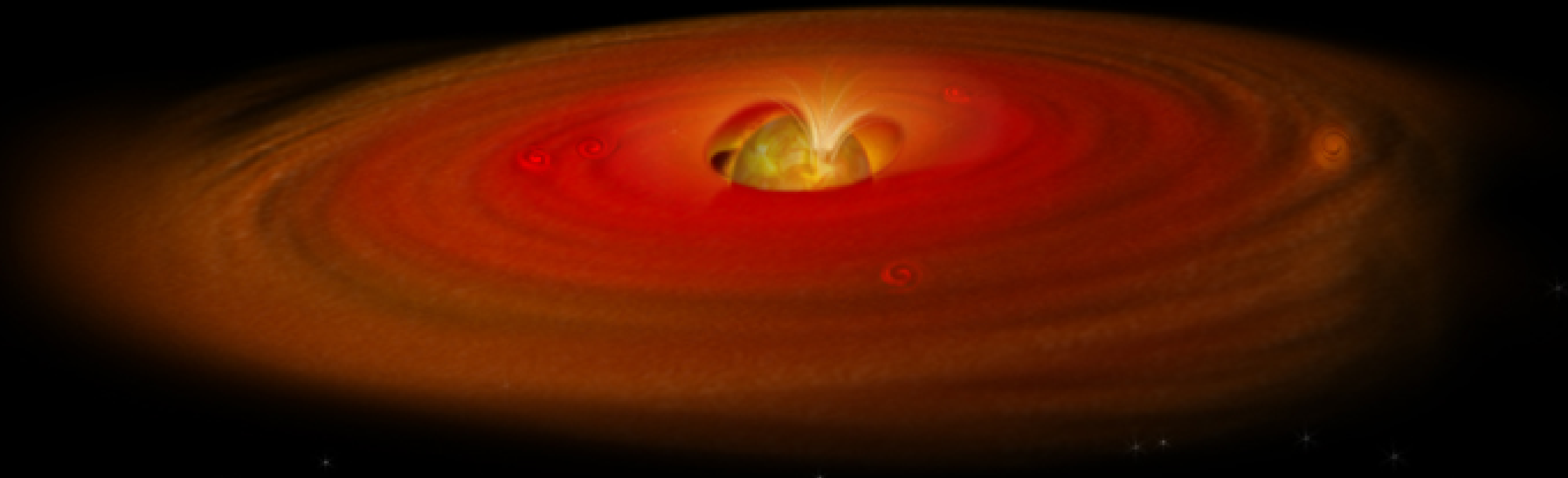
Interferometric Observations of YSOs



Josh Eisner

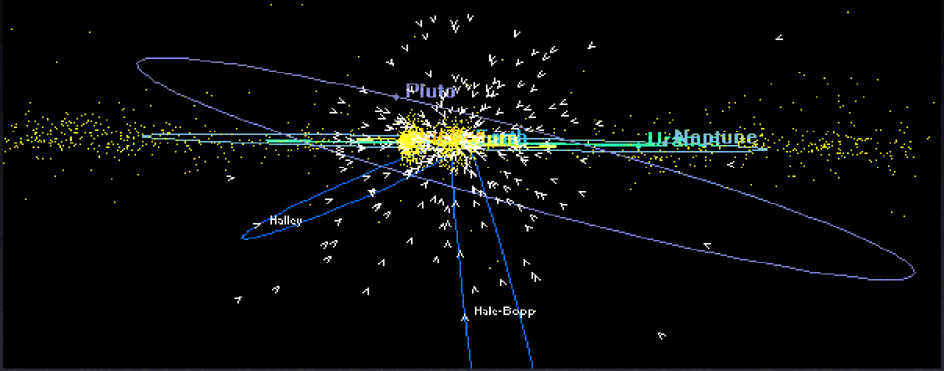
Miller Fellow, UCB

Michelson Summer Workshop
July 26, 2006

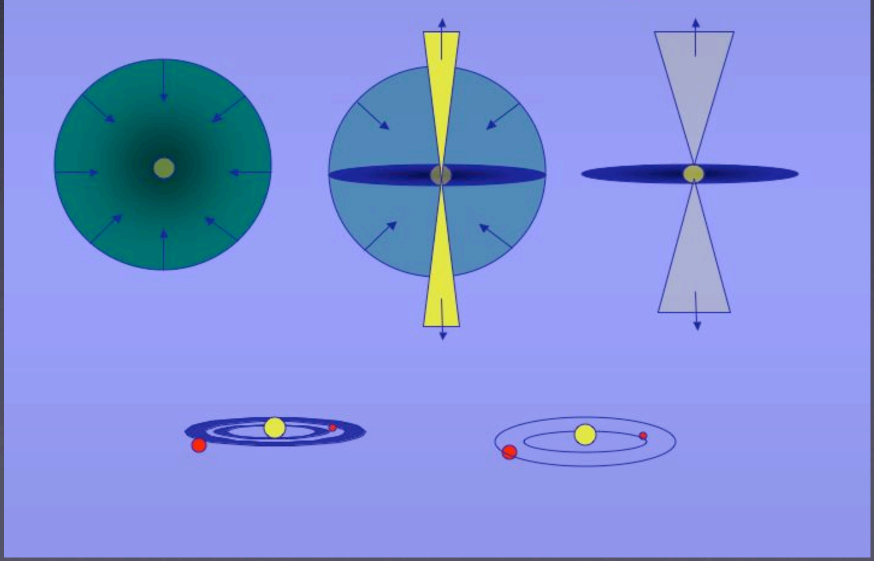
Planets and Disks

- Proto-solar nebula
- Extra-solar planets
- Disks integral to star and planet formation

Solar system; http://ssd.jpl.nasa.gov/orbits_outer.html



Star/Disk Formation Sequence



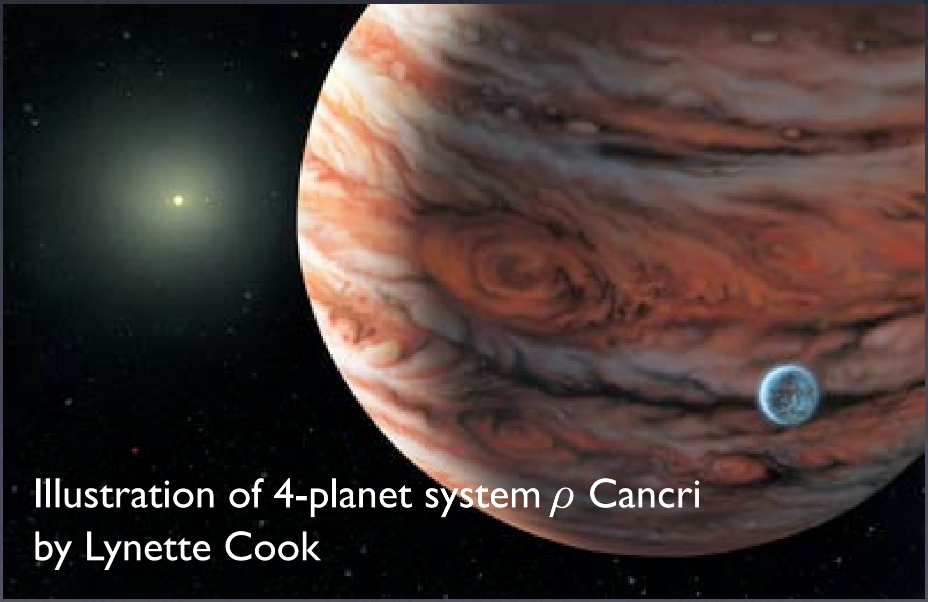


Illustration of 4-planet system ρ Cancri by Lynette Cook

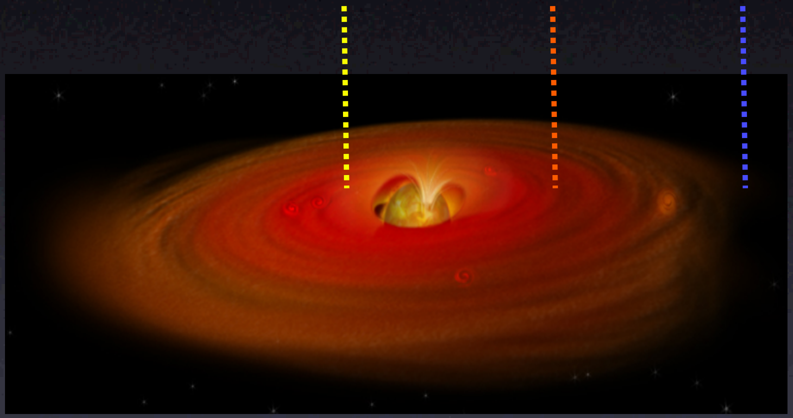
Protoplanetary Disks

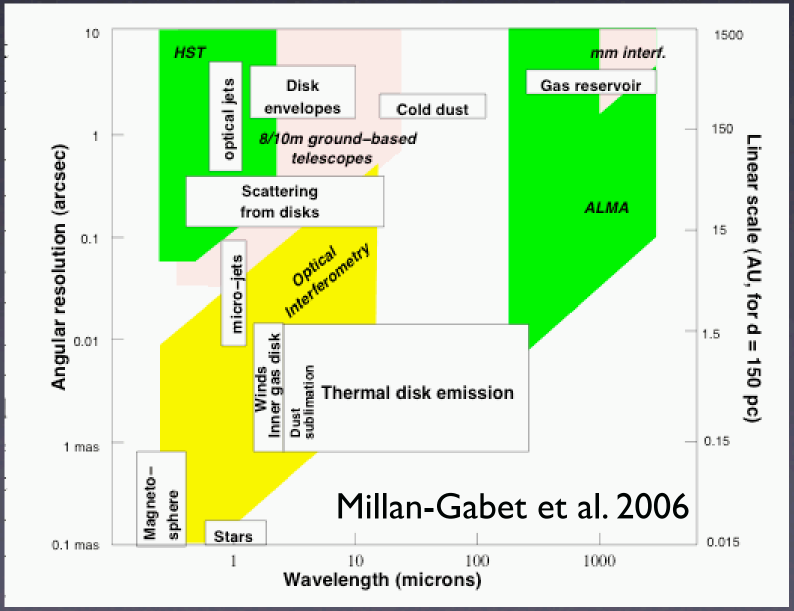
- Initial conditions for planet formation
  - Temperature: suitable for dust, ice?
  - Mass: enough stuff to build Jupiters?
  - Viscocity: accretion onto star before planet formation can occur?
  - Dust properties: how fast are grains built into planetesimals or detroyed?

R~0.1 AU
T~2000 K
$\lambda \sim \mu$m

R ~ 1 AU
T~100 K
$\lambda \sim 10\mu$m

R > 10 AU
T~10 K
$\lambda \sim$ mm

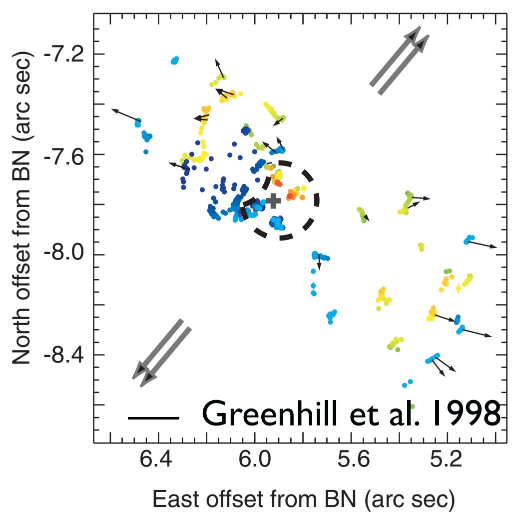




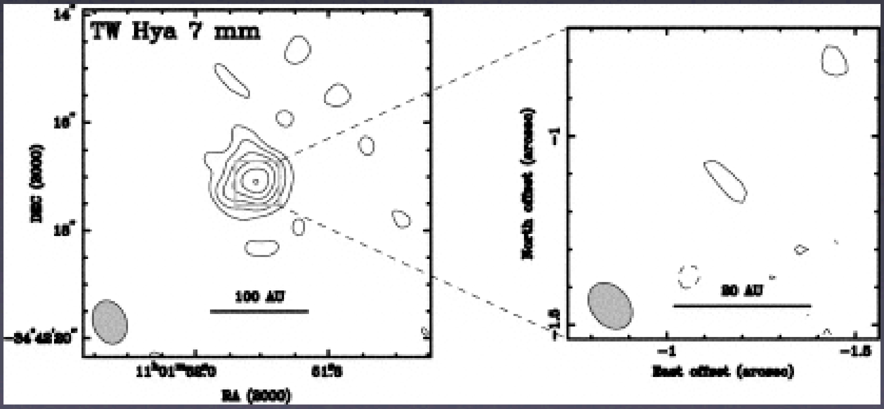
Millan-Gabet et al. 2006

Interferometry of YSOs: A Brief History

- Radio interferometry
  - 1970s: masers in Orion (and other SFRs) probe outflows/disks around massive protostars (Burke et al. 1970; Moran et al. 1973)
  - 1980s-1990s: free-free emission from proplyds detected in Orion (Garay, Moran, & Reid 1987; Felli et al. 1993)
  - Recent: VLA thermal images of dust and gas in YSO disks



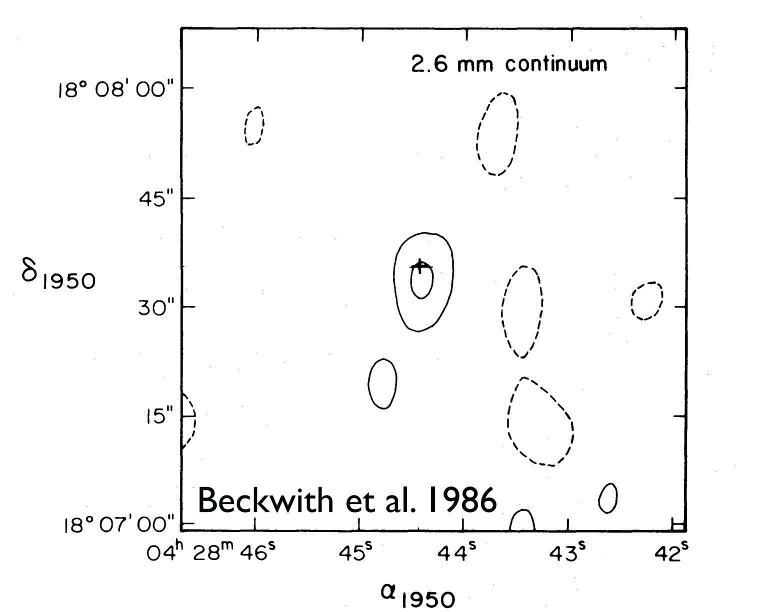
Greenhill et al. 1998



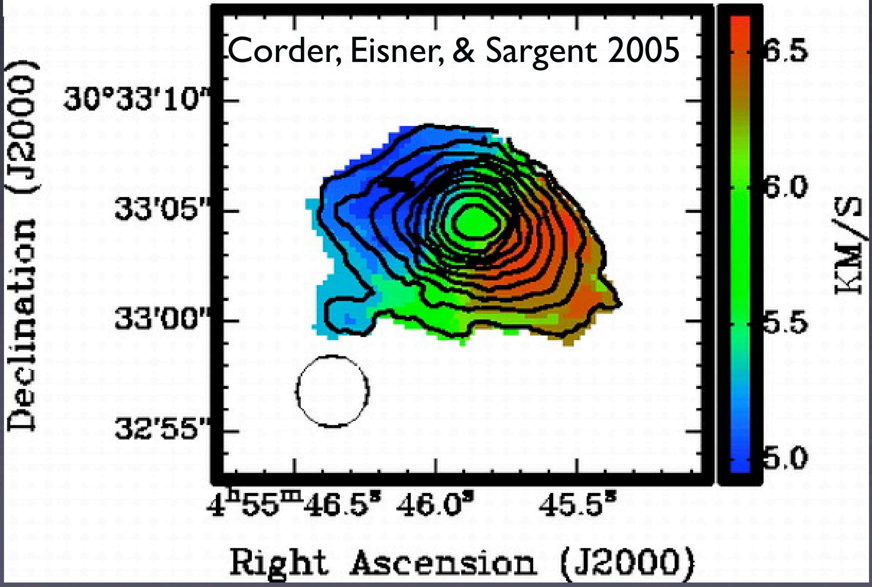
Wilner et al. 2000

Interferometry of YSOs: A Brief History

- Radio interferometry
- Millimeter interferometry
  - 1980s: thermal dust and gas emission detected from few outer disks (e.g., Beckwith et al. 1986)
  - 1990s: spatially & spectrally resolved Keplerian disks
  - 2000s: disk mass distributions in clusters (e.g., orion proplyds; Eisner & Carpenter 06; Williams et al. 06)



