
CO isotopologues

Some gaps in molecules overlap with dust, others do not: no clear link and other mechanisms than gap clearing may be responsible

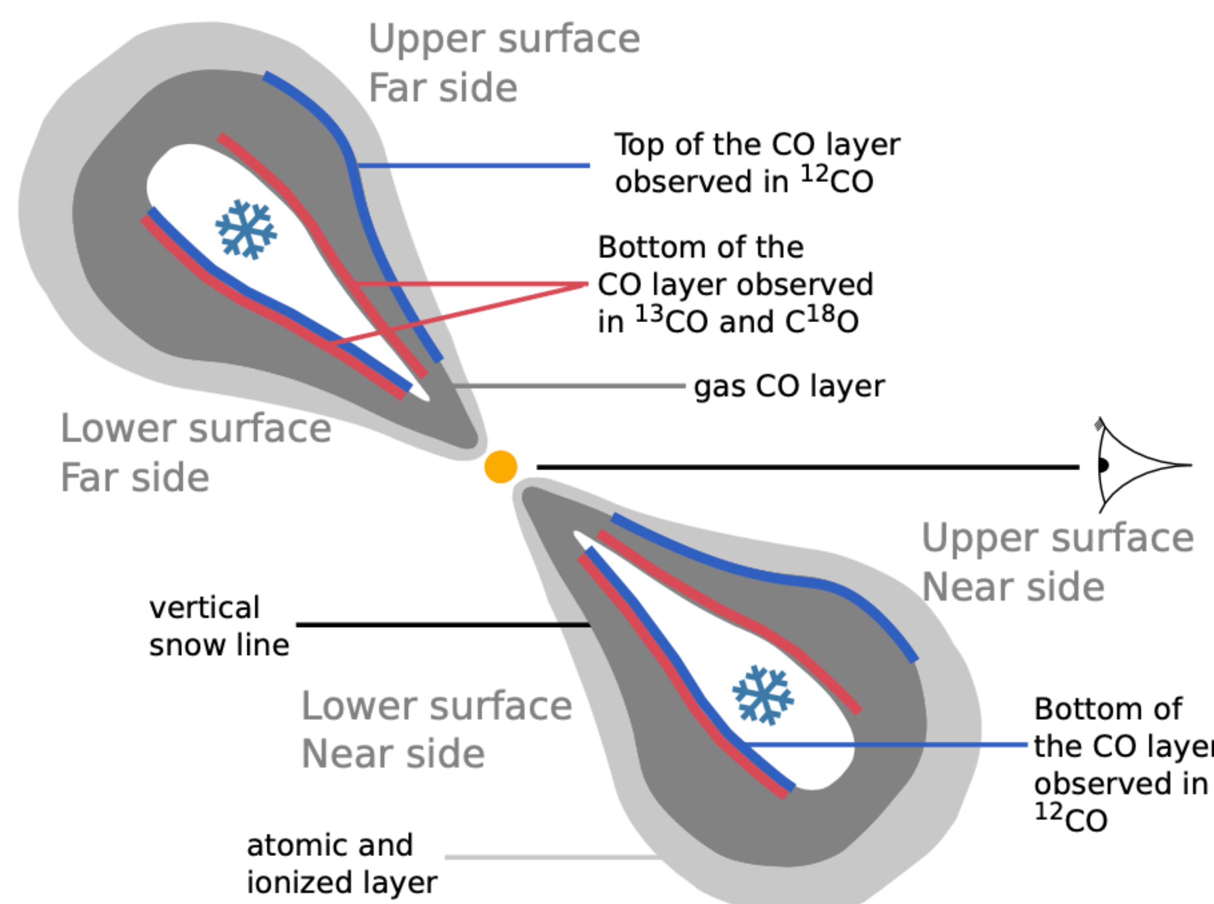
Law et al. 2021 (MAPS)
Jiang et al. 2021

Vertical structure

Inclined disks: use channels



With high spatial and spectral resolution, it is possible to extract the emitting surface height directly from the peak emission in each channel

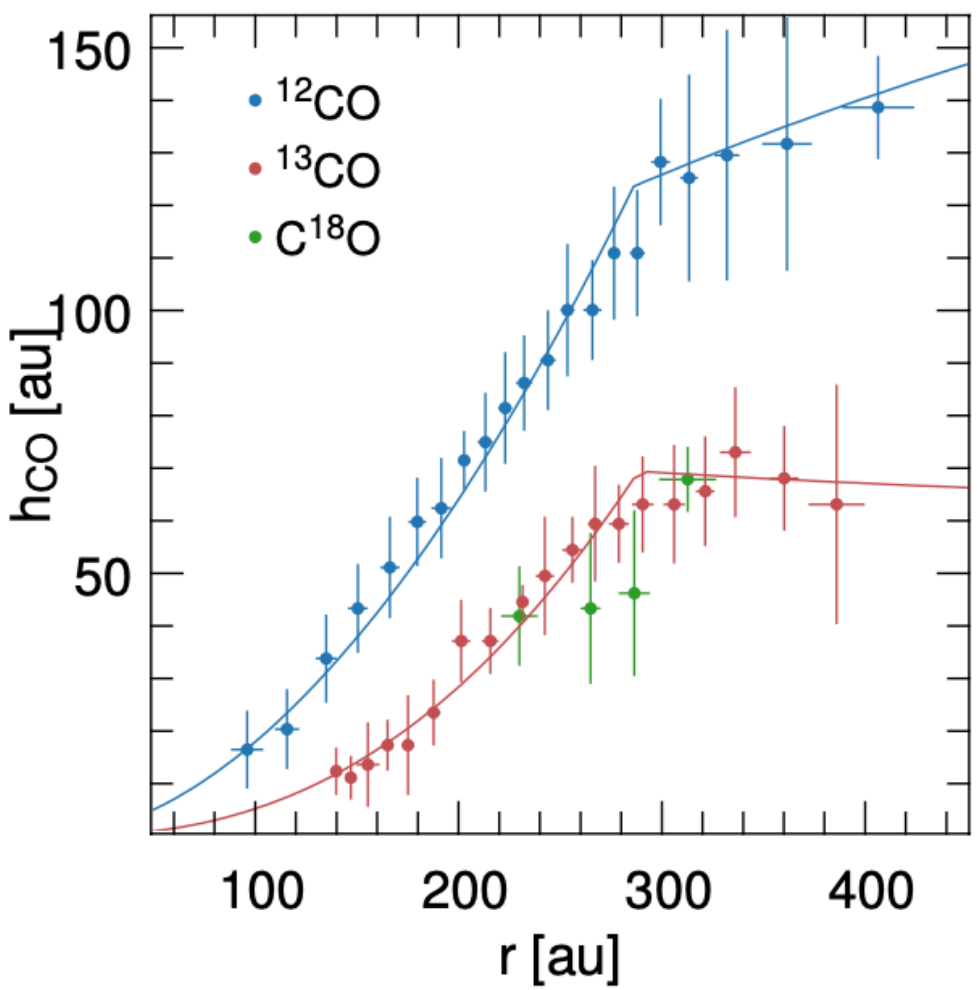


Pinte et al. 2018

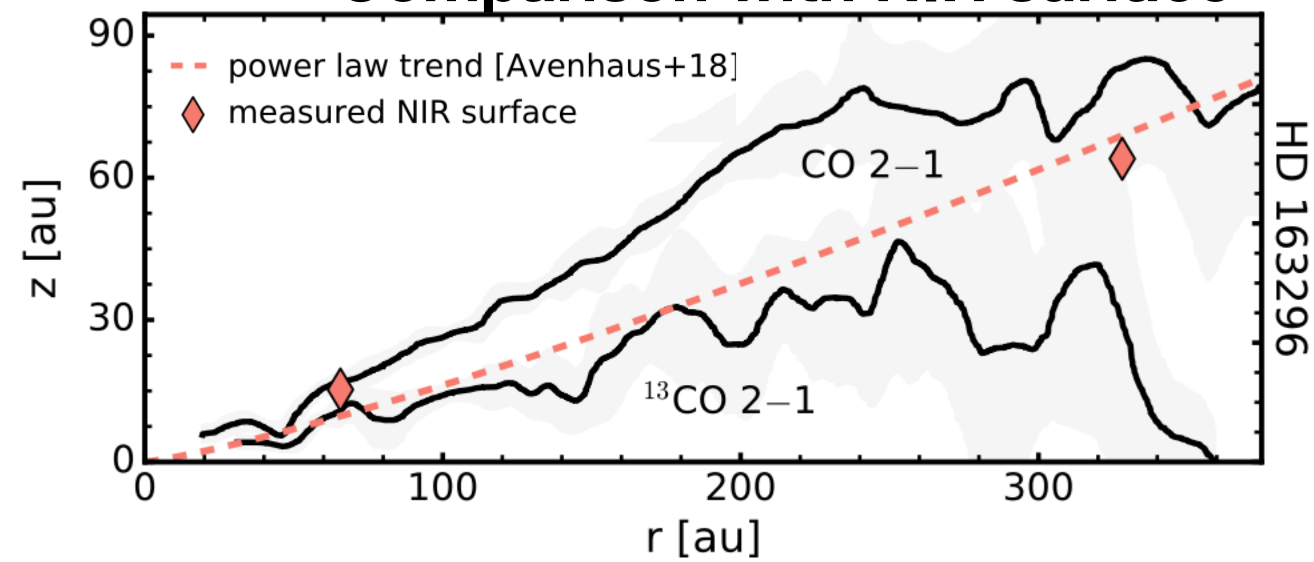
Vertical structure

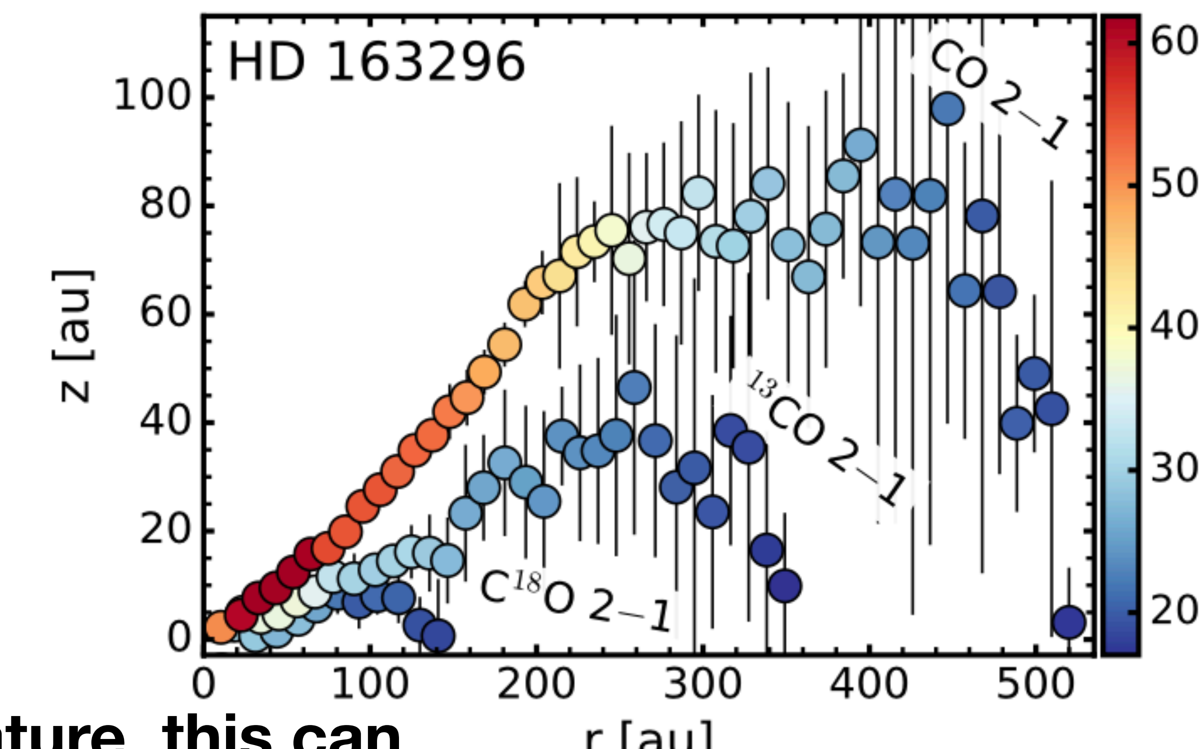
Inclined disks

Different CO isotopologues show different heights (optical depth)



Comparison with NIR surface



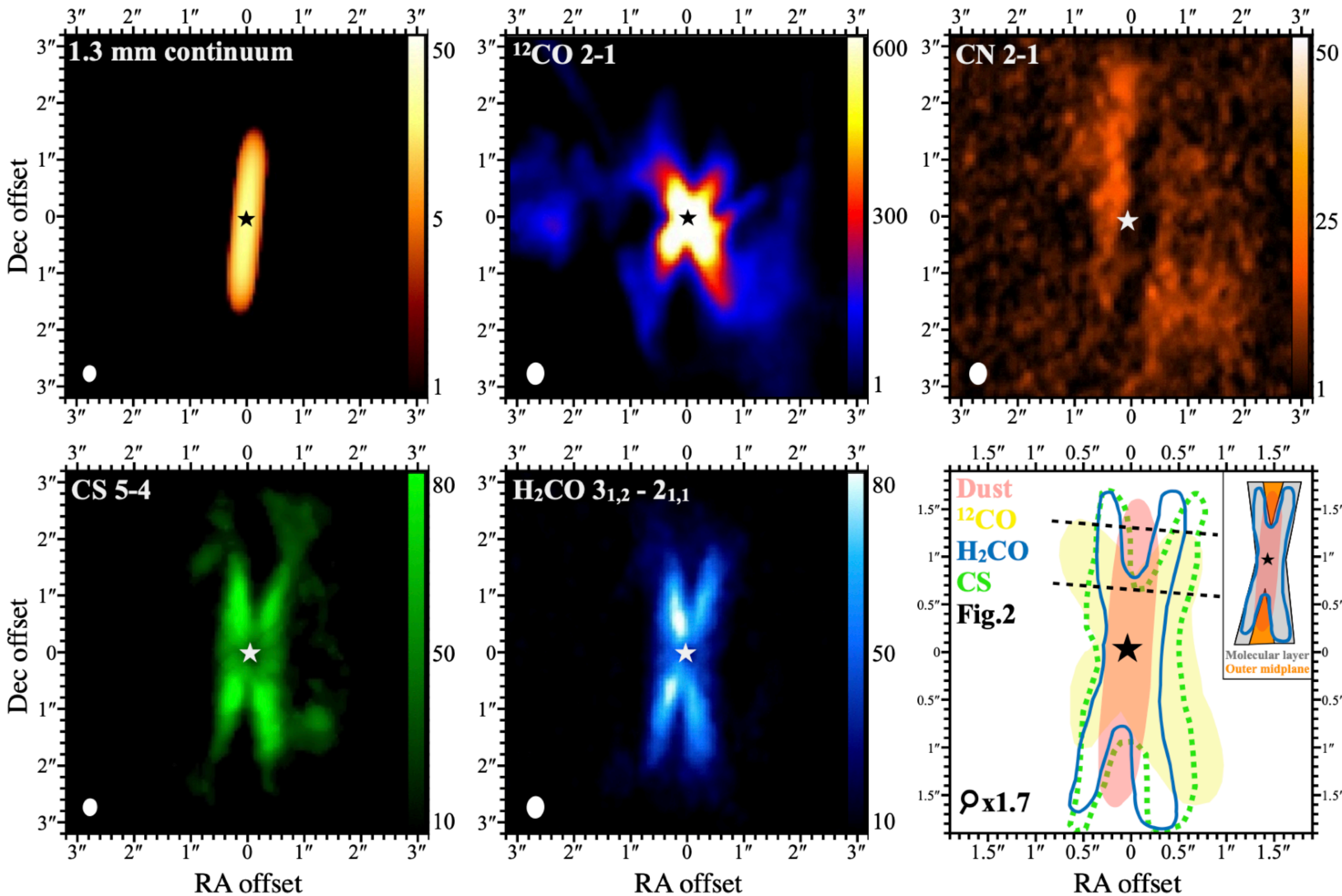


In combination with fits to the temperature, this can constrain the temperature structure in the disk, rather than calculating it with a radiative transfer model

Pinte et al. 2018
Law et al. 2021,2022

Other molecules

Edge-on disks: vertical structure



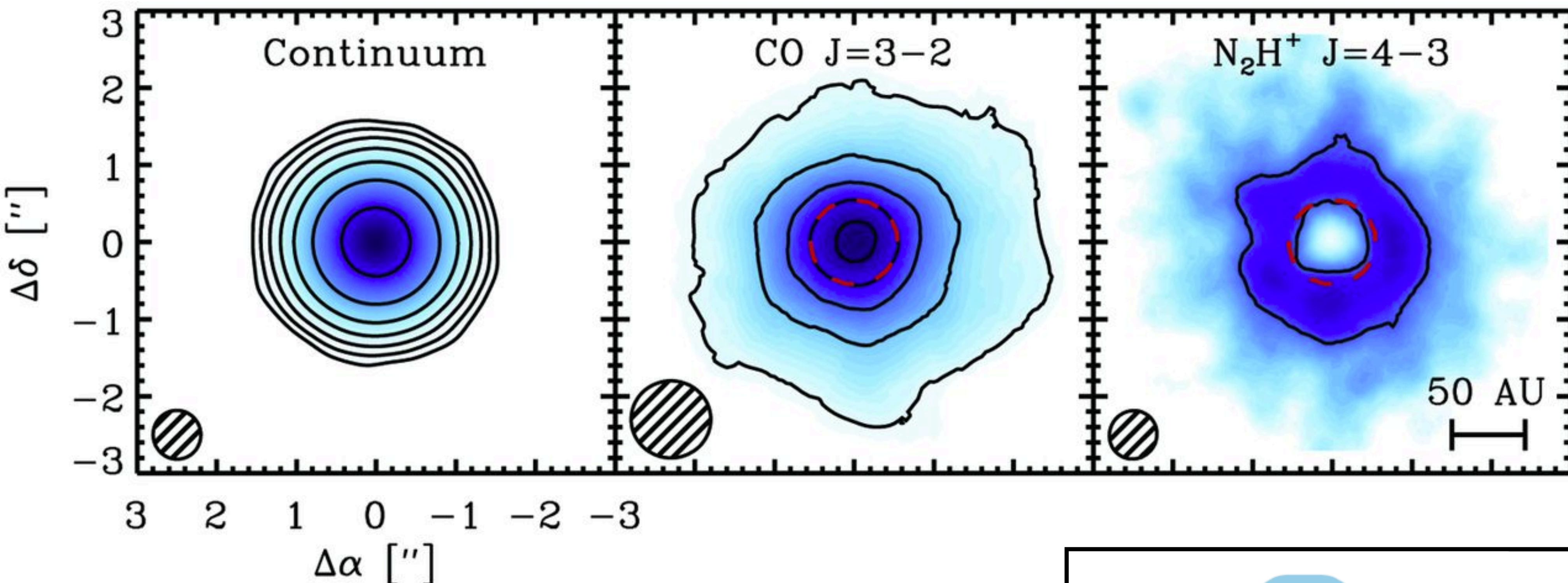
In edge-on disks it is possible to resolve the vertical structure of the molecules: temperature structure

