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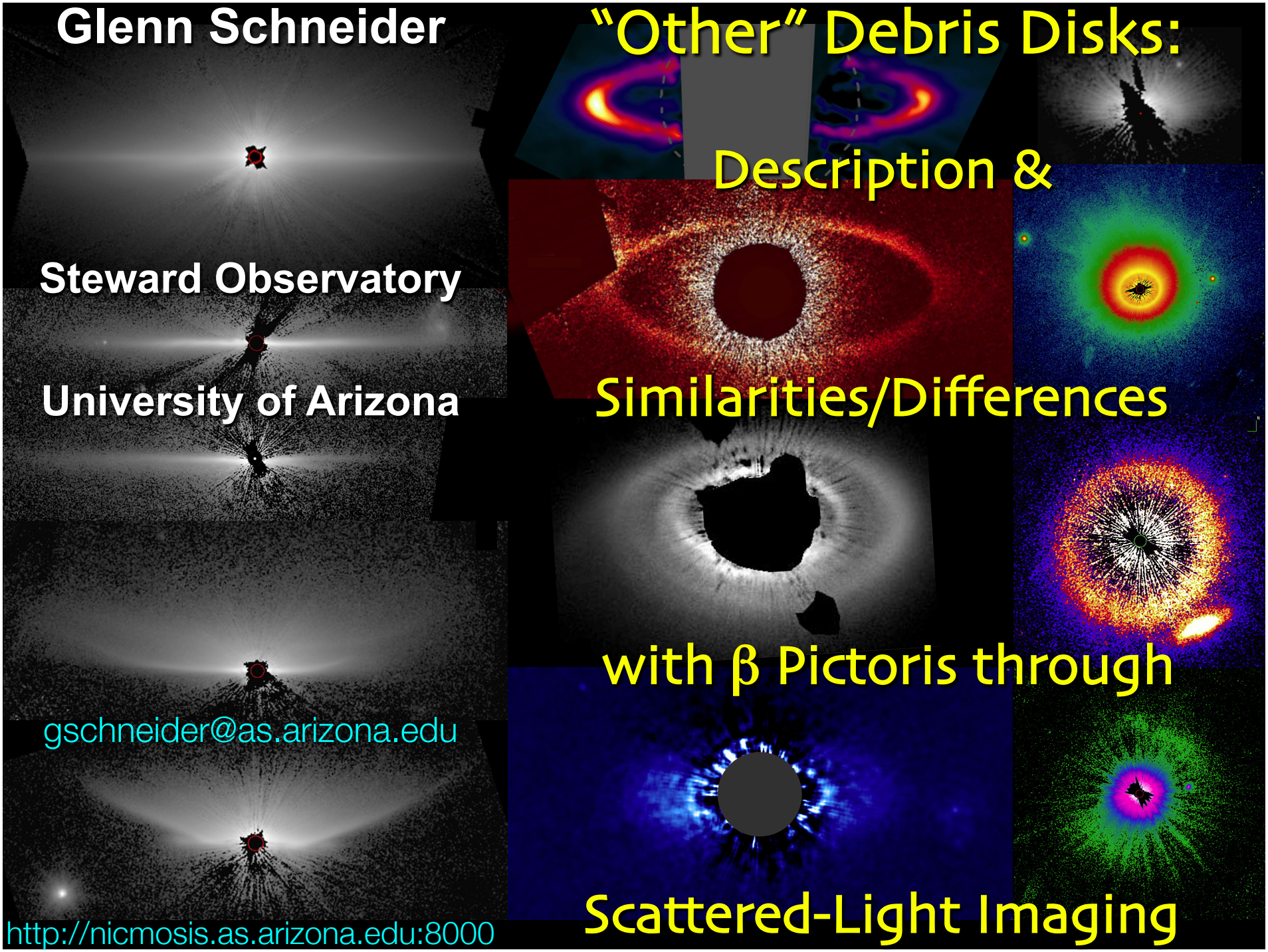
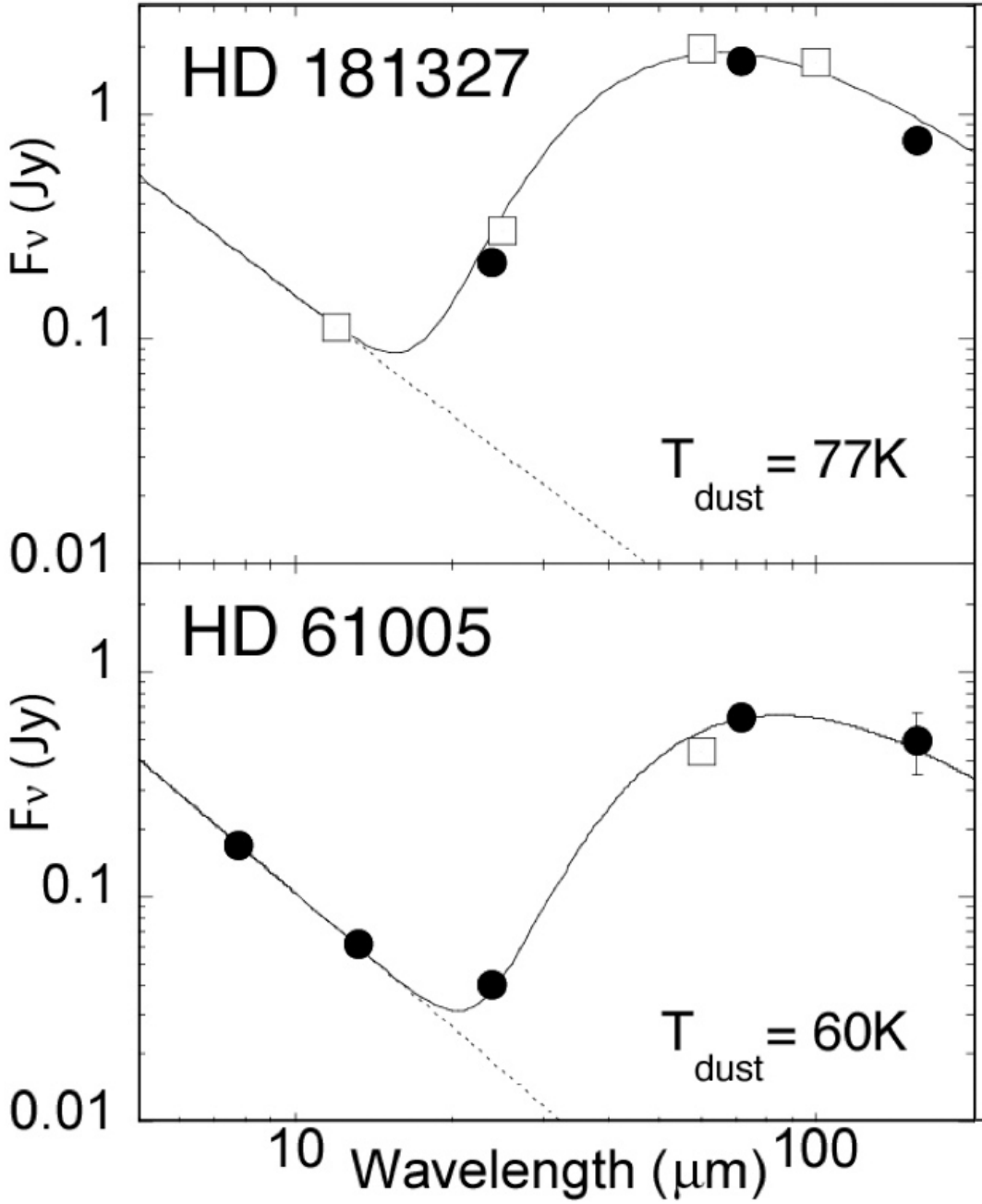
"Other" Debris Disks:

Description & Similarities/Differences with β Pictoris through Scattered-Light Imaging

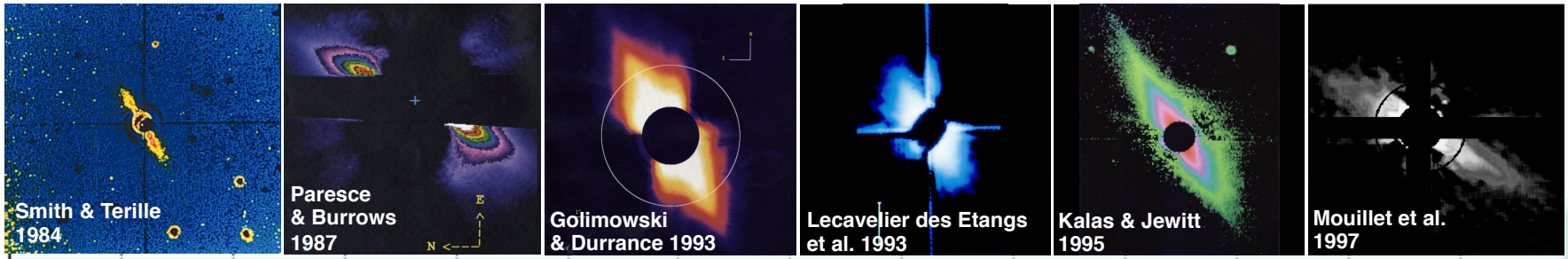


http://nicmosis.as.arizona.edu:8000

OBSERVATIONAL MOTIVATION



[redacted]



First 15 years of β Pic Imaging

1984 - LCO/du Pont 2.5m Coron
1986 - ESO/La Silla 2.2m Coron
1991 - LCO/du Pont 2.5m AOC
1991 - ESO/La Silla 2.2m AB CCD
1993 - UH 2.2m Coron
1995 - HST 2.4m WFPC2
1996 - ESO 3.6m ADONIS Coron
1997 - 2.4m STIS Coron (2000)

β Pic

BUT, NO <u>OTHER</u> LIGHT-SCATTERING DDs IMAGED

1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998

OBSERVATIONAL PROBLEM

IRAS found many "IR excess" stars indicative of CS dust…

- but (pre-HST) *only one* light-scattering disk (Beta Pictoris*)
- using most aggressive ground-based observing techniques

*prototypes are not necessarily good archetypes!

Imaging CS dust-scattered starlight in planet forming environments from the ground proved extremely challenging:

- seeing-limited Strehl ratios
- (posited) generally very high disk-to-star contrast

This *contrast-limited problem* was 1st engaged on the ground, and then (fruitfully) in space with HST CORONAGRAPHY,

and now (EX)/AO-augmented, large ground-based telescopes with high-contrast imagers; E.g., NaCo, NICI, MagAO, GPI, SPHERE, SCExAO…

High-Contrast Imaging for DD Science Planned for HST

1st Generation (April 1990)

SPHERICAL ABBERATION

WFPC-1

0.1% reflective spot

d = 1.2" in PC8 (f/30)

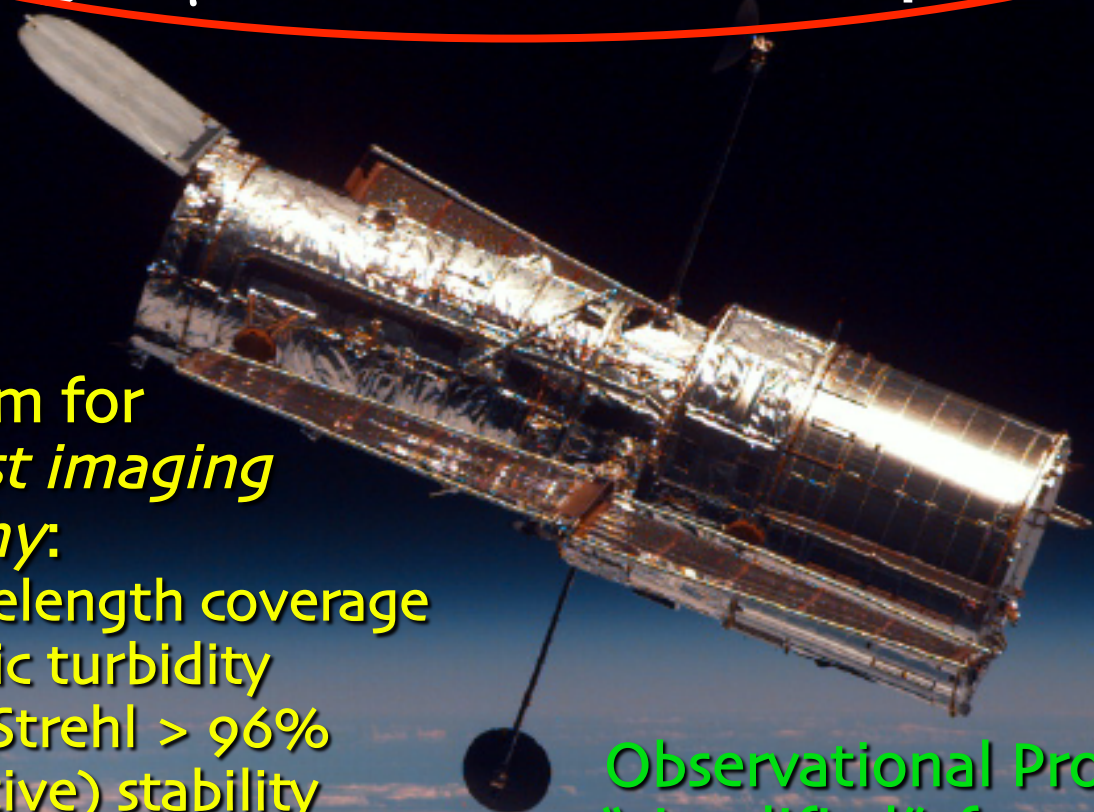
14 λ/D @ 0.5μm

FOC

f/288 optical channel

Lyot coronaraph

7.2 mas/pix, 3.2" FOV



An ideal platform for
for *high contrast imaging*
via *coronagraphy*:

- UVIS/nIR Wavelength coverage
- No atmospheric turbidity
- Panchromatic Strehl > 96%
- Platform (relative) stability
- Combined imaging modes

Observational Problem
"simplified" from space.

High-Contrast Imaging for DD Science Planned for HST

SM1 (December 1993)

WFPC-2
High-contrast spot
eliminated

COSTAR(/FOC)
f/288 optical channel
not "fixed"

HST coronagraphy delayed until post-SM2 (NICMOS & STIS; 1997)

High-Contrast Imaging for DD Science Implemented for HST

2nd Generation

NICMOS

Lyot Coronagraph

r = 0.3”, f/45, 76 mas/pix

1.1–2.4 μm (3.2 λ/D @ 1.1 μm)

1997 – 1998 **2002 – 2009**

High-Contrast Imaging for DD Science Implemented for HST

2nd Generation

NICMOS

Lyot Coronagraph

r = 0.3”, f/45, 76 mas/pix

1.1–2.4 μm (3.2 λ/D @ 1.1 μm)

1997 – 1998 **2002 – 2009**

STIS

Occulting Wedges & Bars

Width: (0.3”*)0.6” - 3”, 50 mas/pix

Unfiltered (CCD broad response)

1997 – 2004 **2009 – …**

*new for cycle 22

High-Contrast Imaging for DD Science Implemented for HST

2nd Generation

NICMOS

Lyot Coronagraph

r = 0.3”, f/45, 76 mas/pix

1.1–2.4 μm (3.2 λ/D @ 1.1 μm)

1997 – 1998 2002 – 2009

STIS

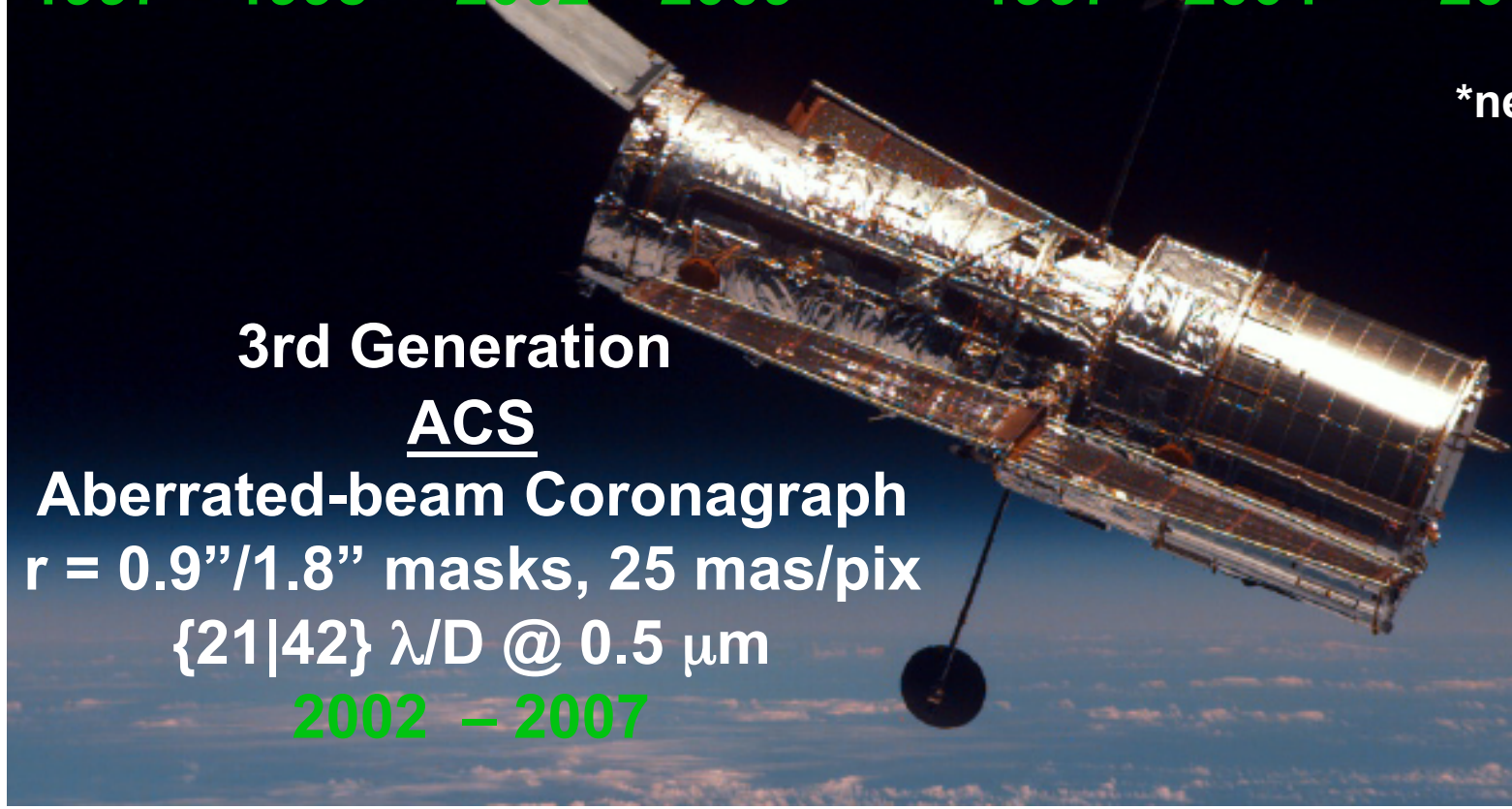
Occulting Wedges & Bars

Width: (0.3”*)0.6” - 3”, 50 mas/pix

Unfiltered (CCD broad response)

1997 – 2004 2009 – …

*new for cycle 22



3rd Generation

ACS

Aberrated-beam Coronagraph

r = 0.9”/1.8” masks, 25 mas/pix

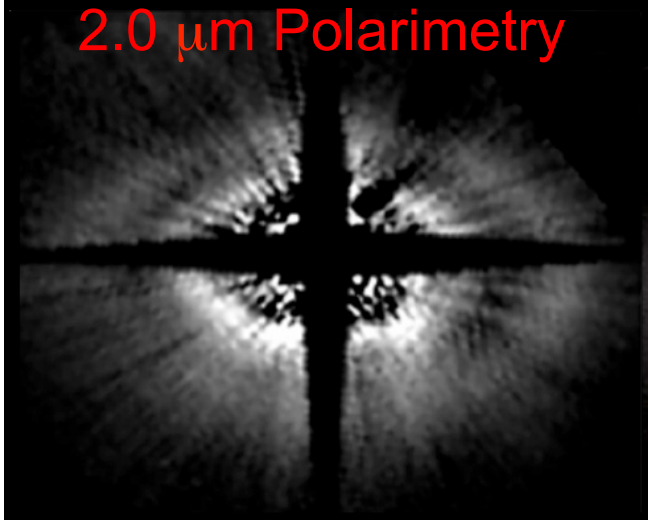
{21|42} λ/D @ 0.5 μm

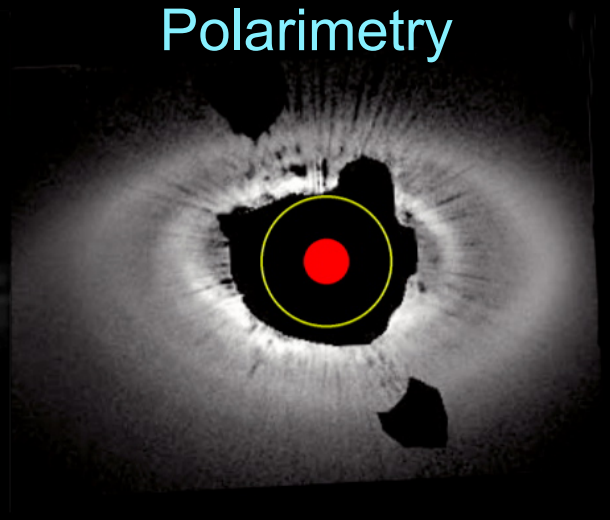
2002 – 2007

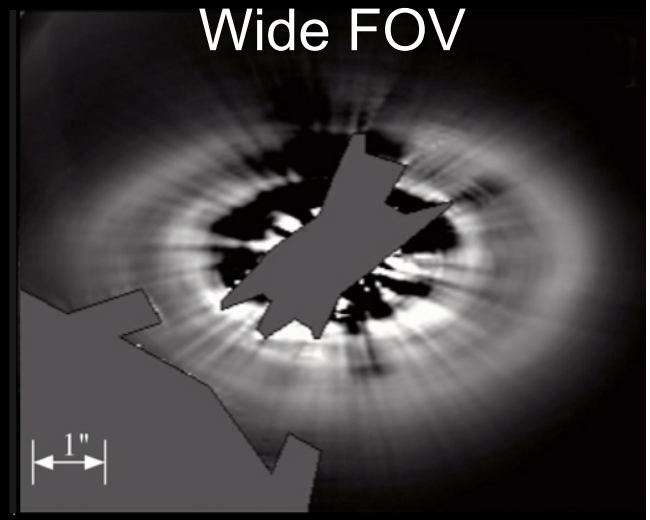
The HST Coronagraphic Suite: Symbiotic Capabilities

Spatially resolved imaging allows dynamical interpertation, but also…

NICMOS	ACS	STIS
nIR (1.1 – 2.4 μm)	Visible (0.4 – 0.9 μm)	~0.2 – 1.03 μm
W,M.N IR filters	M,N,W VIS filters	Unfiltered
small IWA (r=0.3”)	Two circular occulters	wedge-selectable IWA
	Wide FOV	High photon efficiency
2.0 μm Polarimetry	Polarimetry	Wide FOV







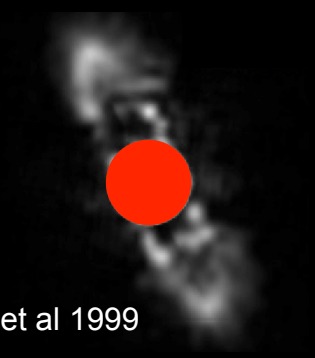
F110W (1.1 μm)	F606W (0.61μm)	50CCD: 0.36 – 0.79 μm
2 x 10 min (8° roll)	2 x 41 min (28° roll)	2 x 26 min (30° roll)
Weinberger et al. 1999	Clampin et al. 2003	Schneider et al. 2001

HD 141569A

Representative HST Debris Disk Discovery Images

NICMOS

HR 4796A

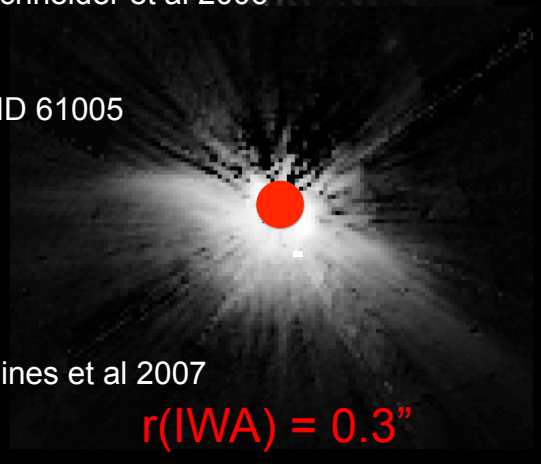


Schneider et al 1999

HD 181327

Schneider et al 2006

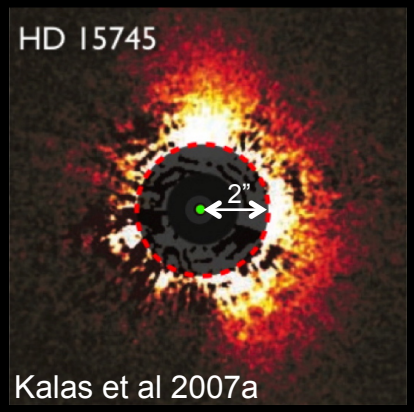
HD 61005



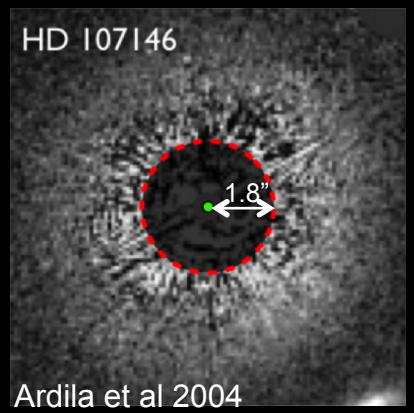
Hines et al 2007

r(IWA) = 0.3”

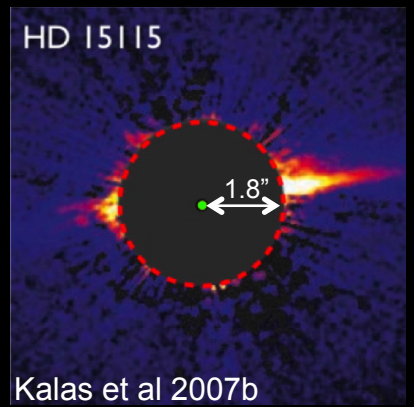
ACS



Kalas et al 2007a



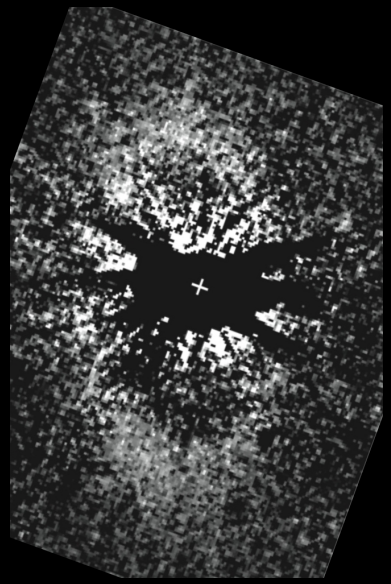
Ardila et al 2004



Kalas et al 2007b

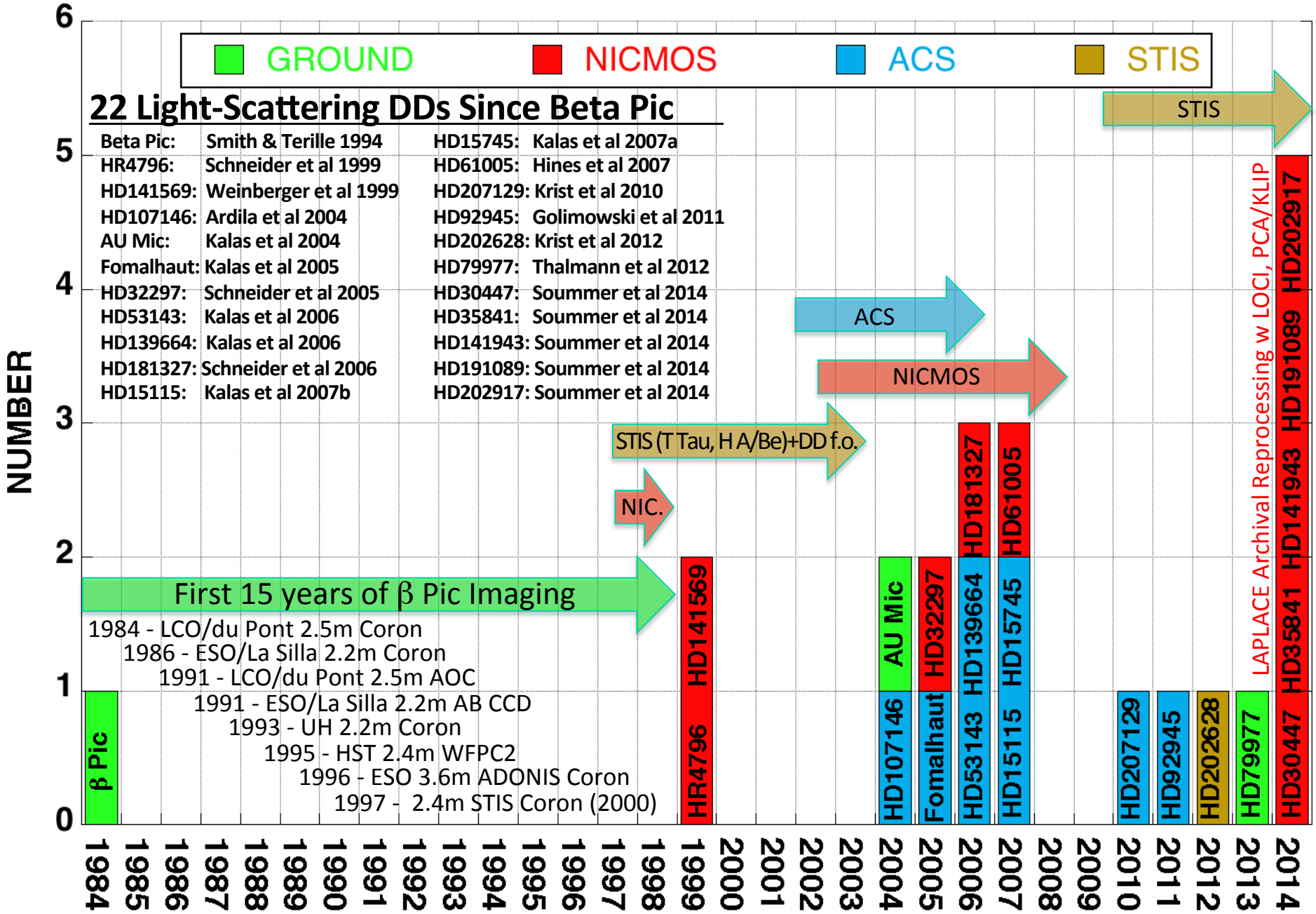
STIS

HD 202628

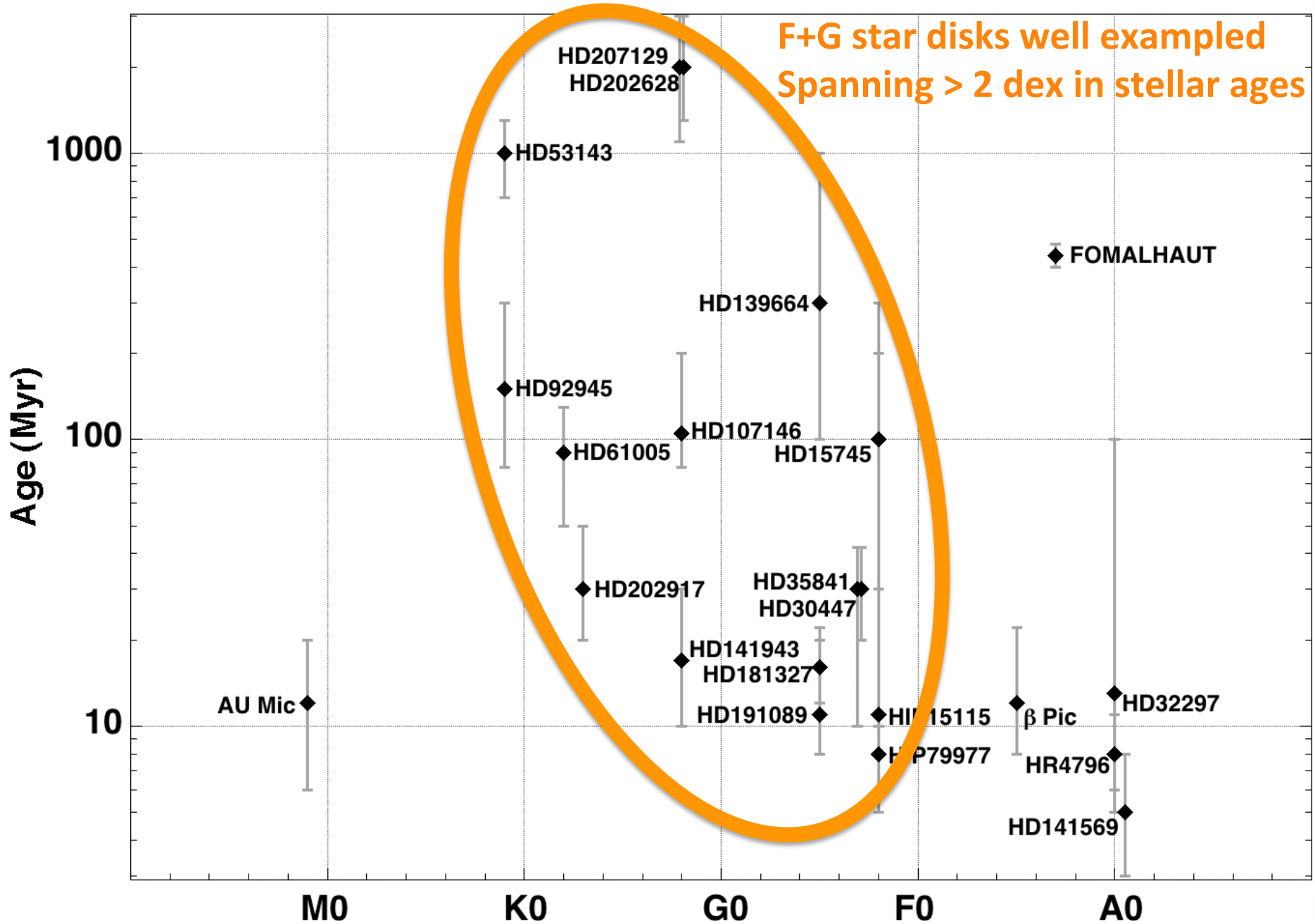


Krist et al 2012

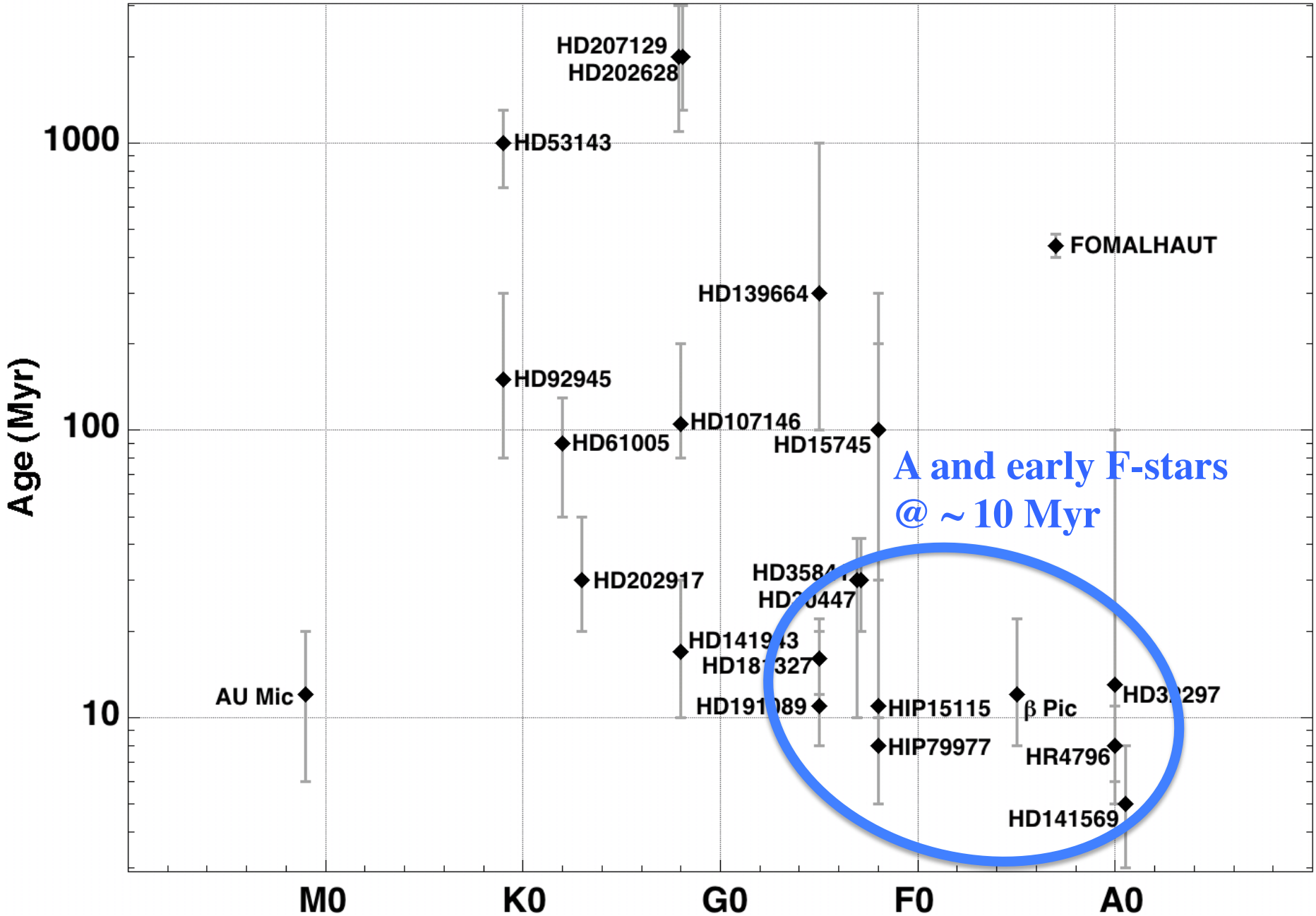
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Discovery Chronology