Beckwith et al. 1986



Corder, Eisner, & Sargent 2005

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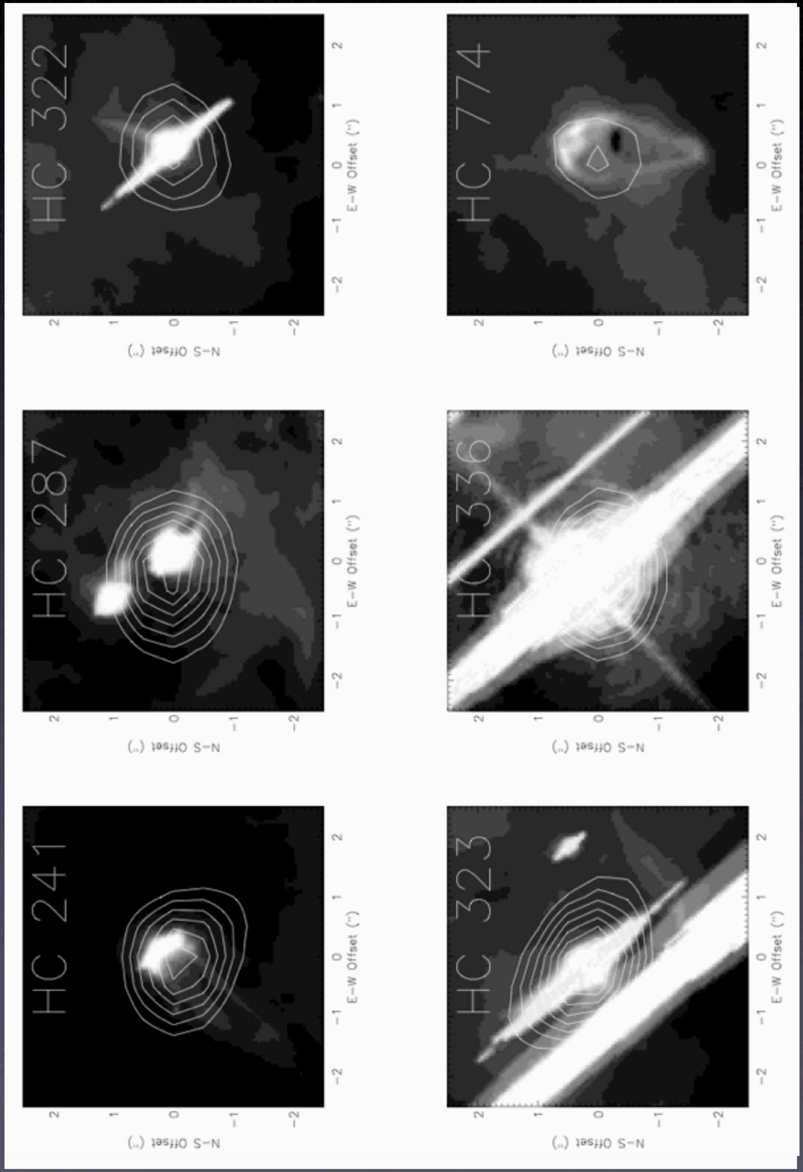
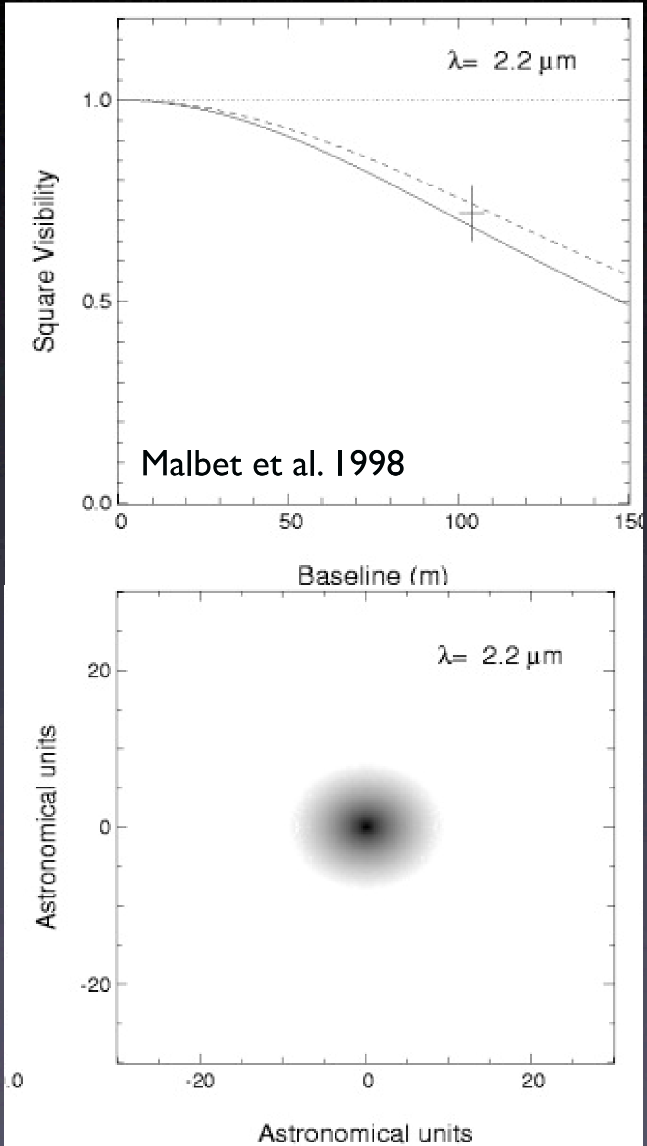


Eisner & Carpenter 2006

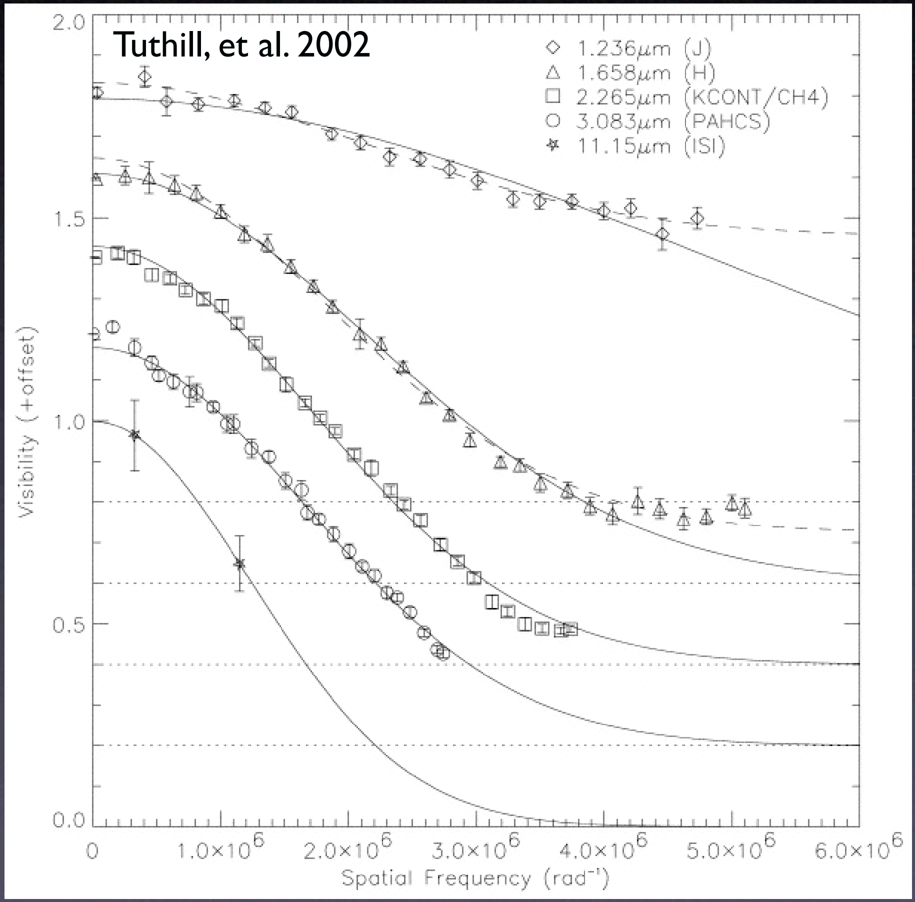
Interferometry of YSOs: A Brief History

- Radio interferometry
- Millimeter interferometry
- Near-IR Interferometry
  - 1998: First YSO inner disk resolved at 2 μm (FU Ori; Malbet et al. 1998)
  - Lots more later...


Malbet et al. 1998

Interferometry of YSOs: A Brief History

- Radio interferometry
- Millimeter interferometry
- Near-IR Interferometry
- Mid-IR Interferometry
  - 2002: observations of disk around luminous YSO (Tuthill et al. 2002)
  - Keck "segment-tilting"
  - Keck nuller & VLTI (more later)

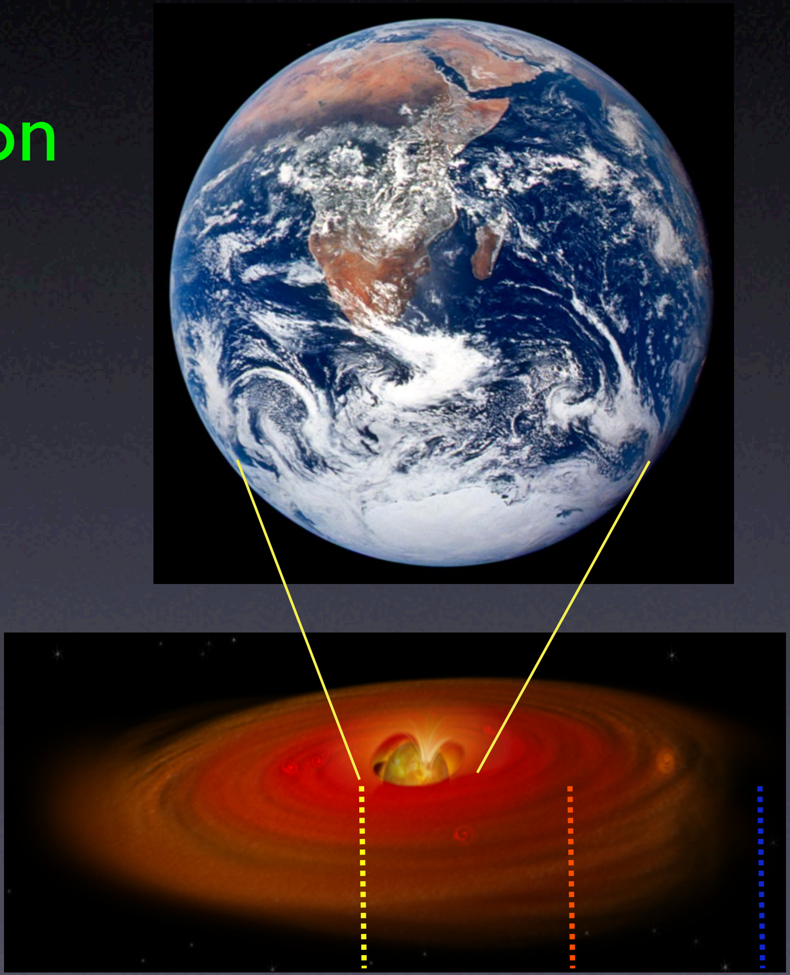


Tuthill, et al. 2002

Focus: Terrestrial Regions

NIR & MIR Interferometry

- Earth-like planet formation
- Hot Jupiters: Migration
- Disk Accretion



R~0.1 AU	R ~ 1 AU	R > 10 AU
T~2000 K	T~100 K	T~10 K
$\lambda \sim \mu$m	$\lambda \sim 10\mu$m	$\lambda \sim$ mm

Focus: Terrestrial Regions

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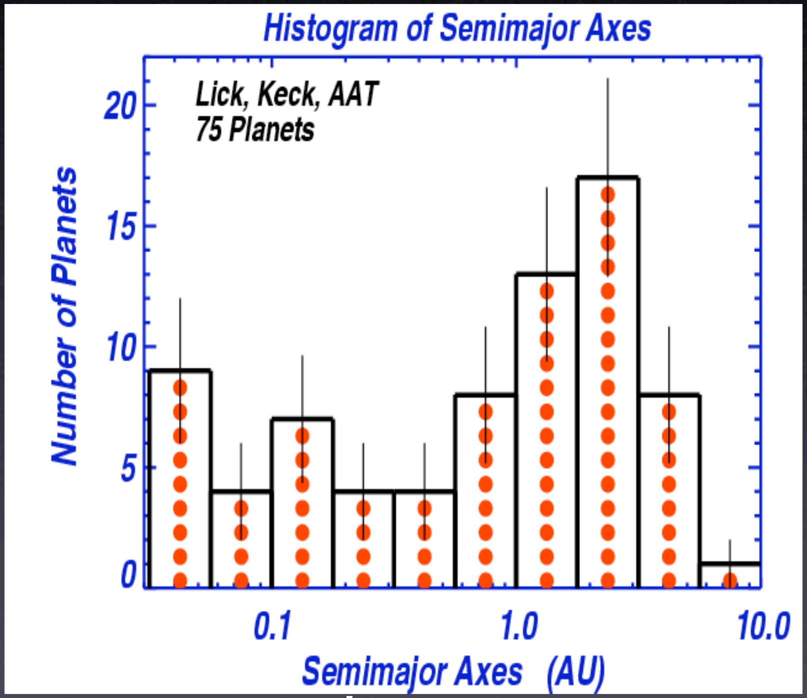

