Protoplanetary Disks around Intermediate-Mass Stars

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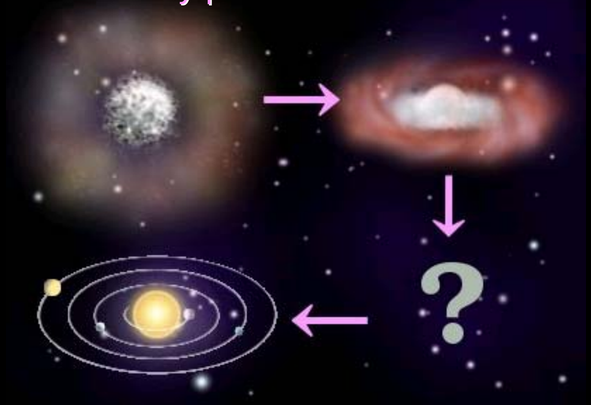
Outline of this talk

1. Disks around young intermediate-mass stars
2. Spatially resolved images of protoplanetary disks
3. Temporal change of disk structure
4. Primordial to debris disks
5. Direct imaging of extra-solar planets

Planets form in circumstellar disks

Disks are by-products of star formation



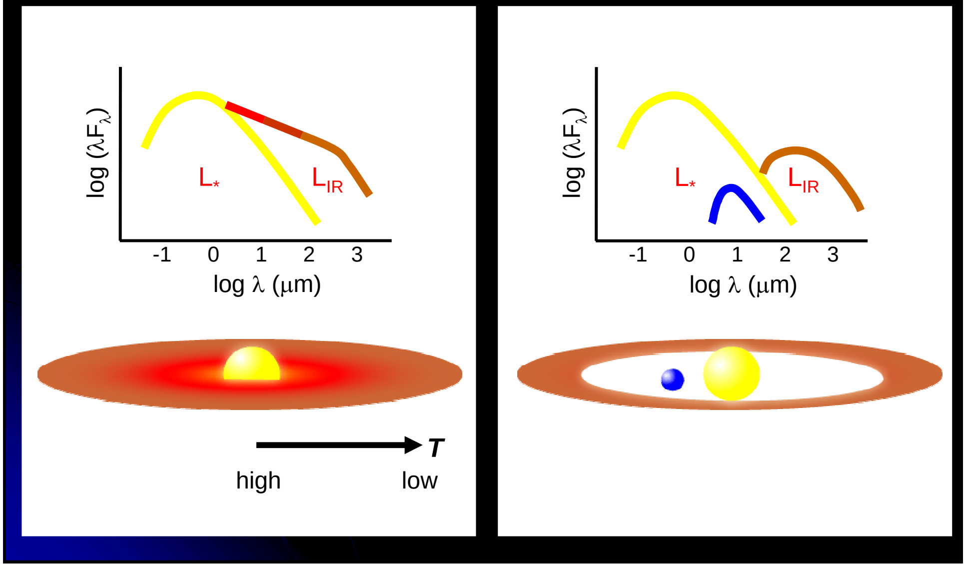
“minimum mass solar nebula” — R > 50 AU, $\Sigma(r) \propto r^{-1.5}$, $M \sim 0.01\, M_\odot$

From the solar system to extra-solar ones

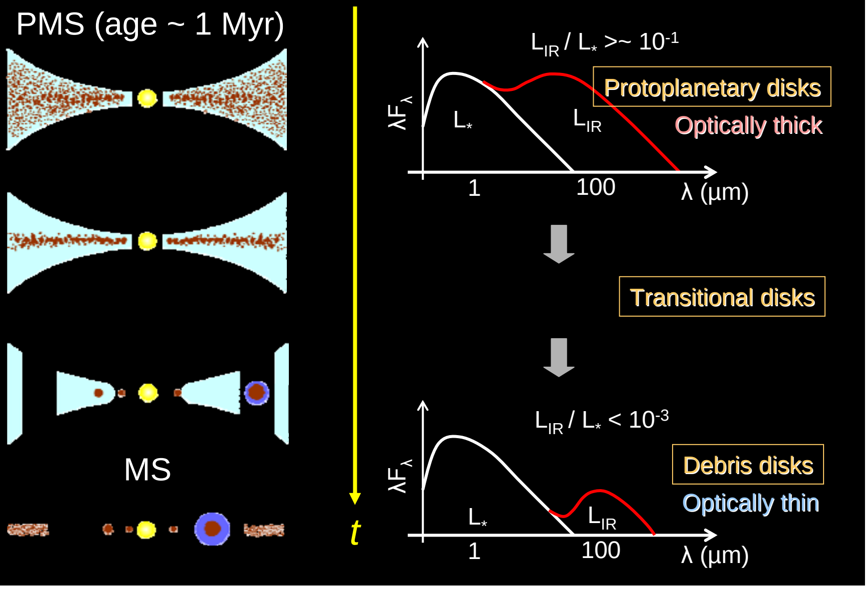
How to study planet formation

- Establishing the initial conditions for planet formation
  - Multi-wavelength, multi-epoch observations are important to understand the disk
- Searching for *footprints* of planets
  - Morphology of disks (massive planets can significantly alter the structure)
- Studying *ingredients* of planets:
  - *Ices, silicates, organic molecules etc.*
- Detecting forming planets in disks
  - Young stars are good targets to search for planets at their birthplaces, and to constrain their formation mechanism.
  - RV might be difficult for young stars (e.g., TW Hya)
  - Direct imaging only reveal outer planets
  - Currently we cannot directly access to terrestrial planets, but we can for giant planets (younger planets are brighter).

