Imaging the birth of exoplanetary systems: Concept study for the "Planet Formation Imager"

Executive team: John Monnier, Stefan Kraus, Mike Ireland

Science Working Group: [team leaders:] Gaspard Duchene, Catherine Espaillat, Sebastian Hönig, Attila Juhasz, Johan Olofsson, Claudia Paladini, Christoph Mordasini, Keivan Stassun, Neal Turner, Gautam Vasisht

[contributors:] Almudena Alonso Herrero, Phil Armitage, Amelia Bayo, Clement Baruteau, Matthew Bate, Jean-Philippe Berger, Myriam Benisty, Bertram Bitsch, Amy Bonsor, Tabetha Boyajian, Andrea Chiavassa, David Ciardi, Robin Dong, Willem-Jan de Wit, Alexandre Gallenne, Poshak Gandhi, John Ilee, Eric Jensen, Steven Kane, Makoto Kishimoto, Wilhelm Kley, Quentin Kral, Kaitlin Kratter, Lucas Labadie, Greg Laughlin, Tim Harries, Frederic Masset, Farzana Meru, Rafael Millan-Gabet, Jean-Francois Gonzalez, Florentin Millour, Alessandro Morbidelli, Chris Mordasini, Andreas Morlok, Richard Nelson, Rene Oudmaijer, Sijme-Jan Paardekooper, Chris Packham, Olja Panic, Joshua Pepper, Arnaud Pierens, Christoph Pinte, Benjamin Pope, Jörg-Uwe Pott, Luis Henry Quiroga Nunez, Cristina Ramos Almeida, Sean Raymond, Zsolt Regaly, Mark Reynolds, Giovanni Rosotti, Michael Smith, Jean Surdej, Konrad Tristam, Gerd Weigelt, Markus Wittkowski, Barbara Whitney, Sebastian Wolf, Ming Zhao, Zhaohuan Zhu

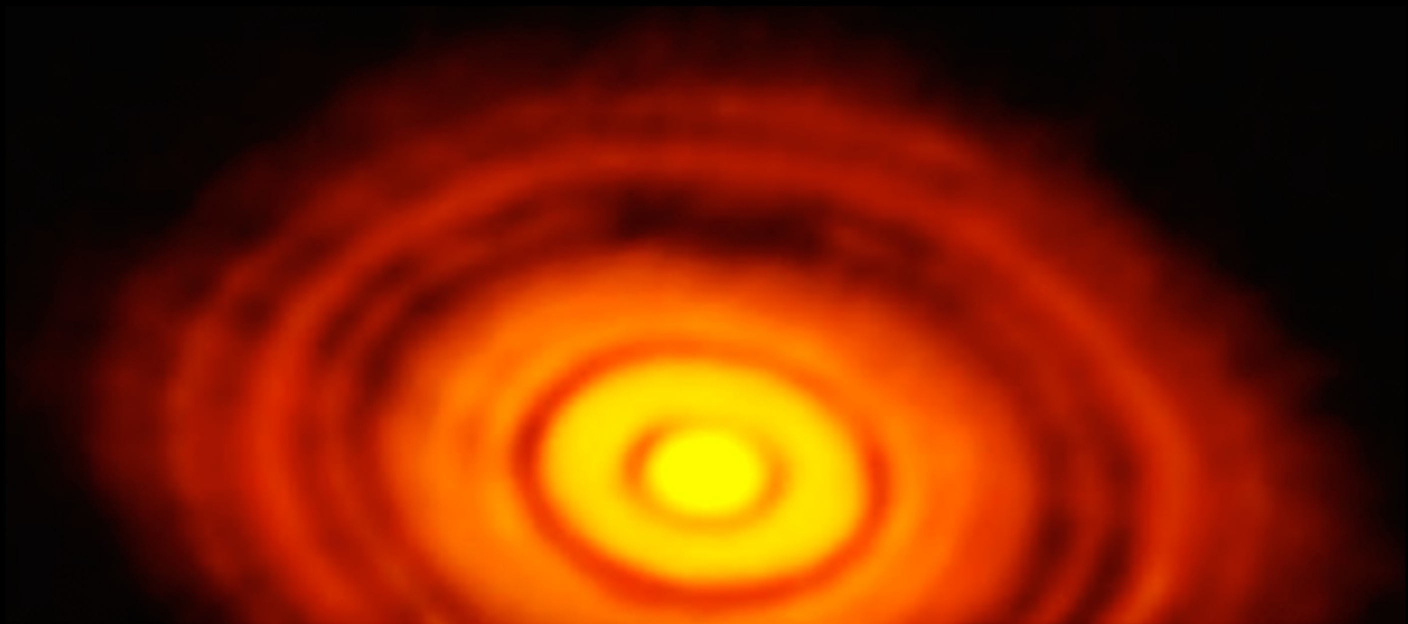
Science Case: Planet Formation

HL Tau image
ALMA 15km data

1 planet opening 2 gaps
(Gonzalez et al. 2015)

ALMA alone does not
provide the answers

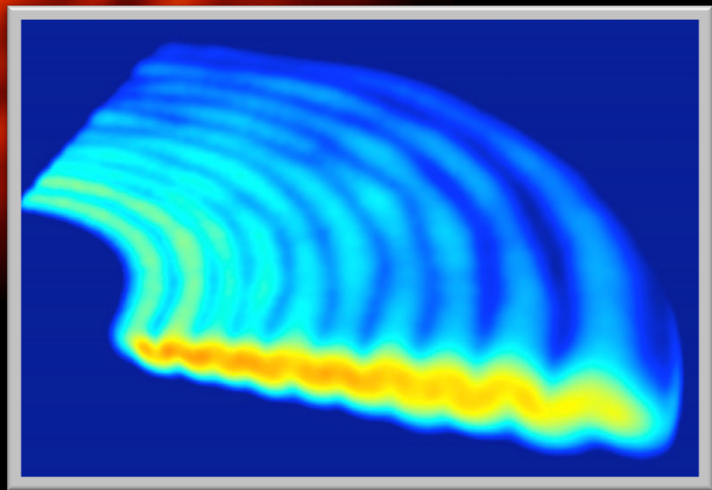
Science Case: Planet Formation



HL Tau image
ALMA 15km data

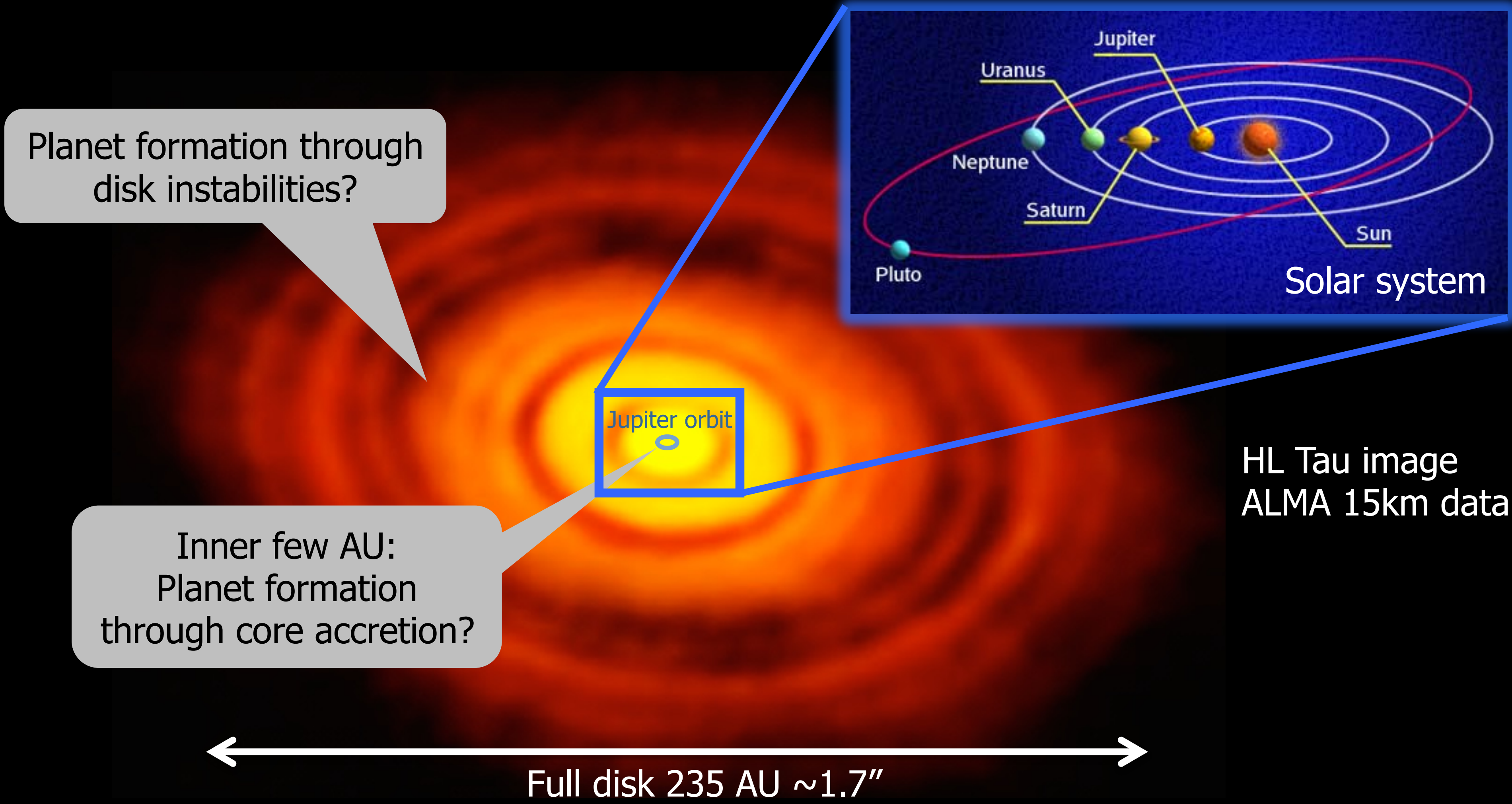
1 planet opening 2 gaps
(Gonzalez et al. 2015)

ALMA alone does not provide the answers



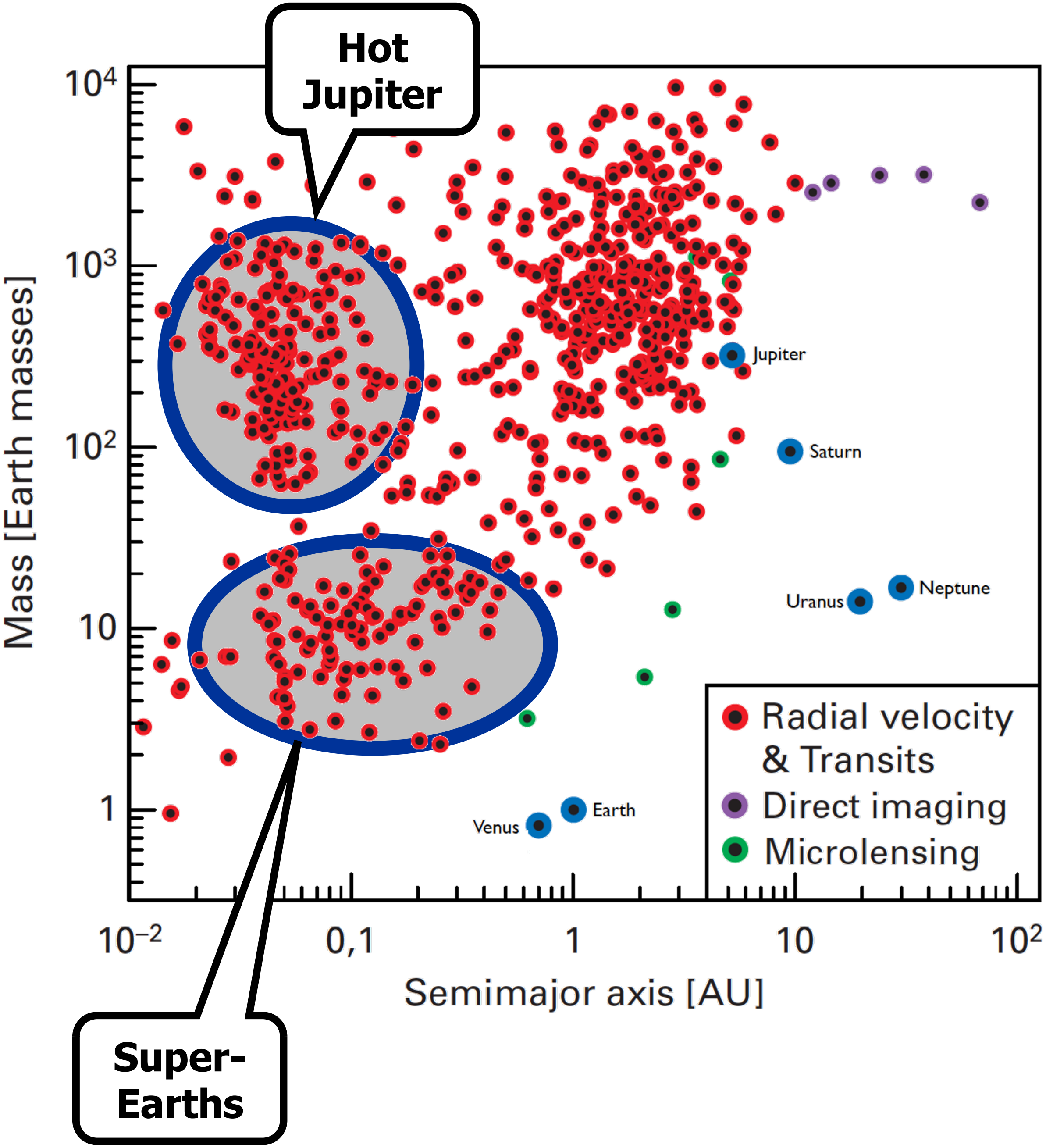
Ring structures in discs <u>without</u> planets
(Toroidal vortices; Loren-Aguilar & Bate 2015)

Science Case: Planet Formation

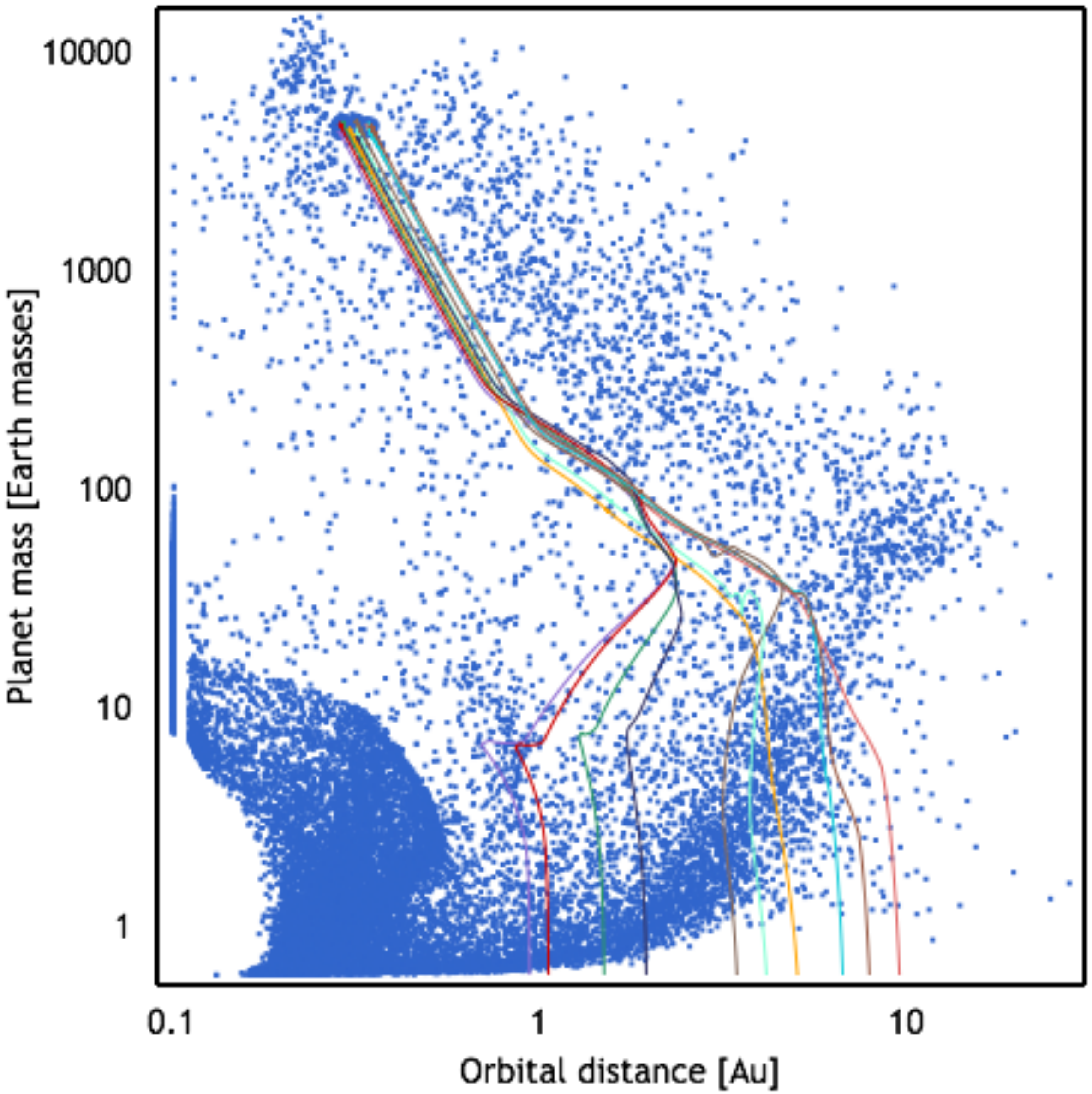


Even with its ultimate performance, ALMA will lack resolution to resolve inner AU, where a different planet formation mode might be at work than in outer disk

