Evolution and Dispersal of Protoplanetary Disks

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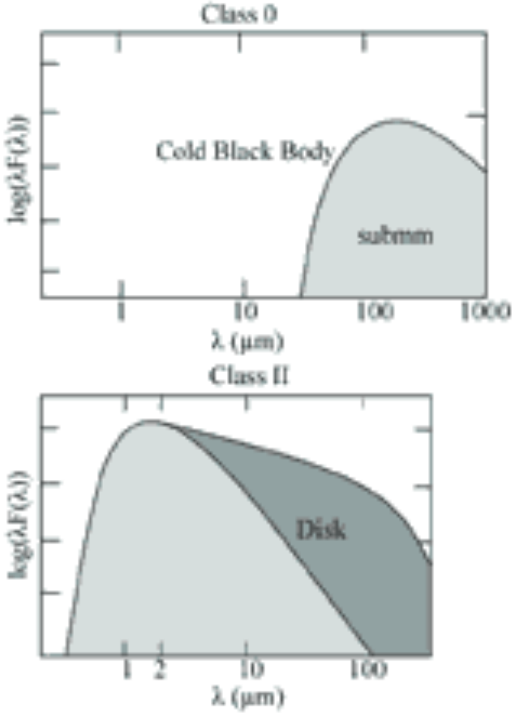
Outline:

- Disk Mass Evolution – Observational Studies
- Disk Dispersal and Photoevaporation – Theory
- ~~Theory vs.~~ Observations (future with SOFIA)

DISK DISPERSAL OBSERVATIONS

Disk Evolution and Lifetimes

- Disk contains gas (mostly H) and solids (dust, a ≤ μm), gas not well probed.
- Dust readily emits (but is only ~1% of mass).
- Dust disk evolves, grains grow, settle, amorphous to crystalline



Disk Evolution and Lifetimes

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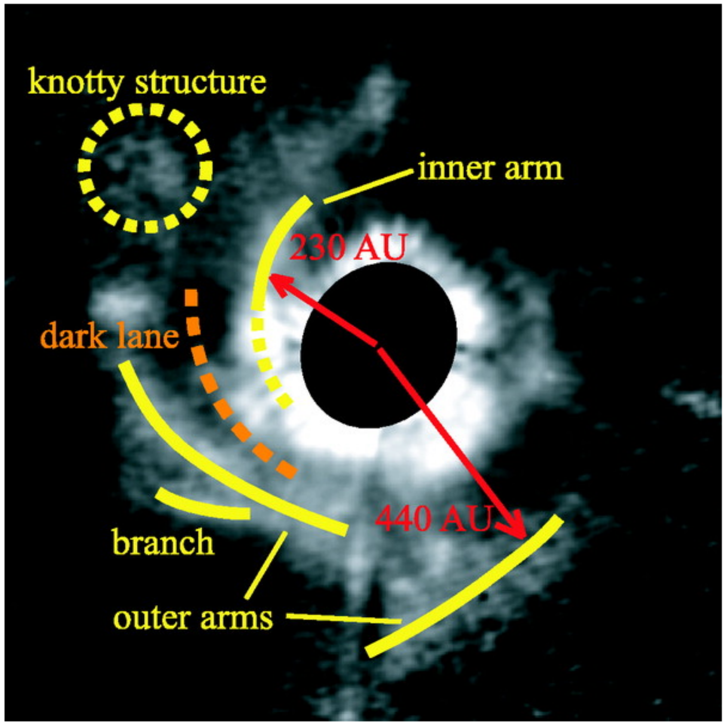
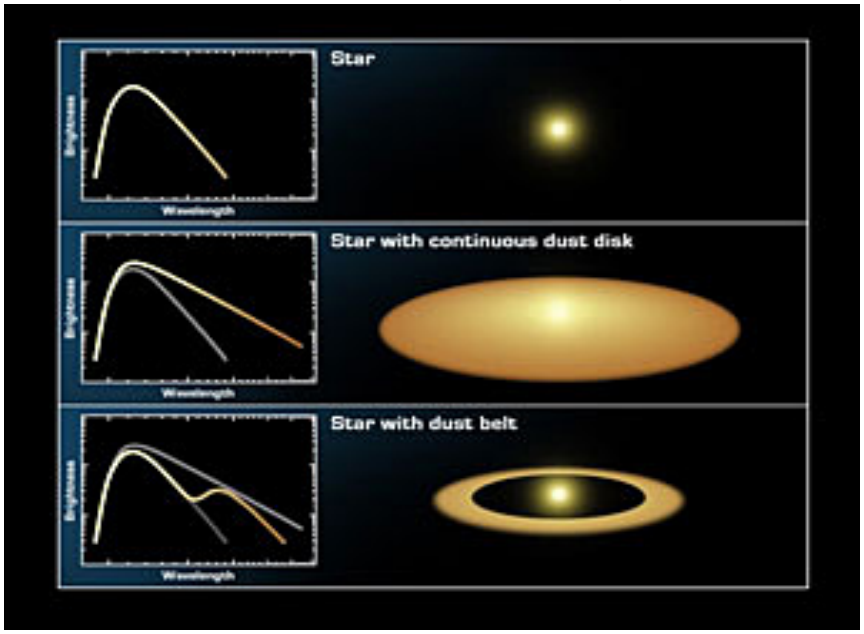
- Dust readily emits (but is only ~1% of mass).
- Dust disk evolves, grains grow, settle, amorphous to crystalline, structure

