

High-Contrast/High-Resolution Scattered Light Imaging of Circumstellar Disks

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HUBBLE SPACE TELESCOPE

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The Dusty Disk/Planet Connection

★ Current theories of disk/planet evolution suggest a presumed epoch of planet-building via the formation and agglomerative growth of embryonic bodies, and the subsequent accretion of gaseous atmospheres onto hot giant planets, is attendant with a significant decline in the gas-to-dust ratios in the remnant protostellar environments.

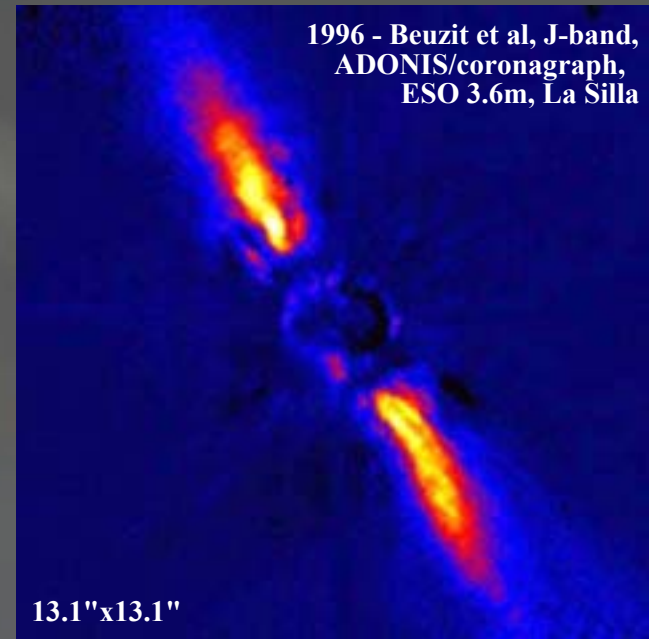
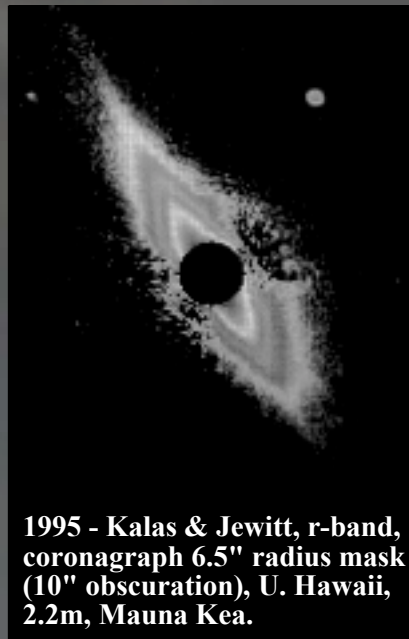
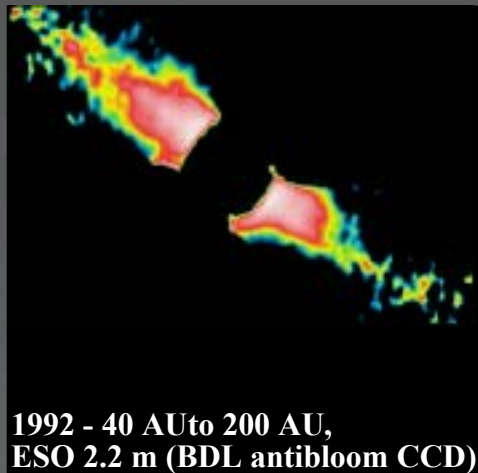
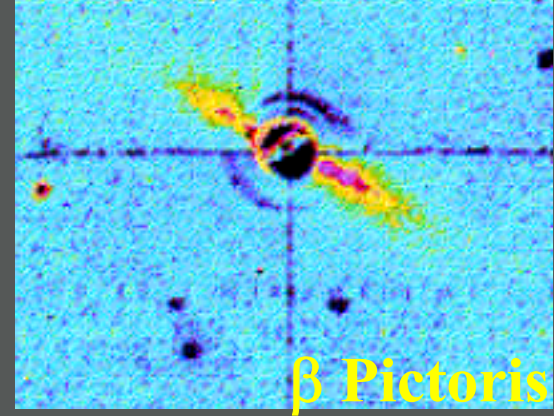
★ In this critical phase of newly formed (or forming) extra-solar planetary systems, posited from a few megayears to a few tens of megayears, the circumstellar environments become dominated by a second-generation population of dust containing larger grains arising from the collisional erosion of planetesimals.

Direct (Scattered Light) Imaging of Dusty Debris

★ Observing scattered light from circumstellar debris has been observationally challenging because of the very high Star:Disk contrast ratios in such systems.

★ Until recently the large, and nearly edge-on disk around β Pictoris remained the only such disk imaged.

1984 - B.A. Smith & R.J. Terrile
6" radius coronagraphic mask,
Las Campanas (discovery image)



Direct (Scattered Light) Imaging of Dusty Debris

Resolved imaging  spatial distribution of dust/debris.

- Asymmetries (radial & azimuthal):
May implicate low-mass perturbers (planets) from:
Rings, Central Holes, Gaps, Warps, Clumps, Arcs, Arclets
- Helps Elucidate the scattering & physical properties of the grains.
Simultaneous Light Scattering & SED Modeling

AU MIC: Large Dust Disk Around Nearby M-Star

β Pictoris



AU Mic (GJ 803)



AU MIC (GJ 803)

**Common Space Motion w/ β Pic
("β Pic moving group")**

Likely coevol w/ β Pic ~ 20 Myr

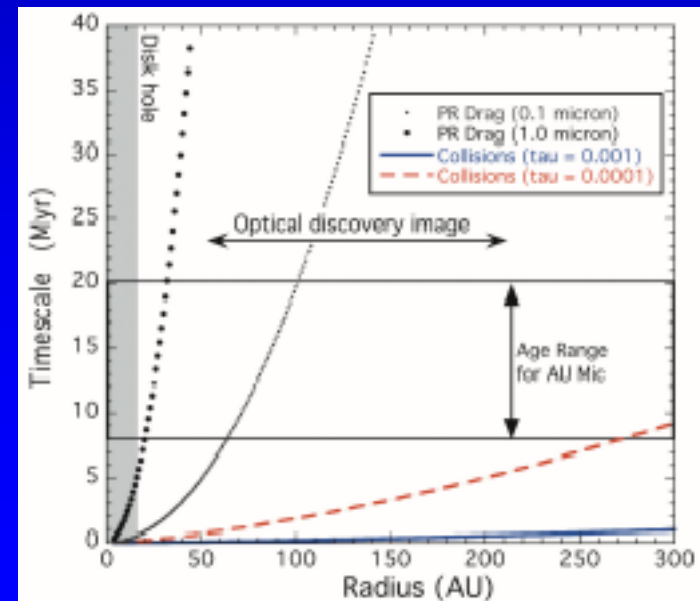
Sub-mm (Kalas & Liu 2004 ApJ):

Dust Mass ~ 1/3 β Pic

Cold (40K) Dust

No Molecular Gas

Likely Inner Hole (r < 17 AU)



TODAY HST Provides a Unique Venue for High Contrast Imaging

- UV/Optical & Near-IR ($<2.4\mu\text{m}$) Diffraction Limited Imaging
- $> 98\%$ Strehl Ratios @ all λ s
- Highly *STABLE* PSF
- Coronagraphy: NICMOS
STIS, ACS

• Intra-Orbit
Field
Rotation



Background Rejection

$1.6\mu\text{m}$: $\sim 10^{-6} \text{ pix}^{-1}$ @ $1''$ ★

$1.1\mu\text{m}$: $\sim 10^{-5}$ in $2''$ - $3''$ annulus ○

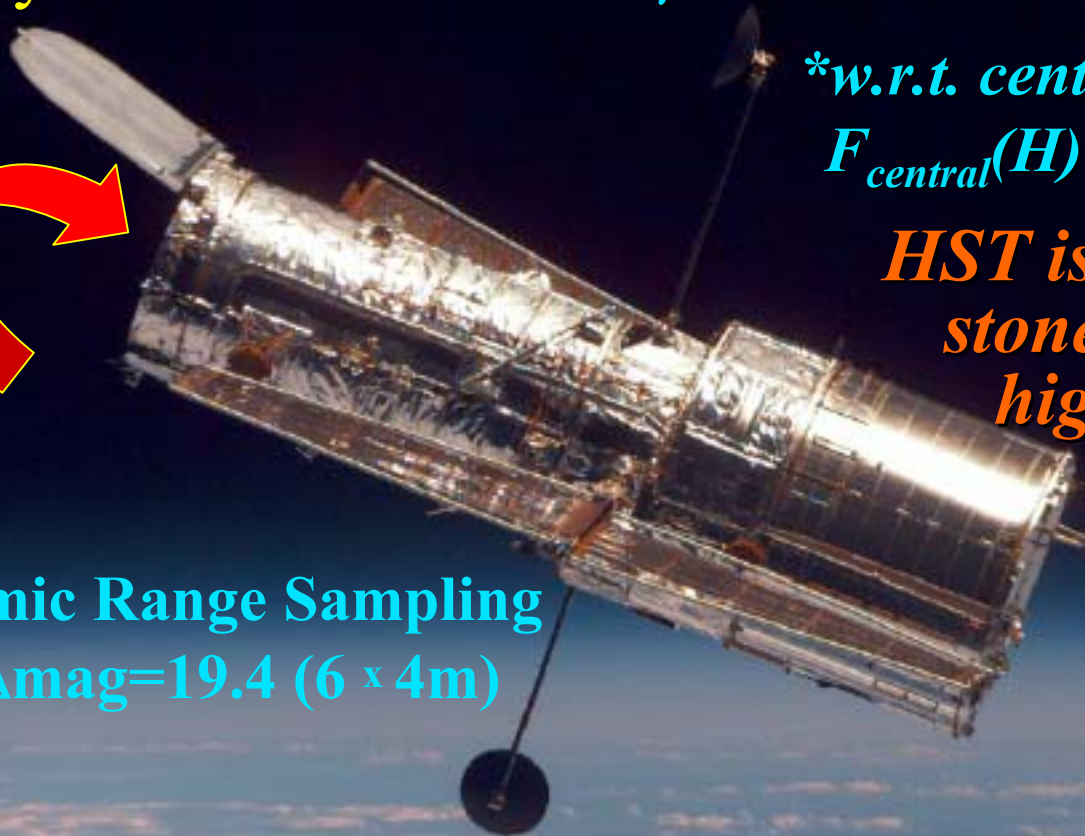
**w.r.t. central pixel*

$$F_{\text{central}}(H) = 11\% F_{\text{star}}$$

*HST is a stepping
stone for super-
high contrast*
imaging*

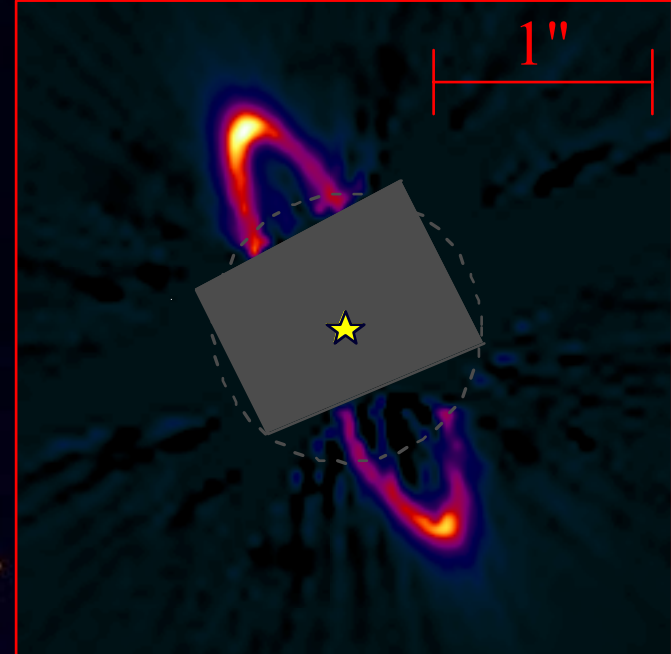
**Background
Rejection
 10^{-9} to 10^{-10}*

NIR High Dynamic Range Sampling
NICMOS/MA: $\Delta\text{mag}=19.4$ ($6 \times 4\text{m}$)

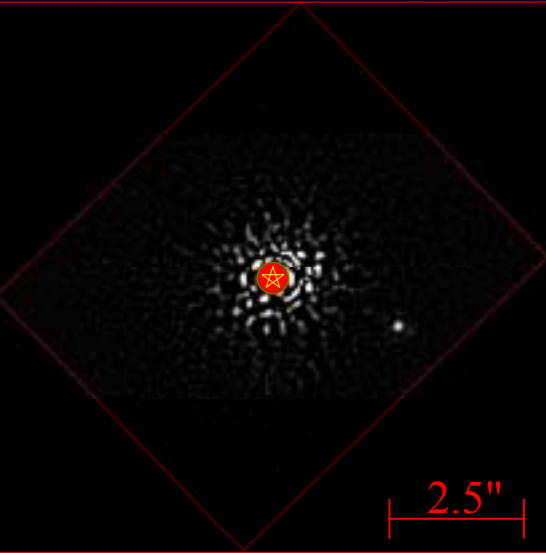


*Areas of Investigation in Planetary System
Formation/Evolution Enabled With Today's
Capabilities on HST via PSF-Subtracted
Coronagraphic Imaging*

Young Extra-Solar Planet* &
Brown Dwarf
Companions



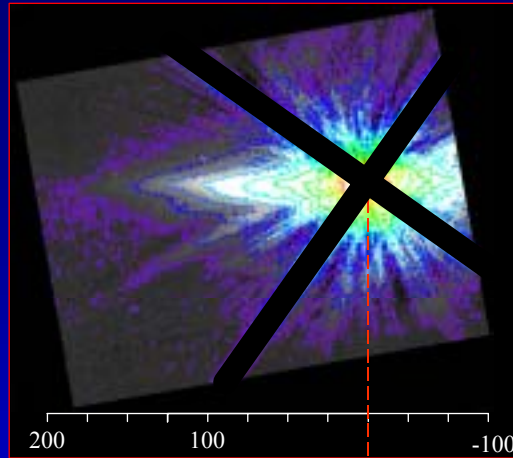
Circumstellar Disks
 $f_{\text{disk}}/f_* > \text{few} \times 10^{-4}$ at 1''
 $\theta > 50 \text{ mas}$



* $< \text{few} \times 10^6 \text{ yr}$ at 1''

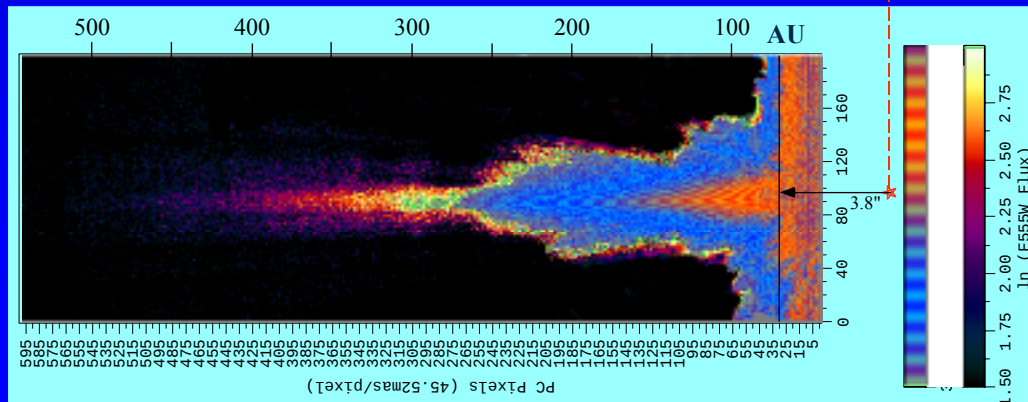
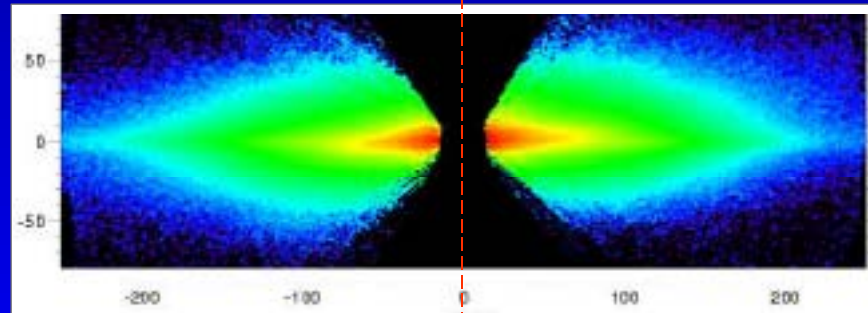


HST Imaging of β Pictoris Disk



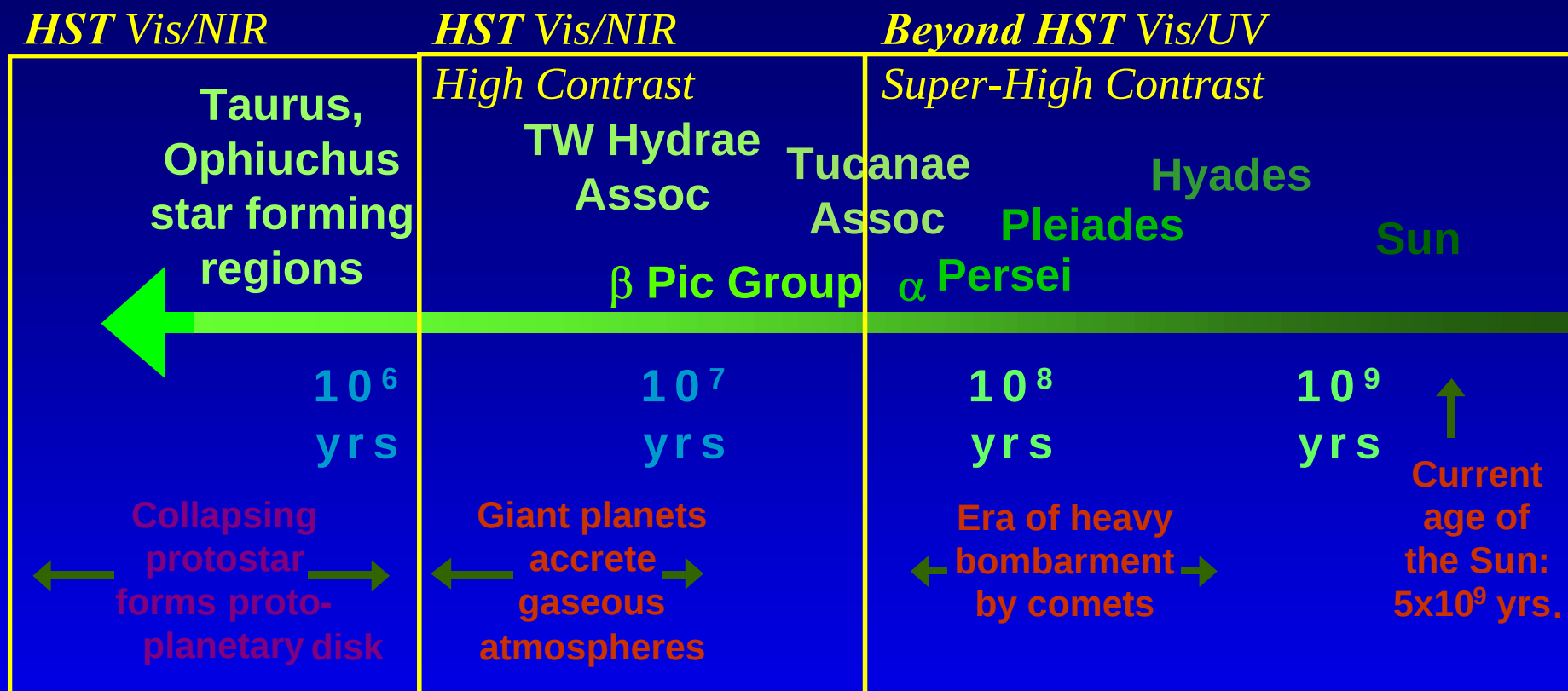
HST/NICMOS Image
Coronagraph
F110W (1.1 μ m)
Smith et al., in prep.

HST/STIS Image
Coronagraph
Broadband 0.2-1.0 μ m
Heap et al., 1999

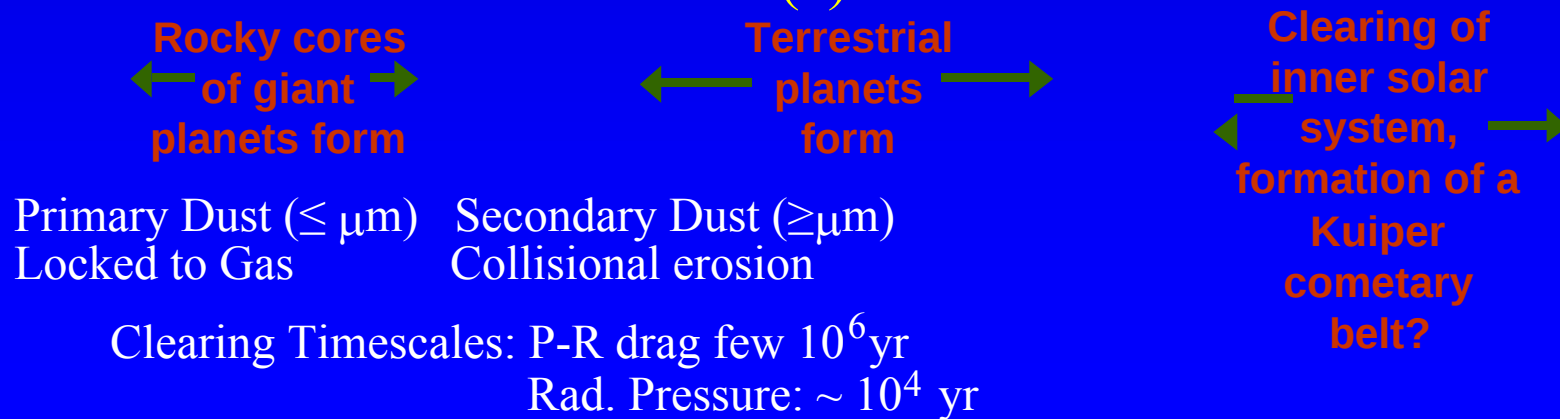


HST/WFPC-2 Image
"Pyramid Edge" Imaging
F555W (0.55 μ m)
Schultz et al., 2001.

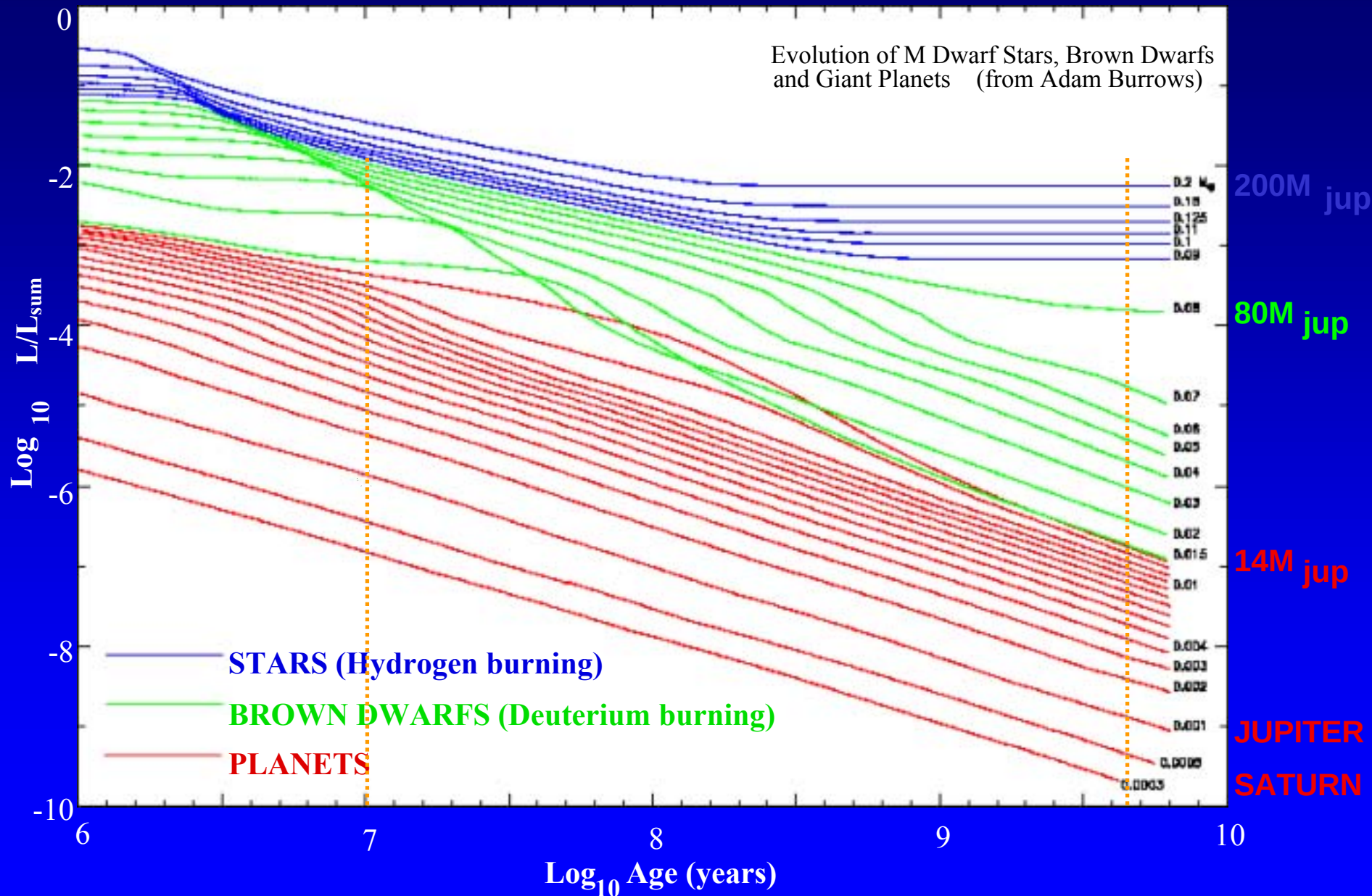
Planet-Building Timeline



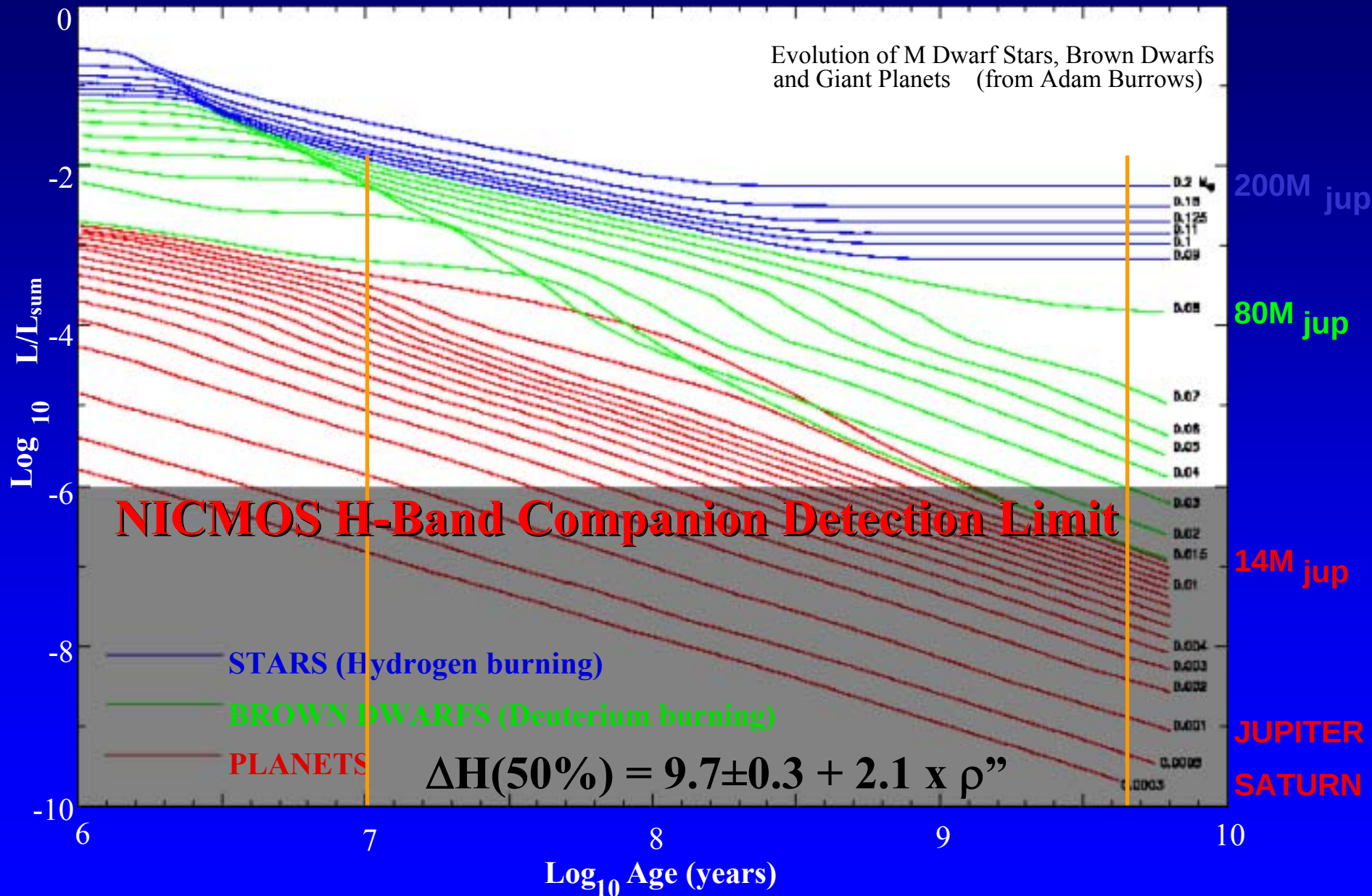
DISK EVOLUTION/DISSIPATION(?)



Cooling Curves for Substellar Objects

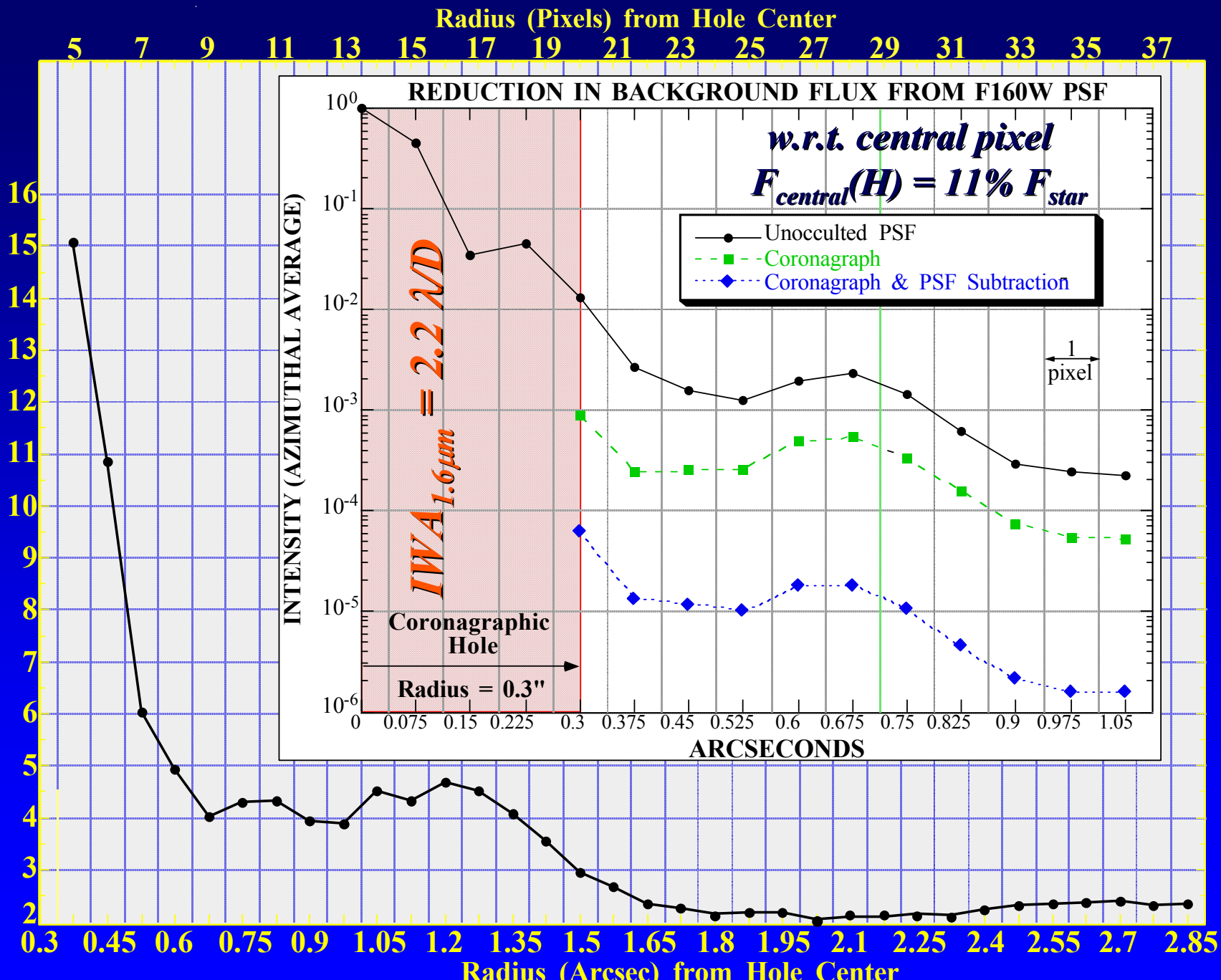


Cooling Curves for Substellar Objects



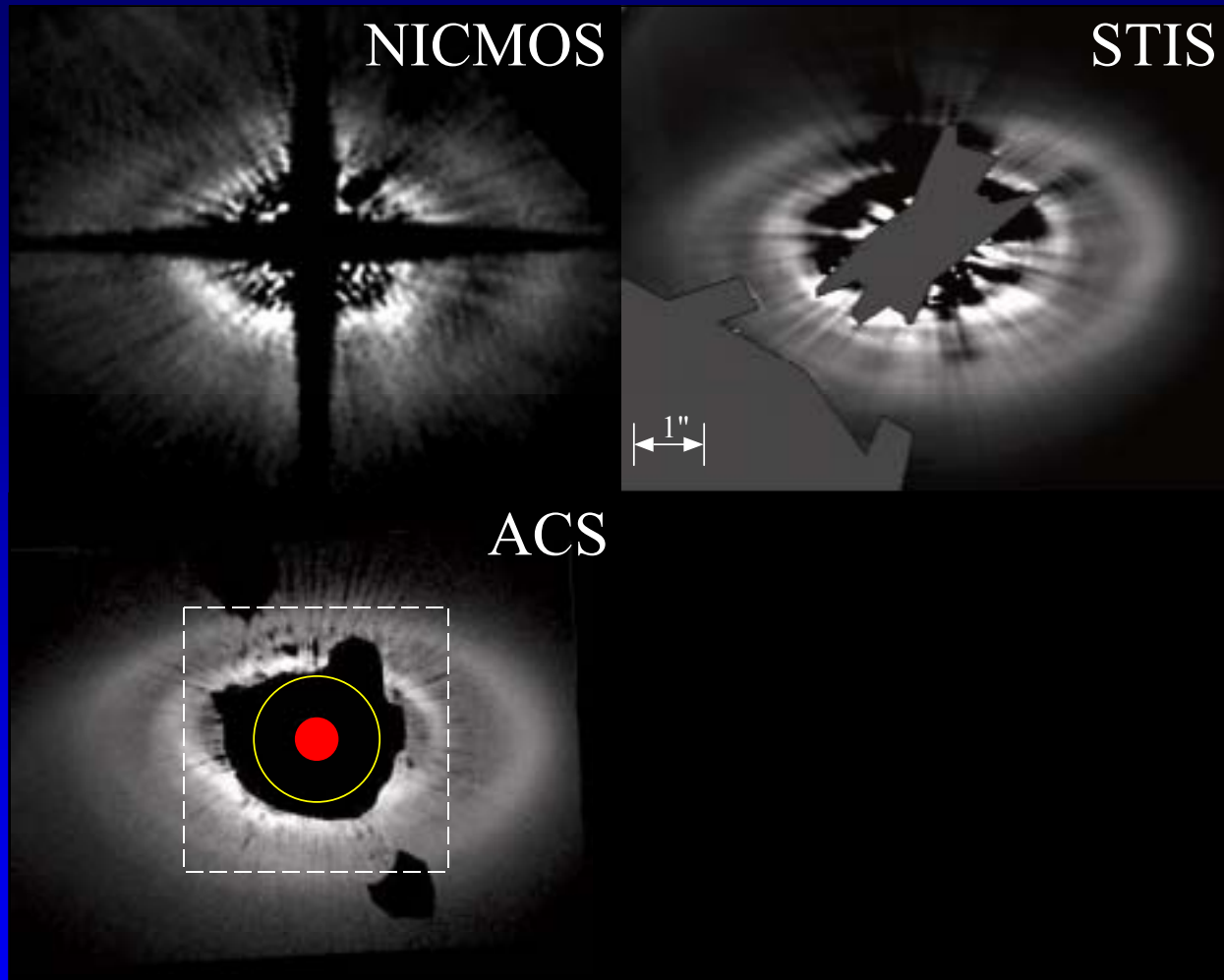
NICMOS F160W (H-band) Coronagraphic Performance (G2V)

BACKGROUND NOISE



*HST PSF-Subtracted
Coronagraphic Imaging
of
Circumstellar Disks*

A Choice of Coronagraphs - The HST Arsenal

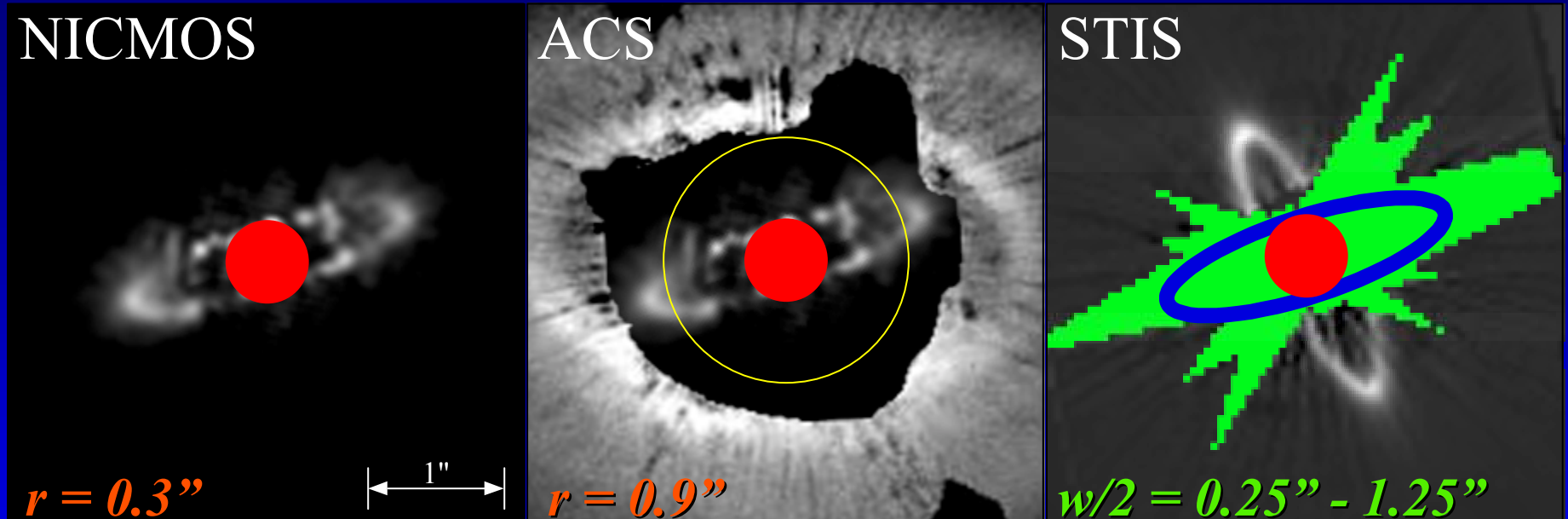


OBSERVATION DETAILS	<u>A(NICMOS)</u>	<u>B(STIS)</u>	<u>C(ACS)</u>	<u>D(PAI)</u>
Wavelength (microns)	1.1	0.5	0.6	2.2
TOTAL Integration	1216s	3155s	4910s	1090s
# Orbits: Target/PSF	1 / 0*	2 / 1	2 / 1	2 NIGHTS
Diff. Orientation	8°	30°	28°	N/A

A Choice of Coronagraphs - The HST Arsenal

Obscured Areas Two-Orientation PSF-Subtracted Coronagraphic Images.

