Gas in debris discs

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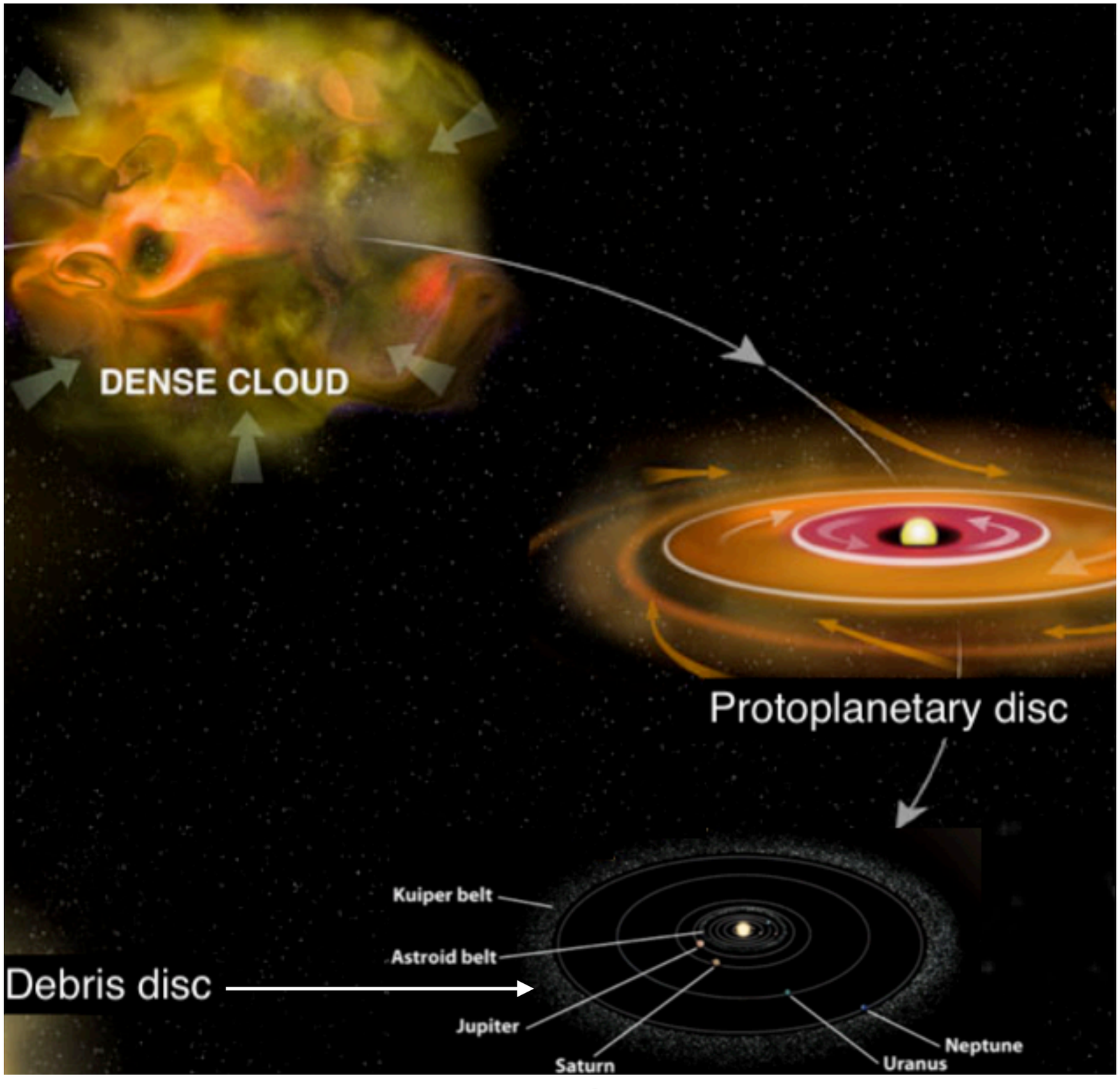
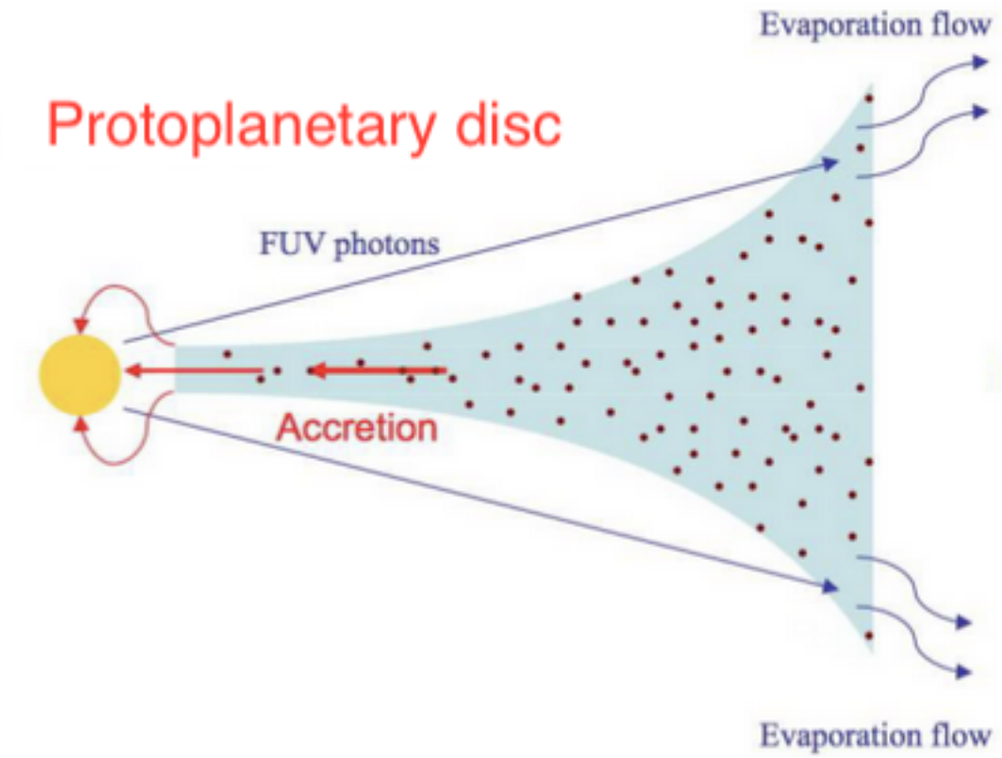
Circumstellar discs

Circumstellar discs: two distinct phases; 1) **Protoplanetary disc**, 2) **debris disc**



Circumstellar discs

1-10 Myr



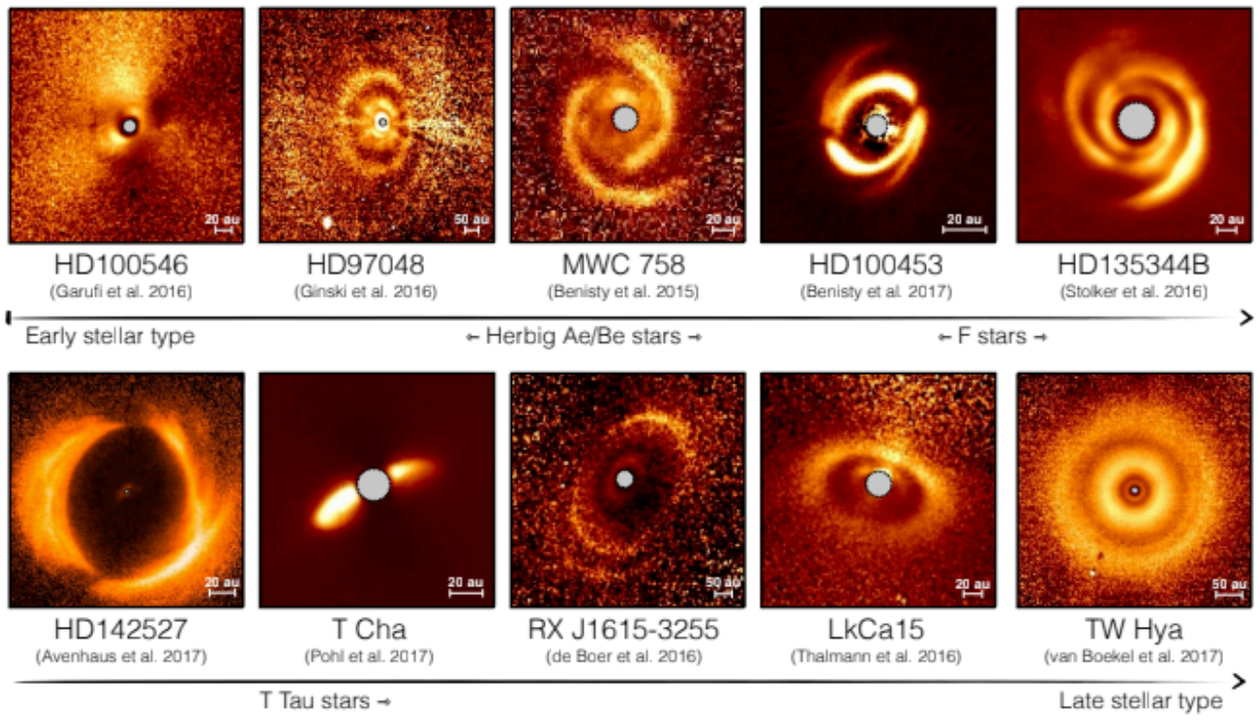
- Young discs full of gas
- Disappear after ~5 Myr
- Disc in which planets form
- Composition of the disc fixes the composition of planets and their atmospheres

10 Myr-a few Gyr

- Remnant of planetary formation
- Older discs depleted in gas
- Can survive for Gyr
- New: gas component now well detected
- —> Composition of the planetesimals accessible

Circumstellar discs

1-10 Myr



Garufi et al. 2017

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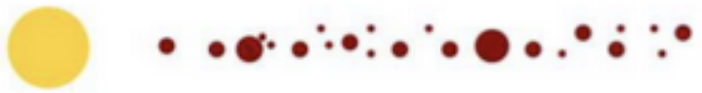

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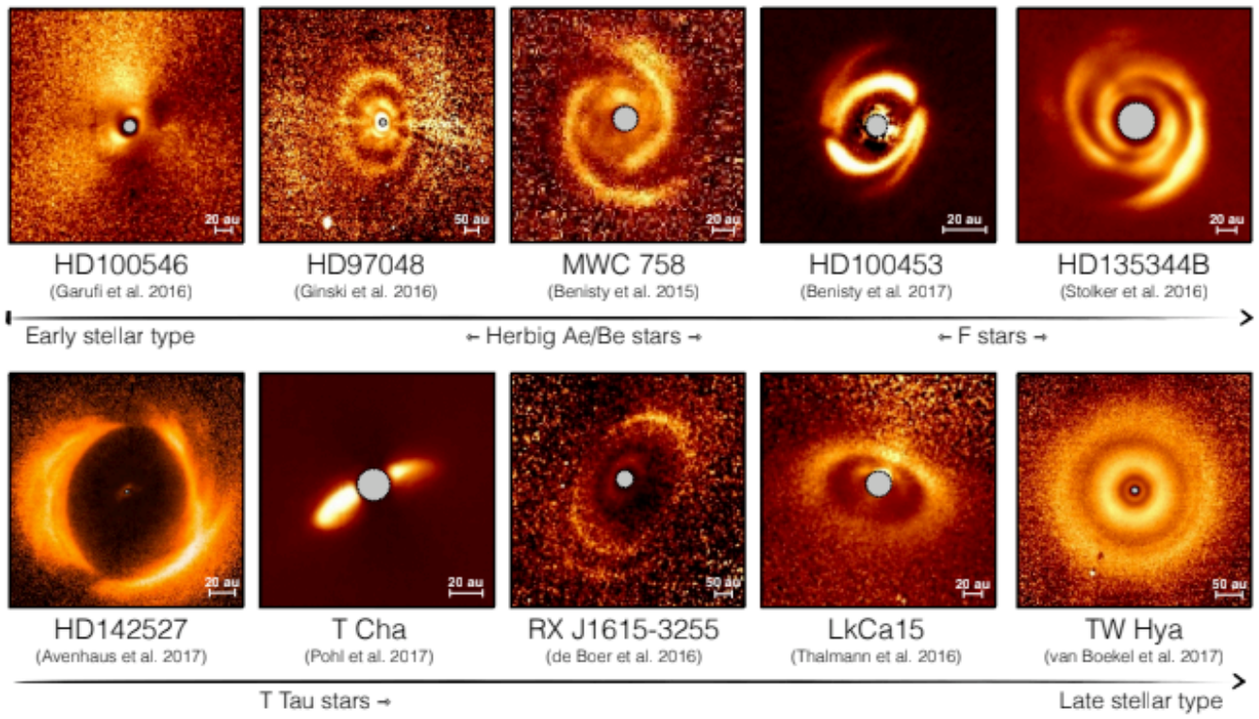

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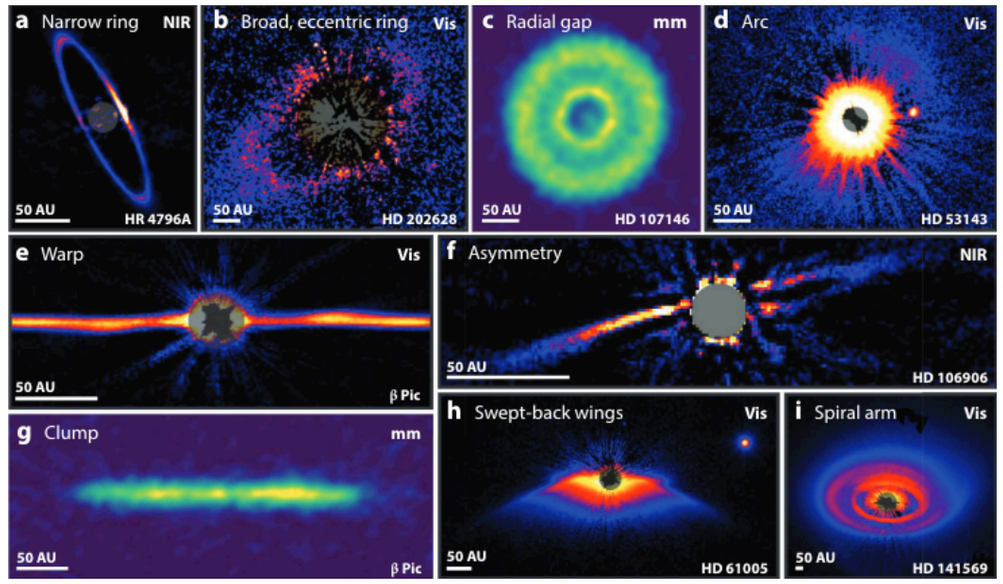

Hughes et al. 2018

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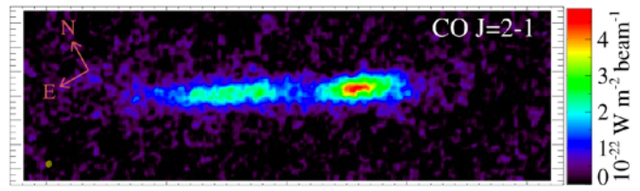
Gas in debris discs: some numbers

~20 debris discs with gas detected so far (some others soon to be added)



Gas is ubiquitous in debris discs (Moor et al. 2017):

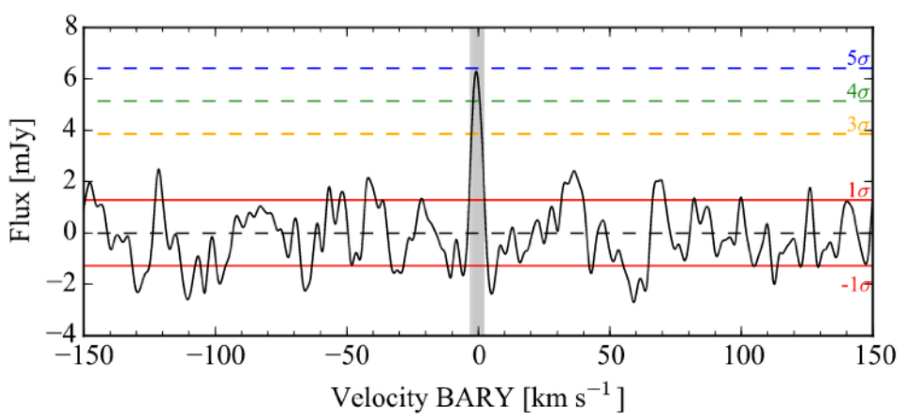
- Volume-limited sample (150pc) of bright A-star debris discs ($f>5\times10^{-4}$) <140K between 10-50Myr: $69^{+9}_{-13}\%$ of this sample has gas.
- For $f>2\times10^{-3}$, they find they all have gas except HR 4796A.

