



Spatially-resolved Debris Disk Studies: Present and Future

Deborah Padgett

NASA Goddard Space Flight Center

(with many thanks to Karl Stapelfeldt)

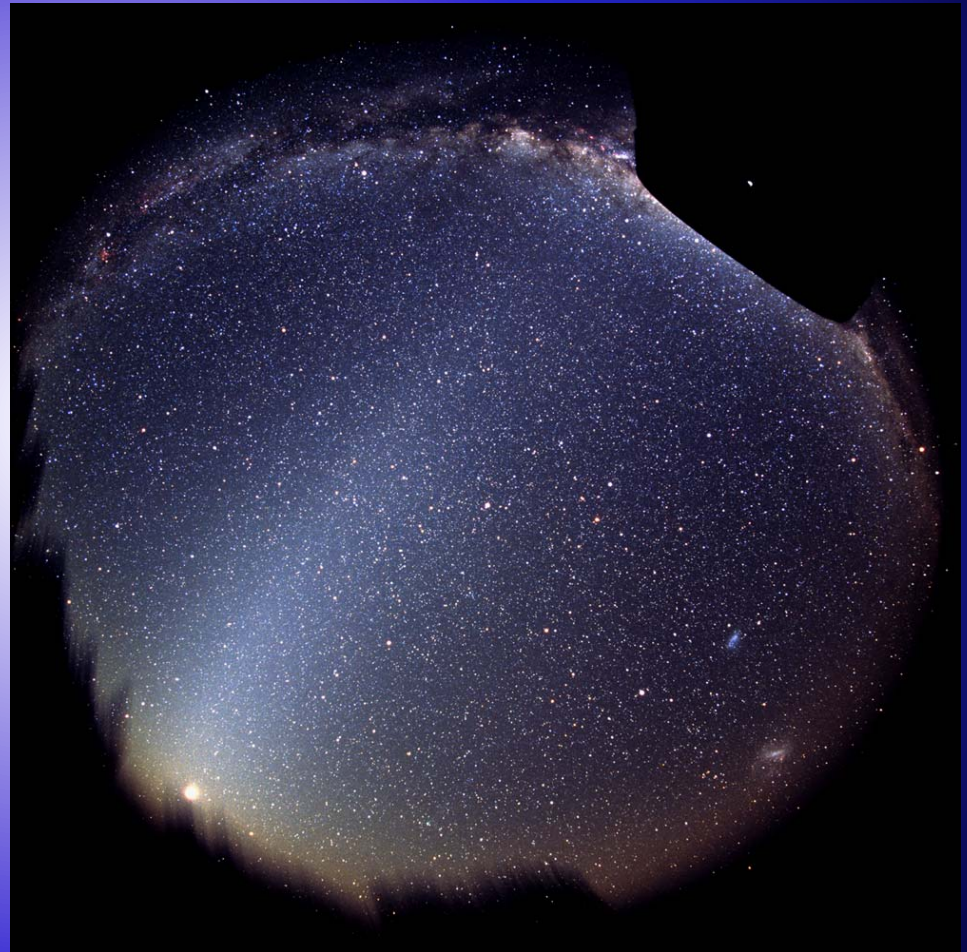
Talk Overview

- History of debris disk detection by IR surveys
- Scattered light imaging
- Case study: WISE debris disks
- Thermal IR imaging
- Inventory of resolved debris disks
- Debris disk imaging with upcoming facilities

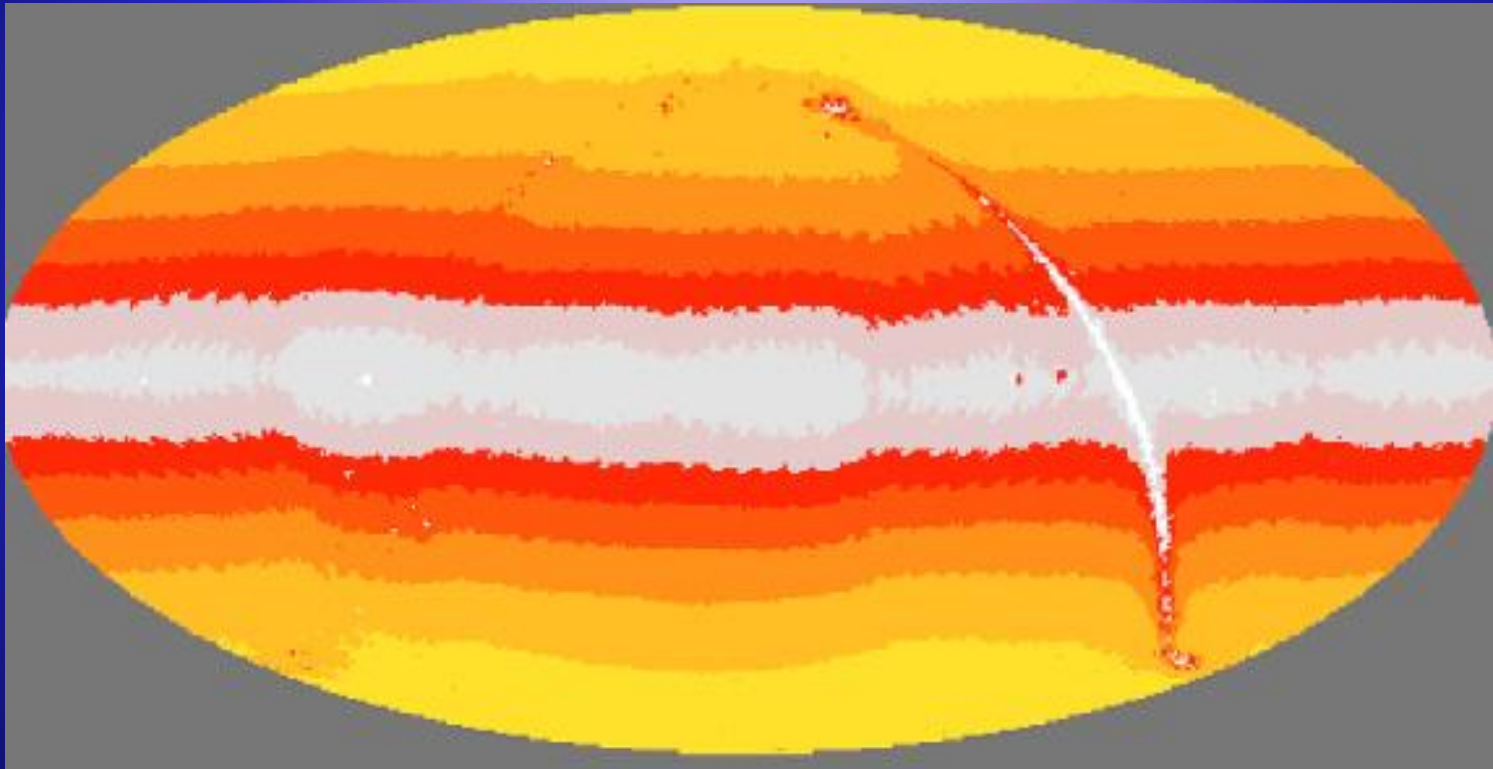
Zodiacal Light:

Our Sun's Warm Debris Disk

- Interplanetary dust particles are released by asteroid collisions & cometary passages
- Particle concentration in the ecliptic plane causes zodiacal light
- Median particle size is $30\ \mu\text{m}$, but a wide size range is seen
- Particles interior to main asteroid belt
- Even though its fractional luminosity is just 10^{-7} of the Sun, the zodiacal light is the most luminous component of our planetary system



All-sky map at $25\ \mu\text{m}$
dominated by warm dust emission

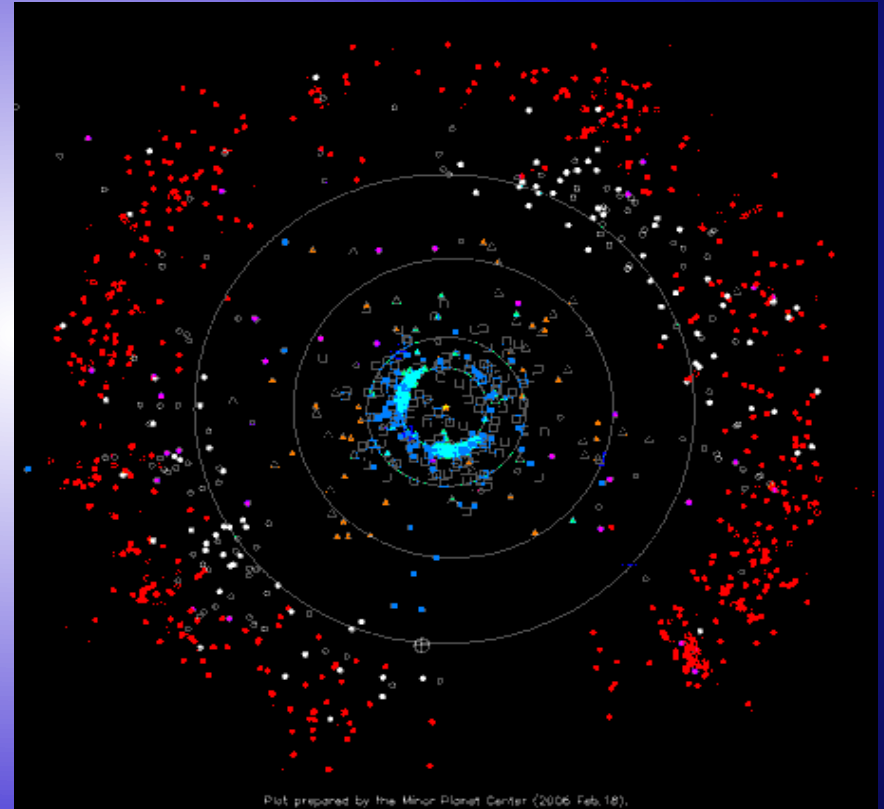


COBE/DIRBE

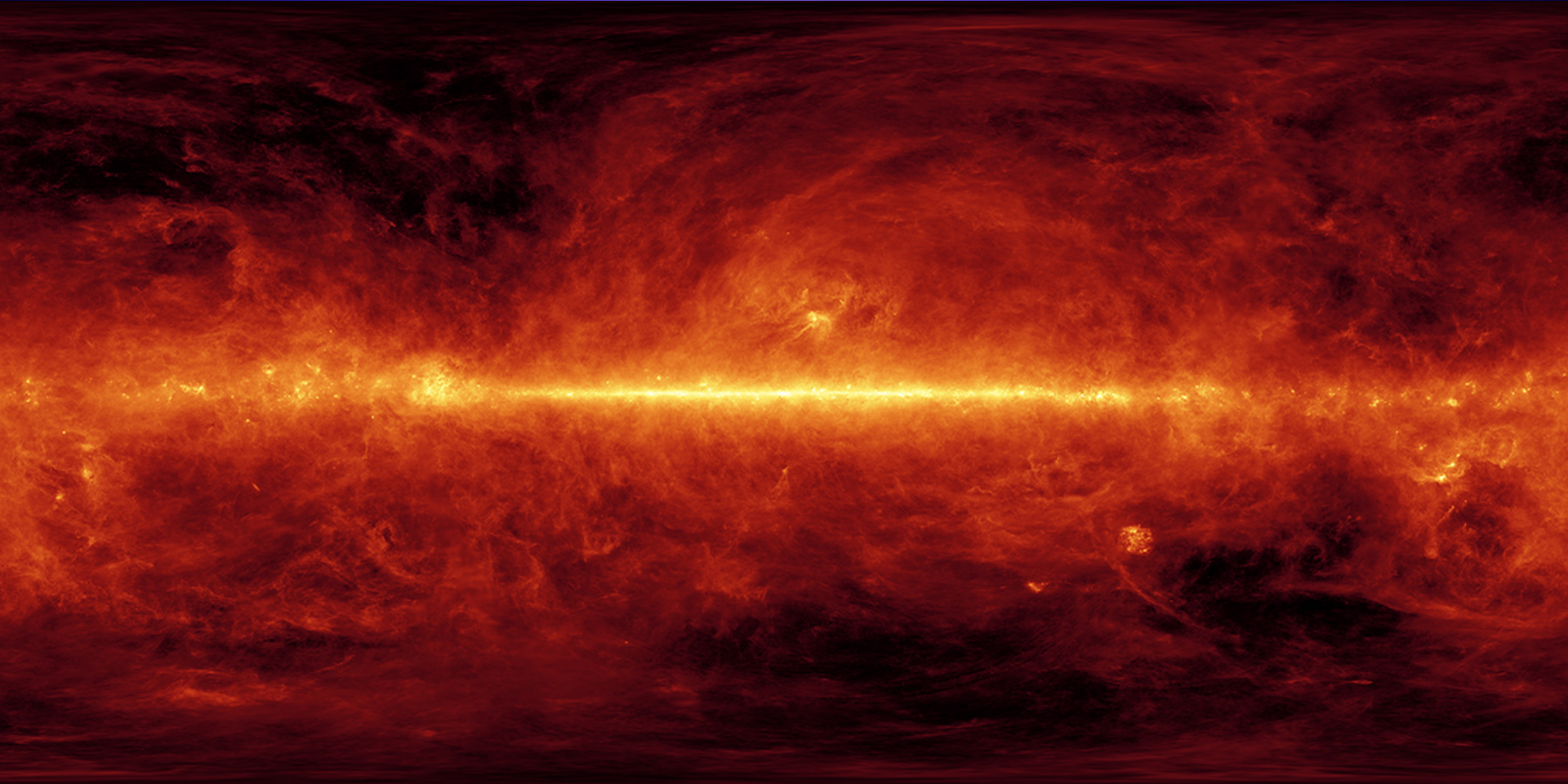
Debris sources in the solar system

Zodiacal light is dust near the Earth originating from the main asteroid belt

Dust in our Kuiper belt is currently unmeasured: not clearly distinguished from foreground zodiacal light



The IRAS Mission (1983)



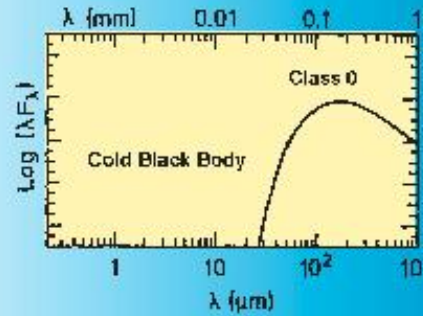
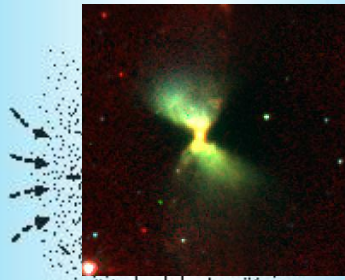
(IPAC) at Caltech

July 23, 2014

Sagan Summer School 2014

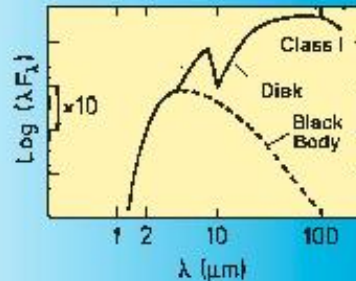
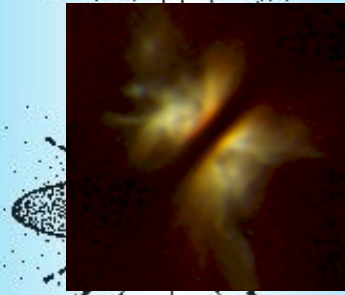
CLASS 0:
Main accretion
phase?

Age $\lesssim 10^4$ years
 $M_{\text{env}} \gtrsim 0.5 M_{\odot}$



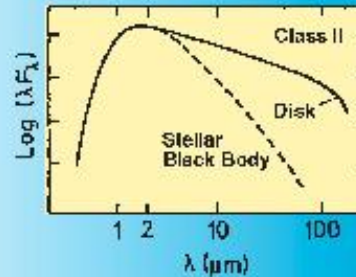
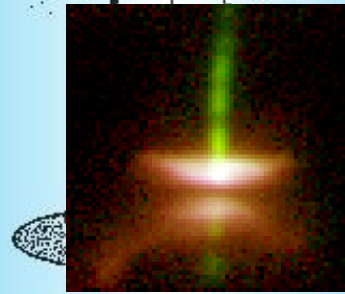
CLASS I:
Late accretion
phase?

Age $\sim 10^3$ years
 $M_{\text{env}} \lesssim 0.1 M_{\odot}$



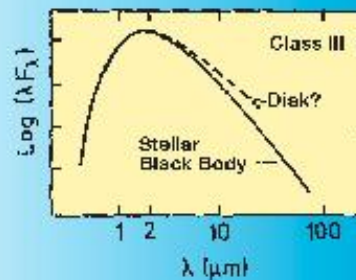
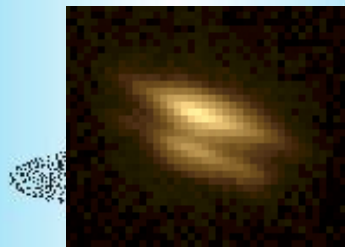
CLASS II:
Optically thick
disk

Age $\sim 10^5$ years
 $\langle M_{\text{disk}} \rangle \sim 0.01 M_{\odot}$

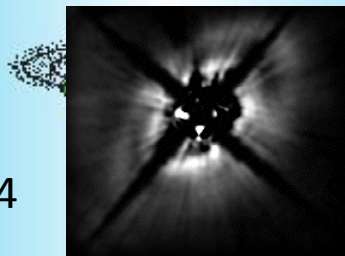


CLASS III:
Optically thin
disk?

Age $\lesssim 10^7$ years
 $\langle M_{\text{disk}} \rangle \lesssim 0.003 M_{\odot}$



Planetary system



IRAS Revealed Young Disk Evolution

IRAS was ideal for detecting the faint glow of cool dust in circumstellar disks where planets form

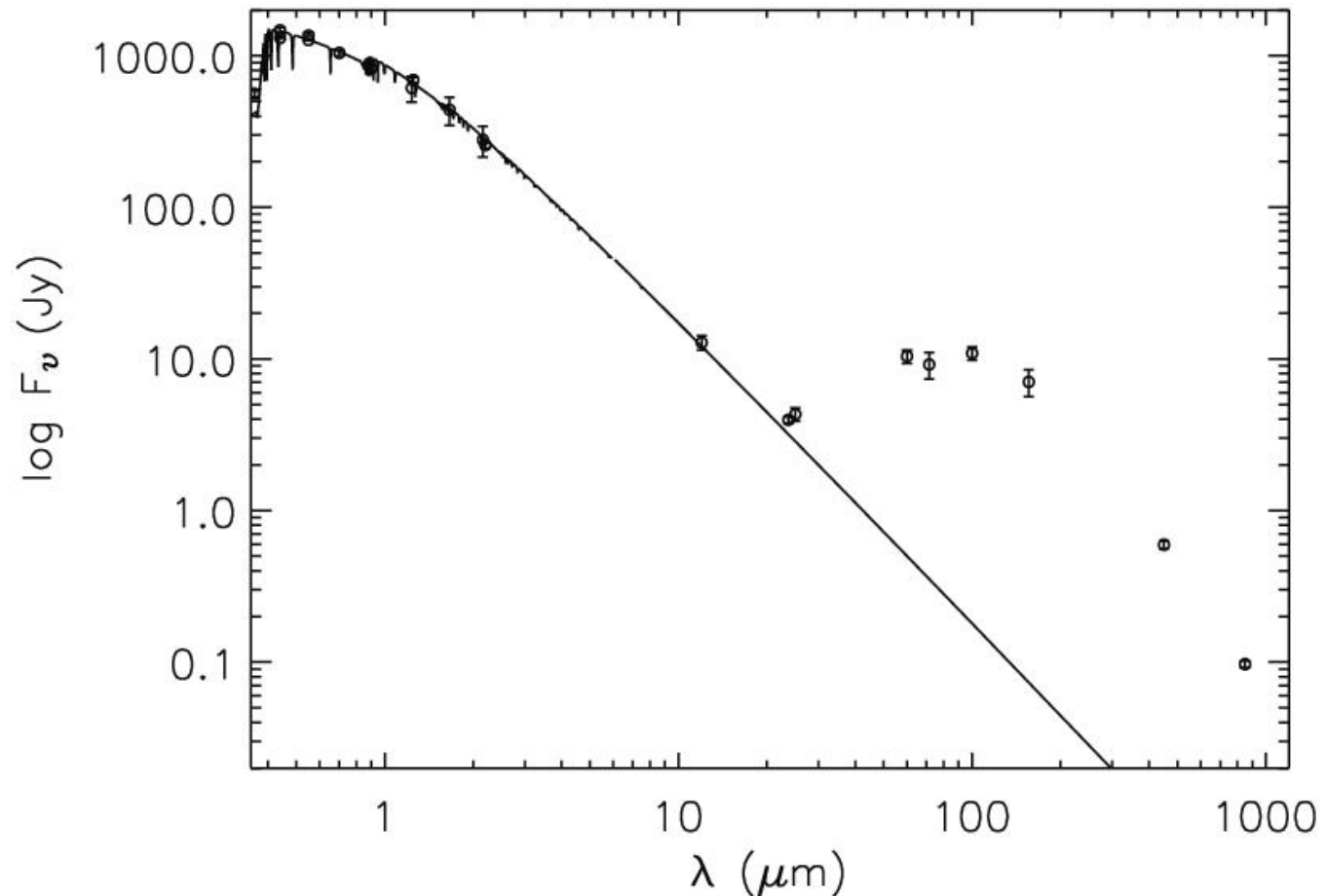
IRAS found dust around more than 50% of young stars in nearby dust clouds ($> 1 L_{\odot}$)

IRAS data allowed astronomers to classify young stellar objects according to IR spectral energy distribution

Hubble and Spitzer have imaged some of these IRAS objects

IRAS Debris Disks

- *IRAS* discovered infrared excesses around many stars
- The “Fab Four”
 - Vega
 - Fomalhaut
 - Epsilon Eridani
 - Beta Pictoris
- Called “debris disks” because of radiation pressure and collisions of small dust particles in the system unless replenished from collisions



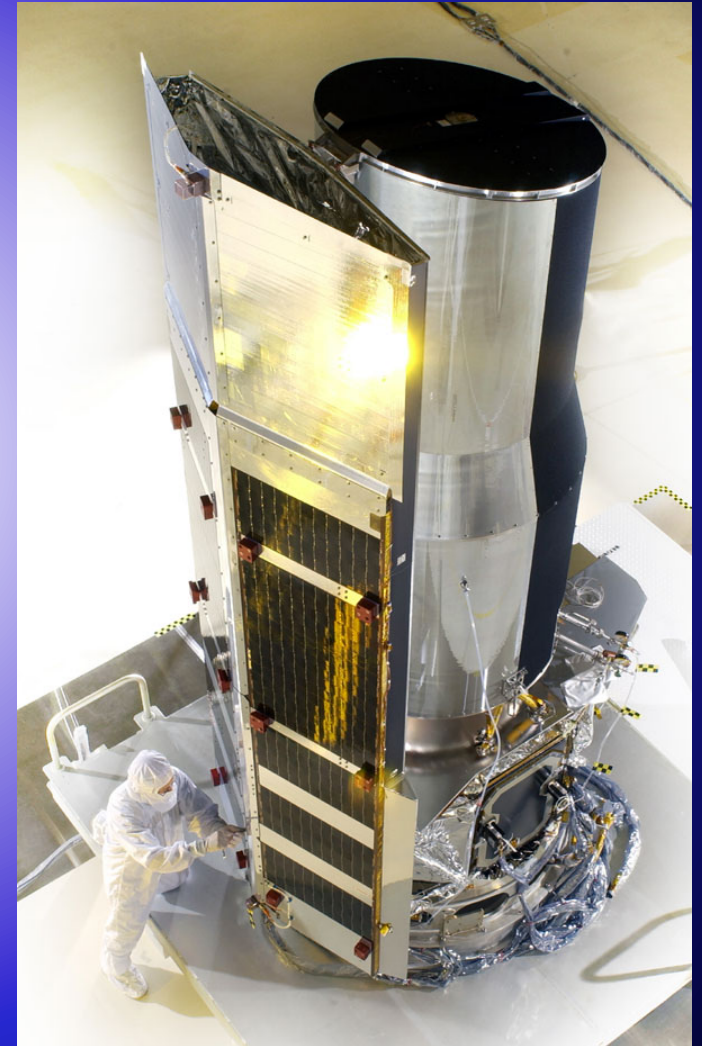


The Legacy of IRAS

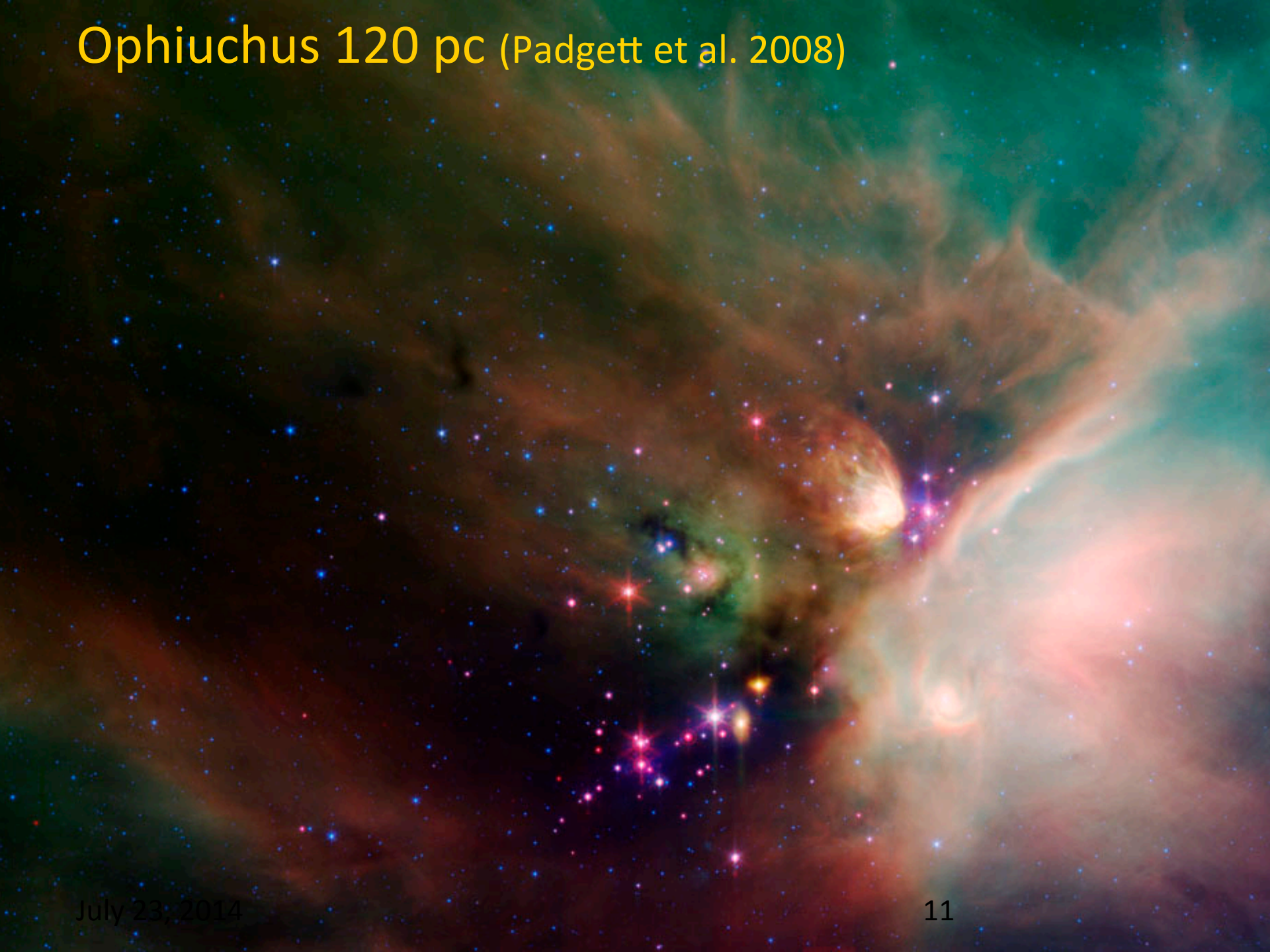
- All-sky survey revealed the brightest mid to far-infrared sources in the sky
- This is especially important for spectroscopic follow-up, which is naturally less efficient than imaging
- Despite primitive detectors and relatively small numbers of sources ('only' 250000 in the Point Source Catalog), this highly reliable catalog has been a gold mine for high resolution imaging and spectroscopic work
- 2009 ADS search shows more than 10,000 articles with "IRAS" in the abstract
- However, many IRAS sources are "confused" with several objects within the position error ellipse due to poor resolution

