Imaging planet-formation signatures with ground-based interferometry
&
European Interferometry Initiative activities

Stefan Kraus
University of Exeter
President EII Science Council

1st FISICA workshop
2014 February 18, Rome

EII Bureau: Paulo Garcia, Olivier Chesneau, Jean-Philippe Berger

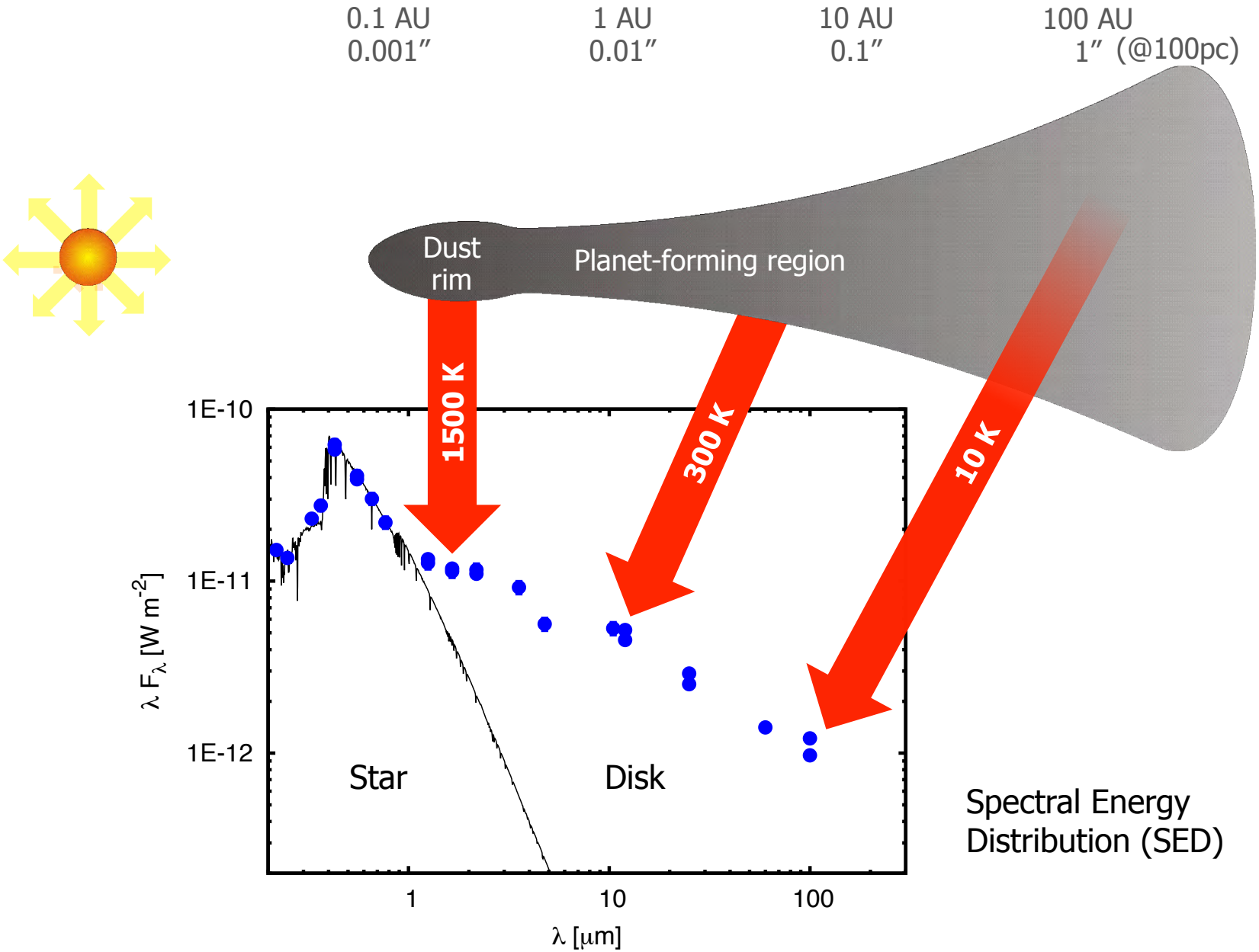
PFI Kick-off committee: John Monnier, Jean-Philippe Berger, Chris Haniff, Mike Ireland, Lucas Labadie, Sylvestre Lacour, Jörg-Uwe Pott, Steve Ridgway, Jean Surdej, Thierry Lanz, Theo ten Brummelaar,Peter Tuthill, Gerard van Belle

Outline

1. The need for high-angular resolution imaging
2. Planet-formation signatures revealed with VLTI
3. Overview of EII activities
4. Future opportunities in optical interferometry
5. Conclusions

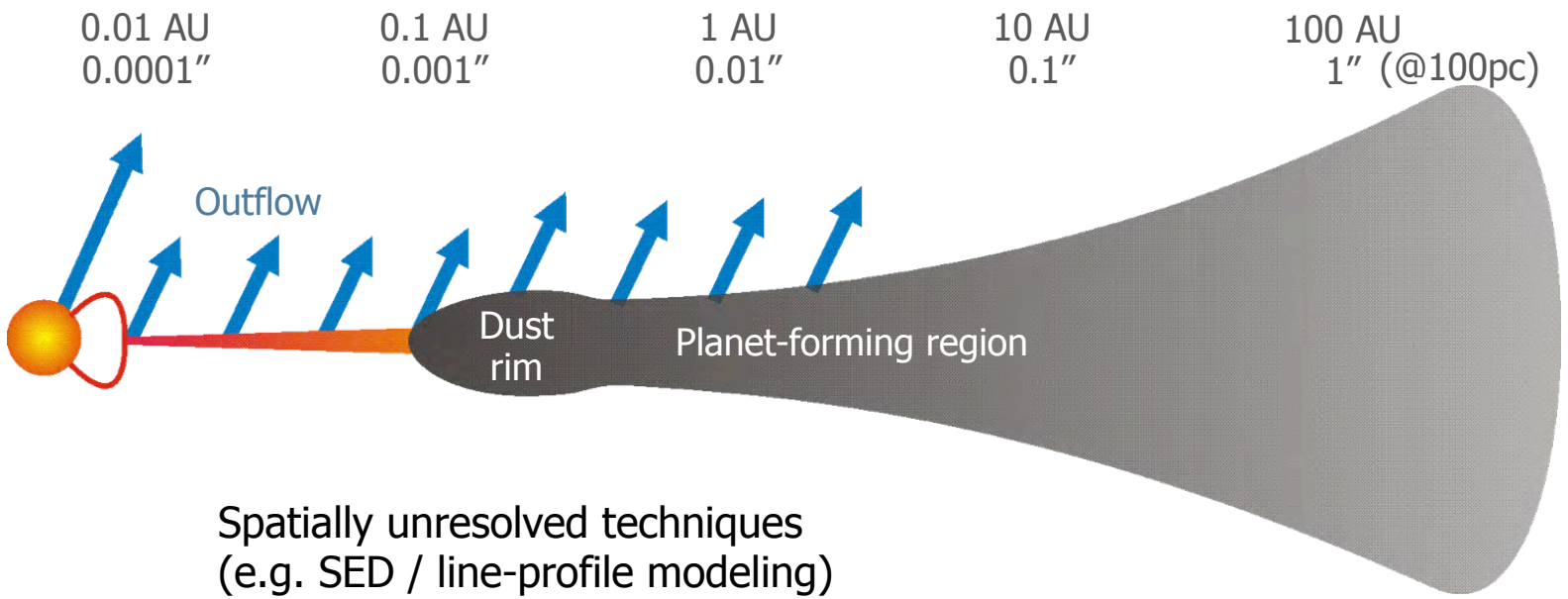
The need for high-angular resolution imaging

Protoplanetary disk structure



Spectral Energy Distribution (SED)

The need for high-angular resolution observations



Spatially unresolved techniques
(e.g. SED / line-profile modeling)
face severe limitations:

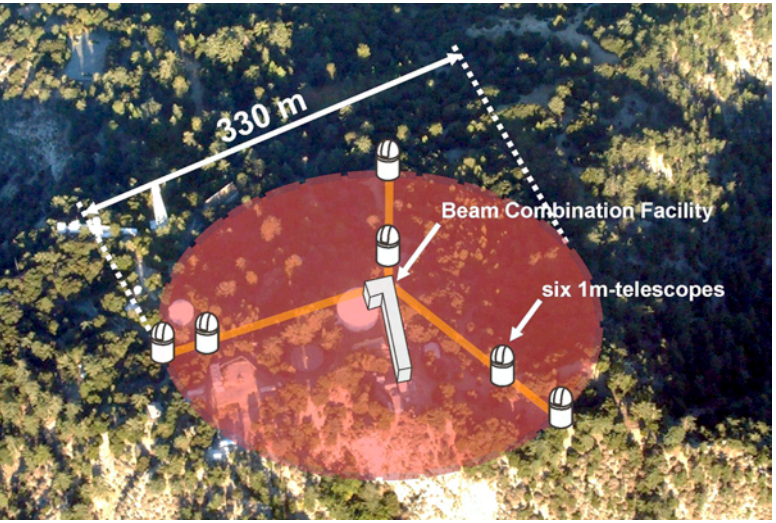
- Parameter degeneracies
- Model degeneracies
  (do we include the right physics?)
- Insensitive to asymmetric structures
  (planet formation, instabilities, …)

➜ **Model-independent IMAGING needed**

Ground-based interferometers

Interferometry breaks the resolution barrier imposed by diffraction (λ/D) and the atmosphere

VLTI (Paranal/Chile)
4x8.2m+4x1.8m
λ=1-13 μm

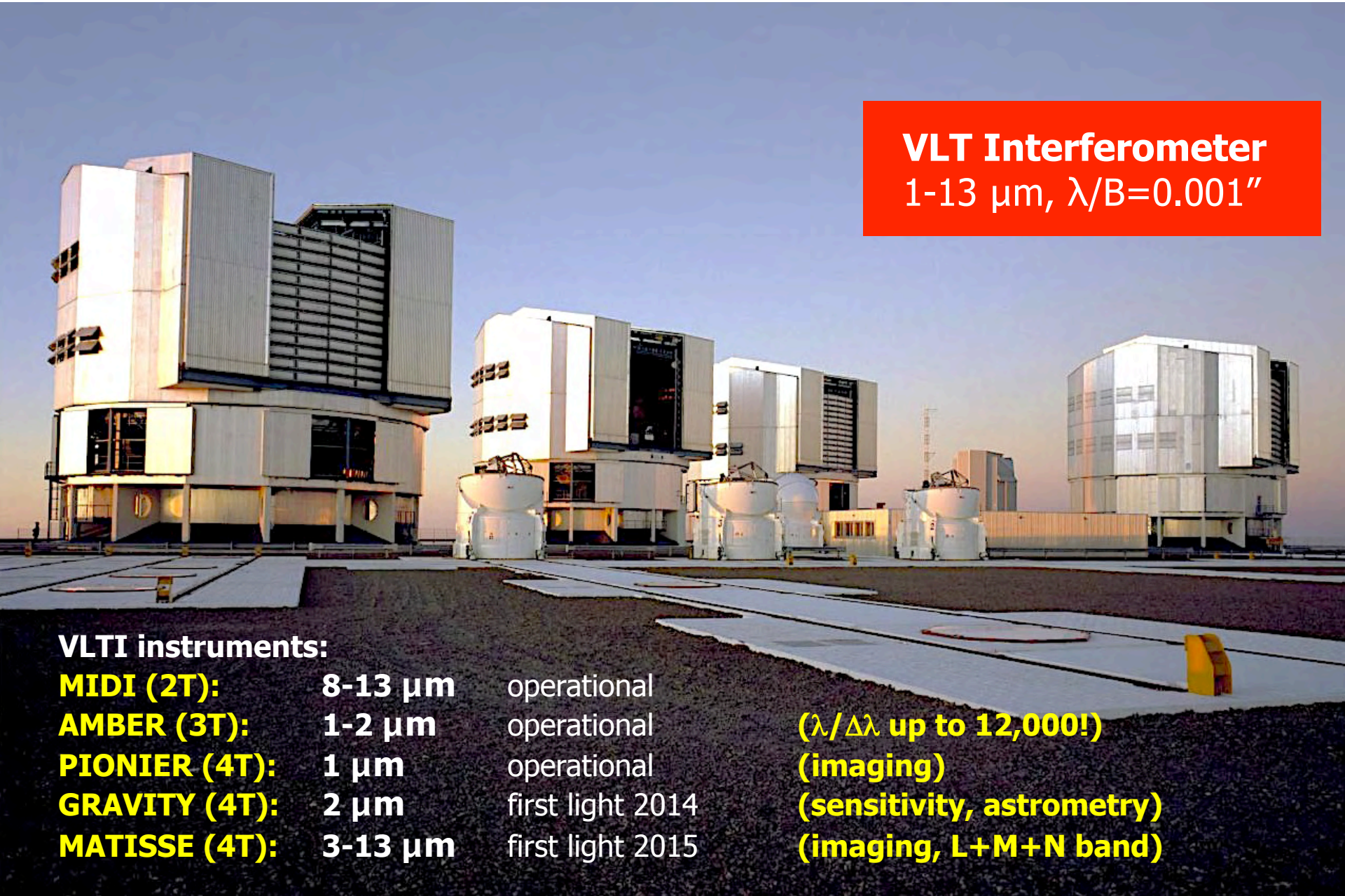


CHARA array (Mt Wilson/CA)
6x1m
λ=0.5-2 μm

NPOI (Flagstaff/AZ)
6x12cm+4x1.8m
λ=0.5-0.9 μm


2

VLTI Interferometry



VLTI instruments:

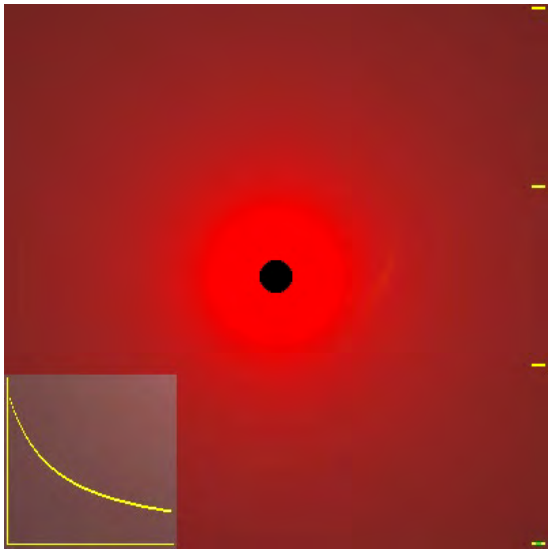
MIDI (2T):	**8-13 µm**	operational	
AMBER (3T):	**1-2 µm**	operational	**(λ/Δλ up to 12,000!)**
PIONIER (4T):	**1 µm**	operational	**(imaging)**
GRAVITY (4T):	**2 µm**	first light 2014	**(sensitivity, astrometry)**
MATISSE (4T):	**3-13 µm**	first light 2015	**(imaging, L+M+N band)**

