April 2nd – 4th 2025
Future role of FIR-Submm
Space Observations
Leiden, The Netherlands

Water gas in protoplanetary disks
- current and future observations -

Shota Notsu (野津 翔太)

Assistant Professor, Department of Earth and Planetary Science,

Graduate School of Science, The University of Tokyo, Japan

2019-2020: postdoc in Leiden Observatory (Ewine van Dishoeck's group)

Water snowline and dust grains in protoplanetary disks

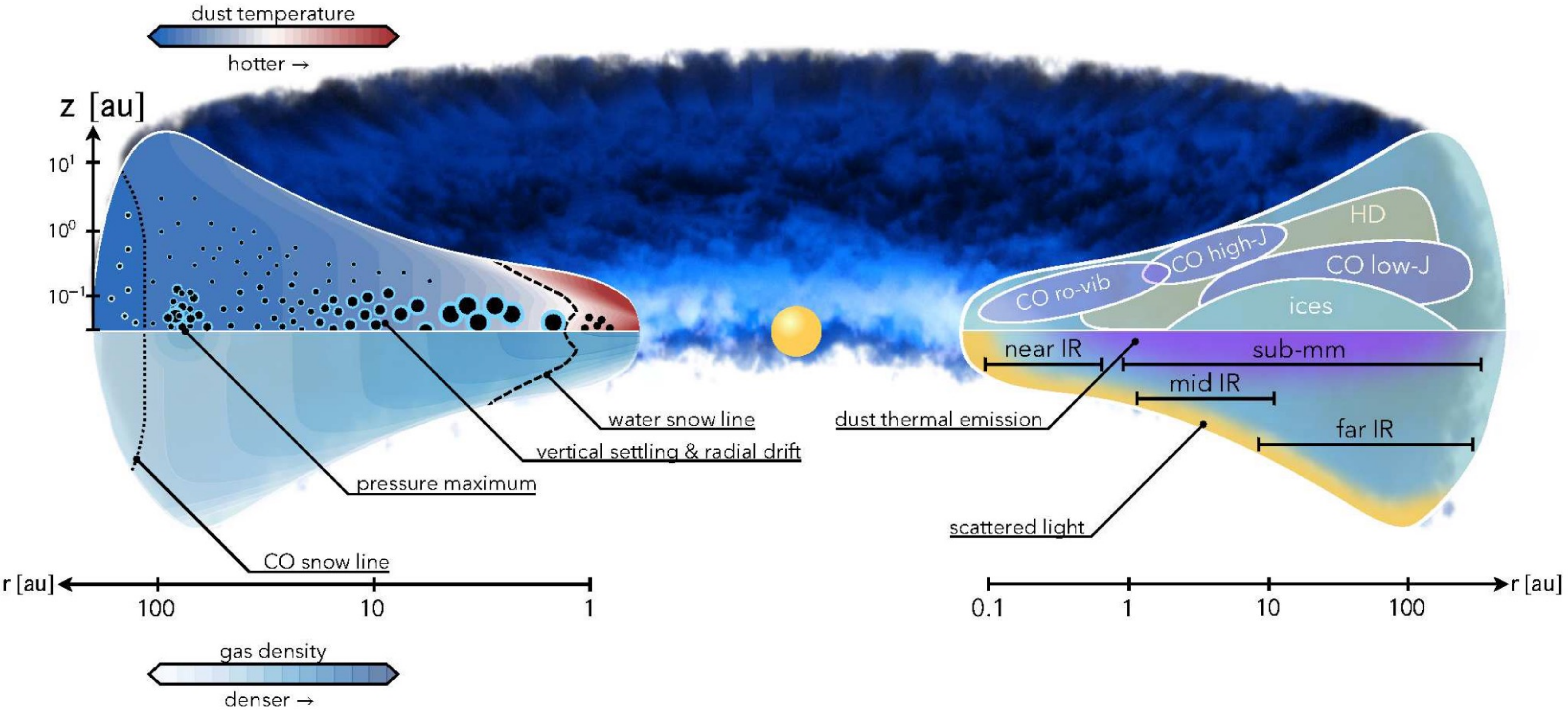


Figure from Miotello et al. 2023 (PPVII)

Snowline positions move inward with time

Snowlines are sublimation front of volatile molecules

In disks and envelopes around Class 0-I protostars, snowline positions are located outside!

Snowline positions are determined by heating of **central star radiation** and **viscous accretion**

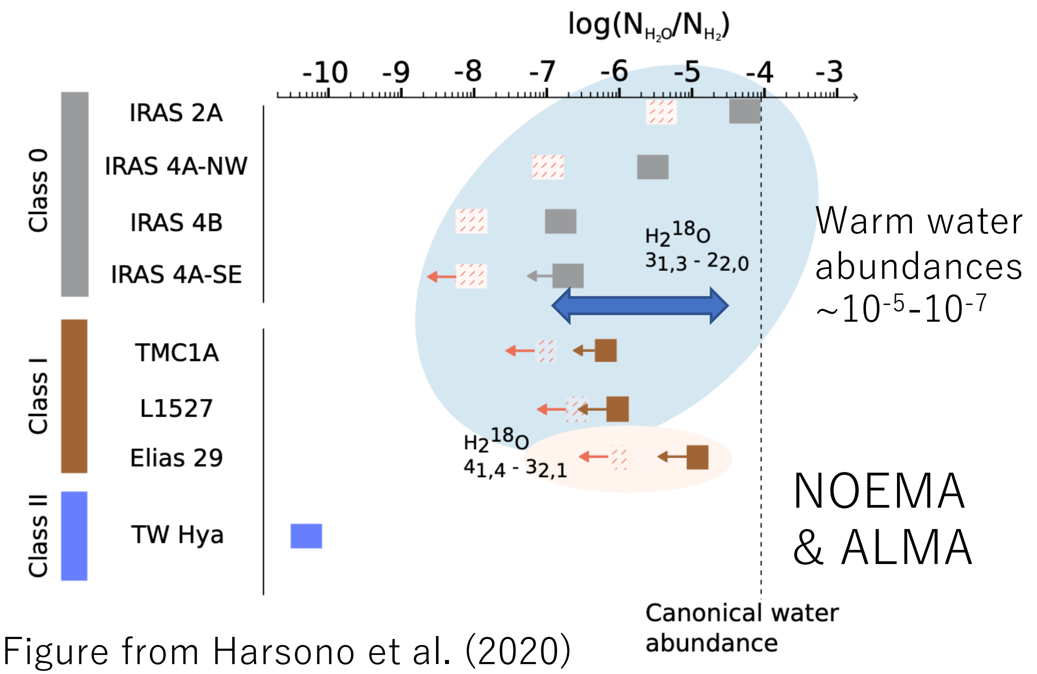
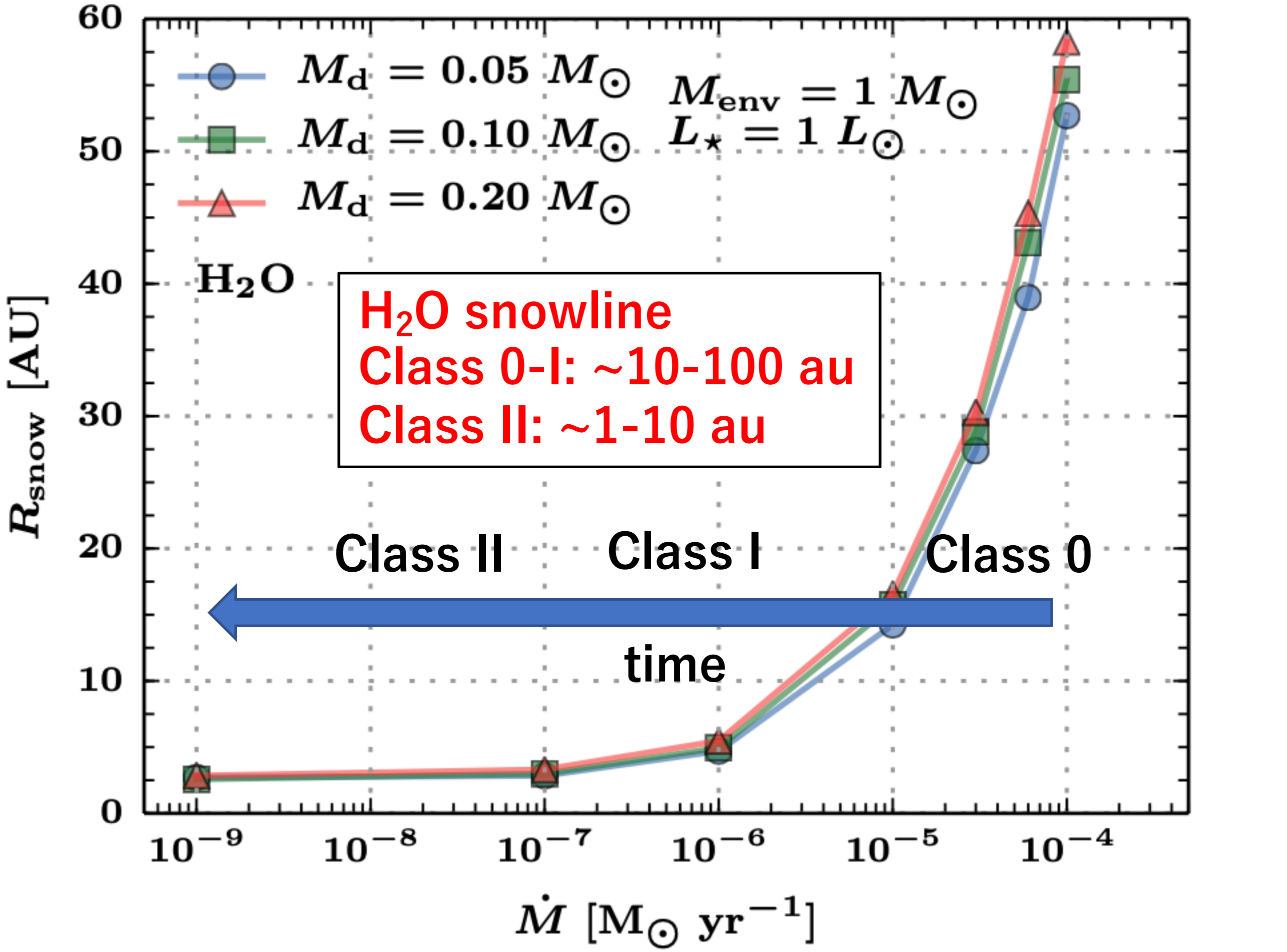


Figure from Harsono et al. (2020)

Figure from Harsono et al. (2015)



Harsono et al. (2015, 2020)
See also e.g., Notsu et al. (2021)

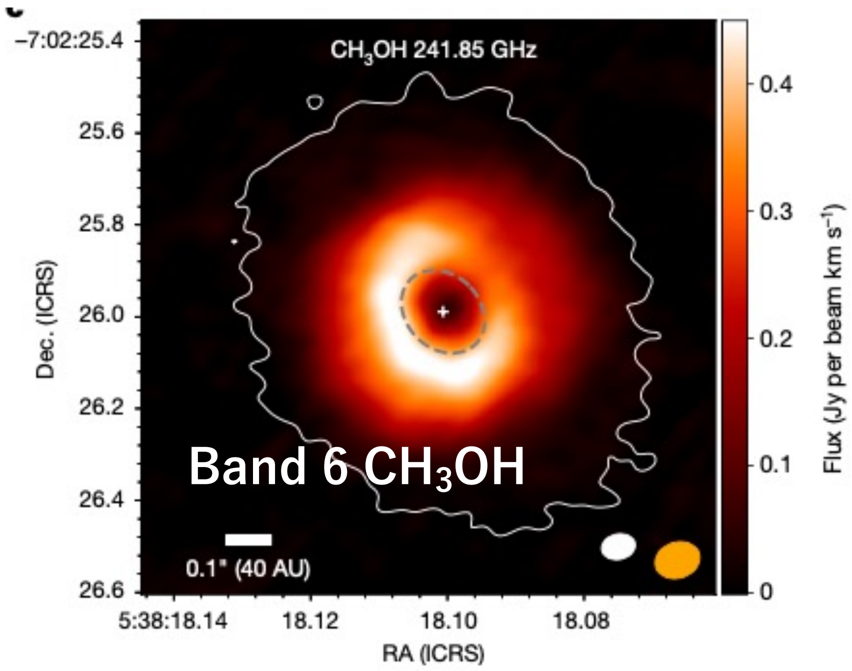
V883 Ori: FU Ori type Class I protostar with accretion burst

V883 Ori : FU Ori type star at Orion Nebula Cluster (d=400 pc), now bursting (~100 yr)
Class I, L_{bol} = 200L_{sun}, M_{star}=1.3M_{sun}

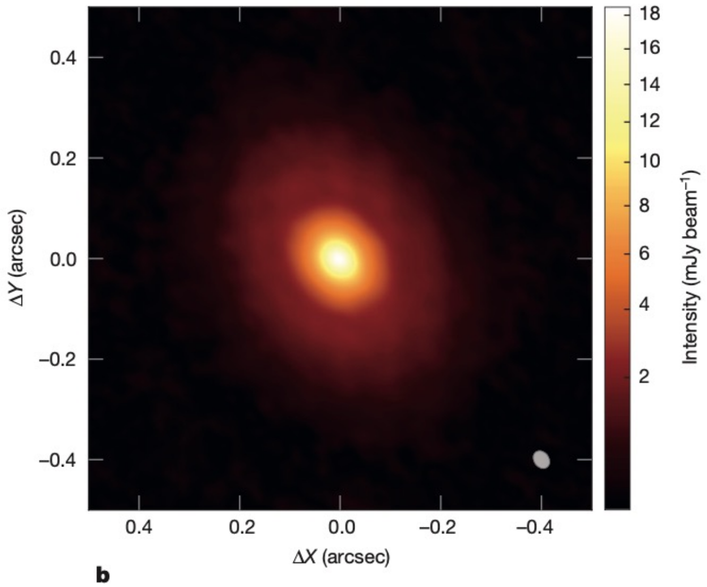
Significant mass accretion heating in the disk and water snowline shift outside.
→ Water and Complex organic molecules (COMs) are released from icy grain-surface to gas.

ALMA Obs.