Infrared excess as a disk diagnostic

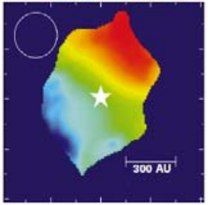


Evolution of disks

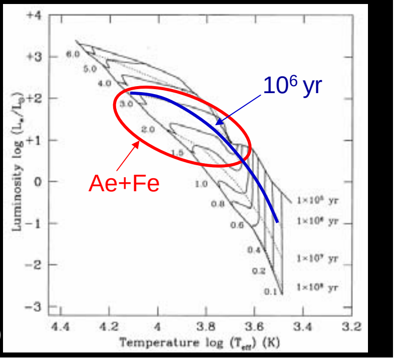


Disks around young intermediate-mass stars

- "Intermediate-mass stars" → Herbig Ae/Be stars
- Be and Ae/Fe are different:
- Disks are ubiquitous around TTS, Herbig Ae, and Fe stars with IR excesses
  - M_{disk} ~ 1– 10% of M_* with significant scatter
  - R ~10 – 1000 AU
- How about Herbig Be stars?
- In general, observations are difficult for massive stars due to fast evolution and large distances (> kpc)



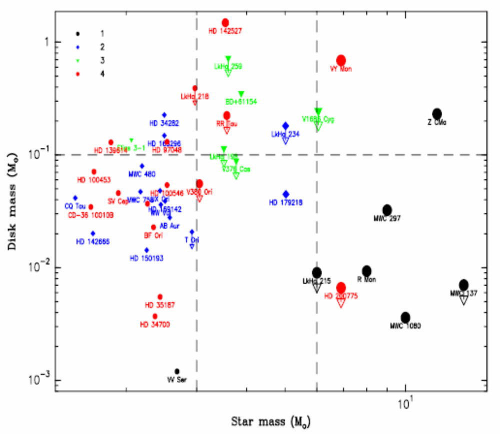
Herbig Ae star, MWC 480 (Mannings et al. 1997)



Palla & Stahler (1999)

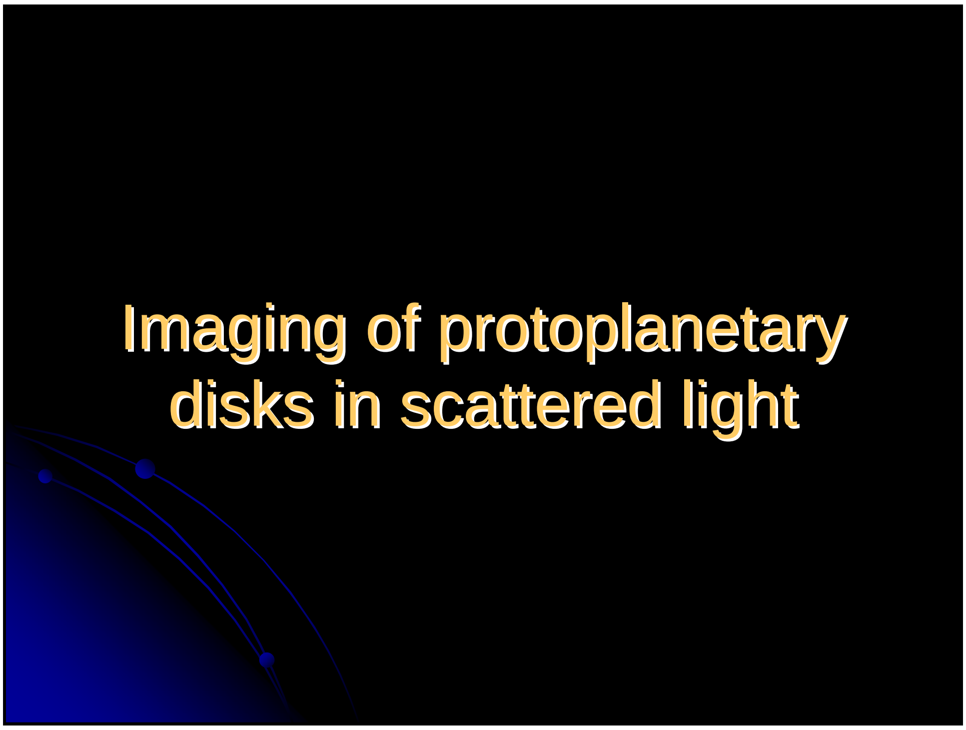
Rapid dispersal due to photoevaporation?

- Disks (+ envelopes) are detected for some cases, but M_{disk} are lower (x5—10) for younger Herbig Be stars.

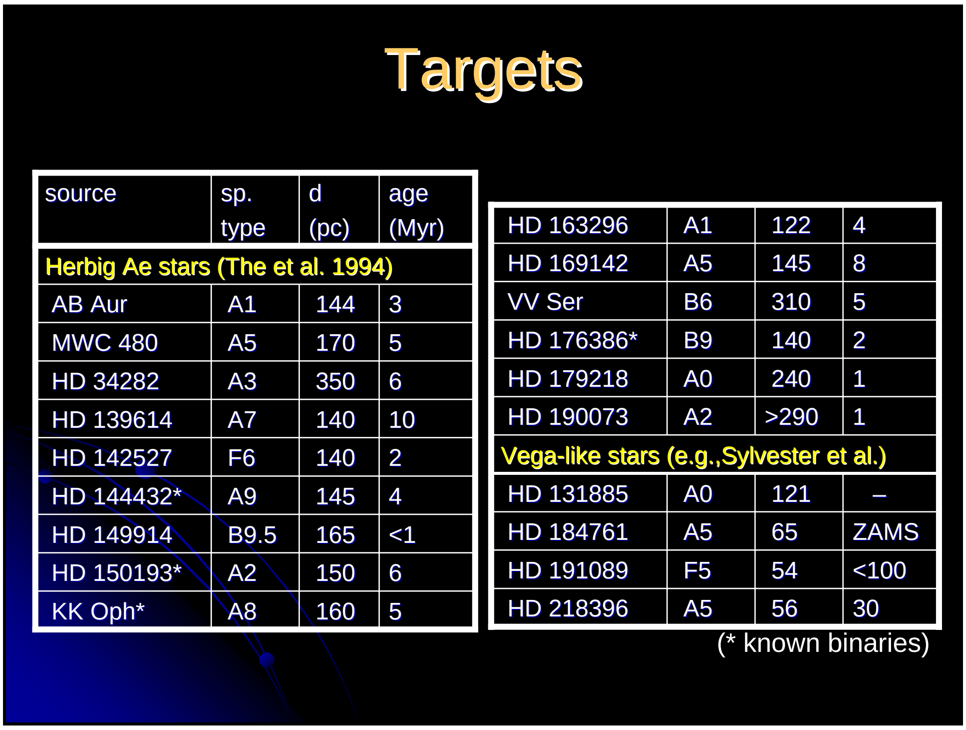


Alonso-Albi et al. (2009)