Planet formation signatures revealed with infrared interferometry

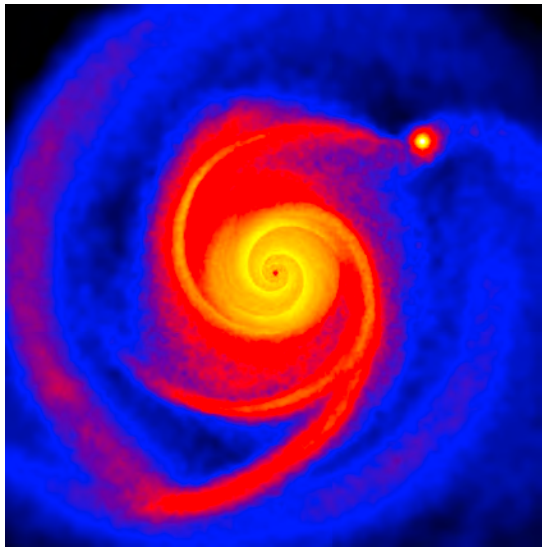
Signatures of planet formation

Planet formation alters the disk structure, causing
disk gaps, spiral arms, resonance effects, disk warping, …

Gap clearing



Disk fragmentation

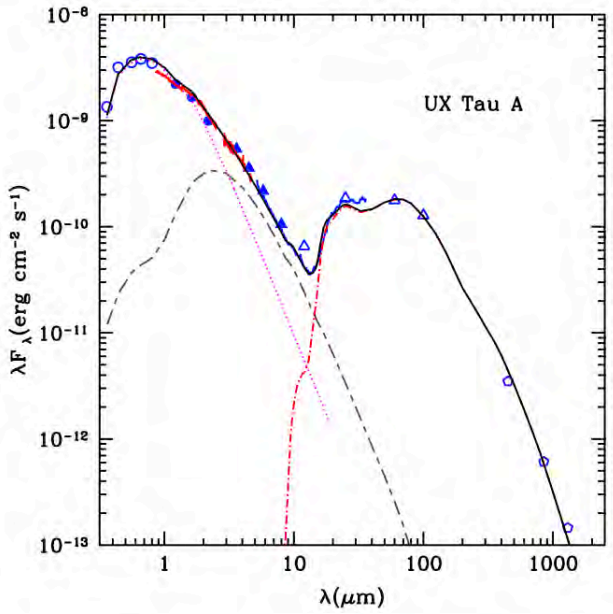


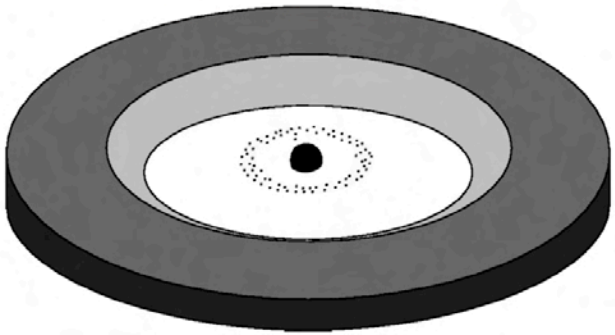
Disk warping

Armitage et al. 2005, Greaves et al. 2008

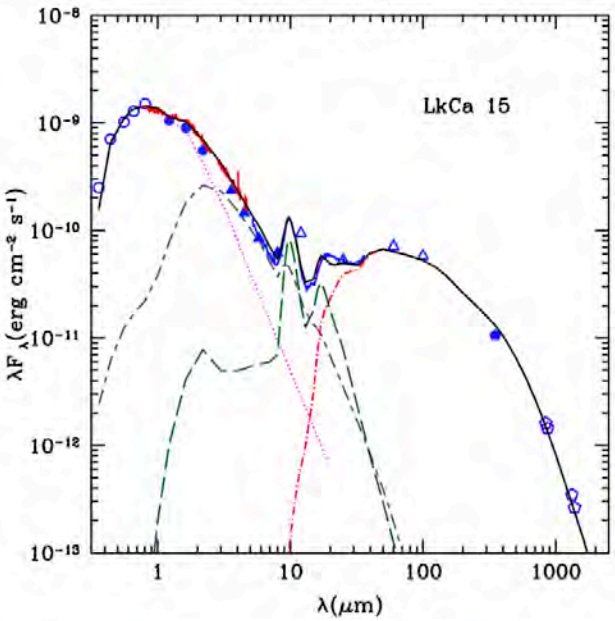
Disk structure in (pre-)transitional disks

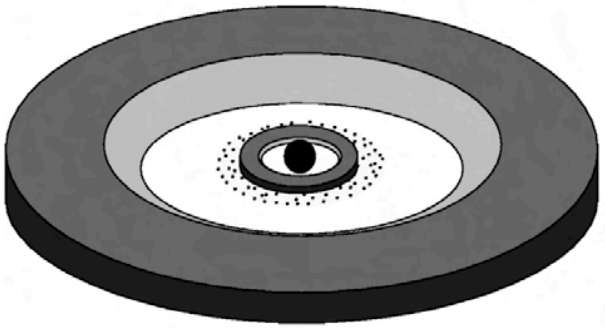
Transitional disks





Pre-transitional disks

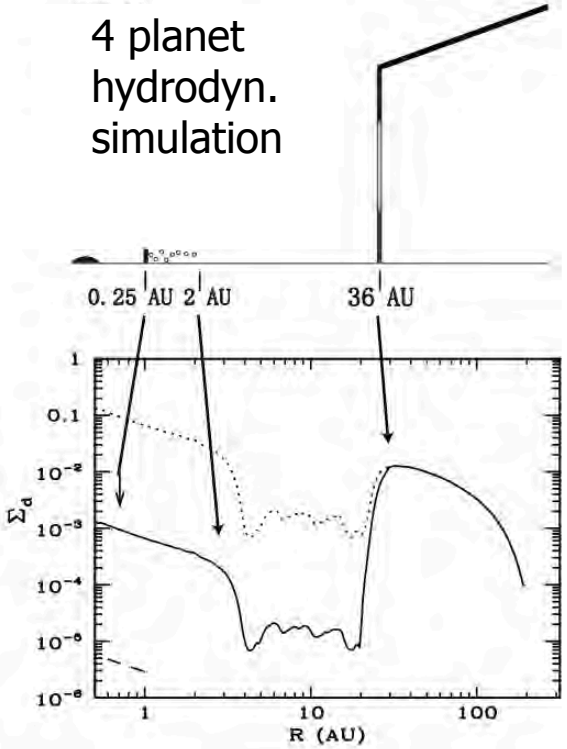




Disk-clearing mechanisms under discussion:

- photoevaporation
- grain growth
- stellar companions
- planet-disk interaction

4 planet hydrodyn. simulation

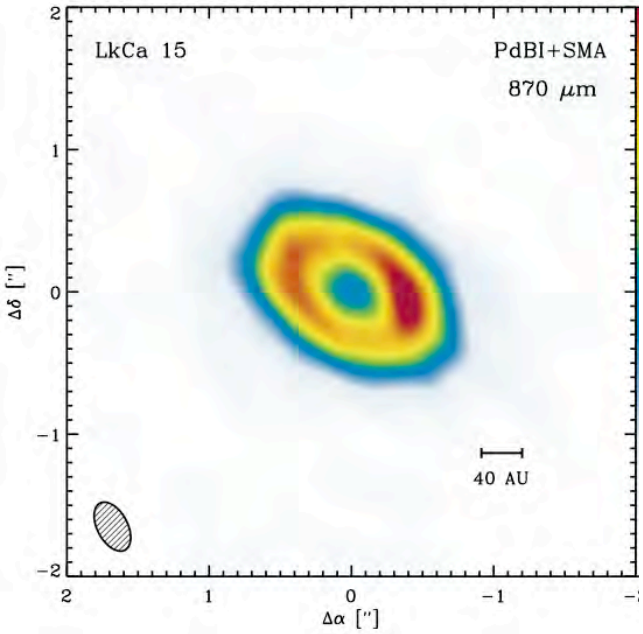


Espaillat al. 2008, 2010; Zhu et al. 2011

Disk structure in (pre-)transitional disks

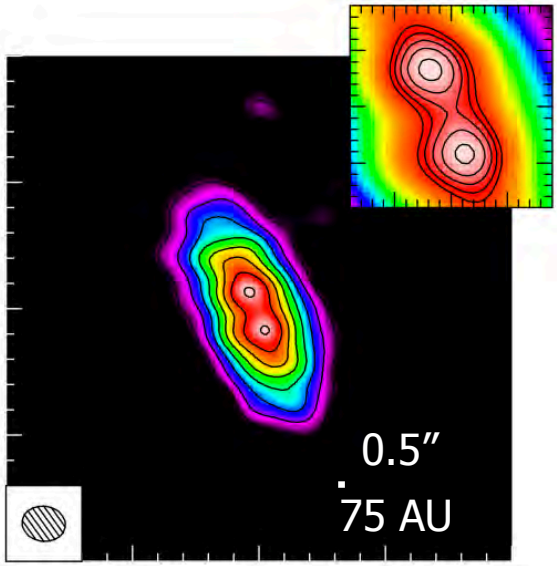
(Sub-)millimeter interferometry has revealed central density depressions

LkCa15



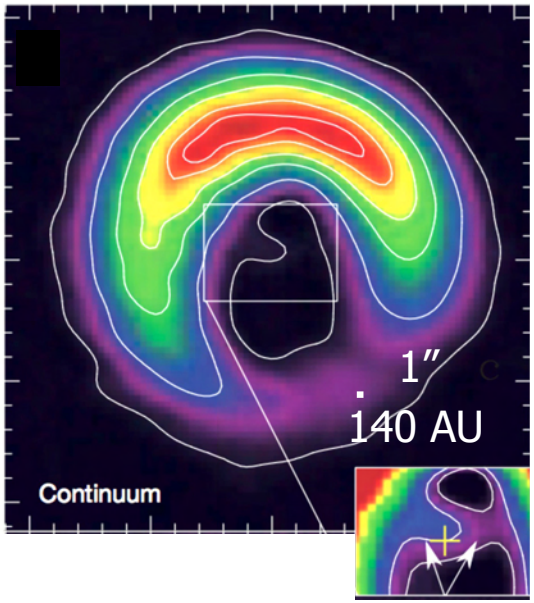
Andrews et al. 2011

RY Tau



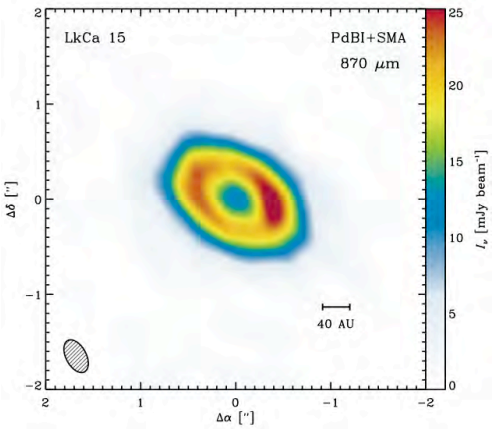
Isella et al. 2011

HD142527



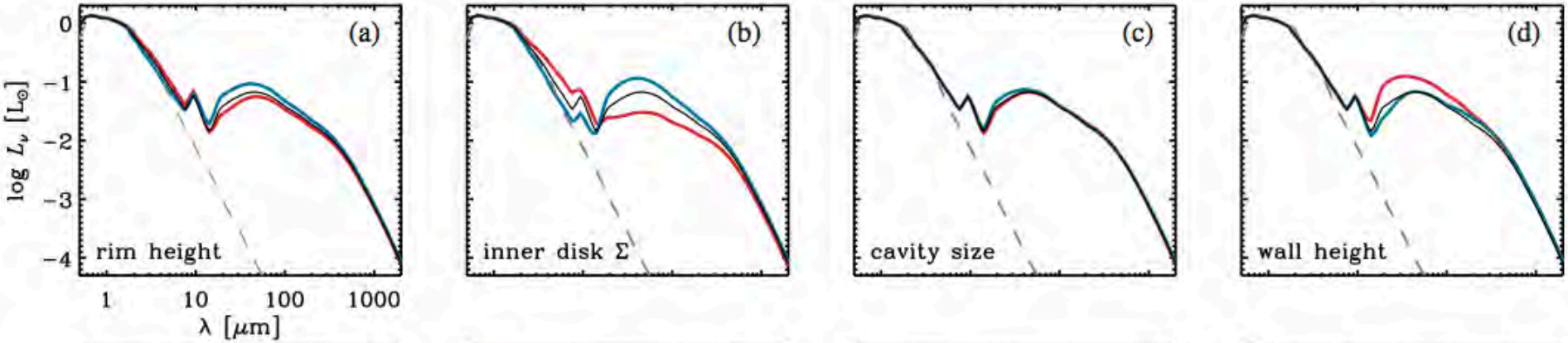
Casassus et al. 2013

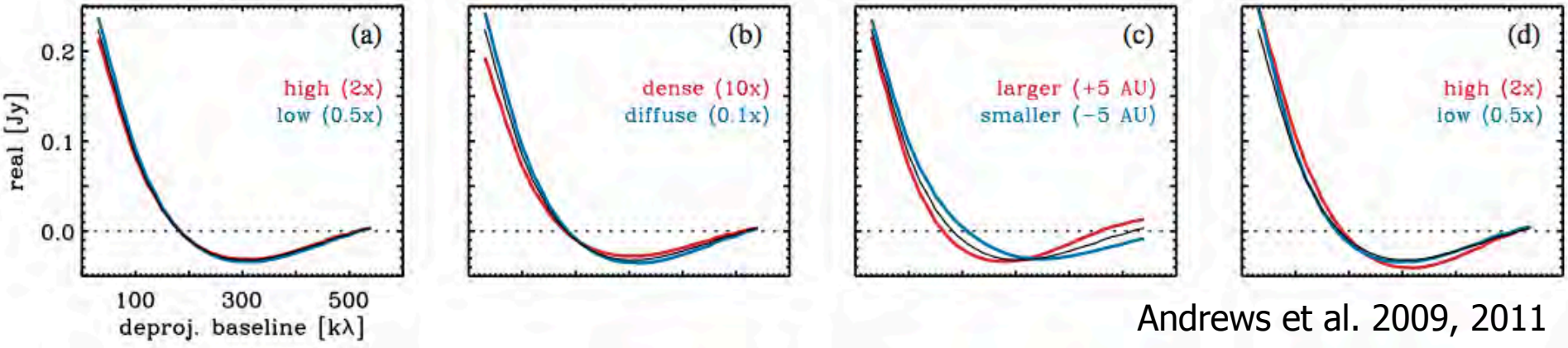
Disk structure in (pre-)transitional disks



