The Planet Formation Imager (PFI) – Mid IR Frequency Combs for Heterodyne (Astronomical) Interferometry

Gautam Vasisht
Jet Propulsion Laboratory
Credit: Stefan Kraus (For partial talk)

<u>PFI project collaborators:</u>

Executive team: John Monnier, Stefan Kraus, David Buscher, Mike Ireland

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

KISS workshop
November 2, 2015

*“Werke der Natur [...] lernt man nicht kennen
wenn sie fertig sind; man muss sie im Entstehen aufhaschen,
um sie einigermassen zu begreifen.”*

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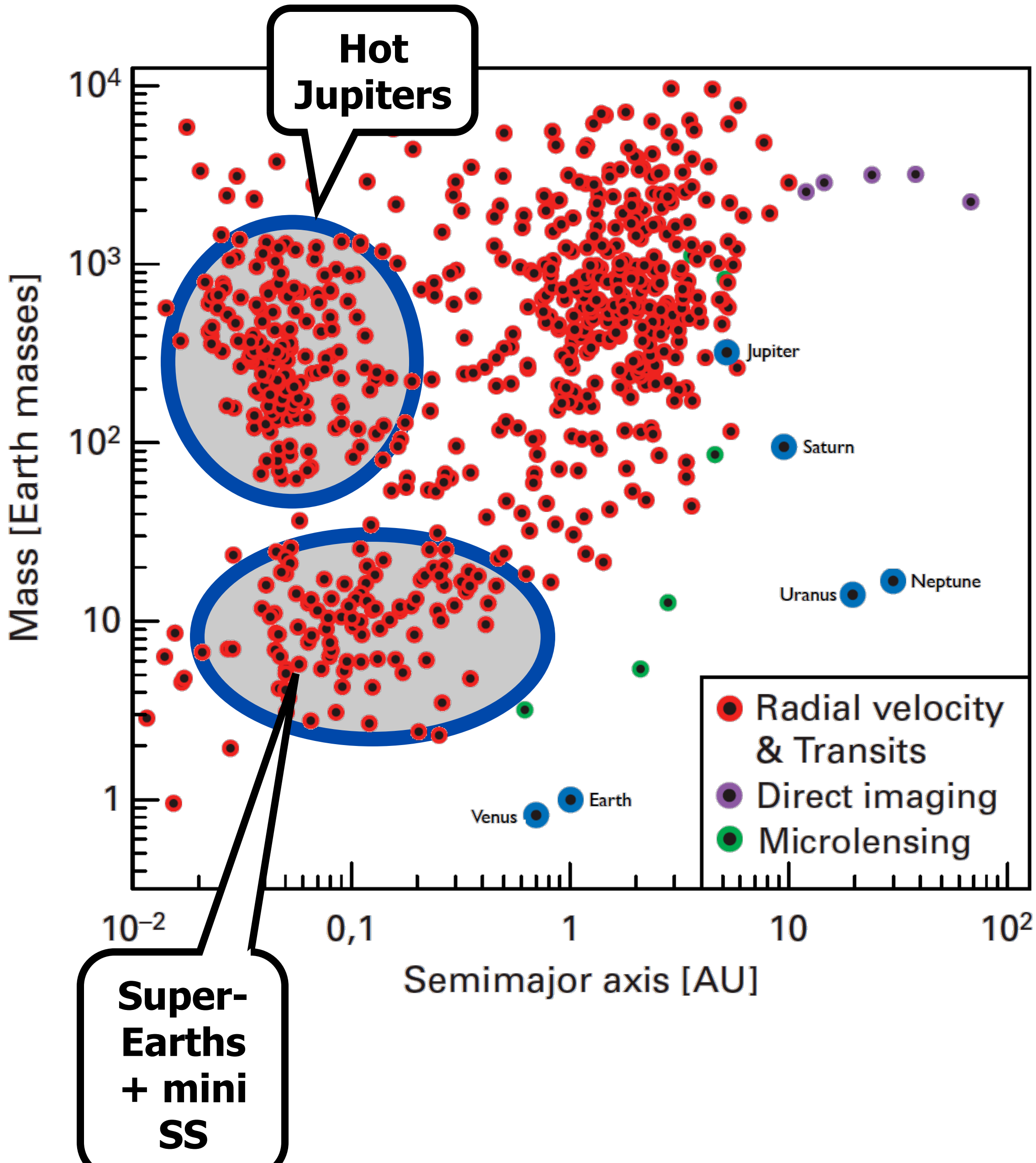
*"You can't get to know the works [...] of nature
when they have been finished;
you must grasp of them while they are coming into being
in order to gain any degree of understanding of them.”*

J.W. von Goethe, 1803

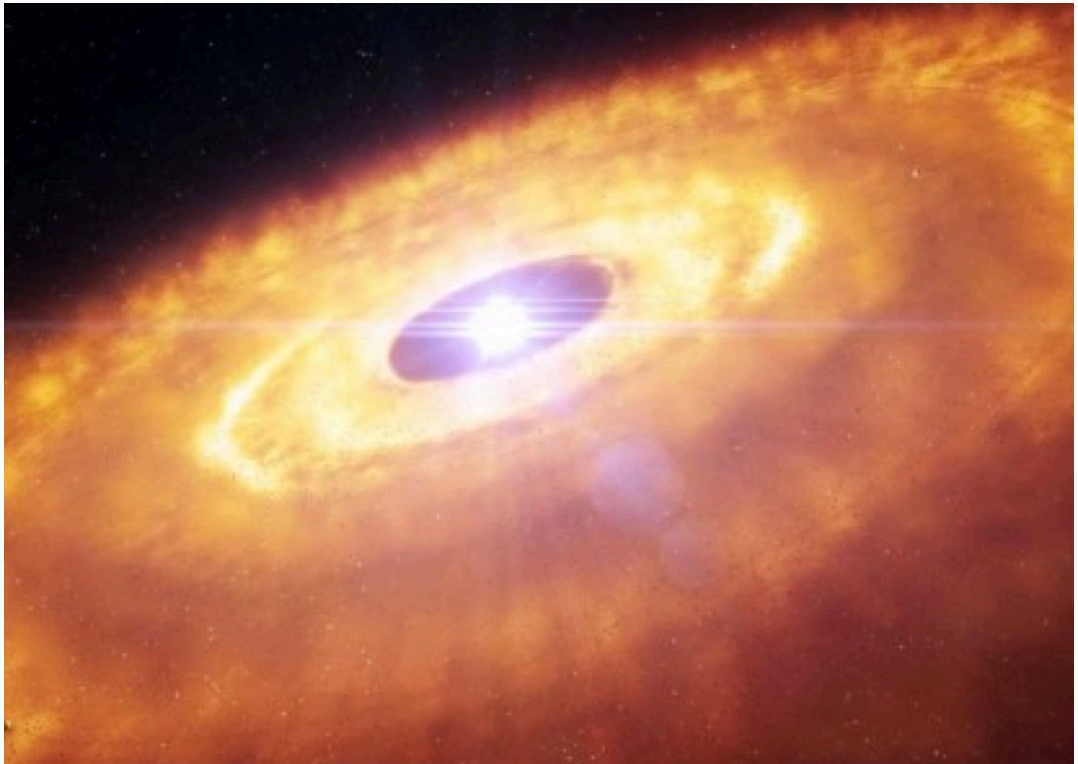
Exoplanetary systems



Exoplanetary systems show surprising diversity

Mordasini et al. 2014

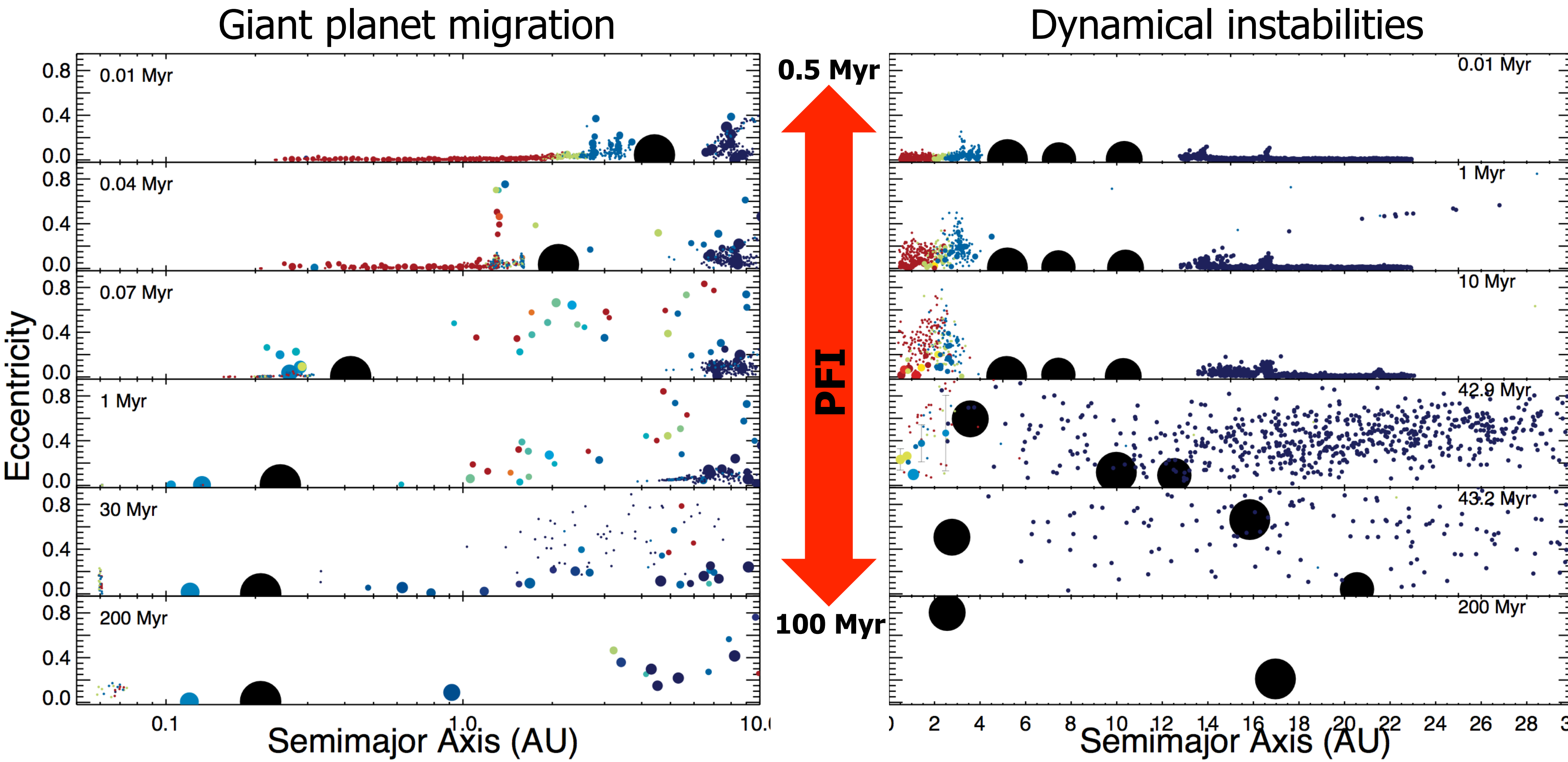
Exoplanetary systems: Formation



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
- …

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:

- One of the most exciting fields in astronomy, connecting star formation with exoplanets
- Strong momentum in the field, poised with advances with ALMA, GPI/SPHERE, ELTs, …

