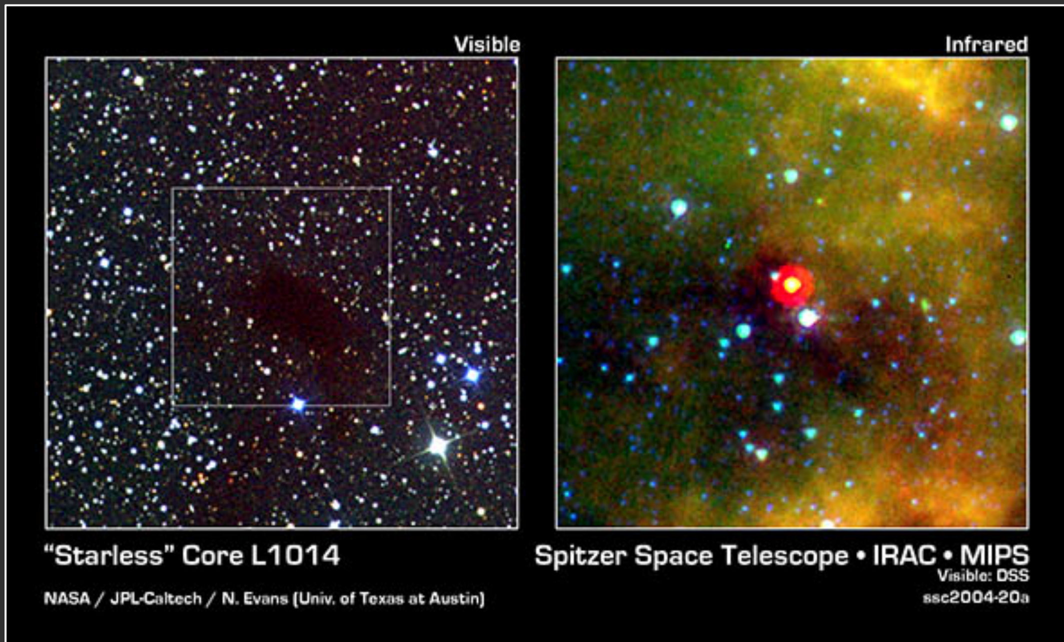
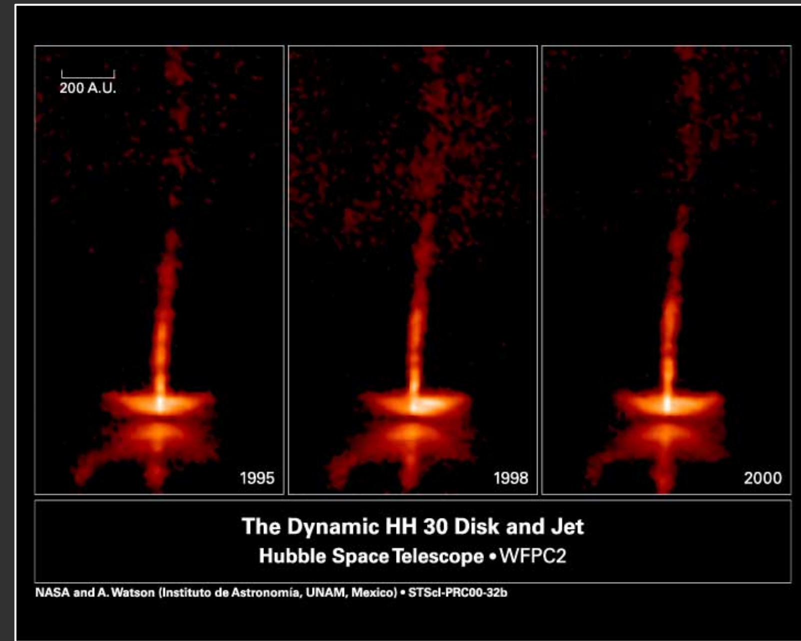
Photoevaporation and The Evolution Of Protoplanetary Disks

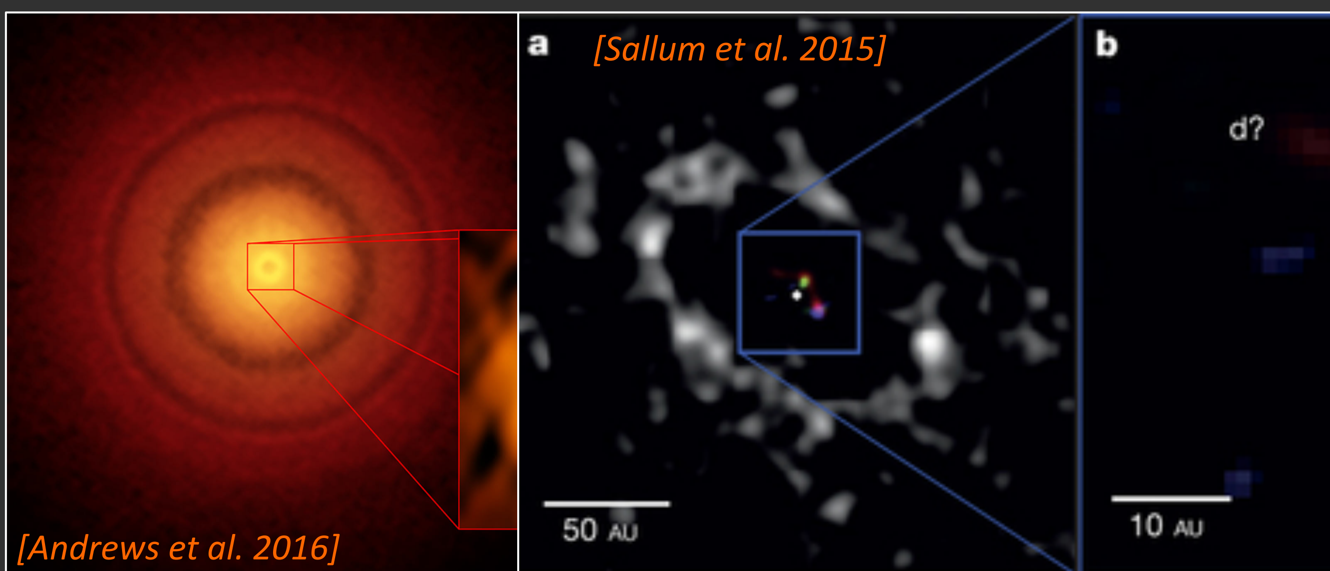
Uma Gorti

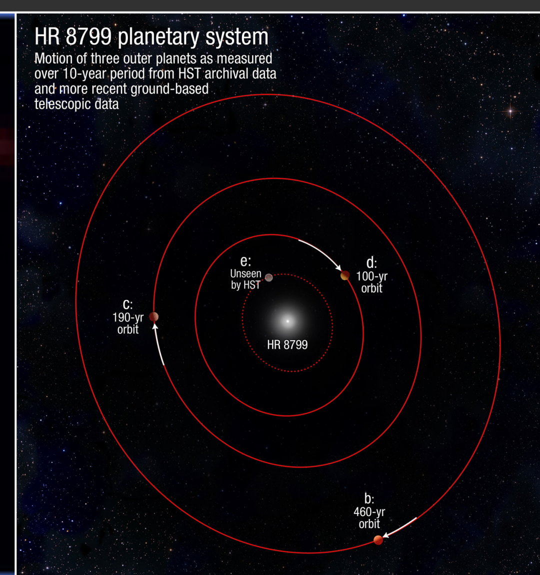
NASA Ames/SETI
&
KITP

Protostellar Phase









Protoplanetary Phase

Disk Evolution Theory

1. Accretion
2. Photoevaporation
3. Planet Formation (Dust coagulation/fragmentation)

Disk Evolution Theory

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Question: How are disks dispersed and how does the mass in the disk evolve?

Disks evolve through accretion

Conservation of mass, angular momentum imply that the surface density ∑(r,t) evolves as

$$\partial\Sigma/\partial t = 3R^{-1}\,\partial/\partial R\,\{R^{1/2}\,\partial/\partial R\,[\nu\Sigma R^{1/2}]\}$$

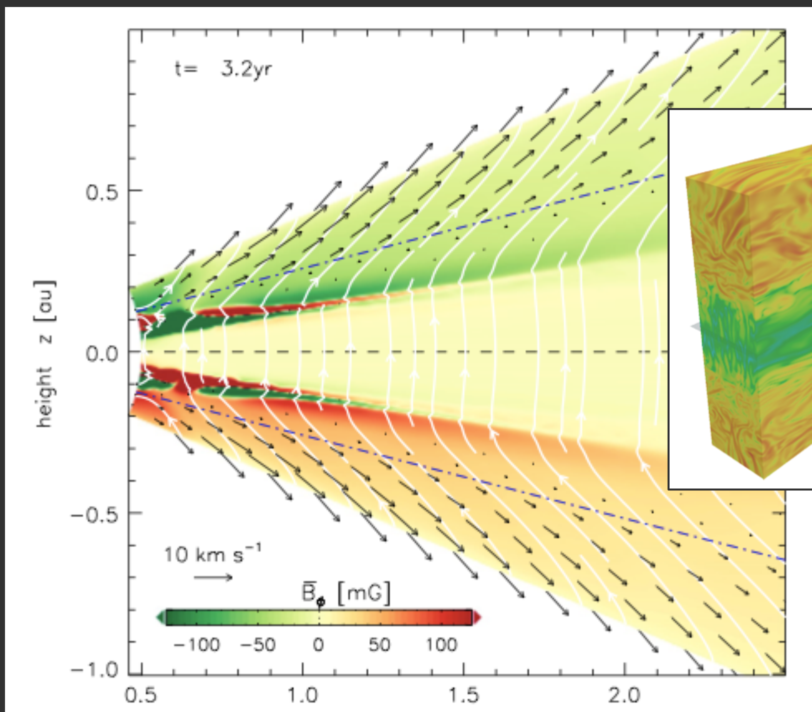
where the viscosity $\nu = \alpha c_s H$

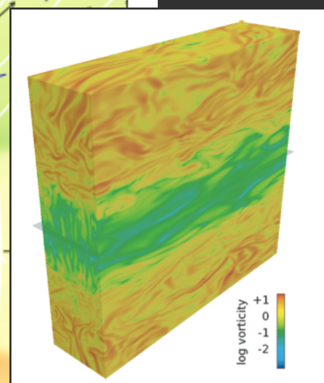
[Pringle 1981]

with a parameter

$$\alpha = \frac{v_t}{v_s} + \frac{B^2}{4\pi\varrho v_s^2}$$

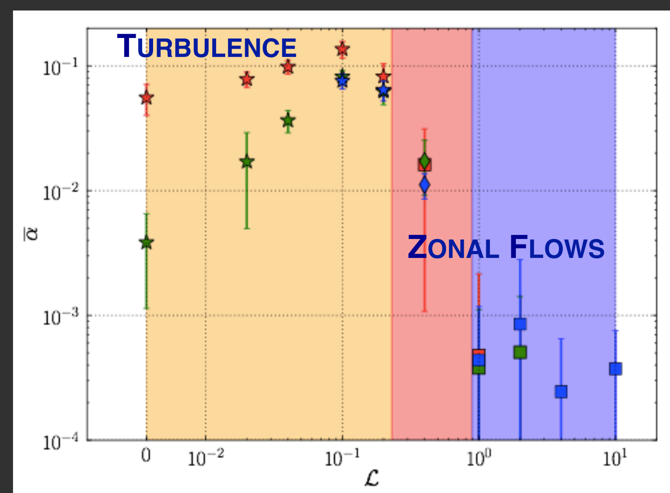
[Shakura & Sunyaev 1973]





MRI

[Turner+ 2014]

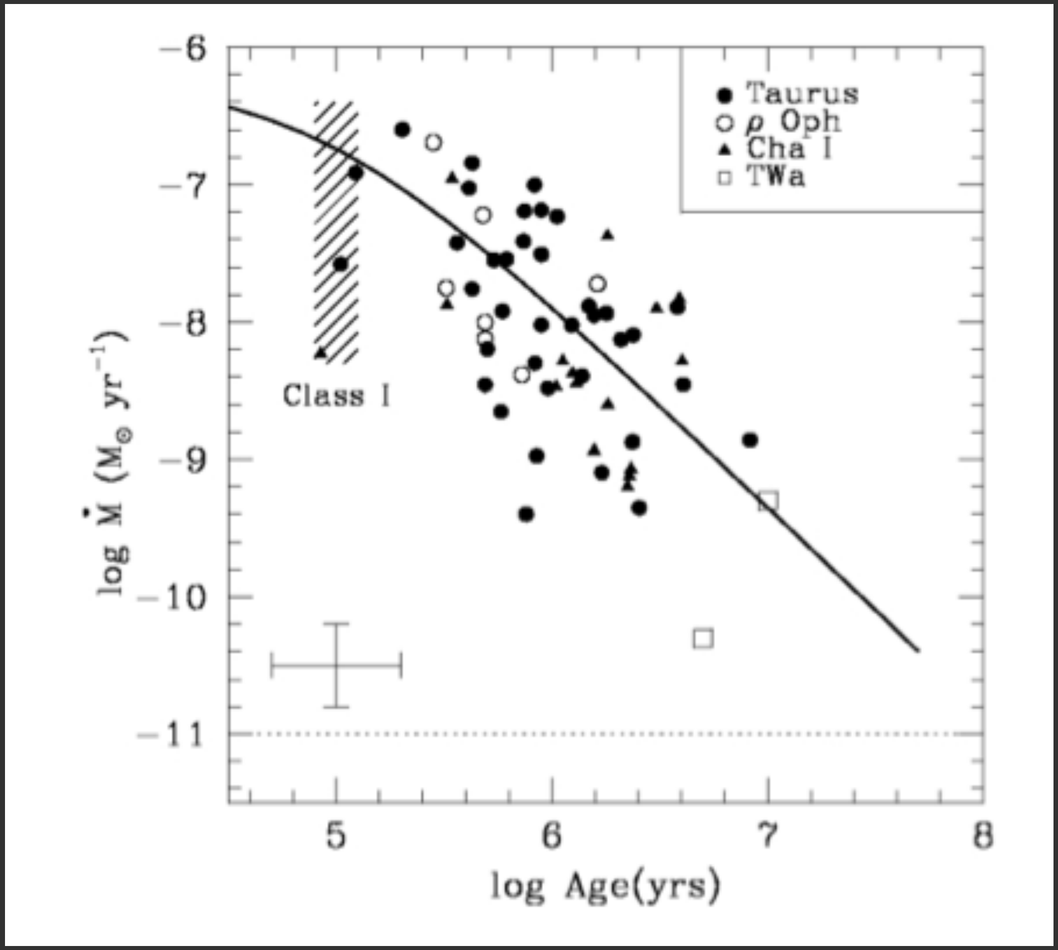


[Gressel+ 2015]

