Toward a complete view of planet-forming disks with PRIMA

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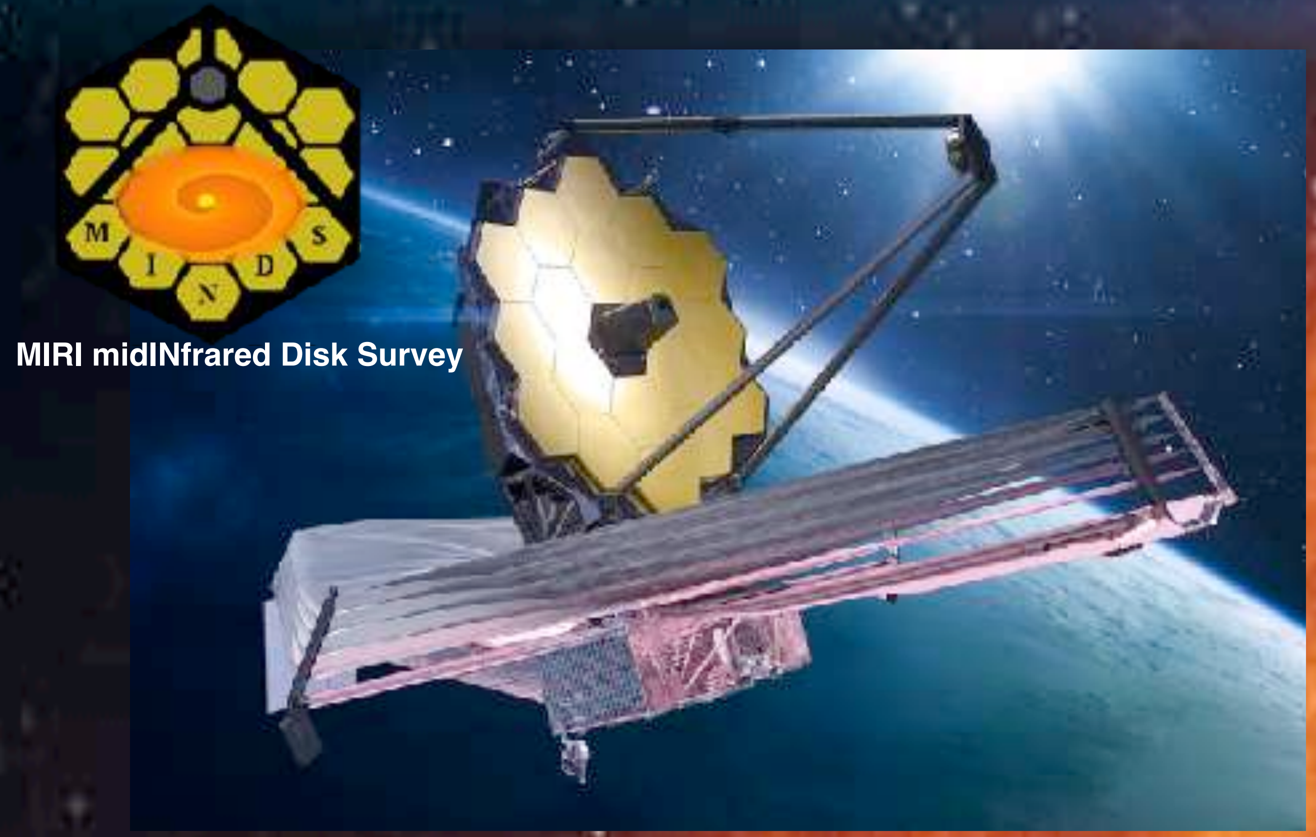
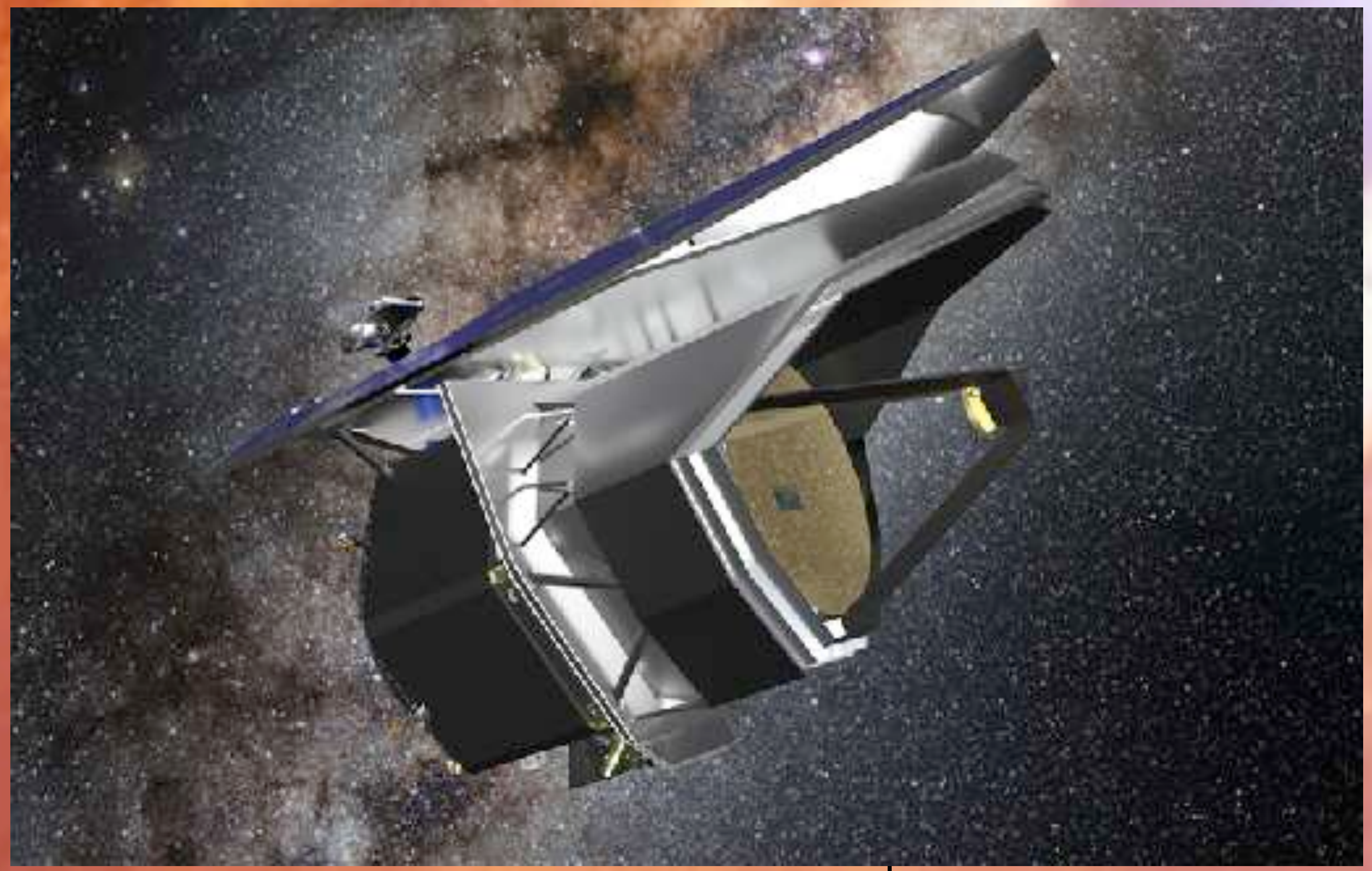
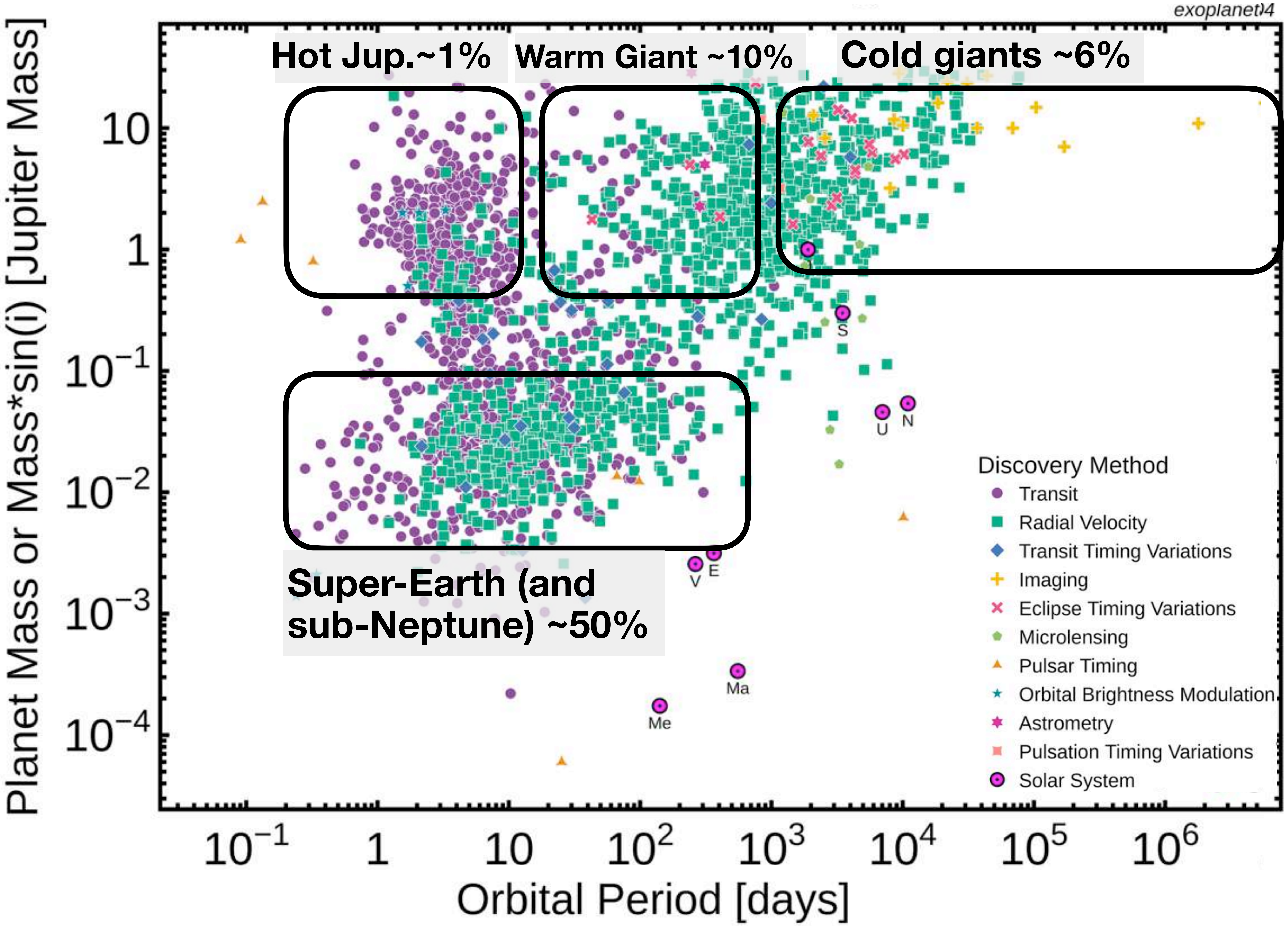




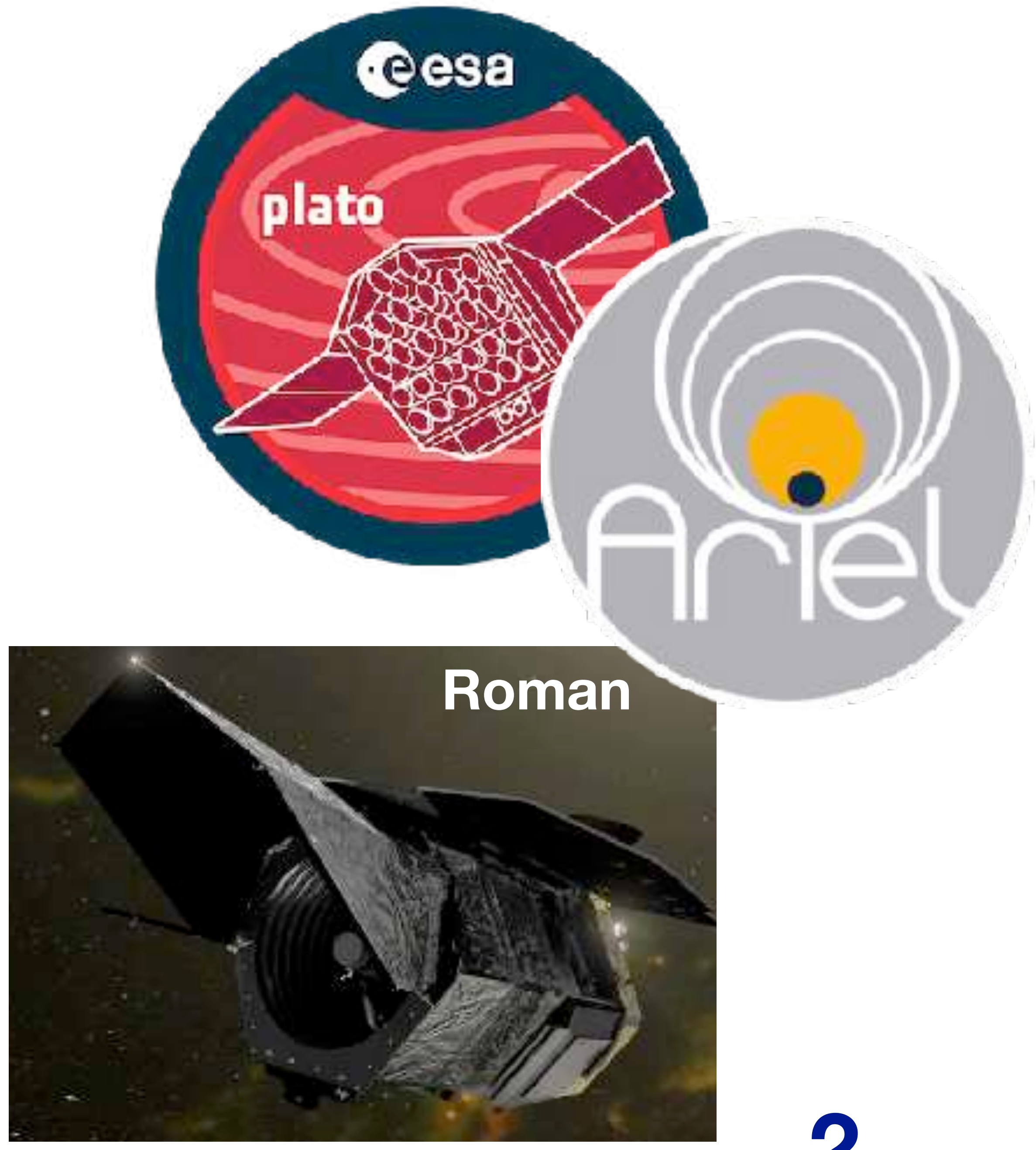
Prima conference, Marseille, March 31

Big question

What is the origin of the diversity and habitability of exoplanets?