Spitzer Space Telescope Overview

- 85 cm f/12 beryllium telescope, $T \sim 5.5\text{K}$
- $6.5\text{ }\mu\text{m}$ diffraction limit
- Two science cameras (IRAC and MIPS), plus a low/moderate resolution spectrograph (IRS); $3 < \lambda < 180\text{ }\mu\text{m}$
- Earth-trailing solar orbit
- 10-1000x more sensitive than 1983 IRAS mission

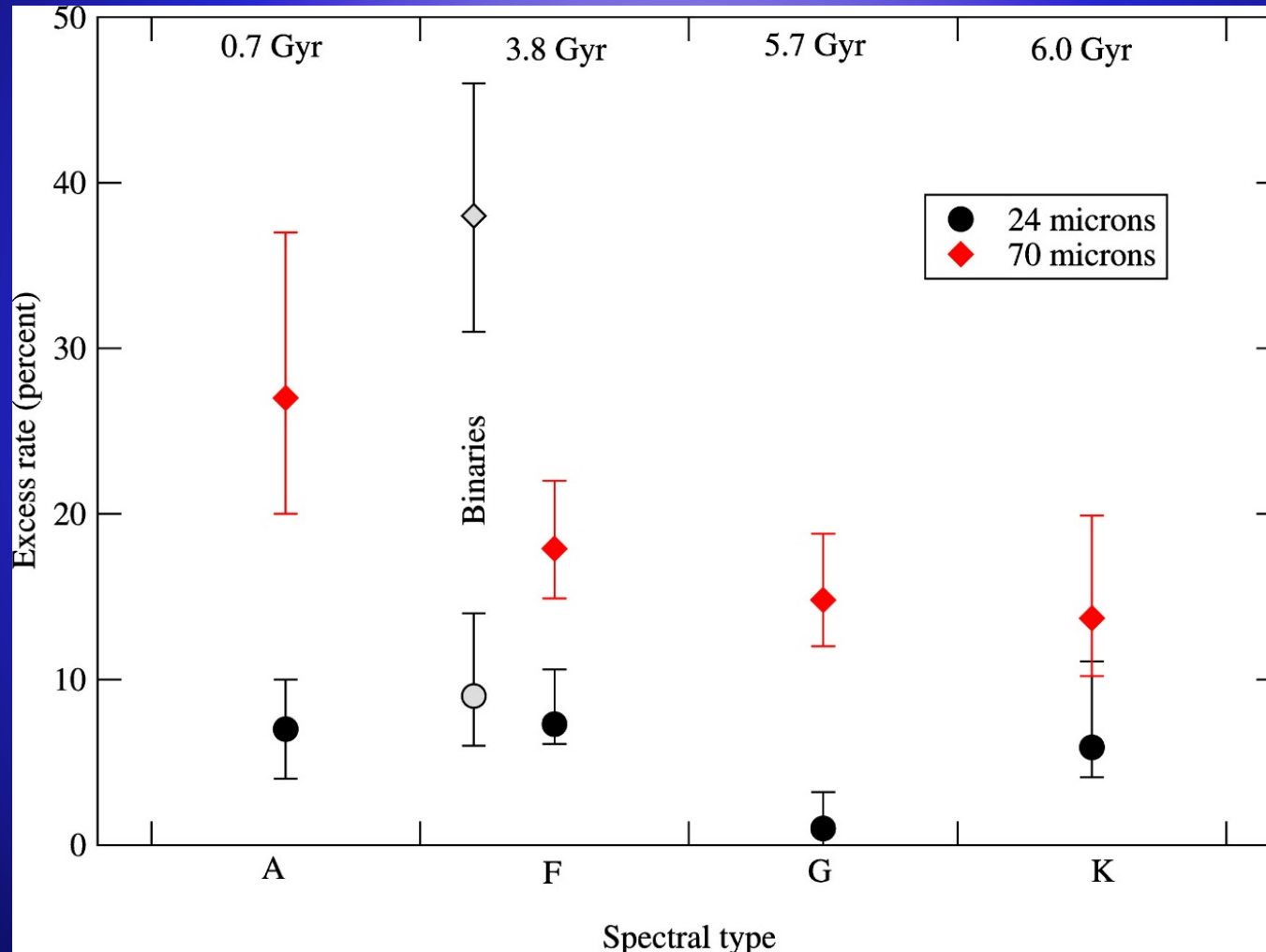


Ophiuchus 120 pc (Padgett et al. 2008)

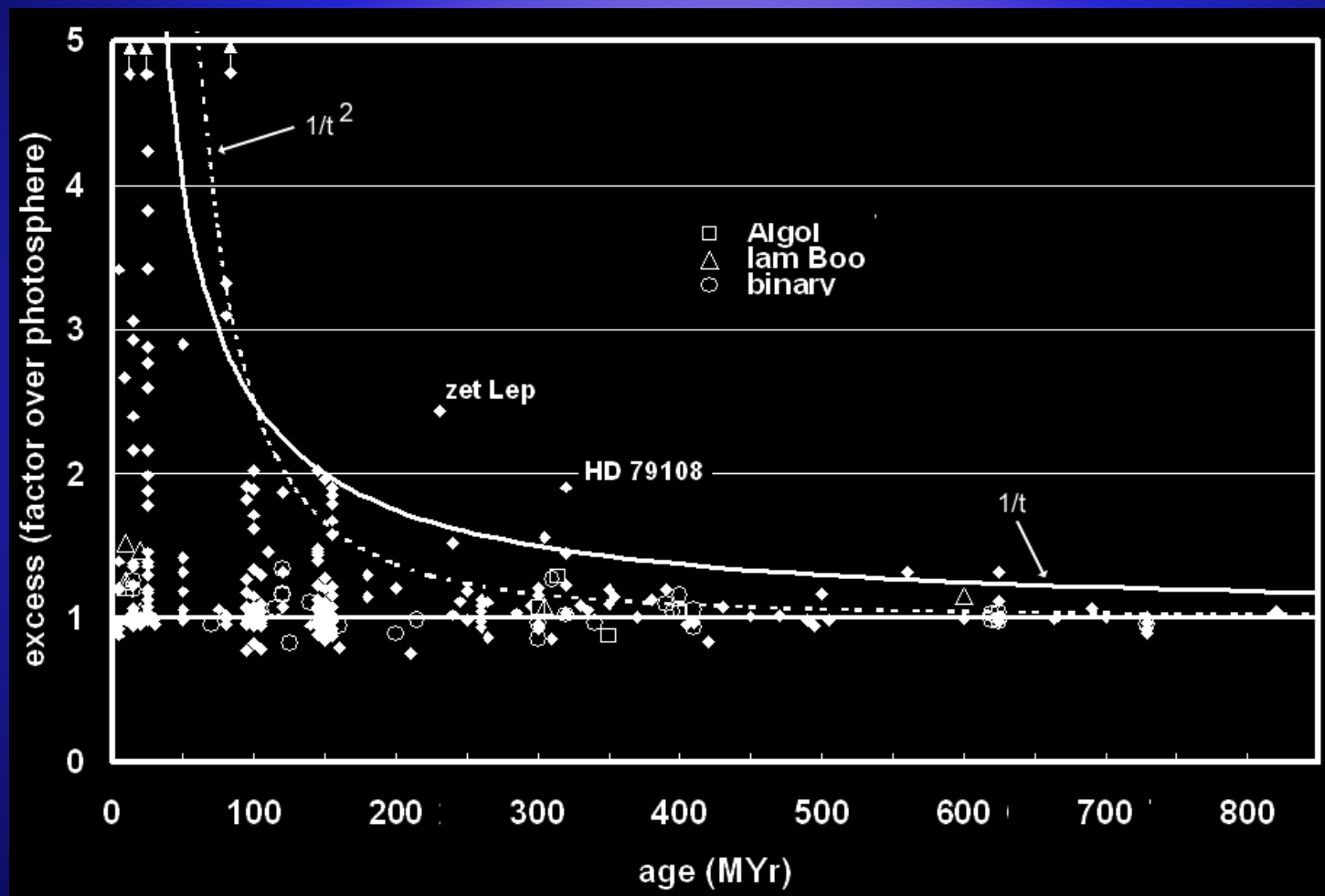


Debris Disk Frequency from Spitzer Surveys

(Trilling et al. 2008)



A star 24 μm excesses vs. time: decay $\propto 1/t$ over ~ 200 Myr; but many stars of all ages have little or no excess. (Rieke et al. 2005)

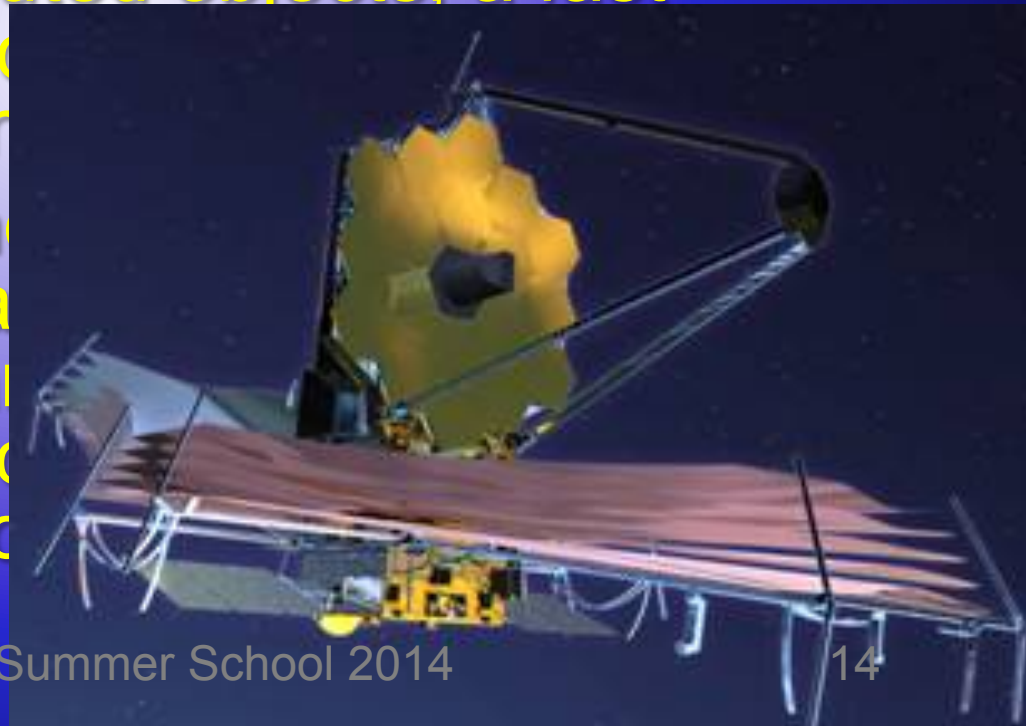


Why All Sky?

For superlative and/or unique objects, such as the nearest stars or the most luminous galaxies (or debris disks!), only an all-sky survey will do.

For uniformly distributed objects, a fast shallow survey finds more objects in less time than a deep narrow survey.

An all-sky survey finds more objects in a class, which are then picked up in detail with larger telescopes like the James Webb Space Telescope. Hubble's successor.



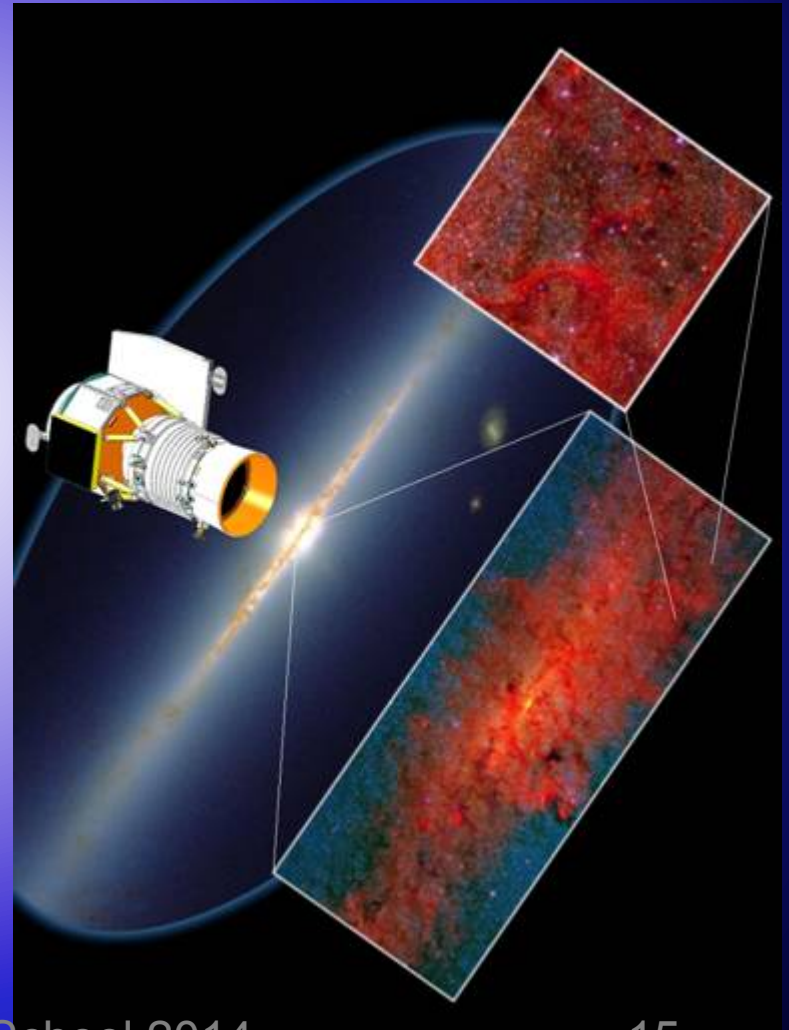
WISE covers the entire sky

Wide Field Infrared Survey Explorer

Salient Features

4 imaging channels covering 3 - 22 microns wavelength
40 cm telescope operating at <11K (-439° F)
Two stage solid hydrogen cryostat
Delta launch from Vandenberg December 14, 2009
Sun-synchronous 6am/6pm 500km orbit
Scan mirror provides efficient mapping
Operational life: 10 months, 8 with all bands
4 TDRSS tracks per day to transmit data
100x more sensitive than IRAS, 10x the resolution

NOT a debris disk imager due to small size





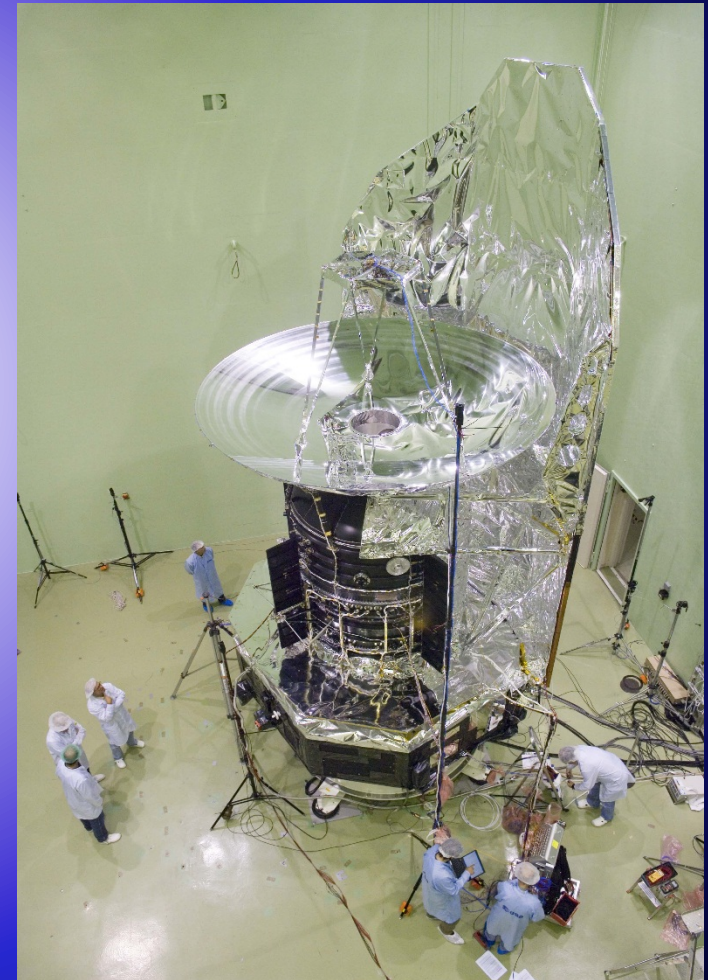
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Herschel Space Observatory

- 3.5 meter primary mirror
- 70 μm imaging resolution 4x sharper than Spitzer; resolving central holes & disk asymmetries
- Sensitivity to lower levels of $L_{\text{IR}}/L_{\text{star}}$ at 100 & 160 μm
- 600 nearby targets surveyed by DUNES and DEBRIS key programmes, plus ~200 others in small GO projects

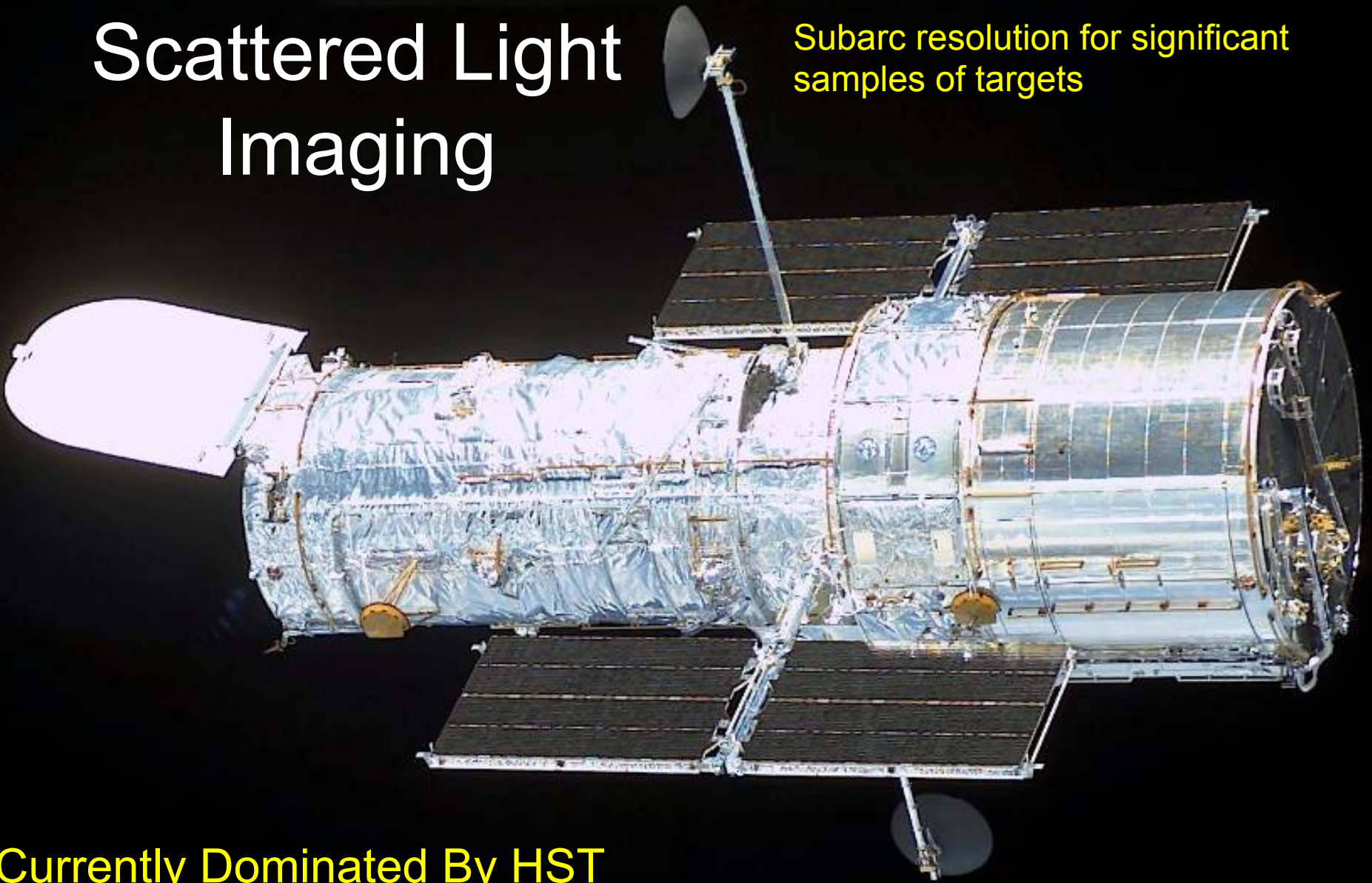


What is Learned from High Resolution Debris Disk Imaging?

- Confirms basic disk morphology of dust distribution
 - position angle
 - major and minor axes (outer radius of disk)
- Measurable disk parameters
 - Radial disk structure (gaps, rings)
 - Azimuthal disk structure (asymmetries)
 - Vertical density structure (warping)
- Derivable disk parameters via modeling scattered light (thermal emission)
 - Inclination
 - Radial surface brightness profile → radial density (x temperature) profile
 - Vertical disk structure if nearly edge-on → scale height
 - Dust mass-opacity product, phase function, polarizability, their λ dependence
 - Dust grainsizes with thermal emission resolved at 2 or more wavelengths
- Some of the derivable properties are degenerate

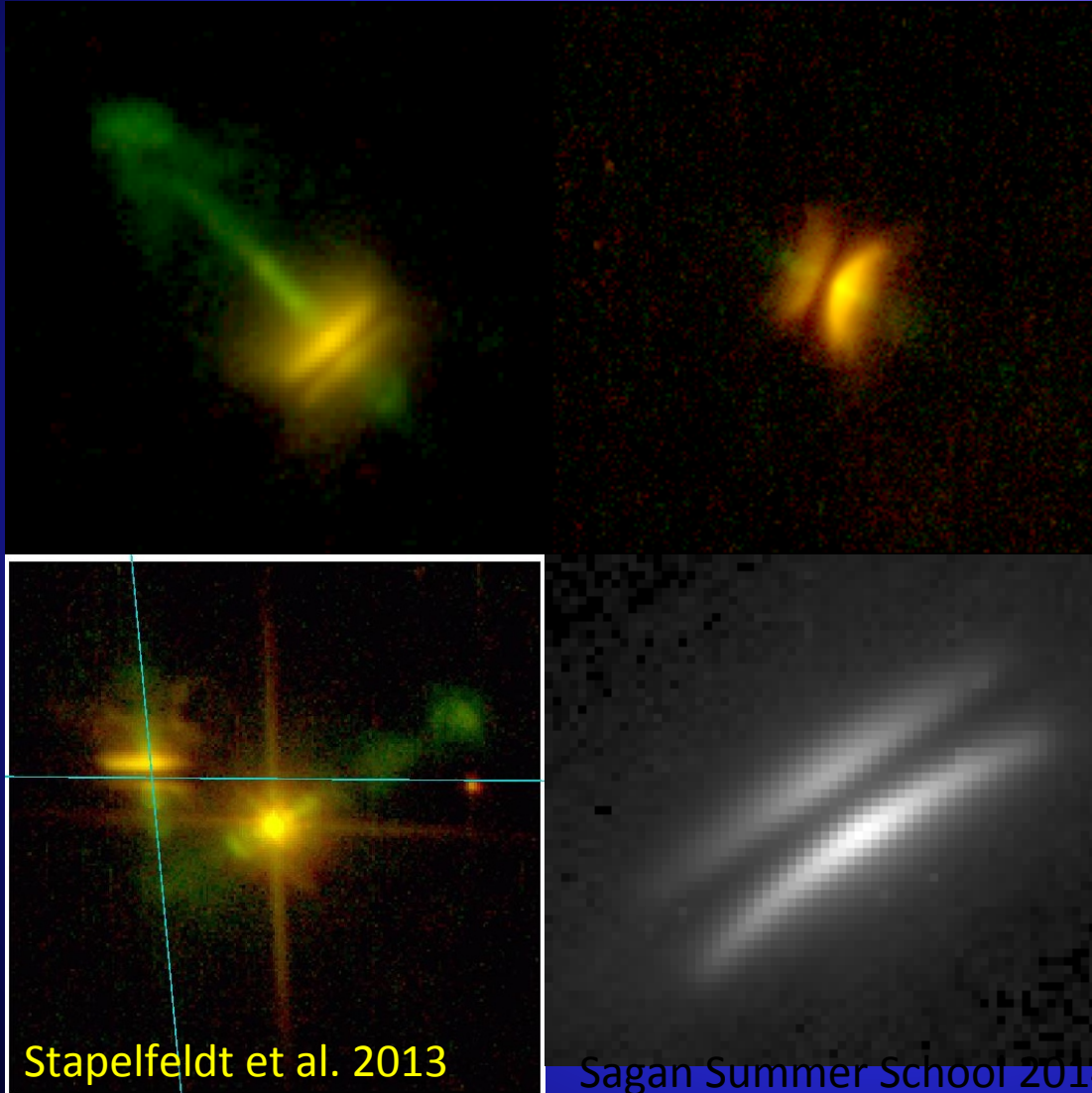
Scattered Light Imaging

Subarc resolution for significant samples of targets



Currently Dominated By HST

A Menagerie of Edge-On Young Stellar Disks



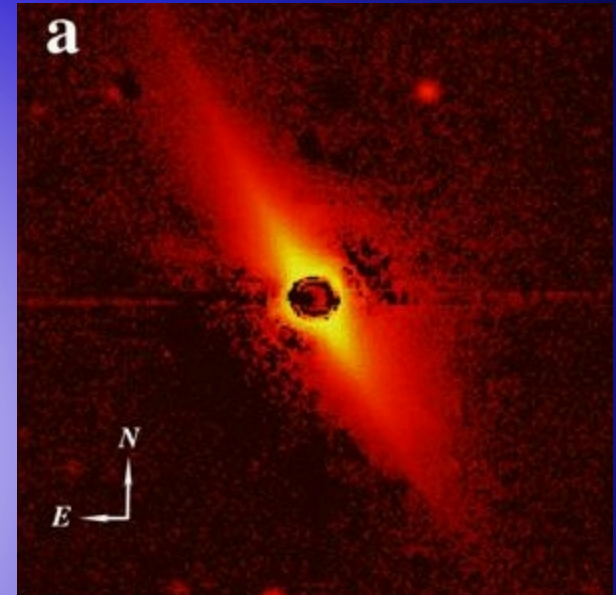
Edge-on disks are
natural
coronagraphs!

Size and shape
differences due to
age, environment

Dozens of YSO
imaged by HST in
scattered light either
as edge-on disks or
with PSF subtraction..

