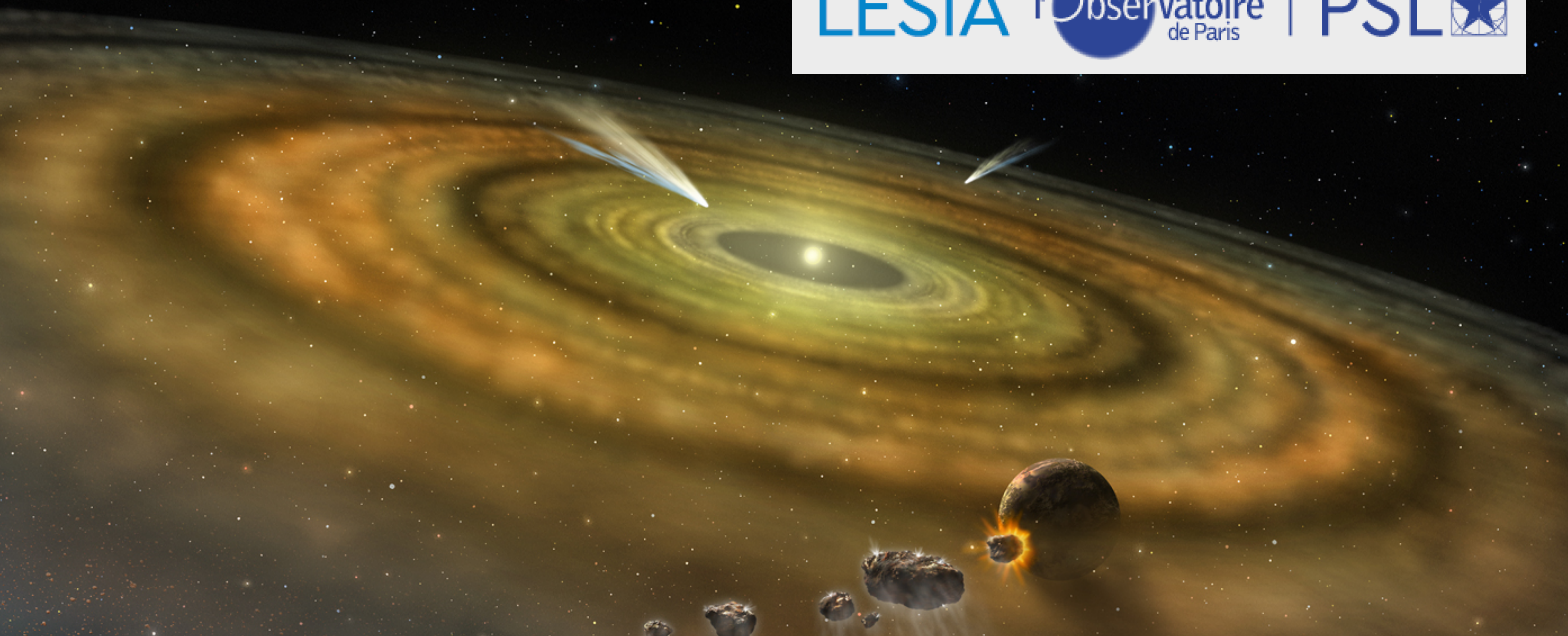


The importance of late gas disks for planet formation

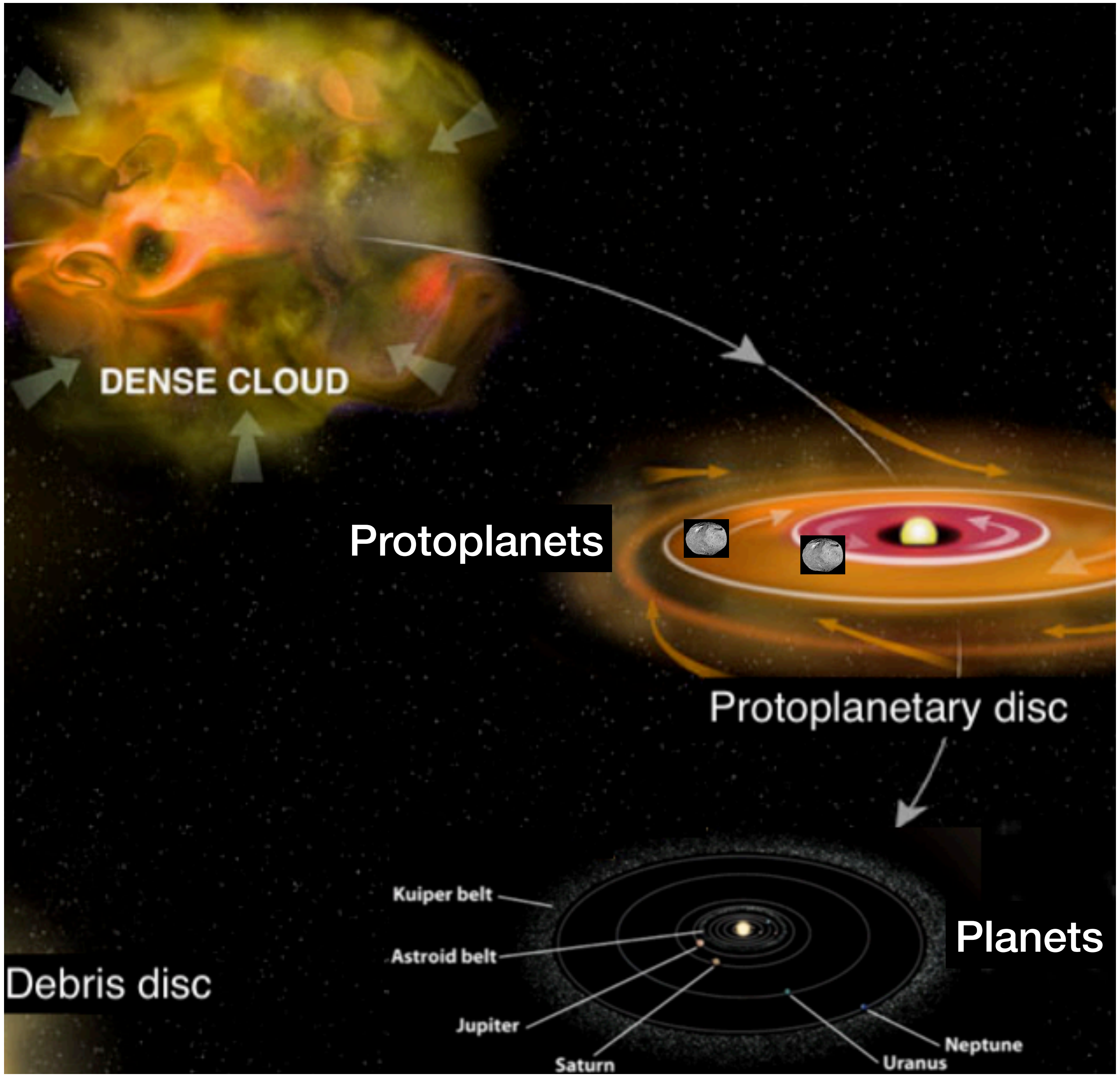
Quentin Kral, Astronomer
Paris Observatory

