Protoplanetary Disk Structure and Planet Formation Signatures resolved with Interferometry

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UNIVERSITY OF EXETER

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Outline

Part 1: Planet-formation signatures revealed with infrared interferometry

Part 2: The Planet Formation Imager (PFI) project

PFI project collaborators:

Executive team: John Monnier, David Buscher

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

Science WG coordinators: Jean-Charles Augereau, Gaspard Duchene, Catherine Espaillat, Sebastian Hönig, Attila Juhasz, Claudia Paladini, Joshua Pepper, Keivan Stassun, Neal Turner, Gautam Vasisht

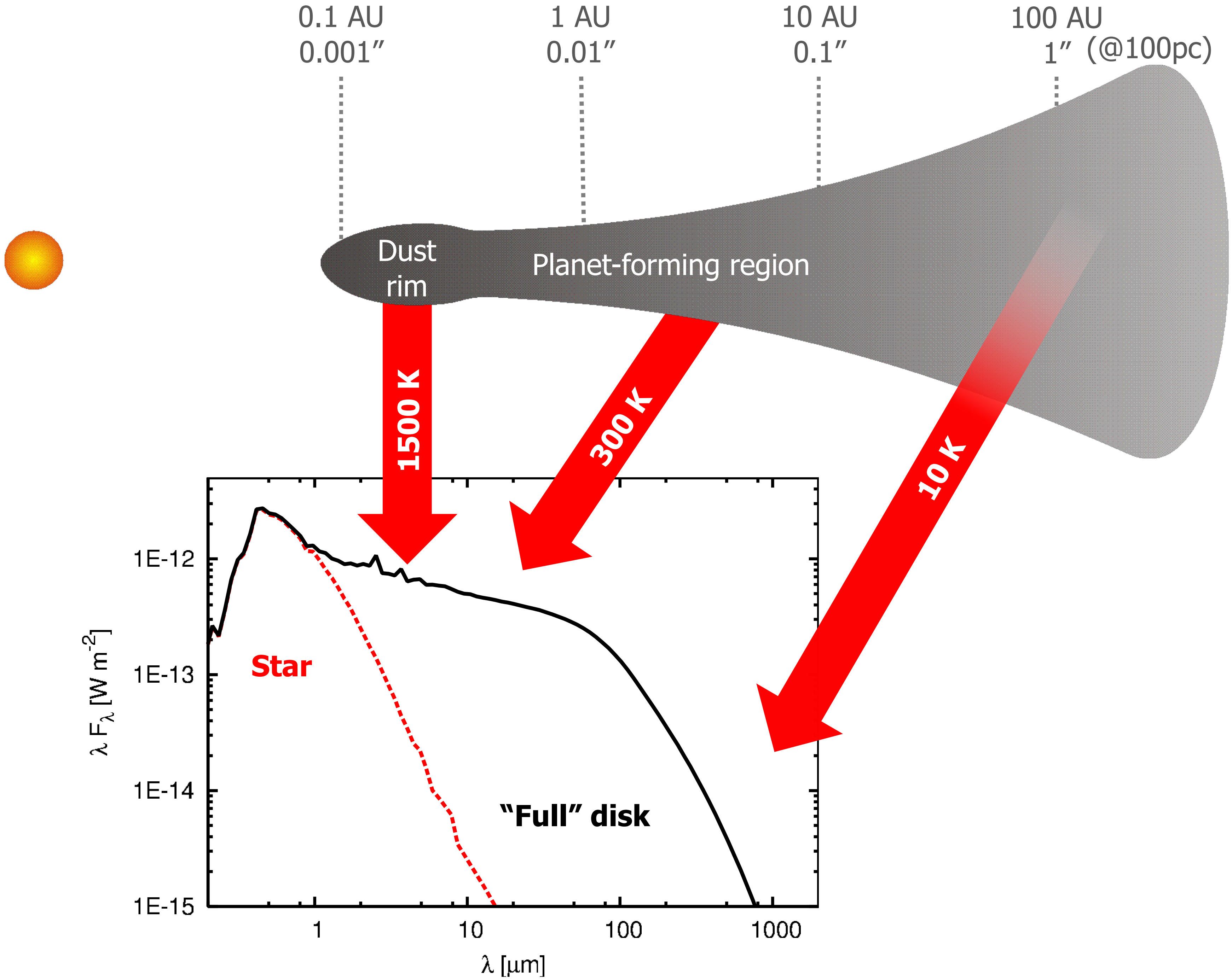
Science and Technical WG members

Simulations: Matthew Bate, Robin Dong, Tim Harries, Barbara Whitney, Zhaohuan Zhu

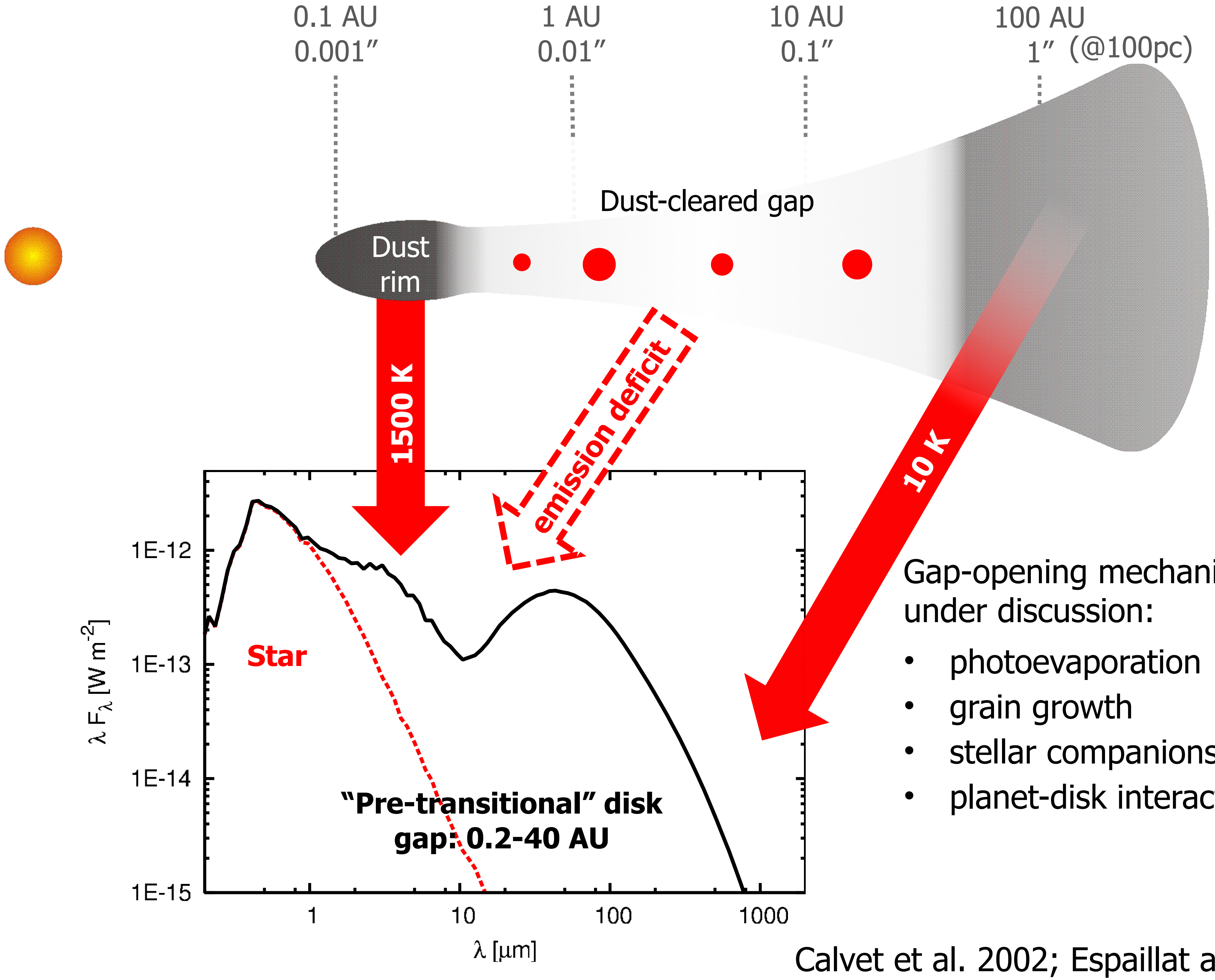
Part 1:

Planet formation signatures revealed with infrared interferometry

Protoplanetary disk structure



Disk structure in transitional disks

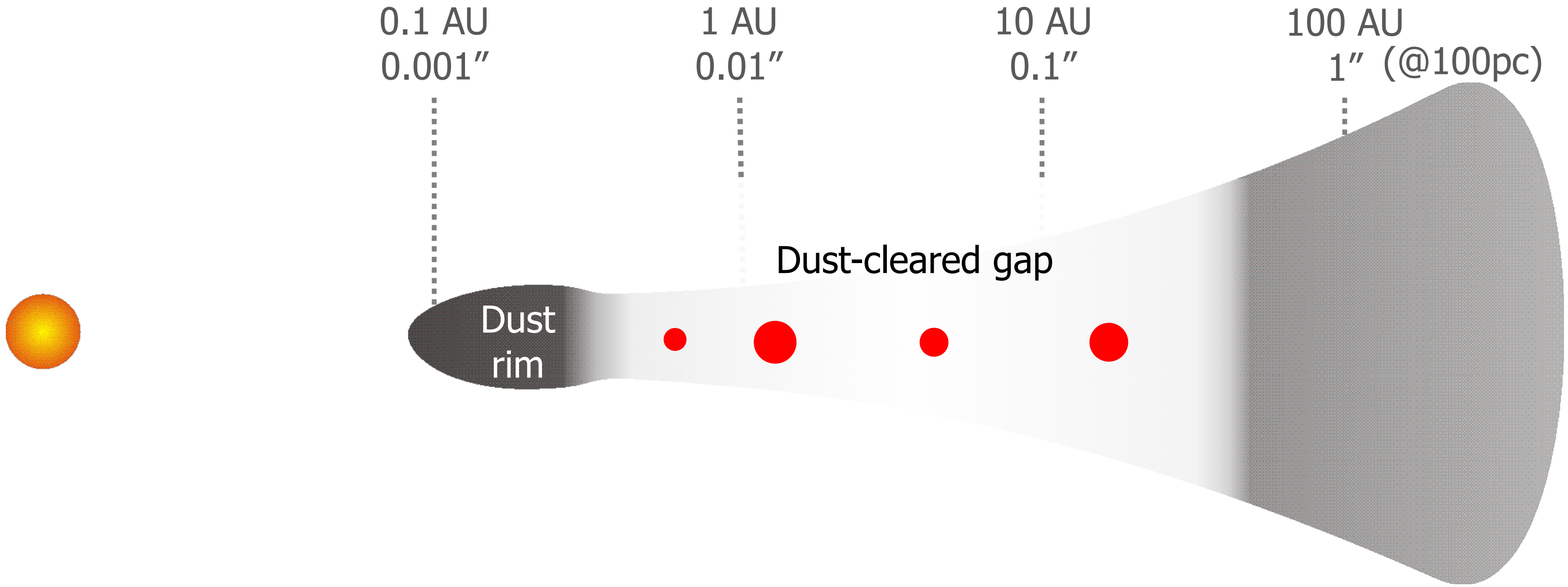


Gap-opening mechanisms under discussion:

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

Calvet et al. 2002; Espaillat al. 2014

Disk structure in transitional disks

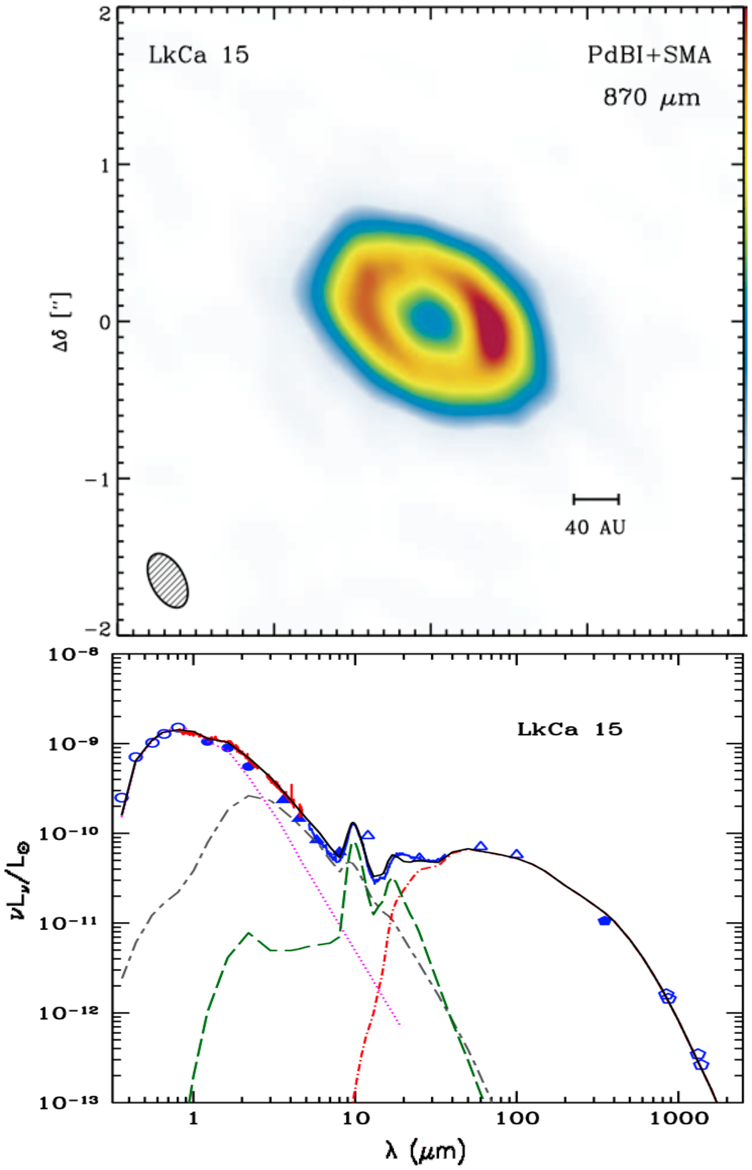


Spatially unresolved techniques face severe limitations:

- Parameter degeneracies
- Planet-disk interaction results in complex / asymmetric structures
  ➜ Direct imaging essential
- Dynamical processes accompanied by changes in dust mineralogy (e.g. dust filtration or dust traps)
  ➜ Need to probe multiple grain sizes (=multiple wavelengths)

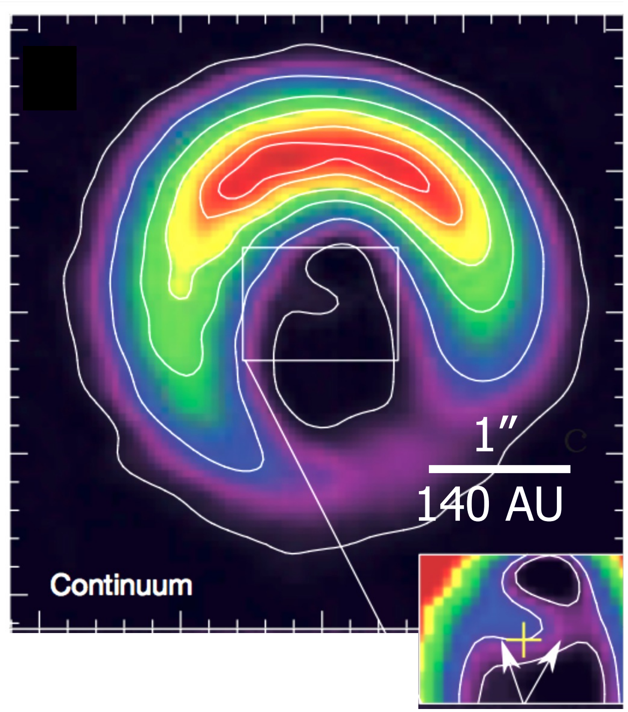
Disk structure in transitional disks

LkCa15



Andrews et al. 2011

HD142527



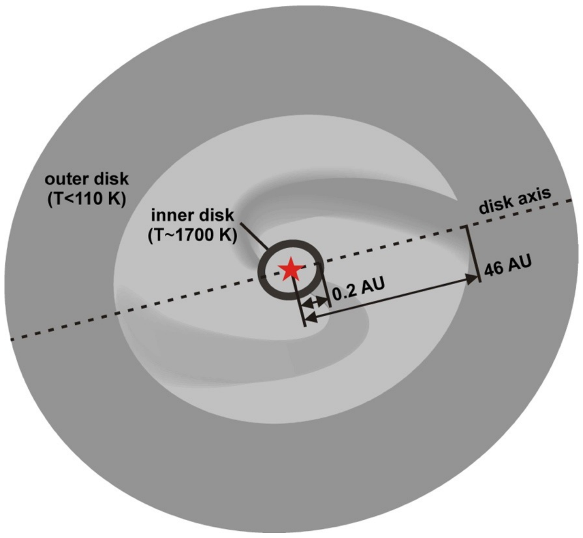
Casassus et al. 2013

(Sub-)millimeter interferometry reveals central density depressions


2

IR interferometric studies on transitional disks

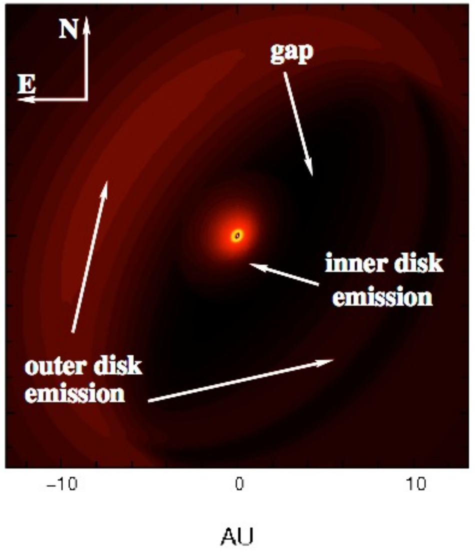
V1247 Ori



- Gap 0.2 – 46 AU, partially depleted
- Gap contains optically thin carbonaceous dust