exoplanets.org

Focus: Terrestrial Regions

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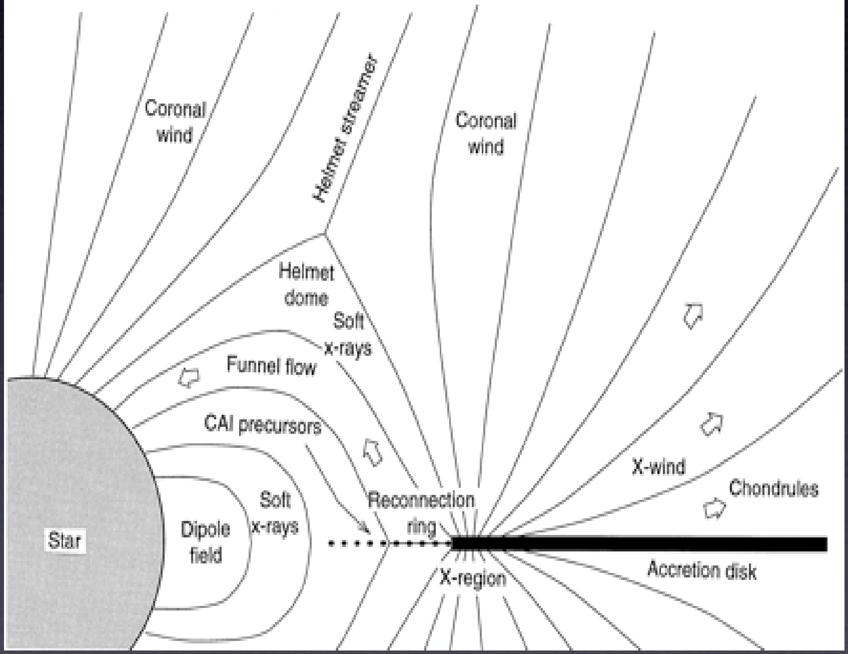
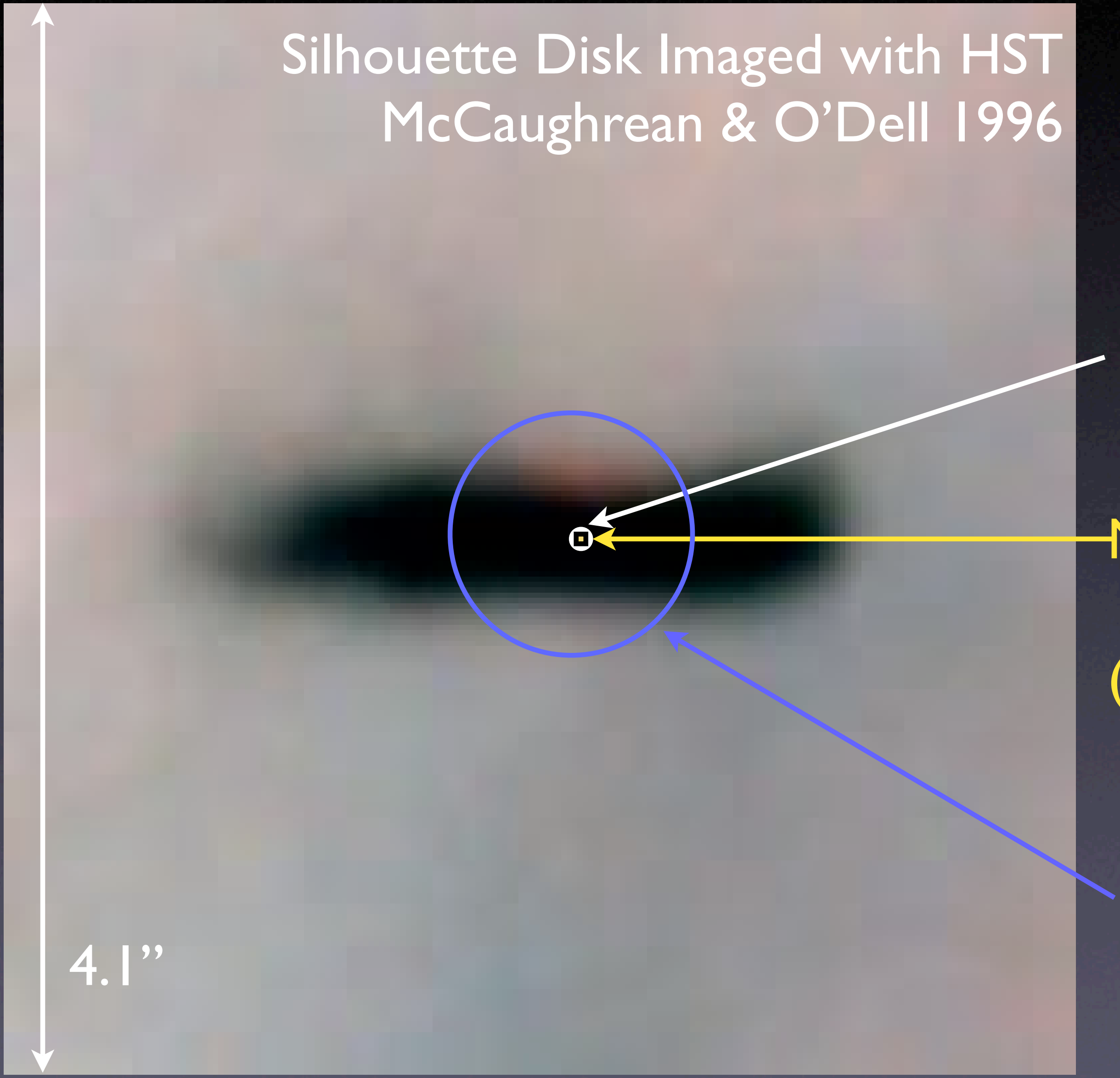


Shu et al.

Interferometry



Silhouette Disk Imaged with HST
McCaughrean & O’Dell 1996

HST Res ~ 100 mas
(~40 AU)

NIR Interf. Res ~ 1 mas
(FOV ~ 50 mas!)
(< 1 AU for close SFRs)

MM Interf. Res ~1”

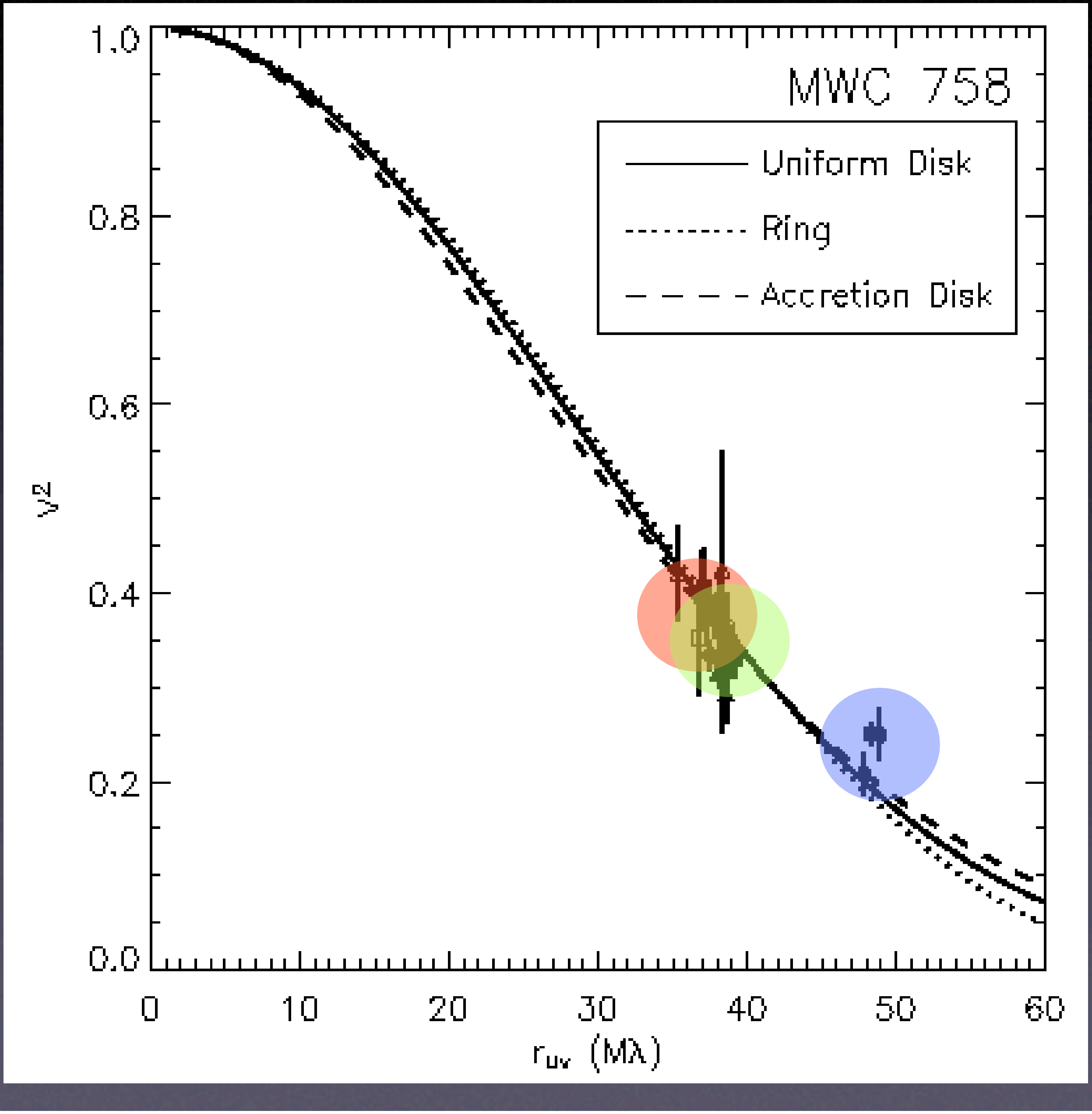
Mechanics

How to get physical information out of interferometry data...

Measurements & Modeling

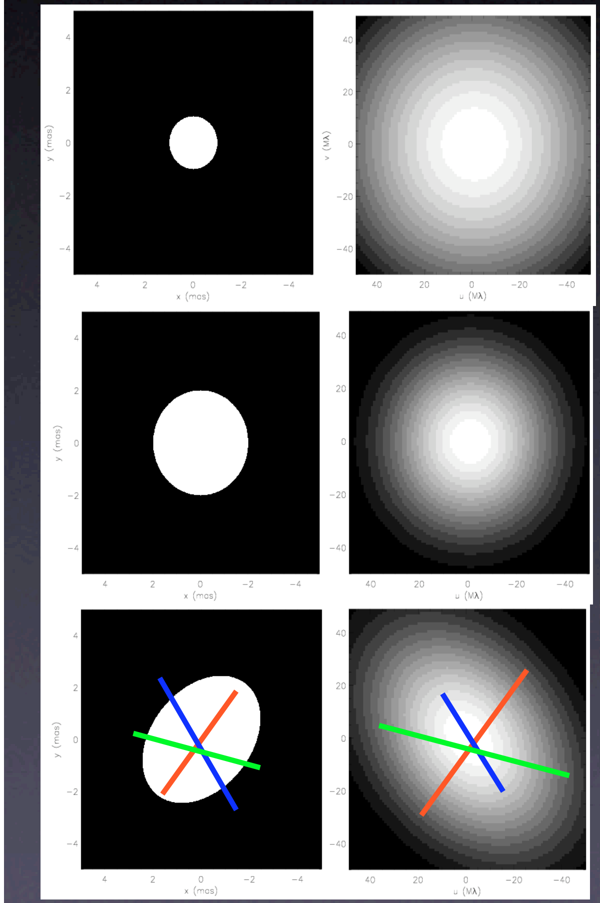
- Current near- and mid-IR interferometers measure visibilites (not direct images)
- Observations are interpreted in the context of simple models
  - FT of model BD gives model visibilities for comparison to data
  - e.g., uniform disk with ang. diam θ gives $V = \dfrac{2J_1(\pi r_{\mathrm{uv}}\theta/\lambda)}{\pi r_{\mathrm{uv}}\theta/\lambda}$
  - inclined uniform disk using transform to circular coords (e.g., Eisner et al. 2003):
    $(x,y)_{\mathrm{elliptical}} \rightarrow (x,y)_{\mathrm{circular}};\ (u,v)_{\mathrm{elliptical}} \rightarrow (u,v)_{\mathrm{circular}}$

Geometry from Visibilities



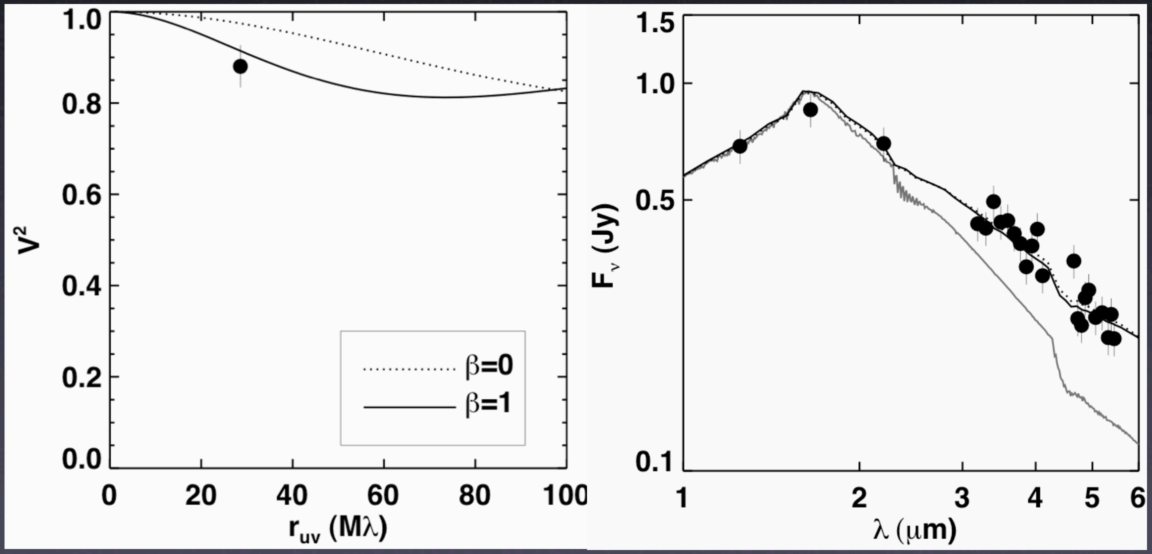
Sky ⟷ U-V

FT



Physically-Motivated Models

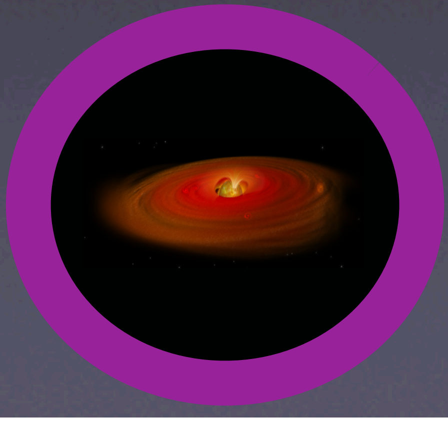
- Using visibilities + flux measurements (e.g., SEDs, spectra), we model star+disk systems
  - SEDs alone cannot distinguish geometry, *T*, dust grain properties

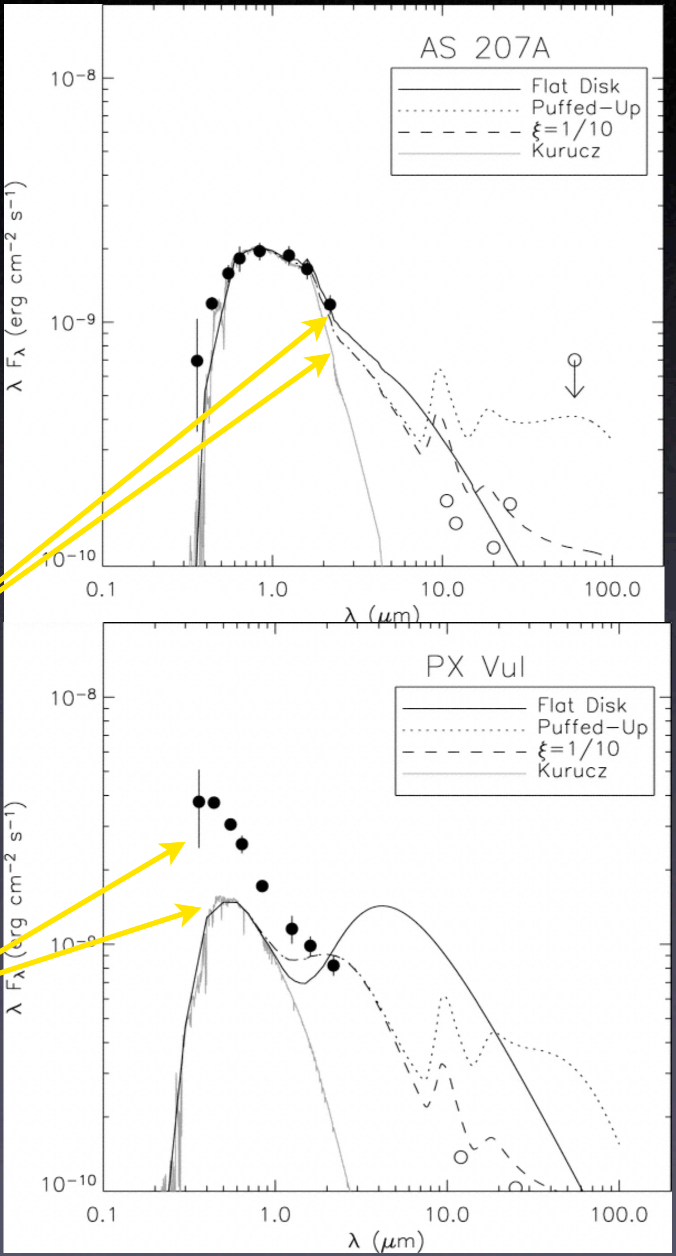


Eisner, Chiang, & Hillenbrand 2006

Star/Disk Contributions

- Star + accretion: unresolved emission
- Outer disk-scattered light, envelopes, "halos": incoherent light
- Spectral info needed to account for these effects
  - veiling gives F_*/F_{disk} (can also use spec decomposition)
  - these data also yield info on system properties: e.g., stellar mass, accretion rates





