A Far-IR Determination of Gas Mass and Carbon Depletion in Protoplanetaery Disks

+ future directions with SOFIA...

Credit: NASA

Melissa McClure (Fellow, ESO Garching)

Mass measurements in protoplanetary disks from hydrogen deuteride

McClure et al. (2016), in press

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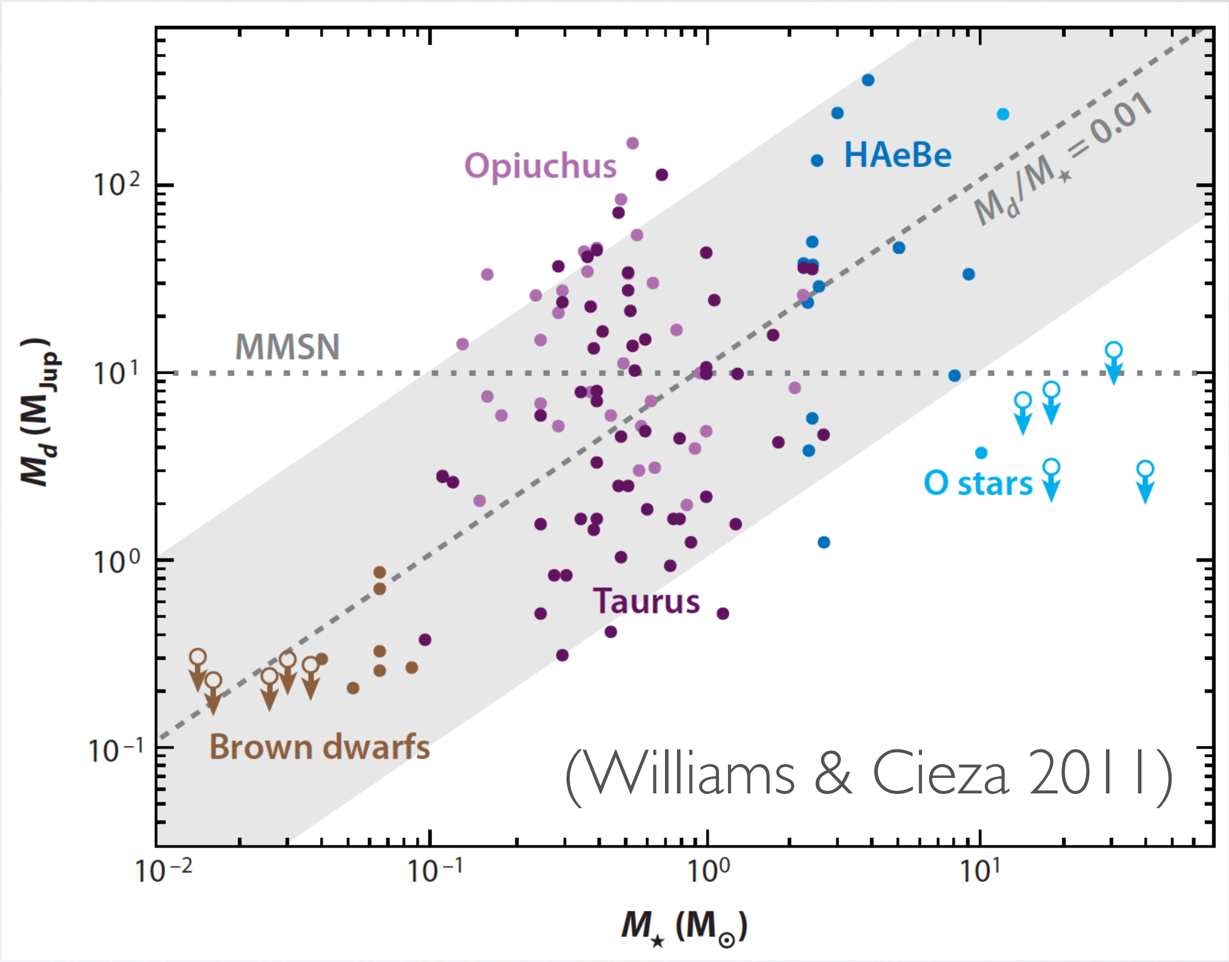
Ewine van Dishoeck *(Leiden)*
Geoff Blake *(Caltech)*
Neal Evans *(UT Austin)*

Joel Green *(STScI)*
Thomas Henning *(MPIA)*
Karin Öberg *(CfA)*
Klaus Pontoppidan *(STScI)*
Colette Salyk *(Vassar)*

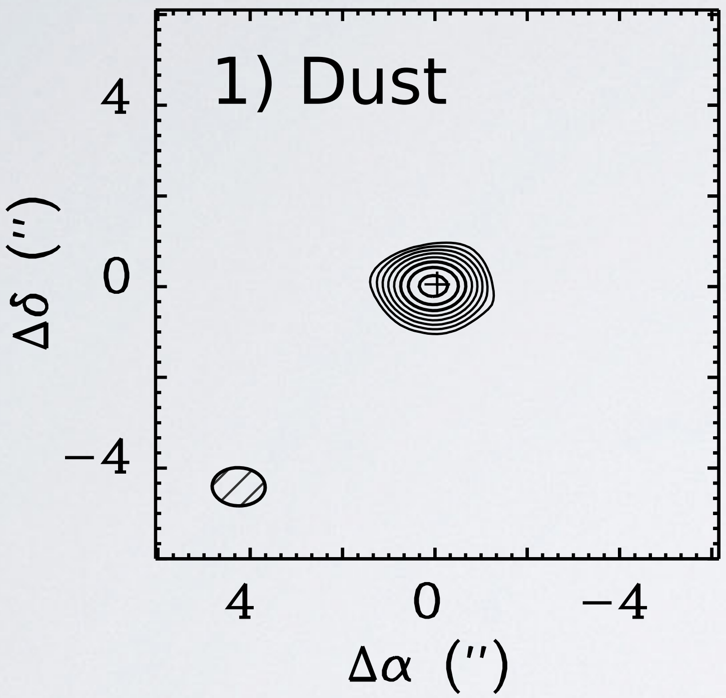
SIGNIFICANCE OF GAS MASS

- outcome of cloud collapse
- fundamental disk property
- determines planet formation outcomes: number, size, system architecture
- MMSN = 0.01 M_{sun}, but wide range



Problems with measurement of gas mass.

GAS MASS TRACERS (I)

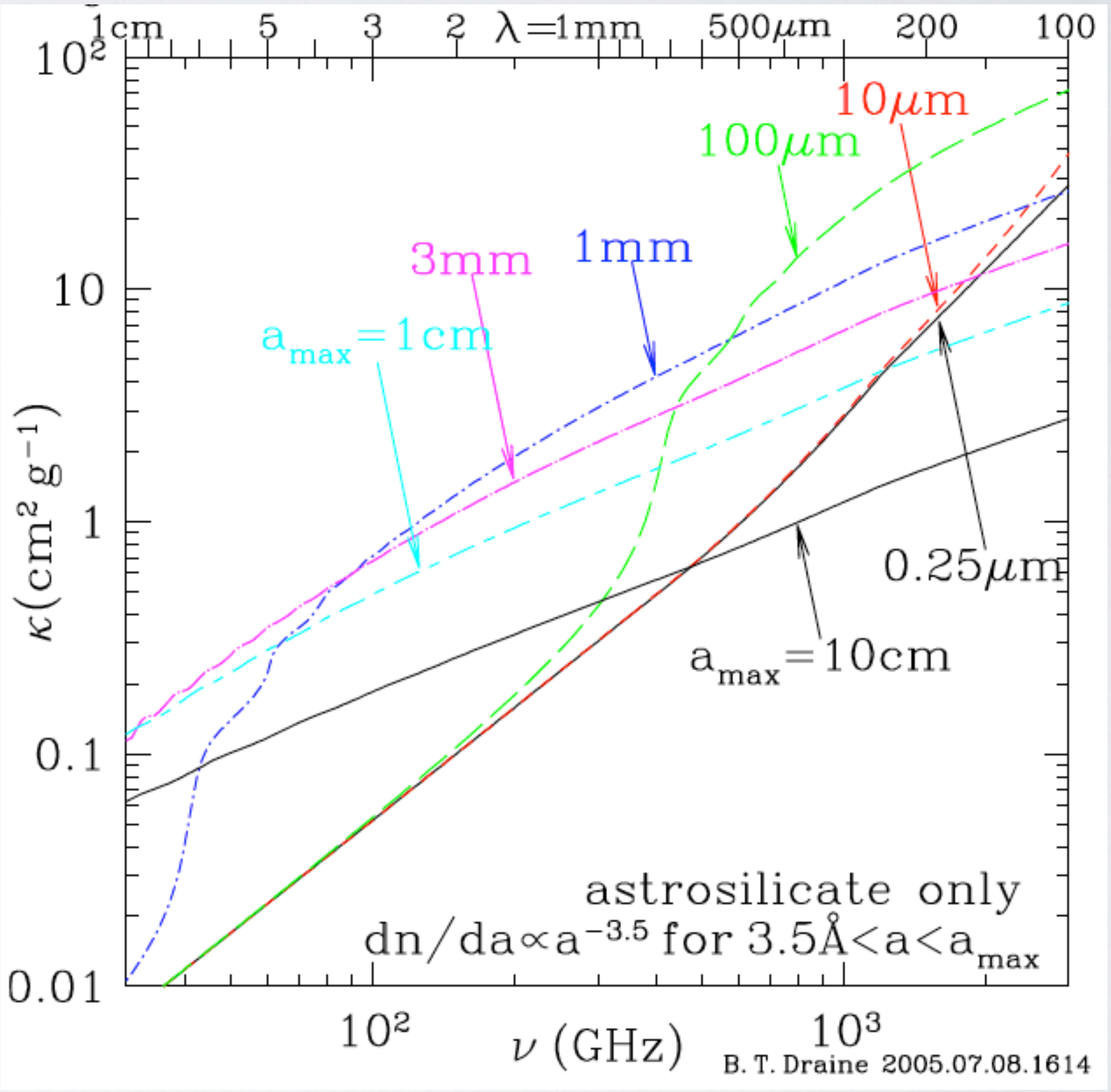


Williams & Best (2014)

