

Observations of protoplanetary disks

A bright, glowing star is centered in the upper half of the image. Below it, a faint, diffuse disk of gas and dust is visible. To the right of the star, a small, yellowish planet is shown in orbit.

NBI Summer school Protoplanetary disks
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August 6th 2019

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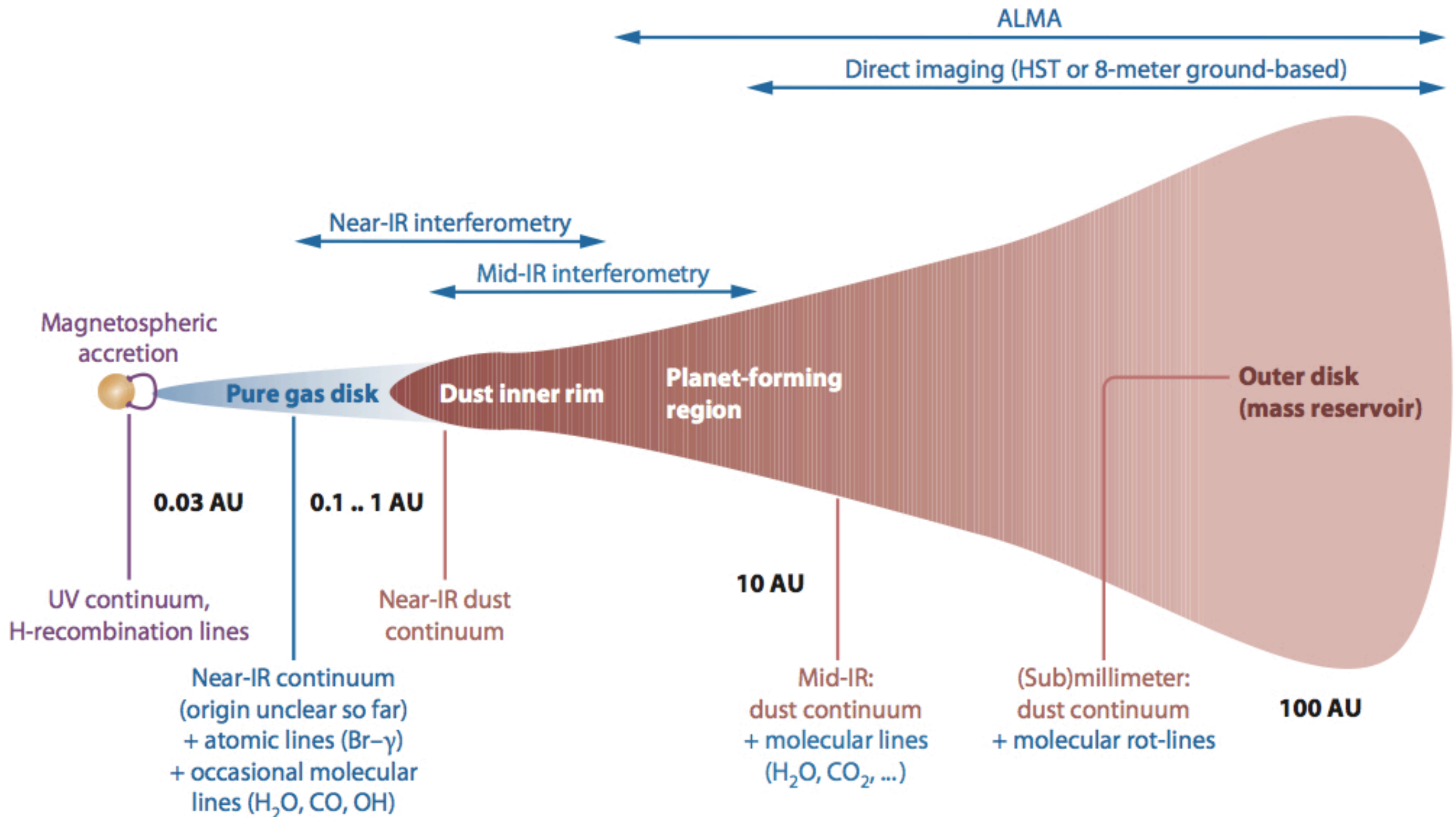
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**Remember: not embedded in the cloud,
so it is possible to study the disk
directly in all wavelengths**

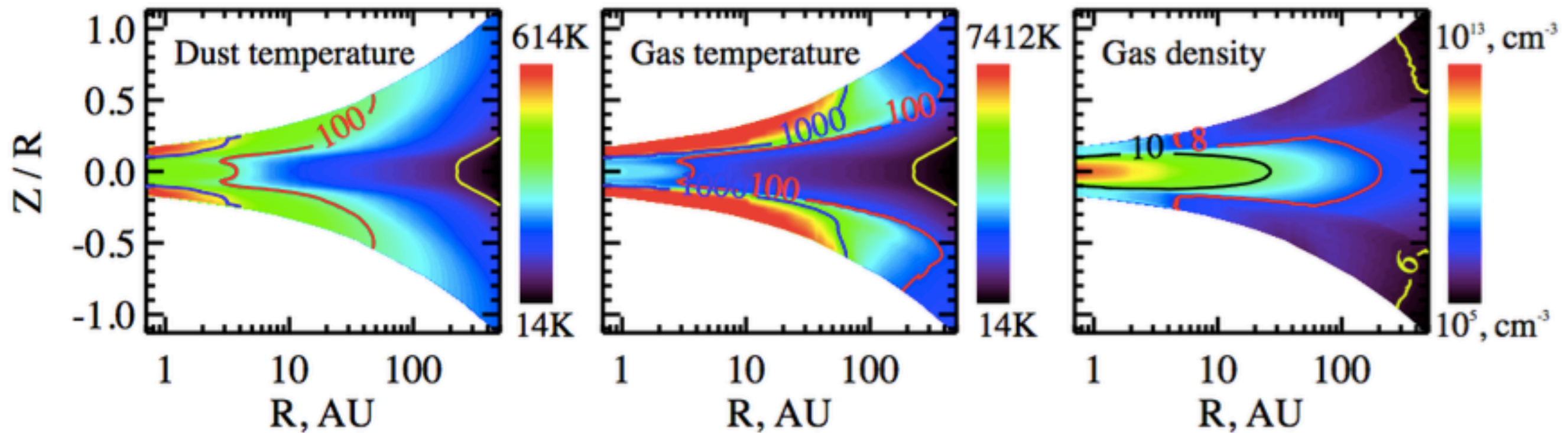
**Today: primarily discussing
unresolved observations
Tomorrow: gaps in disks (resolved)**

Slides available at www.nienkevandermarel.com!

Disk structure



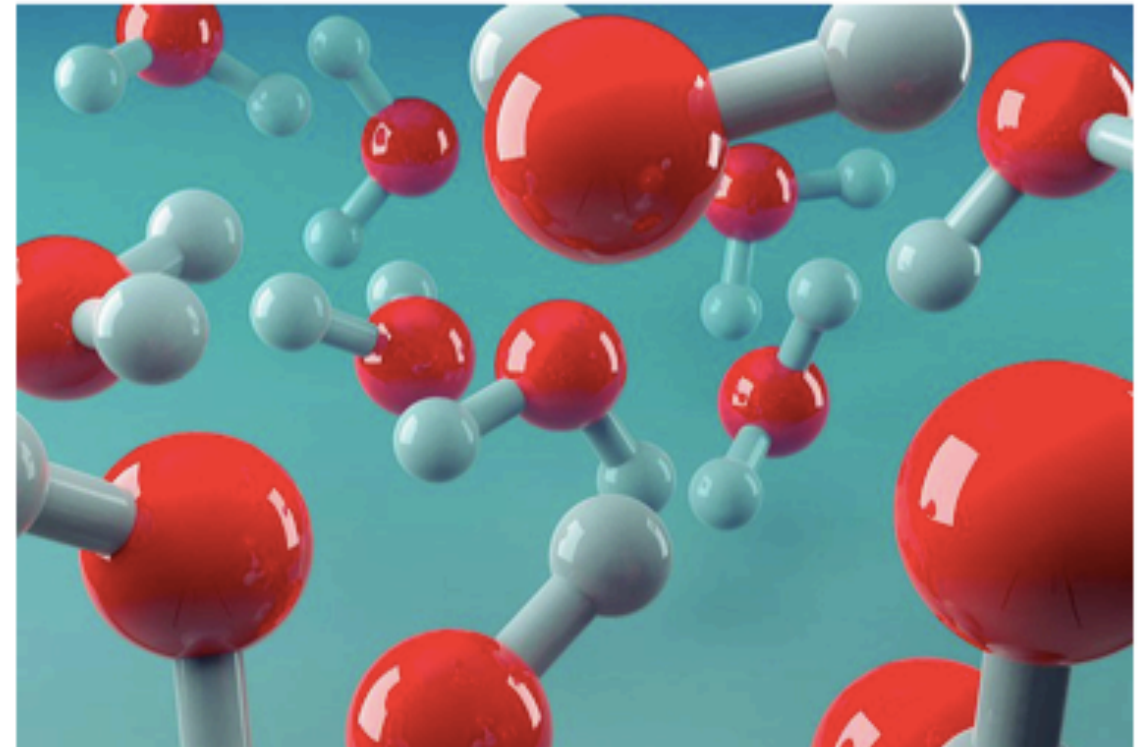
Disk structure



How to observe



**Dust particles heat up by stellar radiation and become blackbodies: emit radiation at longer wavelengths depending on the temperature
'continuum emission'
(broadband emission)**

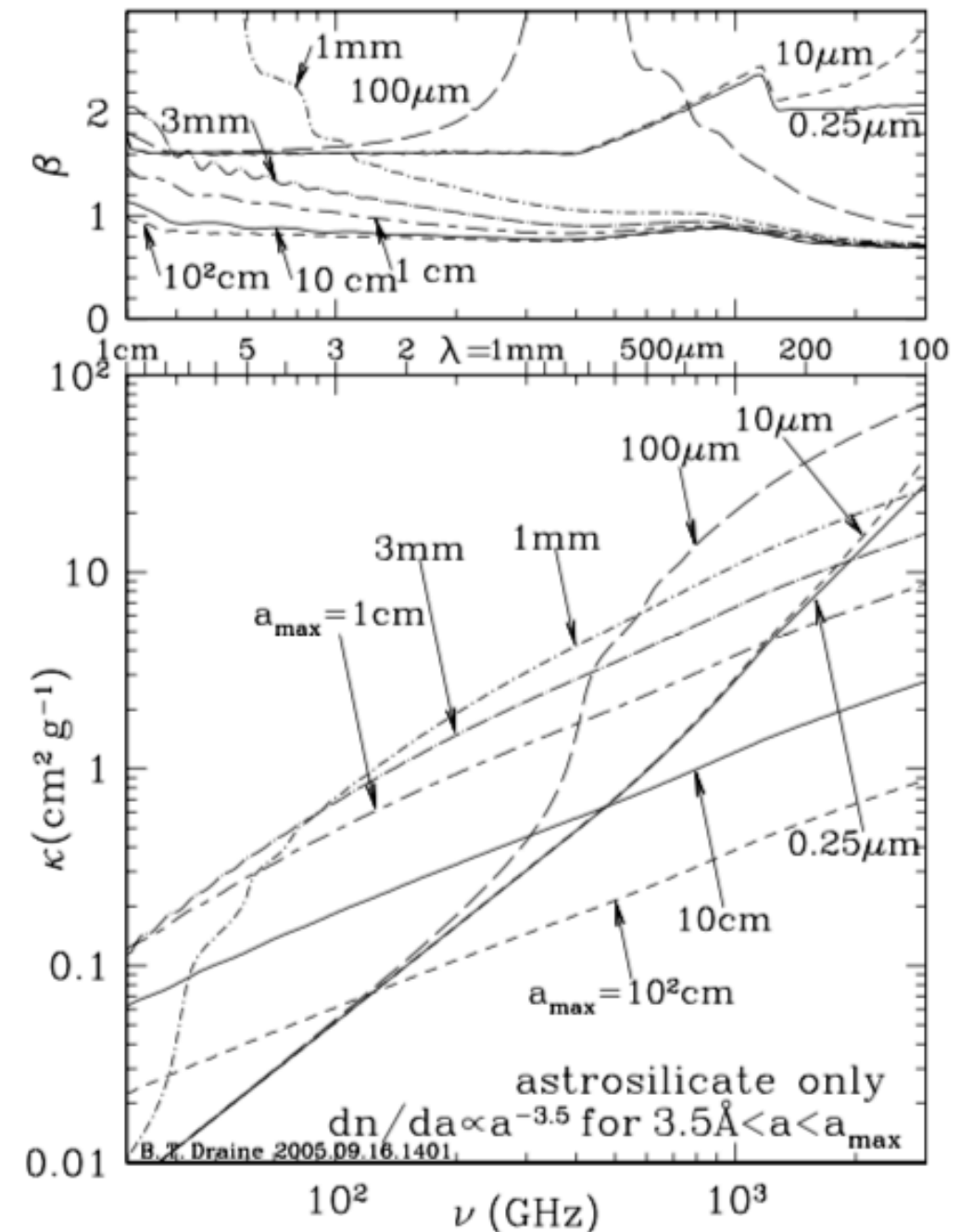


**Gas particles are molecules: emission through 'molecular lines'
(narrow emission)**

How to observe

Dust

- Flux density
(Jansky = $\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$) $F_\nu = \int I_\nu d\Omega$ $\nearrow 1/d^2$
- Specific intensity
($\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$) $I_\nu = B_\nu(T)(1 - e^{-\tau_\nu})$
- Planck function $B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$
- Optical depth $\tau_\nu = \frac{\kappa_\nu \Sigma_{\text{dust}}}{\cos i}$
- Dust opacity $\kappa_\nu \sim \nu^\beta$
 $\kappa_\nu \sim n(a) \propto a^{-p}, a_{\text{max}}, a_{\text{min}}$
+ composition



Dust opacity wavelength dependence: at wavelength λ you are sensitive to grains up to size $\sim 3 \lambda$

How to observe

Dust

Optically thin: $\tau_\nu \ll 1$:

$$F_\nu = \frac{B_\nu(T) \kappa_\nu M_{dust}}{d^2}$$

Commonly used to derive disk dust masses

Rayleigh-Jeans: $B_\nu(T) \sim \nu^2$

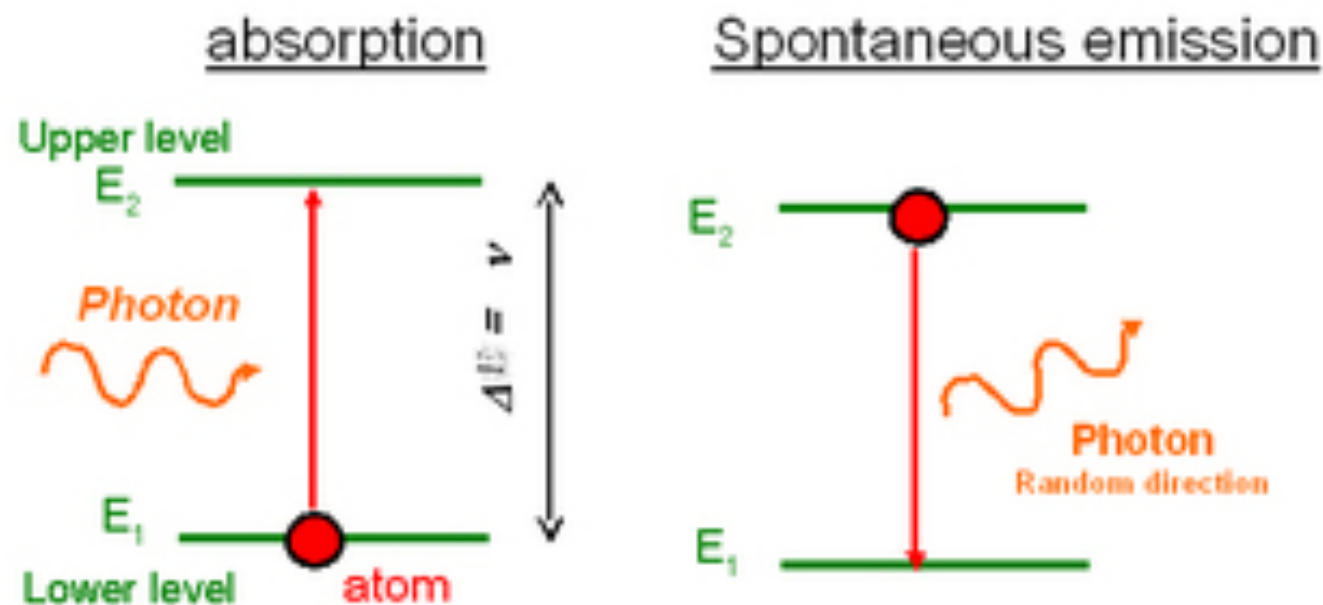
$$F_\nu \sim \nu^2 \kappa_\nu \sim \nu^{2+\beta} \sim \nu^\alpha$$

In practice:

- Dust opacity tables can be computed using Mie-theory: many tables available online
- Either integrated flux (entire disk) conversion to mass
OR
- Full radiative transfer: compute dust temperatures throughout the disk based on a stellar radiation field and dust density structure, and compute SED and images at various wavelengths and compare with data
- Flux density is function of frequency/wavelength: remember: superposition blackbodies and opacities
- Radiative transfer codes: e.g. RADMC, MCFOST, etc. (see Thursday hands-on)

How to observe

Line Local Thermodynamic Equilibrium (LTE): collisions lead to excitation and spontaneous emission photon