H_2O and CH_3OH snowline ~ 80 au



Band 6 Continuum



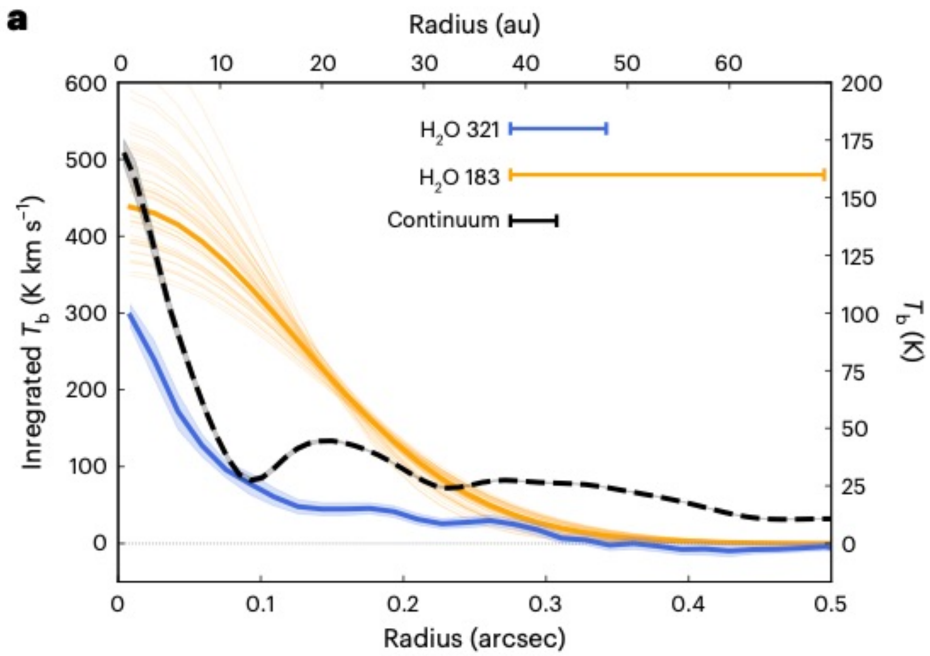
Tobin et al. (2023)
See e.g., van't Hoff et al. (2018), Lee et al. (2019), Yamato et al. (2024), Jeong et al. (2025)

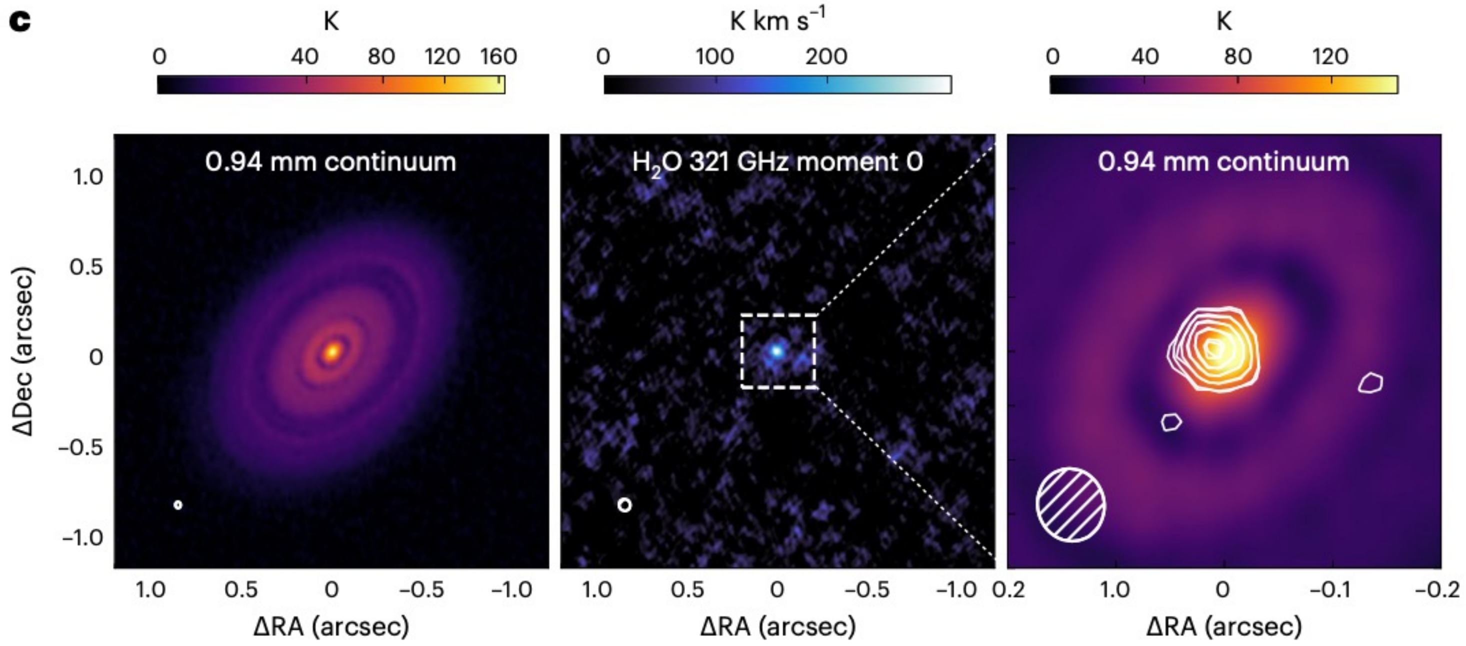
Band 3 COMs distribution and $^{12}C/^{13}C$ ratios in COMs
→ Yamato, Notsu et al. (2024)

H_2O line detection in Class I disk HL Tau with ALMA

Detected lines: $H_2{}^{16}O$ 183GHz, 321GHz, 325GHz (Band 5, Band 7)
They trace the hot water vapor within the water snowline (based on the model calculations)

Facchini et al. (2024, Nature Astronomy)

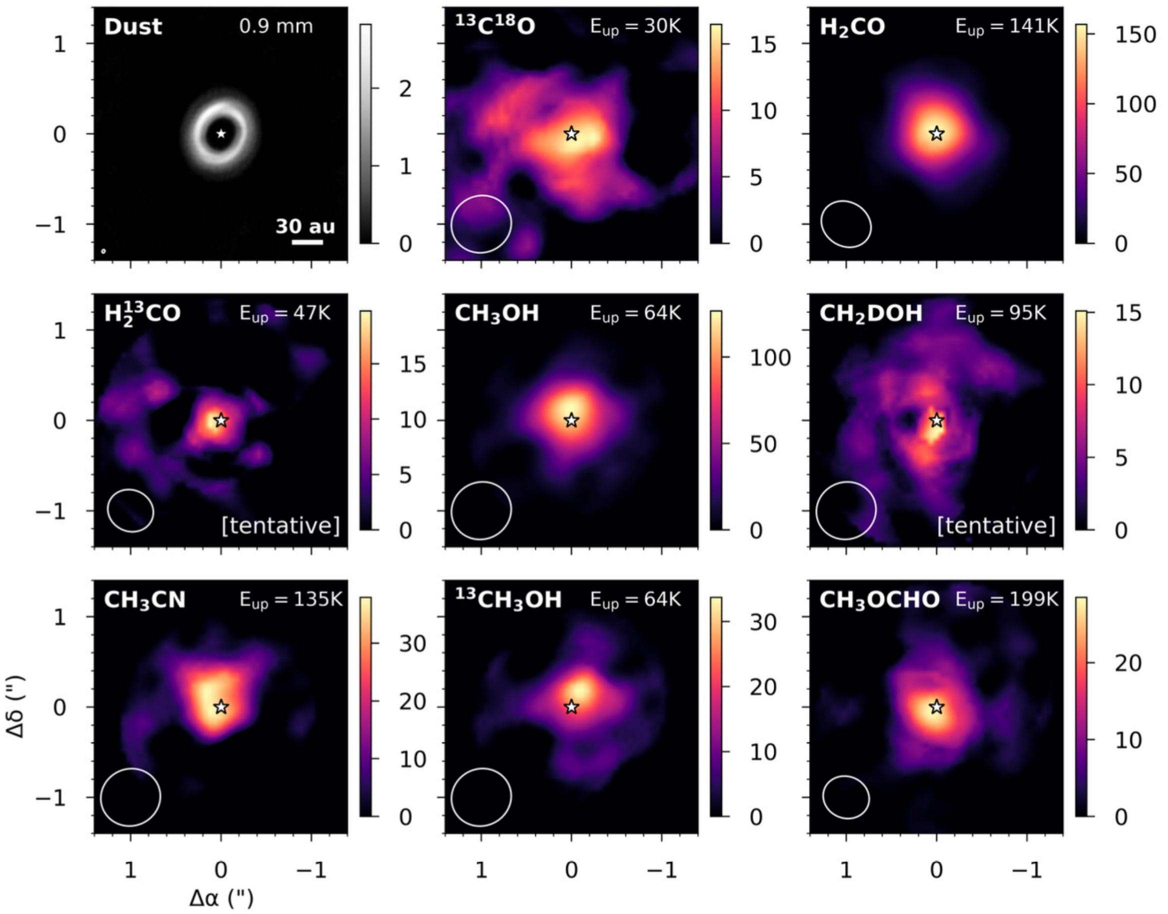




H_2O snowline position: within 17 au
(consistent with the position of 10 au tiny inner gap?)
Water mass is more than 3.7 Earth Mass

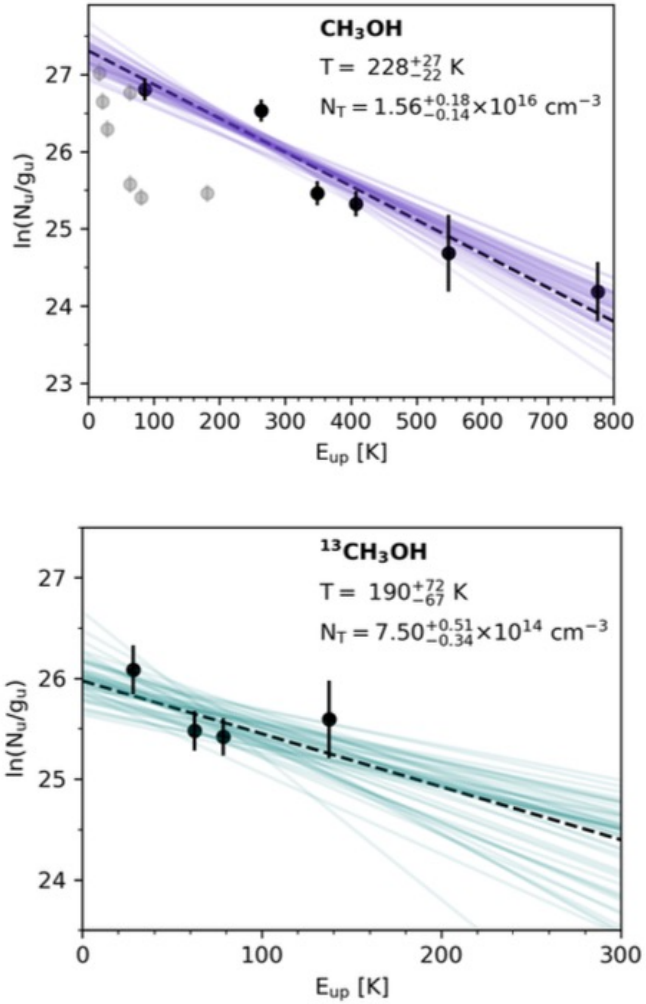
COMs have been detected in Herbig disks with ALMA

$T_{snowline}$ (H_2O) ~ $T_{snowlone}$ (CH_3OH) ~ 100-150K



HD 100543

T_{rot}(CH_3OH) ~200 K

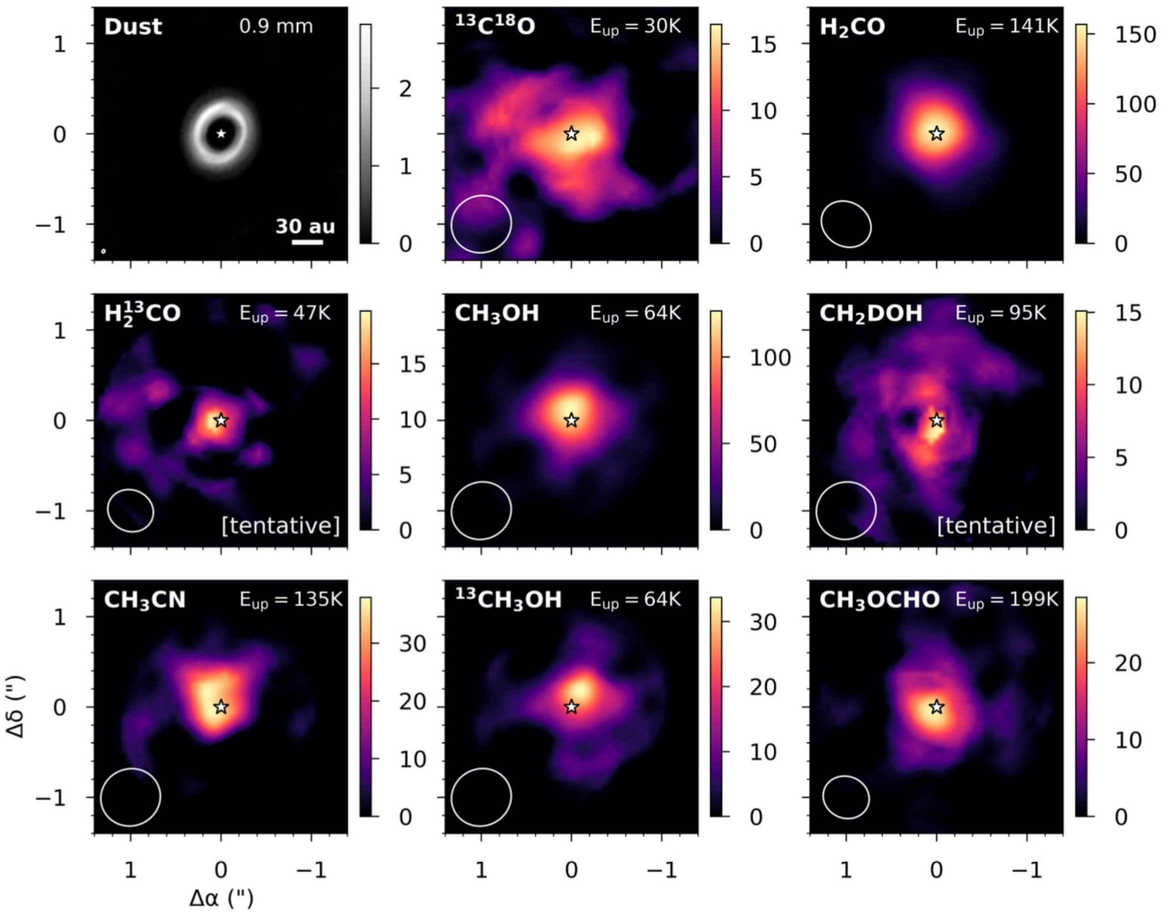


Alice S. Booth
(Harvard/CfA)

Booth....Notsu et al. (2025)
See also e.g., Booth et al. (2024a&b), Yamato et al. (2024b), Evans et al. (2025), Temmink et al. (2025)

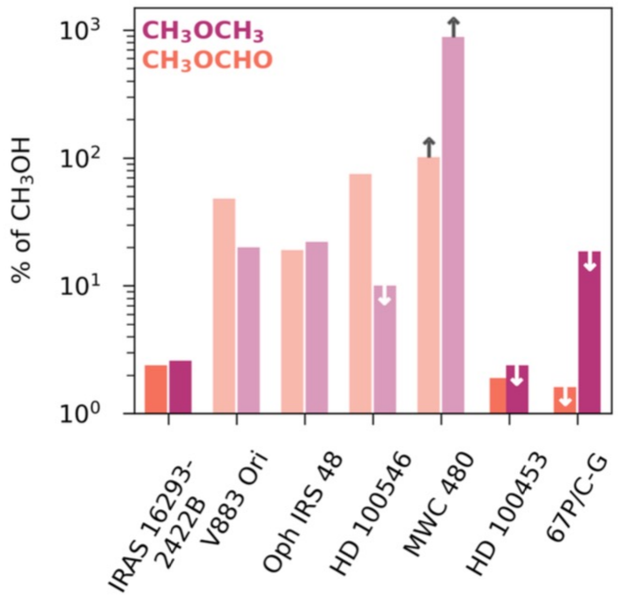
COMs have been detected in Herbig disks with ALMA

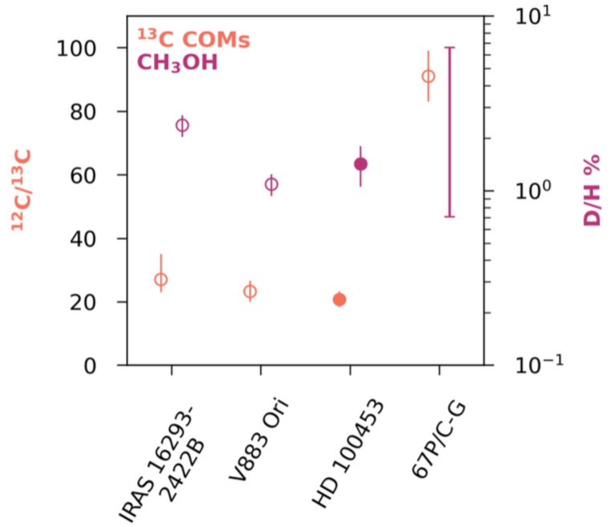
$T_{snowline}$ (H_2O) ~ $T_{snowlone}$ (CH_3OH) ~ 100-150K



T_{rot}(CH_3OH)~200 K

HD 100543





Upcoming ALMA observations:
We expect to detect water lines in several
Class II Herbig Ae/Be disks with COMs detections!
(Class II T Tauri is too weak to observe with ALMA…)

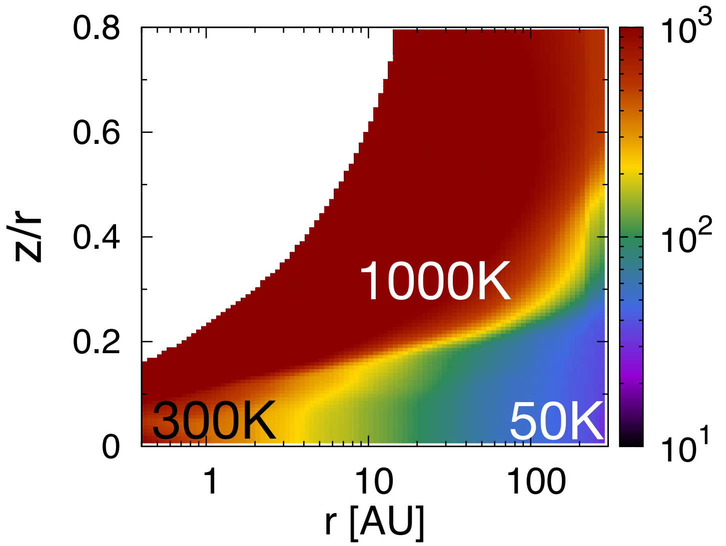
Alice S. Booth
(Harvard/CfA)