Podio et al. 2020

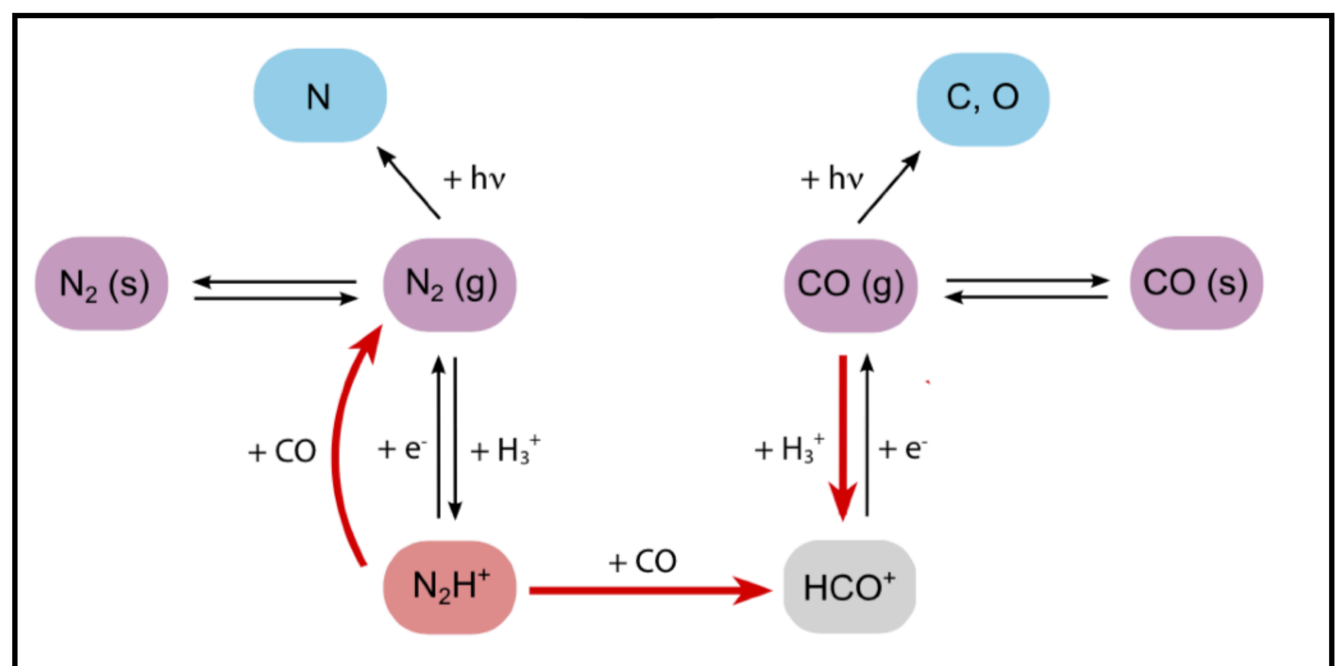
Why do we need snowline tracers in disks?

Other molecules

Snowline tracers: N_2H^+



Disk with an N_2H^+ ring:
CO snowline (T_{subl}~22 K)?
=> N_2H^+ can only form when CO is frozen out

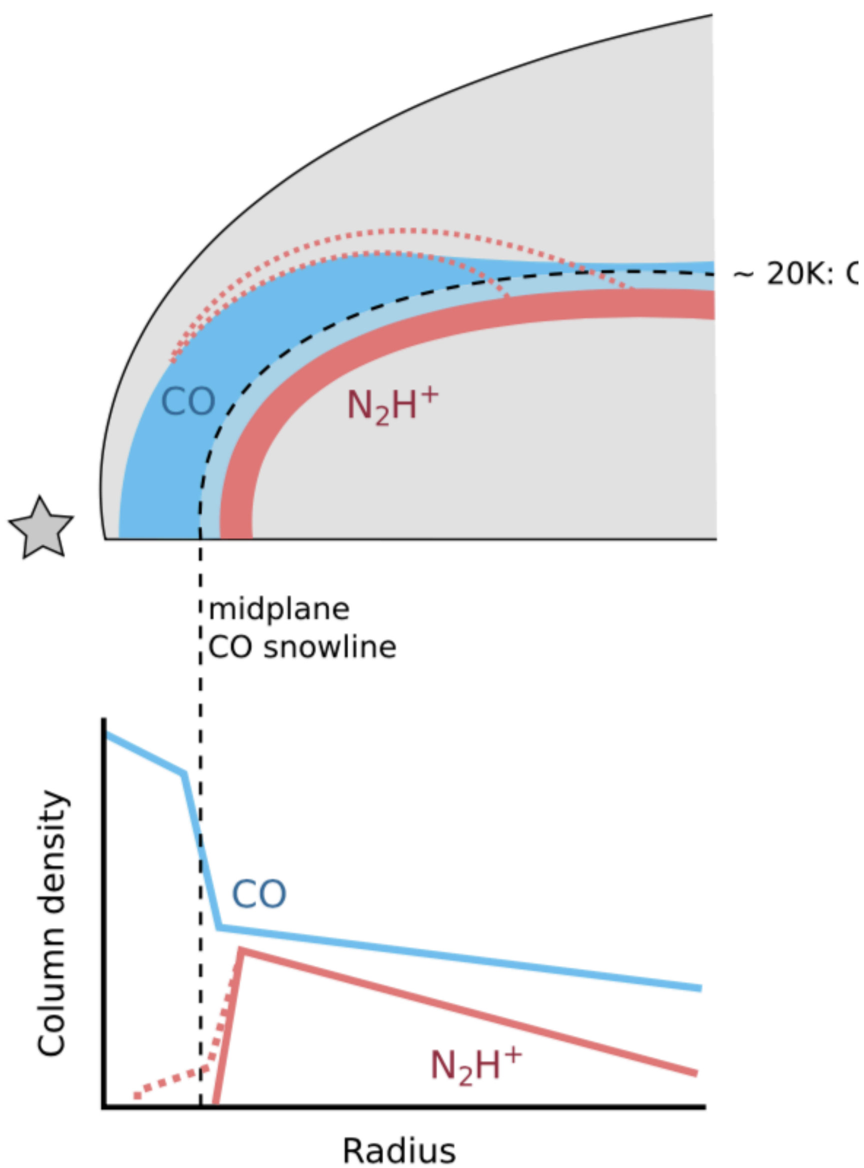


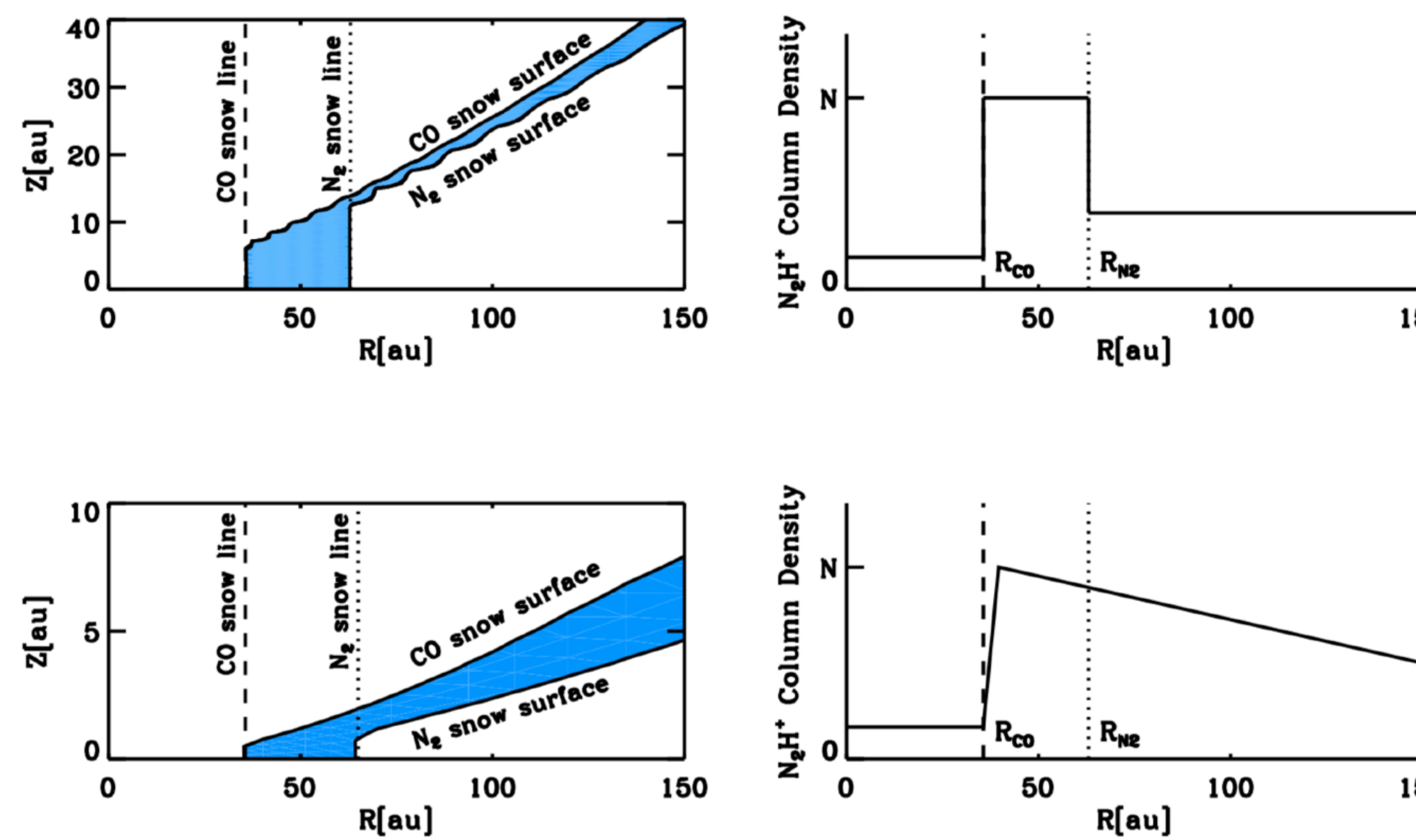
Qi et al. 2013
Van t Hoff et al. 2016

Other molecules

Snowline tracers: N_2H^+

Detailed modeling: CO snowline is actually CO snow surface in 2D disk
=> interpretation N_2H^+ not straight-forward



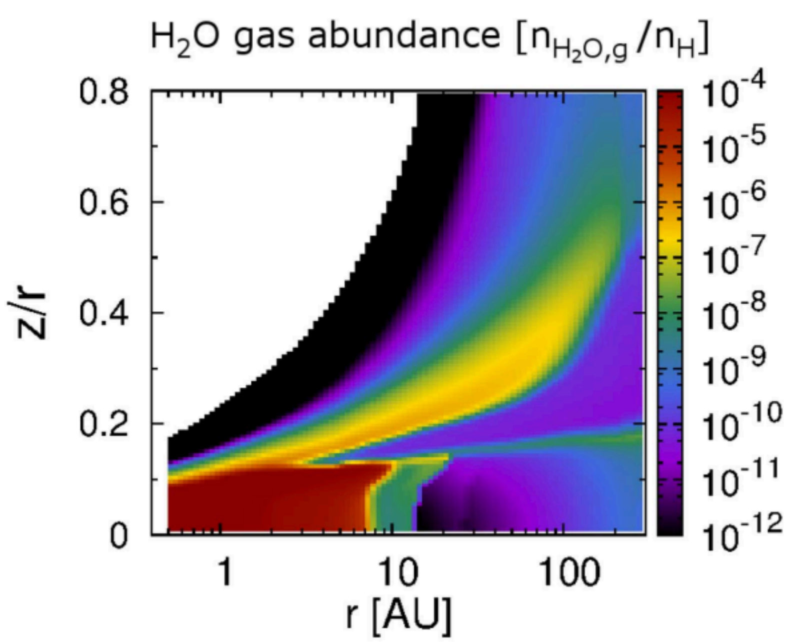


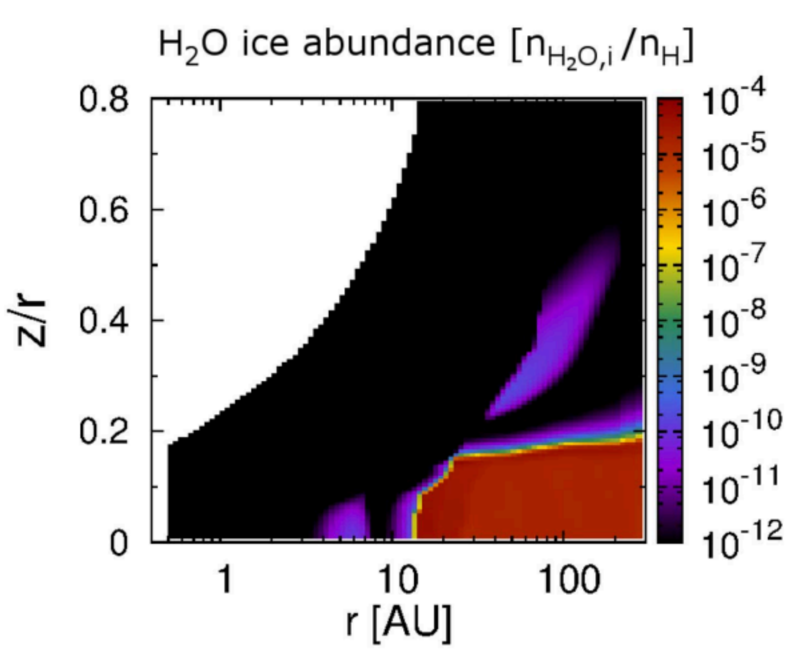
Van t Hoff et al. 2017
Qi et al. 2019

Other molecules

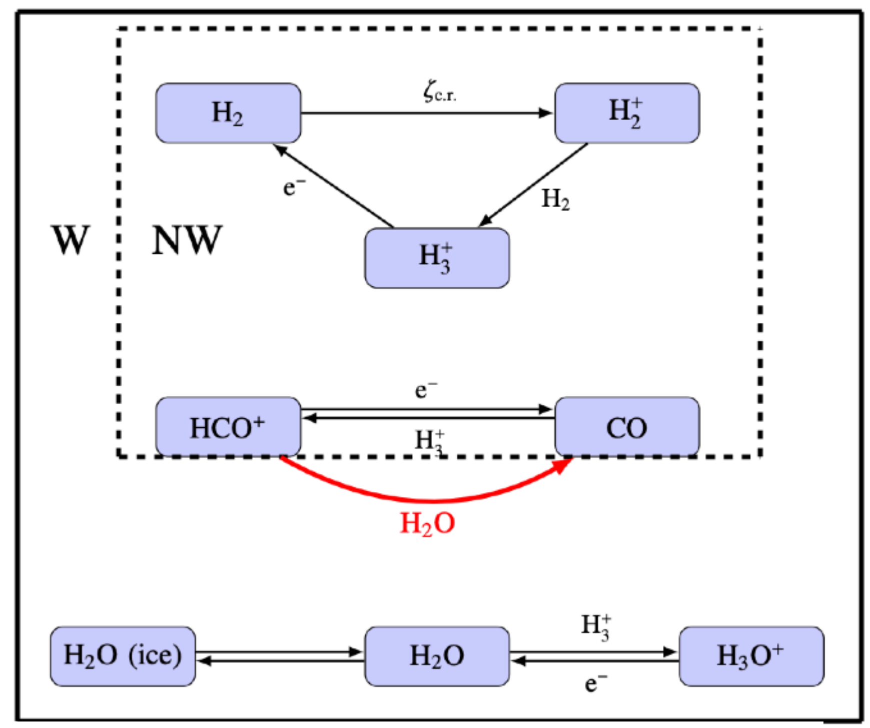
Snowline tracers: HCO^+

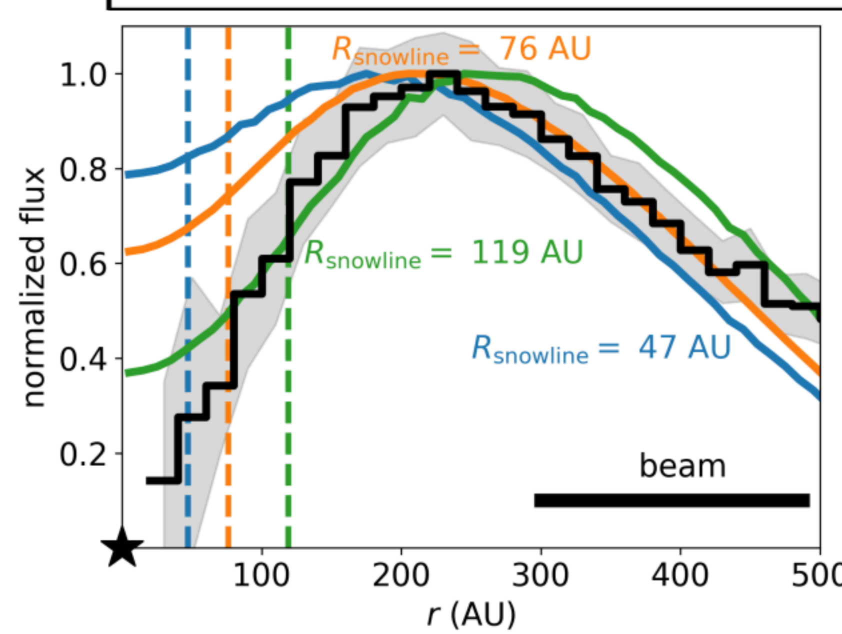
H_2O snowline (T_{subl}~120 K) tricky: close to host star and inaccessible from ground

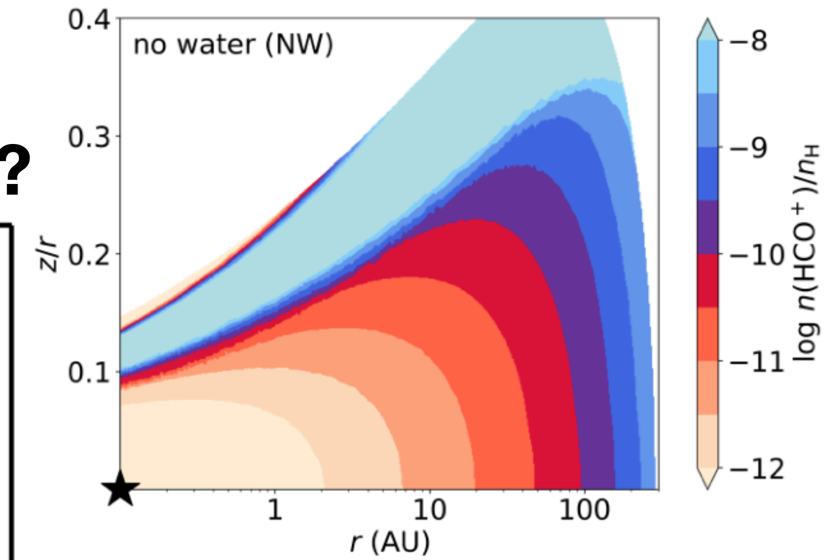


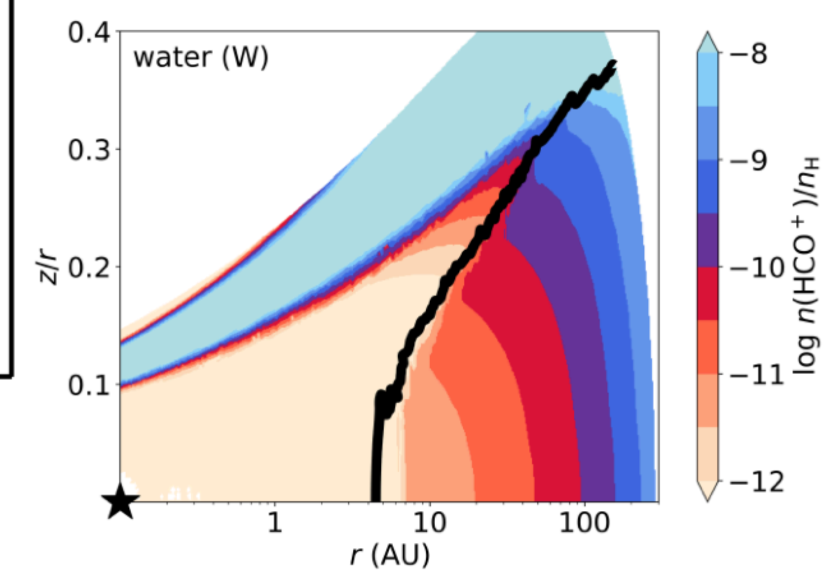


HCO^+ as tracer?









