The Planet Formation Imager (PFI) Project

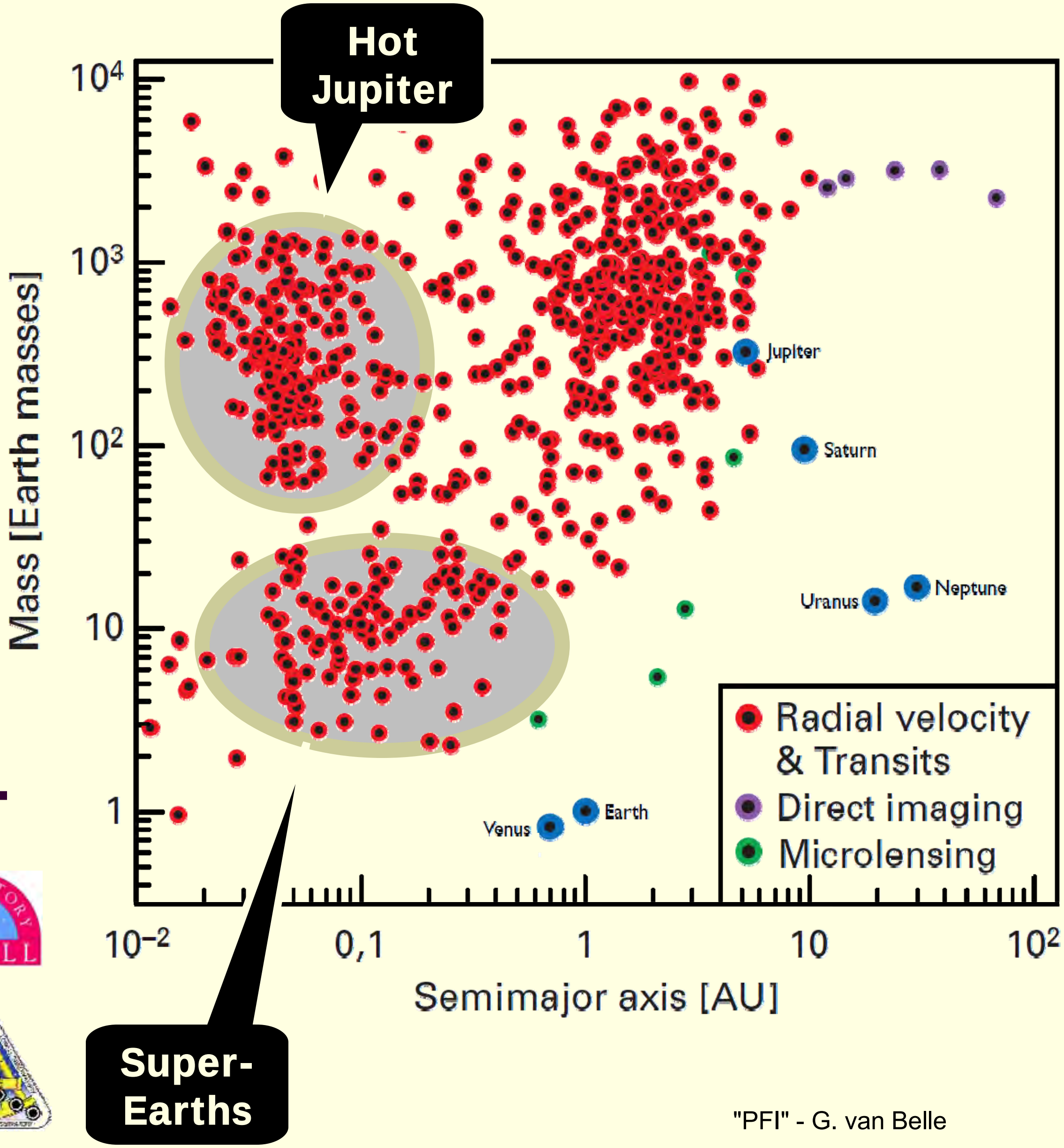
2015 Annual CHARA Gathering

Dr. Gerard van Belle, PFI Kick-off Committee
Lowell Observatory
March 18th, 2015

Project Collaboration

- ***Executive team:*** John Monnier, Stefan Kraus, David Buscher, Mike Ireland
- ***Kick-off committee:*** Jean-Philippe Berger, Chris Haniff, 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
- ***Simulations:*** Matthew Bate, Robin Dong, Tim Harries, Barbara Whitney, Zhaohuan Zhu