Higher mass stars are younger (~ 10^5 – 10^4 yr)



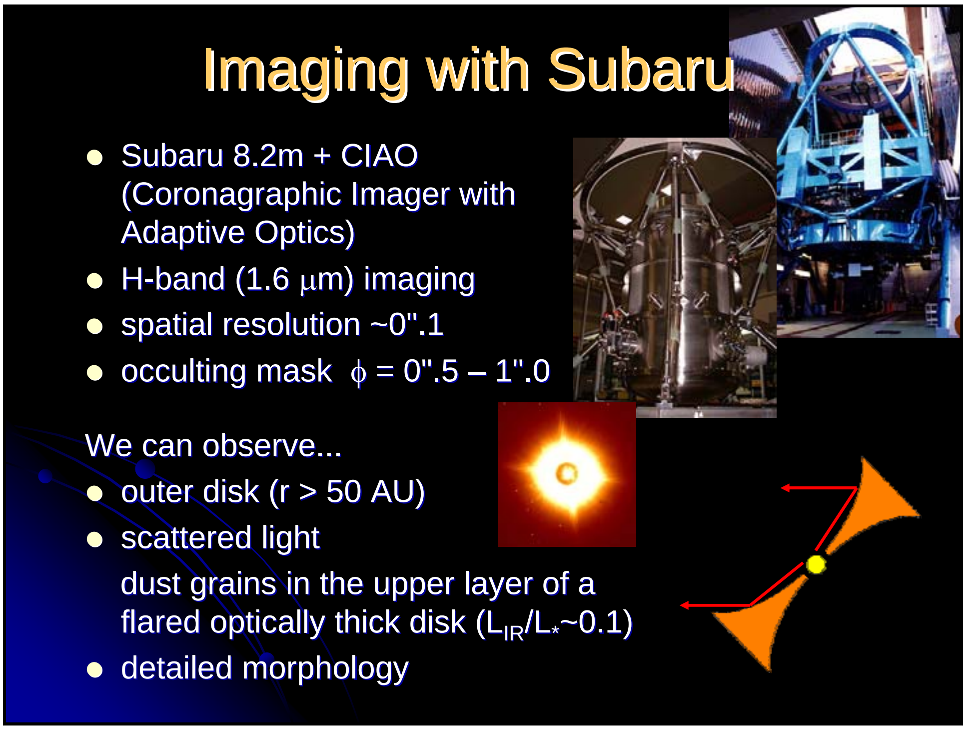
Imaging of protoplanetary disks in scattered light



Targets

source	sp. type	d (pc)	age (Myr)
Herbig Ae stars (The et al. 1994)			
AB Aur	A1	144	3
MWC 480	A5	170	5
HD 34282	A3	350	6
HD 139614	A7	140	10
HD 142527	F6	140	2
HD 144432*	A9	145	4
HD 149914	B9.5	165	<1
HD 150193*	A2	150	6
KK Oph*	A8	160	5
HD 163296	A1	122	4
HD 169142	A5	145	8
VV Ser	B6	310	5
HD 176386*	B9	140	2
HD 179218	A0	240	1
HD 190073	A2	>290	1
Vega-like stars (e.g.,Sylvester et al.)			
HD 131885	A0	121	–
HD 184761	A5	65	ZAMS
HD 191089	F5	54	<100
HD 218396	A5	56	30

(* known binaries)



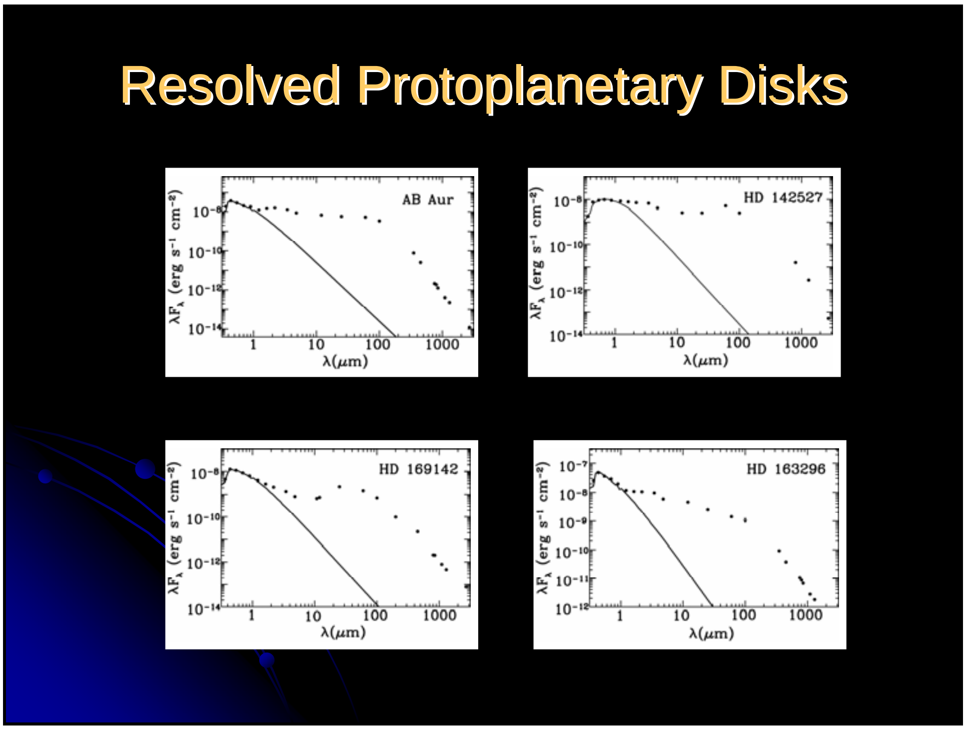
Imaging with Subaru

- Subaru 8.2m + CIAO (Coronagraphic Imager with Adaptive Optics)
- H-band (1.6 μm) imaging
- spatial resolution ~0".1
- occulting mask ϕ = 0".5 – 1".0