Conclusion: Gas in debris discs may be the rule rather than the exception

Gas in debris discs: what do we see?

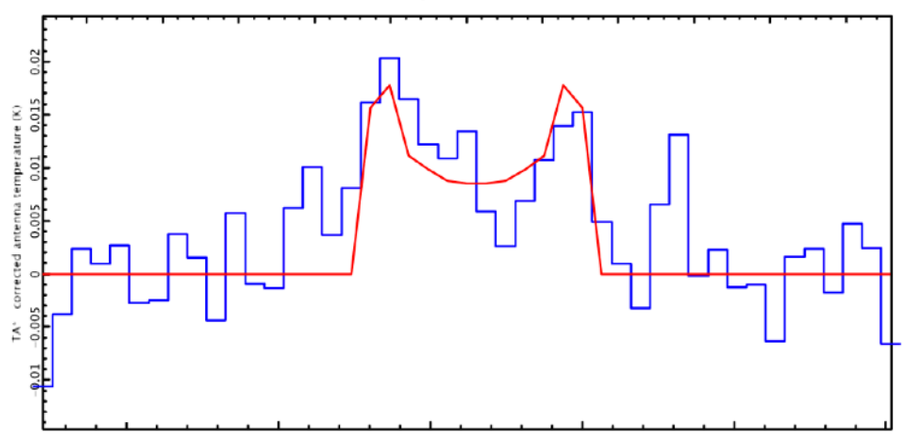
CO emission (sub-mm mostly with ALMA)

F star-23Myr-Mco~1-3x10^{-6} $M_\oplus$



HD 181327 (Marino et al. 2016)

A star-~30Myr-Mco>10^{-3} $M_\oplus$



HD 32297 (Greaves et al. 2016)

A star-440Myr-Mco~1-40x10^{-7} $M_\oplus$

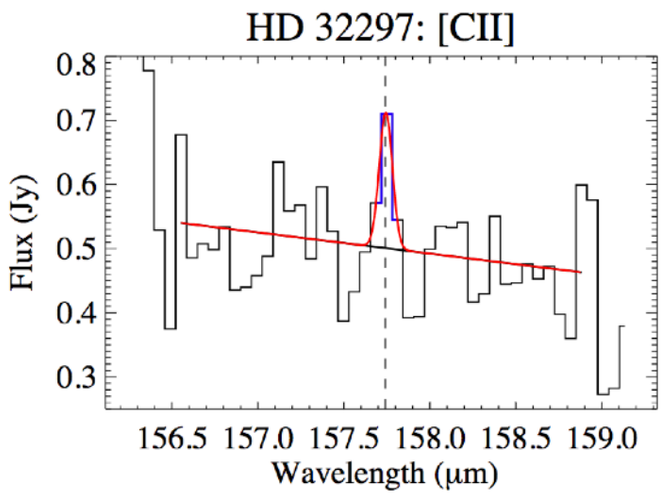
Fomalhaut (Matra et al. 2017)

CO detection around different stellar types, ages, and huge variation in mass

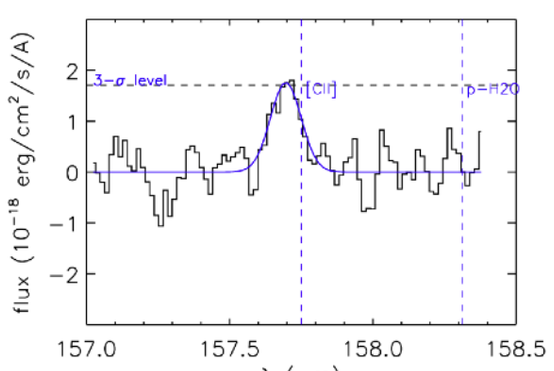
Gas in debris discs: what do we see?

CII and OI emission (The **Herschel** contribution)

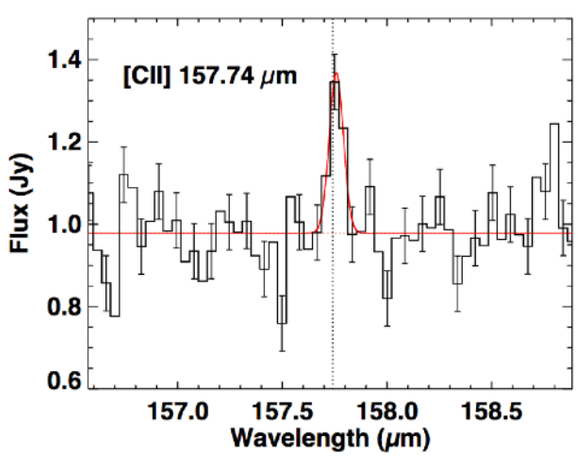
CII



HD 32297 (Donaldson et al. 2013)

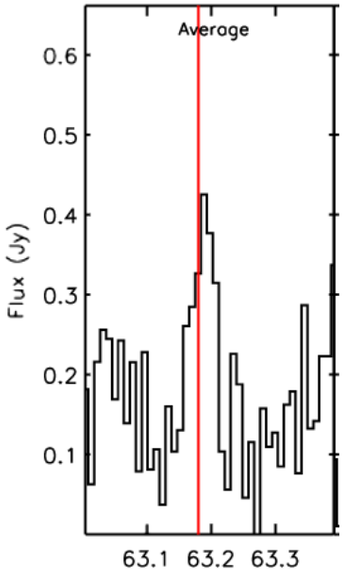


η Tel (Riviere-Marichalar et al. 2014)

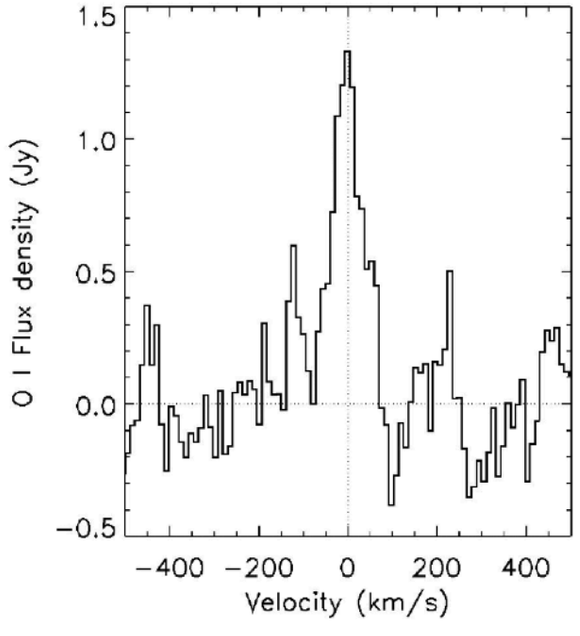


49 Ceti (Roberge et al. 2013)

OI



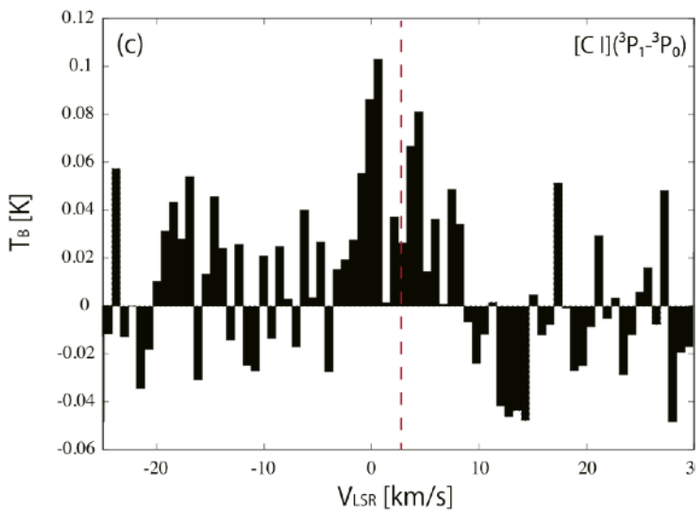
HD 172555 (Riviere-Marichalar et al. 2012)

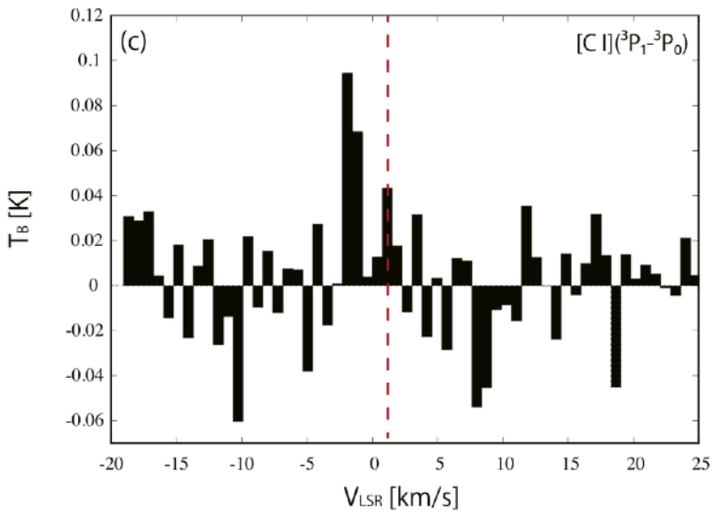


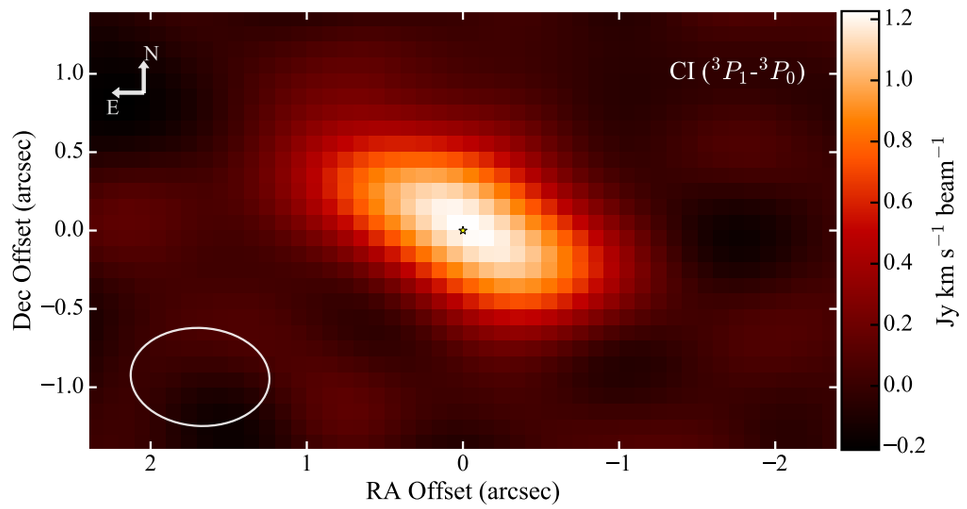
β Pic (Kral et al. 2016)

Gas in debris discs: what do we see?

NEW: [CI] emission (in **sub-mm**)







49 Ceti and β Pic (Higuchi et al. 2017)

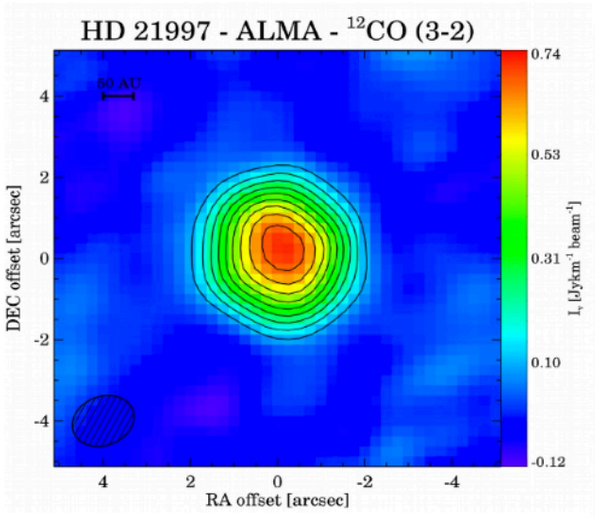
HD 131835 with ALMA (Kral et al. 2018)

[CI] has only been targeted in 5 systems so far and led to 4 detections: [CI] may be an even better tracer of gas than CO.

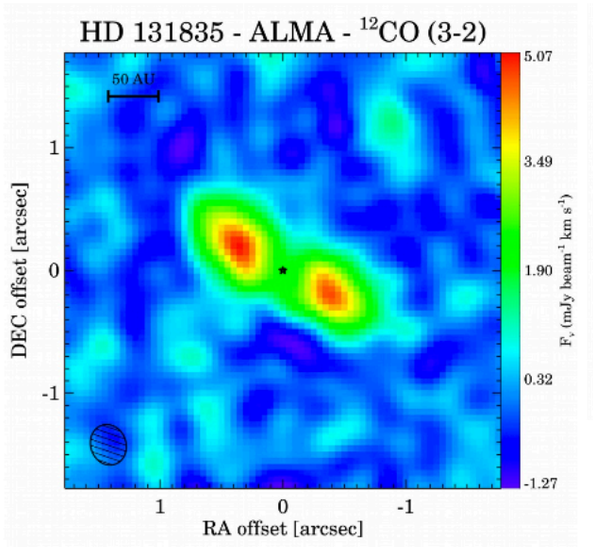
Gas in debris discs: what do we see?

