UTokyo 東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE, THE UNIVERSITY OF TOKYO RIKEN Japan Society for the Promotion of Science 日本学術振興会 Next Generation Astrochemistry

March 31st– April 2nd 2025
PRIMA Conference
Marseille, France

The necessity of PRIMA for star and planet formation sciences and an overview of PRIMA-Japan working group

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Graduate School of Science, The University of Tokyo, Japan

PRIMA The PRobe far-Infrared Mission for Astrophysics

Today's Outline

1. **Overview of PRIMA-Japan science team**
   and
   Summary of GREX-PLUS

2. The necessity of PRIMA for star and planet formation sciences
   and
   Synergies with PRIMA and GREX-PLUS

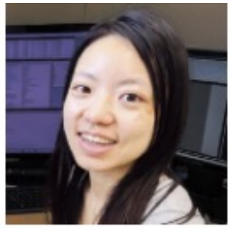
GREX-PLUS Science Book: https://arxiv.org/abs/2304.08104
Kamp et al. 2021: doi:10.1017/pasa.2021.31 (SPICA science summary paper)

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!**

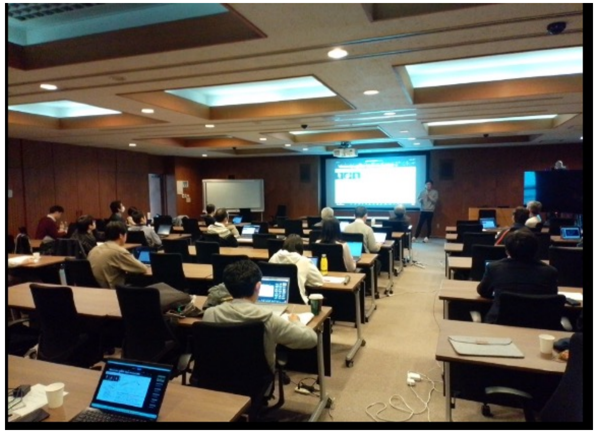
- **Synergies with Ground based telescopes**
  - **such as Subaru (8m) and TAO (6.5m Near-and Mid-IR)**
- **Utilizing SPICA's scientific and technical heritage**
- **Future connections to GREX-PLUS and HWO**



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

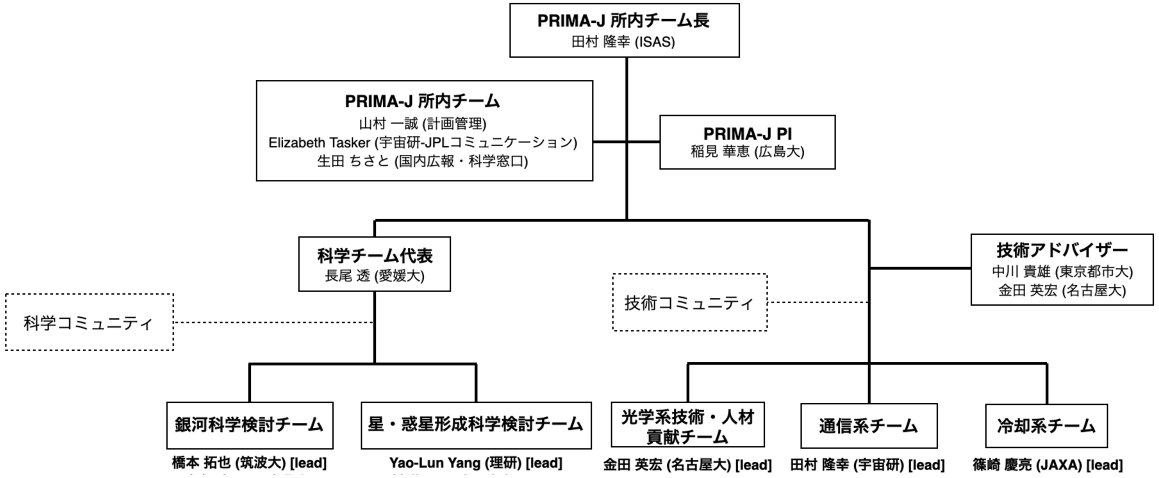
Science team lead: Toru Nagao (Ehime Univ.)
Galactic science sub-team lead:
Takuya Hashimoto (Tsukuba Univ.)
Star and planet formation science sub-team lead:
Yao-Lun Yang (RIKEN)

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

GREX-PLUS

(Galaxy Reionization EXplorer and PLanetary Universe Spectrometer)

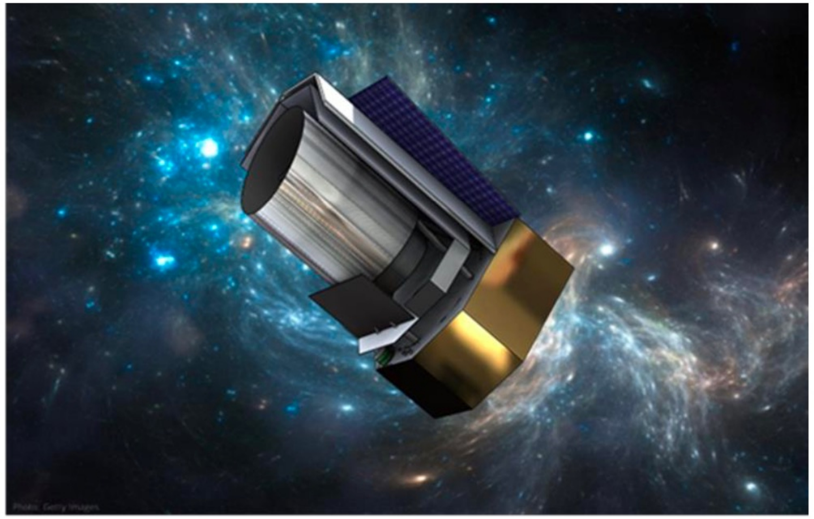
Table 1.1: GREX-PLUS baseline design.

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**

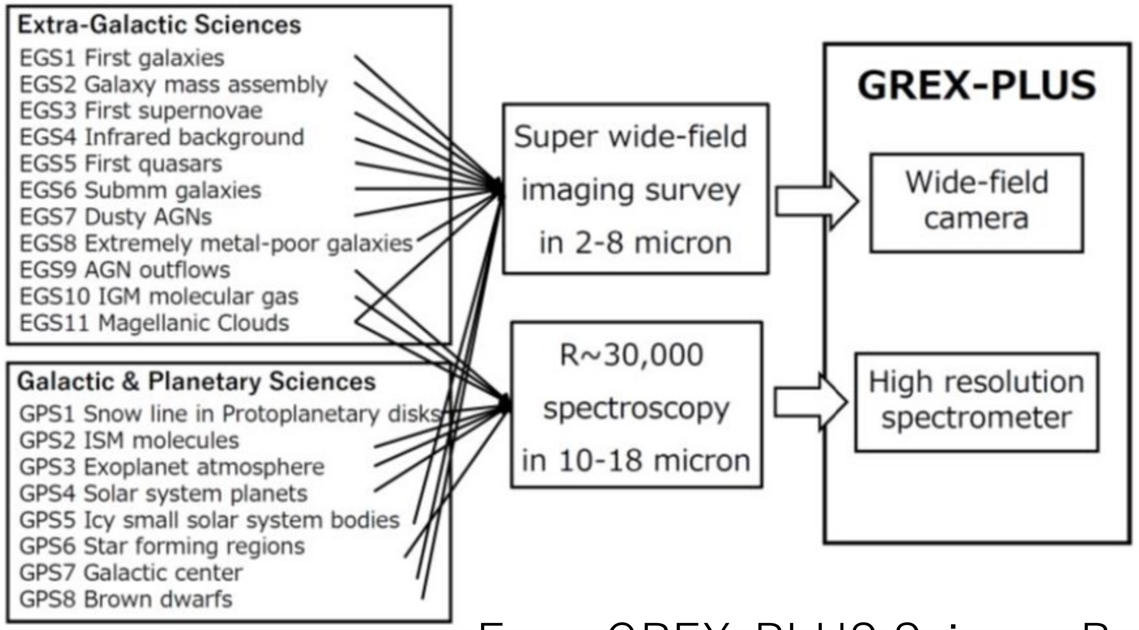
2023~: ISAS/JAXA WG is started
2027?: **Selection** from 3 candidates
JAXA L-class mission

PI: Akio Inoue (Waseda Univ.)