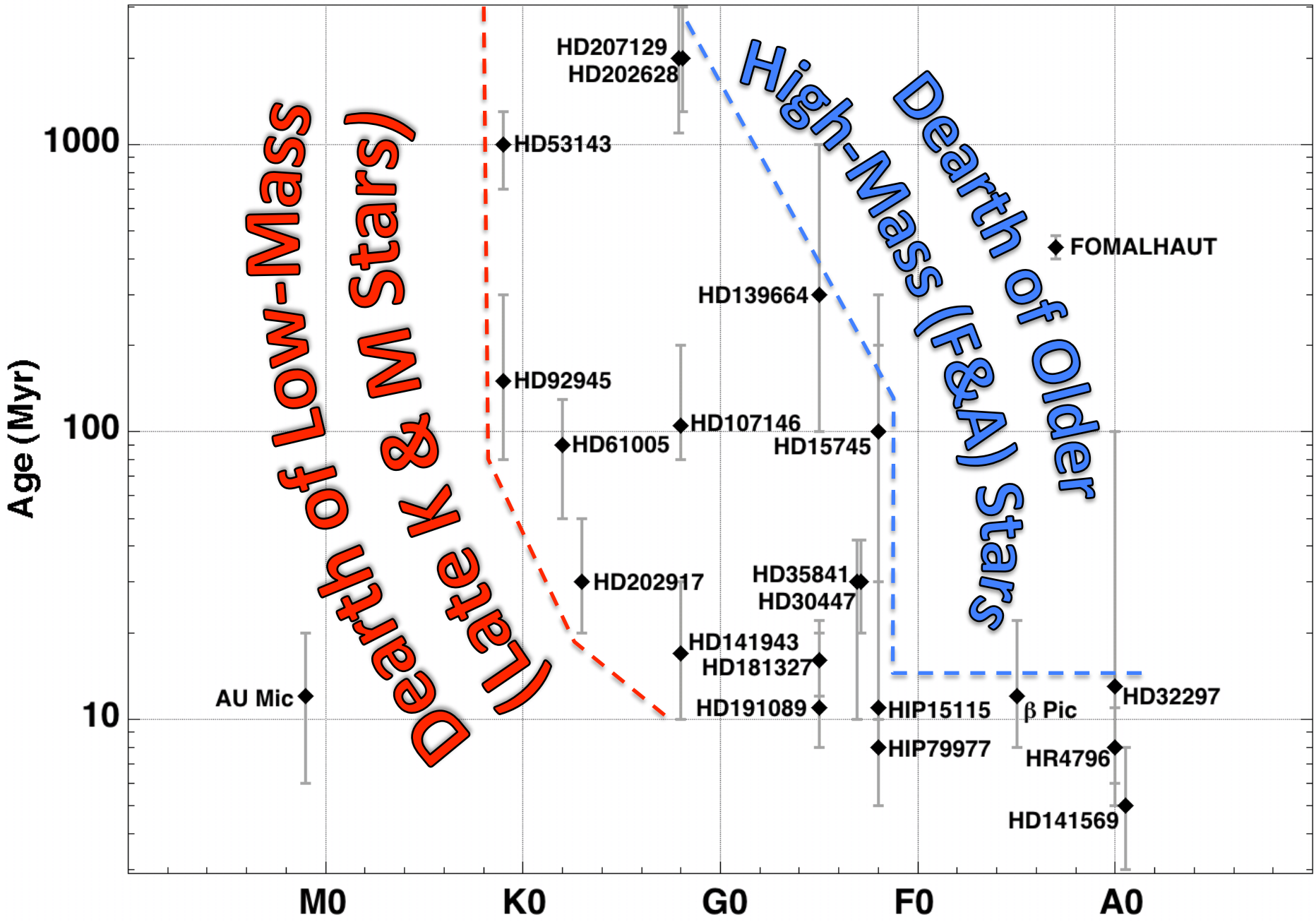
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Age vs. Spectral Type



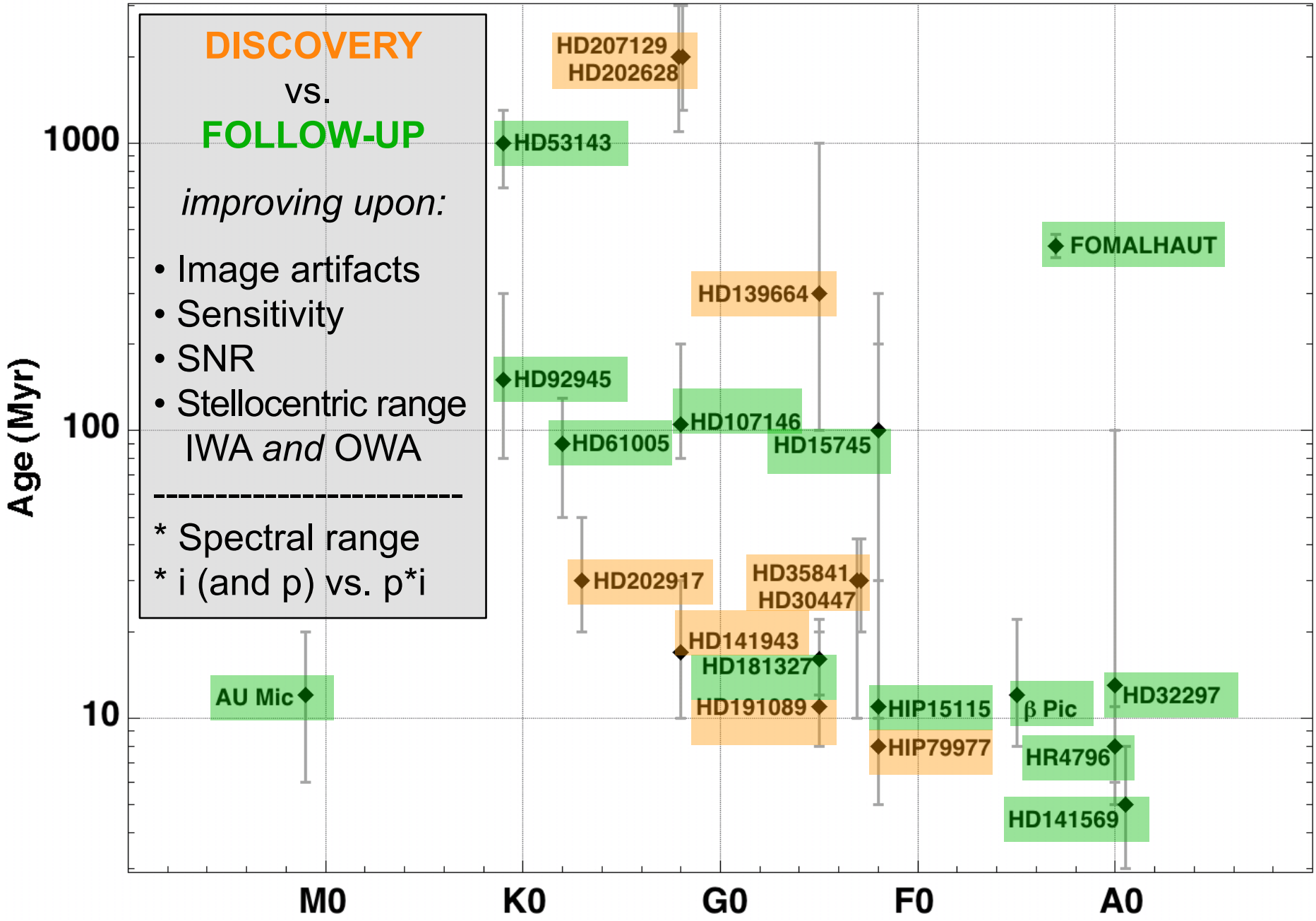
CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Age vs. Spectral Type



CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Age vs. Spectral Type

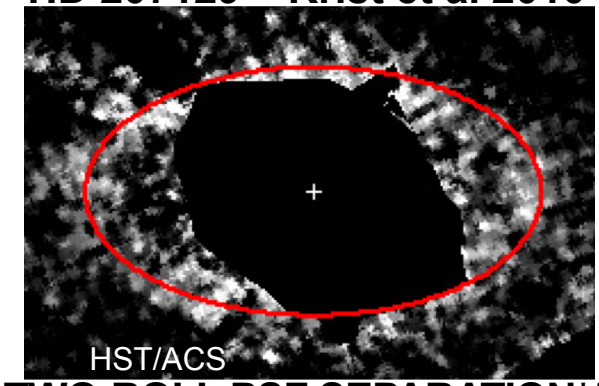


CURRENT CENSUS OF STARLIGHT-SCATTERING DEBRIS DISKS: Imaging Data

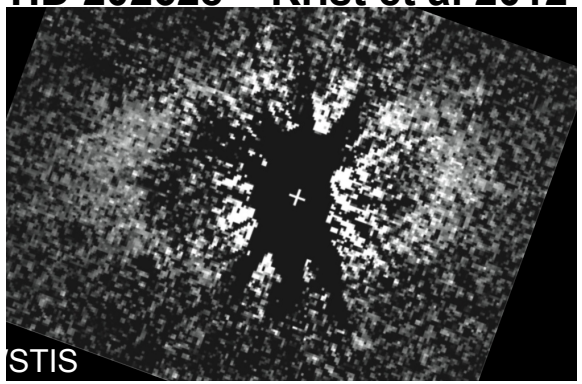


STARLIGHT-SCATTERING DEBRIS DISKS: (yet unimproved) Discovery Imaging

HD 207129 Krist et al 2010



HD 202628 Krist et al 2012

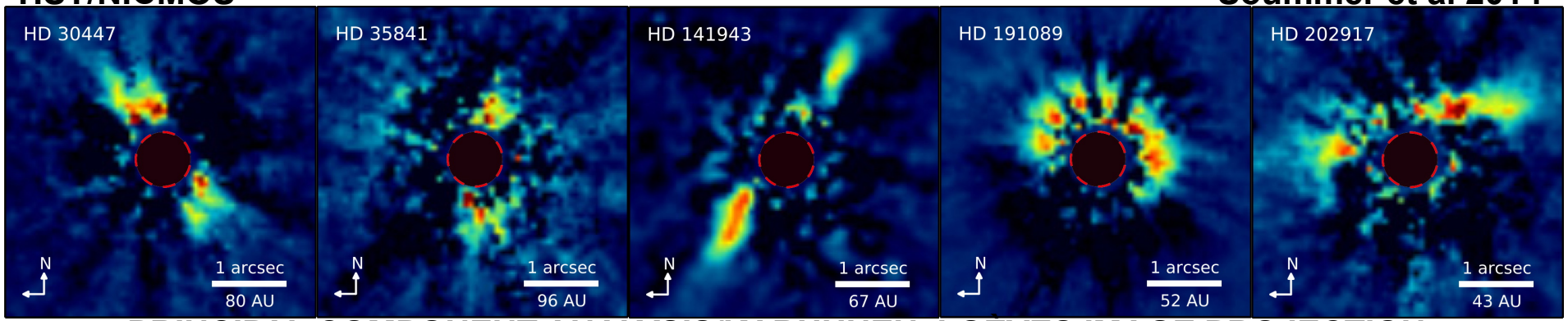


TWO-ROLL PSF SEPARATION*/"SELF-SUBTRACTION" (*Heap et al 2000)

HD 79977 Thalmann et al 2012

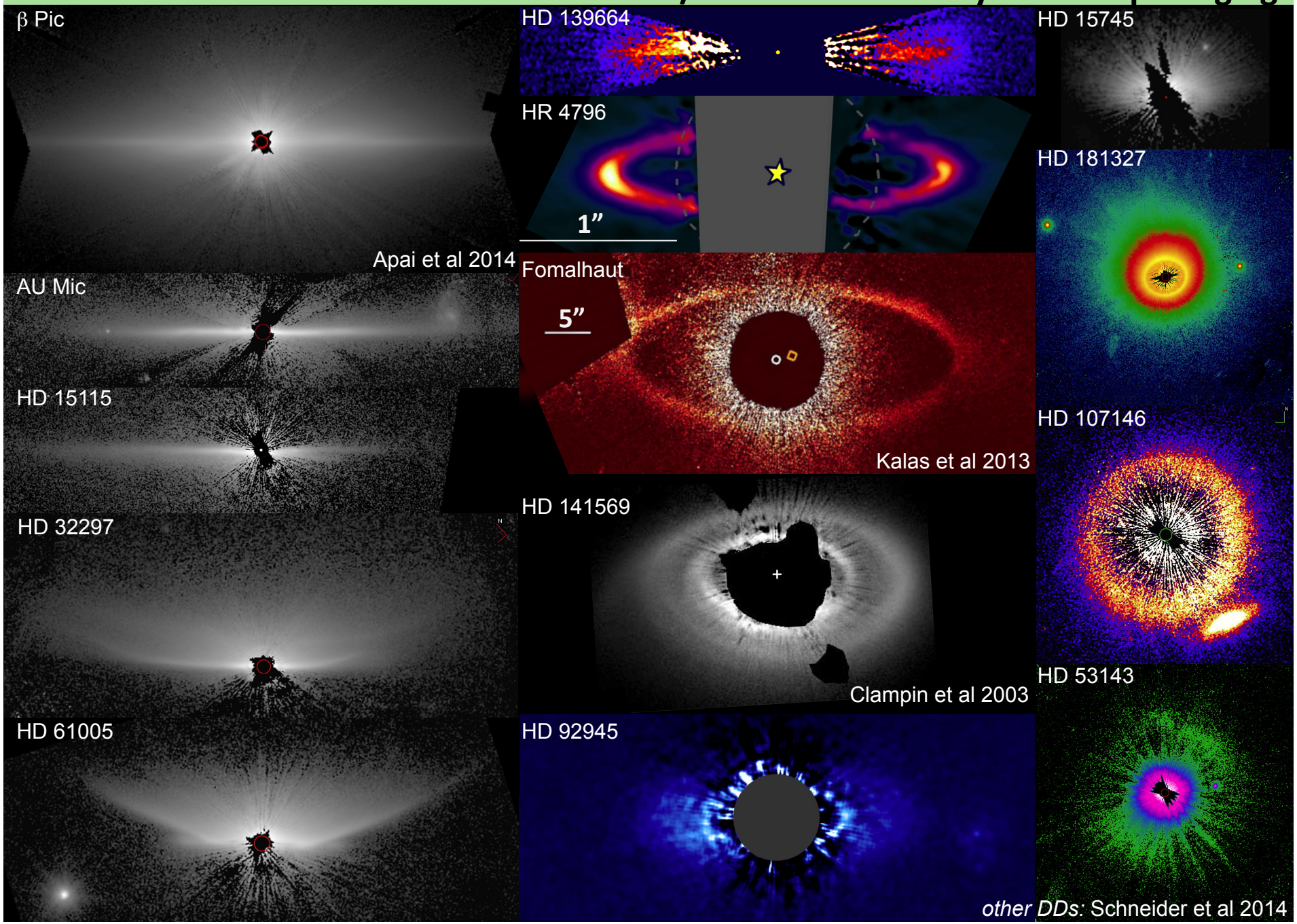
LOCALLY OPTIMIZED COMBINATION OF IMAGES

HST/NICMOS **Soummer et al 2014**



PRINCIPAL COMPONENT ANALYSIS/KARHUNEN–LOEVES IMAGE PROJECTION:
Soummer et al 2012. Using: (NICMOS) LEGACY ARCHIVE PSF LIBRARY – Schneider et al 2011

STARLIGHT-SCATTERING DEBRIS DISKS: HST/STIS Post-Discovery Follow-up Imaging



A WHIRLWIND REVIEW

THROUGH THE MENAGERIE

OF HIGH-FIDELITY

SCATTERED-LIGHT IMAGES OF

"OTHER"

CIRCUMSTELLAR DEBRIS SYSTEMS

HR 4796

Fomalhaut

AU Mic

HD 61005

HD 32297

HD 15115

HD 181327

HD 107146

HD 53154

HD 92945

HD 139664

HR 4796A – 1st DD Imaged Following Beta Pic

- 8 ± 3 Myr (Stauffer 1995), A0V ("Vega-like") star
- TW Hya Association member (Webb et al 1999), d = 72.8 ± 1.7 pc
- Large amount of CS dust inferred from IRAS excess:
  - $L_{disk}/L_* = 5 \times 10^{-3}$ (Jura 1991), ***TWICE that of β Pictoris***.
  - T_{dust} = 110K → lack of material @ r < 40AU, and to be bound at r ≥ 40 AU → > 3 μm grains (Jura 1995)
- Mid-IR imaging (Koerner et al 1998; Jayawardhana et al 1998) suggested inner depleted region.

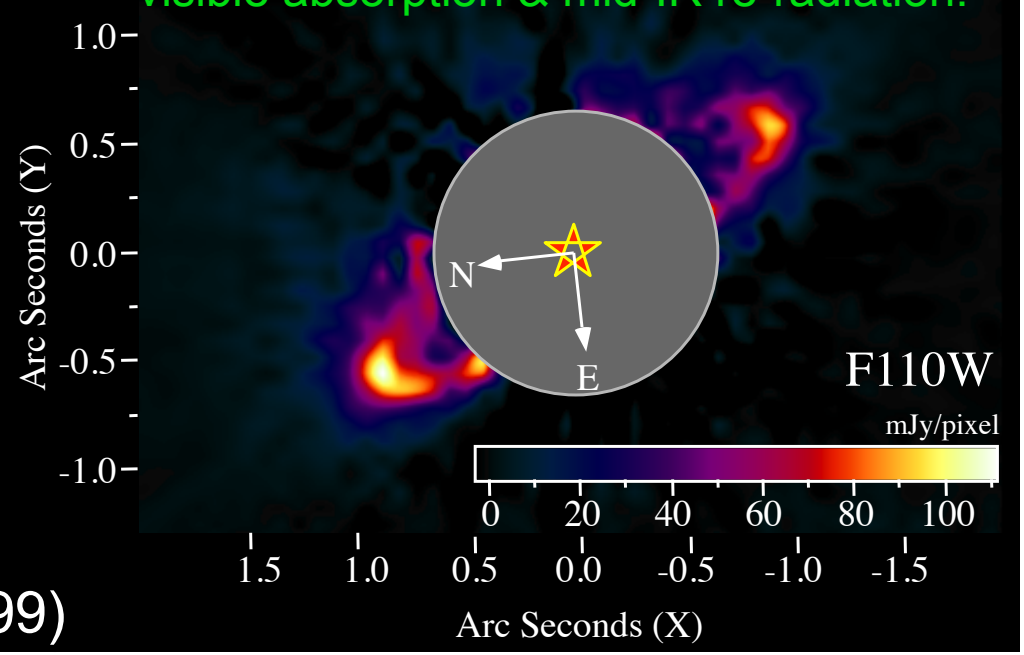
HST/NICMOS Reveals a "Compact" Ring-Like Disk

GEOMETRY/MORPHOLOGY

```
PA = 26.8
i  = 73.1  (PA = 26.8°)
r  = 1.05" (~76.4 AU)
Ring width < 14 AU
  "abrupt" truncation
  "clear" @ r < 50 AU
```

Schneider et al. ApJL 513 127 (1999)

NIR scattered flux in good agreement with visible absorption & mid-IR re-radiation.

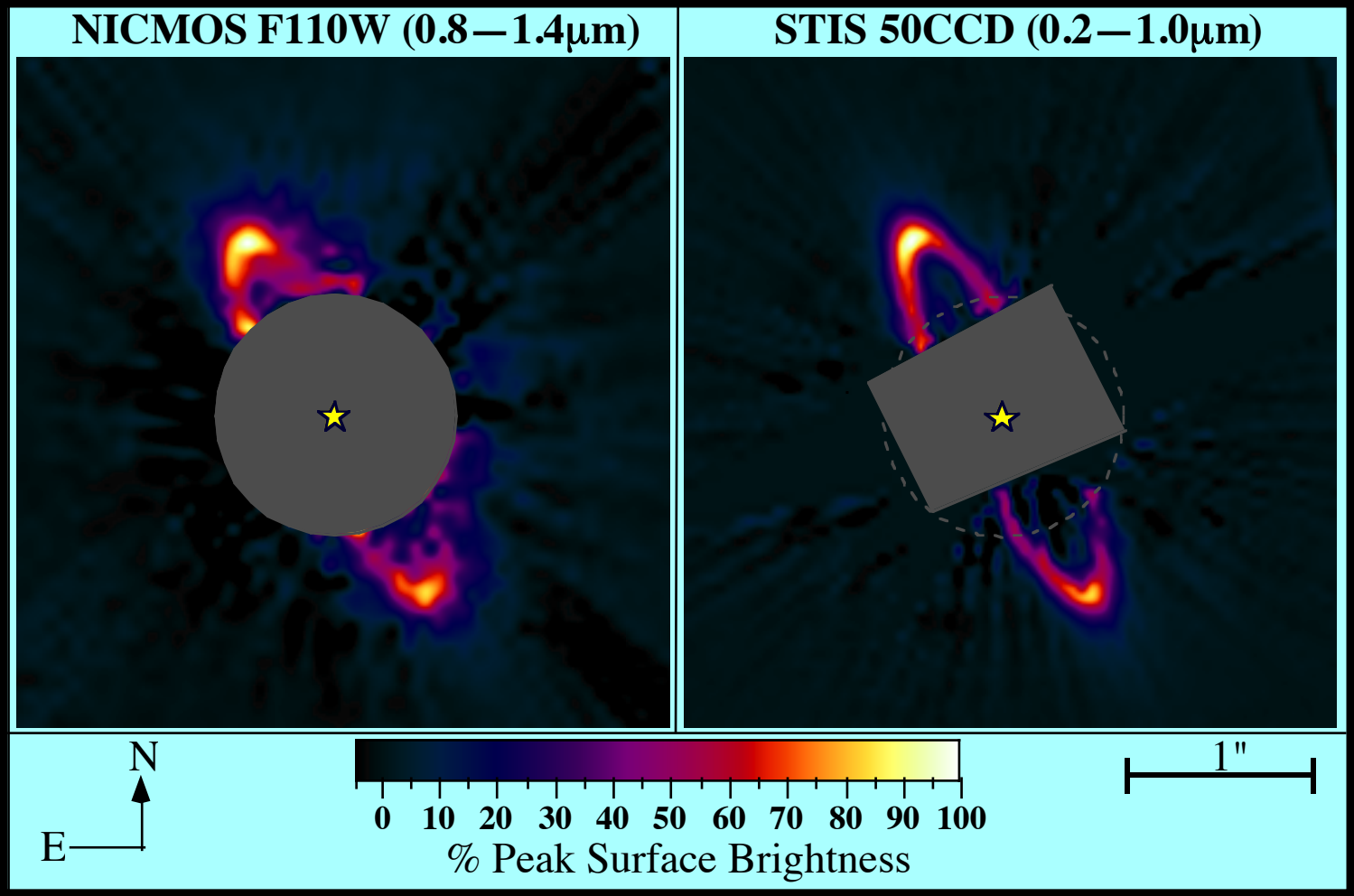


HR 4796A – Post-Discovery Imaging Follow-Ups

- HST/STIS (Broadband Optical High-Resolution Imaging)
  Schneider et al. ApJL 513 127 (1999)
  "STIS imaging of the HR 4796A Circumstellar Debris Ring"
- HST/NICMOS (Multiband Diagnostic Photometry)
  Debes et al. ApJL 673 191 (2008)
  "Complex Organic Materials in the Circumstellar Disk of HR 4796A"
- Subaru/HiCIAO (AO188/H-band; ADI + LOCI)
  Thalmann et al. ApJL 743 6 (2011)
  "The Extended Outer Regions of the Debris Ring Around HR 4796A"
- VLT/NaCO (L'-band; ADI & Sparse Aperture Masking)
  Lagrange et al. A&A 546 A38 (2012)
  "An Insight into the Surroundings of HR 4796"
- Gemini/GPI (K-band Integral Field Polarimetry; p*i and ADI/KLIP i)
  Perrin et al. ApJ, in press (2014)
  "Polarimetry with the Gemini Planet Imager: Methods, Performance at 1st Light, and the Circumstellar Ring around HR 4796A"
- Gemini/NICI (JHKs + CH4L/S 4% wide filters @ 1.6μm)
  Wahhaj et al. A&A 567 A34 (2014)
  "The Gemini NICI planet-finding campaign: The offset ring of HR 4796A"

HR 4796A – STIS High-Resolution Optical Imaging

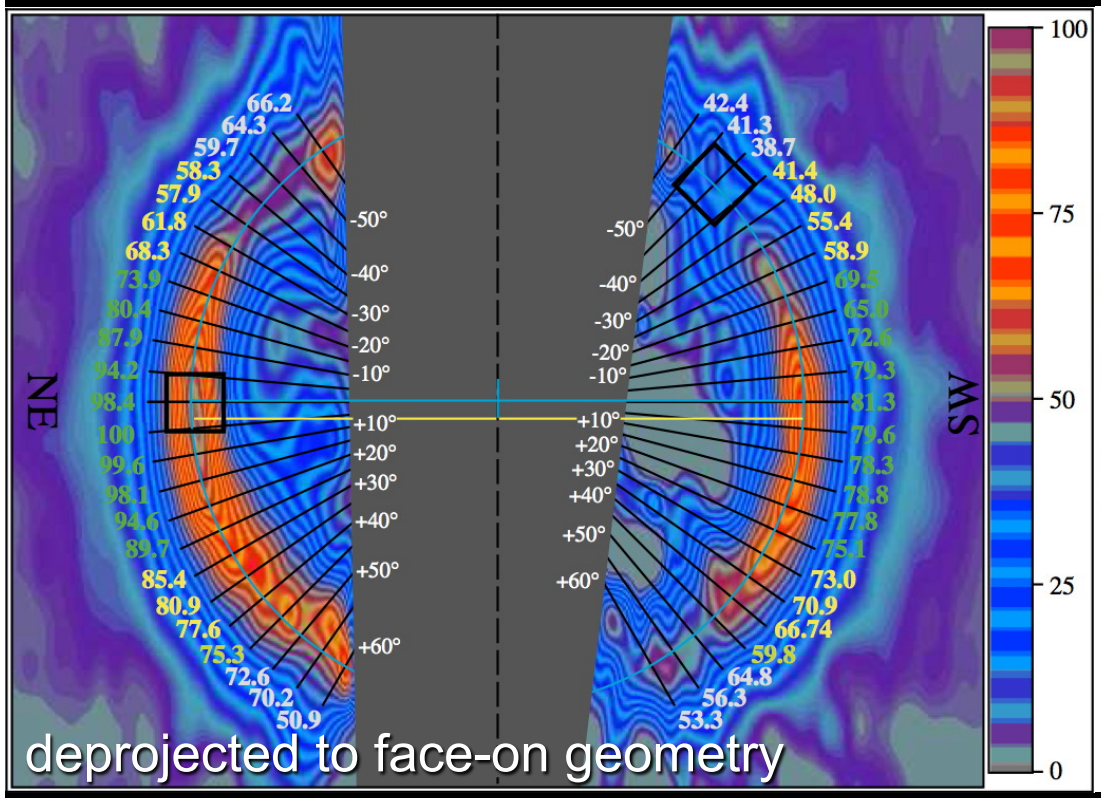
- Improved upon nIR Discovery Imaging Fidelity
- Better Enabled Dynamical Interpretation of Debris Structure
- Provided Optical Dust Scattering Efficiency (vis-nIR colors)

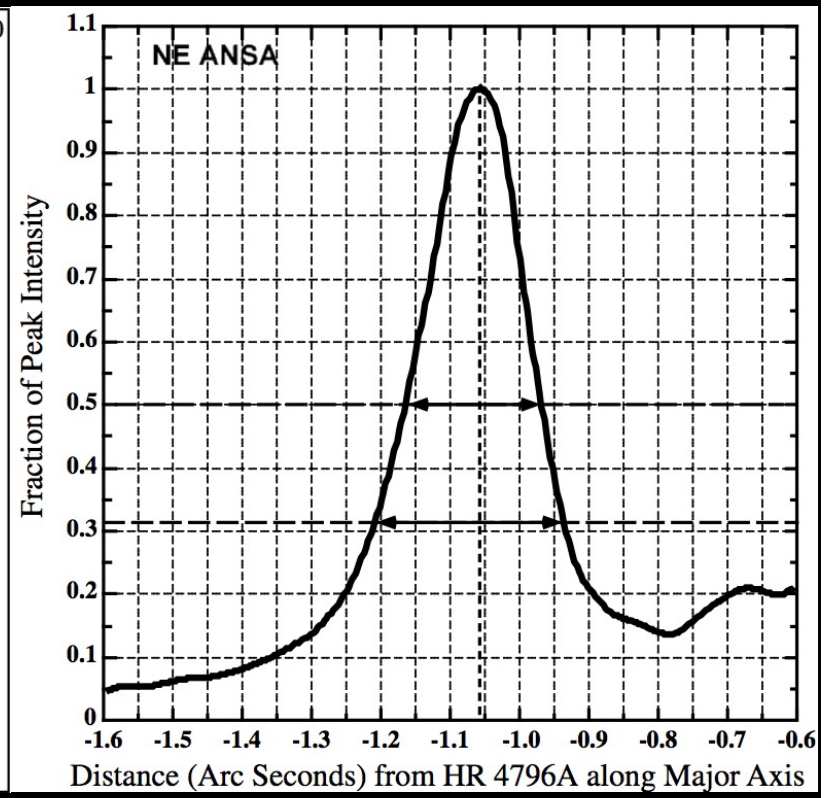


Schneider et al. ApJ 137 53 (2009)

HR 4796A – Debris Ring Dynamics

Radial SB profile of ring (sharp inner and outer slopes) consistent with dynamical confinement of debris by yet unseen co-orbiting planet-mass companion(s).





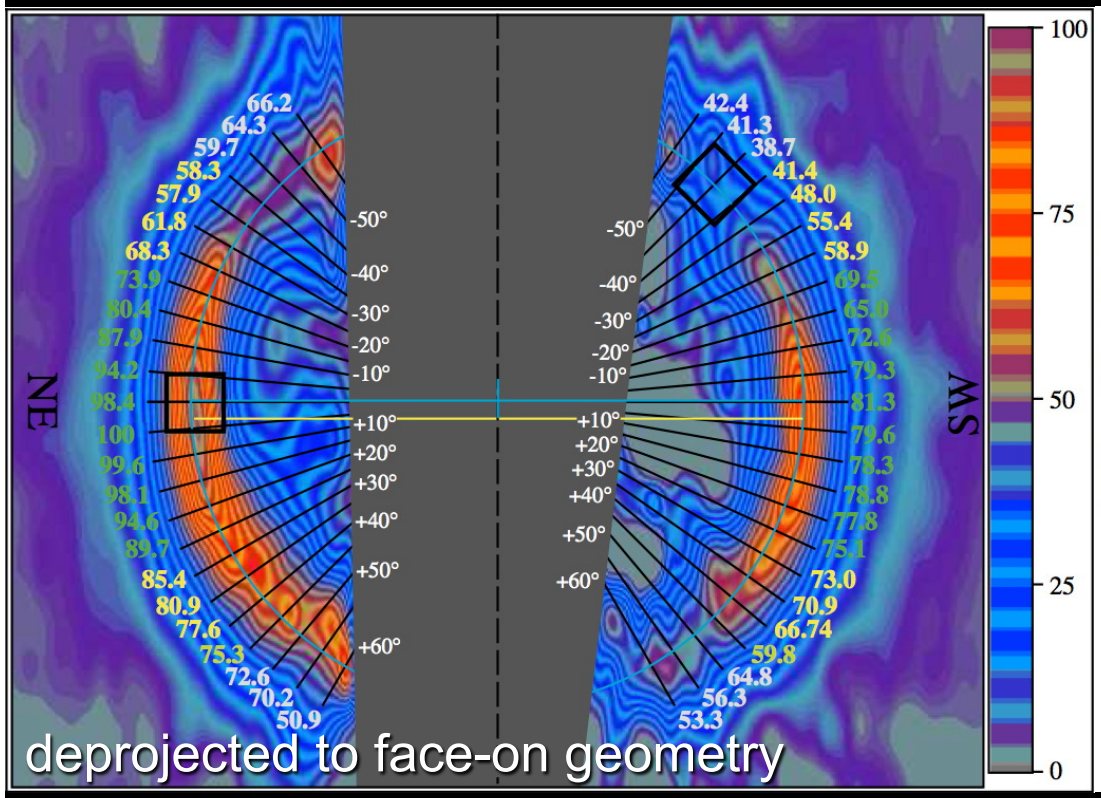
Analogous to Shepherding in Saturnian Ring System?

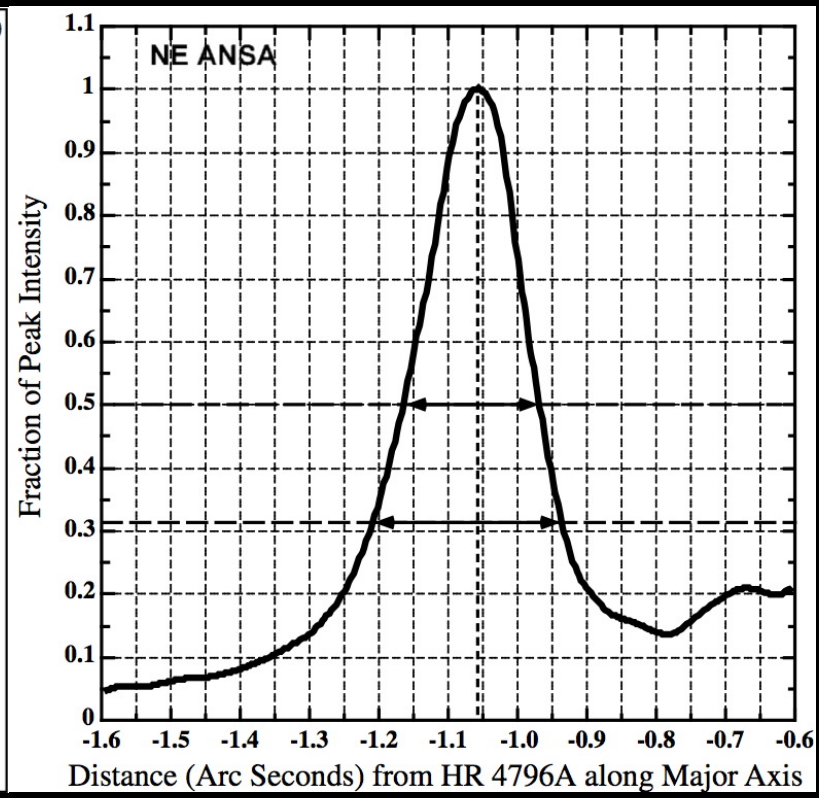
→ but, see Lagrange et al. A&A 546 A38 (2012)

vis-à-vis uncertainty regarding an outer planet, with M-star companion @ 560 AU

HR 4796A – Debris Ring Dynamics

Radial SB profile of ring (sharp inner and outer slopes) consistent with dynamical confinement of debris by yet unseen co-orbiting planet-mass companion(s).