SOFIA workshop: Building the 2020-2025 Instrument Roadmap

23/06/2020

Circumstellar disks

Circumstellar disks: two distinct phases; 1) **Protoplanetary disk**, 2) **debris disk**



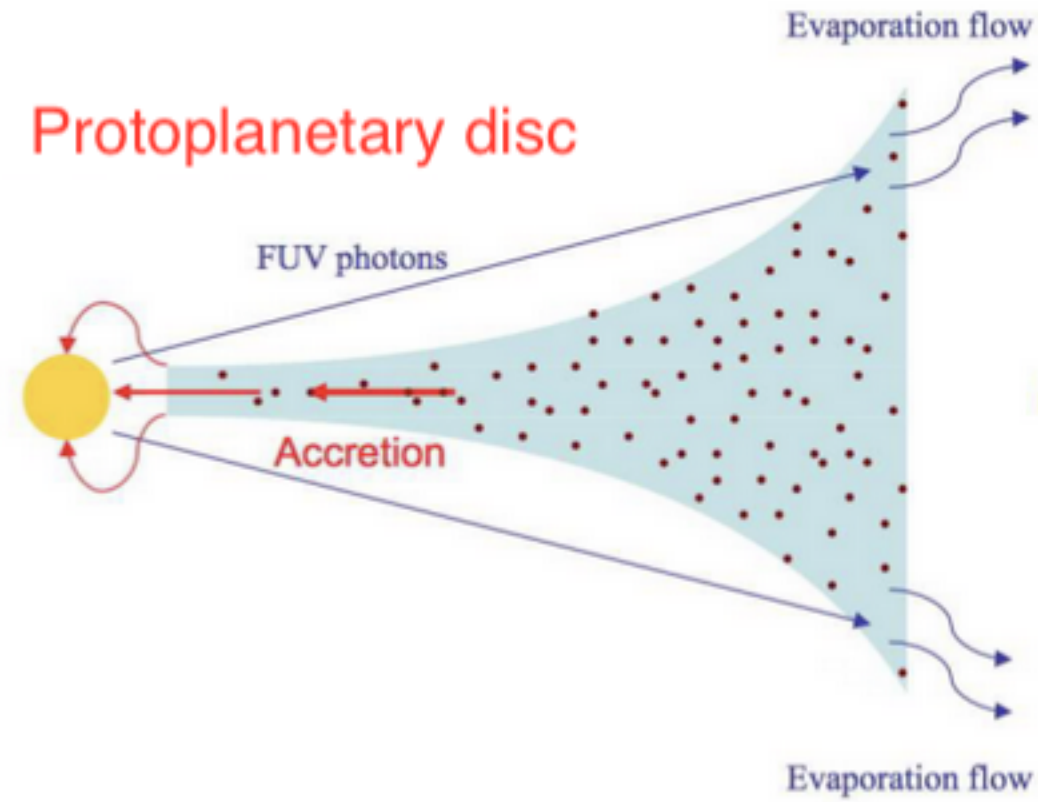
Planet formation happens

Obviously, the protoplanetary disk forges planets!

What about the later debris disk phase?

Circumstellar disks

1-10 Myr



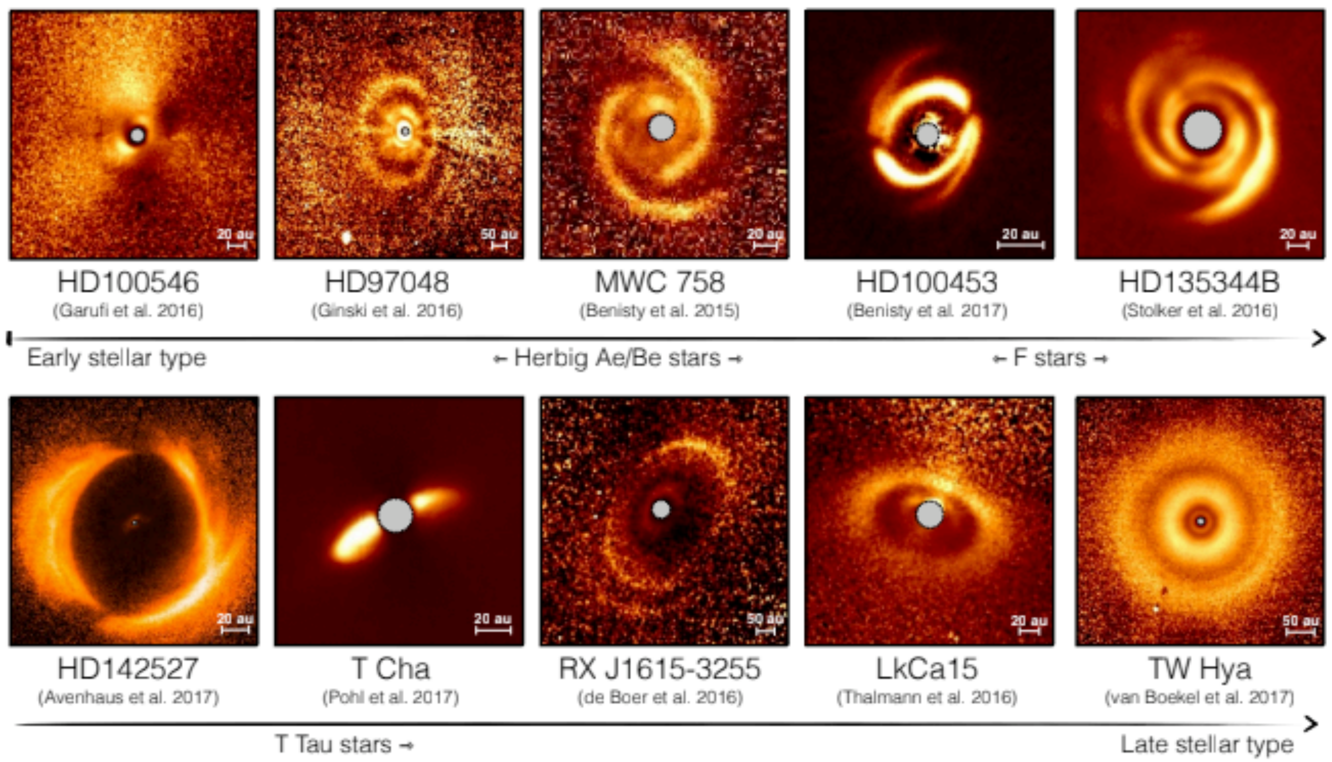
- **Young disks full of gas**
- **Disappear after ~5 Myr**
- **Disk in which planets form**
- **Composition of the disk fixes the composition of planets and their initial atmospheres**

