Rapid evolution of the inner dust disk of protoplanetary disks surrounding intermediate-mass stars

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1. Introduction

Lifetime of protoplanetary disks

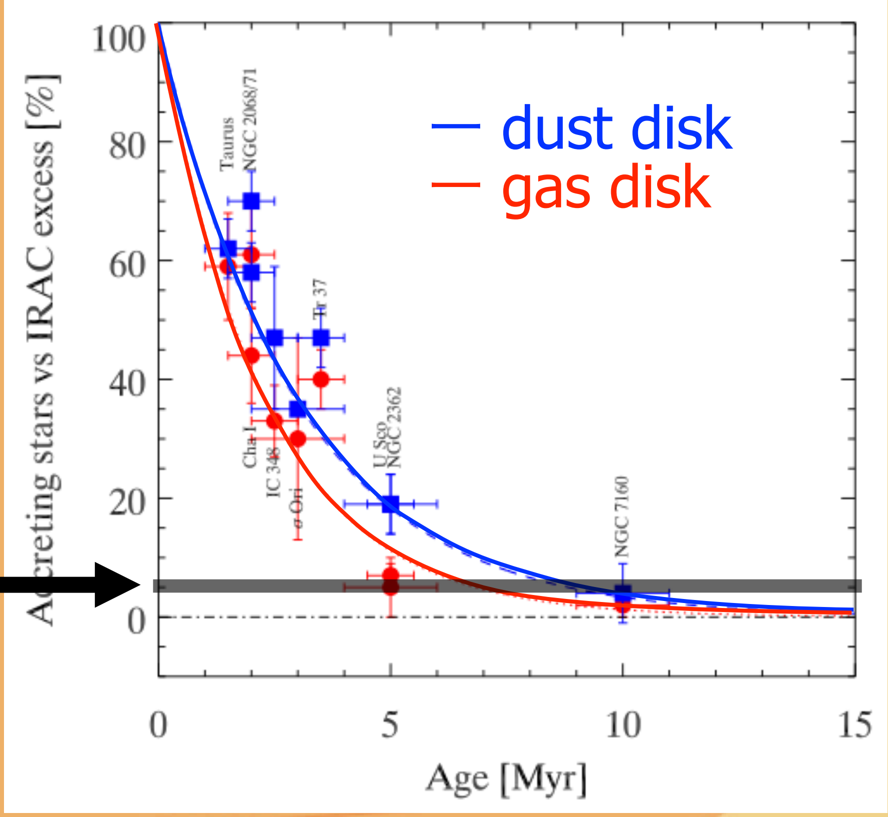
One of the most fundamental parameters of protoplanetary disk because it directly restricts the time of planet formation and star formation

✓ Low-mass (LM) stars ($\lesssim 1 M_\odot$)

～5−10 Myr

- From the time variation of disk fraction of star-forming clusters.
- Disk lifetime is estimated when disk fractions reach ~5-10%