Find transitions + frequencies:
<http://www.splatalogue.net>

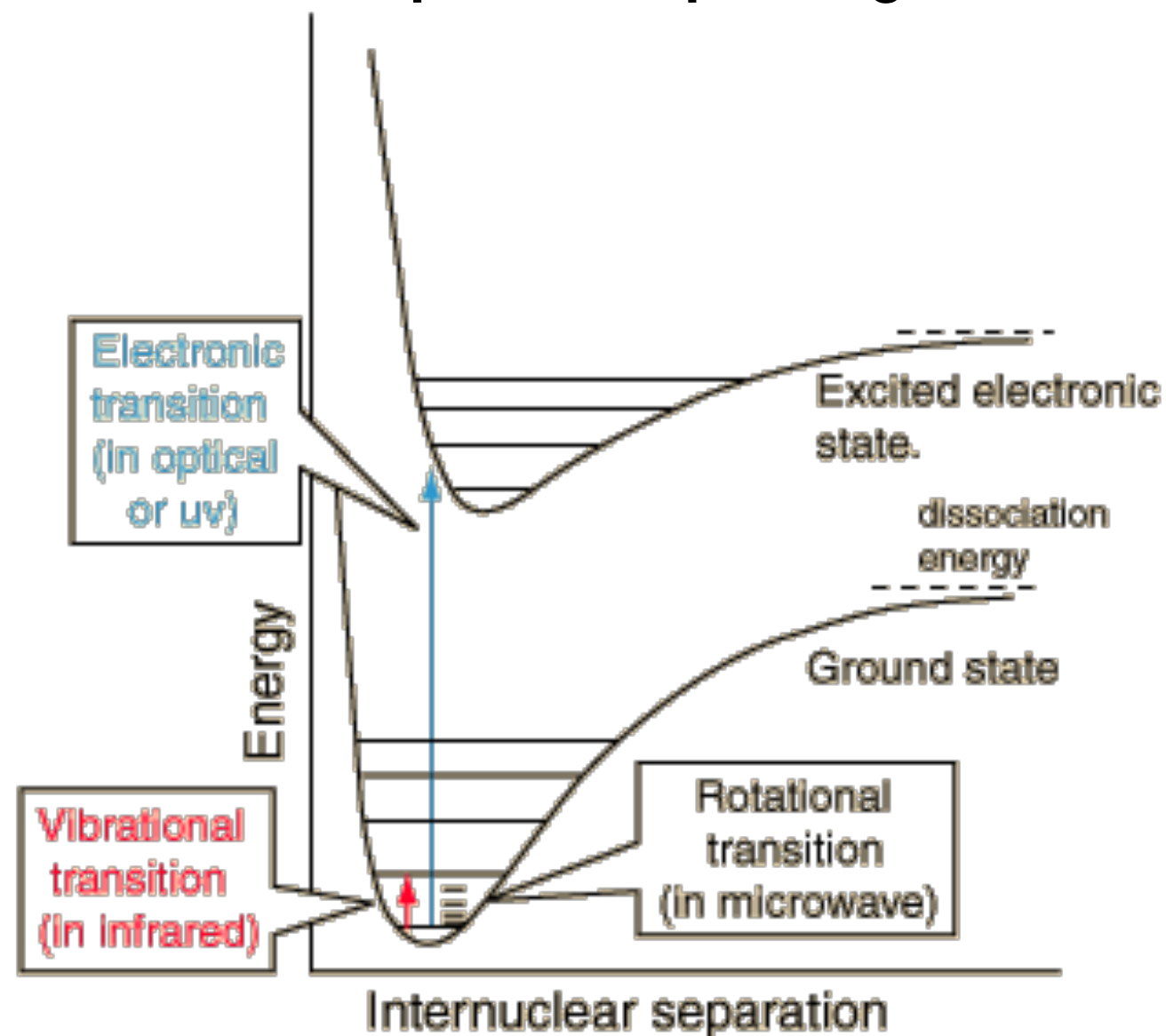
Different electronic states, defined by quantum numbers:

In rovibrational lines, e.g. $v=2-1$

In rotational lines, e.g. $J=3-2$

Fine structure, e.g. $F=5/2-3/2$

Some transitions are 'forbidden' (rare): brackets, e.g. [OI]



How to observe

Line Local Thermodynamic Equilibrium (LTE): collisions lead to excitation and spontaneous emission photon: Boltzmann distribution

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} \exp(-h\nu / kT_{ex}) = \frac{g_u}{g_l} \exp(-(E_u - E_l) / kT_{ex})$$

g = degeneracy of energy level

Calculate molecular column density using integrated line flux, assuming a temperature

$$N_u = \frac{N}{Q(T)} g_u e^{-E_u/kT}$$

$Q(T)$ = partition function

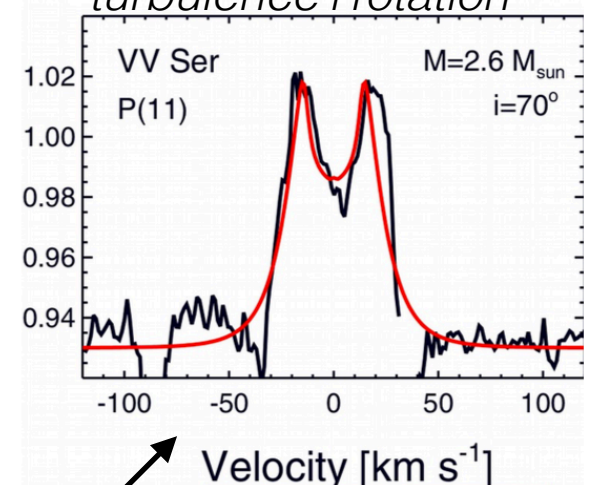
In practice, need to make additional assumptions about abundance throughout disk, and temperature/density gradients:

full physical-chemical models
disk structure

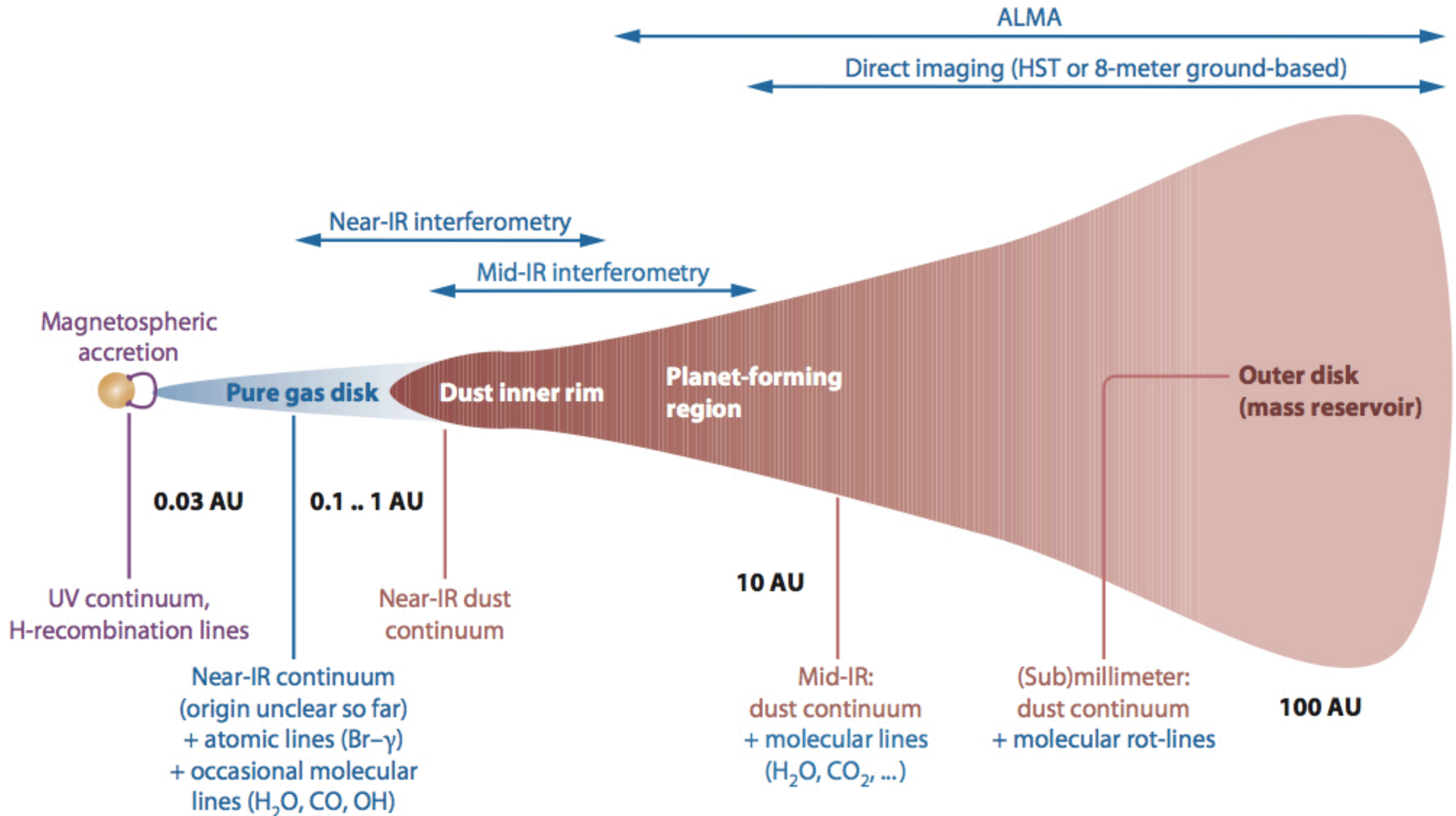
$$N_u = \frac{8\pi k\nu^2}{hc^3 A_{ul}} \int T_{mb} dv$$

A_{ul} = Einstein coefficient
(spontaneous emission rate)

Line broadened by
turbulence+rotation



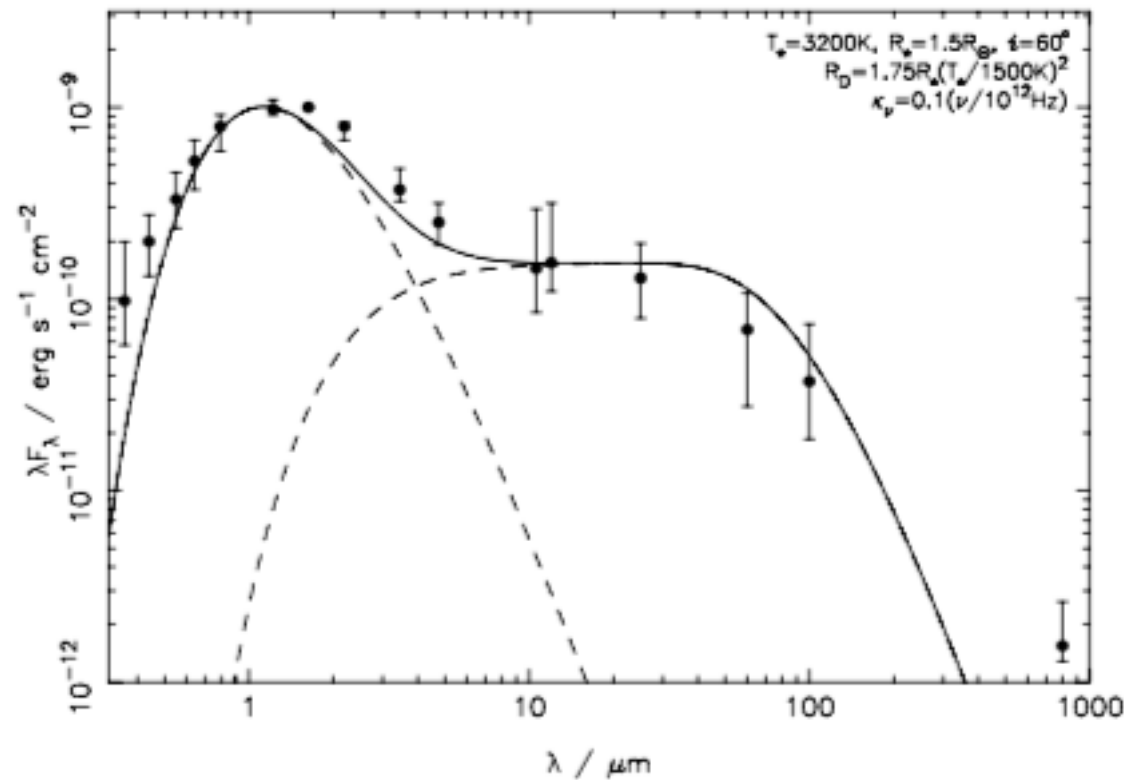
How to observe



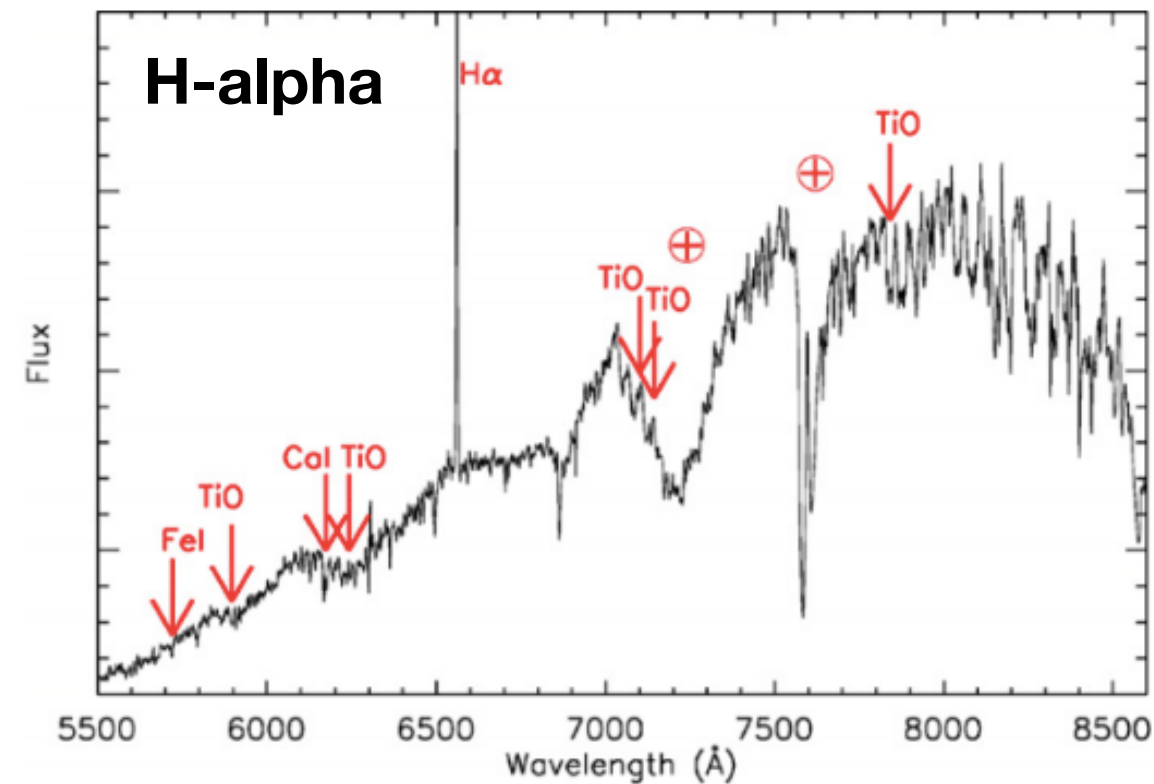
UV and optical

Accretion: matter from the inner disk edge is channeled along the magnetic field lines onto the star, resulting in shocked gas with $T \sim 10^4$ K, shown as UV excess and line emission (e.g. Balmer, Paschen).

UV excess:



Analysis spectra often together with spectral type



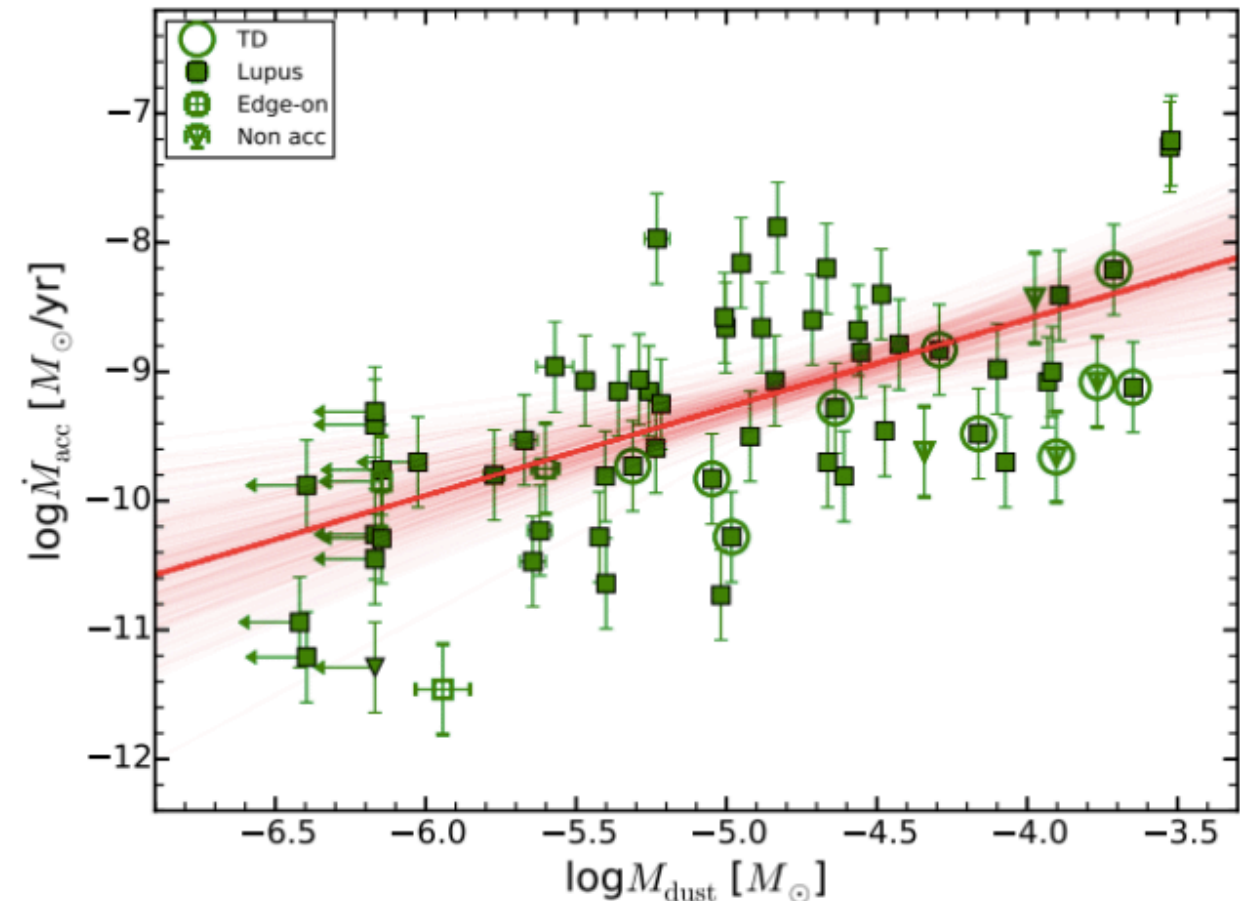
UV accretion luminosity L_{acc} can be converted to accretion rate $\dot{M}_{\text{acc}}$ ($M_\odot \text{yr}^{-1}$).