10 Myr-a few Gyr

- **Remnant of planetary formation**
- **Can survive for Gyr**
- **New: Gas disks now well detected —> called late gas disks**
- **Late gas can be captured onto planets and affect the composition of planet atmospheres (Kral et al. 2020)**

Circumstellar disks

1-10 Myr



Garufi et al. 2017

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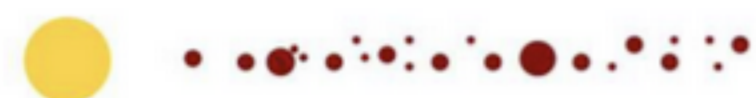
Debris disc



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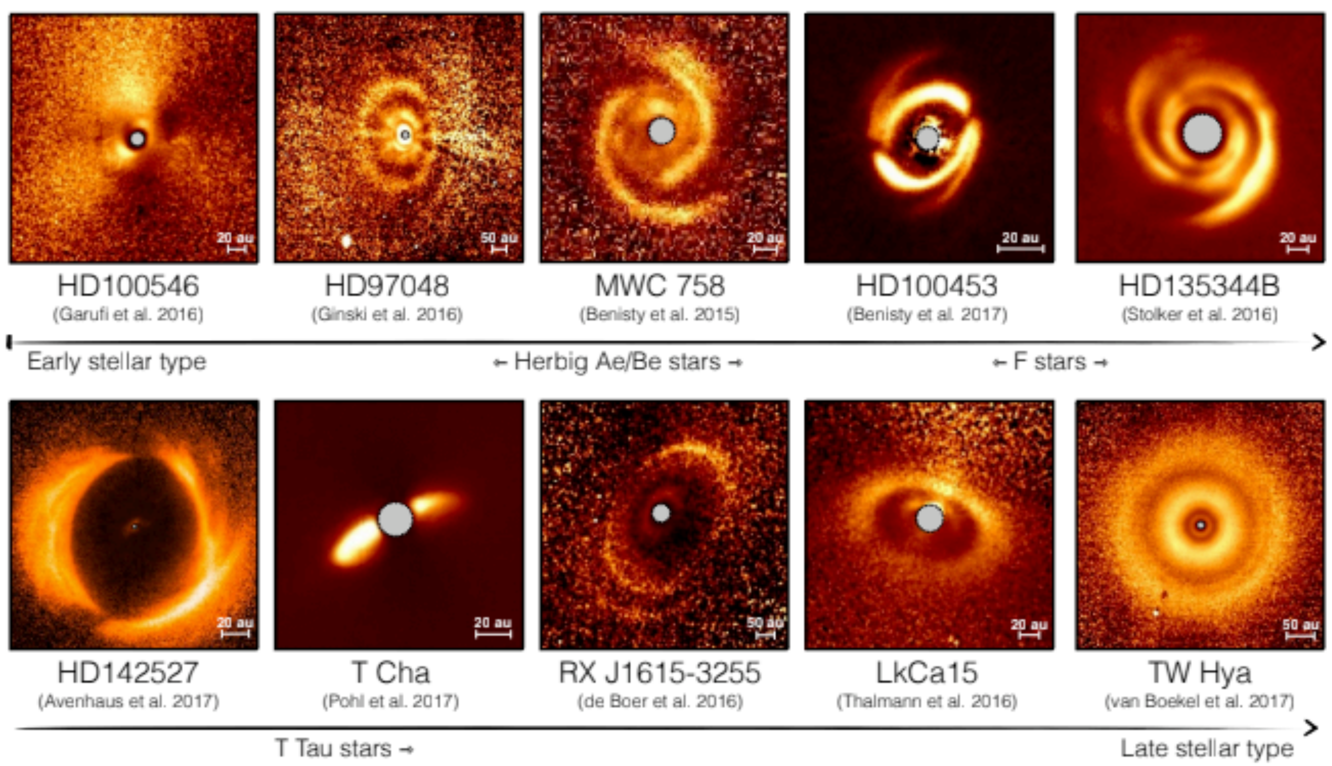

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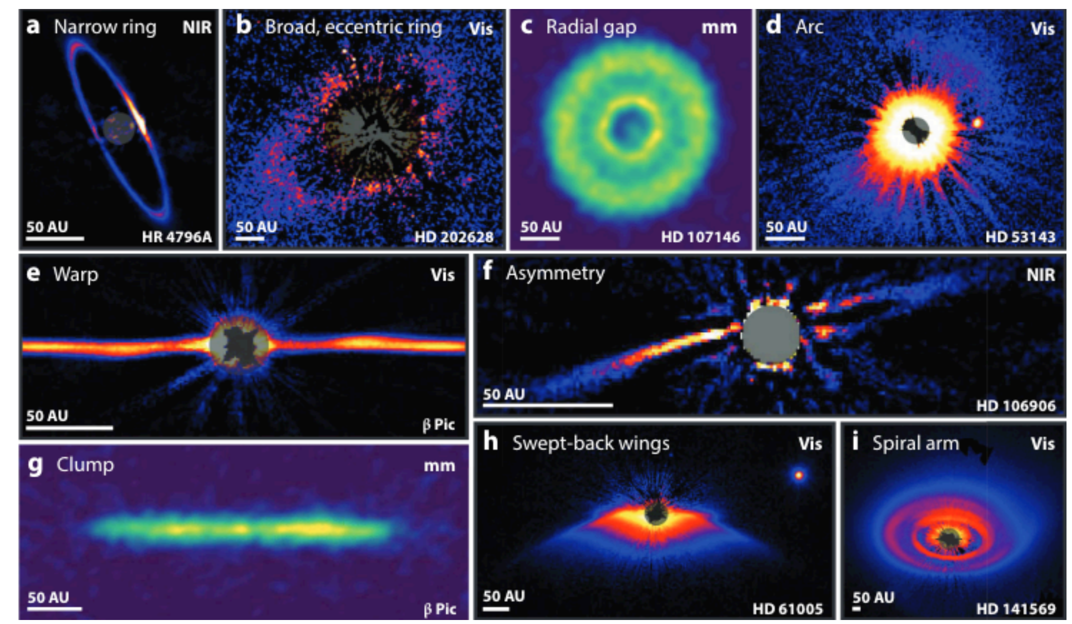