Y. Yamato
(PhD student in UTokyo)
→SPDR Fellow in RIKEN
(April 2024 -)

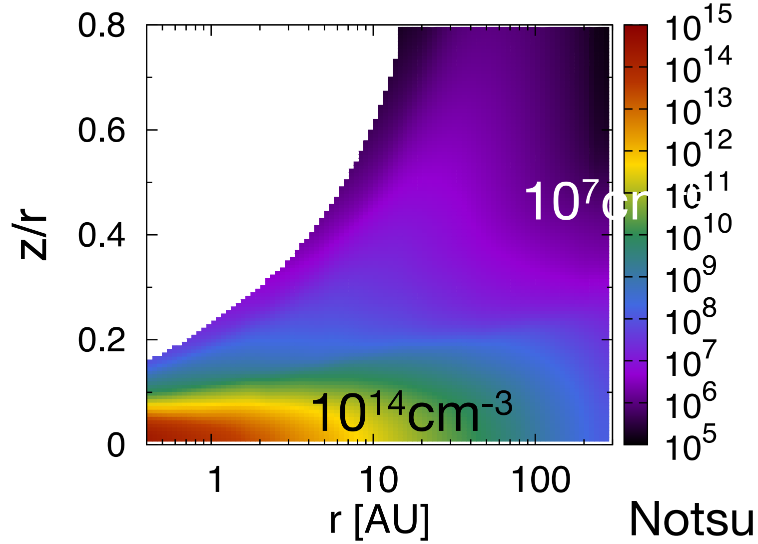
Booth....Notsu et al. (2025)
See also e.g., Booth et al. (2024a&b), Yamato et al. (2024b), Evans et al. (2025), Temmink et al. (2025)

H_2O gas is abundant both in the disk inner midplane and surface

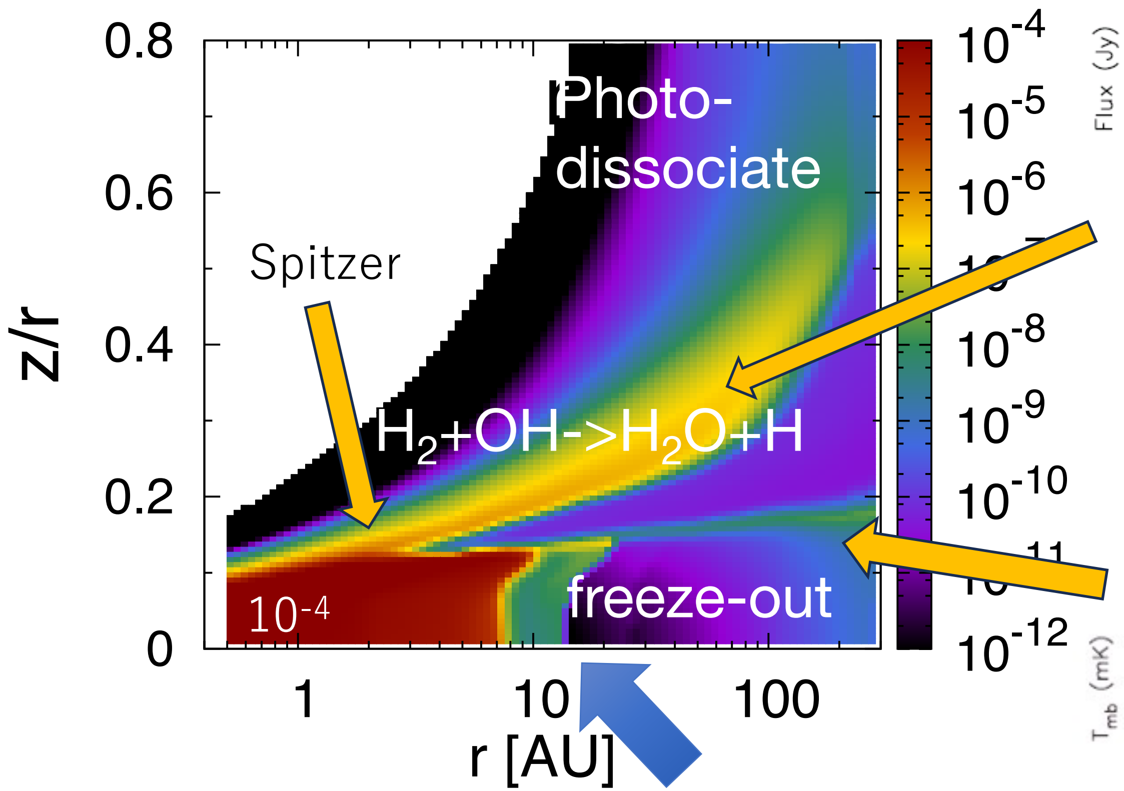
Gas Temperature



Gas Number Density

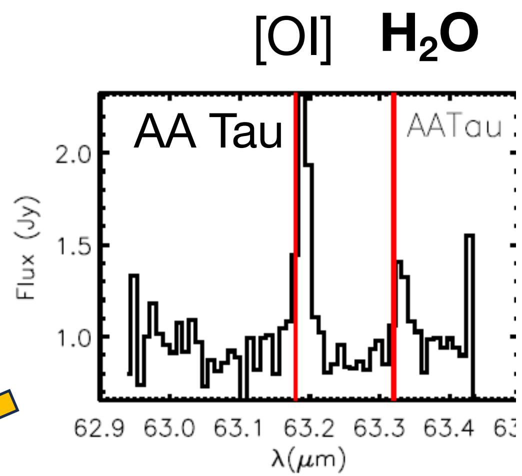


Herbig Ae disk model
($M=2.5M_{sun}$ $T_{eff}=10,000K$ $R=2R_{sun}$)



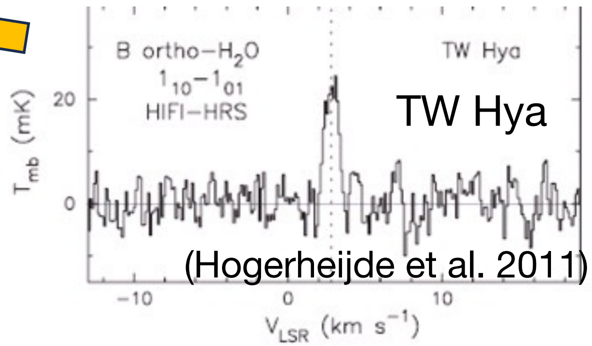
H_2O snowline

(Riviere-Marichalaret al. 2012)



Herschel/PACS

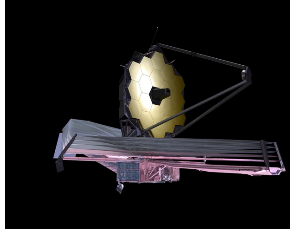
Herschel/HIFI



(Hogerheijde et al. 2011)

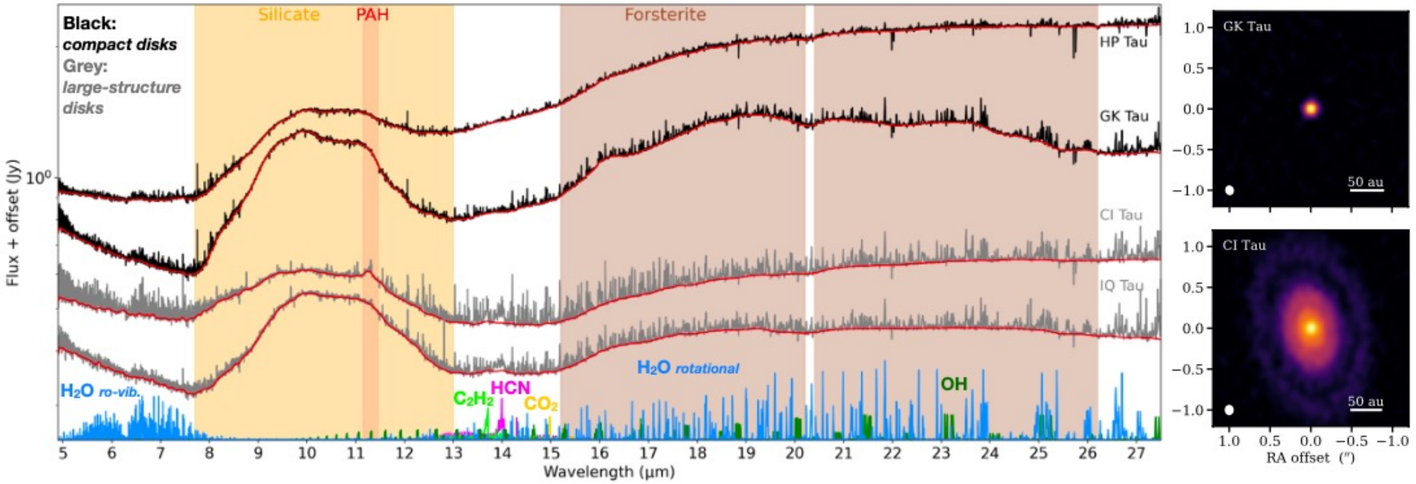
Notsu et al. (2016, 2017, 2018)

Recent JWST/MIRI observations for Class II disks



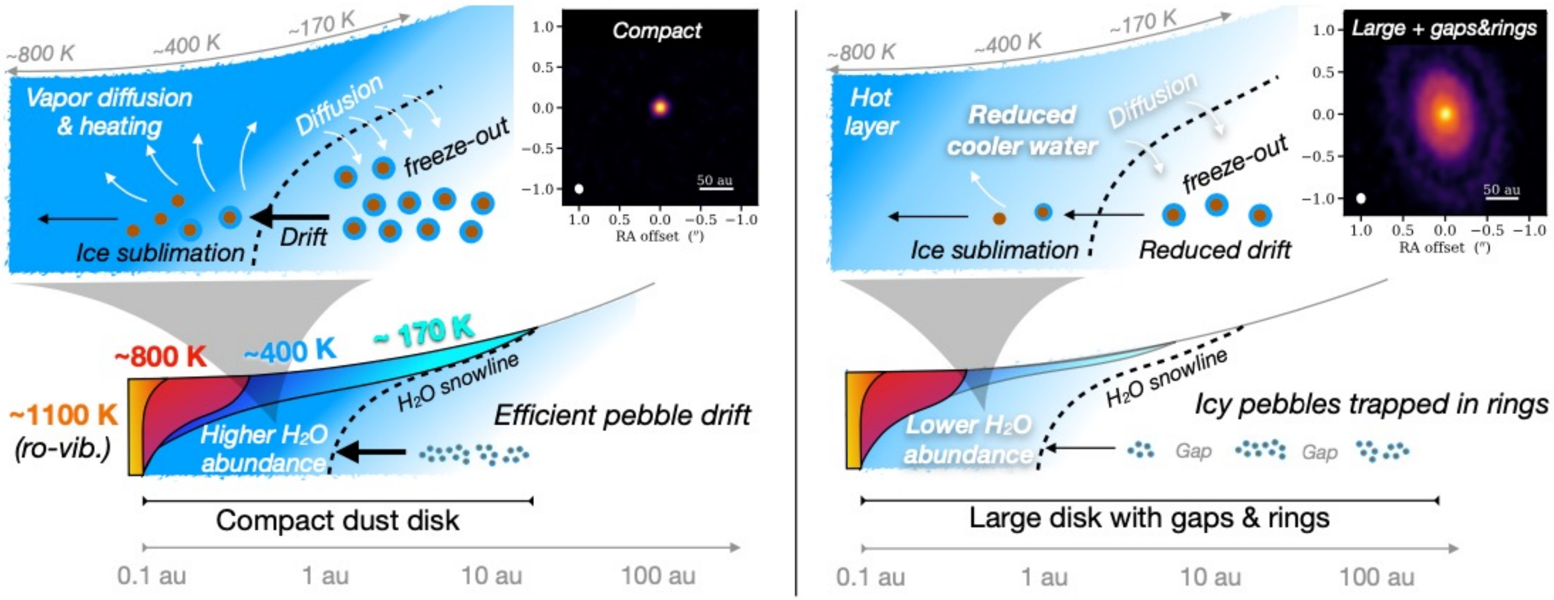
Banzatti et al. (2023, 2025)

See e.g., JWST/MINDS, JDISCS papers



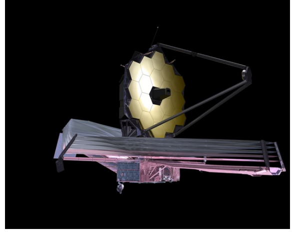
- Various molecular lines which are useful for detecting C/O ratio (CO_2, $^{13}CO_2$, OH, C_2H, HCN, CH_4, H_2 etc.)
- **Higher H_2O abundance in compact disks vs Lower H_2O abundance in large disks**

JWST REVEALS EXCESS COOL WATER IN COMPACT DISKS 9

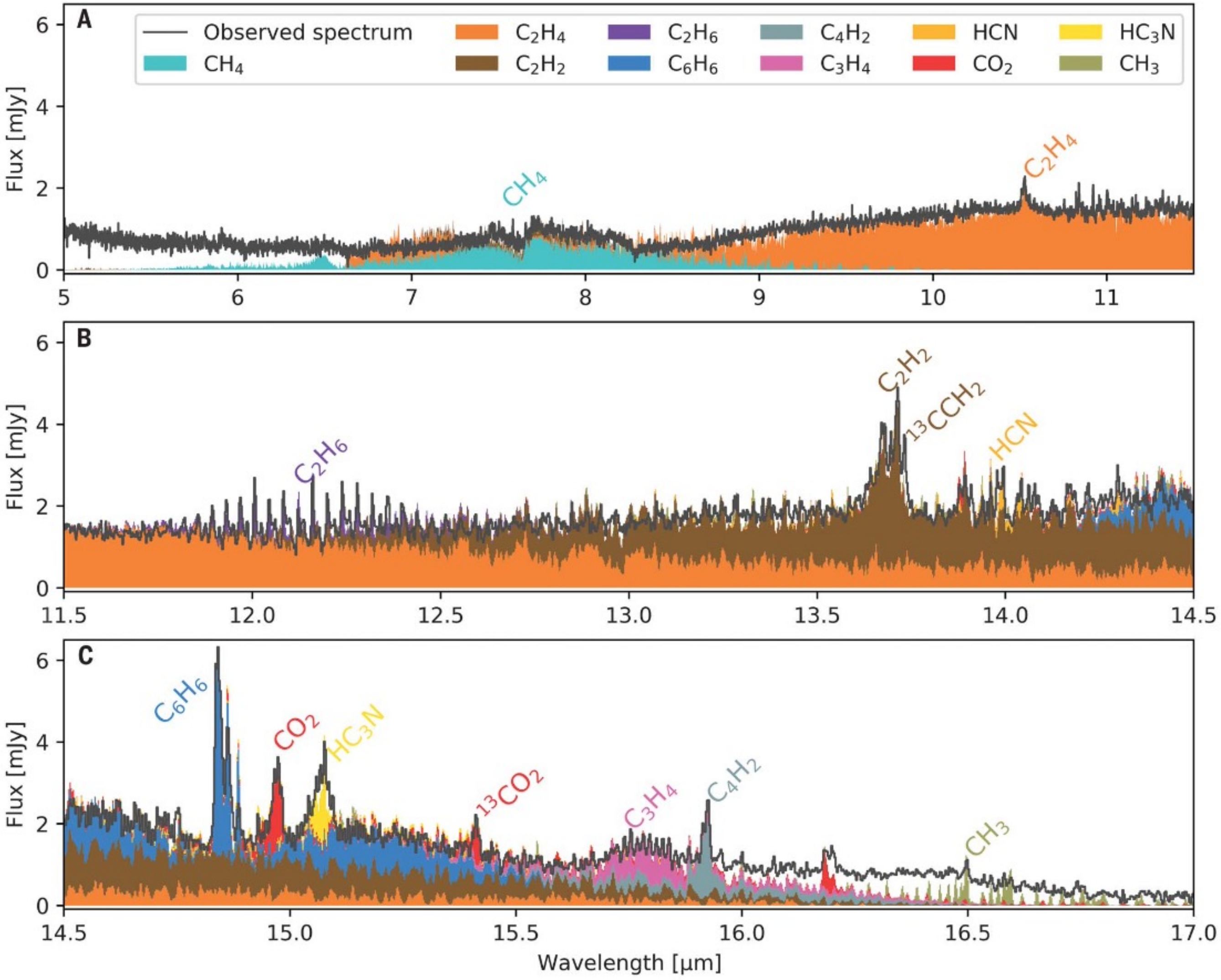


PRIMA and GREX-PLUS:
More precise estimate for emitting region using rotation profiles