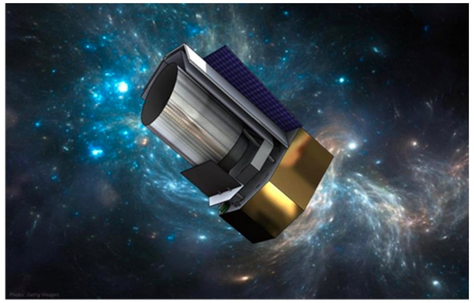
Japan + International collaborations (Arizona, Harvard/CfA···)

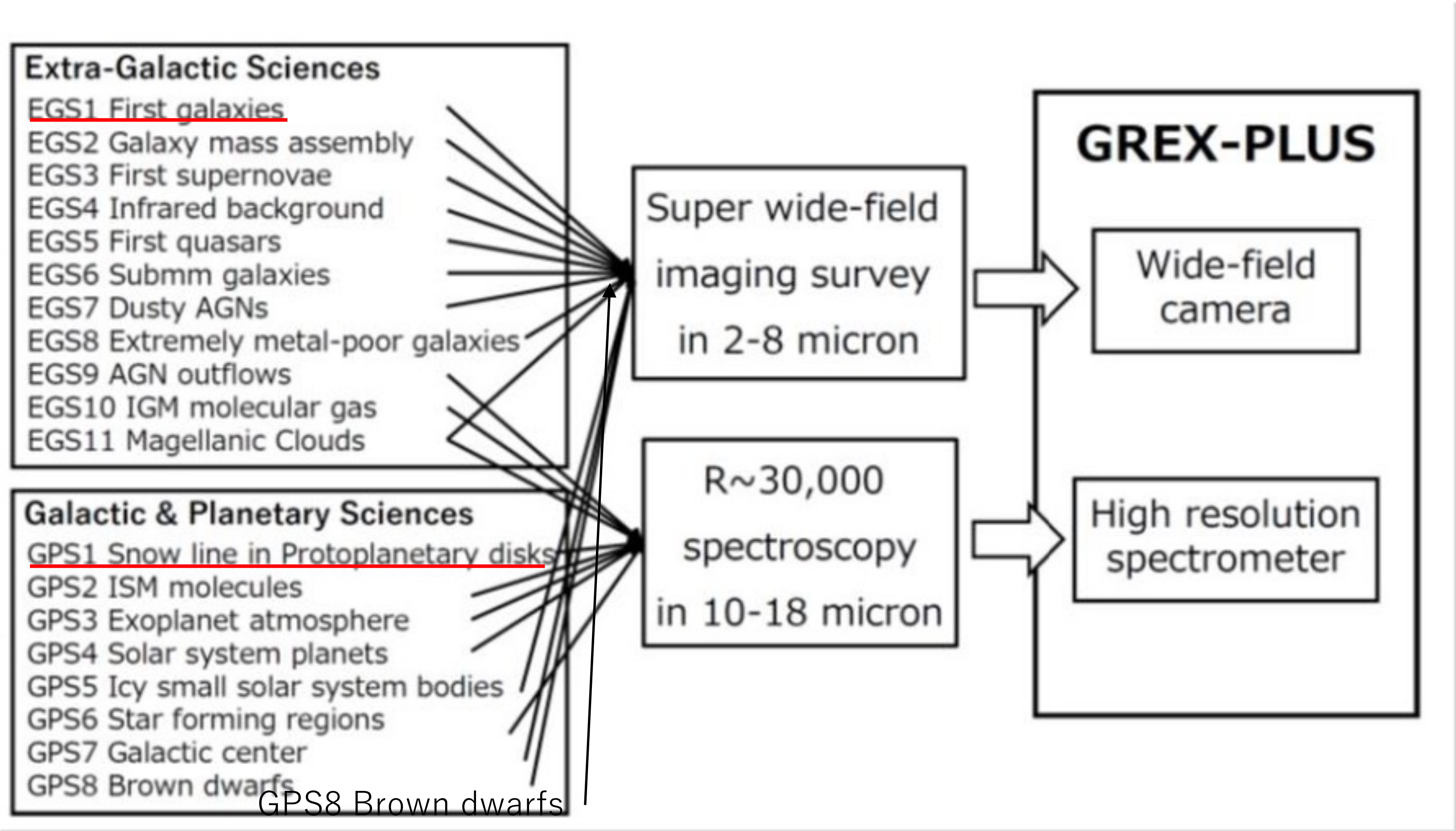
Science Goals and Instruments



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

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Disk chemistry synergy with JWST, ALMA, & ngVLA

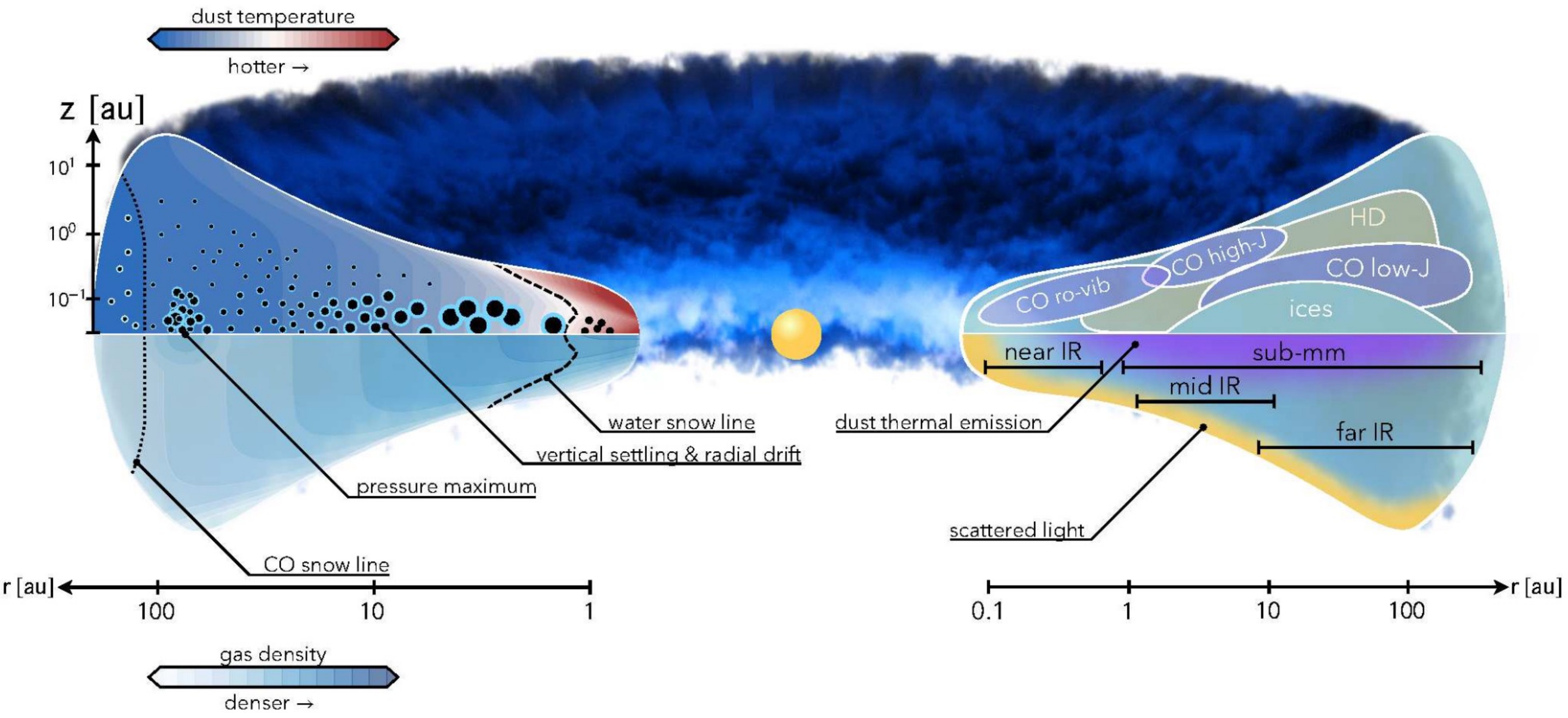
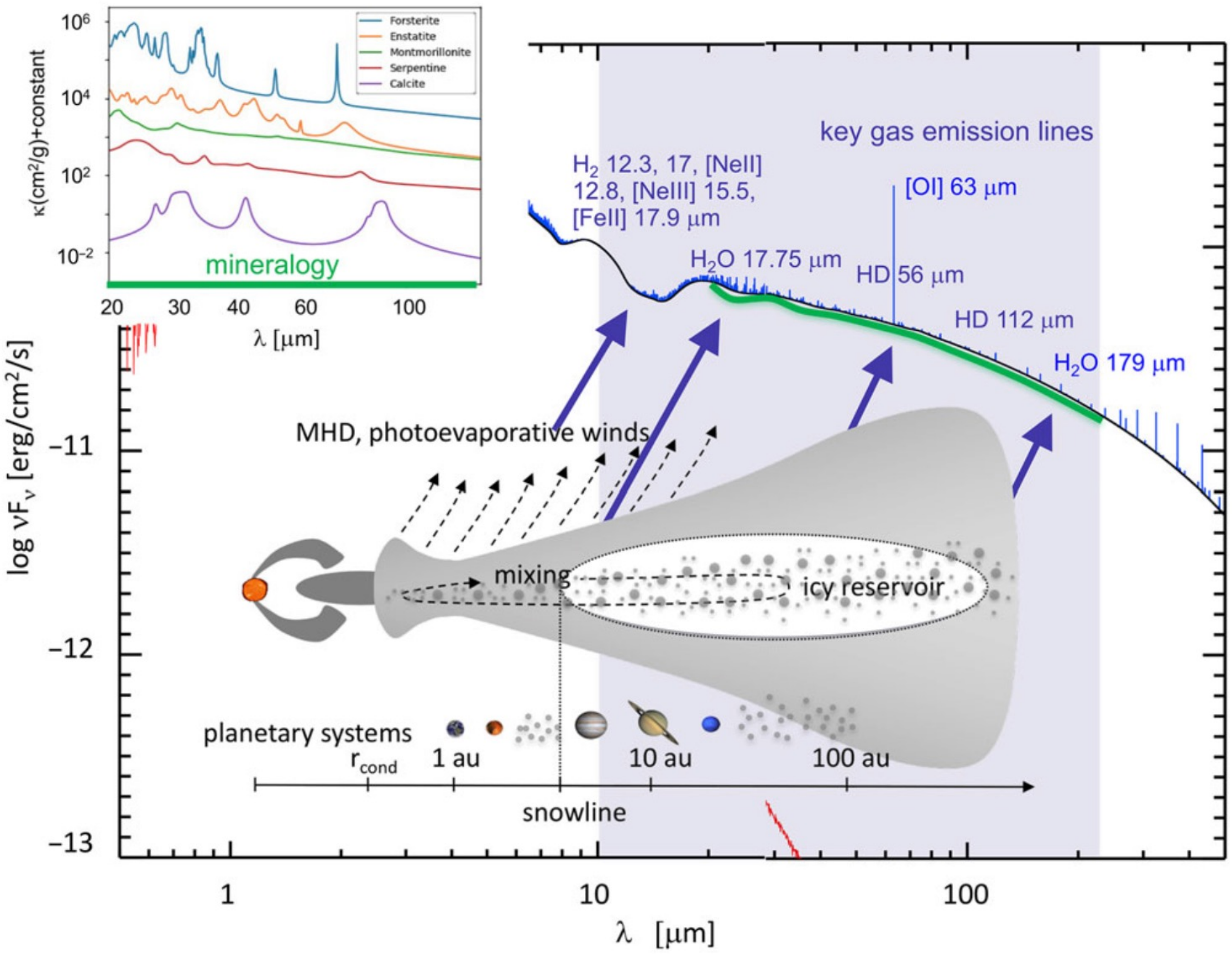


