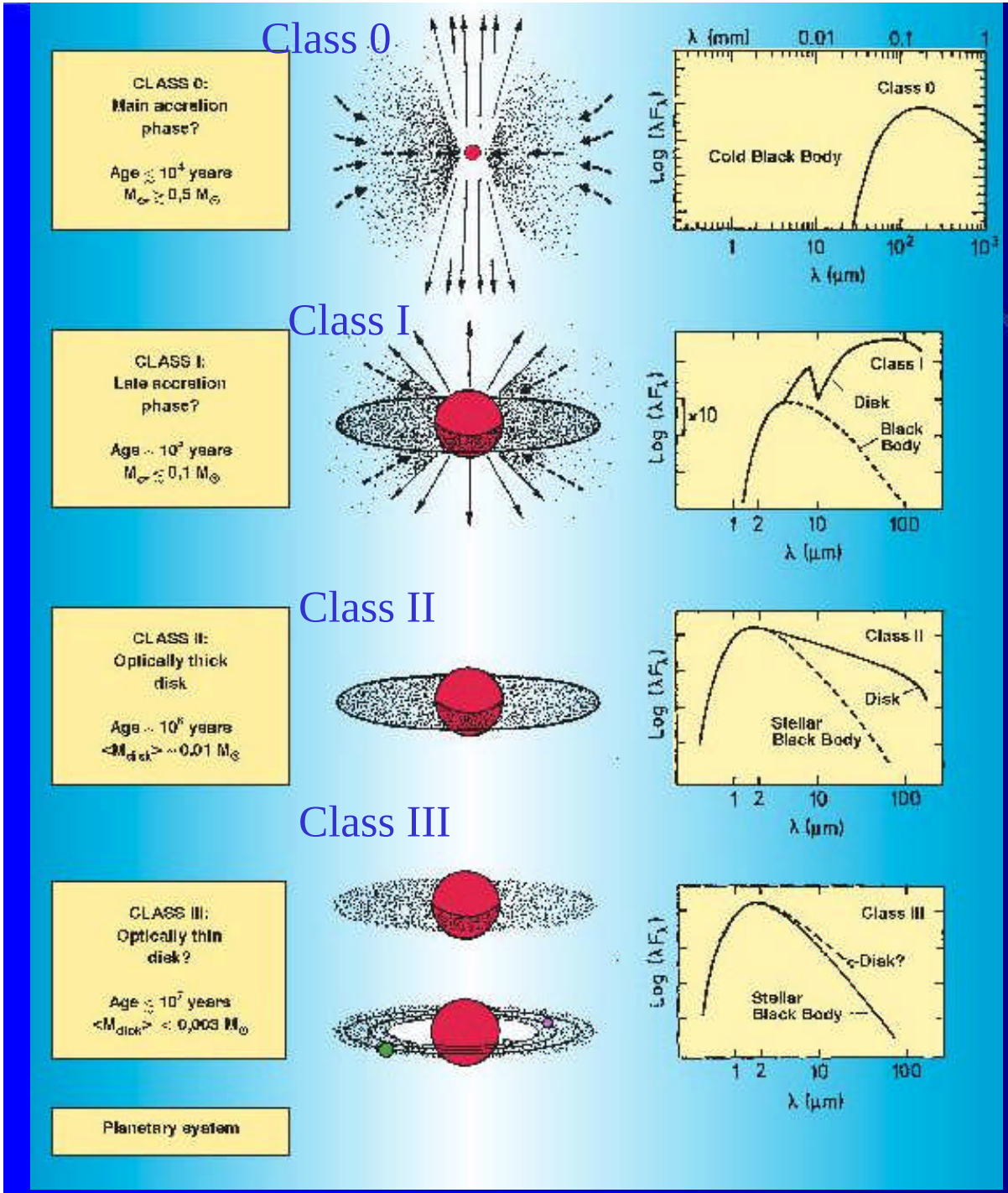
Star and Planet Formation: The Next Generation

Star and Planet Formation

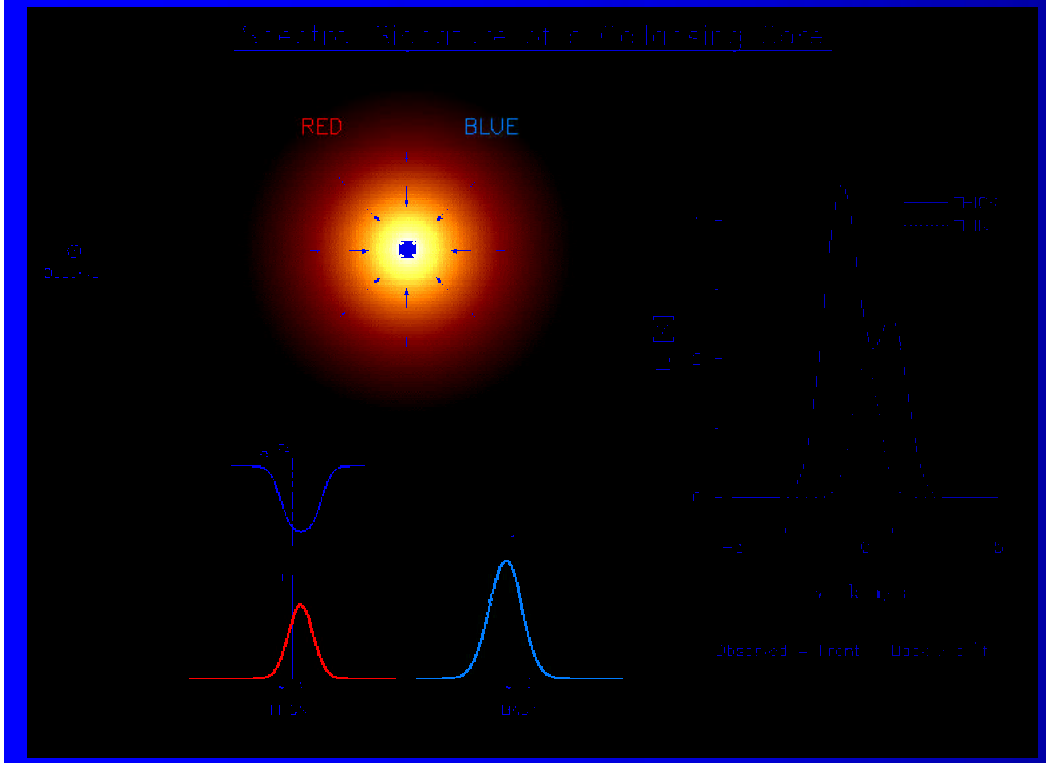
- Part of a unified process
- Hidden from optical/near-infrared in early stages by dust
- Peak of emission in FIR–Submm
- Major Impact from studies by SIRTF, Herschel, SOFIA, ALMA, NGST
- Planet formation on scales of AU (~10 mas at 140 pc –nearest examples)