Exoplanetary systems



Exoplanetary systems

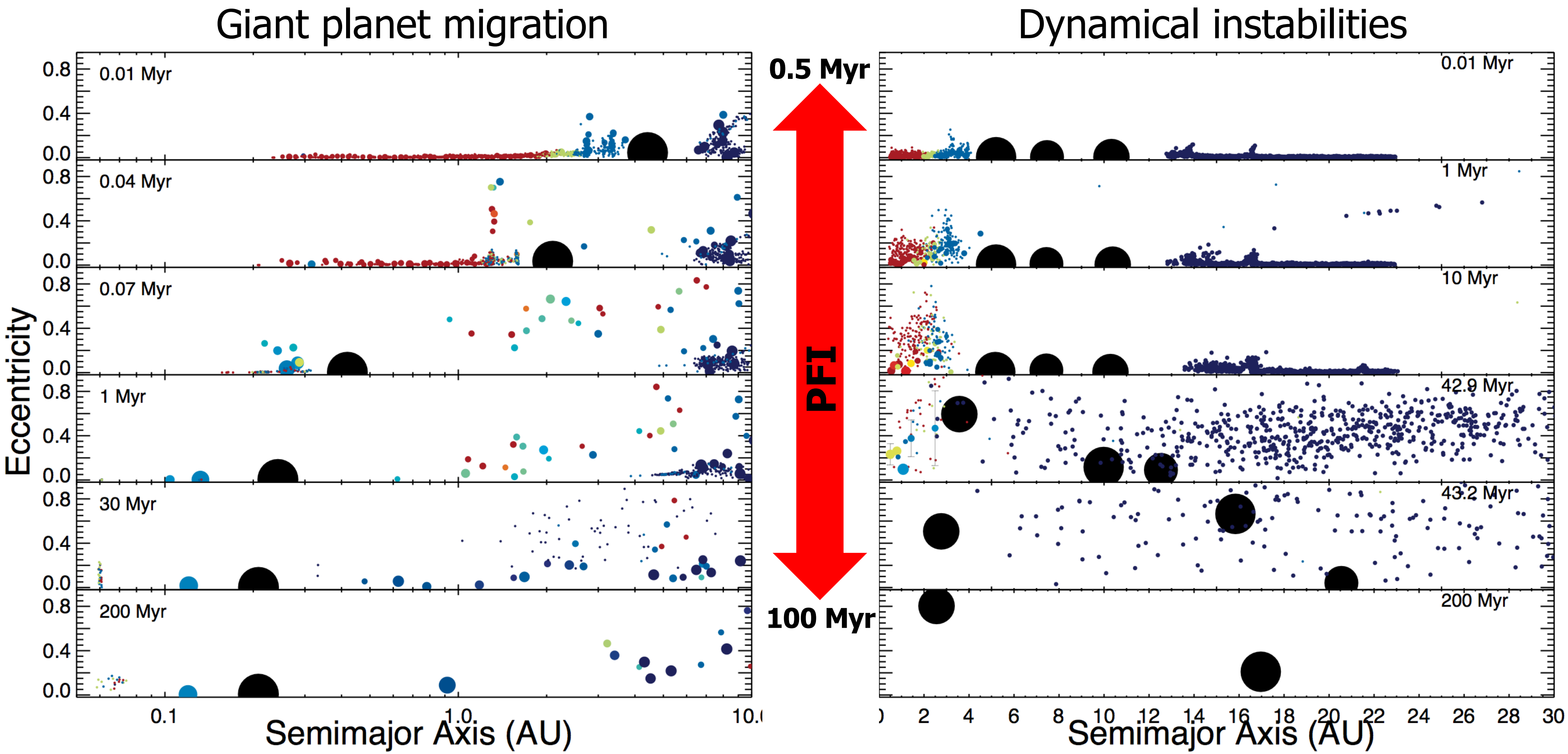


Architecture of planetary systems determined by…

- 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
- …

DACE/Geneva

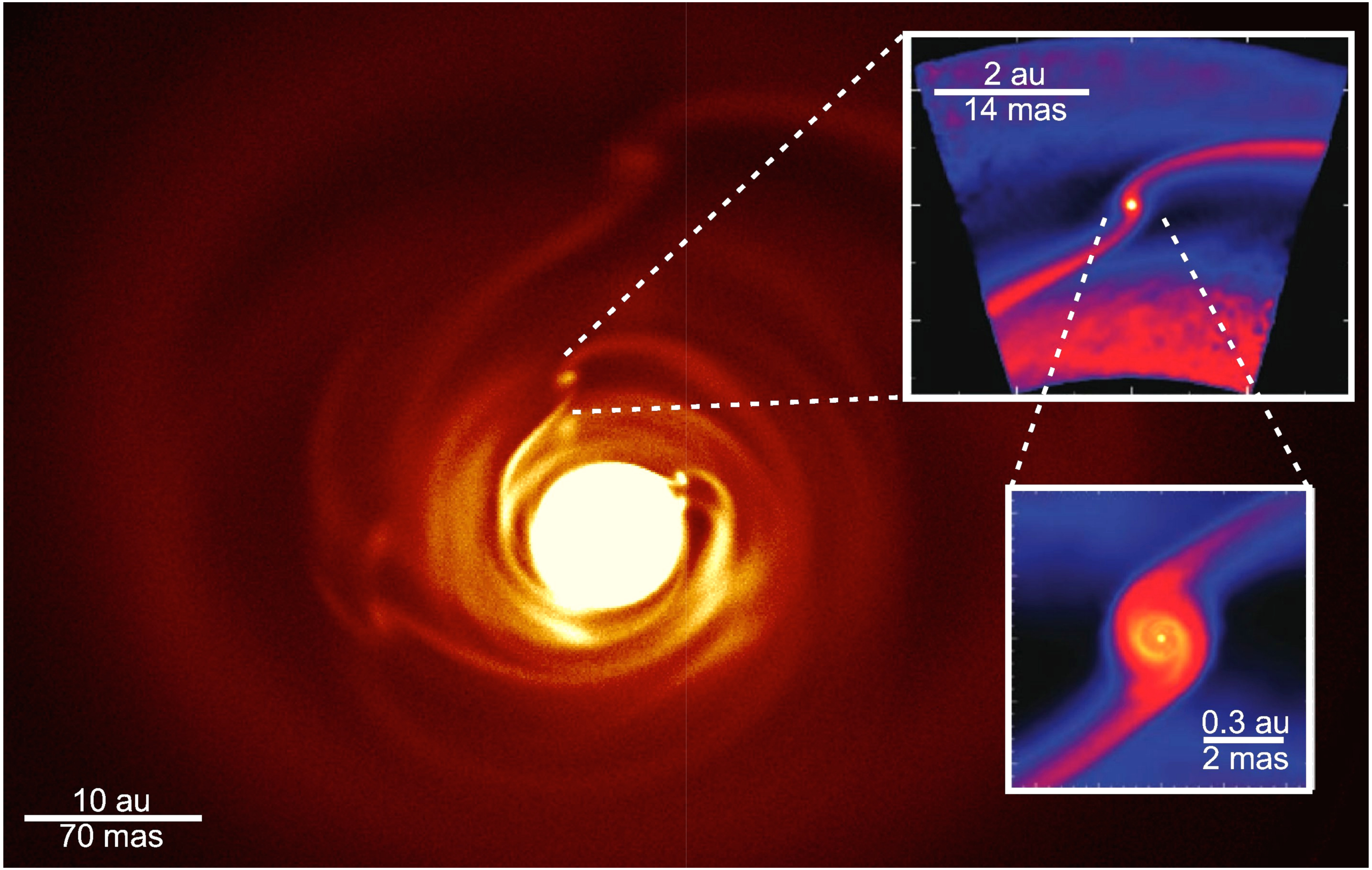
PFI: Exoplanetary systems



PFI locates the planet population during the age range that is most critical for understanding the dynamical evolution of planetary systems

Raymond et al. 2006

Planet Formation Imager (PFI) Concept Studies



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

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;
Implement a roadmap to demonstrate technologies on-sky;
Prepare for upcoming funding opportunities for implementation

We have formed working groups:

Science Working Group (SWG):

Develops and prioritizes key achievable science cases
→ **Science Whitebook**

Technical Working Group (TWG):

Conducts concept studies that will allow us to identify the key technologies and to develop a technology roadmap
→ **Technology Whitebook**

The PFI Science Working Group (SWG)

We structures the work for our science whitebook in the following teams:

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 Johan Olofsson)
5. Architecture of Planetary Systems (lead by Christoph Mordasini)
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)

We need you to tell us how to optimise PFI for the science you want to do with it
→ **www.planetformationimager.org**

Radiation hydrodynamics simulations

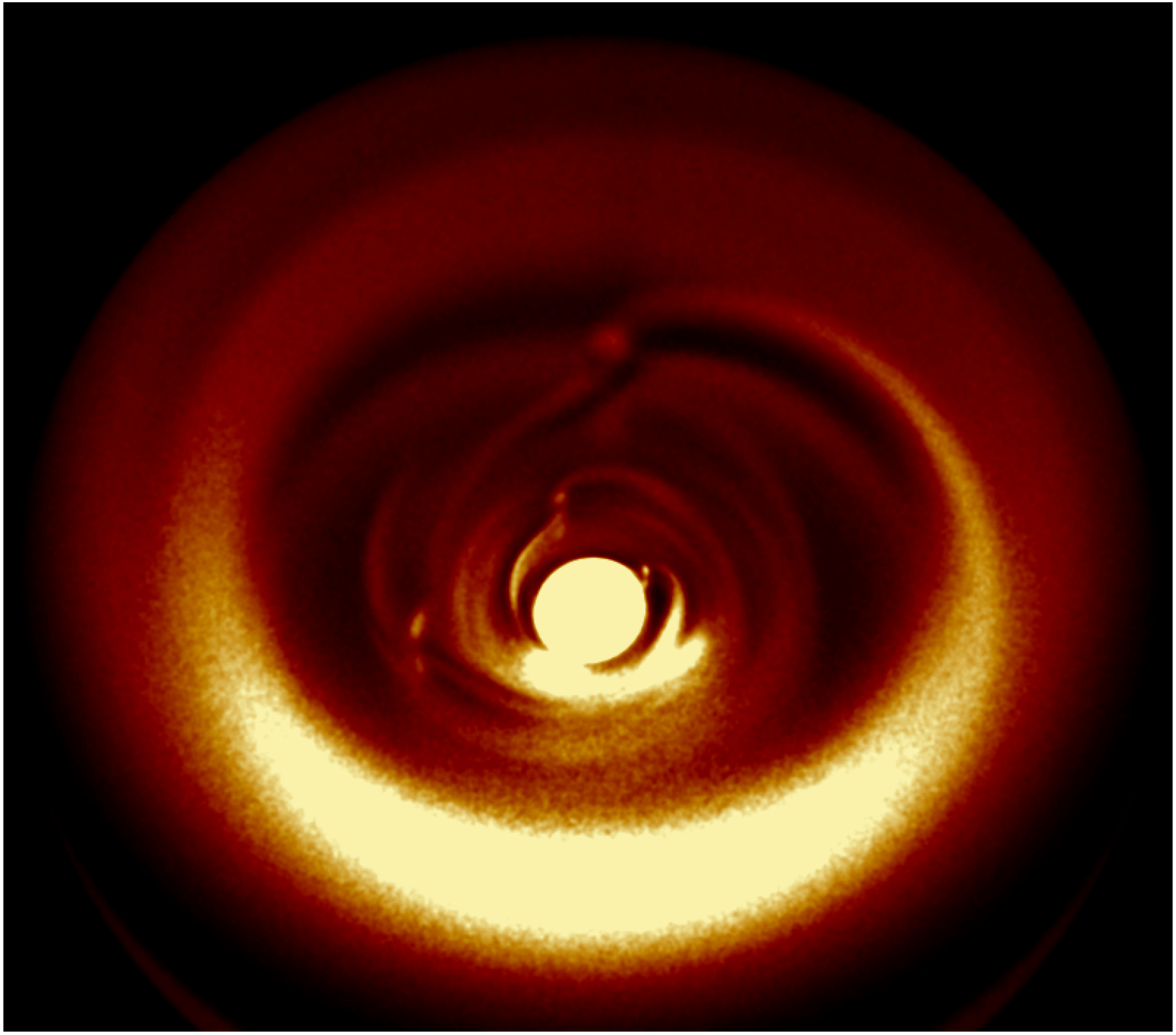
2μm
(K-band)