Hughes et al. 2018

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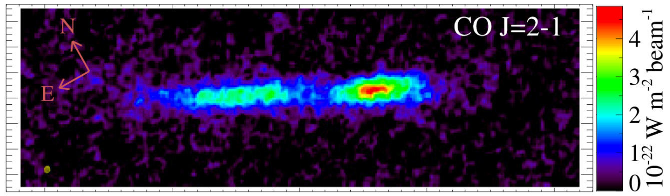
Late gas is ubiquitous

~20 late gas disks detected so far (some others soon to be added)



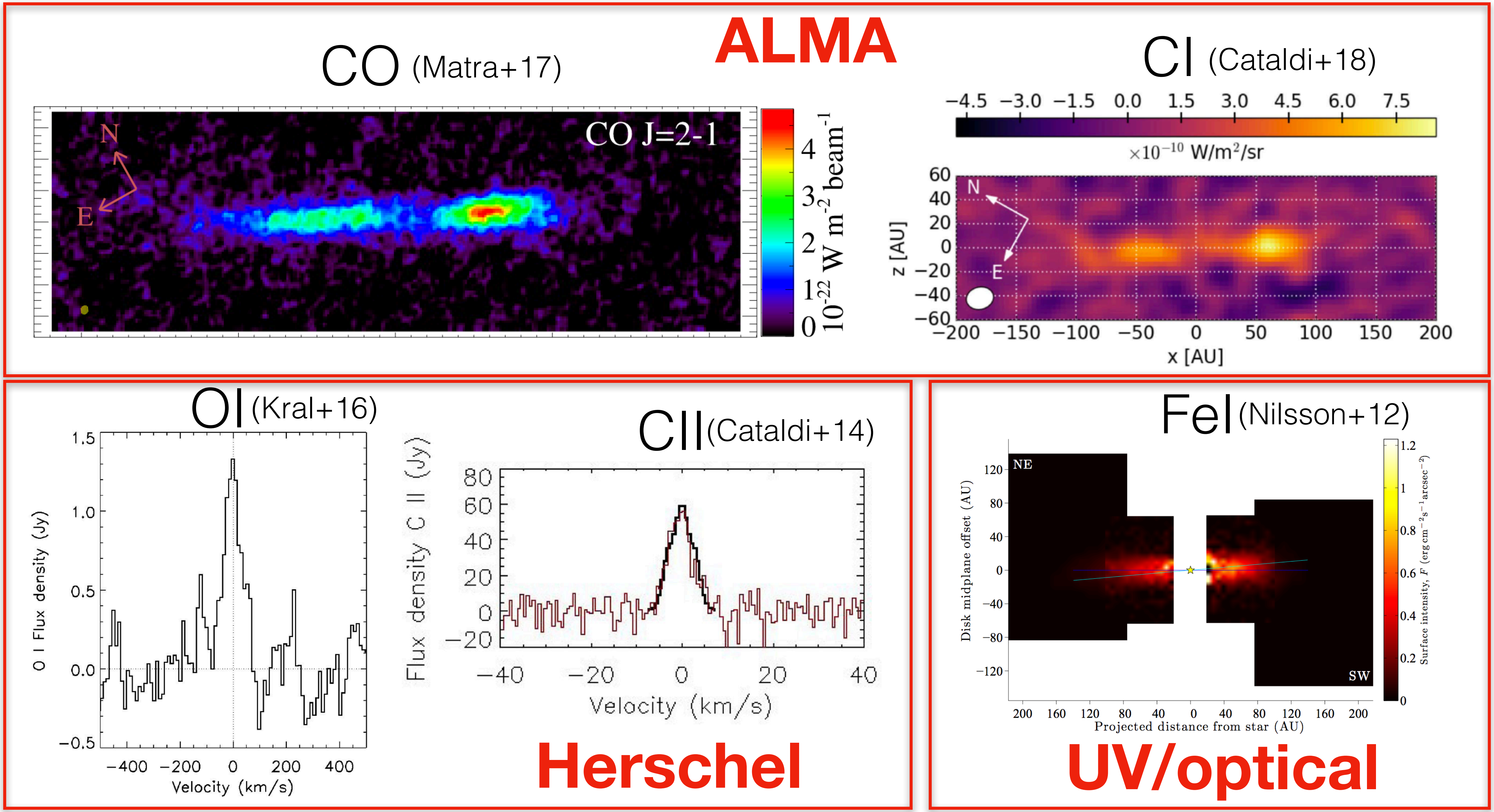
Gas is ubiquitous in debris disks (Moor et al. 2017):

- Volume-limited sample (150 pc) of bright A-star debris disks ($L_{IR}/L_{star}>5\times10^{-4}$) <140K between 10-50Myr: $69^{+9}_{-13}\%$ of this sample has gas.

- For disks with $L_{IR}/L_{star}>2\times10^{-3}$, they find they **all have gas** except HR 4796A.

Conclusion: Late gas disks seem to be the rule rather than the exception

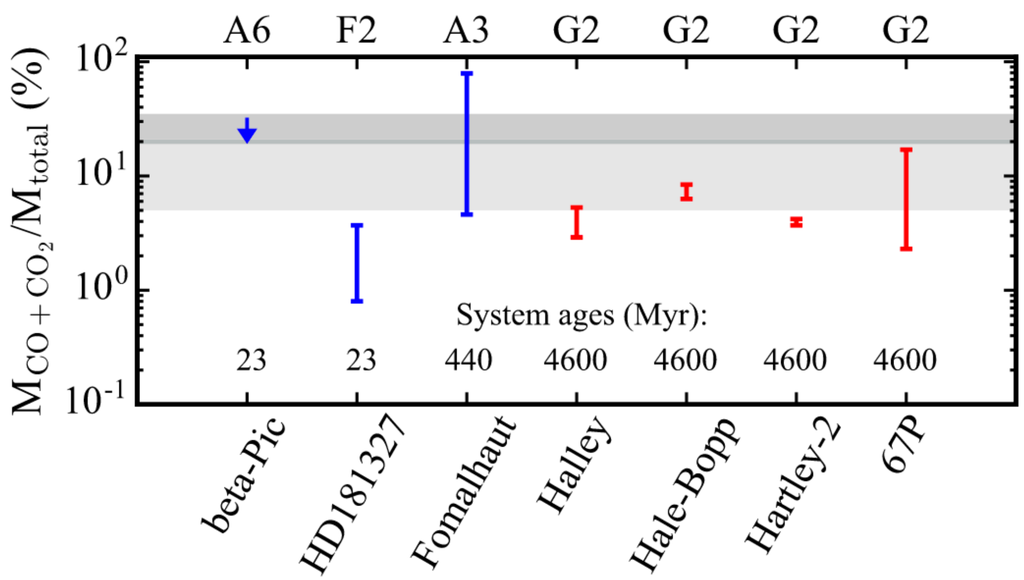
Gas in β Pic: What do we see?