K-band F_*/F_{disk}

$F_{accretion}/F_*$

Eisner et al. 2005

Physically-Motivated Models

- Using visibilities + flux measurements (e.g., SEDs, spectra), we model star+disk systems
- Disk temperature, radial & vertical dust distributions: constrains planet formation, accretion processes

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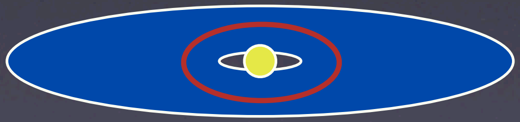
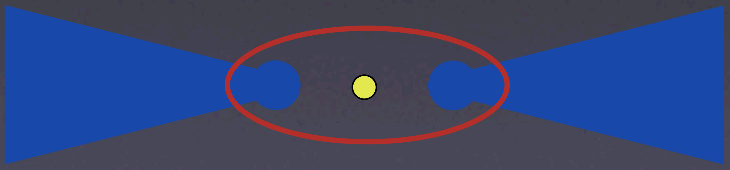
Thin accretion disk



$T(R) \propto R^{-3/4}$

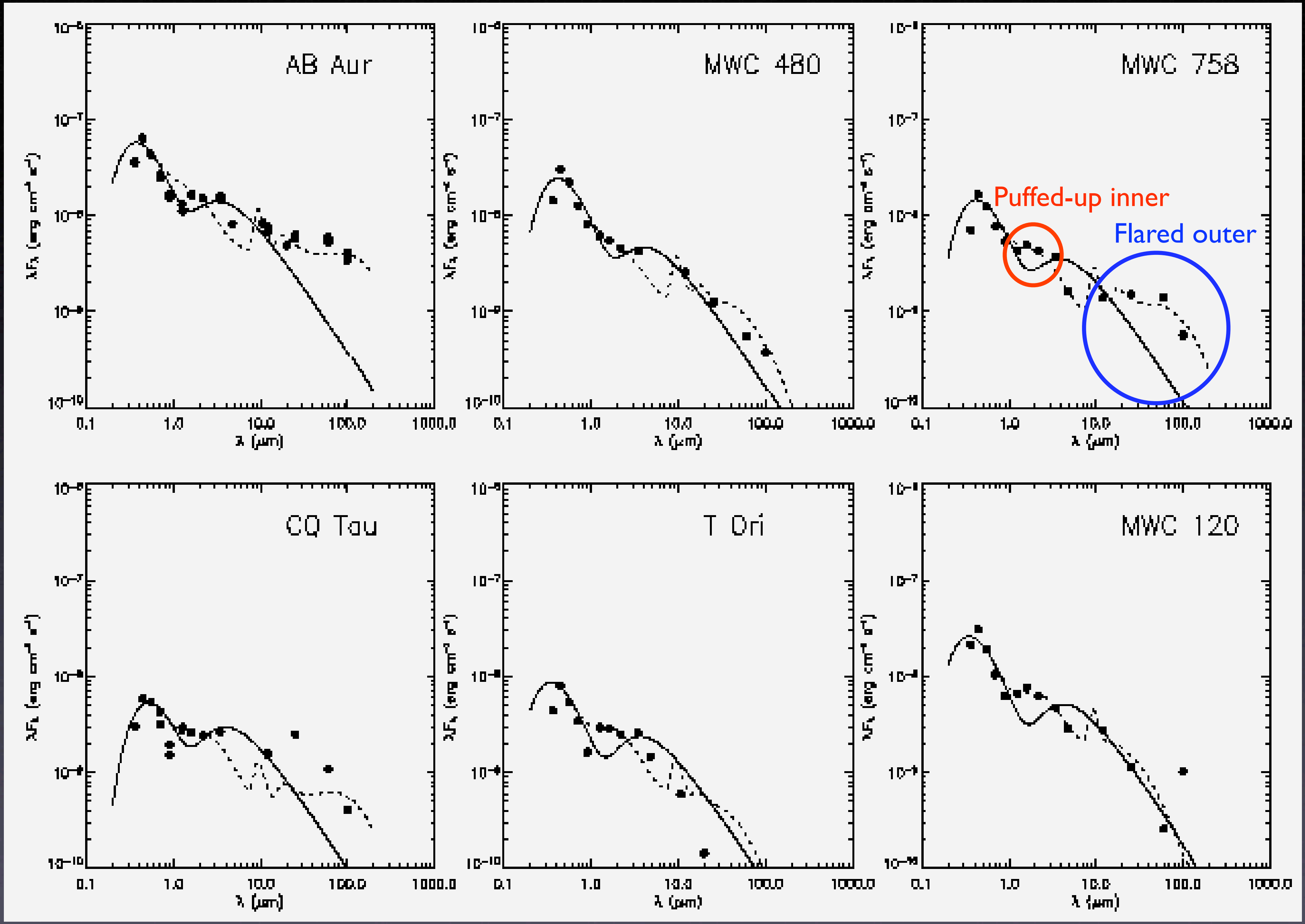
R_{in}, i, T_{in} (R_{out})

Puffed-up inner wall (+flared outer disk)



$T(R) \propto R^{-1/2}$

R_{in}, i, T_{in}, R_{out}, ξ, Σ, κ_ν


AB Aur

MWC 480

MWC 758

CQ Tau

T Ori

MWC 120

Puffed-up inner

Flared outer

Example: start with R_{in}, i from interferometry; use SED to constrain $T(R)$, vertical structure

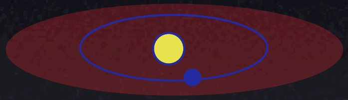
Recent Science

New insights into YSOs from optical/IR interferometry

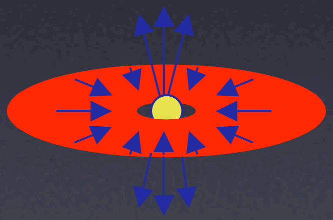
Some YSO Disk Science

Focus on Sub-AU-sized Regions

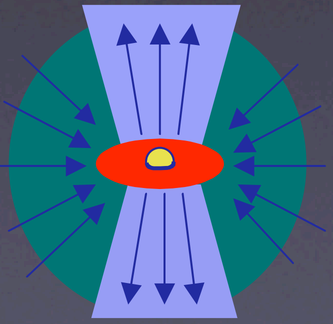
- Optically-thin disk (~10 Myr; older)
  - much of material dispersed
  - planet formation already occurred, on-going?



- Optically-thick disks (~1 Myr; younger)
  - plenty of planetary building blocks (dust & gas)
  - what are initial/early conditions?



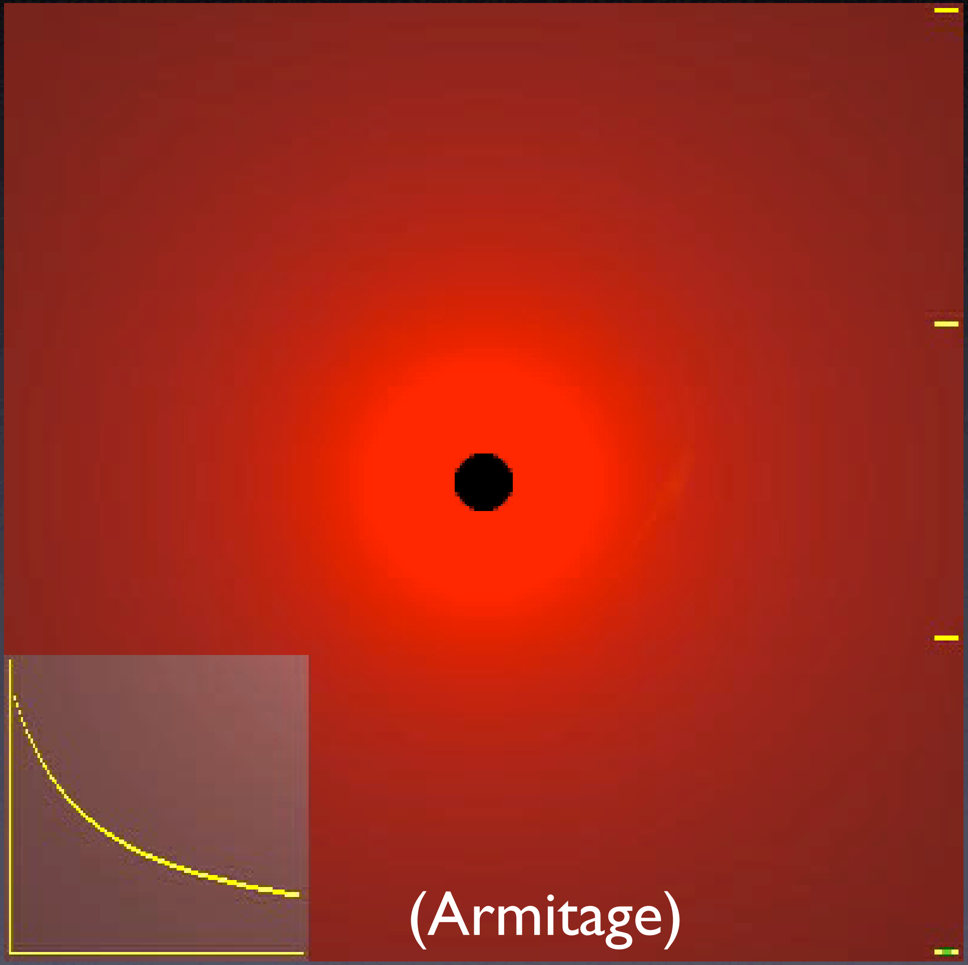
- Outburst ("FU Ori") sources (youngest?)
  - high accretion rates: hot, luminous, violent (?) disks
  - early stages of disk evol? or just peculiar sources?



KI observations of TW Hya

A potential transition object

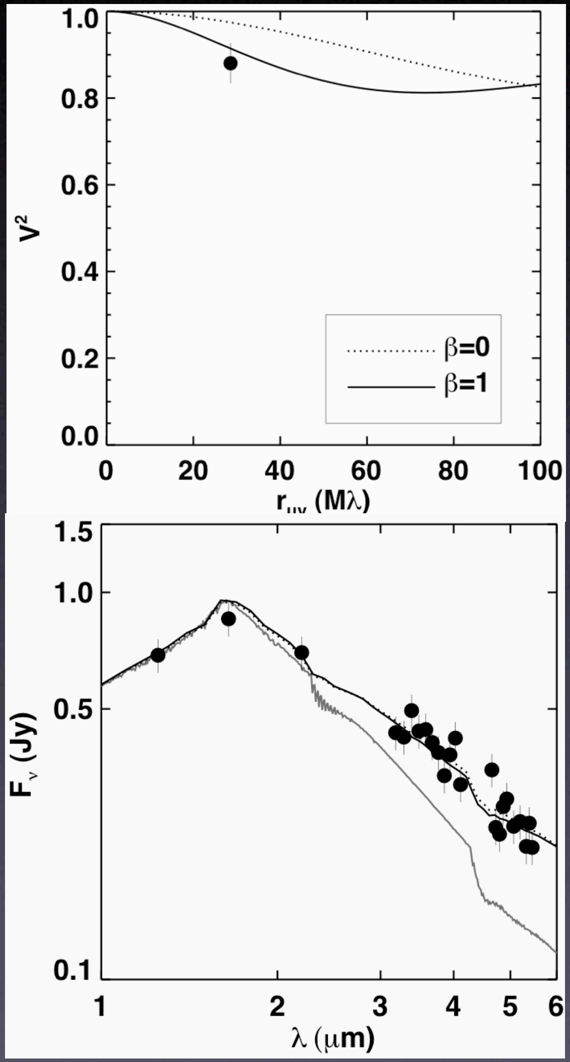
- TW Hya: 10 Myr, ~51 pc, ~0.7 $M_\odot$, ~4000 K
- Lacks NIR emission
    - implies hole at R<4 AU
    - cleared by planet?
        - massive disk (0.1 $M_\odot$) should cause migration, would kill gap on t_{visc}
    - dust coagulation eliminating small dust grains?



(Armitage)

Resolving the Disk

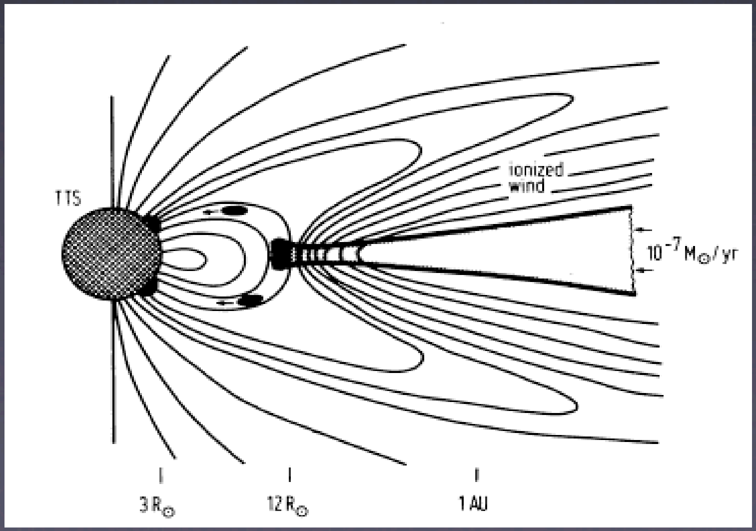
- if no circumstellar dust, $V^2=1$ (central star unresolved)
- KI obs: $V^2 < 1$ (at 2 μm)
    - Non-disk explanation?
        - scattering- unlikely based on HST imaging (Weinberger et al. 2002)
        - binary- unlikely based on lack of imaged or RV companions
        - wind?
    - Disk models with small dust grains
        - $\beta=1$ (or >1): submicron-sized dust
        - $R_{in} = 0.06$ AU, $T_{in} = 1100$ K



Eisner, Chiang, & Hillenbrand 2006

Implications: R_{in}

- Disk truncated at radius > expected for dust sublimation ($T_{in} \sim 1100$ K $< T_{sub} \sim 1500$ K)
- Magnetospheric truncation...
  - stellar B-field disrupts disk where accretion balances magnetic pressure (Königl 1991)



$$\frac{R_{\rm mag}}{R_*} = 2.27 \left[\frac{(B_0/1\,{\rm kG})^4 (R_*/{\rm R}_\odot)^5}{(M_*/{\rm M}_\odot)(\dot{M}/10^{-7}{\rm M}_\odot\ {\rm yr}^{-1})^2} \right]^{1/7}$$

$$\rightarrow R_{\rm mag} \sim 0.09\ {\rm AU} \approx R_{\rm in} = 0.06\ {\rm AU}$$

