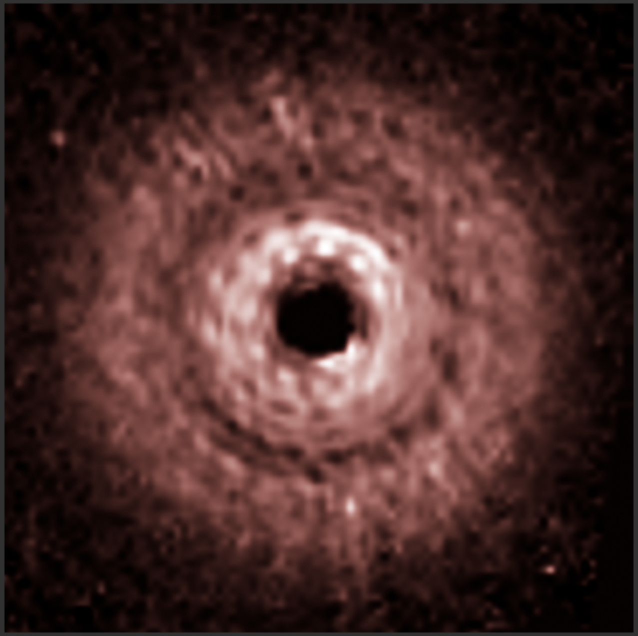
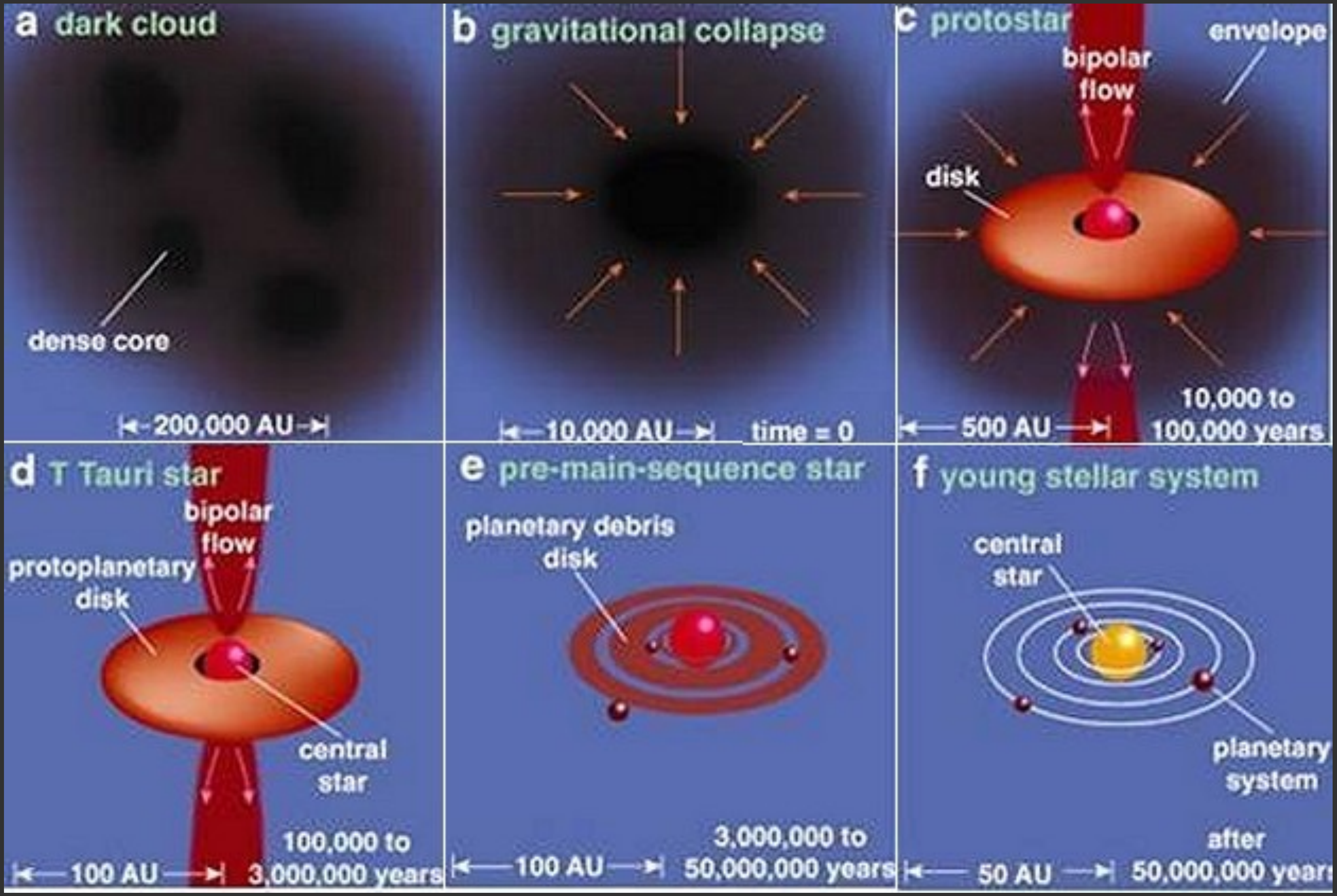
Protoplanetary Disks

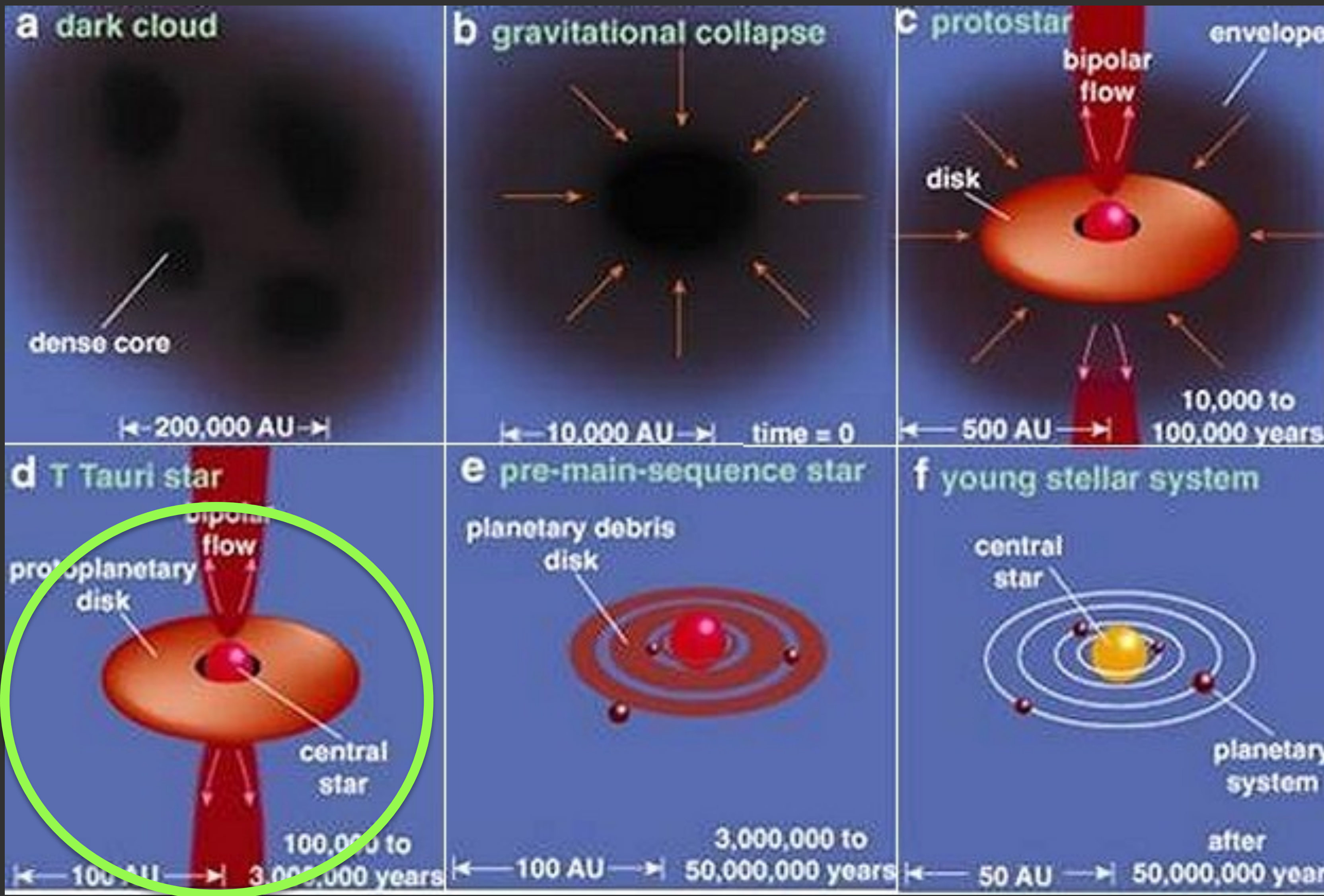


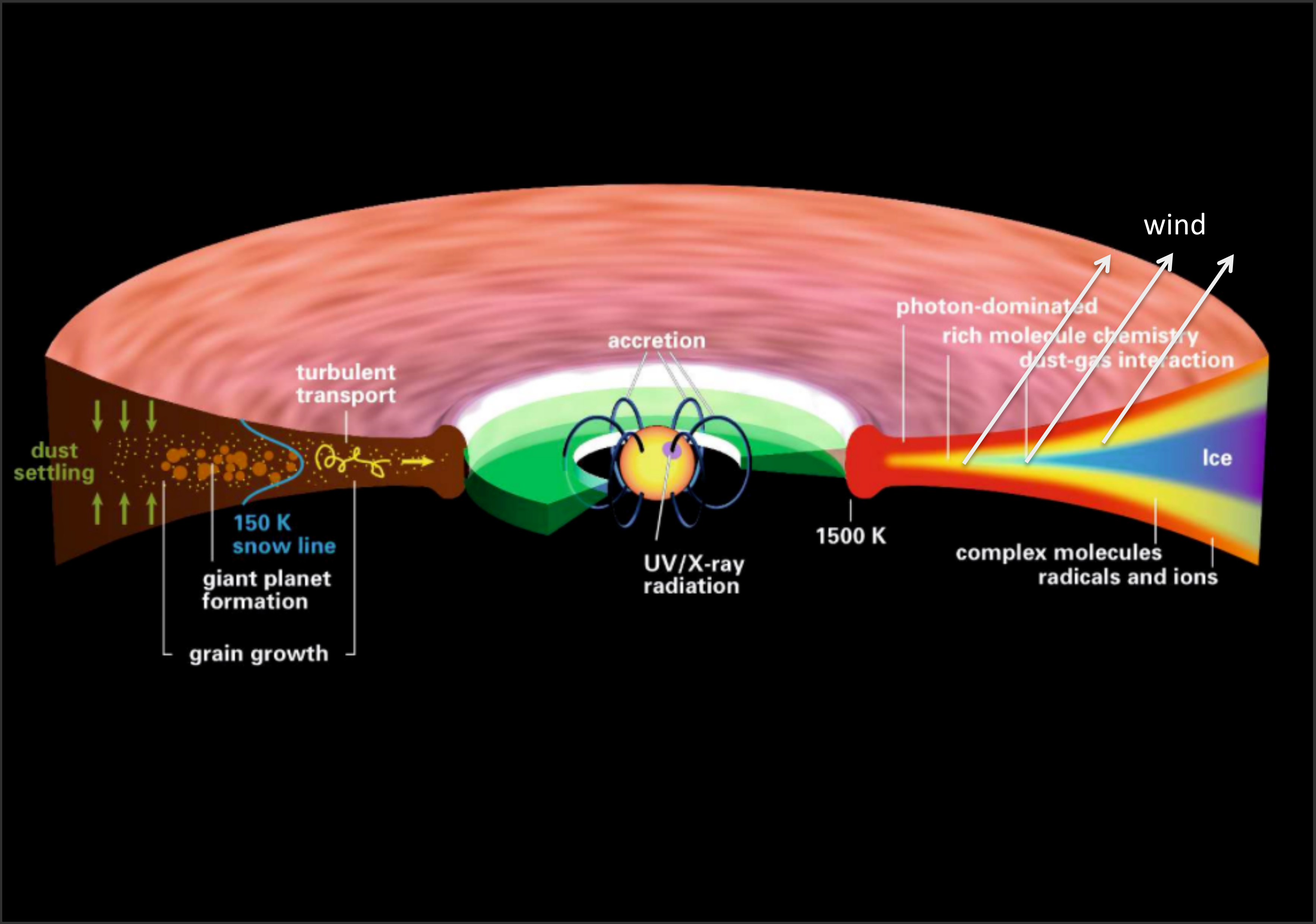
Uma Gorti
(SETI Institute/NASA Ames)

Stages of Star Formation



Stages of Star Formation



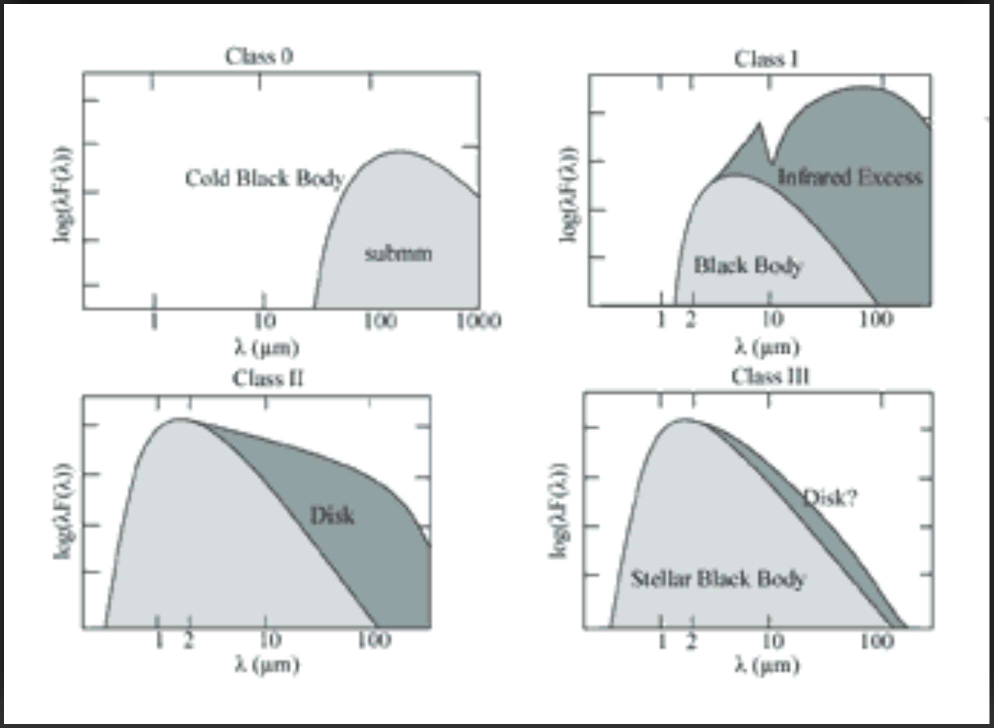


[Henning & Semenov 2013]

Dust in protoplanetary disks

Dust in Disks

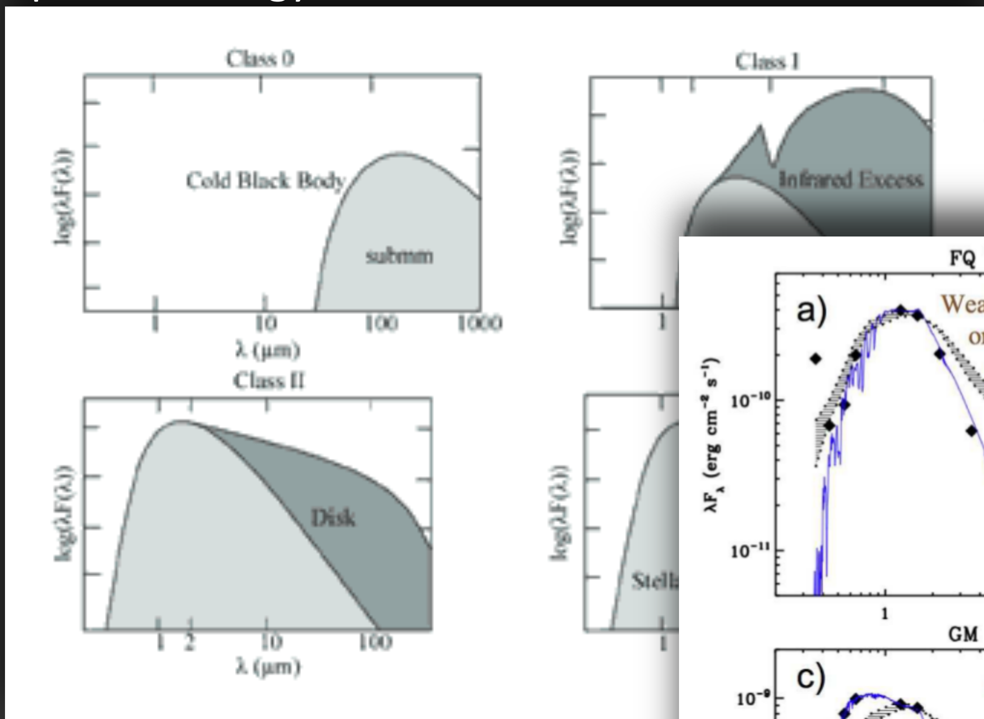
Spectral Energy Distributions



[Lada 1987; Andre et al. 1993]

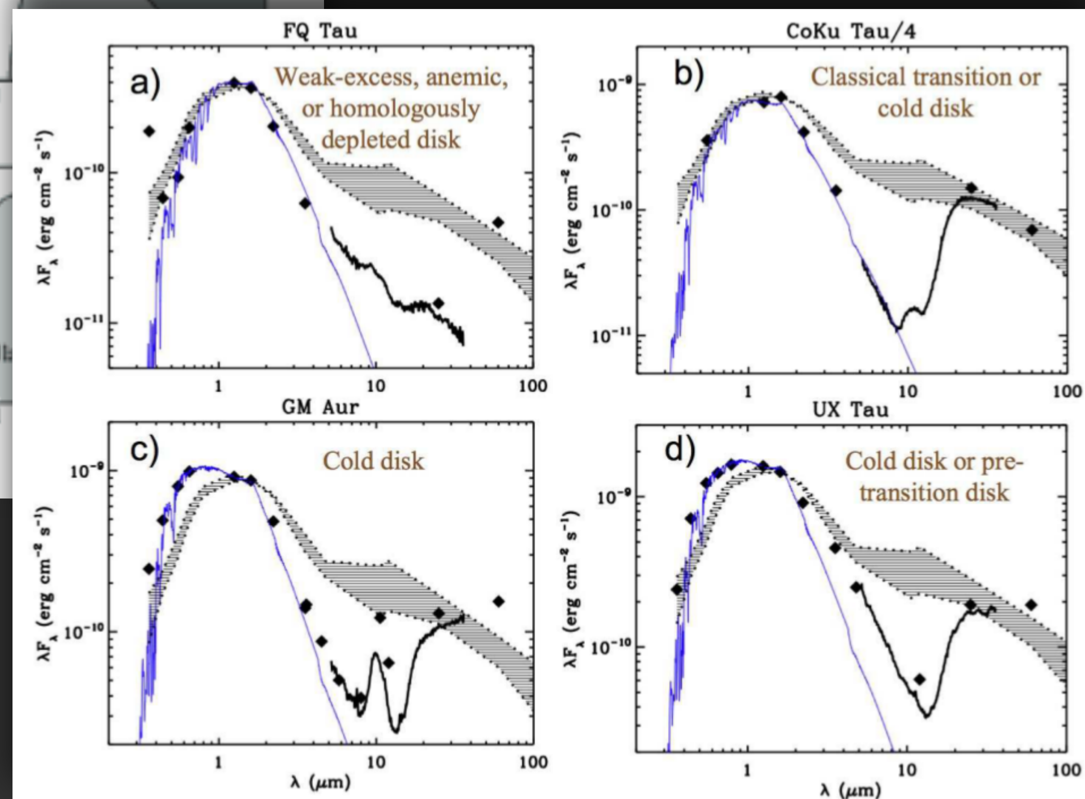
Dust in Disks

Spectral Energy Distributions



[Lada 1987; Andre et al. 1993]

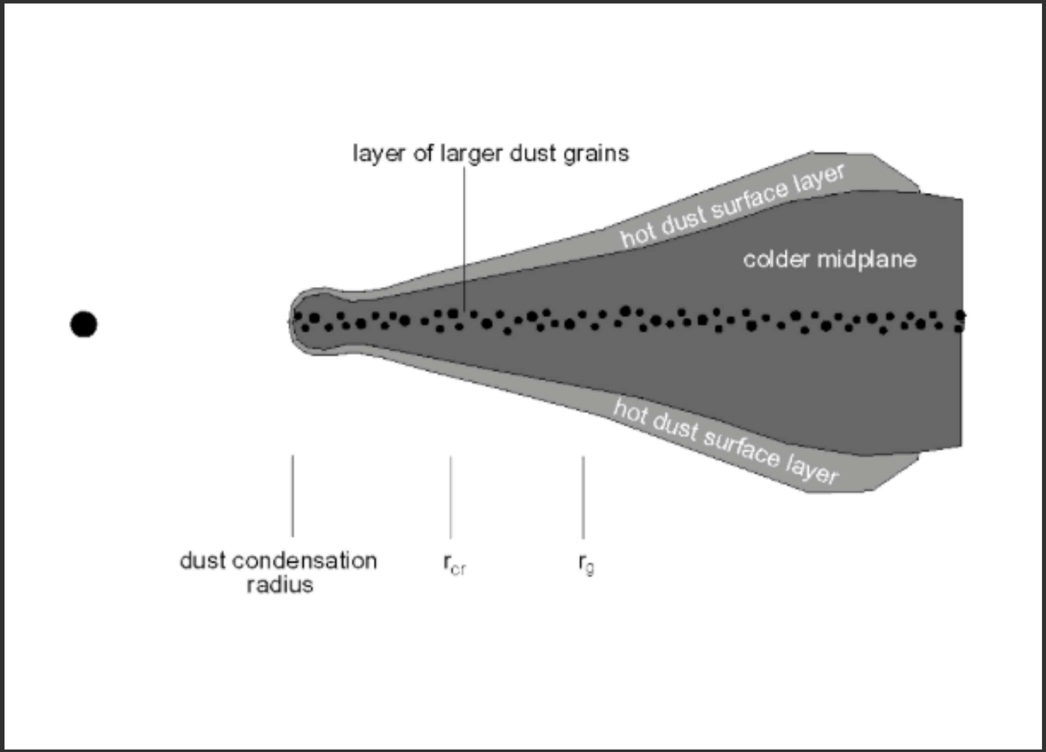
[Williams & Cieza 2011]



Disk Dissipation: Class II SED evolves with time along multiple pathways

Dust in Disks

Detailed modeling of SED to infer spatial distribution of dust in disks.