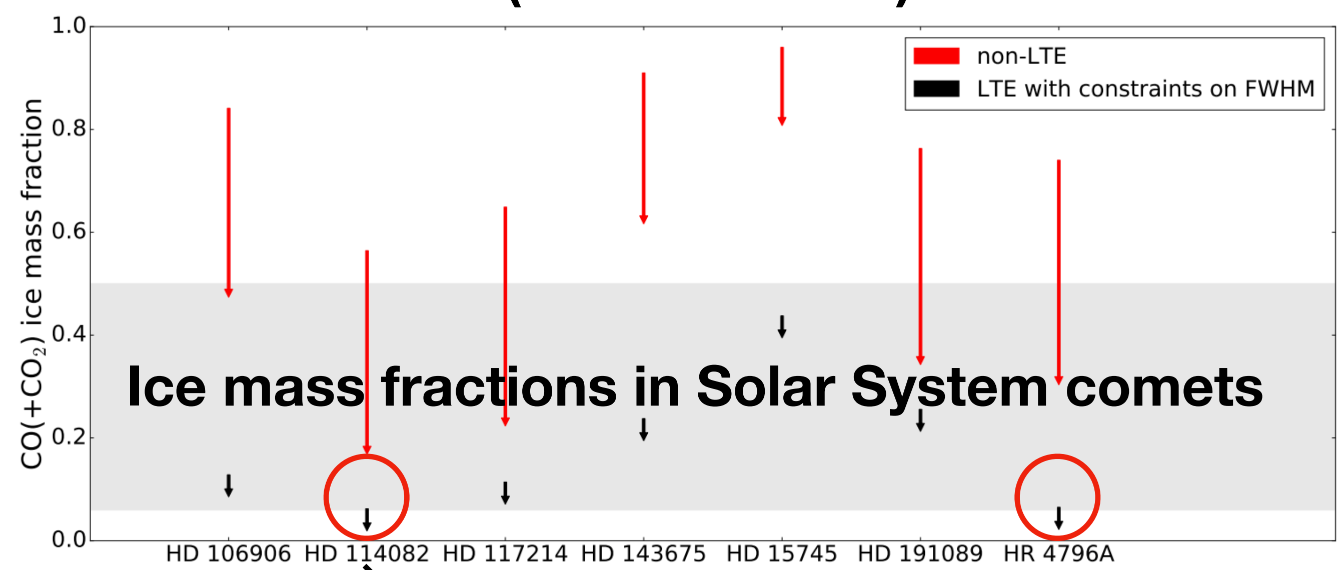
+ HI (Wilson et al. 2017) + other metals (Roberge et al., Brandeker et al., …)

Get exocomet composition from late gas disks

CO ice mass fraction from CO detections with ALMA (Matra et al. 2017)



CO ice mass fraction upper limits from non-detections in CO (Kral et al. 2020)



Can start investigating CO content in EXOplanetesimals around main-sequence stars

Upper limits already show less CO than in Solar System comets for some systems

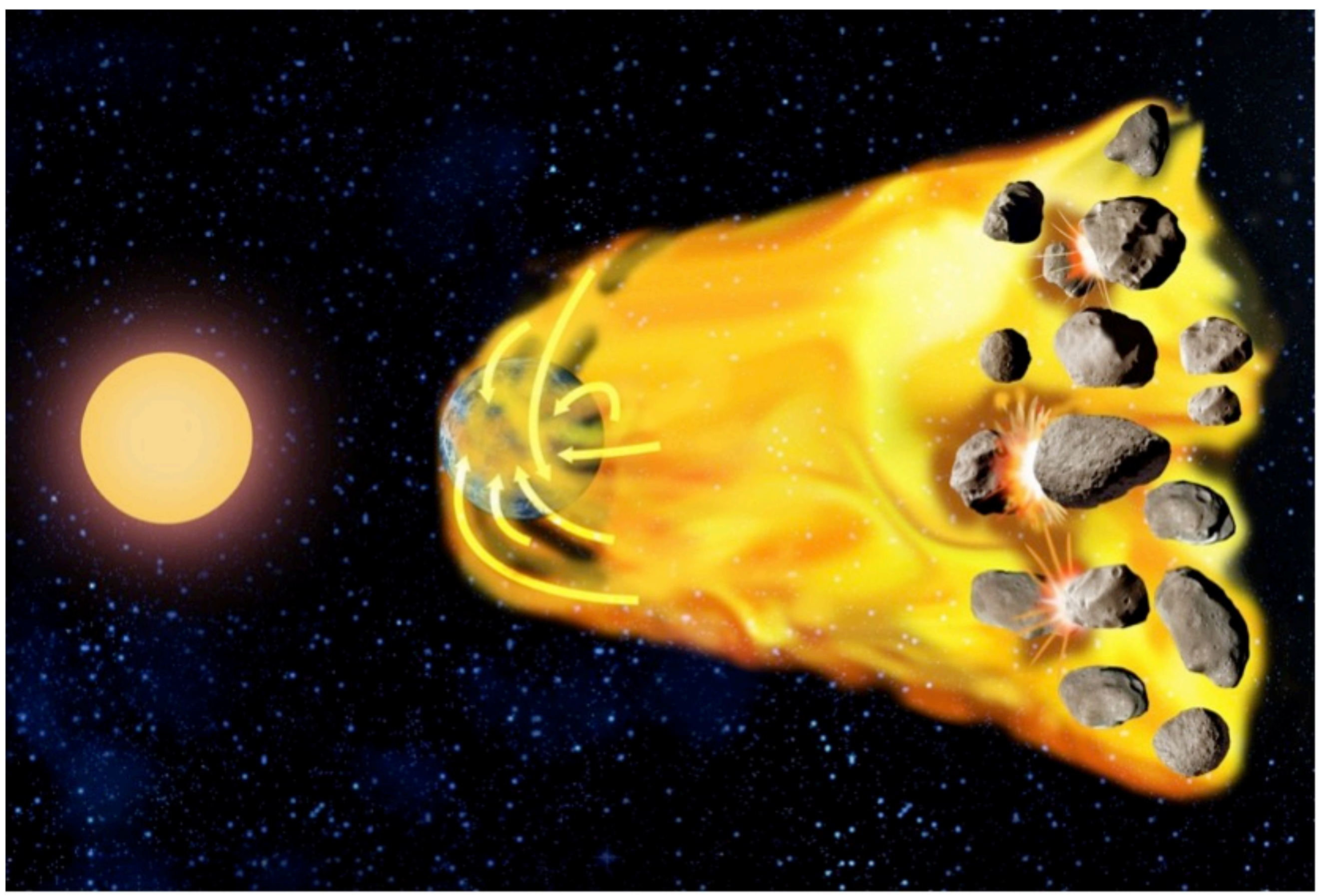
So far CO ice mass fraction seems consistent with range of compositions of Solar System comets except for a few systems with less CO.

