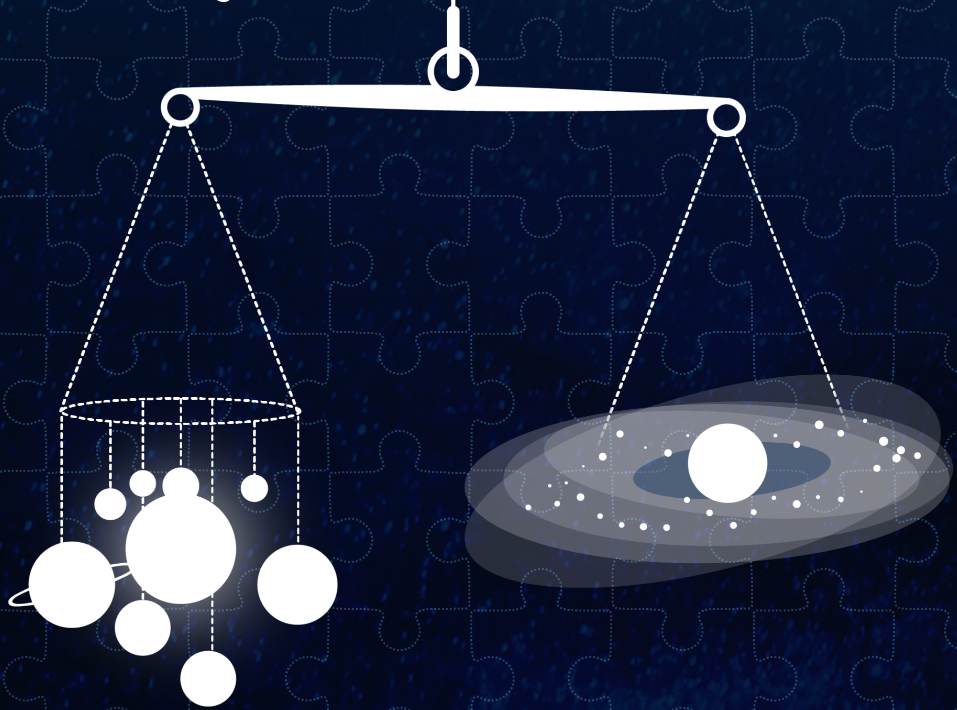
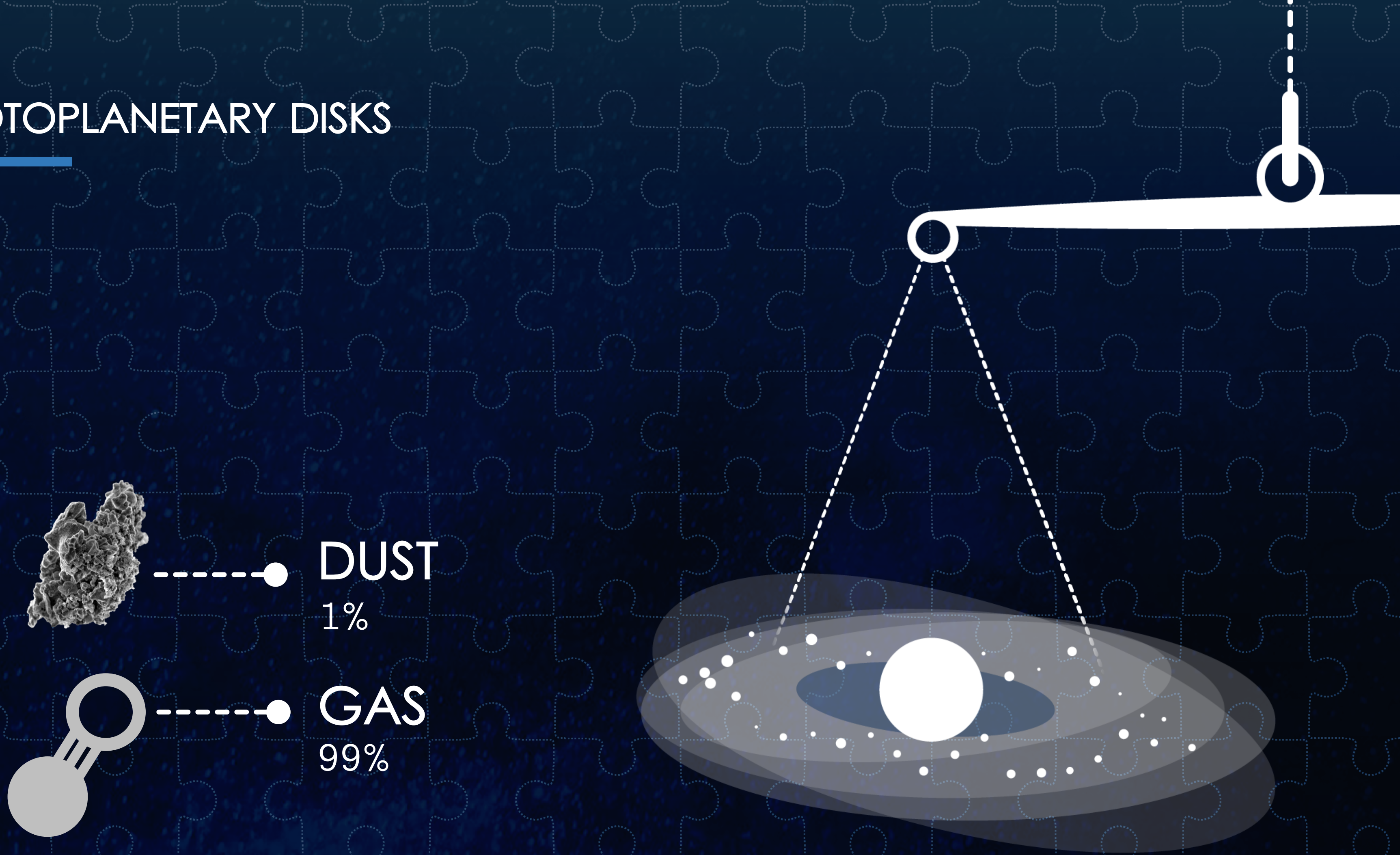
THE PUZZLE OF disk masses

Anna Miotello



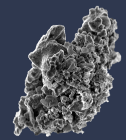
ESO :	L. Testi
	S. Facchini
	C. F. Manara
	E. Sanchis Melchor
Milano:	G. Lodato
	M. Ubeira Gabellini
Leiden:	L. Trapman
	G. Rosotti
	E. F. van Dishoeck
MPE :	P. Cazzoletti
	S. Bruderer
IfA :	J. P. Williams
UCB:	M. Ansdell
IoA :	M. Tazzari
IPAG:	M. de Simone

PROTOPLANETARY DISKS



DISK TOTAL MASS

from dust thermal emission



$$M_{\rm disk} = \frac{F_\nu \Psi D^2}{\kappa_\nu B_\nu(T_{\rm dust})},$$

GAS/DUST MASS RATIO

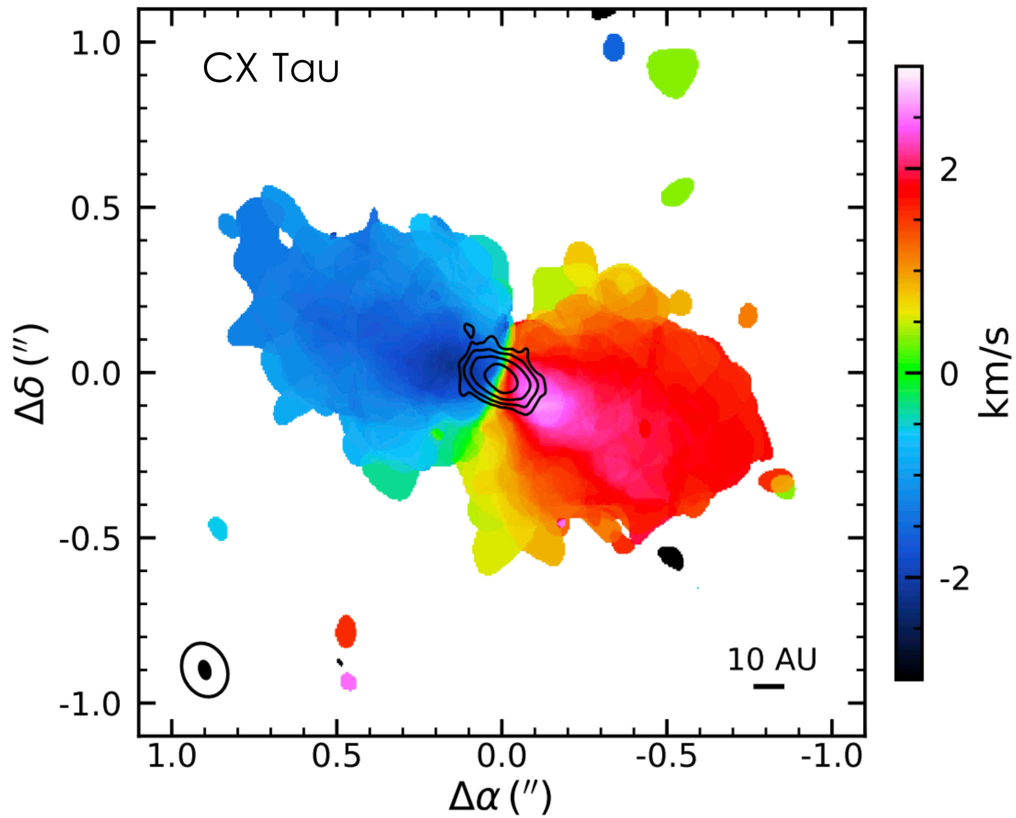
Armitage (2012), Andrews et al (2016), Ubeira Gabellini et al., 2019; Facchini et al. (2019)