Figure from Miotello et al. 2023 (PPVII)

Summary of PRIMA 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

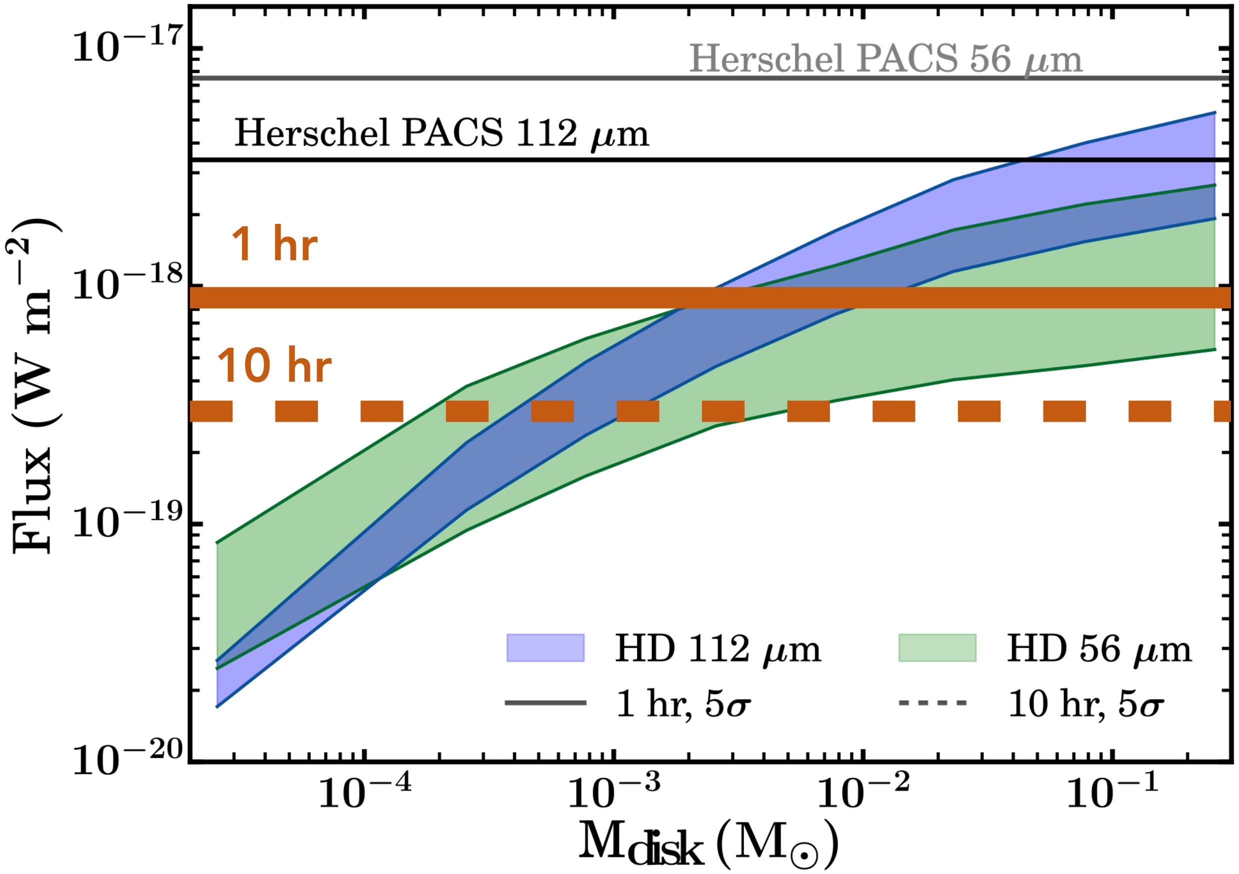
etc.

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

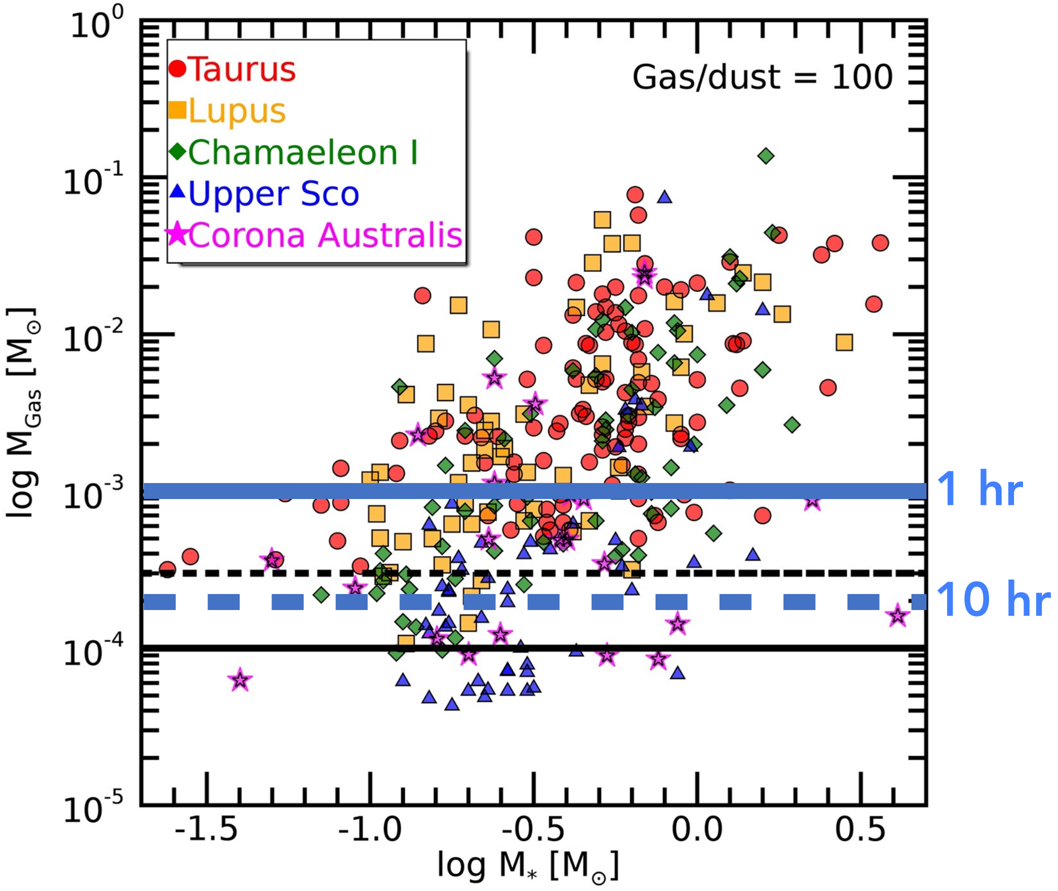
Figure from Kamp et al. (2021)

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



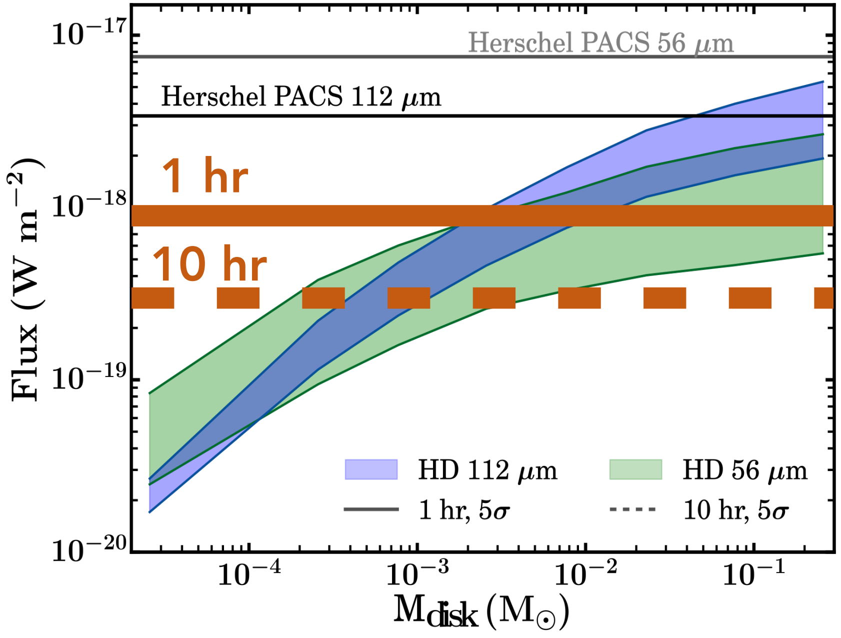
Modified from Kamp et al. (2021)