Fukugawa et al. 2004



e.g. AB Aur shows disk asymmetries, spiral structure

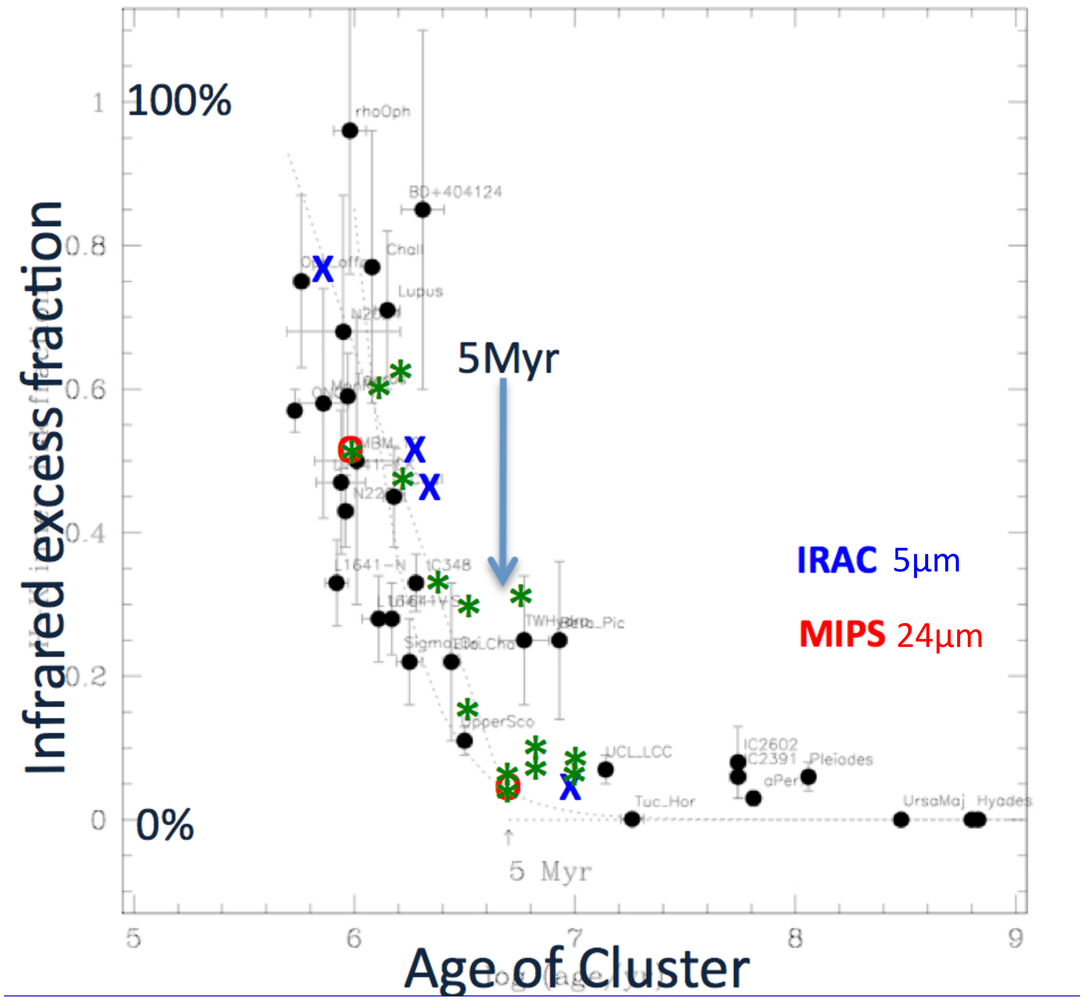
Image: D. Hines



SED changes indicate gaps/holes, rings

Disk Evolution and Lifetimes

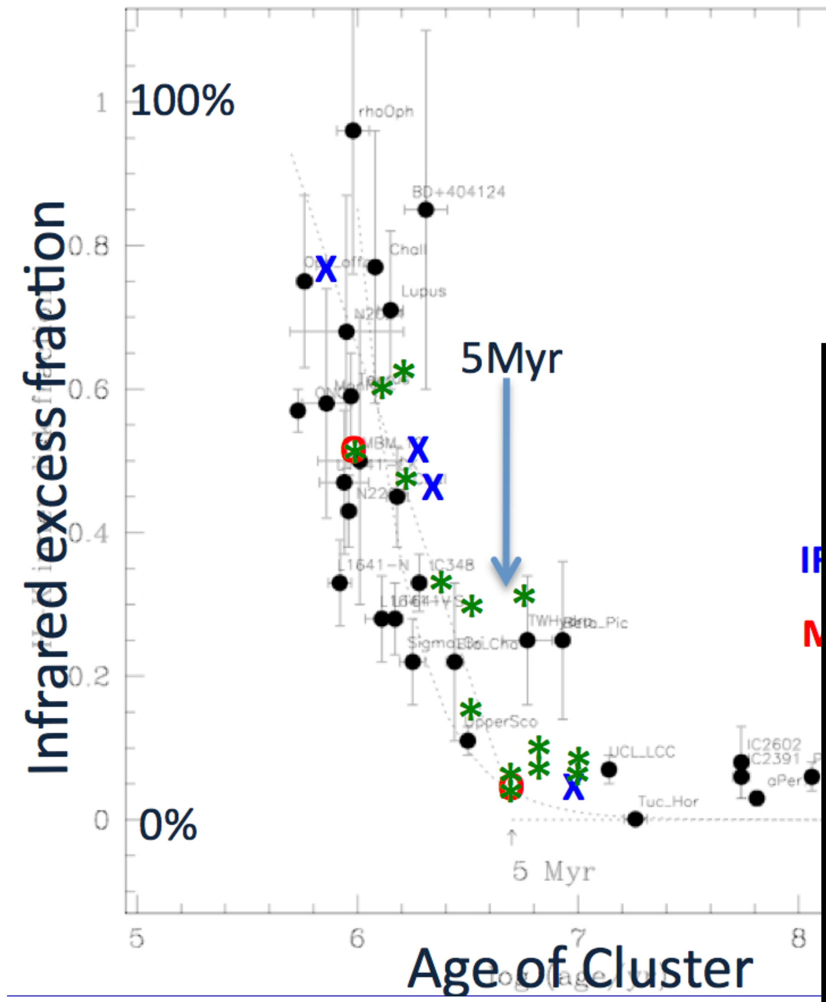
(Hillenbrand 2008)



Dust disk lifetimes ~ 5 Myrs.

Disk Evolution and Lifetimes

(Hillenbrand 2008)



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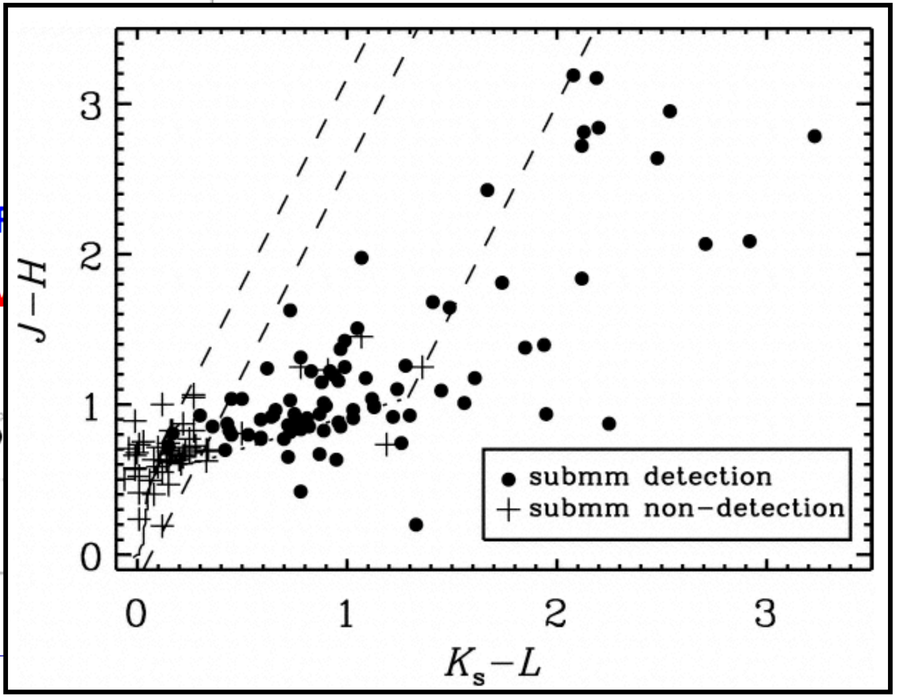
Andrews & Williams 2005



Disk Evolution and Lifetimes

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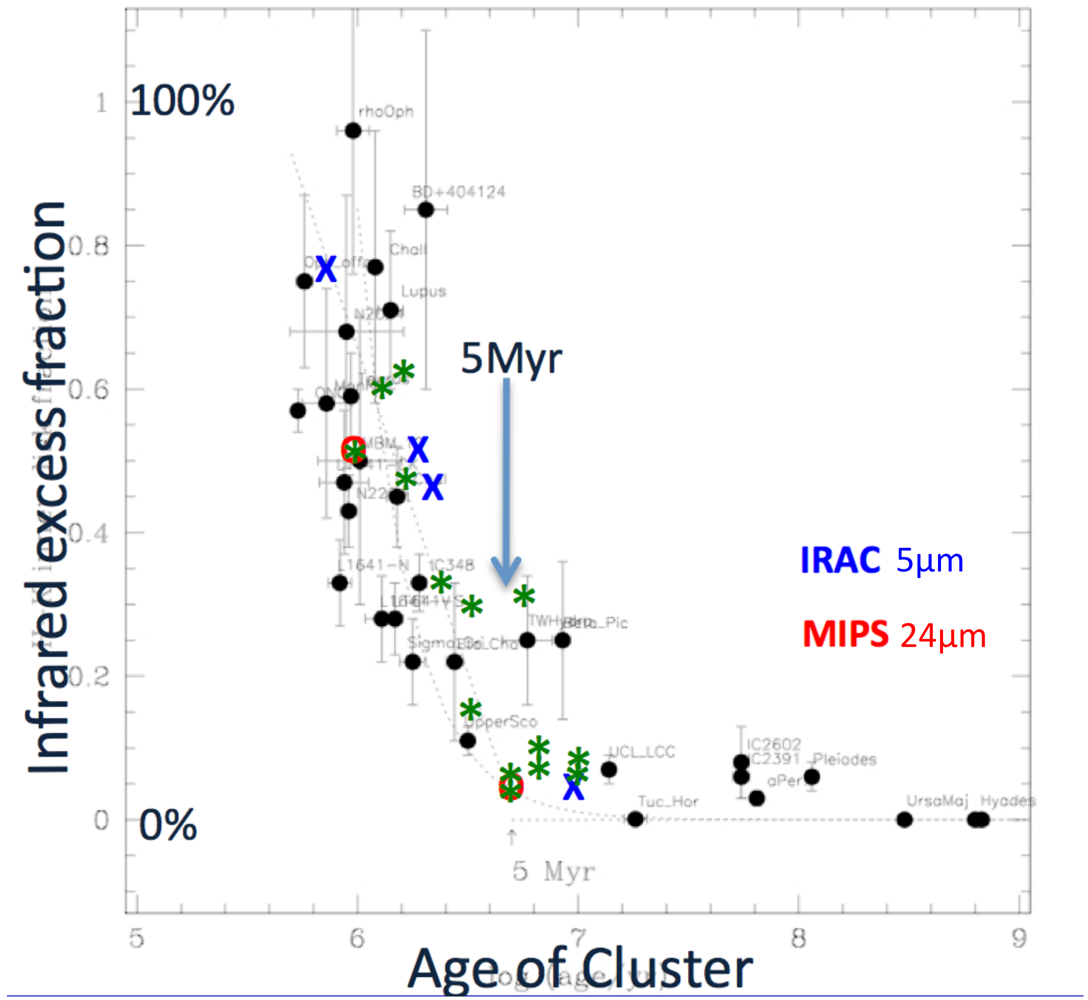
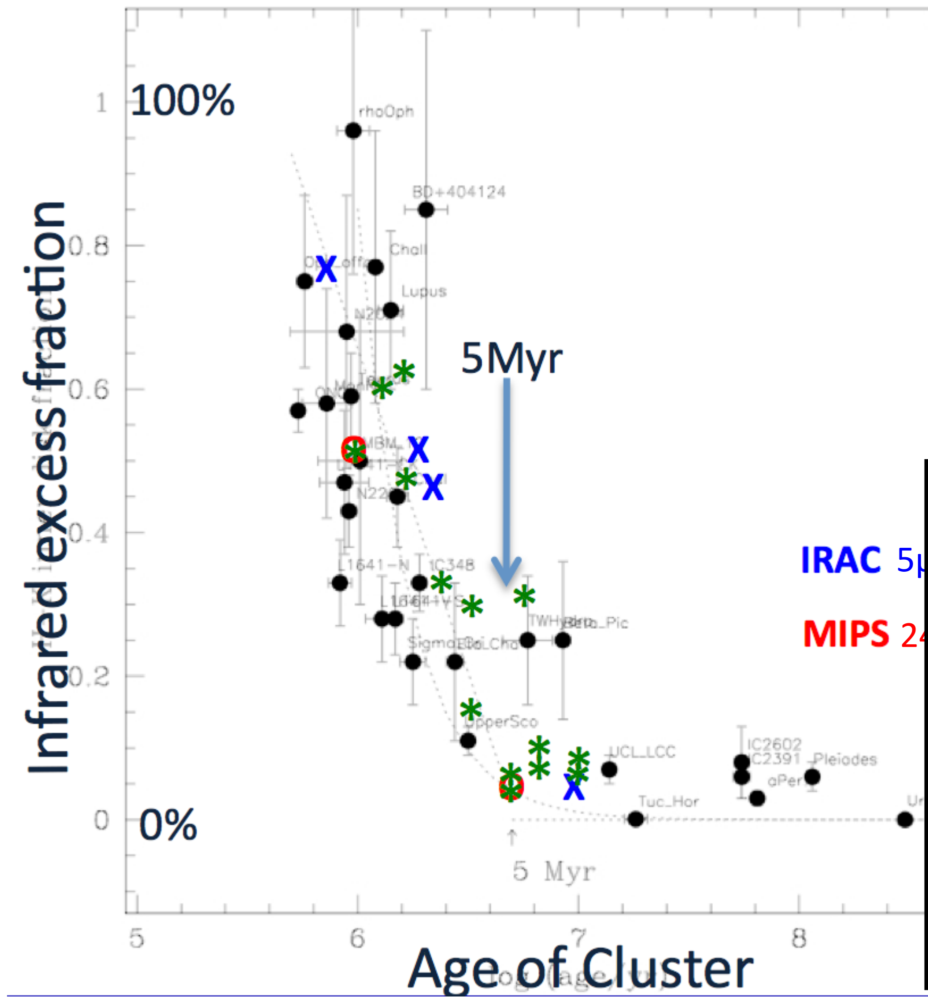


