

## Outline

### Photoevaporation and the Dispersal of Disks

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Collaborators: **David Hollenbach**, Kees Dullemond, Ilaria Pascucci, Gennaro D'Angelo

- Disk Dispersal
- Photoevaporation
- Theoretical models
- Current Research

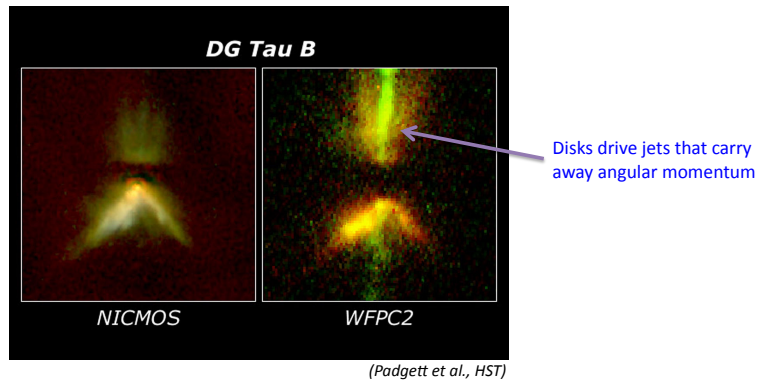
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## Disk Dispersal

- Disks facilitate star formation and are the sites of planet formation.



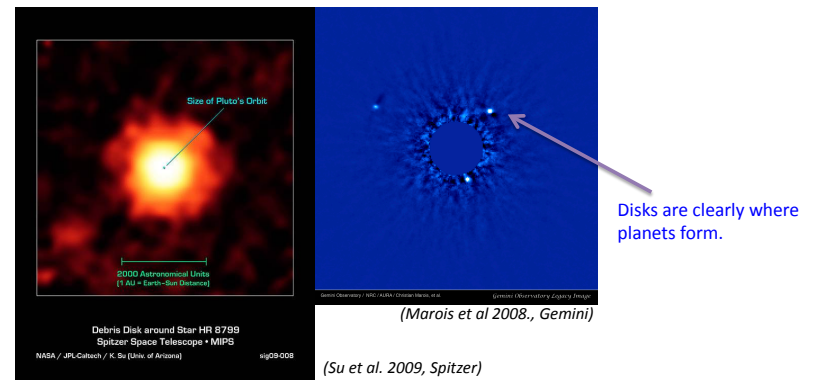
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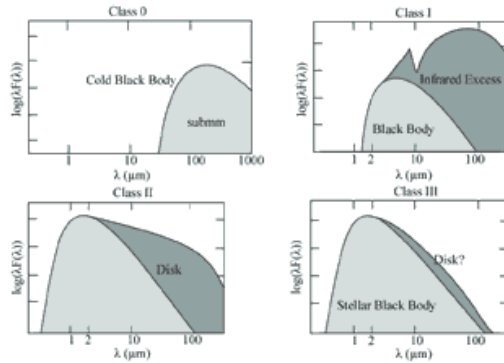
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## Disk Dispersal

- Disks facilitate star formation and are the sites of planet formation.
- Disks are short-lived.
  - Disk dust emission in the infrared decreases as protostar evolves.



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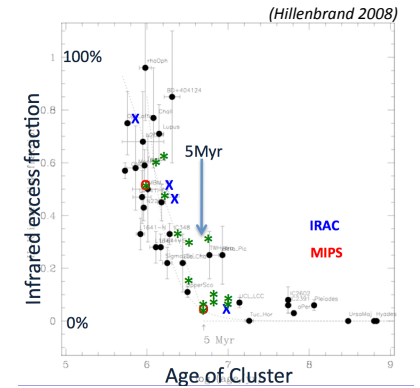
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  - Infrared excesses decline with age.

Disk IR excess decreases on similar timescales at 1-2 $\mu$ m, 5-8 $\mu$ m, and 24 $\mu$ m, across disk radii up to at least tens of AU.



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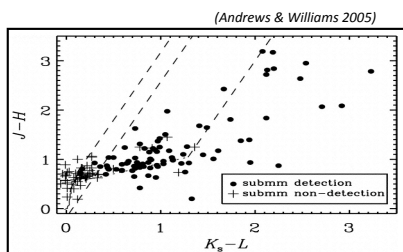
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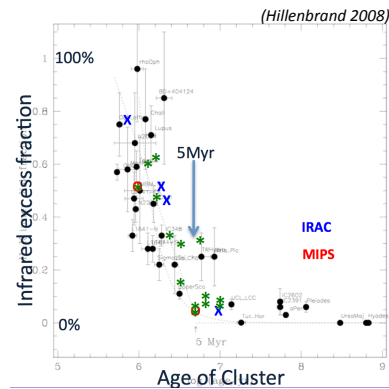
Sub-mm detections are correlated with the presence of inner dust.



