The Outer Disks of Herbig Ae Stars in the UV-NIR

C. Grady (Eureka Scientific), M.Fukagawa, Y. Maruta, & Y. Ohta (Osaka U.), J. Wisniewski & J. Hashimoto (U. Oklahoma), Y. Okamoto and M.Momose (Ibaraki U.),
T. Currie (U. Toronto), M. McElwain (NASA's GSFC),
T. Muto (Kogakuin U.), T. Kotani & Nb. Kusakabe (NAOJ), K. Follette (U. Arizona), M. Bonnefoy & M. Feldt (MPIA-HD), M. Sitko (U. Cincinnati), M. Takami & J. Karr (ASIAA),
M. Tamura (Tokyo U. & NAOJ) & the SEEDS consortium

Talk Roadmap

* 1. What we knew at the Amsterdam meeting
* 2 What has changed in the last 20 years
* 3. Combining SEDS and High-Contrast Imagery
* 4. The path forward

At the A'dam meeting

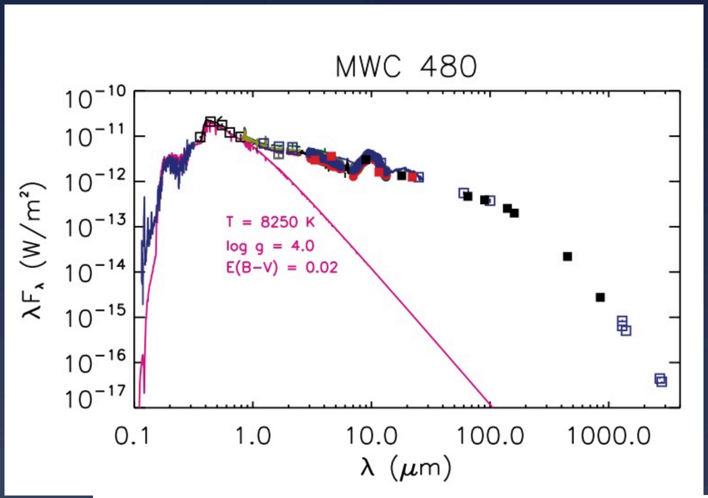
- Wind activity and variability well-documented from IUE, geometry still uncertain.
- Herbig Ae stars recognized to have IR excesses indicating multi-temperature dust (Hillenbrand et al. 1992; Oudmaijer et al. 1992)
- Geometry and nature of IR excess unknown
- Distances and ages not known
- Resemblance to T Tauri stars still controversial

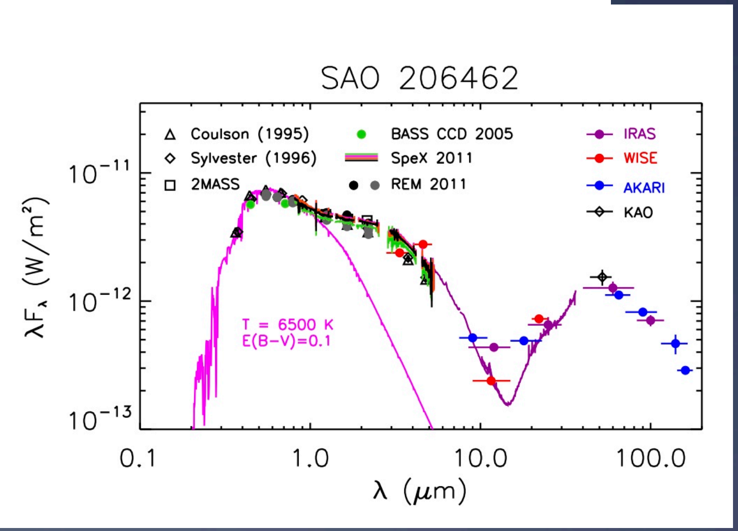
In the last 20 years

* Hipparcos: first distance estimates to Herbig Ae stars (van der Ancker et al. 97, 98)=> luminosities and first secure dating
* ISO, Spitzer, and Herschel: complete sampling of the IR SED, dust mineralogy, gas features
* High-contrast imagery with HST, CIAO, NaCo, HiCIAO, first light for MagAO, VisAO, GPI
* ALMA, Interferometric observations at NIR and Mid-IR

3. IR SEDS and Imagery

- HAe stars have 2 distinct types of spectral energy distributions (Meeus et al. 2001; Acke & van den Ancker 04).
- Group II – power law to 200 microns – interpreted as disks with grain growth and settling -Dullemond & Dominik 2004a,b
- Group I – interpreted as power law + BB (Meeus et al. 2001), historically interpreted as flared disks
- Early HST data found scattered light detections were more common (55%), but not universal for group I, and non-detections more common for group II, but again not universal.





HST Coronagraphic Imagery

* Of the 14 HAe stars in Meeus et al. (2001), 12 have HST data. Disk detections for 6 of these.
* Detections are predominantly for Meeus group I, only 1 for Meeus group II.
* Could not exclude the non-detections being for the trivial reason that the disk was fully occulted, since some of these still lack sub-mm interferometry.
* Detection rate climbs for additional objects observed with NICMOS (IWA=0.3"), but still includes non-detections, including some with known, large mm disks.
* Need alternate high-contrast imaging dataset with smaller IWA.

High-Contrast Imaging

- Working Instruments:

Instrument	λ	mode	IWA	Strehl
Subaru/HiCIAO	J,H,Ks	PI, ADI	0.15"	0.2-0.3
VLT/NaCo	H,Ks,L'	PI, ADI	0.1"	0.2-0.3
GPI	Y,J,H,Ks	PI, I	0.1"	0.7-0.9
MagAO	L',M	I	0.2"	0.7-0.9

- In Development/Commissioning:
- Subaru/SCExAO, Sphere

The SEEDS YSO Survey

- 1-10 Myr old objects, both single and binary/multiple stars
- 210 objects which are to be searched for both disks and the presence of planets in/near the disks.
- Bulk of stars studied at H-band using Polarimetric Differential Imaging (Hinkley et al. 2009) + Angular Differential Imaging (Thalmann et al. 2010).
- Sample includes nearby Herbig Ae-Fe stars, with bias toward Group I systems.