Disk dispersal processes with PRIMA and GREX-PLUS

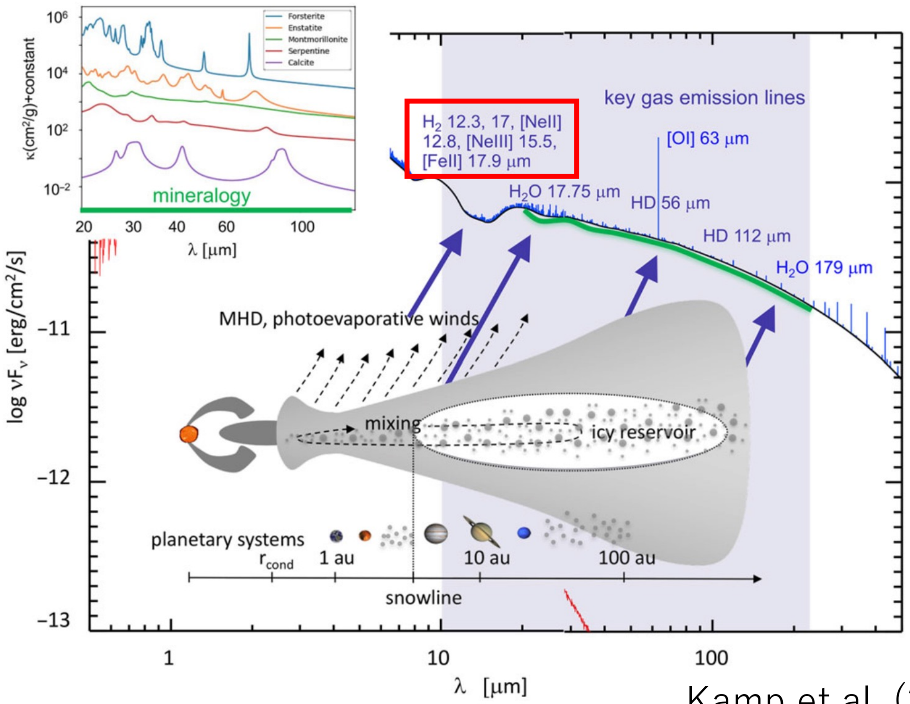
HD line (PRIMA):
Precise estimate of disk masses

HD lines J=1-0 112μm, J=2-1 56μm

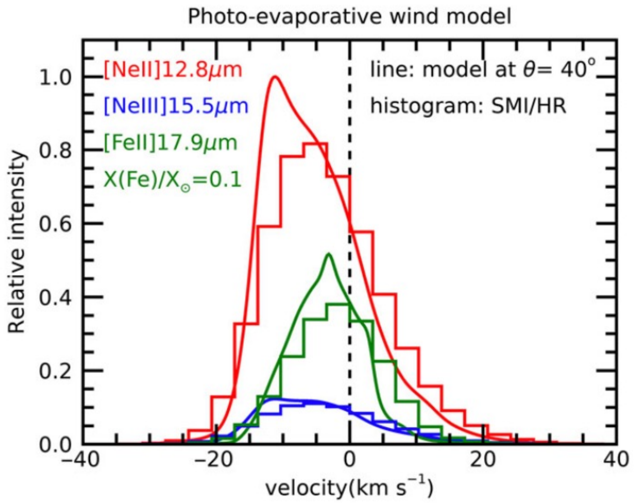
High-dispersion spectroscopy (GREX-PLUS)
H_2 S(1) 17μm, H_2 S(2) 12μm, [Ne II] 12.8μm lines
→Investigating disk dispersal processes



Trapman et al. (2017)



Kamp et al. (2021)

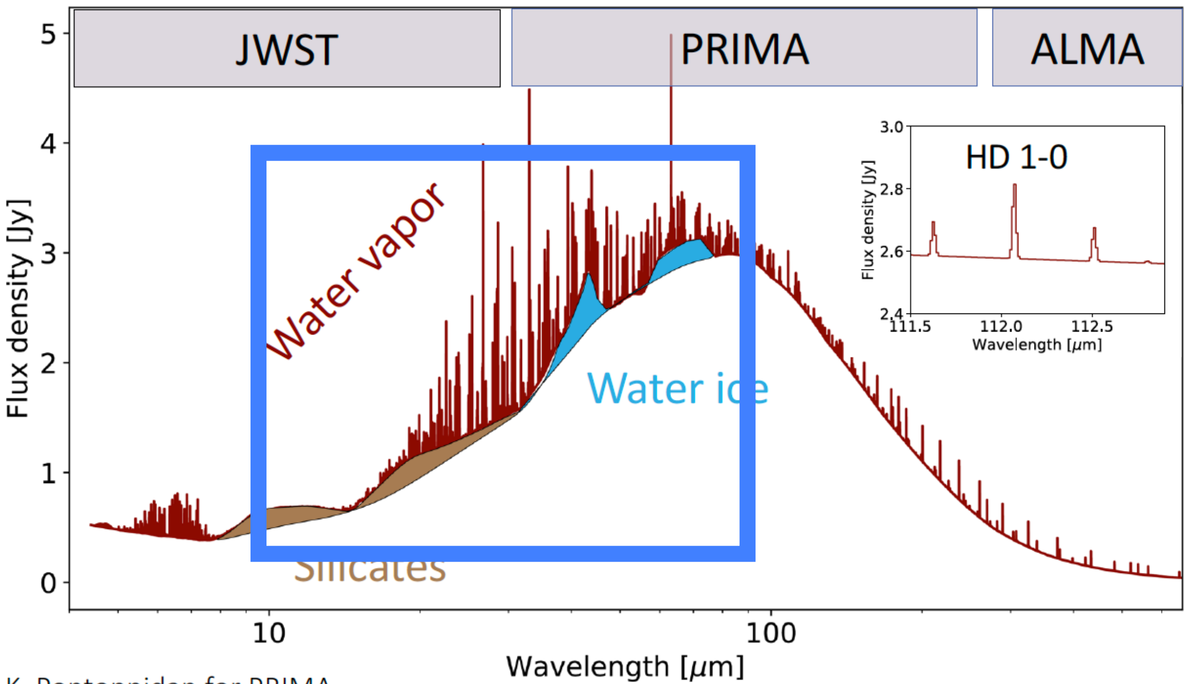


MHD, Photo-evaporative winds

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

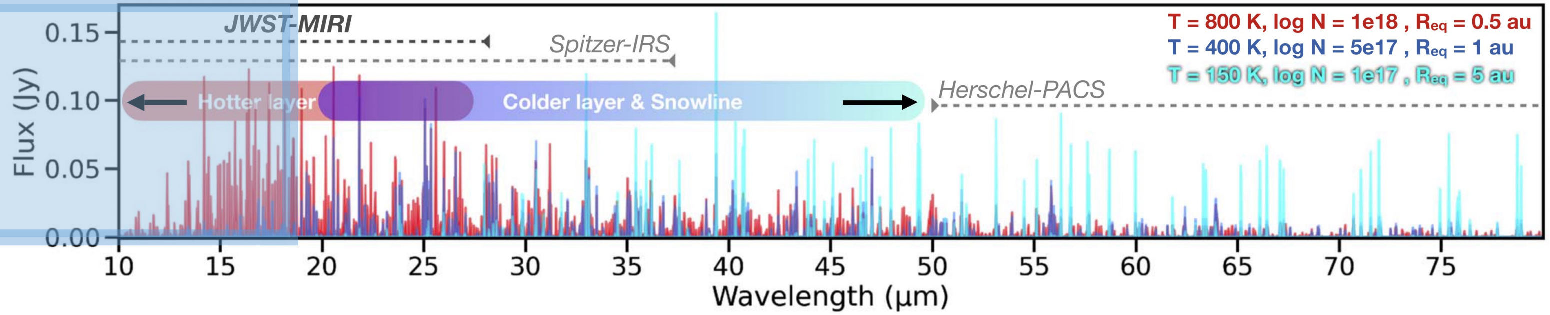
PRIMA can trace multiple “cold” water lines