GAS VS DUST

Two different behaviors

DUST AND GAS NOT EQUALLY DISTRIBUTED

CO EMISSION IS 4 TIMES MORE EXTENDED THAN MM-SIZED DUST EMISSION



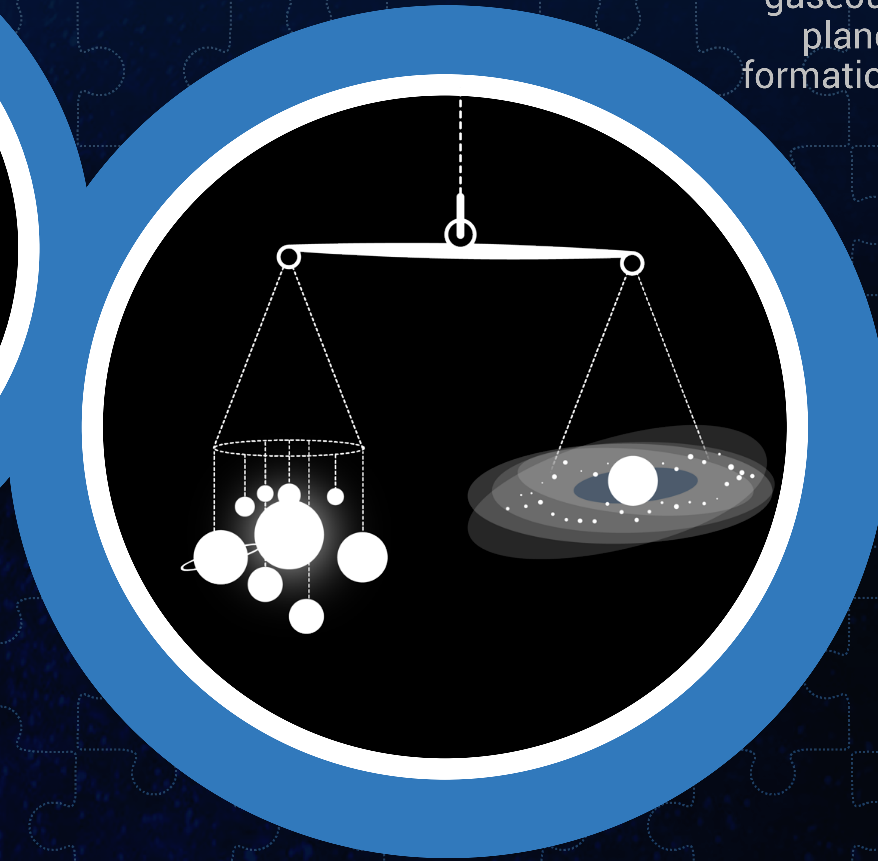
Facchini et al. 2019

GAS DISTRIBUTION

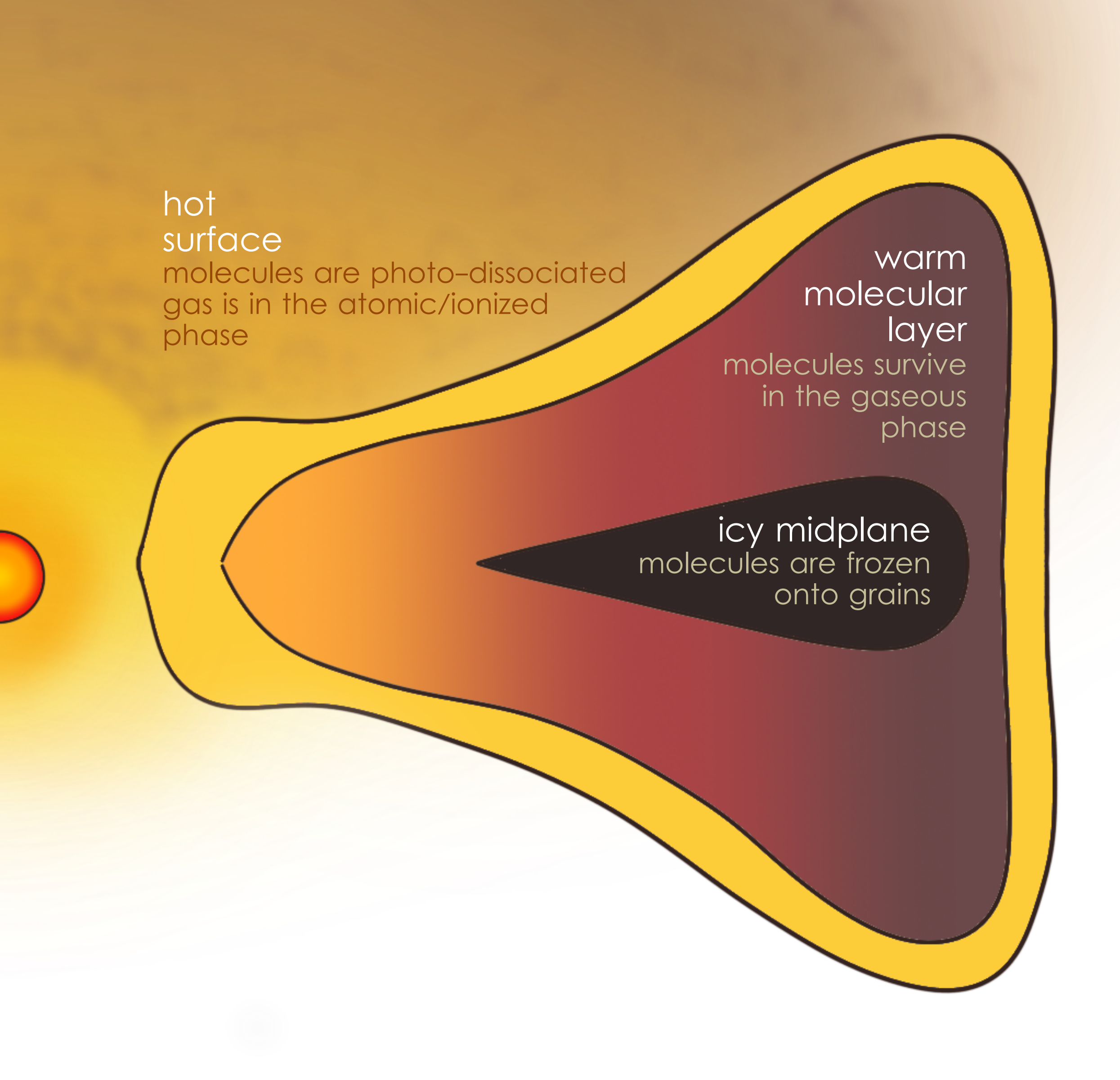
disk dynamics
and evolution

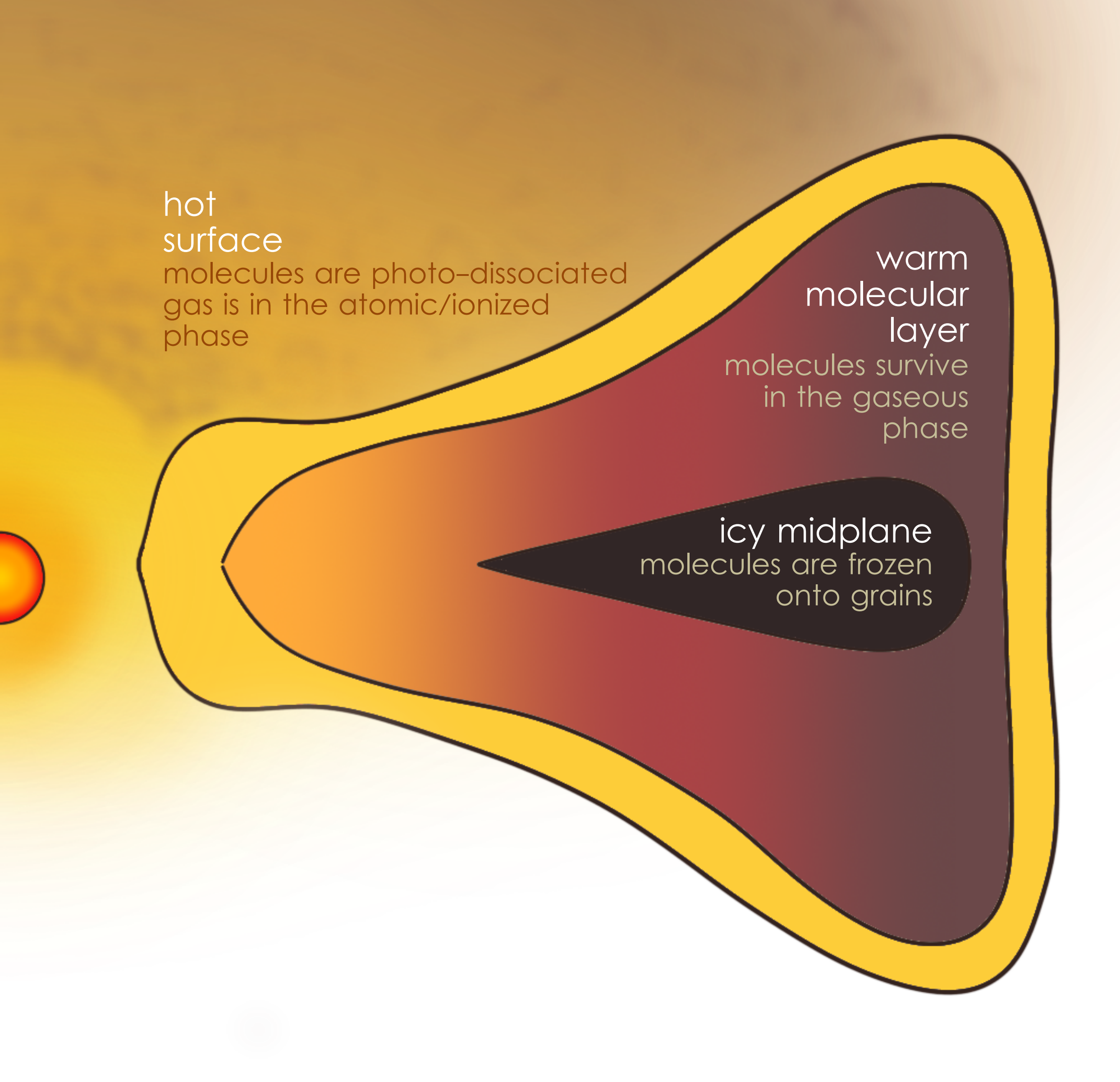
GAS MASS