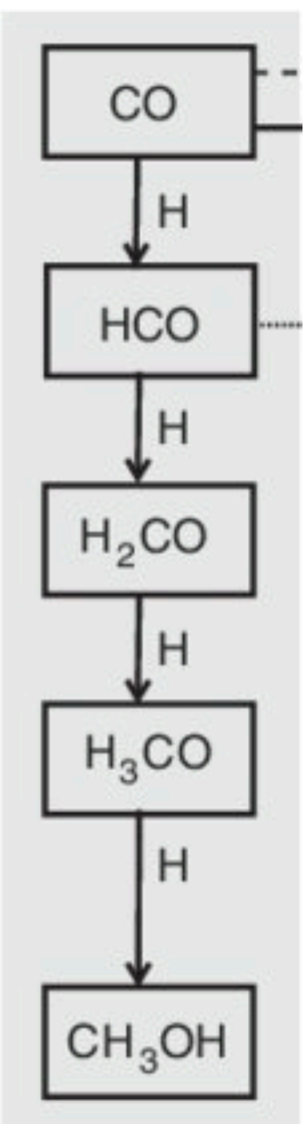
V883 Ori: outburst (100*brighter): Snowline further out!

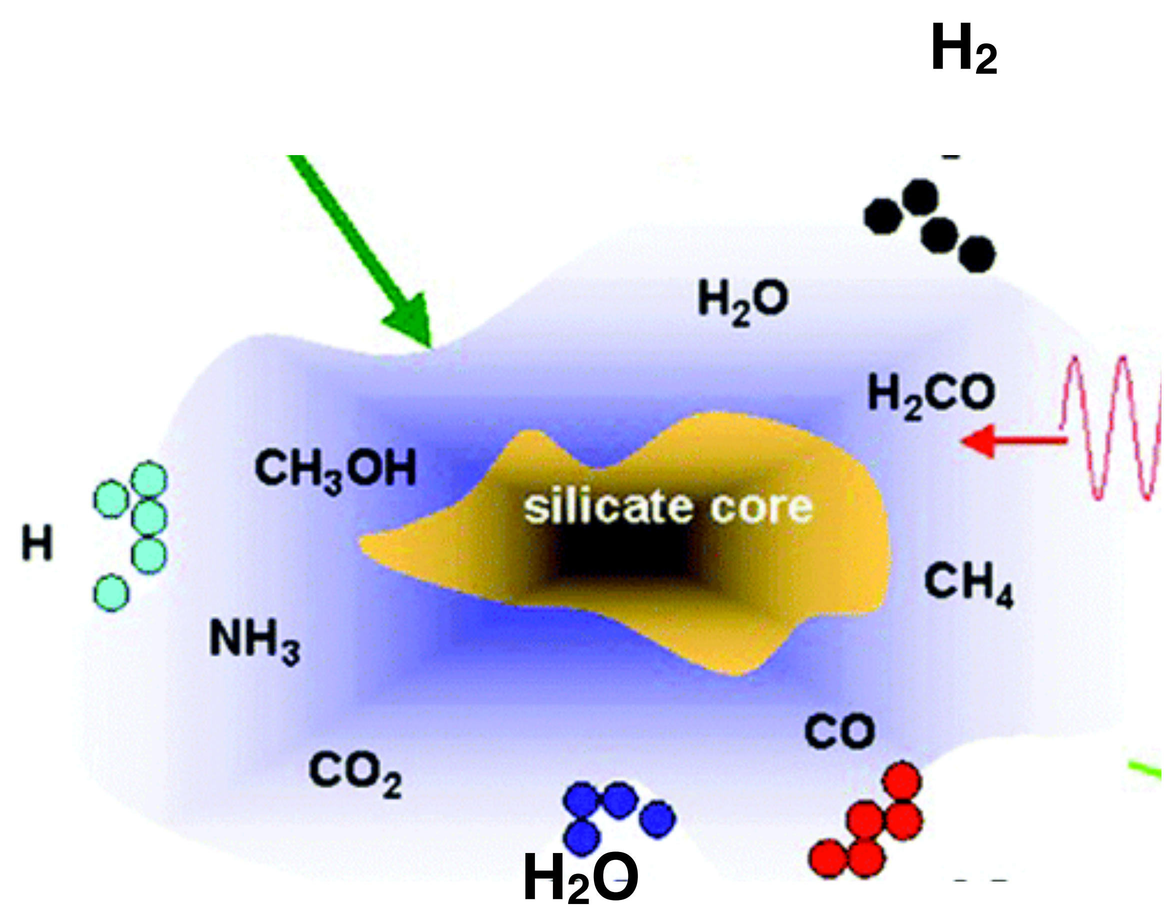
Notsu et al. 2017
Van t Hoff et al. 2018
Leemker et al. 2021

Other molecules

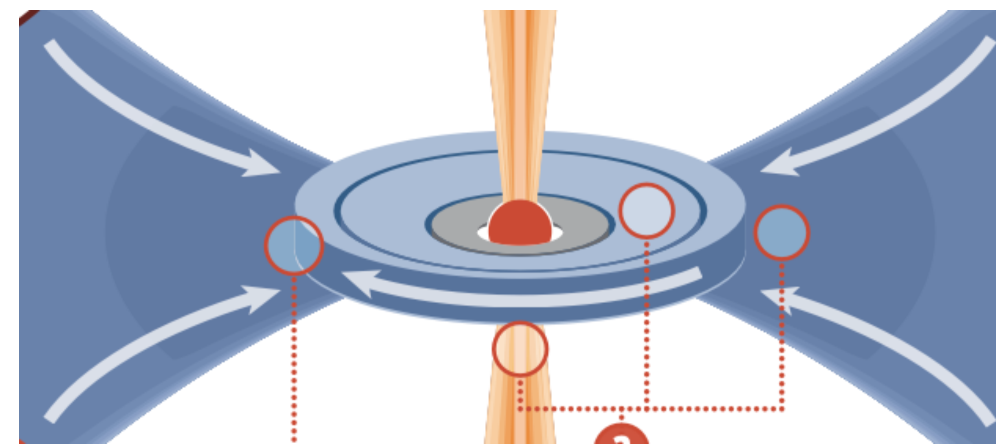
COMs

Complex Organic Molecules formed in CO ice on grains and sublimated at T>100 K (or strong UV), e.g. CH_3OH





Hydrogenation of CO-ice

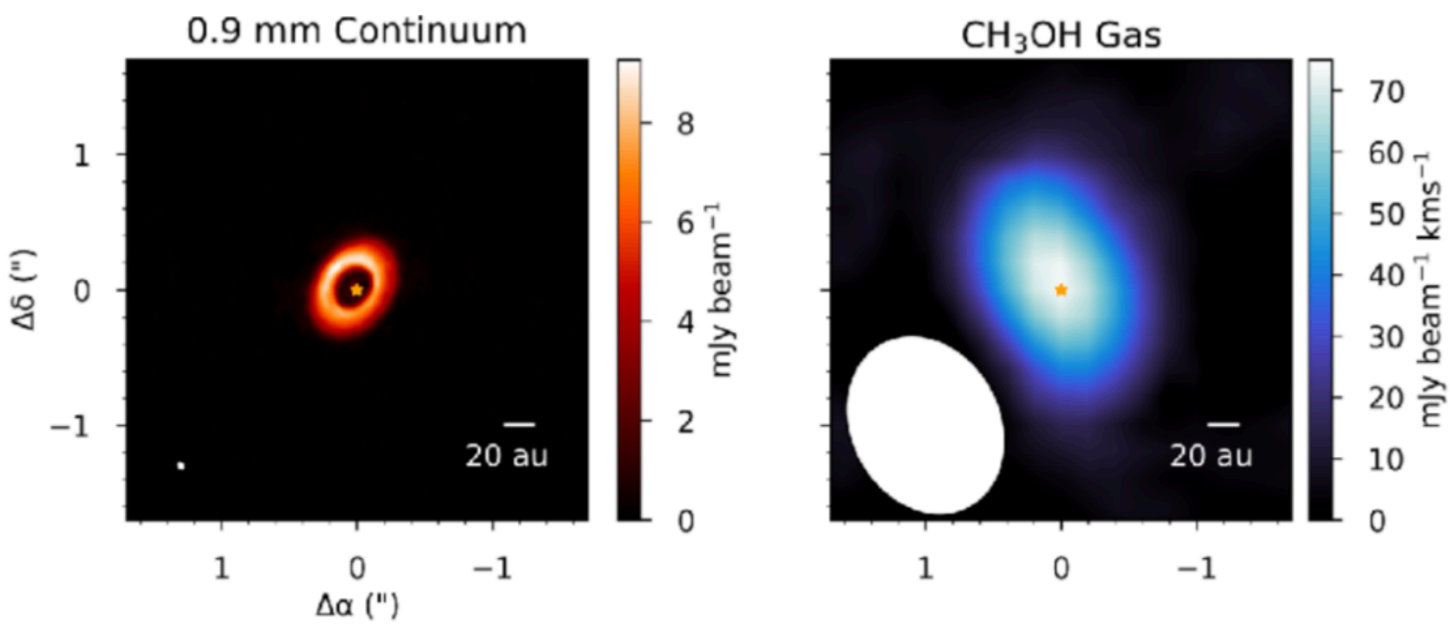


Commonly found in protostellar envelopes (cold environment), but not in disks: **frozen out** or **destroyed** in disk**?**

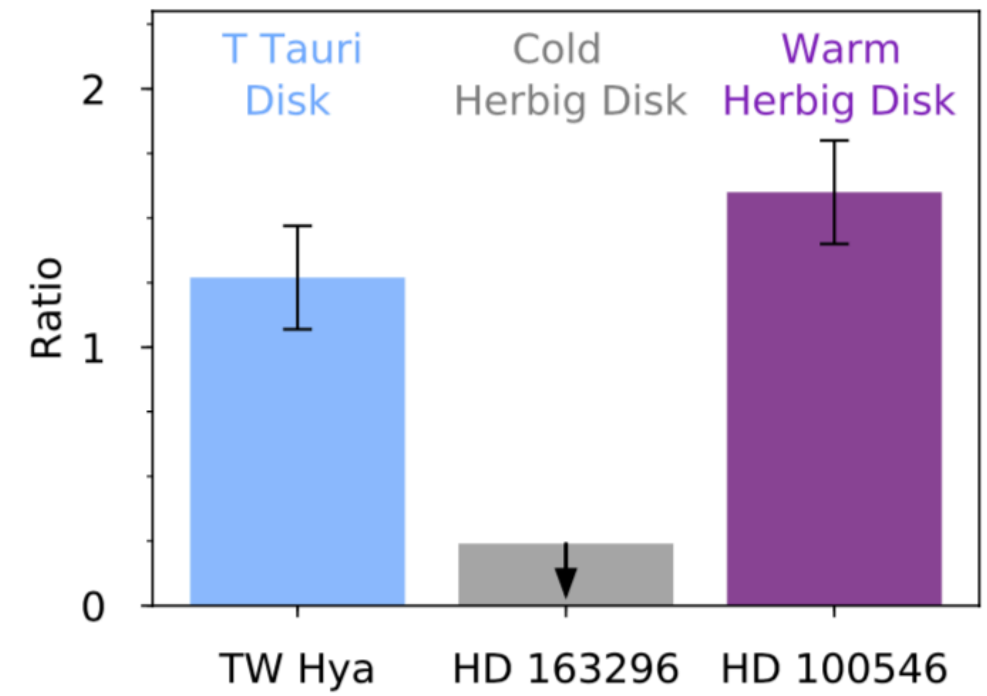
Oberg & Bergin 2020

Other molecules

COMs: strong detection CH_3OH in HD100546



CH_3OH/H_2CO

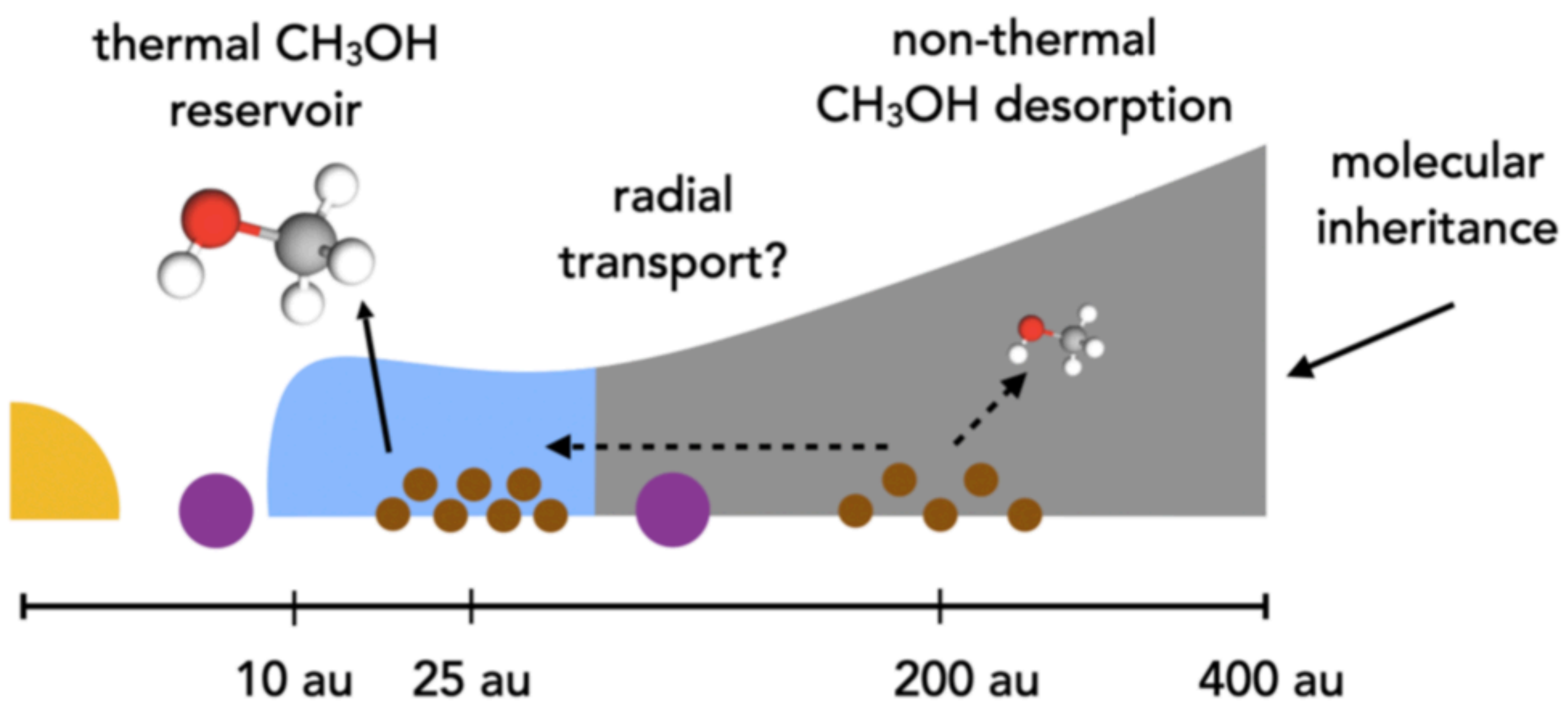


10^{-12} $<10^{-12}$ 10^{-8}

$[CH_3OH]$

Much higher abundance than other disks

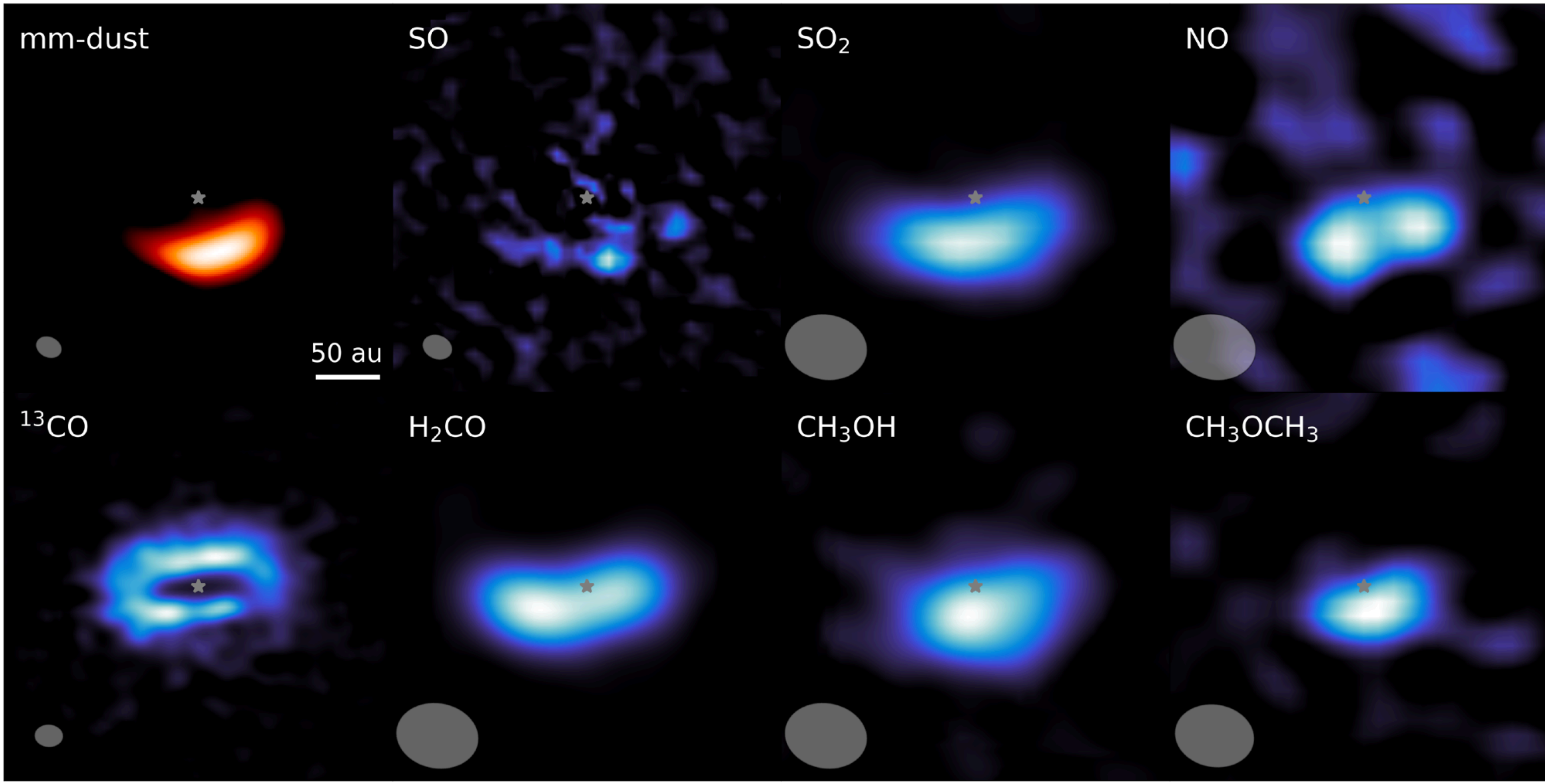
Inheritance cloud?



