# The inner regions of disks with infrared interferometry

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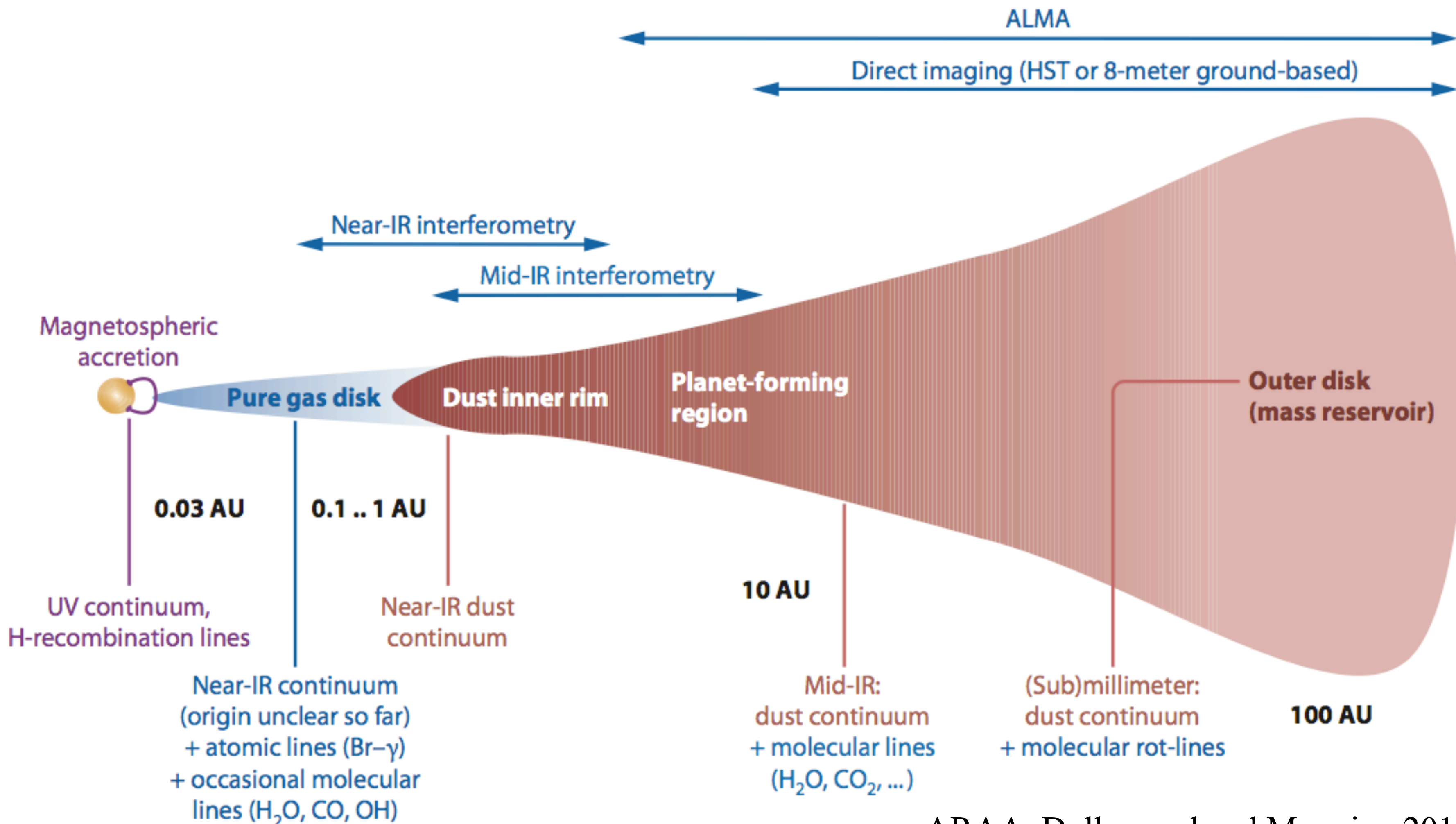
# Outline

- Early observations
- Inner rim shape
- What's inside the dust?
- Disk evolution and the main sequence
- Outstanding issues and open questions

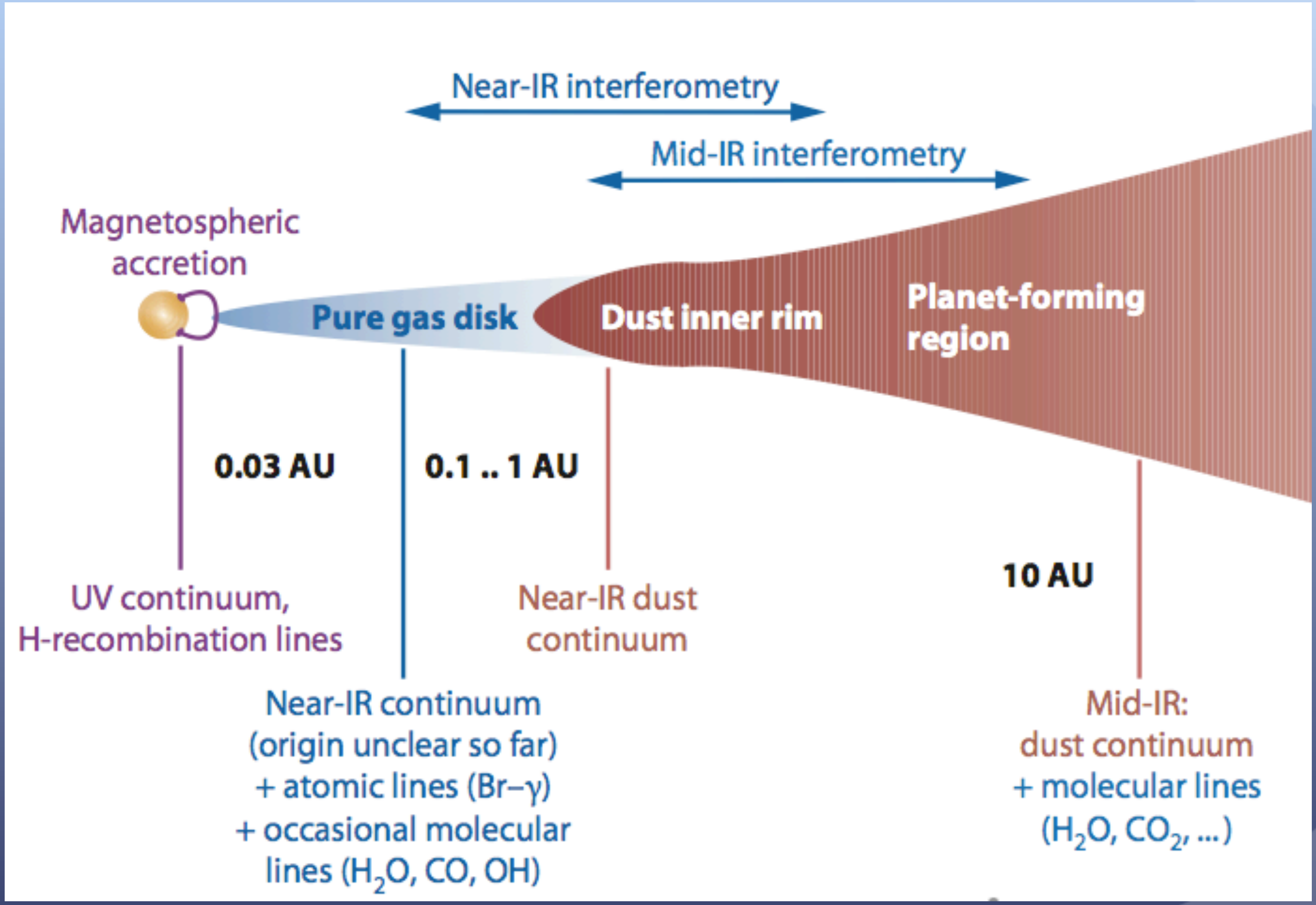
- Covered in later talks: dust evolution and winds, more on massive stars