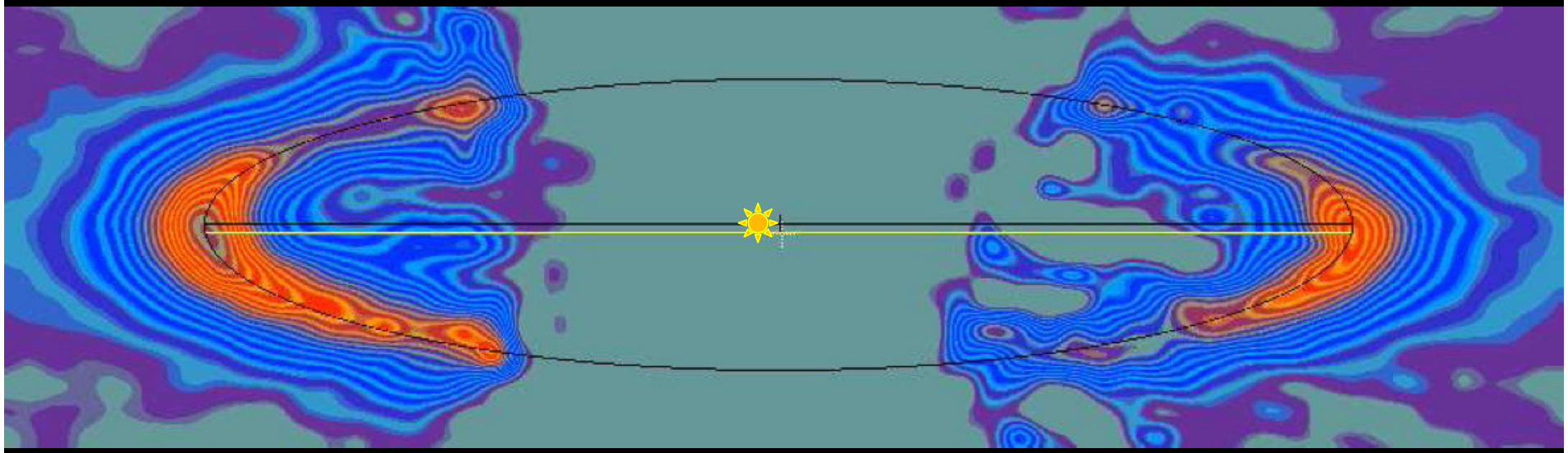


HR 4796A: Sharp outer fall-off, SB(r) ~ r^{-8}
Beta Pic: Smooth SB(r) ~ $r^{-3.6}$

see: Thebault & Wu (2008)
"Outer Edges of Debris Disks"
(development & longevity)

HR 4796A – Debris Ring Dynamics

- Center of Ring Offset from Position of Star by 1.4 ± 0.4 AU



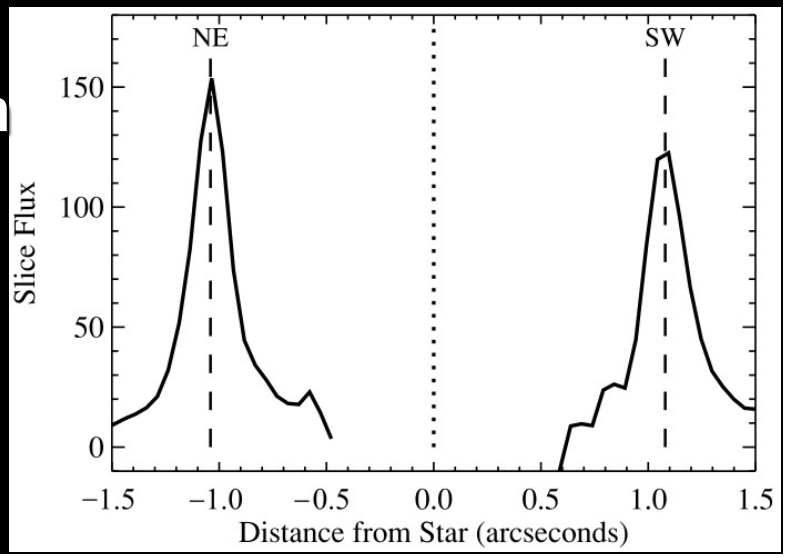
- Ansal Brightness Asymmetry ~ 2x > 1/r^2 Differential

Cause (?):

- Inhomogeneous grain population
- Non-uniform spatial destruction of homogeneous population

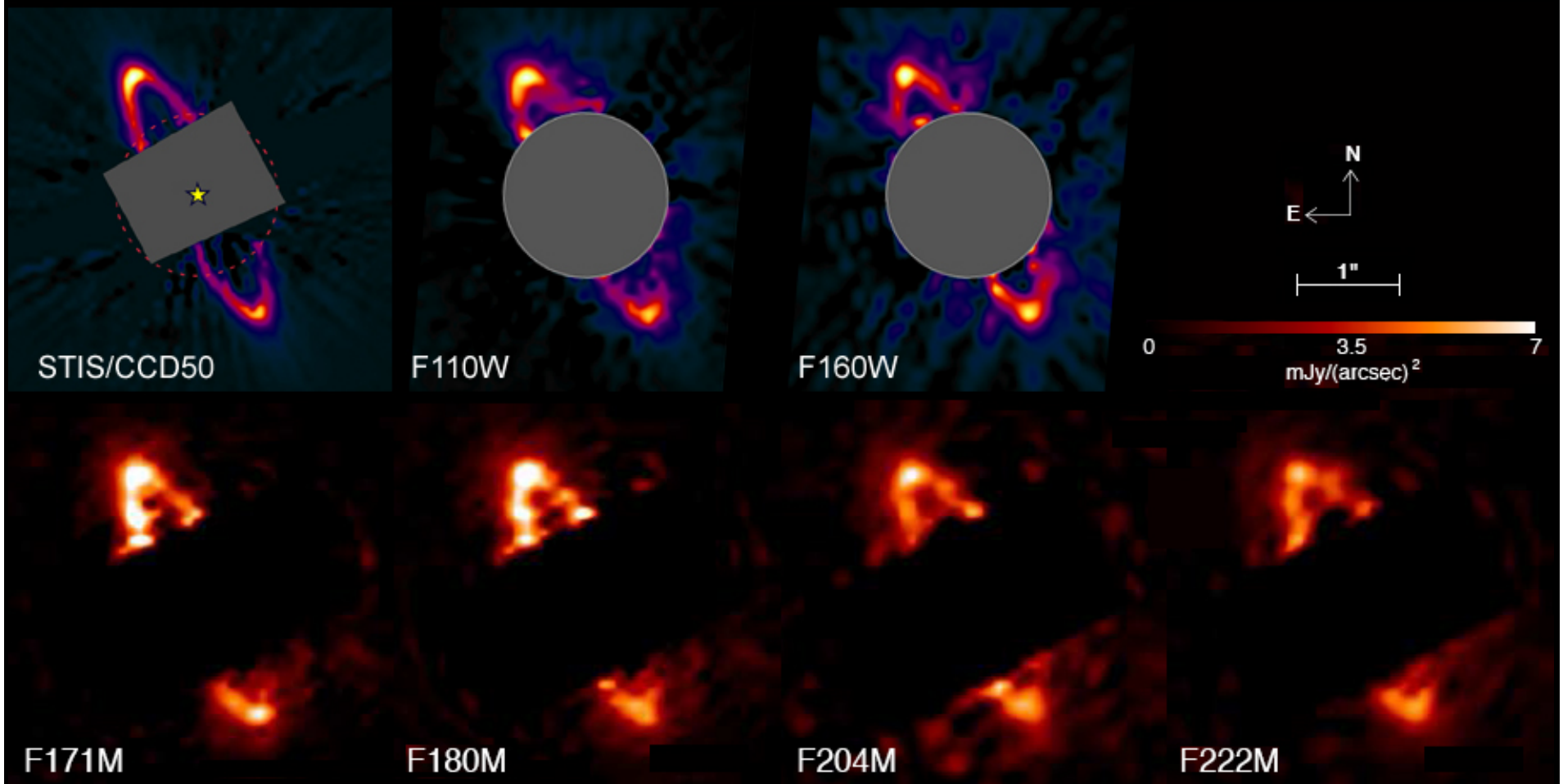
T_{orbit} = 350 yr, Age ~ 8 Myr

"expectation" → well-mixed azimuthally, if not perturbed



HR 4796A – Optical + nIR Colors Constrain Composition
(scattering efficiency and phase angle dependency with λ)

Debes et al. ApJL 673 191 (2008)



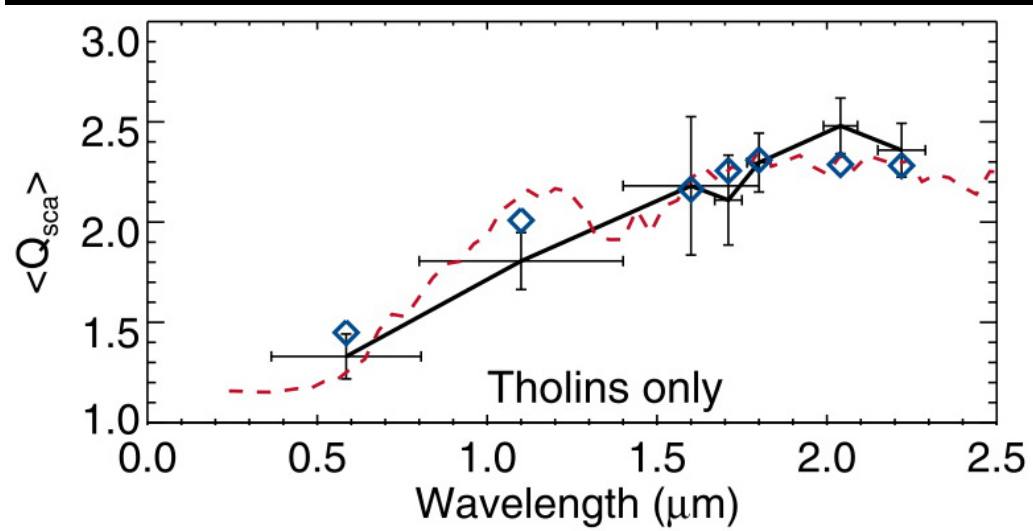
STIS (Optical) + NICMOS (nIR filter-band) Imaging Photometry

HR 4796A – Optical + nIR Colors Constrain Composition (scattering efficiency and phase angle dependency with λ)

Debes et al. ApJL 673 191 (2008)

Filter	Scaling[a]	Flux Density (mJy)	Total Disk Flux Density (mJy)	NE : SW Ratio	g
STIS 50CCD	0.705	5.5 ± 0.2	9.4 ± 0.8	0.74 ± 0.07	0.16 ± 0.06
F110W	0.78 ± 0.03	5.2 ± 0.3	8.1 ± 0.6	0.9 ± 0.08	0.06 ± 0.07
F160W	...[b]	3.7 ± 0.5	5.7 ± 0.9	1.0 ± 0.1	0.0 ± 0.06
F171M	0.819 ± 0.007	2.8 ± 0.1	4.8 ± 0.5	0.62 ± 0.08	0.3 ± 0.1
F180M	0.79 ± 0.01	2.9 ± 0.1	4.7 ± 0.3	0.71 ± 0.07	0.2 ± 0.1
F204M	0.79 ± 0.02	2.5 ± 0.1	4.2 ± 0.2	1.02 ± 0.09	0.2 ± 0.1
F222M	0.79 ± 0.03	2.1 ± 0.1	3.5 ± 0.2	1.0 ± 0.1	0.1 ± 0.1

Best fit suggestive of radiationally evolved complex organic polymers;



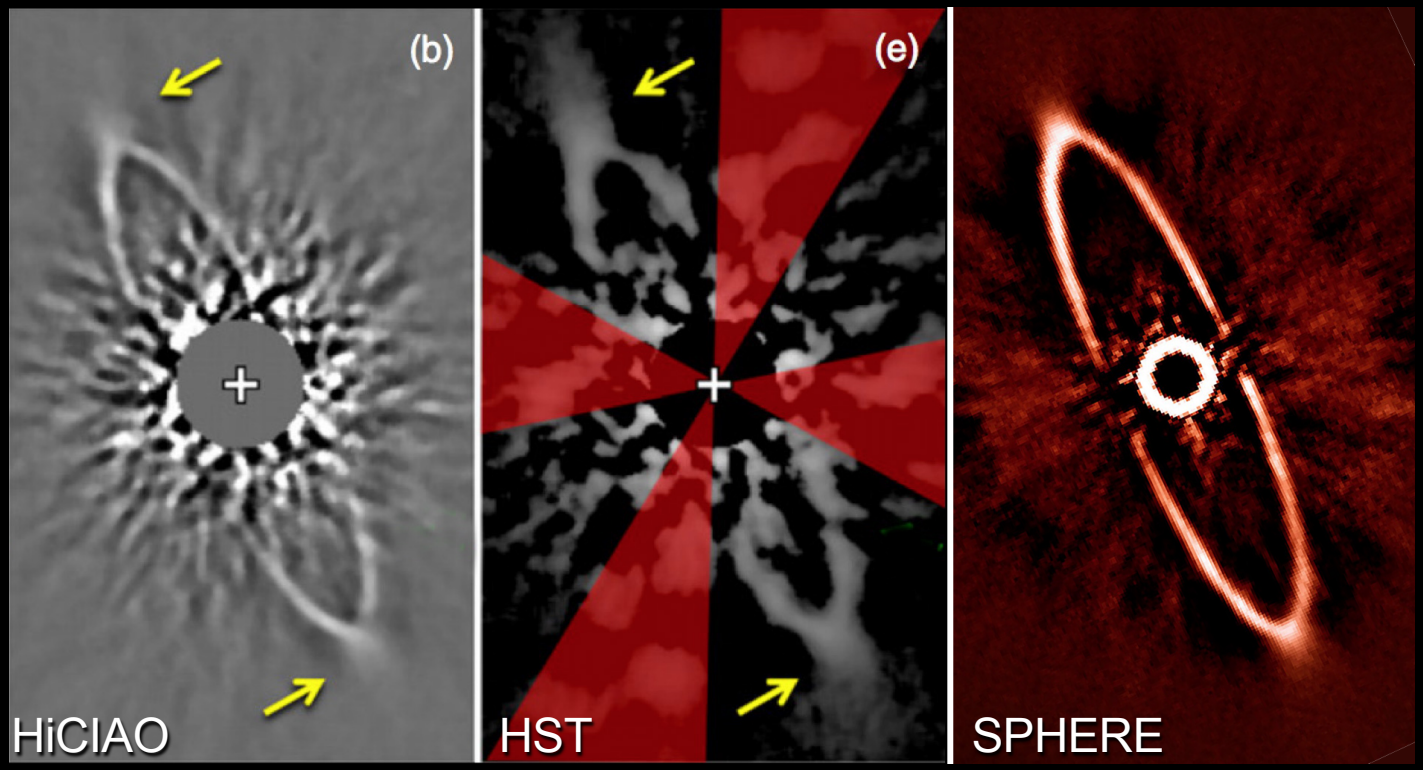
i.e., tholins, as found on the small icy bodies in our own solar system (e.g., 5145 Pholus) and in the atmosphere of Titan.

HR 4796A – Other Debris System (sub)-Structures?

Thalmann et al. ApJL 743 6 (2011)

"Streamers": exo-ring material detected beyond the ansae.

Seen also in HD 61005 ground-based ADI processing by Buenzli et al A&A 524 (2010).
Questioned by Milli et al A&A 545 A111 (2012) potential w.r.t. ADI artifacts.

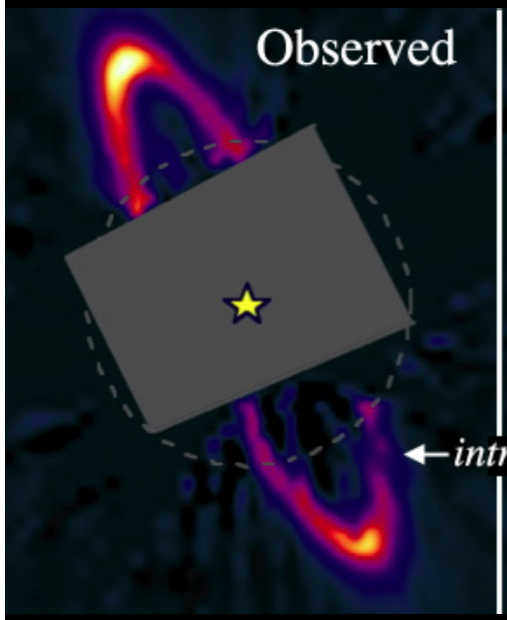


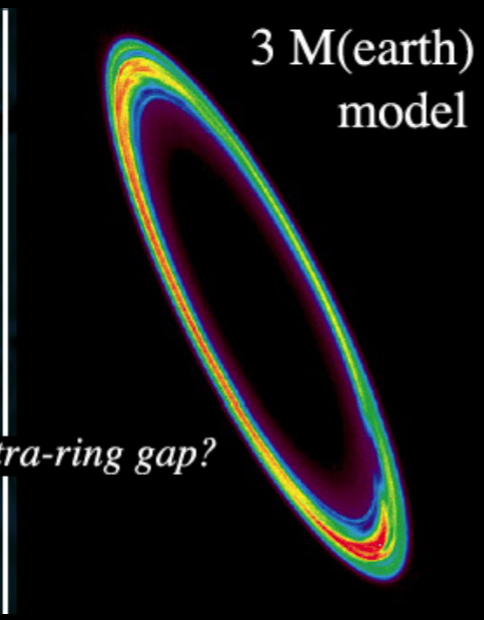
Left: Subaru/HiCIAO, H-band, 2600 s, ADI: 260 rots over 23°, LOCI: 10000 with footprints
Middle: HST/STIS, Vis. Broadband, 260s, PSF-template subtraction, 2 rots 18° combined
Right: VLT/SPHERE (ESO PR # 1417; H-band/ADI+PCA) – *see talk by Mouillet Wed. Noon*

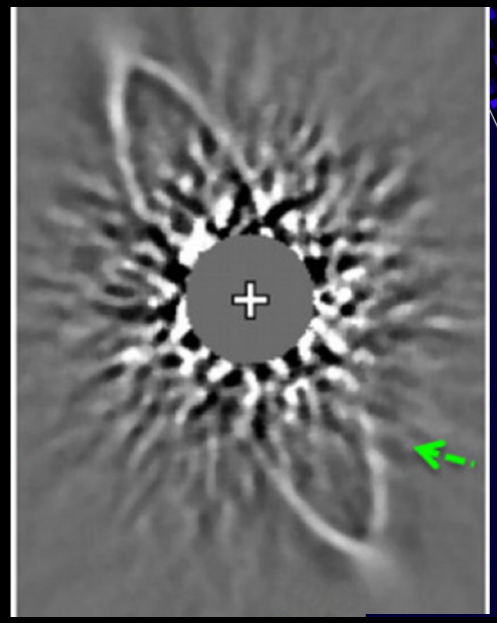
HR 4796A – Other Debris System (sub)-Structures?

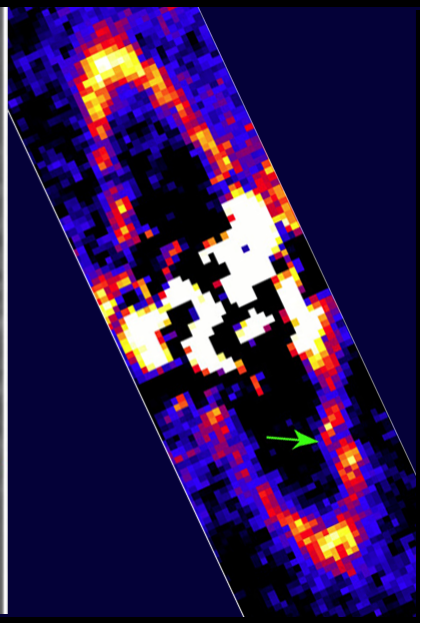
Intra-Ring "Gap"? – artifact or further evidence of a co-orbiting planet?

"…this feature could be due to noise. However, it seems to be at the same position as that pointed by Thalmann et al. (2011) in their data as well as Schneider et al. (2009) data as well as, in L'-data obtained at Keck by Marois & McIntosh (priv. comm.)" – Legrange et al 2012 (pA39)









HST/STIS
Vis. Broadband
216 s
PSF-subtraction
2 rots combined
Schneider et al 2009

Unpub. Model
by C. Stark
Following Stark
& Kuchner ApJ
707 543 (2009)

Subaru/HiCIAO
H-band 2600 s
ADI: 260 rots
23°
LOCI: 10000 ftpt.
Thalmann et al. 2011

VLT/NaCo
L'-band 2600 s
SAM+ADI
Lagrange et al.
A&A 546 A38 (2012)

HR 4796A – Polarized Light (GPI)

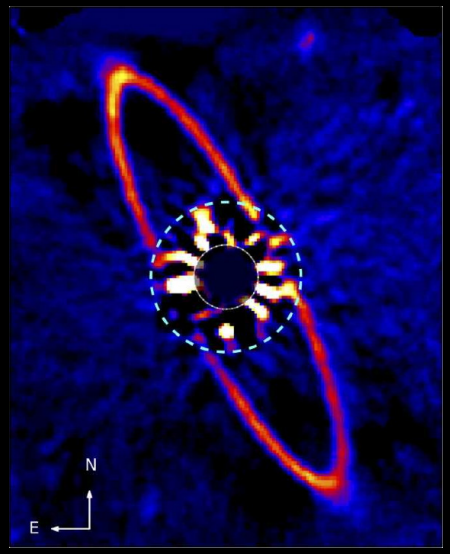
Perrin et al 2014 ApJ, in press

See talk by Kalas Wed. 10:30 AM

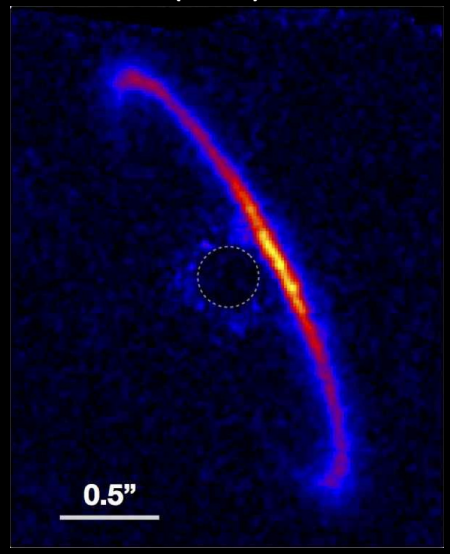
GREAT PERFORMANCE…

GPI (K band) – 12 orientations x 60 s

TOTAL LIGHT
ADI+KLIP PSF-subtraction

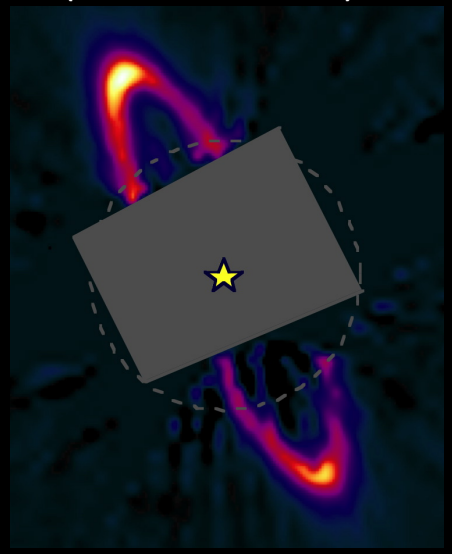


POLARIZED LIGHT
(P x I)



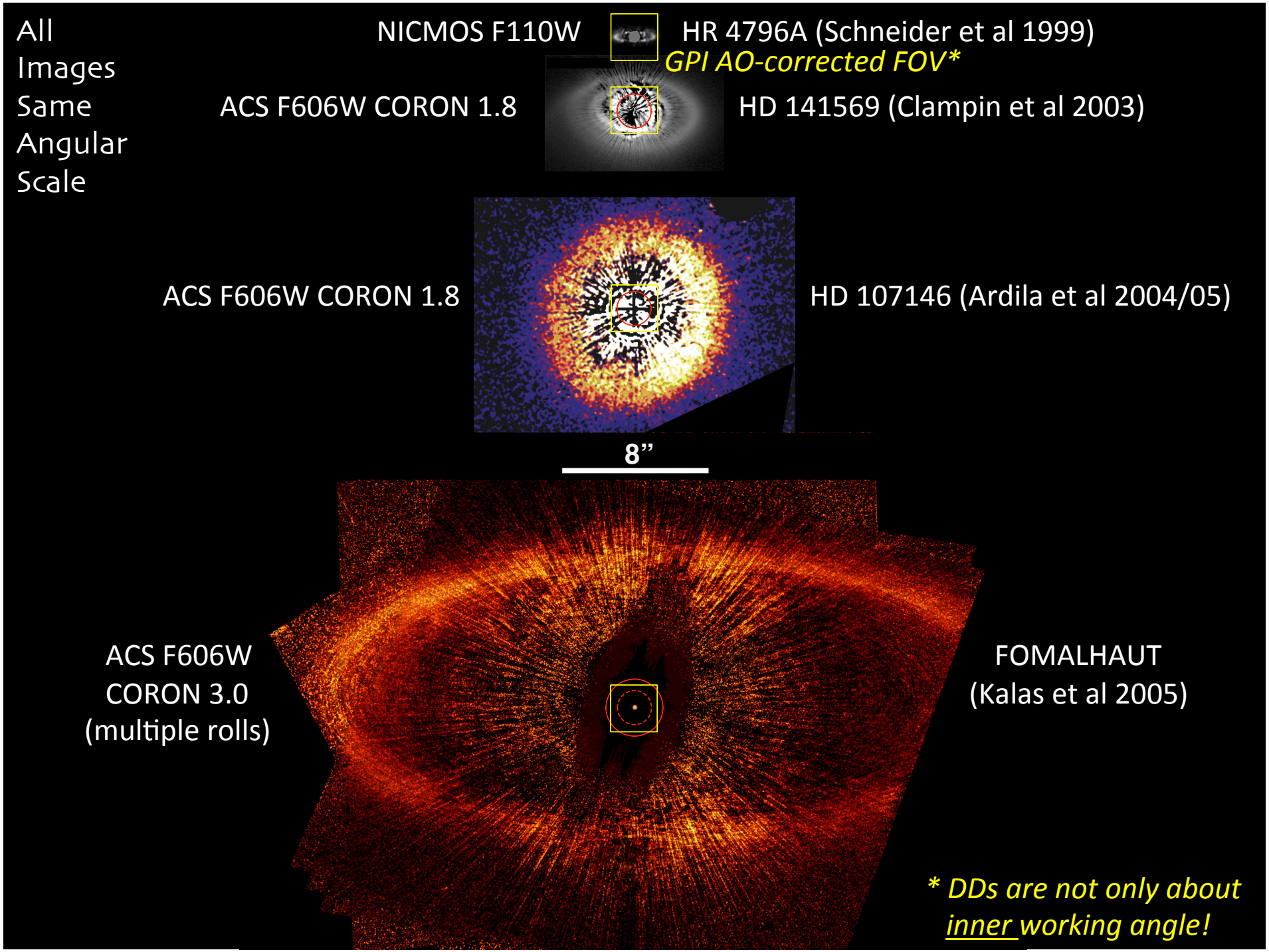
STIS – 2 orients x 108s

TOTAL LIGHT
(PSF Subtraction)



PUZZLING RESULTS!

(1) Relatively isotropic TOTAL intensity phase function
→ small particle Rayleigh scattering. BUT:
(2) Counter-indicated by p*I not peaking at the ring ansae
(3) VERY strong (> 9x) minor-axis opposed w. side brighter p*i asymmetry
→ speculation the disk is optically **thick** / self-shadowed on w. side

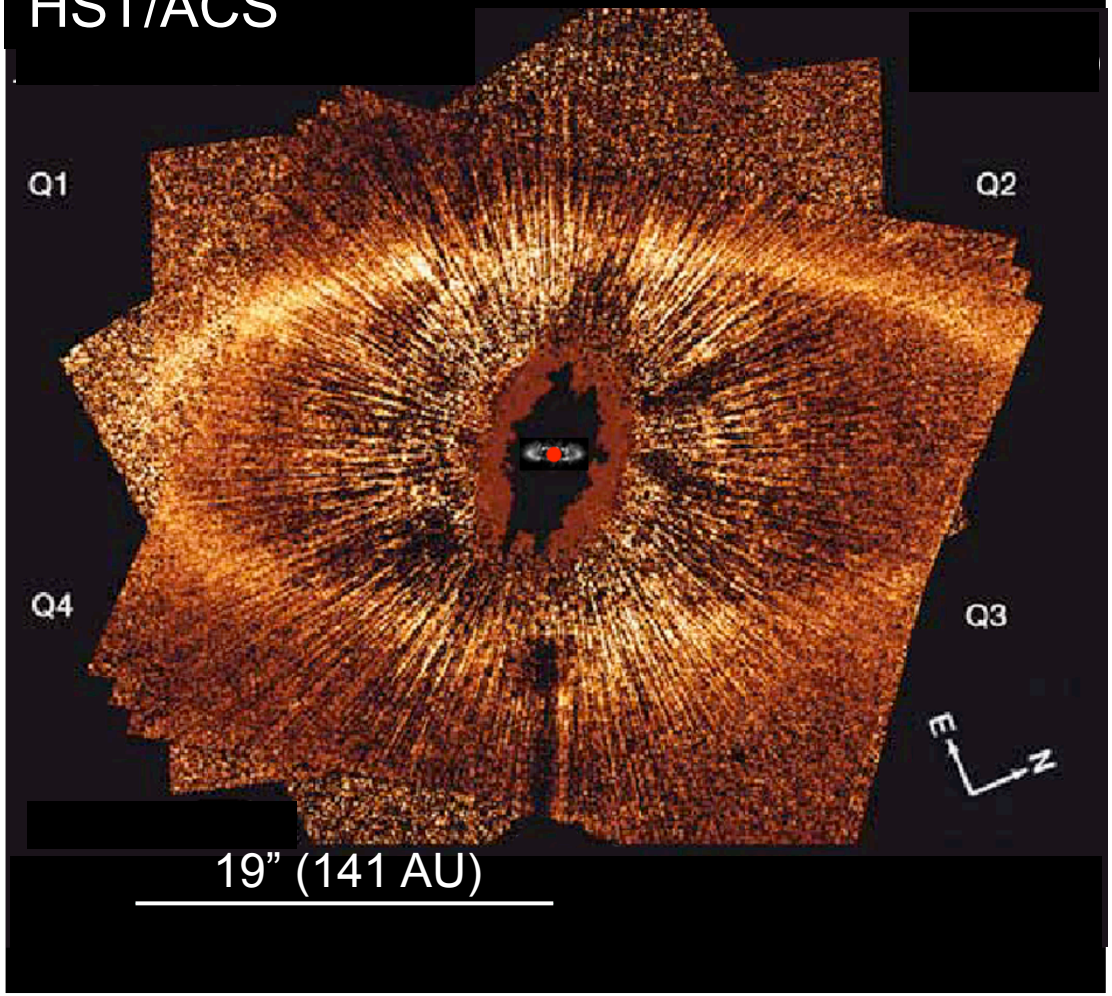

All Images Same Angular Scale
NICMOS F110W
HR 4796A (Schneider et al 1999)
GPI AO-corrected FOV*
ACS F606W CORON 1.8
HD 141569 (Clampin et al 2003)
ACS F606W CORON 1.8
HD 107146 (Ardila et al 2004/05)
8”
ACS F606W CORON 3.0 (multiple rolls)
FOMALHAUT (Kalas et al 2005)
* DDs are not only about inner working angle!

COMPARISON TO FOMALHAUT (A3V, 7.7 pc, ~ 200 Myr)

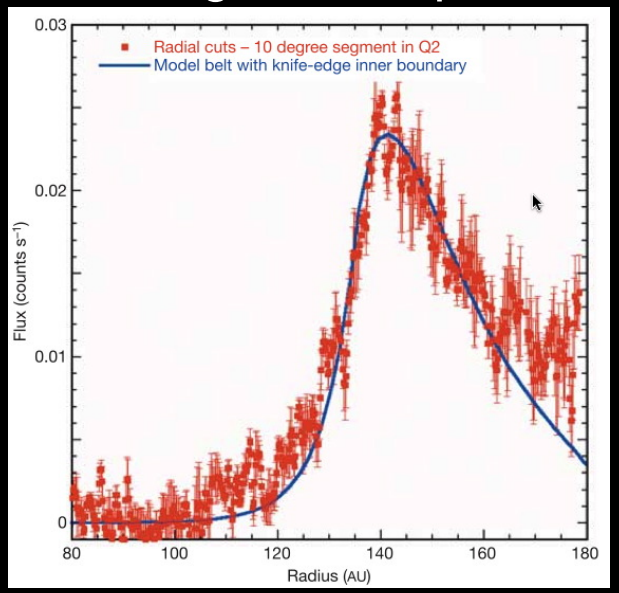
Fomalhaut is 10x closer than HR 4796, and its r = 140 AU debris ring is ~ 2x larger

Kalas et al Nature 435 1067 (2005)

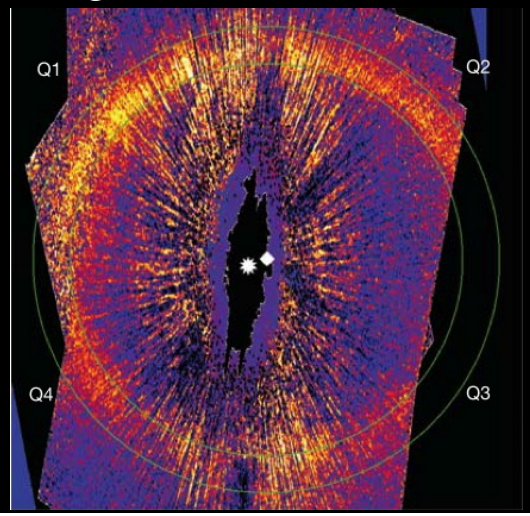
HST/ACS



with a very similar steep *inner* edge, radial profile,



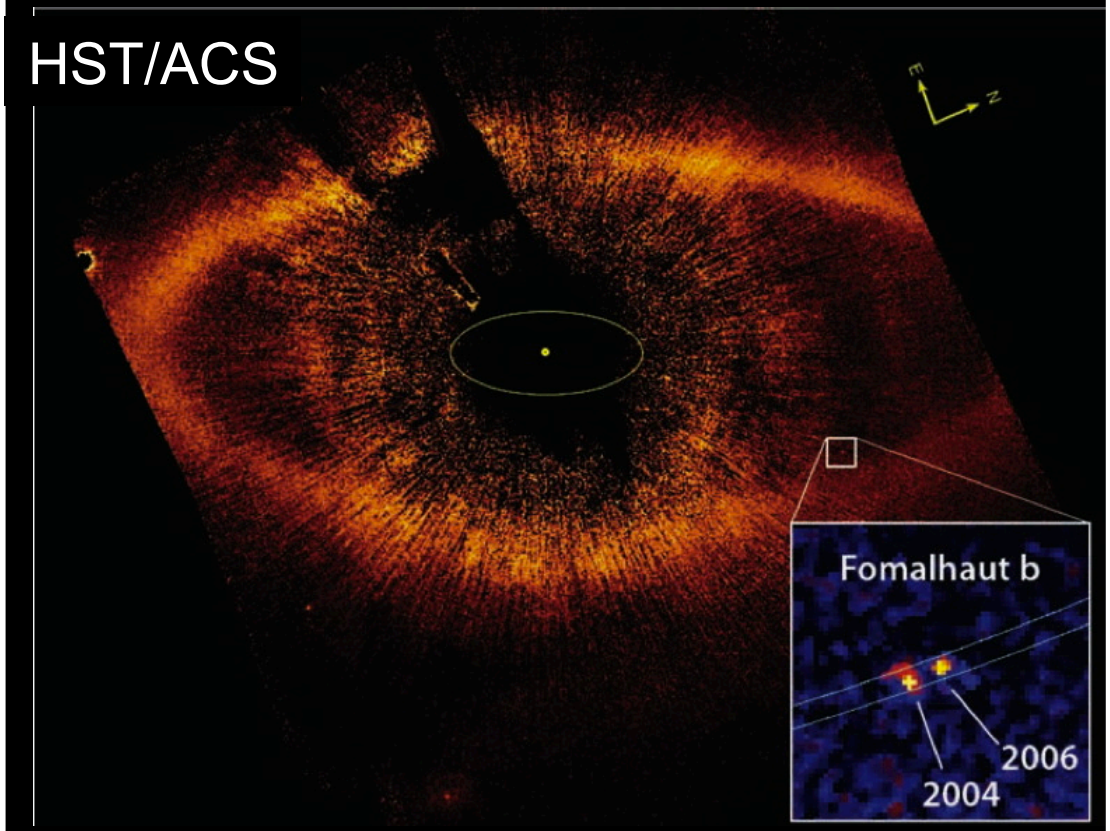
and large stellocentric offset



COMPARISON TO FOMALHAUT (A3V, 7.7 pc, ~ 200 Myr)

Only light-scattering DD other than β Pic for which a planet is directly imaged.

Structure postulated as arising from dynamical interactions with now-imaged and possibly other (additional) planet(s).



Kalas et al. Science 322 1345 (2008)

Fomalhaut b (confirmed):
Kalas et al ApJ 77 556 (2013)

Follow-up/combined 2010/2012 HST/STIS observations

Photometry (brightness)
→ Dwarf planet with dust ring?

Highly eccentric ("ring-crossing") orbit:
e = 0.8 ± 0.1
a = 177 ± 68 AU
q = 32 ± 24 AU

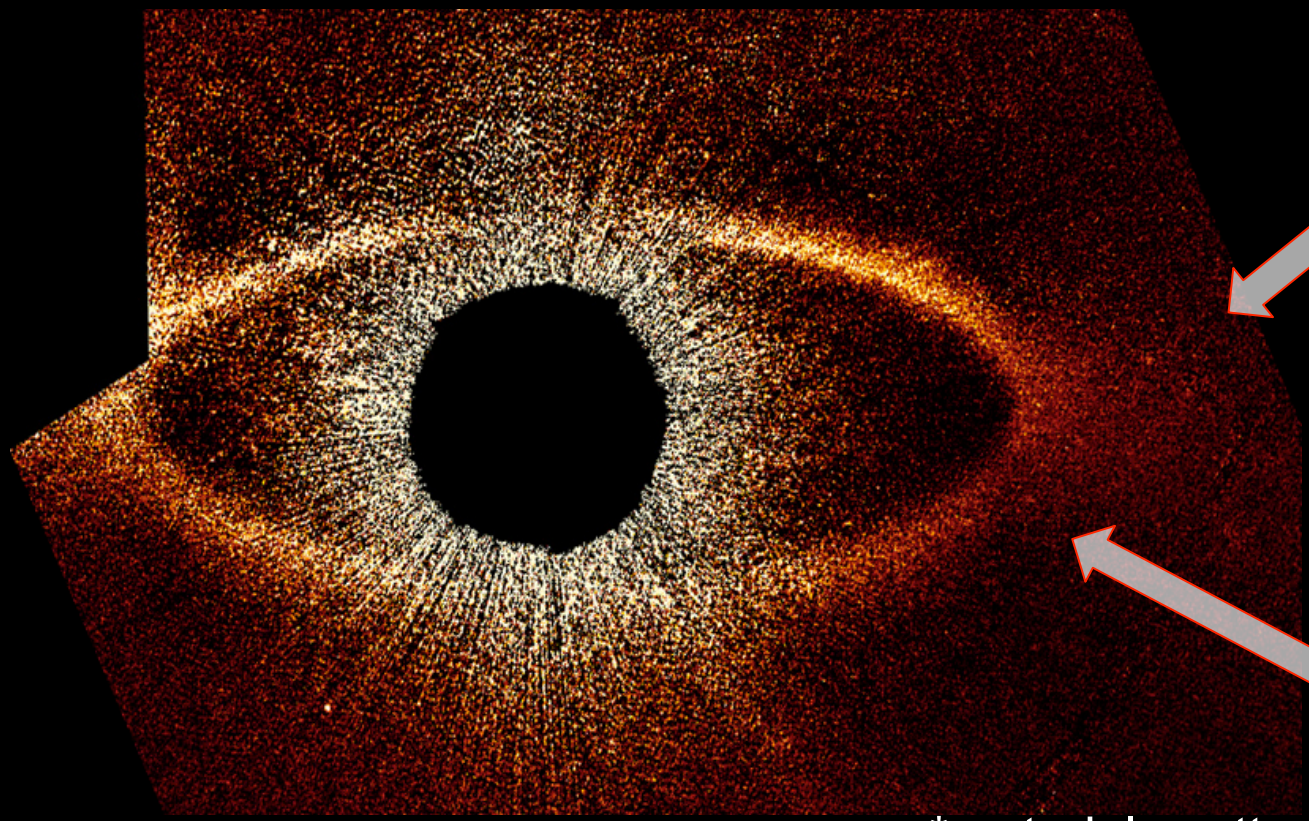
→ Posited interaction with Speculative "Fom c"

See talks Wed: Kalas 10:30 AM
Faramaz 11:45 AM

COMPARISON TO FOMALHAUT (A3V, 7.7 pc, ~ 200 Myr)

Kalas et al ApJ 77 556 (2013)

HST/STIS follow-up observations



Material beyond main-belt (NE) ansa

morphological similarities to HR 4796A

Intra-ring (3° wide) azimuthal "gap"*

19" (141 AU)

*material scattered by planet crossing?
giant impact scenario?
nodal+apsidal alignment?