β Pictoris: A hard act to follow

- 1984 coronagraphic detection in visible light of edge-on disk around a bright, nearby IRAS source
- No other debris disks detected in scattered light for 15 years after IRAS
- Beta Pic now recognized as exceptionally young (12 Myrs) and dusty
- Imaging of other disks prevented by seeing-limited image quality: needed HST and adaptive optics to make progress in scattered light imaging

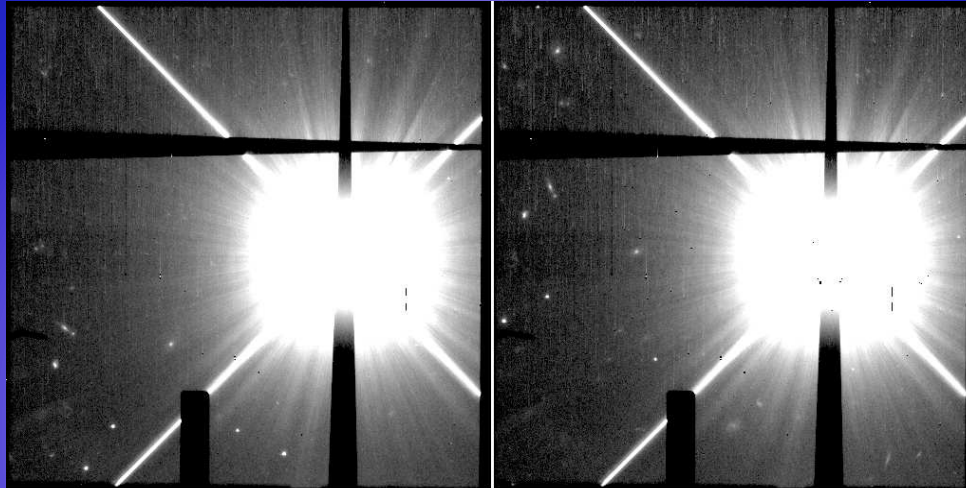


Central 1600 AU of
edge-on
 β Pictoris disk;
Kalas & Jewitt 1995

Reduction of STIS Coronagraphic Images

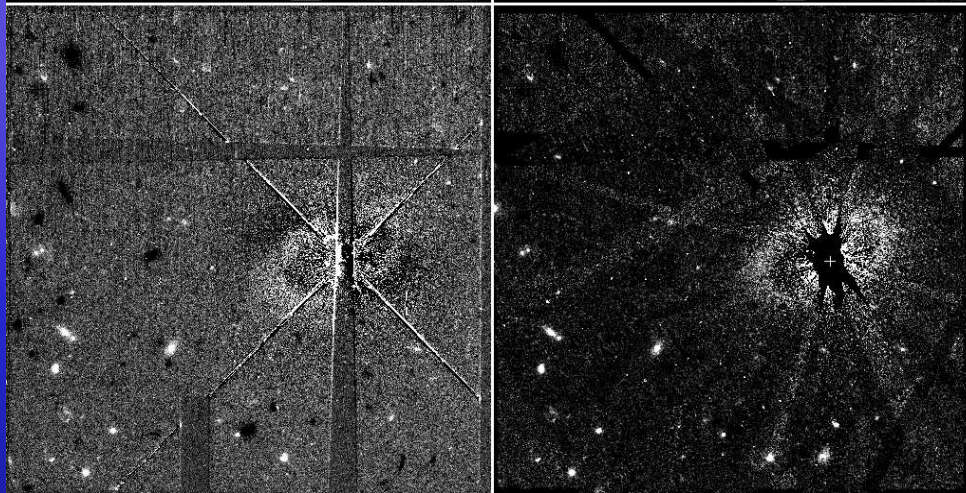
(Krist et al. 2012)

Roll 1



Roll 2

Simple
Difference



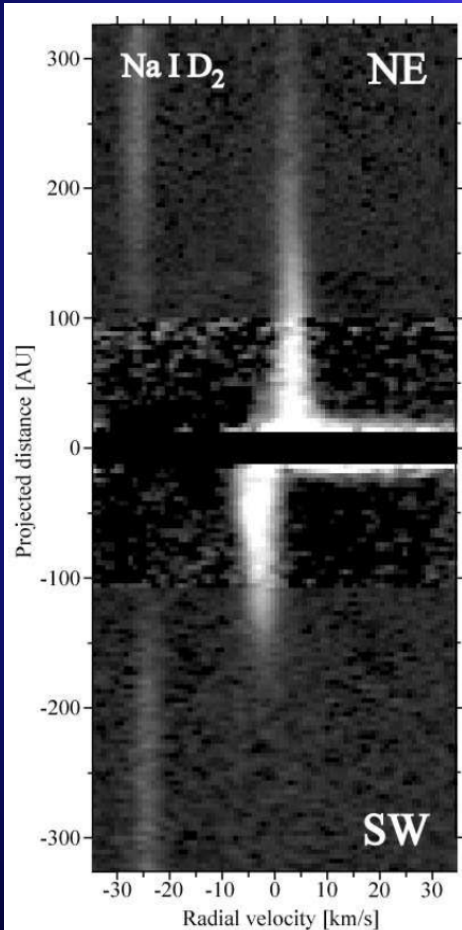
Iterative
Subtraction

(Krist et al. 2010)

β Pictoris imaging today

Na I velocity map

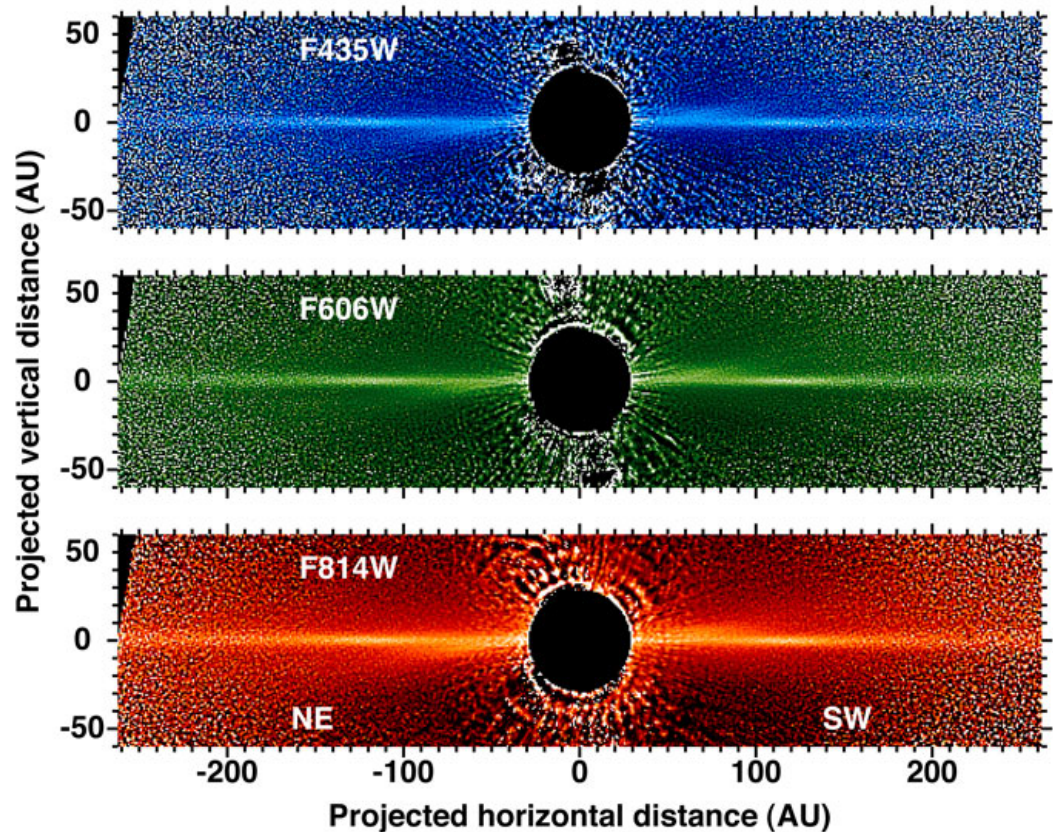
Brandeker et al. 2004



HST multicolor coronagraphy

Inner disk warp

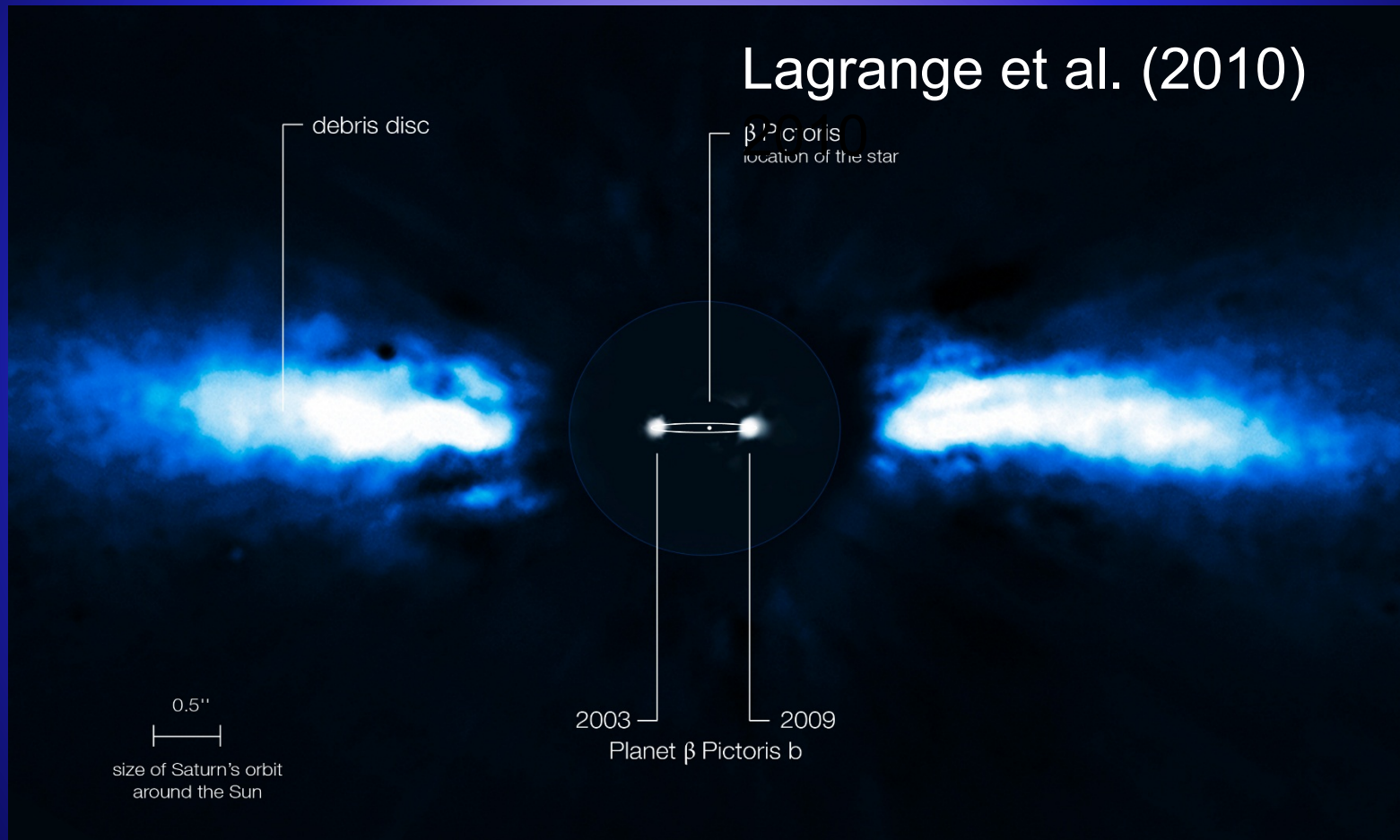
Slightly red disk color, peaking at $r > 120$ AU



Golimowski et al. 2006

2010: Planet beta Pictoris b confirmed.

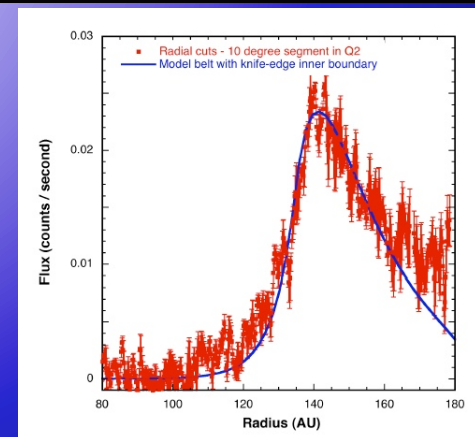
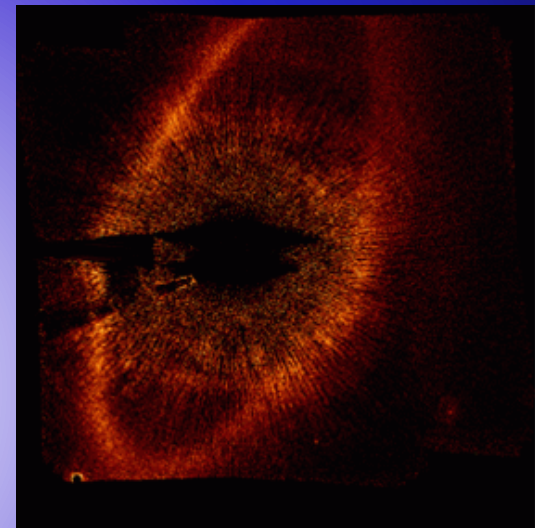
Orbital Parameters Lagrange et al. (2014)



Fomalhaut Eccentric Ring: HST

(Kalas et al. 2005)

- HST detection in $0.6\ \mu\text{m}$ scattered light
- Ring geometry: center is offset $2''$ from the star; shape fit with $e = 0.11$
- Ring has sharp inner edge, as if dynamically sculpted
- Brighter on E side, consistent with modest forward scattering
- Herschel results fully in accord with this picture



Deprojected orbit
semi-major axis of
115 AU:
4x Sun-Neptune
distance !

Common proper
motion with star: not
a background object

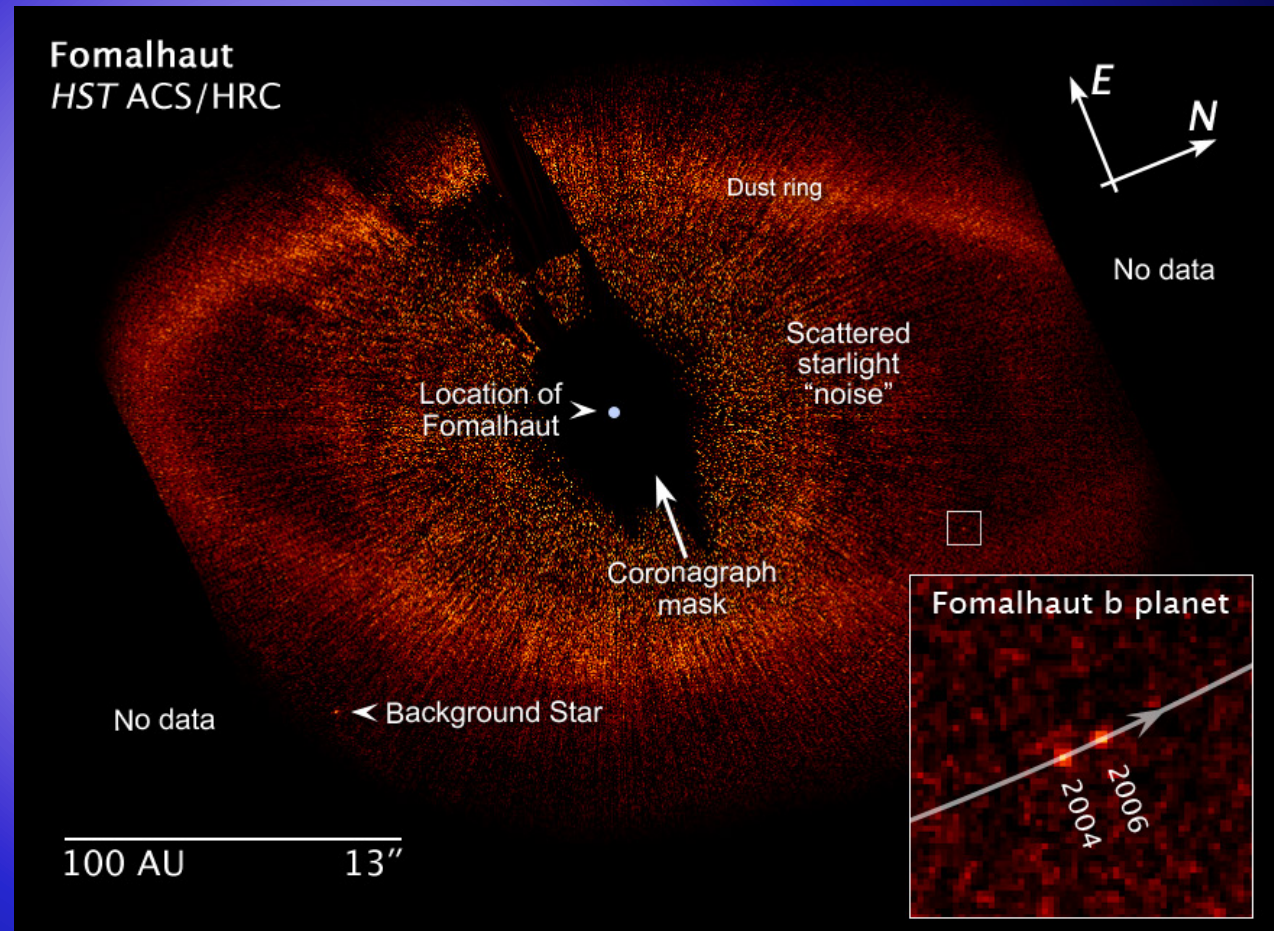
Orbital motion initially
seen parallel to ring
inner edge; consistent
with Kepler's law

Follow-up shows that
this object is a ring-
crosser

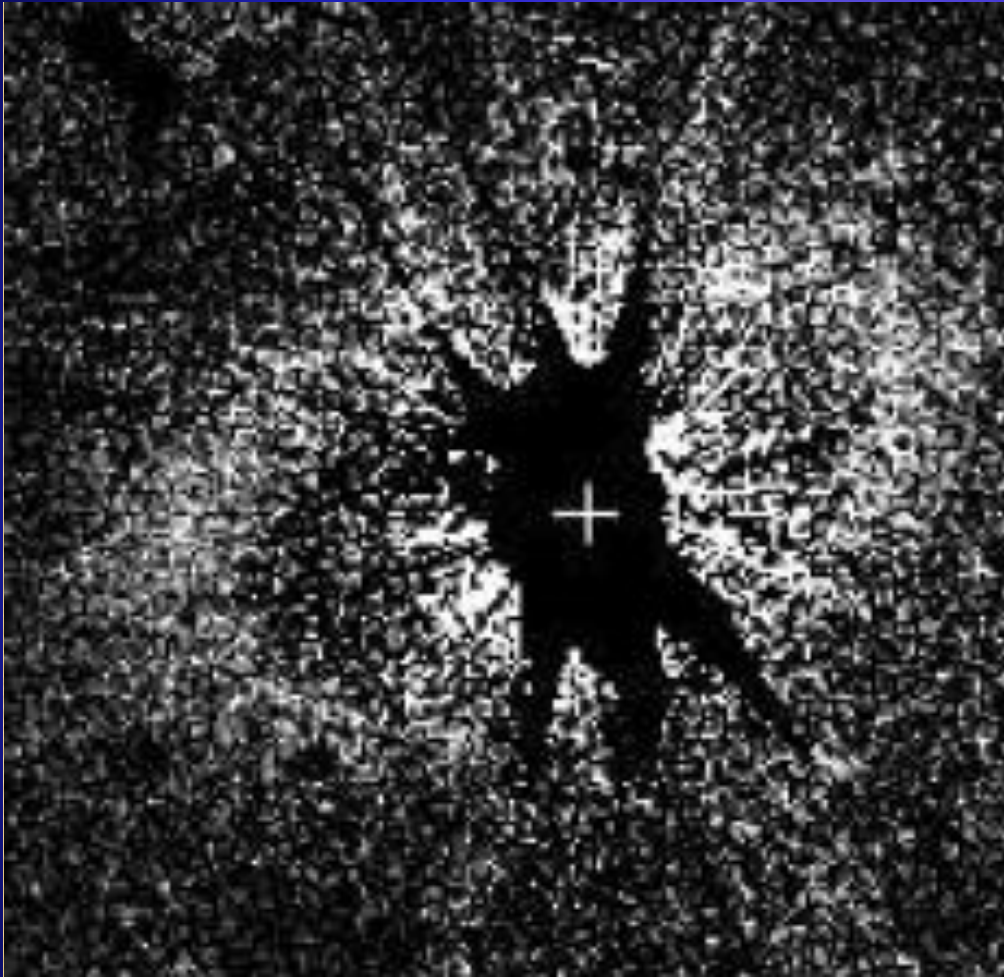
Needs JWST

Planet reported in 2008

Kalas et al.



HD 202628: G2 V star at 24 pc



Krist et al. 2012

Broad ring with central clearing. Diameter of ~ 16 arcsec (400 AU).

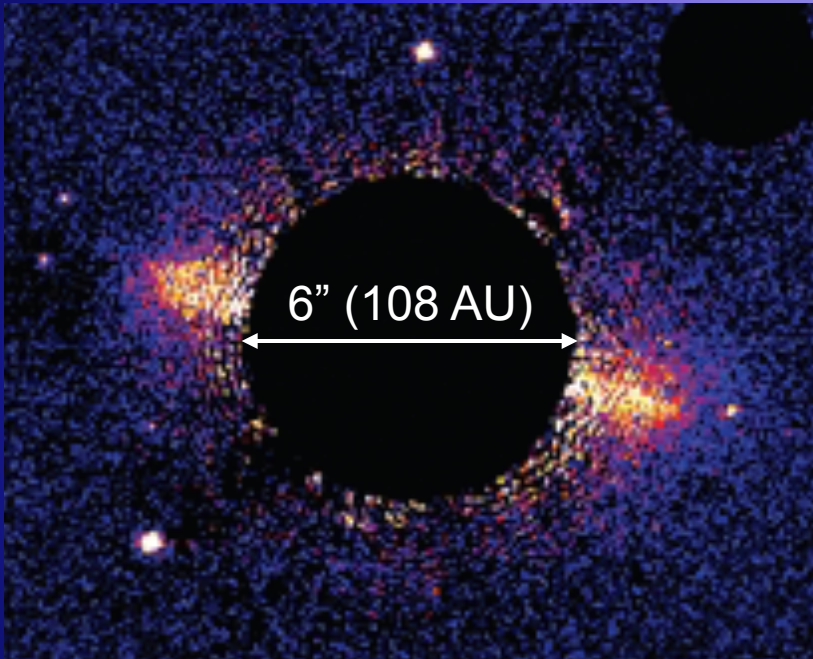
Mean surface brightness is $V \sim 24$ mag arcsec $^{-2}$: Faintest debris disk yet detected with HST.

Clearly asymmetric:
Inner edge is 139 AU from star in the NW, 161 AU in the SE.

Star is offset from ring center by $0.8''$ (20 AU)

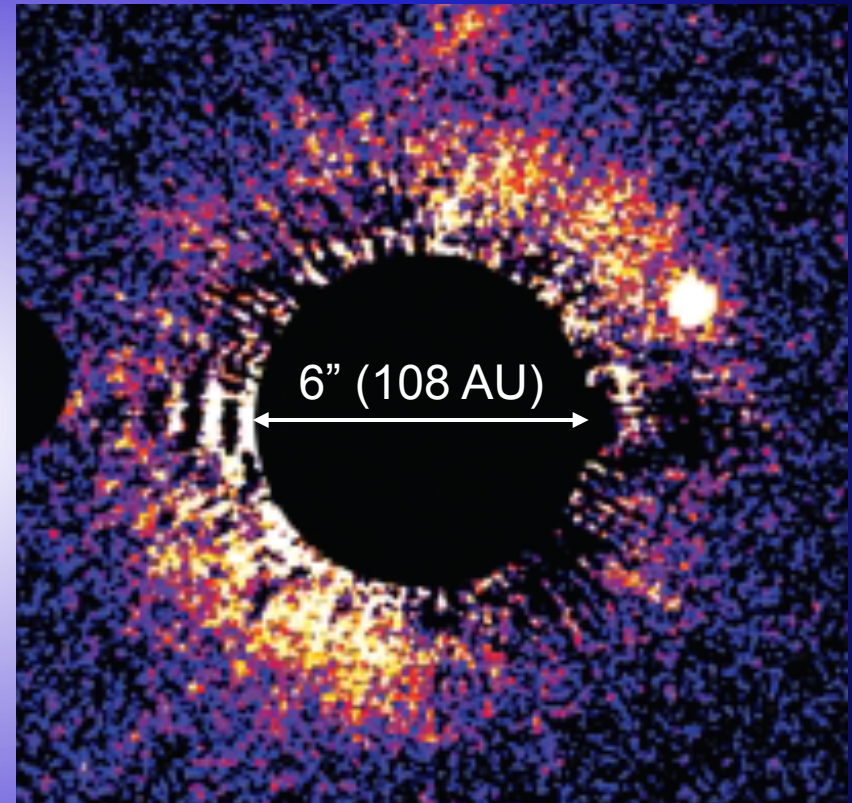
HD 139664

*F5V, 18 pc, 100-1000 Myr,
 $L_{\text{d}}/L_{*}=1 \times 10^{-4}$*



HD 53143

*K1V, 18 pc, ~1 Gyr,
 $L_{\text{d}}/L_{*}=3 \times 10^{-4}$*

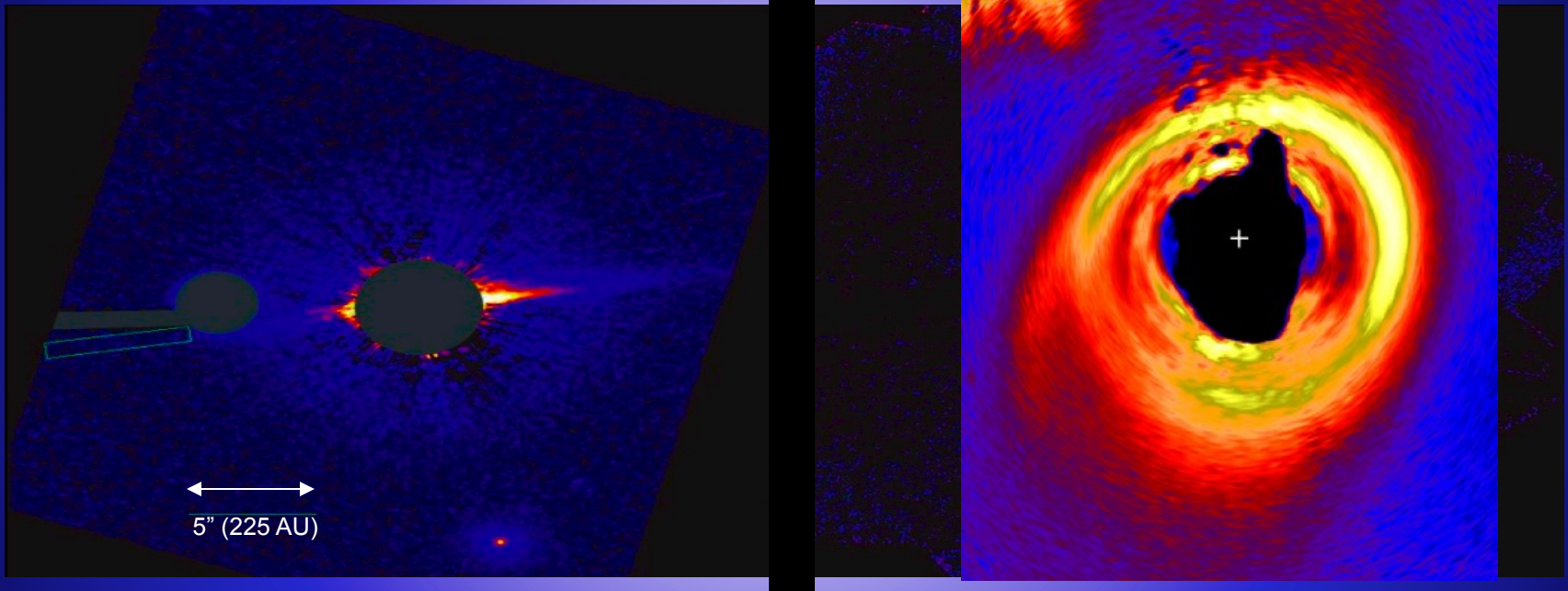


Both ACS Wide V band, Kalas et al. (2006)