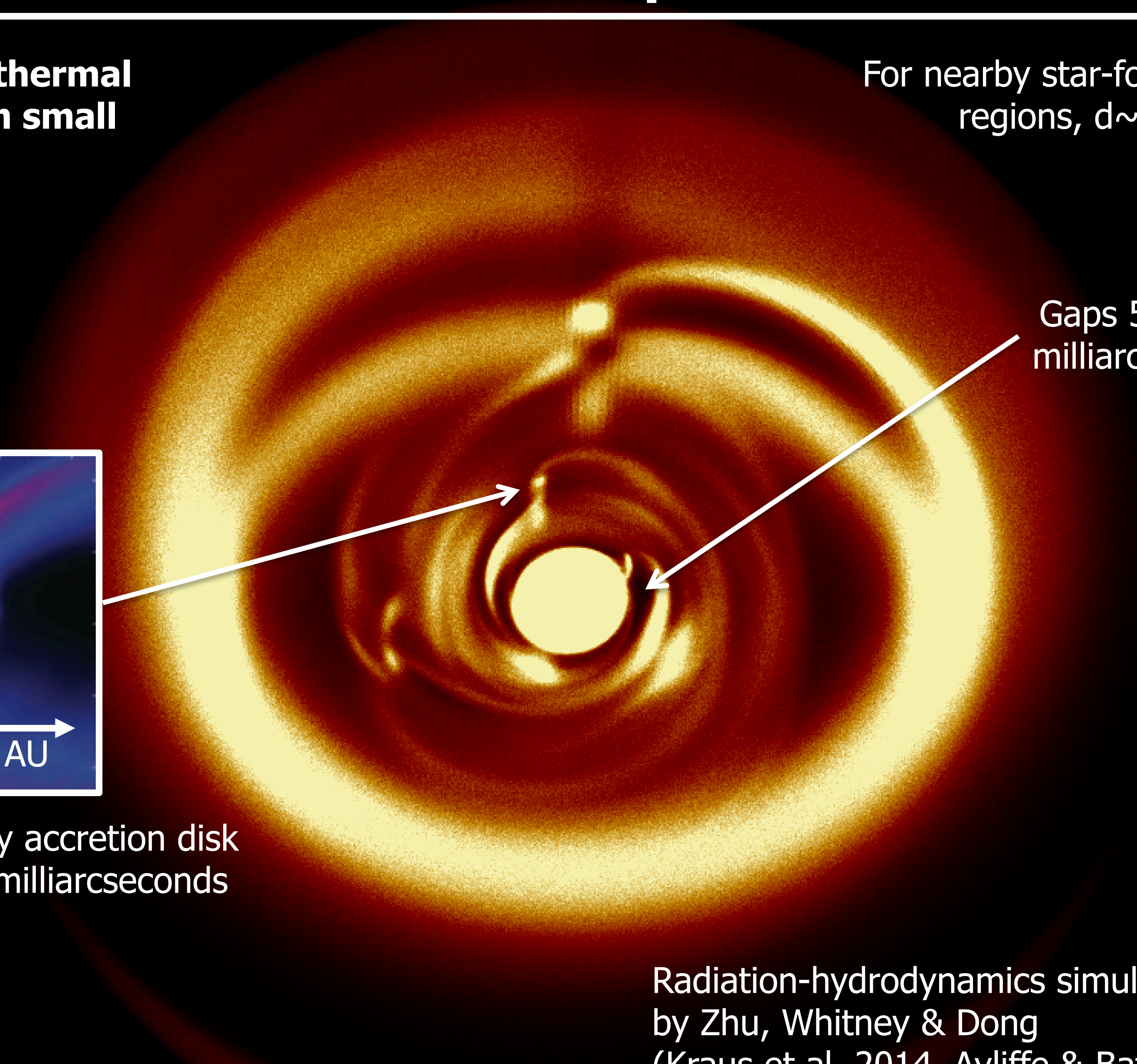
We expect complexity beyond what ALMA and single apertures can ever resolve

➔ **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, …)

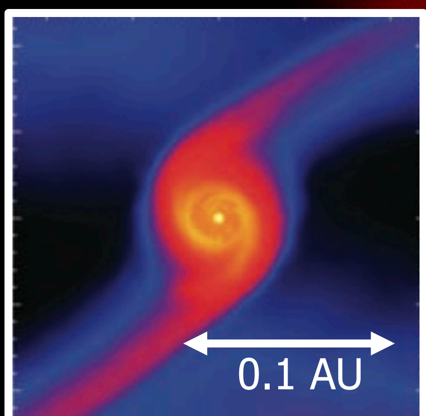
What are the relevant spatial scales?

Mid-infrared thermal emission from small dust grains

For nearby star-forming regions, d~100pc



Gaps 5AU ~50 milliarcseconds



Circumplanetary accretion disk
0.03 AU = 0.2 milliarcseconds

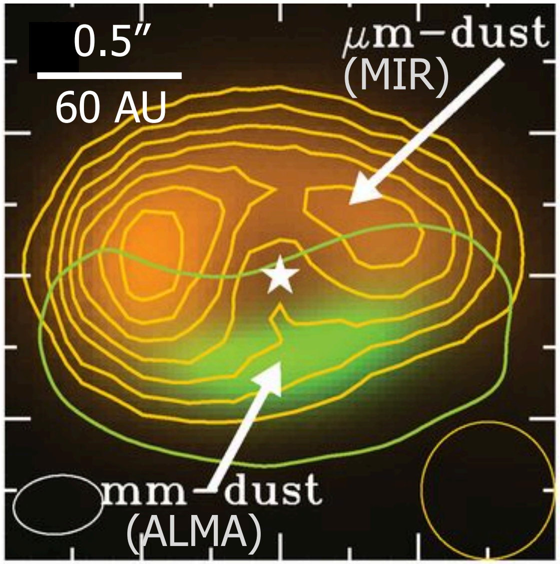
Radiation-hydrodynamics simulation by Zhu, Whitney & Dong
(Kraus et al. 2014, Ayliffe & Bate 2009)

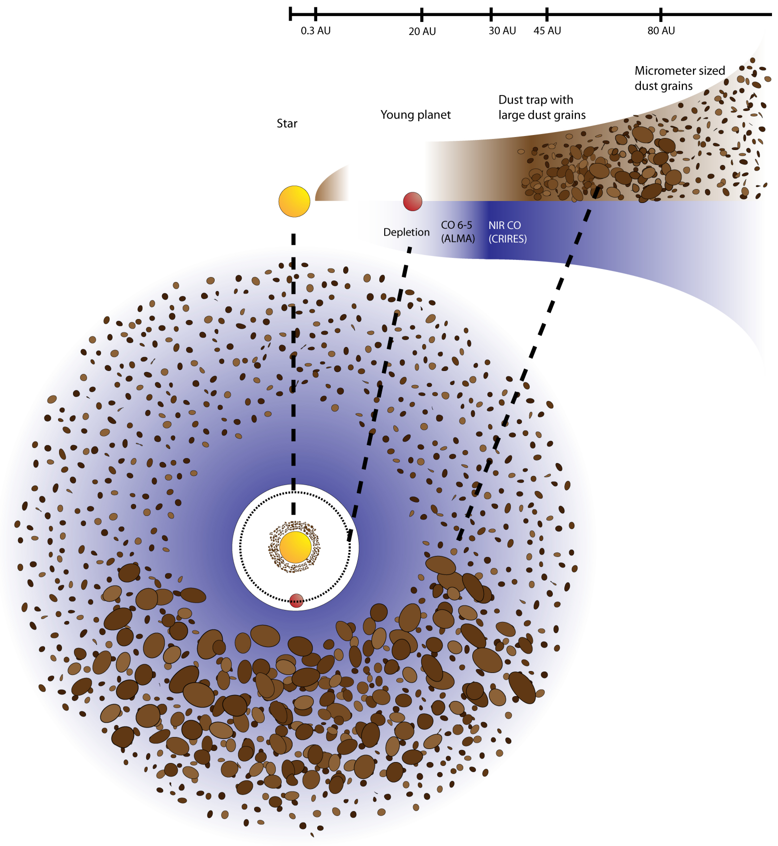
PFI+ALMA: Tracing complementary dust species

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

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

Oph IRS48



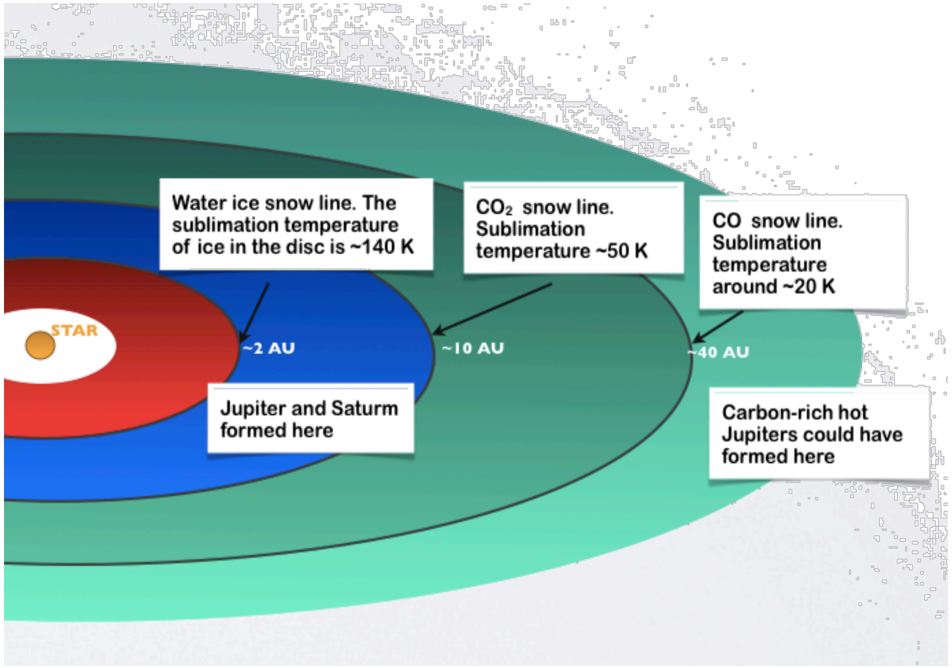


van der Marel et al. 2013

PFI+ALMA: Tracing complementary molecular lines

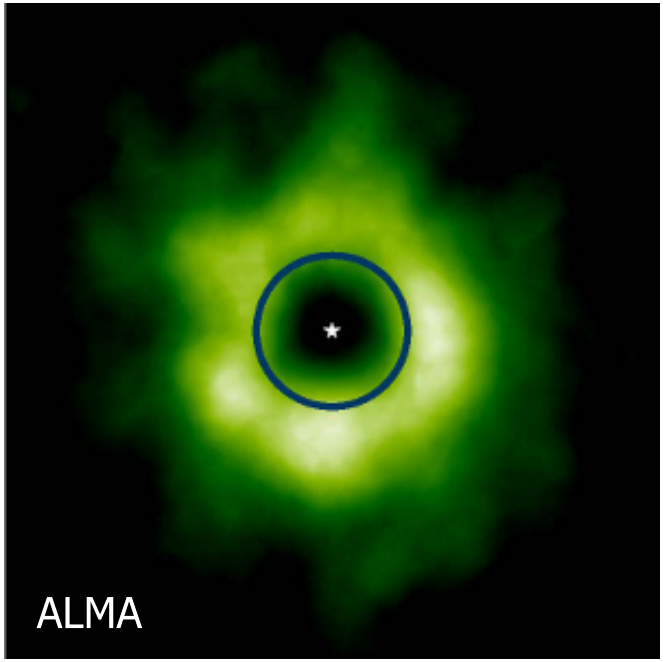
Objective: Determine distribution of water & ices

➔ link to habitability



Öberg et al.

CO snow line in TW Hya



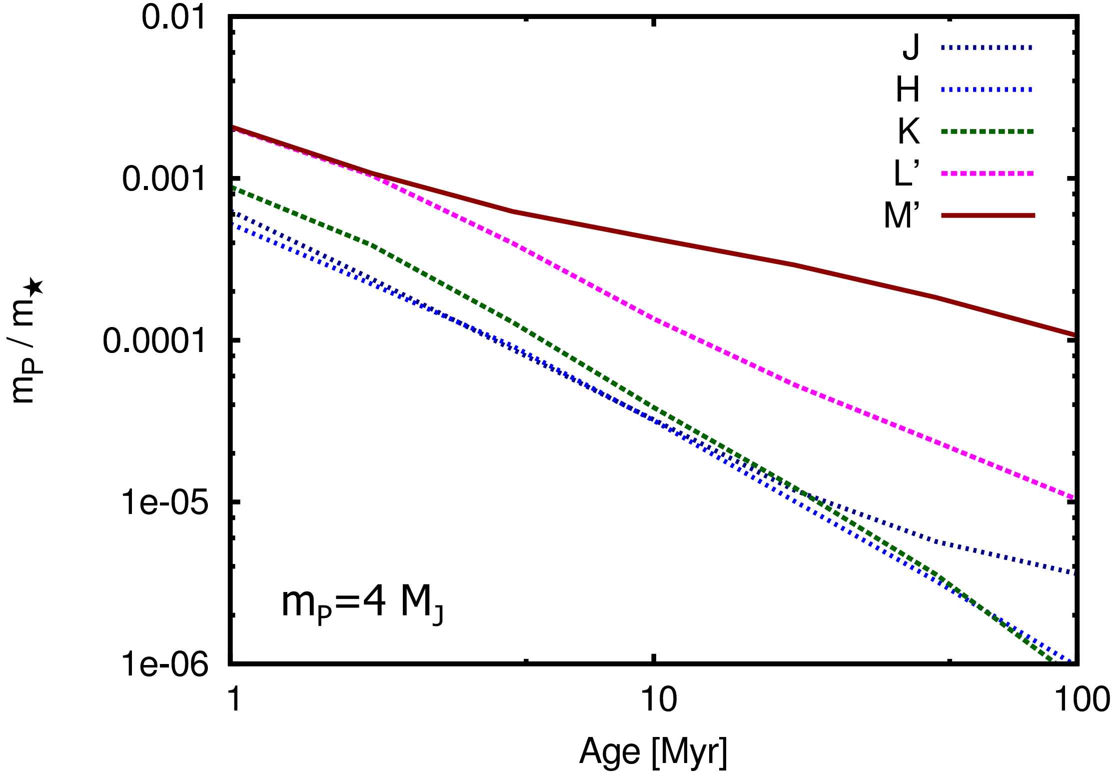
Qi et al. 2013

Water on terrestrial planets:

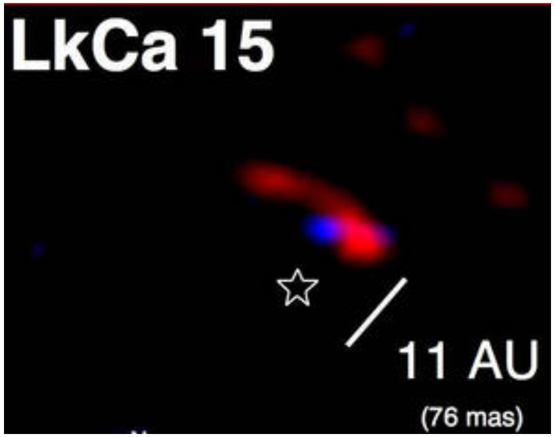
- Planetesimal delivery (Morbidelli et al. 2000)
- Atmospheric capture in the inner disk (Ikoma et al. 2006)

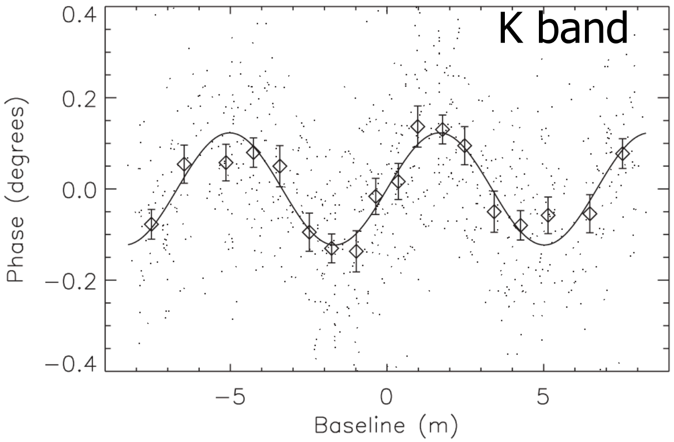
Detect accreting young protoplanets

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)

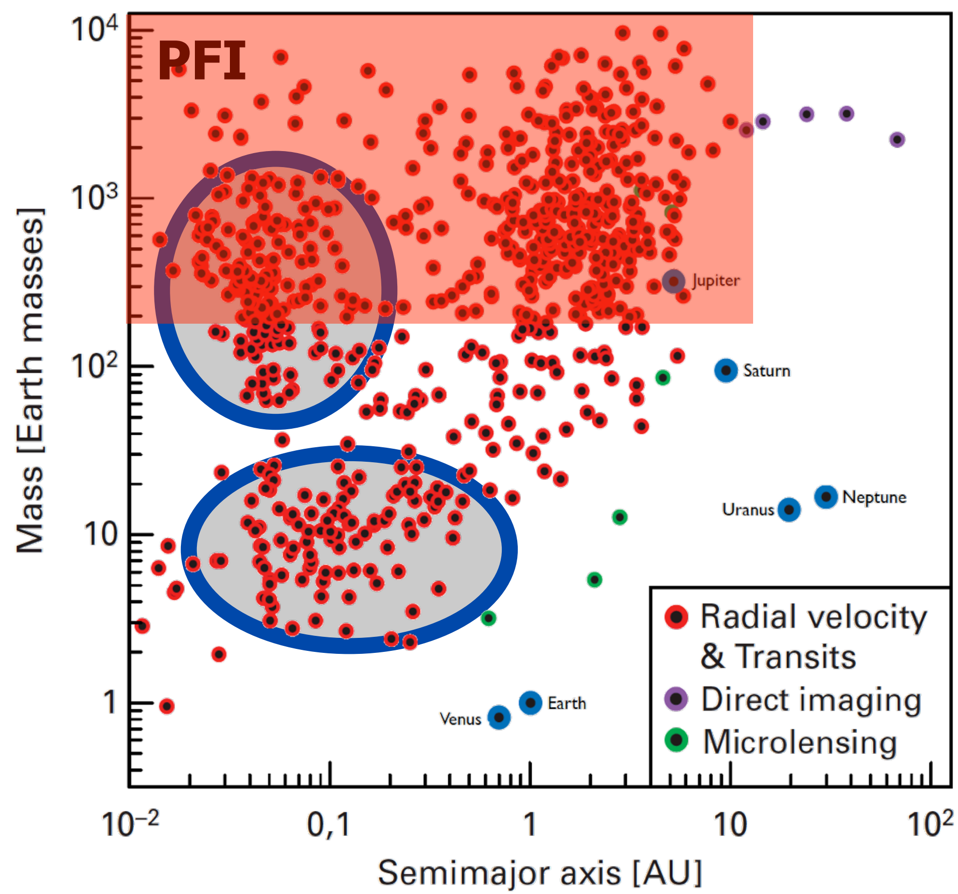
Architecture of planetary systems

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

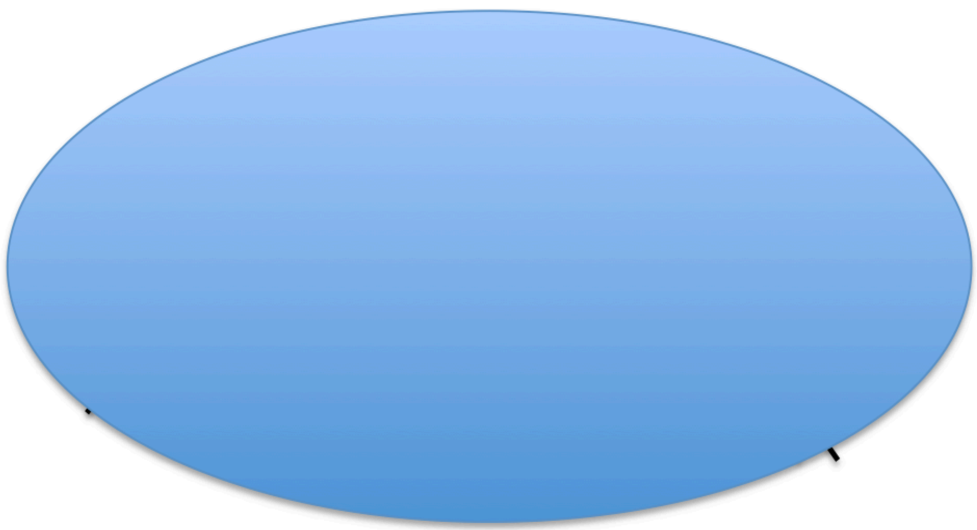


Mordasini et al. 2014

PFI:
Technology architectures under investigation

An Interferometer

- Need a very large telescope to get **Ultra-high angular** resolution
  - Technically difficult and costly to construct + hard to point

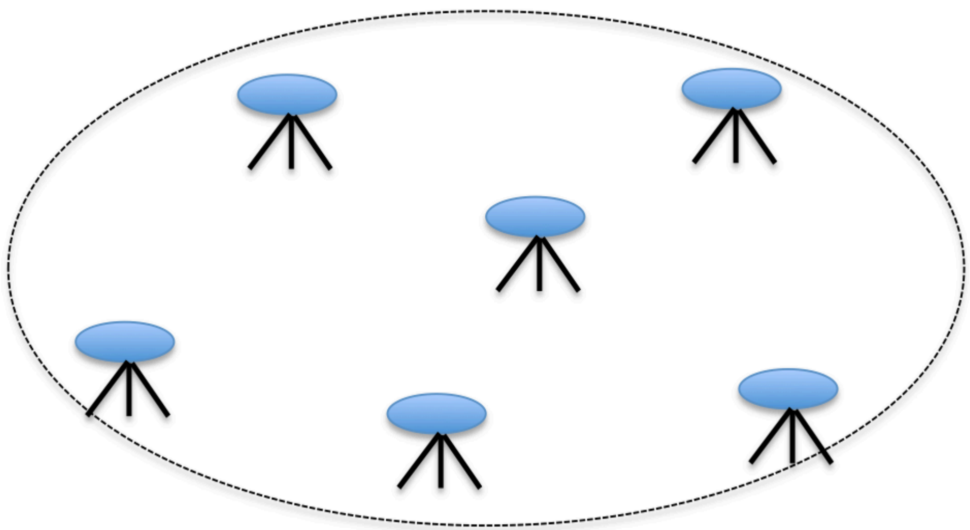


- Break the large dish into many smaller dishes!

Credit: Next few primer slides from NRAO presentation

An Interferometer

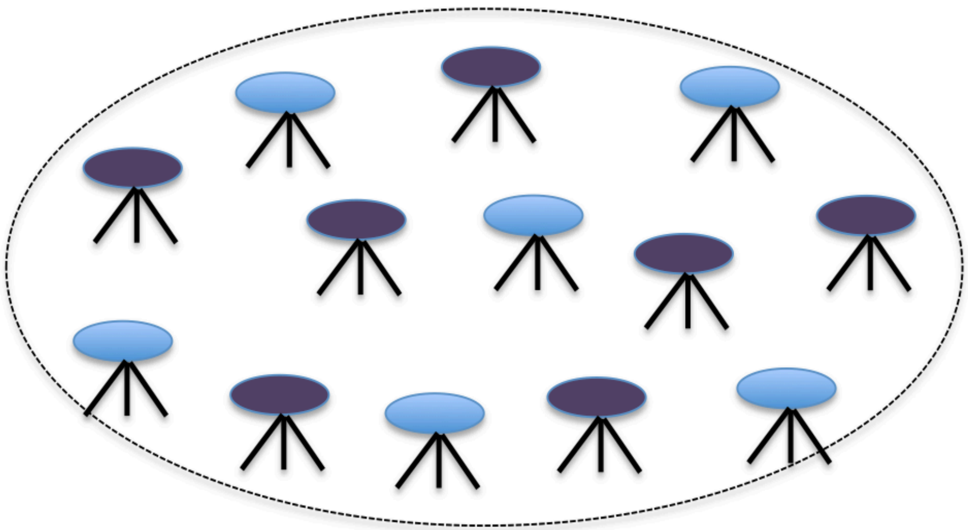
- One problem: Our telescope has holes in it!
  - Less light collecting power
  - Unfilled aperture → sensitive to only certain spatial scales!



An Interferometer

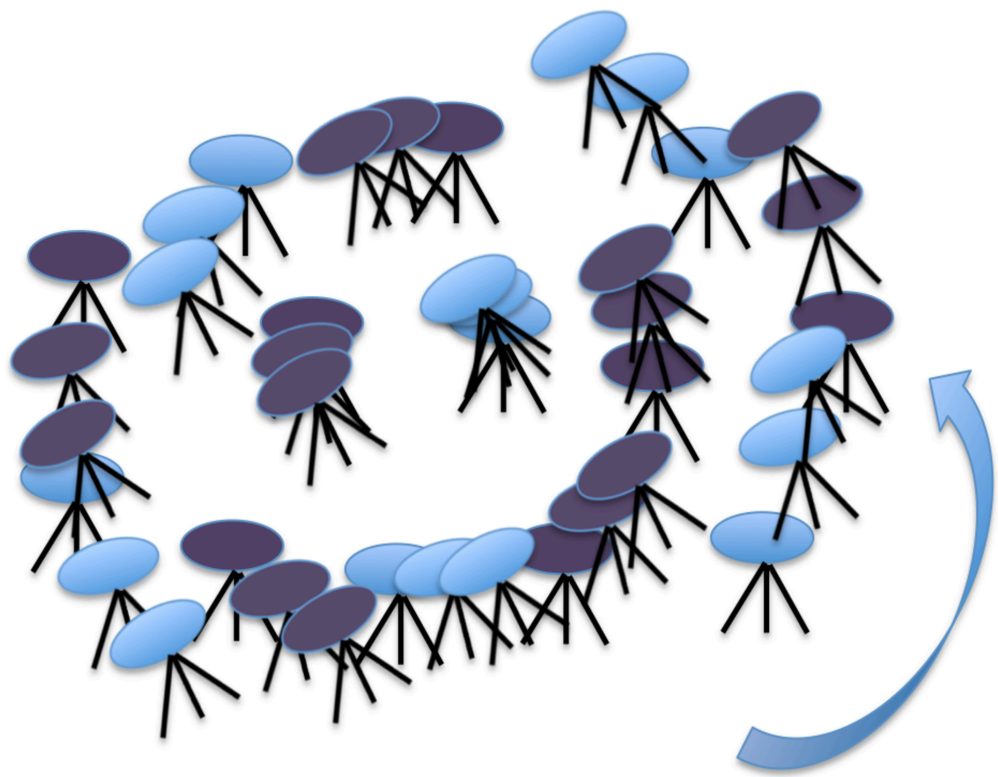
- How can we fill the aperture?