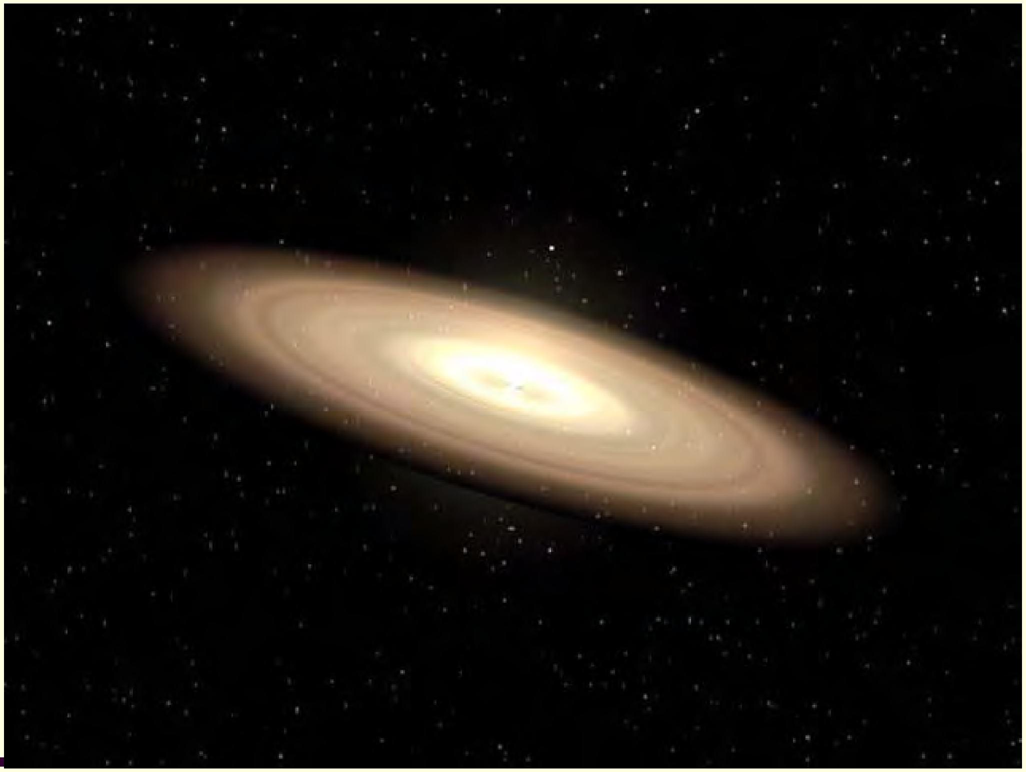
Exoplanetary systems



Exoplanetary systems show surprising diversity

Mordasini et al. 2014

Exoplanetary systems

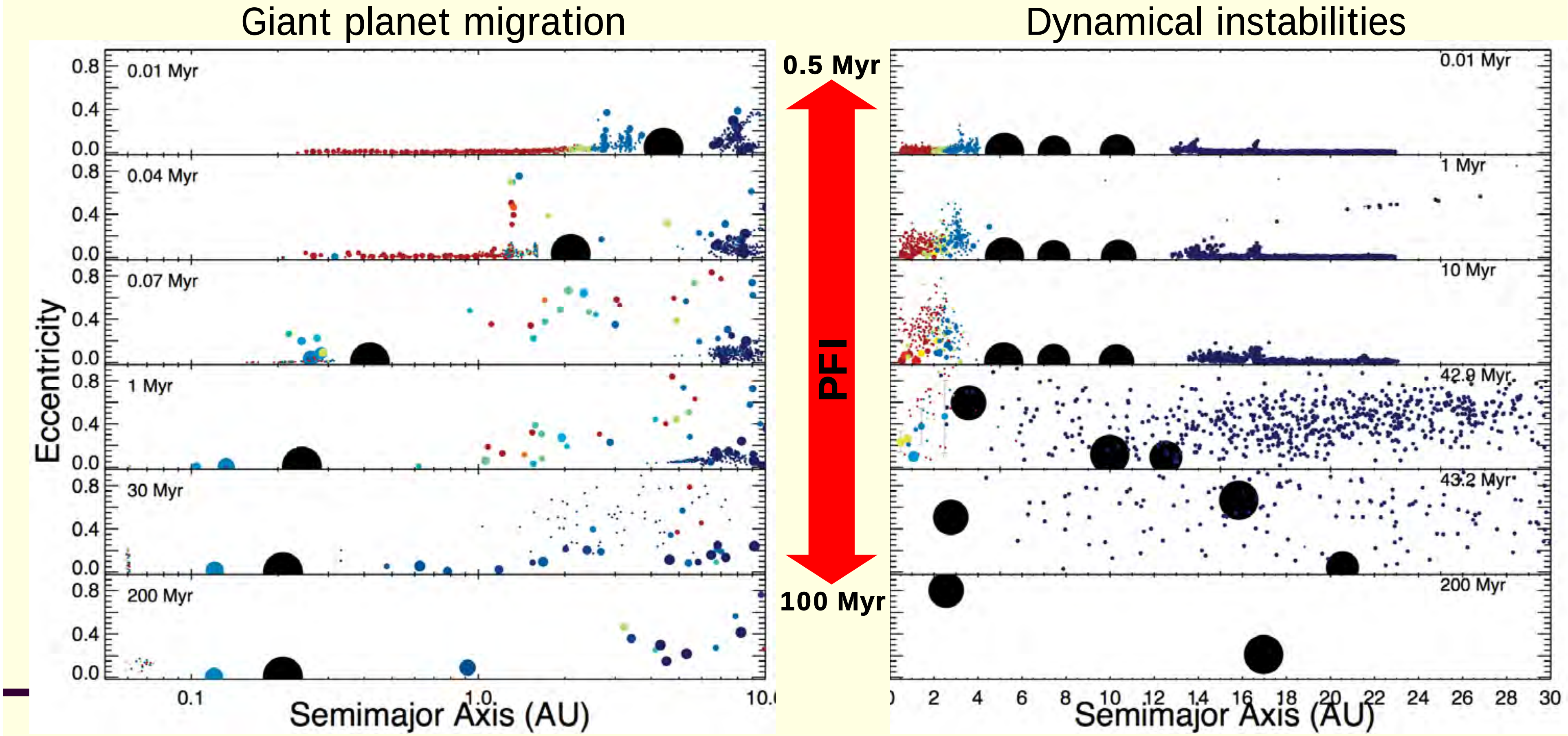


Dynamical interaction with gas-rich disk

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
- ... other unexpected physics?

Exoplanetary systems



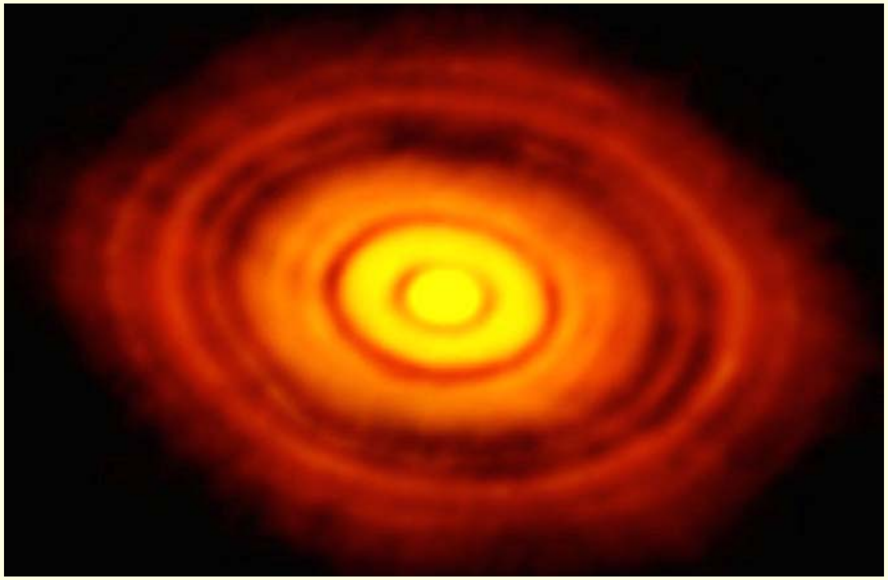
PFI probes the age range that is most critical for understanding the dynamical evolution of planetary systems

Raymond et al. 2006

Science Case: Planet Formation

- Planet formation is one of the most exciting fields in astronomy, connecting star formation with exoplanets

- **Strong existing momentum** in the field,
  poised with many advances with ALMA, GPI/SPHERE, ELTs, …



ALMA SV data
15km baseline

- We expect complexity beyond what ALMA and single apertures can ever resolve

Complexity requires imaging!
A dedicated high-angular resolution facility would **fill a gap** in the instrumentation plan for the 2020/30’s (complementing ELTs, JWST, LSST, ...)