Implications: β=1

- β = 1 (or >1): sub-micron-sized dust
- radiation pressure blows out a < 1 μm:

$$a_{\rm blow} \sim \frac{3}{8\pi}\frac{L_*}{GM_* c\rho_{\rm dust}} \sim 0.5\mu{\rm m}$$

- gas mediates removal via momentum stopping time: for μm-sized grains at 1 AU and gas density <10^{-15} g/cc (Herczeg et al. 2004),

$$t_{\rm stop} \sim \frac{a\rho_{\rm dust}}{\rho_{\rm gas}c_{\rm s}} \geq 10^{-2}\,{\rm yr} \rightarrow v_{\rm term} \geq 1\,{\rm km\,s}^{-1}$$

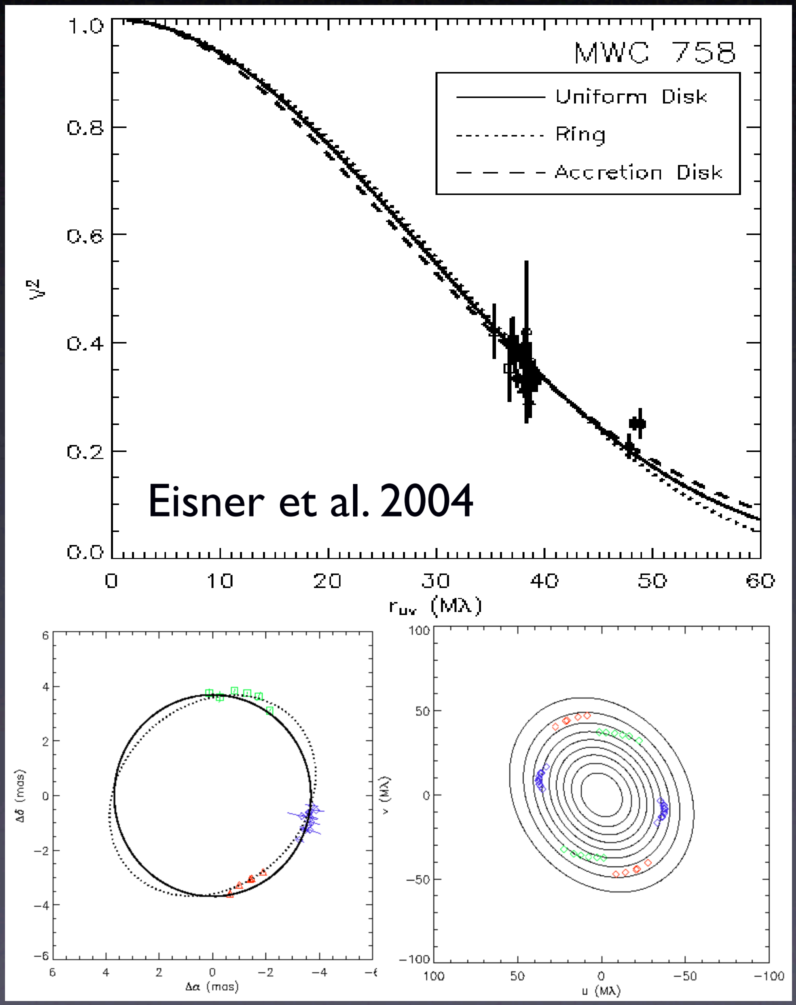
$$\boxed{\rightarrow t_{\rm removal} \leq 1\,{\rm yr}}$$

- Short-lived dust must be **re-generated** (“debris”); possibly erosive collisions of **large parent bodies, already present**

T Tauri and HAe/Be Stars

Sample of younger (~1 Myr) sources

- Many observations (IOTA, PTI, KI, VLTI)
- K5-09 (~1-10 $M_\odot$)
- Virtually all resolved:
  - θ ~ 1-6 mas
- Most asymmetric:
  - i ~ 10-85 deg



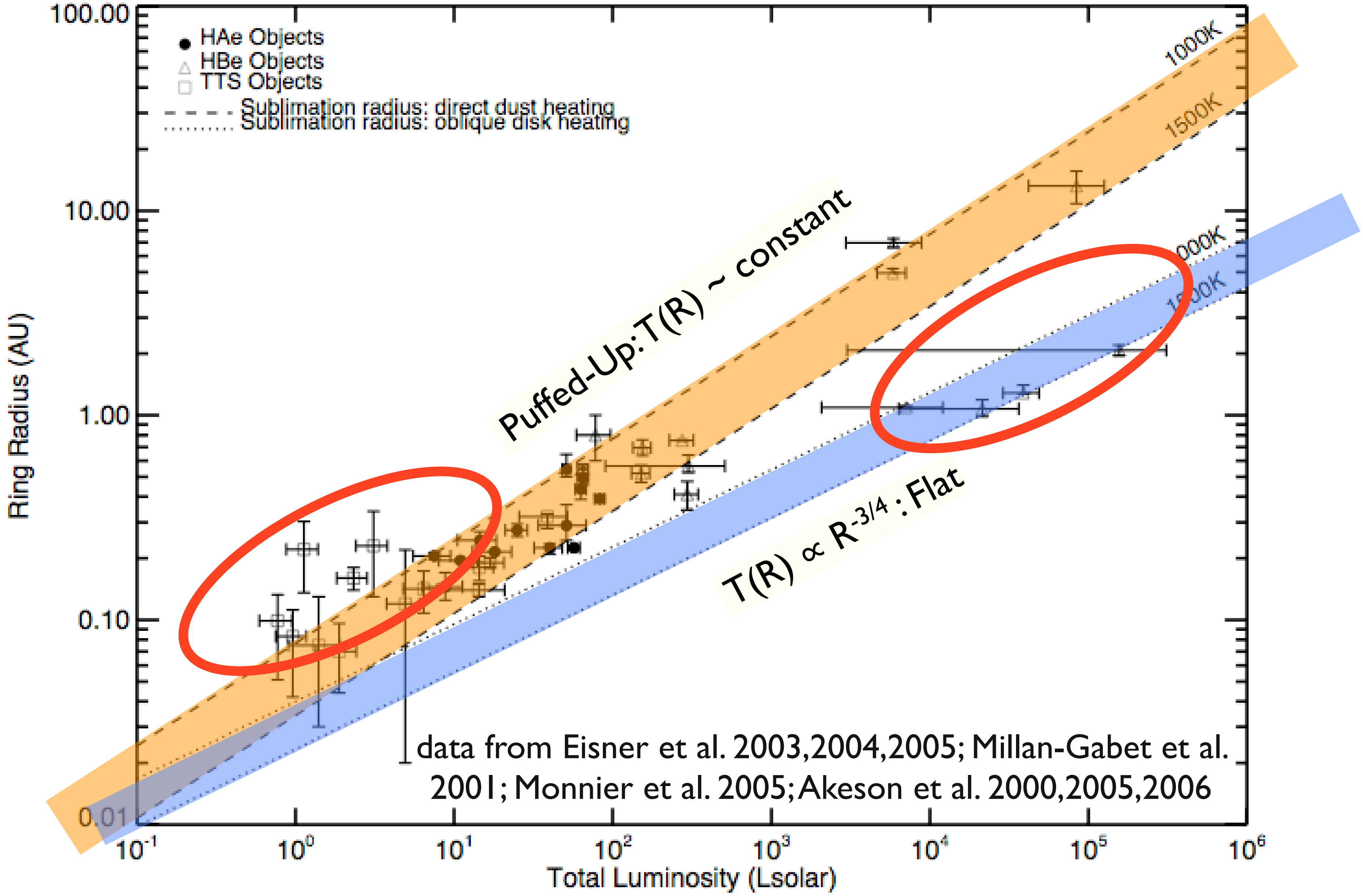
Eisner et al. 2004

Sky

UV

Inner Disk Radii

Adapted from Millan-Gabet et al. PPV Review



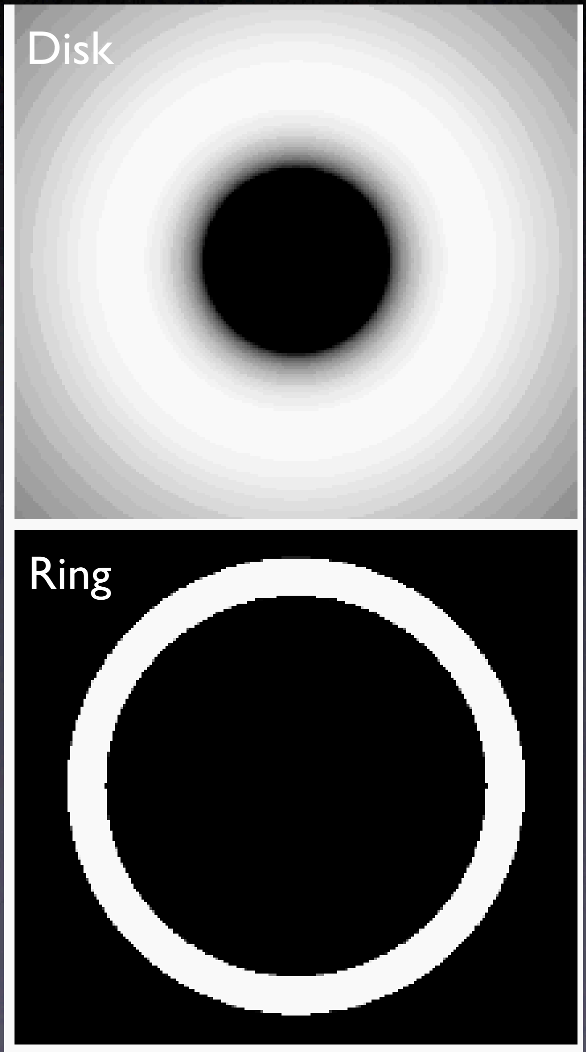
Puffed-Up: T(R) ~ constant

T(R) $\propto R^{-3/4}$: Flat

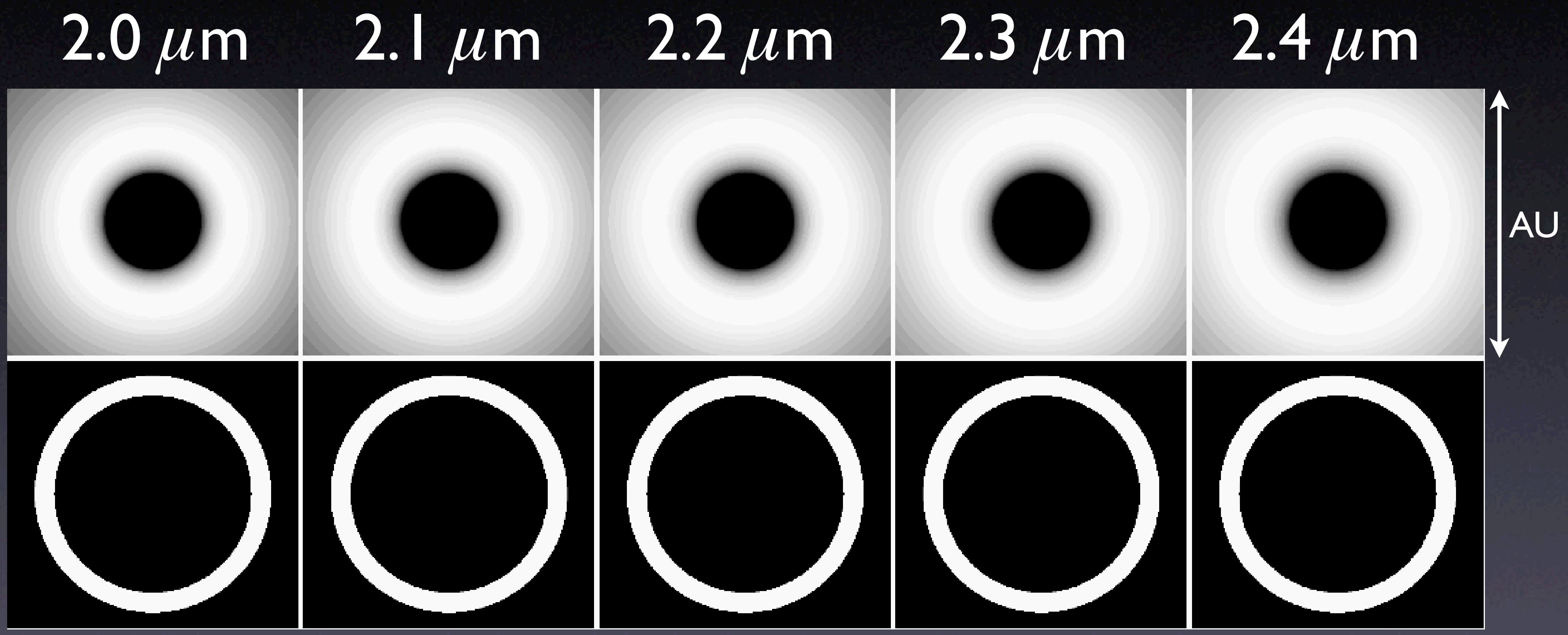
data from Eisner et al. 2003,2004,2005; Millan-Gabet et al. 2001; Monnier et al. 2005; Akeson et al. 2000,2005,2006

Model Images

- Data appear more consistent with ring-like models (e.g., puffed-up inner disk rims)
    - different inner radii for same flux-averaged emission size
- Further tests possible...