1. Add Antennas!



An Interferometer

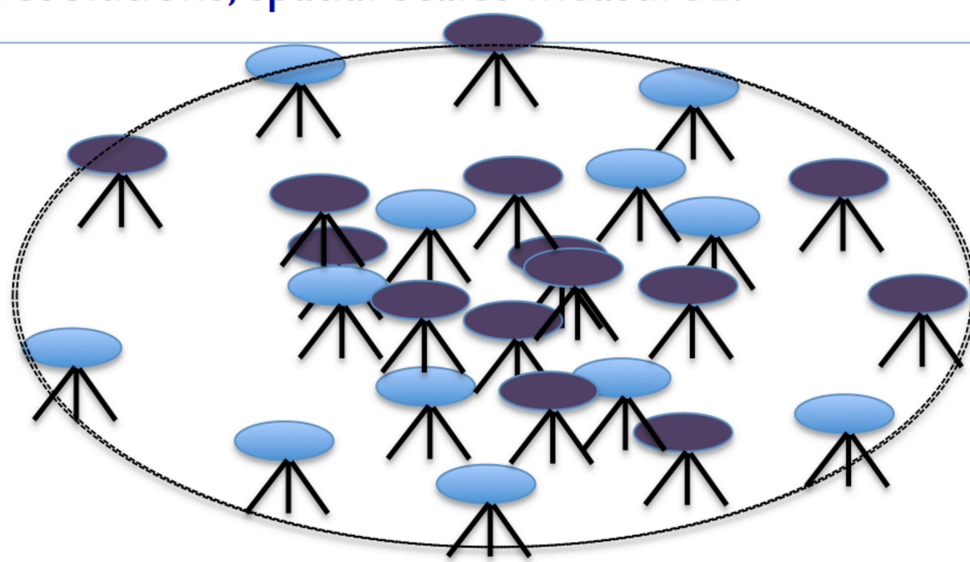
- How can we fill the aperture?



Use the rotation of the earth!

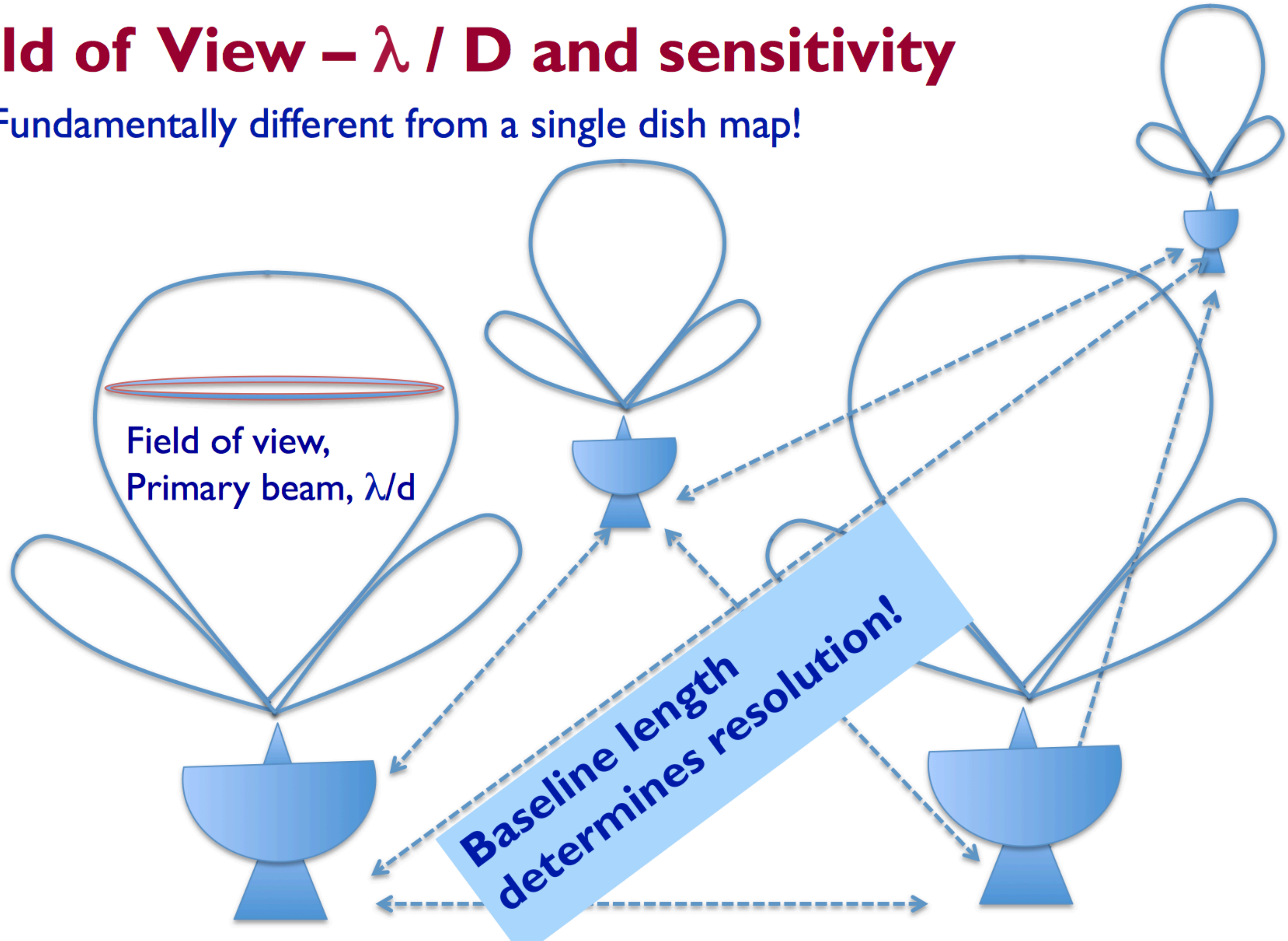
An Interferometer

- We simulate a large telescope and get better and better imaging by
  1. Adding antennas (usually fixed once construction is completed)
     - More baselines, more collecting area = higher sensitivity!
  2. Using earth's rotation for synthesis imaging
     - Different spatial scales due to projected baselines
  3. Moving telescopes into different configurations
     - Different resolutions, spatial scales measured!



Field of View – λ / D and sensitivity

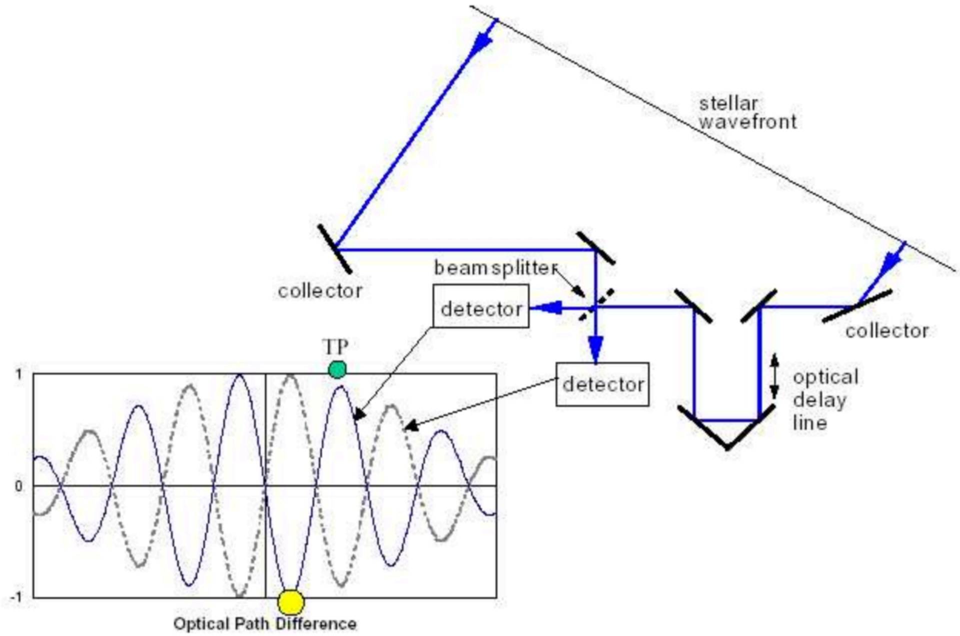
- Fundamentally different from a single dish map!

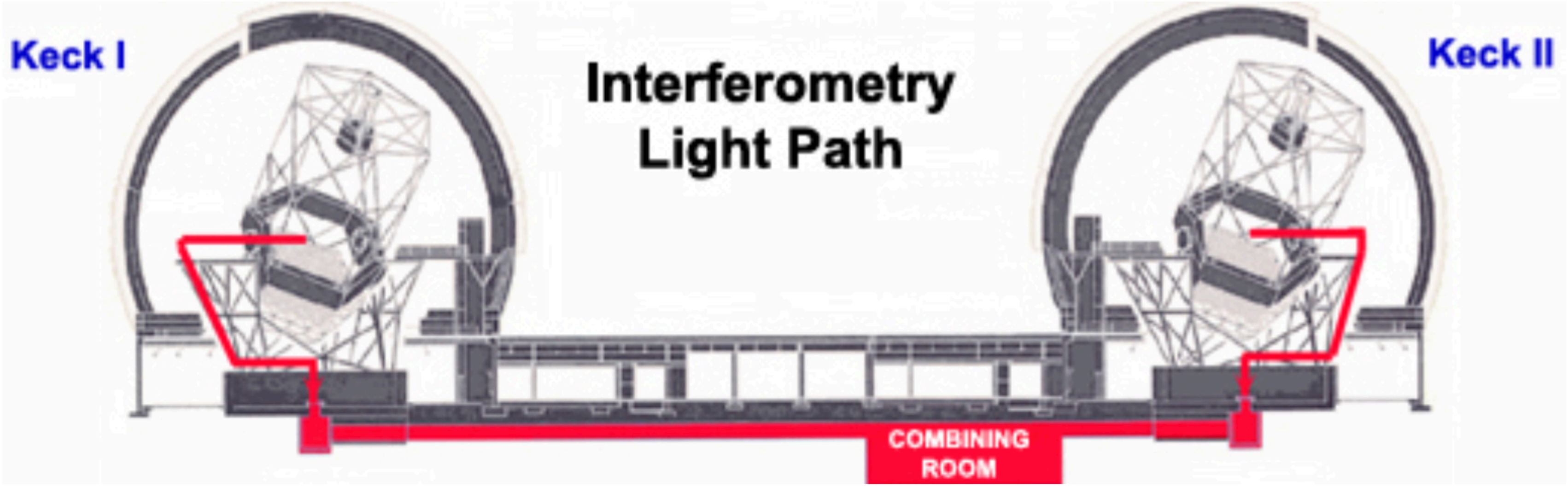


Top-Level Science Requirements (Preliminary!)