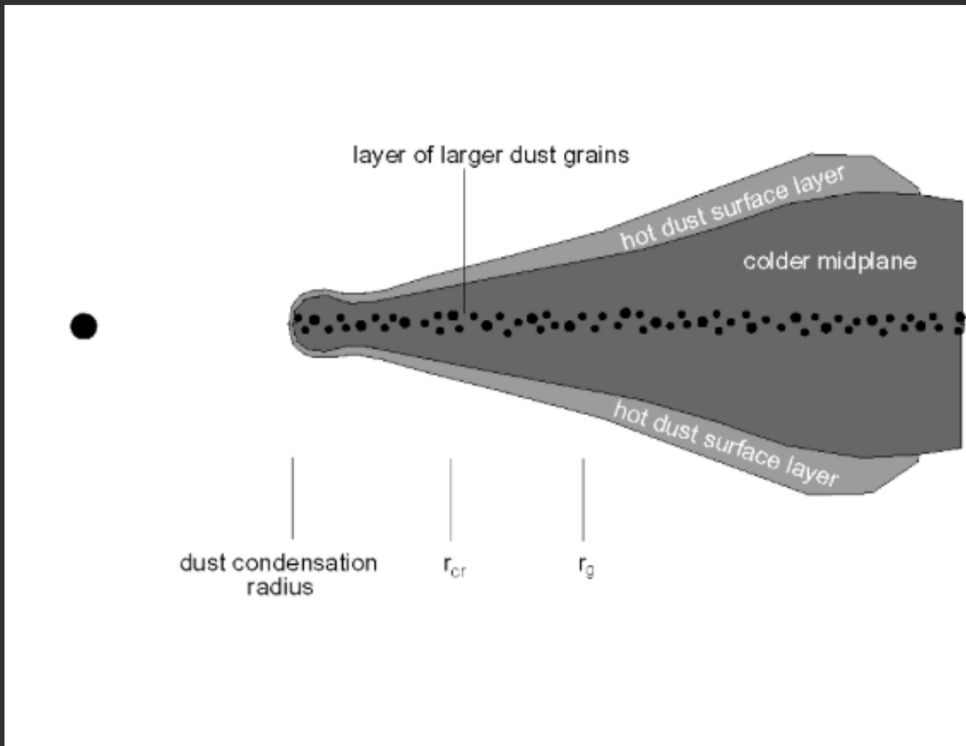


[Dullemond+ 2007]

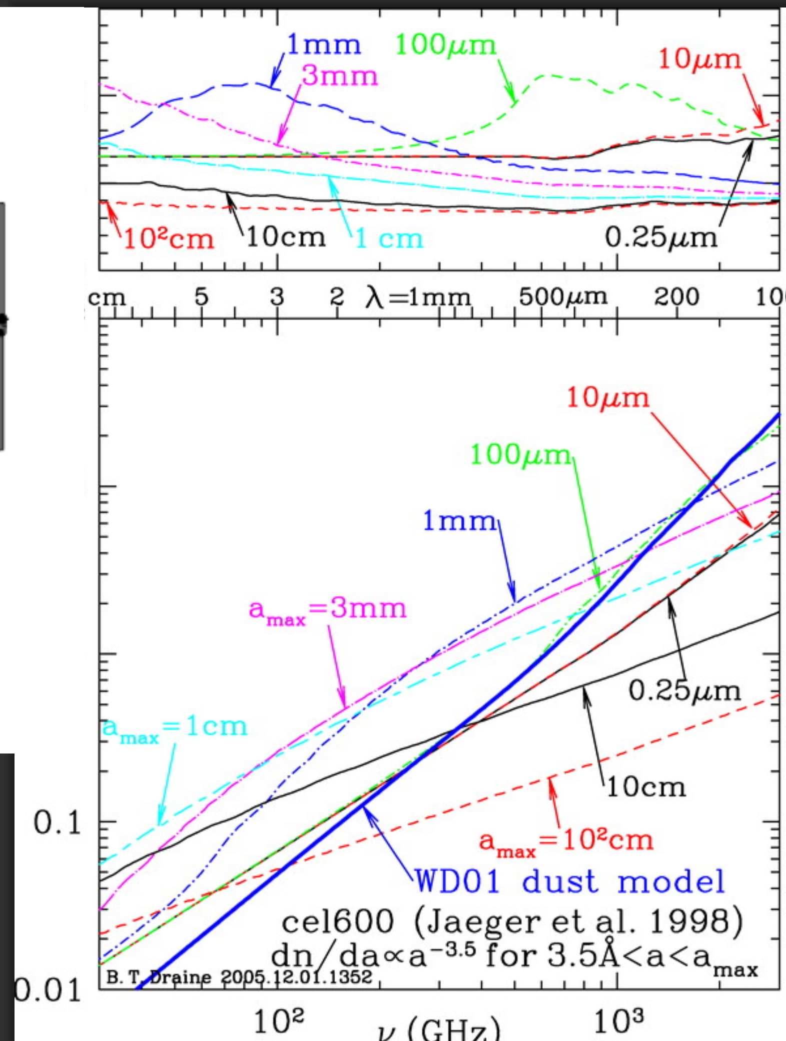
Dust in Disks

Detailed modeling of SED to infer spatial distribution of dust in disks.

[Draine 2006]



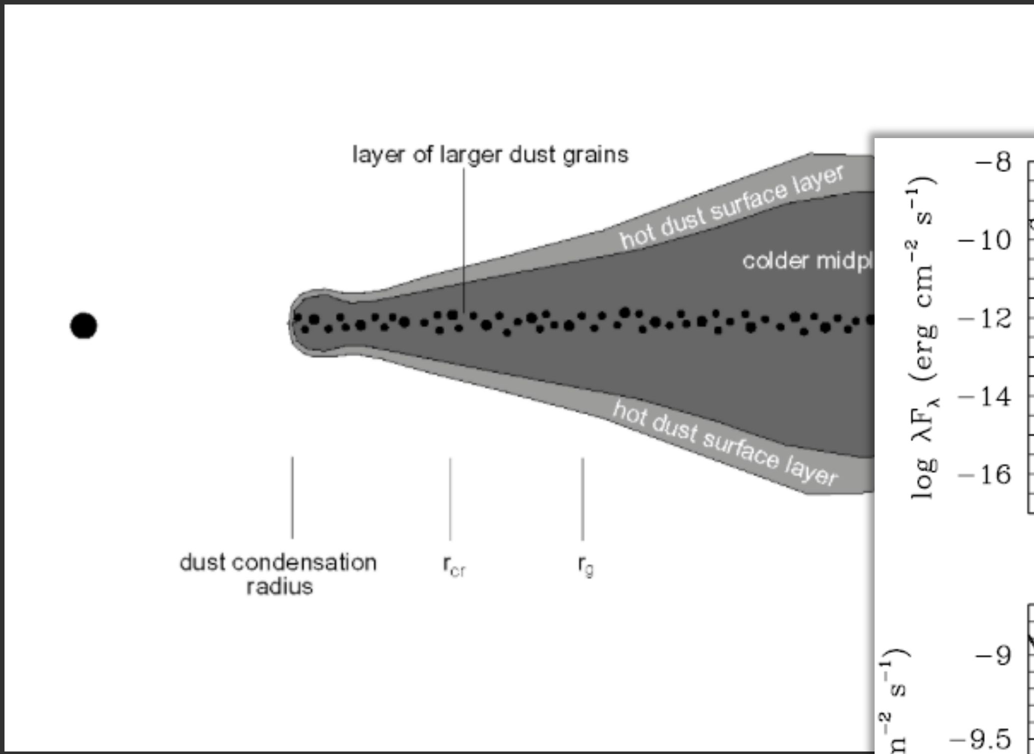
[Dullemond+ 2007]



Dust Opacities
(composition ,grain sizes)

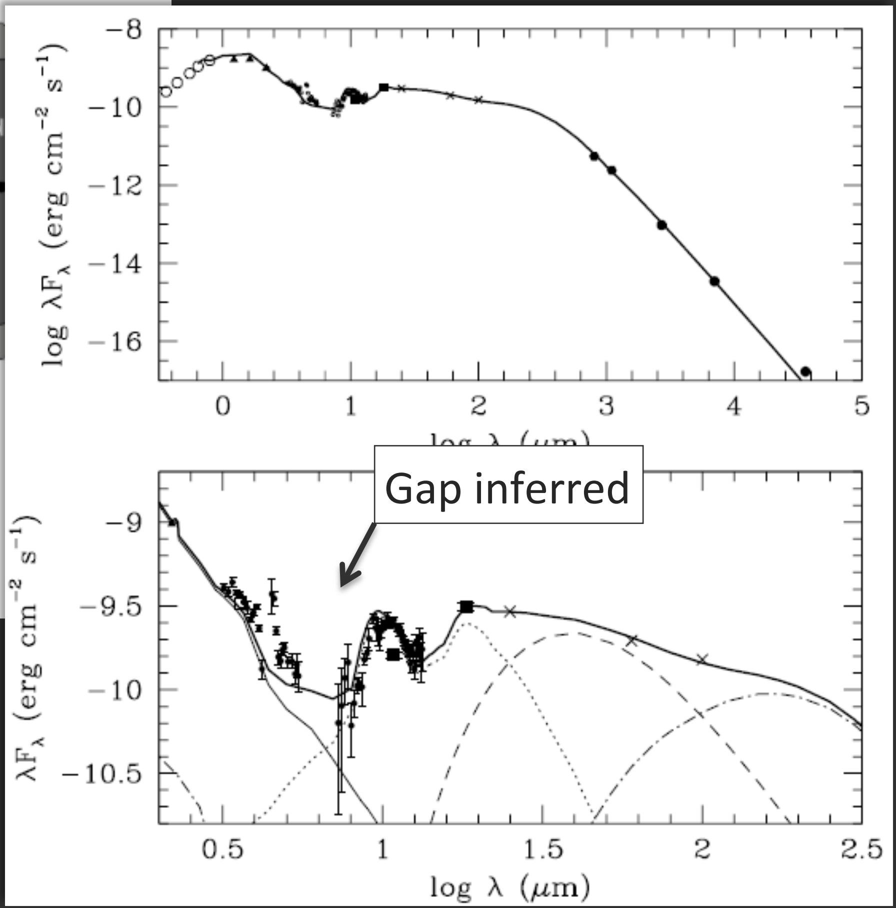
Dust in Disks

Detailed modeling of SED to infer spatial distribution of dust in disks.



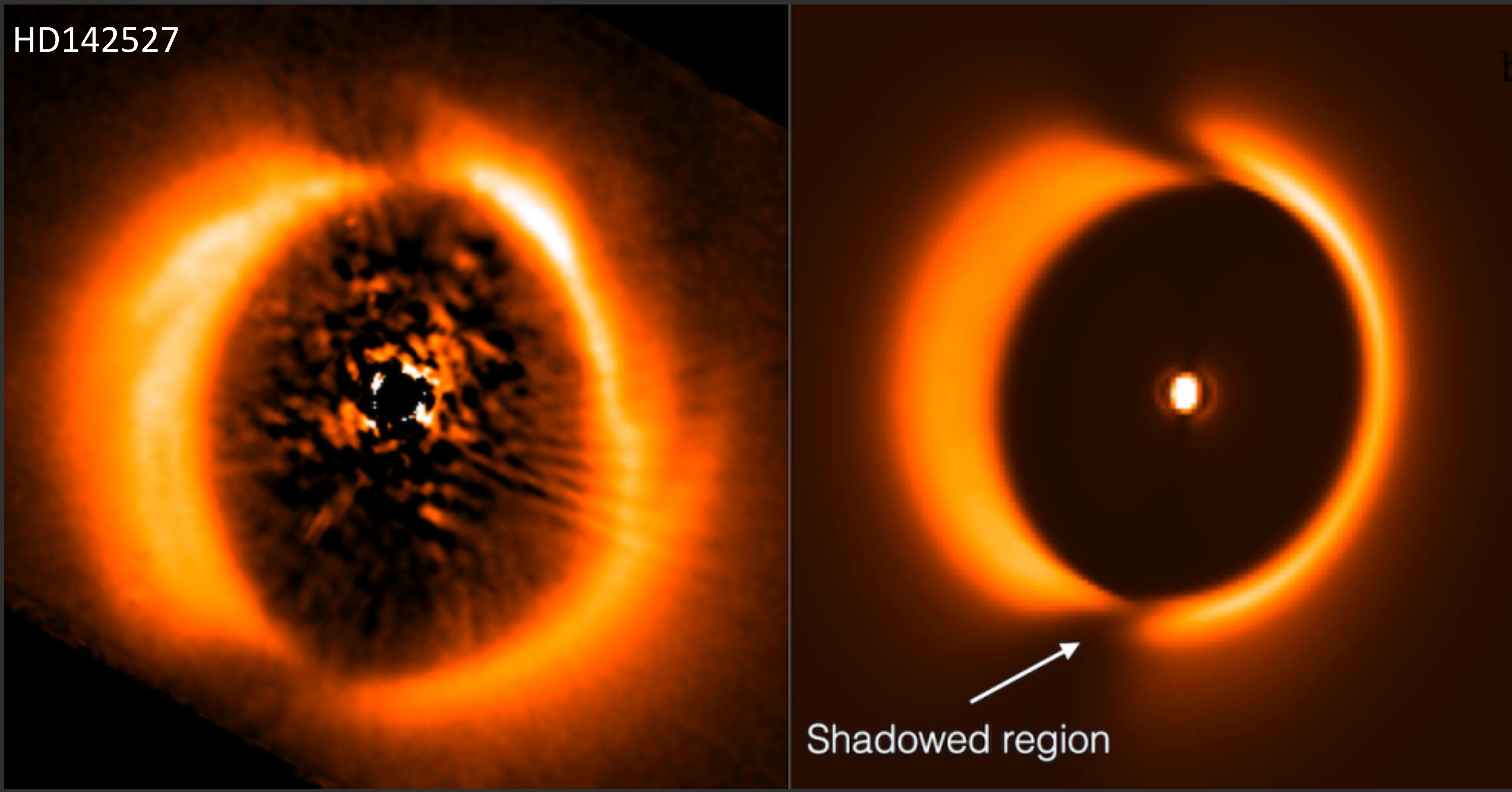
[Dullemond+ 2007]

[Calvet + 2005]



SED model of TW Hya

Dust in Disks

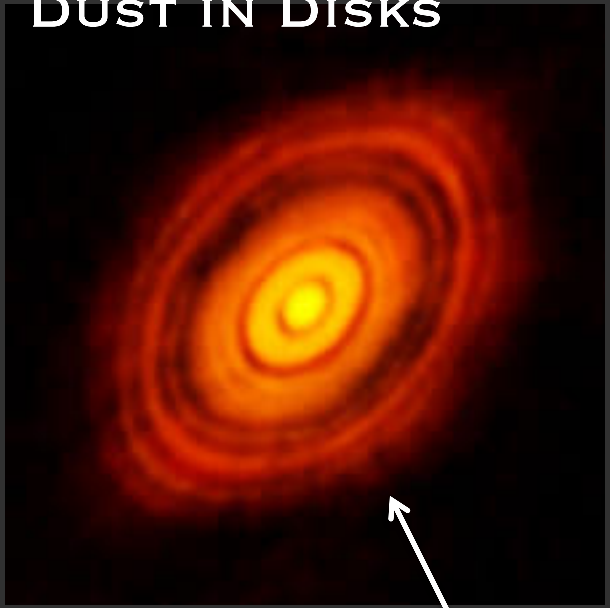


[Marino+ 2015]

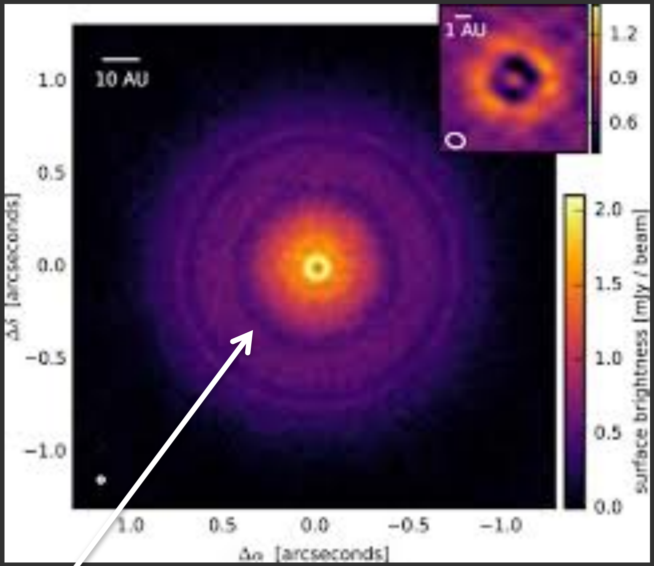
3D RT models:

MCFOST
MCMax
RADMC
TORUS, etc.