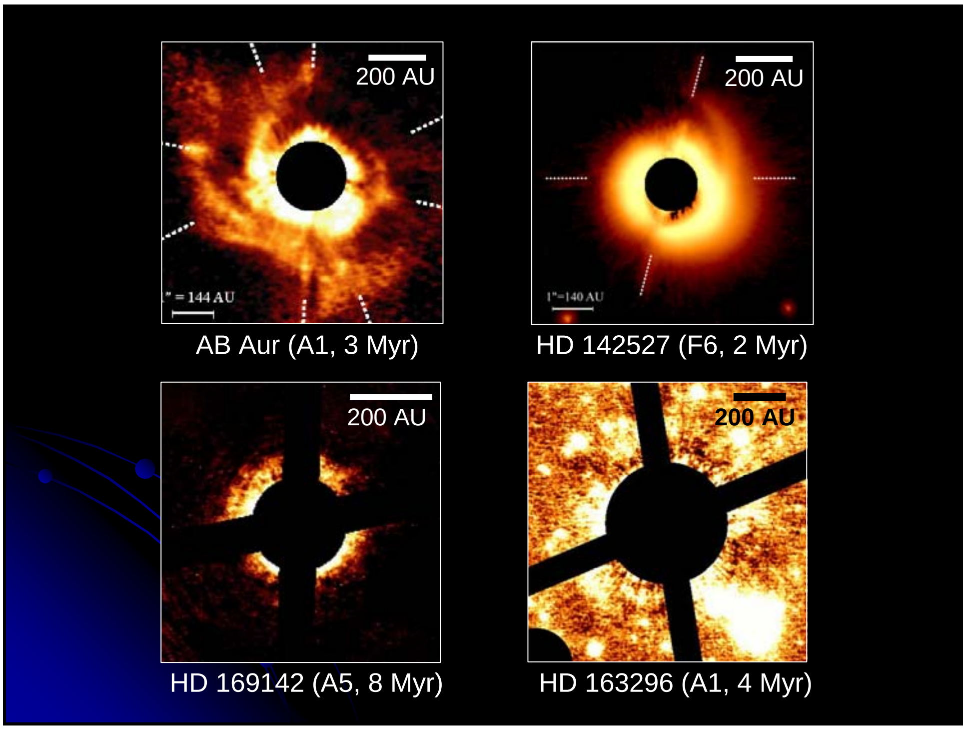
We can observe...

- outer disk (r > 50 AU)
- scattered light

  dust grains in the upper layer of a flared optically thick disk (L_{IR}/L_{*}~0.1)
- detailed morphology



Resolved Protoplanetary Disks

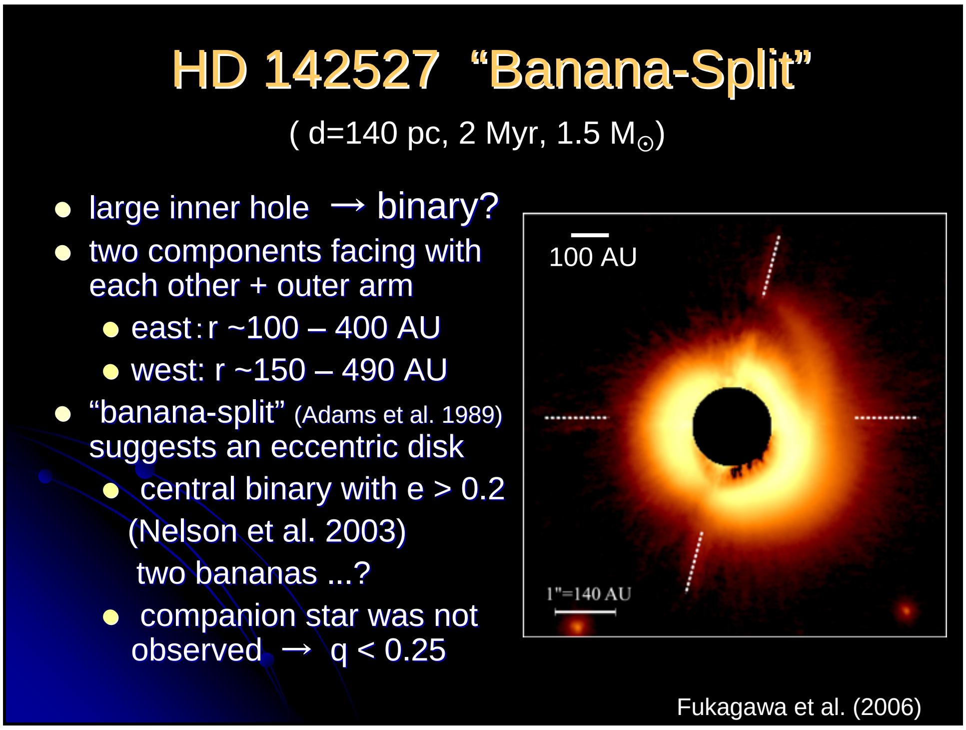


AB Aur (A1, 3 Myr)

HD 142527 (F6, 2 Myr)

HD 169142 (A5, 8 Myr)

HD 163296 (A1, 4 Myr)

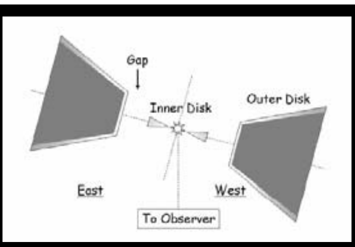


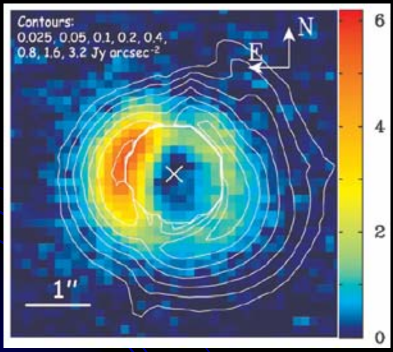
HD 142527 “Banana-Split”

(d=140 pc, 2 Myr, 1.5 $M_\odot$)

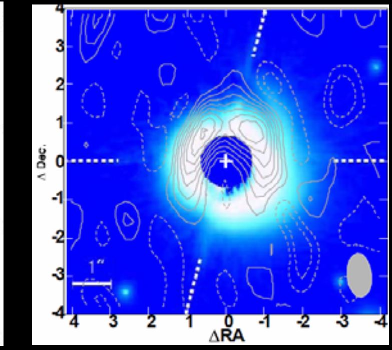
- large inner hole → binary?
- two components facing with each other + outer arm
  - east : r ~100 – 400 AU
  - west: r ~150 – 490 AU
- “banana-split” (Adams et al. 1989) suggests an eccentric disk
  - central binary with e > 0.2 (Nelson et al. 2003)
    two bananas ...?
  - companion star was not observed → q < 0.25

