Star & Planet Formation Science with SALTUS

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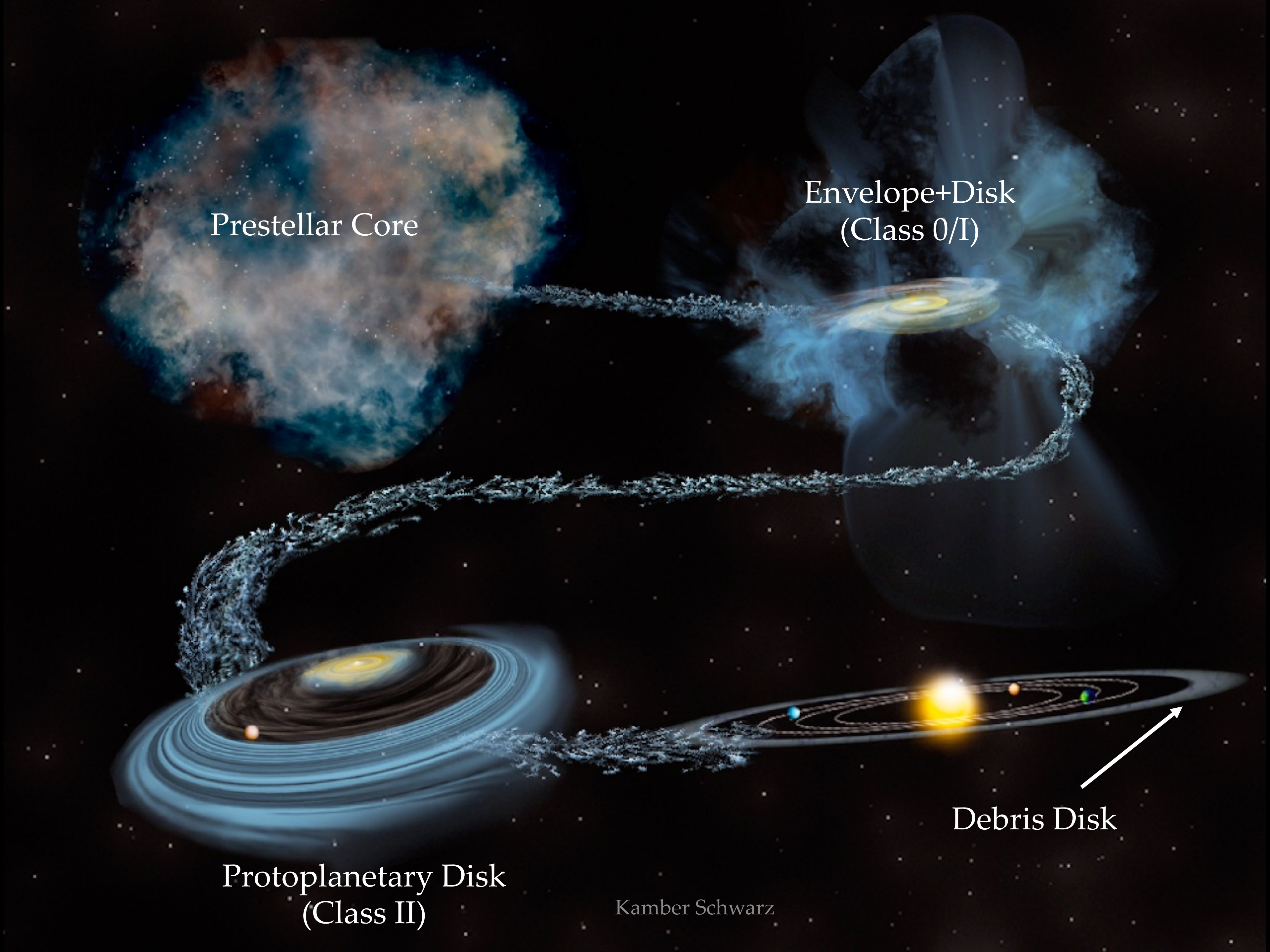
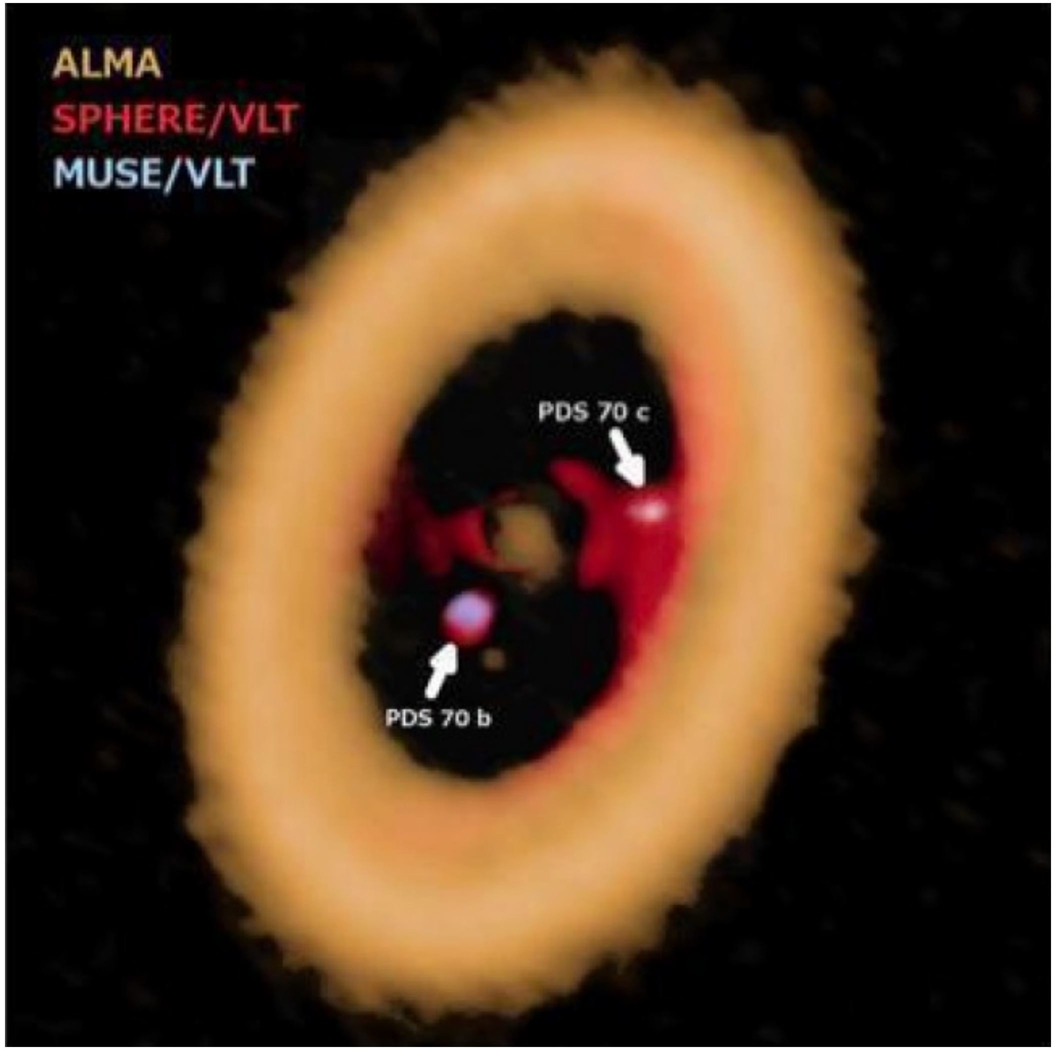
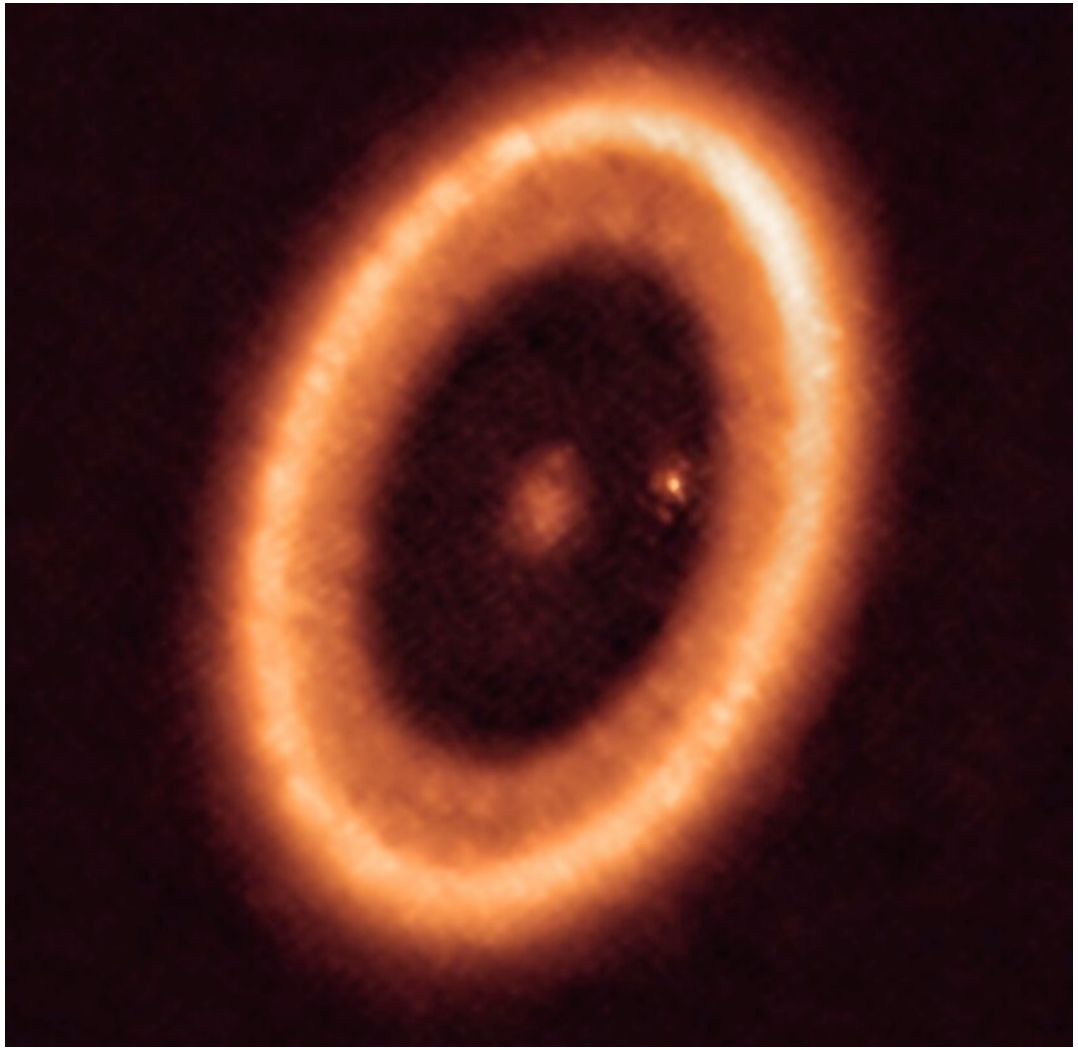