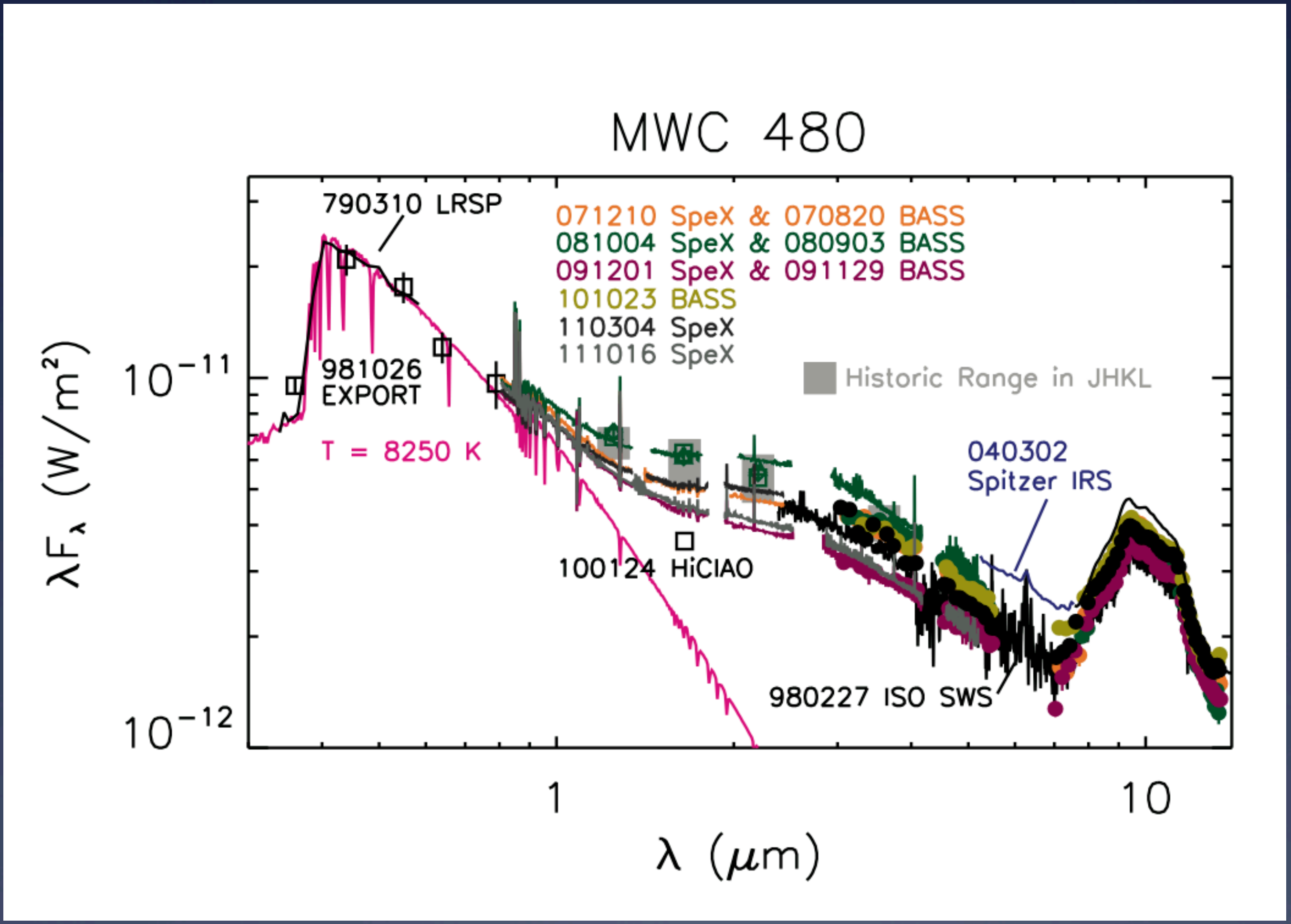
SEEDS Herbig Ae Observations

- AB Aur, HD 34282, HD 179218, Oph IRS 48, V1247 Ori, MWC 758, HD 163296, MWC 480, HD 169142,
- Herbig F stars: CQ Tau, HD 142527, SAO 206462
- Early type T Tauri stars: RY Tau, LkHa 330, SR 21
- Still getting some additional data…

Meeus Group II Disks

- Best studied examples are HD 163296, MWC 480, and HD 150193. Disk chemistry extensively explored by ALMA for HD 163296, (talks by Schneider, Mendeguitia, Woitke)
- HD 163296 and MWC 480 have history of NIR light variability (Sitko et al. 08)
- HD 163296 has history of outer disk illumination variability (Wisniewski et al. 08).
- Night to night changes in outer disk illumination seen by HST – speed implies shadowing structure is in inner dust disk
- Star for which we have coordinated observations of the SED and the disk – MWC 480. - History of HST non-detections.