Kraus et al. 2013

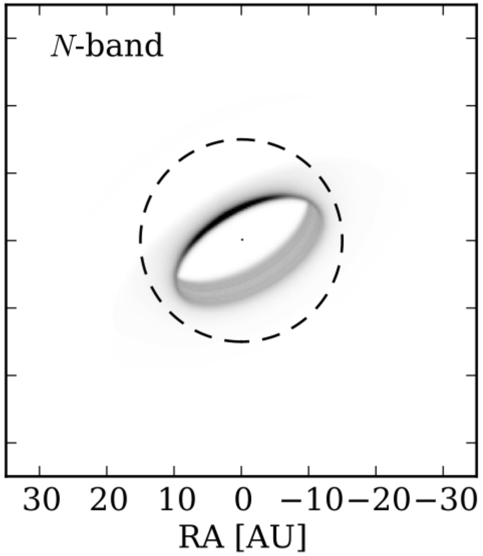
HD100546



- Gap 0.3 – 29 AU, fully depleted
- Companion candidate (Quanz et al. 2013)

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

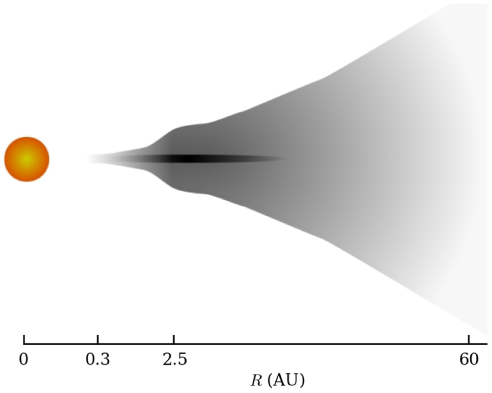
T Cha



- Gap 0.1 – 25 AU, fully depleted
- Companion candidate (Huelamo et al. 2011)

Olofsson et al. 2011, 2013

TW Hya

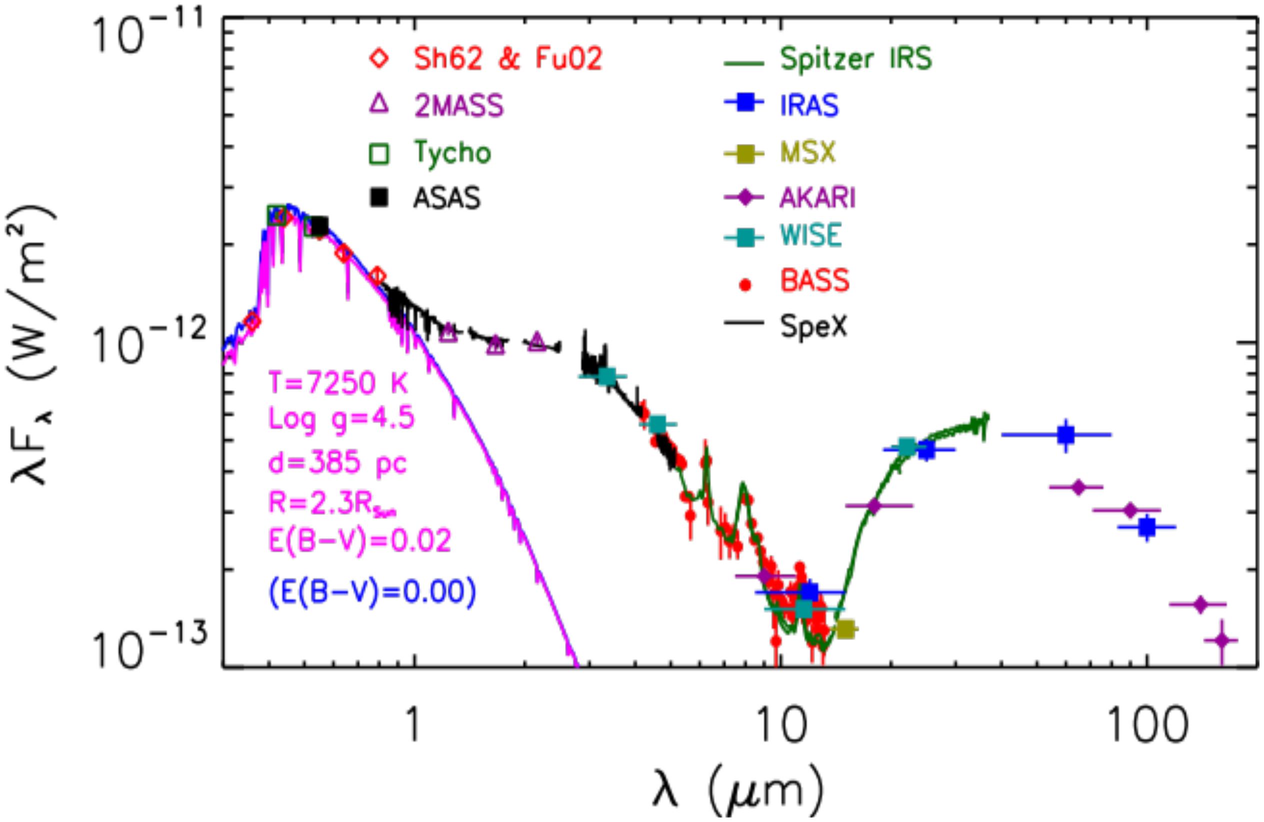


- Depleted region <2.5 AU with very large settled grains

Eisner et al. 2006
Ratzka et al. 2007
Akeson et al. 2011
Arnold et al. 2012
Menu et al. 2014

time??