gaseous
planet
formation



BULK GAS


hot surface
molecules are photo-dissociated gas is in the atomic/ionized phase
warm molecular layer
molecules survive in the gaseous phase
icy midplane
molecules are frozen onto grains

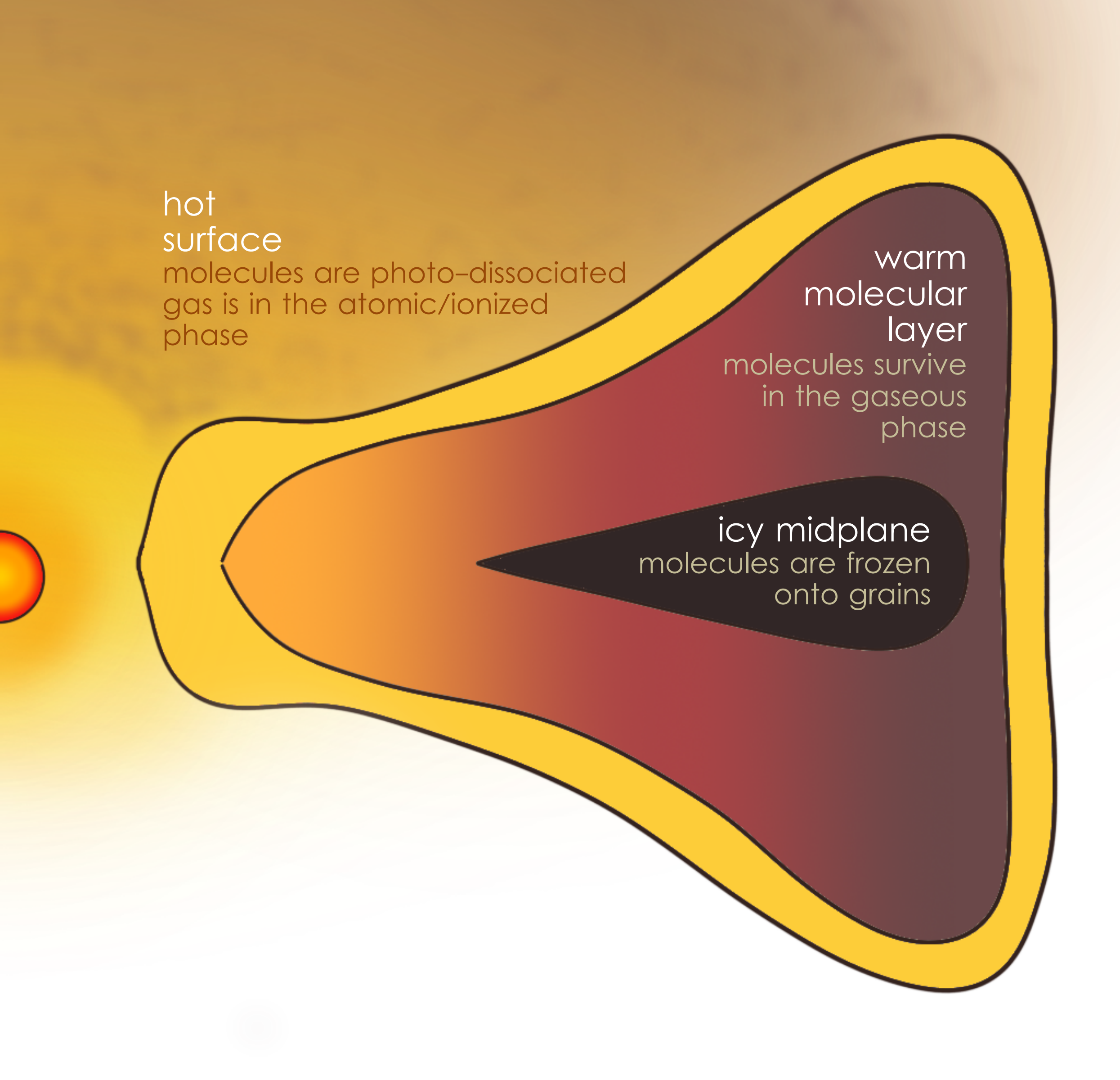


BULK GAS

H_2

- most abundant constituent
- no permanent electric dipole moment:

very weak rotational and vibrational lines

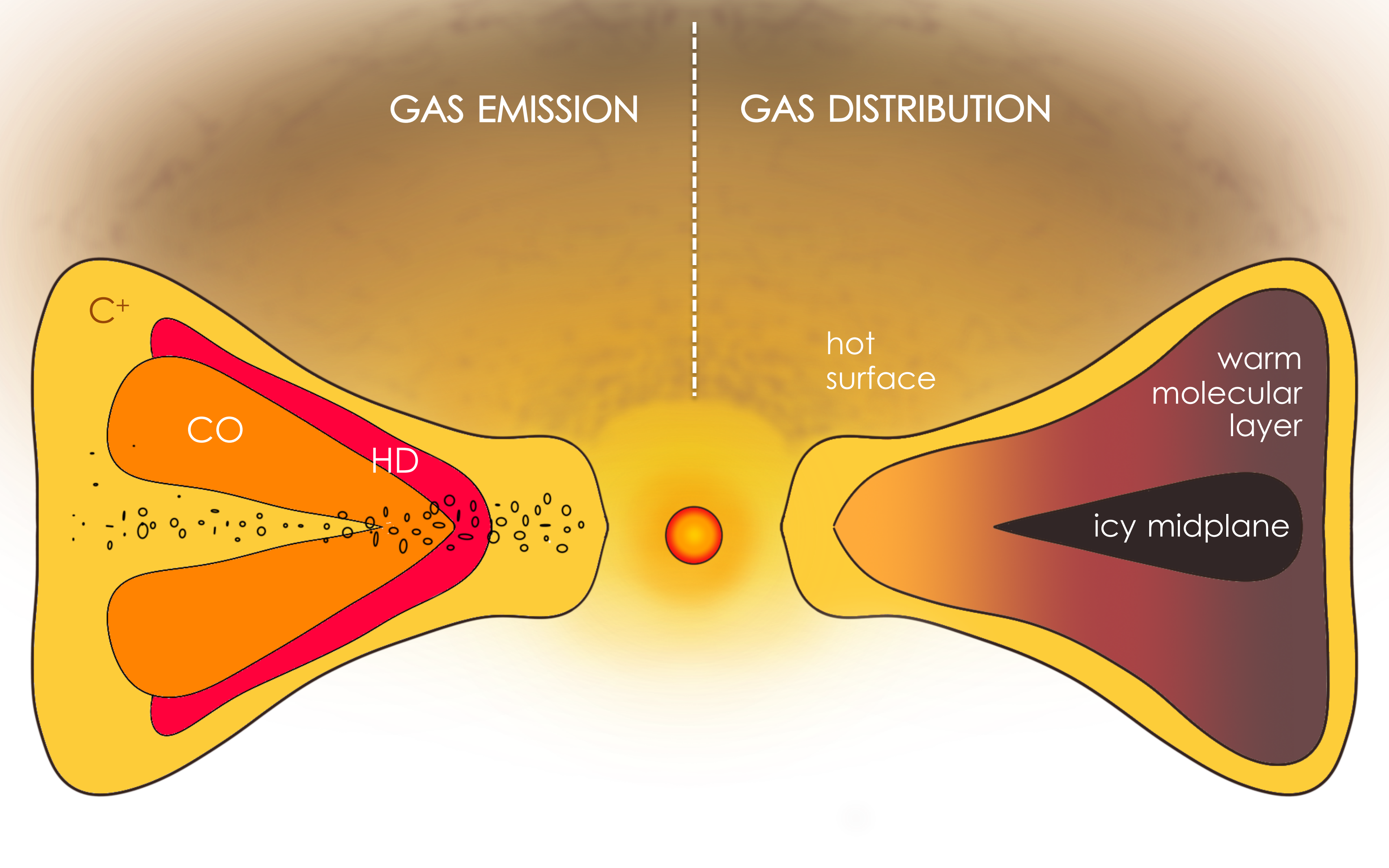


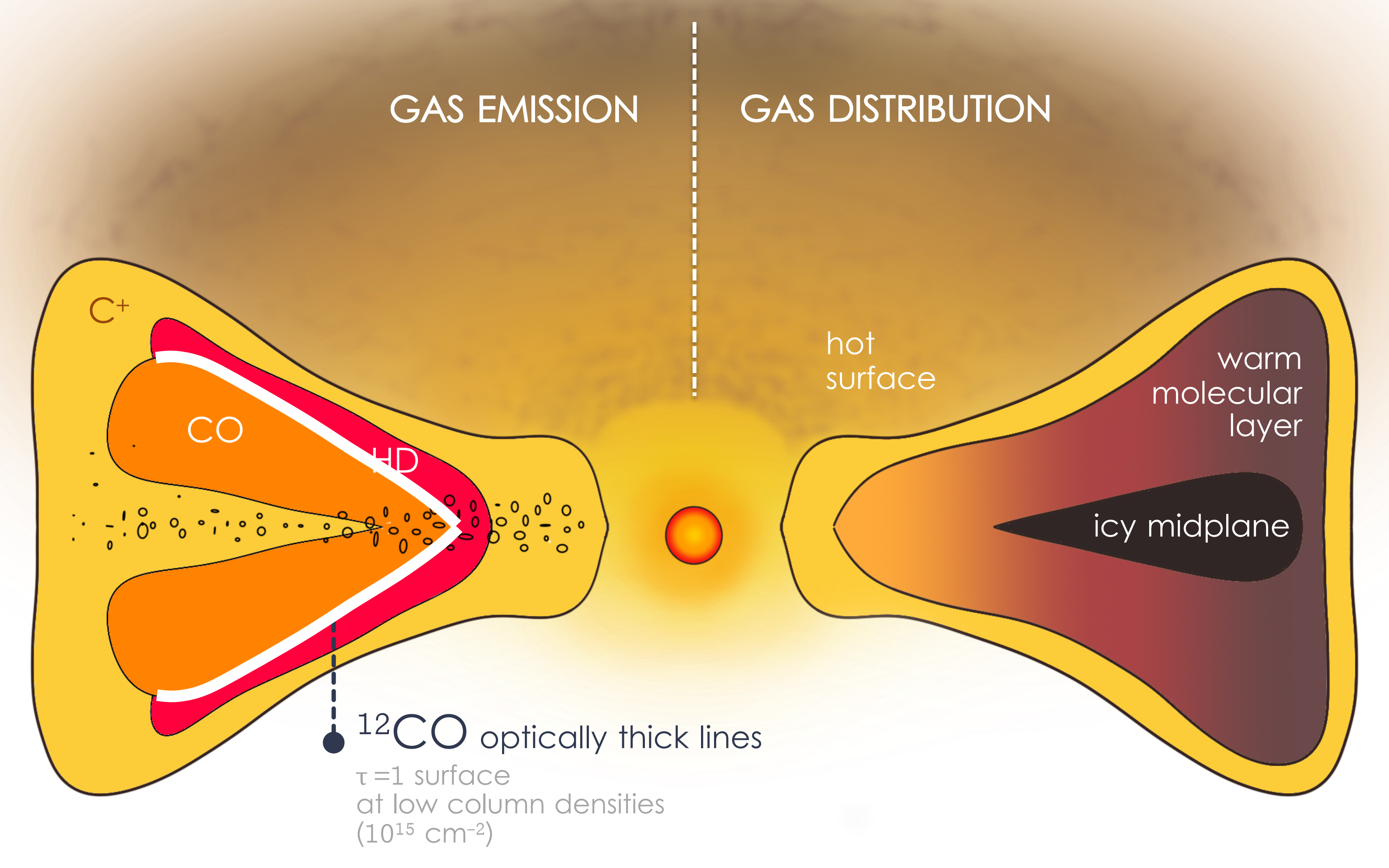
BULK GAS

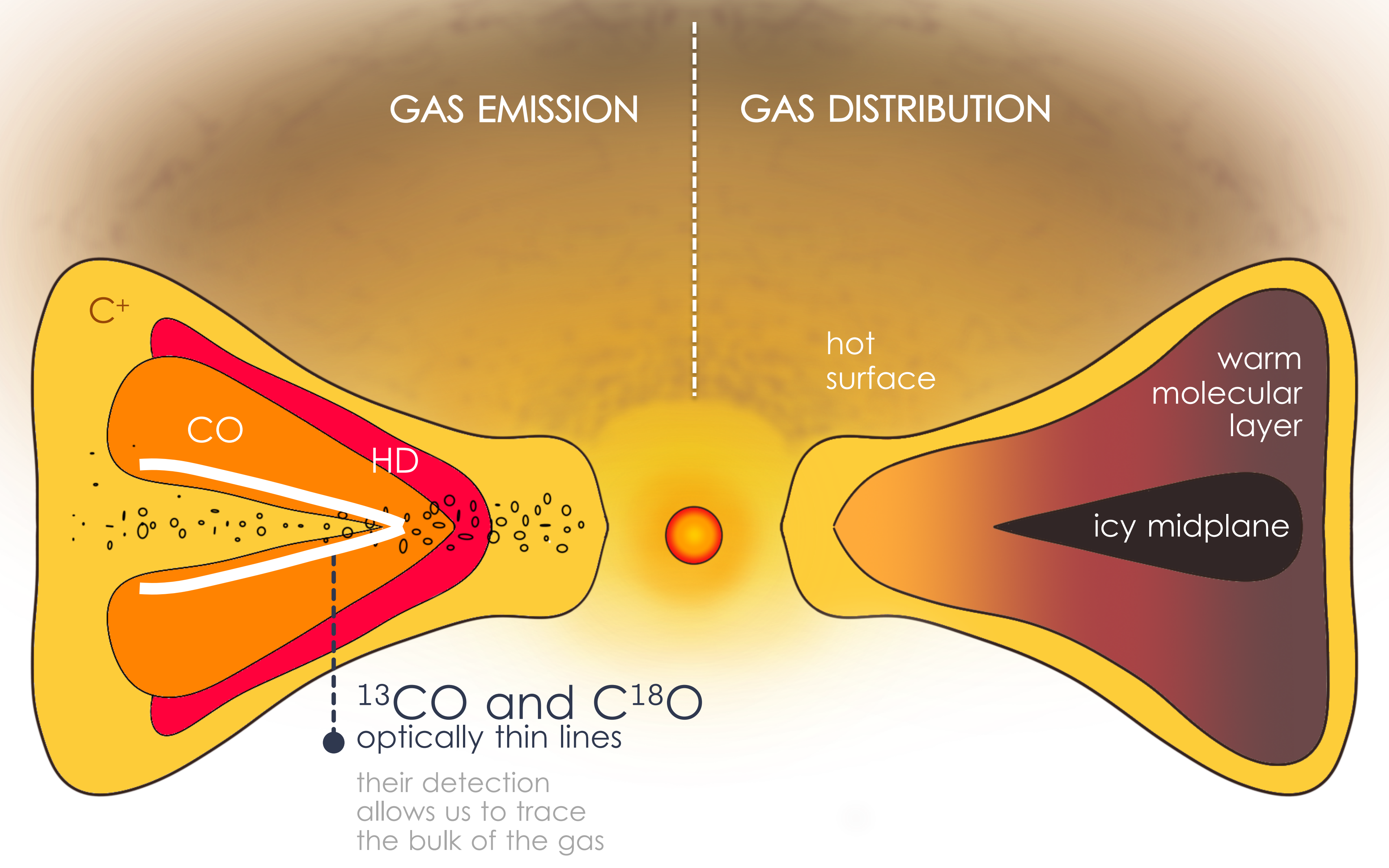
CO

- second in abundance to H_2
- very well studied chemistry

readily detectable pure rotational lines at mm wavelengths


GAS EMISSION
GAS DISTRIBUTION
C+
CO
HD
hot surface
warm molecular layer
icy midplane


GAS EMISSION
GAS DISTRIBUTION
C+
CO
HD
hot surface
warm molecular layer
icy midplane
^{12}CO optically thick lines
τ =1 surface at low column densities (10^{15} cm^{-2})


GAS EMISSION
GAS DISTRIBUTION
C+
CO
HD
13CO and C18O
optically thin lines
their detection
allows us to trace
the bulk of the gas
hot
surface
warm
molecular
layer
icy midplane

CAVEATS

CAVEATS

$C^{18}O \rightarrow CO$

isotope
selective
processes

taken into account with
physical-chemical
disk modeling

DALI, Bruderer et al. 2012
Miotello et al., 2014b; 2016

Van Dishoeck & Black, 1988
Visser et al., 2009

CAVEATS

$C^{18}O \rightarrow CO \rightarrow H_2$

isotope selective processes
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DALI, Bruderer et al. 2012
Miotello et al., 2014b; 2016