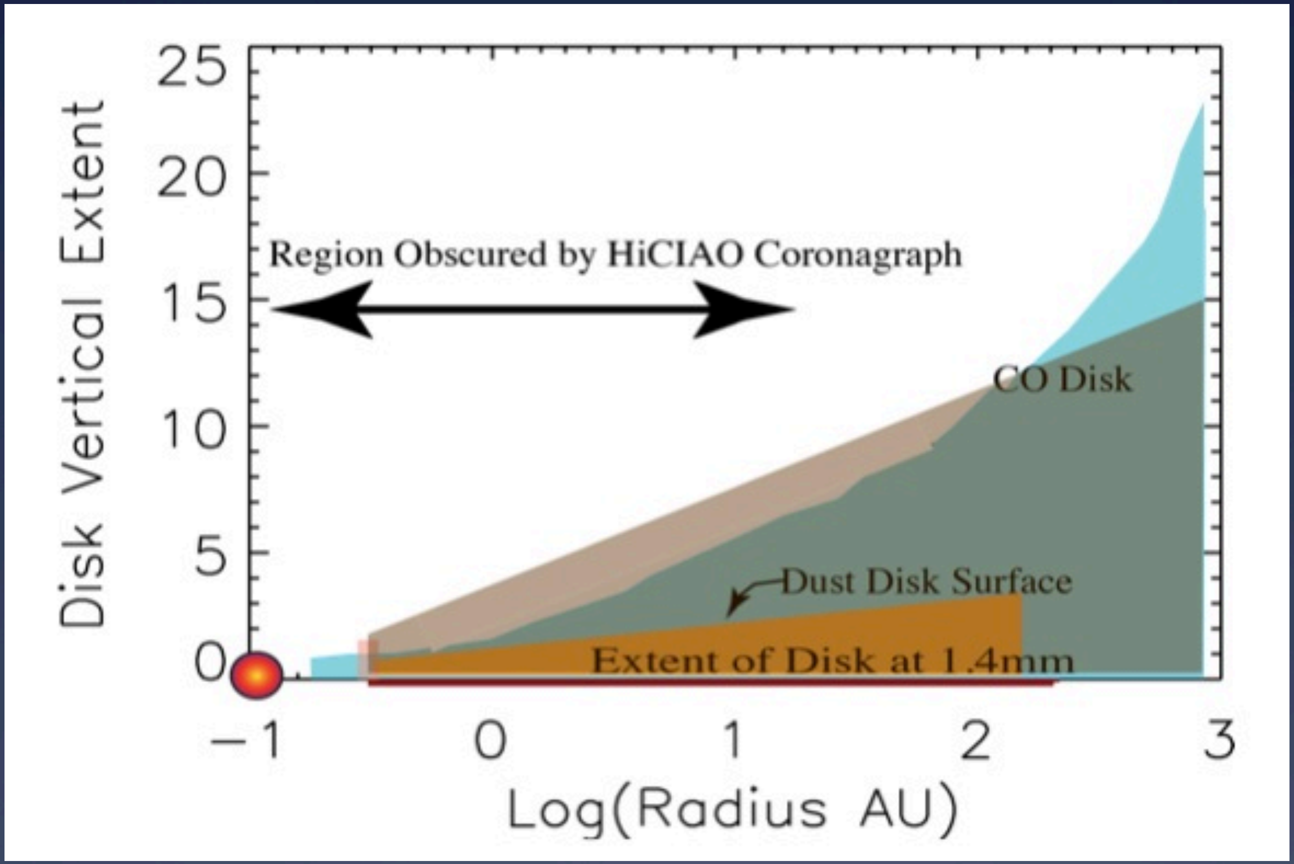
NIR to Mid-IR Variability



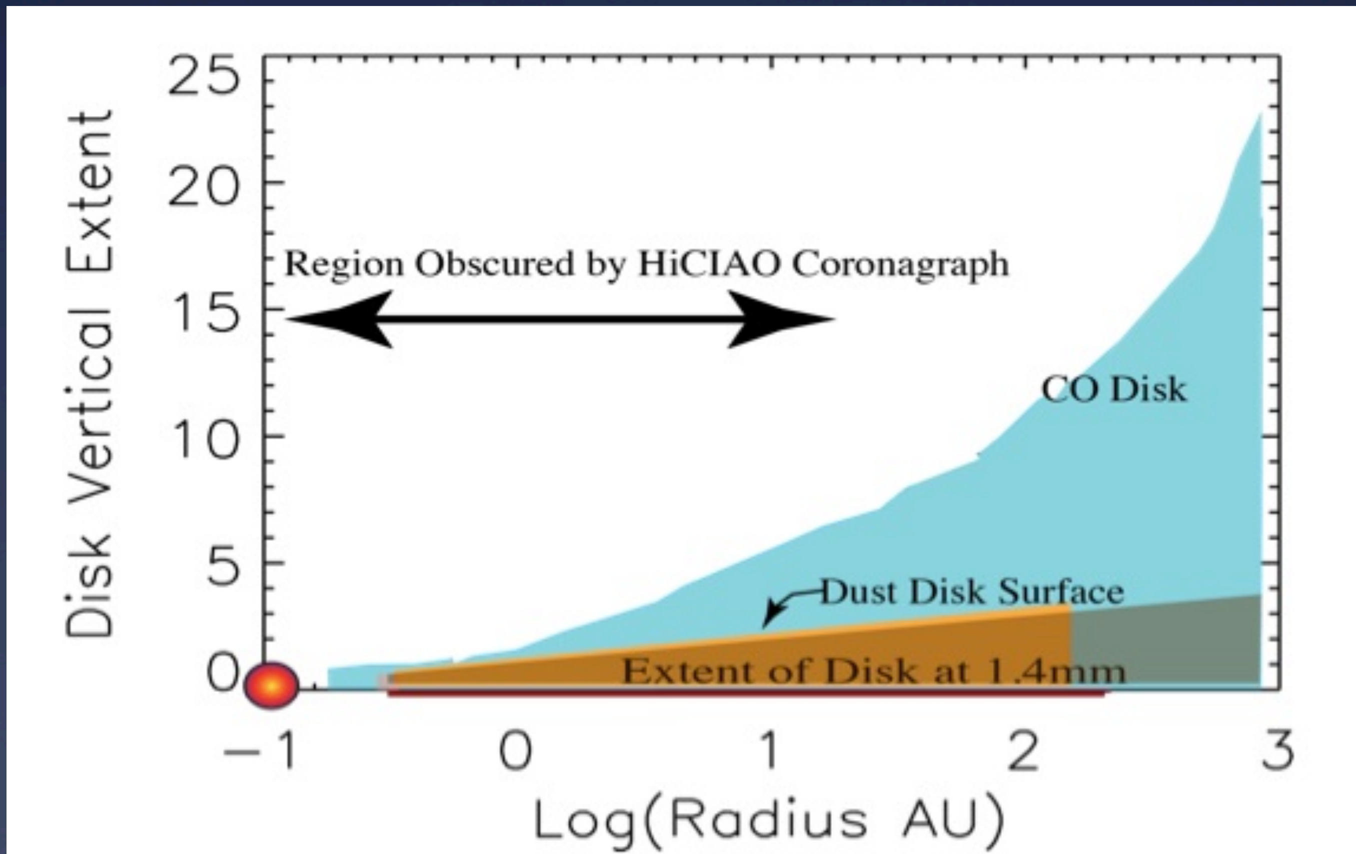
Implications of SED Variability

* Amplitude of NIR excess changes with time, no temperature change observed
* Indicates change in surface area over a small region in the disk, temperature is consistent with material at the dust sublimation radius
* Use the amplitude to estimate changes in vertical extent of disk at that point, and size of shadow cone cast.
* HD 163296: shadow can extend several hundred AU from the star and cover all or part of the disk.
* MWC 480: bulk of disk is shadowed most of the time.