Some key parameters remain difficult to constrain:

rim height, inner disk density,
cavity size, wall height, …

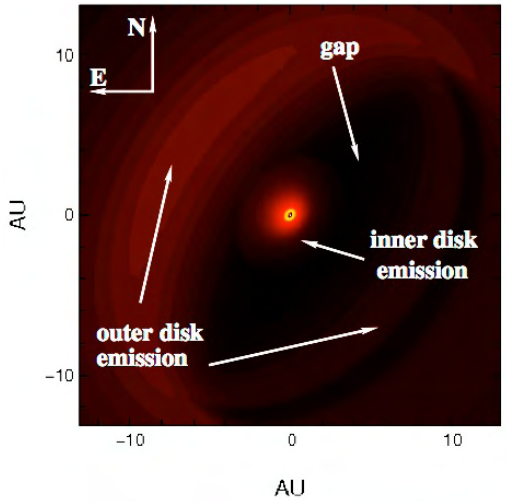




Andrews et al. 2009, 2011

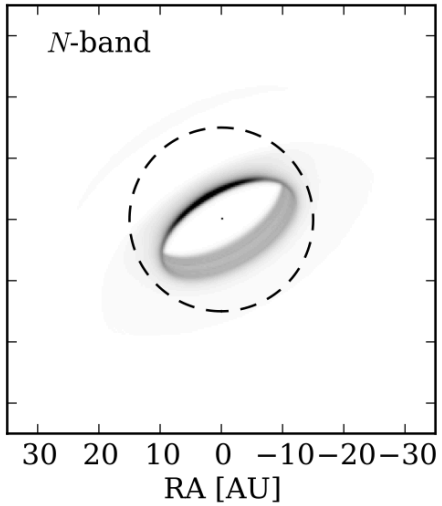
Disk structure in (pre-)transitional disks

HD100546



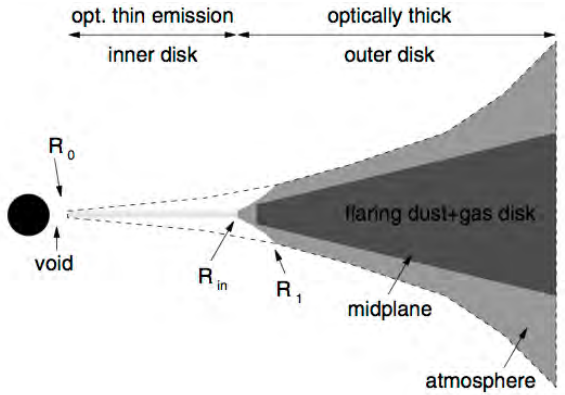
Benisty et al. 2010
Tatulli et al. 2011
Panic et al. 2012
Mulders et al. 2013

T Cha



Olofsson et al. 2011, 2013

TW Hya



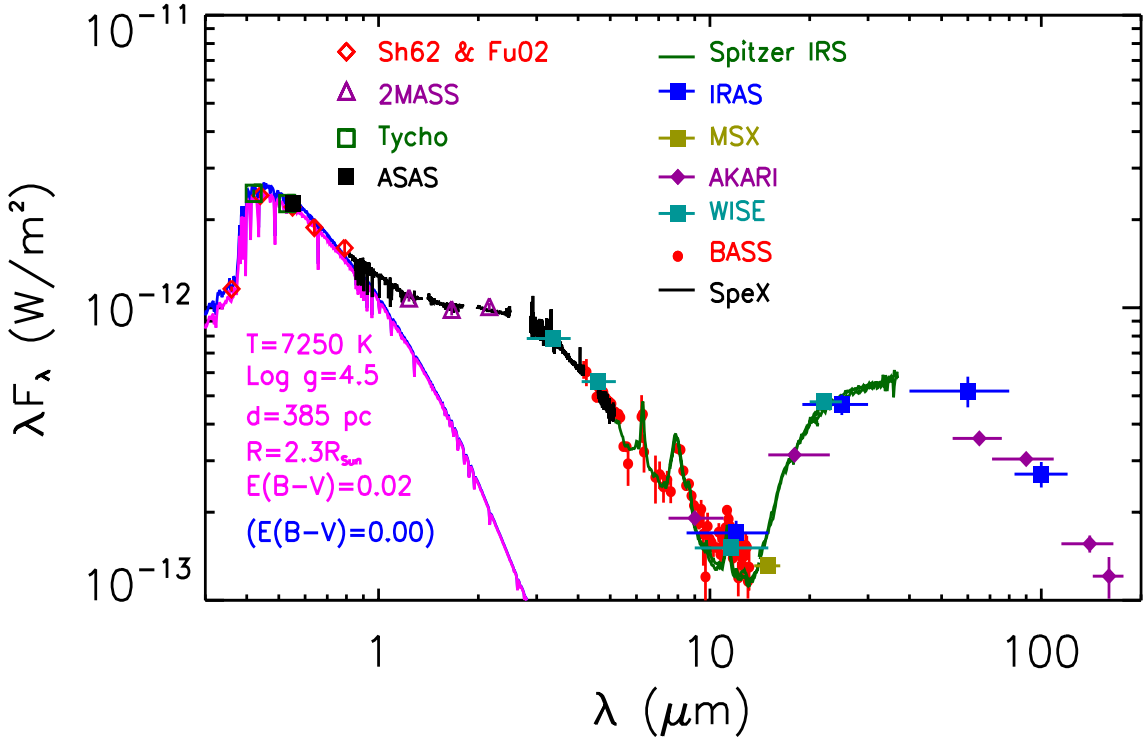
Eisner et al. 2006
Ratzka et al. 2007
Akeson et al. 2011
Arnold et al. 2012

Open questions:

(1) Can we find evidence for disks with partially cleared gaps?
➜ establish evolutionary sequence of disk clearing

(2) How does the disk structure/clearing mechanism depend on stellar mass?
➜ larger object sample needed, in particular in intermediate-mass regime

V1247 Orionis



Spectral type F0V
T_{eff} = 7250±100 K
d = 385±15 pc
M = 1.86 $M_\odot$
Age = 7.4±0.4 Myr