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**

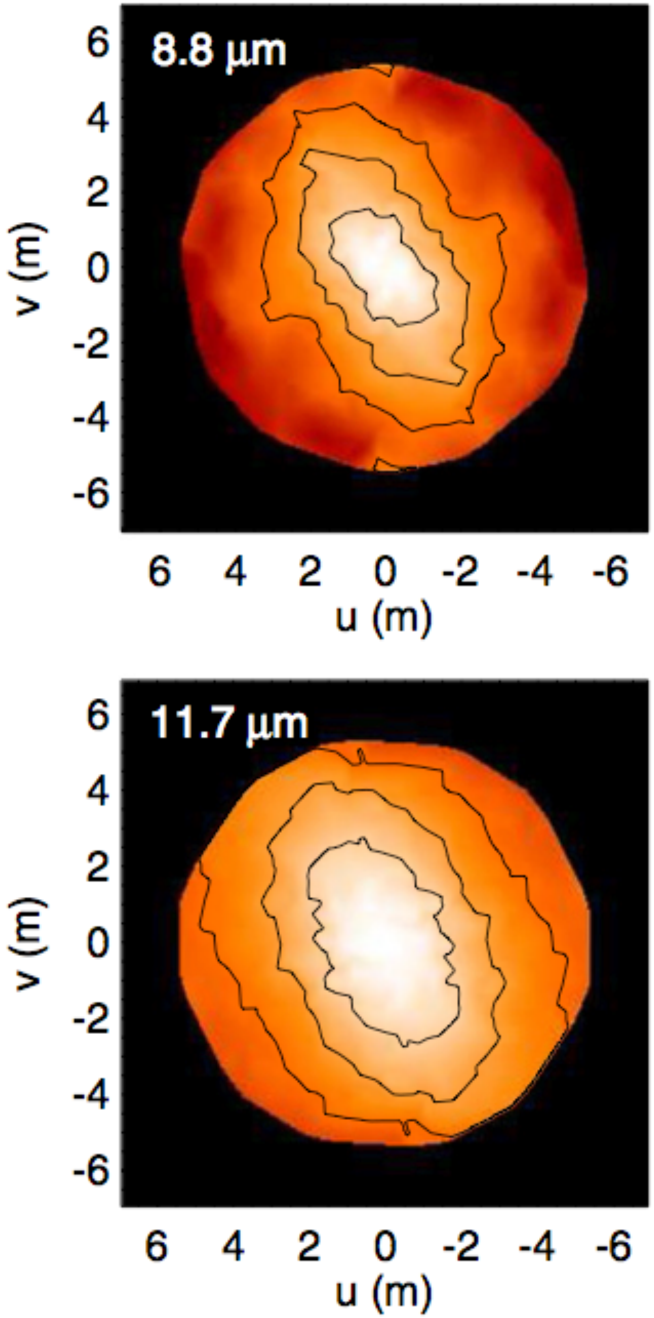
Kraus et al. 2013

V1247 Orionis

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

➜ **Inclination: 31±7°**
PA: 104±15°

Gemini/TReCS



V1247 Orionis

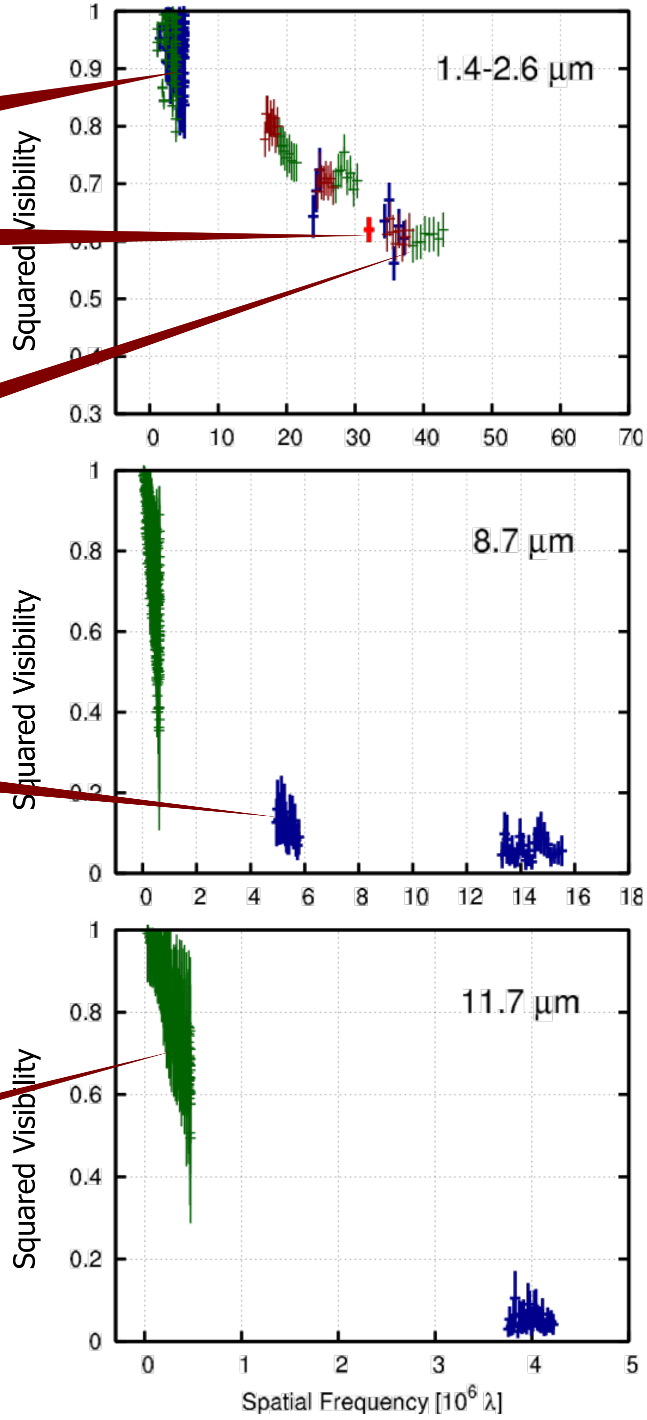
Keck/NIRC2

Keck/V2-SPR

VLTI/AMBER

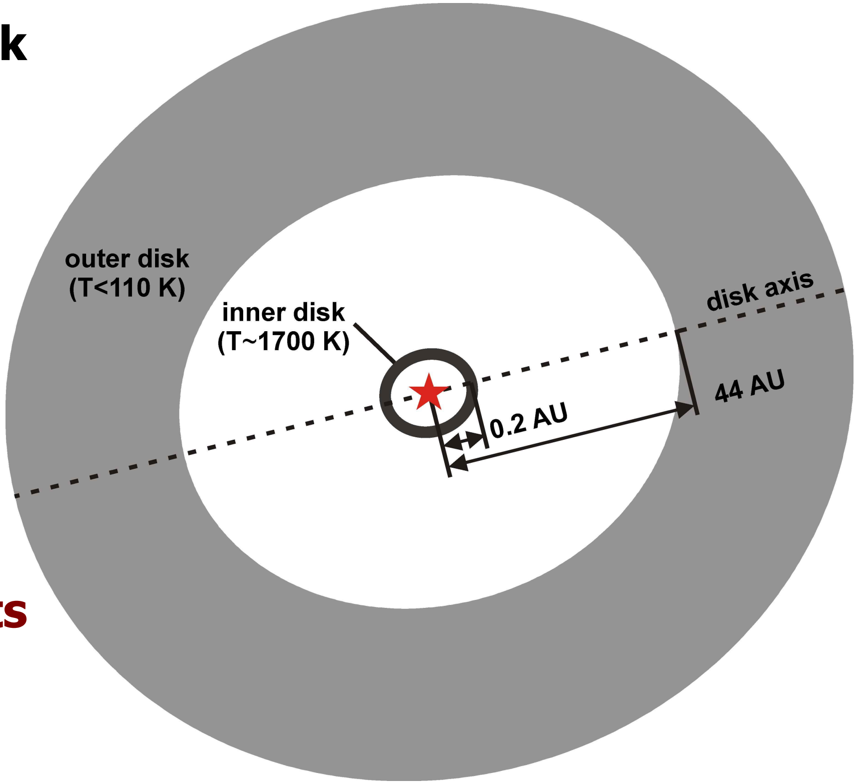
VLTI/MIDI

Gemini/TReCS

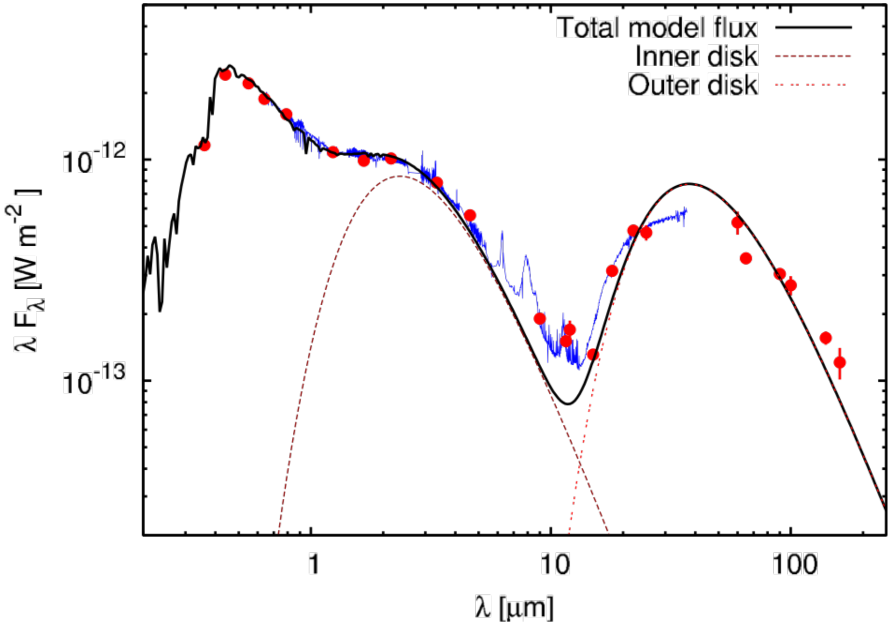


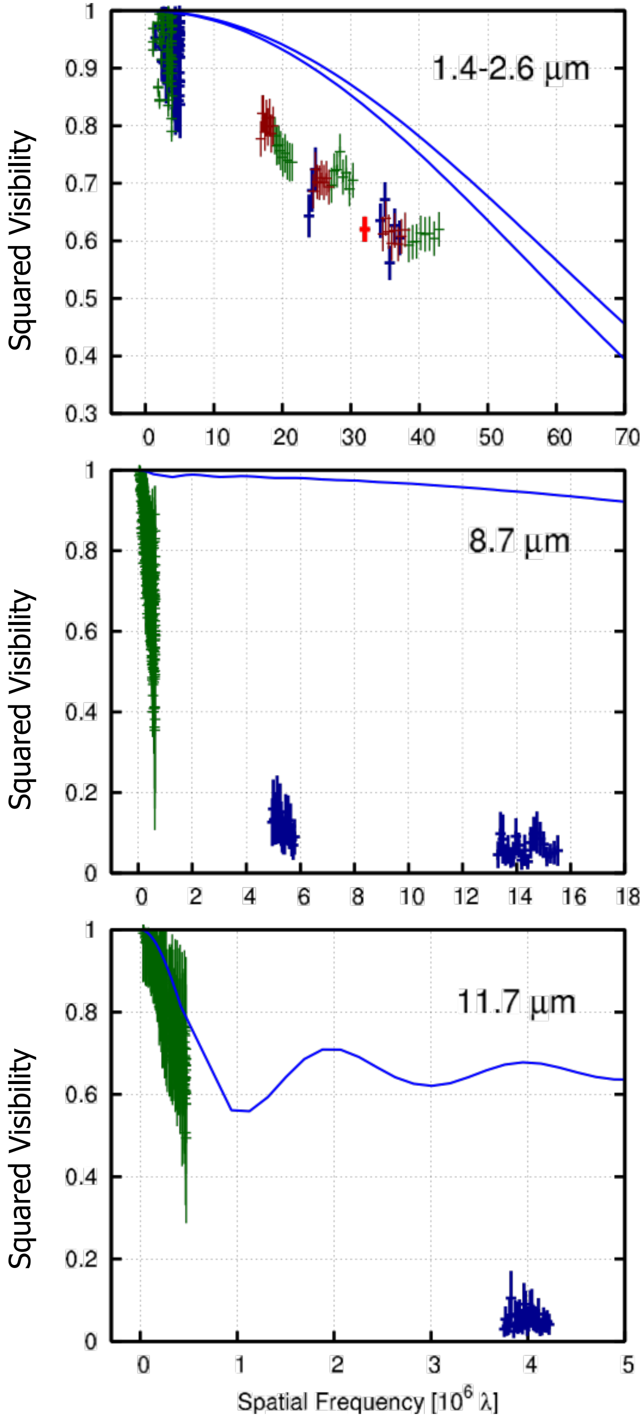
V1247 Orionis

Scenario 1: Gapped disk



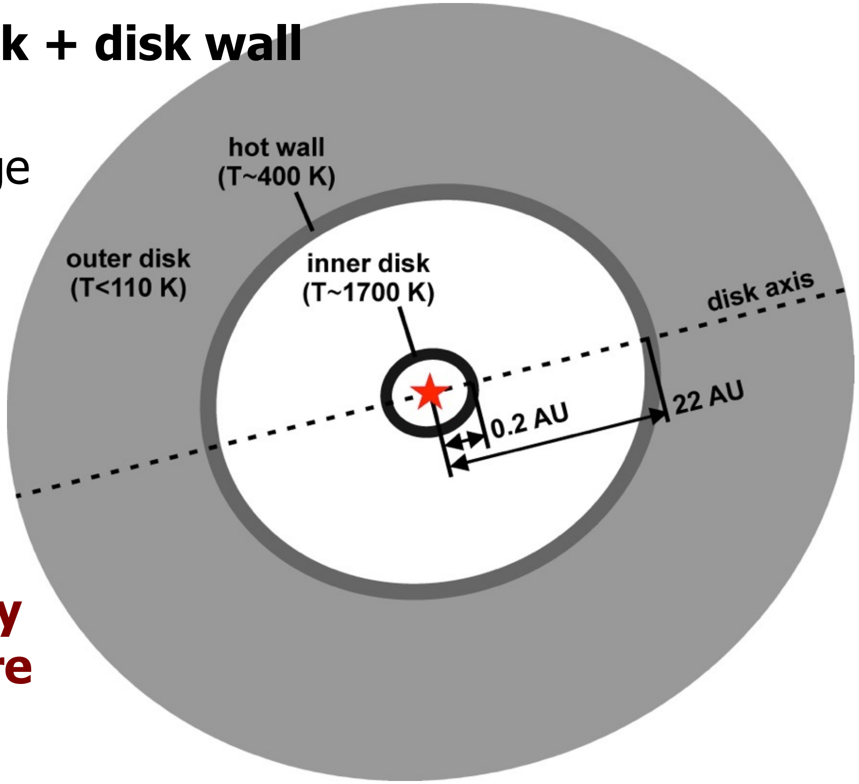
➜ **Model under-predicts MIR size by order of magnitude**





V1247 Orionis

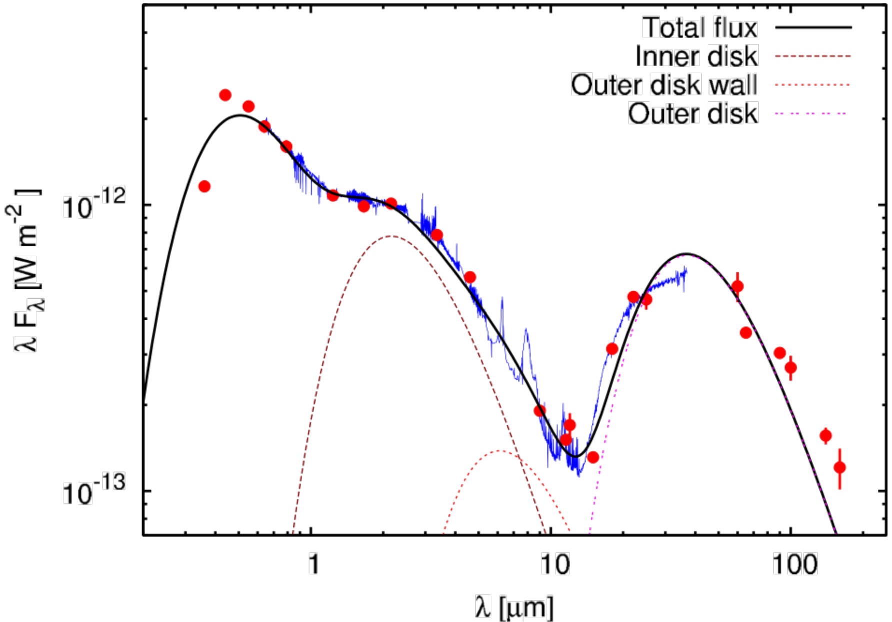
Scenario 2: Gapped disk + disk wall

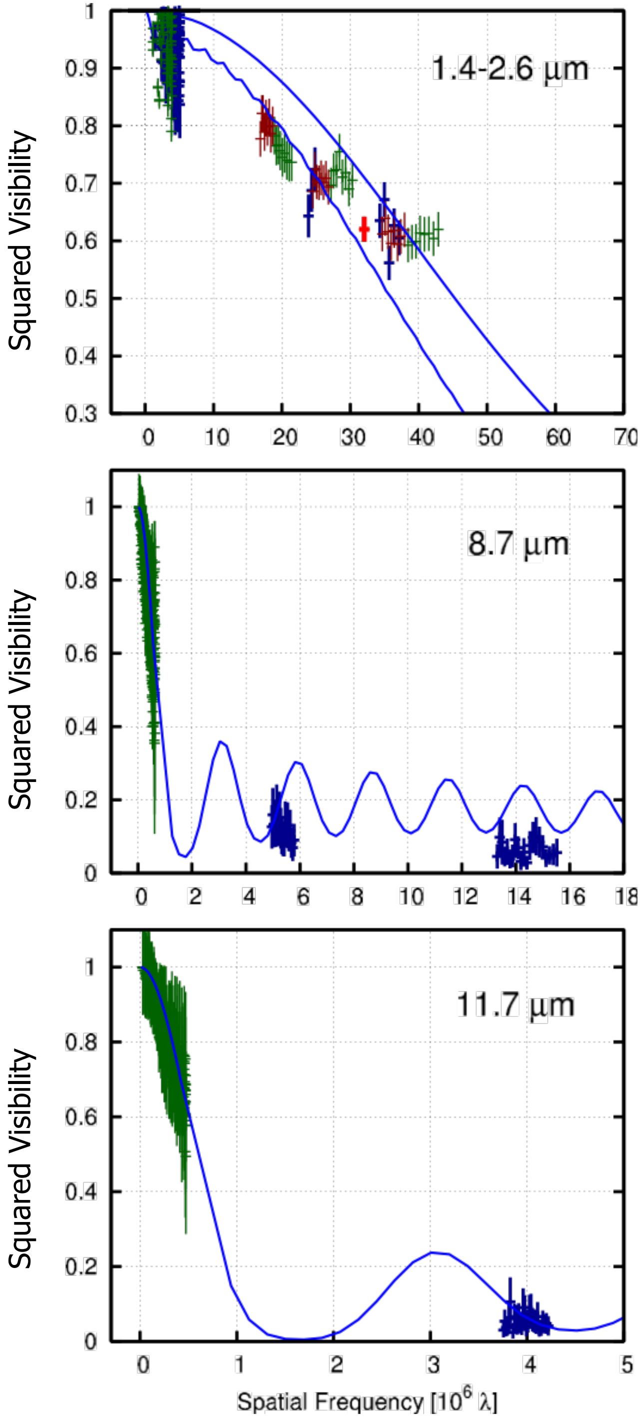


Realistic temperature range for wall @ 22 AU:

90K for grey dust
160K for 0.1µm grains

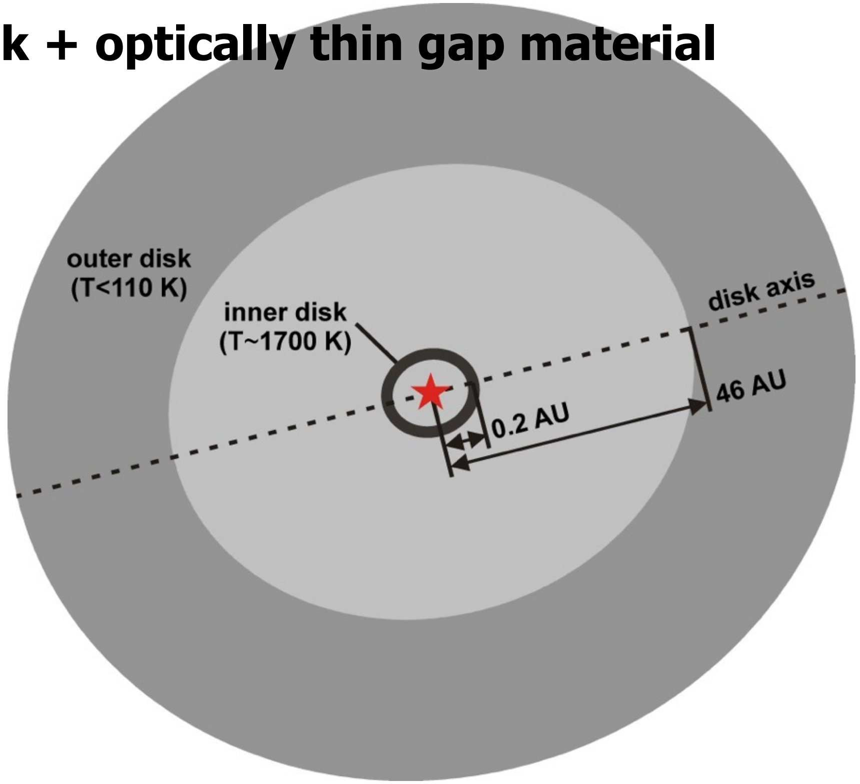
➜ **Requires unphysically high wall temperature of 400 K @ 22 AU**