Late disks very important for planet formation

nature astronomy 2020 LETTERS
https://doi.org/10.1038/s41550-020-1050-2
Check for updates

Formation of secondary atmospheres on terrestrial planets by late disk accretion

Quentin Kral, Jeanne Davoult and Benjamin Charnay



Kral et al. (2020): **Late gas (in the debris disk phase >10 Myr) captured onto planets and is dominant at setting up the final composition of terrestrial planet atmospheres.**

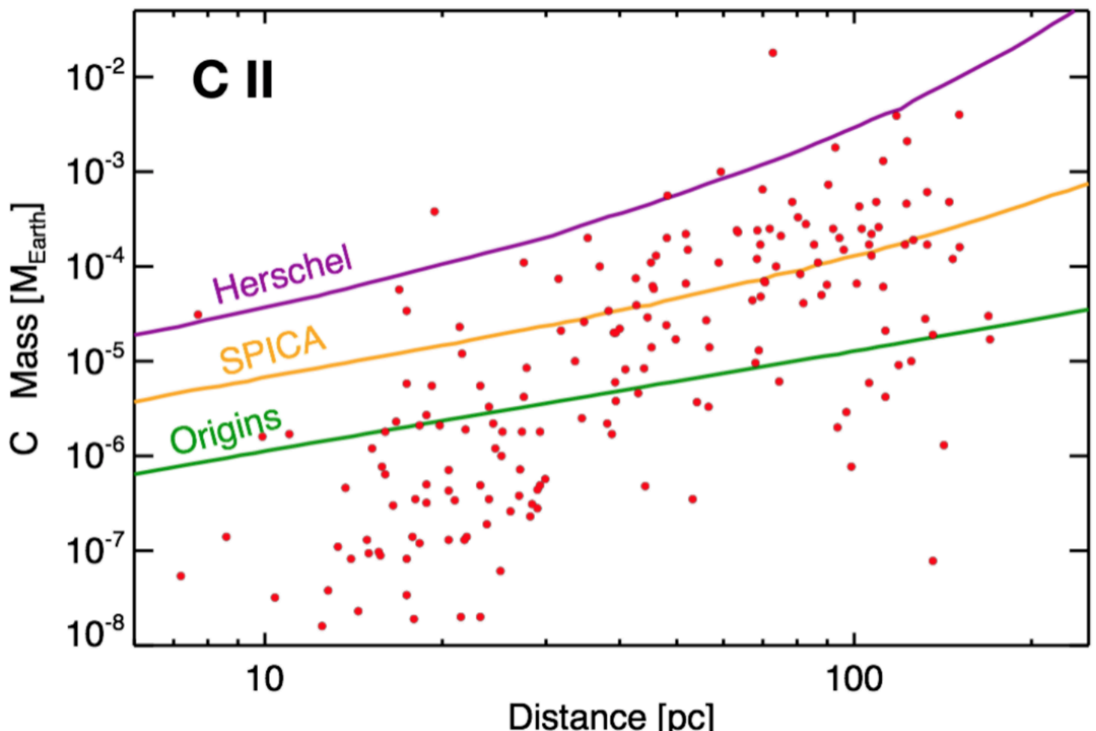
Late gas is composed of CO, CN, H2O feeding the planets for 100s of Myr —> could help the *development of the first bricks of life*.

Late gas in our Solar System could have played a role in planetary atmosphere composition?

Need for a refinement of our knowledge on the composition of the gas captured onto planets to estimate composition of atmospheres created by late gas disks.

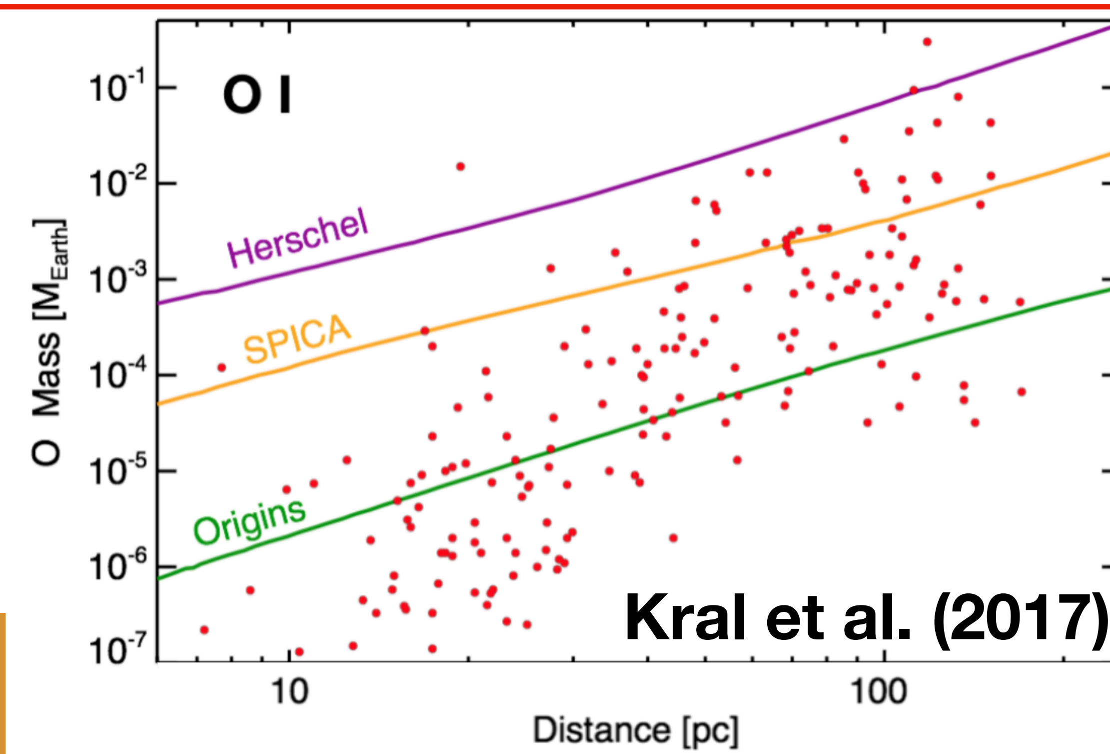
What do we need to go forward?