Red circle shows size of NICMOS 0.3" radius coronagraphic hole.



$$IWA_{1.1\mu m} = 3.2 \lambda/D$$

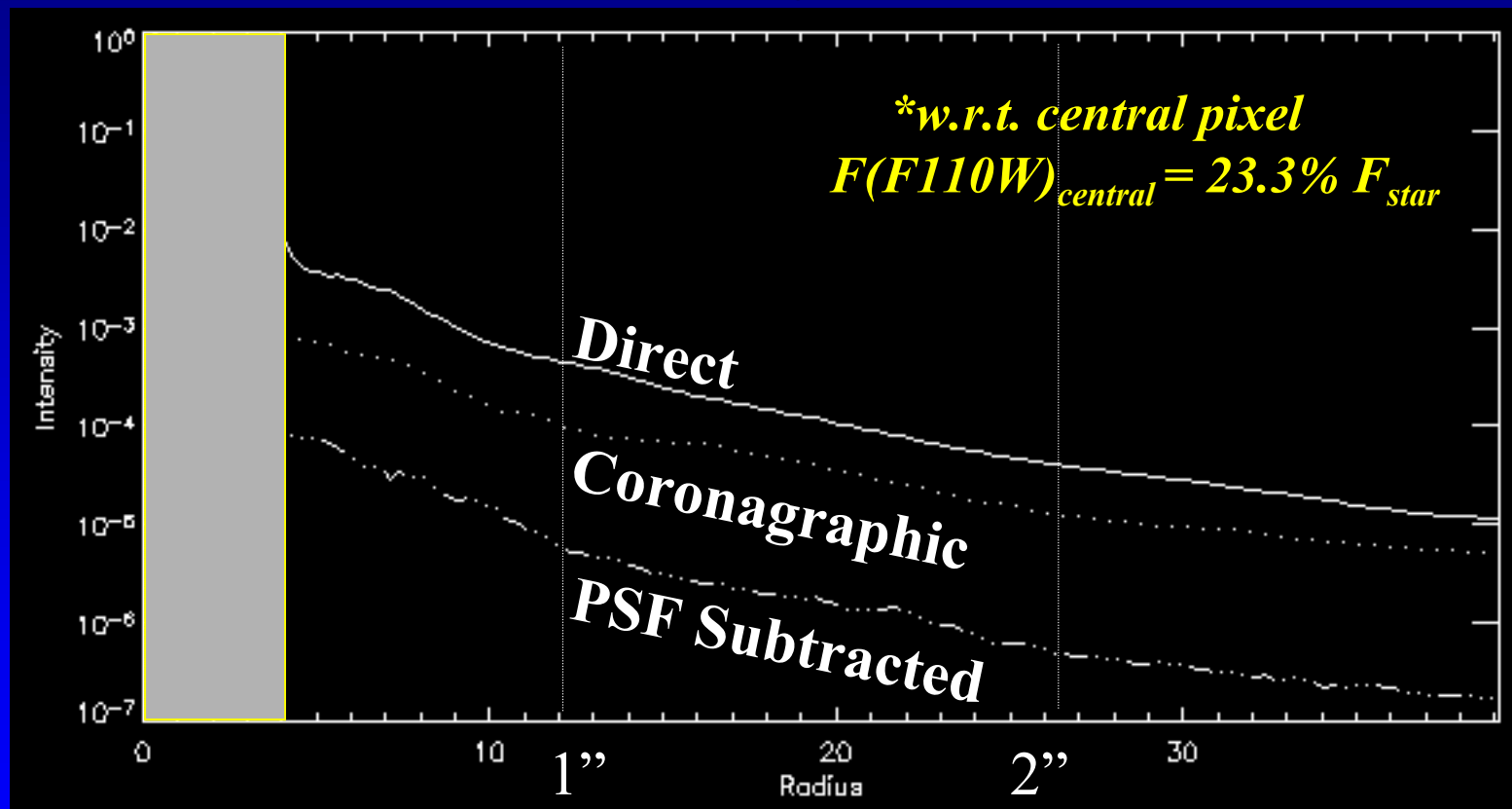
$$IWA_{0.5\mu m} = 21 \lambda/D$$

PSF-Subtracted Rejection / arcsec⁻² @ 1" w.r.t. Total Stellar Flux:

- NICMOS (F110W for disk imaging) $\sim 20,000$ / Total Stellar Flux
Largely Color Independent, Target-PSF $|J-H| < 0.3$
- STIS $\sim 3,000$ / Total T-Tauri Stellar Flux, may improve x10 for A *s
Color Dependent, Large Variations, Target-PSF $|B-V| < 0.08$
- WFPC-2 $\sim 1,750$ (non-Coronagraphic) - Field/Color Dependence

NICMOS F110W (~ J-Band) Coronagraphic Performance (G2V)

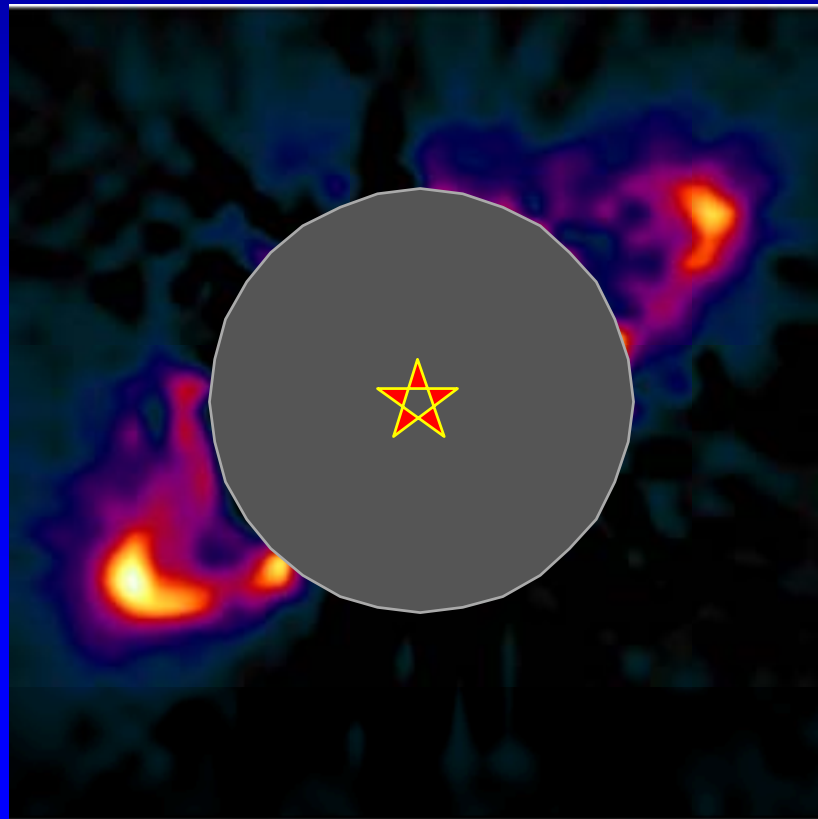
Normalized Radial Profiles (Azimuthal Median)*



Mechanics: To Minimize Image Artifacts from Reference PSF Subtractions, Target & Reference PSFs Should Be:

- Obtained in the same (when possible) or adjacent visibility periods
- Of Similar Spectral Type (particularly for “wide” pass bands)
- At Least as Bright as the Target

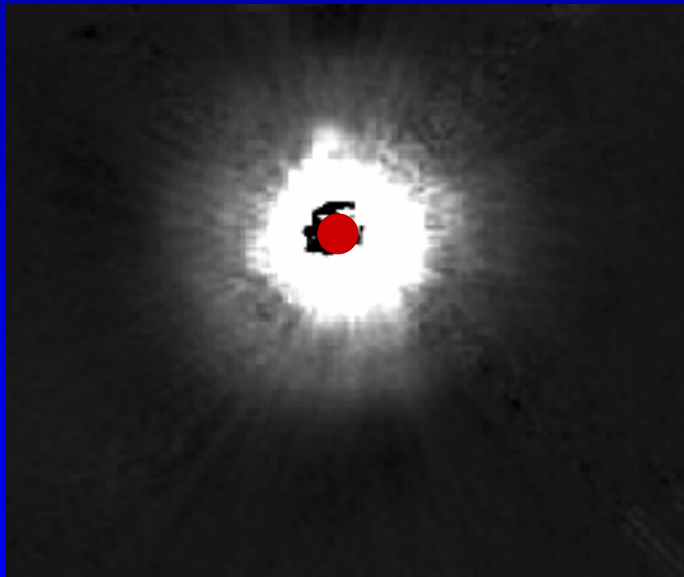
HR 4796A



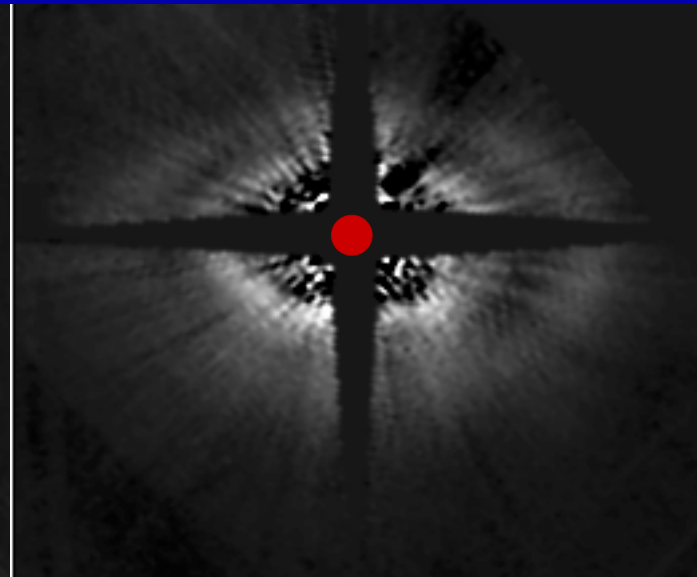
Mechanics: To Minimize Image Artifacts from Reference PSF Subtractions, Target & Reference PSFs Should Be:

- Obtained at Two or More Spacecraft Roll Orientations

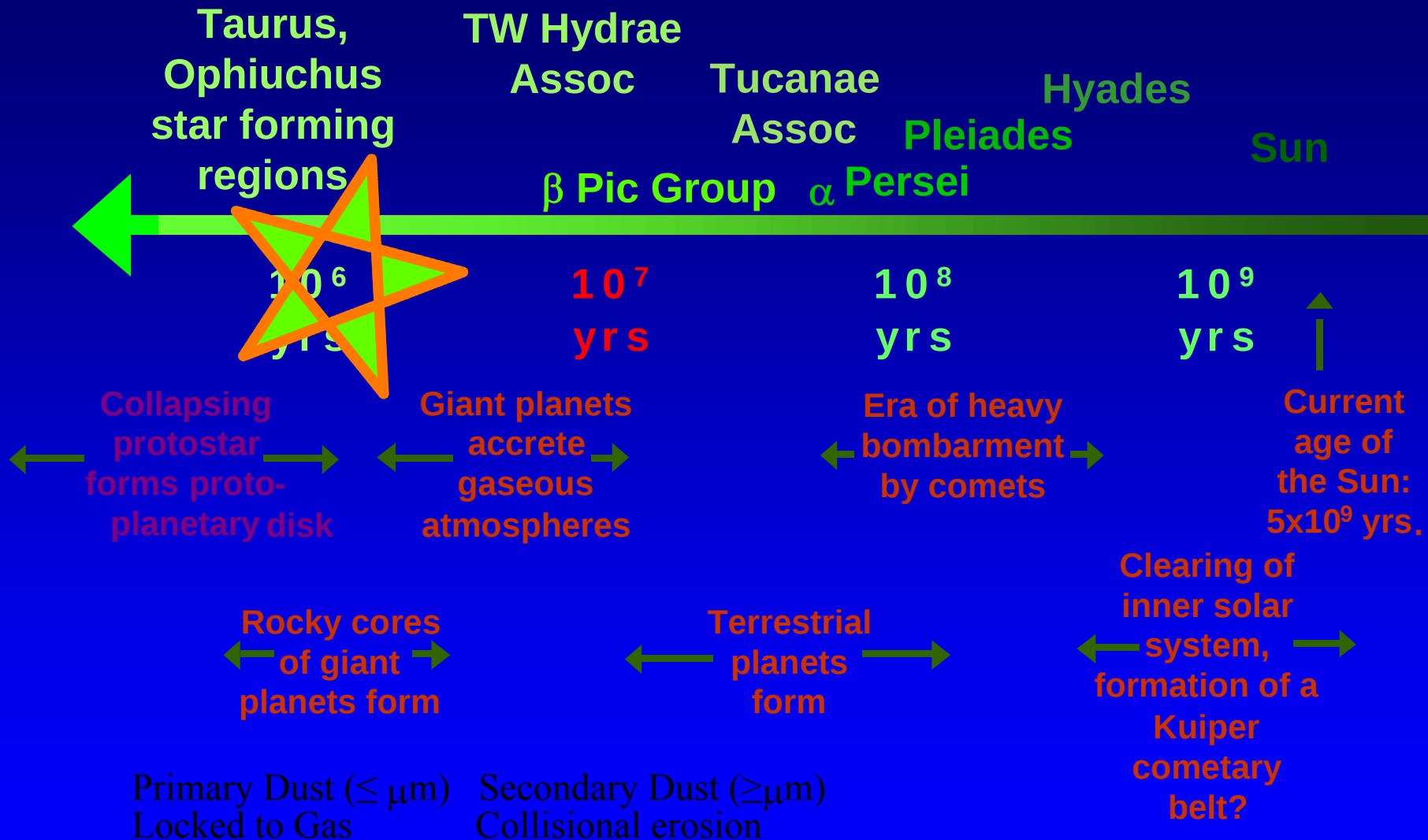
TW HYDRAE



HD 141569A



Planet-Building Timeline



Clearing Timescales: P-R drag few 10^6
 Rad. Pressure: $\sim 10^4$

HH30 Obscured



Direct Image

T Tau/Protoplanetary Circumstellar Disks...

Observing young circumstellar disks

With obscured central stars is not difficult.

Disk systems with unembedded, or only marginally obscured central stars are much more observationally challenging and require PSF-subtracted coronagraphy.

HH30 Obscured

GM AUR Unembedded ($A_v < 0.5$)

Red Polar Lobes
 $10 \mu\text{Jy arcsec}^{-2}$

Direct Image

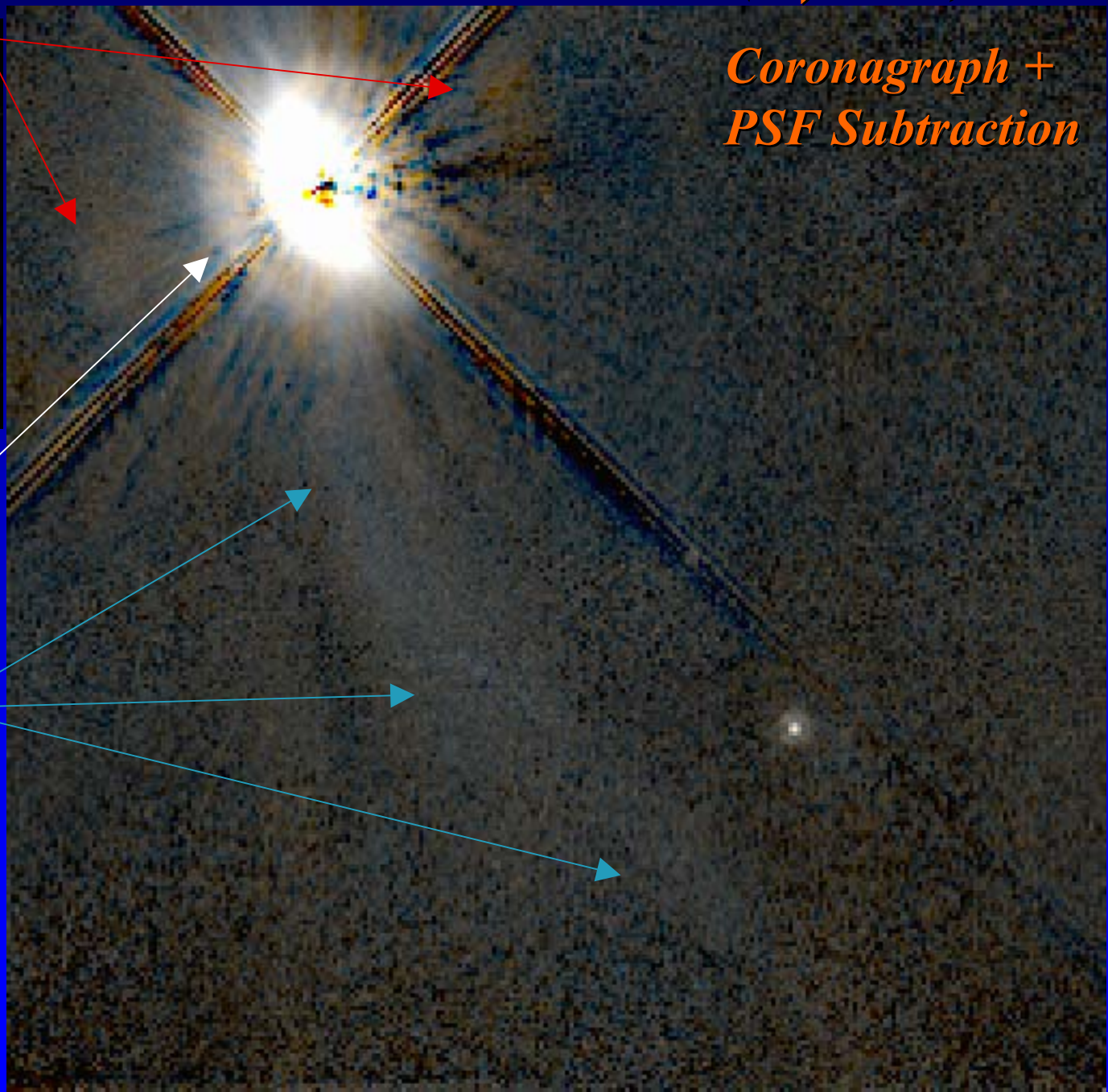
*Coronagraph +
PSF Subtraction*

Lower Scattering Surface
 $200 \mu\text{Jy arcsec}^{-2}$

Faint Blue Ribbon

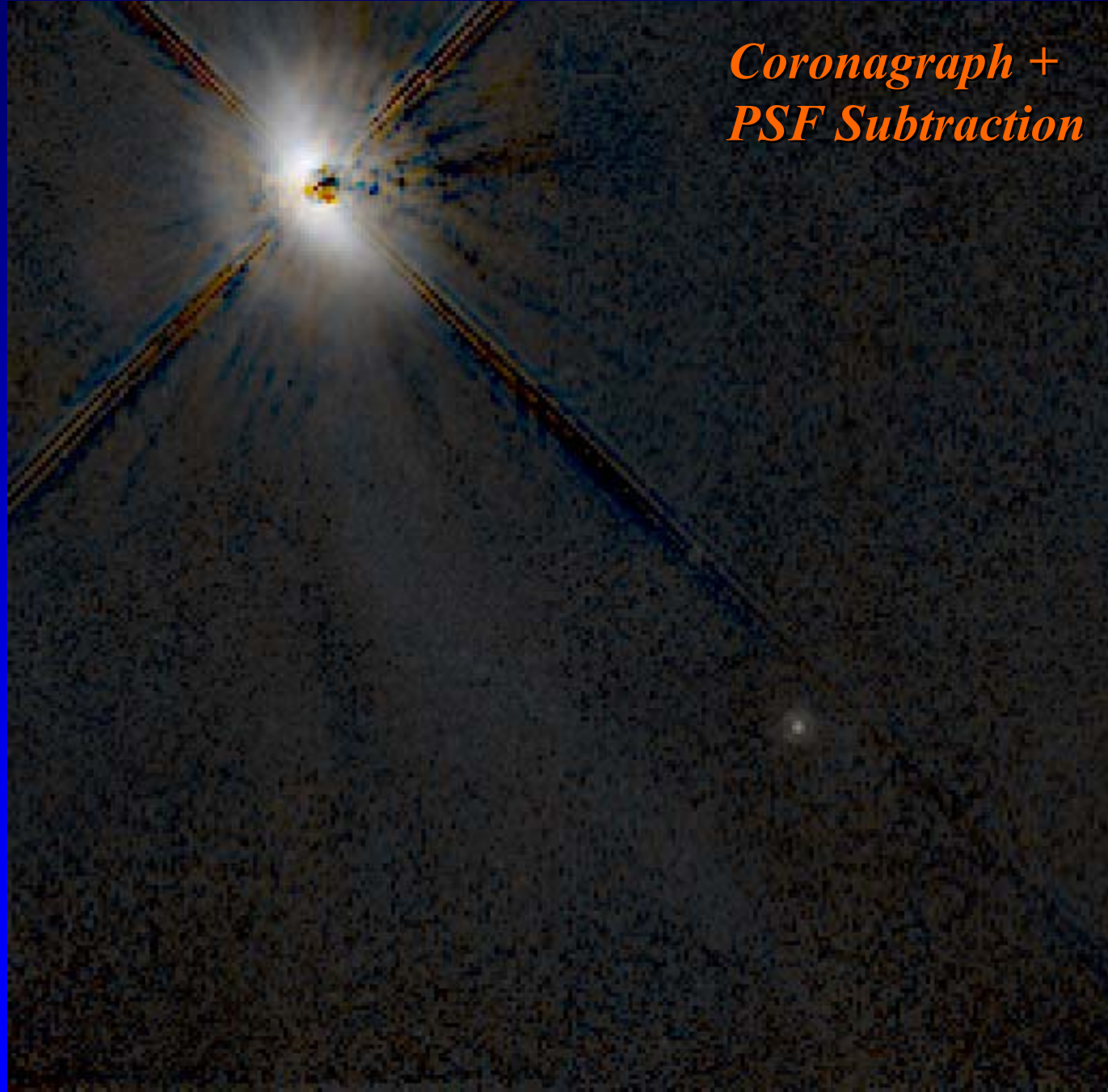
$J_* = 0.33 \text{ Jy}$

$H_* = 0.40 \text{ Jy}$



GM AUR Unembedded

*Coronagraph +
PSF Subtraction*



cTTs (K7V)

Age: 1.3+/-0.3 Myr

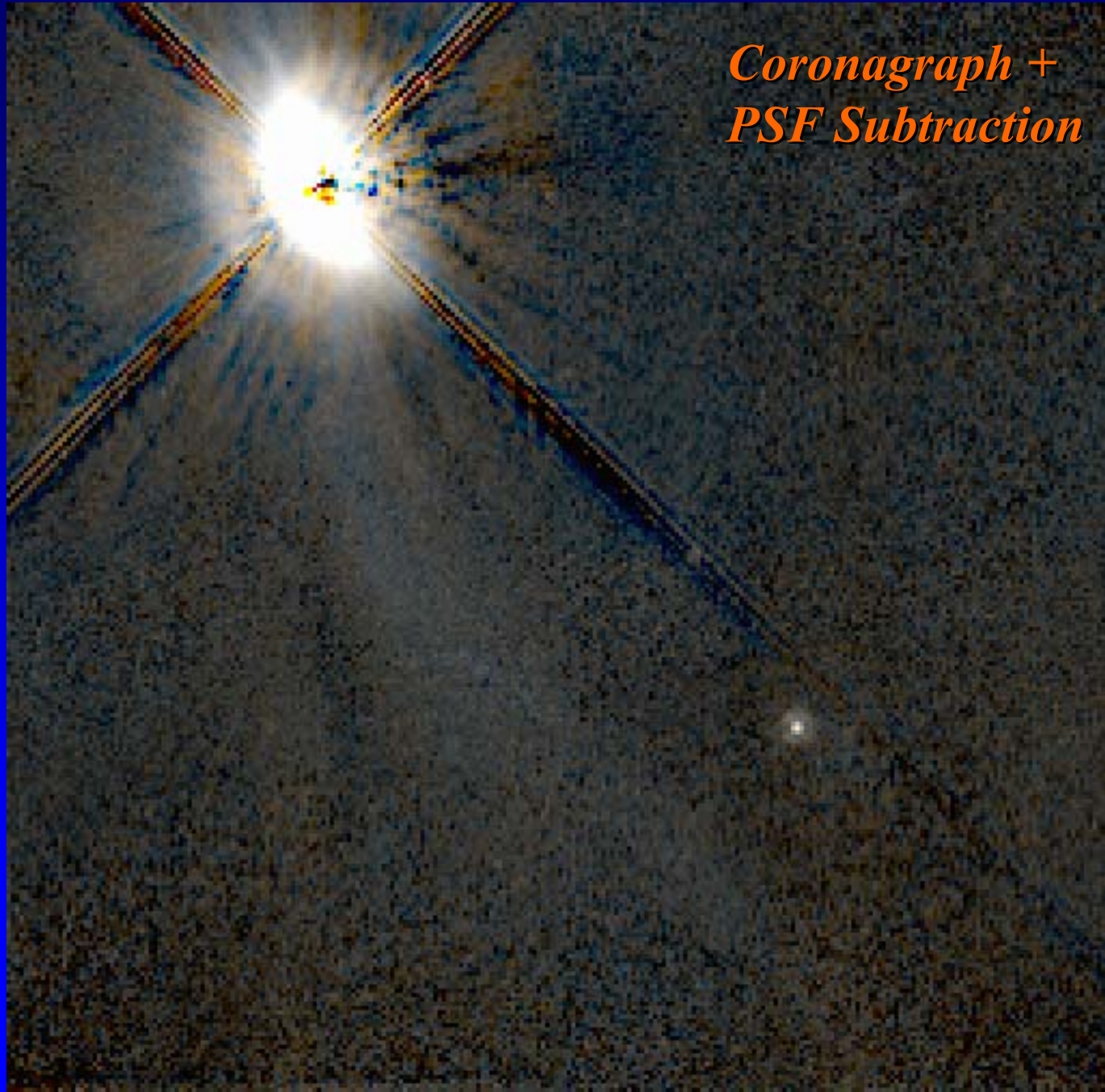
**Beckwith et al 1990:
Dust inferred from
1.3mm continuum**

**Koerner, Sargent &
Beckwith 1993:
¹³CO(2->1) emission,
Keplerian rotation.**

**Stapelfeldt et al 1997:
WFPC-2 imaging,
flared inclined disk.**

GM AUR Unembedded

*Coronagraph +
PSF Subtraction*



cTTs (K7V)

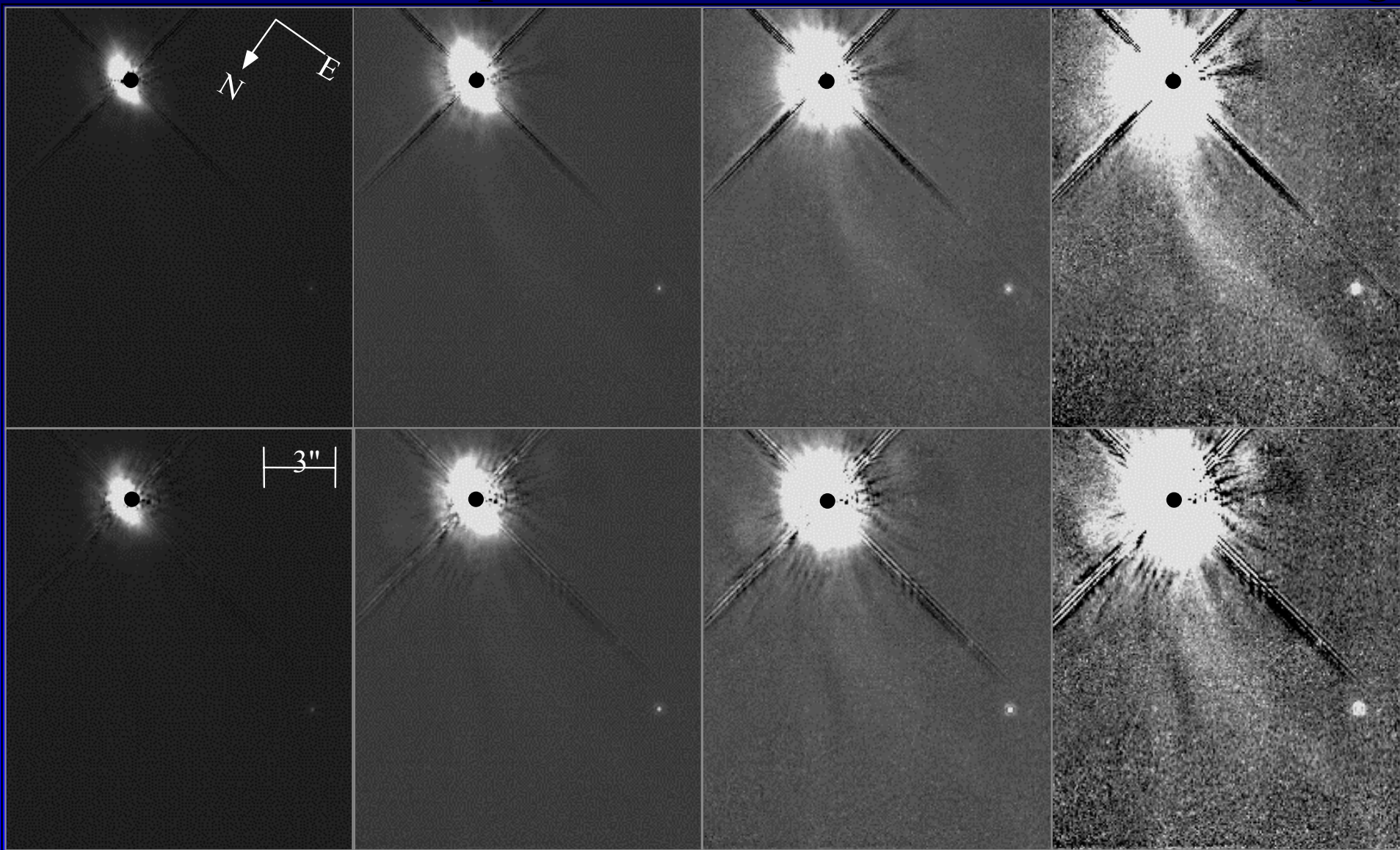
Age: 1.3 ± 0.3 Myr

Beckwith et al 1990:
Dust inferred from
1.3mm continuum

Koerner, Sargent &
Beckwith 1993:
 $^{13}\text{CO}(2 \rightarrow 1)$ emission,
Keplerian rotation.

Stapelfeldt et al 1997:
WFPC-2 imaging,
flared inclined disk.

GM AUR F110W (top) & F160W(bottom) NICMOS Imaging



-1 to + 10

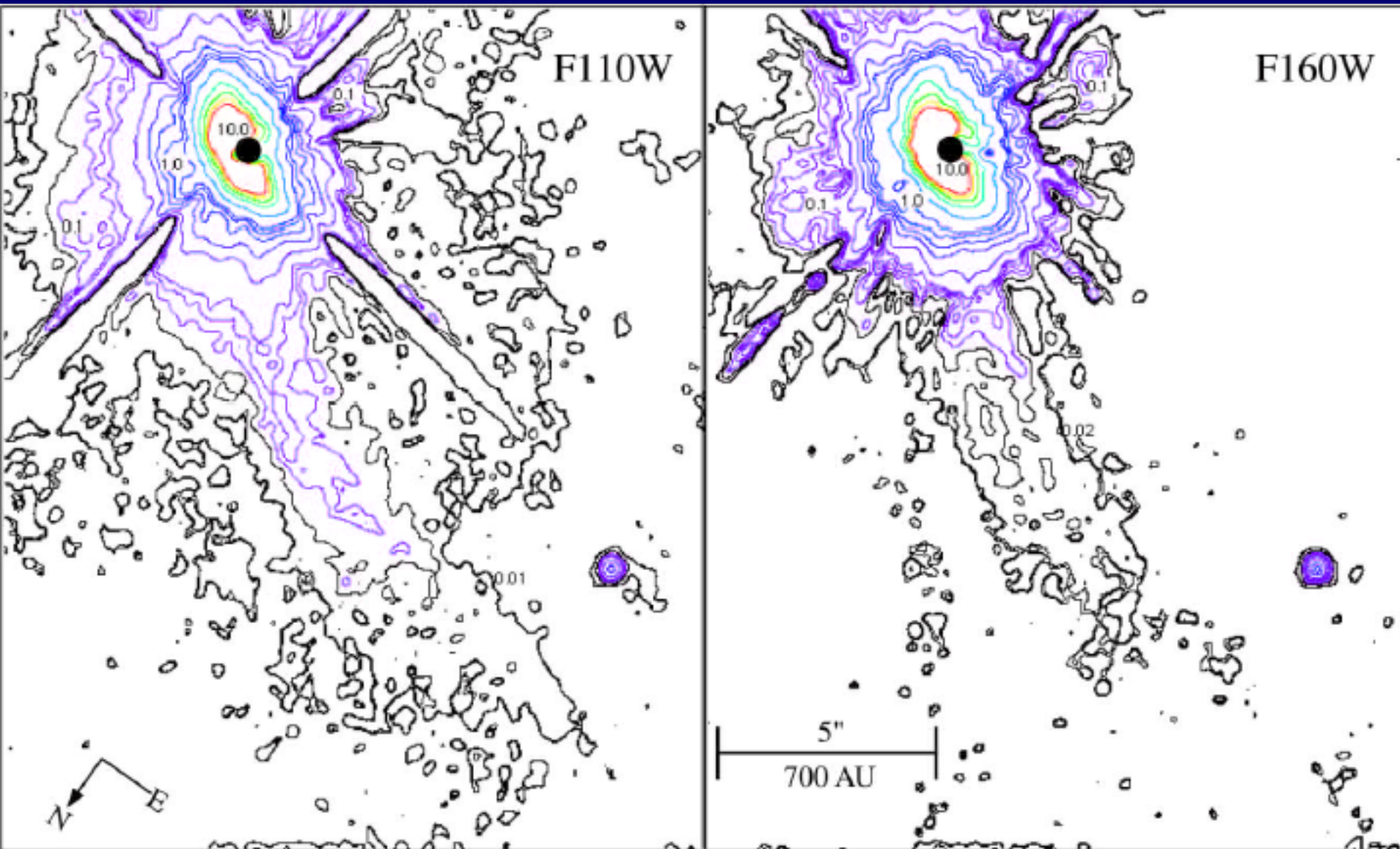
-0.5 to + 2.0

-0.2 to +0.5

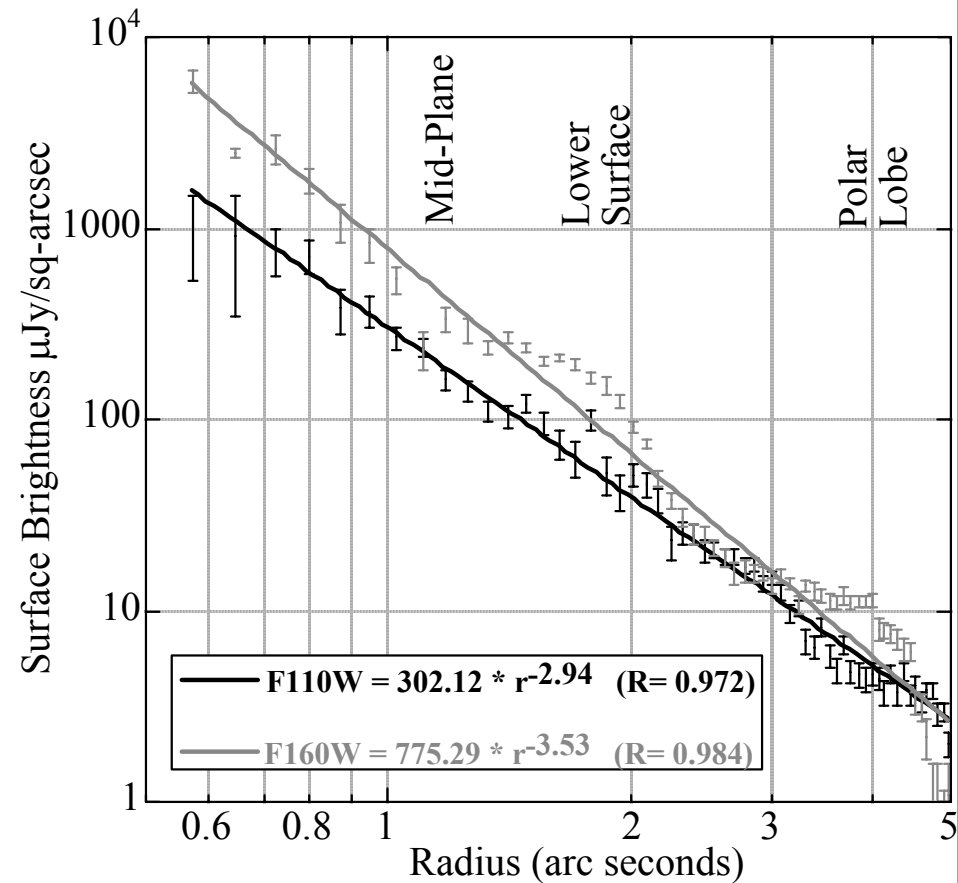
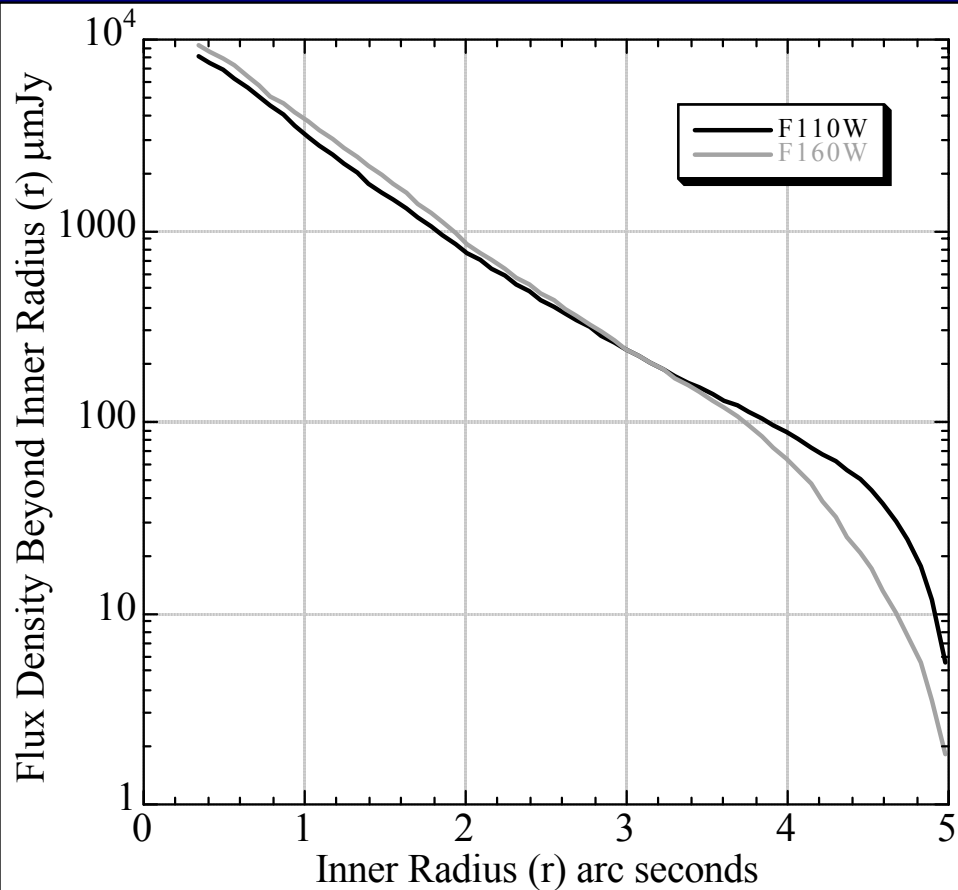
-0.05 to + 0.1

