Disks and their evolution: future prospects

This is NOT a conference summary!

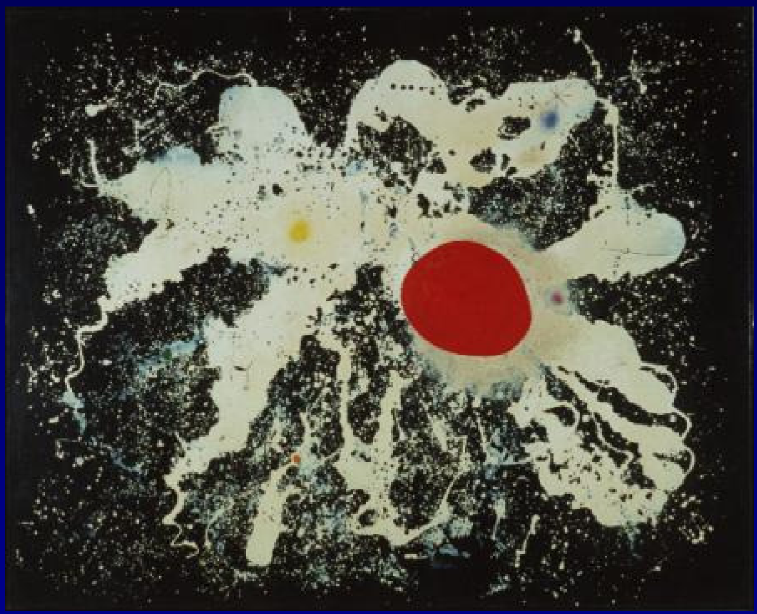
Ewine F. van Dishoeck

Leiden Observatory / Max-Planck für Extraterrestrische Physik

With thanks to many colleagues for providing input!

Serpens core, IR image 2'x2' VLT-Hawk-I

Disks in art….



Miró: red disk

China: Bi-disk with grains

…..And their evolution

Primordial disk

Phaistos disk
Crete ~1600 BC

‘Transitional’ disk

Used by G. Rieke in
first Spitzer press release

Modern disk

Age is not the only parameter determining evolution!

First fruits

Edouard Vuillard
1899

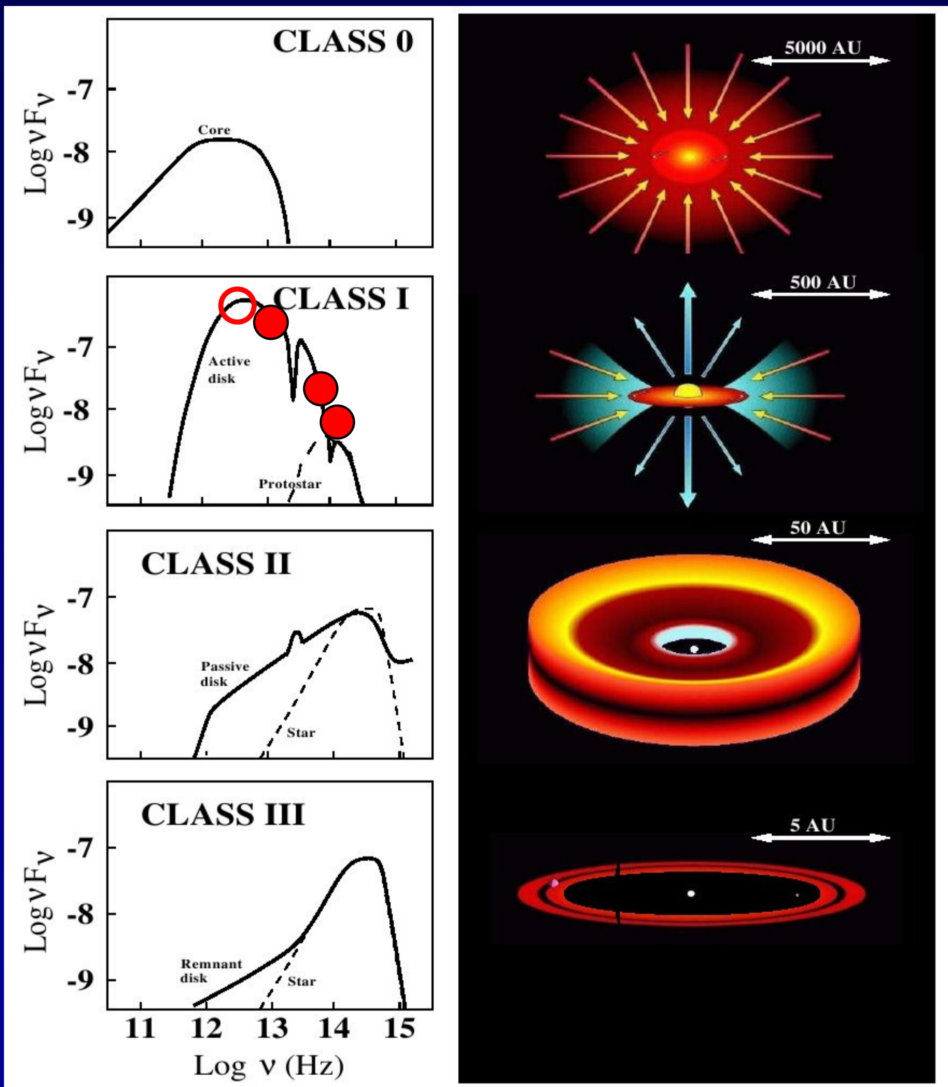
Norton Simon
Museum
Pasadena

- *'In "First Fruits," the decorative pattern takes precedence over the objects represented and unifies the painted surface'*
- **Inspiration for Mike Werner's et al. 'First Fruits' ARA&A 2005 review?**

Some general thoughts

- Spitzer has been a *huge* success
- Disk science is evolving rapidly
  - Recall that definitive proof of disks came <15 yr ago
- Golden age for disk studies with so many top-class IR and mm facilities in this and next decade
- Subsequent decades may not be as rich in major new IR/mm facilities => *make best use of what will be there!*

Need broad wavelength coverage



Many source lists for future facilities will come from large-scale Spitzer surveys, at least for low-mass YSOs Class 0-II at < 1 kpc

⇒Complete, unbiased catalogs with thousands of sources, many of which are still poorly characterized

Why we need broad wavelength coverage

	Optical & near-IR	Mid-IR 3-28 μm	Far-IR 28-350 μm	Submm 0.3-3 mm	Radio cm
Cont	Stars	Warm dust	Cooler dust, SED peak	Cold dust	Large grains, ionized gas
Solid		Silicates, oxides, ices, PAHs, ….	Hydrous silicates, ices, carbonates		
Gas	[O I] 6300Å	Simple (symmetric) molecules	H_2O, OH, hot CO, [OI], [C II]	Myriad of molecules	Heavy mol, H

See also diagram by Millan-Gabet et al. 2007

Panchromatic view

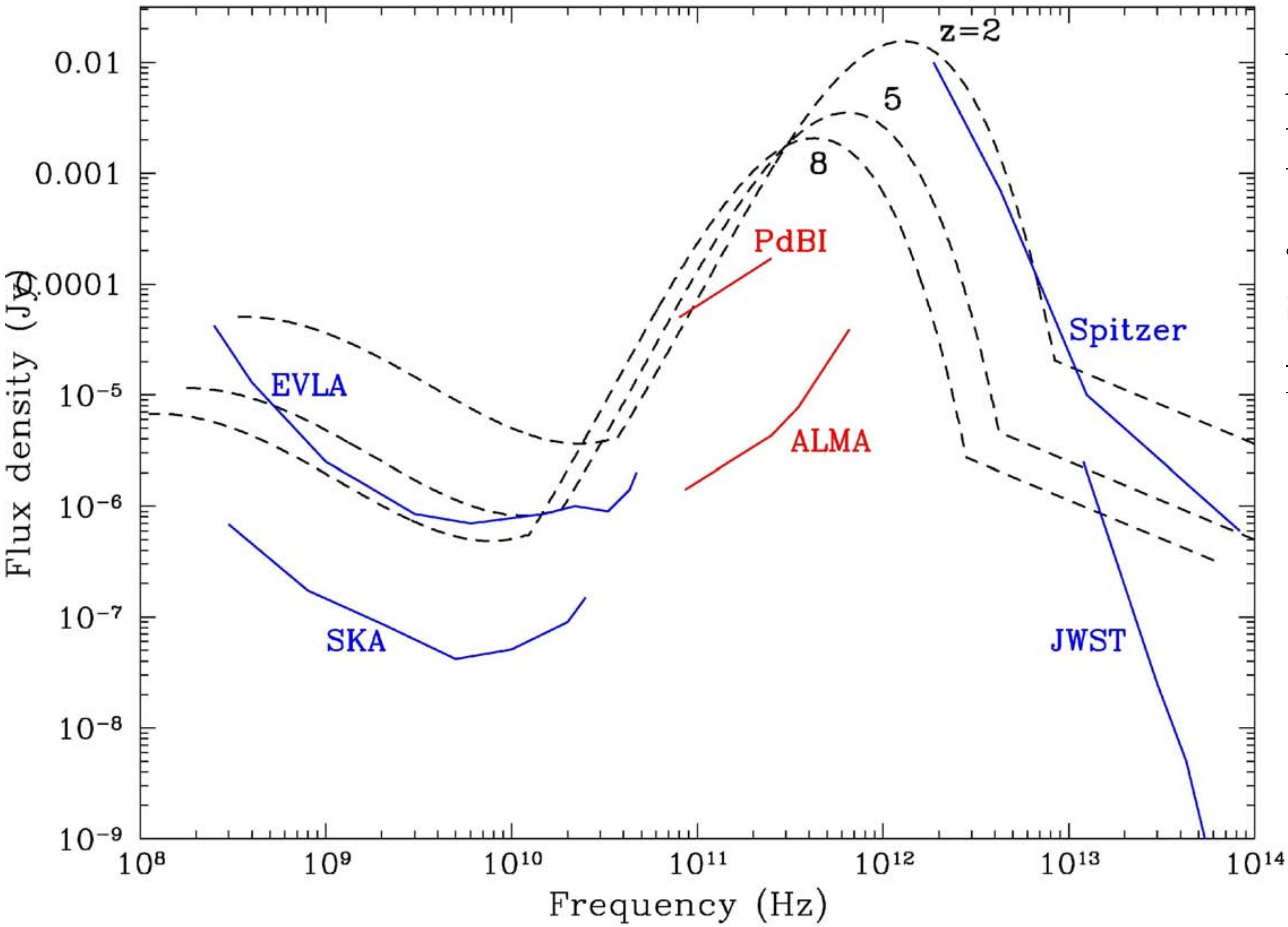


Figure for Red-shifted galaxies, but same holds for disks

Cox, priv. comm

Future facilities have jump of factor 10-100 in sensitivity!

This talk

- Few words about status of each of the major future facilities
- Illustrate main questions for each evolutionary stage with a few recent examples
- Focus mostly on low-mass star formation

WISE

- 40 cm telescope
- All-sky survey at 3.3, 4.7, 12 and 23 μm
- Sensitivity factor 500 better than IRAS
- Launch late 2009

Strength

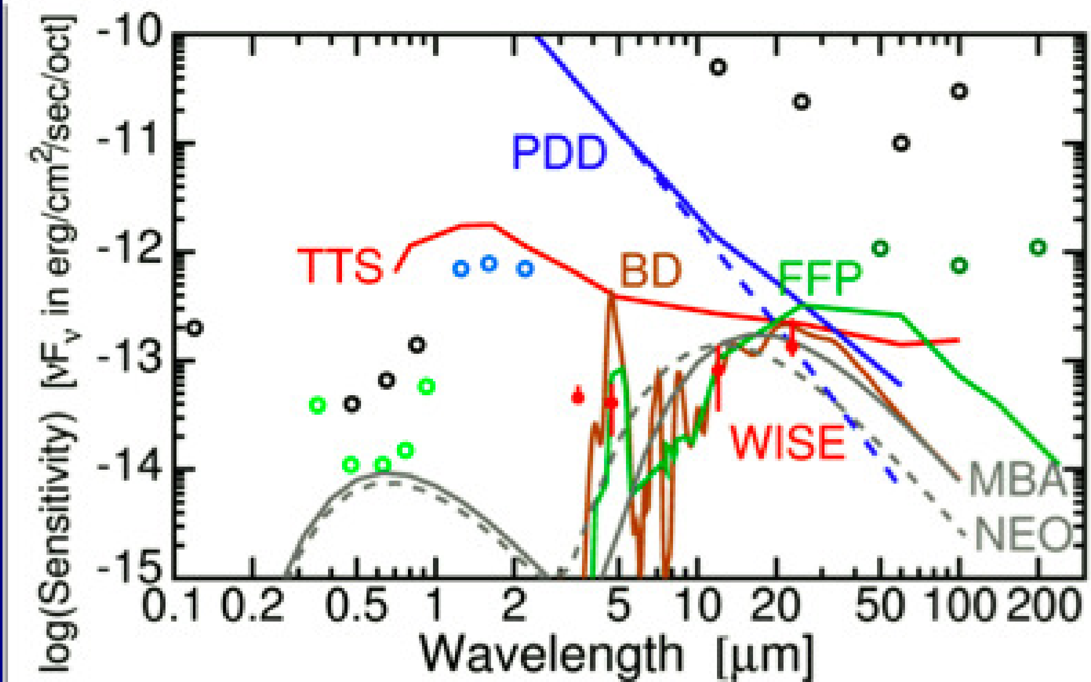
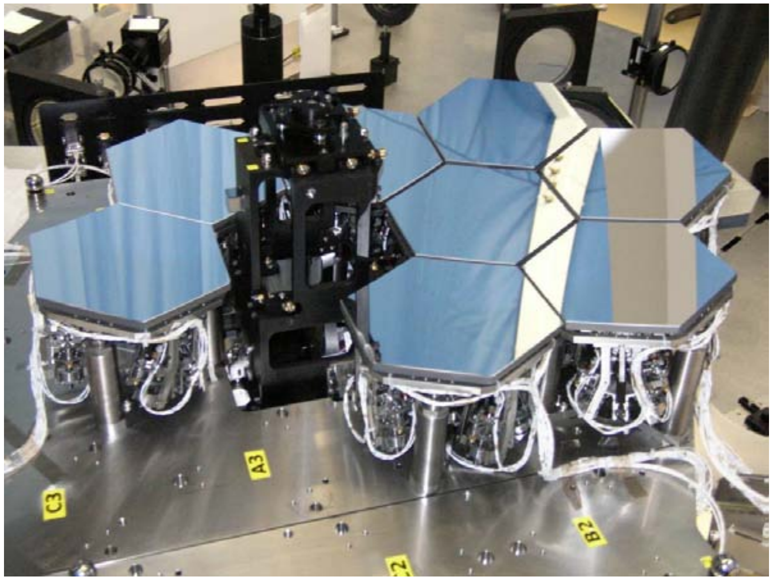