MCF Disk Winds

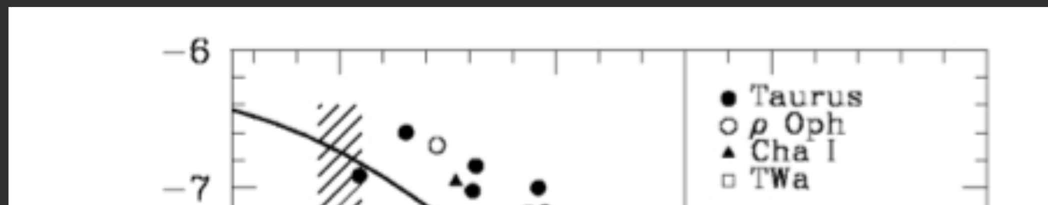
[Bethune+ 2016]

Disks evolve through accretion

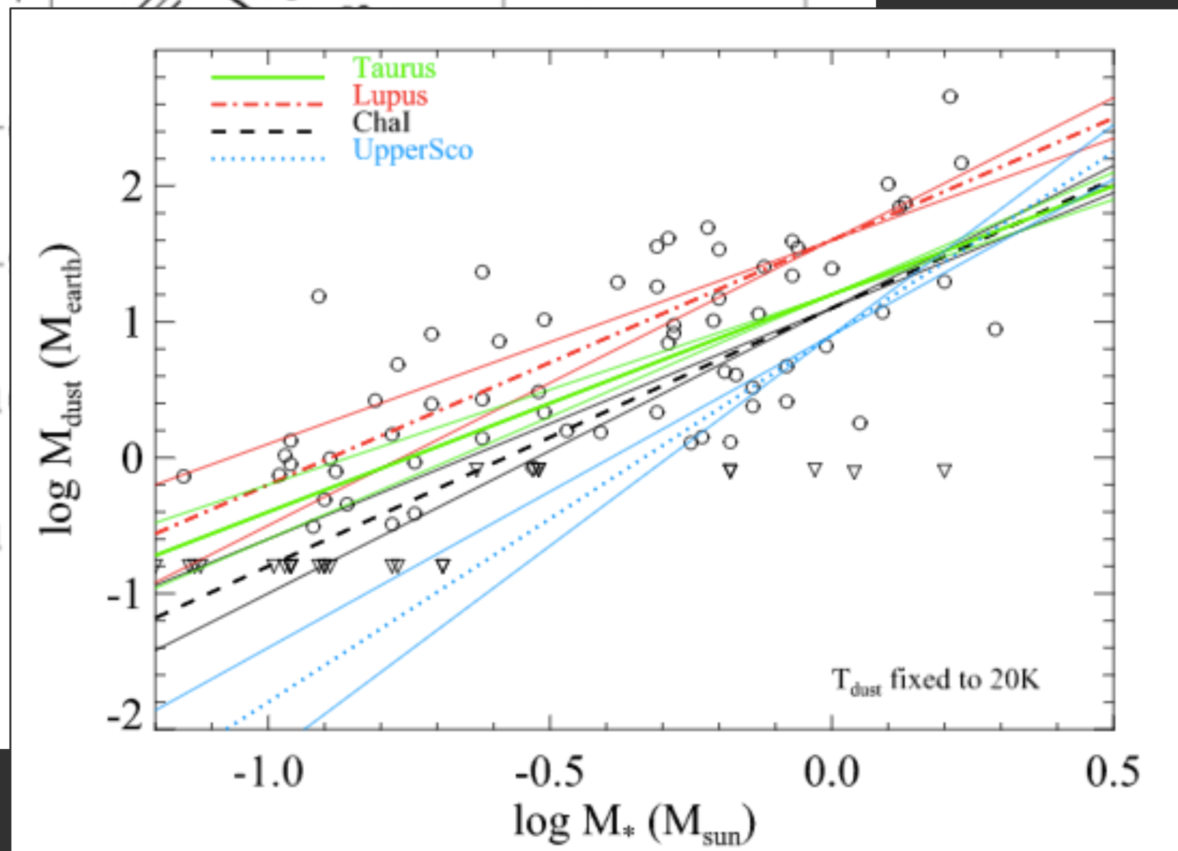


[Hartmann+ 1998]

Disks evolve through accretion



[Hartmann+ 1998]

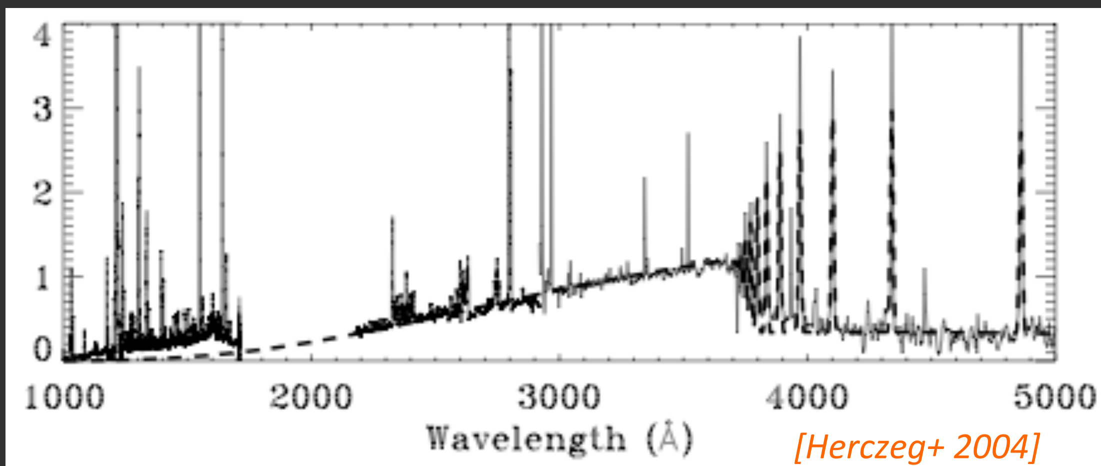


[Pascucci+ 2016]

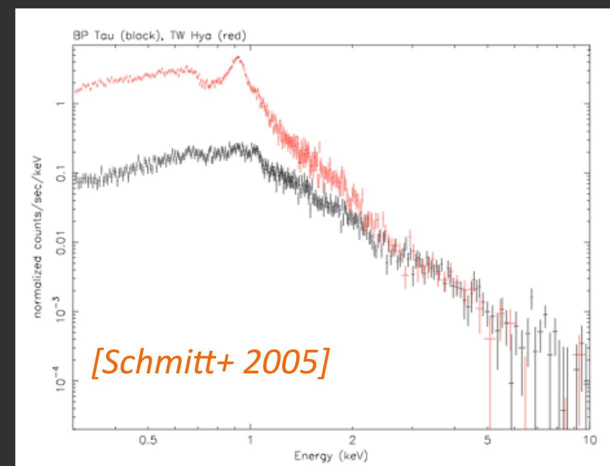
Protostars are UV and X-ray luminous and drive photoevaporation.

Young stars produce UV and X-rays – accretion + active chromospheres

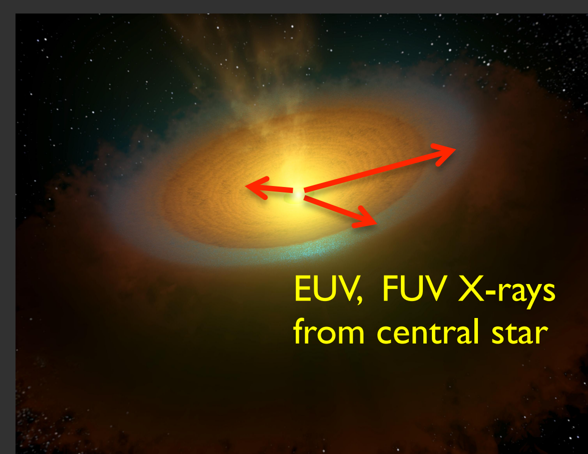
FUV FROM TW HYA



X-RAYS FROM BP TAU & TW HYA



- Gas is heated to thermal escape speeds
- Mass loss in a slow, subsonic wind (photoevaporation)



Disk Evolution Theory:

- Solve for surface density evolution by viscous accretion
    - Prescription for Disk Viscosity [α parameterization]

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r}\frac{\partial}{\partial r}\left(\sqrt{r}\frac{\partial}{\partial r}\left(\nu \Sigma \sqrt{r}\right)\right) - \dot{\Sigma}_{\rm pe}(r, t)$$

Kinematic viscosity

$$\nu \equiv \alpha c_s^2 / \Omega_K$$

Instantaneous local Photoevaporation rate

Disk Evolution Theory:

- Solve for surface density evolution by viscous accretion
  - Prescription for Disk Viscosity [α parameterization]

- Photoevaporative mass loss term

$$\frac{dM}{dt} = \rho\, r^2\, v_{flow} \sim \rho \text{ Area } c_s$$

Heating dense gas to high temperatures over a large area increases mass loss

1. EUV — low penetration depth, (13.6-100eV), $T \sim 10^4$ K, $n \sim 10^4$ cm^{-3}
2. FUV — penetrate deeper (6-13.6eV), $T \sim 100\text{-}5000$ K, $n \sim 10^5$ to 10^9 cm^{-3}
3. X-rays — Soft X-rays (<500eV) behave like EUV,
   intermediate (0.5-2keV) like FUV,
   hard X-rays (> 2keV) do not do much

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cannot be detected

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- Solve for surface density evolution by viscous accretion
  - Prescription for Disk

- Photoevaporative mass

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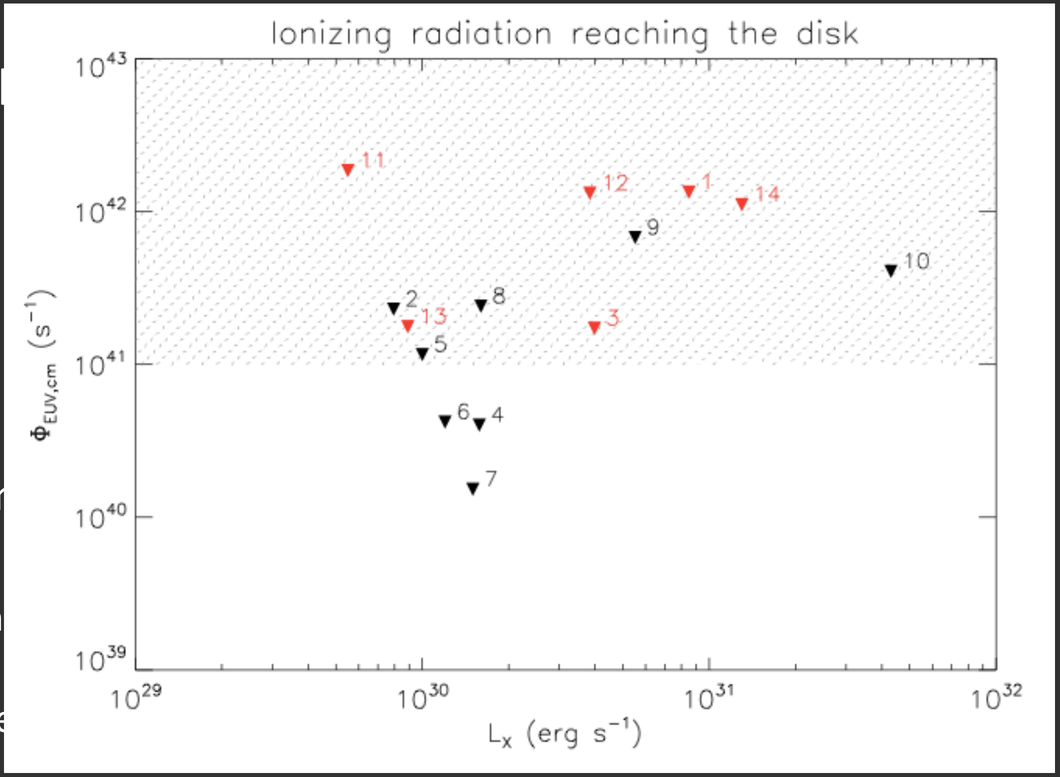

[Pascucci, Gorti & Hollenbach 2012, Pascucci + 2014]

Disk Evolution Theory:

- ➢ Solve for surface density evolution by viscous accretion
    - Prescription for Disk Viscosity [α parameterization]

- ➢ Photoevaporative mass loss term
    - Heating by EUV, FUV and X-rays
    - Thermo-chemical model of disk (heating, cooling, chemistry)
        - UV – grain photoelectric emission, pumping
        - X-rays, cosmic rays – direct heating of gas
        - Chemical processes – exothermic reactions
        - Viscous heating