HD 15115

F2V, 45 pc, ~12 Myr?, $L_d/L_ = \sim 5 \times 10^{-4}$*

ACS (Wide V band)



“Blue Needle”

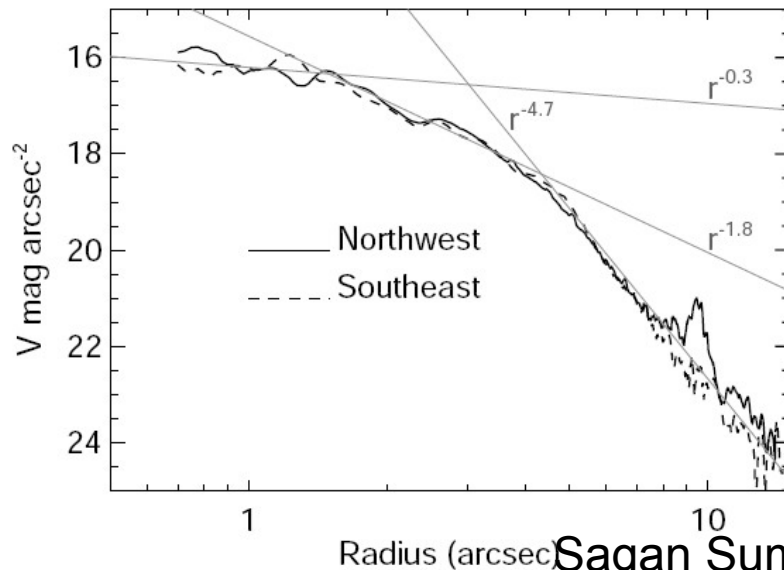
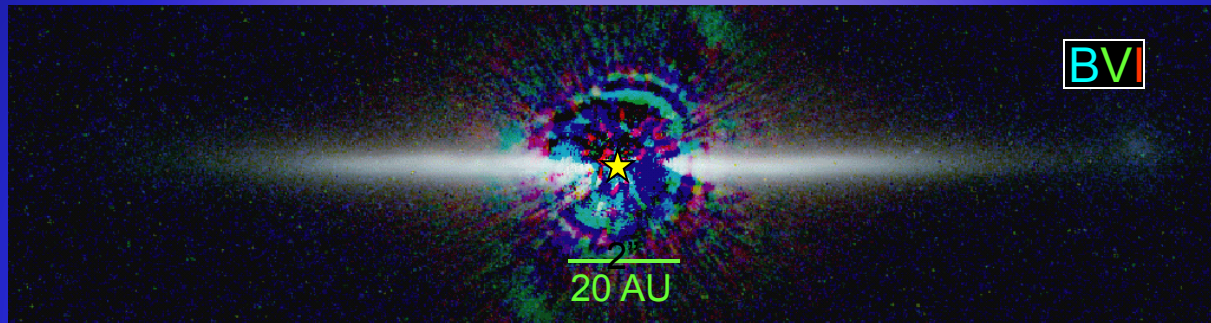
Kalas et al. (2007)

*Very asymmetric edge-on disk. Possible fly-by candidate identified
Disk is blue relative to star based on V-H colors, and becomes more
blue at larger radii*

AU Mic

M1V, 10 pc, 12 Myr, $L_{\text{d}}/L_{\star}=4 \times 10^{-4}$

ACS (B,V,I)

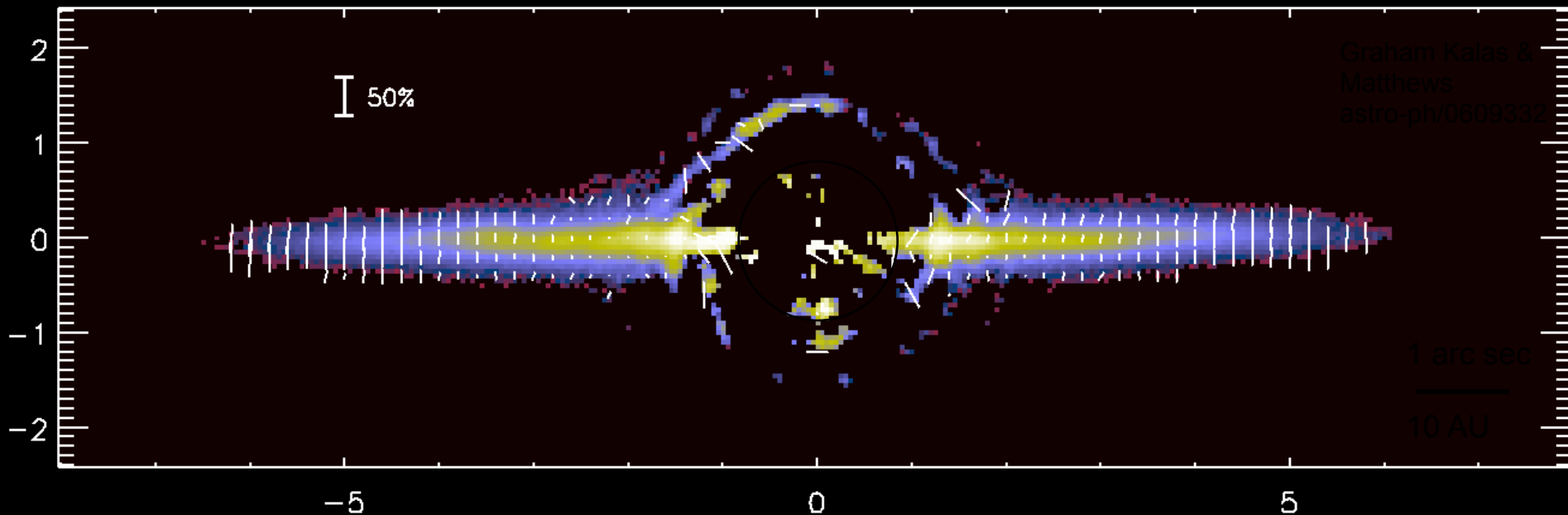


*Cleared inner hole < 12 AU
Flat surface density $12 < r < 49$ AU
 $\Sigma \propto r^{(2.2 \text{ to } 2.7)}$ beyond 49 AU*

Krist et al. (2005)

AU Mic in Polarized Light

(Graham et al. 2006)



- HST R band coronagraphic imaging polarimetry
- Peak polarization of 41% indicates single scattering by sub-micron size particles
- Consistent with highly porous, micron-sized dust aggregates

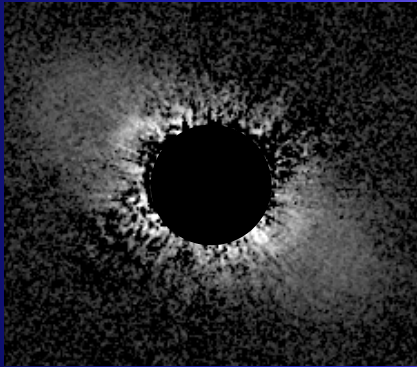
Degree of Forward Scattering

$g = 0$ Isotropic

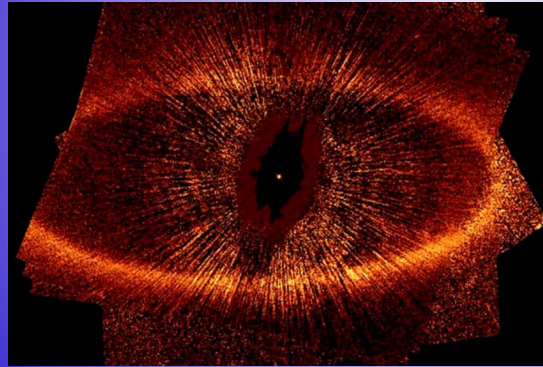
$g = 1$ Full forward scattering

$g = -1$ Full backward scattering

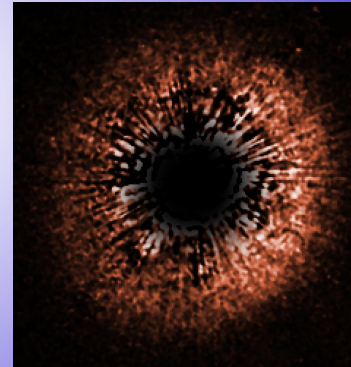
$g = 0$



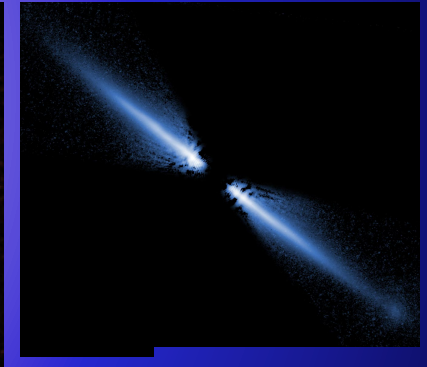
$g = 0.2$



$g = 0.3$



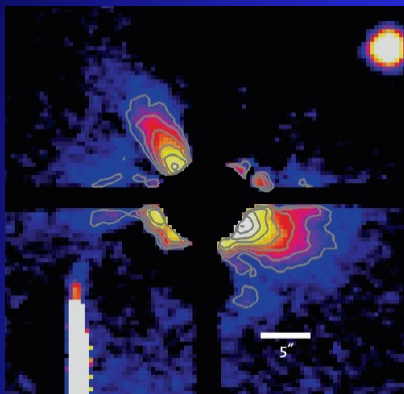
$g = 0.4 (0.7?)$



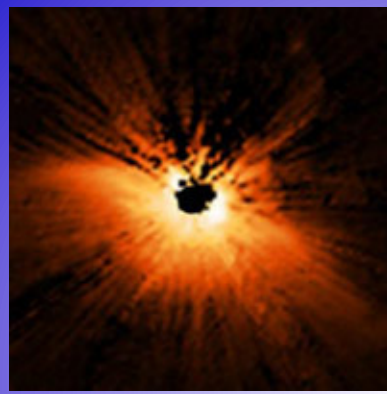
Strong forward scattering suggests smaller particles

Disks with ISM interactions

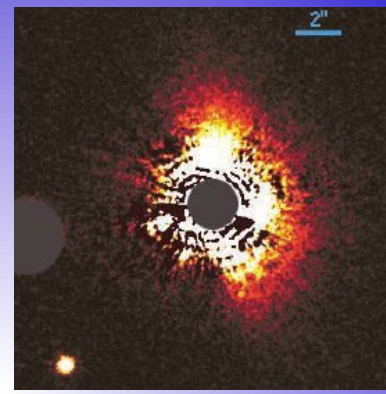
Morphologies swept-back from star's proper motion



HD 32297
Kalas et al. 2005
R band
Mauna Kea

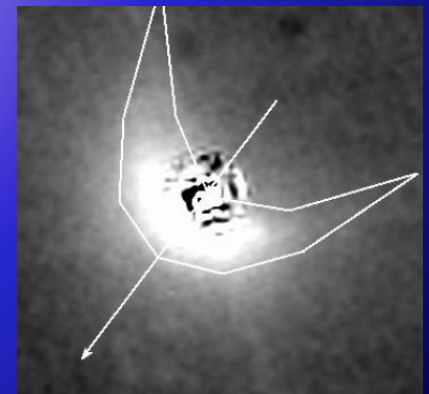


HD 61005
Hines et al.
2007
J band
HST/NICMOS



HD 15745
Kalas et al.
2007
R band
HST/ACS

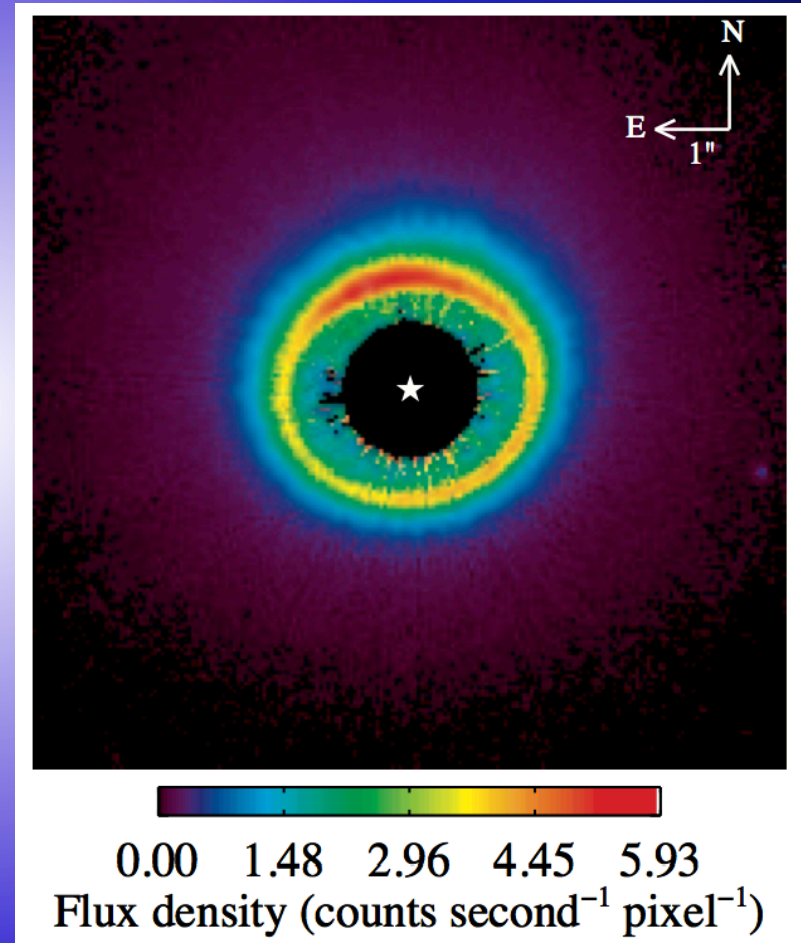
δ Vela
Gáspár et al.
2007
24 μ m
Spitzer/MIPS
bowshock,
not disk



HD 181327

(Stark et al. 2014)

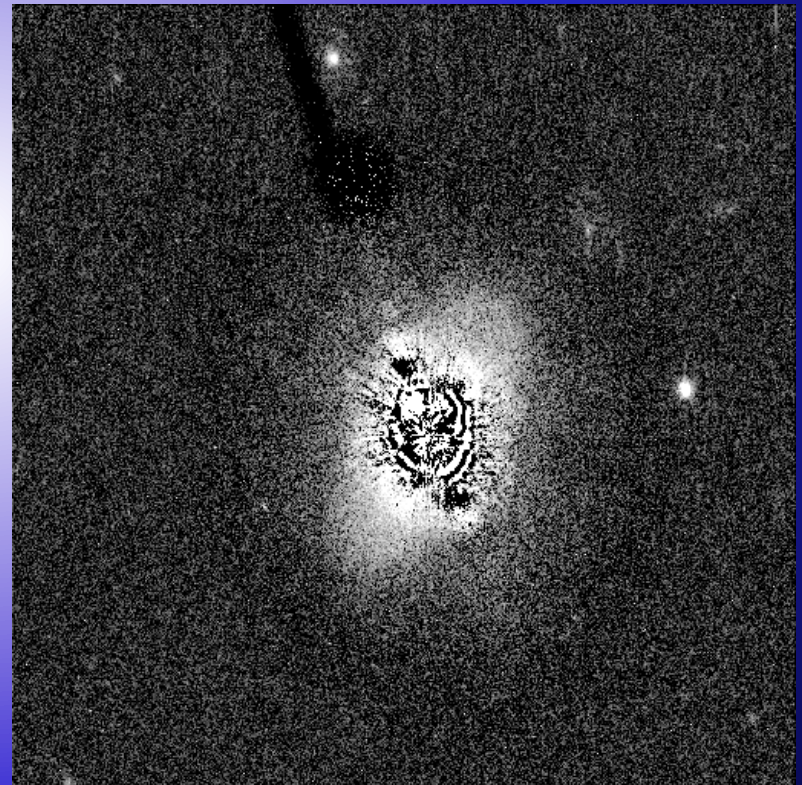
- F5/6 12 Myr β Pic moving group member
- New multi-roll STIS coronagraph processing
- Forward scattering enhanced; not well fit by Henyey-Greenstein function
- Large asymmetry potentially due to recent collision in system or ISM interaction



HD 92945: Young K1.5 star at 22 pc

Golimowski et al, 2011

HST/ACS direct V image, and after PSF subtraction

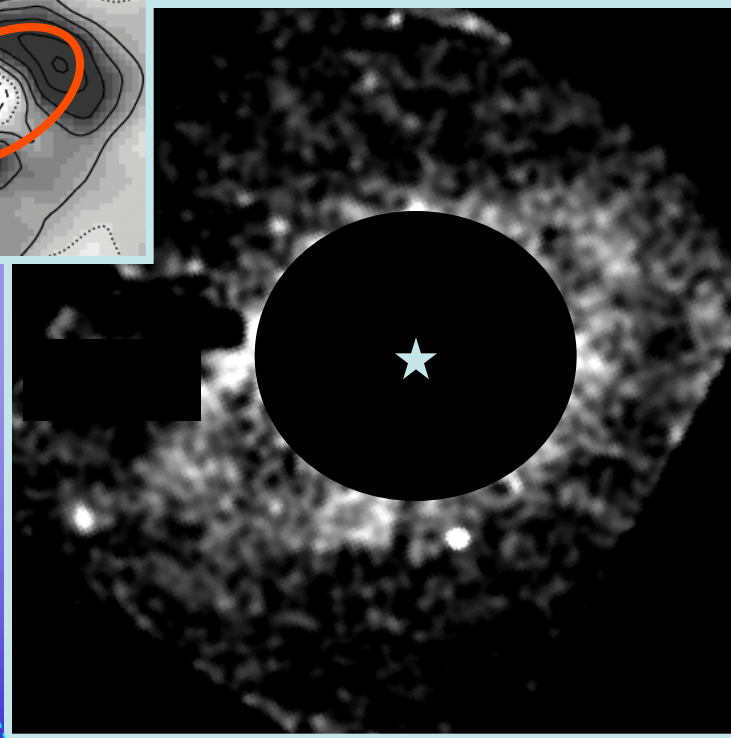


HD 207129

G0V, 16 pc, ~6 Gyr, $L_d/L_* = 1 \times 10^{-4}$

Spitzer 70 μm
Bryden et al. in prep

HST ACS (Wide V band)



*Smoothed,
4x4 Binned*



470 AU (30")

- Seen only in roll self-subtractions
 - Faintest disk yet seen
- $V = 24 \text{ mag / arcsec}^2$

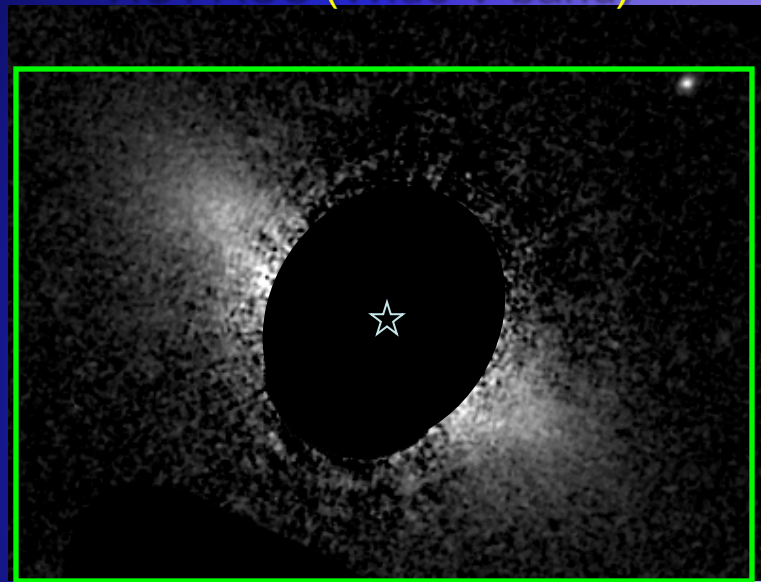
Krist et al. in prep
Sagan Summer School
2014

HD 10647 (HR 506, ϵ^1 Eri)

$F9V$, 17 pc, 0.3-7 Gyr, $L_d/L_* = 3 \times 10^{-4}$

Has R-V planet: $a = 2$ AU, $M \sin i = 0.91 M_{\text{Jup}}$

HST ACS (Wide V band)

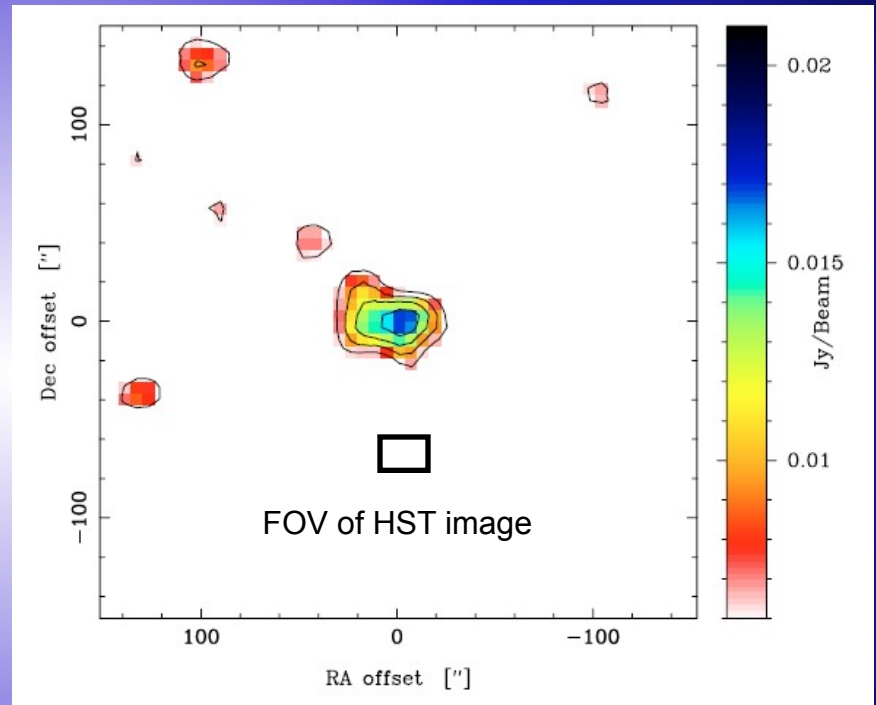


350 AU (20")

*Inclined ring, $r = 80-120$ AU
Slight asymmetry*

Stapelfeldt et al. (in prep)

APEX/LABOCA 870 micron

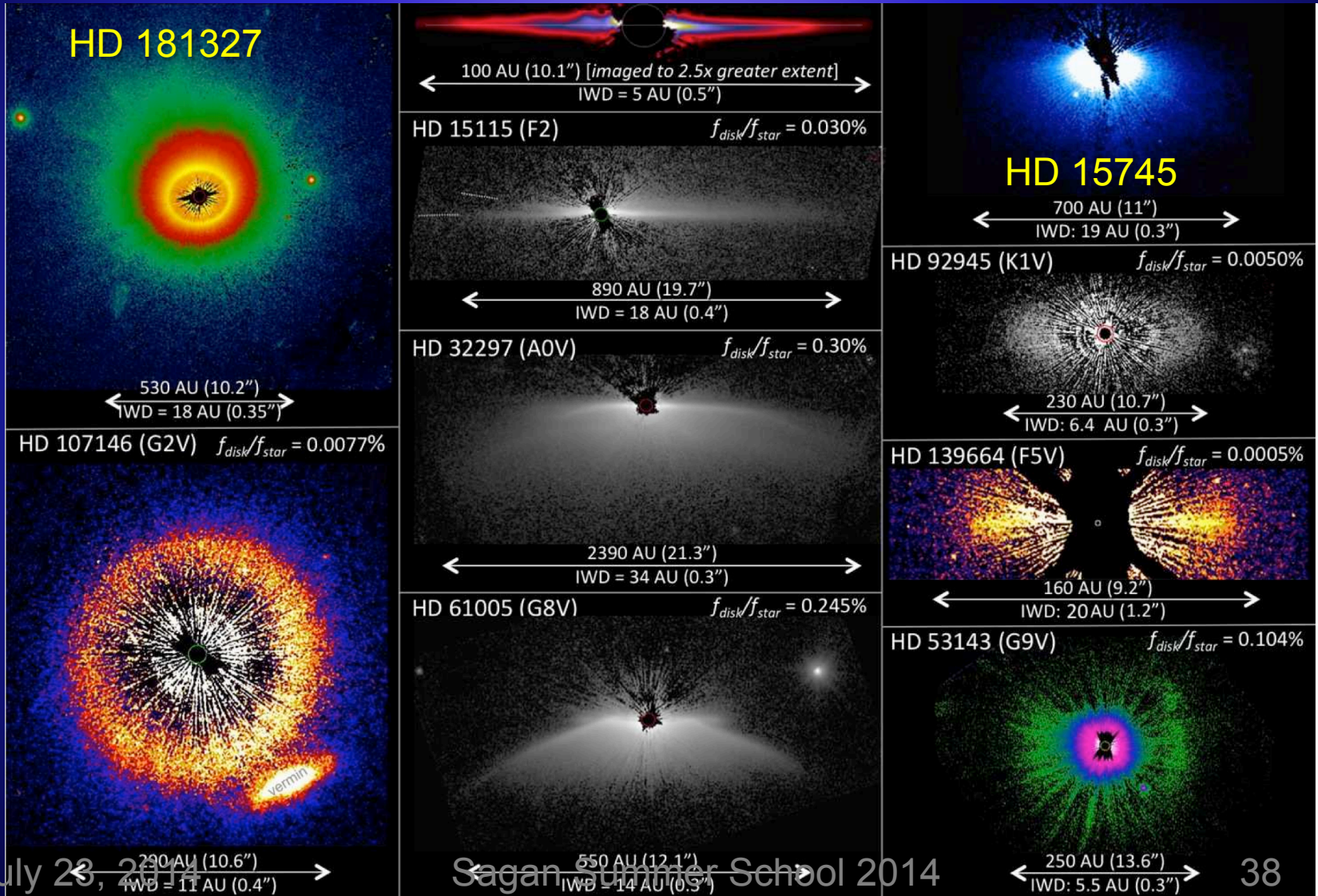


*Gaussian source
HWHM = 275 AU
Liseau et al. 2008*

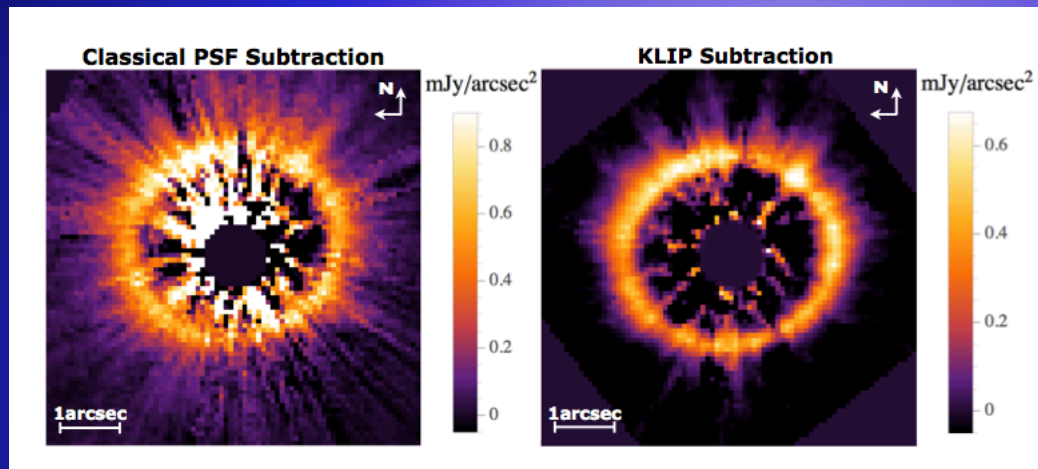
*Cold material extending to 2x radius of
scattered light & 70 μm emission !*