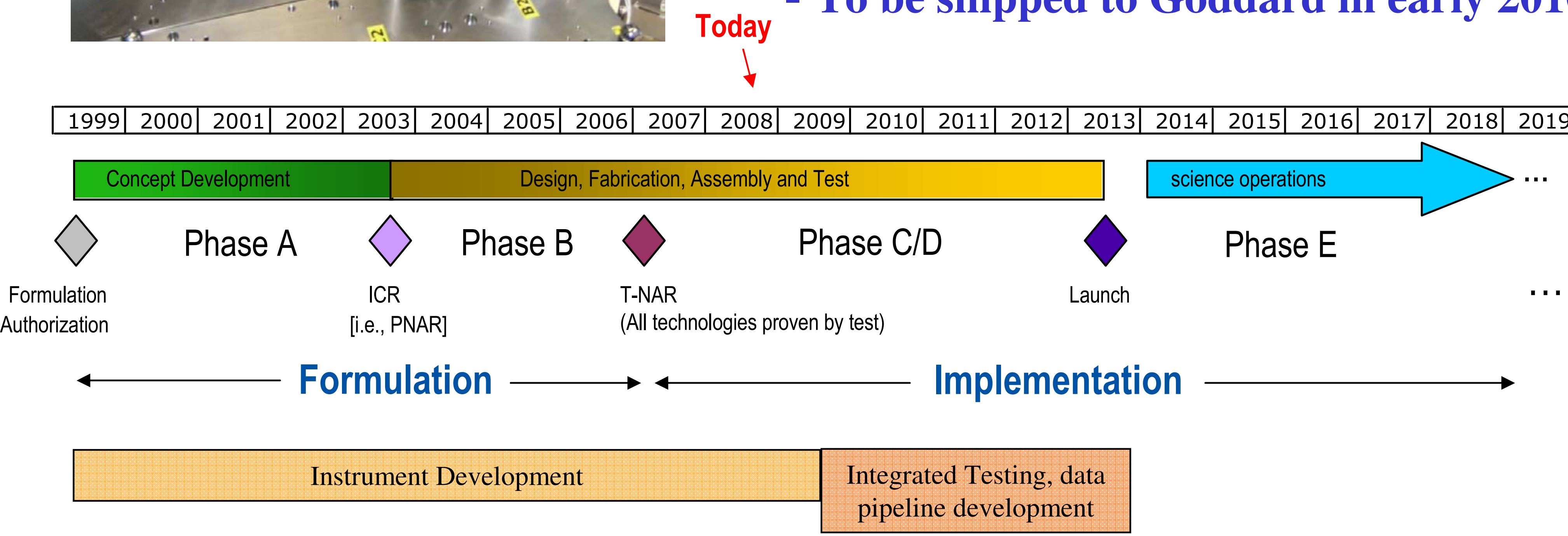
Figure FO1-3: Nearby objects detectable by NGSS: NEO (dashed) —230-m NEO at 1 au; MBA—1.1-km main belt asteroid at 2.5 au; FFP—Jupiter at 1 light year; BD—200 K brown dwarf at 1.3 pc; PPD—ξ Lep like system at 400 pc; TTS—M0 T Tauri star at 4.7 kpc.

- **Unbiased survey for primordial and debris disk fraction OUTSIDE clouds**
  - **~7000 G stars, 26000 A stars, 240 M0 stars**
- **Kinematics young stellar groups and associations (proper motions with 2MASS)**

JWST

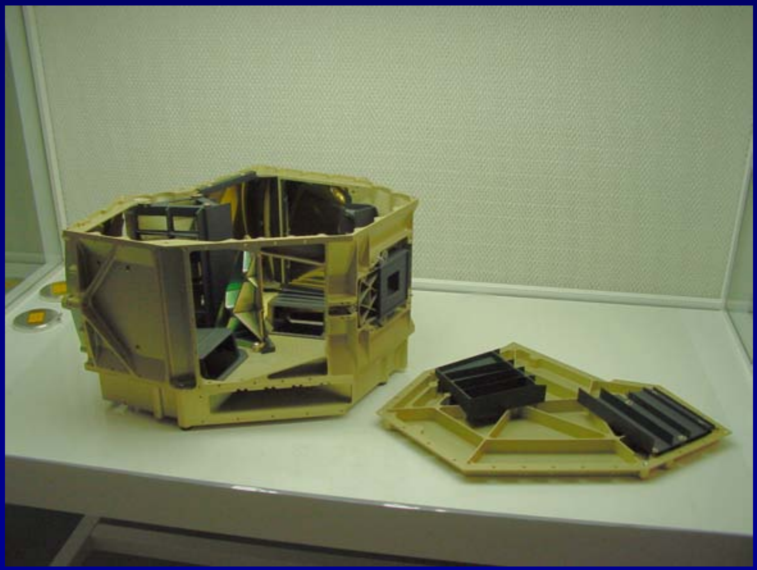


- On schedule for a late 2013 launch
- All key technologies reached appropriate technology readiness in 2007; approved for implementation in 2008
  - Flight mirrors in production
  - Flight instruments being built and tested
  - To be shipped to Goddard in early 2010



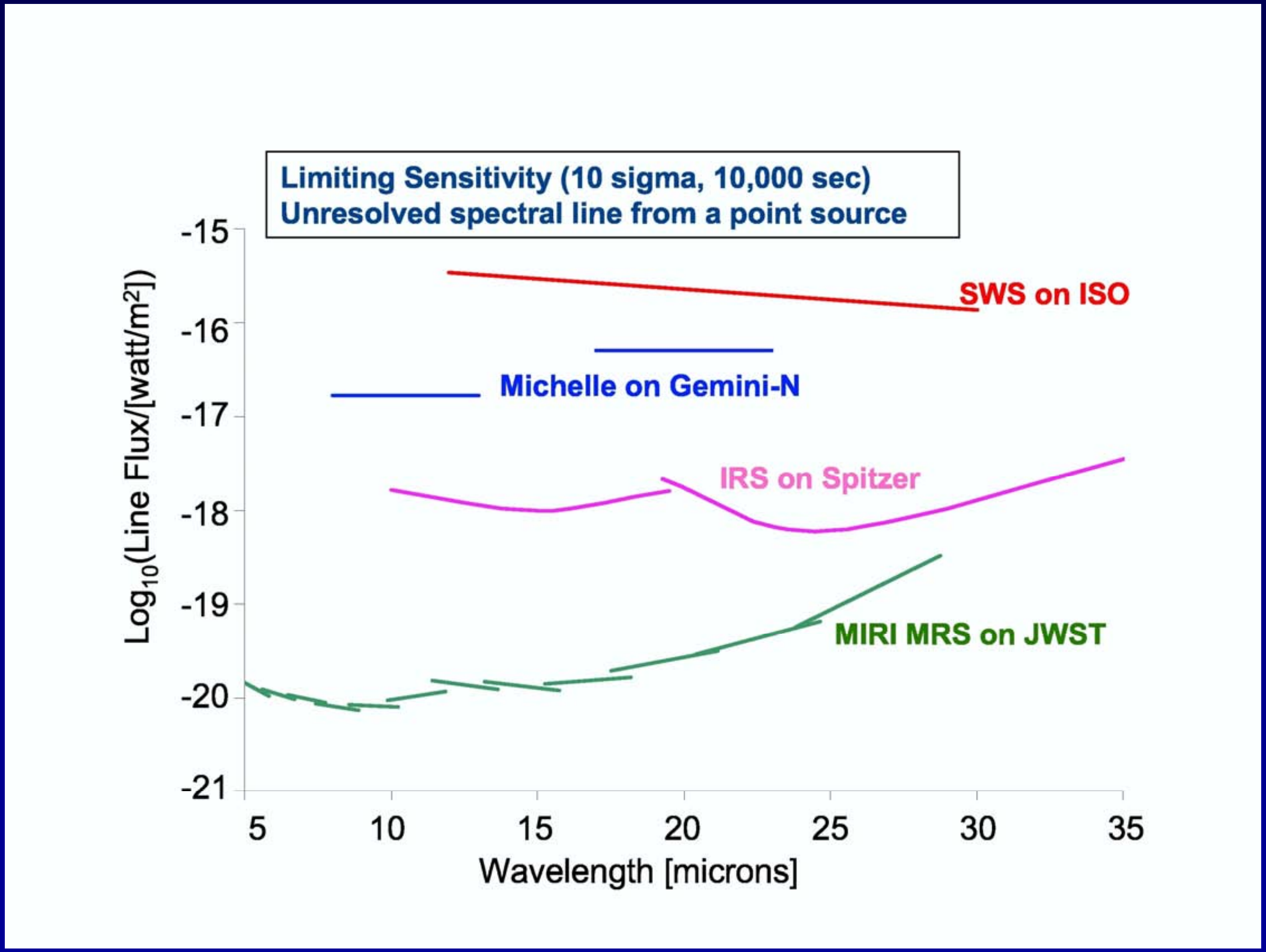
JWST Instruments

- NIRCAM 0.6-5 μm 2'x2'
- NIRSPEC 1-5 μm
  - Multi-object R=1000
  - IFU R=3000
- MIRI 5-28 μm
  - Imager
  - IFU R=3000
- Tunable Filter Imager
  - 1.5-5 μm, R~100



MIRI flight hardware

Example: JWST-MIRI spectrometer sensitivity

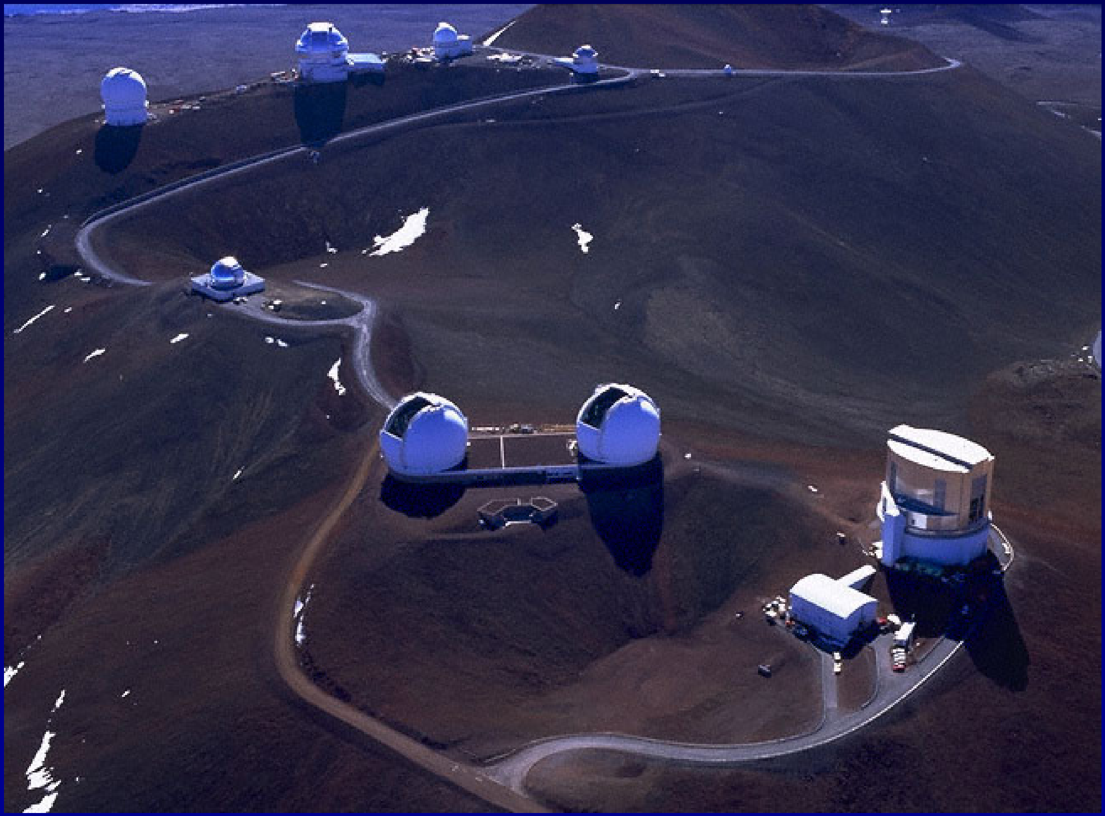


- Gain by order of magnitude in spatial resolution with Spitzer
- Gain in spectral resolution compared with Spitzer (R~3000 vs 600)

JWST strengths

- Raw sensitivity
  - But over a small few arcmin field
- Spatial resolution: 0.2’’ at 5 μm
- Coronagraphy at near- and mid-IR
  - Exo-planets
  - Disks
- Medium resolution spectroscopy R~3000 unhindered by atmosphere
  - Solids + gas-phase lines

Existing 8m optical telescopes

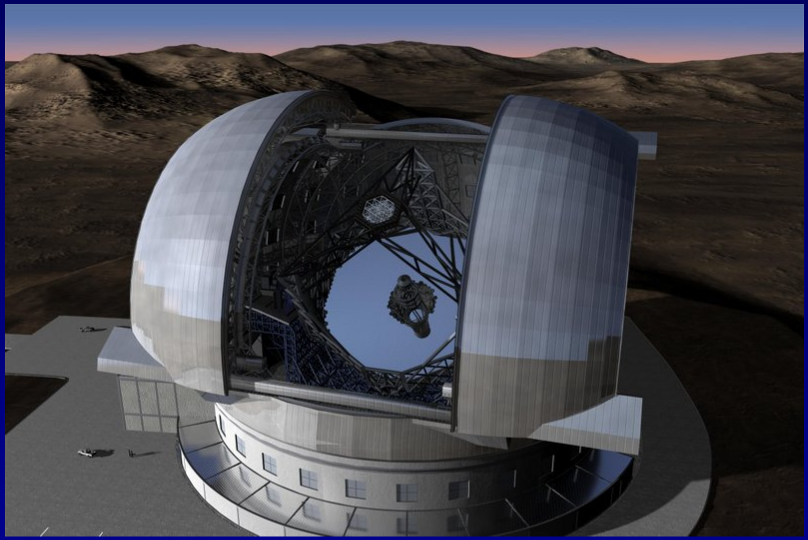


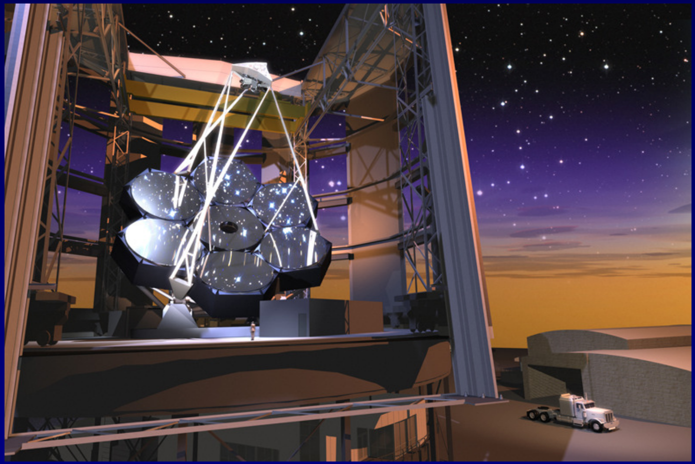
Mauna Kea

- Need deep wide-field imaging and (multi-object) spectroscopy to characterize the thousands of YSOs found by Spitzer and other instruments