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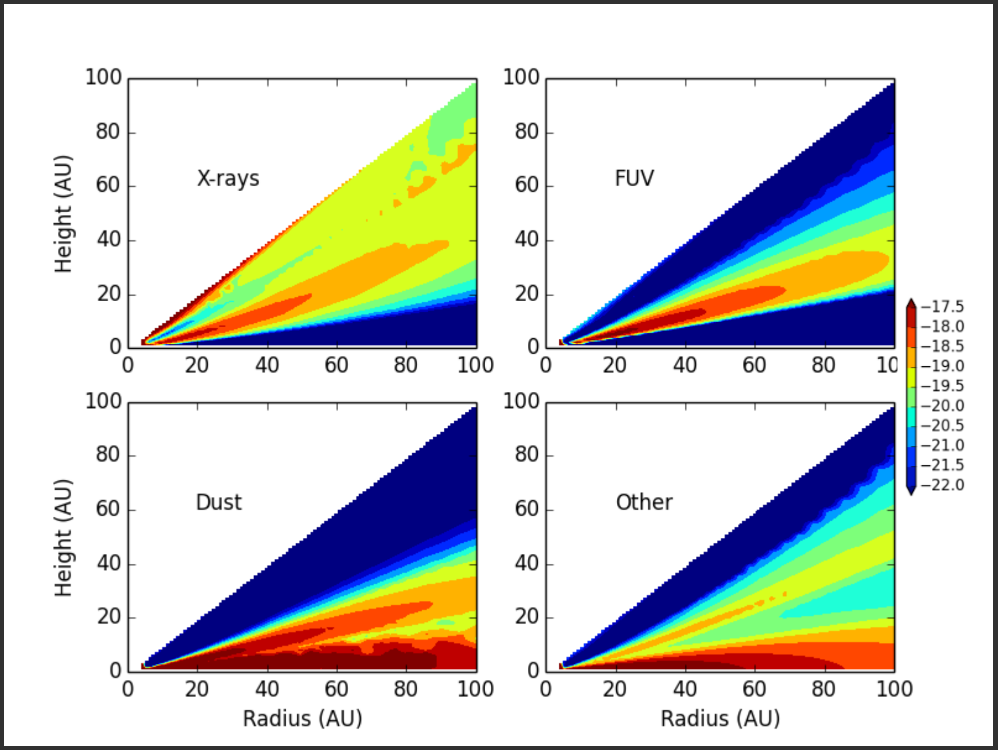
    - Chemical processes – exothermic reactions
    - Viscous heating
    - Cooling by collisions with dust, gas emission lines

CHEMISTRY

Disk Evolution Theory:

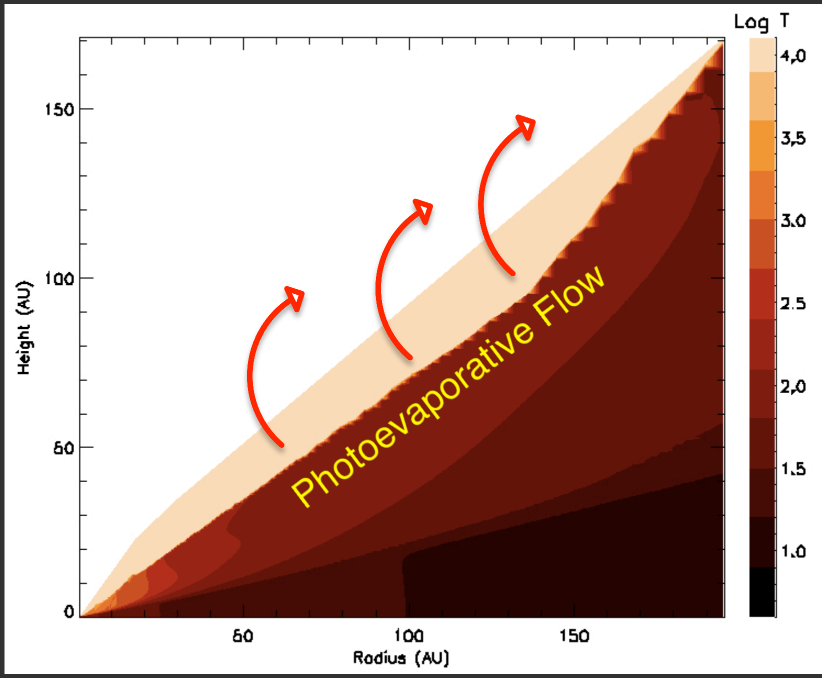
Instantaneous surface density profile used to determine vertical structure using thermochemical modeling (dust and gas)

Heating of Gas at Disk Surface



[Gorti & Hollenbach 2008]

Gas Temperature Structure of Disk

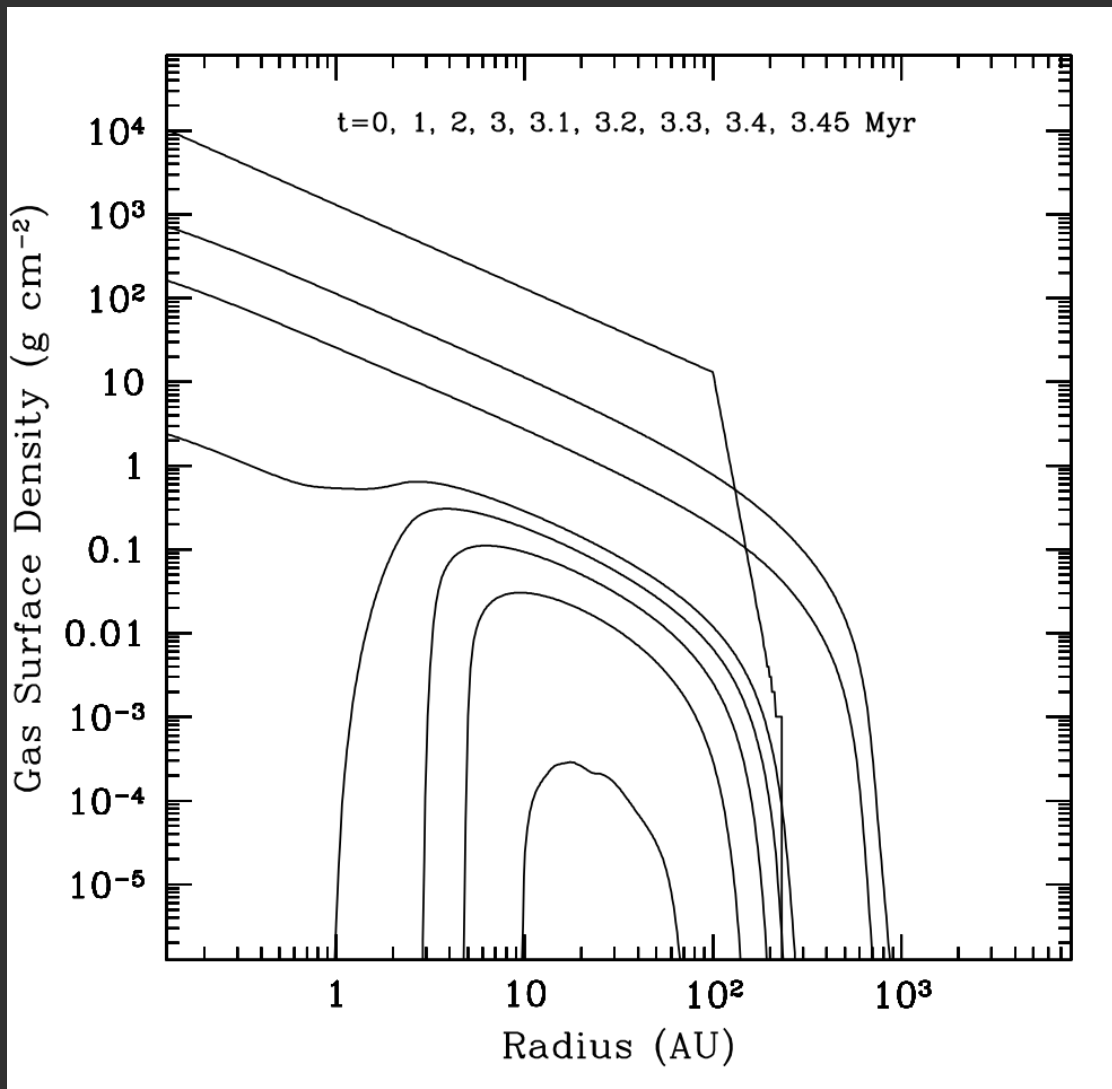


Disk Evolution Theory:

Solve for surface density evolution by viscous accretion and photoevaporation

- ✧ Prescription for Disk Viscosity [α parameterization]
- ✧ Photoevaporative mass loss term
    - Heating by EUV, FUV and X-rays
    - Thermo-chemical model of disk (heating, cooling, chemistry, RT)

Disk Dispersal due to viscous accretion and photoevaporation

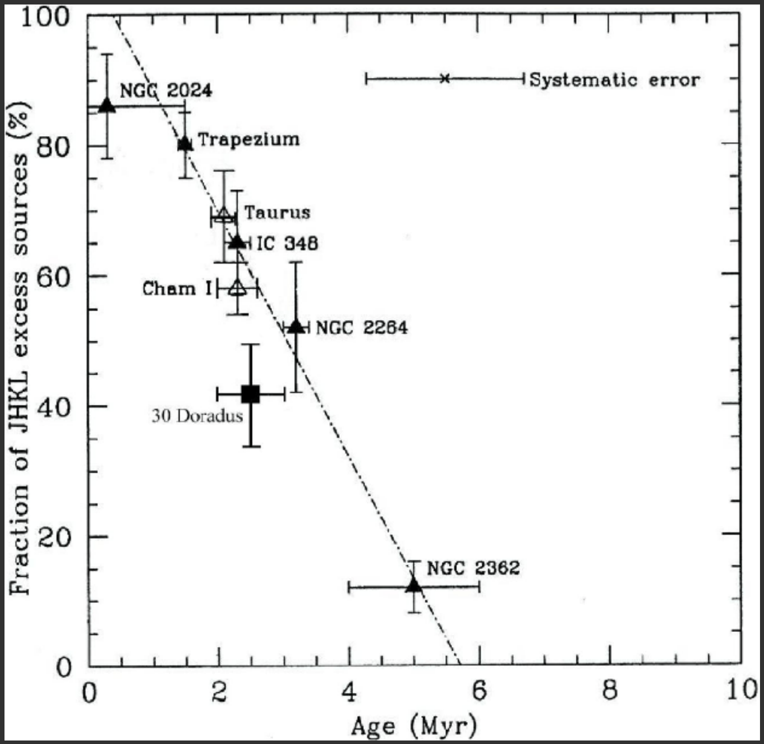


A typical disk around a $1M_o$ star survives for a few Myrs.

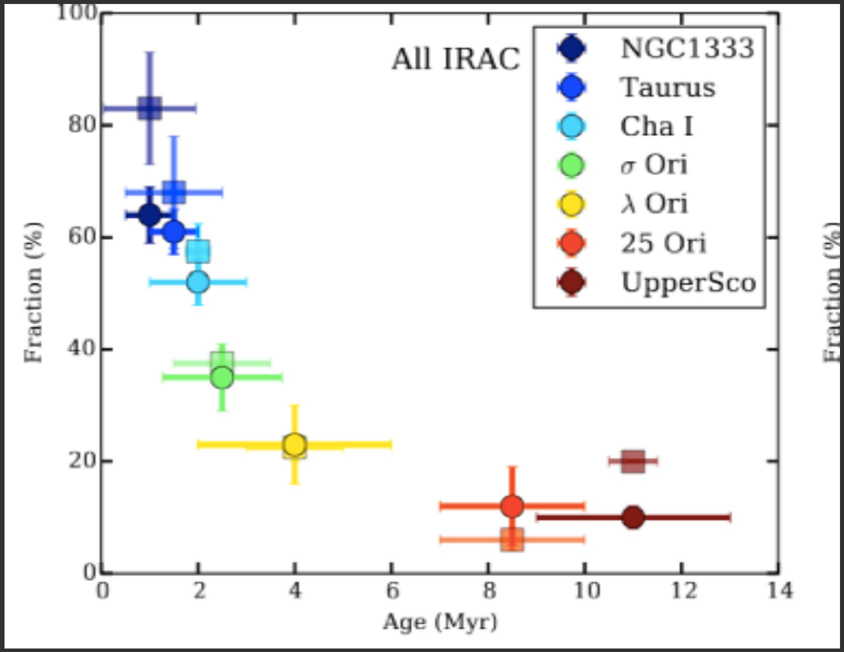
[Gorti, Dullemond & Hollenbach 2009]

Disk Dispersal due to viscous accretion and photoevaporation

Disk dispersal times are similar to inferred dust disk evolution timescales ~ few Myrs



[Haisch, Lada & Lada 2001]



[Ribas+ 2015]

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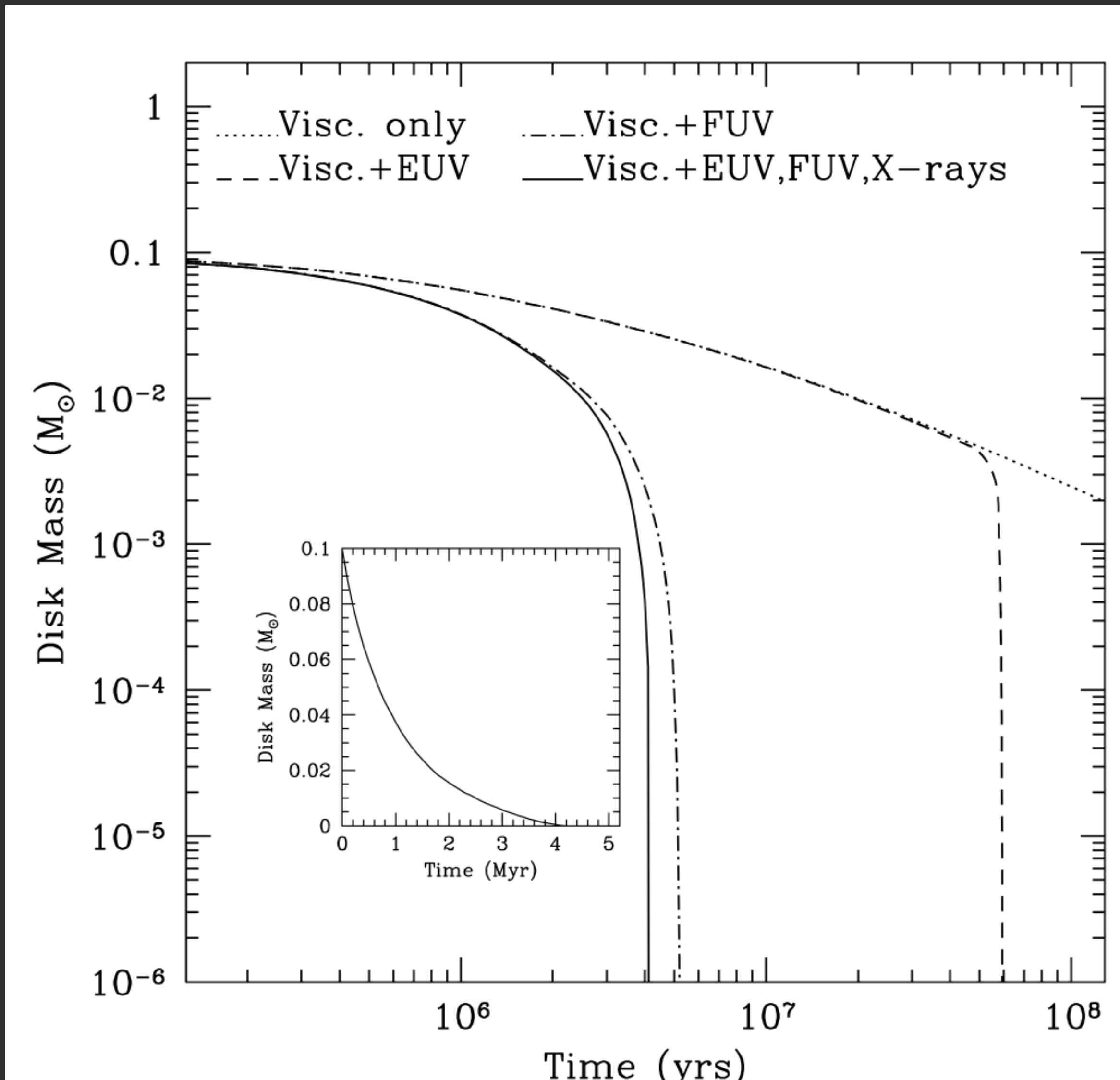


A typical disk around a $1M_o$ star survives for a few Myrs.