Evolutionary Scenario

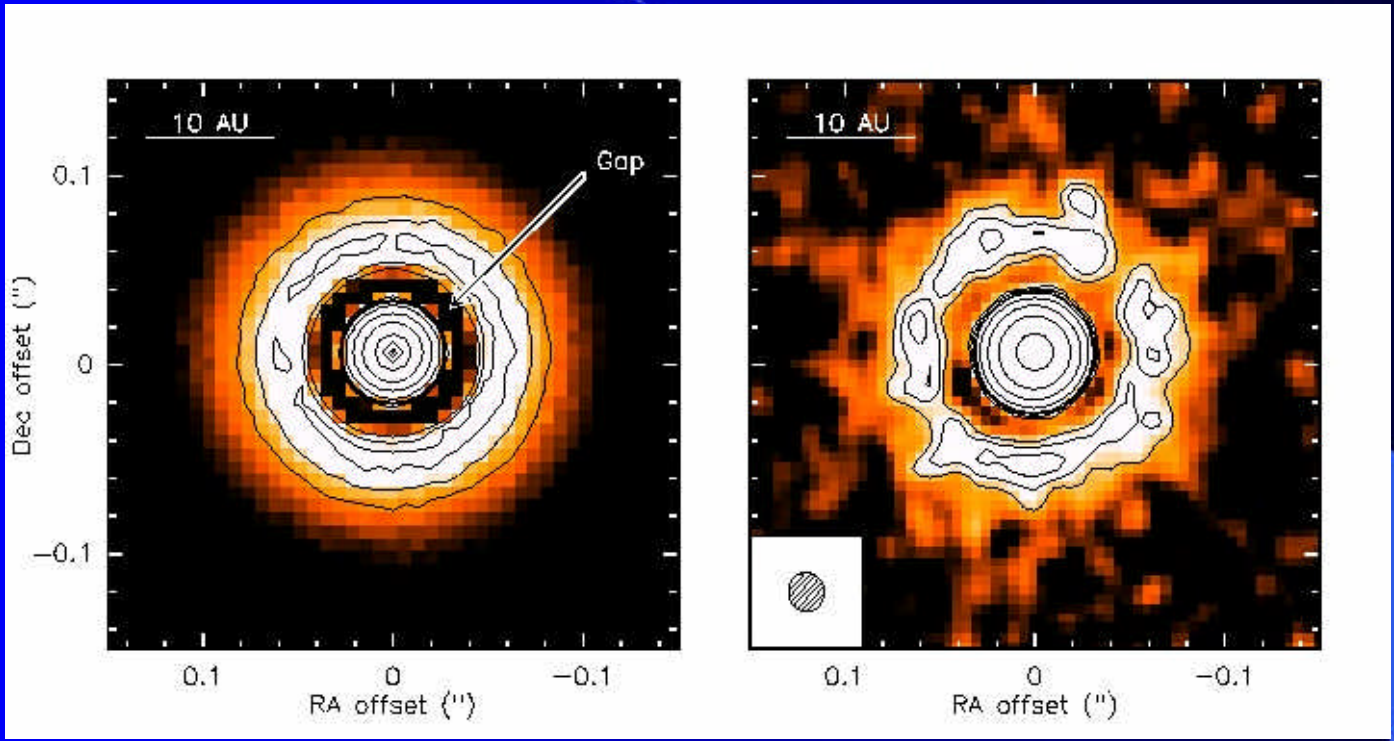
Paradigm: material in an envelope falls onto a rotating circumstellar disk, feeding a forming star and planets.
A bipolar flow allows loss of angular momentum.

Observing Infall



- A key observation is to observe the infalling gas in redshifted *absorption* against the background protostar
- Very high spectral resolution (<0.1 km/s) is required

Protoplanetary Disks



- We want to study the formation of planets by observing the gaps they clear in the inner circumstellar disk. Resolution on the scale of AU is needed for these studies.

The “Current” Generation

- SIRTF 3.6–170 μm, 0.85 m
- SOFIA 1–600 μm, 2.5 m
- Herschel 60–670 μm, 3.5 m
- ALMA 350–10,000 μm, 10 km (64 x 12 m)

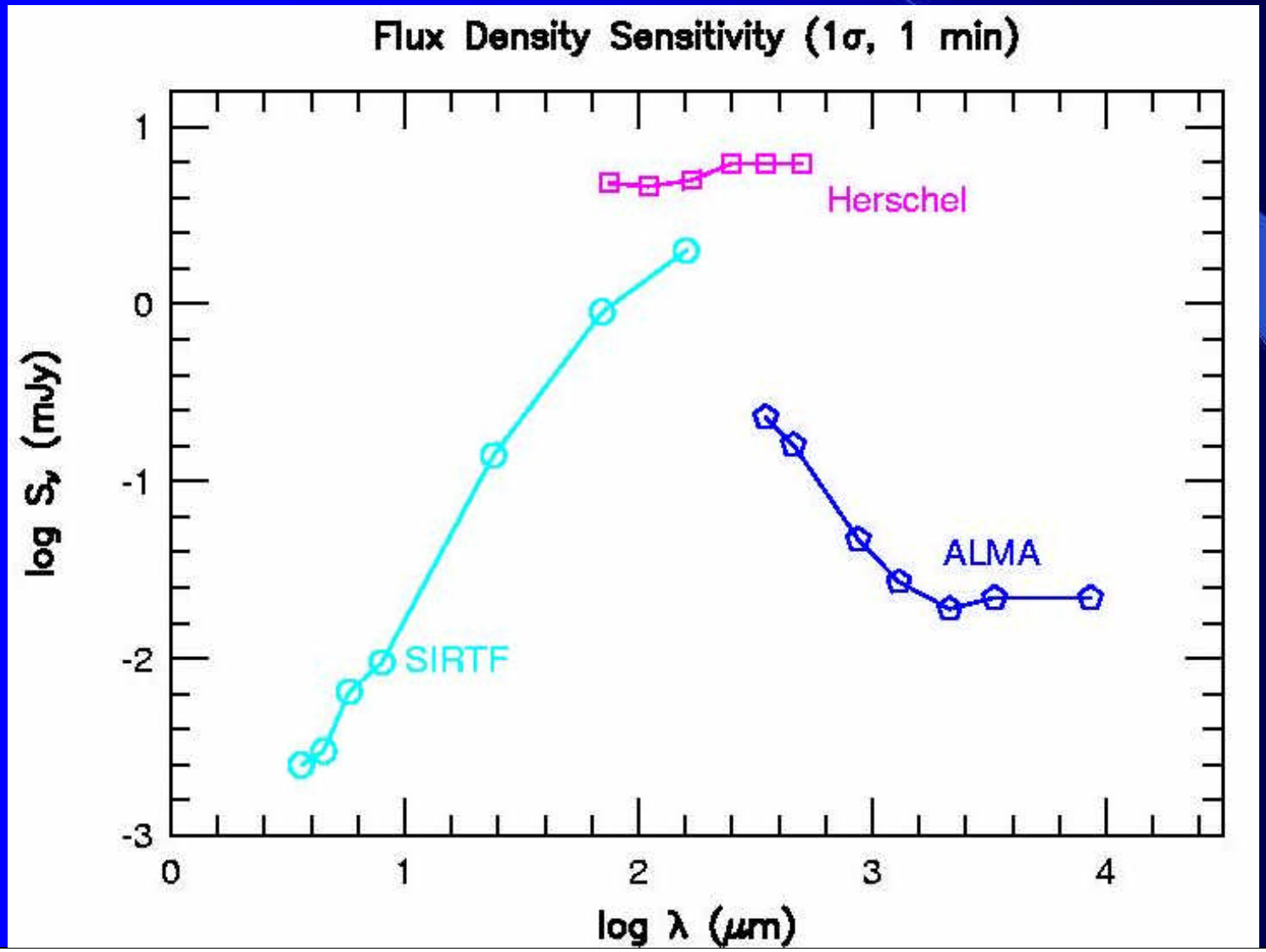
The “Current+” Generation

- NGST 0.6–27 μm, 6.5 m
- GSMT 0.3–25 μm, 30 m
- EVLA >6000 μm, 300 km (27 x 25m)
- LAT 0.5–200 μm, 15 m
- SAFIR 30–300 μm, 8 m
- TPF 3–30 μm, 1 km (4 x 3.5 m)