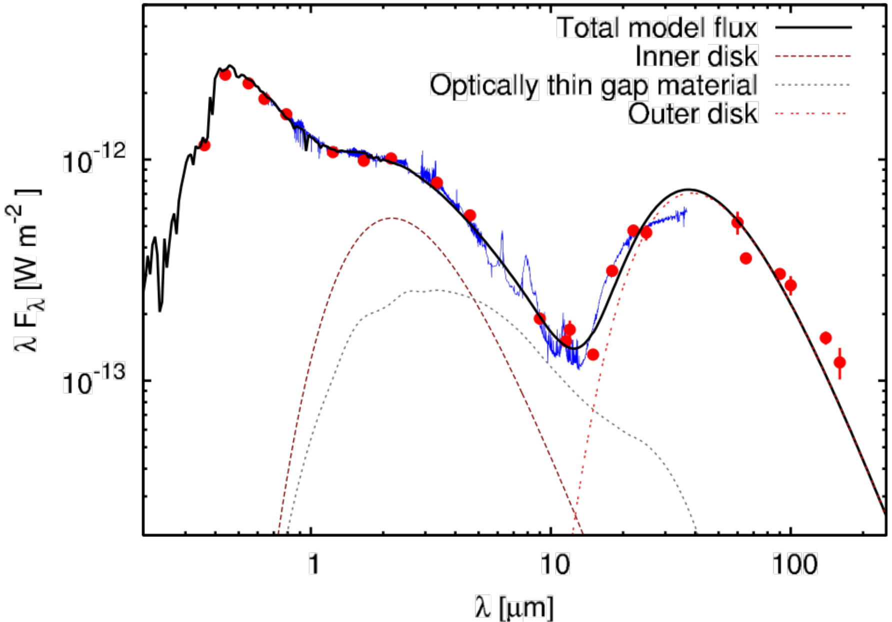


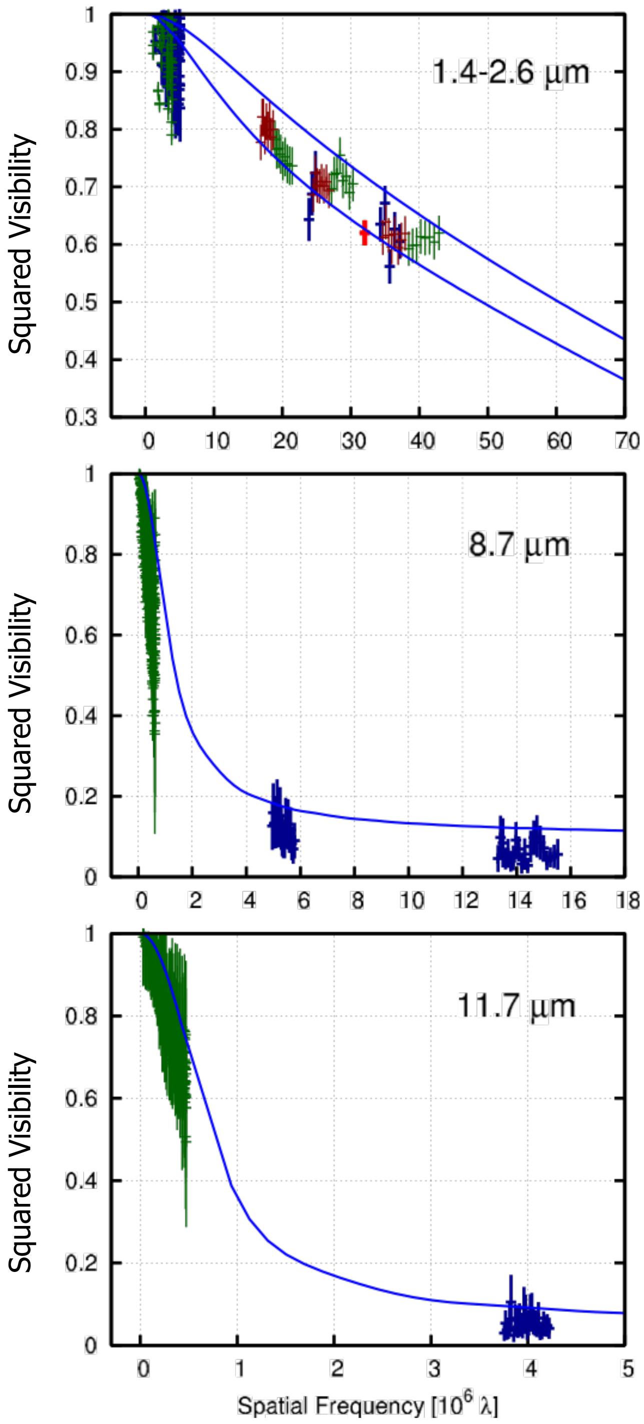
V1247 Orionis

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**

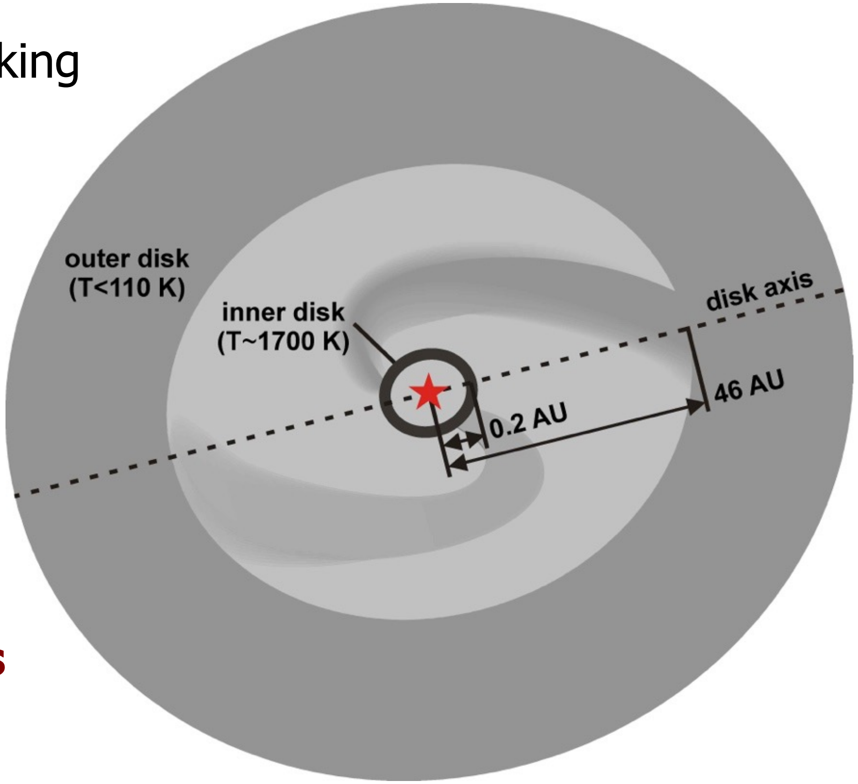


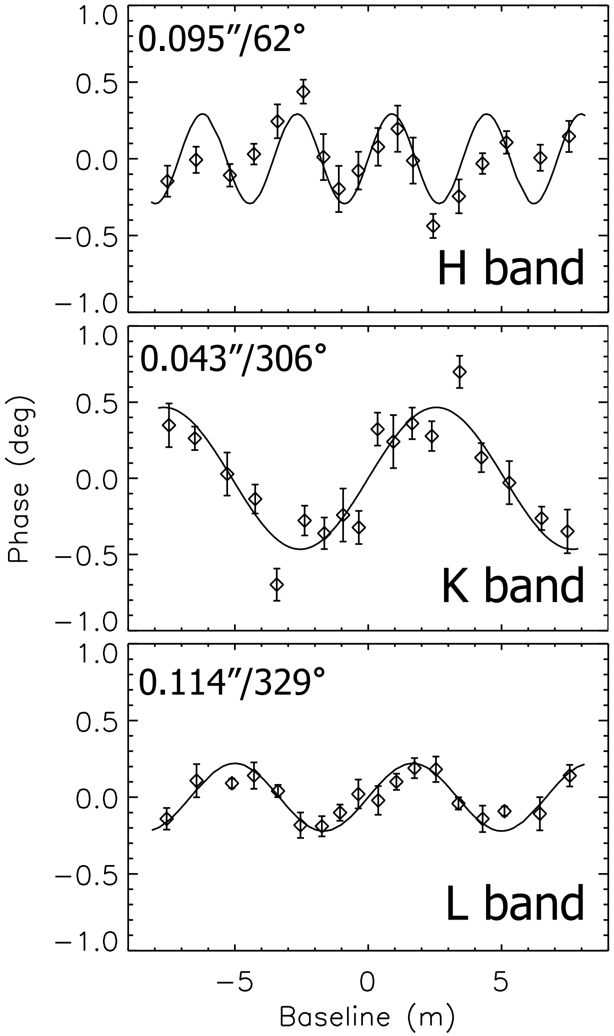


AU-scale asymmetries: Disk inhomogeneities

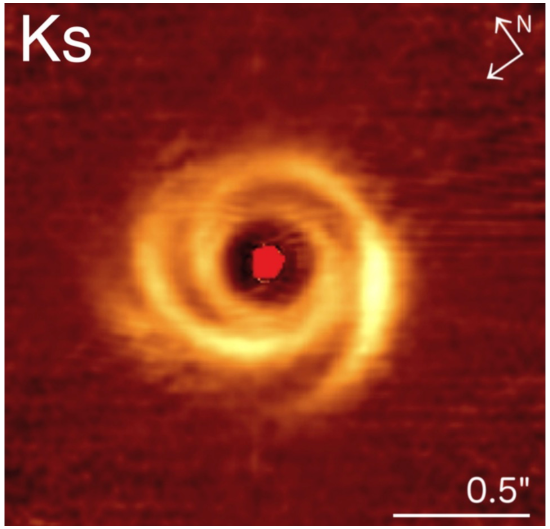
Keck/NIRC2 aperture masking reveals asymmetries