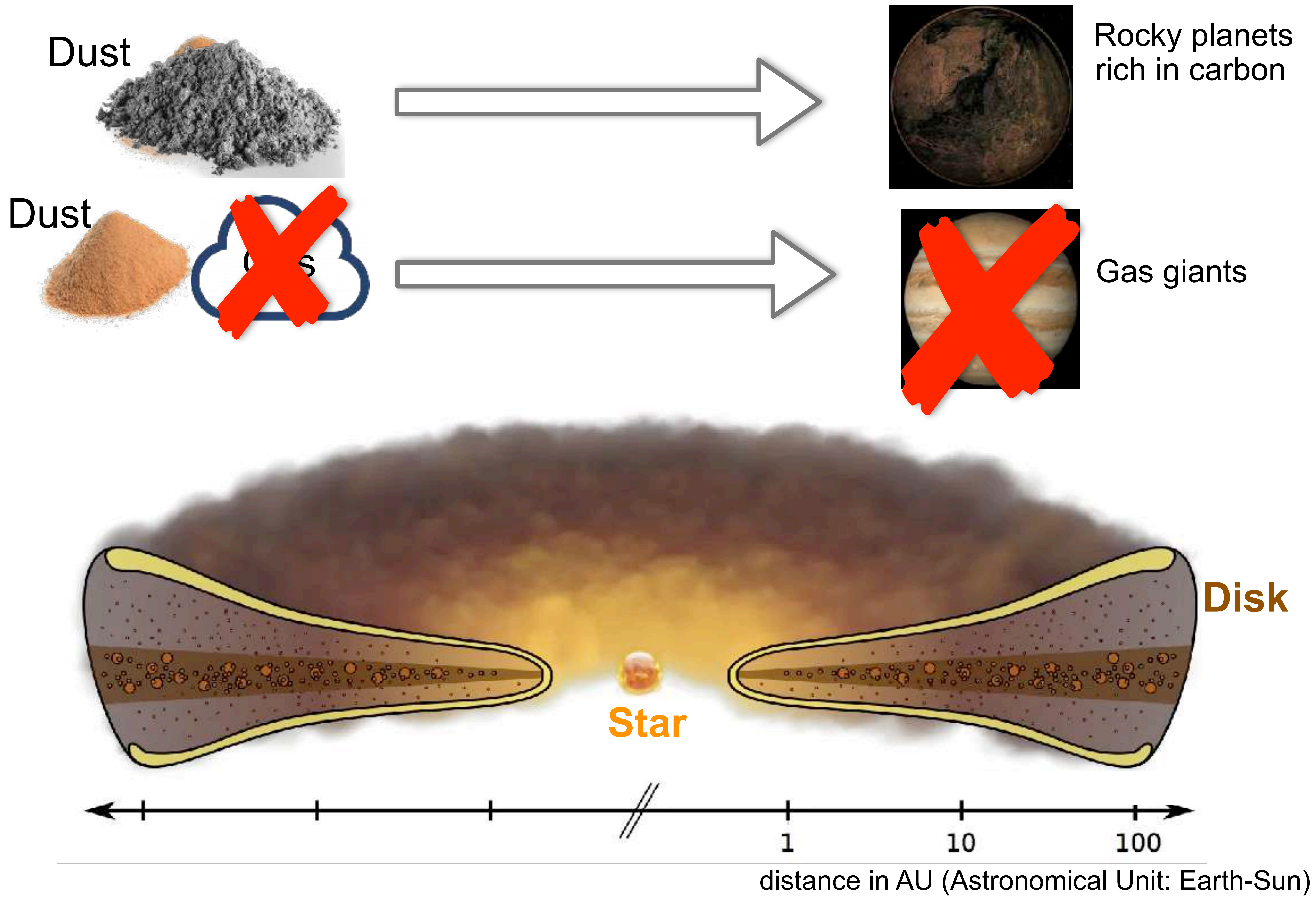


Census to be continued with:



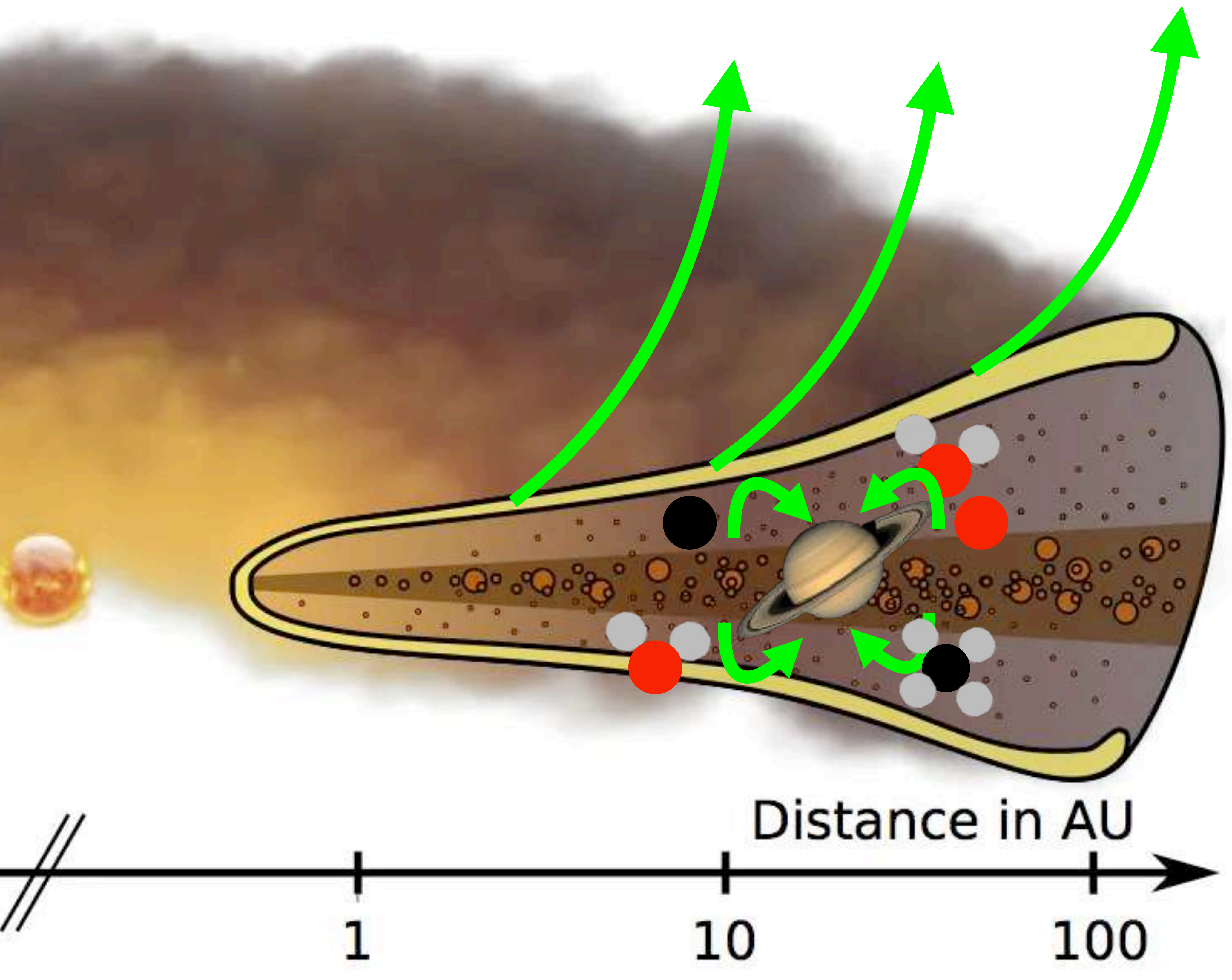
Disks: the birthplace of planets

Physical and chemical structure of disk determines which planet forms



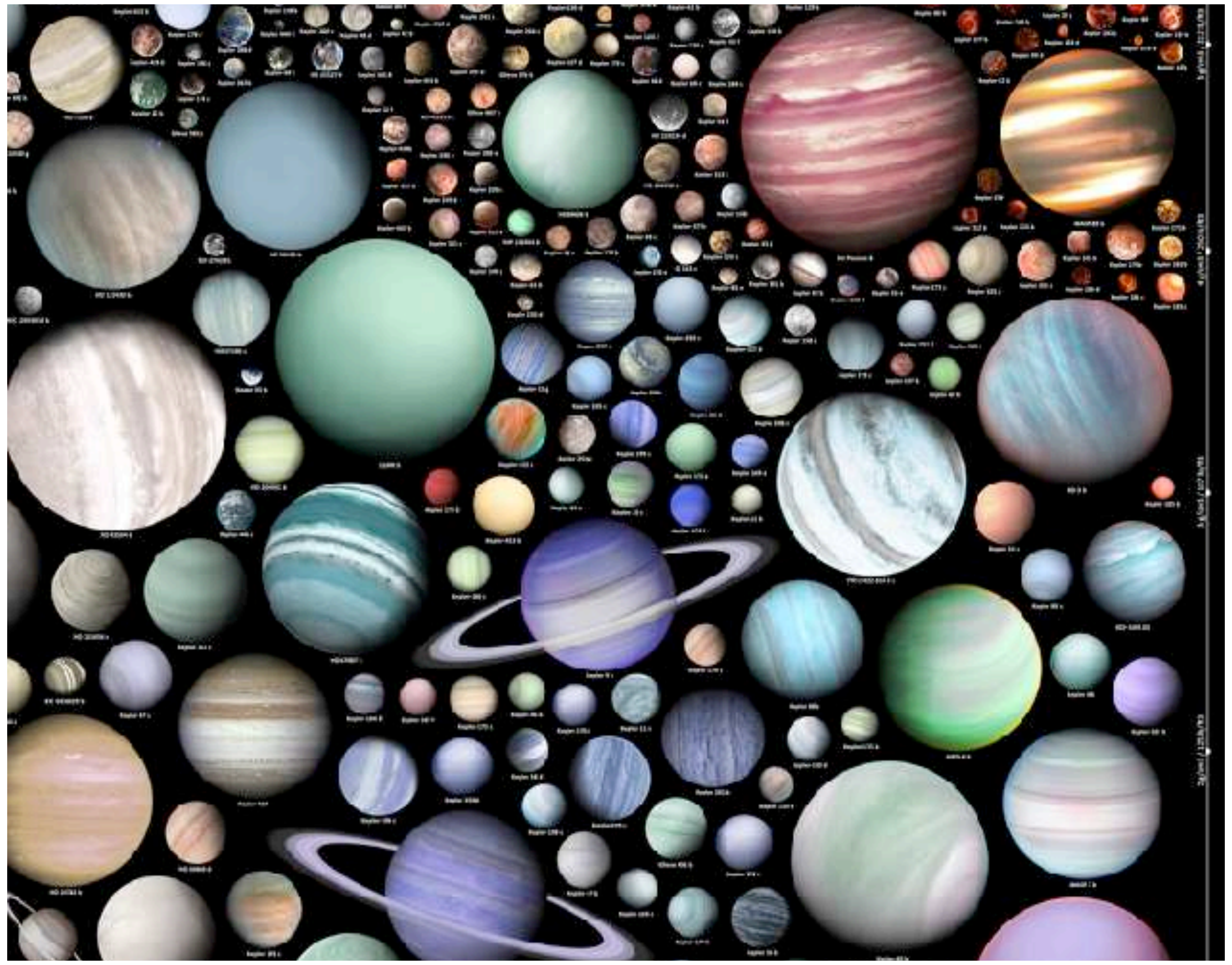
Challenge: linking exoplanet properties to their formation history

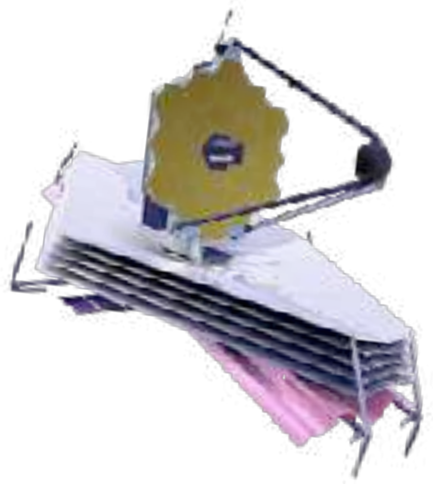
What is the physical, chemical, and dynamical evolution of disks?

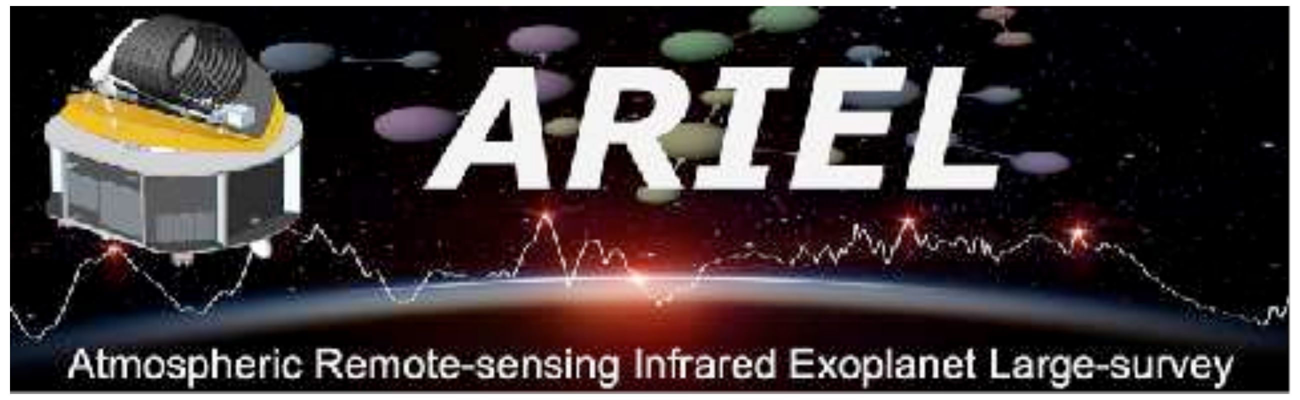


Planet formation models

End-product: populations of exoplanets







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The need for a panchromatic view of planet-forming disks

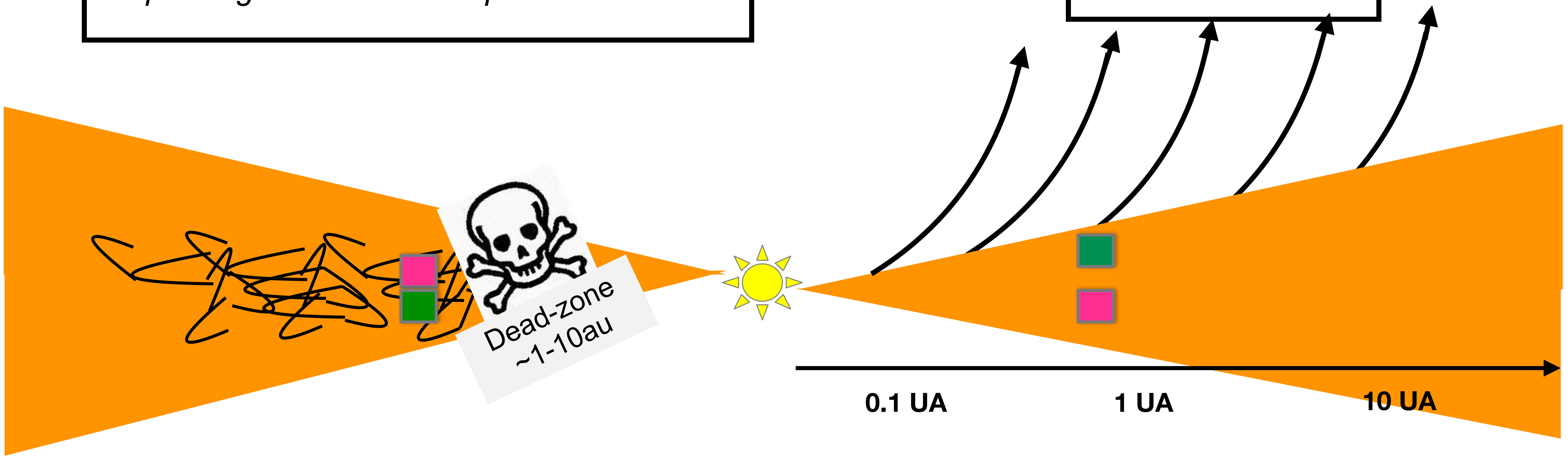
Linking exoplanet to disks: fundamental disk parameters

How the gas reservoir evolves?
How is angular momentum transported?

- Total gas mass remains poorly known even with ALMA
- Accretion-ejection processes controls the mass budget and all the steps of planet formation and migration!

Radial transport via MRI turbulence
= *paradigmatic model for planet formation*

Vertical transport
MHD disk-wind



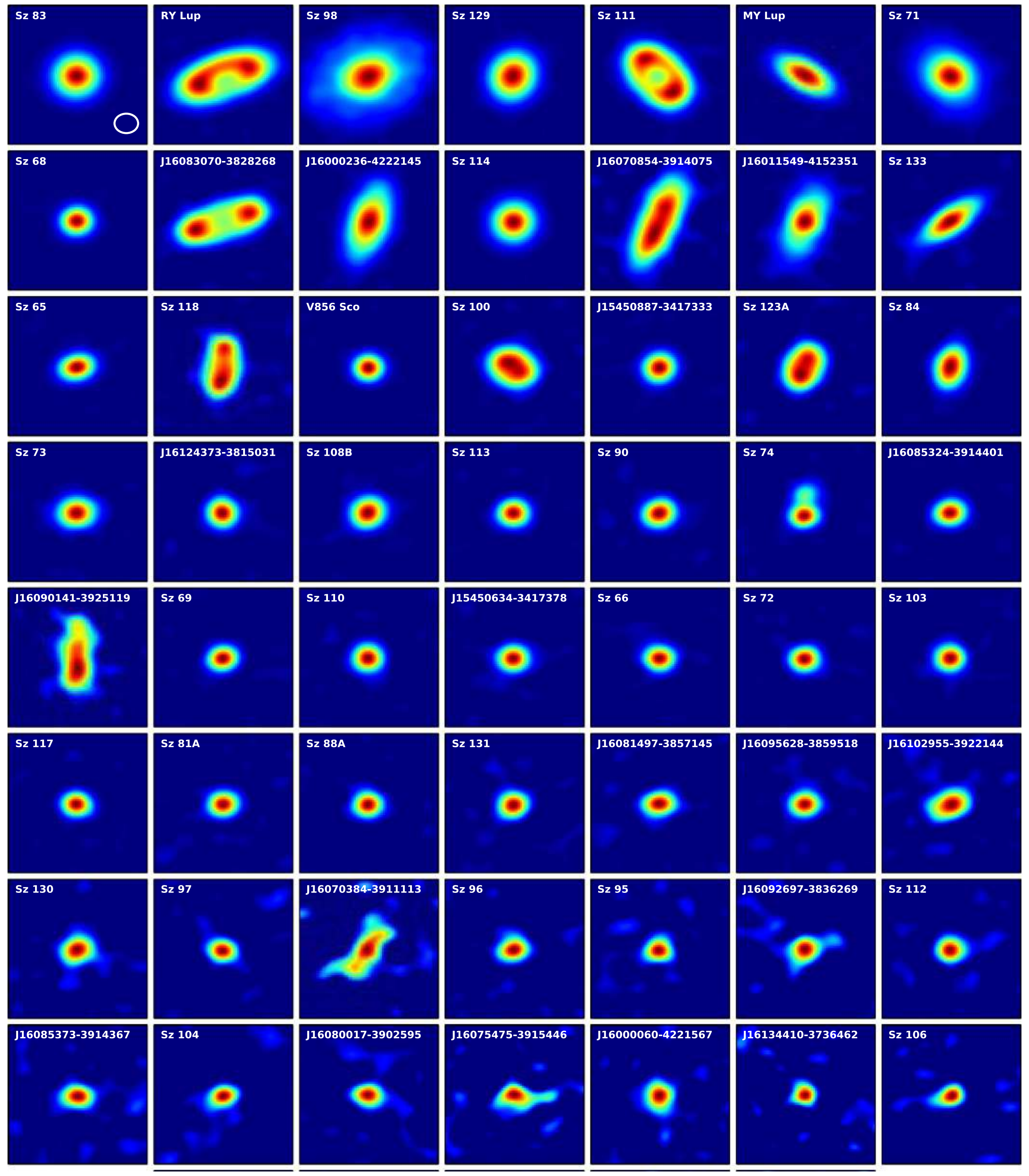
What sets the evolution of the disk mass?