A disk survey using FIRESS FTS mode to get full spectra of these disks



K. Pontoppidan for PRIMA

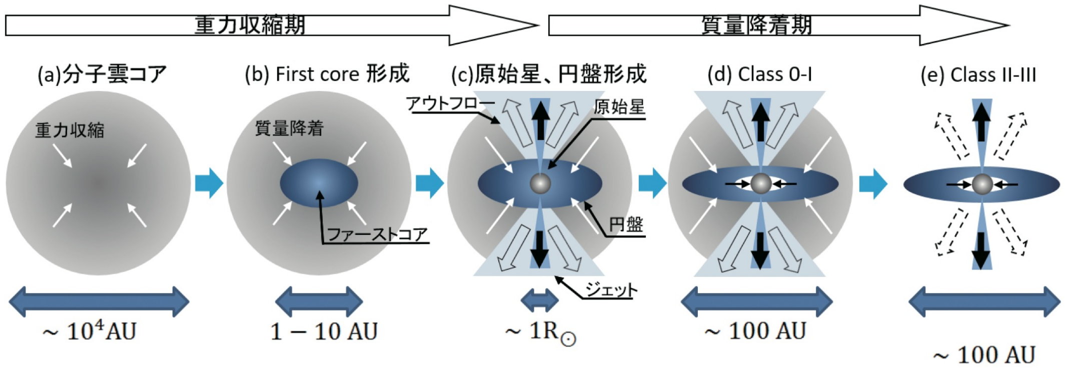
GREX-PLUS
synergy



Banzatti et al. 2023

Snowline positions move inward with time

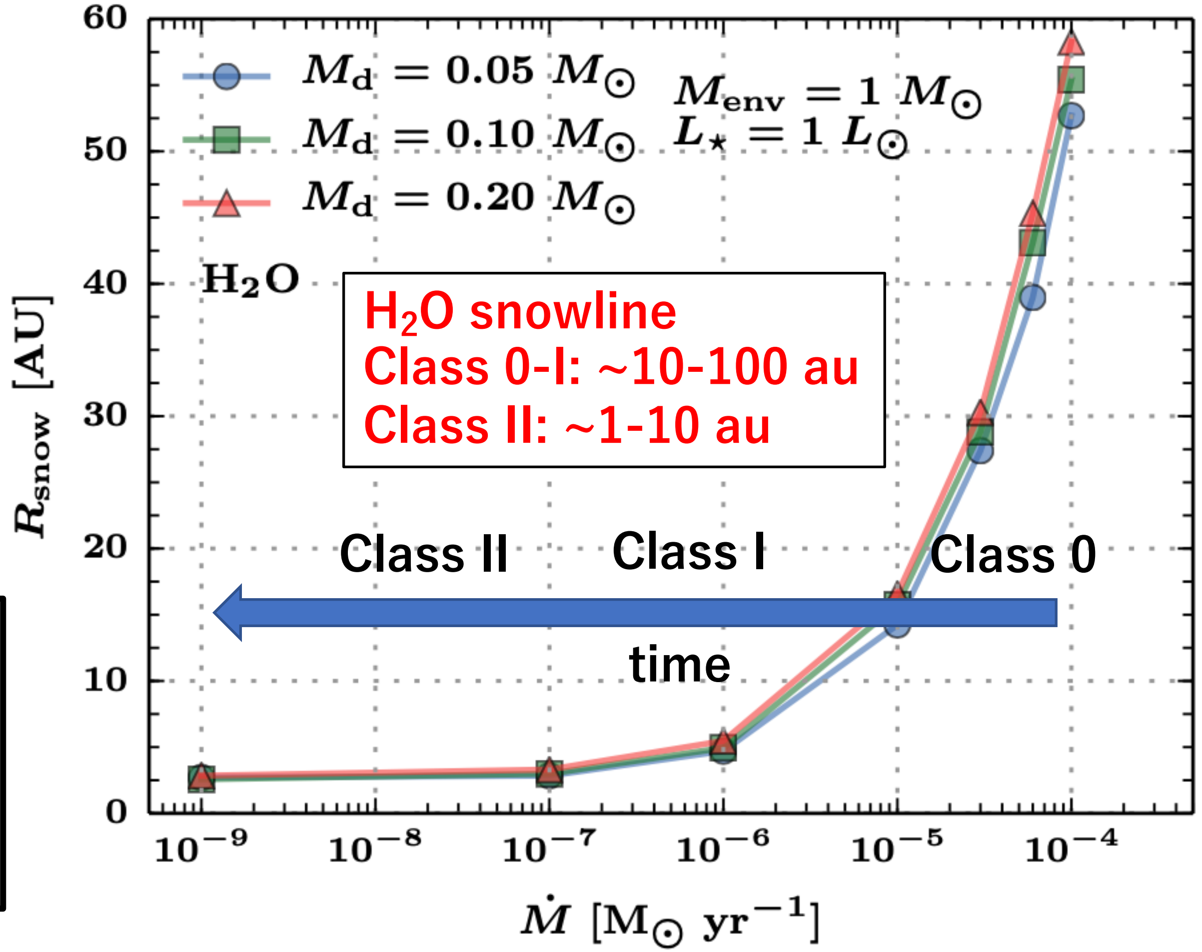
Snowlines are sublimation front of volatile molecules.



塚本さん遊星人原稿より

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**



Harsono et al. (2015)
See also e.g., Oka et al. (2011), Notsu et al. (2021)

Locating the snowline positions from Keplerian line profiles

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

PPDs：(almost) Kepler rotation

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

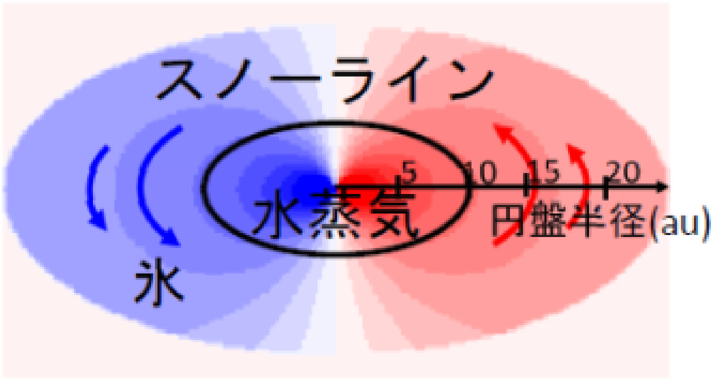
i: inclination angle

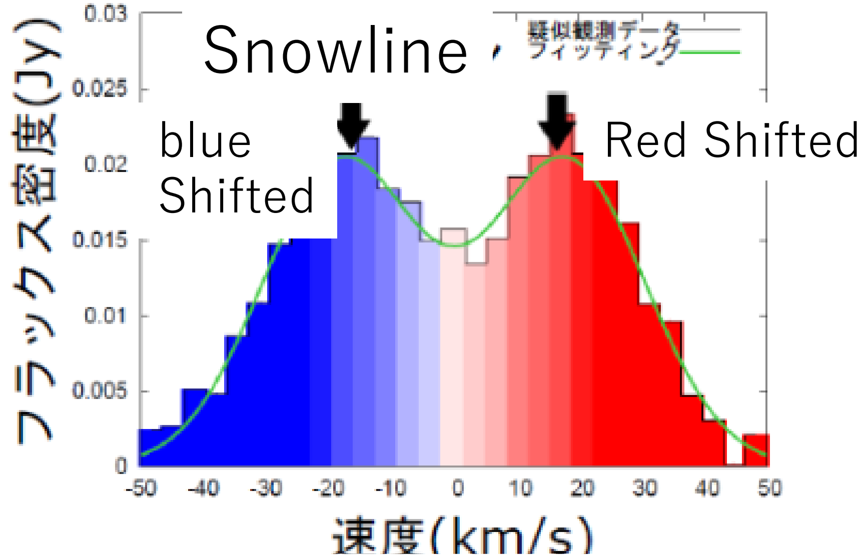
velocity profiles of emission lines
↓
location of snowlines

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

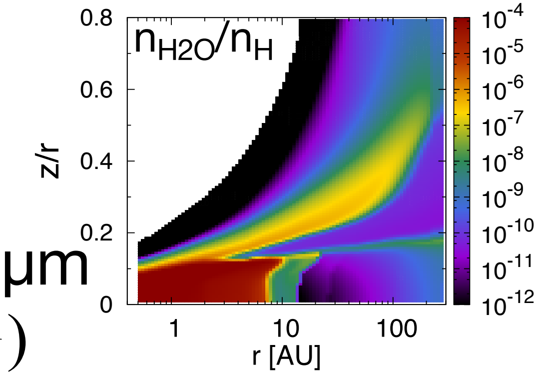
$R \sim \lambda/\Delta\lambda$

Keplerian Rotation



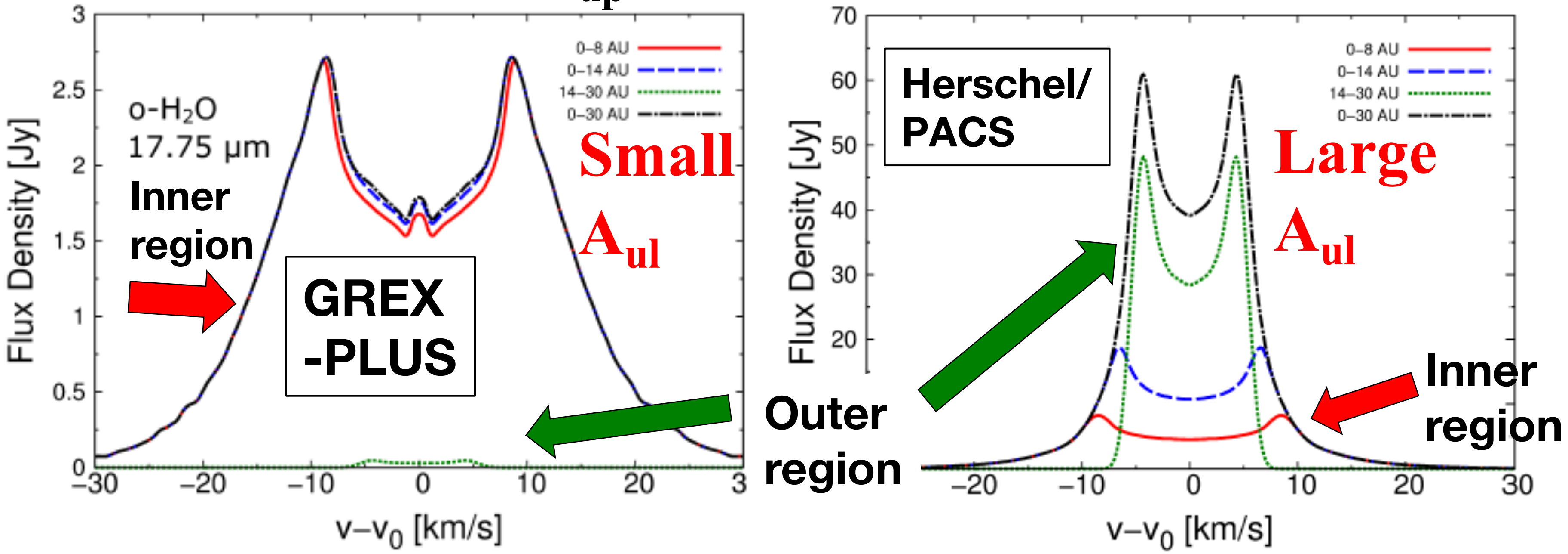


H_2O snowline and water line profiles



ortho-$H_2{}^{16}O$ 17.75μm ortho-$H_2{}^{16}O$ 63.32μm

A_{ul} ~ 2.9×10^{-3} (s^{-1}) **E_{up}~1000K** A_{ul} ~ 1.7 (s^{-1})