AU Mic

A very Near-by (9.9 pc), ~ 12 Myr,
Low-Mass (0.31 M_{sun}, M1Ve) Star Hosting

Member of β Pic moving group,
likely coeval with Beta Pic

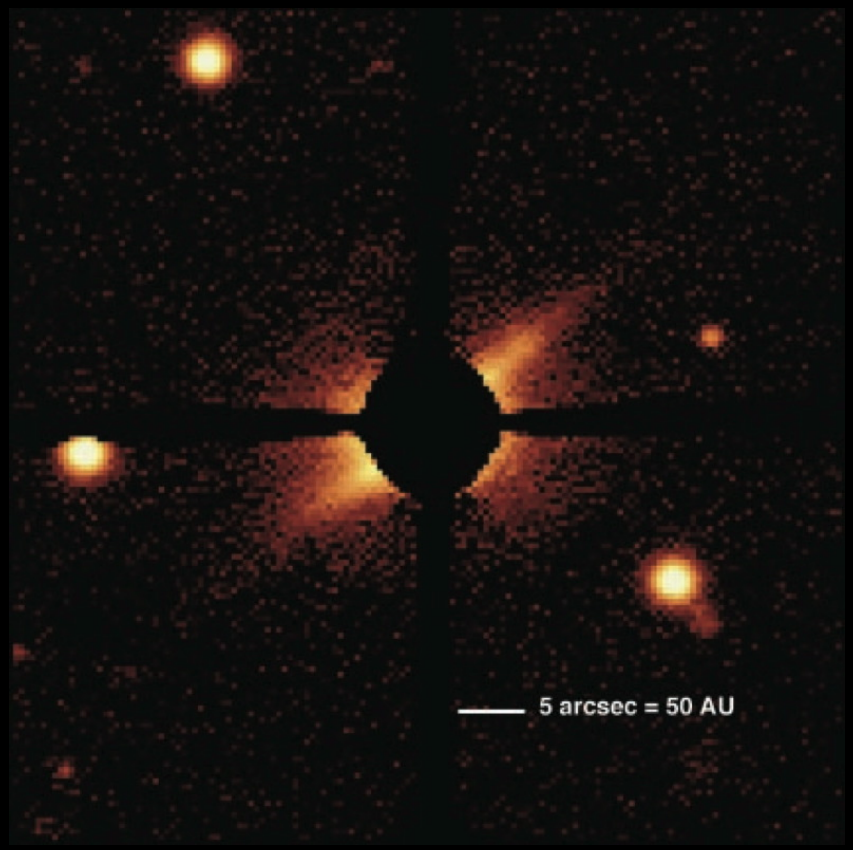
An Edge-On Debris Disk, with

a significant out-of-plane "bump" @ 13 AU, and

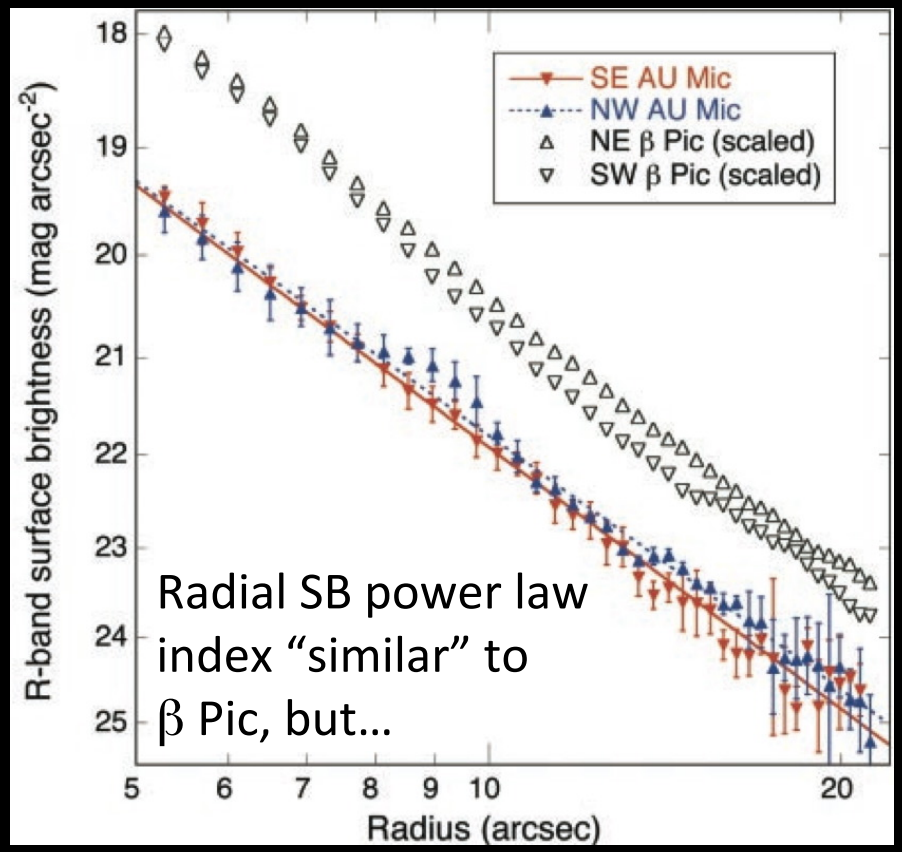
a one-side warp "opposite" the "bump".

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

UH 2.2m + Coronagraph R-band Discovery Image (Kalas et al. 2004)



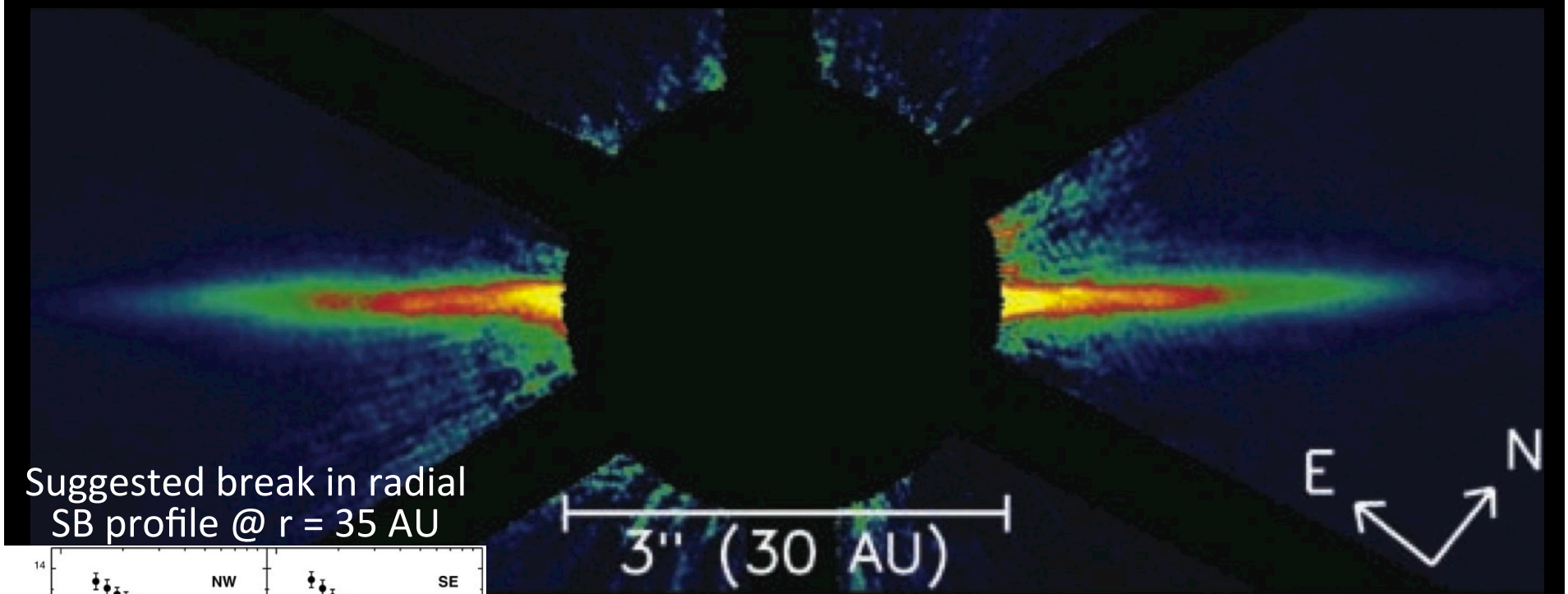
M-star disk imaged from 50 – 210 AU from AU Mic



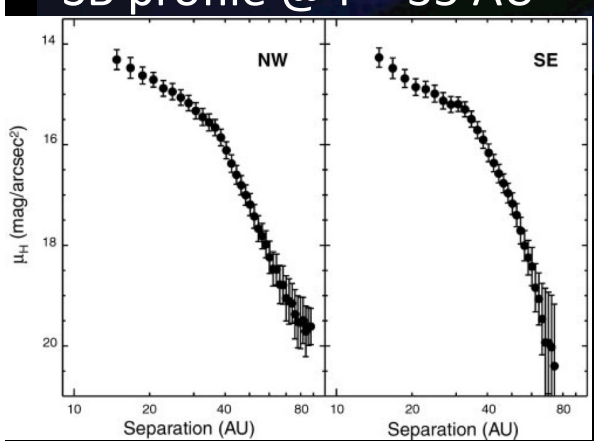
Scaling the stellar brightness of β Pic to AU Mic, the AU Mic disk is ~11x brighter than β Pic's at constant angular radii.

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

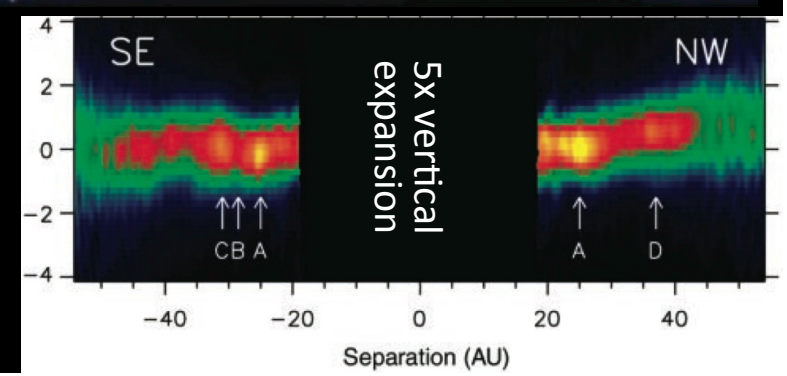
Keck II AO/NIRC2 H-band (Liu 2004):
Edge-on disk imaged to IWD = 15 AU the along mid-plane



Suggested break in radial SB profile @ r = 35 AU

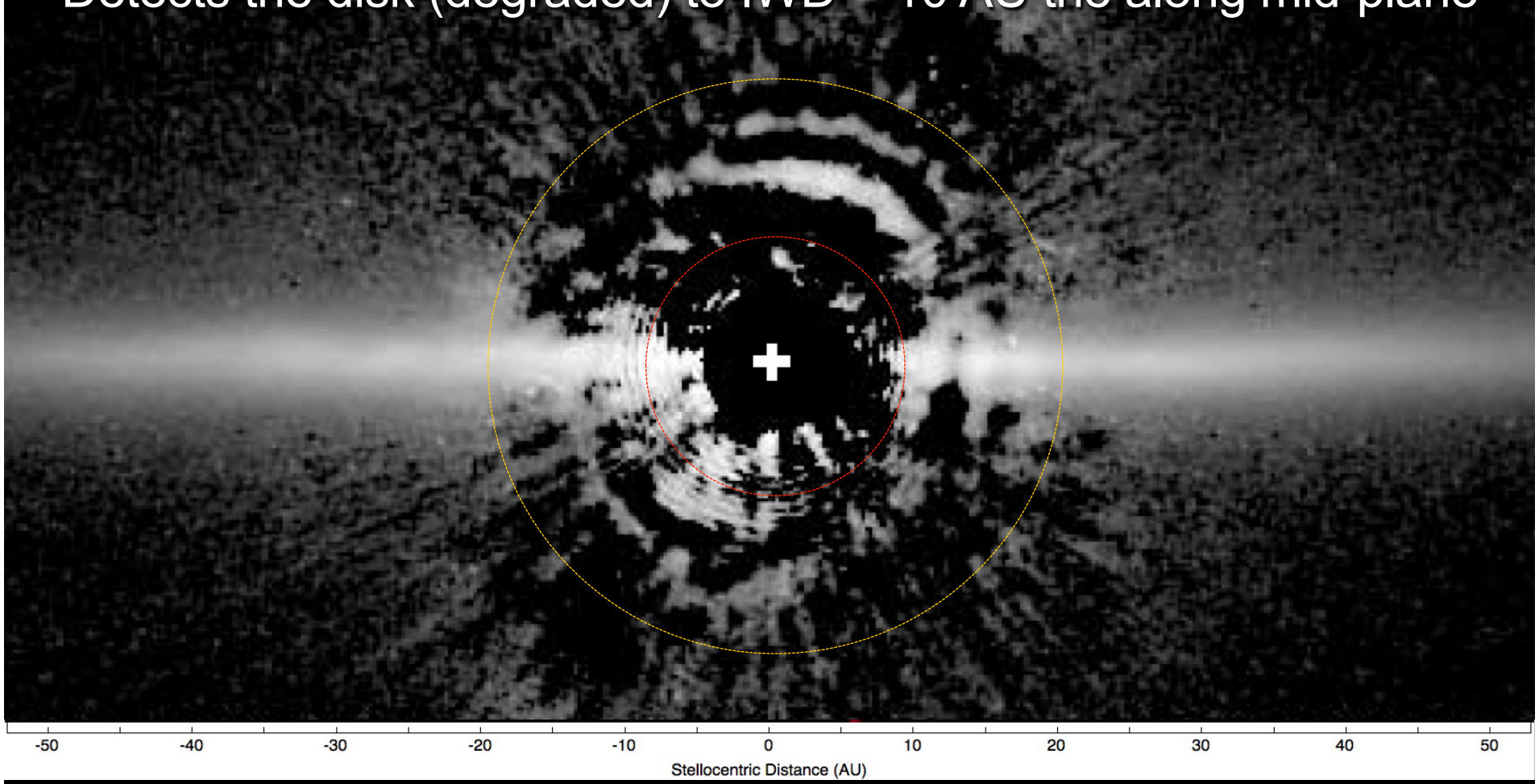


Radial & Vertical → substructure in the disk @ r < 50 AU with some asymmetries



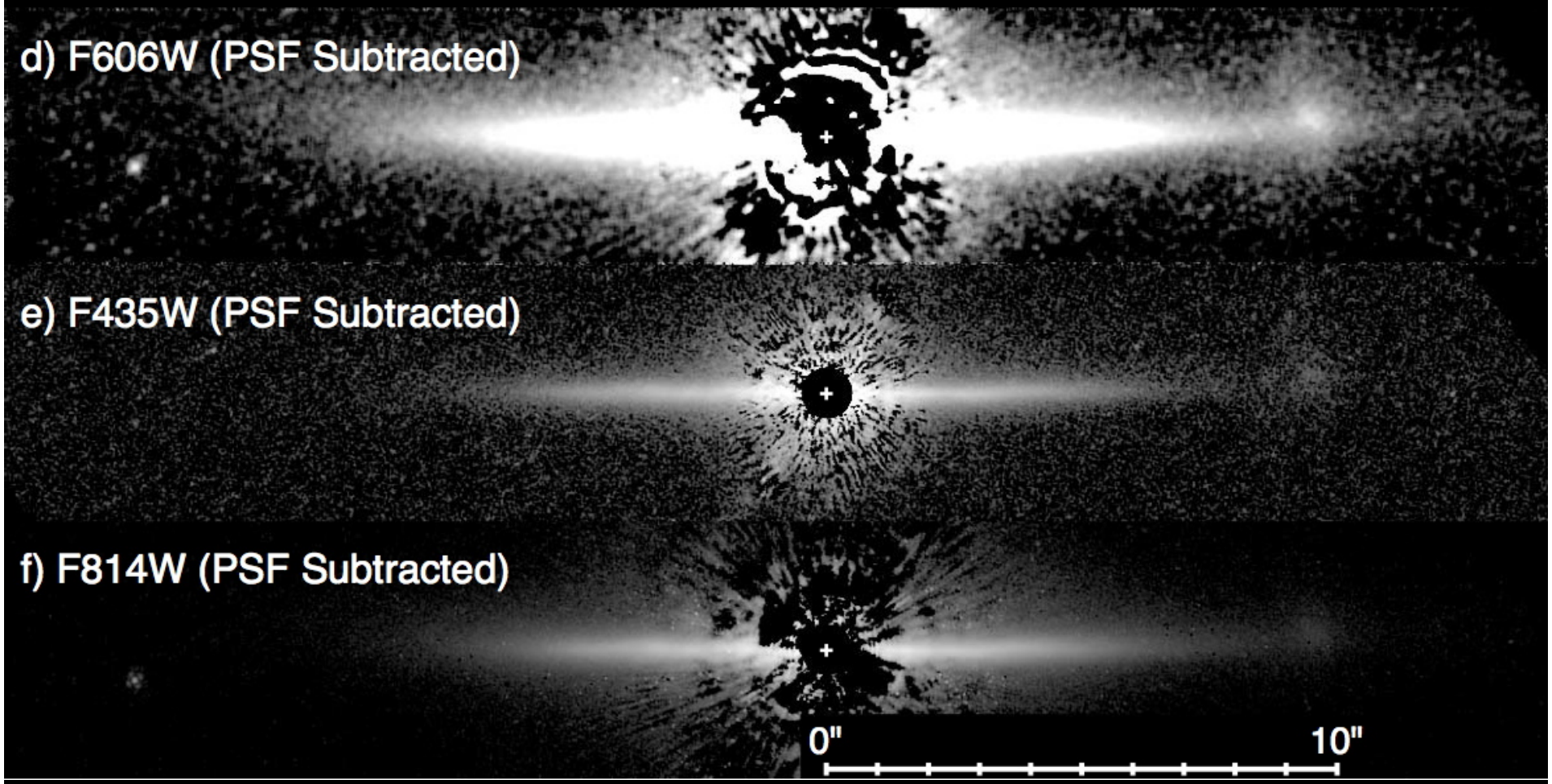
AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/ACS F606W image (Krist et al 2005):
Detects the disk (degraded) to IWD ~ 10 AU the along mid-plane



AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

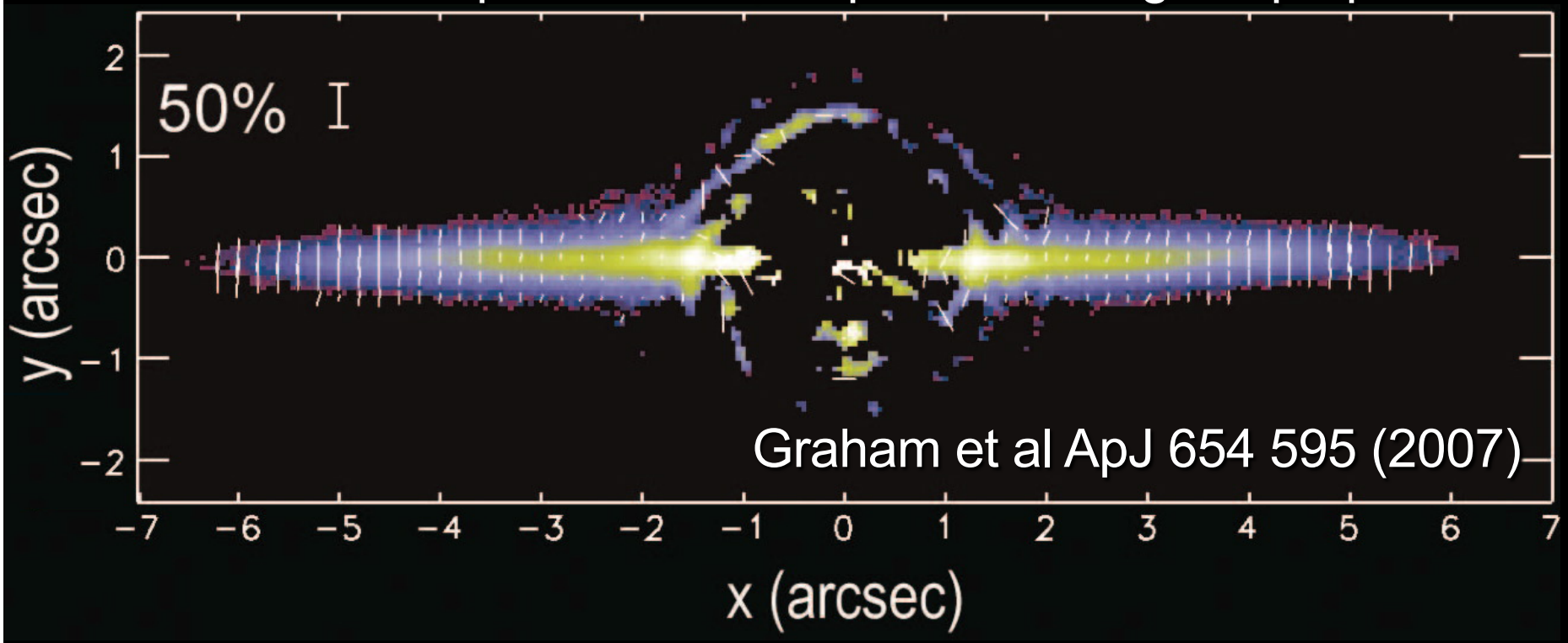
HST/ACS F435W/F606W/F814W imaging (Krist et al 2005):



"BVI" photometry of the disk suggests the disk grains are blue relative to the star. Posited small grain retention compared to neutral/red grains around early type stars. Modeling suggests the inner disk is clear of material at r < 12 AU.

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/ACS F606W POLARIMETRY
In addition to optical colors, helps constrain grain properties

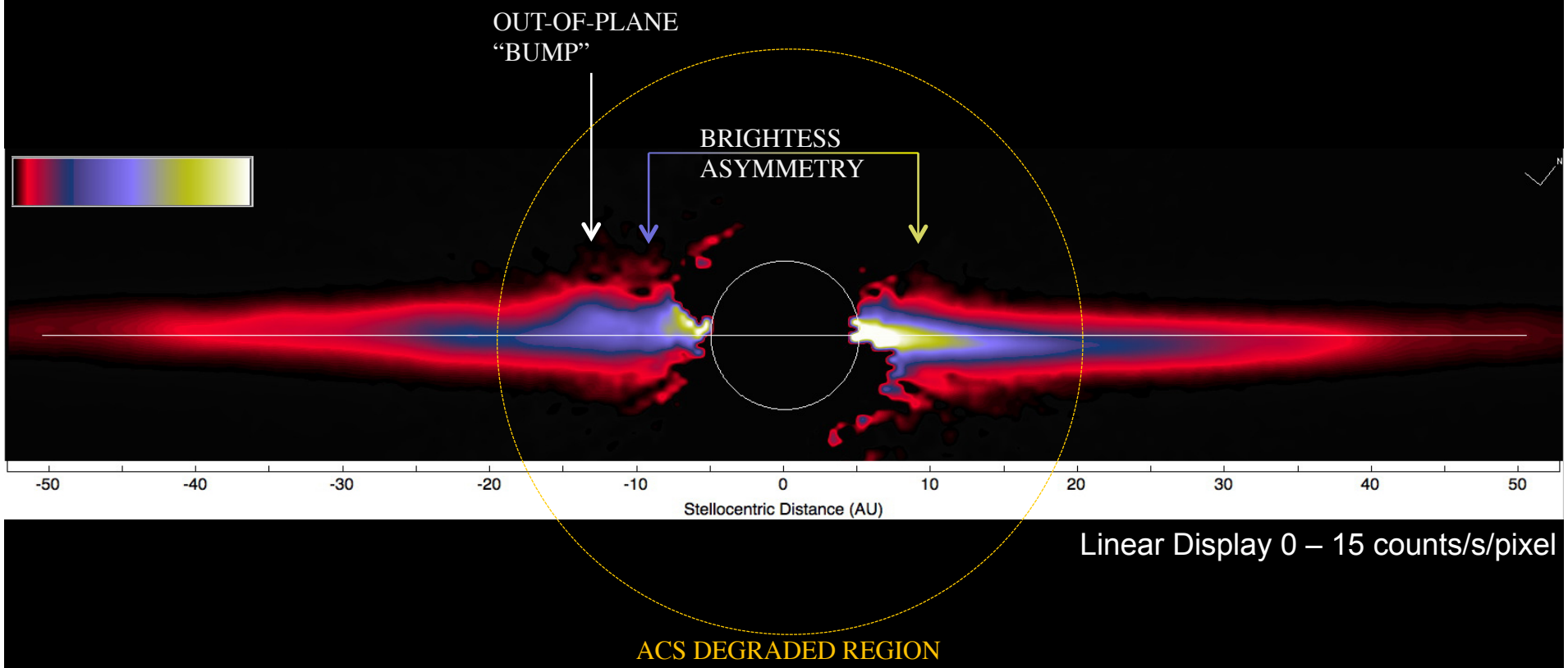


~40% P% (@ 80 AU) – 5% P% (@ 20 AU) ⊥ to mid-plane.
Declining P% with smaller stellocentric distance
in indicative of small optically thin grains

Model: “Hole” interior to ~ 45 AU collision-dominated birth ring
depleted x300 of μm size grains

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al AJ 148 59 2014) ± 50 AU
Resolves the disk to IWD = 5 AU the along mid-plane

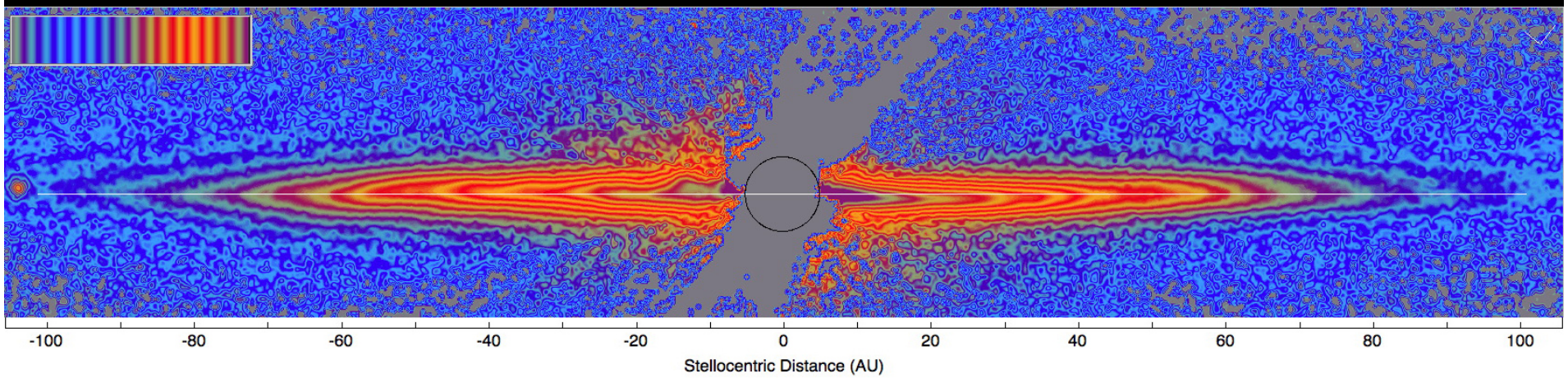


Linear Display 0 – 15 counts/s/pixel

Significant surface brightness asymmetries are seen in the inner disk

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al 2014) ± 100 AU
Defines the morphological (photometric) mid-plane

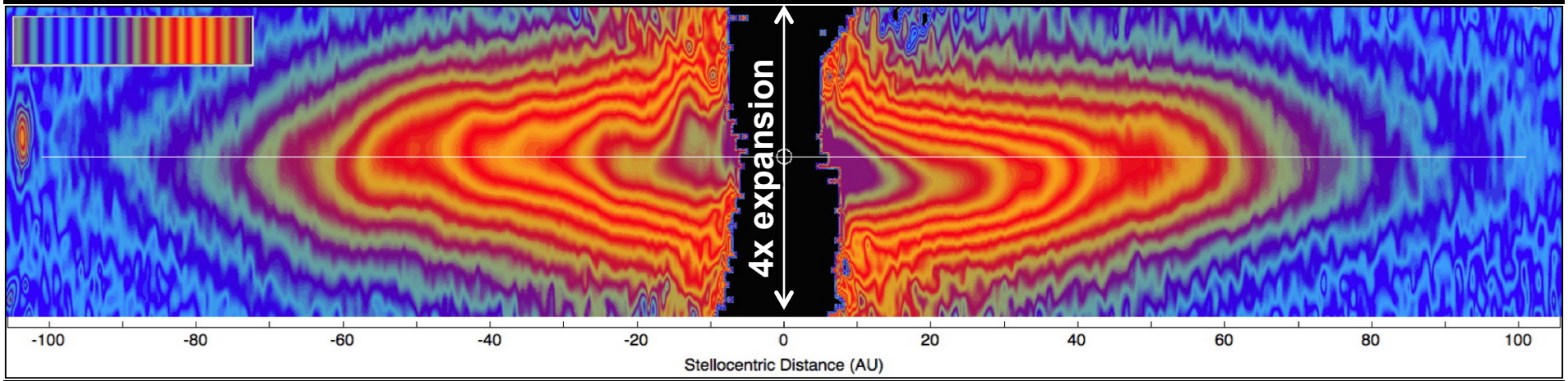


Log10 Display [-1] to [+3] {dex} counts/s/pixel

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al 2014) ± 100 AU
Defines the morphological (photometric) mid-plane

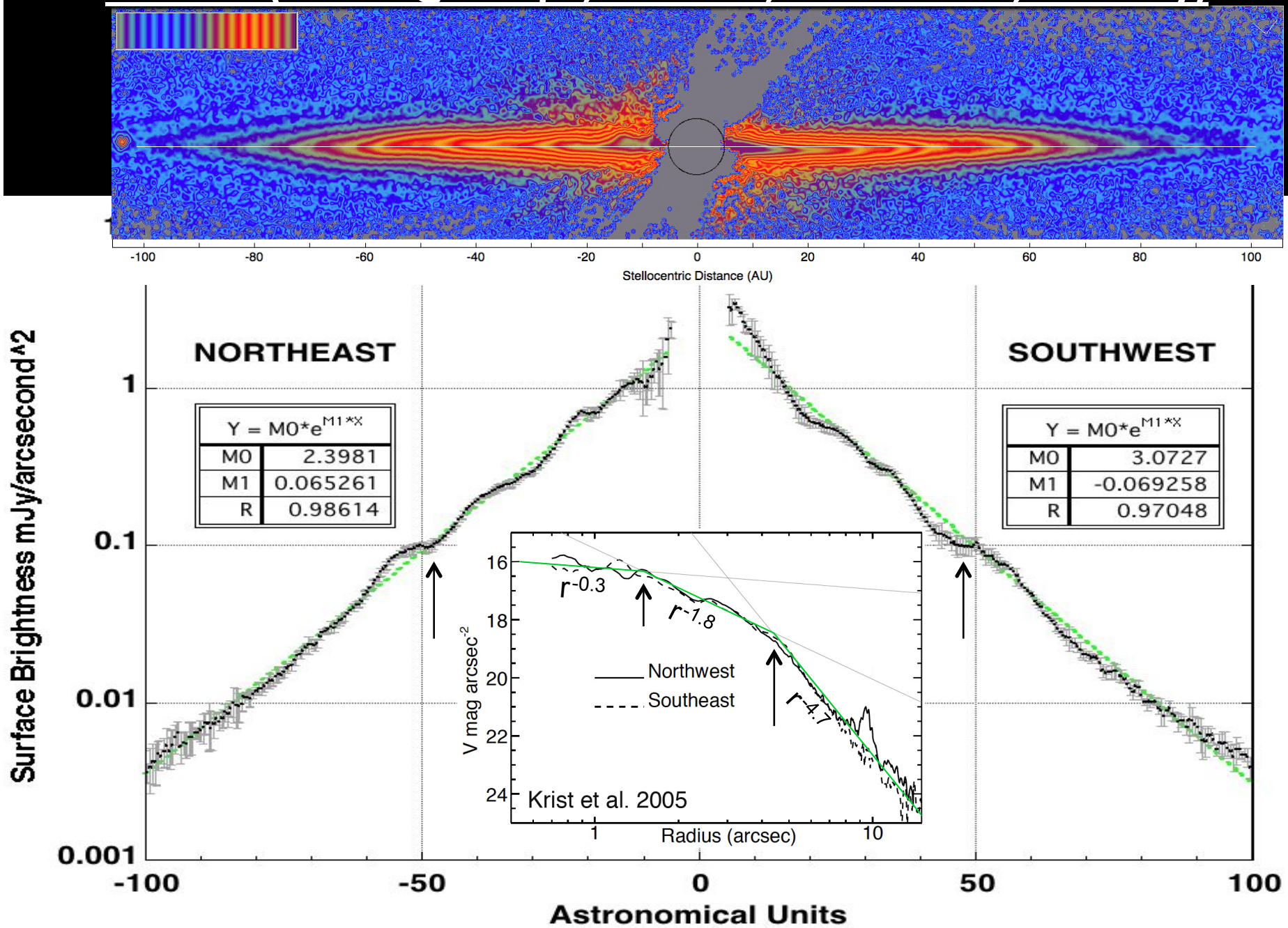
SW side warp below the >50 AU isophotal mid-plane opposite NE “bump”



Log10 Display [-1] to [+3] {dex} counts/s/pixel

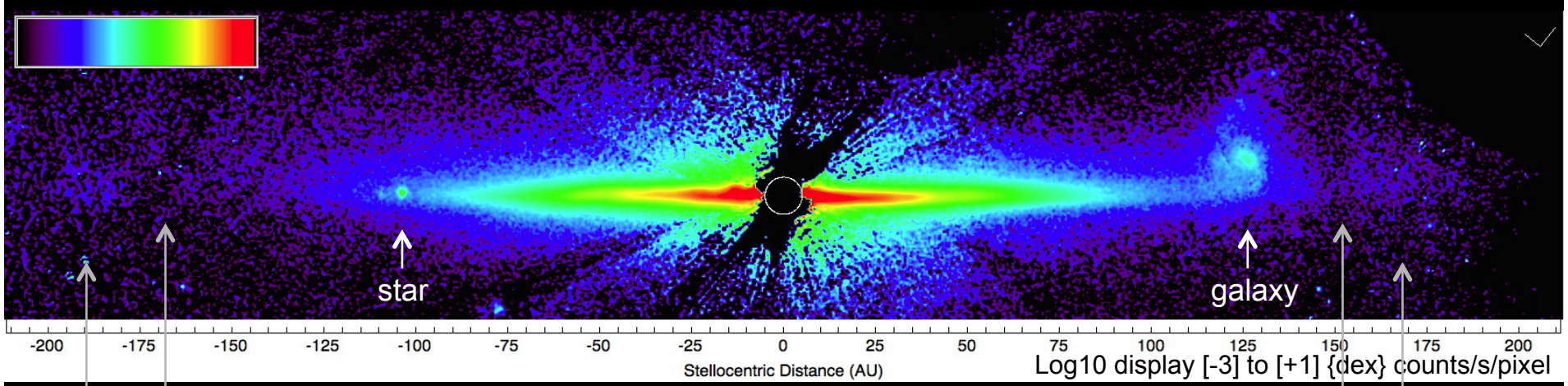
4x vertical (z) expansion in image scale

AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)



AU MIC (M1Ve @ 9.9 pc, V = 8.61, B-V = +1.44, ~ 12 My)

HST/STIS image (Schneider et al 2014) ± 200 AU



radial outer "gap"

Low SB flux
SNR ~ 2-3 resel^{-1}

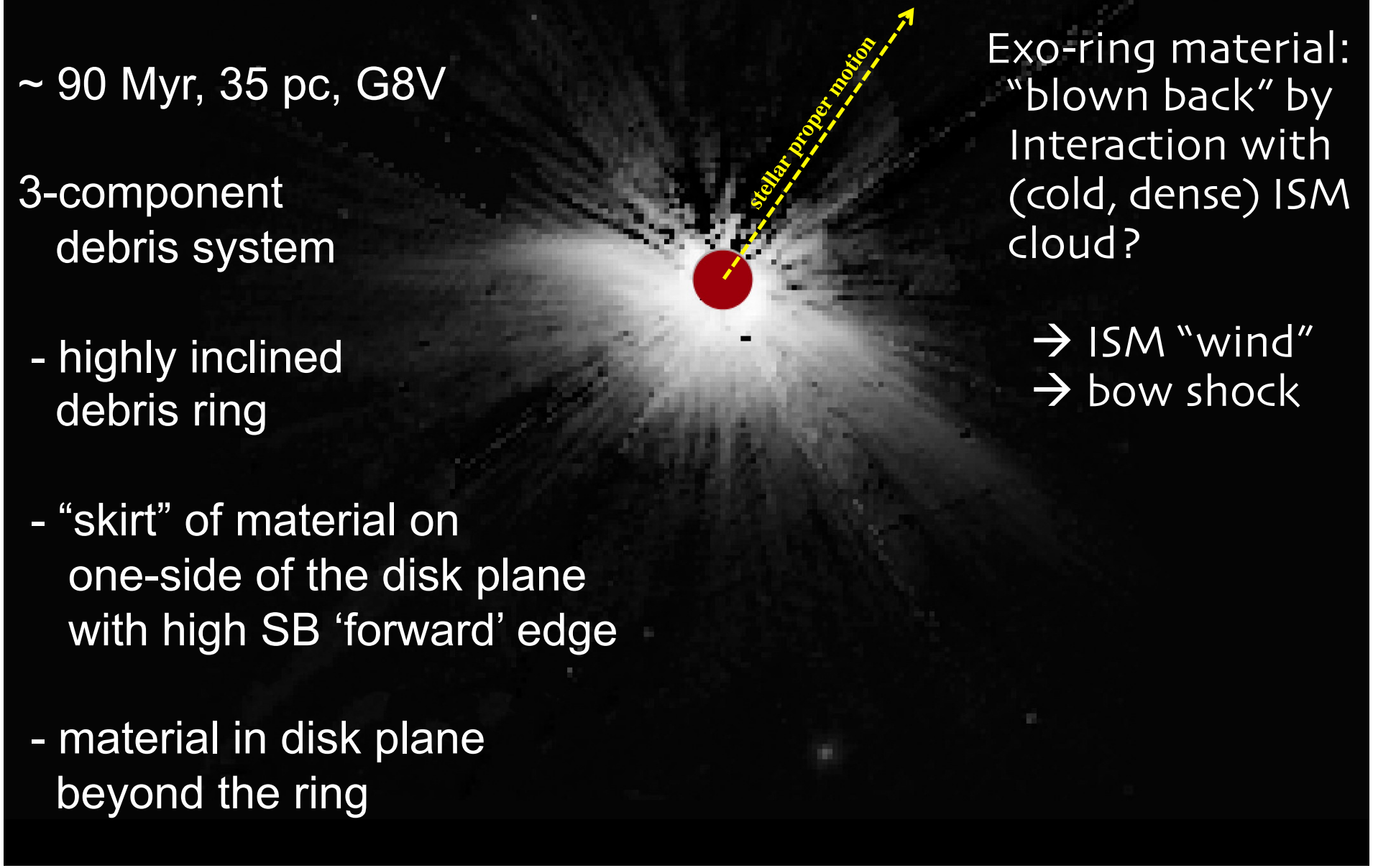
radial outer "gap"?