V1247 Ori exhibits MIR flux deficit compared to typical protoplanetary disks

➜ **Indirect evidence for a gapped disk structure**

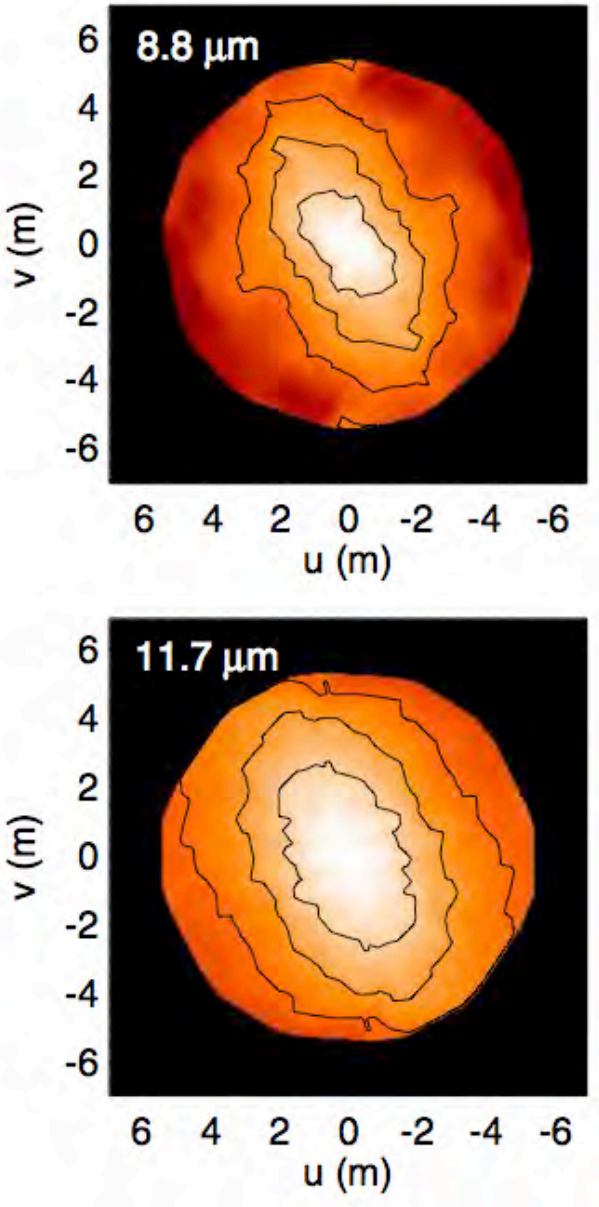
Kraus et al. 2013

Resolving the disk structure

Gemini/TReCS speckle interferometry yields MIR 2-D power spectra

➜ **Inclination: 31±7°**
PA: 104±15°

Gemini/TReCS



Resolving the disk structure

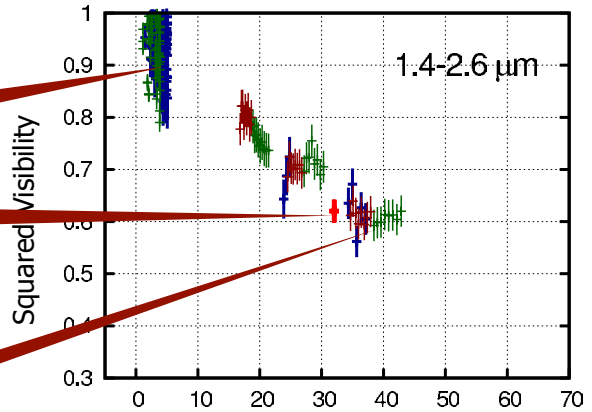
Keck2/NIRC2

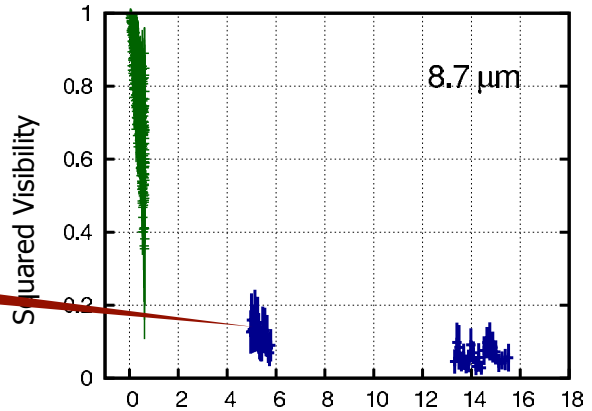
Keck/V2-SPR

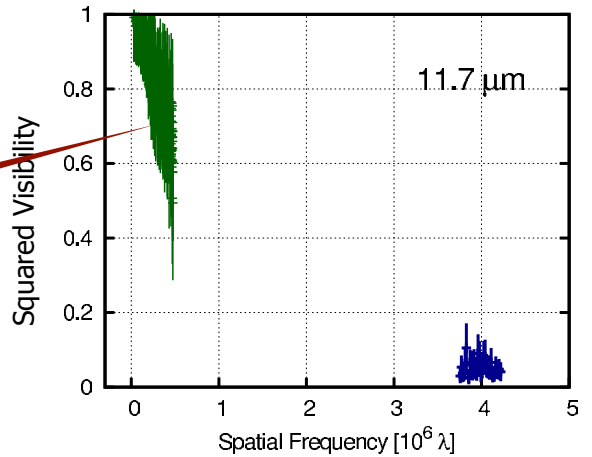
VLTI/AMBER

VLTI/MIDI

Gemini/TReCS

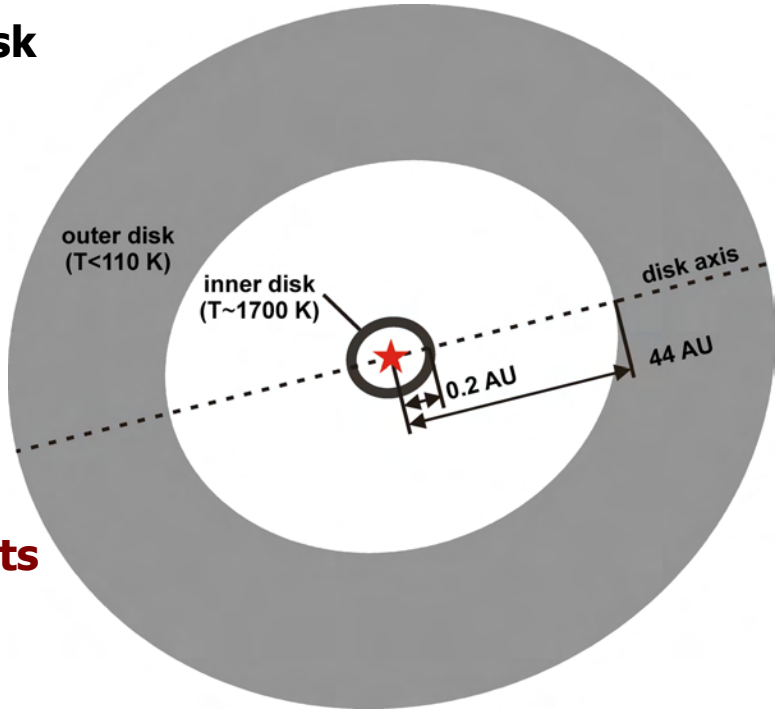




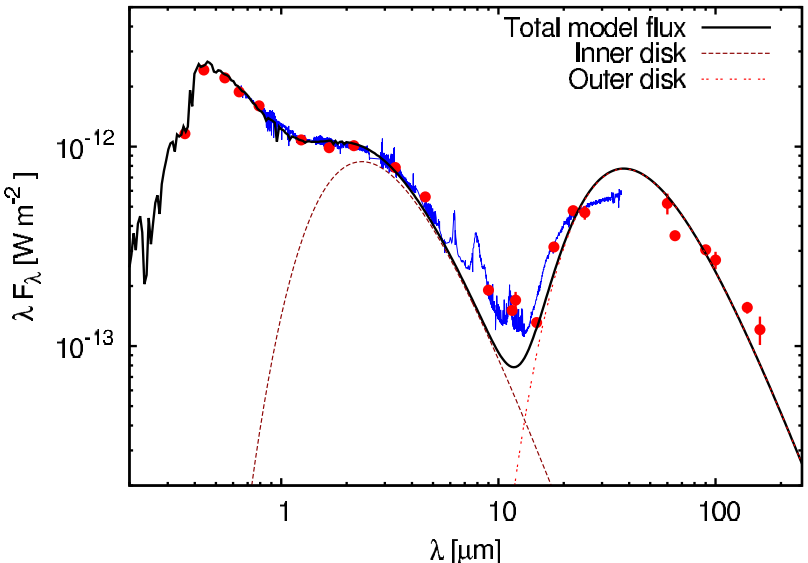


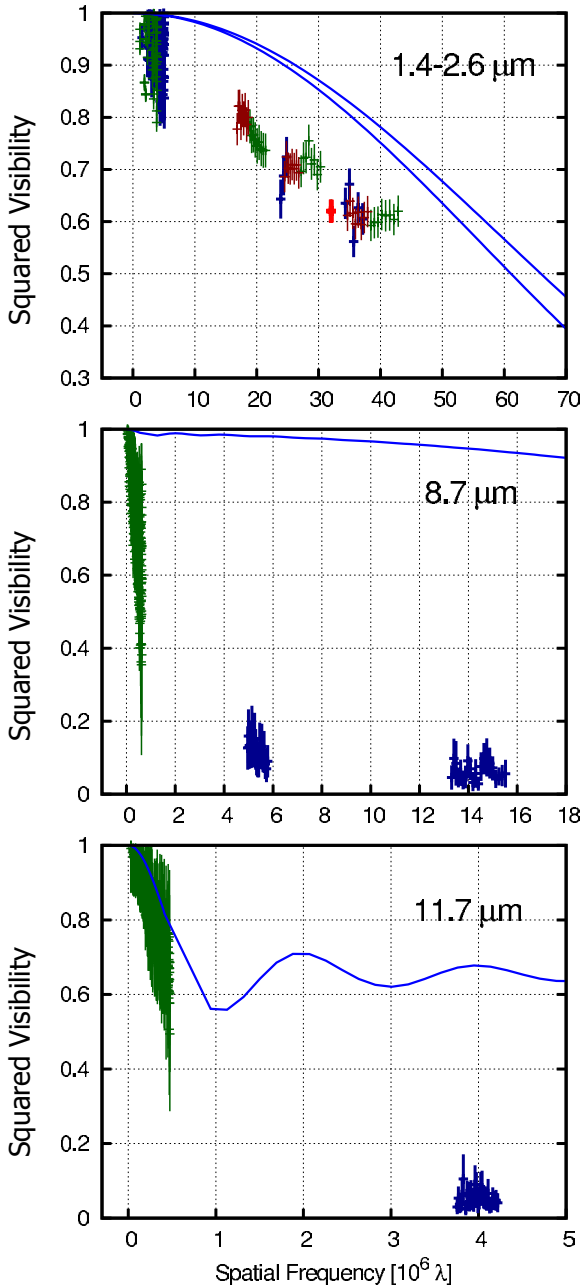
Resolving the disk structure

Scenario 1: Gapped disk



➜ **Model under-predicts MIR size by order of magnitude**



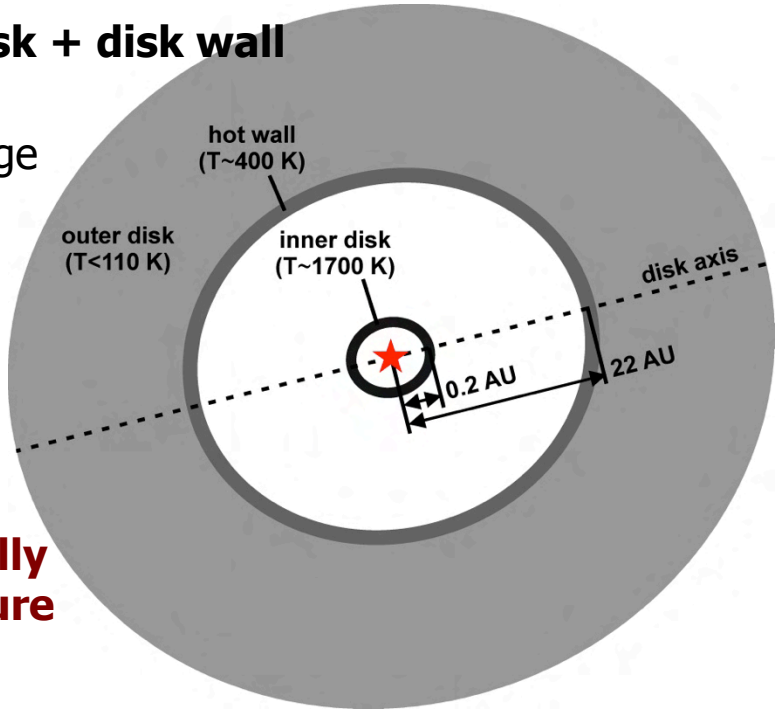


Resolving the disk structure

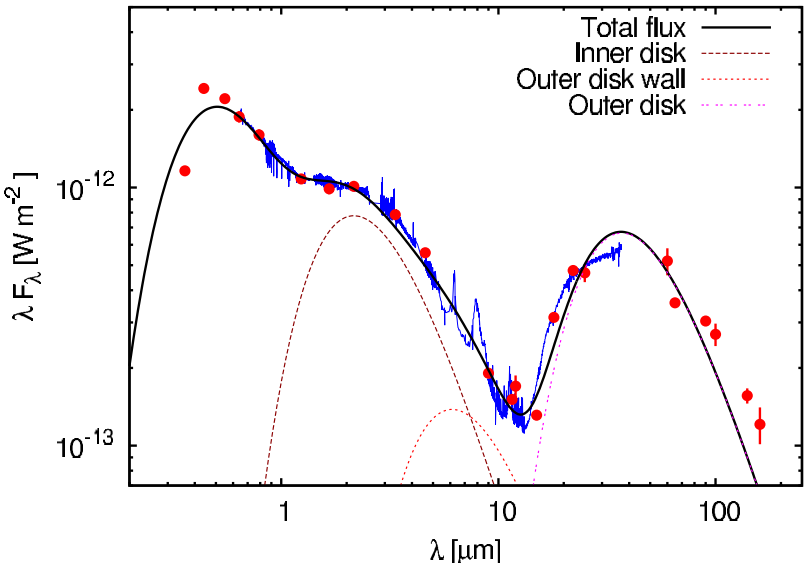
Scenario 2: Gapped disk + disk wall

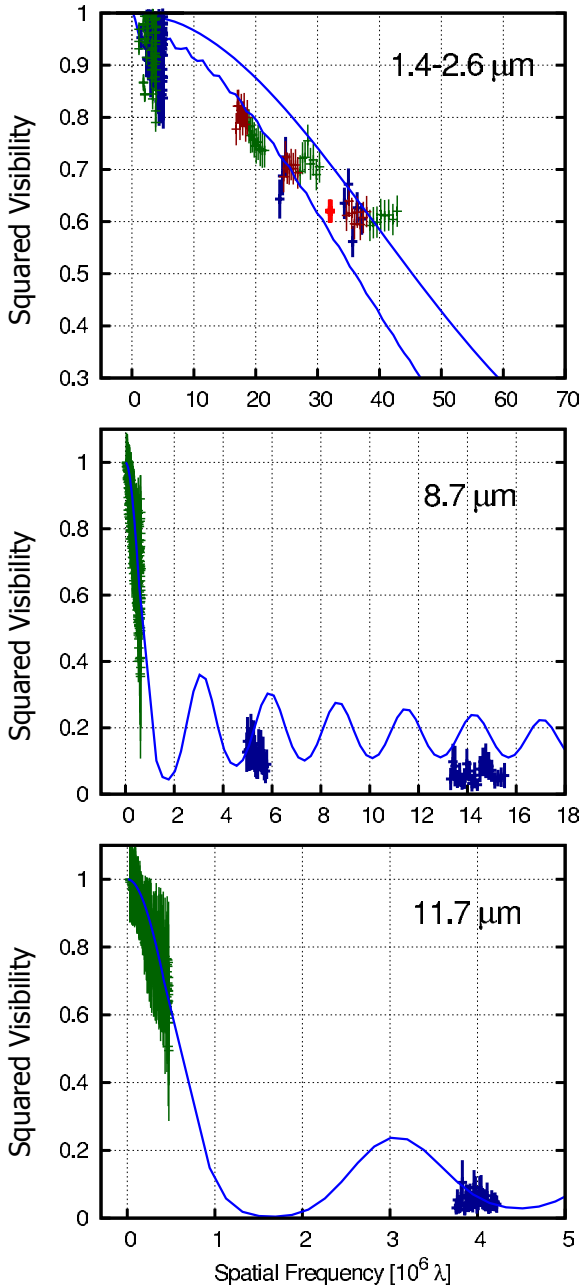
Realistic temperature range for wall @ 22 AU:

90K for grey dust
160K for 0.1µm grains



➜ **Requires unphysically high wall temperature of 400 K @ 22 AU**

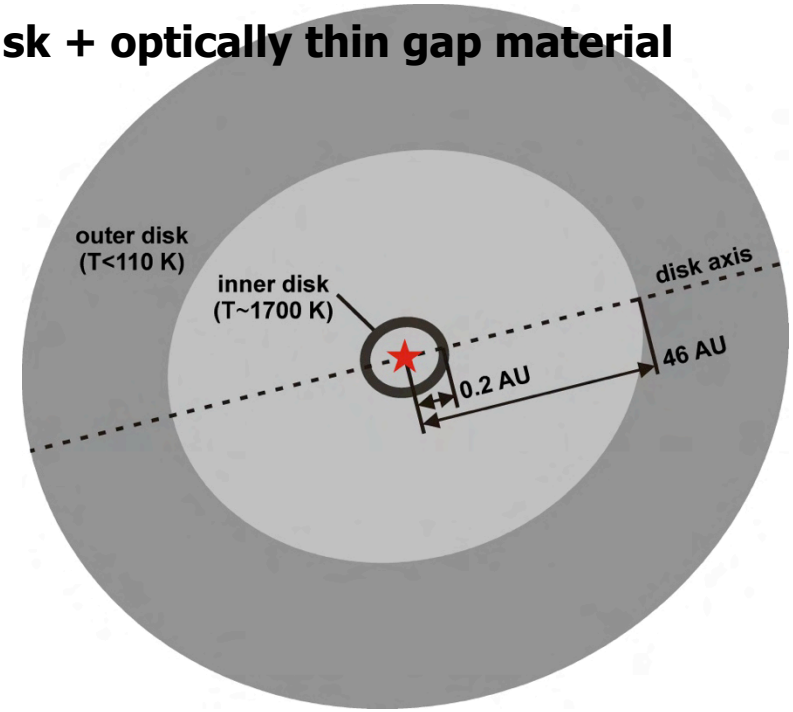


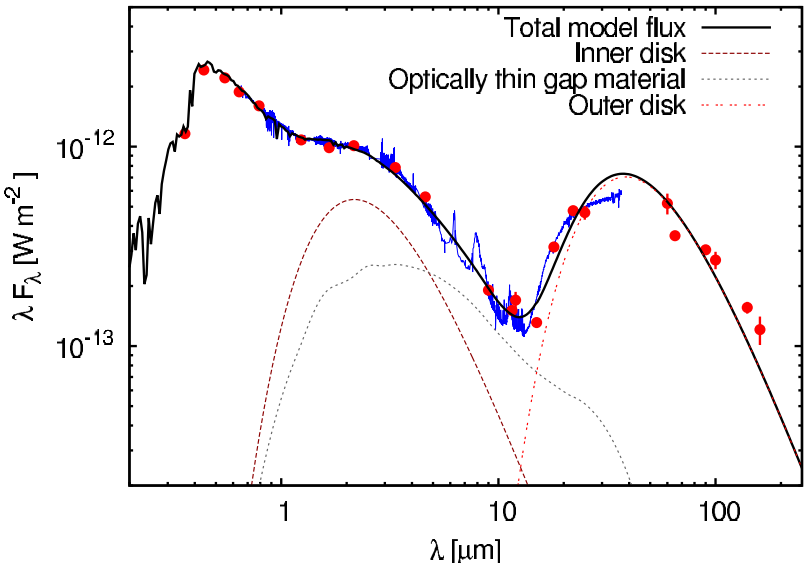


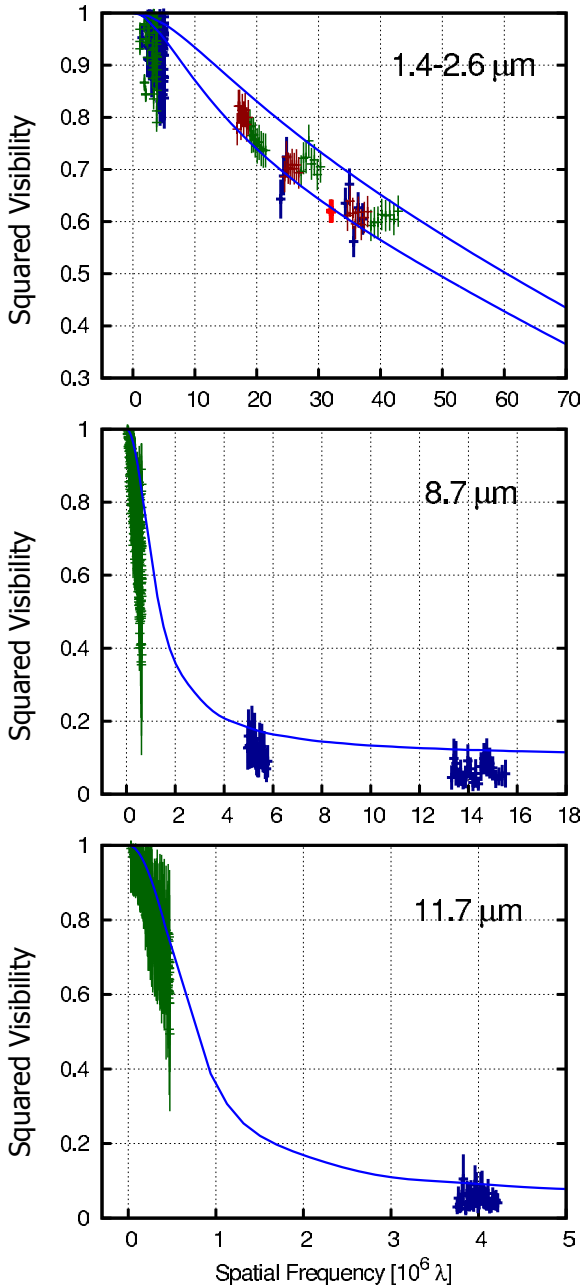
Resolving the disk structure

Scenario 3: Gapped disk + optically thin gap material

- **Gap filled with optically thin dust** $\Sigma_{gap}=9\times10^{-6}$ g/cm^2
- **Gap material dominates MIR emission**