We define by 5% threshold in this talk

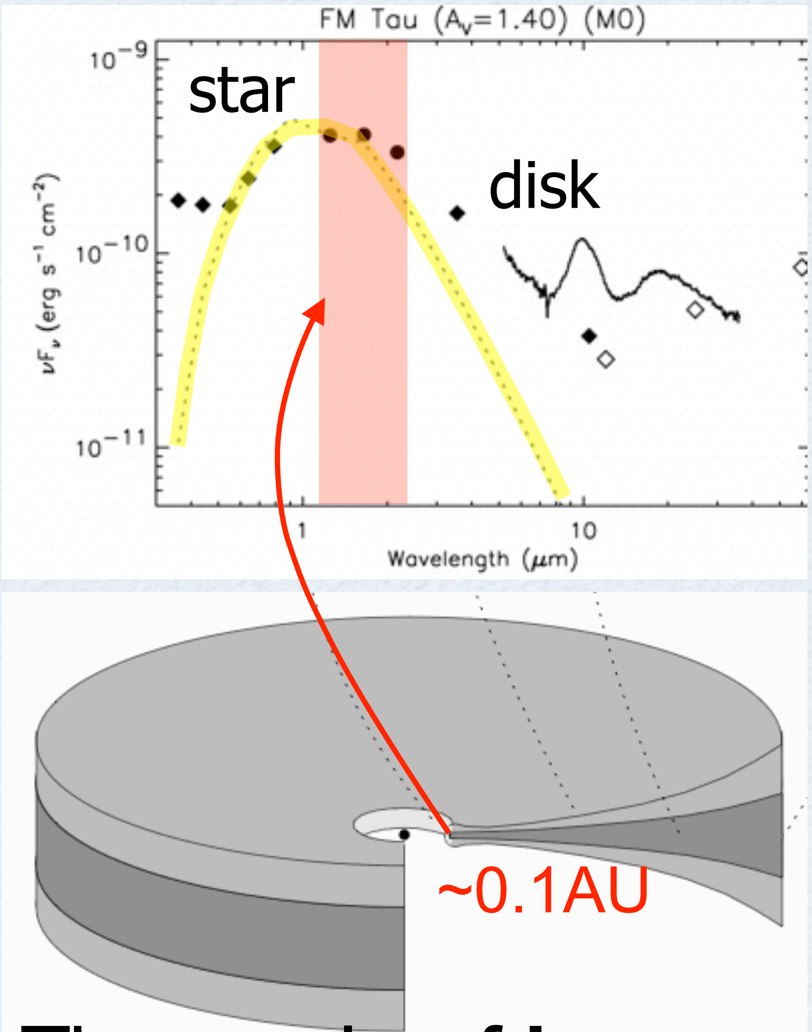


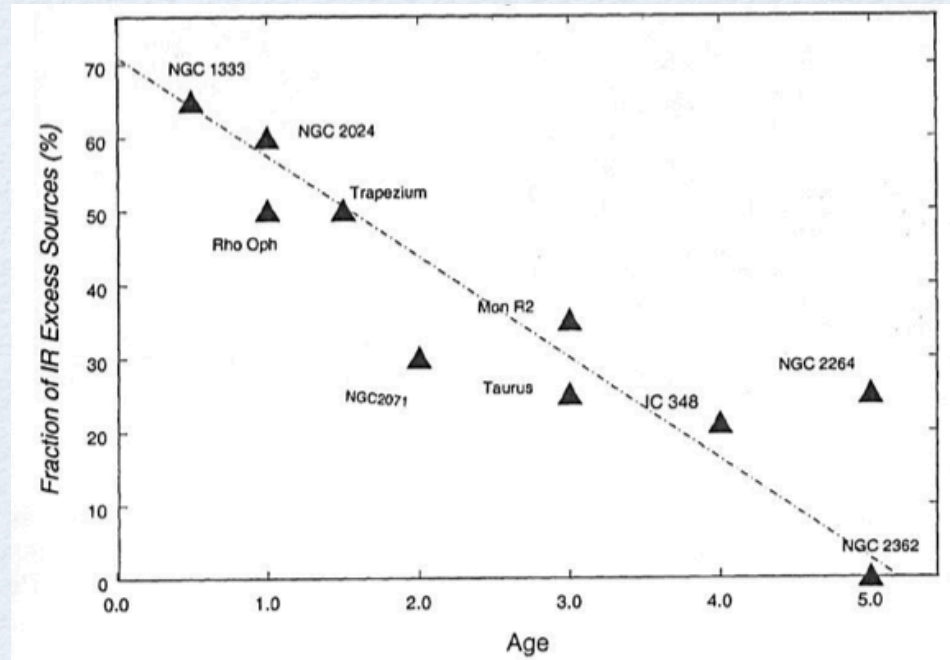
e.g., Fedele+ 2010

Disk evolution

- Dust disk
  - ✓NIR JHK (2.2um): **innermost** disk evolution

    1980s–: Strom+1989, Lada1999





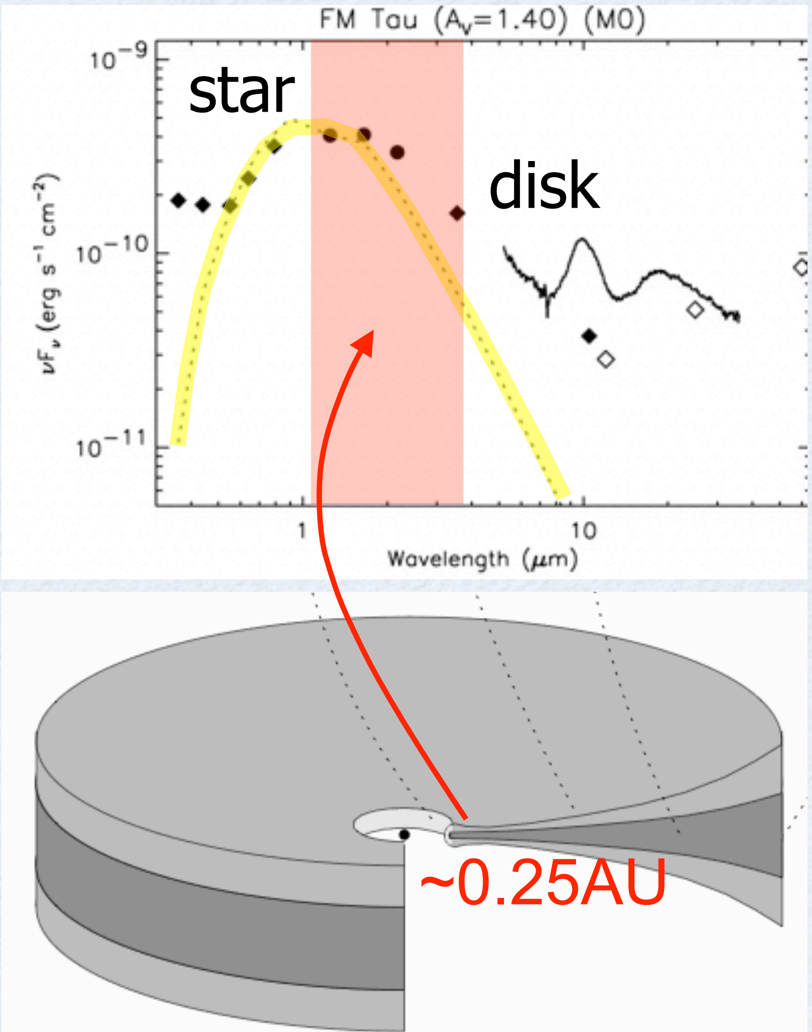
Lada1999

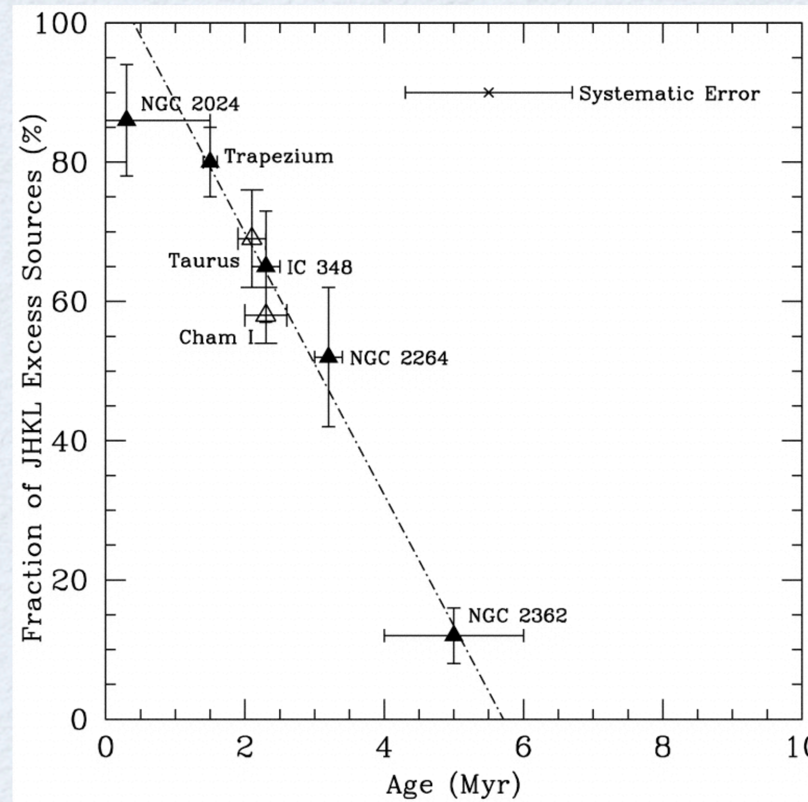
Timescale of **innermost** disk dispersal: ~5Myr

Only for *<u>innermost</u>* *disk?*

✓NIR JHKL (3.6um): **inner** disk evolution

2000s–: Haisch+2001





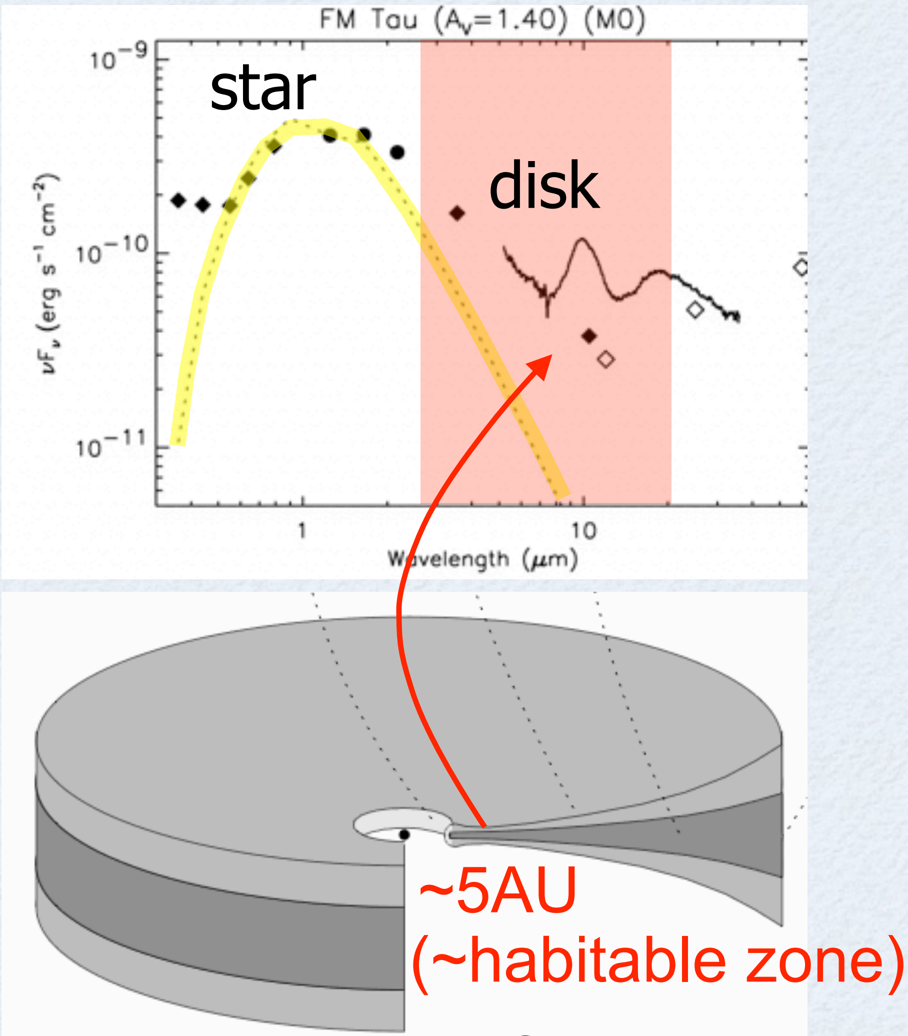
Haisch+2001

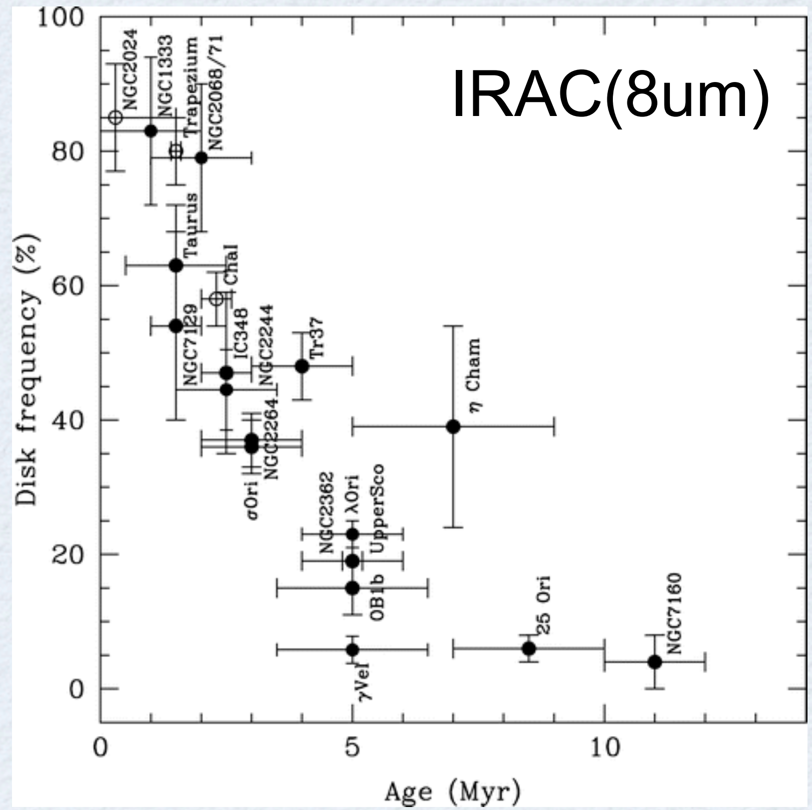
Timescale of **inner** disk dispersal: ~5Myr

Only for <u>inner</u> disk?