Complete survey of dust emission in all nearby star-forming regions + accretion rate

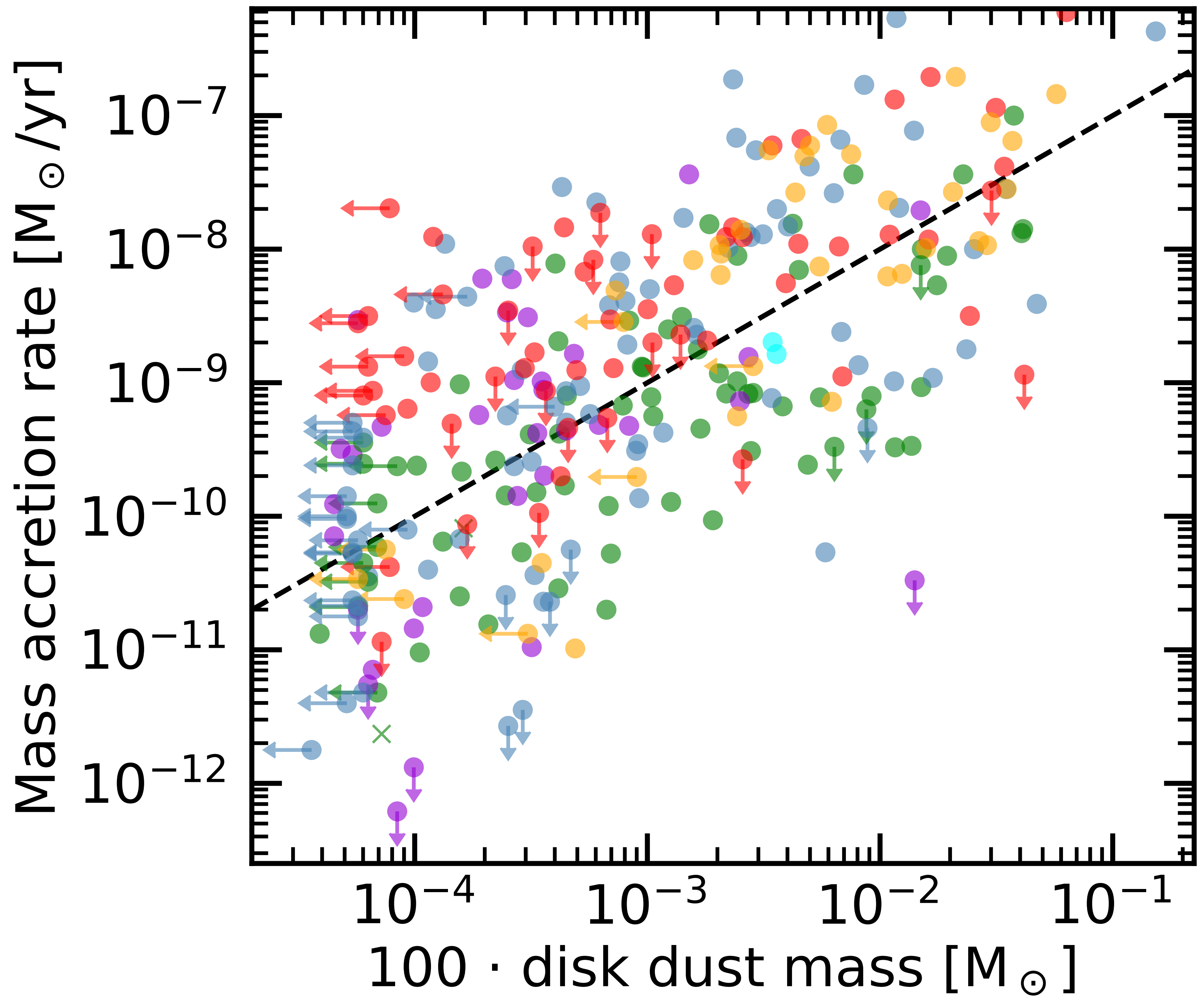
=> *first constraints on the mechanisms driving evolution*

=> *BUT fast pebble drift can strongly bias our gas mass estimates*

Dust mm emission in the Lupus disks



Ansdell+2013

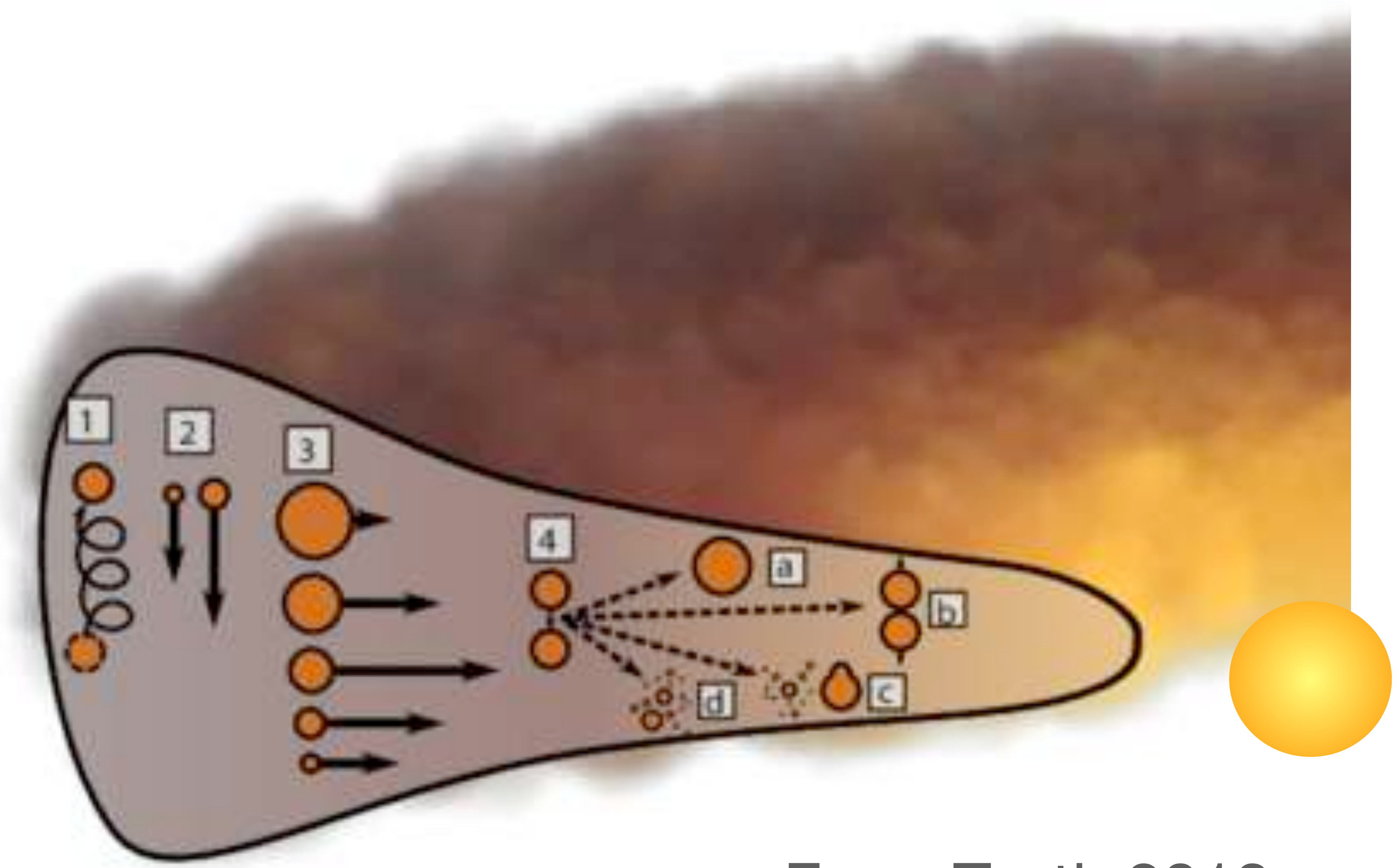


Manara+2023

How to measure gas mass?

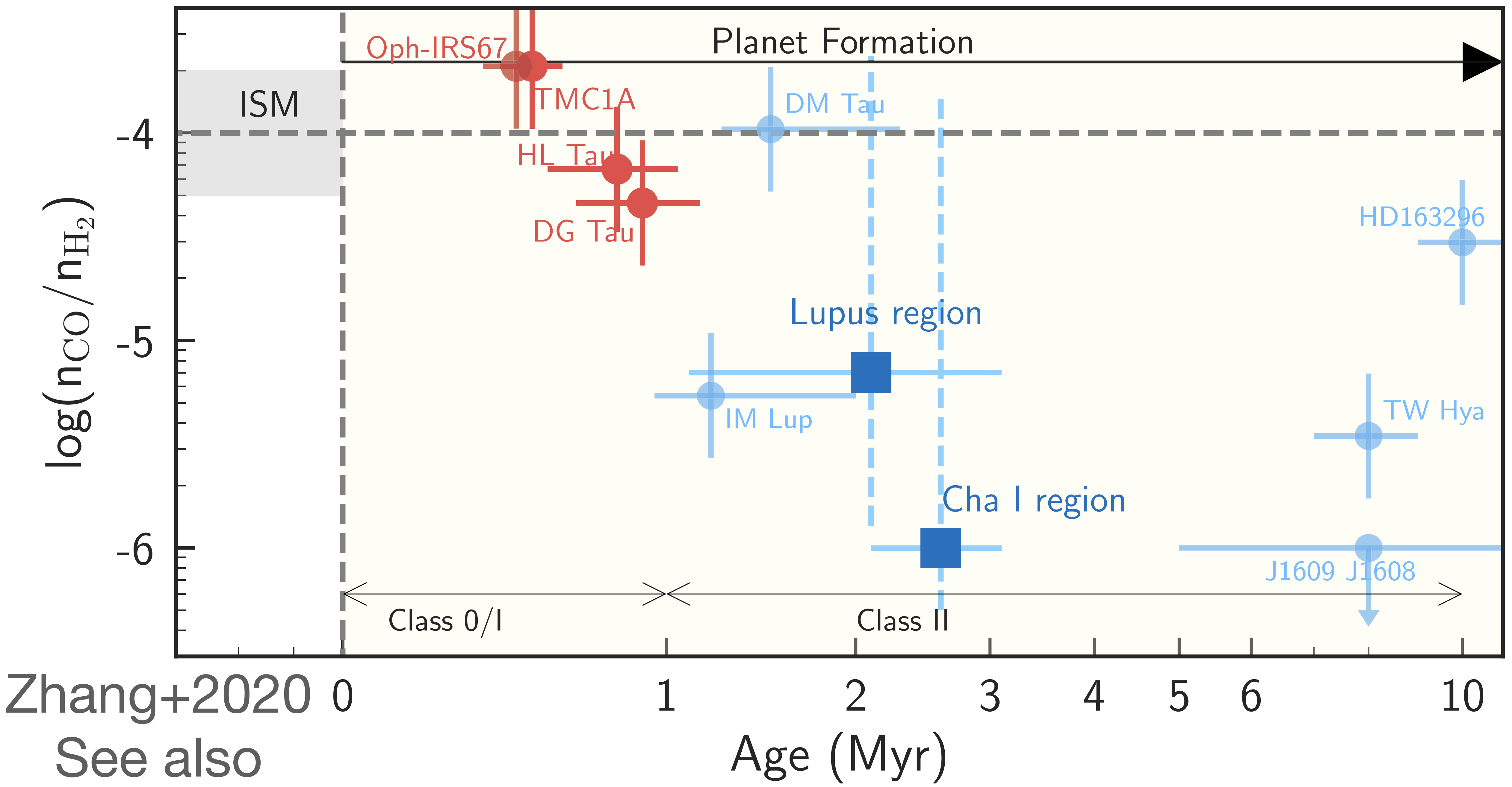
- mm dust emission: subject to radial drift => the gas-to-dust ratio is unknown!
- H_2: first rotational levels too high in energy=> trace only warm gas (>200 K)
- CO rotational lines but need N_2H^+ to estimate the CO abundance!

Pebbles tend to drift inward due to gas drag



From Testi+2013

Evidence of CO depletion in outer disk



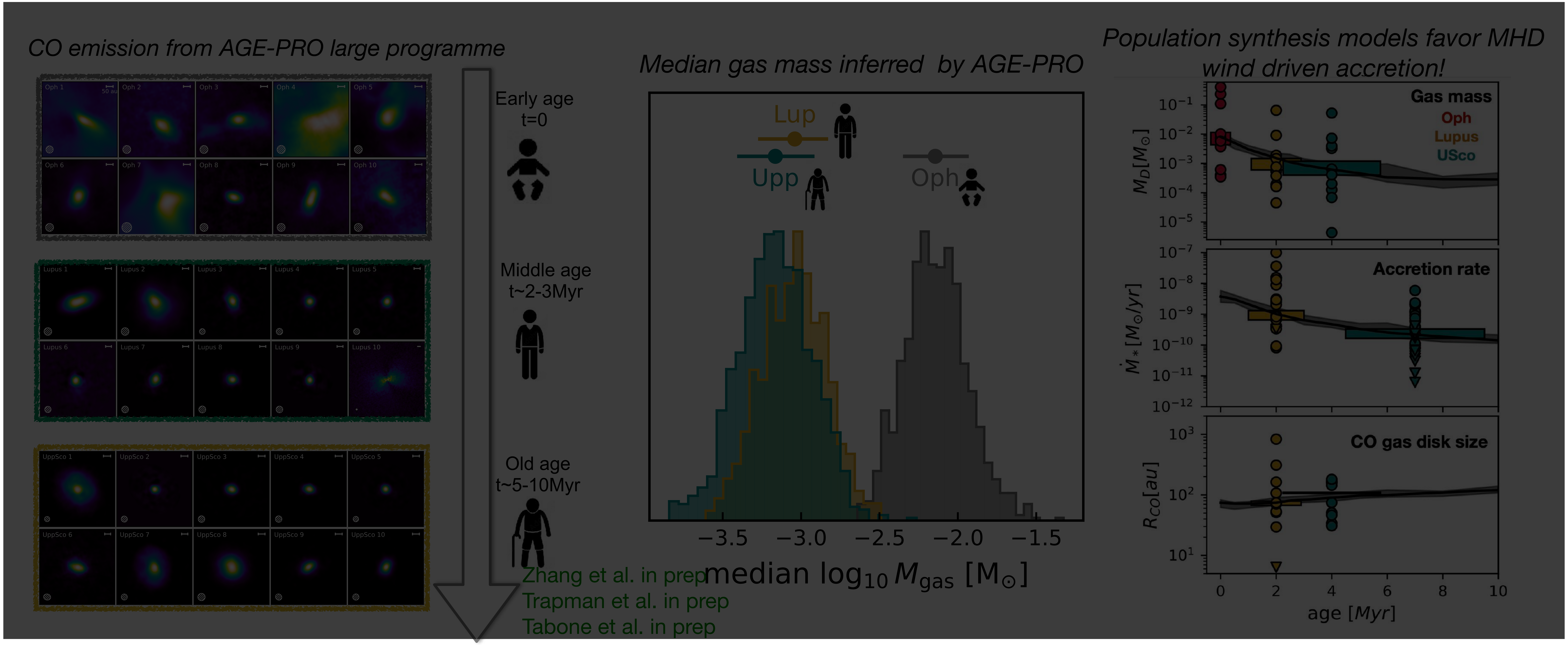
Zhang+2020
See also
Favre+2013
Miotello+2017