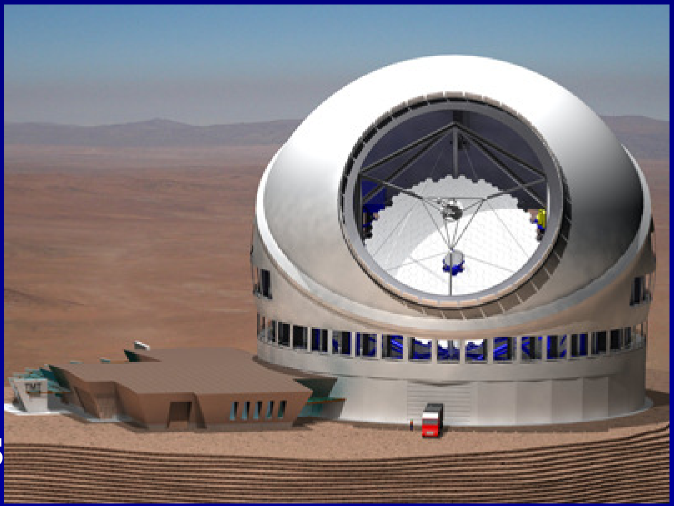
ELTs: ~20-40 m

E-ELT





GMT

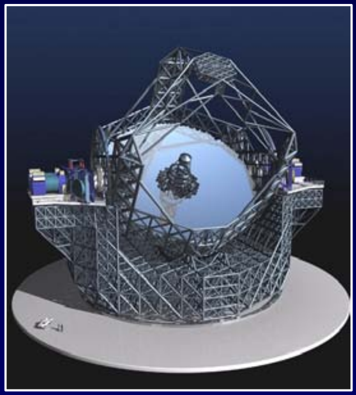


TMT

- Diffraction limited imaging and spectroscopy at optical, near- and mid-IR down to ~10 milli-arcsec =>
  - image Jupiters + ice giants around nearby stars
  - detect (super-)Earths with radial velocity
  - image gaps <20 AU in nearest clouds

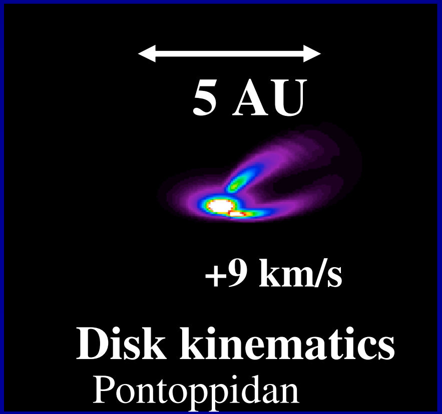
~2017+

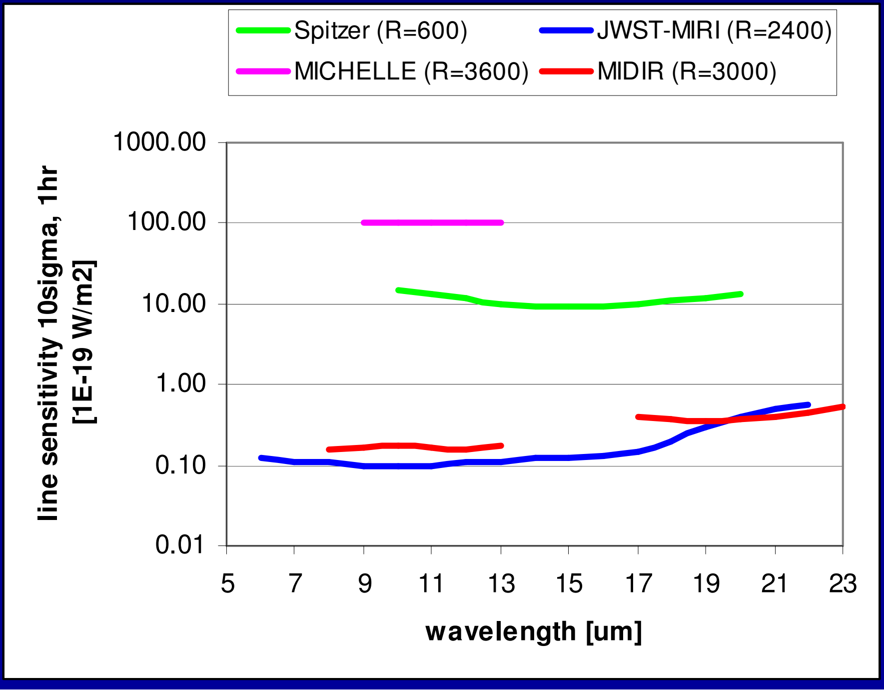
JWST-MIRI ⇔ ELT-METIS *a.k.a. MIDIR*



- continuous spectral coverage
- larger FOV with constant PSF
- better imaging sensitivity
- much better LSB sensitivity
- better spectro-photometric stability
- 100% sky coverage, good weather

- 5 – 8 times higher angular resolution
- high spectral resolution (kinematics!)
- comparable PS spectroscopic sensitivity





IR interferometry

Keck

VLTI

- Imaging and low-medium resolution spectroscopy down to 1 mas, but only on bright sources (K|~7 mag, N~1 Jy)

=> Geometry + structure innermost dust disk, launching winds from disk

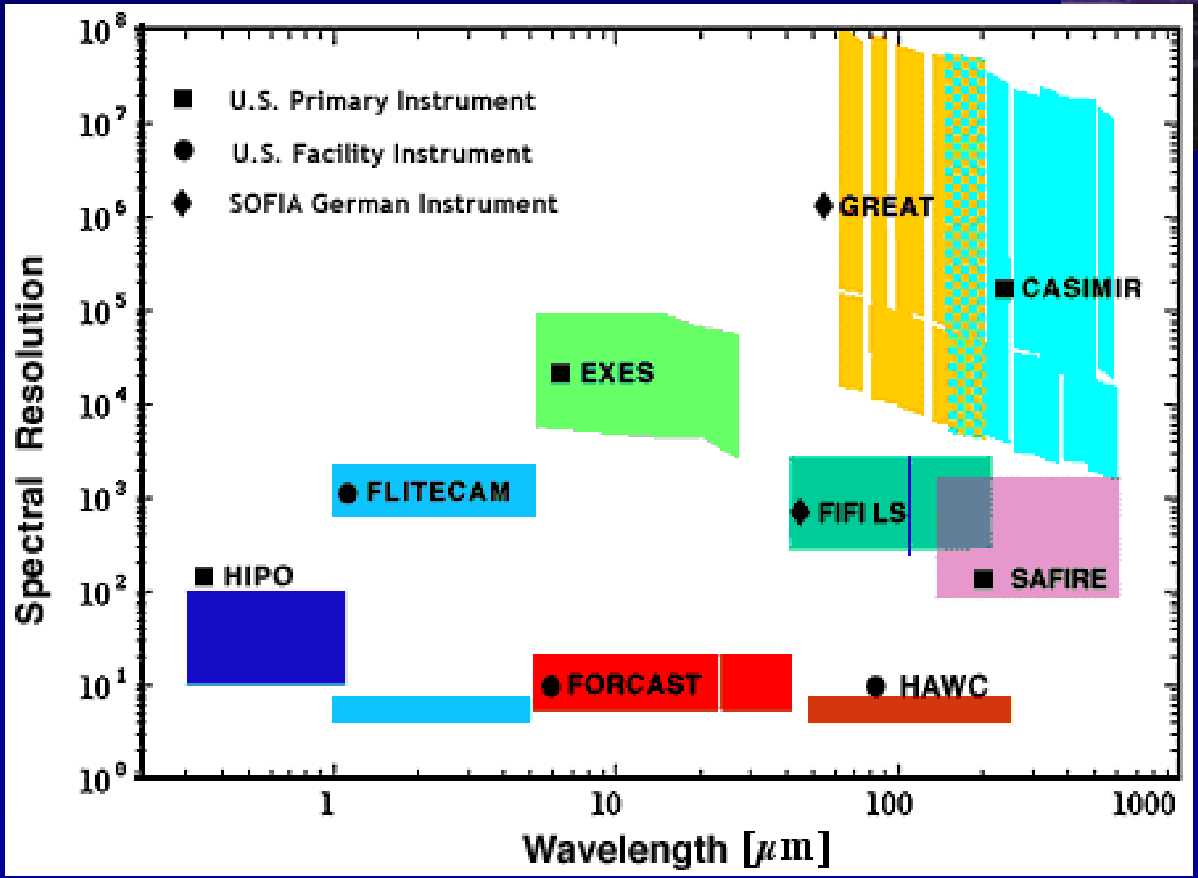
Paranal residencia

Visit the Bond files at the www.eso.org, including VLT a la Bond movie

Premiered yesterday in London….

SOFIA

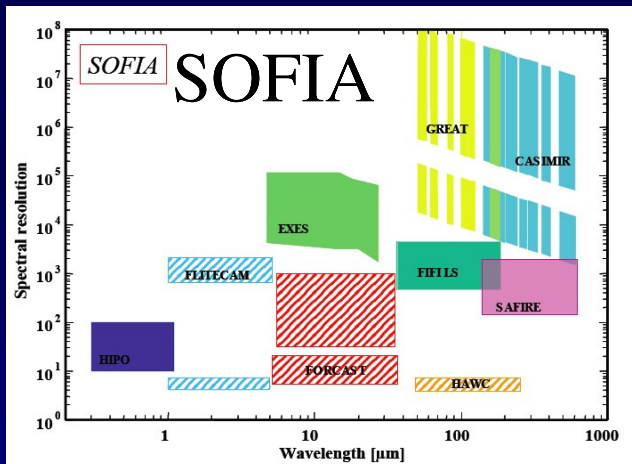
- 2.5m telescope in B747 airplane
- Good spectroscopic capabilities at 5 – 500 μm

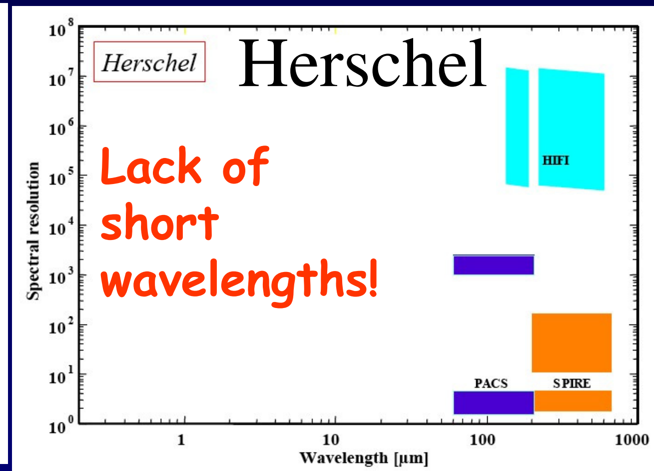


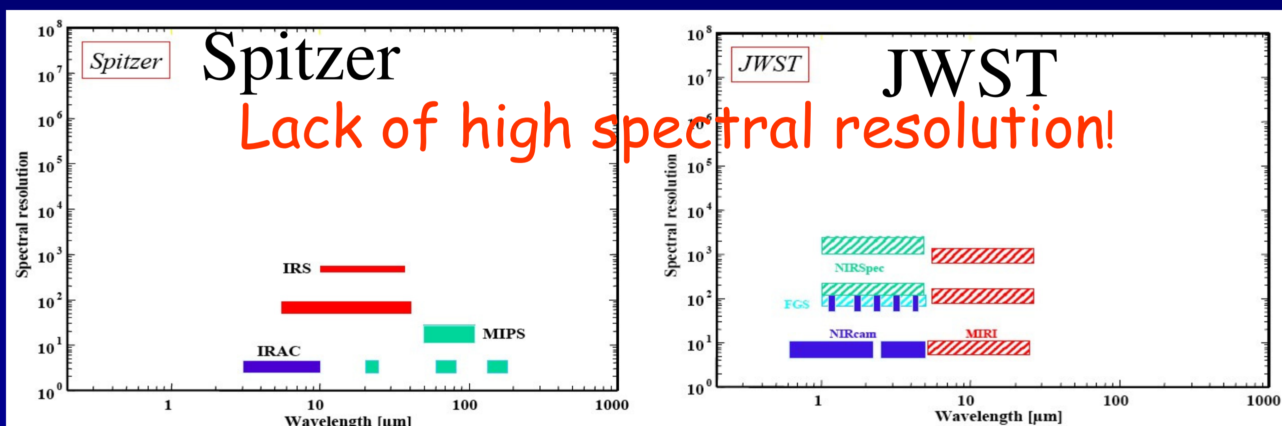
- First science flights mid-2009

Spectral resolution MIR-FIR

Spectral Resolution

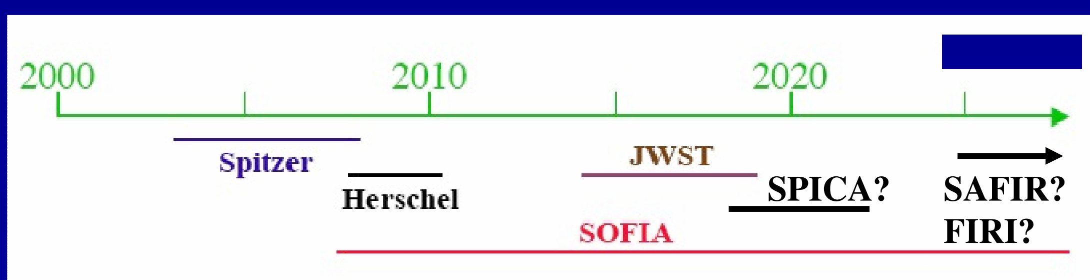






SOFIA unique for high-res spectroscopy 20-200 µm ([O I]!)