Booth et al. 2021a

Other molecules

COMs in IRS48



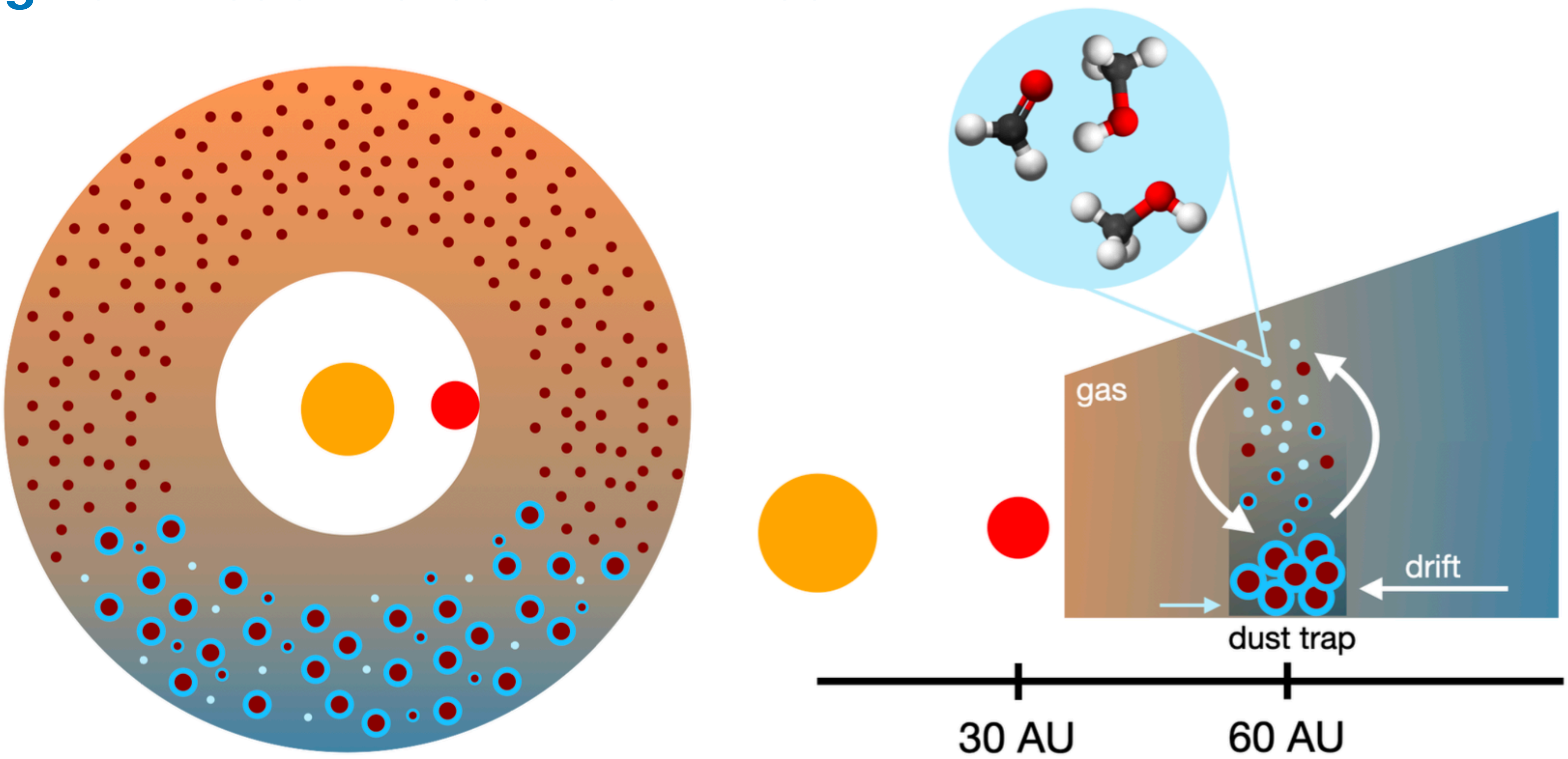
Ice-produced molecules (all but CO) are cospatial with dust trap

Van der Marel et al. 2021b
Booth et al. 2021
Brunken et al. 2022
Leemker et al. 2023

Other molecules

COMs in IRS48: dust transport?

COM-icy pebbles transported inwards through drift: sublimated when T>150 K

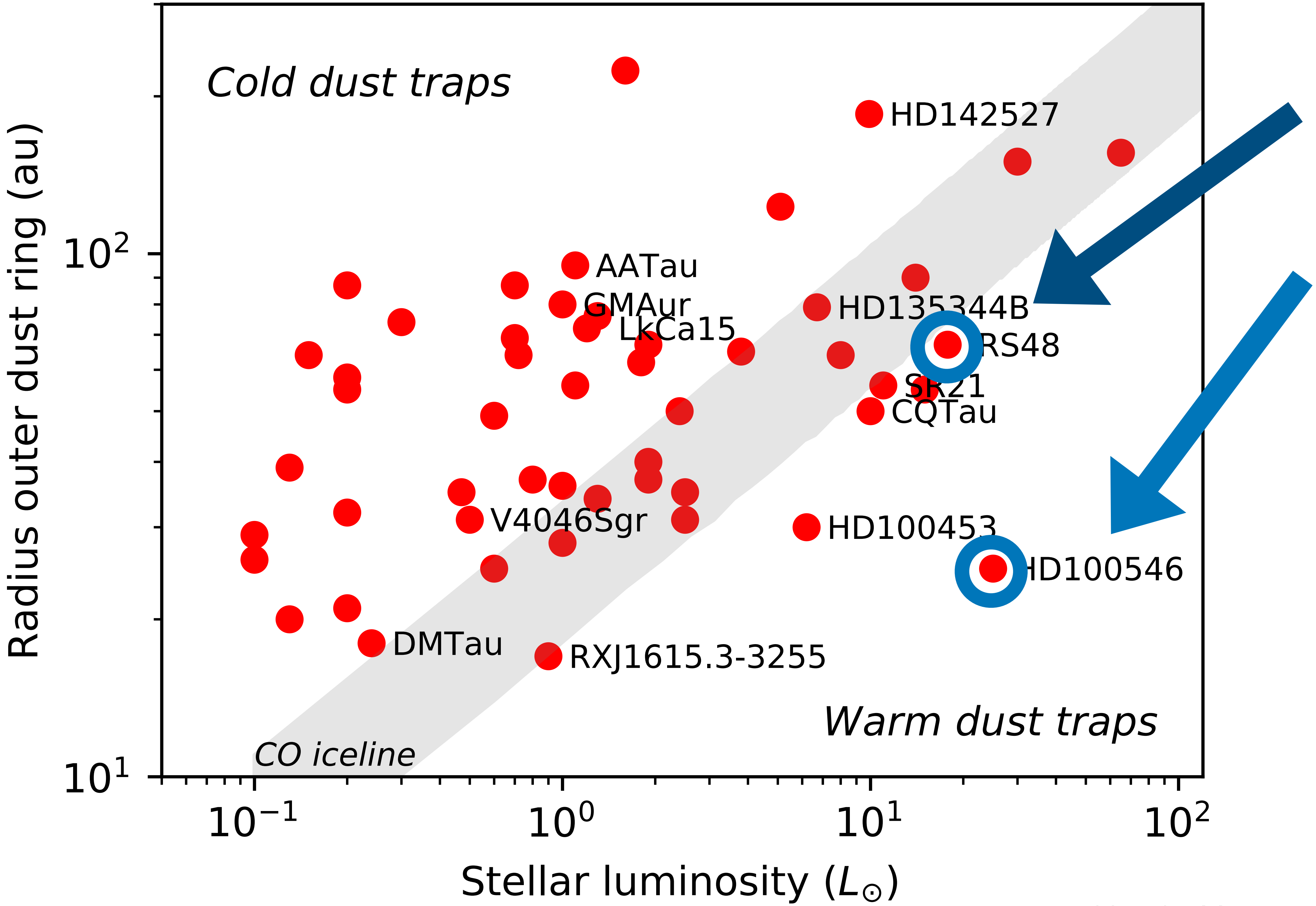


However, most other disks have so far not shown a (strong) COM detection…

Van der Marel et al. 2021b
Booth et al. 2021a,b

Other molecules

COMs: why only these two disks?

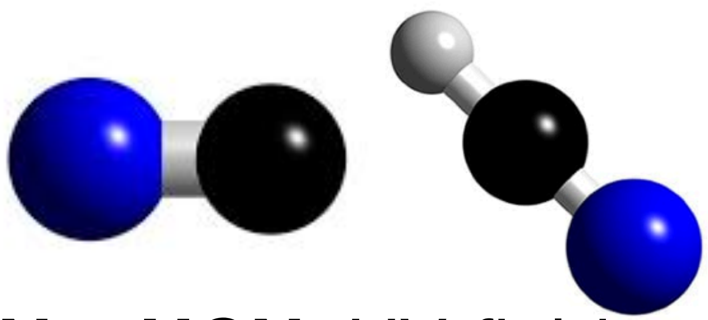


Van der Marel 2023 (EPJ+)

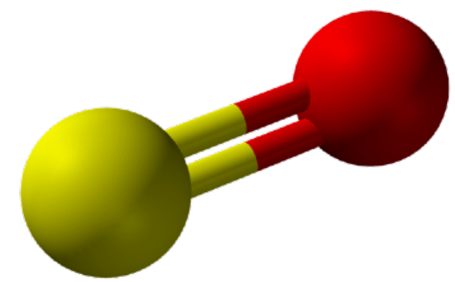
1,436 × 751

Other molecules

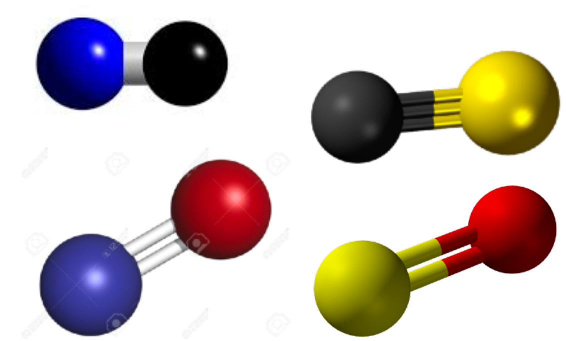
Other tracers of physical properties in disks



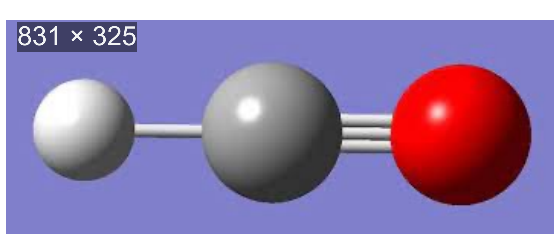
CN + HCN: UV-field
(e.g. Cazzoletti et al. 2018, Bergner et al. 2021)



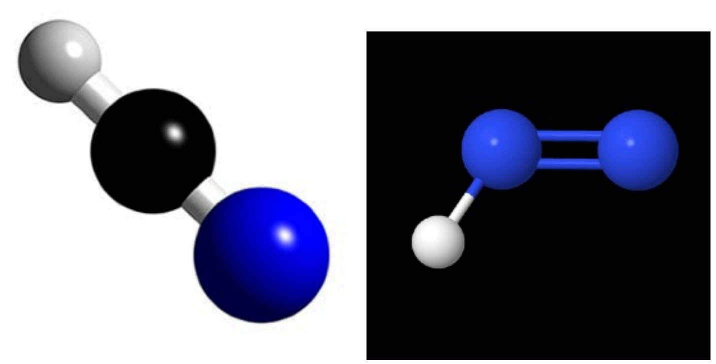
SO: shocks
(e.g. Booth et al. 2018)



CN/NO, CS/SO: C/O ratio
(e.g. Booth et al. 2021, Leemker et al. 2022)



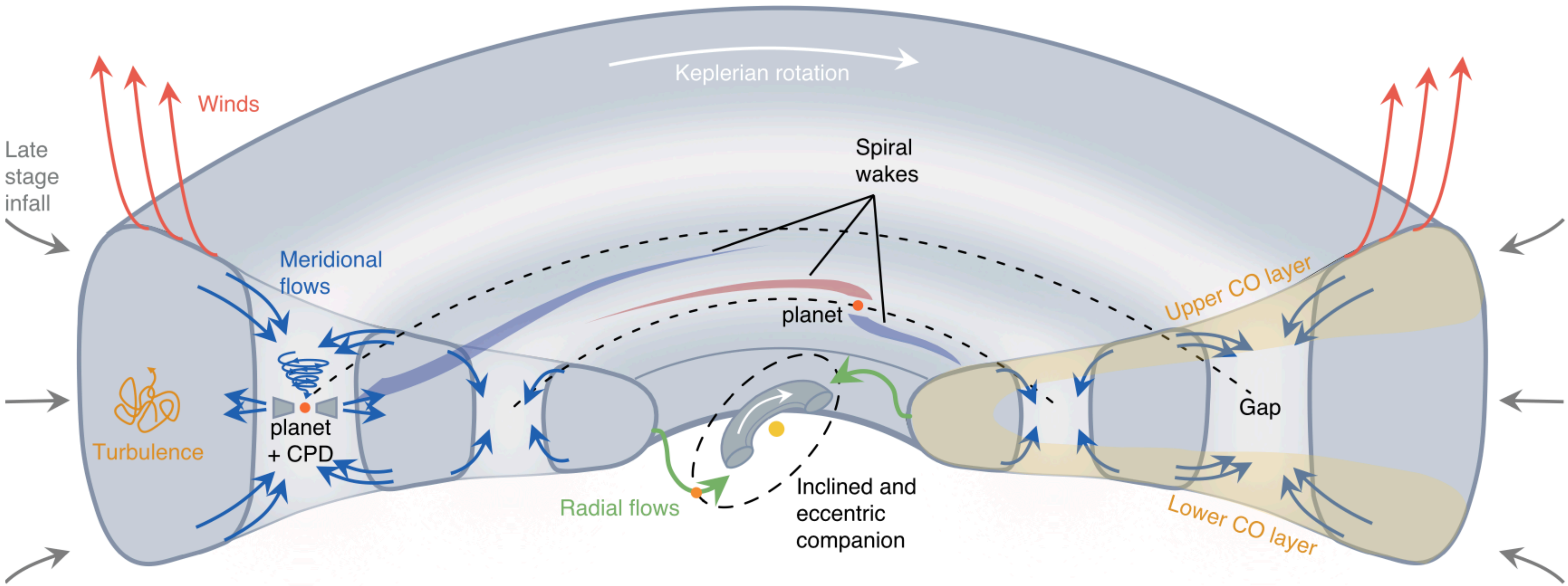
HCO^+: ionisation
(e.g. Cleeves et al. 2015)



DCN, N_2D^+: deuteration
(e.g. Aikawa et al. 2018)

Kinematics

Physical processes



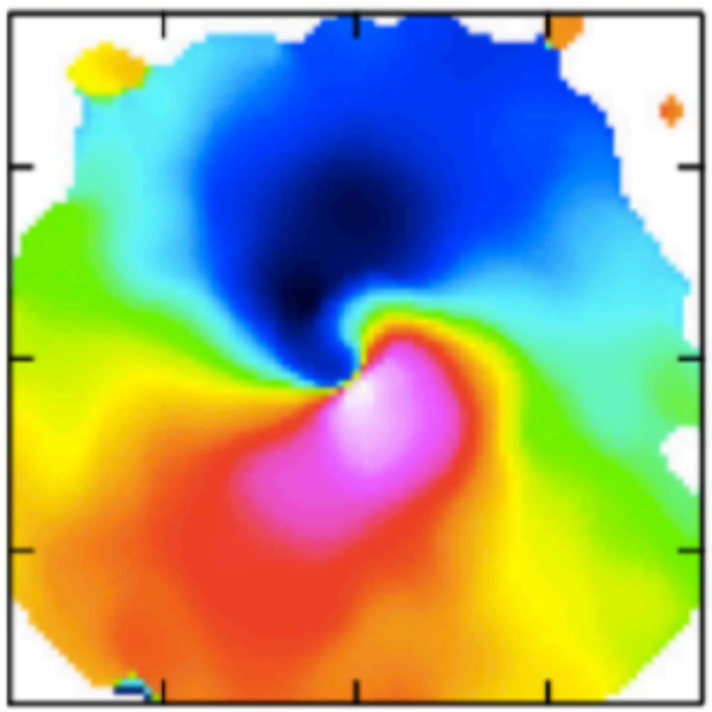
Much more than just Keplerian rotation!