Toward a global view of disk at population level

Unbiased survey of disk populations in CO and N_2H^+

=> *median disk mass drops by one order of magnitude within the first 2Myr*

=> *favor MHD wind driven accretion*

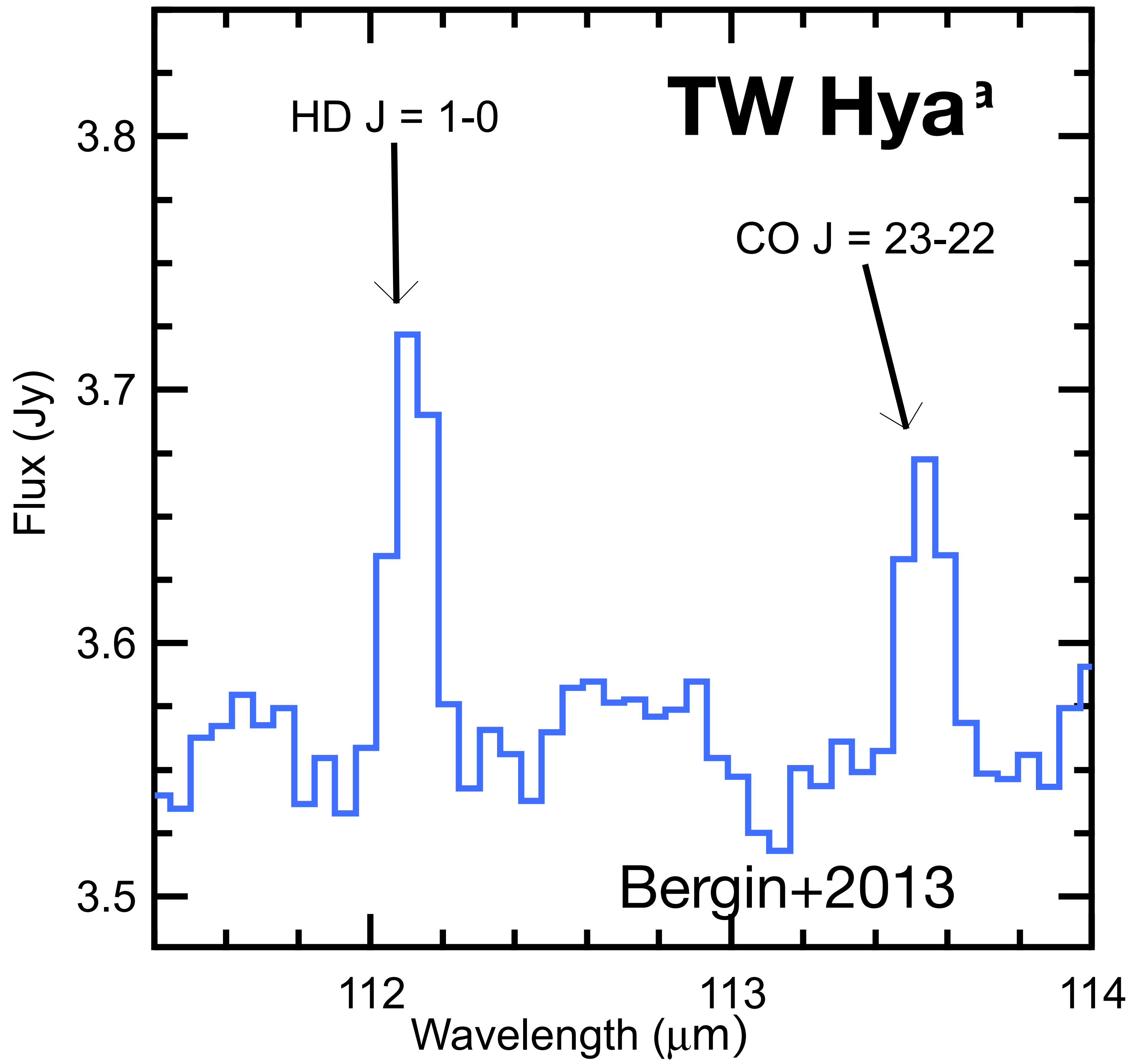


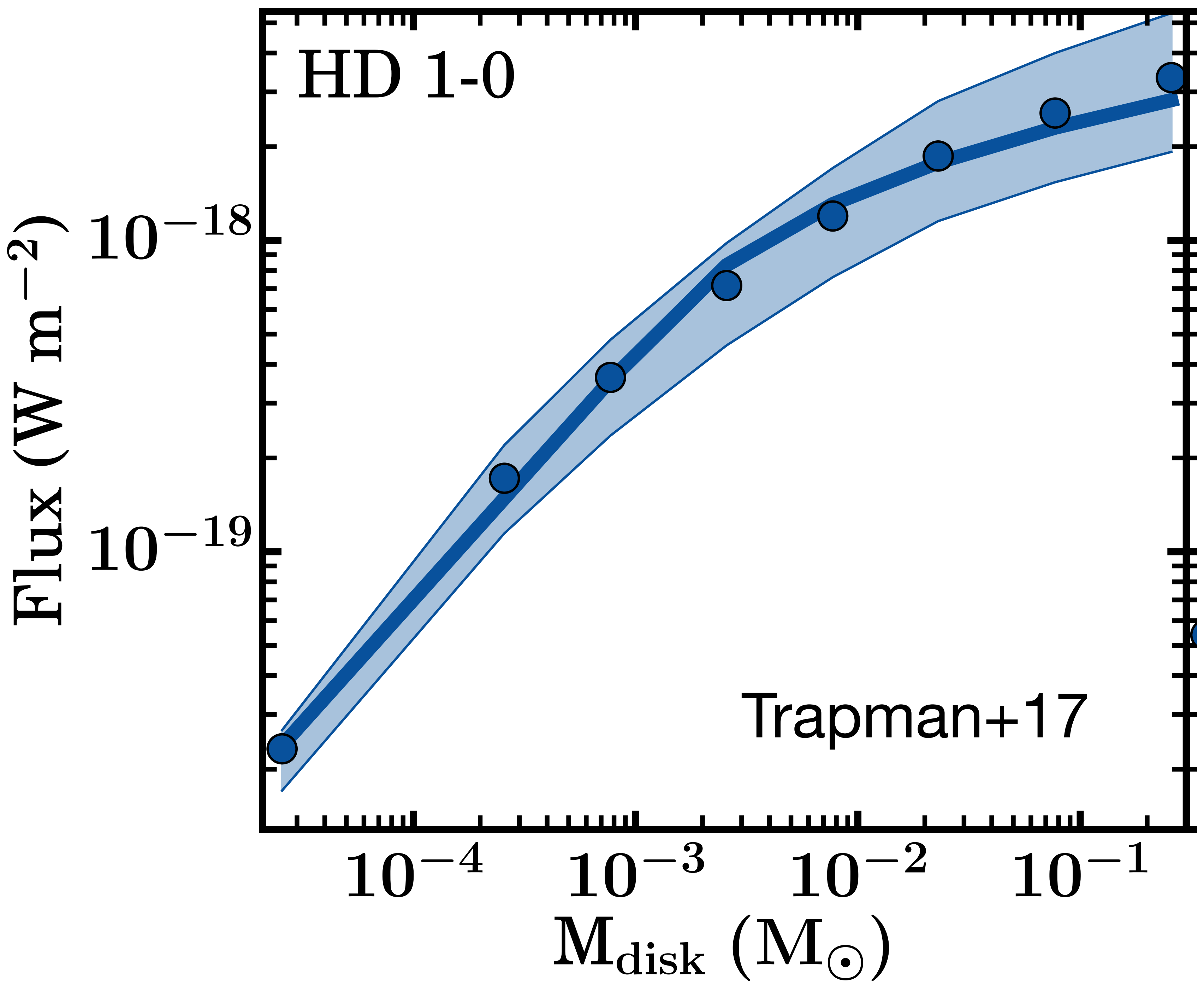
Primary science goal of PRIMA: gas mass with HD

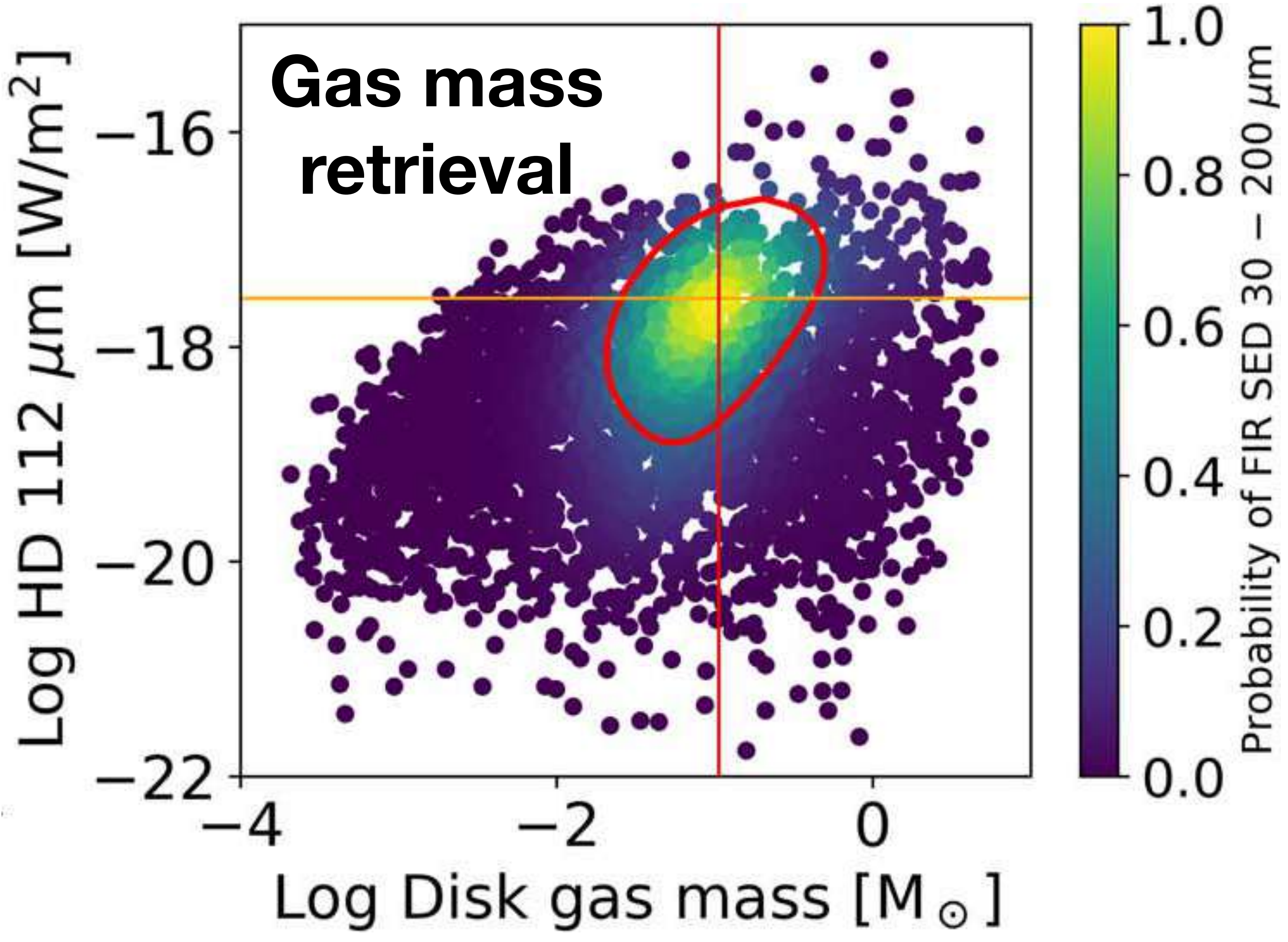
HD unique tracer of gas mass to superseed CO/N_2H^+ and dust emission-based estimates

=> HD(1-0) probes a good fraction of gas (E_{up}~130K)

=> But sensitive to the thermal structure of the disk requiring complementary constraints







Seo+2024

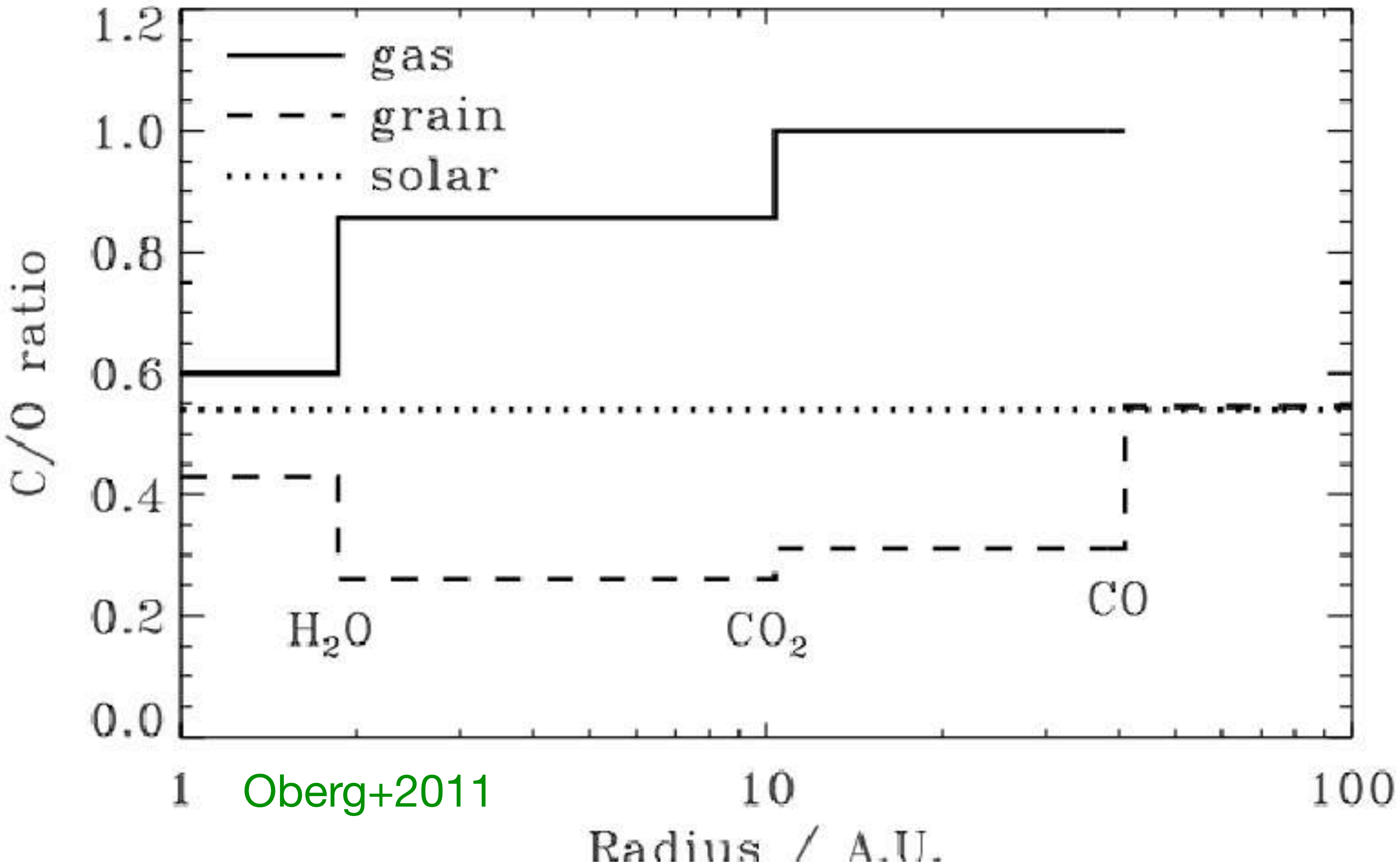
Linking exoplanet to disks: the era of chemistry

The elemental abundances of the gas and in solids (dust+ice) vary in time and space

=> opportunity to constrain the formation history of planets (e.g., ARIEL)

=> large number of processes setting the disk elemental abudances at place

=> need to characterize the chemical makeup of disks across space and time



Oberg+2011

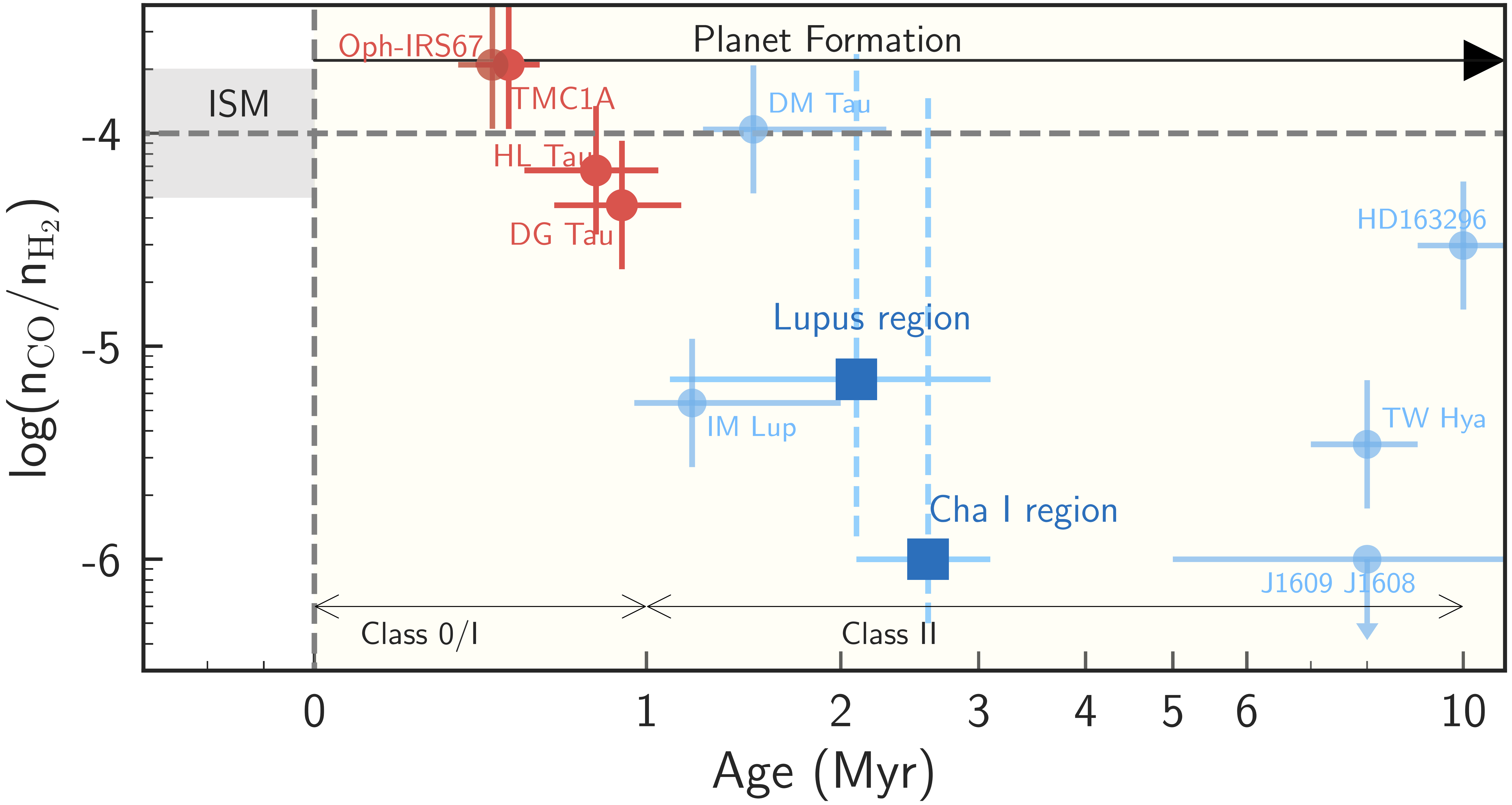
Probing the outer disk with ALMA (and NOEMA)