Low SB flux
SNR ~ 2-3 resel^{-1}

The outer disk

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/NICMOS 1.1μm (Hines et al ApJL 671 165 2007)



~ 90 Myr, 35 pc, G8V

3-component debris system

- highly inclined debris ring

- "skirt" of material on one-side of the disk plane with high SB 'forward' edge

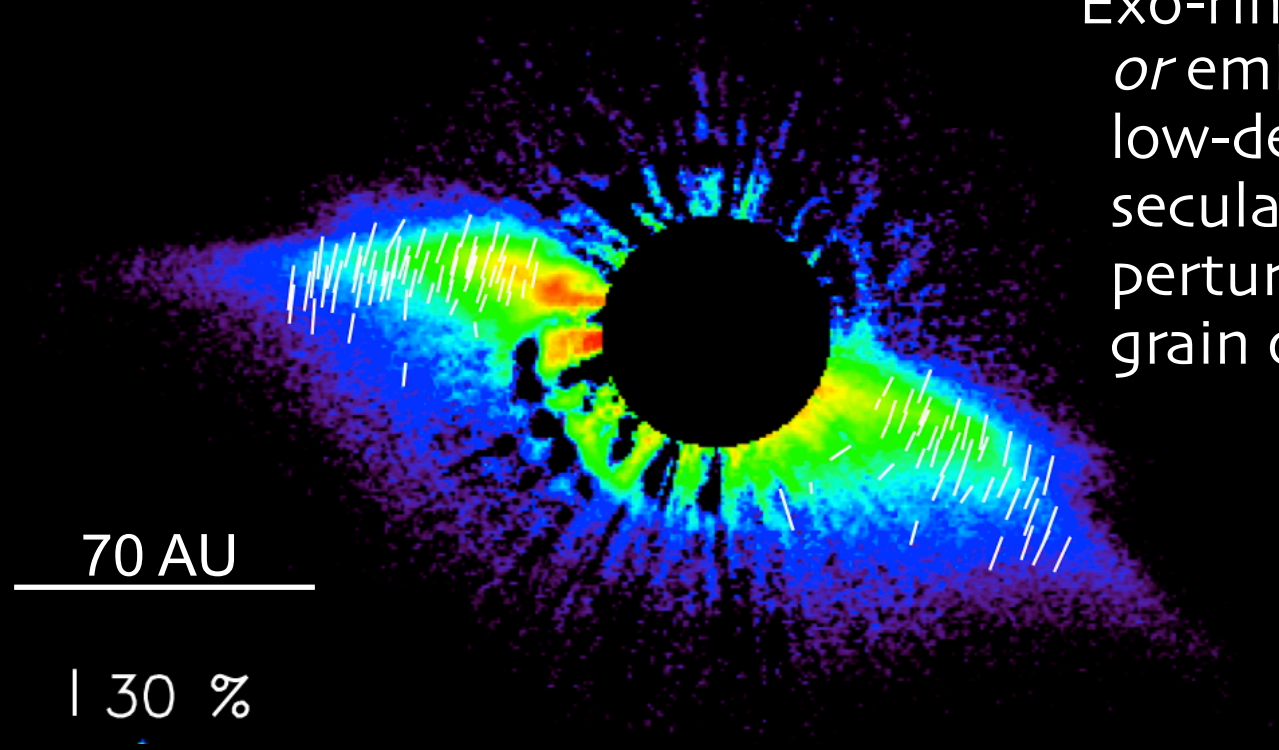
- material in disk plane beyond the ring

Exo-ring material: "blown back" by Interaction with (cold, dense) ISM cloud?

→ ISM "wind"
→ bow shock

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/ACS 0.61μm Imaging Polarimetry
(Maness et al ApJ 7071089 2009)



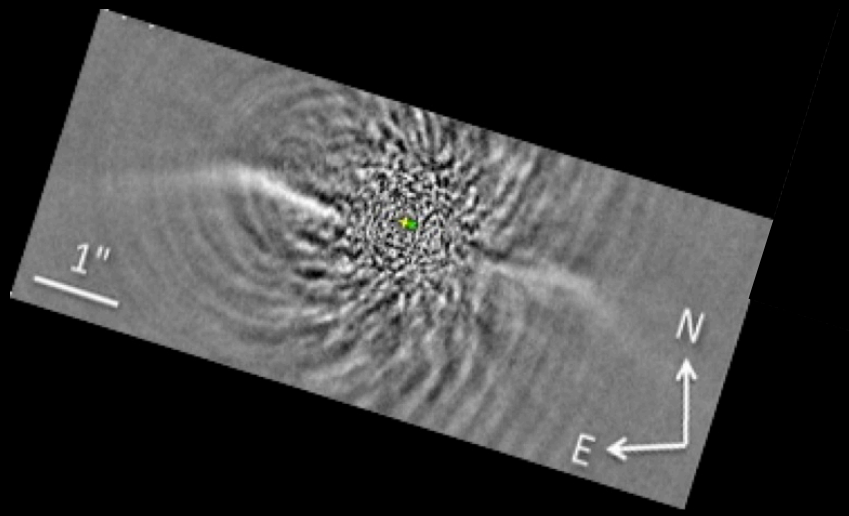
Exo-ring material: *or* embedded in low-density cloud secularly perturbing dust grain orbits

Optical (ACS) + nIR (NICMOS) color + POLARIMETRY suggest blue, sub-micron, grains, with no strong color gradient with stellocentric distance.

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

VLT/NaCo H-band/ADI* (Buenzli et al A&A 524 L1 2010)

Resolving the Nearly-Edge on Ring and Central Hole



* Technical note: Angular Differential Imaging

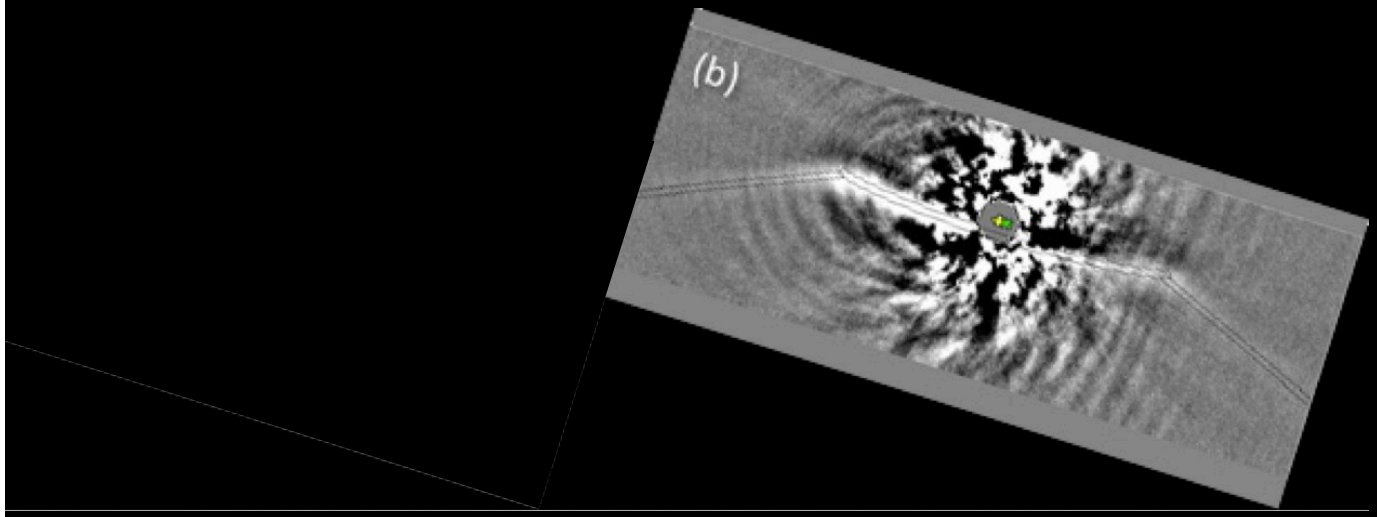
+ enhances local surface brightness gradients (@ high/mid spatial frequencies)

- does not preserve total flux, insensitive to diffuse shallow-gradient SB flux

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

VLT/NaCo H-band/LOCI* (Buenzli et al. 2010)

Resolving the Nearly-Edge on Ring and Central Hole

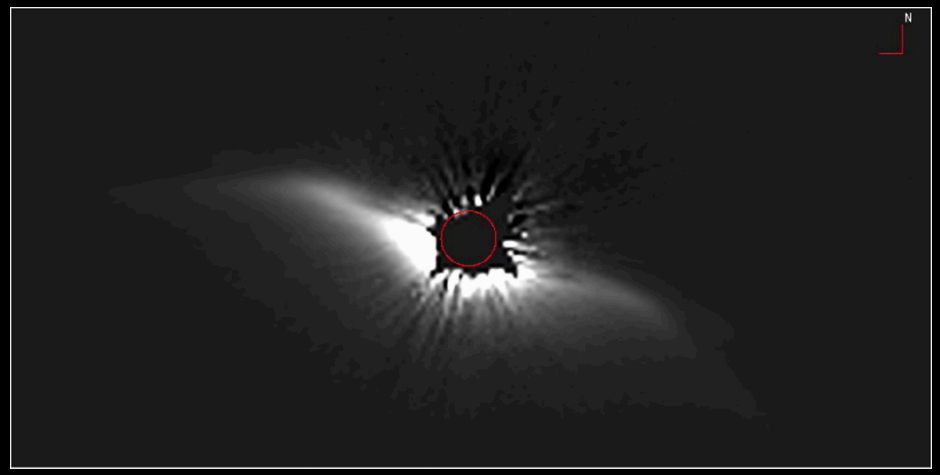


* Locally Optimized Combination of Images

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/STIS Broadband Optical (Schneider et al. 2014)

Resolving the Nearly-Edge on Ring and Central Hole

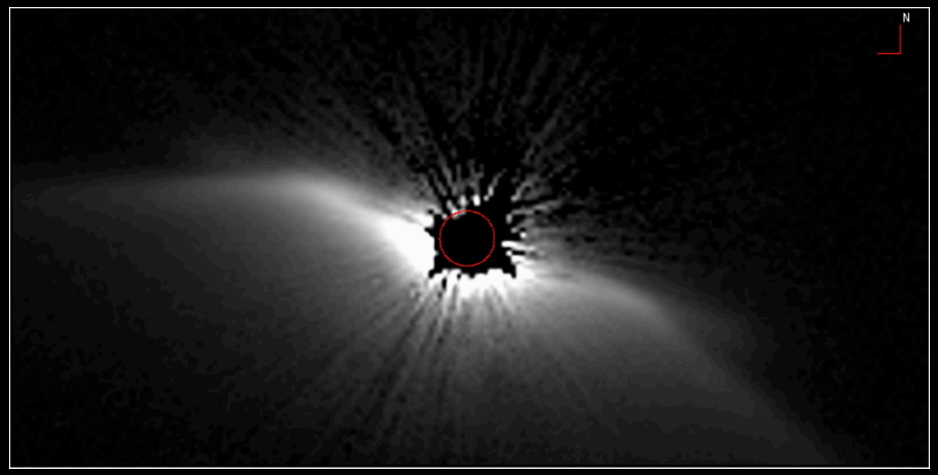


$i \simeq 85°$
$r \simeq 63$ AU
$r_{in} \simeq 40$ AU

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/STIS Broadband Optical (Schneider et al. 2014)

Resolving the Nearly-Edge on Ring and Central Hole



$i \simeq 85°$
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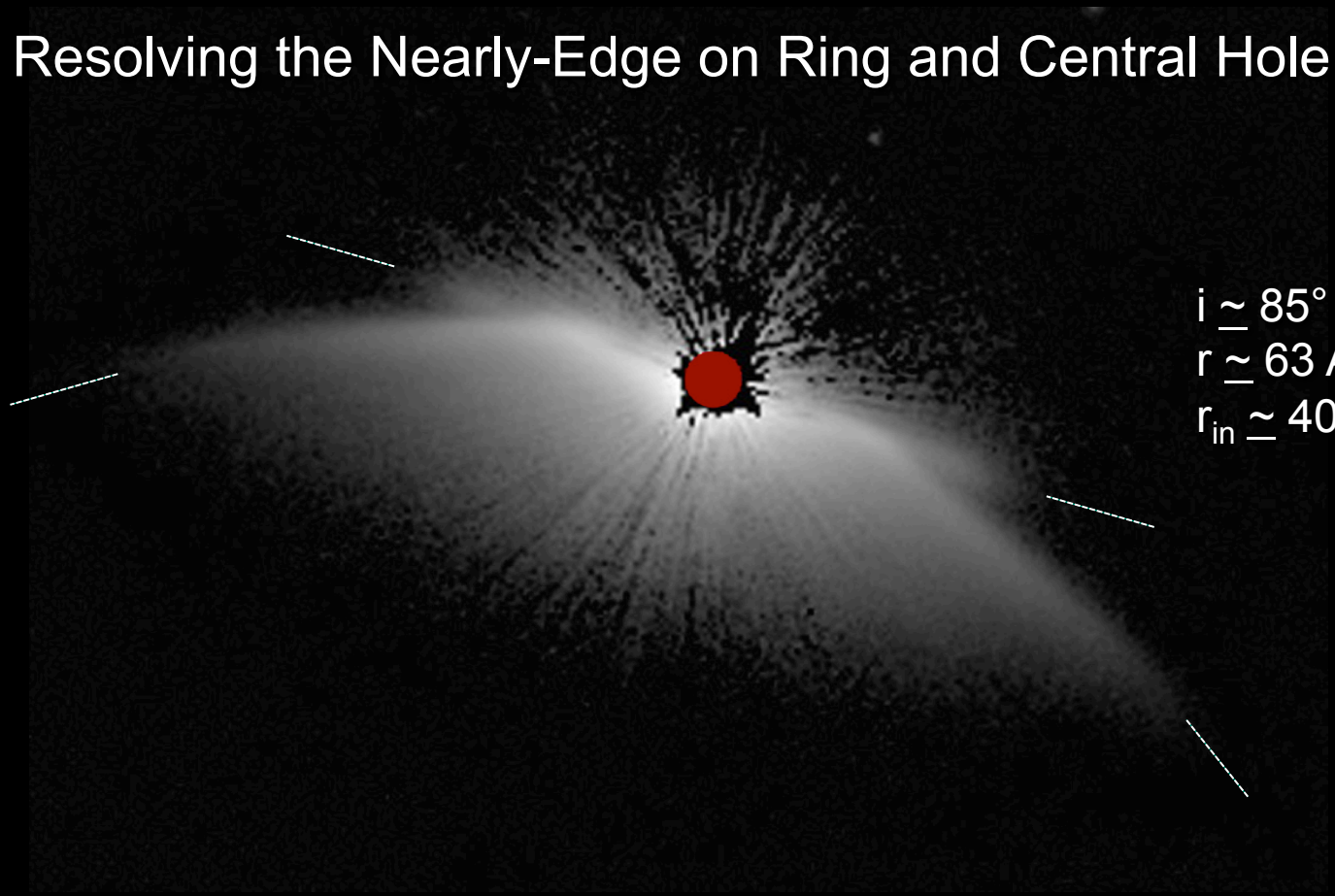
HST/STIS Broadband Optical (Schneider et al. 2014)

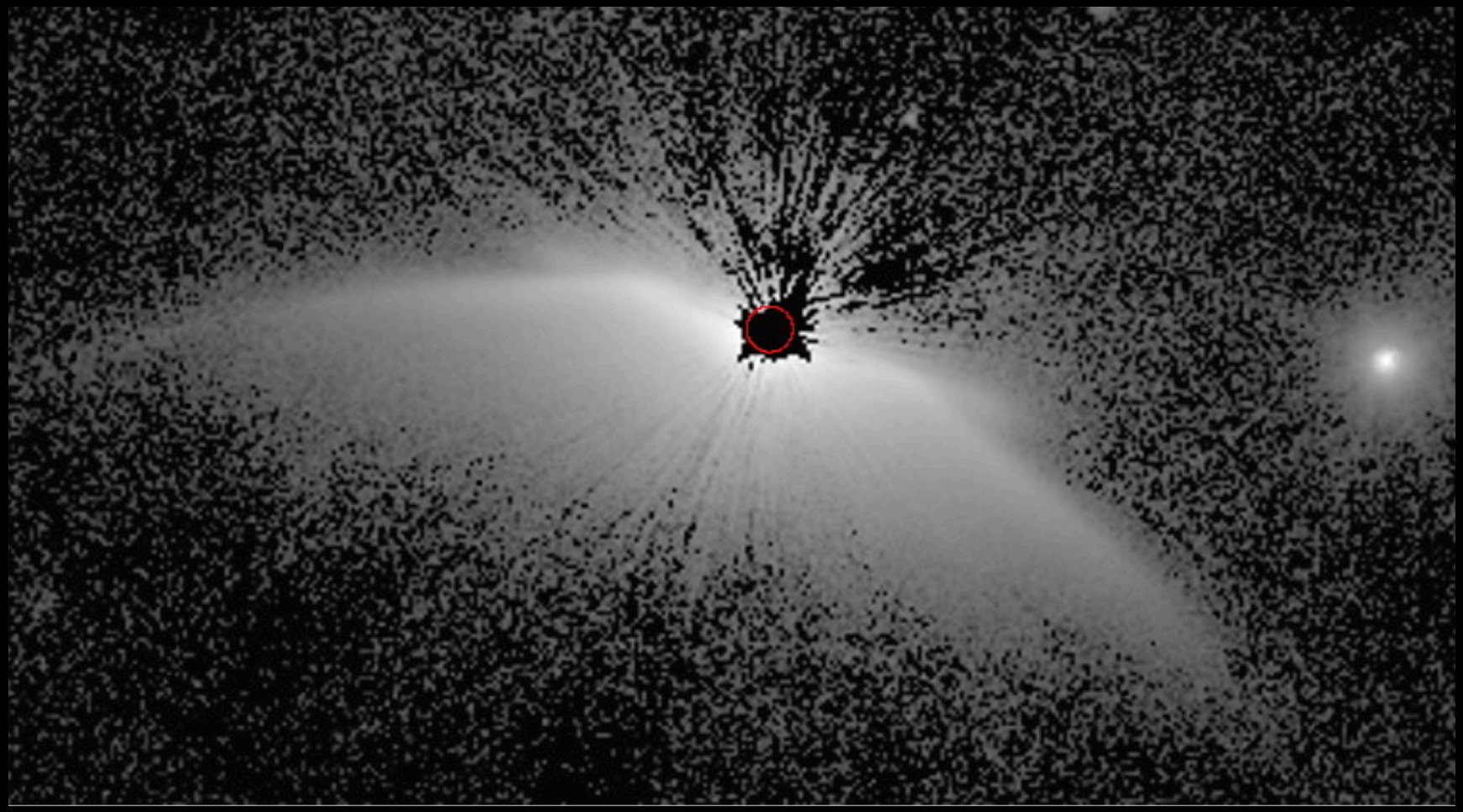
Resolving the Nearly-Edge on Ring and Central Hole



exo-ansal & edge-brightened "skirt" of material

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/STIS Broadband Optical (Schneider et al. 2014)

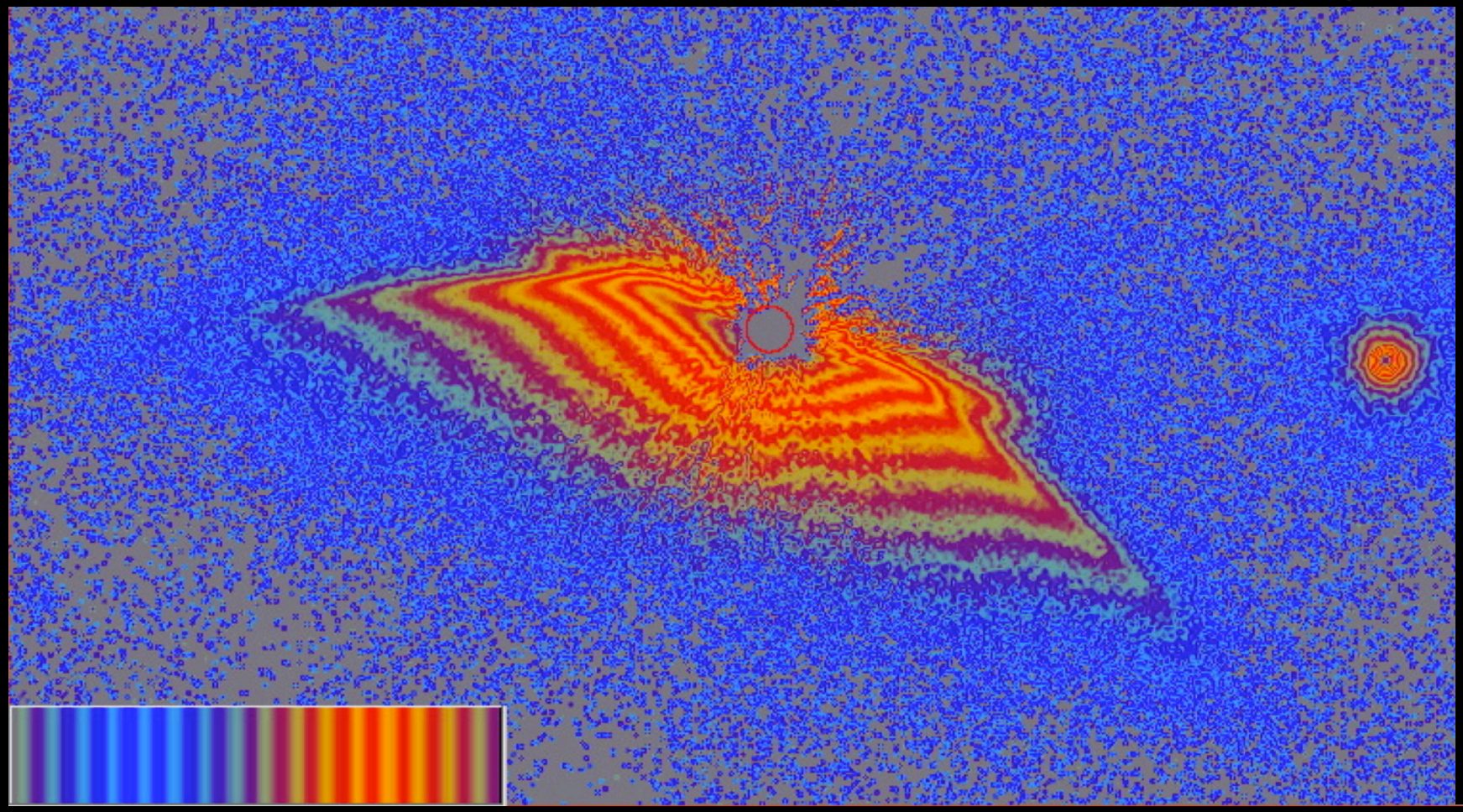


The full (detectable) extent of the debris system

f_{disk} = 4.46 mJy $f_{disk} : f_{star}$ = 0.245%

HD 61005 ("the moth"; G8V @ 34.5 pc, V = 8.22, B-V = +0.72, ~ 90 My)

HST/STIS Broadband Optical (Schneider et al. 2014)



The full (detectable) extent of the debris system

f_{disk} = 4.46 mJy $f_{disk} : f_{star}$ = 0.245%

HD 32297

An ~ 10 Myr A0 star @ 112 pc with a
r ~ 1300 AU, Nearly, Edge-On Debris Structure

Exhibiting a large z-height of scattering grains
on one side (only) of the Disk-Plane

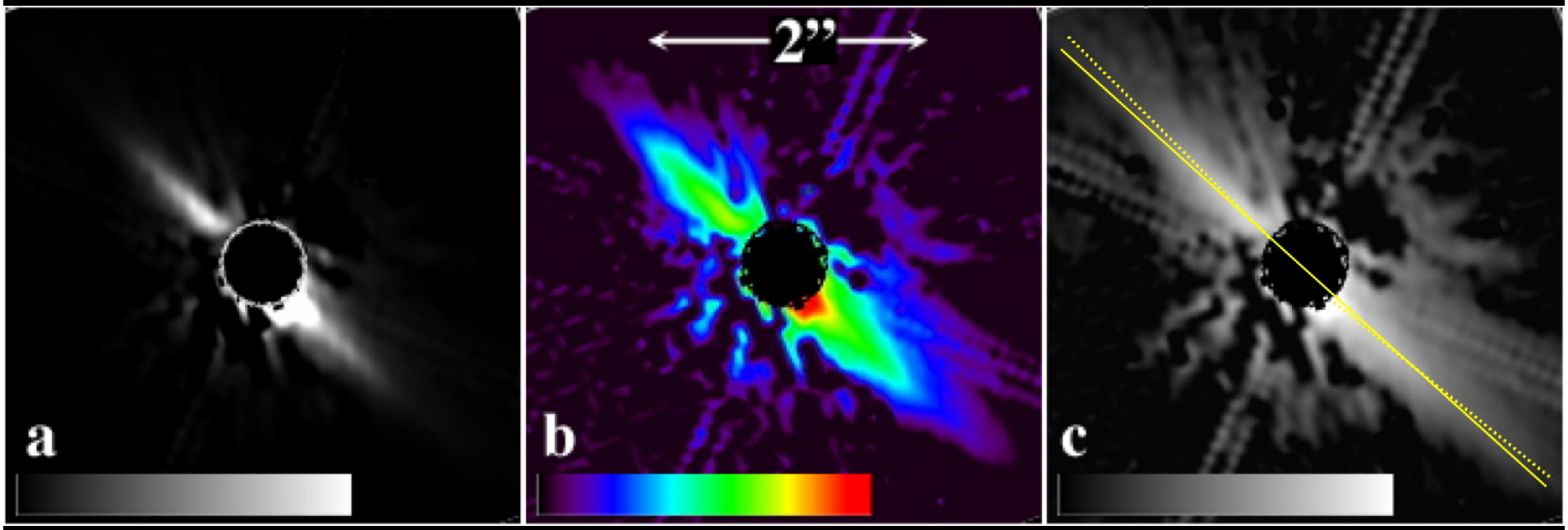
(postulated to be interacting with the ISM)

with also extreme minor-axis mirrored SB
asymmetries,

and out-of-plane structure

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

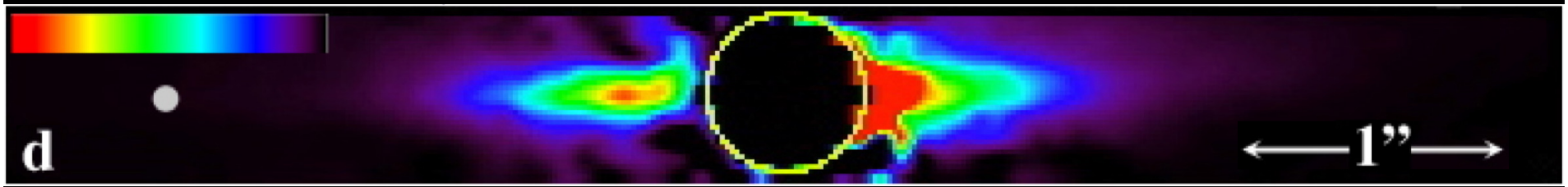
HST/NICMOS 1.1 μm Discovery Image (Schneider et al. 2005)



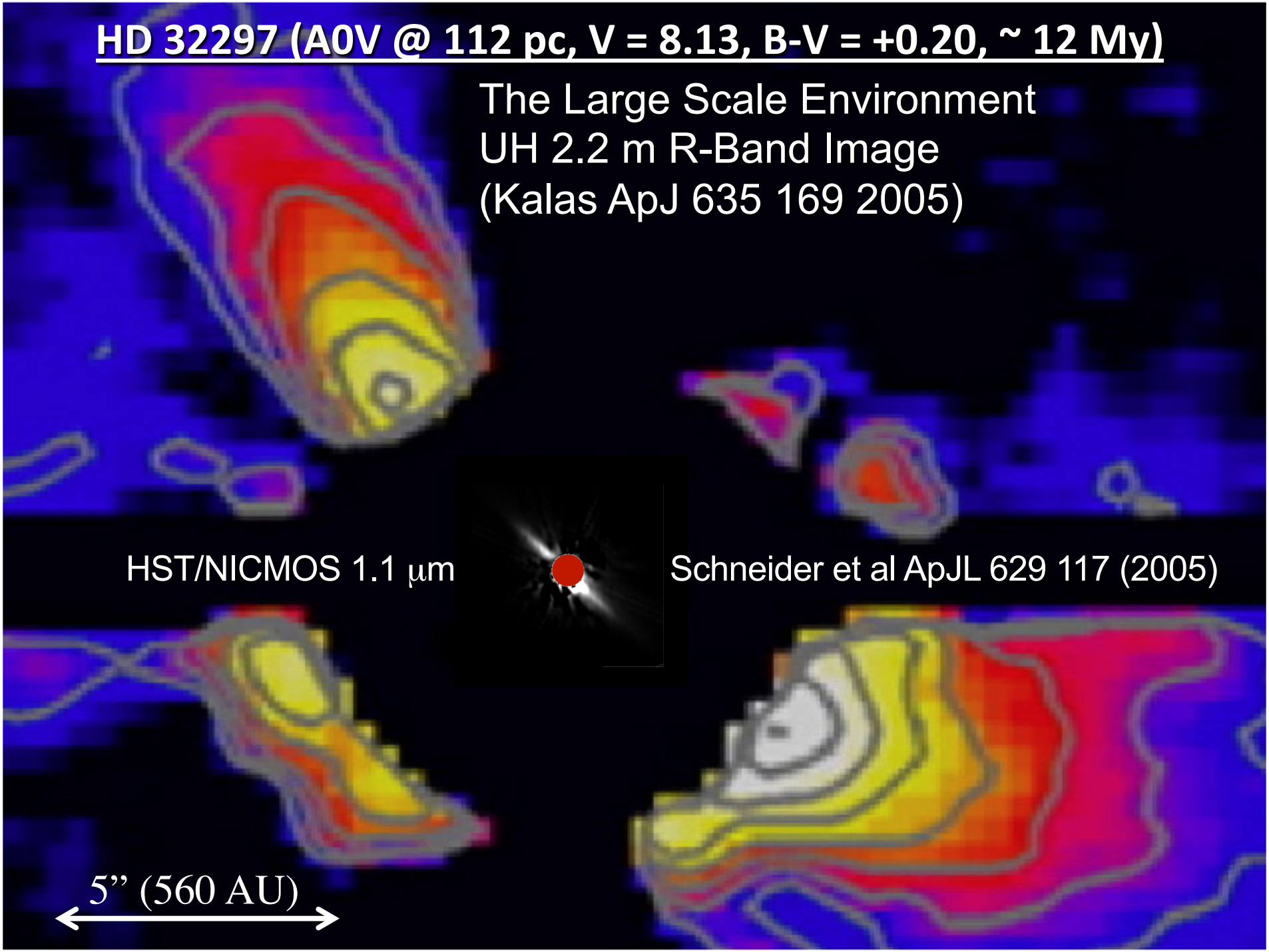
nearly edge-on

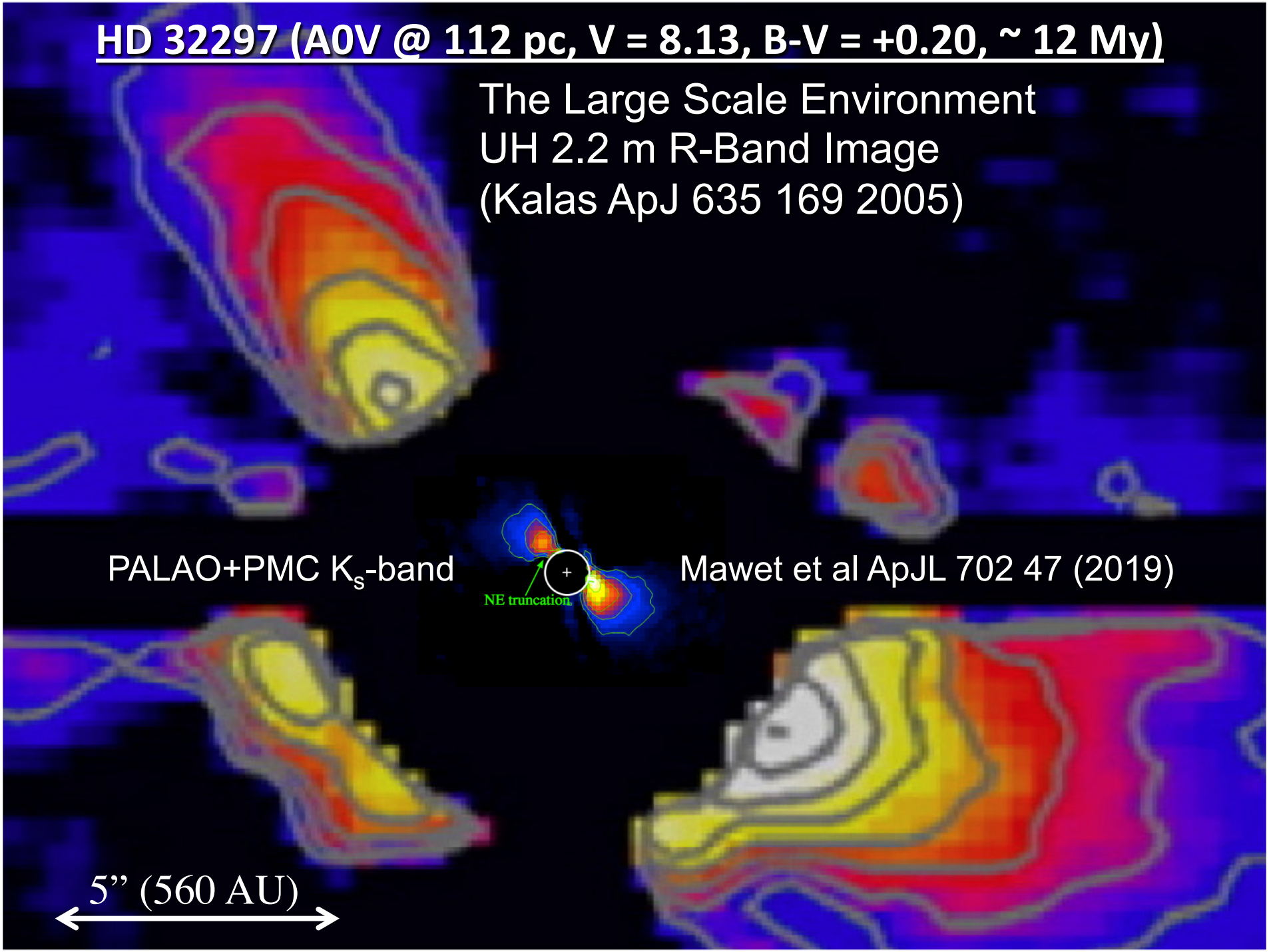
~2x SB asymmetry @ 0.3”–0.5”

