university of groningen
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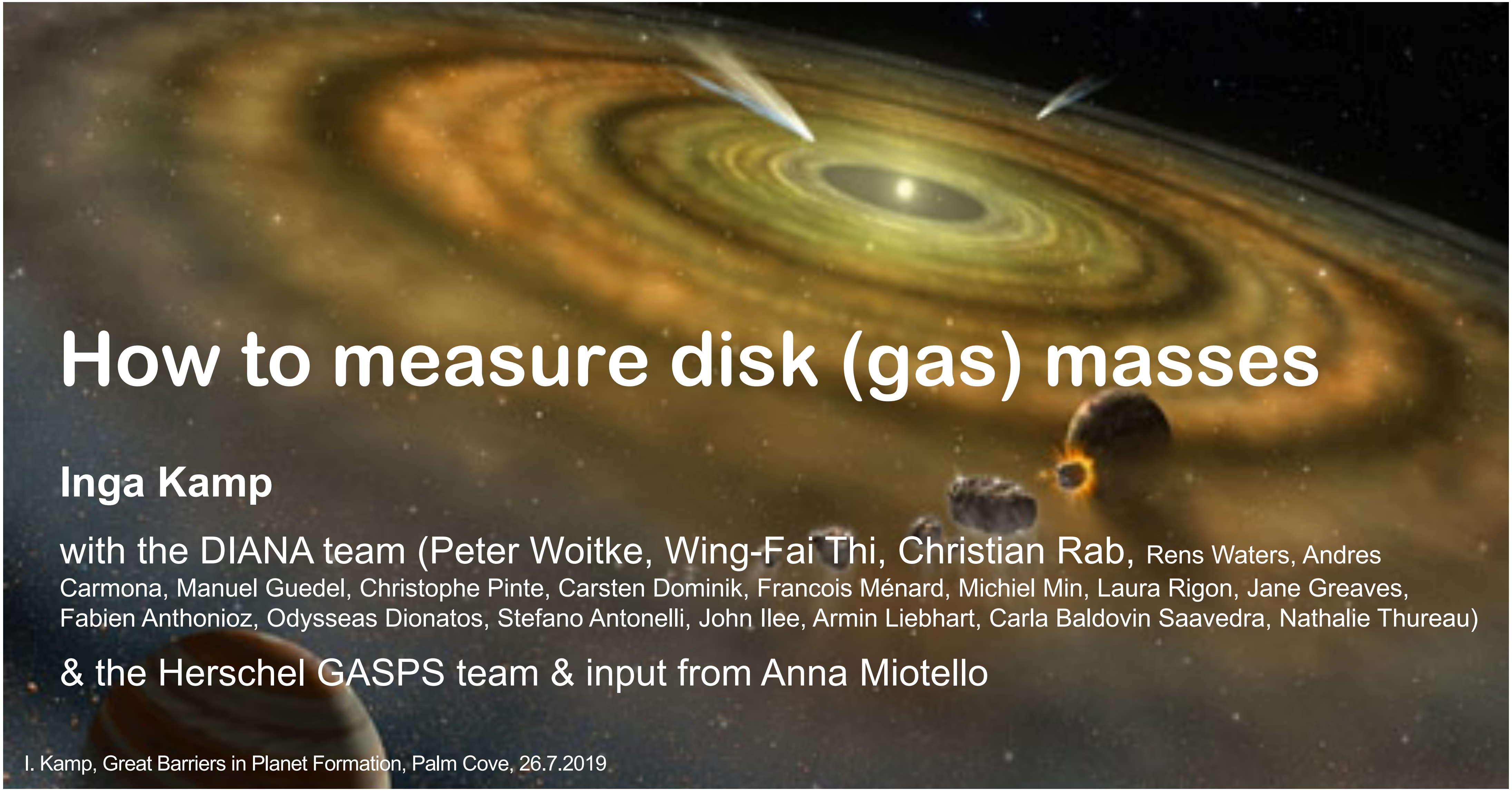


How to measure disk (gas) masses

Inga Kamp

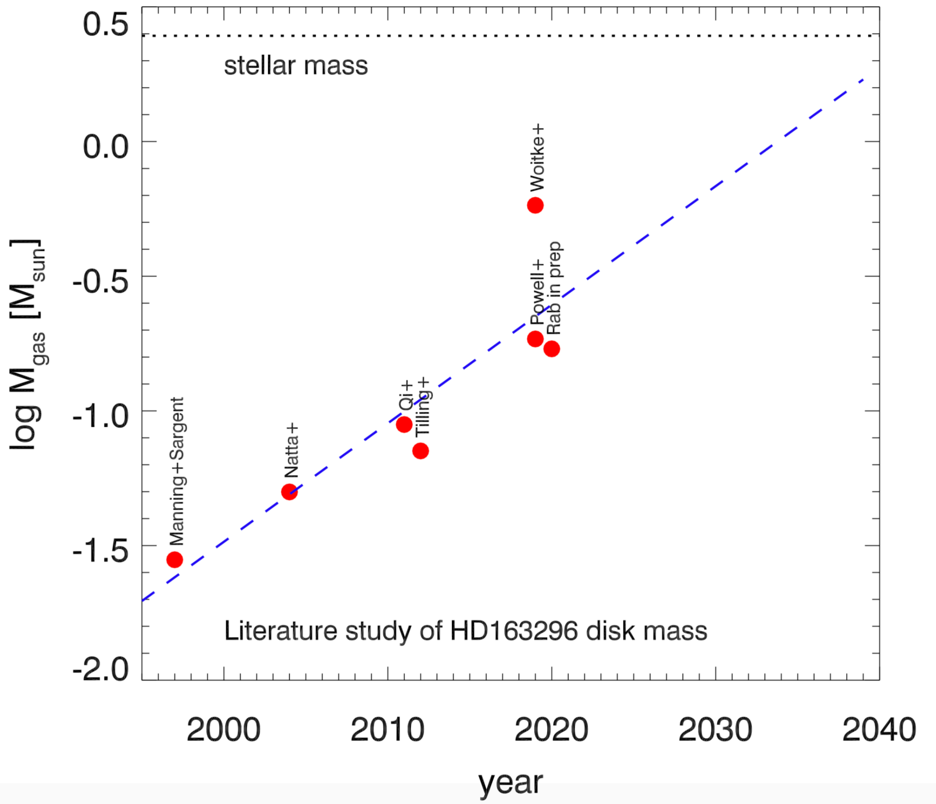
with the DIANA team (Peter Woitke, Wing-Fai Thi, Christian Rab, Rens Waters, Andres Carmona, Manuel Guedel, Christophe Pinte, Carsten Dominik, Francois Ménard, Michiel Min, Laura Rigon, Jane Greaves, Fabien Anthonioz, Odysseas Dionatos, Stefano Antonelli, John Ilee, Armin Liebhart, Carla Baldovin Saavedra, Nathalie Thureau)

& the Herschel GASPS team & input from Anna Miotello

Different methods proposed …

1. Measure dust masses (mm-flux, assume T_{dust} and opacity, need for detailed dust models) *100
2. Get ^{13}CO and $C^{18}O$ integrated line fluxes (ice formation, isotope selective photodissociation, need for higher sensitivity observations) and use empirical relations (based on models) [Williams & Best 2014, Miotello et al. 2016]
3. Get [OI]63 μm and ^{12}CO fluxes and use empirical relations (based on models, need for new far-IR space observatory) [Kamp et al. 2011]
4. Get HD line fluxes (HD not affected by chemistry, only primordial D/H, but T_{gas}-estimate required, need for new far-IR space observatory) and use empirical relations (based on models) [Bergin et al. 2013, Trapman et al. 2017]
5. Get differential dust disk sizes and infer gas mass from drift models (assumptions on dust grains/density, g/d ratio, smooth disk structure, disk ages) [Powell et al. 2017]

Is there a problem?