Resolved emission with ALMA

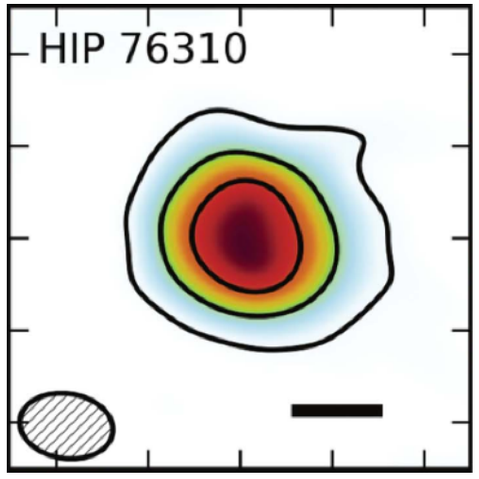
HD 21997
(Kospal et al. 2013)



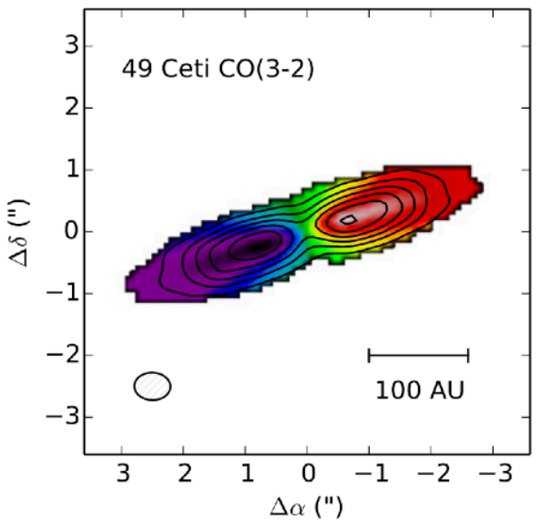
HD 131835
(Moor 2016, talk)



HD 138813
(Lieman-Sifry et al. 2016)



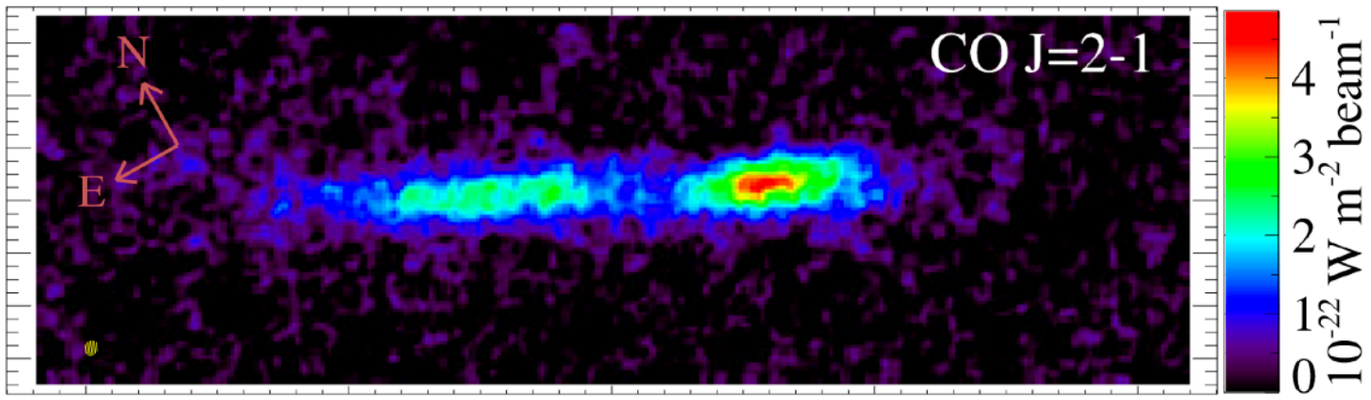
49 Ceti
(Hughes et al. 2017)



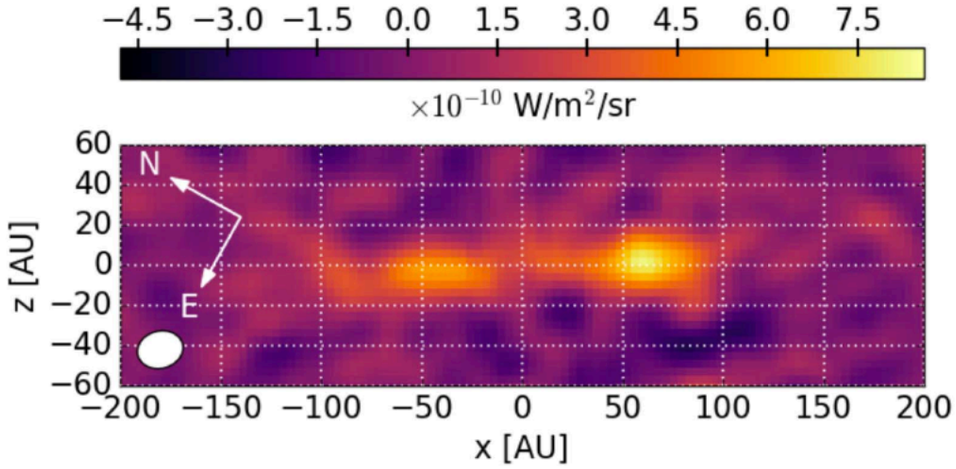
CO mostly colocated with parent belt of planetesimals (some exceptions, e.g. HD 21997): **CO released from planetesimals**

Gas in β Pic: Everything at once

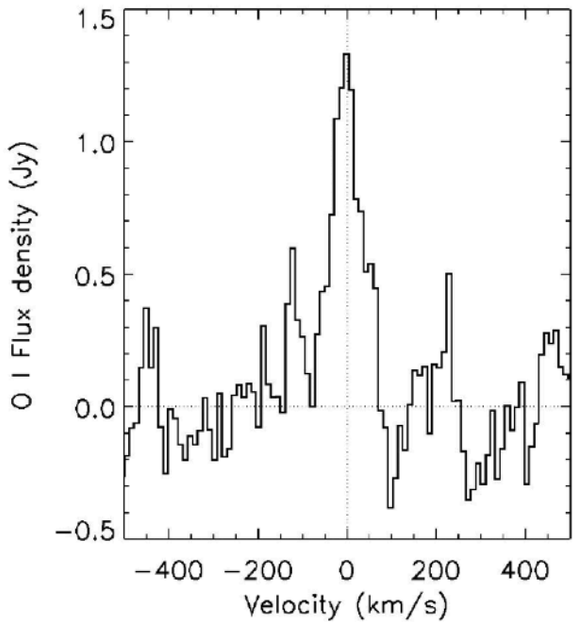
CO (Matra+17)



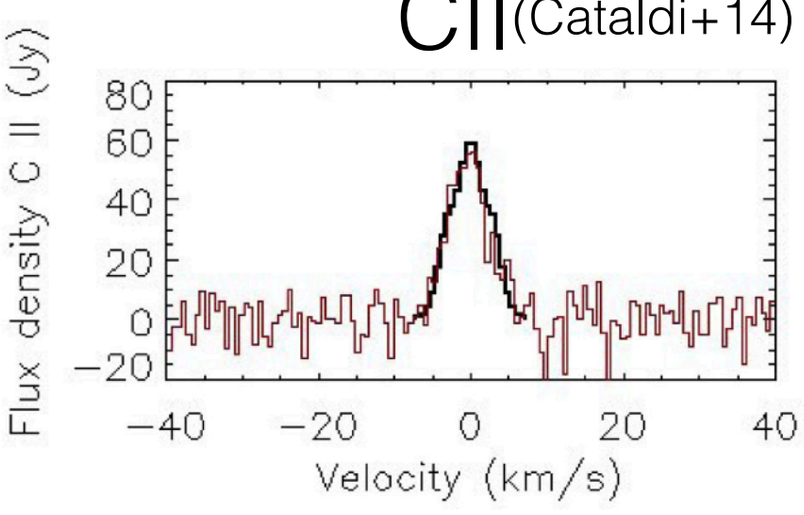
CI (Cataldi+18)



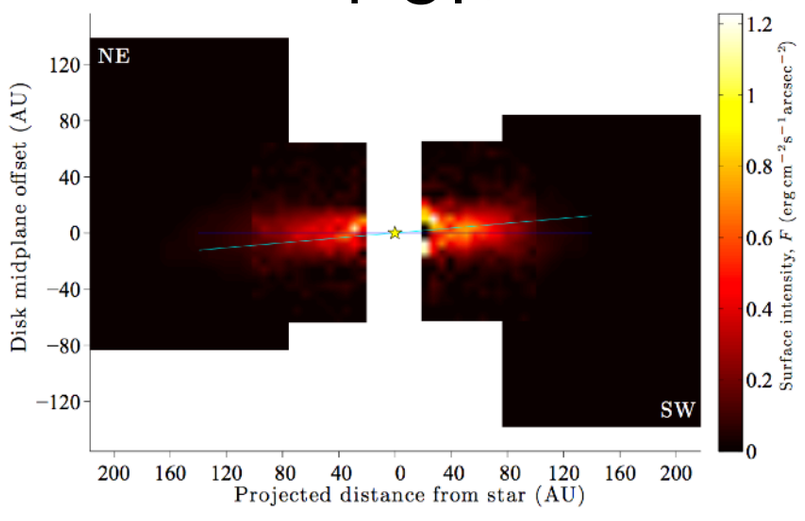
OI (Kral+16)



CII (Cataldi+14)



FeI (Nilsson+12)



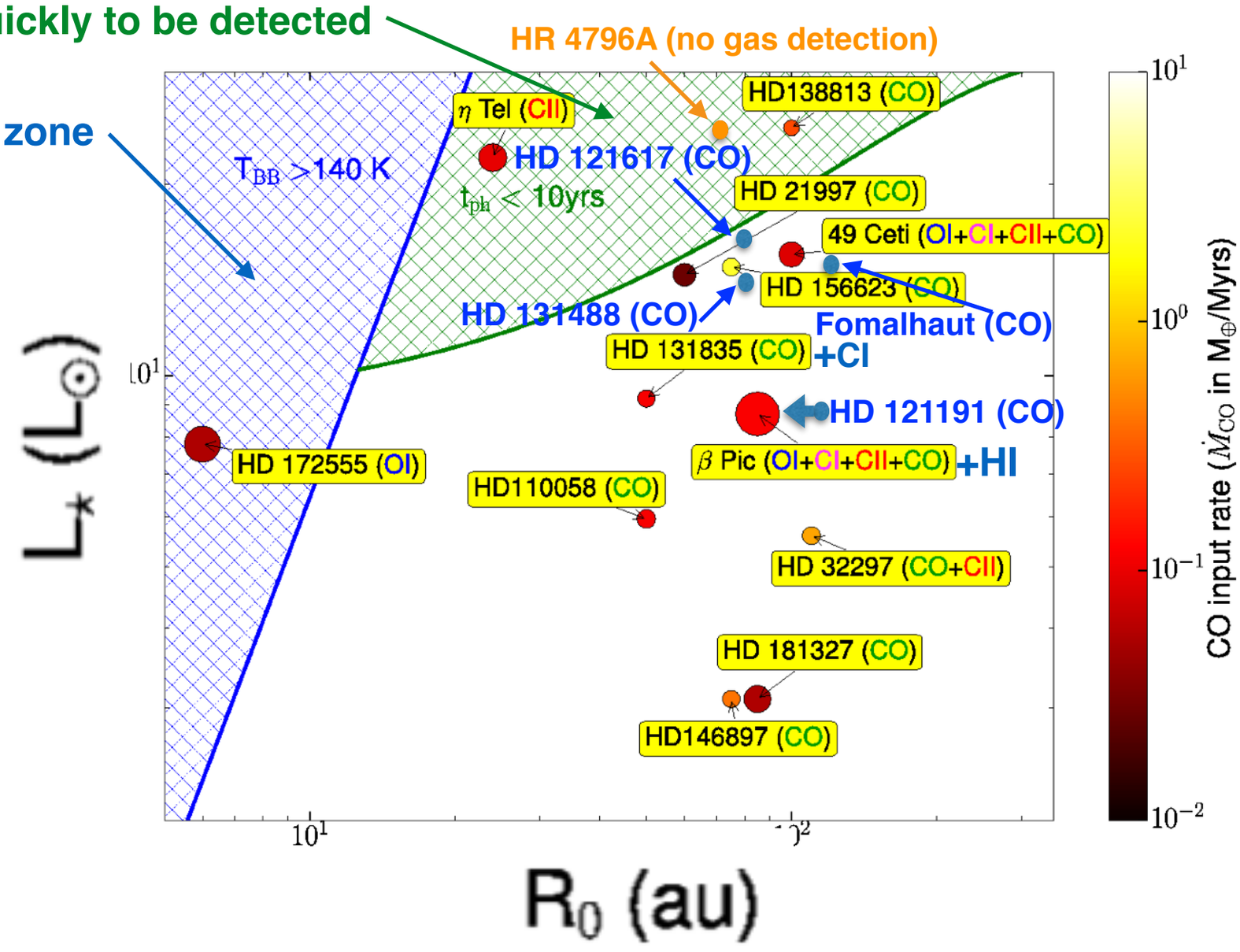
+ HI (Wilson et al. 2017) + other metals (Roberge et al., Brandeker et al., …)

Summary of gas detections so far…

~**20** debris discs

with gas detected

(CO, CI, CII, OI, HI, metals)

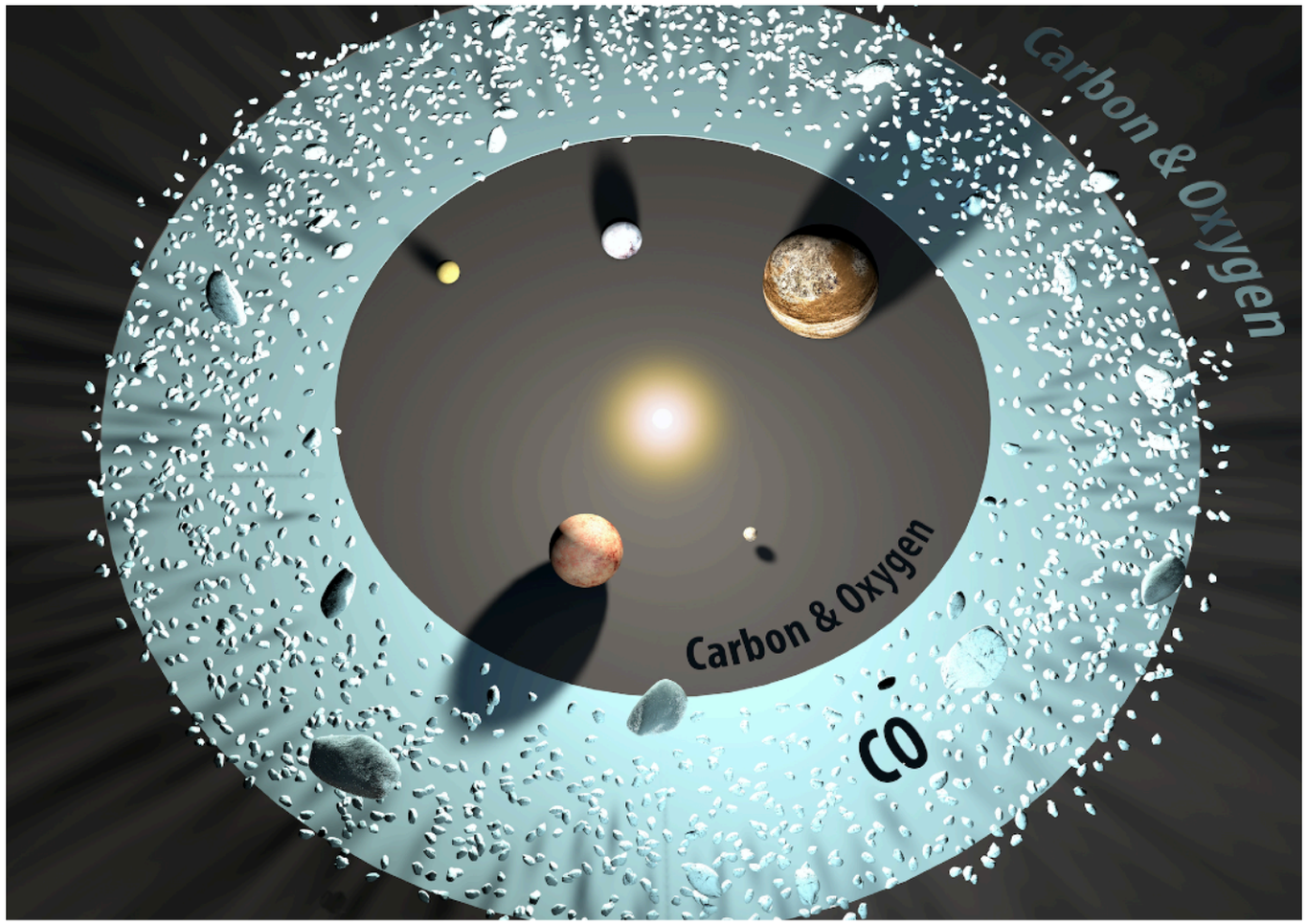


updated from Kral et al. 2017

Good understanding of gaseous component

A new model to explain gas observations (Kral et al. 2016, 2017, 2018)

Model picture: If the planetesimals are mostly made of CO and water (that are the main volatiles of comets in our Solar System) then, when they are destroyed to replenish the dust that is observed, CO and water can be released. Then CO photodissociates in ~100 yr (and water much more quickly), which creates an atomic gas disc made of carbon, oxygen and hydrogen.