Careful: in several papers in 90s and 00s, the width of the H-alpha line (equivalent width, 10% width) is converted to $\dot{M}_{\text{acc}}$ as well. Don't trust these values as these lines also have contributions from disk winds and chromospheric activity. Proper analysis requires full spectra from UV to NIR (X-shooter)

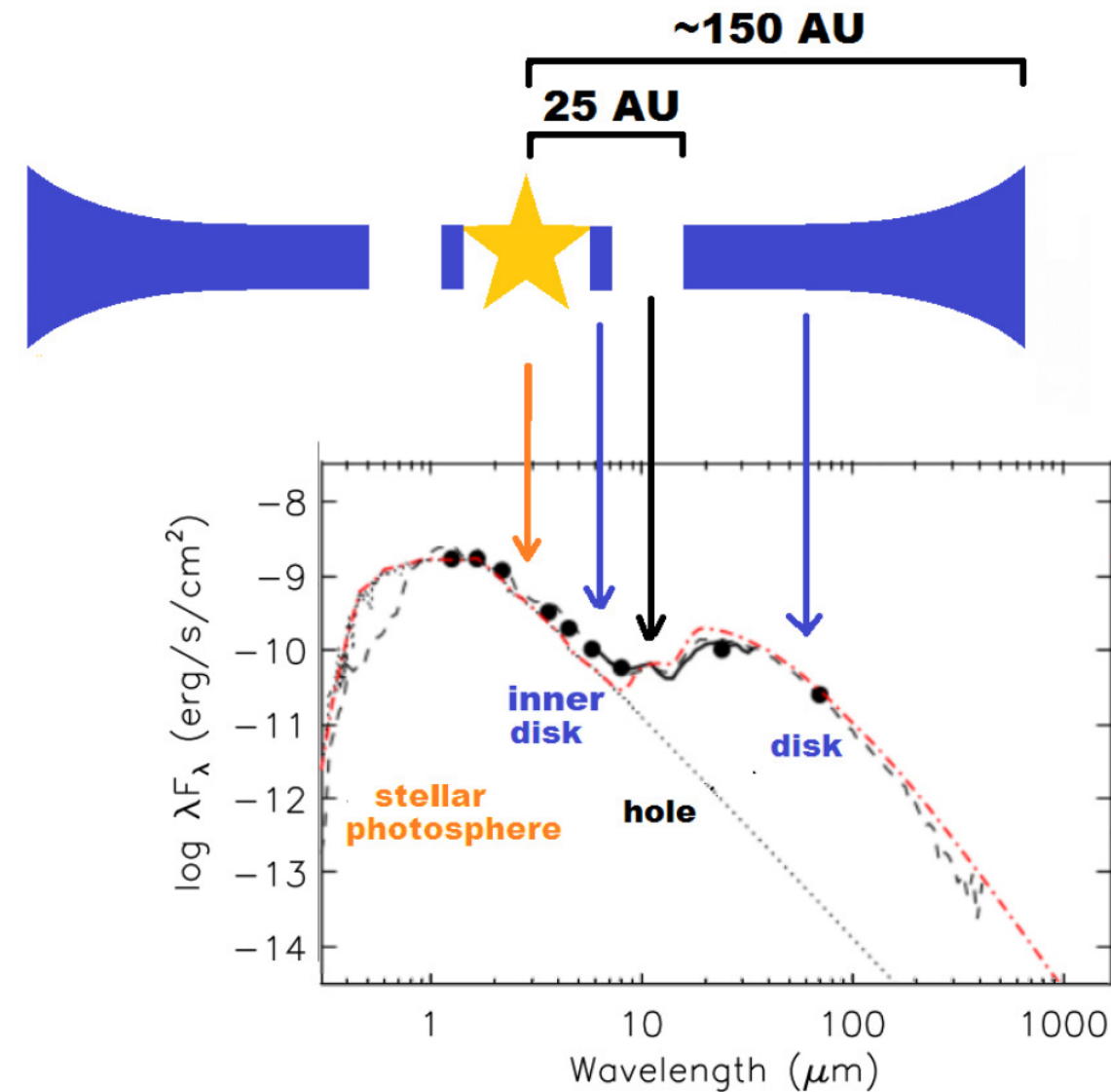
Alcala et al. 2014
Alexander et al. 2006

UV and optical

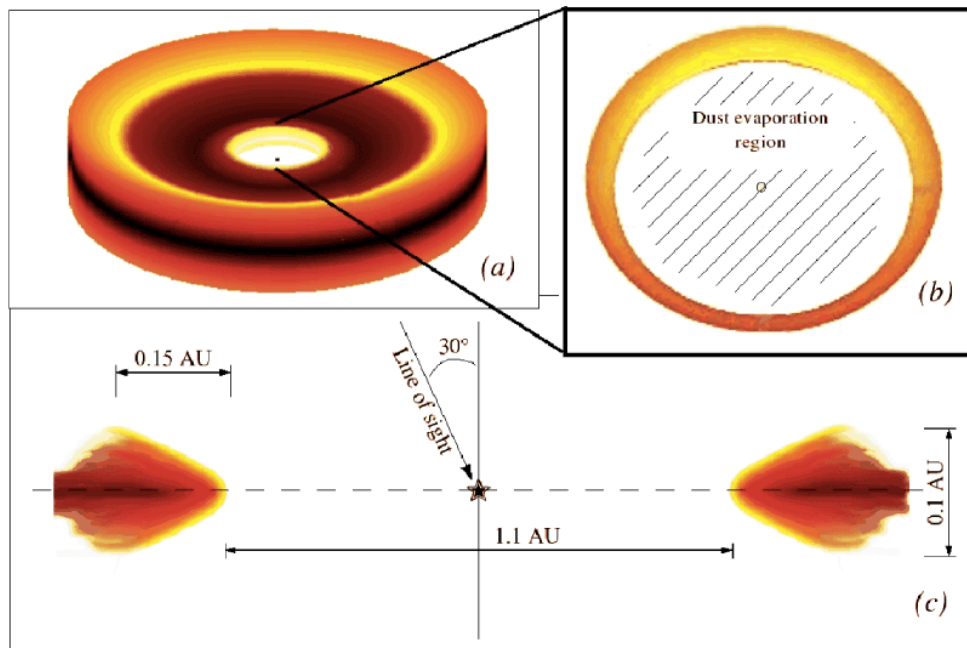
- Typical accretion rates: 10^{-7} to $10^{-11} M_{\odot} \text{ yr}^{-1}$ (detection limit)
- Correlation accretion rate $\sim$ disk mass: consistent with viscous disk model on $\sim$ few Myr time scales
- Terminology: Classical T Tauri Star (CTTS) vs Weak-line T Tauri Star (WTTS): threshold for line-width H-alpha for accreting vs non-accreting disks (but careful! No UV!). Correlation with Class II & Class III disks, respectively.



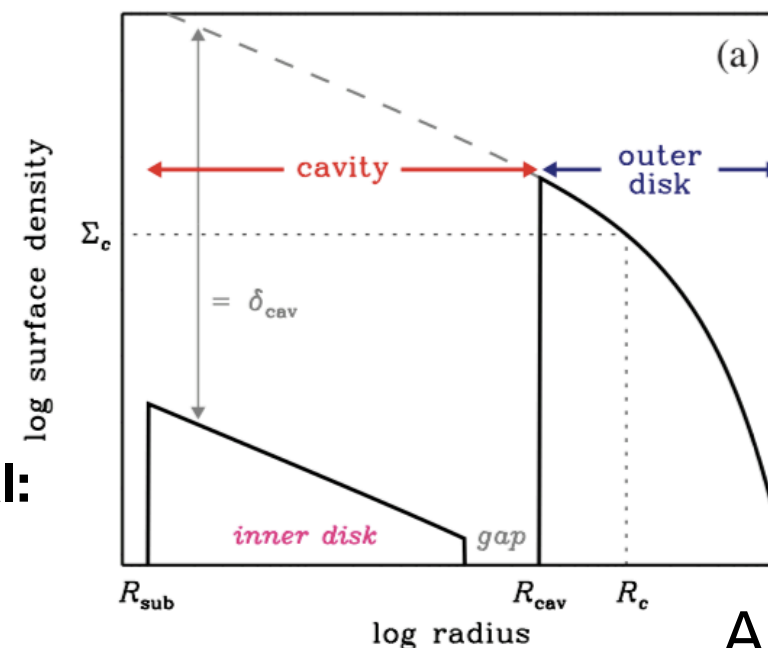
NIR



- NIR excess (in a transition disk) has been studied in detail in SEDs, by fitting a dust surface density profile with an inner disk
- Main limitation: size inner disk unconstrained, sensitive to inner edge
- Inner rim shape modeled physically in detail: smooth increase but puffed up (hydrostatic equilibrium)



Quantify amount of dust in inner disk: d_{cav}



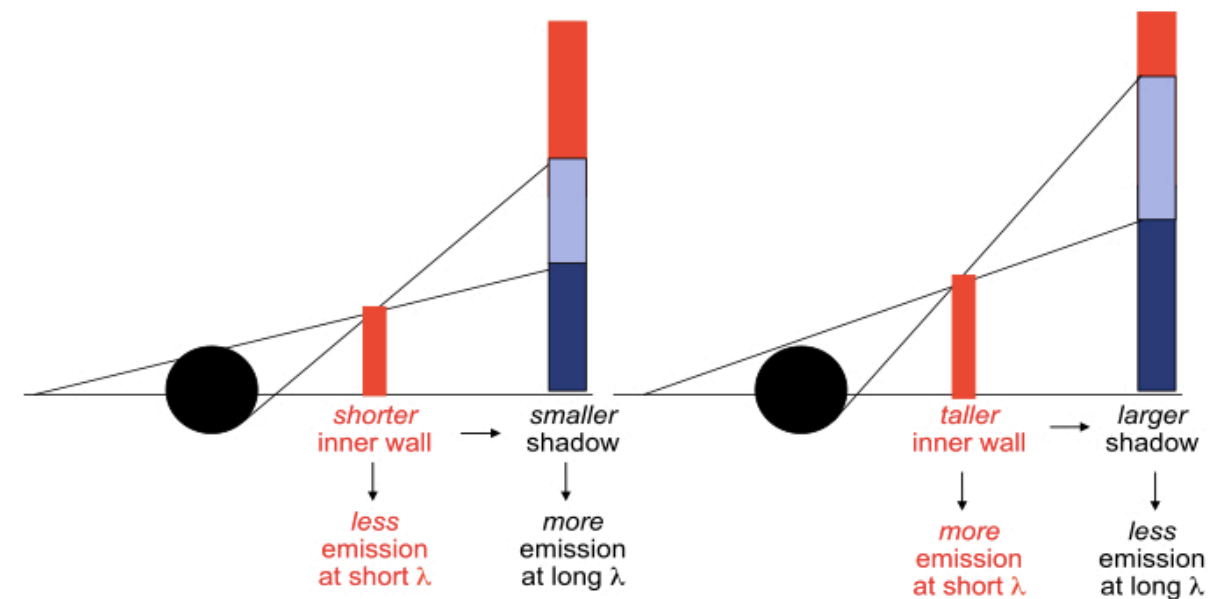
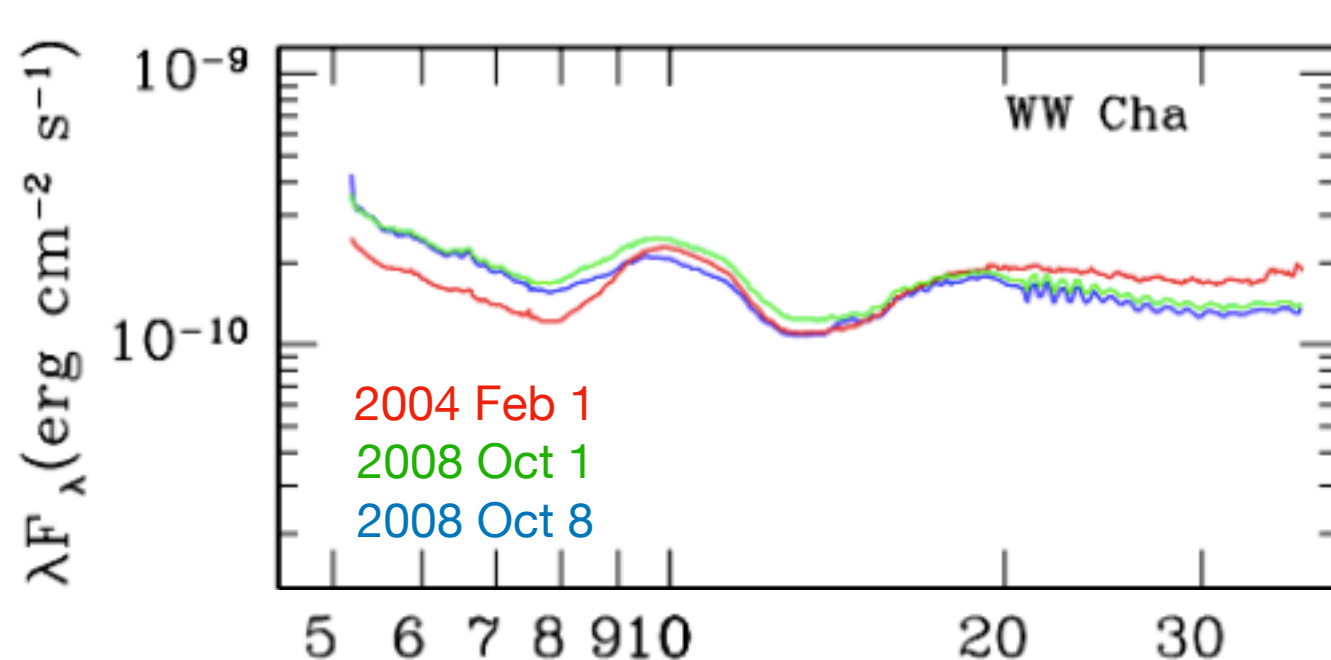
Isella et al. 2004

Andrews et al. 2011

Interest inner disk: accretion rate vs amount of material:
material flowing through gap? Dissipation timescale?
Inner disk radius (sublimation)?

NIR

**Seasaw variability: anti correlation NIR and MIR as function of time:
time scales of weeks and years! (limited data)**



- Explanation: varying shadowing of inner disk wall onto the outer disk wall, due to warping (misalignment of inner disk vs outer disk), perhaps caused by planets?
- Limitation: Spitzer-IRS spectra only taken in multiple epochs for handful of sources
- Need MIR telescope to measure this behaviour: after Spitzer (cold mission) was finished, no more follow-ups

NIR interferometry

- VLTi: infrared interferometry
- Four movable 1.8m telescopes next to 8.2m VLTs
- Instruments: PIONIER (H-band: $1.6\ \mu\text{m}$), GRAVITY (K-band: $2.2\ \mu\text{m}$) and recently: MATISSE (L, M, N-band: $3\text{--}5\ \mu\text{m}$)
- Optical/NIR (OIR) interferometry much more complex than radio, due to photon collection: not possible to amplify signal like in radio waves when splitting it over multiple baselines, so cannot build array of 66 OIR telescopes and limited to bright sources
- Spatial resolution is $\sim$ few milliarcseconds, but imaging not possible due to poor uv-coverage



The Four Auxiliary Telescopes at Paranal

ESO PR Photo 51c/06 (22 December 2006)

© ESO



NIR rovibrational lines

- Rovibrational CO lines (also H₂O, OH, HCN, ..):
excitation temperatures >1000 K
 - originating from inner few AU
 - excitation through a combination of collisional excitation, infrared pumping and UV fluorescence
 - for high spectral resolution (e.g. Keck/NIRSPEC: R~25 000 or 12.5 km/s, or VLT/CRIRES: R~95 000 or 3.2 km/s) lines are spectrally resolved => proxy for spatial location

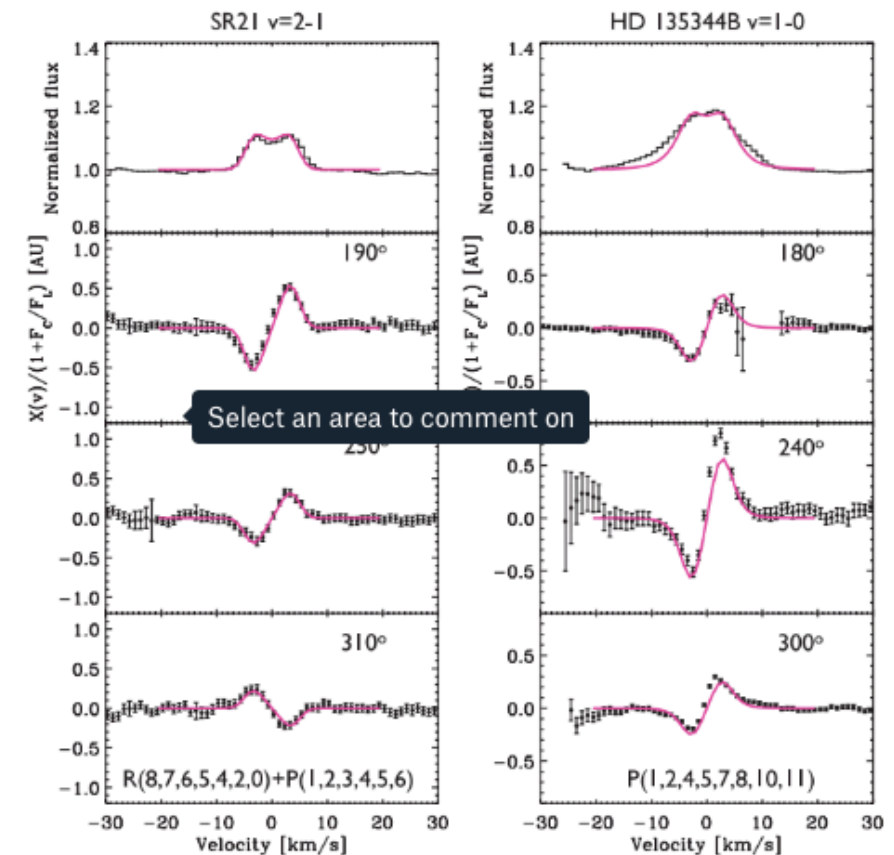
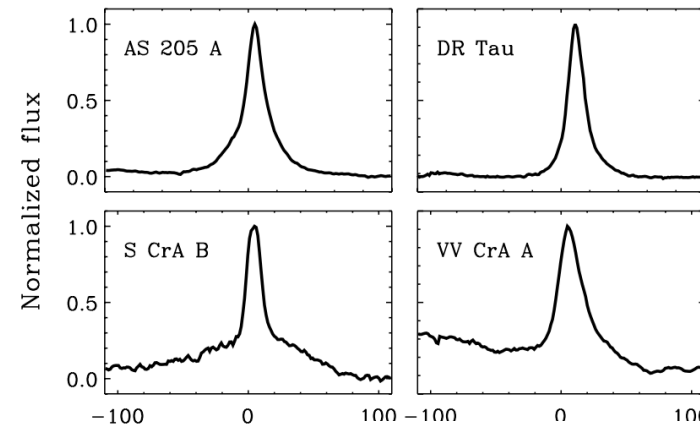
Salyk et al. 2009, 2011

Brown et al. 2012, 2013

Pontoppidan et al. 2008, 2011

NIR rovibrational lines

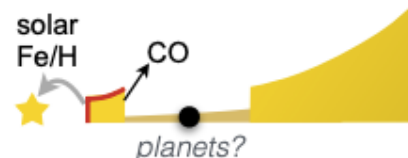
- Line profiles:
 - Many profiles single-peak rather than Keplerian: disk winds?
 - Spectroastrometry transition disks: measure line profile for different orientations across disk and use combination of position and velocity to measure inner radius CO: gas cavity radius < dust cavity radius
 - Keplerian: derive inner radius CO: difference with NIR continuum => relation to planet presence?