hint of “curvature” wrt. linear mid-plane

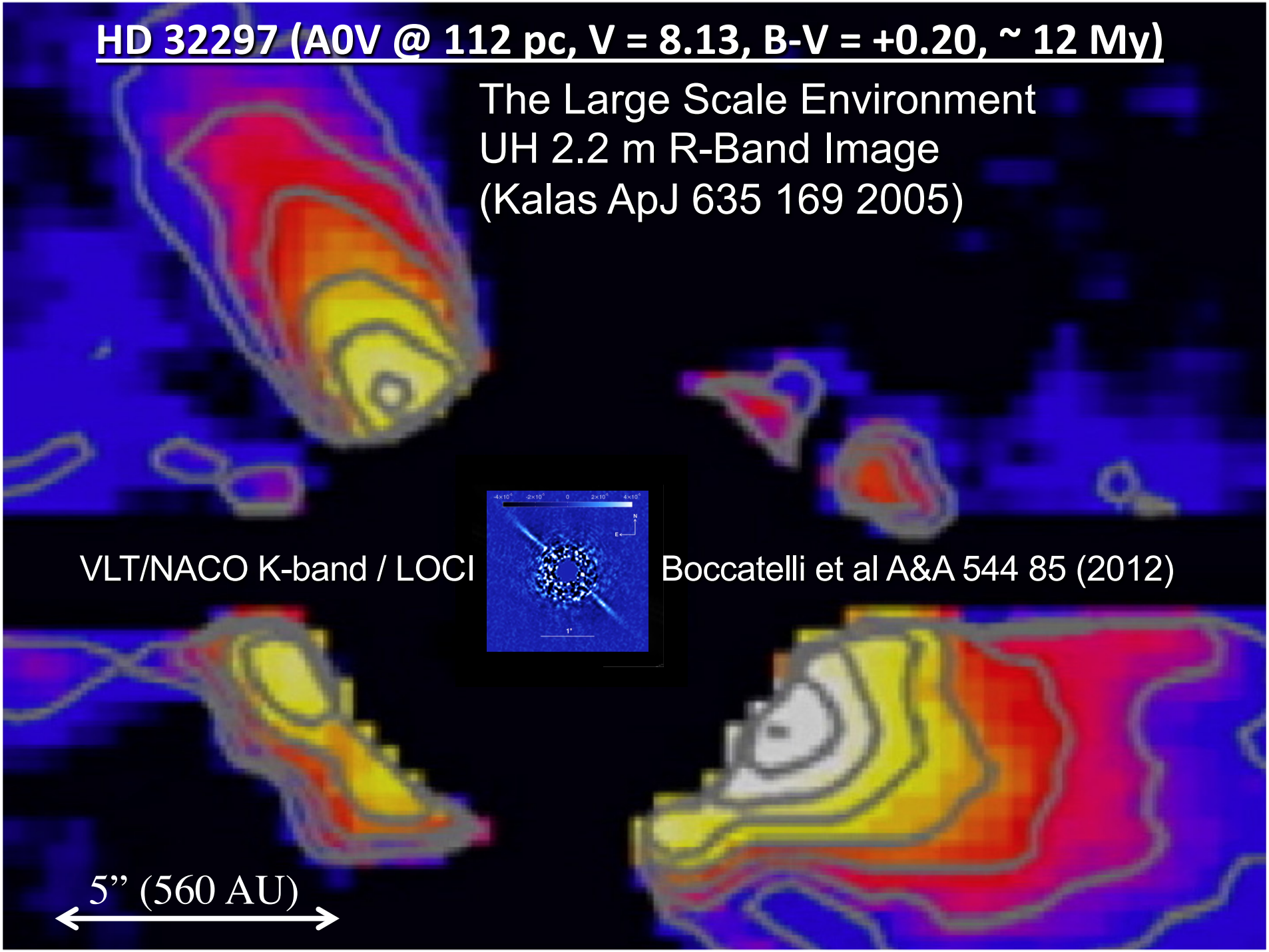


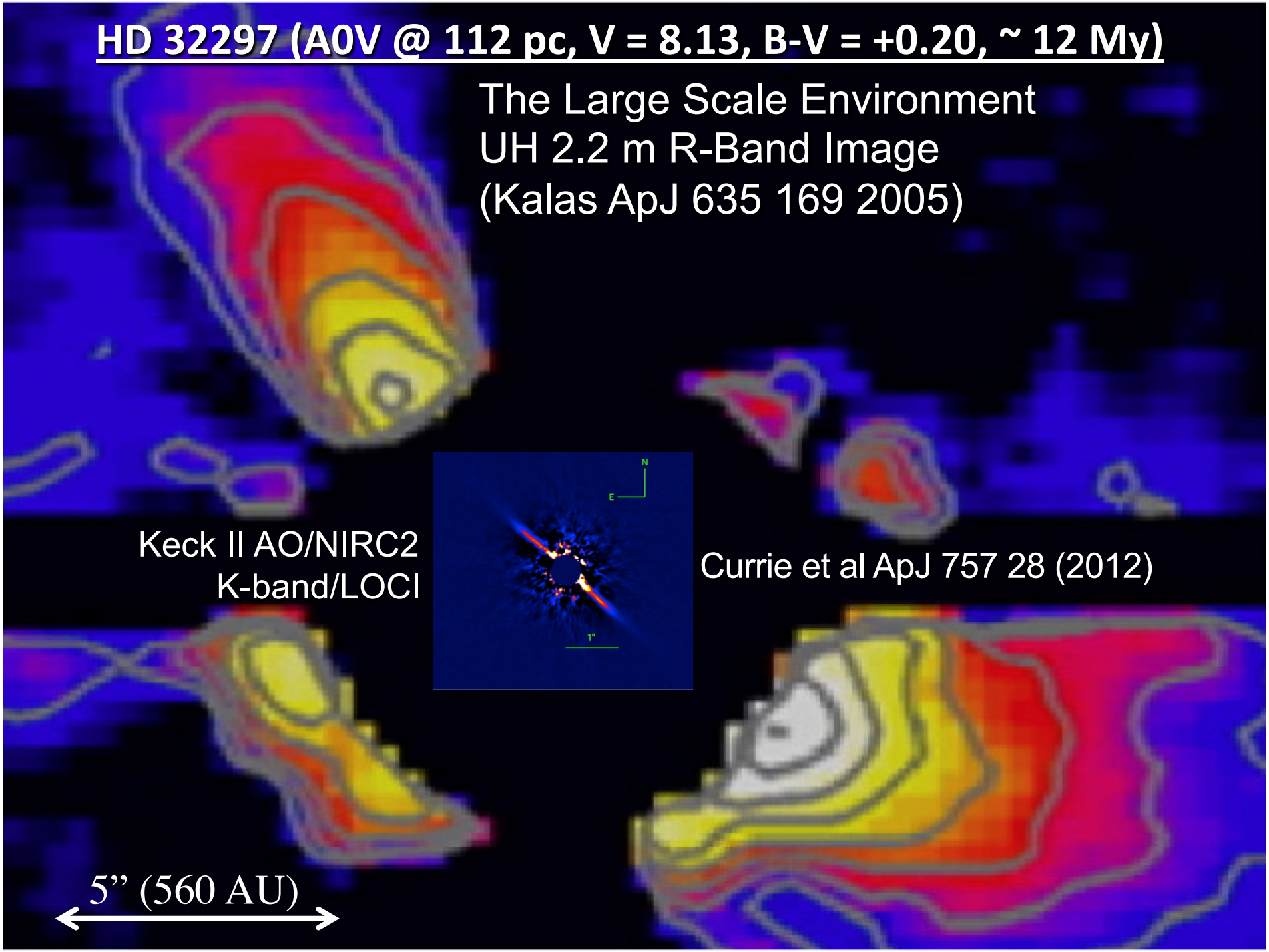
F_{disk}/F_{*} (1.1μm) = 0.36% ± 0.04%

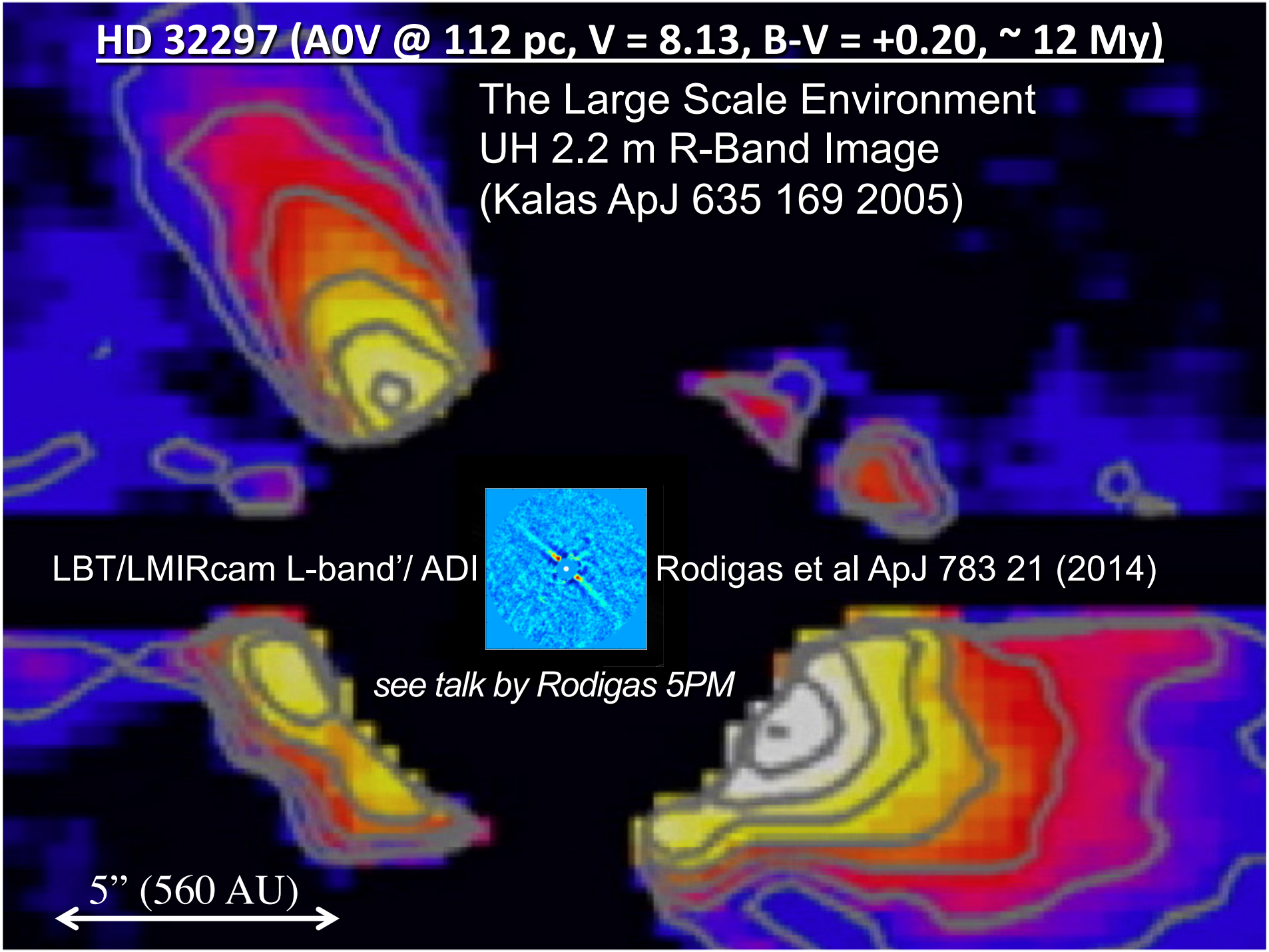

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)
The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)
HST/NICMOS 1.1 μm
Schneider et al ApJL 629 117 (2005)
5" (560 AU)


HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)
The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)
PALAO+PMC K_s-band
NE truncation
Mawet et al ApJL 702 47 (2019)
5" (560 AU)

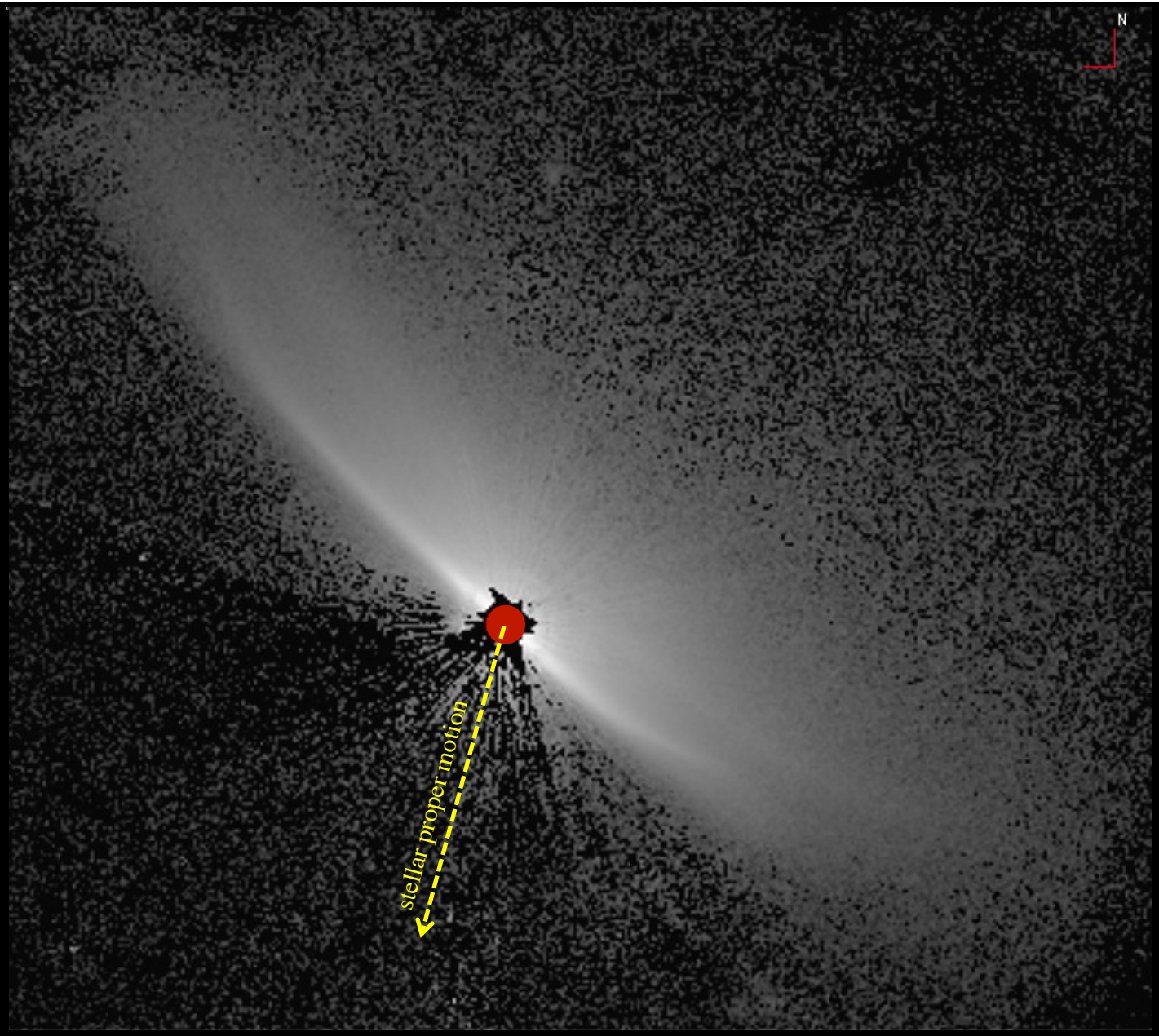
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)




HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)
The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)
Keck II AO/NIRC2
K-band/LOCI
N
E
1"
Currie et al ApJ 757 28 (2012)
5" (560 AU)


HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)
The Large Scale Environment
UH 2.2 m R-Band Image
(Kalas ApJ 635 169 2005)
LBT/LMIRcam L-band'/ ADI
Rodigas et al ApJ 783 21 (2014)
see talk by Rodigas 5PM
5" (560 AU)

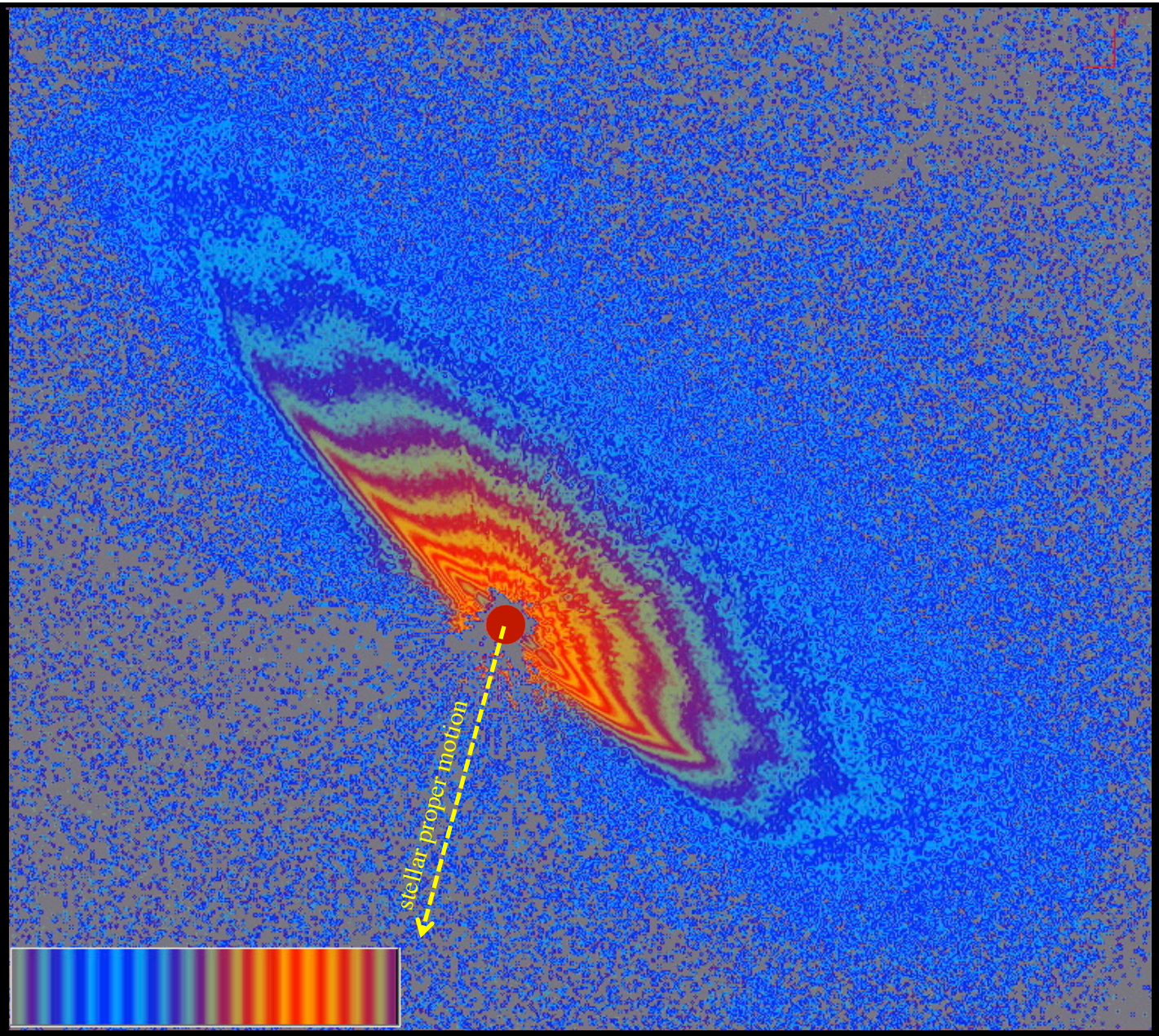
HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)



1”

HST/STIS 6R-PSFTSC (Schneider et al AJ 148 59 2014)

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

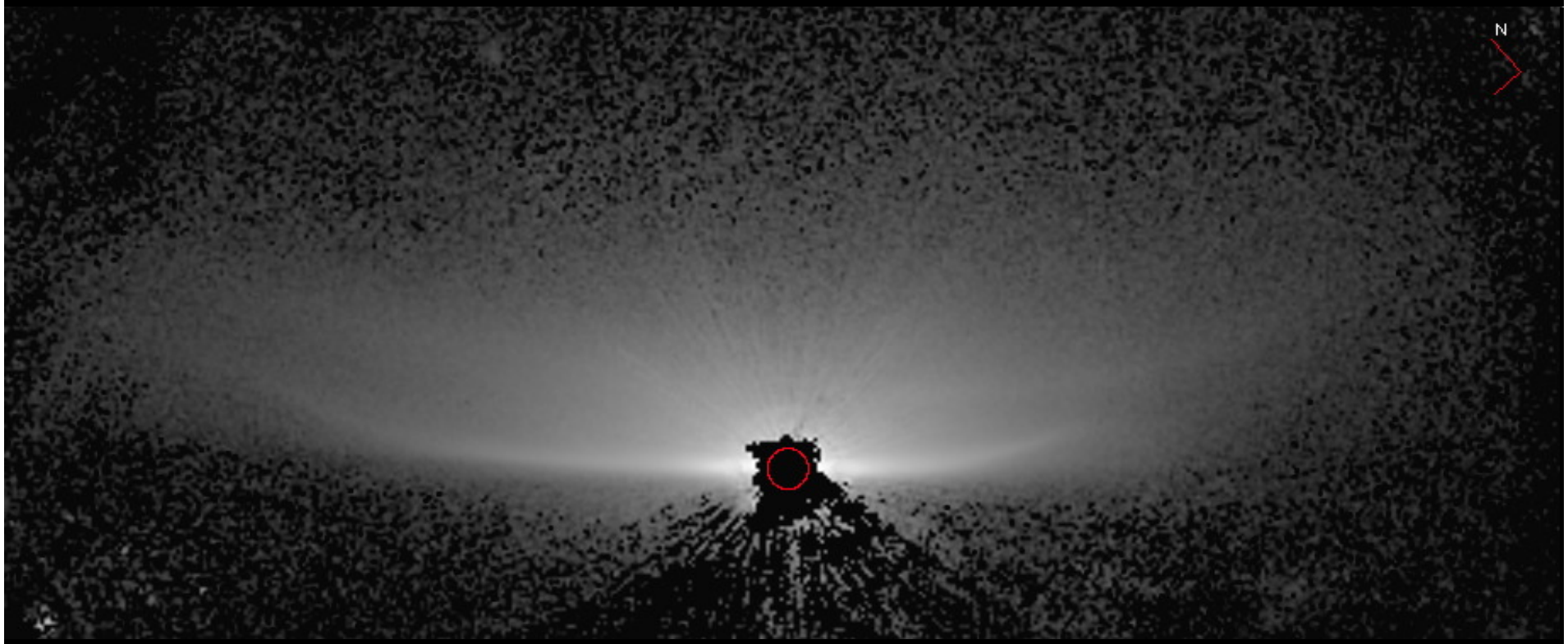


HST/STIS 6R-PSFTSC (Schneider et al 2014)

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

Debris System Structure and Asymmetries

23.2” (2600 AU)

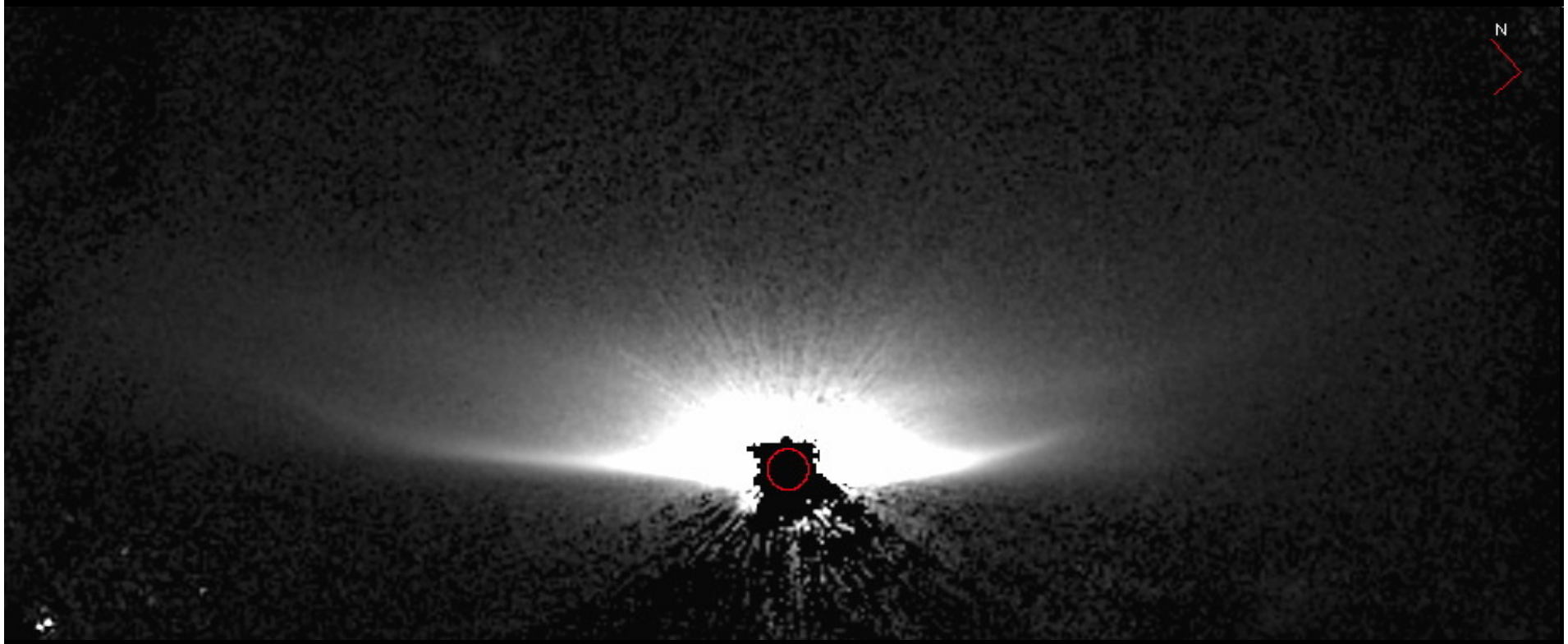


Log10 display from [-3] to [+2.13] dex counts/sec/pixel

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

Debris System Structure and Asymmetries

23.2” (2600 AU)

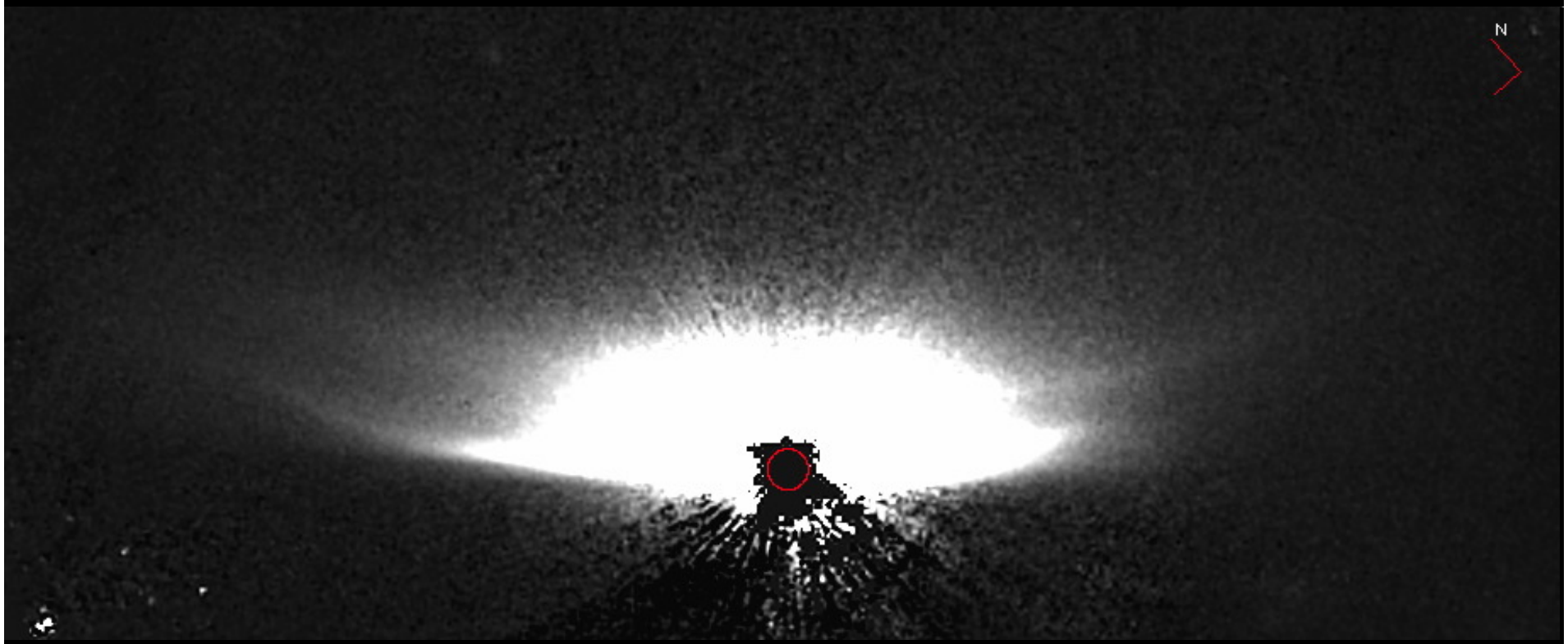


Sqrt display from 0 to 1 counts/sec/pixel

HD 32297 (A0V @ 112 pc, V = 8.13, B-V = +0.20, ~ 12 My)

Debris System Structure and Asymmetries

23.2” (2600 AU)



Linear from -0.01 to +0.2 counts/sec/pixel.

HD 15115 (aka {BLUE/GREY} "Needle")

An ~ 12 Myr, 45 pc distant F2 star (BPMG) with

Nearly edge-on, r ~ 320 AU debris structure

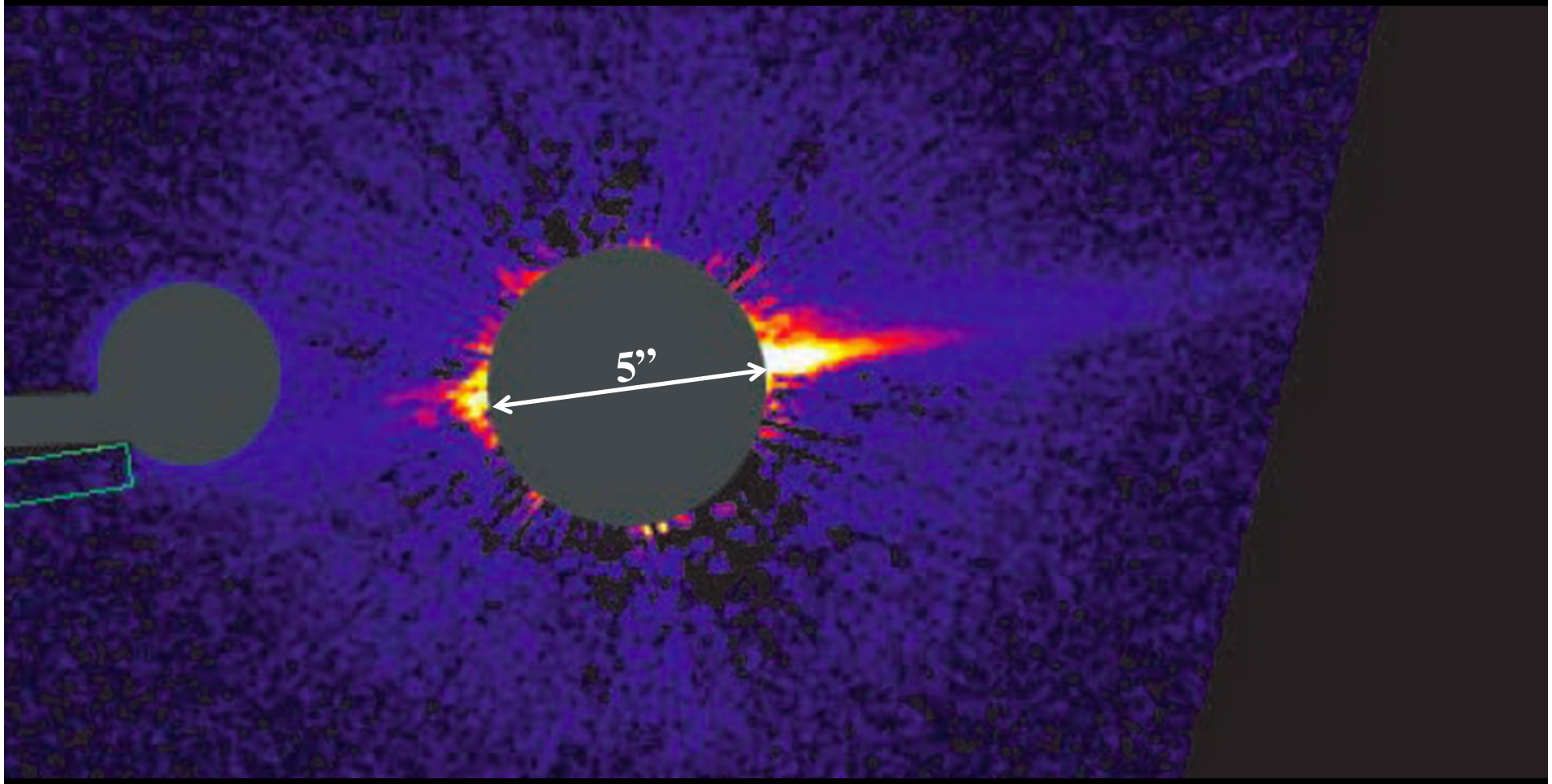
Highly asymmetric (w.r.t. all axes)

Complex sub-structures

ISM/exo-stellar interaction?

HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

HST/ACS F606W Discovery Image (Kalas et al. 2007)

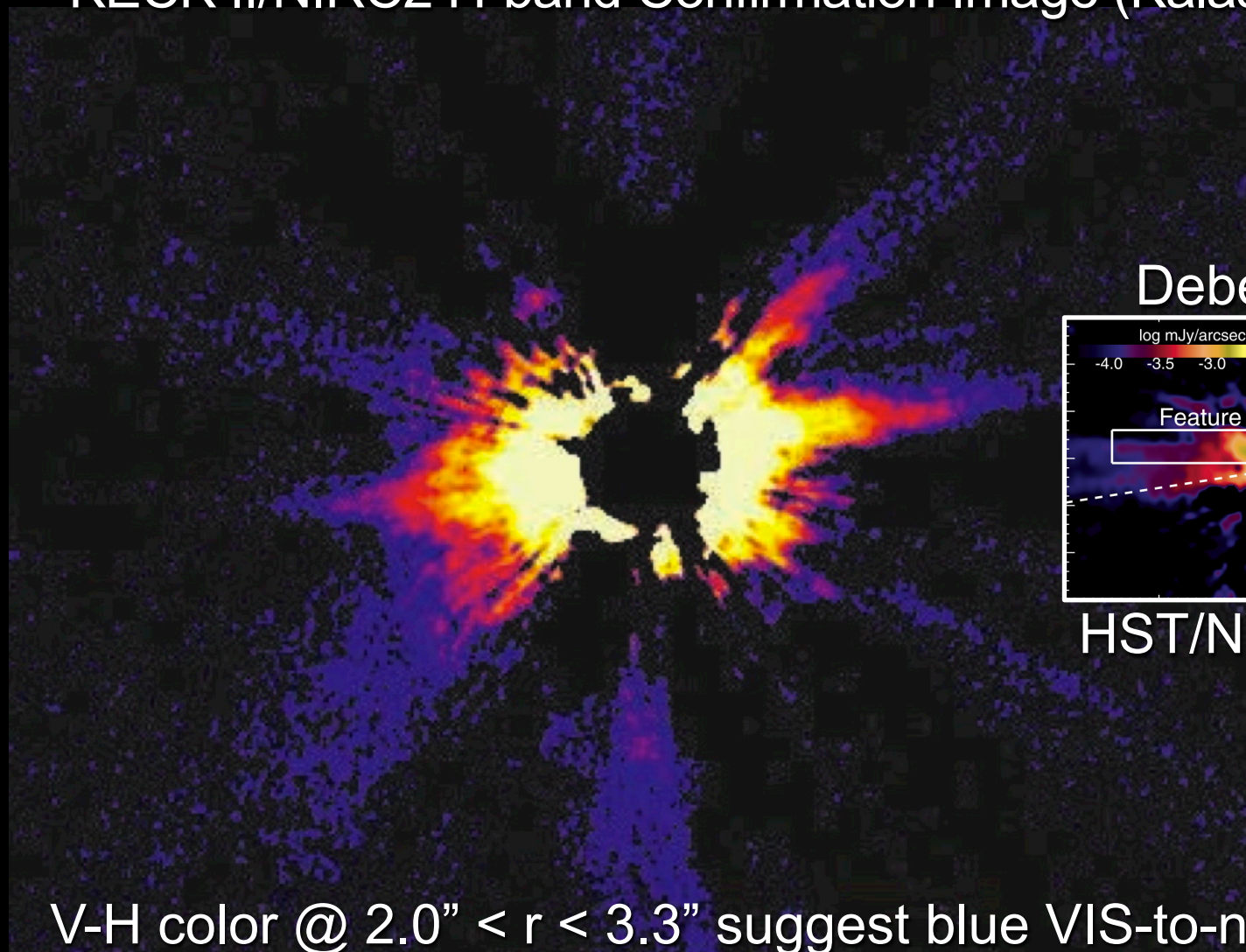


“Extreme” E/W stellocentric asymmetry extent along disk major axis

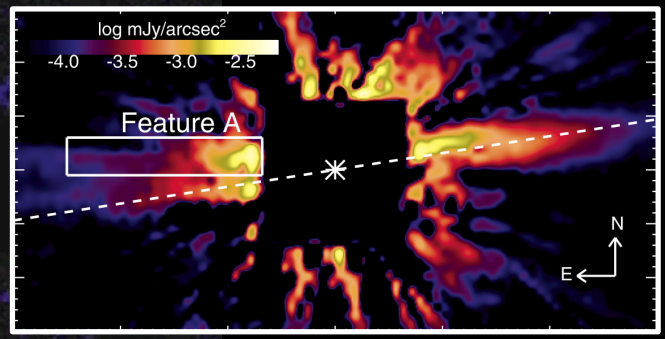
→ Posited dynamical perturbation from nearby comoving M-star HIP 12545

HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

KECK II/NIRC2 H-band Confirmation Image (Kalas et al. 2007)



Debes et al 2008



HST/NICMOS 1.1 μm

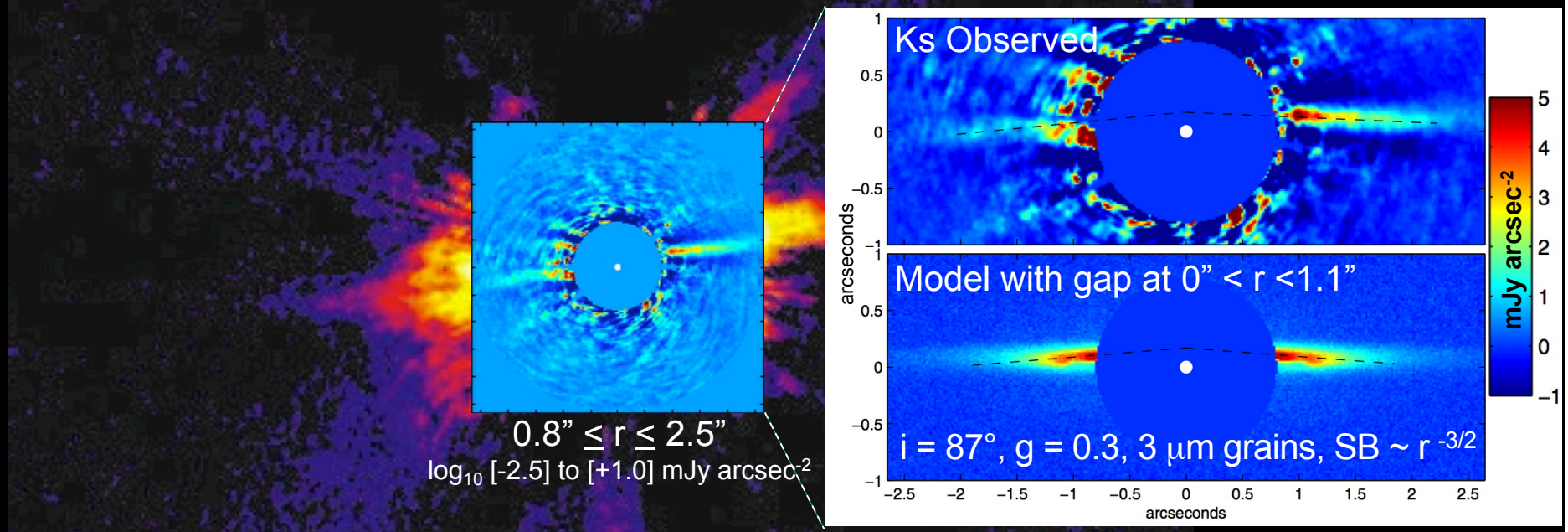
V-H color @ 2.0" < r < 3.3" suggest blue VIS-to-nIR scattering
"may indicate grain properties similar to AU Mic"

Debes et al 2008: V-1.1μm-H color gradients in disk; red @ r = 1

HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

KECK II/NIRC2 H-band Confirmation Image (Kalas et al. 2007)

LBT/AO+PICES Ks (shown), LBTI+LMIRcam L' ADI + LOCI (Rodigas et al. 2012)