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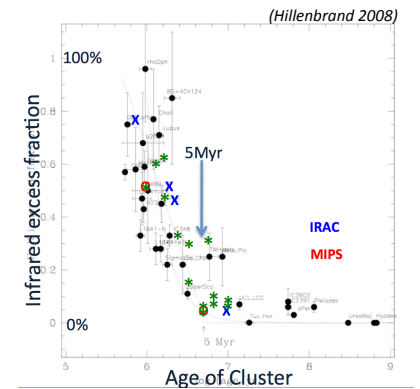
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Dust disk lifetime at all radii  $\sim$  3-5 Myrs.  
However, 99% of the mass is in the gas component.

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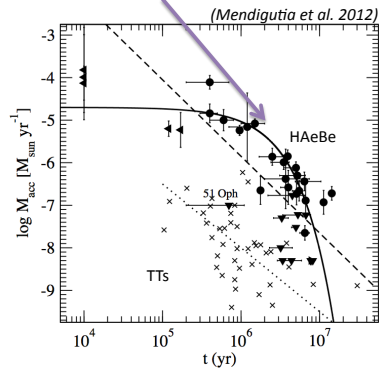
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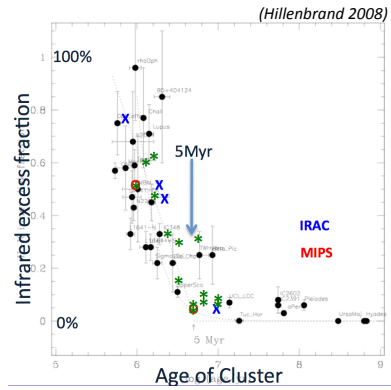
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  - **Accretion rate falls as disk evolves.**



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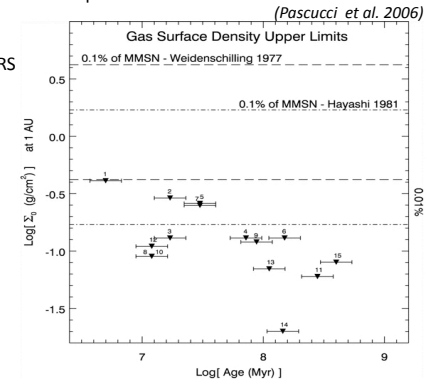


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  - Accretion rate falls as disk evolves.
  - CO rotational lines (>30AU), Spitzer IRS

- Lack of CO in disks with ages >10 Myrs. (Zuckerman et al. 1995)
- No gas in 1-40AU region of disks with ages 5-30Myrs. (Pascucci et al. 2006)



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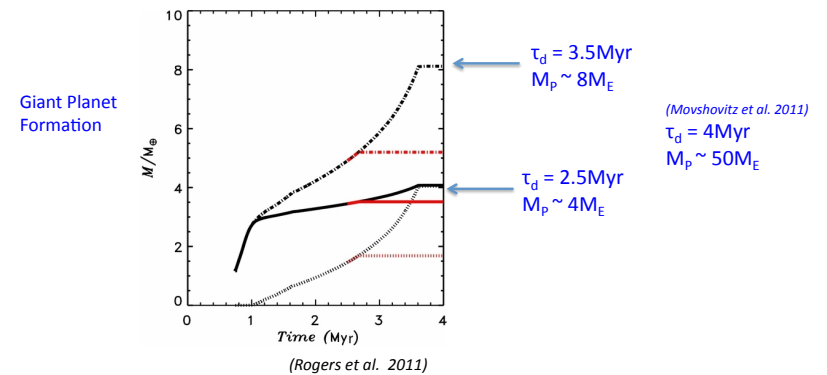
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  - Accretion rate falls as disk evolves.
  - CO rotational lines (>30AU), Spitzer IRS (1-40) AU.
  - Gas disk lifetimes are also short, < 10Myrs.

## Disk Dispersal

- Disks facilitate star formation and are the sites of planet formation.
- Disks are short-lived.
- Planet formation is affected by presence of gas at late stages of disk evolution.