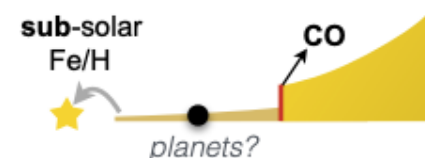
no/small cavities



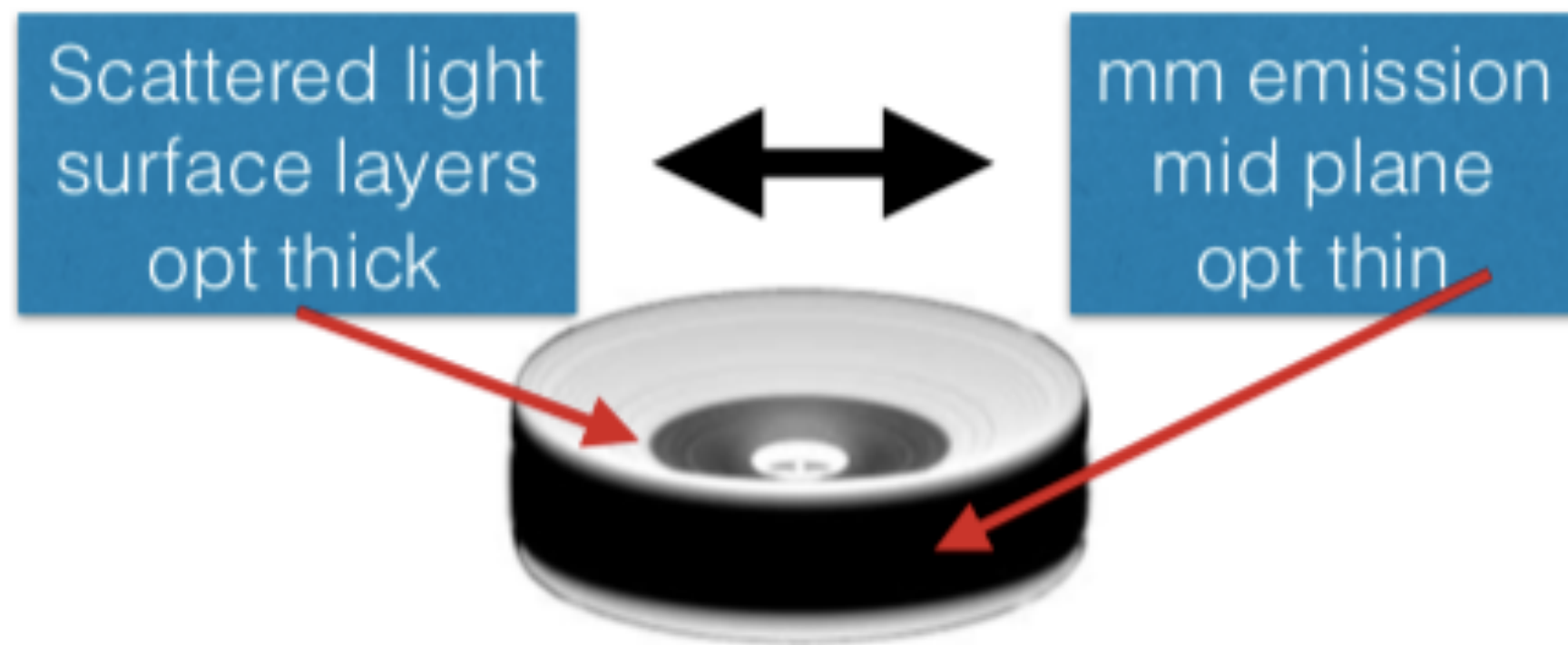
high-NIR cavities



low-NIR cavities

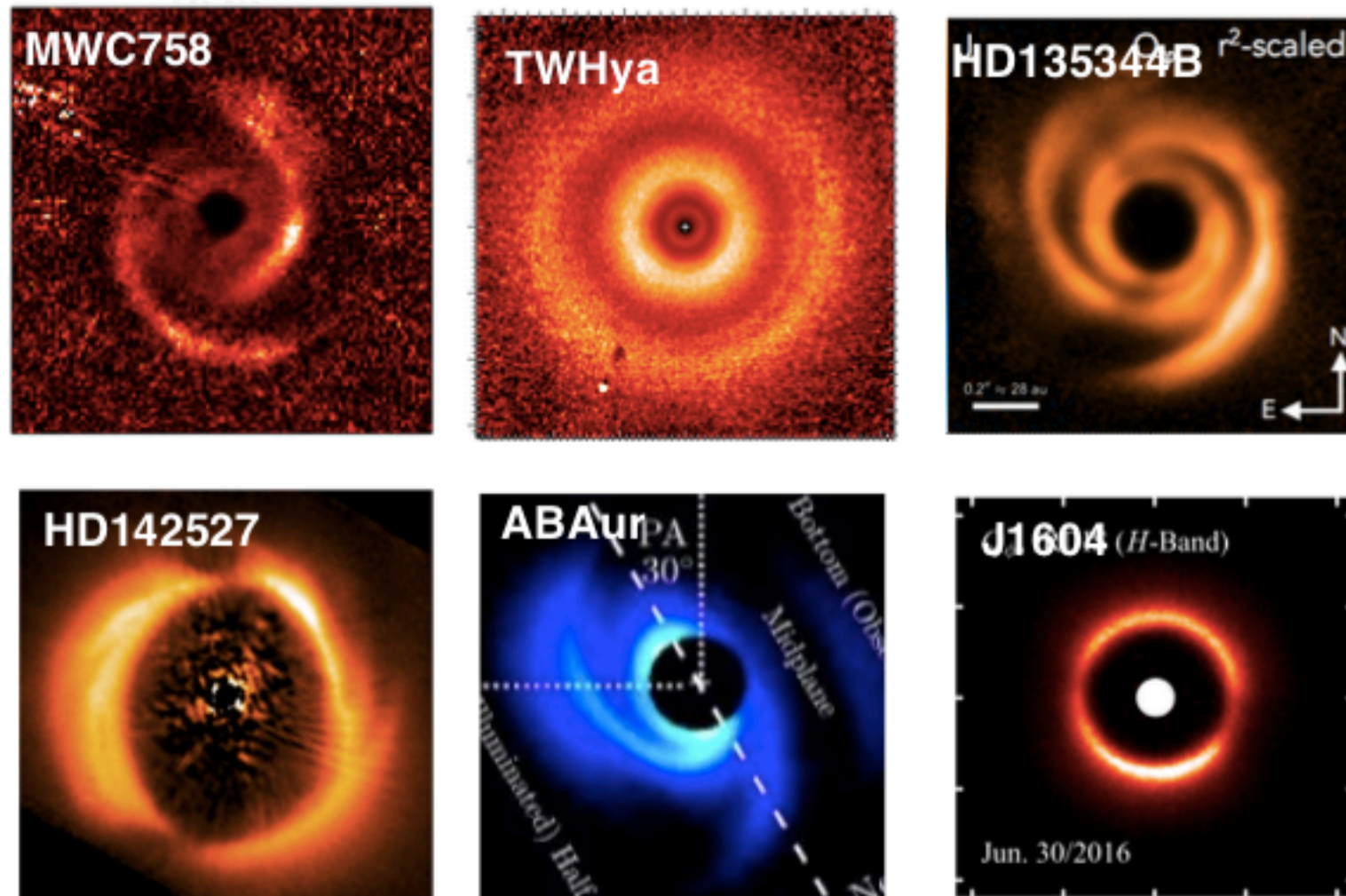


NIR: scattered light images



- **NIR images of scattered light:**
- Sensitive to surface layers only (scattered light or polarised light)
- Sensitive to small dust grains (λ -dependence dust opacity)
- Brightness drops quickly with radius: sensitive out to ~tens of au (not outer disk)
- High spatial resolution: need 8m-class telescope with AO system
- Depending on technique may need coronagraph to block star

NIR: scattered light images

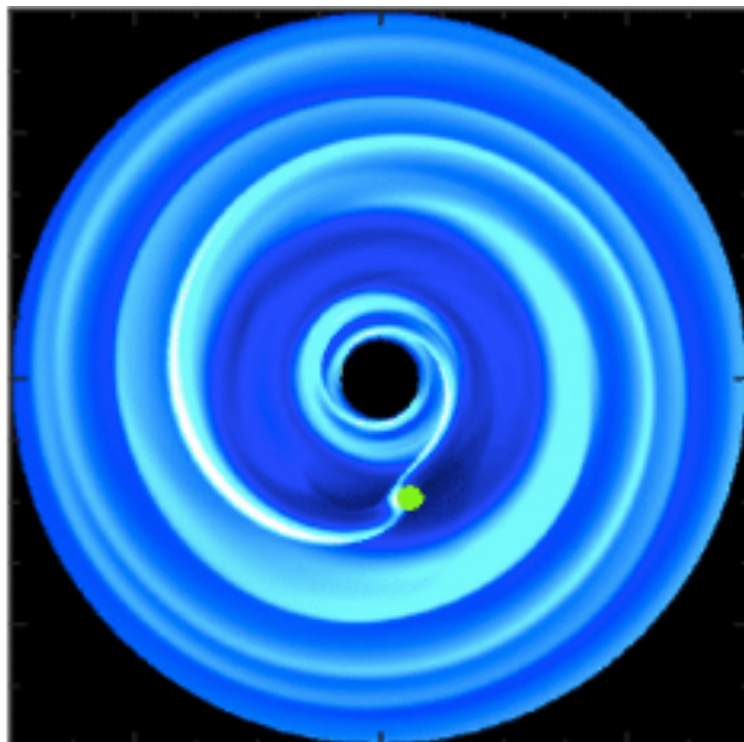


Large variety of structures: rings, gaps, spiral arms, asymmetries

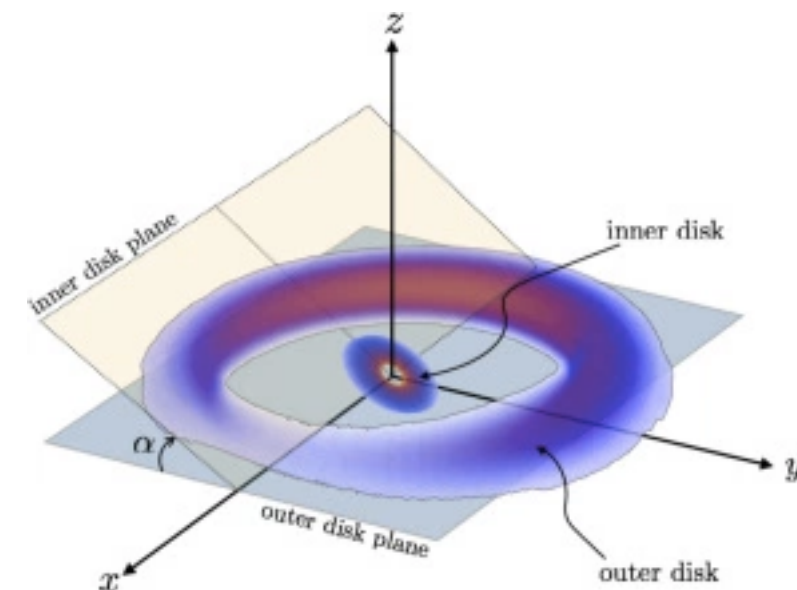
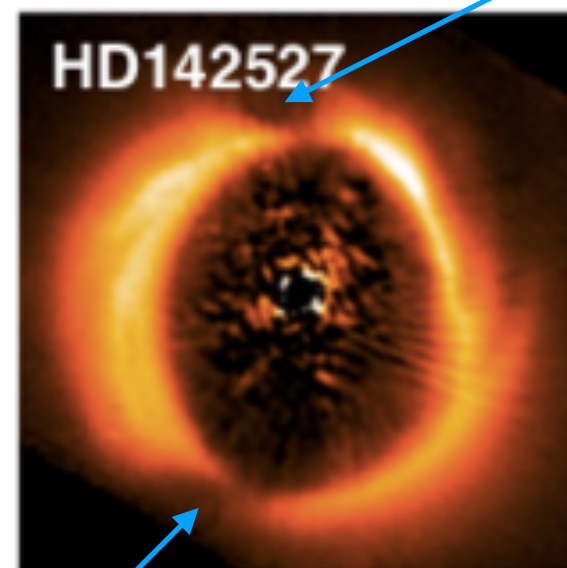
Credits: VLT/SPHERE and Subaru/HICIAO/ScEXAO

NIR scattered light images

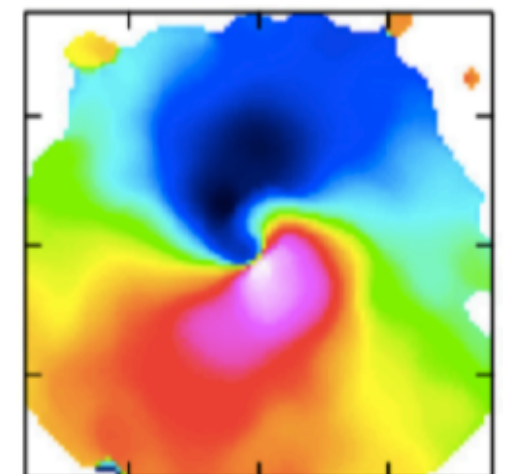
Spiral arms: density waves due to planets?



Shadows: misaligned inner disk (warp) due to companion?



Also seen in velocity profile:



Usually not visible in mm (ALMA): scale-height variations?

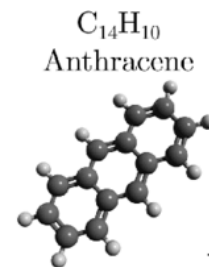
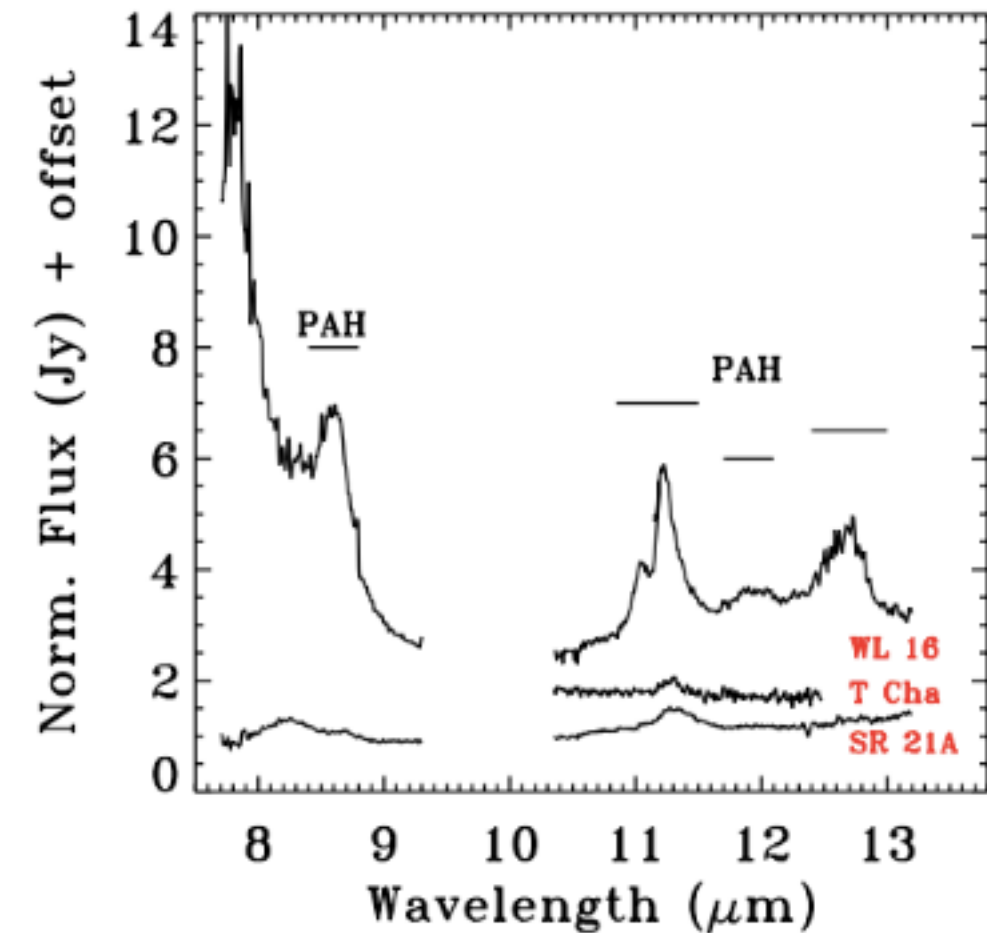
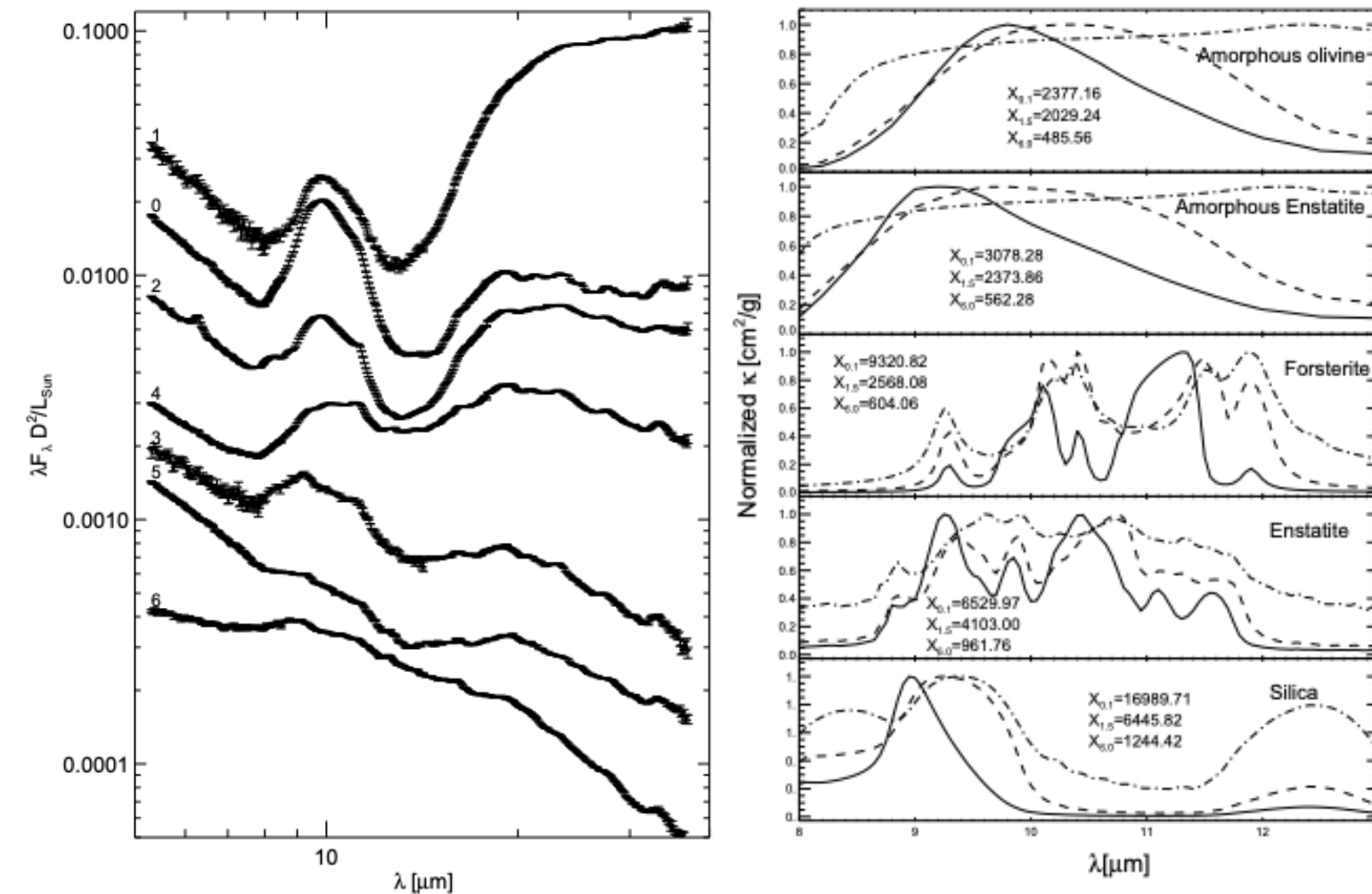
DSHARP spirals: gravitational instability?