Dust disk lifetimes ~ 5 Myrs.

Gas ?
Dominates mass,
but is hard to observe.

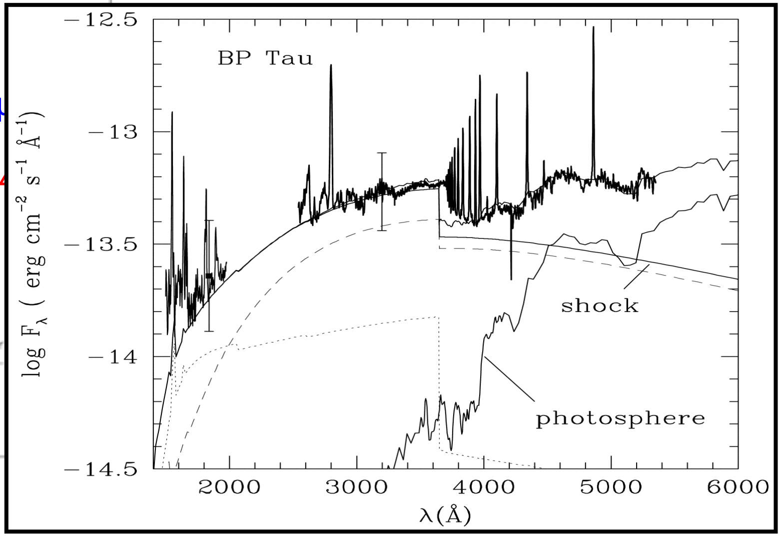
Disk Evolution and Lifetimes

(Hillenbrand 2008)



Dust disk lifetimes ~ 5 Myrs.

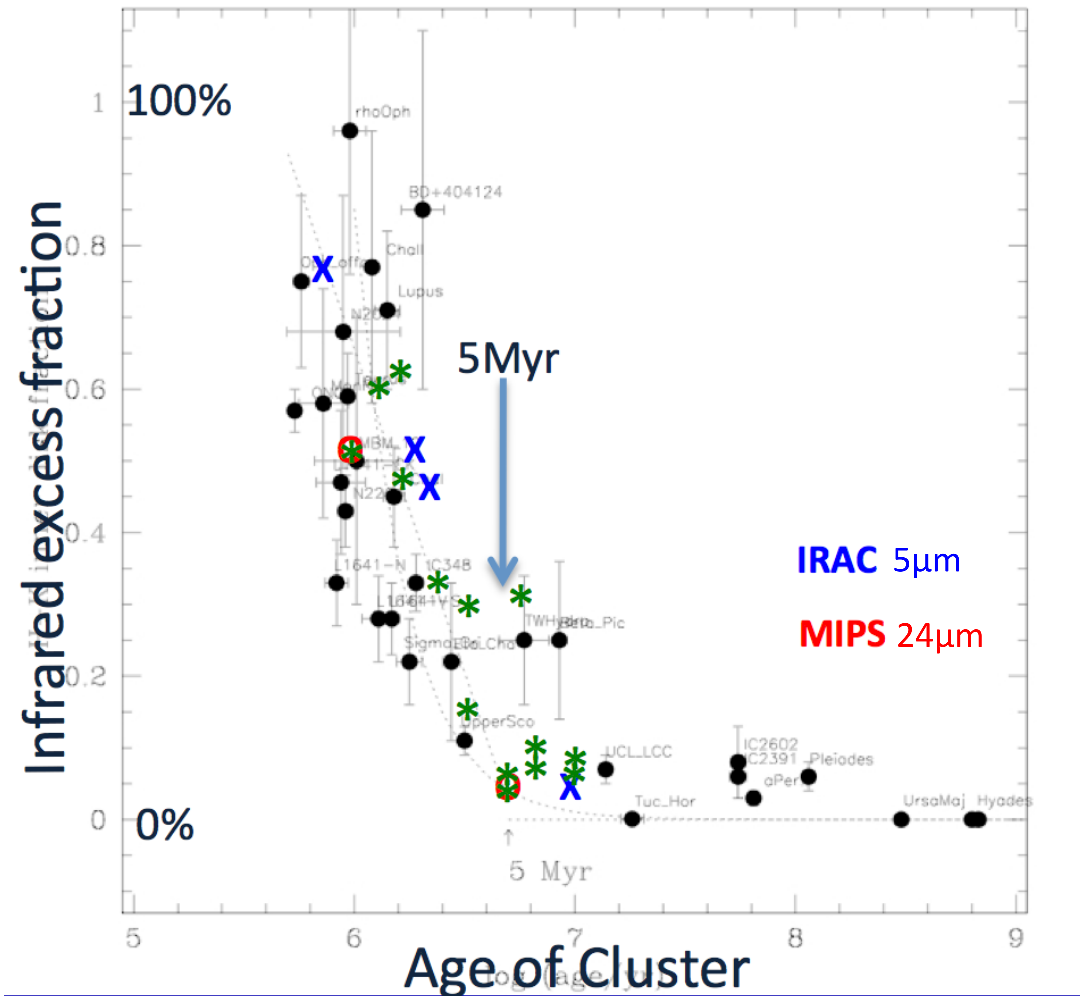
Gas ?
Dominates mass,
but is hard to observe.
Accretes onto star.



(Gullbring et all. 1998)

Disk Evolution and Lifetimes

(Hillenbrand 2008)



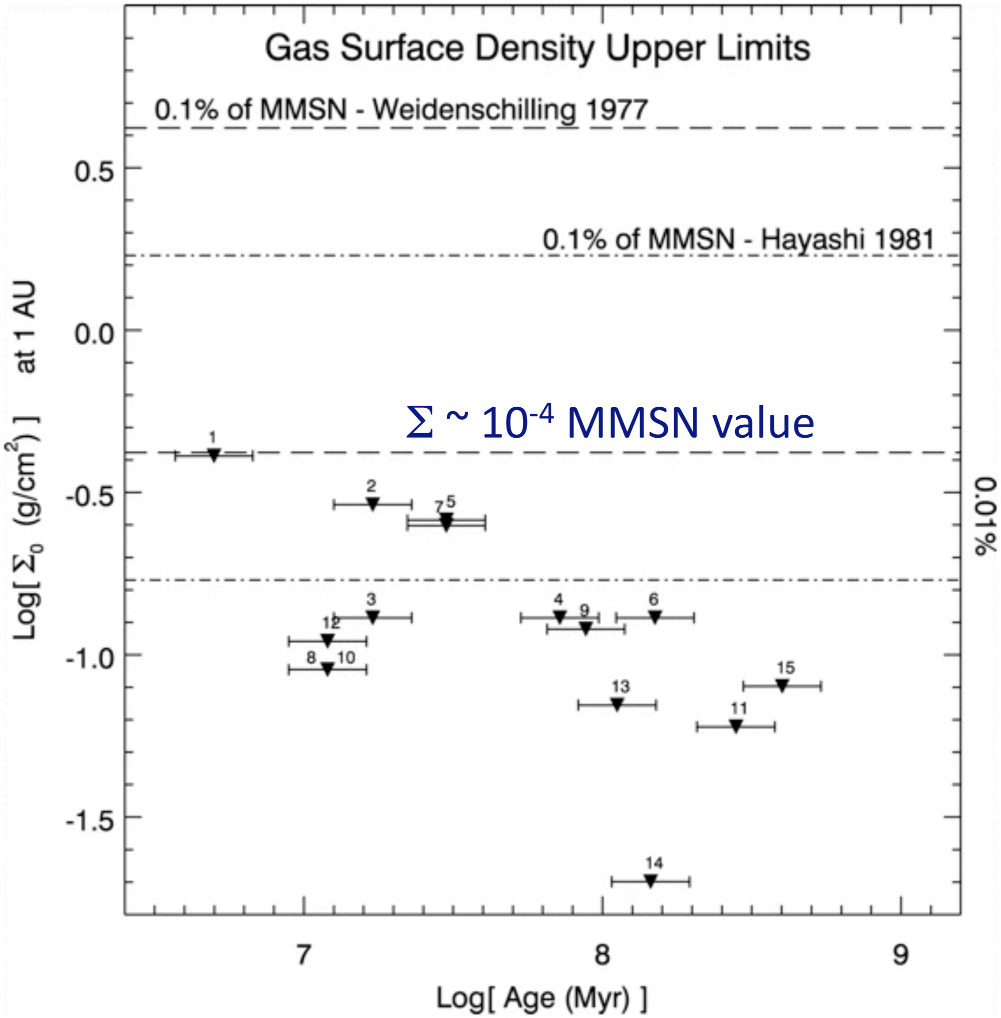
Dust disk lifetimes ~ 5 Myrs.