FUV grain heating is important.

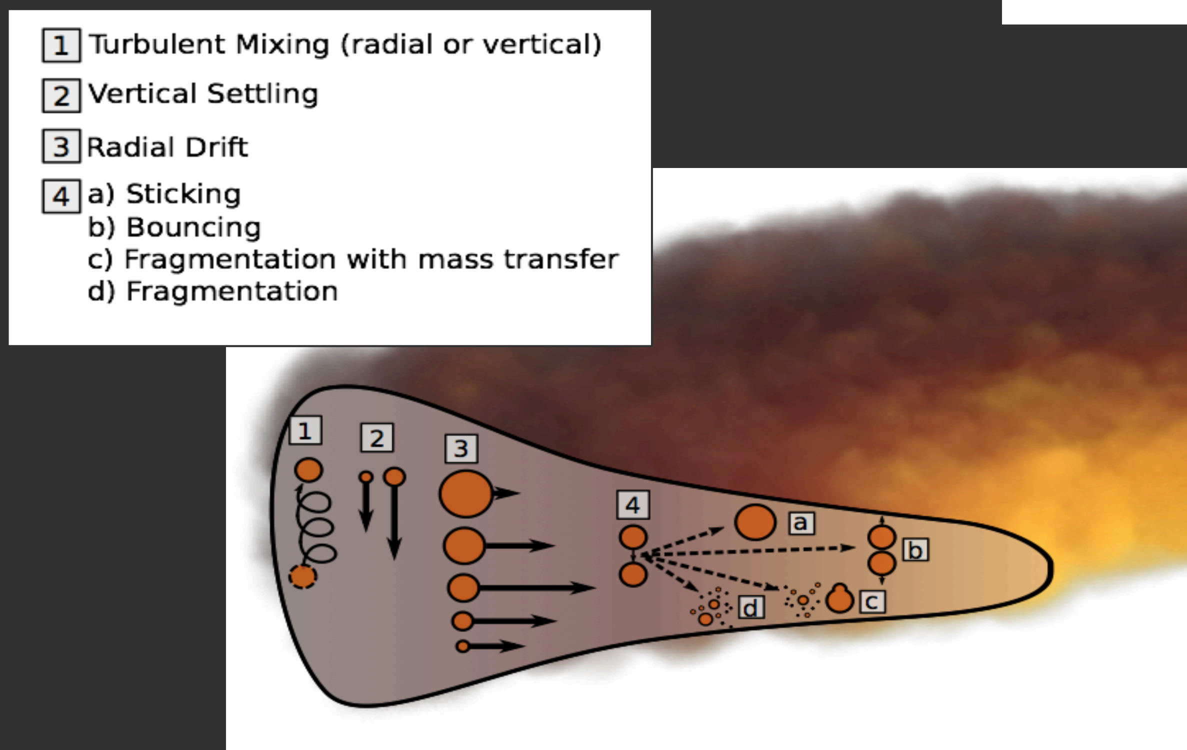
[Gorti, Dullemond & Hollenbach 2009]

Dust and Gas Evolution

FUV Heating is due to small grains, and dust grains evolve in disks

Grain growth could (a) decrease UV extinction and heat denser gas, or,
(b) decrease heating and lower gas velocity

$$\dot{\Sigma} \propto \rho \, c_s \sim \rho \sqrt{T_{gas}}$$



[Testi+ 2014]

Dust and Gas Evolution

- Dust grain size distribution (hence opacity) that evolves with time
- Fragmentation/Coagulation equilibrium from the models of Birnstiel+ 2011, 2012
- Radial drift, drift-limited fragmentation
- Coupling with the gas through a dust evolution equation

$$\frac{\partial \Sigma_d^i}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\Sigma_d^i u_d^i\right) = \frac{1}{r}\frac{\partial}{\partial r}\left[r\Sigma_g D_d^i \frac{\partial}{\partial r}\left(\frac{\Sigma_d^i}{\Sigma_g}\right)\right]$$

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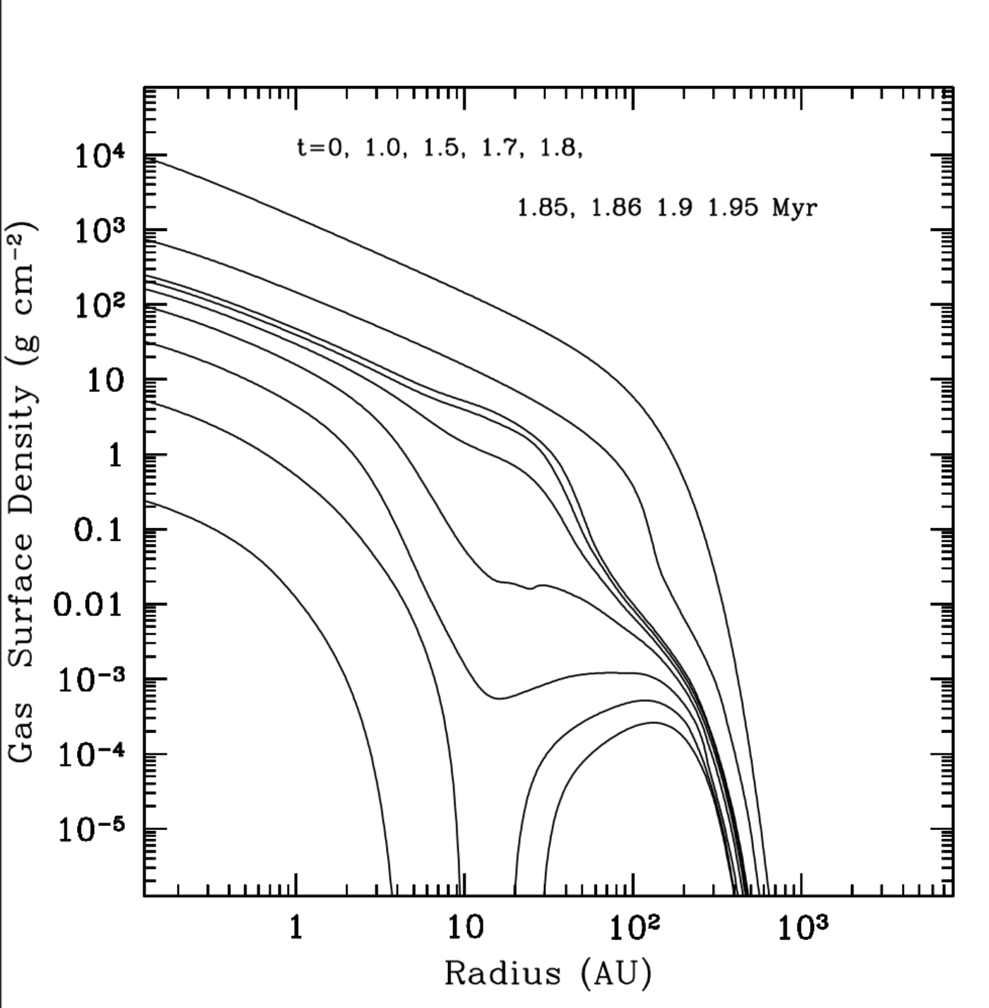
Above processes are sensitive to the local gas density

Dust and Gas Evolution



[Gorti, Hollenbach & Dullemond 2015]

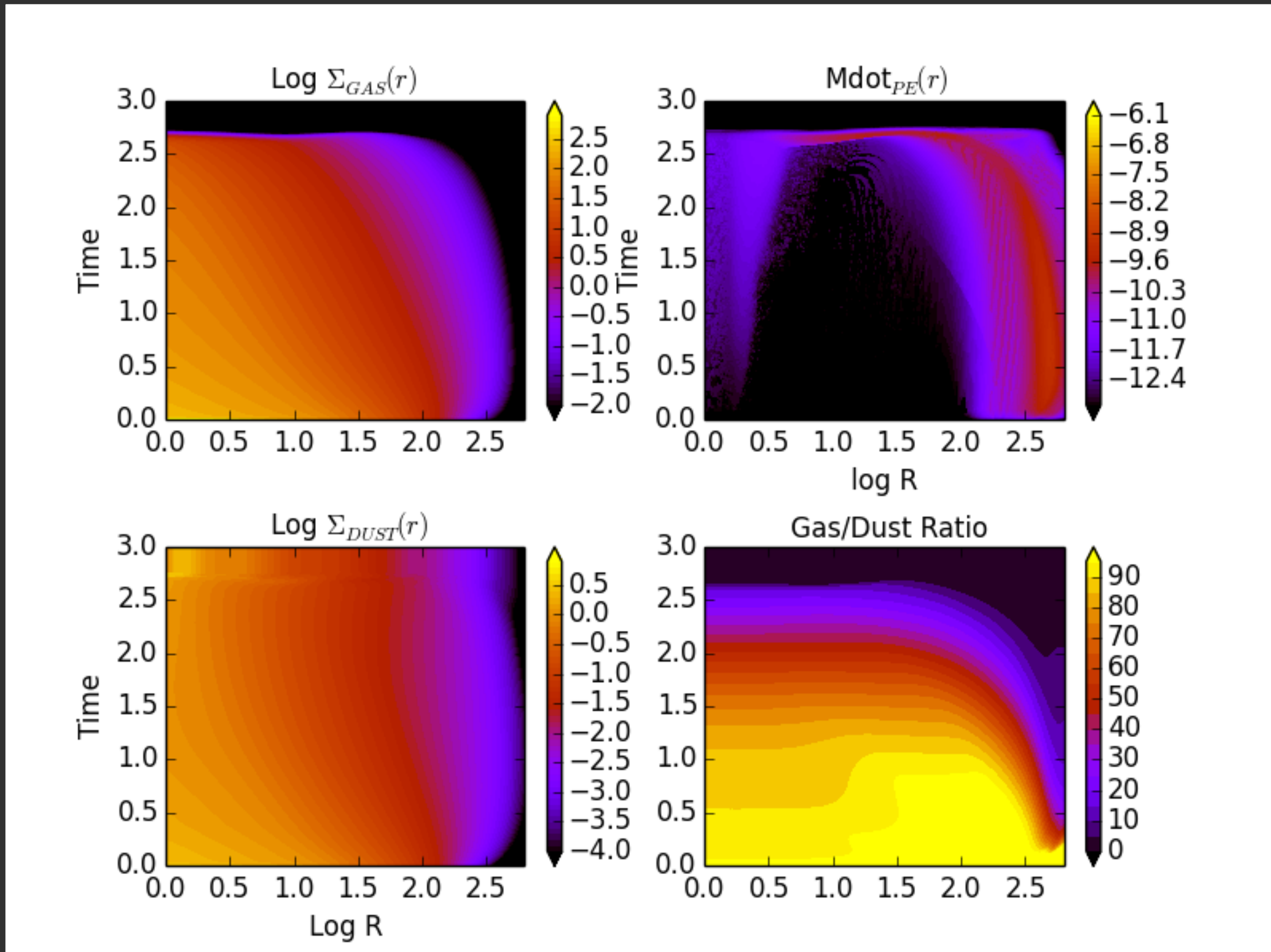
Similar Timescales

Heating α 1/grain size

UV penetration α 1/grain size

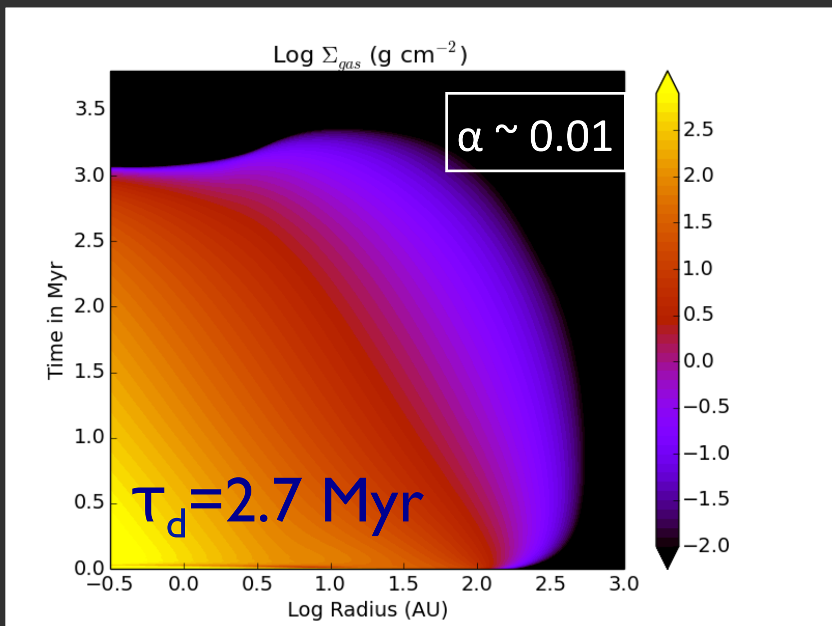
Not much change in mass loss rate

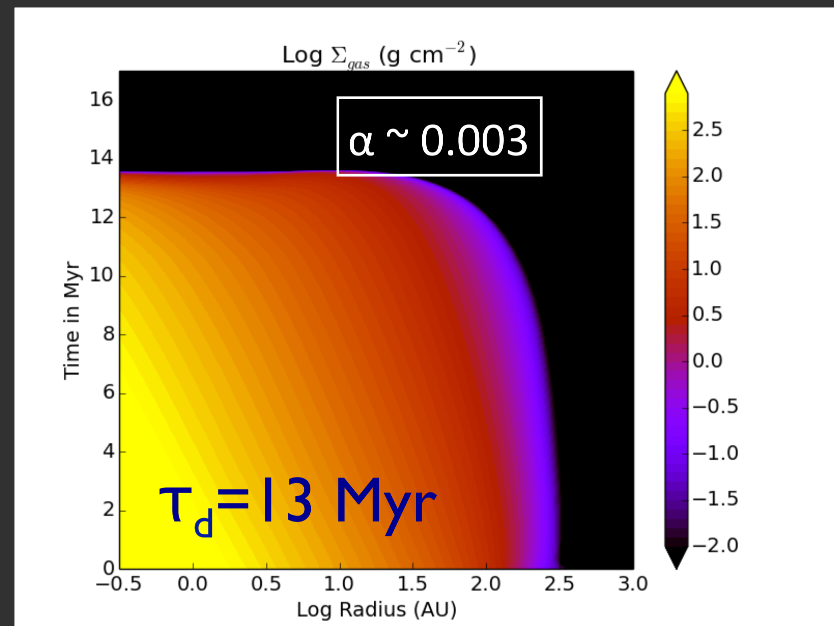
Dust and Gas Evolution



[data from Gorti, Dullemond & Hollenbach 2015]