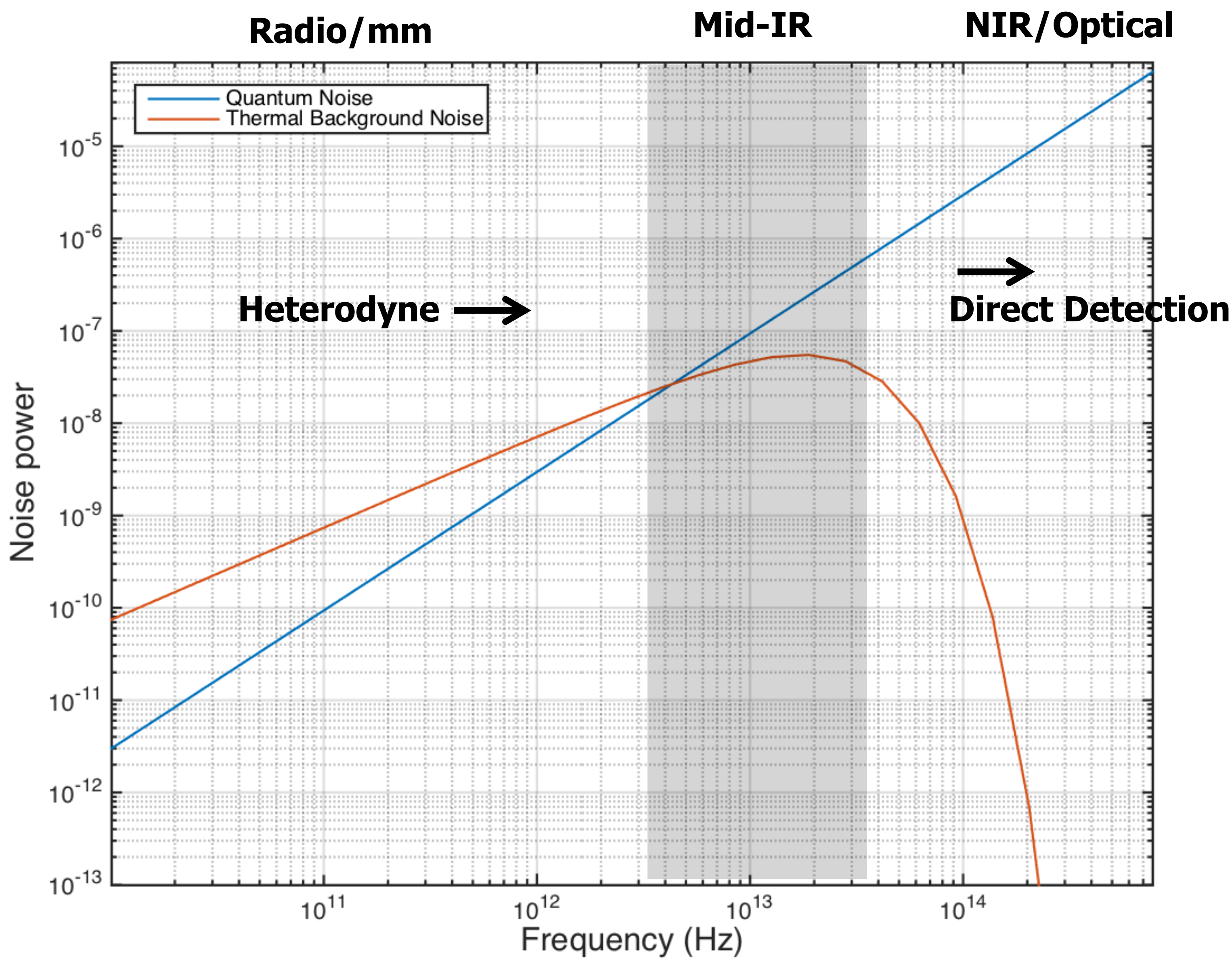
- Sensitivity to thermal emission for 300K grains ➔ **mid-IR (10 µm)**
- "Hill-sphere" size region of Jupiter at 1 AU (0.03 AU)
  in nearby star forming region (140pc)
  ➔ **0.2 milliarcseconds (~1 nanoradian)**
- 0.2 mas at 10 µm
  ➔ requires **10 km baselines**
- Sensitivity to see a circumplanetary 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**

Direct Detection Interferometer: Used commonly > 10^{13} Hz

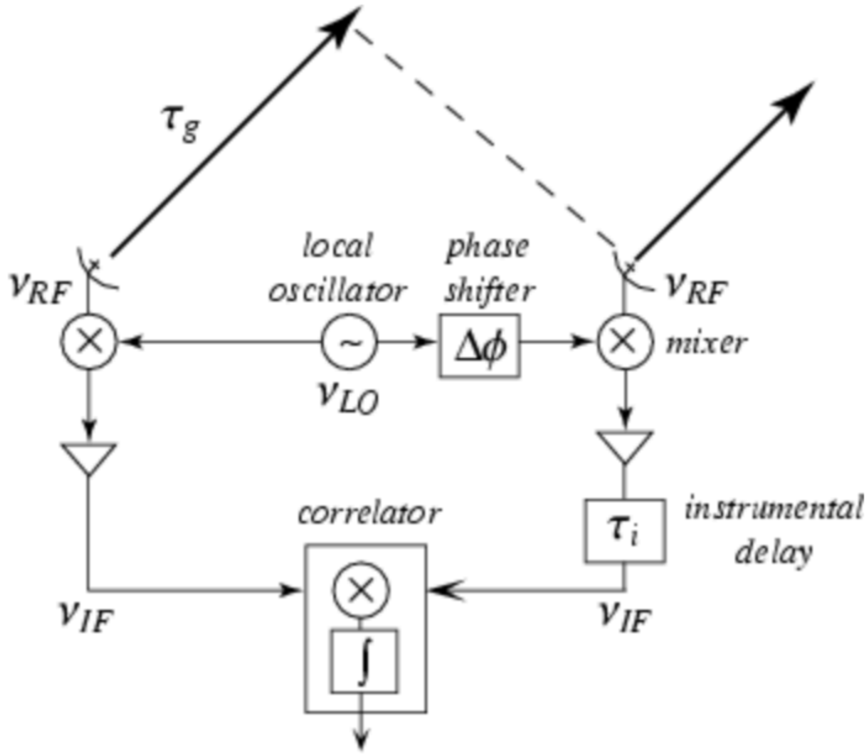




Magdalena Ridge Observatory (MROI)


Radio/mm
Mid-IR
NIR/Optical
Quantum Noise
Thermal Background Noise
Heterodyne
Direct Detection
Noise power
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{11}
10^{12}
10^{13}
10^{14}
Frequency (Hz)

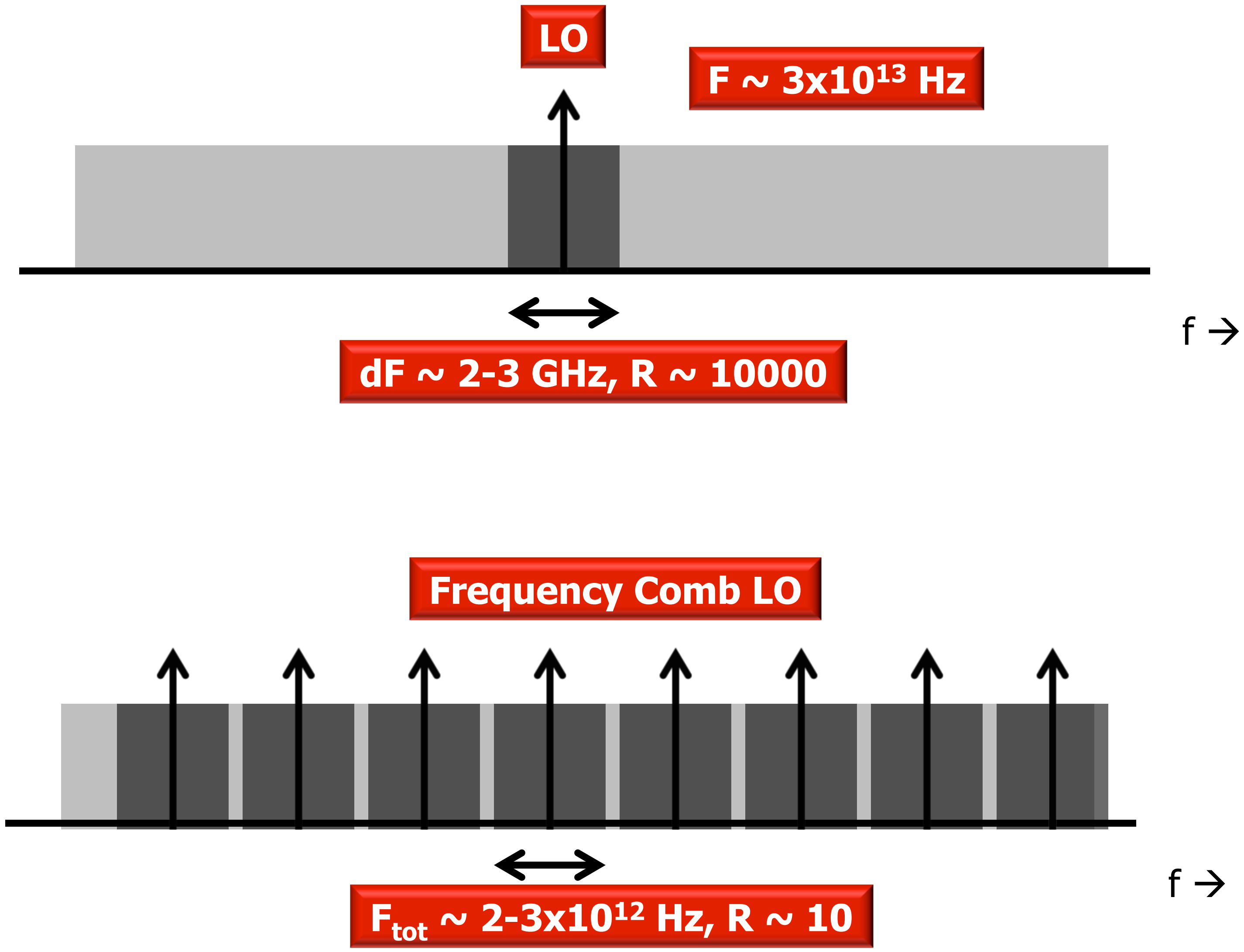
Heterodyne Interferometer: Used commonly at radio



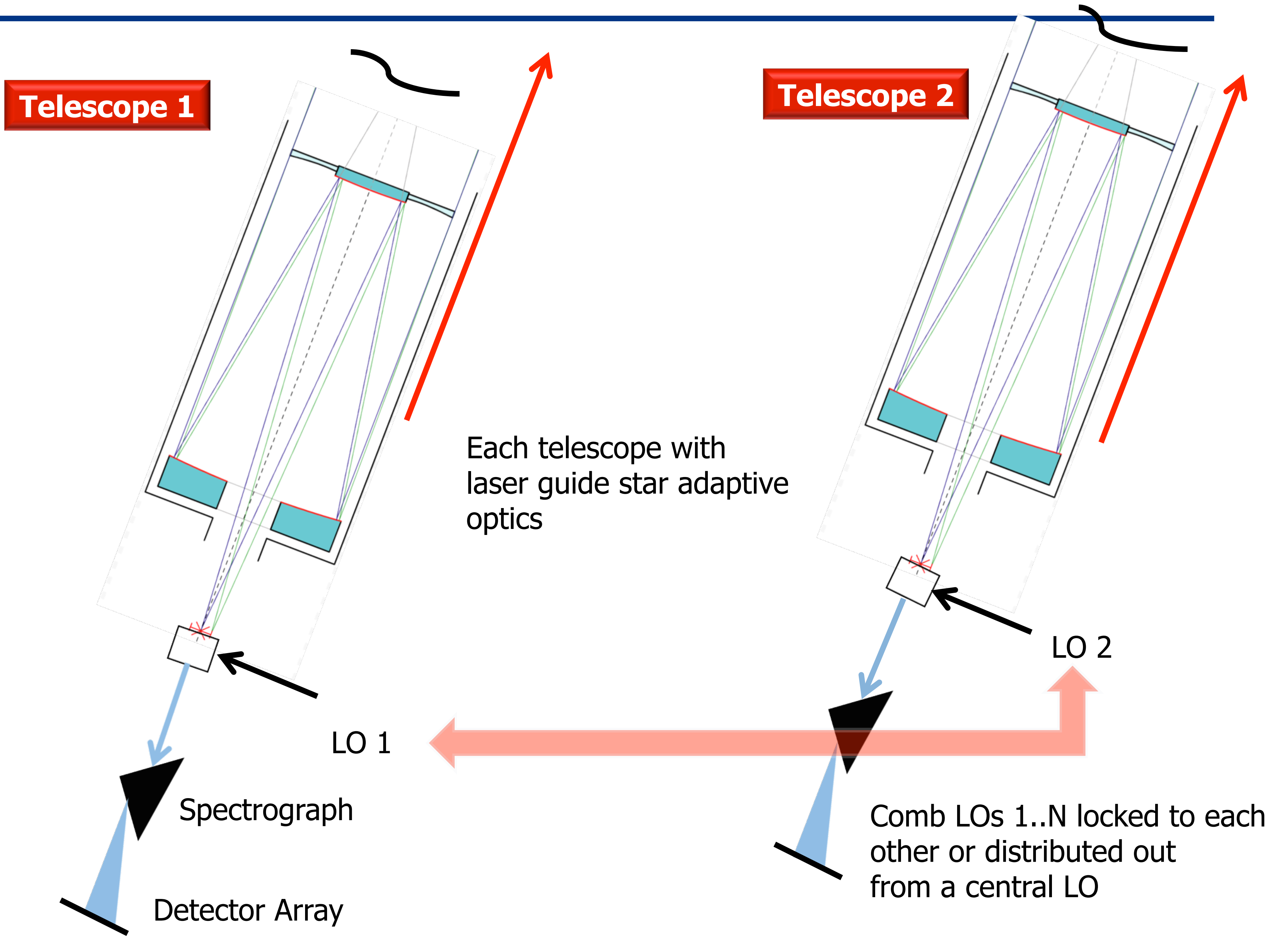
Use local oscillator at each station

Berkeley ISI Interferometer: IR Heterodyne Interferometer

Heterodyne Receiver: Single laser line vs. Comb LO



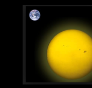
Direct Detection Interferometer: Used commonly > 10^{13} Hz