Credit: MAPS ALMA Large Programme, PI: K. Oberg

The chemical composition of outer disks

Evidence of a chemical conversion of CO in the outer disk and elevated C/O

=> *gas would be metal poor (low C/H, O/H) due to CO converted in less volatile species*
=> *ices would carry significant fraction of O and C and be rich in O!*
=> *requires vertical mixing of the gas but also potential radial transport of species*

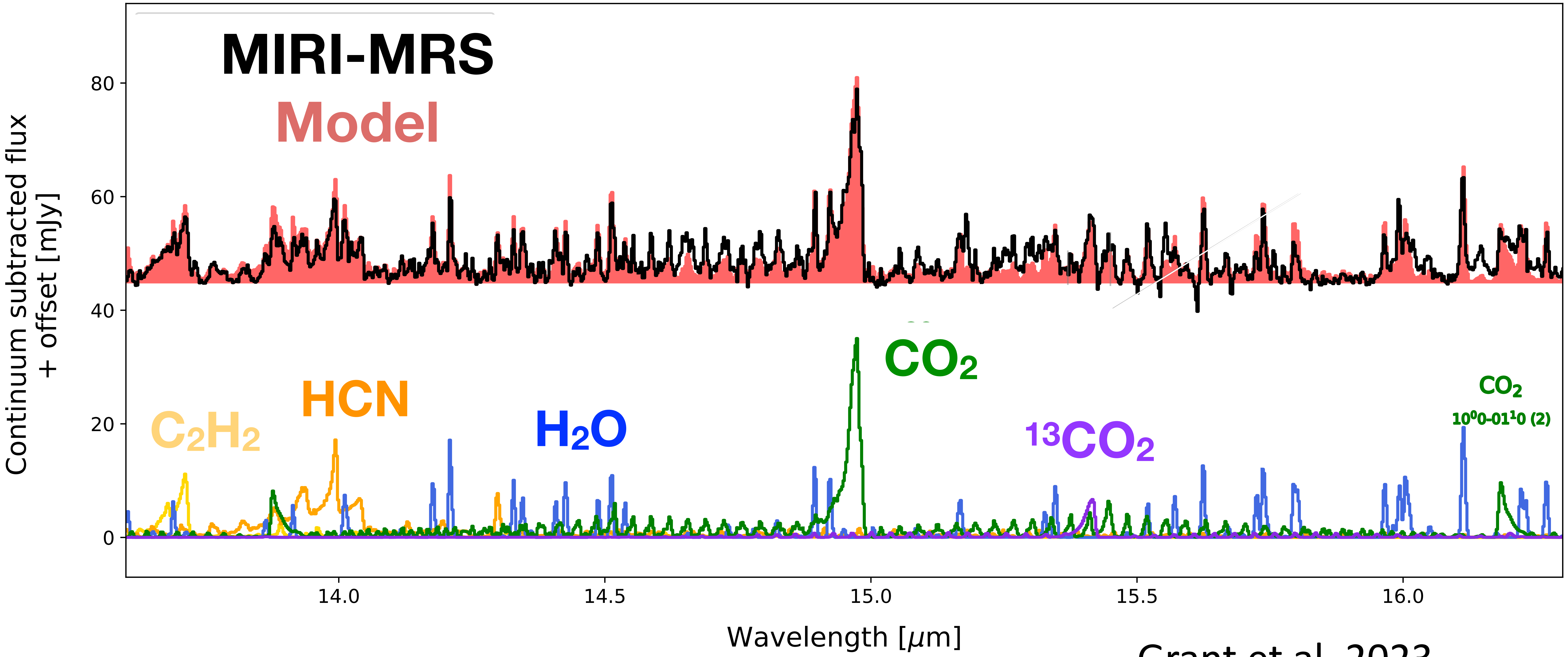


Zhang+2020
See also
Favre+2013
Miotello+2017

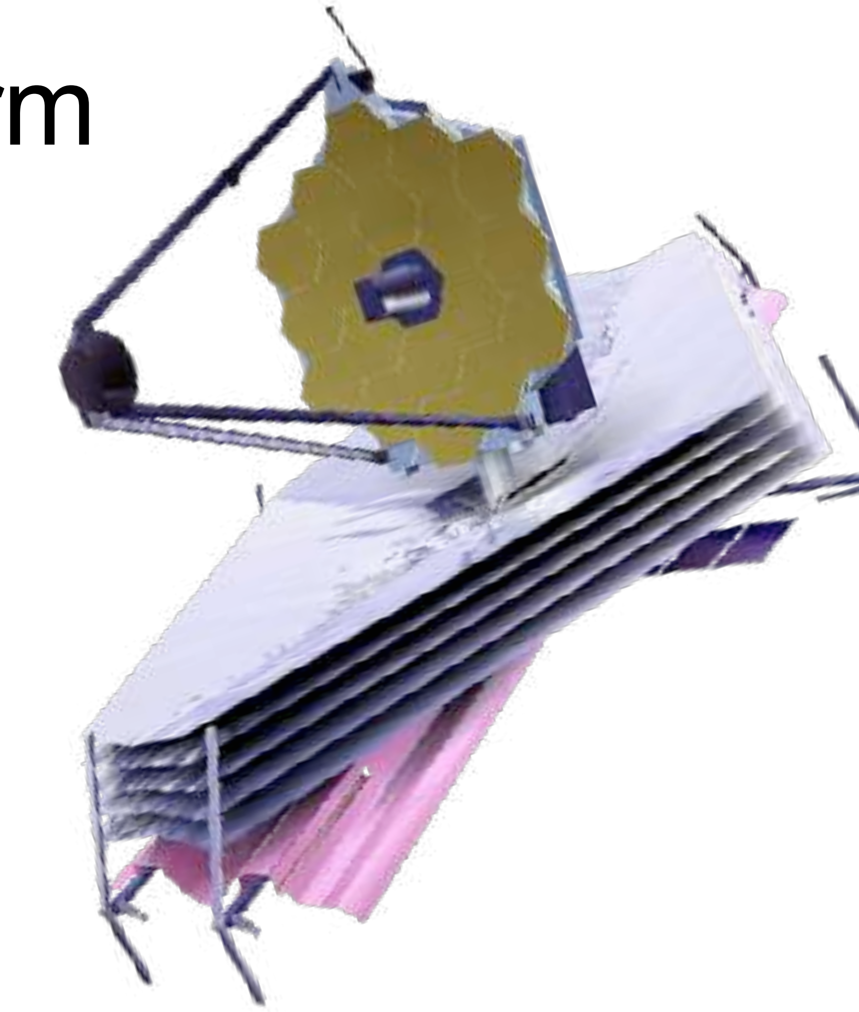
Unveiling the inner regions with JWST

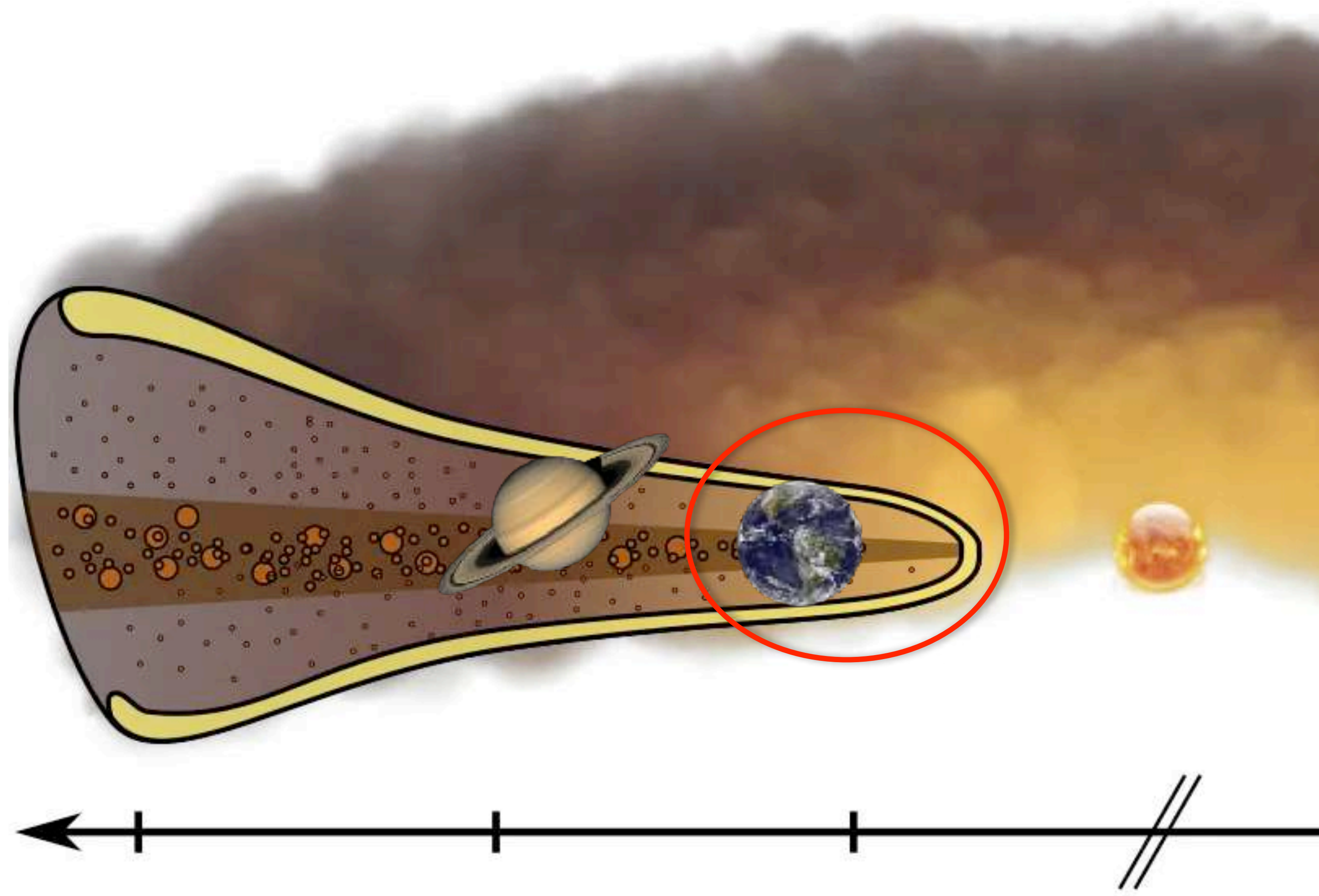
Mid-infrared: inner < 1 au disk

=> region where hot giant and most of the rocky planets are expected to form
=> main C and O carriers observable + mineralogy of small grains