✓MIR (10um): **inner** disk evolution

Spitzer 2003–





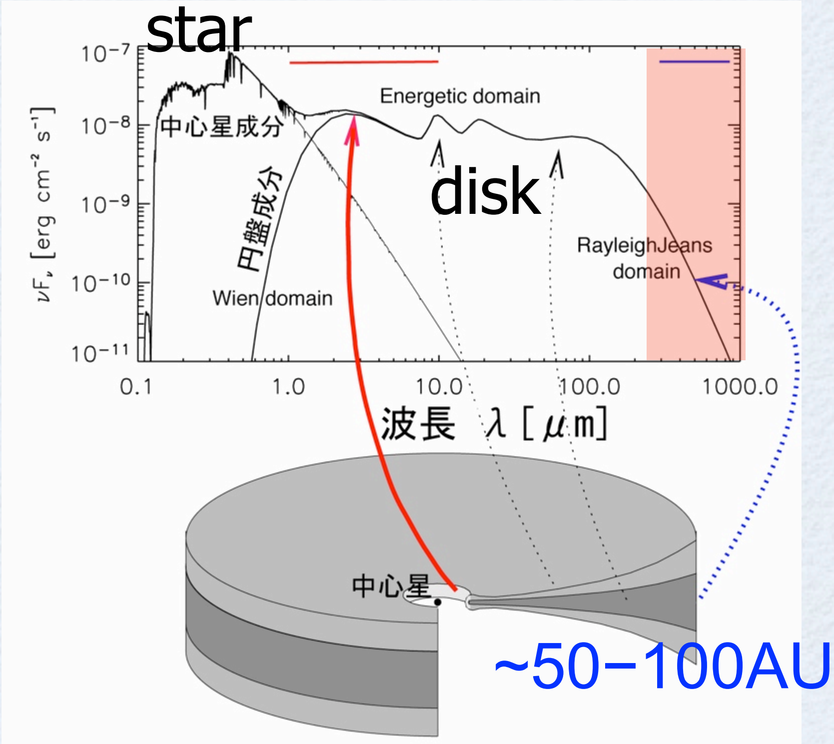
Hernandez+2008

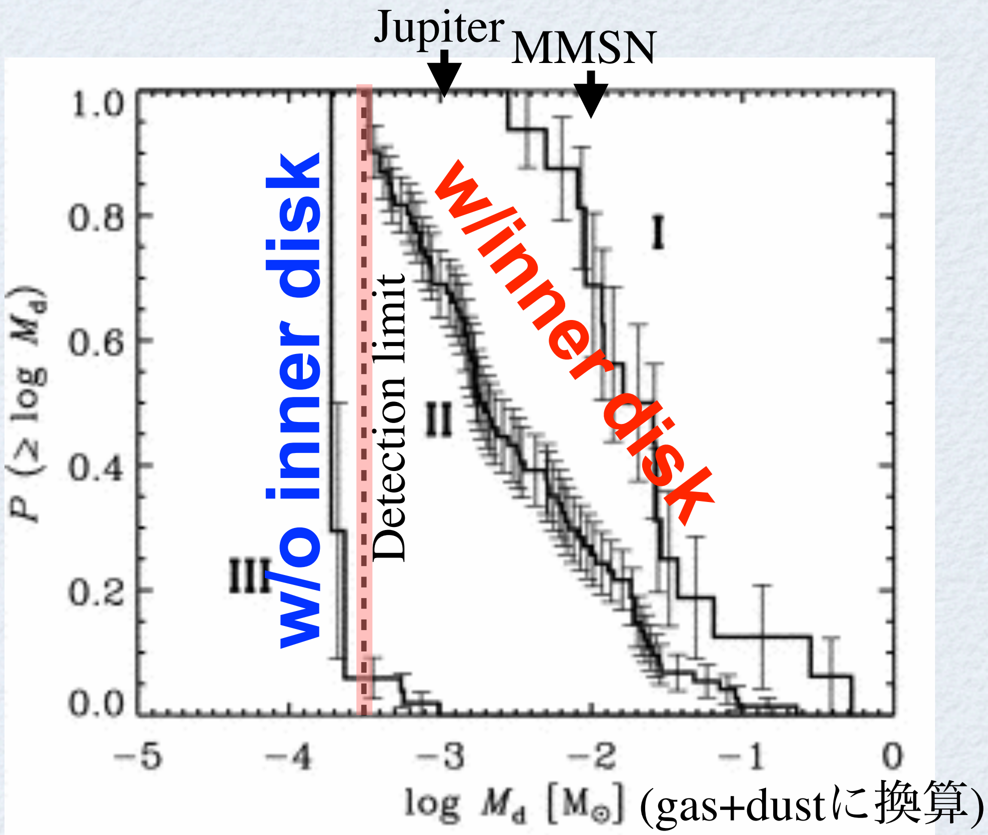
Timescale of **inner** disk dispersal: ~5Myr

Only for inner disk?

✓Submm (1mm): **outer** disk evolution

2005-

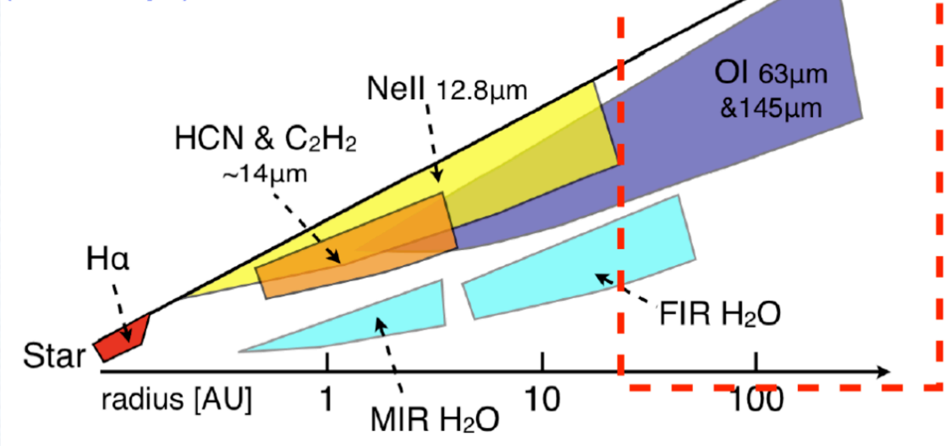




(Andrews&Williams2005)

Well correlated with inner disk

Entire disk (from inner to outer) disperse almost simultaneously in timescale of 5-10Myr

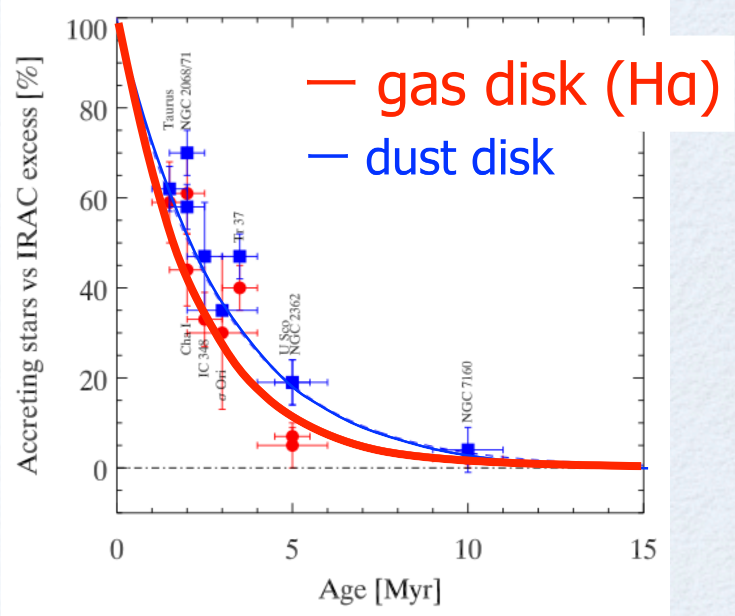


Gas disk

In protoplanetary disks
gas : dust = 100: 1 (mass)