STIS Revisits Known Debris Disks

(Schneider et al 2014)



New Processing of Archival HST Debris Disk Images



HD 181327

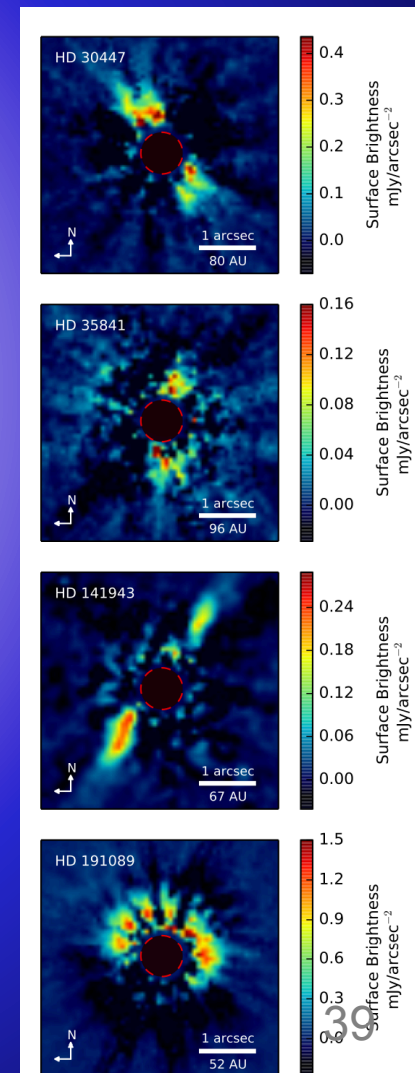
Soummer et al. 2014

See poster

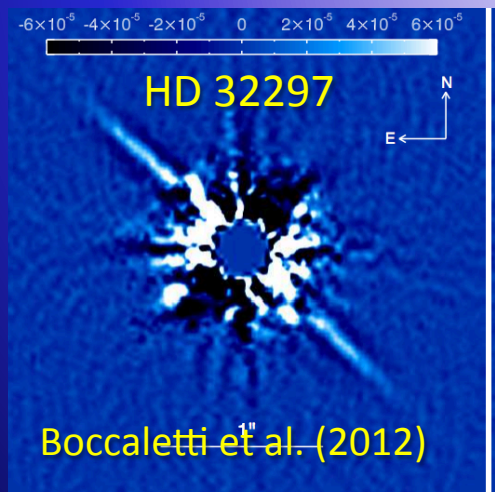
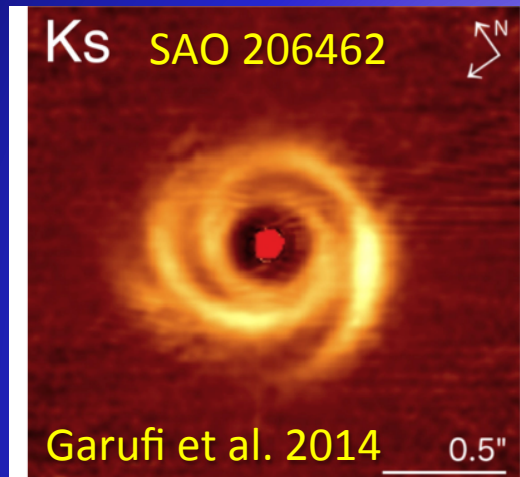
Big improvements in NICMOS
scattered light imagery

July 23, 2014

Sagan Summer School 2014



Ground-based Polarimetric Differential Imaging



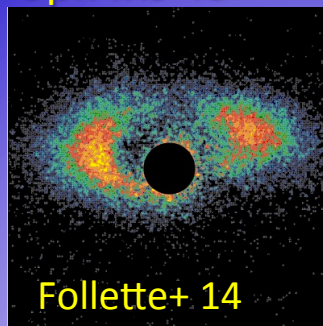
- Uses polarization of scattered light to enable roll self-subtraction
- One flavor of “DI”
- VLT-NACO and Subaru/HICIAO are major players
- Most results are from Herbig AeBe stars and T Tauri stars
- Some edge-on debris disks detected
- Great resolution, but better for sharp features due to AO halo

SAO 206462 is not unique

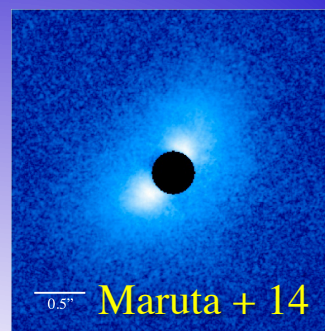
AB Aur



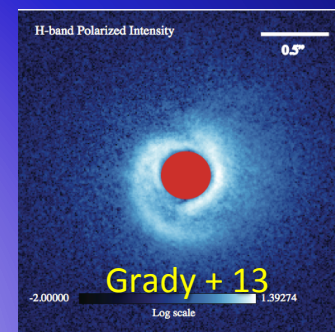
Oph IRS 48



HD 34282



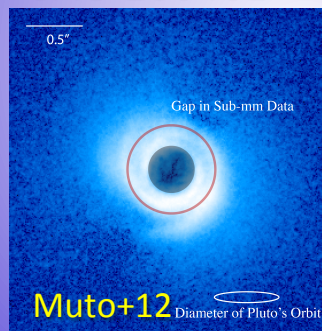
MWC 758



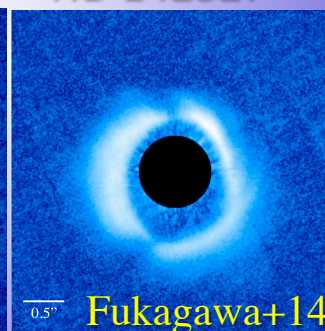
HD 169142



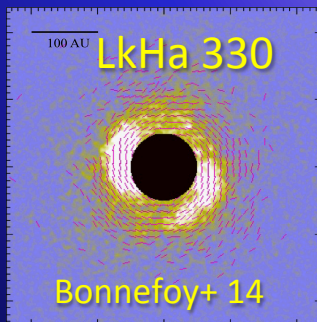
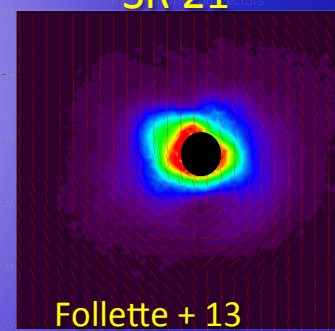
SAO 206462



HD 142527



SR 21



Slide from Carol Grady:
SEEDS/HICIAO results

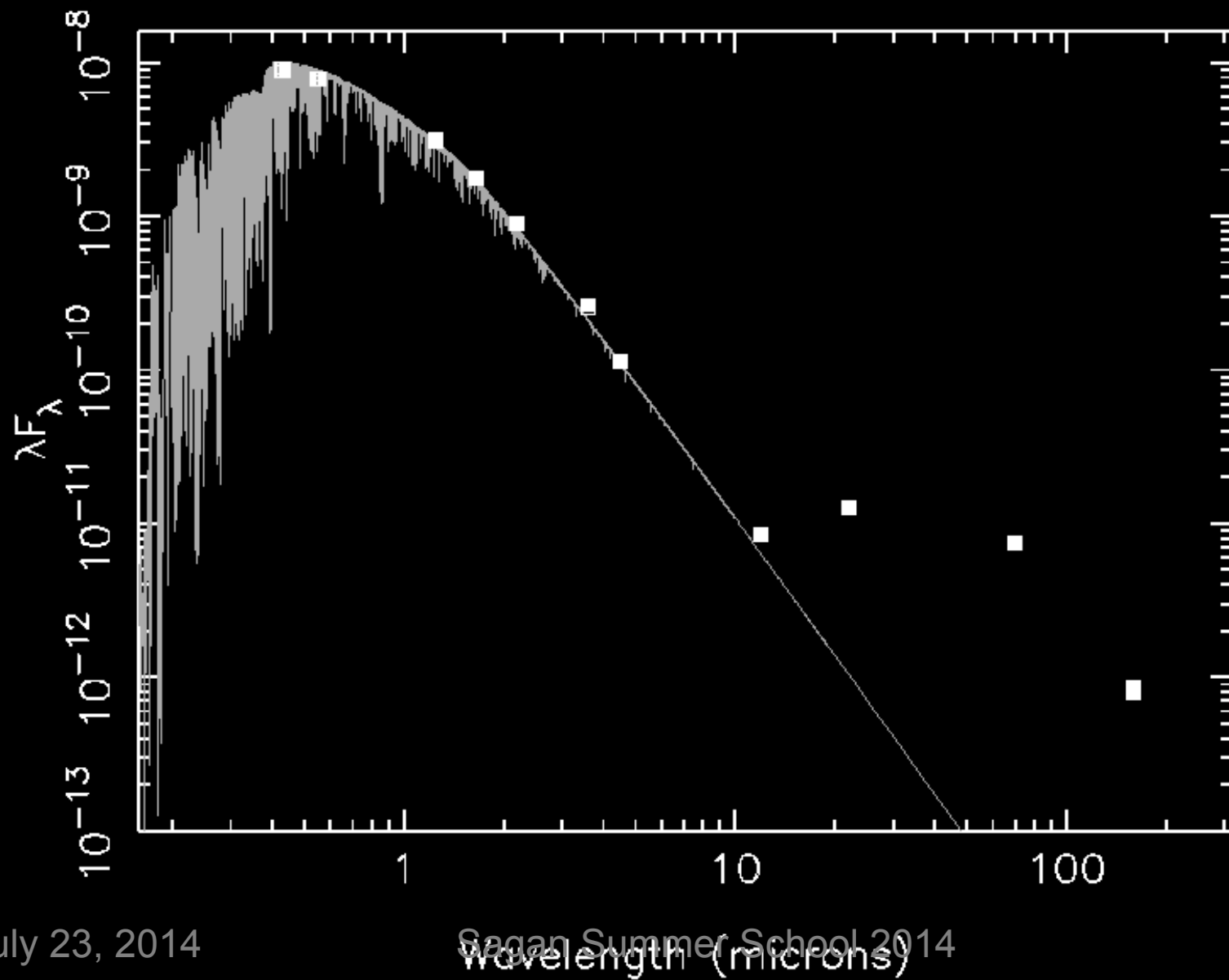
Case Study: WISE/HST Disks

Cross-correlation of WISE 22 μm W1-W4
excess sources with Hipparcos stars

$L_d/L_* > 10^{-4}$, < 120 pc distance, robust warm
WISE, cold Herschel/IRAS excess

Total of 13 stars observed with HST to detect
scattered light from debris disks

STIS coronagraph, 2 rolls each; clear filter
(optical light), 0.05 arcsec pixels



Host Characteristics

G, F, and B stars

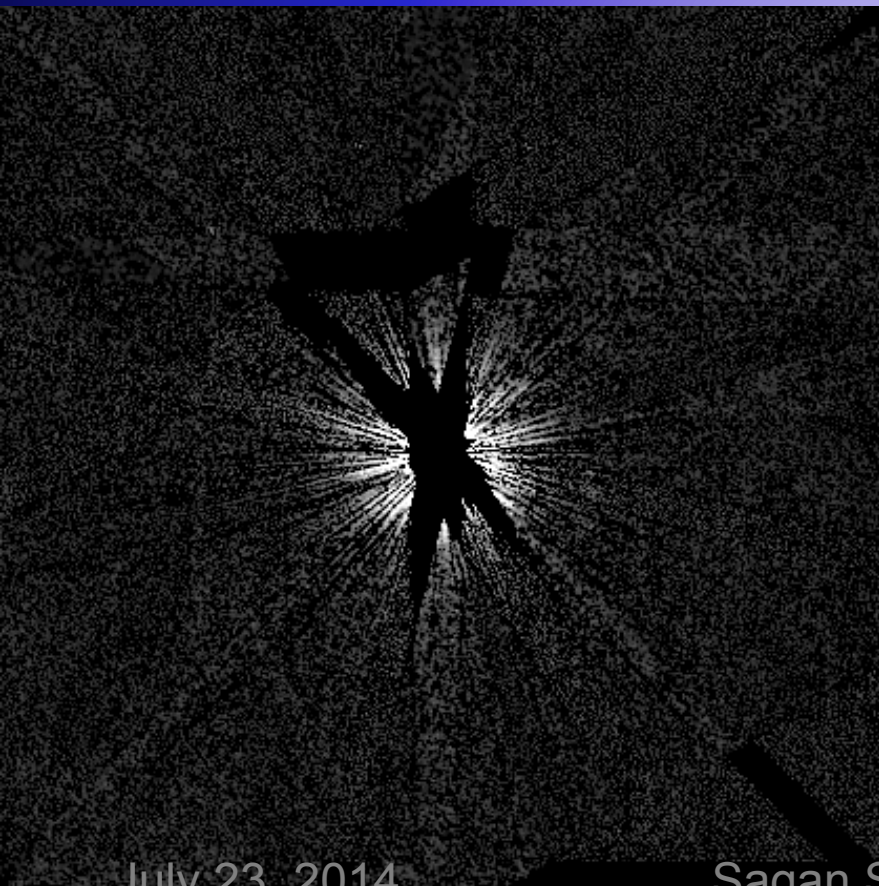
50 -110 pc

Four stars kinematically related to young associations, one unrelated

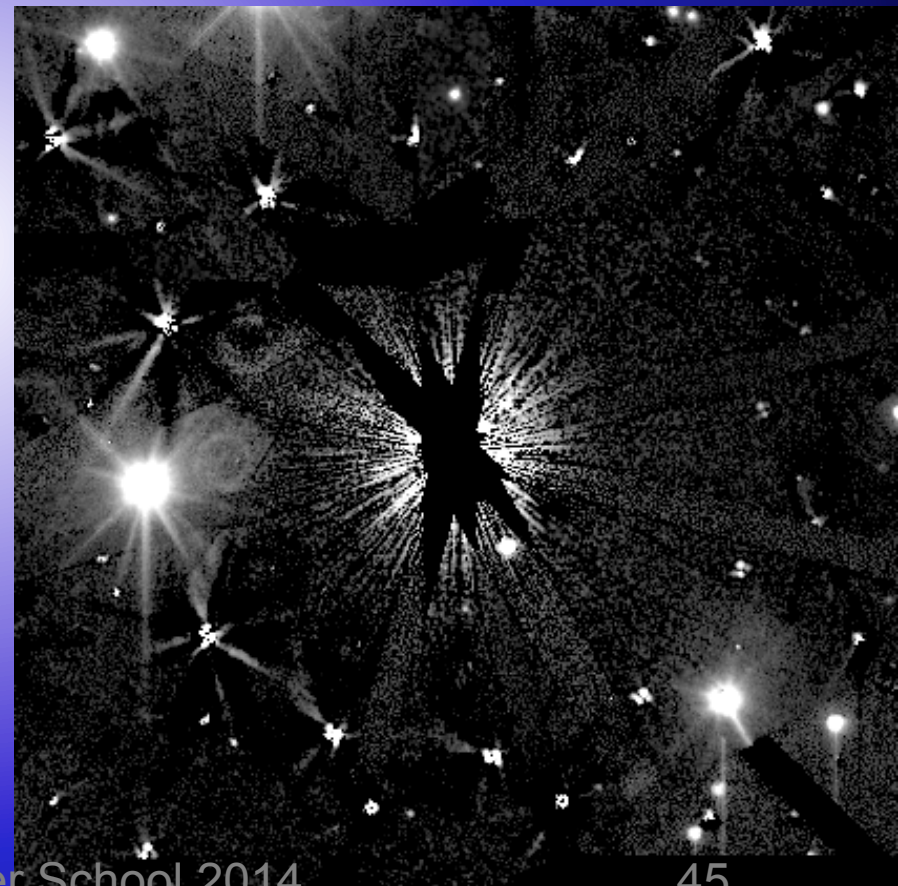
X-ray sources, known young star

STIS/WISE Debris Disk Imagery

Non-detections (6)



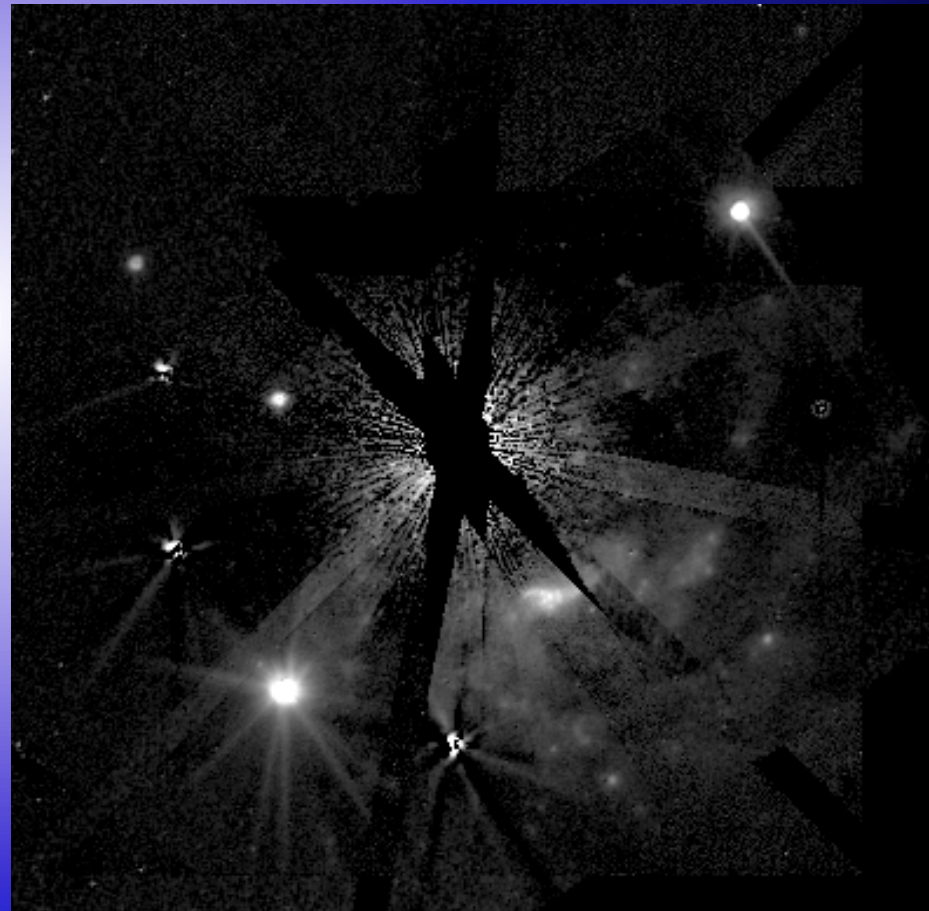
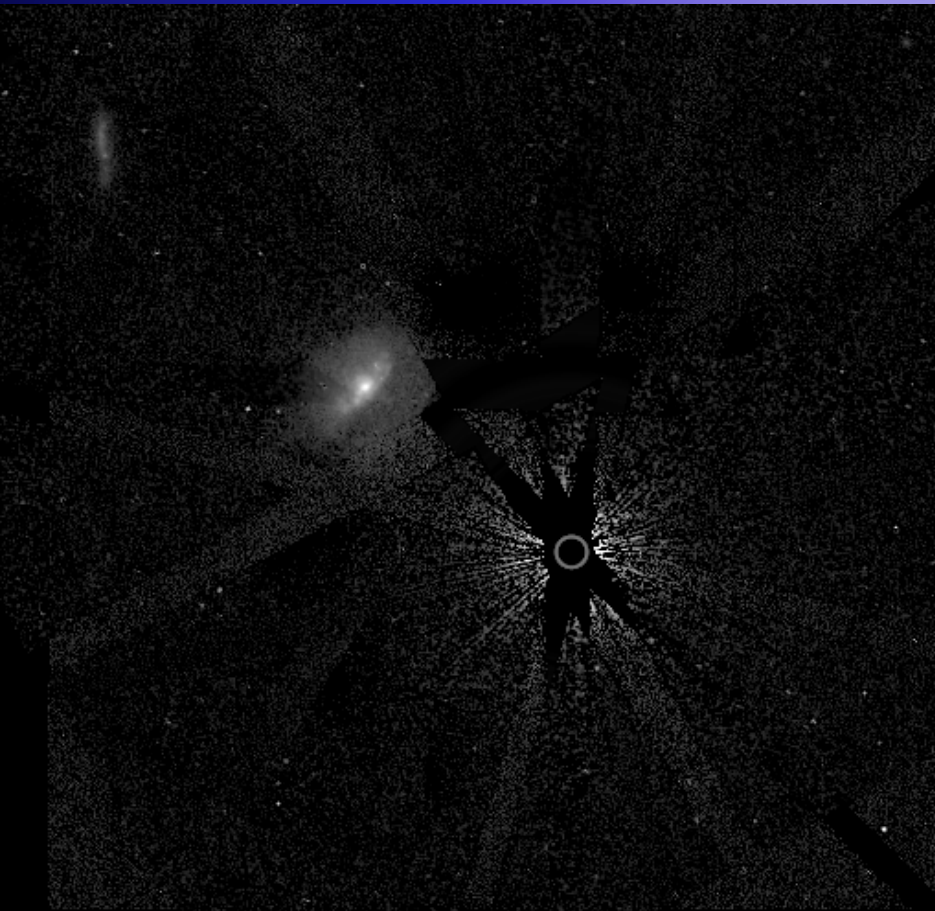
July 23, 2014



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Star/Galaxy Superpositions (2)

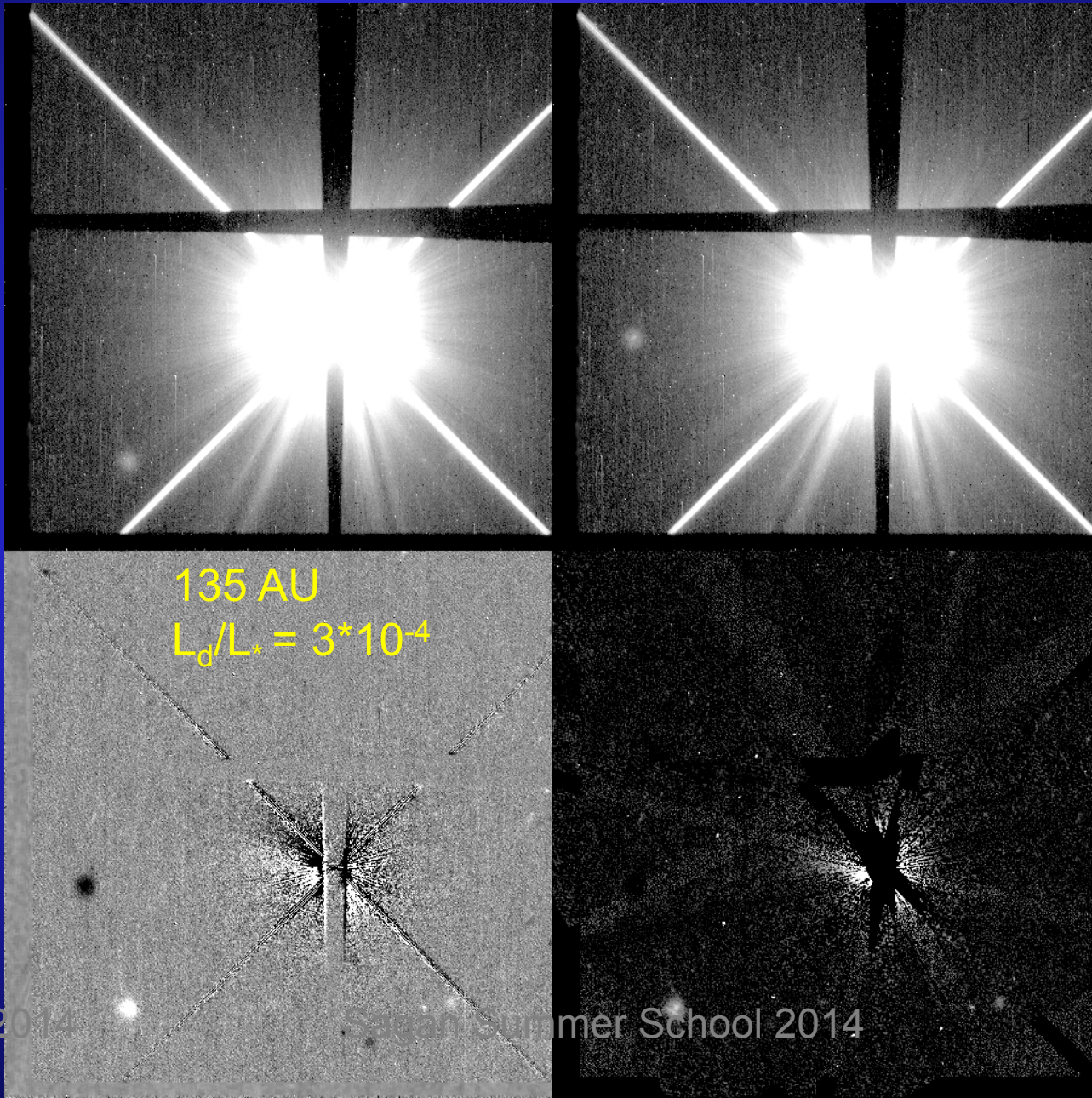


July 23, 2014

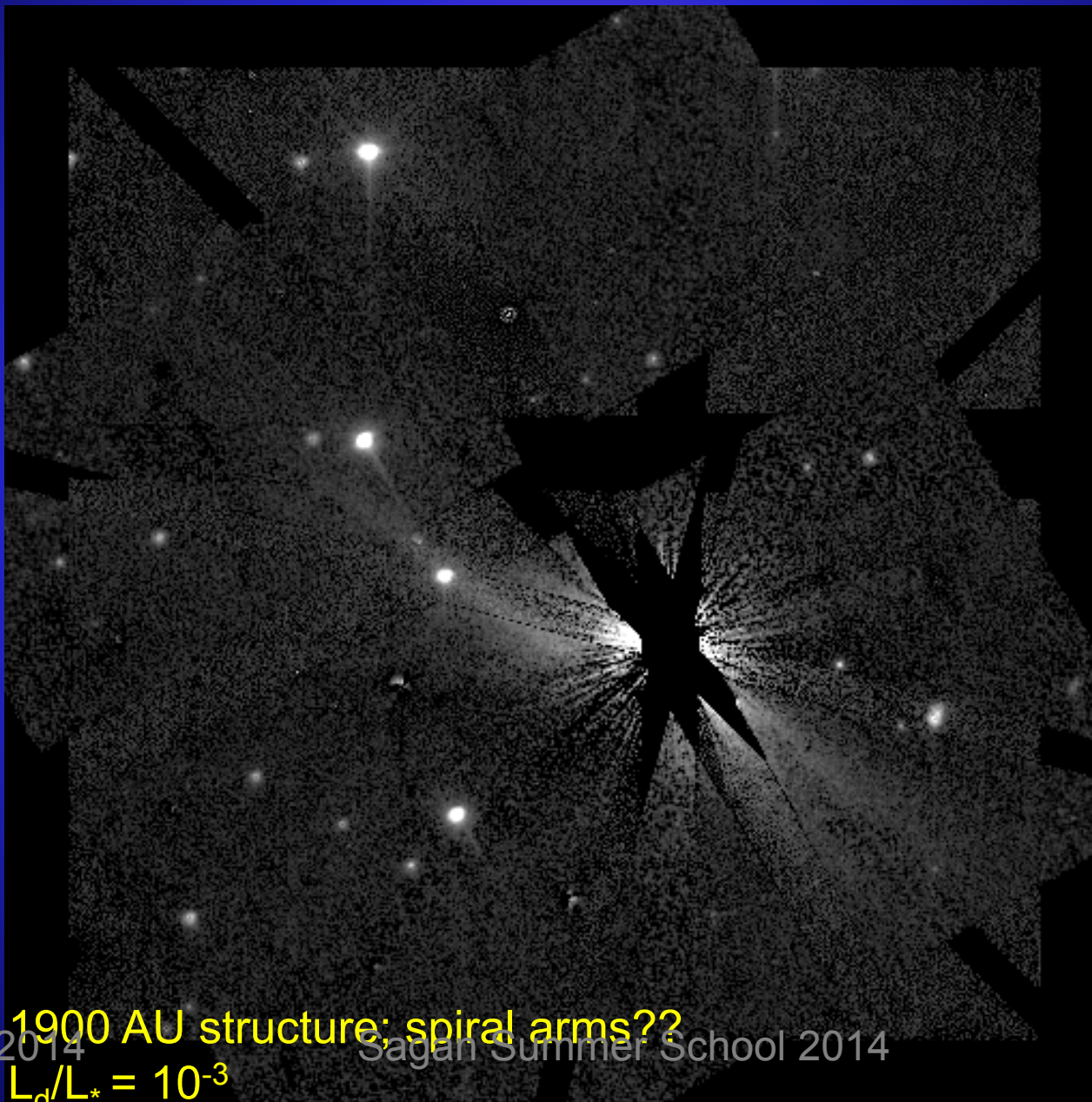
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Marginal Detection



Disk or Nebula?