Pinte et al. 2022 (PPVII)

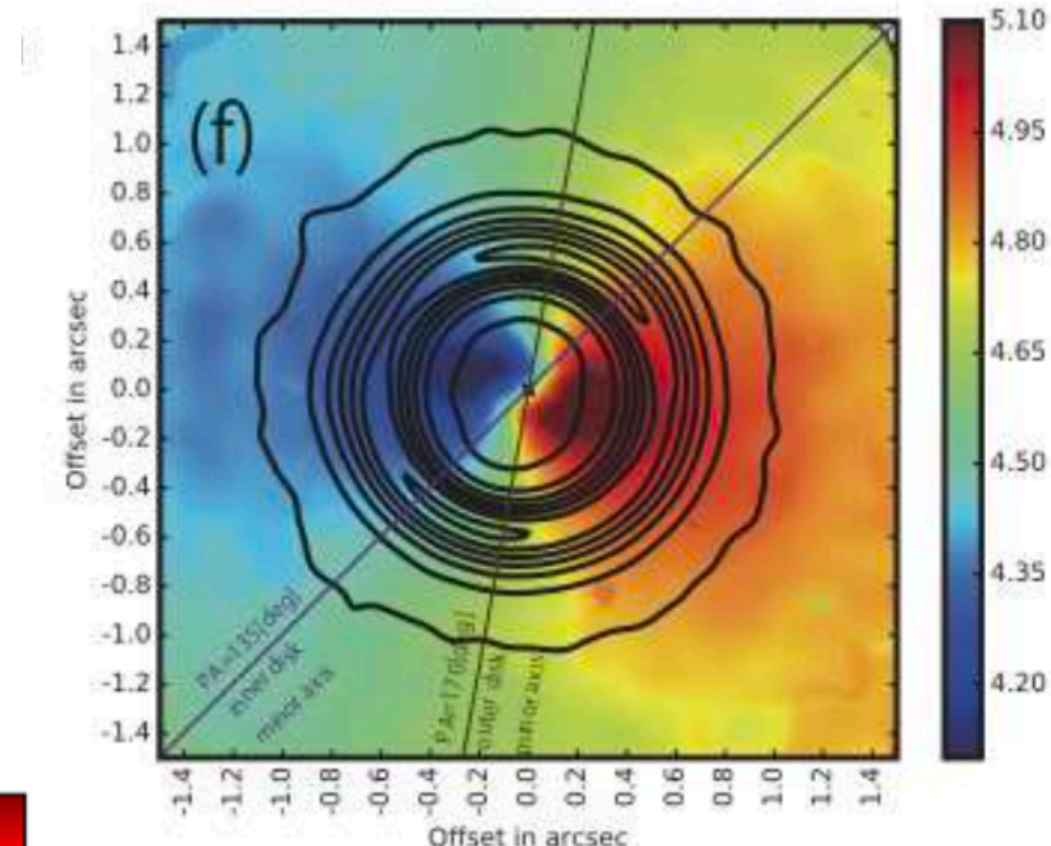
Kinematics

Warps: velocity map

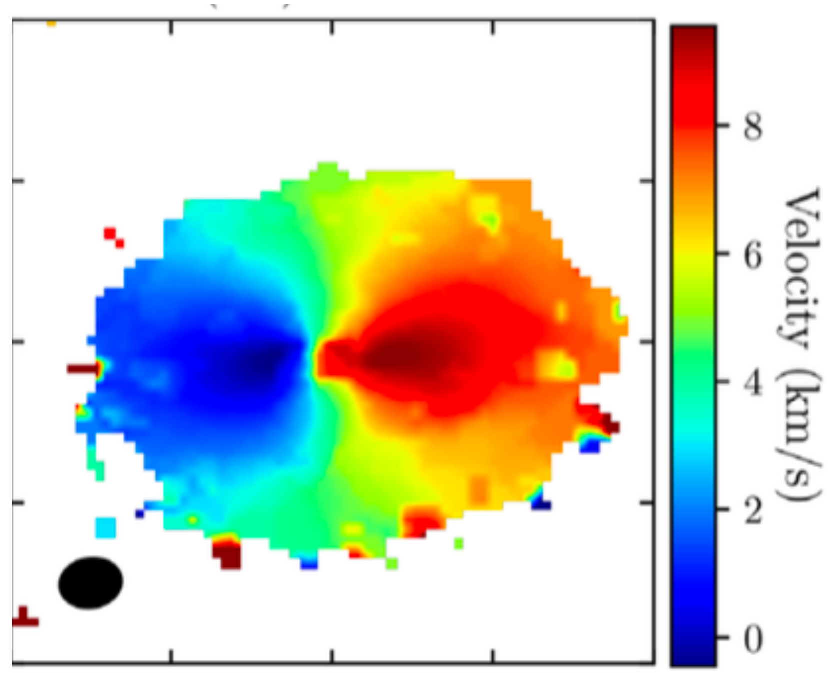
HD142527



J1604-2130



IRS48

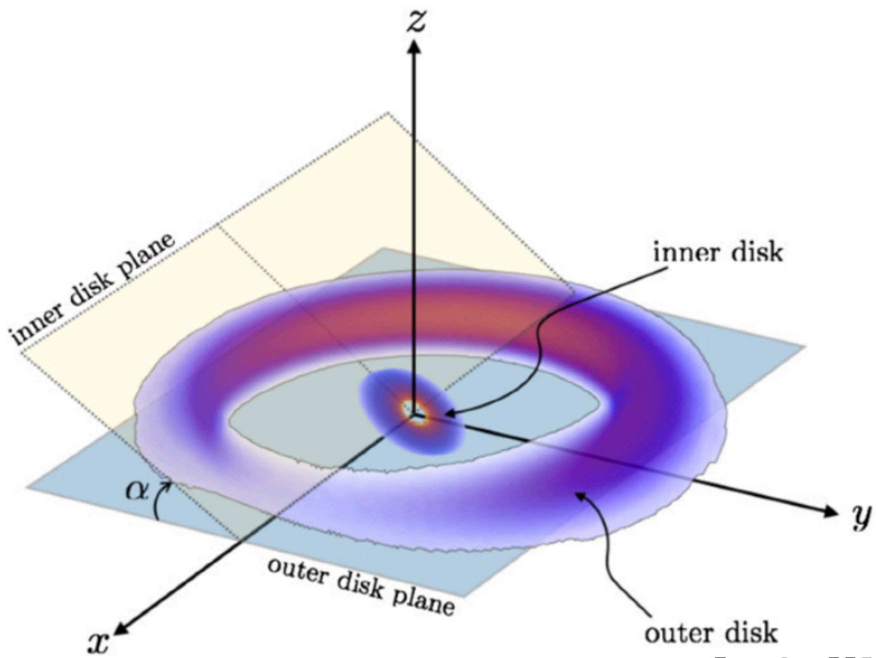


Casassus et al. 2015
Mayama et al. 2018
Calcino et al. 2019

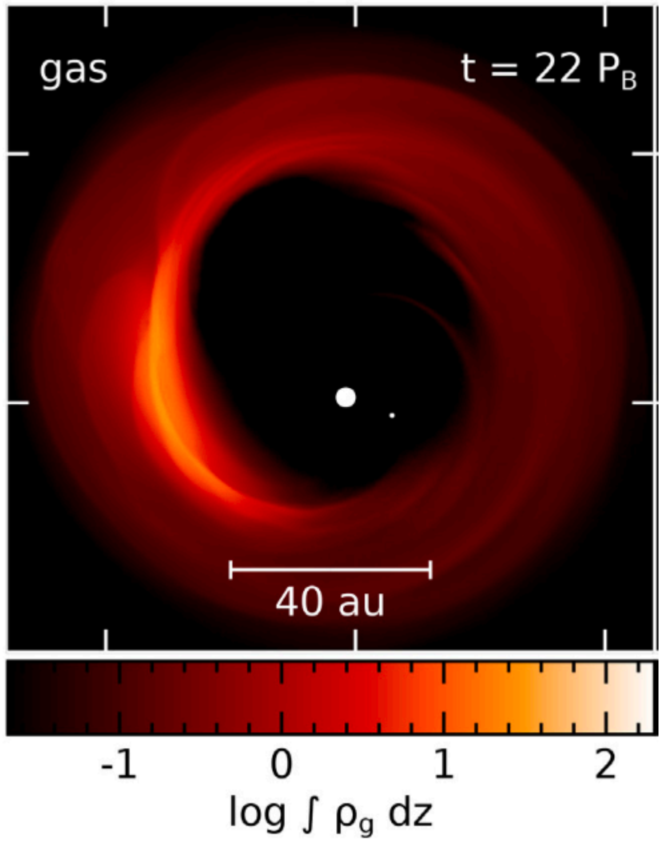
Kinematics

Origin warps

Misalignment between inner and outer disk



Eccentric disk

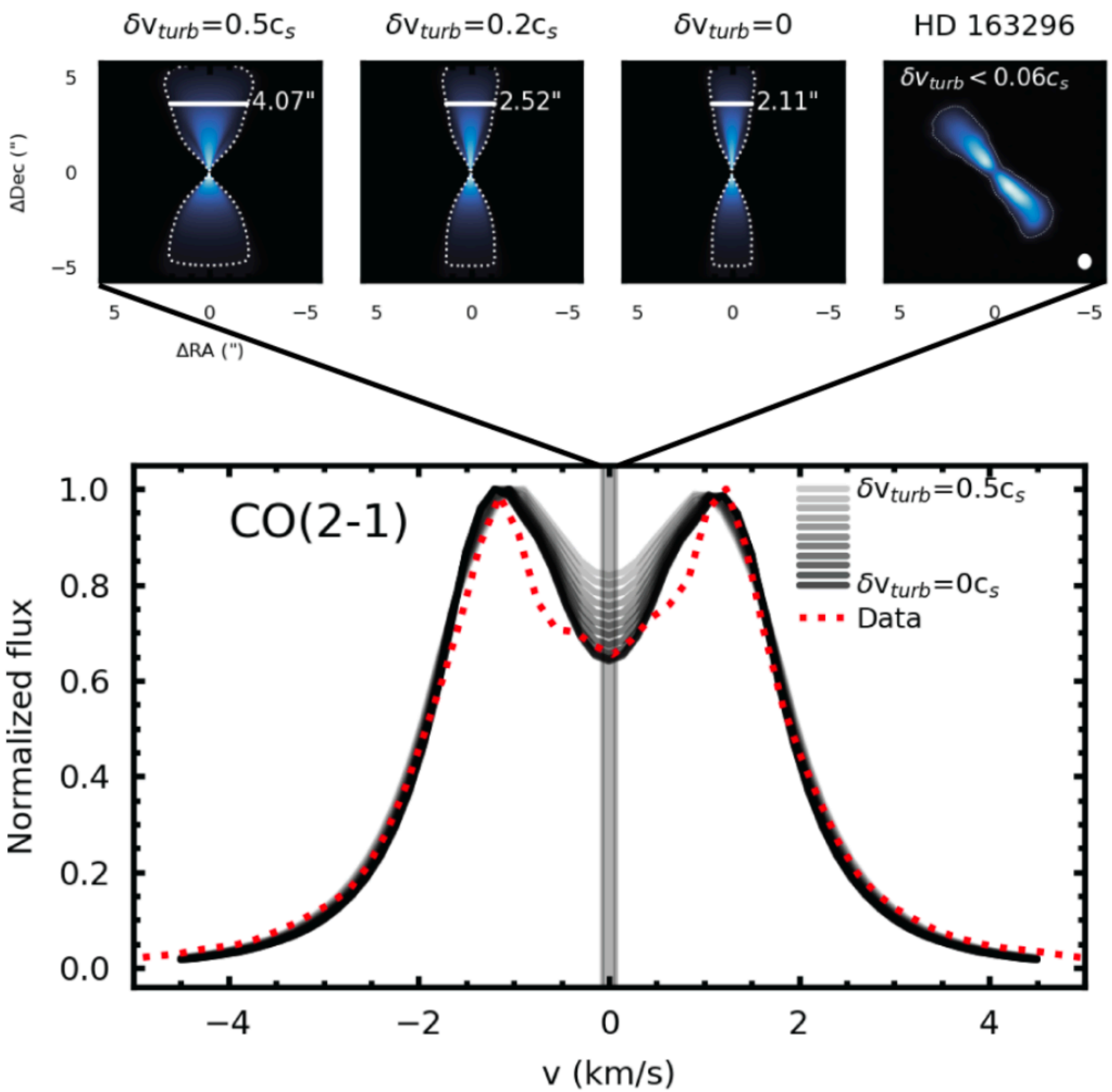


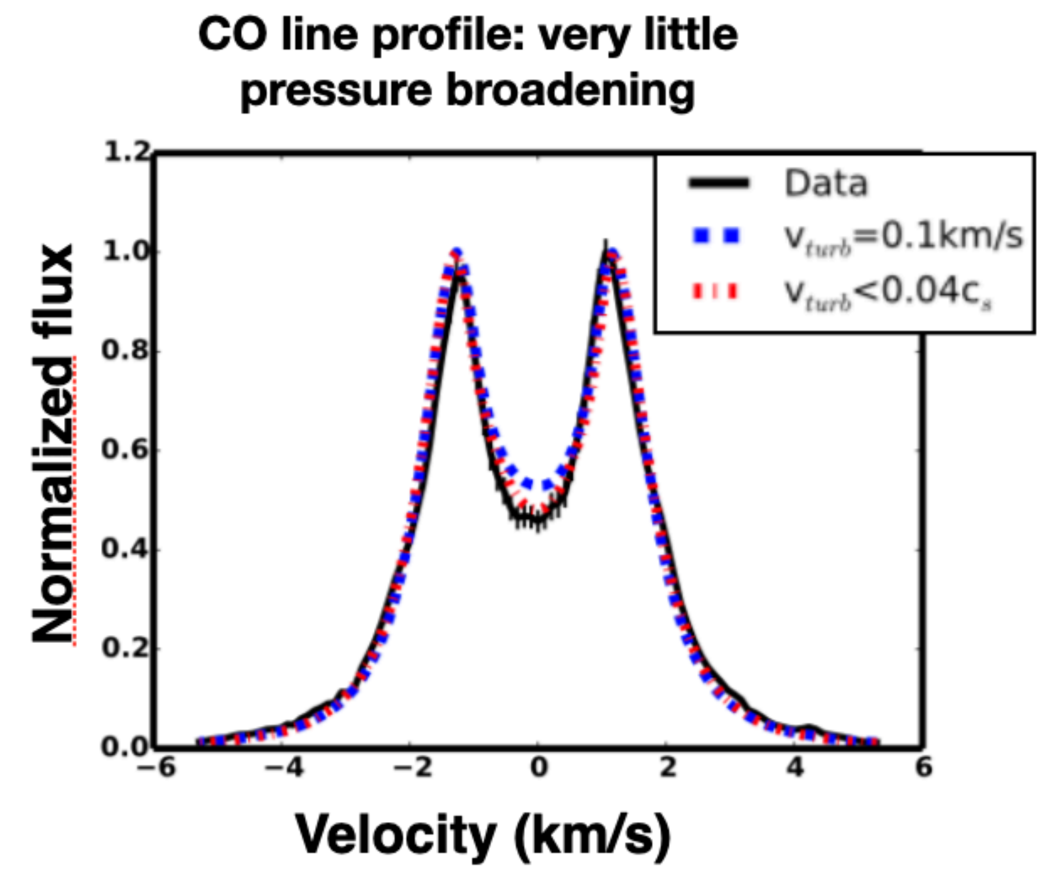
Infalling material through gap (‘radial flows’)

Marino et al. 2015
Zhu 2019
Calcino et al. 2019
Casases et al. 2013
Rosenfeld et al. 2014

Kinematics

Turbulent broadening



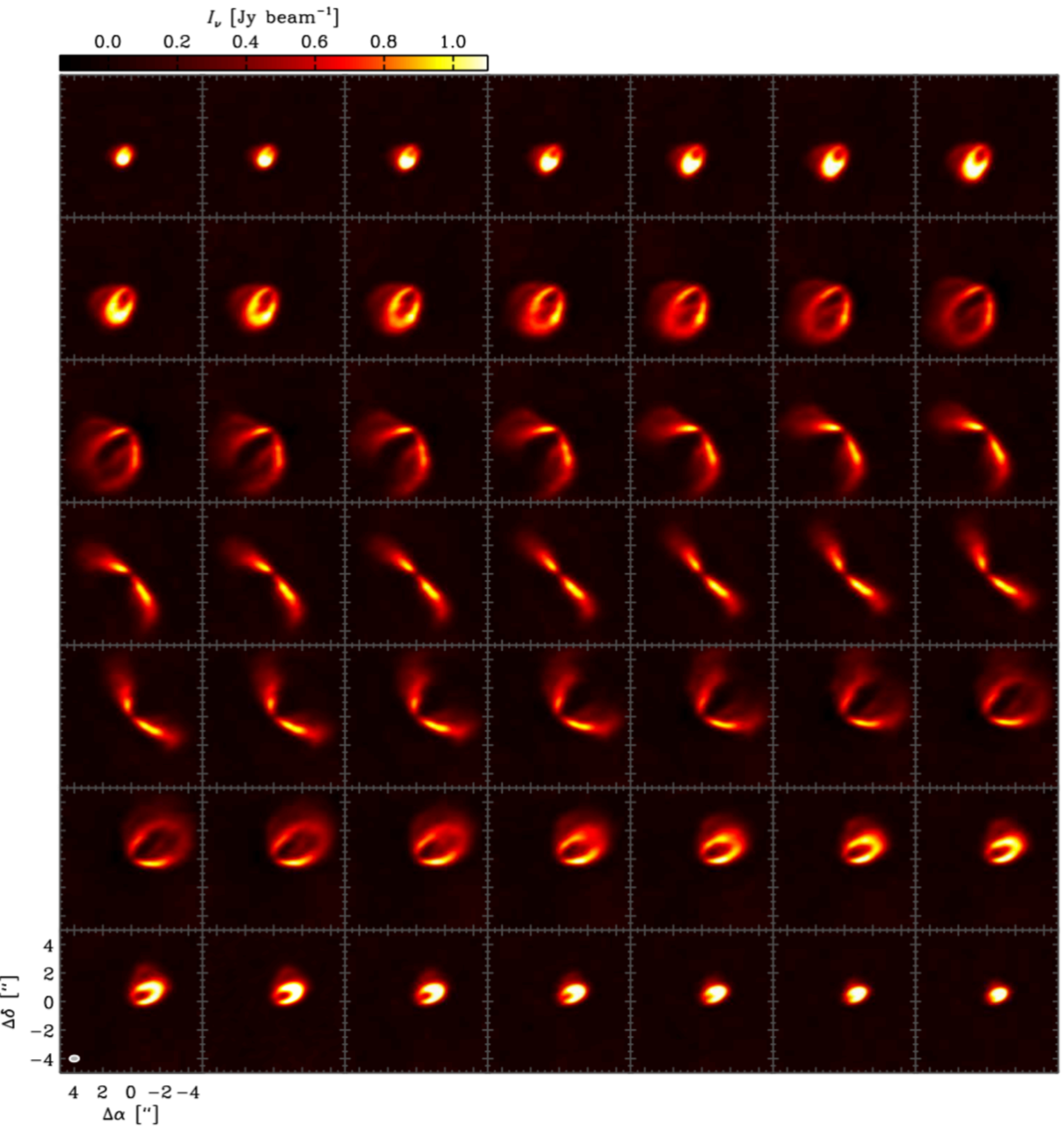


Line profiles and channels allow to measure the turbulent broadening: alpha very low!