Warps are pretty common in disks!

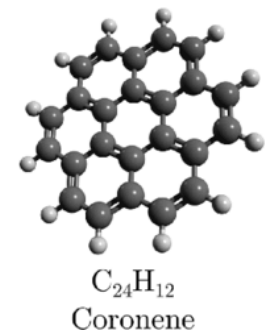
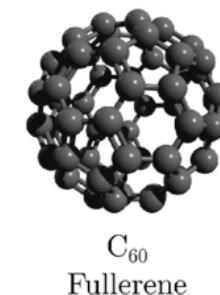
MIR and FIR

MIR continuum spectra (Spitzer IRS):

=> many broad features, originating from different dust species (silicate, olivine, forsterite, etc.) and Poly Aromatic Hydrocarbons (PAHs)

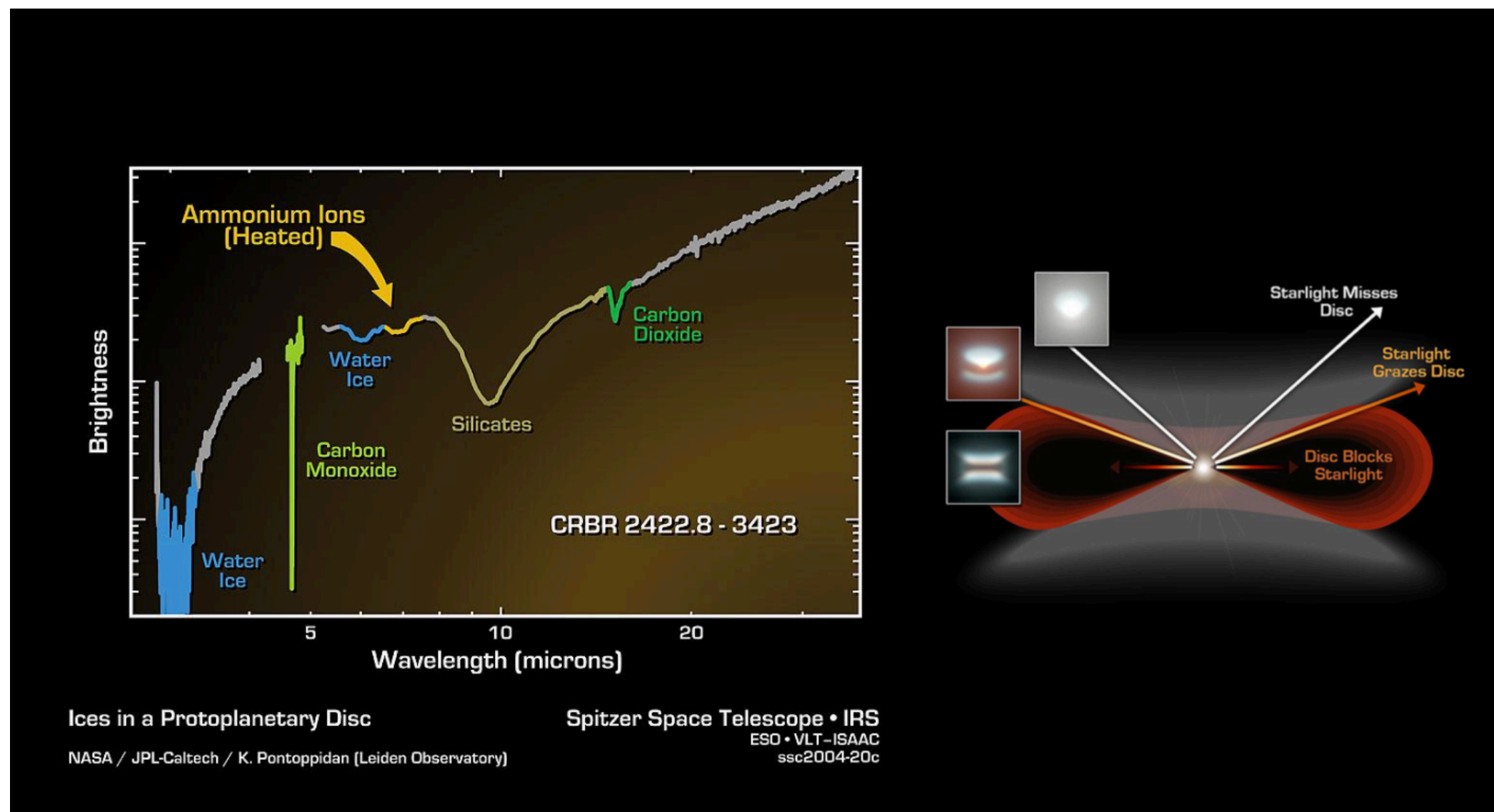


PAHs



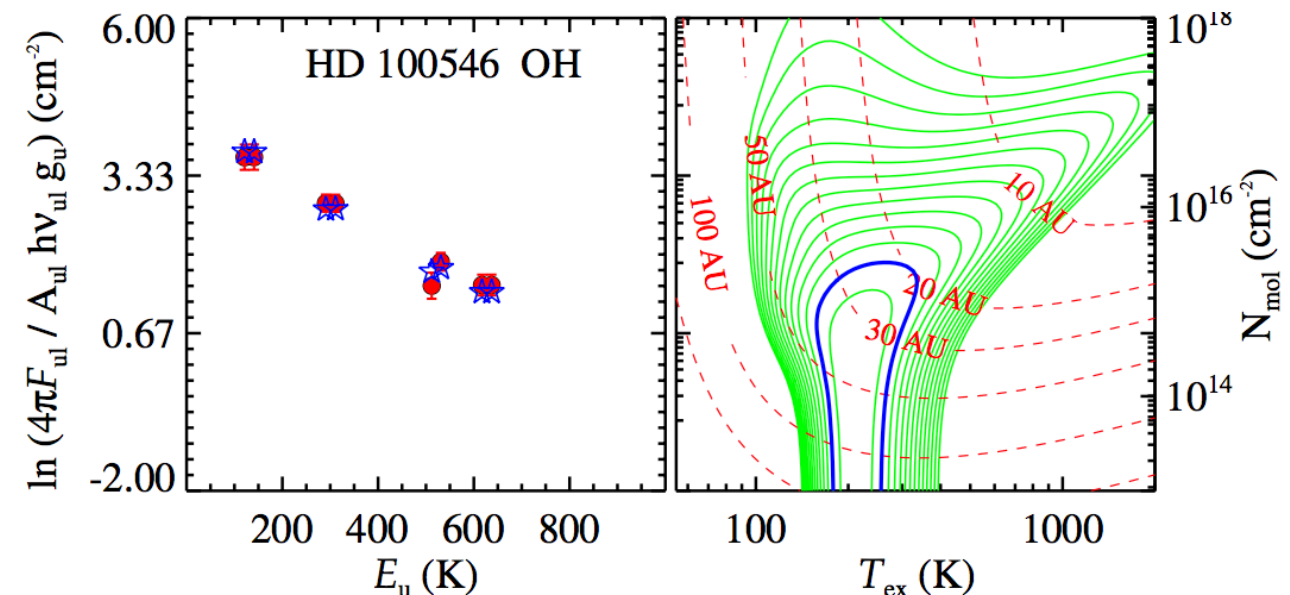
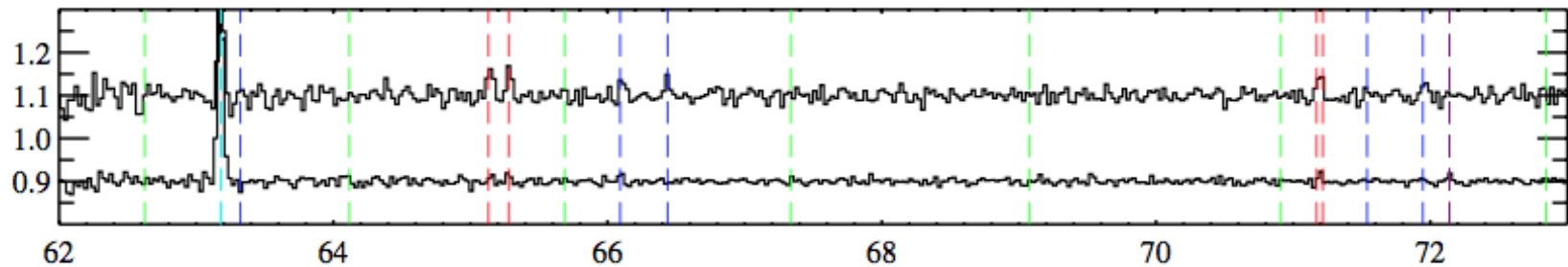
MIR and FIR

- Edge-on disks: ices => IR absorption



MIR and FIR

- **Herschel:** Far infrared lines: disk atmosphere
 - CO ladder (J transitions >15)
 - [OI]: 63, 145 μm
 - [CI]: 370, 810 μm
 - [CII]: 158 μm
 - H₂O: e.g. 179, 78 μm
- Approach: estimating excitation temperature (few 100 K), number of molecules using simple models => origin of the lines
- Disk Herschel surveys: GASPS (GAS in Protoplanetary Systems), DIGIT (Dust, Ice Gas In Time)



Reminder:
$$N_u = \frac{N}{Q(T)} g_u e^{-E_u/kT}$$

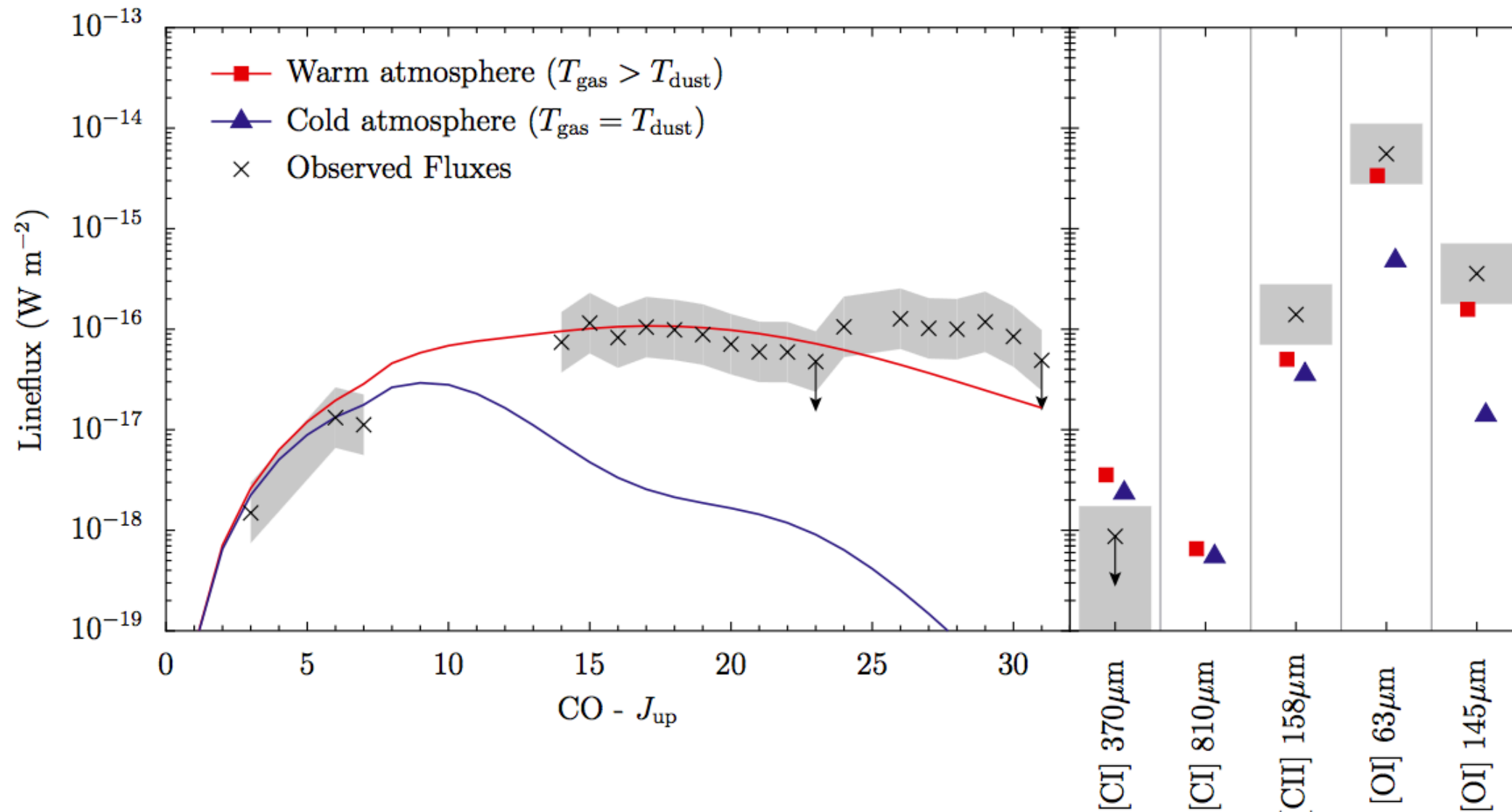
$$\underbrace{\ln\left(\frac{N_u}{g_u}\right)}_y = \underbrace{-\frac{1}{T}}_a \underbrace{E_u[\text{K}]}_x + \underbrace{\ln\left(\frac{N}{Q(T)}\right)}_b$$

Linear relation:
Rotational diagram

Meeus et al. 2010,2012
Fedele et al. 2013

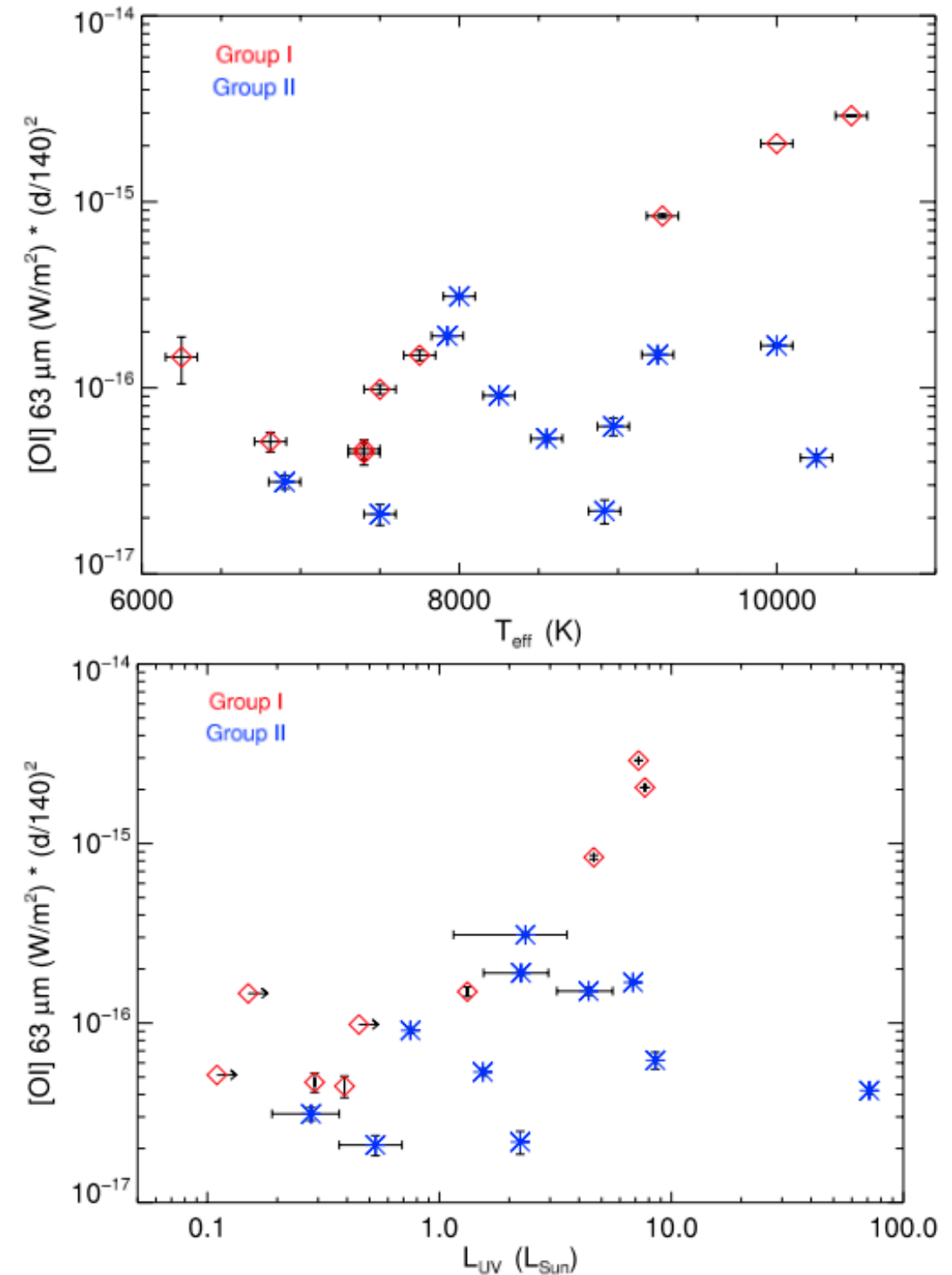
MIR and FIR

- CO ladder using Herschel data:
Full disk model of HD100546



MIR and FIR

- Search for correlations between different lines and disk properties
- General conclusion: large variety of line strengths throughout sources, unclear origin