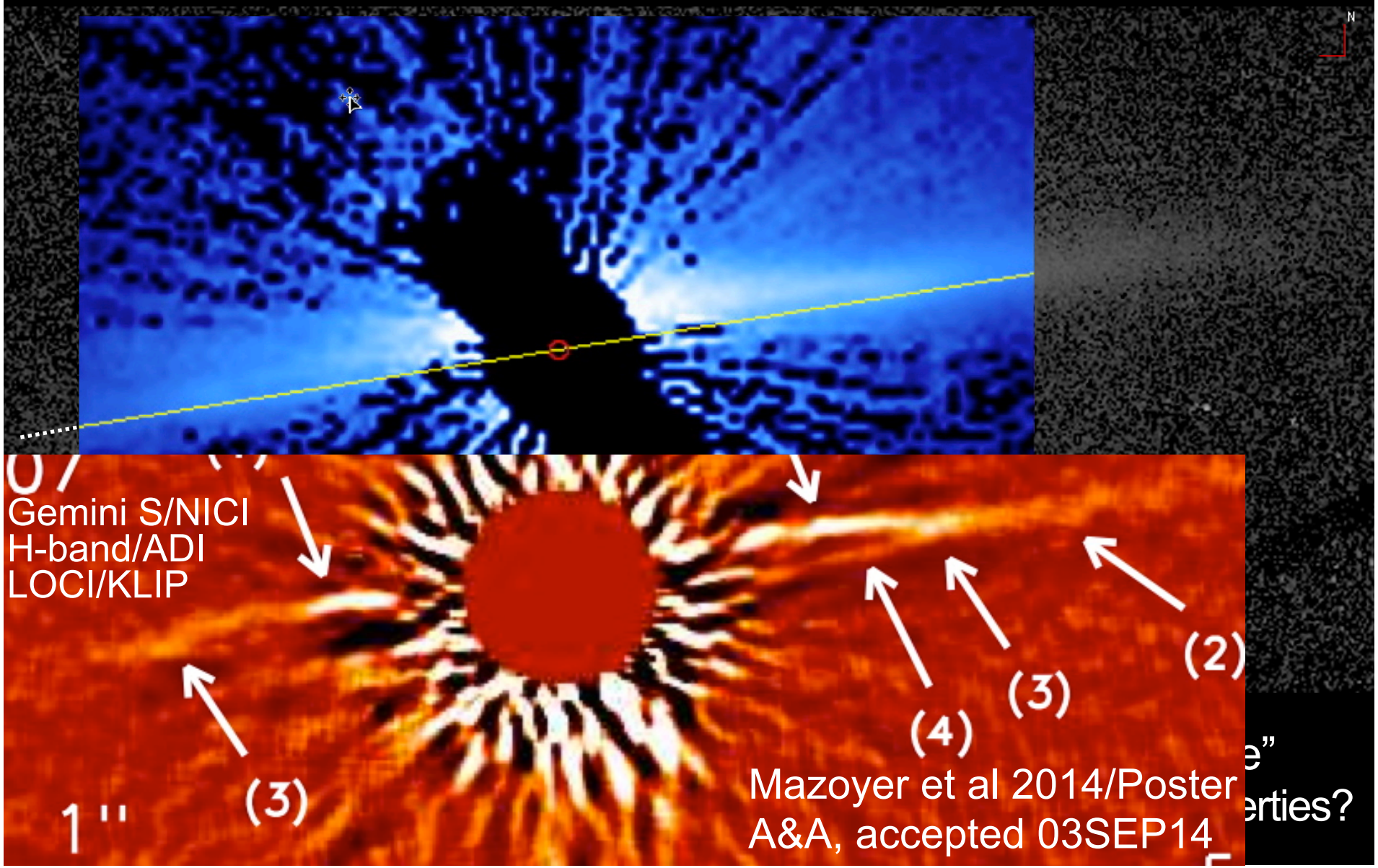
Ks – L' color is grey from 1.10 – 1.45 AU

1-10 μm grains on W side, 3-10 μm grains on E side

→ Supports ISM interaction scenario, agreement with Debes et al 2009

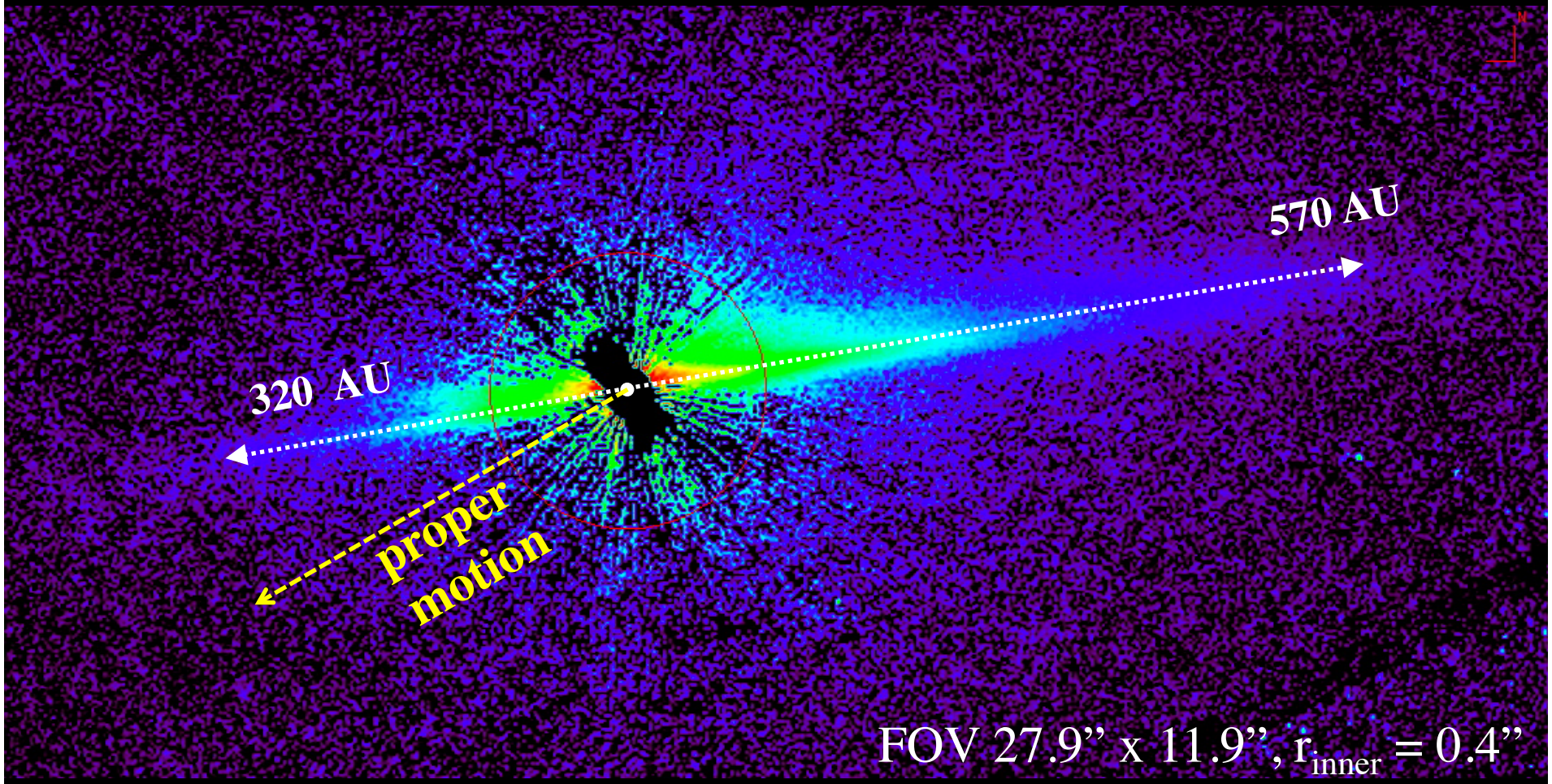
HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

HST/STIS F606W 6R-PSFTFC Image (Schneider et al. 2014)



HD 15115 (F2 @ 45.2 pc, V = 6.80, B-V = +0.35, BPMG, ~ 12 My)

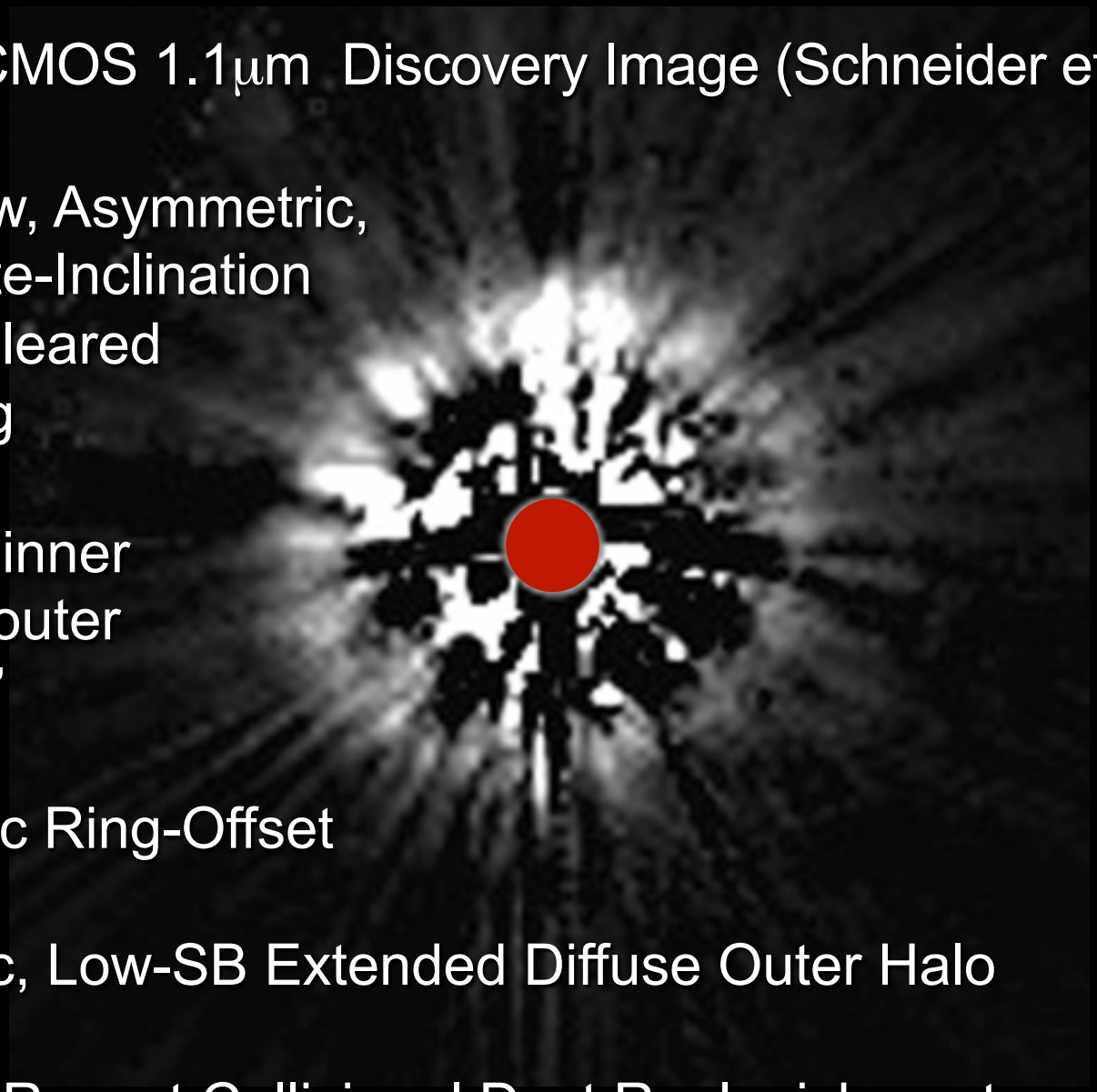
HST/STIS F606W 6R-PSFTFC Image (Schneider et al. 2014)



"Extreme" E/W stellocentric asymmetry extent along disk major axis
→ Possible ISM interaction?

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

HST/NICMOS 1.1μm Discovery Image (Schneider et al 2005)



W/D Narrow, Asymmetric,
Intermediate-Inclination
Centrally-Cleared
Debris Ring

Very steep inner
And steep outer
"truncation"

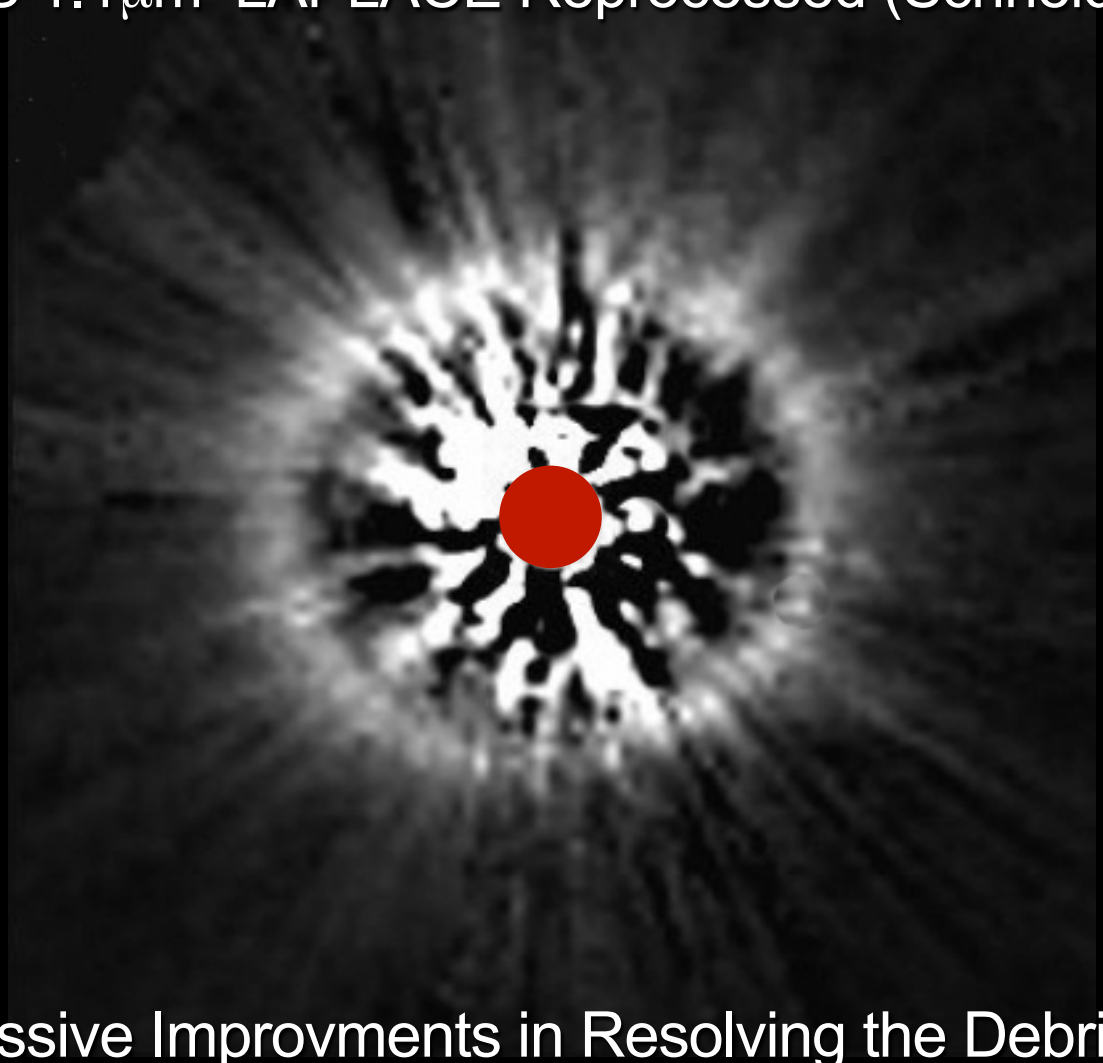
Stellocentric Ring-Offset

Asymmetric, Low-SB Extended Diffuse Outer Halo

Postulated Recent Collisional Dust Replenishment

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

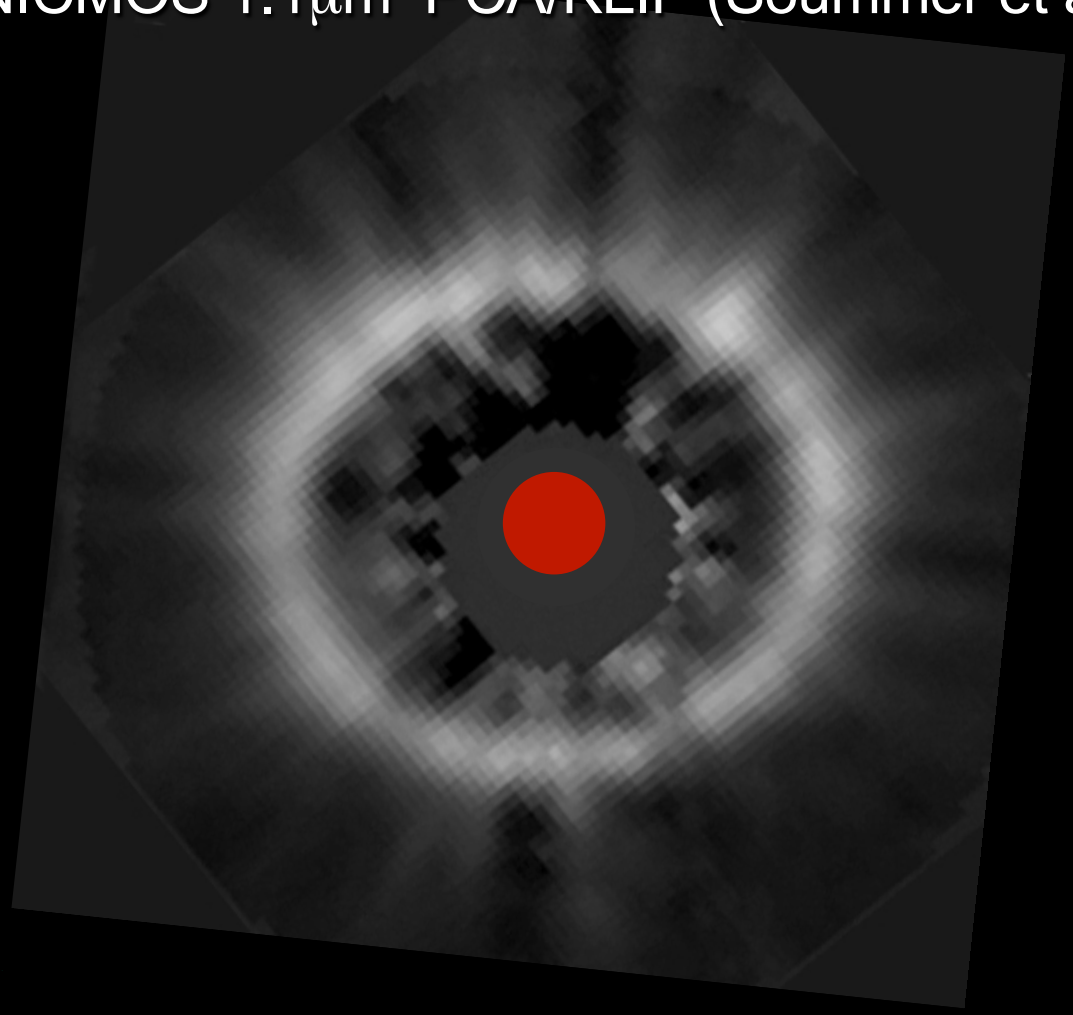
HST/NICMOS 1.1μm LAPLACE Reprocessed (Schneider et al 2011)



Successive Improvments in Resolving the Debris Ring

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

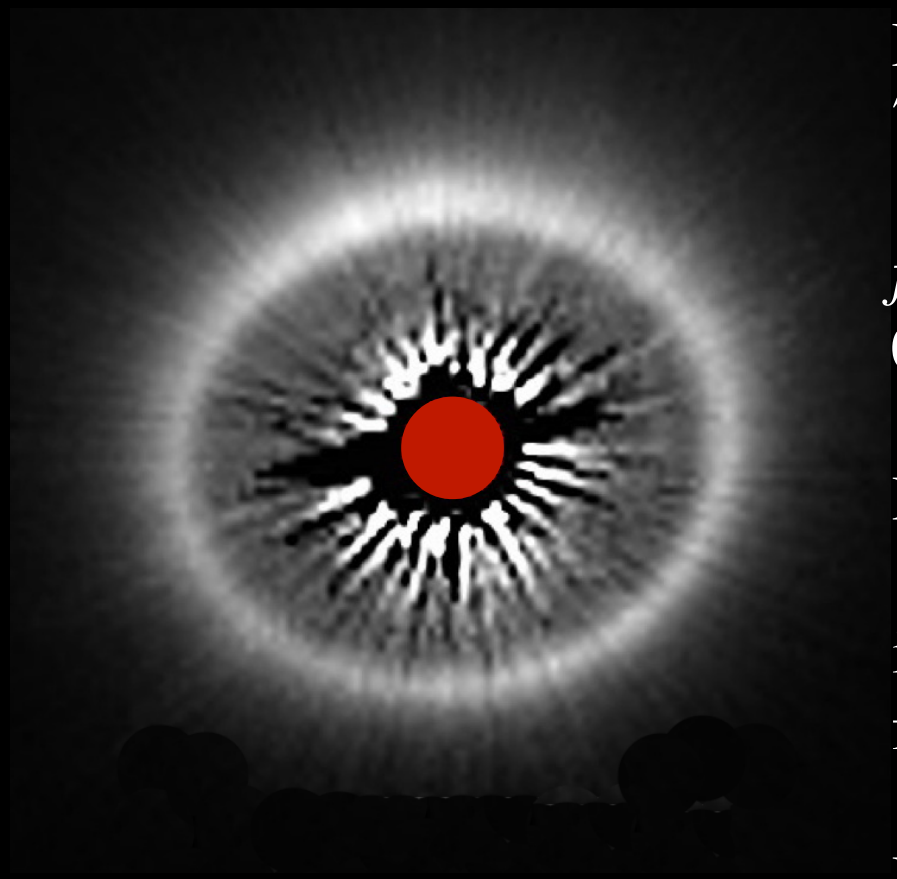
HST/NICMOS 1.1μm PCA/KLIP (Soummer et al 2012)



Successive Improvments in Resolving the Debris Ring

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

HST/STIS Broadband Optical (Schneider et al 2014)



Flux Density:
7.81 mJy (± few%)

f_{disk}/f_{star}:
0.17±0.015%

PA = 102° ± 4°

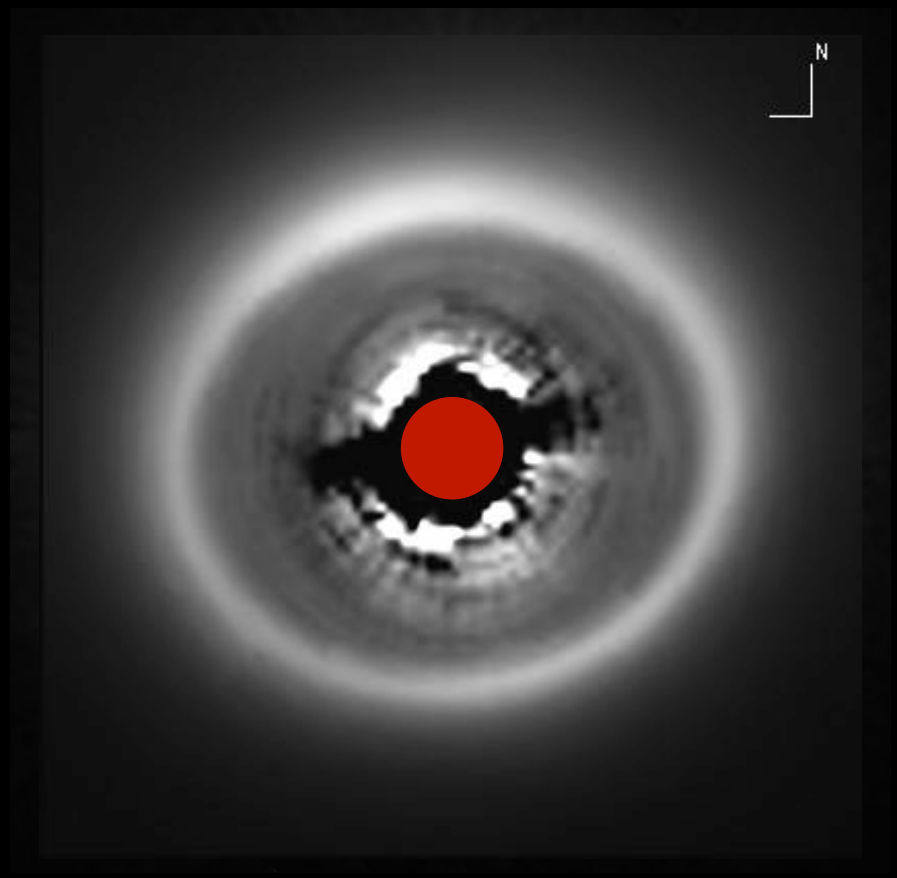
i = 30.1° ± 1.2°
from face-on

D_{ring} = 177.7 AU

W/D(SW) = 0.131

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Data: HST/STIS Broadband Optical (Schneider et al 2014)

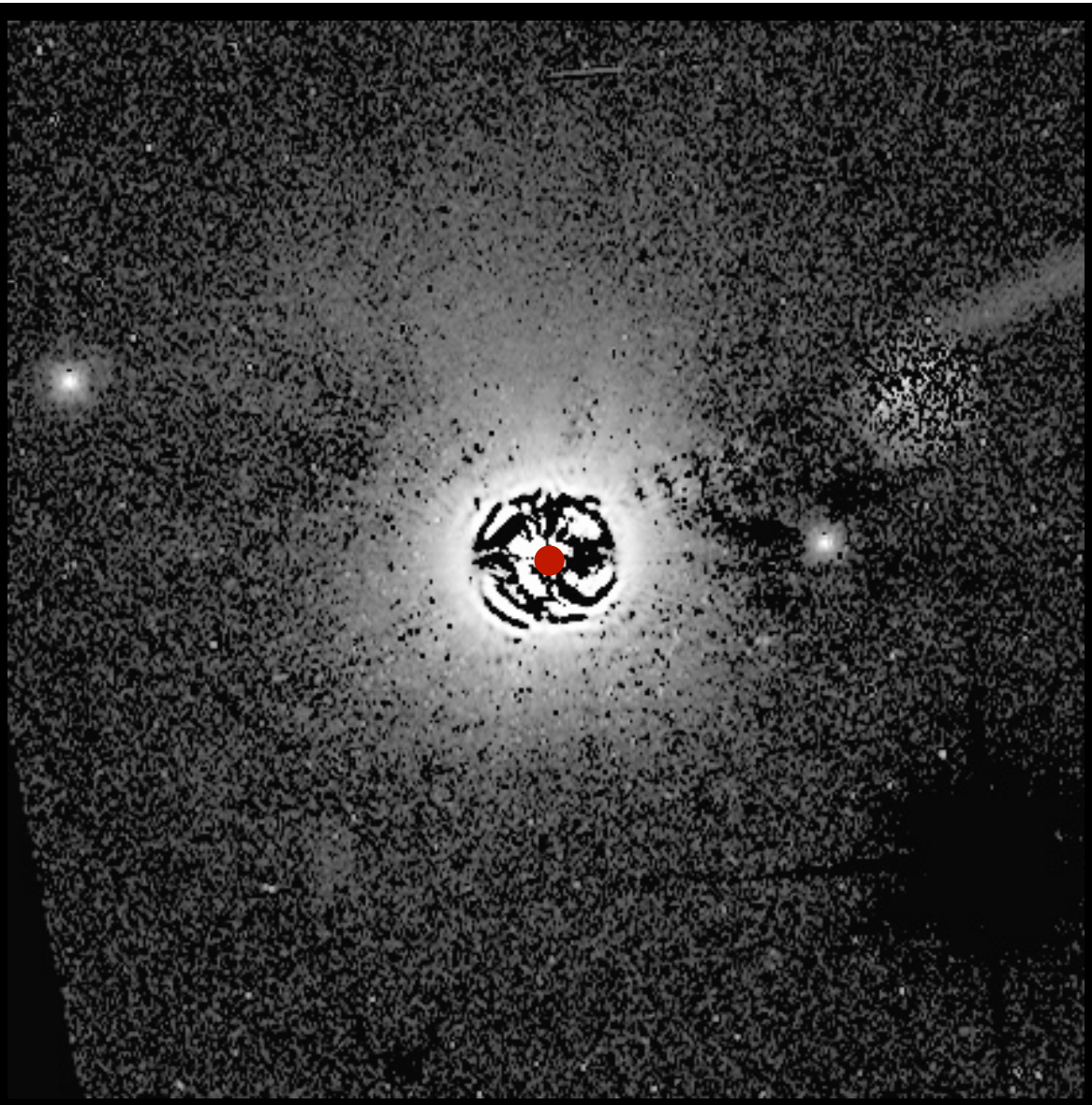


Multiple-Roll Residual Removal (Stark et al 2014)

+

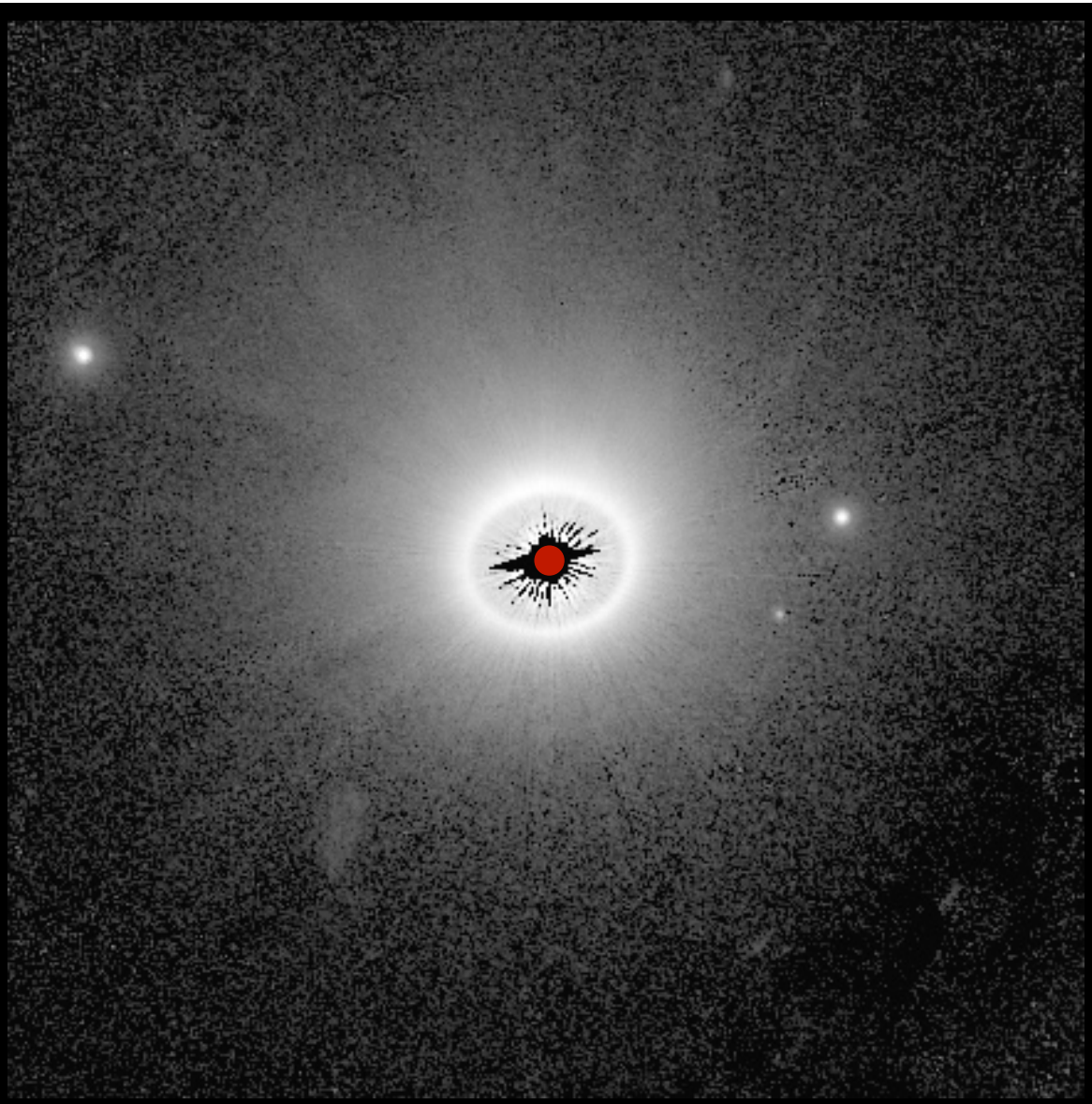
Radially Adaptive Iterative Azimuthal Filtering (Schneider et al in prep)

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)



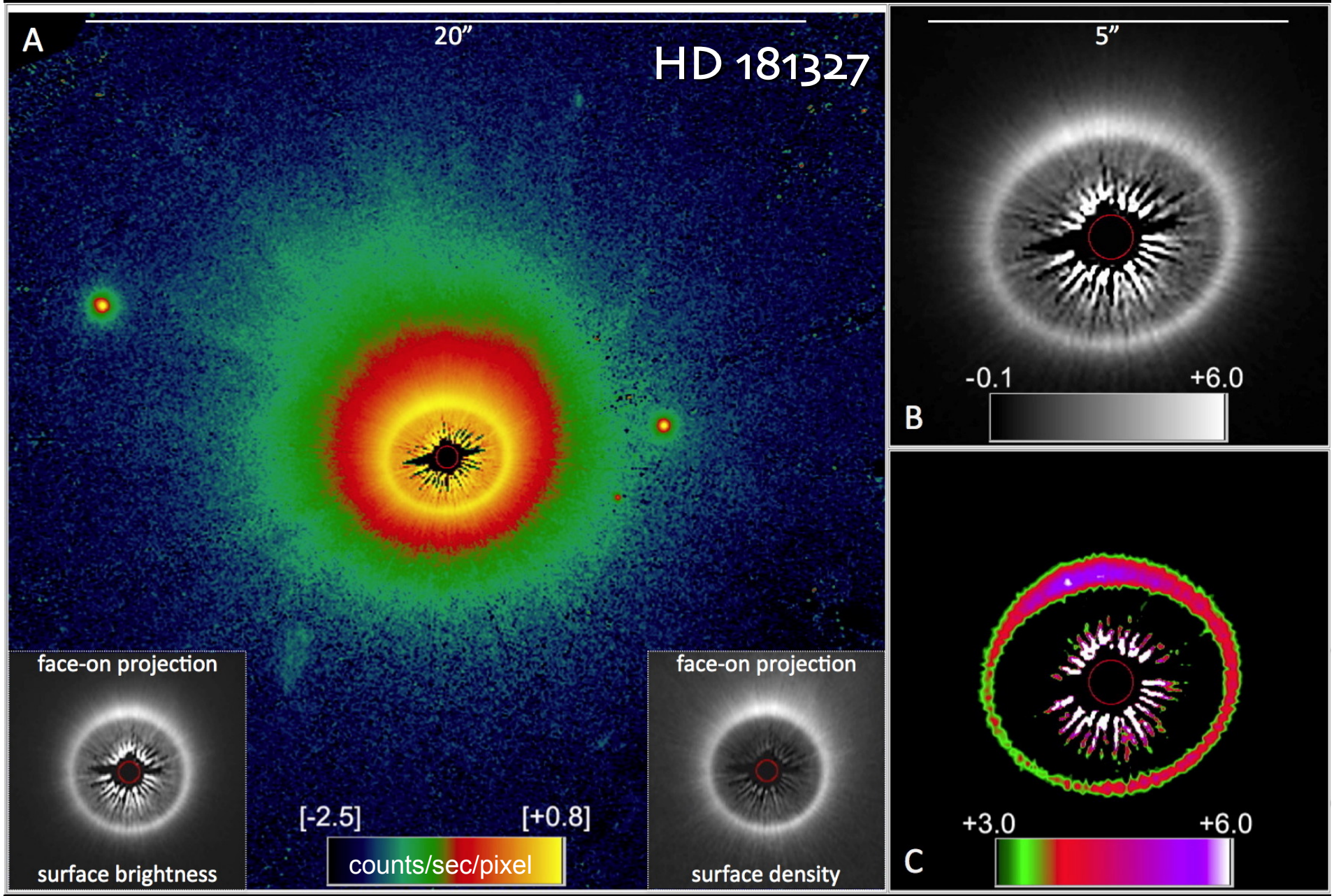
HST/ACS 0.61μm co-Discovery Deep Image (Schneider et al 2005)

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)



HST/STIS Optical Broadband Deep Image (Schneider et al 2014)

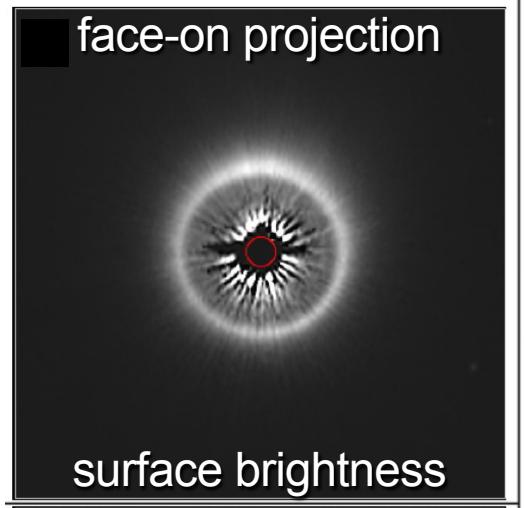
HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

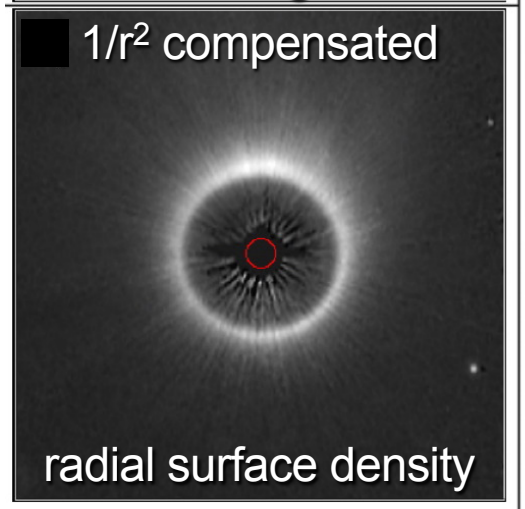


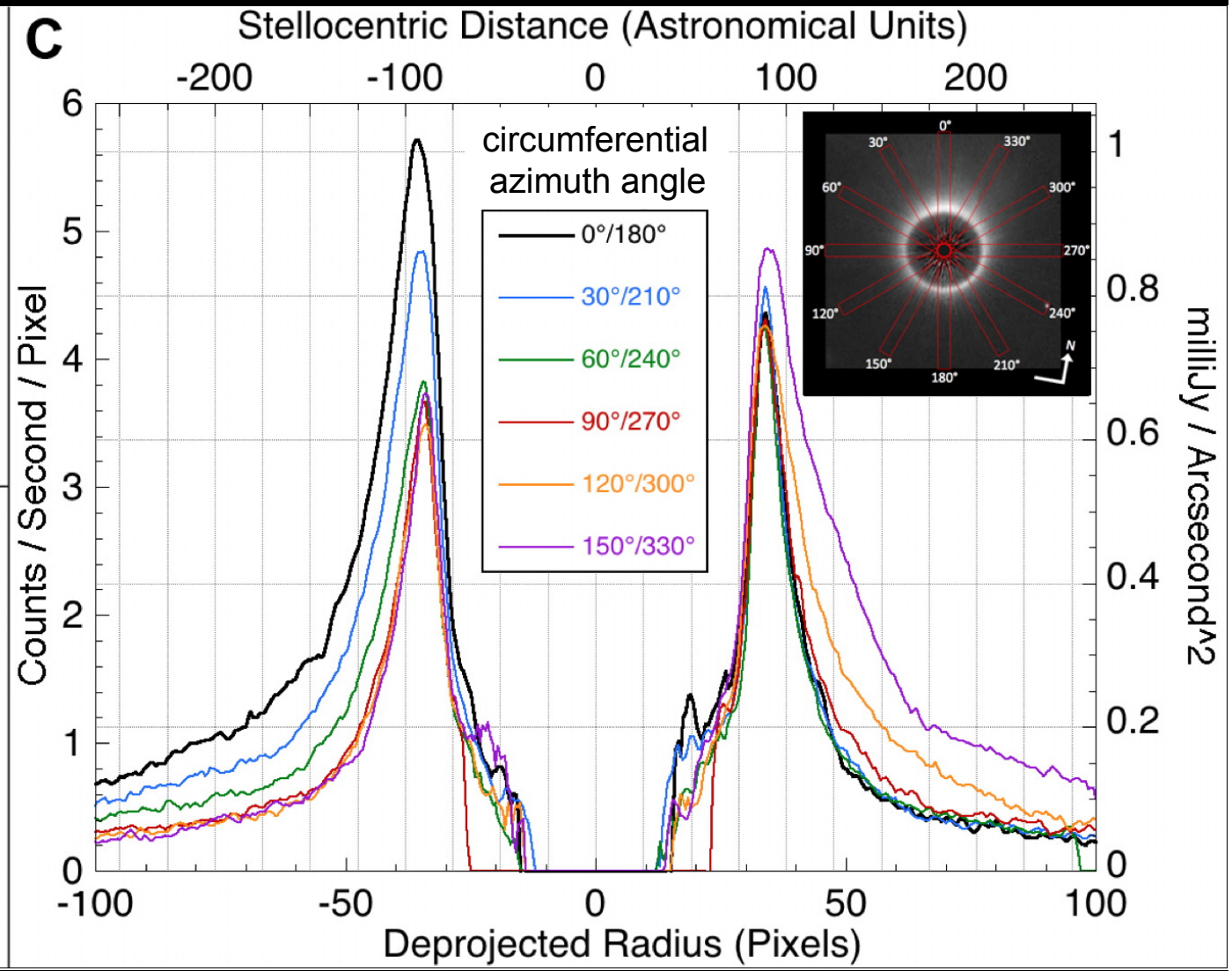
A: Log display - ring and diffuse asymmetric halo B & C: Linear display - narrow width,sharpness, SB asymmetries.