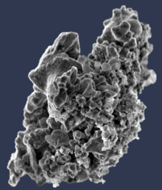
Van Dishoeck & Black, 1988
Visser et al., 2009

carbon abundance relative to H_2
difficult to quantify

TW Hya
Favre et al., 2013
Kama et al., 2016
Schwarz et al., 2016

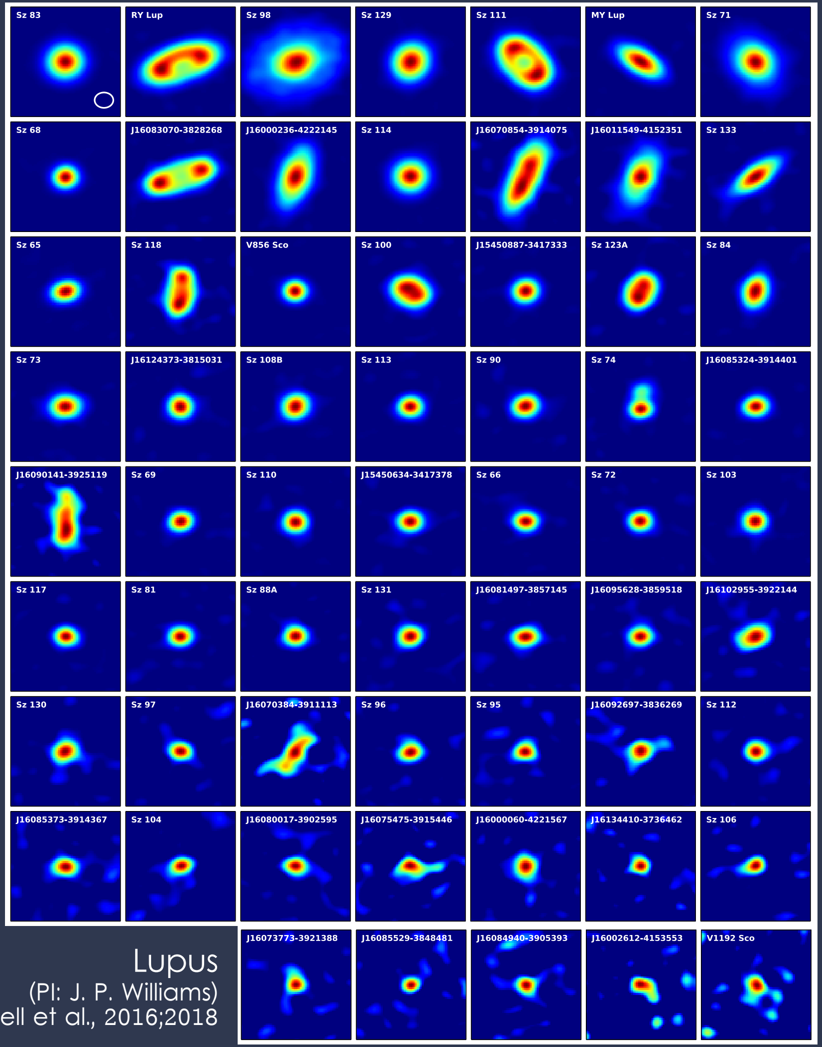
ALMA DISK SURVEYS

Lupus (Ansdell et al. 2016;2018, Manara et al., 2016; Miotello et al. 2017, van Terwisga et al., 2019)
Chamaeleon I (Pascucci et al. 2016; Mulder et al., 2017, Long et al. 2017,2018)
σ–Orionis (Ansdell et al. 2018)
Taurus (Long et al. ,2018)
Upper Scorpius (Barenfeld et al. ,2018)



Continuum
0.89, 1.2 mm

^{12}CO (J=2–1)
^{13}CO (J=2–1,3–2)
$C^{18}O$ (J=2–1,3–2)

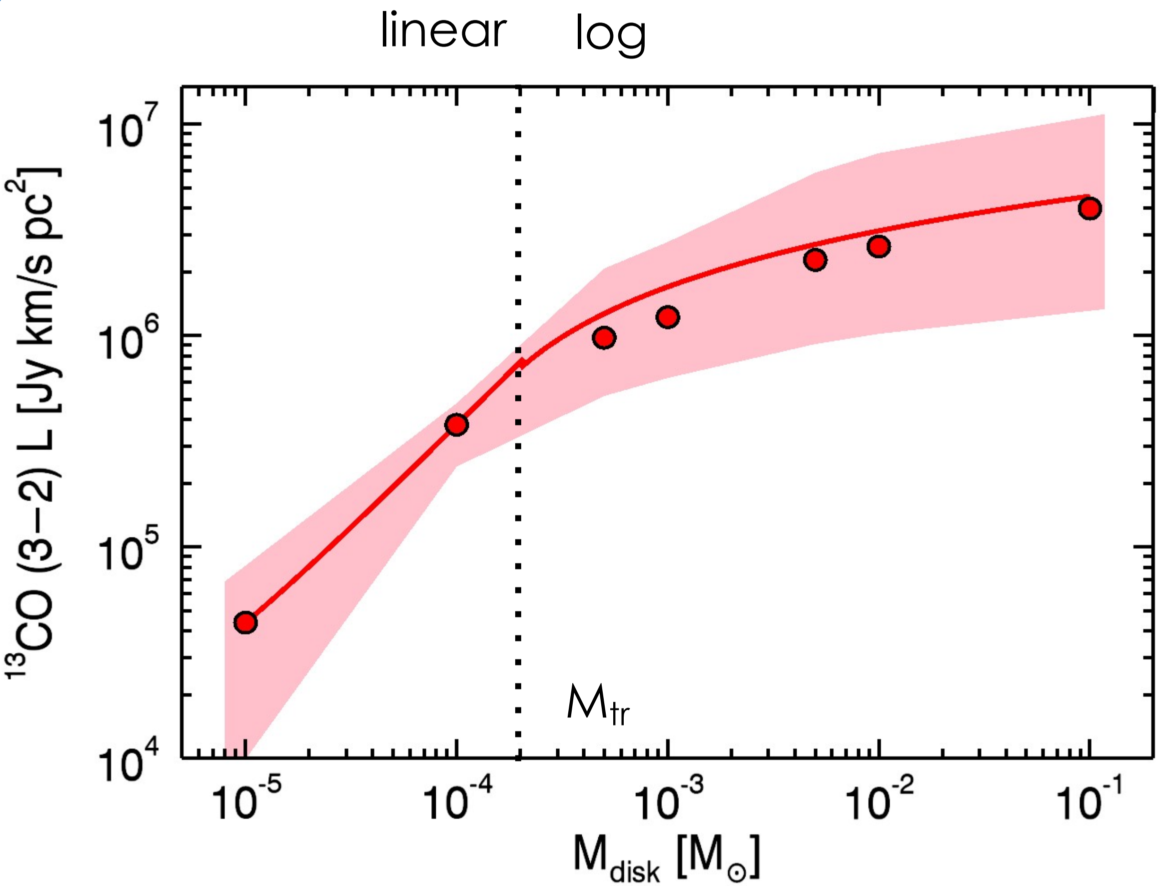


Lupus
(PI: J. P. Williams)
Ansdell et al., 2016;2018

GRID OF MODELS

Analytic expressions of the line emission as function of the disk mass

^{13}CO



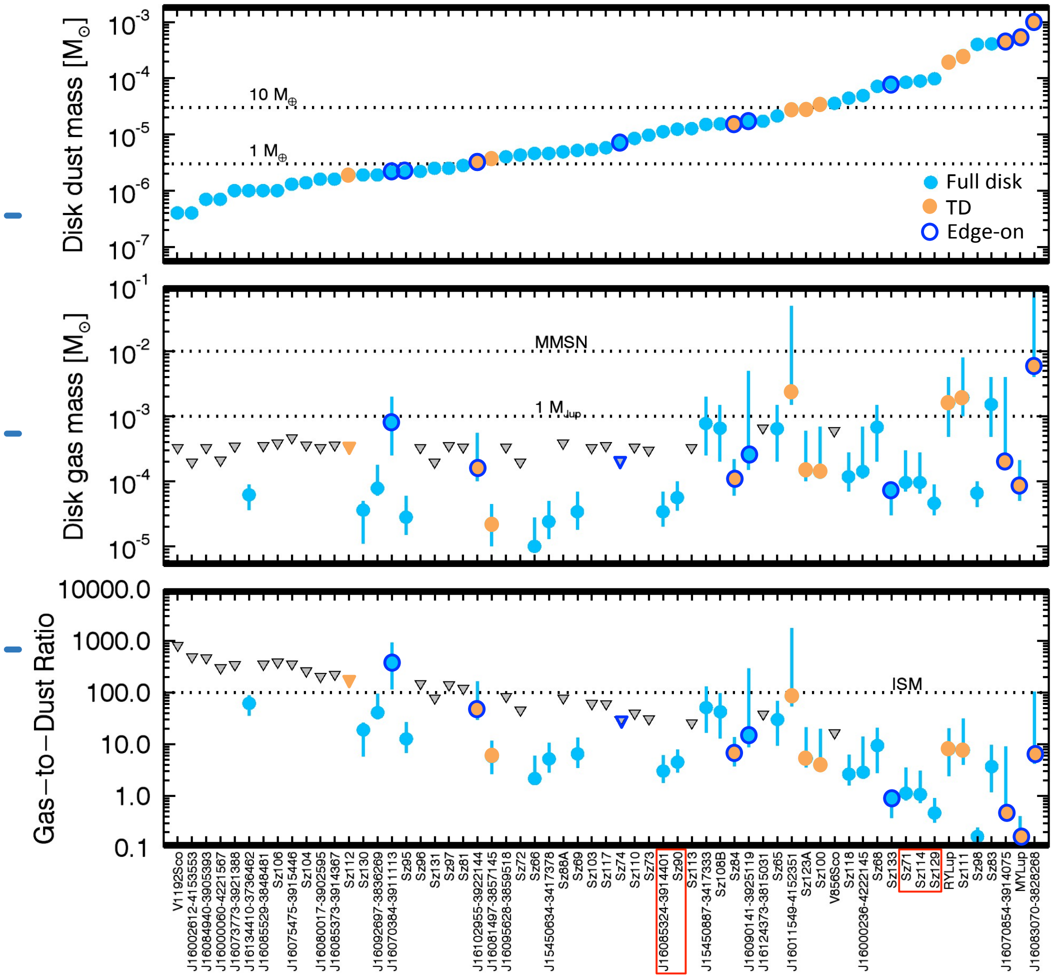
Miotello et al., 2017

DISK MASSES FROM CO

dust masses

^{13}CO-based gas masses

^{13}CO-based gas/dust ratio



Miotello et al., 2017

LOW GAS/DUST OR HIGH C DEPLETION?