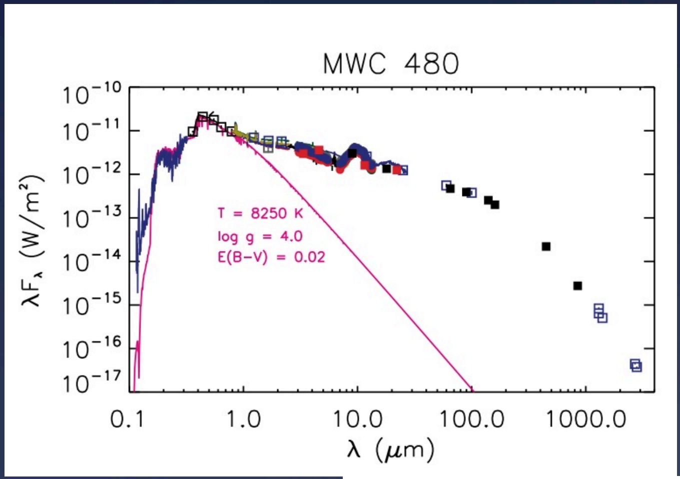
At NIR Maximum Light

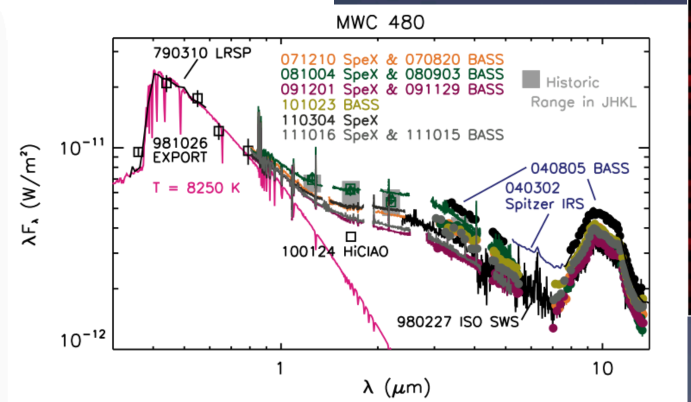


At minimum Light Shadow Cone Shrinks

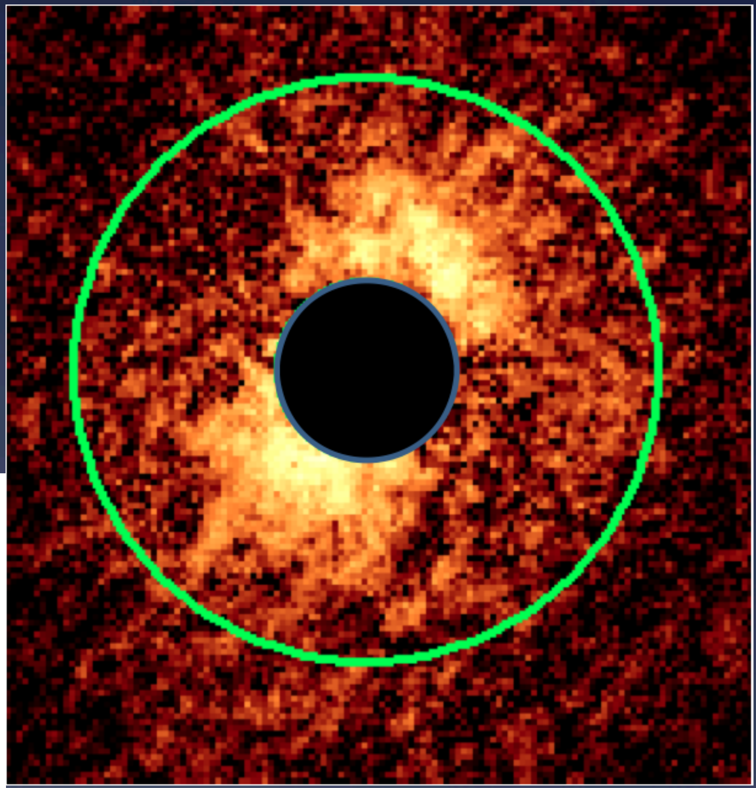


MWC 480 – minimum NIR light disk detection





Kusakabe et al. 12



H band PI, Kusakabe et al. 2012

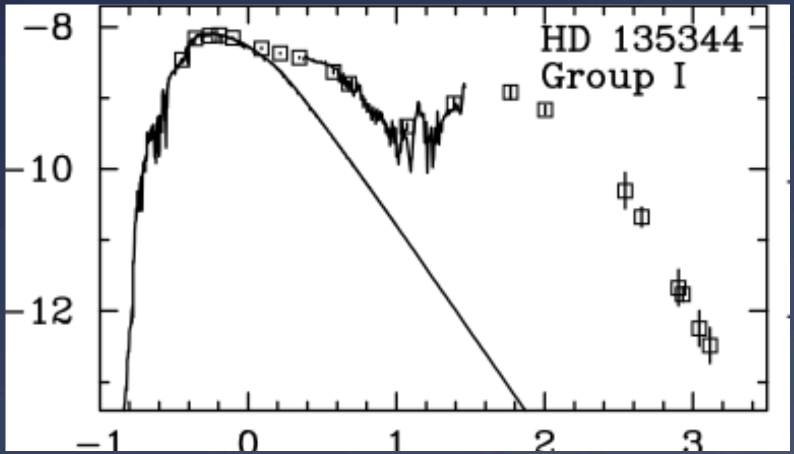
Id as group II:

Acke & van den Ancker 04

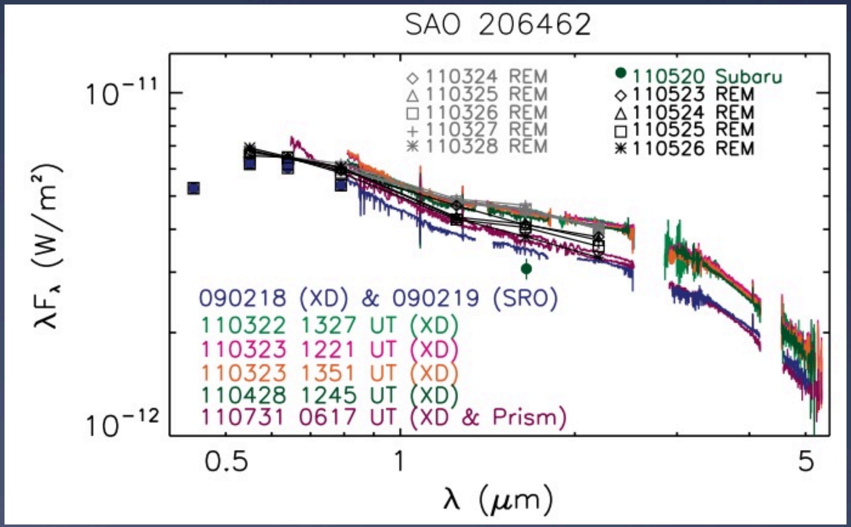
Disk Properties for MWC 480

- At 100 AU, dust disk surface is ~3AU above midplane. Gas scale height is ~10 AU (Pietu et al. 2007)
- Dust disk is settled and grains have grown, consistent with identification of this disk as the brightest HAe star in the mm (Koerner et al. 95)
- Validates inferences of Meeus et al. (2001) and Dullemond & Dominik (2004a,b).
- HD 163296 thought to be similar, just don't have the correlated H band photometry and disk imagery data for the full range – yet.

IR SEDS- Meeus Group I



Acke & van den Ancker 04



Are Meeus I Disks the missing Herbig Transitional Disks?

* Suggested to be flared disks (Meeus et al. 2001) HST detections tend to have radial SB profiles for the outer disk proportional to r^{-3}. Typical of wedge not flared disks.
* Honda et al. (2012) suggest that these are transitional disks, and specificially ones with inner disk components (pre-transitional in notation of Espaillat et al. (2010).
* Mid-IR data favor interpretation as transitional disks (Maaskant et al. 2013).
* 66% of the HiCIAO sample have inner cavities seen in sub-millimeter interferometry – limit set by available sub-mm data
* Conclude that the majority of the well-studied Herbig stars with Meeus I SEDS are transitional disks – same conclusion reached by Maaskant et al. (2013) based on mid-IR data.

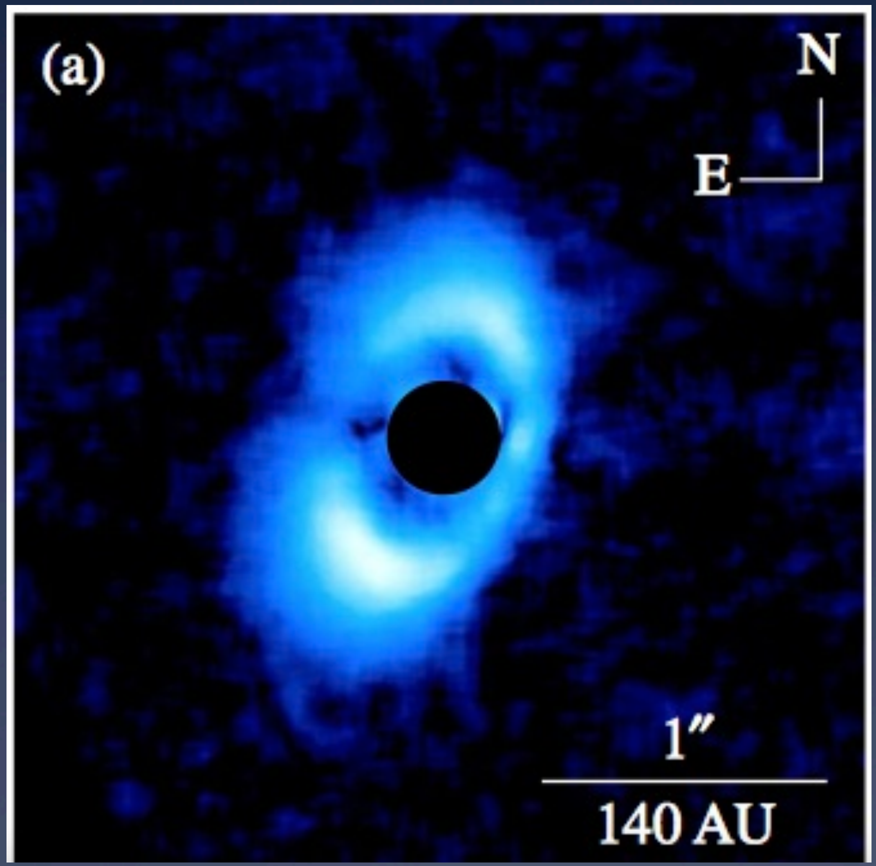
Meeus I Disks with High-Contrast Imagery

- HD 100546 (NaCo), HD 97048 (NaCo), AB Aur, Oph IRS 48, HD 34282
- MWC 758, HD 169142 (HiCIAO and NaCo), SAO 206462 (HiCIAO and NaCo)
- HD 142527(HST NICMOS, NIRI, NaCo, HiCIAO), LkHa 330, SR 21
- V1247 Ori, HD 179218, CQ Tau undergoing analysis