Radiation
hydrodynamics
simulation

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

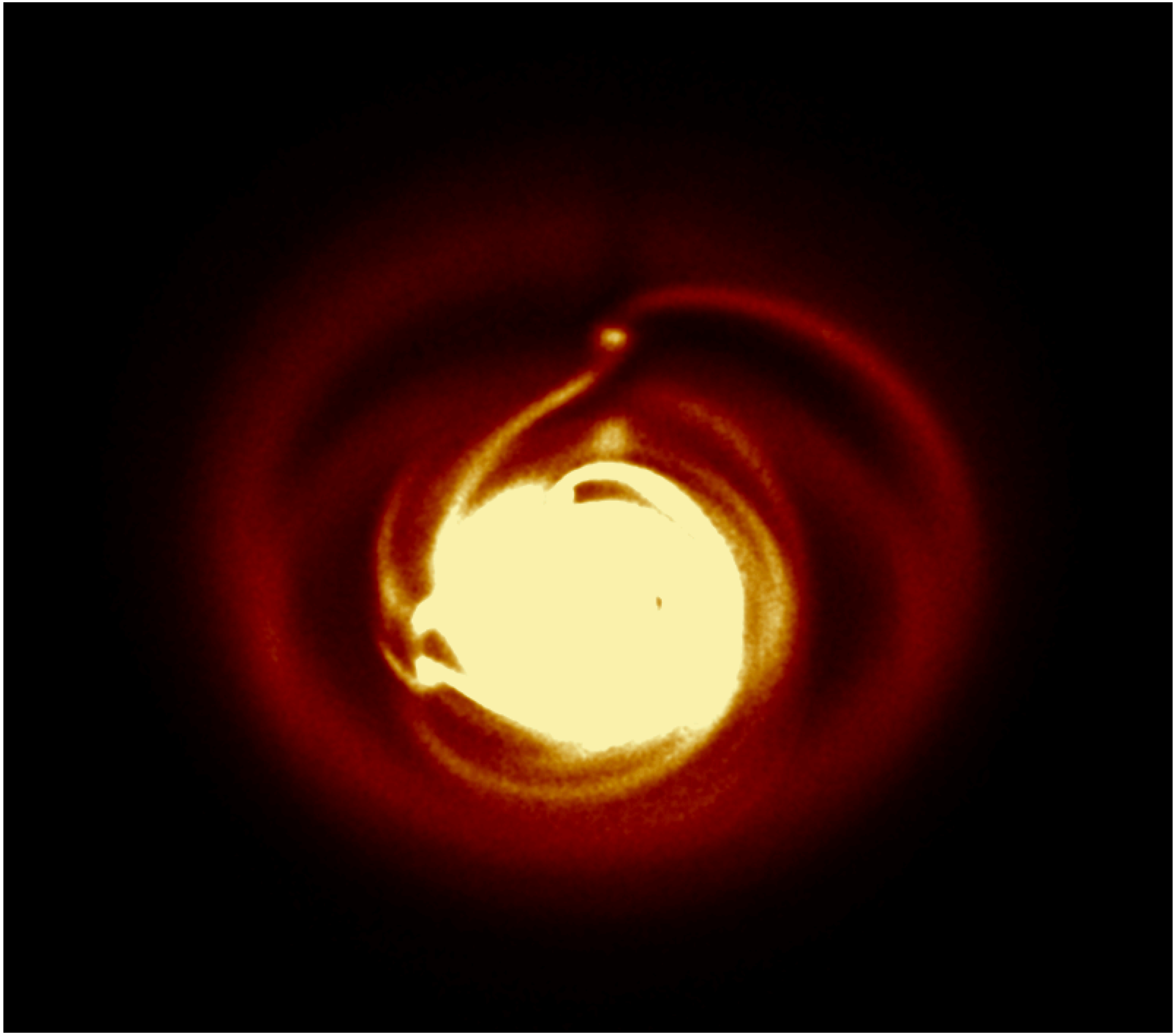
NIR dominated by scattered light

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

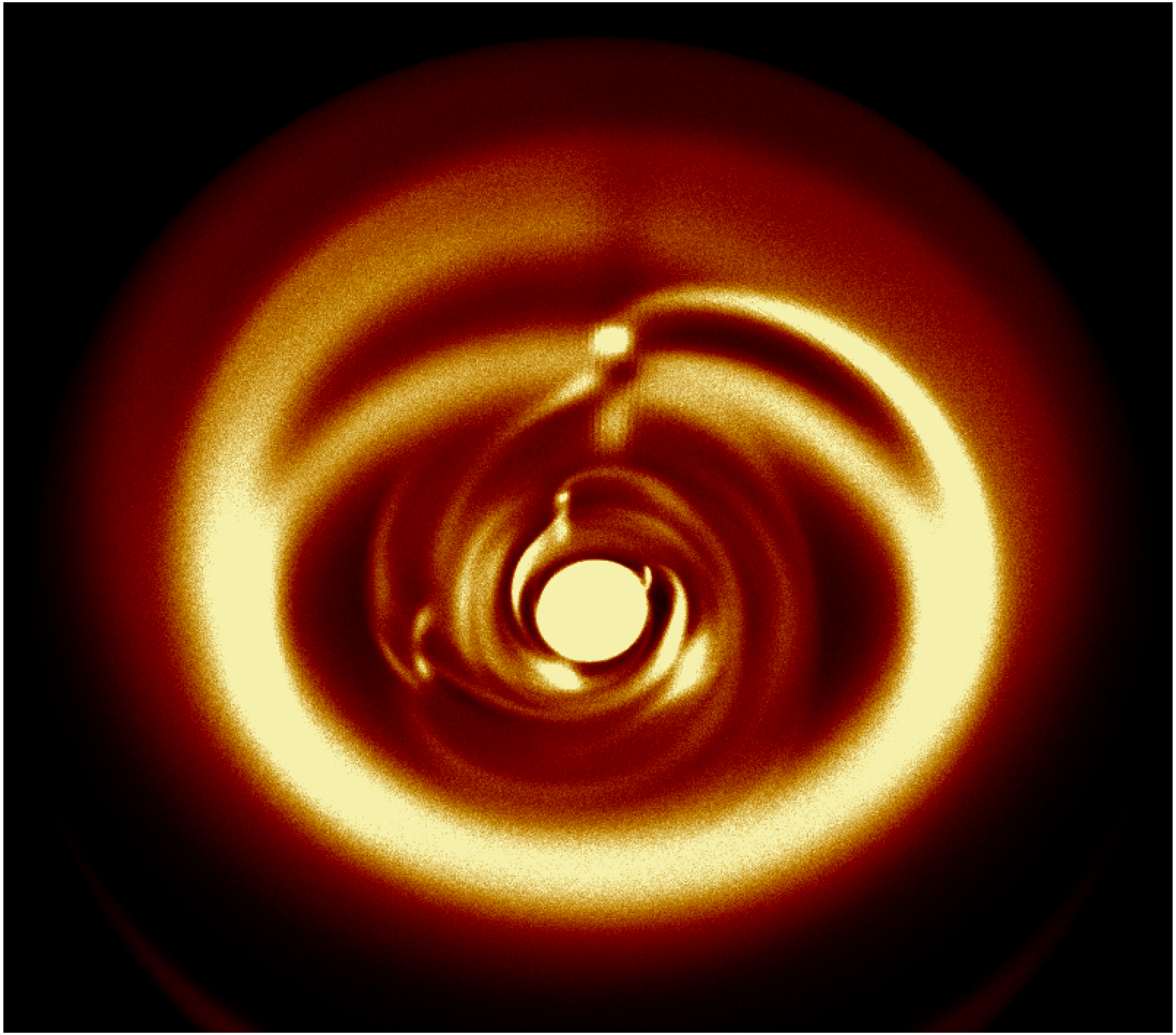
24μm
(Q-band)

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

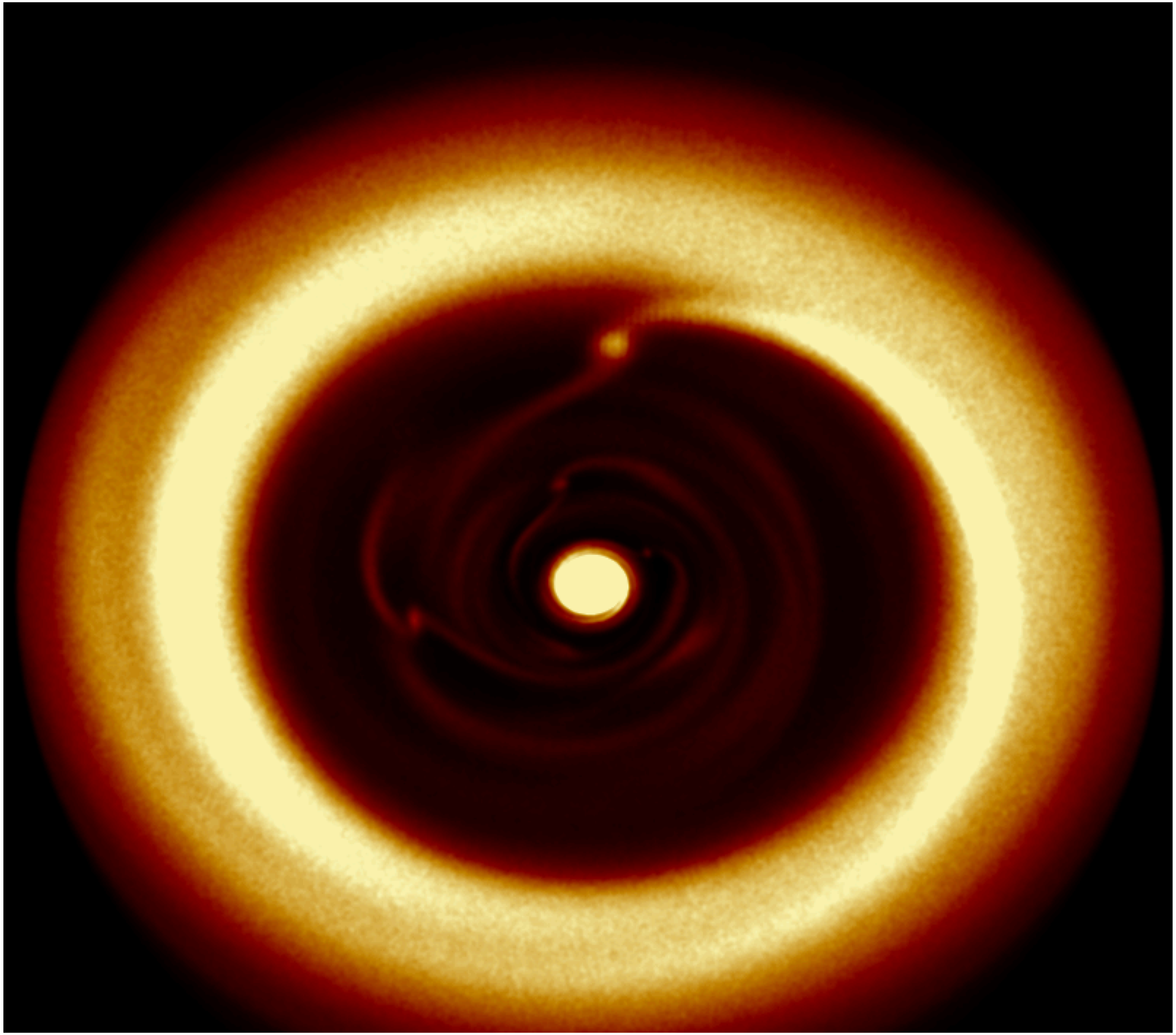
100μm
(FIR, space)

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



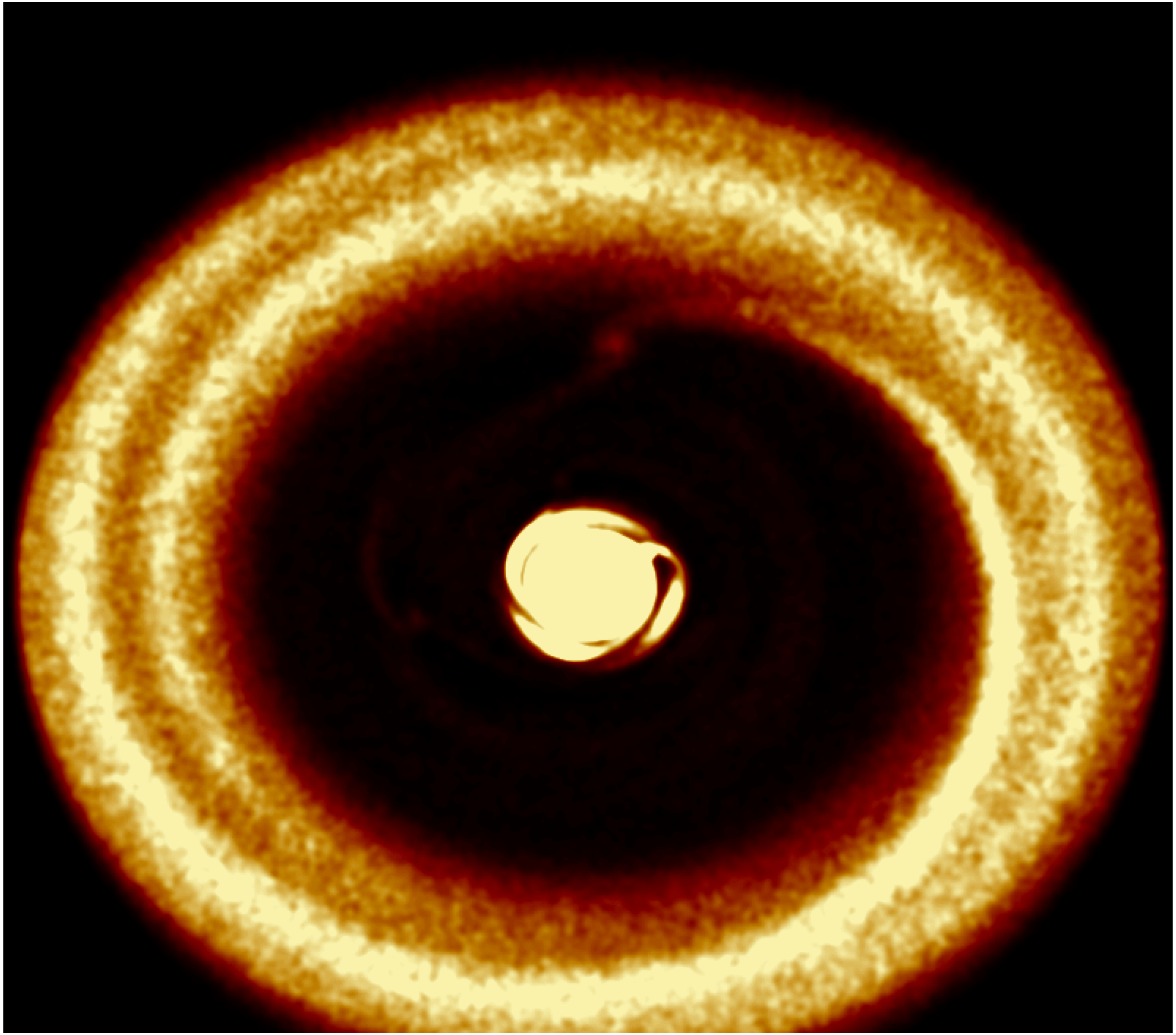
Radiation hydrodynamics simulations

400µm
(sub-mm,
ALMA)

Radiation hydrodynamics simulation

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

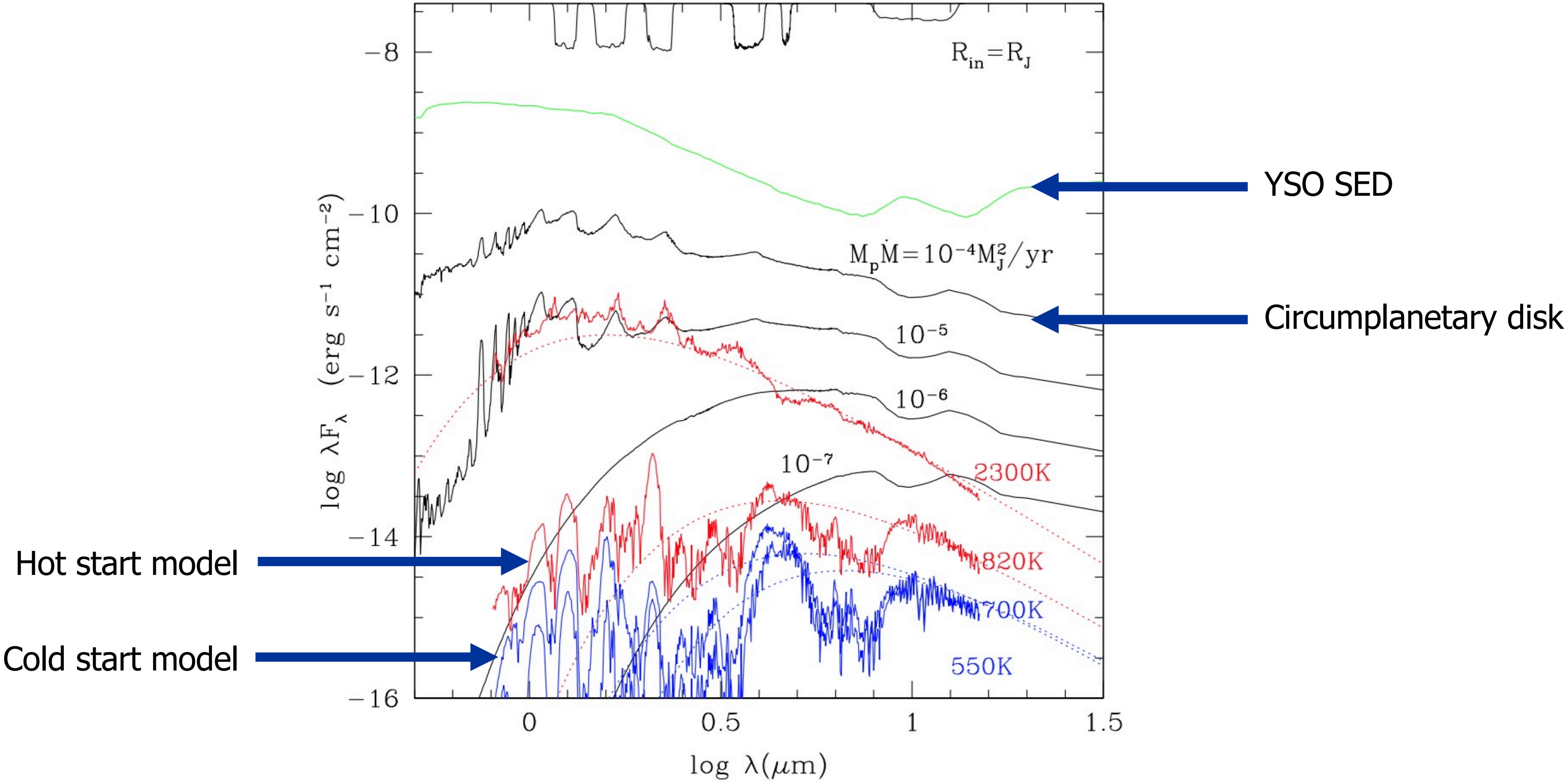
FIR/sub-mm traces primarily emission from large grains at gap edges



Zhaohuan Zhu, Barbara Whitney, Robin Dong

Detect accreting young protoplanets

Objective: Detect young accreting protoplanets (continuum)