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;
Build support in the science & technology community;
Prepare for upcoming funding opportunities (OPTICON, decadal review)

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

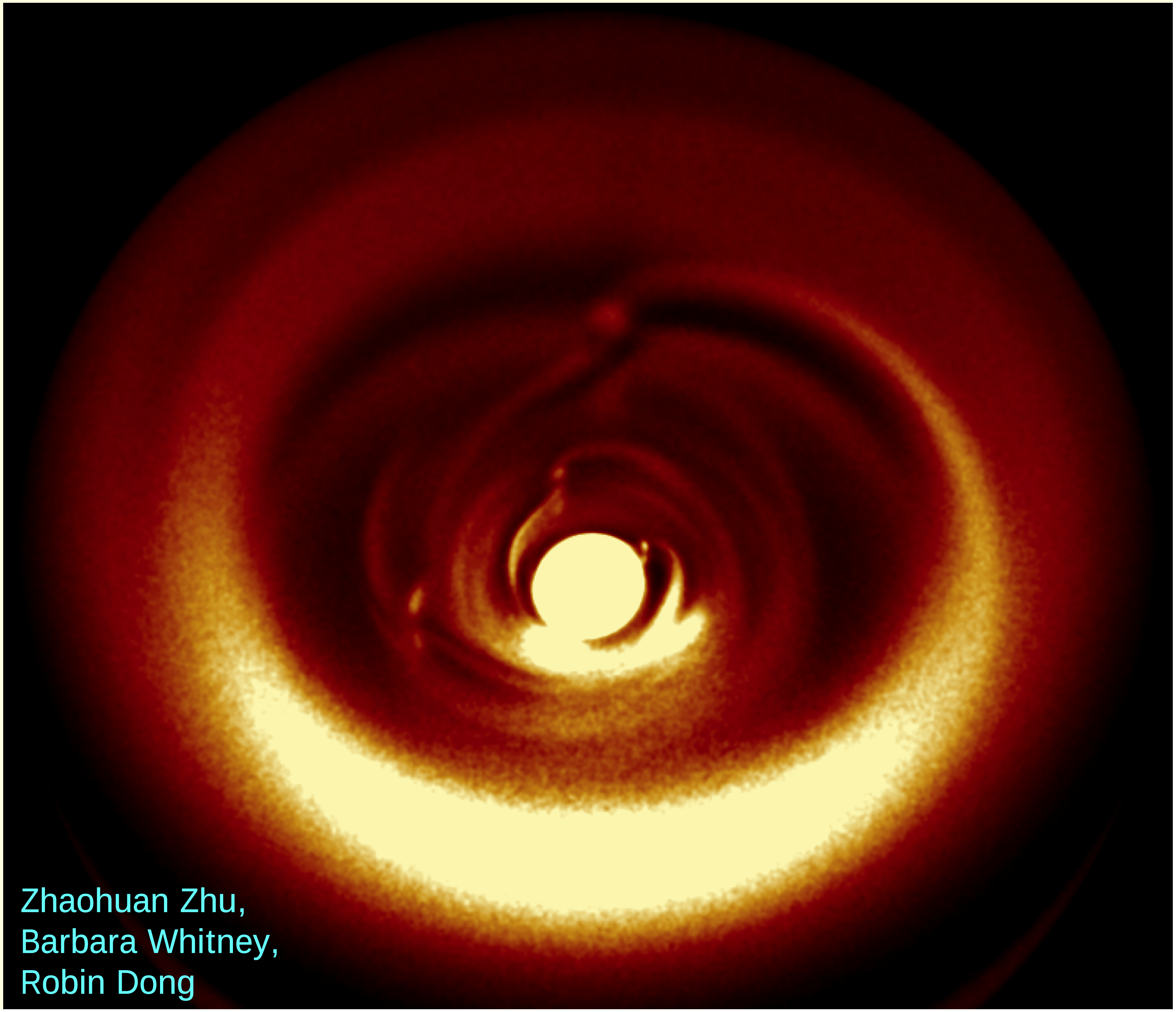
Radiation hydrodynamics simulations

2 μ m
(K-band)

Radiation
hydrodynamics
simulation

$M\ \ =0.5\ M_{\odot}$
inclination=30°
4 planets of 1 M_{Jup}

NIR dominated by scattered light


Zhaohuan Zhu,
Barbara Whitney,
Robin Dong

2015-03-18

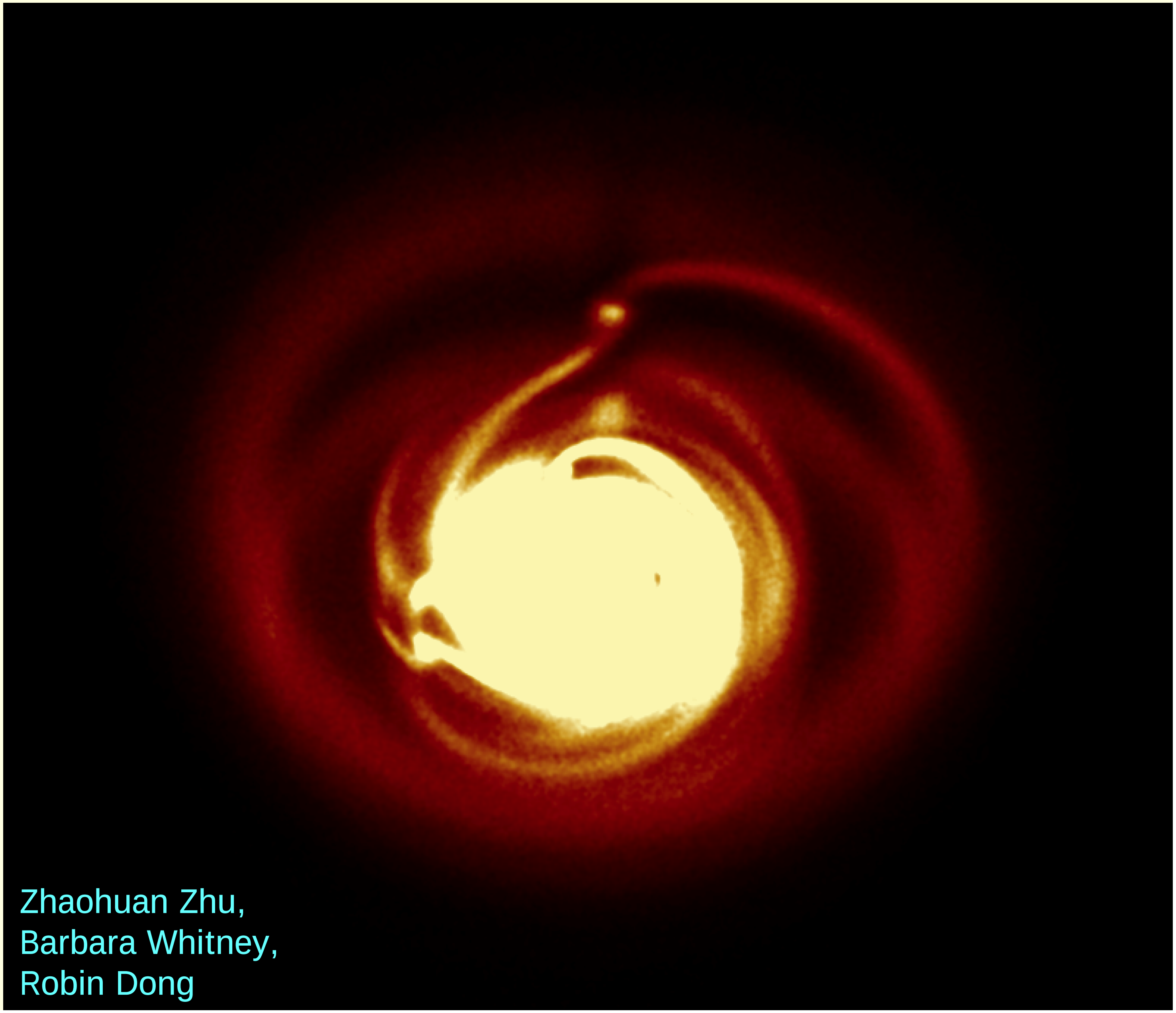
Radiation hydrodynamics simulations

10 μ m
(N-band)