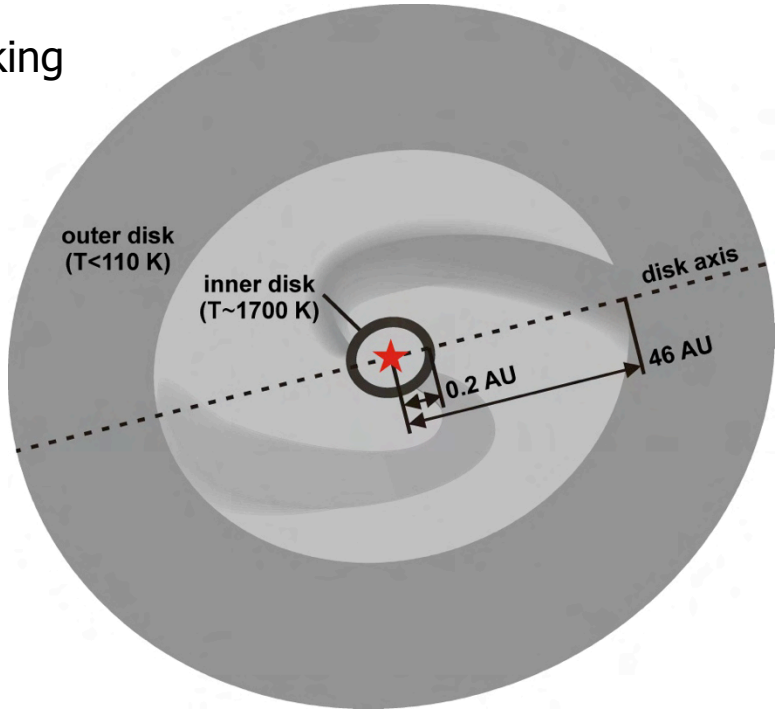


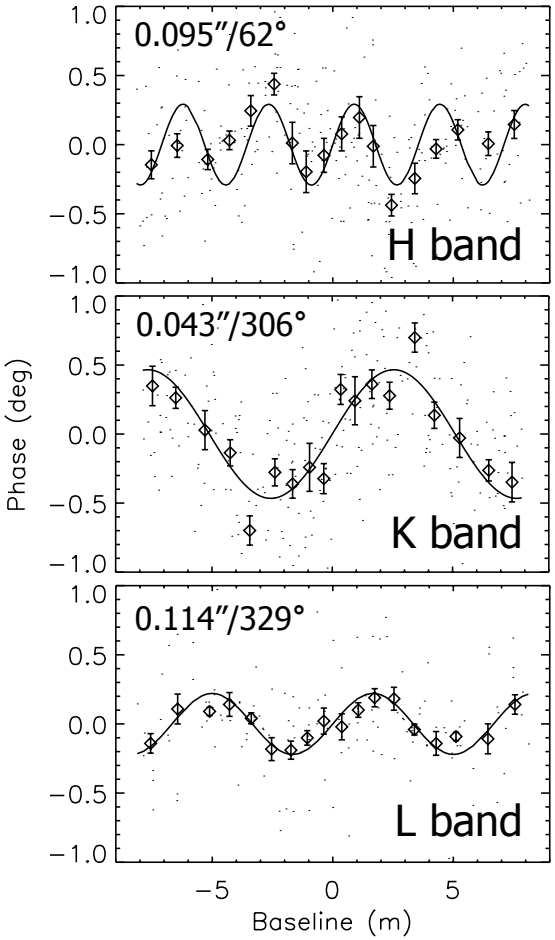


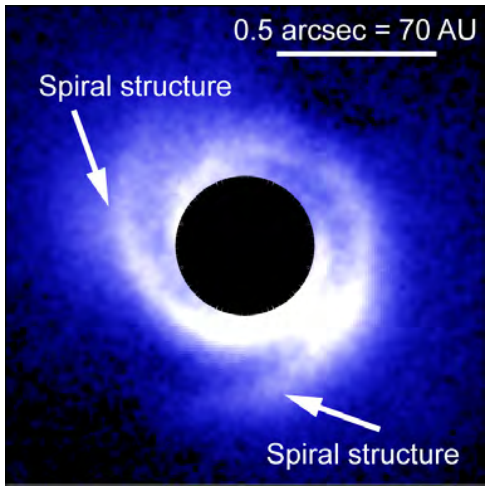
AU-scale asymmetries: Disk inhomogeneities

Keck/NIRC2 aperture masking reveals asymmetries

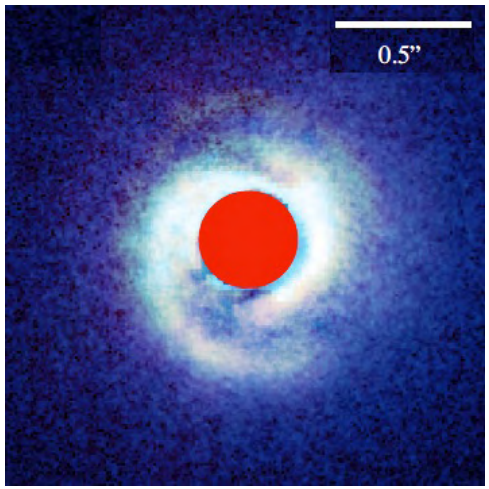
- ➜ **Not consistent with companion scenario**
- ➜ **Complex density structures in the gap region, possibly due to dynamical interaction with gap-opening planets**







SAO206462, Dong et al. 2012

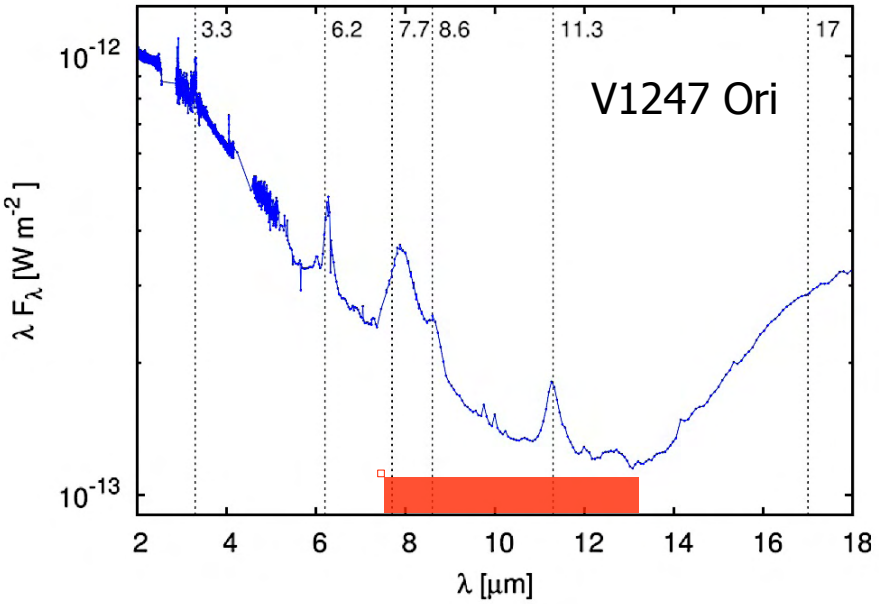


MWC758, Grady et al. 2013

Kraus et al. 2013

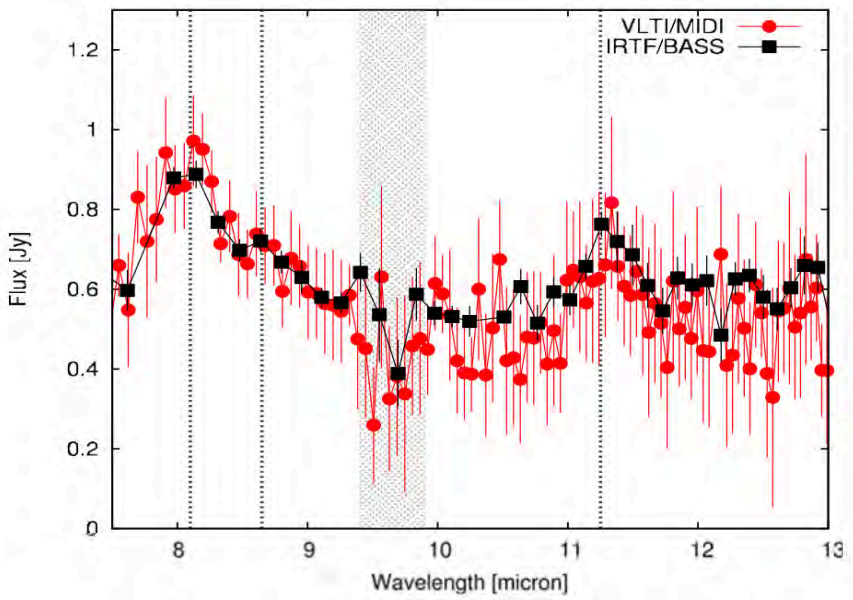
Dust mineralogy

➜ **Carbon-dominated dust mineralogy required**
(other carbon-rich systems: Fomalhaut, 55 Cnc e, …)



Spectrally dispersed MIDI visibilities constrain origin of hydrocarbon features

➜ **PAH emission originates in the outer disk**



Kraus et al. 2013

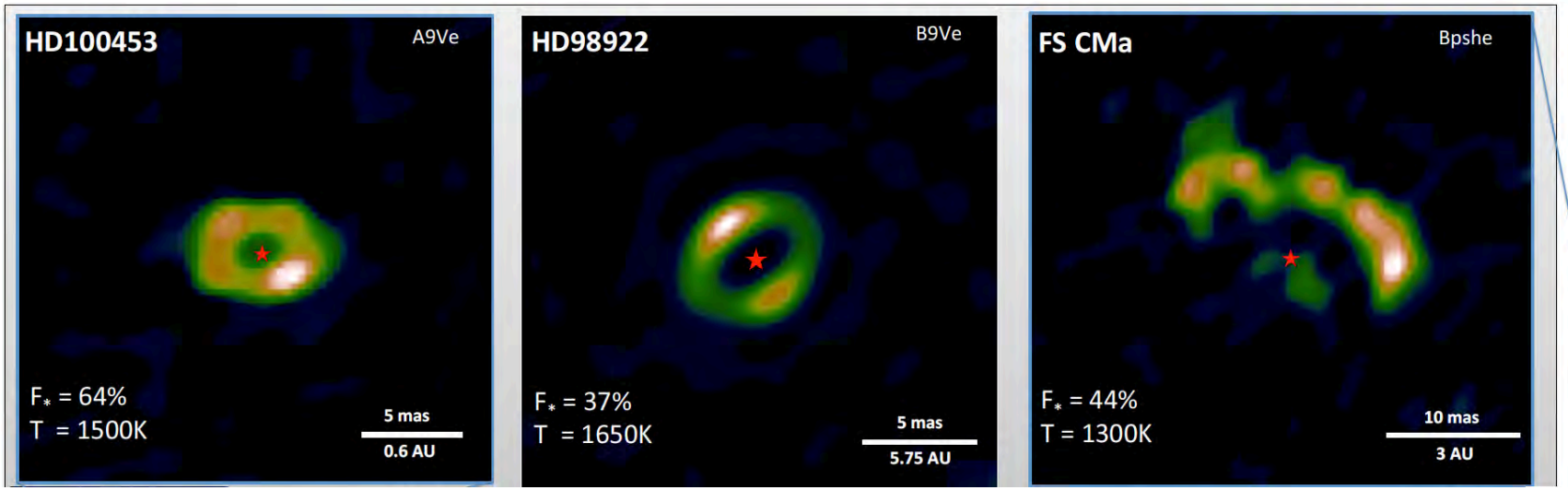
Aperture synthesis imaging

First images from the PIONIER/VLTI optical interferometry imaging survey of Herbig Ae/Be stars

J. Kluska[1,*], F. Malbet[1], J.-P. Berger[2], M. Benisty[1], B. Lazareff[1], J.-B. Le Bouquin[1], F. Baron[3,7], C. Dominik[4], A. Isella[5], A. Juhasz[6], S. Kraus[7], R. Lachaume[8], F. Ménard[1,9], R. Millan-Gabet[5], J.D. Monnier[7], C. Pinte[1], W.-F. Thi[1], E. Thiébaut[10], G. Zins[1].

[1] Institut de Planétologie et d'Astrophysique de Grenoble (IPAG), France, [2] ESO Santiago de Chile, Chile, [3]Georgia State University, [4]University of Amsterdam, [5]California Institute of Technology, [6]Leiden Observatory, Leiden, The Netherlands, [7]University of Michigan, [8]Ponitificia Univ. Católica de Chile, [9]UMI-FCA , CNRS y U. de Chile, [10]Université de Lyon 1.