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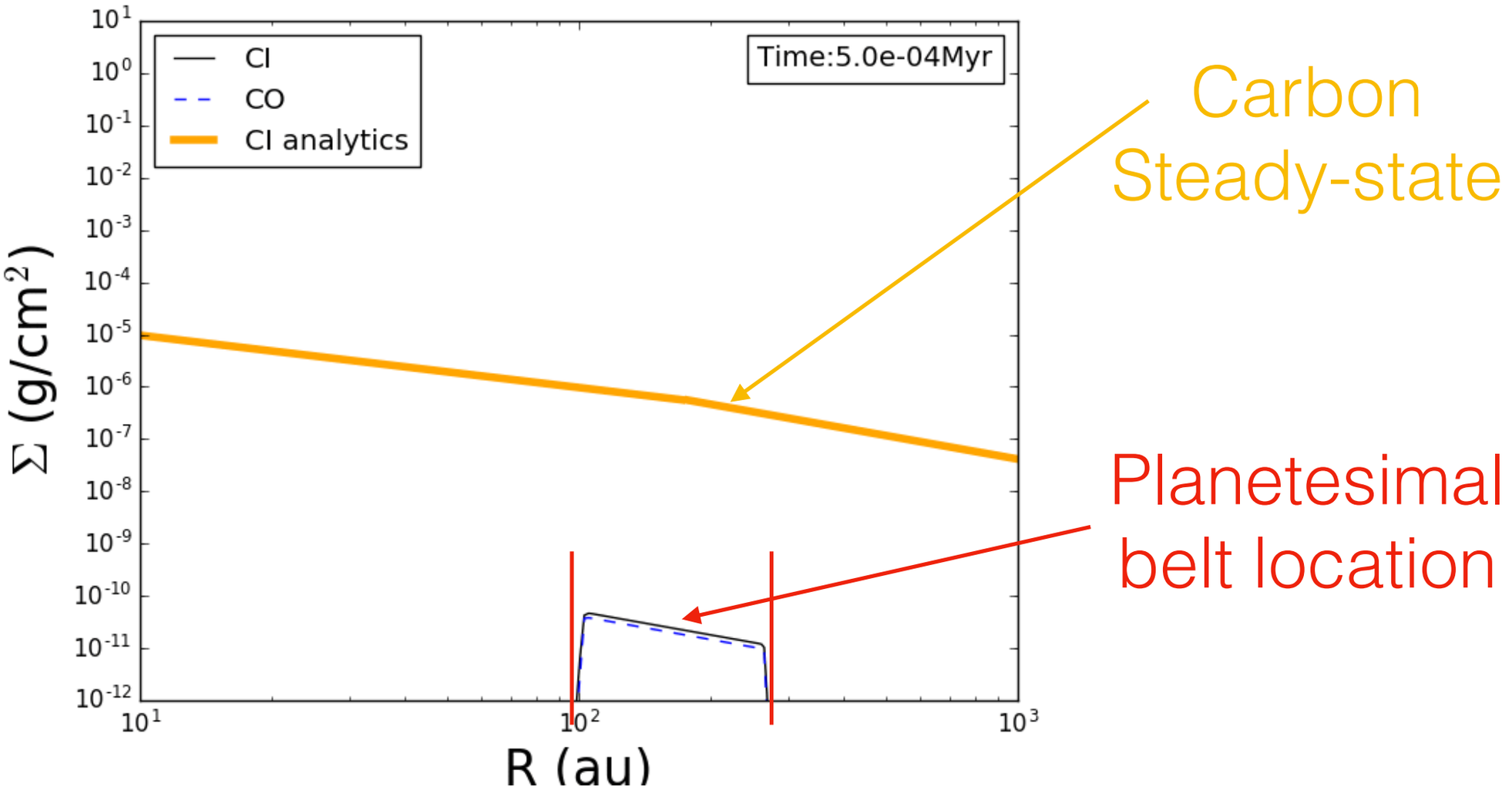

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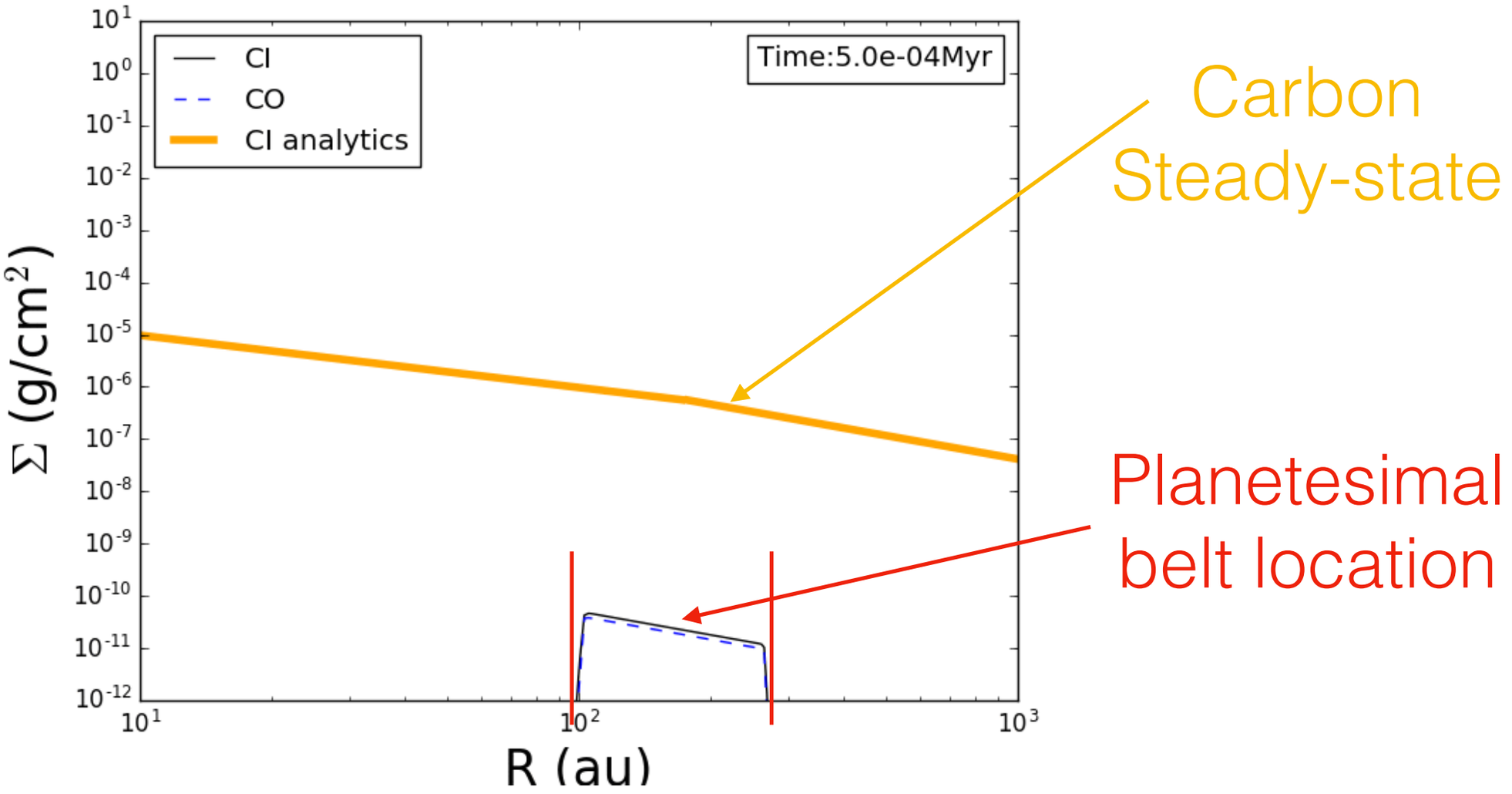


Can extract composition of exocomets

From CO detections, you get the CO-to-dust mass ratio:

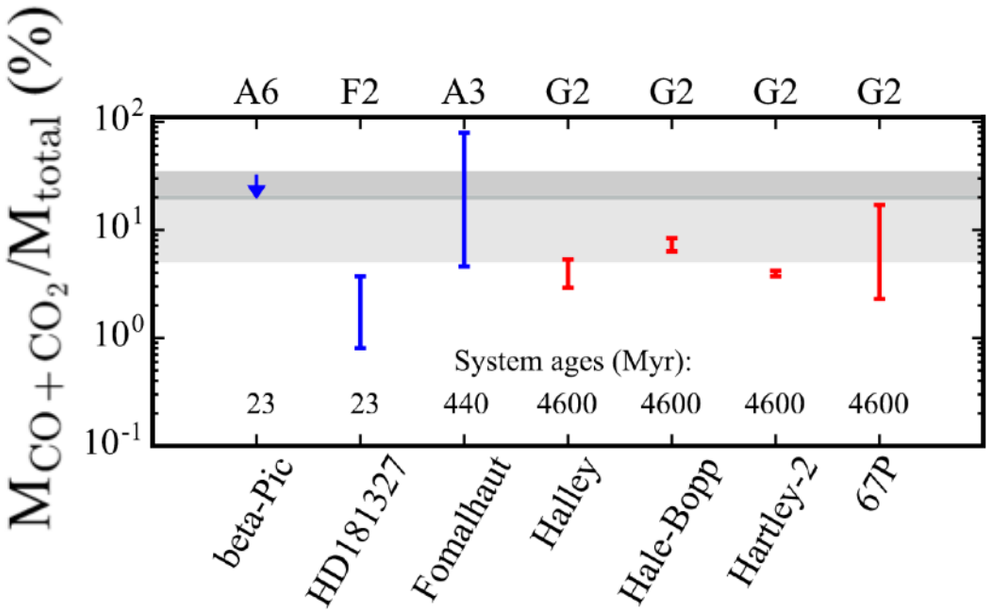


Figure 6. $CO+CO_2$ mass fraction (%) in solar system comets where both measurements are present (red, assuming a dust-to-ice ratio of ~4 as measured in comet 67P; Rotundi et al. 2015) and in exocometary belts observed so far (blue, derived in the steady-state framework). The tick labels on the top x axis indicate the spectral type of the host star. Compositions were derived from Matrà et al. (2017) (β Pic), Marino et al. (2016) (HD 181327), this work (Fomalhaut), and Le Roy et al. (2015) and references therein for solar system comets. Shaded regions represent the ranges of mass fractions expected from direct inheritance of ISM compositions (assuming 100% CO trapping within comets and no grain surface chemistry), in the cases where comets formed outside (darker gray) or inside (lighter gray) the CO ice line within the protoplanetary disk.

Matra et al. (2017)

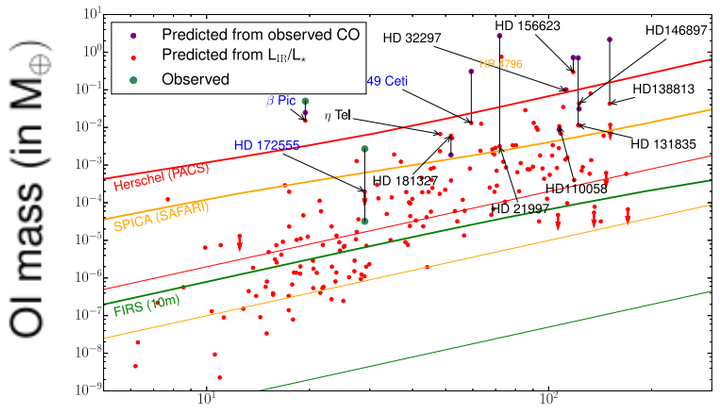
From OI detections, you get the H_2O-to-CO ratio:

Table 4. Gas number density ratio when assuming extra hydrogen in the disc.

In the gas disc	H/C	~3
	O/C	~2.5
	O/H	~1
In planetesimals	H_2O/CO	1.5

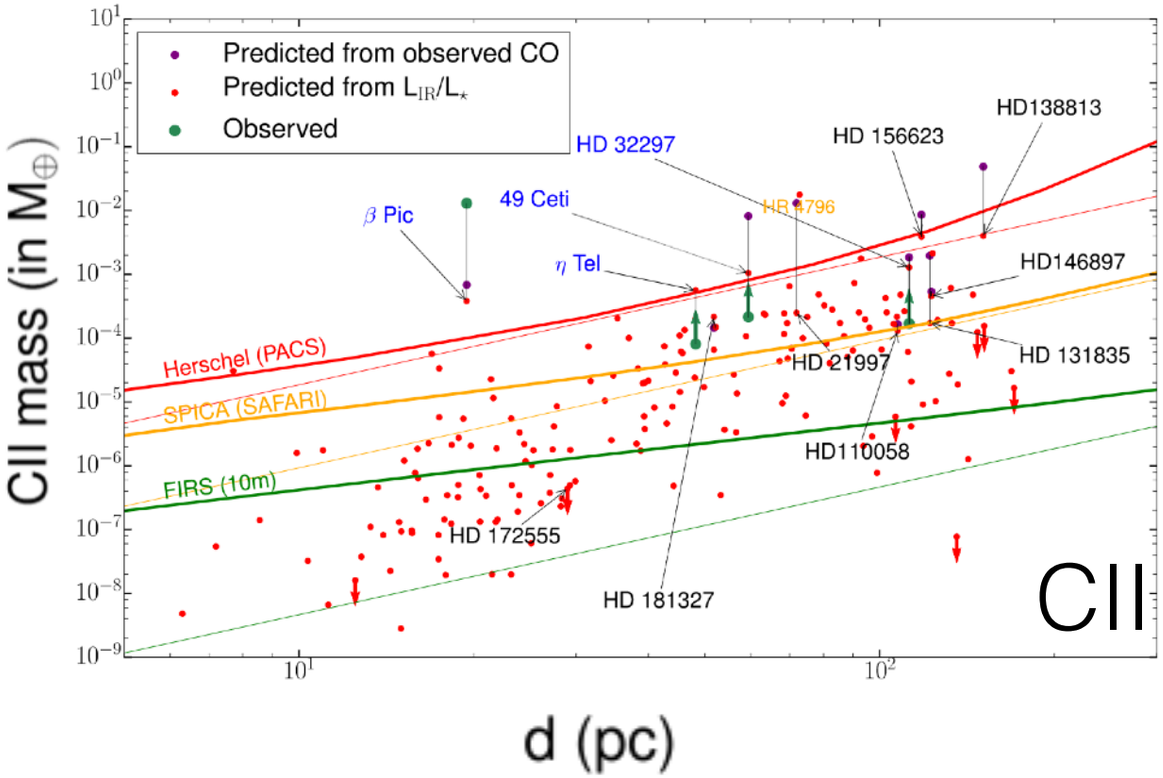
Kral et al. (2016)

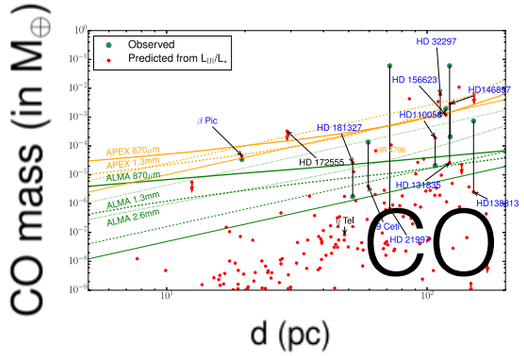
Only applied to β Pic so far as need CO+O detections to do it but future is bright with SPICA or OST.