Linear Display Range in $\mu\text{Jy} / \text{pixel}$

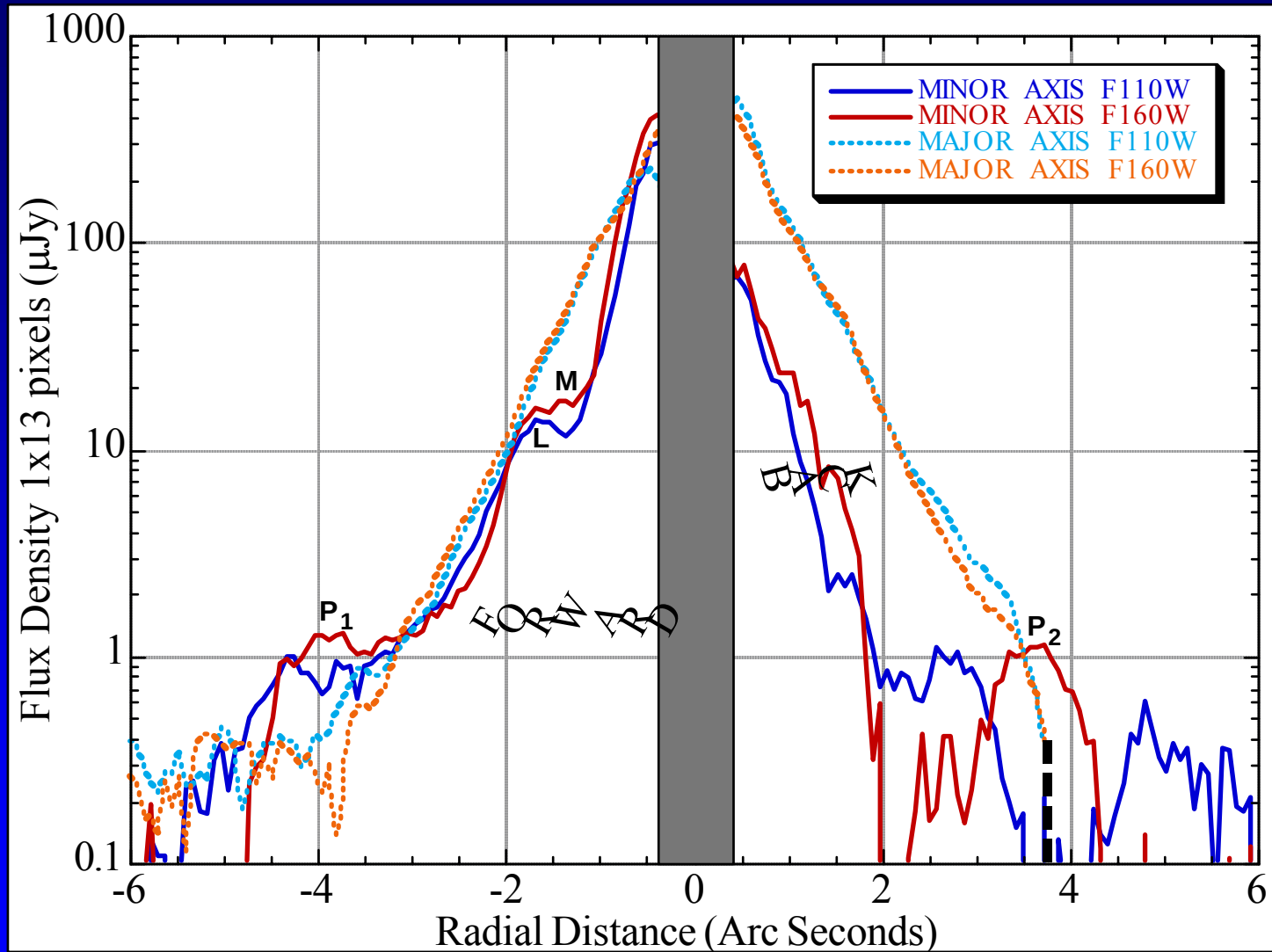
GM AUR F110W & F160W NICMOS Imaging



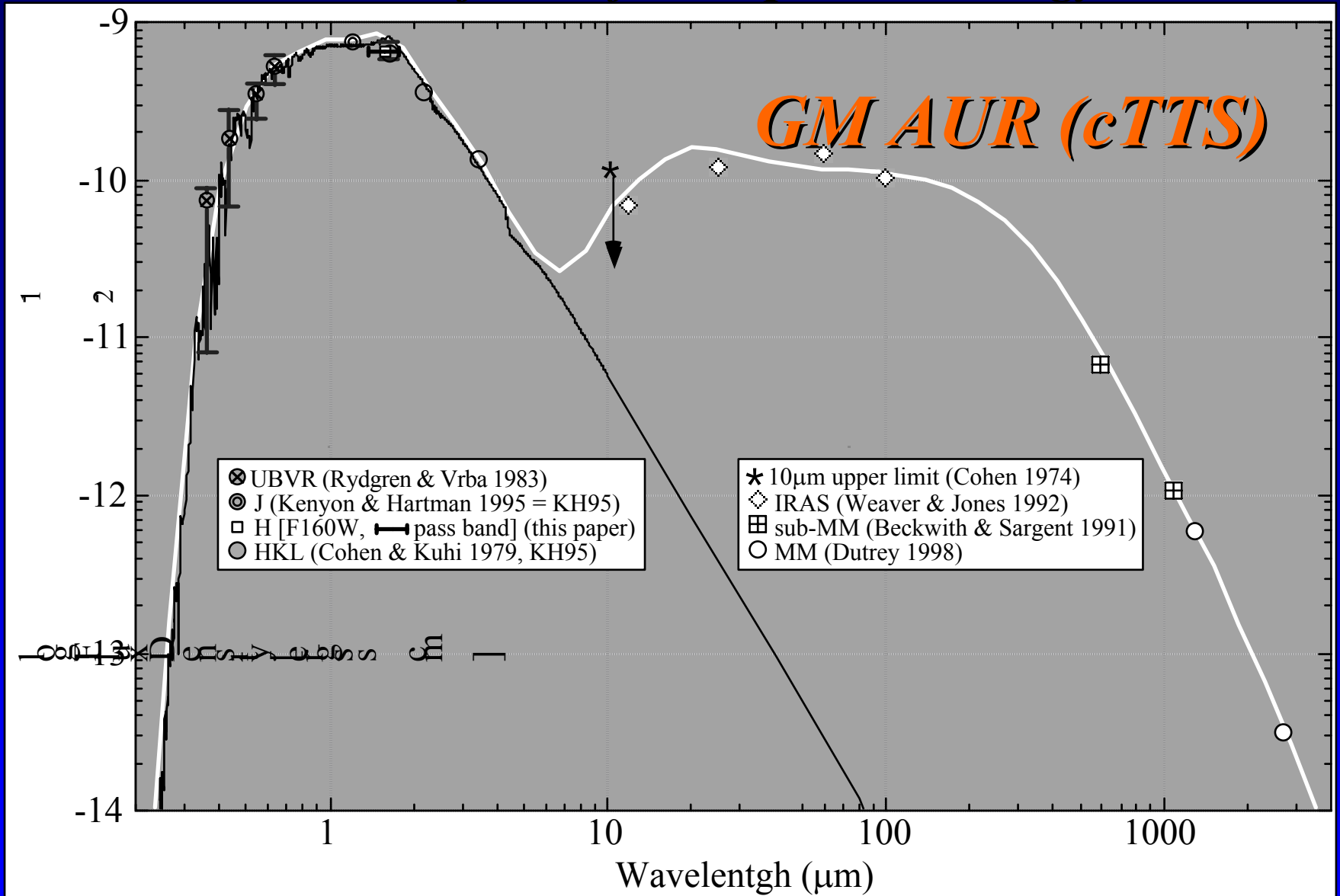
GM AUR F110W & F160W Surface Brightness



GM AUR F110W & F160W Front/Back Scattering



Circumstellar Dust Inferred from Spectral Energy Distribution



SED & Spatial Dust Distribution Simultaneously Constrain Disk Models

Model as Passively Heated Disks to Determine:

Geometry: Orientation, Inclination, Size

Physical Characteristics: Disk Mass, Scale Height, Envelope Infall Rate

Dependency of Grain Properties (λ Dependent):

Dust Lane Width, Scattered Light Pattern, long- λ SED slope

(Disk dust opacity, $\kappa \sim \lambda^{-1}$, shallower than ISM grains, as in other disks)

Simultaneously Model Scattered Light & SED:

- Envelope: Tereby, Shu & Cassen (84) Rotational Collapse Geometry
Curved Bipolar Evacuated Cavity (Whitney & Hartmann 93)
- Dust Model & Grain Parameters per Wood (00)
- Adopted Flared Disk Structure (300 AU radius, 1000 AU envelope)

$$\rho_d = \rho_0 (R_*/\varpi)^\alpha \exp -\frac{1}{2} [z/h(\varpi)]^2$$

ρ_0 = disk density extrapolated to stellar surface

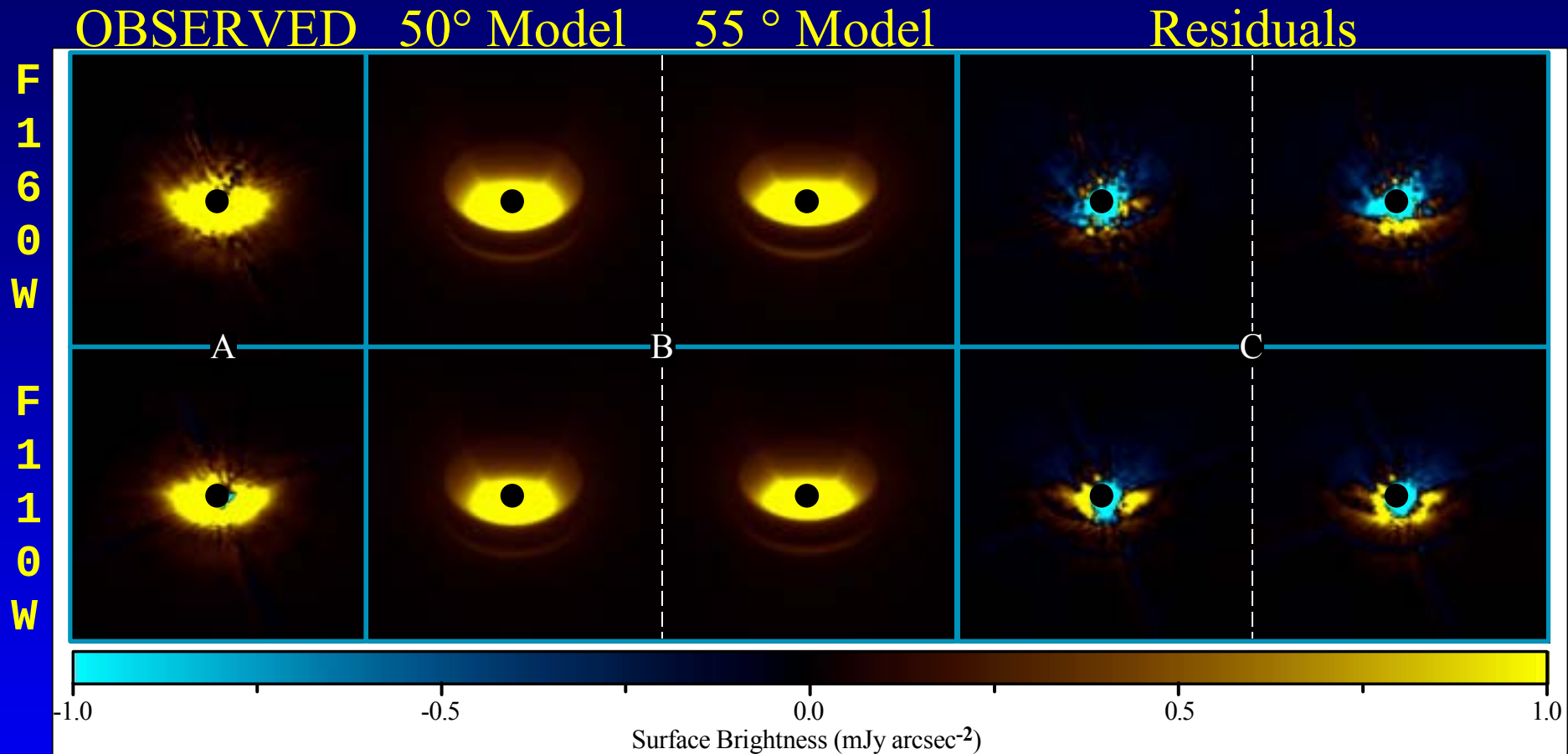
ω = radial coordinate in disk midplane

h = scale height increasing with radius = $h_0(\omega/R_*)^\beta$

-> $\beta = 1.25$; $\alpha = 2.25$; surface density $\Sigma \sim 1/\omega$ (D'Alessio et al 99)

- Monte Carlo scattered light modeling (Whitney & Hartmann 92)

GM AUR Model Fitting Results



LOS Inclination = 52.5°

Disk Mass = $0.04 M_{\text{sun}}$

Envelope Mass = $0.001 M_{\text{sun}}$

PA Major Axis = 328.5°

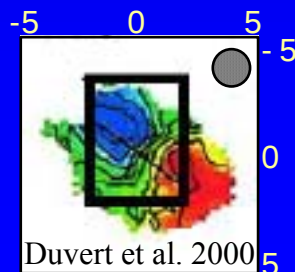
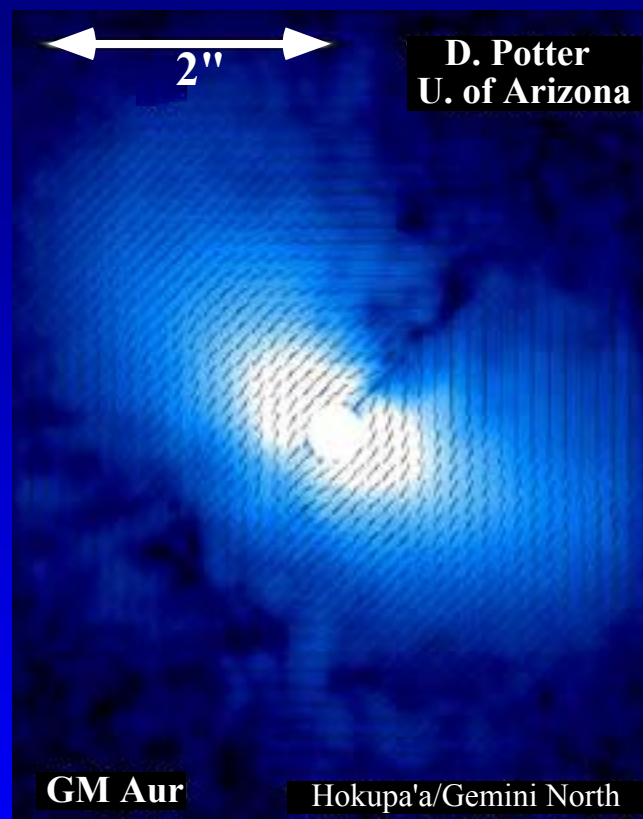
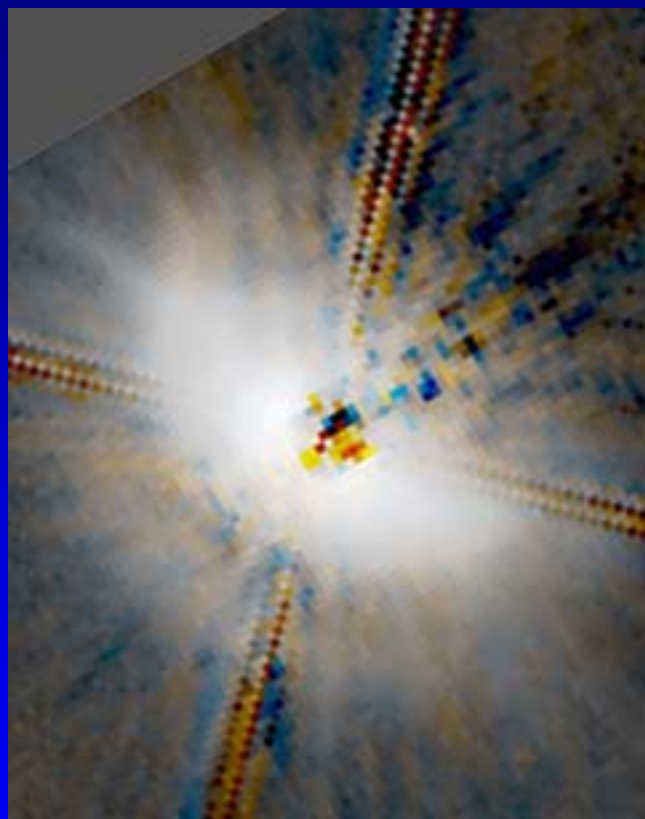
Infall Rate = $1.5 \times 10^{-7} M_{\text{sun}}/\text{year}$

Scale Height = $0.008 R_*$ ($z=8\text{AU}$ @ $r=100\text{ AU}$)

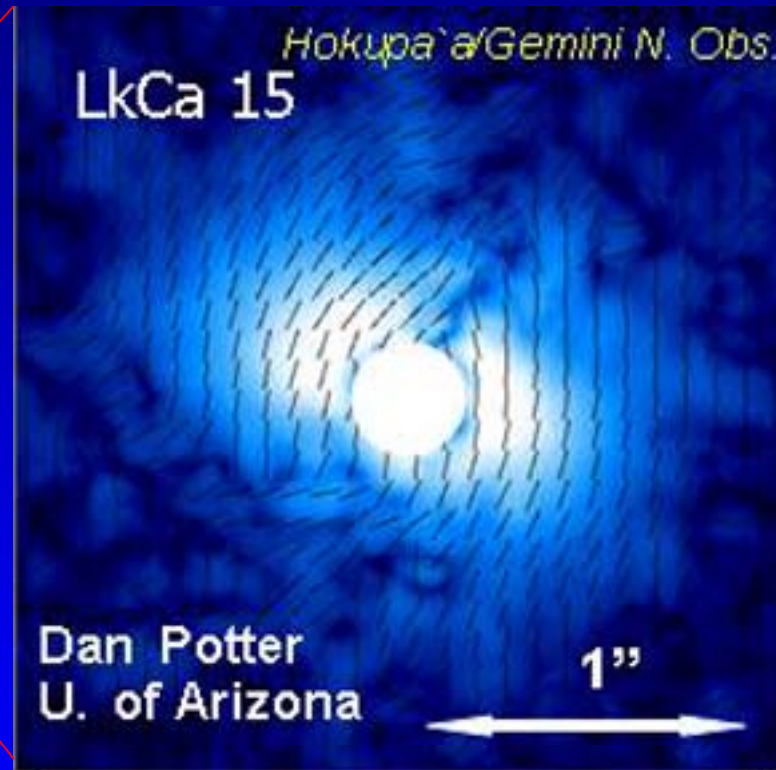
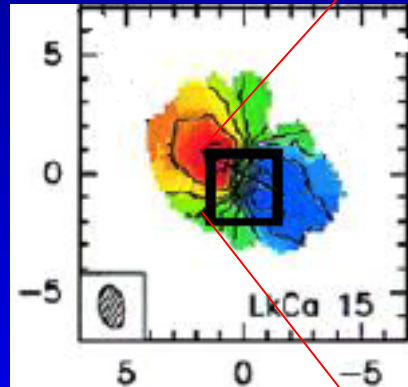
Ground-Based AO
and
Dual-Beam Polarimetry
of
cTTS Circumstellar Disks

GM Aur: Coronagraphy & Dual Beam Polarimetry

HST/NICMOS Hokupa'a/Gemini N.

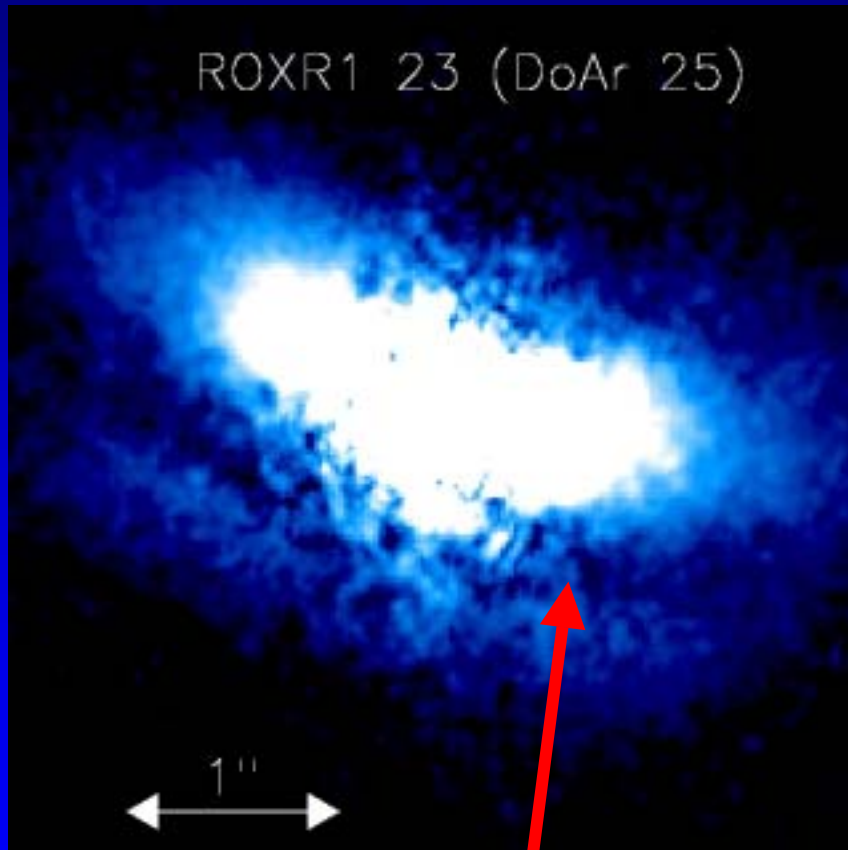


Lk Ca 15 Dual Imaging Polarimetry with Gemini/Hokupa`a



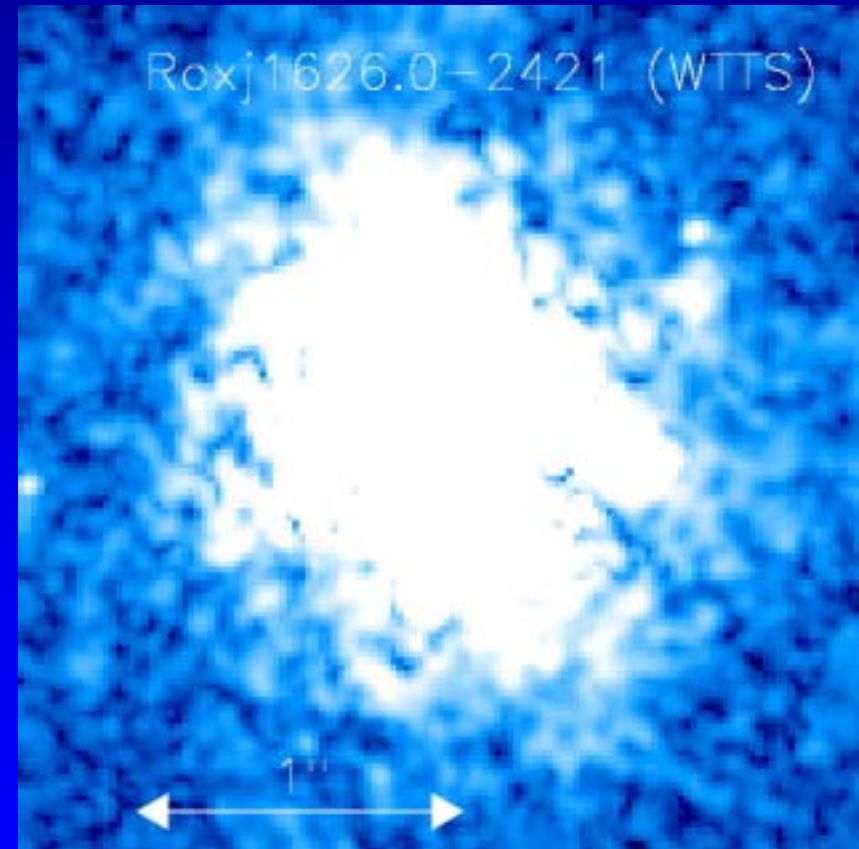
More Results from Dual Imaging Polarimetry with Gemini/Hokupa`a

Young CTTs in Rho Ophiuchus



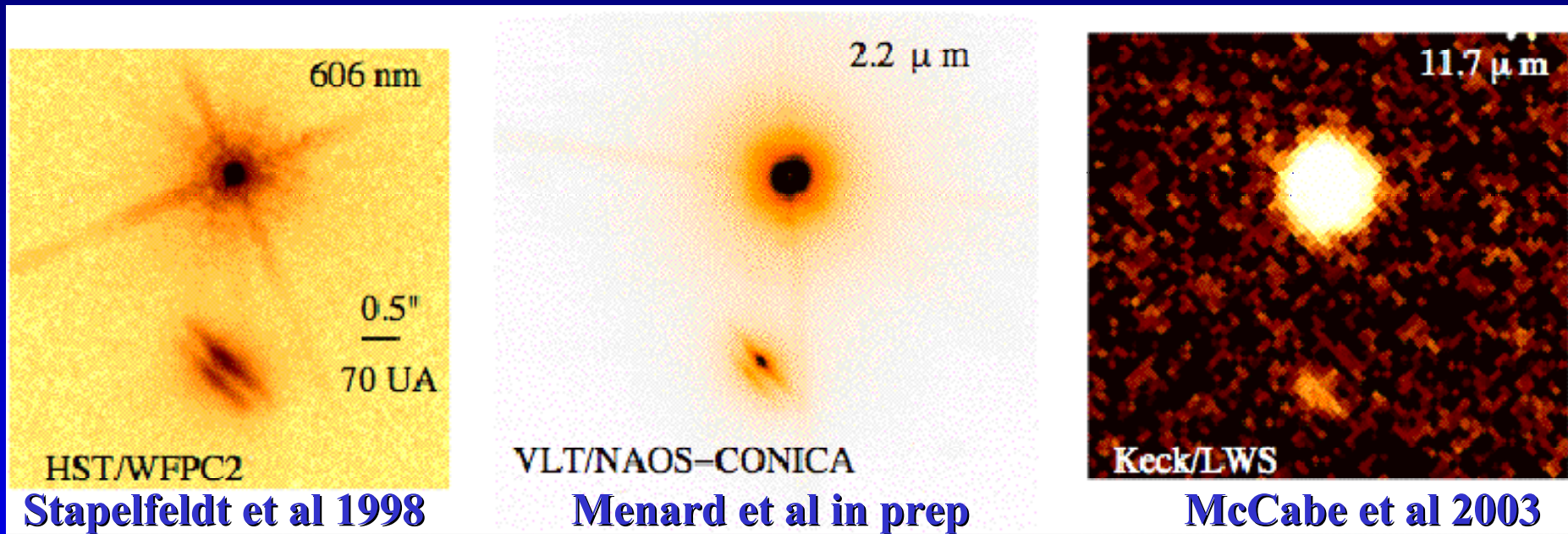
Optically Thick
Lane

Resolved disk around a WTTS in Rho Ophiuchus



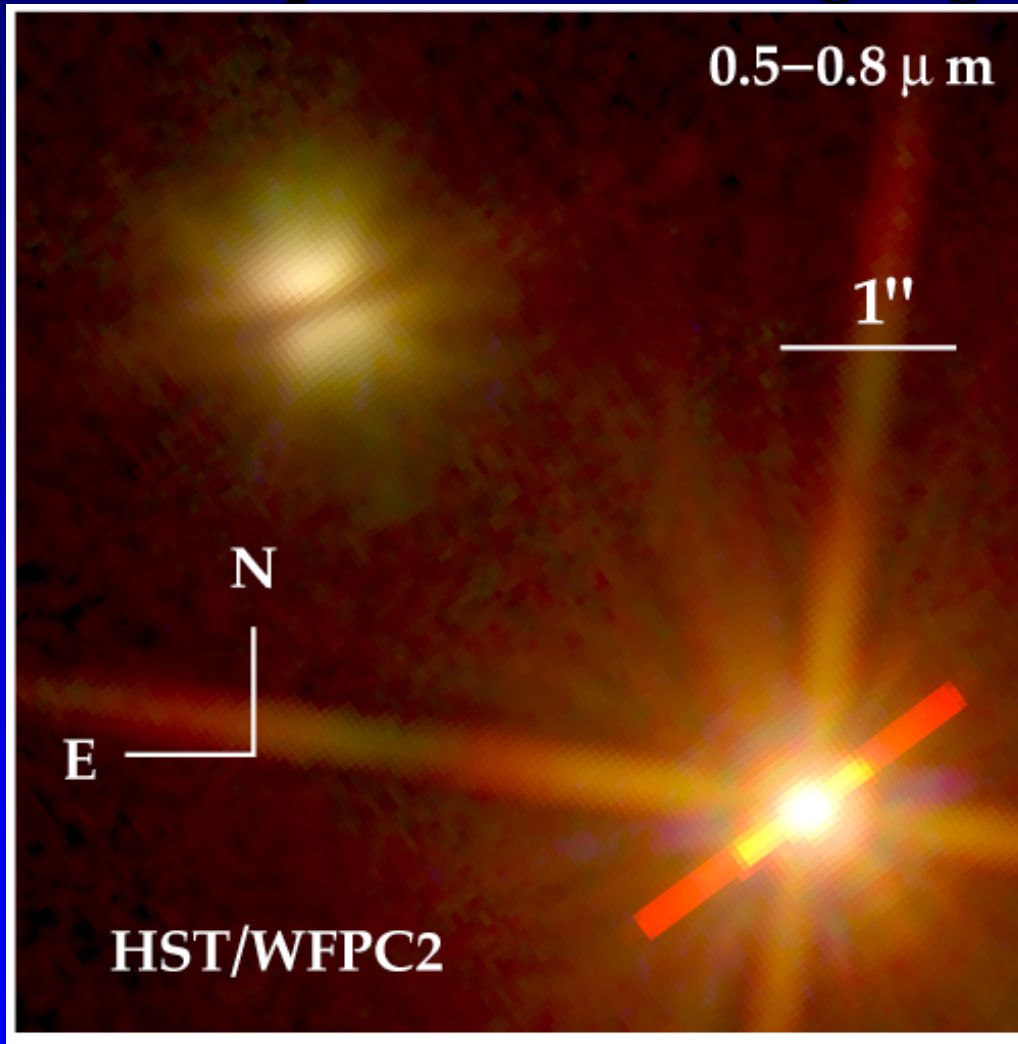
D. Potter, U. Arizona

Space/AO/Long λ Imaging of HK Tau

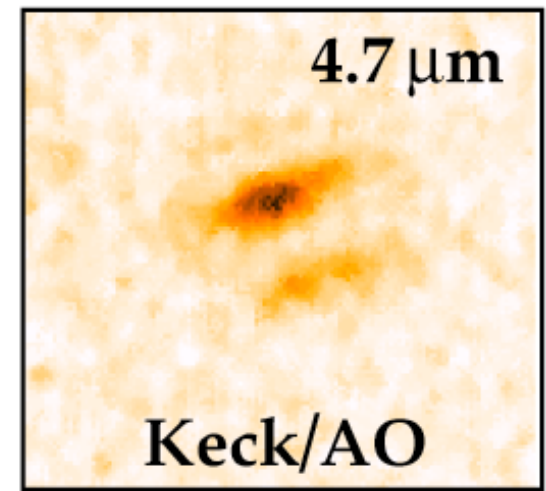
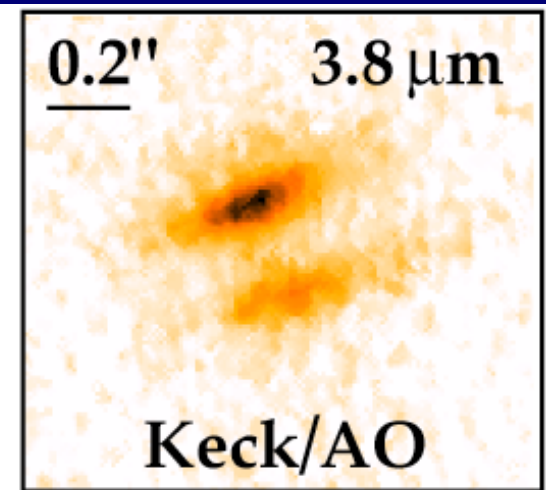


- Scattering from larger ($> 1 \mu\text{m}$; evolved; non-ISM grains)
- Likely stratified (larger grains deeper; longer λ observations)

Space/AO Imaging of HV Tau

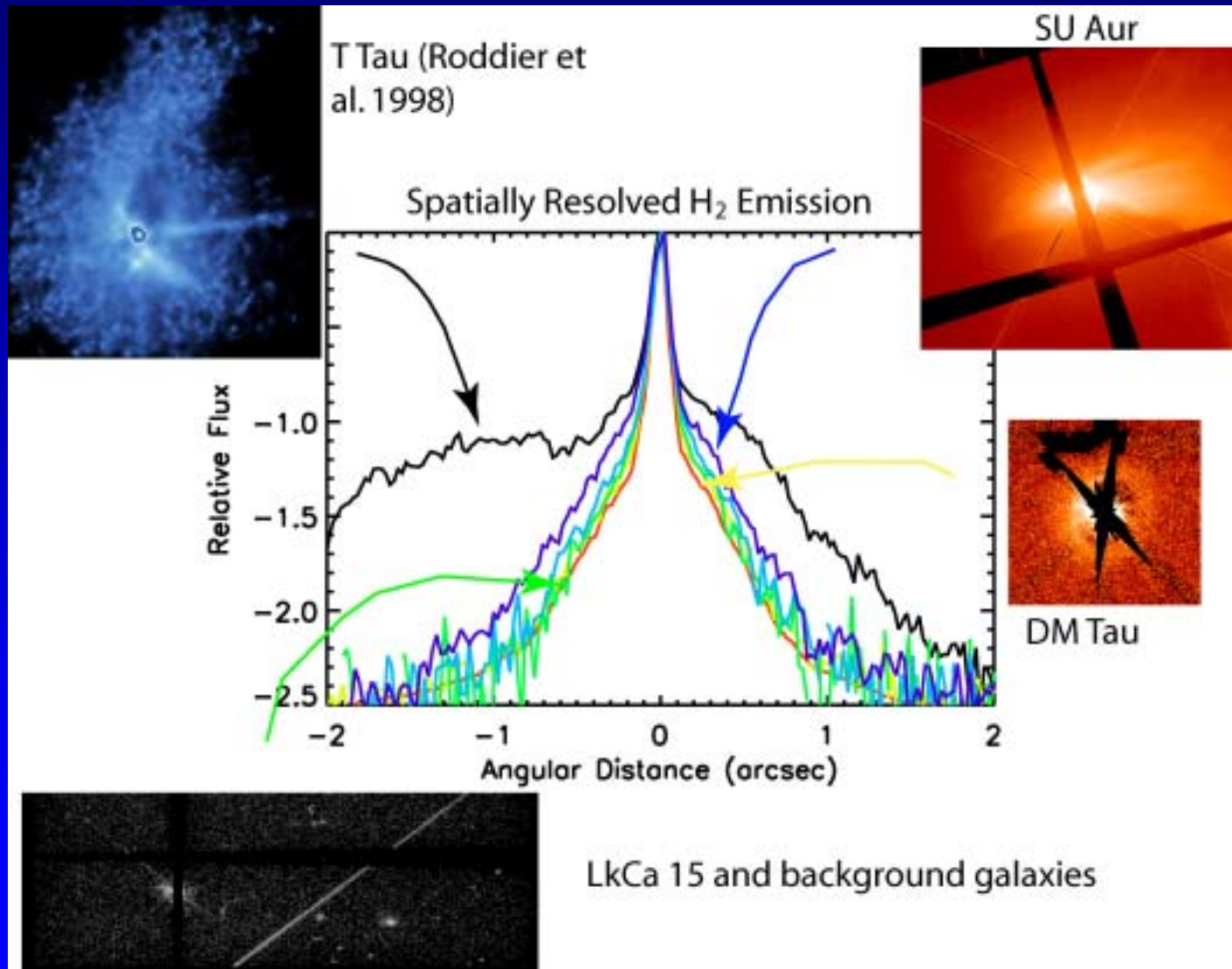


Stapelfeldt et al 2003



Courtesy of G. Duchene

Nebular Environments of T Tau Stars: Surface Brightness Scales with H_2 Flux

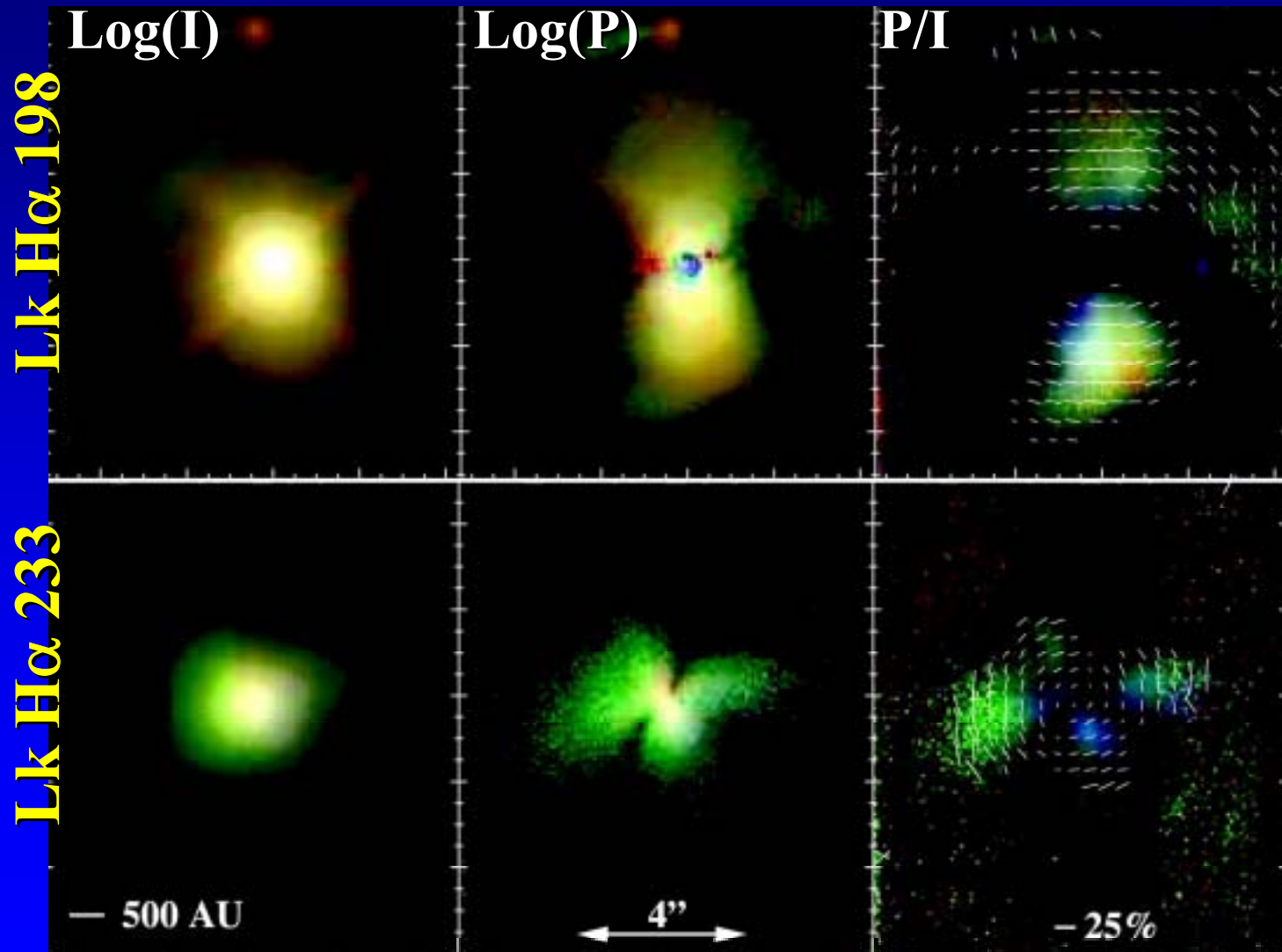


See Grady et al poster (this conference)

LGS + AO Dual Channel Imaging Polarimetry

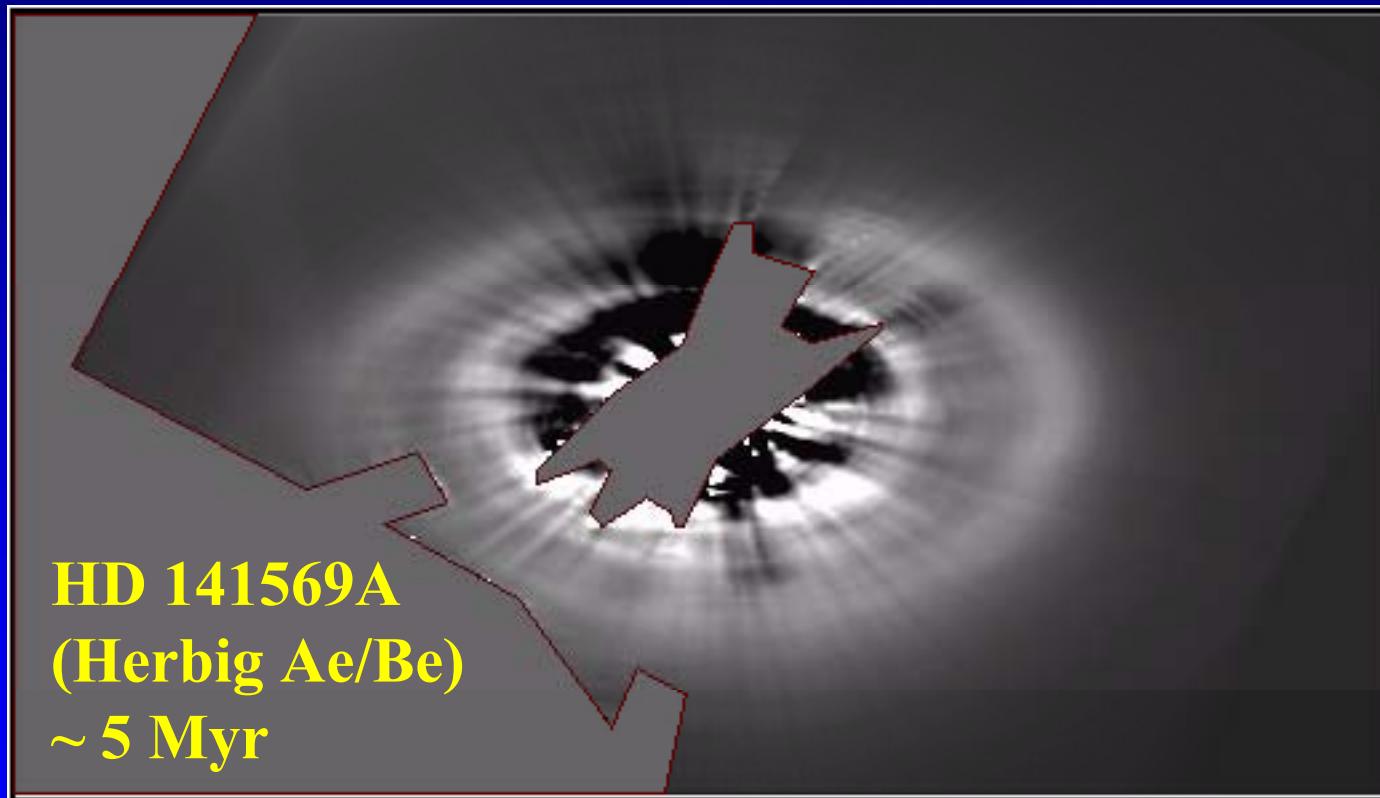
Lick/Shane 3m + IRCAL (J, H, Ks)

Intermediate Mass HAeBe Stars with T Tau-like *envelopes*



Perrin et al 2004 Science 303 1345

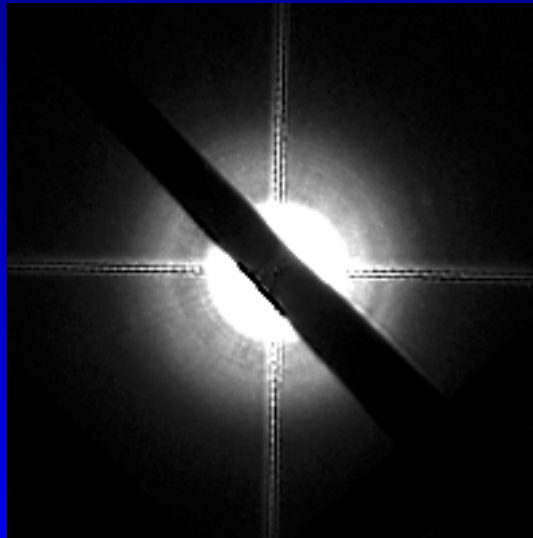
Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.