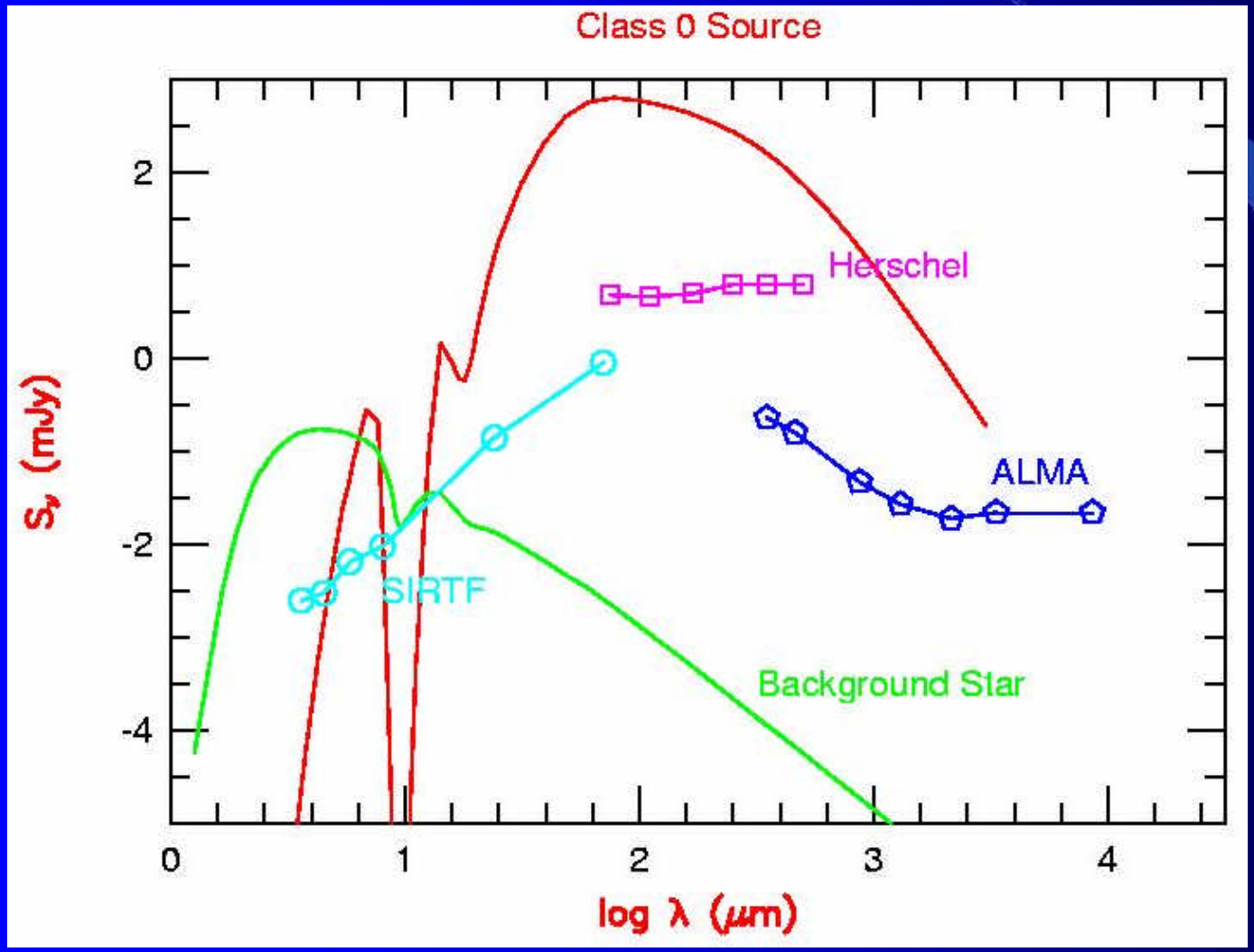
Sensitivity of "Current" Generation is Excellent

- SIRTF
  - Detects all sources down to 0.001 L_{sun} in nearby clouds
  - Detects debris disks to 0.1 M_{moon}
- ALMA
  - Detects down to ~ 1 M_{earth} at $\tau < 1$ wavelengths
- Herschel
  - Detects dust down to $A_V < 0.01$ mag

Continuum Sensitivity

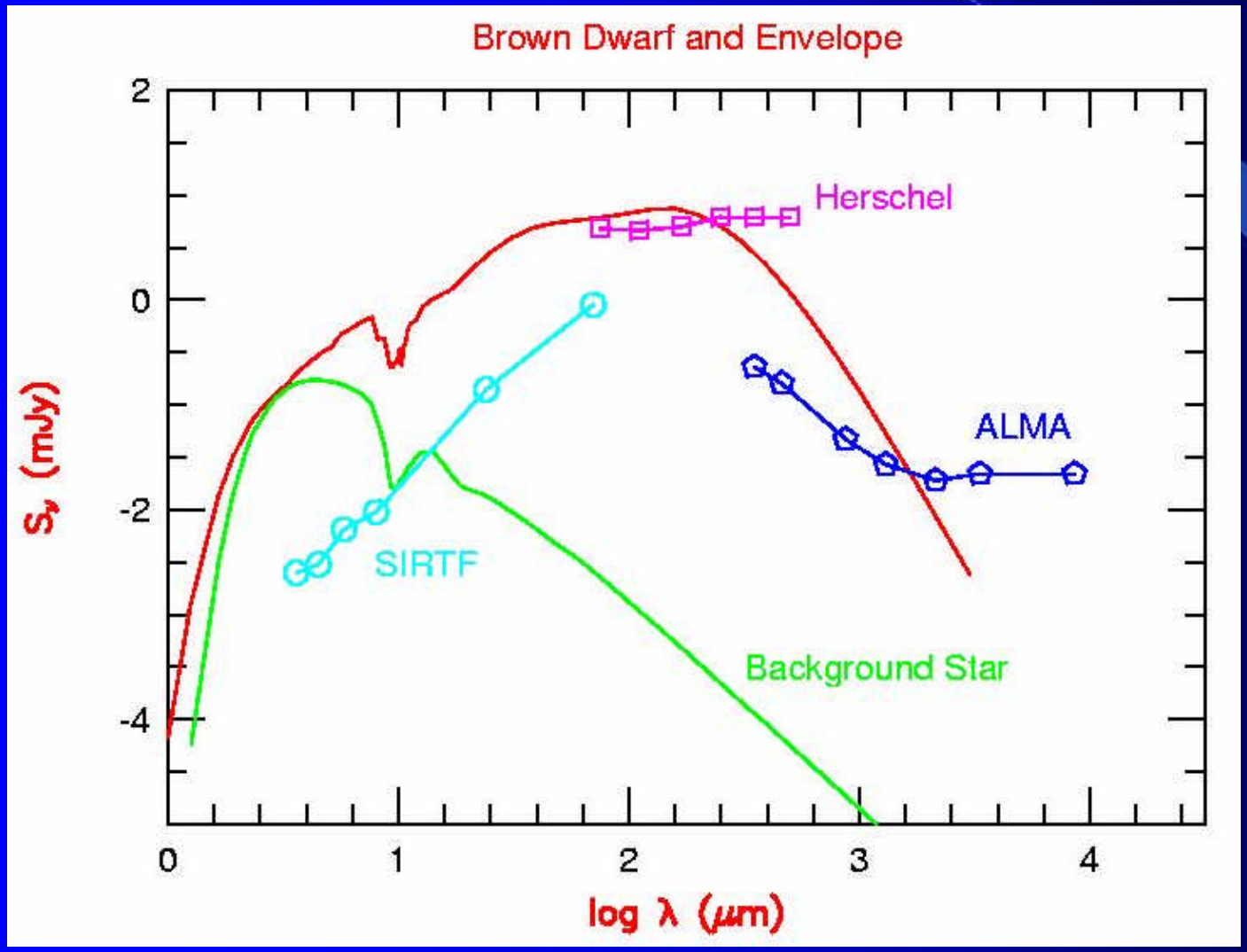


Deeply Embedded Protostar (Class 0)