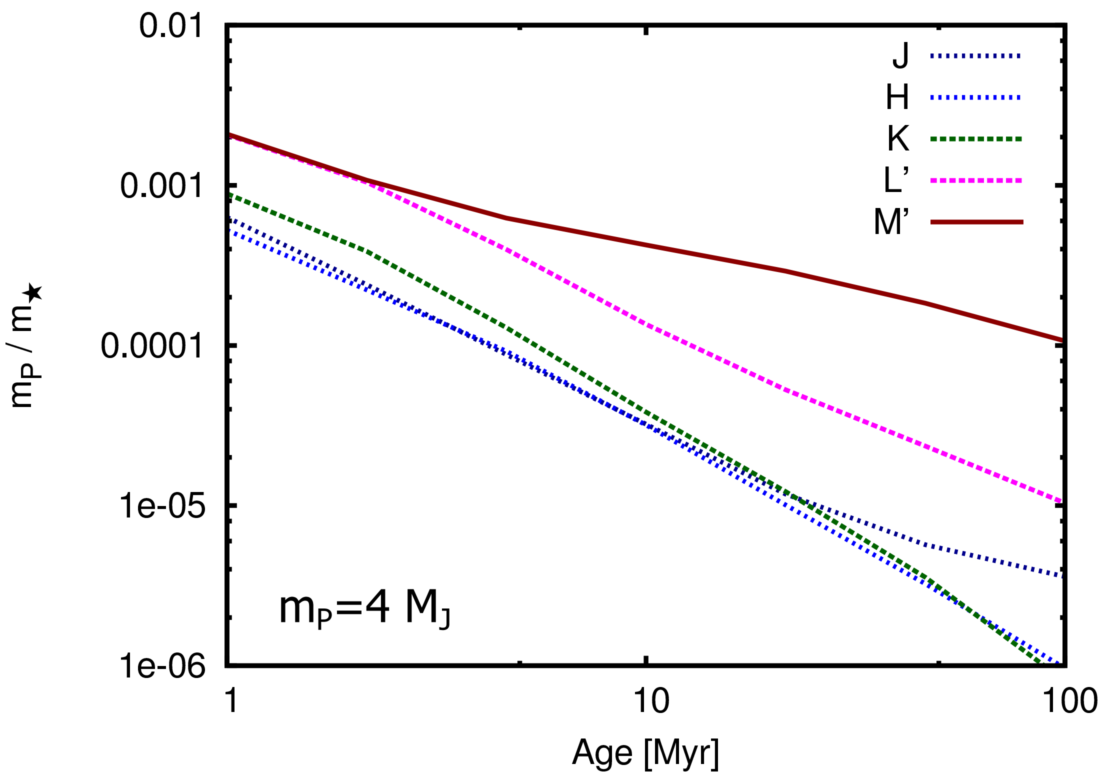


Zhu et al. 2015

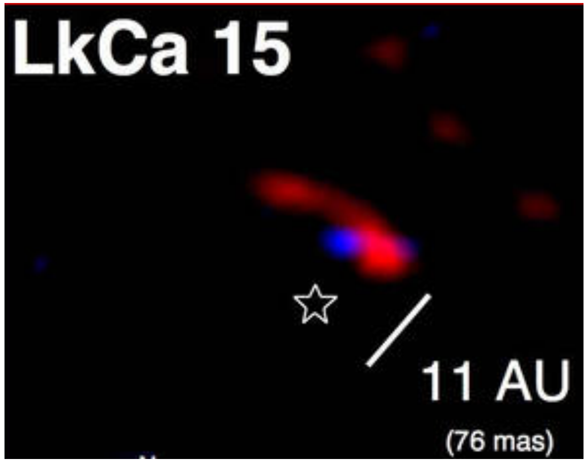
→ Characterisation of the circumplanetary disk and protoplanet through spatially-resolved spectroscopy

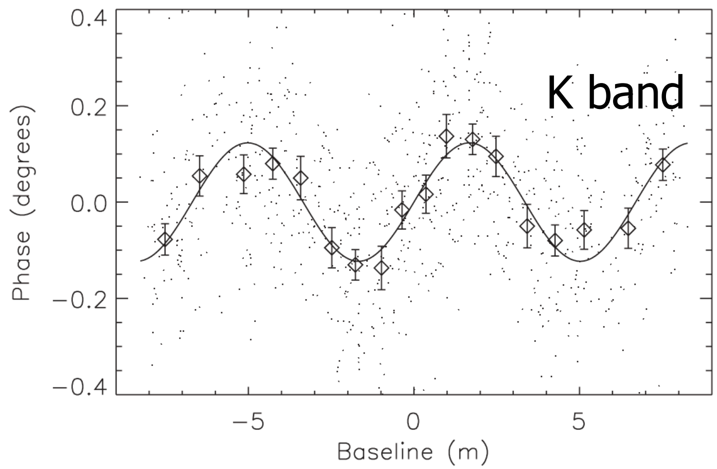
Detect accreting young protoplanets

Objective: Detect young accreting protoplanets (continuum)



Forney et al. 2008



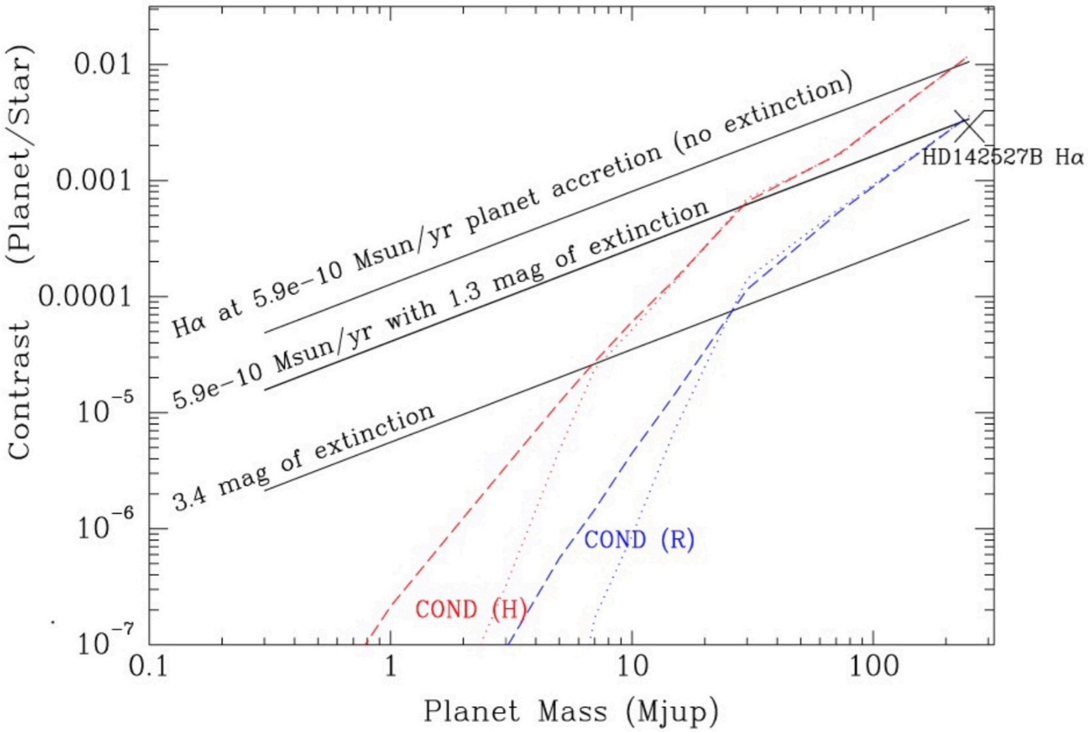


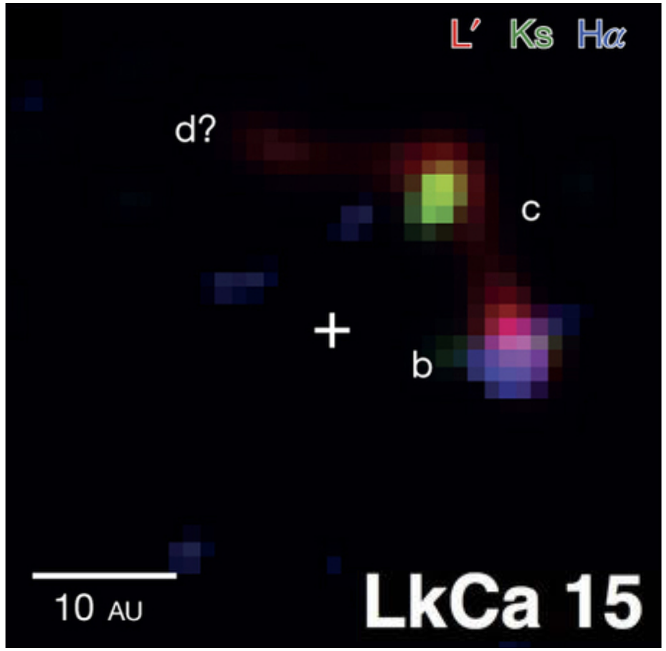
Kraus & Ireland 2012

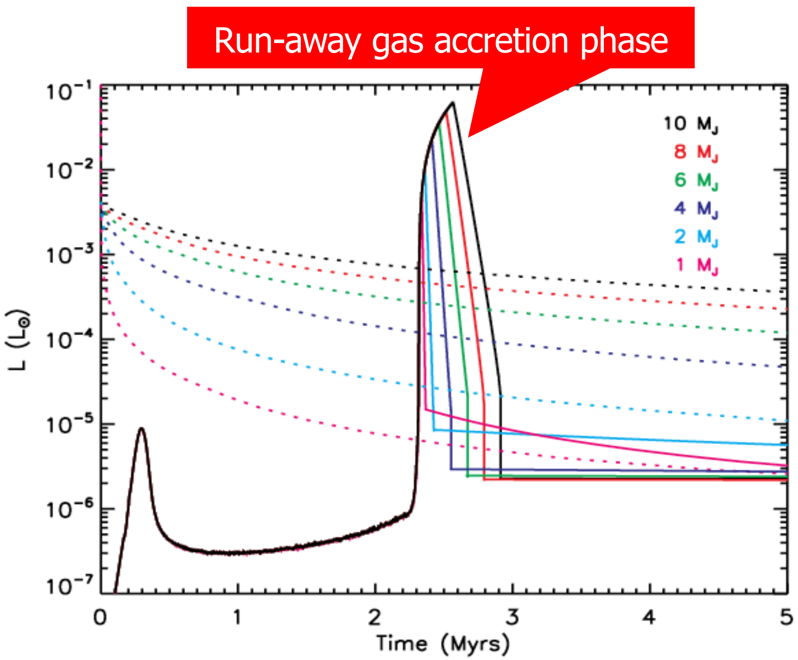
→ MIR likely sweet spot for tracing planets in relevant age range (0.1 … 100 Myr)

Detect accreting young protoplanets

Objective: Detect young accreting protoplanets
(line emission)