A 400 AU radius disk, with a broad, partially filled asymmetric gap containing a “spiral” arclet.

Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.

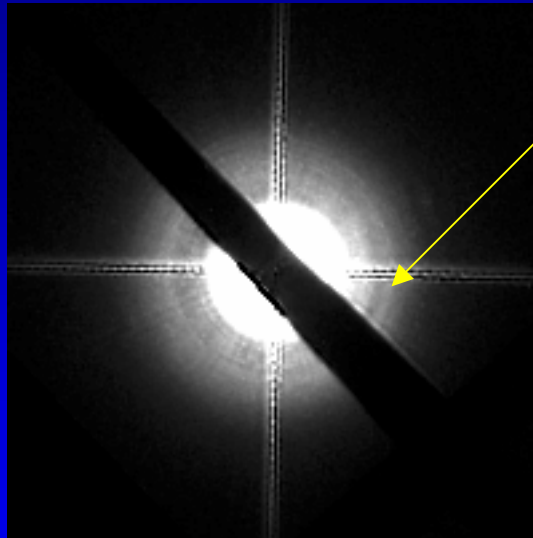
**TW Hya
K7Ve cTTs
“Old” PMS Star**



Near pole-on, near circularly symmetric disk with a break in its surface brightness profile at 120 AU (2").

Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.

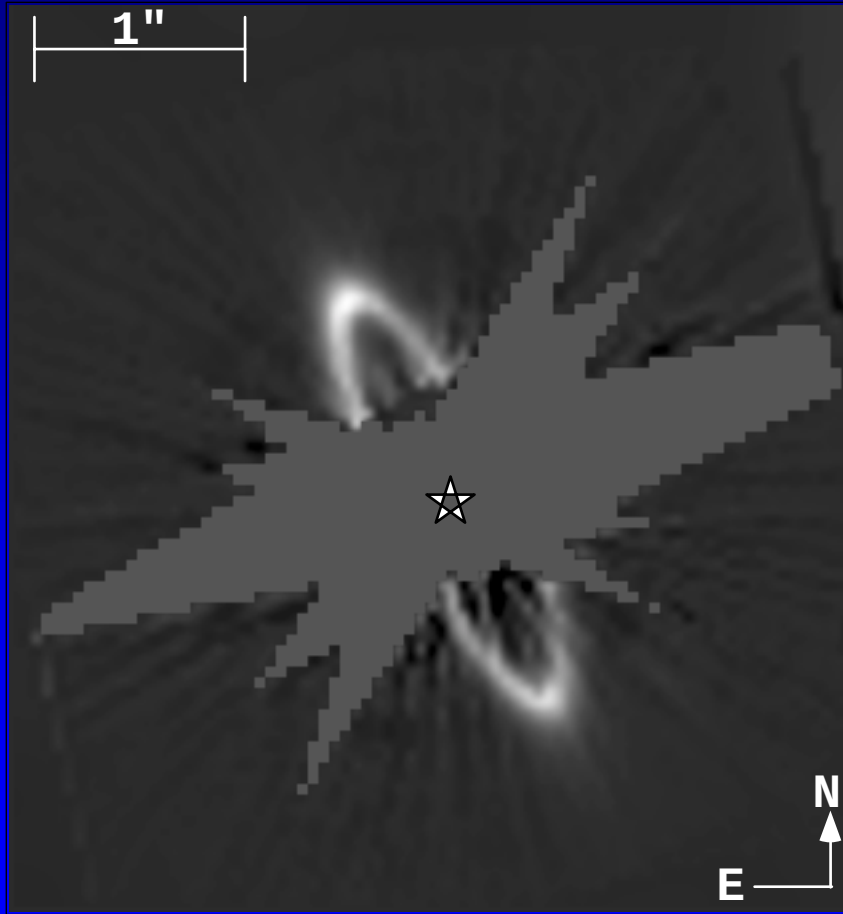
**TW Hya
K7Ve cTTs
“Old” PMS Star**



*and, possibly, a
radially and
azimuthally confined
arc-like depression.*

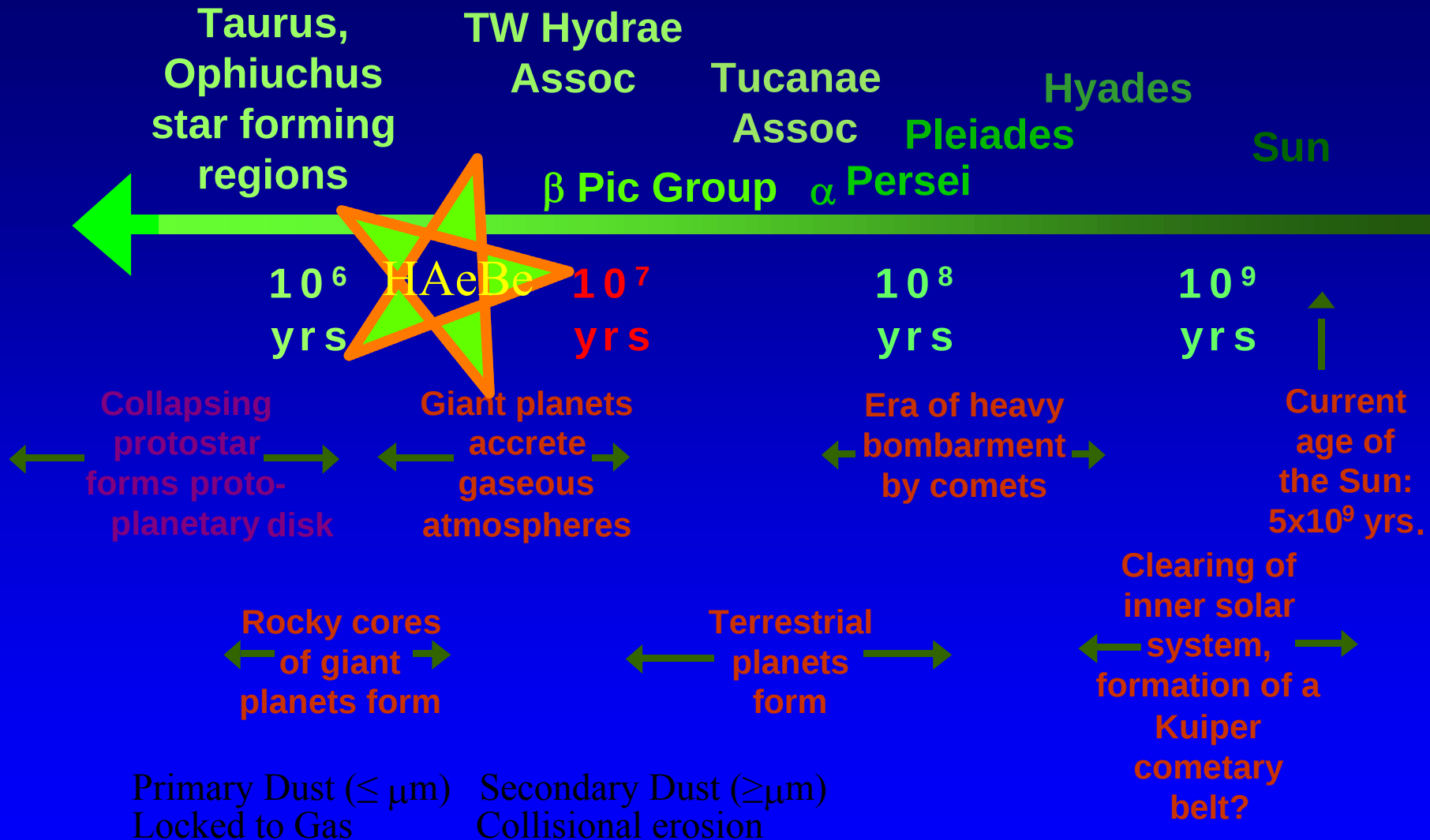
**Near pole-on, near circularly symmetric disk with a
break in its surface brightness profile at 120 AU (2").**

Examples of Dusty Disks with Radial and Hemispheric Brightness Anisotropies and Complex Morphologies, Possibly Indicative of Dynamical Interactions with Unseen Planetary Mass Companions, Spatially Resolved and Imaged Around Young (< 10 Myr) Stars by HST.



**HR 4796A (A0V), ~ 8 Myr
A 70AU radius ring, ~ 12
AU wide ring of red
material, exhibiting strong
forward scattering and
anisally asymmetric
hemispheric flux densities.**

Planet-Building Timeline



Clearing Timescales: P-R drag few 10^6
 Rad. Pressure: $\sim 10^4$

HD 141569A

Herbig Ae/Be Star (B9V, H = 6.9)

d = 100 pc, Age ~ 5 Myr, Mass ~ 2.3 M_{sun}

L_{IR} / L_{*} = 8.4x10⁻³ (few x β Pic, HR 4796A)

Hierarchical Triple with 2 M-Dwarf Companions

HD 141569A - Thermal IR Disk Detection / Imaging

HD 141569

PSF STAR

12.5

17.9

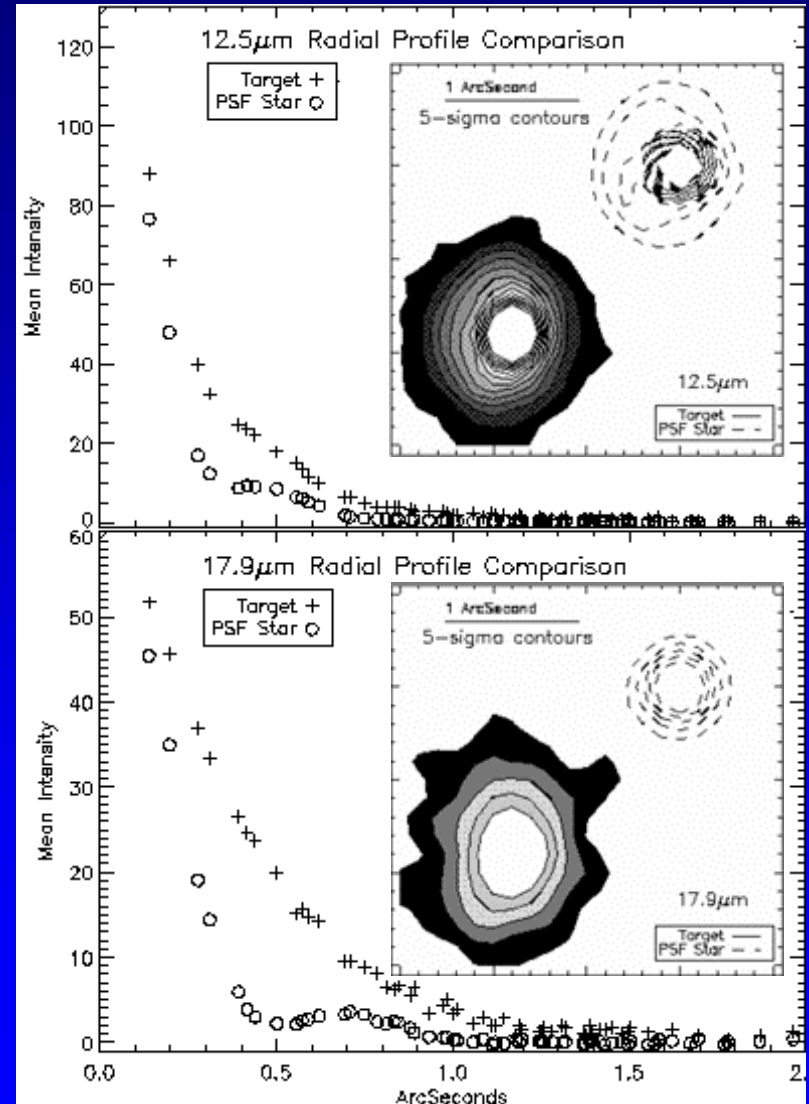
20.8

0.26" FWHM

0.37" FWHM

0.43" FWHM

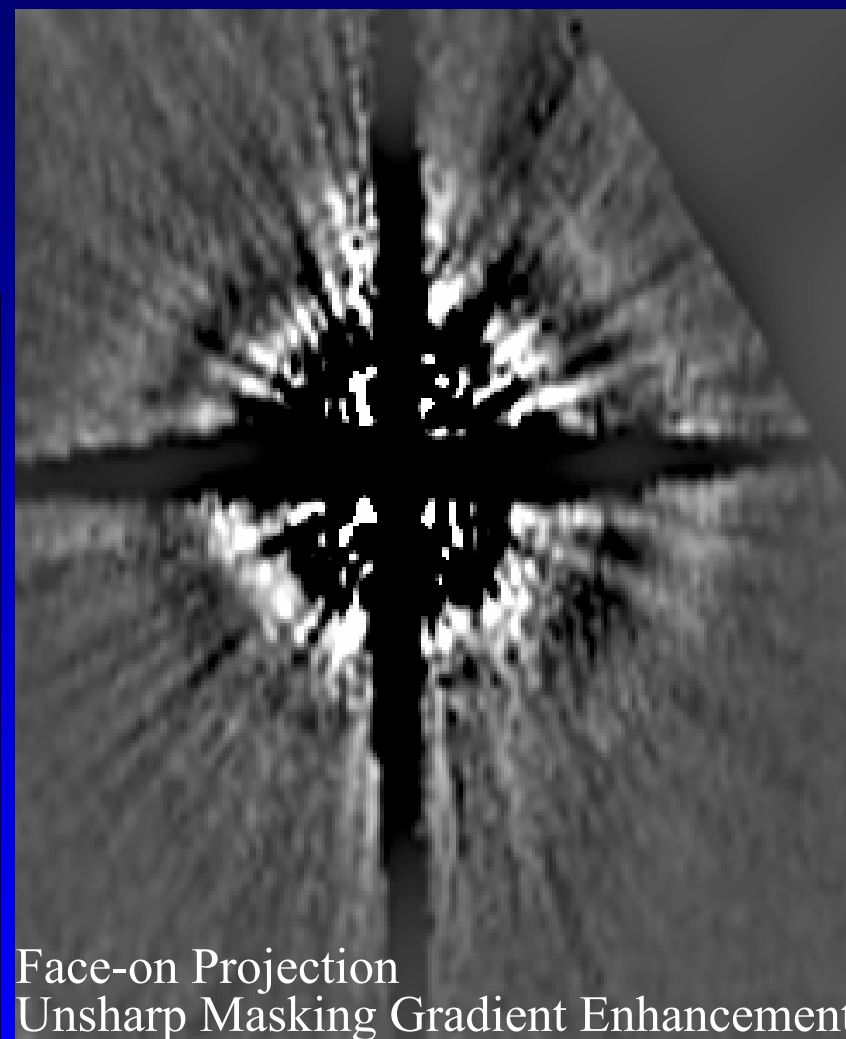
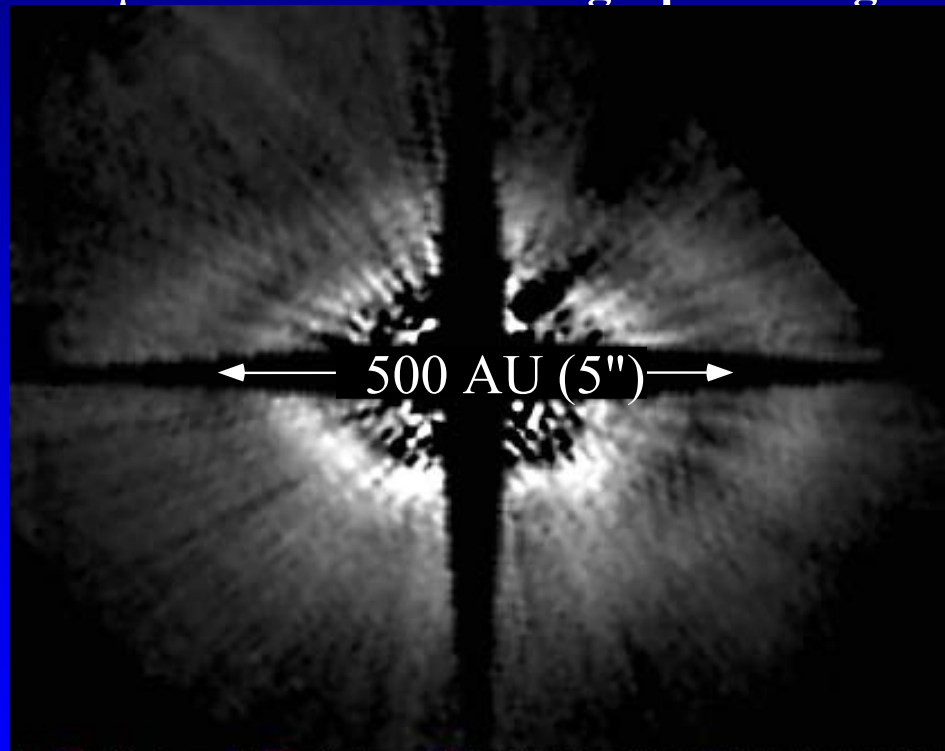
Silverstone 1999



HD 141569A - NICMOS Coronagraphic Imaging

Disk Radius = 400 AU
Gap Radius = 245 AU
Gap Width ~ 40 AU

1.1 μm NICMOS Coronagraphic Image



Also observed by Augereau et al. at 1.6 μm

Scattering by cold dust is *OUTSIDE* region of thermal emission.

HD 141569A - Circumstellar Disk & “Gap”

Flux Density = $8 \pm 2 \text{ mJy}$ ($r > 0.6''$)

SB @ 190 AU = $0.3 \text{ mJy arcsec}^{-2}$

$\omega \sim 0.3$ @ $< 190 \text{ AU}$, 0.4 @ $> 190 \text{ AU}$

Inclination to LOS = $51^\circ \pm 3^\circ$

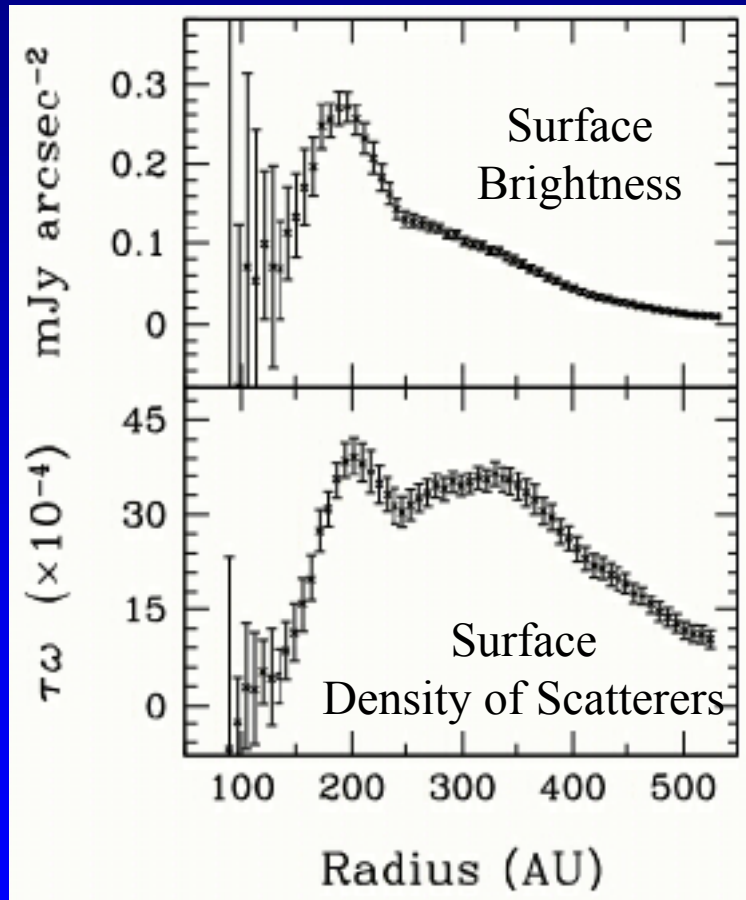
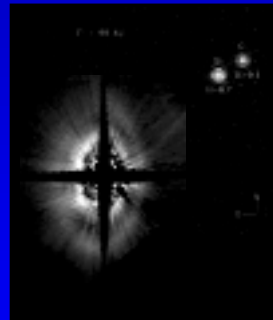
Intrinsic Scattering Function results in Brightness Anisotropy in ratio $1.5 \pm 0.2:1$ in direction of forward scattering.

Gap partially cleared of material (by an unseen planetary companion?).

Hierarchical triple system

$d_{A(\overline{BC})} = 8.3''$, $d_{BC} = 1.3''$

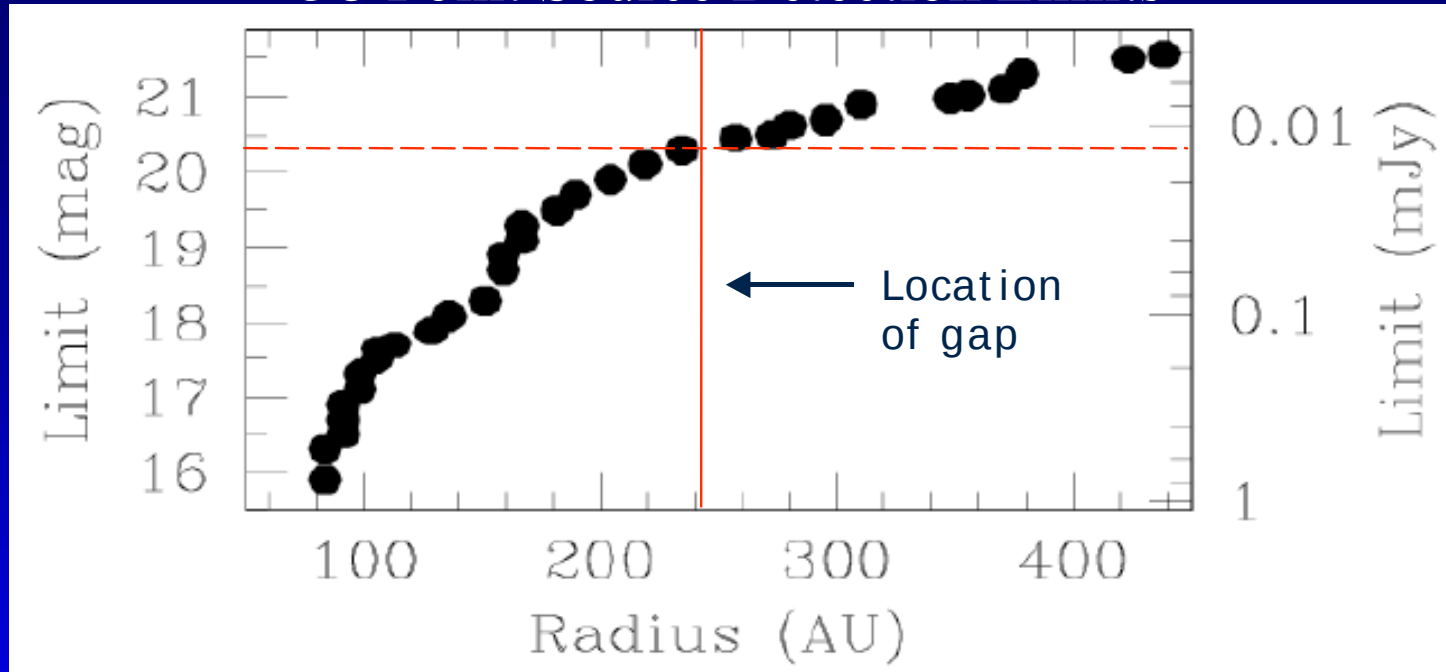
M2V/M4V companions may influence disk dynamics.



Weinberger, et al 1999 ApJ 522 L53

HD 141569A - “Embedded” Planet Detection Limits

3σ Point Source Detection Limits



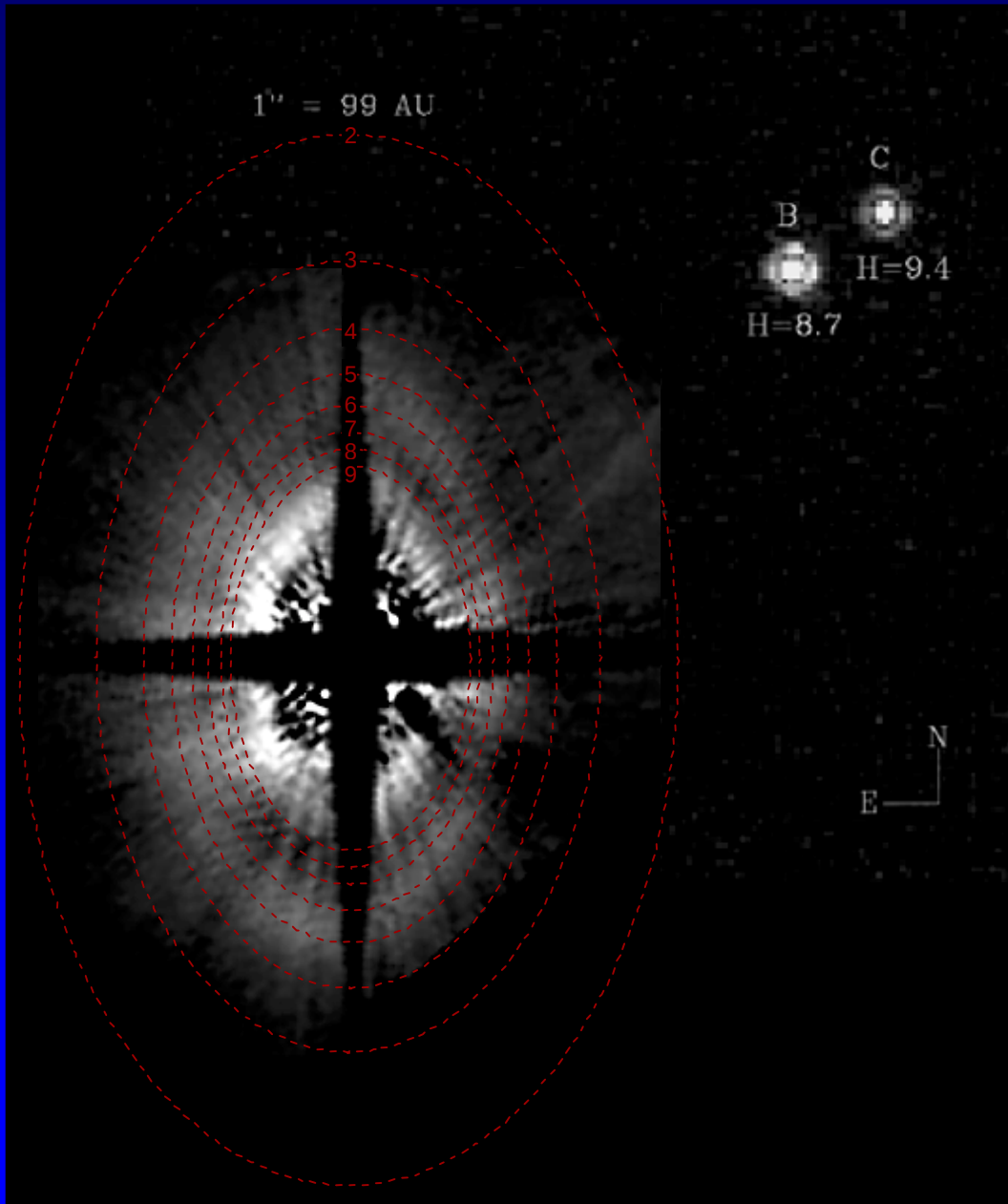
In gap (83% area observed) F110W detection limit = 20.3 $\Rightarrow$ $\sim 2 M_{\text{jup}}$ @ 5 Myr

Gap Width: Radius implies planetary mass of $\sim 0.9 M_{\text{jup}}$ -- UNDETECTABLE
Mass of Planet to Clear Gap: $M/M_* \sim c(\Delta a/a^3)$ where $c \sim 0.1$ (Lissauer 1993)
for $\Delta a = 50$ AU, $a = 240$ AU $\rightarrow M = 0.9 M_{\text{jup}}$, below detection threshold.

At 240 AU with $M = 2.3 M_{\text{sun}}$, $P = 2500$ yr $\Rightarrow$ 2000 orbits (at 5 Myr).

Gaseous disk clearing in ~ 300 orbits (Bryden et al 1999), 0.8 Myr.

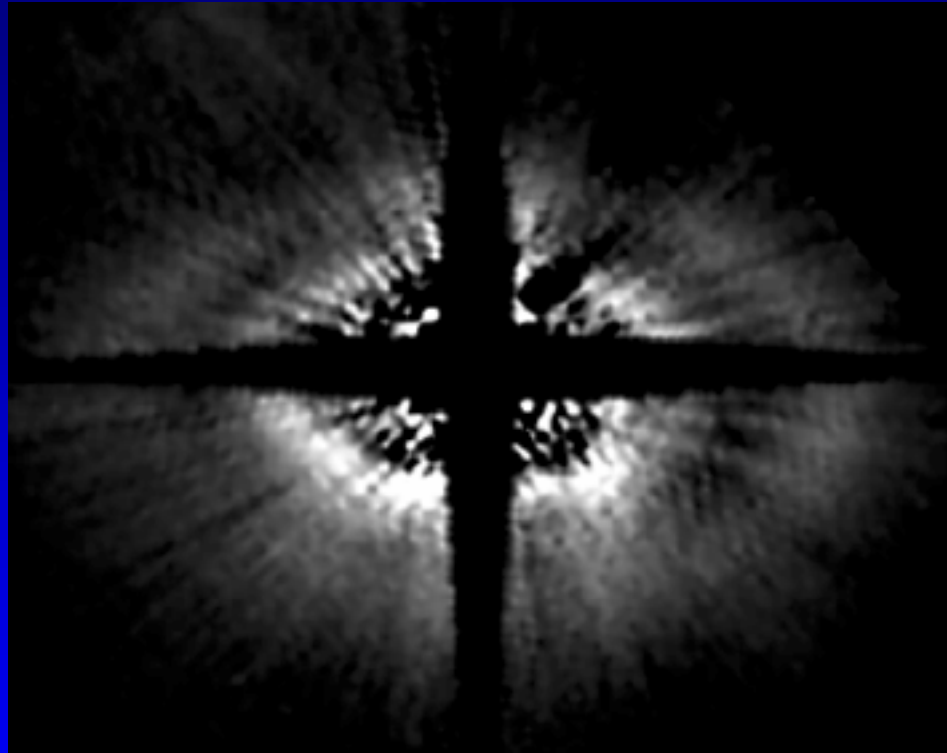
HD 141569 (A, BC) - Dynamical Sculpting by Companions?



- Density of Scatters:
Equal at 200 AU and 360 AU.
If non-coplanar companions can excite vertical velocities in disk.
- Circular 50 AU-wide Gap @ 250 AU
Continual clearing to remove P-R and RP driven transiting particles.
- Gap circularity implies dynamical stability on long time-scales.
- If co-planar Lindblad resonances from 1053AU distant CoM (BC) (9:1) @ 243 AU, (8:1) @ 263AU closest to gap.

HD 141569A

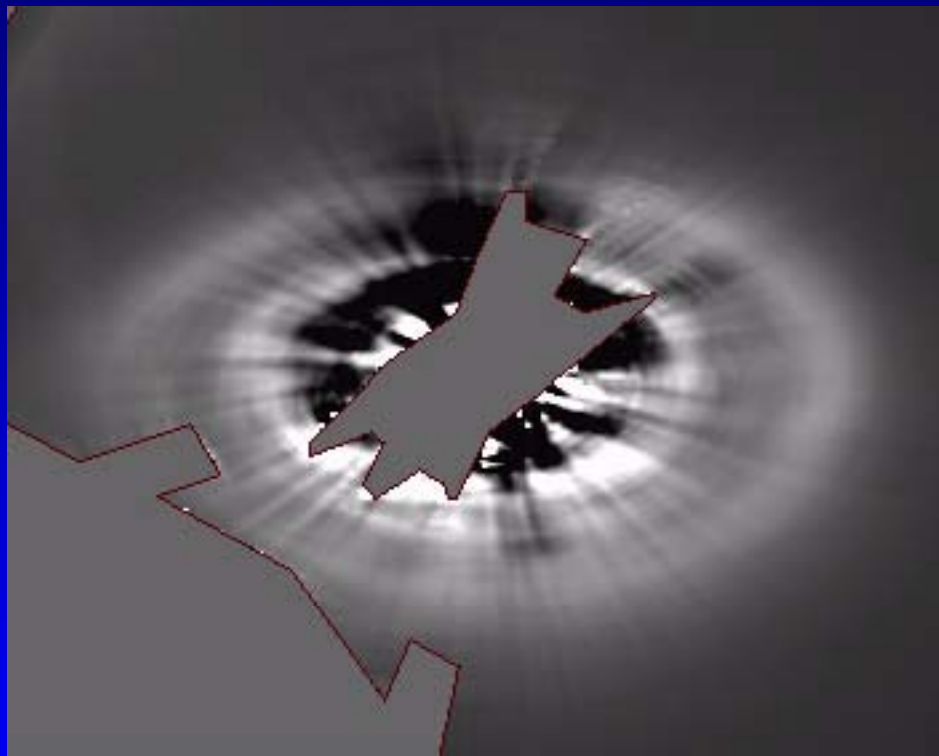
NICMOS (0.11" Resolution)



Knowing the Flux Density, Orientation, Size, etc.,
Allowed Planning an Effective Follow-up...

