From MIDI to MATISSE and the "Planet Formation Imager"

Stefan Kraus
UNIVERSITY OF EXETER

European Interferometry Initiative:

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

EII Science Council Members:
Josef Hron, Jean Surdej, Pavel Koubsky,
Malcolm Fridlund, Jean-Philippe Berger,
Alain Chelli, Thomas Henning, Laszlo Mosoni,
Sebastiano Ligori, Erez Ribak, Walter Jaffe,
Andrzej Niedzielski, Carlos Eiroa,
Didier Queloz, David Buscher

PFI Project:

PFI Executives:
John Monnier, Stefan Kraus,
David Buscher

PFI 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

concluding MIDI Science Group meeting, Heidelberg
2014 May 6

Outline

1. The European Interferometry Initiative

2. MATISSE as the successor of MIDI

3. Concept Studies for a "Planet Formation Imager"

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)

A strong lobbying activity for interferometry in Europe is still necessary:

- We are in the E-ELT era
- ALMA is very strong and strongly supported
- Next big projects are SKA, LSST … no large OIR interferometer!
- VLTI still needs strong support and strong vision
(with a consistent roadmap for the future)

EII - Governing bodies

Bureau:

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

Science Council:

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 2^{nd} generation facility" (FP7-1, 2009-2012)
  ➔ 2010 JENAM session
- "Integrating interferometry into mainstream astronomy" JRA (FP6)
  ➔ Feasibility studies for 2^{nd} 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:

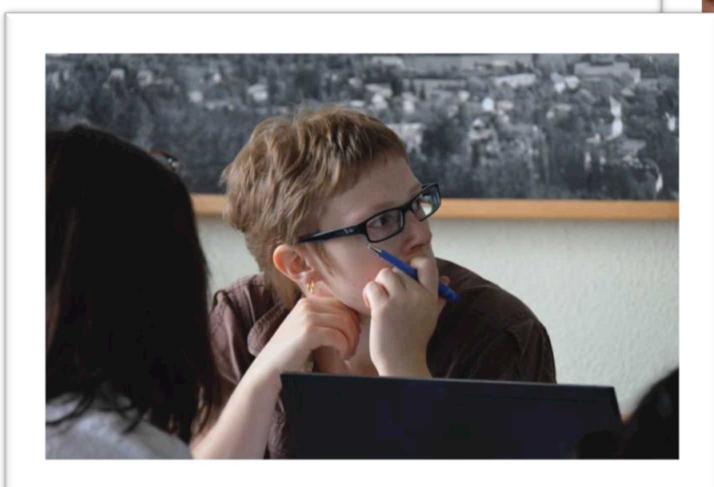
- Fund short research/technical/training exchange visits (1 week – 1 month)
- Priority to young researchers and "knowledge poor” institutes
- Competitive calls twice a year (March and September)

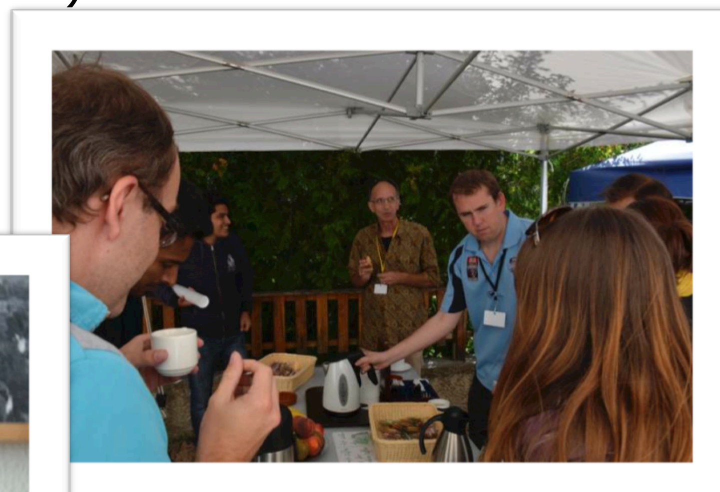
Around 80 grants awarded between 2009-2012 (pressure around 1.5)

Next deadline on September 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

Coordination

GRAVITY and MATISSE are coming and require full attention in order to make them a success!

At the same time, start planning for the time after GRAVITY and MATISSE:

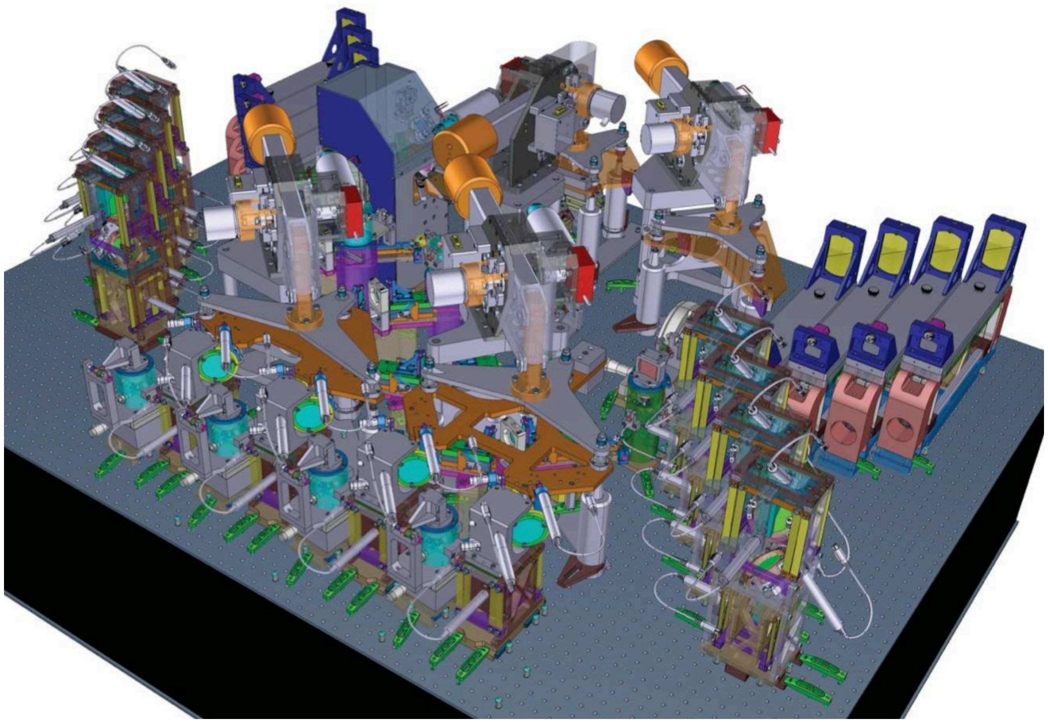
➔ **Future VLTI instruments:**
Community feedback now could guide upcoming VLTI infrastructure decisions;
Future VLTI instrument proposals will compete with UT instrument proposals

➔ **Long-term scientific vision:**
Helps to justify further technological developments in OIR interferometry.

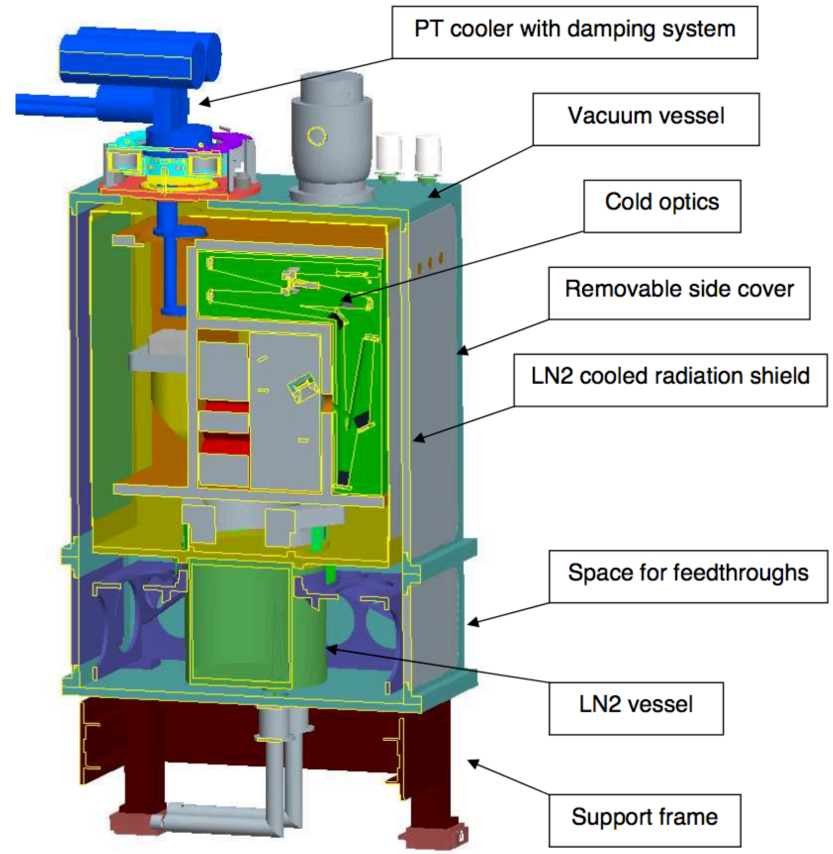
MATISSE as the successor of MIDI

VLTI/MATISSE

Warm optics



Cold optics

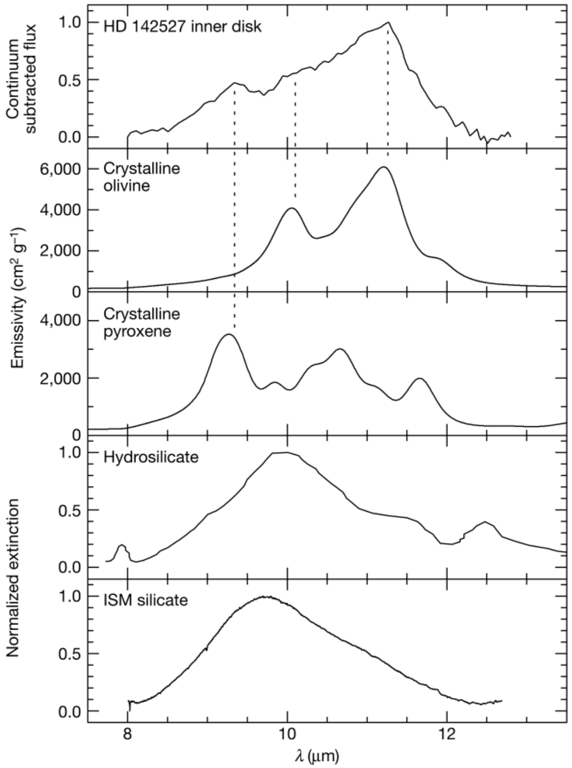


4T beam combiner, 2 detectors:

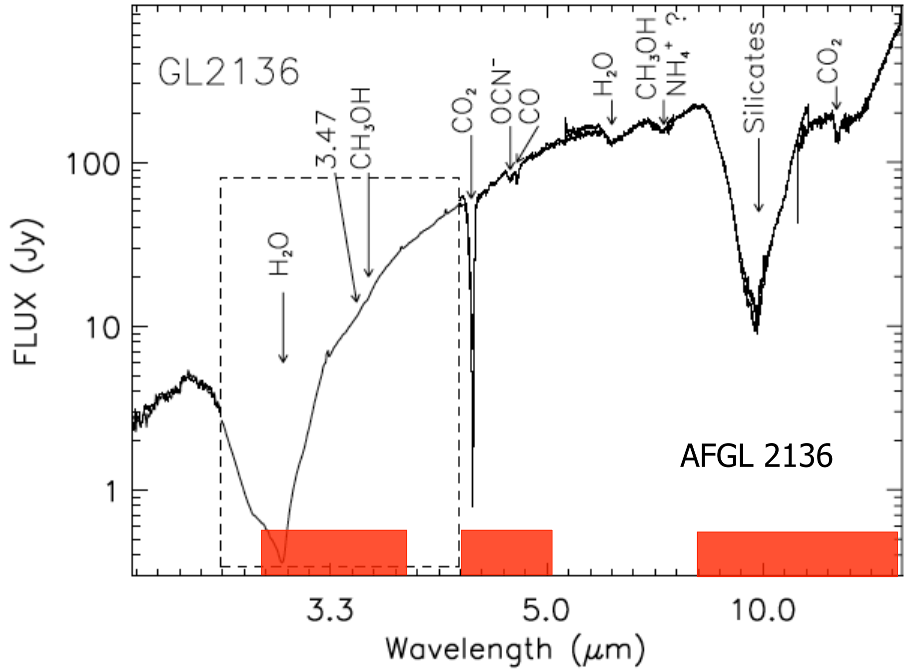
L / M / L+M band:	R=30, 500, 950, 5000	Hawaii-2RG
N-band:	R=30, 220	Aquarius FPA

Dust / Ice features

Dust:



Ices:



Selection of spectroscopic features covered by MATISSE:

Silicate, fosterite, enstatite, … (N band)

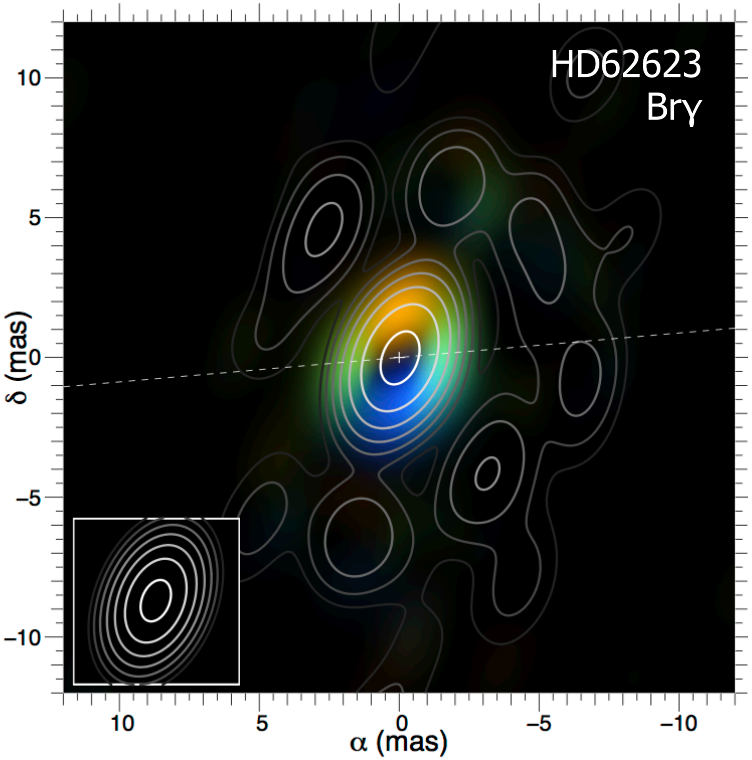
H_2O ice (3.1μm), CH_3OH ice (3.5μm), NH_3 ice (3.0μm)

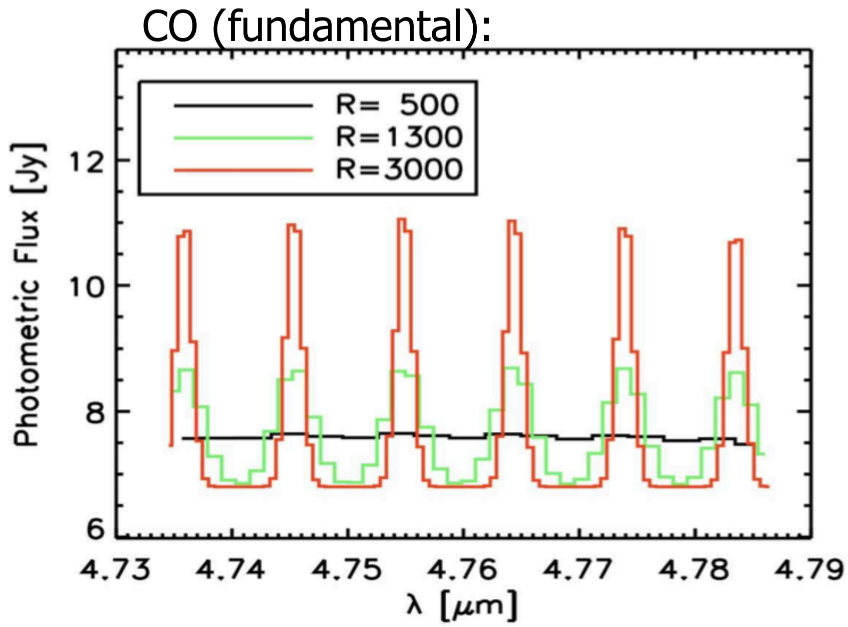
PAH stretching/bending/vibration modes (3.3μm, 8.6μm, 11.3μm)

C-H nanodiamonds (3.4-3.5μm)

van Boekel et al. 2004; Dartois et al. 200.

Interferometry in spectral lines





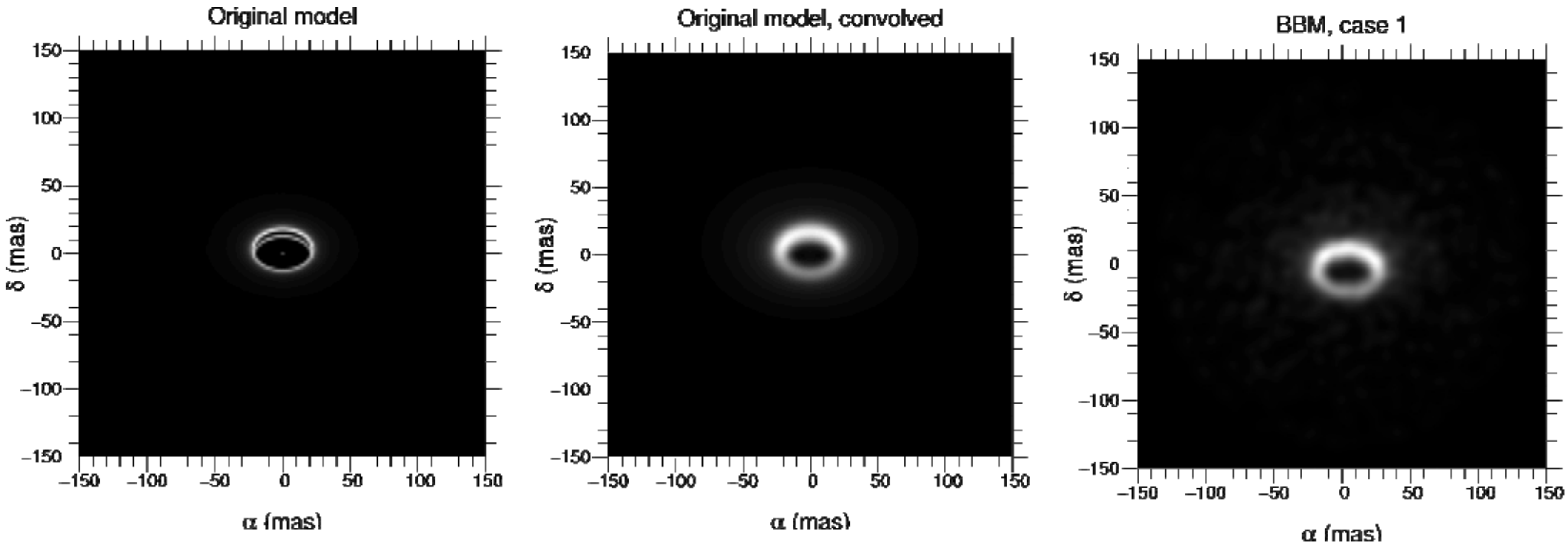
MATISSE will allow efficient imaging in spectral lines,
enabling studies on complex velocity fields (at relatively low spectral resolution)

Important new gas phase tracers:
HI (Pfund δ, γ), CO (fundamental, 4.7μm), H_2O (3.0μm, 5.0μm), HCN (3.1μm, 3.8μm), H_2C_2 (3.1μm, 3.8μm), OH (2.8μm), SiO (4.1μm)

Millour et al. 2011; MATISSE SC doc.

MIR interferometric imaging

Simulation assuming full tracks on 7 configurations in 4T mode



4T beam combination:

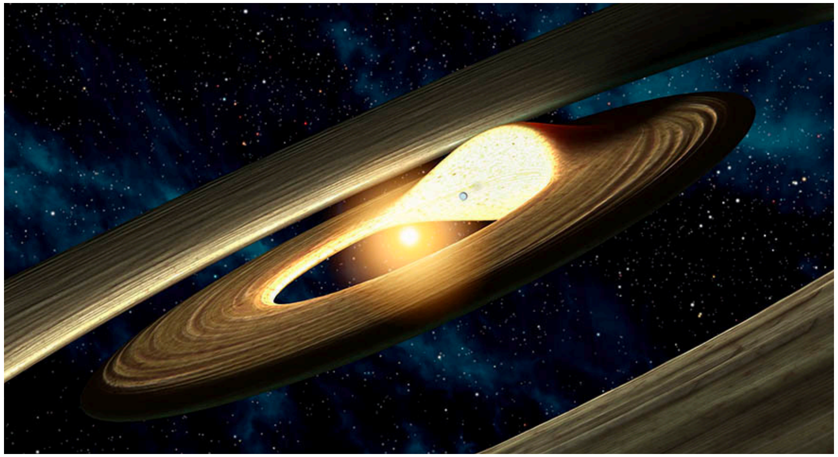
➜ enables for the first time **L+M+N band interferometric imaging**