# Circumstellar disk structure




ARAA, Dullemond and Monnier, 2010

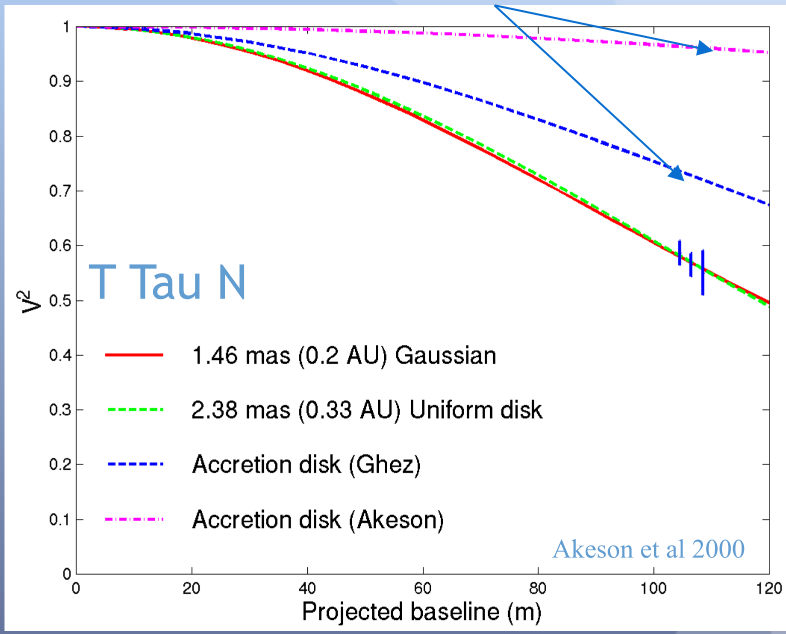
# Infrared Interferometry focuses on the inner disk



# Where we were ~10 years ago: First YSO observations

- FU Oris
  - FU Ori (Malbet et al 1998) consistent with accretion disk model
- Herbig Ae/Be stars
  - AB Aur (Millan-Gabet et al 1999, IOTA)
  - Survey of 15 Herbigs (Millan-Gabet et al 2001, Infrared Optical Telescope Array - IOTA)
  - General conclusions:
    - Late type Herbigs NOT consistent with flat accretion disks (**too large**, too few inclined sources)
- T Tauris
  - 2 sources observed at Palomar Testbed Interferometer – PTI (Akeson et al 2000)
  - Also **larger** than predicted, but inclined disks observed

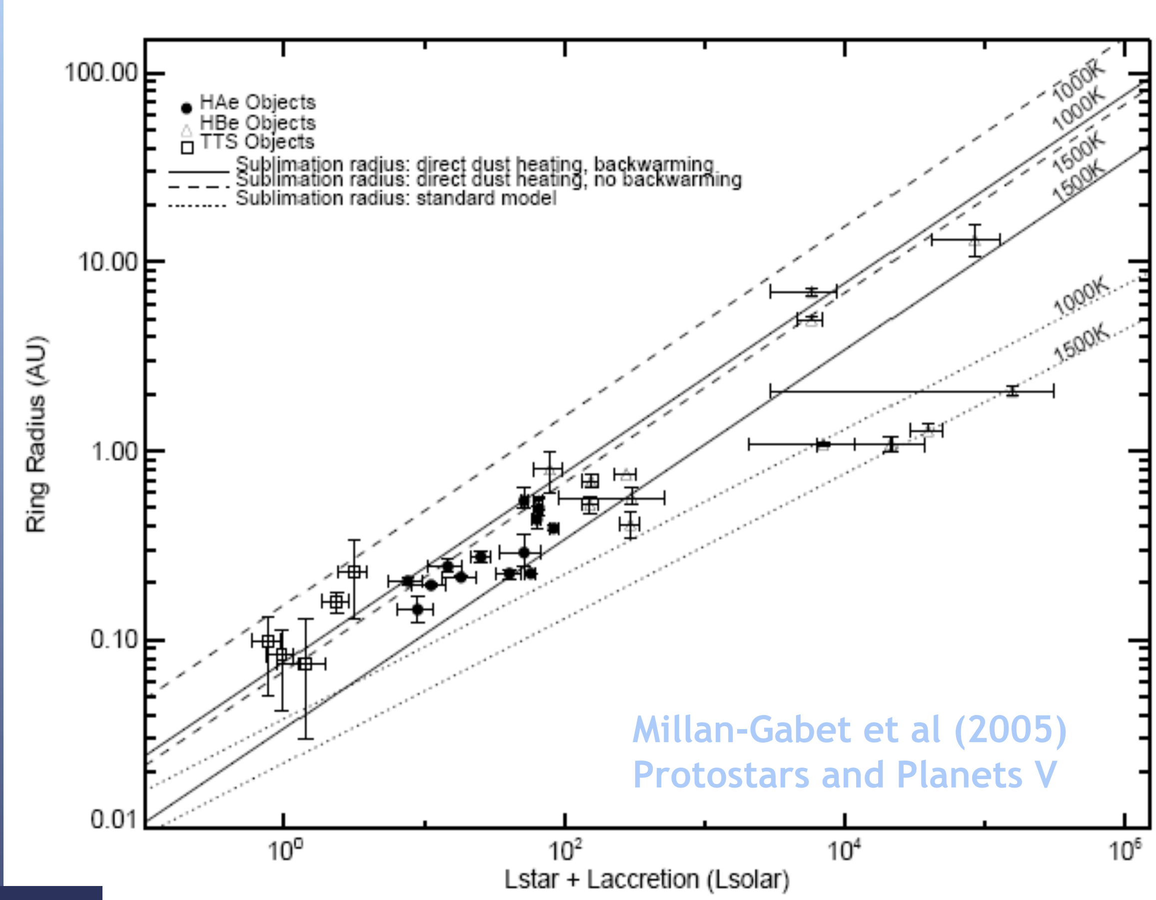
Size predictions from disk models fit to other kinds of data