✓Inner disk

H emission lines

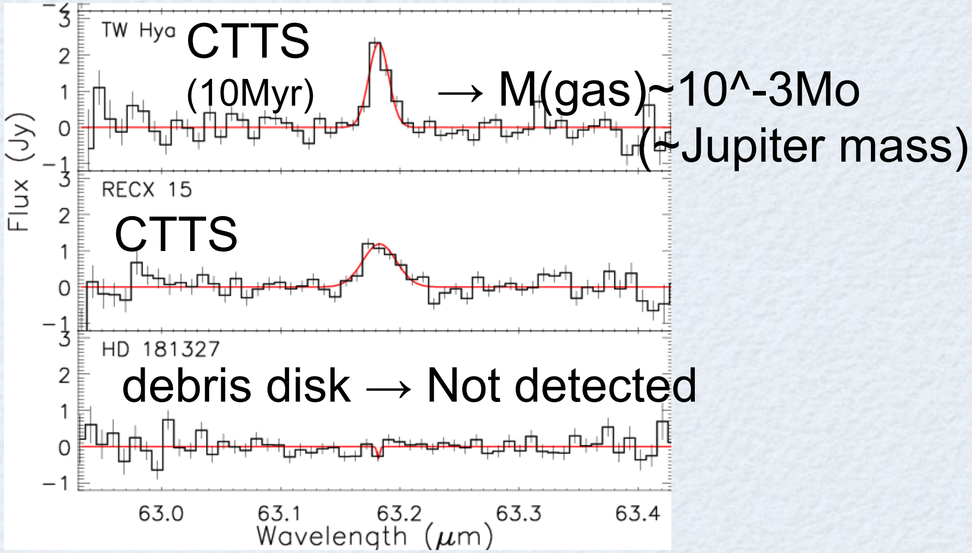


e.g., Fedele+ 2010

✓ Outer disk

2010s– (*Herschel* 2009–)

FIR [OI] 63.2 μm



Mathews+2010

Gas disk is also correlated with dust disk

Entire **disk disperse almost simultaneously**

(inner + outer / dust+gas disk) **(~10Myr)**

Lifetime of protoplanetary disks

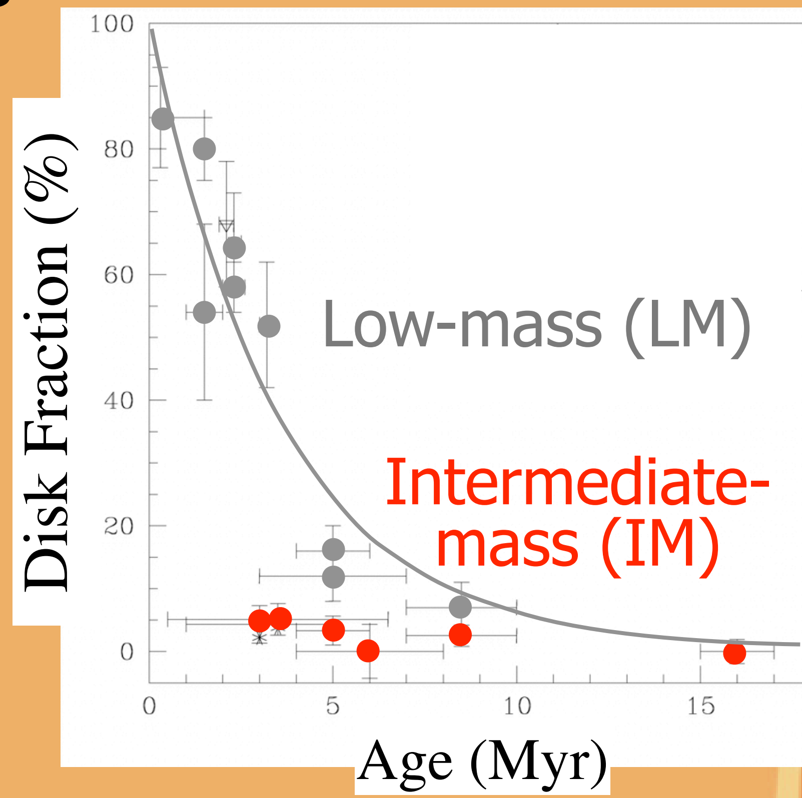
✓ Intermediate-mass (IM) stars (≧$1.5M_{\odot}$)

Shorter disk lifetime is suggested

- Hernandez+2005
  6 OB associations (age: 3–6 Myr)
- Kennedy & Kenyon 2009
  <10 clusters (age: 1–10 Myr)

However,

no quantitative derivations of disk lifetime



Hernandez+2005

Topic of this talk:

Derivation of disk lifetime for IM stars
to study stellar mass dependence

2. Derivation of IMDF

IMDF (= intermediate-mass disk fraction)

✓ Selection of IM stars

- Defined mass range: 1.5–7$M_\odot$
- Based on spectral types with the assumed cluster ages (Siess+2000 PMS isochrone model)

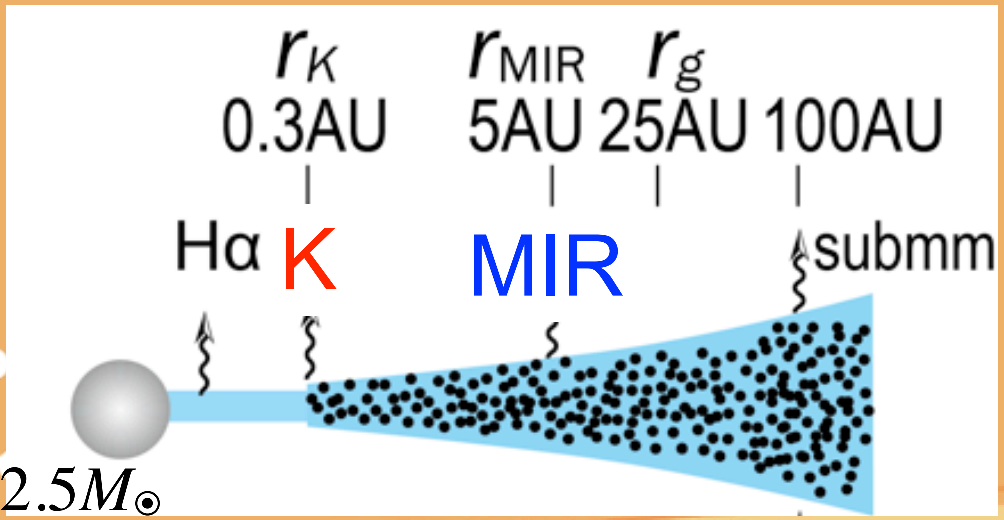
ex.) In the case of 1Myr old, B2.5–K5 type stars

✓ Selection of disk excess sources

For K disk & MIR disk excess sources

HAeBes = Stars with K disk excess sources

(Hernandez+2005)