SAO 206462

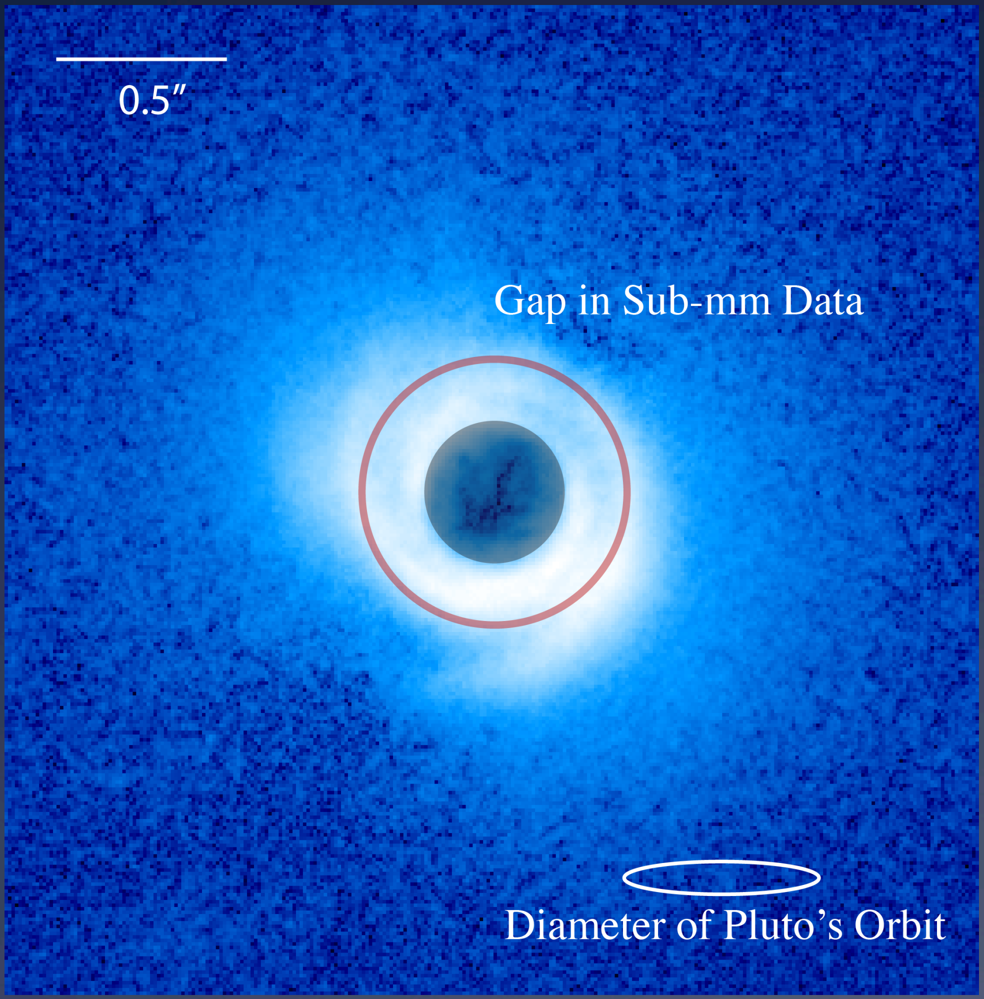
* Disk routinely detected in scattered light
* i~14° from pole-on (Pontoppidan et al. 2008): disk should appear circular -Most frequently seen as a bar-like or bow-tie like geometry in scattered light - shadowing
* HST may have seen variation in outer disk illumination.
* Shadowed zone coincides with the azimuthally-asymmetric ring seen by ALMA (Perez et al. 14) and outside spiral arms seen by HiCIAO and VLT/NaCo
* Takami et al. (2014) find the spiral arms are concave on their illuminated sides – flared structures. Shadowing of outer disk complicates assessment of flaring beyond the arm region.

What we had expected to see:



PDS 70, Hashimoto et al. 2012

This is what we saw:

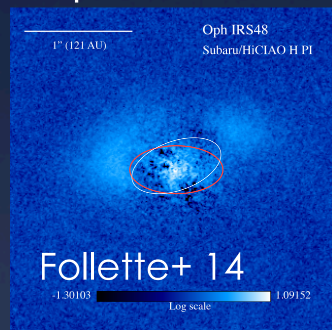


- material in region of SMA & ALMA gap
- disk is not ~circular in Scattered light
- spiral arms

This is what we see

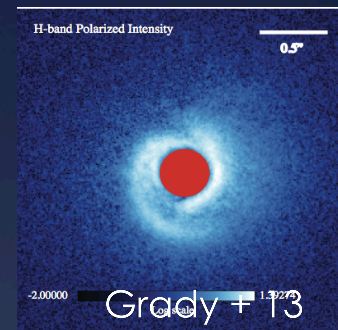
AB Aur

Oph IRS 48

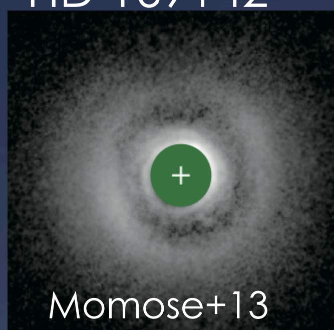


HD 34282

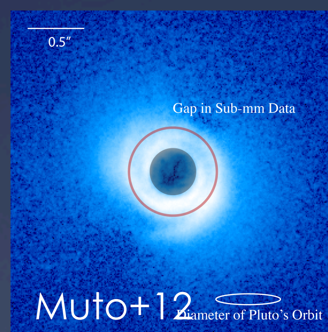
MWC 758



HD 169142

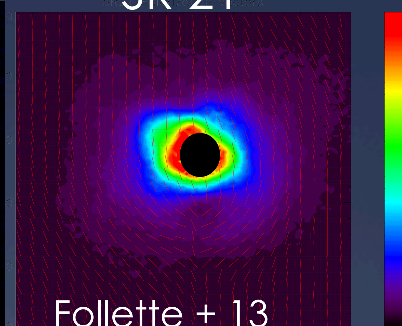


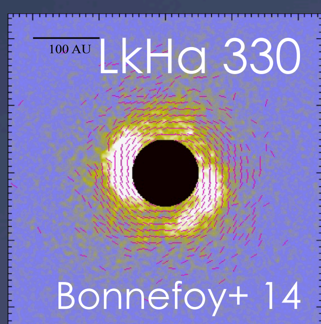
SAO 206462



HD 142527

SR 21





Meeus I disks are Diverse

- HiCIAO data confirm some HST non-detections are due to angular size of disk (HD 34282, HD 179218),
- NIR PI detection rate is at least 92% and may reach 100%
- Hashimoto (13) has classifiedT Tauri transitional disks into featureless with single SB powerlaw, broken powerlaw, and gapped disks. For the HAes, featureless disks:~ 25% of sample – predominantly more distant objects
- Gapped disks visible in NIR – 44% of HiCIAO sample ↑ as IWA ↓
- Broken powerlaw systems: 0 hard to find, given other structure
- 45% have spiral arms/features at some wavelengths – may rise with higher contrast provided by extreme AO systems
- 35% of the HiCIAO sample have eccentric gaps