sign of disk evolution

1

physical evolution

gas is dissipated

$M_{gas}<M_{jup}$

giant planet formation is quick or rare

chemical evolution

2

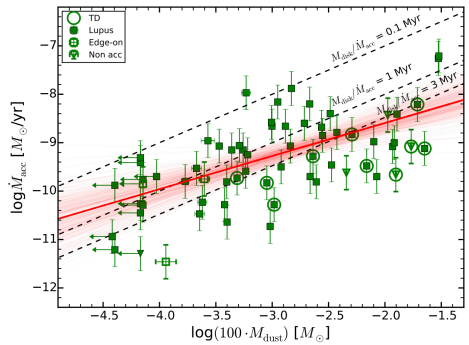
volatile carbon is locked up in large icy bodies or turned into more complex species

Ansdell et al., 2016
Manara et al., 2016
Miotello et al., 2017
Miotello et al., submitted

LOW GAS/DUST OR HIGH C DEPLETION?

sign of disk evolution

Manara et al., 2016

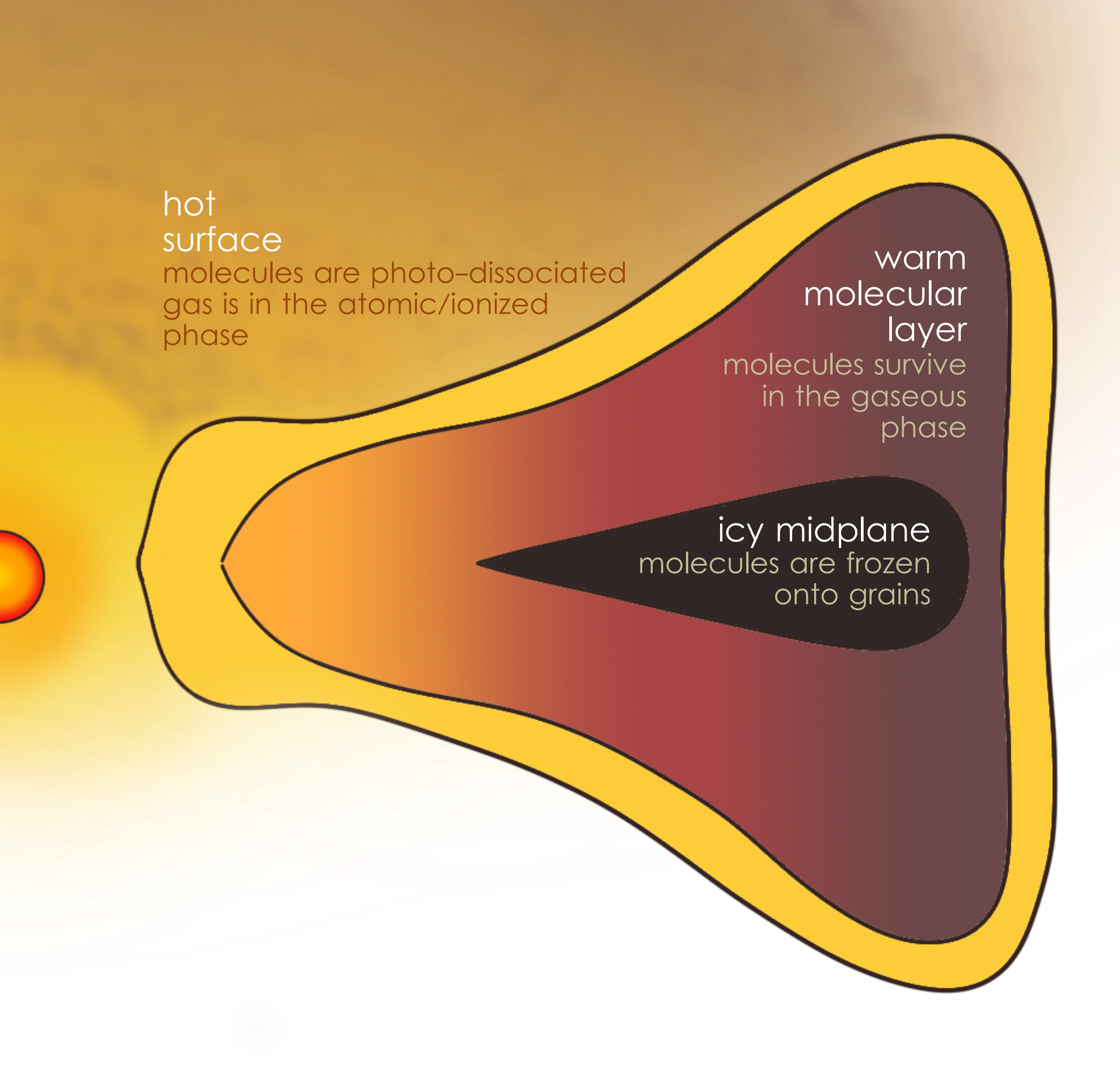


chemical evolution

2

volatile carbon
is locked up
in large icy bodies
or turned into
more complex species

Aikawa et al. 1996;
Bergin et al. 2014;
Du et al. 2015;
Eistrup et al. 2016, 2018;
Yu et al. 2017a,b;
Bosman et al. 2017, 2018;
Schwarz et al. 2018;
Krijt et al. 2018



BULK GAS

HD

- Less abundant isotopologue of molecular hydrogen

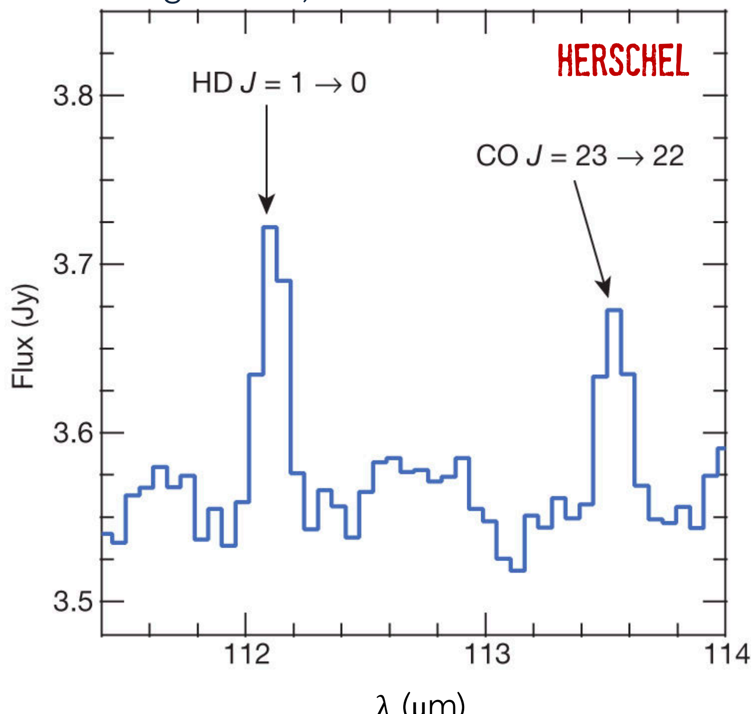
rotational transition *J* (1–0) detectable with *Herschel* (PACS)

