Formation of stars and planets

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Outline

- Science cases on star formation
- Science cases on planet formation
- Possible key programs

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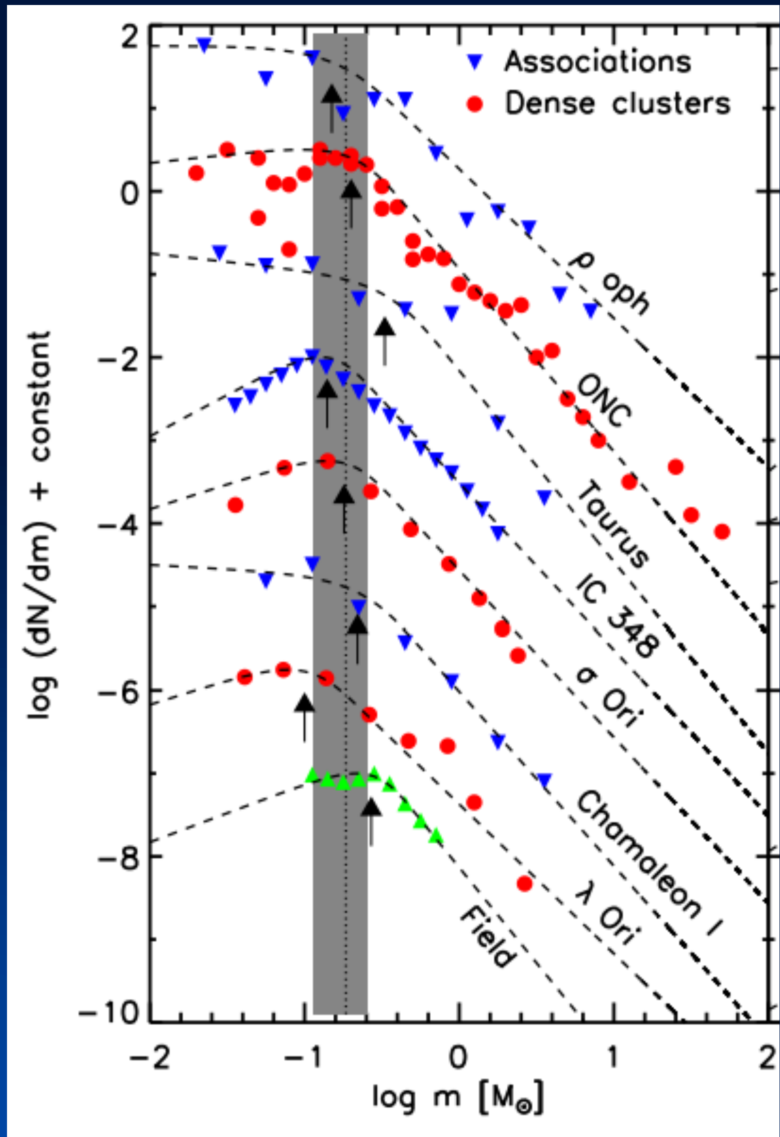
Star formation:

What determines stellar (sub-stellar) mass?

IMF

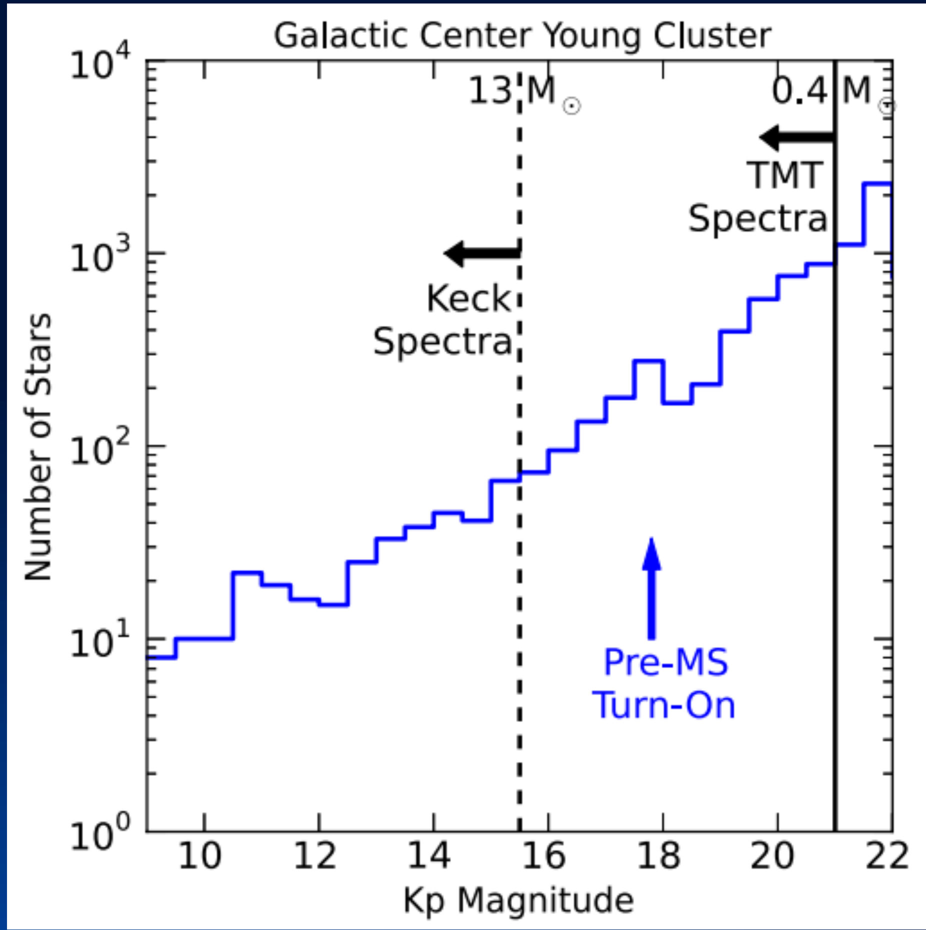
- Counting individual stars in young clusters
- In our Galaxy
  - Mostly “Universal”
  - Deviation suggested at the center of MW
- Need measurements under various physical environments
  - metallicity
  - cloud gas density
  - external pressure
  - cluster density