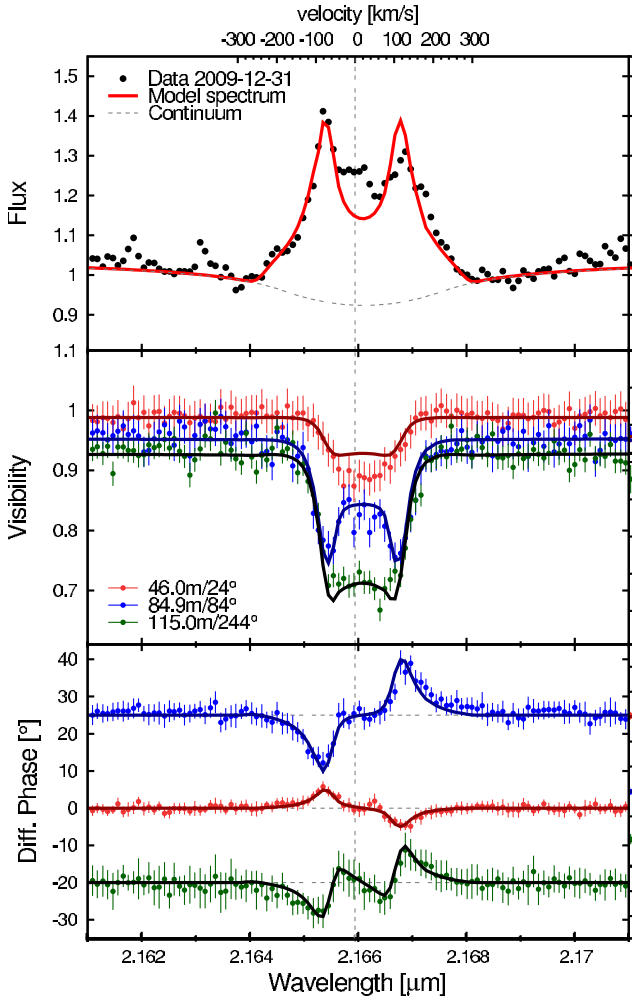
* E-mail : jacques.kluska@obs.ujf-grenoble.fr

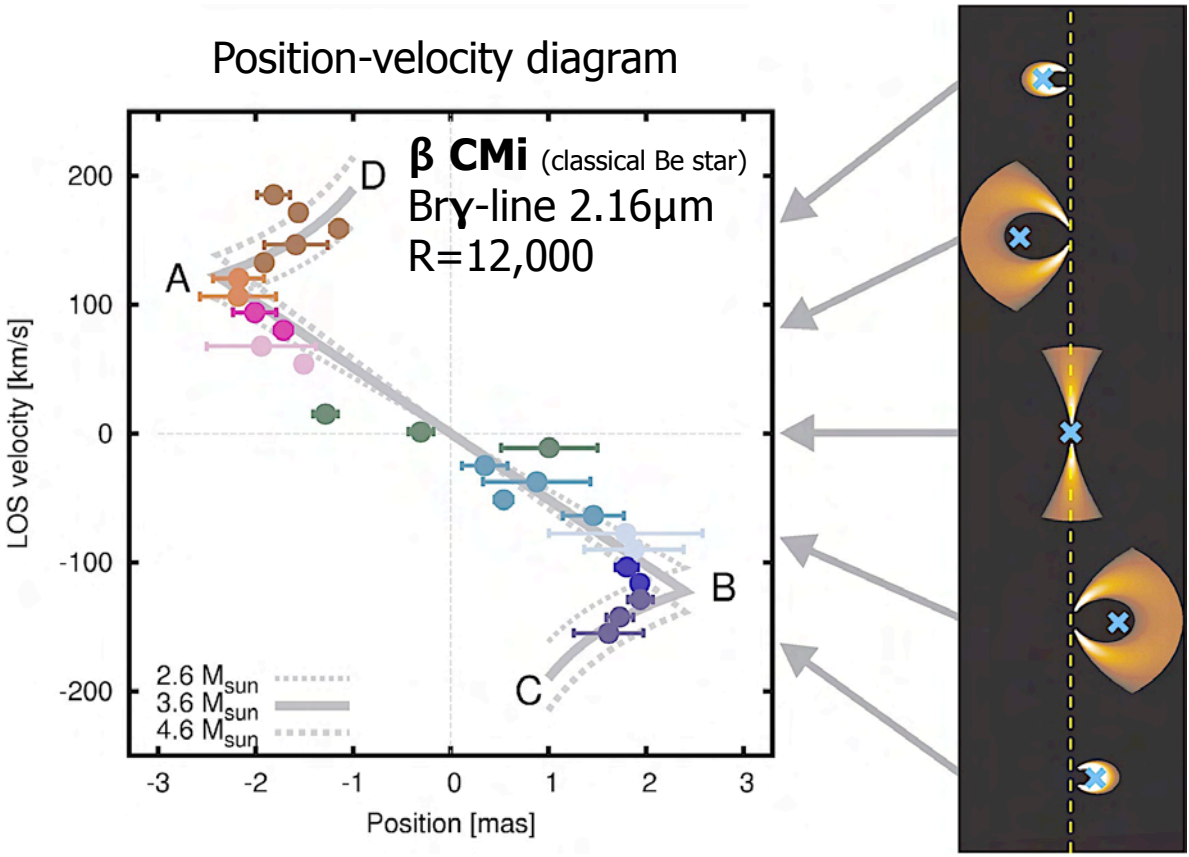


➜ **With the upcoming 4T beam combiners (PIONIER, soon GRAVITY and MATISSE), imaging gets much more routine and efficient**

Kluska et al. 2013, PPVI poster

Gas kinematics studies





$$v(r) = r^{-0.5\pm0.1} (=\text{Keplerian})$$
$$M_\star = 3.6 \pm 0.2 M_\odot$$
$$i = 38.5 \pm 1.0^\circ$$
$$\text{PA} = 140.0 \pm 1.7^\circ$$

➜ **Spectrally dispersed interferometry constrains the gas kinematics**

Kraus et al. 2012a

The European Interferometry Initiative (EII)

The European Interferometry Initiative

Open association of institutes and laboratories willing to collaborate on the exploitation and development of long baseline interferometry in optical/infrared astronomy.

EII is *the* place where (ground-based) interferometry in Europe is discussed and organised on trans-national level

EII & ESO: EII should act aside ESO for scientific vision
(trigger ESO's scientific thoughts, e.g. 2005 workshop on 2nd-gen.)
and act together with ESO to organize the community
(e.g. VLTI Community Meetings)

Lobbying with funding agencies and decision makers

EII - Governing bodies

Bureau:

President	Stefan Kraus
Vice-President	Olivier Chesneau
Secretary	Paulo Garcia
VLTI Project Scientist	Jean-Philippe Berger

Science Council:

President	Stefan Kraus
Austria	Josef Hron
Belgium	Jean Surdej
Czech Republic	Pavel Koubsky
ESA	Malcolm Fridlund
ESO	Jean-Philippe Berger
France	Alain Chelli
Germany	Thomas Henning
Hungary	Laszlo Mosoni
Italy	Sebastiano Ligori
Israel	Erez Ribak
Netherlands	Walter Jaffe
Poland	Andrzej Niedzielski
Portugal	Paulo Garcia
Spain	Carlos Eiroa
Switzerland	Didier Queloz
United Kingdom	David Buscher

OPTICON FP7 workpackages

Active working groups / Joint Research Activities:

- "Interferometric Image Reconstruction" JRA (2013-2016, chair: Eric Thiebaut)
- "Future of Interferometry in Europe" WG (2013-2016, chair: Jean Surdej)

Completed:

- "AGNs and the Galactic Center" (FP7-1, 2009-2012)
  ➔ 2011 Lisbon workshop
- "Circumstellar disks and planets" (FP7-1, 2009-2012)
  ➔ 2010 Kiel workshop & AARA article
- "Science cases for a 2nd generation facility" (FP7-1, 2009-2012)
  ➔ 2010 JENAM session
- "Integrating interferometry into mainstream astronomy" JRA (FP6)
  ➔ Feasibility studies for 2nd generation VLTI instruments
  ➔ Offline data reduction: Model-fitting (LITpro) + image reconstruction
- Radiative transfer (FP6)
- Interferometry and astroseismology (FP6)

Fizeau exchange grants

Goals:

- **Strengthen** nascent collaborations
- **Spread** interferometric knowledge across Europe
- **Enhance** the active participation of new countries in VLTI

Methods:

- Fund short research/technical/training exchange visits (1 week – 1 month)
- Priority to young researchers and "knowledge poor" institutes
- Competitive calls twice a year (March and September)

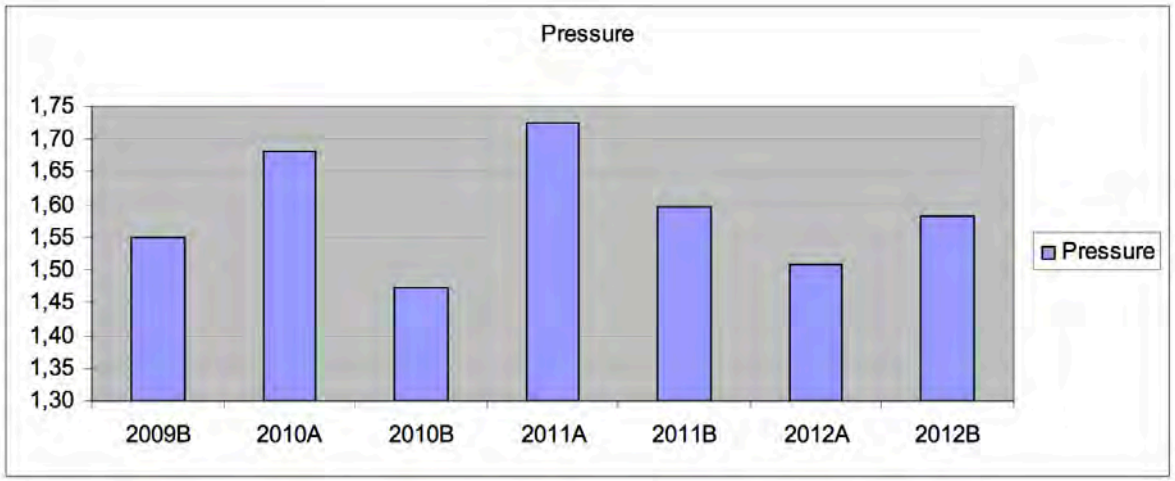
Selection from an independent project office (chair: Josef Hron)

Fizeau exchange grants

Publicity: Announced at OLBIN and through posters

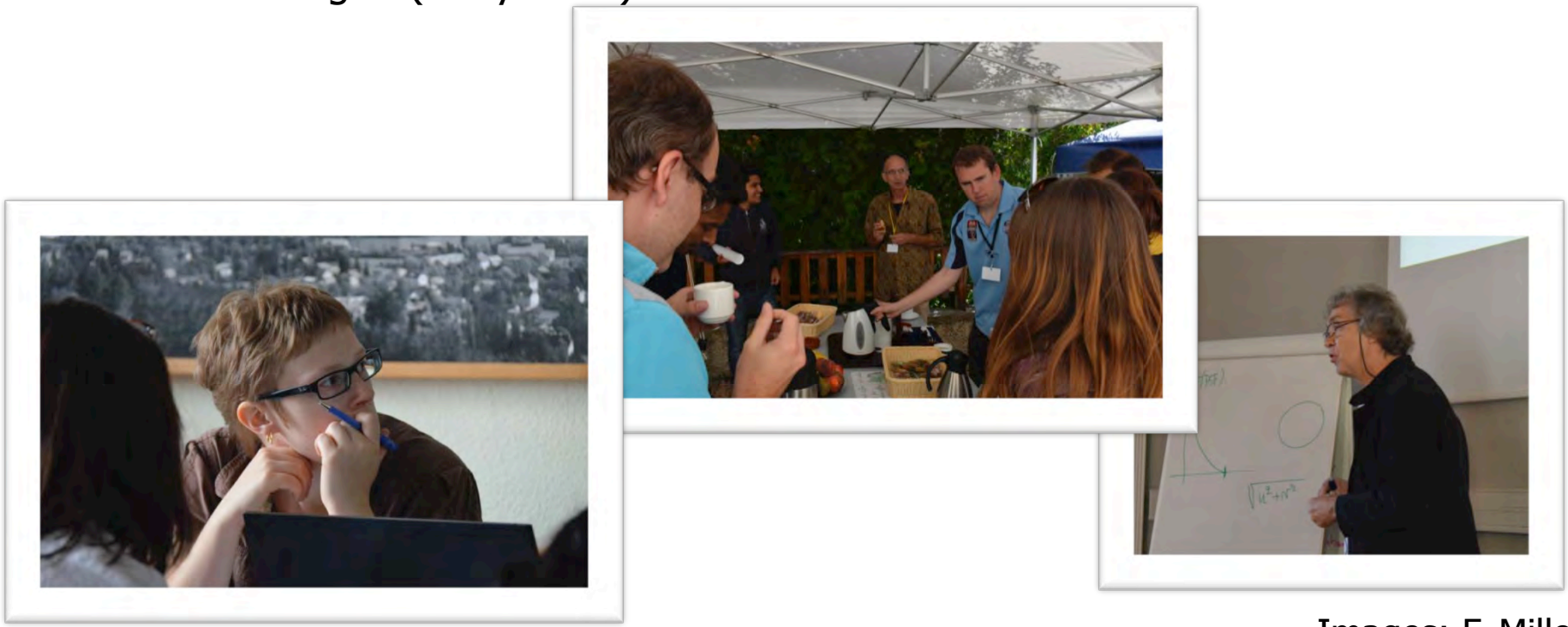
Around 80 grants awarded between 2009-2012

Next deadline on March 15



VLTI schools

2006	"Observation and Data Reduction with the VLTI", Goutelas
2007	"Circumstellar disks and planets at very high angular resolution", Porto
2007	"AGNs at the highest angular resolution", Torun
2008	"Astrometry and Imaging with the VLTI", Keszthely
2010	"High spatial resolution in astronomy", Porquerolles Island
2013	"High angular resolution for stellar astrophysics", Barcelonnette
next:	Cologne (likely 2015)



Images: F. Millour

Future opportunities in ground-based optical interferometry

Future of Interferometry in Europe

EII working groups:

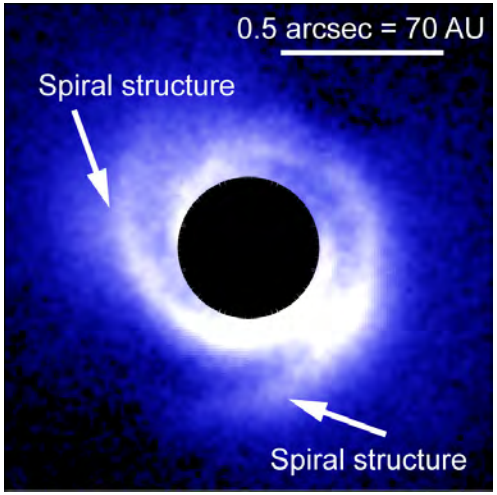
- "Circumstellar disks and planets" (2009-2012)
- "AGNs and the Galactic Center" (2009-2012)
- "Science cases for a 2nd generation facility" (2009-2012)
- "Future of Interferometry in Europe" (since 2013)