➜ important to extend user base

Simulation by K.-H. Hofmann

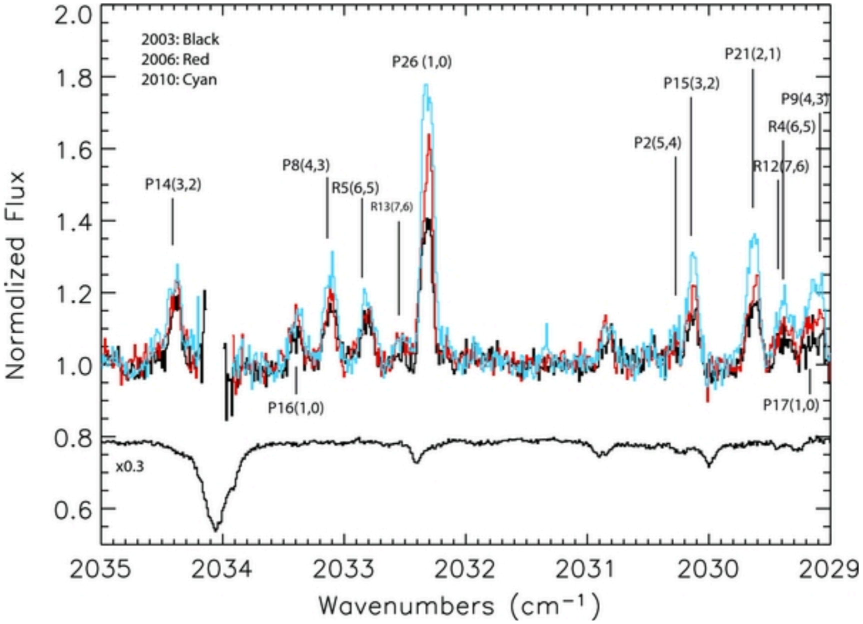
MIR interferometric imaging

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

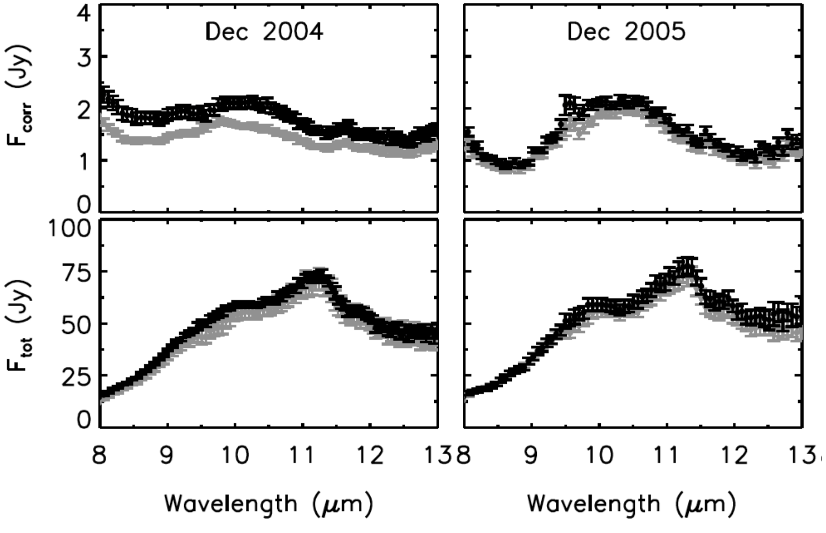


Artists Impression, Muzerolle et al. 2009

Spectroscopic variability
(HD100546)



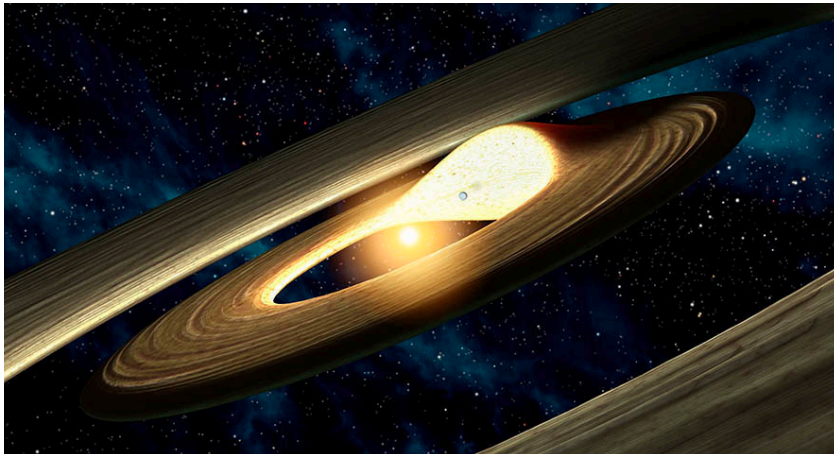
Structural variability
(HD100546)



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

MIR interferometric imaging

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



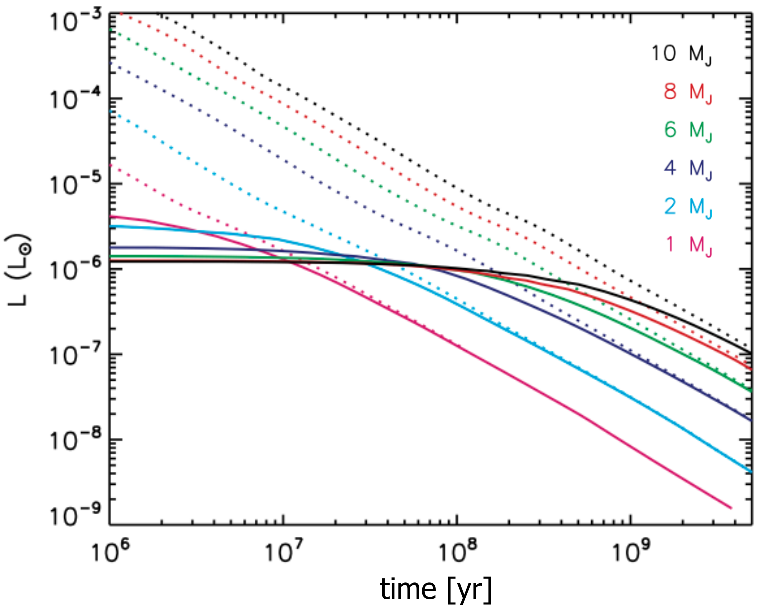
Artists Impression, Muzerolle et al. 2009

➜ **Multi-epoch interferometric imaging could reveal origin of variability**

New challenges:

- ➜ Coordinated spectroscopic + interferometric observations necessary
- ➜ Frequent & rapid configuration changes necessary to achieve uv-coverage (in particular as structures are likely more complex than in the NIR with diffuse extended emission)

MIR interferometric imaging

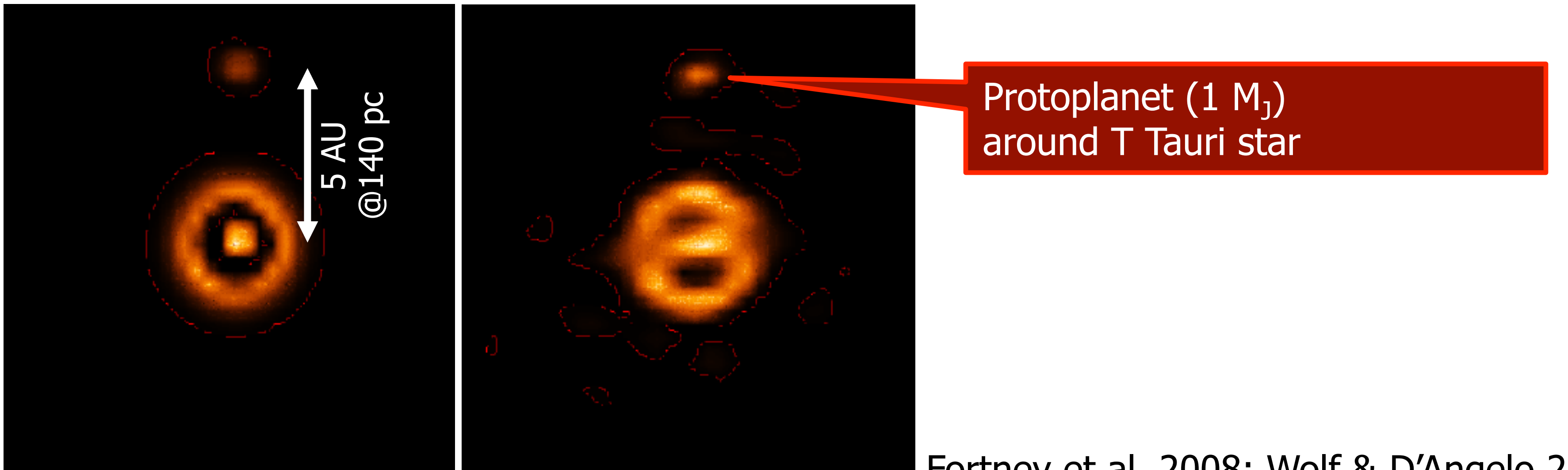


Young accreting planets emit significantly at mid-infrared wavelengths

➜ **MATISSE could detect protoplanets on scales of a few AU**

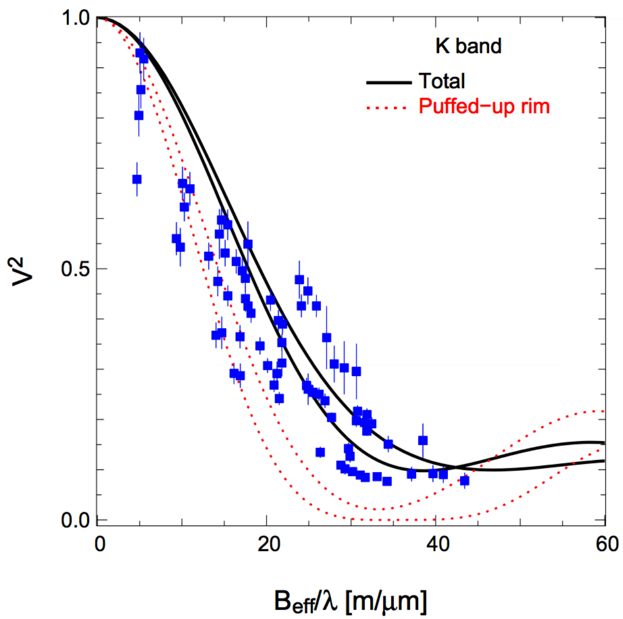
Simulated image (10 µm)

Reconstructed image



Fortney et al. 2008; Wolf & D’Angelo 2005

Need for longer baselines



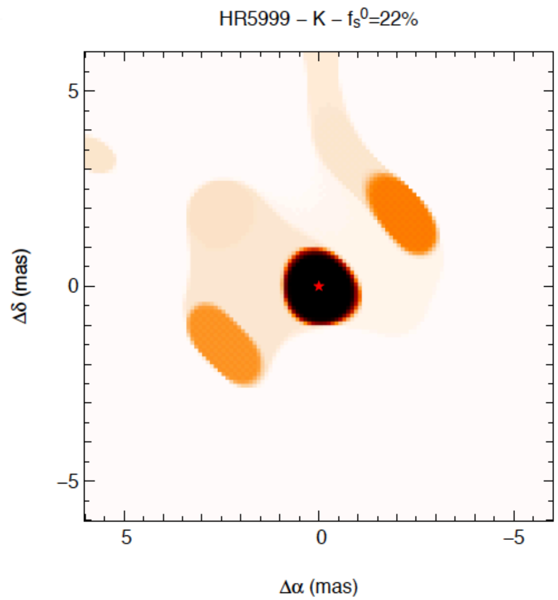
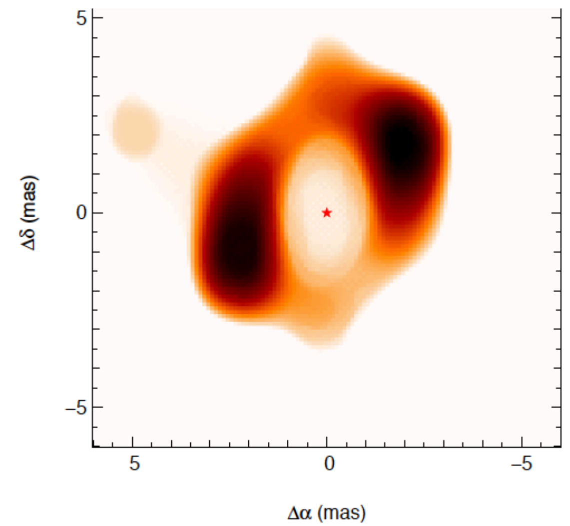
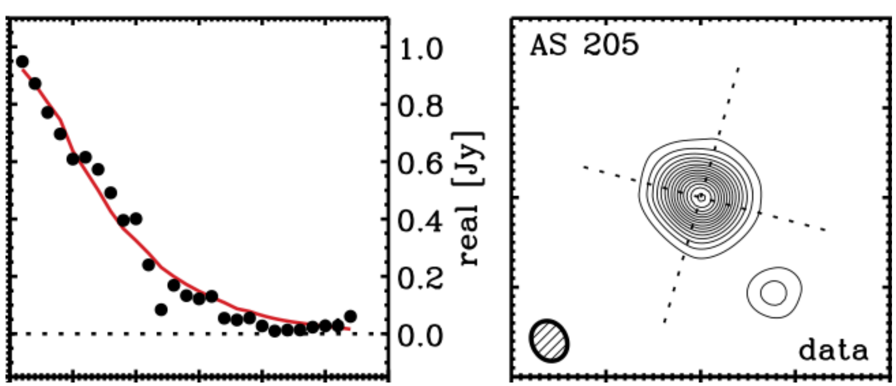