Pinte et al. 2023 (PPVII)
Flaherty et al. 2015

Kinematics

Channel maps



A picture is worth a thousand words.
An ALMA observation is worth **3.8 million**.
(almost 8 copies of War & Peace)

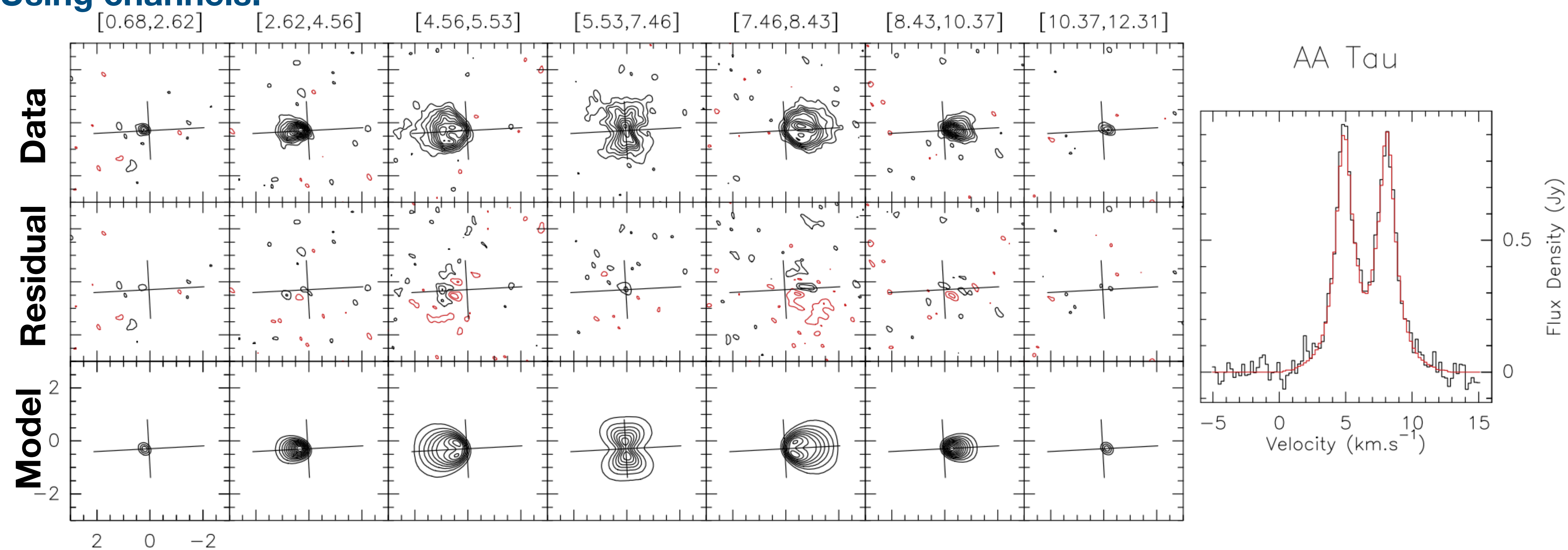
Credits Richard Teague

Kinematics

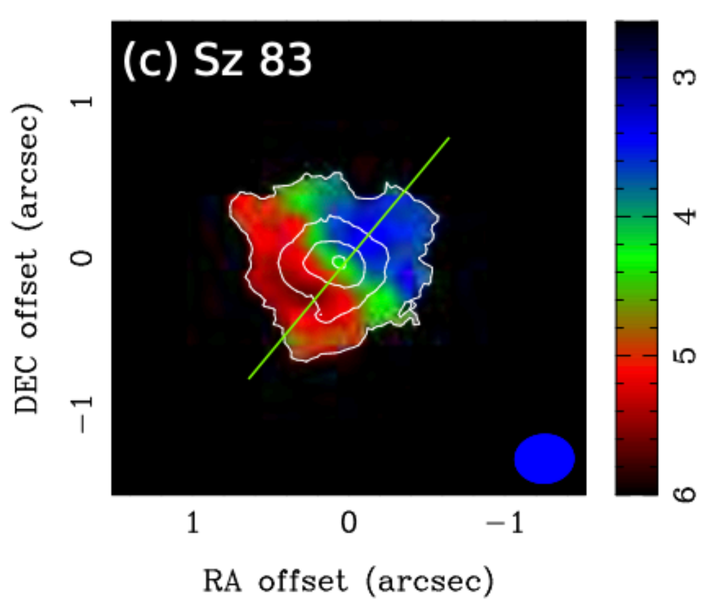
Determining stellar mass

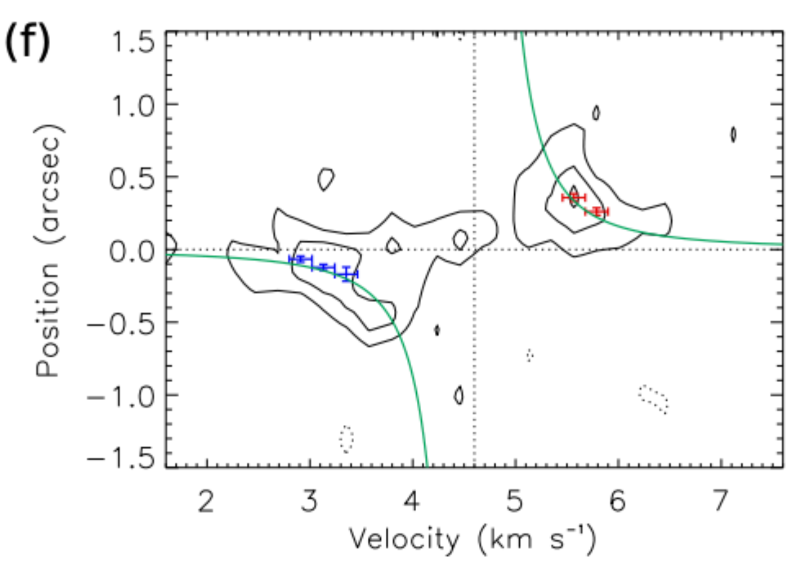
Shape channels depends on stellar mass and inclination => better tracer than stellar isochrones

Using channels:



Using velocity map major axis: position-velocity diagram

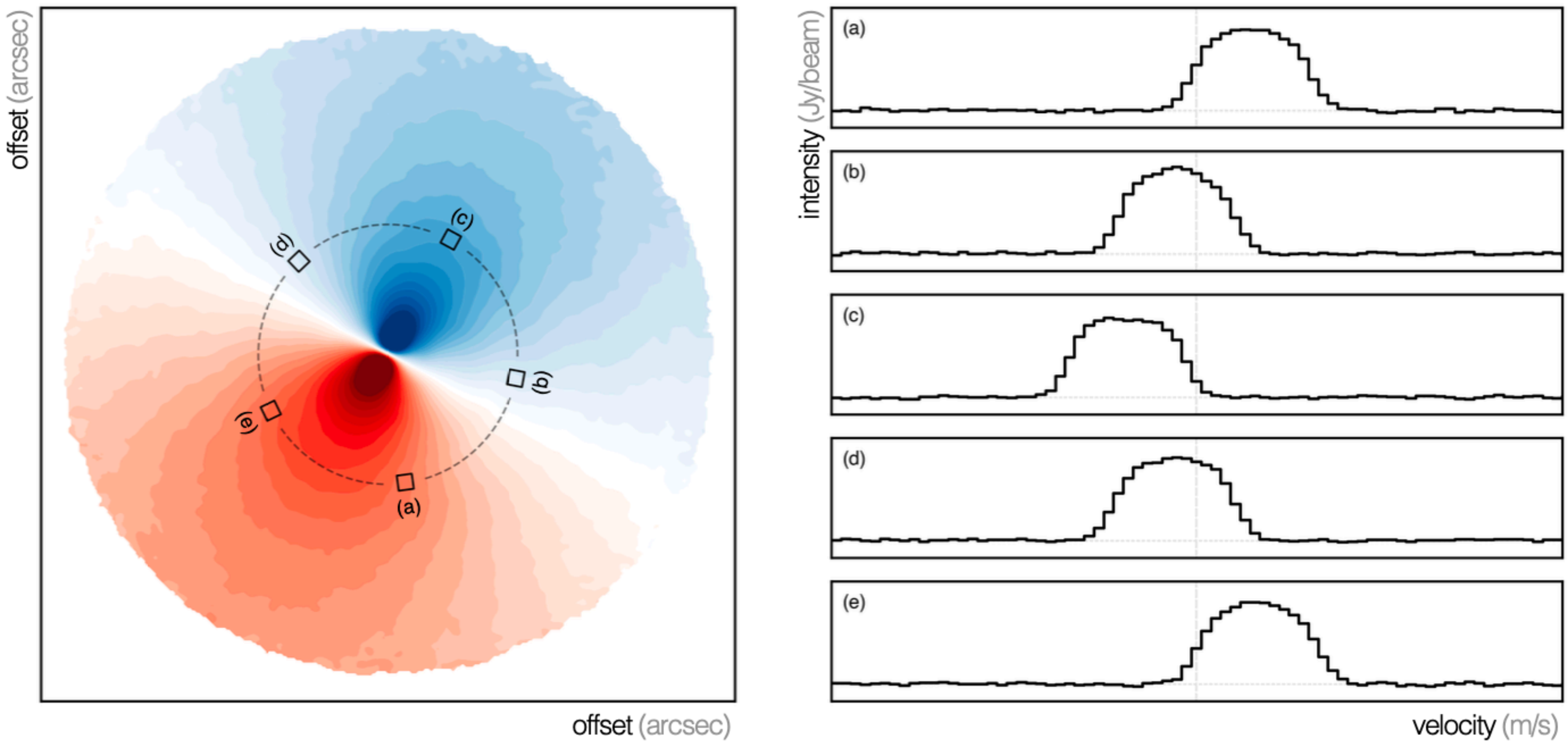




Simon et al. 2017, 2019
Yen et al. 2018
Braun et al. 2021

Kinematics

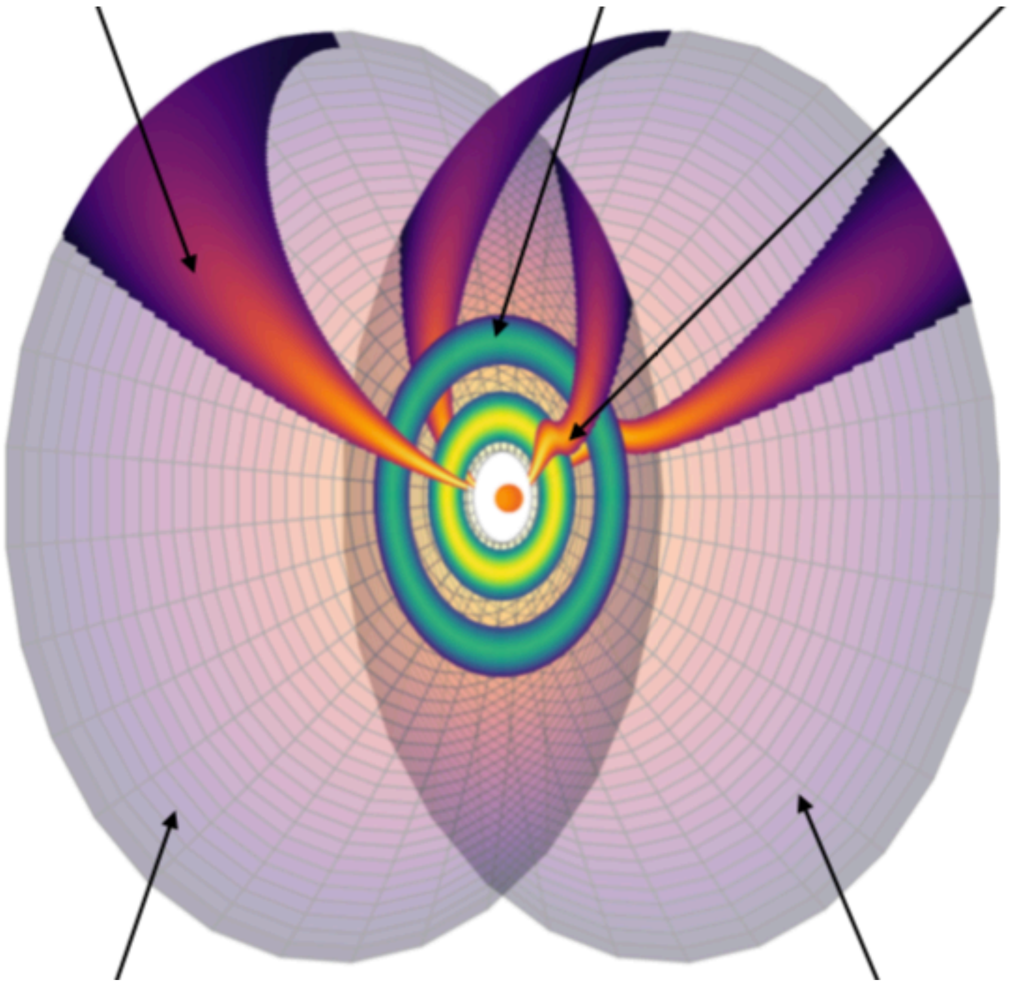
Spectra at different locations



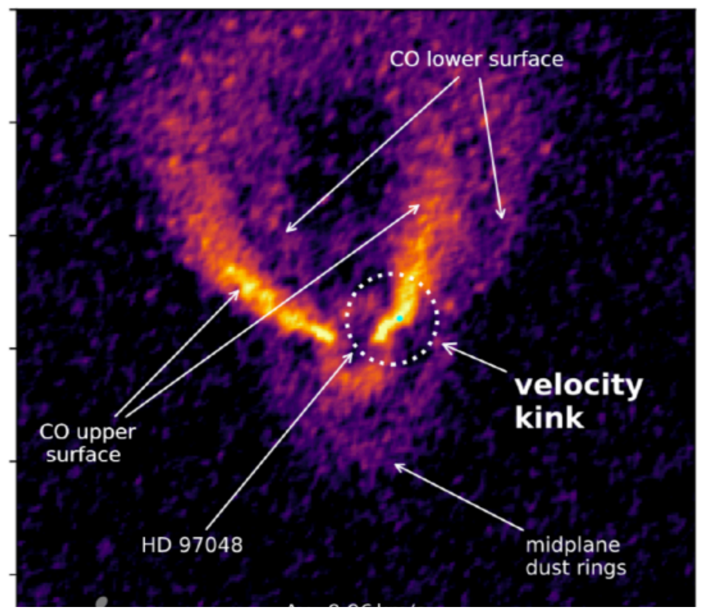
Each pixel is an emission line that has been Doppler shifted relative to the systemic velocity.