Credit: Bill Saxton

Protoplanets!





Kamber Schwarz

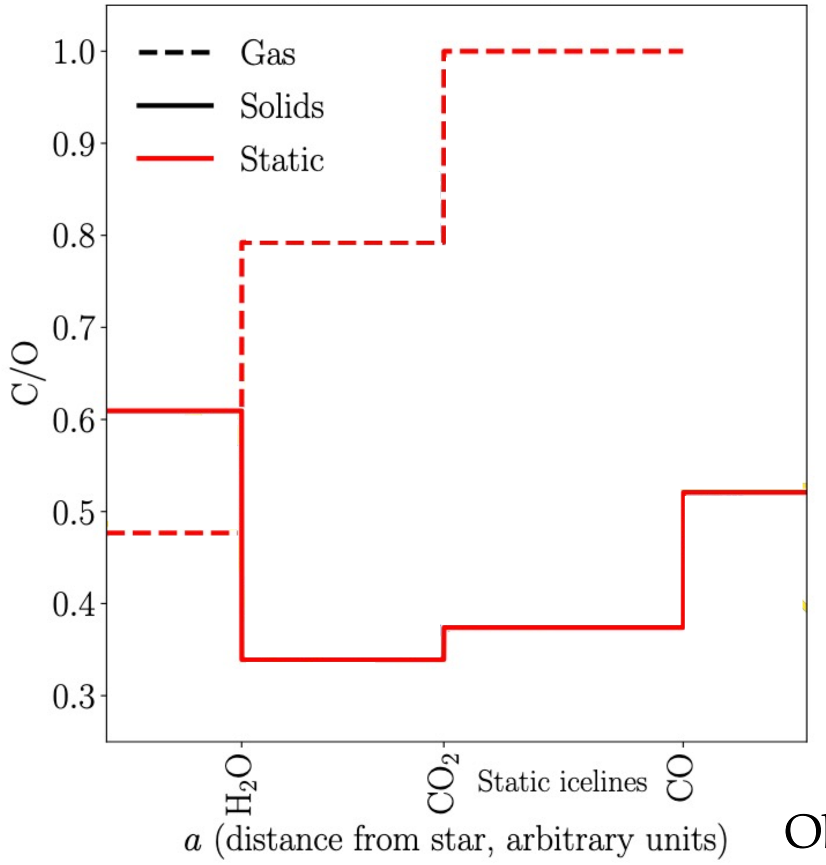
Isella et al.

Benisty et al. 2021

Observable signatures of planet migration?

„Atmospheric elemental ratios, particularly carbon to oxygen, may record the location of formation of the planet with respect to various snowlines.“ – 2020 Decadal E-Q1c

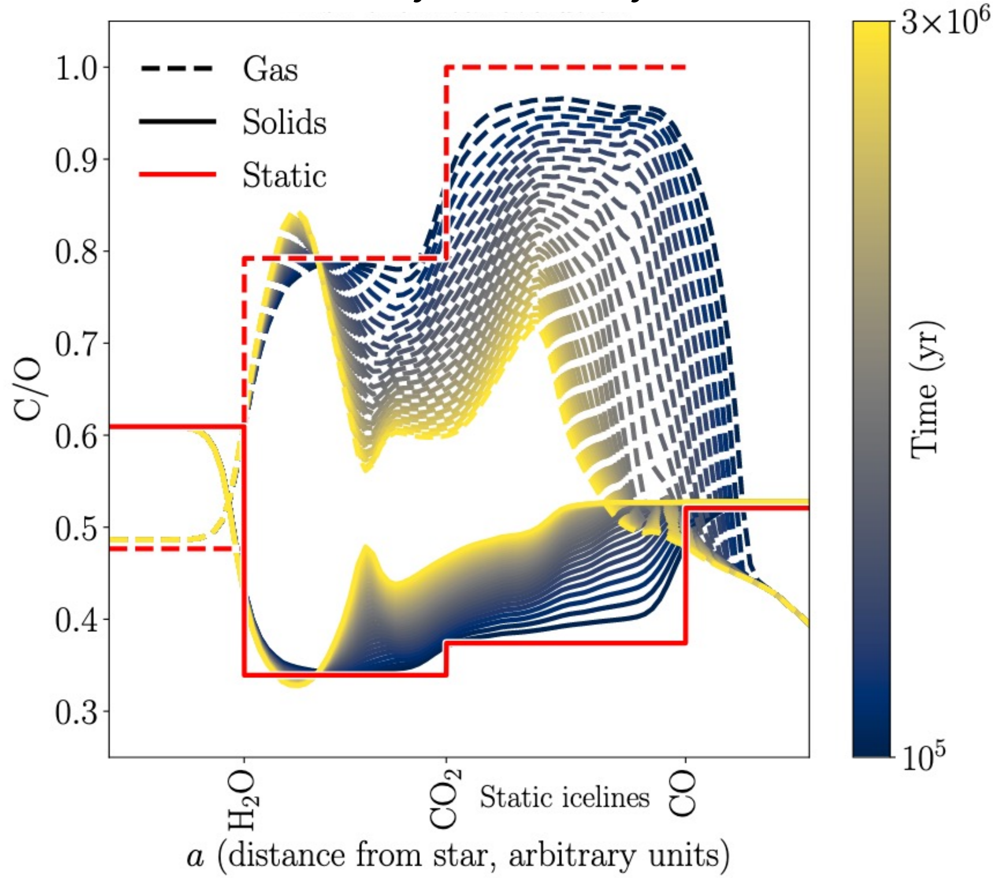
0th order assumption: C/O only changes at snowlines



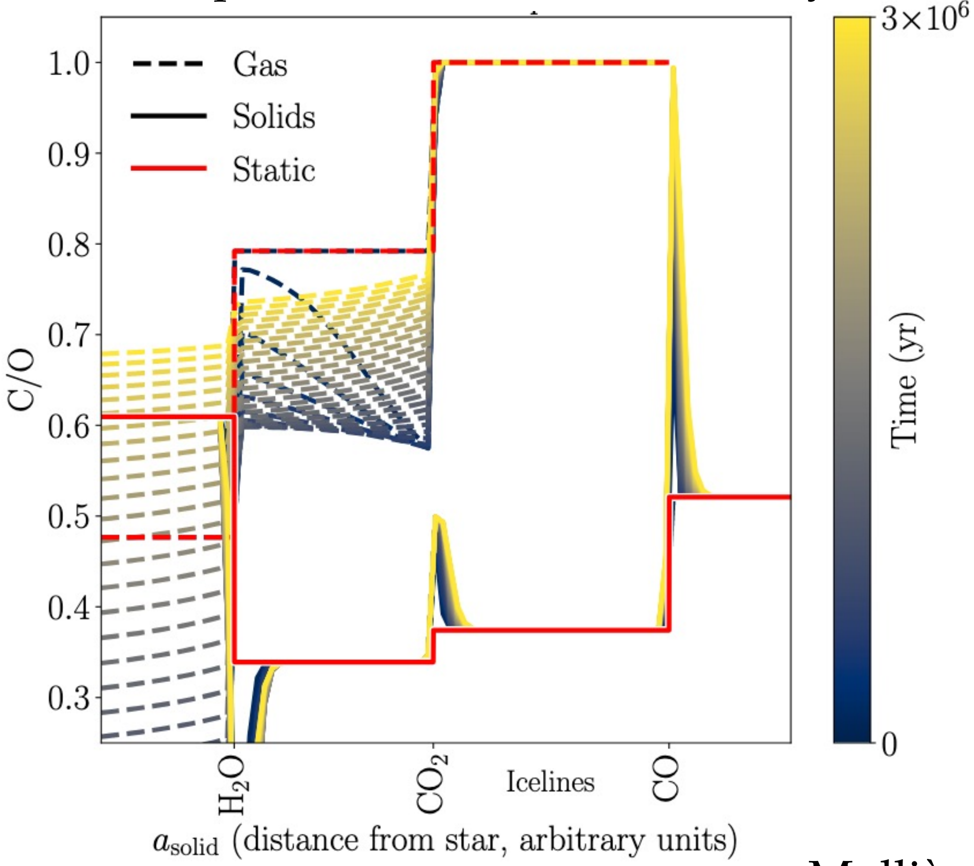
Oberg+11

C/O Changes Over Time

Add chemistry but no dynamics:



Add pebble drift but no chemistry:



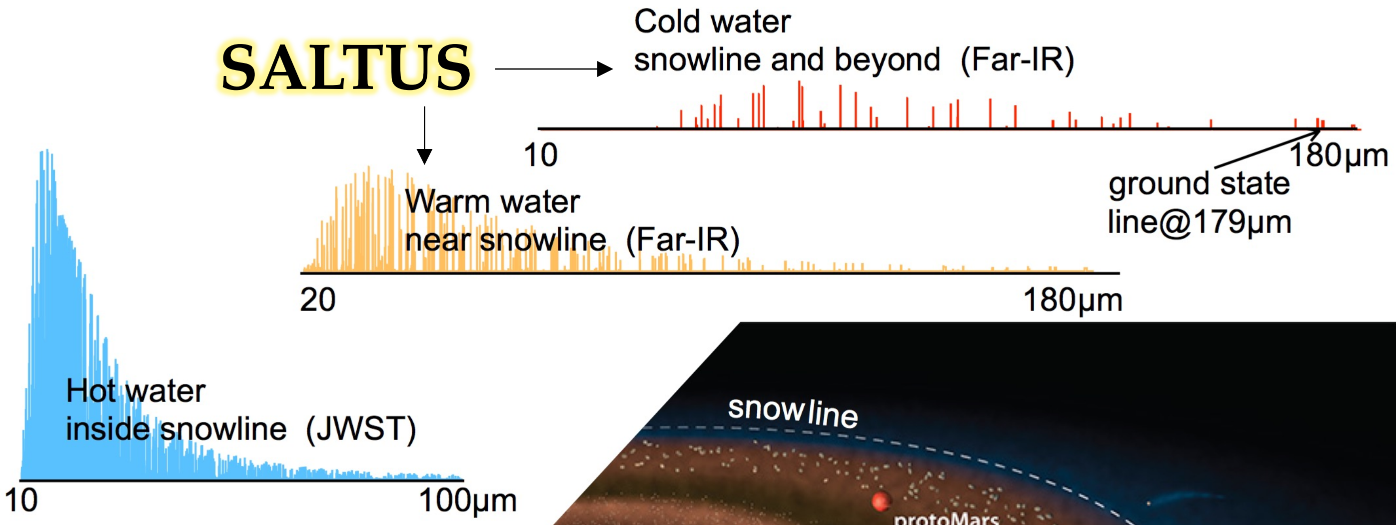
Mollière+22

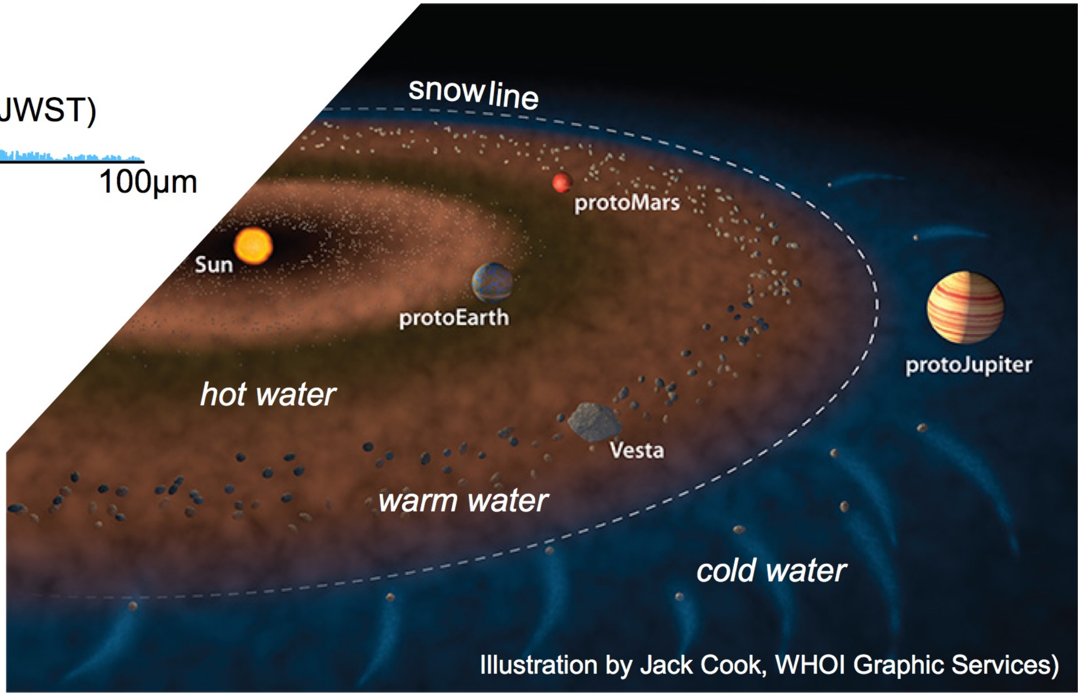
A statistical sample of C/O across evolutionary stages is needed to connect to planets

Mapping Water Vapor in Disks

„JWST will probe the warm regions of disks, **while longer wavelengths are needed for colder regions.“** – 2020 Decadal E-Qc1

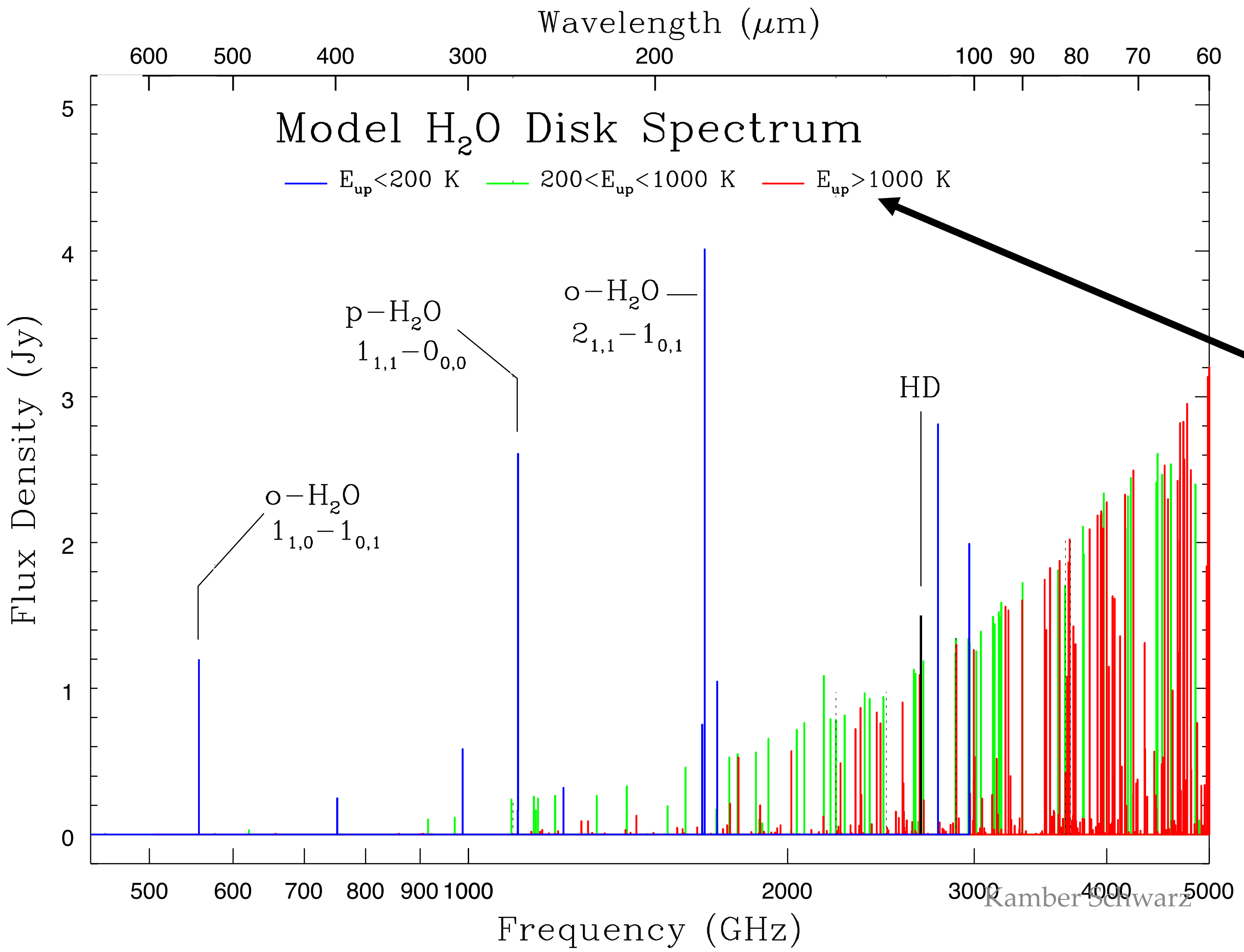
- Warm CO covered by ALMA
- CO_2 & hot water covered by JWST
- SALTUS covers cold→warm water vapor