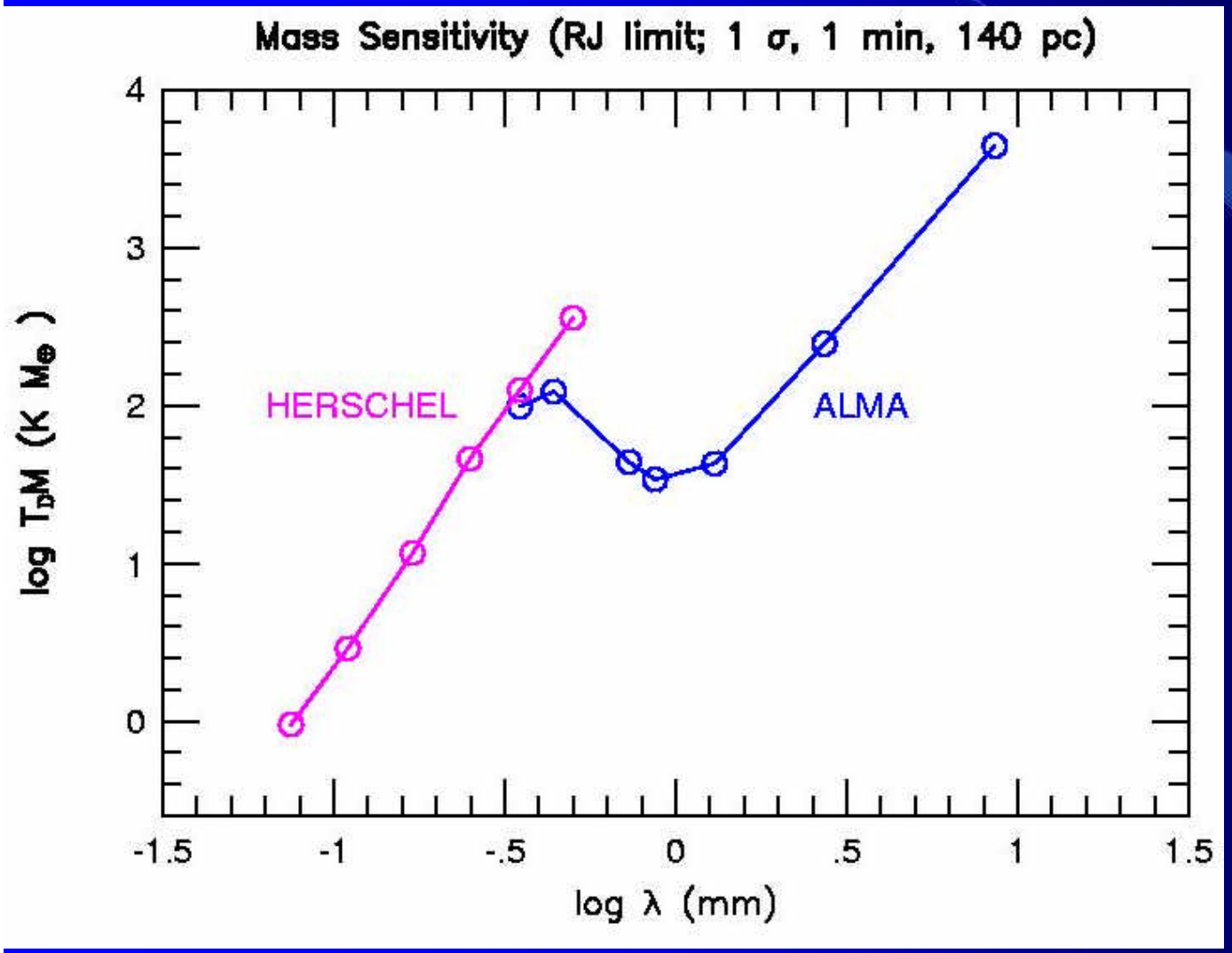
* 0.1 $L_\odot$ Protostar At 300 pc

Brown Dwarf in Envelope



* Brown Dwarf with 0.003 $L_\odot$
* At 300 pc
* 1 M_{jup} Envelope 0.1–300 AU

Sensitivity to Mass



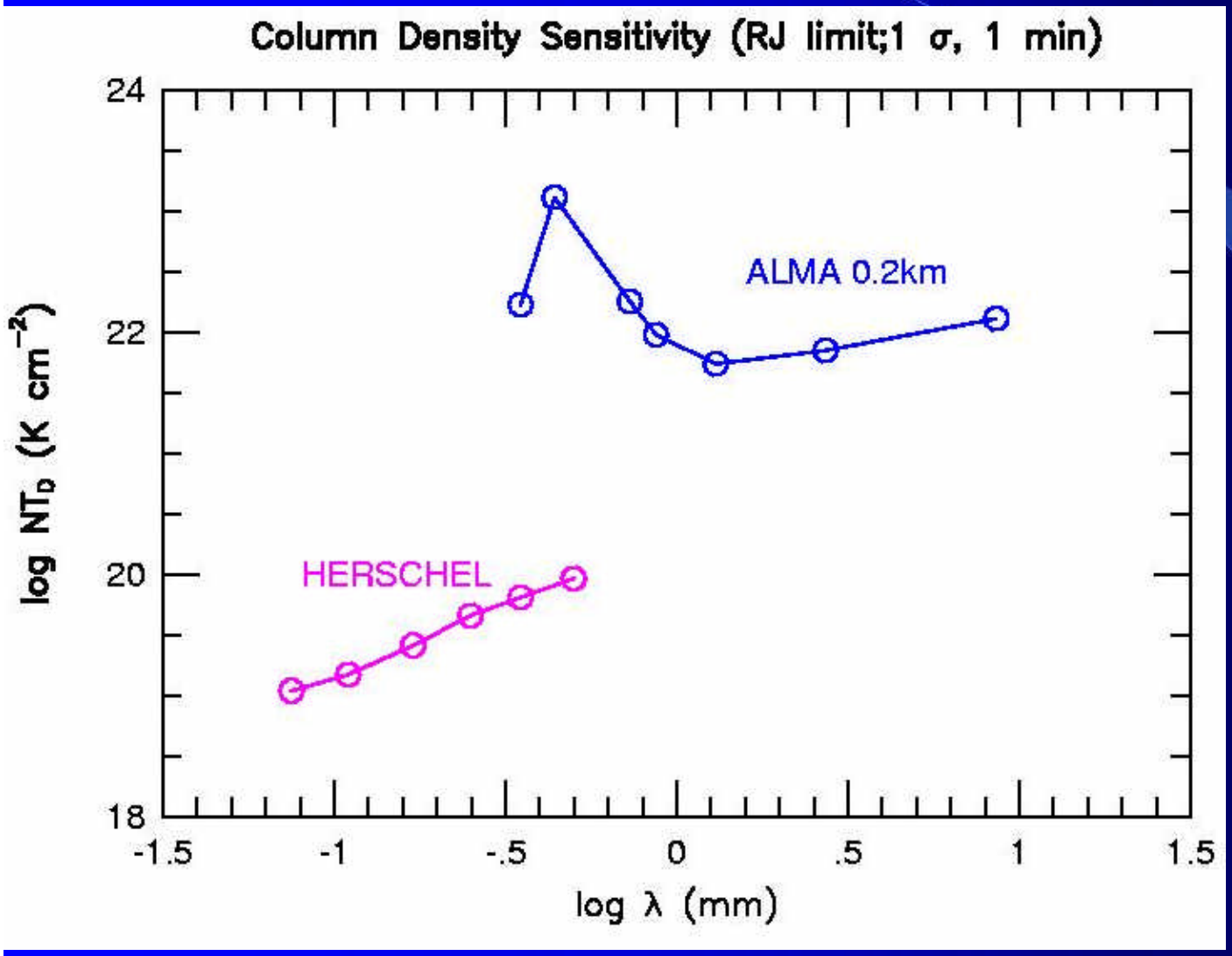
Dust emission in Rayleigh-Jeans limit

Diffraction-limited $\kappa_\nu = 0.02 / \lambda_{mm}$ $cm^2\ g^{-1}$ of gas