Outer Disk Partial Shadowing

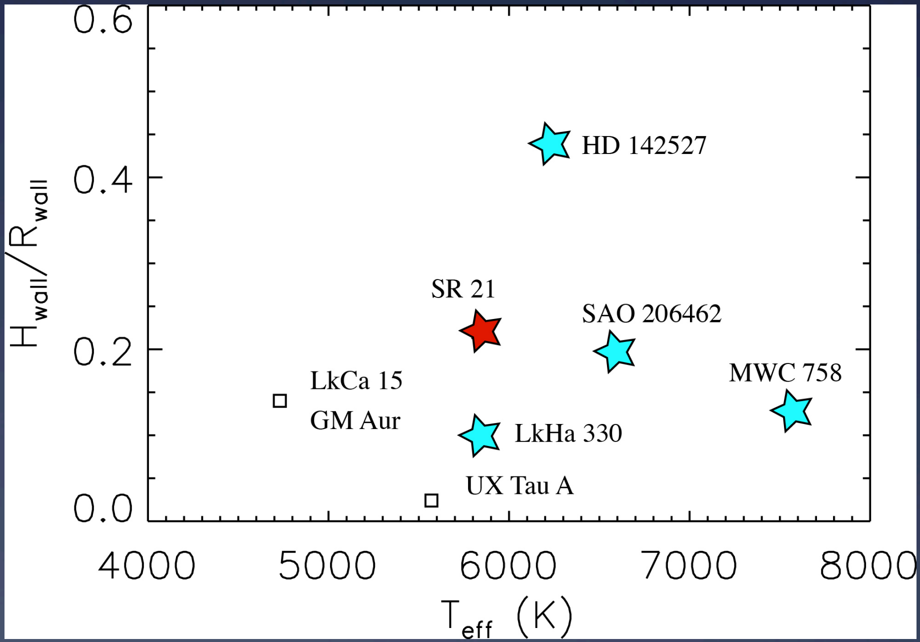
- Demonstrated for SAO 206462, MWC 758 and now HD 142527 (Christiaens +14)
- Indicates that the arm/shadowing structures are at high altitude: for HD 142527 wall H/R=0.42, in outer disk more like 0.1
- Optically thick = cast shadows
- May account for some of the prior HST non-detections (MWC 758 with STIS)
- Can't assume that shape of disk in scattered-light imagery reliably informs on geometry

Statistics (con't)

- Diverse grain properties: Some disks can be fit with MCRT codes using compact grains (HD 142527), others require porous grain aggregates (Oph IRS 48), and some can be modeled using either.
- 2 flavors of spiral – some dominated by ISM-like grains (AB Aur) and extend beyond mm disk – envelope material (Tang et al. 2012); others seen throughout NIR and clearly associated with disks.
- Meeus II disks are harder to get telescope time for due to shadowing. Some, however have small disks – and stellar companions (e.g. HD 104237) - not suitable for high-contrast imaging, better with interferometry

Why and When are we seeing structured disks?

- Andrews et al. (2011 - same model for T Tauri and HAe transitional disks - Hwall/R_wall
- Expect loosely wrapped arms for dynamically warm disks – easier to detect arms in modest contrast data
- Some of our arm non-detections (SR 21) have large H/R but were observed at low Strehl ratio –contrast matters.
- Some of the non-detections are for systems viewed at i-50-55° – projection effect?

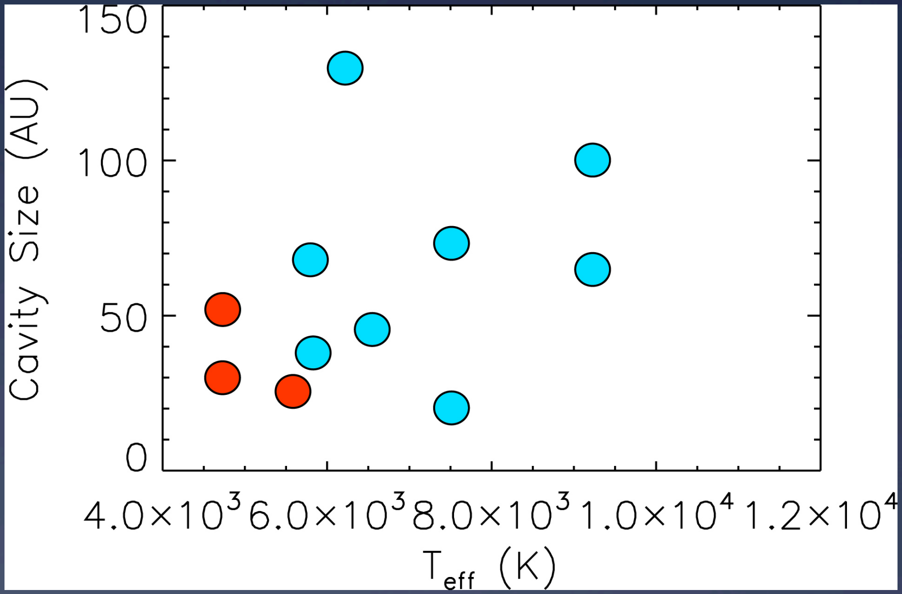


Origin of Structure

* 3 options have been proposed:
  * Grain growth and settling so that the relevant part of the disk is shadowed – problem is that this should be bright in the sub-mm – inconsistent with SMA and ALMA data
  * Photoevaporation of Grains
    * Predict - most pronounced near the star
    * Should see correlation with FUV+Xray radiation field
  * Dynamical Origin – Talk by Sasha Quanz

Gap Properties for Meeus I disks

- All disks are pre-transitional; no significant shadowing of the outer disk by the inner disk. - disks are not flat like Meeus II.
- Gap size is uncorrelated with FUV radiation field (correlated with T_{eff} see Meeus et al. 2012) or X-ray emission
- Exclude photoevaporation as dominant source of clearing

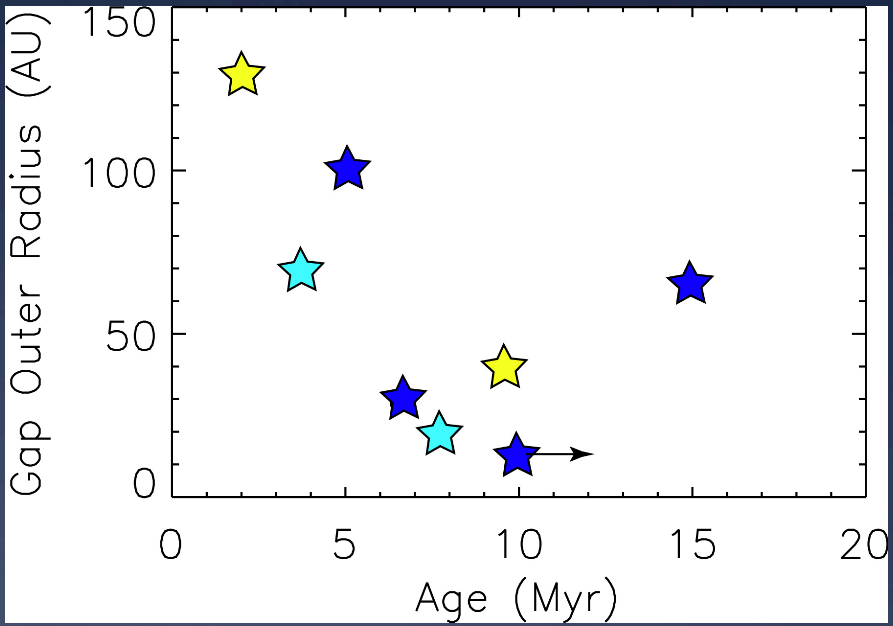


Gap Properties for Meeus I disks

- Gap size is
  - Not correlated with age…

- Dynamical origins are suggested by the fact that one of these systems hosts 2 exoplanet candidates and another has a stellar companion.