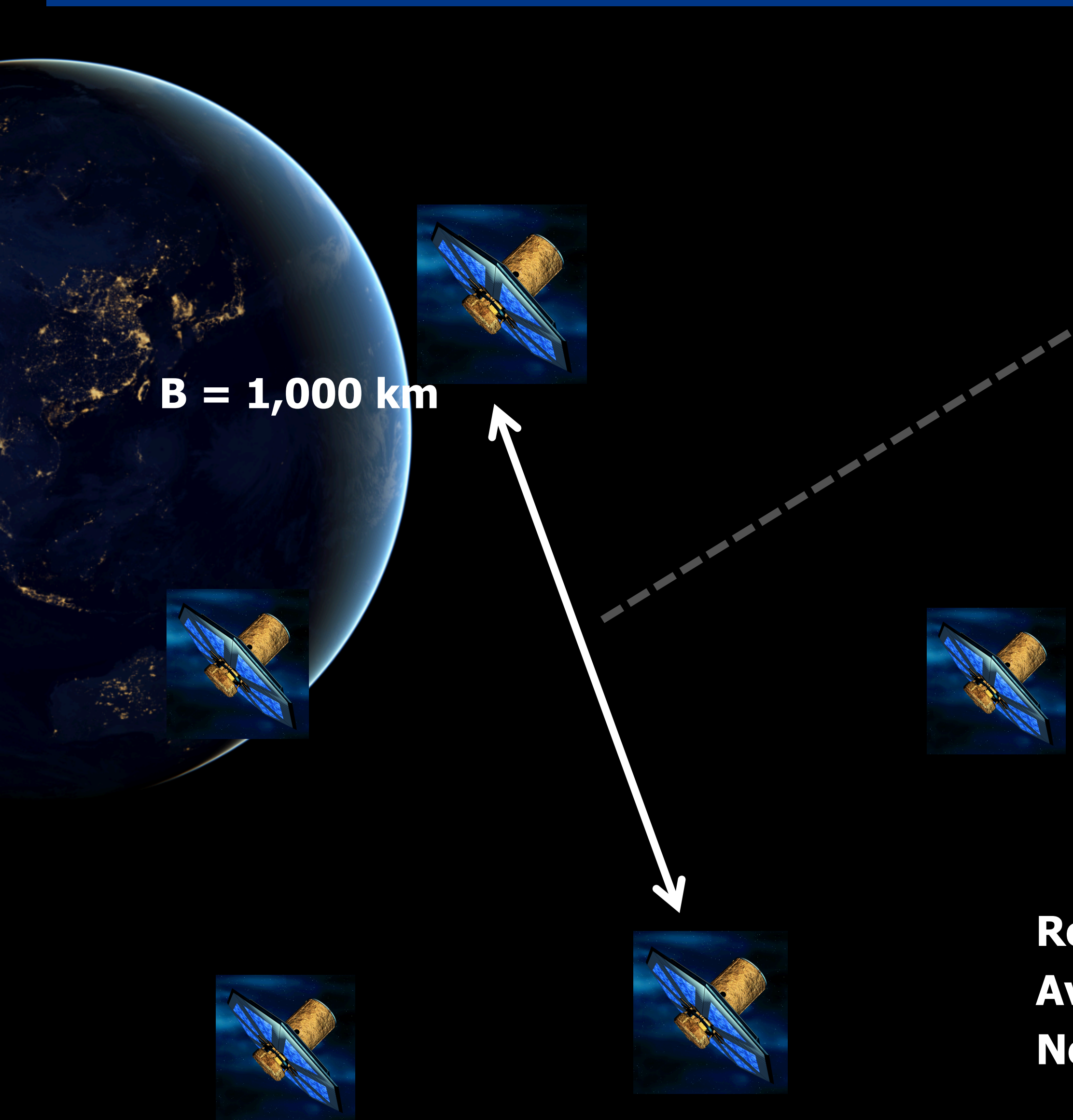


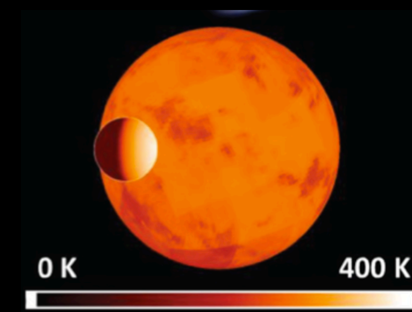
Architecture 2: Heterodyne Interferometry Review

- Charlie Townes' Infrared Spatial Interferometer (ISI) is a mid-IR interferometer
  - Limiting magnitude 500 Jy
  - BUT… this is largely due to tiny ISI bandwidth ($\lambda/\Delta\lambda$ = 10,000)
- Dispersing the light and mixing it with Laser Frequency Combs allows to create thousands of ISI bandwidths ➔ $\mathrm{SNR} \propto \sqrt{N}$
- Advantages
  - Higher throughput to detection
  - Ideal beam combination 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
- Needs 30+ 2-4 m class telescopes

Resolving Exo-Earth Disks at 10 pc





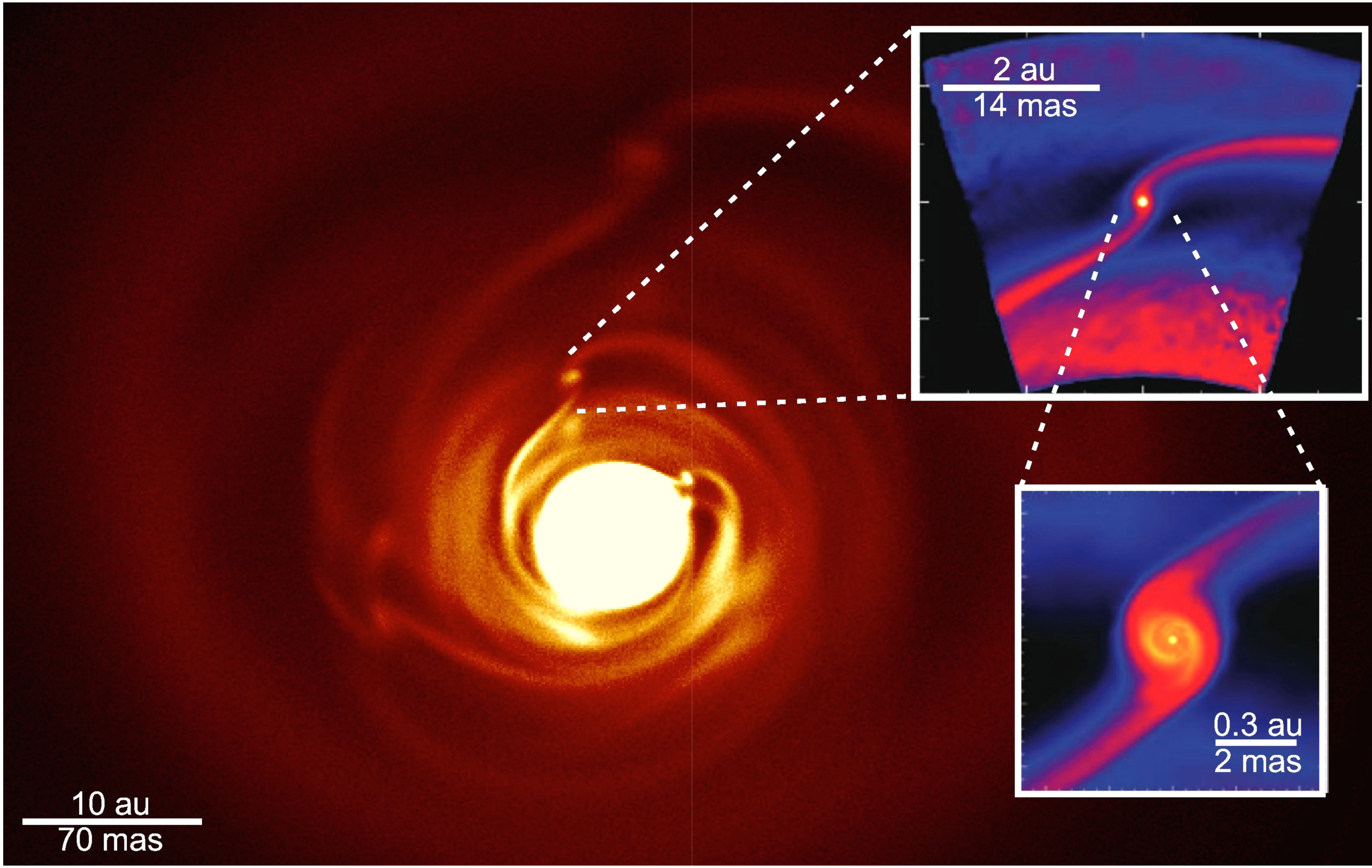


Model thermal
Image of Earth-Moon

Room Temperature ~10 m telescopes
Average surface quality
No special formation flying needed

Interlocked 10-20 micron comb laser LOs

Planet Formation Imager (PFI) Concept Studies

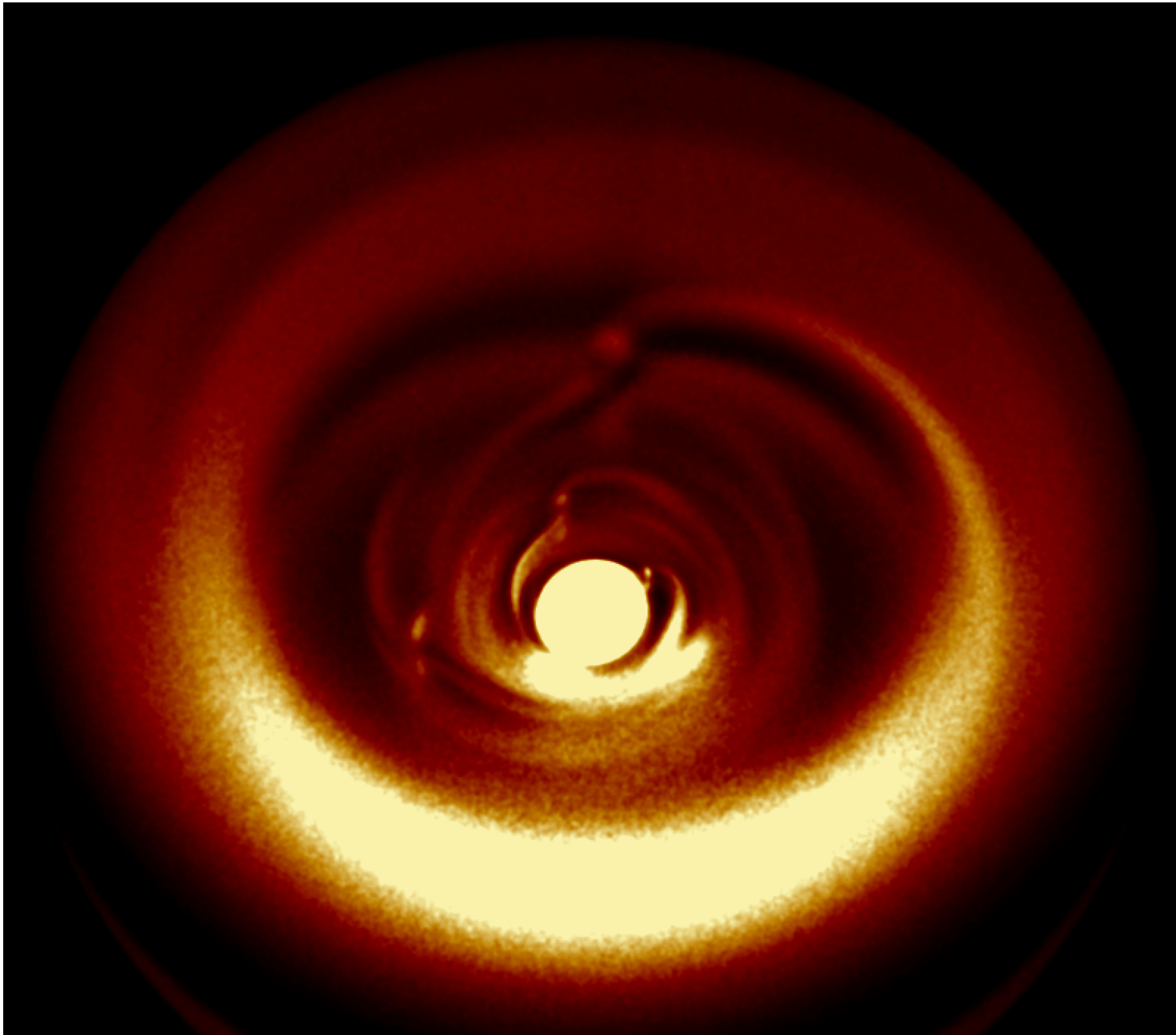


Learn more and join us at: **www.planetformationimager.org**
(Series of SPIE papers can be found in “Resources” section)