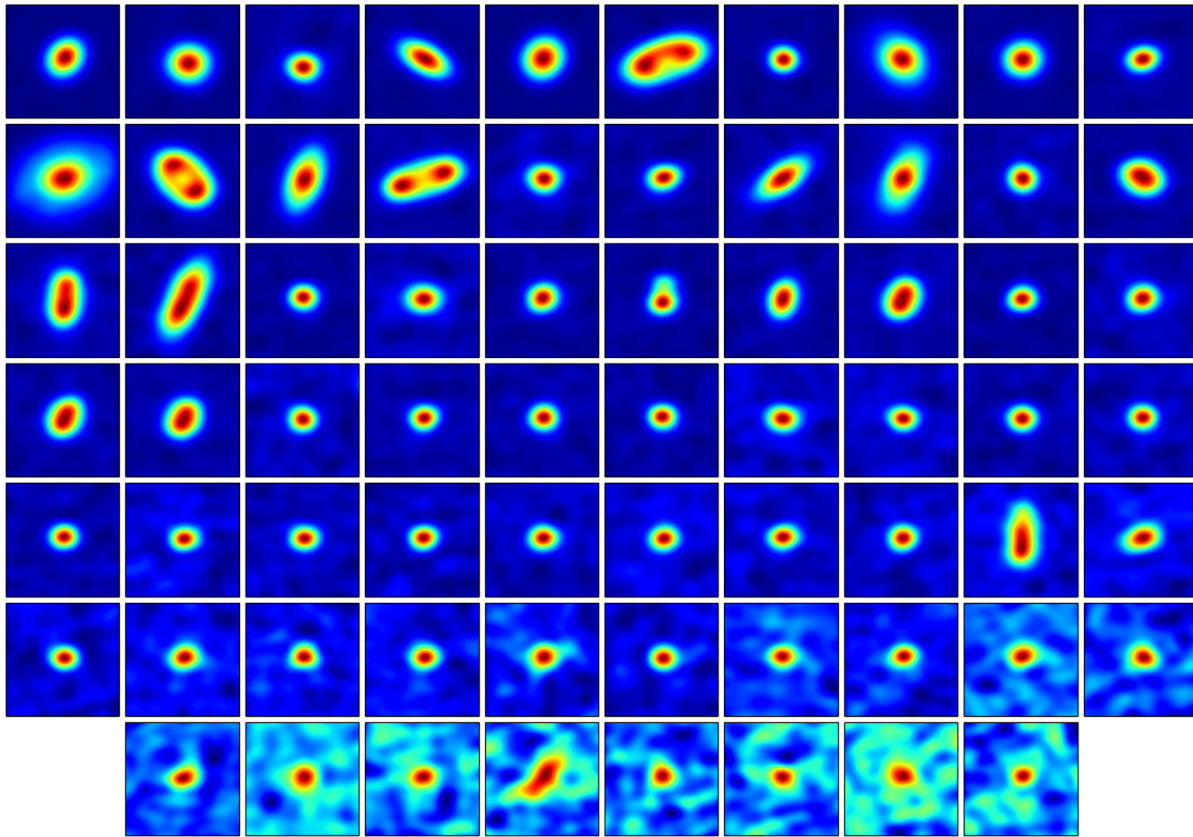
(Sub)millimeter

- Range: $\sim 350 \mu\text{m} - 3 \text{ mm}$ or $100 - 750 \text{ GHz}$ (radio instrumentation!)
- Optically thin wavelengths: trace full disk mass!
- Single dish observations tricky:
due to resolution $\sim \lambda/D$, even for 30m telescope:
res $\sim 15''$ (confusion with surroundings!)
- Most reliable disk observations use millimetre interferometry: SMA, PdBI, CARMA and ALMA (not necessarily resolved)
to measure integrated disk fluxes, both continuum and molecular lines
- Disk dust mass: $F_\nu = \frac{B_\nu(T)\kappa_\nu M_{\text{dust}}}{d^2}$
+ assumption
on gas-to-dust-ratio=100 (ISM):
=> total disk mass

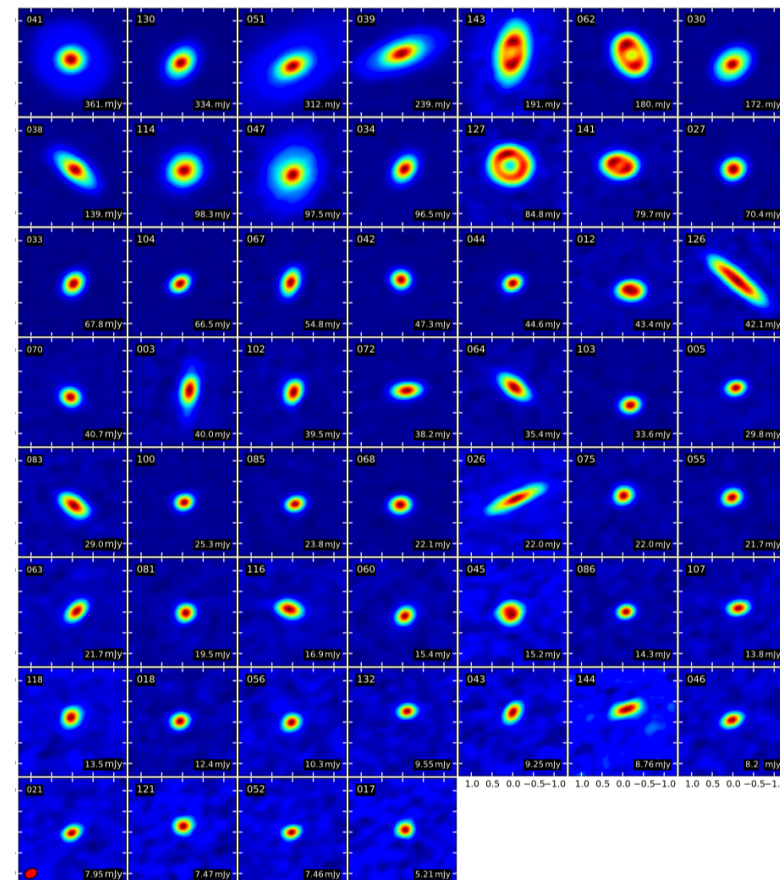
(Sub)millimeter

Low-resolution disk snapshot surveys with ALMA at $\sim 0.8\text{--}1.3\text{mm}$:
continuum + CO isotopologues (^{12}CO , ^{13}CO , C^{18}O) integrated fluxes
and derive dust and gas masses

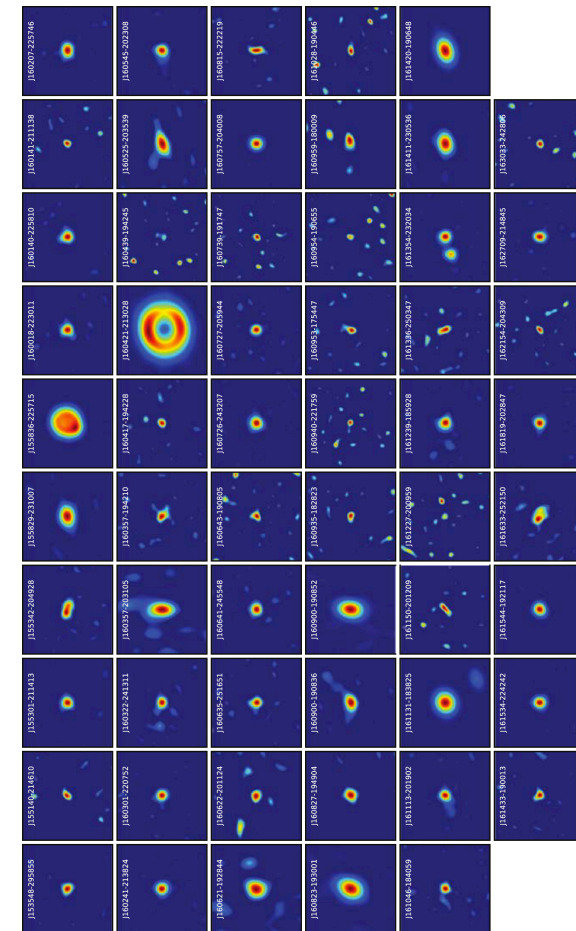
Lupus



Ophiuchus



Upper Sco

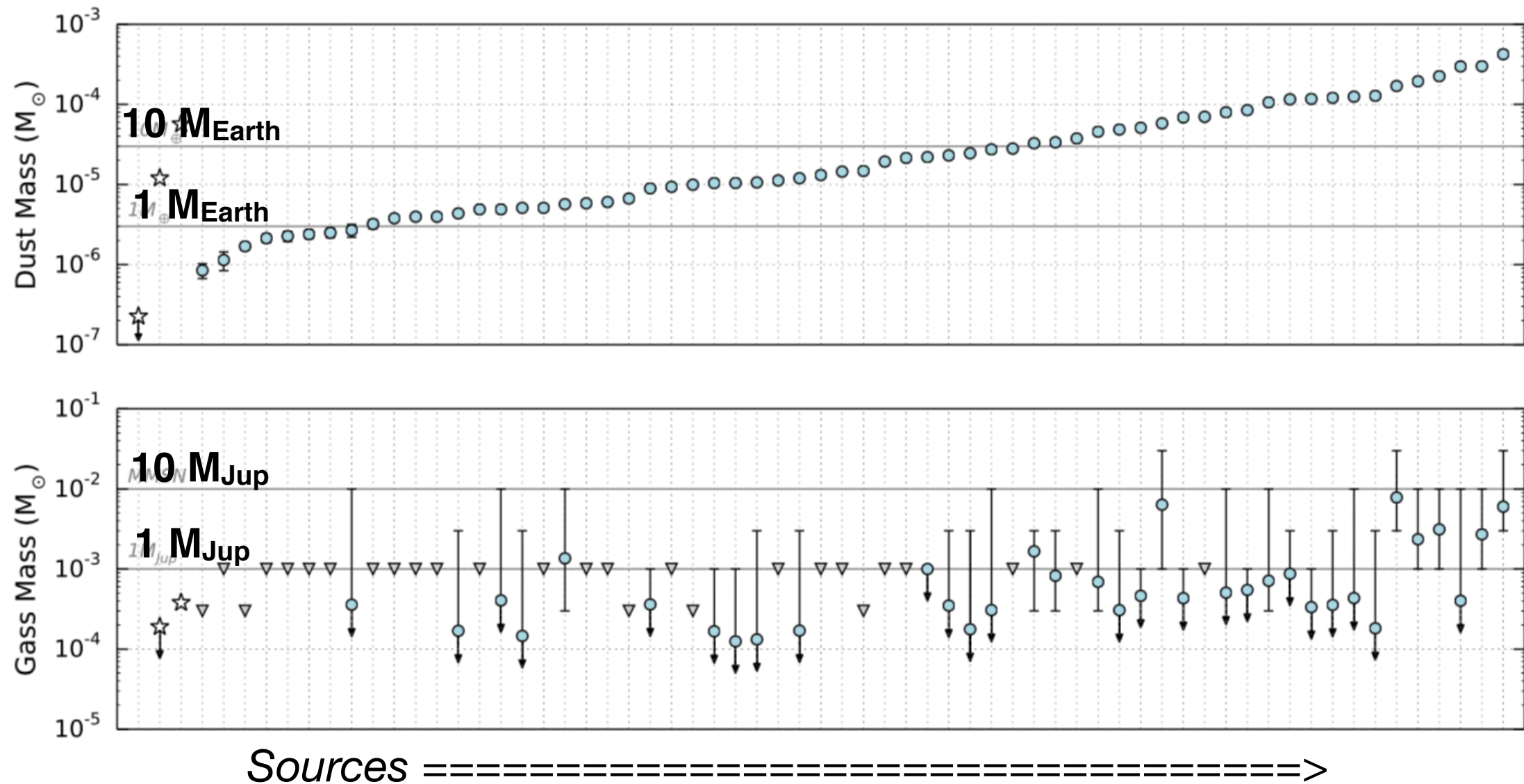


Survey: all Class II disks within a star forming
region for statistical study of disk properties

Ansdell et al. 2016
Cieza et al. 2018
Barenfeld et al. 2016

(Sub)millimeter

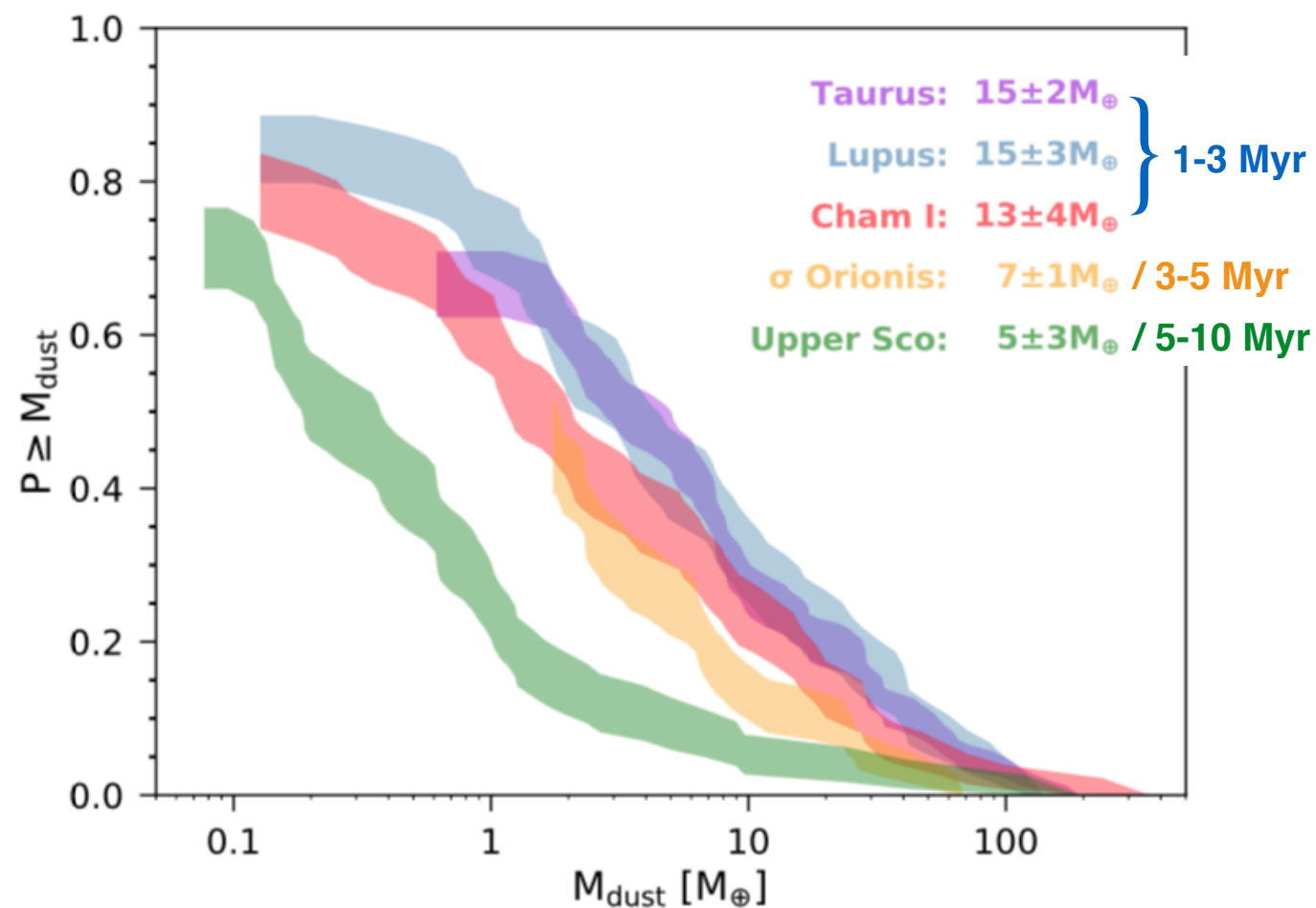
Disk masses in Lupus disk survey (2 Myr old region)



- Majority of disks has $<10 M_{\text{Earth}}$ of dust and $<1 M_{\text{Jup}}$ gas left: planet formation finished?
- Gas-to-dust ratio is more like 1-10: lower than ISM $\Rightarrow$ gas-poor disks $\Rightarrow$ disk dissipation?
- At least half of the disks unresolved: <25 au radius (much smaller than 100 au!!)