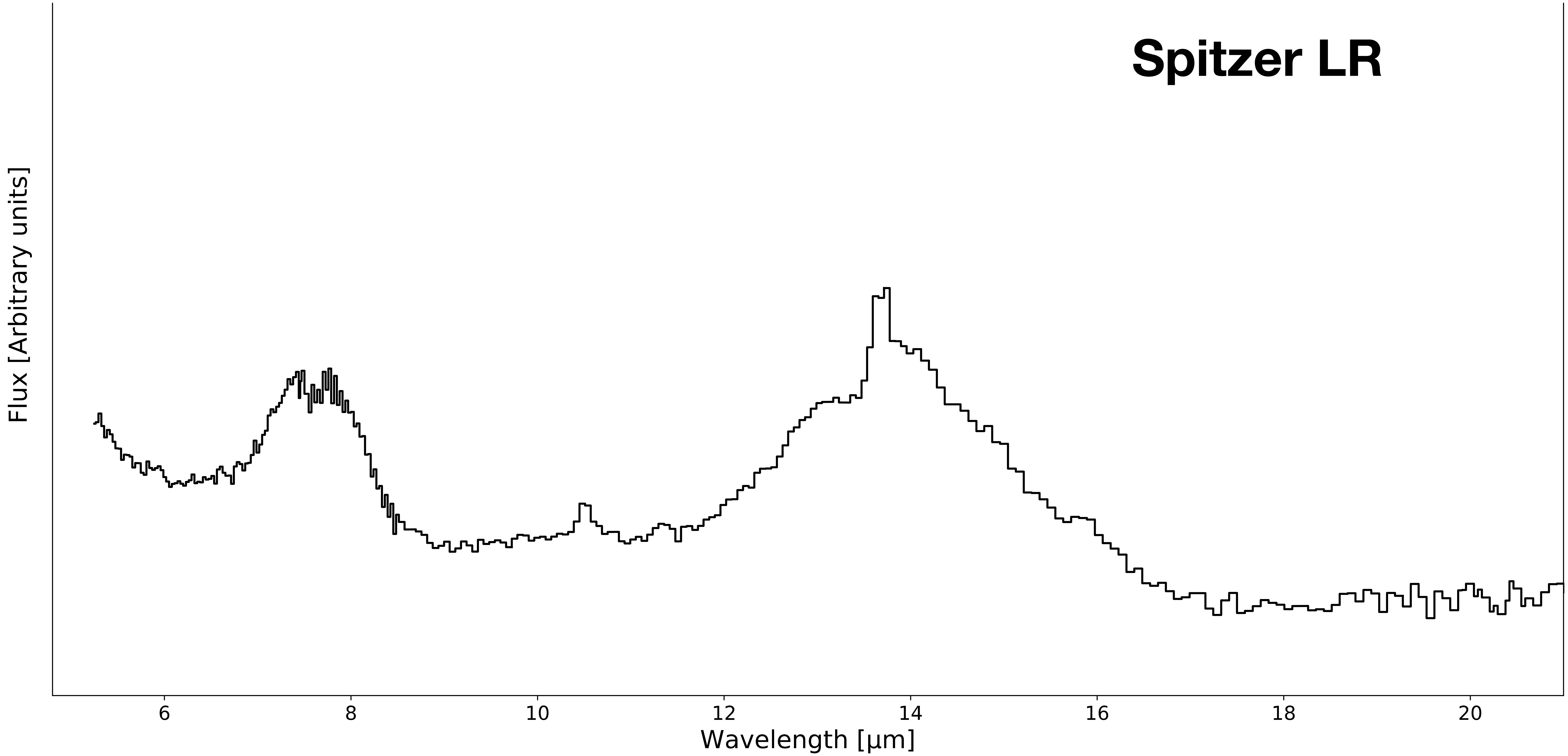


Grant et al. 2023



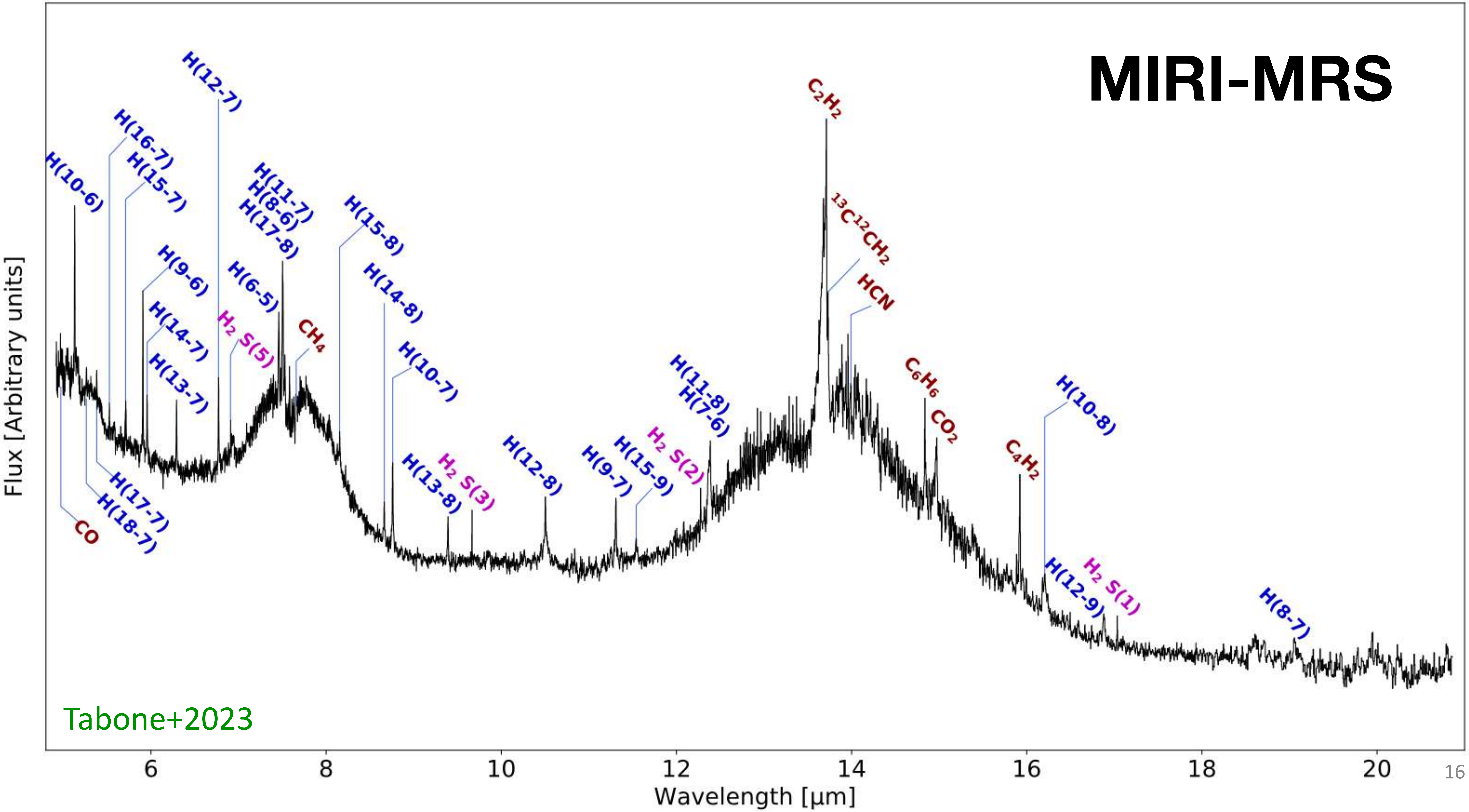


Spectroscopy with JWST



Credit: G. Bettoni

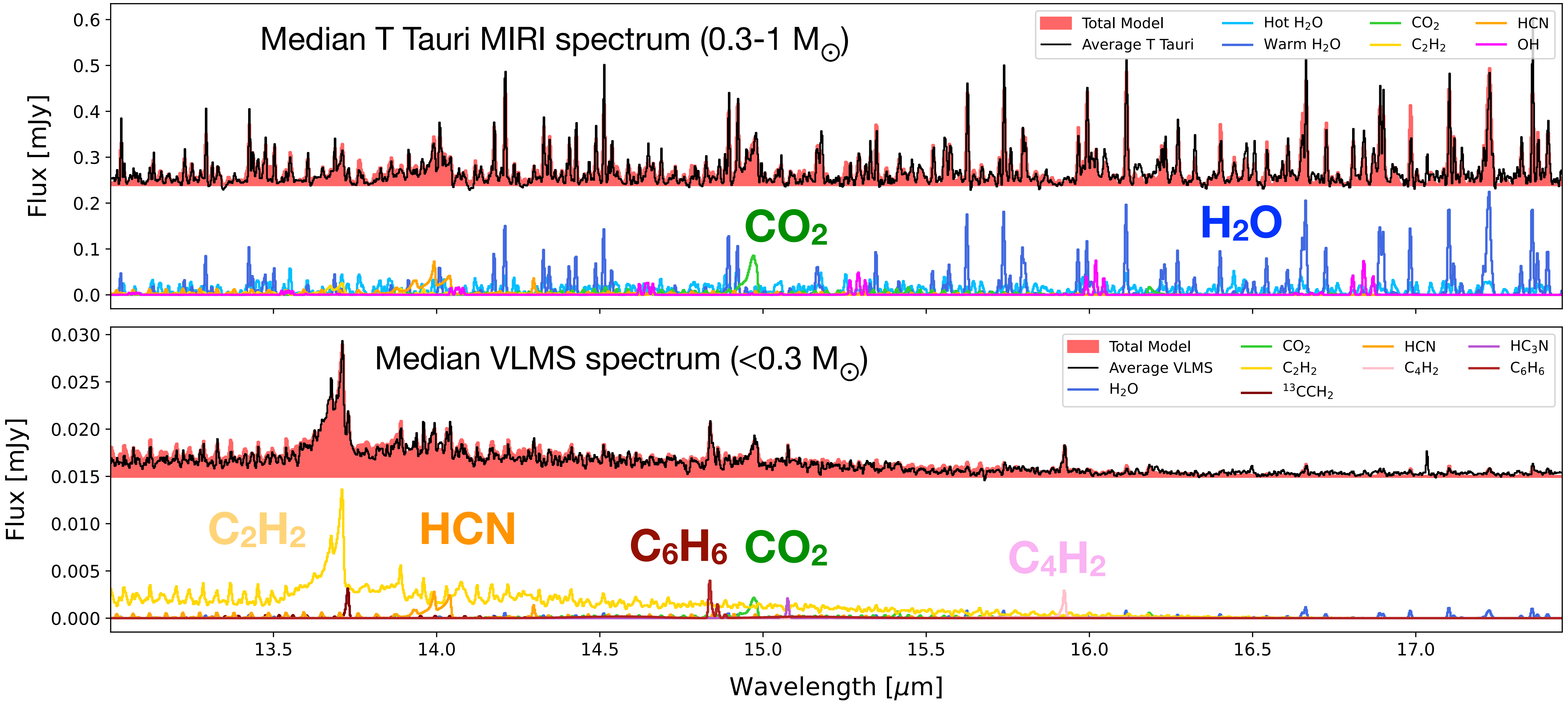
Spectroscopy with JWST

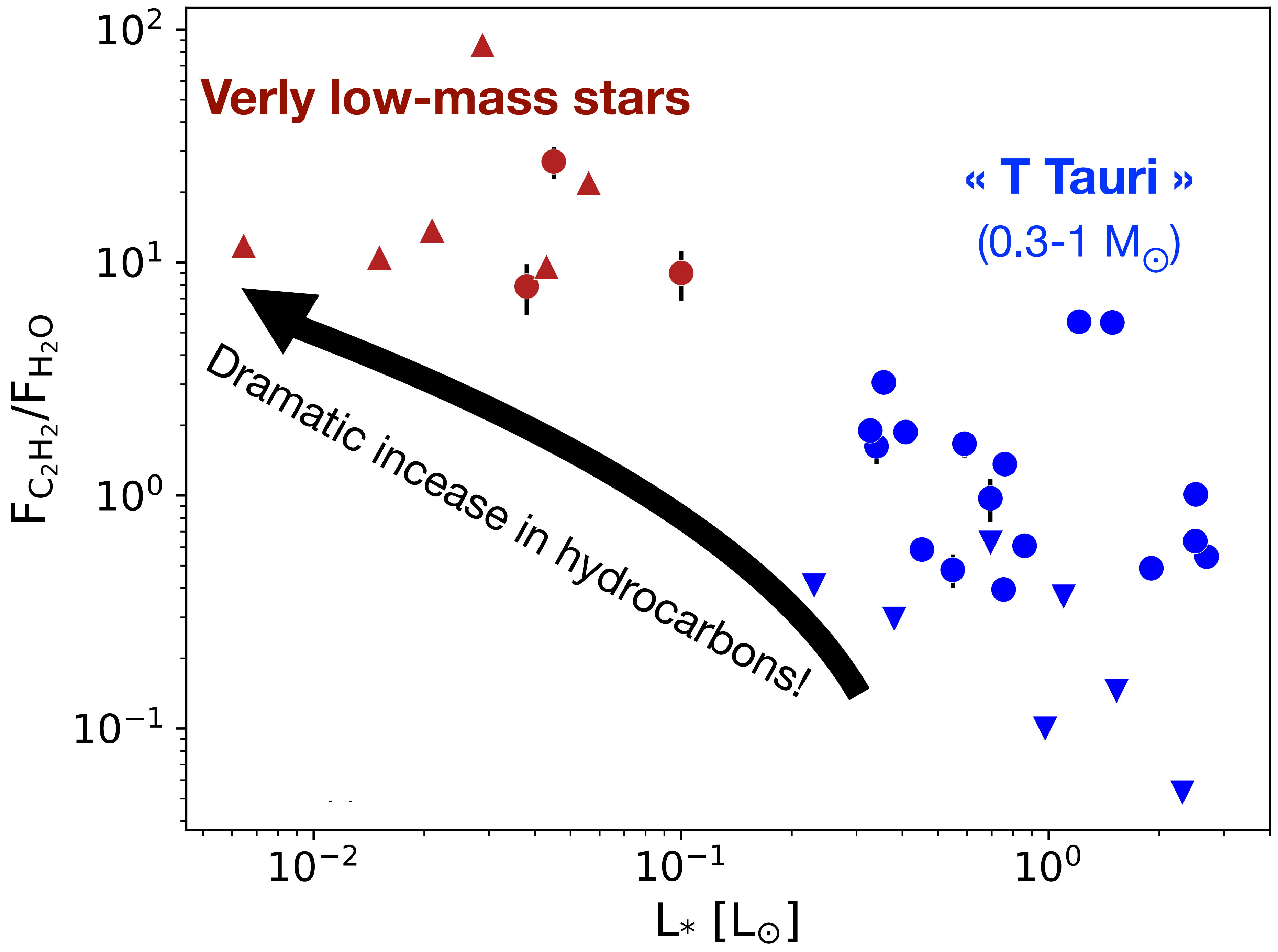


Molecular makeup of inner disk depends on stellar mass

- VLMS disks show prominent C_2H_2, C_6H_6 and little H_2O =/= Sun-like star with prominent H_2O
- Potential dependency on age with some O-rich VLMS disk which are also young

=> *the composition of exoplanet are likely highly dependent of the stellar mass!*



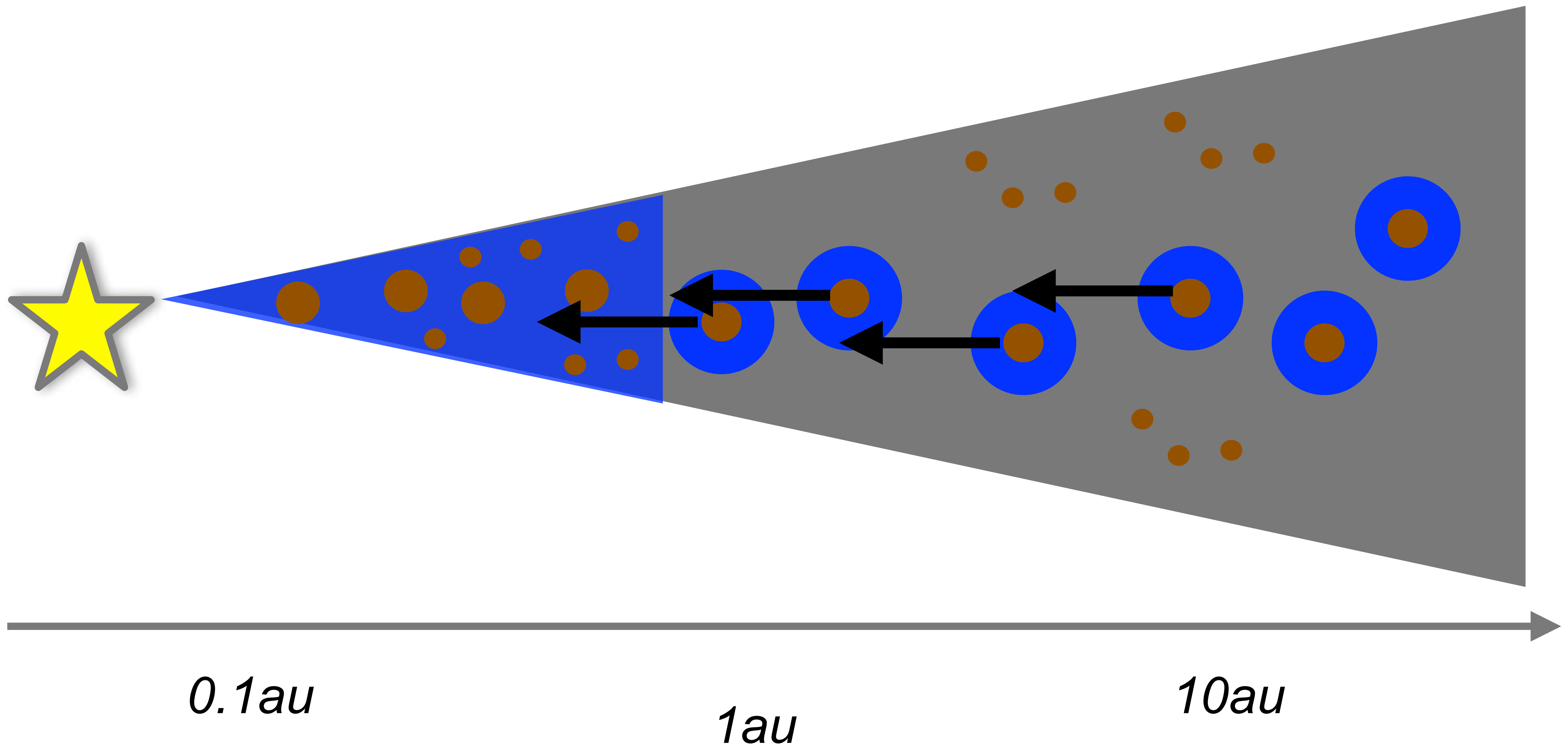


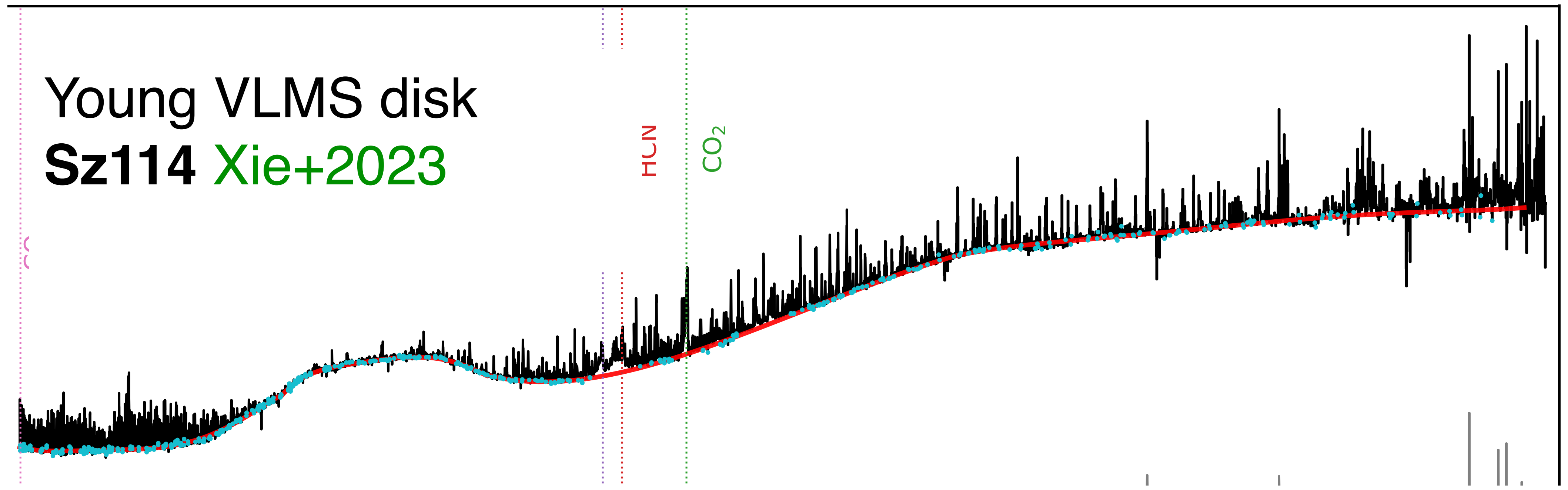
Grant+ sub.

Scenario: pebble drift faster around VLMS

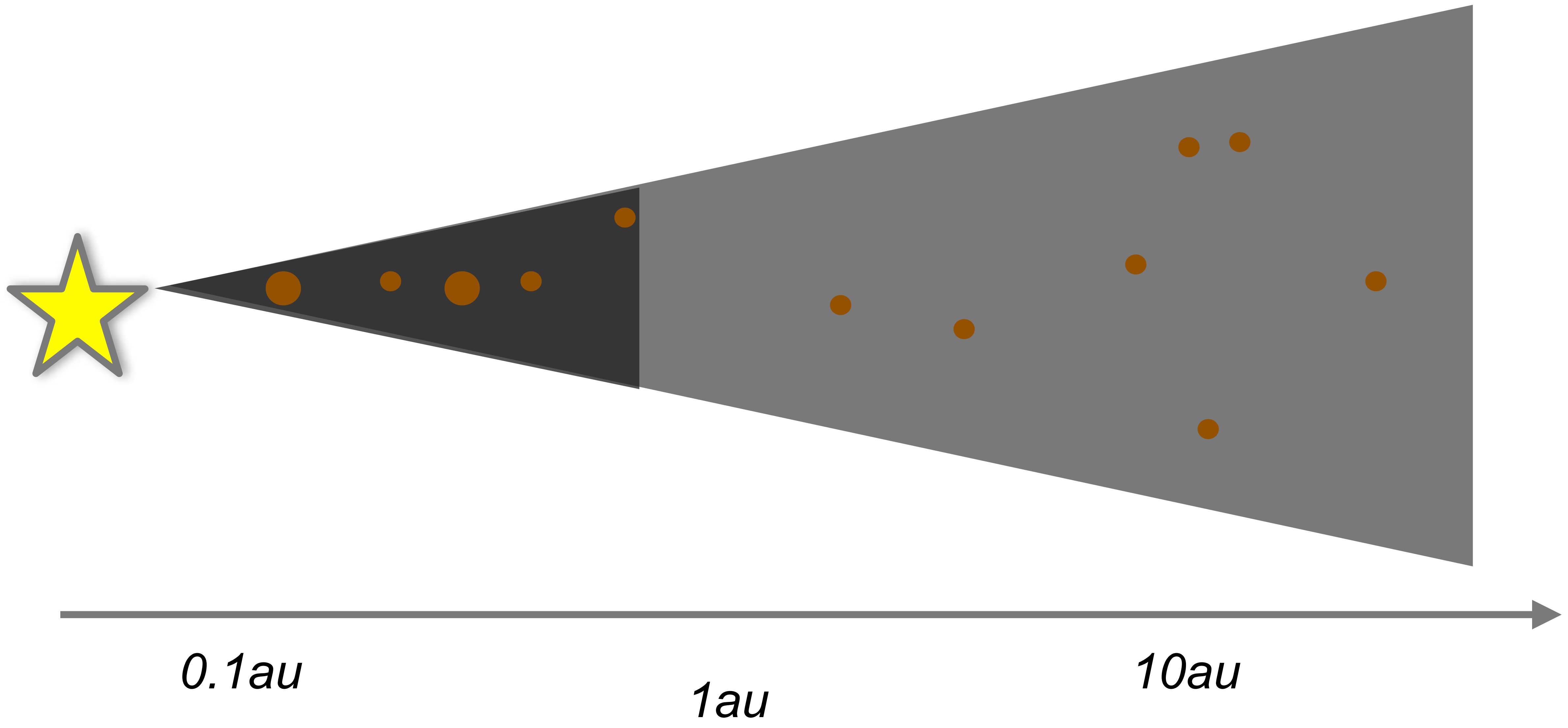
Mah+ 2023
Arabhavi+ sub.