Tracing the Water Snowline

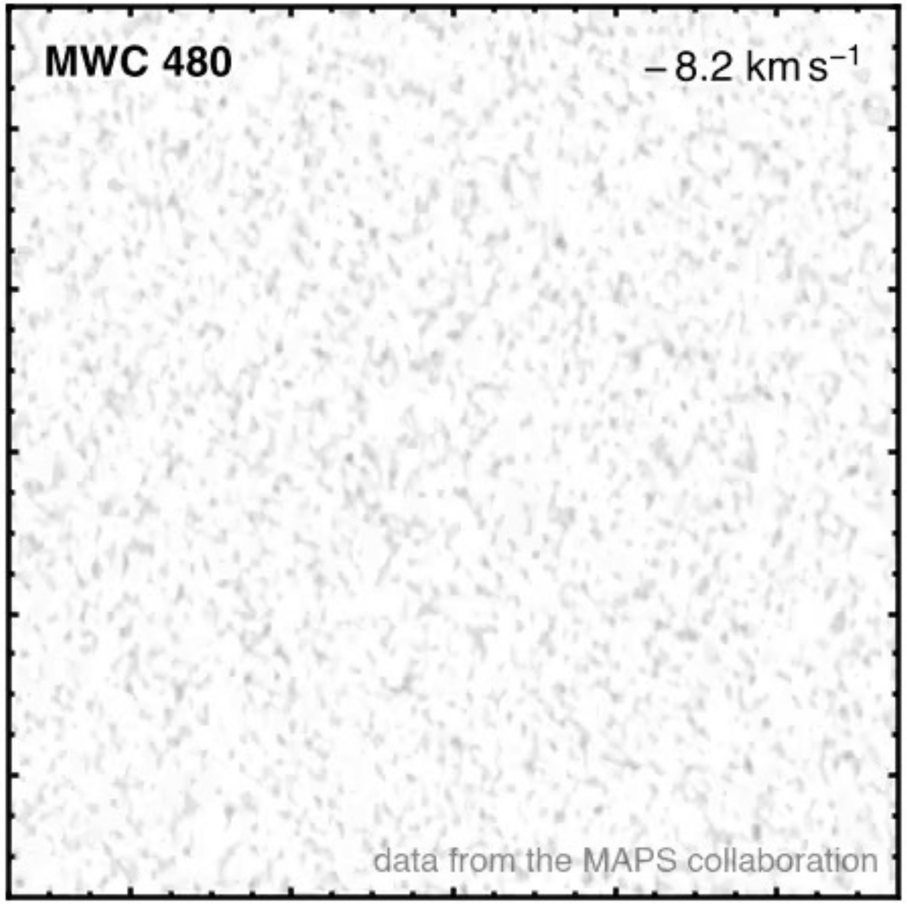
SALTUS HiRX HEB



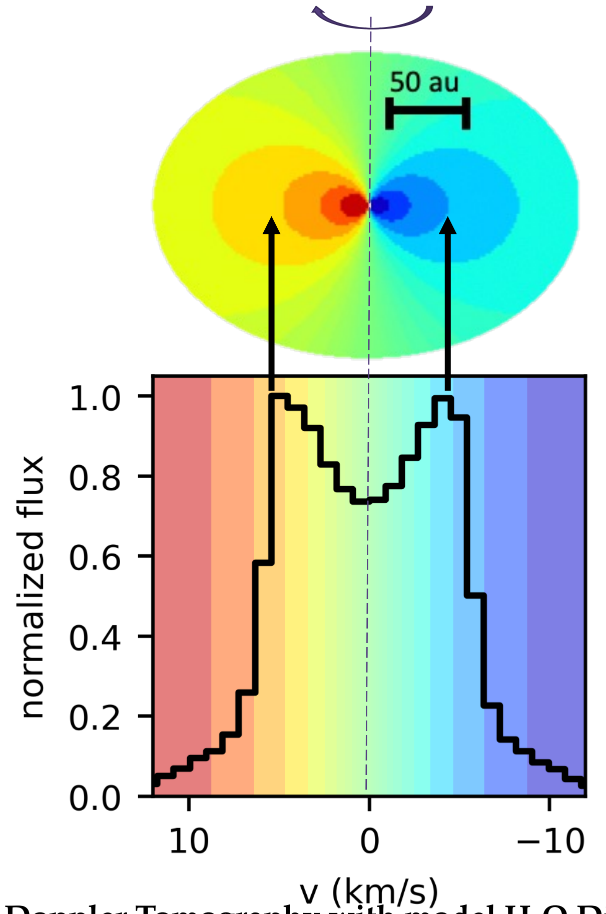
Transitions with E_{up} > 1000 K originate near the snowline (Notsu+16)

Doppler Tomography

High Spatial Resolution:



High Spectral Resolution:



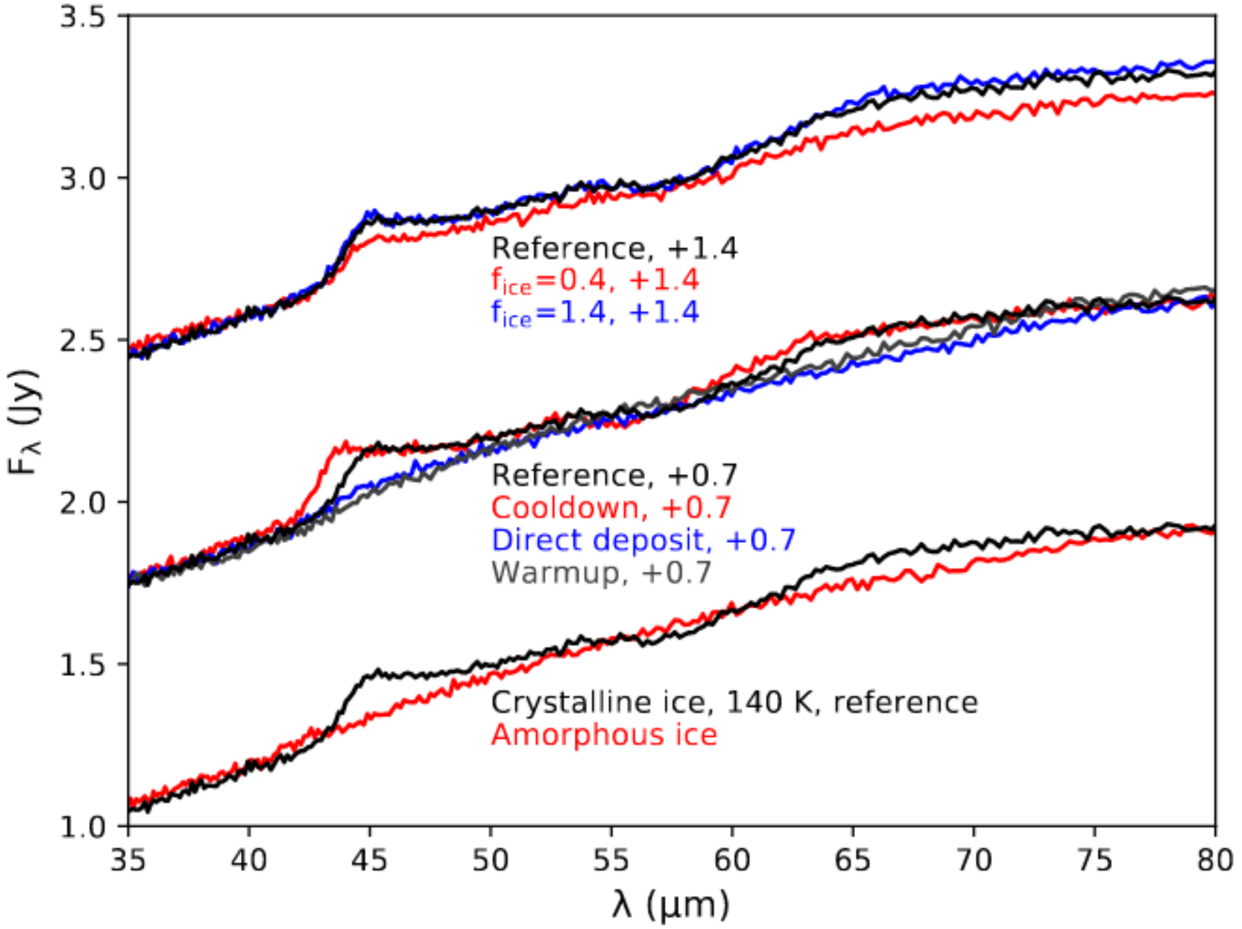
Doppler Tomography with model H_2O Disk Spectra

HiRX's high spectral resolution ($R \sim 10^6$) will map the emission radius using Doppler tomography

Ice Phonon Modes

- Mid-IR ice features only probe surface
- Lower optical depth in far-IR → Tracing bulk ice content
- Far-IR features in emission
  - Not dependent on viewing angle
- SAFARI-Lite can detect water ice at 45 & 63 microns & differentiate between environmental conditions

Simulated 10 minute exposure w/ SAFARI



Kamp+18

What Is the Range of Physical Environments Available for Planet Formation? - Decadal F-Q4b