HYDROGEN DEUTERIDE

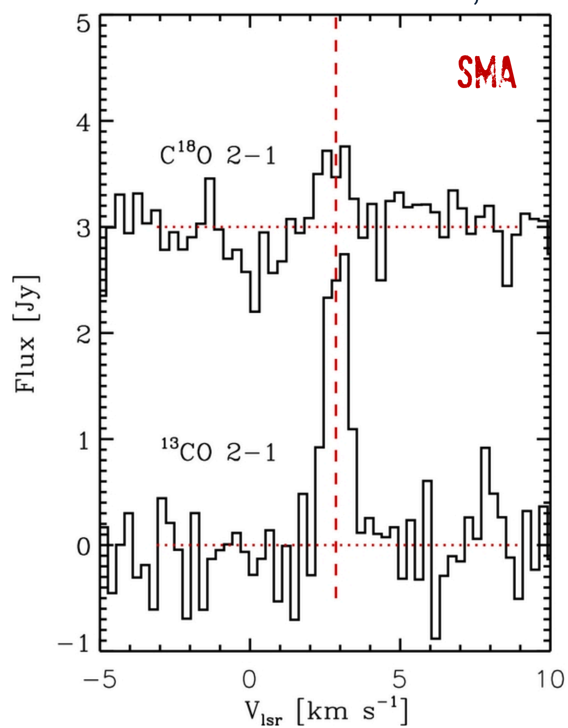
An alternative to measure disk masses

TW HYA

Bergin et al., 2013



Favre et al., 2013



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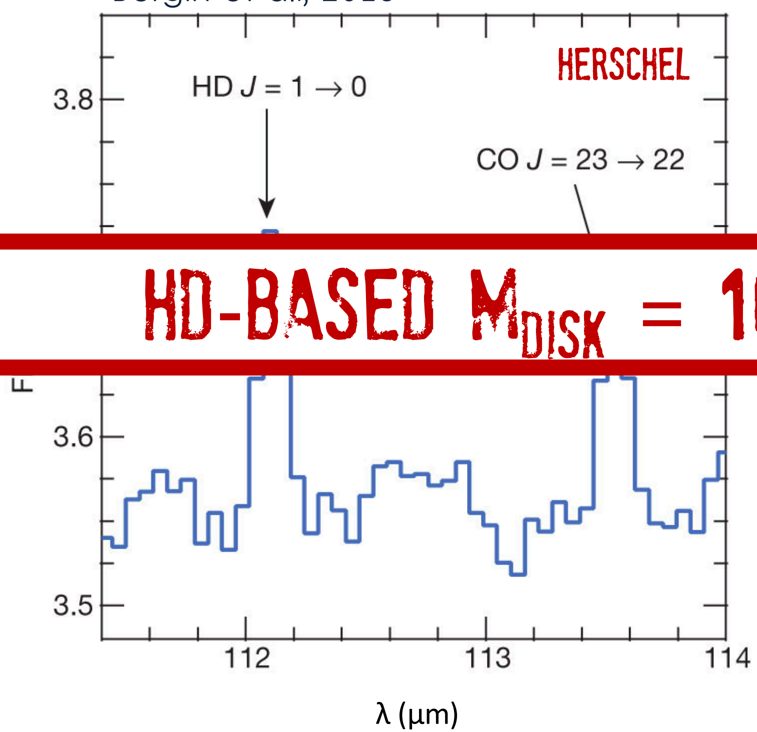
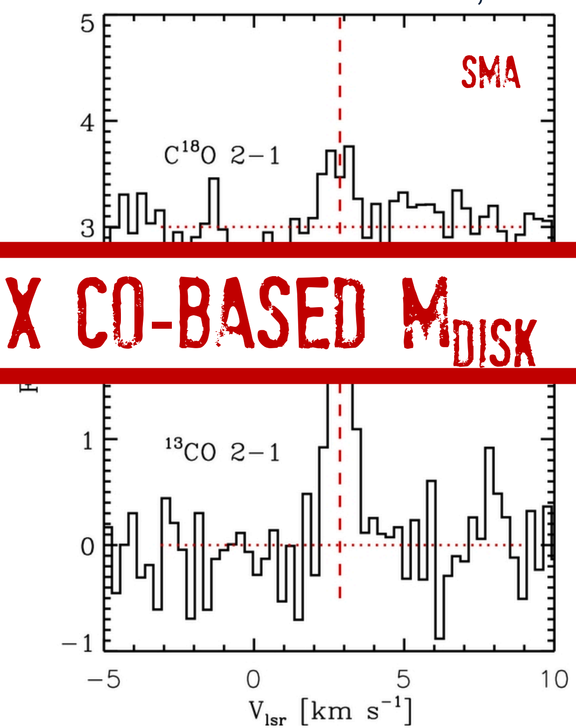


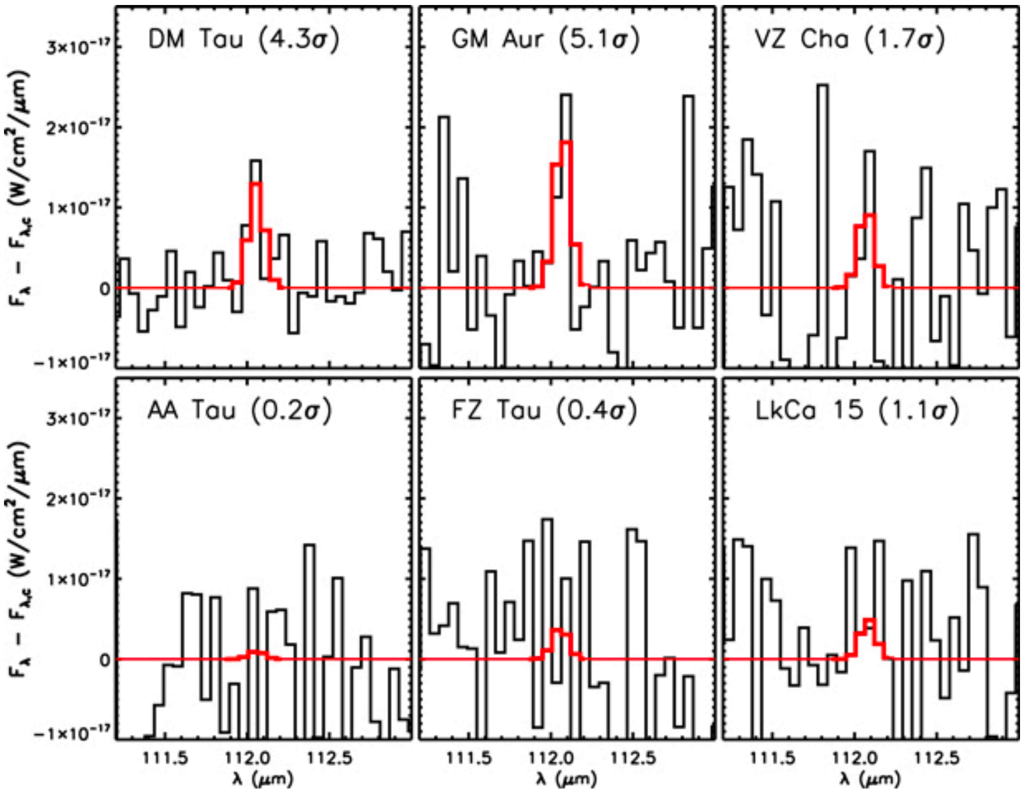
Favre et al., 2013



HD-BASED M_{DISK} = 100 X CO-BASED M_{DISK}

HYDROGEN DEUTERIDE

An alternative to measure disk masses



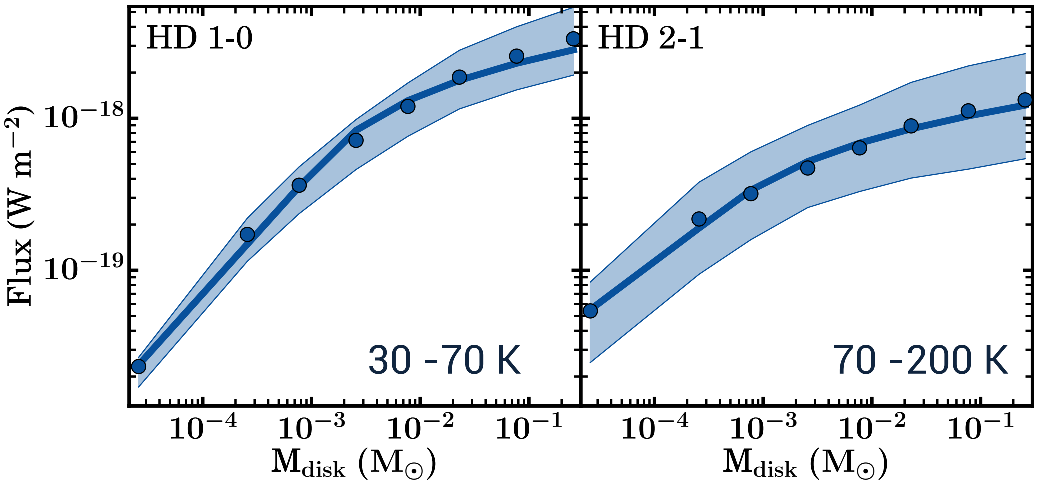
2 more sources
with detection of HD

Need for HD-based mass measurements in a statistically significant sample

McClure et al., 2016

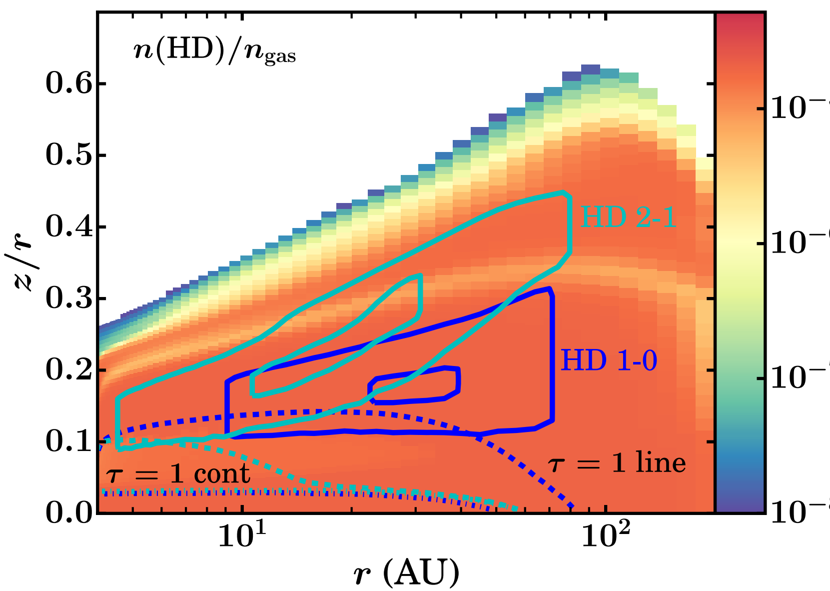
HD: A GOOD MASS TRACER?