1900 AU structure; spiral arms??

$$L_d/L_* = 10^{-3}$$

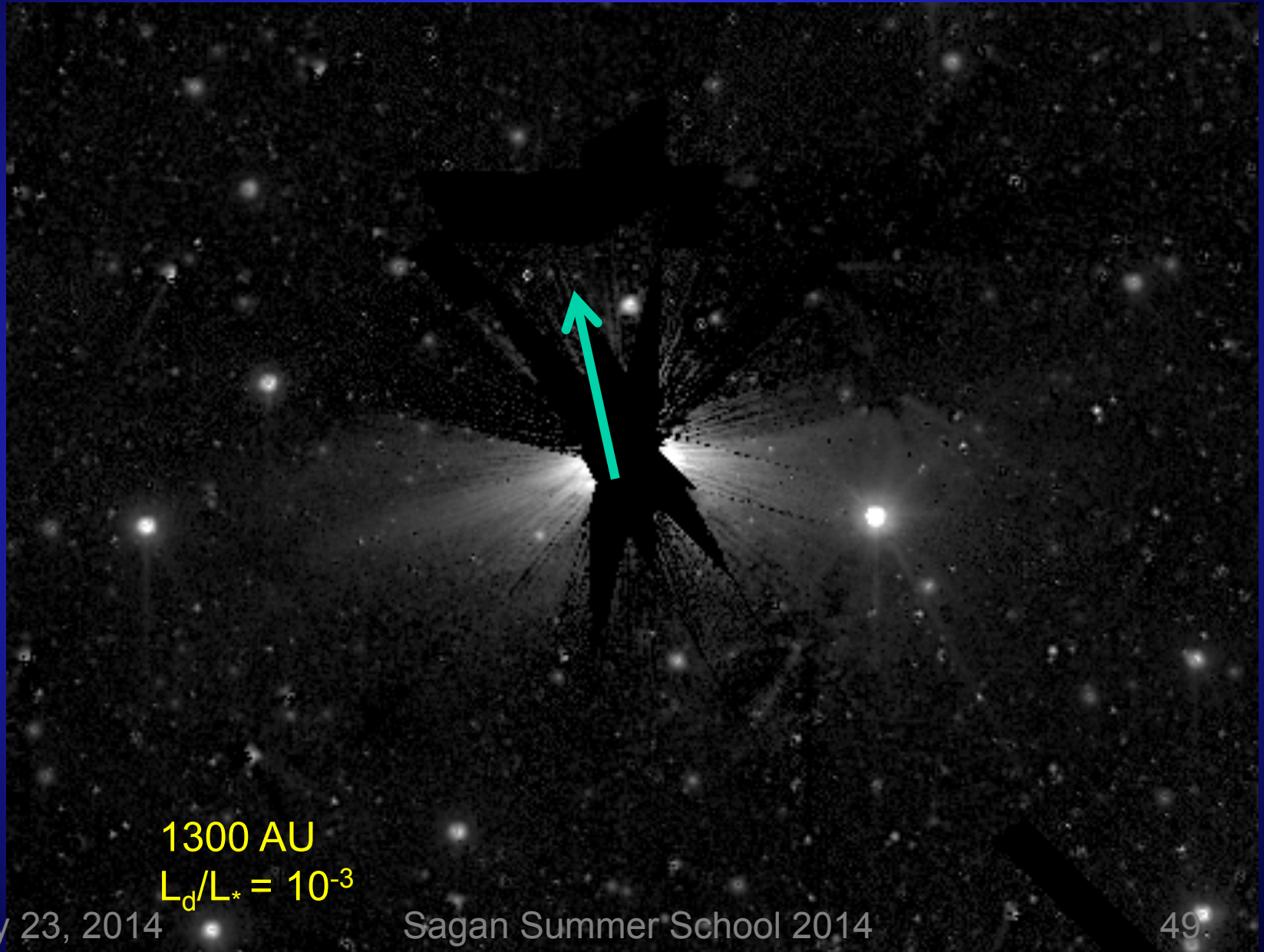
July 23, 2014
Self-

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entatic 48;

how +/-

Disk Distorted by Ram Pressure



1300 AU

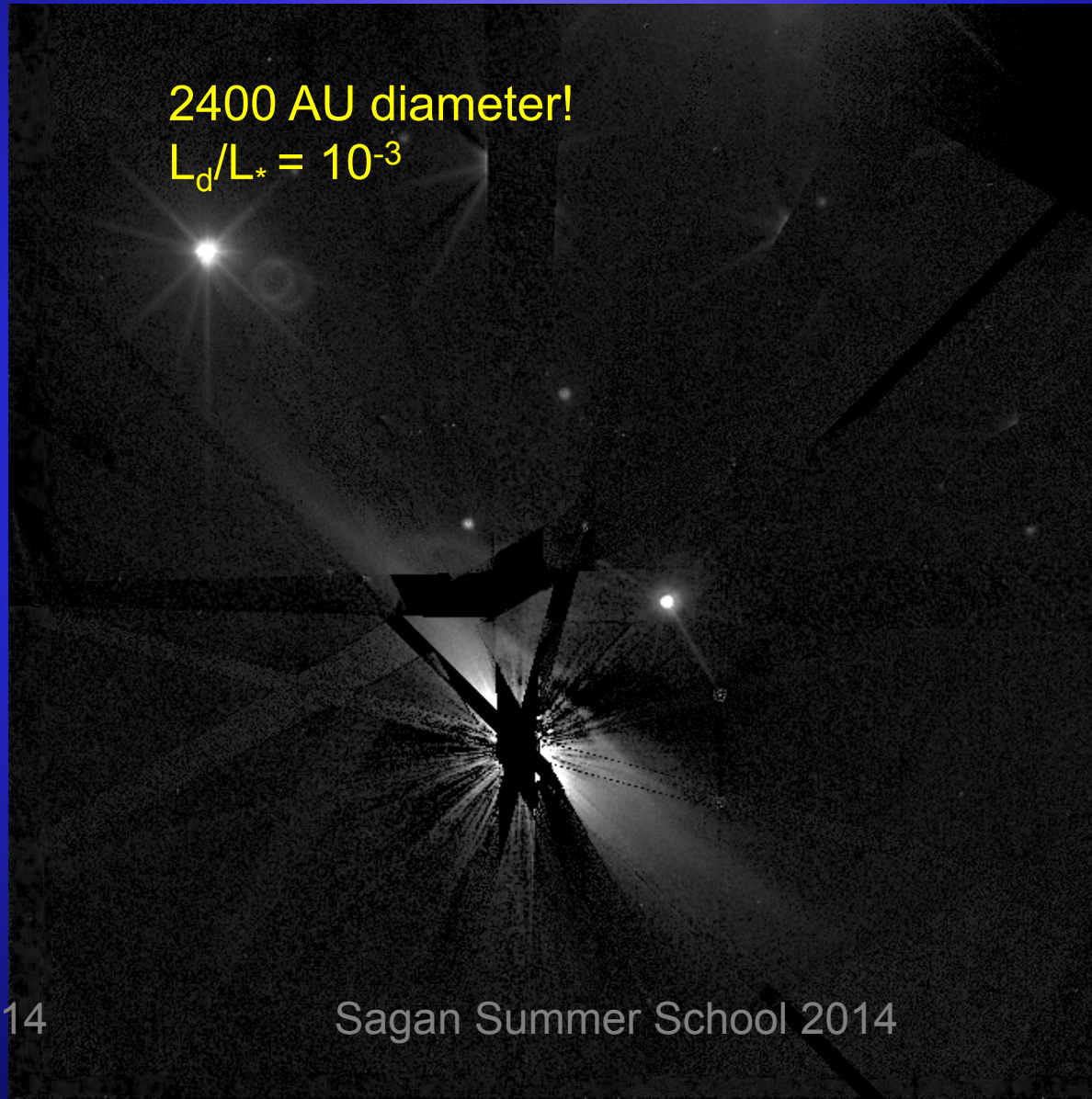
$L_d/L_* = 10^{-3}$

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Big Disk or Nebula?

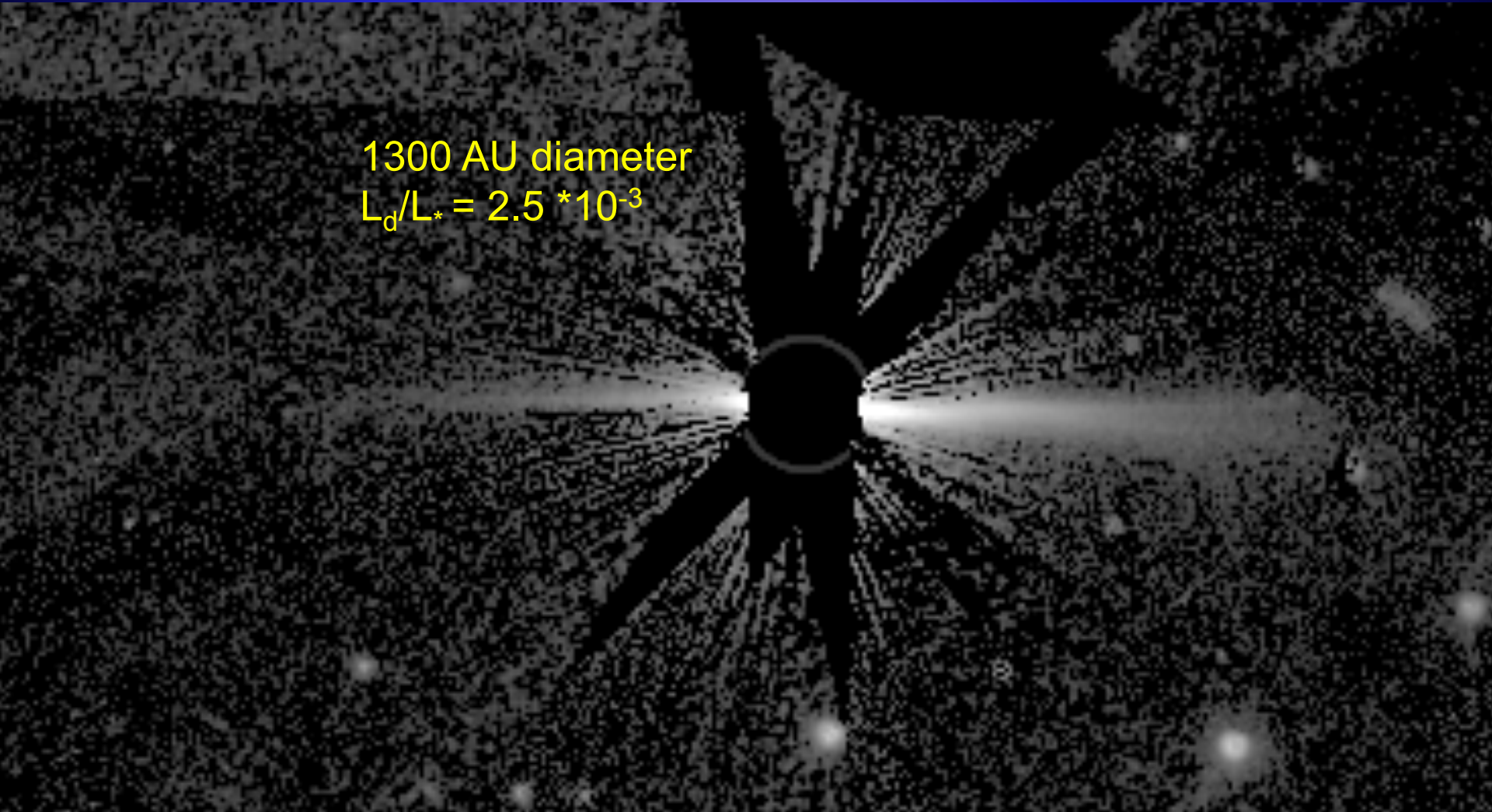


2400 AU diameter!

$$L_d/L_* = 10^{-3}$$

HD15115 Clone

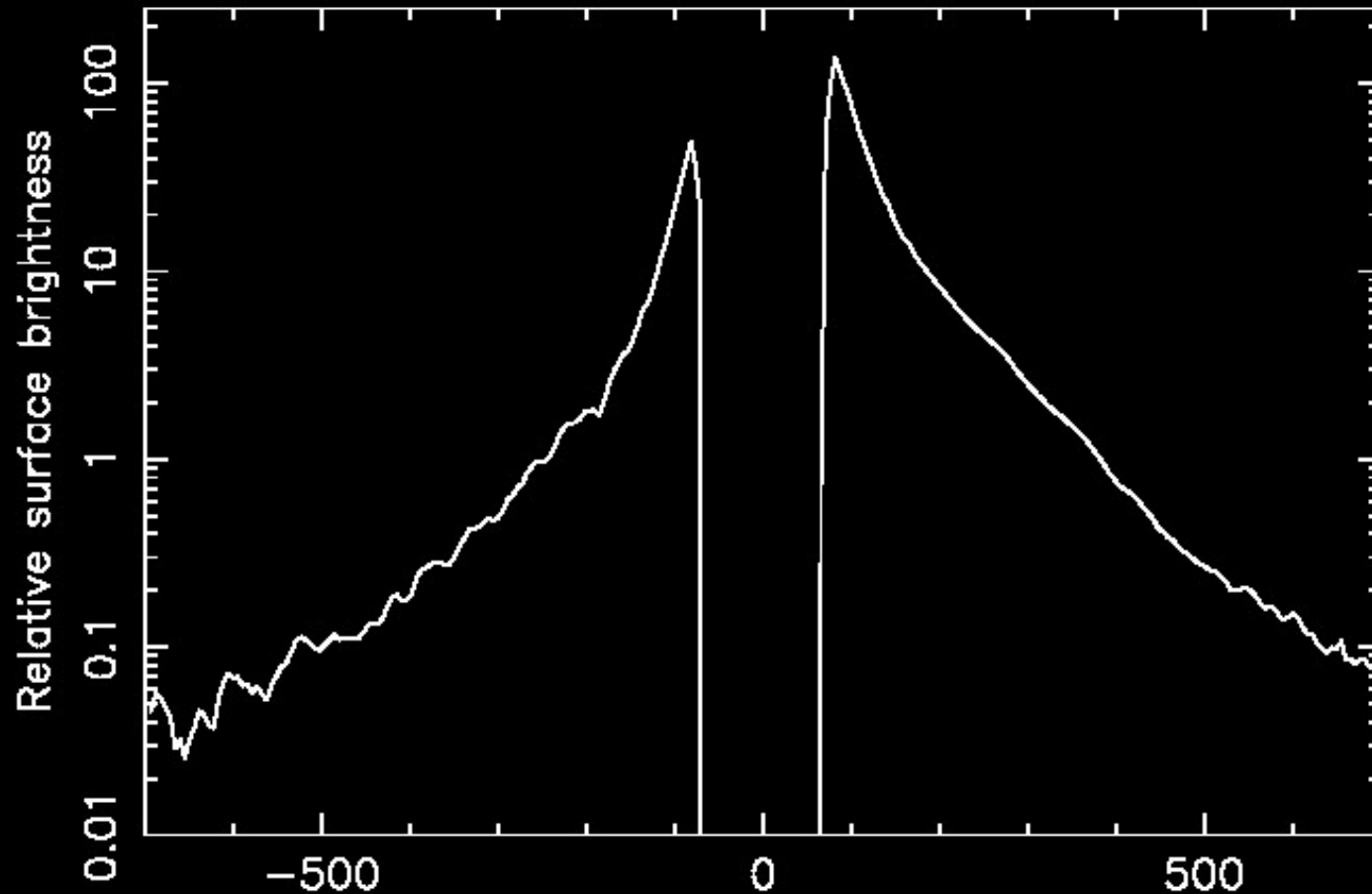
1300 AU diameter
 $L_d/L_* = 2.5 \times 10^{-3}$



Bifurcation and Warp in Disk



Radial Brightness Profile



Thermal IR Imaging of Debris Disks

ALMA continuum imaging

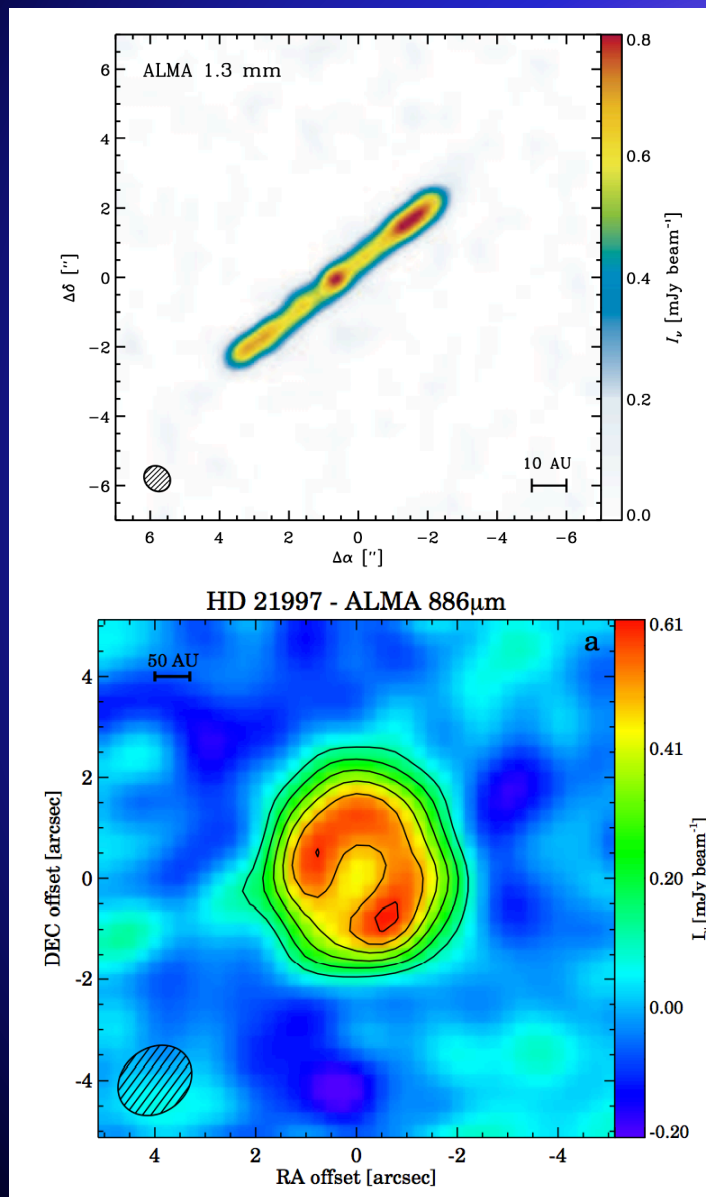
AU Mic
MacGregor et al. (2014)

Numerous targets should be accessible for mapping at subarcsec resolution

HD 21997
Moór et al. (2014)

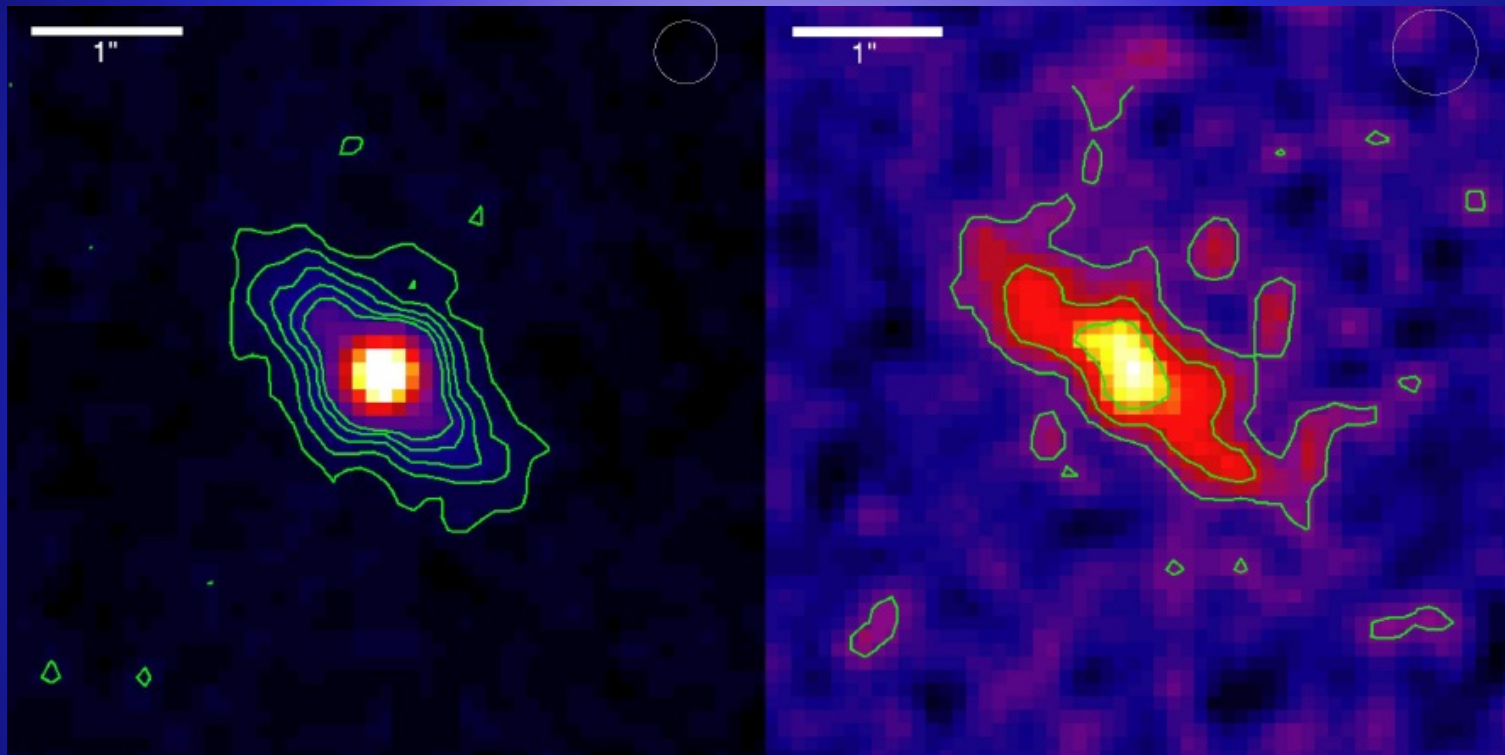
Few debris disk systems are bright enough for mapping at 0.1'' resolution
(small F_{ν} , large sizes)

See P42, 48



Groundbased Thermal IR I. HD 32297

Moerchen et al. 2007.



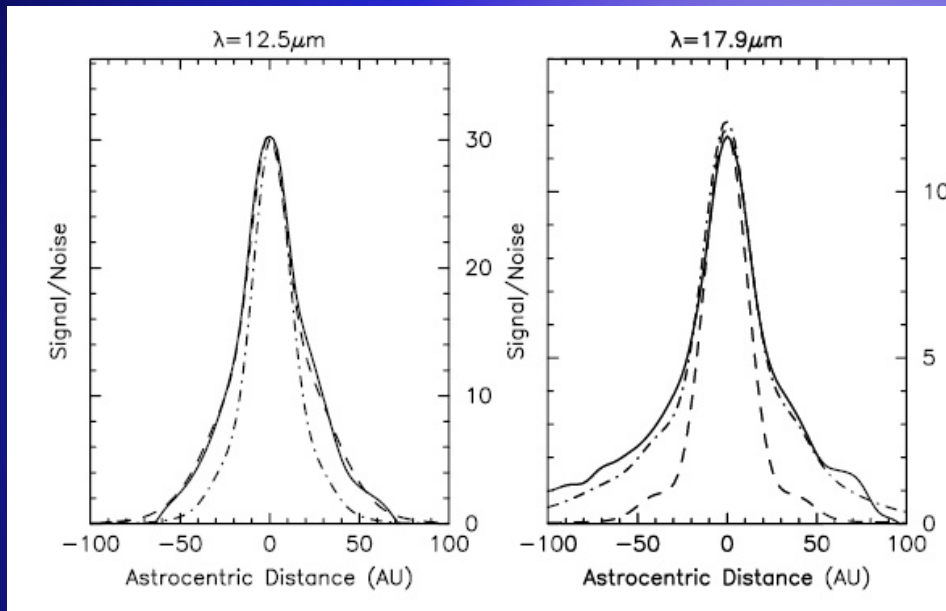
12 μm

18 μm

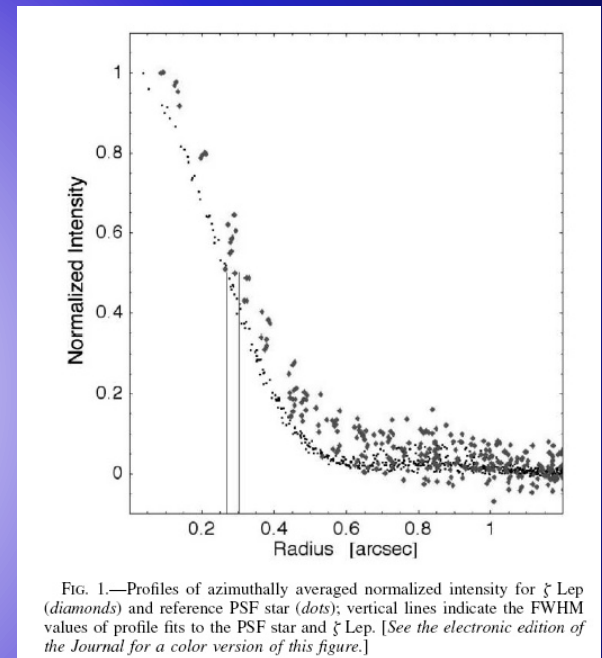
See also Fitzgerald et al. 2007

Groundbased Thermal Infrared II.