$M_{dust} \propto \kappa^{-1} S_\nu$

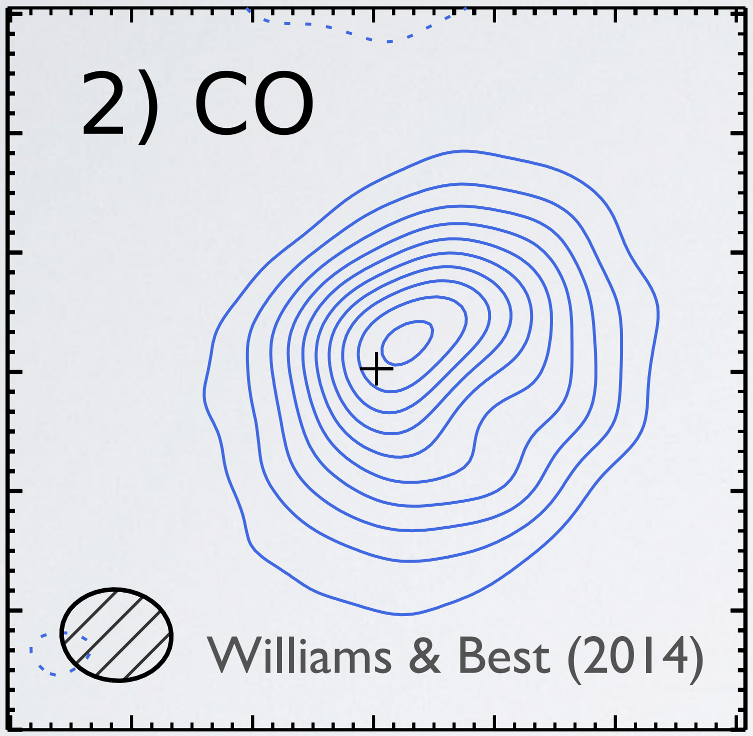
$M_{gas} = \chi M_{dust}$

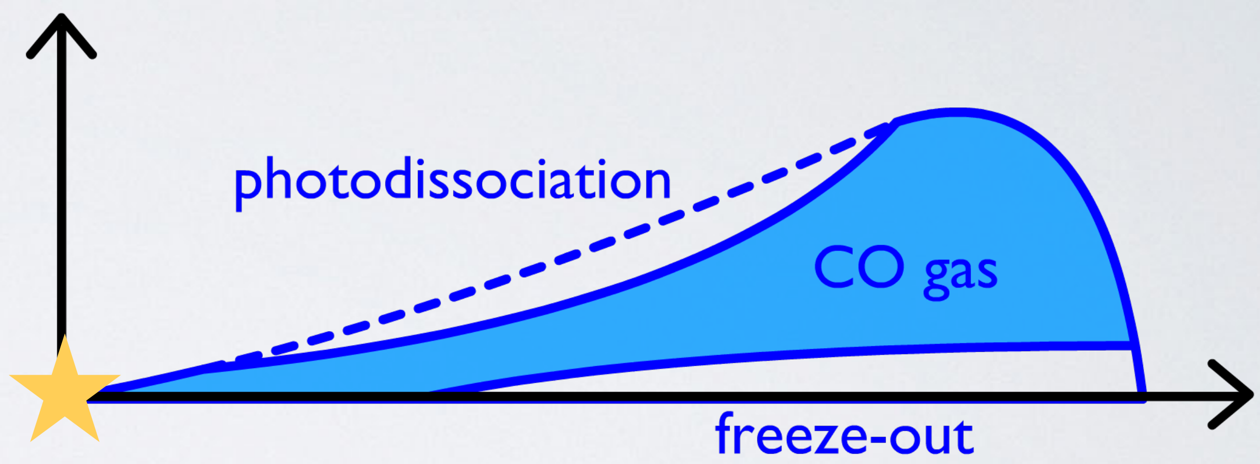
May overestimate gas mass.



Draine (2006)

Disk gas mass tracers (2)





May underestimate gas mass due to:

- photodissociation and freeze-out
- isotope selective photodissociation
- chemical depletion

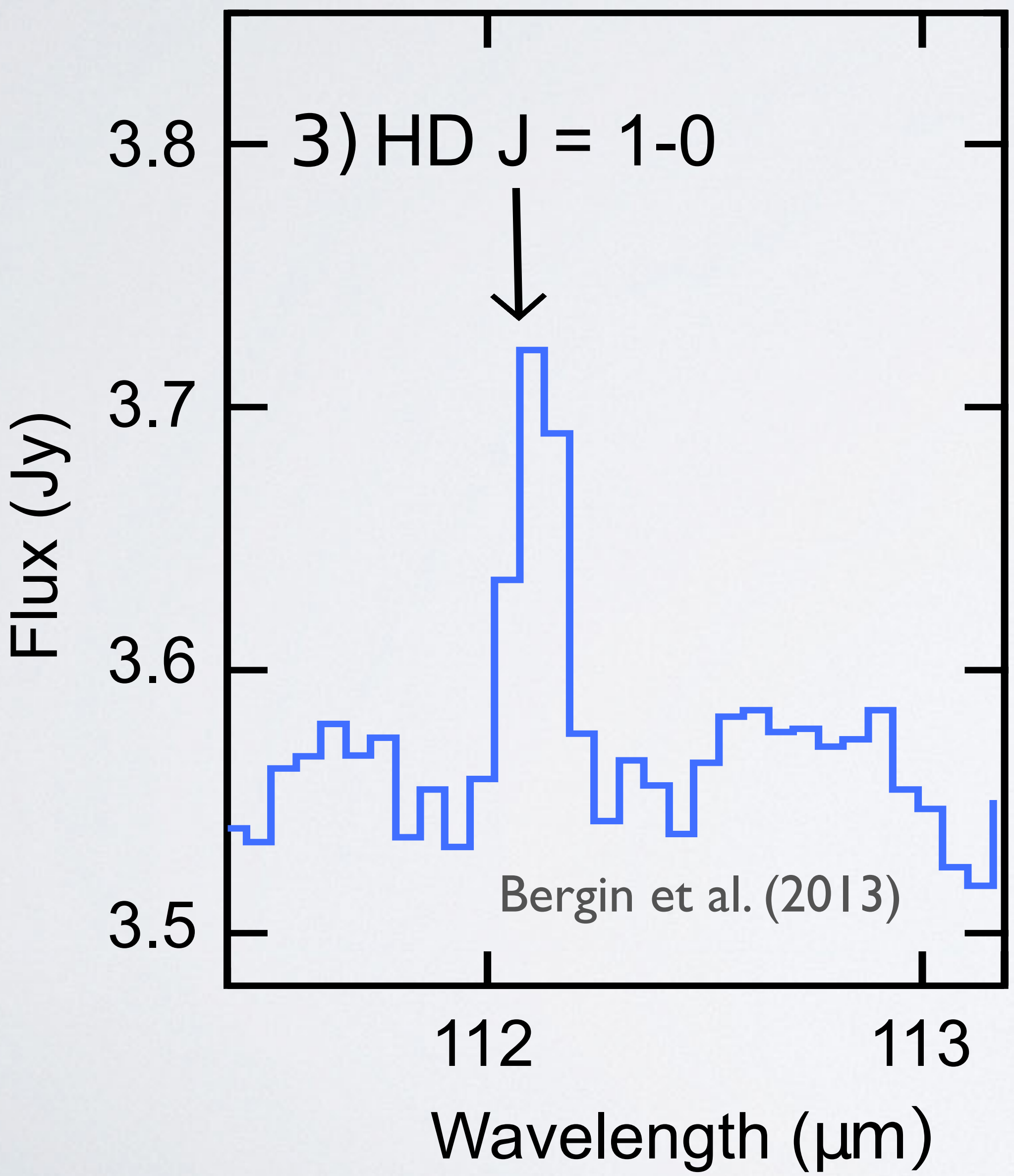
$M_{CO} \propto N_{CO}$

$M_{CO} = 2\times10^{-4}\ M_{H2}$

(Williams & Best 2014; Miotello et al. 2014, 2016; Favre et al. 2013)

DISK GAS MASS TRACERS (3)

(*Herschel*, PACS)