Dust in Disks



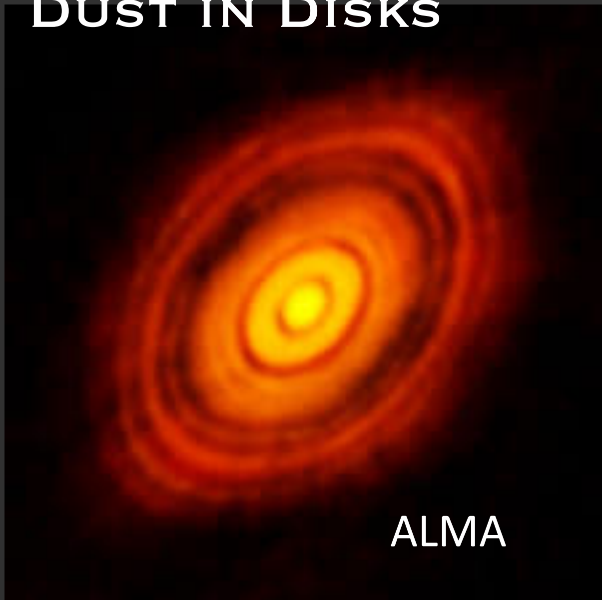
[ALMA Partnership 2015]

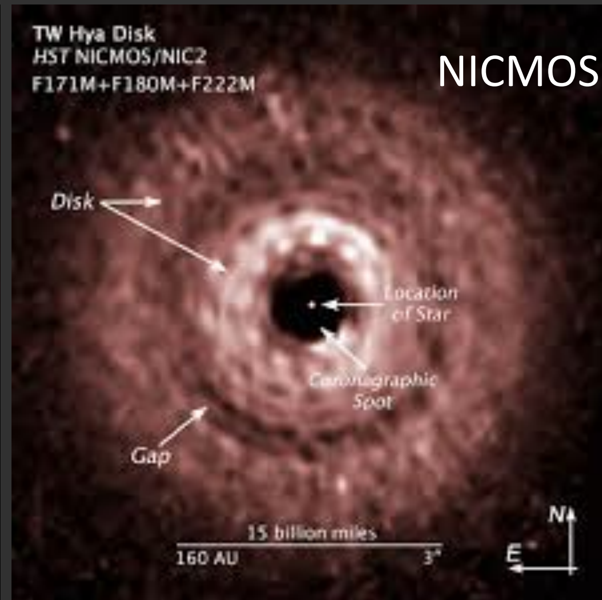


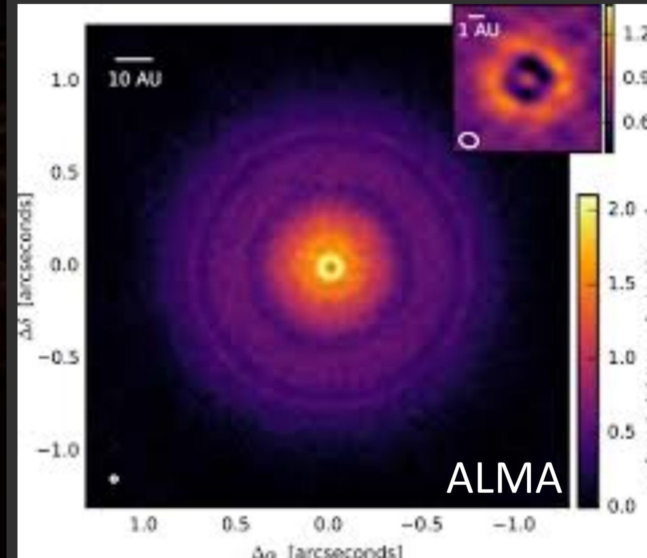
[Andrews+ 2016]

Gaps in ~ 1 Myr disk around HL Tau and ~ 10 Myr disk around TW Hya

Dust in Disks





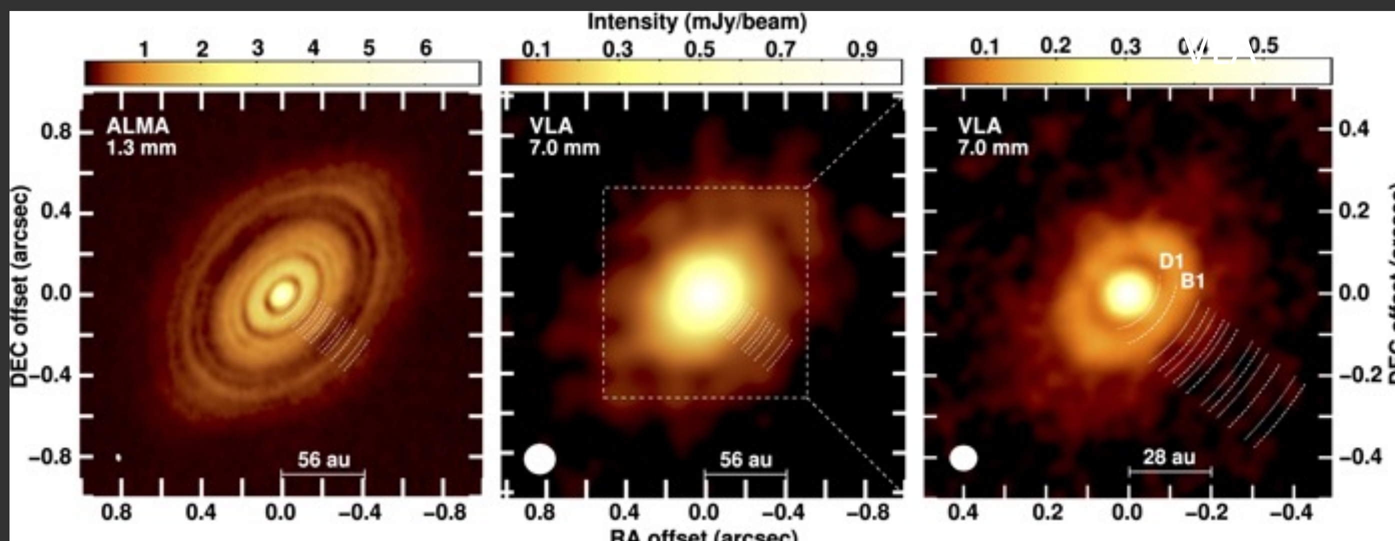


[ALMA Partnership 2015]

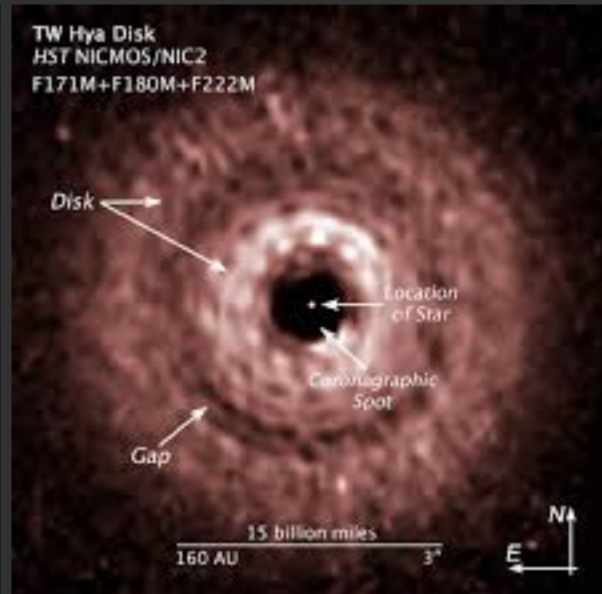
[Debes+ 2013]

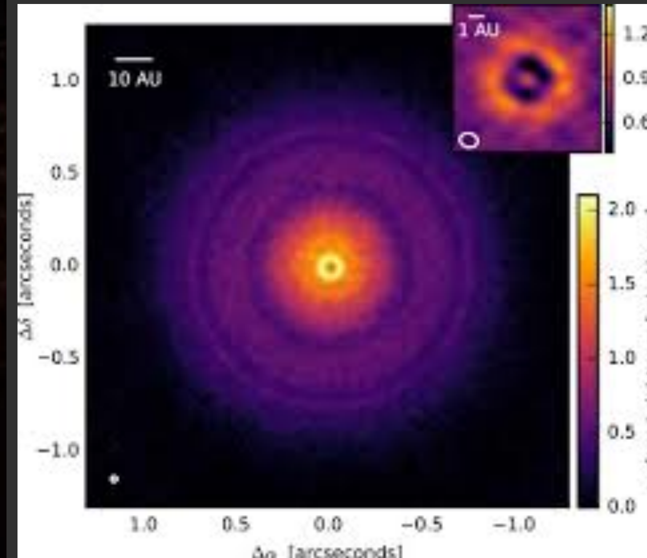
[Andrews+ 2016]

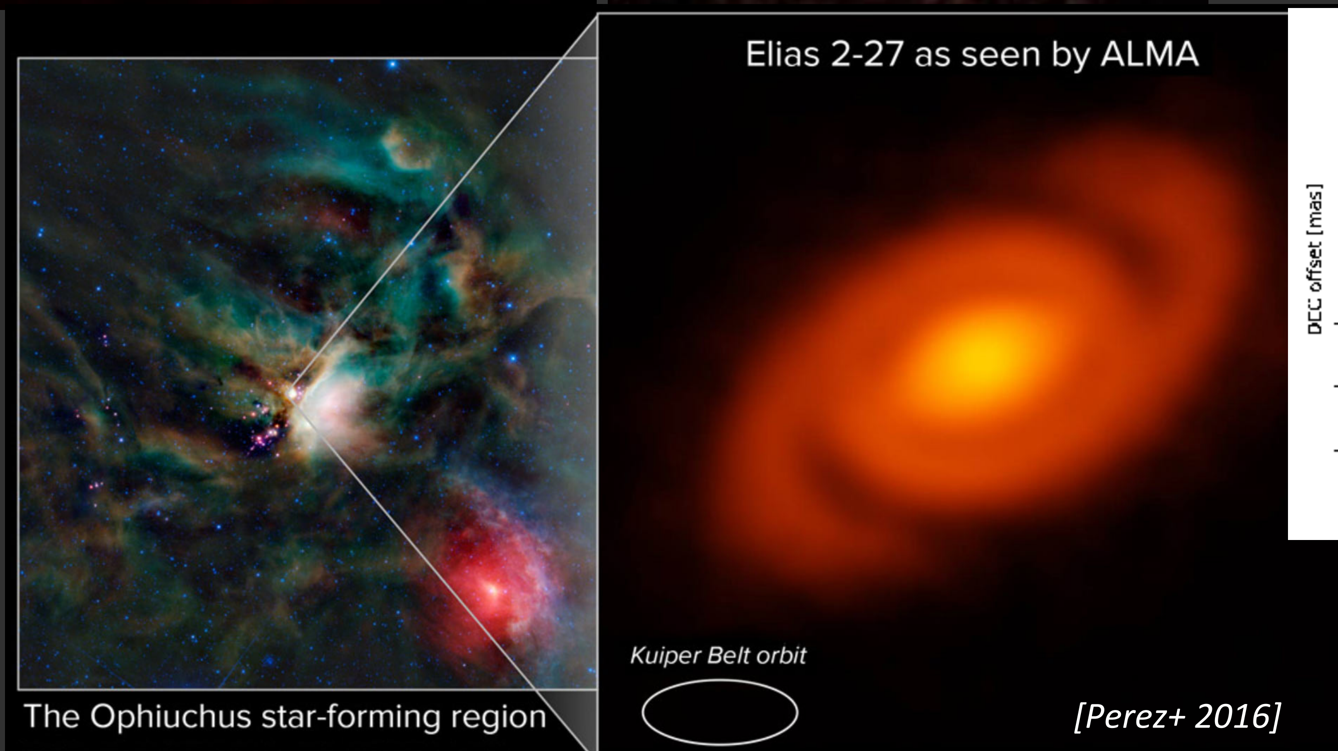
Gaps and rings
at all wavelengths

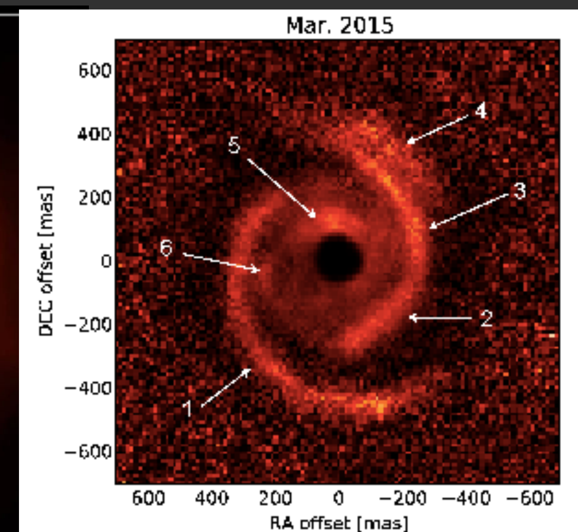


Dust in Disks





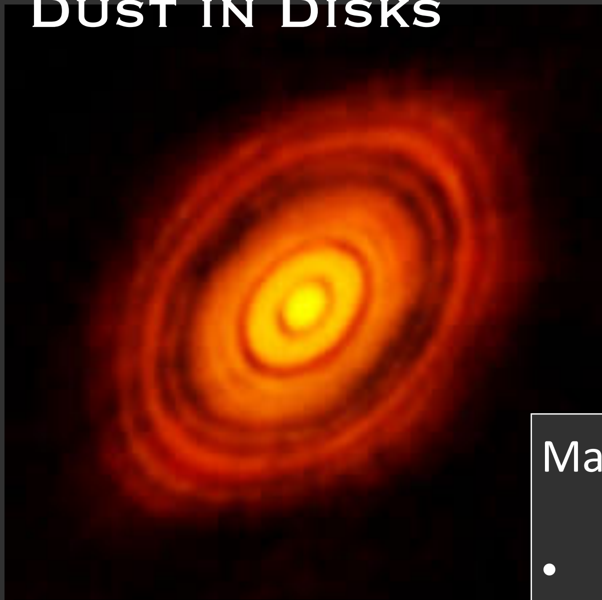


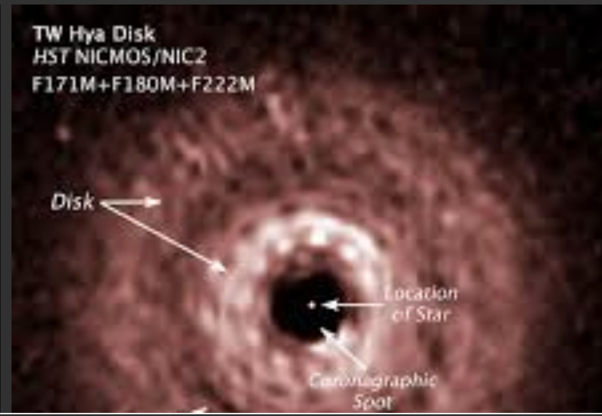


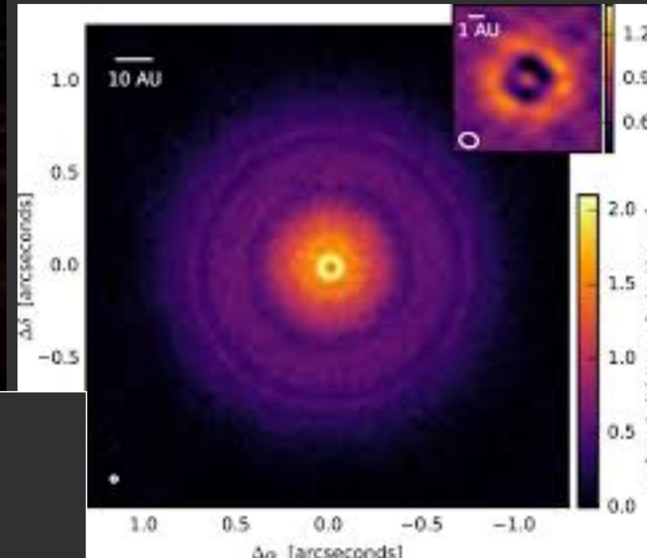
[Benisty+ 2016]

Spiral Structures

Dust in Disks

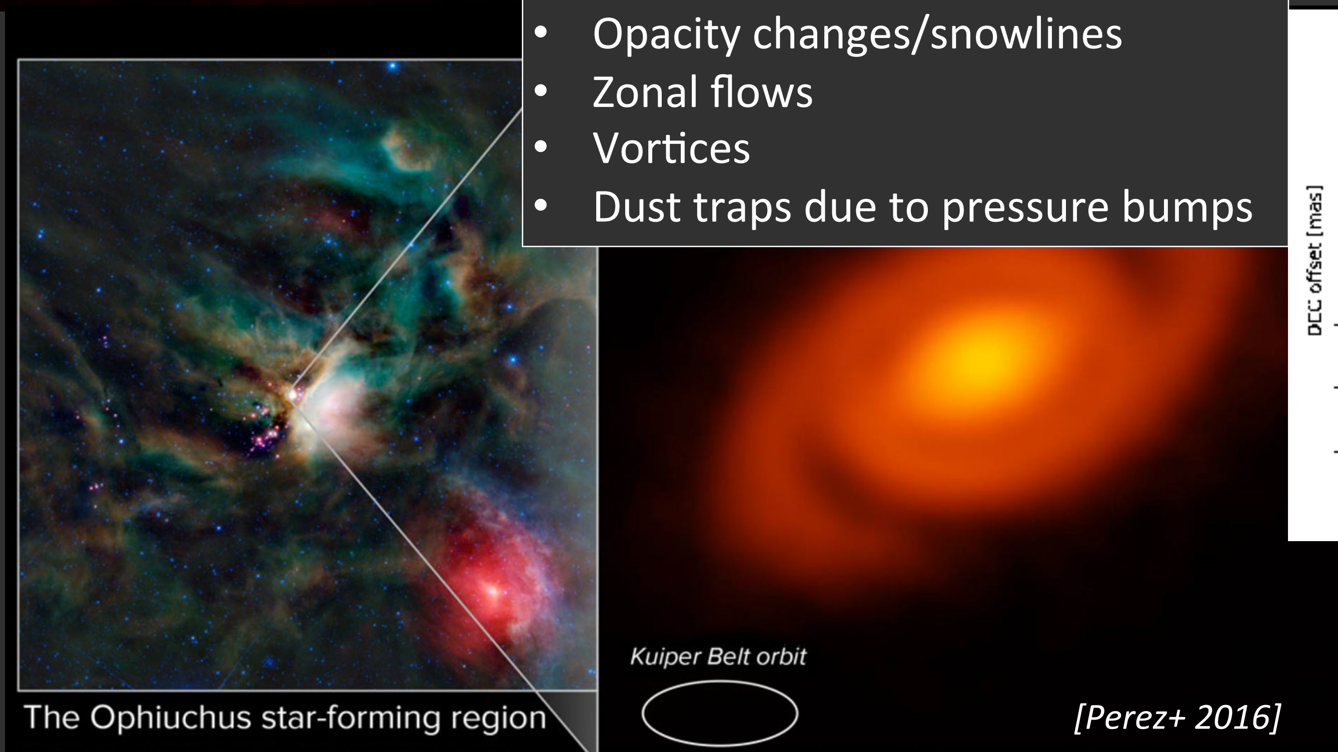




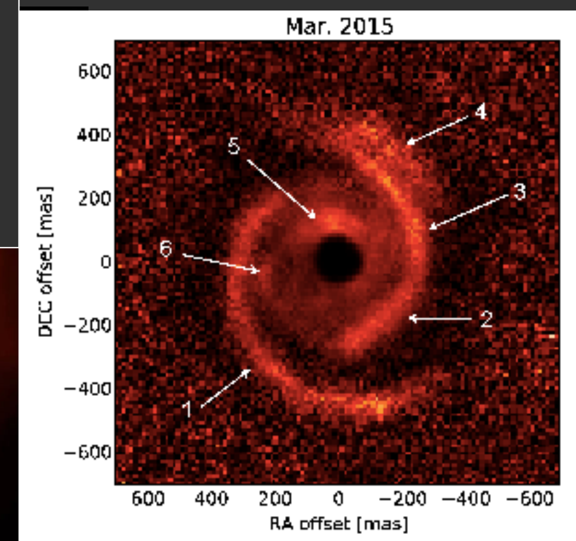


Many explanations for structure:

- Planets
- Opacity changes/snowlines
- Zonal flows
- Vortices
- Dust traps due to pressure bumps



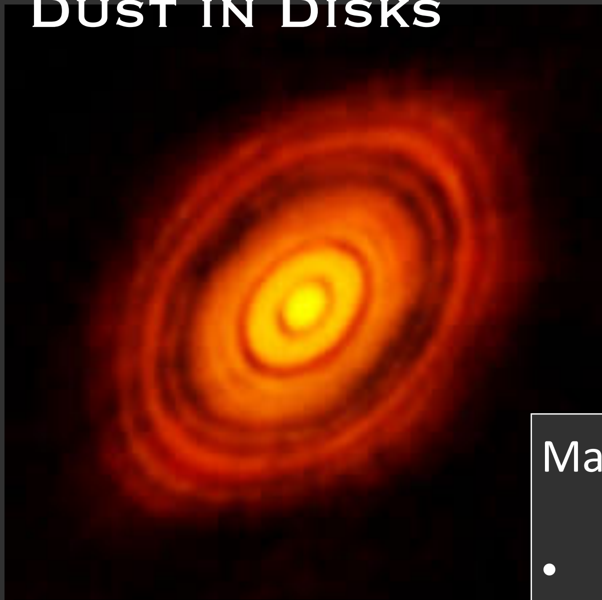
[Perez+ 2016]

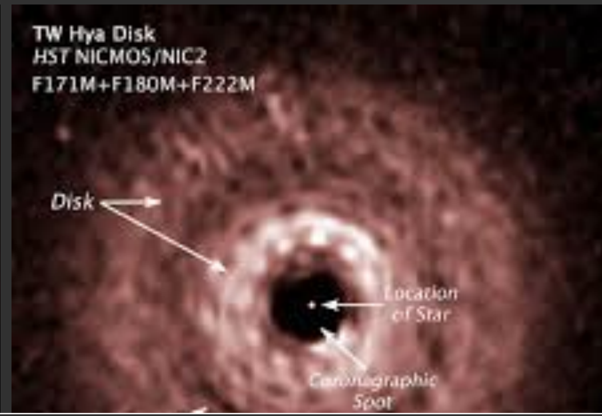


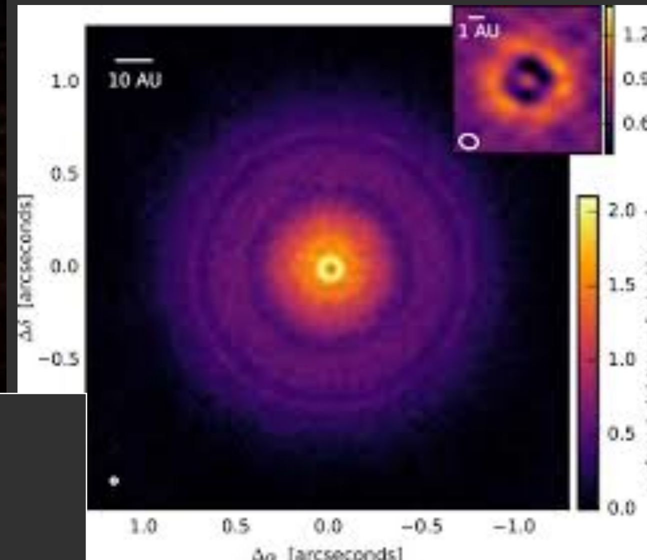
[Benisty+ 2016]