Bastian (2010)

IMF in distant regions in MW

- IMF covering characteristic mass ($<<1\ M_\odot$) with IRIS spectroscopy
- Photometric sensitivity allows us to go down to brown-dwarf regime at the galactic center



Model Kp-band luminosity function
(Lu et al. 2013)

Beyond our Galaxy

Very nearby low-metal galaxies

	d (kpc)	$Z_\odot$
NGC 6822	490	~0.3
M33	840	~0.5
IC 10	950	~0.3

Arches-like cluster in M33 (photometric crowding)

Radius (Re)	Limiting K mag	Limiting mass ($M_\odot$)
1.0	18.9	65
2.0	22.3	3
5.0	27.5	1.1

K = 27.5 can be detected with IRIS photometry at 5σ in 1 hour, though the mass limit would lie ~40 $M_\odot$ for IFU

High & low-mass end of IMF

- *How do massive stars form?*
  - Spatially and kinematically resolving circumstellar environment of young massive stars in NIR and MIR (up to 24 μm)
  - structure of the gas envelope, accretion disk, outflows, multiplicity, (low-mass) protostellar crowding around the forming massive protostar …
  - d = 3 kpc for typical Galactic massive protostars

    → structures on ~1000 AU scales, e.g. corresponding to disk diameters, extend over ~0.3 arcsec.

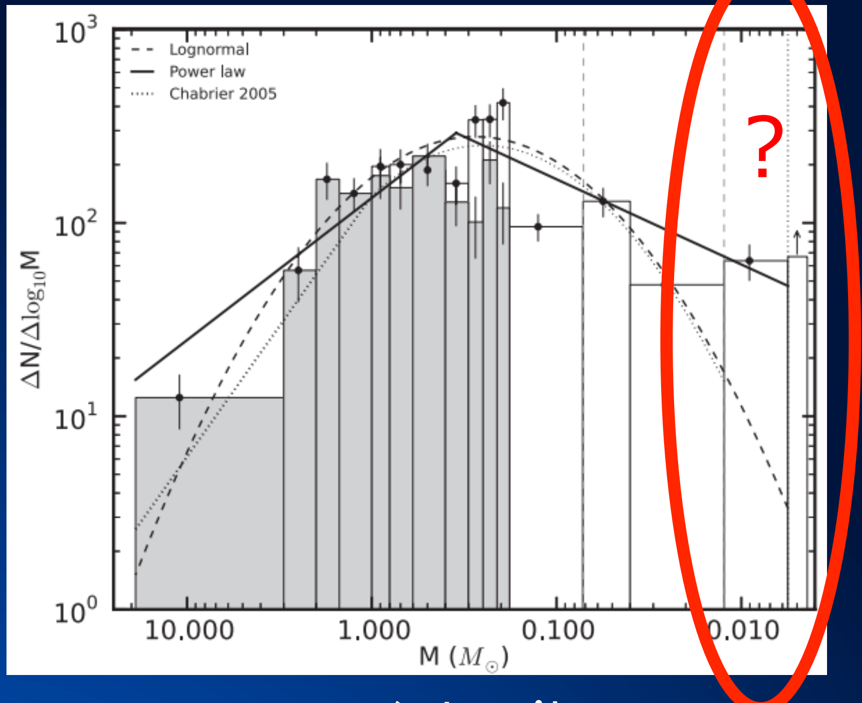
High & low-mass end of IMF

- *How do free-floating planets form? Fragmentation or dynamical ejection?*

▶ Detecting bottom end of the IMF, under various environment (e.g., cluster density)