Fukagawa et al. (2006)





24.5 μm
Subaru/COMICS
(Fujiwara et al. 2006)



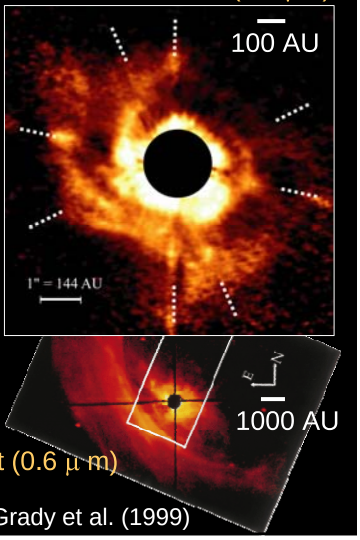
345 GHz continuum
SMA
(Ohashi et al. PPV)

AB Aur "Spiral Arms"

(d=144 pc, 4 Myr, 2.4 $M_\odot$)

- disk (r = 580 AU)
  + envelope (>1000 AU in optical)
- spiral arms
  - firstly suggested by the HST optical imaging
    (Grady et al. 1999)
  - NIR imaging is not so much affected by scattered light from the envelope
  - CO disk (e.g., Corder et al. 2005)
    → arms are trailing

NIR (1.6 μm)



UH2.2m, opt (0.6 μm)

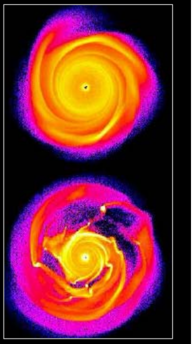
Grady et al. (1999)

Spiral Structure

- What is the cause of spiral?
  - perturber (companions):not observed
  - gravitational instability?

$$Q = \frac{c_s\Omega}{\pi G\Sigma} \le 1 \qquad M_d = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T)}$$

→ Q *could be* ~2; marginally unstable
mass supply from the surrounding envelope onto the outer disk may play a role



Mayer et al. (2002)

- How common ?
  - envelope → at most ~10% of Herbig Ae disks
- planet formation in spiral disks ...? (e.g., Rice et al. 2004)

Resolved Disks at 1.6 μm

source	$L_{disk} / L_{(* + IR)}$	observed radii	morphology
optically thick (protoplanetary) disks			
AB Aur	$(1.2\pm0.2)\times10^{-2}$	120–580 AU	spiral
HD 150193	$(1.3\pm0.3)\times10^{-2}$	59–225 AU	truncated by companion?
HD 142527	$(3.2\pm0.2)\times10^{-2}$	105–420 AU	banana
HD 163296	$\sim2\times10^{-4}$	232–430 AU	ring (ansae at opt.)
HD 169142	$(1.5\pm0.2)\times10^{-3}$	123–200 AU	without structure
HD 100546 (1)	$(1.6\pm0.2)\times10^{-2}$	46–380 AU	(spiral at opt.)
optically thin (debris) disks			
HD 141569 A (2)	$(2.2\pm0.2)\times10^{-3}$	190–891 AU	ring, (spiral at opt.)
HR 4796 A (3)	$(2.4\pm0.5)\times10^{-3}$	44–104 AU	ring
β Pic	$(1.8\pm0.4)\times10^{-3}$	50–140 AU	warp, (rings at opt./ MIR)

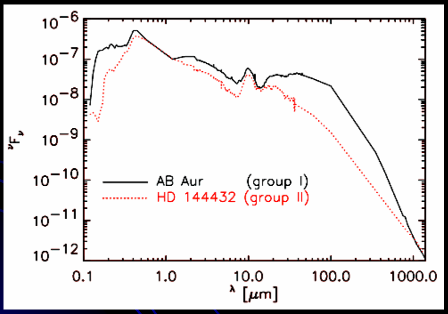
(1) Augereau et al. (2001), (2) Weinberger et al. (1999), (3) Schneider et al. (1999)

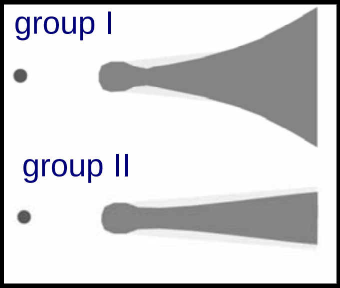
Detection in Scattered Light

prediction: SED classification by Meeus et al. (2001)

group I flared disk → detected in scattered light

group II flat disk → not detected in scattered light

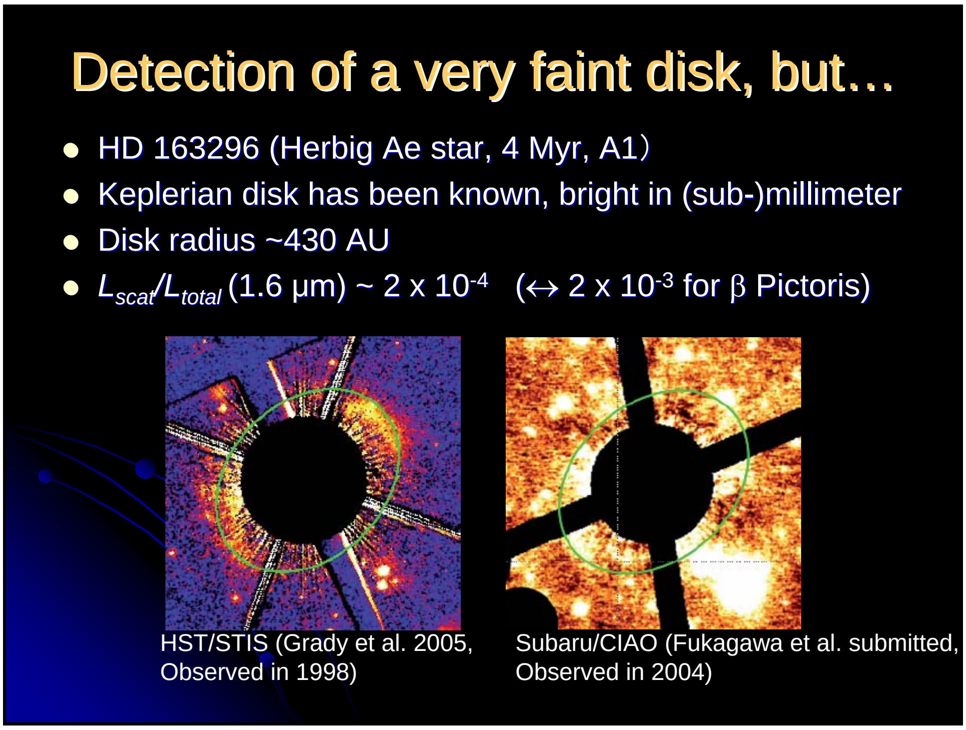




Dullemond & Dominik (2004)