These observations plus the Herbig SED NIR bump can both be explained by an inner dust rim at the dust sublimation radius (Natta et al 2001, Tuthill et al 2001)

# Where we were ~5 years ago

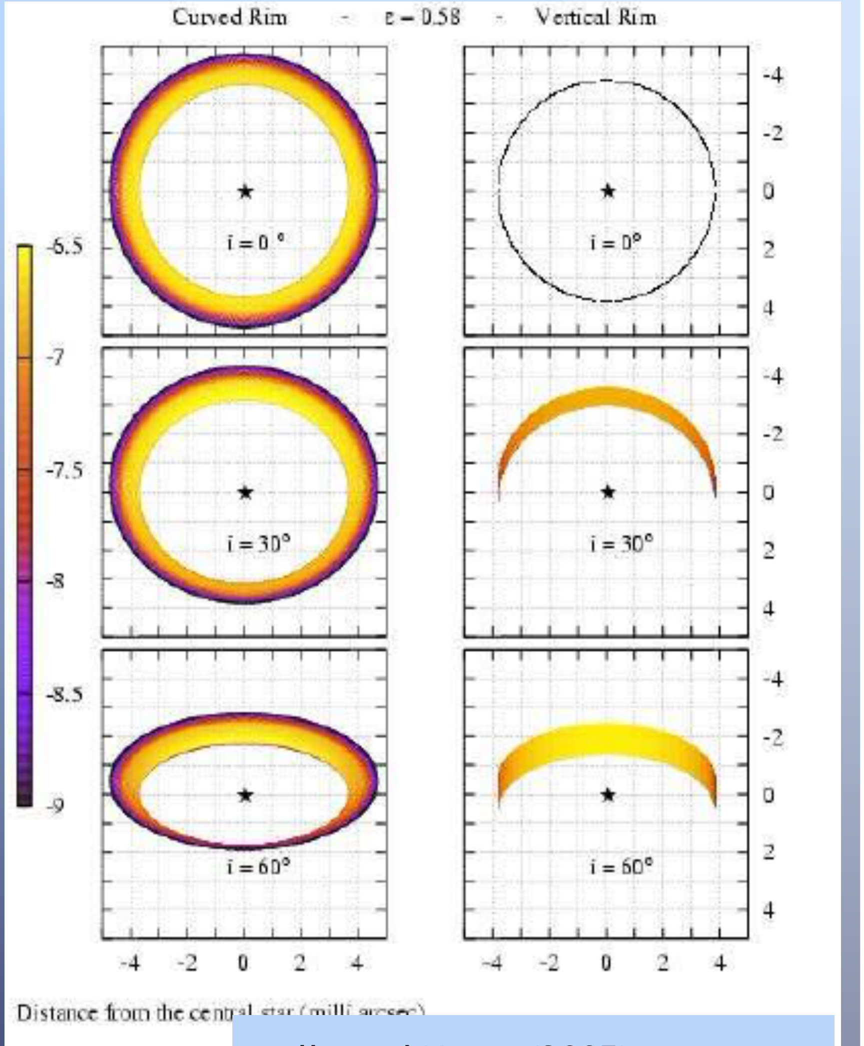
- Inner dust disk size related to luminosity (stellar and accretion) over several orders of magnitude in luminosity
- Some of the more massive Herbigs (early Be) are consistent with optically thick inner cavity



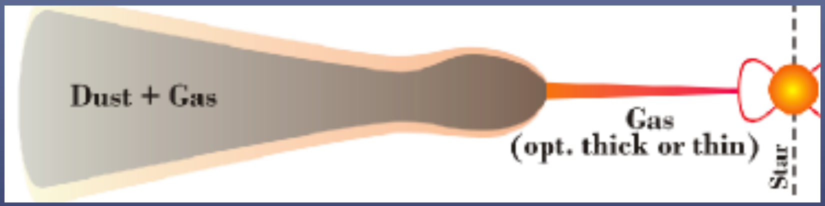

Near-infrared data from IOTA, PTI, KI

# Shape of the inner rim

- The first inner rim models had vertical inner walls with the height set by the temperature and radius
- However, due to the dust evaporation temperature dependence on density, a rounded rim is predcited
- The shape of the inner rim (vertical vs. curved, is best measured by closure phases)

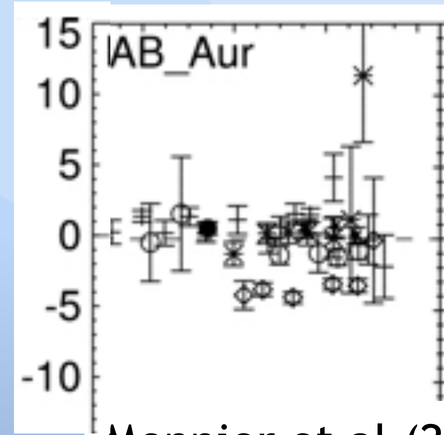



Isella and Natta (2005)