Spiral Structures

Dust in Disks







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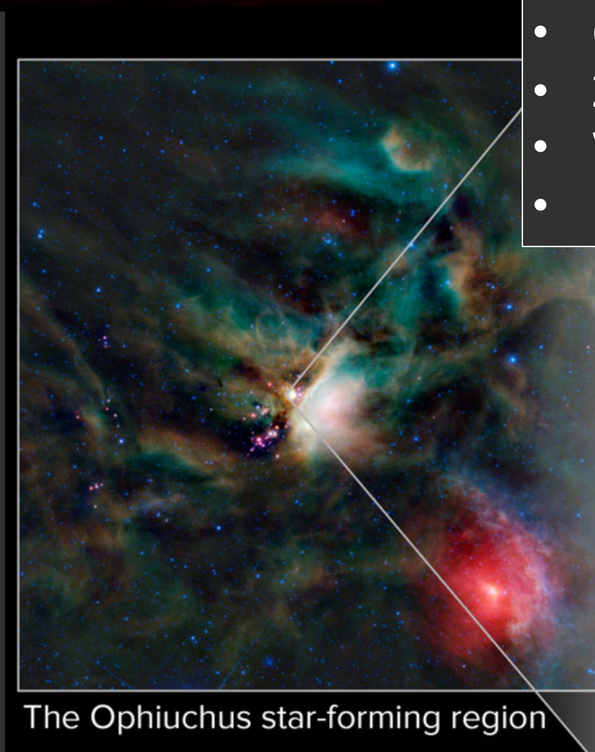
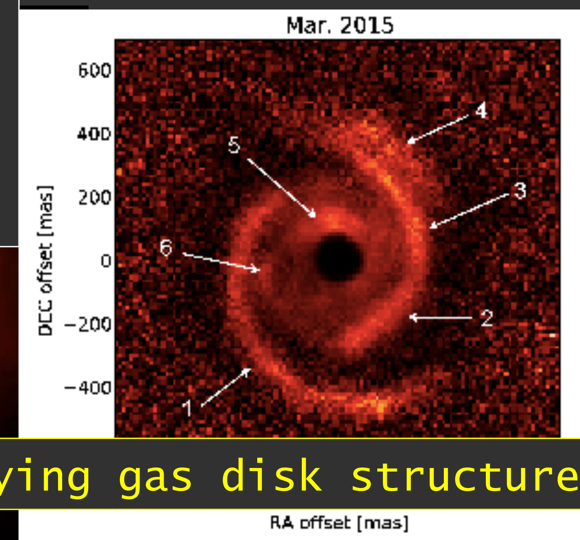


[Perez+ 2016]



Need underlying gas disk structure

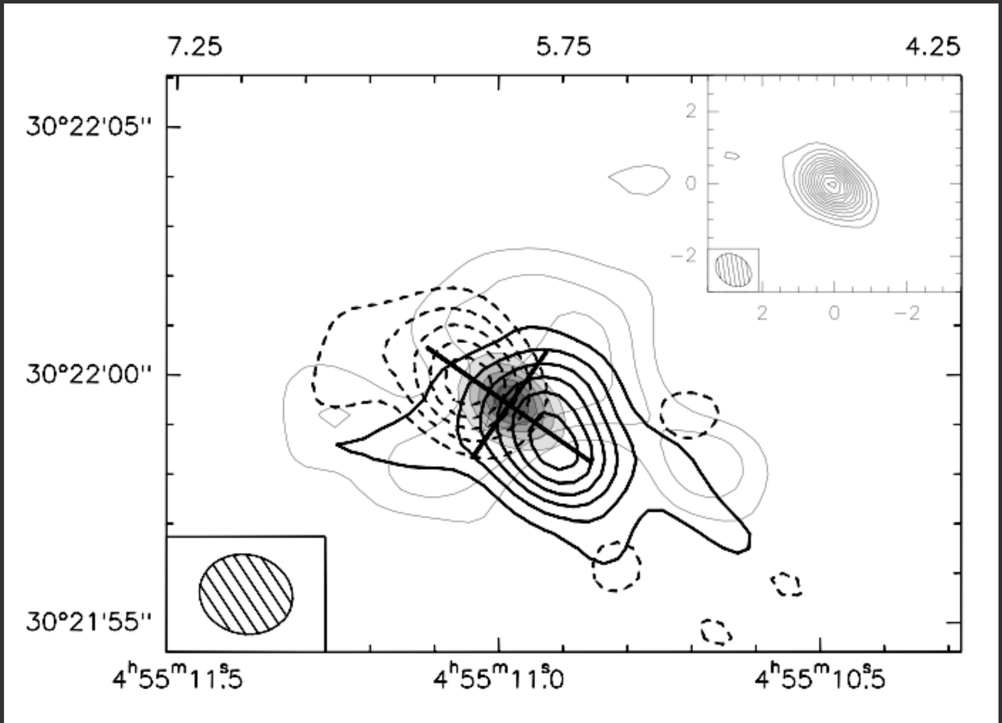
[Benisty+ 2016]

Spiral Structures

Gas in protoplanetary disks

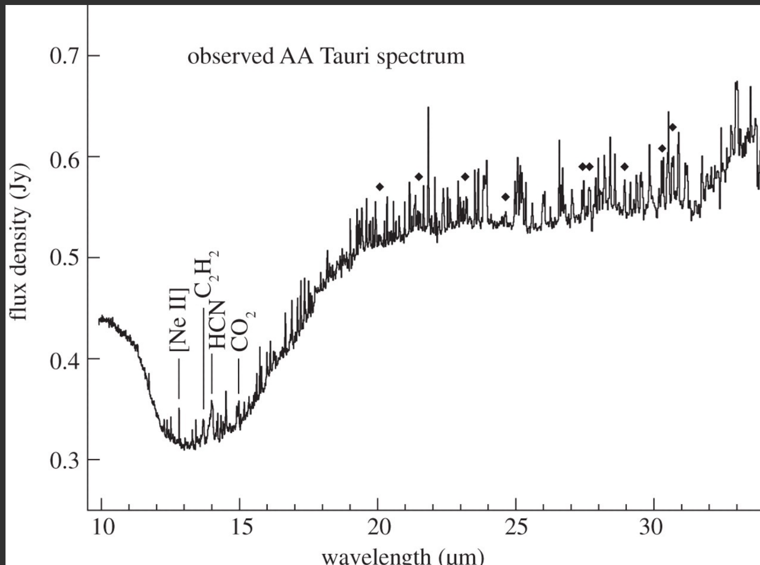
Gas in Disks

[Dutrey+ 1998]

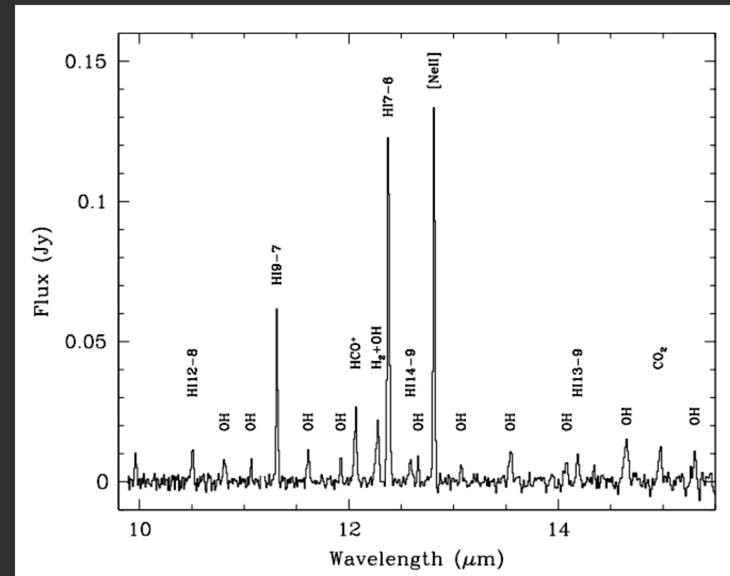


CO from disk shows Keplerian rotation

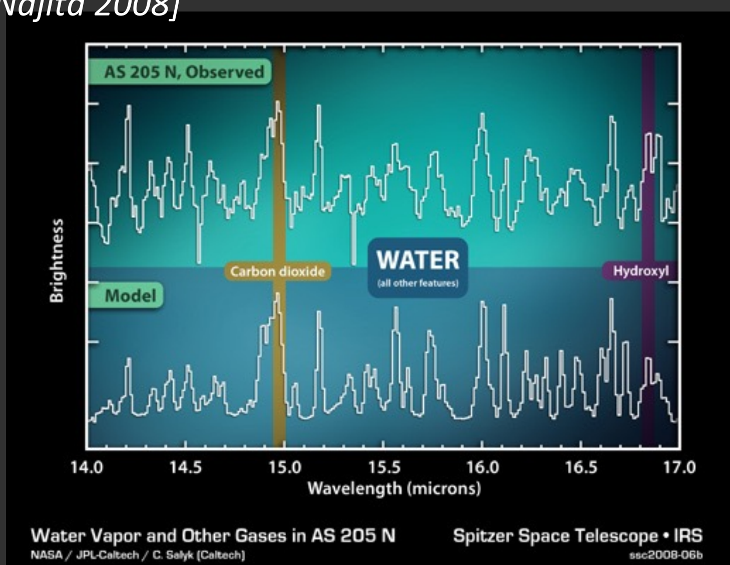
Gas in Disks



[Carr & Najita 2008]



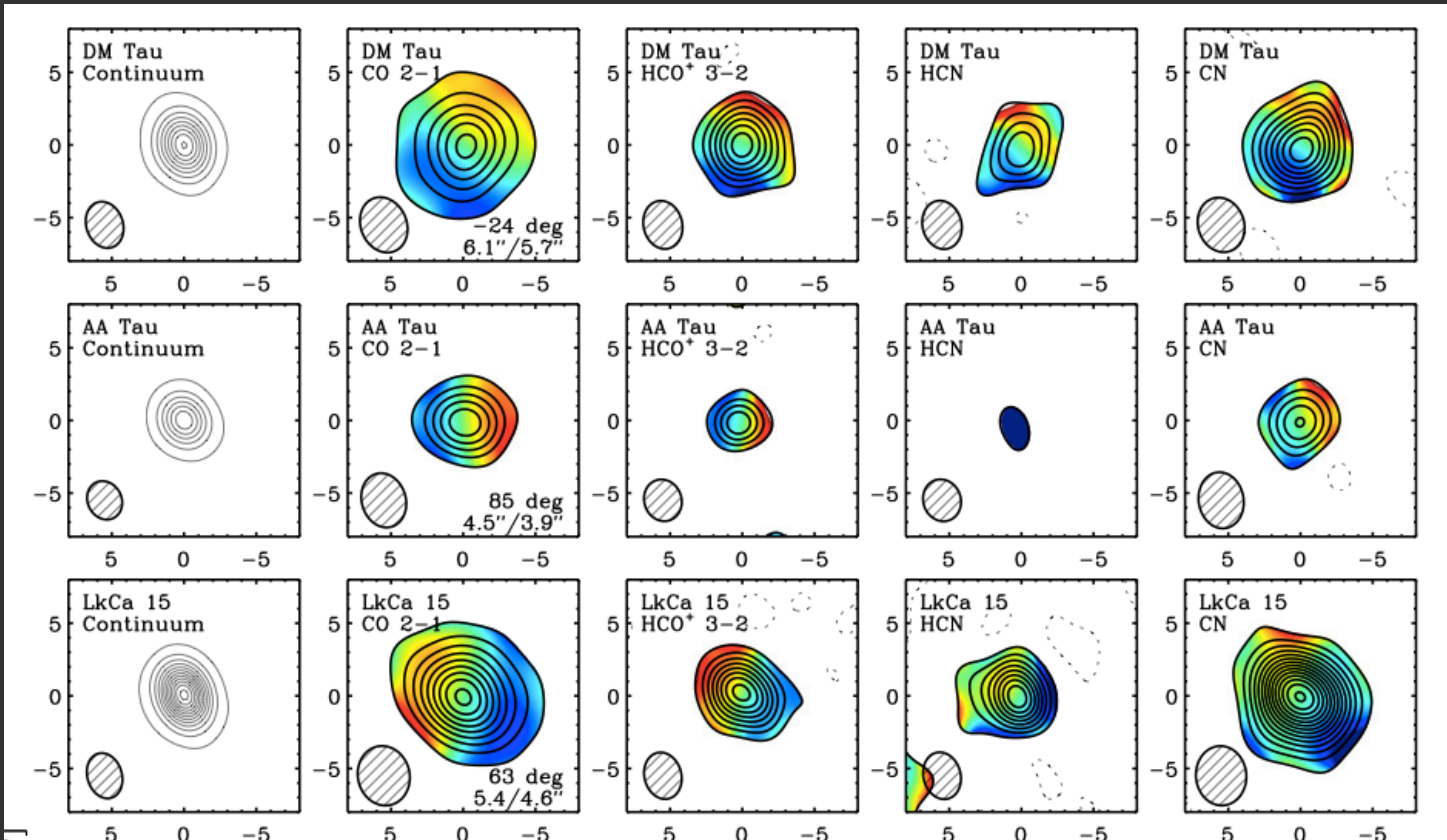
[Najita+ 2010]



[Salyk+ 2008]

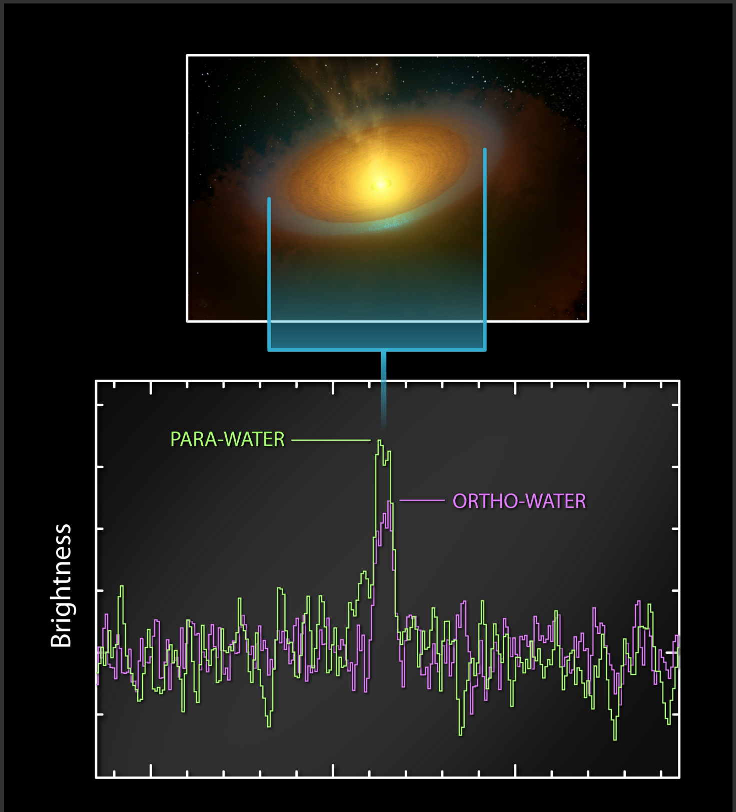
Spitzer studies of disks detect H_2O, OH, NeII and organics

Gas in Disks



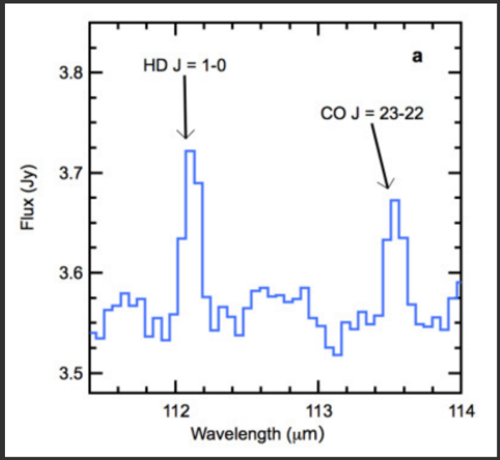
[Oberg+ 2010]

Gas in Disks

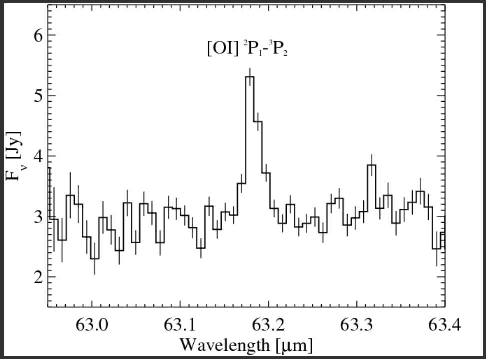


HIFI Spectroscopic Signatures of Water Vapor in TW Hydrae Disk
ESA/NASA/JPL-Caltech/M. Hogerheijde (Leiden Observatory)

[Hogerheijde+ 2010]



[Bergin+ 2013]

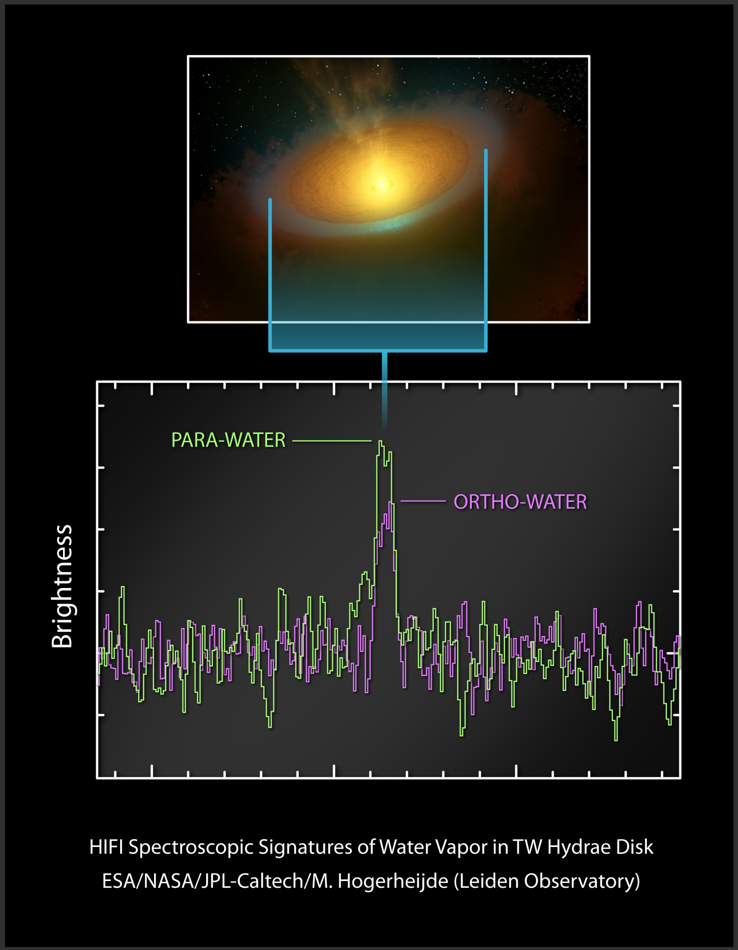


[Thi+ 2010]

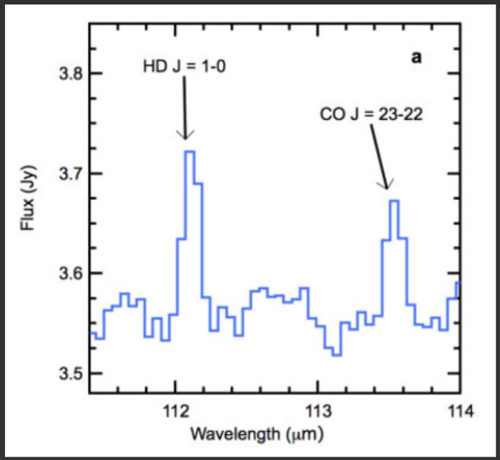
Herschel detects water, HD and OI from disks

Goran Sandell's talk on OI

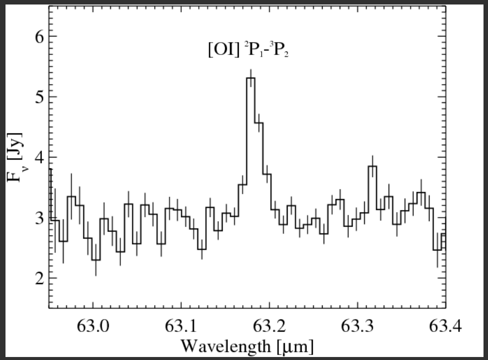
Gas in Disks



[Hogerheijde+ 2010]



[Bergin+ 2013]



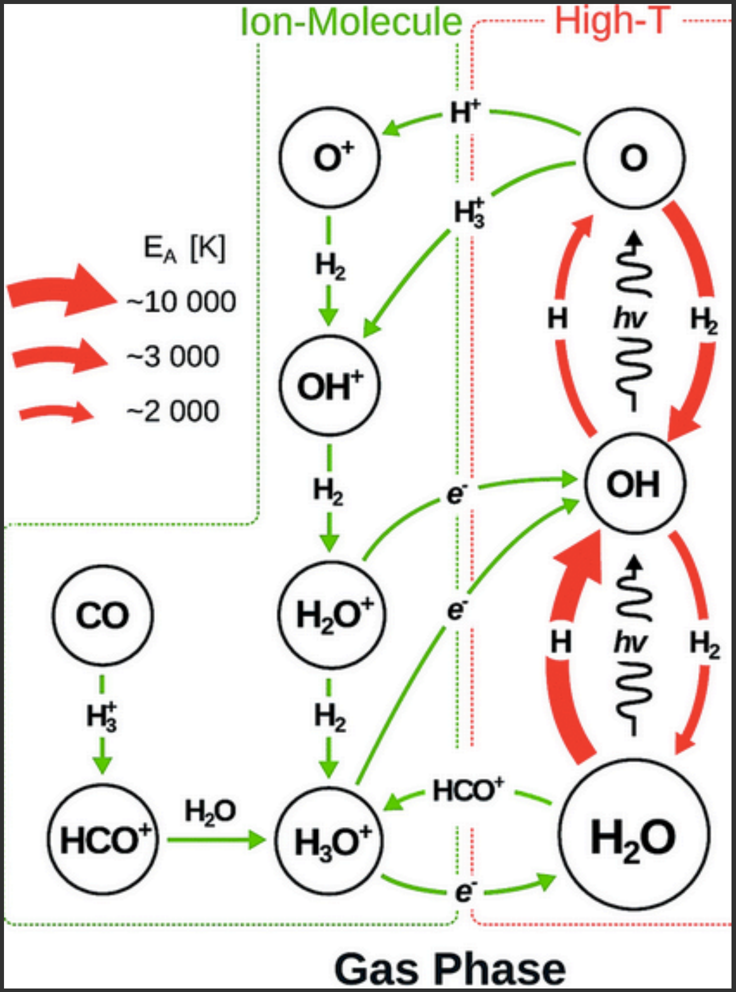
[Thi+ 2010]