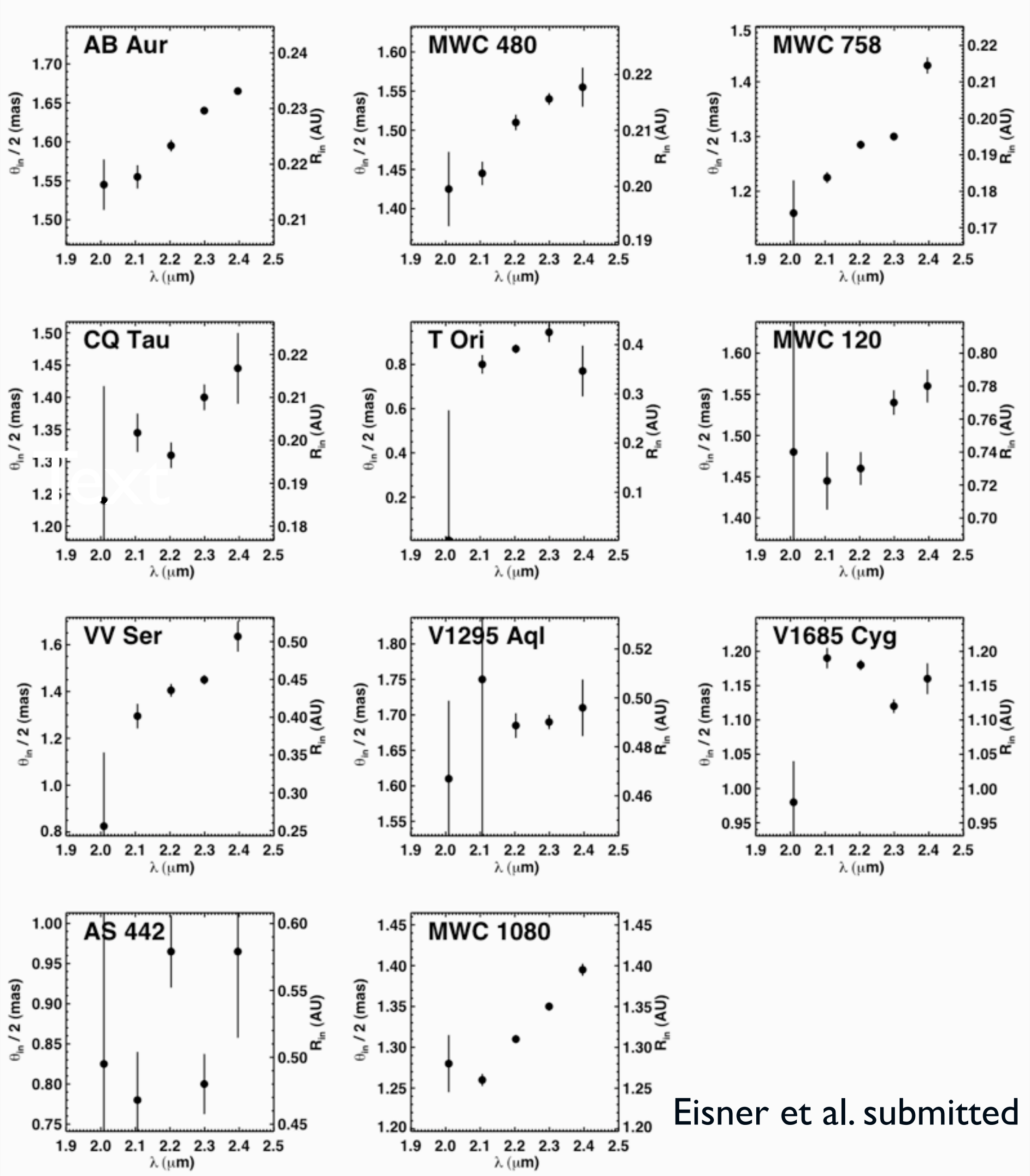
Spectral Dispersion



Disks with T gradients look different at different λs;
not so for single-T rings

Spectrally dispersed data

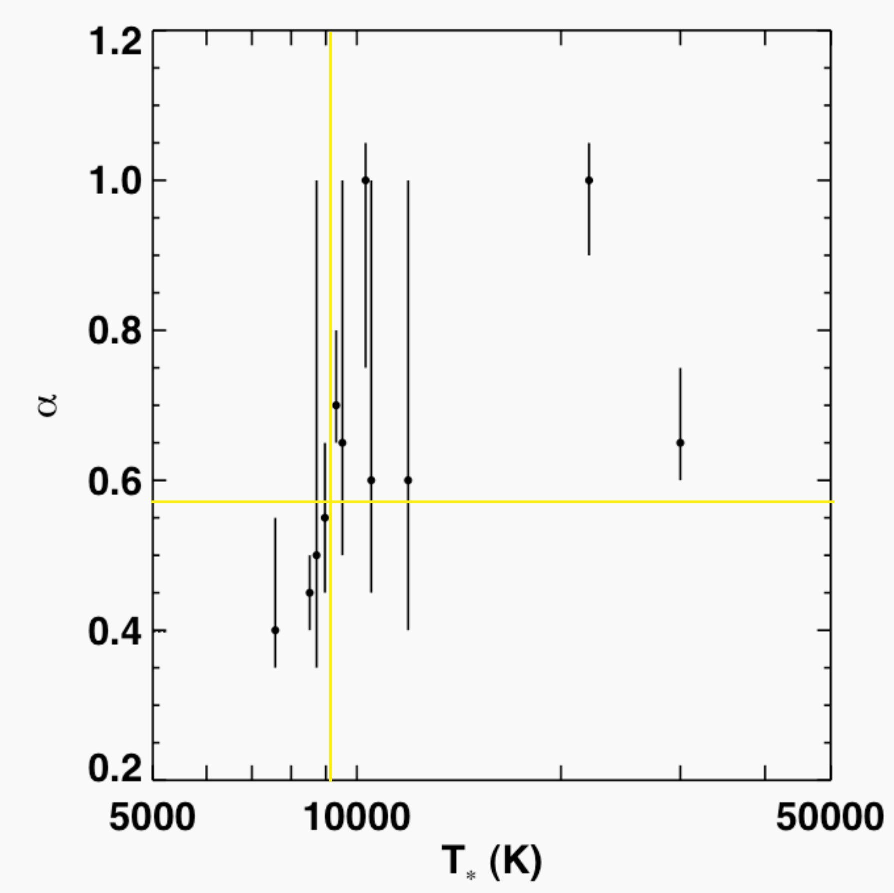
- "SDI" can probe inner disk structure
- 5-channel PTI data (R=25) for HAEBEs
- Constrain exponent of *T(R)* directly as well as R_{in}, T_{in}



Eisner et al. submitted

Spectrally dispersed data

- Simple puffed-up inner rims are single-T rings
  - not consistent with data
- Syst. shallower profiles for low-mass stars
  - need more realistic puffed-up inner rims with shallow gradients
  - *n.b.* will get smaller R_{in} than for single-T ring models

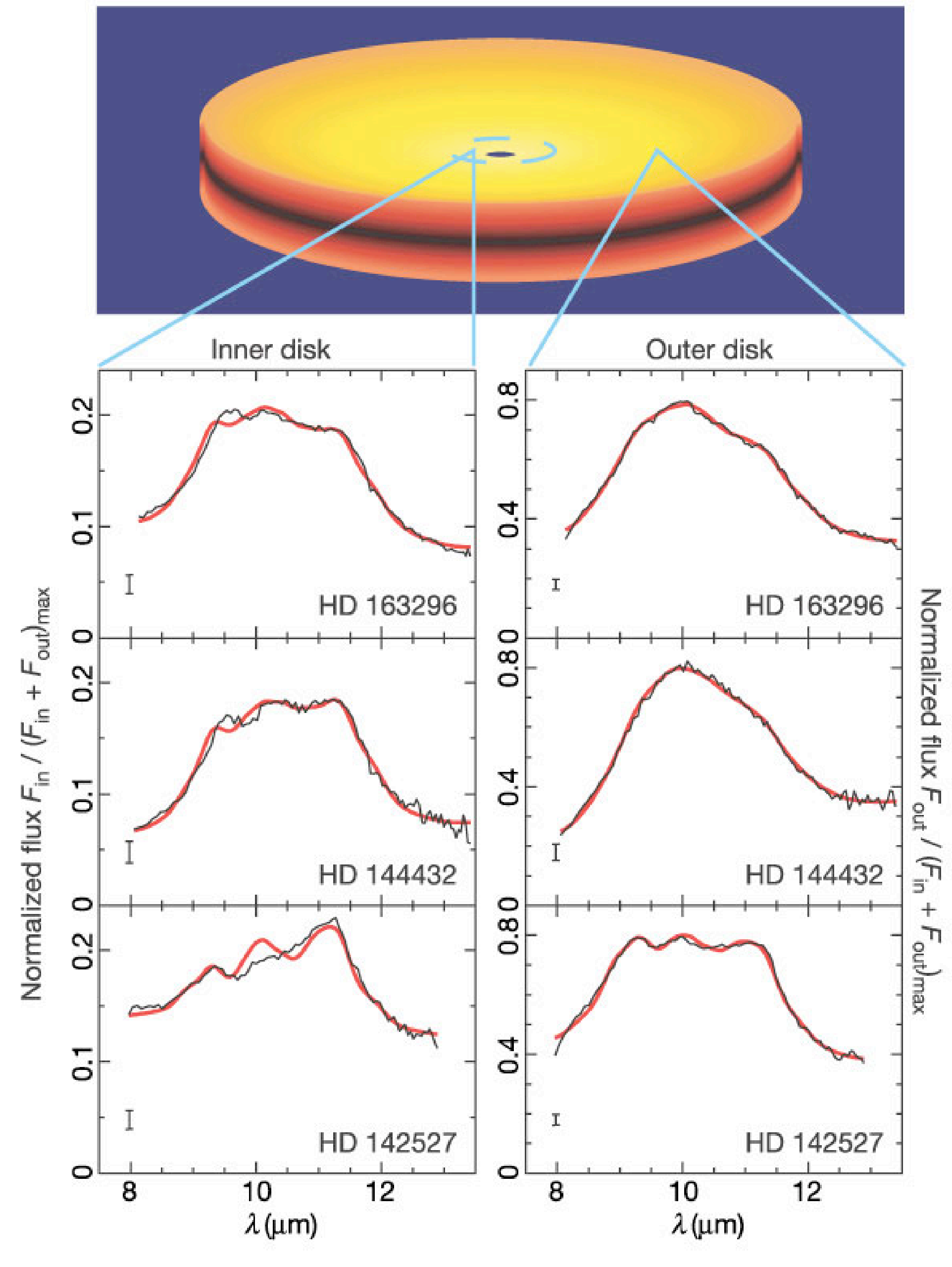


Eisner et al. submitted

Spectrally dispersed 10 μm data

- Disk geometry (compare size vs. wavelength)
  - redder objects typically more flared (Leinert et al. 2004; see also Liu et al. 2005)

- Dust grain composition
  - crystallization/annealing



van Boekel et al. 2004

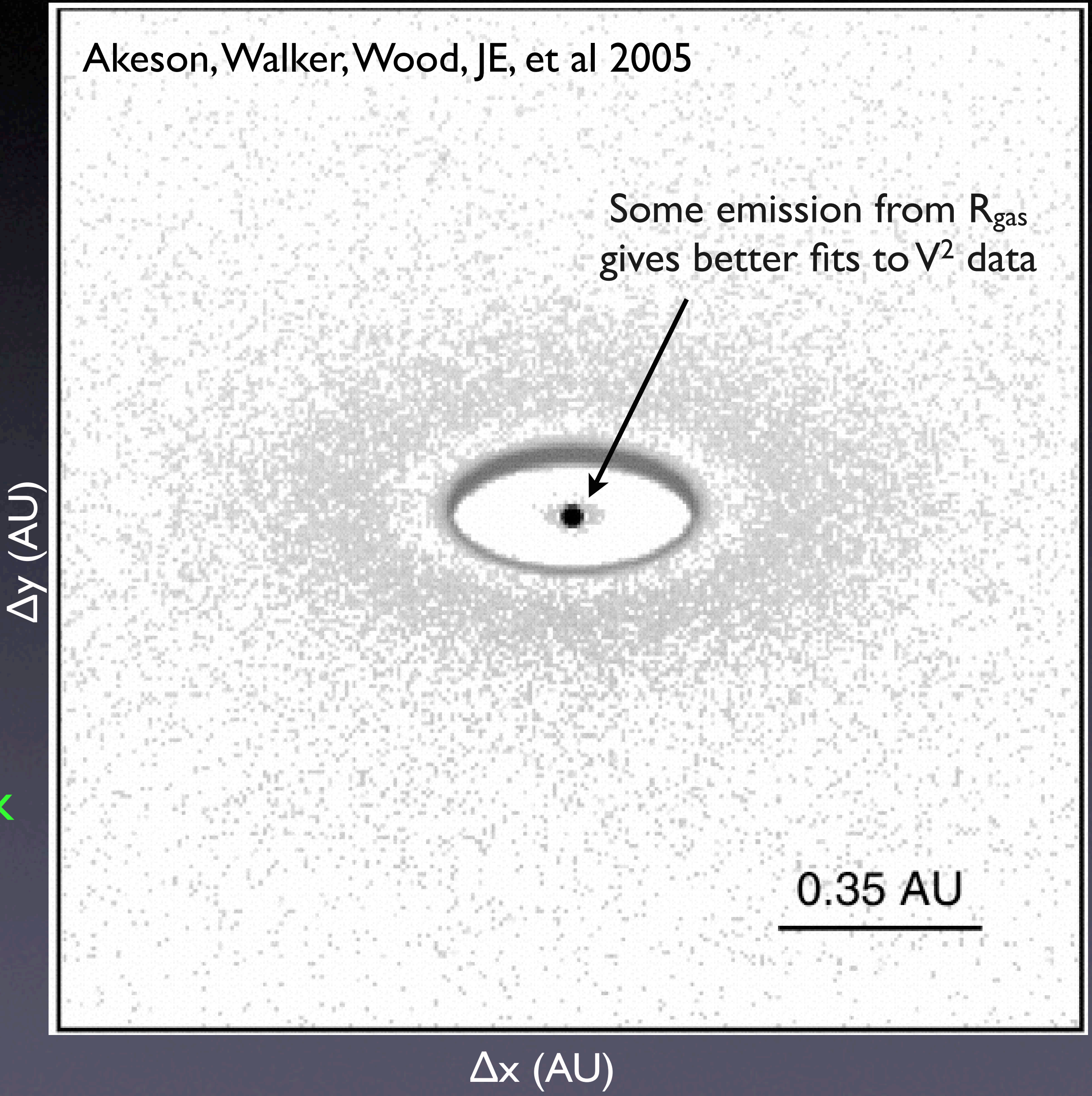
Dust & Gas Truncation

- $R_{mag} \approx R_{corot}$ (R_{gas})
- $R_{meas} > R_{mag}$

- Higher M_{dot}: larger R_{sub}, smaller R_{gas}

- Planet formation exterior to dust sublimation radius at ~0.1 AU
  - terrestrial planets: ok
  - hot Jupiters: no

migration...

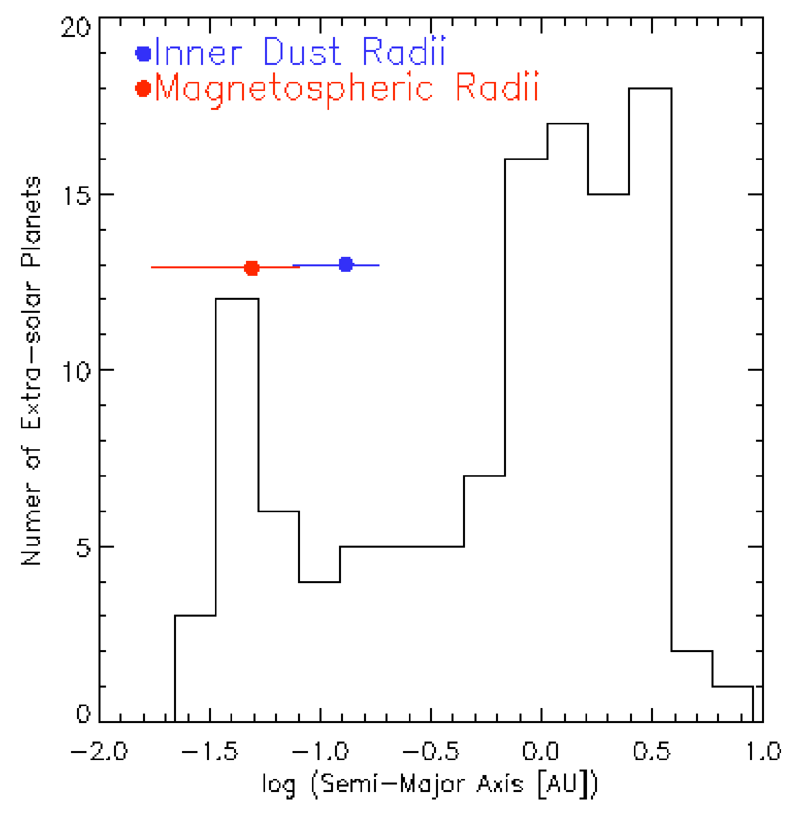


Akeson, Walker, Wood, JE, et al 2005

Some emission from R_{gas} gives better fits to V^2 data

Planetary Migration

Source	0.63 R_{in} (dust) (AU)	0.63 R_{mag} (gas) (AU)
AS 205A	0.09	0.02
AS 207A	0.15	0.08
V2508 Oph	0.08	0.07
PX Vul	0.20	0.03

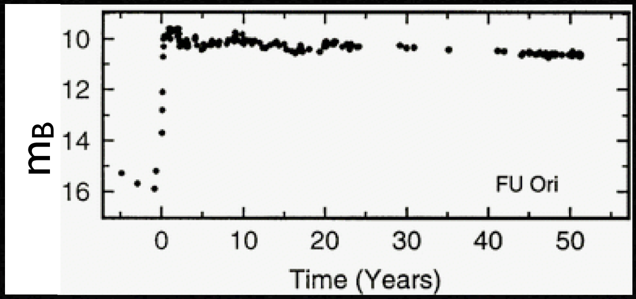


- Migration halts in 2:1 resonance with disk edge (gaseous: Lin et al. 1996; dust: Kuchner & Lecar 2002)

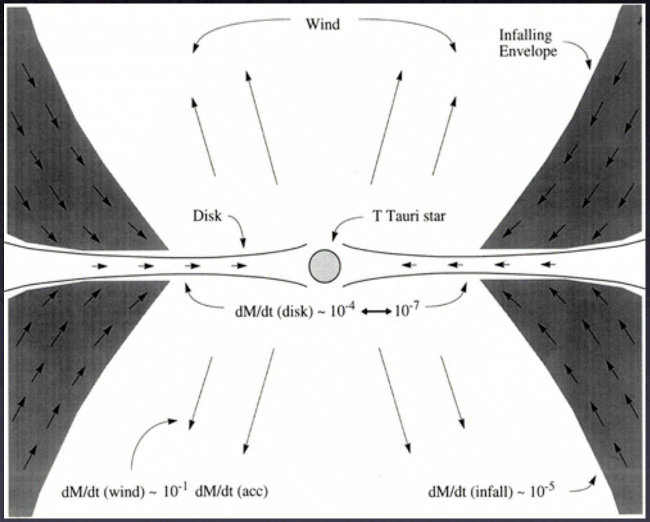
Smaller R_{in} vals possible for shallower $T(R)$ profiles (e.g., Eisner et al. submitted); but gas still preferred...