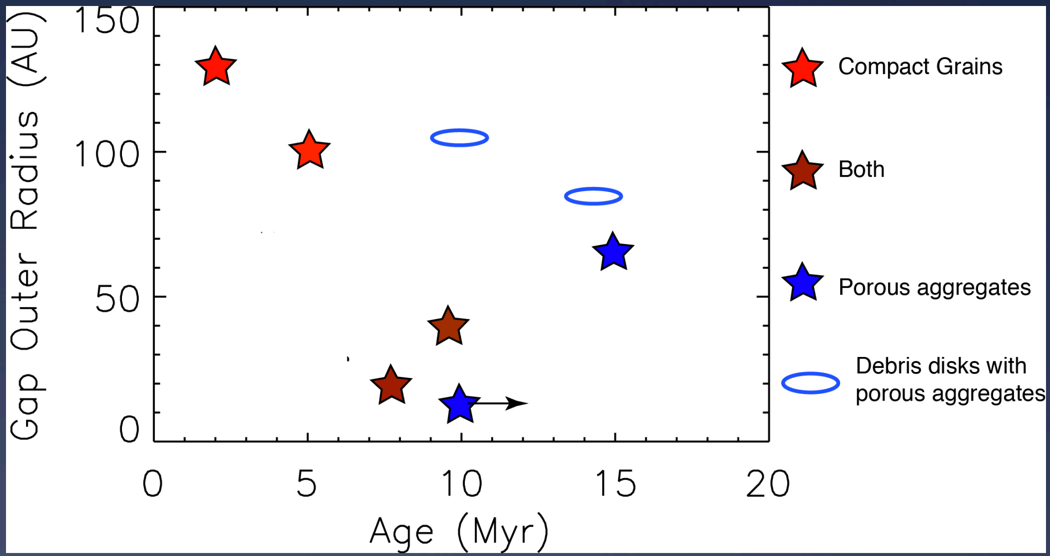
- With the exception of the circumbinary disk around HD 142527, gap outer radius is in the range of debris disk sizes for A stars



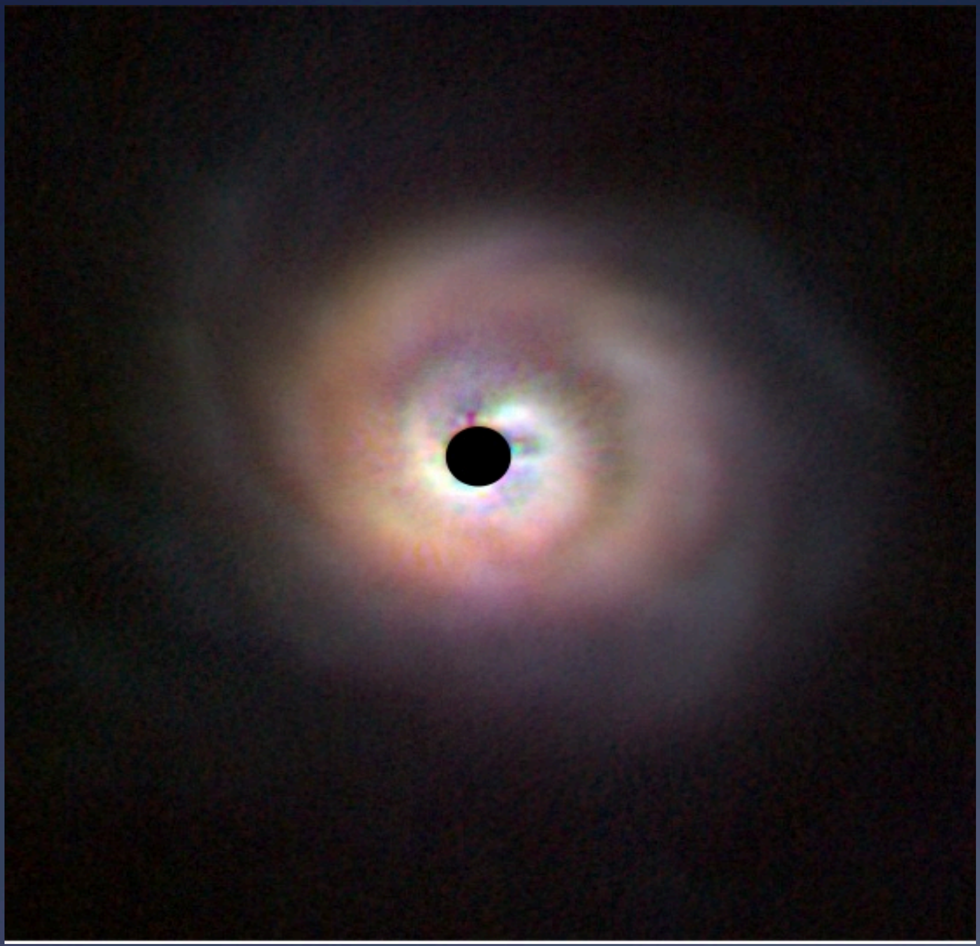
Age estimates from Meeus et al. (2012)
And Brown et al. (2012)

Possible trend of grain properties with age

- Youngest sample members have high polarization fraction consistent with scattering by small, compact grains
- Oldest sample members of the sample have scattering by porous aggregates, similar to debris disks.
- Age estimates Meeus et al. (2012), Brown et al. (2012)



And with radius: AB Aur



* AB Aur outer arms very blue – tiny grains
* Can see the region of the sub-mm ring (Tang et al. 2012) – reddish NIR color, larger grains?
* Material interior to the ring has neutral color – micron-sized material
* Evidence for grain filtration by a dust trap?

Differences in NIR and Sub-MM Gap Size

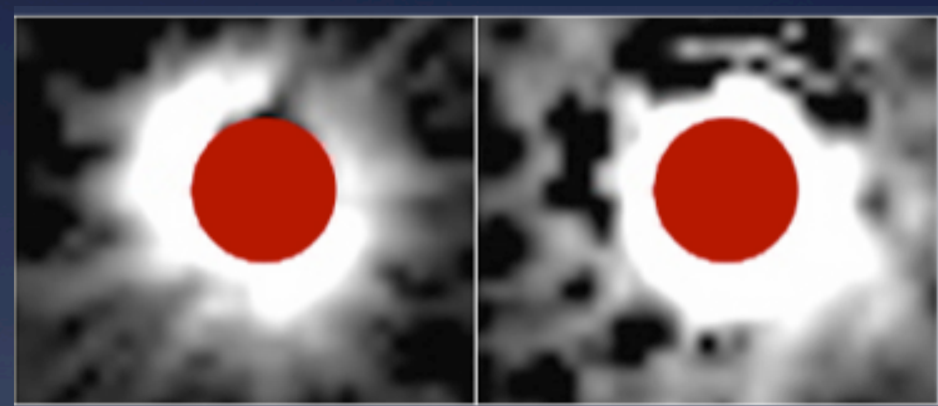
* 5 of our intermediate mass stars have SMA or ALMA continuum interferometry permitting us to measure gap size in sub-mm (Andrews et al. 11; van der Marel et al. 13; Casassus et al. 13)- sample will grow as ALMA cycle 1 data are taken…

* 60% of these show smaller gaps in the NIR than in the sub-mm; 40% have same size gap as seen in the sub-mm; fractional size of the NIR gap ranges between <33% to 100%

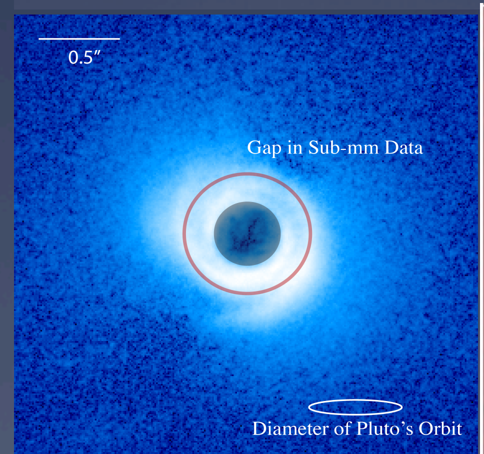
* Inconsistent with photoevaporation and dust grain growth and settling alone. Together with eccentric cavities, point to dynamical origin (see talk by Quanz).