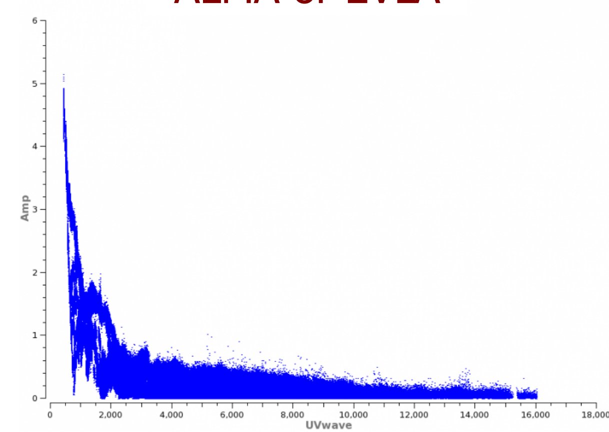
Image after removing photospheric and inner disk contributions



SMA



ALMA or EVLA



Benisty et al. 2011, Kluska et al. 2014, Andrews et al. 2009

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

The “Planet Formation Imager” Project

Science Case: Planet Formation

Goal: **Study the formation process of exoplanetary systems on spatial scales of the Hill sphere of the forming planets**

- Science case appears well suited to **gather support** from the wider astronomical community (see ASTRONET roadmap & US decadal review!)

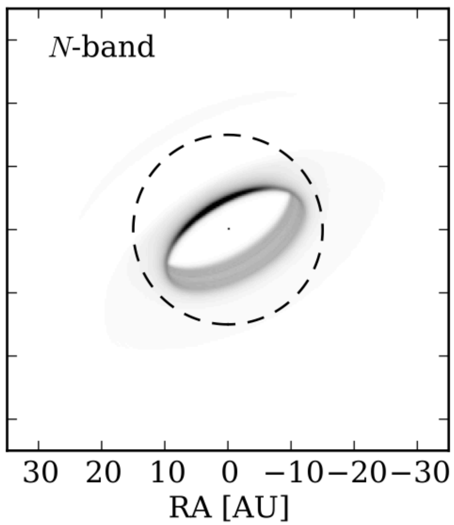
- **Strong existing momentum** in the field (in particular due to ALMA)

- **Complementary aspects** to ALMA:
  - ➔ higher resolution allows probing terrestrial planet-forming zone, which is dominated by other mechanisms than outer disk (dust sublimation, gas-disk truncation, magnetospheric accretion, …)
  - ➔ NIR/MIR probes complementary opacity regimes, grain sizes, and line tracers

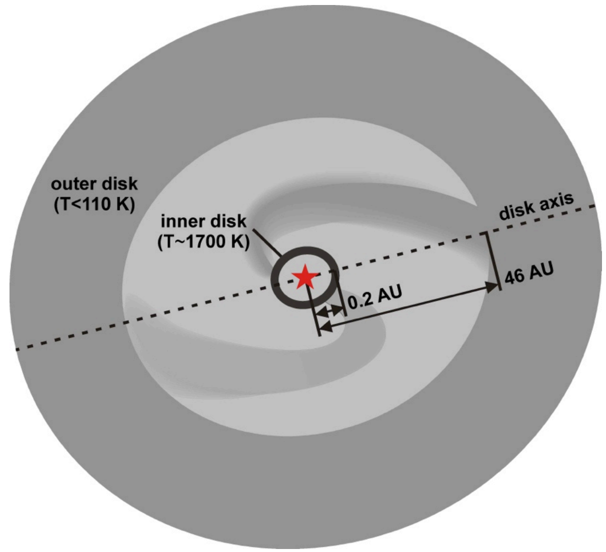
- A dedicated high-angular resolution facility would fill a gap in the instrumentation plan for the 2020/30's (complementing ELTs, JWST, LSST, …)

- **Interesting results** from existing facilities:
  - ➔ MIDI demonstrated that the sensitivity goals are within reach
  - ➔ Detection of interesting signatures (but not direct imaging yet)

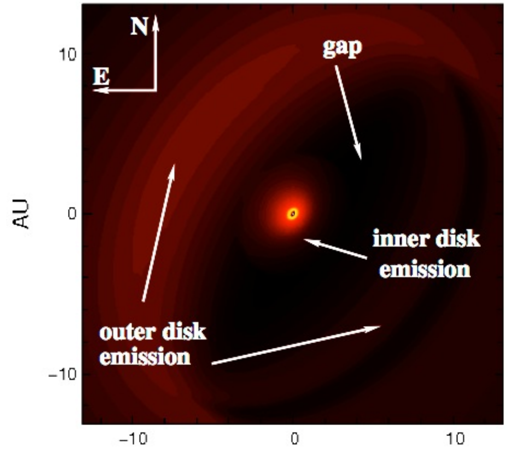
Science Case: Planet Formation



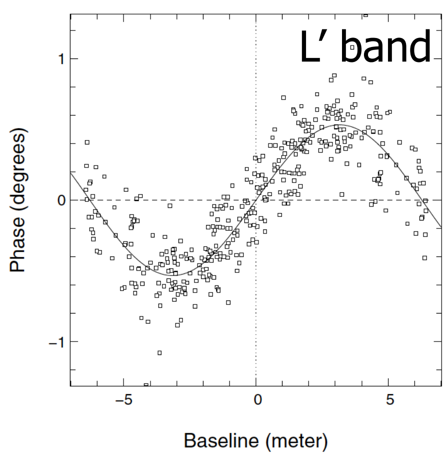
Huélamo et al. 2011
Olofsson et al. 2011, 2013

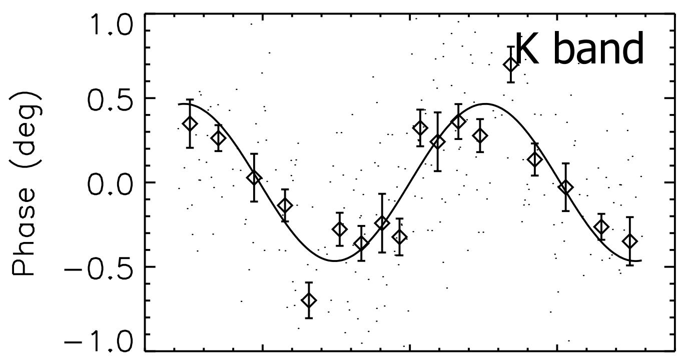


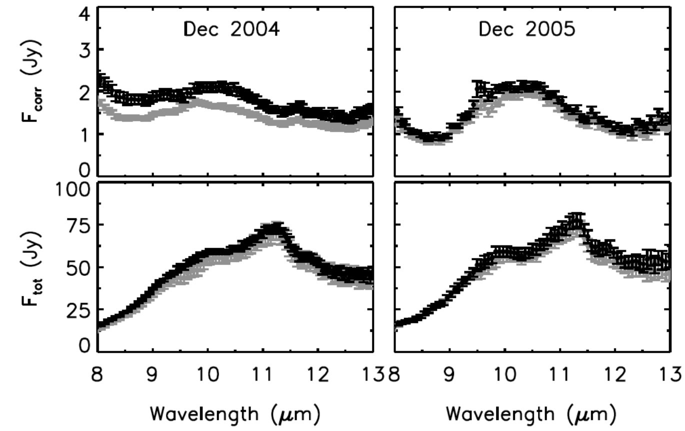
Kraus et al. 2013



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







➔ Emission from outer disk?
Companion signature?

➔ Disk asymmetries

➔ Temporal changes

Radiation hydrodynamics simulations

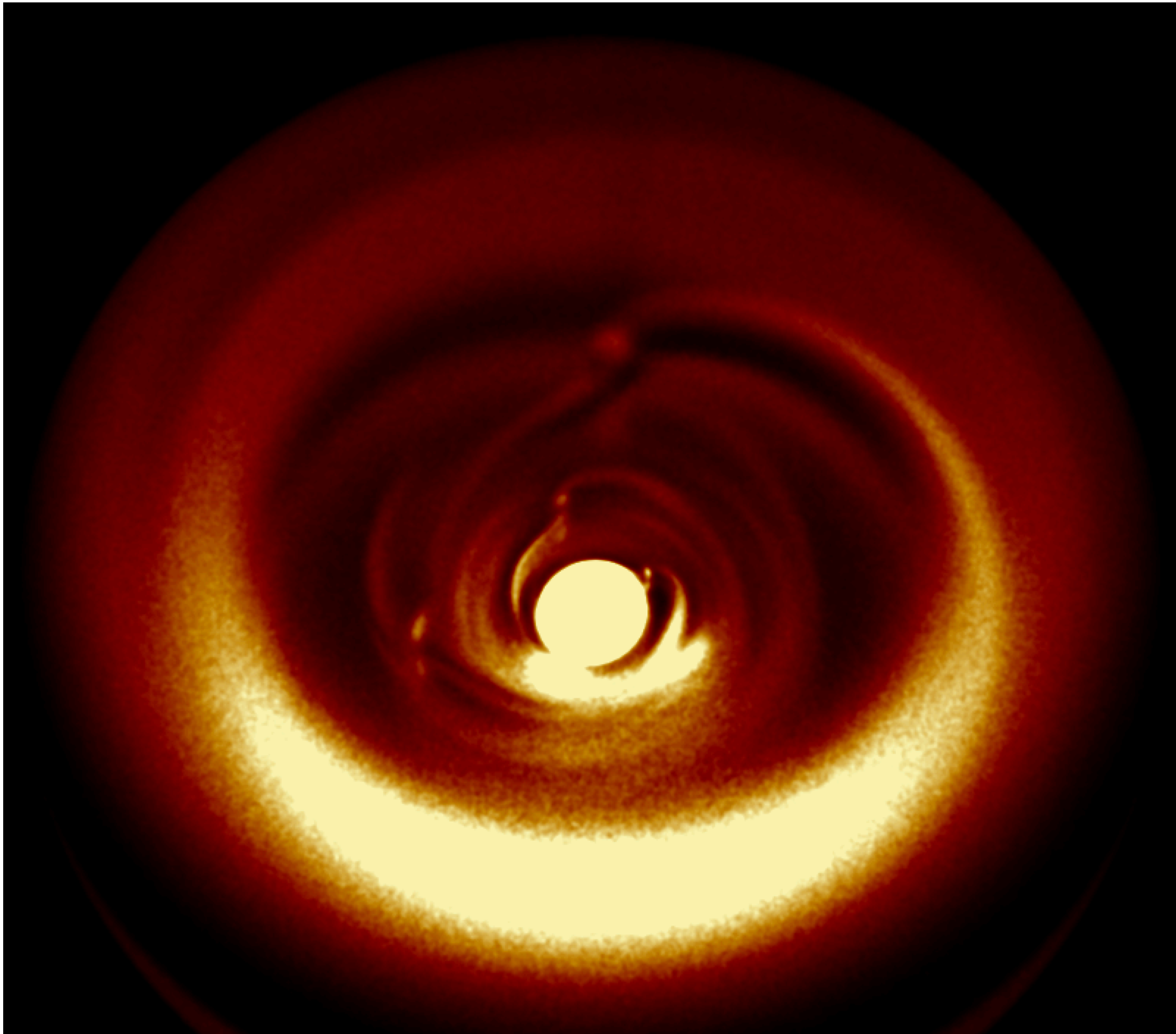
2μm
(K-band)