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

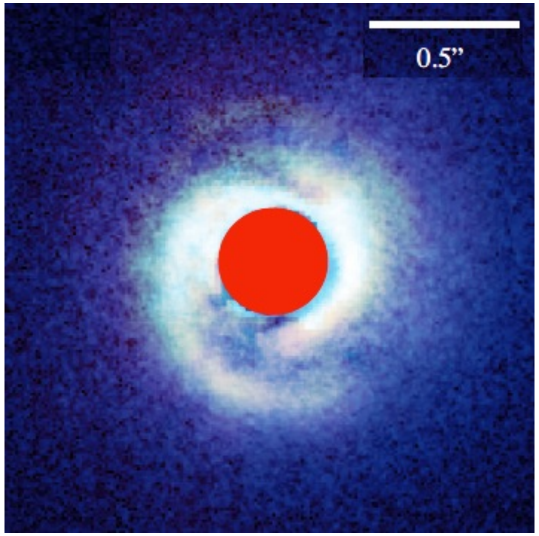




Kraus et al. 2013

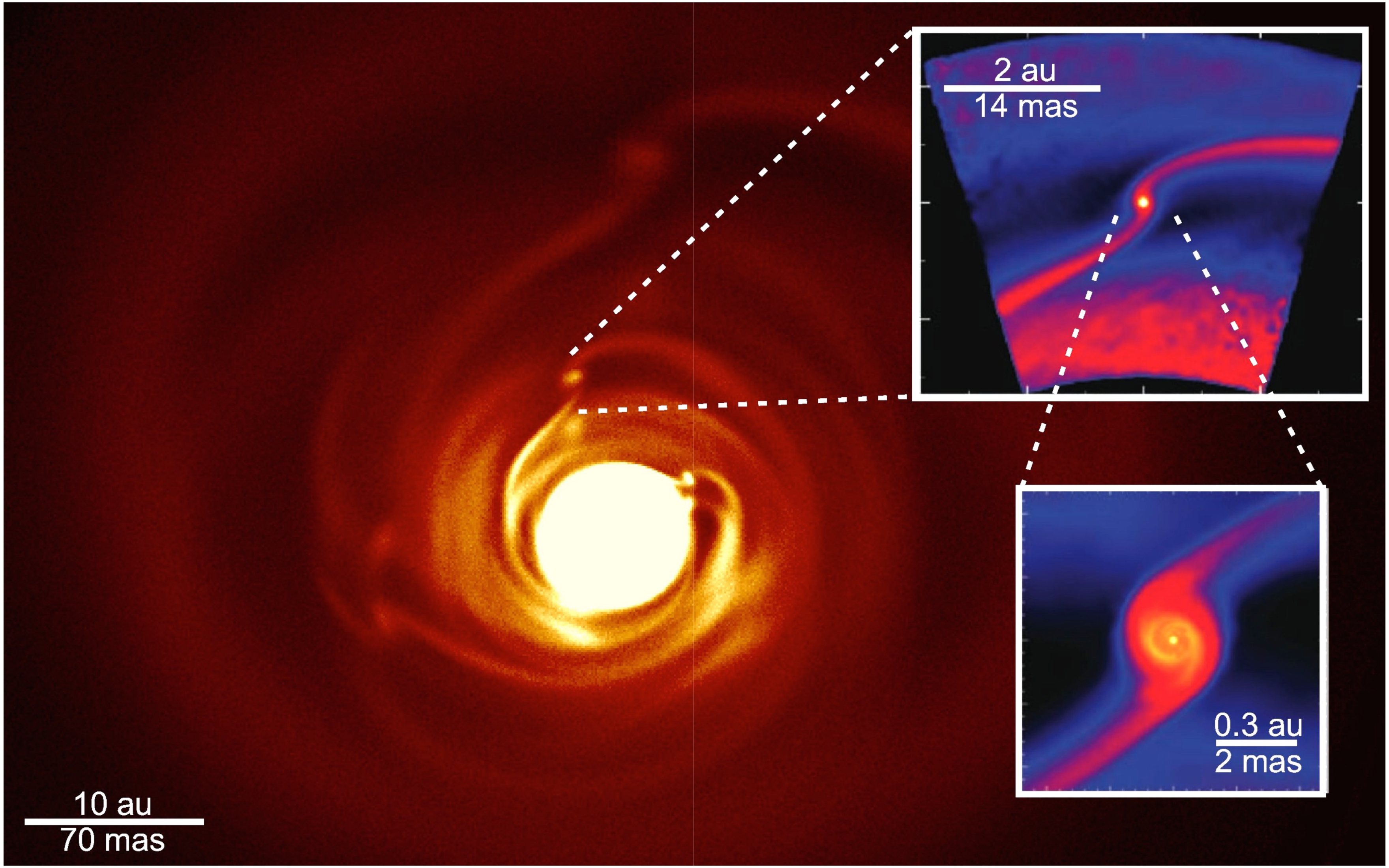


SAO206462, Garufi et al. 2013



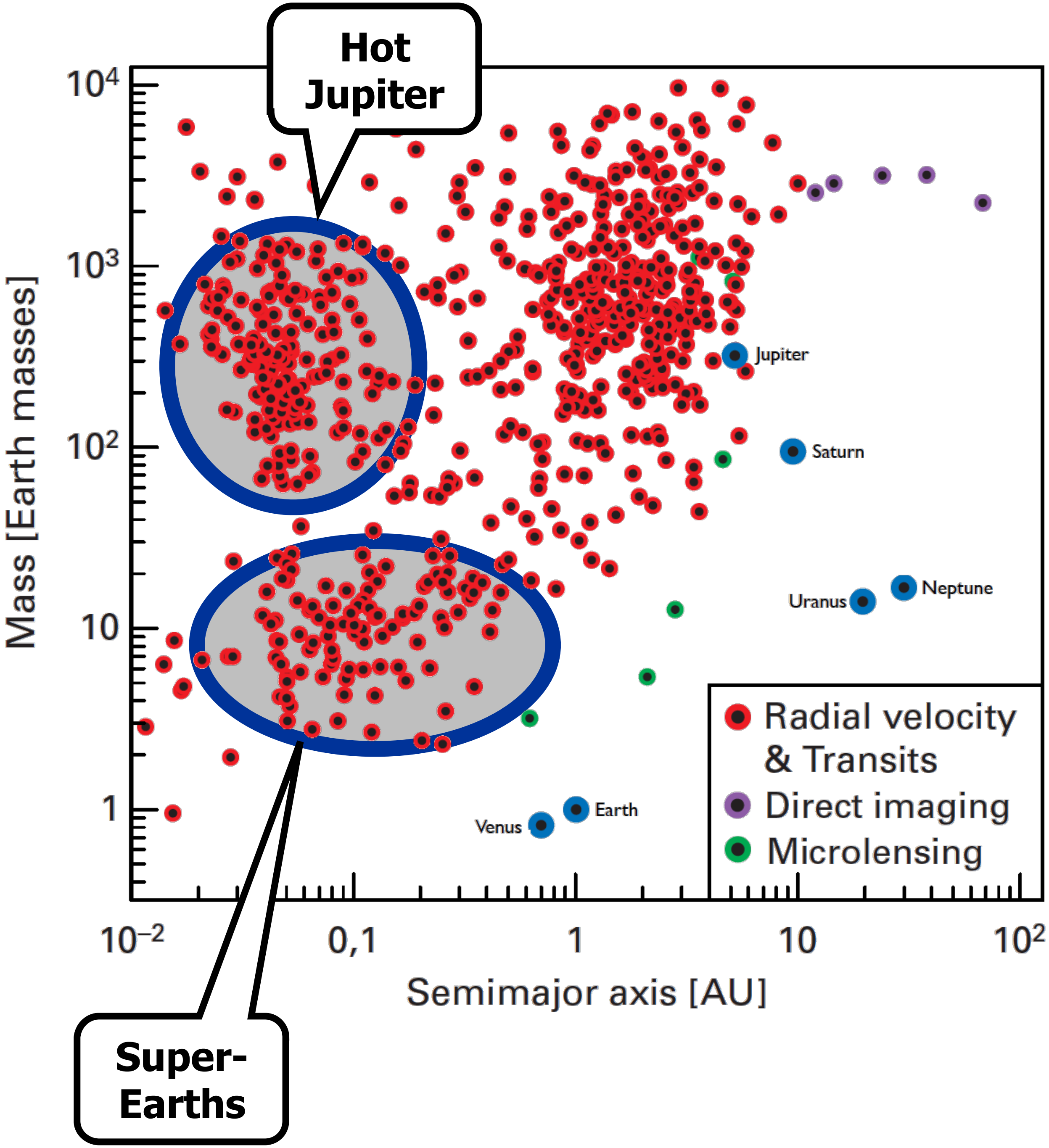
MWC758, Grady et al. 2013

Part 2:
The Planet Formation Imager (PFI) Project



simulations by Dong, Whitney, Zhu, Ayliffe & Bate

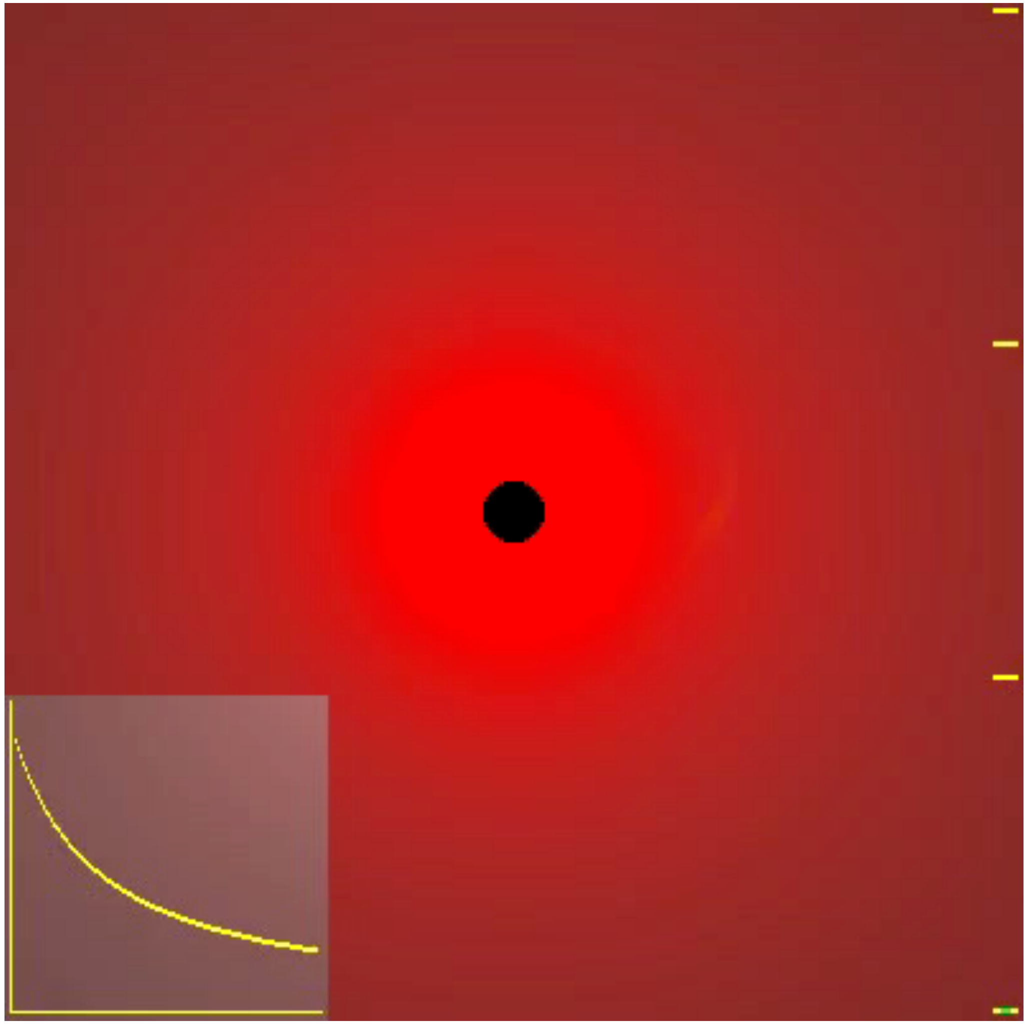
Architecture of planetary systems



Exoplanetary systems show surprising diversity

Mordasini et al. 2014

Architecture of planetary systems



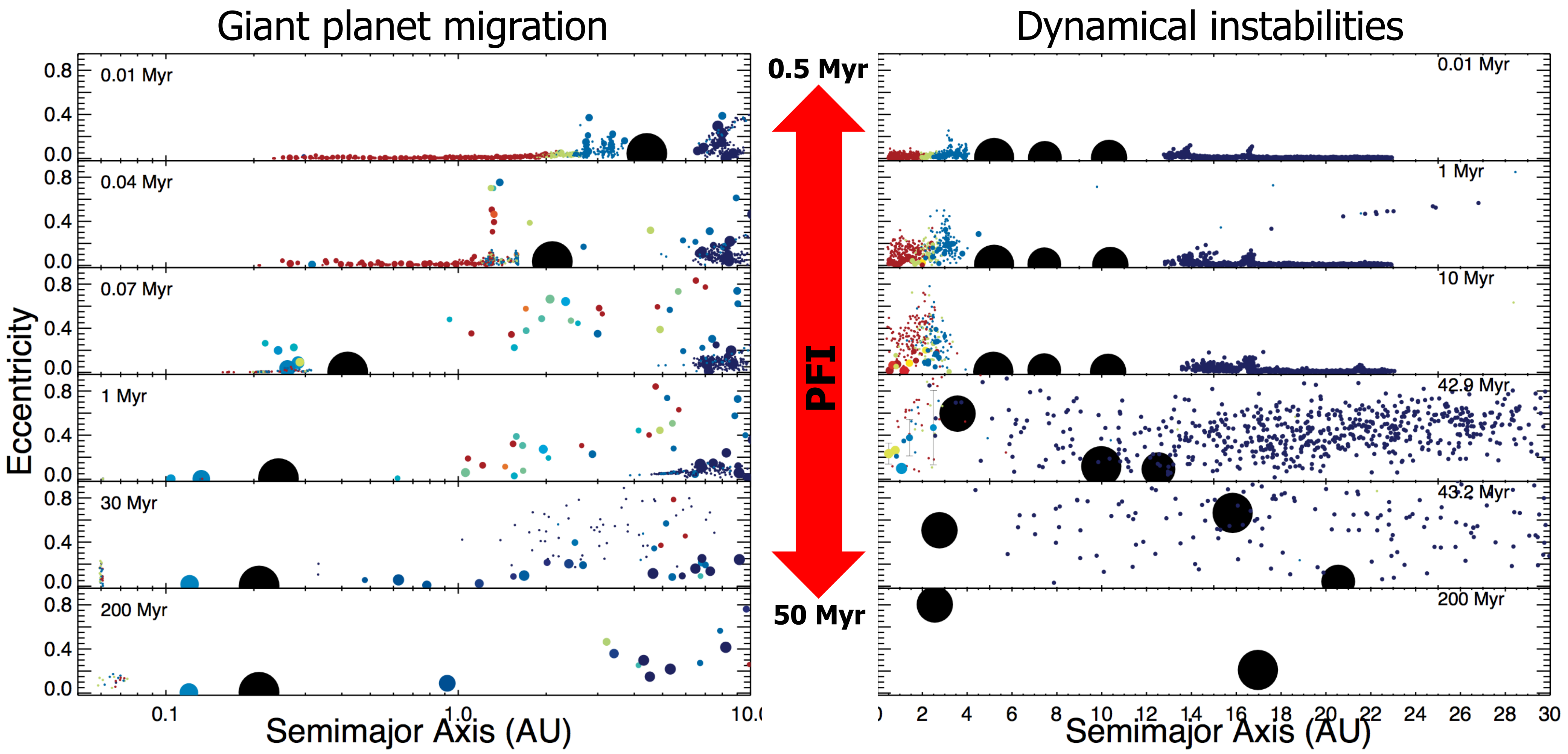
Dynamical interaction with gas-rich disk

Architecture of planetary system determined by…

- Initial conditions of PMS disk
- Planetesimal formation/growth
- Planet-disk interaction
  (type I/II migration)
- Migration traps
  (deadzones, disk truncation, …)
- Planet-planet scattering
  (resonances, planet ejection, …)
- Disk evolution and
  environmental factors
- Scattering with
  planetesimal disk
- …

Masset et al.

Architecture of planetary systems



PFI probes the age range that is most critical for understanding the dynamical evolution of planetary systems

Raymond et al. 2006

The Planet Formation Imager (PFI) Project

Goal of PFI:

Study the formation process and early dynamical evolution of exoplanetary systems on spatial scales of the Hill sphere of the forming planets

Strategy:

- Formulate the science requirements and identify the key technologies (considering ground & space as well as non-interferometric techniques)
- Build support in the science community & interferometry community
- Start lobbying with decision makers (e.g. NSF, ASTRONET, ESO,…)
- Prepare for upcoming funding opportunities (US decadal review, OPTICON)

The project executives have been elected in February:

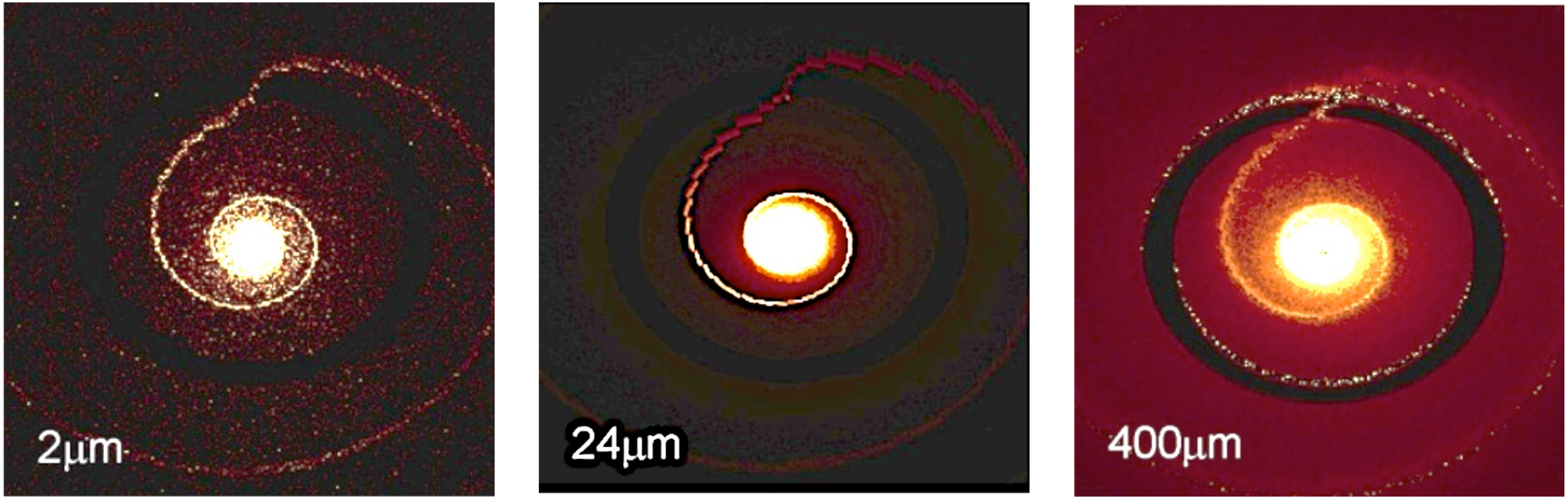
Project Director:	John Monnier (University of Michigan)
Project Scientist:	Stefan Kraus (University of Exeter)
Project Architect:	David Buscher (University of Cambridge)

We have formed working groups:

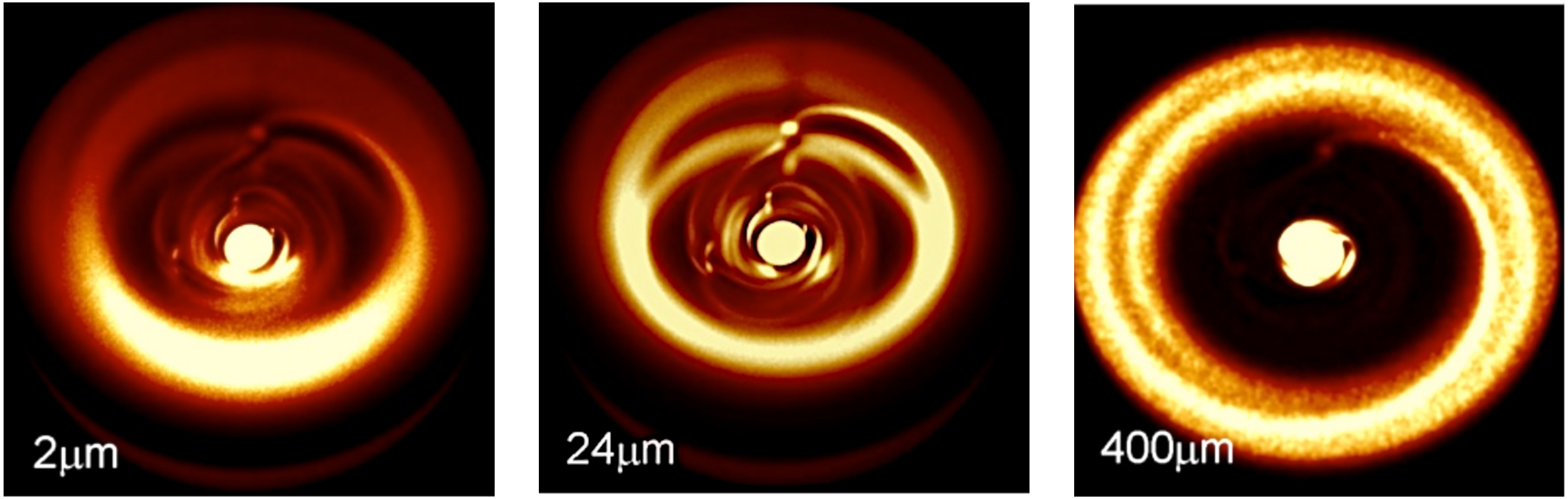
- **Science Working Group (SWG):**
  Develops and prioritizes key achievable science cases
- **Technical Working Group (TWG):**
  Conducts concept studies that will allow us to identify the key technologies and to develop a technology roadmap

Radiation hydrodynamics simulations

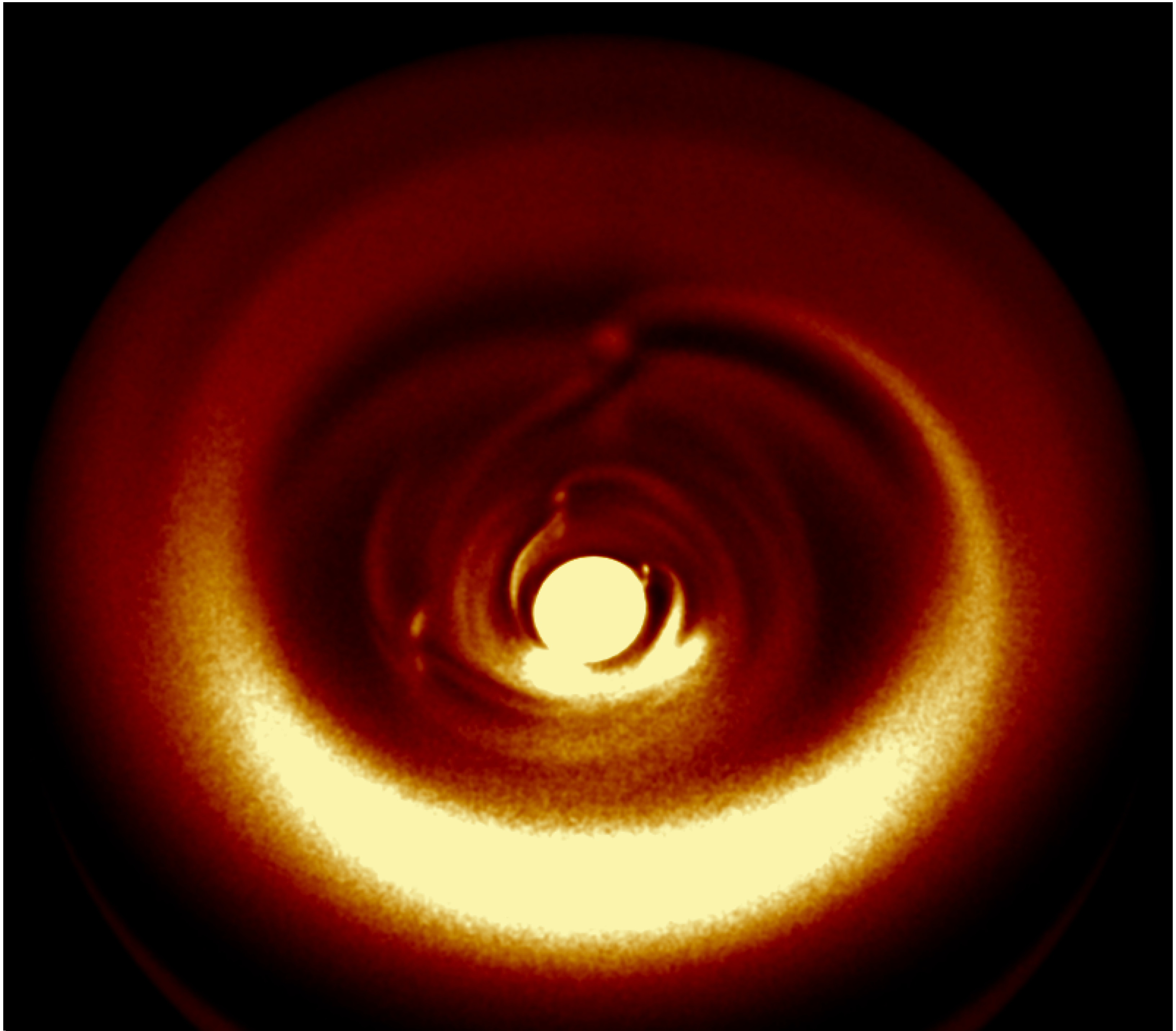
1-planet simulation (Tim Harries, Matthew Bate)



4-planet simulation (Robin Dong, Barbara Whitney, Zhaohuan Zhu)



Radiation hydrodynamics simulations



2μm
(K-band)

Radiation hydrodynamics simulation

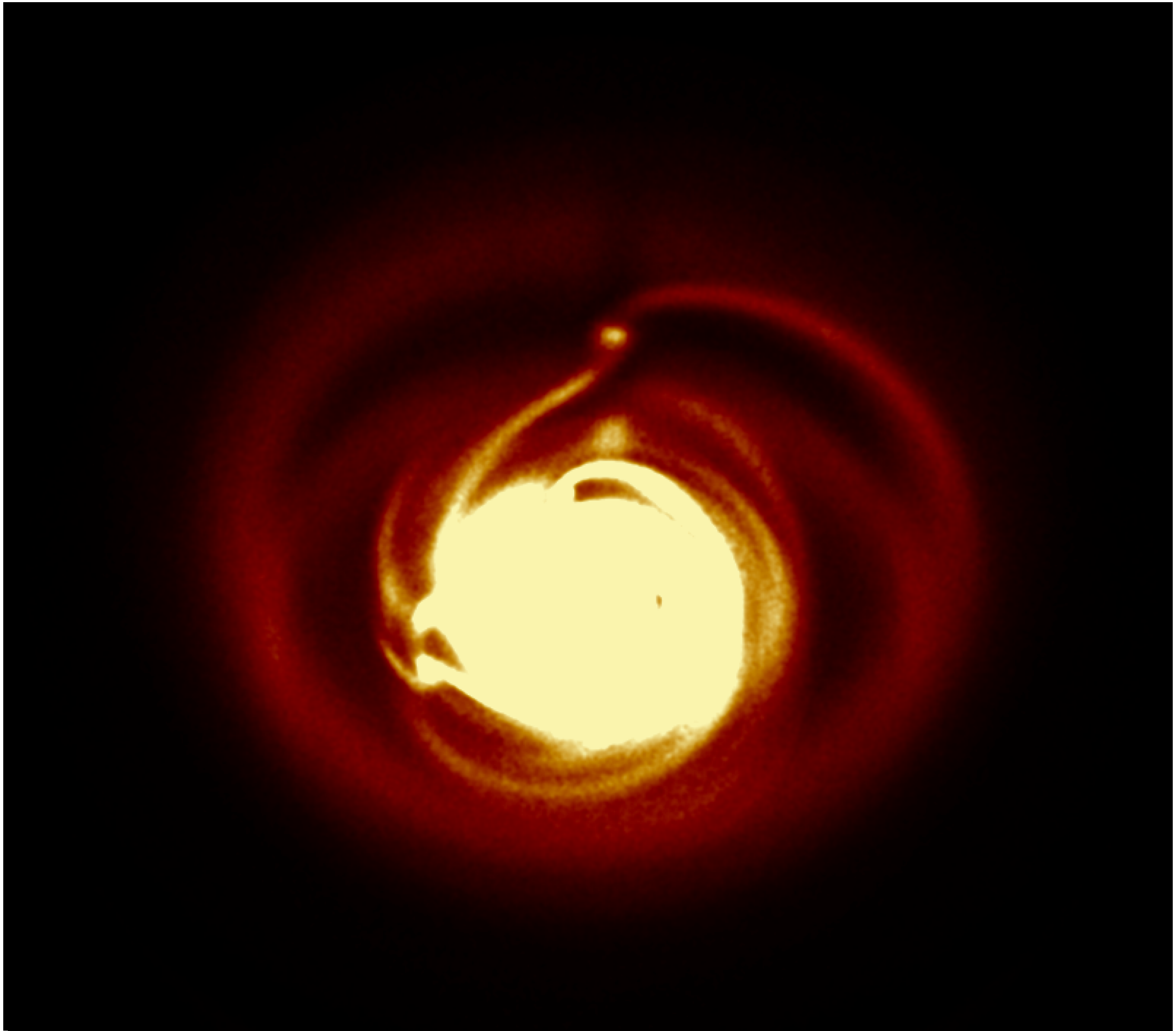
$M_\star = 0.5\ M_\odot$

inclination=30°
4 planets of 1 M_{Jup}

NIR dominated by scattered light

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong

Radiation hydrodynamics simulations



10μm
(N-band)