Dust and Gas Evolution



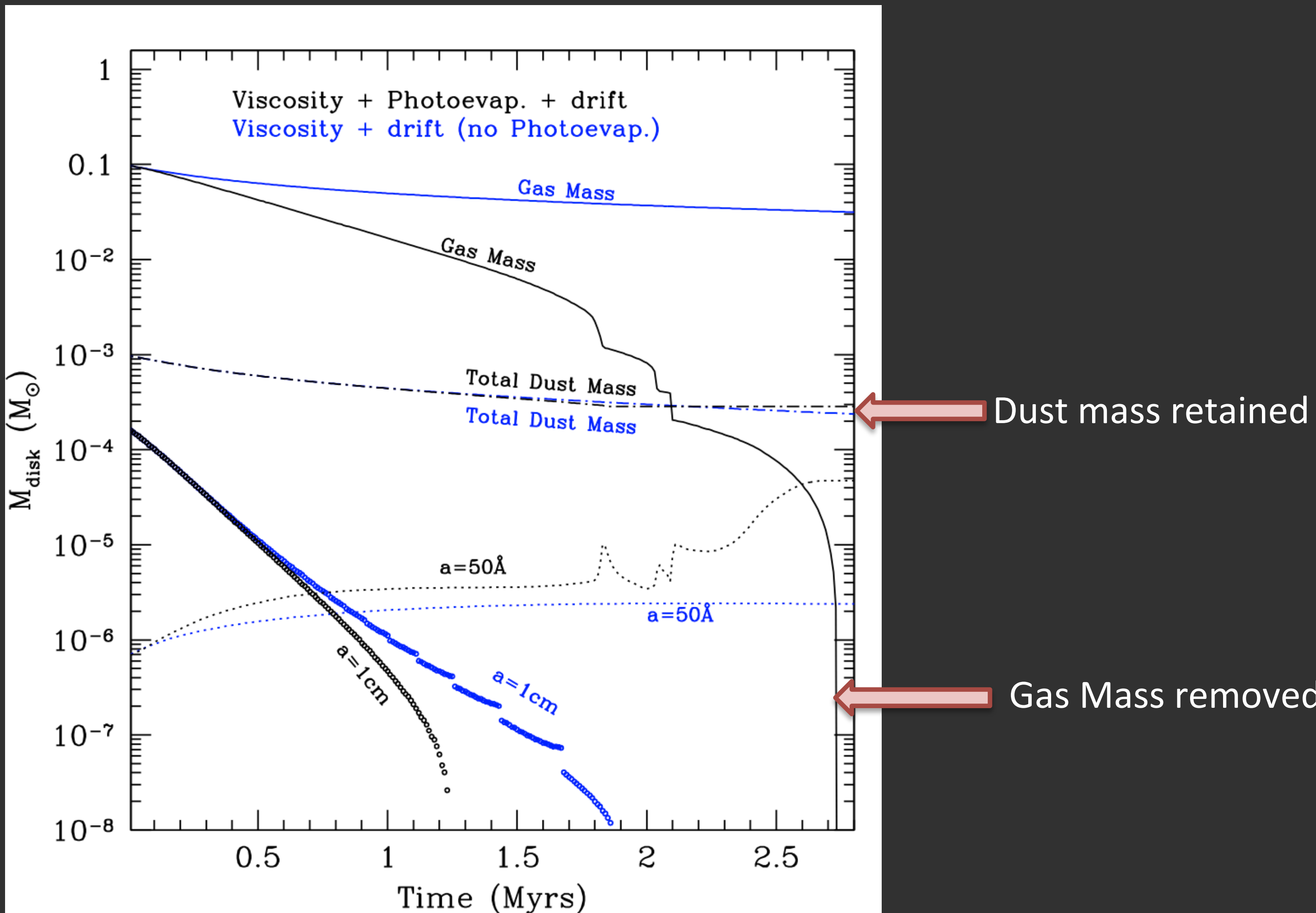


[data from Gorti, Dullemond & Hollenbach 2015]

Disk lifetime is very sensitive to the level of viscosity in disk

- Overall evolution timescale
- Accretion luminosity
- Dust size distribution through turbulent speeds.

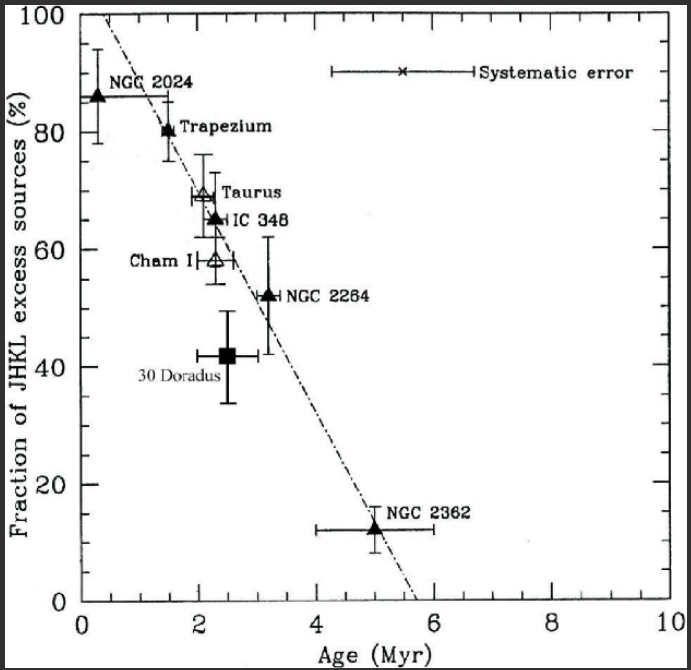
<u>Dust and Gas Evolution</u>



[see Gorti, Dullemond & Hollenbach 2015]

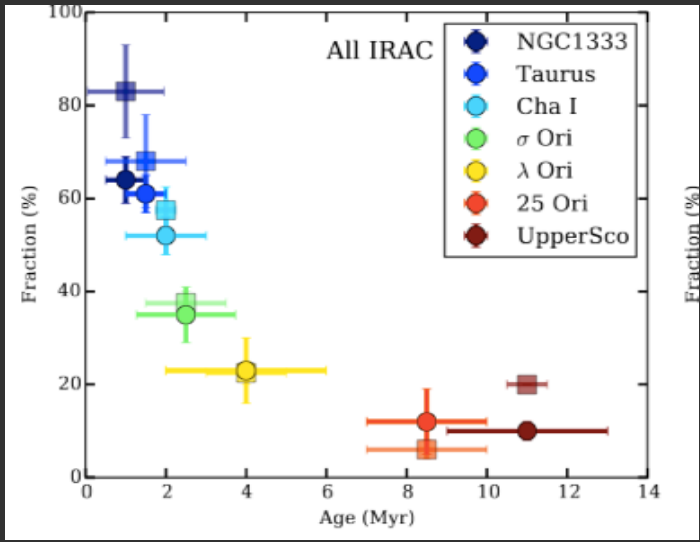
Dust and Gas Evolution

Dust and gas evolution may not be necessarily aligned



[Haisch, Lada & Lada 2001]

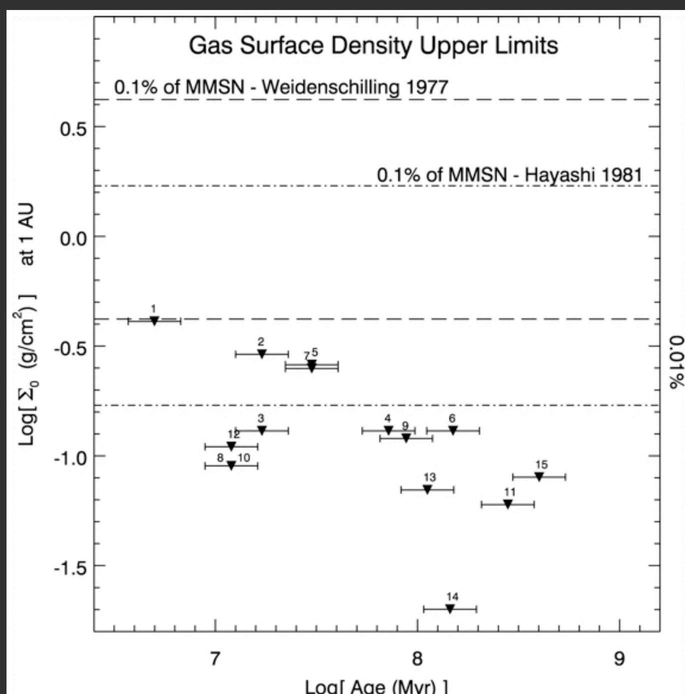
Planet Formation?



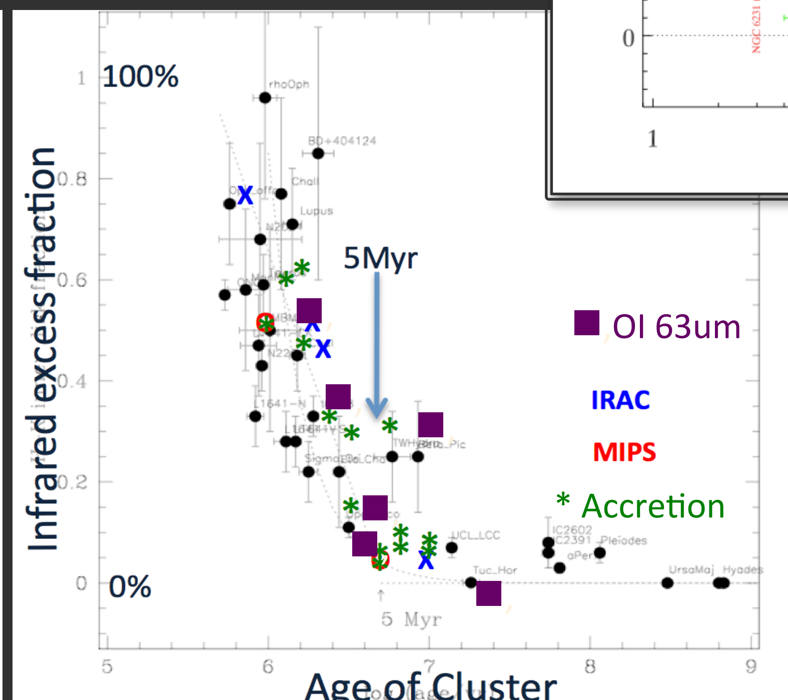
[Ribas+ 2015]

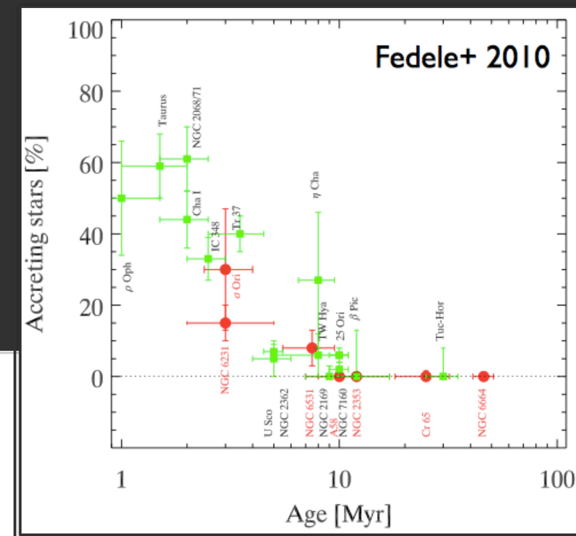
Dust and Gas Evolution

Gas disk lifetimes are not known (< 10-30 Myr)



[Pascucci, Gorti + 2006]





[Hillenbrand 2005, Hernandez+ 2008, Fedele+ 2010, Dent+ 2013]