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

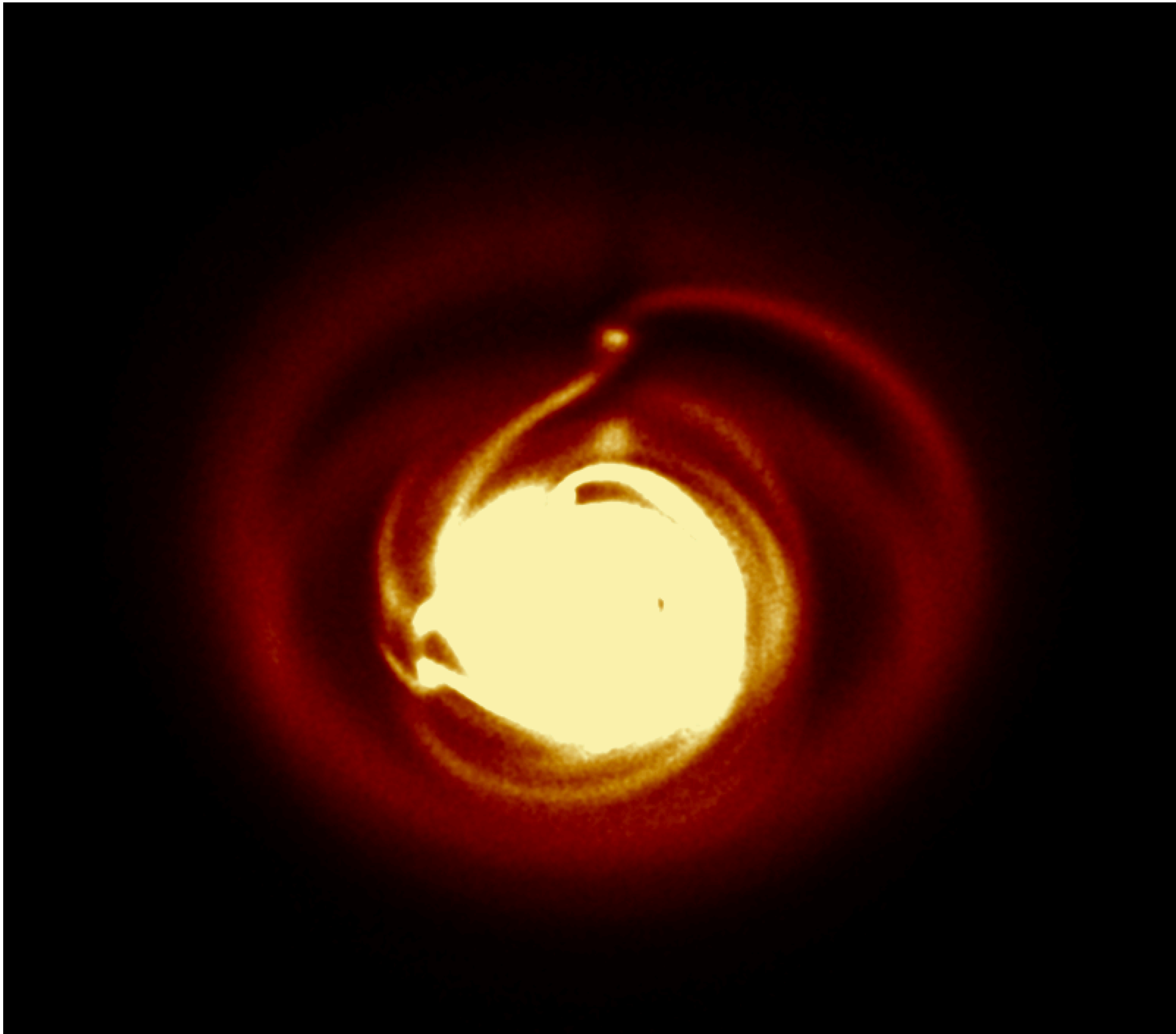
10μm
(N-band)

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

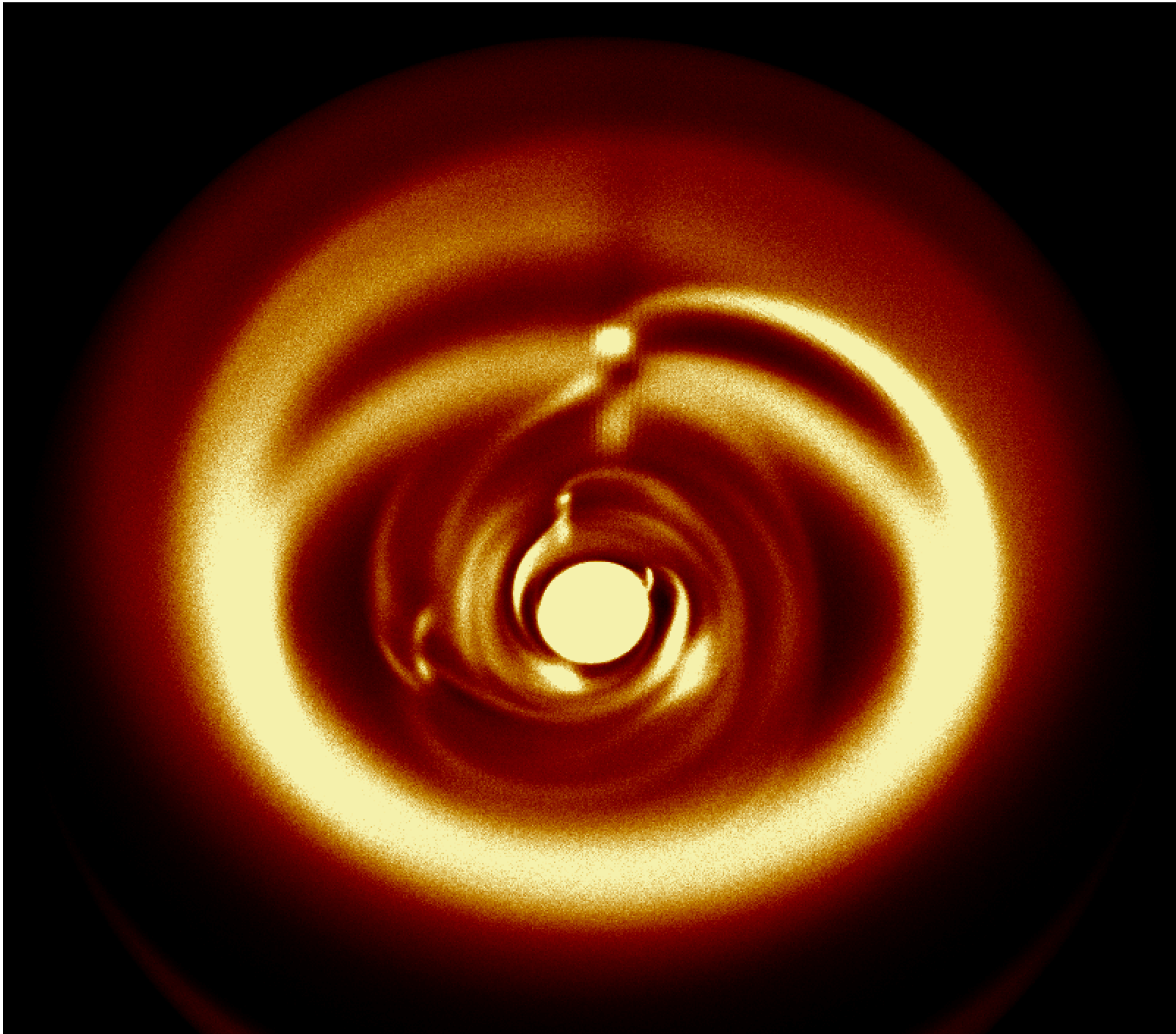
24μm
(Q-band)

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

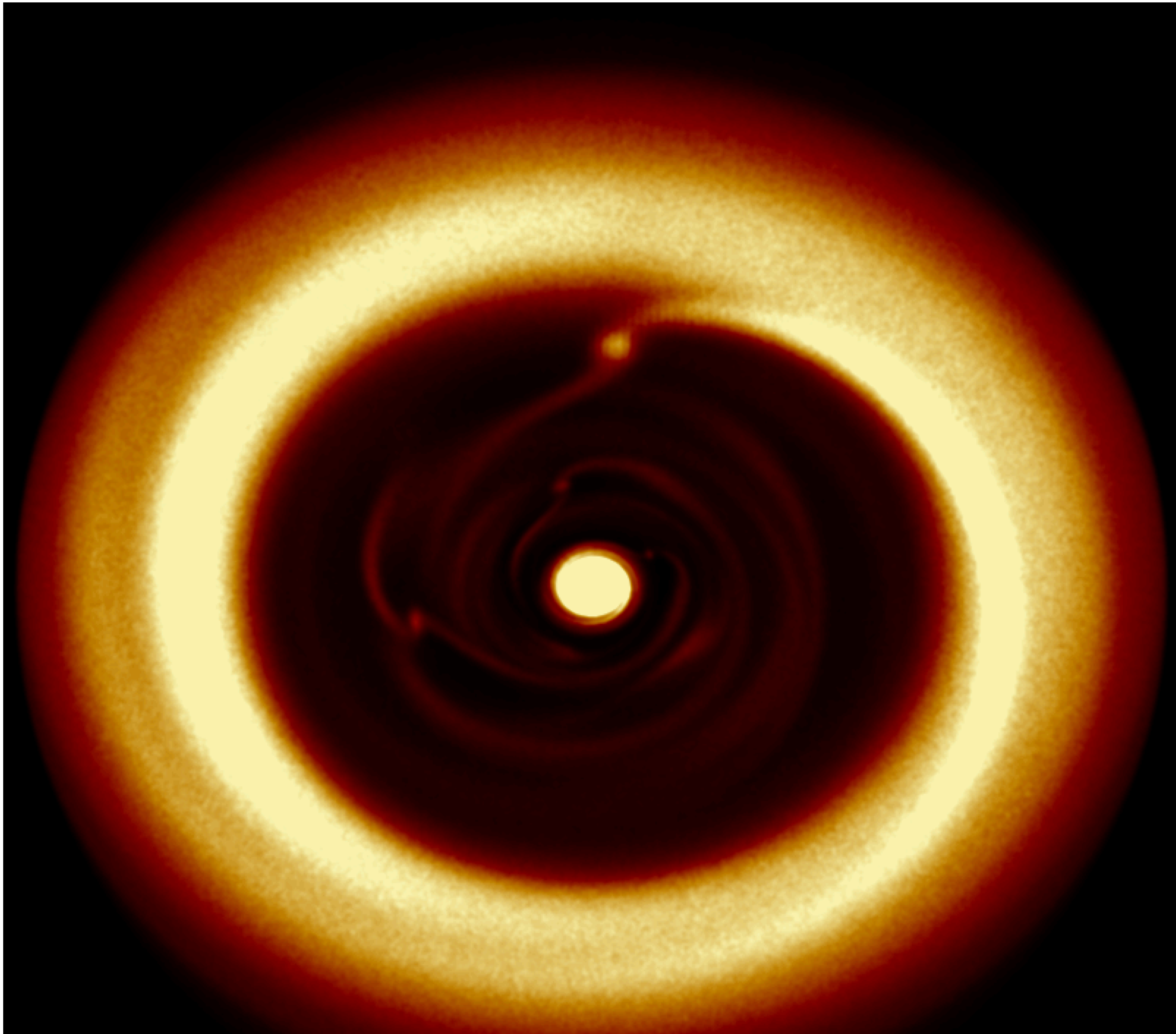
100μm
(FIR, space)