Dedicated workshops on the Future of Interferometry:

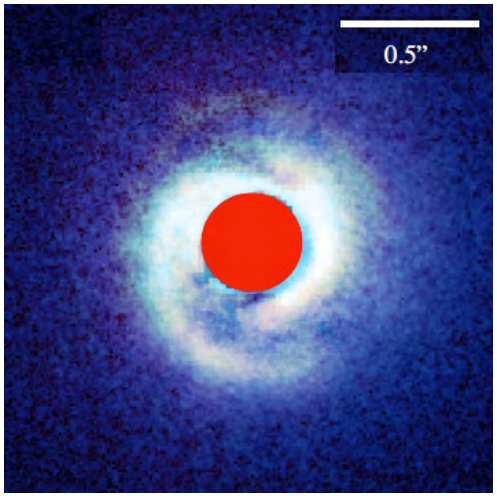
- 2004: Workshop "Science cases for next generation OIR interferometric facilities", Liege
- 2005: Workshop "Technology Roadmap for Future Interferometric Facilities", Liege
- 2010: JENAM session "Science Cases for OIR Interferometers – Present and Future", Lisbon
- 2013: EWASS session "Science with present & future interferometric instruments", Turku
- 2013: Workshop "Improving the performances of current optical interferometers & future designs", OHP

Similar efforts in the US (Interferometry Forum) and in national communities

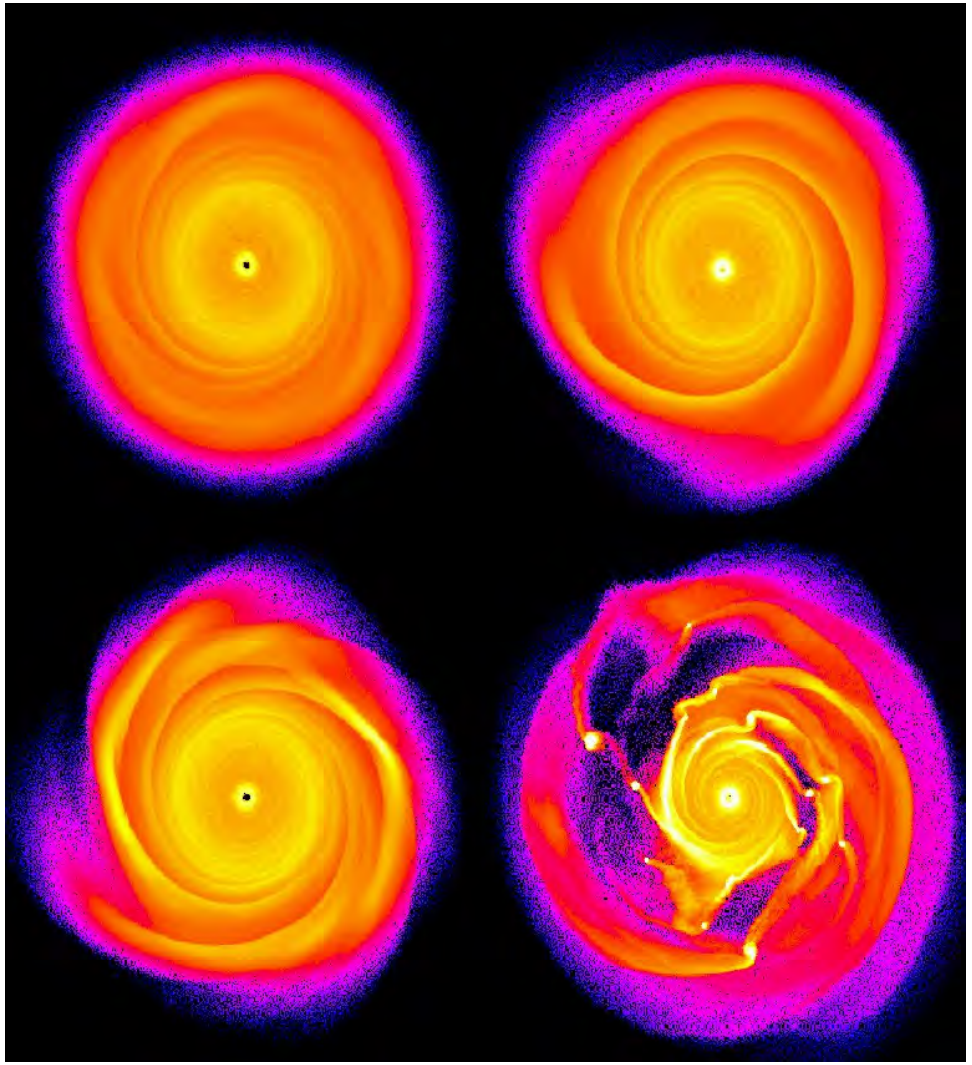
Prospects: Imaging planet formation in action



SAO206462, Dong et al. 2012



MWC758, Grady et al. 2013

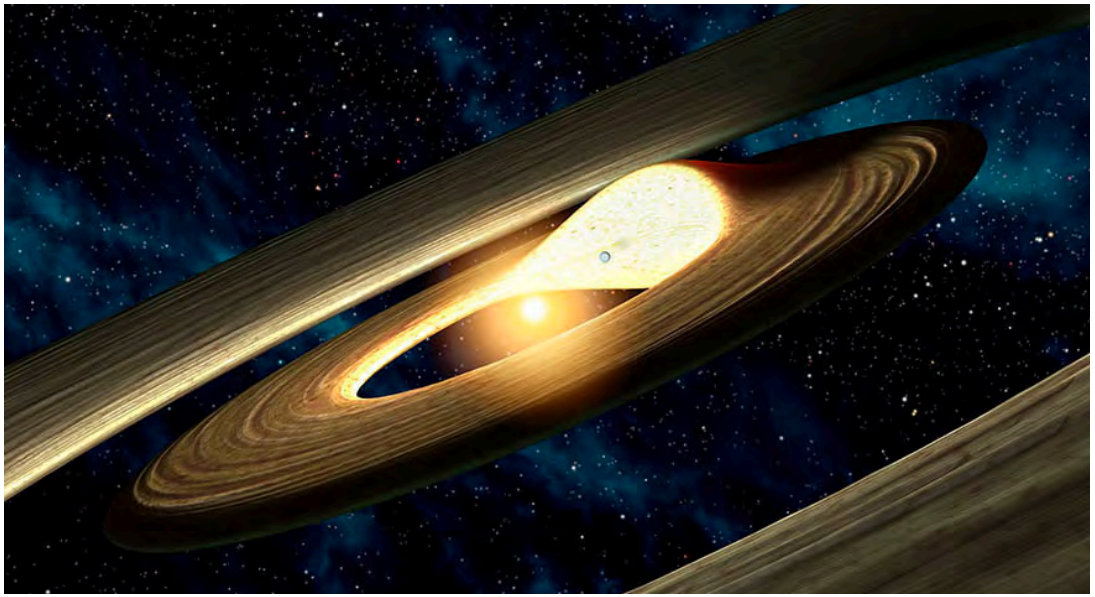


Quinn et al. 2002

Prospects: Imaging planet formation in action

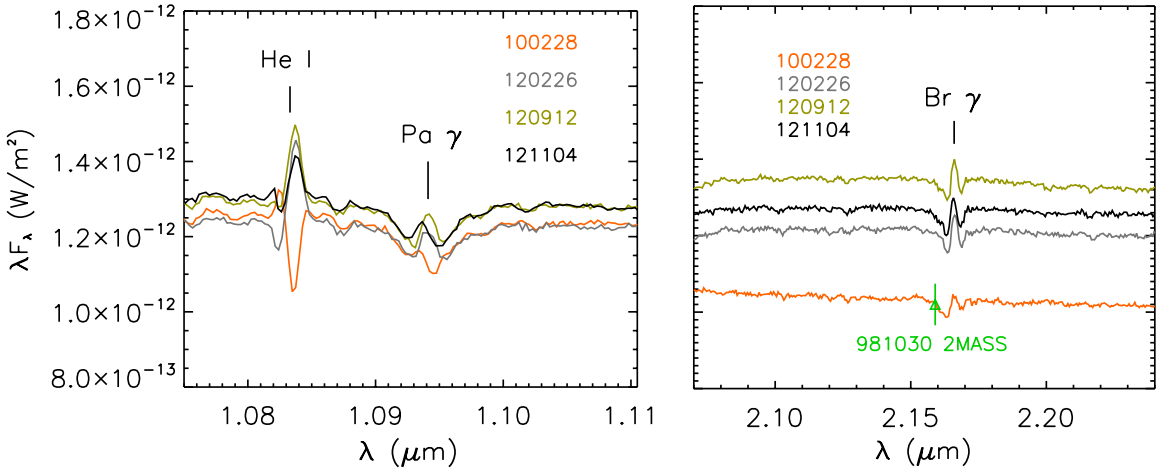
Pre-transitional disks exhibit **quasi-periodic variability on time scales of months,** indicating structural changes in the inner disk regions

Objective: Image the complex & highly dynamical processes in the innermost AU and study their temporal evolution

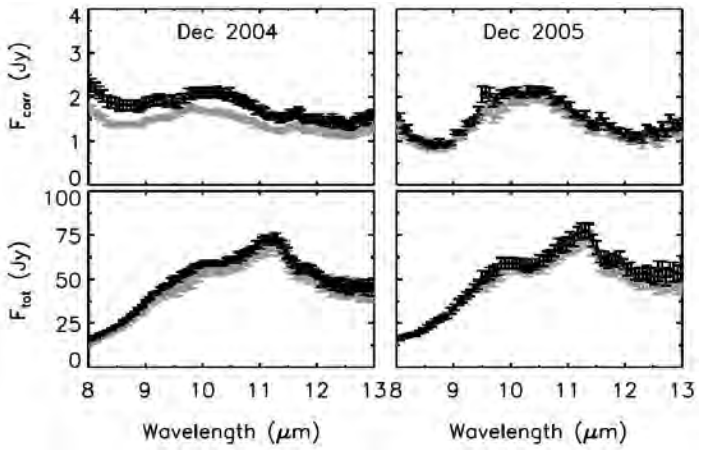


Artists Impression, Muzerolle et al. 2009

Spectroscopic variability (V1247 Ori)



Structural variability (HD100546)



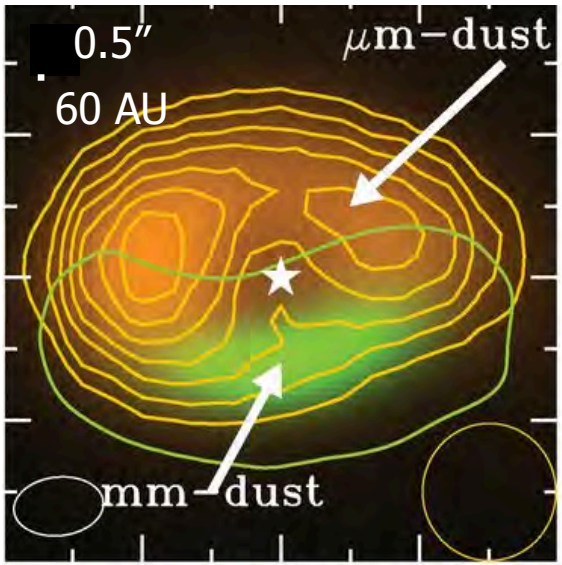
Panic et al. 2012, Kraus et al. 2013

Prospects: Imaging planet formation in action

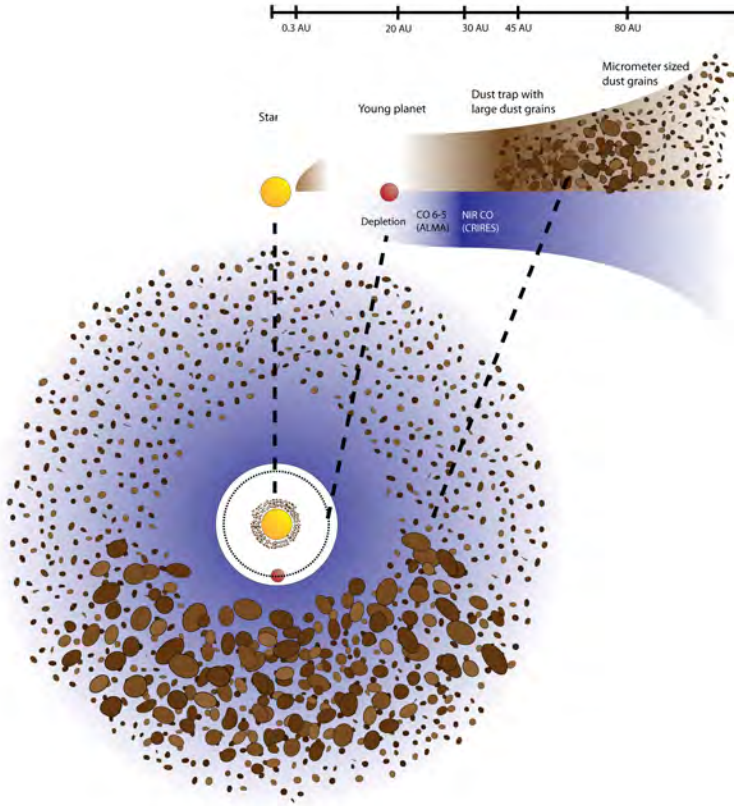
Objective: Trace small dust grains & detect spatial variations in dust mineralogy