Recent JWST/MIRI observations for Class II disks



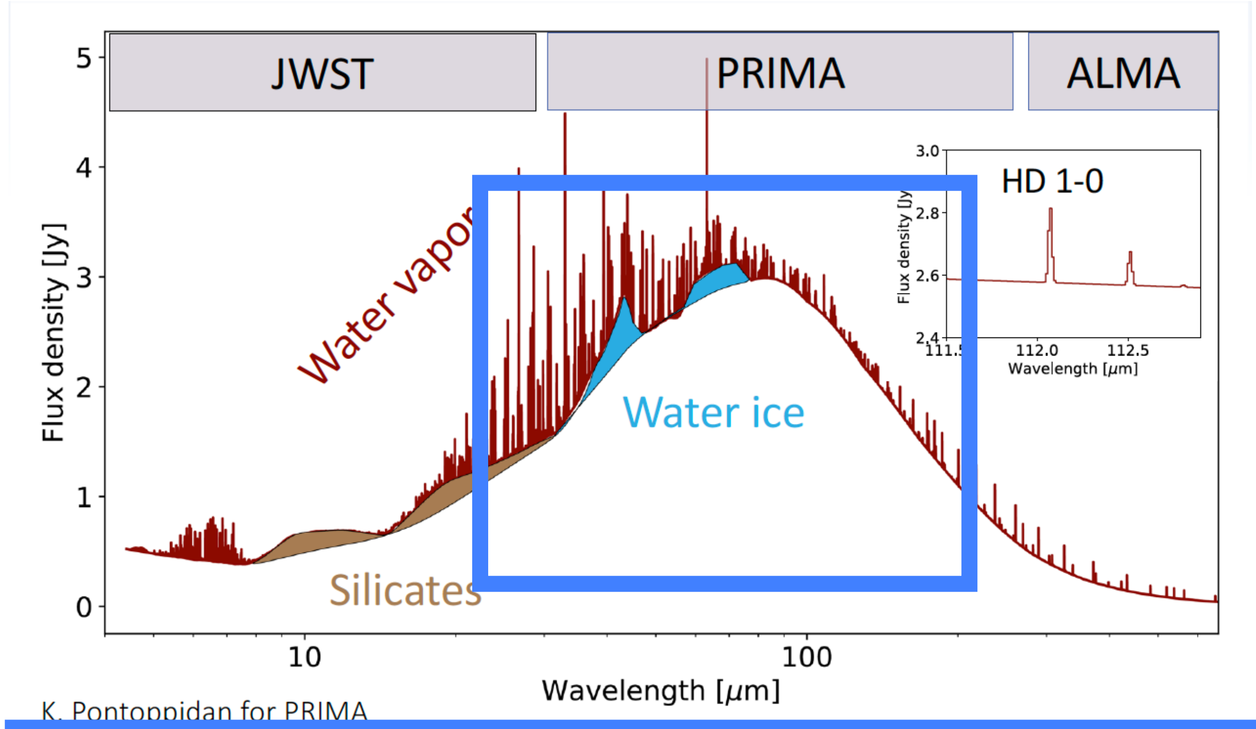
See e.g., JWST/MINDS, JDISCS papers



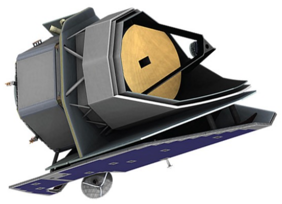
Abundant hydrocarbons
Around a very low-mass protostars
(Arabhavi et al. 2024)

PRIMA can trace multiple "colder" water lines

PI Science: A disk survey using FIRESS FTS mode to get full spectra of ~200 disks



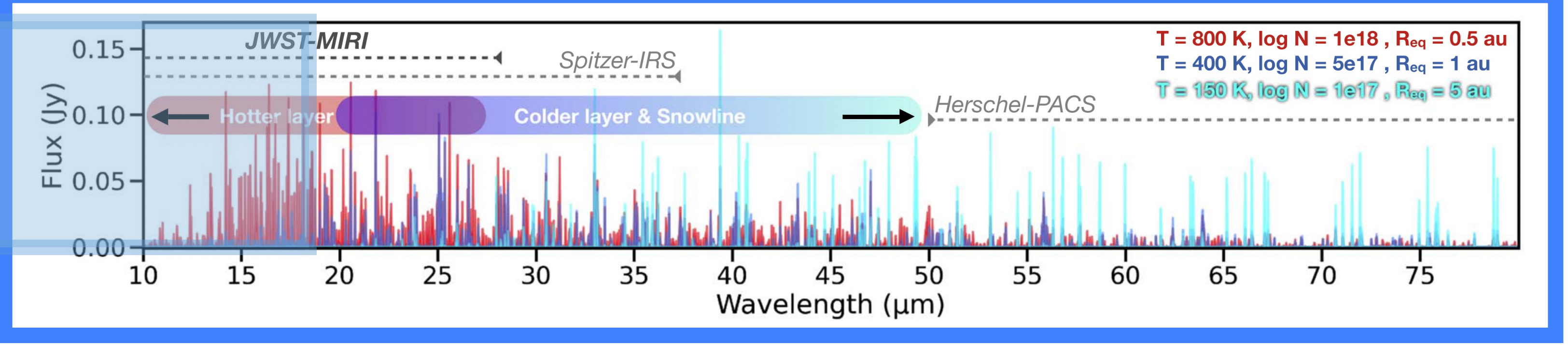
PRIMA The PRobe far-Infrared Mission for Astrophysics



R~λ/Δλ~4000*(112μm/λ)

Various E_{up}

GREX-PLUS synergy



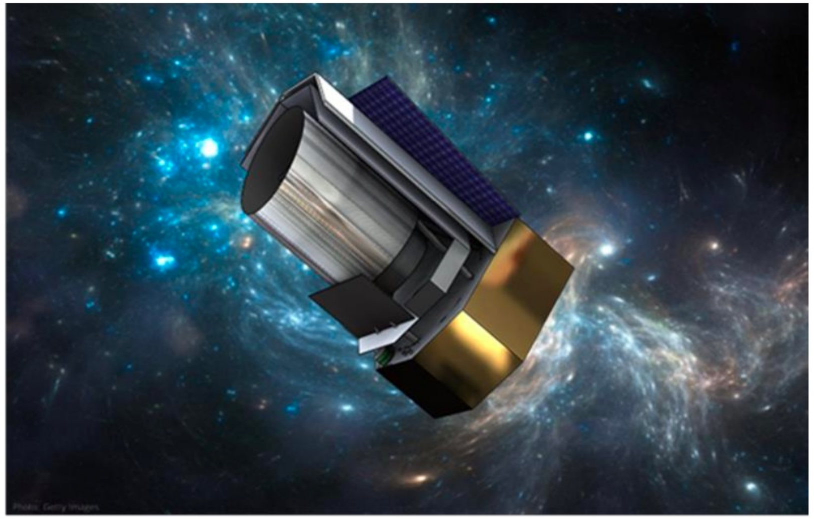
Banzatti et al. 2023

GREX-PLUS
(Galaxy Reionization EXplorer and PLanetary Universe Spectrometer)

Table 1.1: GREX-PLUS baseline design.

Telescope	ϕ1.2 m, 50 K, diffraction limit at 4 μm
Wide-field camera	1,260 arcmin^2 divided into 5 bands in 2-8 μm
high resolution spectrometer	Resolving power $R = 30,000$ in 10-18 μm
Life time	5 years (Goal; +5 or more years)
Orbit	Sun-Earth L2 or Earth trailing
Launch	2030s by JAXA's H3 launch vehicle

※ In April 2024, we decided to change the diameter of the telescope to **Φ1.0m**



Japan + International collaborations (Arizona, Harvard/CfA…)

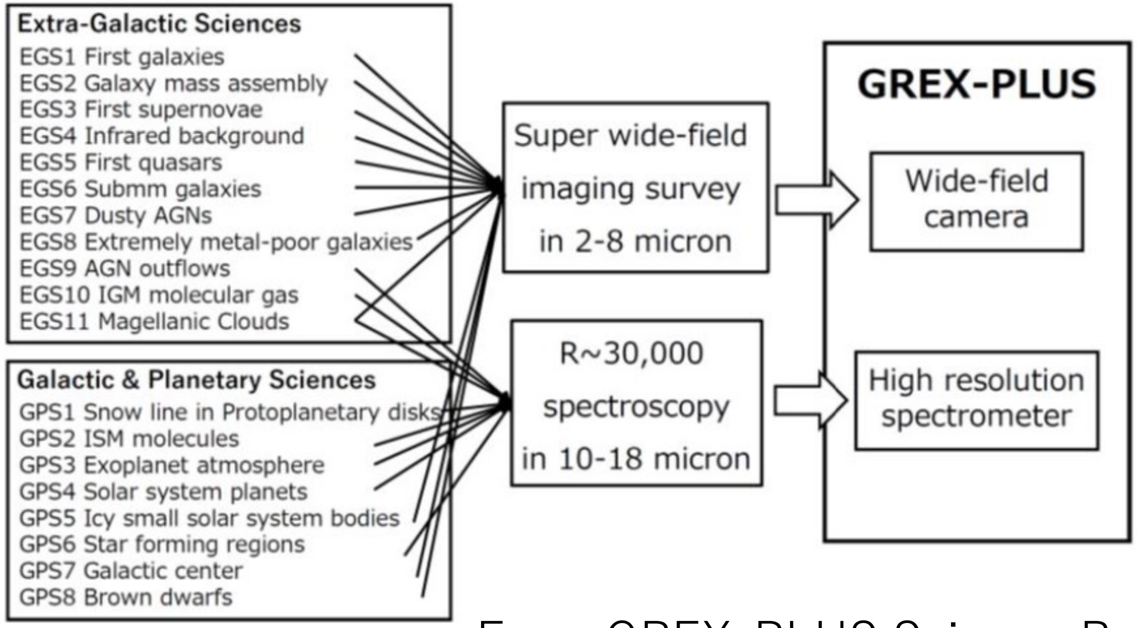
2023~: ISAS/JAXA WG is started

2027?: Selection from 3 candidates

JAXA L-class mission

PI: Akio Inoue (Waseda Univ.)

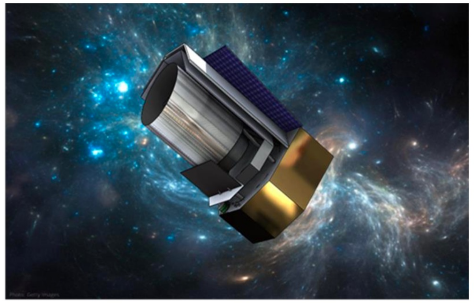
Science Goals and Instruments

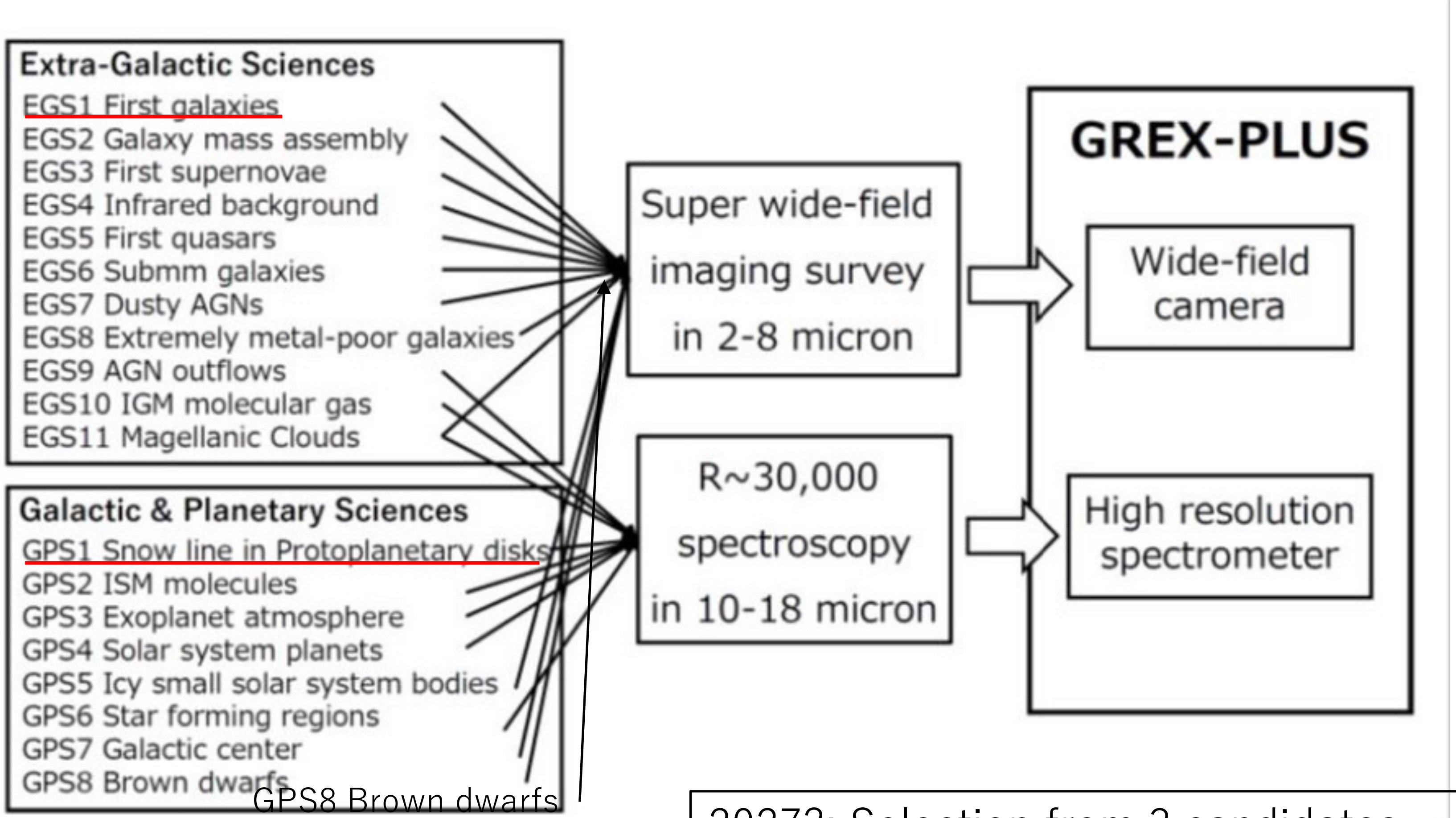


From GREX-PLUS Science Book

Science Goals & Instruments of GREX-PLUS

(Galaxy Reionization EXplorer and PLanetary Universe Spectrometer)

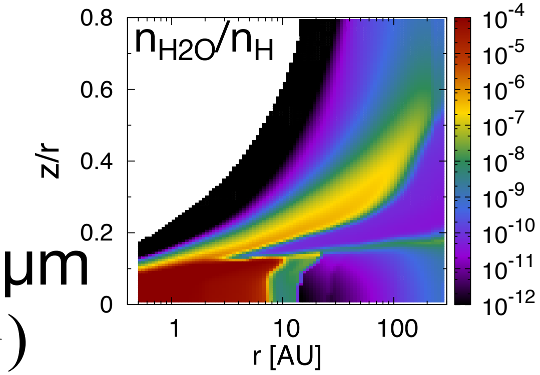




GREX-PLUS Science Book (31 authors)
arXiv:2304.08104

2027?: Selection from 3 candidates
Mid-2030s?: launching (**After PRIMA, 2032?**)
JAXA L-class mission