Mission operations timeline



But limited sensitivity

Herschel Space Observatory

-HIFI: heterodyne spectrometer $R=10^6$
480- 1250; 1410-1910 GHz
500-200 μm, 158 μm

-PACS: photometry
imaging spectrometer R=1500
60-200 μm

-SPIRE: photometry
FTS spectrometer R<1000
200-670 μm

2009
launch

Photometry at long λ
H_2O, [O I], [C II]
Complete spectral scans

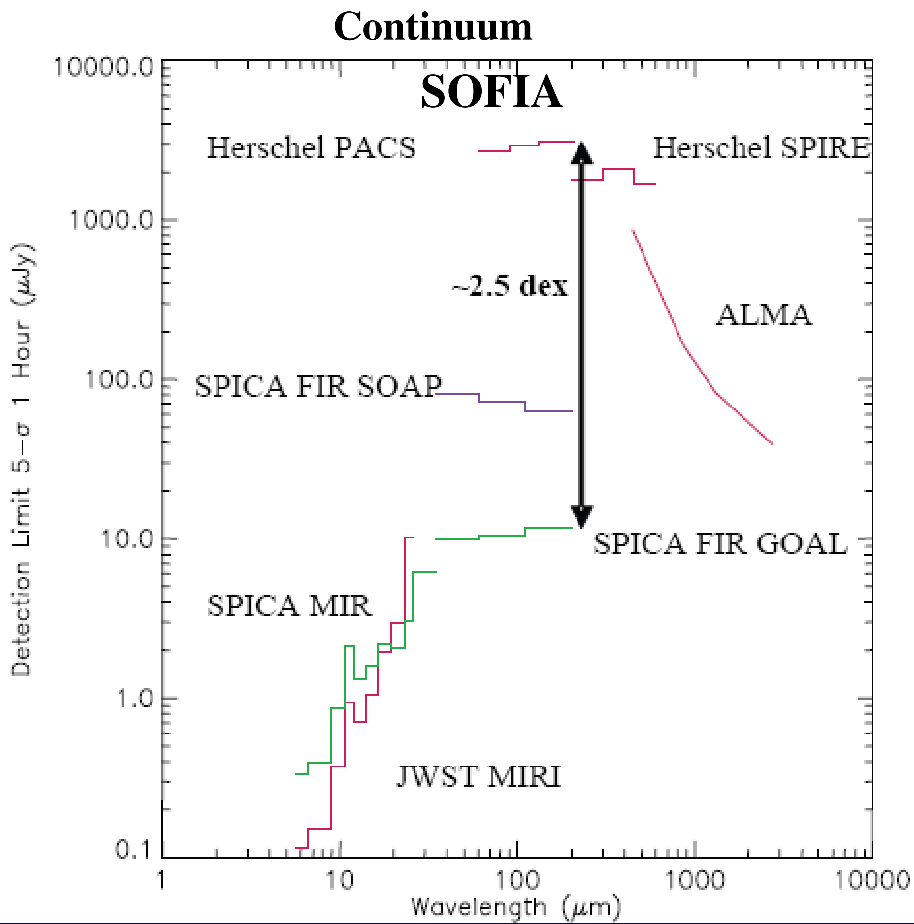
Approved Herschel KP on disks

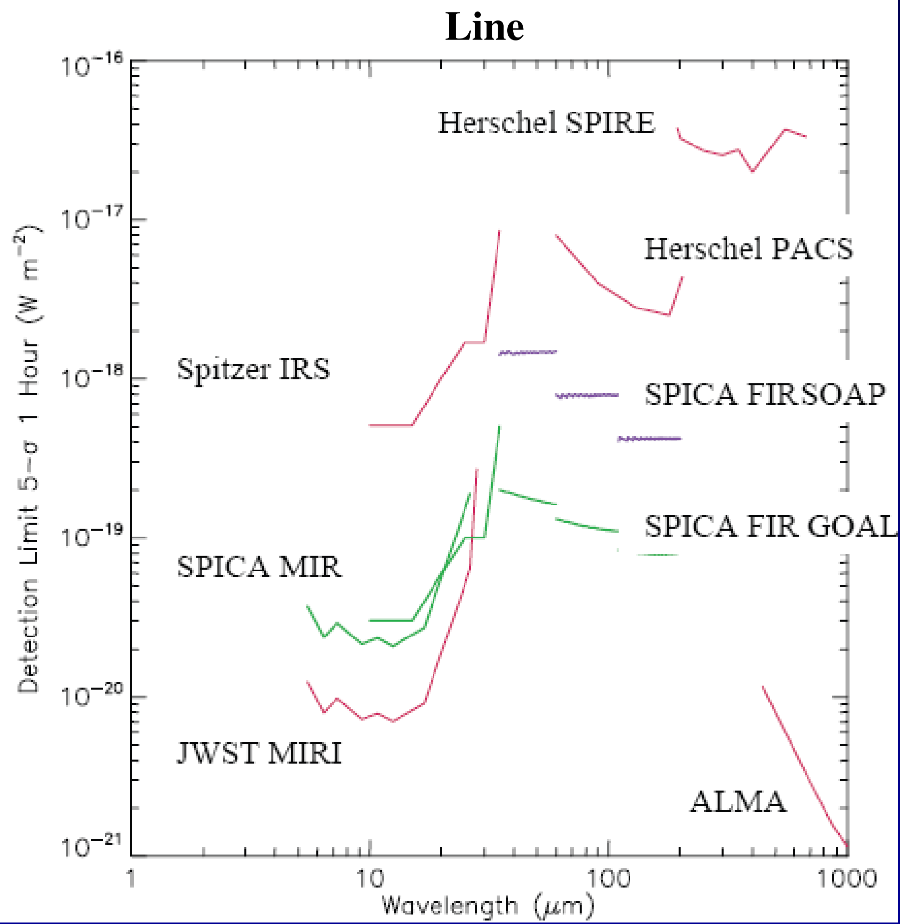
- **Guaranteed Time**
  - **WISH:** deep HIFI searches for H_2O in dozen disks and many protostars
  - **Olofsson et al.:** imaging (debris) disks, including Fab Four

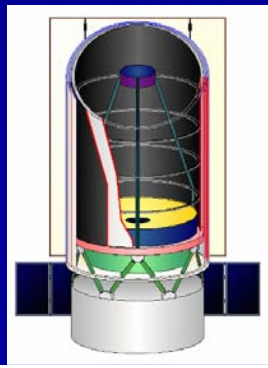
- **Open Time**
  - **DIGIT:** full, high S/N PACS scans of protostars + disks, plus photometry wTTs
  - **HOPS:** photometry and spectroscopy Class 0 – Flat in Orion
  - **GASPS:** PACS [O I], [C II] gas lines in 274 disks plus H_2O follow-up
  - **DEBRIS:** photometry 450 nearby A-M stars
  - **DUNES:** photometry 283 stars within 25 pc

Several KPs have a strong link with *Spitzer*

FIR in perspective

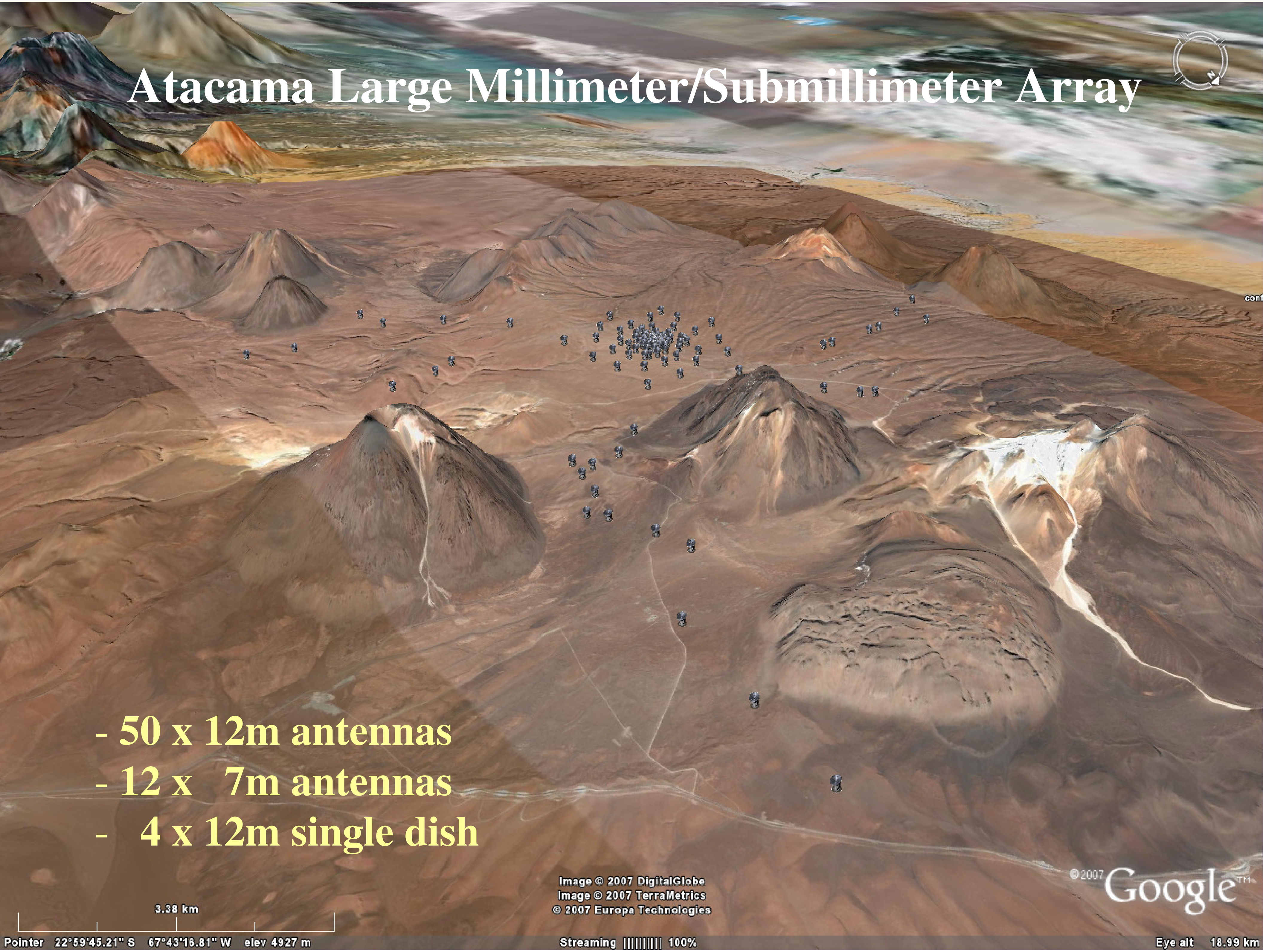






- Note large jump sensitivity SPICA at > 30 μm

Atacama Large Millimeter/Submillimeter Array



- 50 x 12m antennas
- 12 x 7m antennas
- 4 x 12m single dish

Antennas at the OSF in Chile

- 10 telescopes in Chile
- First front-end
- Correlator being installed

- AIV + commissioning starting
- Early science observing within next few years

Strength of ALMA

- High angular resolution, with enough sensitivity to image continuum down to 0.01”: ~1 AU at 150 pc, 30 AU at 3 kpc
  - Separate disk and envelope in embedded phase
  - Image entire disk structure (not just surface)
  - Image terrestrial planet forming zones
  - Detect protoplanets directly
- High spectral resolution $R > 10^6$
  - Down to 0.01 km/s => kinematics and dynamics
  - Multitude of lines => chemistry
- Long wavelengths
  - Dust optically thin => dust disk masses down to 0.01 M_{Earth} at 150 pc

IR surveys: statistics => timescales
ALMA: physics + chemistry

Low frequency radio telescopes
(up to 25 GHz)

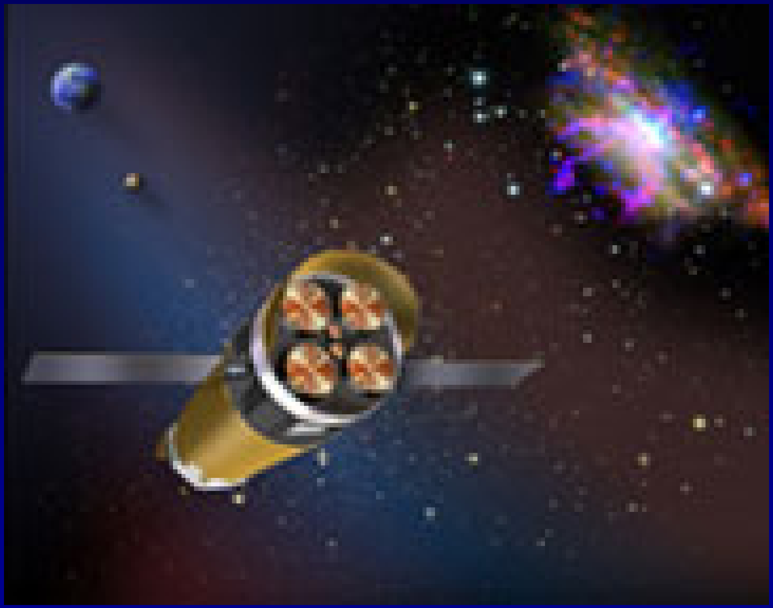
eVLA

- **Optically thin dust inner disk**
- **Large grains (pebbles)**
- **Largest complex molecules**

- SKA-high unlikely to materialize before 2025

X-ray and UV

IXO >2017

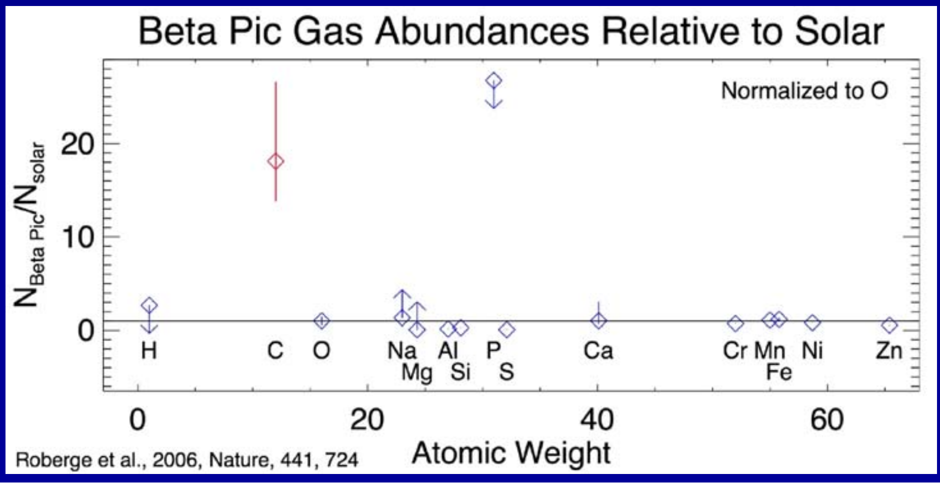


International X-ray Observatory, jointly between NASA, ESA and JAXA

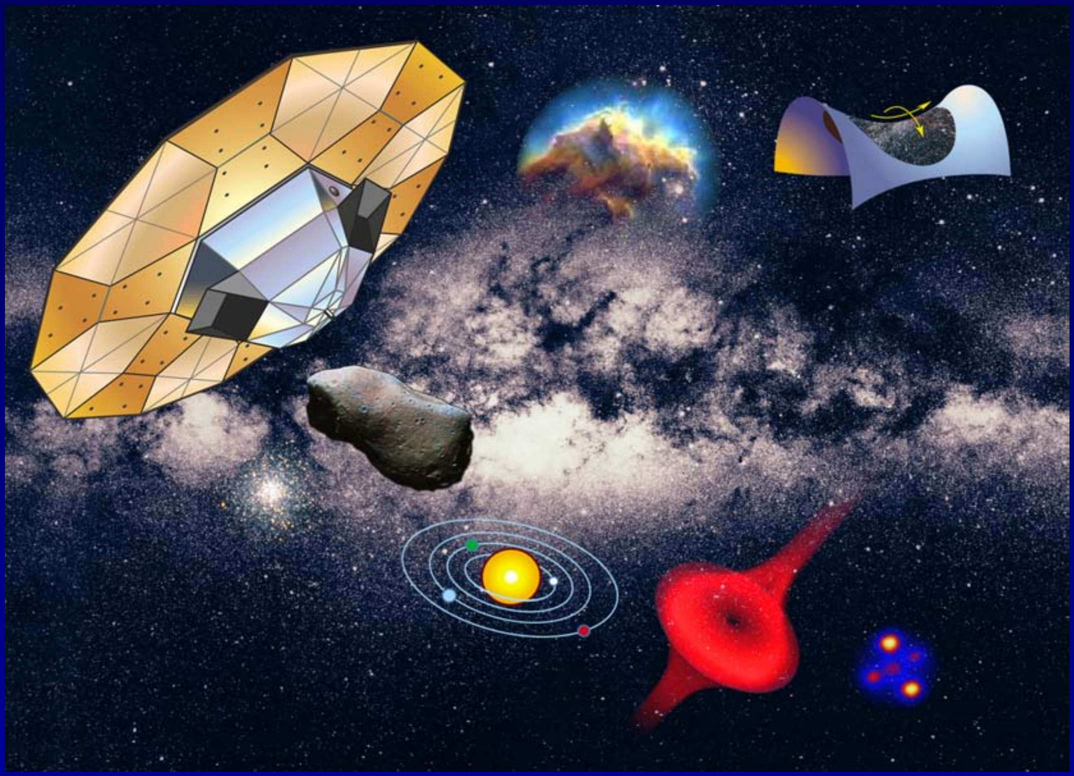
Hubble-COS: 2009

Strengths

- Unbiased census of Class III sources
- Characterizing the radiation field incident on disks
  - Photoevaporation and disk dispersal
  - Ionization rate
- Atomic and molecular UV lines as diagnostics of gas, including debris disks
  - C^+, O, …
  - H_2