Kinematics

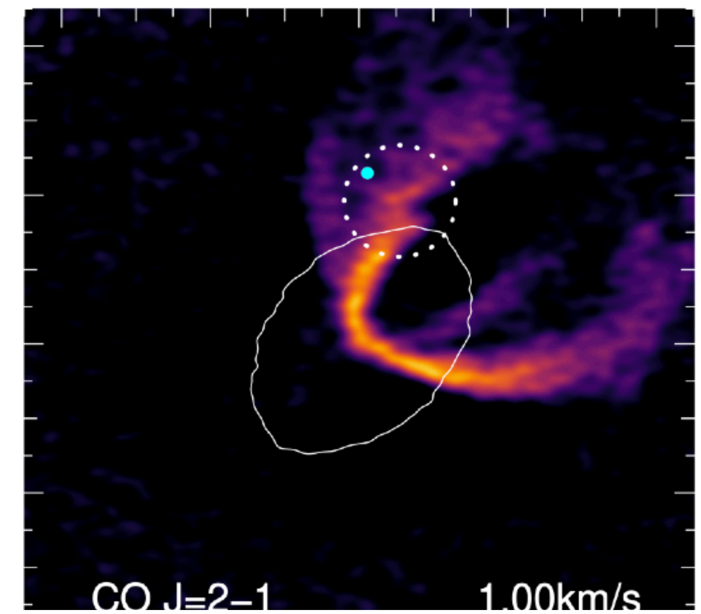
Kinks in channels

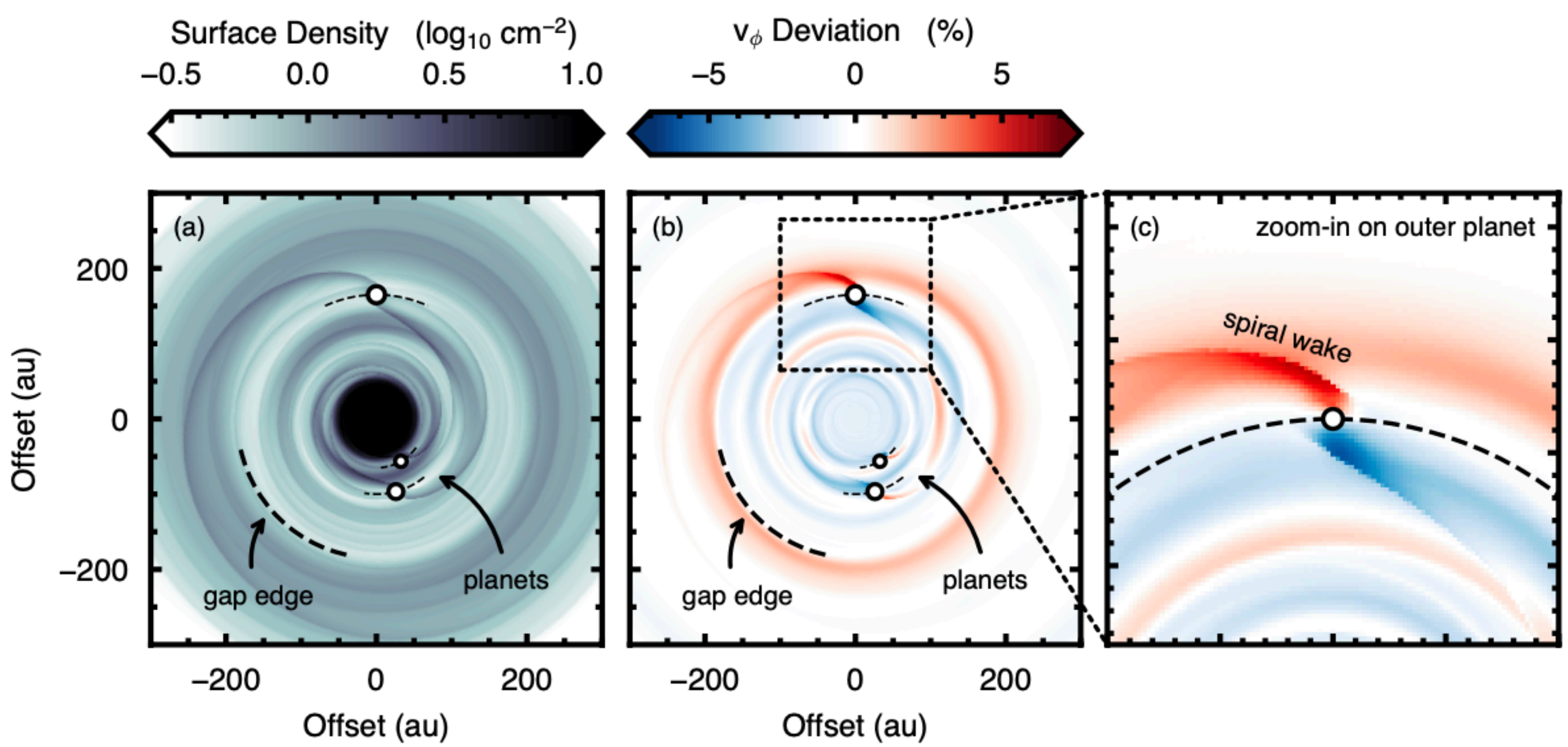


HD97048



HD163296





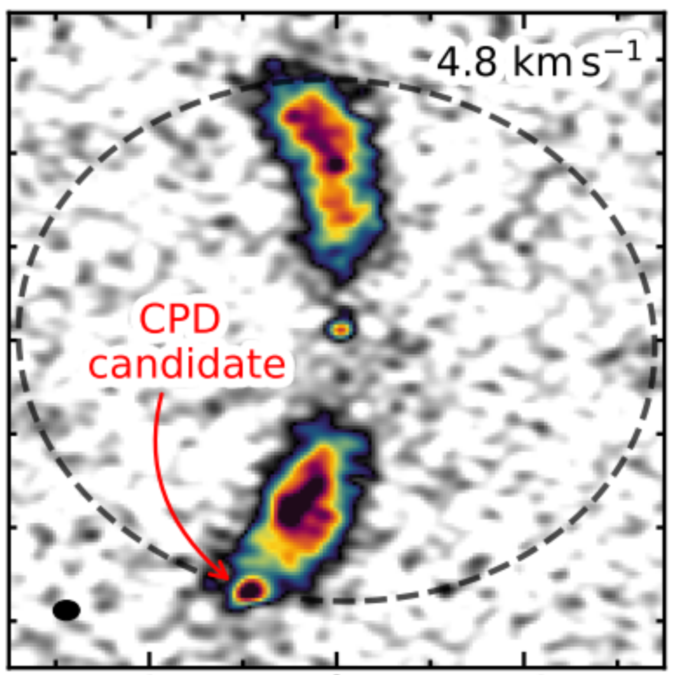
Deviations from Keplerian rotation in CO are thought to be velocity perturbation in the gap caused by the planet

Pinte et al. 2018, 2019

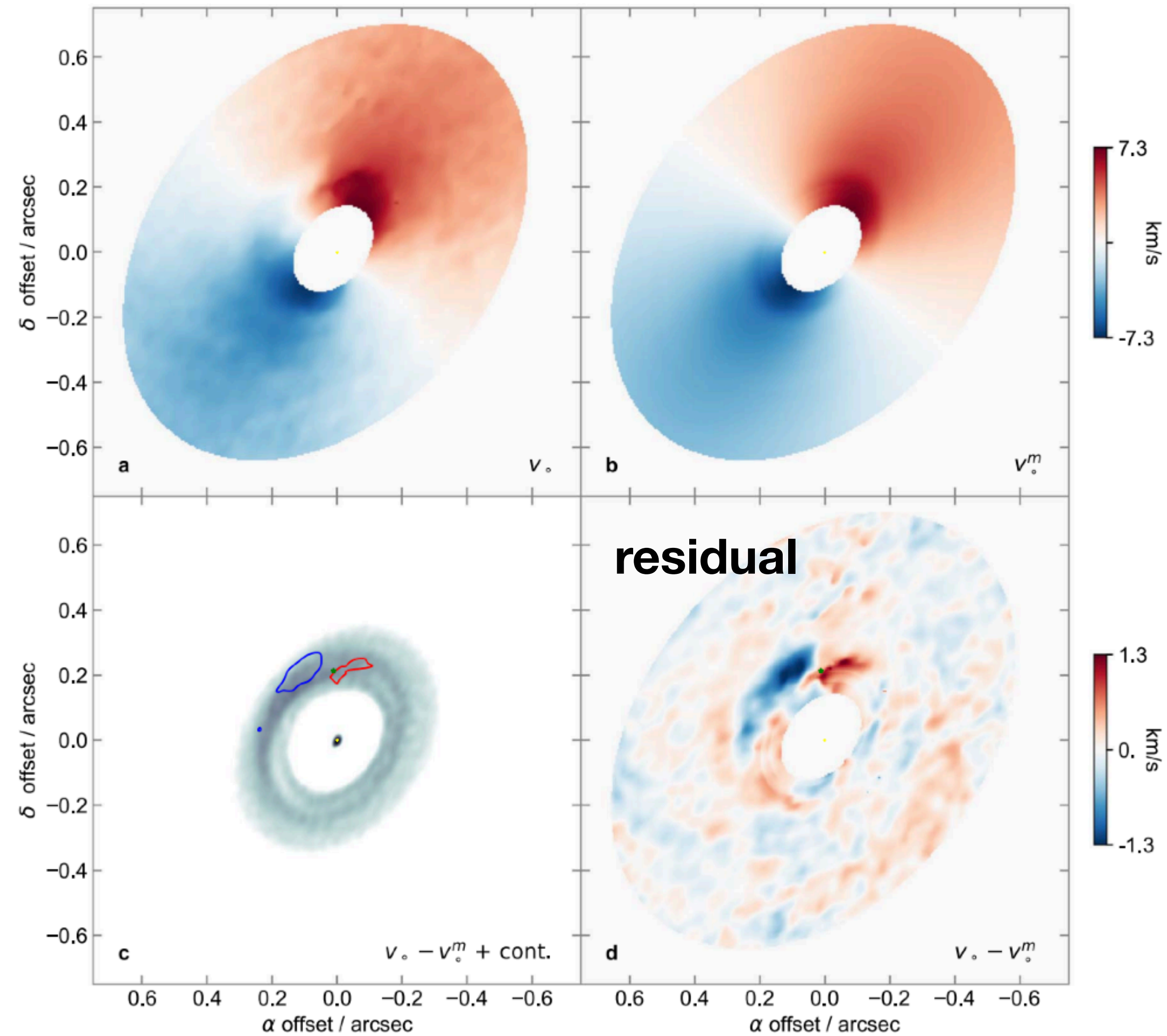
Kinematics

Circumplanetary disks?

AS209: ^{13}CO 2-1 blob: CPD because of morphology



HD100546: 'Doppler flip' in ^{12}CO in residual

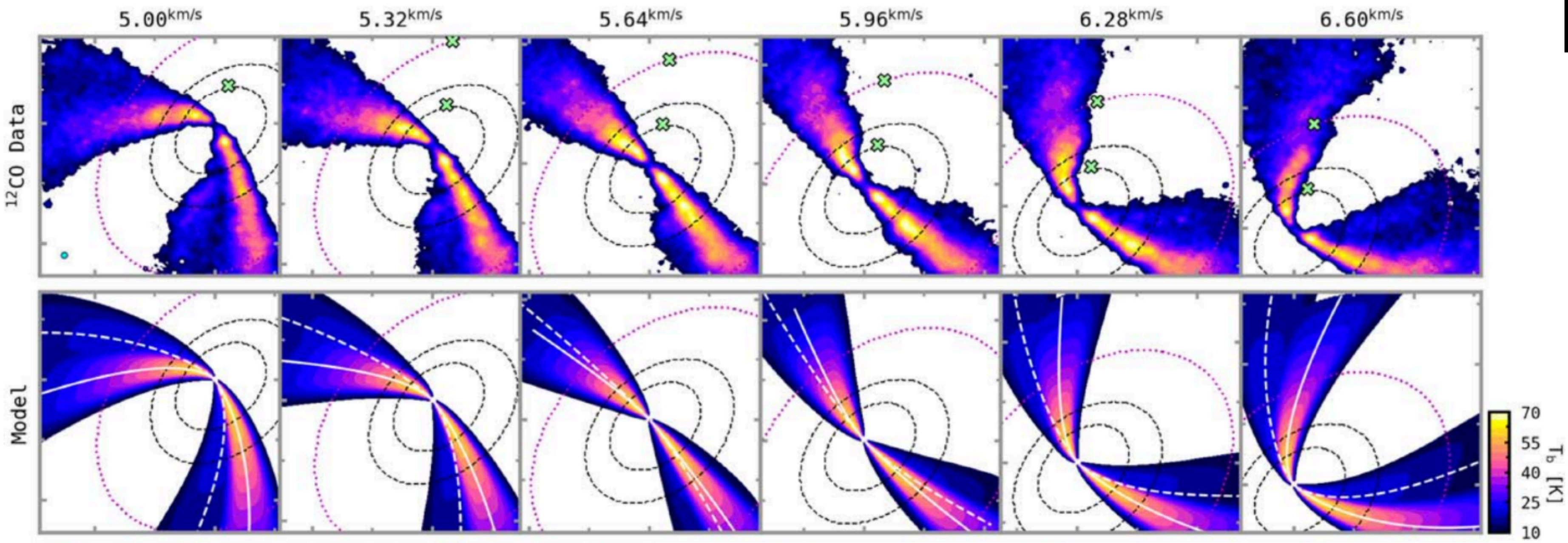


Bae et al. 2022
Casassus & Perez 2019
Norfolk et al. 2022

Kinematics

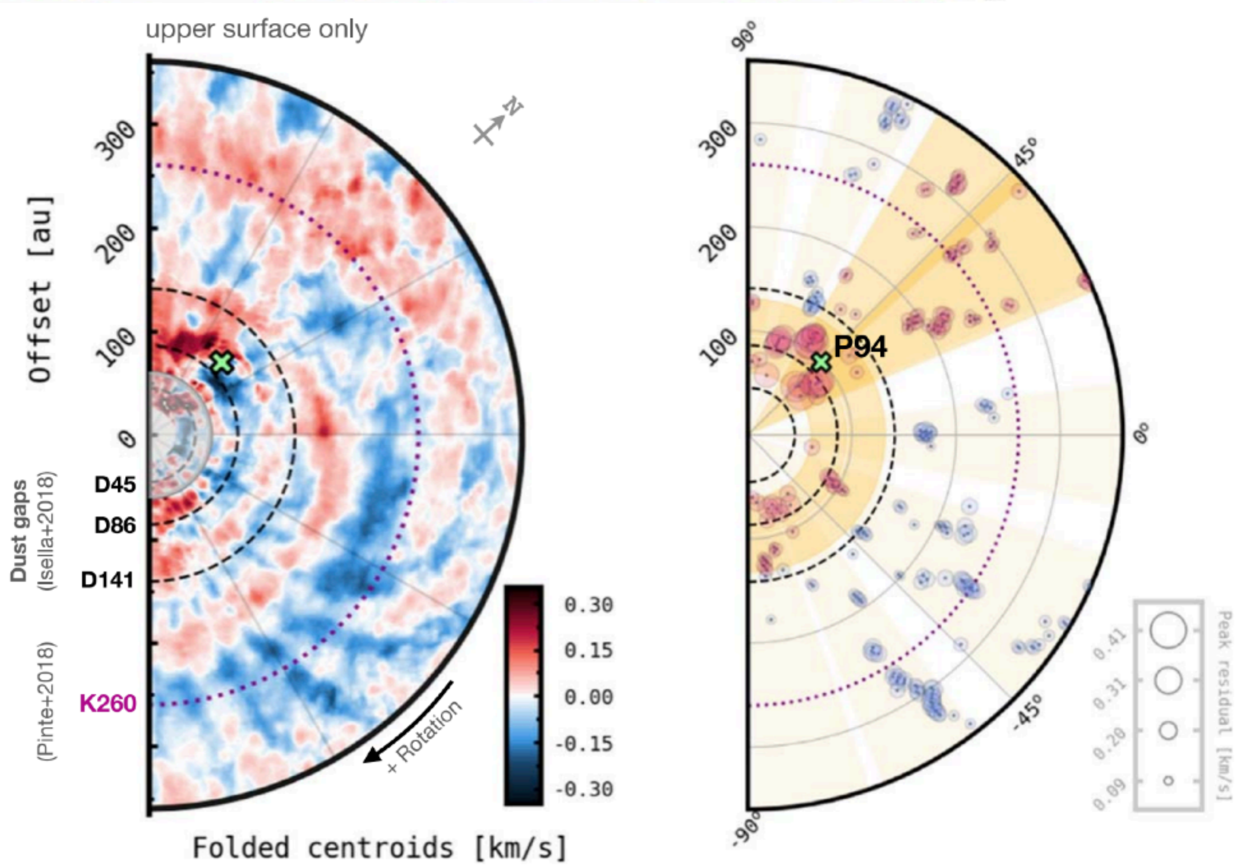
Auto-detect non-Keplerian features

Discminer: Try yourself at https://github.com/andizq/discminer



Approach: develop a full model of 3D velocity structure of CO in Keplerian disk, and subtract from the data

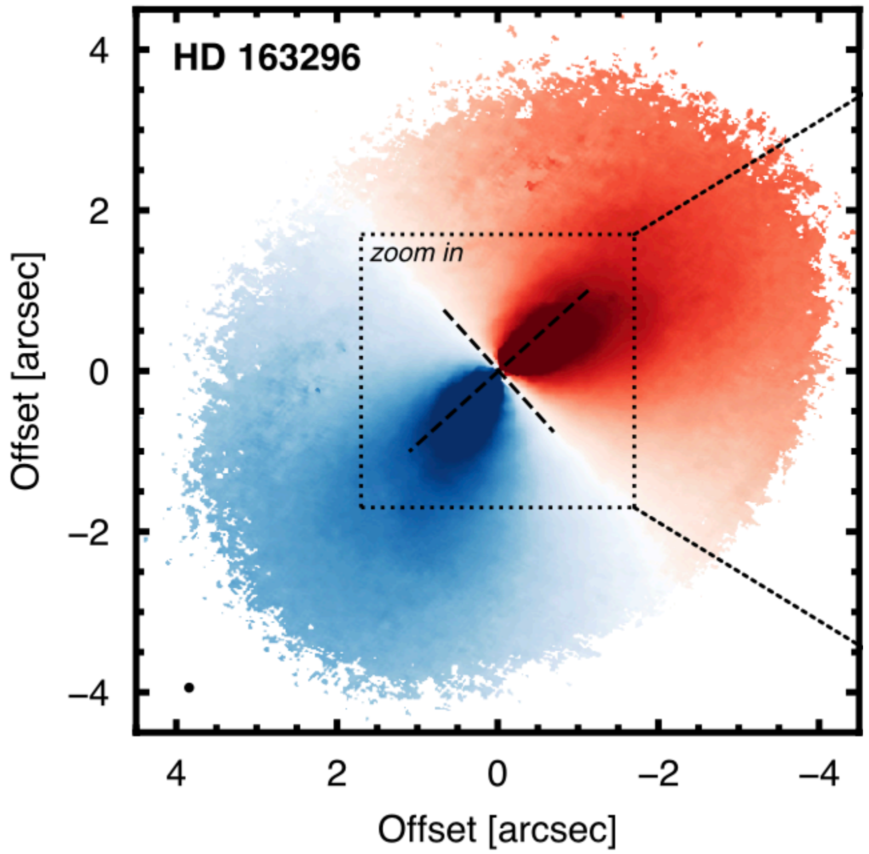
Look for localized perturbations in velocity centroids (left) and clusters of peak velocity (right) in residual maps

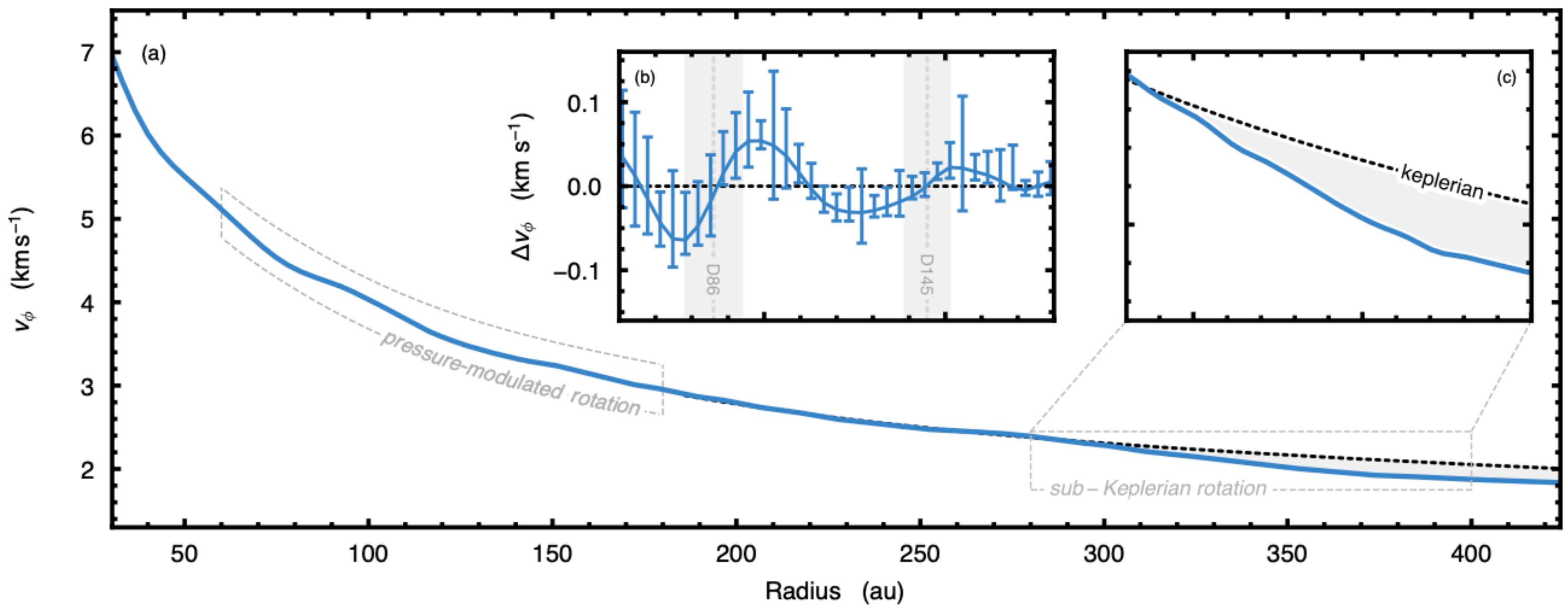


Izquierdo et al. 2022

Kinematics

Rotation curve





From a first moment map it is possible to extract a rotation curve: azimuthal velocity as function of radius

By assuming azimuthal symmetry, we can extract a rotation curve achieving a precision of less than 10 ms^{-1}.