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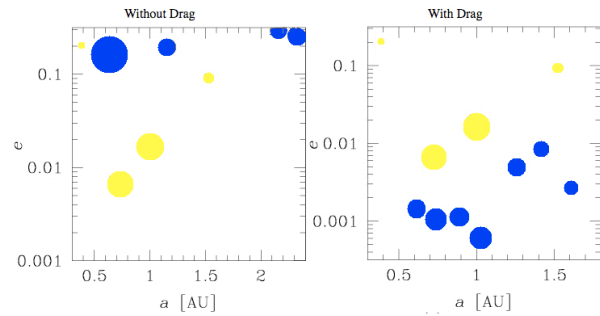
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Drag forces due to gas affect planetary orbits.

(Kominami & Ida 2002)

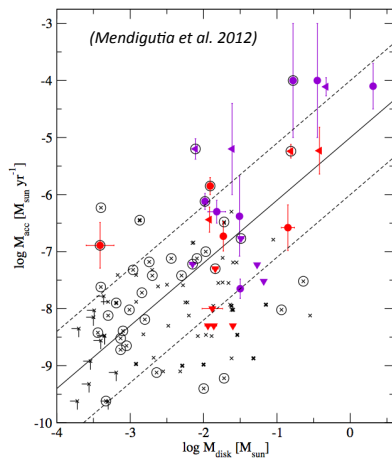
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How are disks dispersed?

## Photoevaporation

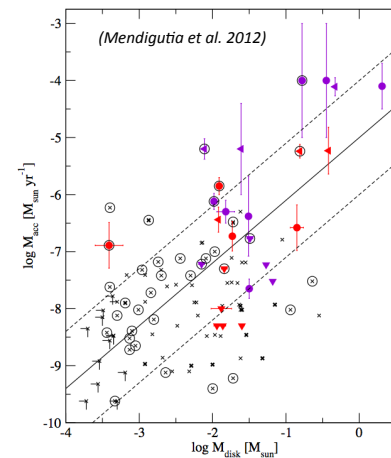
- Disk mass is removed by the processes of viscous accretion, photoevaporation and planet formation.



Consistent with viscous disk evolution, a significant fraction of disk mass is probably accreted onto the star.

## Photoevaporation

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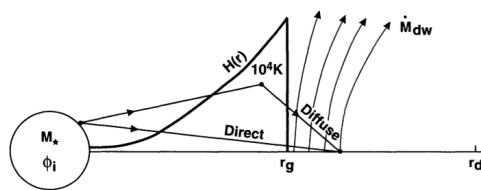


Consumes mass in solids.  $\sim 3 \times 10^{-4} M_{\odot}$  for solar system (Chiang & Youdin 2010)

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## Photoevaporation

- Disk mass is removed by the processes of viscous accretion, photoevaporation and planet formation.
- Disks are most likely dispersed by photoevaporation due to heating by high energy photons.
  - Central star photoevaporation by O and B stars (*Hollenbach et al. 1994*)



Thermal evaporating wind

$$r_g \sim G M_* / c_s^2$$

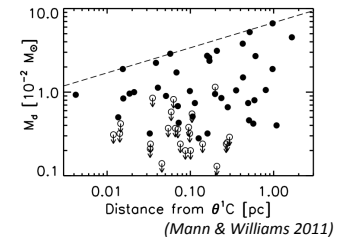
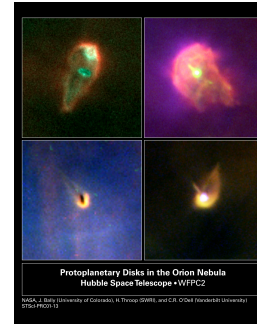
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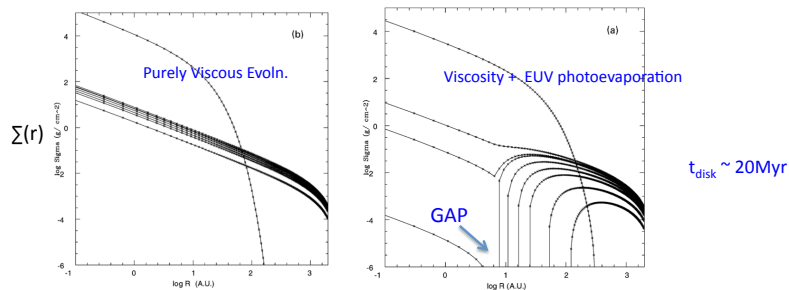
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  - Viscous accretion coupled with EUV photoevaporation for  $1M_\odot$  star – Gap opening (*Clarke et al. 2001*)