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

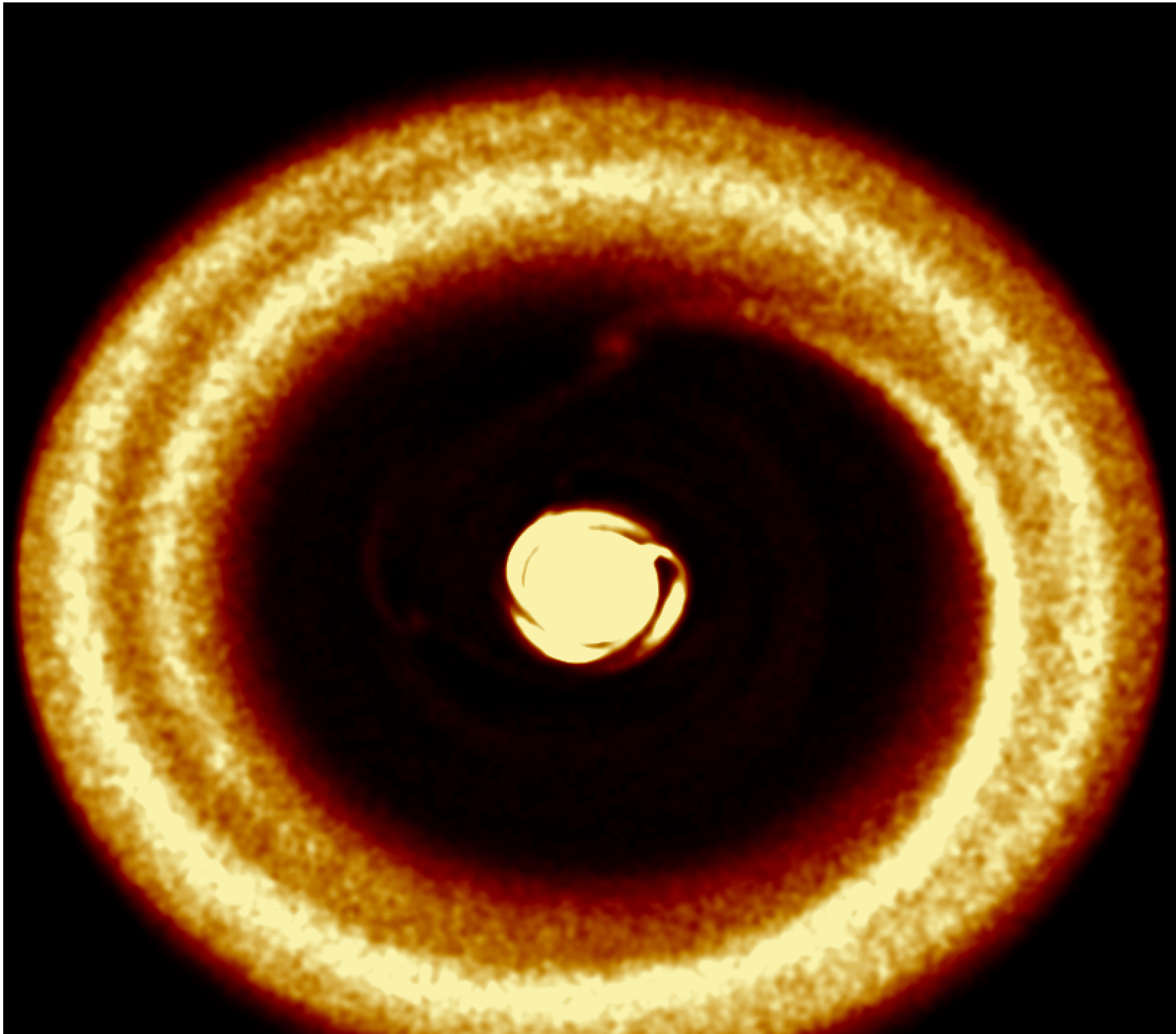
400μm (sub-mm, ALMA)

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

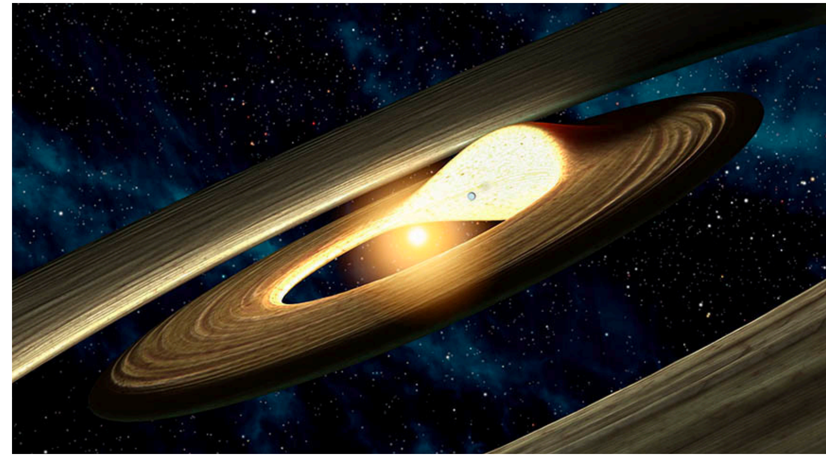
Zhaohuan Zhu, Barbara Whitney, Robin Dong



Resolving planet-induced disk structures

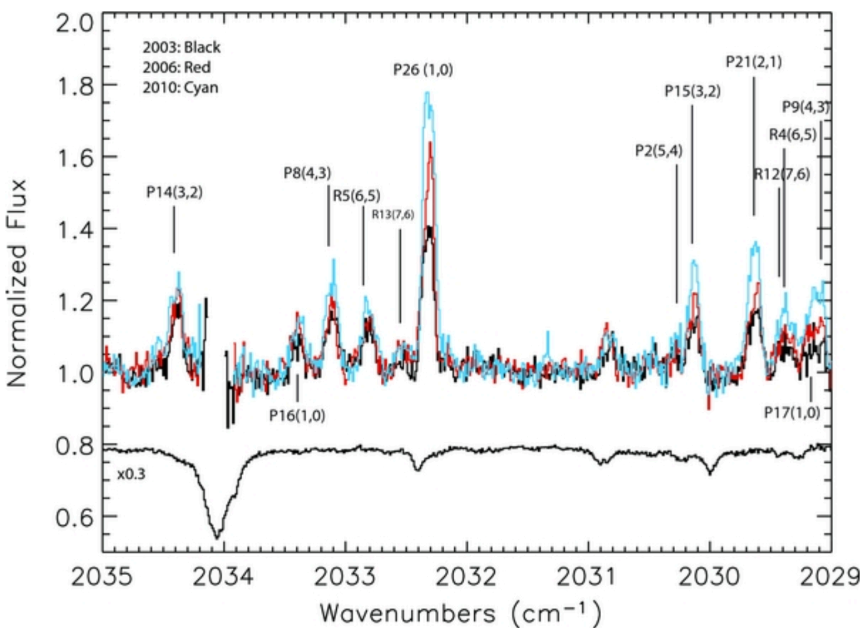
Objective: Image the complex & highly dynamical processes in the innermost AU and study their temporal evolution

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

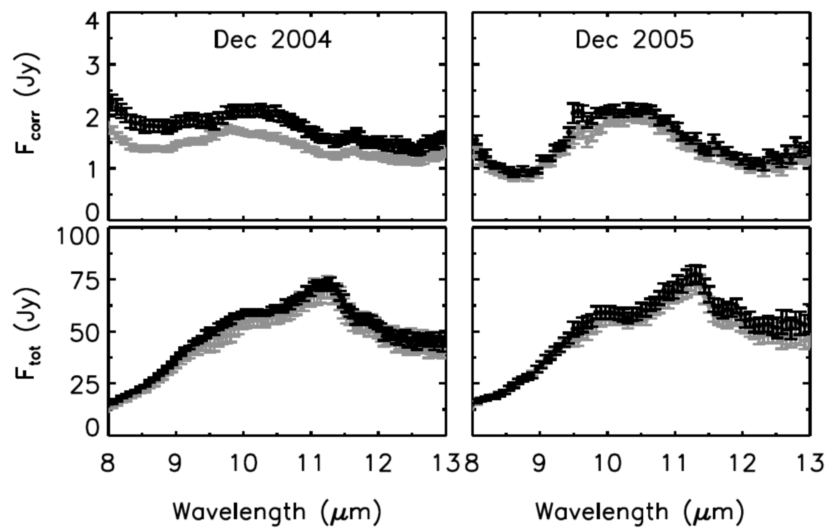


Artists Impression, Muzerolle et al. 2009

Spectroscopic variability
(HD100546)



Structural variability
(HD100546)



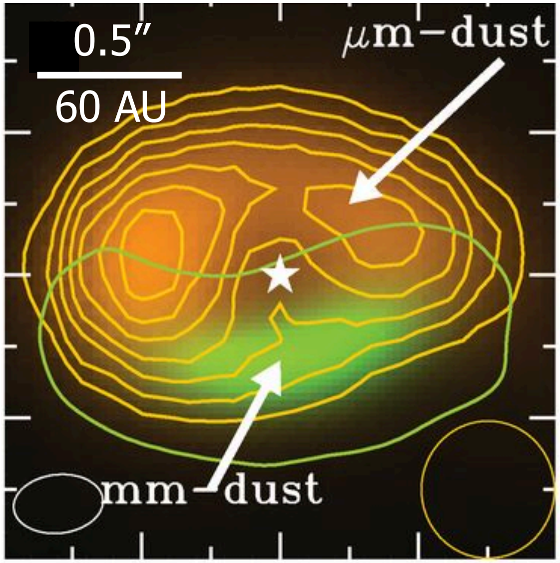
Panić et al. 2014; Brittain et al. 2013
also: Mosoni et al. 2013

ALMA+PFI: Tracing complementary dust species

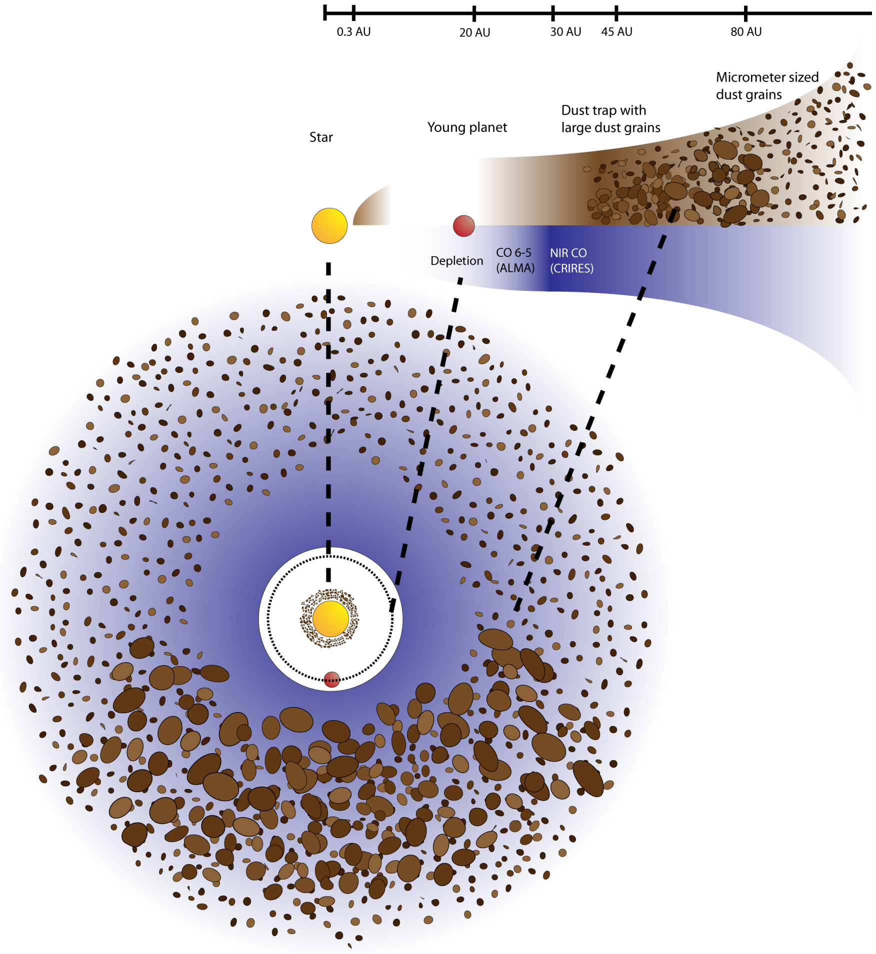
Objective: Trace small dust grains & detect spatial variations in dust mineralogy