# Measuring the inner rim

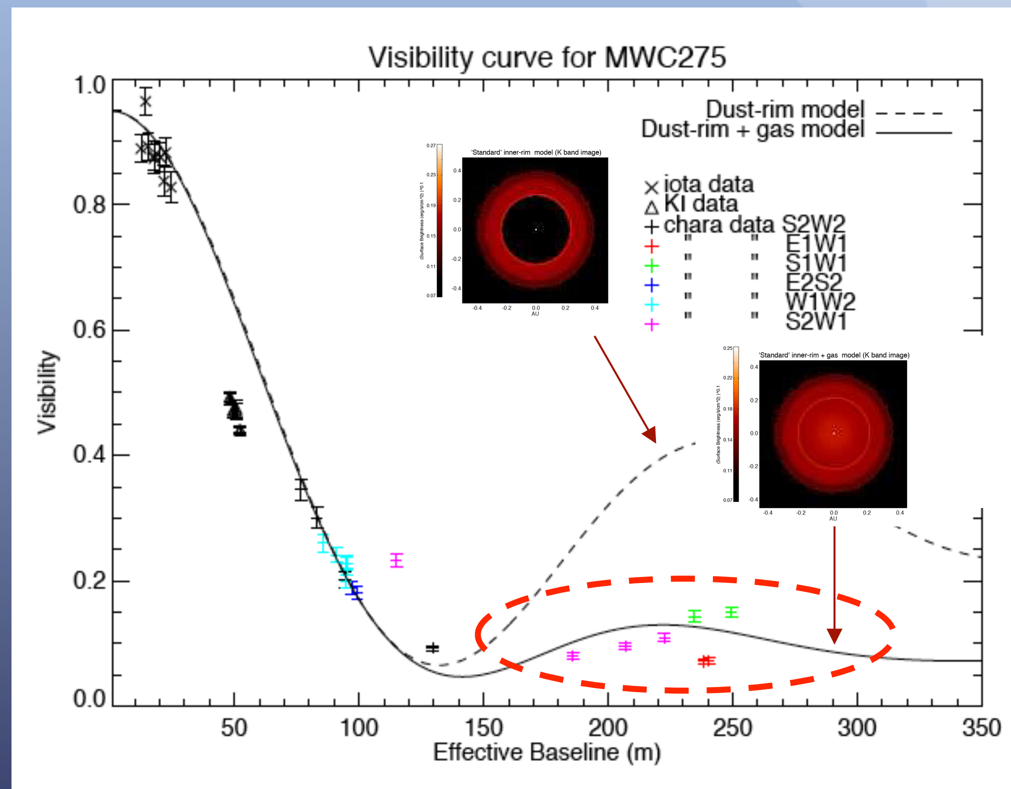
- Early closure phases observations (e.g. Monnier et al 2006, IOTA) had a surprisingly high degree of centro-symmetry, very rounded inner dust rims




Monnier et al (2006)

- The very low visibilities measured by the CHARA longest baselines (~300m) cannot be reproduced by detailed models of inner dust rim (they cannot be made smooth enough).

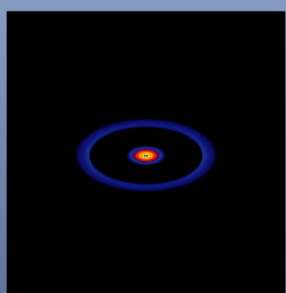
- Best explained by adding NIR emitting gas inside the dust sublimation radius.



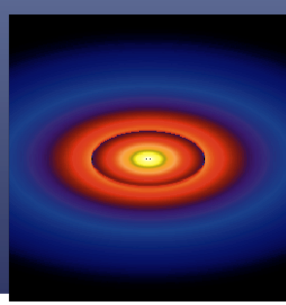

Tannirkulam, Monnier, Millan-Gabet et al., ApJ, 2008

# Gas within the dust radius: Multi-wavelength observations

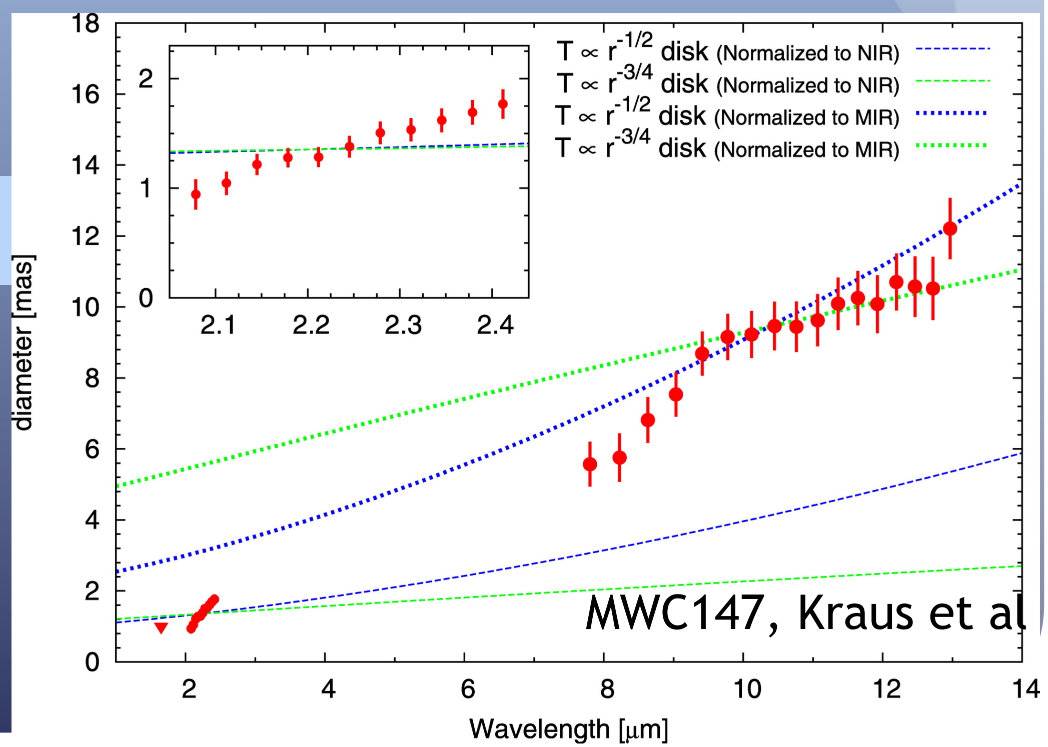
- Kraus et al (2008) combine H (IOTA), K (AMBER) and N (MIDI)
- Measured size not consistent with T ∝ r-3/4
- 2-D radiative transfer modeling -> optically thick gaseous disk inside of the dust sublimation radius
- See also Isella et al (2008, MWC 758), Benisty et al (2010, HD 162396)