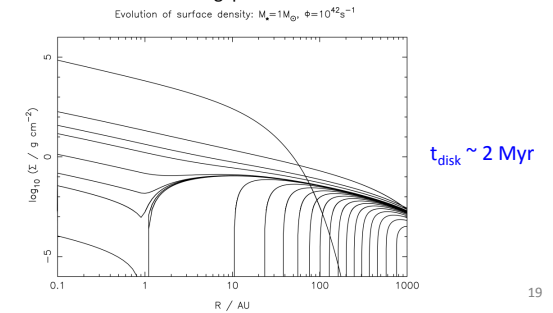
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  - Direct irradiation by EUV of the inner disk rim after gap – Shorter disk lifetimes (*Alexander et al. 2006*)
  - X-ray and FUV photoevaporation, earlier onset of disk dispersal, higher mass loss rates. (*Ercolano et al. 2008, Gorti & Hollenbach 2009, Owen et al. 2010*)

X-rays and FUV penetrate deeper into the disk, act at earlier epochs.  
Chromospheric activity and accretion result in high luminosities.  
Measured fluxes, unlike EUV.

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## EUV, FUV and X-ray Photoevaporation Models

- Photoevaporative flows begin at the disk surface, depend sensitively on gas density and temperature.
- FUV/X-ray heated gas can be ~ 100 - 5000 K, complex gas chemistry and many different coolants.
- Need to solve accurately for gas structure, detailed models needed.

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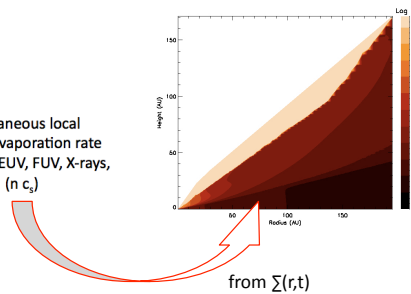
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$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left( \sqrt{r} \frac{\partial}{\partial r} (v \Sigma \sqrt{r}) \right) - \dot{\Sigma}_{pe}(r, t)$$

Kinematic viscosity  
 $v \equiv \alpha c_s^2 / \Omega_K$

Instantaneous local  
Photoevaporation rate  
due to EUV, FUV, X-rays,  
 $\dot{\Sigma}_{pe} \propto (n c_s)$



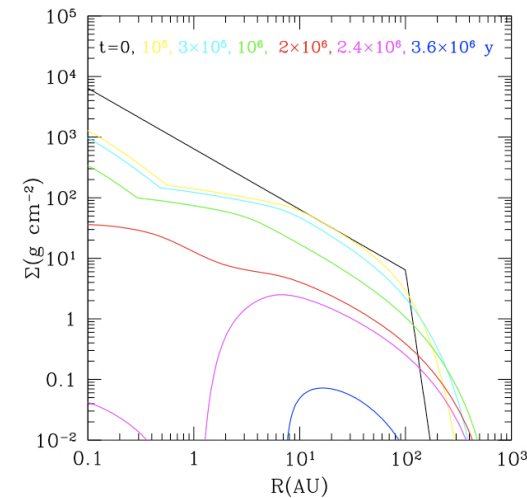
from  $\Sigma(r, t)$

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## EUV, FUV and X-ray Photoevaporation Models



EUV: 10<sup>30</sup> erg s<sup>-1</sup> (10<sup>41</sup> s<sup>-1</sup>)

X-rays: 10<sup>30</sup> erg s<sup>-1</sup>

FUV: From  $dM_{acc}/dt$   
+ 10<sup>30</sup> erg s<sup>-1</sup> from  
chromosphere

$M_{disk}(t=0) = 0.1 M_{\odot} = 0.1 M_{\odot}$

t=0 is really t ~ 0.5 Myr  
(Ignore early epochs)