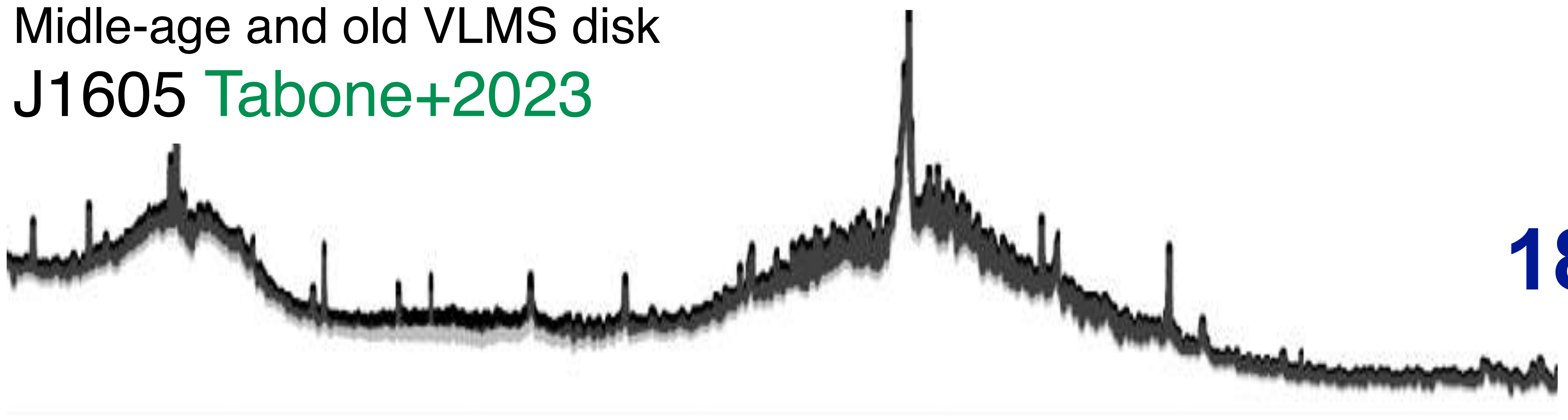
Early time: avalanche of icy pebbles
=> inner disk enriched in gas-phase H_2O





Late time: deficit in pebbles and H_2O accreted onto the star
=> inner disk rich in gas-phase C forming C_2H_2 and hydrocarbon





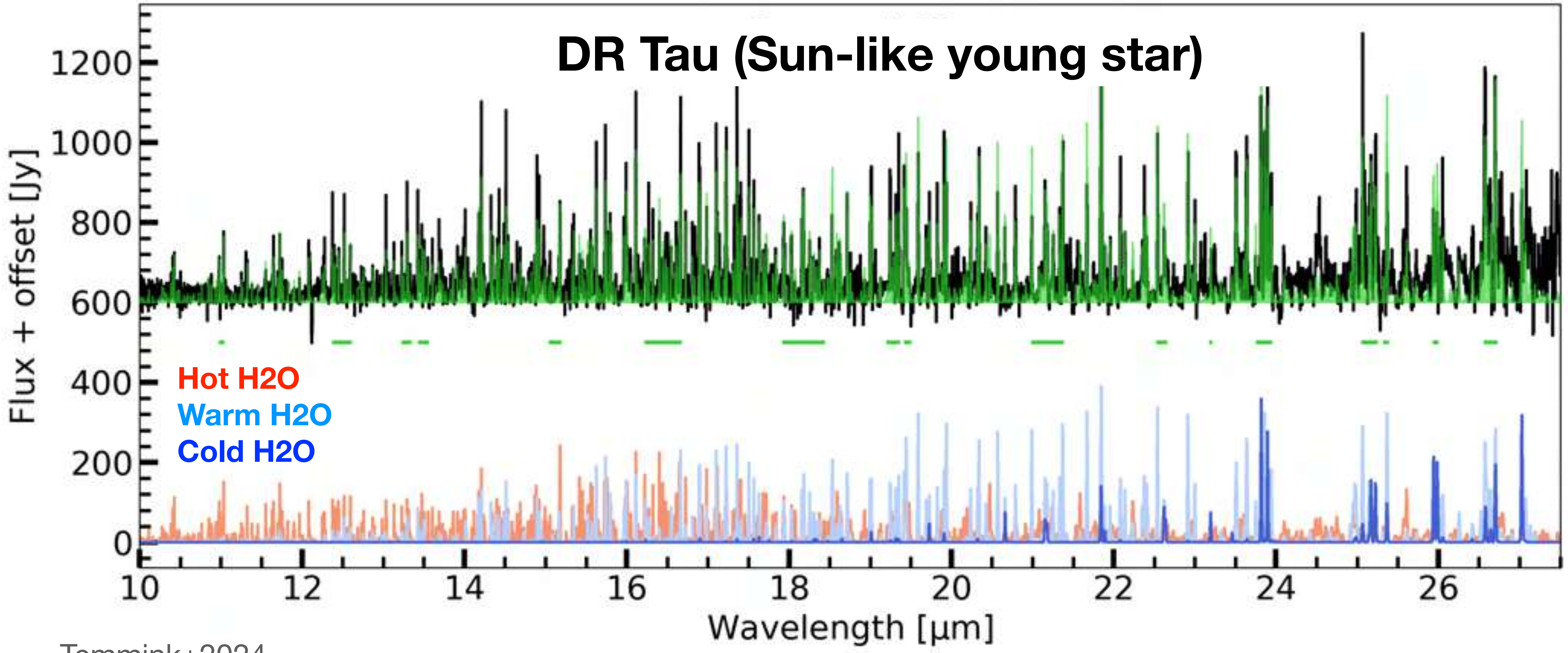
Spectral mapping of inner disks

Unresoved observations but complete spectral coverage allow us to map H_2O distribution!

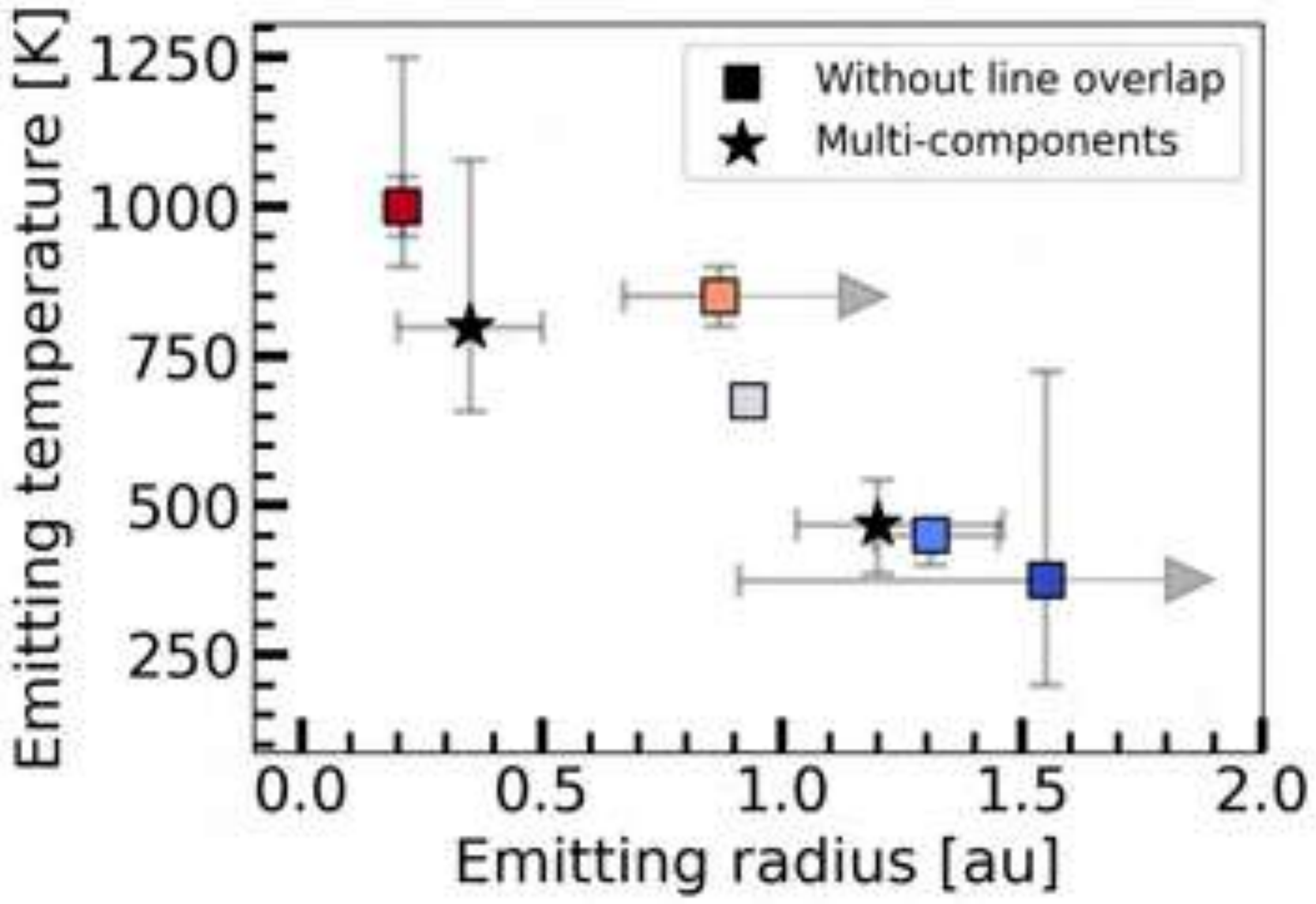
=> *joint analysis of all H_2O lines to reconstruct the radial profile of N(H_2O) and TK*

=> *spectral resolution of FIRESS-FTM transformative to pinpoint emitting regions (at short wavelength)*

Results of a fit of H2O emission by a 3-component slab model



Evidence for a temperature gradient



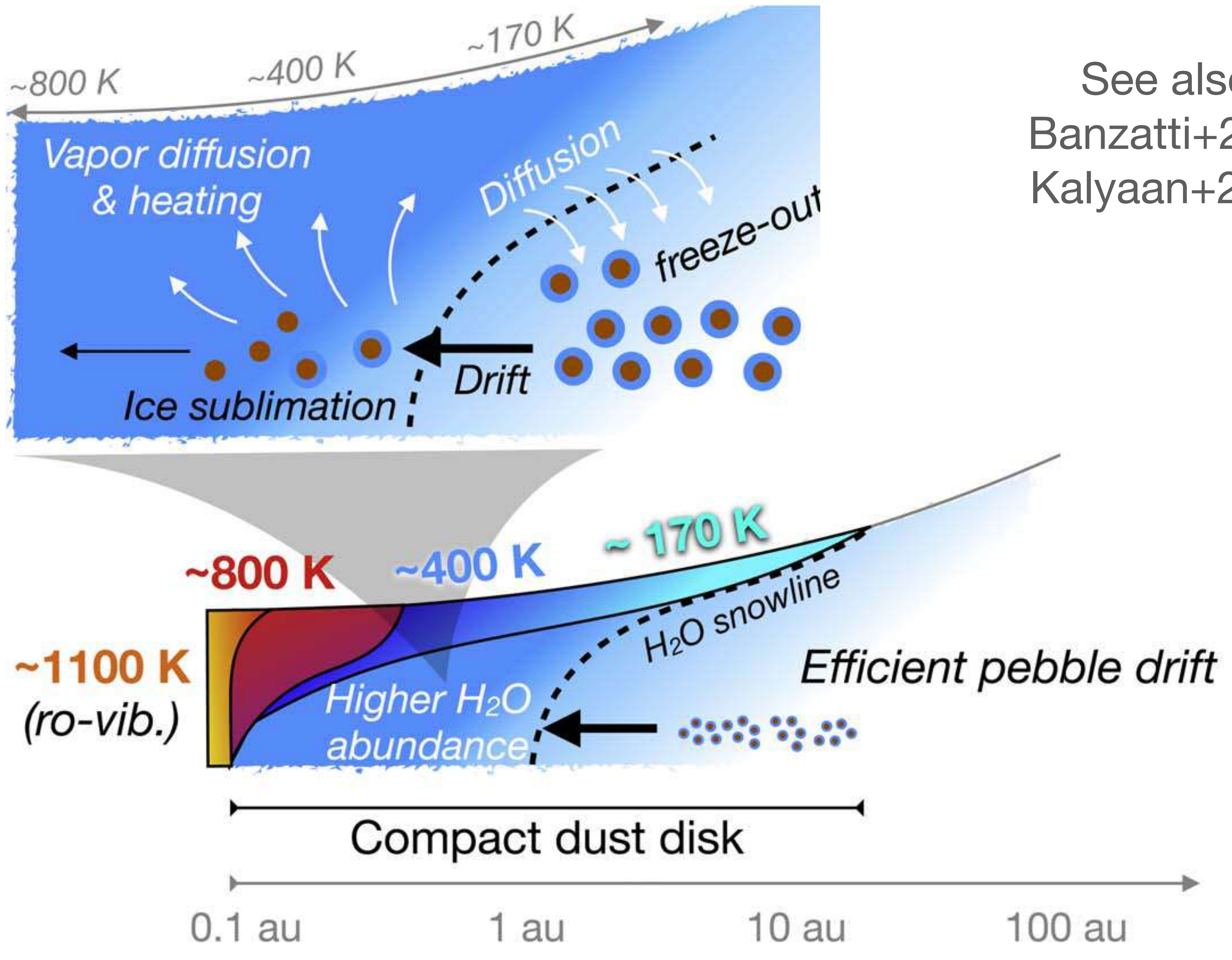
Temmink+2024
Temmink+2025
See also : Romero-Mirza+2024

Spectral mapping of inner disks: evidence of pebble drift from cold water lines

Excess of cold water in compact disks

=> interpreted as inflow of H_2O-rich pebble followed by diffusion but based on few H_2O lines

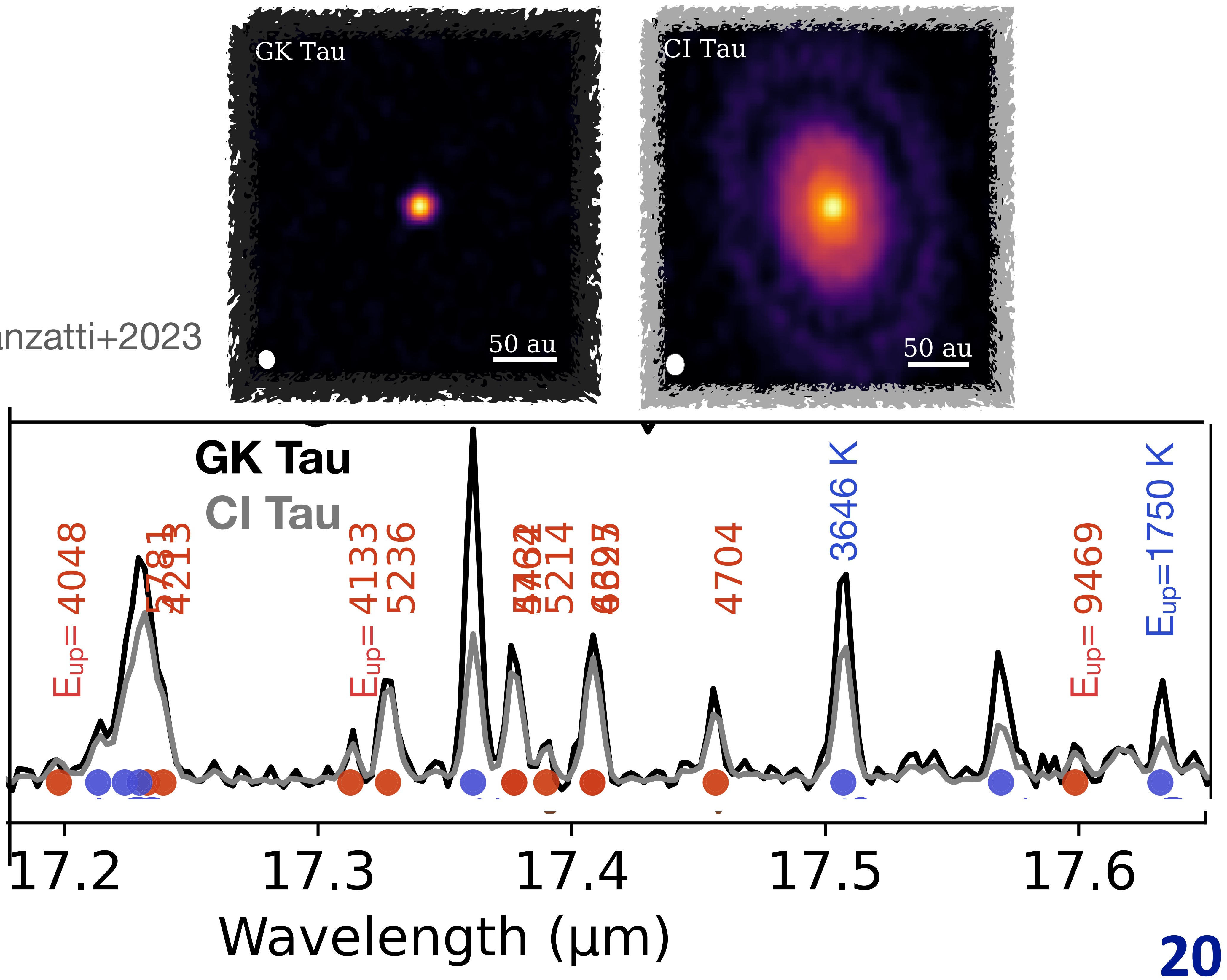
=> molecular lines not only tracing chemistry but also dynamical processes