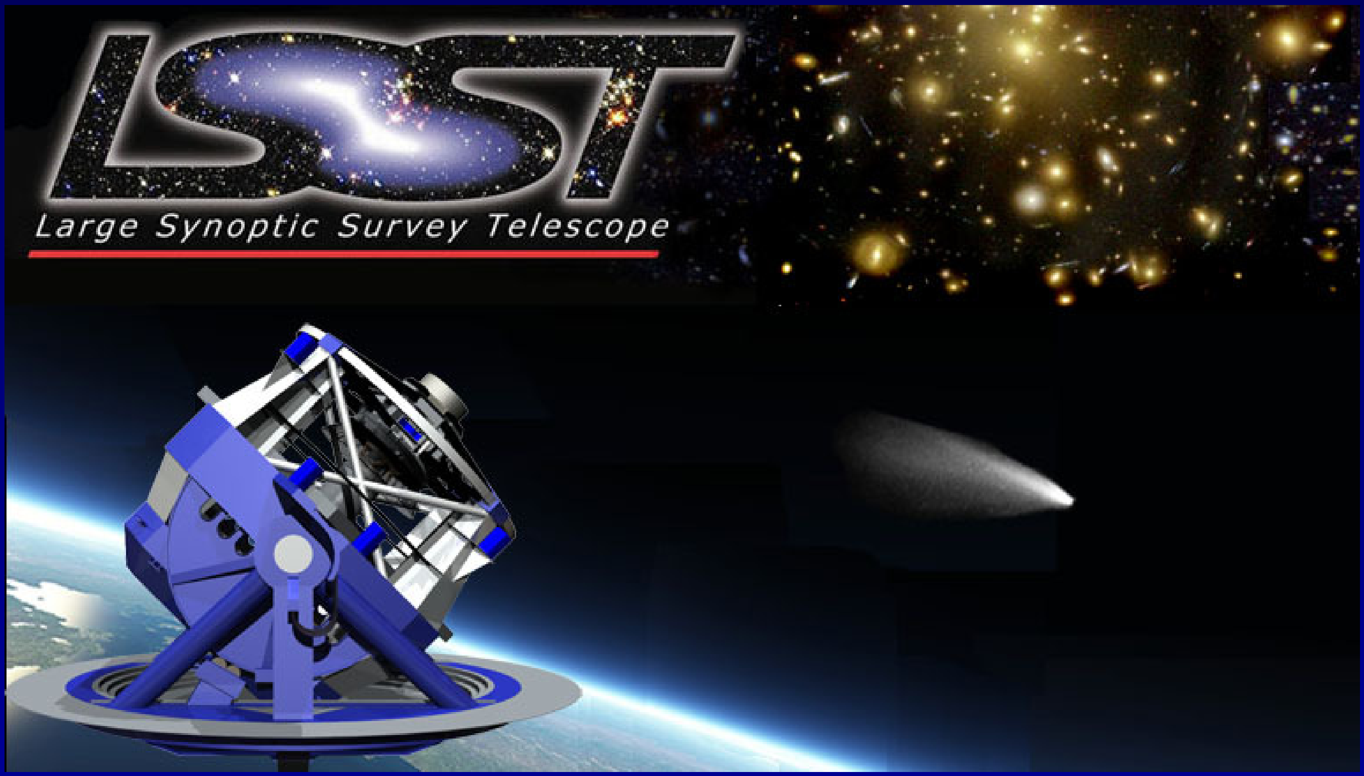
Astrometry
⇒ proper motions, distances!



- GAIA: launch 2012, 20 μarcsec, all sky down to R~20 mag
- SIM: ~4 μarcsec, input catalog, down to 19 mag

Combine with radial velocities => 3D view

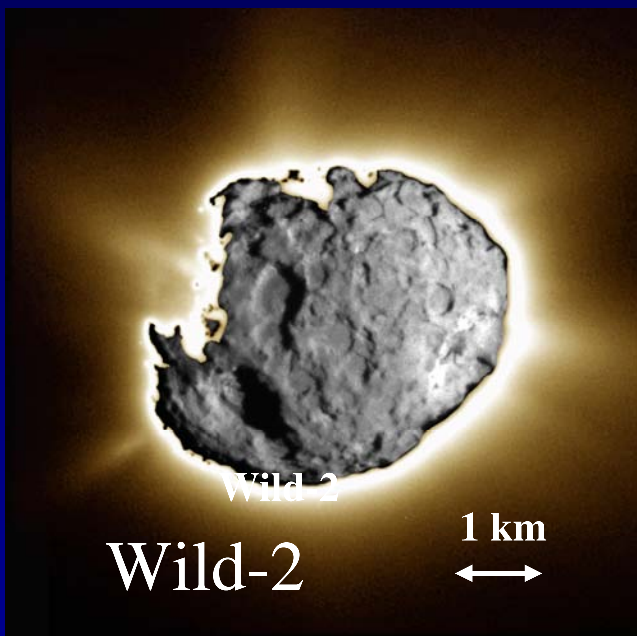
Exploring the time domain



- How about time domain at other wavelength regions?

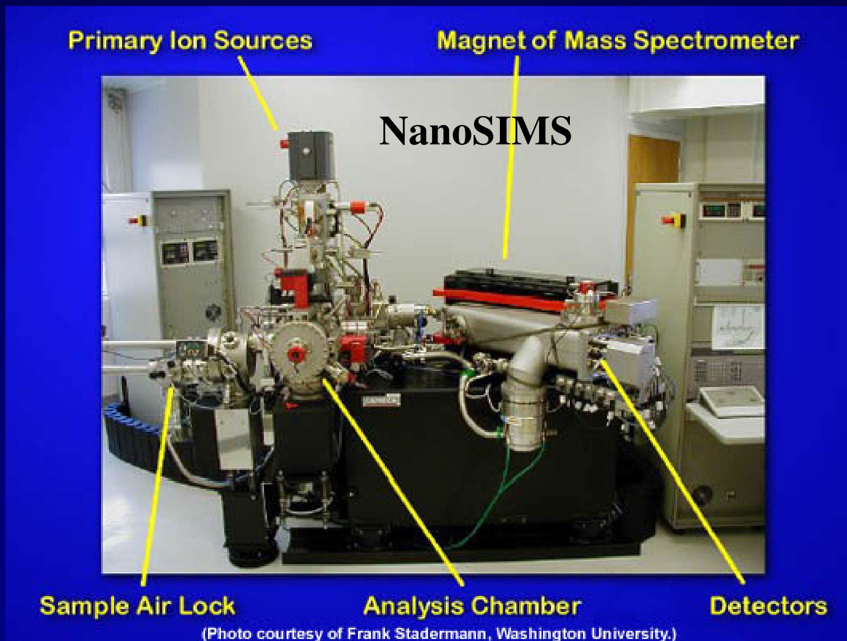
Fly-bys and sample return

- **Primitive material in solar-system disk**

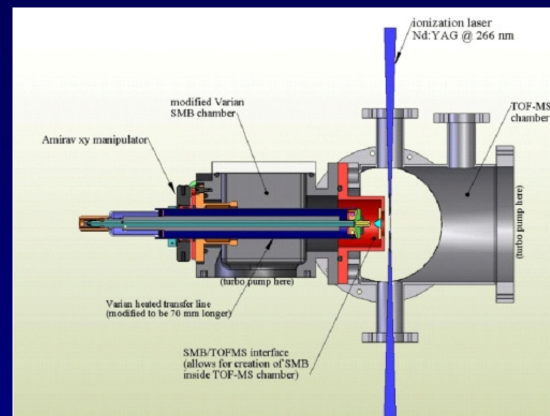


- Complex organics detected
- Some crystalline silicates => mixing in disk of our solar system extended to comet-forming zones

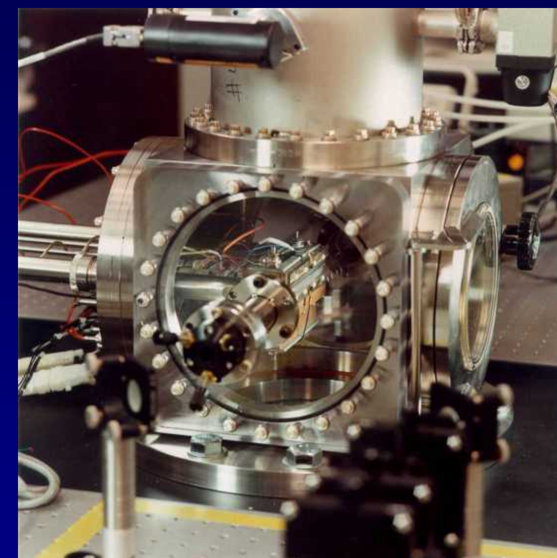
Importance of lab astrophysics

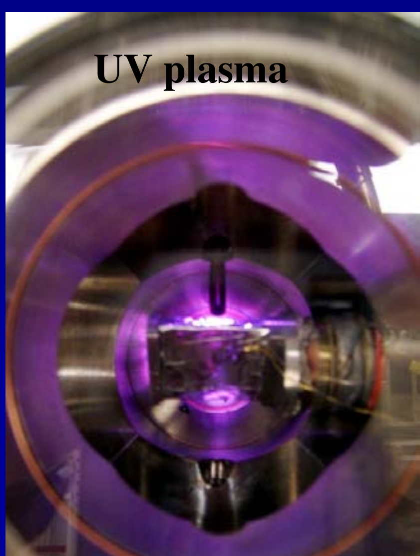


Ultra-L_2MS



Cavity Ringdown Spectroscopy

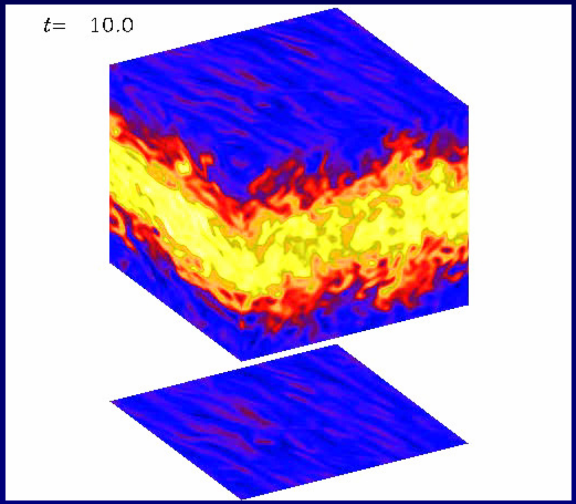




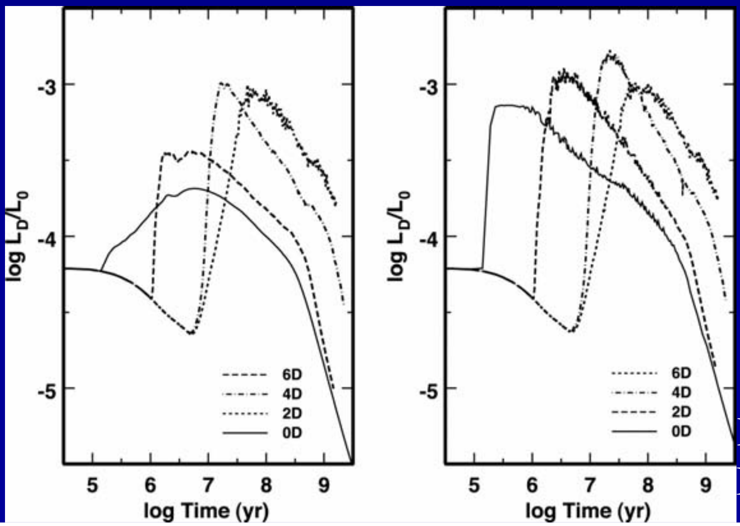
UHV surface science

Importance of theory

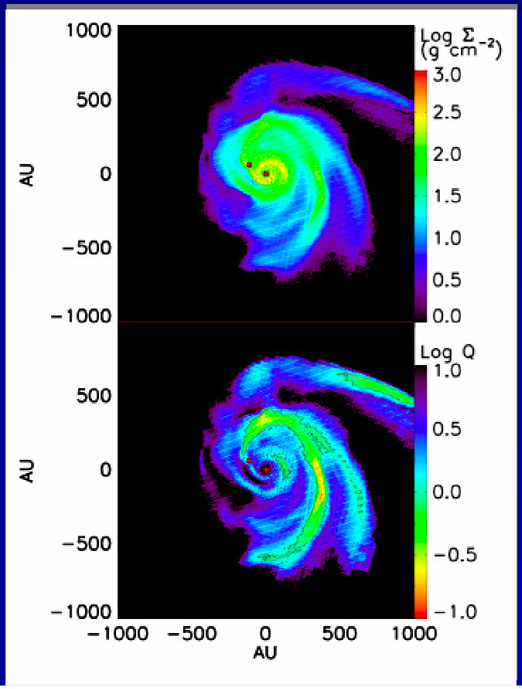
- Radiative transfer
  - Line and continuum
- (Magneto)hydrodynamics
- N-body simulations
- Thermal structure gas+dust
- Chemistry
- …..