H and K band sensitive to hot gas and dust

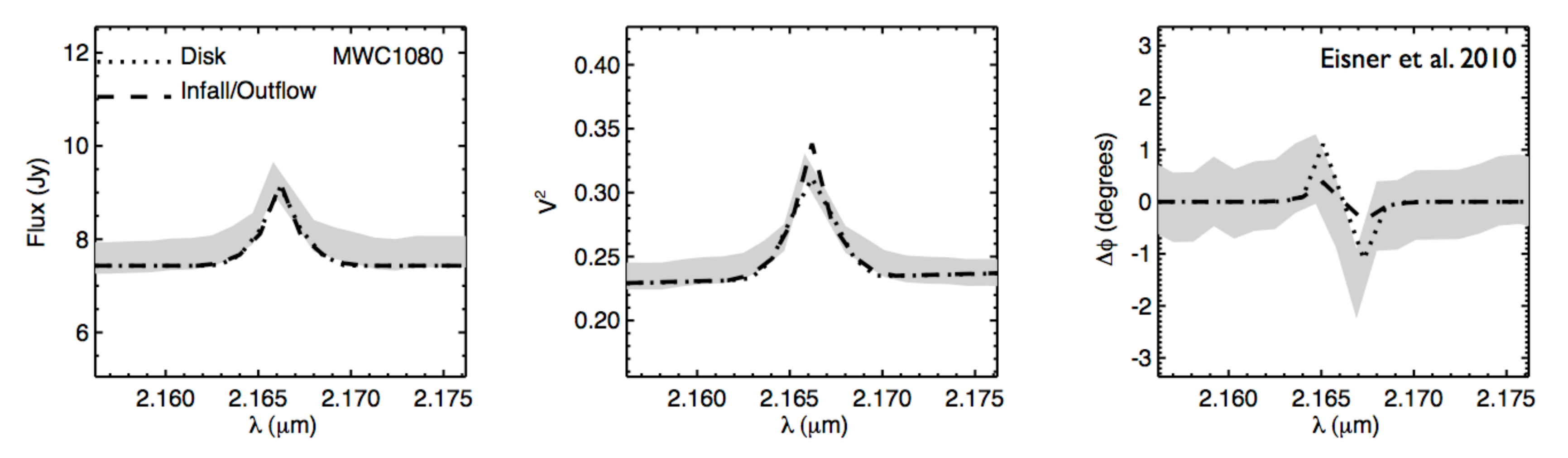


N band sensitive to both gas and dust emission

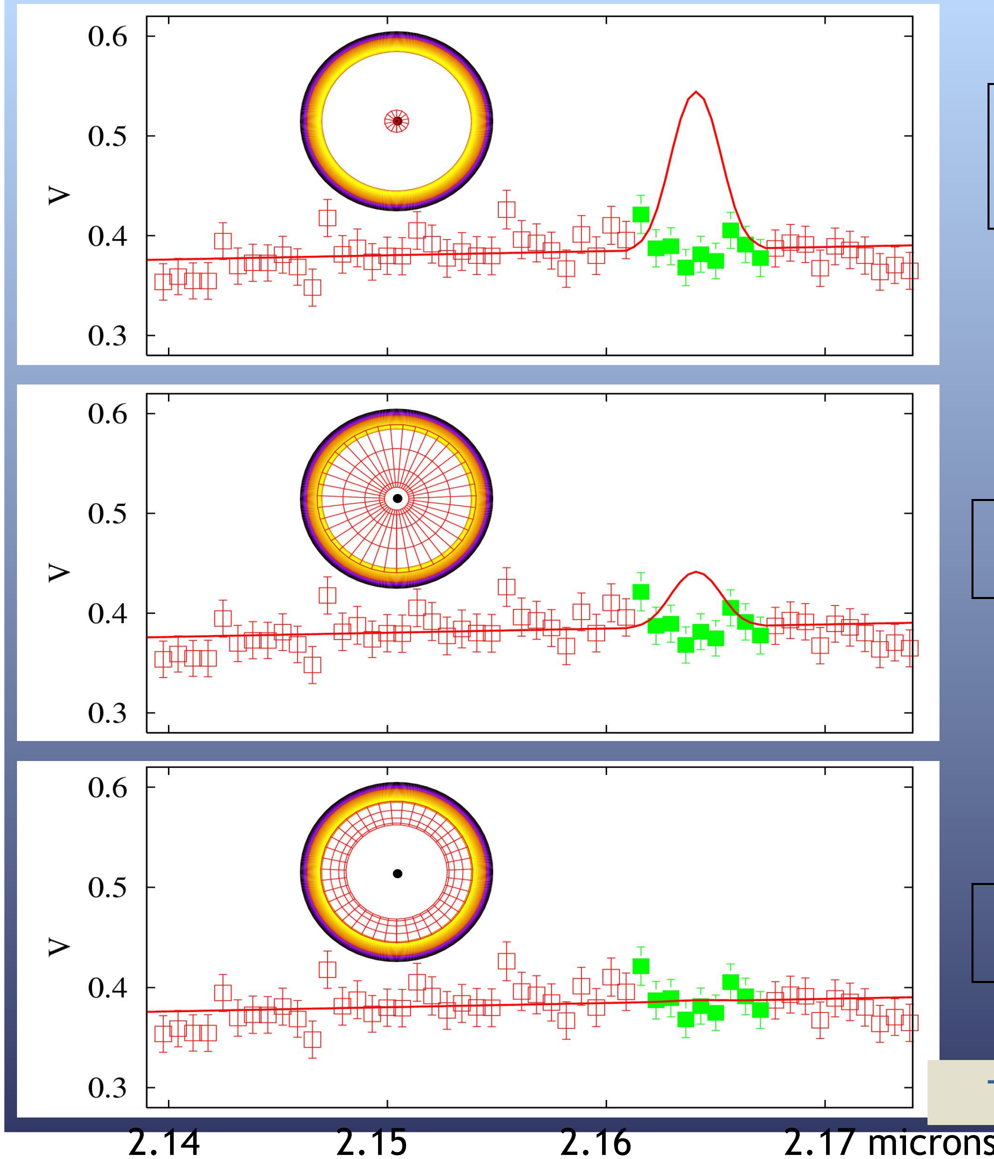


# High spectral resolution to probe gas

- High spectral resolution first demonstrated at VLTI (Malbet et al 2007, MWC 297)
- Eisner et al (2010) resolved the Brackett gamma line in 15 young stellar objects
  - Example object MWC 1080 (young B star): Brackett gamma is more compact than the continuum and is consistent with a disk origin for the emission line