Gas:

* Fedele et al 2010
Mass accretion rate
fraction in clusters,
measures <u>gas</u>.

Disk Evolution and Lifetimes

(Pascucci et al. 2006)



Σ ~ 10^{-4} MMSN value

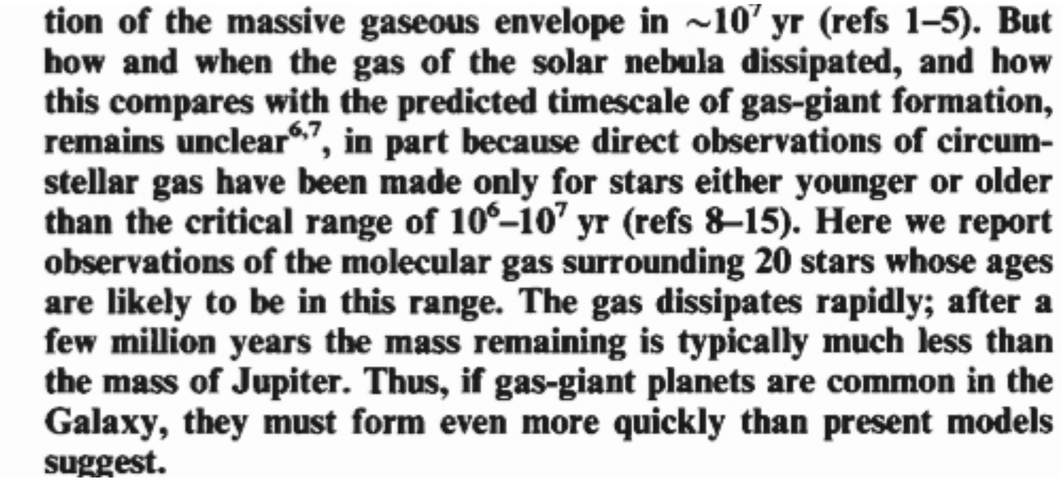
Dust disk lifetimes ~ 5 Myrs.

Gas in (1-40AU) region has lifetimes less than ~5-30Myr.

Disk Evolution and Lifetimes

Dust disk lifetimes ~ 5 Myrs.

Zuckerman, Forveille & Kastner 1995



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Gas in (1-40AU) region has
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CO observations of young disks; inferred lifetimes ~ 10 Myrs

Disk Evolution and Lifetimes

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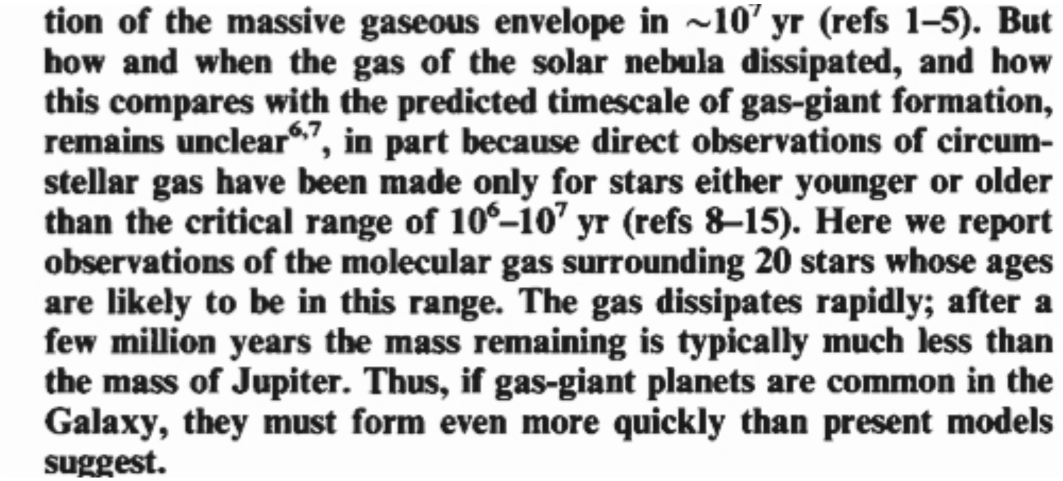

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Dust disk lifetimes ~ 5 Myrs.

Gas in (1-40AU) region has lifetimes less than ~5-30Myr.

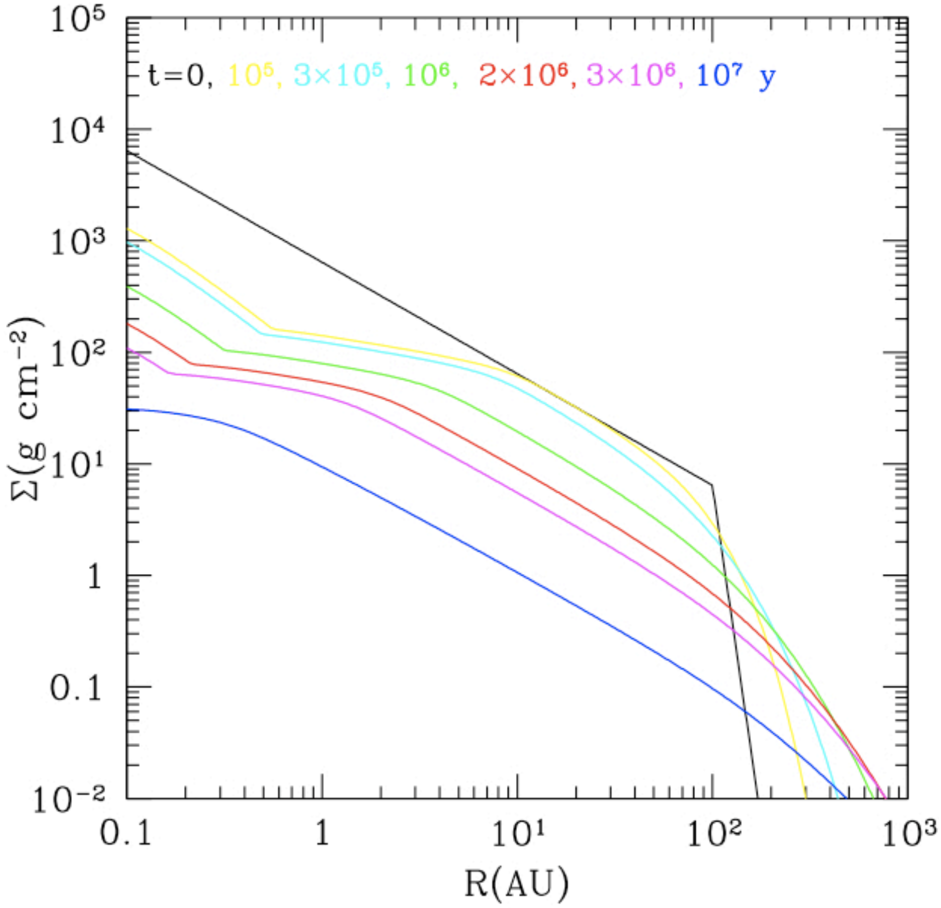
← CO observations of young disks; inferred lifetimes ~ 10 Myrs

Dust disks ~ 5Myrs, Gas disks ~ 5-30Myrs
ENTIRE DISK IS DISPERSED

DISK DISPERSAL THEORY

Disk Dispersal

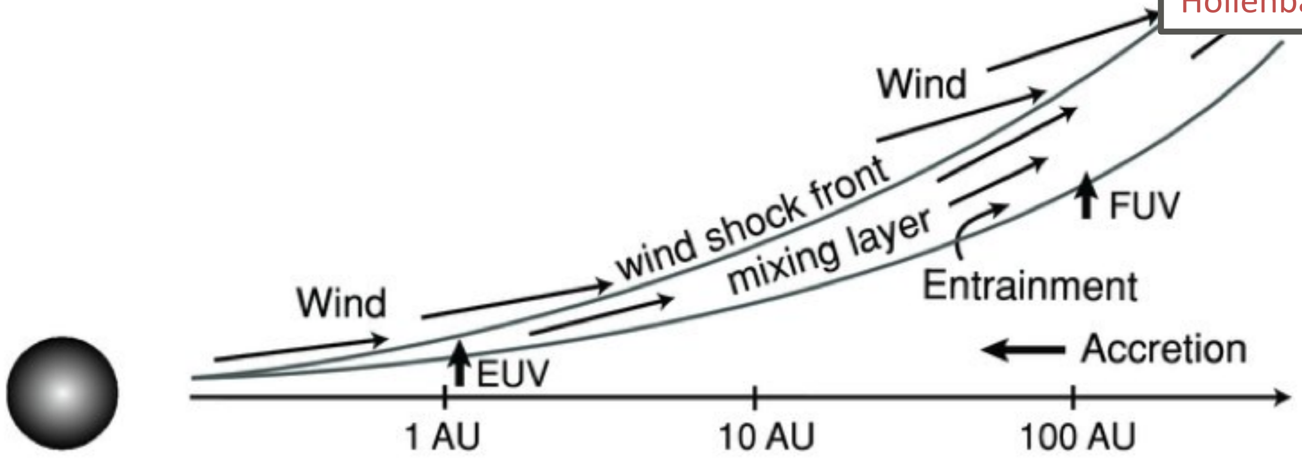
1. Viscous Evolution



Disk Dispersal

1. Viscous Evolution – Long timescales
2. Stellar winds

Not important,
need $dM_w/dt \sim dM_{acc}/dt$
(Matsuyama, Johnstone & Hollenbach 2010)



Disk Dispersal

1. Viscous Evolution – Long timescales
2. ~~Stellar winds~~
3. Close stellar encounters and tidal stripping

Need very close encounters, only possible in very dense star clusters, hence cannot be a general mechanism.