▶ Spectroscopy (may not need R~4000) for ~1 M_{Jup} or sub-Jupiter-mass objects

→ comparison with bound planets



~6 Jupiter-mass

(Peña Ramírez et al. 2012)

Synergy with other observatories

- ALMA
  - Resolving clumps, dense cores, YSOs with jets and outflows in distant regions and beyond MW
- SOFIA
  - Providing good targets for massive protostars
- Wide-field AO for 8 m telescopes
  - Improving IMF
  - Detecting least massive free-floating planets →spectroscopic follow-up

Planet formation:

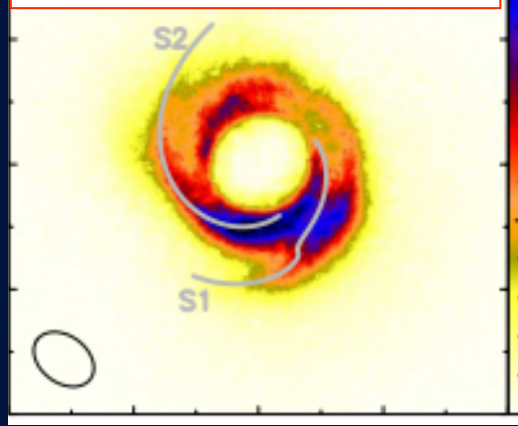
When, where and what kind of planets form in what type of disks?

How planets and a disk mutually evolve?

Protoplanetary disks

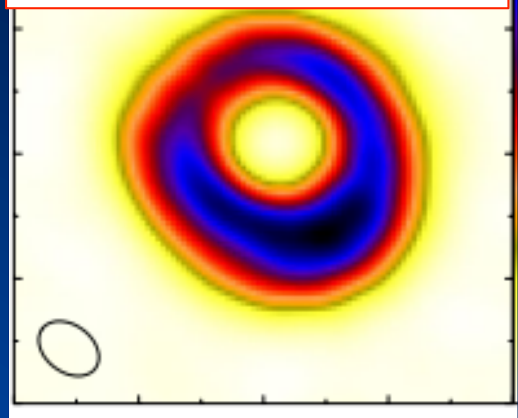
1. Planet formation will occur, or is ongoing
   - Initial condition
2. Planet formation has recently finished
   - Interaction between planets and disks, evolution of planetary orbits, triggered formation of more planets?
   - Forming planets in disks

NIR scat. light
($\Delta\theta$~60 mas)



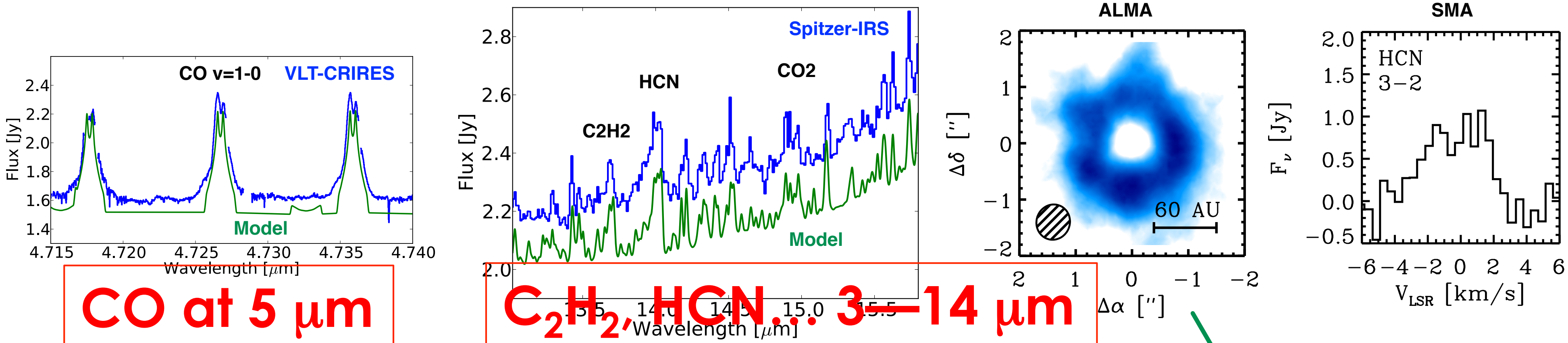
(Muto et al. 2012; Perez+ 2014)

submm thermal
($\Delta\theta$~200 mas)



(Perez et al. 2014)