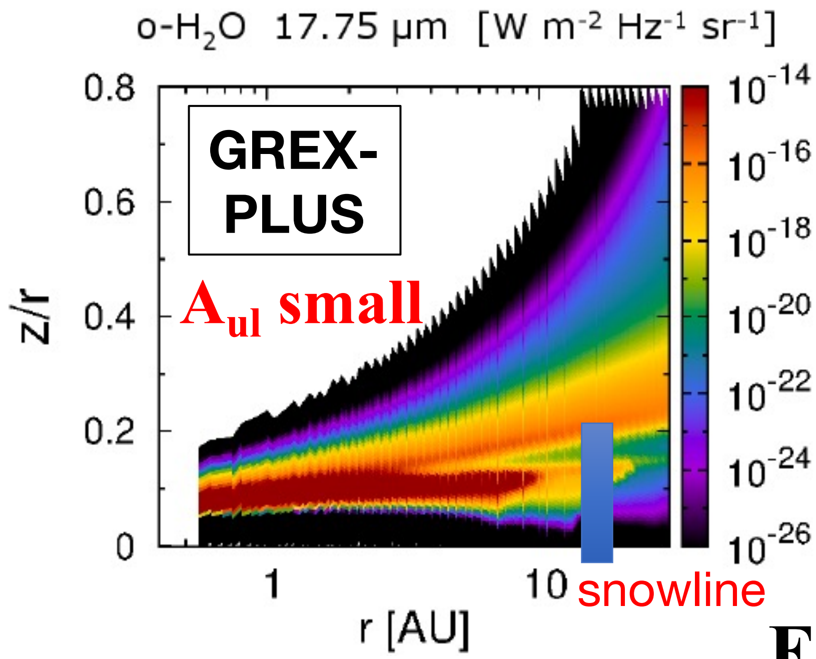
Notsu et al. (2016, 2017,2018)

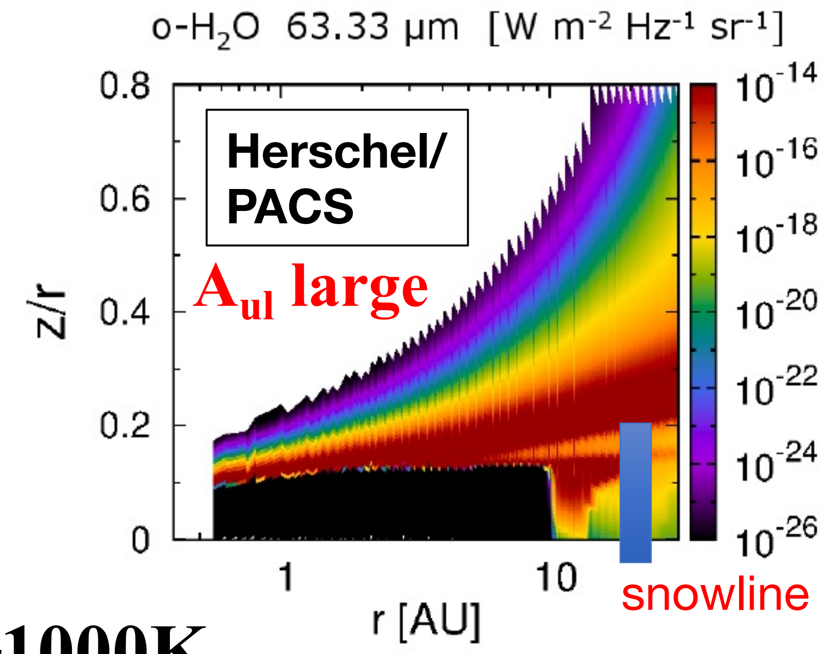
i=30° Distance:140pc

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).

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

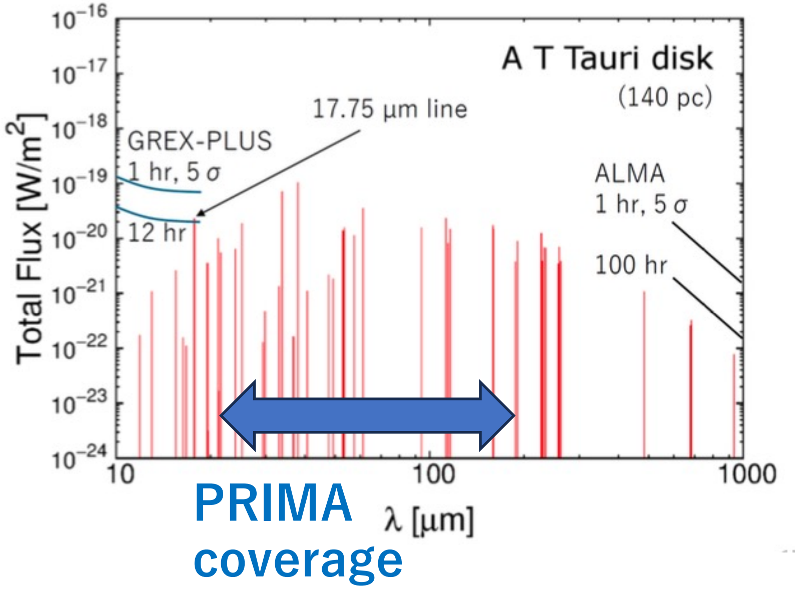
ortho-$H_2{}^{16}O$ 63.32 μm
A_{ul}= 1.7 (s^{-1})

Notsu et al. (2016, 2017,2018)

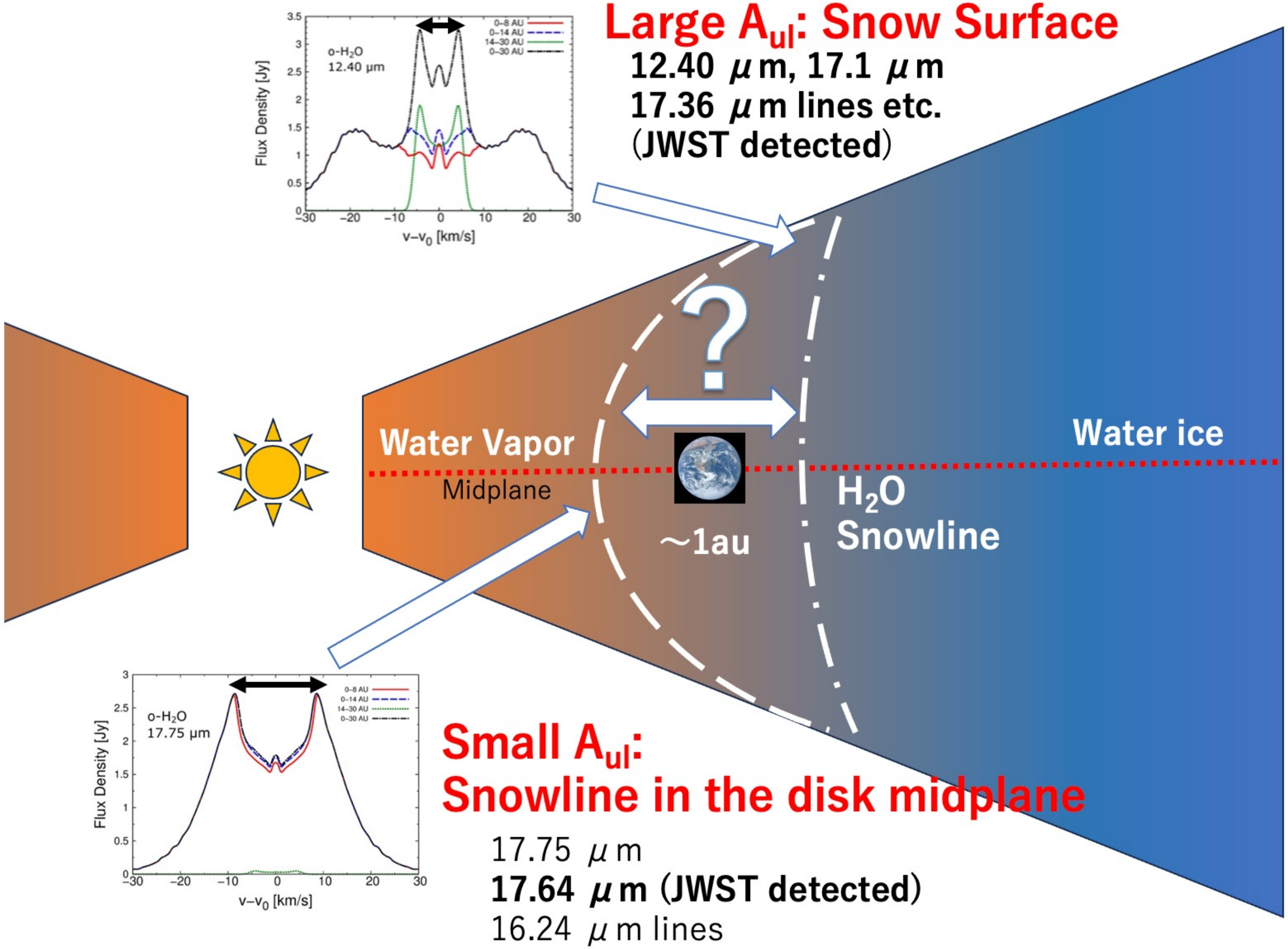
Small A_{ul} → emission from the outer optically thin surface layer << emission from the optically thick region inside the H_2O snowline
→ H_2O snowline tracer !