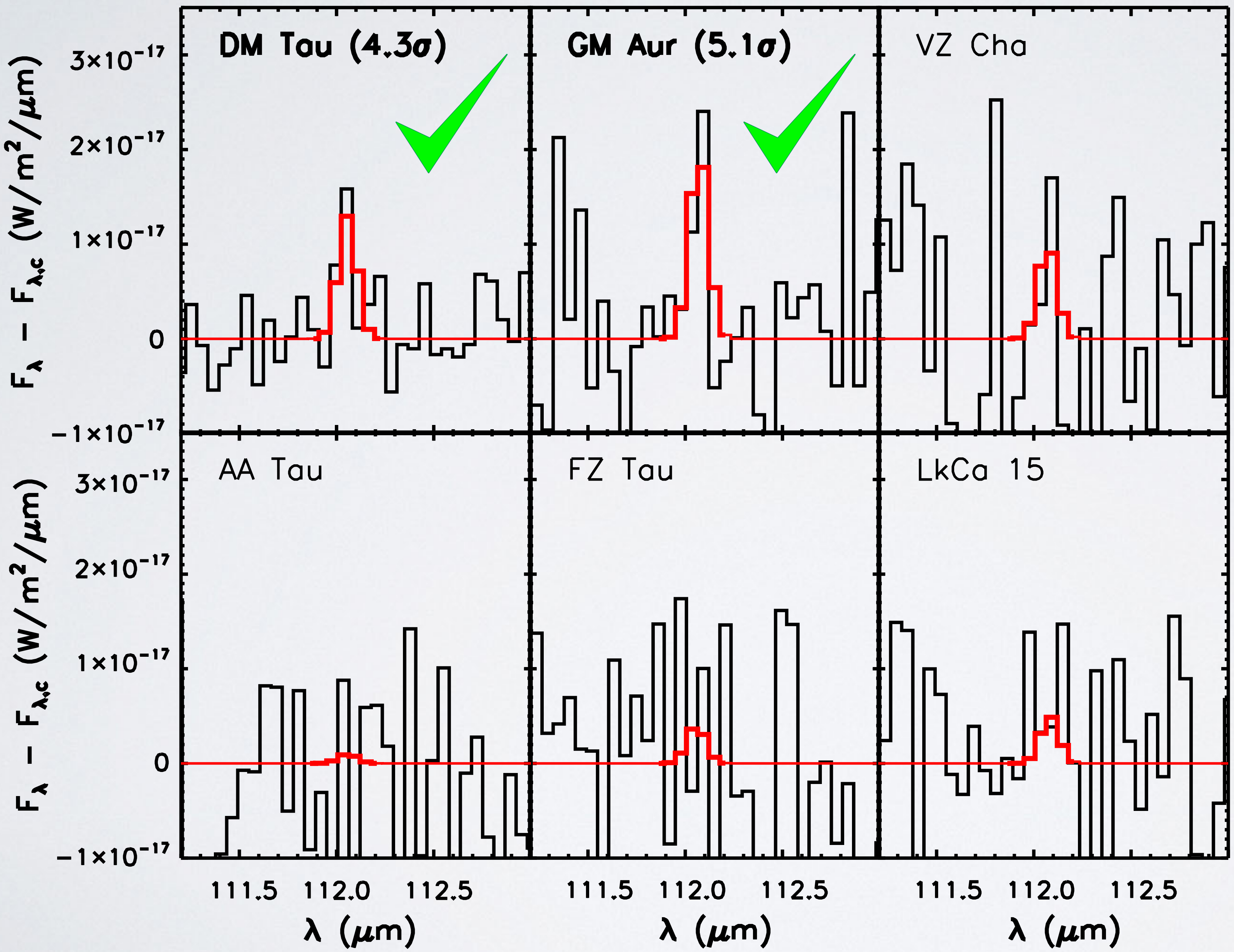
HD (isotope of H_2),
D/H=1.5×10^{-5} in local bubble

No freeze-out or chemical depletion, depends on T(R,z)

TW Hya M_{gas} (from HD) = 0.06 $M_\odot$ > M_{gas} (from CO). *Chemical depletion of CO?*

(Linsky et al. 1998; Bergin et al. 2013)

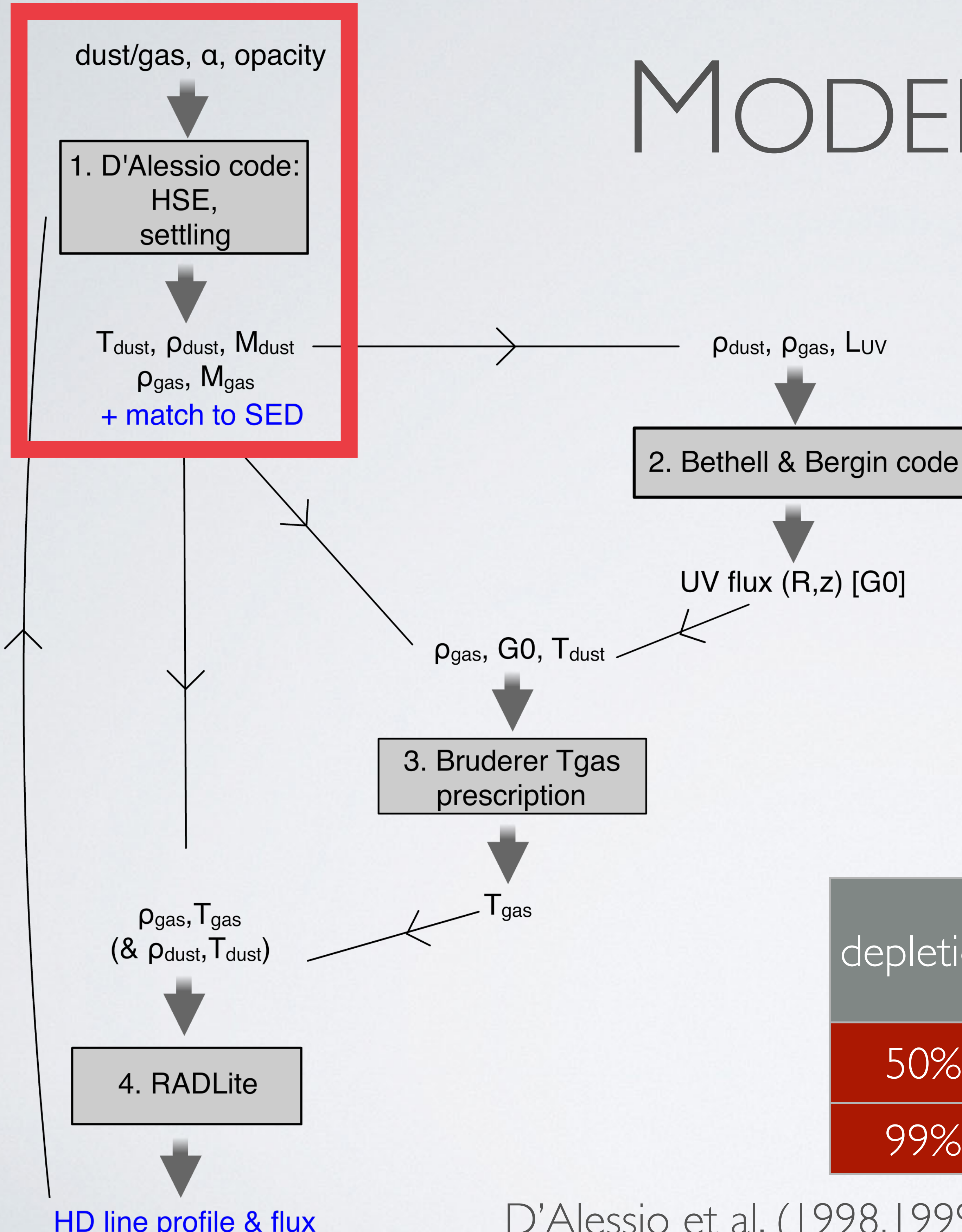
SAMPLE & OBSERVATIONS

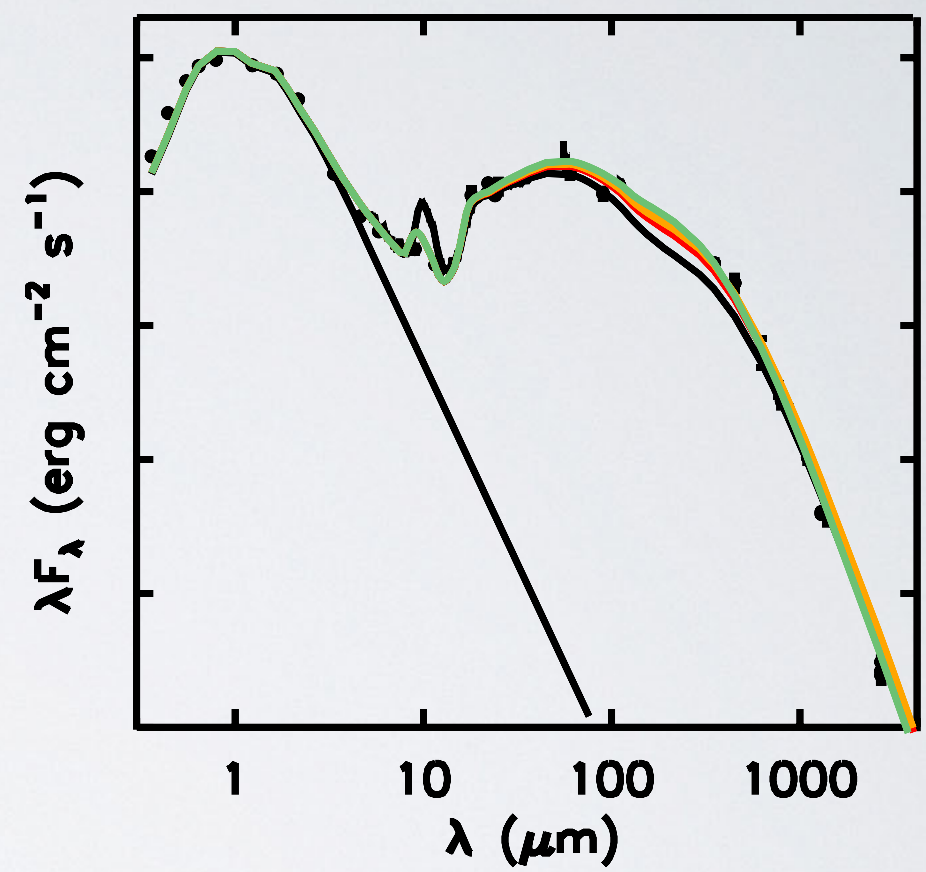


HD J=1-0 integrated fluxes ($\times 10^{-18}$ W/m²)	
DM Tau	**1.6±0.4**
GM Aur	**2.5±0.5**
VZ Cha	*<2.1*
AA Tau	*<2.2*
FZ Tau	*<3.6*
LkCa 15	*<1.7*