group I → II evolution? No. : Many of the detected Group I objects have lower accretion rates than the Group II, do not drive jets, and in several cases are older than the Group II.

Variability of disk sources

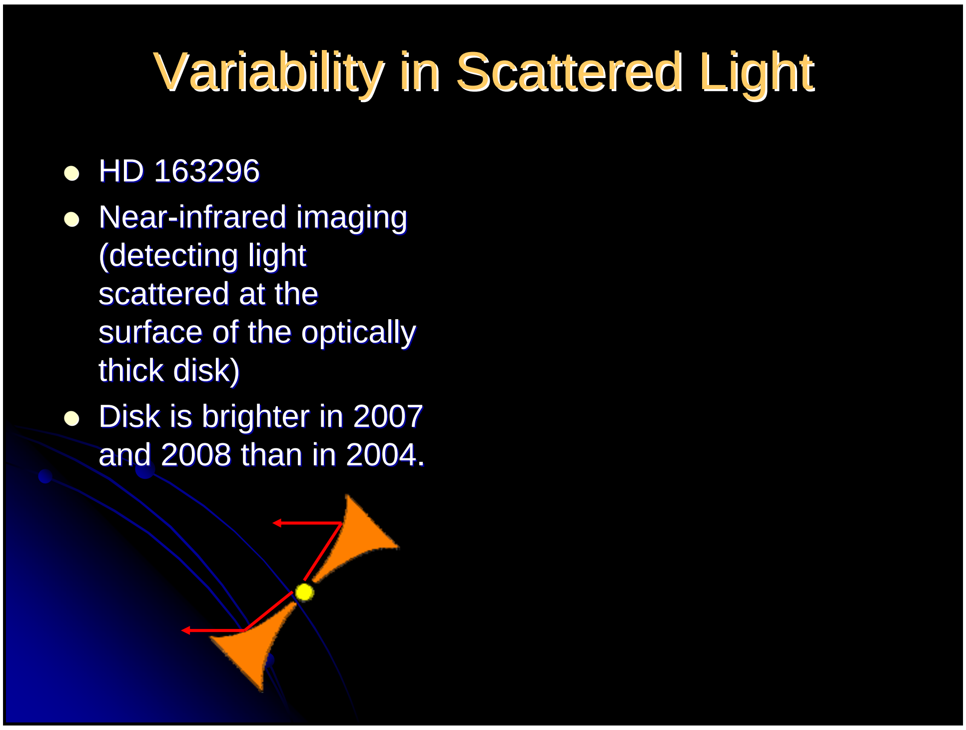


Detection of a very faint disk, but…

- HD 163296 (Herbig Ae star, 4 Myr, A1）
- Keplerian disk has been known, bright in (sub-)millimeter
- Disk radius ~430 AU
- L_{scat}/L_{total} (1.6 μm) ~ 2×10^{-4} (↔ 2×10^{-3} for β Pictoris)

HST/STIS (Grady et al. 2005, Observed in 1998)

Subaru/CIAO (Fukagawa et al. submitted, Observed in 2004)

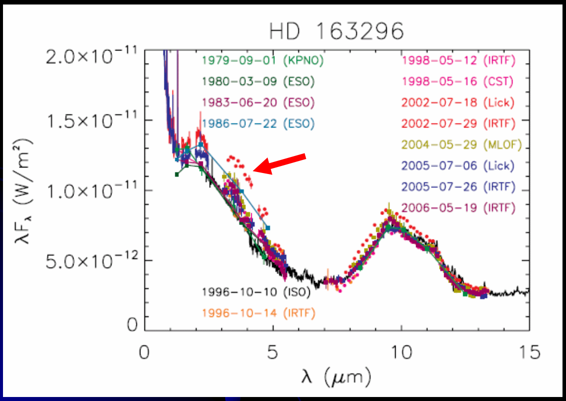


Variability in Scattered Light

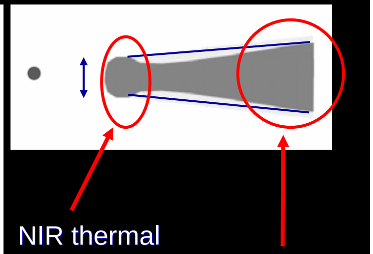
- HD 163296
- Near-infrared imaging (detecting light scattered at the surface of the optically thick disk)
- Disk is brighter in 2007 and 2008 than in 2004.

Variability of Thermal Infrared Emission

- Brightness change of ~30% was observed in 2002
- This kind of *event* might happen in a timescale of years (time sampling is not enough)



Sitko et al. (2008)

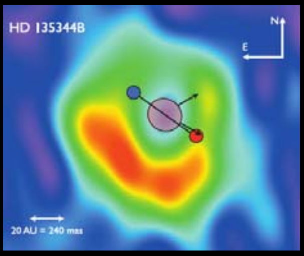


NIR thermal

Scattered light
If not shadowed

Variability for a Pre-Transitional Disk

- SAO 206462 (Age ~ 8 Myr, F-type stars)
- Pre-transitional disk
  - Transitional disk: few NIR excess + abundant MIR excess
- Gap at 3—10 AU (e.g., Pontoppidan et al. 2008, Fedele et al. 2008)



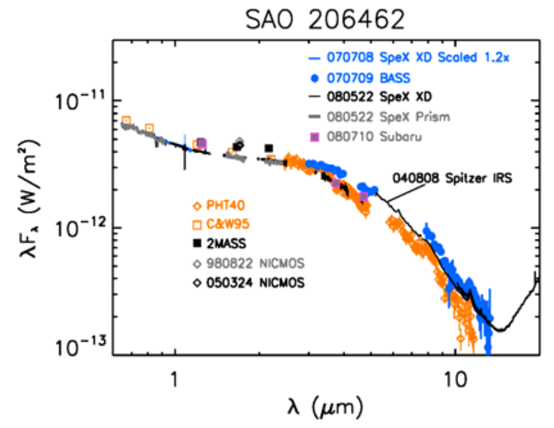
Pontoppidan et al. (2008)

Bryden et al. (1999)

Variability for a Pre-Transitional Disk

- Variability (>3σ) observed from NIR to 10 micron region
- Color is variable
- Warm state: small grains confined in a narrow belt from 0.08-0.2 AU

→ dust production due to mutual collisions of planetesimals…?