Radiation
hydrodynamics
simulation

M =0.5 $M_\odot$
inclination=30°
4 planets of 1 M_{Jup}

MIR dominated by thermal emission of small grains



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Barbara Whitney,
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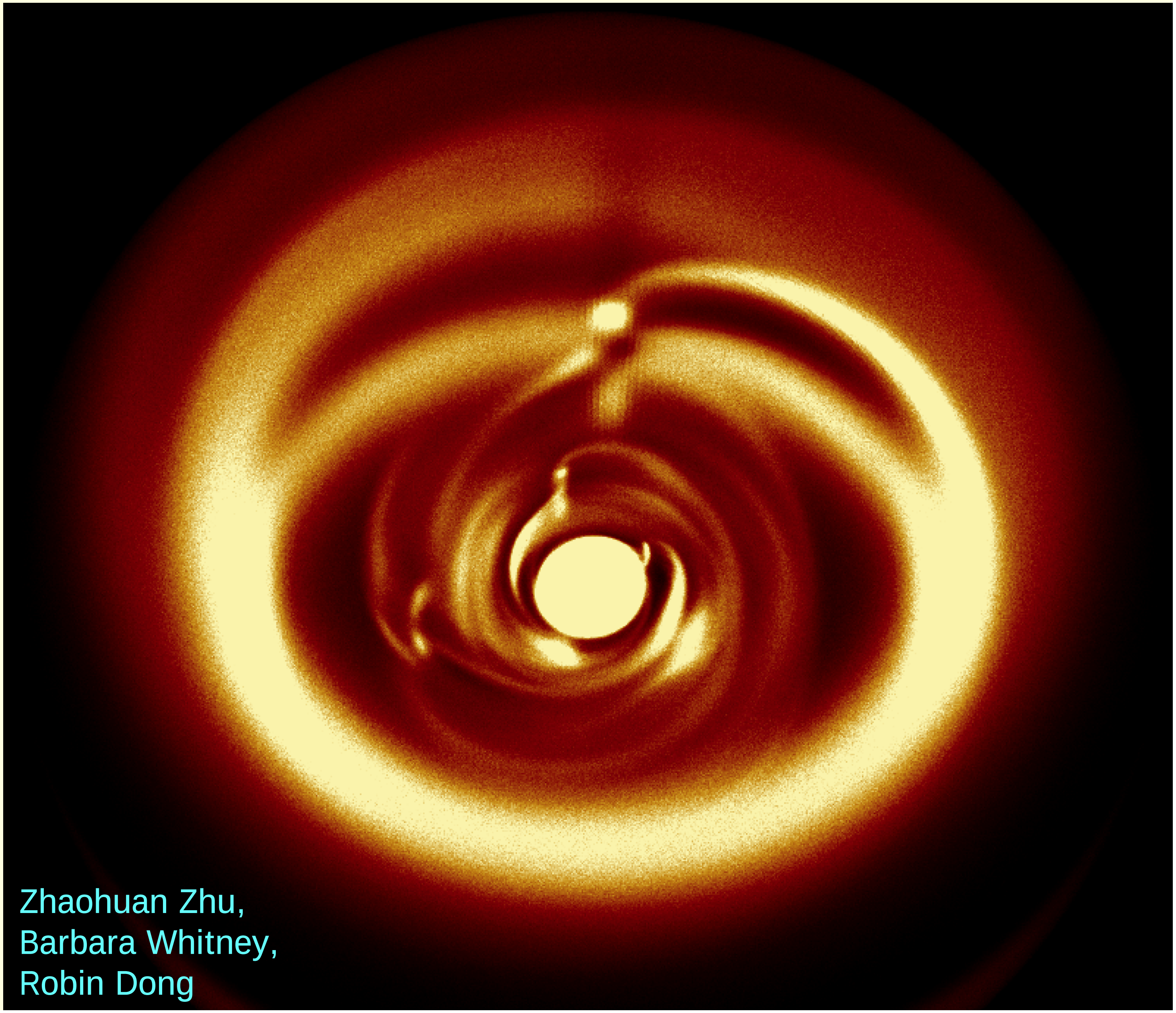
Radiation hydrodynamics simulations

24 μ m
(Q-band)