M$_*$=2.5$M_\odot$

Inner edge is determined by dust sublimation in radiative equilibrium condition

Method of selecting disk excess sources

✓JHK IMDF

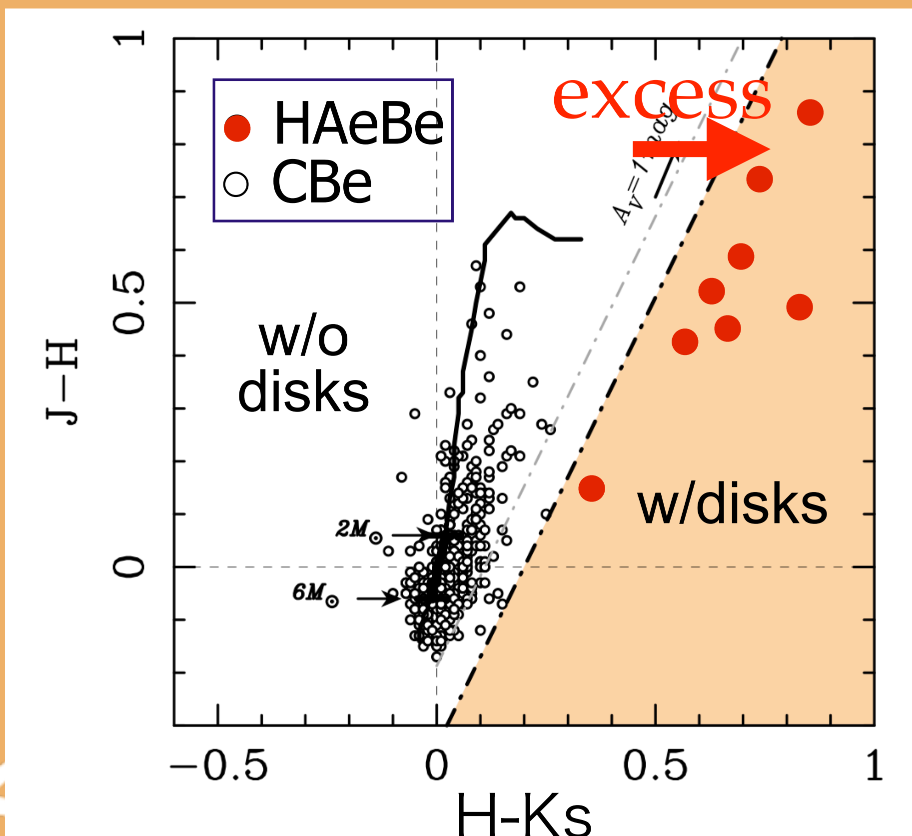
- Data: *2MASS* JHK
- JHK color-color diagram
  IM stars w/K disk (=HAeBes) show large H-K excess

clearly selected

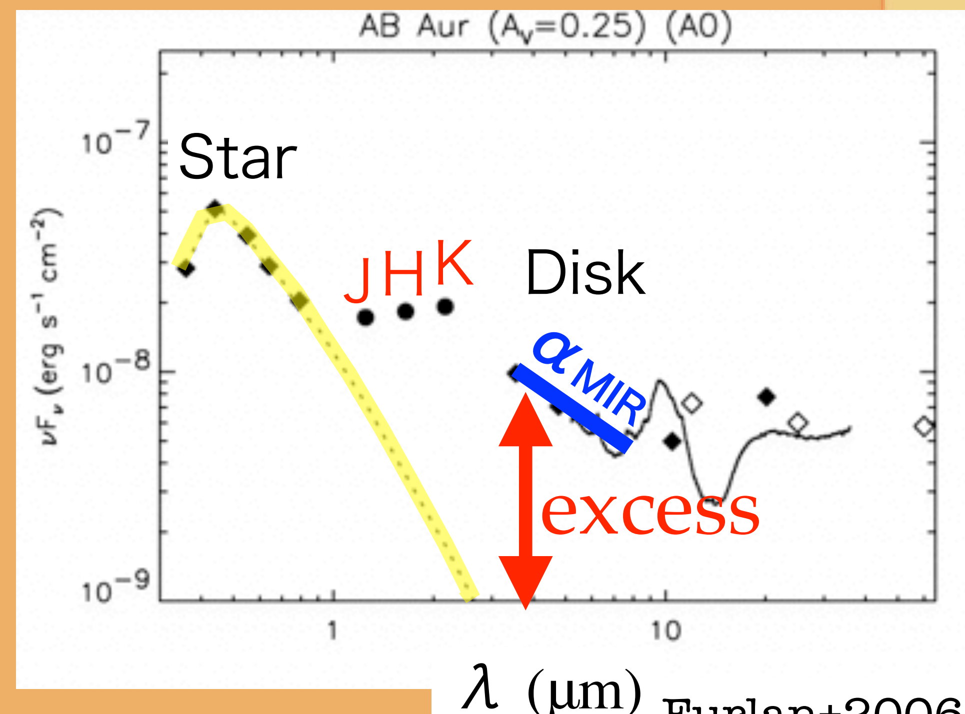
✓MIR IMDF

- Data: *Spitzer* IRAC (3.6–8μm data)
- From MIR SED slope
  $\alpha_{MIR} \geq -2.2$: w/MIR disk
  ($\alpha = d \ln \lambda F_\lambda / d \ln \lambda$)

Kennedy&Kenyon 2009



Yasui+2014 in prep
(Data from Hernandez+2005)



Furlan+2006

Target clusters

Clusters previously studied for low-mass disk fraction studies

(Haisch+2001; Hernandez +2005, 2008, Kennedy & Kenyon 2009, Mamajek 2009; Gaspar+2009; Fedele+2010, Roccatagliata+2011)

- Solar neighborhood: D ≦ 2kpc
- Young age: ≲10Myr

→ ~20 young clusters

Cluster	Membership Ref[a]	Age (Myr)	SpT[b]	SpT Ref[c]	*JHK* IMDF[d] (%)	MIR Ref[e]	MIR IMDF[f] (%)
NGC 1333	St76,As97,Wi04	1±1	B2.5–K5	Win10,Co10,SB	17±17 (1/6)	Gu09	100±50 (4/4)
Trapezium	Hi97	1±1	B2.5–K5	Hi97	9±3 (8/89)	—	—[g]
ρ Oph	Wi08	1±1	B2.5–K5	Wi08	0±5 (0/20)	Wi08	80±20 (4/5)
Taurus	Fu06, Fu11	1.5±1.5	B3–K5	Fu06, Fu11	31±10 (9/29)	Fu06,Lu06	72±16 (21/29)
Cha I	Lu04	2±1	B3–K5	Lu04	29±13 (5/17)	Lu08	60±35 (3/5)
NGC 2068/71	Fl08	2±1.5	B3–K5	Fl08	15±11 (2/13)	Fl08	69±23 (9/13)
IC 348	Lu03	2.5±0.5	B3–K5	Lu03	0±3 (0/34)	La06	21±8 (7/34)
σ Ori	He07a	3±1	B3–K4	Ca10,Re09,SB	0±4 (0/23)	He07a	17±9 (4/23)
NGC 2264	Re02	3±1	B3–K4	Re02	0±2 (0/55)	—	—[g]
Tr 37	Si05	4±1	B3–K4	Si05,SB	3±2 (2/69)	Si05, Si06	22±10 (5/23)
Ori OB1bc	He05	4±3	B3–K4†	He05	4±2 (4/94)	—	—[g]
Upper Sco	Ca06	5±1	B3–K4	Ca06	0±1 (0/94)	Ca06	2±2 (2/94)[h]
NGC 2362	Da07	5±1	B3–K4	Da07	0±5 (0/19)	Da07	0±5 (0/19)
γ Vel	He08	5±1.5	B3–K4†	Ho78,SB	0±6 (0/17)	He08	0±6 (0/17)
λ Ori	He09	5±1	B3–K4†	He09	8±8 (1/13)	He09	4±4 (1/27)
Per OB2	He05	6±2	B3–K3†	He05	0±3 (0/31)	—	—[g]
η Cham	Me05	7±1	B3–K2	Me05	0±33 (0/3)	Me05	—[i]
Ori OB1a	He05	8.5±1.5	B2–K1†	He05	2±1 (2/98)	—	—[g]
NGC 7160	Si05	11±1	B3–G7	Si05	0±1 (0/82)	Si06	3±2 (2/78)

3. Results

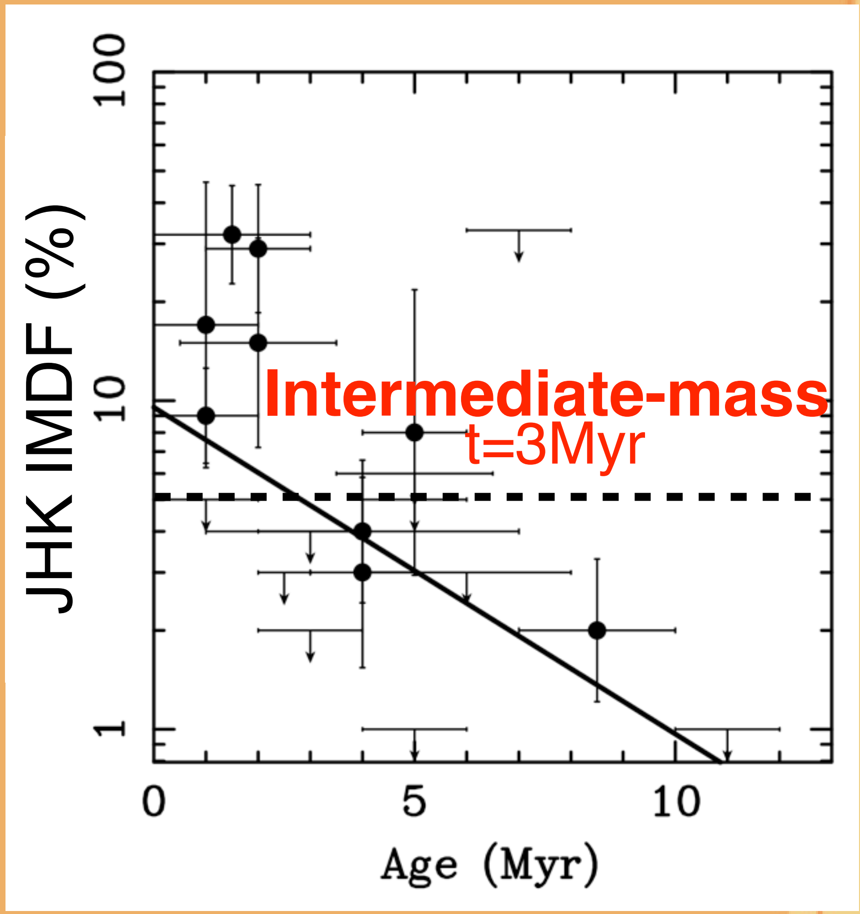
K-disk (*innermost* disk; ~0.3AU)