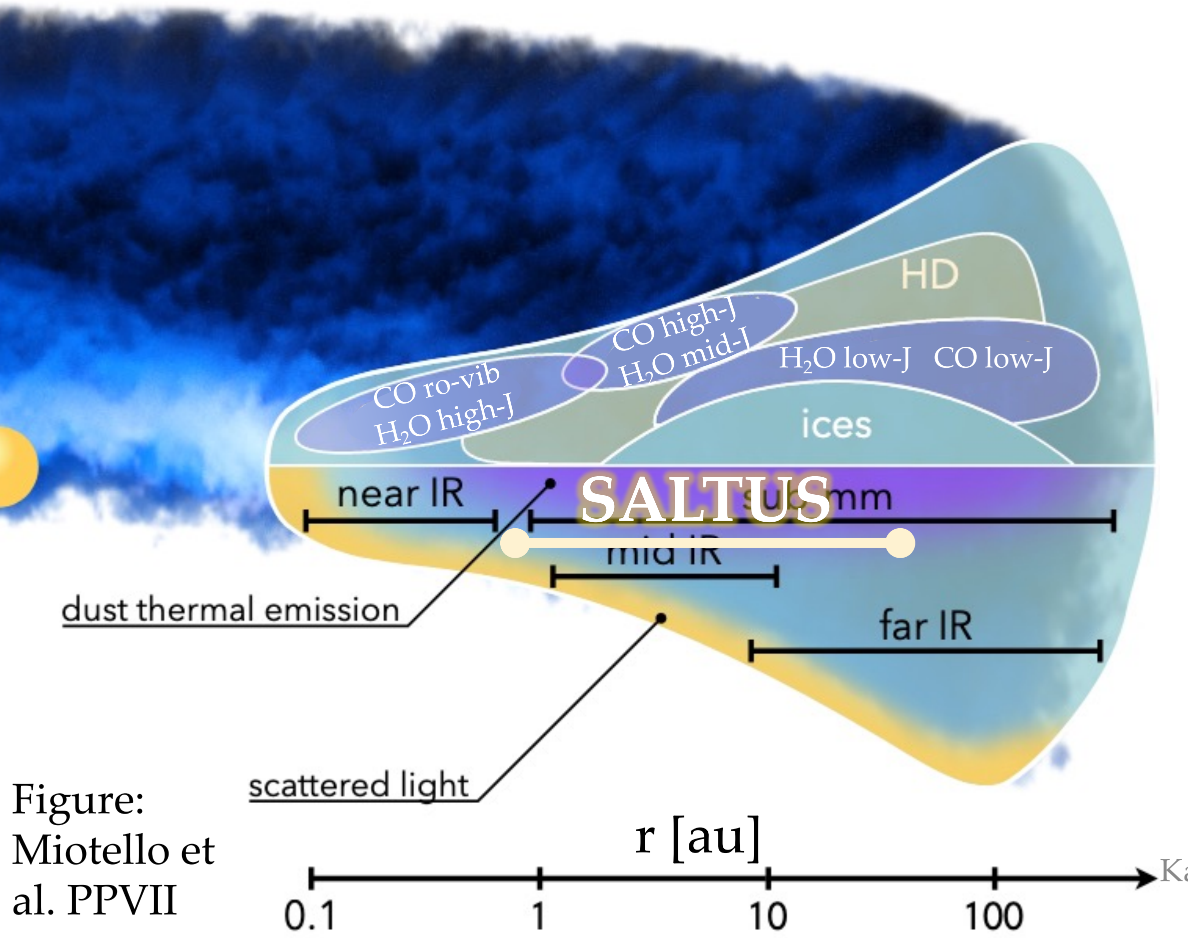


Figure: Miotello et al. PPVII

- Combine multiple lines tracing different parts of the disk + Doppler tomography
  - Optically thick -> 2D temperature map
  - Optically thin -> 2D abundance distribution

SALTUS will map 2D temperature distributions by observing optically thick H_2O & CO lines with a large range of E_u

Kamber Schwarz

What Is the Range of Physical Environments Available for Planet Formation? - Decadal F-Q4b

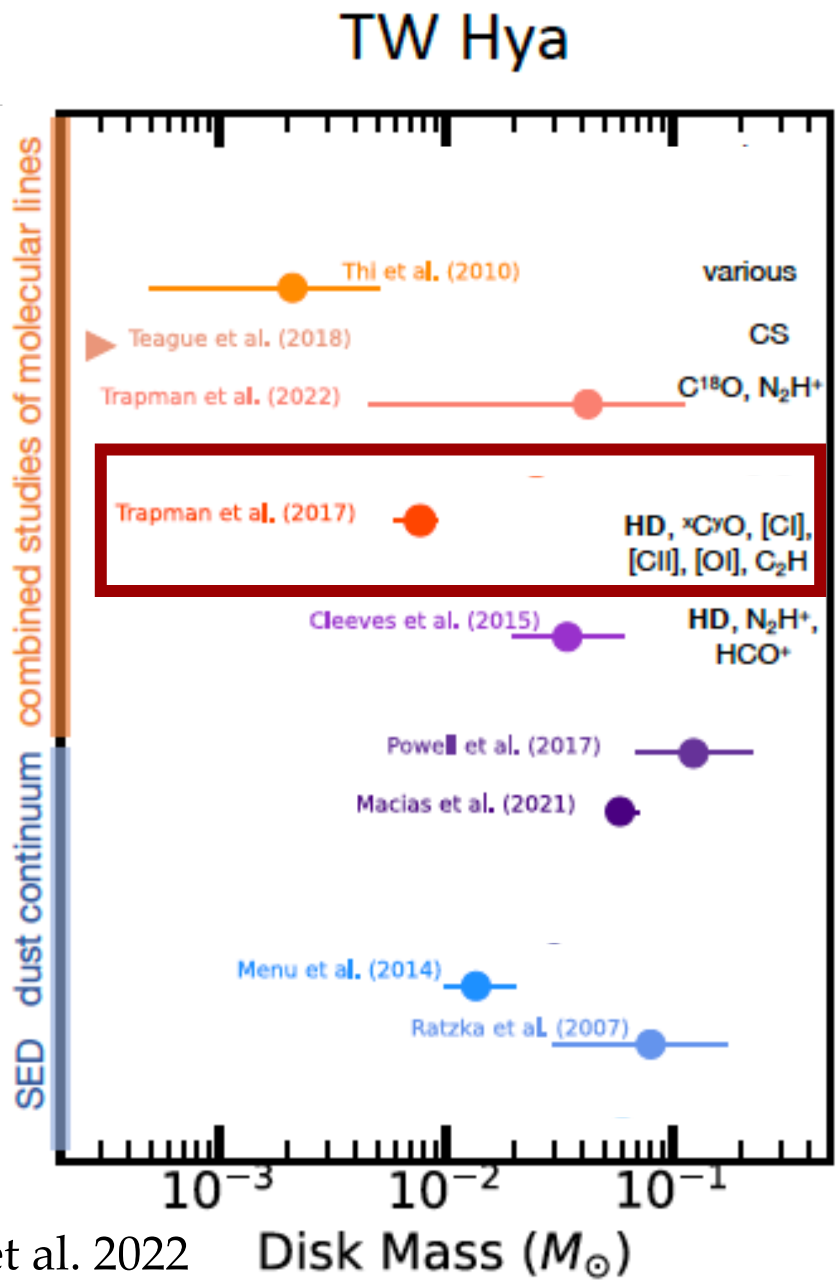
„The most promising options for determining the temperature, density, chemical, and dynamical structure of the gas rely on spatially and spectrally resolved observations of molecular emission lines"

- Chemical structure: Total (gas+ice) water abundance ✓
- 2D gas temperature ✓
- Density ?

„To anchor estimates of column densities onto an absolute scale, reference to measurements of a more direct gas mass tracer, **particularly the isotopologue HD**, would be beneficial"

Measuring Gas Mass with HD

- Traditionally dust or CO emission is used to trace gas mass; they disagree
- Various assumptions limit utility of the above tracers
- HD ground state @ 112 μm is the MOST DIRECT gas mass tracer
  - *Herschel* observed 7 srcs; detected 3
  - Requires additional lines to break temperature-abundance degeneracy
- **No current observatory is capable of observing HD**



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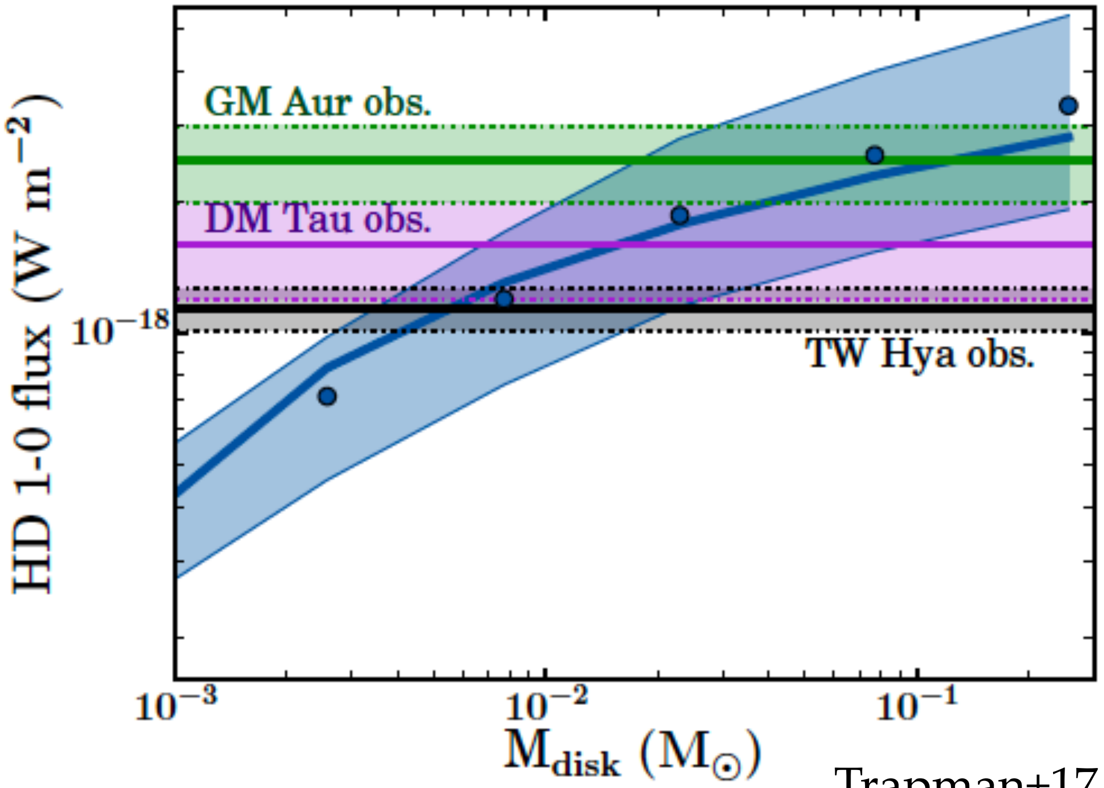
Miotello et al. 2022