Herschel detects water, HD and OI from disks

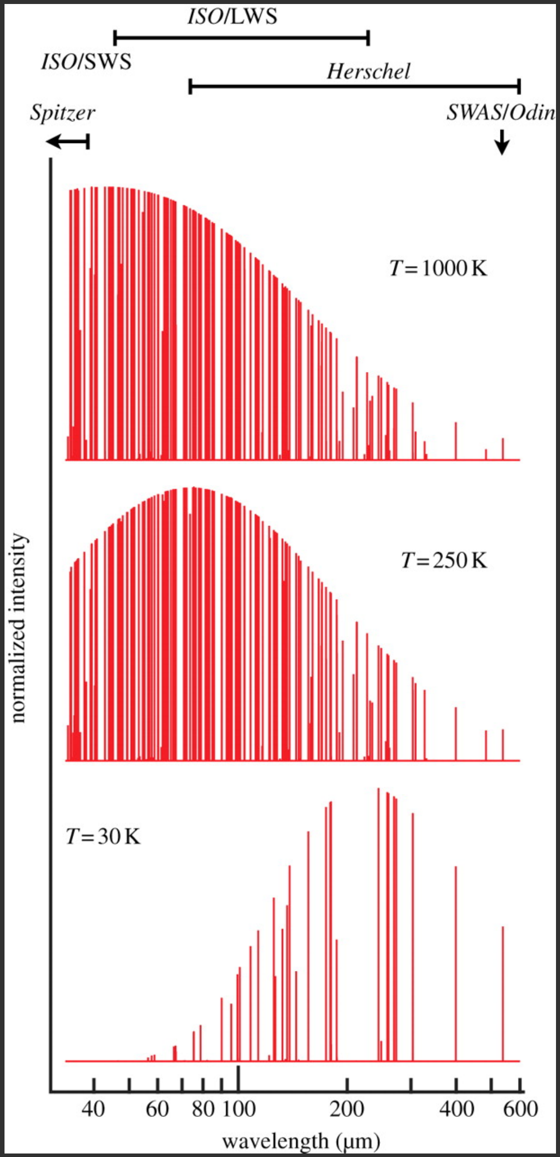
Interpretation not straightforward

Gas in Disks

Emission depends on abundance hence
Chemistry which is sensitive to gas temperature

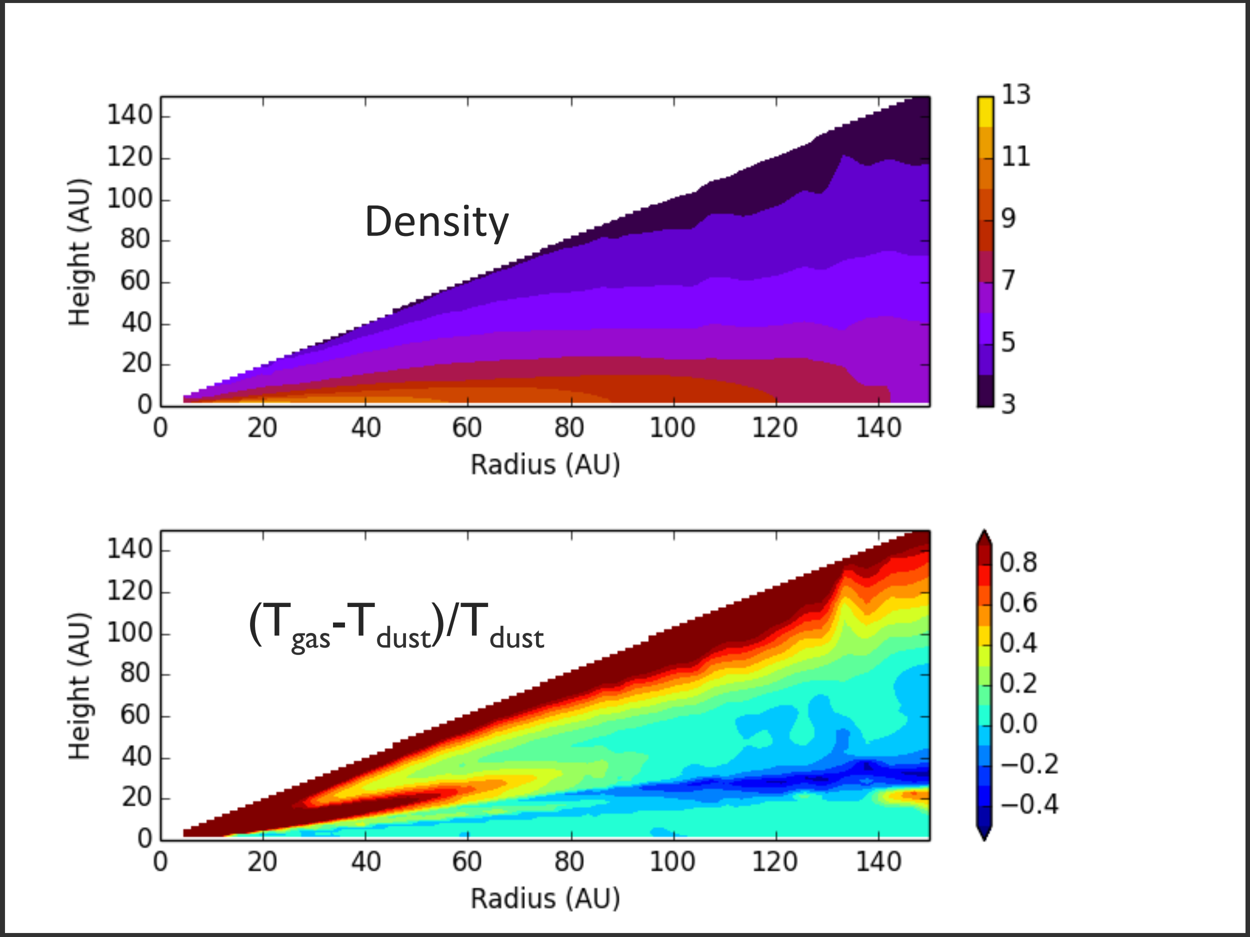


[van Dishoeck 2014]



[Bergin & van Dishoeck 2012]

Gas in Disks



Gas and dust temperatures are not equal

Need for thermochemical modeling

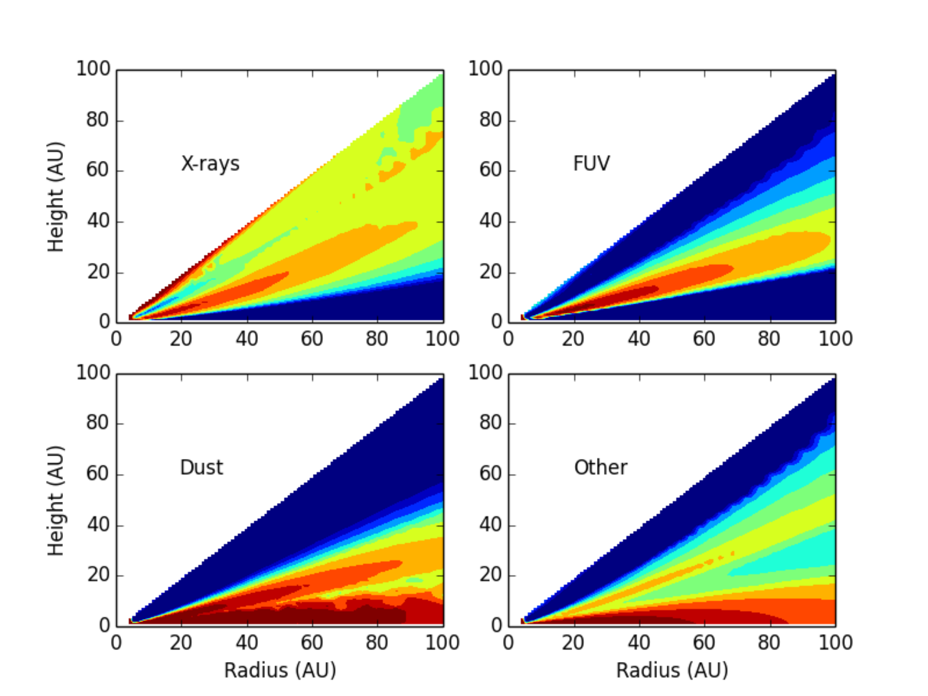
Gas in Disks

Heating mechanisms:

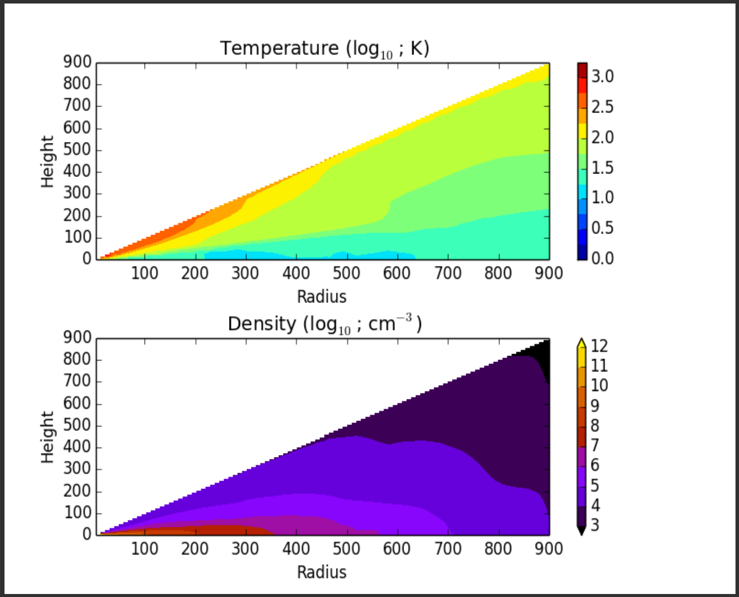
Dust, UV-grain photoelectric emission, UV pumping, X-rays, cosmic-rays, chemical processes, viscous heating, magnetic reconnections, shocks, other local or transient effects

Cooling mechanisms:

Emission from atoms, ions, molecules, dust

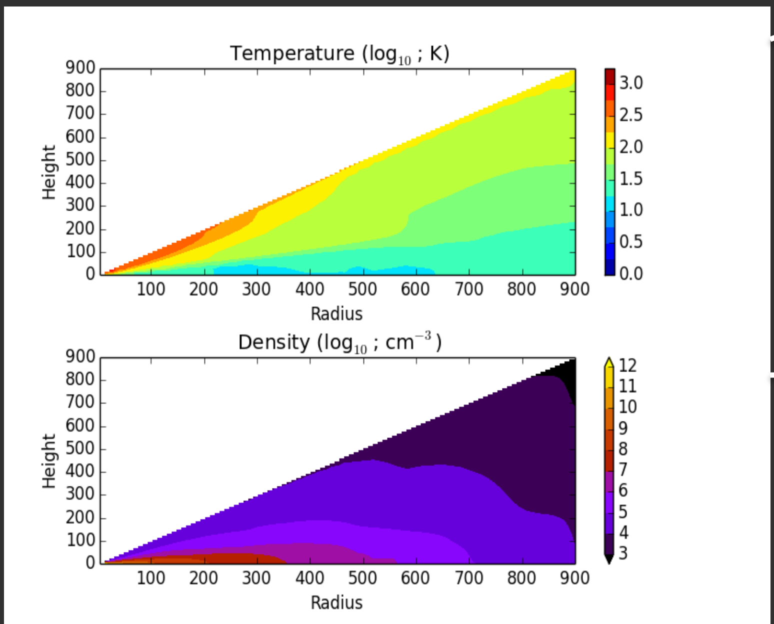


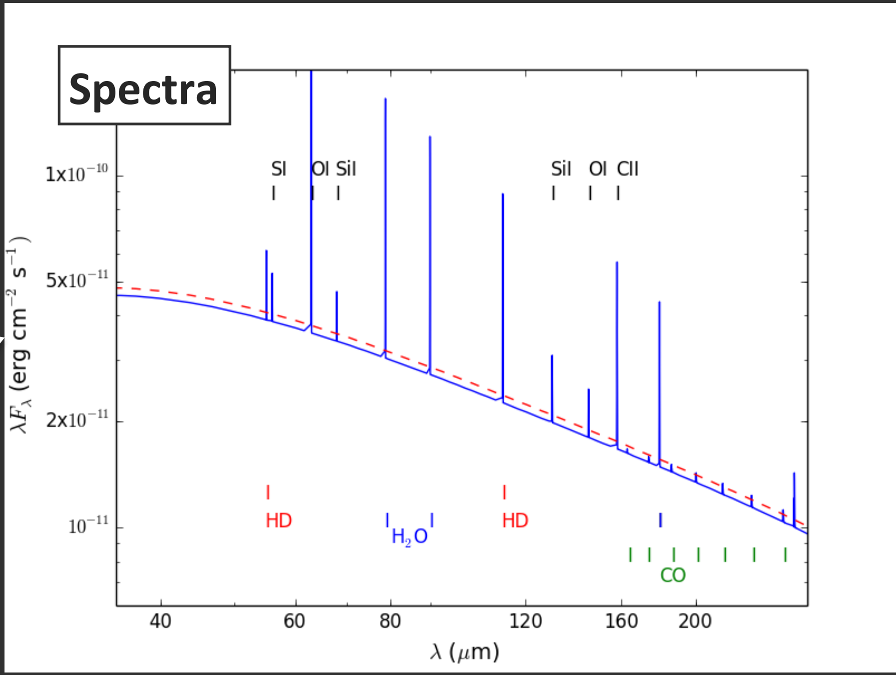
Chemistry + Radiative Transfer
+ Pressure balance (Vertical HSE)

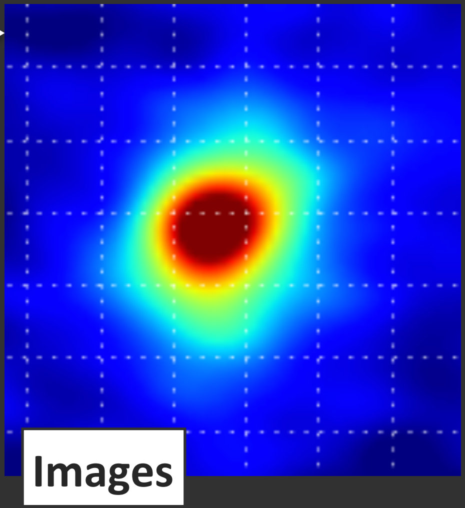


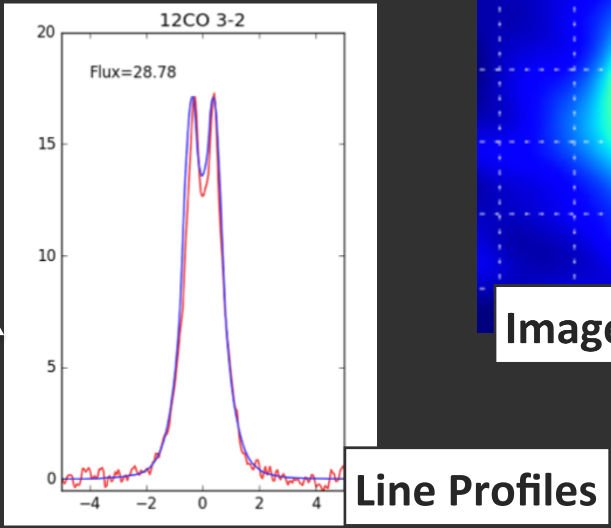
Gas in Disks

Disk density, temperature structure, abundances with Radiative transfer

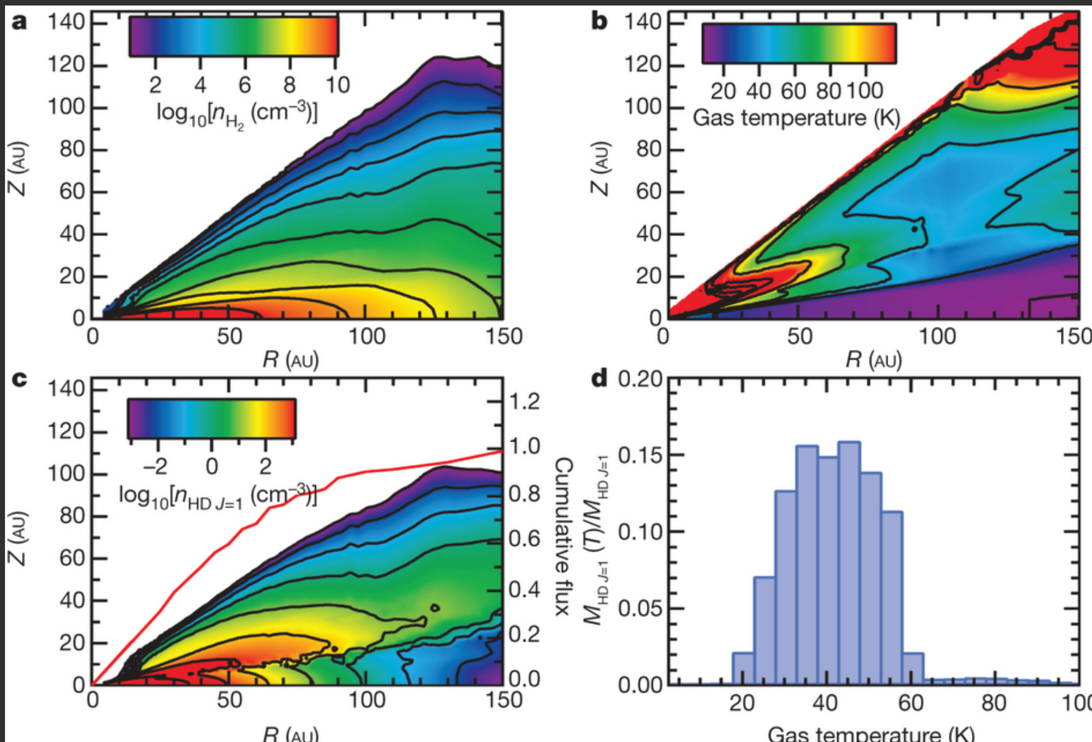






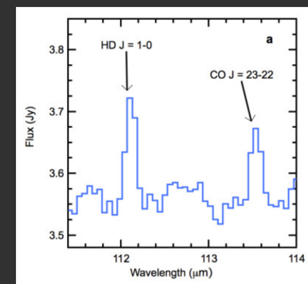


Gas in Disks

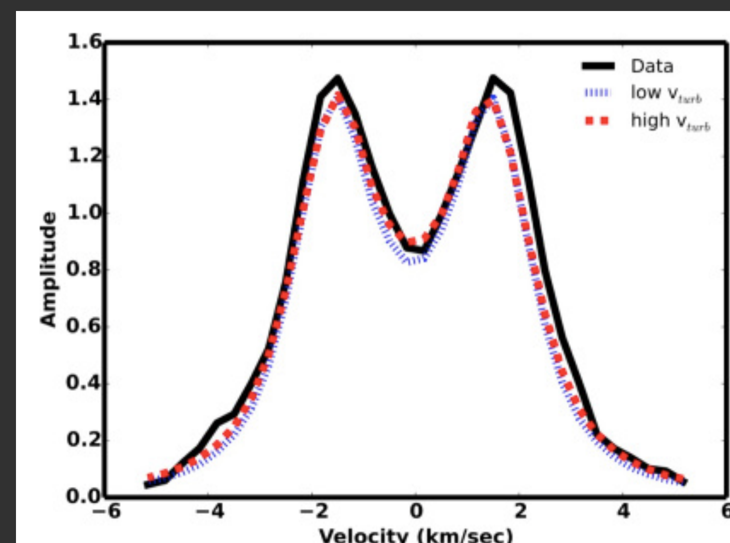


[Bergin+ 2013]

Mass of disk around TW Hya



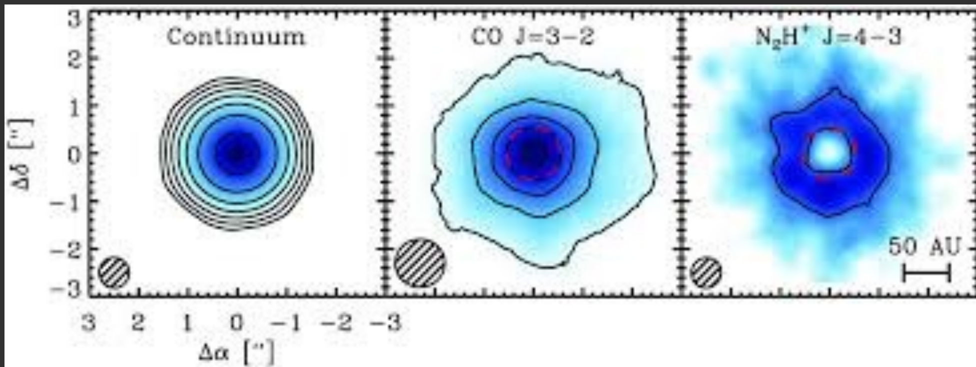
[Flaherty+ 2015]