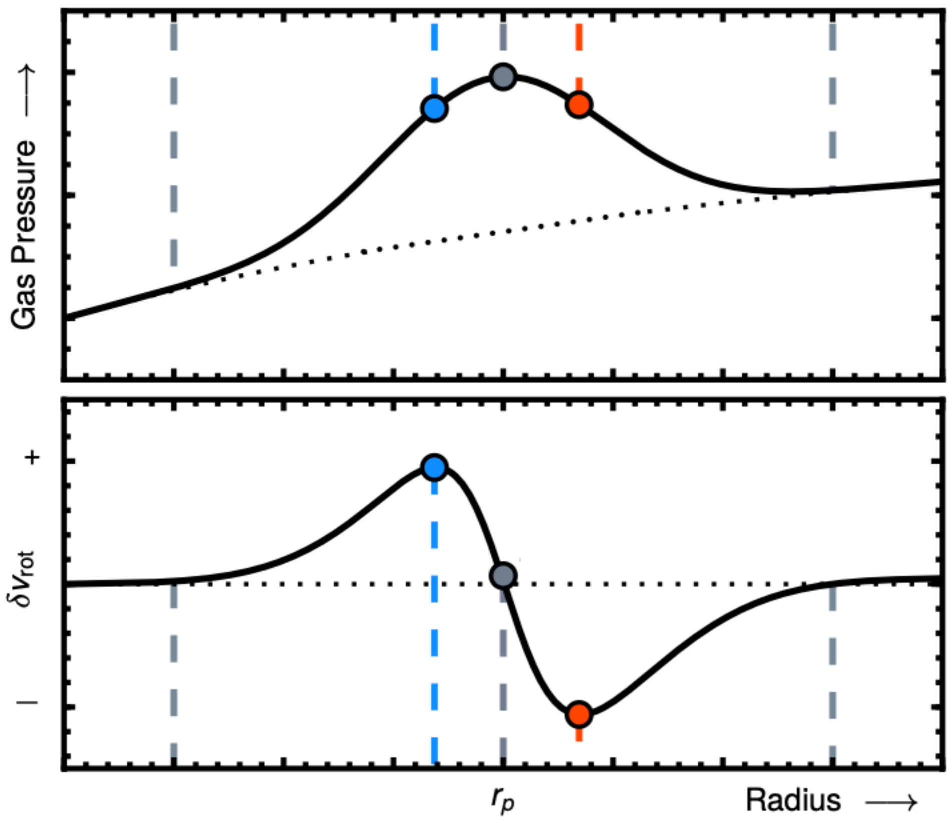
conerot (Casassus et al., 2021) // eddy (Teague 2019)

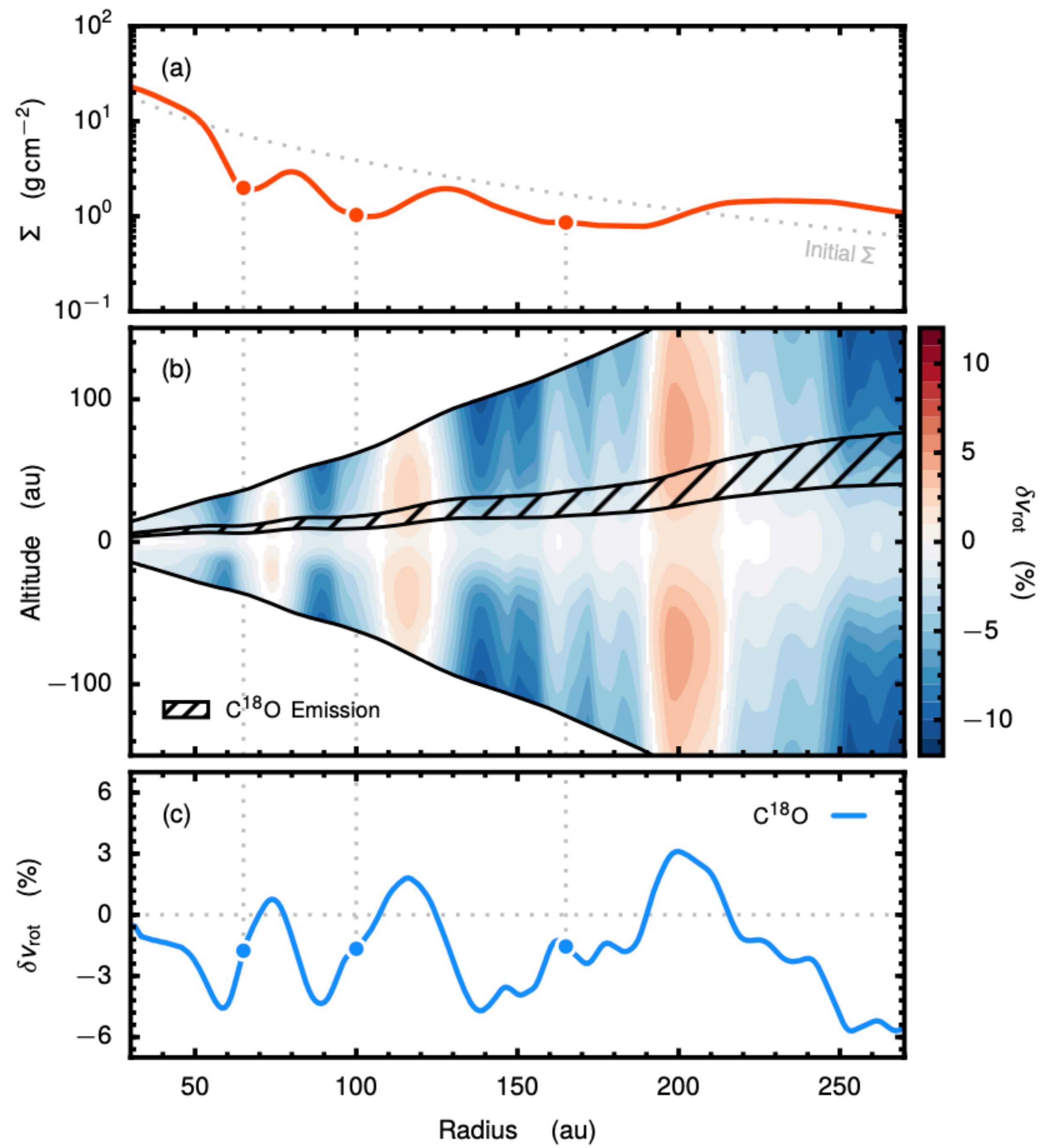
Eddy: try yourself at <u>https://github.com/richteague/eddy</u>

Teague et al. 2018

Kinematics

Rotation curve





Localized changes in the rotation velocity allow to infer the presence of substructure in the gas pressure.

Changes in dV_{rot} can be converted to pressure => gas surface density gaps

Teague et al. 2018

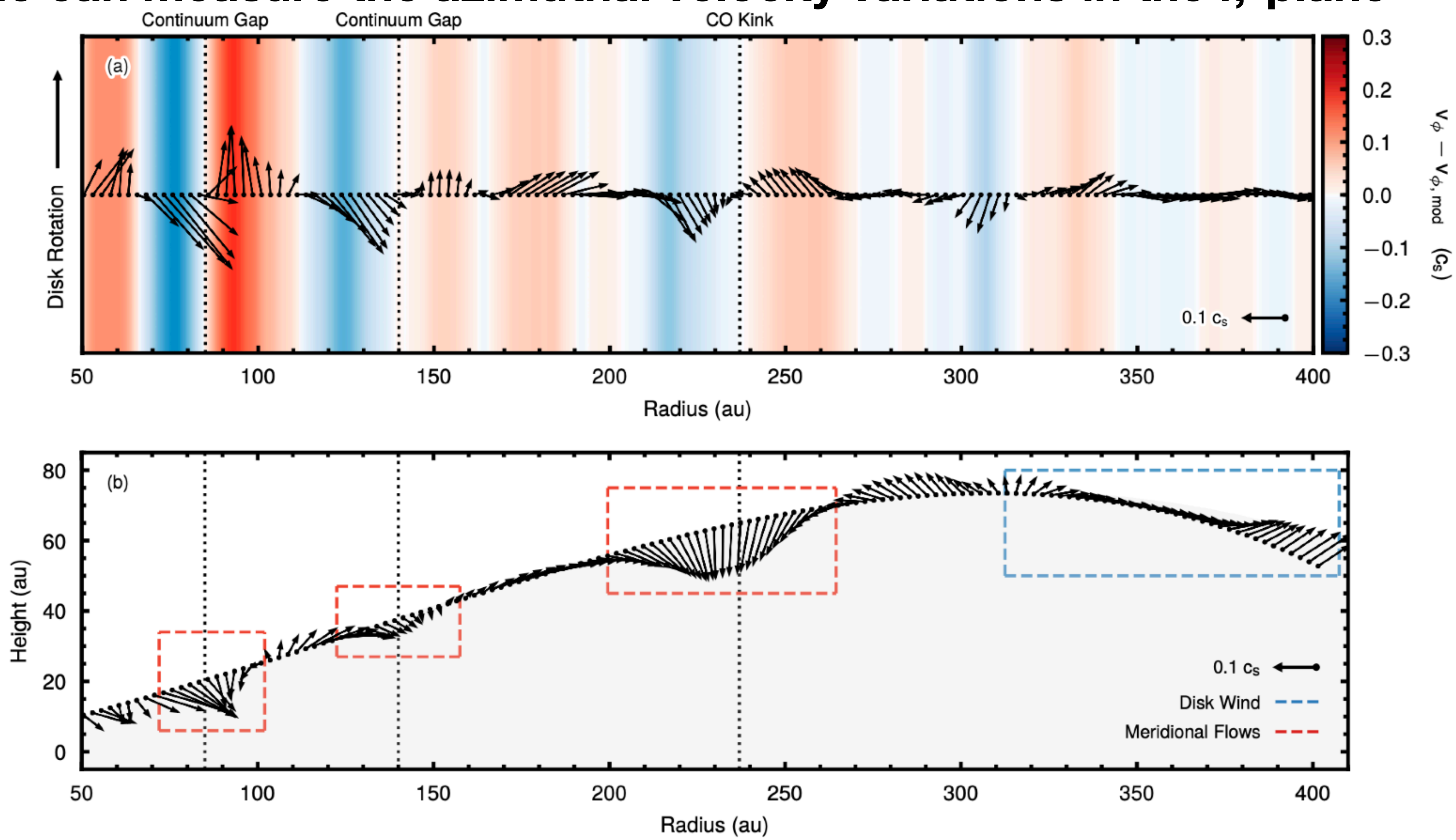
Kinematics

Decomposition

Velocity profile can be decomposed in three dimensions:

$$v_0 = v_\phi \cos(\phi)\,|\sin(i)| + v_r \sin(\phi)\sin(i) + v_z \cos(i) + v_{\mathrm{LSR}}$$

So now one can measure the azimuthal velocity variations in the r,-plane

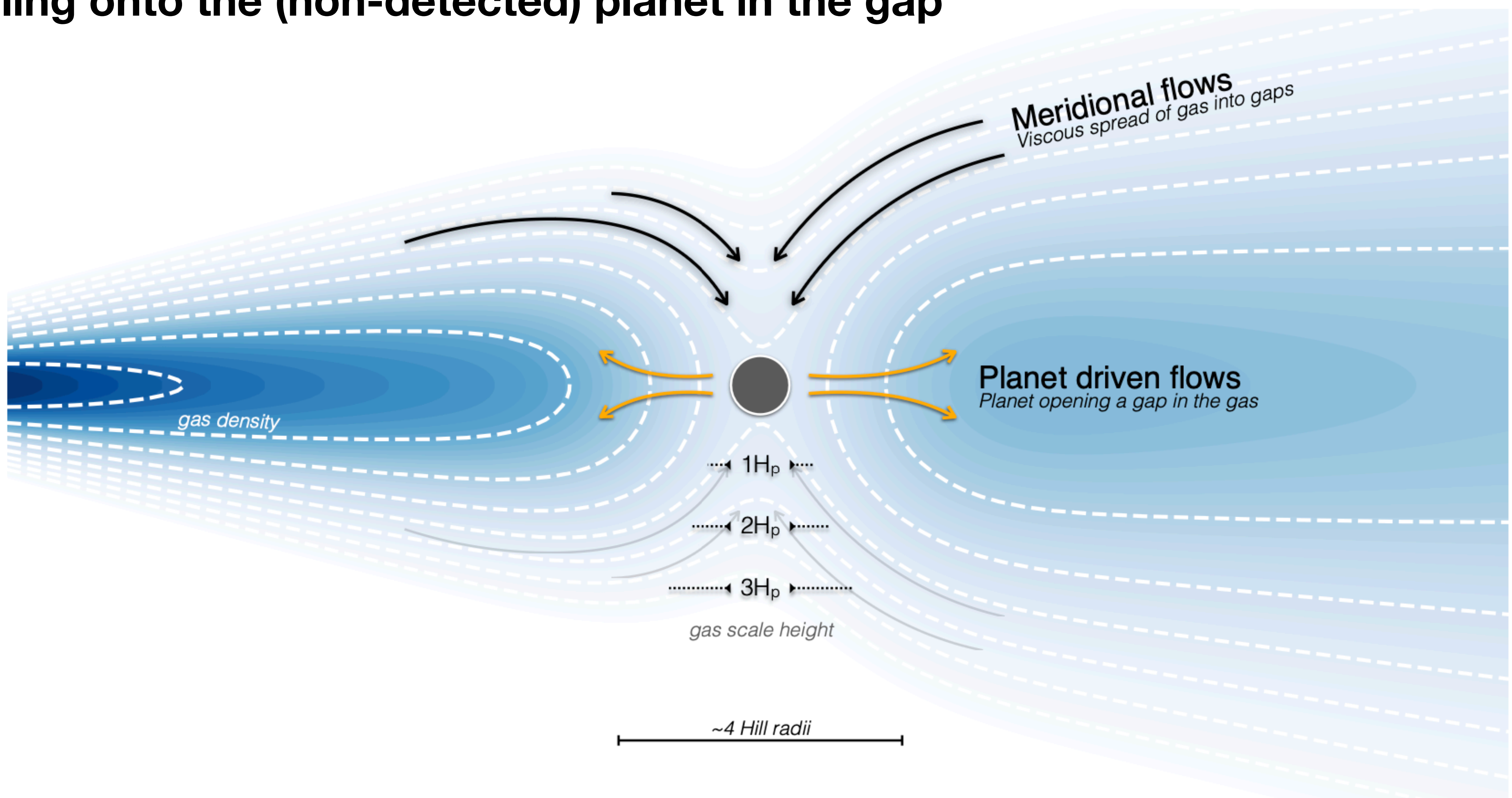


Teague et al. 2019

Kinematics

Meridional flows

The variations are interpreted as flows of material falling onto the (non-detected) planet in the gap



Teague et al. 2019

Kinematics

Alternative method for deriving disk gas mass

Small perturbations in the velocity field due to disk self-gravity would directly probe the disk mass.

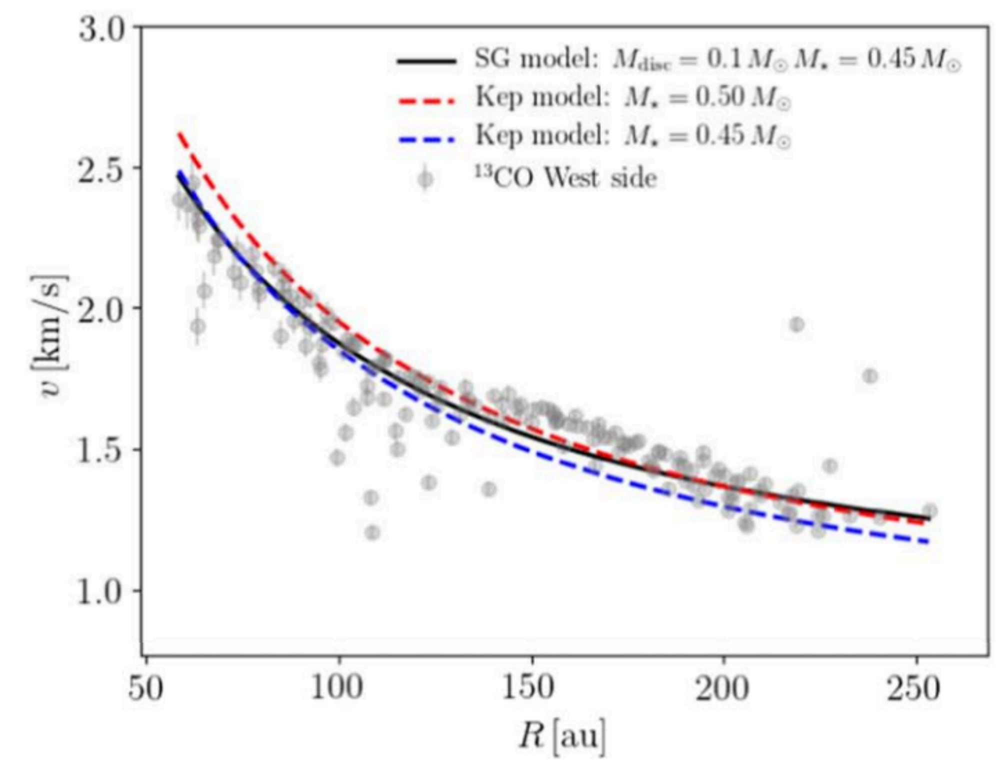
Self gravity
of the disk
leads to super
Keplerian velocity
→ marginal contribution

$$\frac{v^2}{r} = \frac{GM_*r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\text{gas}}}\frac{\partial P_{\text{gas}}}{\partial r} + \frac{\partial \phi_{\text{gas}}}{\partial r}$$

Keplerian
velocity
due to stellar
gravity

Pressure
gradient
leads ro
sub-Keplerian
velocities

One application: tentative evidence for SG disk, gas-to-dust ratio of 80



Rosenfeld, et al., 2013
Pinte et al., 2018a; 2018b
Teague et al., 2018a,b
Veronesi et al. 2021

Kinematics

Much more expected

Website http://www.exoalma.com
Many software tools already available

exoALMA

Finding exoplanets with ALMA
(PI: Richard Teague)

Survey of 15 disks in ^{12}CO, ^{13}CO and CS at 26 m/s resolution to look for kinematic signatures of embedded planets and other effects

bettermoments

Generate better moment maps from your data.

wakeflow

Generate and manipulate semi-analytic models of planet wakes.

discminer

The channel map modeling code.

disksurf

Extract the 3D structure of a disk.

eddy

Model the dynamical structure of a protoplanetary disk.

MPoL

Python framework for Regularized Maximum Likelihood (RML) imaging.

Keep an eye out for the outcome of this program!

Questions?