ALMA: Detection of ~20 disks with CO (and some with neutral carbon)
Herschel: So far 5 systems with CII and/or OI
-Would a **sensitive, high resolution, far-infrared spectrometer similar to the HIRMES** instrument concept help to go further?



Sensitivity (5 sigma, 1 hr):
Herschel ~ 7e-18 W/m^2
SPICA ~1.5e-19W/m^2
Origins ~3.5e-21 W/m^2

Ionized Carbon
(CII line at 157 microns)



Oxygen
(OI line at 63 microns)

Instrument with far-IR sensitivity between Herschel and SPICA could allow tens of new C or O detections and give access to more information on the gas composition in late gas disks —> improve our knowledge on how it impacts planet atmospheres and how gas is released and evolves.

Why is it interesting to go to far-IR?

ALMA
CO
CI
CN?

Complementarity

far-IR
Hirmes-like
Instrument
OI
CII

Needs synergy between far-IR and ALMA to get**:**

- True **carbon mass** (neutral+ionized carbon)
- **Electron** density (main colliders in late gas disks)
- Find out about whether **water** is released from planetesimals and captured by planets
- Get **C/O ratio** —> could affect C/O ratio in atmospheres of giant planets
- Get **right composition** of disk gas that is captured by terrestrial planets —> can form new atmospheres on terrestrial planets —> continuous delivery of volatiles for 10-100s Myr is **favorable to life**?

An instrument similar to the HIRMES-like concept would provide a strong push to our field and would pave the way to potential future long term missions such as SPICA (>2032) or Origins (>2035).

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WATER

From OI+CII+CI+CO detections: get H_2O-to-CO ratio

Using this technique, Kral et al. (2016) find low-water content in β Pic (confirmed recently by observations, Cavallius et al. 2019)

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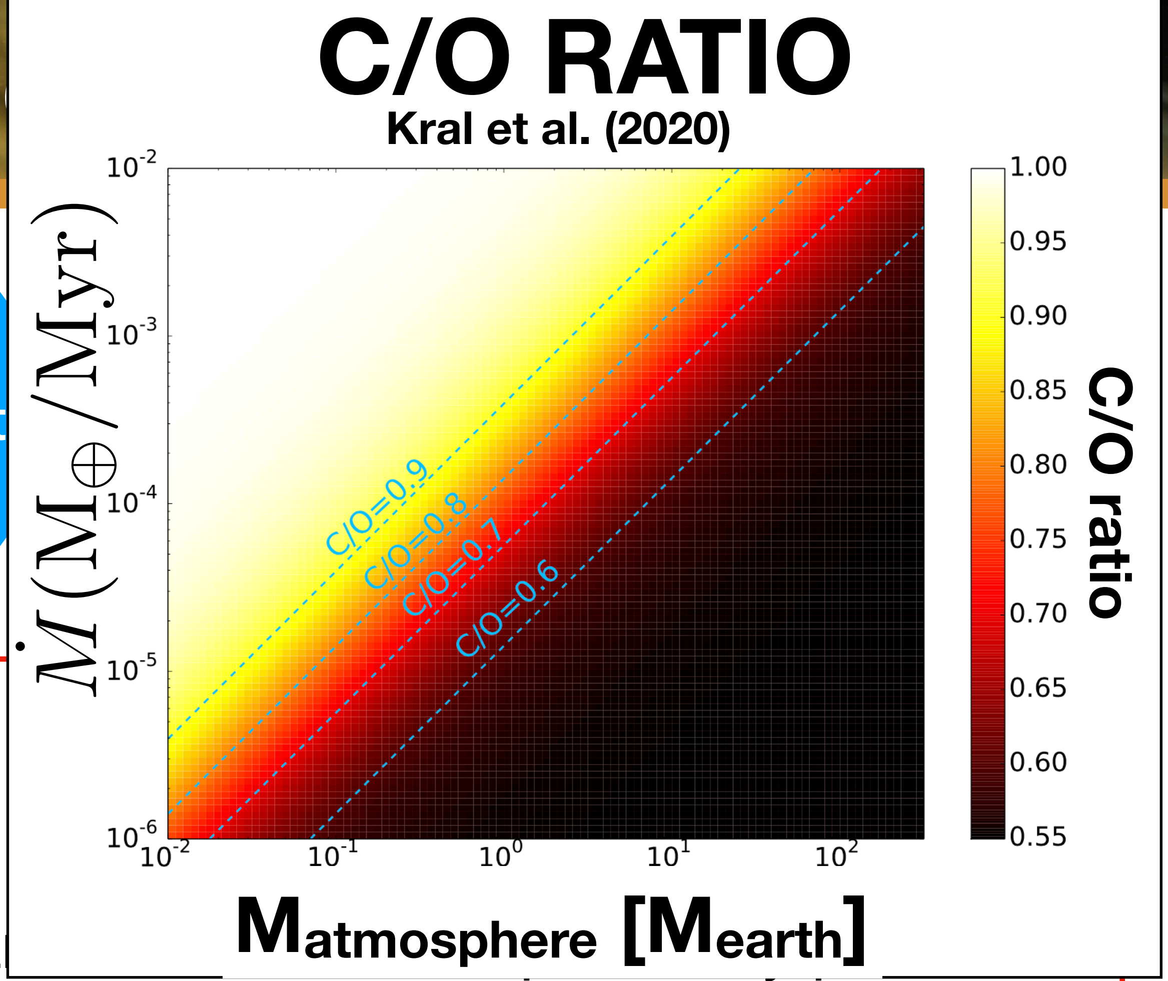