McClure et al. (2016)

MODEL FLOWCHART

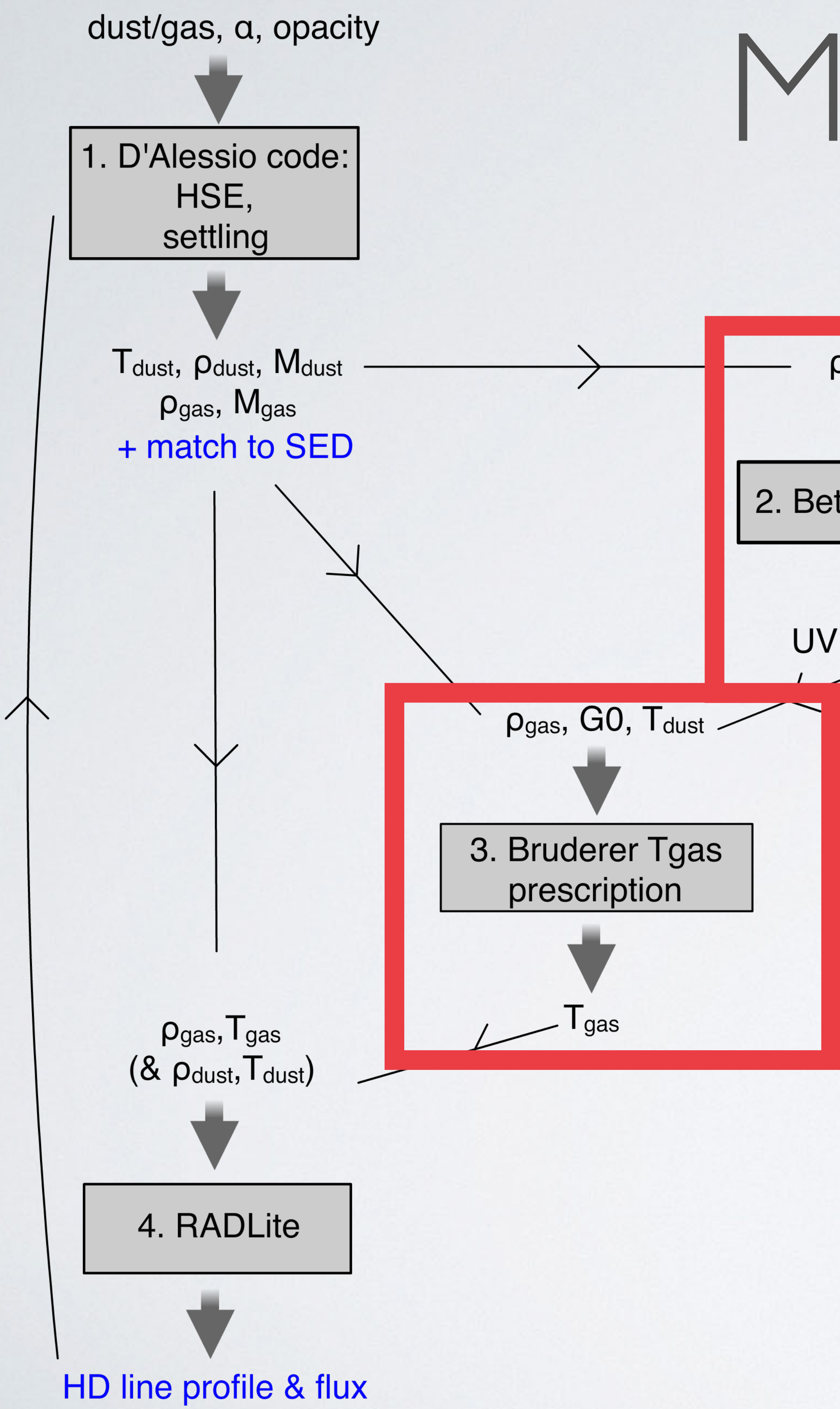


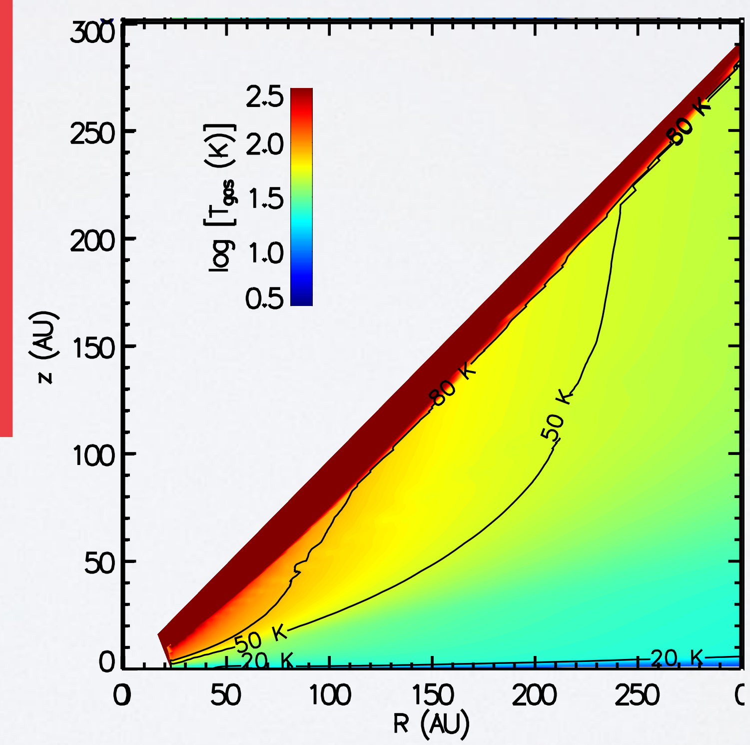


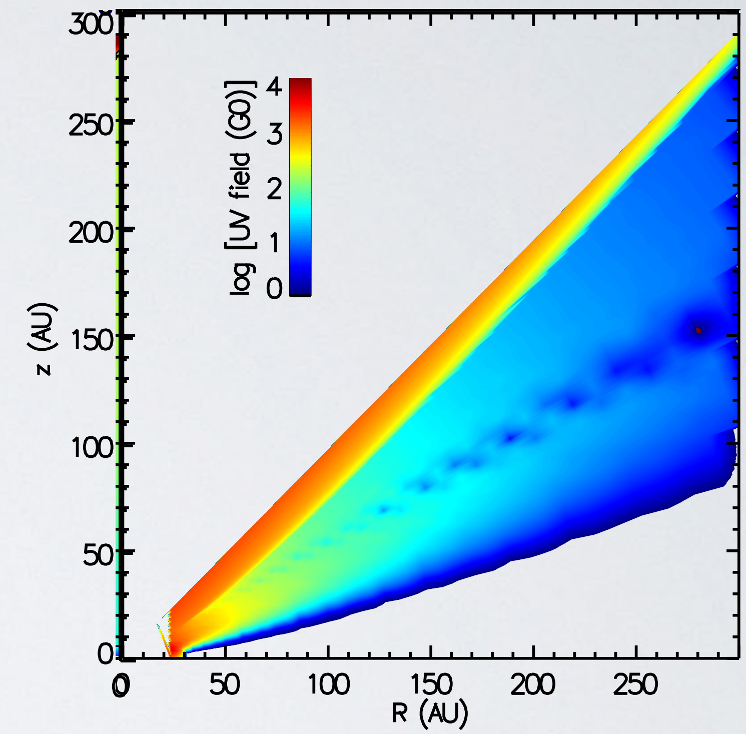
depletion	gas/dust upper layers	gas/dust midplane
50%	200	17
99%	10^4	8

D'Alessio et al. (1998,1999, 2004, 2006), Espaillat (2009), McClure (2014)