Maybe not …, just wait !

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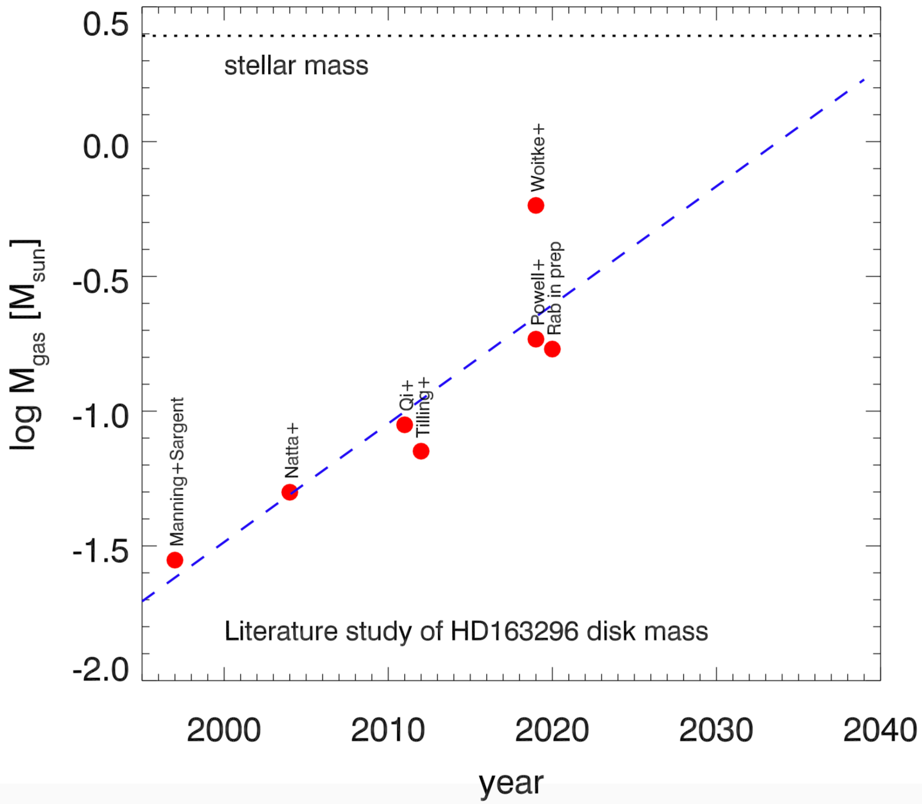

Maybe not …, just wait !

Gas masses ”seem” to be too low when derived from ALMA CO isotopologue data

Why?

We like to think that class II disks should have primordial gas-to-dust mass ratio.

We like to think that disks have ISM-like elemental abundances.

[C depletion from fitting [CII], [CI], CO lines: e.g. Bruderer et al. 2012, Kama et al. 2016; from C_2H, c-C_3H_2 observations: e.g. Bergin et al. 2016]

It is clear that both gas and dust are evolving even in the first Myr … into planetesimals, planetary cores, minor bodies and/or dispersing.

[e.g. Connelly et al. 2012, ALMA Partnership et al. 2015, Andrews et al. 2012, DSHARP+++ papers]

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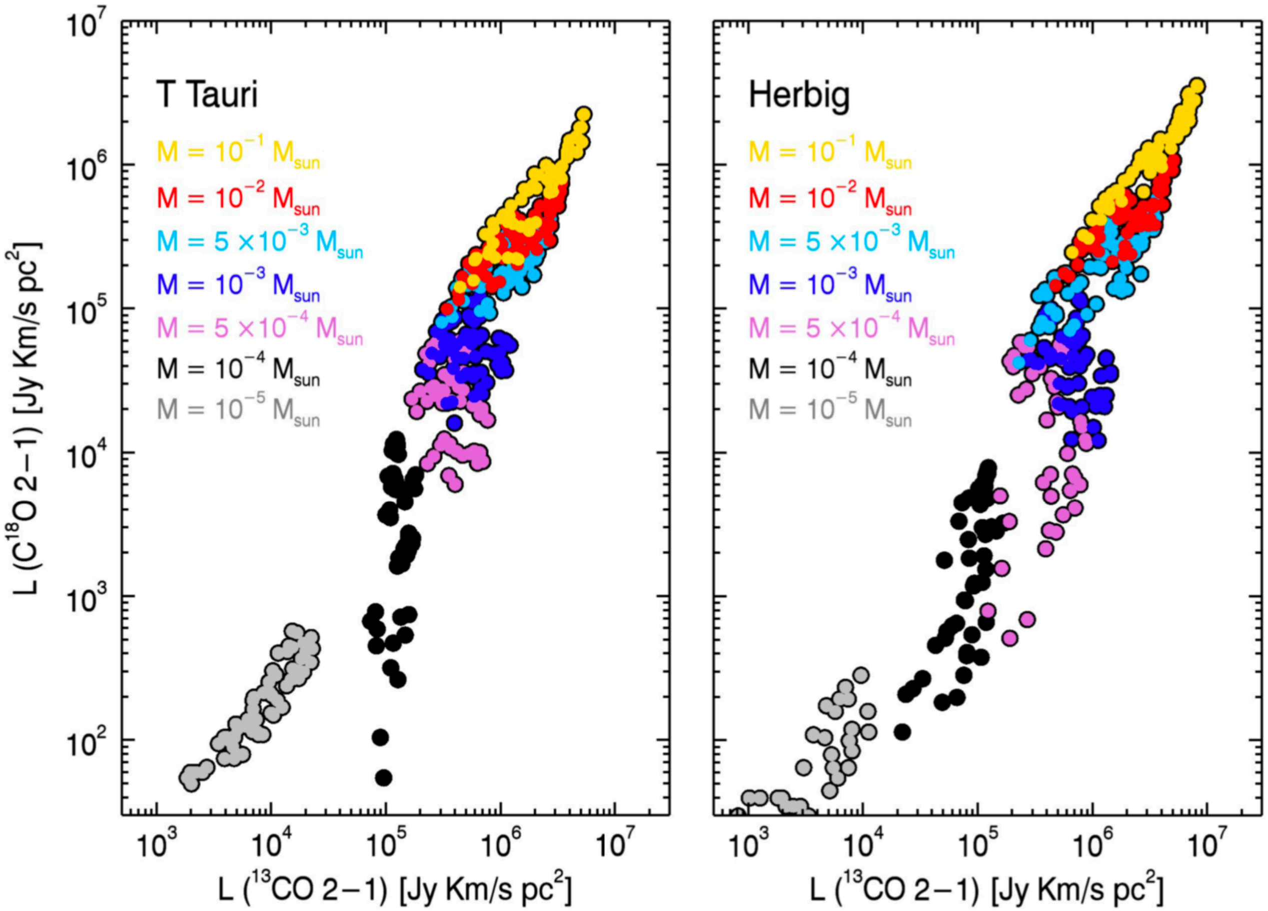
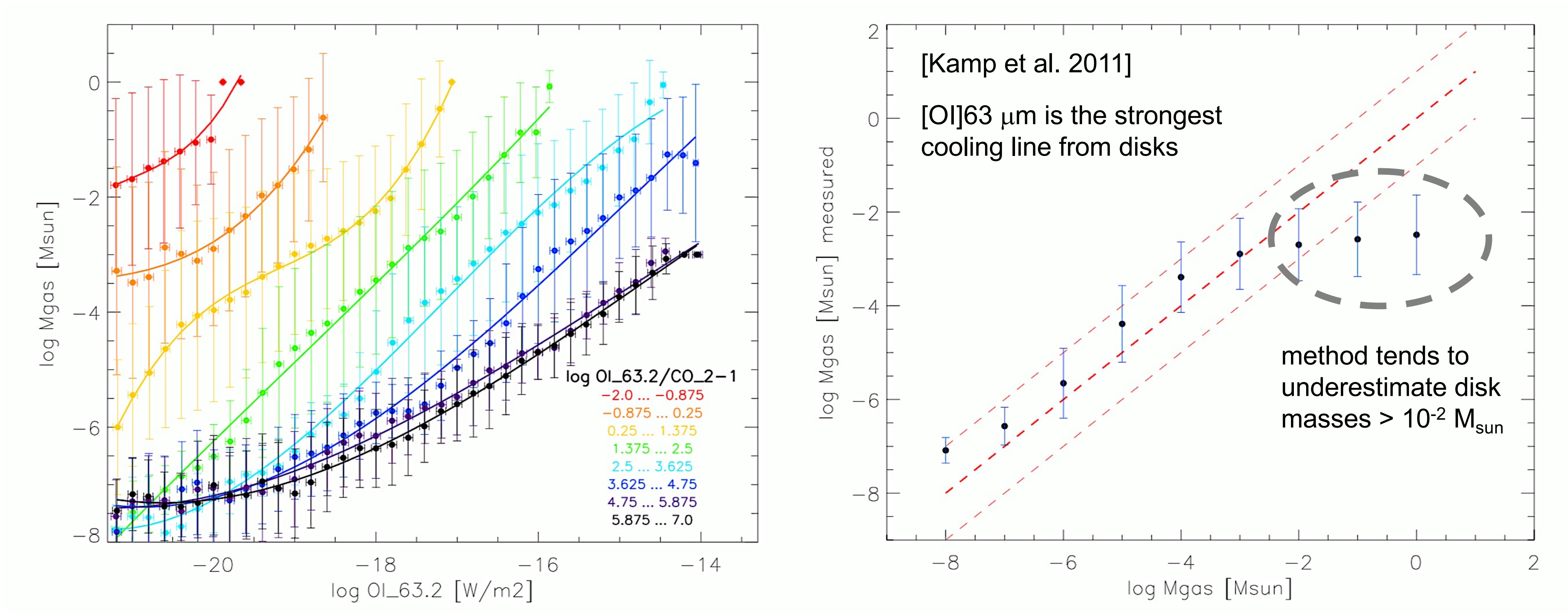
Method 2- CO isotopologues