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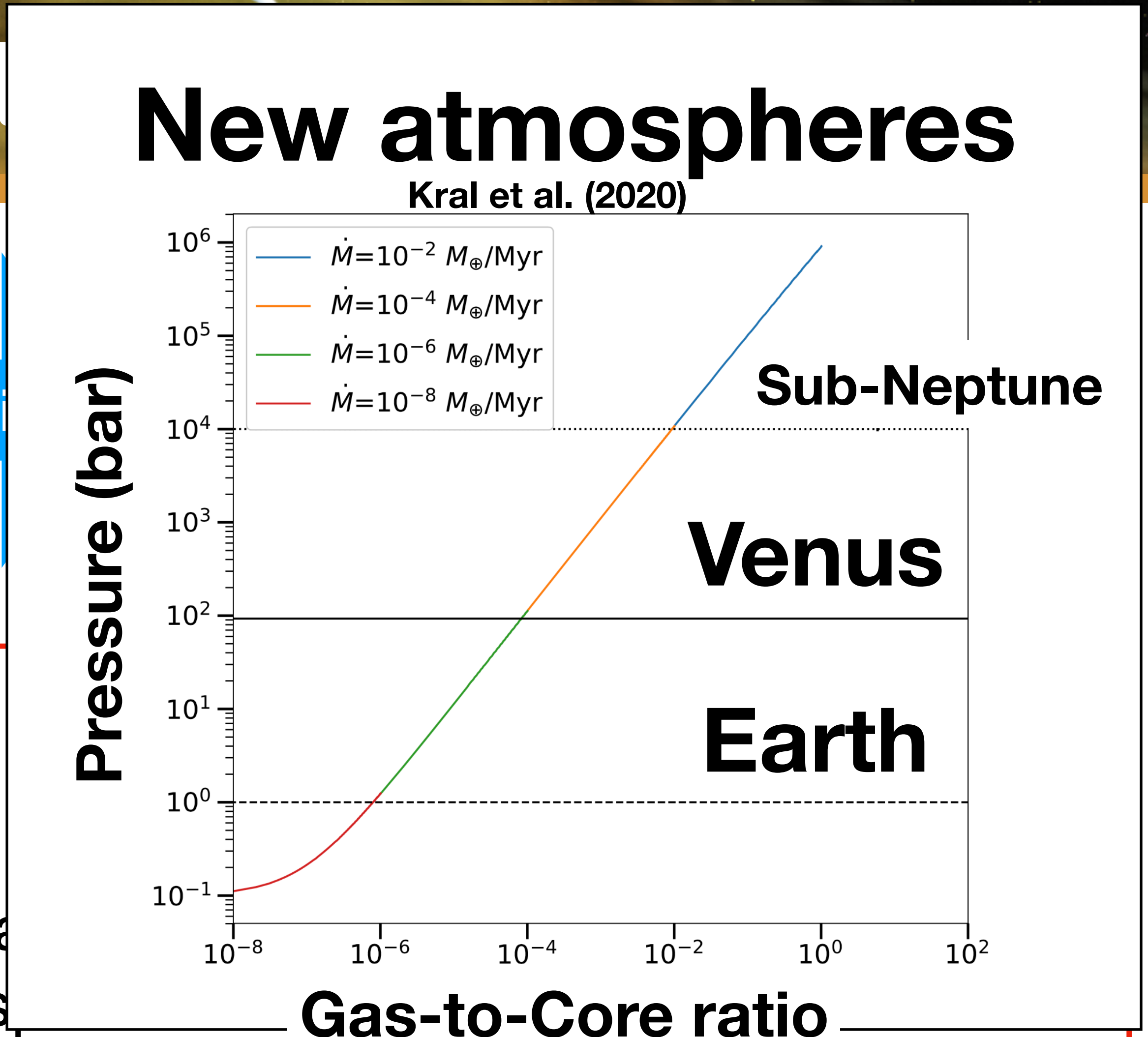

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Broad Perspectives

Now (mm/sub-mm):
ALMA will continue targeting **C^0, CO and may find CN** (or some surprises) by going deeper.

far-IR:
Could detect 10 to 100s of systems with C^+ and O
-*HIRMES-like* *(between Herschel and SPICA sensitivities)*: could detect **tens of systems with oxygen, ionized carbon at high spectral resolution (which would give spatial info to follow gas evolution).**
-*SPICA/SAFARI*: Could detect **~80 of systems with carbon and/or oxygen but poor spectral resolution (no spatial info).**
-*Origins (OST-OSS)*: Could detect **hundreds of systems with carbon and oxygen, water, OH and spectrally** (+ spatially for the closest) **resolve them. Quantify water abundance in many systems.**

mid-IR:
-*JWST*: rovibrational transitions of **CO_2, H_2O and OH.** But depends on excitation provided by UV, IR pumping from the central star (need good models first). **Cannot make surveys**.

UV:
-*LUVOIR/LUMOS*: inventory of abundances of H, C, O, N, … spatially resolved maps, different ionization stages.

Radio:
-*ngVLA, SKA*: Would target **H, NH_3, OH.**

New far-IR mission much awaited to fill in the >20 yr gap between Herschel and a potential very sensitive spatial far-IR mission such as Origins.

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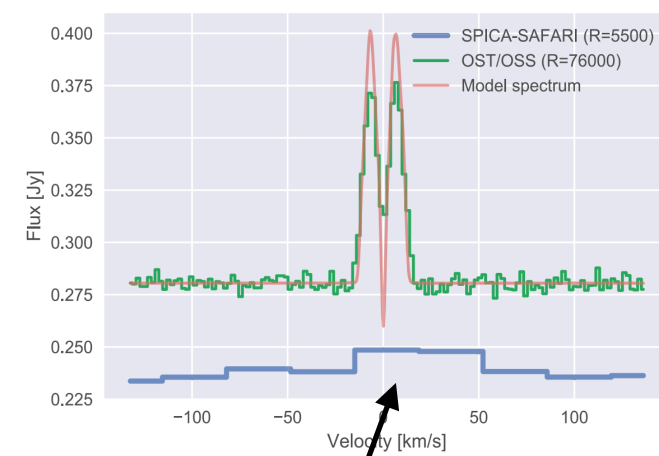

Figure 1.2-11 Simulated high-resolution spectra of the [OI] line using a model for Beta Pic, but shifted to a larger distance of 150 pc [Kral et al. 2016]. The noise level is relevant for a 1 hour observation with both OST/OSS and SPICA-SAFARI. This plot illustrates the importance of spectral resolution for detecting fine-structure far-infrared lines in debris disks.

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Take-away points

- Observational sample of debris disks with gas constantly growing and now reached ~20 systems with gas.
- Access to the volatile composition of exocomets for the first time around main-sequence stars.
- Late gas disks important for planet formation and can affect planetary atmospheres (C/O ratio of giant planets or create new secondary atmospheres on terrestrial planets) in a way that could bring volatiles for 10-100s of Myr that may be interesting for the development of life.
- Could be strong synergy between ALMA (CO, CI) and a new far-IR high-spectral resolution, high-sensitivity HIRMES-like concept (CII, OI)
- **Such new far-IR instrument would fill in the >20 yr gap between Herschel and a potential very sensitive spatial far-IR mission such as Origins.**