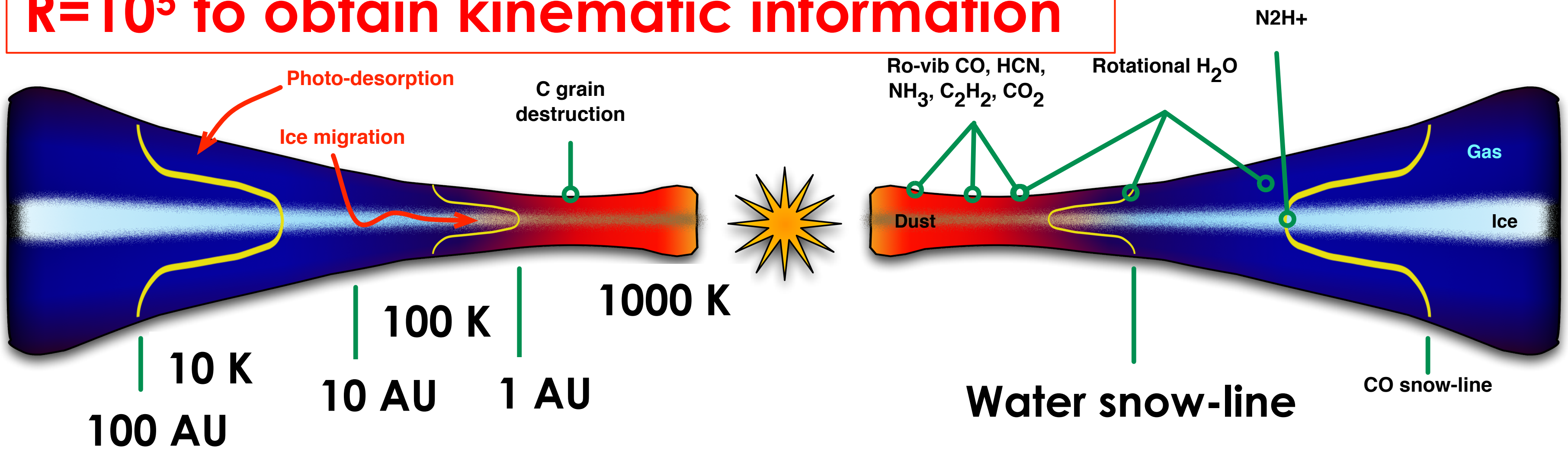
TMT can probe inner, planet-forming region (≲10 AU)



CO at 5 μm

C_2H_2, HCN... 3–14 μm

R=10^5 to obtain kinematic information

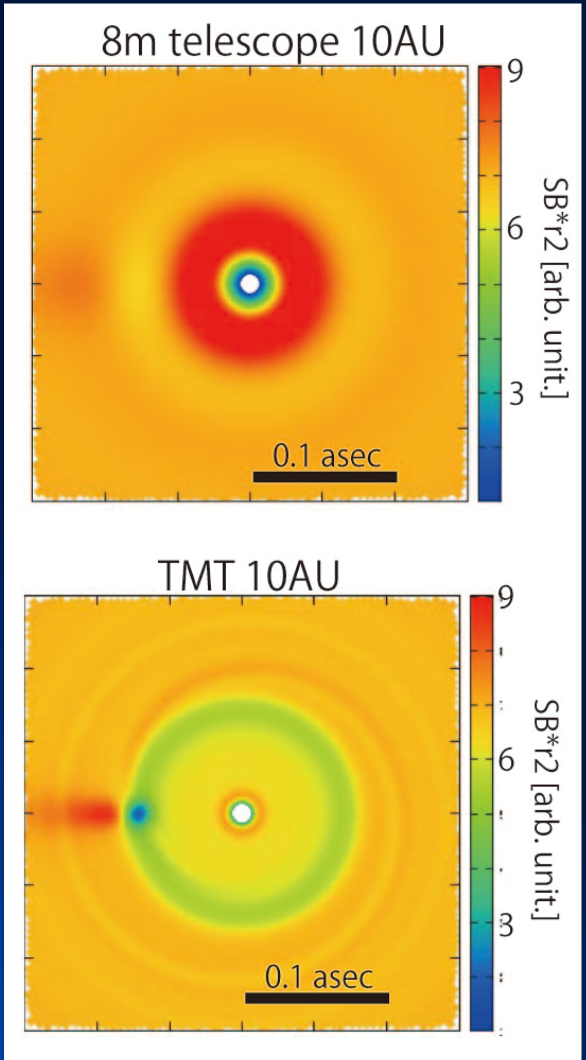


(courtesy K. Pontoppidan, Taken from the DSC2014 draft)