Profile Fitting

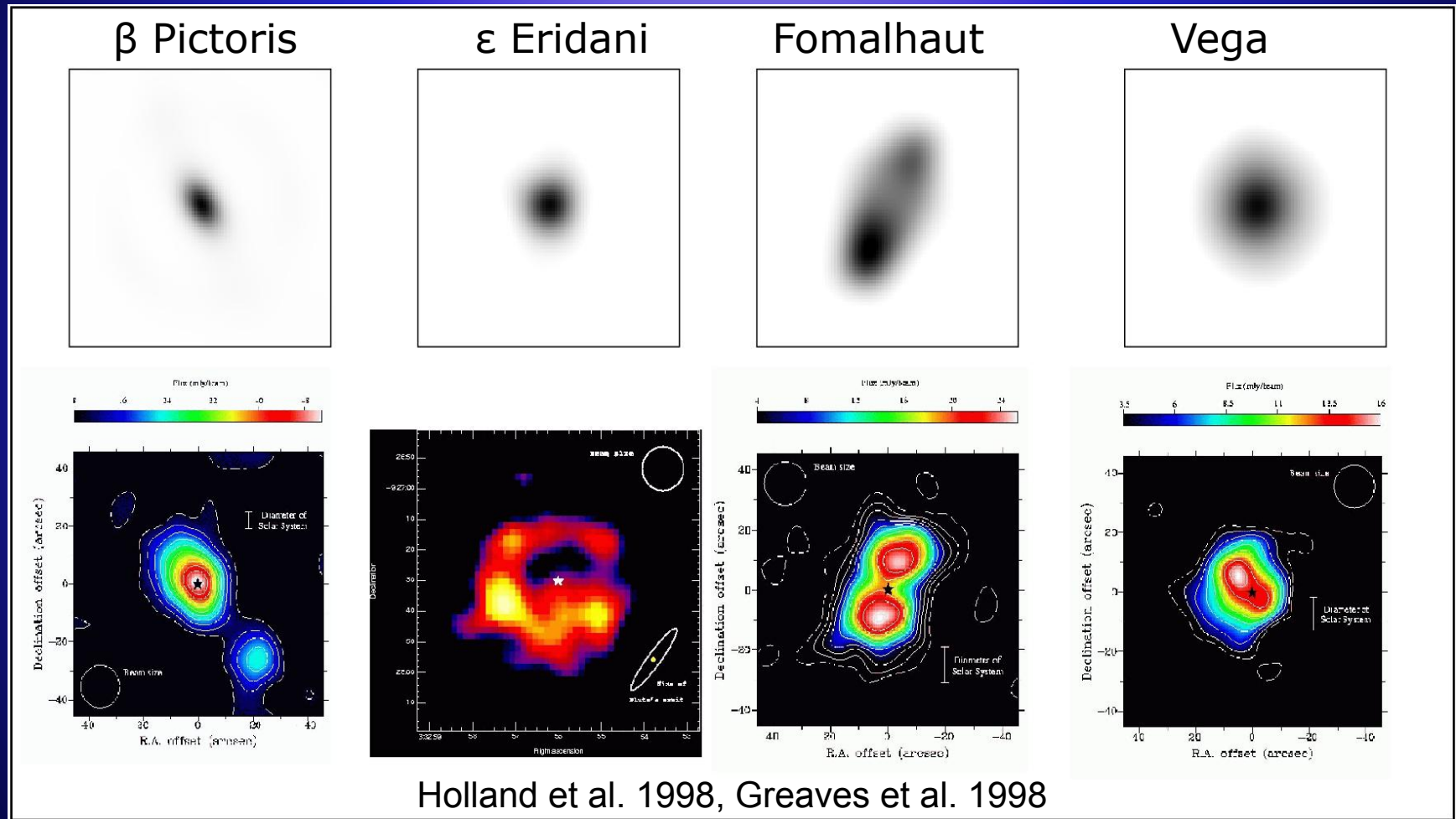


49 Ceti
Wahhaj et al. 2007



Zeta Lep
Moerchen et al. 2007

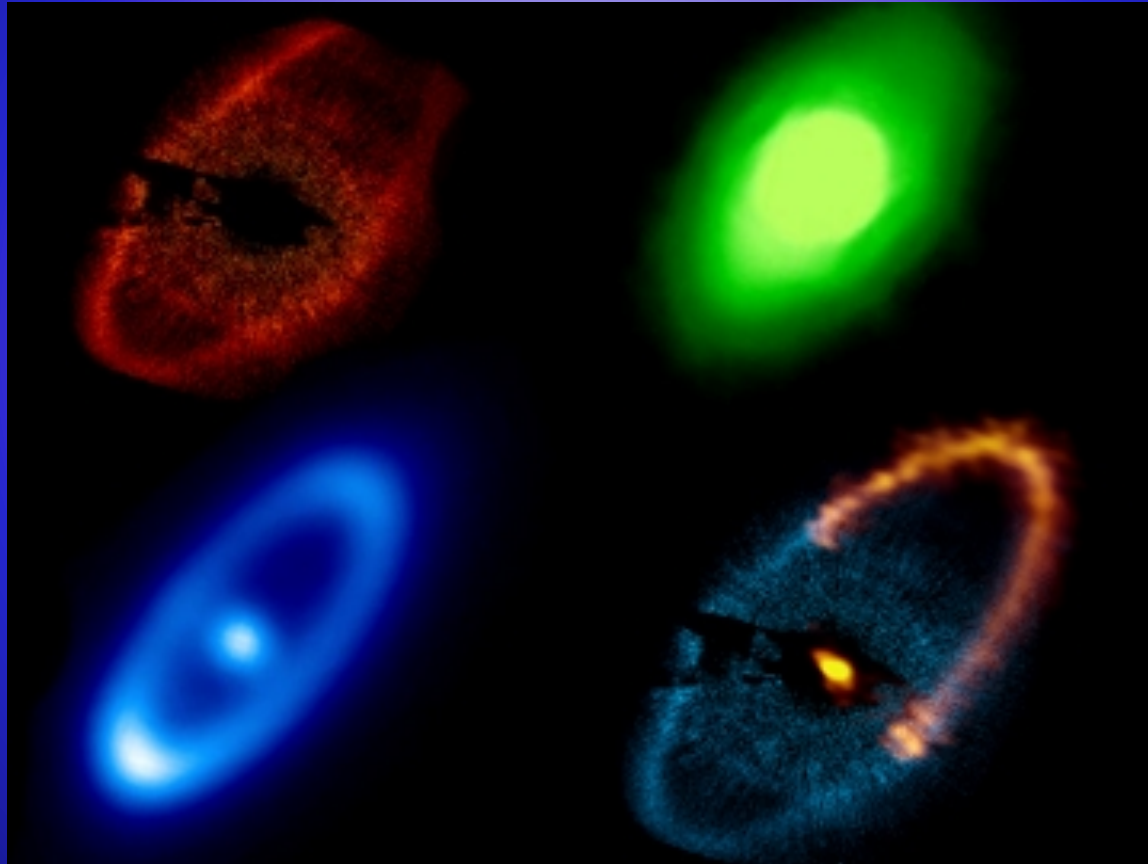
The Fabulous Four Debris Disks: Spitzer/MIPS 70 μm vs. JCMT 850 μm



Fomalhaut Eccentric Ring: Far-IR and submm

HST
Kalas
2005

Herschel
70 μm
Acke 2012

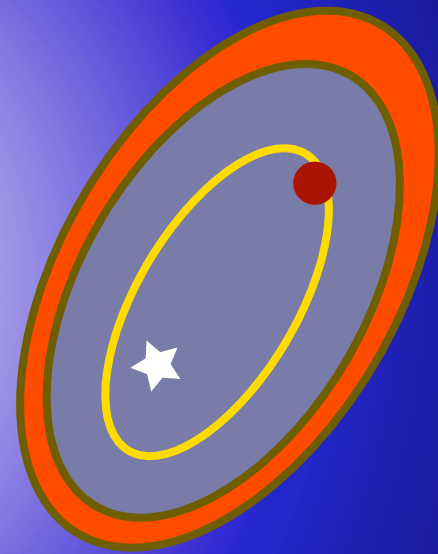


Spitzer
24 μm
2004

ALMA
870 μm
Boley
2012

Eccentric ring model (Wyatt et al. 1999)

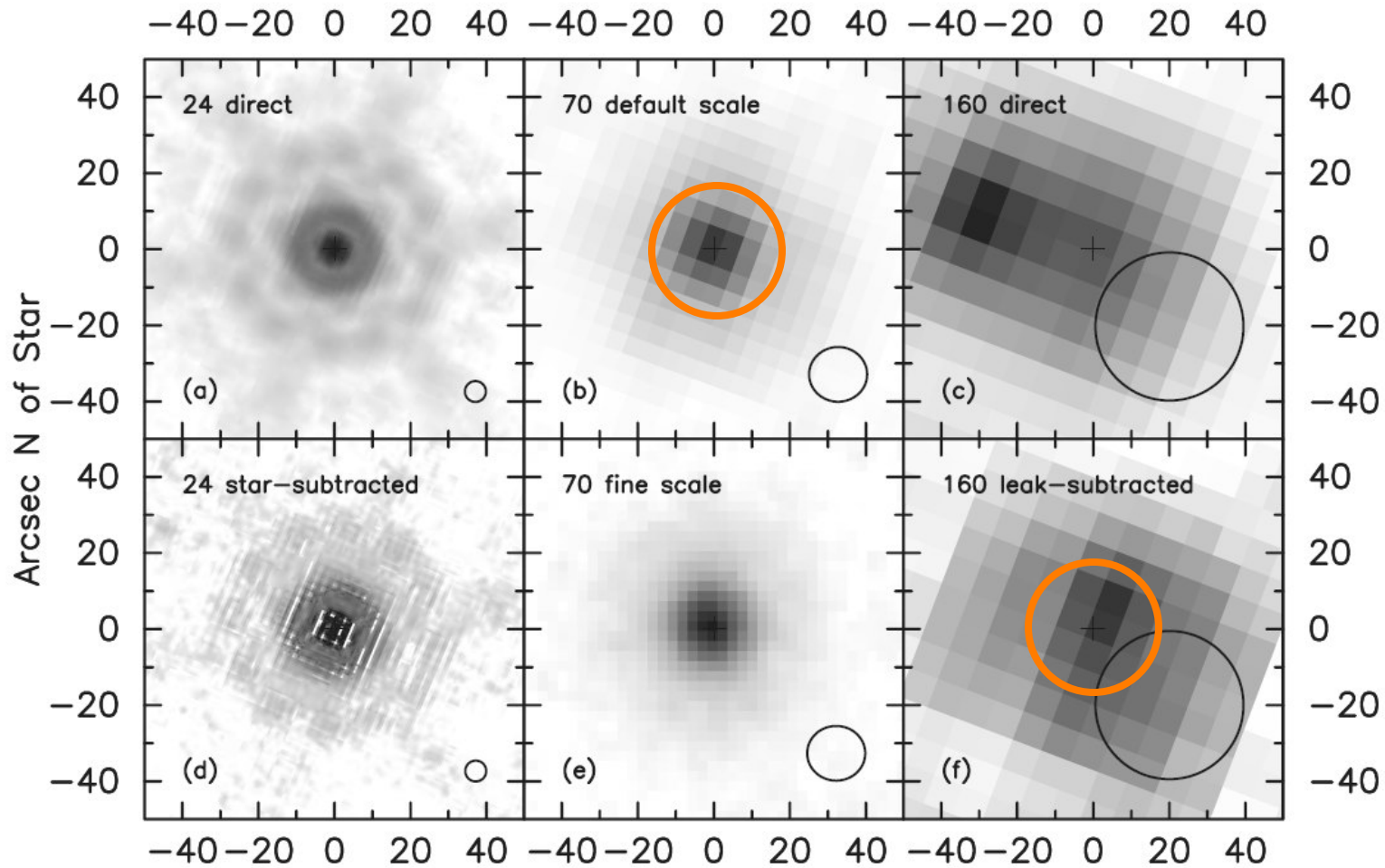
- Outer ring is perturbed by eccentric interior planet
- Produces brightness asymmetry in thermal emission from the Fomalhaut disk
- Models predict mass of perturber:
 - 0.06 to 0.3 M_J , if located at ring inner edge (Quillen 2006)
 - Higher planet mass required if it is located well inside ring



ϵ Eridani Spitzer/MIPS

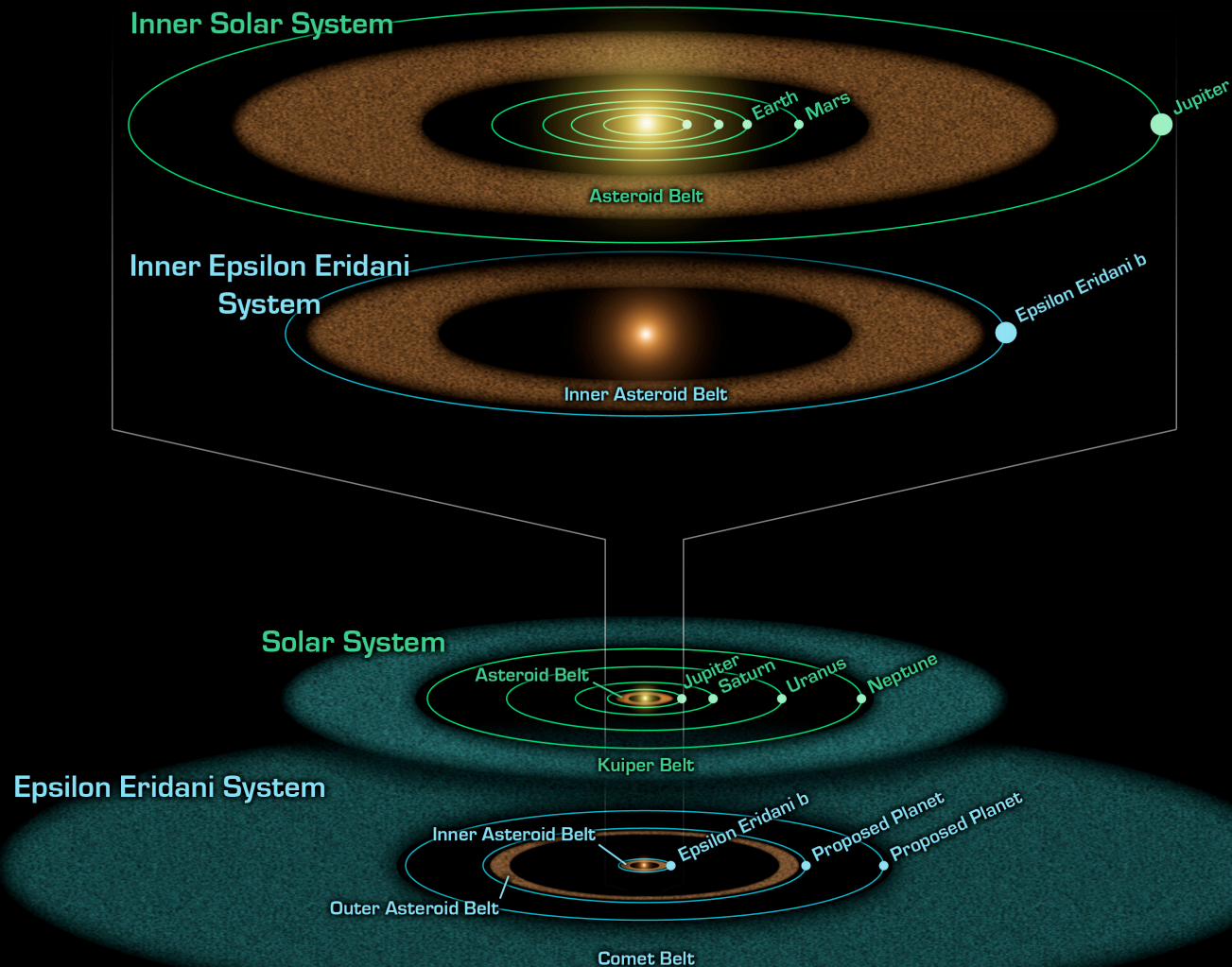
Backman et al. 2009, arXiv/0810.4564

Submm ring size



Arcsec W of Star Black circles indicate MIPS beam size

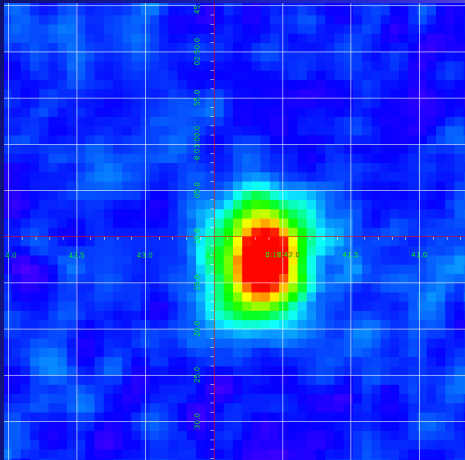
ϵ Eridani vs. our solar system



Newly resolved debris disks

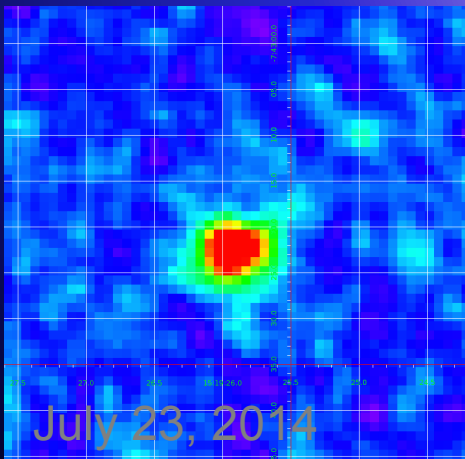
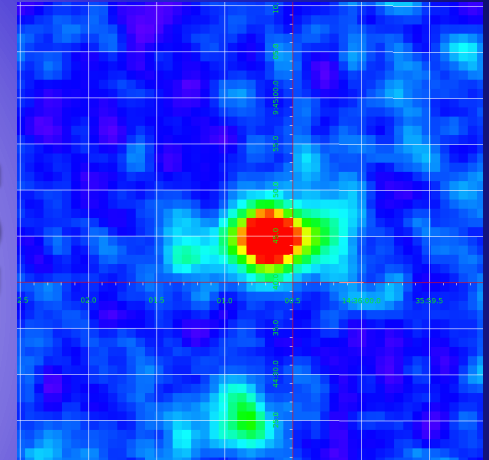
Bryden
et al.

Four stars with Spitzer-detected IR excess,
the Herschel images provide good constraints on
the location of the emitting dust.



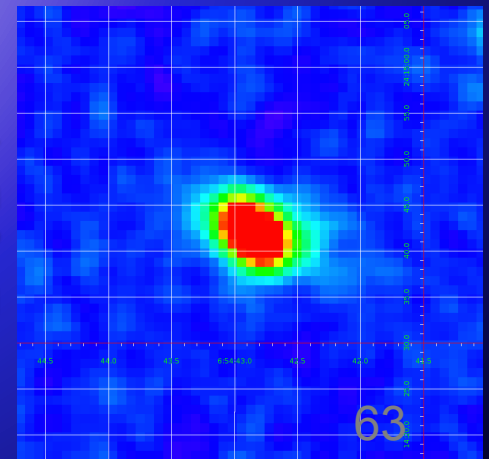
HD 1461
100um
(FWHM $\sim 6''$)
disk radius $\sim 4''$
= 100 AU

HD 128311
70um
(FWHM $\sim 4''$)
 ~ 50 AU



GJ 581
70um
 ~ 10 's of AU
(larger at 160um)

HD 50554
70um
disk radius $\sim 4''$
= 120 AU



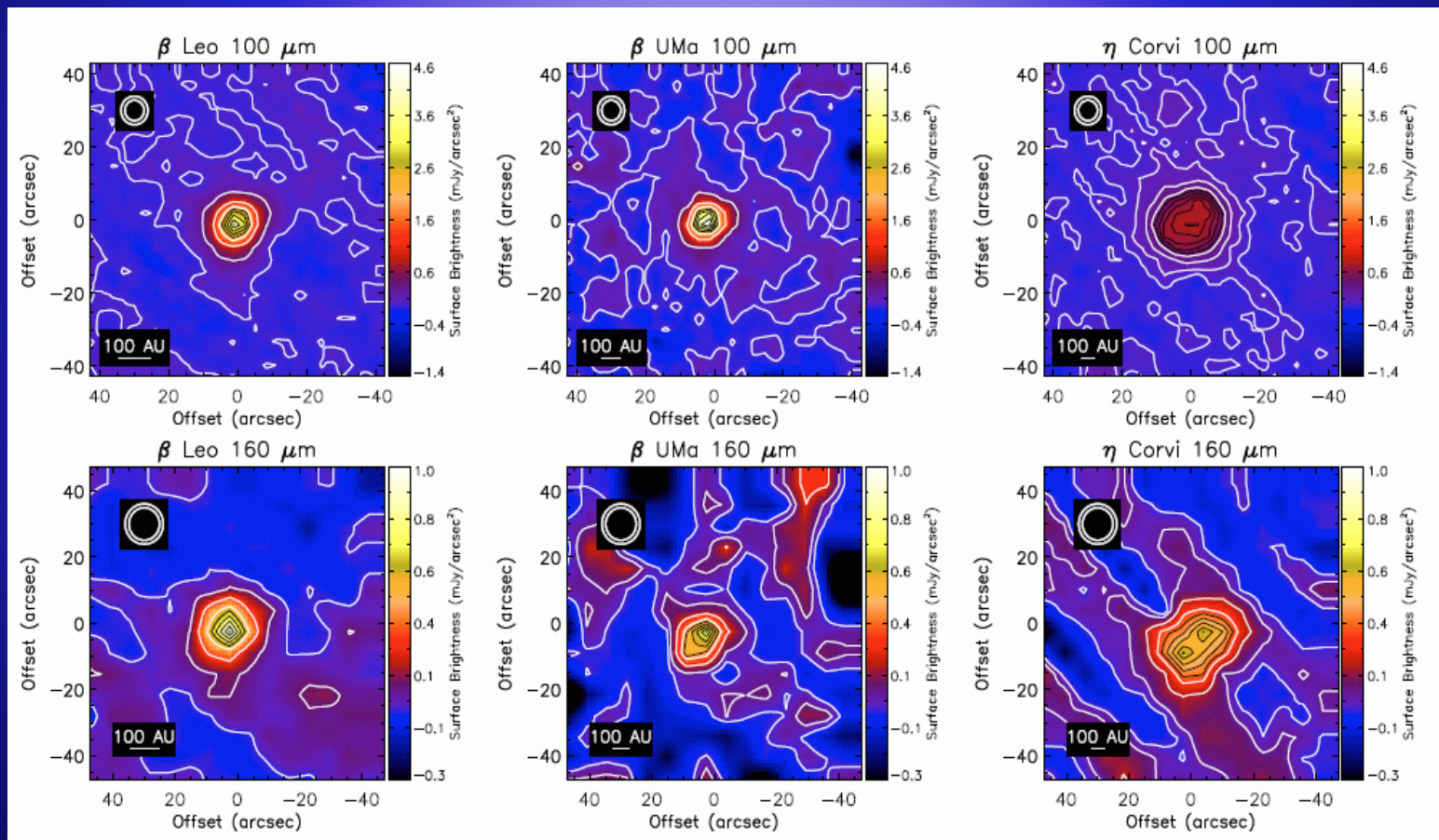
Two new resolved disks, structure in a third

(Matthews et al. 2010)

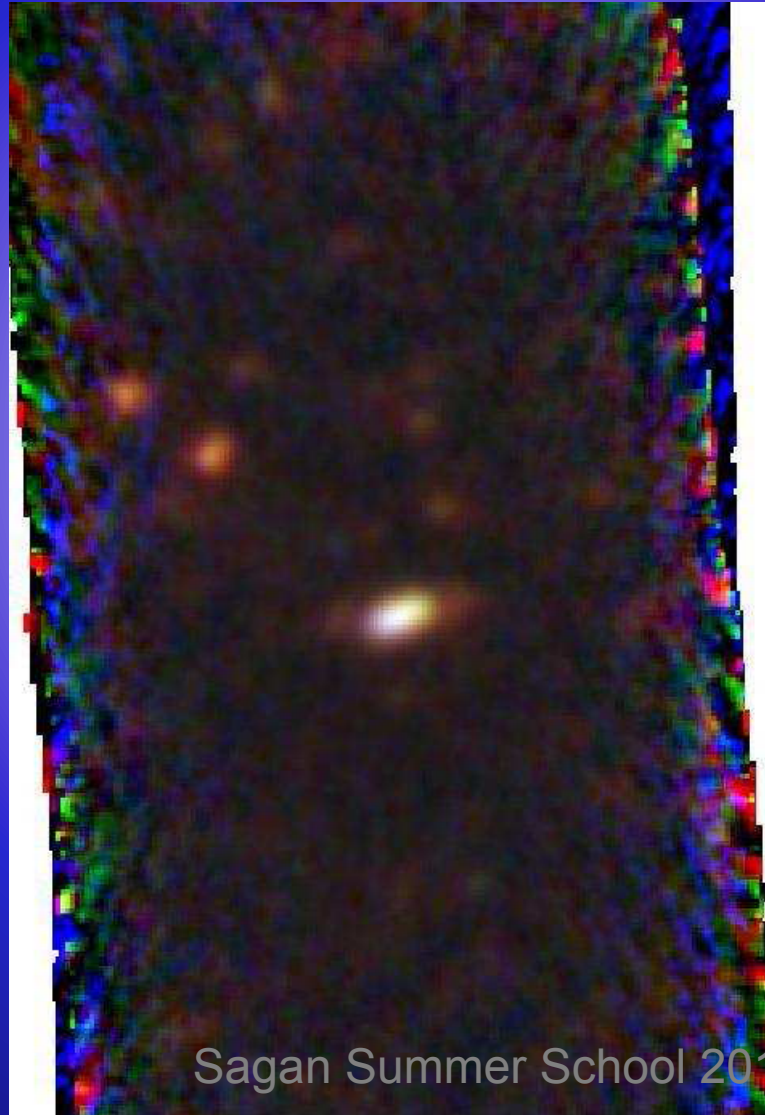
R= 40 AU

R= 45 AU

R= 145 AU



Herschel/PACS image of HIP 32480



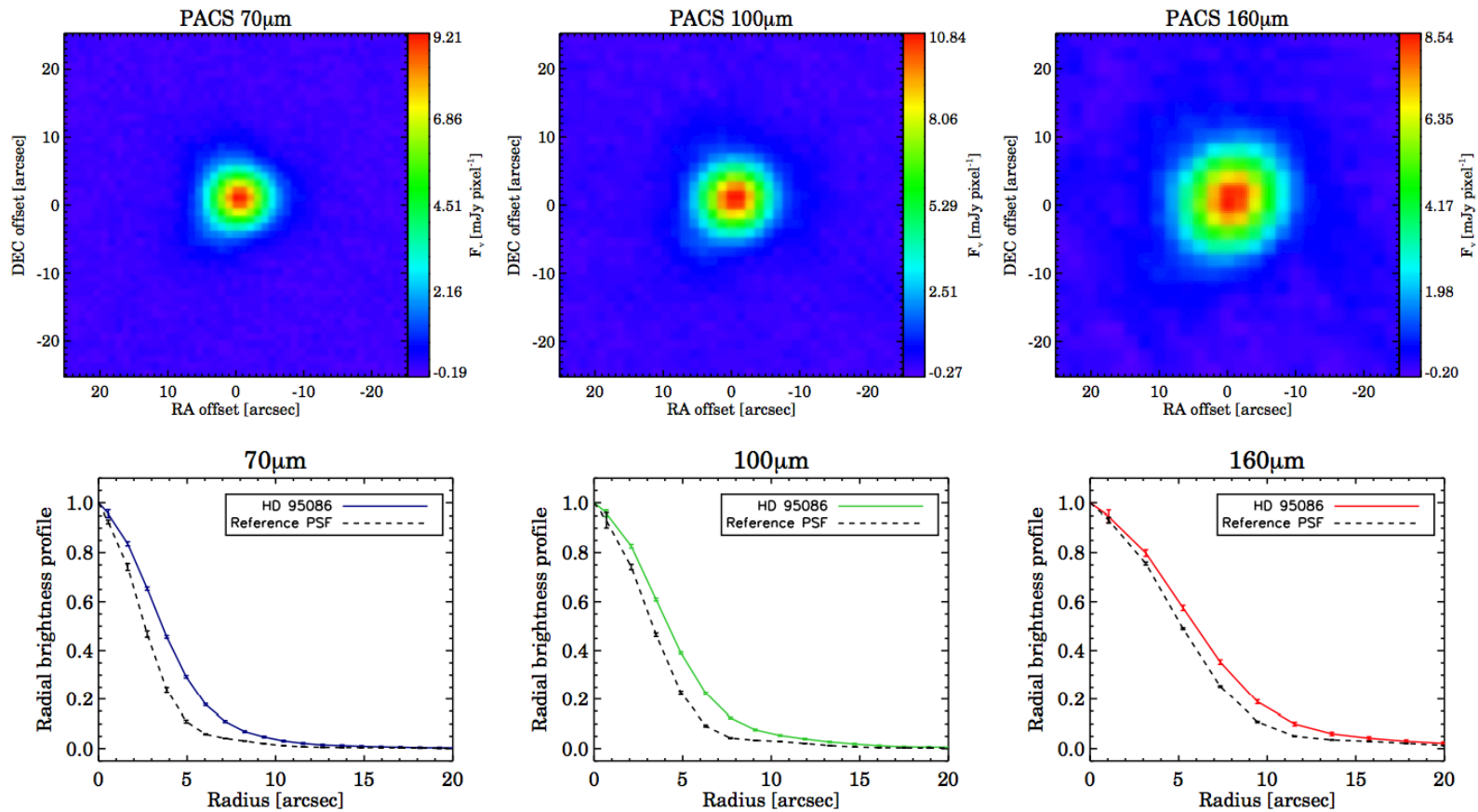
Disk radius of
8 arcsec (150 AU)