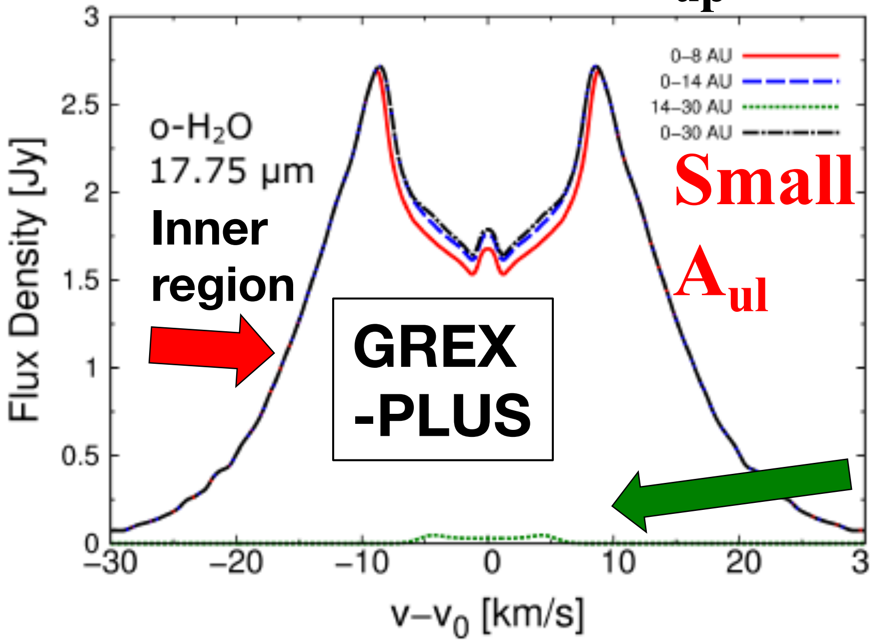
H_2O snowline and water line profiles

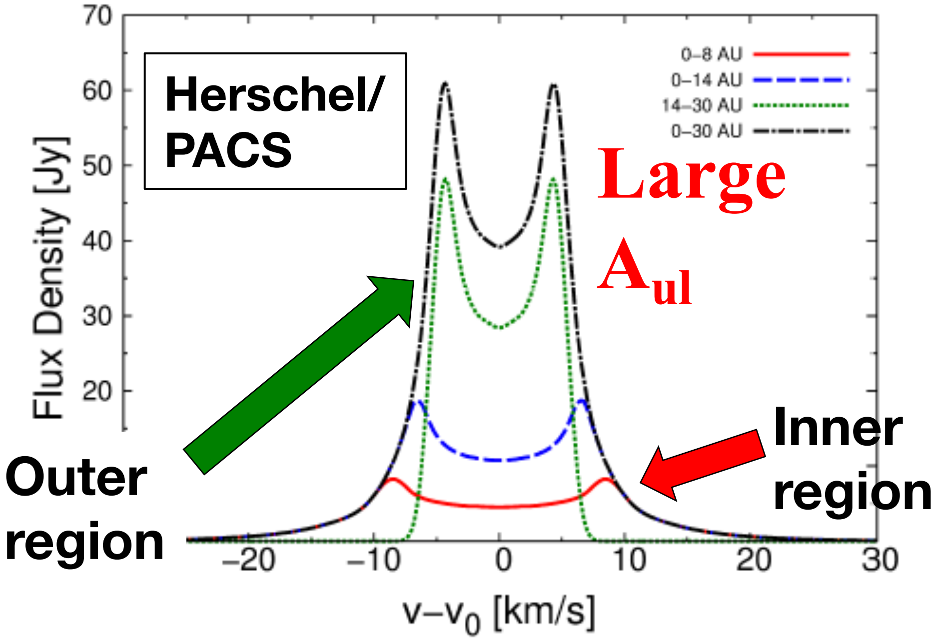


ortho-$H_2{}^{16}O$ 17.75μm — $A_{ul} \sim 2.9\times10^{-3}$ (s^{-1})

E_{up}~1000K

ortho-$H_2{}^{16}O$ 63.32μm — $A_{ul} \sim 1.7$ (s^{-1})



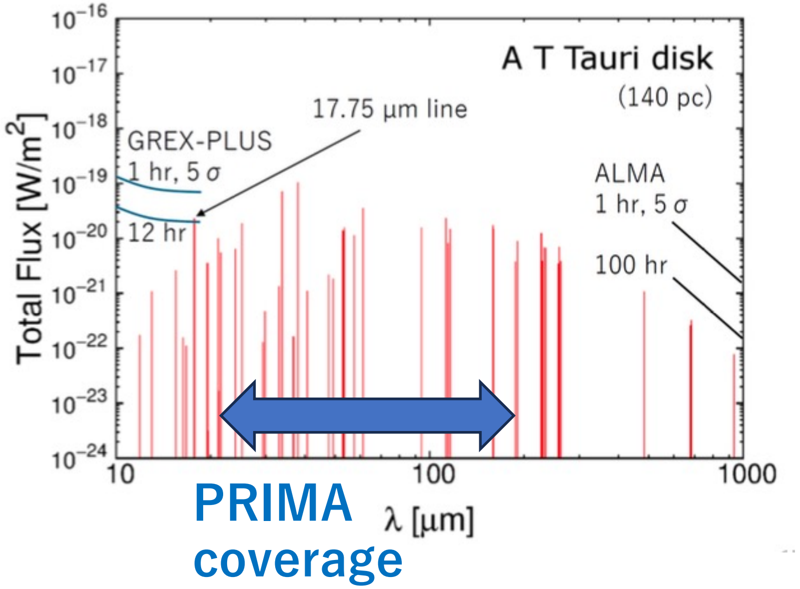


Notsu et al. (2016, 2017,2018)

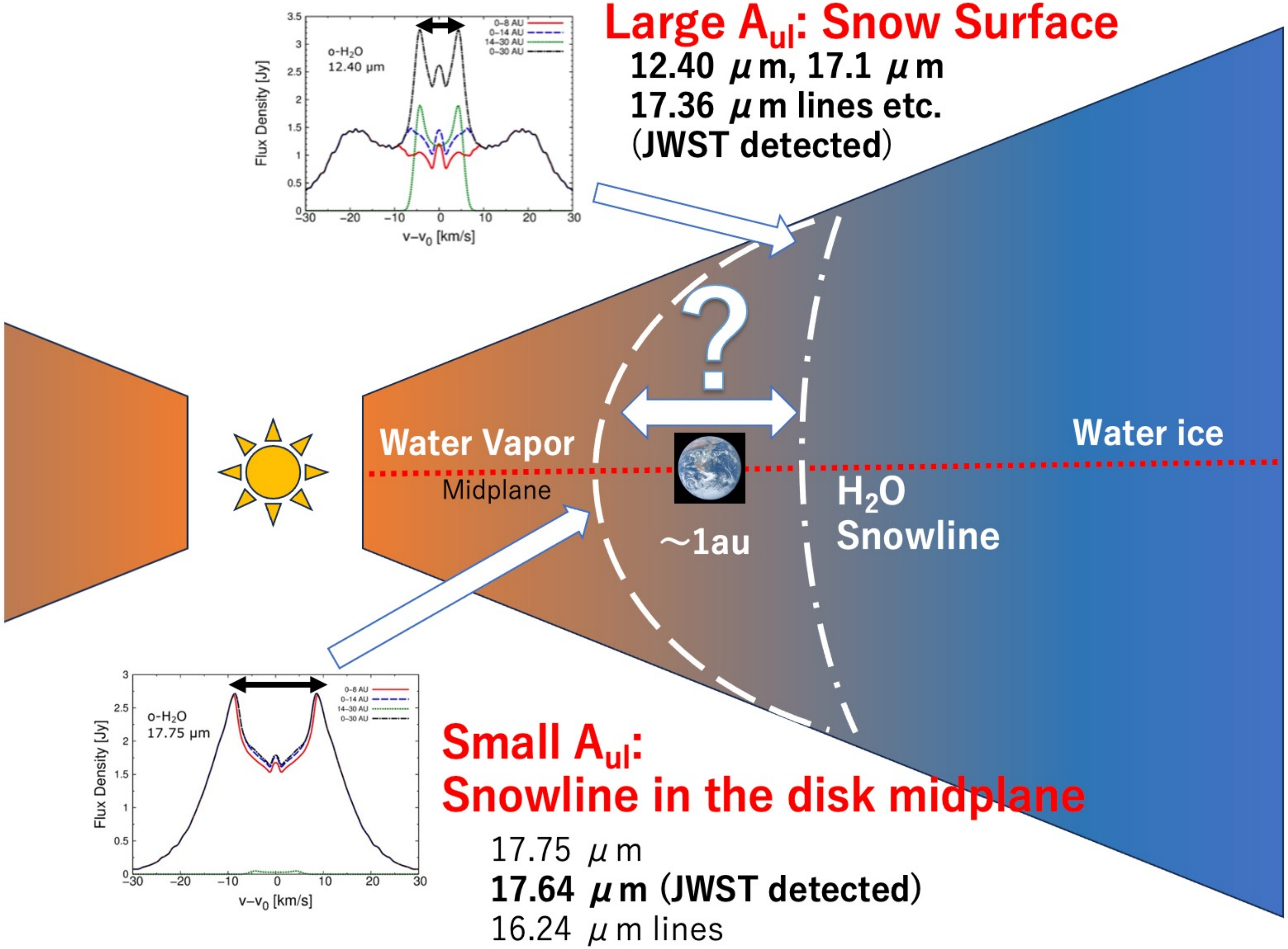
i=30° Distance:140pc

We can locate the positions of the H_2O snowline from the profiles of emission lines with small A_{ul} (10^{-6}~10^{-3} s^{-1}) and relatively large E_{up} (~1000K).

Difference in line emitting regions among water lines (Water snowline tracers and disk surface tracers)



↑ Total Fluxes of the water snowline tracer lines in the T Tauri disk model



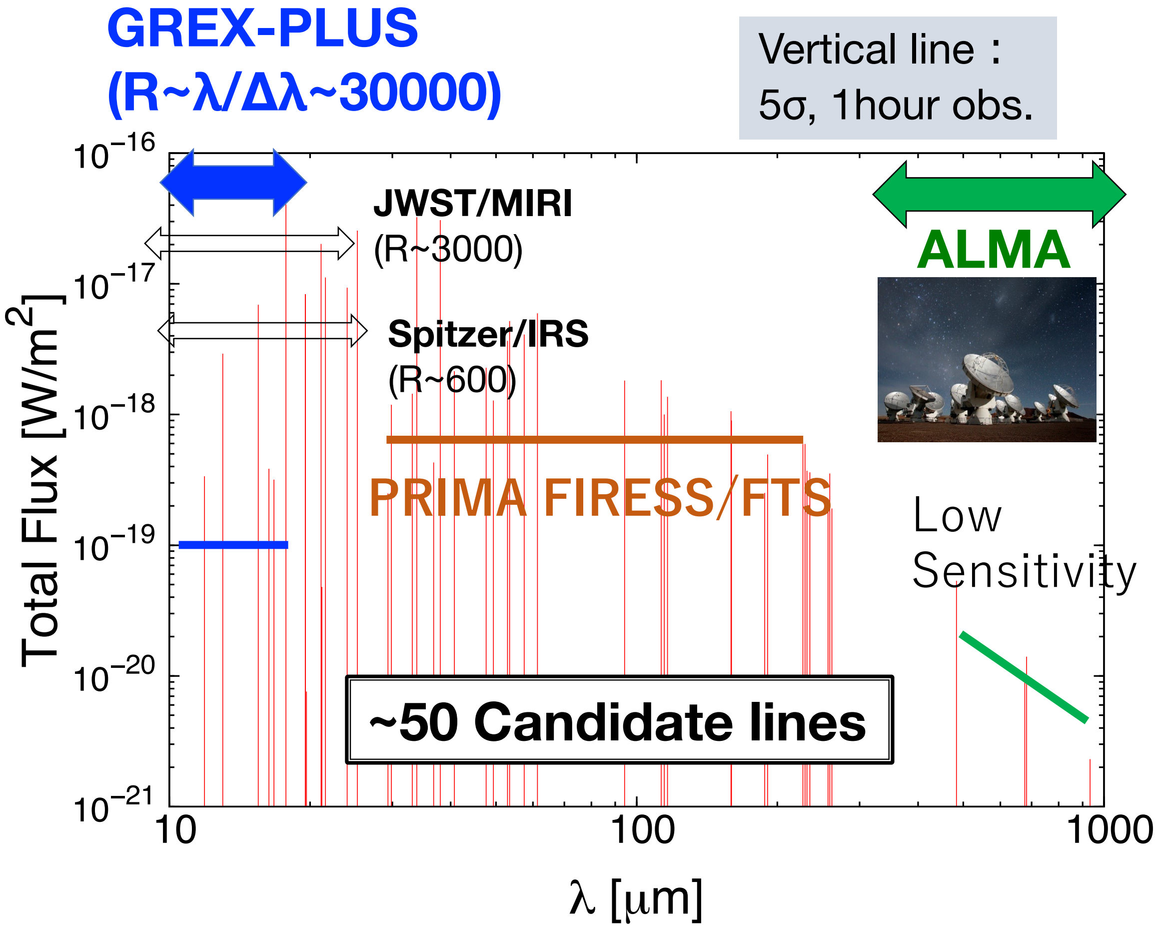
From GREX-PLUS Science Book

Notsu et al. (2016, 2017, 2018, 2019)
Kamp et al. (2021): SPICA Science paper

Model fluxes of candidate water snowline tracer lines for future observations

Notsu et al. (2016, 2017, 2018, 2019)
Kamp et al. (2021): SPICA science paper

Flux distributions of the candidate **ortho-$H_2{}^{16}O$** lines for a Herbig Ae disk

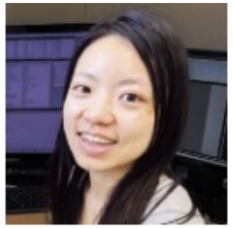


i=30°, d=140 pc
$10^{-6}<A_{ul}<10^{-2}$ s^{-1}, 700K$<E_{up}<$2010K

Water lines that can locate the H_2O snowline exist from mid-infrared (Q band) to far-infrared and sub-millimeter wavelengths.

PRIMA: R~λ/Δλ~ 4400 * (112μm/λ)
→ We may be also able to resolve line profiles and/or measure the line widths with Keplerian rotation in the shortest wavelength lines ?!

PRIMA-Japan Science Team



- Great enthusiasm among early–carrier scientists in Japan for PRIMA
- Some technical contributions (such as data reception support and cooling system)

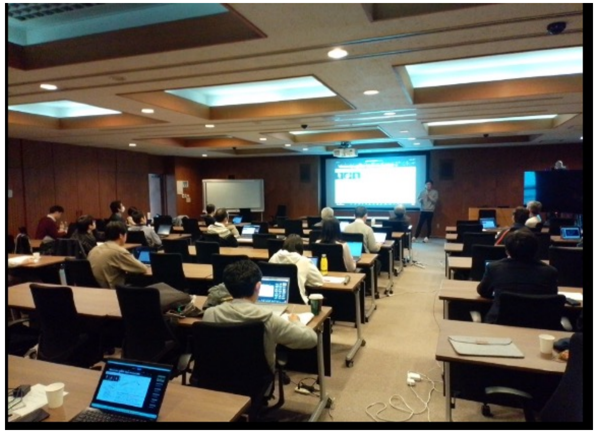
→ PRIMA-Japan science team started last year!

- Synergies with Ground based telescopes
  - such as Subaru (8m) and TAO (6.5m Near-and Mid-IR)
- Utilizing SPICA's scientific and technical heritage
- Future connections to GREX-PLUS and HWO (and more?)