Turbulence in HD 163296 is low ($\alpha < 0.003$)

Gas in Disks

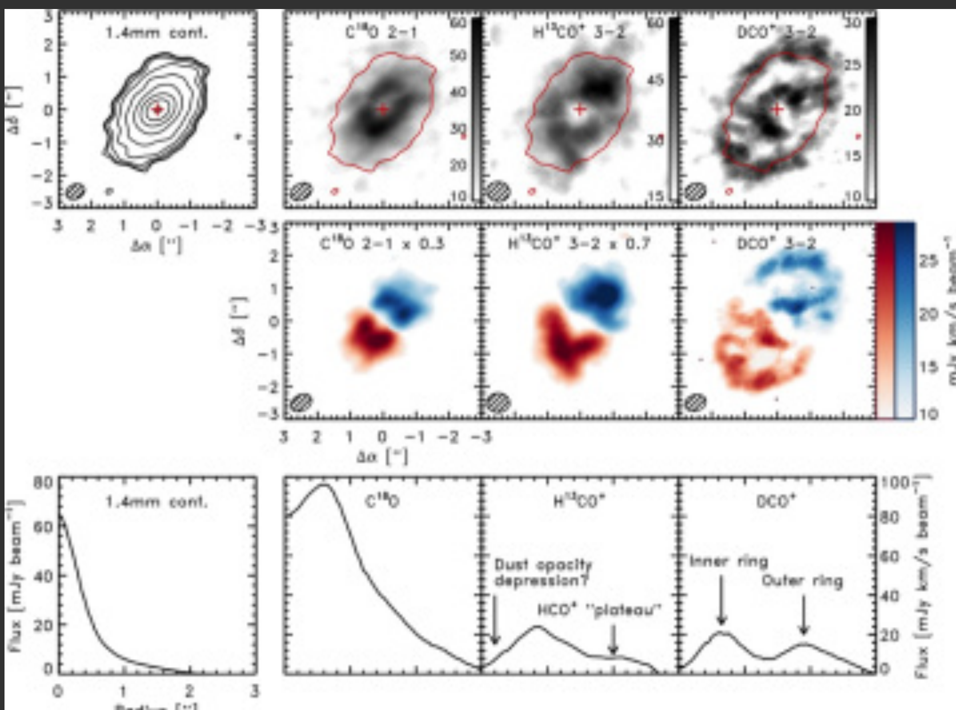
[Qi+ 2013, 2015]

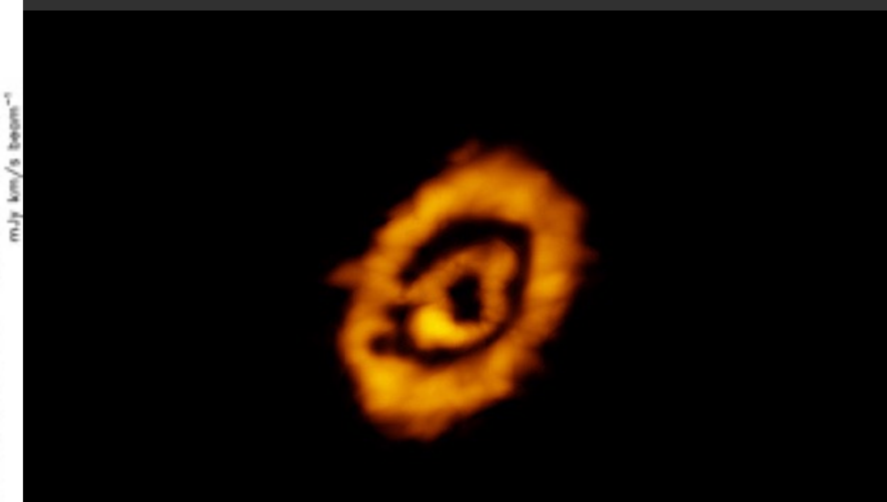


N_2H^+ in TW Hya

Snow lines everywhere!

Grain surface chemistry is important.



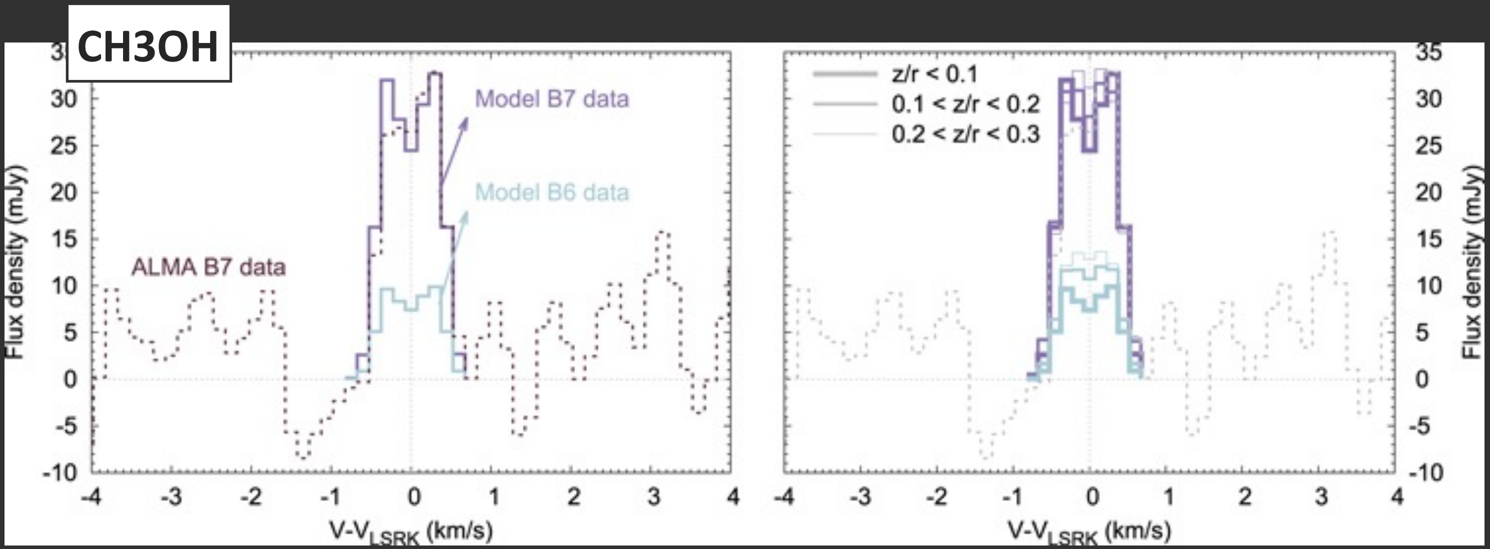


DCO^+ in IM LUP

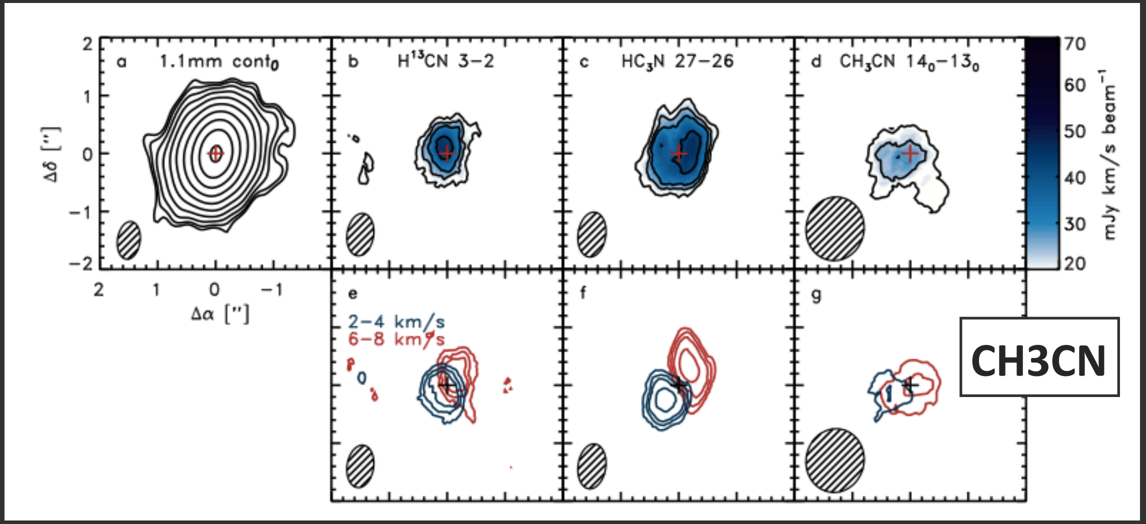
[Oberg+ 2015]

Gas in Disks

Complex chemistry in disks



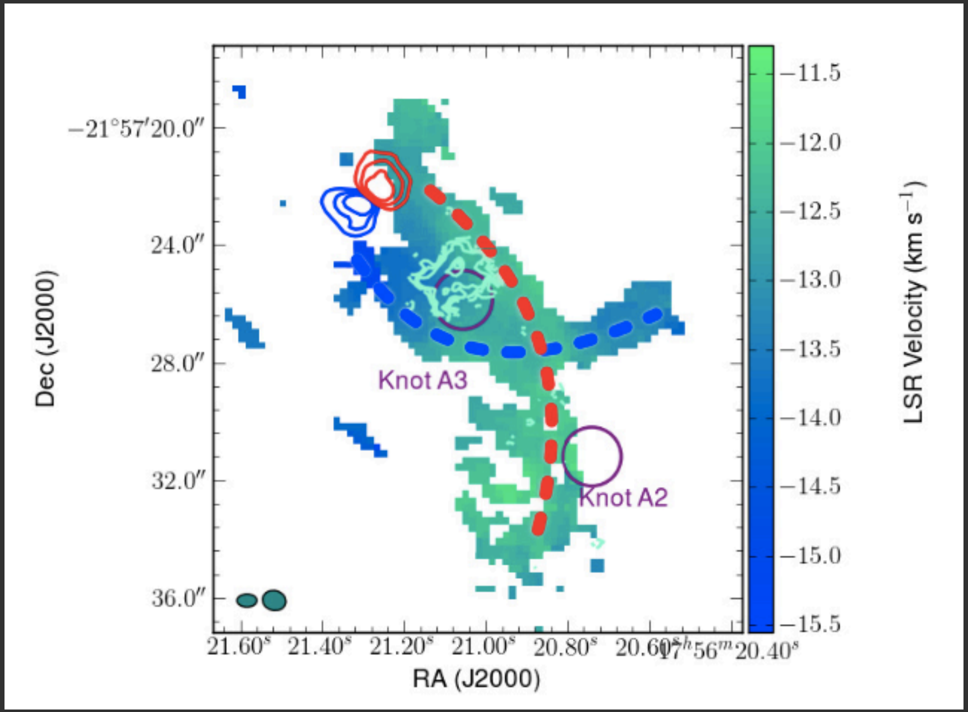
[Walsh+ 2016]



[Oberg+ 2015]

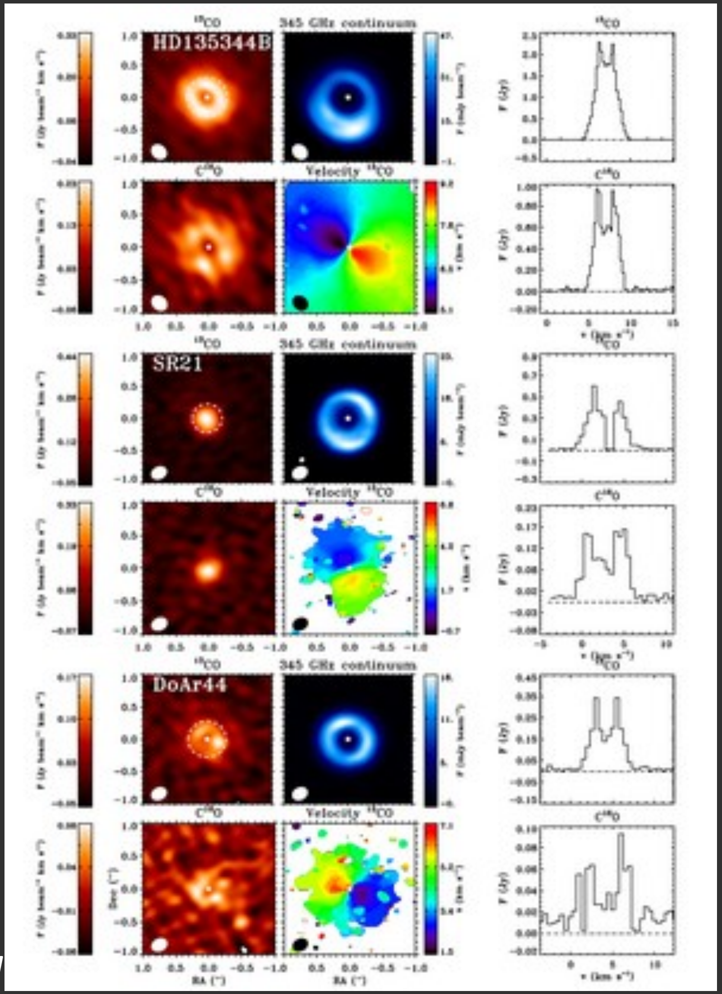
Gas in Disks

CO Wind from HD163296



[Klaassen+ 2013]

Gas interior to dust holes

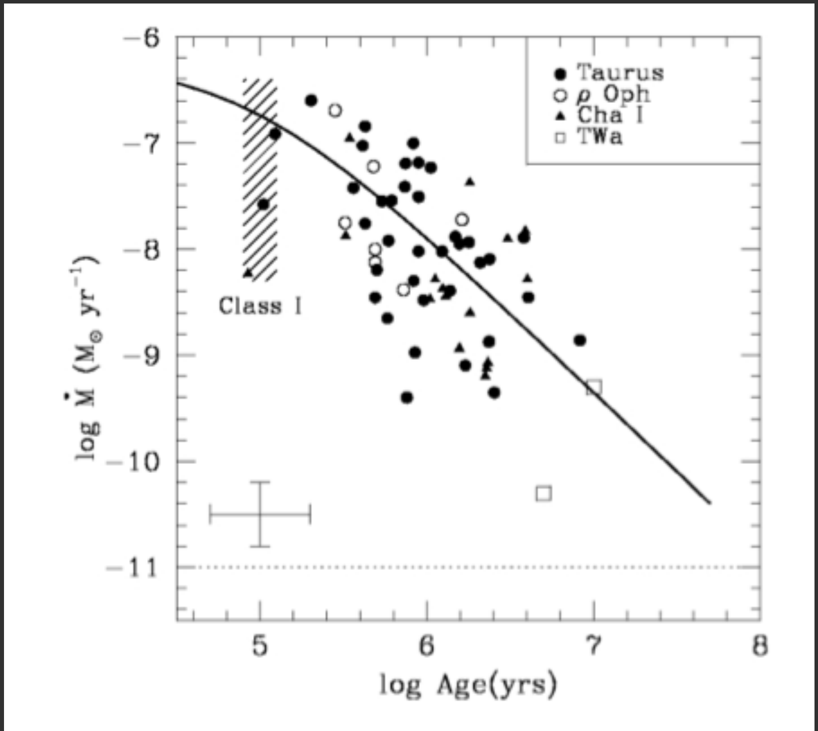


[van der Marel+ 2015]

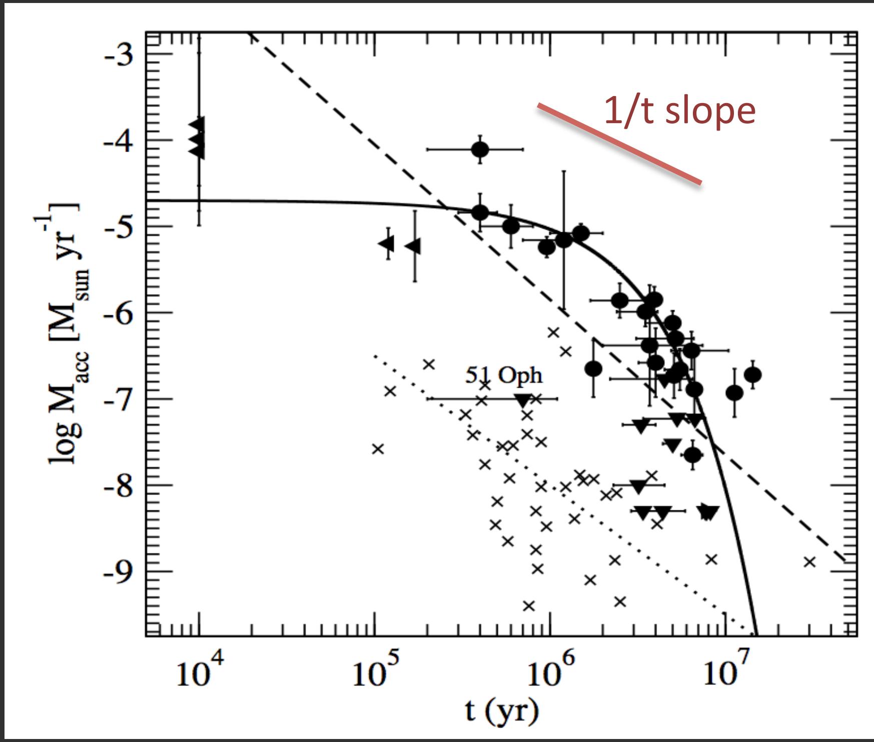
Insights from disk surveys

Disk surveys

Accretion rate onto star decreases with time



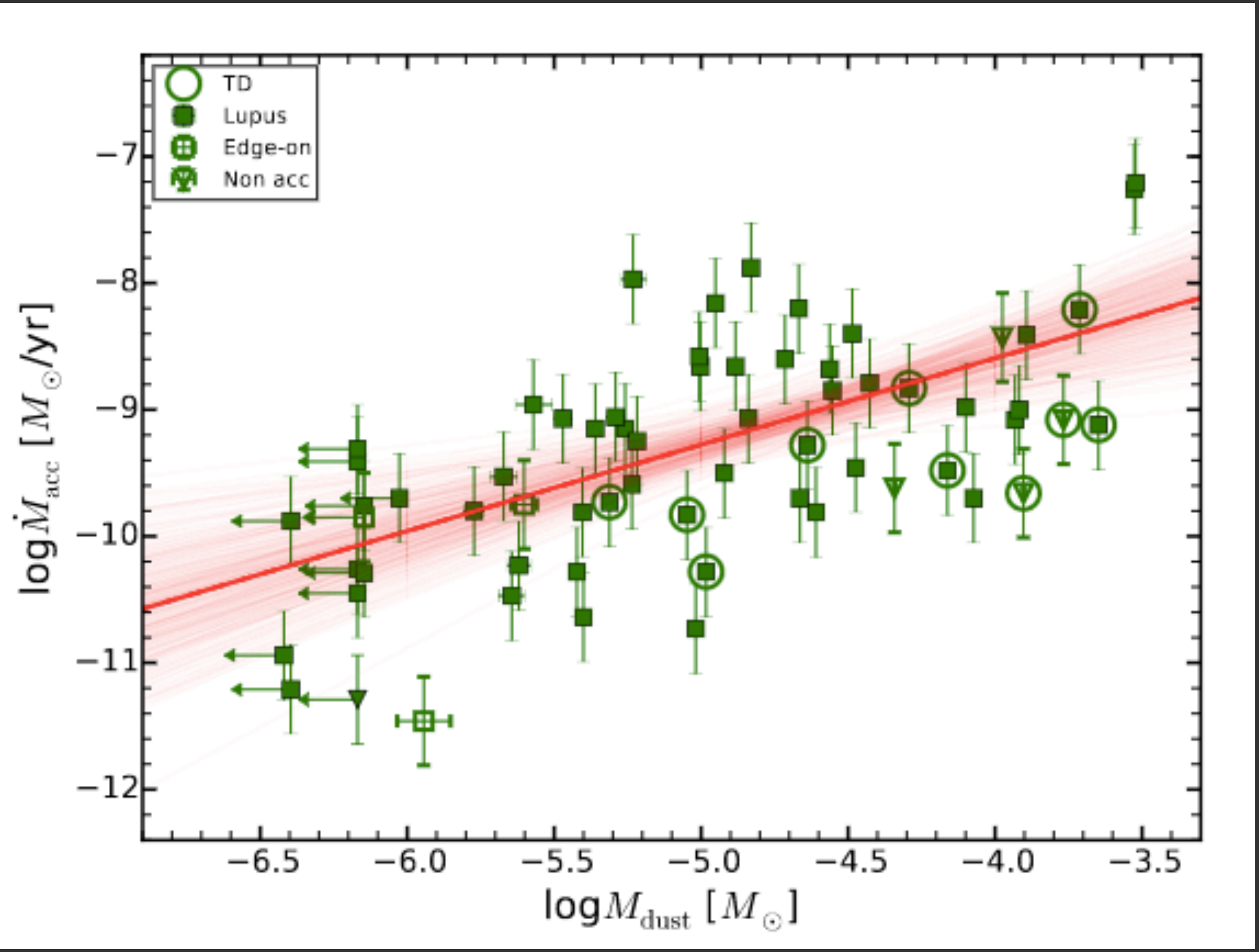
[Hartmann+ 1998]