[Miotello et al. 2016]



based on 210 radiation thermo-chemical disk models (**DALI** [Bruderer et al. 2009, 2012], 5 free parameters) to support the interpretation of ALMA surveys of SFRs

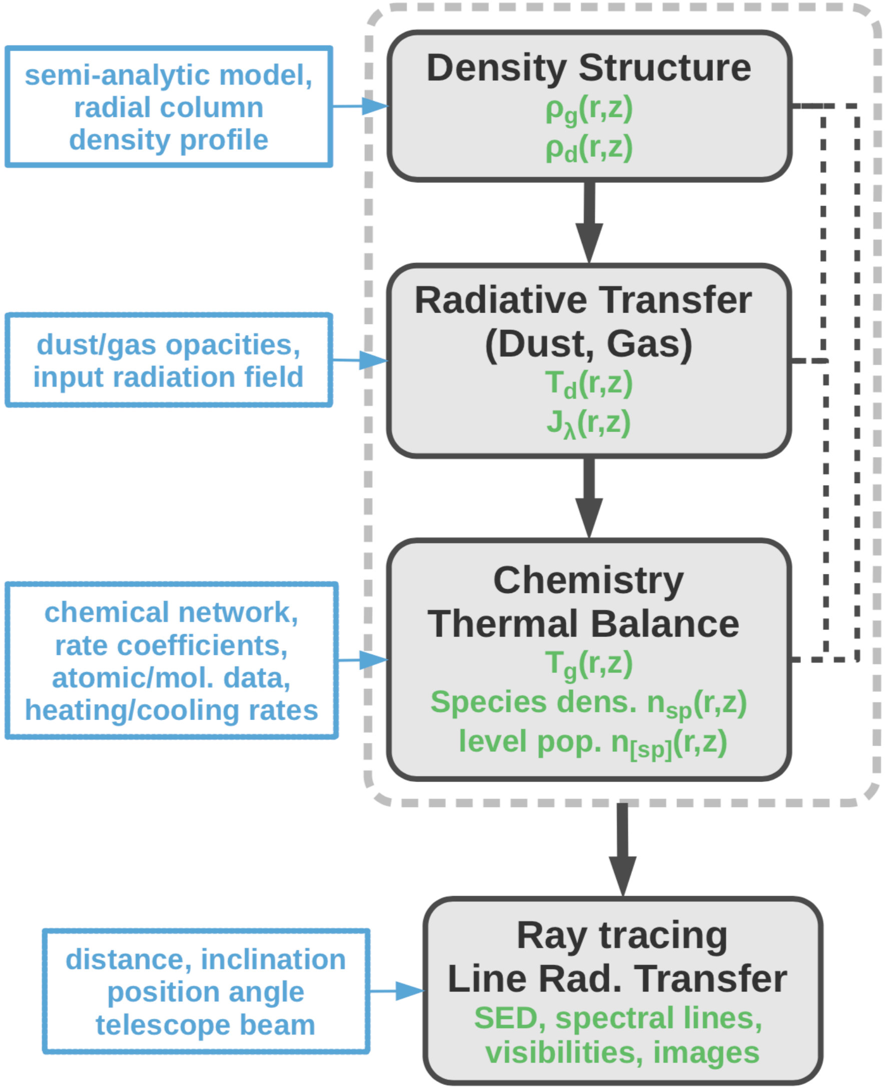
Method 3 – [OI]63μm/^{12}CO



based on 300 000 radiation thermo-chemical disk models (**MCFOST+ProDiMo**, 11 free parameters) to support the Herschel OT KP Gas in Planetary Systems (GASPS, PI: Dent)

[Woitke et al. 2010, Kamp et al. 2011; applied in several GASPS and related papers: Pinte et al. 2010, Mathews et al. 2012, Aresu et al. 2012, Mathews et al. 2013, Keane et al. 2014, Riviere Marichalar et al. 2016, Alonso Martinez et al. 2017]

Disk models: Our virtual laboratories ...



ProDiMo

[Woitke et al. 2009, Kamp et al. 2010, Thi et al, 2011, …**61 papers total** including applications to Class I objects (disk plus envelope), circumplanetary disks, and even AGN]

publically available, see https://www.astro.rug.nl/~prodimo/

interfaced with **MCFOST** and **MCMAX**

[Pinte et al. 2006, 2009, Min et al. 2009]