Radiation hydrodynamics simulation

M =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

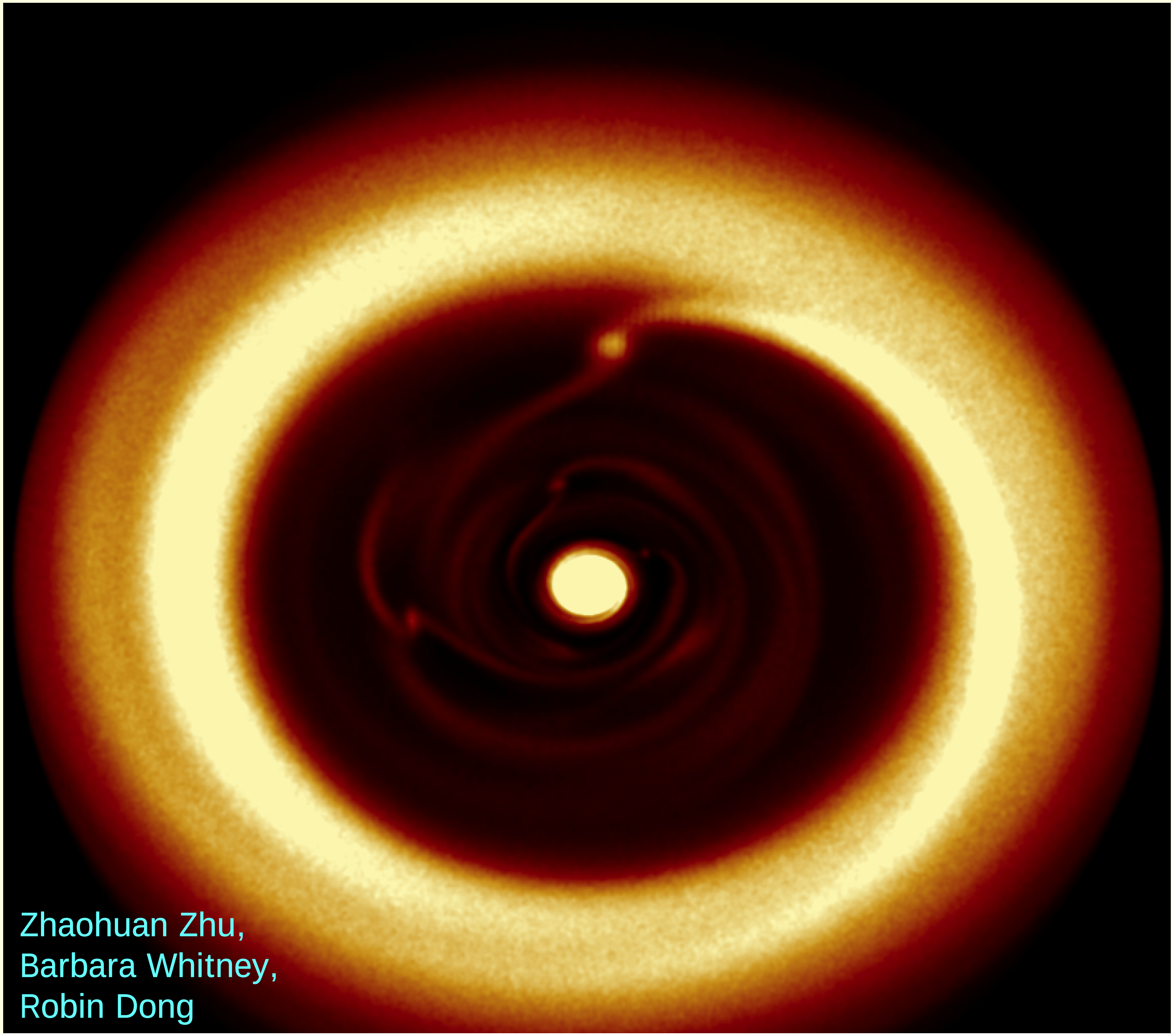
Radiation hydrodynamics simulations

100 μ m
(FIR, space)

Radiation hydrodynamics simulation

M =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,
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Robin Dong

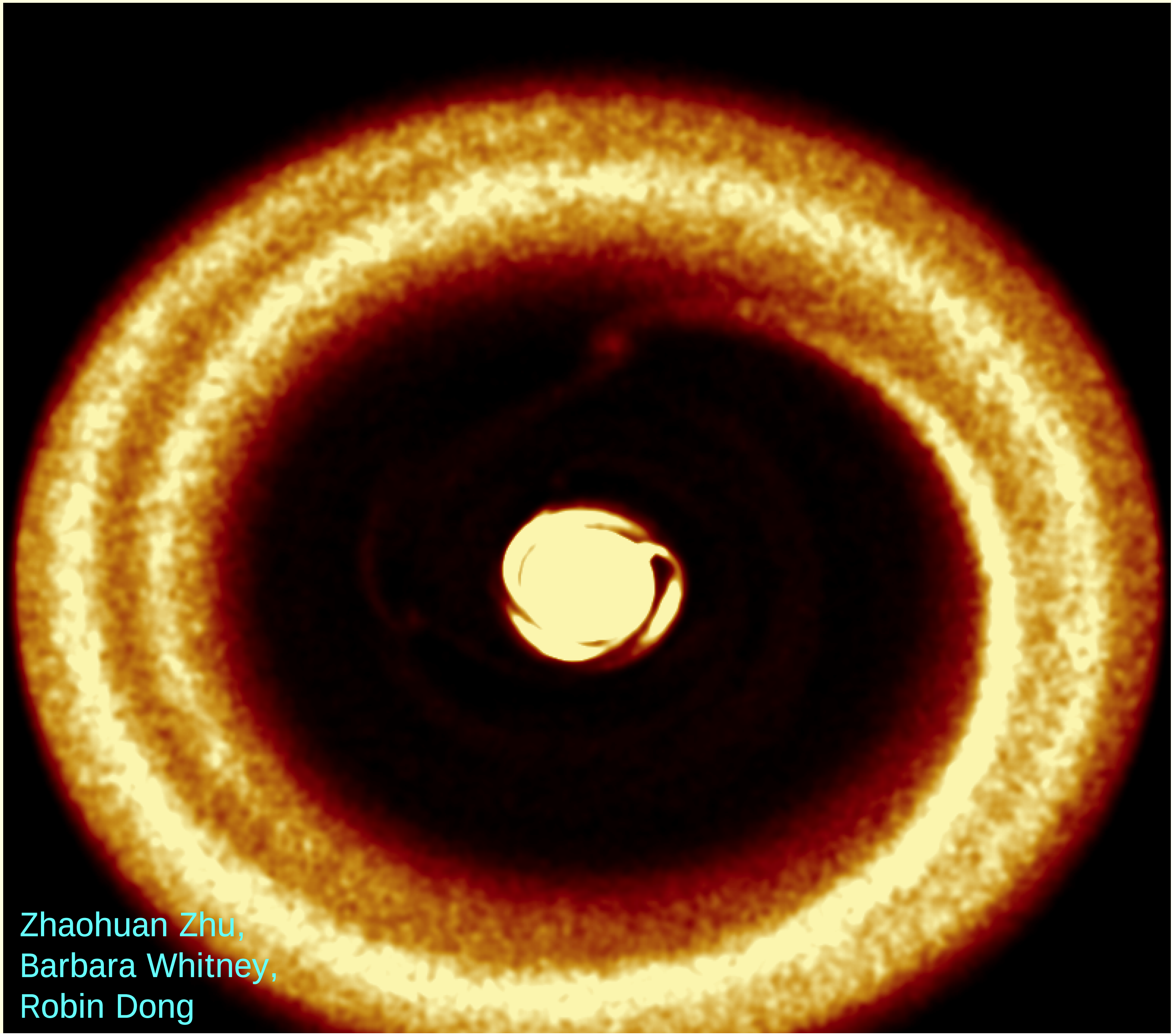
Radiation hydrodynamics simulations

400 μm
(sub-mm,
ALMA)