Radiation hydrodynamics simulation

$M_\star = 0.5\ M_\odot$

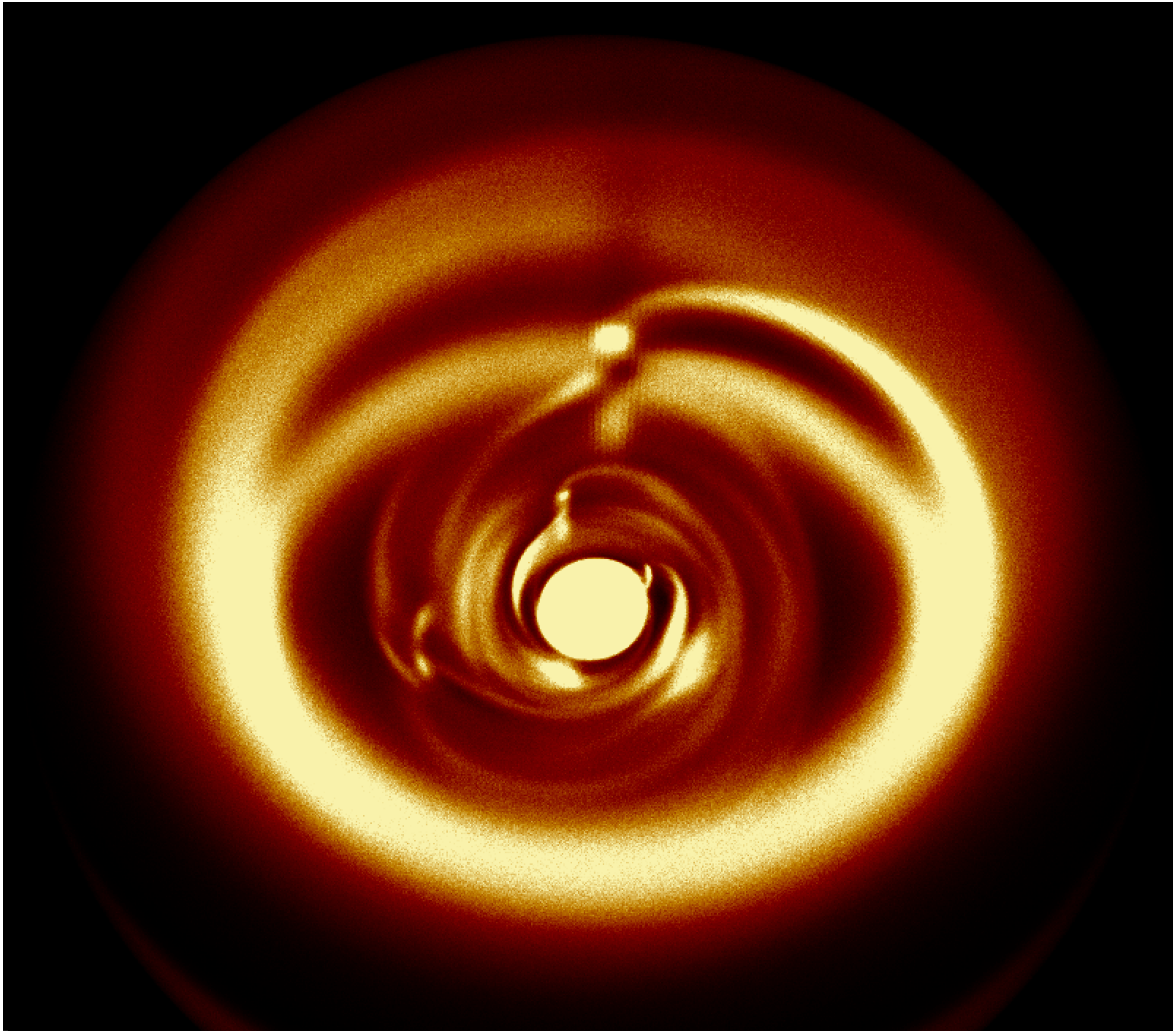
inclination=30°
4 planets of 1 M_{Jup}

MIR dominated by thermal emission of small grains

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong

Radiation hydrodynamics simulations

24μm
(Q-band)



Radiation hydrodynamics simulation

$M_{\star}=0.5\ M_{\odot}$

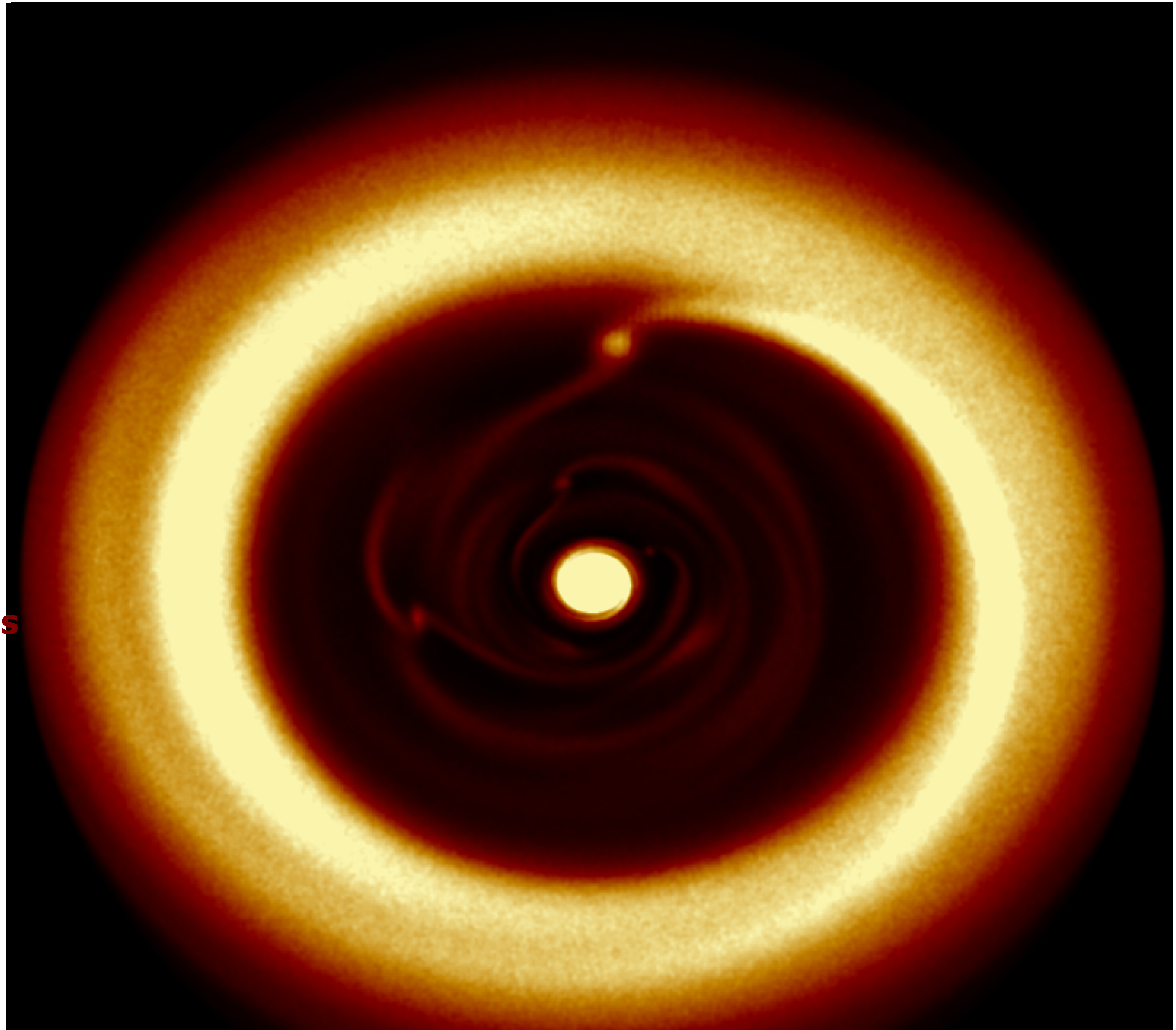
inclination=30°
4 planets of 1 M_{Jup}

MIR dominated by thermal emission of small grains

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong

Radiation hydrodynamics simulations

100µm
(FIR, space)



Radiation hydrodynamics simulation

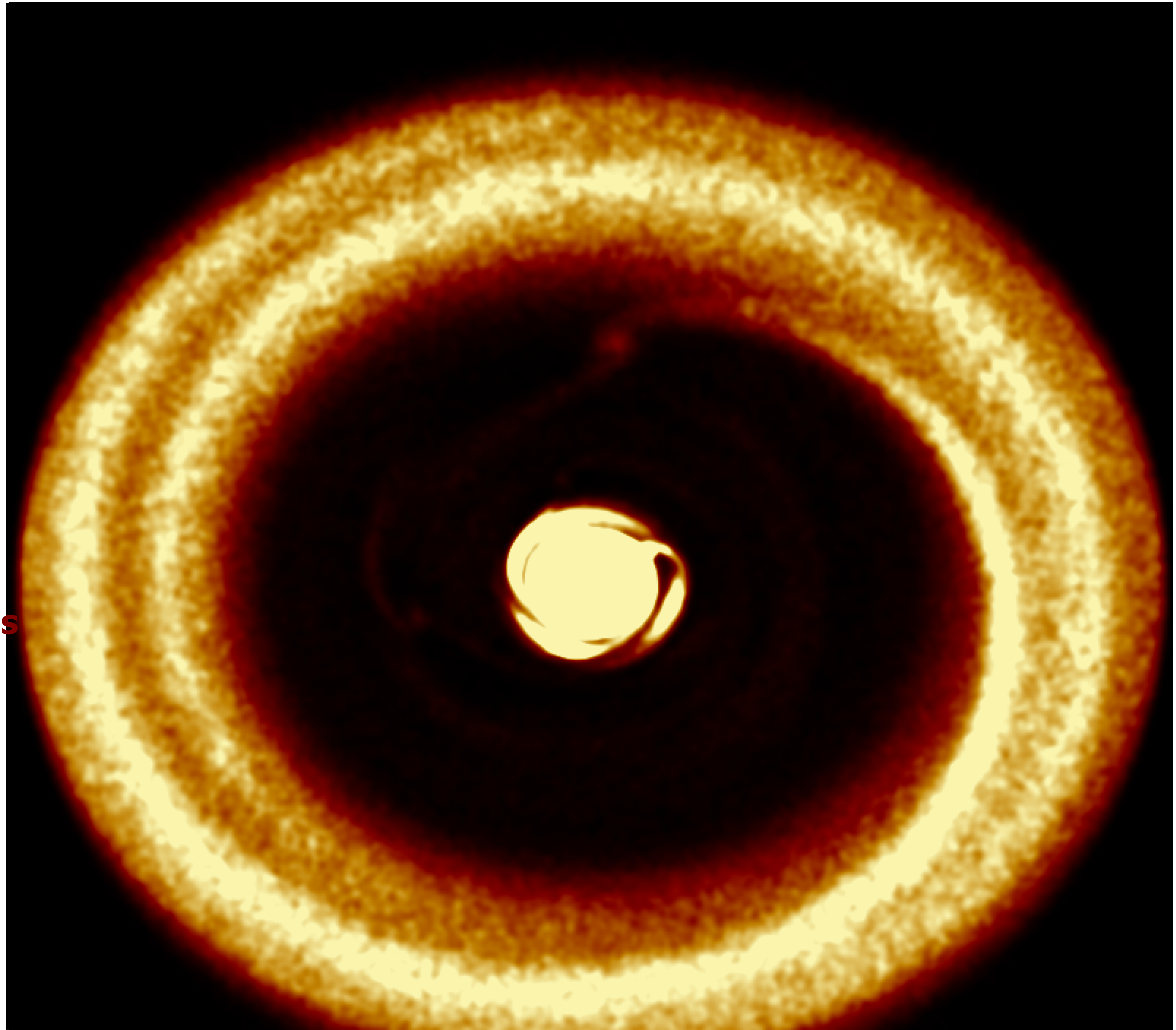
$M_\star = 0.5\ M_\odot$

inclination=30°
4 planets of 1 M_{Jup}

FIR/sub-mm traces primarily emission from large grains at gap edges

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong

Radiation hydrodynamics simulations



400μm (sub-mm, ALMA)

Radiation hydrodynamics simulation

$M_\star = 0.5\ M_\odot$

inclination=30°

4 planets of 1 M_{Jup}

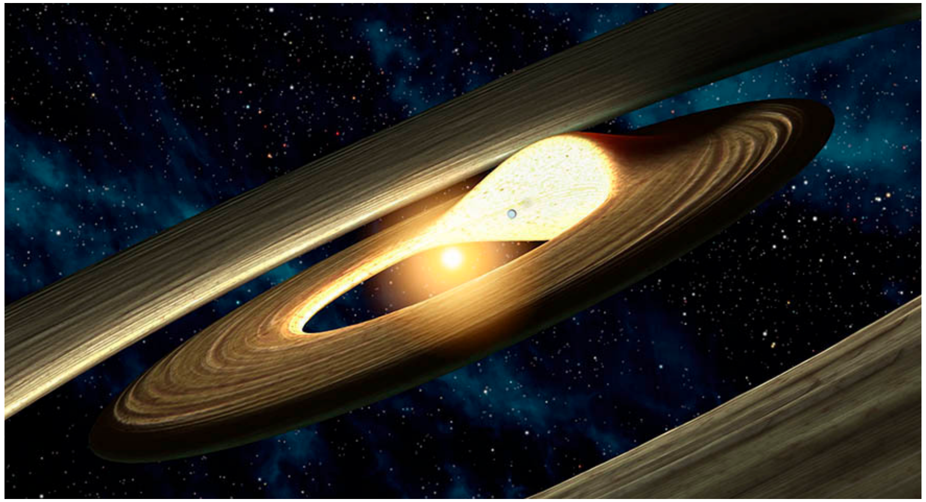
FIR/sub-mm traces primarily emission from large grains at gap edges

Zhaohuan Zhu,
Barbara Whitney,
Robin Dong

Resolving planet-induced disk structures

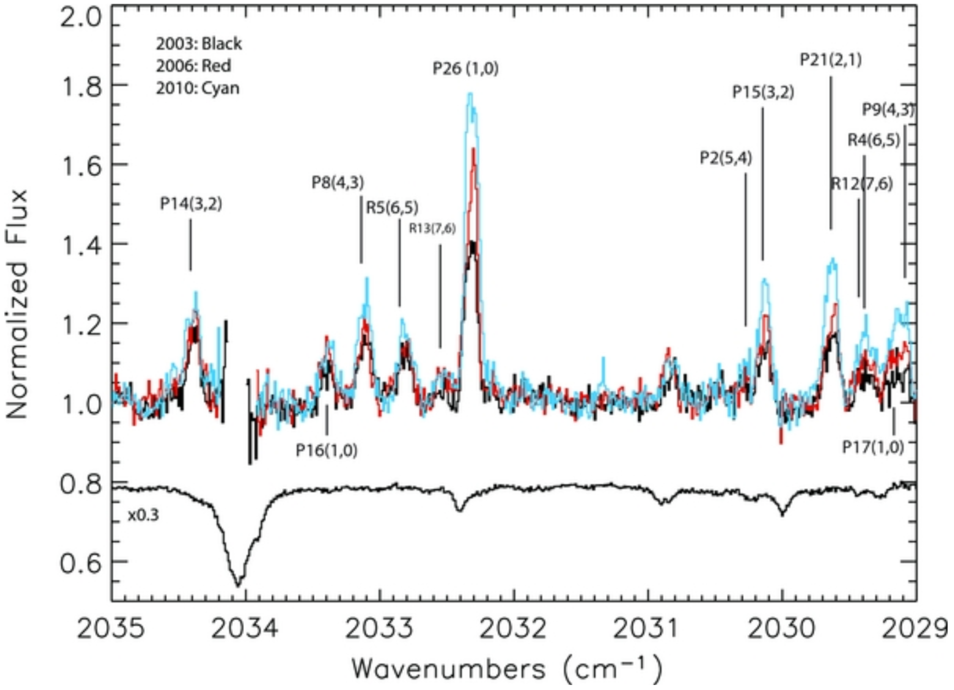
Objective: Image the complex & highly dynamical processes in the innermost AU and study their temporal evolution