PRIMA-J PI: Hanae Inami (Hiroshima Univ.)
(also Provisional Co-I of PRIMA Science Team)

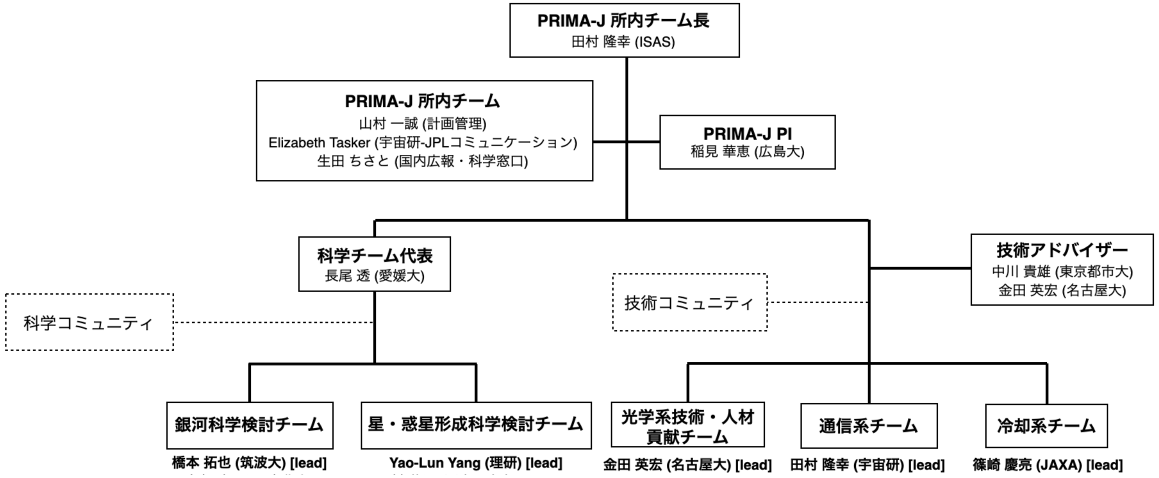
Science team lead: Toru Nagao (Ehime Univ.)
Galactic science sub-team lead:
Takuya Hashimoto (Tsukuba Univ.)
Star and planet formation science sub-team lead:
Yao-Lun Yang (RIKEN)

Technical Team; ISAS/JAXA, Nagoya Univ. etc.



FIR future science WS at ISAS/JAXA (February 2024)

PRIMA Japanese Workshop at NAOJ (June 2024)



Slide from Hanae Inami and Yao-Lun Yang

Summary +α: Observation prospects of water snowline tracer lines with ALMA, JWST, PRIMA, GREX-PLUS (and POEMM?)

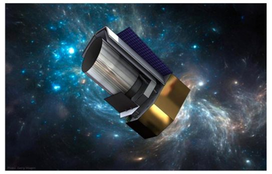
e.g., Notsu et al. (2016, 2017, 2018, 2019), Kamp et al. (2021)

ALMA

- **Several Herbig Ae disks and younger T Tauri disks** in nearest star forming regions (<150pc)
- Obs. Time per object: >10 hours per source (much longer than GREX-PLUS and PRIMA)
- Higher spectral resolution (R>100,000)

Japan 1.0m MIR GREX-PLUS (mid-2030's)

- Much higher sensitivity than ALMA for water detections
- Several candidate ortho- and para-water lines (e.g., 17.75 μm, **17.64 μm (JWST detected)**,16.24 μm lines)
- Surveys of the water snowline positions for
  - bright T Tauri disks ($>10^{-20}$ W m^{-2}) in <150pc : ~190 min. per source
  - many Herbig Ae disks ($>10^{-18}$ W m^{-2}) in <150pc: <30 min. per source
  - Herbig Ae disks in Orion star forming regions (~400pc, $>10^{-19}$ W m^{-2}): <1 hours per source



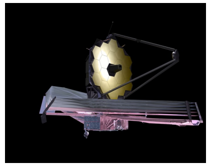
US 2m FIR probe PRIMA (2032?~)

PRIMA-Japan WG started last year

- We expect to detect multiple snowline tracer water lines (mainly for Herbig Ae/Be stars?)
- **Since R~λ/Δλ~4000 * (112μm/λ), it might be possible to measure the line widths, and confirm the existence of the inner emission components using many candidate water lines**

JWST/MIRI (R~3000)

- Diversity in water abundances have been found (related with pebble accretion)
- We can also make target selections for PRIMA and GREX-PLUS using JWST spectra



Note: Preferred capabilities for the next (2040s) FIR missions

1st priority in 2030s: **PRIMA!**

2040s: Assuming PRIMA has successfully completed PI & GO sciences within 2030s,

(1) High spectral resolution mode (R>100,000) for multiple water lines (20-200 μm), to resolve the water line profiles and to locate the water snowline positions.

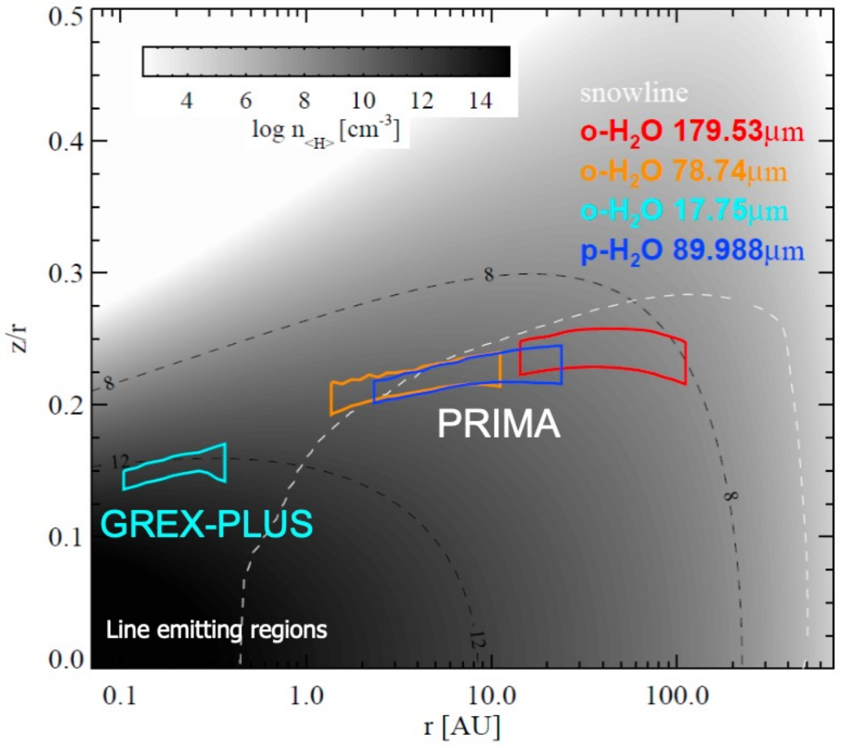
(2) Interferometer to obtain spatially resolved images of water line emission within the water snowline (at least smaller than 0.1 arcsec, for snowlines in Herbig disks)

Note: We require similar or higher sensitivities than PRIMA for both cases

Back up slides

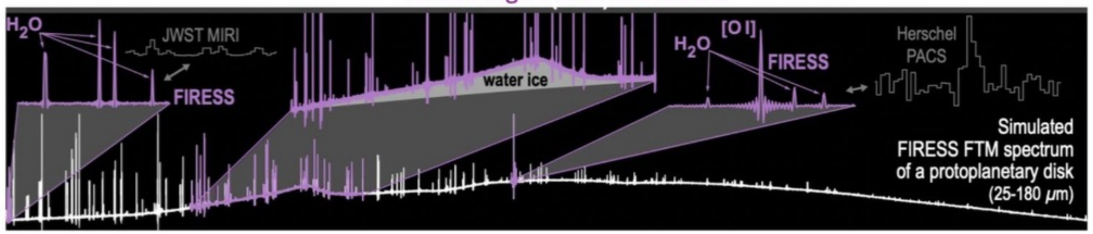
H_2O in protoplanetary disks

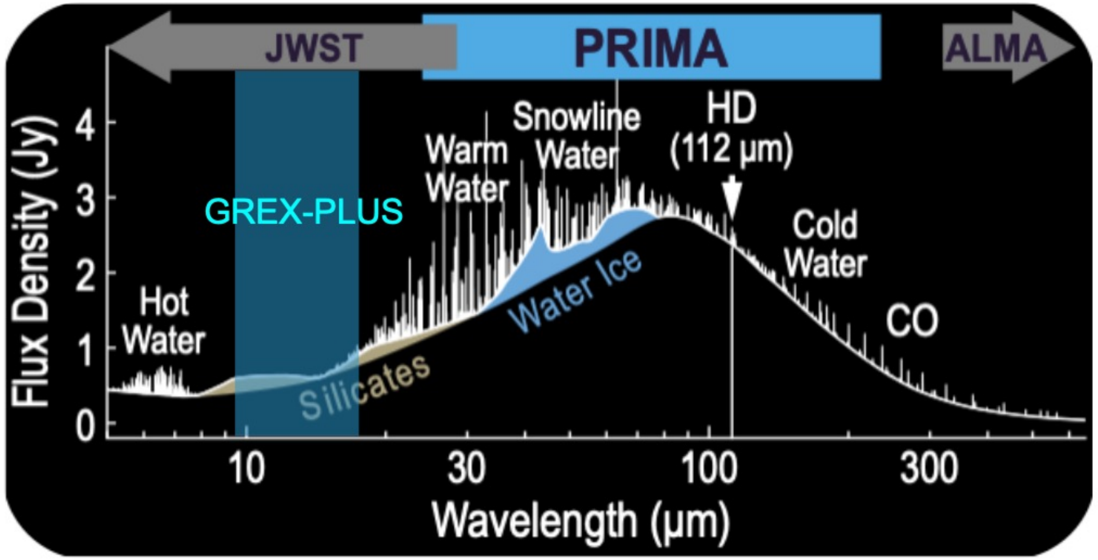
T Tauri disks, 1-hr & 10 hrs integration



Kamp et al. 2011, 2017, 2021

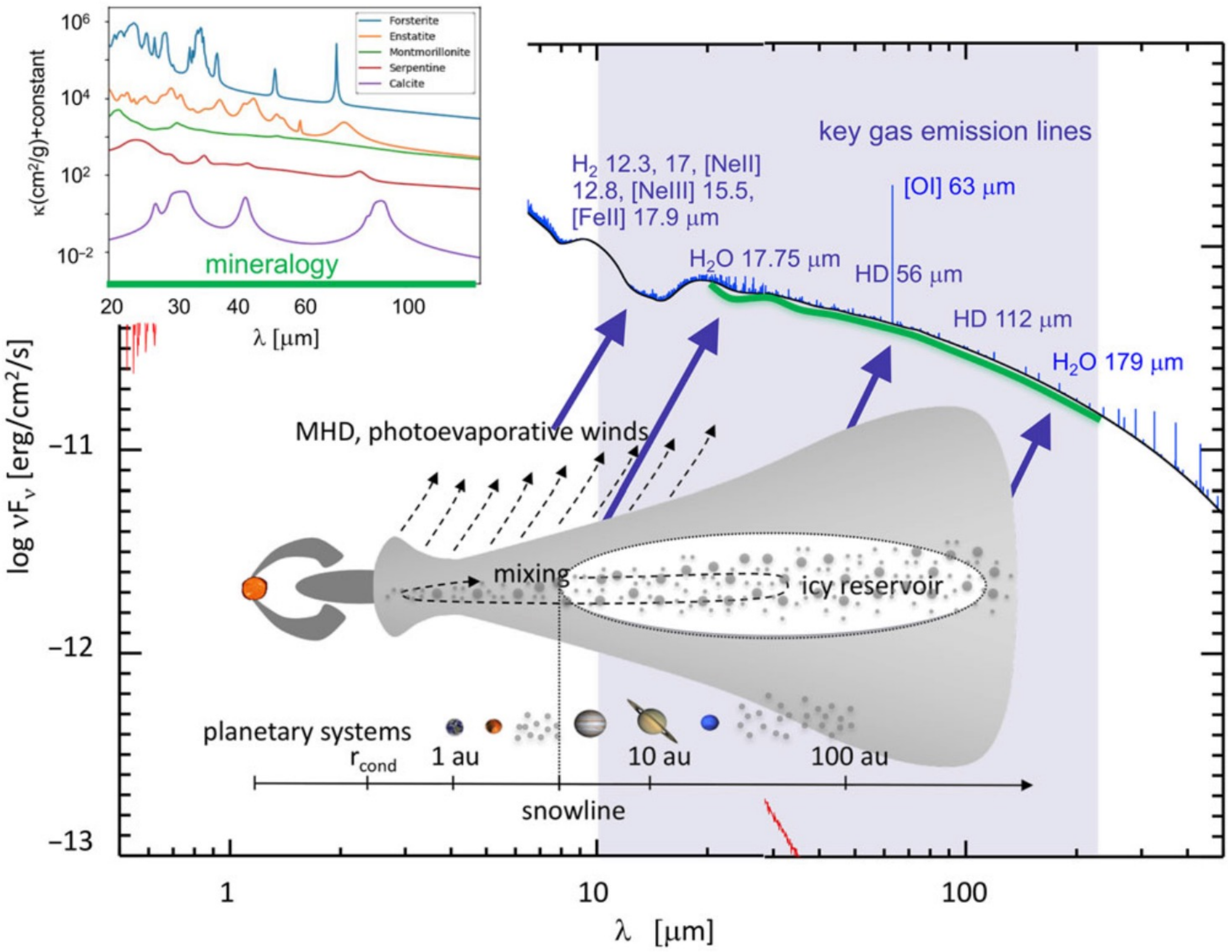
FIRESS high-res FTM module





From PRIMA webinar slide

FIR science and potential tracers



Potential Tracers

Multiple H_2O transition lines

HD 1-0 112 μm & 2-1 56 μm

CO ladders

[O I] 63 μm and [C II] 158 μm
for disk winds and
C/O ratios in debris disk

Silicate features at 69 μm
Water ice features at 44 μm & 63 μm
→Crystallization in the cold cometary forming region

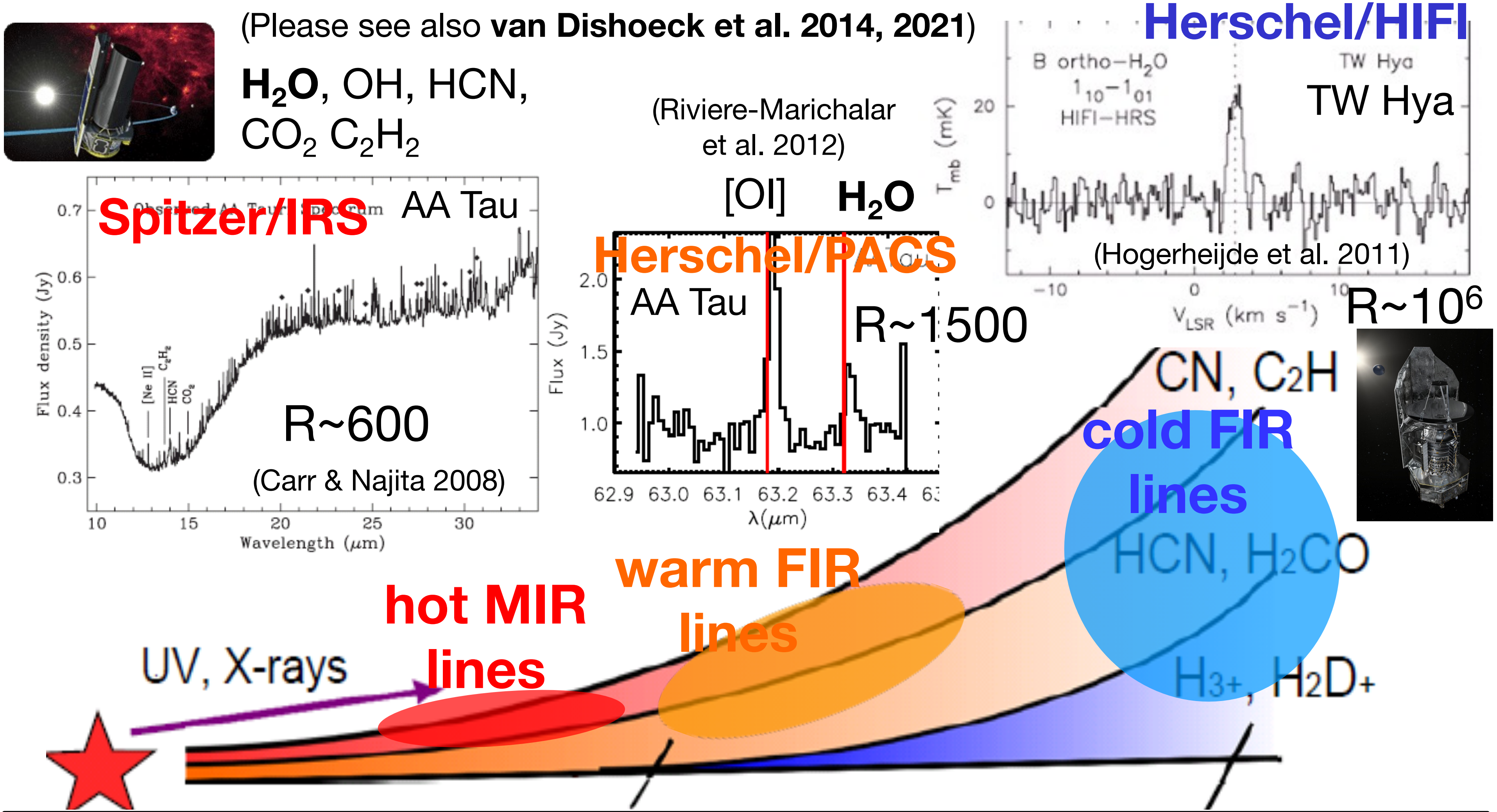
GREX-PLUS Science Book: https://arxiv.org/abs/2304.08104
Kamp et al. 2021: doi:10.1017/pasa.2021.31

Figure from Kamp et al. (2021)

Space observations of H_2O lines from PPDs

(Please see also **van Dishoeck et al. 2014, 2021**)

H_2O, OH, HCN, CO_2 C_2H_2



Previous infrared water line observations trace the disk surface and the photodesorption region of the outer disk.
→They are not good tracer of the H_2O snowline in disk midplane.