Uncertainty in HD Based Mass



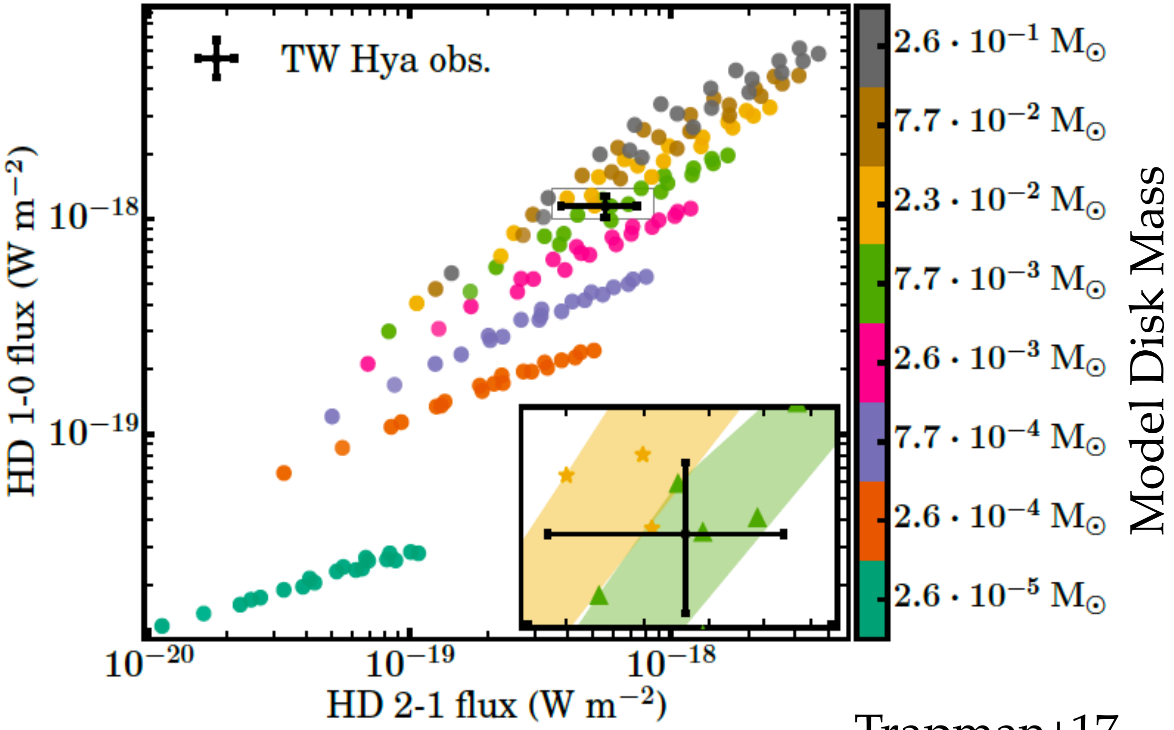
Trapman+17

For 100 MMSN (1 $M_\odot$) disk:

- Order of magnitude uncertainty on disk mass using just HD 1-0 (Trapman+17)

Uncertainty in HD Based Mass

HD 1-0 + HD 2-1 + Model



Trapman+17

For 100 MMSN (1 M$_\odot$) disk:

- Order of magnitude uncertainty on disk mass using just HD 1-0 (Trapman+17)
- Lower uncertainty with knowledge of vertical structure OR HD 2-1

SALTUS will observe HD 1-0, 2-1 and multiple water & CO lines (for temperature) simultaneously

SALTUS is a High Sensitivity Machine

HiRx

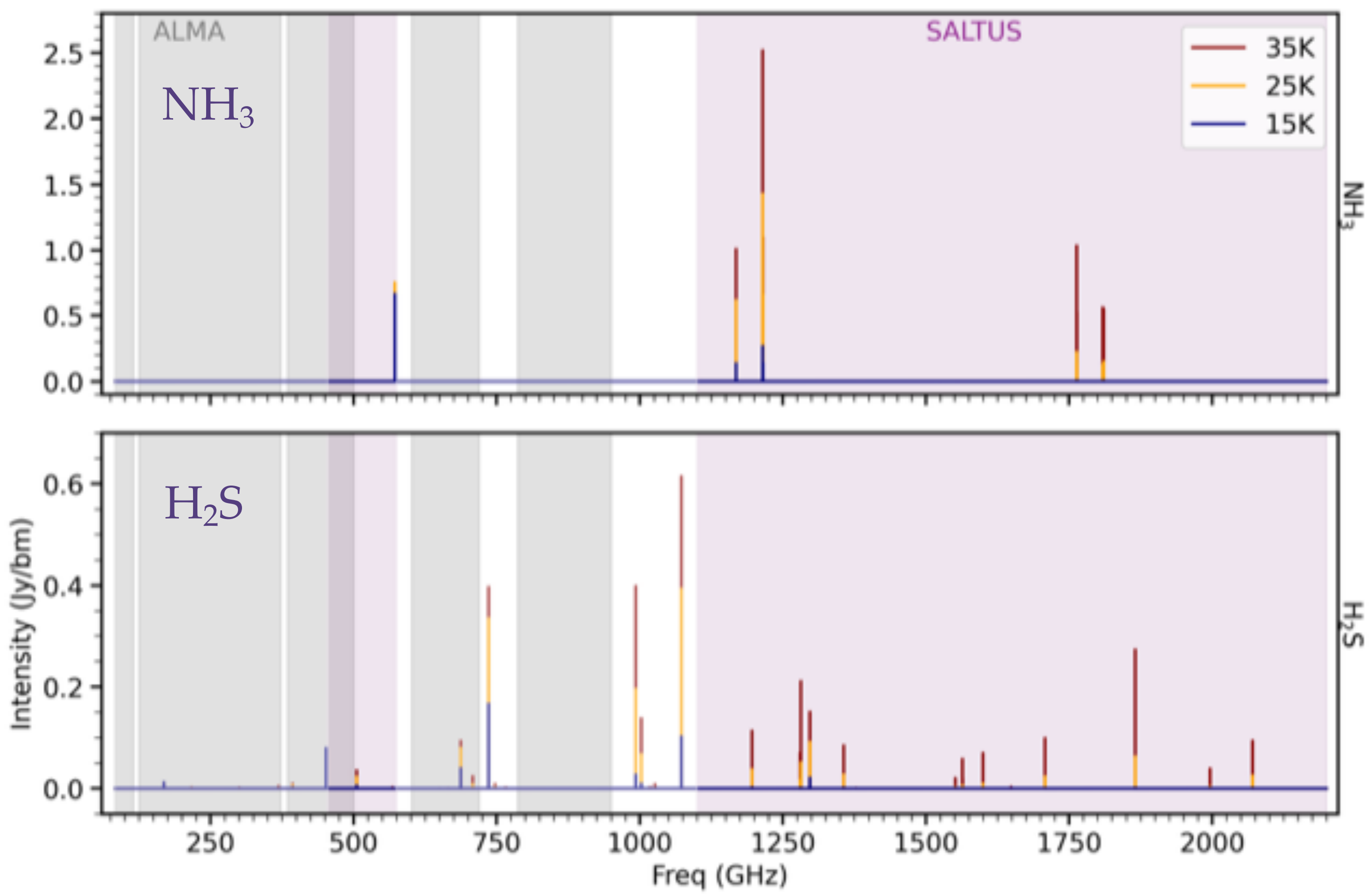
- 10 hours for 5σ detection of HD 2-1 out to dv=10 km s^{-1}
    - 10^{-3} $M_\odot$ disk at 160 pc
- Simultaneous observing allows for high S/N H_2O detections while integrating on HD 2-1
- 10 disks in Year 1

SAFARI-LITE

- 10 minute integration to detect & determine state of H_2O ice
- 1 hour for 7σ of integrated HD in 10^{-4} $M_\odot$ disk
- **In 70 minutes integration get:**
    - **Gas Mass**
    - **Gas-phase Water**
    - **Water Ice**
- 100 disks in Year 1