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

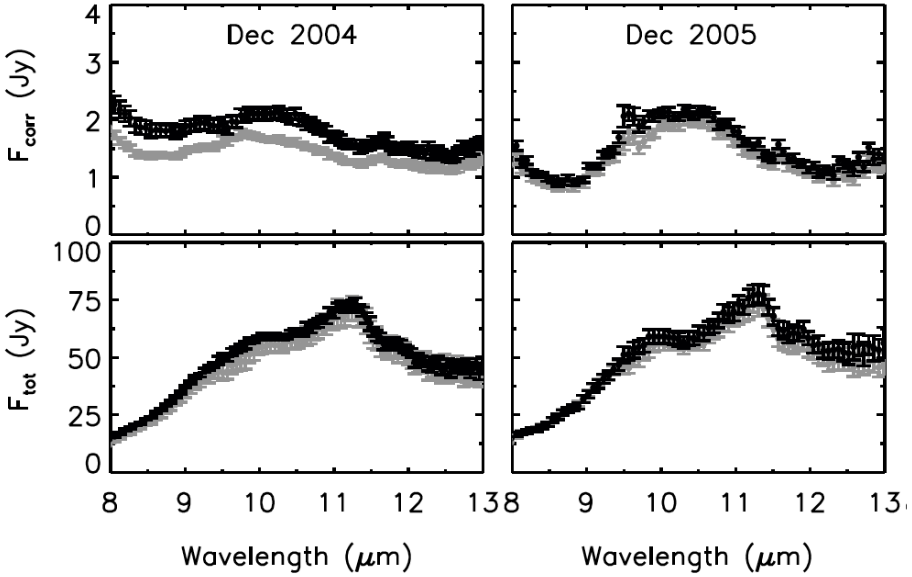


Artists Impression, Muzerolle et al. 2009

Spectroscopic variability
(HD100546)



Structural variability
(HD100546)



Panić et al. 2014; Brittain et al. 2013
also: Mosoni et al. 2013

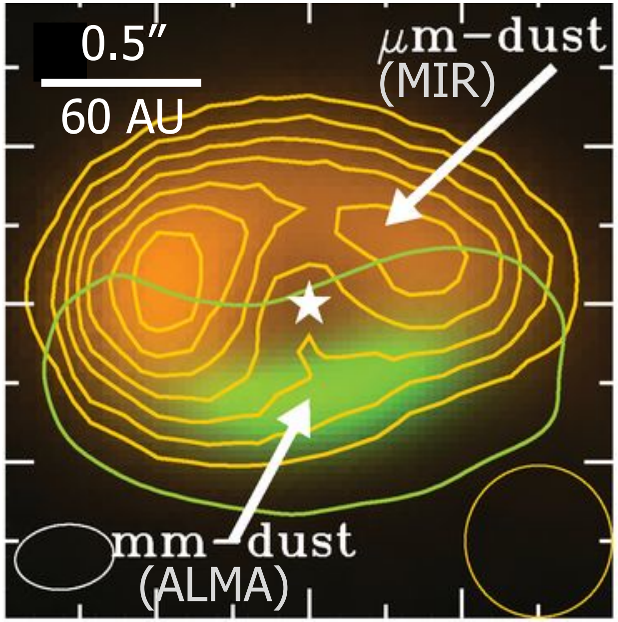
PFI:
Complementarity with ALMA

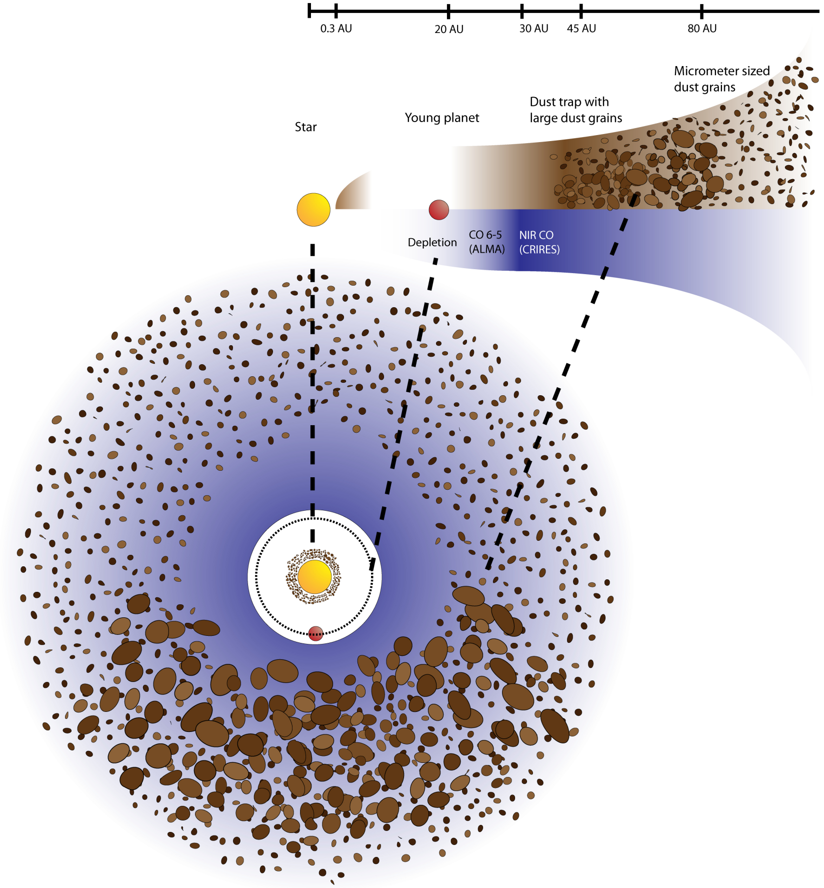
PFI+ALMA: Tracing complementary dust species

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

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

Oph IRS48



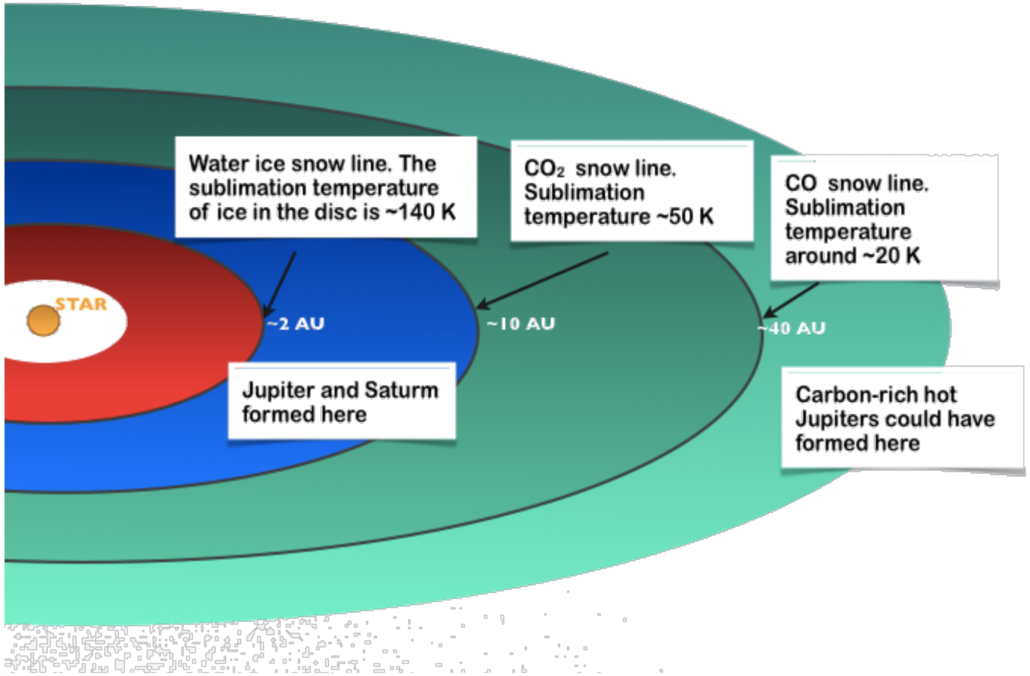


van der Marel et al. 2013

PFI+ALMA: Tracing complementary molecular lines

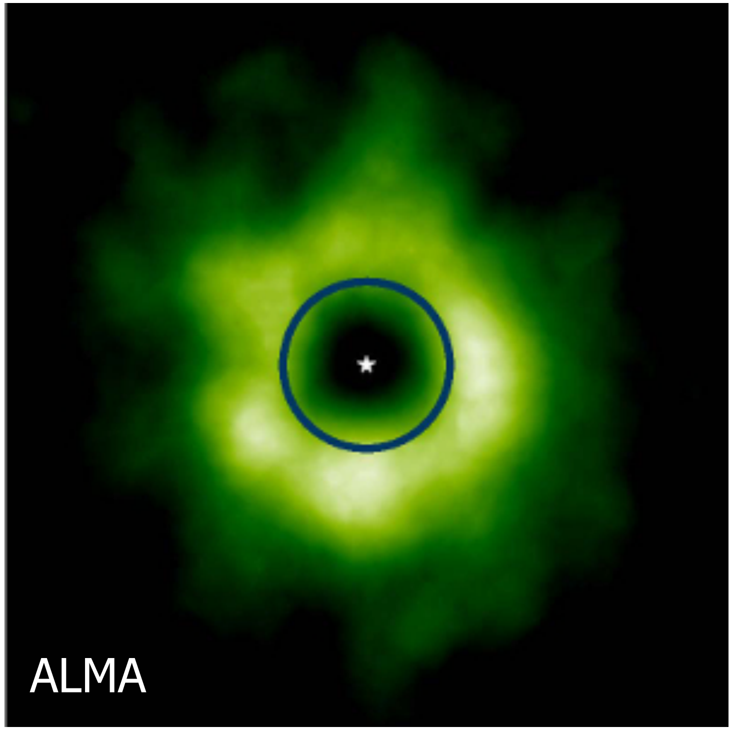
Objective: Determine distribution of water & ices

➜ link to habitability



Öberg et al.

CO snow line in TW Hya



Qi et al. 2013

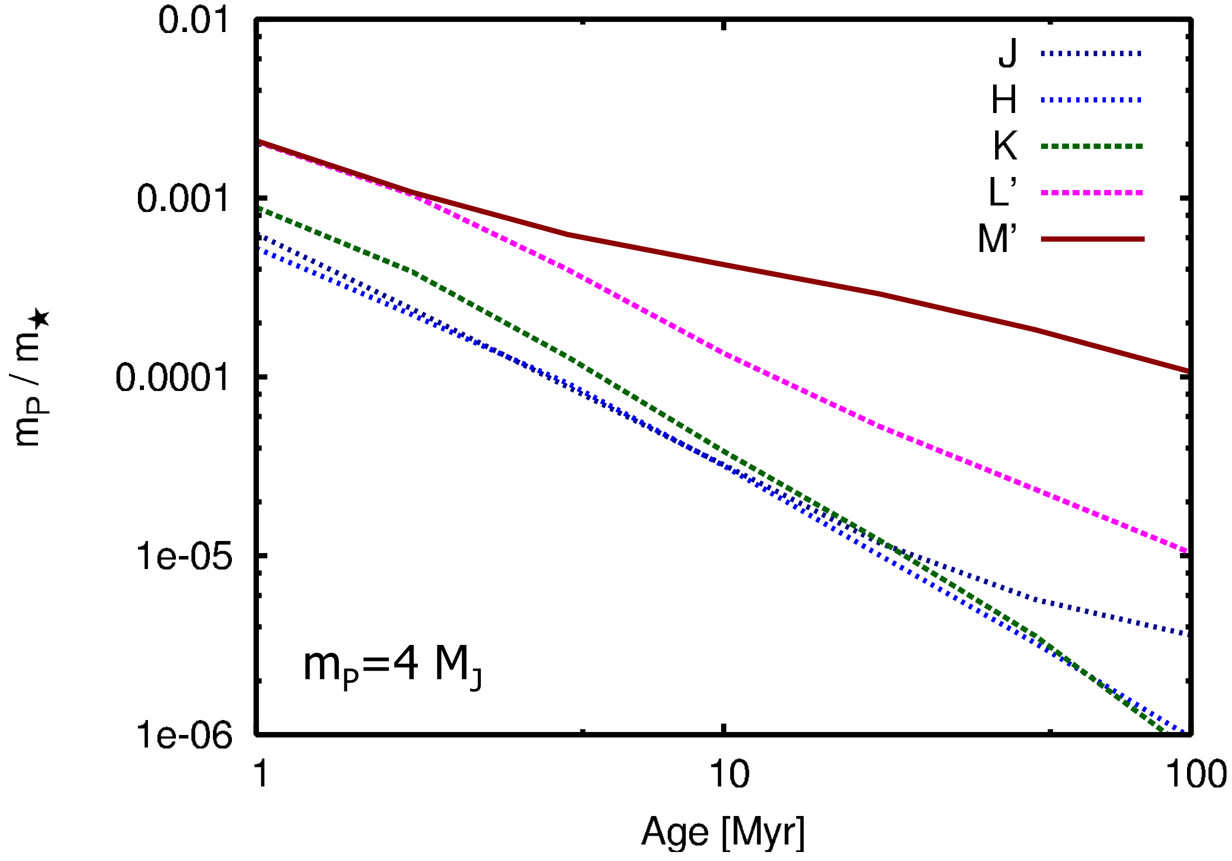
Water on terrestrial planets:

- Planetesimal delivery (Morbidelli et al. 2000)
- Atmospheric capture in the inner disk (Ikoma et al. 2006)

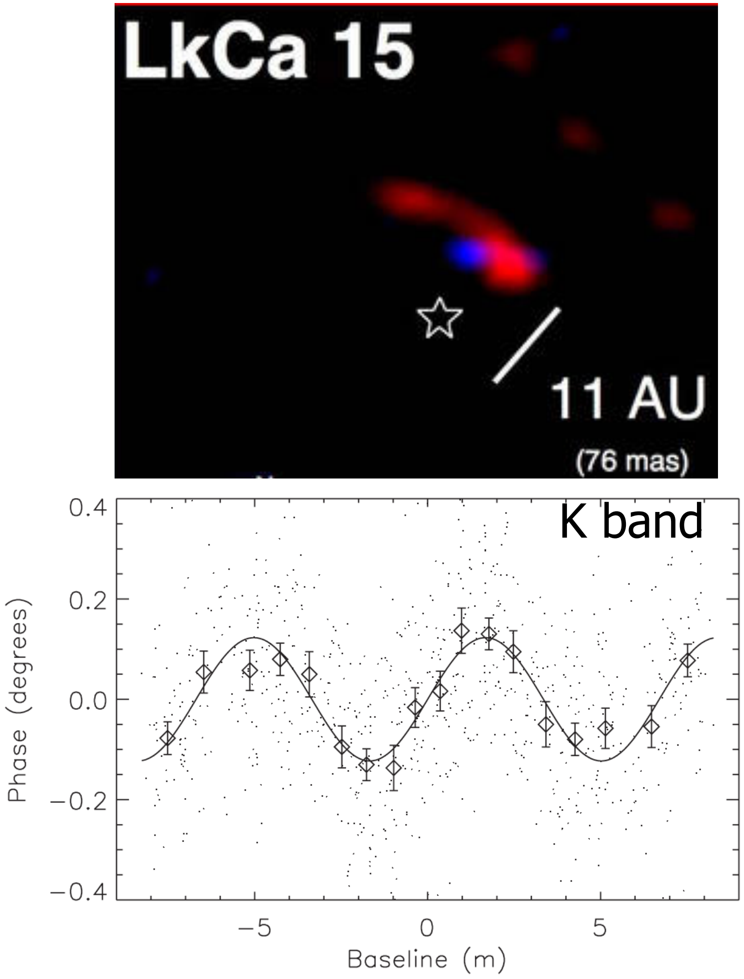
PFI:
Protoplanet detection &
Planetary system architecture