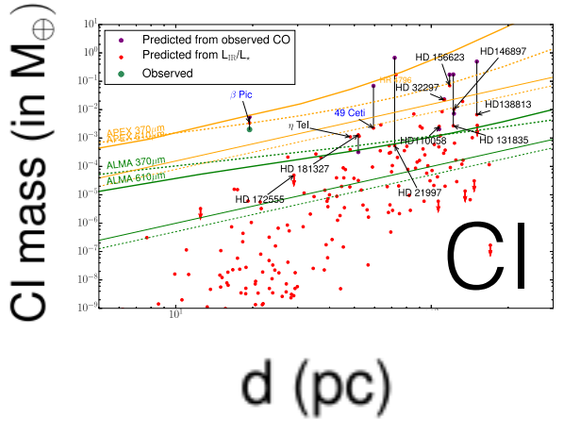


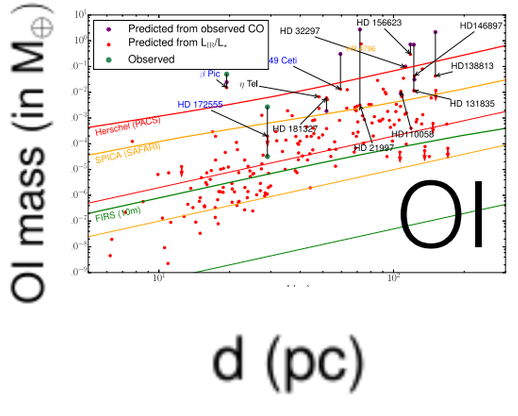
Explaining observations with this model

Application of this model to all detections and non detections (Kral et al. 2017)





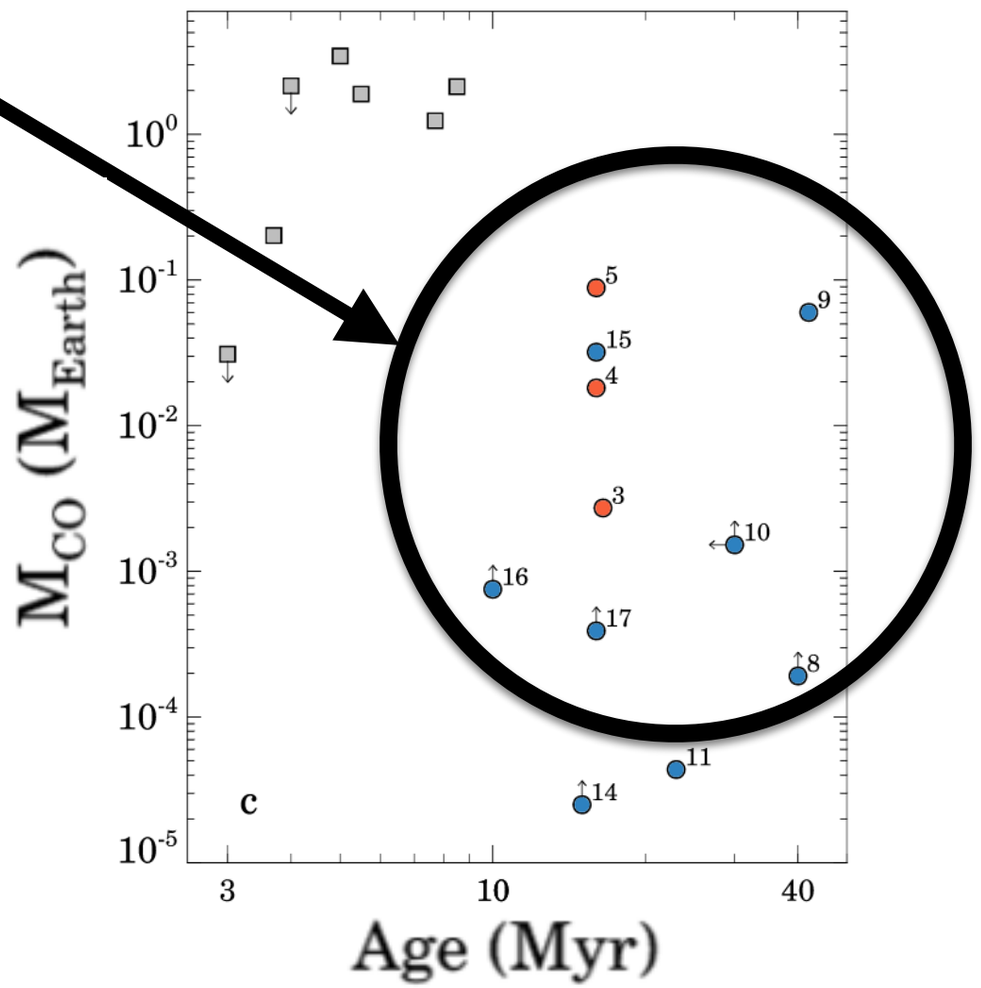




We can explain most CO, CI, CII, OI detections and non-detections so far, except for the very massive gas discs, i.e. discs with CO masses close to 10^{-2} $M_\oplus$ or above.

BUT problem for massive gas discs…

Massive gas discs in debris disc systems



1 - HD 98363	10 - HD 32297
2 - HD 109832	11 - β Pic
3 - HD 121191	12 - HD 95086
4 - HD 121617	13 - HR 4796
5 - HD 131488	14 - HD 110058
6 - HD 143675	15 - HD 131835
7 - HD 145880	16 - HD 138813
8 - 49 Cet	17 - HD 156623
9 - HD 21997	

Moor et al. 2017

They are possibly **up to 9 massive discs** discovered so far (HD 131835, HD 21997, HD 138813, 49 Ceti, HD 32297, HD 156623, HD 121191, HD 121617, HD 131488), which don't seem to be explainable as being of secondary origin…

How to explain these massive gas discs?

Primordial origin?

Suggested in a few papers because of the high CO mass but no models to back that up:

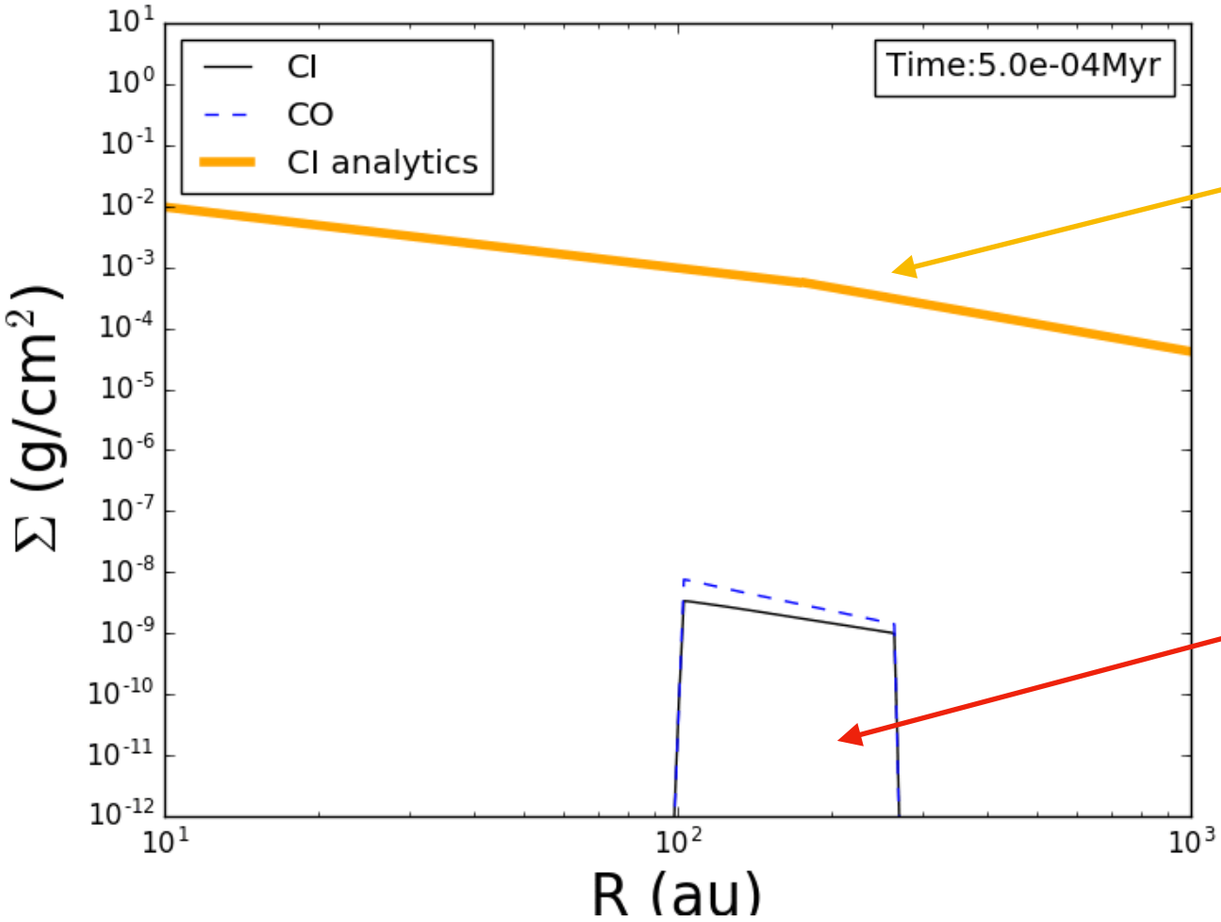
- How to explain that these gas discs can survive against photo-evaporation for tens of Myr?
- How to explain low gas temperatures measured (much lower than dust temperatures)?
- Scale-height of 49 Ceti seems to favour a secondary origin (Hughes et al. 2017)

What about revisiting the secondary origin scenario in more details?

Push our secondary model into a new regime...

Secondary origin?

What happens for high CO input rates and low values of viscosity (say $\alpha = 10^{-3}, \dot{M}_{\rm CO} = 10^{-1} {\rm M}_\oplus/{\rm Myr}$)?



Neutral carbon Steady-state

Planetesimal belt location

New viscous diffusion code (Kral et al., in prep)

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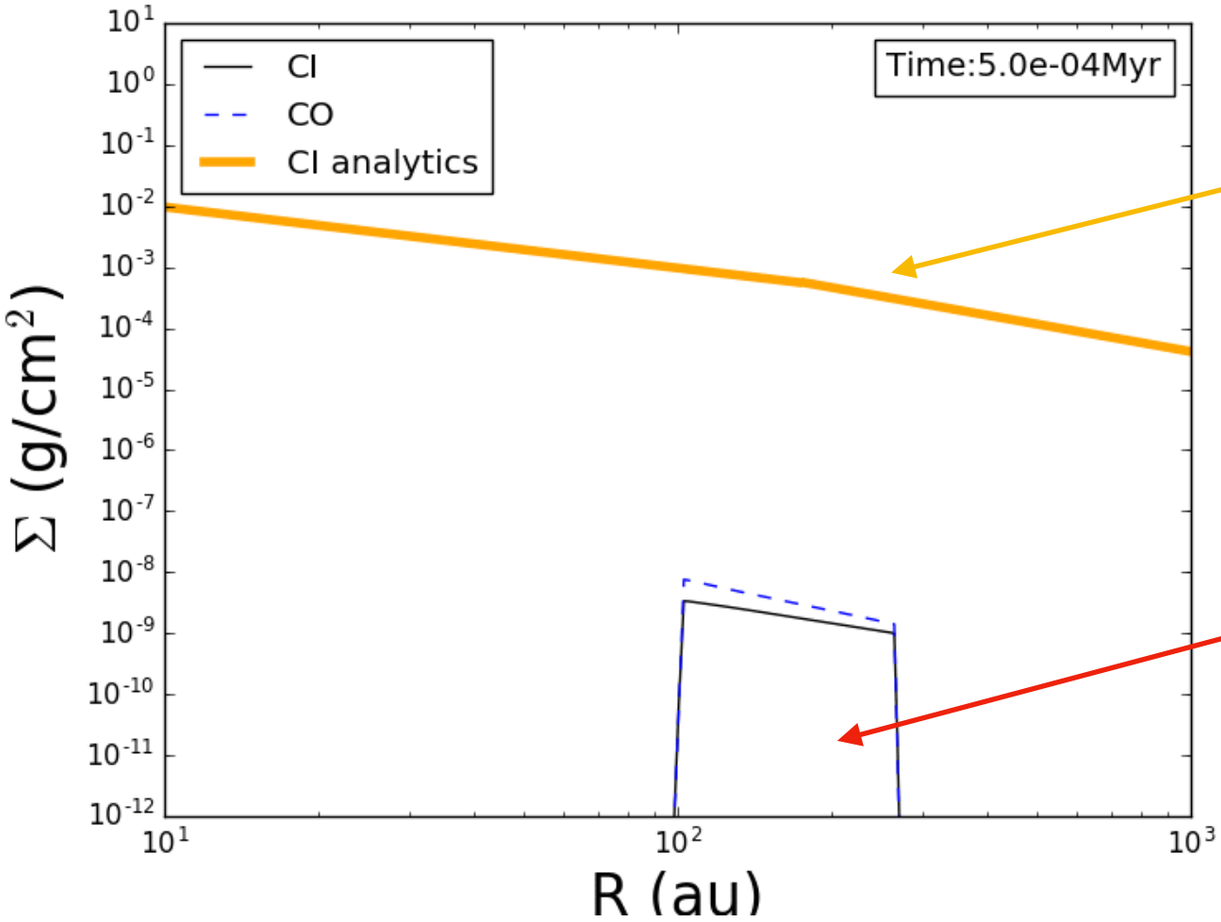