recently also coupled with dust migration & evolution models from T. Birnstiel

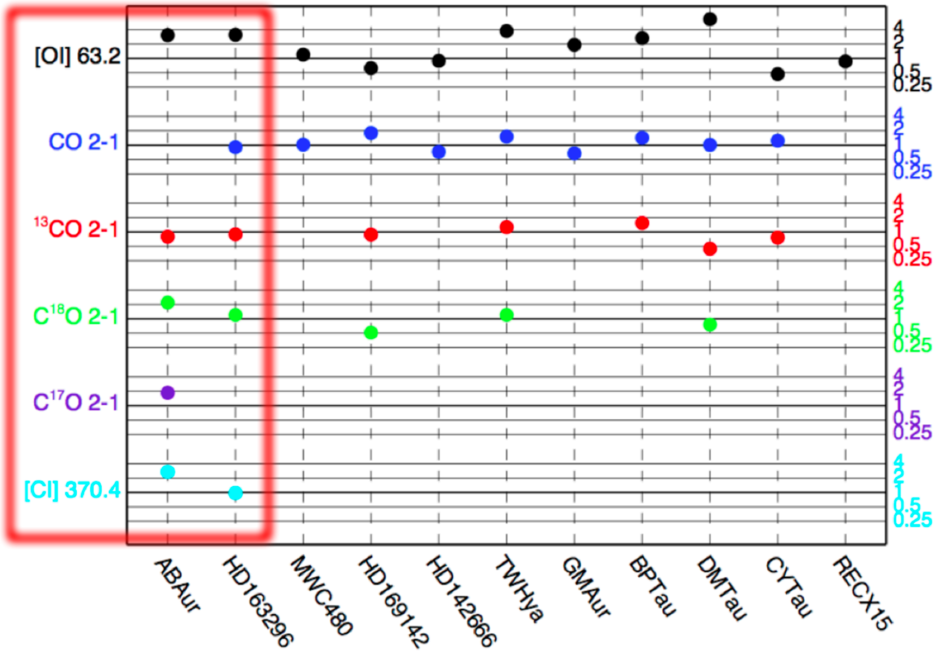
[Birnstiel et al. 2012, Greenwood et al. 2019]

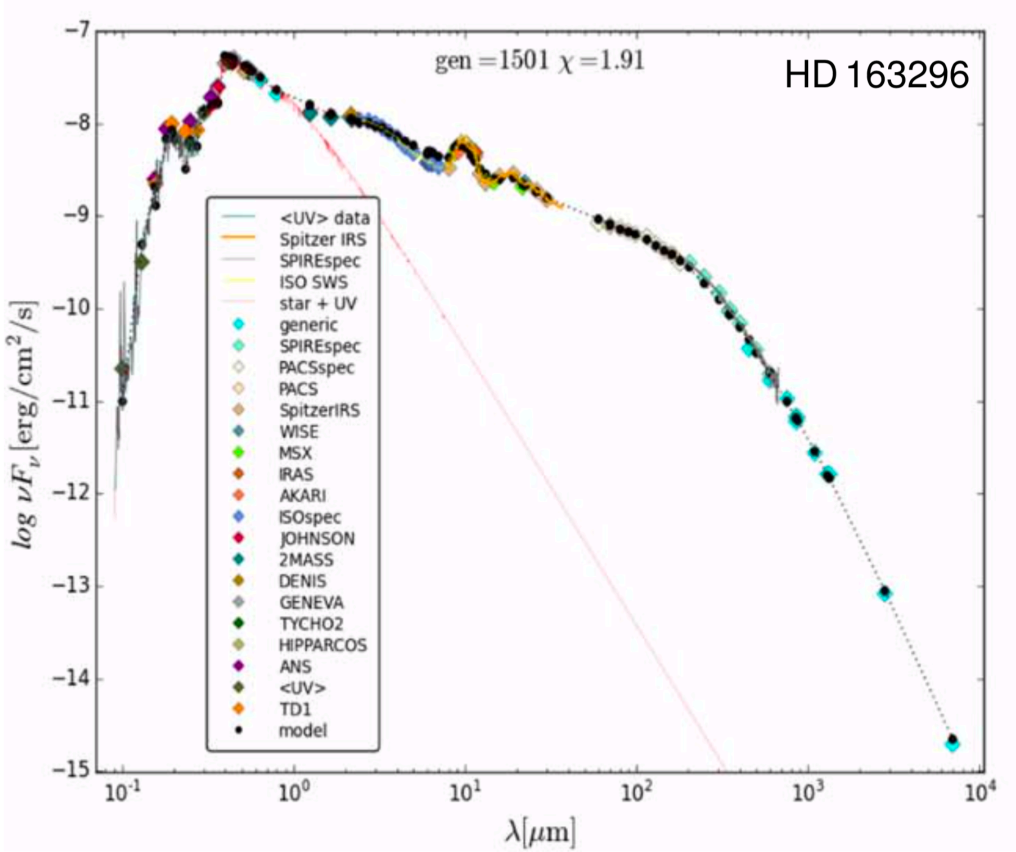
Disk models: Our virtual laboratories ...

Why do we need a high level of consistency between gas and dust?

- H_2 forms on dust grains (surface area/T_{dust}) => initial step for gas chemistry
- molecules form on (icy) dust grain surface (surface area/T_{dust} and composition/surface structure) => surface chemistry => dust coagulation
- continuum opacities in most cases dominate the UV penetration => gas heating/chemistry (photodissociation and photodesorption)
- photoelectric heating (dust sizes, composition) sets the gas temperature in disk surface => gas heating/line emission
- continuum opacities limit the “depth” to which we “see” => line emission
- the IR background radiation from dust can excite molecules => gas heating/line emission
- dust temperatures (grain size distribution/composition) affect formation of ices => gas chemistry
- gas pressure affects dust migration and settling => dust spatial distribution/opacity => gas heating/chemistry

DIANA models



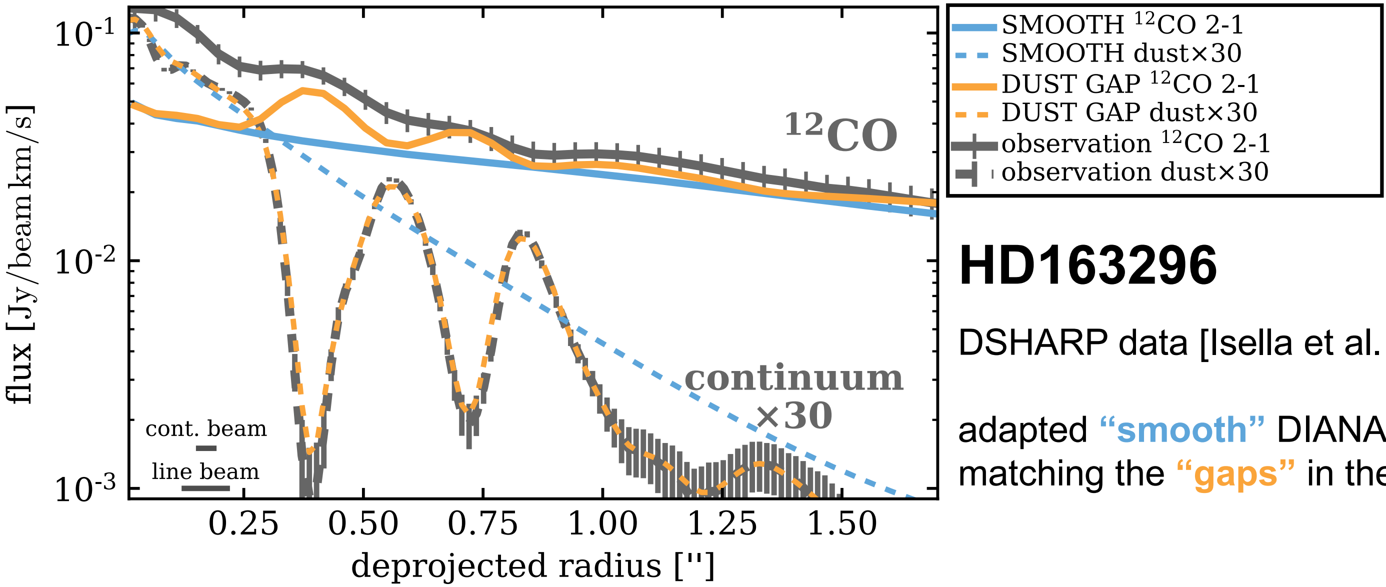


Coherent data collection, analysis and multi-wavelength fitting of 27 objects using SED+mid-IR spectra, and a subset of 14 objects using dust+gas data