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

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)

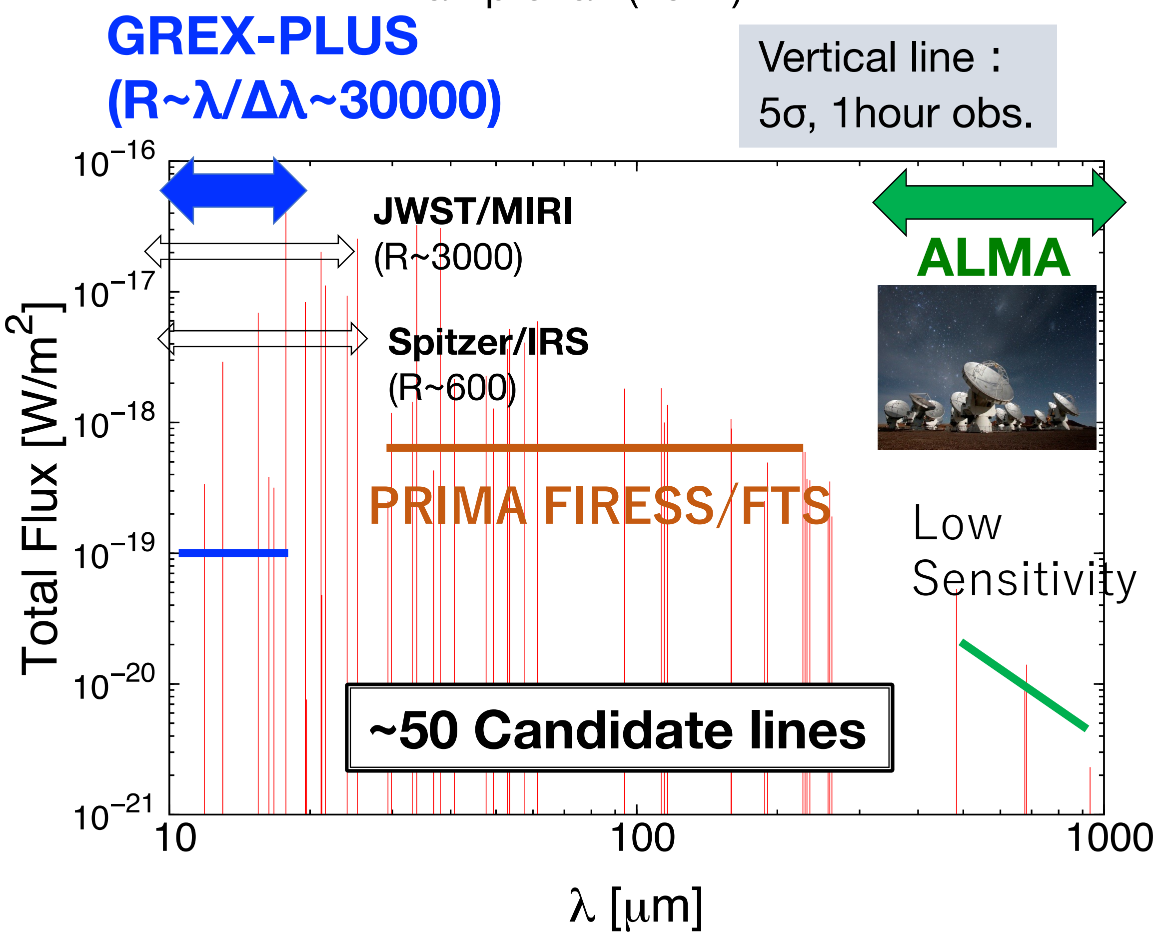
Model fluxes of candidate water snowline tracer lines for future observations

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

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 able to resolve line profiles and/or measure the line widths with Keplerian rotation in the shortest wavelength lines ?!

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



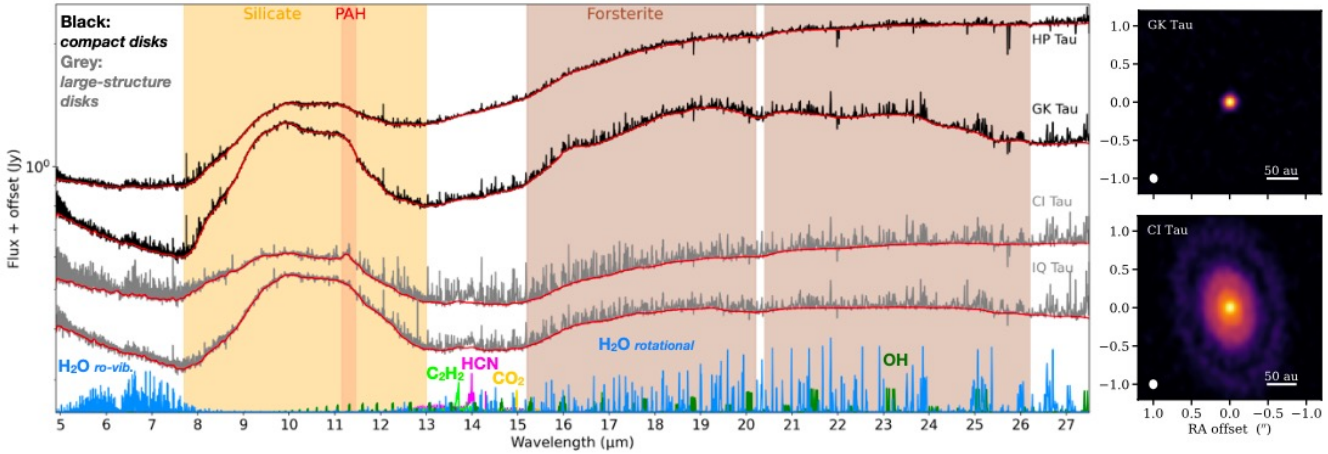
i=30°, d=140 pc
$10^{-6}<A_{ul}<10^{-2}\ s^{-1}$, 700K<$E_{up}$<2010K

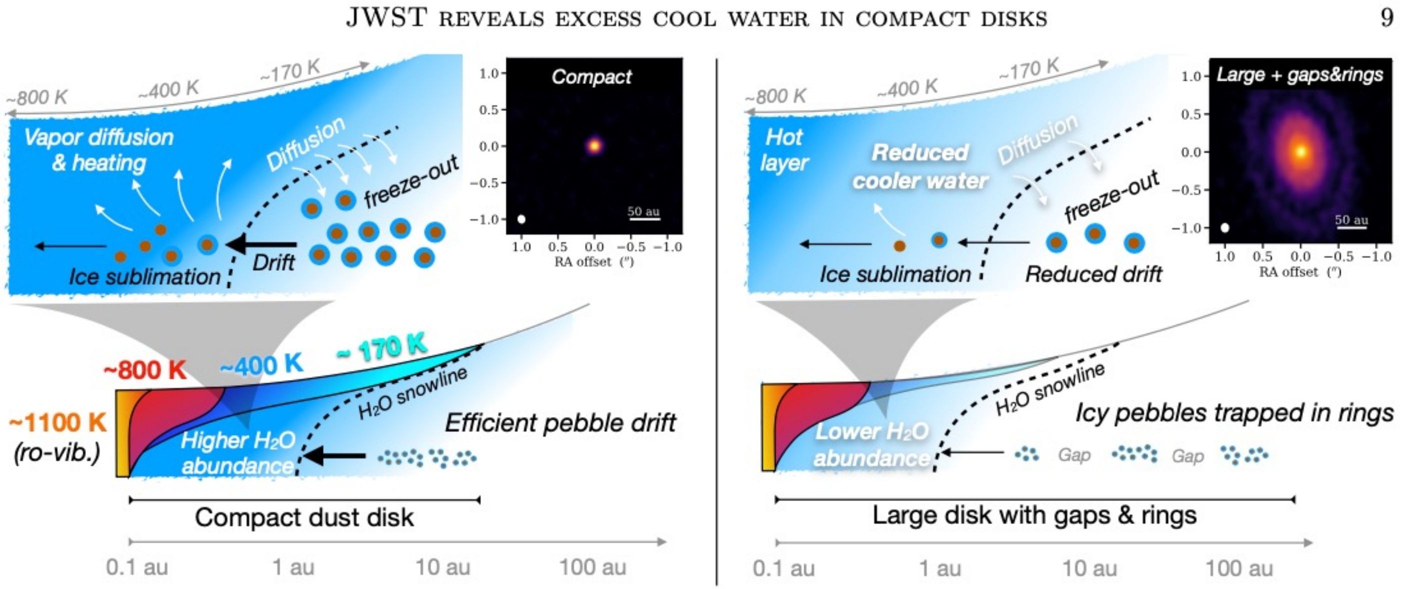
Recent JWST/MIRI observations for Class II disks

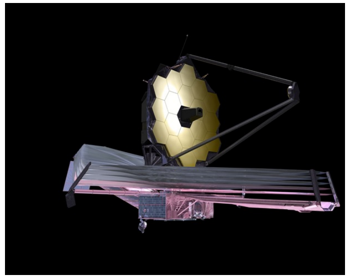
Figure from Banzatti et al. (2023)
See also e.g., Banzatti et al. (2025)

- Many water lines with various E_{up} especially at λ ~16-18 um
- 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**

GREX-PLUS & PRIMA:
More precise estimate for emitting region







JWST/MIRI (R~3000)
- We will not be able to resolve the line profiles sufficiently.
- We can make target selections for GREX-PLUS and PRIMA !