Planet-disk interaction

- Most T Tauri stars cannot be observed with ExAO on 8-10 m telescopes
  - → Waiting for TMT for the inner region (<20—30 AU) and/or small-scale (≲8 AU) structure

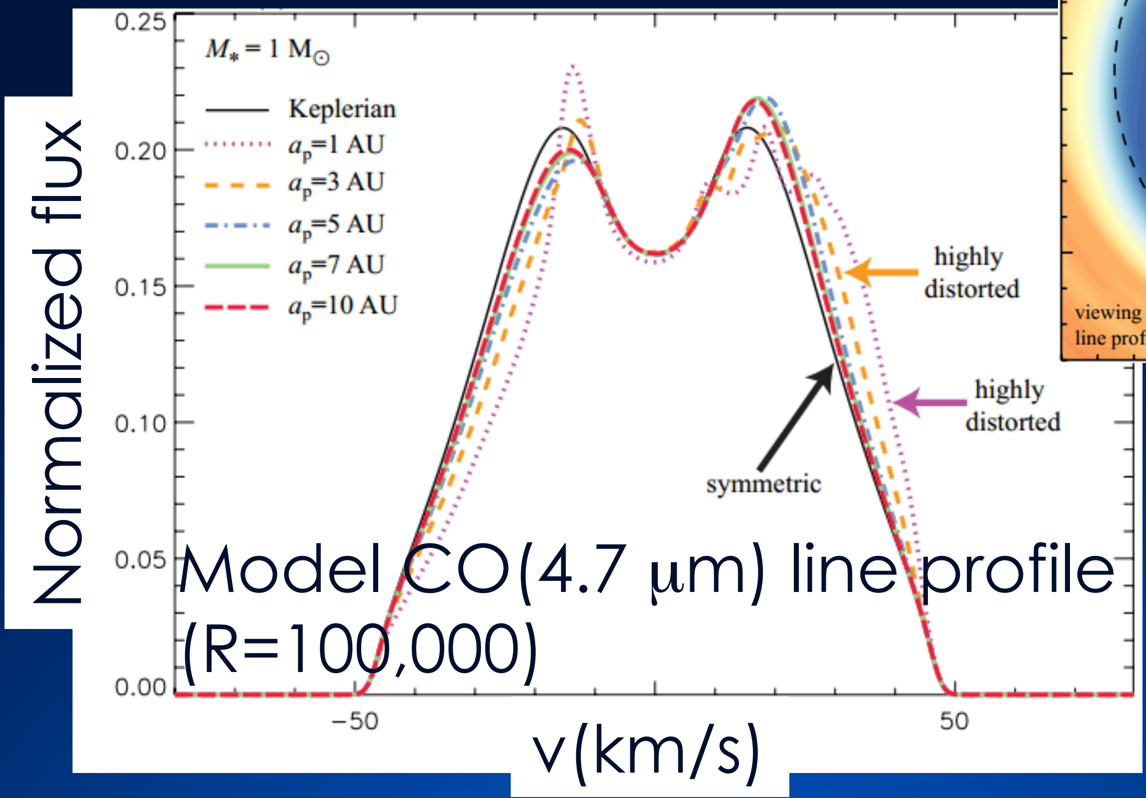
- Indirect evidence of planets (≲0.1 M_{Jup}) by scattered-light imaging; spiral arms

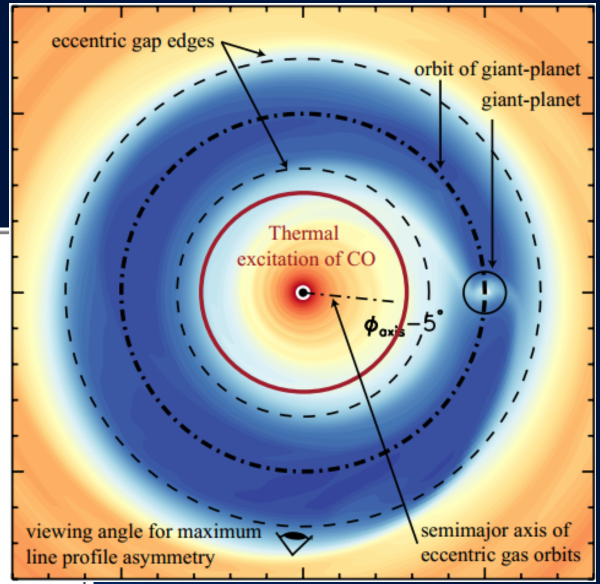


(courtesy T. Muto, from the DSC2014 draft)