Disk Dispersal

1. Viscous Evolution – Long timescales
2. ~~Stellar winds~~
3. ~~Close stellar encounters and tidal stripping~~
4. Planet Formation – May deplete solids, but gas dispersal needed

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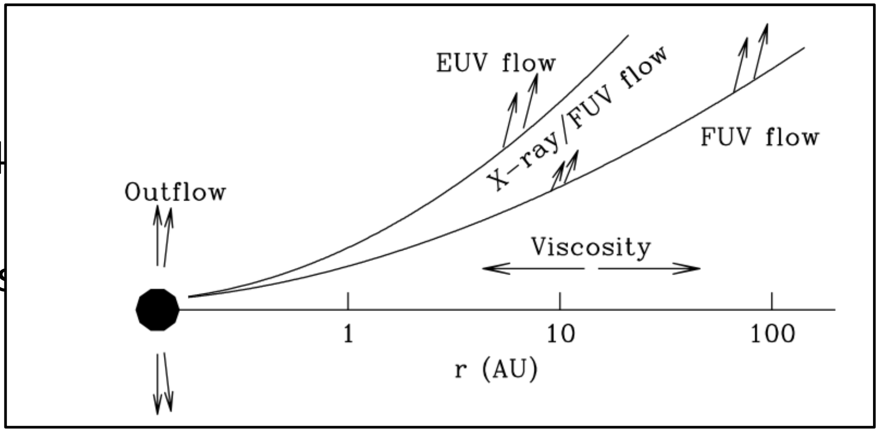

5. Photoevaporation

- Disk surface is irradiated by high energy photons (EUV, FUV, X-rays).
- Gas is heated to thermal speeds that exceed escape speeds.
- Mass is lost from disk resulting in *photoevaporation.*
- Gravitational radius $R_G \sim GM/c_s^2 \sim 7$ AU for 10^4 K gas for a $1M_o$ star
- Angular momentum support gives $R_{crit} \sim 0.1\text{-}0.2\ R_G$

Disk Dispersal

⇨ 1. Viscous Evolution – Long timescales -Mainly inner disk, ~ 50% of mass?

2. ~~Stellar winds~~

3. ~~Close stellar encounters and tidal stripping~~

⇨ 4. Planet Formation – Gas dispersal needed - Some fraction (?) of solid mass

⇨ 5. Photoevaporation - Mainly outer disk, ~50% of mass?

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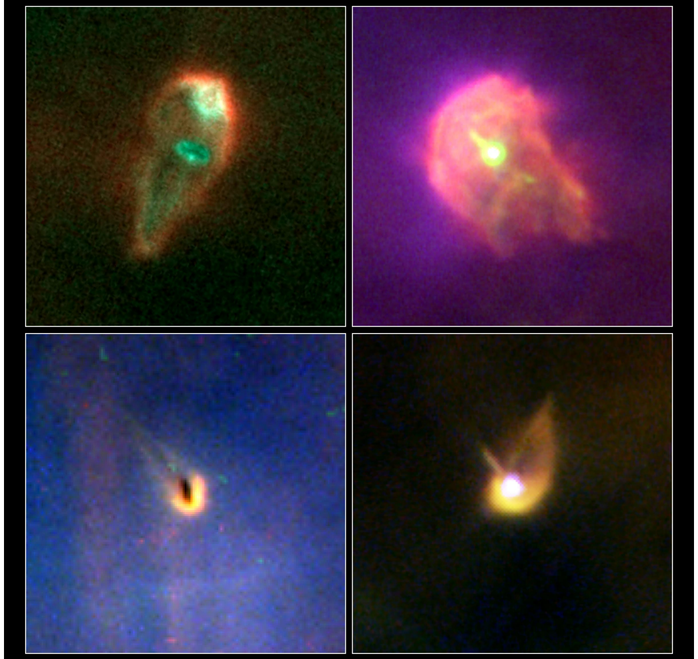
Disk Dispersal: Photoevaporation

- First applied to disks in clusters near the high radiation field of massive OB stars.

(Hollenbach et al. 1994)



Protoplanetary Disks in the Orion Nebula
Hubble Space Telescope • WFPC2

NASA, J. Bally (University of Colorado), H. Throop (SWRI), and C.R. O'Dell (Vanderbilt University)
STScI-PRC01-13

External irradiation of disks by a nearby massive O star

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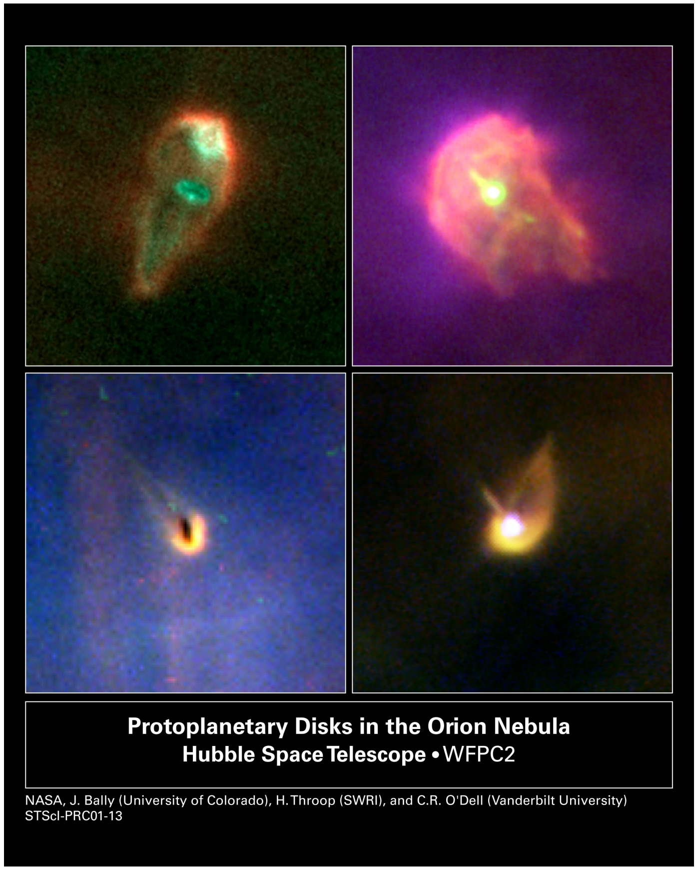

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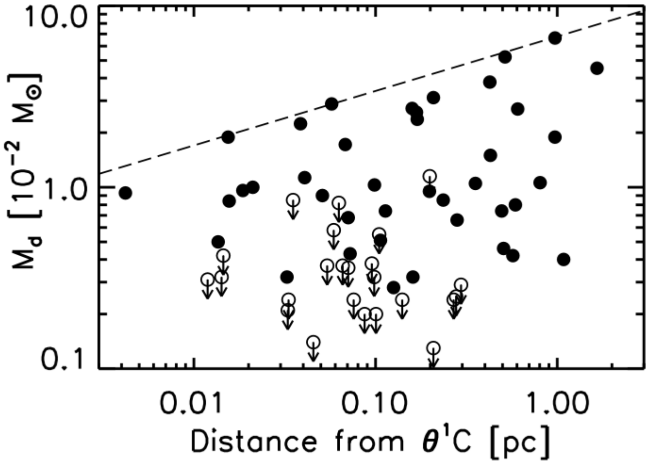

(Mann & Williams 2011)

Disk Dispersal: Photoevaporation

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- Young, low-mass stars are very UV and X-ray luminous, central star can also photoevaporate disk. (Alexander et al. 2006, Gorti & Hollenbach 2008, Ercolano et al. 2009)

$$r_g = \frac{GM_*}{c_s^2} \approx 10\mathrm{AU}\left(\frac{10^4}{T}\right)\left(\frac{M_*}{1\mathrm{M}_\odot}\right)$$

Higher Temperatures → Greater Escape Speeds

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- Heating by Extreme Ultraviolet (EUV) ($h\nu > 13.6$eV) photons
- EUV photoevaporation of disk around central star *(e.g., Shu et al 1993, Hollenbach et al. 1994, Johnstone et al. 1998, Richling & Yorke 2000)*

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- Combined effects of EUV radiation from central star and viscosity "Ultraviolet switch" scenario (Clarke et al. 2001) $t_{disk} \approx 20$ Myrs

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Higher Temperatures → Greater Escape Speeds

- Heating by Extreme Ultraviolet (EUV) ($h\nu > 13.6$eV) photons
- EUV photoevaporation of disk around central solar-type star *(e.g., Shu et al 1993, Hollenbach et al. 1994, Johnstone et al. 1998, Richling & Yorke 2000)*

- Combined effects of EUV radiation from central star and viscosity "Ultraviolet switch" scenario (Clarke et al. 2001) $t_{disk} \approx 20$ Myrs
- Alexander et al. (2006) considered direct EUV illumination of gap once it forms, and disk disperses rapidly after gap opens. (High EUV fluxes, low disk masses)

Disk Dispersal: Photoevaporation

FUV and X-rays are important for disk photoevaporation

(Ercolano et al. 2008, 2009, Gorti & Hollenbach 2008, 2009, Gorti, Dullemond & Hollenbach 2009, Owen et al. 2010 2012)

- FUV and X-rays have longer penetration depths and are incident on the disk earlier in its evolution.