Model flowchart

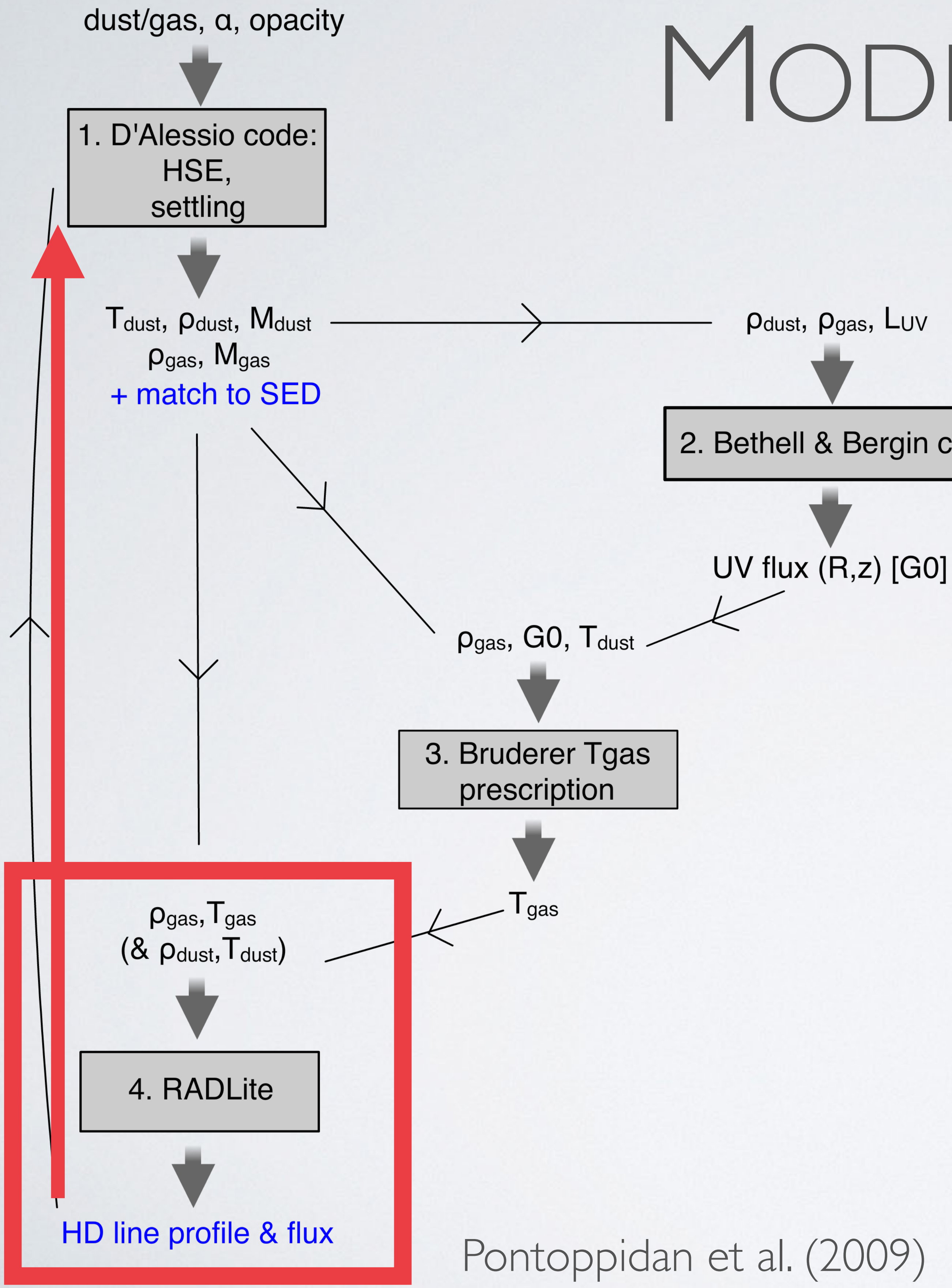






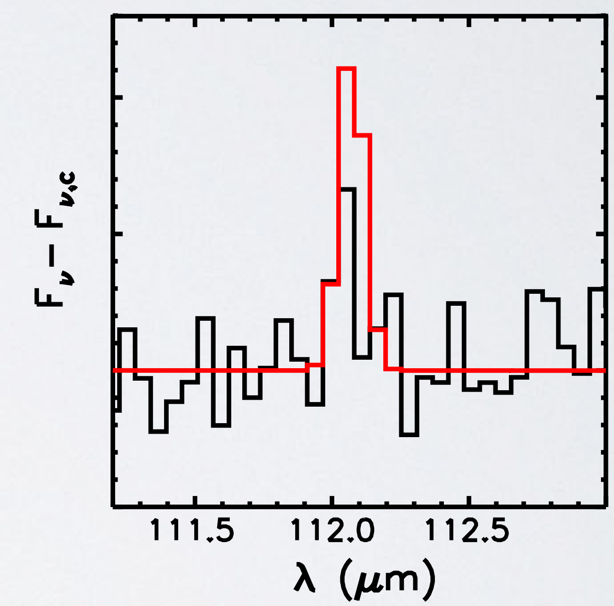
Bethell & Bergin (2009), Bruderer et al. (2012, 2013)

MODEL FLOWCHART



Pontoppidan et al. (2009)

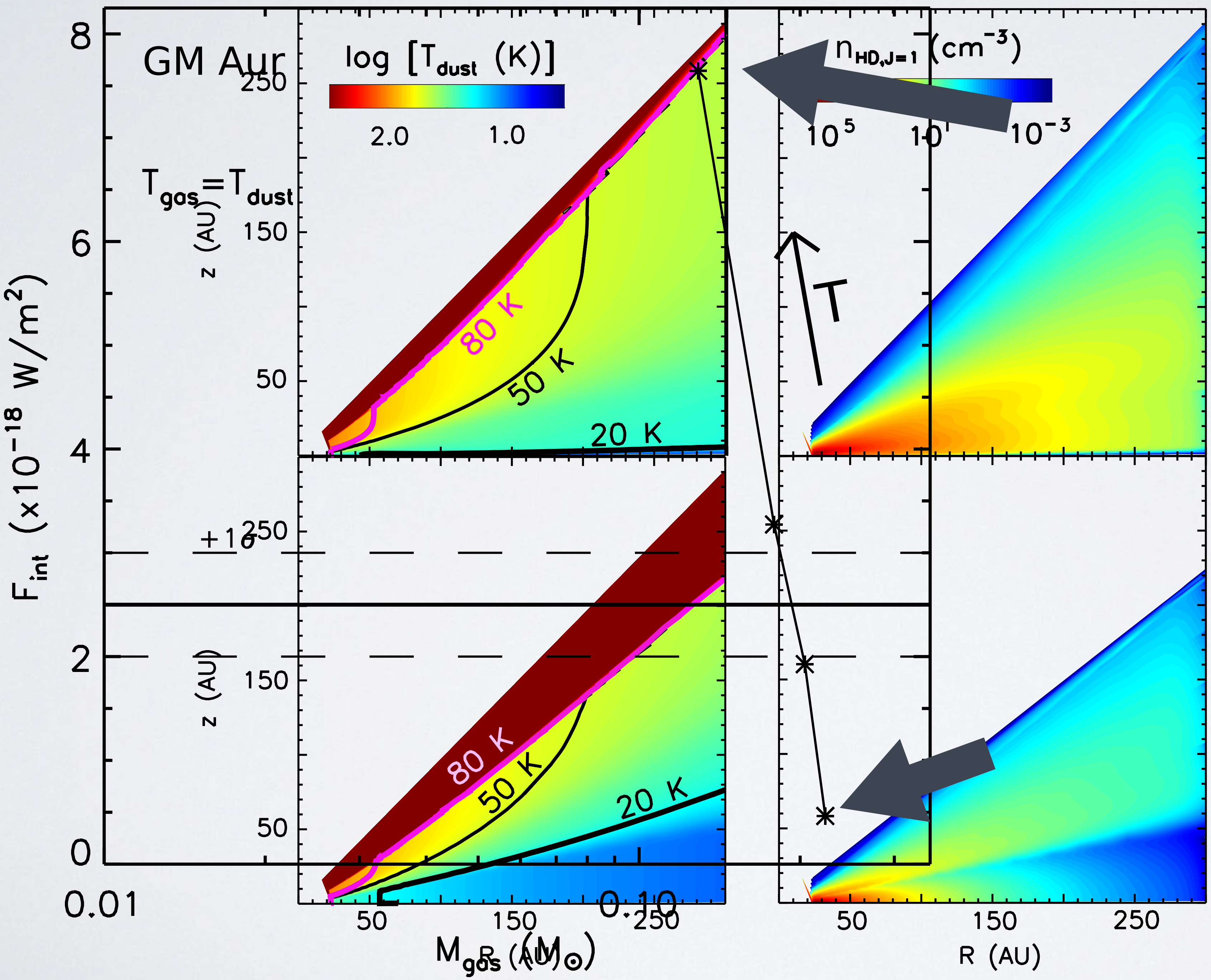
disk structures +
LTE level populations



Iterate for model families with range of:

Σ (via α)
T(R,z) (via d/g)
HD line intensity

EFFECT OF TEMPERATURE STRUCTURE ON HD LINE

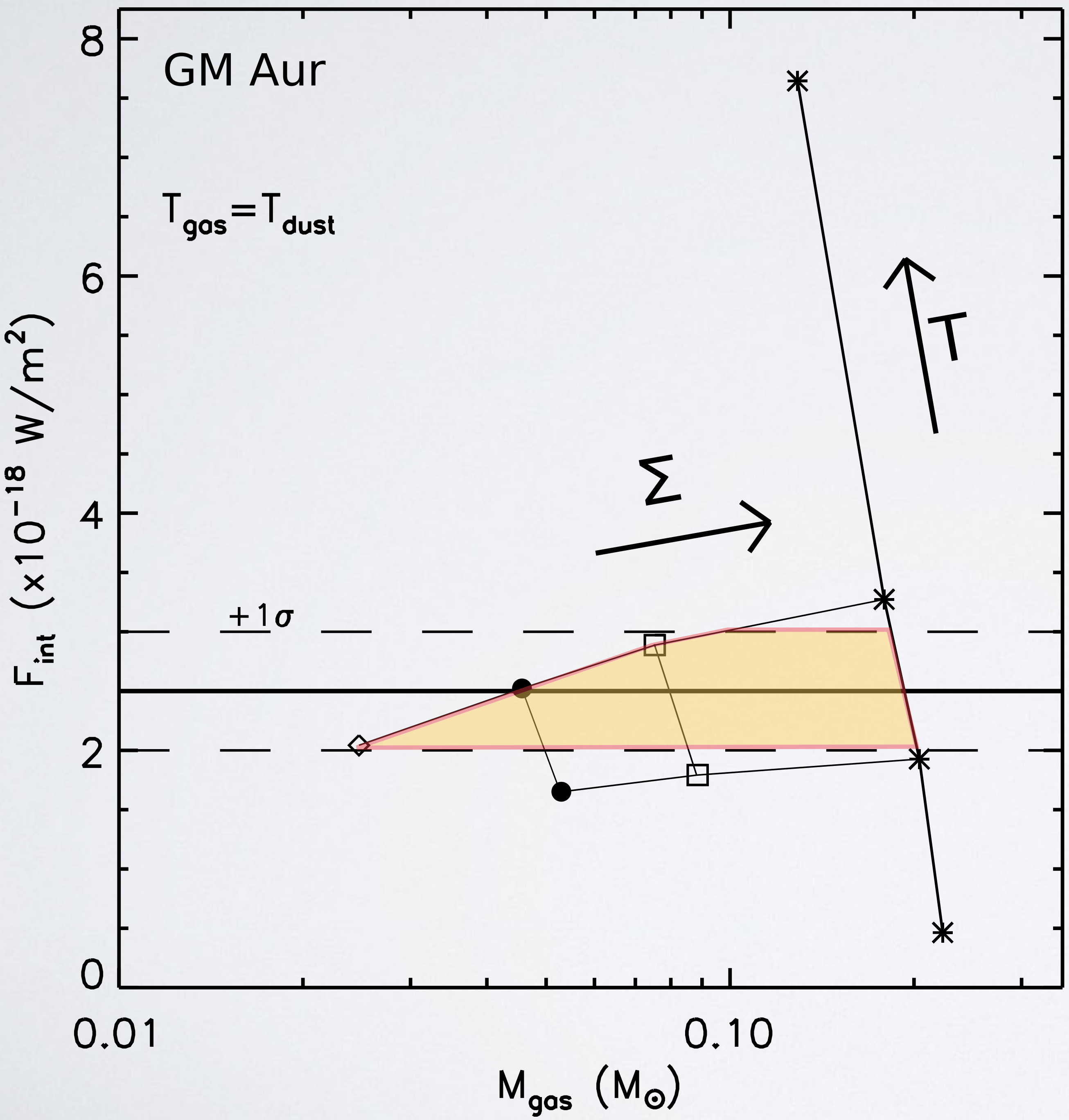


99% dust settling

50% dust settling

McClure et al. (2016)

EFFECT OF SURFACE DENSITY AND FINAL MASSES



Decrease **Σ** (M_{dust} fixed to submillimeter photometry)

M_{dust}:
GM Aur: 12.5 $\times 10^{-4}$ $M_\odot$
DMTau: 2.9 $\times 10^{-4}$ $M_\odot$

M_{gas}:
GM Aur: 0.025-0.204 $M_\odot$
DMTau: 0.01-0.047 $M_\odot$

McClure et al. (2016)

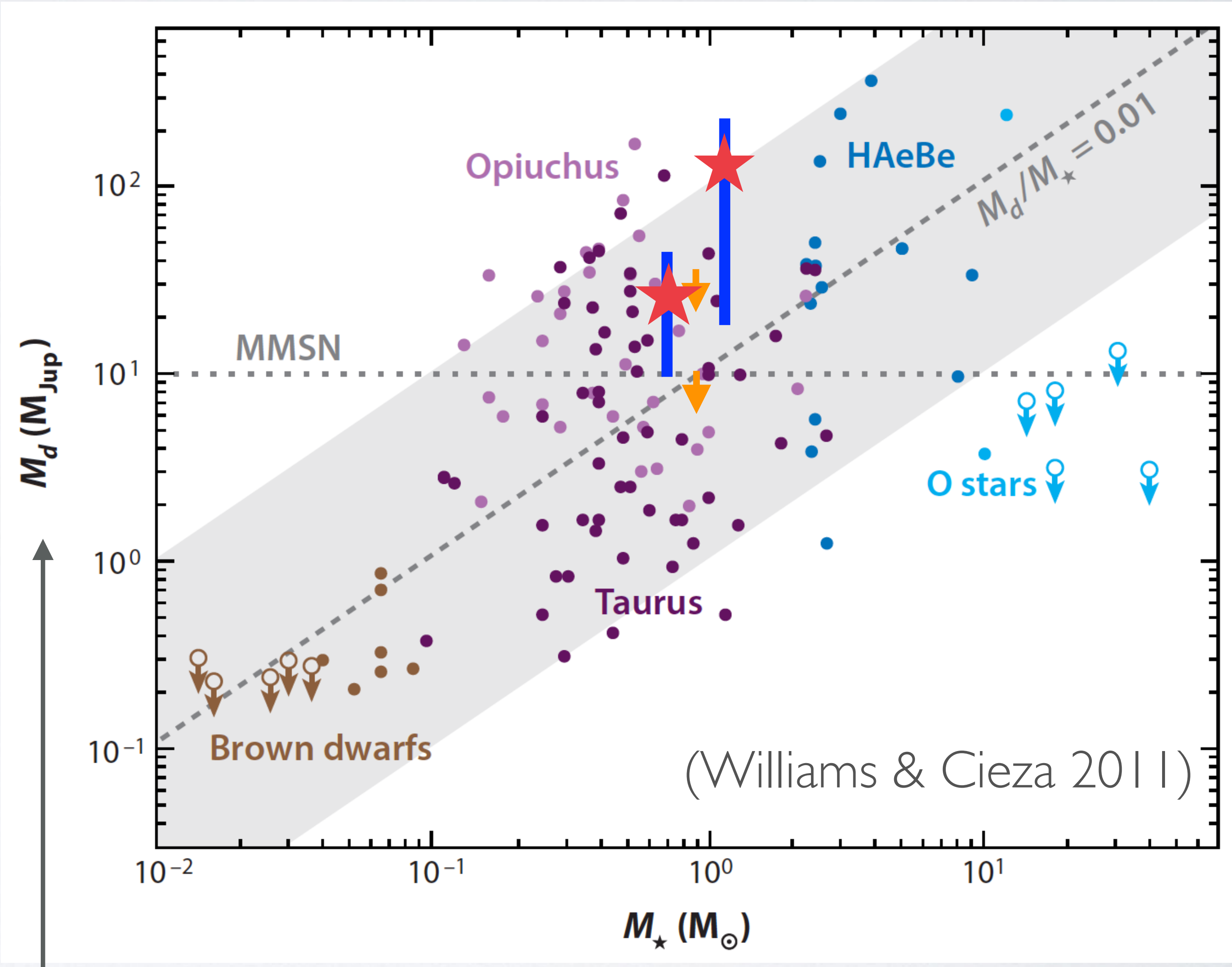
COMPARISON WITH OTHER DISKS VIA DUST-GAS CONVERSION

Massive!

M_{disk}/M_{star} ~0.02-0.2

Upper limits of 0.009-0.03 $M_{\odot}$ for two non-detections.

100x M_{dust} ~Mgas



M_{gas} (from M_{dust})

COMPARISON WITH CO-DERIVED GAS MASSES

Value	DM Tau	GM Aur
M_{gas} (from HD) [$M_{\odot}$]	**0.01-0.047**	**0.025-0.204**
M_{gas} (from CO*) [$M_{\odot}$]	1.4×10^{-3}	$<0.35 \times 10^{-3}$
M_{gas} (from CO**) [$M_{\odot}$]	9.0×10^{-3}	-

McClure et al. (2016)

*Dutrey et al. (1996)