# Nature of Brγ in the Herbig Ae star HD104237




Disk truncated by magnetosphere

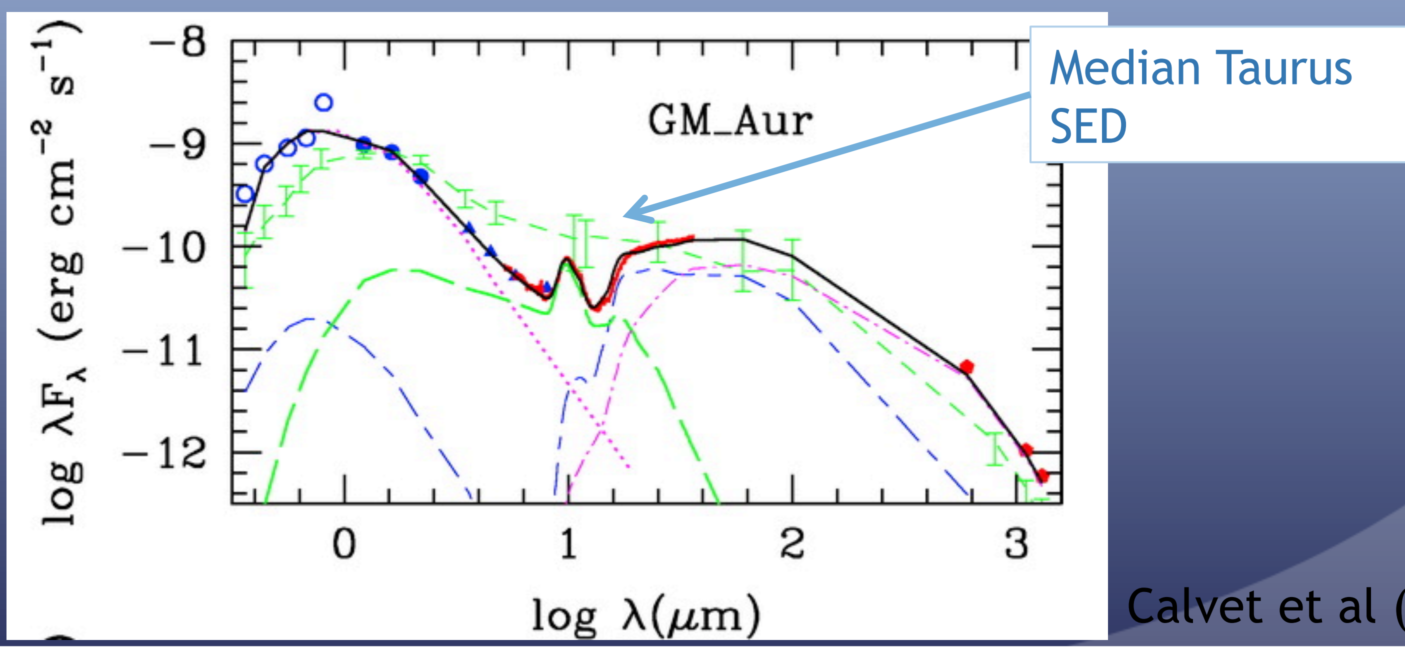
Gas within the disk

Outflowing wind

Tatulli et al. (2007)

# Transition disks

- Transition objects have spectral energy distributions suggesting an opacity hole in the inner (1 to 20 AU) disk
  - Could be cleared or contain optically thin material
  - Suggested clearing mechanisms include grain growth, dynamical clearing from a companion (stellar or planetary) or photoevaporation

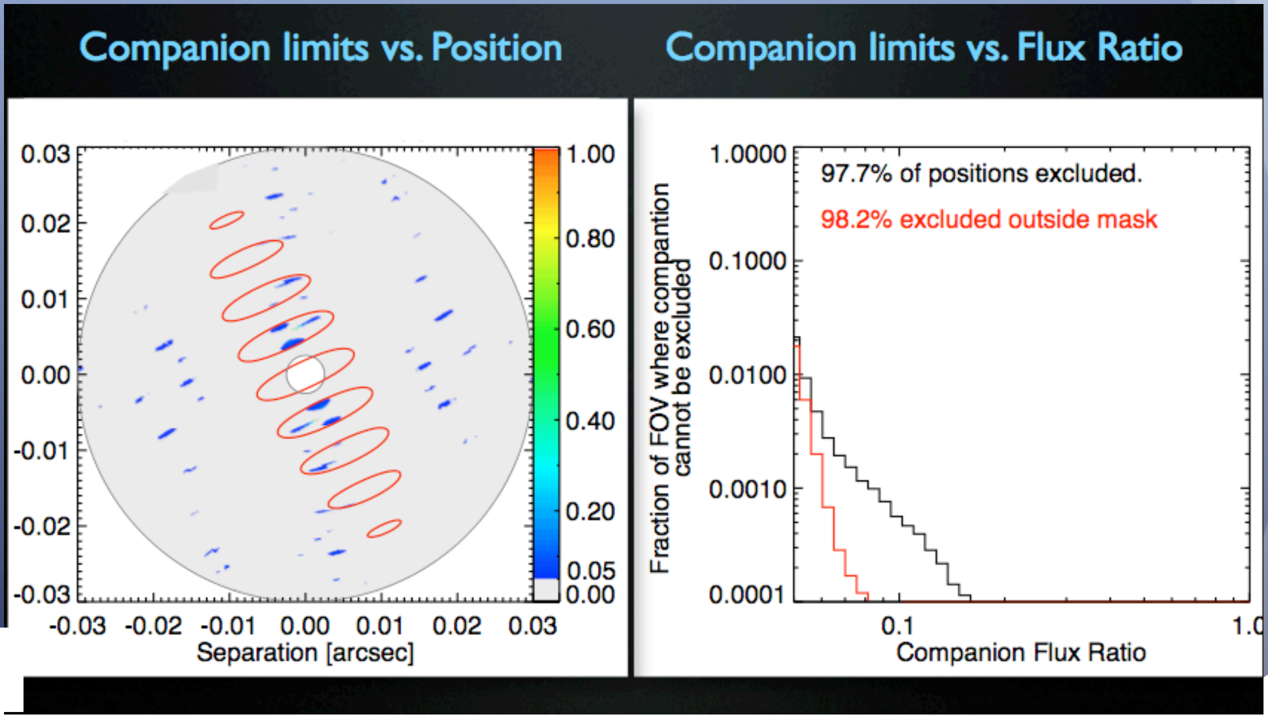



Calvet et al (2005)

# Transition disk survey

- Survey 5 transition disks with KI to search for companions and constrain disk size
  - Binaries with 20:1 flux ratios ruled out for over 95% of KI field of view (50 mas) for all 5 sources