HD 141569A

STIS (0.05" Resolution)

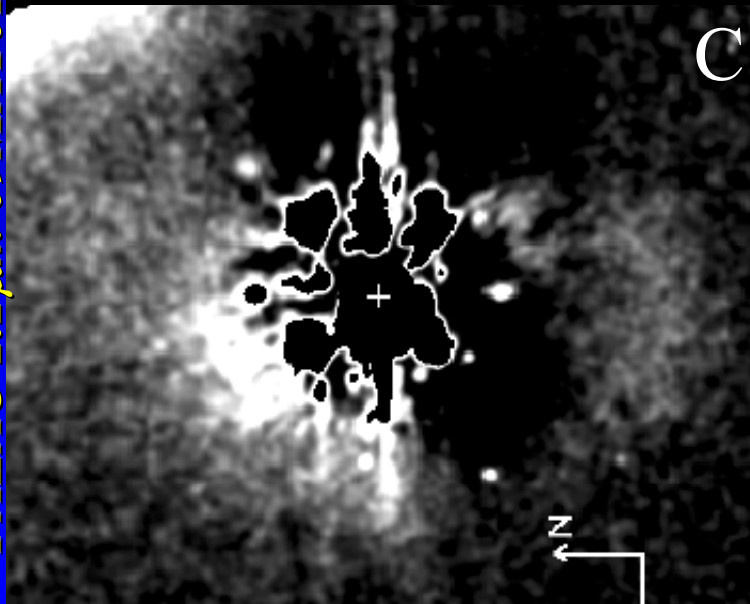
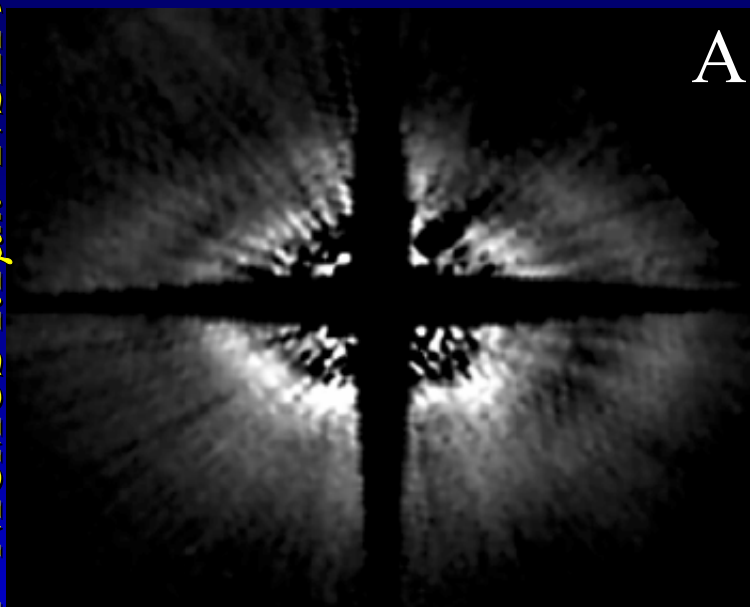


Global structure better described by “concentric ring” morphology.

“Gap” broader and partially filled.

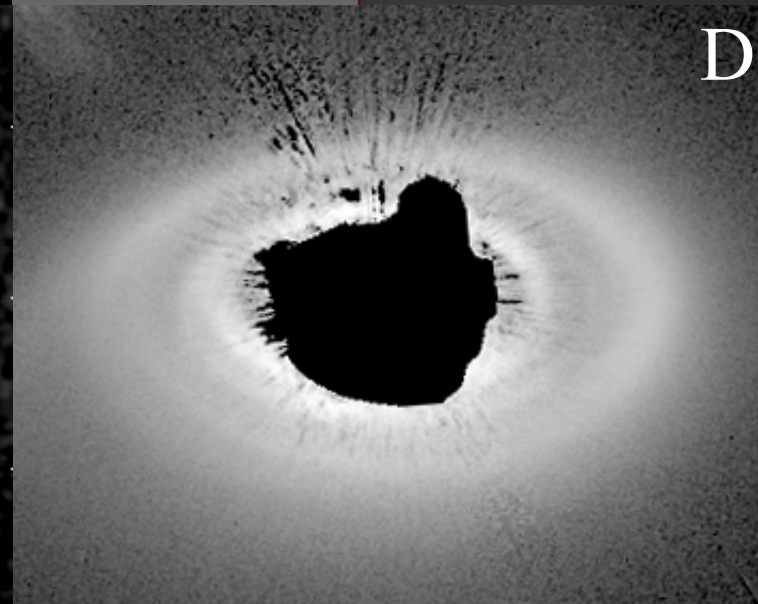
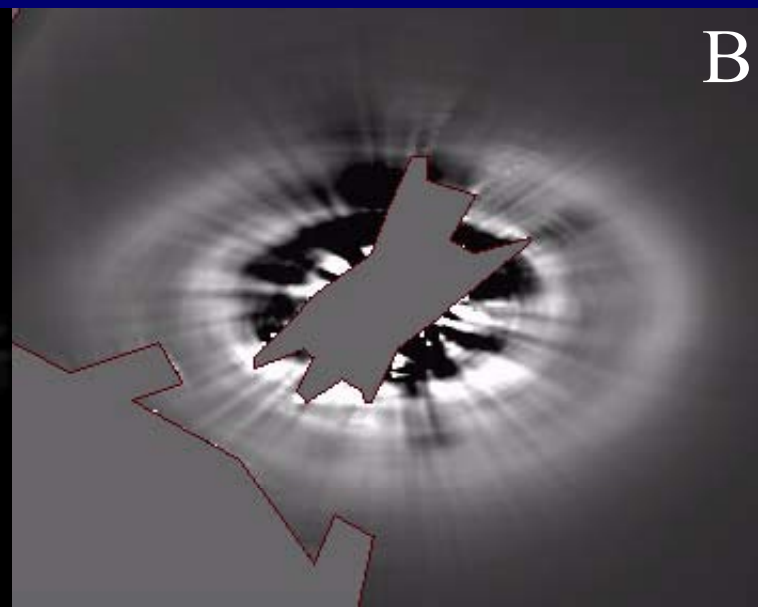
“Spiral arclet” structure seen in disk gap.

PALAO 2.2 μ m 09MAY01 NICMOS 1.1 μ m 27SEP98



A: Weinberger et al 1999

C: Boccaletti et al 2003



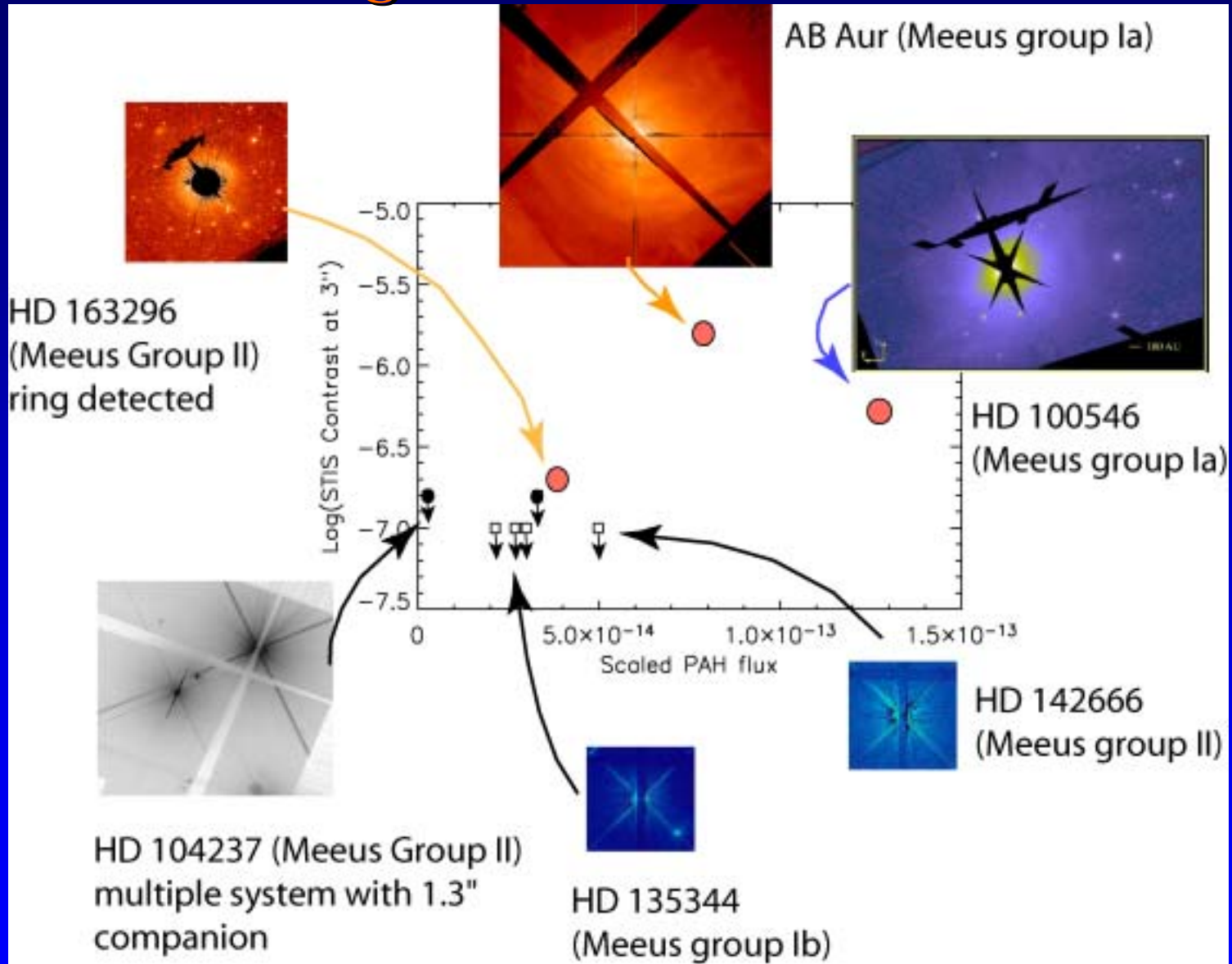
B: Schneider et al 2001

D: Clampin et al 2003

STIS 0.5 μ m 06APR01

ACS 0.6 μ m 21JUL02

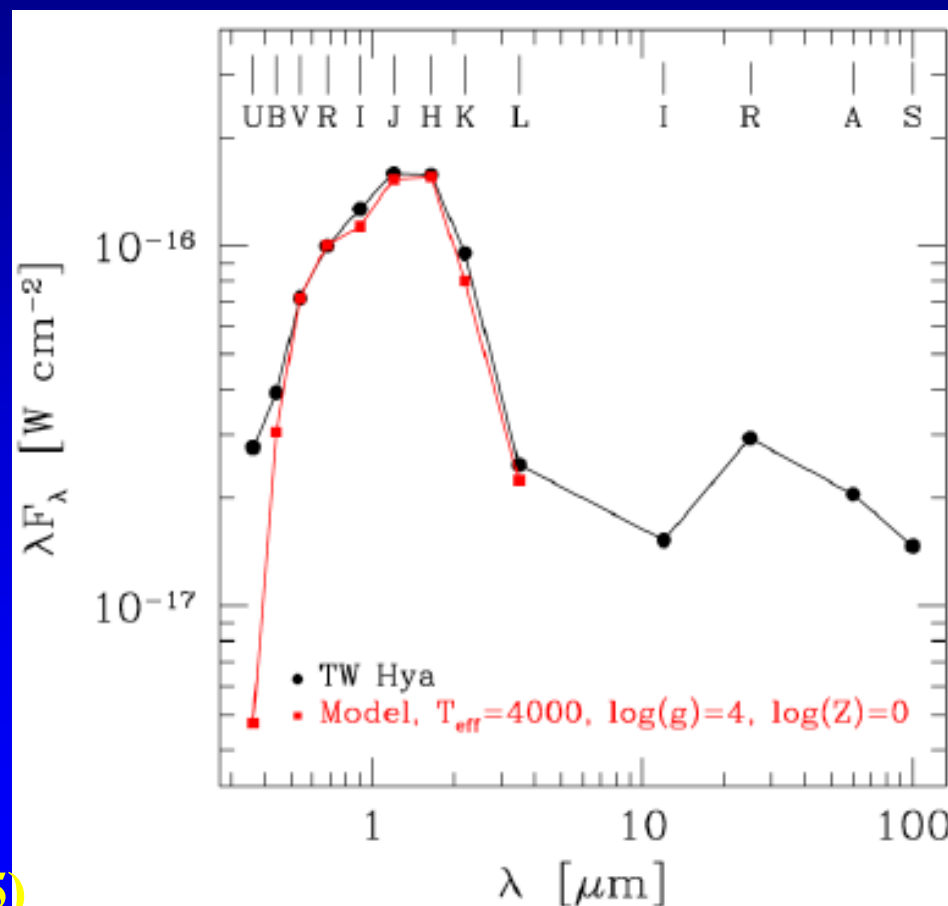
HAeBe Disk Brightness Correlates with PAH Flux



See Grady et al poster (this conference)

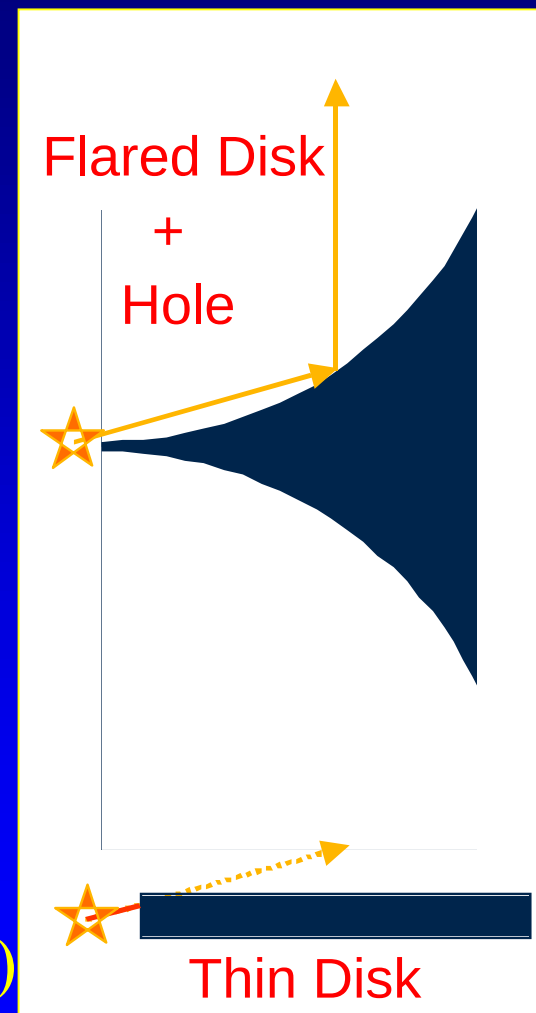
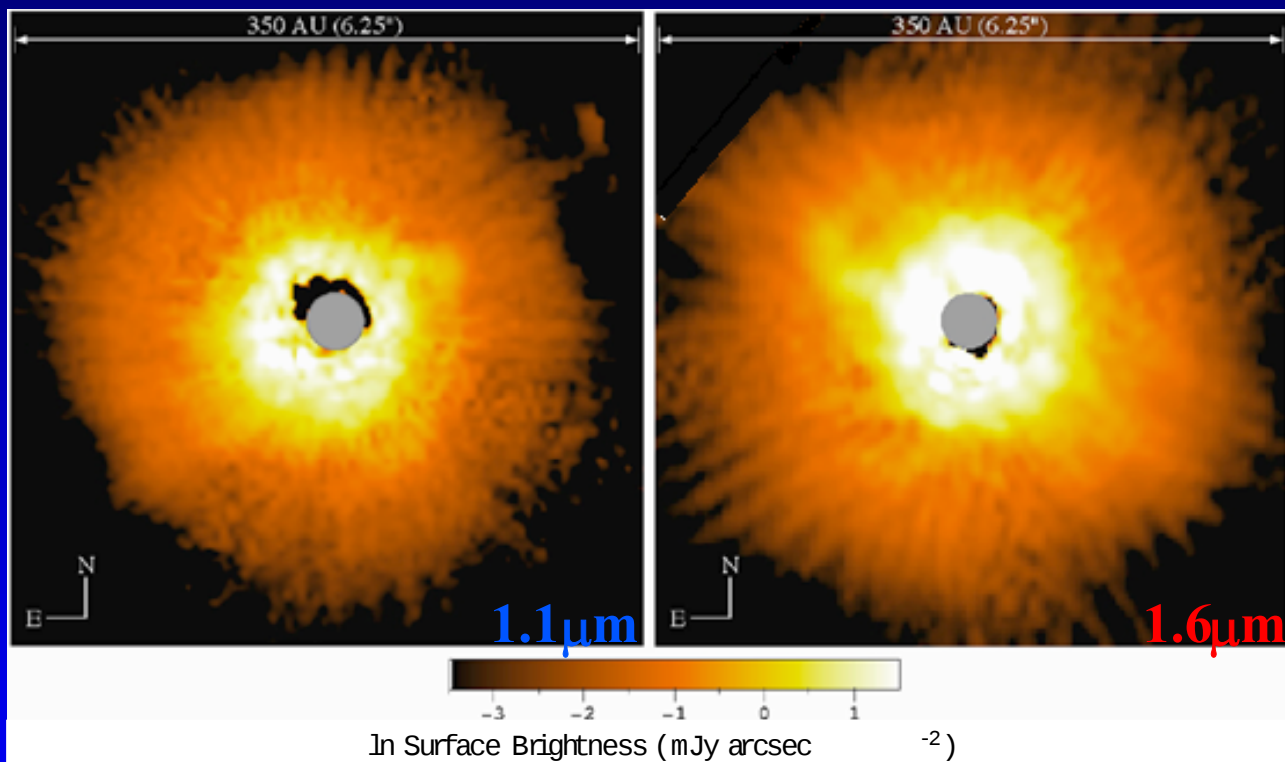
TW Hydrae

- K7Ve (Rucinski & Krautter, 1983)
- Distance: 56 ± 7 pc (Hipparchos)
- Age: ~ 6 Myr
- H α and UV Excesses
Isolated Classical T-Tauri Star
- Member TW Hya Association
(TWA ~ 10 Myr, 60 pc)
- Long Wavelength Excesses
 $\tau \sim L_{\text{disk}}/L_{\text{star}} \sim 0.3$ (IRAS)
CO emission (Zuckerman et al. 1995)



TW Hydrae - NICMOS Coronagraphic Imaging

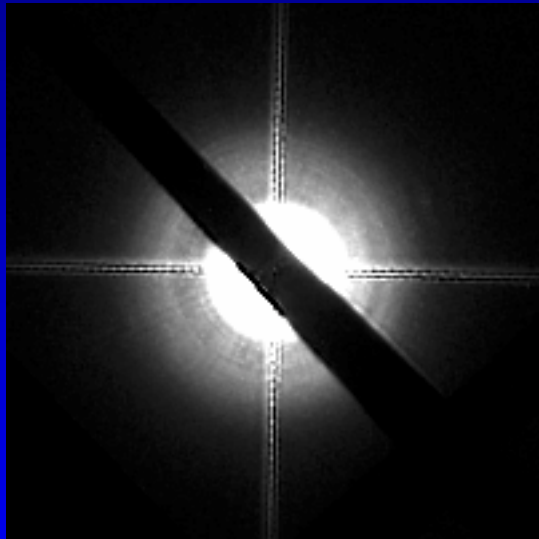
“Face-On”, Optically Thick, 190 AU radius Flared Disk



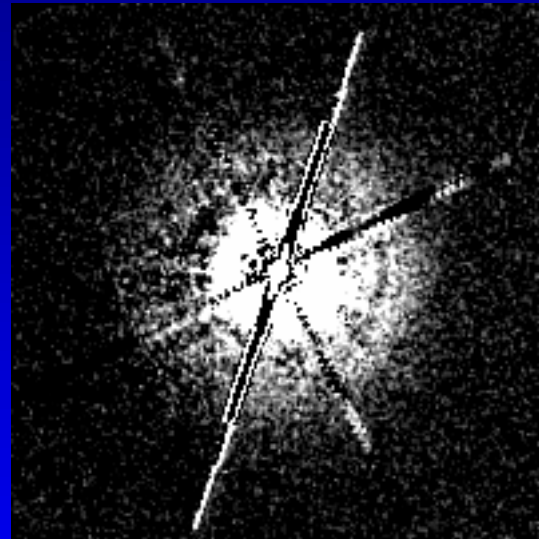
- Gray scattering:
 $F110W - F160W = \sim 0.96 \text{ mag (same as star)}$

TW Hydrae

Also seen in HST Optical Band-Passes



STIS ($0.5\mu\text{m}$)



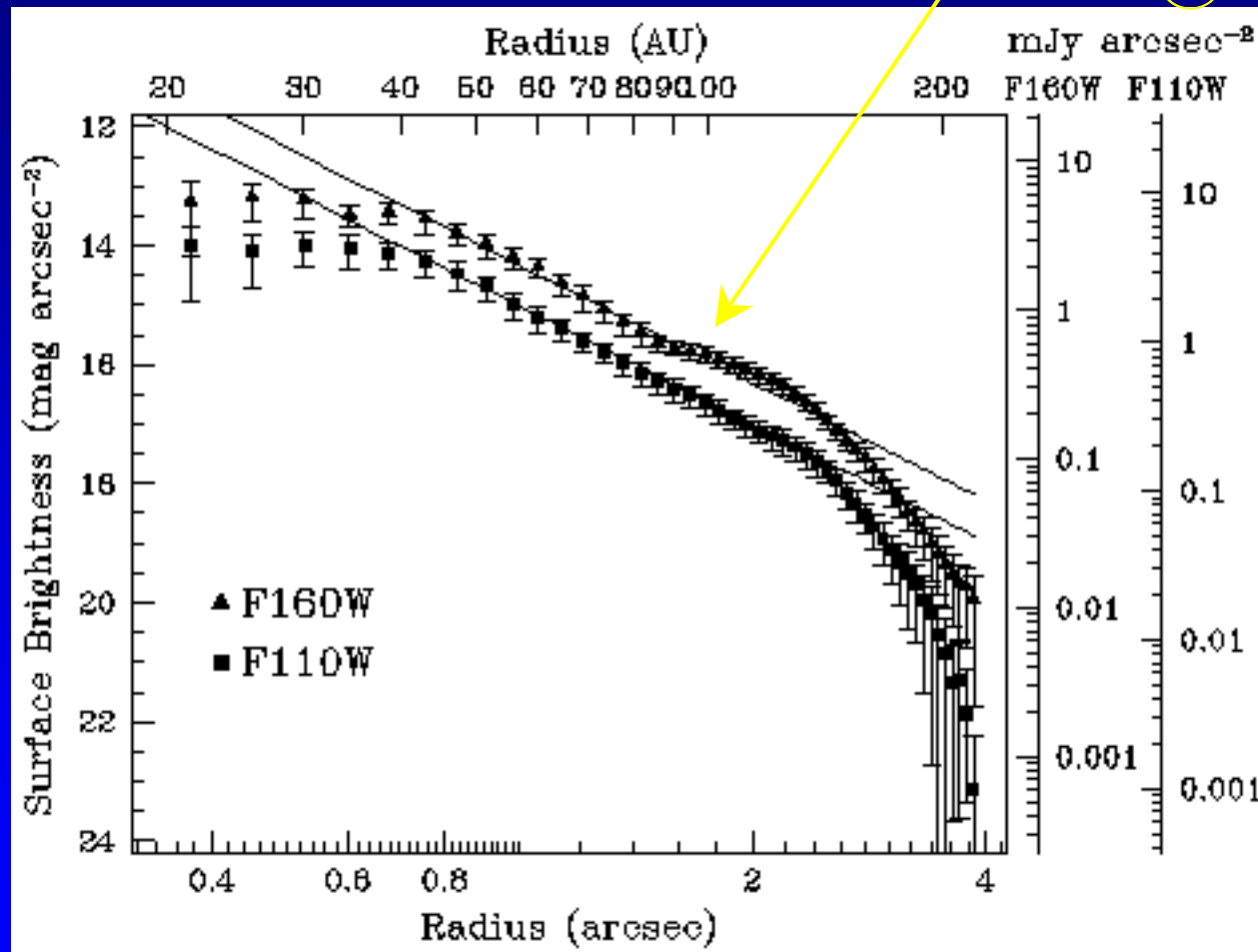
WFPC-2 ($0.8\mu\text{m}$)

*And, Subsequently Observed from the Ground:
e.g., Trilling et al 2001 (CoCo); Apai et al 2004 (NACO)*

TW Hydrae - NIR Surface Brightness Profile

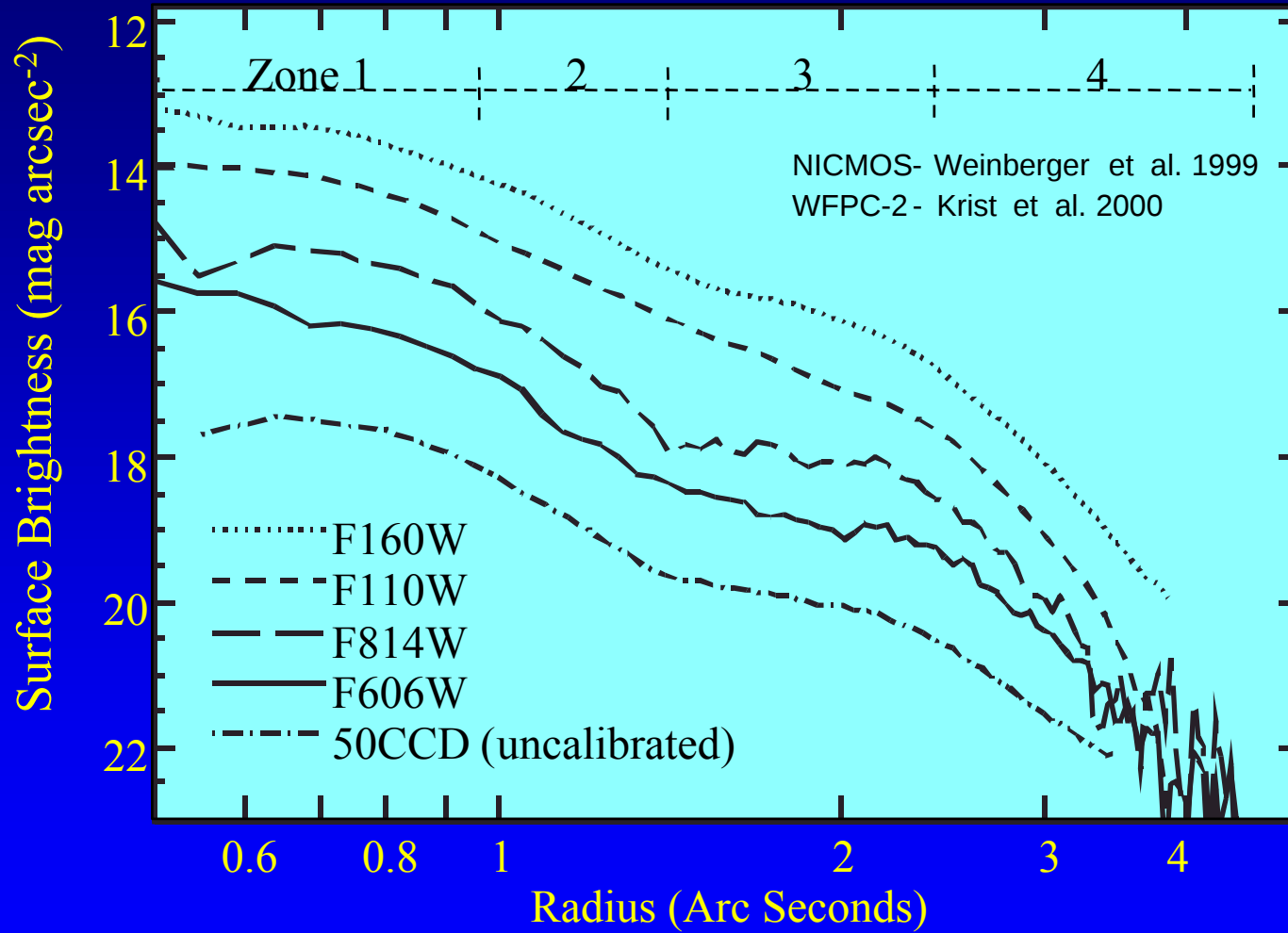
Flux density Power Law: $r^{-2.6 \pm 0.1}$ @ $35 \text{ AU} < r < 135 \text{ AU}$

Break @ 100 AU

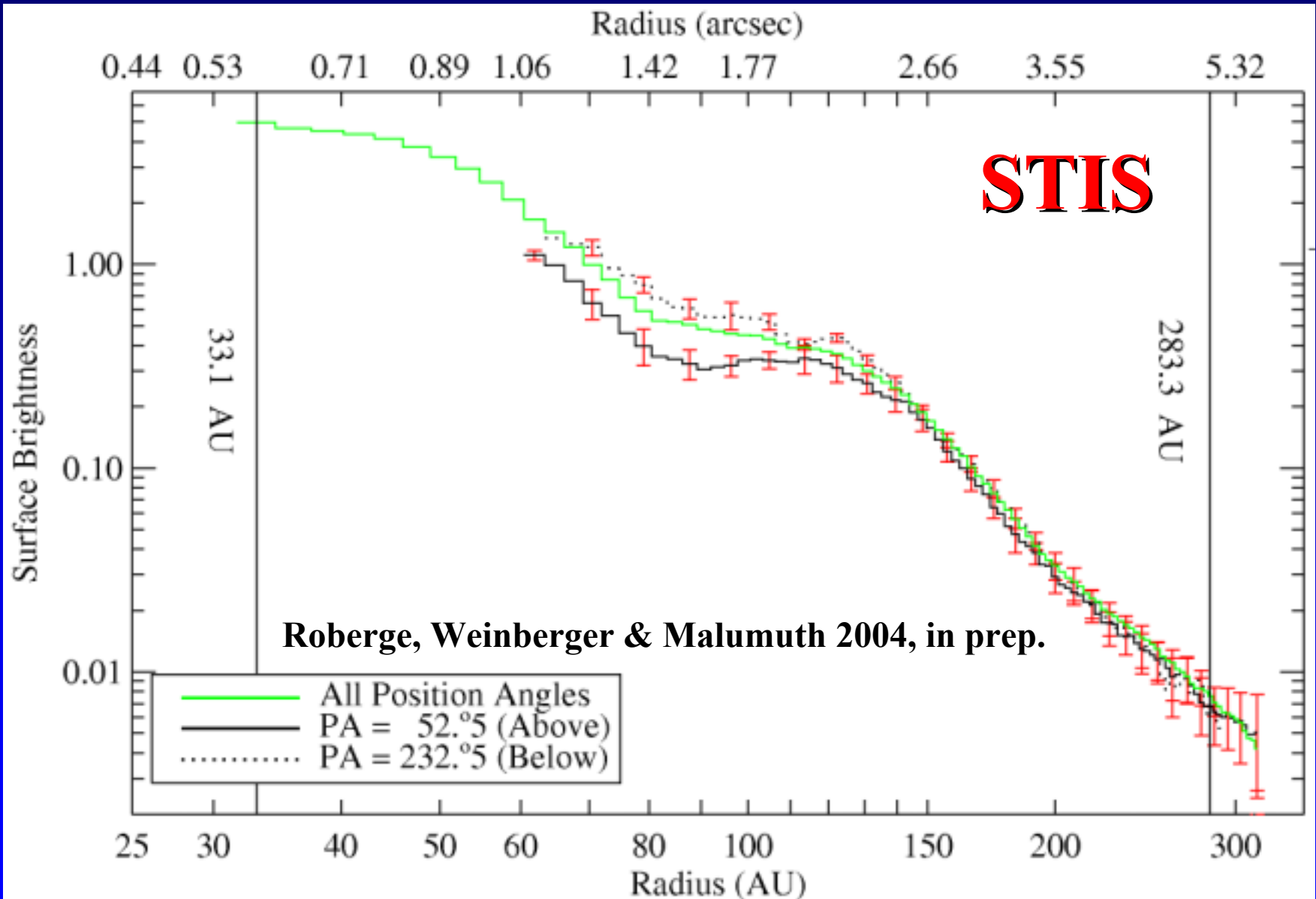


TW Hydrae - Surface Brightness Profile

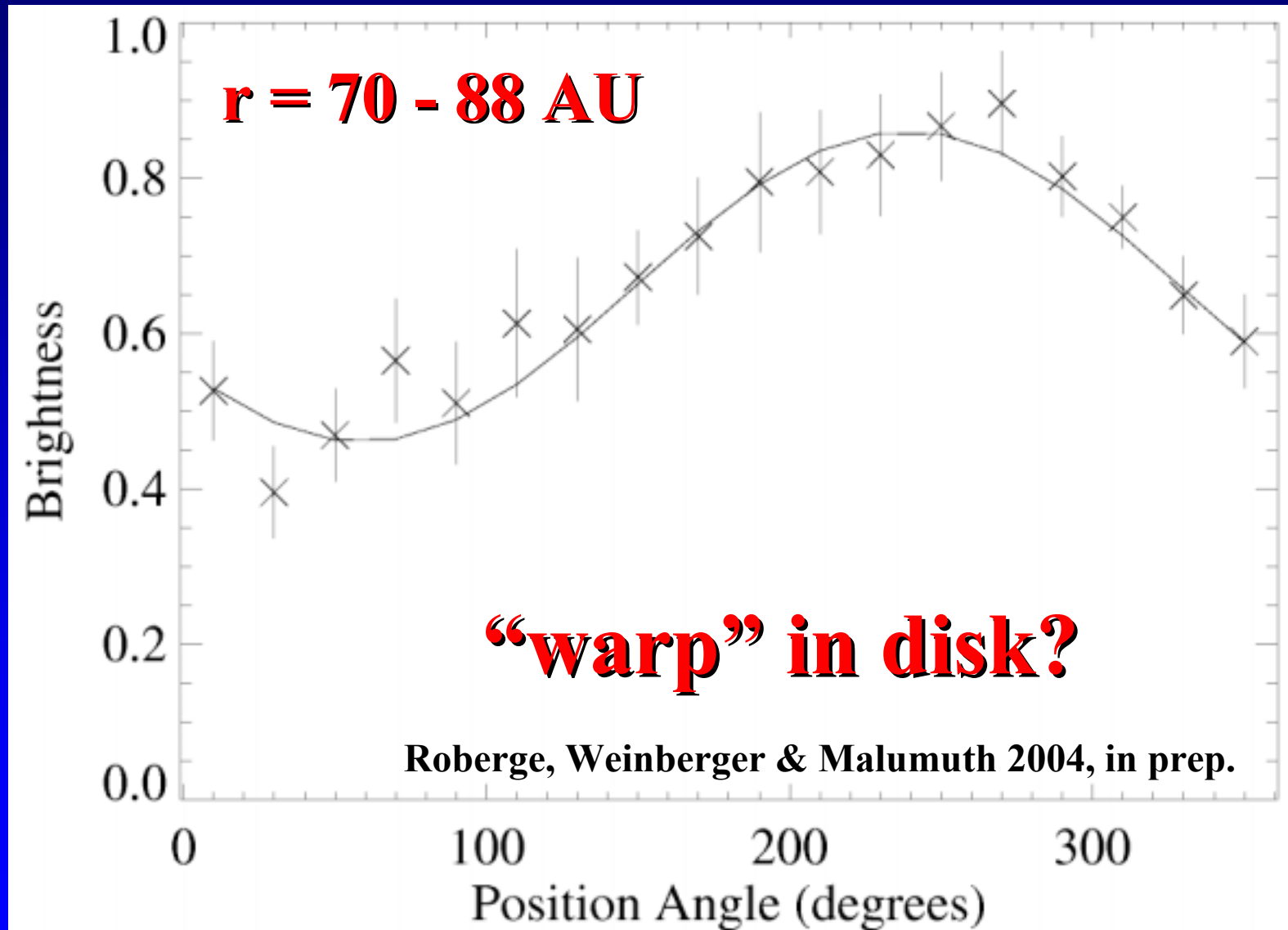
“Zone 2-3 Break” *may* implicate sculpting by grains



TW Hydrae - Optical Surface Brightness Profile

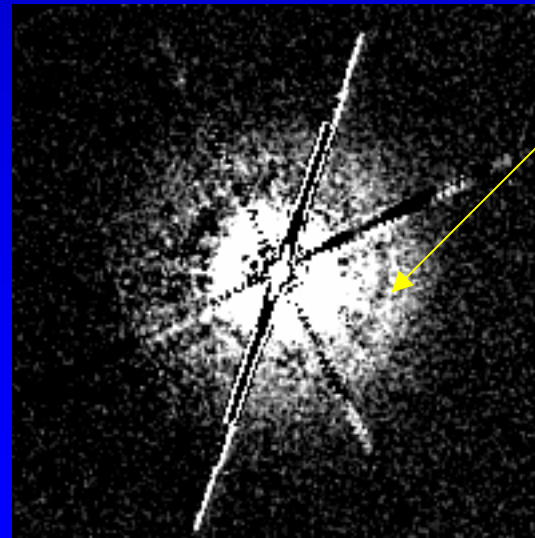
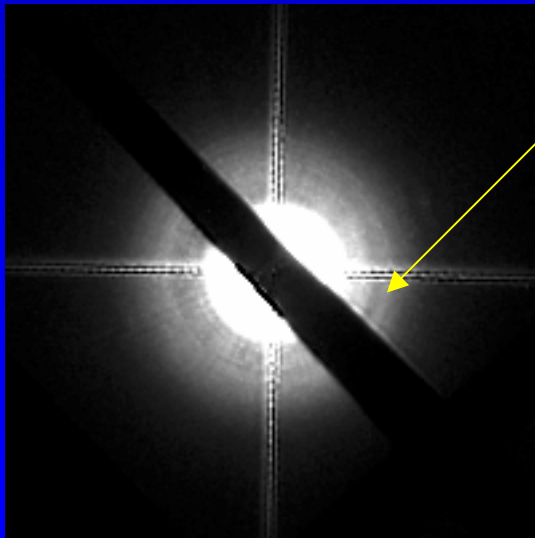
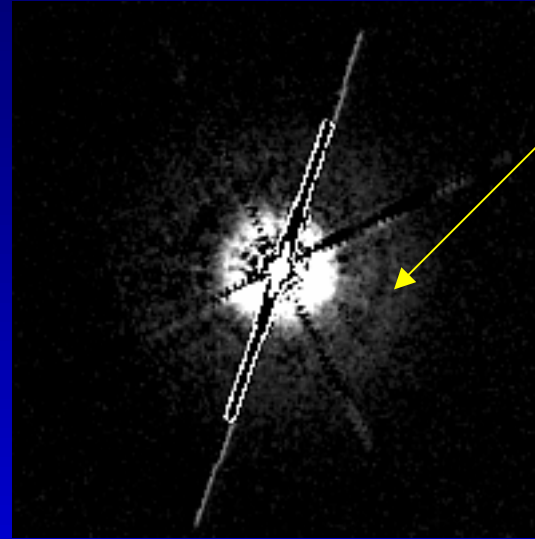
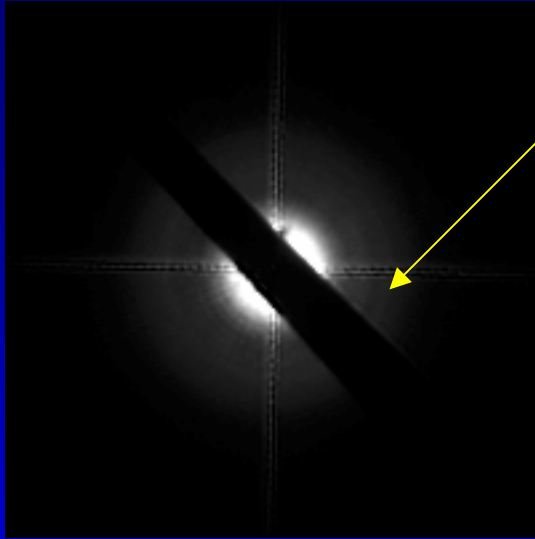


TW Hydrae - Azimuthal Brightness Variation

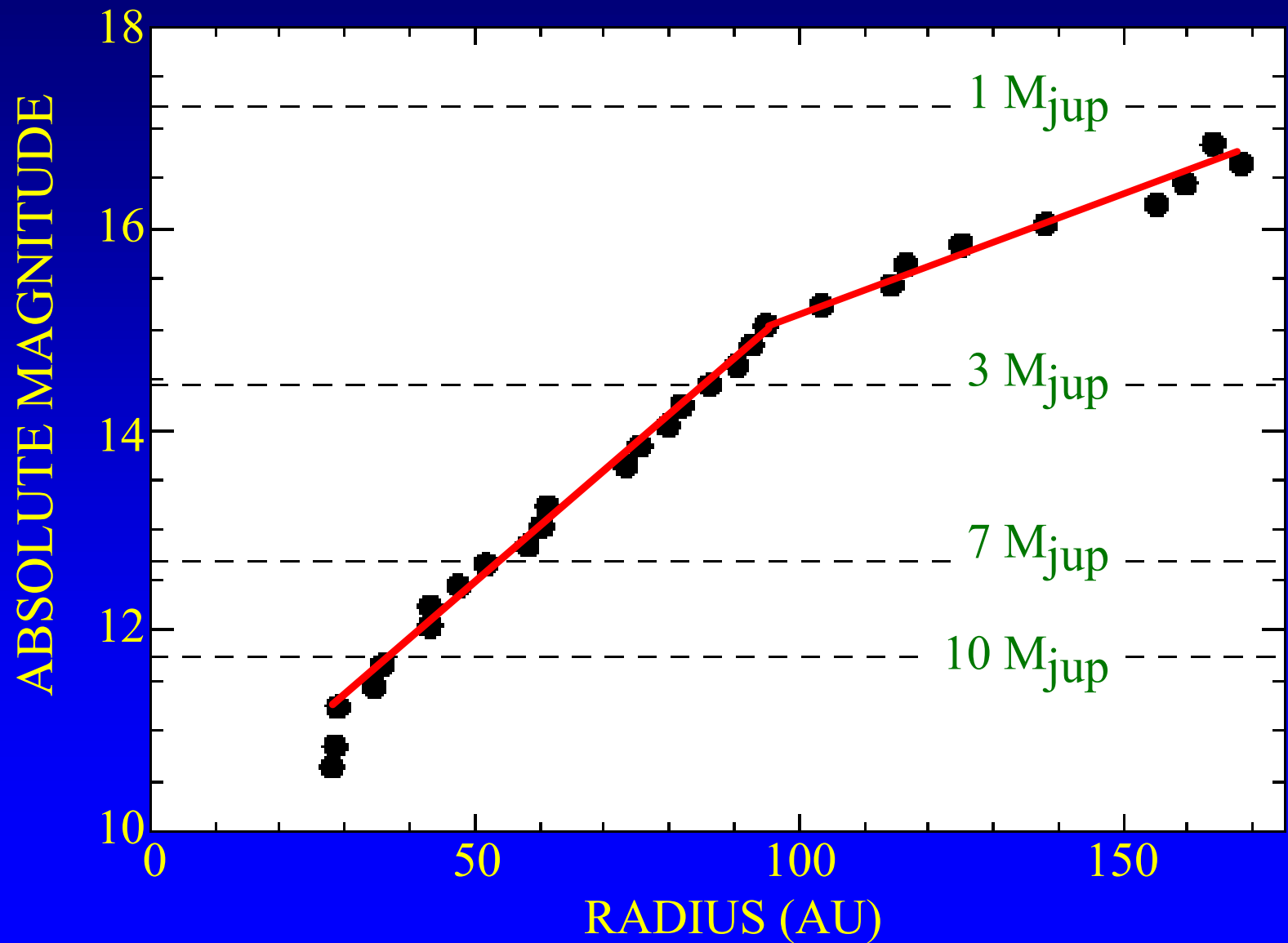


TW Hydrae - Optical Asymmetries?