Planet-disk interaction

- Accreting/growing planets
  - Local non-Keplerian velocity



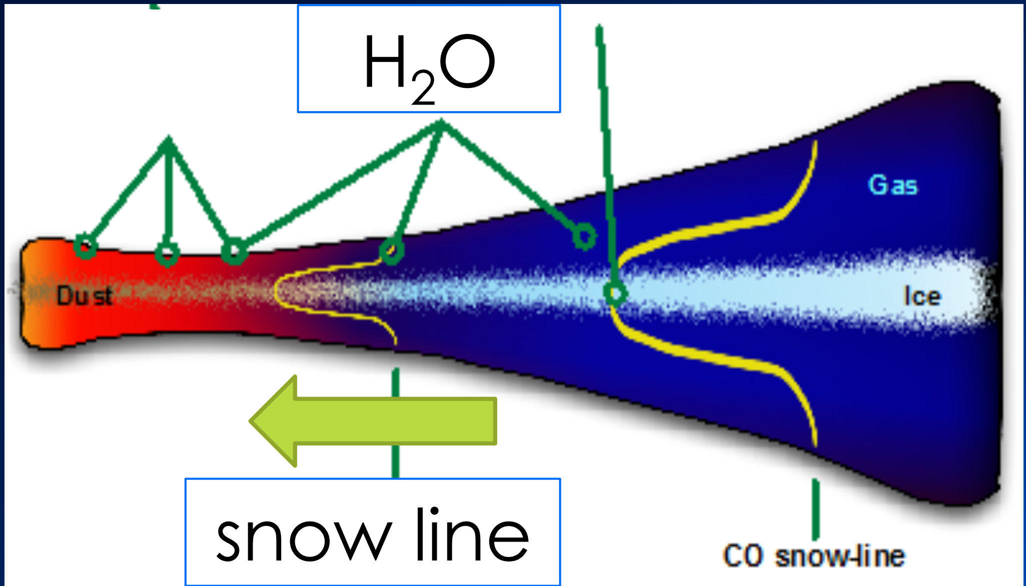


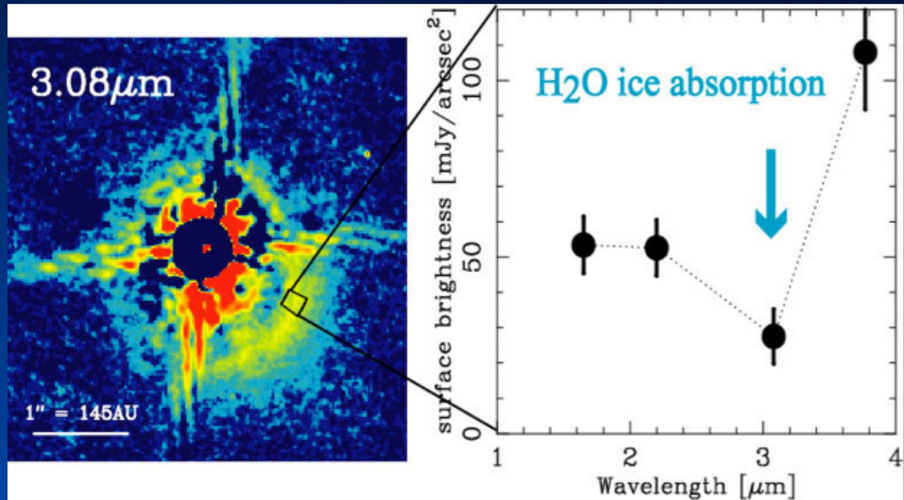
(Regaly et al. 2014)

Water snow line

- Enhanced accretion of planetary cores, origin of the water in terrestrial planets

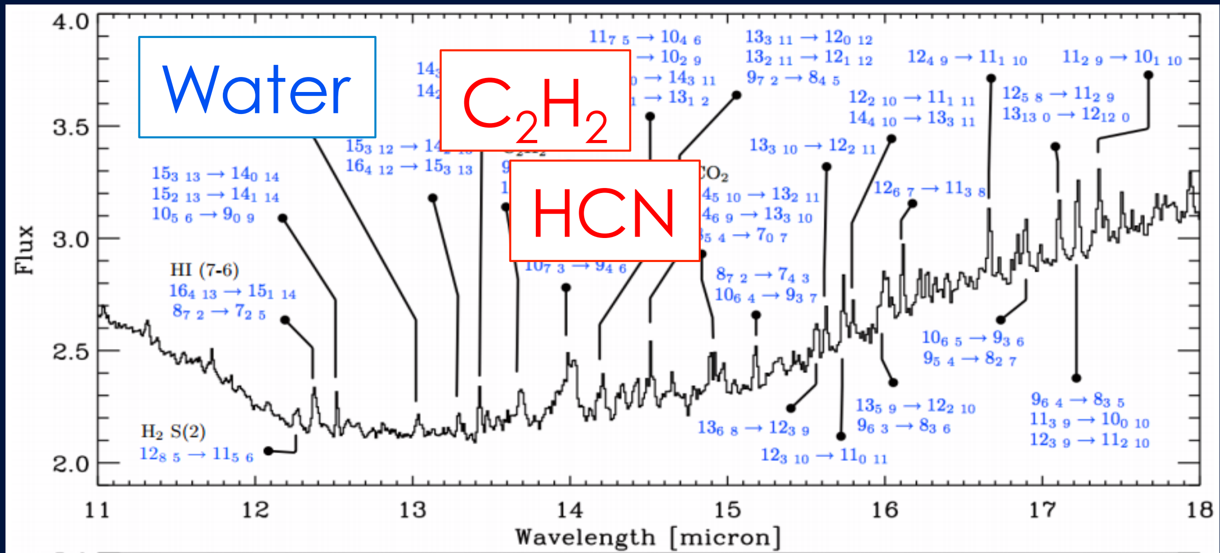
1. Water vapor in NIR and MIR → prediction of underlying snow line
2. Icy grain feature at 3.1 μm in scattered light → snow line at the disk surface