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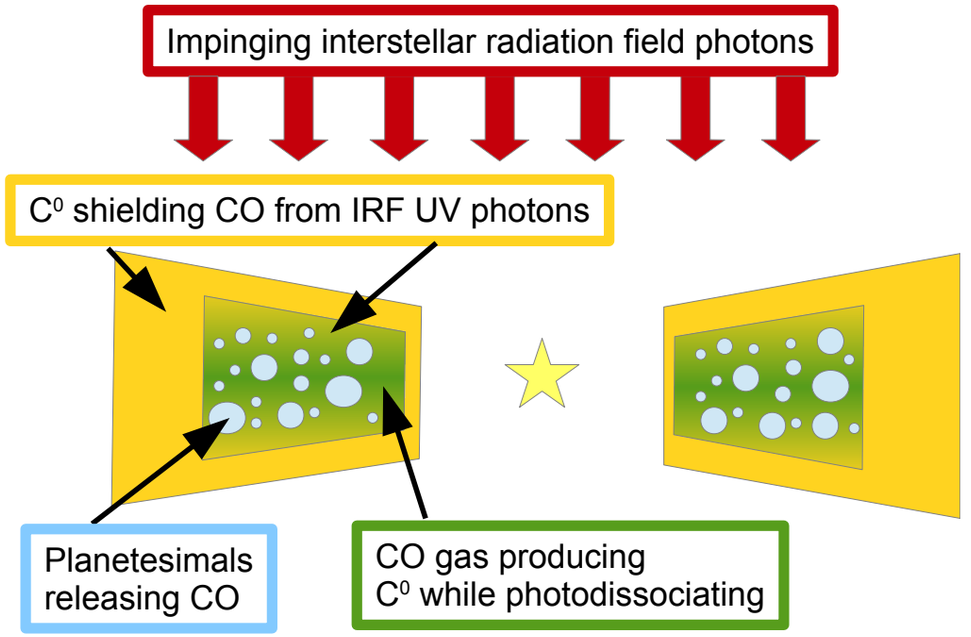
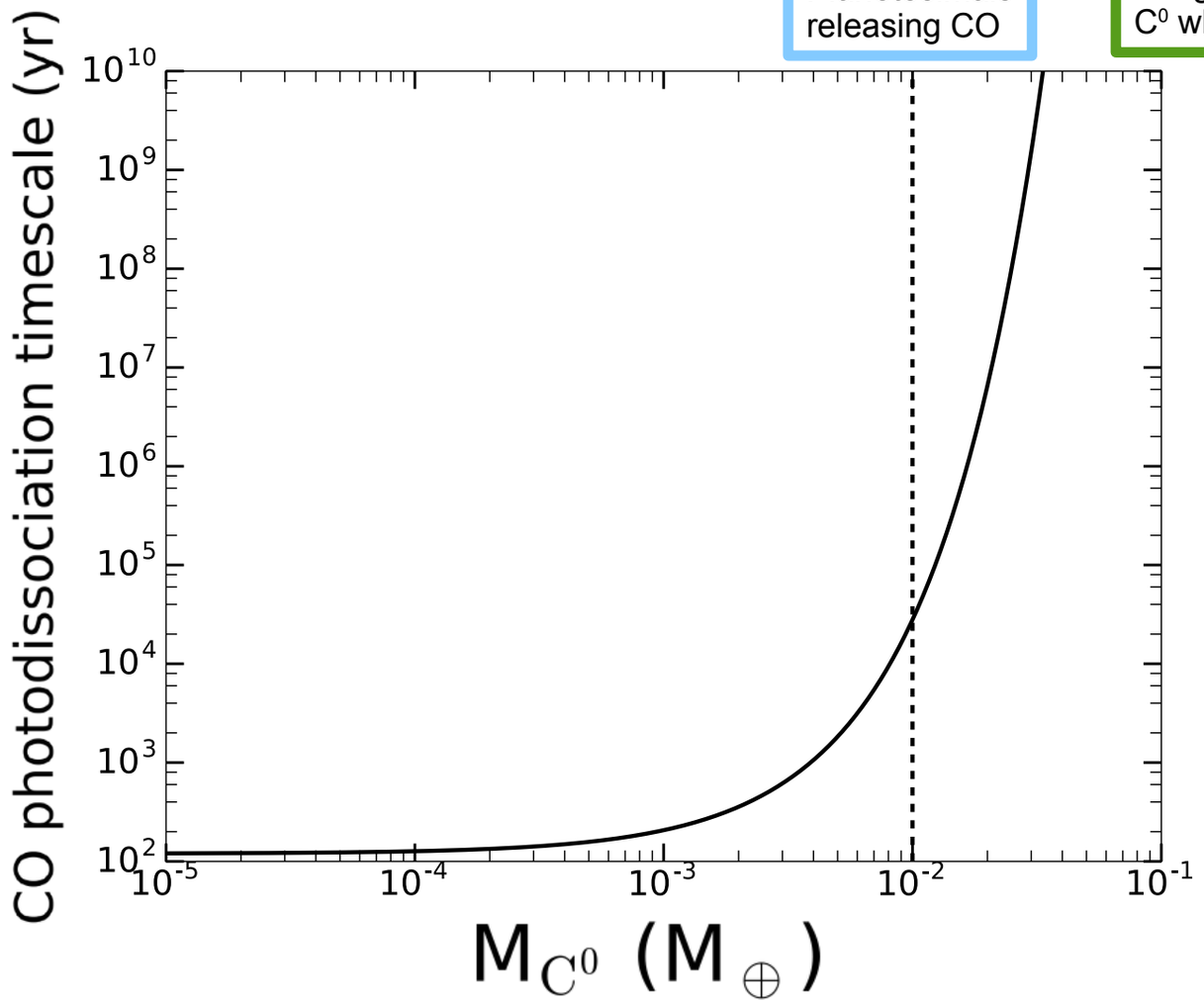
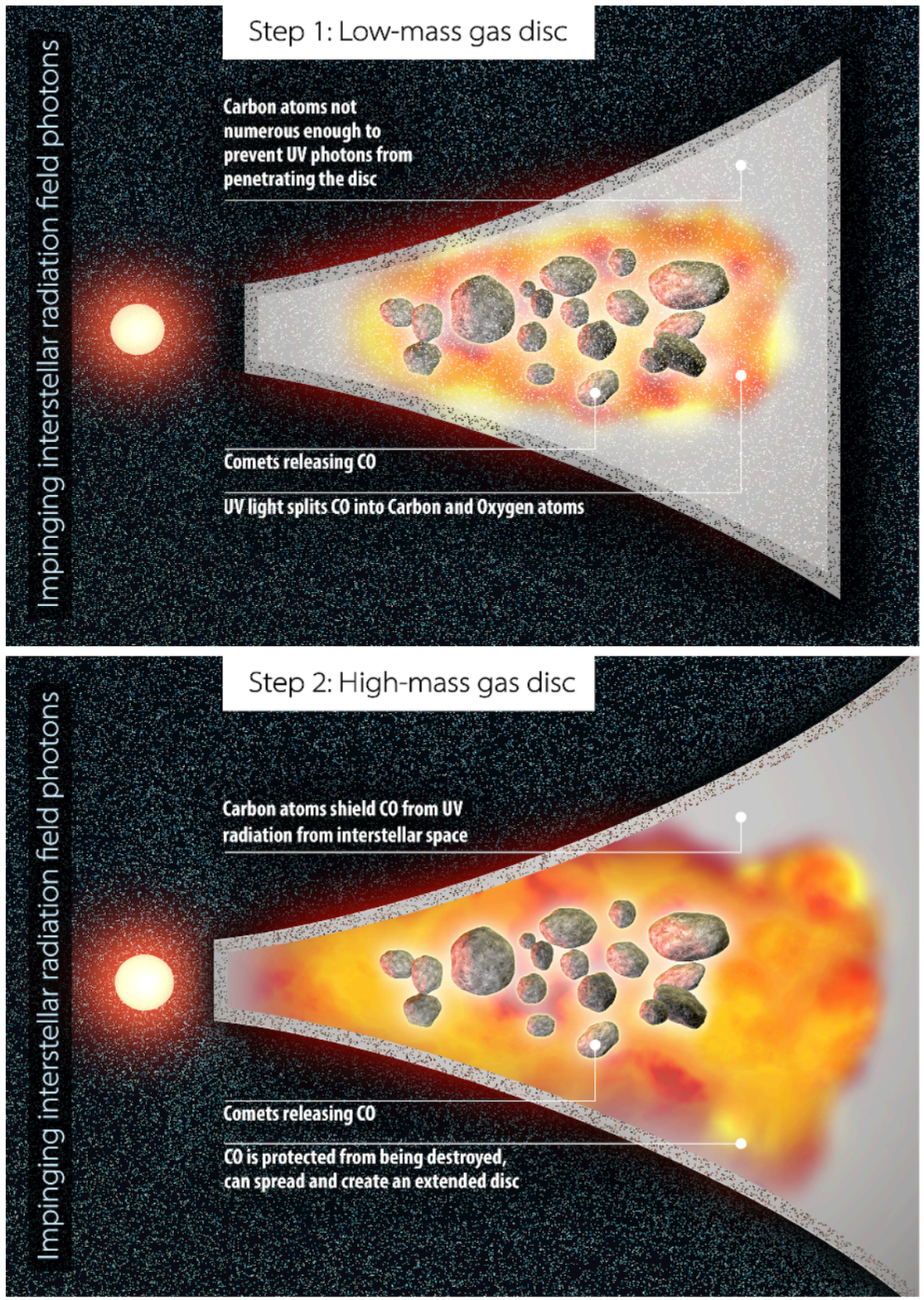
Why does it produce massive CO discs?

Missing ingredient in previous model: Shielding of CO by C^0 (Kral et al., 2018)



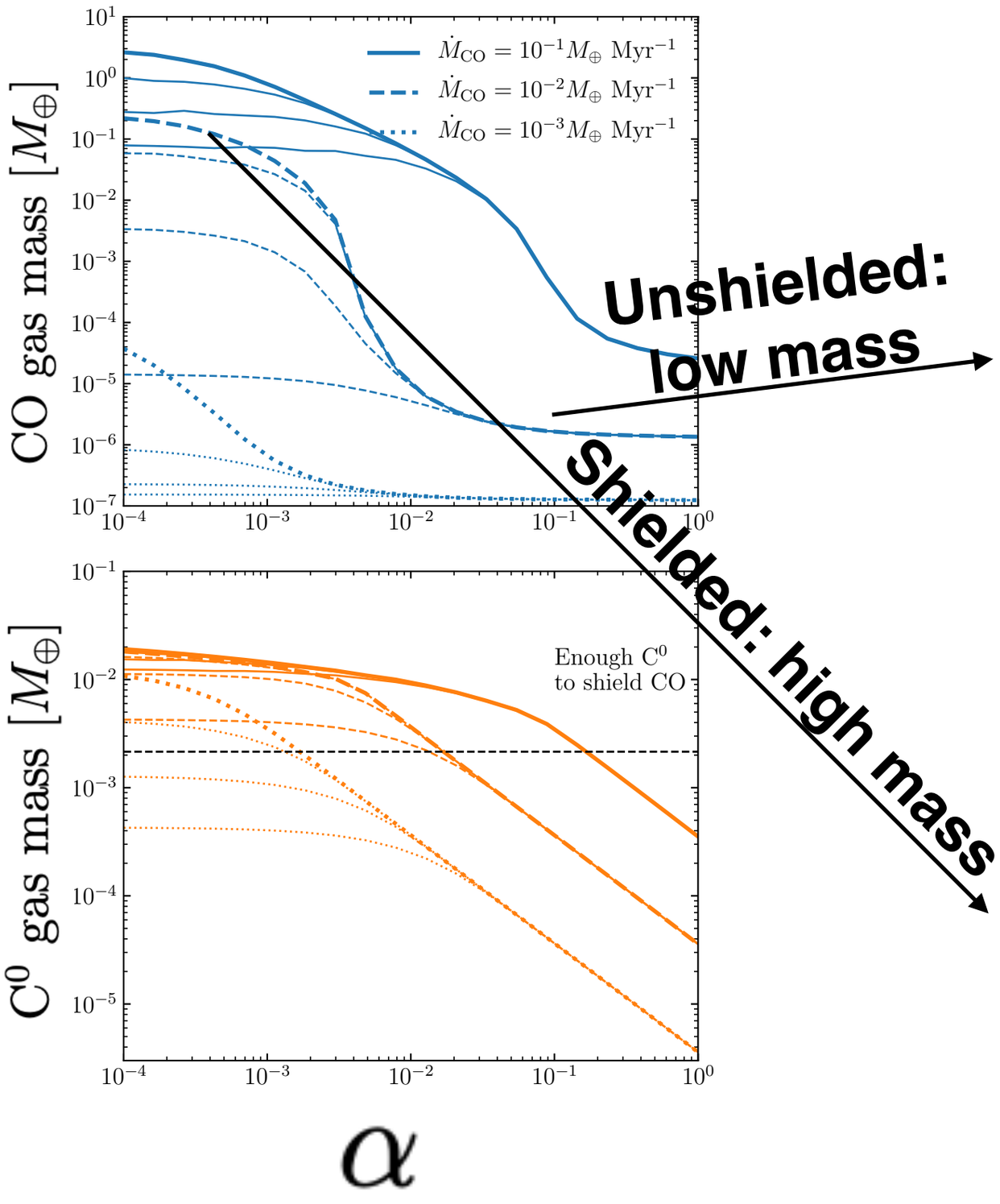


The shielding model: How does it work in action?



From the press release of Kral et al. (2018)

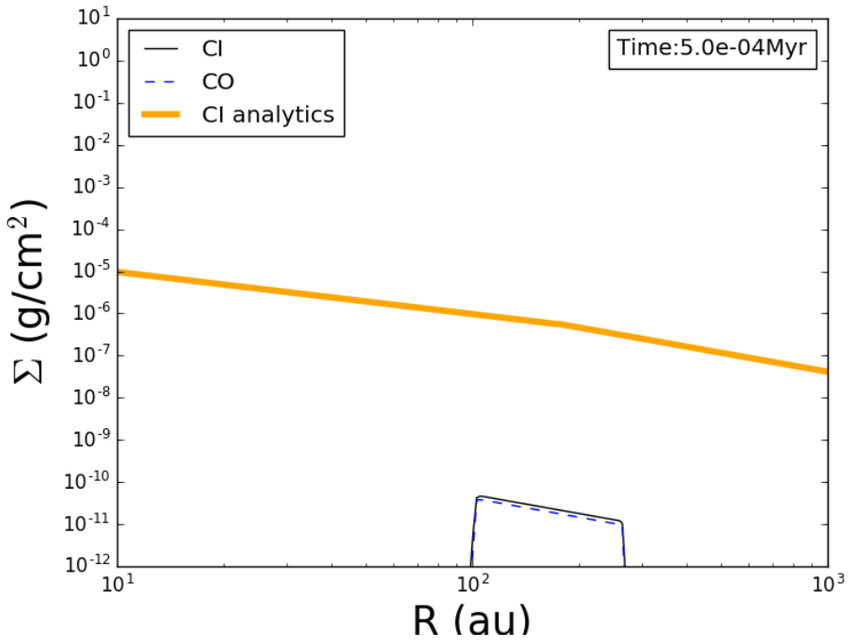
Unshielded or shielded discs: Two clearly different regimes



Unshielded: low mass

Shielded: high mass

$\alpha = 10^{-2}, \dot{M}_{\rm CO} = 10^{-3} \mathrm{M}_\oplus/\mathrm{Myr}$



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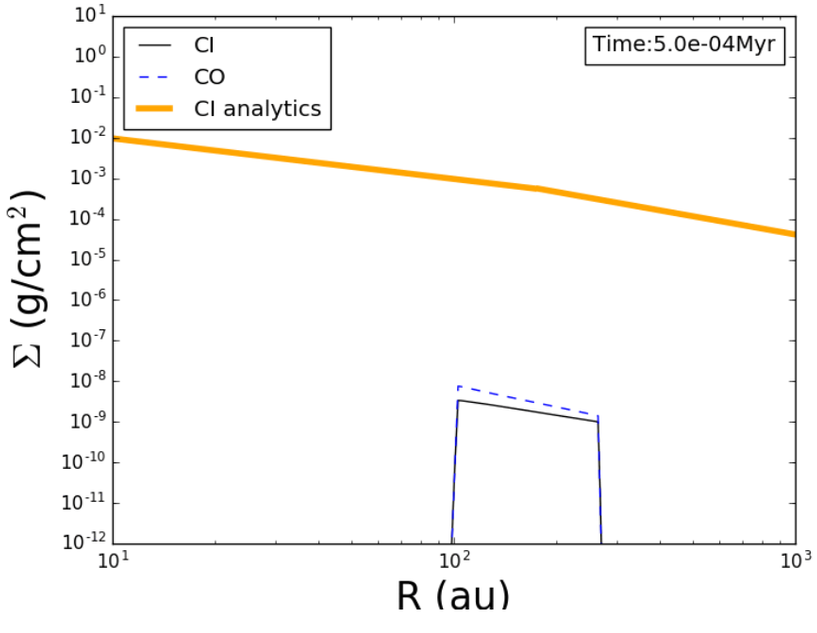

Kral et al. 2018

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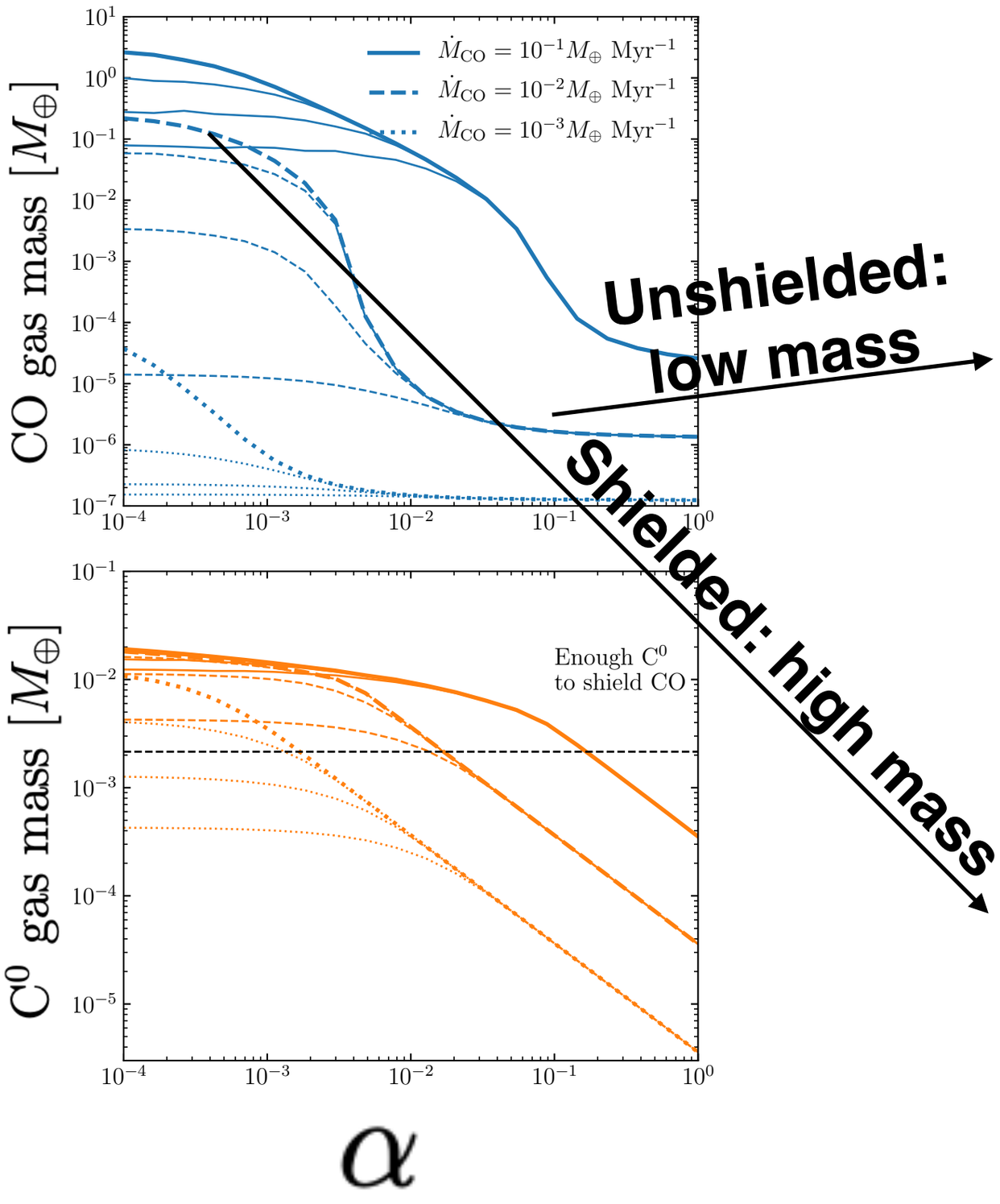