At 140 pc

Subtract log T_D for Sensitivity in log $M_\oplus$

Sensitivity to Column Density



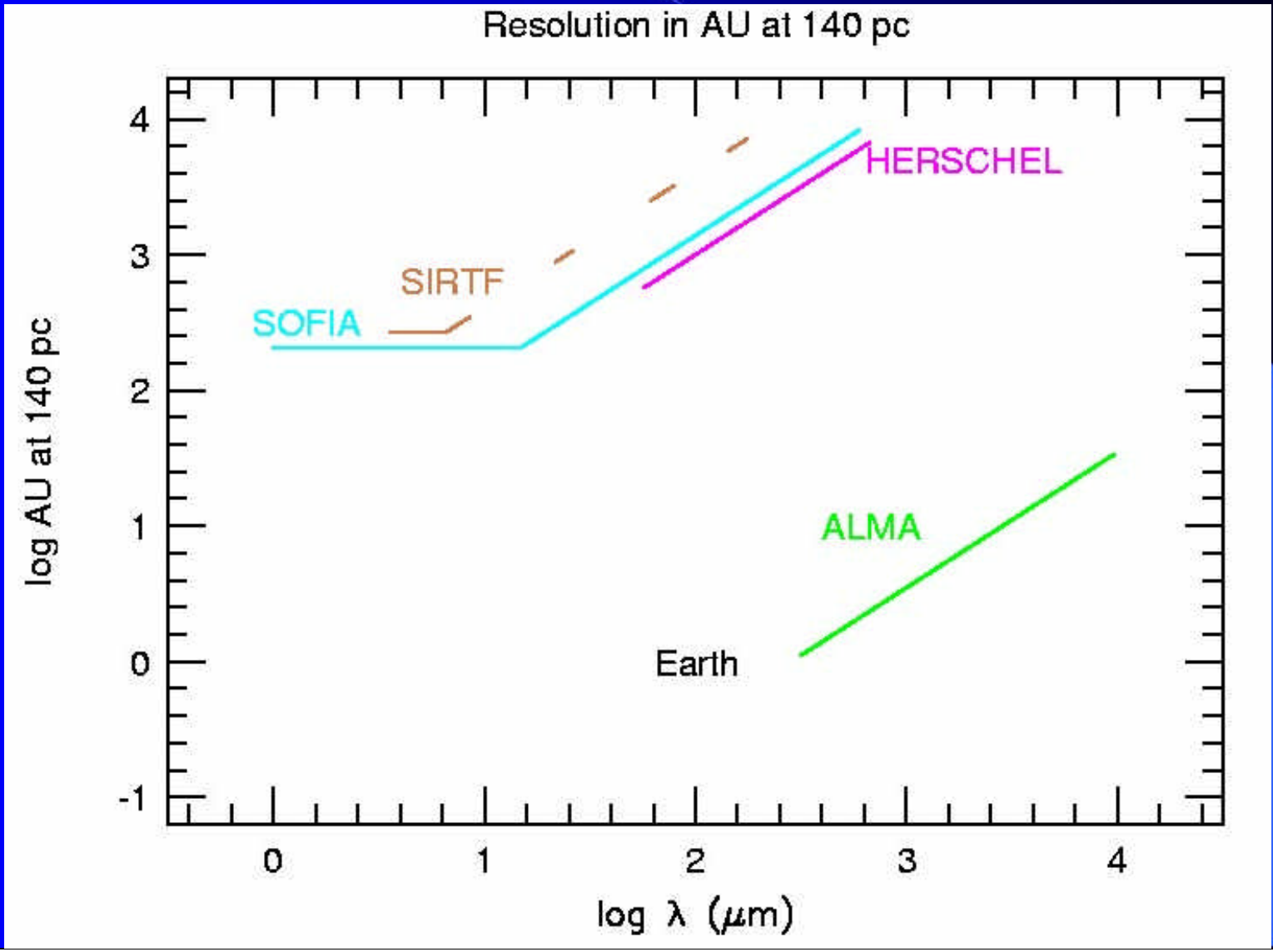
Dust emission in Rayleigh-Jeans limit

Diffraction-limited $\kappa_\nu = 0.02 / \lambda_{mm}$ $cm^2\ g^{-1}$ of gas

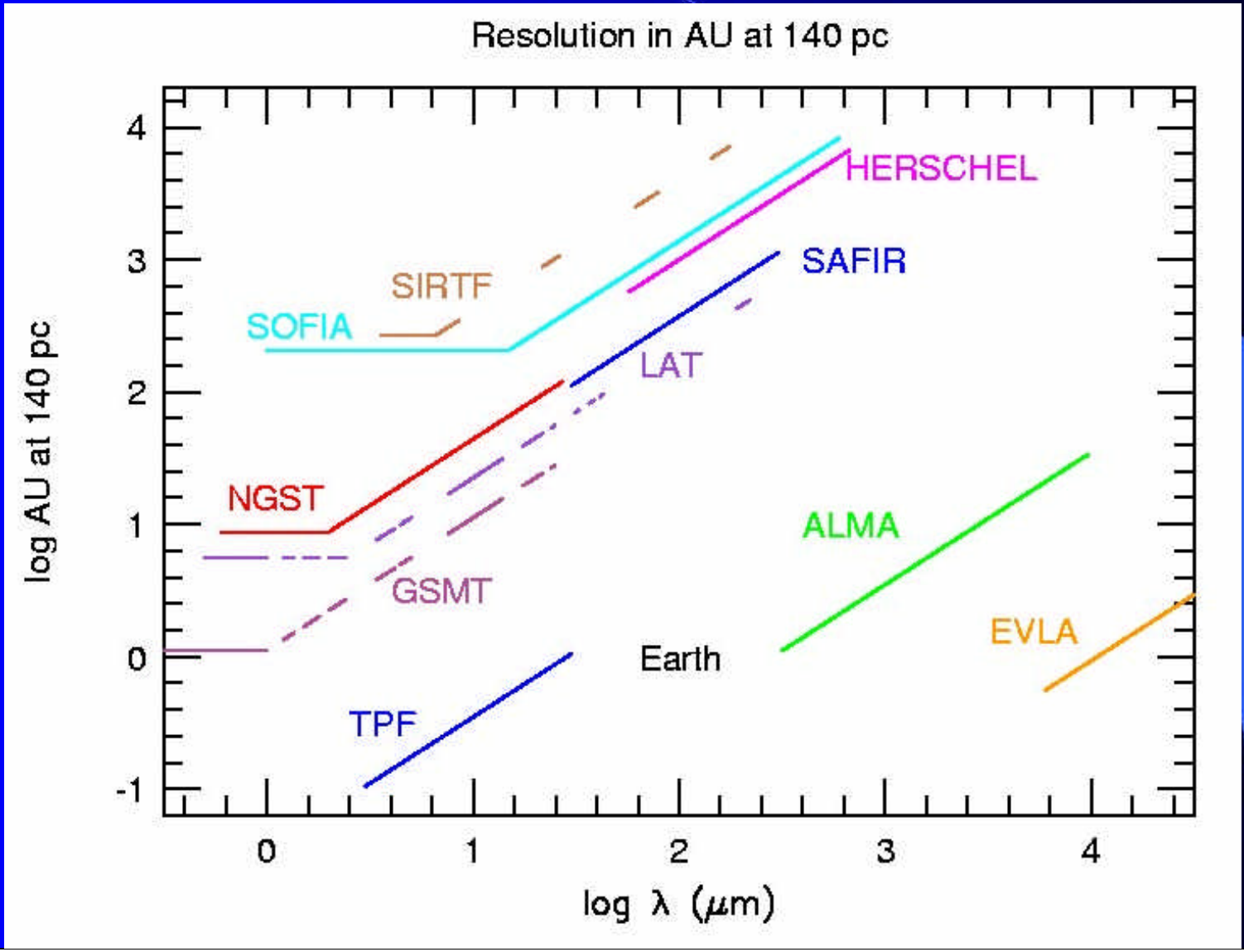
Subtract log T_D for Sensitivity in log N_{gas}