[methodology: Woitke et al. 2016, opacities: Min et al. 2016, chemistry: Kamp et al. 2018, FLiTS: Woitke et al. 2018, Database: Dionatos et al. 2019, Results: Woitke et al. 2019]

=> no need to invoke carbon depletion yet ([CI], CO isotopologues matched within a factor of 3)

DIANA+ models

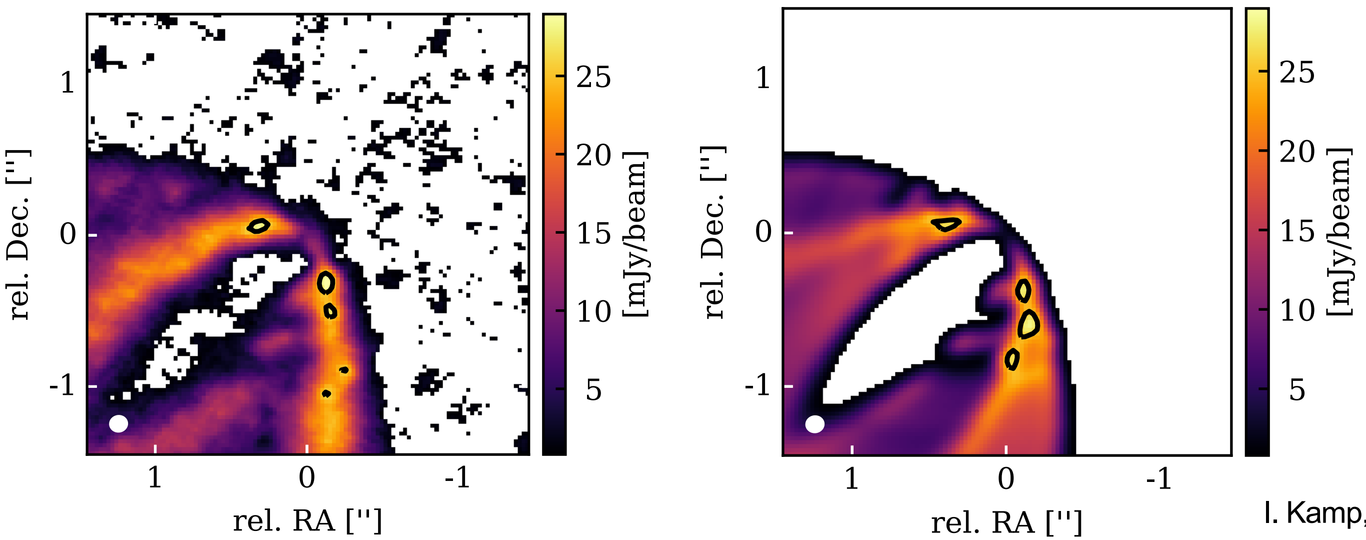


[Rab et al. in prep.]

HD163296

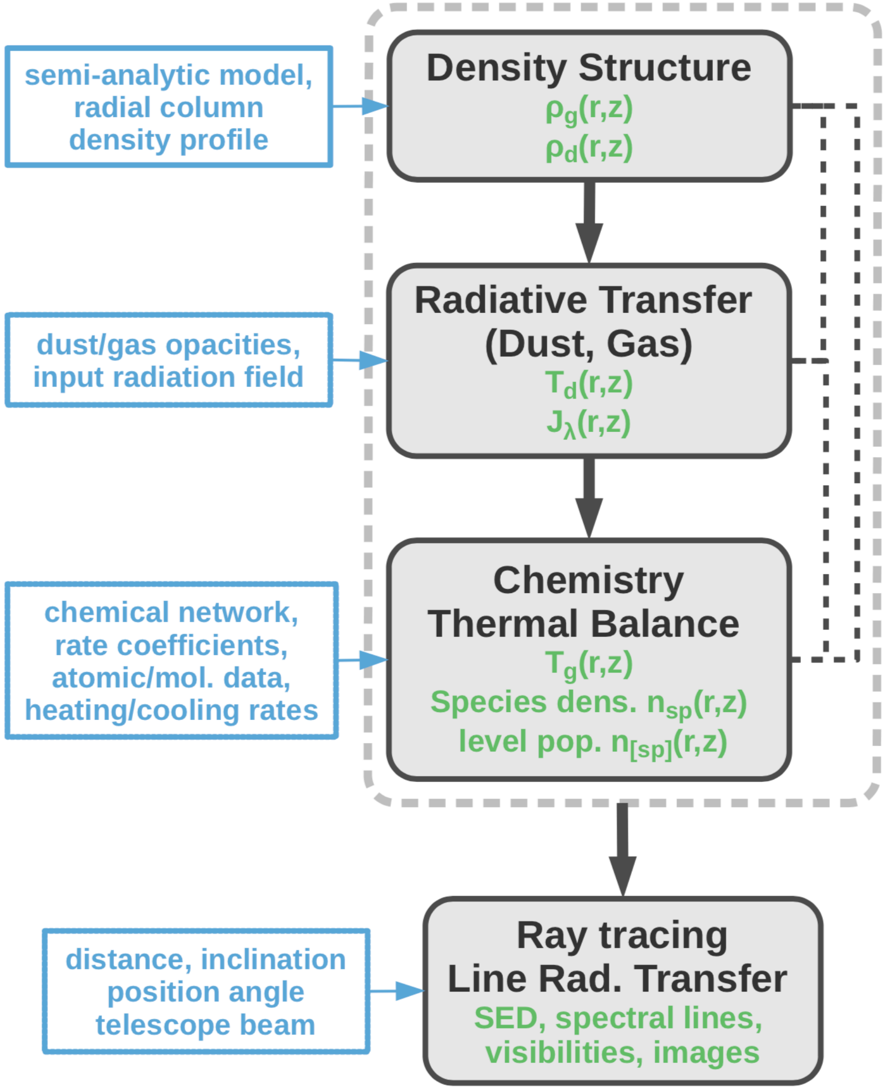
DSHARP data [Isella et al. 2018]

adapted **"smooth"** DIANA model without rings – iterated for matching the **"gaps"** in the dust emission at 1.3mm



CO surface brightness requires consistent detailed gas+dust models required to interpret the gas data (opacity, T_{gas}, T_{dust})

Disk models: Our virtual laboratories ...



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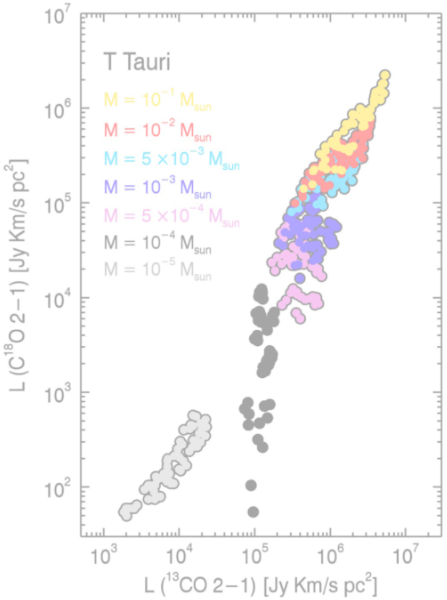
Predict observables based on “realistic” disk models