Grady et al. (2009)

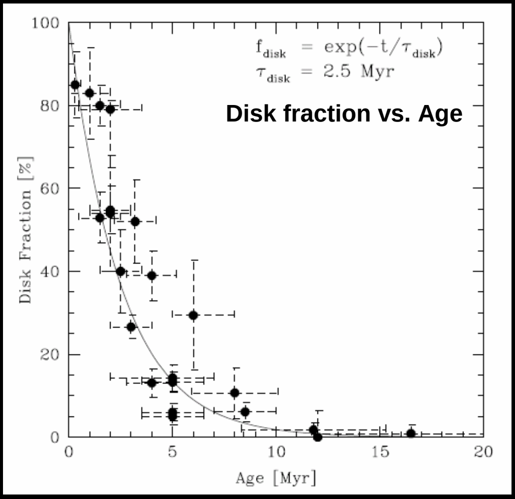
Summary

- "Diversity" of disk morphology has been revealed by AO imaging.
- Disk brightness in scattered light is not correlated with stellar age and millimeter flux/infrared excess: detection simply means that the disk is vertically flared to intercept the stellar light.
- Bright & highly structured disks are still surrounded by the remnants of envelopes.
- The significant diversity of disk structure can be attributed to the multiplicity and the initial condition of the local star-forming environments.
- "Variability" of disk structure is another key factor that can affect the planet formation.
- Systematic study on variability has just begun…

Primordial to debris disks

Disk lifetime

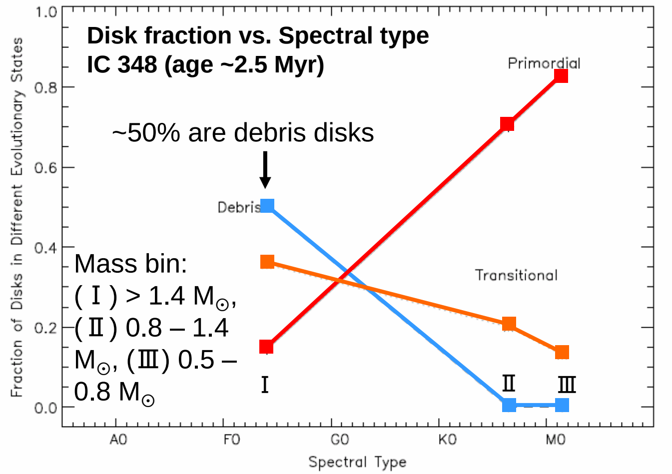
- Lifetime
  - → constrain the timescale for planet formation
  - → may affect inward migration



Disk fraction vs. Age

Mamajek (2009)

Evolution Depends on Stellar Mass



Disk fraction vs. Spectral type
IC 348 (age ~2.5 Myr)

~50% are debris disks

Mass bin:
(I) > 1.4 $M_\odot$,
(II) 0.8 – 1.4 $M_\odot$, (III) 0.5 – 0.8 $M_\odot$

Currie & Kenyon (2009)

- For higher-mass stars, giant planet formation should occur by 3 Myr and terrestrial planet formation could occur in ~3 Myr
- Rapid disperse → photoevaporation?

What infrared excess tells us

Protoplanetary Disks

- Disk fraction appears to decay with timescale of 2.5 Myr (exponential decay), but the lifetime could be stellar-mass dependent. Disks around lower mass stars can live longer.
- Large scatter in disk morphology and lifetime indicates significant dispersion in initial conditions of planet formation.
- Evolution could proceed from inside-out.

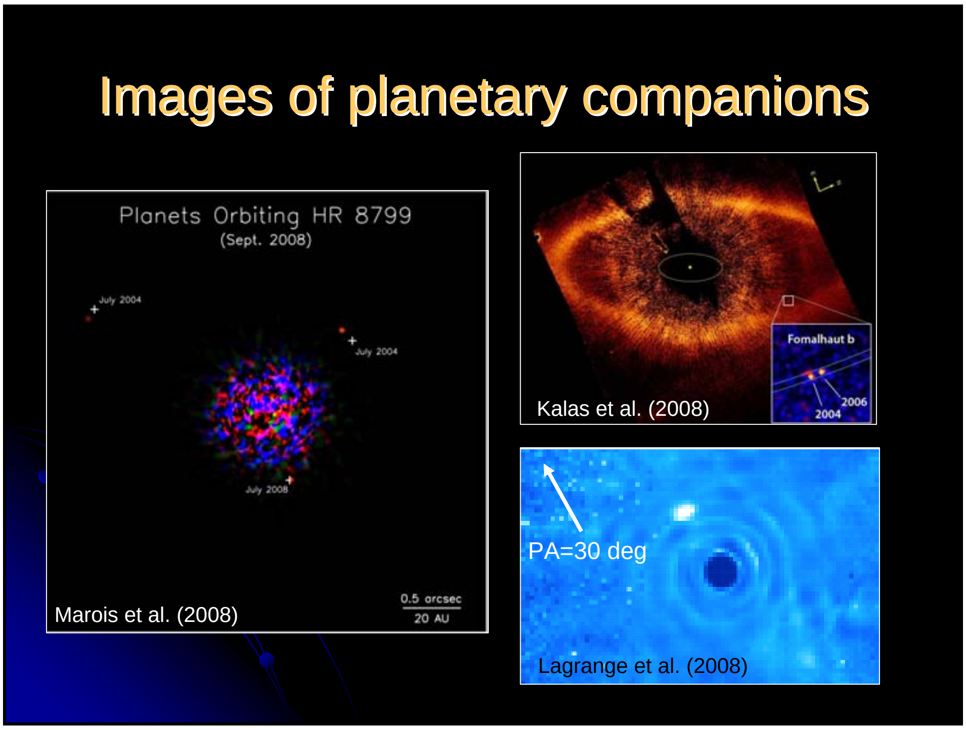
Transitional Disks

- Transition time from primordial to debris might be less than or similar to 1 Myr. The number of transition disks relative to primordial disks tends to increase with stellar age.
- Higher mass stars move to the debris disk phase faster than lower mass stars.