Subtract 21 for Sensitivity to $A_V T_D$

“Current” Spatial Resolution



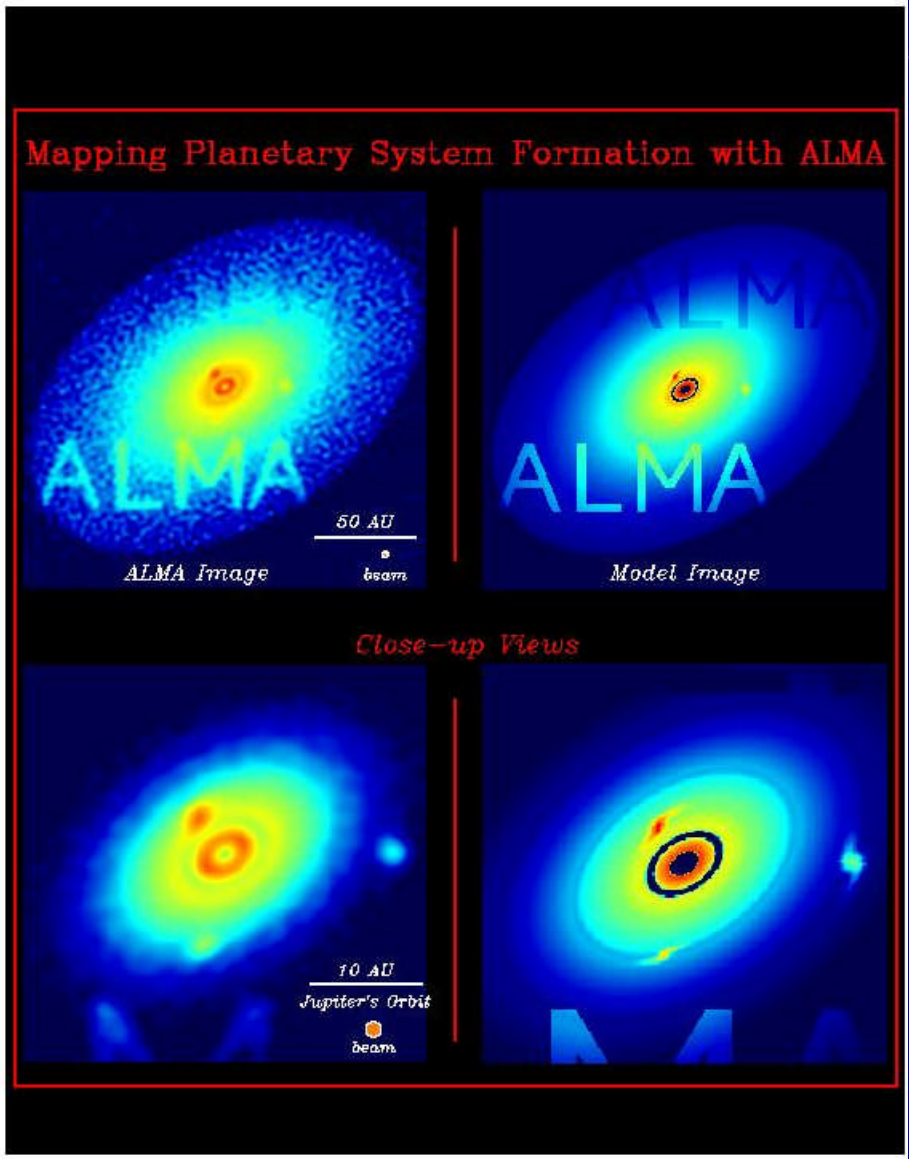
“Current+” Spatial Resolution



The Resolution Gap

- "Current" spatial resolution is >100 times worse for $\lambda < 300\ \mu m$
- "Current+" spatial resolution between 30 and 300 μm will still be 100 times worse
- Crucial wavelengths for tracing energy
- Observe small amount of dust in gaps
- Study energy in planet formation

Gaps in Disks



Observed Model

Simulation Contains:

* 140 AU disk
* inner hole (3 AU)
* gap 6-8 AU
* forming giant planets at: 9, 22, 46 AU with local over-densities
* ALMA with 2x over-density
* ALMA with 20% under-density
* Each letter 4 AU wide, 35 AU high

Observed with 10 km array

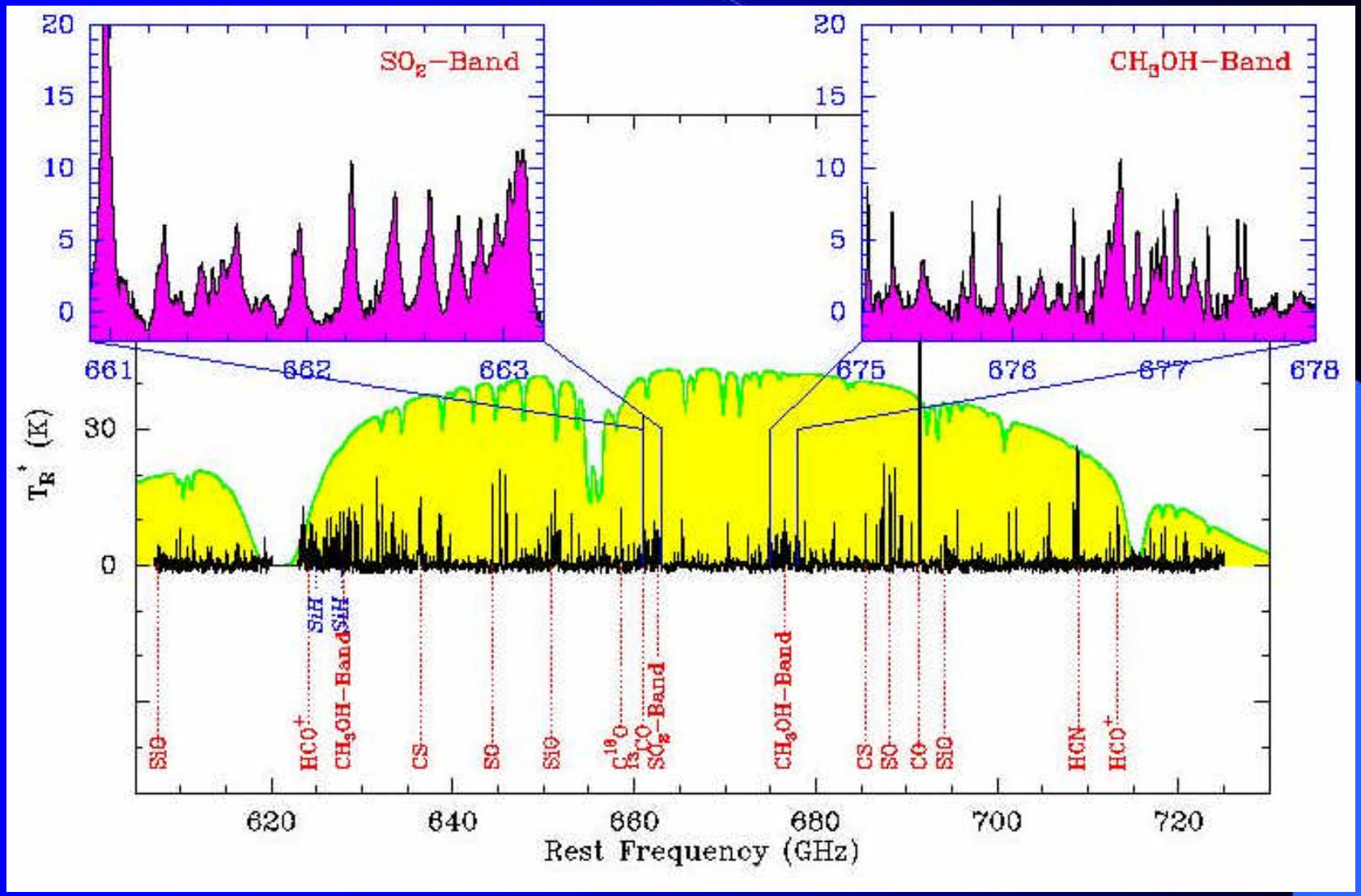
At 140 pc, 1.3 mm

L. G. Mundy

Spectral Resolution Essential

- Dust emission has no direct dynamical information
- Use velocity structure to probe scales still smaller than accessible to direct imaging
- Study slow motions (e.g. cloud collapse)
- Follow evolution of chemical abundances
- Locate reservoirs of biogenic materials
- Require spectral resolution (0.05–1 km/s)