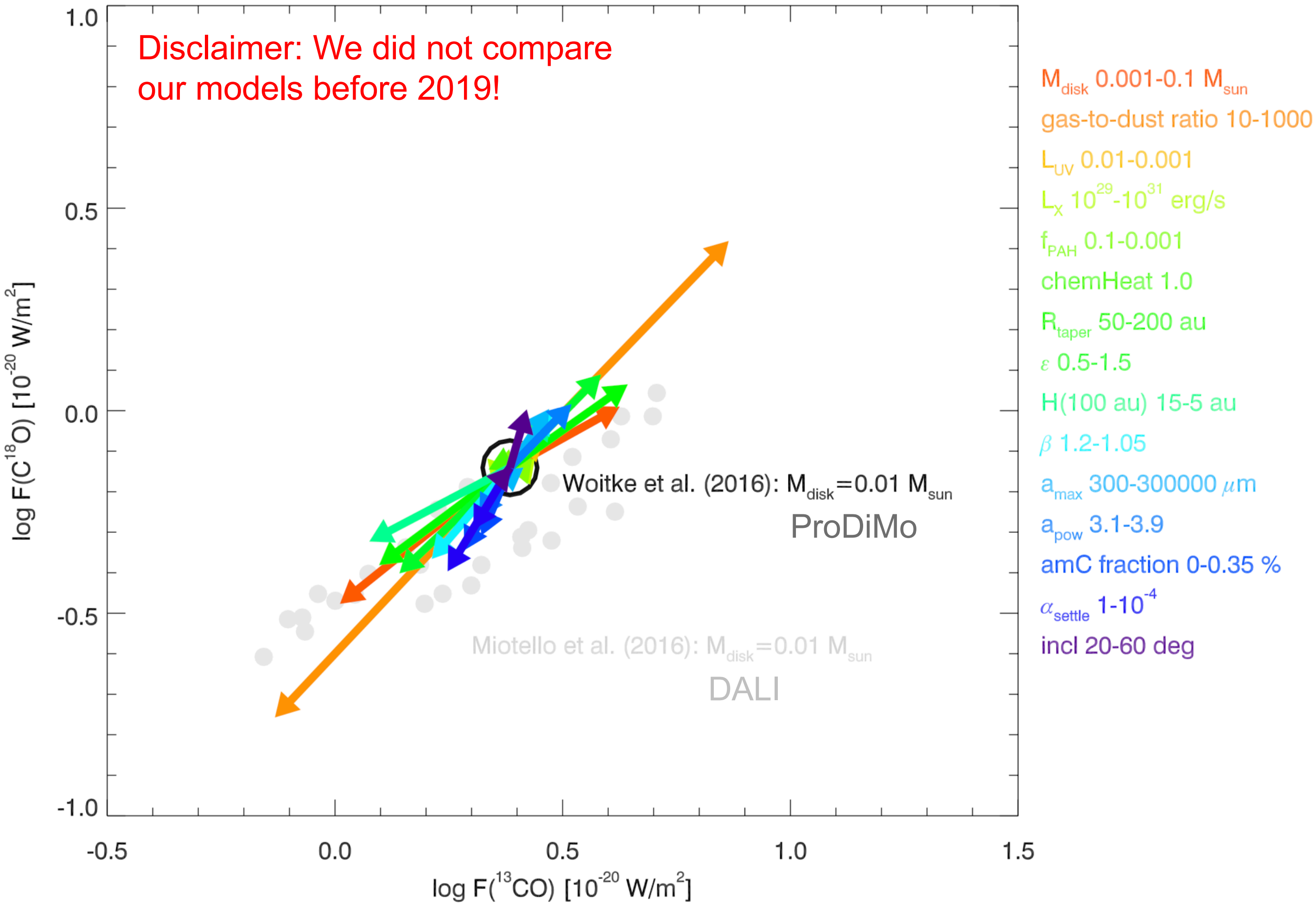
[e.g. DIANA models, Woitke et al. 2019]

=> apply methods 2 and 3 and check if the input parameters M_{gas}, M_{dust} , are recovered

Test of CO isotopologues (method 2) ...



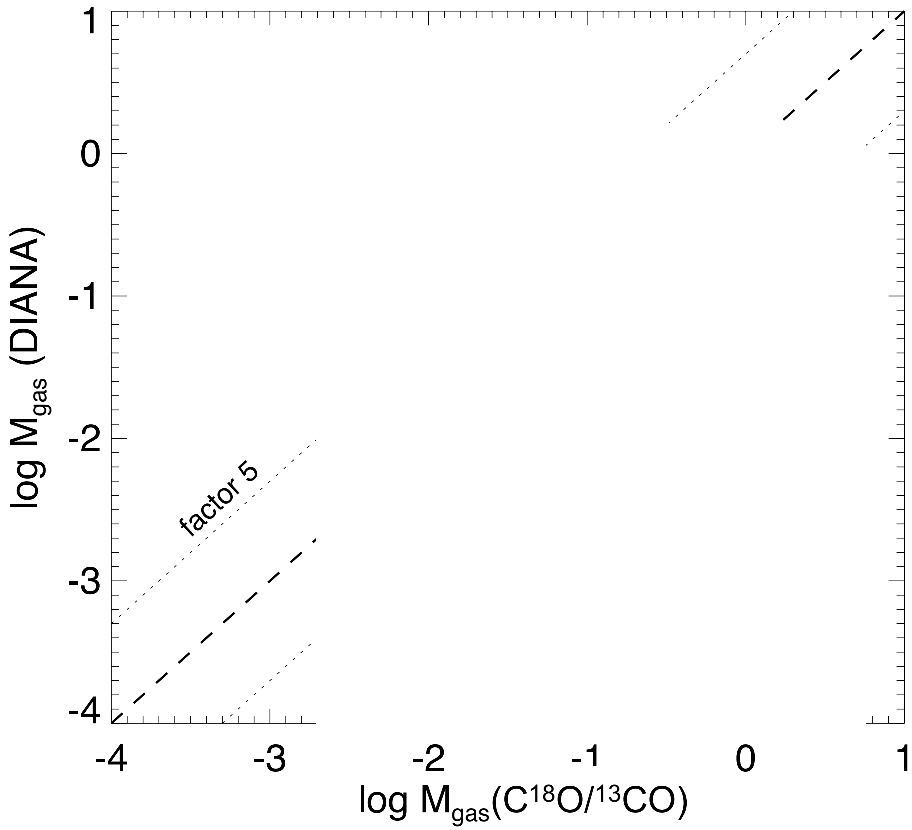
Impactogram [based on data from Woitke et al. 2016]



gas-to-dust ratio affects CO isotopologue lines by factor 3-5

=> Needs to be included in disk mass diagnostic !

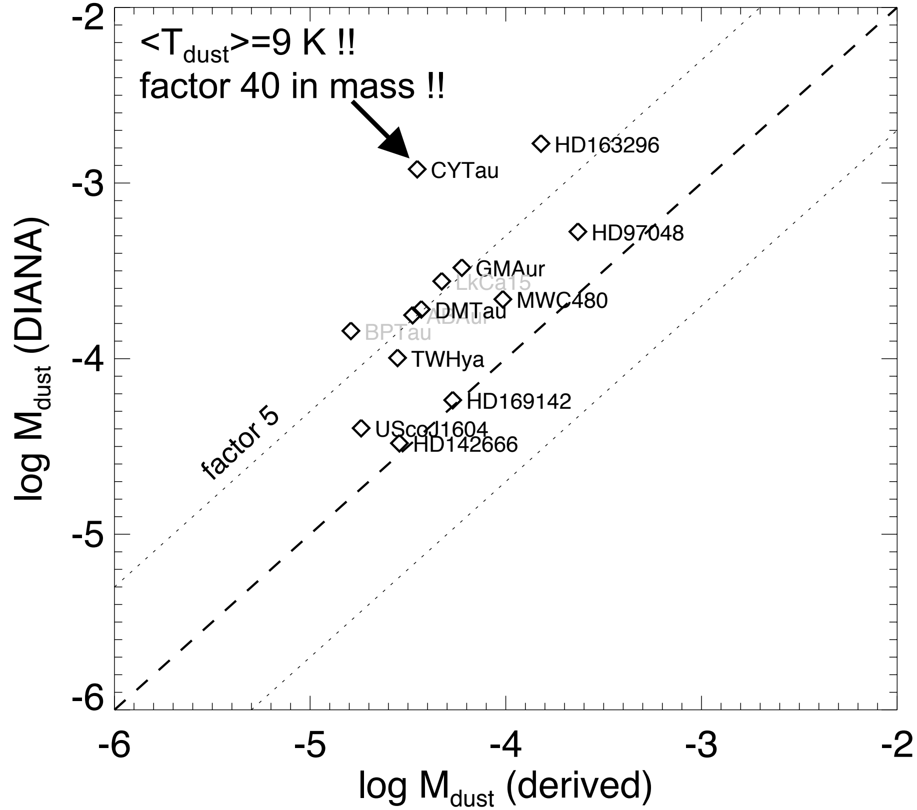
Test of CO isotopologues (method 2) ...