Klahr, Johansen, Henning, …



Kenyon & Bromley 2004

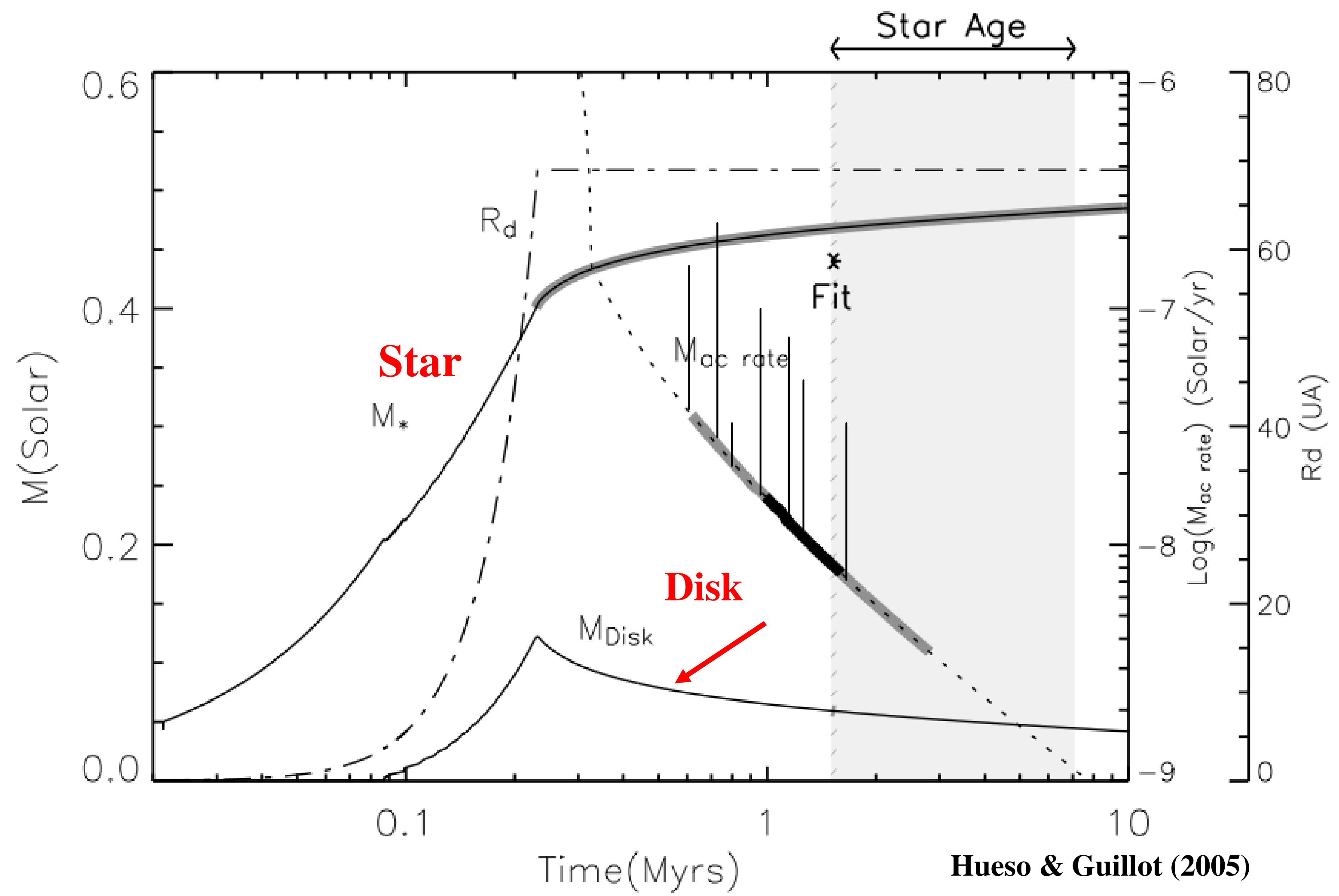


Kratter & Matzner 2006

Questions to be answered by future instruments

From embedded to debris-disk phase

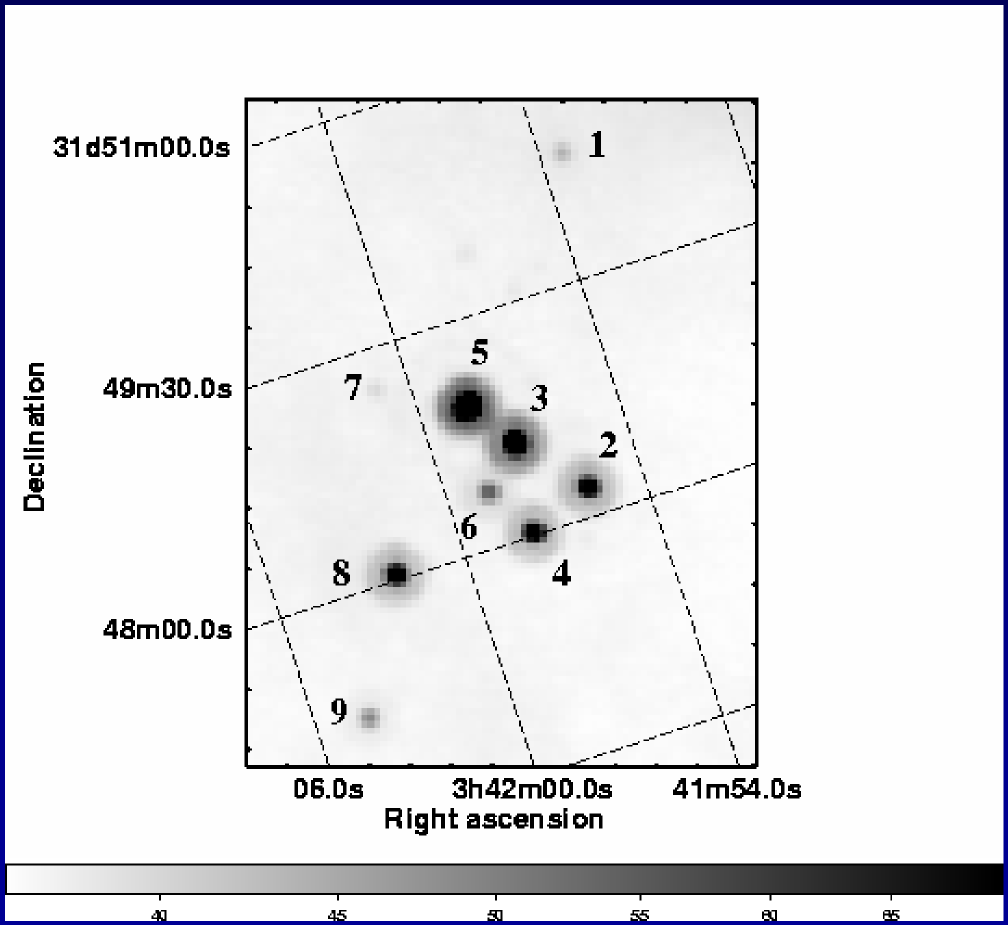
How do disks form and grow with time?
Can we see episodic accretion in embedded phase?
Initial masses of disks?



Hueso & Guillot (2005)

- ALMA
- JWST

What determines rate of evolution Class 0 - III?
How does it vary within cluster?
Origin of viscosity?



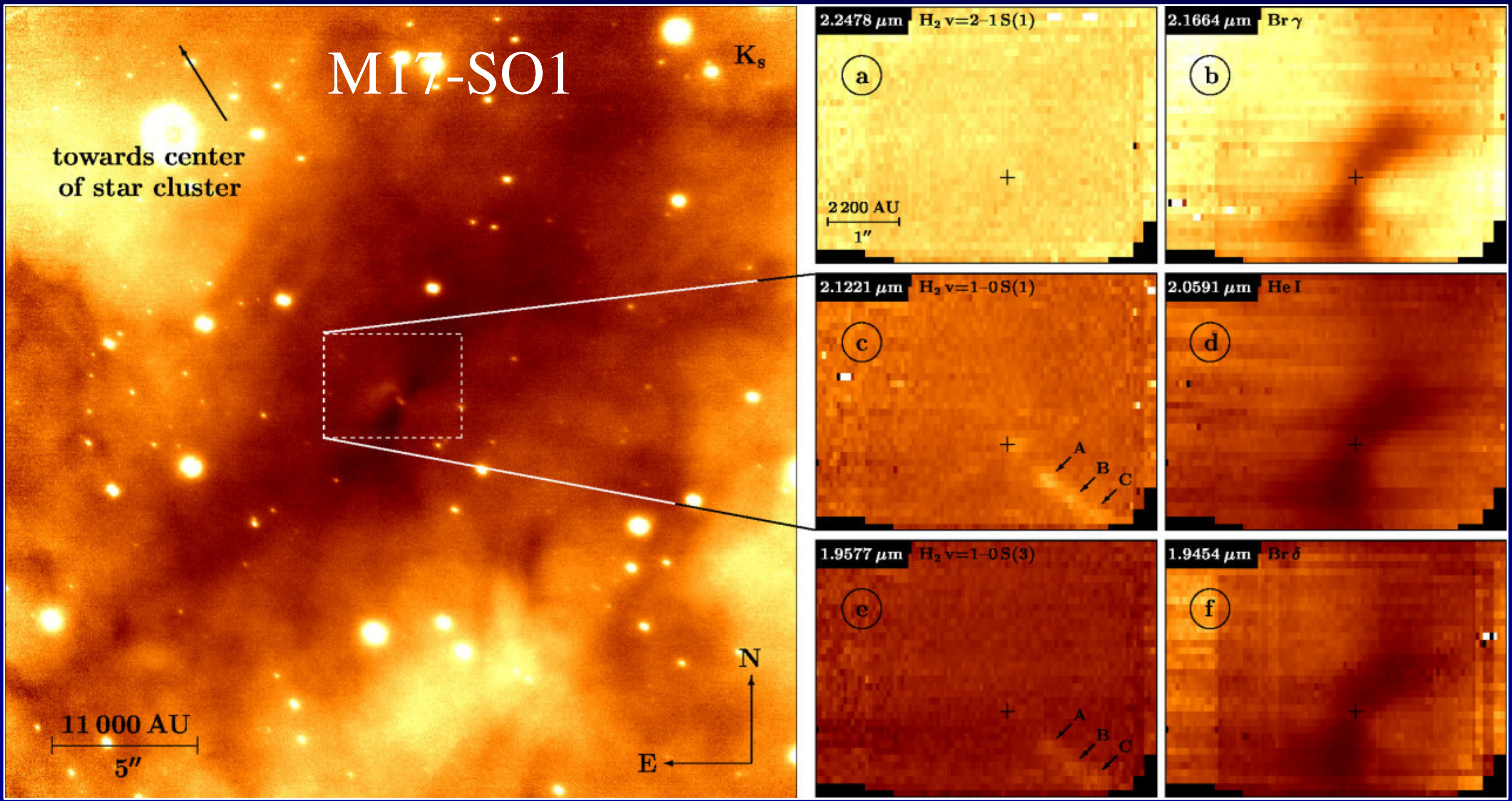
MIPS 24 image Perseus

9 sources within 0.1pc
with very different SEDs =>
different evolutionary stages

Rebull et al. 2007

- Combination of all instruments

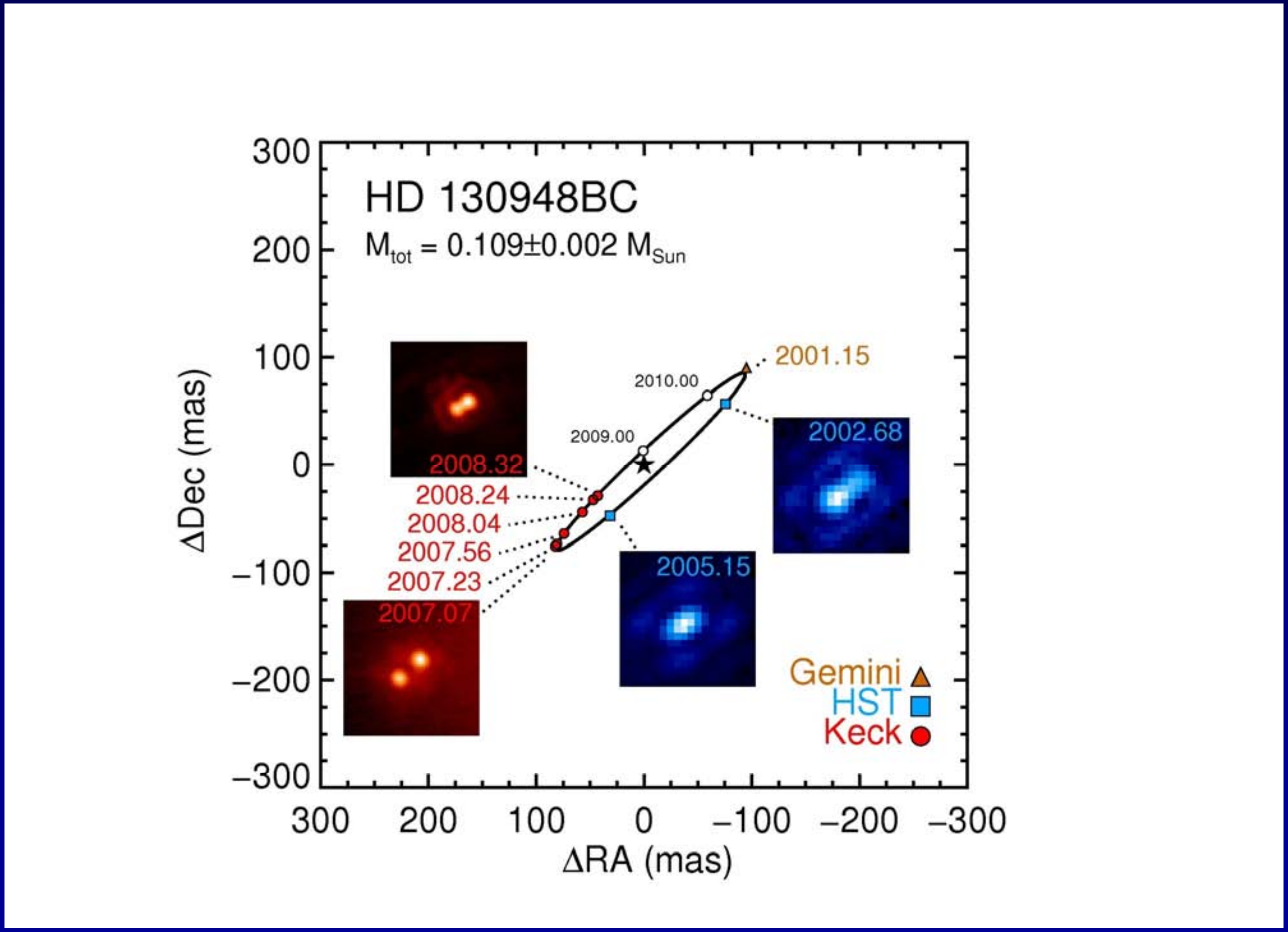
Characteristics disks around massive stars?