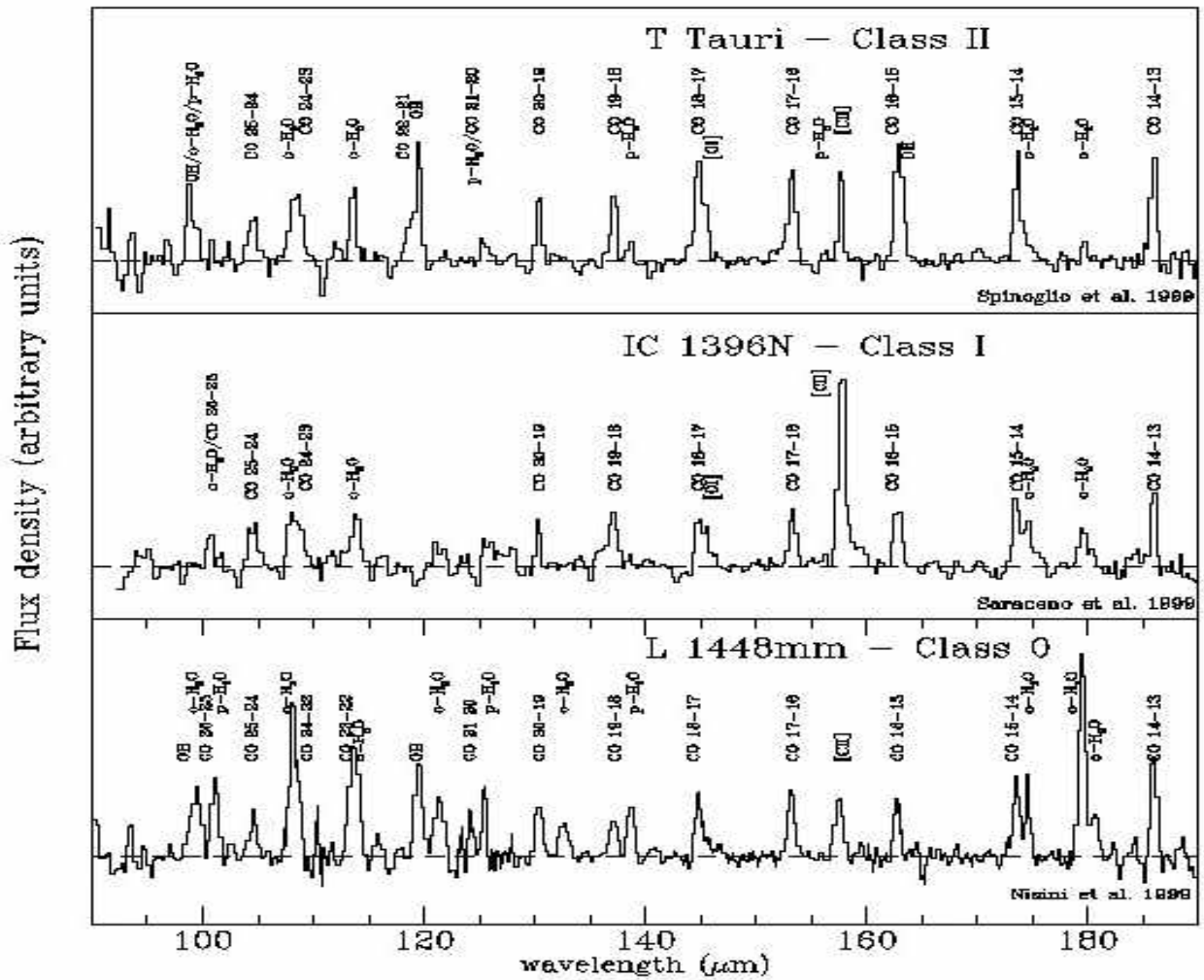
Submillimeter Spectroscopy



Far-infrared Spectroscopy

ISO-LWS spectra
90–190 μm
3 low-mass forming Stars, oldest at top
High J CO, H_2O, OH
(van Dishoeck 2001)

These lines are unresolved: Need higher spectral resolution to learn where they arise