Disk dispersal and planet formation appear to be linked

Dust and Gas Evolution

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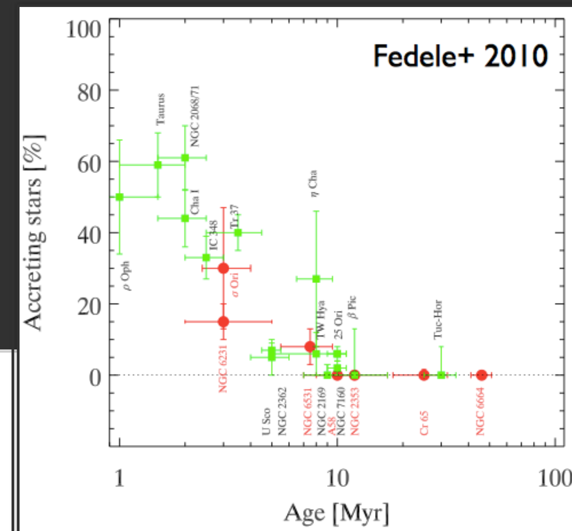
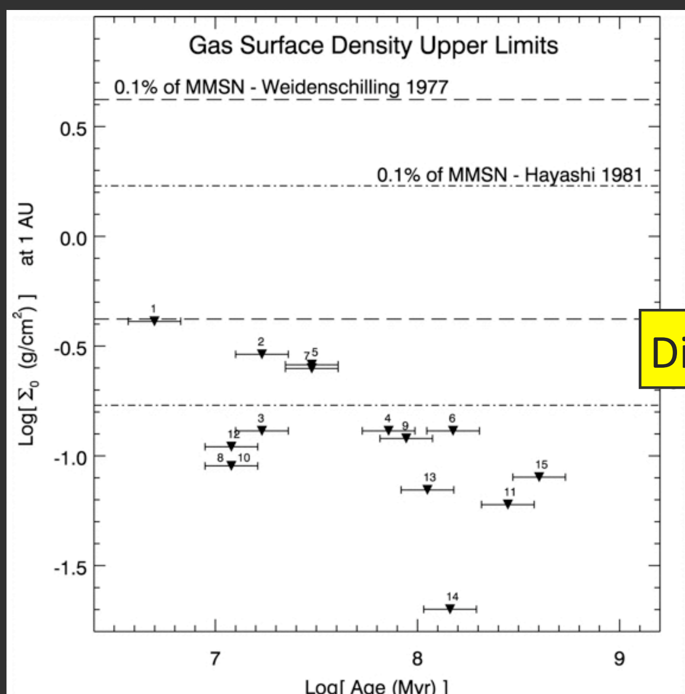
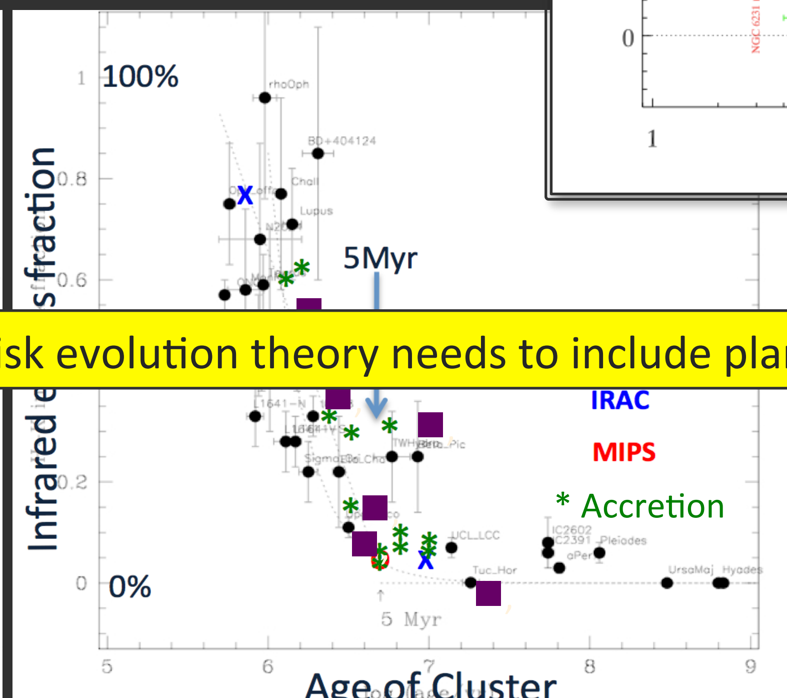




[Pascucci, Gorti + 2006]



Disk evolution theory needs to include planet formation

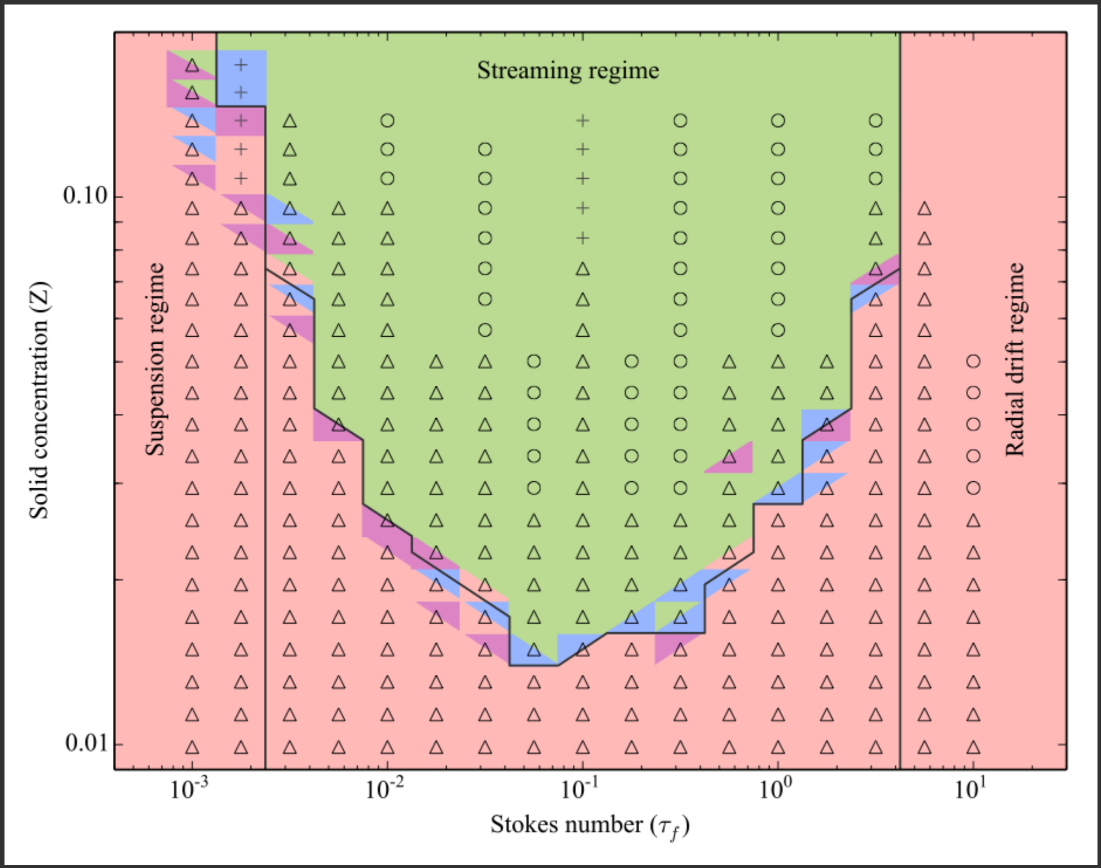
[Hillenbrand 2005, Hernandez+ 2008, Fedele+ 2010, Dent+ 2013]

Disk dispersal and planet formation appear to be linked

<u>Dust Evolution and Planetesimal Formation via the Streaming Instability</u>

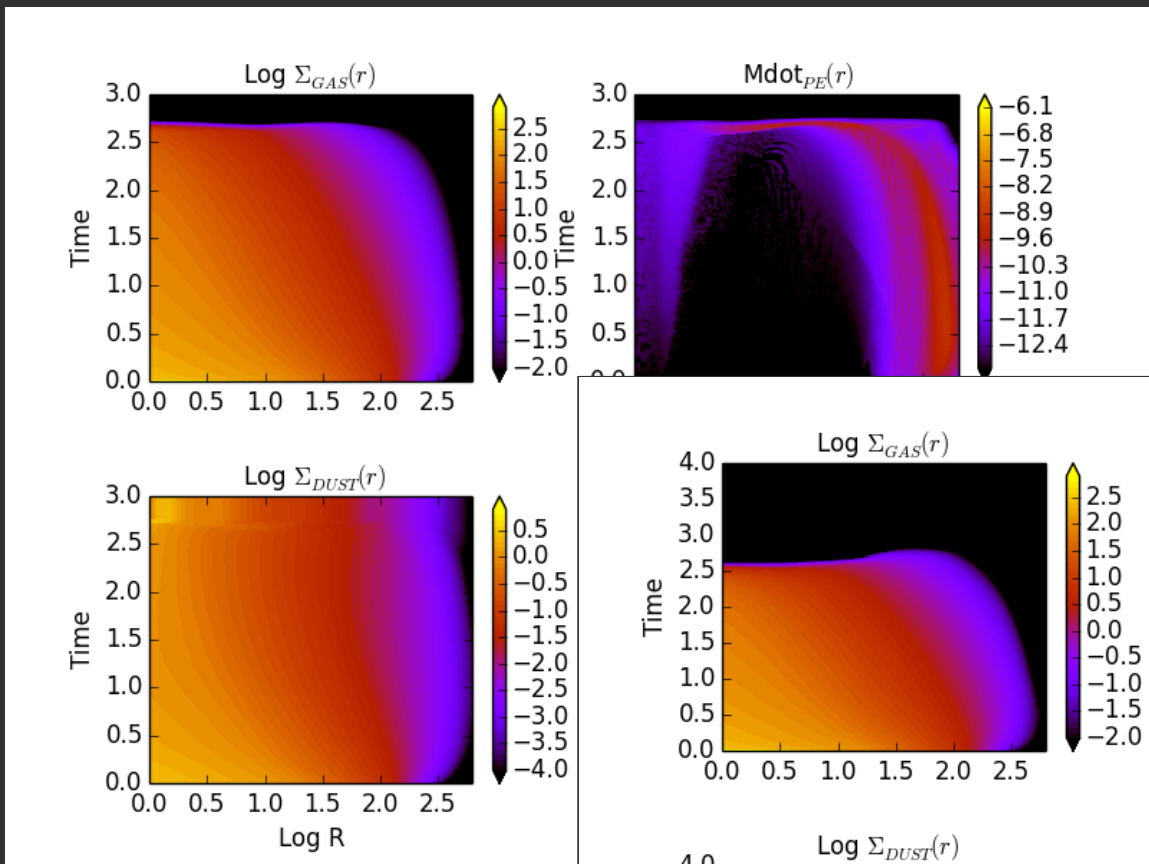
[Carrera+ 2015]

Gas/Dust Mass Ratio



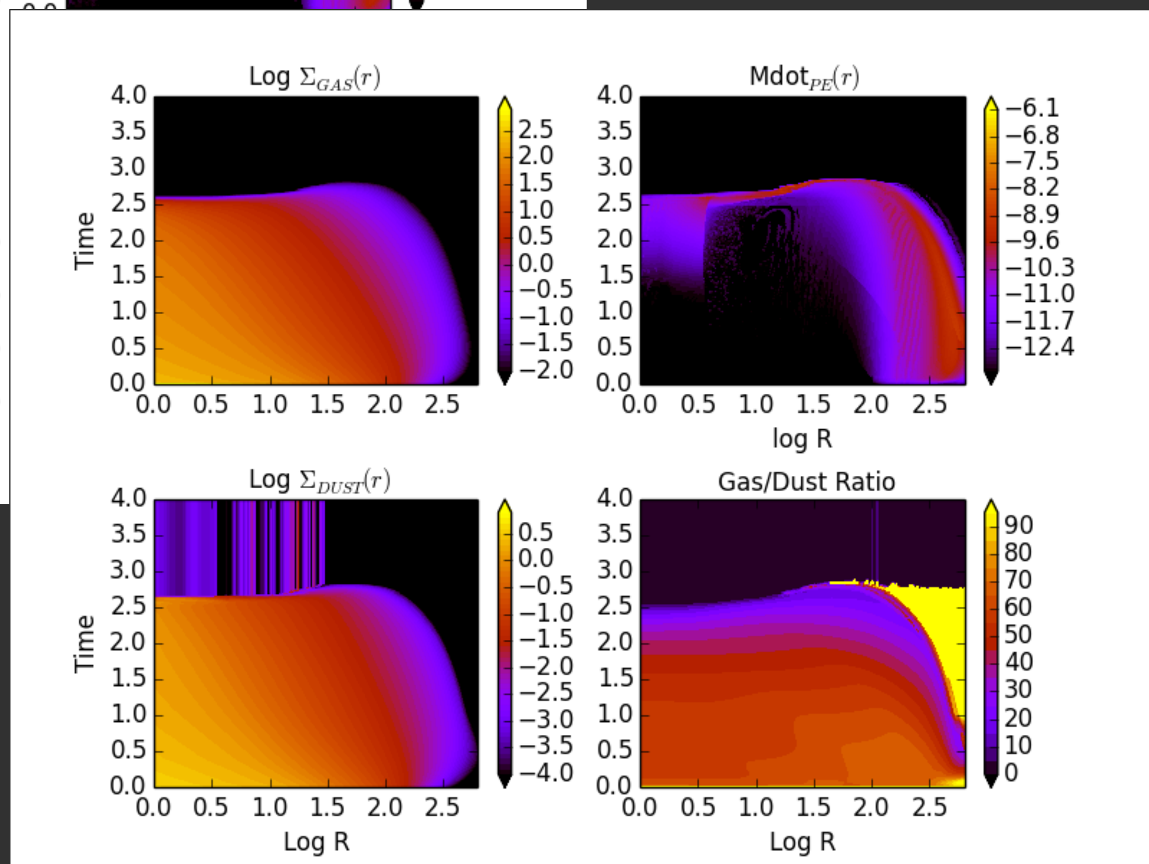
Grain size

Dust Evolution and Planetesimal Formation via the Streaming Instability



[Without SI]

[With SI]