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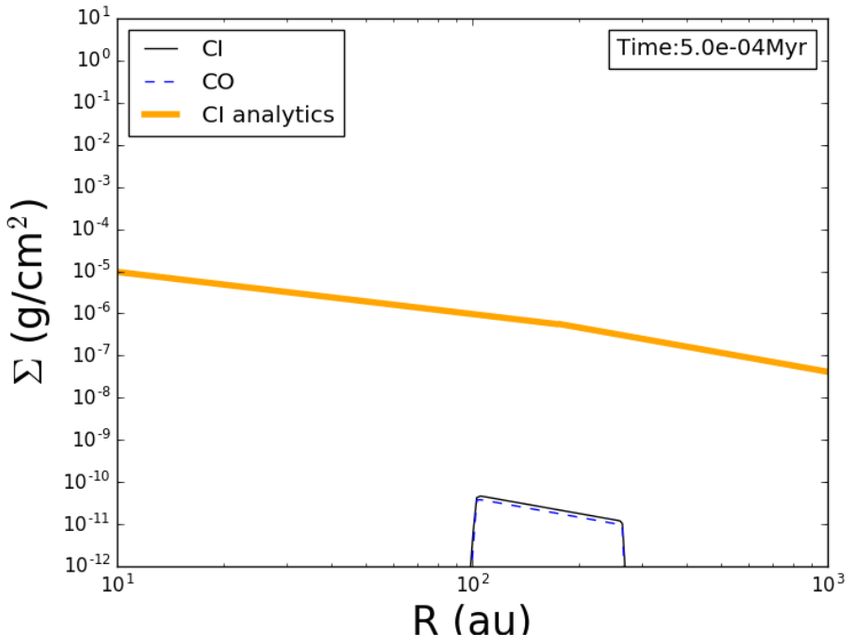

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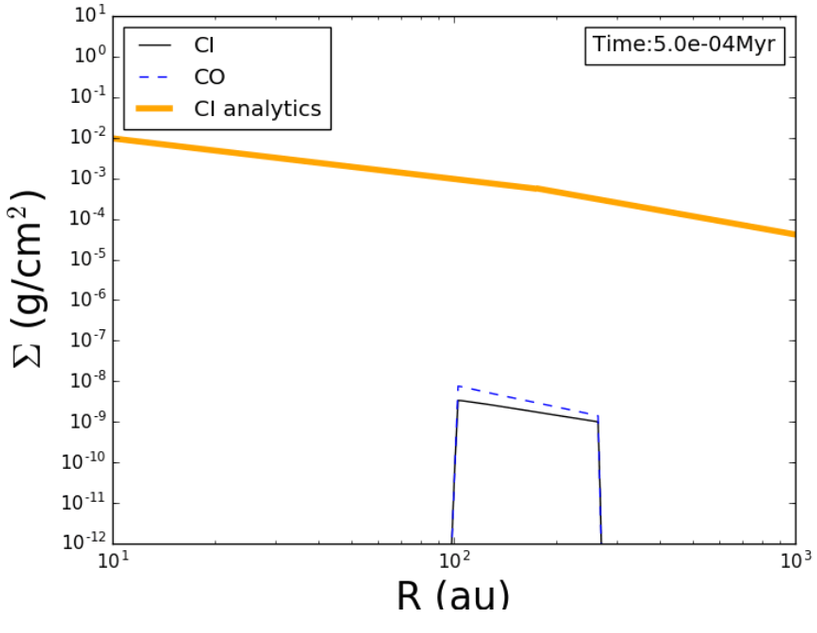

Kral et al. 2018

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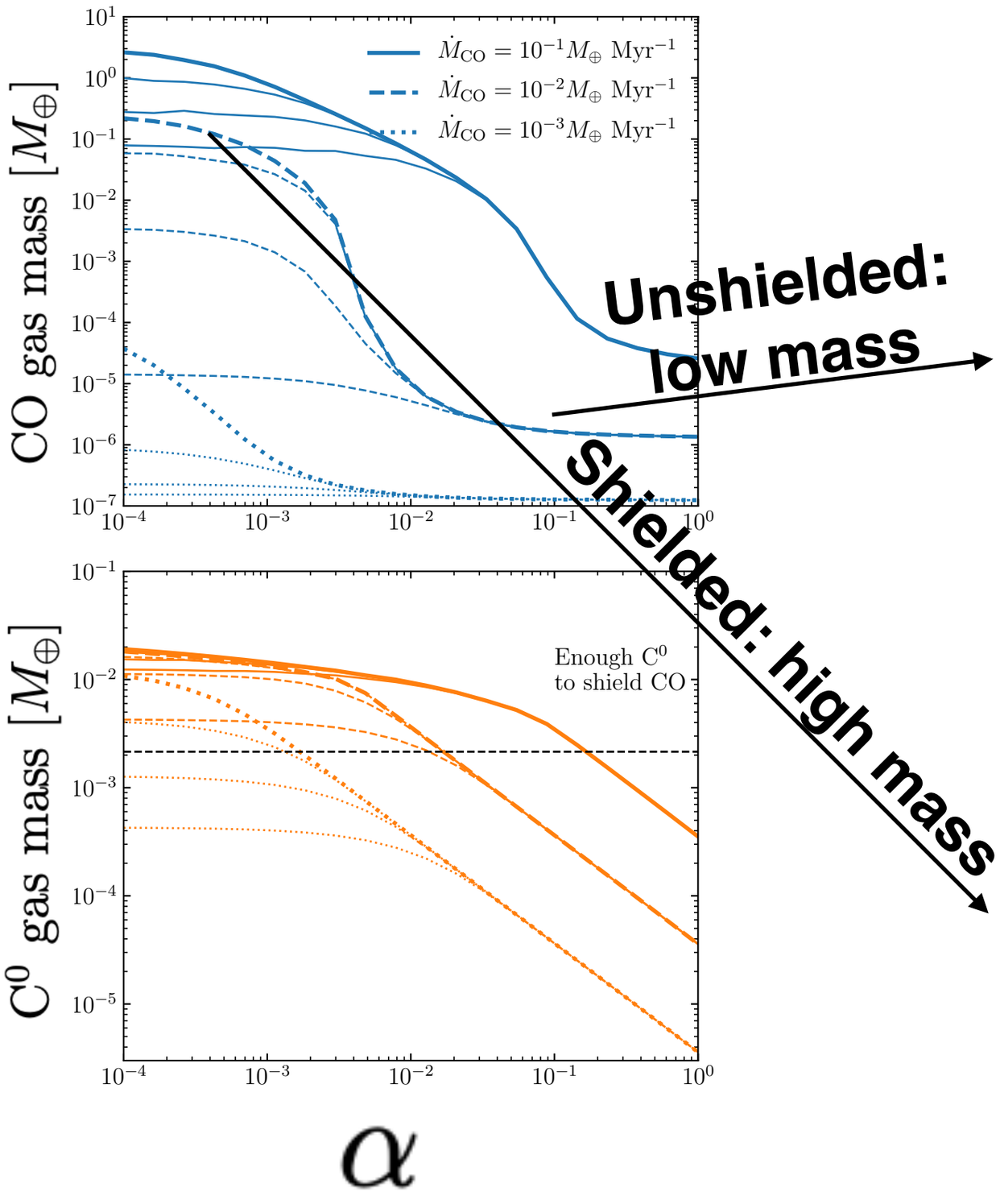

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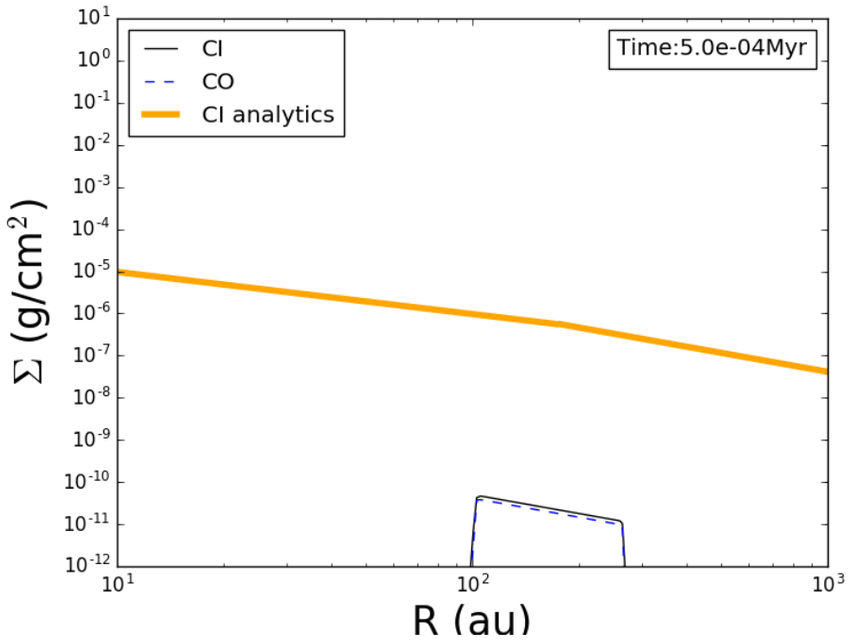

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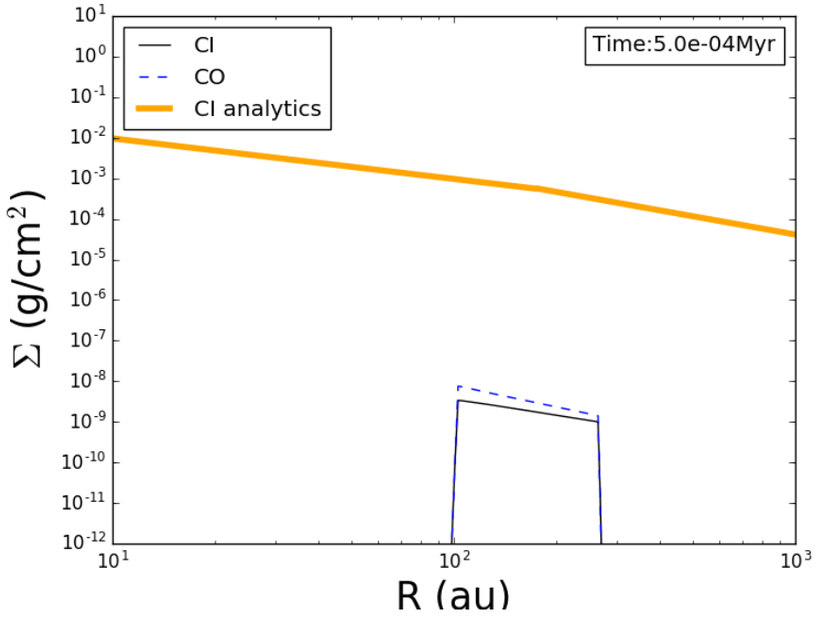
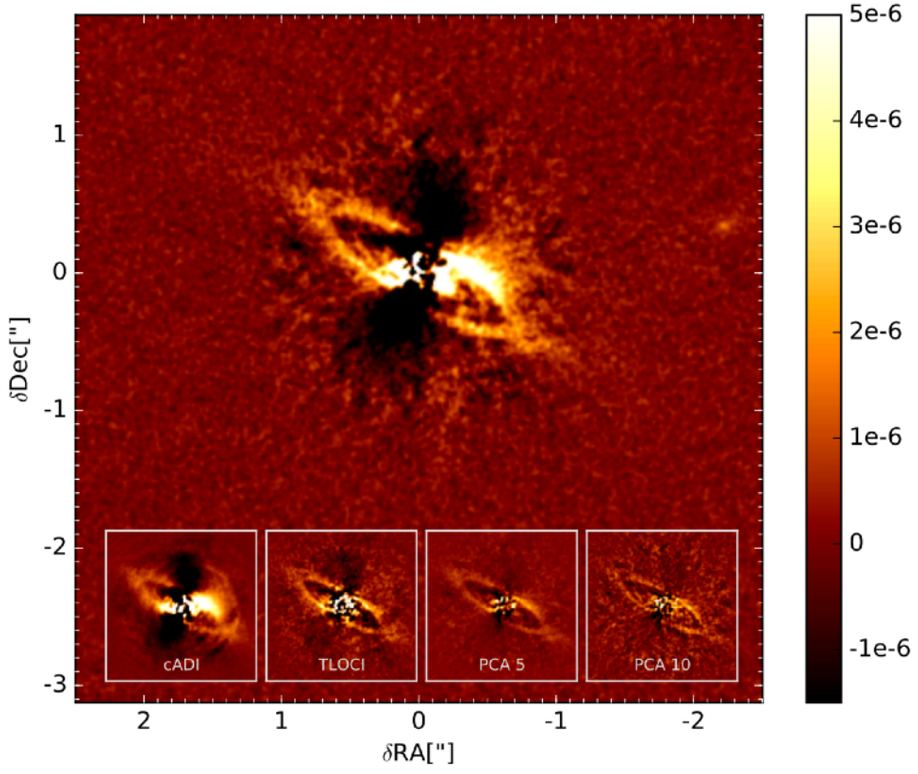


Kral et al. 2018

Testing the shielding model on real data: HD 131835



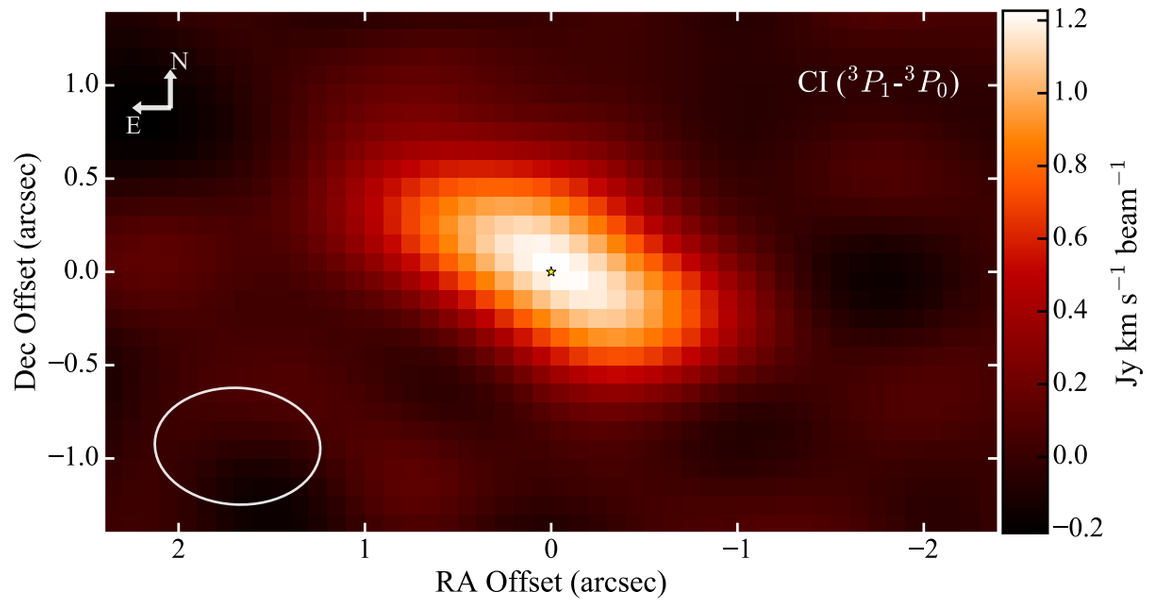
SPHERE image of HD 131835 (Feldt+17)

Outer belt between 80-120au (+multiple concentric rings), highly inclined (~77deg), high fractional luminosity (1.5×10^{-3}), ~15Myr, A4V, UCL moving group in Sco Cen association.