Constant viscous  $\alpha = 0.01$

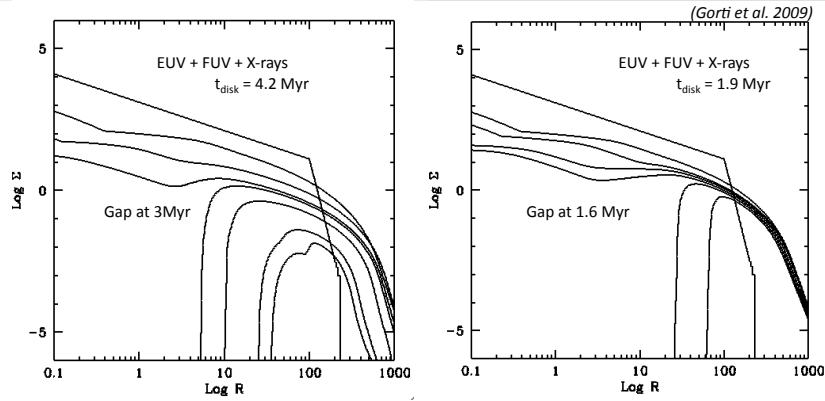
$t_{disk} \sim 4-5$  Myr

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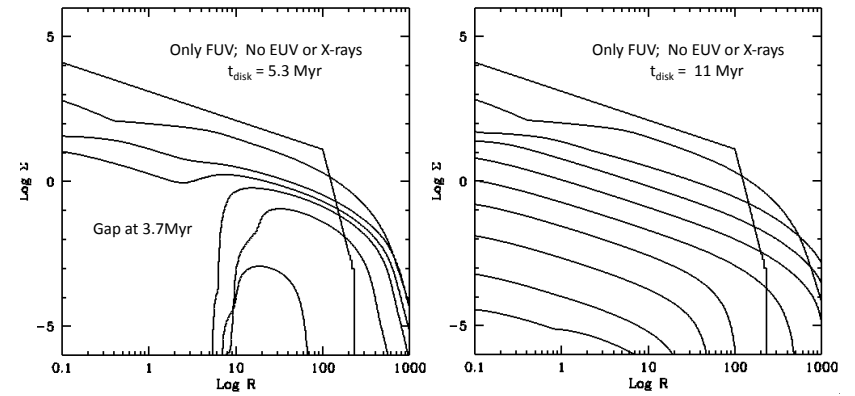
EUV, FUV and X-ray Photoevaporation Models



$L_x = 10^{30} \text{ erg s}^{-1}$   
 HARD X-ray spectrum peaks at 2 keV

$L_x = 10^{30} \text{ erg s}^{-1}$   
 SOFT X-ray spectrum, power law to 0.1 keV

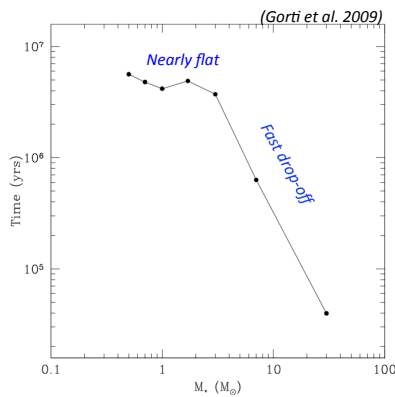
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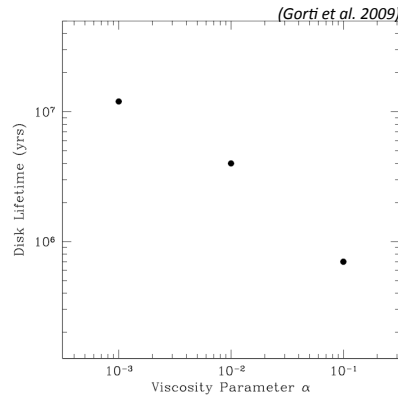
FUV opens a gap in inner disk.  
 Chromospheric FUV =  $5 \times 10^{-4} L_*$

Gap cannot be sustained without FUV from accretion.  
 Chromospheric FUV =  $5 \times 10^{-5} L_*$

EUV, FUV and X-ray Photoevaporation Models



Disk lifetime ~ few Myr for low mass stars,  
 short for stars with  $M_* > 3 M_\odot$ .



Disk lifetime depends on  $\alpha$   
 $\alpha$  unknown function of  $r$  and  $t$

Current Work: Observational diagnostics

➤ What drives photoevaporation? EUV, FUV or X-rays?

Different morphologies with different implications for planet formation.

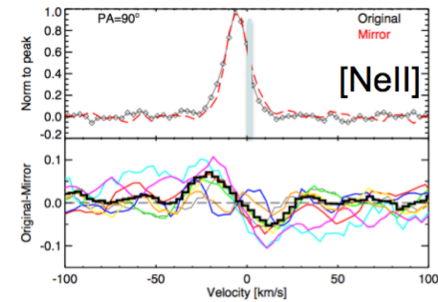
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- What are typical mass loss rates?  $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$  for EUV,  $10^{-9}$  for FUV/X-rays.