Assumption:

optically thin dust emission

T_{dust} = 20 K , $\kappa_{1.3mm}$ = 3.4 cm^2/g



Assumption:

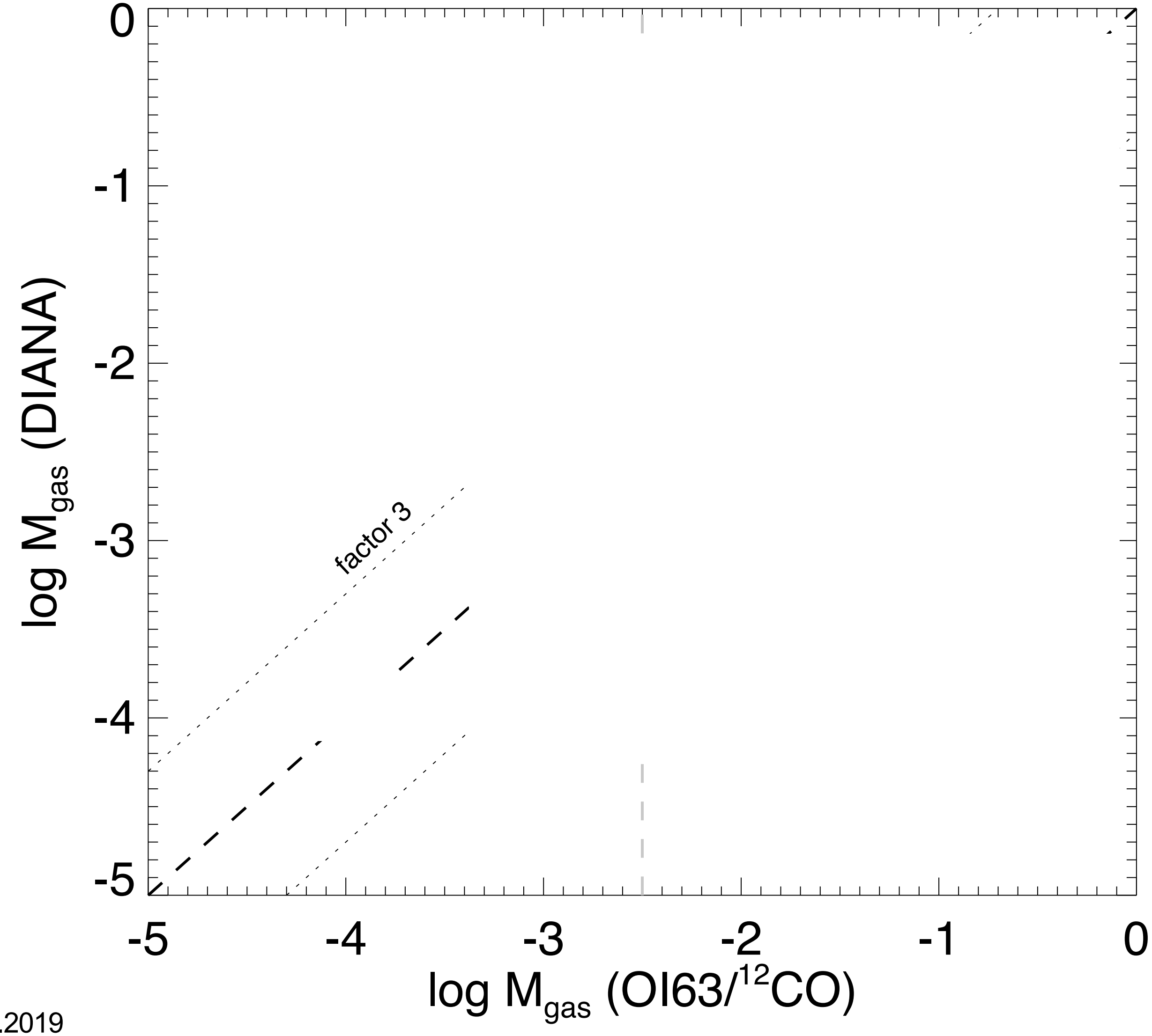
$C^{18}O$ 3x weaker for M_{gas} < 5 10^{-3} M_{sun} disk models (isotope selective photodissociation)

Test of [OI]63μm/^{12}CO (method 3) …

GASPS detection rate for [OI]63 μm in Taurus: 62%

[Dent et al. 2013]