FU Oris

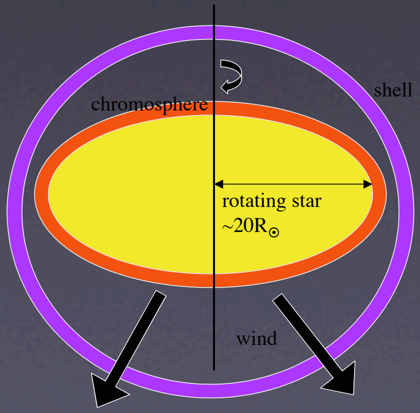
Outbursts; Possible Protostars?



- Disk instability: enhanced accretion & L_{acc} (e.g., Hartmann & Kenyon 1996)
  - linked to protostellar accretion? (e.g., Kenyon et al. 1993; Eisner et al. 2005b)

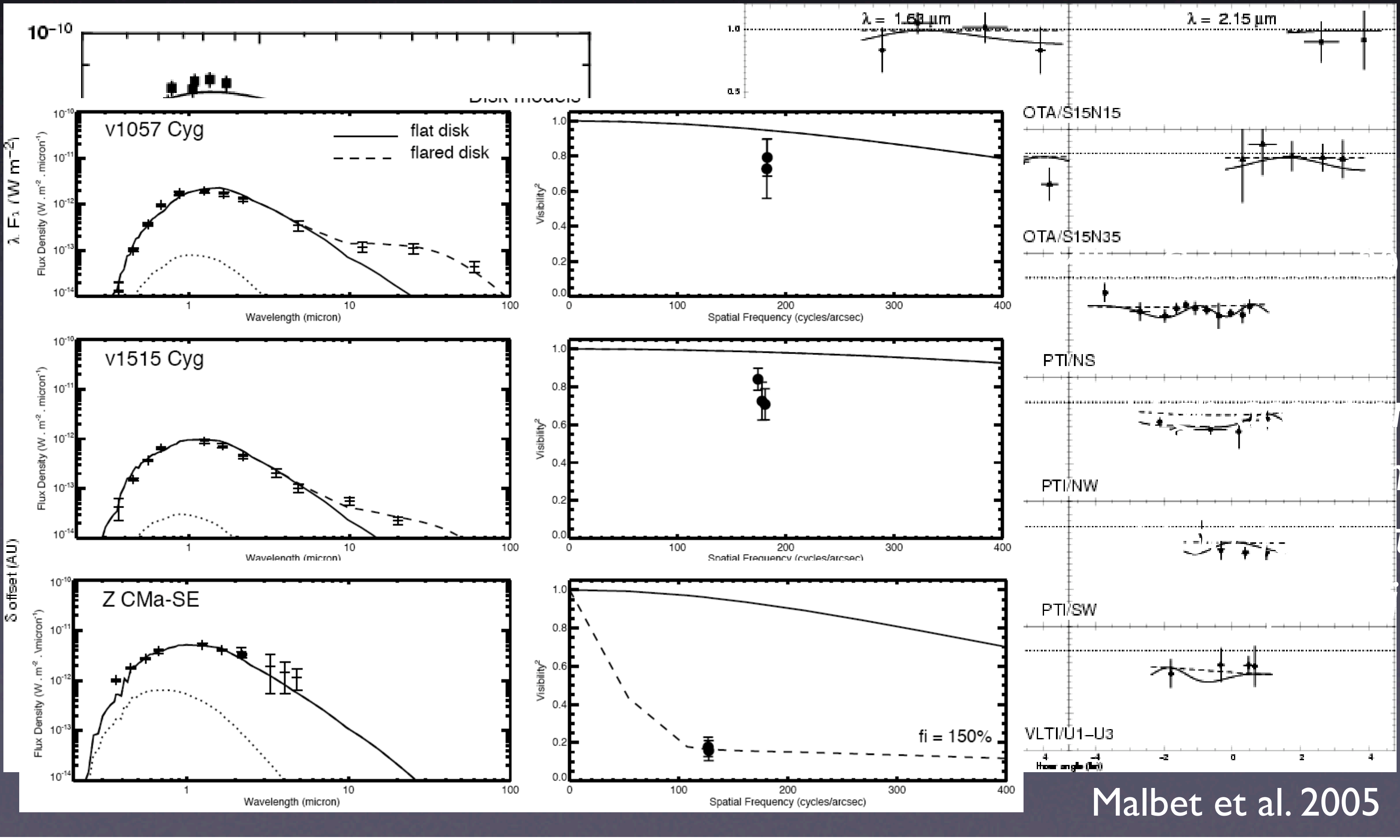


- Elongated star undergoes instability (Larson 1980; Petrov & Herbig 1992)



FU Oris

- Accretion-dominated disks
  - in prototype, FU Ori, paradigm works: disk extends to star



06

n rate,

alos:

tostellar

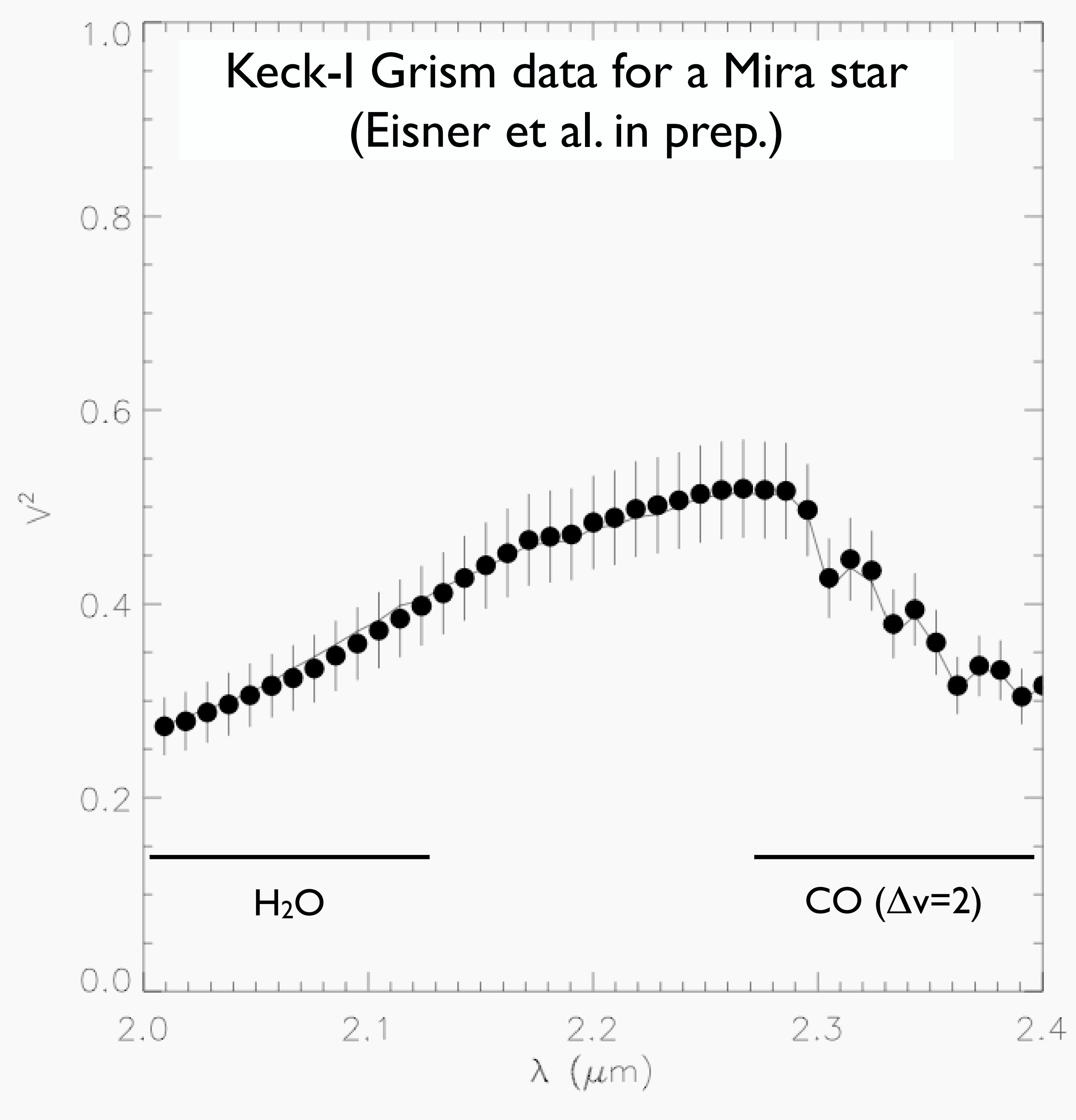
on?

Malbet et al. 2005

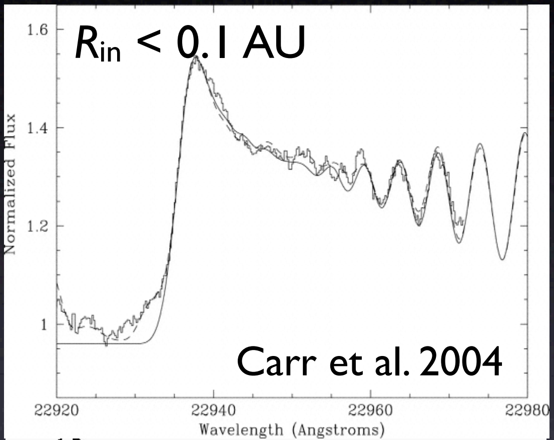
Future Directions

- Inner disk gas really traced by R_{mag}, R_{corot}?
  - spectroscopy
- Radial temp/density structure of inner disk
  - spectroscopy, polarimetry
- Inner disk geometry, e.g., how puffed-up, rounded is inner edge?
  - closure phases, imaging
- Consistency of inner/outer disk geometries inferred from different techniques

as

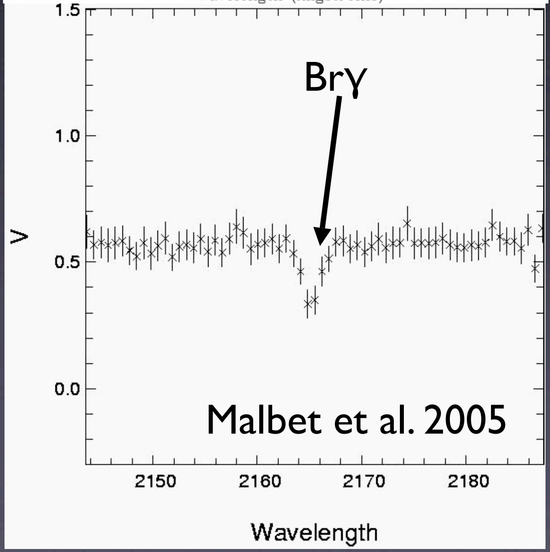


Keck-I Grism data for a Mira star
(Eisner et al. in prep.)



R_{in} < 0.1 AU

Carr et al. 2004



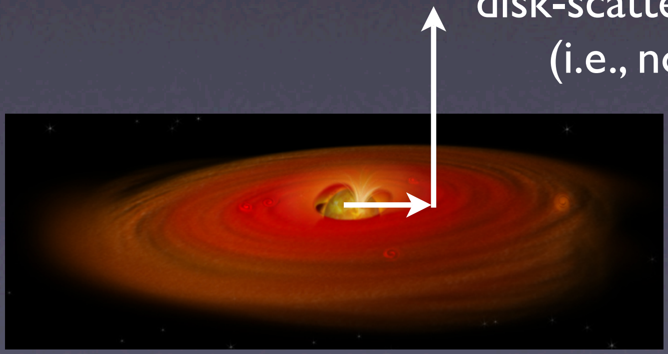
Malbet et al. 2005

Temperatures/Densities

- Spectroscopy can probe *T(R)*
- but *T(R)* is (often) degenerate with $\tau(R)$:

$$F_\nu \propto B_\nu(T_{\rm dust})\left(1 - e^{-\tau}\right)$$

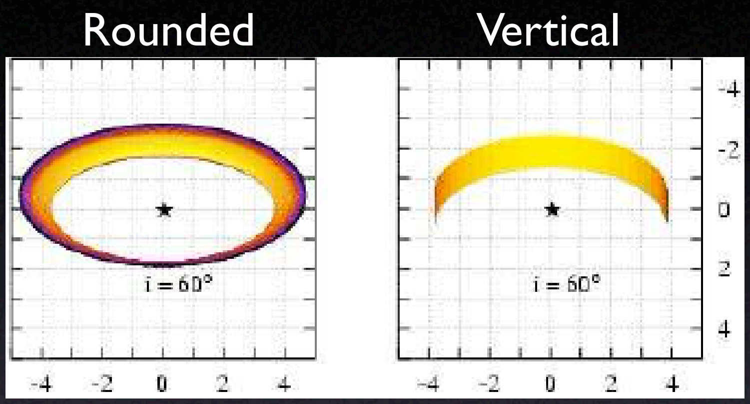
- polarimetry sensitive to disk-scattered light; probes $\tau(R)$ directly & removes degeneracy



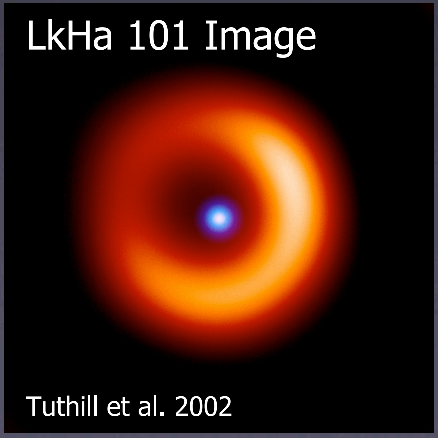
disk-scattered light looks like stellar spectrum (i.e., not dependent on $T_{\rm dust}$), polarized

Better Inner Disk Geom.