Locating the snowline positions from Keplerian line profiles

PPD: ProtoPlanetary Disks

H_2O snowline: a few au @PPD around Solar-mass T Tauri stars.
→Direct imaging observations are difficult.

PPDs : (almost) Kepler rotation

$$\Delta v = \sqrt{\frac{GM_s}{r}} \sin i$$

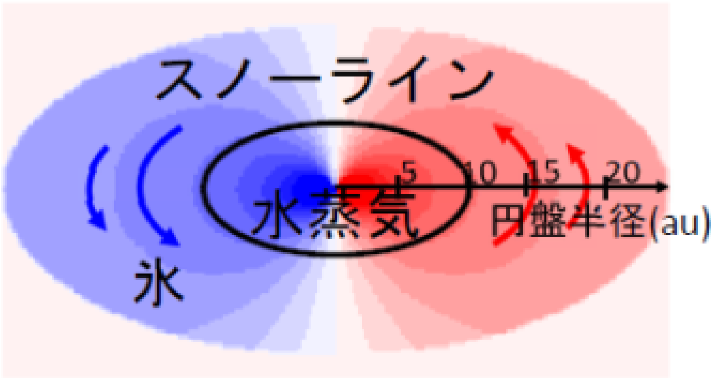
i: inclination angle

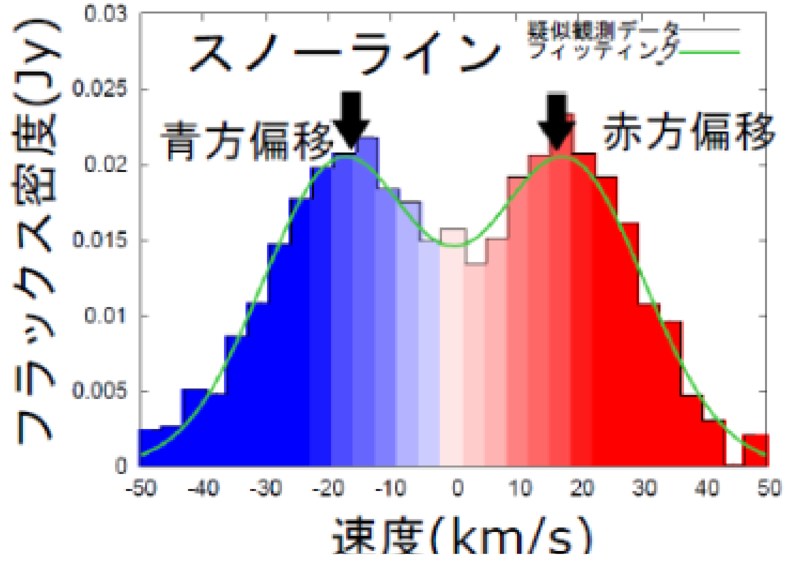
velocity profiles of emission lines
↓
location of snowlines

Typical width of lines from PPDs :
Δv~10-20km/s
→ need very high-R (R~30000) for analyzing profiles.

$R \sim \lambda / \Delta\lambda$

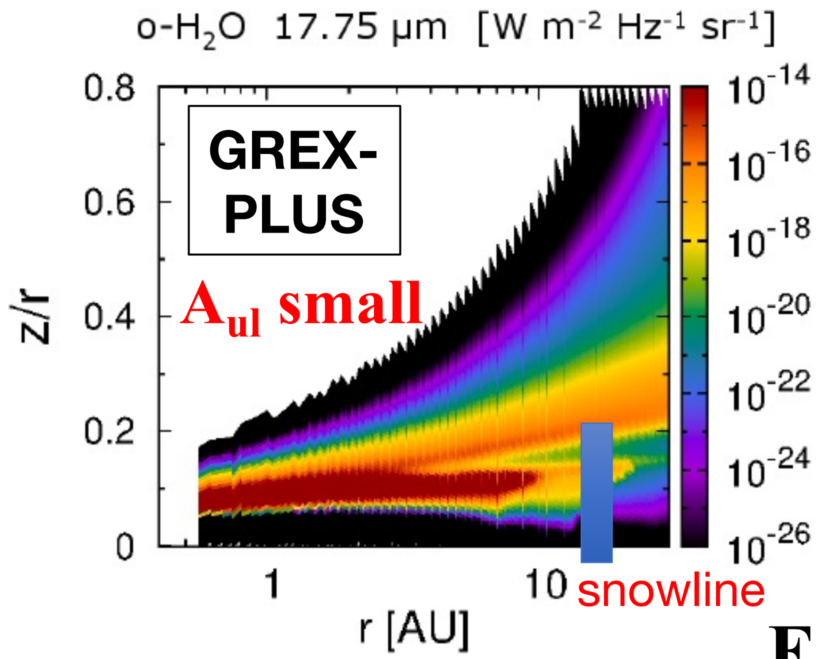
Keplerian Rotation

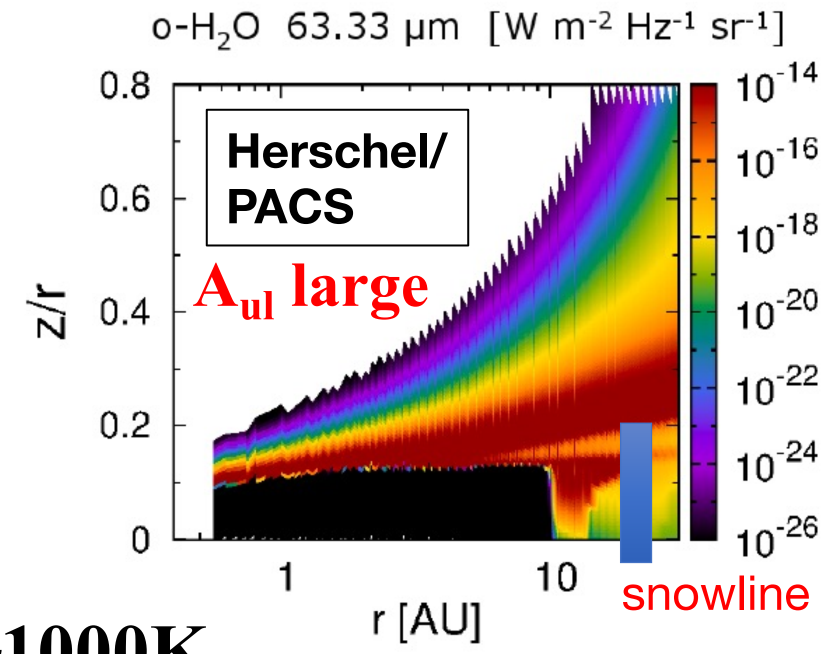




Local intensity distributions (i=0°, line of sight)

emissivity*exp($-\tau_{ul}$)*ds





ortho-$H_2{}^{16}O$ 17.75 μm
A_{ul}= 2.9×10^{-3} (s^{-1})

E_{up}~1000K

Herbig Ae disk

ortho-$H_2{}^{16}O$ 63.32 μm
A_{ul}= 1.7 (s^{-1})

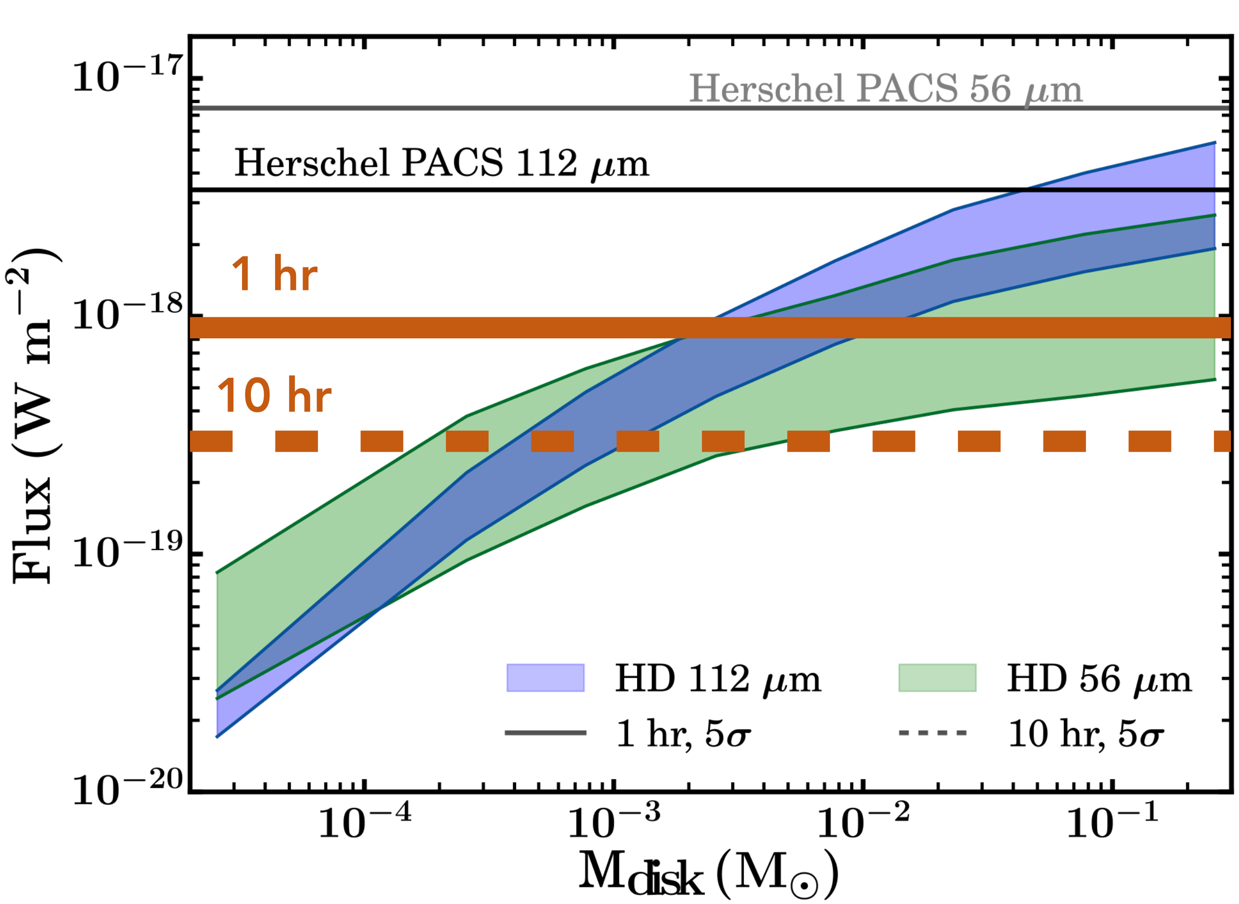
Notsu et al. (2016, 2017,2018)

Small A_{ul} → emission from the outer optically thin surface layer << emission from the optically thick region inside the H_2O snowline
→ H_2O snowline tracer !

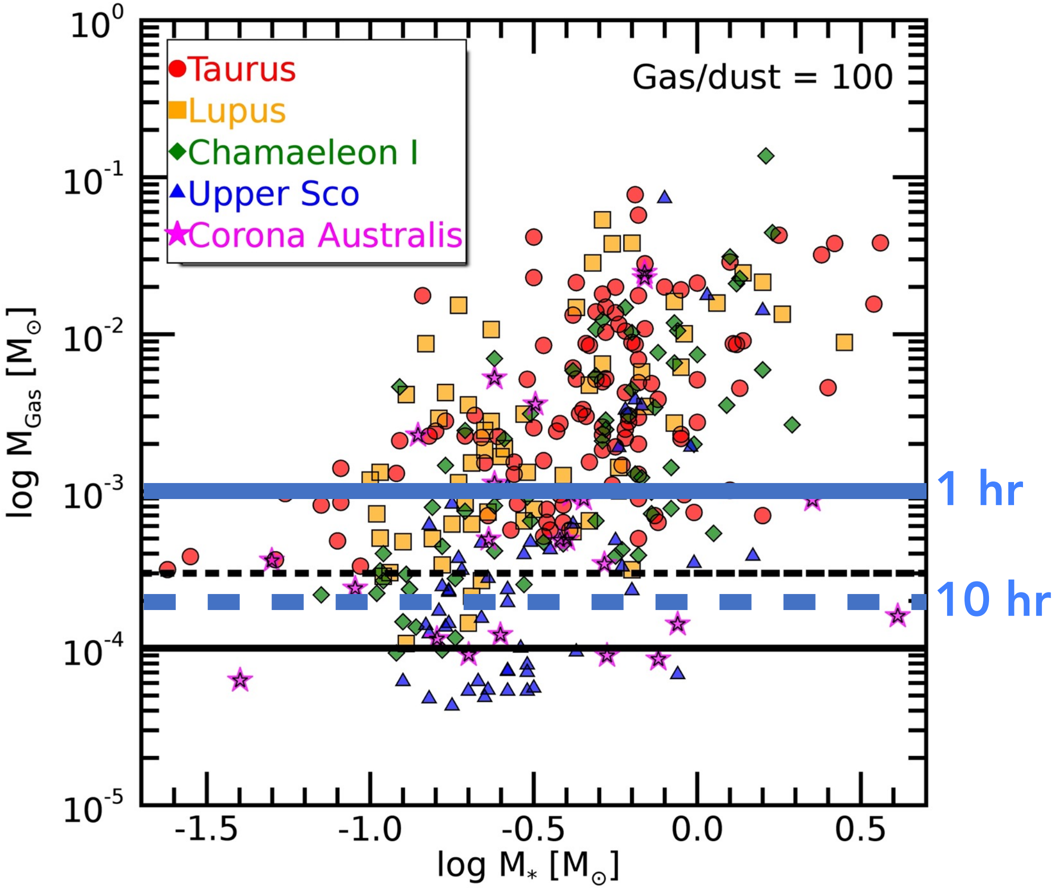
Optically thin (τ_ν<<1)
$F_\nu \propto n_{up}(E_{up}) A_{ul}$
Optically thick (τ_ν>>1)
$F_\nu \propto B_\nu(T)$

Measuring disk mass precisely via HD

PRIMA can detect ~10^{-3} M⊙ in a shallow survey (1 hr per source) and ~2×10^{-4} M⊙ in 10 hr



Modified from Trapman+2017



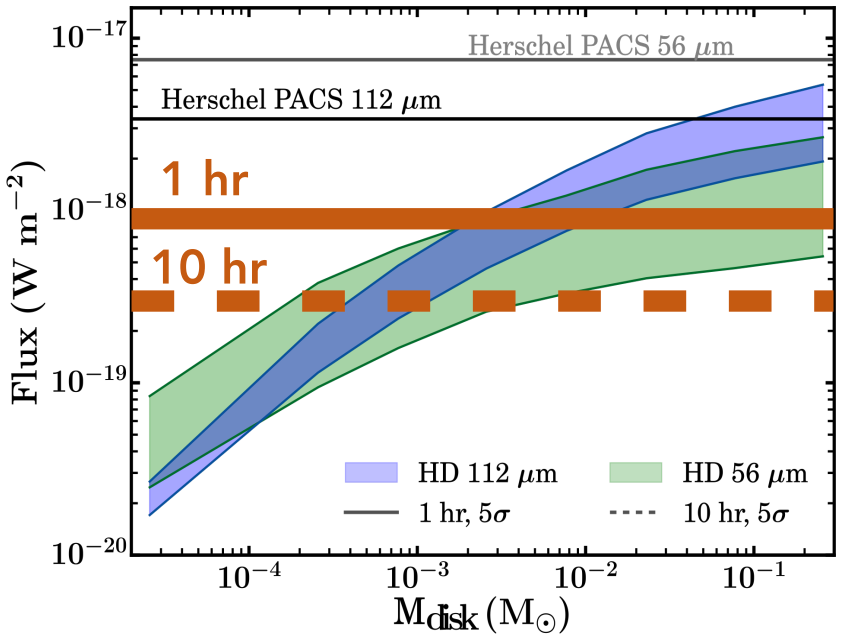
Modified from Kamp et al. (2021)