Radiation
hydrodynamics
simulation

M =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

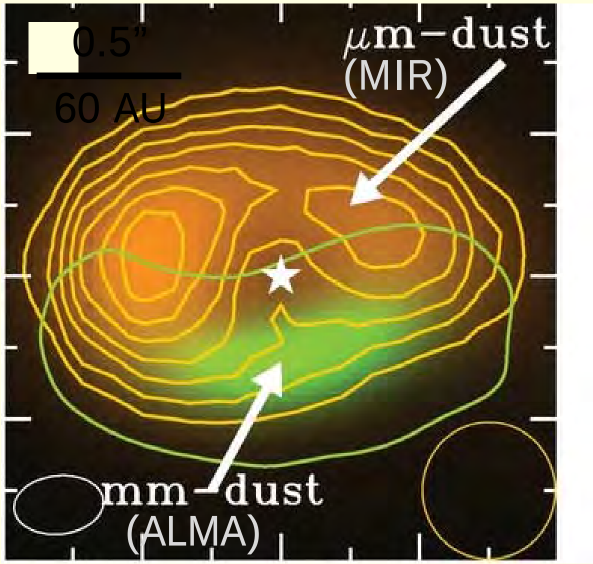
PFI:
Complementarity with ALMA

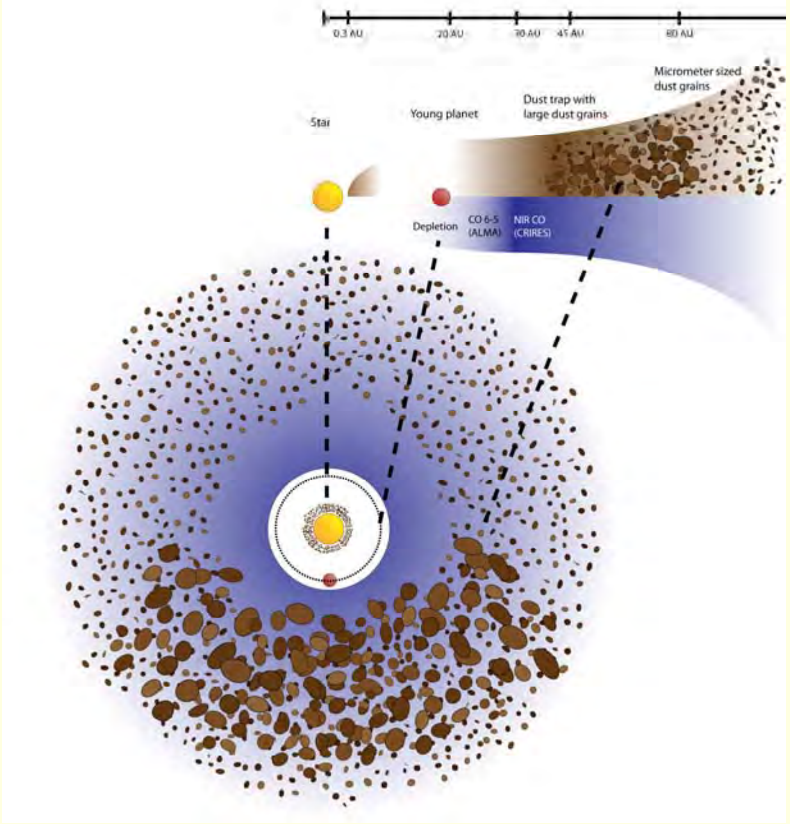
PFI + ALMA: Tracing complementary dust species

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

early stages of grain growth and gap opening, dust filtration

Oph IRS48



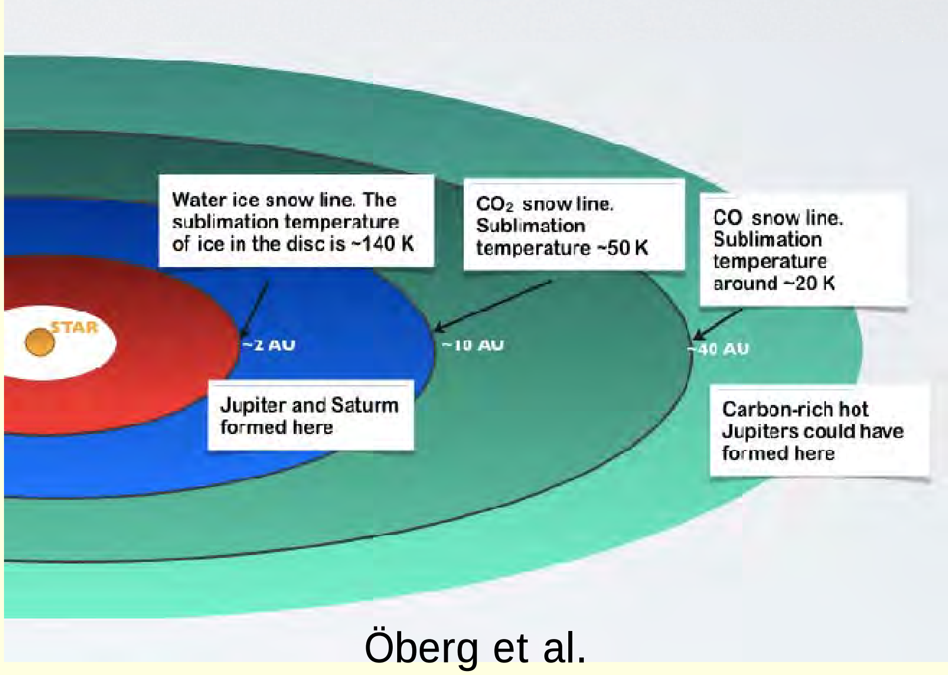


van der Marel et al. 2013

PFI+ALMA: Tracing complementary molecular lines

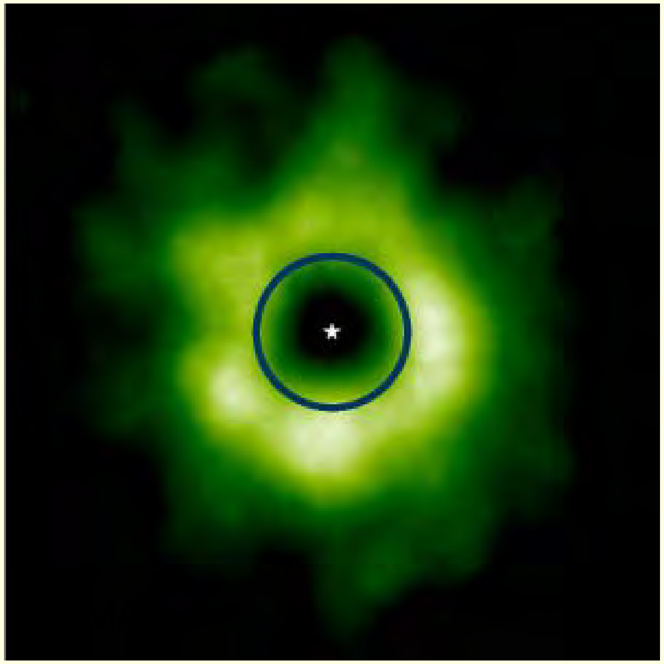
Objective: Determine distribution of water & ices

⎩ link to habitability



Öberg et al.

CO snow line in TW Hya



Qi et al. 2013

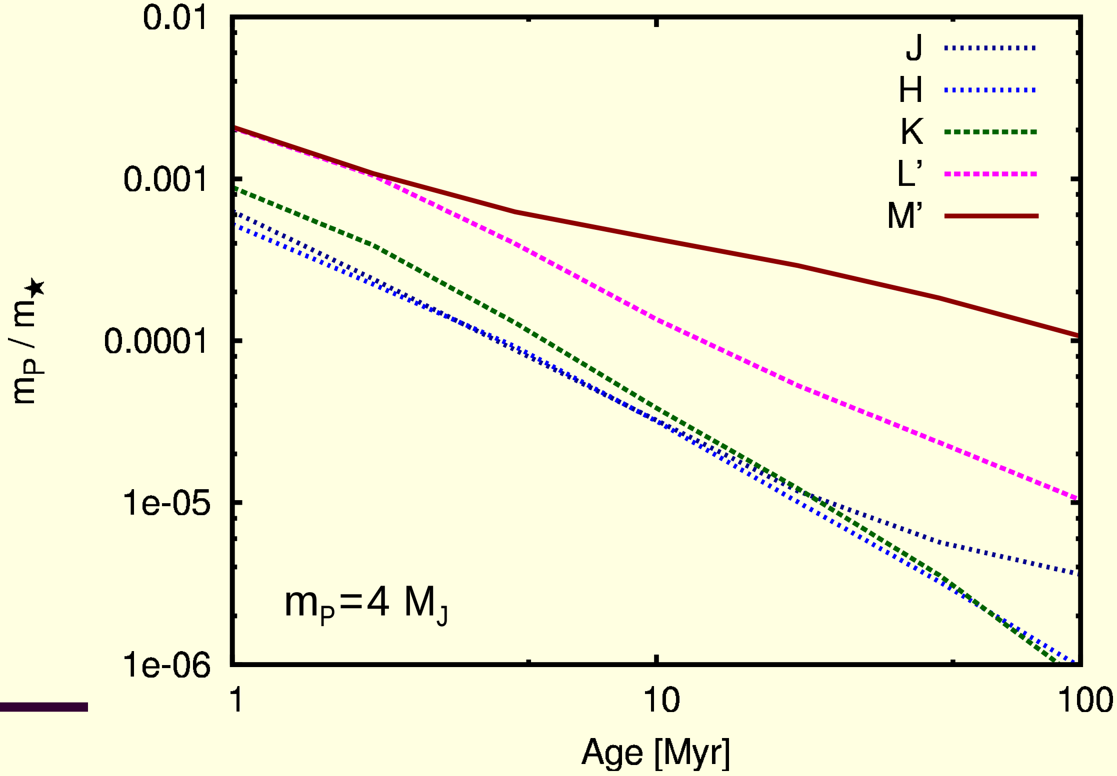
Water on terrestrial planets:

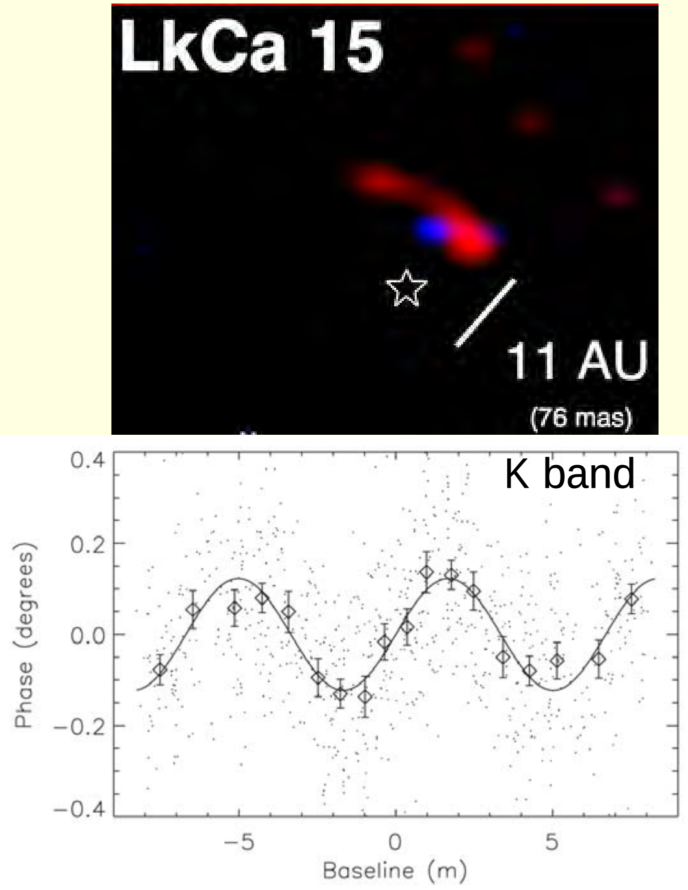
- Planetesimal delivery (Morbidelli et al. 2000)
- Atmospheric capture in the inner disk (Ikoma et al. 2006)