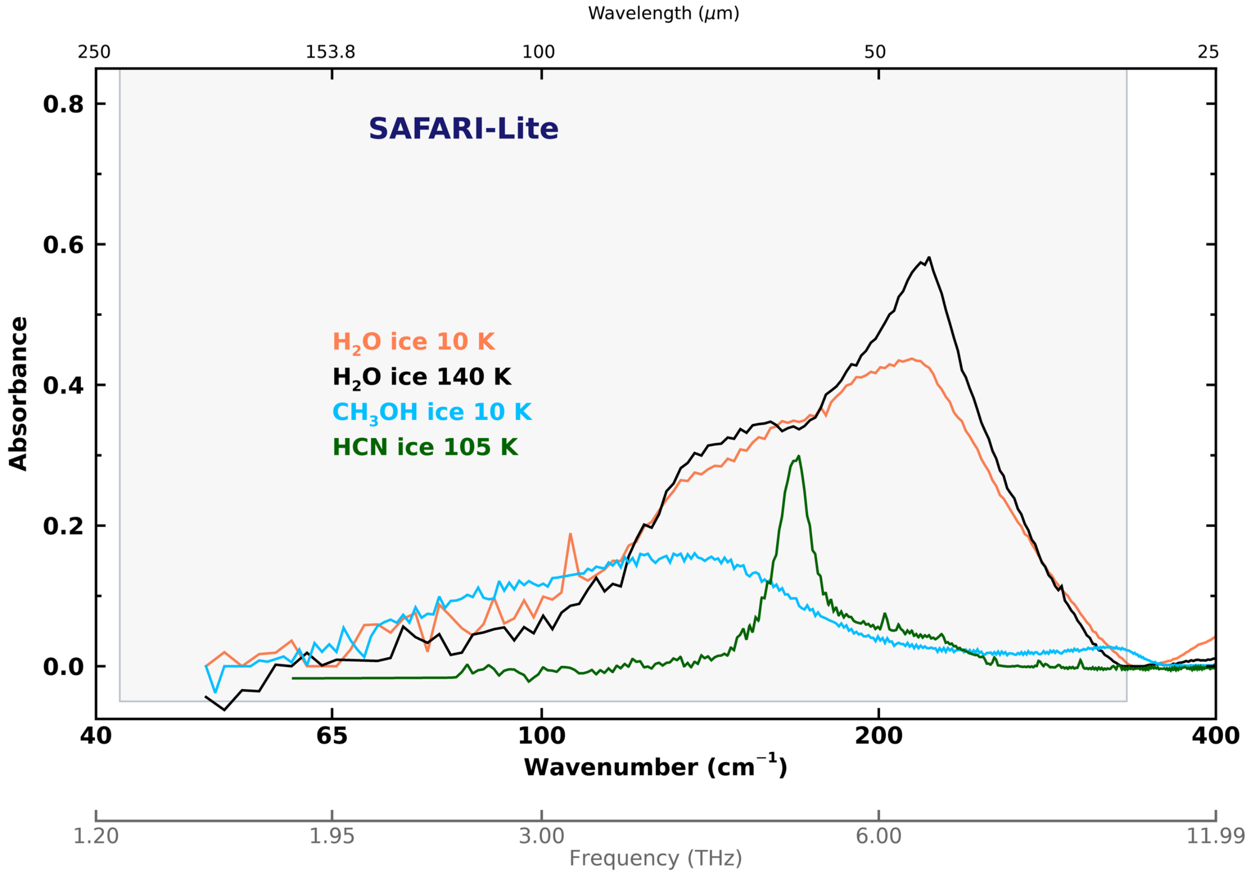
Measuring Major O, N, S Carriers in Gas Disks

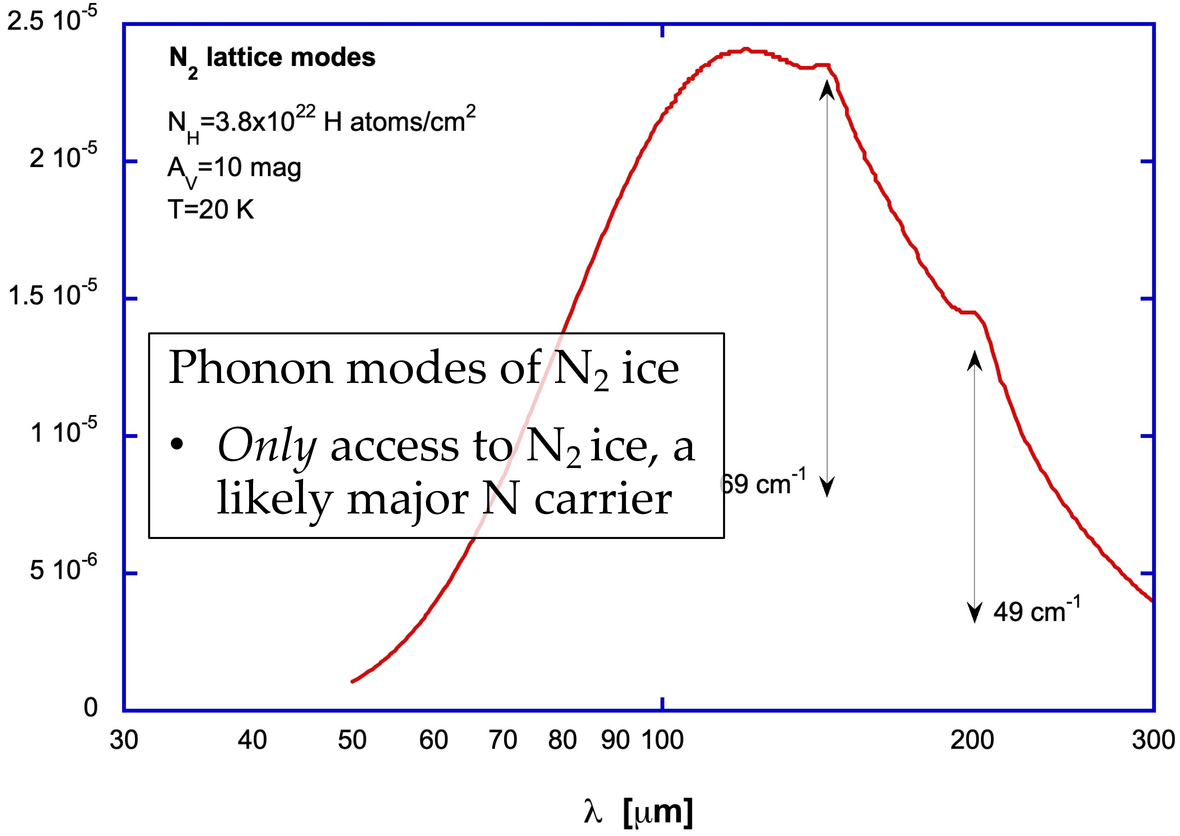
- Major volatiles: CHONS
  - Important for habitability
- O, N, & S distribution largely unknown
- Only 1 detection of NH_3 gas in an outer disk (Salinas et al. 2016)
- Major carriers (H_2O, H_2S, NH_3) require THz instrument to observe