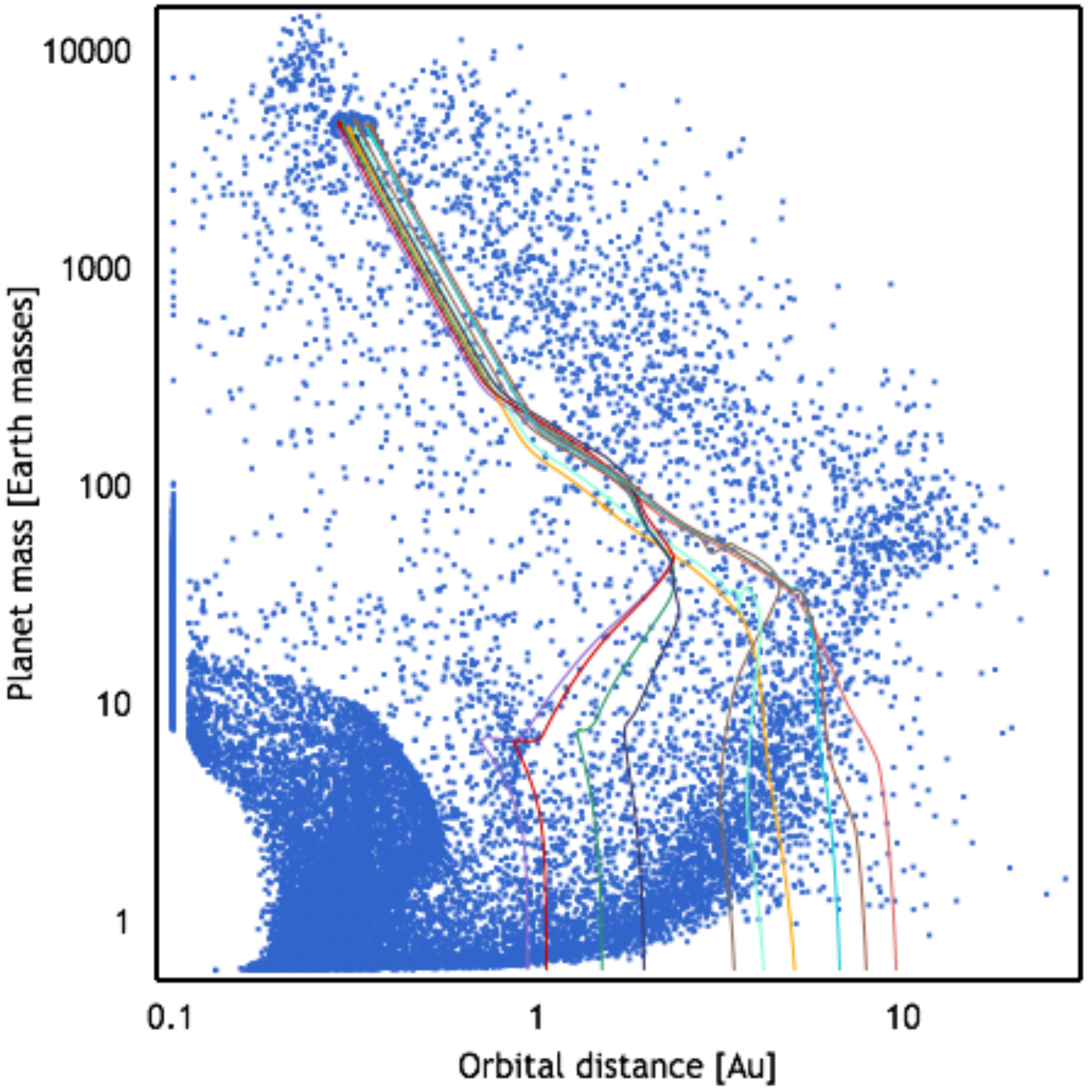


→ Accretion-tracing lines optimal to trace even low-mass planets

Close et al. 2014, Sallum et al. 2015, Marley et al. 2007

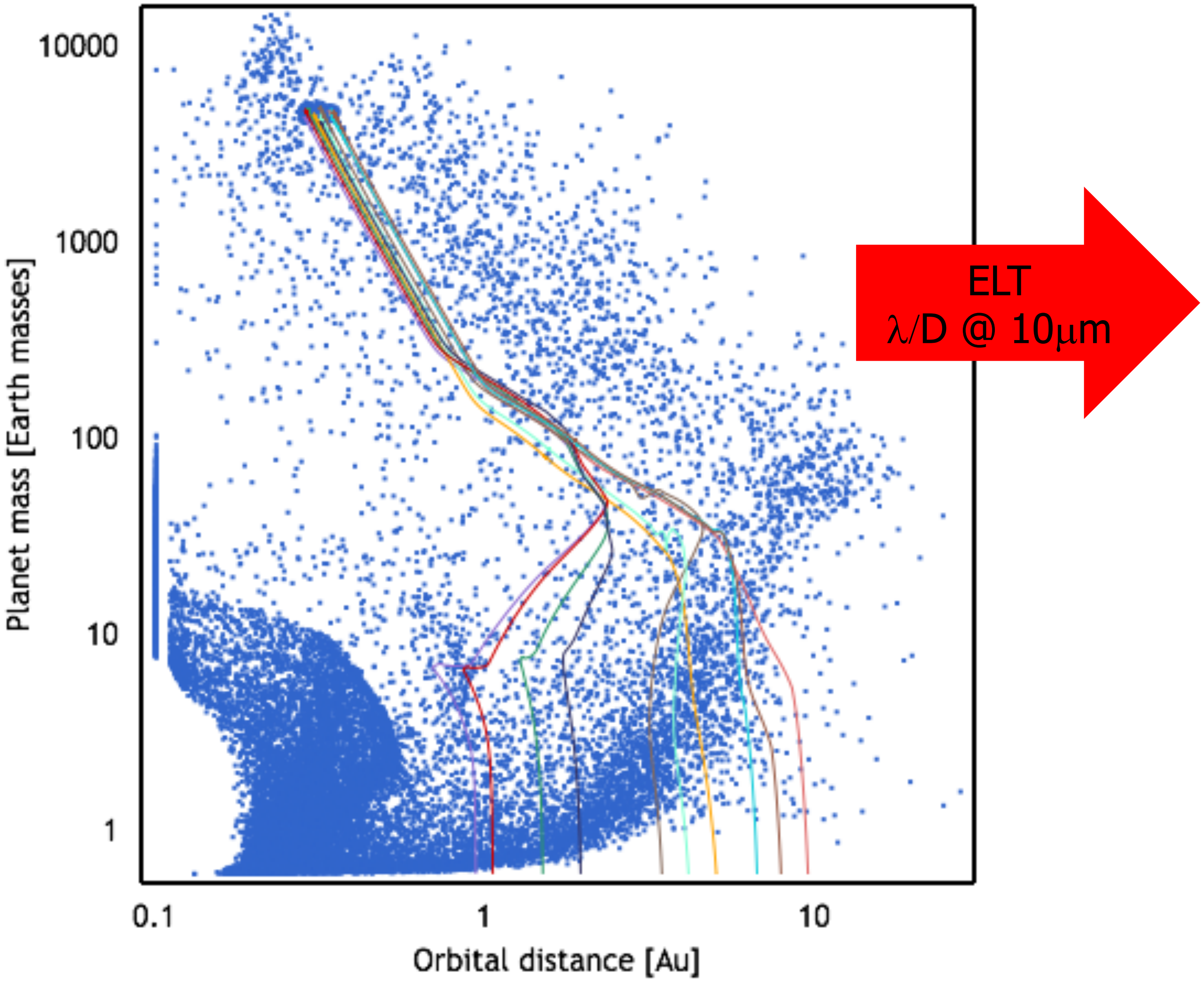
Detect accreting young protoplanets

Planet detectability range covered by
PFI versus 40m ELT



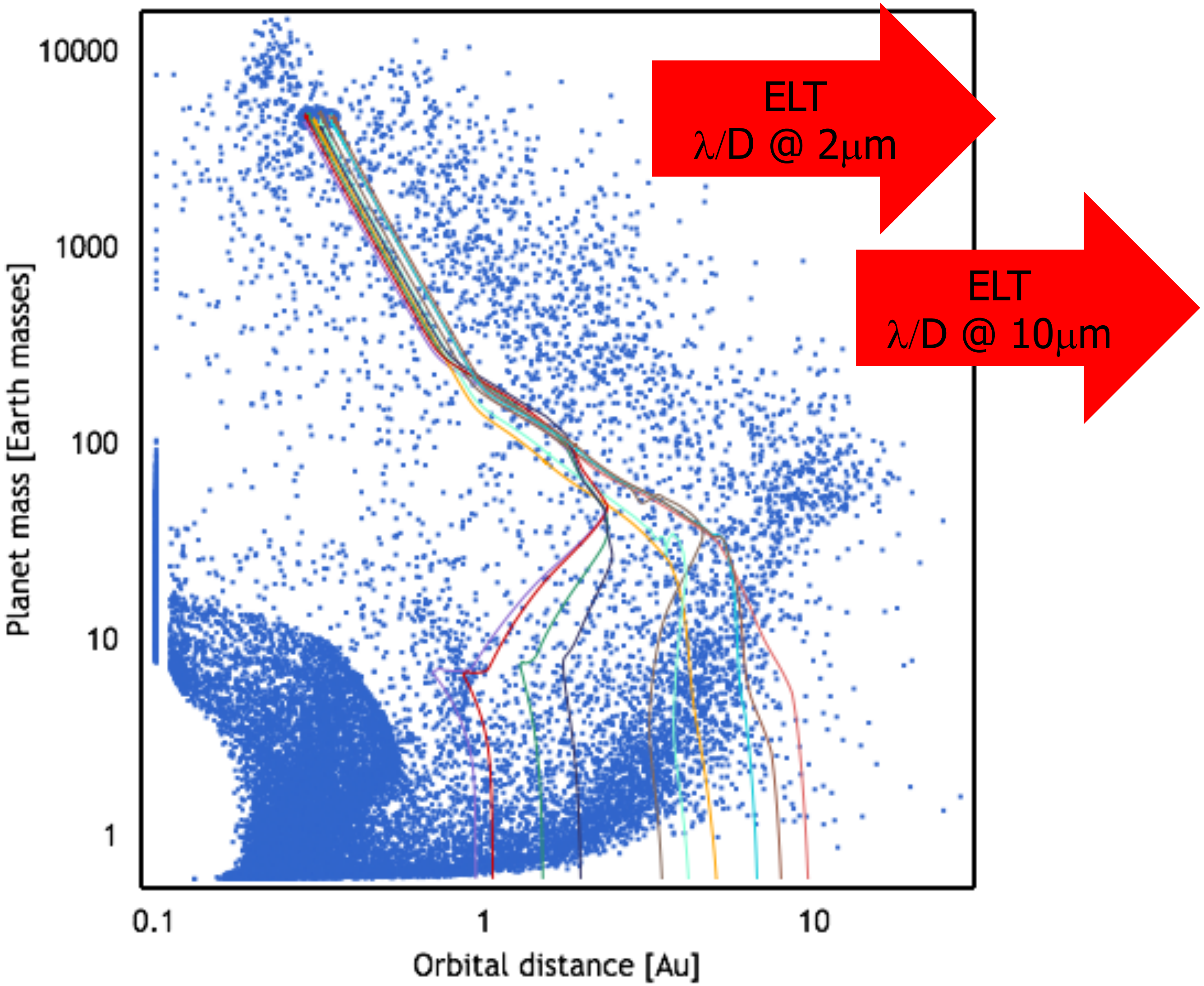
Detect accreting young protoplanets

Planet detectability range covered by
PFI versus 40m ELT



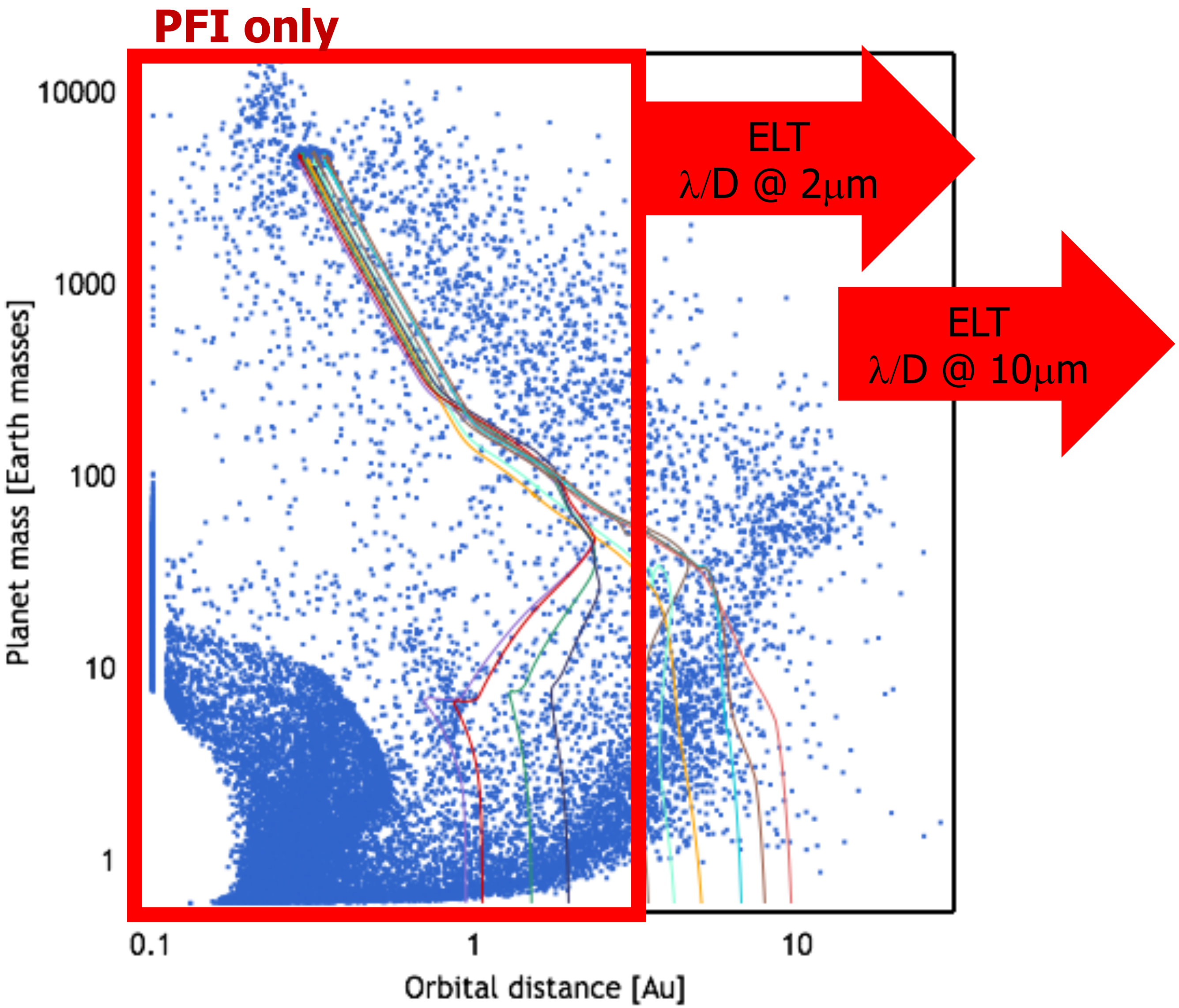
Detect accreting young protoplanets

Planet detectability range covered by
PFI versus 40m ELT



Detect accreting young protoplanets

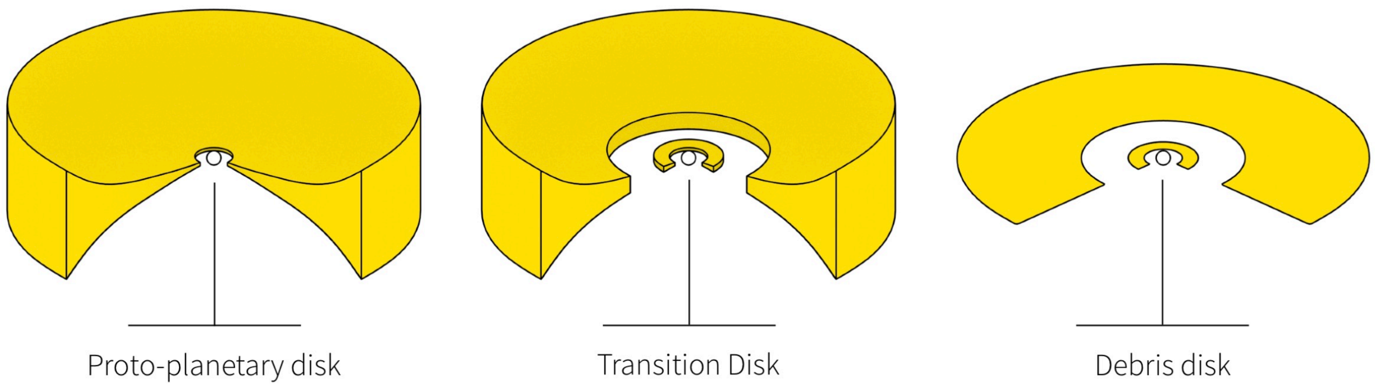
Planet detectability range covered by
PFI versus 40m ELT



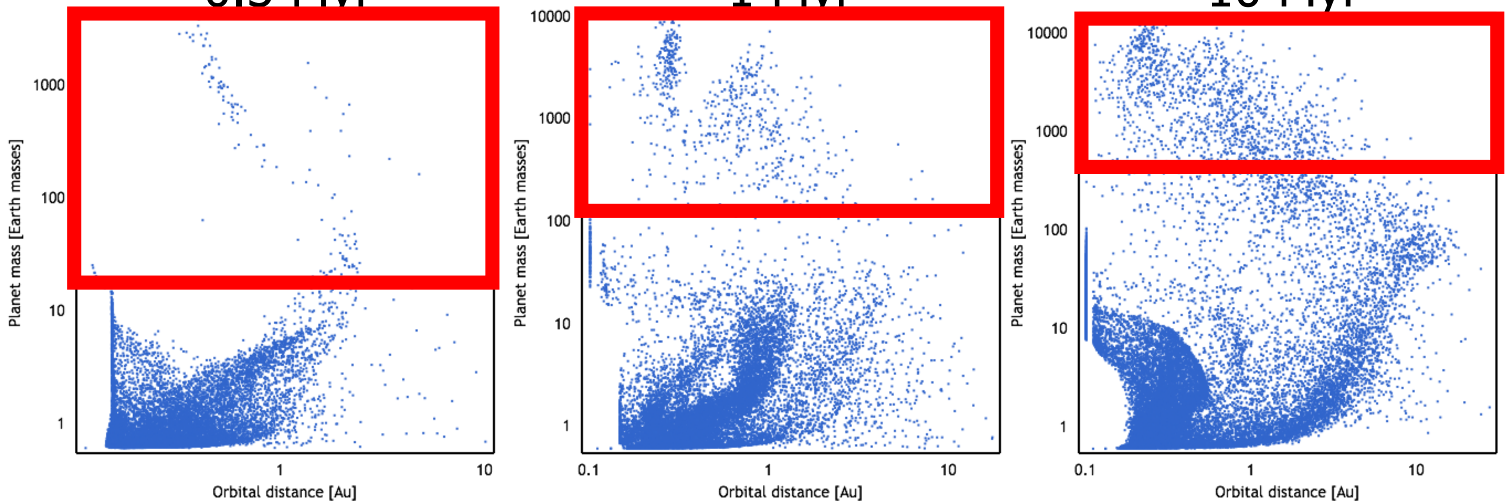
Architecture of planetary systems

Objective: Measure planet population for a statistically significant sample of systems at different evolutionary stages:

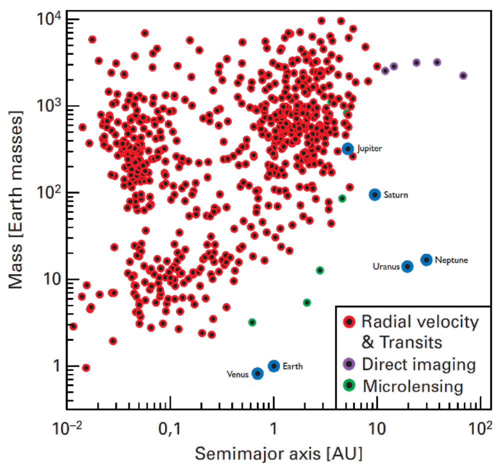
>100 systems @ 0.5 Myr | **>100 systems @ 5 Myr** | **>100 systems @ 50 Myr**



0.3 Myr | 1 Myr | 10 Myr



Exoplanet population > 1 Gyr



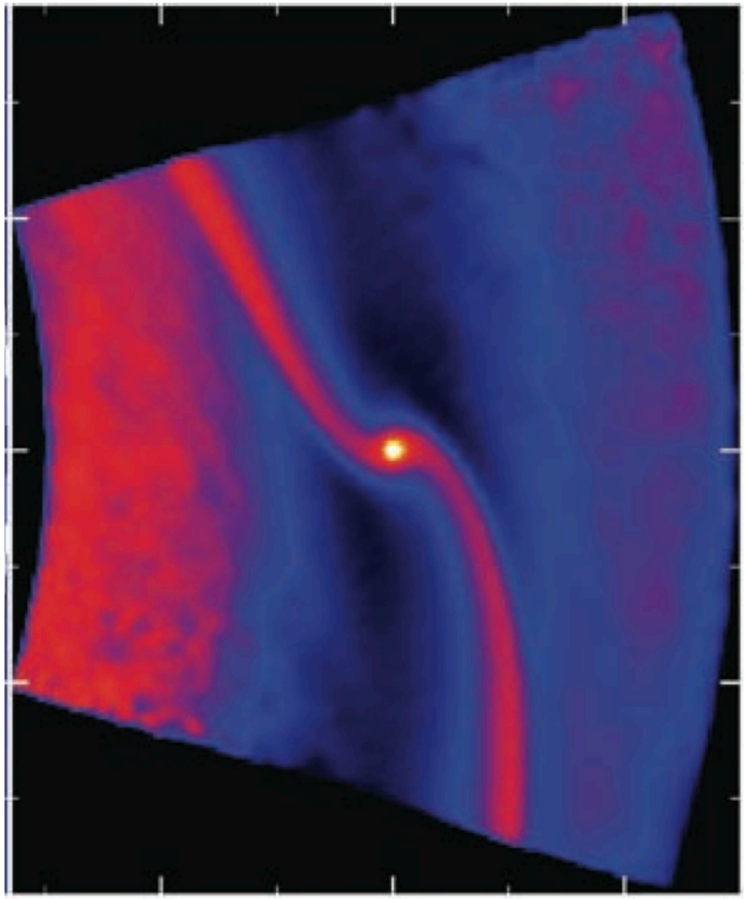
Simulation: DACE/Geneva; Illustration: Olofsson