✓Disk lifetime

By survival analysis

$DF[\%] = DF_0 \cdot \exp(-t[Myr]/\tau_{disk})$

$t_{(IM, JHK)}$ = 3 Myr



3. Results

K-disk (*innermost* disk; ~0.3AU)

✓Disk lifetime

By survival analysis

$DF[\%] = DF_0 \bullet \exp(-t[Myr]/\tau_{disk})$

$t_{(IM,\ JHK)}$ = 3 Myr

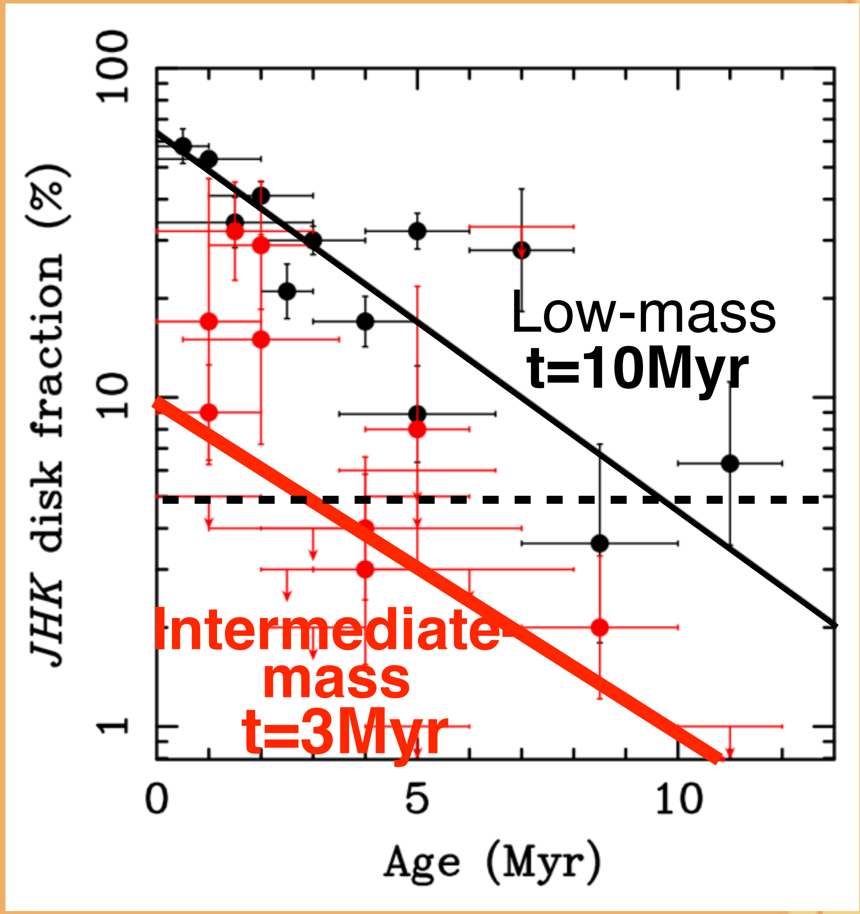
✓Stellar mass dependence

IM-stars ($2.5M_\odot$): $t \simeq 3$Myr

LM-stars($0.5M_\odot$): $t \simeq 10$Myr

Assuming $t \propto M_*^{\,a}$

$t_{(JHK)} \propto M_*^{-0.8\pm0.7}$



Probable stellar mass dependence

MIR-disk (*inner* disk; ~5AU)