Hemispheric? Azimuthally confined arc-like depression?



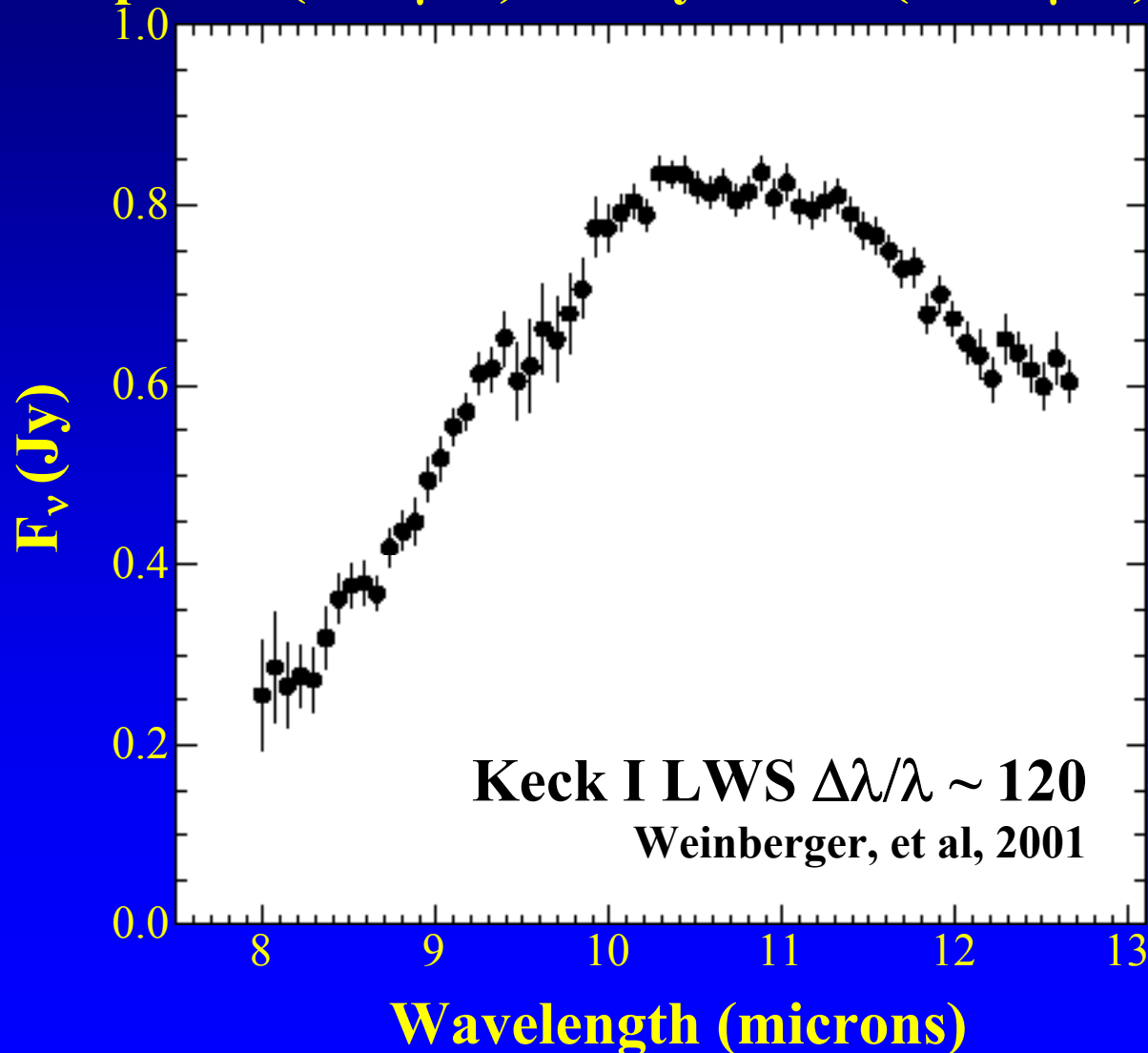
TW Hydrae - NICMOS Companion Detection Limits



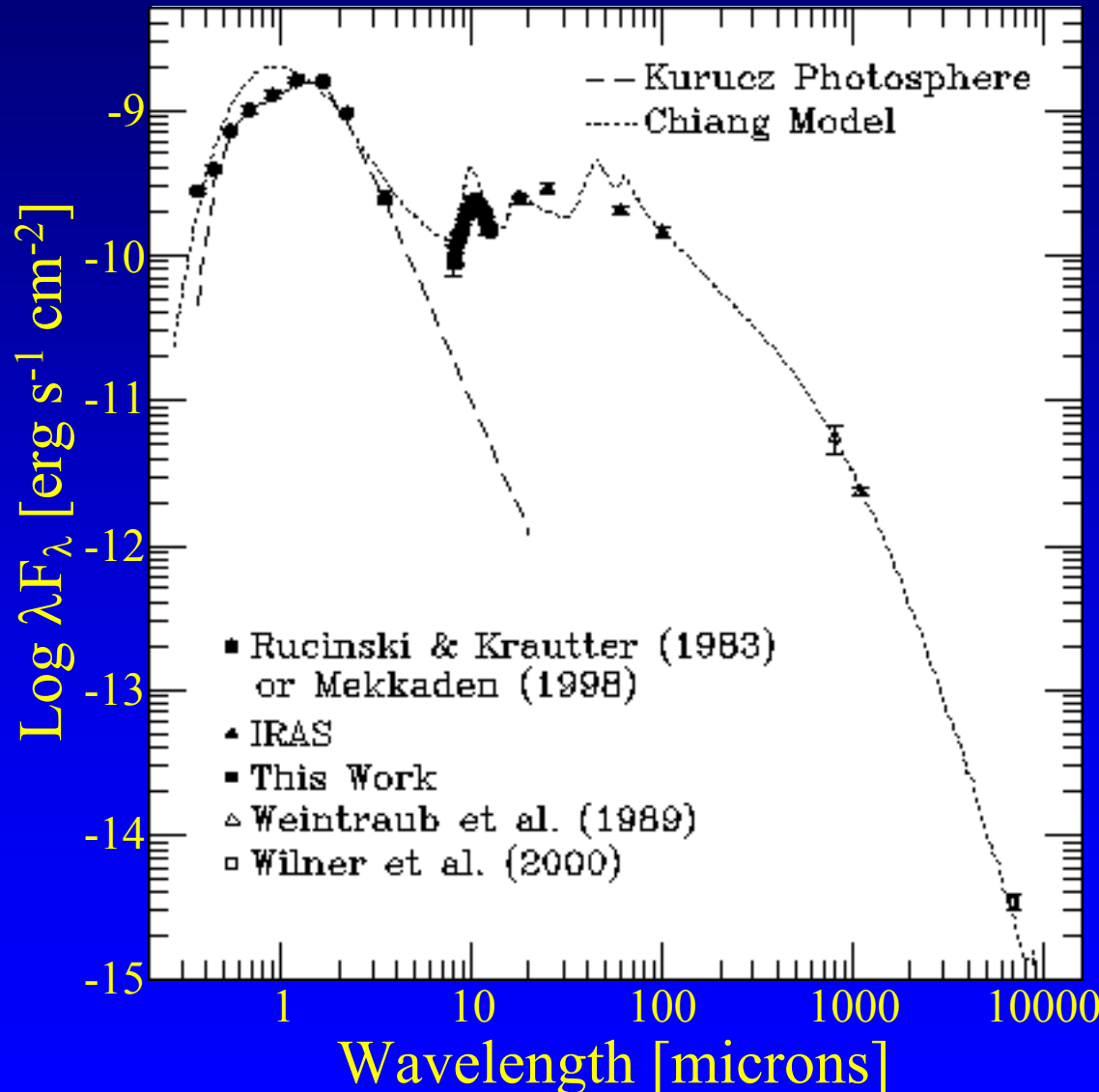
TW Hydrae - Mid-IR (8—13 μm) Spectrum

(Spatially Unresolved @ 11.7 & 17.9 μm)

Peak: Amorphous ($\sim 9.6 \mu\text{m}$) & Crystalline ($\sim 11.2 \mu\text{m}$) Silicates.



TW Hydrae - SED Model from All Spectral Bands



ala Chaing et al. (2001)

Surface grains $< 2\mu\text{m}$

Interior grains $< 12\text{mm}$

Grain Size Distribution

$dN/dr \text{ (interior)} \sim r^{-1}$

$dN/dr \text{ (surface)} \sim r^{-3.5}$

Dust Surface Mass Density

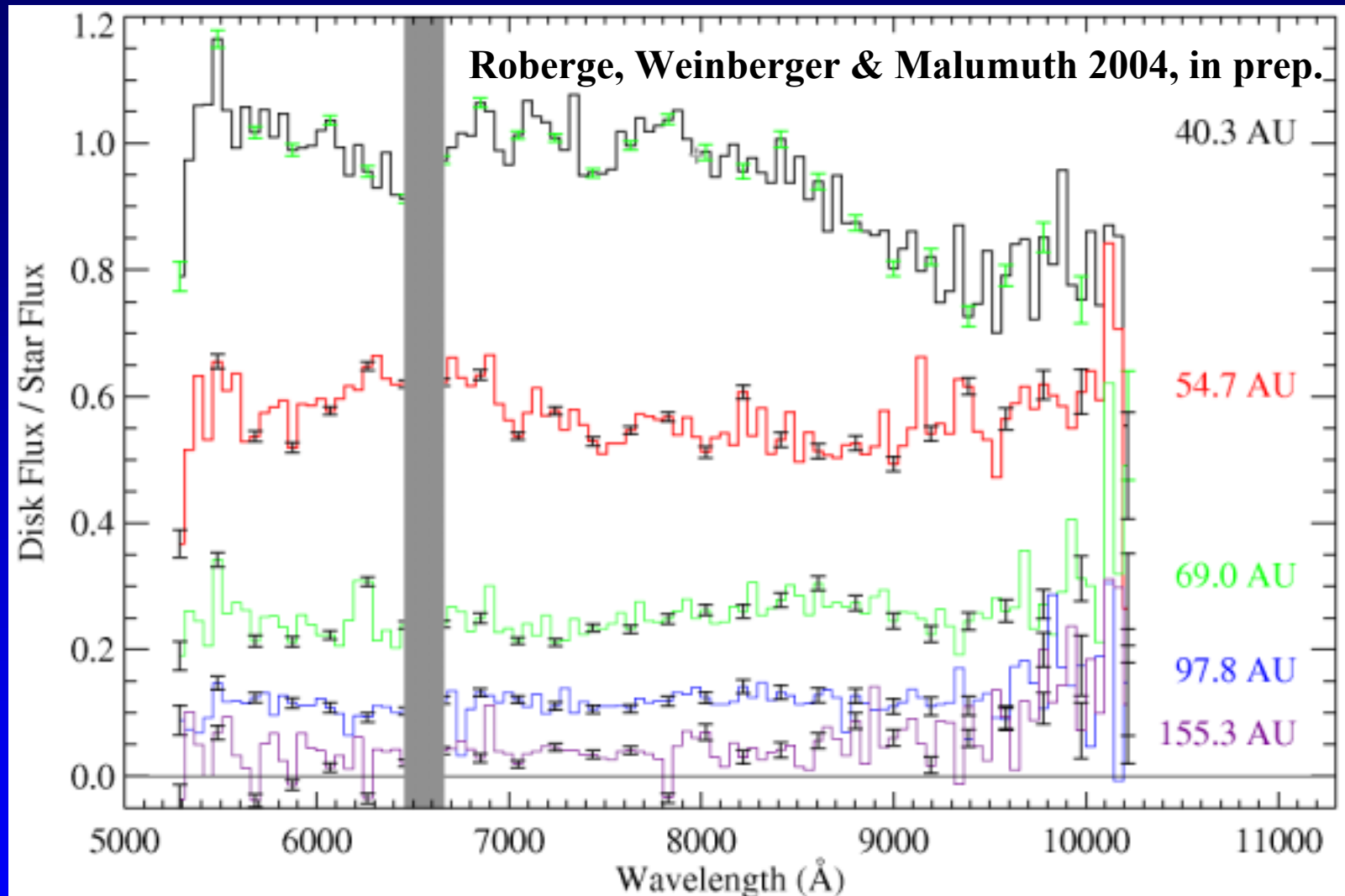
$10 (r/\text{AU})^{-1} \text{ cm}^{-2}$

Disk Radii:

Inner = 0.05 AU

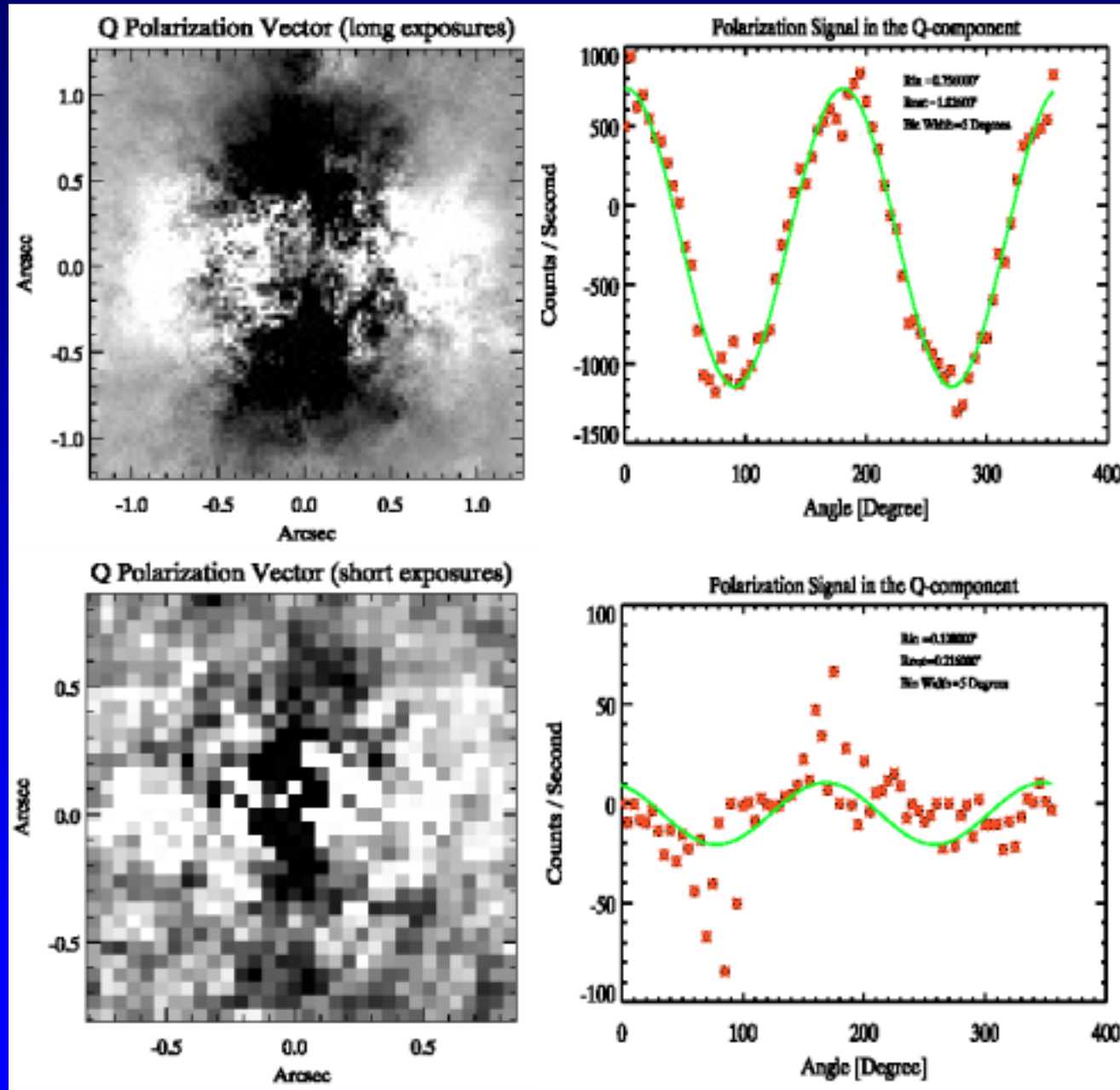
Outer = 200 AU

TW Hydrae - STIS Coronagraphic Spectroscopy



λ dependent scattering $\Rightarrow$ $>1\mu\text{m}$ grains to large radii.
Inner disk *possibly* bluer than outer $\Rightarrow$ smaller grains near star.

TW Hydrae - VLT/NACO Polarimetric Differential Imaging



Apai et al 2004

Polarized Disk
Emission at
 $0.1'' < r < 0.4''$

TW Hydrae - Summary

TTS surrounded by Optically Thick dust disk.

Disk must be flared given scattered light radius and thermal SED.

“Break” in Surf. Brightness @ $\sim 95\text{AU}$ *may* be due to dynamical effects.

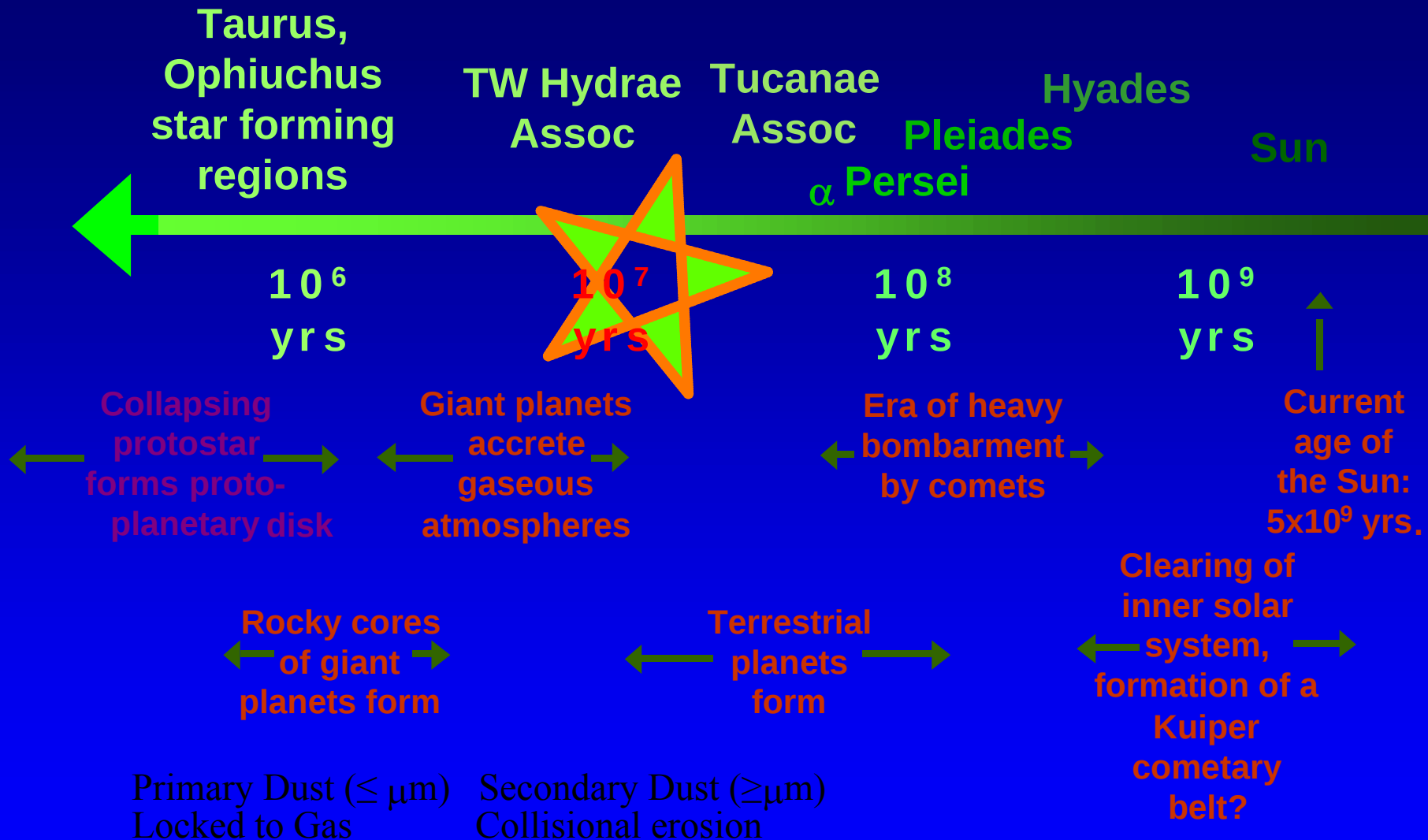
No Companions found to $10\text{---}2\text{ }M_{\text{jup}}$ @ $40\text{---}100\text{ AU}$ limit.

Disk Mass: $\sim \text{few} \times 10^2$ Earth Masses of Condensed Silicates & Ices.

Dust mass few times $>$ “typical” Taurus & Ophiuchus TTS Disks.

Good evidence for grain growth within the disk.

Planet-Building Timeline



Clearing Timescales: P-R drag few 10^6
 Rad. Pressure: $\sim 10^4$

HR 4796A

HR 4796A - Observational Chronology

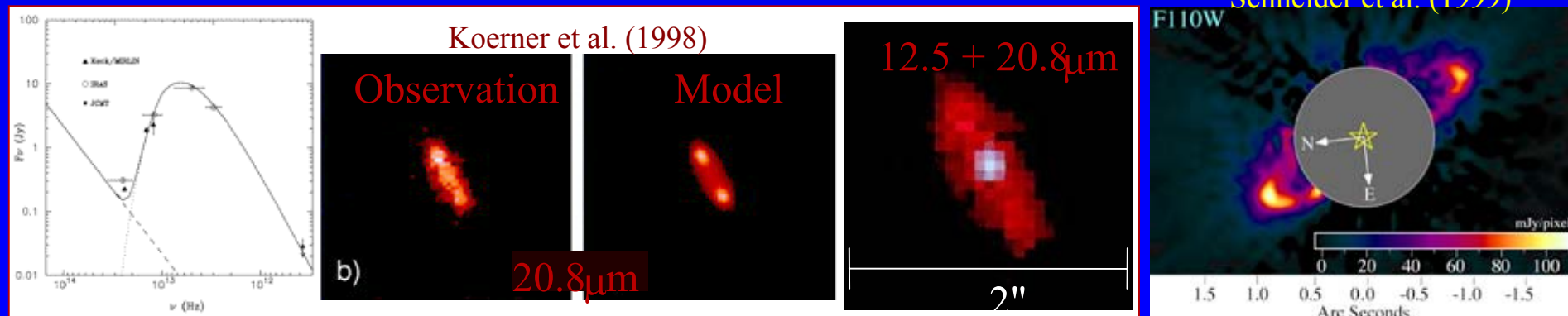
1991 - Jura (ApJ, 383, L79) inferred presence of large amount of circumstellar dust from IRAS excess. Estimated $\tau_{\text{dust}} = L_{\text{disk}}/L_{\text{star}} = 5 \times 10^{-3}$ ($\sim 2 \times \beta$ Pictoris).

1995 - Jura et al. (ApJ, 445, 451) noted earlier 110K estimate of dust temperature indicated lack of material at < 40 AU. Required grains $> 3 \mu\text{m}$ to be bound gravitationally at $40 < r < 200$ AU. No close companions with $M_* > 0.125 M_{\text{sun}}$ seen (speckle).

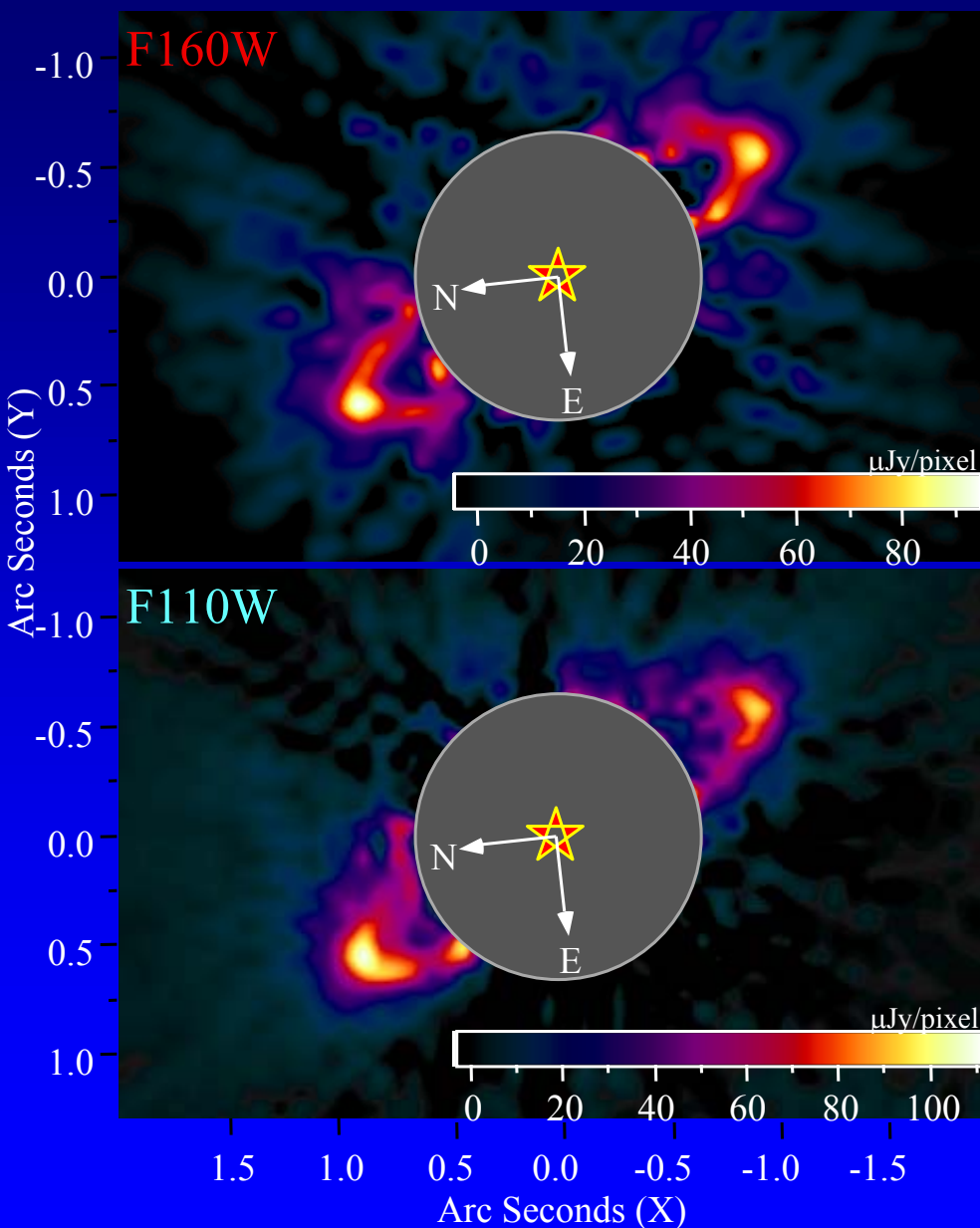
1998 - Koerner et al. (ApJ, 503, L83) and Jayawardhana et al. (ApJ, 503, 79) independently image mid-IR disk. Inner depleted region evident in high resolution $20.8 \mu\text{m}$ image reproduced with a model suggesting: $i = 72^\circ$ ($+6^\circ, -9^\circ$), $\text{PA} = 28^\circ \pm 6^\circ$, $R_{\text{in}} \sim 55$ AU, $R_{\text{out}} \sim 80$ AU $\rightarrow$ Kuiper belt-like dust ring.

1999 - Schneider et al. (ApJ, 513, L127) report on morphology and photometry of well-resolved NIR images in two NIR colors (1.1 and $1.6 \mu\text{m}$) of a narrowly confined ring-like circumstellar disk, with characteristic properties predicted by Koerner et al, from $\sim 0.1''$ resolution NICMOS coronagraphy obtained contemporaneously with 1998 mid-IR images.

Schneider et al. (1999)



NICMOS Observations of the HR 4796A Circumstellar Debris Ring



GEOMETRY

$$\text{PA} = 26.8^\circ \pm 0.6^\circ$$

$$i = 73.1^\circ \pm 1.2^\circ$$

$$a = 1.05'' \pm 0.02''$$

MORPHOLOGY

$$r = 70 \text{ AU}$$

$$\text{width} < 14 \text{ AU}$$

"abrupt" truncation

"clear" @ $r < 50 \text{ AU}$

FLUX DENSITY

$$12.8 \pm 1.0 \text{ mJy @ } 1.1 \mu\text{m}$$

$$12.5 \pm 2.0 \text{ mJy @ } 1.6 \mu\text{m}$$

$$H(\text{F160W}) = 12.35 \pm {}^{0.16}_{0.19}$$

$$J(\text{F110W}) = 12.92 \pm 0.08$$

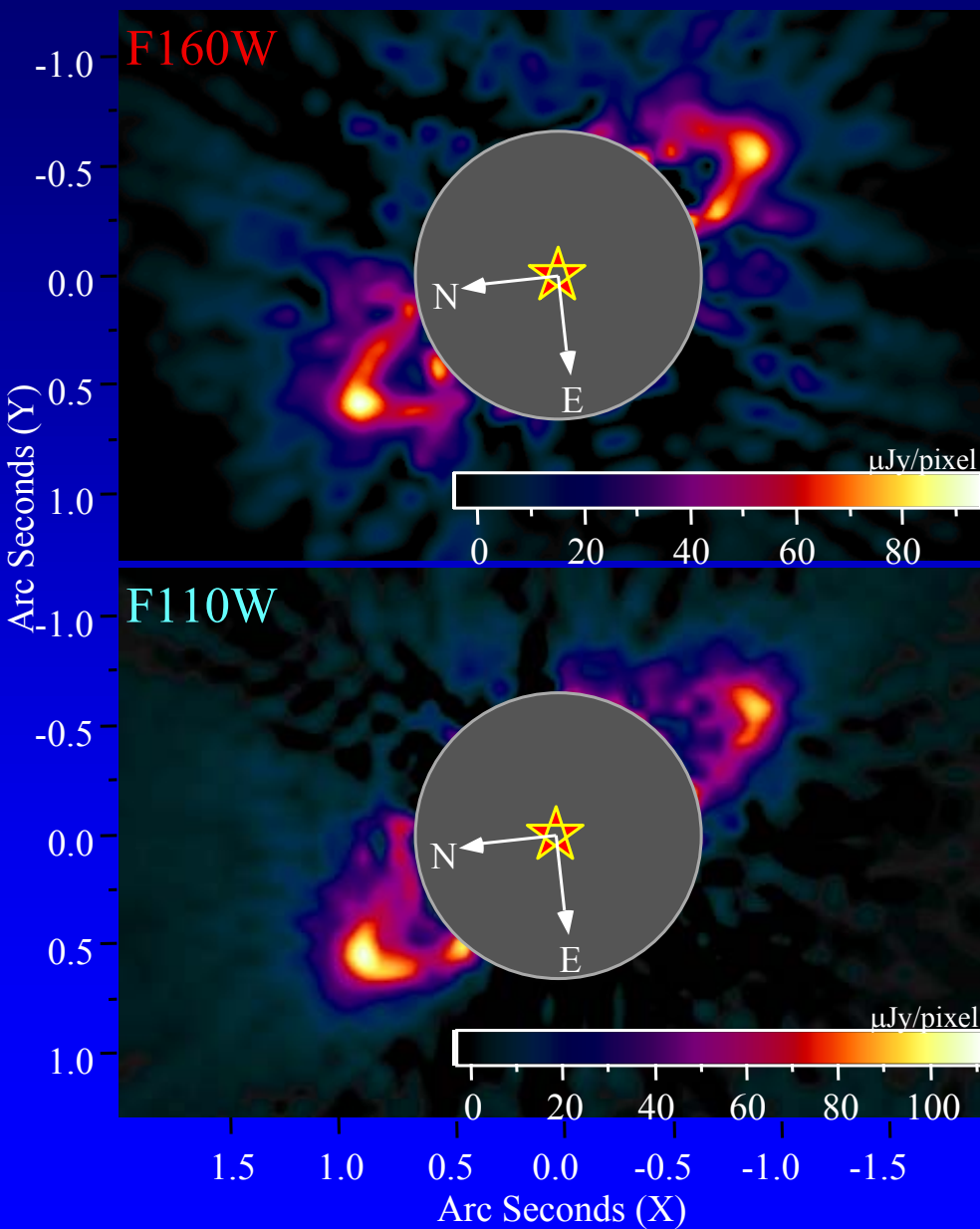
$$T_{\text{dust}} \sim L_{\text{disk}}/L_*$$

$$1.4 \pm 0.2 \times 10^{-3} \text{ @ } 1.1 \mu\text{m}$$

$$2.4 \pm 0.5 \times 10^{-3} \text{ @ } 1.6 \mu\text{m}$$

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

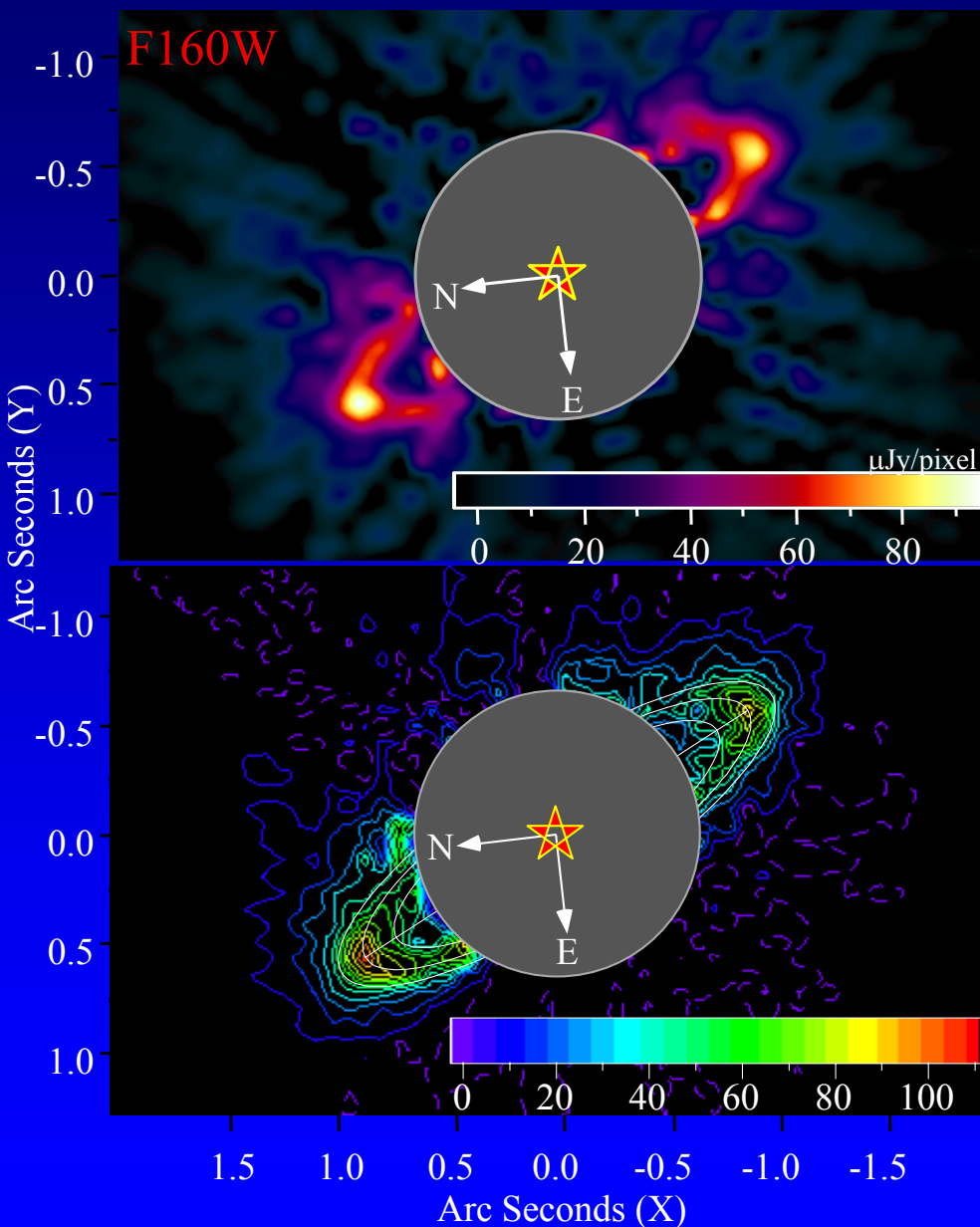
NICMOS Observations of the HR 4796A Circumstellar Debris Ring



Anisotropies

**NE ansa ~ 15% brighter
than SW ansa.**

NICMOS Observations of the HR 4796A Circumstellar Debris Ring



Anisotropies

NE ansa $\sim 15\%$ brighter than SW ansa.

Suggestion of preferential (forward) scattering to SE.

Implications

Possible dynamical confinement of particles by one or more unseen bodies.

Mean particle size $> \text{few } \mu\text{m}$. debris origin, not I.S. dust.