Detect accreting young protoplanets

Objective: Detect young accreting protoplanets



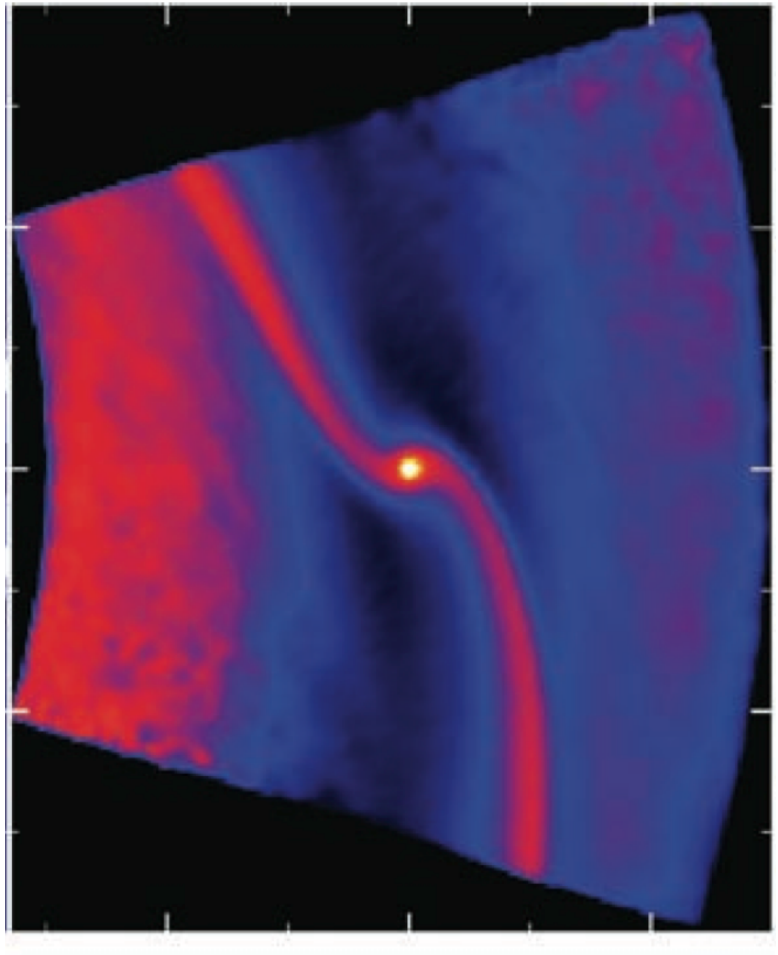
Forney et al. 2008



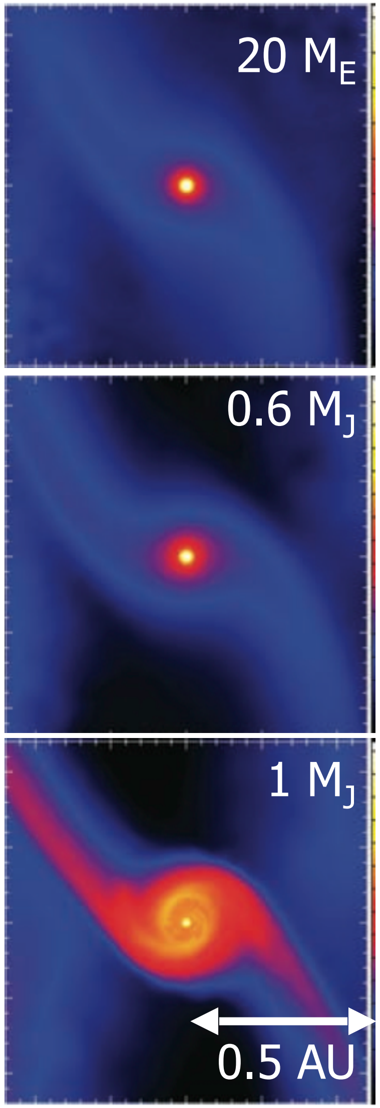
Kraus & Ireland 2012

➜ MIR likely sweet spot for tracing planets in the most relevant age range (0.1 … 100 Myr)

Resolving the circumplanetary accretion disk



Ayliffe & Bate 2009



Size circumplanetary disk (≈0.3 R_H) for Jupiter-mass planet

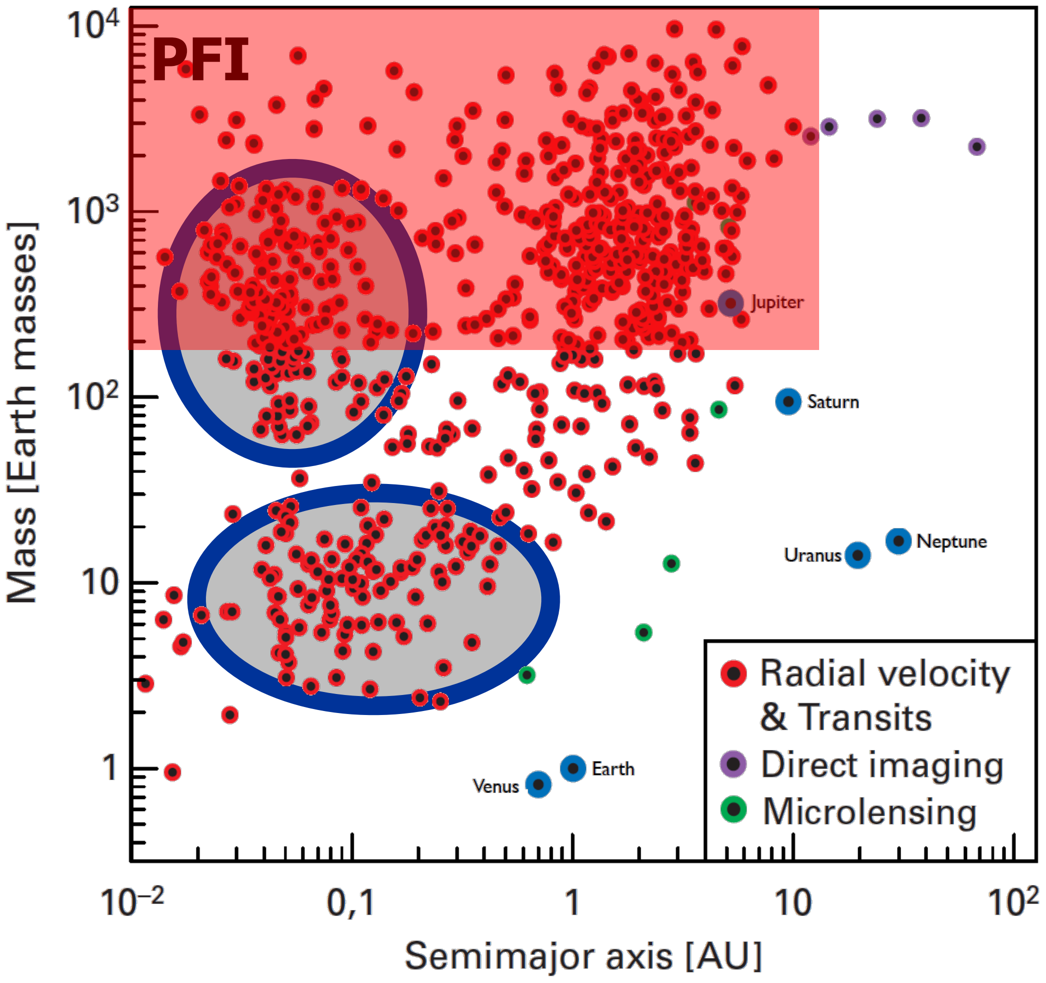
at r=5.2 AU: 0.11 AU = 0.79 mas @ 140 pc

at r=1 AU: 0.02 AU = 0.14 mas @ 140 pc

Architecture of planetary systems

Objective: Measure system architecture for a statistically significant sample of systems at different evolutionary stages (e.g. 100 systems @ 0.5 / 5 / 50 Myr)

- ➜ Enables direct comparison of the exoplanet population during the PMS and main-sequence phase with population synthesis models
- ➜ Reveals the dynamical mechanisms that determine planetary system architecture
- ➜ Links the disk properties with the planet properties



Mordasini et al. 2014

The PFI Science Working Group (SWG)

Develops and prioritizes key achievable science cases

We currently set up working group on the following topics:

1. Protoplanetary Disk Structure & Disk Physics (lead by Neal Turner)
2. Planet Formation Signatures in PMS Disks (lead by Attila Juhasz)
3. Protoplanet Detection & Characterisation (lead by Catherine Espaillat)
4. Late Stage of Planetary System Formation (lead by Jean-Charles Augereau)
5. Architecture of Planetary Systems (lead by Joshua Pepper)
6. Planet formation in Multiple Systems (lead by Gaspard Duchene)
7. Star Forming Regions / Target Selection (lead by Keivan Stassun)
8. Secondary Science Cases: Exoplanet-related Science (lead by Gautam Vasisht)
9. Secondary Science Cases: Stellar Astrophysics (lead by Claudia Paladini)
10. Secondary Science Cases: Extragalactic Science (lead by Sebastian Hönig)

Interested scientists are welcome to join ➜ **www.planetformationimager.org**

PFI:
Technology architectures under investigation

Slides from SPIE talk
by John Monnier

Top-Level Science Requirements (Preliminary!)

- Sensitivity to thermal emission for 300K grains ➔ mid-IR (10 μm)
- "Hill-sphere" size region of Jupiter at 1 AU (0.03 AU)
  in nearby star forming region (140pc)
  ➔ 0.2 milliarcseconds
- 0.2 mas at 10 μm
  ➔ requires 10 km baselines
- Sensitivity to see a circumplanetary disk
  - T Tauri star N_{mag}=7.5
  - Best case circumplanetary disk: N_{mag}=11
- Also should image exoplanets themselves for <100 Myr clusters to probe dynamical relaxation of giant planet architectures
  - 10Myr: 1 M_{Jup} = N_{mag} ~15.7
  - 100MYr: 1 M_{Jup} N_{mag} ~18.5
- Very complex scenes... Like 400x400 pixel imaging

Architecture Overview

1. NIR/MIR Conventional Direct Detection Interferometer
2. MIR Heterodyne Interferometer
3. MIR/FIR Space Interferometer
4. ALMA ++
5. Coronagraph, Occulter

Architecture 1:
Conventional ground-based interferometer design

- Basics
  - Mid-infrared key science
  - 7 km baselines (>0.4m vacuum pipes)
  - 2m *minimum* telescope diameter for NIR fringe tracking
    - Natural guide star AO is sufficient for YSO case
  - 8m maximum telescope diameter to maintain at least 0.25” field of view
  - N>20 telescopes due to complex imaging

Architecture 1:
Conventional ground-based interferometer design

- Sensitivity considerations
  - 4m telescopes with H/K band fringe tracking
  - 10s coherent integrations can get to N~7.5
    - Compatible with water vapor "seeing"
  - 10 hours integration of bispectra can get down to N=15 *in principle (detect individual giant planets)*
  - SWG/TWG will validate SNR model using realistic simulations

Architecture 2: Heterodyne Interferometry

- Charlie Townes' Infrared Spatial Interferometer (ISI) is a mid-IR interferometer
  - Limiting magnitude 500 Jy, N_{mag}= -2
  - BUT… this is largely due to tiny ISI bandwidth (λ/Δλ = 10,000)
- Dispersing the light and mixing it with Laser Frequency Combs allows to create thousands of ISI bandwidths ➔ $\mathrm{SNR} \propto \sqrt{N}$ (see Ireland et al. 2014, SPIE)
- Advantages
  - Higher throughput to detection
  - Ideal beam combining which is crucial for complex imaging
- Must still phase up MIR using NIR fringe tracking
  - However, it is sufficient to phase up 4-5 nearest neighbors
- Also need 2-4m class telescopes

Architecture 3: Space-Interferometry

- Advantages of space
  - 26 million times less background
    - Cooled 1mm telescope in space has same SNR as 8m on ground…
  - Access to wide range of interesting wavelengths, dust temperatures
- Will require formation flying over >10 km
  - With >10 elements?
- Quite different than DARWIN/TPF-I – worth a second look
  - Incredibly broad science – extragalactic, star formation
  - Great JWST follow-up mission
- Connects with far-IR interferometry groups
  - But they interested in shorter baselines, fewer elements: FISICA, Hyper-FIRI
  - Some shared technology requirements

Architecture 4:
ALMA with longer baselines

- Advantage of extending an existing successful facility
- Disadvantages:
  - sensitivity only to large dust grains, cool grains
  - no access to complementary new line tracers
- LLAMA: Long Latin American Millimeter Array

Non-interferometry architectures

- Ground-based Coronagraph
  - Visible 30m extreme AO – 4 milliarcseconds
  - Insufficient resolution for core science… but complementary and very exciting!

- Space occulter
  - $$\text{Resolution} \propto \sqrt{\frac{\lambda}{d}}$$

    ➔ Distance between spacecraft and shade: 30AU (and 10km shade – use asteroid?)

The PFI Technical Working Group (TWG)

Identifies the key technologies and develops a technology roadmap

Concept architectures:

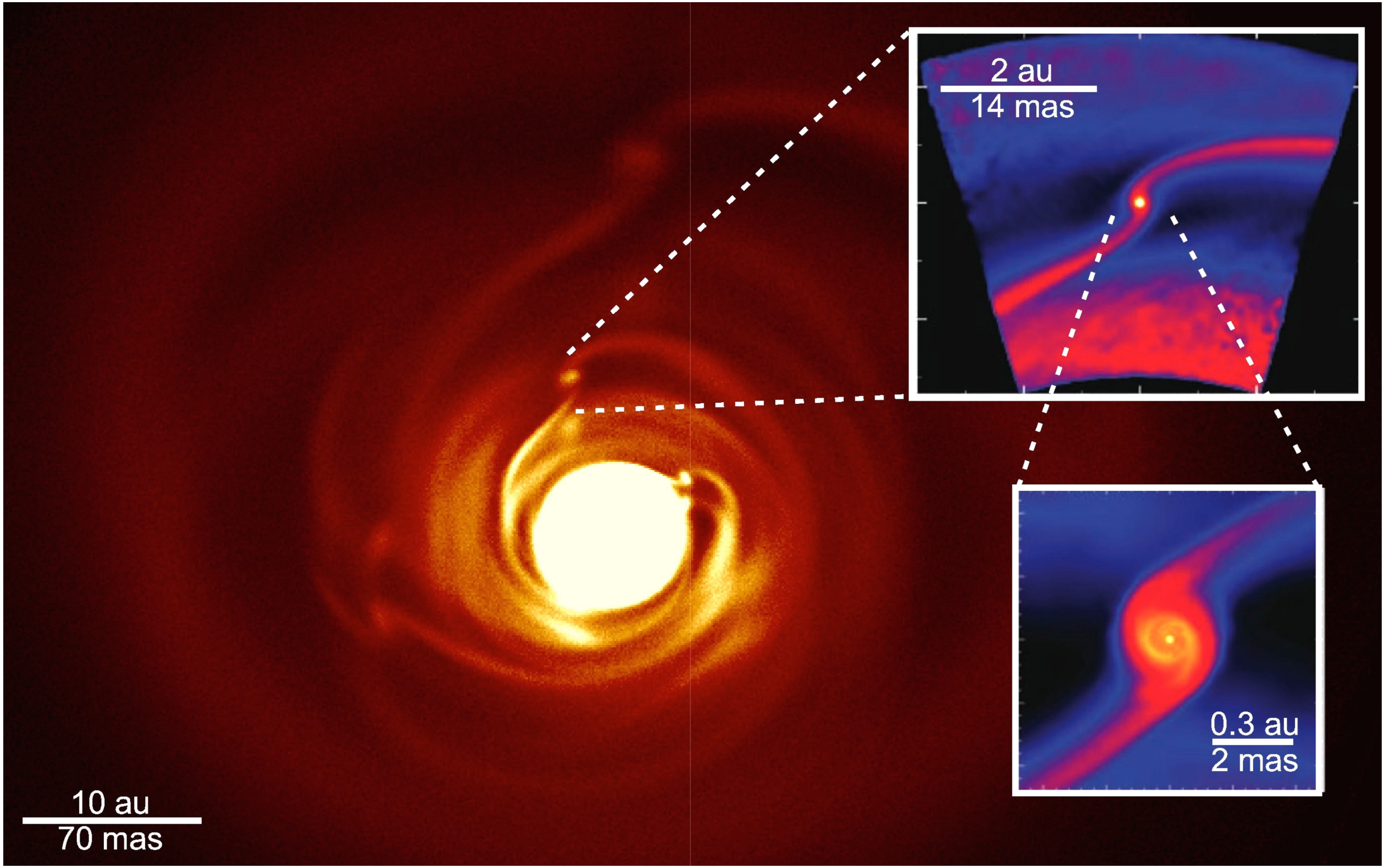
1. Visible and NIR interferometry (lead by Romain Petrov)
2. Mid-IR interferometry – direct detection (lead by David Buscher)
3. Mid-IR interferometry – heterodyne (lead by Michael Ireland)
4. Far-IR interferometry (lead by Stephen Rhinehard)
5. mm-wave interferometry (lead by Andrea Isella)
6. Non-interferometric techniques: Occulters, ELTs, Hypertelescopes, …

Technology Roadmap Team:

1. Space-based systems (lead by Gautam Vasisht and Fabien Malbet)
2. Heterodyne systems (lead by Ed Wishnow)
3. Adaptive optics and laser guide stars (lead by Theo ten Brummelaar)
4. Fringe tracking (lead by Antoine Merand)
5. Polarimetry (lead by Karine Perraut and Jean-Baptiste LeBouquin)
6. Telescopes and enclosures (lead by John Monnier and Jörg-Uwe Pott)
7. Beam relay (lead by David Mozurkewich)
8. Delay lines (lead by David Buscher)
9. Beam combination optics (lead by Stefano Minardi)
10. Detectors
11. Nonlinear optics for mid-IR frequency combs
12. Image Reconstruction

Interested scientists are welcome to join ➜ **www.planetformationimager.org**

Planet Formation Imager (PFI) Concept Studies



Learn more and join us at: **www.planetformationimager.org**
(Series of SPIE papers can be found in the “Resources” section)