- FUV and X-rays are measured, can be high. FUV initially comes mainly from accretion, and rates are high at early epochs.

For young solar-type stars,

- $L_X \sim 10^{28\text{-}30}$ erg s^{-1} (~ 100 higher than present-day sun)(Chromosphere)
- L_{EUV} ~ Unknown! Estimates range from $\phi_{EUV} \sim 10^{40\text{-}44}$ s^{-1} (Alexander, Clarke & Pringle 2005)
  If chromospheric, $10^{28\text{-}30}$ erg s^{-1}, $\phi_{EUV} \sim 10^{40\text{-}42}$ s^{-1}
- $L_{FUV} \sim 10^{29\text{-}32}$ erg s^{-1} (~ 10^4 higher than present-day sun) (Accretion shocks + Chromosphere)

Disk Dispersal: Photoevaporation

- 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 gas disk structure models needed.

Disk Evolution Models

Disk surface density evolution is studied.

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

Kinematic viscosity

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

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

Photoevaporation included as a sink term.

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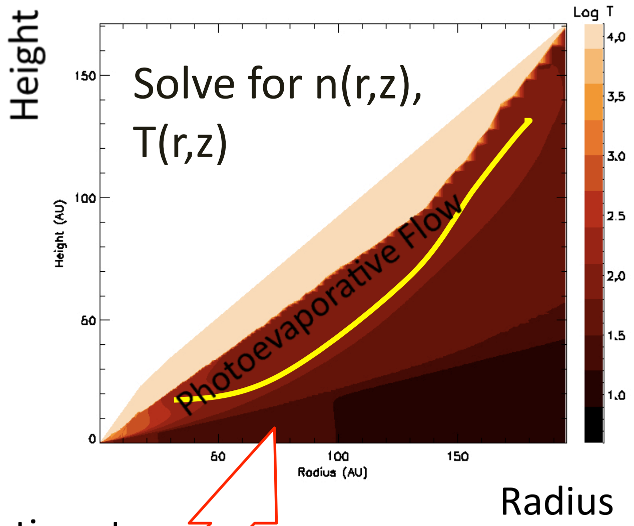


At every timestep

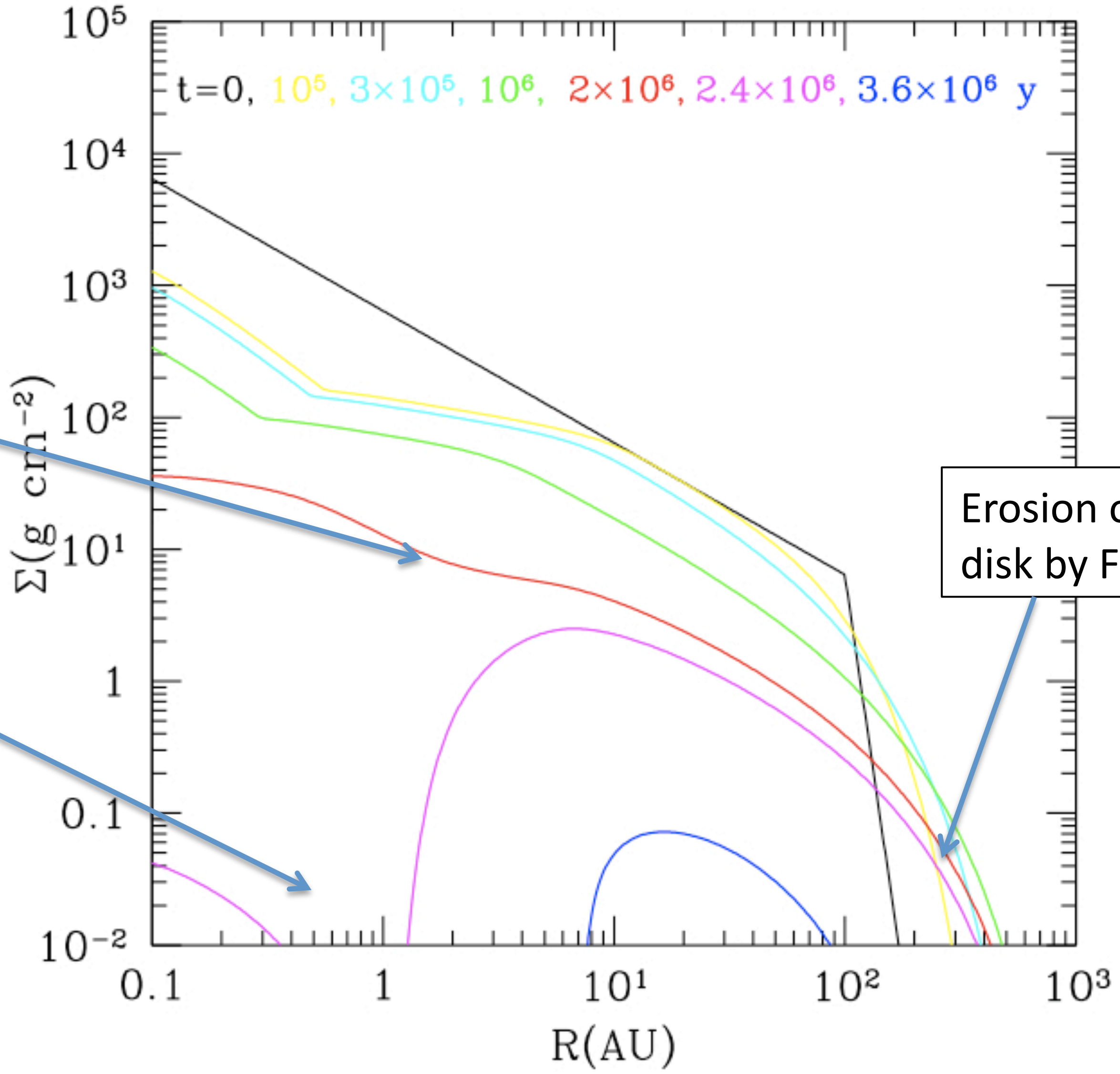
from ∑(r,t)

Photoevaporation included as a sink term.

Dust model with grain size distribution, radiative transfer via 1+1D model
Gas heating and cooling, radiative transfer – thermal balance solved with chemistry