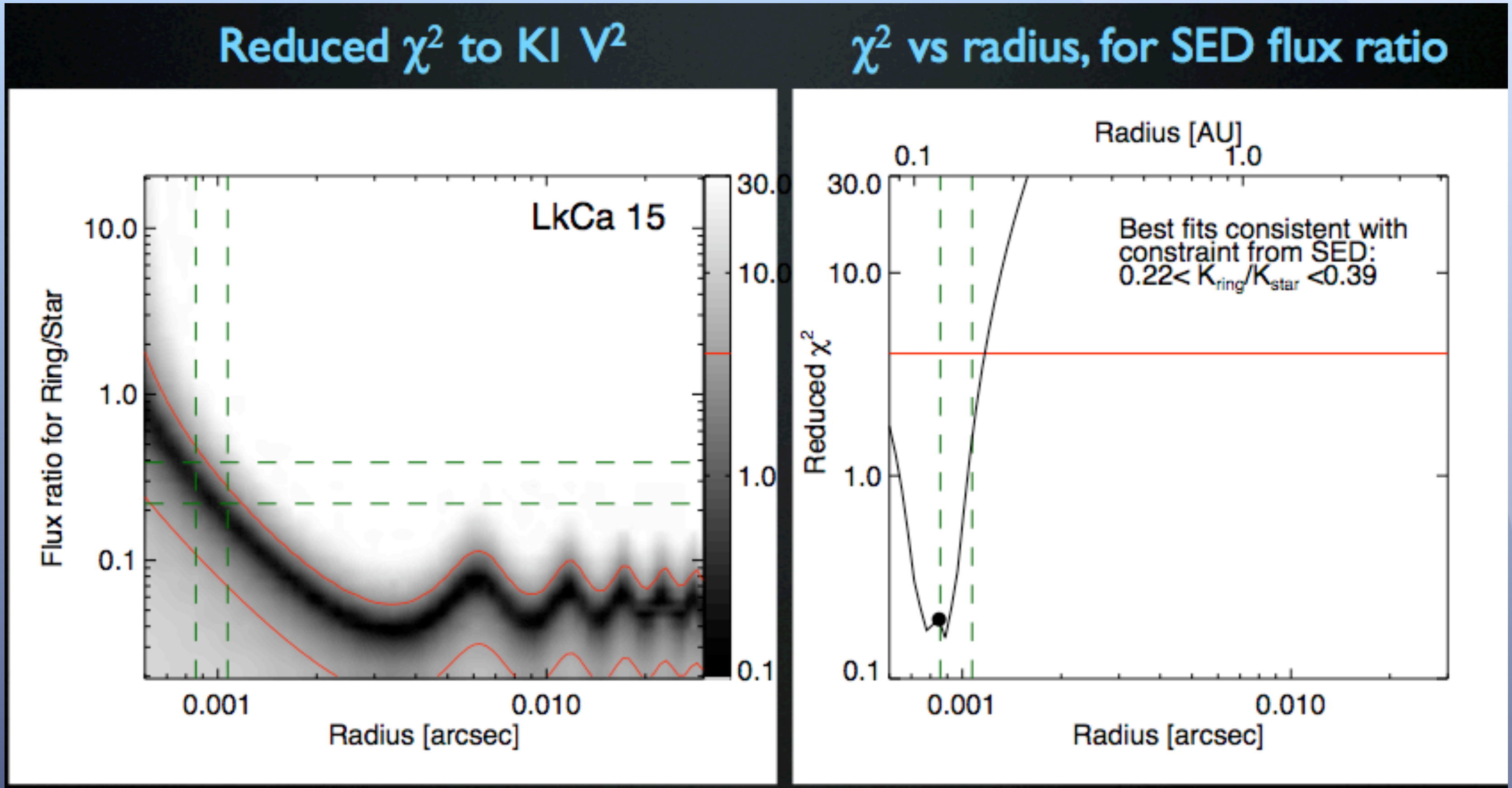
Pott et al, 2009




LkCa 15

# Transition disk sizes

Pott et al (2009)



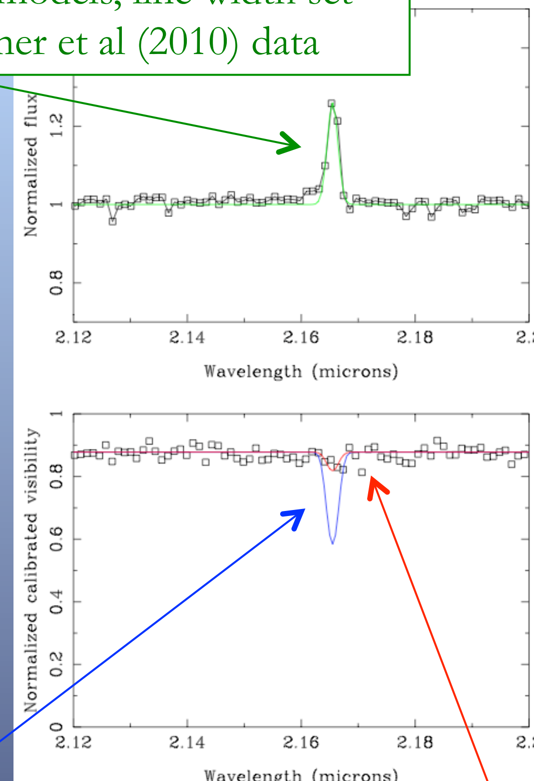

SED fit ring radius: 0.12 - 0.15 AU (Espaillat et al. 2008)

KI Best-fit ring radius: 0.12 ± 0.01 AU

# Gas in a transition disk: TW Hya

- TW Hya is one of the closest YSOs (50 pc
  - Previous observations indicated an inner disk radius of 4 AU
- Akeson et al (2011) used KI and CHARA data to constrain the inner disk structure
  - Near-infrared interferometry shows a significant scattering component in the inner tens of AU: modeling this data along with mid-infrared and mm interferometry requires an opacity thick material within 4 AU followed by a gap
- New KI data detects the Br gamma line (Akeson et al, in prep)
  - Using simple geometric models, the Br gamma emission arises from scales less than 3.0 mas or 0.16 AU

Green line: flux profile the same for both models, line width set from Eisner et al (2010) data




Blue model: Br gamma has same spatial distribution as near-infrared dust; can clearly be ruled out

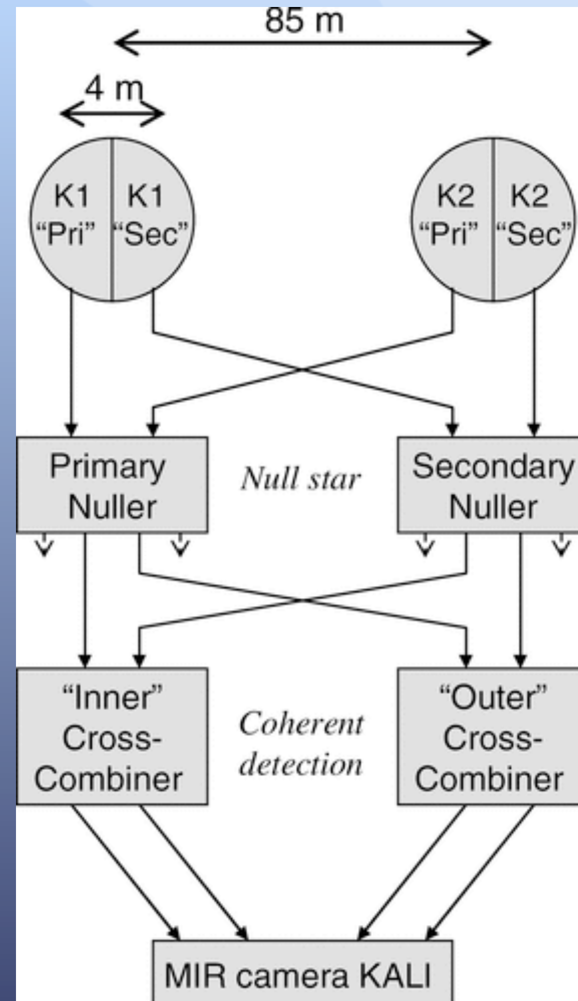
Red model: best fit to visibility; Br gamma size scale < 0.16 AU