PFI:
Protoplanet detection

Detect accreting young protoplanets

Objective: Detect young accreting protoplanets



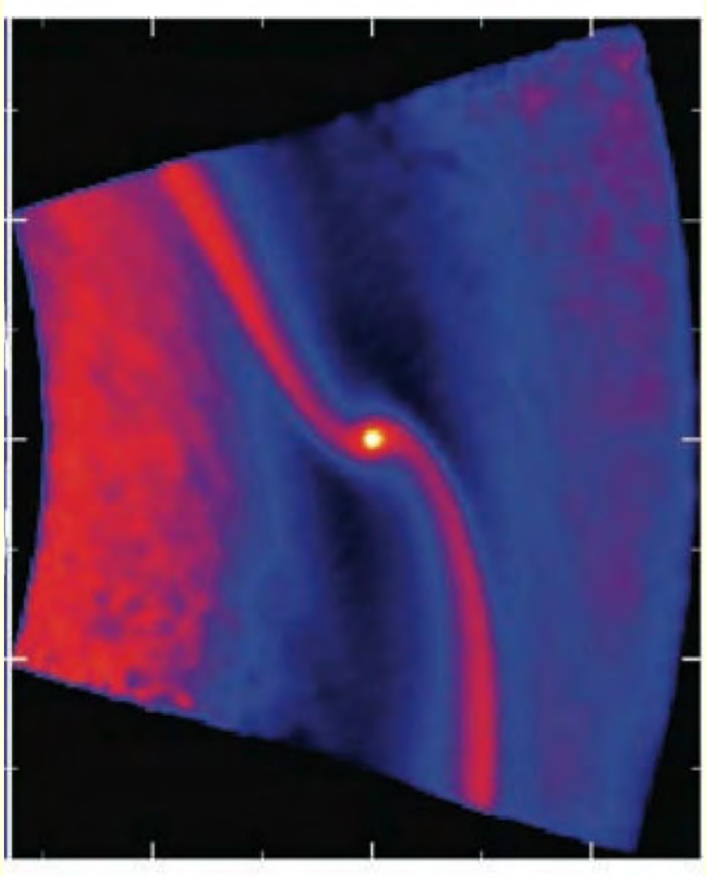


Kraus et al. 2014, Forney et al. 2008

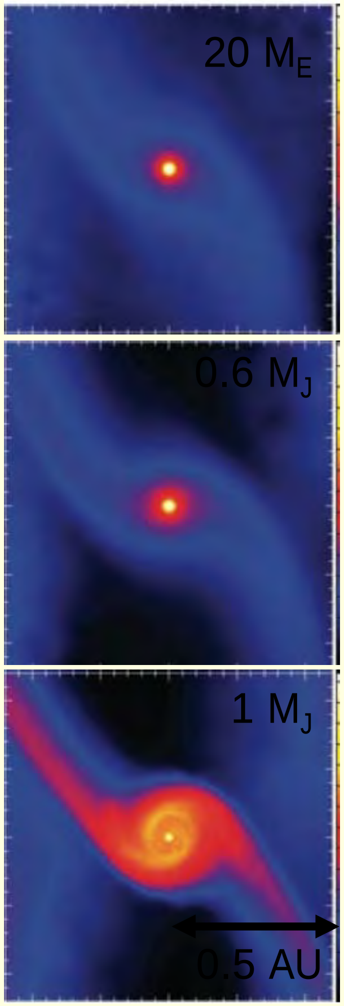
Kraus & Ireland 2012

- 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



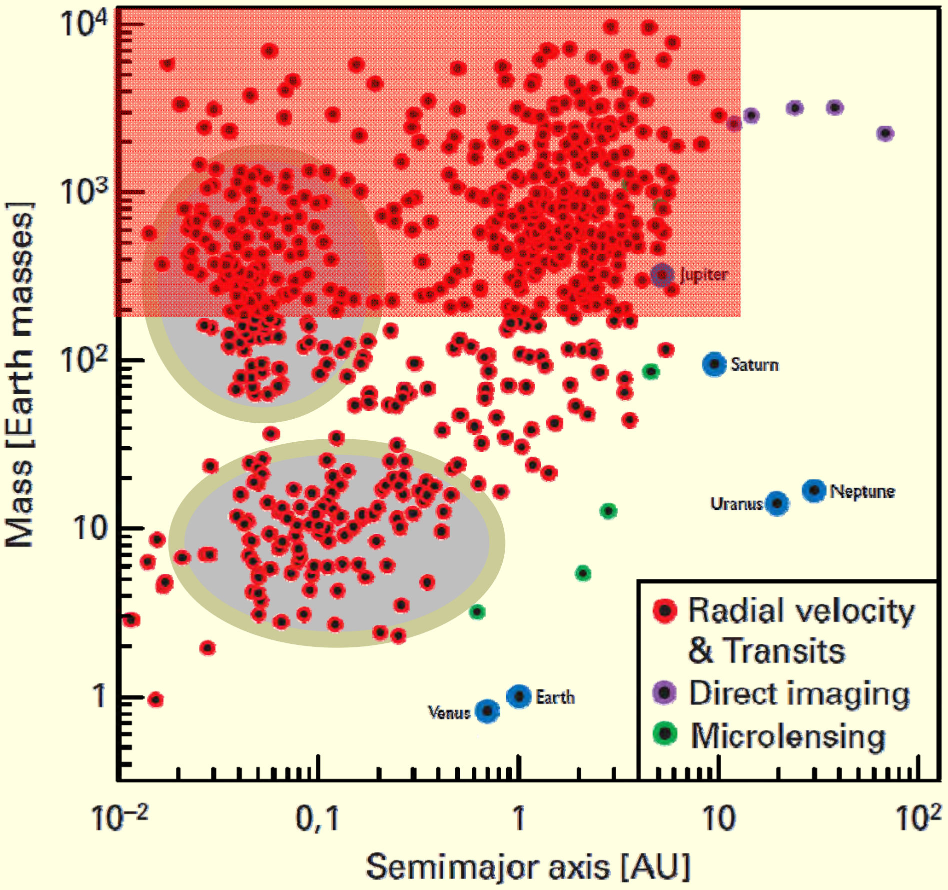
Size circumplanetary disk (0.3 R_H) for Jupiter-mass planet
at r=5.2 AU: 0.11 AU = 0.79 mas @ 140 pc
at r=1 AU: 0.02 AU = 0.14 mas @ 140 pc

PFI:
Architecture of planetary systems

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



PFI:
Technology architectures under investigation

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

- NIR/MIR Conventional Direct Detection Interferometer
- MIR Heterodyne Interferometer
- MIR/FIR Space Interferometer
- ALMA ++
- Coronagraph, Occulter

Architecture 1: Conventional ground-based interferometer design

- 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: 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, Nmag= -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
  - 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 Science Working Group (SWG)

Develops and prioritizes key achievable science cases
Lead by PFI Project Scientist: Stefan Kraus

About 100 scientist investigate 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**

The PFI Technical Working Group (TWG)

Identifies the key technologies and develops a technology roadmap
Lead by PFI Project Architect: David Buscher

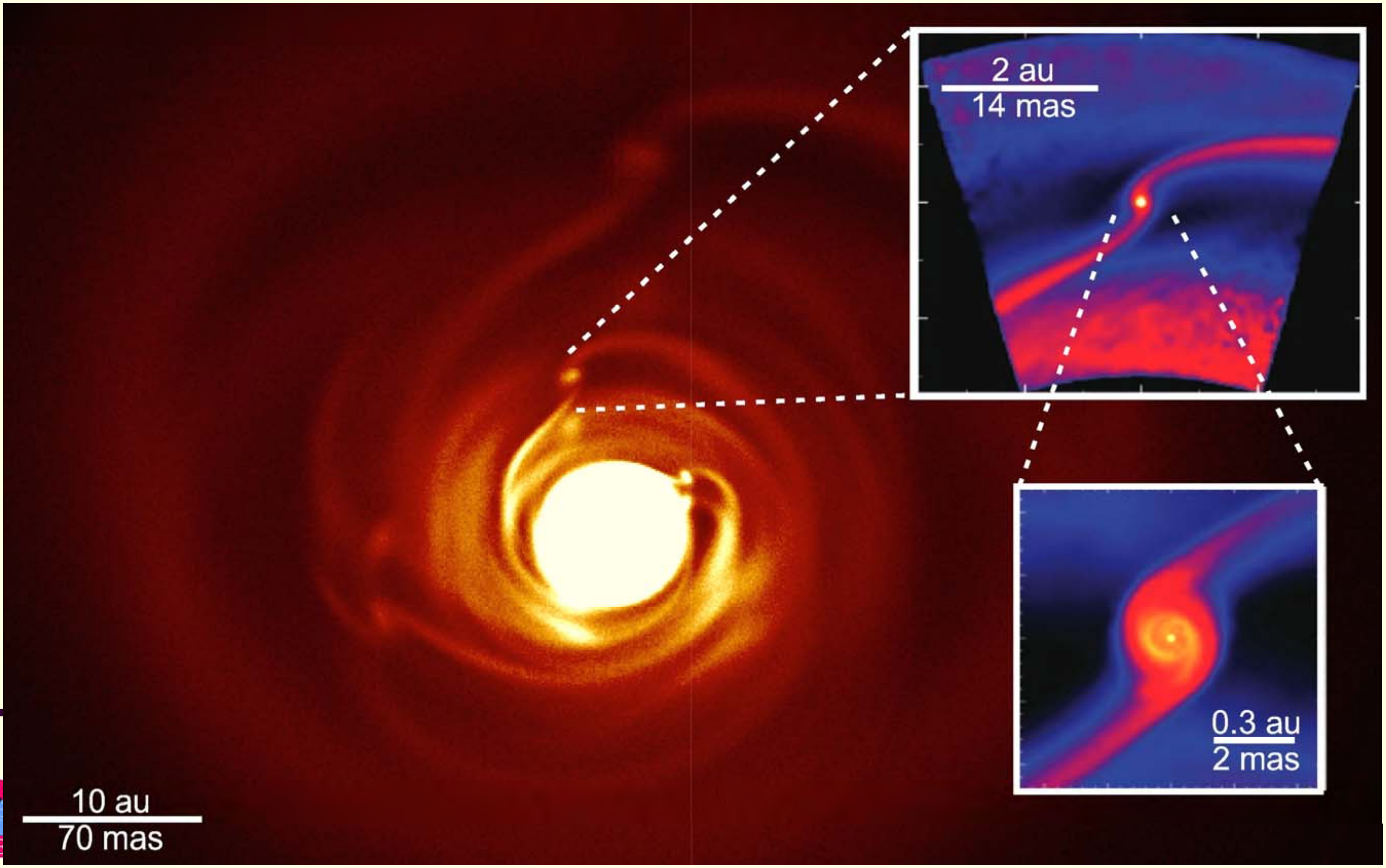
Concept architectures:

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

Planet Formation Imager (PFI) Concept Studies



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