✓ Disk lifetime

By survival analysis

$DF[\%] = DF_0 \cdot \exp(-t[Myr]/\tau_{disk})$

$t_{(IM,\ MIR)} = 6.5$ Myr

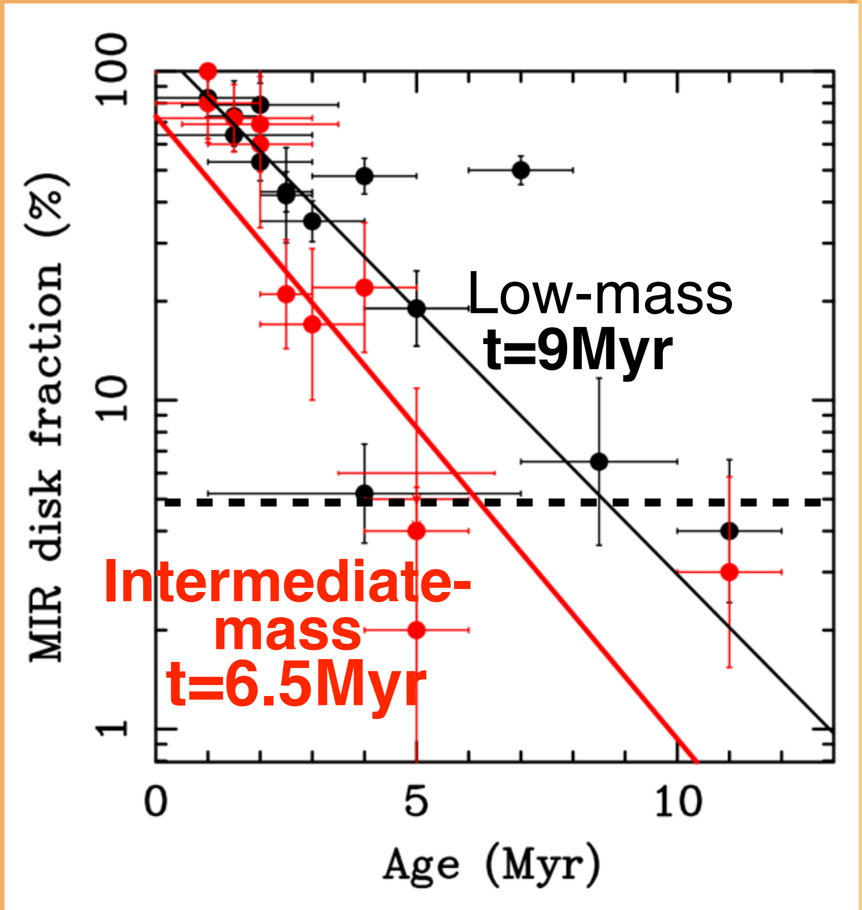
✓ Stellar mass dependence

IM-stars ($2.5M_\odot$): t≃6.5Myr

LM-stars($0.5M_\odot$): t≃ 9Myr

Assuming $t \propto M_*{}^{a}$

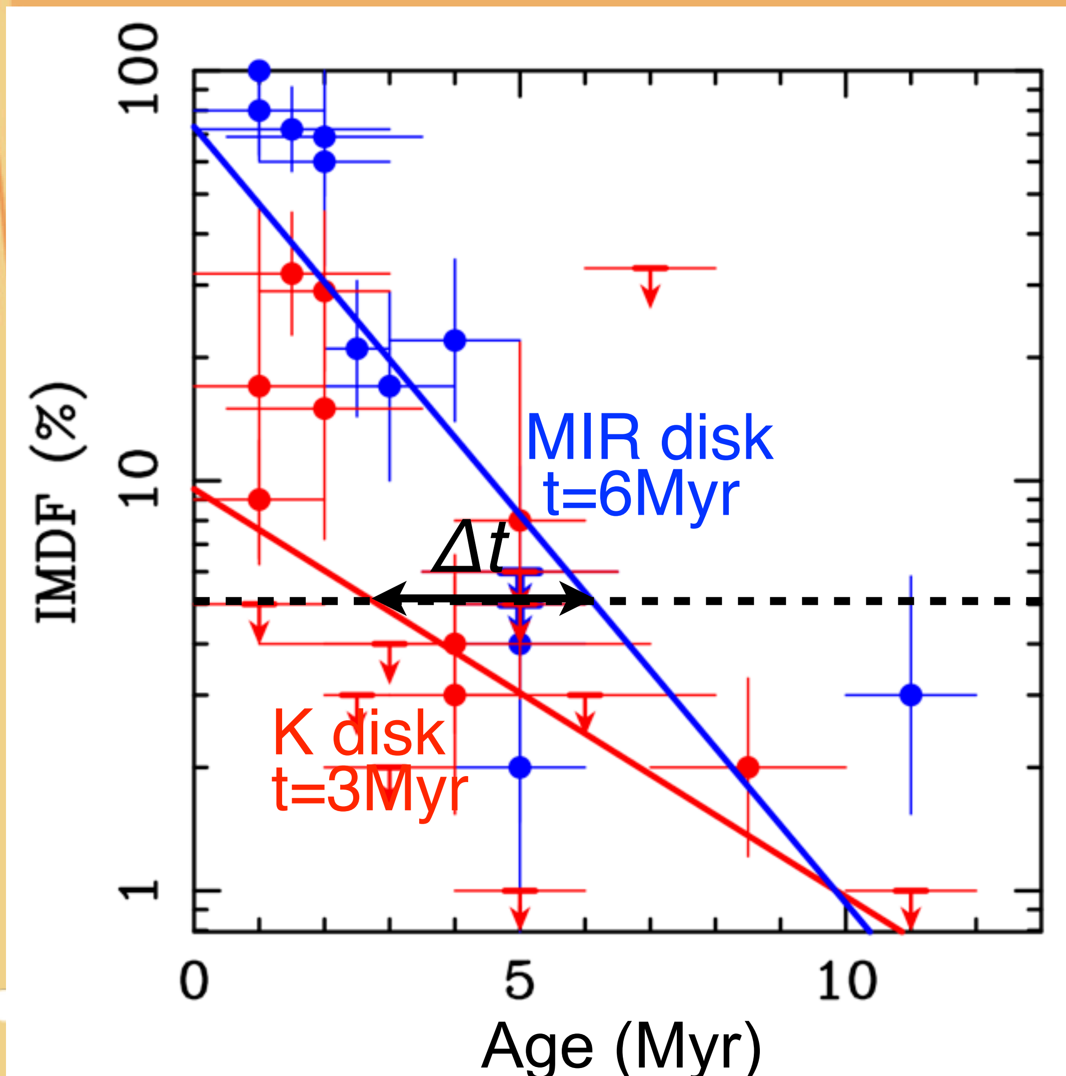
$t_{(MIR)} \propto M_*^{-0.2\pm0.2}$



Weak stellar mass dependence

Comparison between K vs. MIR disks

Systematically JHK < MIR IMDF



The *innermost* (K) disk disappear much earlier than *inner* (MIR) disk (Δt=3Myr)

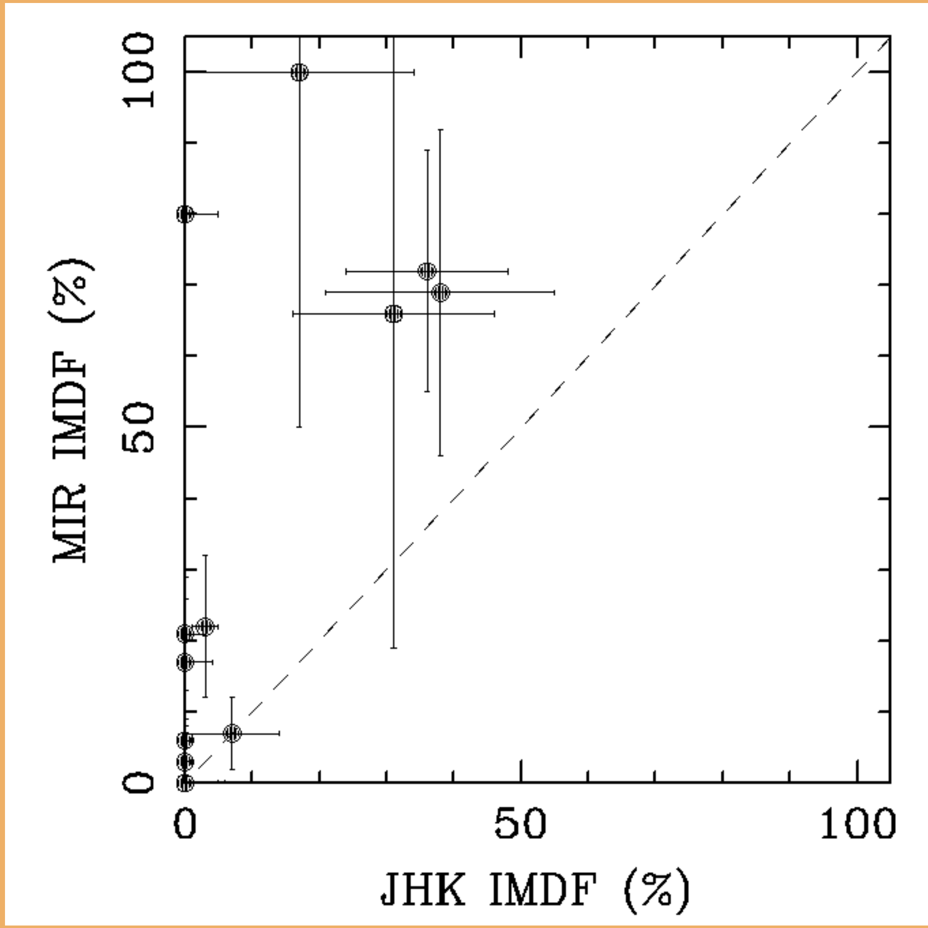
↓

IM-stars may have a substantially long **"transitional phase"**

(Cf. Transitional disk fraction of LM-stars <~20%; Muzerolle+2010)

Direct comparison

For all clusters having both JHK/MIR IMDF

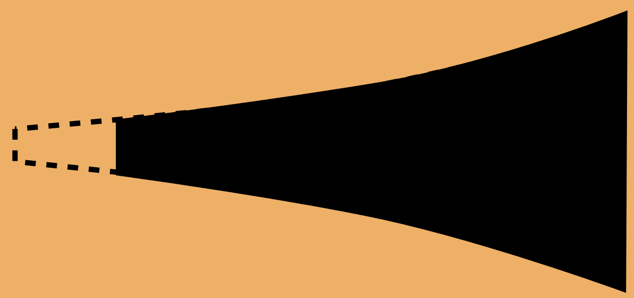


JHK IMDF is systematically lower than MIR IMDF

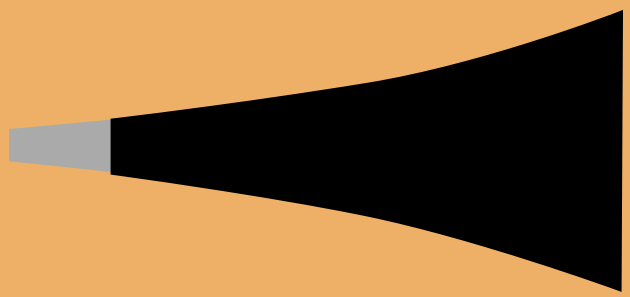
4. Discussion

☆Mechanism of the K disk disappearance

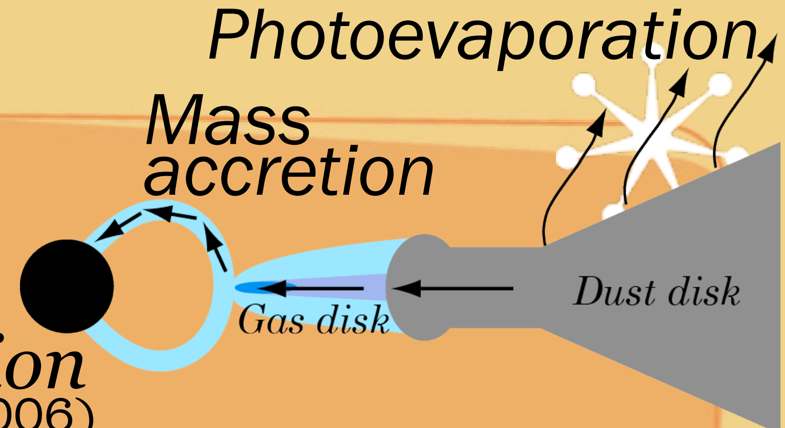
✓Possibility ①:
Disk dispersal
Cleared out?