See also:
Banzatti+2017
Kalyaan+2021

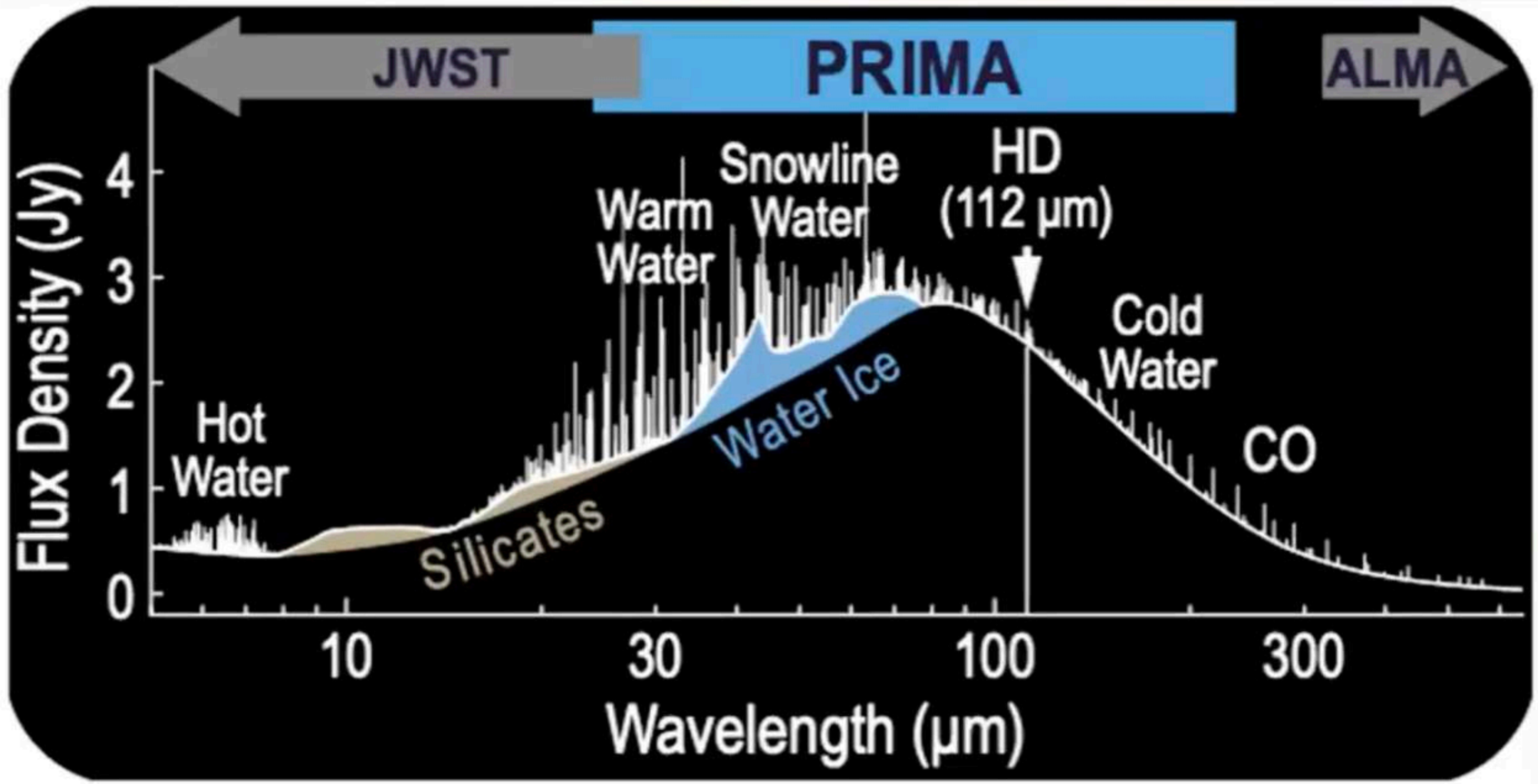
Excess of cold water emission in a compact disk

Banzatti+2023



Primary science goal of PRIMA: the role of water in driving planet formation

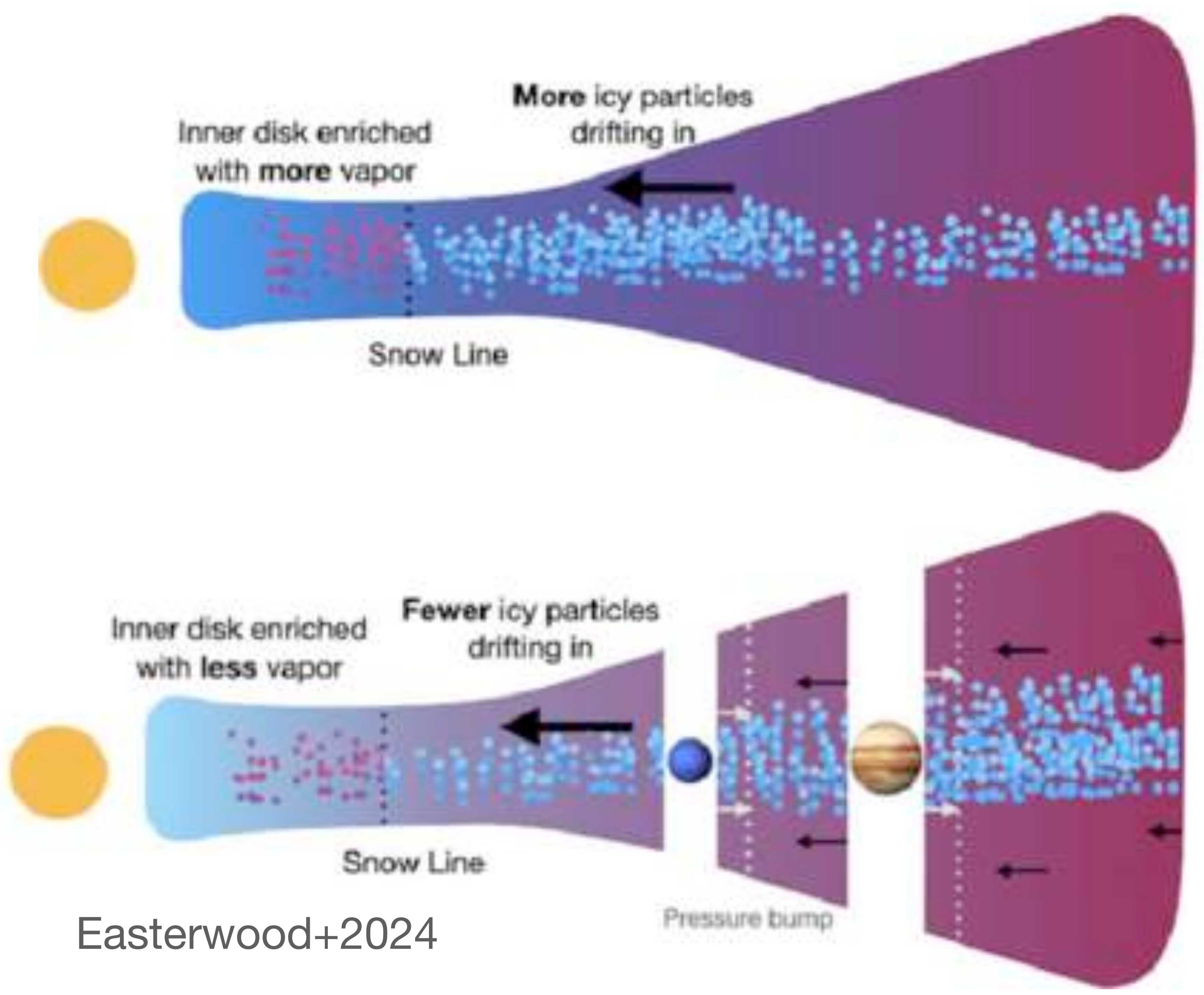
Water lines probed by Prima will best probe the water iceline superseeding JWST studies
=> spectral resolution at short waelength enough to pinpoint emission location
=> with HD(2-1), access to the O/H rati, crucial form planet formation and to test pebble drift scenario



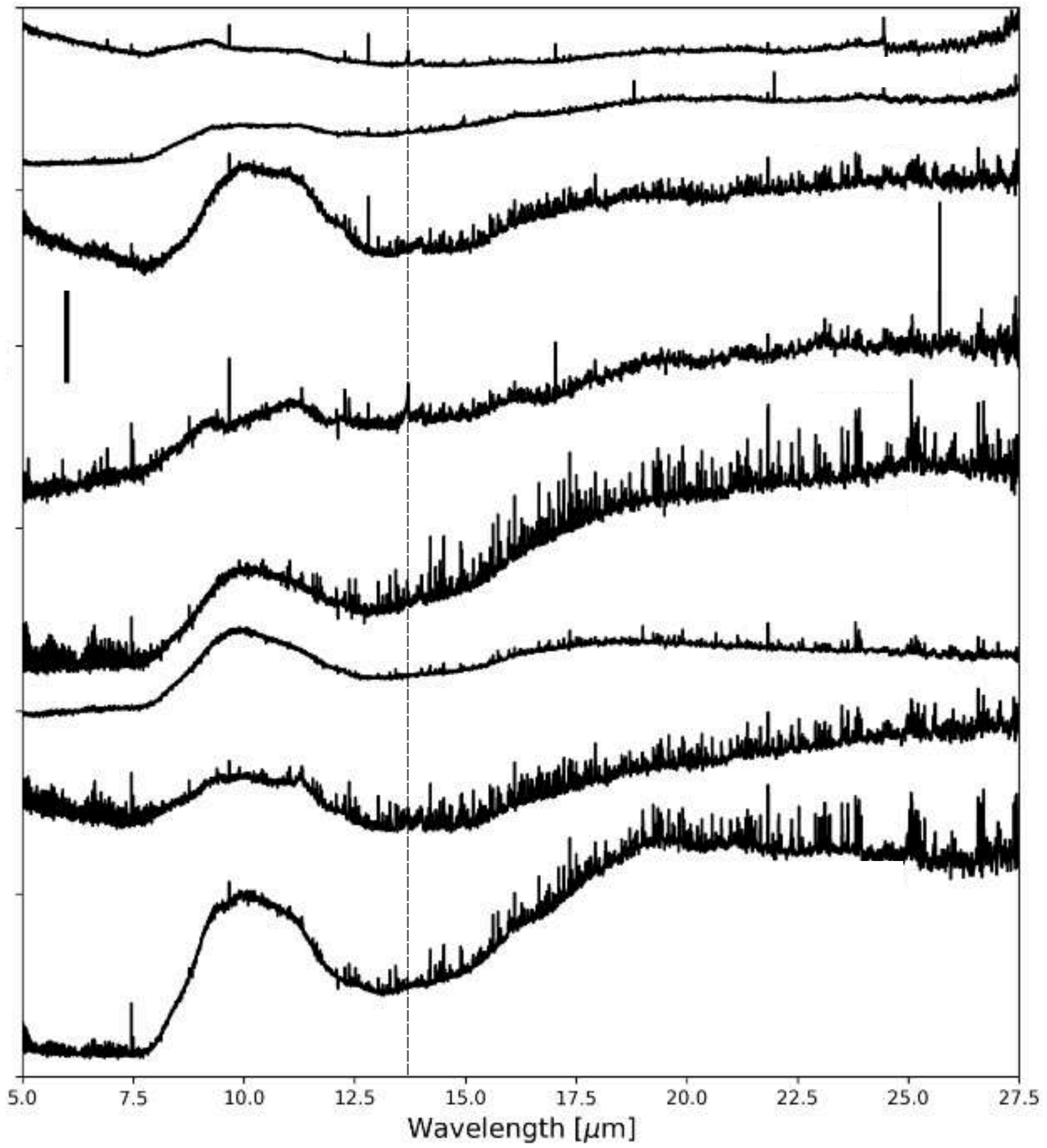
Origin of the diversity: dust radial transport?

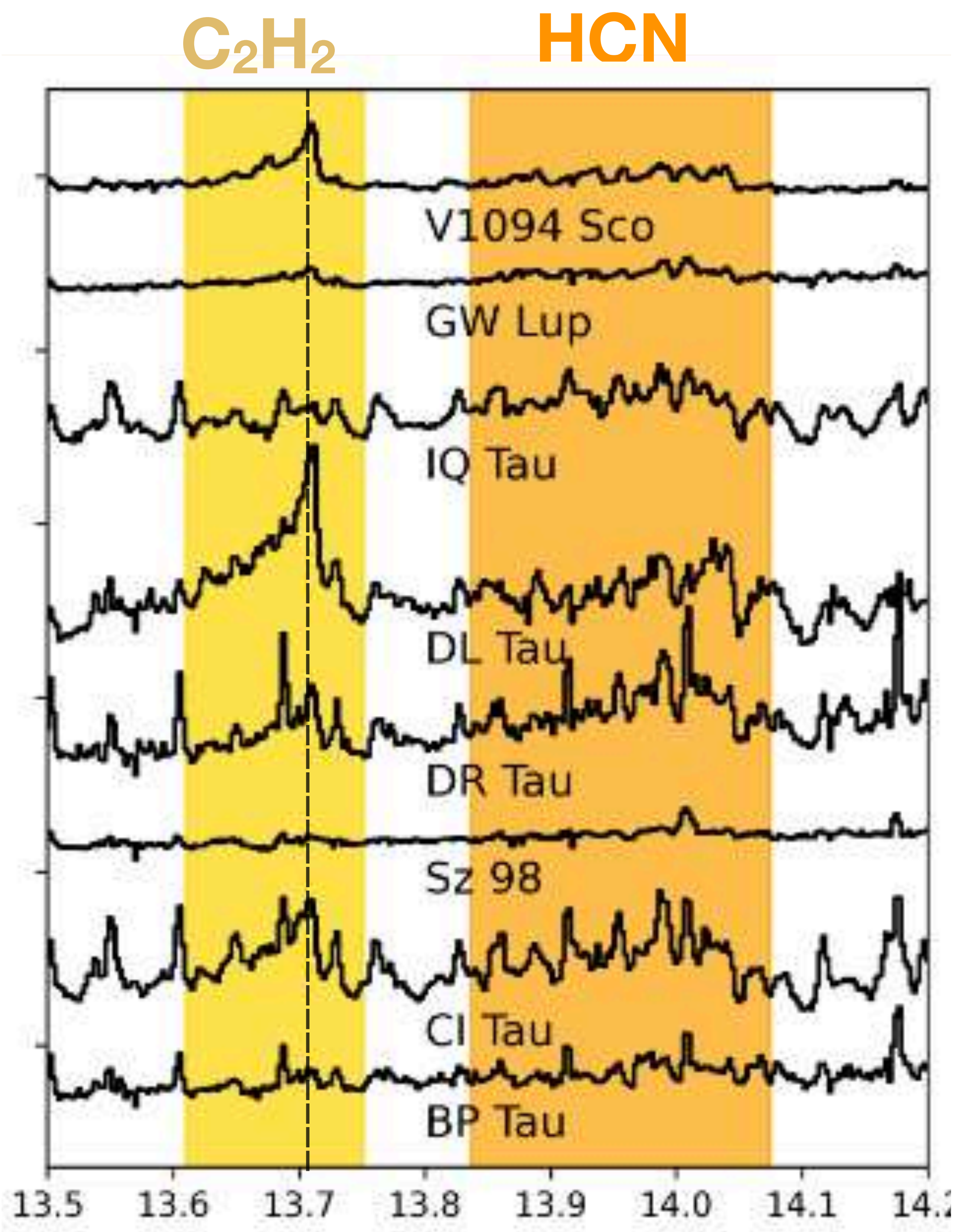
Emerging paradigm suggest that inner disk chemical makeup set by advection of gas and icy pebbles from outer disk

=> *diversity in inner disk linked to the location of various substructures?*
=> *first JWST-ALMA results challenge this interpretation but mismatch in scale*
=> *need the intermediate scales with PRIMA targeting species other than H_2O + large samples!*



Easterwood+2024





Gasman+2025

Toward of global view of the chemical composition of disks

PRIMA, in synergy with JWST and ALMA is vital to enable the interpretation of exoplanet composition

Inner most disk with JWST (<1 au)
=> full coverage 5-27micron unique to spectrally map inner regions
=> unique diversity in chemical makeup with T Tauri disk oxygen rich in general
=> could be the result of radial transport of species

Inner disk with PRIMA (1-10 au)
=> full coverage 25-300micron with FIRESS will be transformative
=> spectrally resolve lines to infer emitting region directly with FIRESS-FTM
=> some species not accessible without PRIMA (small hydrides like NH3)

Outer disk with ALMA (>10 au)
=> rare giant planets on wide orbit
=> but also gas and dust advected toward the inner regions