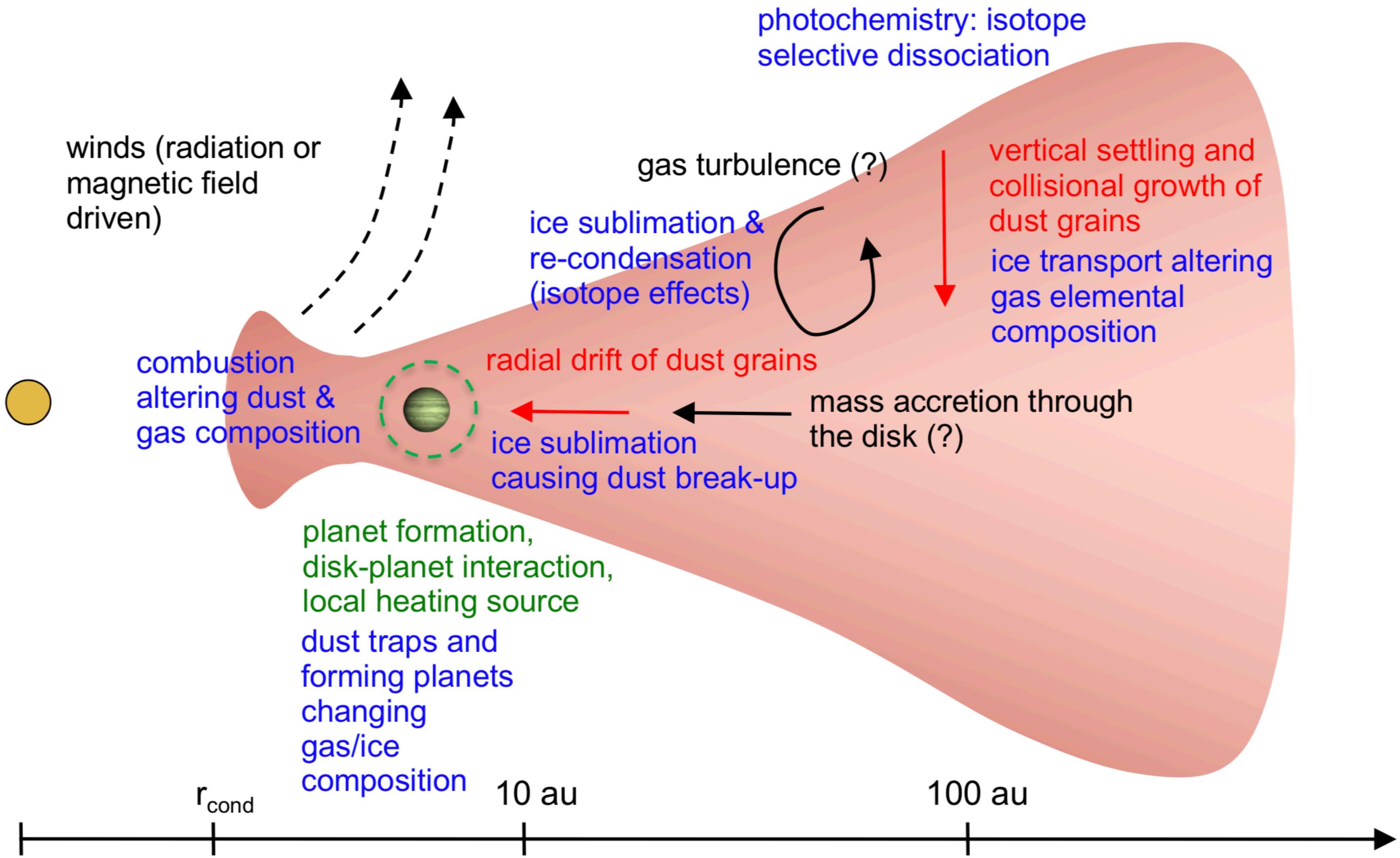
=> need ^{12}CO from ALMA



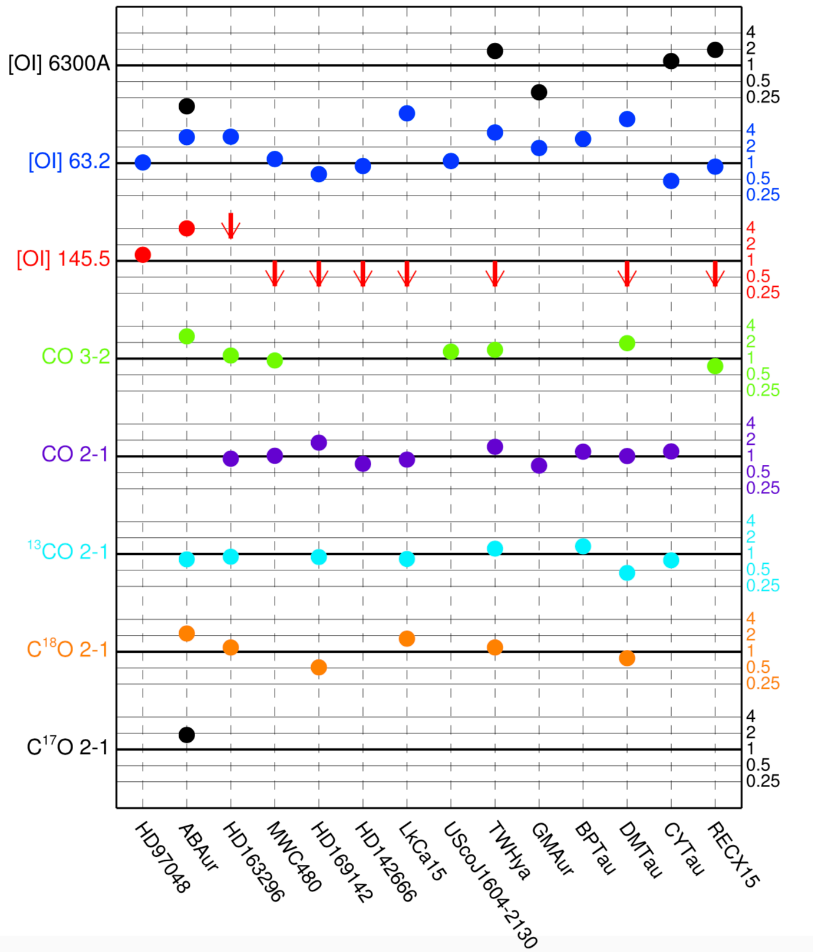
Future work/pathways

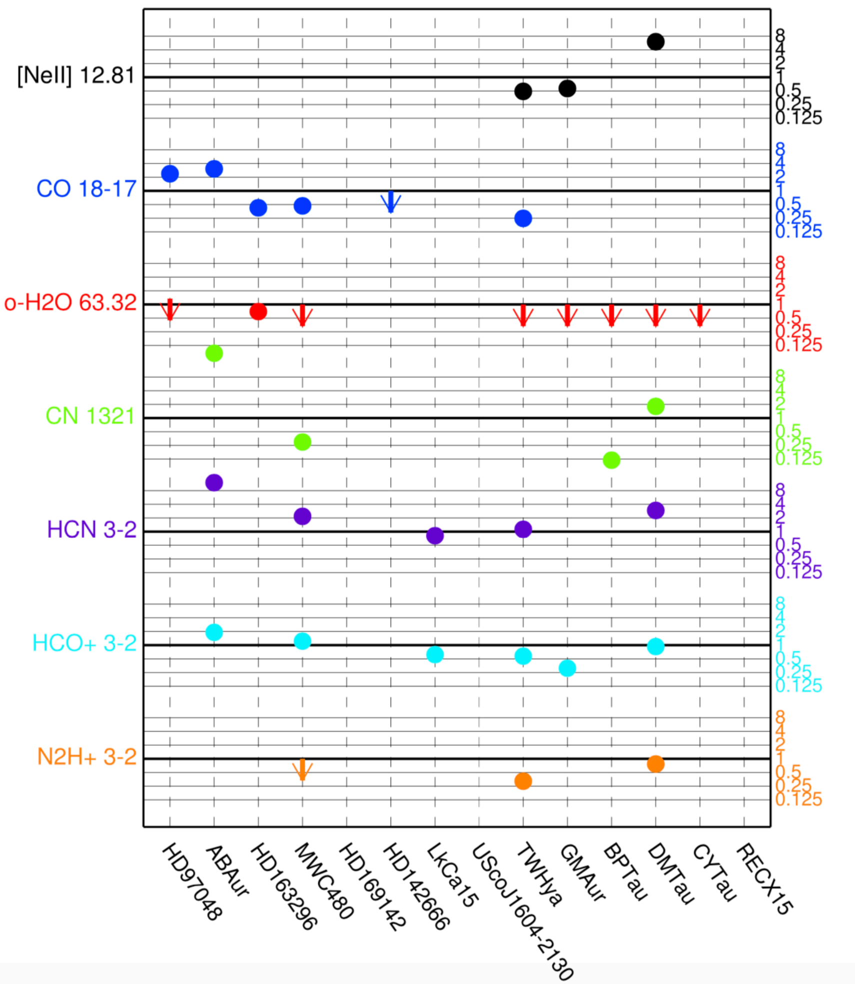
- The interpretation of disk observations requires combined gas and dust modeling
- Radiation-thermo-chemical disk models do show a high level of agreement – we may only have different pre-conceptions on dust opacities, elemental abundances, …
- Disk gas masses *could* be good to a factor of 3-5 – now the challenge lies in better dust mass estimates …
- We need deep ALMA gas observations to detect all "dust disks" in CO (^{12}CO, ^{13}CO, $C^{18}O$, $C^{17}O$!!!) including the small inconspicuous ones
- We need to continue exploiting complex disk models (hydro, dust evolution, radiation-thermo-chemical) to "test/challenge" our disk mass determination methods
- We need a new infrared space observatory to get [OI] 63 & 145 μm, HD 56 & 112 μm to have a final calibration of disk gas masses in all major SFRs

Disk models: Our virtual laboratories ...



DIANA models





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