[Mendigutia+ 2012]

Disk surveys

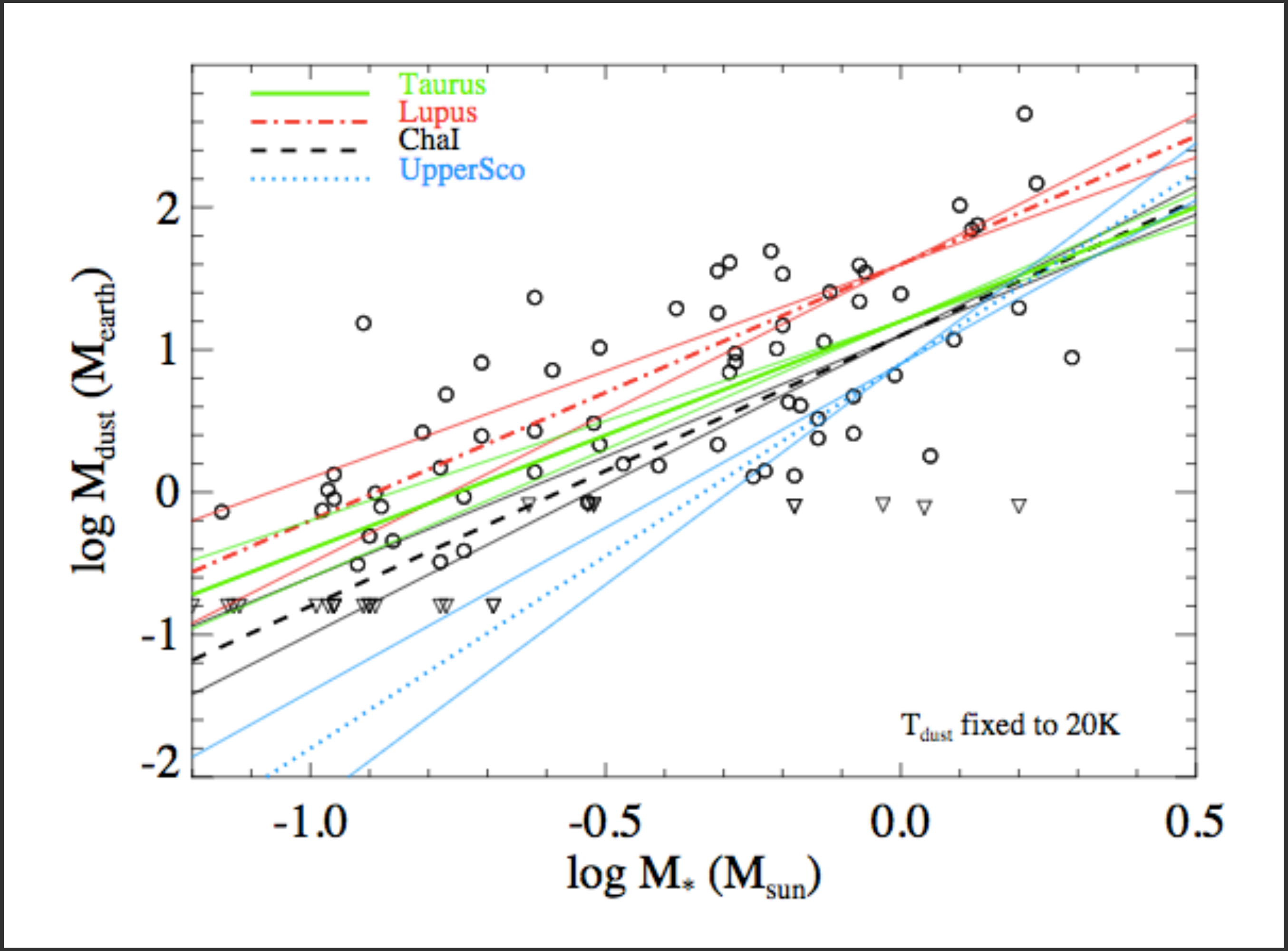
Accretion rate is proportional to dust disk mass



[Manara+ 2016]

Disk surveys

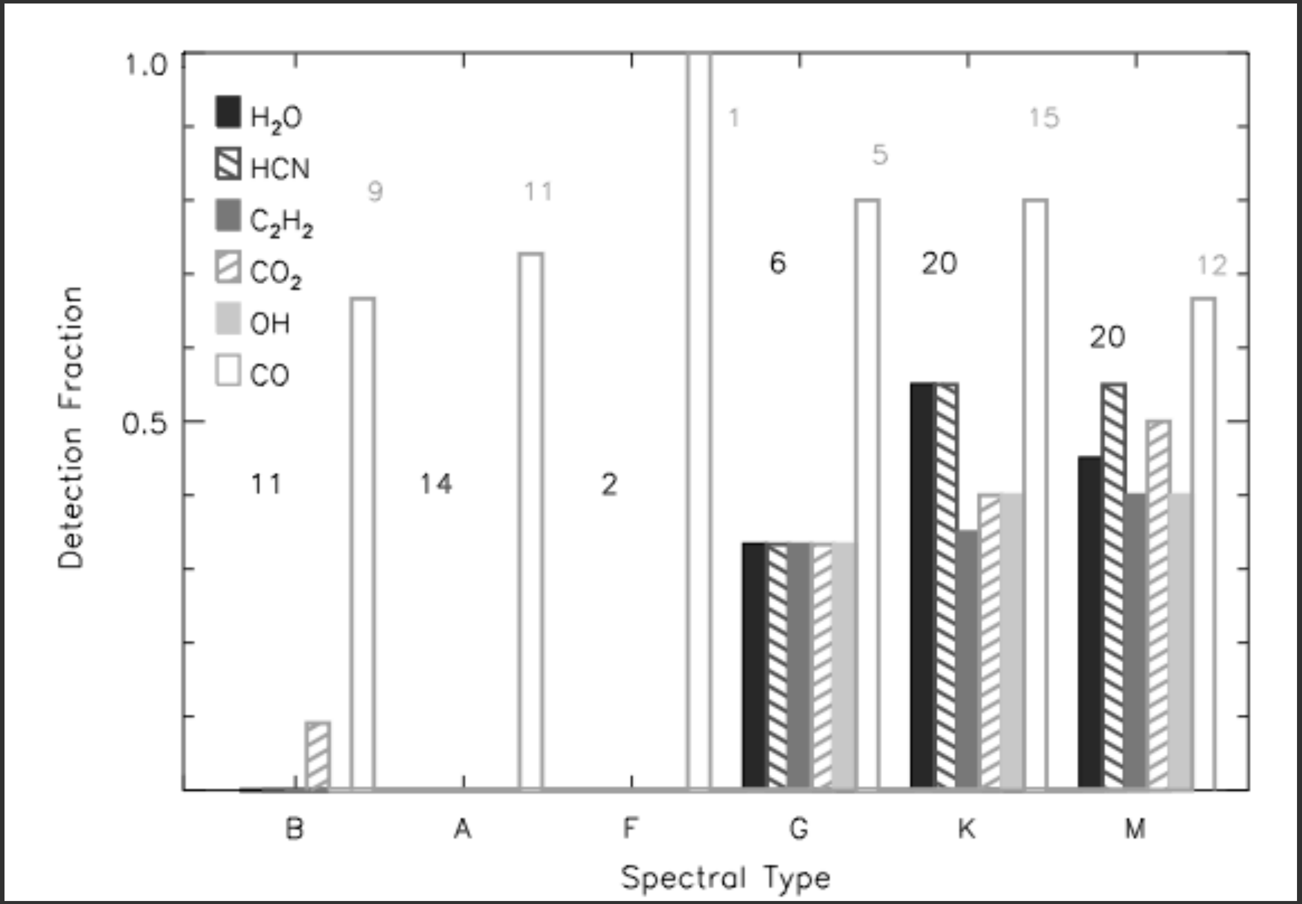
Disk dust mass is proportional to stellar mass, relation steeper in older SFRs



[Pascucci+ 2016]

Disk surveys

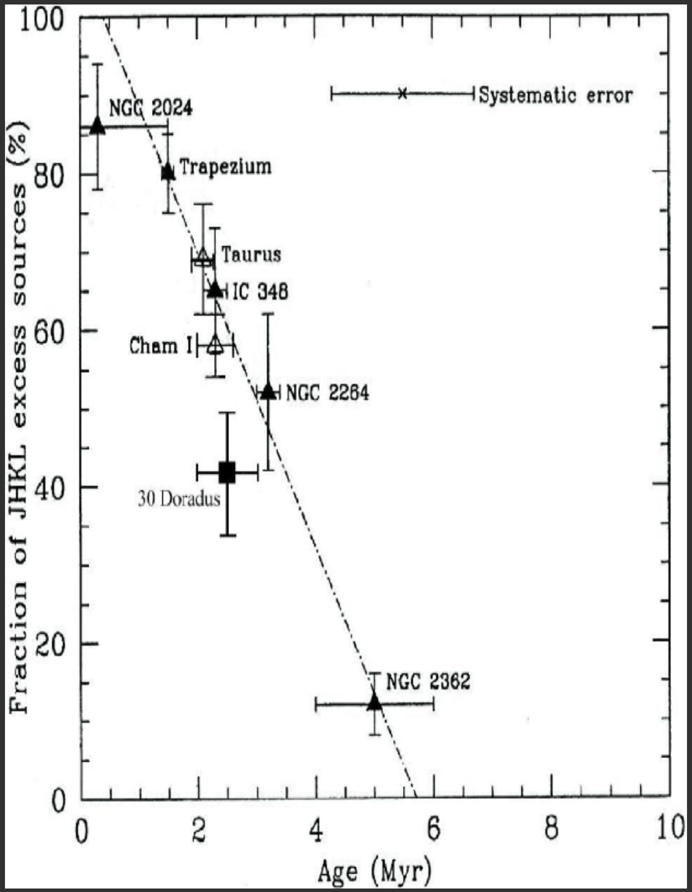
Detection rate of pre-organic molecules depends on stellar mass



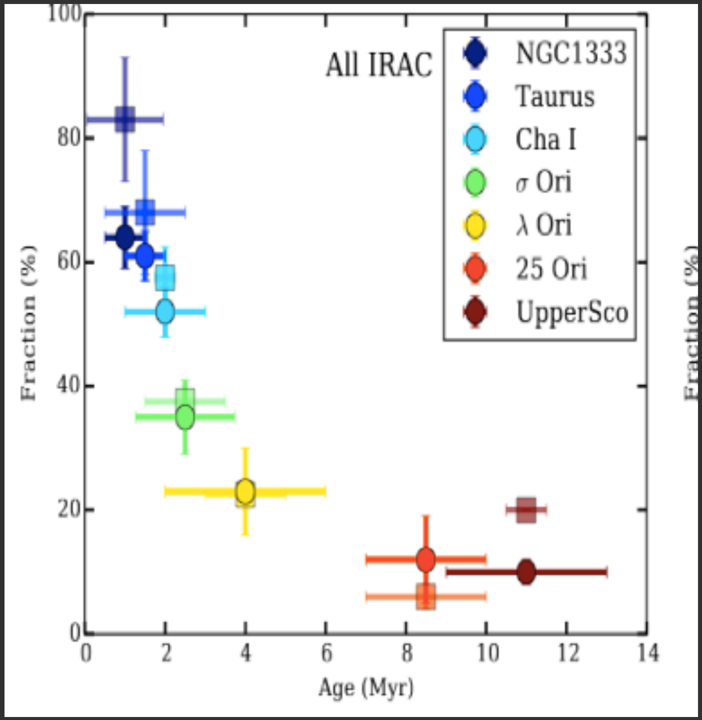
[Pontoppidan+ 2010]

Disk surveys

Dust disk lifetimes are ~ 3-5 Myrs



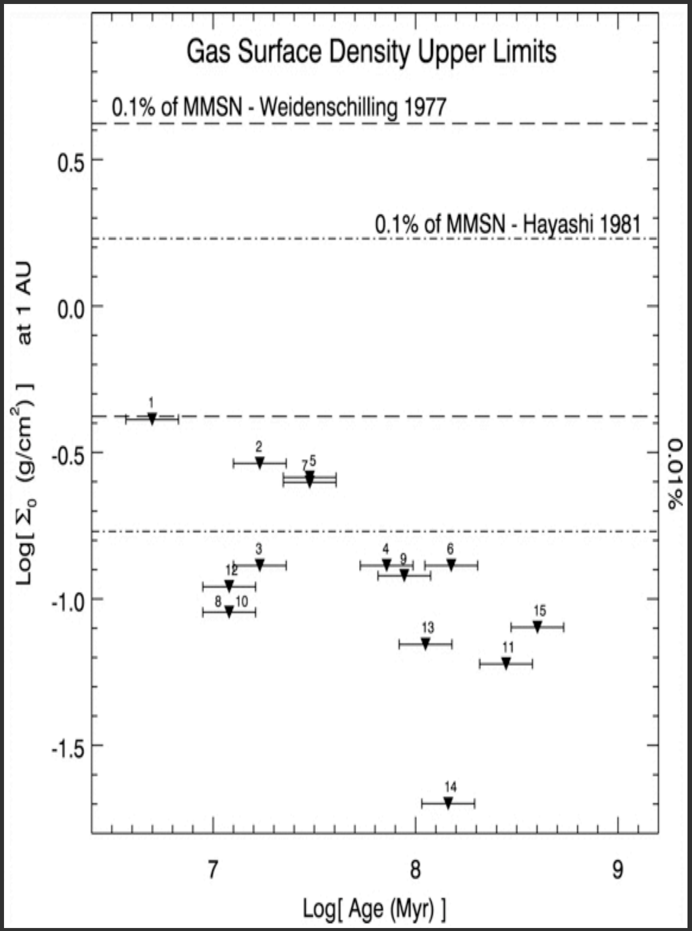
[Haish+ 2001]



[Ribas+ 2015]

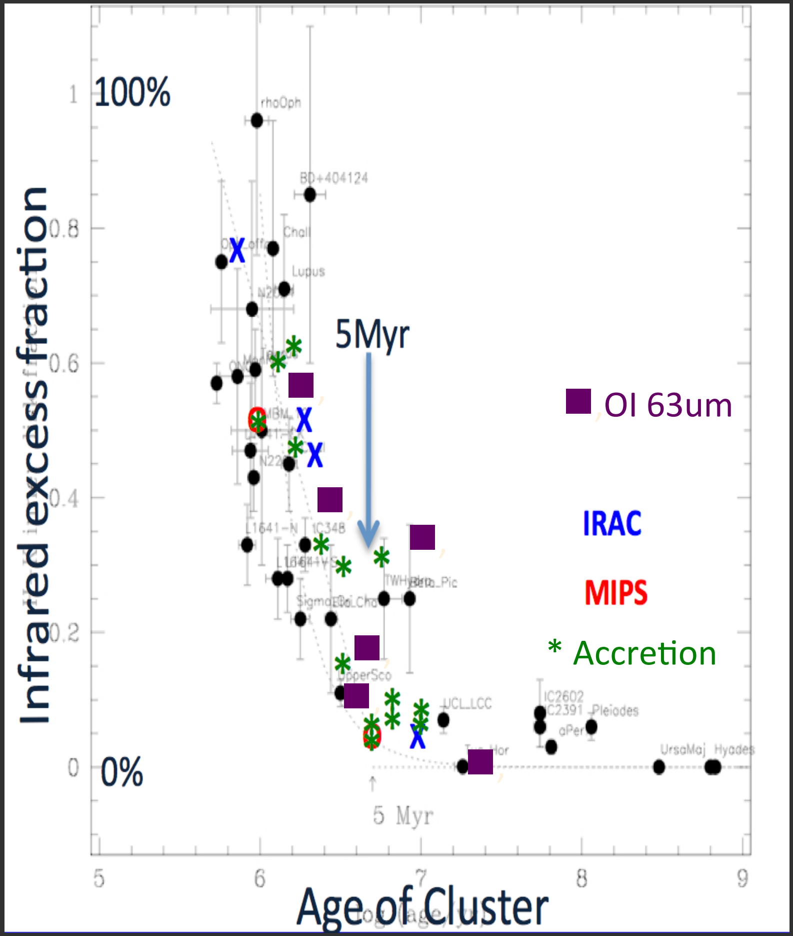
Disk surveys

Gas disk lifetimes are < 5-30 Myrs



[Pascucci+ 2006]

[Hillenbrand+ 2009]



[Dent+ 2013]

Disk surveys

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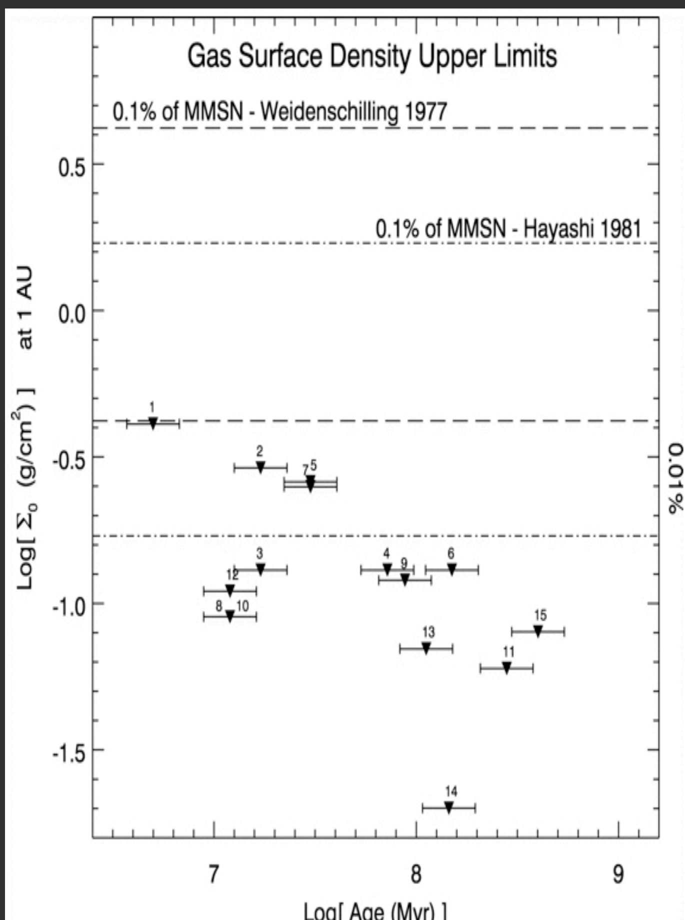

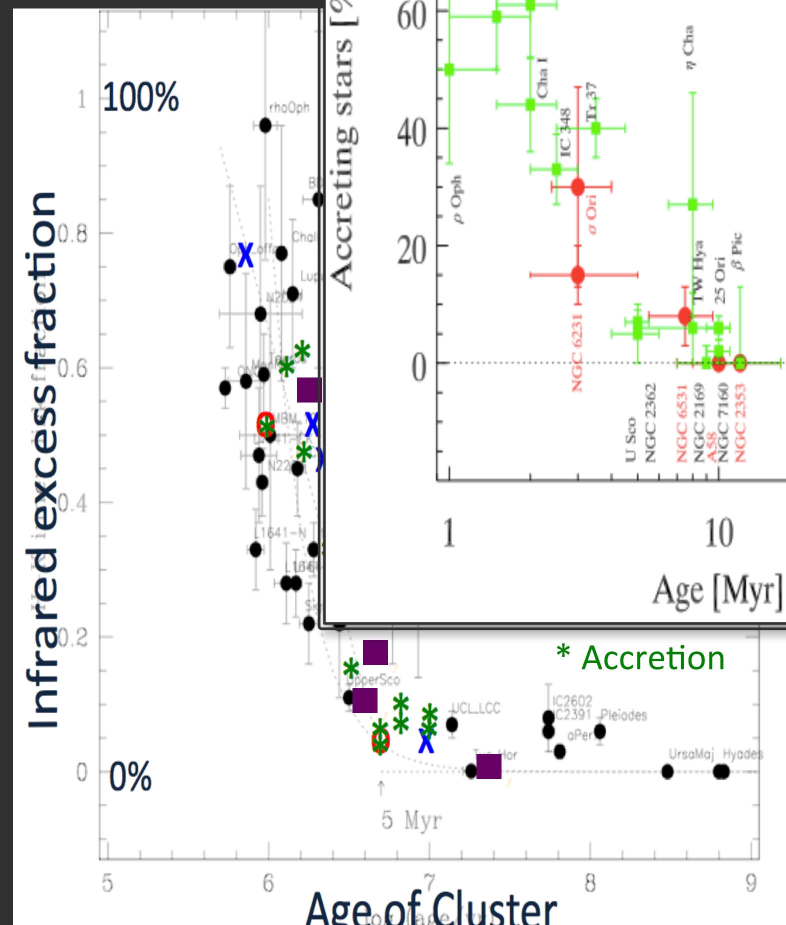

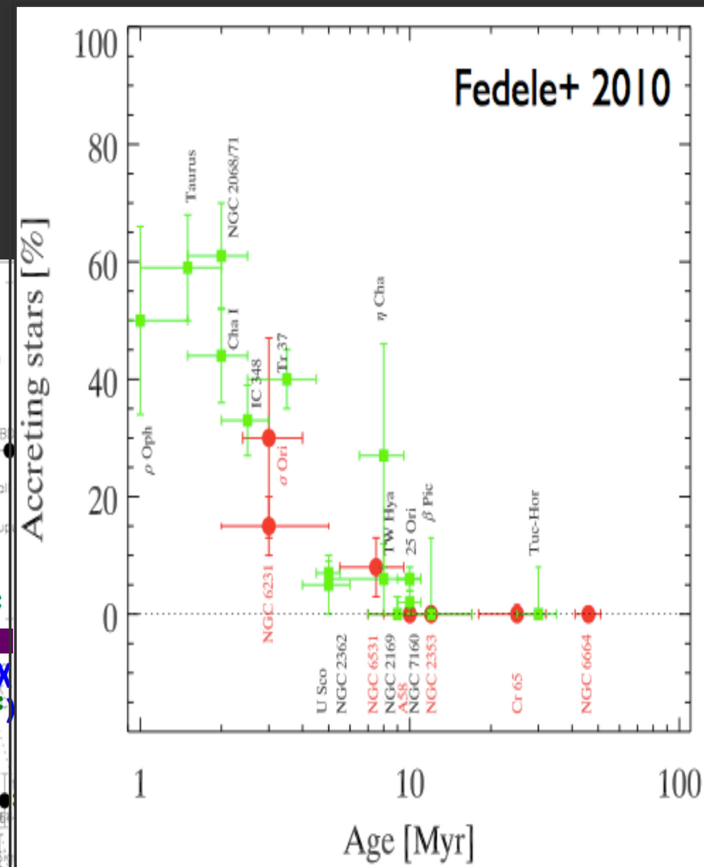

Recap:

- Dust: Rings, gaps at all stages, spirals, dust grain growth and drift
- Gas: Complex species, Growing role for grain surface chemistry, slow winds
- Disk accretion rate declines with time (viscous accretion theory)
- Disk dust mass is correlated with accretion rate (accretion models predict this)
- Disk mass is correlated with stellar mass (to be expected)
- More complex molecules detected in cooler stellar environments (UV dissociation)
- Gas and Dust Disk lifetimes are < 10 Myrs (planets form, gas photoevaporates)

Many questions remain!