Nürnberger et al. 2007

- **ALMA**
- **ELTs**

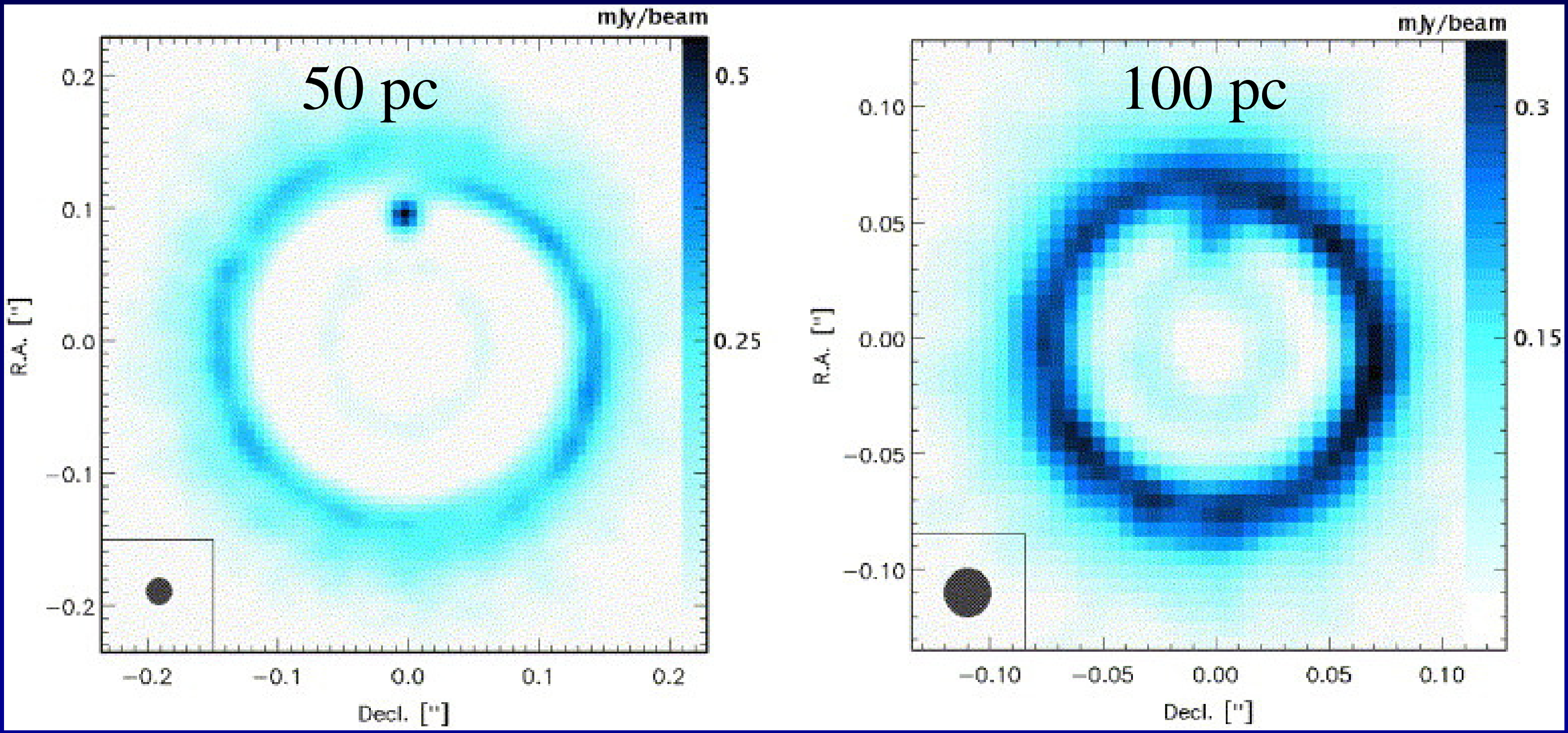
What are the ages of young stars?
How many are binaries?
Testing stellar structure and evolution codes



Dupuy et al. 2008

- **ELTs**
- **JWST**

Where are the protoplanets? When and how formed? Gravitational instabilities or core accretion?

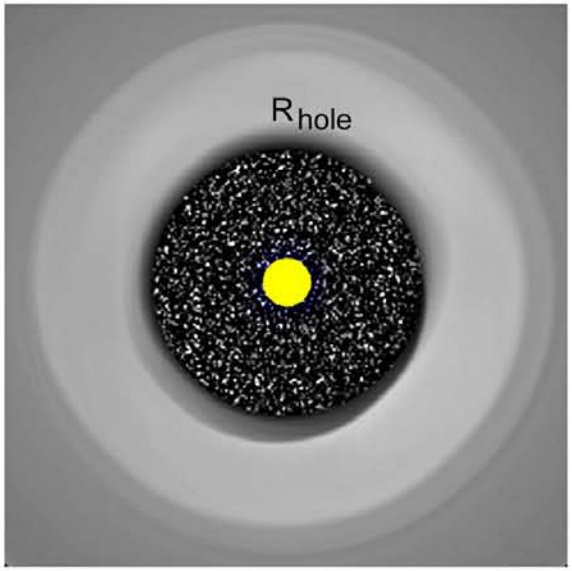


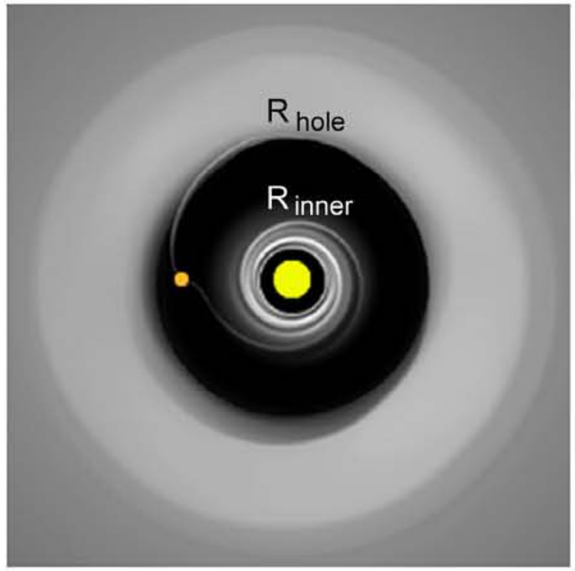
ALMA simulation 850 GHz, 1 M_{Jup} around 0.5 M_{Sun} at 5 AU

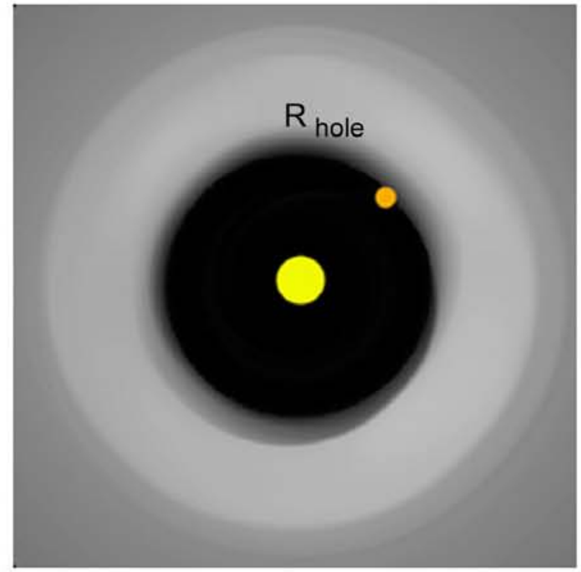
Wolf & d'Angelo 2005

- **ALMA**
- **IR with coronagraphs**

Multiple paths for disk evolution primordial → debris?







Strom, Najita

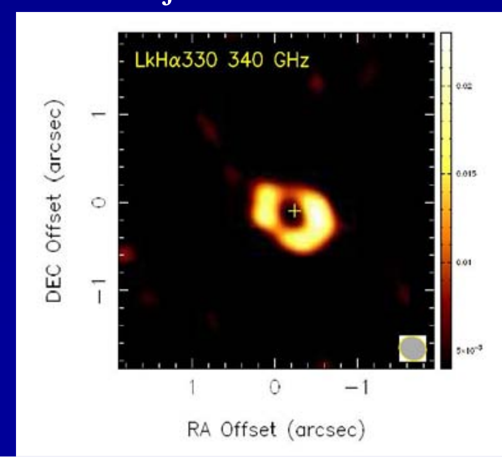
Grain growth:
Planetesimals

Jupiter-type planets

Supra Jupiter-type planets
(5-10 M_J)

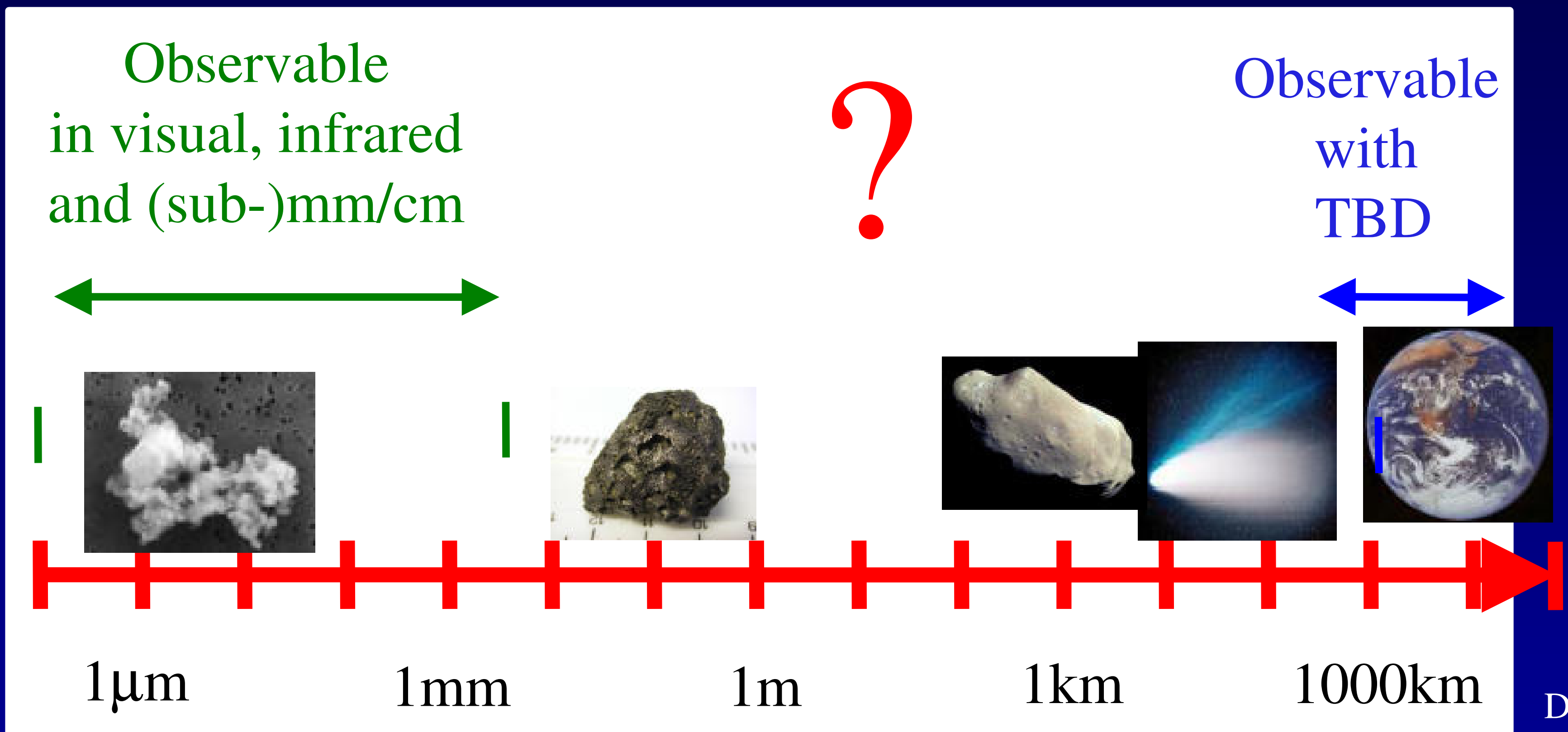
- **All instruments**

Need ALMA to do more of these



Brown et al. 2007

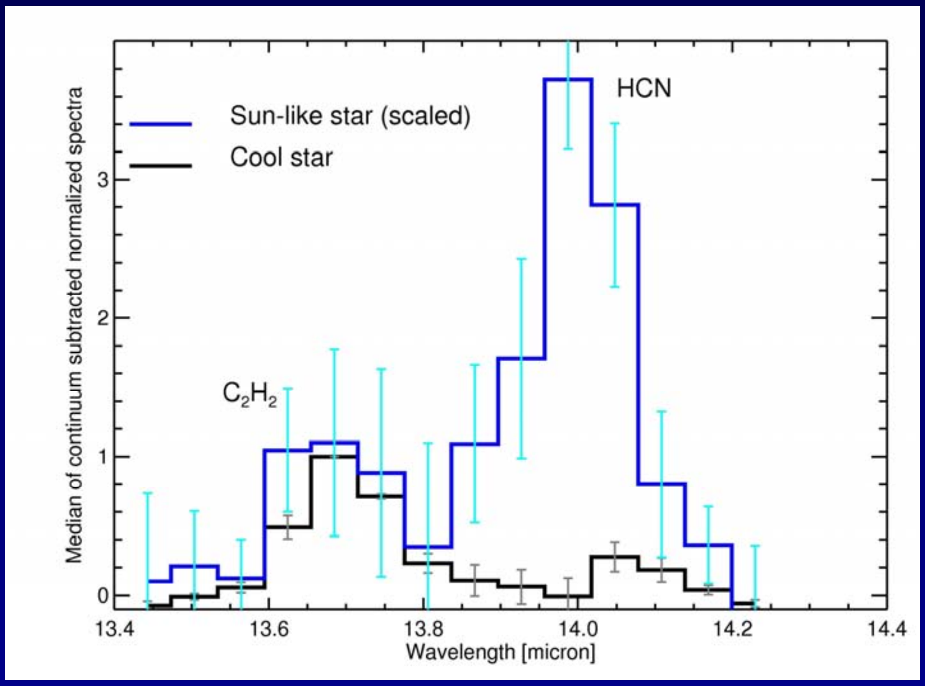
How and where does grain growth and crystallization occur?
What does it tell us about radial mixing?



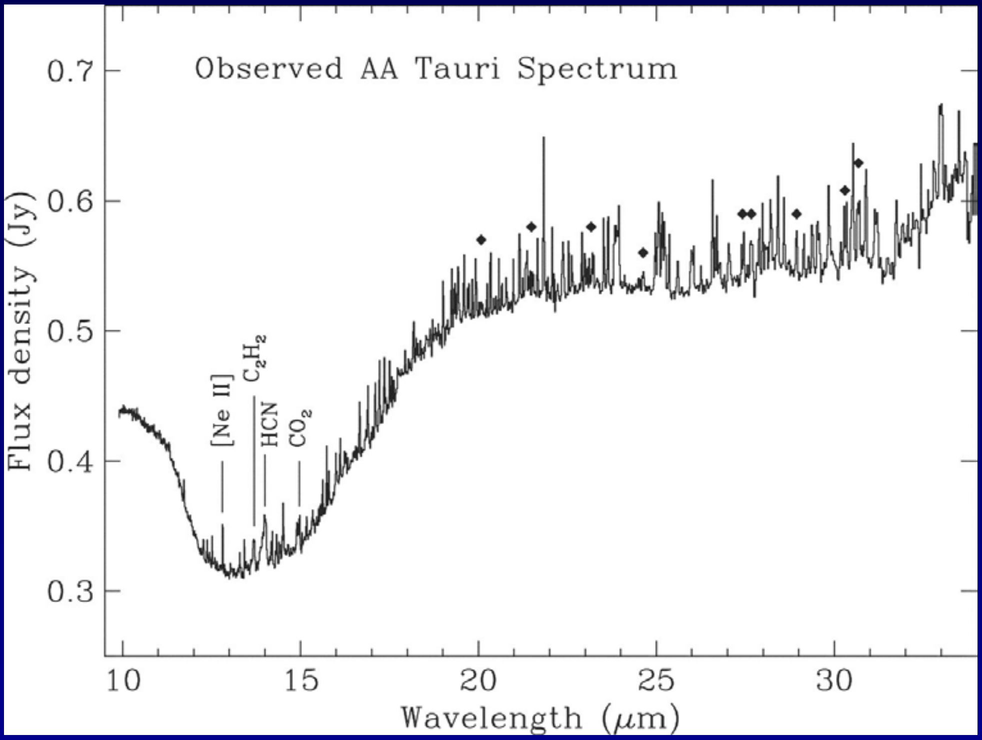
Dullemond

- ALMA multi-wavelength mapping across entire disk
- Mid-IR interferometry of inner disk
- In-situ sample return missions

Origin complex organics in inner disk? Prebiotic molecules?