**Williams & Best (2014)

Model with no CO **photodissocation or freeze-out:** 7-33x, 70-600x less

Model with **photo-dissocation & freeze-out:** 1-5x less mass

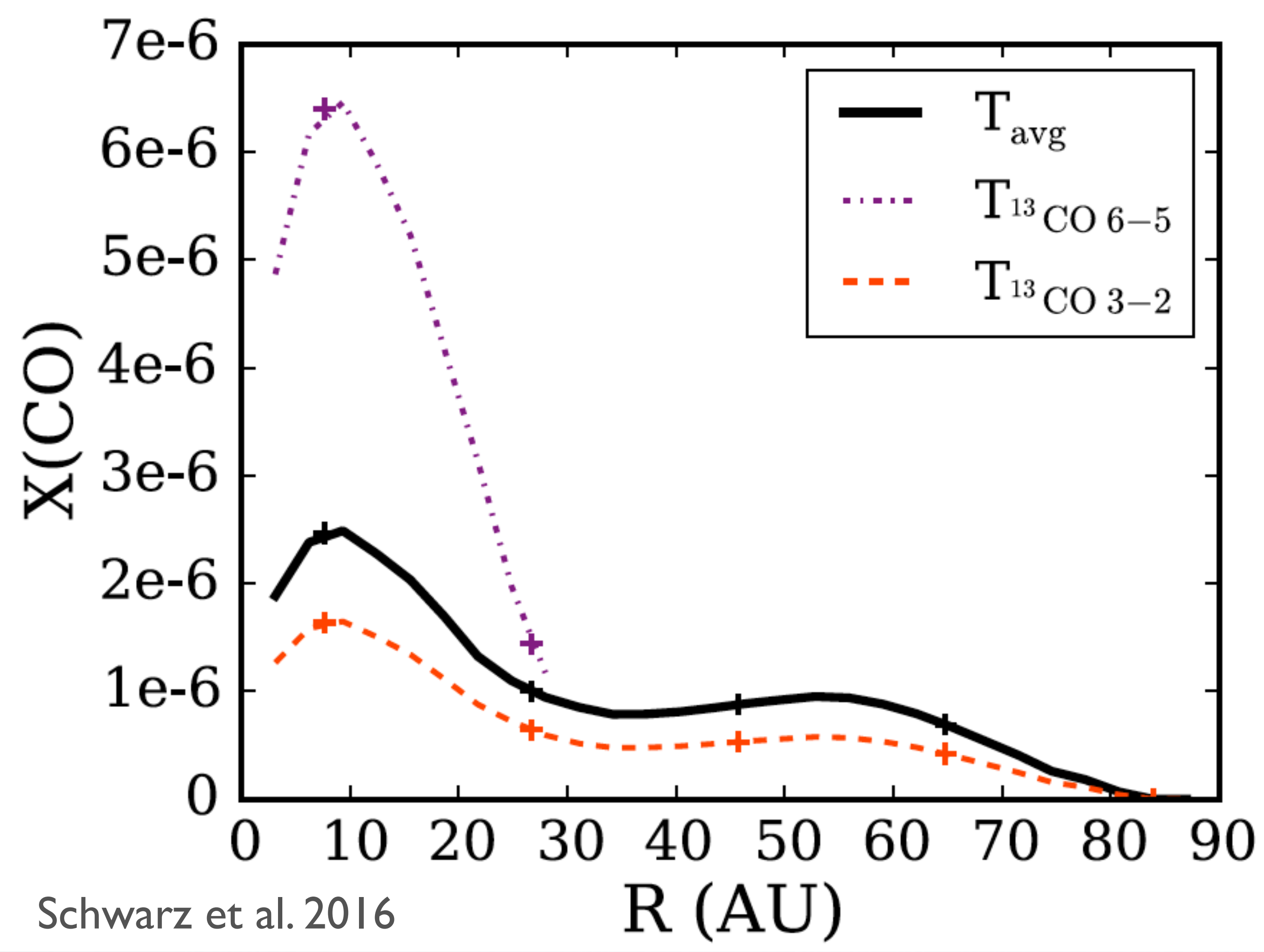
Evidence for chemical depletion of carbon?

DM Tau:
HD M_{gas} up to 5x CO M_{gas} measurement. Likely CO chemical depletion.

GM Aur:
CO depletion >~600, corrected to100 if scaled for photodissociation/freeze-out.

How realistic are these depletion factors?

CO-DEPLETION IN TW HYA



ALMA CO observations measure ~**100x** CO depletion in TW Hya **(Schwarz et al. 2016)**

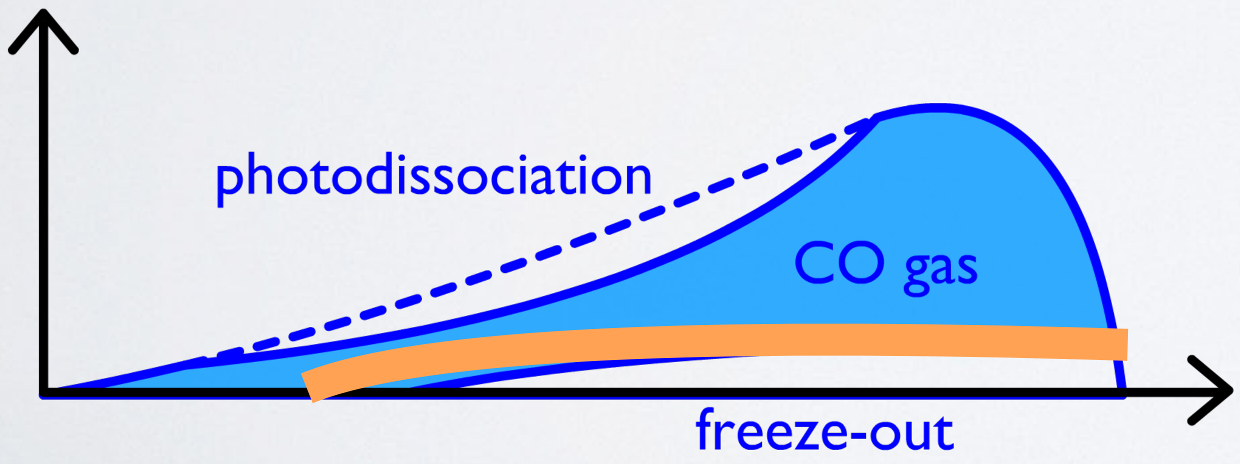
C I line ~100x C depletion vs ISM **(Kama et al. 2016a)**

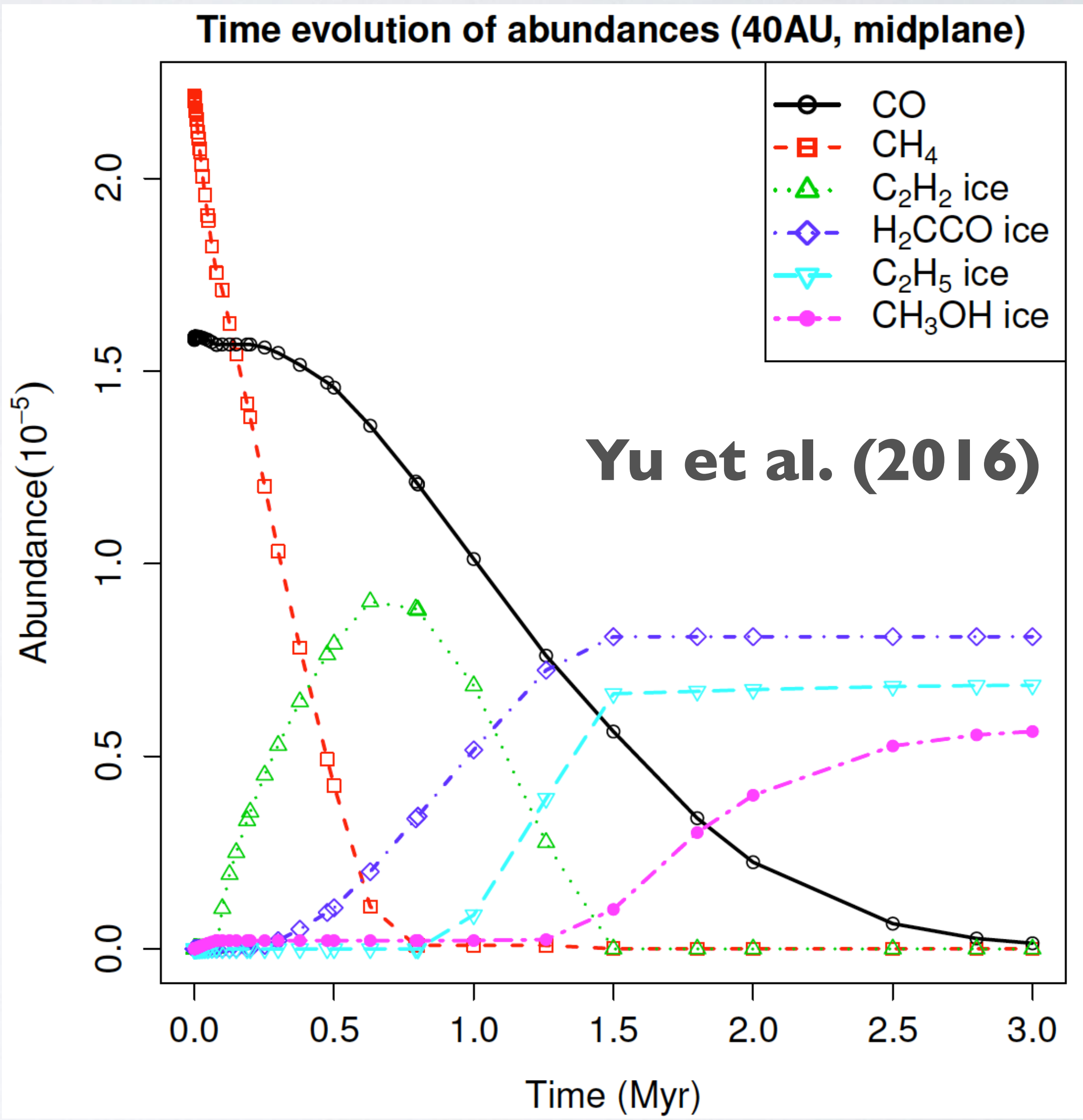
Accepted follow-up proposal (**PI Schwarz**, McClure co-I, grade A) to confirm CO depletion and masses of DM Tau and GM Aur.

WHERE IS THE DEPLETED CO?