Dust Evolution and Planetesimal Formation via the Streaming Instability

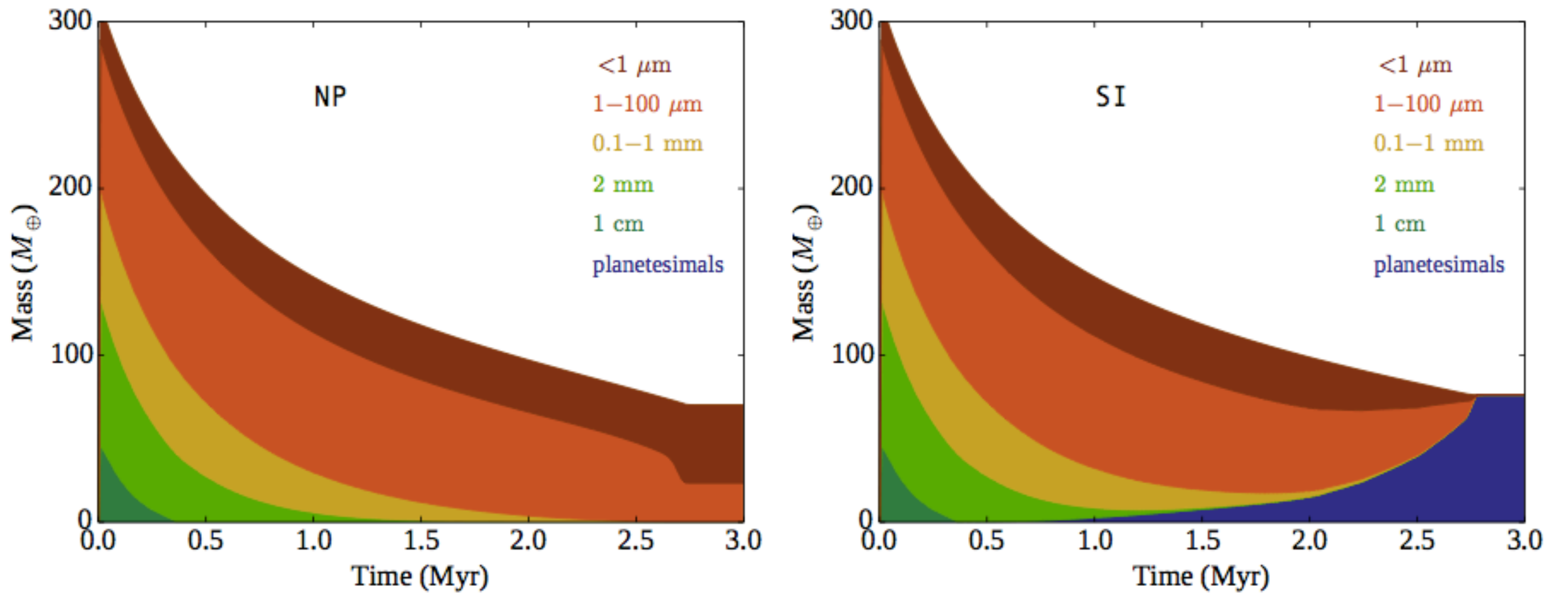
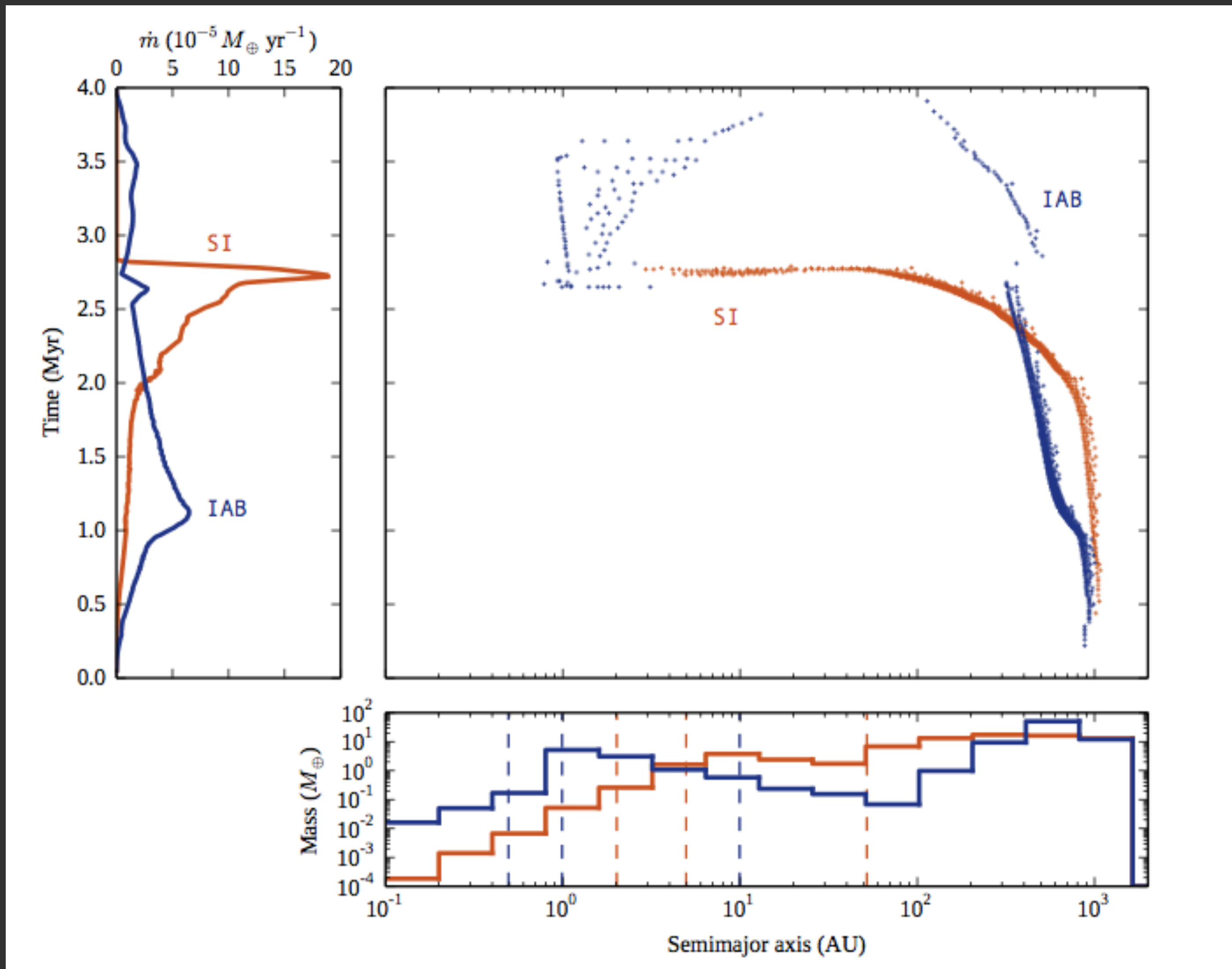


Figure 3. Total mass in planetesimals and in various dust size bins as a function of time. In Model NP (left) there is no mechanism to remove dust grains once photoevaporation forms an inner cavity. This model leaves behind 47 $M_\oplus$ of sub-μm dust, 23 $M_\oplus$ of 1–100 μm dust, and trace amounts of larger grains. In Model SI (right), dust is efficiently converted into planetesimals. This model converts 76 $M_\oplus$ of dust into planetesimals, leaving behind only 0.002 $M_\oplus$ of sub-μm and trace amounts of larger grains.

[Carrera, Gorti, Johansen & Davies 2017, sub.]

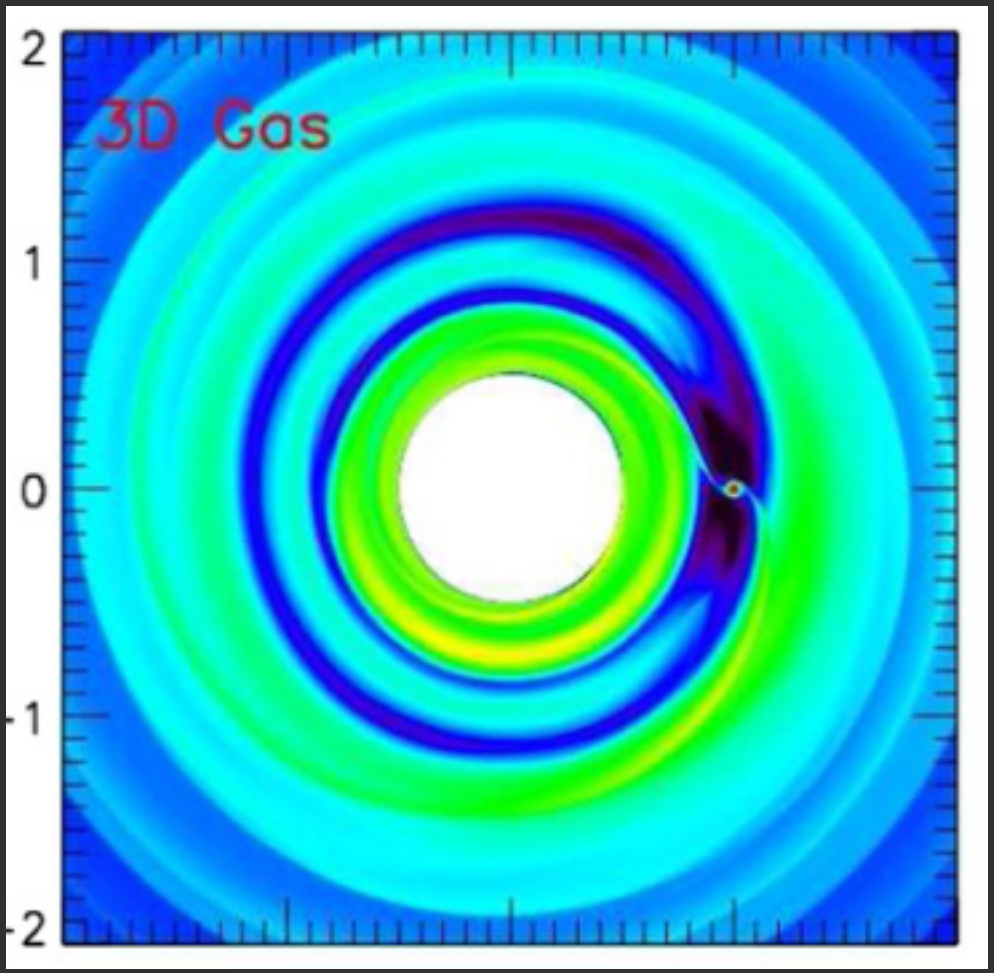
Dust Evolution and Planetesimal Formation via the Streaming Instability



[Carrera, Gorti, Johansen & Davies 2017, sub.]

Unresolved Questions

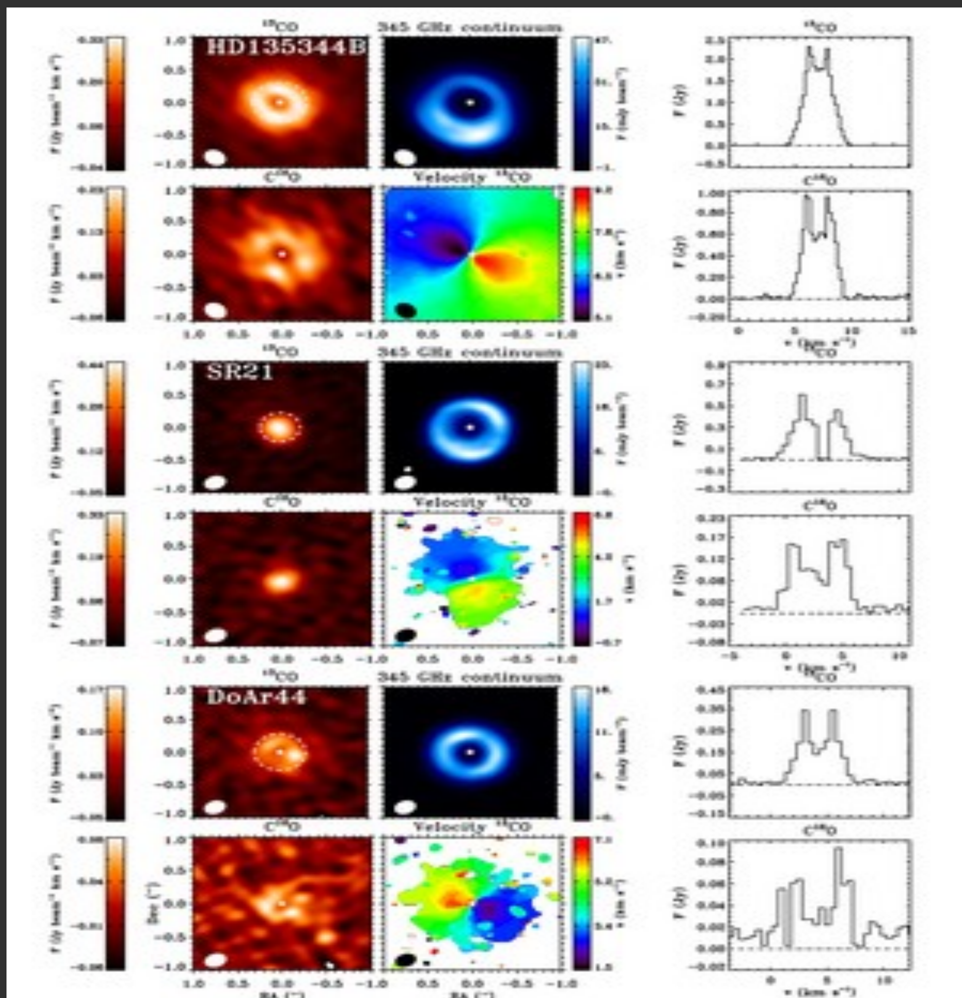
Unresolved Issues



[Zhu+ 2014]

Planet formation affects gas disk structure

Unresolved Issues



[van der Marel+ 2015]

Transition disks with dust holes are often massive and accreting - evolutionary status Is unclear

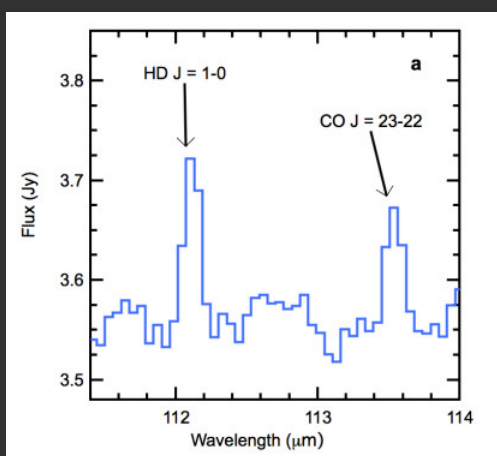
Varied disk evolutionary paths?