(Honda et al. 2009)

Pre-biotic chemistry



Pontoppidan et al. (2010)

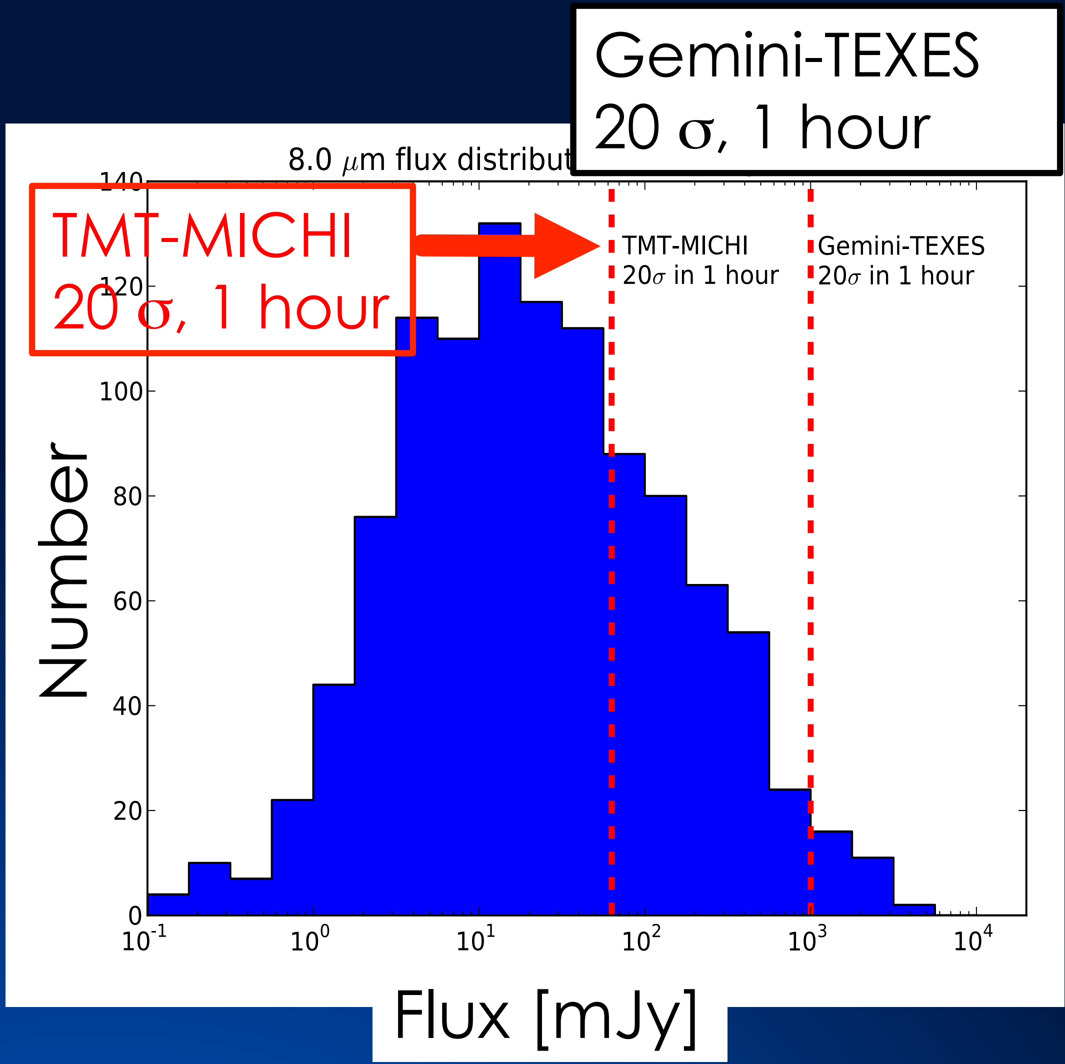
Ground-based detection: e.g., Mandell et al. (2012)

- The amount and molecular form of CHONPS molecules delivered to potentially habitable planets ultimately provide the basis for the formation and evolution of terrestrial atmospheres
- Depletion of C on the Earth: universal?