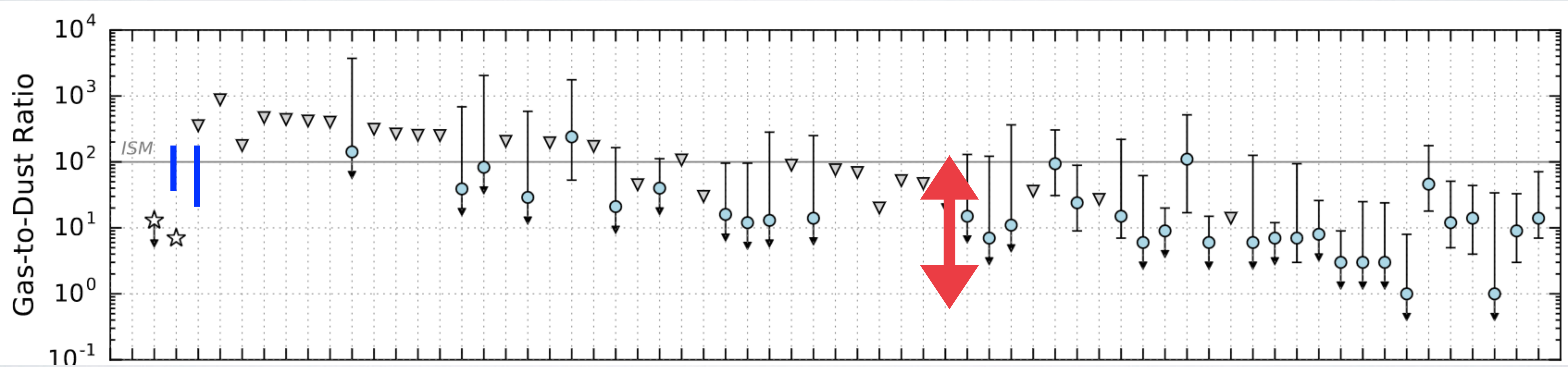
Schwarz et al. (2016),
Yu et al. (2016):

- formation of complex organics depletes gas phase CO
- COMs freeze-out on grains





Implications for CO depletion



Ansdell et al. (2016), using Williams & Best (2014) CO models for gas mass

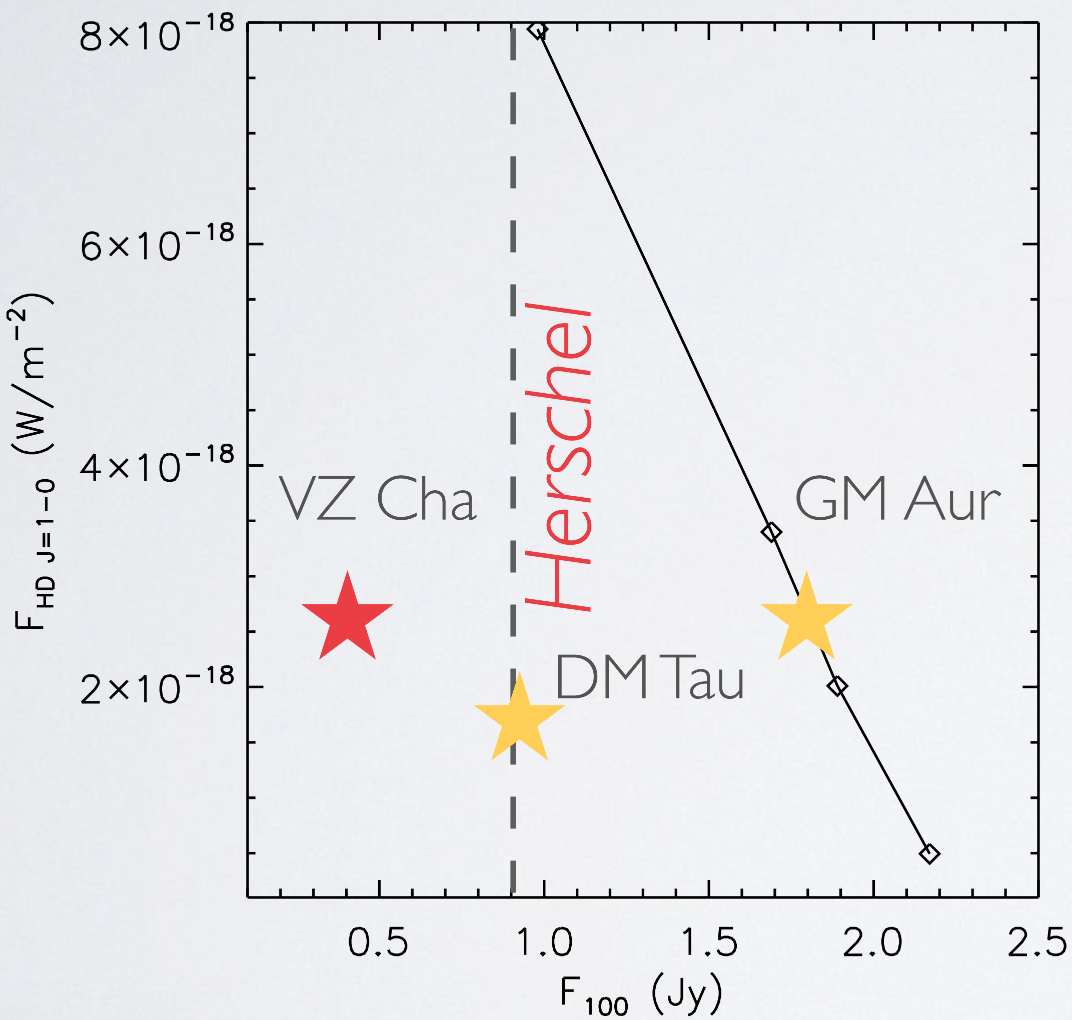
Gas/dust ratios < 10^2 from ALMA survey; CO chemical depletion?

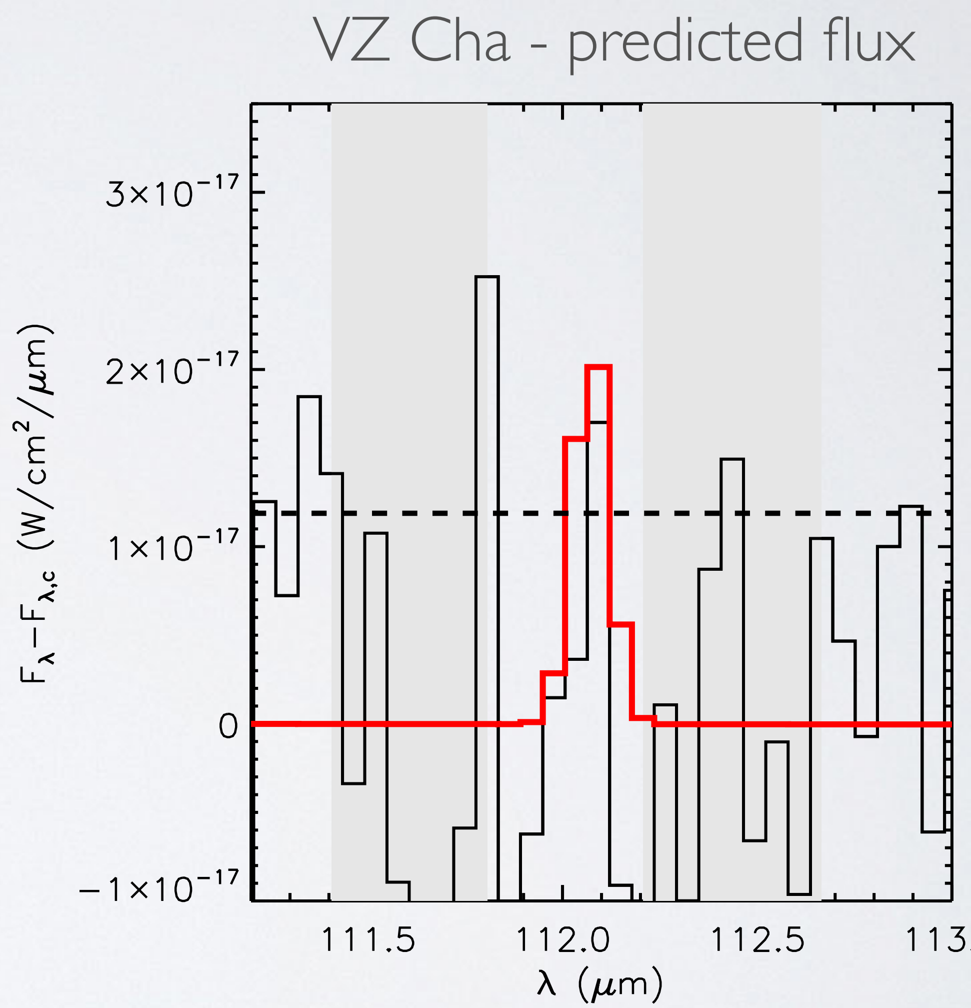
Global gas/dust = 20-165 for DM Tau, GM Aur

Need more HD measurements in disks to confirm!

CHALLENGE OF LARGER SAMPLE

Line flux increases with decreasing continuum flux.





Difficult to observe fainter targets with current instruments (e.g. FIFI-LS).

Future possibilities

Upcoming far-IR instruments with improved sensitivity:

- **HIRMES - SOFIA 3rd generation spectrograph (see Neufeld talk); 2019, R~100,000(?) additionally resolve line**
- SAFARI - SPICA's far-IR spectrograph (2029)
- Origins Far-IR Surveyor (2030+)

Conclusions

- M_{gas}~0.02-0.2 $M_\odot$ (GM Aur) and ~0.01-0.05 $M_\odot$ (DM Tau)
- CO gas phase chemical depletion ~5-100x
- Combine HD with other line observations (e.g. range of CO lines) for more precise masses/depletion factors
- 100x dust-to-gas conversion factor good approximation

Future with SOFIA-HIRMES, SPICA-SAFARI, NASA Origins Far-IR Surveyor