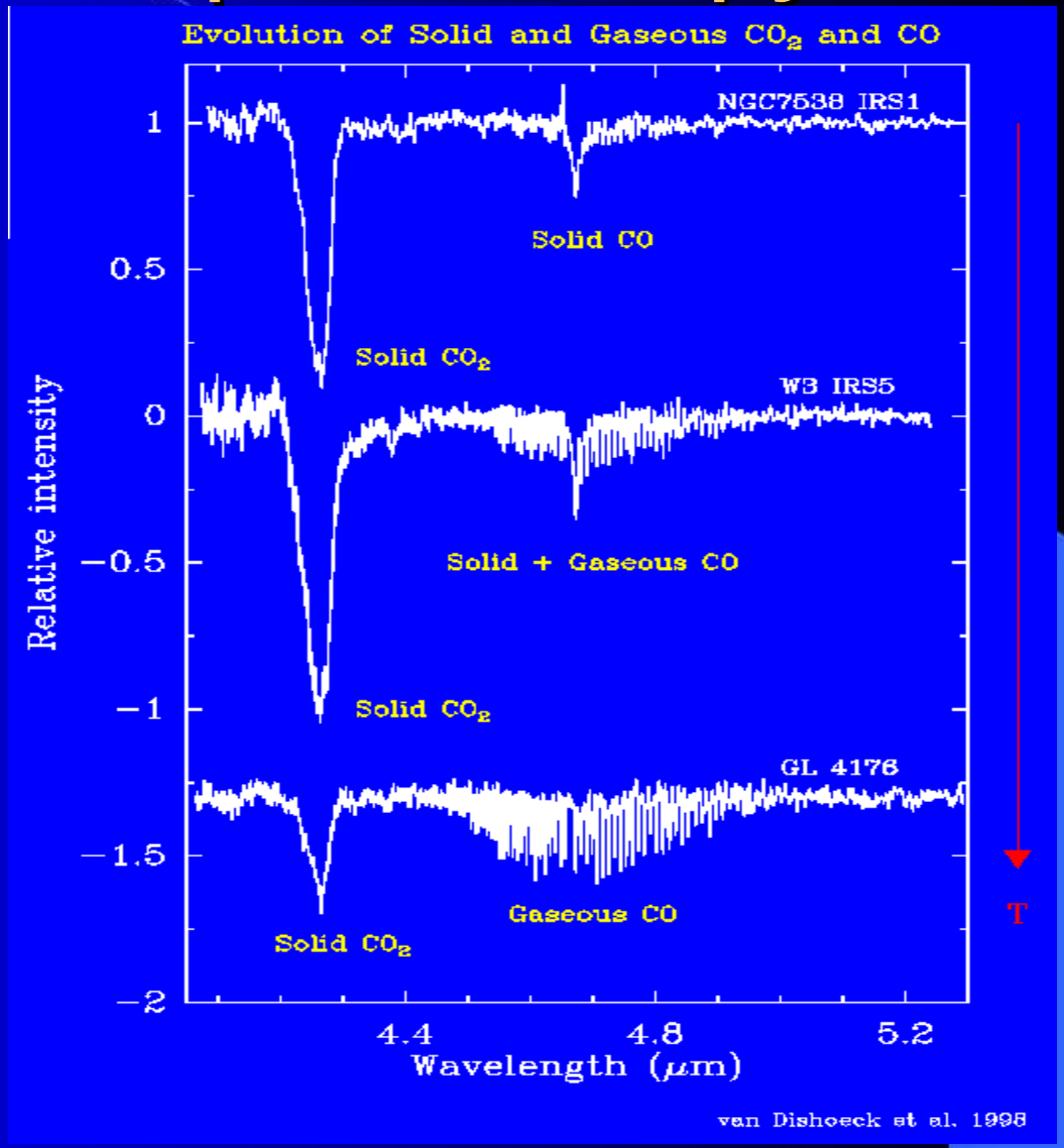


Mid-infrared Spectroscopy

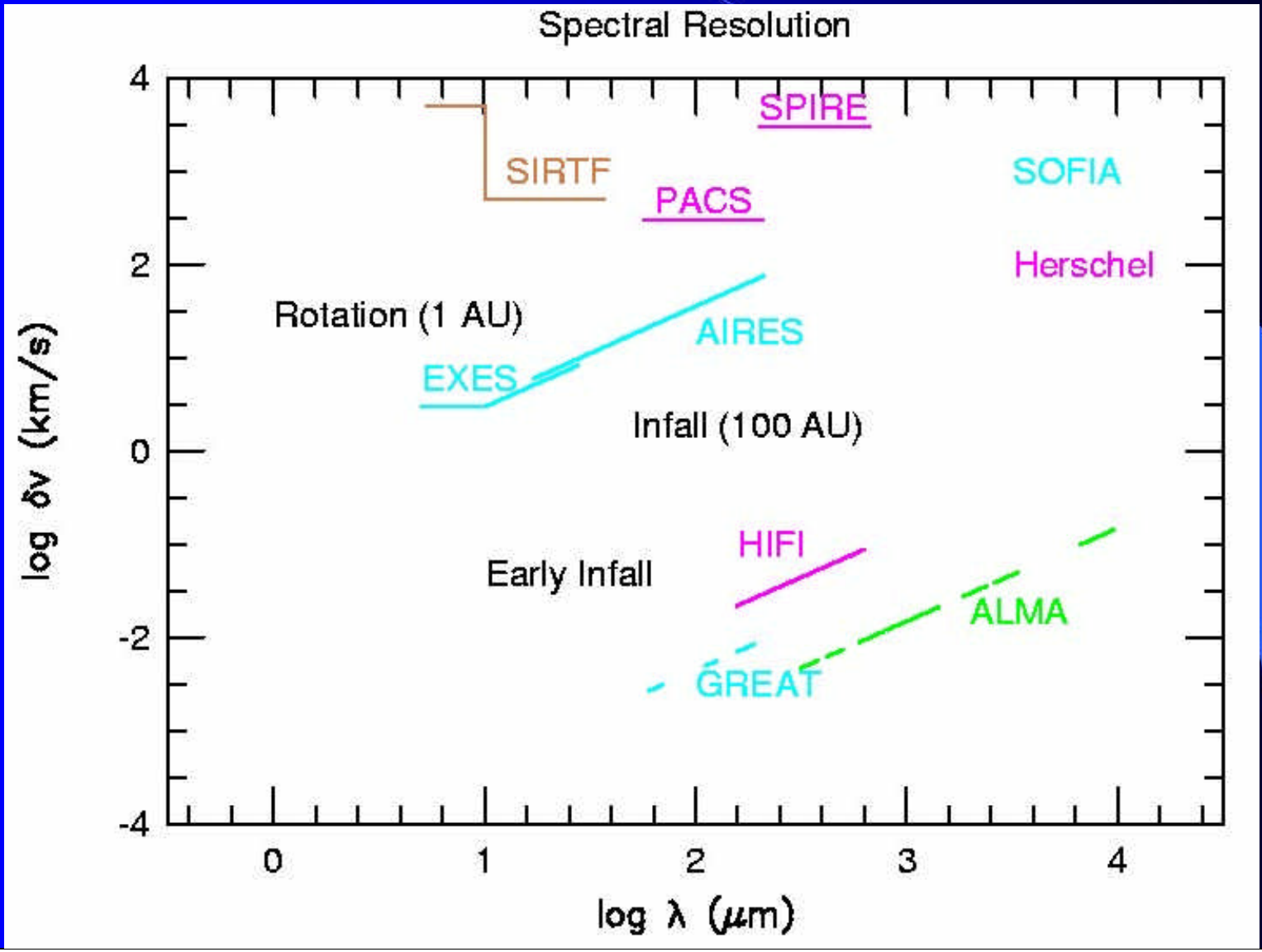
Ro-vibrational lines in MIR
Reveal physical state:
Solid or gaseous
Temperature and density

Example here:
CO and CO_2 bands show
Evaporation of grain mantles
As forming stars heat the cloud
(van Dishoeck et al. 1998)

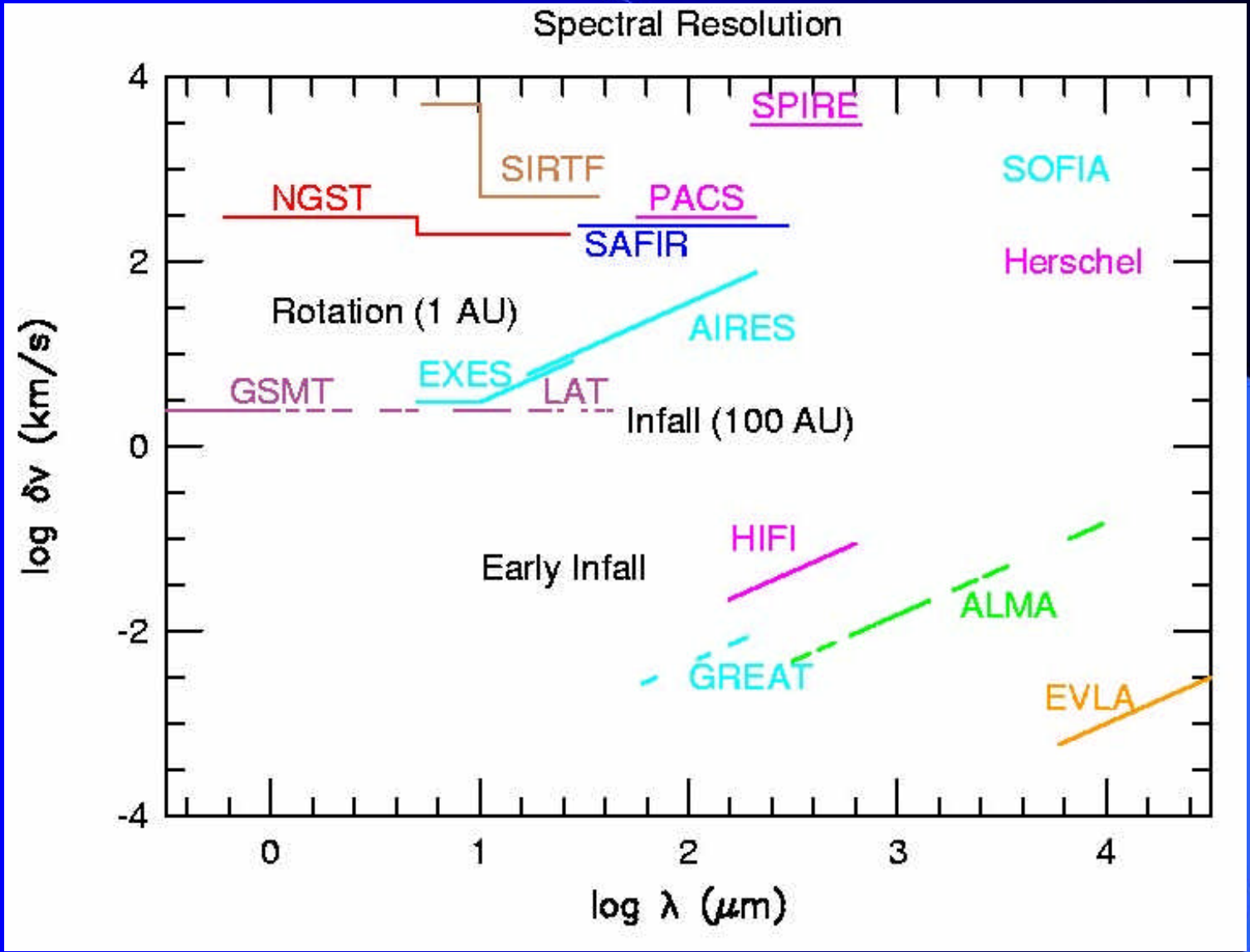
Higher spectral resolution will
allow study of chemistry in
disks as function of radius



“Current” Spectral Resolution



“Current+” Spectral Resolution



Spectral Resolution "Cliff"

- Excellent resolution ($\delta v < 0.03$ km/s) for ALMA, HIFI (Herschel), GREAT (SOFIA)
- Powerful spectral probes exist in NIR–MIR
- Best δv at $\lambda < 300$ μm is ~ 3 km/s (e.g., EXES on SOFIA)
- Most are much worse (>100 km/s)

Requirements for the Next Generation

- Resolution, resolution, …
- Spatial resolution of ~AU or better (few mas at distance of nearby clouds)
- Baselines of ~100m x $\lambda(\mu m)$
- Spectral resolution of < 1 km/s
- Adequate aperture for good sensitivity
- Excellent uv-plane coverage

Scientific Goals

- Understand envelope-disk-star mass flow
- Characterize binary star formation
- Learn how properties of protostellar disks map into planetary systems
- Image giant planet formation, gaps, migration
- Study chemical evolution from cores to planets
- Characterize extrasolar planetary atmospheres
- Search for sites and signs of life