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

Oph IRS48



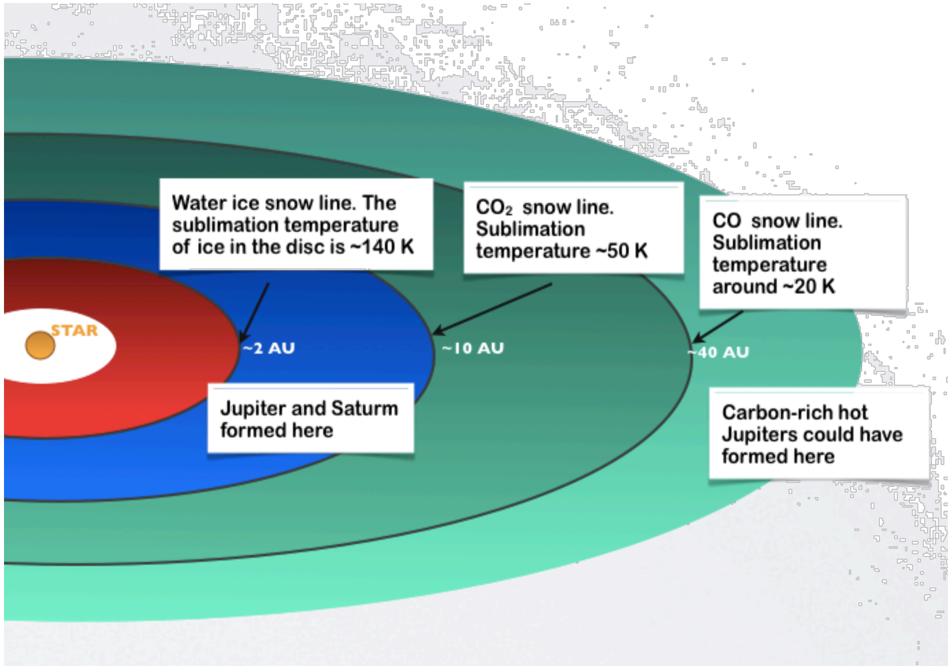
van der Marel et al. 2013



ALMA+PFI: Tracing complementary molecular lines

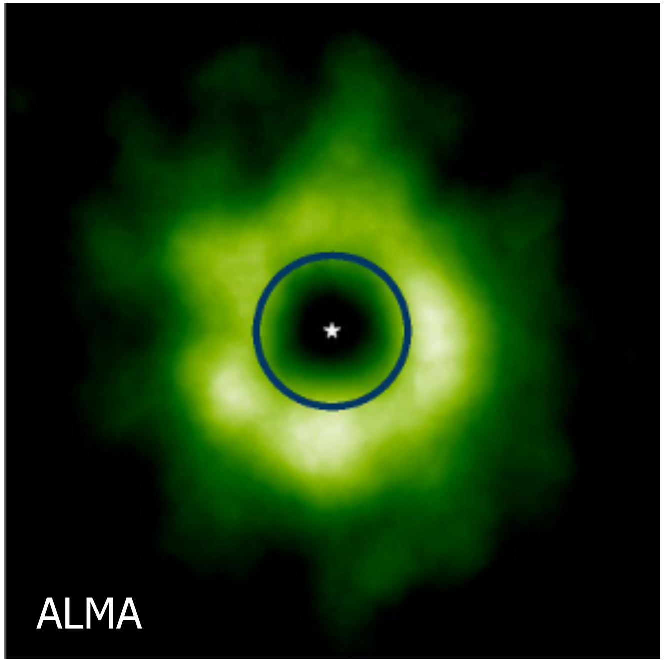
Objective: Determine distribution of water & ices

➔ link to habitability



Öberg et al.

CO snow line in TW Hya



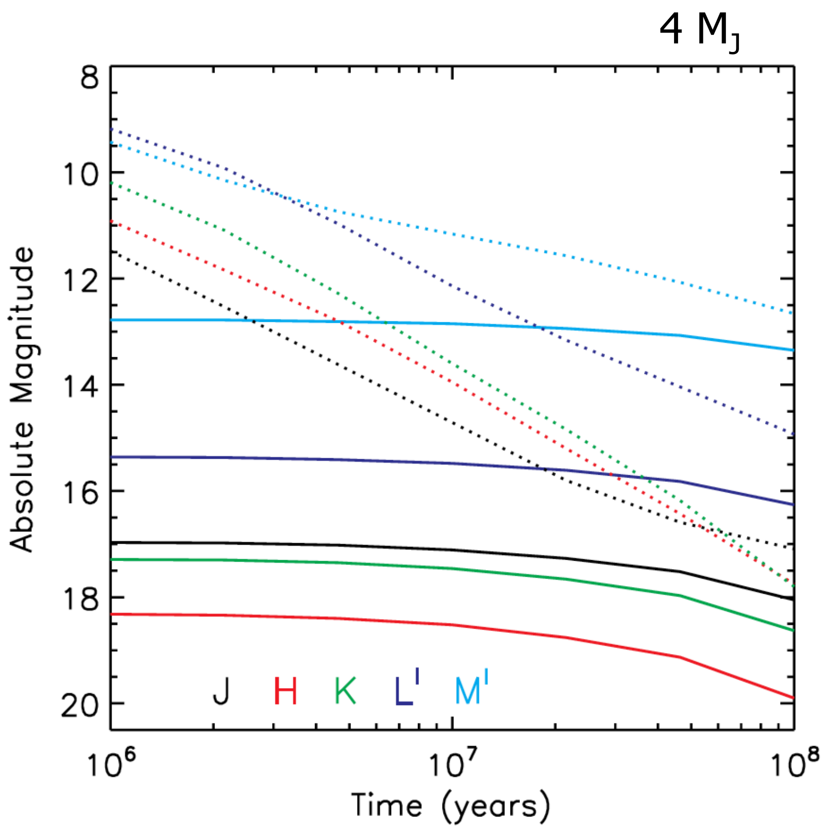
Qi et al. 2013

Water on terrestrial planets:

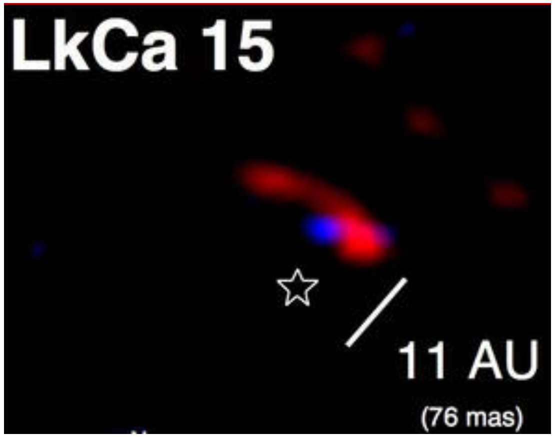
- Planetesimal delivery (Morbidelli et al. 2000)
- Atmospheric capture in the inner disk (Ikoma et al. 2006)