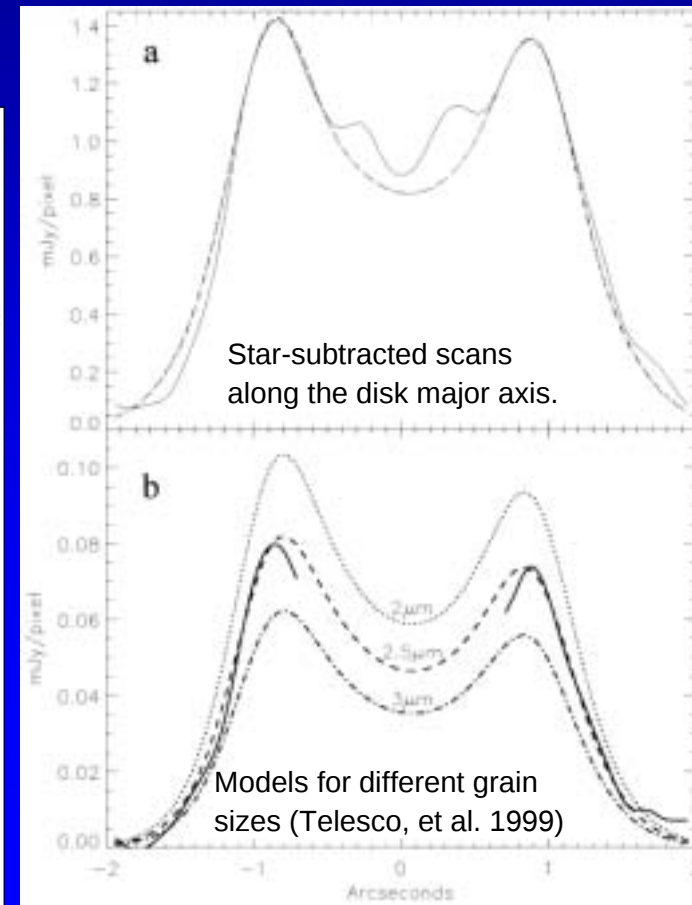
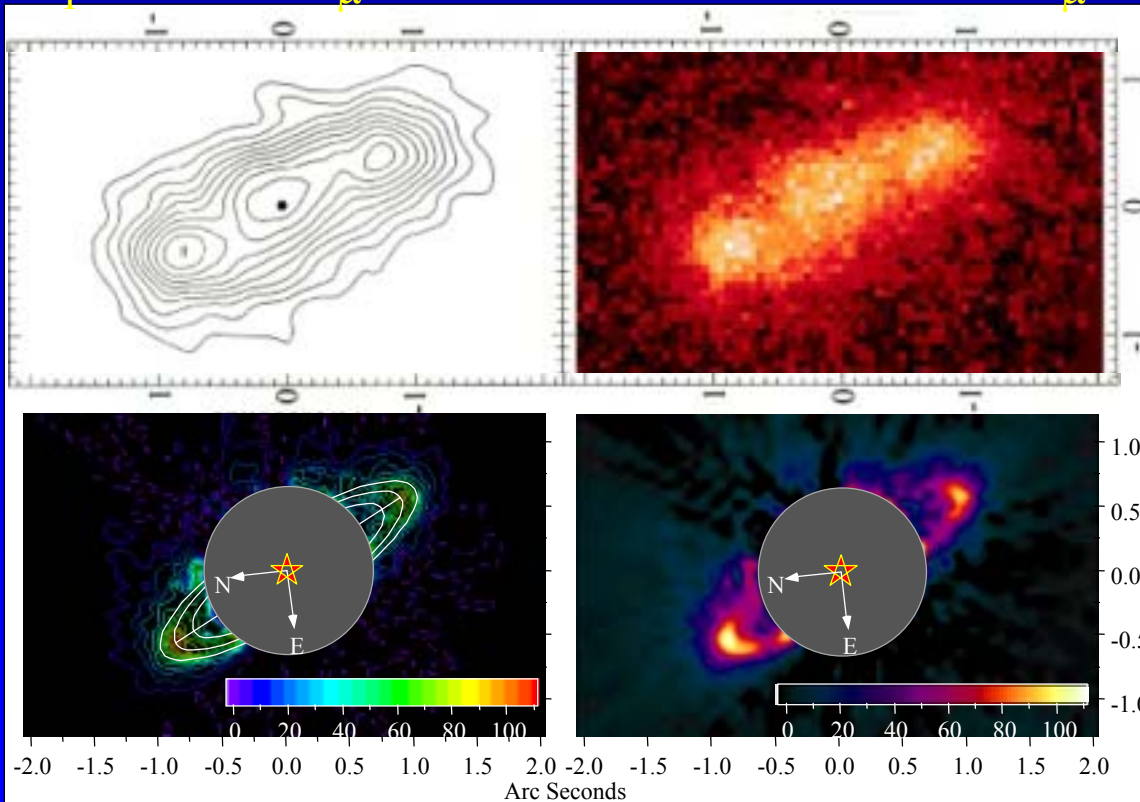
HR 4796A - OSCIR Thermal IR Imaging

1999 - Telesco et al. (A&A):

- Indicate comparable sizes of 10.8 and 18.2 μm emitting regions.
- Confirm central hole is largely cleared (τ_{central} zone $\leq 3\%$ of main part of the disk).
- Inward fall-off from the ring is shallower at 18.2 μm than in near-IR.
- Brightness asymmetry in OSCIR images (similar to NICMOS) possibly suggesting the existence of a gravitational perturber (Wyatt, et al 2000).

Top: OSCIR 18.2 μm

Bottom: NICMOS 1.1 μm

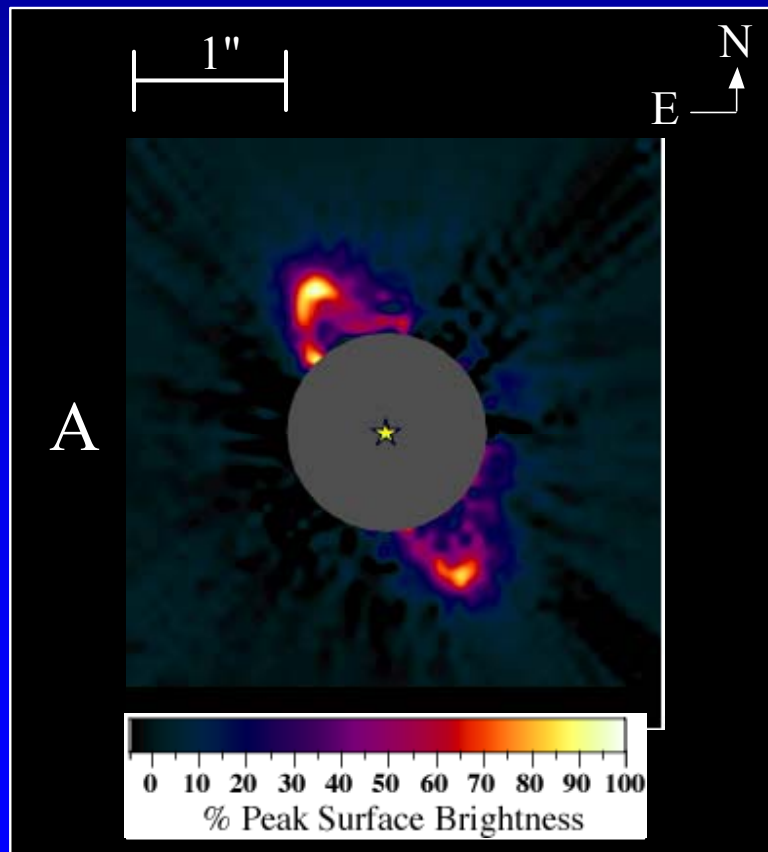


HR 4796A - Observational Chronology

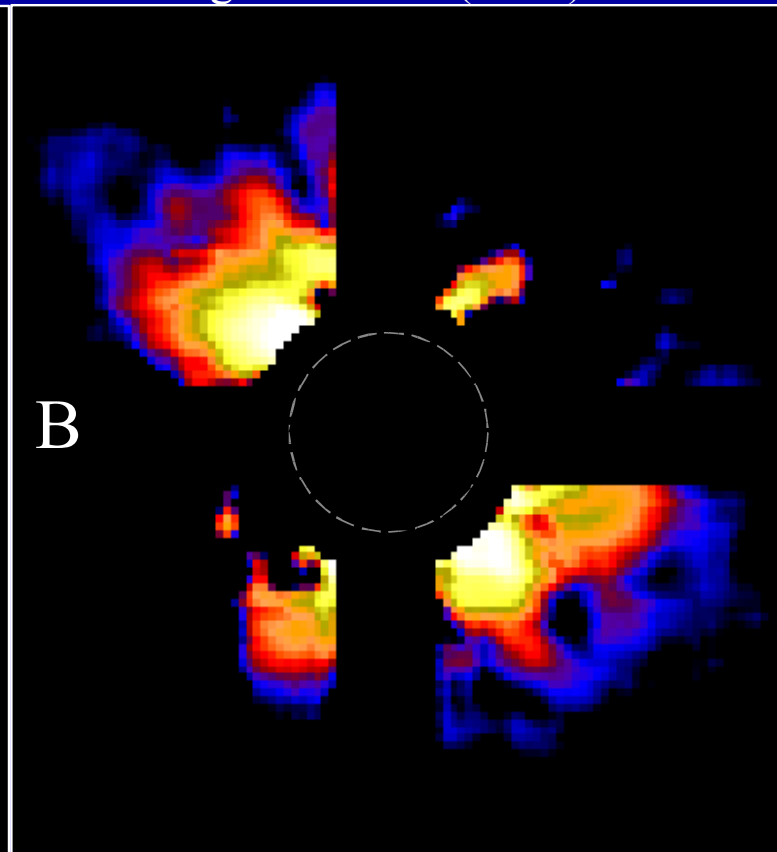
1999 - Greaves et al. obtain JCMT/SCUBA 450 and 850 μm flux excess measures of 0.18 and 0.019 Jy, respectively, and estimate total gas mass $< 1\text{--}7$ Earth masses.

1999 - Augereau et al. re-reduce K' observations of Mouillet et al. 1997 and find excess in agreement with Schneider et al at $\sim 1''$ in low S/N image showing extension in NE/SW directions. They estimate a lower limit for dust mass of ~ 4 Earth masses.

Schneider et al. (1999)



Augereau et al. (1999)



HR 4796A - Kenyon & Wood (2000) Dynamical Evolutionary Model

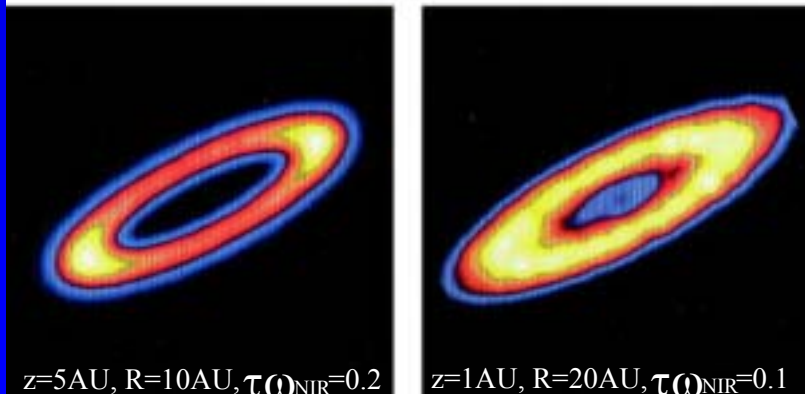
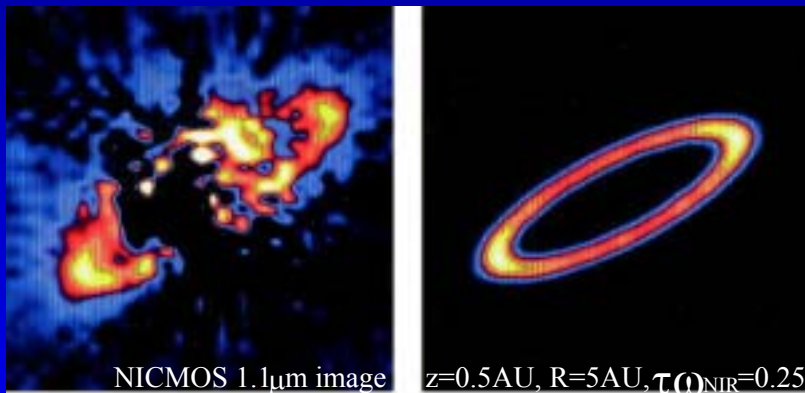
Produces observed dust distribution in 10 Myr w initial $10\text{--}20 M_{\text{MMSN}}$

Monte Carlo runs constrain geometry & τ_{dust}

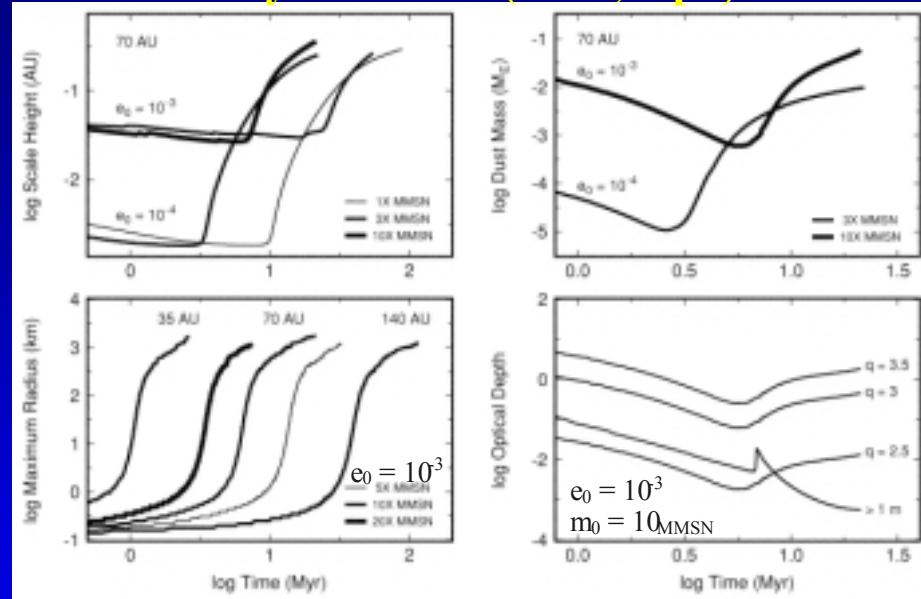
Assumes: isotropic scattering

$\omega = 0.3$ (Augereau et al, 1999)

Adjust to obtain $\tau = 1.5 \times 10^{-3}$



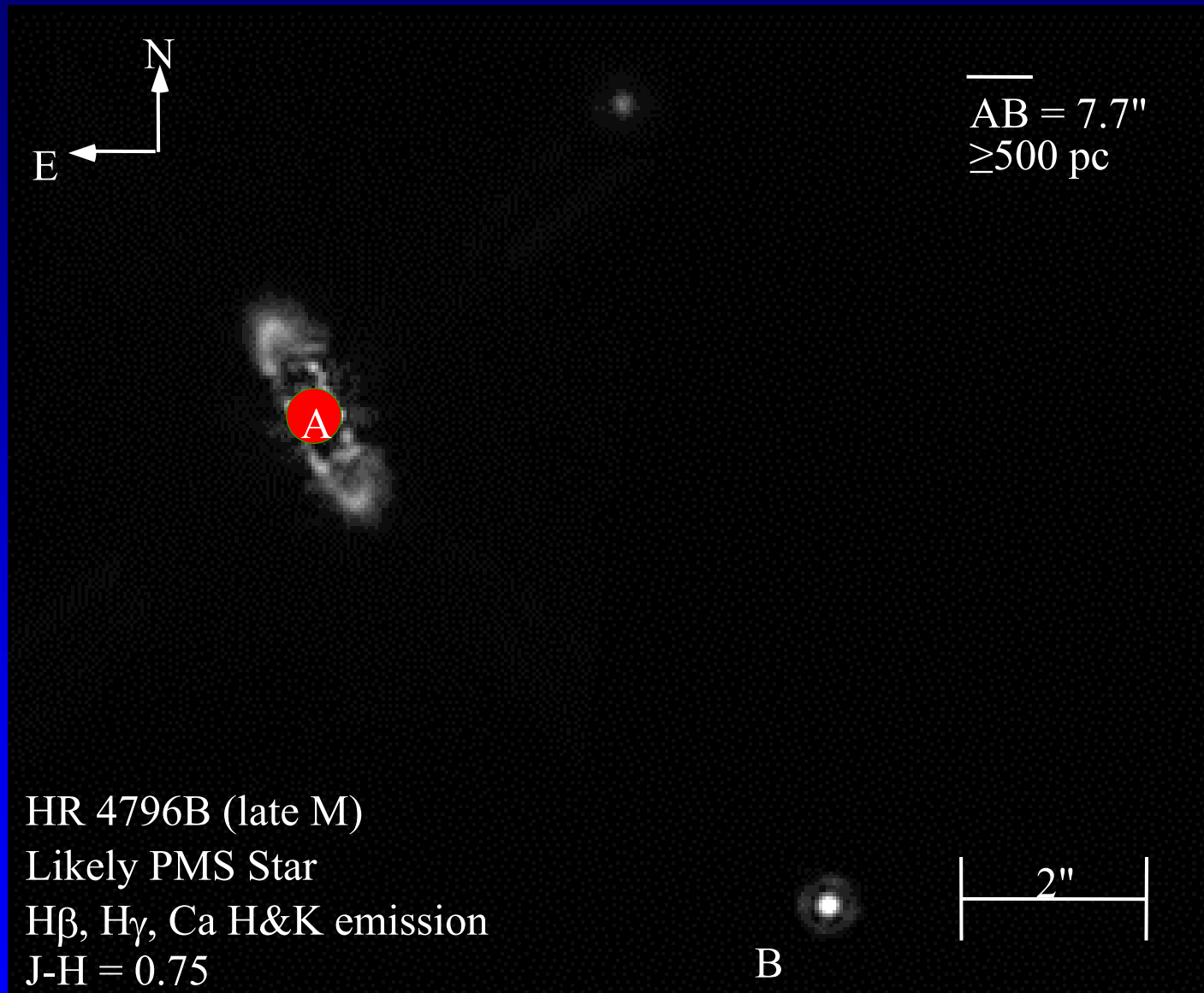
Kenyon & Luu (1999, ApJ)



CONCLUSIONS:

- Planet formation @ 70 AU in 10 Myr possible with initial disk mass = $10\text{--}20 M_{\text{MMSN}}$
- Dust production associated with planet formation is then confined to a ring with $\Delta a = 7\text{--}15$ AU.
- Optical depth in ring satisfies constraints on scattered light at $1\text{--}2\text{ }\mu\text{m}$ and on thermal emission at $10\text{--}100\text{ }\mu\text{m}$ if the dust size distribution is $N \sim r_i^{-q}$ with $q \geq 3$ for $r_i \leq 1\text{ m}$.
- Models with disk masses smaller than $10 M_{\text{MMSN}}$ fail to produce planets and an observable dusty ring in 10 Myr.

HR 4796A - Has an M-Dwarf Companion



... which could help to truncate the outer portion of the disk

HR 4796A - Augereau et al. (1999) Physical Model

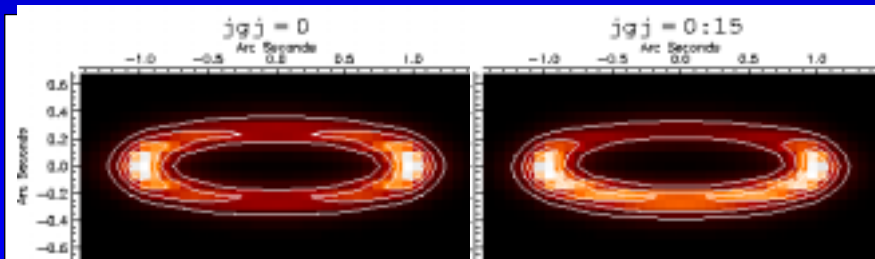
Two-component model reproduces all then-available observations: "the full spectral energy distribution from the mid-infrared to the millimeter wavelengths, resolved scattered light and thermal emission observations".

a) cold amorphous (Si and H₂O ice) grains > 10 μm in size (cut-off in size by radiation pressure), with porosity ~ 0.6 , peaking at 70 AU.

b) hot dust at ~ 9 AU of "comet-like" composition (crystalline Si and H₂O), porosity ~ 0.97 .

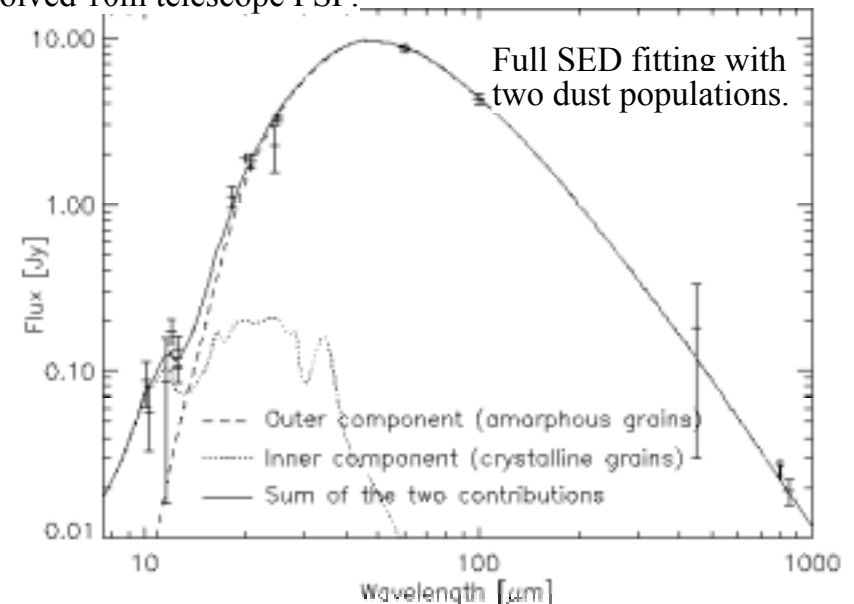
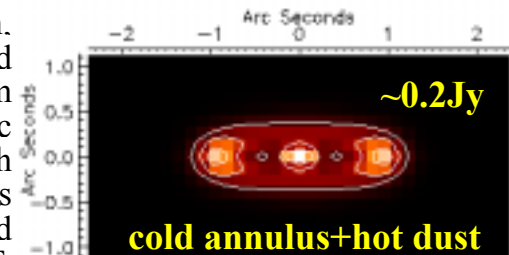
Collisions are common in both populations.
Bodies as large as a few meters are required.

Model gives rise to a minimum mass of a few M_{earth} with gas:dust < 1.

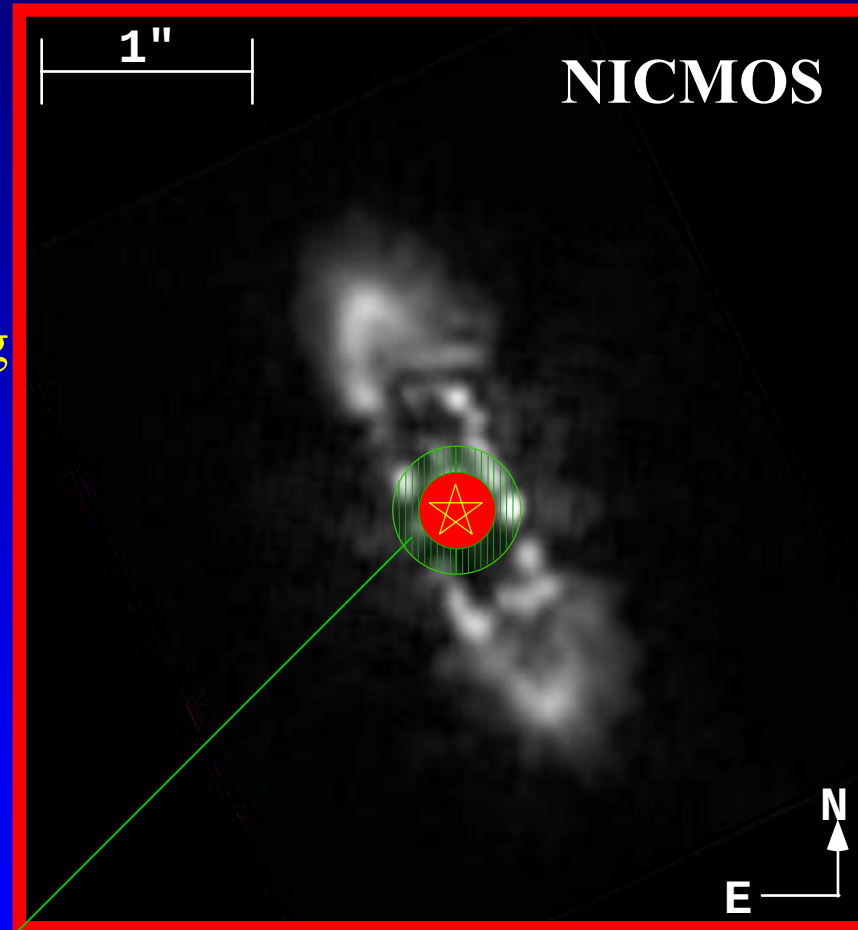


Simulated images of the cold annulus peaked at 70 AU in scattered light at 1.1 μm (with 0.076" pixels as in NICMOS) for two asymmetry factors considered assuming a Henyey-Greenstein phase function (The inner hot dust not observable has not been added). The NICMOS observation suggests $|g| < 0.15$. The flux density predicted in the region outside $r > 0.65''$ is 5.2 mJy, in good agreement with the 7.5 ± 0.5 mJy observed with HST.

Simulated disk at 20.8 μm , assuming grain properties and surface density derived from the SED fitting and a β Pic like vertical structure, with 0.14" pixels like observations by Koerner et al. (1998) and convolved 10m telescope PSF.



HR 4796A - NICMOS Post-Processing Pushing the Edge of the Hole



Additional processing recovered ring flux closer in and suggested somewhat higher inclination ($\sim 76^\circ$).

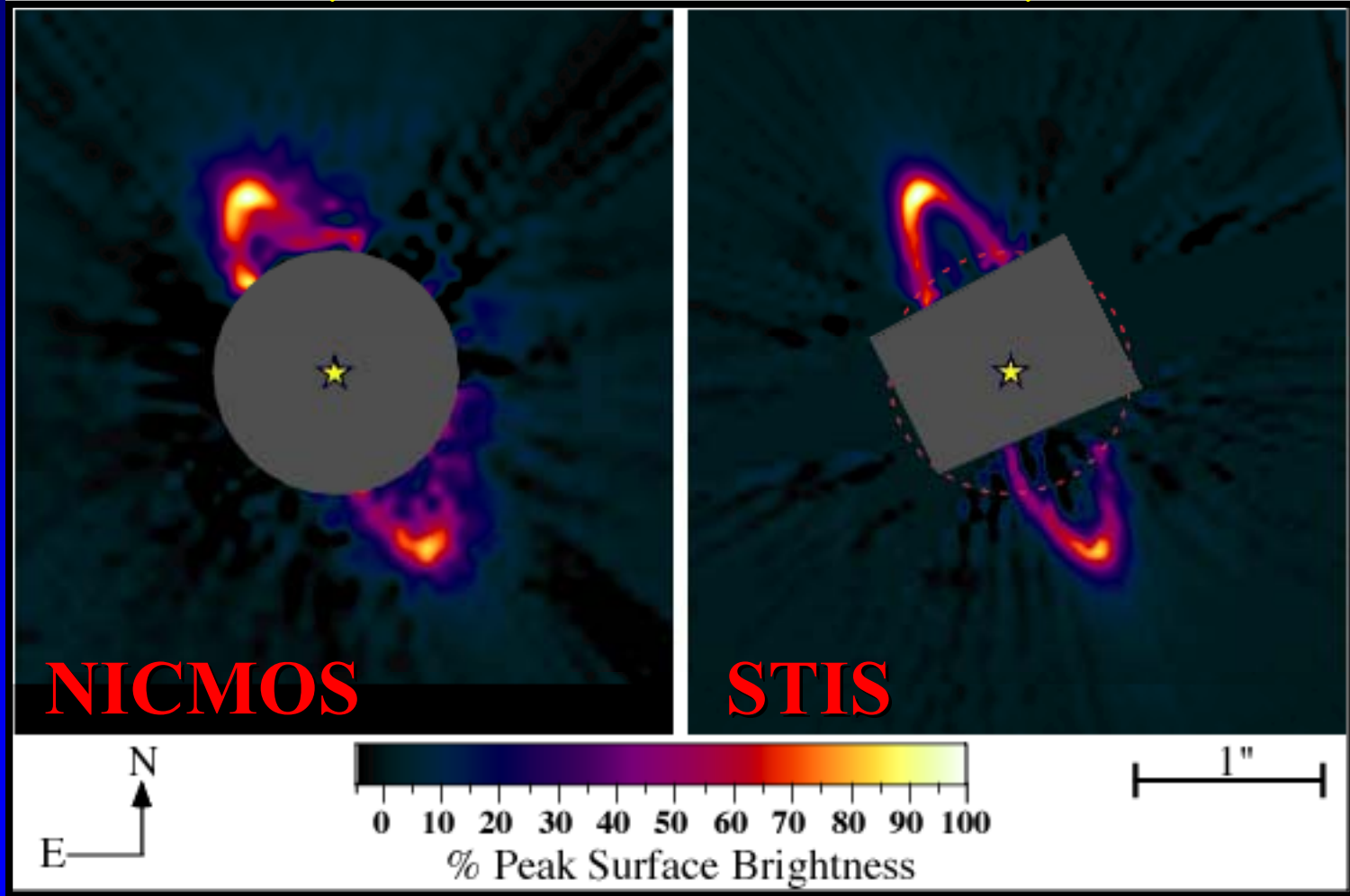
“Clumpiness” due to residuals in PSF subtraction, not attributed to structure of ring.

Here Be Dragons!

HR 4796A - Higher Spatial Resolution

1.1 μm

0.58 μm

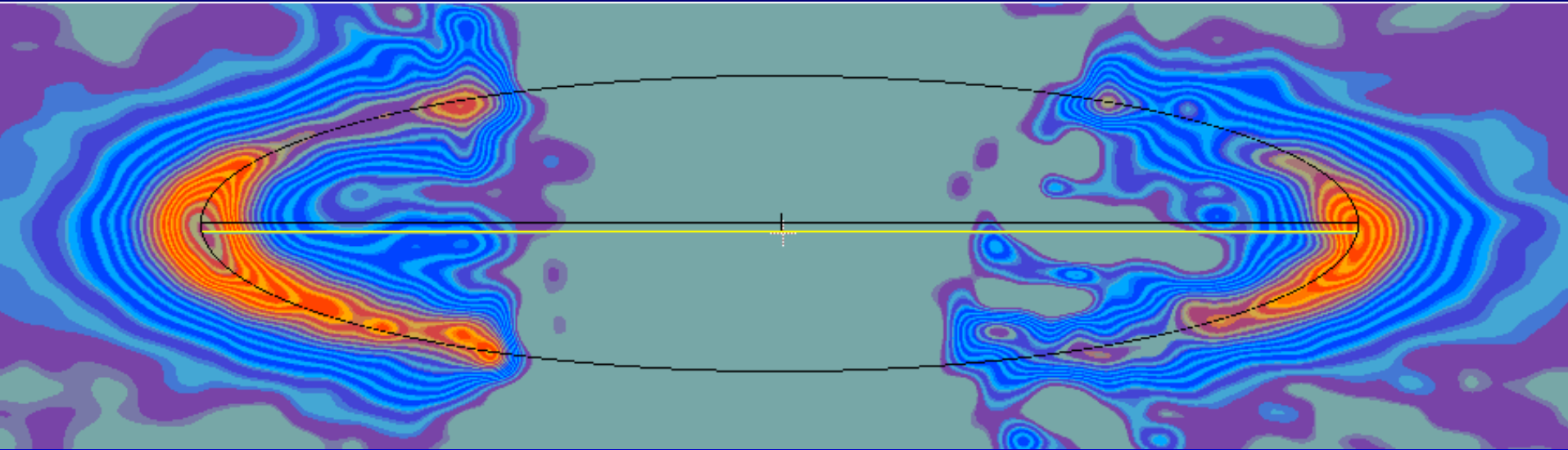


HR 4796A RING GEOMETRY
(Least-Squares Isophotal Ellipse Fit)



HR 4796A RING GEOMETRY

(Least-Squares Isophotal Ellipse Fit)

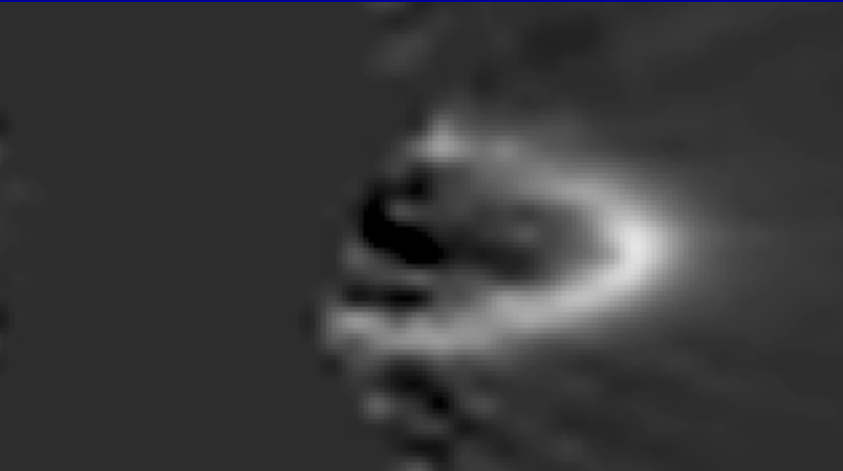
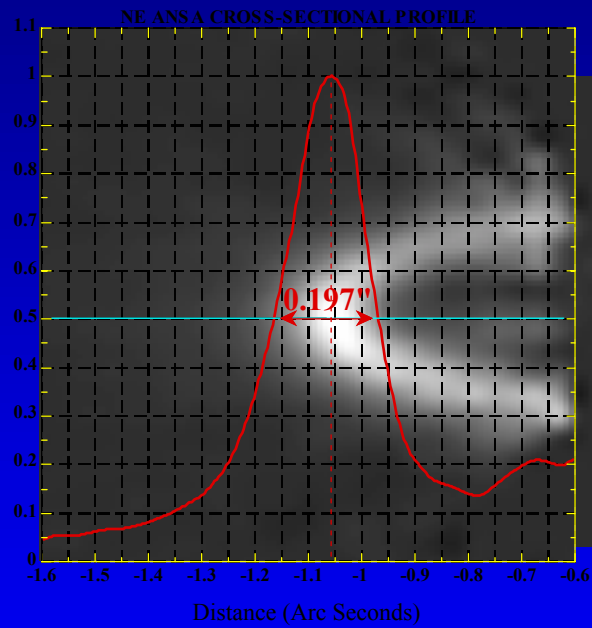


Ansa Separation (Peaks)	= $2.107'' \pm 0.0045''$
Major Axis of BFE	= $2.114'' \pm 0.0055''$
P.A. of Major Axis (E of N)	= $27.06^\circ \pm 0.18^\circ$
Major:Minor Axial Length	= $(3.9658 \pm 0.034):1$
Inclination of Pole to LOS	= $75.73^\circ \pm 0.12^\circ$
Photocentric Offset from BFE(Y)	= $-0.0159'' \pm 0.0048''$
Photocentric Offset from BFE(X)	= $+0.0031'' \pm 0.0028''$