Architecture of planetary systems

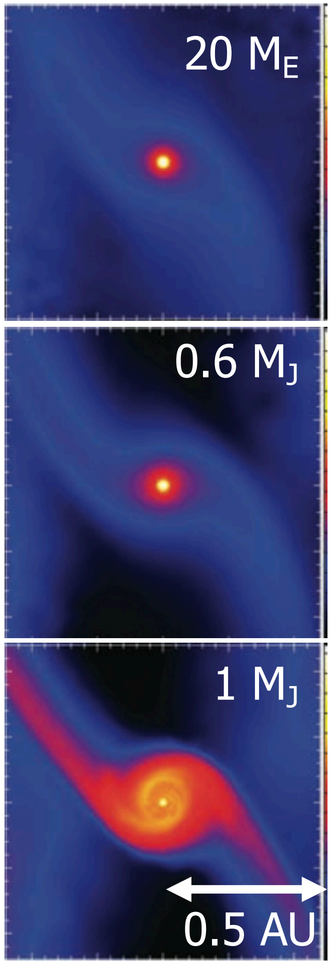
Objective: Measure planet population for a statistically significant sample of systems at different evolutionary stages:

- 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

Resolving the circumplanetary accretion disk



Ayliffe & Bate 2009



Size circumplanetary disk (≈0.3 R_H) for Jupiter-mass planet at 140 pc:

r=5.2 AU: 0.11 AU = 0.79 mas
r=1 AU: 0.02 AU = 0.14 mas

Possible diagnostic lines:

- HI (7-6) (e.g. Rigliaco et al. 2015)
- H_2O (in particular outside the snow line)
- CO
- CO_2
- CH_4
- C_2H_2
- NH_3

Spectrally-resolved imaging of the **circumplanetary disk** in accretion-tracing lines:

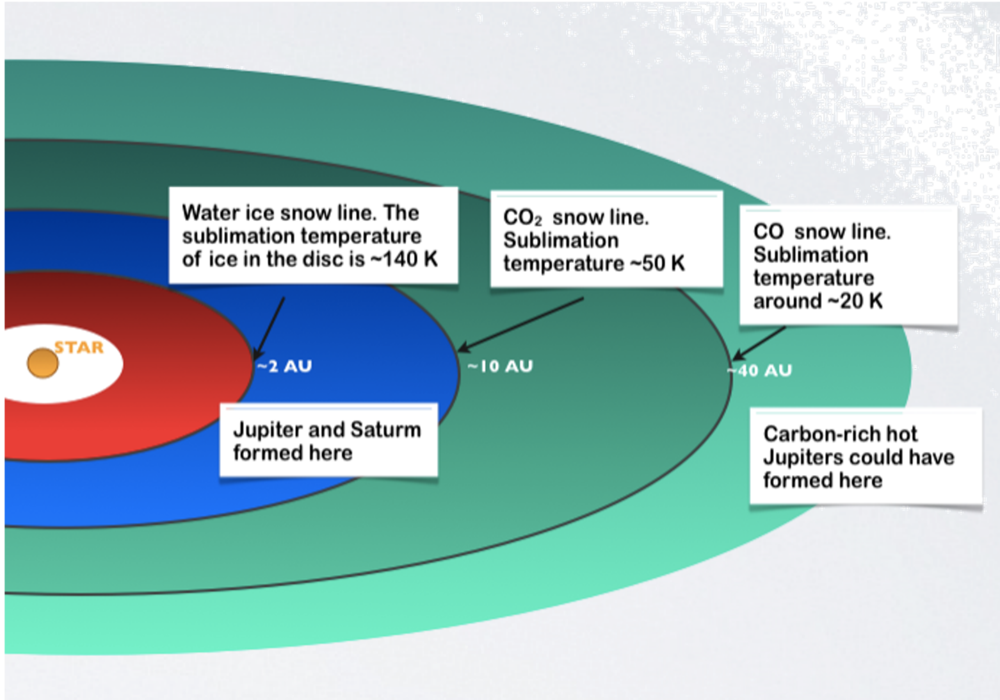
→ **Dynamical masses of protoplanets** to calibrate planet formation models!
→ **Ultimate test on how planets accrete!** (geometry, jets, etc.)

PFI+ALMA: Tracing complementary molecular lines

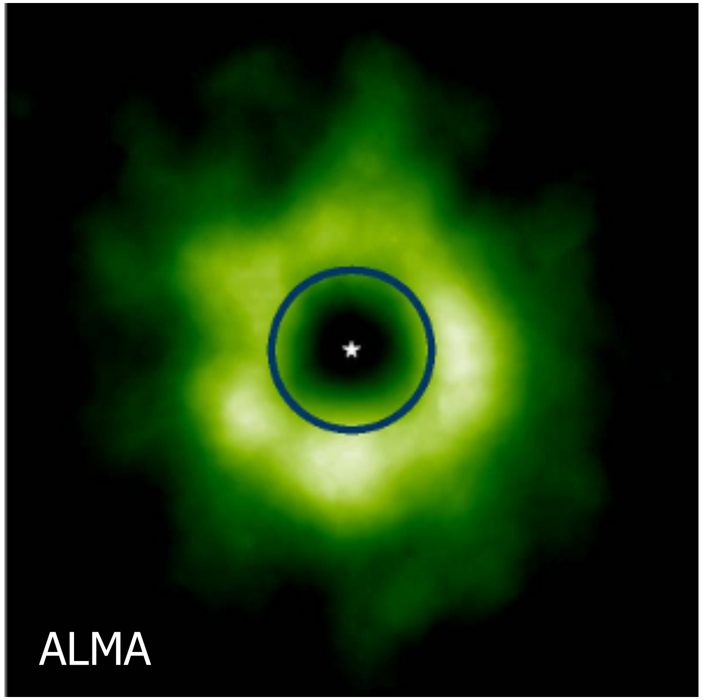
Objective: Determine distribution of water & ices

→ link to habitability

CO snow line in TW Hya



Öberg et al.



Qi et al. 2013

Water on terrestrial planets:

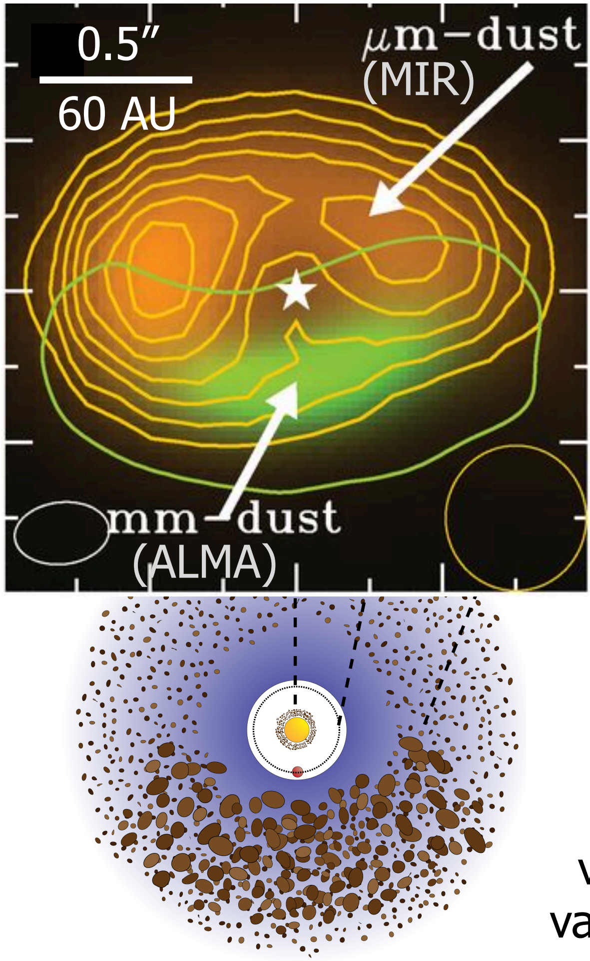
- Planetesimal delivery (Morbidelli et al. 2000)
- Atmospheric capture in the inner disk (Ikoma et al. 2006)

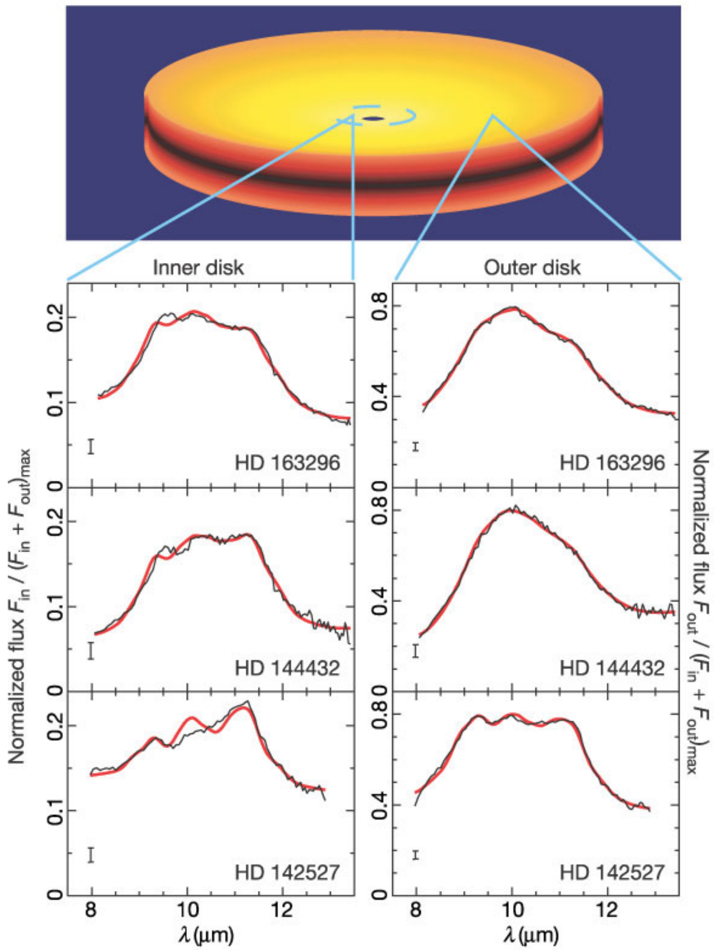
PFI+ALMA: Tracing complementary dust species

Objective: Map spatial variations in dust mineralogy (SiO, PAH, …)

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

→ complements ALMA resolution (5 mas)
(resolution of ELTs insufficient at 10μm: 70 mas = 10 AU)

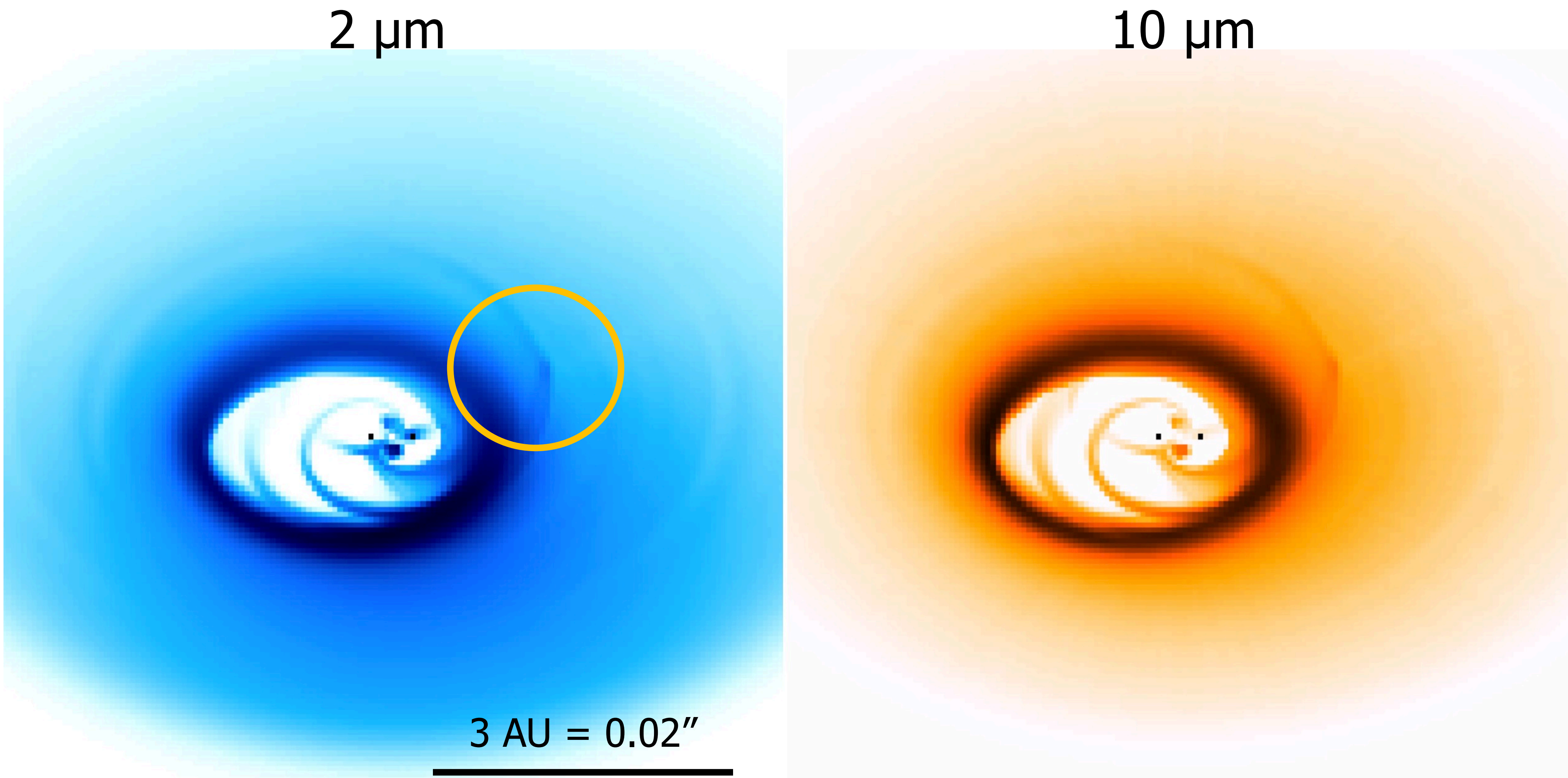




van Boekel et al. 2004
van der Marel et al. 2013

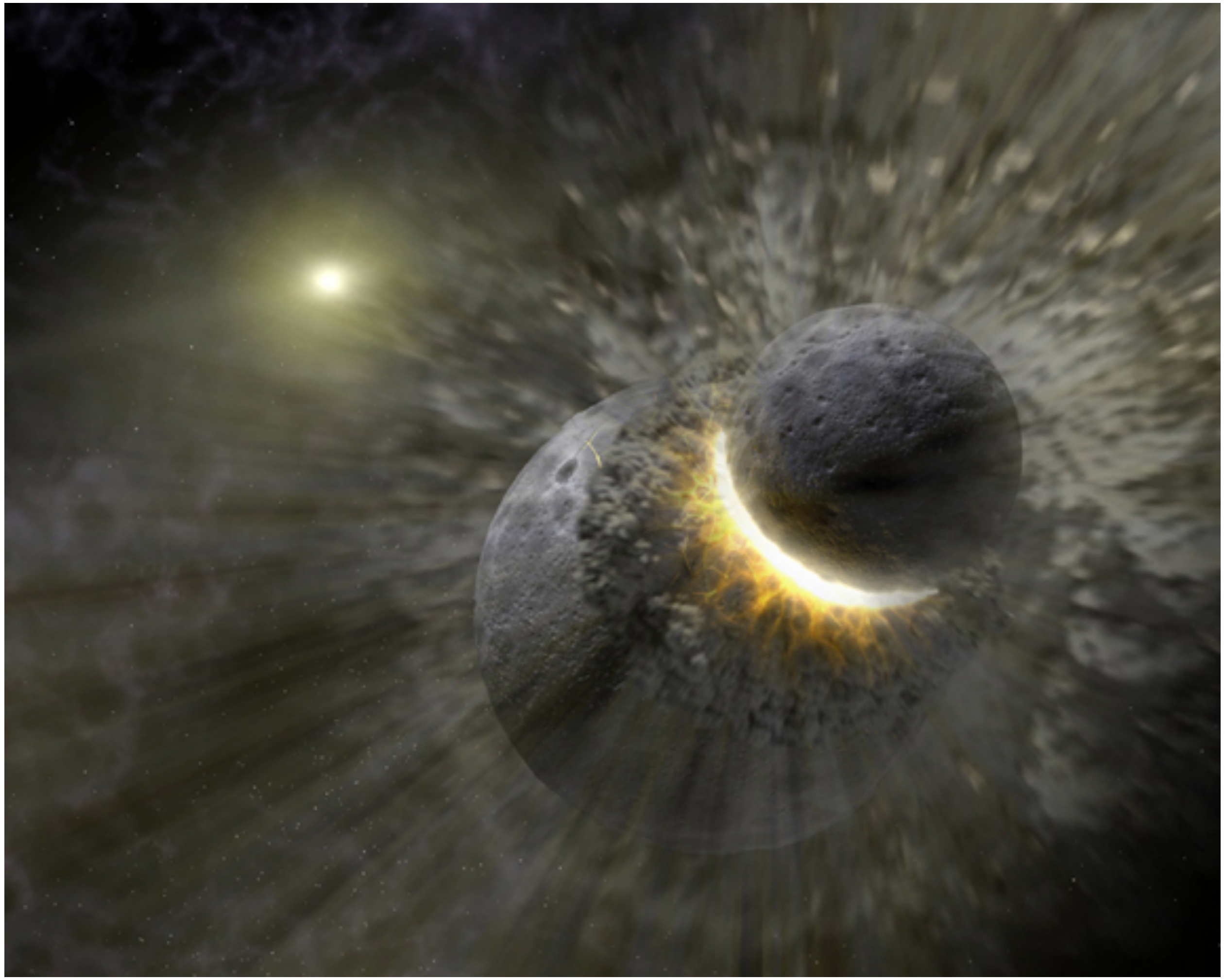
Planet formation in binary systems

Simulation of **Kepler 34 system** (Stellar orbit: a=0.25 au, *e*=0.5; 1:1 mass ratio; R_{in}=0.5 AU; Planet orbit: 0.9 AU, e=0.2)