Measuring C, O, N, S in ices

H_2O, HCN, NH_3, N_2, H_2S, CO, CO_2, CH_3OH, H_2CO





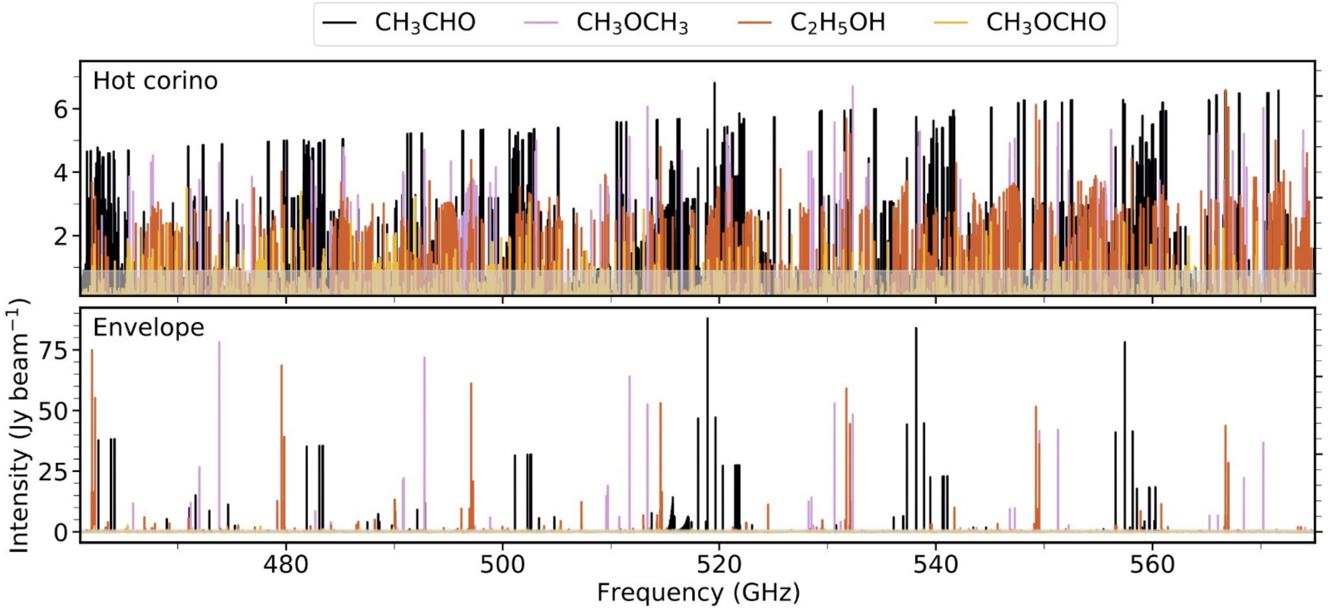
Phonon modes of N_2 ice

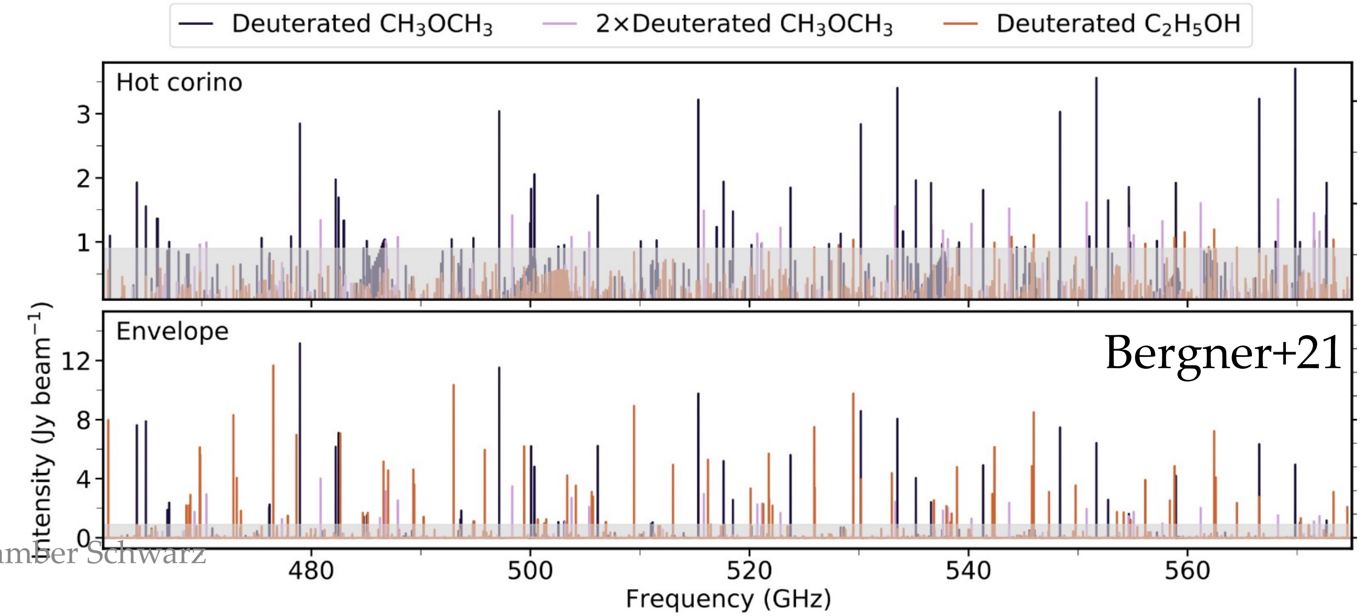
- *Only* access to N_2 ice, a likely major N carrier

Organics in Protostellar Cores

„ What generates the observed chemical complexity of molecular gas?“
– Decadal F-Q2c

- Emission from sublimated ices
- Isotopologue abundance traces formation
- Previous surveys suffer from beam dilution or resolve out emission

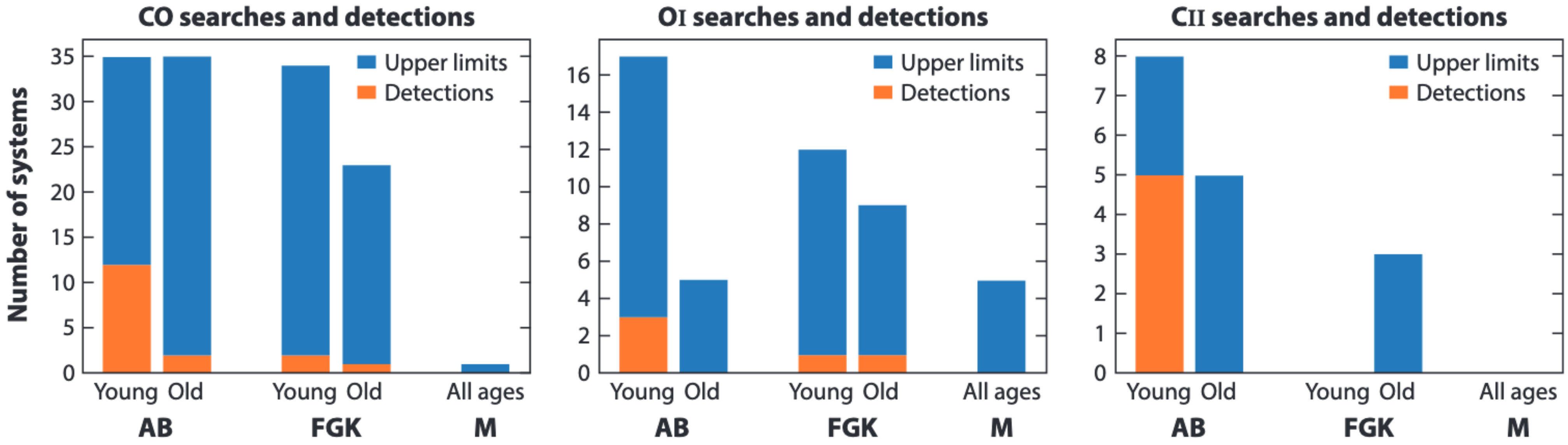




Bergner+21

Probing C, O in Debris Disks

- Gas released from colliding planetesimals
- May facilitate late gas accretion by planets, affect planet atmospheres (Kral+20)
- Detections to date: 25, mostly A stars



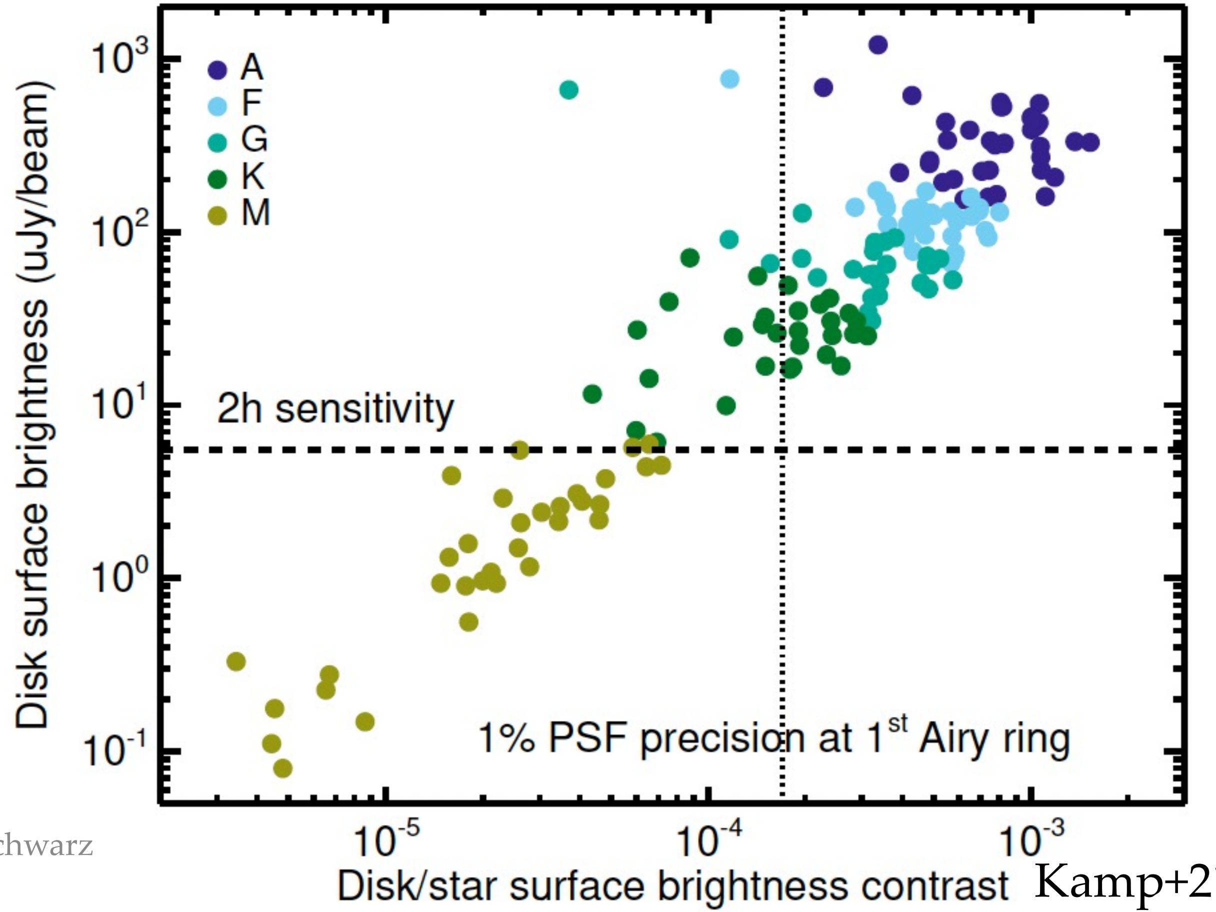
Hughes et al. 2018

SALTUS will detect CII and OI in >10 debris disks in Year 1

Deep Integrations on Debris Disks

„How Does the Distribution of Dust and Small Bodies in Mature Systems Connect to the Current and Past Dynamical States Within Planetary Systems?"
– 2020 Decadal E-Q1d

- Emission from exo-Kuiper Belt peaks in FIR
  - No current detections
- Constrain frequency of exo-Kuiper Belts



Kamp+21

Why SALTUS

Strengths

- Large aperture → high sensitivity
- Above Earth's atm → access to FIR diagnostics (HD, H_2O, N_2, H_2S,…)
- Broad λ coverage → many ice and gas species, transitions
- High spectral res → spatially resolve disk in velocity-space
- Low spectral res → solid state species

Science Highlights

- First census of reliable disk gas masses with HD
  - Fundamental constraint on theories
- Inventory disk ices, gaseous molecules, measure ice lines (H_2O, NH_3…)
  - Enables retrieval of planet formation & migration histories from composition
- Census of typical debris disks
  - Put Solar System in context