Central 100 AU
largely cleared



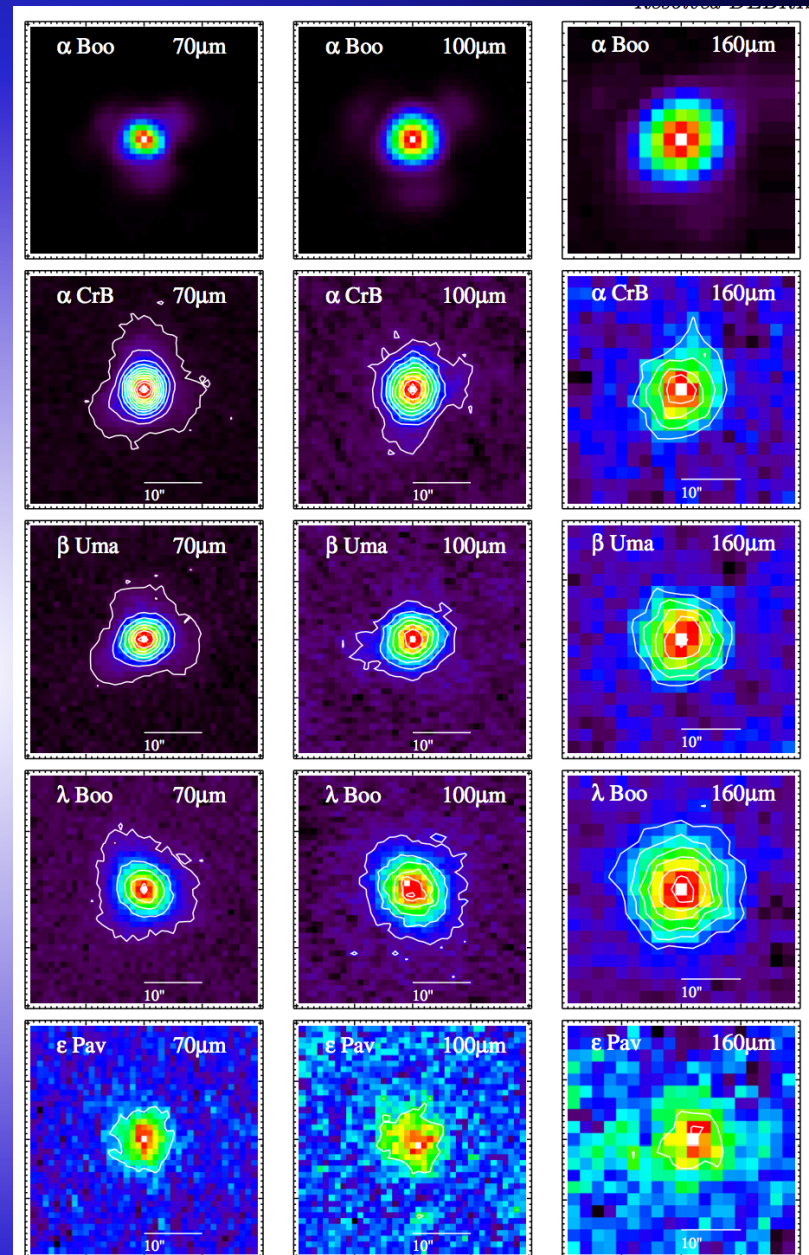
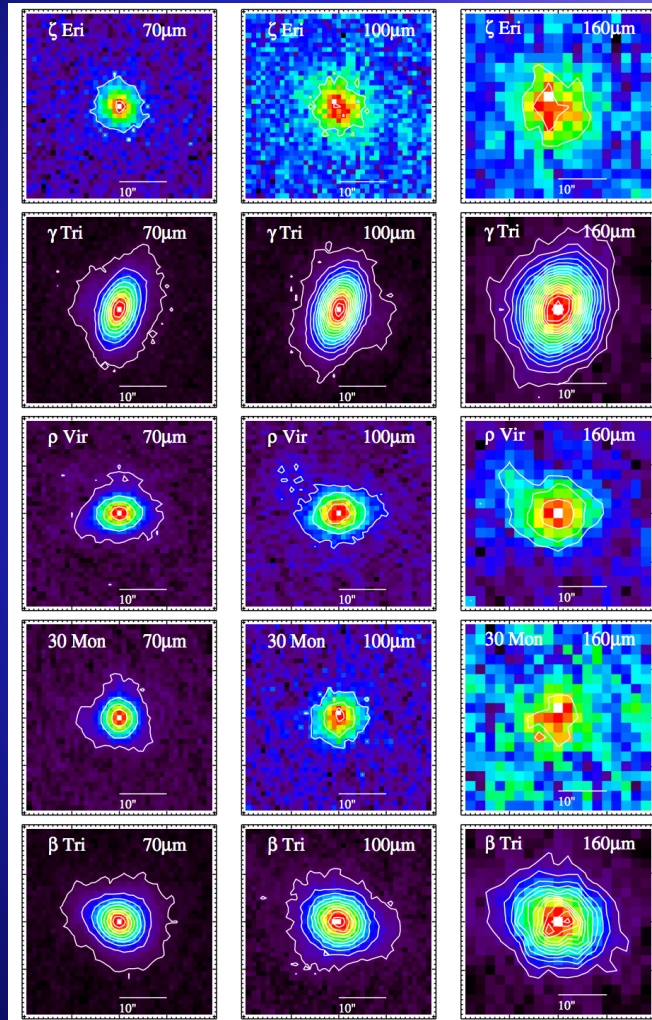
HD 95086 – Planet Host Star with Herschel

(Moór et al. 2013)



Herschel A Stars

(Booth et al. 2014)



Inventory of Resolved Debris Disks. I

(objects with at least 1 refereed publication)

Star Name	Spec Type	Lir/Lstar	Outer Radius AU	Resolved by
HD 141569A	B9	8.0E-03	370	HST, IR, submm
HD 32297	A0	3.0E-03	325	HST, IR, submm
HD 181327	F5	2.0E-03	85	HST, IR, submm
HD 61005	G8	2.0E-03	100	HST, submm
HD 15745	F2	2.0E-03	240	HST
beta Pic	A5	2.0E-03	250	HST, IR, submm
HR 4796A	A0	1.0E-03	70	HST, IR
HD 107146	G2	1.0E-03	200	HST, IR, submm
49 Ceti	A1	9.0E-04	200	IR, submm
HD 92945	K1	6.0E-04	110	HST, IR
HD 15115	F2	5.0E-04	435	HST
AU Mic	M0	5.0E-04	145	HST
HD 53143	K1	3.0E-04	55	HST
HD 10647	F9	3.0E-04	120	HST, IR, submm

Inventory of Resolved Debris Disks II.

(objects with at least 1 refereed publication)

Star Name	Spec Type	Lir/Lstar	Outer Radius AU	Resolved by
HD 202628	G2	1.4E-04	240	HST, IR
HD 139664	F5	1.0E-04	105	HST
HR 8799	A5	1.0E-04	500	IR, submm
HD 207129	G0	1.0E-04	160	HST, IR
eps Eri	K2	1.0E-04	105	IR, submm
zeta Lep	A2	9.8E-05	3	IR
gamma Oph	A0	9.0E-05	520	IR
Fomalhaut	A3	8.0E-05	158	HST, IR, submm
eta Corvi	F2	3.0E-05	100	IR, submm
beta Leo	A3	2.0E-05	40	IR
Vega	A0	2.0E-05	545	IR, submm
99 Her	F7+K4	1.4E-05	120	IR
beta UMa	A1	1.3E-05	47	IR
tau Ceti	G8	1.0E-05	65	submm

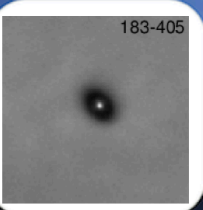
+ many new Herschel A stars, etc.

Track disk imaging at <http://circumstellardisks.org>

www.circumstellardisks.org

Most Visited Latest Headlines SIMBAD Astrono... SAO/NASA ADS C... WebTADS Remove NYT Coo... TCAT Tompin... Inbox - debipac@... Google News

Home What's new Search Description of the catalog Contribute to the database **Catalogs:** Resolved disks Unresolved disks Refuted disks

 **Catalog of Circumstellar Disks**

Created by Caer McCabe; Redesigned by Isabelle Jansen
Last updated 27 Mar. 2013; Maintained by [Karl Stapelfeldt](#)



Catalog of Resolved Disks

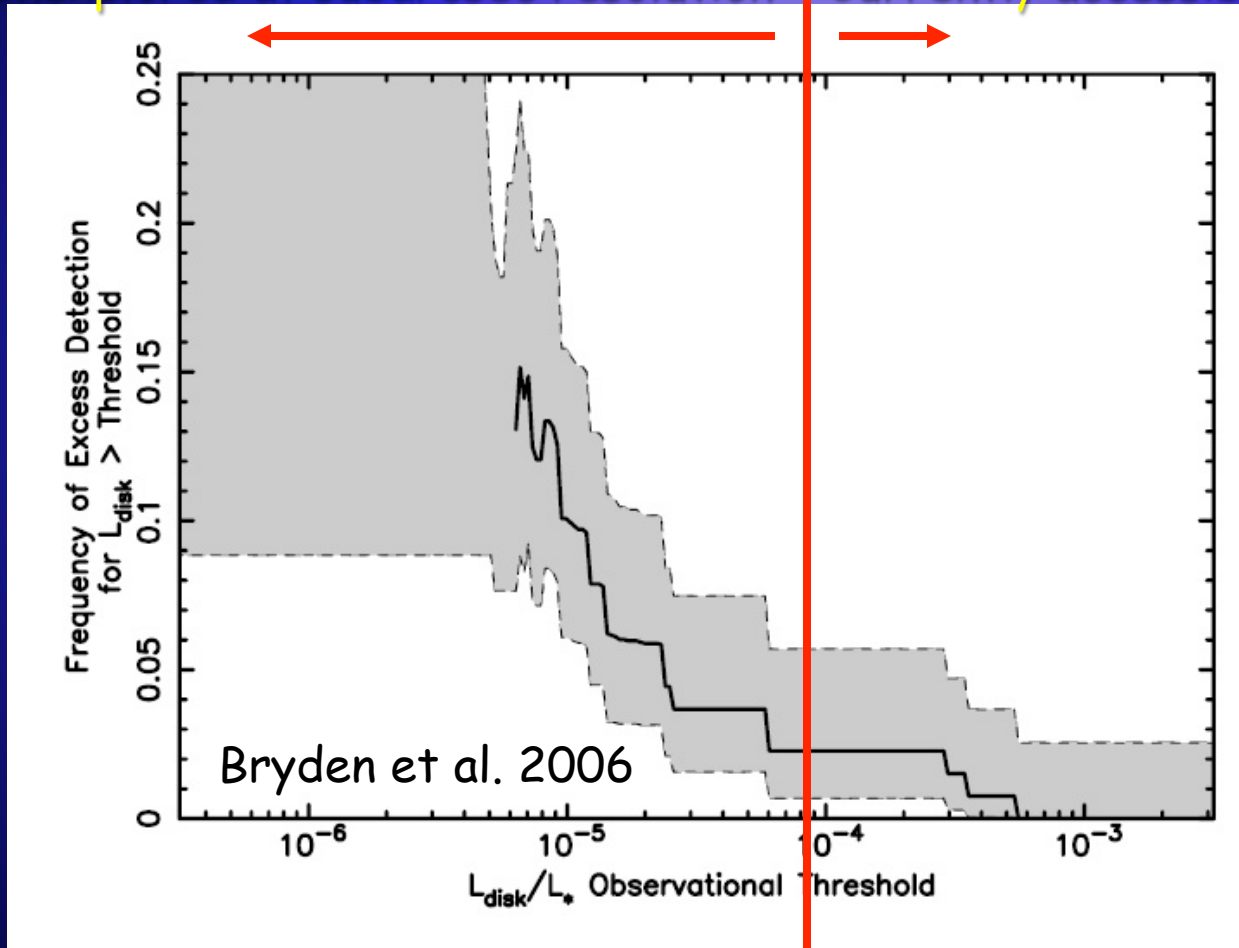
TOTAL NUMBER OF DISKS: 170 (PRE-MAIN SEQUENCE DISKS: 130, DEBRIS DISKS: 40)

Object	Category	SpTy	R band (mag)	Distance (pc)	Disk Diameter (")	Disk Diameter (AU)	Inclination	How Well Resolved	At ref. wavelength (micron)	# References
49 Cet	MS	A1	5.6	61	4.5	274.5		4.1	1300.39	30
HD 10647	MS	F8 V	5.5	17.35	37	642	52	2.5	870	9
Tau Ceti	MS	G8 V	3.5	3.6	37	133.2	60	3.2	850	14
beta Tri	giant	A5 III	2.9	38.9	5.6	218	41	0.9	70	5
gamma Tri	MS	A1V	3.9	34.4	8	275	83	1.4	70	6
HD 15115	MS	F2	6.8	45	19.38	872.1	90	372.1	0.61	12
HD 15745	MS	F2	7.5	64	7.5	480	67	147.7	0.59	6
LkHa 263 C	TT	M0	13.7	275	1.1	302.5	87	25.9	1.65	705
zeta02 Ret	MS	G1	4.9	12.1	25	302.5		6.1	70	3
ADS 41	TT			212	22	2222	22	27	2.2	2

Scattered Light Imaging accesses only high LIR/Lstar debris disks

Unexplored at subarcsec resolution

Currently accessible in scattered light

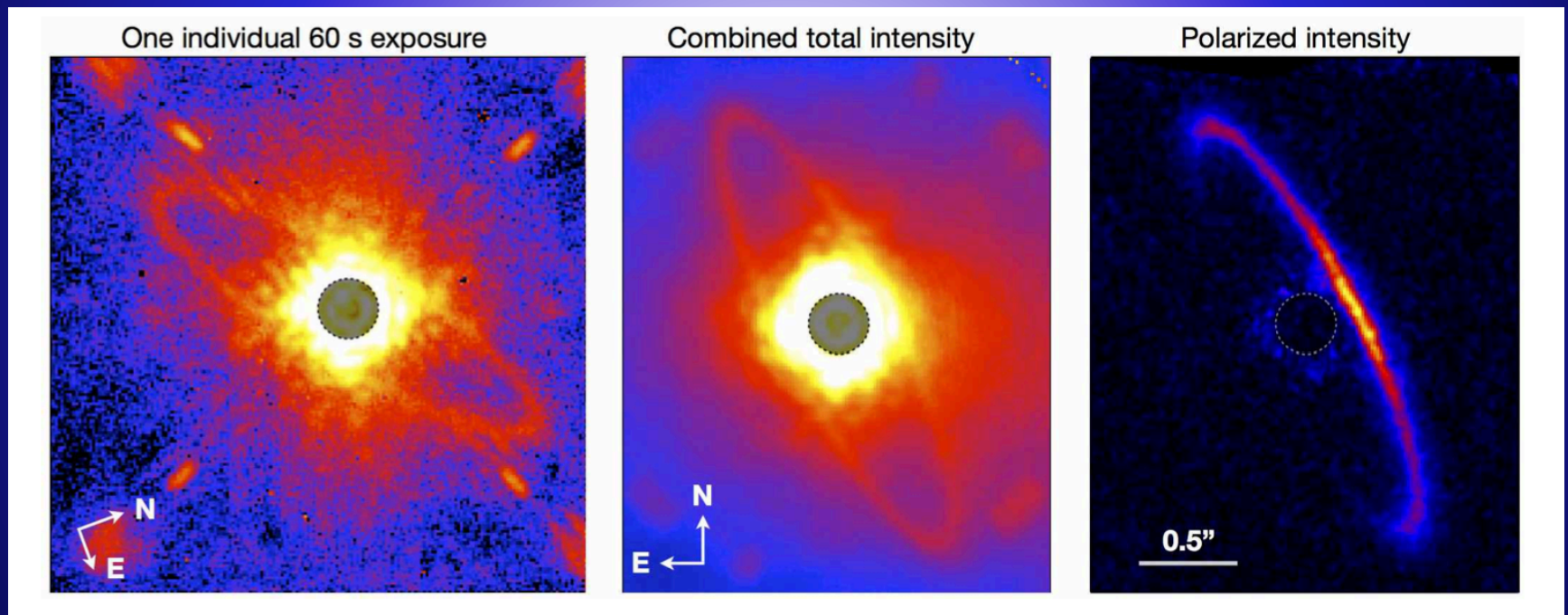


Future progress:

- Complete surveys of high LIR/Lstar targets with existing facilities
- Develop & deploy new capabilities to image at higher contrasts: ExAO.
- Polarimetry of younger / later type objects with smaller grains

Ground-based Extreme AO Coronagraphs

HR 4796A with GPI (Perrin et al. 2014)



LBTI is coming online

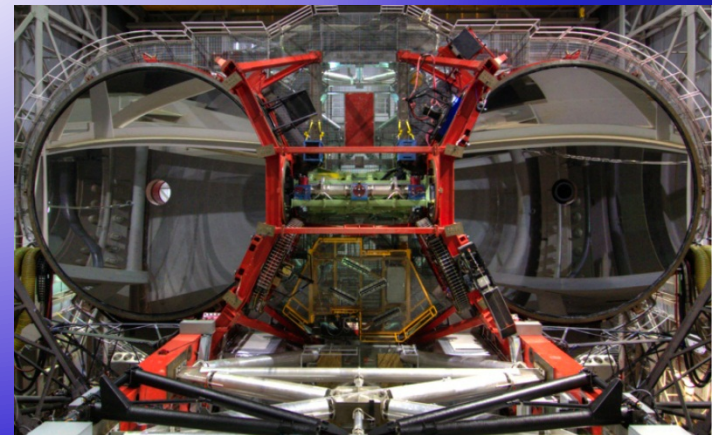
Twin 8.4m telescopes at
U. of Arizona

NASA-funded 10 μm
nulling interferometer

61 nights over 5 years for
survey of exozodiacal
dust of nearby stars

Predicted sensitivity down
to 10 zodis; detection,
not imaging

Results will drive design
of future planet finders

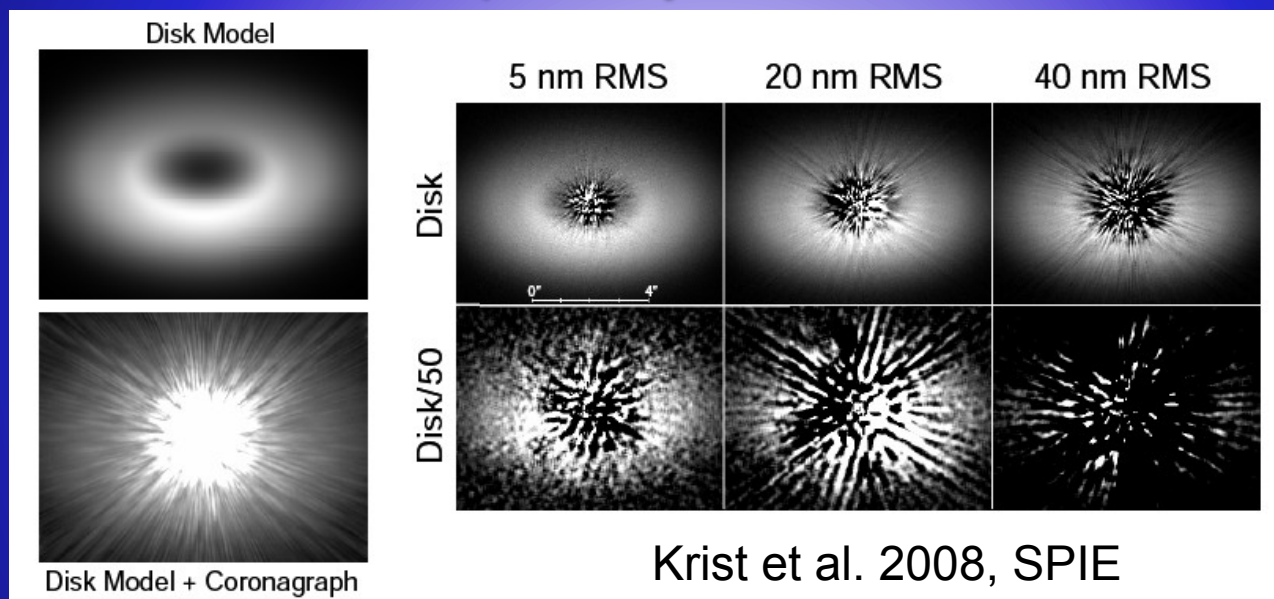




JWST & disk scattered light

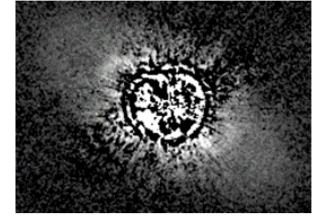


Simulated NIRCAM coronagraph K band images of an LIR/
Lstar = 0.008 disk vs. primary mirror wavefront stability



Conclusion: In the near-IR, JWST disk imaging won't probe a new contrast domain. 3-5 μm scattered light will be a unique niche.
25 μm thermal imaging should resolve 1-2 dozen debris disks

Debris Disk opportunity for future high contrast imaging



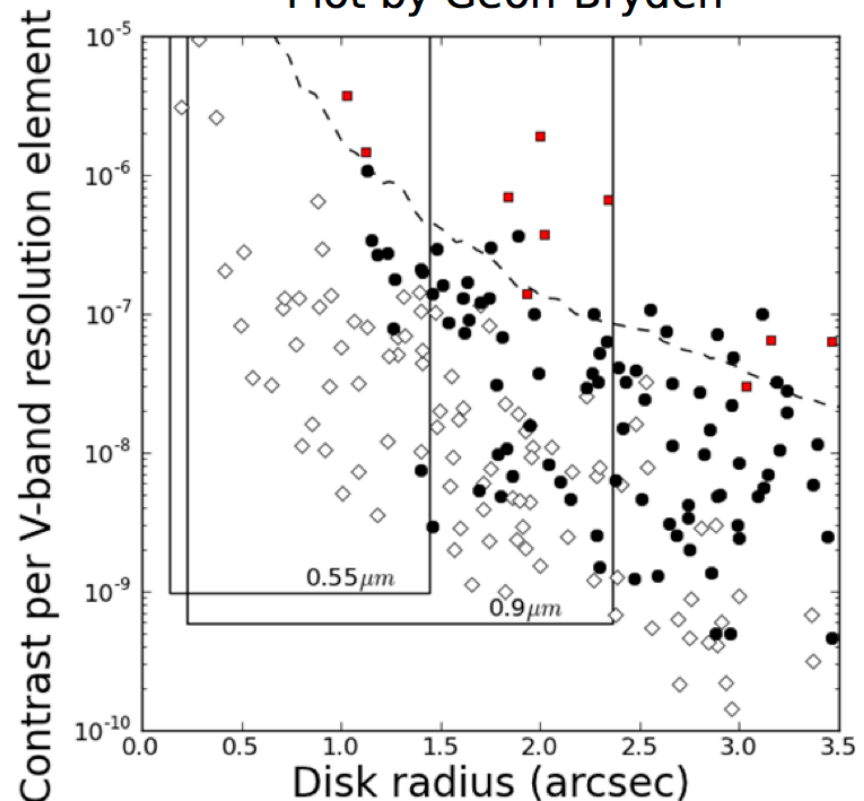
Plot by Geoff Bryden

Predicted disk sizes & contrasts
for Herschel disks $d < 40$ pc

Red points: Disks detected in
Scattered light

Black points:
Disks with sizes measured
with Herschel

Hollow points:
Disks with sizes estimated
from far-IR SED



- The contrast (10^{-8}) and resolution (0.2") needed are less challenging than for reflected light exoplanets

Coronagraph Probe Study



Exo-C Technical Overview



- Highly stable Earth-trailing orbit for three year science mission
- Coronagraphs with $\sim 2 \lambda/D$ inner working angle, $\sim 1.5\text{m}$ off-axis telescope
- Two stage vibration isolation for science payload
- Bright science target star is used as a reference for precision pointing and compensation of low order wavefront drifts
- Commercial Kepler-like spacecraft bus, Intermediate class launch vehicle
- 2015 decision by NASA HQ on path forward

See <http://exep.jpl.nasa.gov/stdt/exoc/>



Summary

1. Debris disk imaging provides essential information on dust spatial distributions and particle properties. No single wavelength tells the whole story.
2. 40+ debris disks are spatially resolved today, but only ~20 have high resolution. This won't change greatly until future instrument developments expand our ability to image more tenuous systems.
3. Searches for companions perturbing the disk structures are becoming increasingly important.
4. Spitzer, WISE, and Herschel debris disk surveys have given us the target list for imaging studies over the next 1-2 decades.