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Inner "hole", peak, and exo-ring radial "surface density" profiles



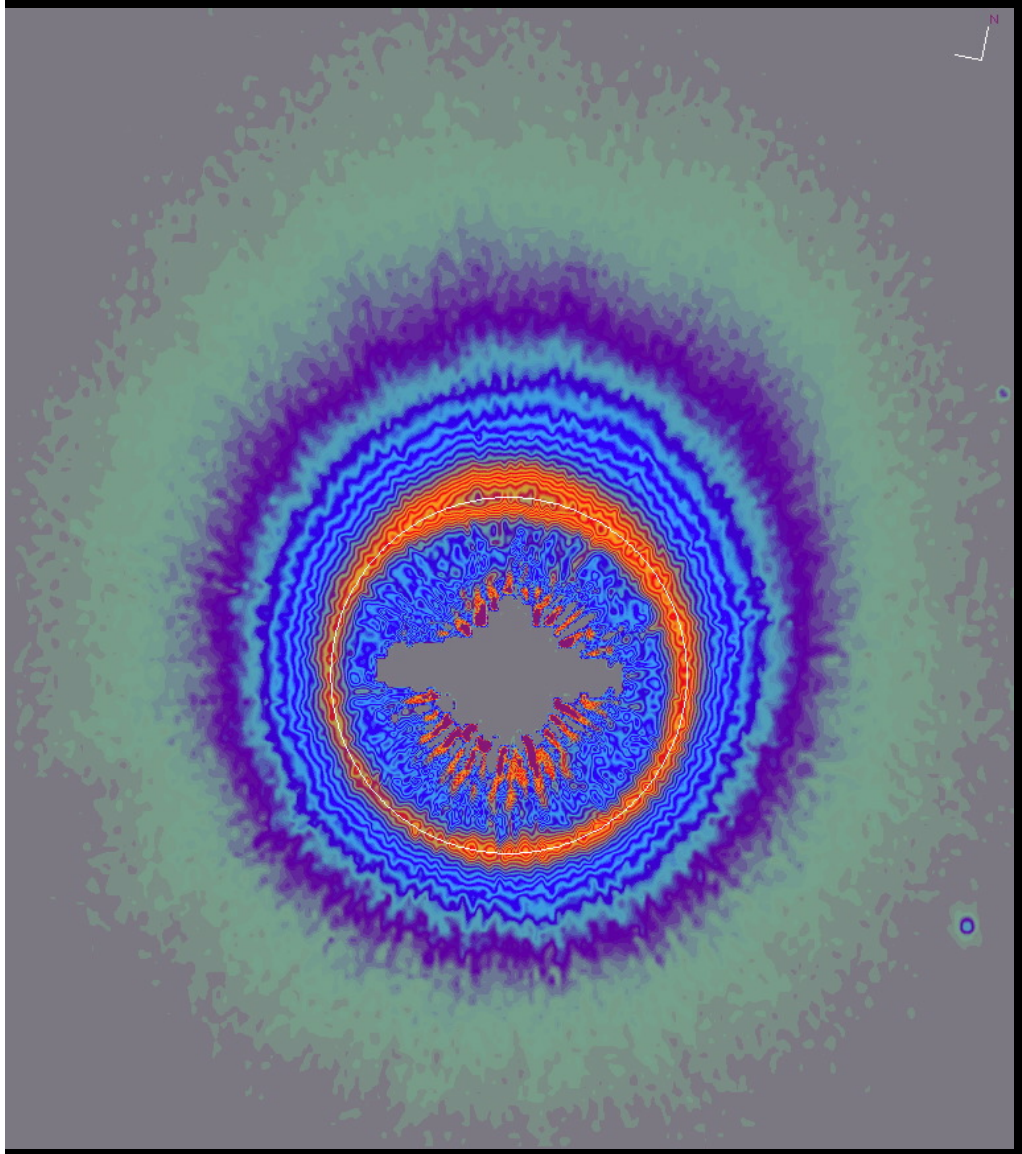


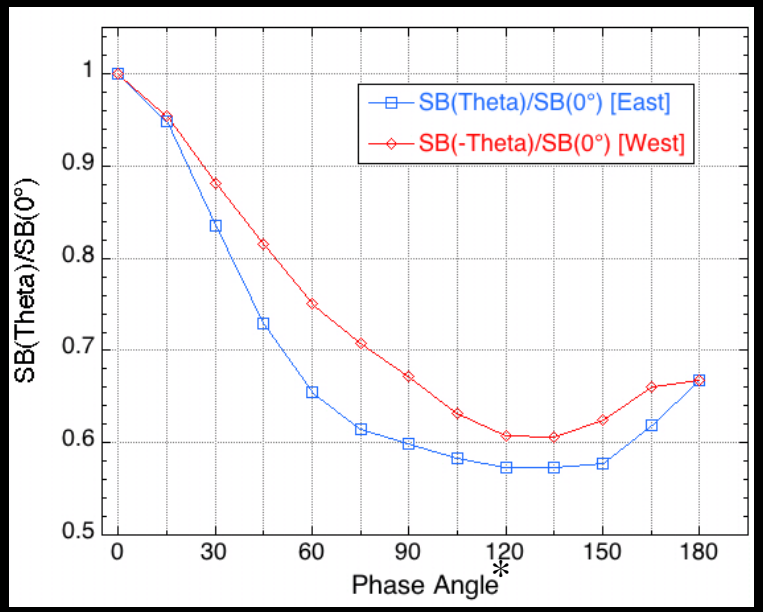


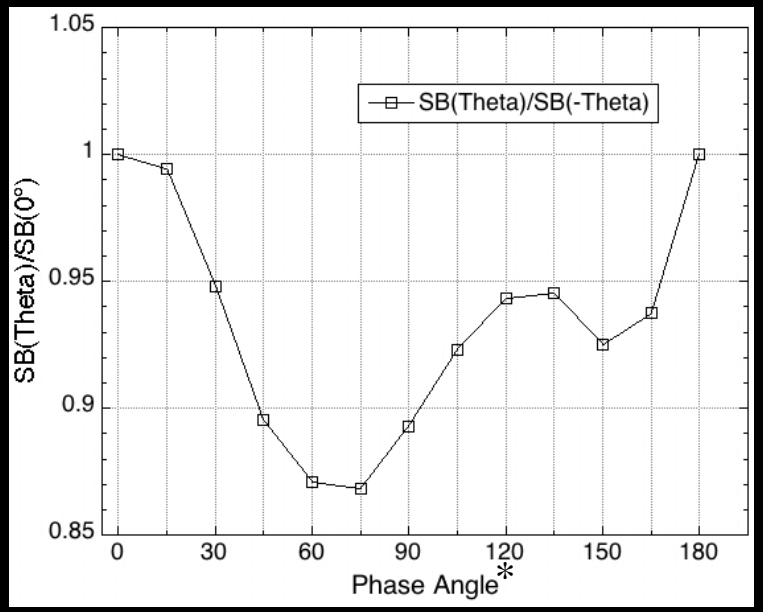
Stellocentric position uncertainty: 4.4 mas RMS

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Radial & Azimuthal SB asymmetries



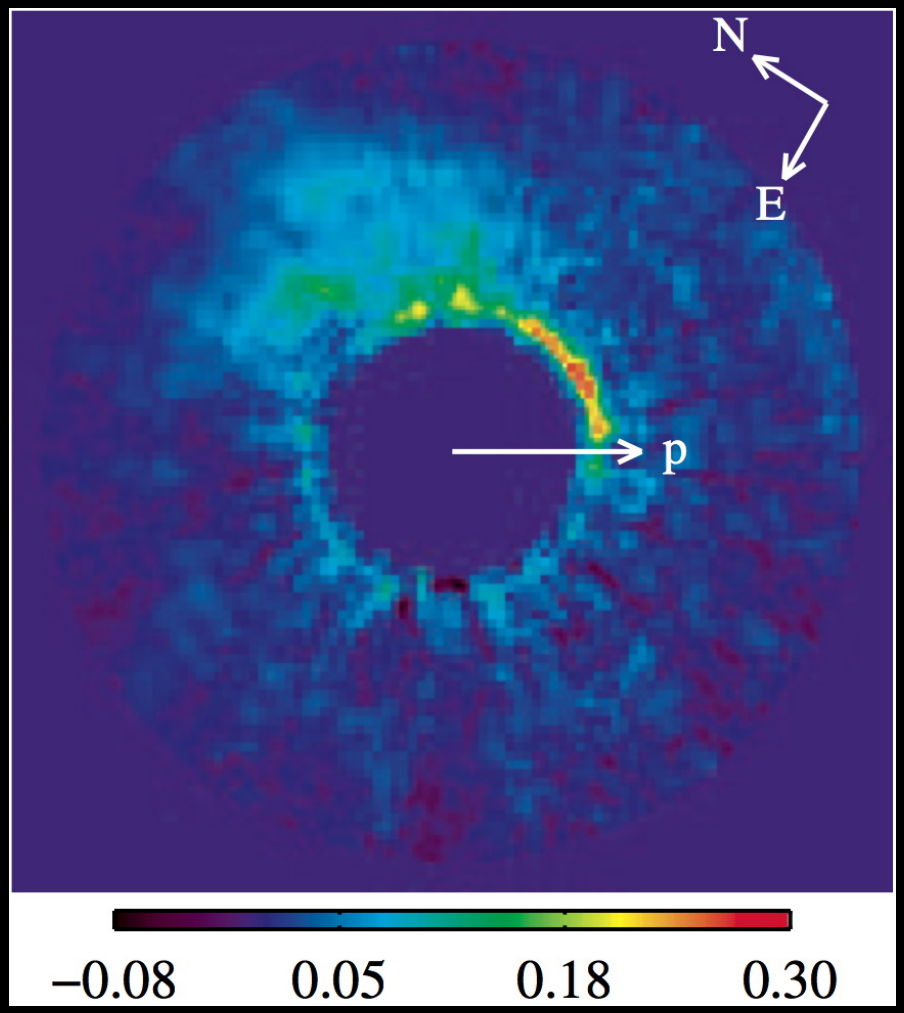




* w.r.t. azimuth of peak SB along the ring

HD 181327 (F6V @ 51.8 pc, V = 7.03, B-V = +0.48, 12-20 My)

Stark et al ApJ 789 59 (2014) models HD 181327 SB asymmetries



Optical depth deviations from a uniform disk (face-on projected)

Inconsistent with emperically determined scattering phase function (not well-represented with H-G SPF) assuming an unpretured disk → unseen planet

Consistent with:

- Recent catastrophic distruption of body with ≥ 1% M_{pluto}
- Disk "warping" with strong ISM interaction

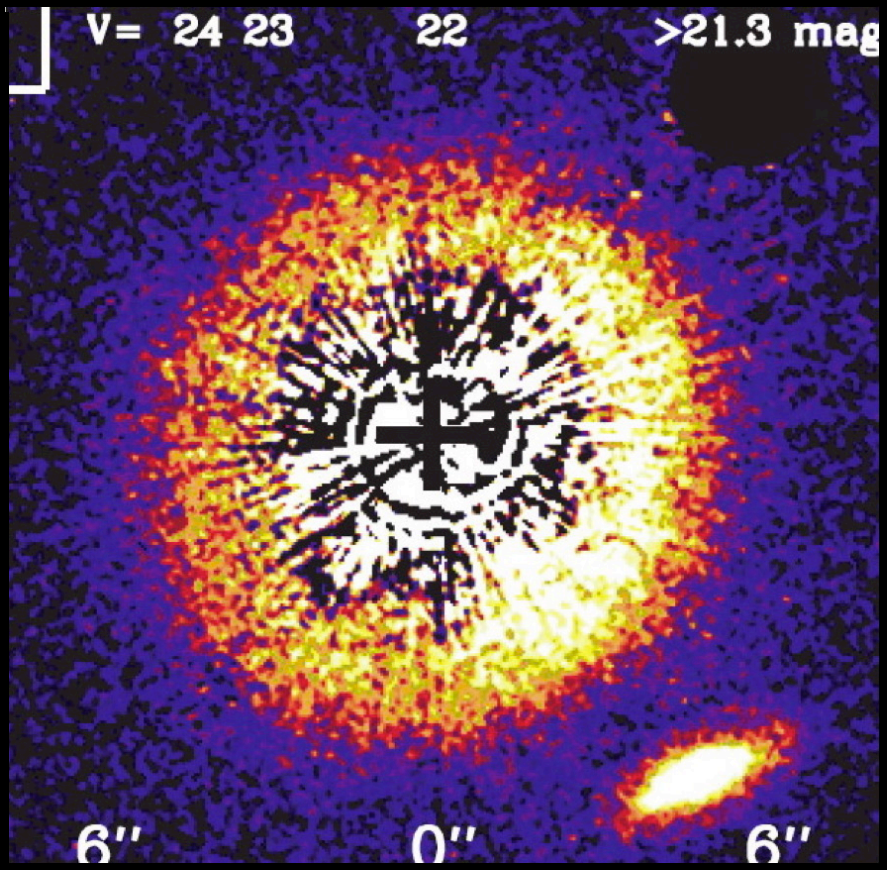
A VERY QUICK LOOK AT SOME

“OTHER” (WELL-RESOLVED)

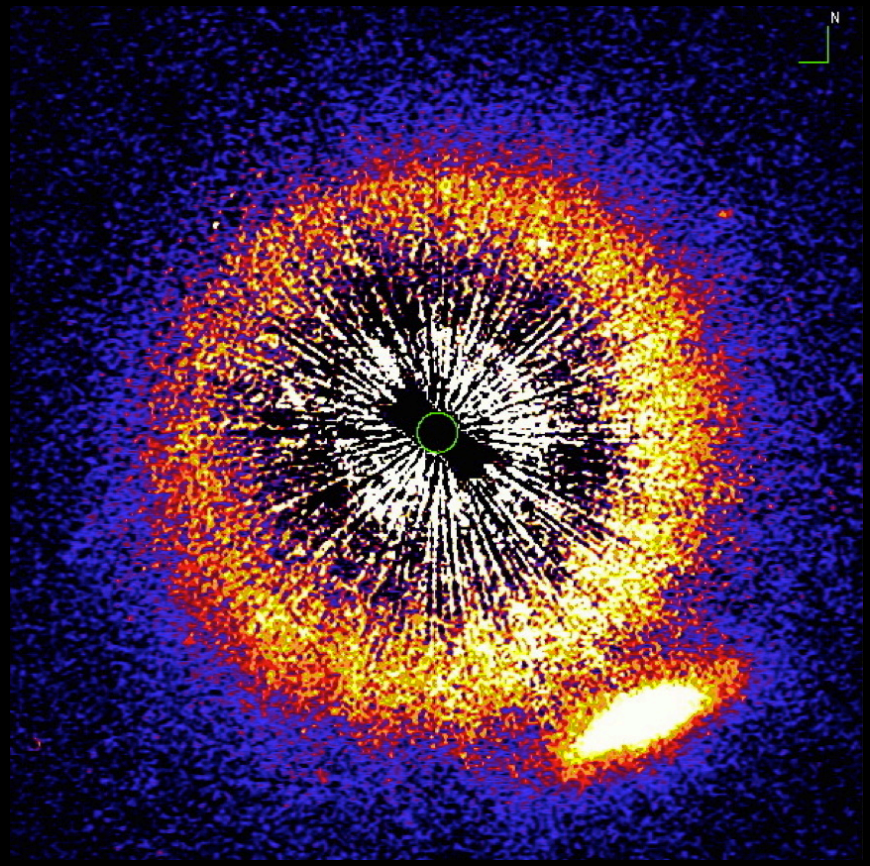
LIGHT-SCATTERING DEBRIS SYSTEMS

HD 107146 (G2V @ 27.5 pc, V = 7.07, B-V = +0.63, 80-200 My)

HST/ACS V (shown) & I Discovery Imaging
Ardila et al. 2004/05

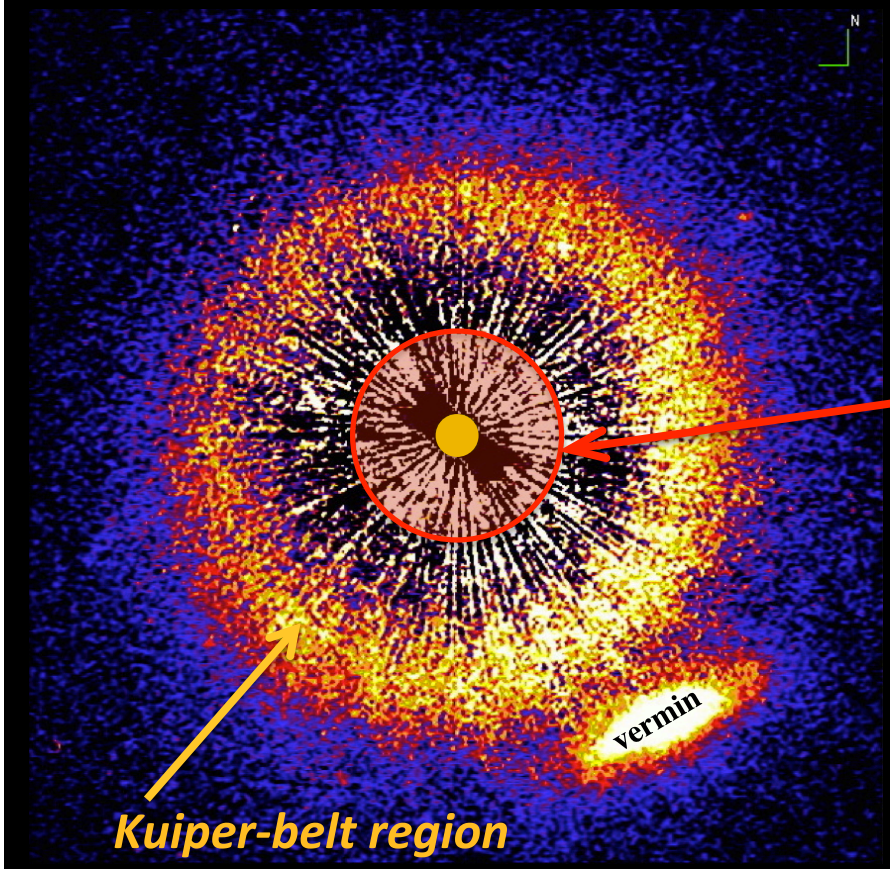


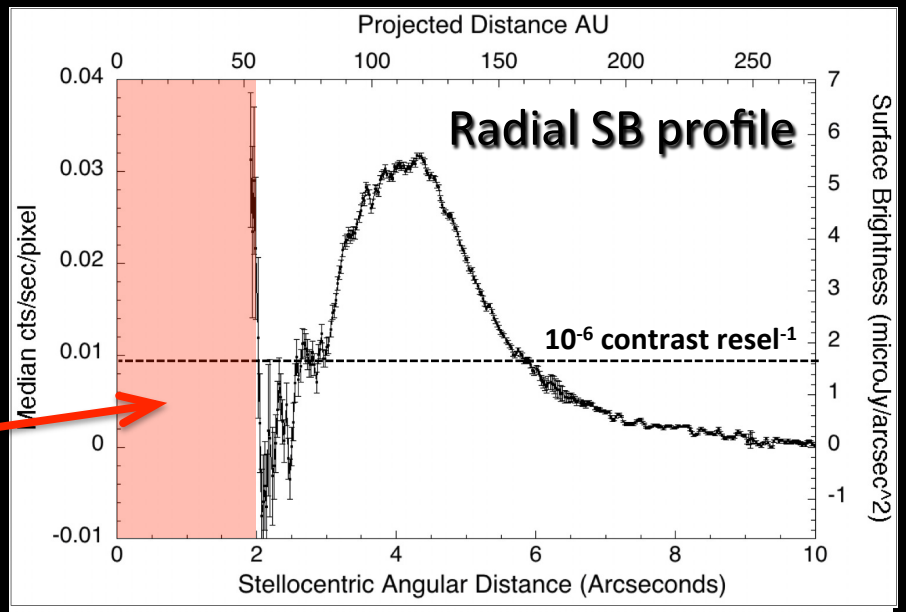
HST/STIS Broadband Optical
Schneider et al. 2014

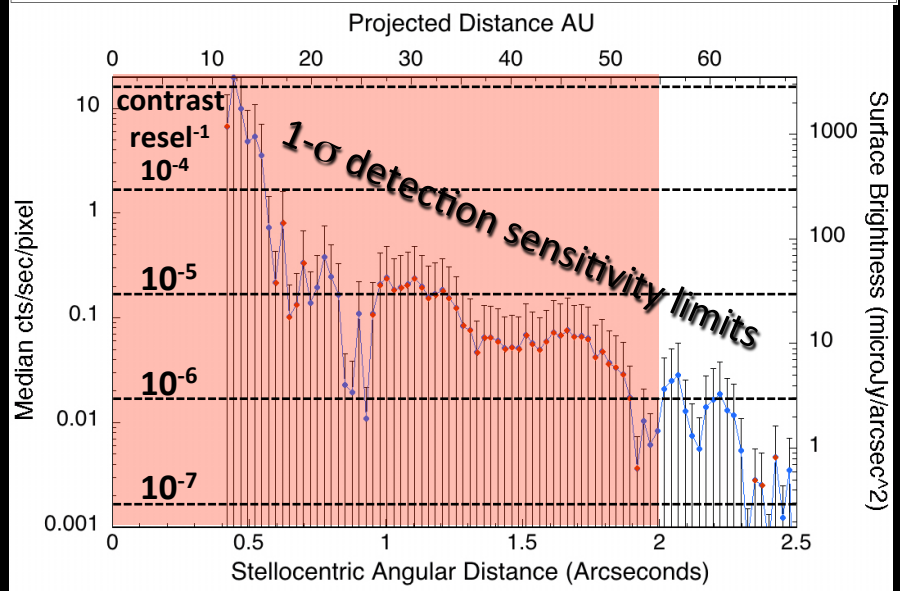


Broad ("Featureless"), Axisymmetric, Centrally-Cleared Ring-Like DD

HD 107146 (G2V @ 27.5 pc, V = 7.07, B-V = +0.63, 80-200 My)







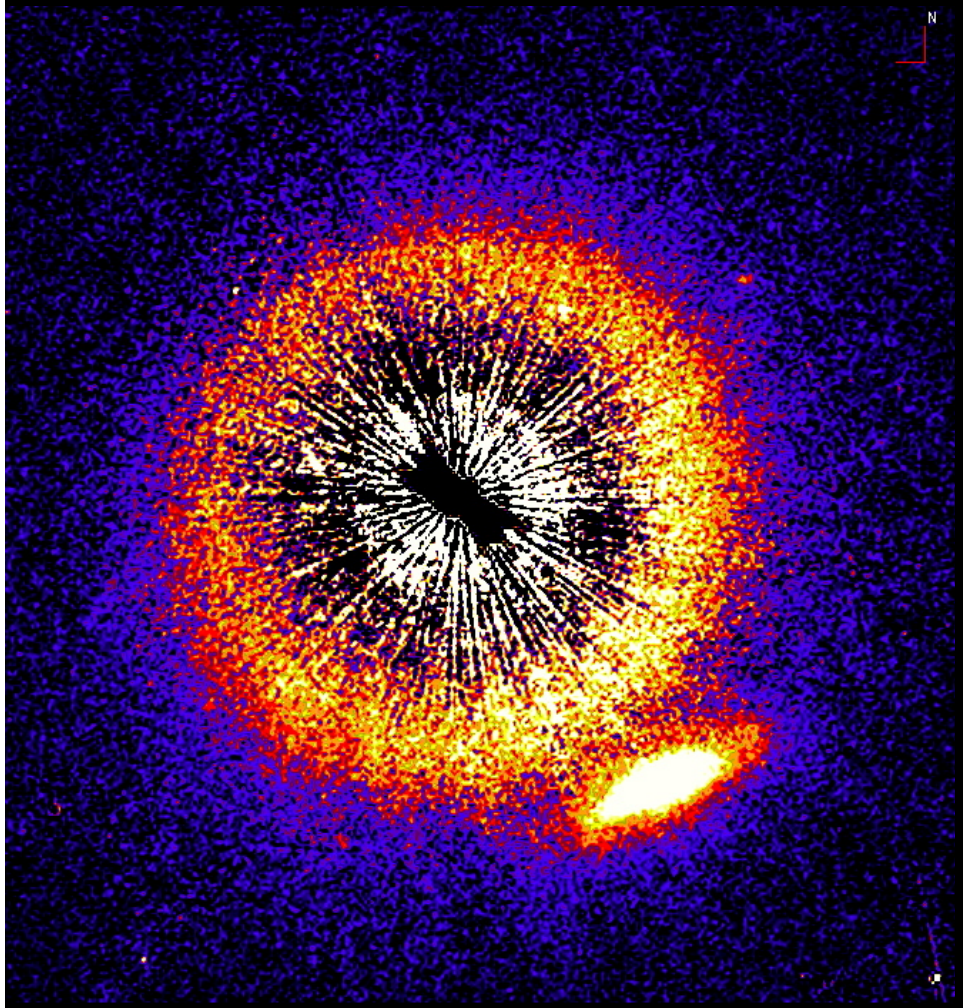
Fdisk = 0.40 mJy,

F_{disk}/F_{star} = 0.0077 ± 0.0004%

r_{ring} = 100 AU

HD 107146 (G2V @ 27.5 pc, V = 7.07, B-V = +0.63, 80-200 My)

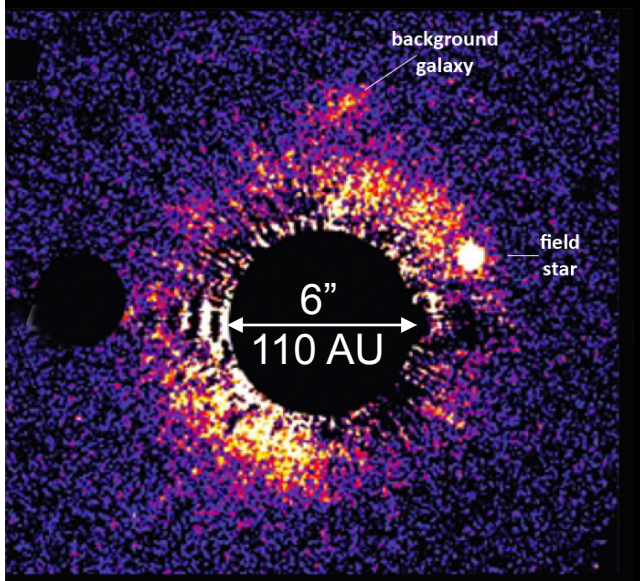
WARNING for FUTURE OBSERVERS



APRIL 2011

HD 53154 (G9V @ 18.3 pc, V = 6,82, B-V = +0.80, 1000 ± 300My)

HST/ACS 0.61 μm
Kalas et al 2006
Discovery Image

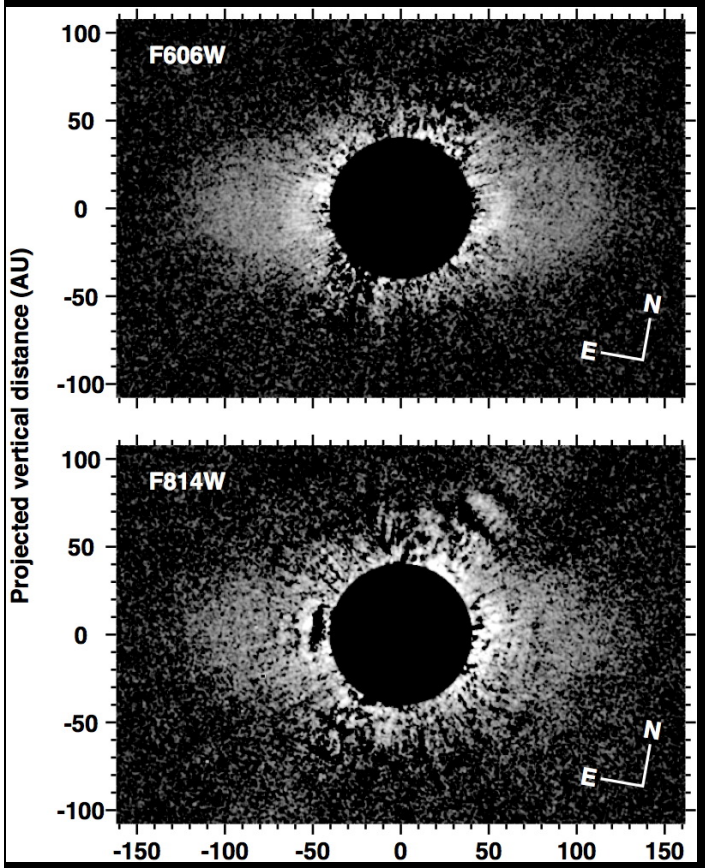


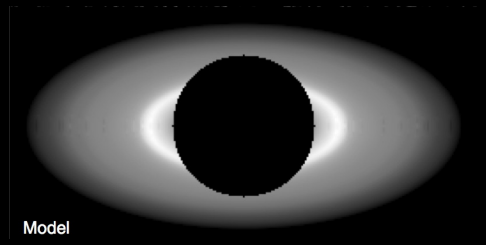
suggested ~ 45° incl.

But…

HD 92945 (K1V @ 21.4 pc, V = 8.59, B-V = +0.89, 80/150 - 300My)

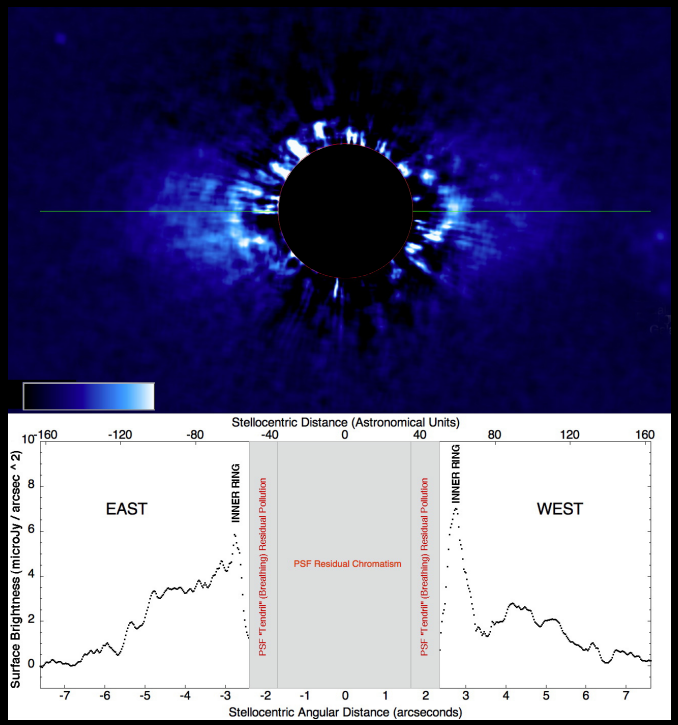
HST/ACS
Krist et al 2011
Discovery Imaging





Krist et al 2011
Scattered-Light
Model

HST/STIS
Schneider et al 2014
Broadband Optical



F_{disk} = 0.143 mJy

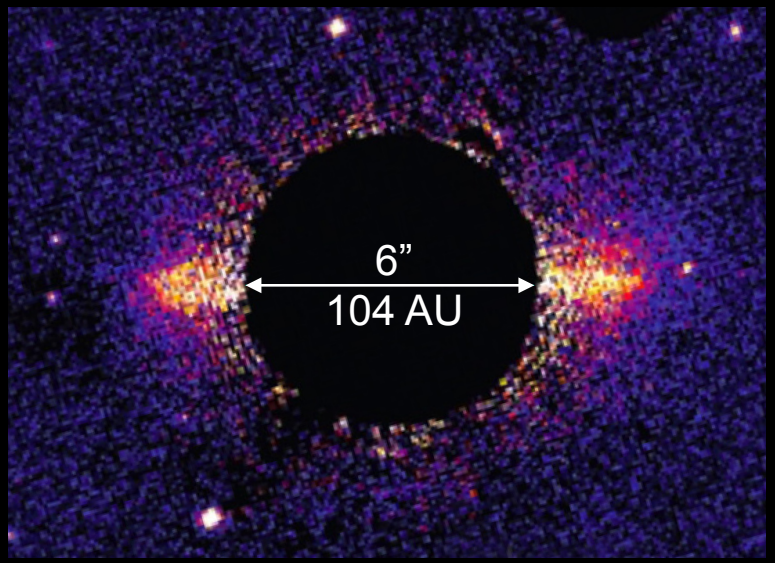
$F_{disk}/F_{star} \simeq 0.0051\%$

r_{ring} = 59 AU

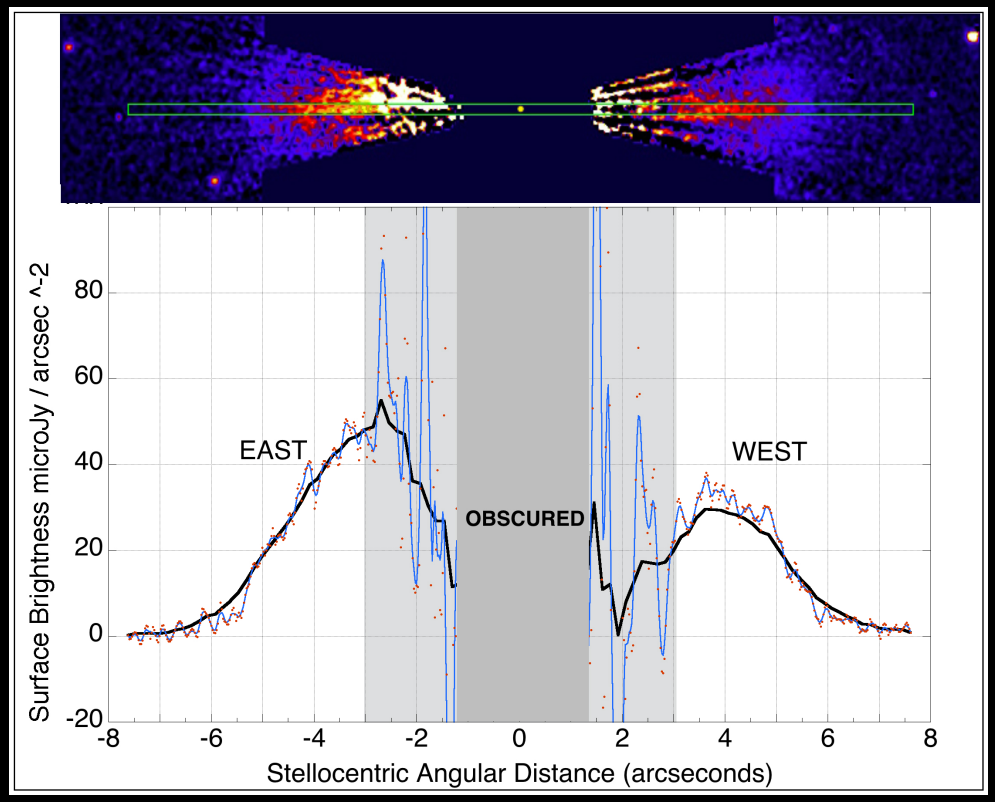
IWD_{LIMIT} = 50 AU

HD 139664 (F5V @ 17.4 pc, V = 4.64, B-V = +0.40, 100-1000 My)

HST/ACS
Kalas et al 2006
0.6 μm Discovery Imaging



HST/STIS
Schneider et al 2014
Broadband Optical



F_{disk} = 0.26 mJy
$F_{disk}/F_{star} \simeq$ 0.0005%
IWD_{LIMIT} = 23 AU

CONCLUDING REMARKS (Philosophical Comments)

1) The Beta Pictoris Debris Disk is a Prototype, *NOT* an Archetype

2) Circumstellar Debris Disks are Incredibly Diverse

3) There is NO such thing as a "Symmetric" Circumstellar Debris Disk

4) Circumstellar Debris Disks & Planets are Inexorabely Linked

5) Circumstellar Debris Disks CANNOT be considered in Isolation

6) The (EX)/AO era is upon us – exploit symbiotic & unique cpabilities

7) They are not "DISKS"! → Exoplanetary Debris Systems

CONCLUDING REMARKS (Philoosphical Comments)

1) The Beta Pictoris Debris System is a Prototype, *NOT* an Archetype

2) Exoplanetary Debris Systems are Incredibly Diverse

3) There is NO such thing as a "Symmetric" Exoplanetary Debris System

4) Exoplanetary Debris Systems & Planets are Inexorabely Linked

5) Exoplanetary Debris Systems CANNOT be considered in Isolation

6) The (EX)/AO era is upon us – exploit symbiotic & unique cpabilities

7) They are not "DISKS"! → Exoplanetary Debris Systems