Higher disk mass at gap-opening epochs, availability of gas for planet formation

Current Work: Observational diagnostics

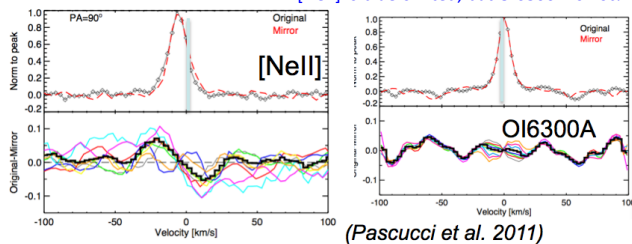
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- [OI]6300A blue-shifted emission predicted by the X-ray models (Ercolano & Owen 2010)

[NeII] is blue-shifted, but OI6300A is not!



(Pascucci et al. 2011)

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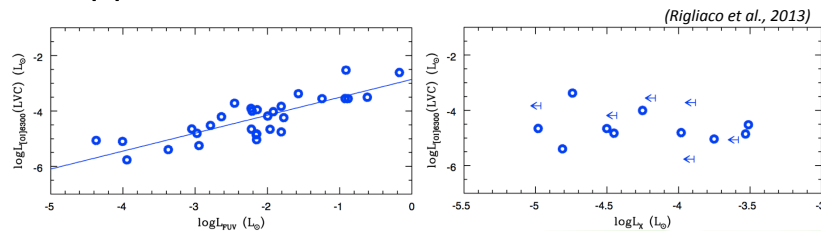
EUV-heating?

Free-free emission indicates EUV is likely too low. (Pascucci et al. 2012)

X-ray heating. But [OI]?

## Current Work: Observational diagnostics

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- What are typical mass loss rates?  $\sim 10^{-10} M_{\odot} \text{ yr}^{-1}$  for EUV,  $10^{-9}$  for FUV/X-rays.
- [NeII] 12.8 $\mu\text{m}$  emission is blue-shifted, indicates EUV or X-ray heating of wind.
- [OI]6300Å blue-shifted emission predicted by the X-ray models (Ercolano & Owen 2010)
- Does [OI] trace an FUV flow?



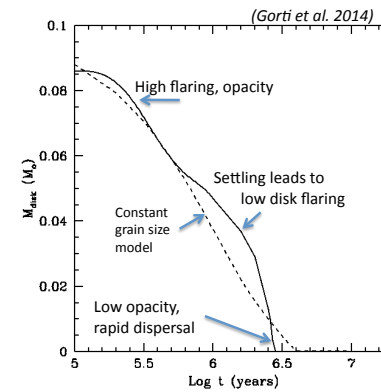
OI flux is correlated with FUV, but not with X-rays.  
[OI]6300 could arise from photodissociation of OH.

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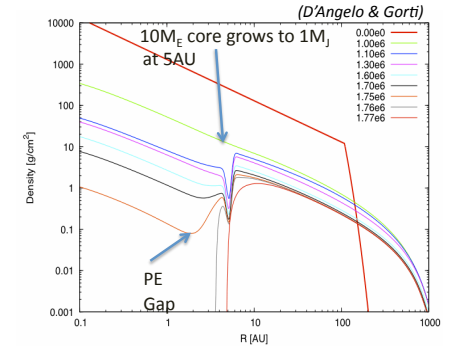
## Current Work: Theory



Dust evolution with viscosity and photoevaporation.  
Flaring angle affects interception of photons.  
Dust opacity affects disk structure, penetration depths.

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Giant planet exerts torques on disk.  
Gap created may accelerate dispersal.

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## Summary

- Disks disperse in a few million years, before which they must form planets.
- Photoevaporation and viscosity are mainly responsible for disk dispersal.
- EUV, FUV and X-rays have all been suggested as photoevaporation agents, disk evolutionary scenarios and predicted mass loss rates in each case differ.
- Stellar mass and radiation field, disk properties, magnitude of viscosity, and dust evolution all play significant roles in determining the evolution of the disk and its lifetime.
- Observational diagnostics of photoevaporative flows include [NeII] and perhaps [OI]. These are at present inconclusive and better diagnostics are needed.

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