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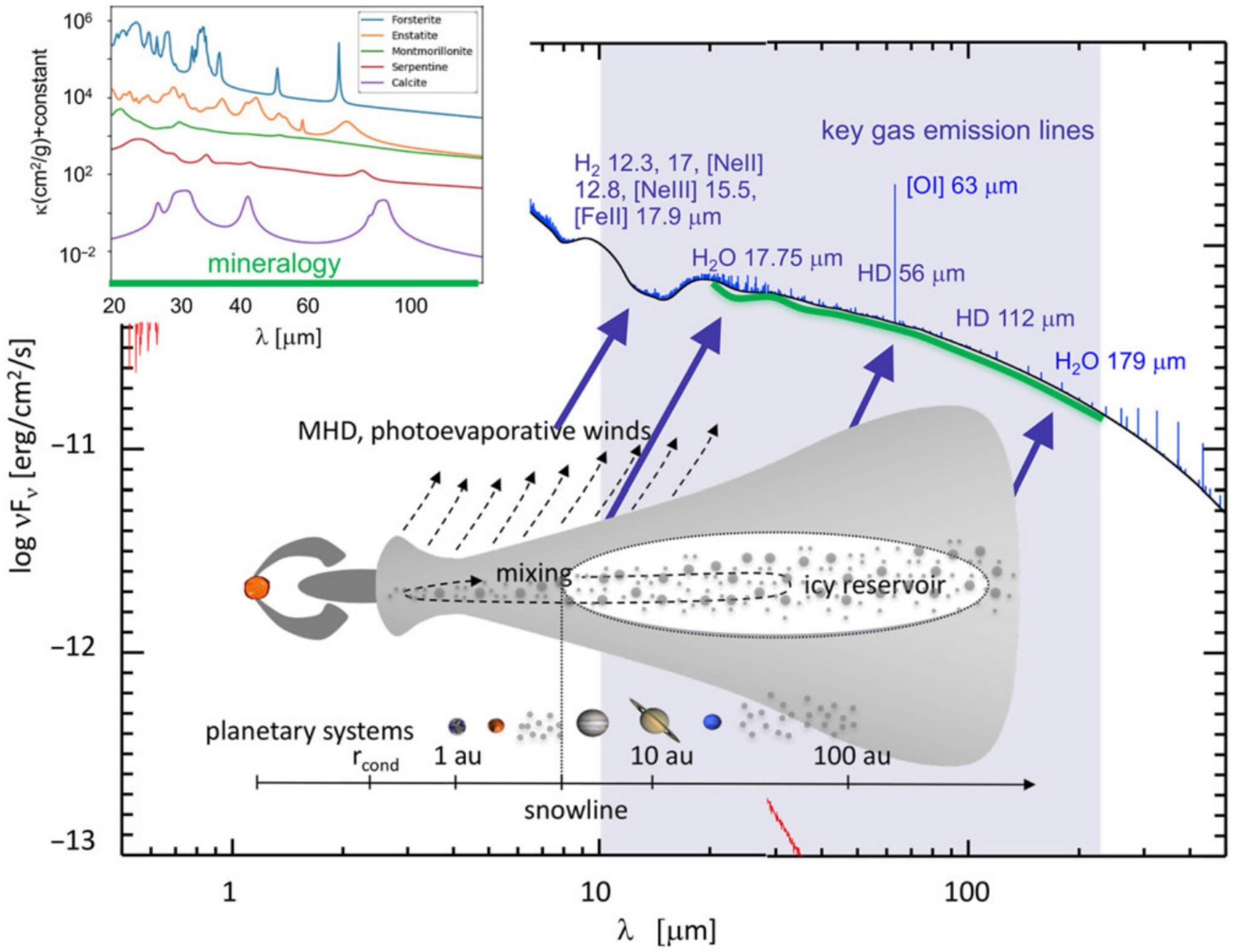

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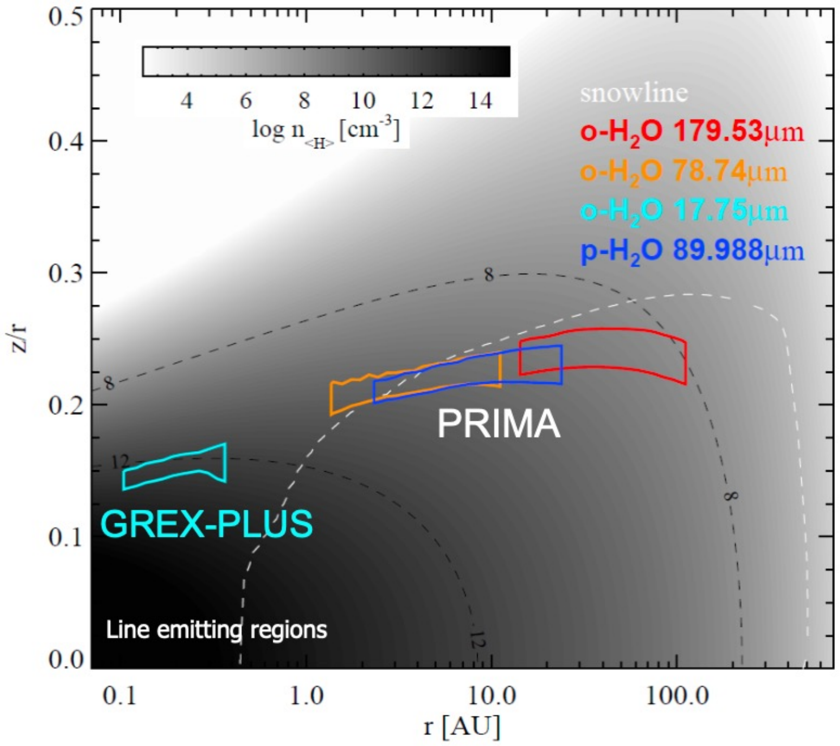
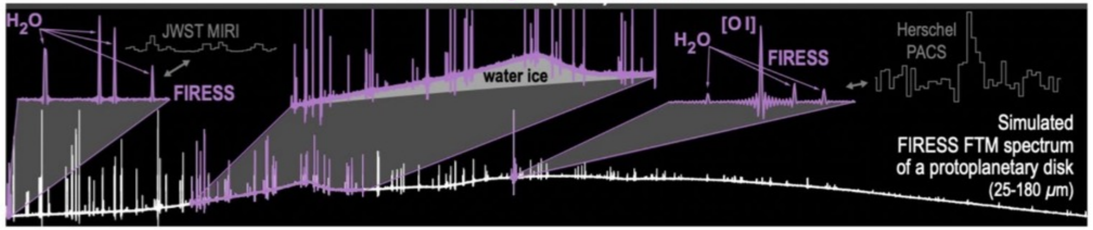
H_2O in protoplanetary disks

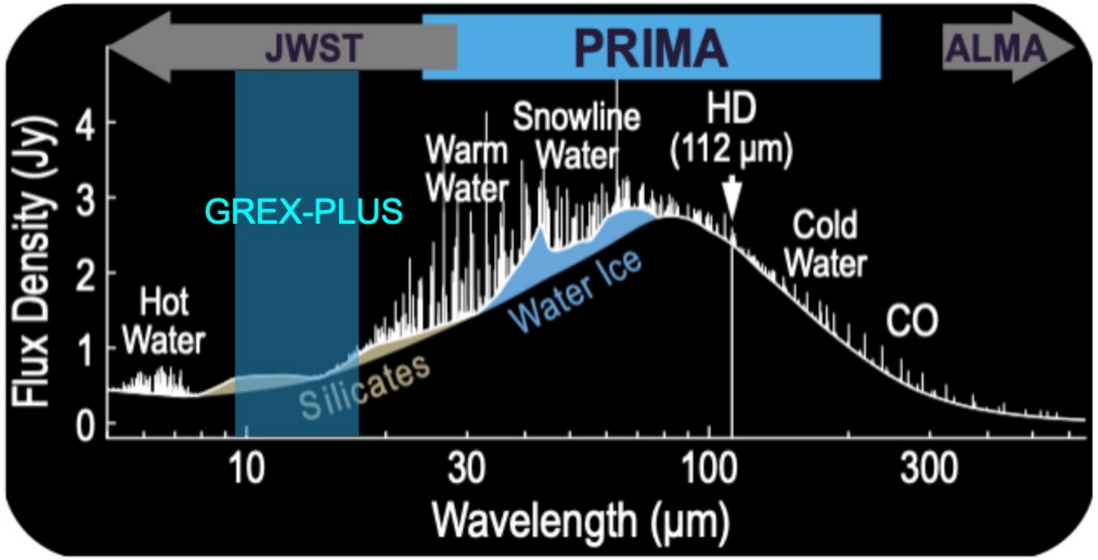
T Tauri disks, 1-hr & 10 hrs integration



Kamp et al. 2011, 2017, 2021

FIRESS high-res FTM module





From PRIMA webinar slide