Potential of Extreme AO

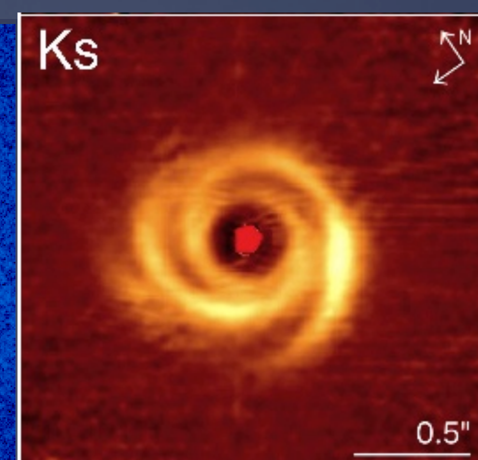
HST NICMOS



- SCExAO - smaller IWA – 4x better than HiCIAO, 2x better than NACO - image in to 7AU at d=140pc; GPI coronagraph has IWA 0.125'' but offers excellent starlight suppression.
- More stable PSF – may be able to get I images to go with PI data– probe of grain properties
- Smaller IWA will also allow us to probe amount of material in the NIR cavity
- Classification of disks can change with IWA –e.g. SAO 206462 – would classify as a filled disk with spiral arms from HiCIAO, but NaCo data clearly demonstrate a cavity which is smaller than seen in the sub-mm.

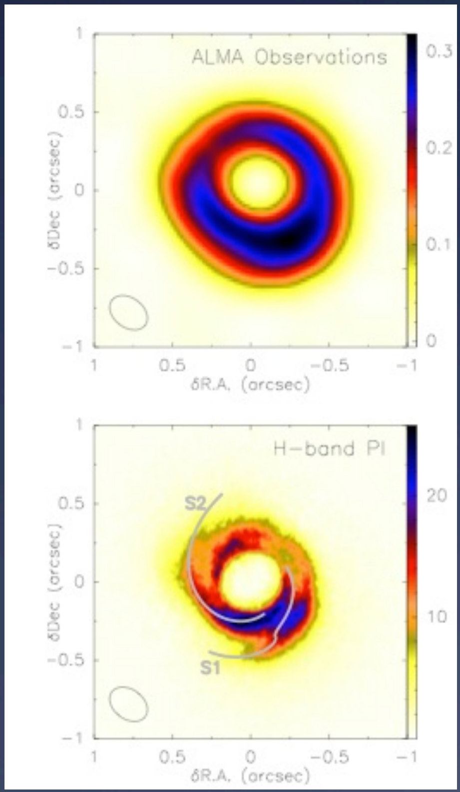


Muto et al. 2012



Garufi et al. 2013

Synergy between scattered light imagery and ALMA

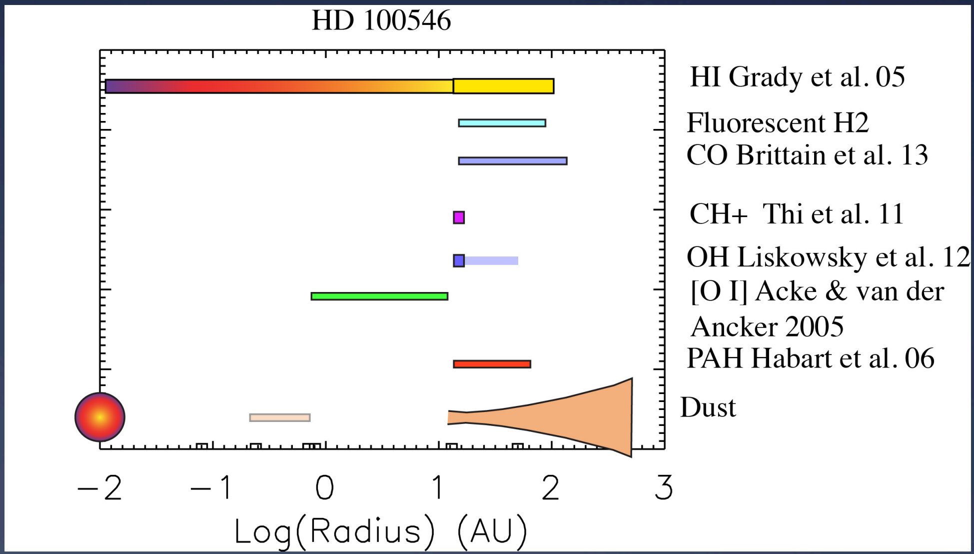


Pérez et al. 2014

* Band 9 ALMA continuum for SAO206462 has a gapped ring, similar to SMA. SE "wall" coincides with SE arm.
* Gapped ring morphology appears typical for the transitional disks in the sub-mm continuum.
* Can expect ALMA data to evolve as interferometer comes fully on-line.

Disk Composition

* More data for the inner disk (r< a few AU), but some data for two stars, HD 100546 and HD 142527.
* HD 142527: Honda et al. (2009) found water ice at the inner edge of the outer disk, as expected for material >100 AU from the star.
* HD 100546: we see water ice dissociation products at the inner edge of the outer disk. Difference is likely due to size of gap and difference in radiation field of stars.



Temporal spread in disk clearing tied to composition?

* Clearing is expected to be rapid (<10^5 years), but we have examples from 1 Myr (circumbinary disks) to >10 Myr.
* HD 100546 is a mild λ Boo star – deficits in material which should have formed the earliest generation of dust grains in the protoplanetary nebula. This pattern is not just stellar, but also extends to the infalling material and the dust composition– small NIR –UV cavity size, with signatures of what may be planet formation farther out in the disk (Quanz et al. 2013) and a planet within the gap (Brittain et al. 2013). The star is at the ZAMS.
* 50% of HAe stars are λ Boo (Folsom et al. 2013) – underabundant in the 1st generation of grains
* Did some disks get off to a late start by virtue of when dust grains can grow and settle based on composition?

Summary

- Structure in the form of spiral arms, gaps, etc. Is extremely common in Intermediate-mass transitional disks. May prove to be as distinctive a signature of planetary to stellar mass companions as structure in SED and cavities in the sub-mm.
- Gap size and visibility in the scattered light imagery does not correlate with *stellar* properties (mass, luminosity, age)
- Expect additional disks to show structure as the IWA, Strehl ratio, and contrast of the data improve.

Conclusions: much progress since the 1990s

* Herbig Ae stars host disks, a number of which have high contrast imagery, mid-IR imagery, complete SEDS and demonstrations of variability, and a steadily enlarging set of interferometric observations.
* Meeus group II SEDS are indeed associated with disks which are settled, but are younger than the Meeus I disks
* Meeus group I disks have spectacular structure which may have a dynamical origin.
* Disk evolutionary processes similar to T Tauri stars, disk clearing timescale independent of stellar properties.