Debris Disk

- Higher frequency were observed for higher mass stars.
- Evolution appears to proceed from inside-out. Warm dust (< 30 micron) is rare for > 300 – 500 Myr stars.
- Connection to planetary systems is still unclear.

Direct Imaging of Planets



Images of planetary companions

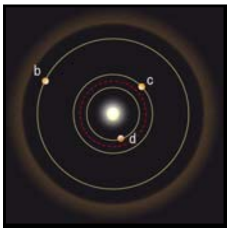
Marois et al. (2008)

Kalas et al. (2008)

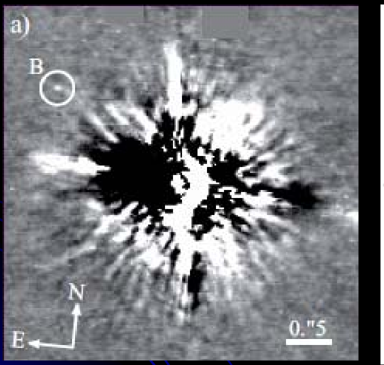
Lagrange et al. (2008)

Planetary Companion Candidates Imaged so far

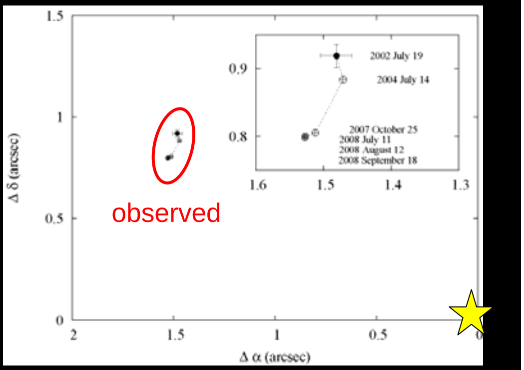
Star	Age (Myr)	Stellar mass ($M_\odot$)	Companion mass (MJ)	Projected Separation (AU)	Reference
Fomalhaut	100—300	2.0	≤ 3	98 (~119)	Kalas et al. (2008)
HR 8799	60—150	1.5 ±0.3	7[5–11], 10[7–13], 10[7–13]	68, 38, 24	Marois et al. (2008)
β Pictoris	12	1.8	~8	8	Lagrange et al. (2008)
CT Cha	2±2	0.7	17±6	440	Schmidt et al. (2008)
AB Pic	~30	K2	~13	~260	Chauvin et al. (2004)
GQ Lup	< a few	0.7	1 ~ 40	114±33	Neuhaeuser et al. (2005)
2M1207	8 ±4	0.024	5±2	55	Chauvin et al. (2004)

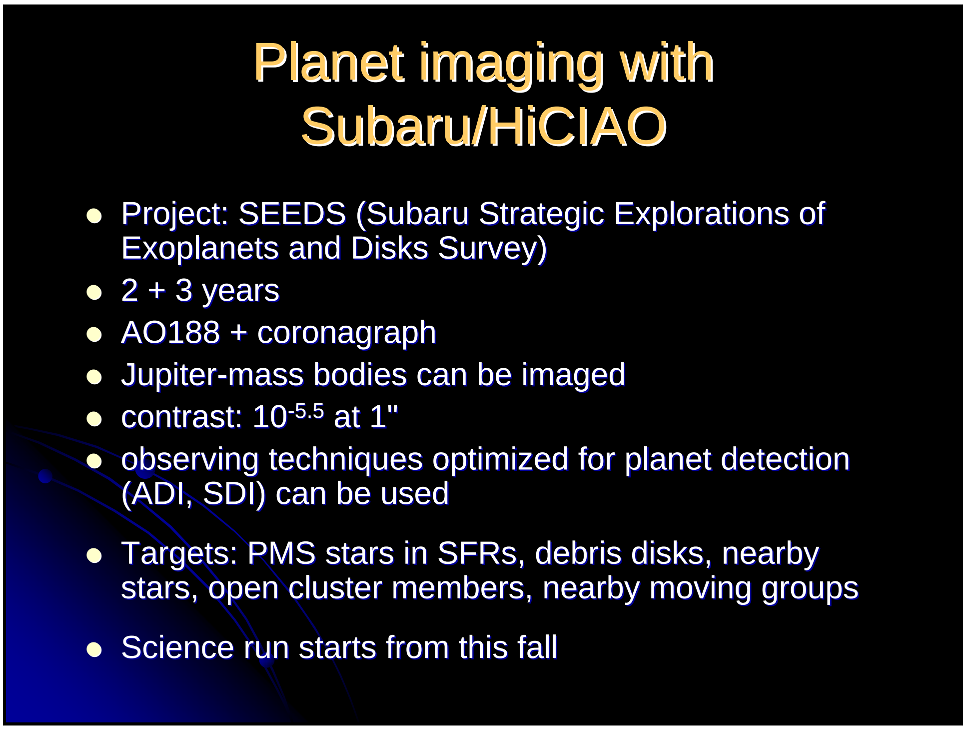


HR 8799b in 2002



Fukagawa et al. (2009)





Planet imaging with Subaru/HiCIAO

- Project: SEEDS (Subaru Strategic Explorations of Exoplanets and Disks Survey)
- 2 + 3 years
- AO188 + coronagraph
- Jupiter-mass bodies can be imaged
- contrast: $10^{-5.5}$ at 1"
- observing techniques optimized for planet detection (ADI, SDI) can be used
- Targets: PMS stars in SFRs, debris disks, nearby stars, open cluster members, nearby moving groups
- Science run starts from this fall