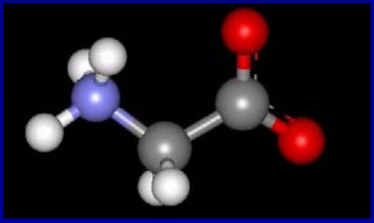


Pascucci et al. 2008

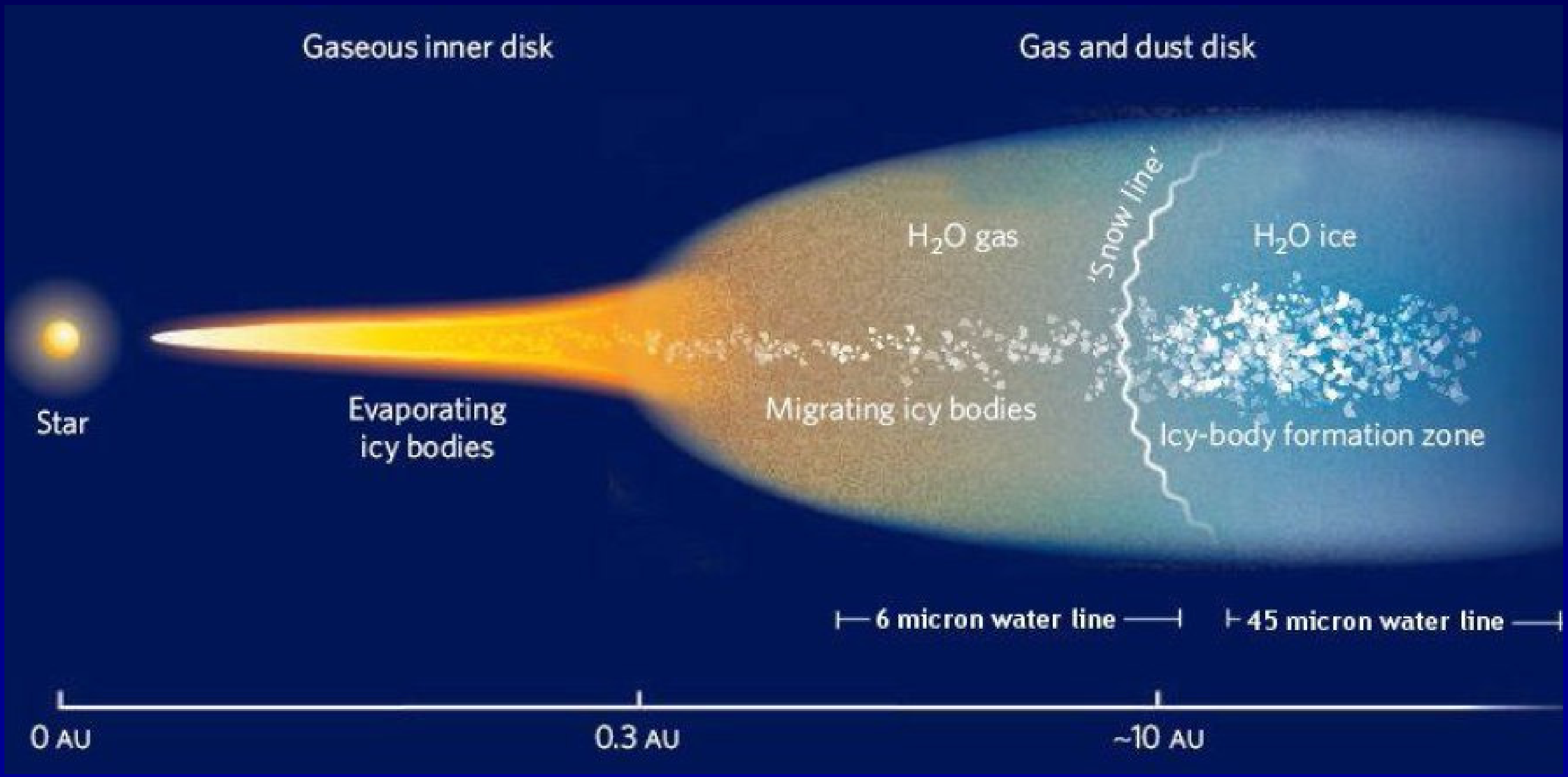


Carr & Najita 2008

- **JWST-MIRI**
- **ELTs – mid-IR in inner disks**
- **ALMA in outer disk (>10 AU)**



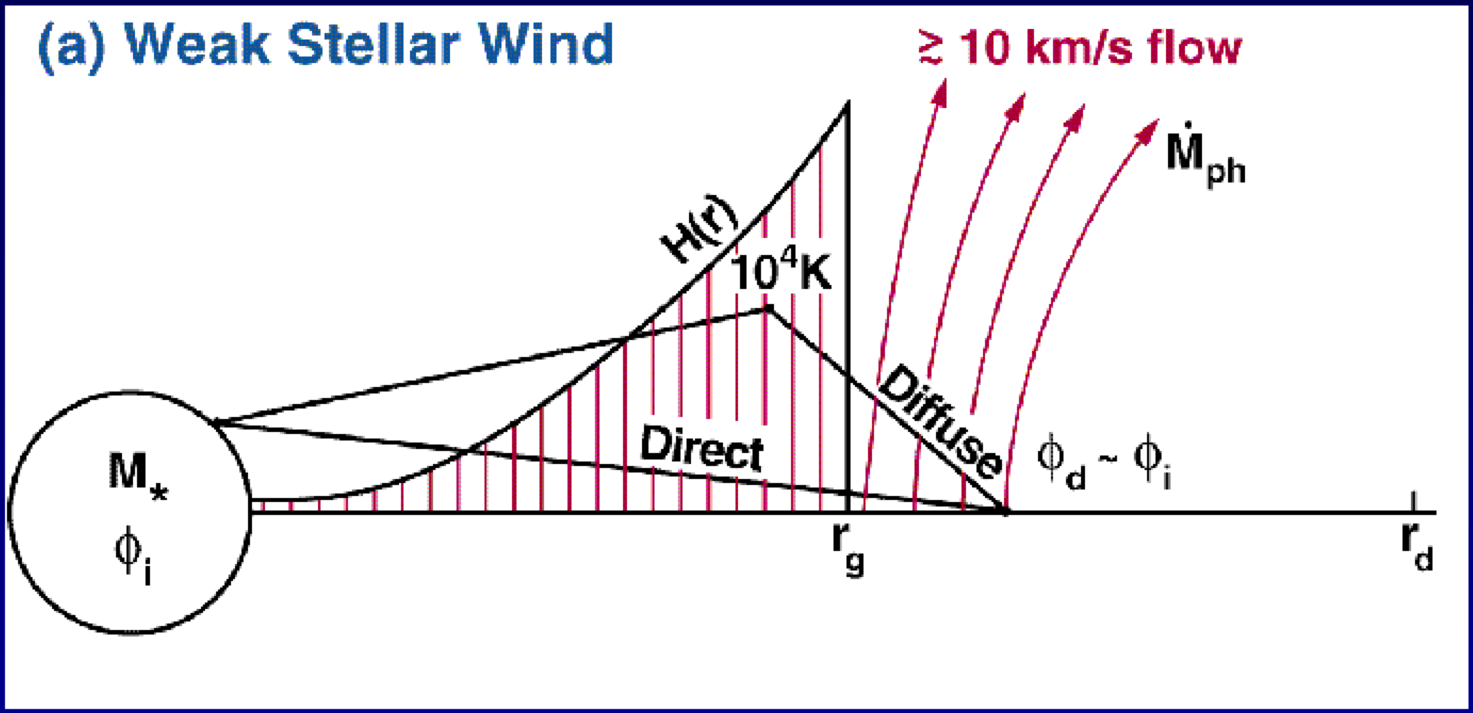
Where is the snow-line in disks?



van Boekel 2007

- SOFIA 6 μm H_2O gas, 45 μm ice
- Herschel far-IR H_2O gas, 60 μm ice
- ELTs 3 μm, 10-13 μm H_2O gas

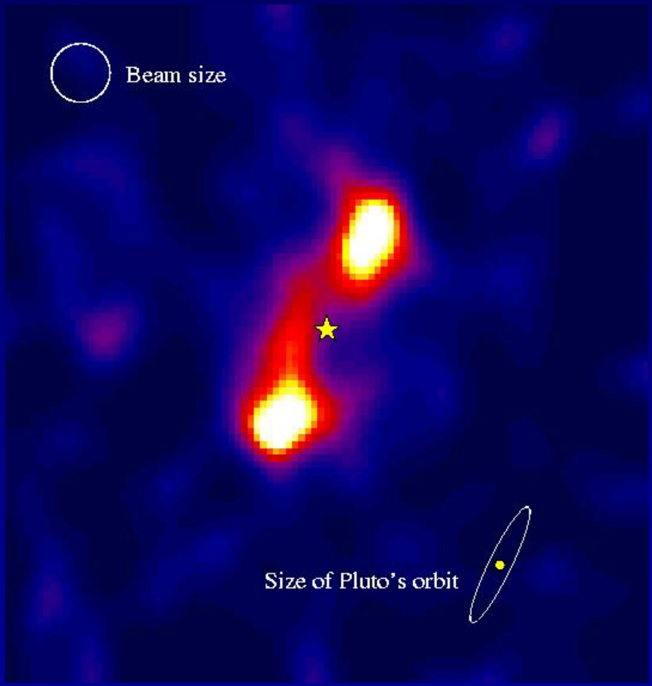
How and when is gas lost from disks?



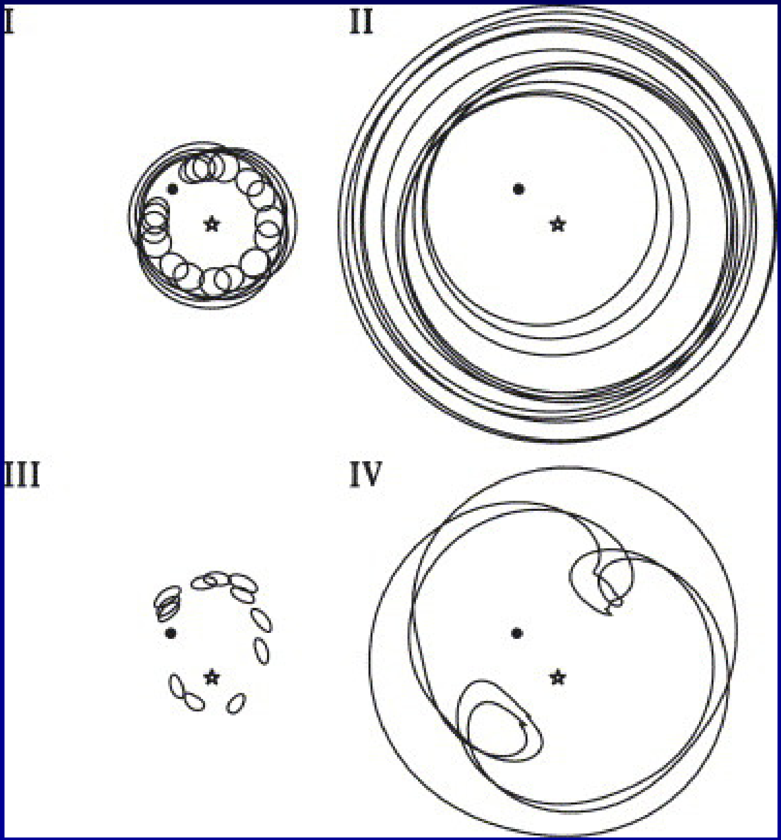
Hollenbach et al. 2000

- Herschel and SOFIA [O I] and [C II]
- ALMA CO and [C I]
- JWST and ELTs H_2 and [Ne II]
- SPICA [O I]
- Future UV mission: H_2 emission?

How do young planetary systems evolve? What planetary architectures are inferred from debris disk structures? Diversity? Relation with observed mature systems?



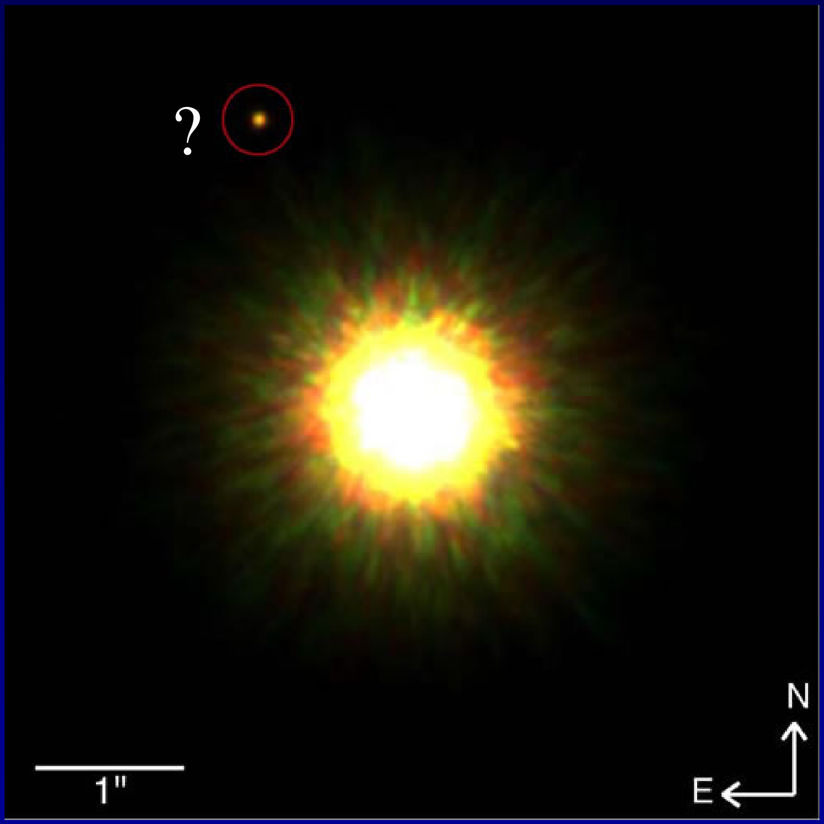
Holland et al. 1998



Kuchner & Holman 2003

- **ALMA (but not at best resolution)**
- **JWST with coronagraphy**
- **ELTs with coronagraphy, polarimetry**
- **New mission?**

Multiple paths to planets? Origin free floating planets?



Lafrenière et al. 2008

- **Deep wide field imaging**
- **JWST**
- **ELTs**

Conclusion

- Many exciting opportunities in next decade(s)
- Enjoy them!
- Do good science to train next generation, and to motivate and advocate future instruments

Thanks!

- **Thanks to *Spitzer* for providing fantastic data**
- **Thanks to Debbie, Karl and their team for organizing a wonderful conference**