# Dust disks around main sequence stars

- Dust grain lifetimes are much shorter than stellar ages, so grains are not from the primordial disk, but arise from collisions of larger bodies
- Fractional luminosity is much, much smaller than for circumstellar disks so observing is more difficult
- Two approaches
  - High precision visibilities (FLUOR/CHARA, IOTA, VINCI & PIONIER at VLTI, etc)
    - Several intermediate-mass stars found to have inner hot dust (Absil et al 2006, 2008, Akeson et al 2009)
  - Suppress light from star – interferometric nulling (KI, LBTI)

# NASA Exo-zodical Dust Survey Key Project

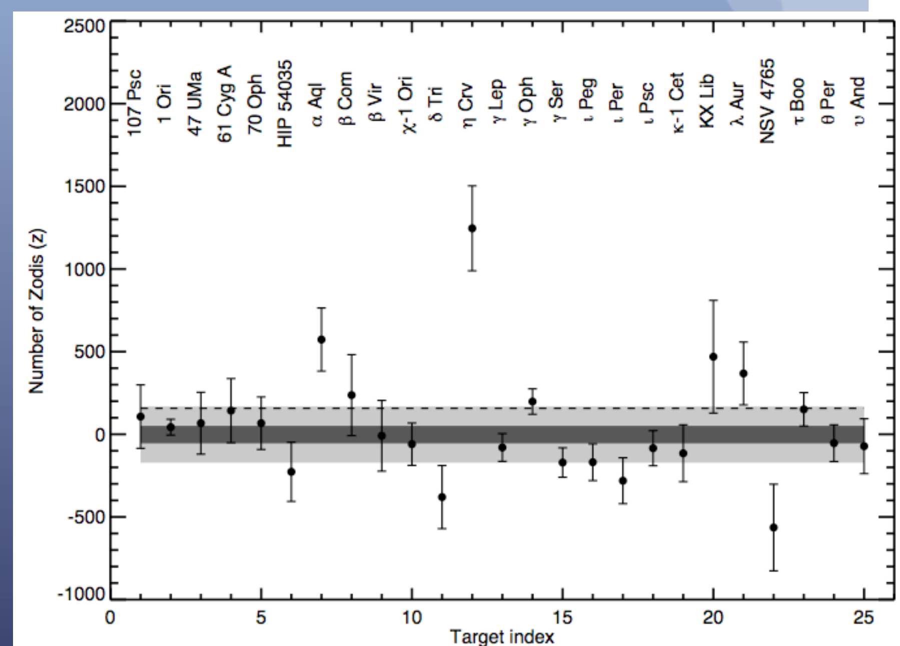
- One of the original goals of KI was a survey of nearby main sequence stars for exo-zodical dust
  - This dust can obscure Earth-like planets
  - Knowledge of the level and prevalence of exo-zodical dust is necessary in designing future planet finding and characterization missions
- Three teams competitively selected
  - PIs: P. Hinz, M. Kuchner and E. Serabyn
- Detailed description of data and analysis in Colavita et al (2009), PASP
- Science usage
  - 44 unique targets observed out of 46 submitted
  - No significant excess for 40 targets
  - Improvement in factor of 3-5 over Spitzer limits on warm dust



# Results from Serabyn team

- 1 clear detection:
  - η Crv: z = 1250 ± 260
  - Spectrum has adequate S/N, Si feature observed
- 2 possible detections:
  - γ Oph: z = 200 ± 80
  - α Aql: z = 600 ± 200
  - On-going follow up work to confirm these detections and try to detect any corresponding near-IR dust emission (using CHARA interferometry.
- 22 non-detections: derive exozodi upper limits.
  - For the individual stars, exozodi 3σ upper limits are in the range 200 – 1000 zodis.
  - ×2-3 better limits than Spitzer/ IRS.

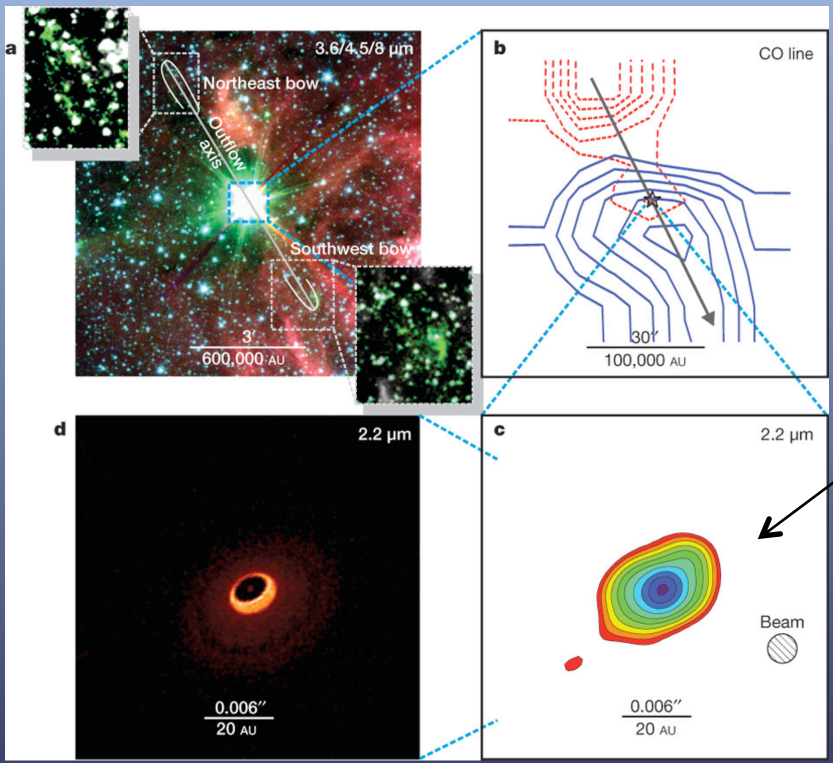
- Consider non-detections as a population
  - Mean: z = +2 ± 50 zodis
  - Mean exozodi level for the non-detections: < 150 (3 σ)




***Millan-Gabet et al. ApJ, 2011***

# What's next?

- Imaging with enough baselines can greatly reduce the number of assumptions that go into a model




IRAS 13481-6124 at 2 microns
(Kraus et al 2010)

# Circumstellar disk summary

- Infrared interferometry has had major impact in constraining disk structure
  - T Tauris and late Herbigs
    - Near-IR emission dominated by dust sublimation radius
    - Significant gas is present within that radius
  - Details of inner rim need to be determined
    - Exact shape
    - Transition disk holes and gaps
- Future directions
  - Gas emission in T Tauri's and transition disks
  - Imaging
  - Multi-wavelength detailed studies of more objects