Disk Evolution Models

Viscosity, Photoevaporation by EUV, FUV and X-rays



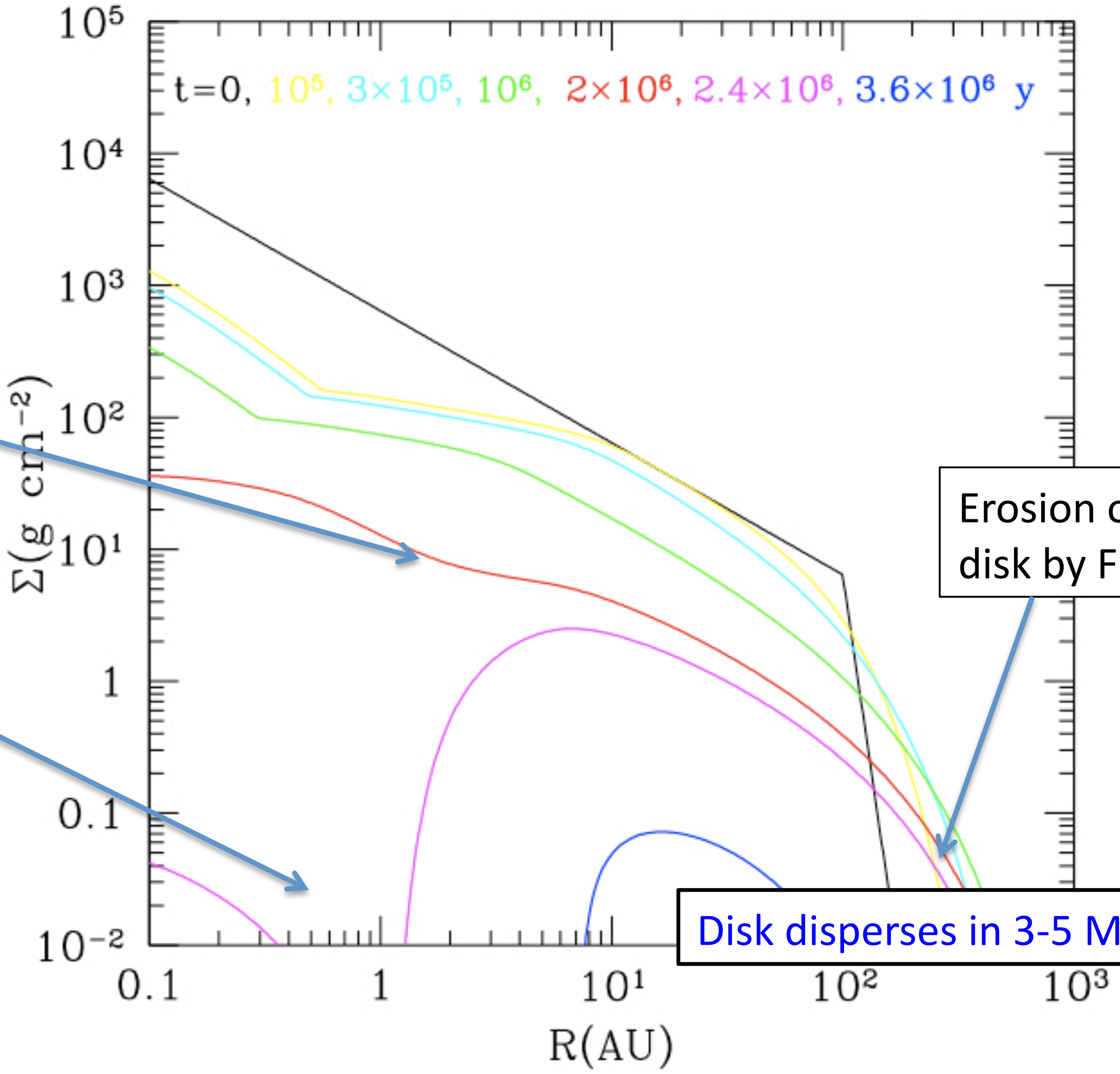
$dM_{acc}/dt < dM_{PE}/dt$

GAP by
X-rays
or
high FUV

Erosion of outer
disk by FUV

Disk Evolution Models

Viscosity, Photoevaporation by EUV, FUV and X-rays



$dM_{acc}/dt < dM_{PE}/dt$

GAP by
X-rays
or
high FUV

Erosion of outer disk by FUV

Disk disperses in 3-5 Myrs

Disk Evolution: - Key Questions Remain

- How does the disk surface density distribution evolve?
  - Transition disks with inner dust holes, e.g. TW Hya
  - Planet formation, presence of gas, Jupiters vs. Neptunes
  - Planetary dynamics, migration, orbit circularization

- Disk dispersal – Photoevaporation mass loss rates?
  - Accretion and photoevaporation, their fractions
  - FUV, EUV or X-rays?
  - Nature of dispersal, inside-out or outside-in
  - Wind diagnostics needed

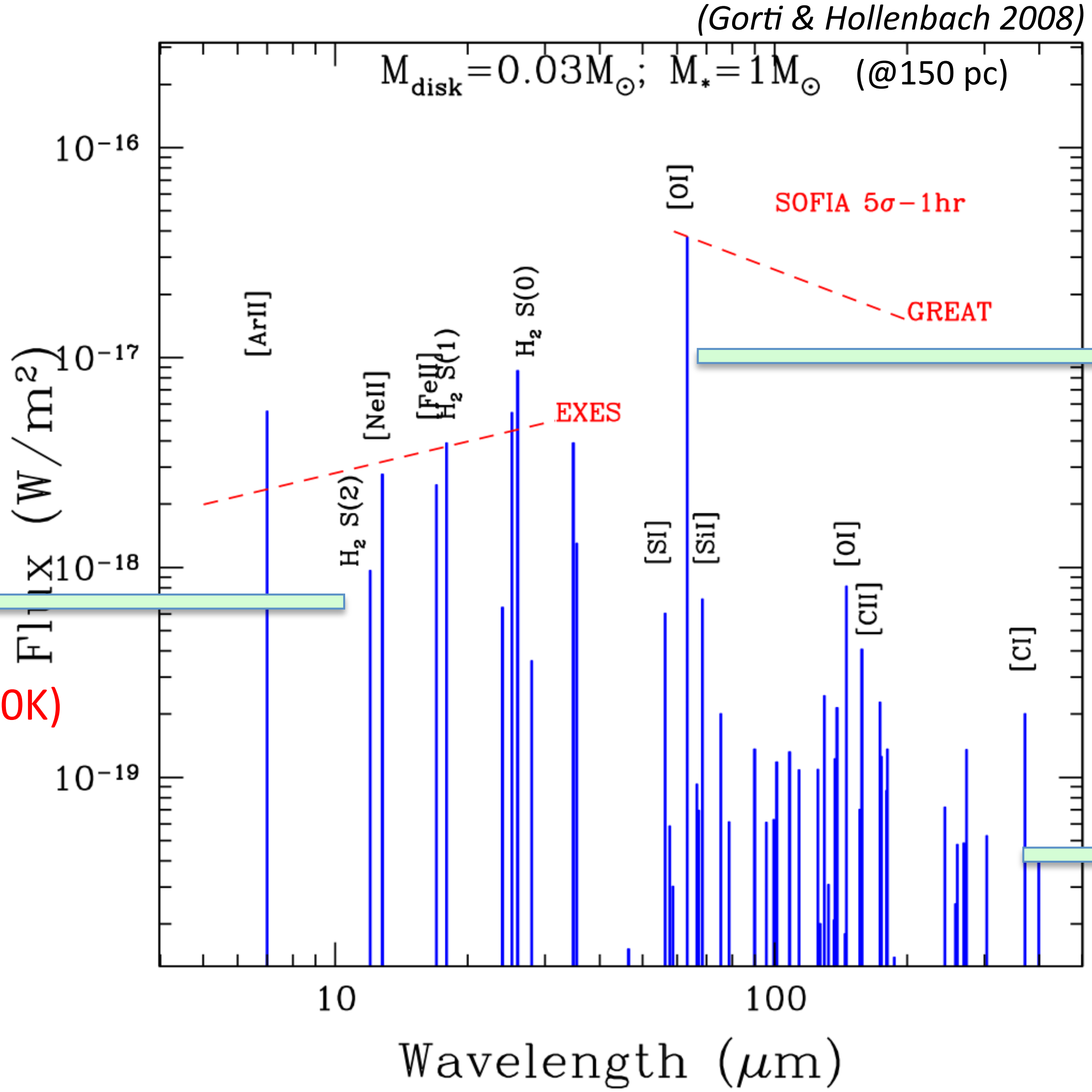
- Disk lifetimes – How long and what do they depend on?
  - Stellar mass, radiation, T Tauri stars and Herbig AeBe stars
  - Disk properties, initial angular momentum, viscosity, dust
  - Planet formation, any feedback?

DISK DISPERSAL: Future Observations

DISK DISPERSAL: Future Observations

- Disk Mass Evolution
- Photoevaporation Diagnostics

Disk Mass/Surface Density Evolution



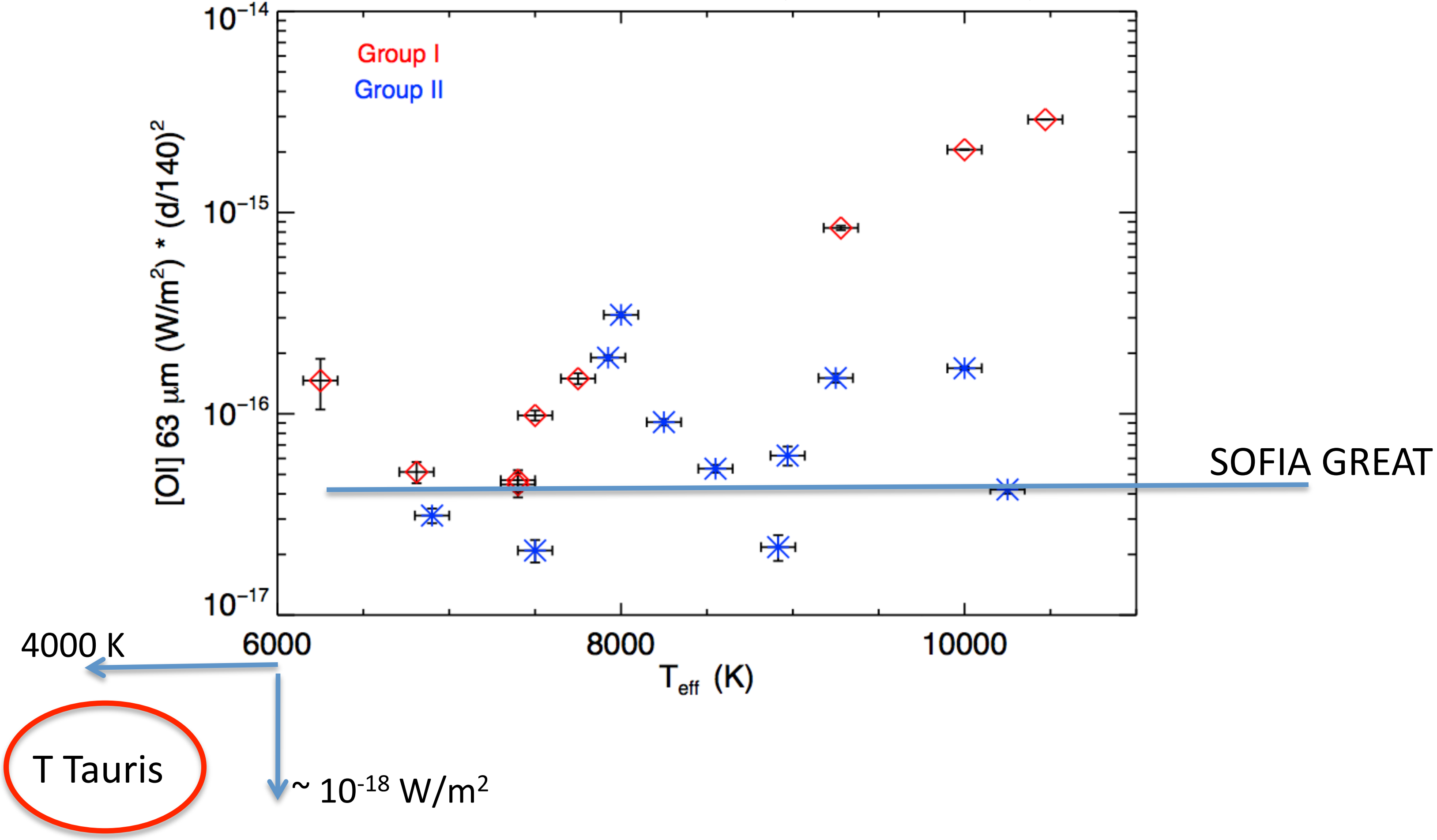
An "optimistic" model

Herschel PACS, detected in many disks, unresolved, background emission.