Back up material

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

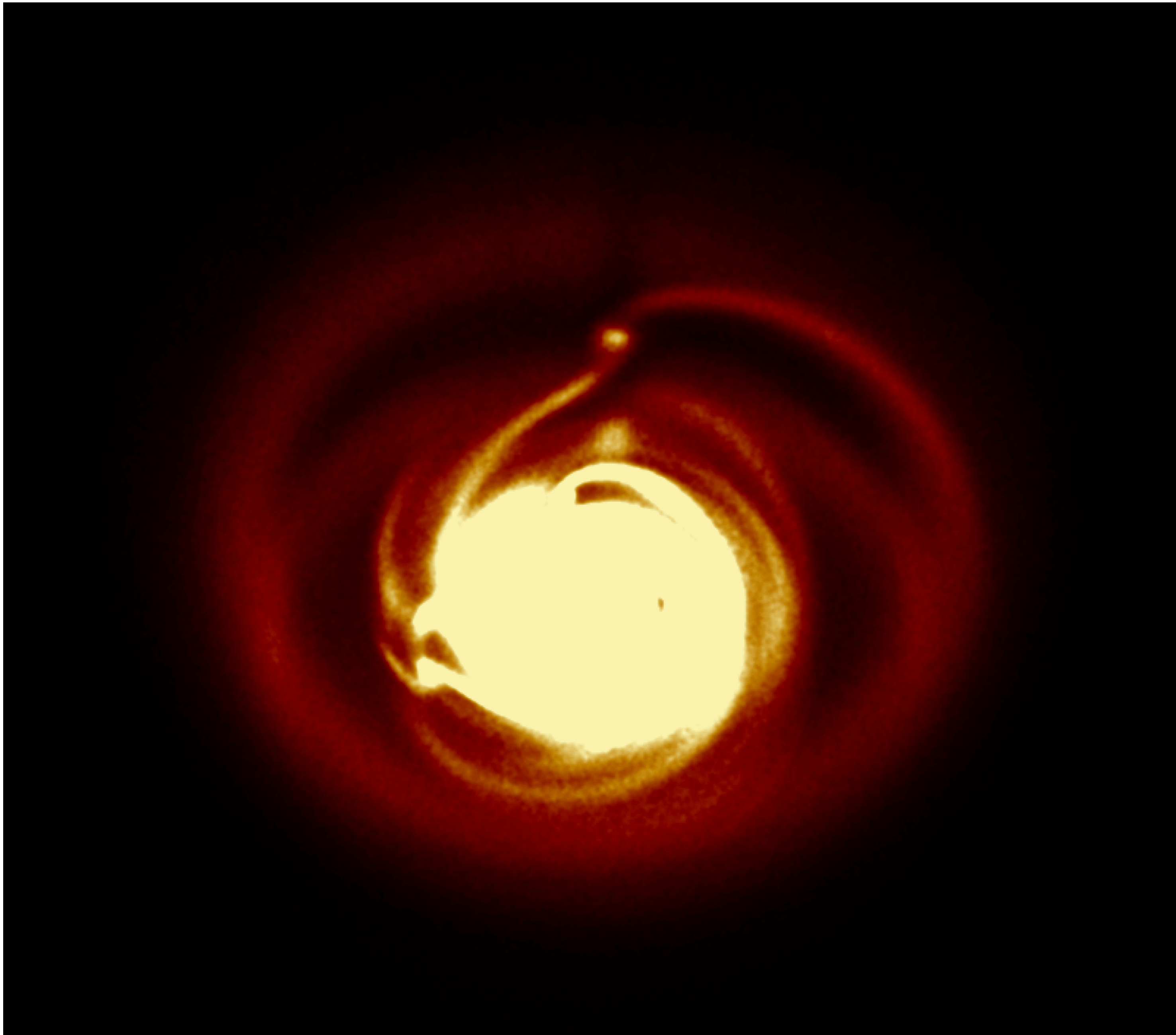
Radiation hydrodynamics simulations

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

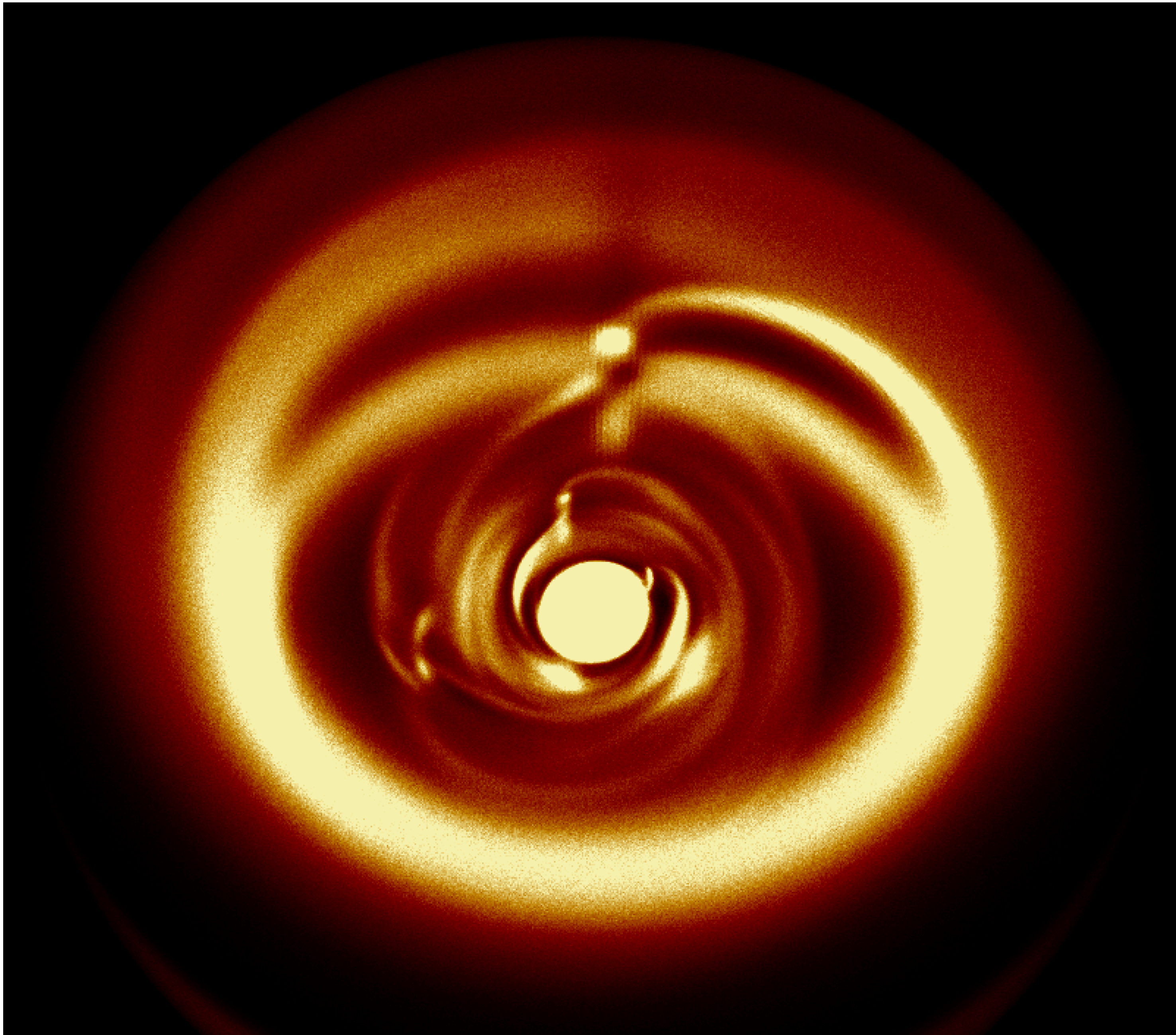
24μm
(Q-band)

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

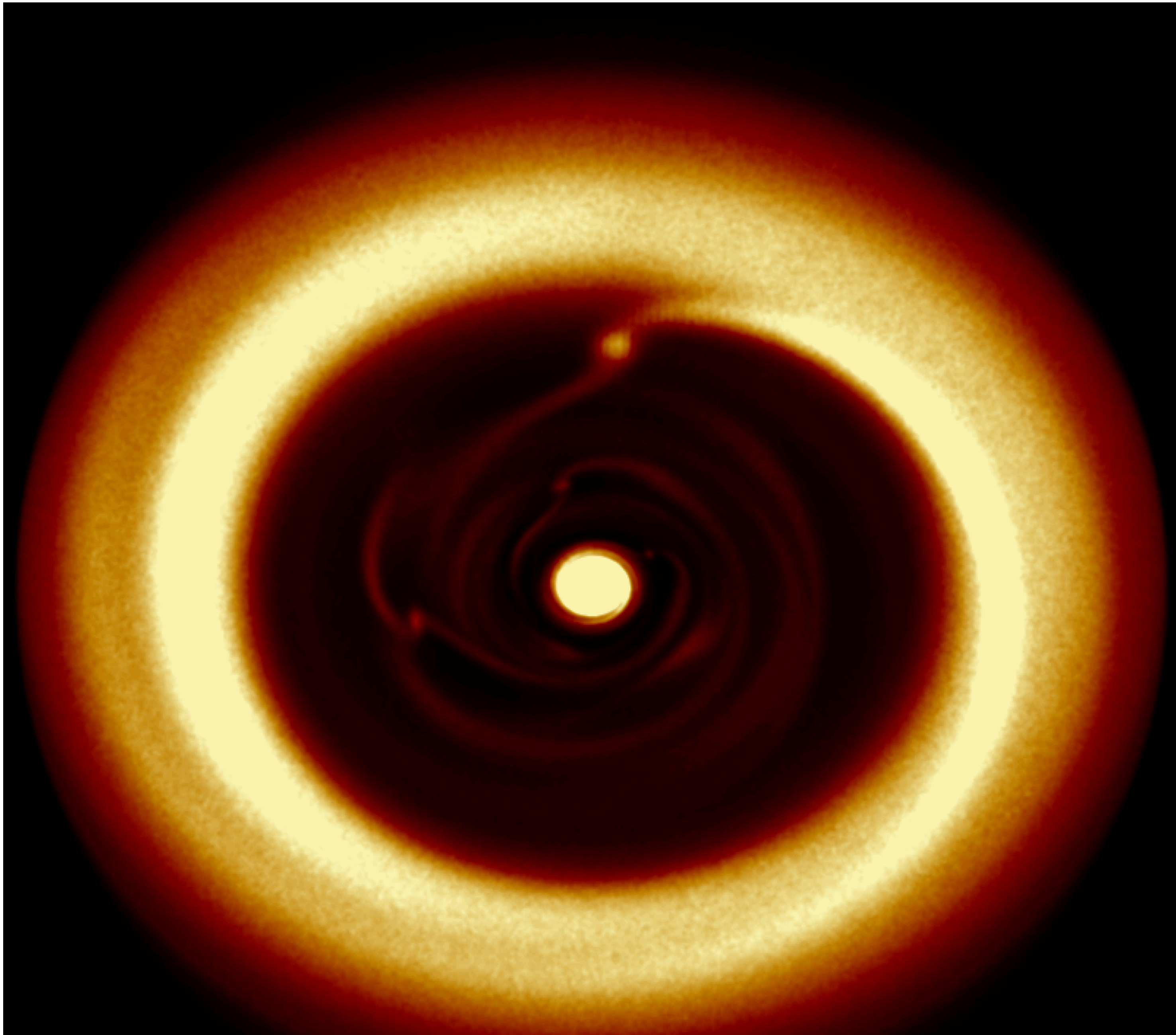
100μm
(FIR, space)