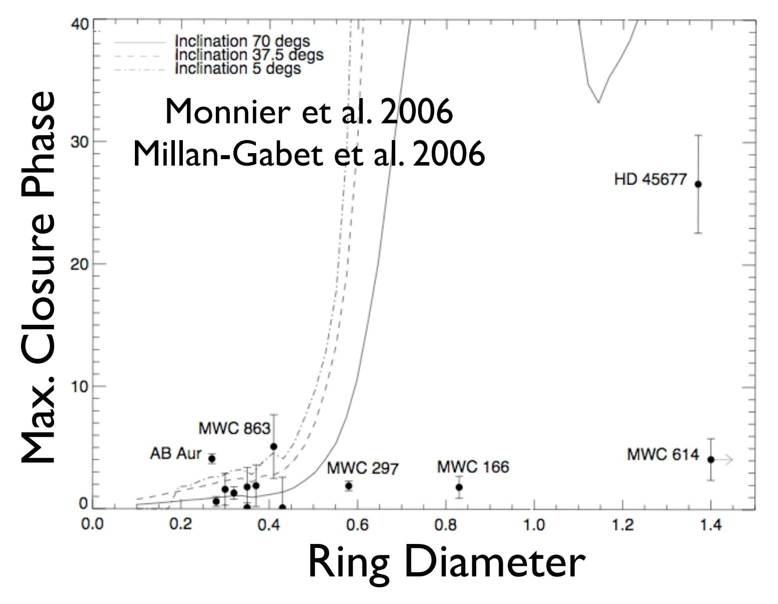
- Some info about geom. from V^2
- temp. gradients from spectroscopy also probe rim geom.
- skewness from closure phases
- with enough telescopes, can construct real (simple) images



Isella & Natta 2005

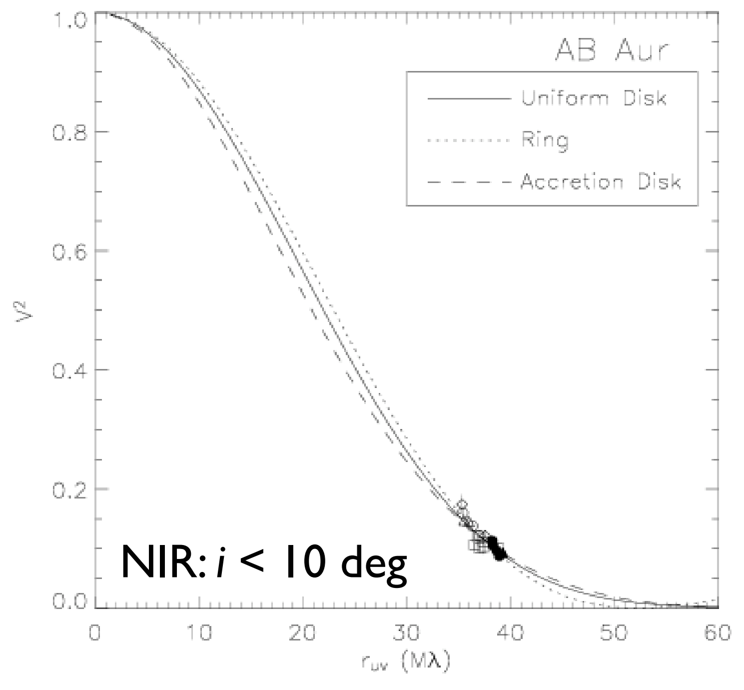


Tuthill et al. 2002

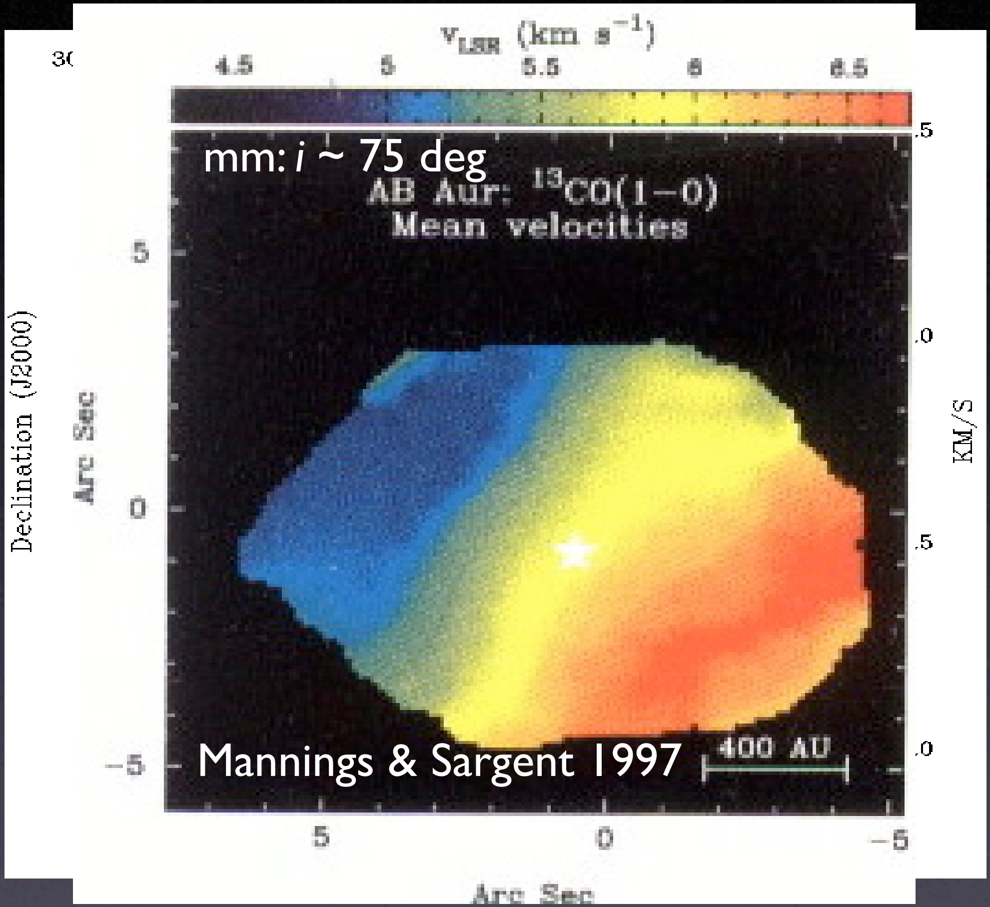


Monnier et al. 2006
Millan-Gabet et al. 2006

Inner vs. Outer Disks



NIR: i < 10 deg



mm: i ~ 75 deg

Mannings & Sargent 1997

- Warped disks?
- Halos?
- Hard to tell at present: inner & outer disk measurements still uncertain

Current Instruments

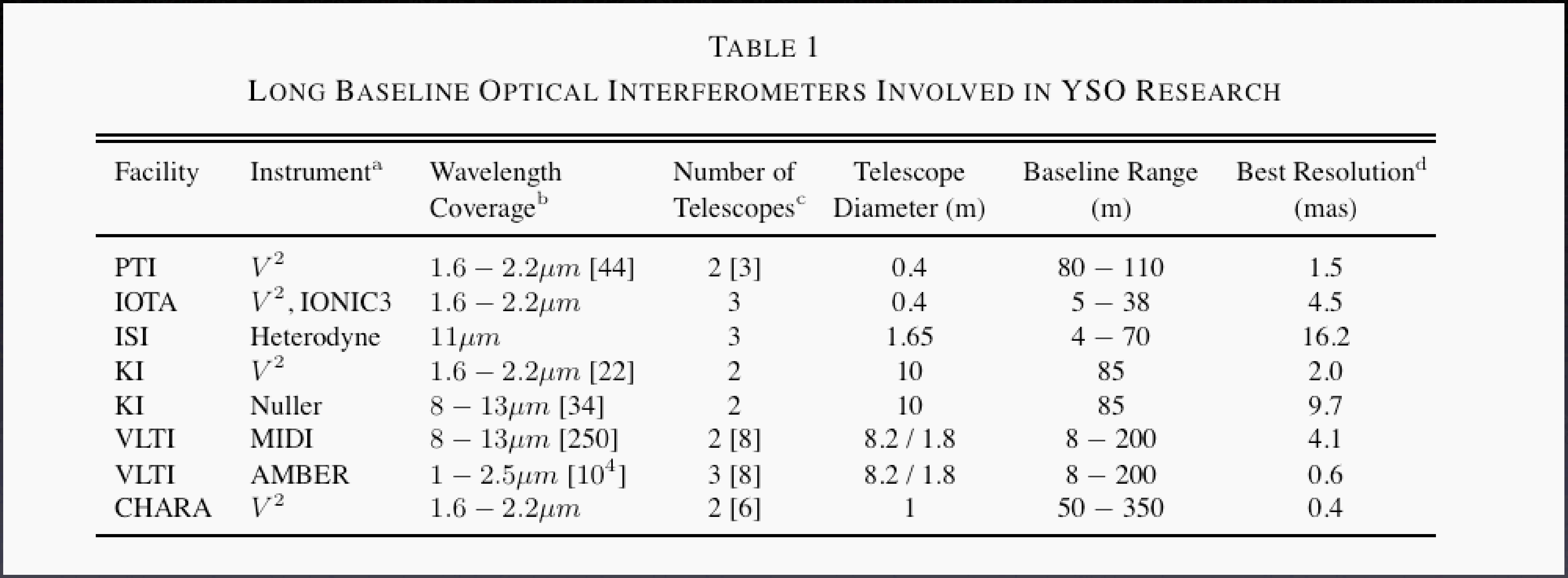


TABLE 1

LONG BASELINE OPTICAL INTERFEROMETERS INVOLVED IN YSO RESEARCH

Facility	Instrument[a]	Wavelength Coverage[b]	Number of Telescopes[c]	Telescope Diameter (m)	Baseline Range (m)	Best Resolution[d] (mas)
PTI	V^2	$1.6 - 2.2\mu m$ [44]	2 [3]	0.4	80 – 110	1.5
IOTA	V^2, IONIC3	$1.6 - 2.2\mu m$	3	0.4	5 – 38	4.5
ISI	Heterodyne	$11\mu m$	3	1.65	4 – 70	16.2
KI	V^2	$1.6 - 2.2\mu m$ [22]	2	10	85	2.0
KI	Nuller	$8 - 13\mu m$ [34]	2	10	85	9.7
VLTI	MIDI	$8 - 13\mu m$ [250]	2 [8]	8.2 / 1.8	8 – 200	4.1
VLTI	AMBER	$1 - 2.5\mu m$ [10^4]	3 [8]	8.2 / 1.8	8 – 200	0.6
CHARA	V^2	$1.6 - 2.2\mu m$	2 [6]	1	50 – 350	0.4

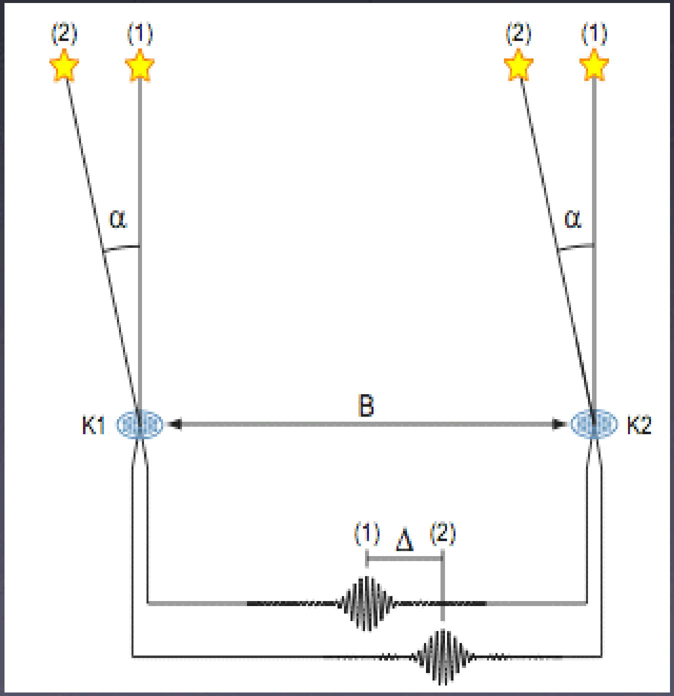
Millan-Gabet et al. 2006

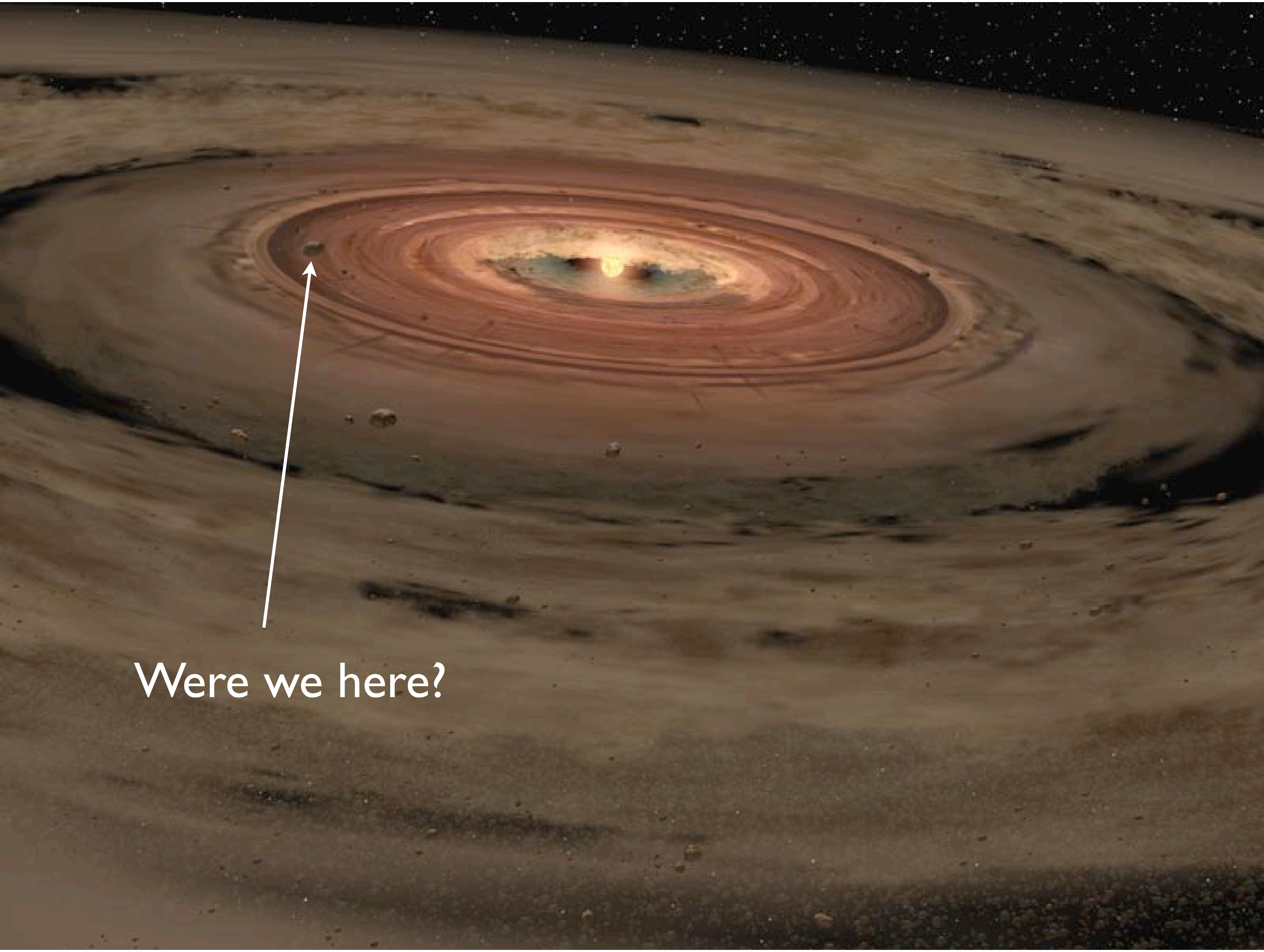
- For ancillary data:
  - Spectroscopic veiling: big telescopes, like Keck, Magellan, Gemini, VLT
  - Photometry: smaller telescopes, like 2MASS or Palomar 60-inch

Next-Gen Interferometers

- KI, VLTI, CHARA, SIM?, (ALMA, SKA)
  - sensitivity, spectroscopy, closure phases

- Keck-I Upgrade (recently funded)
  - “Dual-Star”: Phase Referencing & Astrometry
    - Disks: larger sample, lower-mass stars, spectroscopy
    - planet search (old & young stars): M_{pl} direct
    - Astrometry of young stars near GC: black holes, GR,GC distance





Were we here?