Dependence of HD emission on disk masses



HD emission depends on temperature

➔ on disk vertical structure



Trapman, **Miotello**, et al., 2017

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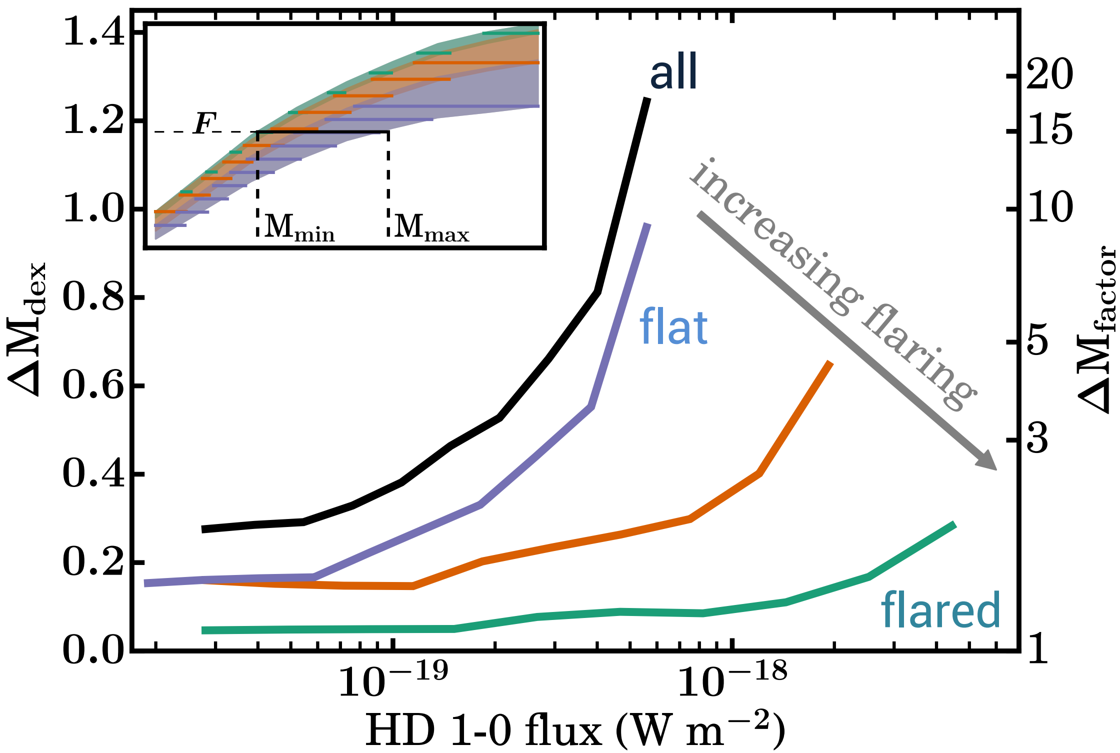
Dependence of HD emission on disk masses



knowledge about vertical structure diminishes the uncertainties on HD-based disk masses

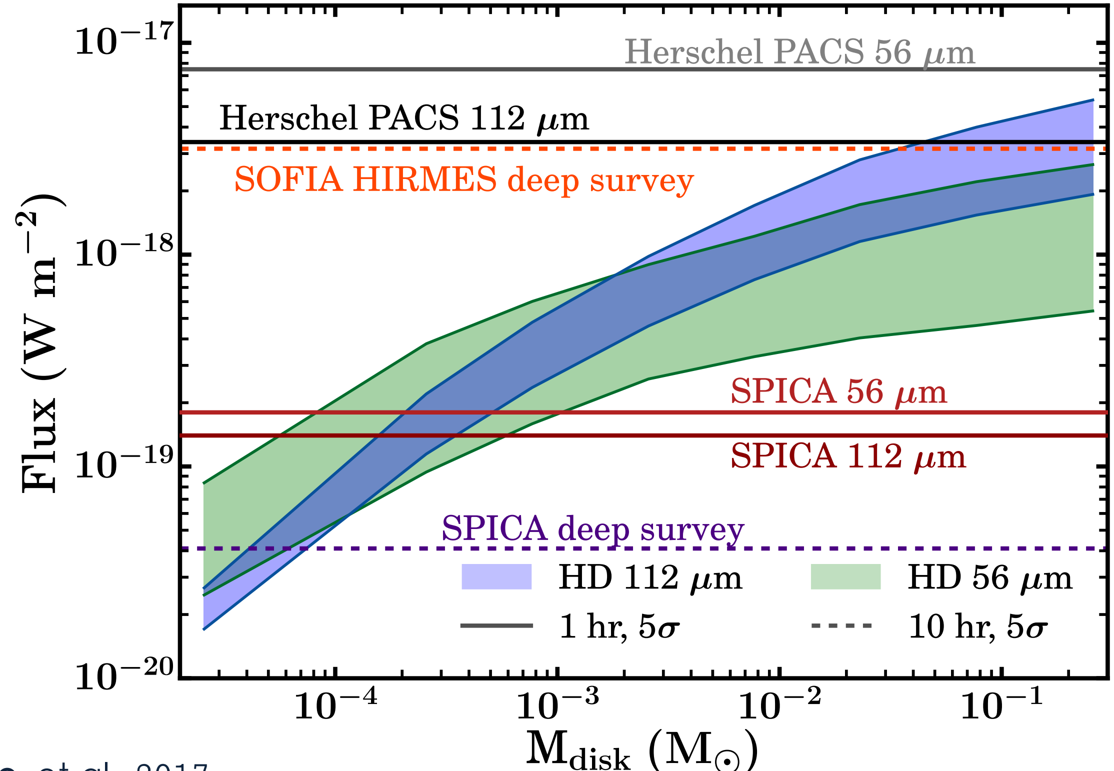
Trapman, **Miotello**, et al., 2017

SENSITIVITY

Detection of a statistically significant number of disks

SPICA

SAFARI



Bergin E., priv. comm.
Richards et al. (2018)

Roelfsema et al. (2014)

Trapman, **Miotello**, et al., 2017

GRAVITATIONAL MASS

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

IS THIS FEASIBLE ?

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

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

Keplerian velocity
due to stellar gravity

Pressure gradient
leads ro sub-Keplerian velocities

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

Self gravity
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IS THIS FEASIBLE ?

OTHER IDEAS?

See e.g., Powell et al. (2019)

GRAVITATIONAL MASS

Self gravity
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Keplerian velocity
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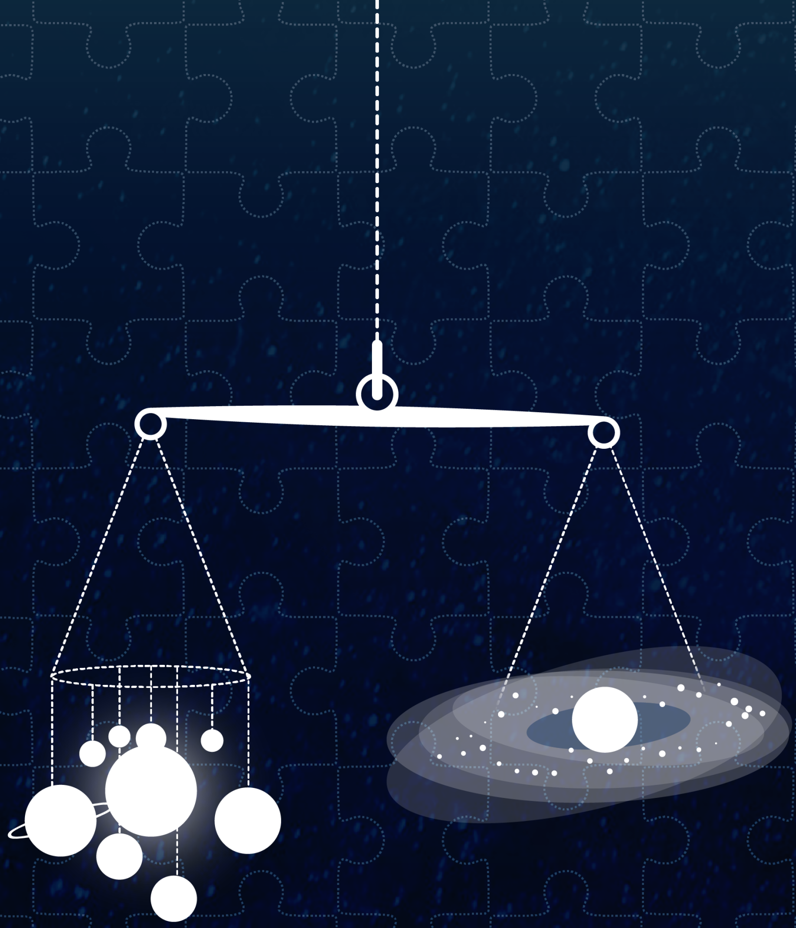
SEE TALK BY BENEDETTA VERONESI

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



Take home

1. **CO-based disk masses are low:**
   gas dispersal or carbon depletion?
   Miotello et al., 2017

2. **HD is a promising alternative to derive disk masses**
   Information on the vertical structure needed
   Trapman, Miotello et al., 2017

3. **Direct measurements of the gravitational mass**
   are needed to calibrate traditional mass determination methods