✓Possibility ②:
Dust growth/settling
Became optically thin?



Possibility ①: Disk dispersal

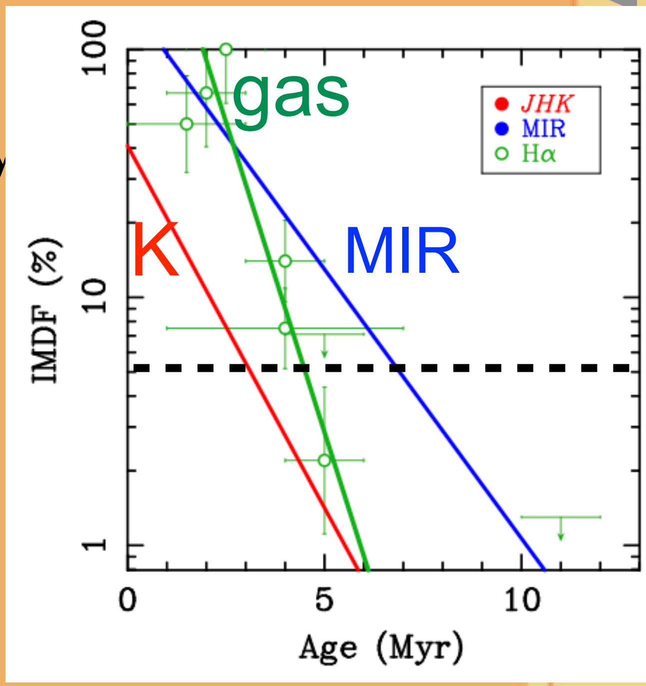


Two main processes:
mass accretion & photoevaporation
(e.g. Clark+2006)

✓Mass accretion

Gas/dust disks should disappear simultaneously, but gas disk (Hα) shows a longer lifetime.

(Hα data from Kennedy & Kenyon 2009)



✓Photoevaporation

Effective for outside of gravitational radius

$r_g \gg r_K$ (r_g~25AU, r_K~0.3AU @2.5$M_\odot$)

Not directly related to innermost disk dispersal

Disk dispersal is unlikely the main cause for the early disappearance of innermost disk

Possibility ②: **Dust growth / settling**

(e.g. Kenyon & Hartmann 1987, Dullemond & Dominik 2005, Hernandez+2005)

Theoretically, rapid dust growth occur in the inner disks

According to simple theoretical expectation:

$t_{grow} \sim \Sigma_g/\Sigma_d \cdot h_d/z \cdot T_K \rightarrow t_{grow} \propto r^{3/2}$ (e.g. Nakagawa+1981)

Although quantitatively weaker r-dependence,

qualitatively consistent with our results

Shorter K disk lifetime (t~3Myr, r_K~0.3AU)

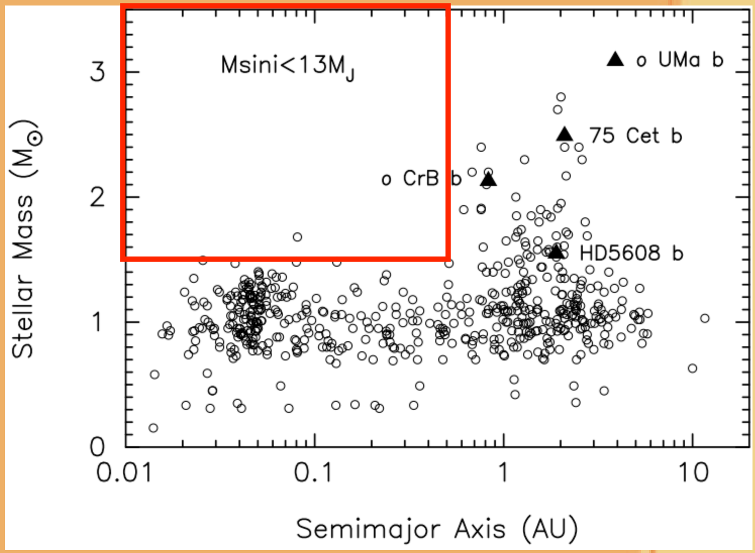
than that of MIR disk (t~6.5Myr, r_{MIR}~5AU)

Disk growth/settling could generally explain the early disappearance of innermost disk

Implication for planet formation around IM stars

- Lack of close-in planets (r<~0.5AU) (Johnson+2007, Wright+2009)

One of the most remarkable trends for exoplanets of IM stars



Sato et al. (2012)

Proposed causes:

i) Planet engulfment in red giant branch phase (Villaver & Livio 2009)

Unlikely? (Kunitomo+2011)

ii) Type II migration

- Shorter gas-disk lifetime for IM-stars (Currie+2009)

  $t(\text{gas}) \propto M_*^{\beta}$: $\beta = 0.75 - 1.5$

  The planets around IM stars cannot migrate to inner orbits.

- Larger inner edge radius of dead zone (Kretke+2009)

  $r_{\text{dead}} \propto M_*$

  The inner edge of the dead zone effectively determines the semimajor axes of giant planets because the dead zone traps inwardly migrating solid bodies

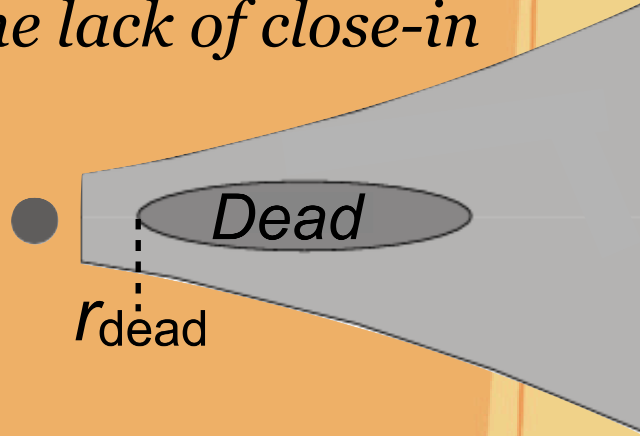
Comparison of our results with Type II migration

For both idea, Qualitatively consistent with our results

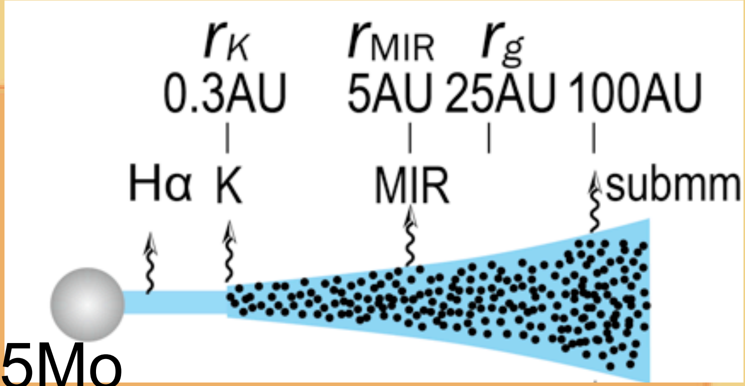
However, the smooth stellar mass dependence of migration time cannot explain the observed sharp outward step in giant planet orbits (Kennedy & Kenyon 2009)

Our results that "the early disappearance of the innermost disk" suggest that **the r_{dead} becomes even larger because of low opacity**, which makes the formation of dead zone difficult.

If the critical stellar mass is observationally determined, this dead zone idea may be able to explain the lack of close-in planets with the sharp cut-off at 0.5 AU



5. Summary



Derivation of disk lifetime of IM-stars (1.5–7$M_\odot$)

For many (~20) young clusters

✓ Disk lifetime

t = 3Myr (K disk) ／**t = 6.5Myr** (MIR disk)

✓ Stellar mass dependence

$t \propto M_*^{-0.8}$ (K disk)／ $t \propto M_*^{-0.2}$ (MIR disk)

Implication to disk evolution of IM-stars

✓ Significant time-lag (Δt~3Myr) between innermost K disk and inner MIR disk evolution

✓ The long transition phase
Rapid dust growth/settling occur in the innermost disk?

HAeBes may not be ubiquitous??

Implication to planet formation

✓ The shorter disk lifetime and expected large inner edge radius of dead zone may be the possible reason for the paucity of close-in planets