➔ early stages of grain growth and gap opening, dust filtration

Oph IRS48



van der Marel et al. 2013

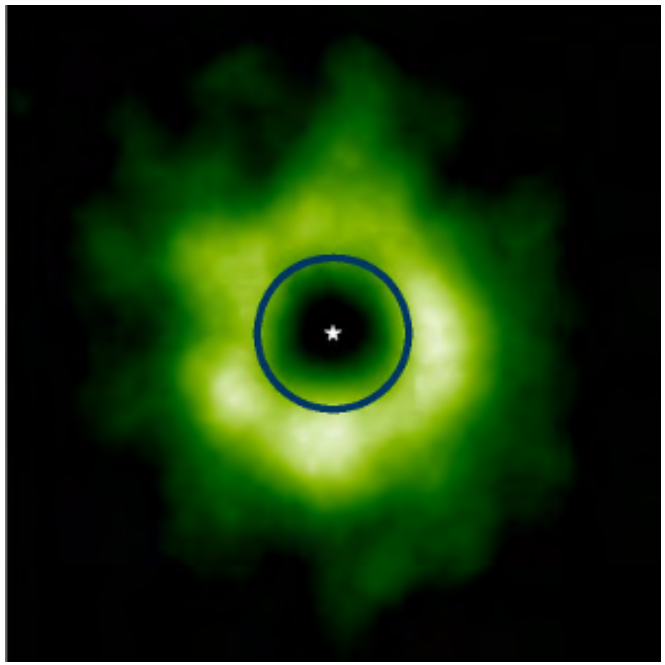


Prospects: Imaging planet formation in action

Objective: Determine distribution of water & ices

➔ link to habitability

TW Hya

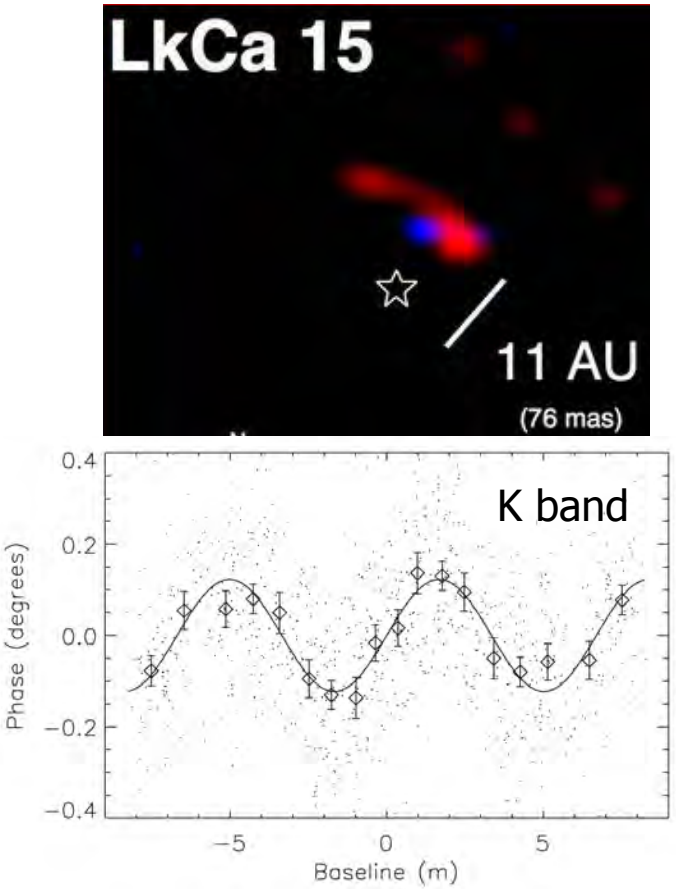


CO „snow line"
imaged with ALMA

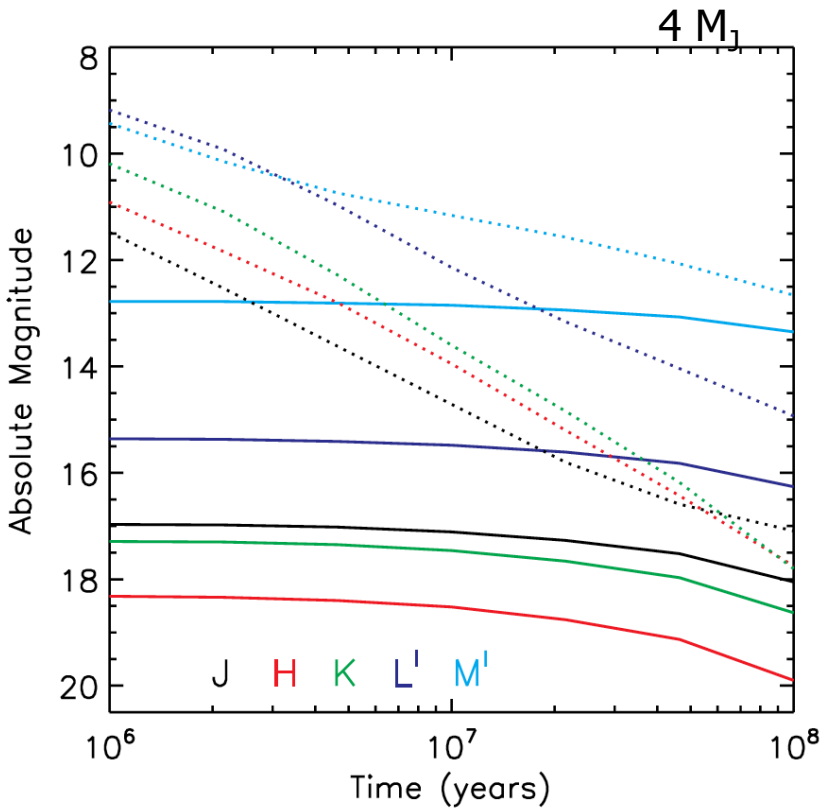
Qi et al. 2013

Prospects: Imaging planet formation in action

Objective: Detect young accreting protoplanets



Kraus & Ireland 2012



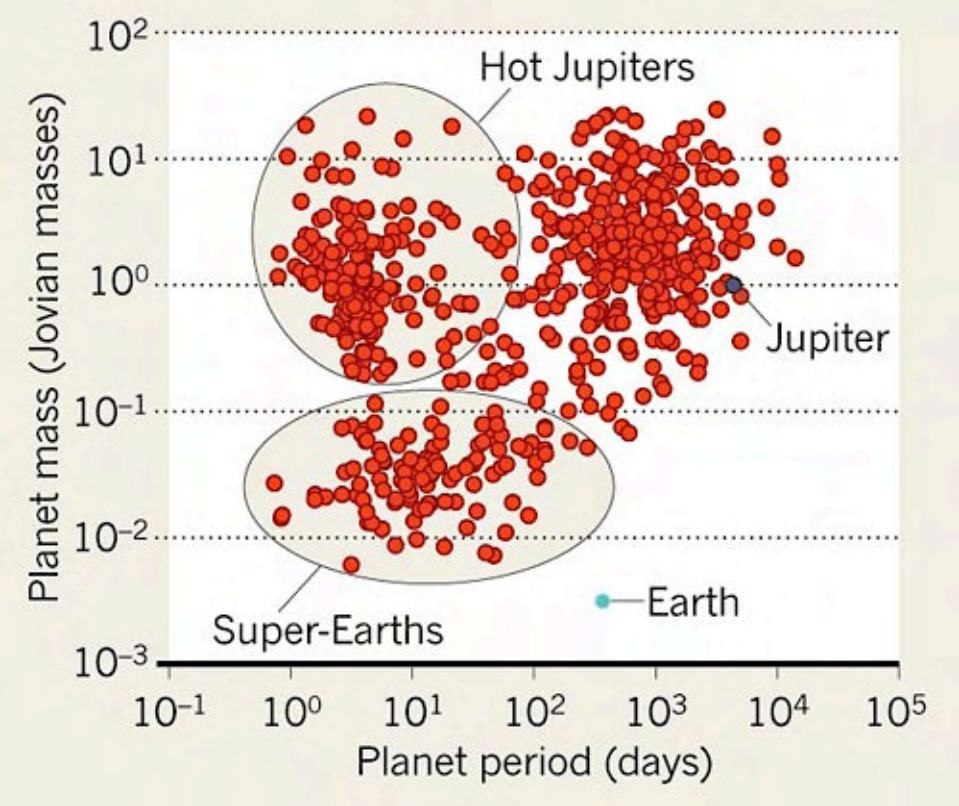
Forney et al. 2008

Prospects: Imaging planet formation in action

Objective: Detect young accreting protoplanets

➔ constraints on **planetary migration**

➔ link to **exoplanet statistics**



Hand 2010

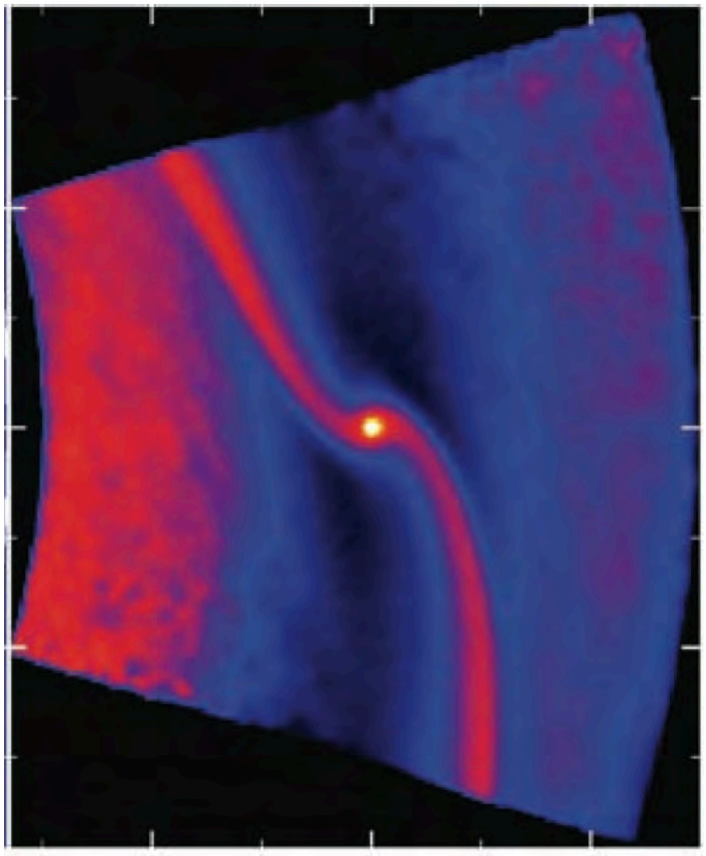
Key questions:

(1) What determines the architecture of planetary systems?

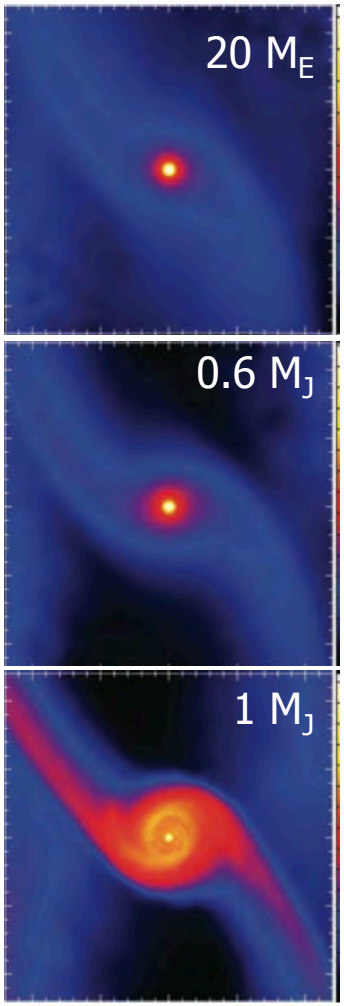
(2) Did the planets form where we observe them, or did they migrate due to planet-disk interaction?

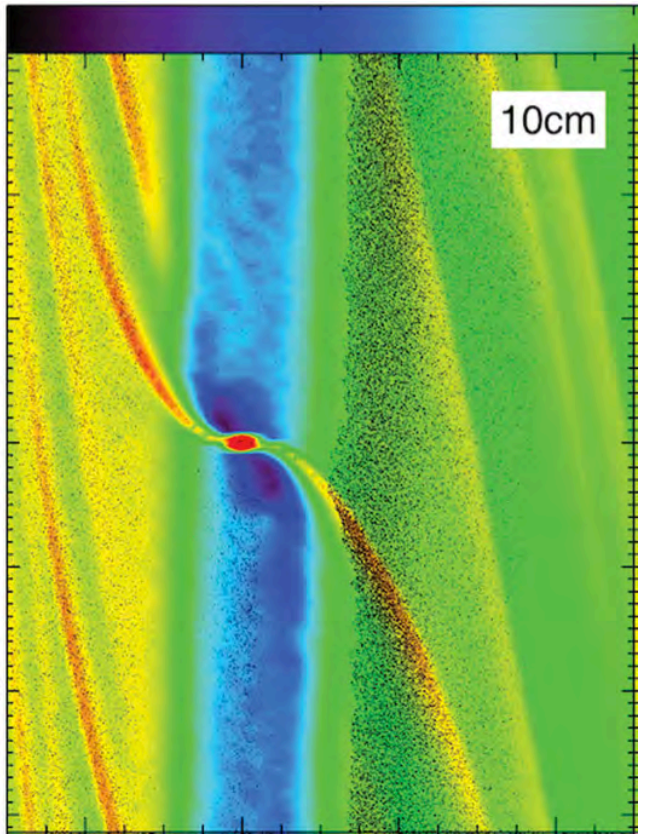
Prospects: Imaging planet formation in action

Objective: Resolve the protoplanetary accretion disk



Ayliffe & Bate 2009





Ayliffe et al. 2012

Planet Formation Imager (PFI) initiative

Complementary aspects to ALMA:

- ➔ higher resolution allows probing terrestrial planet-forming zone, which is dominated by other mechanisms (dust sublimation, gas-disk truncation, magnetospheric accretion, …)
- ➔ NIR/MIR/sub-mm probes complementary opacity regimes, grain sizes, and line tracers

Tentative international "Kick-off committee" has been formed, including representatives from EU, US, Australia, and IAU commission 54:

- ➔ Set up **Project Steering Committee**
- ➔ Define **Scientific Working Group** to develop and prioritize key science cases
- ➔ Define **Technical Working Group** to develop a technology roadmap

Exciting new technology developments are on the horizon
(MIR fibers, detectors, heterodyne beam combination with coherent laser combs, …)

- ➔ Upcoming dedicated session at SPIE (Montreal, June 2014)

We invite participation from wider scientific community:
➔ Sign up for PFI Mailing List: www.planetformationimager.org

Conclusions

NIR+MIR interferometry provides new constraints on the
AU-scale structure of protoplanetary disks and the disk clearing mechanism

Interferometry in spectral features provides detailed constraints on
dust mineralogy & gas kinematics.

Interferometric imaging is still challenging, but becomes more routine with the upcoming generation of 4T and 6T beam combiners

"Planet Formation Imager": Initiative for a NIR/MIR facility that will be optimized to image planet-formation processes on (sub-)AU scales.