CO detection by APEX and ALMA (Moor et al.). Mco~0.04 $\mathrm{M}_{\oplus}$ from optically thin $C^{18}O$.

New [CI] ALMA data of HD 131835

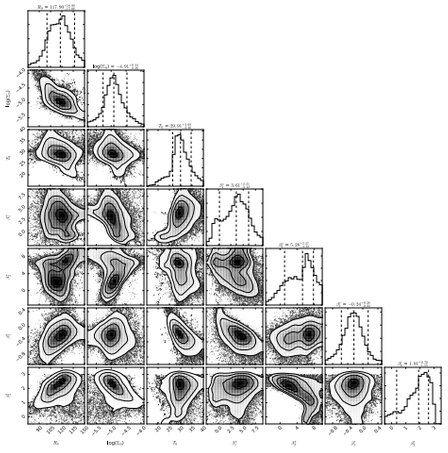
[CI] with ALMA around HD 131835



S/N~20
same PA and inclination as dust belt

Is there enough neutral carbon to start shielding CO?

Fitting the ALMA data: MCMC calculations on [CI] visibilities



Two models: 1) Gaussian - 2) Double power law

Good fit for HD 131835

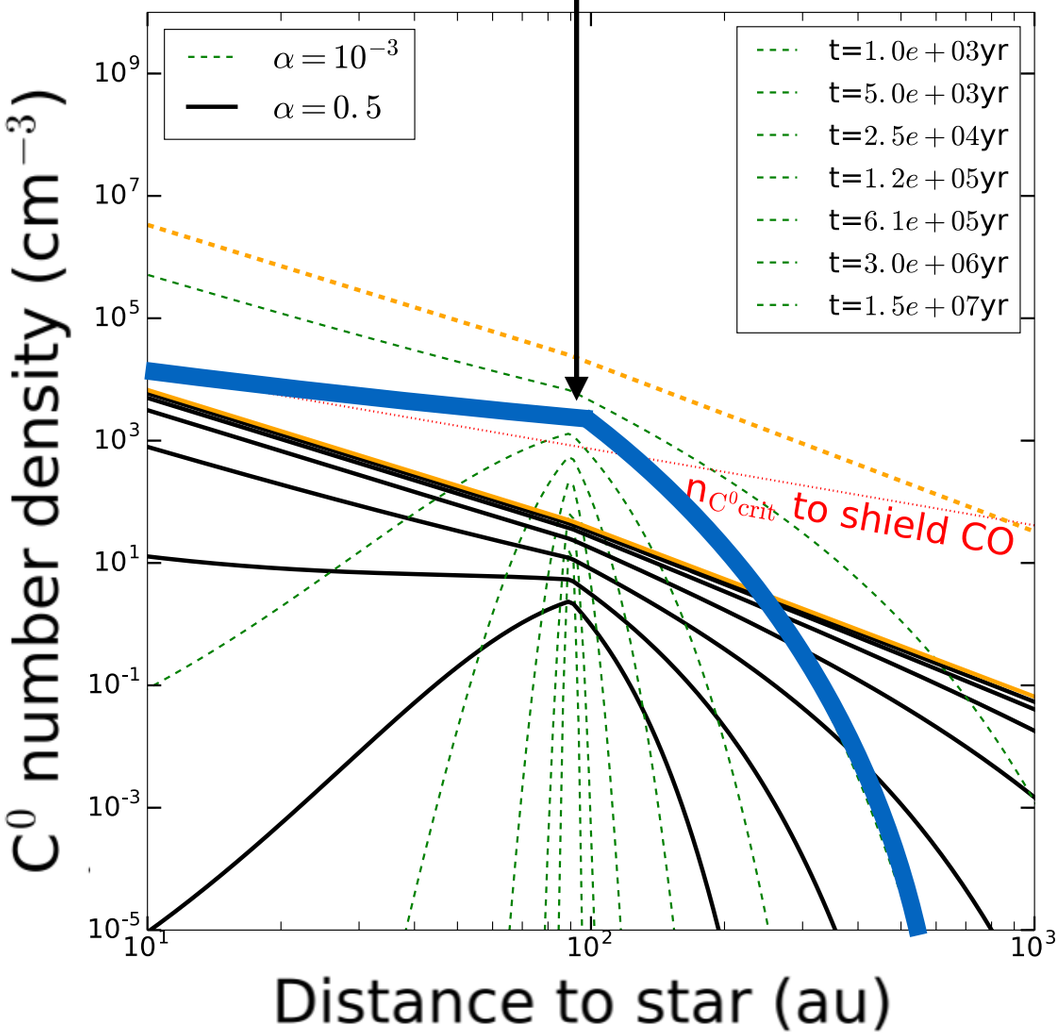
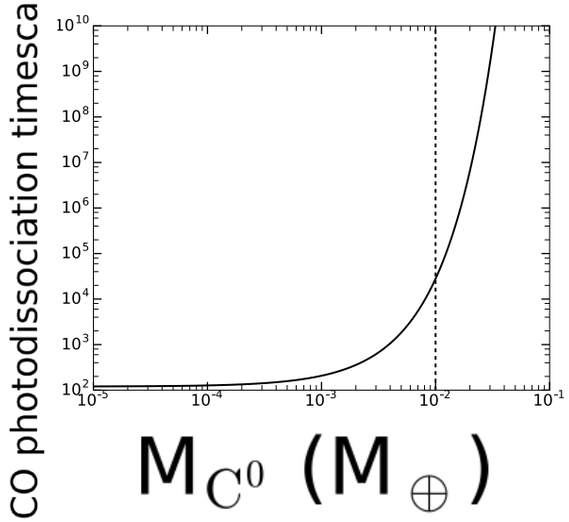


Table 2. Table describing the best-fit parameters of the Gaussian and double power law [CI] gas modelling using an MCMC method (see Sec. 4.2). We list the median ± uncertainties, which are based on the 16th and 84th percentiles of the marginalised distributions.

Parameters	Best-fit values	
	Gaussian	Double power law
R_0 (au)	97^{+17}_{-8}	118^{+19}_{-18}
$\Sigma_0/10^5$ (kg/m^2)	$1.7^{+2.1}_{-0.4}$	$1.2^{+2.2}_{-0.7}$
T_0 (K)	28^{+4}_{-4}	30^{+5}_{-4}
ΔR (au)	86^{+18}_{-10}	-
β_1^s	-	3.6^{+3}_{-3}
β_2^s	-	5.3^{+3}_{-4}
β_1^t	$0.9^{+0.4}_{-0.6}$	$-0.2^{+0.4}_{-0.3}$
β_2^t	$1.2^{+0.9}_{-0.6}$	$1.9^{+0.7}_{-1.6}$
i (deg)	-	$77^{+3.1}_{-2.4}$
PA (deg)	-	59^{+1}_{-1}
$v_\star$ (km/s)	-	$3.57^{+0.1}_{-0.1}$

$3x10^{-3} < M_{C^0} < 10^{-2}\ M_\oplus$



M_{C^0} high enough to shield CO

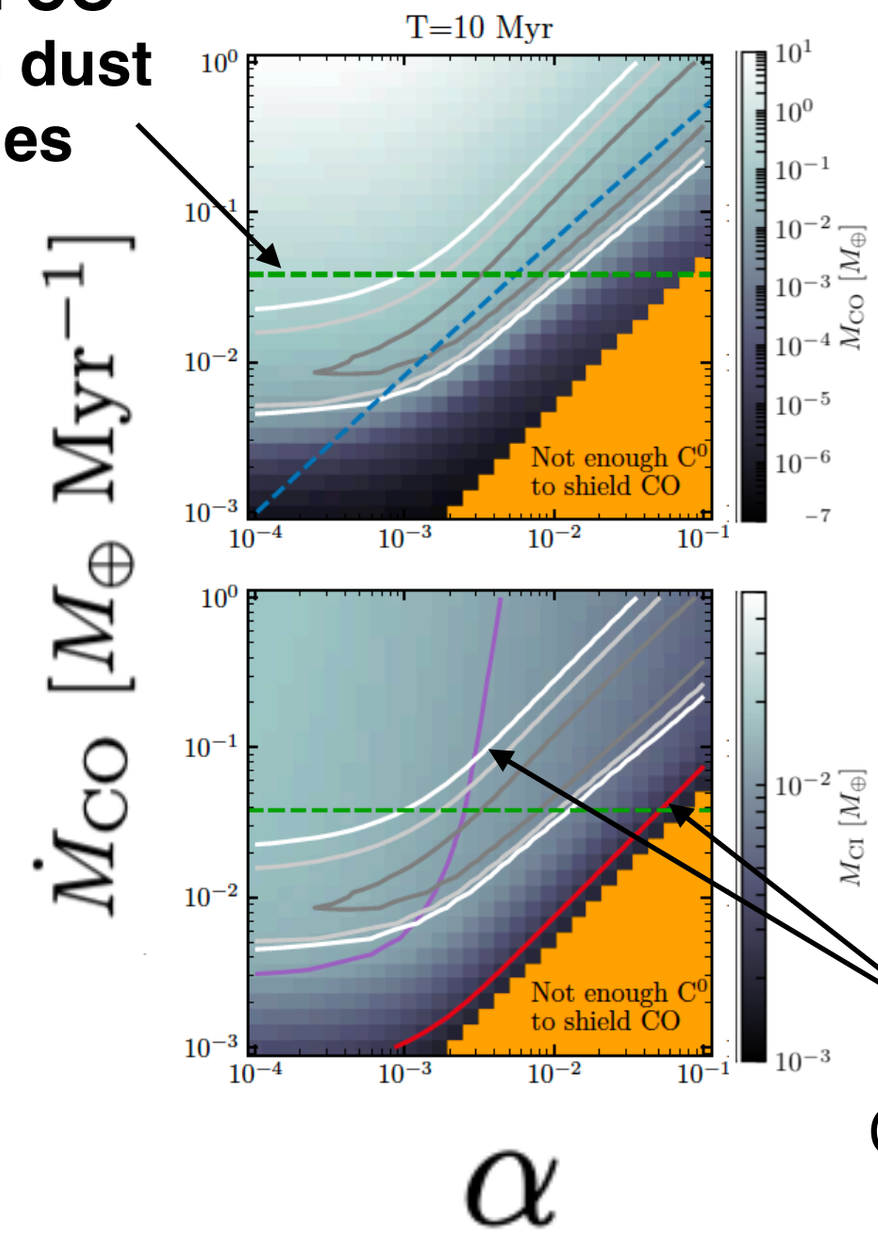
Finding the best fit model

Let's take Mco~0.04$M_\oplus$ (Moor et al. 2017) in HD 131835 and find the parameters of the model that can fit this CO mass

Constraint on CO input rate from dust belt properties

CO

C⁰



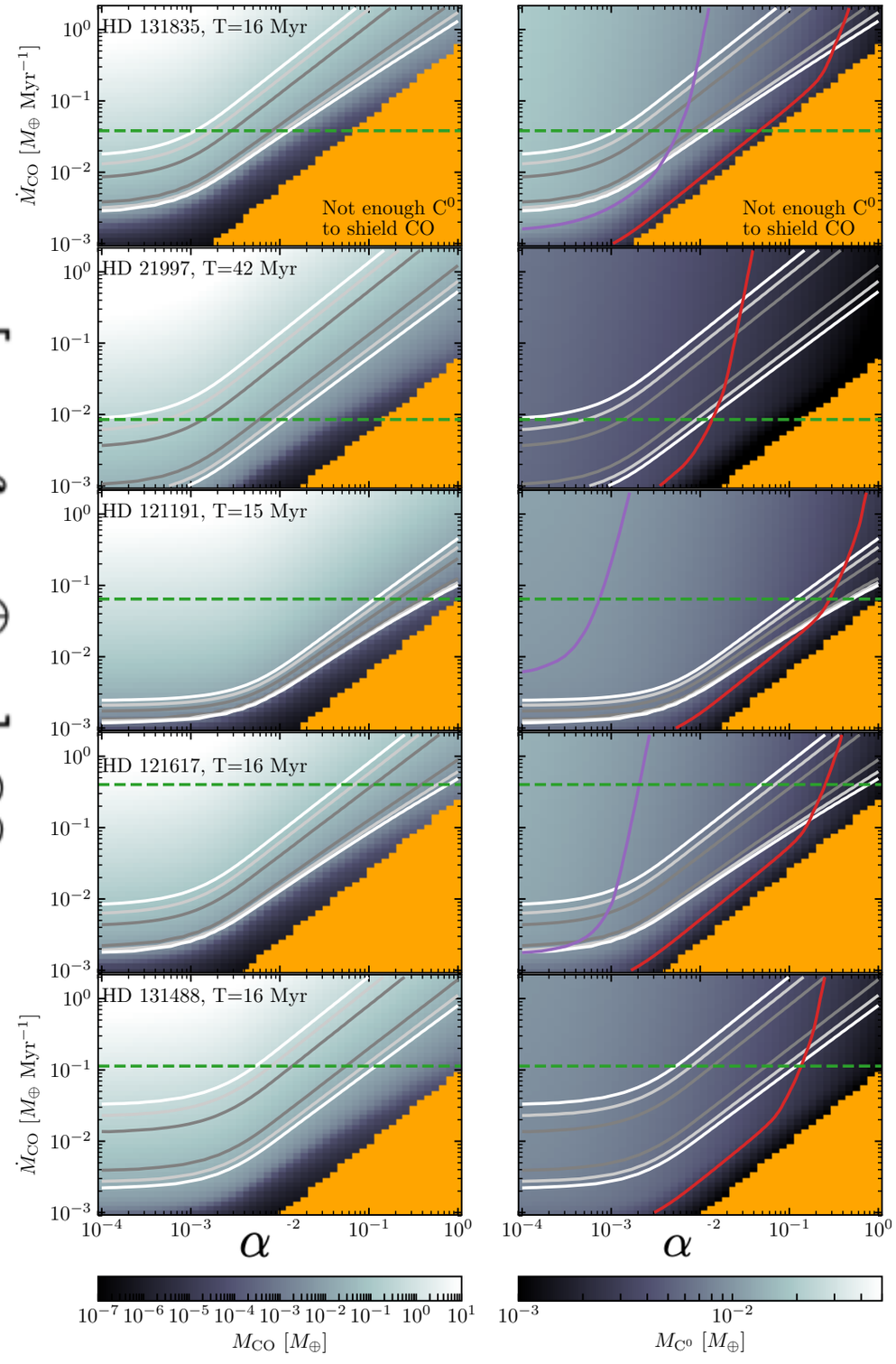
Best-fit for $\alpha \sim 10^{-3}$

But large uncertainties, we need higher resolution observations!

Observational constraints on C⁰ mass

Can all massive discs actually be of secondary origin?

CO C^0



Can we explain other massive CO discs?

YES!

And we can predict the [CI] emission level that is detectable with ALMA—> Let's do it.

Take-away points

- **Observational sample of debris discs with gas constantly growing and now close to ~20 systems with gas.**
- **[CI] is a promising tracer of gas and could probe the inner bits of planetary systems. Let's look for more [CI] and get high-resolution observations.**
- **Our model works well, we have a good understanding of the gas observations and can predict gas production rates around a specific belt.**
- **This model gives access to the composition of exocomets for the first time around main-sequence stars.**
- **Very massive gas discs in debris disc systems could all be of secondary origin and may not be primordial as suggested in the past but rather shielded secondary discs.**
- **Important question: How these massive gas discs that can live for tens of Myr are going to affect terrestrial planet atmospheres embedded in it? Good for habitability?**