Disk dispersal processes with PRIMA and GREX-PLUS

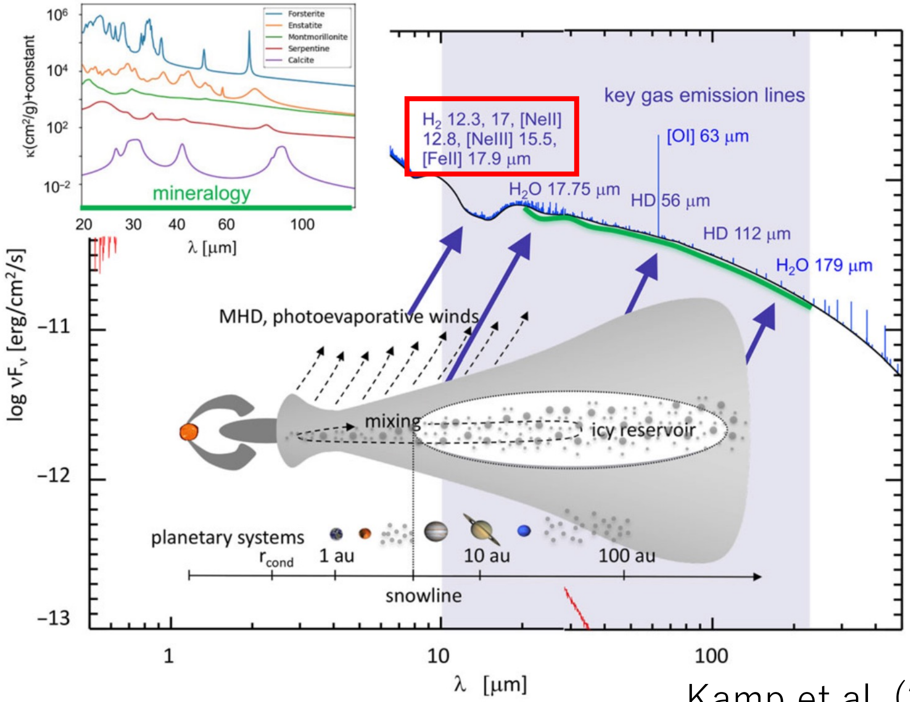
HD line (PRIMA)： Precise estimate of disk masses

HD lines J=1-0 112μm, J=2-1 56μm

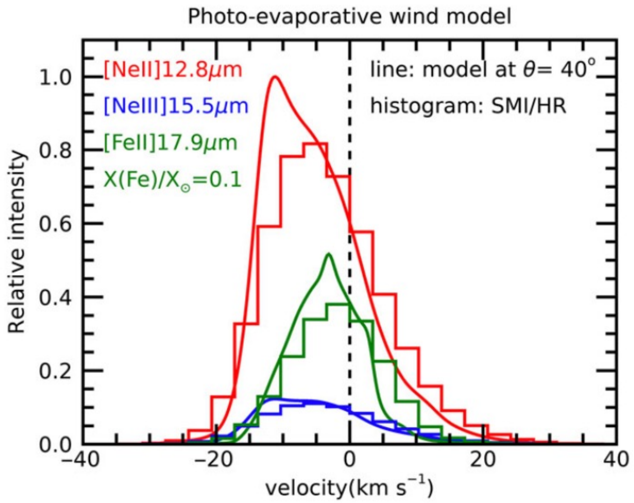
High-dispersion spectroscopy (GREX-PLUS)
H_2 S(1) 17μm, H_2 S(2) 12μm, [Ne II] 12.8μm lines
→Investigating disk dispersal processes



Trapman et al. (2017)

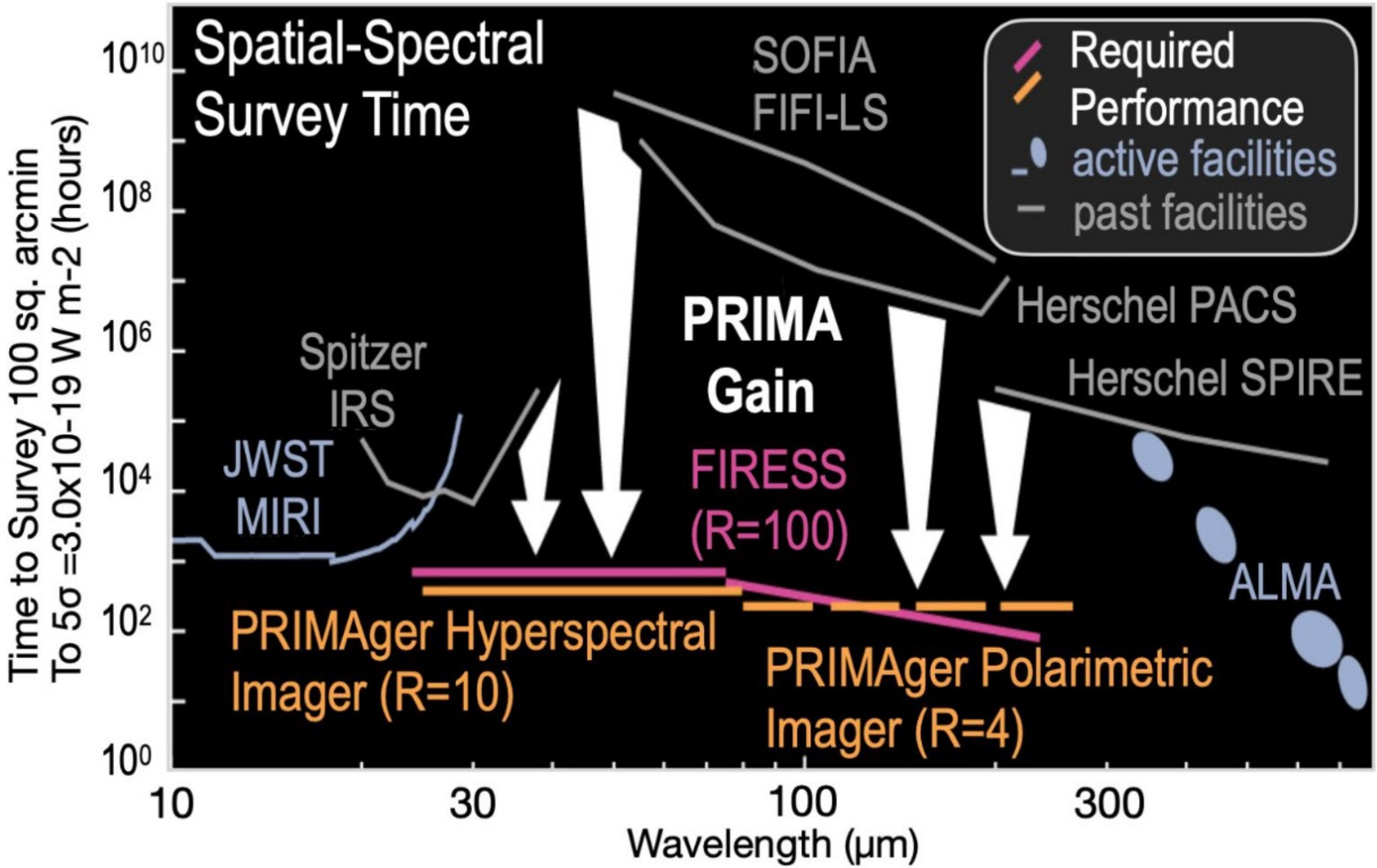


Kamp et al. (2021)



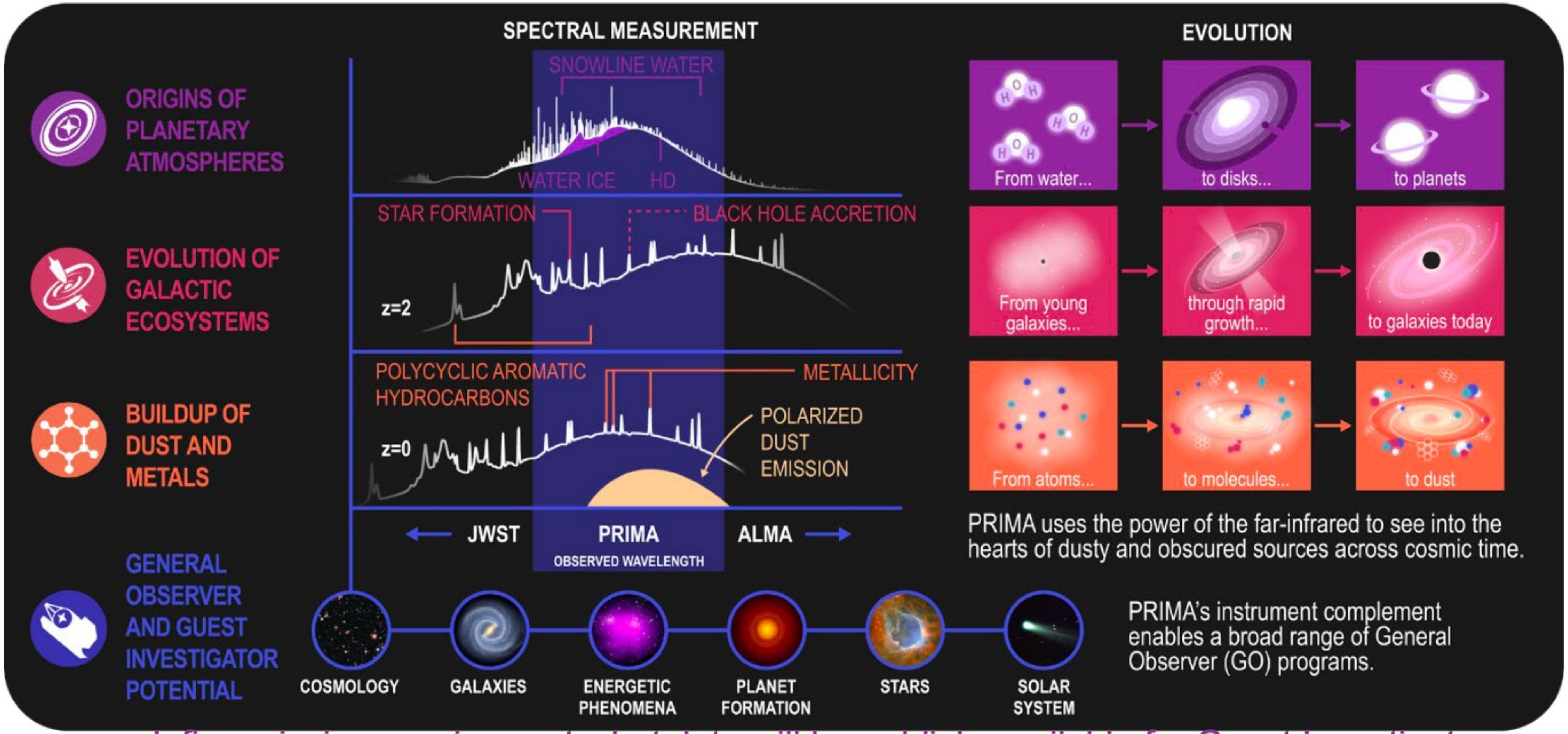
MHD, Photo-evaporative winds

These observations can be done within the same disk survey observations for the water snowline



From PRIMA webinar slide

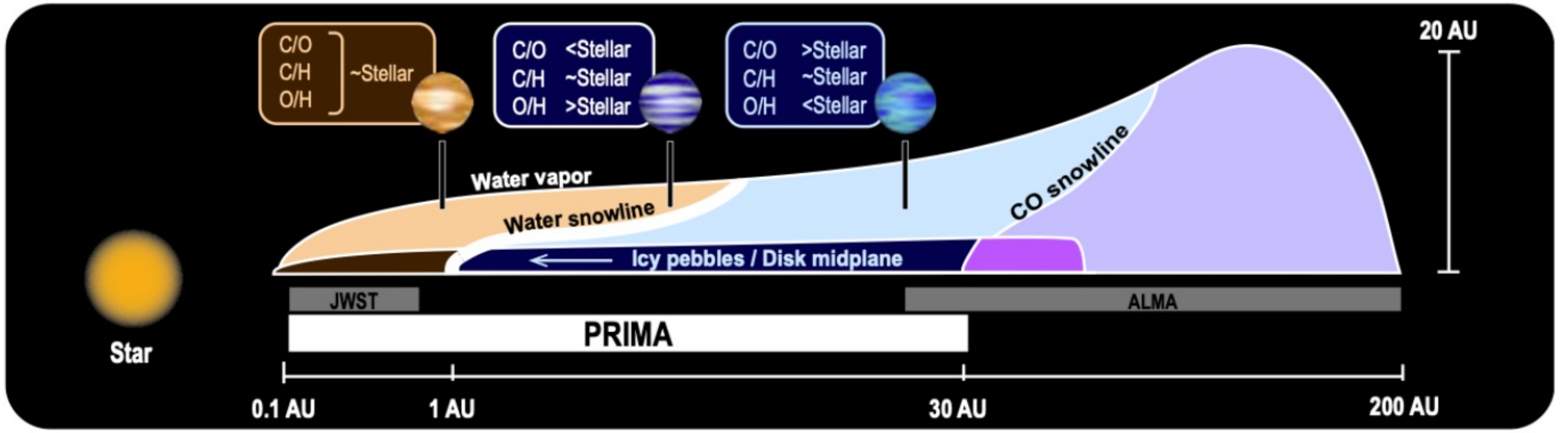
PRIMA's PI science is organized around 3 themes: How planets get their atmospheres, How black holes and galaxies evolved together, and How dust and metals build up in galaxies



PI surveys define mission requirements, but data will be publicly available for Guest Investigator science

From PRIMA webinar slide

Planet Growth in Disks

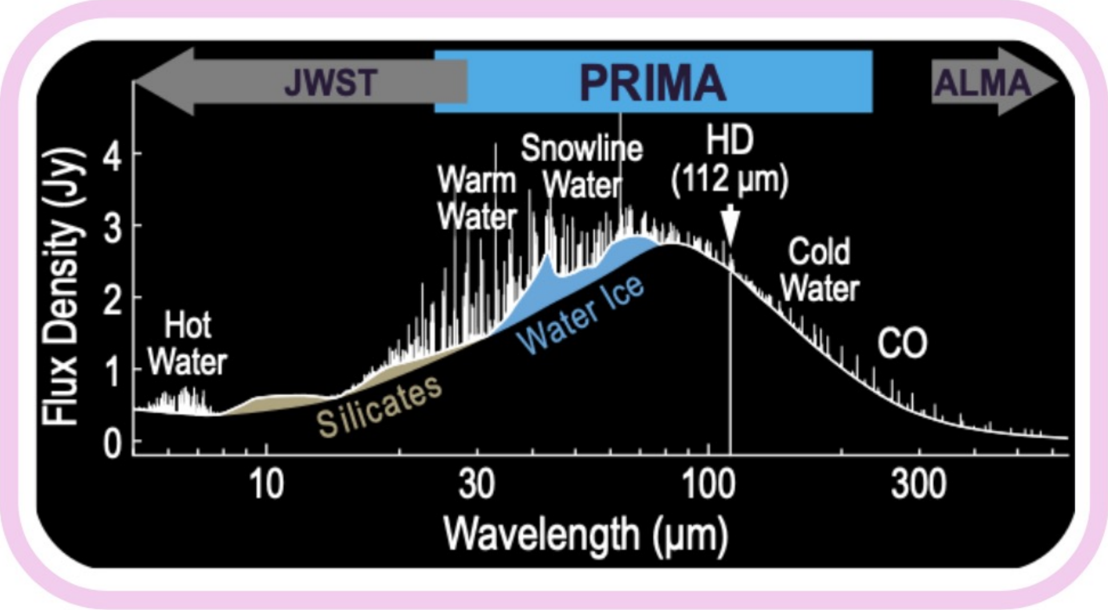


Do disk abundances of C and O map to stellar metallicities?

- PRIMA will use HD to determine accurate disk masses for absolute abundance measurements

Do icy pebbles drive planetesimal accretion?

- PRIMA will measure water vapor distribution in disks



From PRIMA webinar slide