HR 4796A Circumstellar Debris Ring - WIDTH

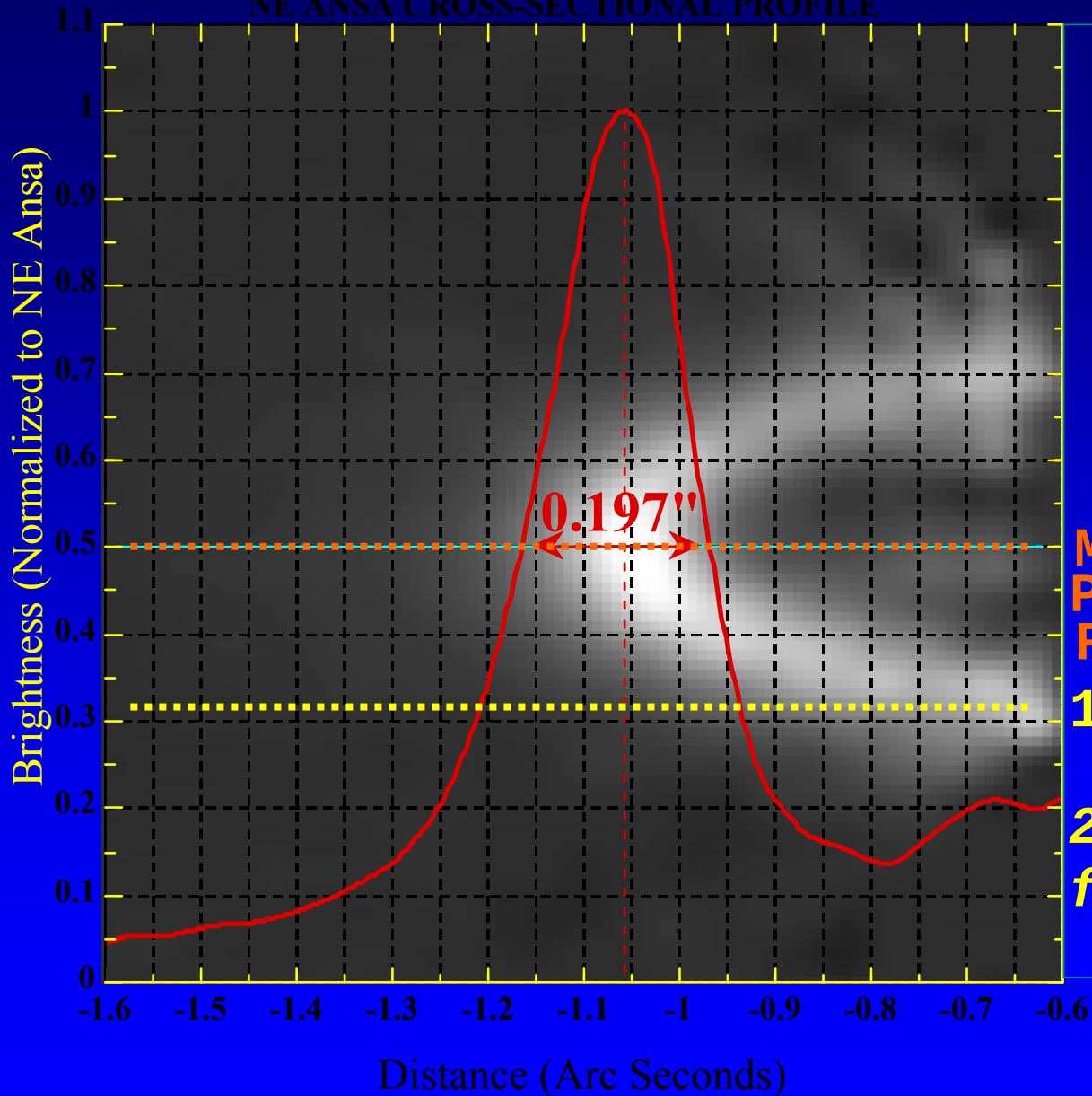


HR 4796A Circumstellar Debris Ring - WIDTH



HR 4796A Circumstellar Debris Ring - WIDTH

NE ANSA CROSS-SECTIONAL PROFILE



WIDTH AT NE ANSA

FWHM: $12.3 \pm 0.7 \text{ AU}$

8.7% D_{ring}

$1-e^{-1}$: $17.7 \pm 10.1 \text{ AU}$

12.5% D_{ring}

Measured = $0.197''$

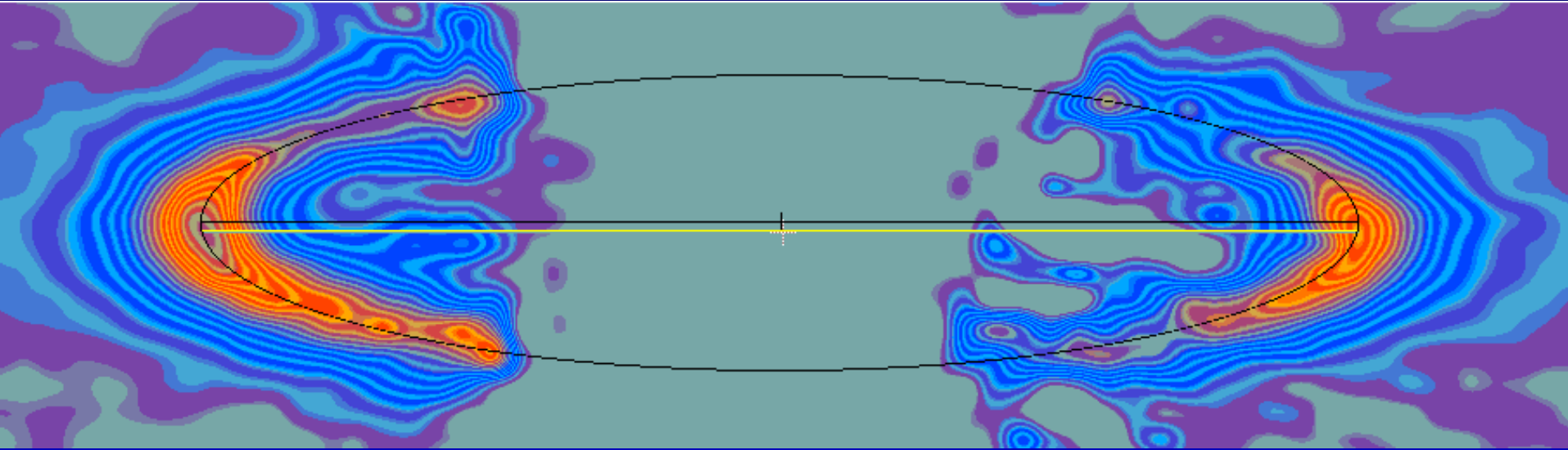
PSF_{point source} = $0.070''$

FWHM_{ring} = $0.184''$

$1-e^{-1} = 0.265''$

20% inner:outer
fall-off asymmetry

RING GEOMETRY - Least-Squares Isophotal Ellipse Fit



Ansa Separation (Peaks) = $2.107'' \pm 0.0045''$

Major Axis of BFE = $2.114'' \pm 0.0055''$

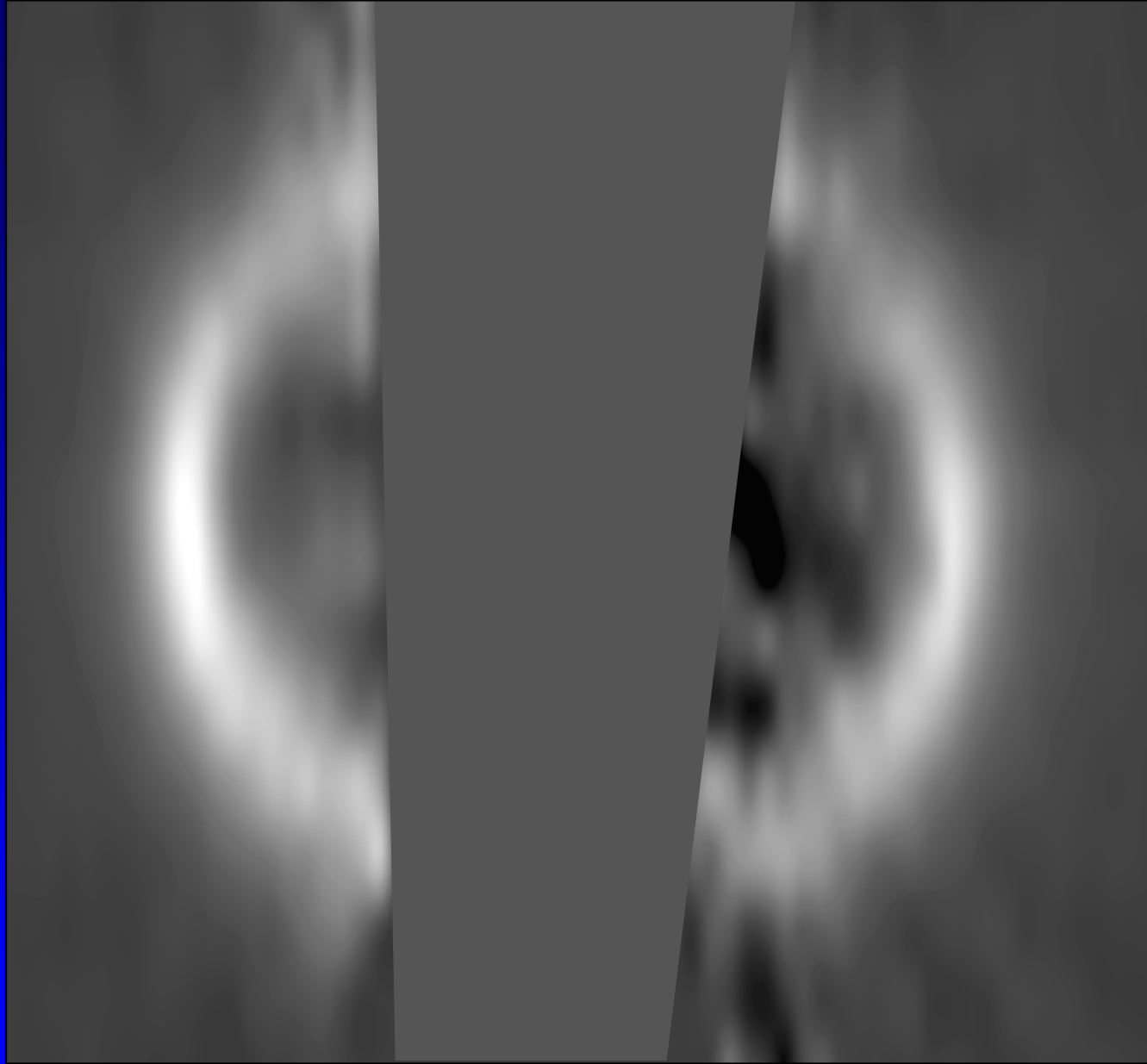
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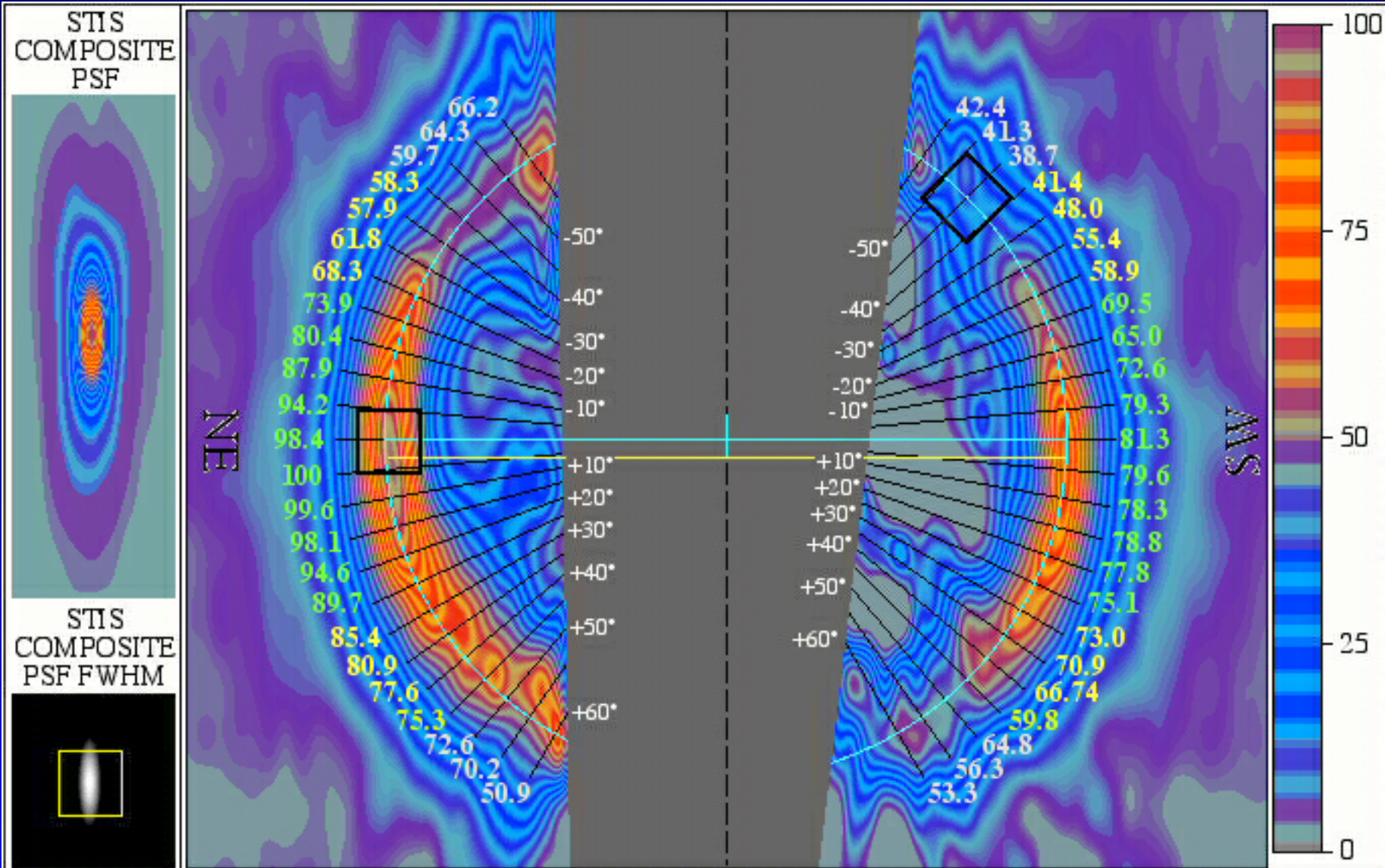
Inclination of Pole to LOS = $75.73^\circ \pm 0.12^\circ$

Photocentric Offset from BFE(Y) = $-0.0159'' \pm 0.0048''$

Photocentric Offset from BFE(X) = $+0.0031'' \pm 0.0028''$



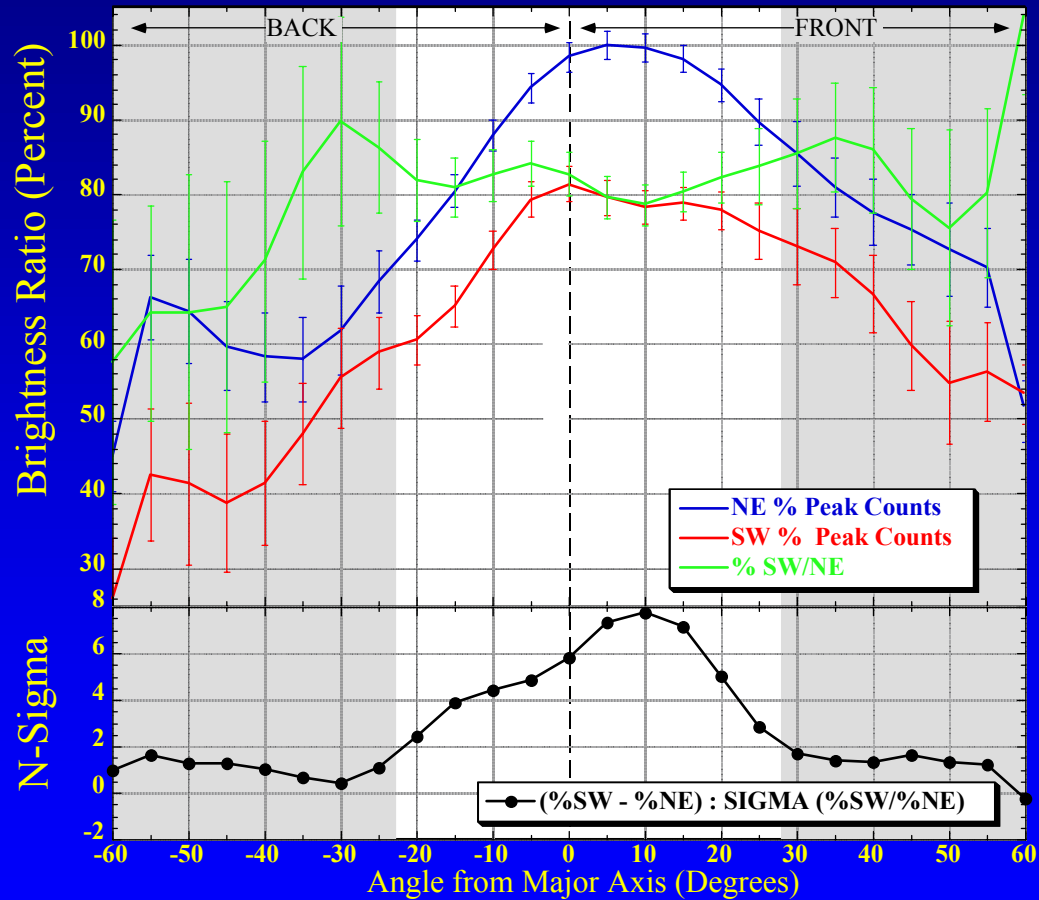
“FACE-ON” PROJECTION - With Flux Conservation



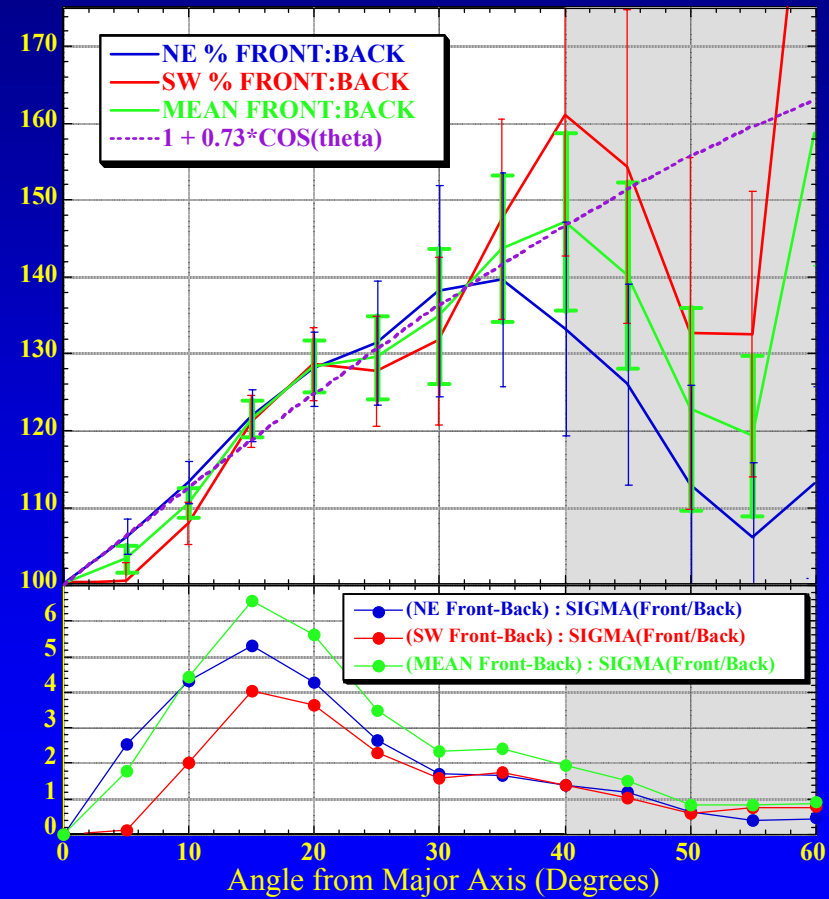
Spatially Resolved Relative PHOTOMETRY of the Ring
“FACE-ON” PROJECTION - With Flux Conservation

Surface Brightness Anisotropies

NW:SE (“Left/Right”)



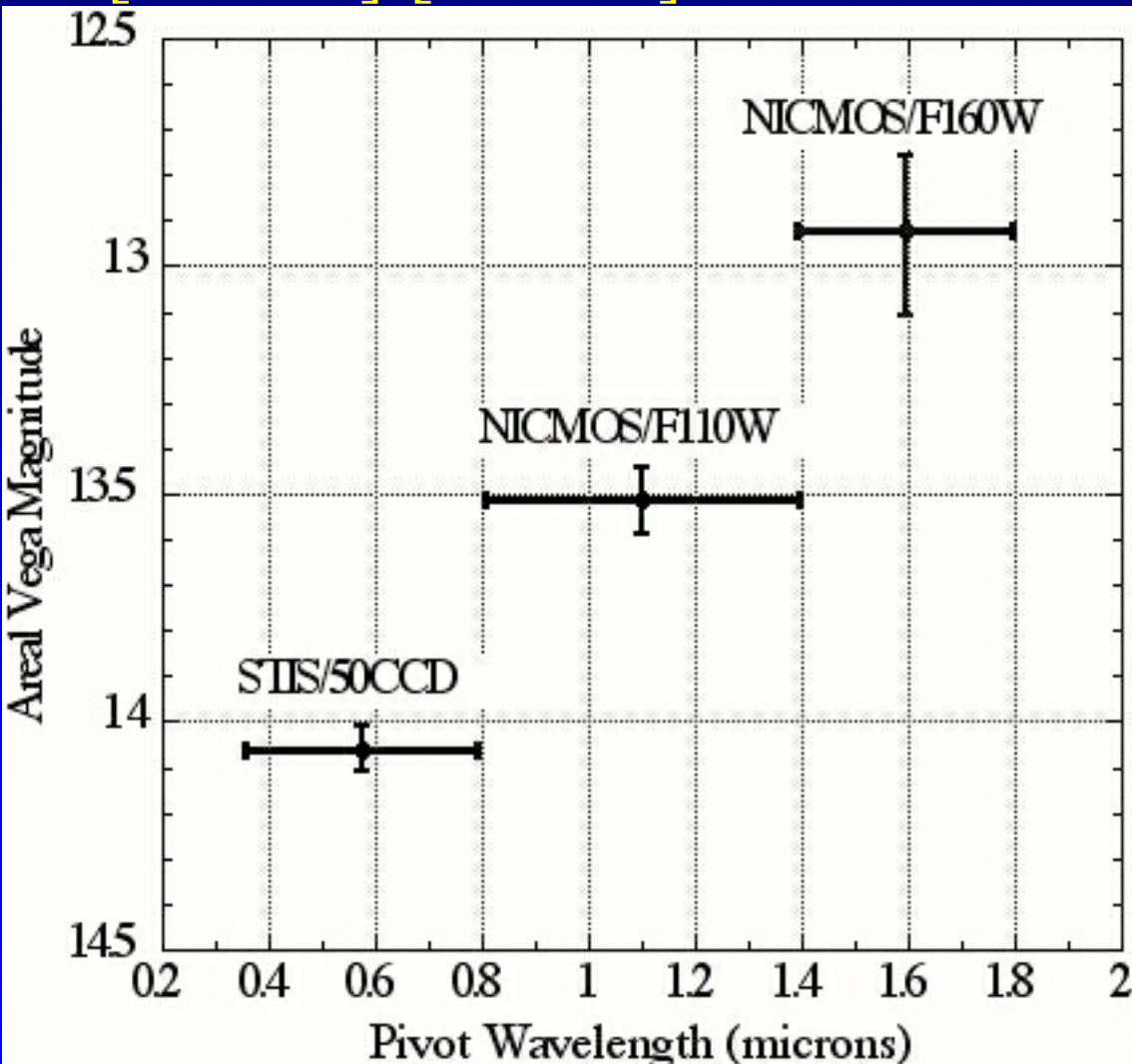
Front/Back



Broad Colors of the HR 4796A Debris Ring

$$[50\text{CCD}]-[F110\text{W}]=0.55\pm0.09$$

$$[50\text{CCD}]-[F160\text{W}]=1.14^{+0.20}_{-0.17}$$



Intrinsically red grains

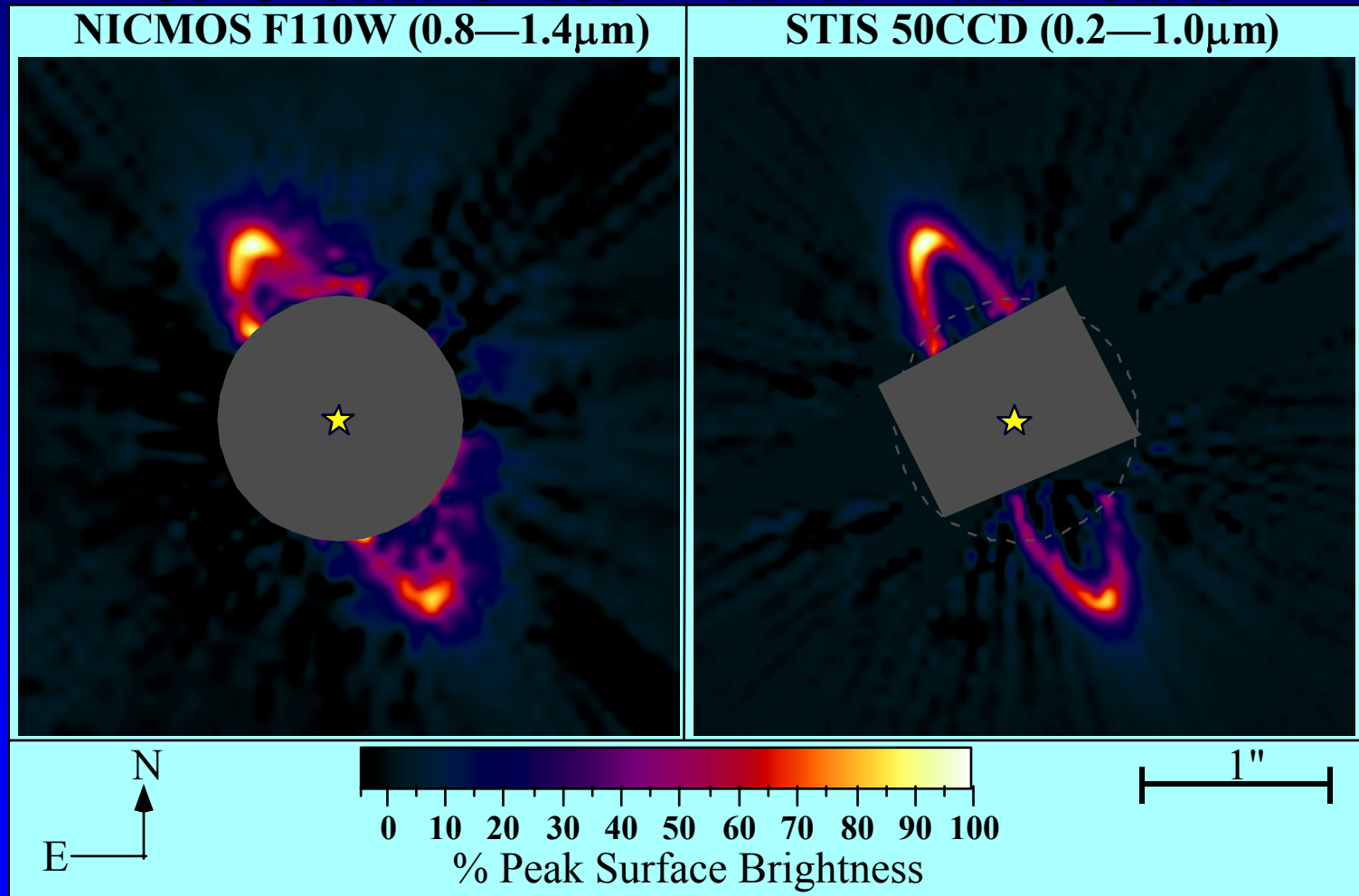
- Consistent with collisionally evolved population of particle sizes > few microns
- Not primordial ISM grains
- Similar intrinsic colors to TNOs in our solar system: $[V]-[J]=+1.07^*$
- Consistent with laboratory* irradiation experiments of organics to study reddening of D & P type asteroids with distance from Sun.

*Barucci et al (1993); Andronico et al (1987)

HR 4796A SUMMARY

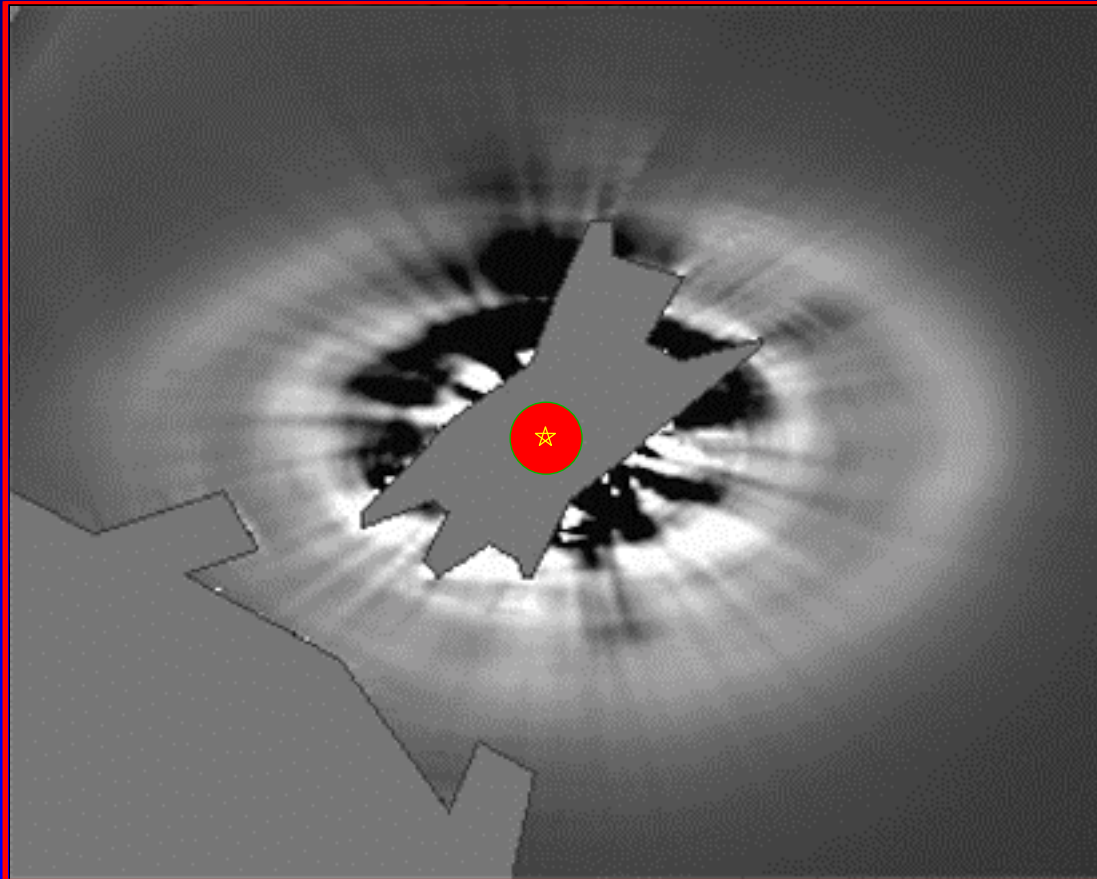
- ★ Ring geometry/astrometry defined by NICMOS improved by higher resolution STIS observations ($i = 2.6^\circ$ larger than *original* NICMOS solution).
- ★ Spatially resolved photometry of ring with $\pm 2\%$ uncertainty at ansae ($1''$), and $\pm 6\text{---}8\%$ uncertainty at $0.5''$.
- ★ Characteristic width $\sim 10\%$ of 70 AU radius ring.
- ★ “Left/Right” brightness anisotropy or $\sim 20\%$ along at least 50° wide diametrically opposed arcs centered on ansae.
- ★ “Front/Back” brightness anisotropy, roughly symmetric in both L/R “hemispheres”, increasing with longitudinal distance from ansae to 35% difference at 30° from ansae.
- ★ Ring is uniformly **RED** from “V” to H with 1:1.7:2.9 spectral reflectance in CCD50(“V”):F110W($1.1\mu\text{m}$):F160W(H).

*Brightness Anisotropies, “Confinement” & Color
Consistent with Dynamical Interactions of
Evolved (non-ISM) Grains with
Co-Orbital Unseen Planet-Mass Bodies*



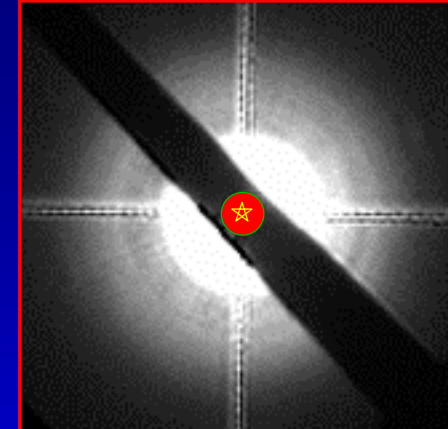
*Today we have only a handful of
Spatially Resolved Images of Dusty Circumstellar Disks*

HD 141569



370 AU PEAK
490 AU GAP
800 AU

TW HYDRAE



300 AU

HR 4796A



140 AU

many more are needed...

HST Cycle 13 - 52 Target Disk Imaging Survey

Solar Systems in formation: A NICMOS Coronagraphic Survey of Protoplanetary and Debris Disks

Glenn Schneider (PI), Murray Silverstone, Karl Stapelfeldt, Deborah Padgett,
Carol Grady, Dean C. Hines, Angela S. Cotera, Francois Menard,
Bringfried Stecklum, Thomas K. Henning, Sebastian Wolf, Mark Clampin,
David Wilner, John Krist, Jinyoung Serena Kim, Caer-Eve McCabe

**26 optically thick, < 10 Myr, YSO Disk
Candidates (18 G—M T Tau stars, $d < 150$ pc),
8 A-F stars (4 HAeBe) with IR/mm excesses.**

**26 optically thin, > 10 Myr Dust-Dominated
Debris Disk Candidates (A0—K2 IR excess
Main sequence stars, $d < 150$ pc) with
 $L_{\text{ir}}/L_* > 3 \times 10^{-4}$.**



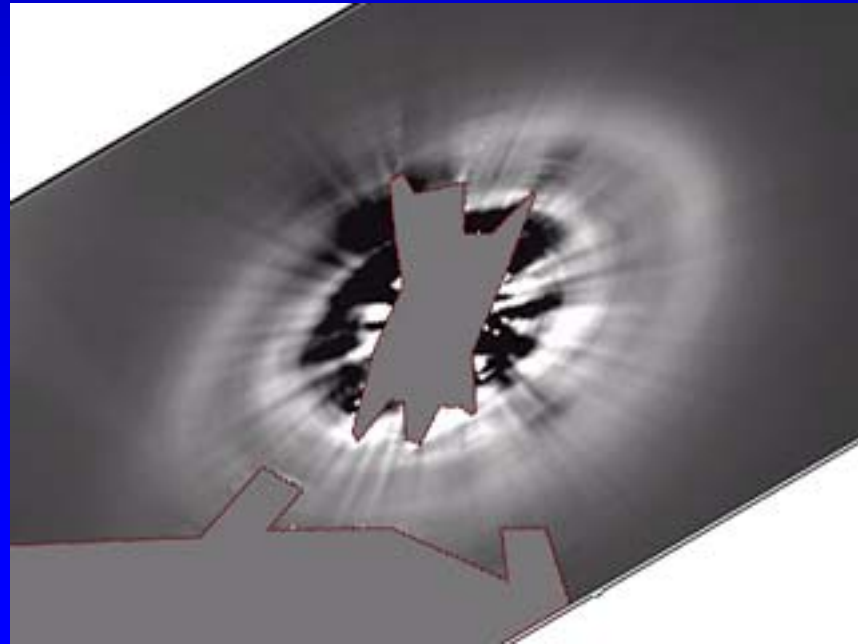
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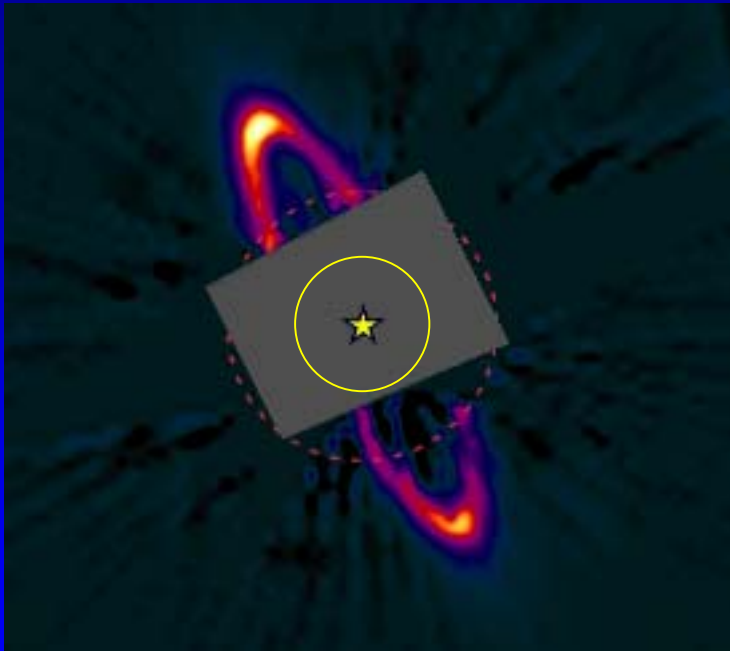
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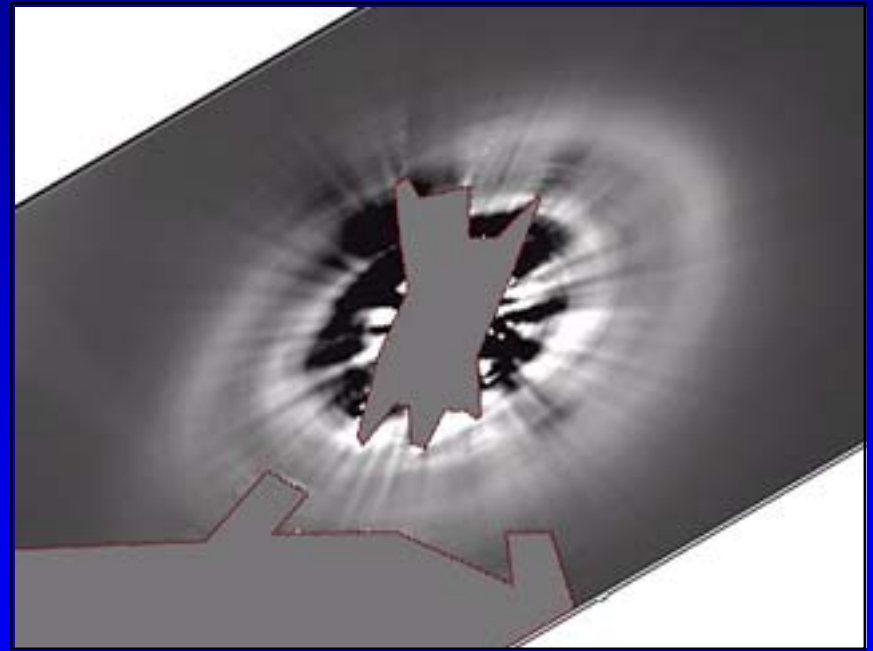
Inner Regions of Evolved Disks

Cannot yet be probed in scattered light. Yet, as inferred from mid-IR:

An inner tenuous component of warm zodi-like dust may be confined within a few AU of HR 4796A.



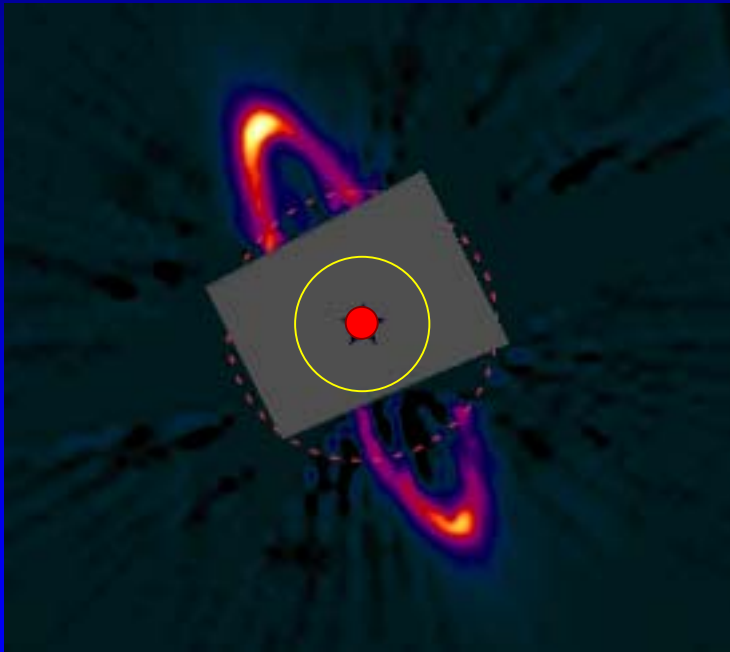
12–20 μm thermal emission is contained completely within the large inner “hole” of HD 141569A.



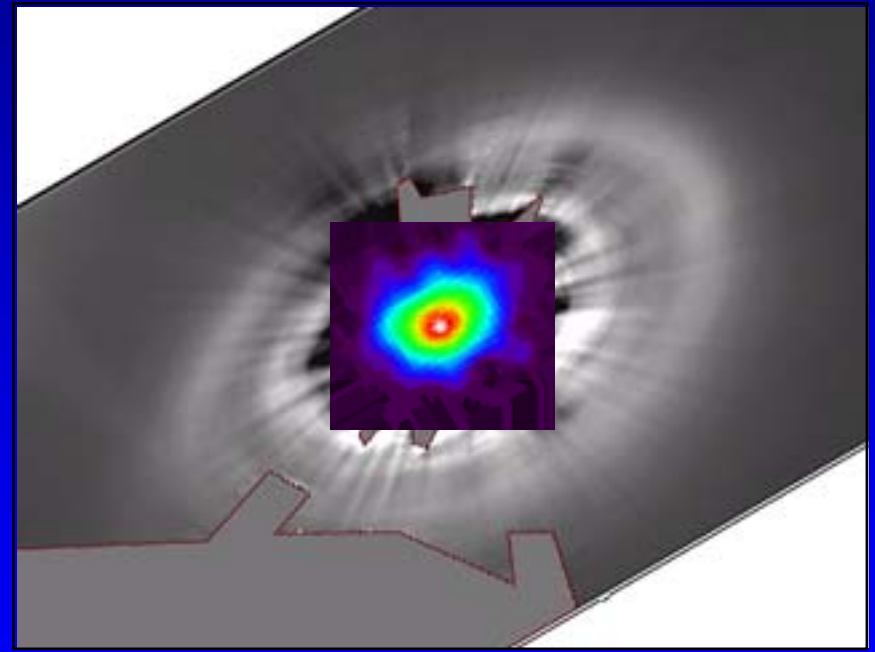
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12–20 μm thermal emission is contained completely within the large inner “hole” of HD 141569A.



What evolutionary and dynamical interactions may be going on between *unseen planets* and *unseen dust* which will shape these systems?

Requires “Super-High” contrast and resolution.

Scattered-light imaging and spectroscopy of collisionally evolved circumstellar debris and co-orbital bodies will play a pivotal role in furthering our understanding of the formation and evolution of extrasolar planetary systems.

Extrasolar Planet Imaging & Spectroscopy:
(Hot Jovian) $\text{few} \times 10^6 \text{ yr}$ at $1''$

Disk Imaging & Spectroscopy:
 $f_{\text{disk}}/f_* > \text{few} \times 10^{-4}$
 $\theta > 50 \text{ mas}$



To study physical processes acting on sub-AU scales and time scales comparable to the age of our solar system will require a 3—4 orders of magnitude improvement in instrumental stray light rejection (i.e., image contrast) over performance currently obtainable with HST.

Extrasolar Planet Imaging & Spectroscopy:

(Hot Jovian) $\text{few} \times 10^6 \text{ yr at } 1'' \Rightarrow$ (Terrestrial) $> 10^9 \text{ yr (solar age) at } 1''$

TPF/Darwin

Disk Imaging & Spectroscopy:

$f_{\text{disk}}/f_* > \text{few} \times 10^{-4} \Rightarrow \leq 10^{-6}$

$\theta > 50 \text{ mas} \Rightarrow \text{a few mas}$
(sub-AU at 200pc)