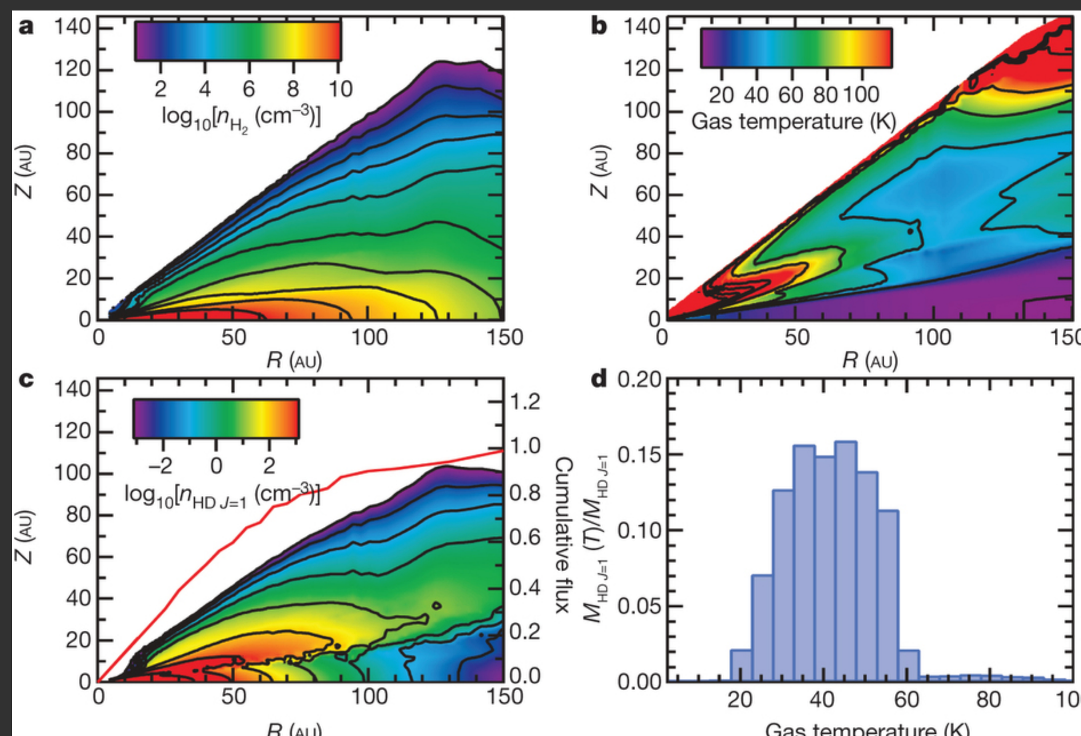
Unresolved Issues

[Andrews+ 2015]

Disk gas masses are very uncertain:

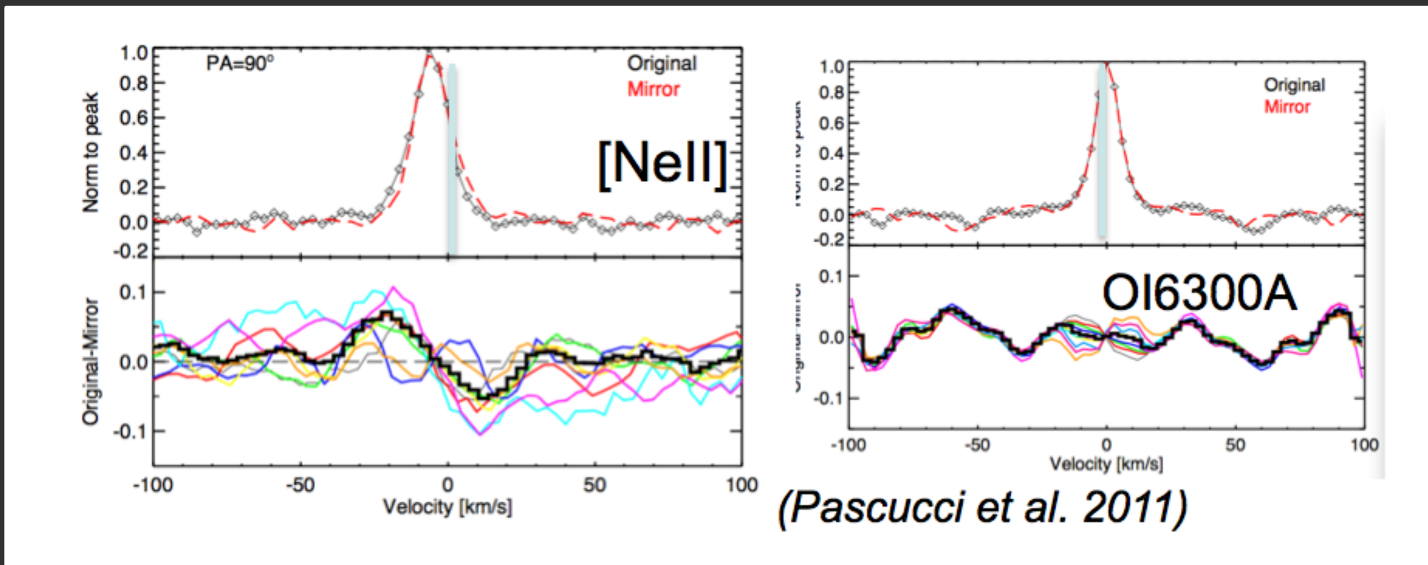
Estimated masses for TW Hya differ by large factors





[Bergini+ 2013]

Unresolved Issues

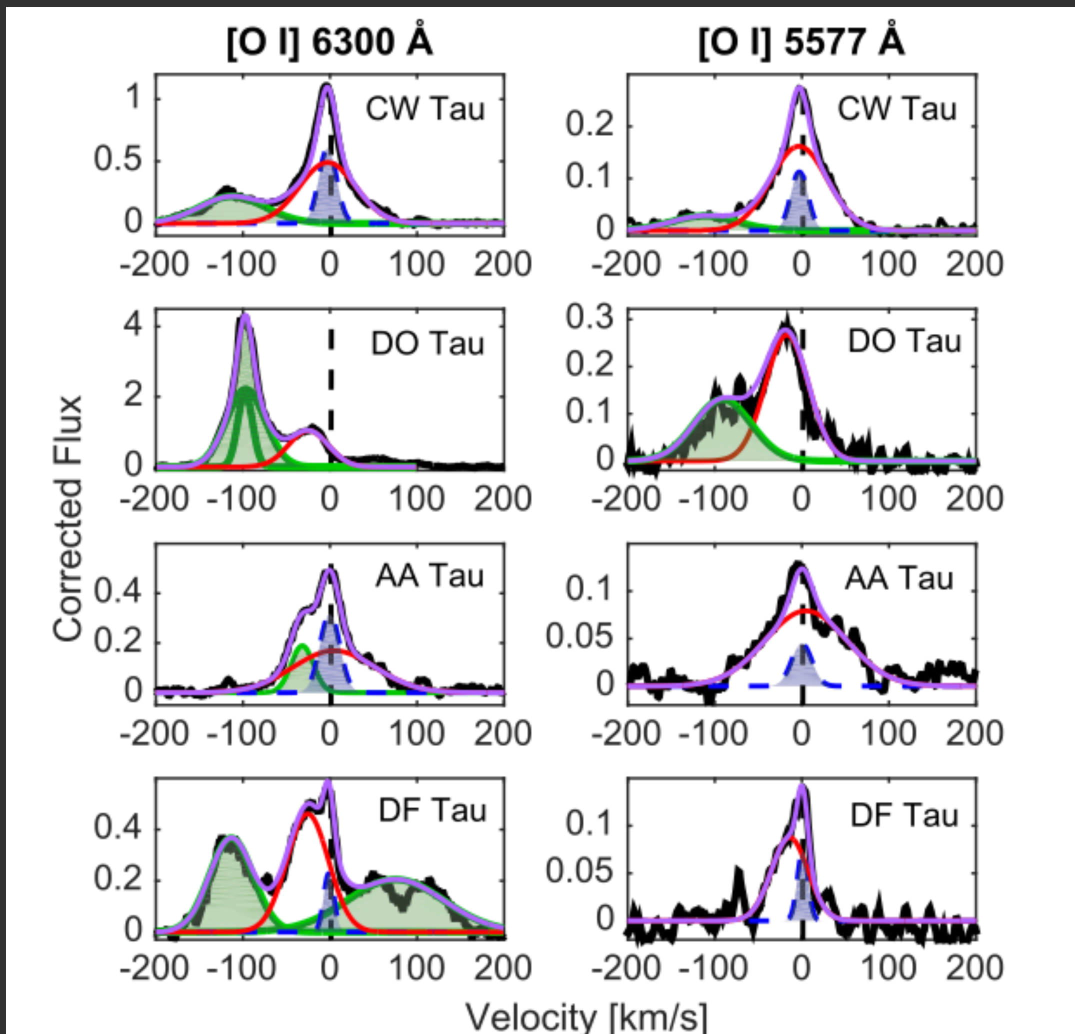


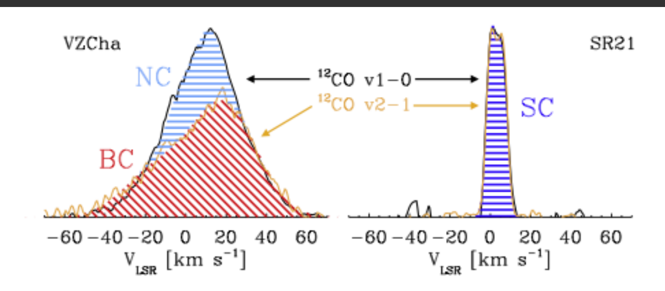
Photoevaporative wind tracers remain elusive.

Mass loss rates from NeII could differ by orders of magnitude

Unresolved Issues

[Banzatti & Pontoppidan 2015]



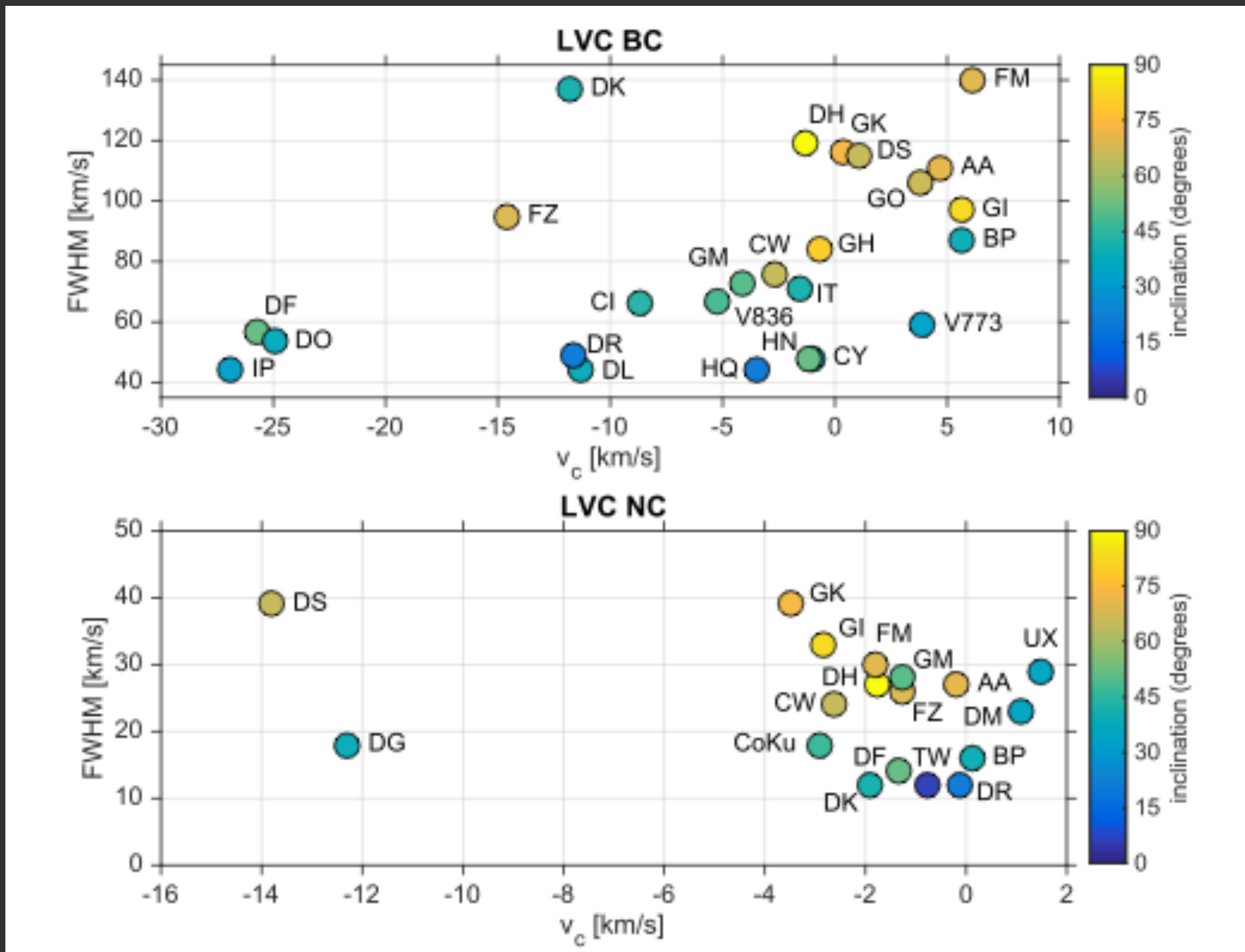


[Simon+ 2016]

Forbidden line emission traces slow winds with multiple components

Similar emission in CO 4.7um

Unresolved Issues



[Simon+ 2016]

LVC broad component likely MHD disk wind, narrow component could be bound or PE

Summary of Disk Photoevaporation Model Results

- Disks may accrete ~ 50% of their gas mass and some dust in the later stages of evolution (Class II), rest of gas mass is removed by photoevaporation
- Disk evolution is very sensitive to accretion processes.
- Dust evolution does not affect FUV photoevaporation rates, dust is not coupled to the gas due to low densities in the flowing gas.
- Incorporating a simple prescription for the operation of streaming instability results in an efficient conversion of dust into planetesimals, although mostly in the outer disk and near the snow line.
- Many unknowns including effects of planet formation, role of MHD disk winds, gas disk masses, photoevaporative wind tracers.

THANK YOU!