(Sub)millimeter

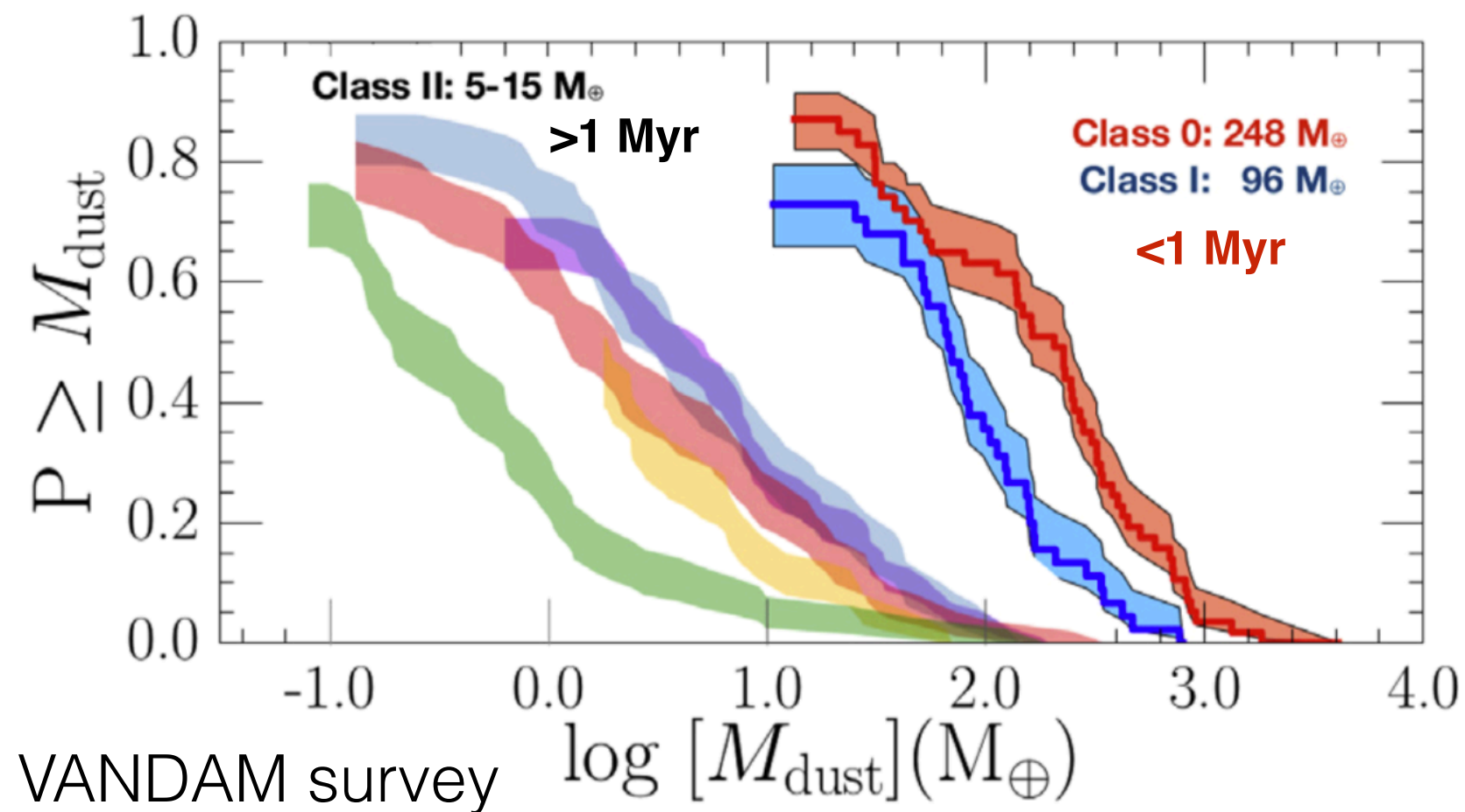
Compare disk dust masses in different clusters with ages



Dust mass declines with age!

(Sub)millimeter

Embedded disks much more massive

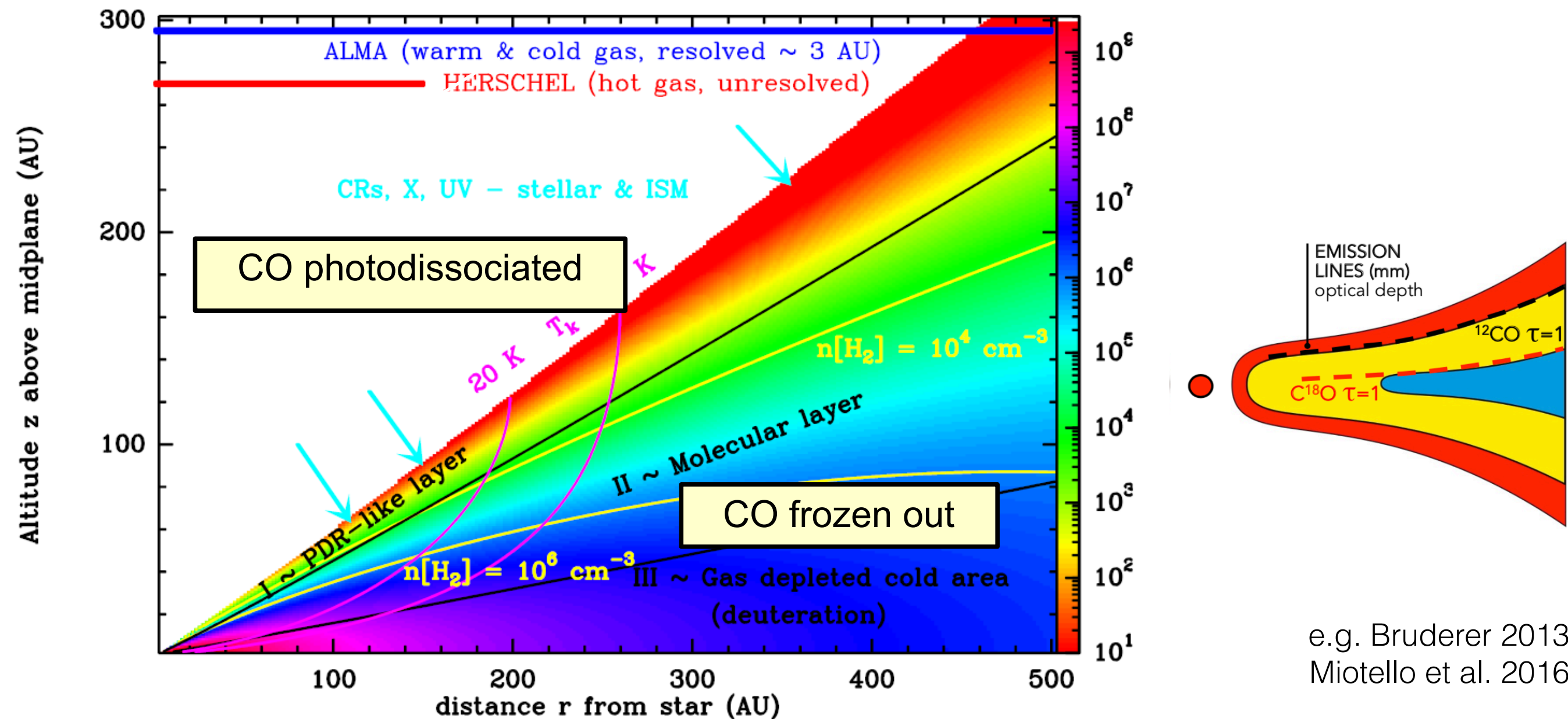


Does planet formation start in embedded stage?

(Sub)millimeter

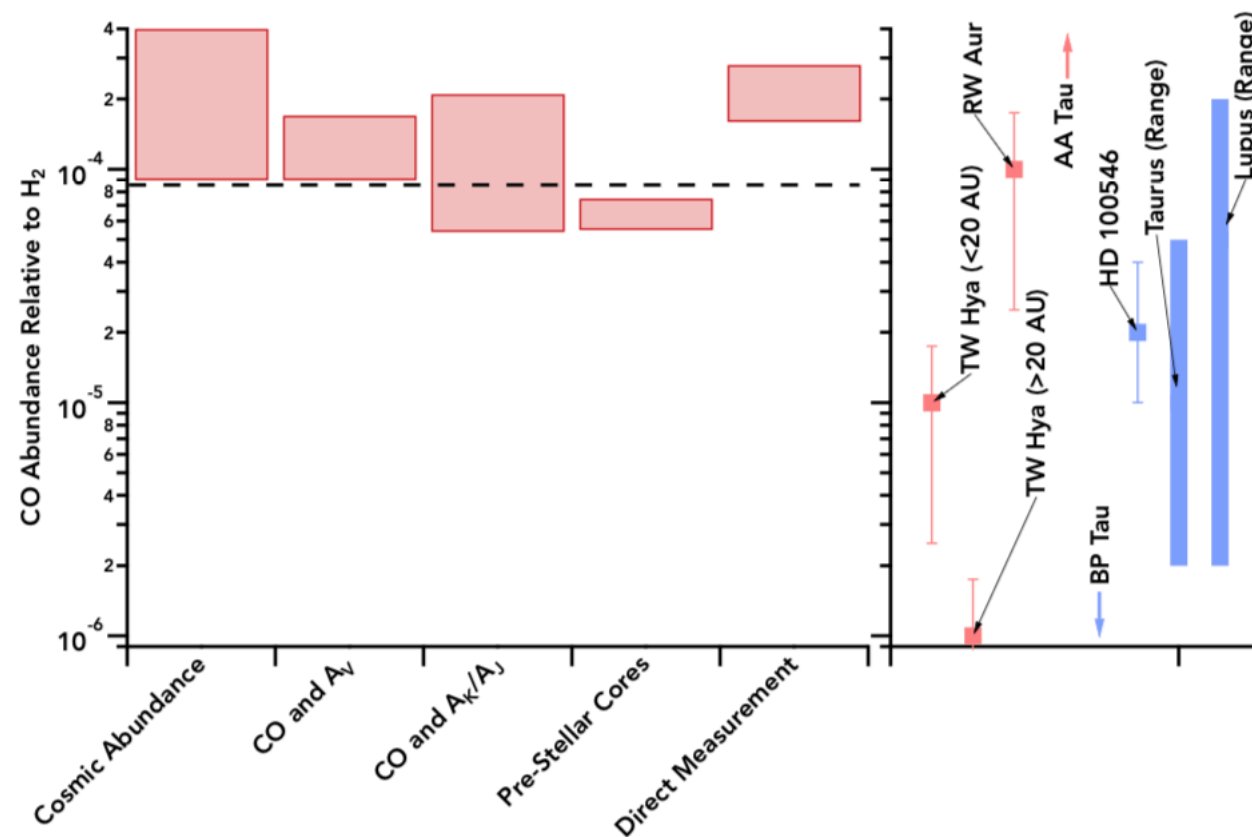
Using CO isotopologues to derive gas mass:

Take into account dissociation, freeze-out, chemistry, temperature, optical depth

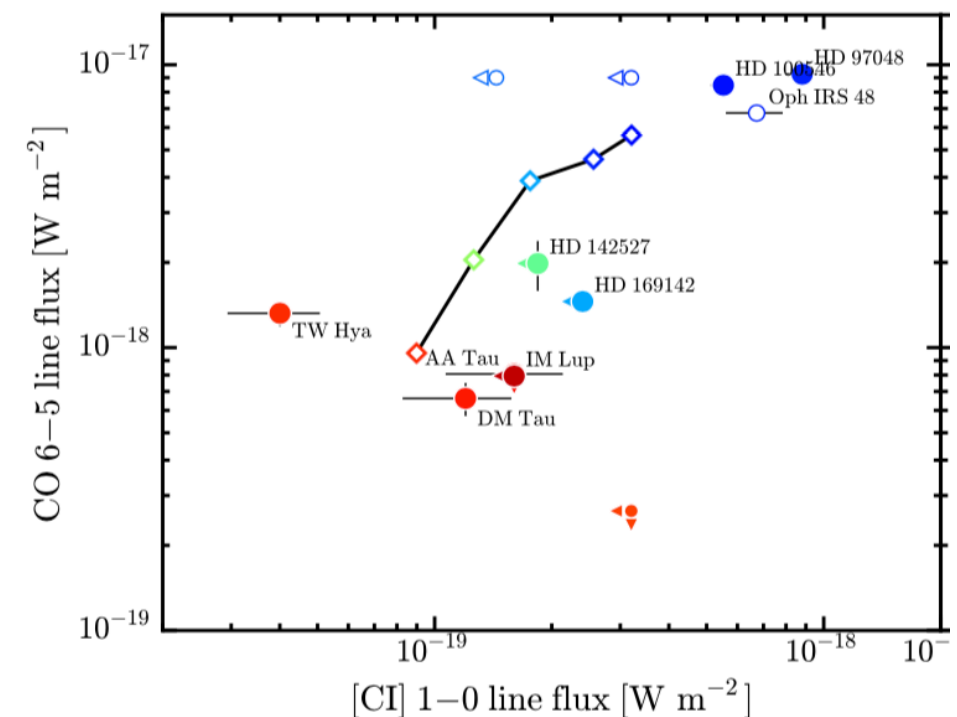


=> need physical-chemical models to quantify CO: e.g. DALI, ProDiMo

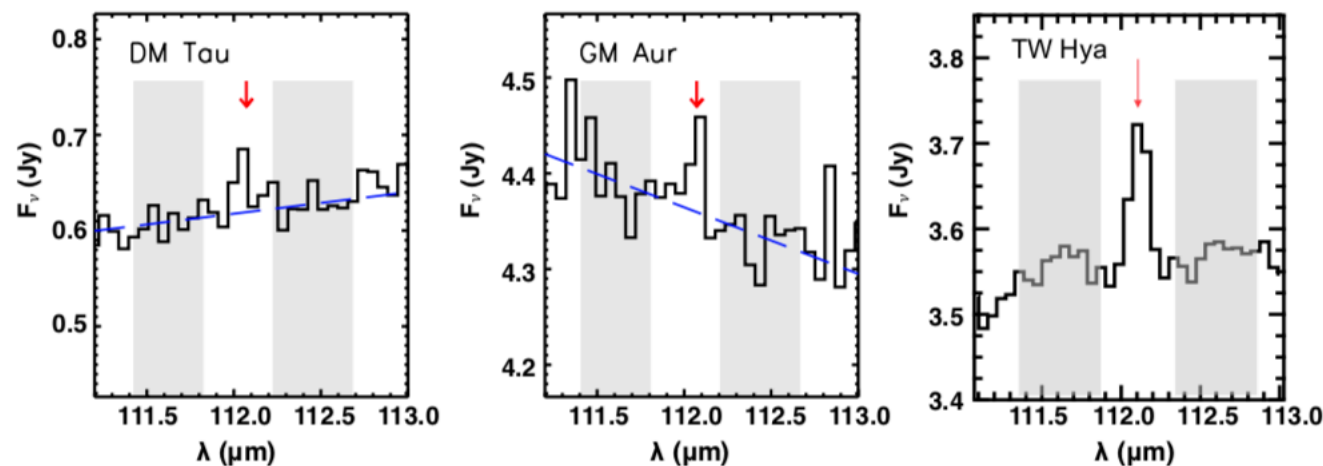
(Sub)millimeter vs IR



CI and CII observations suggest either carbon-depletion or gas-poor disks



FIR HD observations suggest CO/H₂ << 10⁻⁴



**Is some carbon locked up (either in grains or COMs)?
Can we really use CO as mass tracer?**

Bergin & Williams 2017
McClure et al. 2016
Kama et al. 2016

(Sub)millimeter

Chemistry: complex molecules => building blocks of life?

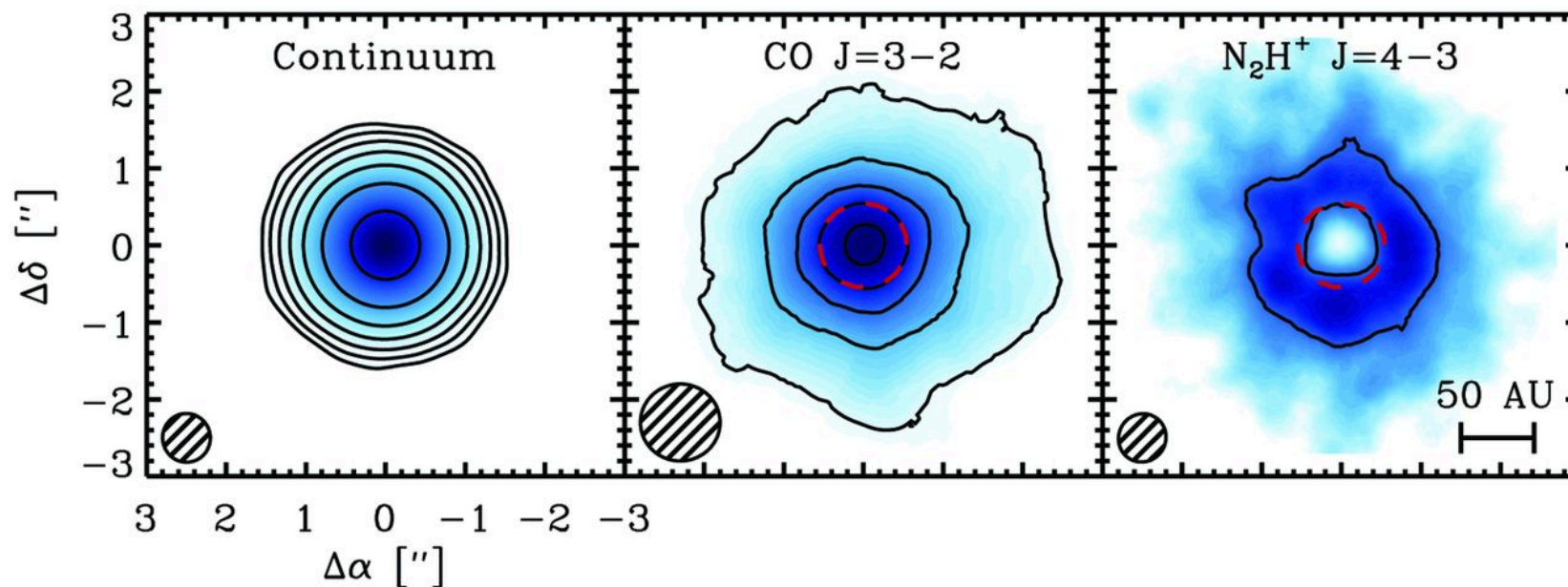
Complex organic molecules in disks so far: H_2CO (formaldehyde), CH_3OH (methanol), CH_3CN (acetonitrile), CH_3OCHO (methyl formate), etc.
(hard to localize/quantify)

Oberg et al. 2011, 2015

Walsh et al. 2014, 2016

Lee et al. 2019

CO snowline through N_2H^+ ?