H_2 – Ideal, but weak, warm gas (100K)

ALMA – CO
Cold gas tracer
Chemistry?
Freezes

Disk Mass/Surface Density Evolution



(Meeus et al. 2012) GASPS

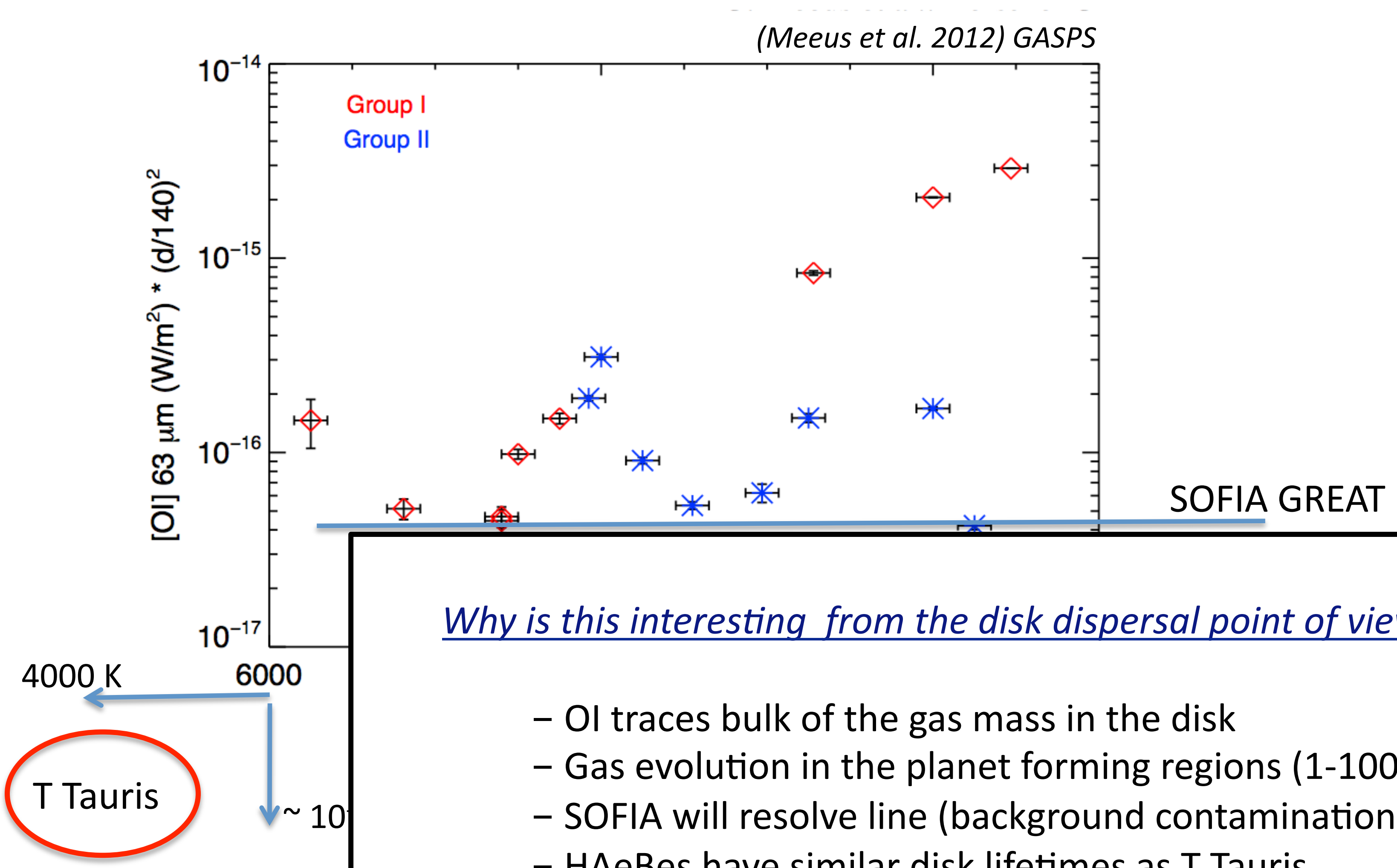
SOFIA GREAT

4000 K

T Tauris

~ 10^{-18} W/m^2

Disk Mass/Surface Density Evolution



Why is this interesting from the disk dispersal point of view ?

- OI traces bulk of the gas mass in the disk
- Gas evolution in the planet forming regions (1-100AU)
- SOFIA will resolve line (background contamination)
- HAeBes have similar disk lifetimes as T Tauris

Disk Dispersal Diagnostics

Photoevaporative mass loss rates? Depends on the dispersal agent, qualitatively different evolutionary scenarios.

- EUV – Disk evolves mainly by viscosity for a long period. Disk primarily accreted.
  However, EUV flux unknown. dM/dt ~ ?? (~ 10^{-10} M_o yr^{-1})

- X-rays – High mass loss rates predicted, disk again evolves viscously until gap
  opening. Disk disperses inside-out. (Different models differ.)
  X-ray flux is well measured. (dM/dt ~ 10^{-8} M_o yr^{-1})

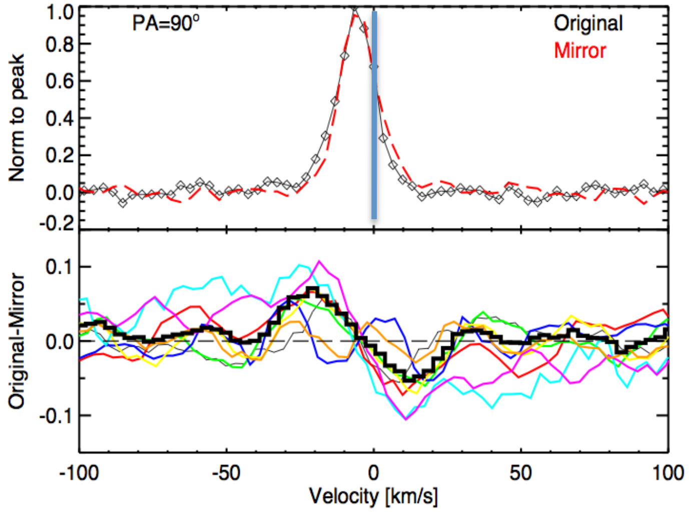
- FUV – Qualitatively different evolution – Neutral flows dominated by mass loss in the
  outer disk. Expected dM/dt ~ 10^{-9} M_o yr^{-1}. Predict disk truncation.
  Gap formation (or not) depends on level of chromospheric FUV and X-rays.
  FUV dominates disk dispersal for intermediate mass stars.

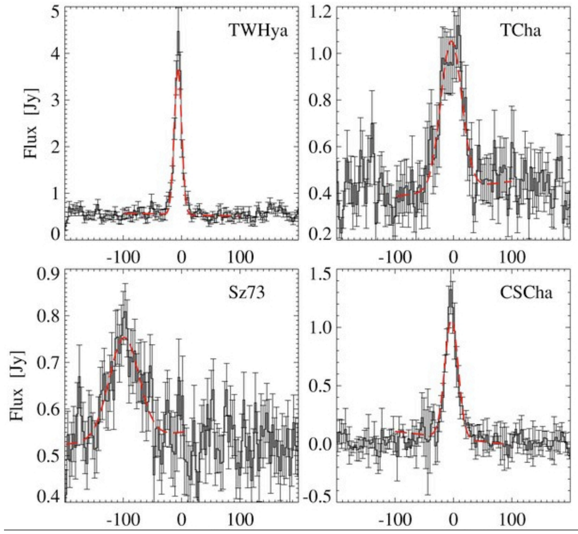
Different implications for planet formation in disk

Disk Dispersal Diagnostics

(Pascucci et al. 2011)

[NeII] blueshift seen





(Pascucci & Sterzik 2009)

- Models predict equally strong ArII emission.
- Velocity information with EXES – location of emitting gas.
- NeII/ArII ratios may distinguish between EUV X-rays photoevaporation.
- Blue-shifts will provide evidence of wind.
- Possible blue-shifts in OI63um?

Summary

- Disk gas mass evolution is not well understood: Disk lifetimes ~ 10^7 yrs and comparable to dust disk lifetimes of a few Myrs. Planets must form on these timescales.

- Photoevaporation and viscous evolution may explain disk evolution qualitatively, with lifetimes ~ few Myrs for low mass stars and shorter for intermediate to high mass stars. Mass loss rates depend on whether flows are EUV, FUV or X-ray driven.

- Gas emission lines will provide valuable information on how disks evolve and get dispersed.

- SOFIA can detect [OI]63um, H_2 rot. lines, [NeII]12.8um, [ArII]7um and other lines, and high resolution observations will determine gas kinematics.

- Dust continuum – *(not discussed)* SOFIA fills important niche FIR region which can discriminate between degenerate dust configurations (SED-matching.)