Recap:

- Dust: Rings, gaps at all stages, spirals, dust grain growth and drift
- Gas: Complex species, Growing role for grain surface chemistry, slow winds
- Disk accretion rate declines with time (viscous accretion theory)
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Questions we still have:

- Viscosity levels in disk (rate of transport)
- What are the gas masses of disks?
- Spatial distribution of gas with time, gas/dust ratio
- Rate of dispersal, gas present at late stages
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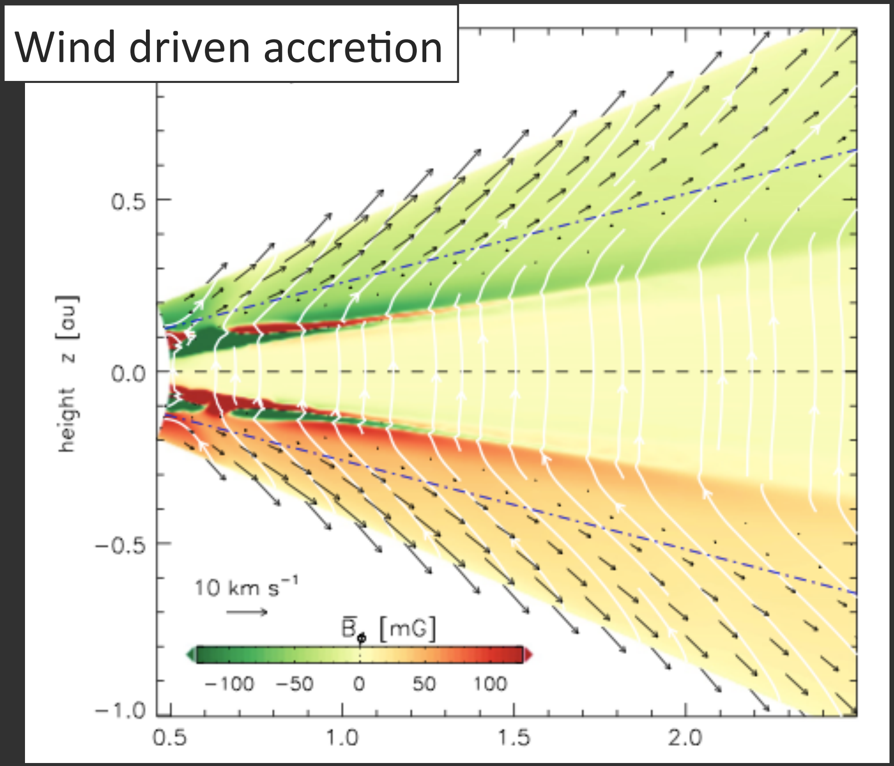
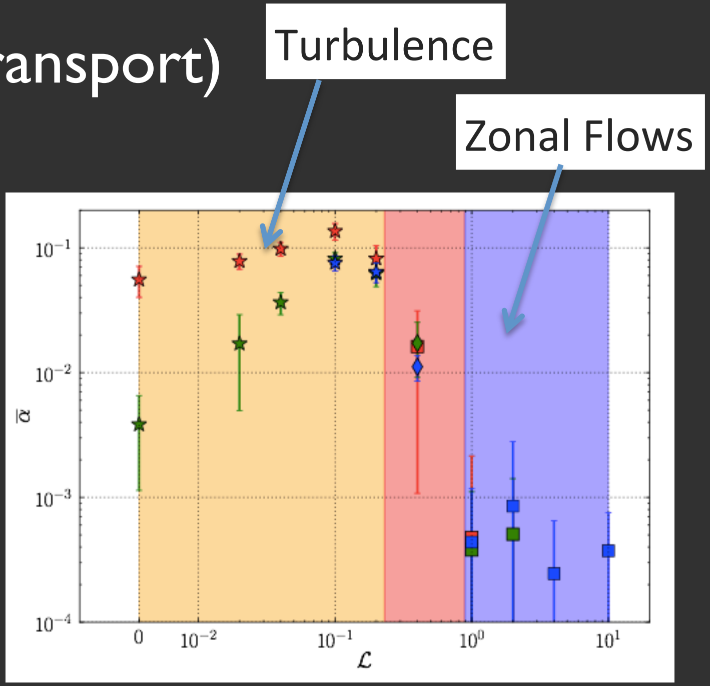


[Gressel+ 2015]



[Bethune+ 2016]

Measure turbulence in more disks

Questions we still have:

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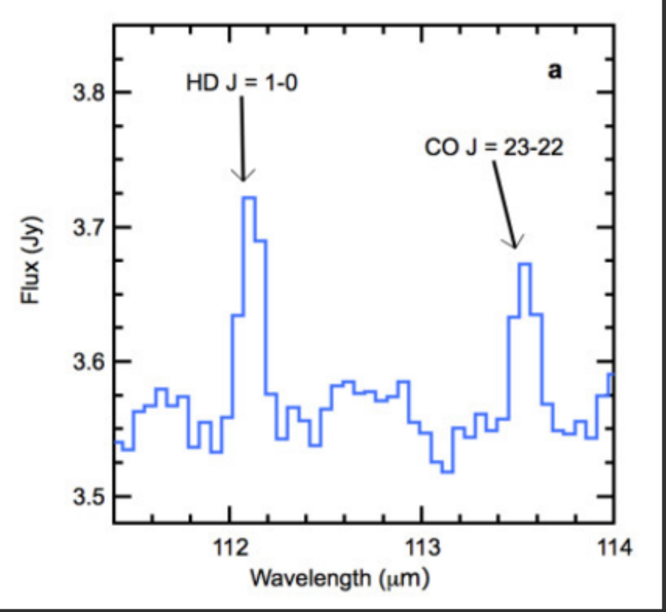


[Bergin+ 2013]

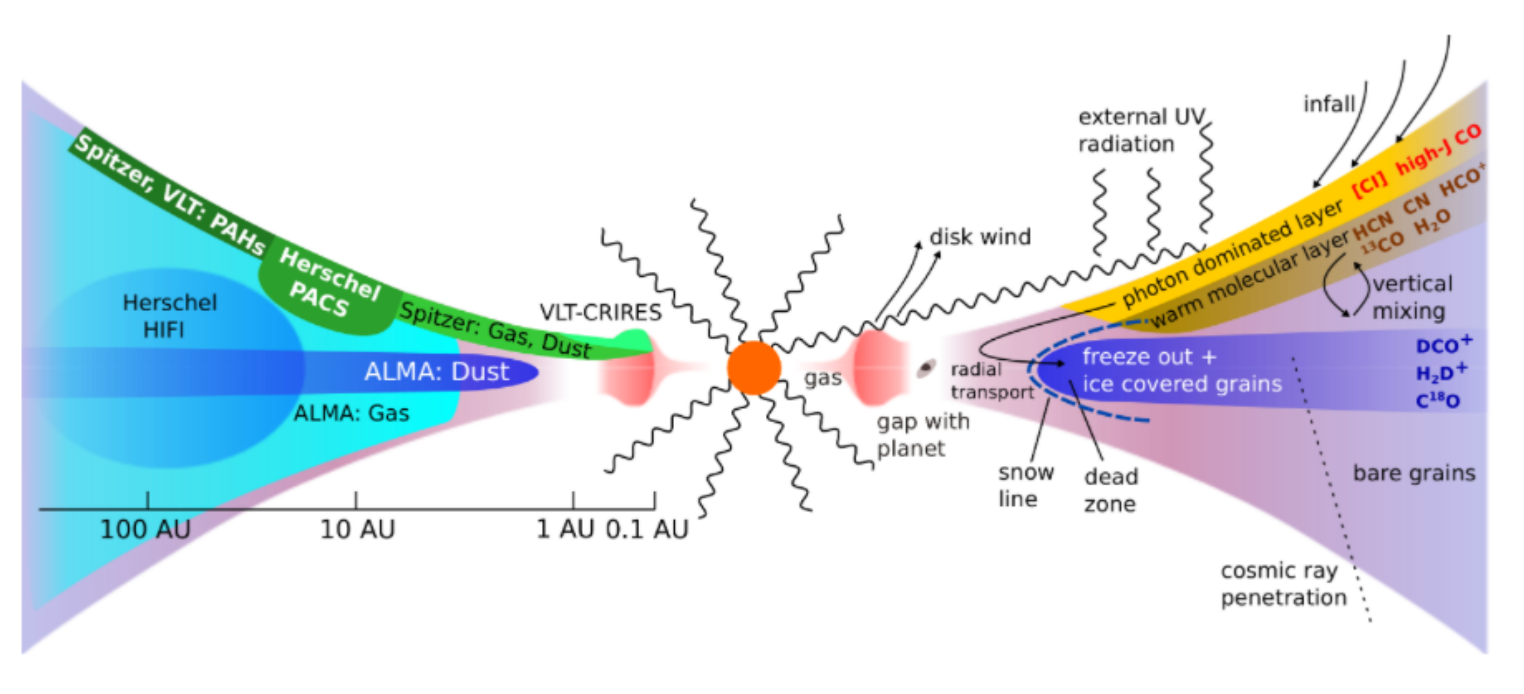
- HD 55um and 112um – mass tracer
- ALMA and spatial/velocity resolved CO isotope data
- CO depleted in disks ?

Melissa McClure’s talk

Questions we still have:

- Spatial distribution of gas with time, gas/dust ratio

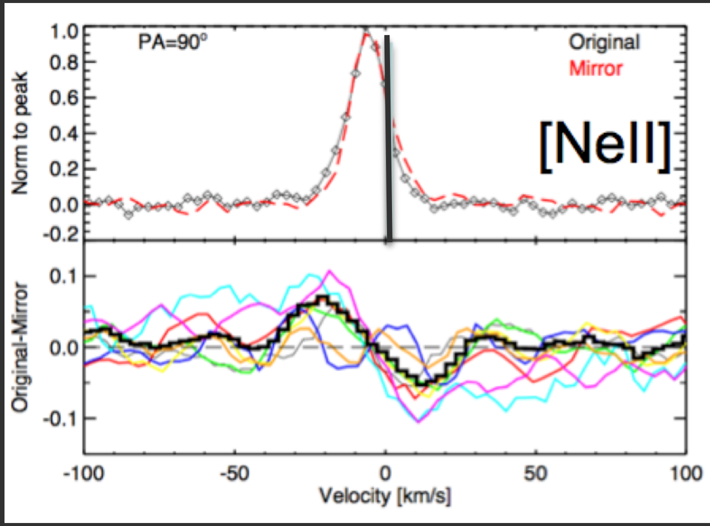
Multiwavelength surveys of disks probing different regions



[van Dishoeck 2014]

Questions we still have:

- Rate of dispersal, gas present at late stages

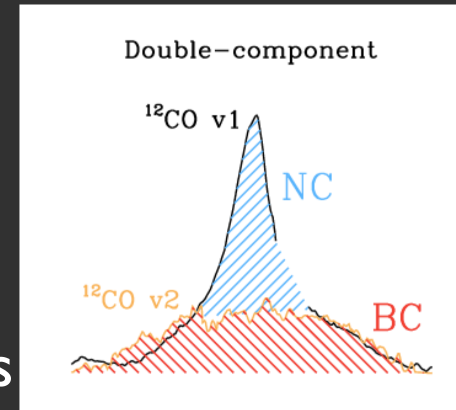


[Pascucci+ 2012]

Blue-shifted NeII

Slow winds from disks:
Current mass loss estimates range from 10^{-11} to 10^{-7} M_o yr^{-1} !

[*Banzatti & Pontoppidan 2015*]



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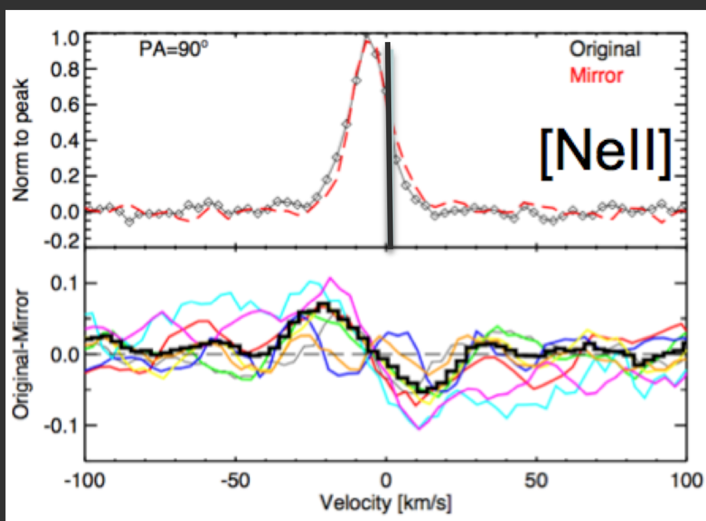
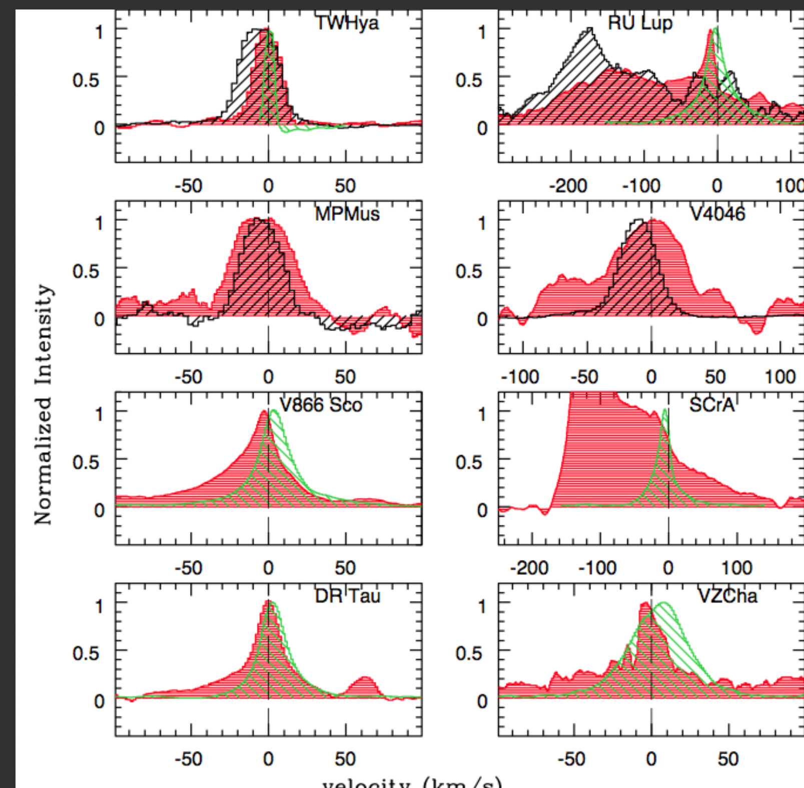


Winds in other tracers
[OI]6300A, CO vib. lines

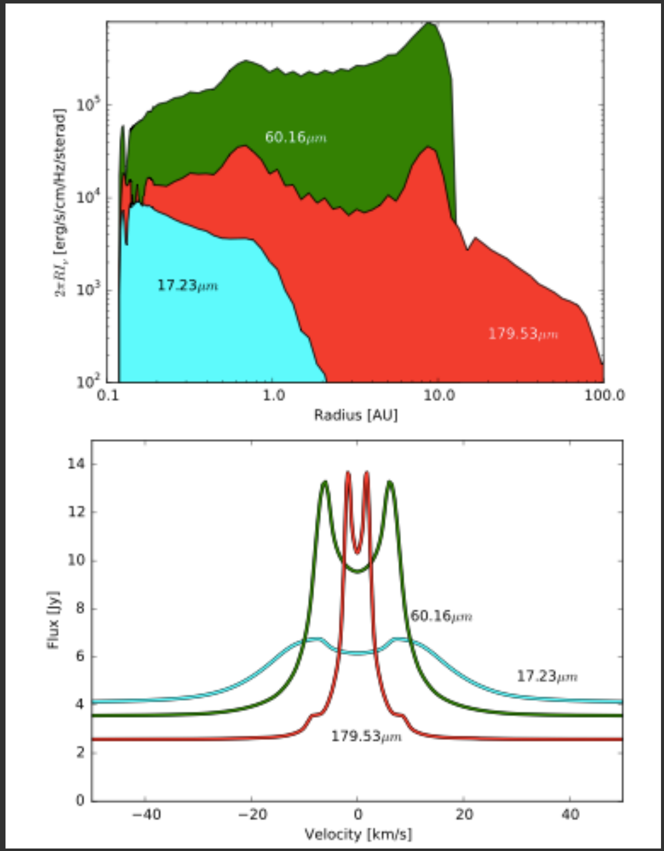


[Rigliaco+ 2013]

Questions we still have:

- Chemistry in disks and planet composition

[Blevins+ 2016]



Water is key molecule – icy grains have implication for planet formation.

Ground state transitions of H2O, OH in the far-infrared
[most disk gas is cold]

OI and CII – provide measures of the C/O ratio at surface

<u>Questions we still have:</u>

- Chemistry in disks and planet composition

[Min+ 2016]

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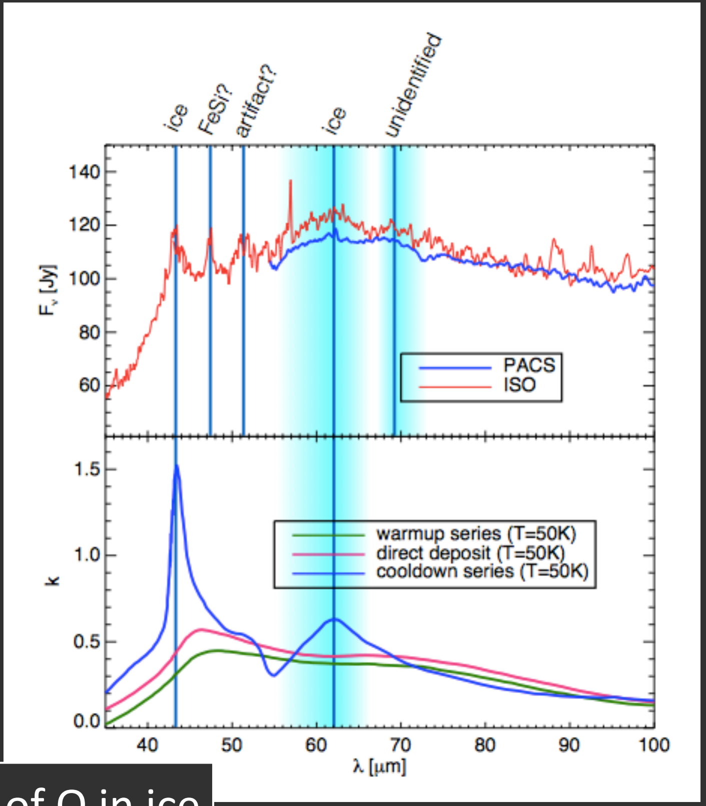
H2O depletion – Icy grains and planet formation



80% of O in ice

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- What are the gas masses of disks? HD
- Spatial distribution of gas with time, gas/dust ratio HD OI
- Rate of dispersal, gas present at late stages OI CII
- Chemistry in disks and planet composition H_2O OH

The Far Infrared is a key piece of the puzzle

Thank you!