Chemistry: N_2H^+ can only form efficiently when CO is frozen out
=> cloud tracer snowlike

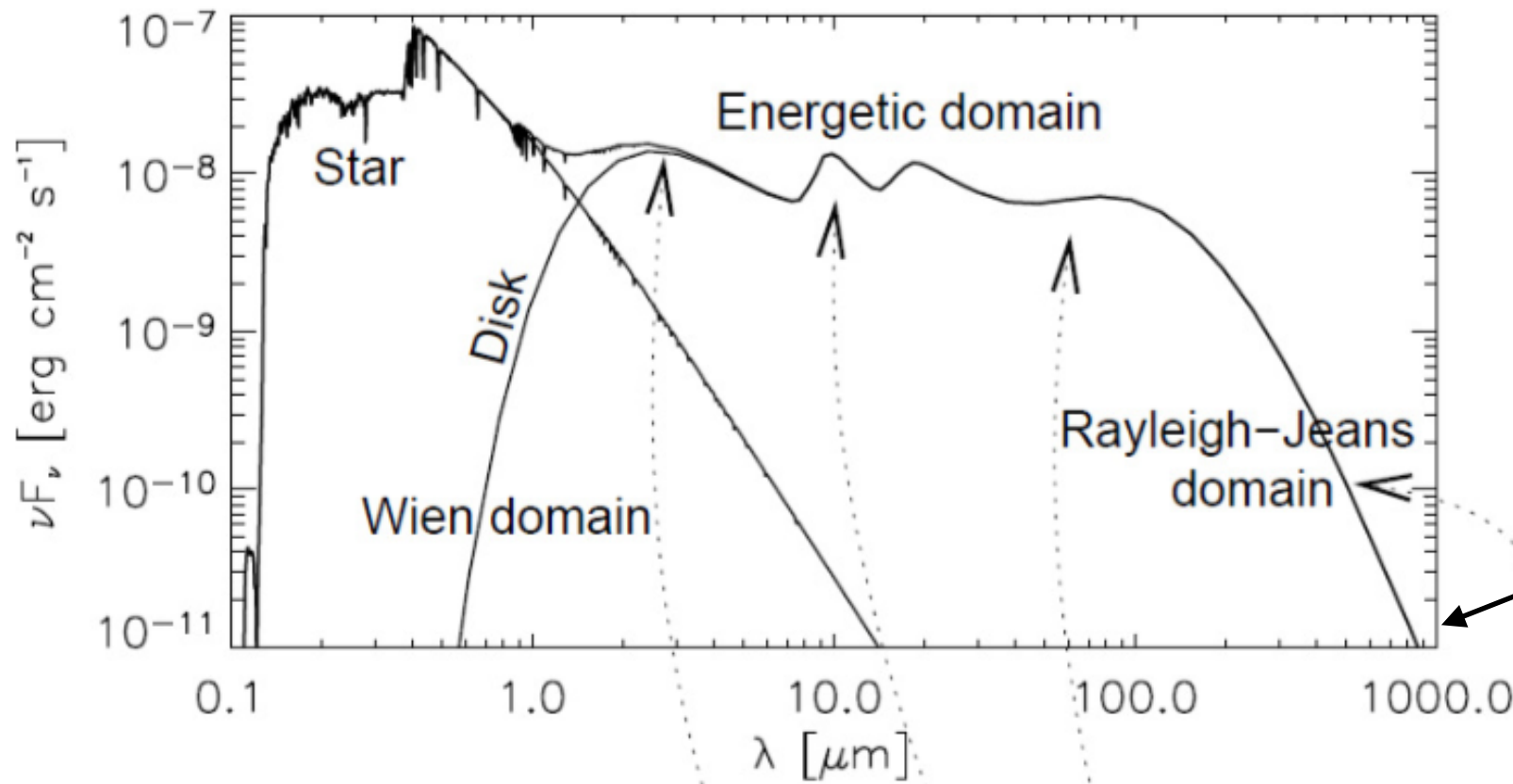
Detailed physical-chemical modeling:
CO snowline not that simple for disks

=> vertical temperature gradient produces a CO 'snow surface'

Qi et al. 2013

Van t Hoff et al. 2017

Centimeter and beyond

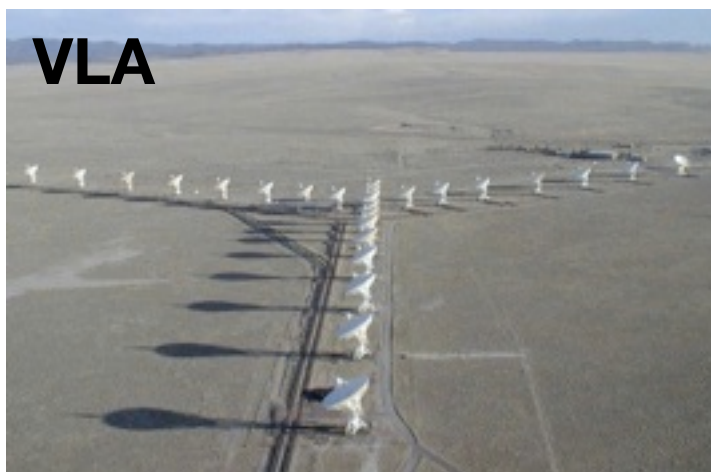


**What happens at longer wavelengths?
Centimeter-sized grains?**

Is grain size $\sim 3 \lambda$?

Emission at longer wavelengths:

JVLA (New Mexico): 6mm - 410 cm & ATCA (Australia): 3mm-27 cm



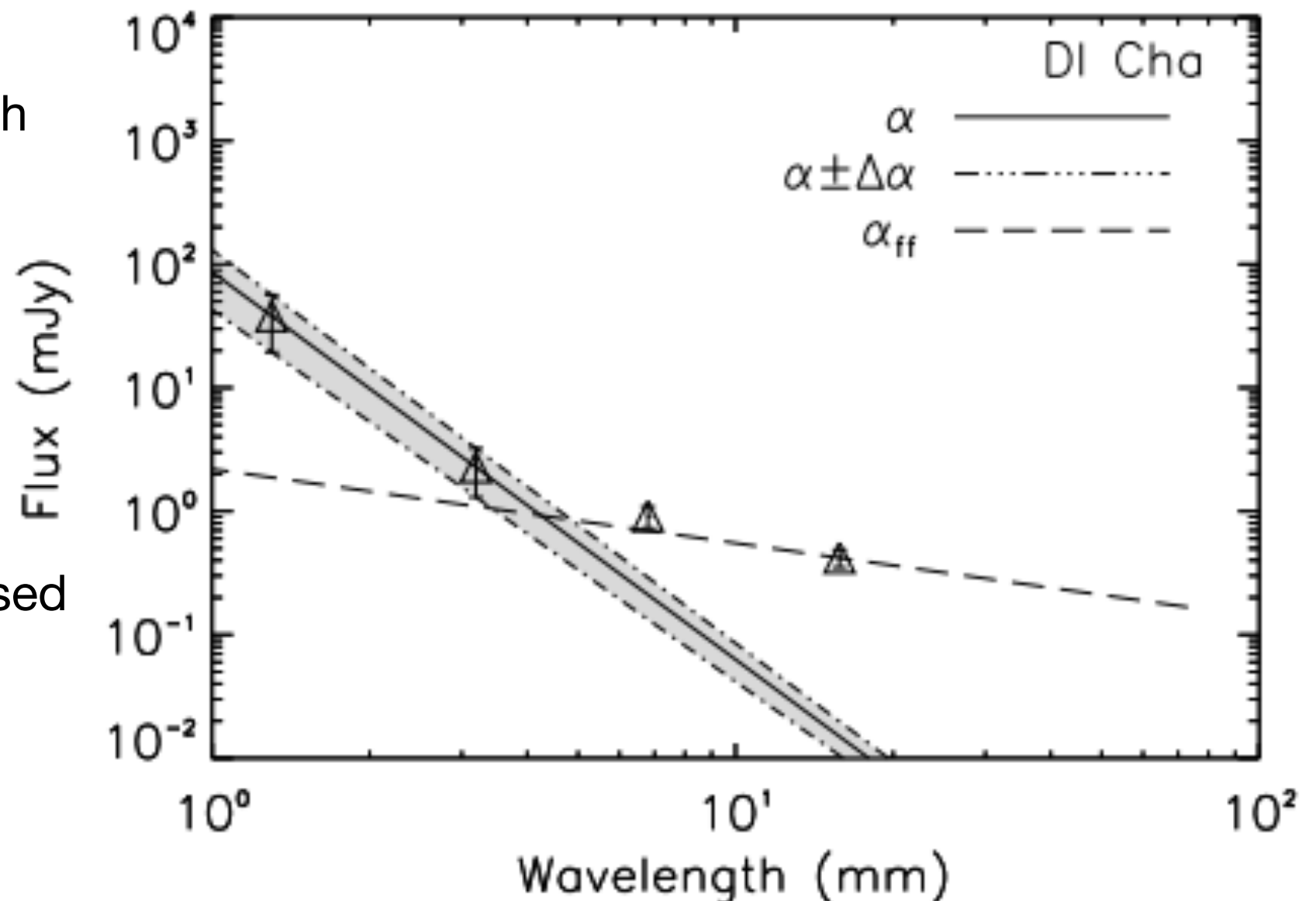
Centimeter and beyond

Measured fluxes of disks at
centimeter-wavelengths:

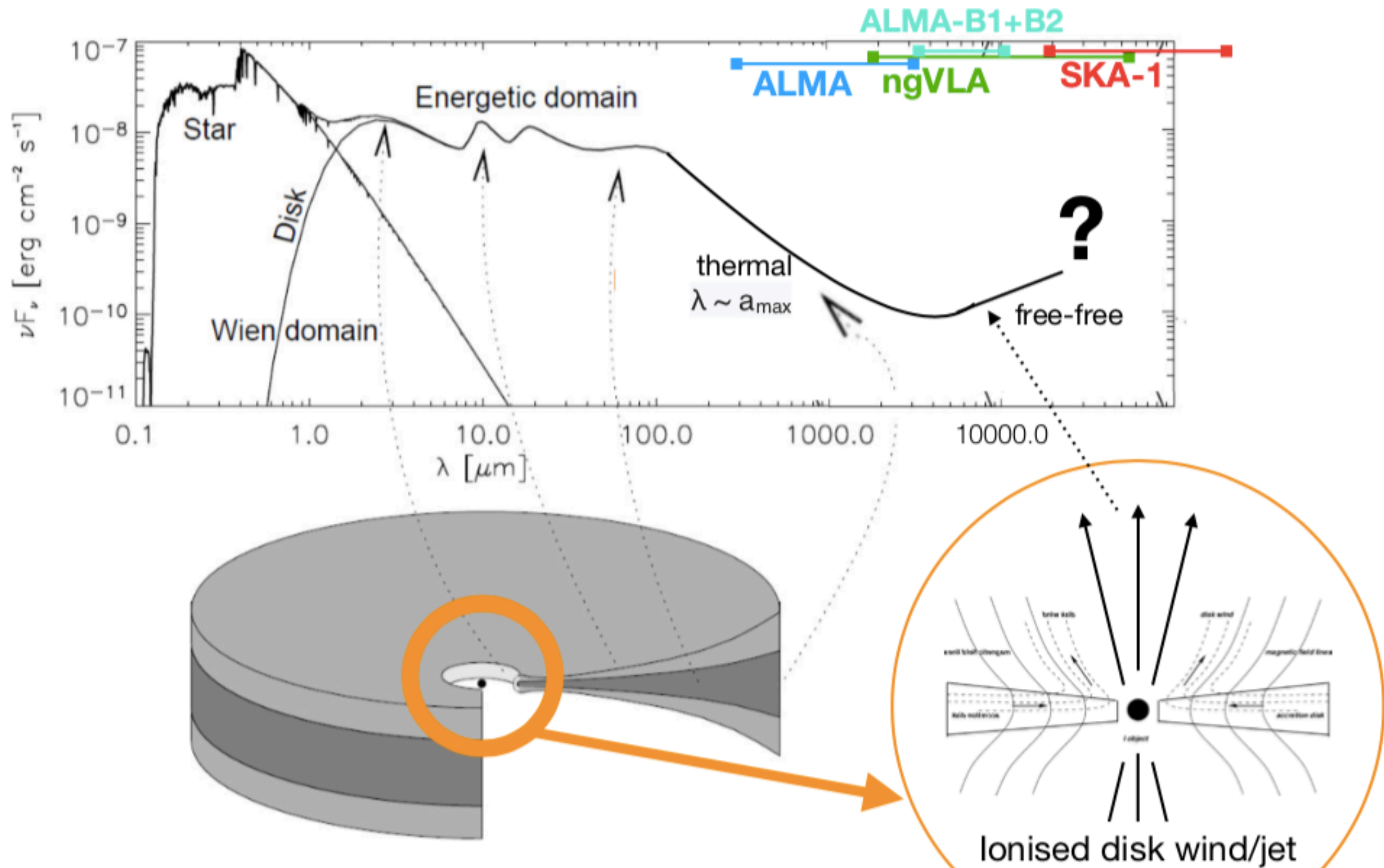
Not continuing steep slope with
 $\alpha \sim 2.5$ from flux relation

$$F_\nu \sim \nu^\alpha$$

Additional component with
slope $\alpha < 0.5$:
non-thermal emission,
e.g. free-free emission from ionised
gas: disk wind?



Centimeter and beyond



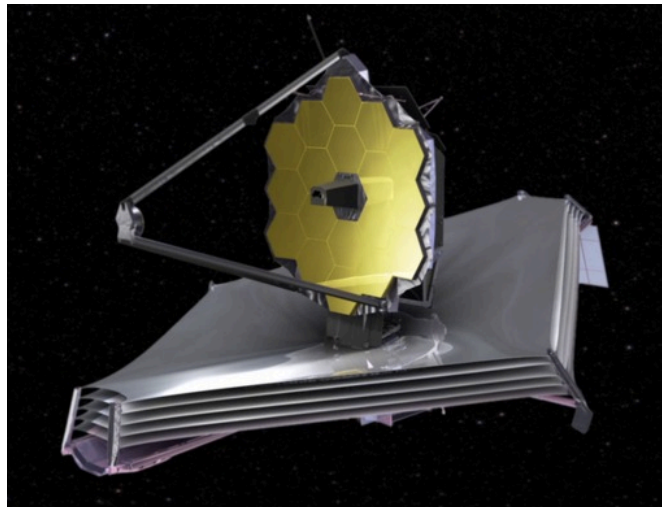
Future: ALMA-lowfrequency, ngVLA and/or SKA
 resolve free-free emission and investigate origin:
 Stellar surface? Centimetre grains? Disk wind?

Future facilities

JWST

$\lambda=0.5\text{-}28\ \mu\text{m}$

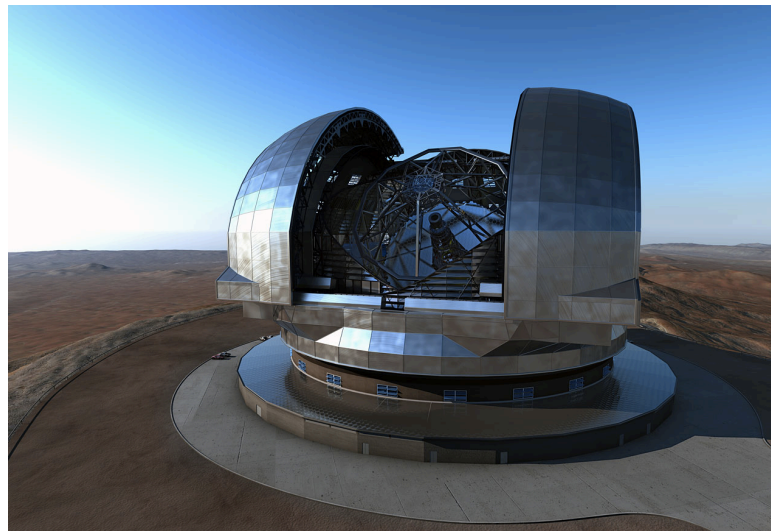
Planned launch ~2021



E-ELT

$\lambda=0.3\text{-}14\ \mu\text{m}$

Planned first light: ~2024



TMT

$\lambda=0.3\text{-}28\ \mu\text{m}$

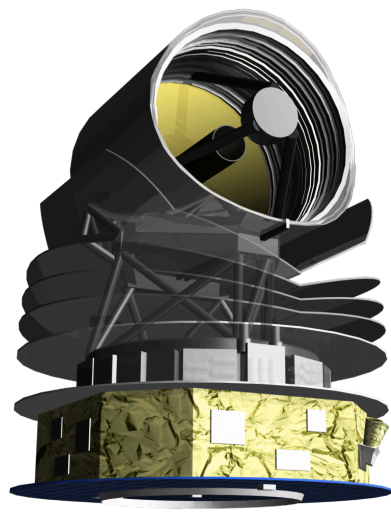
Planned first light: ~2027(?)



SPICA

$\lambda=12\text{-}230\ \mu\text{m}$

Planned launch: ~2032

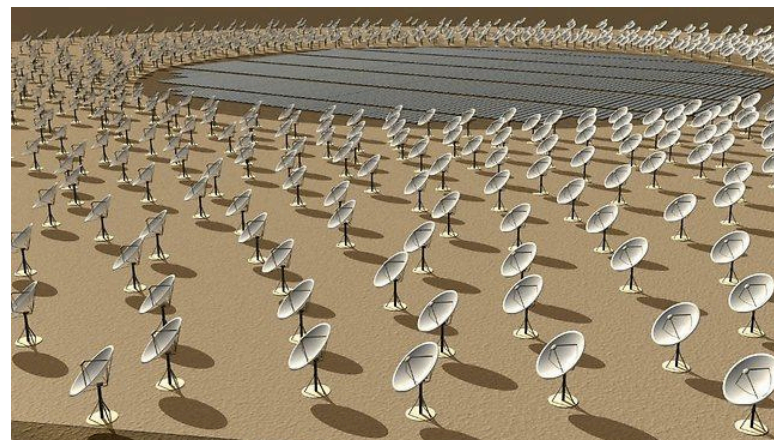


JAXA / SPICA Team

SKA

$\lambda=3\text{-}600\ \text{cm}$

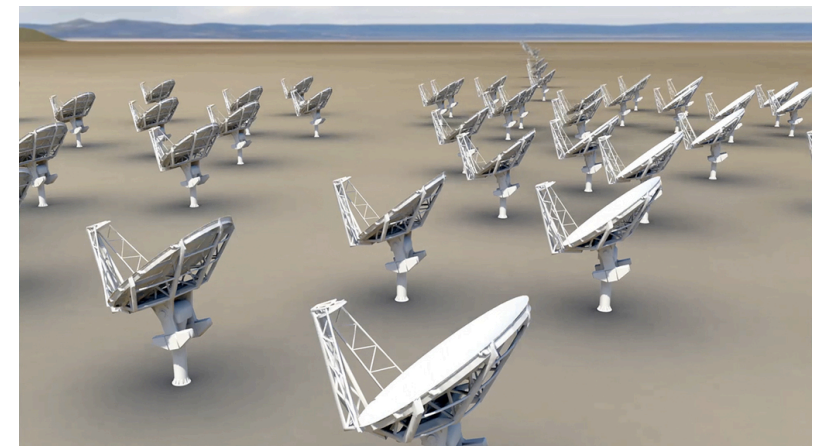
Planned first light ~2025-2030



ngVLA

$\lambda=0.3\text{-}20\ \text{cm}$

Planned first light ~2025-2030



Summary

- Disks emit radiation anywhere between UV and centimetre wavelengths, originating from different parts of the disk, tracing different physical processes
- Unresolved measurements still provide a lot of useful information about the physical structure of the disk.
- Disk masses are fundamental for many processes but their values remain highly uncertain
- Future facilities in infrared and millimeter/centimeter wavelengths will provide many more opportunities of detailed studies of disks

Questions?

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