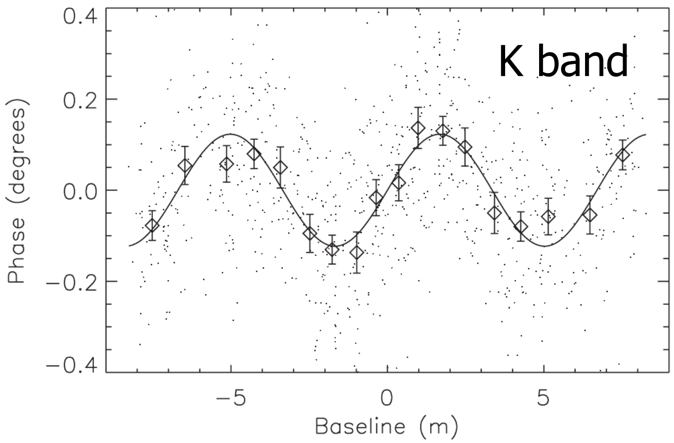
Detect accreting young protoplanets

Objective: Detect young accreting protoplanets



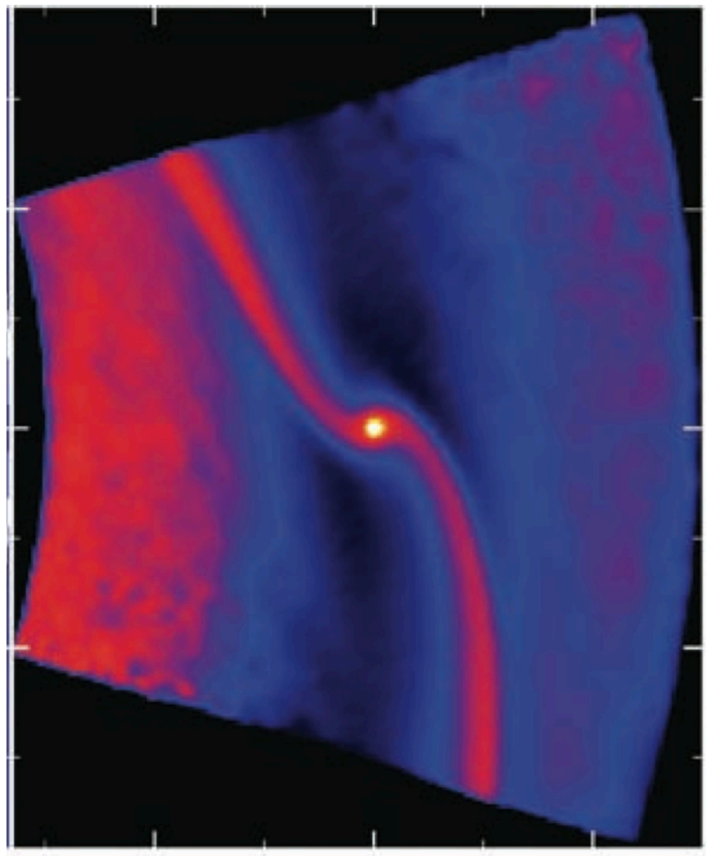
Forney et al. 2008



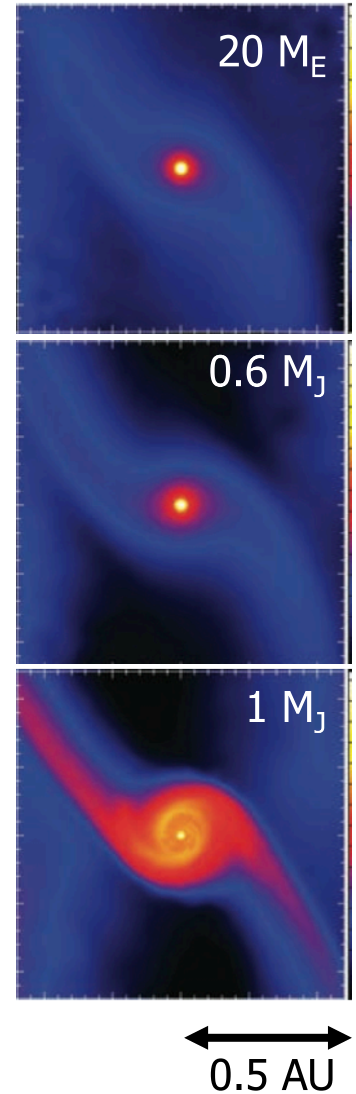


Kraus & Ireland 2012

Resolving the protoplanetary accretion disk



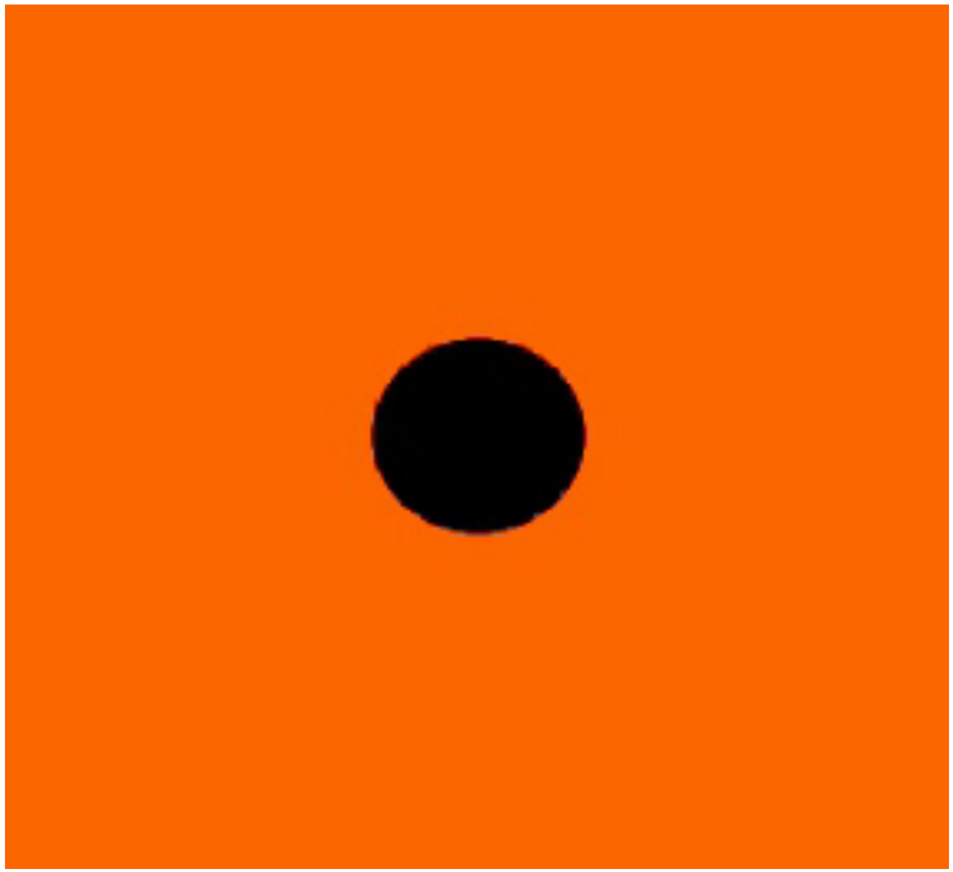
Ayliffe & Bate 2009



Detect accreting young protoplanets

Objective: Detect young accreting protoplanets (for a significant sample)

➔ constraints on **planetary migration**



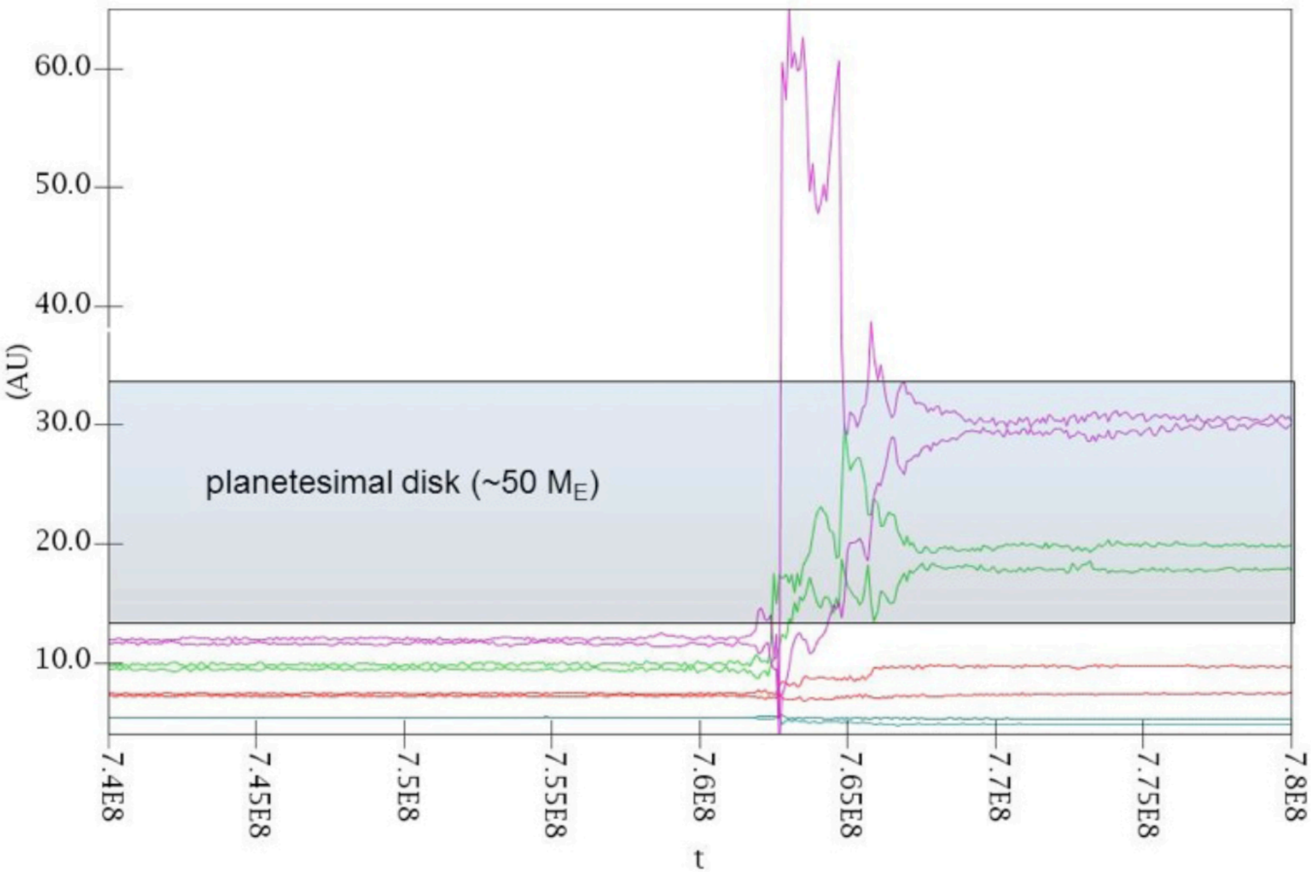
Masset et al.

Dynamical interaction with gas-rich disk

Detect accreting young protoplanets

Objective: Detect young accreting protoplanets (for a significant sample)

➔ constraints on **planetary migration**



"Nice model"

Dynamical interaction with planetesimal disk

Davies et al. 2014, PPVI

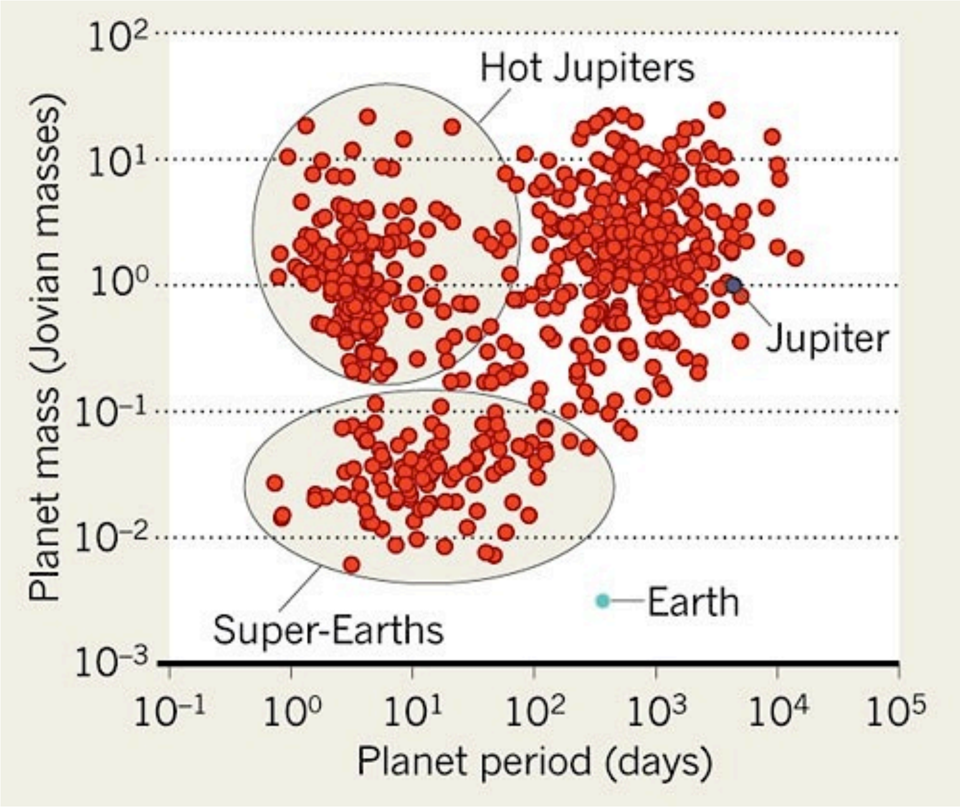
Gomez et al. 2005, Tsiganis et al. 2005, Morbidelli et al. 2005, Levison et al. 2011

Detect accreting young protoplanets

Objective: Detect young accreting protoplanets (for a significant sample)

➔ constraints on **planetary migration**

➔ link to **exoplanet statistics**



Hand 2010

Planet Formation Imager (PFI)

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. ASTRONET, ESO)
- Prepare for upcoming funding opportunities (OPTICON, decadal review)

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)

International "Kick-off committee" with balanced representation from
EU, US, Australia, and IAU C54 has been formed:
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

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)

Planet Formation Imager (PFI)

A **Project Advisory Committee (PAC)** will oversee the progress and implementation of the project and represent the participating institutions

We are in process of forming 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

Immediate goal over the next 12-24 months is (a) to show that PFI will provide unique AND important information and (b) to identify a credible technology roadmap

The work of the SWG and TWG will result in white papers and will be published in refereed papers where appropriate.

PFI will certainly also revolutionize other science areas (stellar astrophysics, AGNs, …)

We invite your participation – state your interest at
www.planetformationimager.org (soft deadline: June 16)