Observations of planet-forming CHONPS molecules with the TMT will provide observable links to the growing population of exoplanets

TMT's high sensitivity

- Statistically study is finally possible
- New molecules, more complex ones; e.g. HCOOH (Nomura@TMT conf. 2013)



The 8 μm brightness distribution (Evans et al. 2009)
Sensitivity for high-R (R=100,000)

Until TMT's era

ExAO on 8 m
Structure at inner AU optically bright, early-type YSOs

TMT
- Structure at ~1 AU scale within ≲10 AU for Solar-mass stars
- Detecting forming planets
- Locating water and organic molecules

ALMA
Density & temperature distribution at ~1 AU scale beyond ~10 AU

JWST
Presence of organic molecules at ≲10 AU for larger sample

Which instrumental capability?

(extracted from the DSC)

Science theme	observations	capabilities
IMF vs. environment • Resolving stellar populations in distant clusters in MW and in Local Groups	• Diffraction-limited imaging and spectroscopy in NIR	**IRIS** **IRMS**
Kinetic evolution • Initial condition of cluster formation • early dynamical mass segregation	• mass, position, and velocity measurements in optical through **MIR**	**IRIS** **IRMS** WFOS NIRES MICHI
Multiplicity • Improving statistics • Constraints on star formation models • New parameter space • Binary formation	• Diffraction-limited NIR imaging • astrometry and spectroscopic orbital monitoring • **High contrast** observations • **MIR** for embedded Class I	**IRIS** WIRC PFI, SEIT HROS NIRES

Science theme	observations	capabilities
High-mass star formation • Protostellar dusty environment • composition and kinematics	• high resolution NIR and **MIR** imaging (imaging at wavelengths of 24 μm or longer is valuable for RT calculations) • **coronagraphic spot** • **requiring relatively large chop throw angles of ≳30 arcsec** • Brγ (2.17 μm), He I (2.06 μm). **[Ne II] (12.8 μm), 10 &18 μm silicate absorption** • **R~9000—30000 in NIR/MIR for kinematics**	**IRIS** MICHI
• **Formation of BDs & PMOs** • Sub-Jupiter mass free-floating planets • Bottom end of IMF	• High sensitivity (resolution) imaging at >~1 μm • High sensitivity (resolution) spectroscopy (R~1000: **check**) • Wide field-of-view	**IRIS** **IRMS** WIRC

Science theme	Observations	capabilities
Planet formation vs host stellar property • Improving statistics • Resolving disk structure in distant star-forming regions	• High spatial resolution/**contrast** imaging/spectroscopy in NIR (including **L band**) and **MIR**	PFI MICHI
Gas dissipation timescale • *In situ* measurements of gaseous reservoir	• **[Ne II] (12.8 μm), CO (4.7 μm)** • **High R (~100,000)** • Spectro-astrometry	MICHI NIRES
Disk structure • Detecting signatures by planets in disks • Signs by sub-Jupiter planets	• Diffraction-limited imaging in NIR and **MIR** • **High-contrast** imaging	**IRIS?** MICHI PFI SEIT

Not included in the 1st light instruments

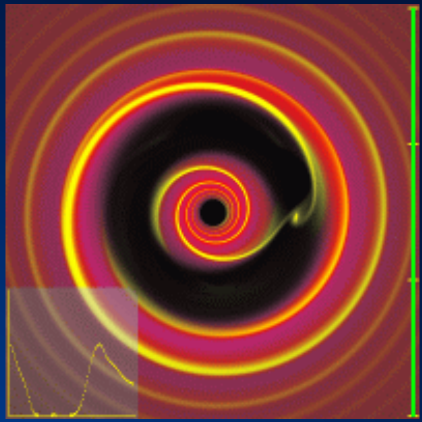
- 3—5 μm
  - CO (4.7 μm), water, ice (3.1 μm)
- MIR (with AO)
- High dispersion spectroscopy (R~100,000) in NIR and MIR

Most of planet formation science cases cannot be done at the 1st light

Candidates of key programs
(under discussion…)

- Planet formation at various ages at different disk radii under different environment (metallicity etc.)
- Planets and disks
  - Observing accreting planets in the disk gap
  - Chemical survey of disks, comparison with exoplanet atmosphere
  - Snow line

Never observed before



(P. Armitage)