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,
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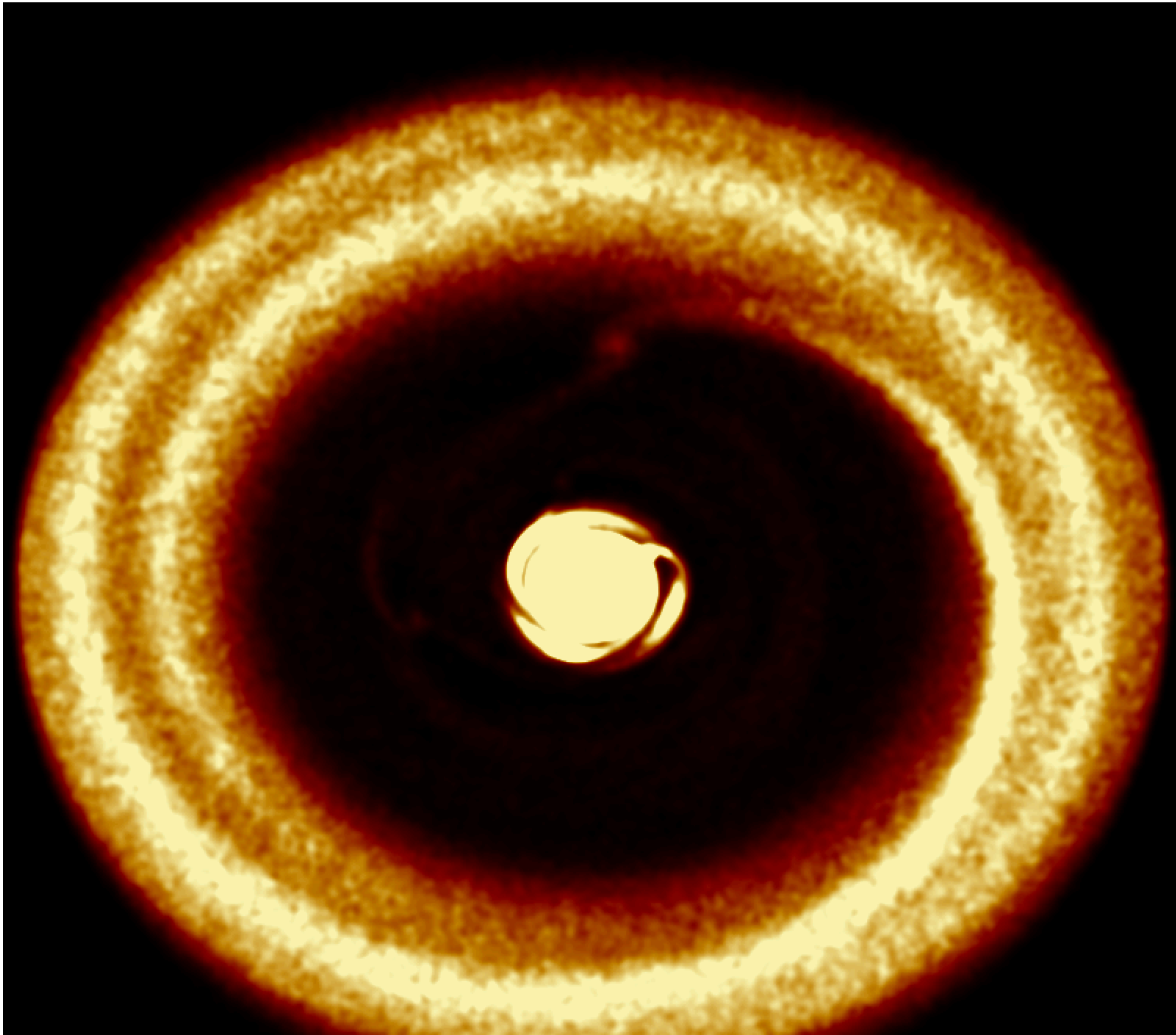


Architecture Overview

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

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
  - $\mathrm{Resolution} \propto \sqrt{\frac{\lambda}{d}}$

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

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

The PFI Technical Working Group (TWG)

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

Concept architectures:

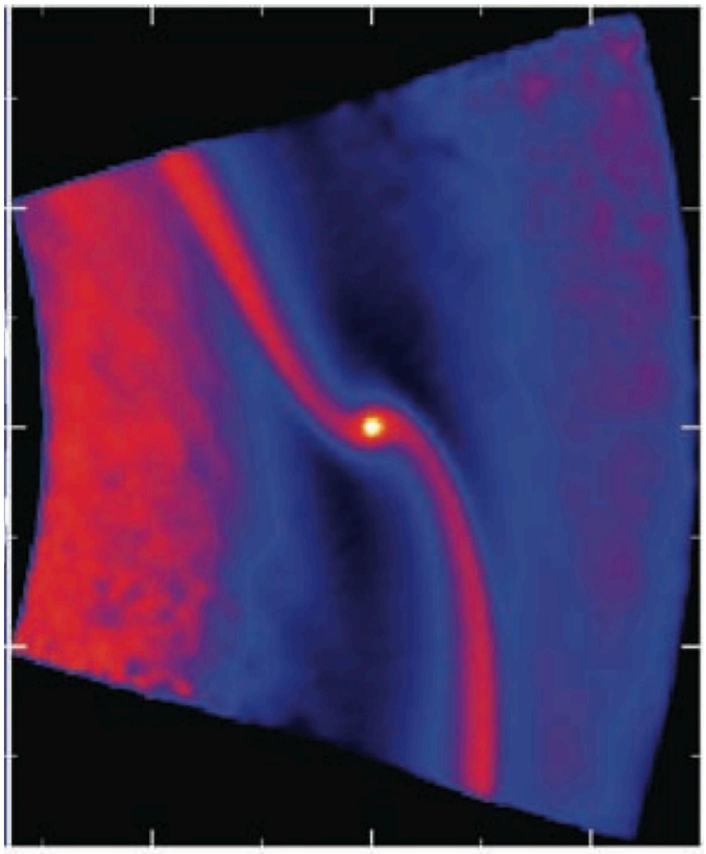
1. Visible and NIR interferometry (lead by Romain Petrov)
2. Mid-IR interferometry – direct detection (lead by David Buscher)
3. Mid-IR interferometry – heterodyne (lead by Michael Ireland)
4. Far-IR interferometry (lead by Stephen Rhinehard)
5. mm-wave interferometry (lead by Andrea Isella)
6. Non-interferometric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

Technology Roadmap Team:

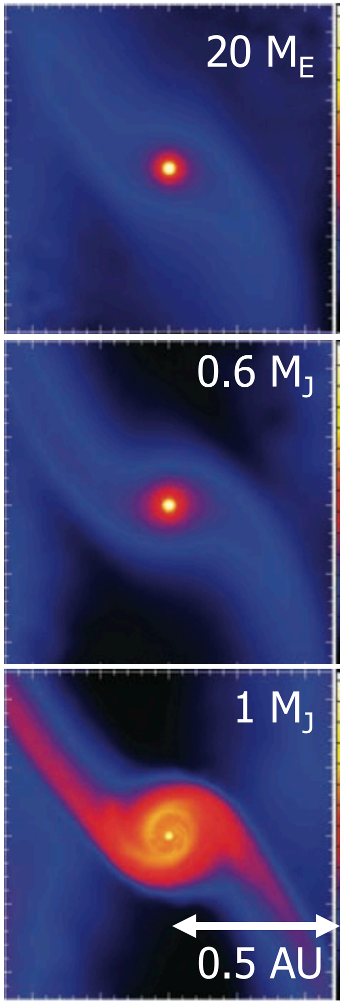
1. Space-based systems (lead by Gautam Vasisht and Fabien Malbet)
2. Heterodyne systems (lead by Ed Wishnow)
3. Adaptive optics and laser guide stars (lead by Theo ten Brummelaar)
4. Fringe tracking (lead by Antoine Merand)
5. Polarimetry (lead by Karine Perraut and Jean-Baptiste LeBouquin)
6. Telescopes 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 (lead by Fabien Baron)

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

Resolving the circumplanetary accretion disk



Ayliffe & Bate 2009



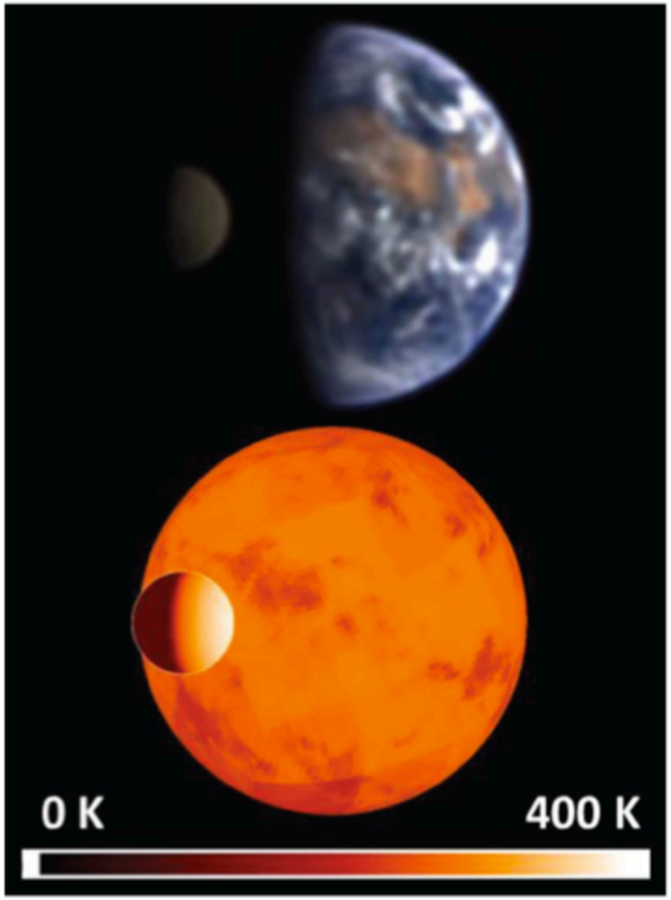
Size circumplanetary disk ($\approx 0.3\ R_H$) for Jupiter-mass planet
at r=5.2 AU: 0.11 AU = 0.79 mas @ 140 pc
at r=1 AU: 0.02 AU = 0.14 mas @ 140 pc

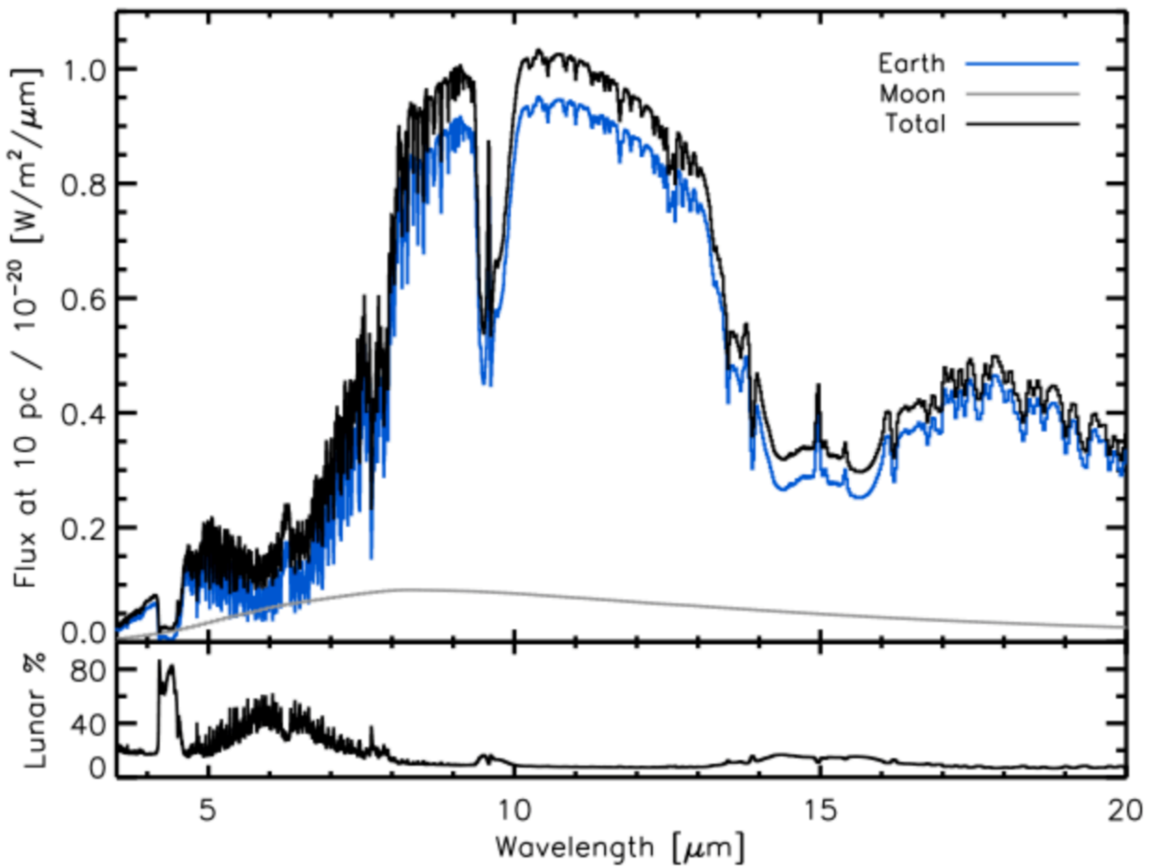
Advantages of Heterodyne Interferometry

Advantages
1. Need telescopes, but otherwise minimal infrastructure
2. Avoids lossy beam transport
3. Allows very long baselines
4. Allows simple, highly replicated system
5. Amplification

Disadvantages
1. Poor receiver noise characteristics at optical wavelengths
2. Low bandwidths

The Earth-Moon System as Emitter





Credit: Virtual Planetary Laboratory

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**

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 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