PFI SWB, credit: Nelson, Duchene, Kley, Pinte

Dust-producing Giant Impact events

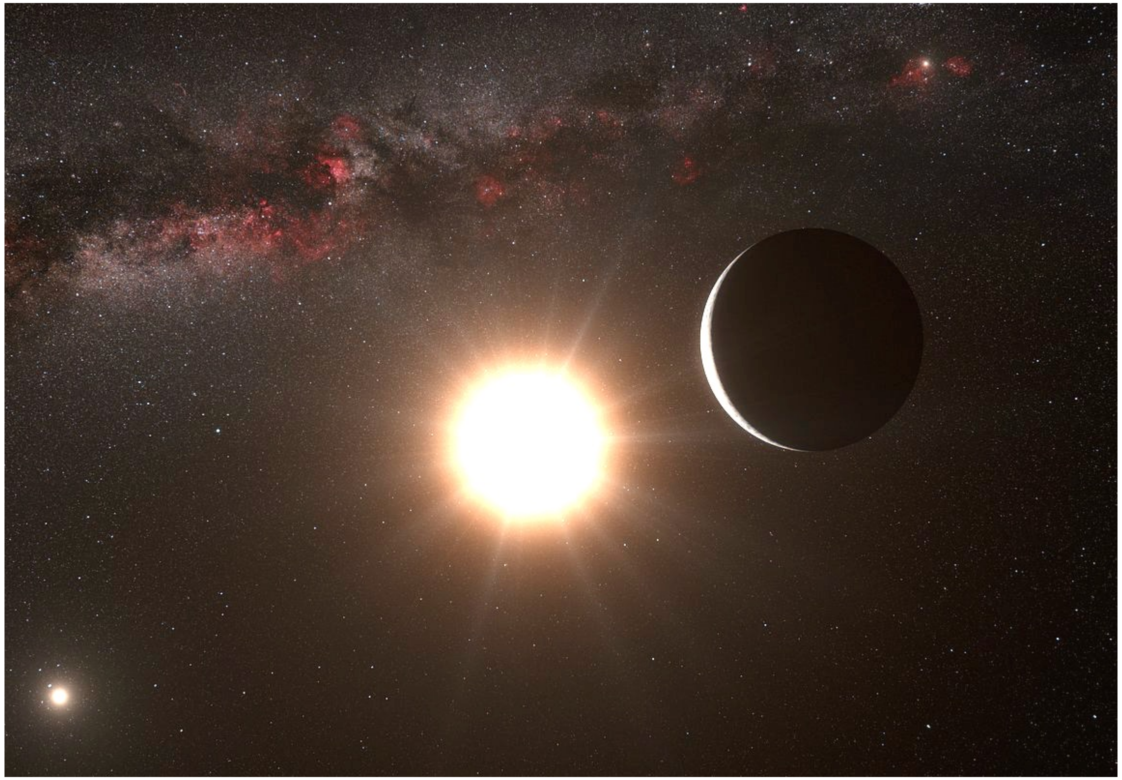


Earth/Moon system formation illustration

age: 105 Myr

In the late stages of planet formation, Giant Impact event must produce large amount of excess dust in an otherwise cleared disk
→ potentially detectable with PFI

Exoplanet characterisation



Hypothetical Earth-like planet in the habitable zone (0.03 AU) around Proxima Centauri (d=1.3 pc, M6 type)

- Separation ∼20 mas
- Contrast $\sim 10^{6 \ldots 7}$ (L-band)
- Planet diameter ∼0.07 mas

PFI could provide (assumes optimisation to achieve contrast requirement):

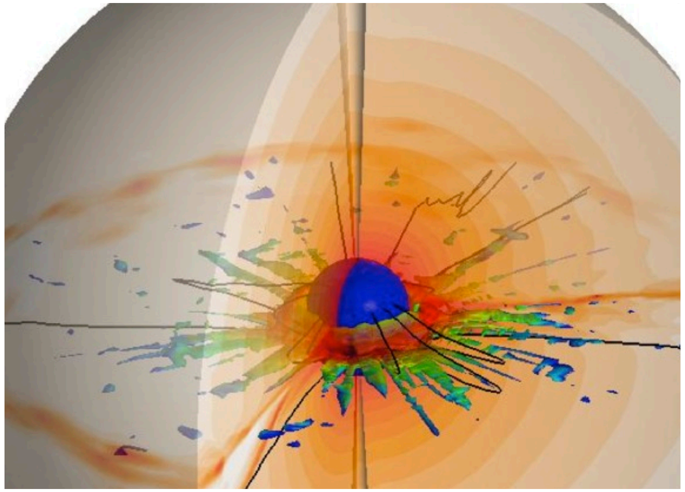
- Astrometric orbit
- Spectroscopic characterisation (L/M/N-band spectrum)
- Measure the diameter of planet itself
- Potentially measuring kinematic signatures from the atmosphere (photocenter shifts)

→ Link with “Project Starshot” from *Breakthrough Initiative*

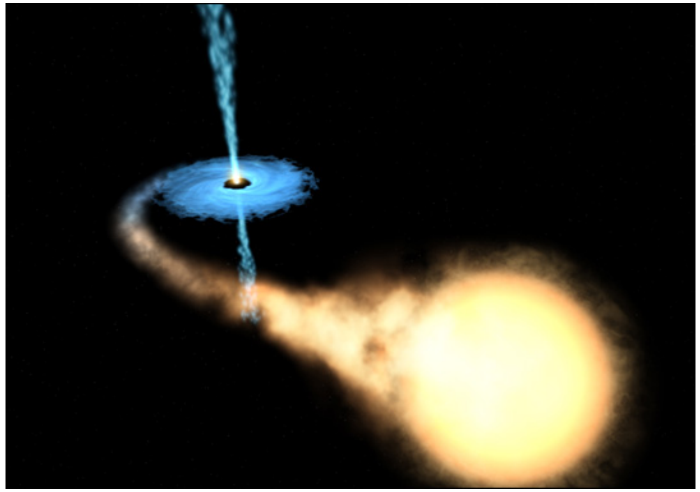
Some secondary science cases

Stellar surfaces

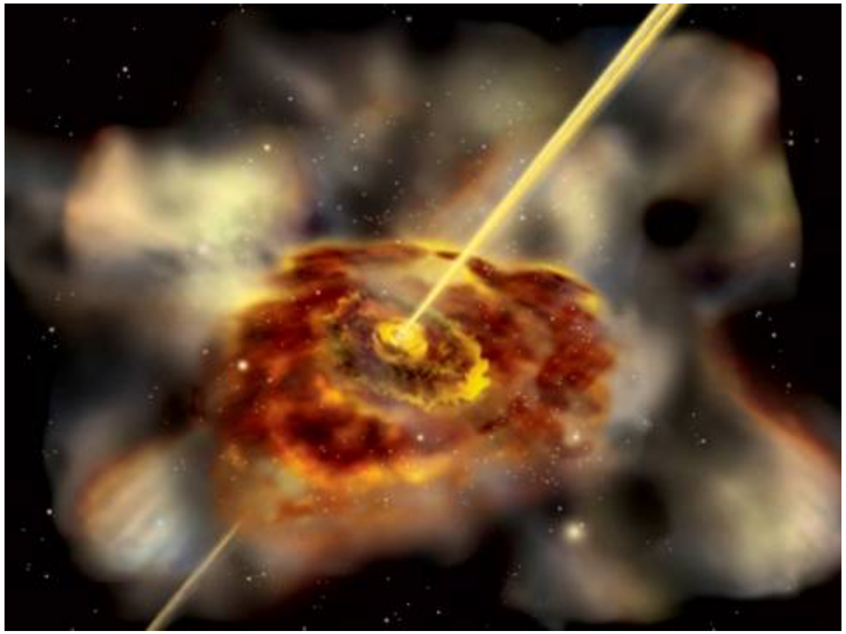
Magnetically-supported outflows



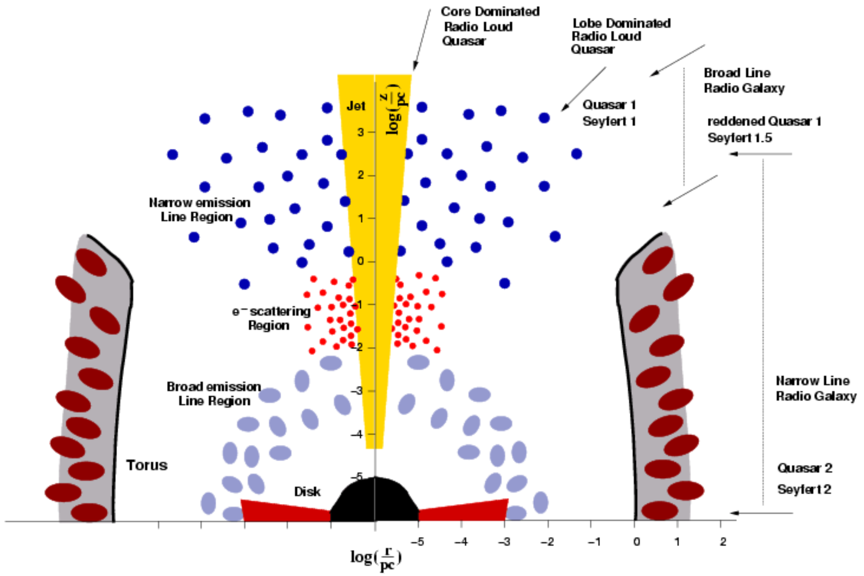
Star/BH binaries



SMBH accretion

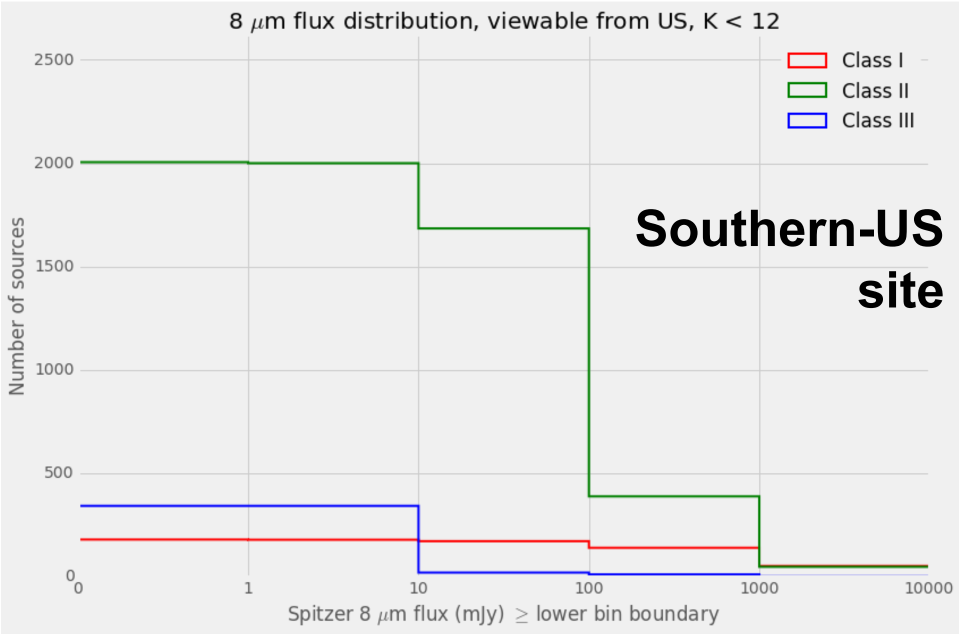


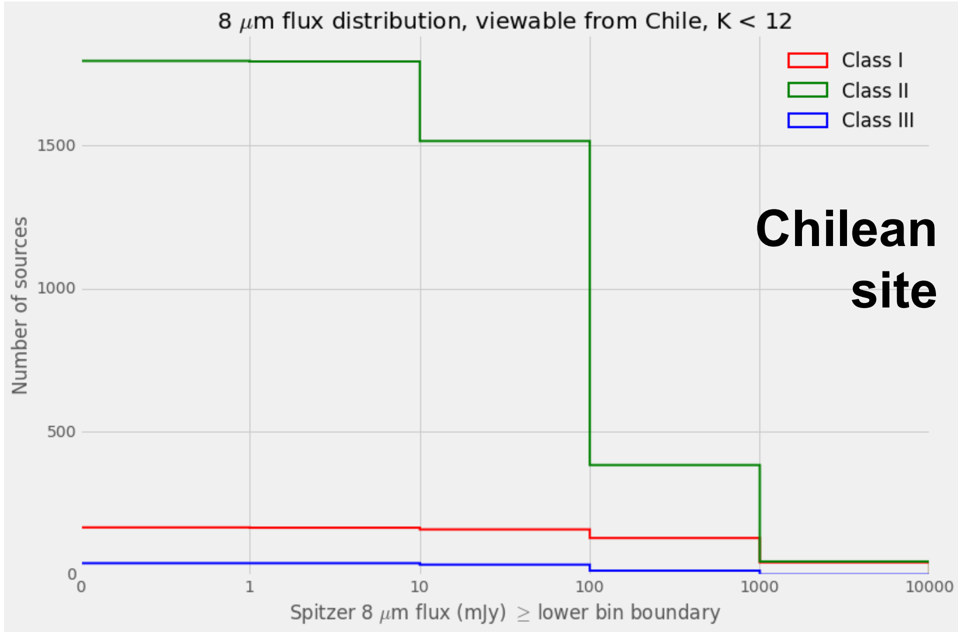
AGN dust distribution / BLR kinematics

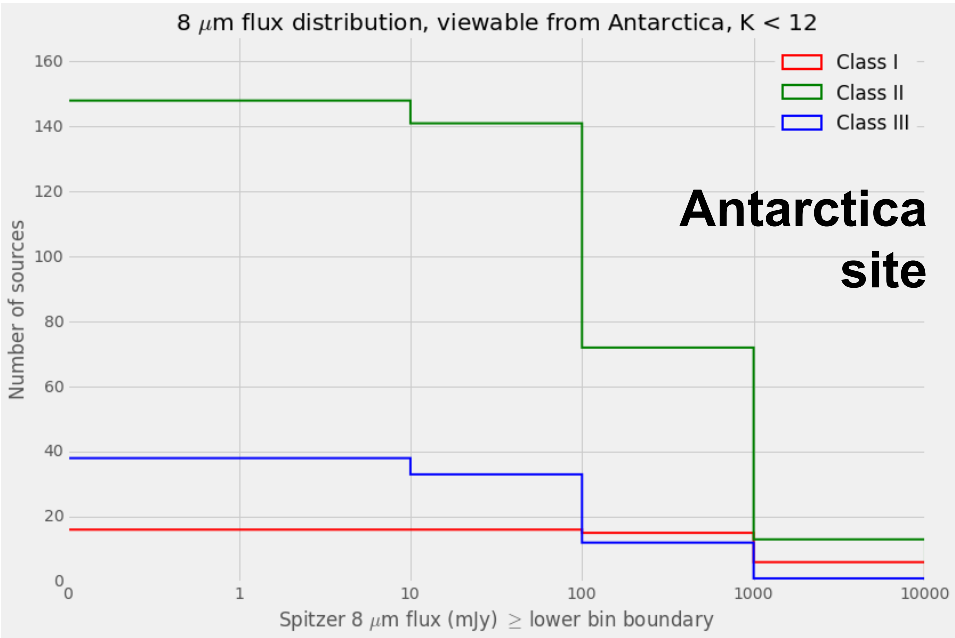


Credits: Chiavassa; ud-Doula et al. 2013; Zier & Biermann 2002

Site selection considerations







Number of objects accessible from potential observatory sites, assuming K<12 mag, N<10 mJy:

Southern-US site: ≈ 2000

Chilean site: ≈ 1700

Antarctica site: ≈ 200

PFI: Top-Level Science Requirements

- Resolve Hill-sphere size region of Jupiter at 1 AU (0.03 AU) in nearby star forming region (140pc)
  → 0.2 milliarcseconds

SCENARIO 1: optimised for **continuum detection**

- **10 µm (N band)** optimal to trace the planets as they cool
- PRO: Circumplanetary continuum emission rather extended
- PRO: Traces protoplanet + disk emission → complex scenes
- PRO: Allows dust mineralogy studies → complementary to ALMA
- Existing models allow to estimate sensitivity requirements:
  Circumplanetary disk: N_{mag}=11
  Protoplanet (1 M_{Jup}): 10 Myr: N_{mag}~16, 100 Myr: N_{mag}~18
- Spectral line tracers: HI (7-6), HI (9-7), [NeII]
- 0.2 mas at 10 µm → 7 km baselines
- Possible implementation:
  Heterodyne, requires high contrast + many apertures

PFI: Top-Level Science Requirements

- Resolve Hill-sphere size region of Jupiter at 1 AU (0.03 AU) in nearby star forming region (140pc)
  → 0.2 milliarcseconds

SCENARIO 2: optimised for **spectral line detection**

- **3-5 µm (L+M band)**
- PRO: Rich line tracers: Pf β, Pf γ, CO, H_2O, …
- PRO: Less confusion with disk emission → fewer apertures needed
- PRO: Powerful constraints on kinematics & physical conditions in circumplanetary disk
- Difficult to make quantitative predictions on sensitivity requirements (accretion geometry unclear)
- Continuum: very compact (1/10 of Hill sphere)
- 0.2 mas at 4 µm → 3 km baselines
- Possible implementation:
  Homodyne, moderate contrast, moderate number of telescopes

Project Status

- Series of SPIE papers published in 2014 (3 papers) and 2016 (7 papers)
- Call to the science and technology community resulted in strong response:
  80/60 scientists volunteered to contribute to SWG/TWG whitebooks
  → Further contributions very welcome → *http://www.planetformationimager.org*
- PASA journal agreed to publish the PFI science white book as a collection of 10 peer-reviewed articles
- First funding for technology developments:
  MIR laser-freq. comb heterodyne lab demonstrator (Gautam Vasisht, JPL)
  NIR heterodyne on-sky demonstrator (Ernest Michael, U. Chile)

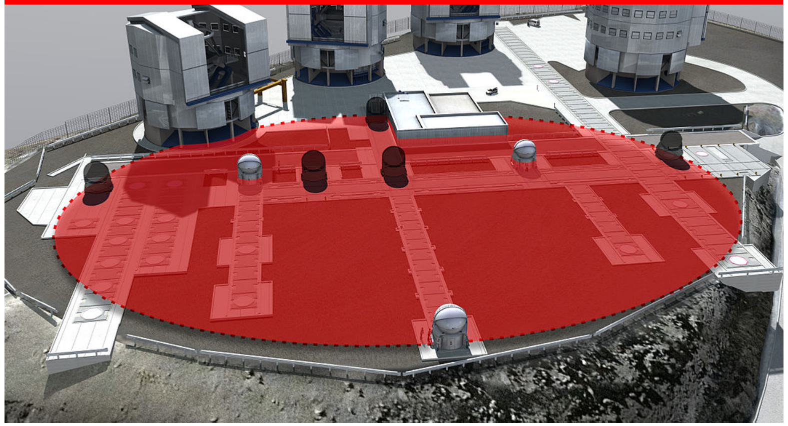
PFI:
Technology architectures under investigation

Architecture Overview

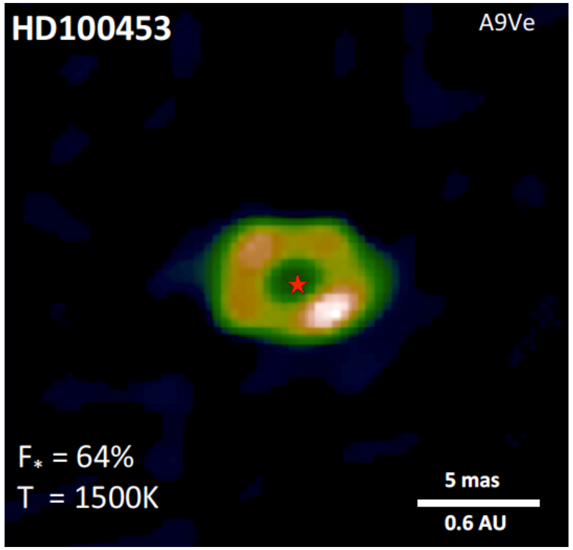
1. NIR/MIR Conventional Direct Detection Interferometer
2. MIR Heterodyne Interferometer
3. [MIR/FIR Space Interferometer]
4. [ALMA ++]

Architecture 1:
Conventional ground-based interferometer design

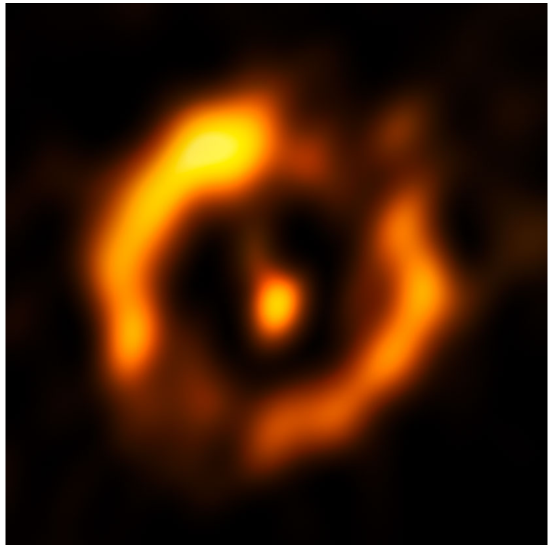
VLTI: 4T (10 observables)

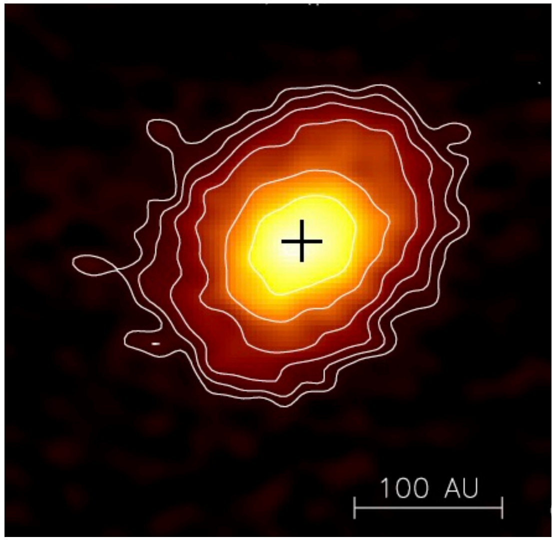


VLTI: Dust sublimation rim
HD100453
(Kluska et al. in prep)



VLTI: Circumbinary disk
around post-AGB star
(Hillen et al. 2016)

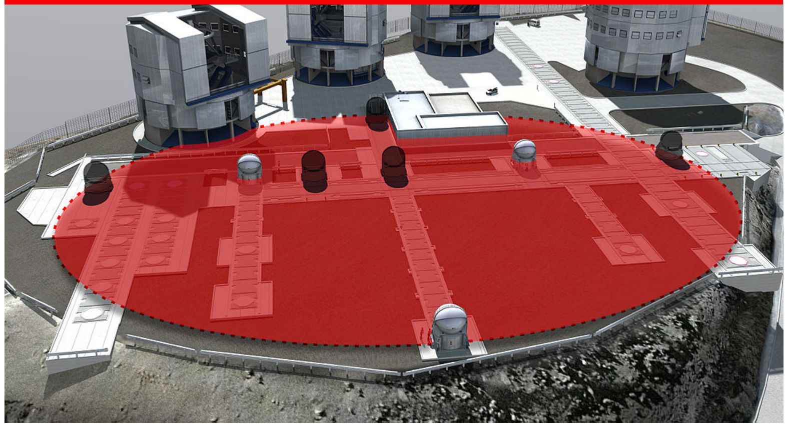




For comparison:
CARMA, HL Tau image
(Kwon et al. 2011)

Architecture 1:
Conventional ground-based interferometer design

VLTI: 4T (10 observables)



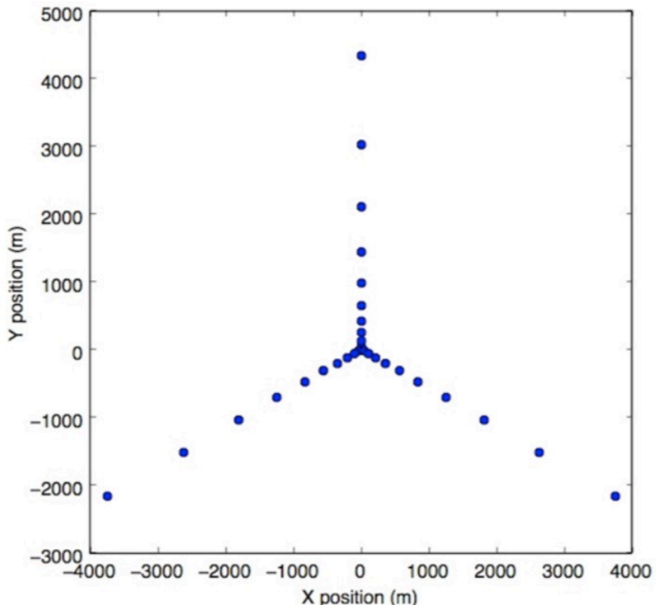
Scale it up?

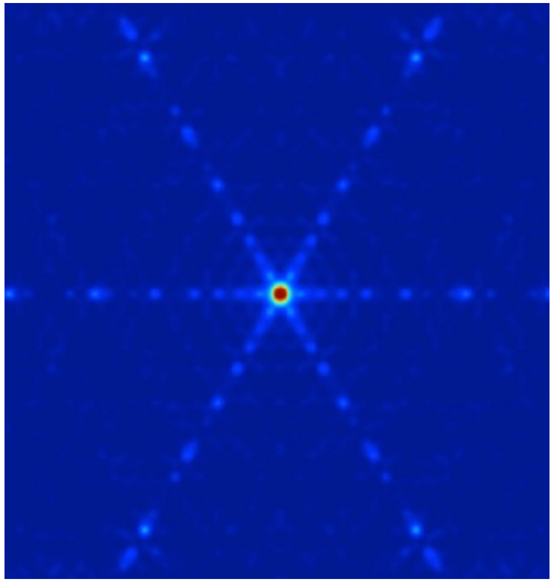
20T (1330 observables)

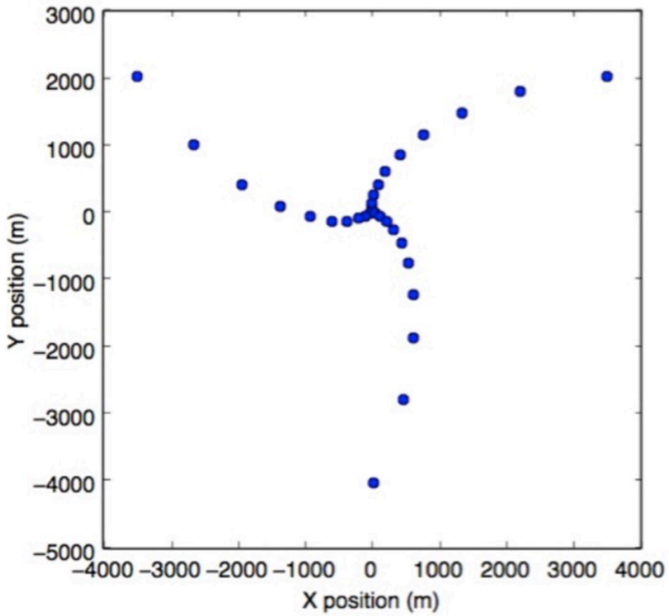
Architecture 1:
Conventional ground-based interferometer design

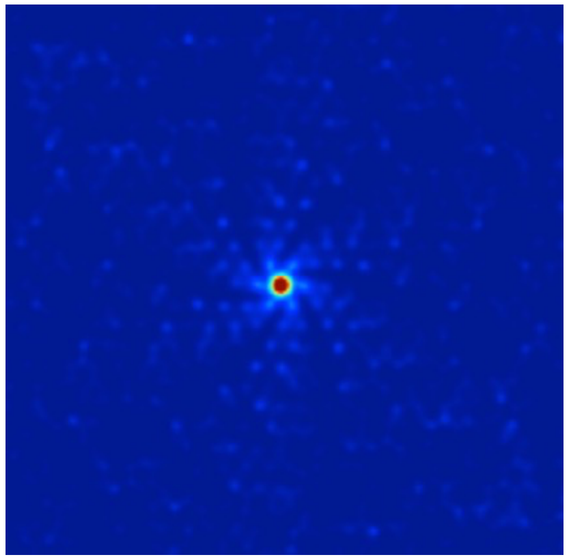
N>20 telescopes due to complex imaging

7 km baselines









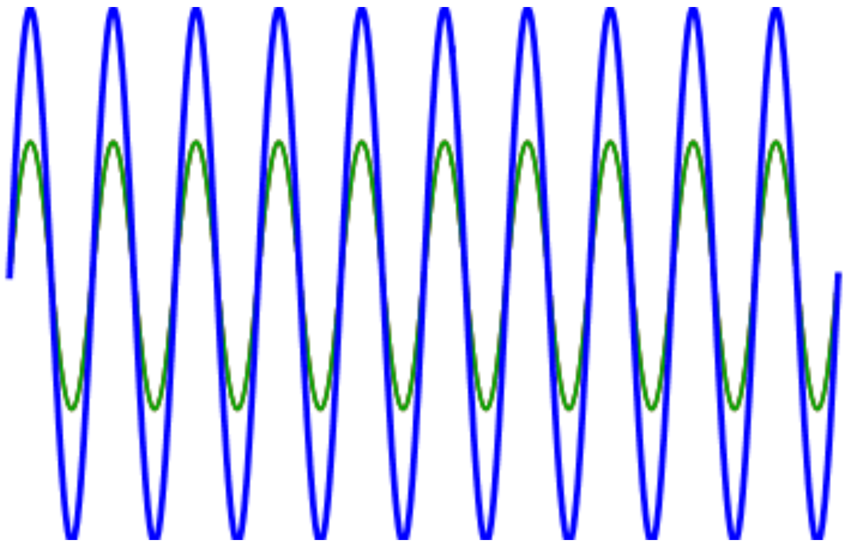
Architecture 1: Conventional ground-based interferometer design

- Sensitivity considerations
  - 2m *minimum* telescope diameter for NIR fringe tracking
    - Natural guide star AO is sufficient for YSO case
  - 4m telescopes with H/K band fringe tracking
  - 10s coherent integrations get to N~7.5 (VLTI/MIDI)
    - Compatible with water vapor “seeing”
  - 10 hours integration of bispectra can get down to N=15 *in principle (detect individual giant planets)*
  - SWG/TWG validate SNR model using realistic simulations

- Expensive, e.g. vacuum pipes alone would require 30,000 tons of steel, with 15 MEUR costs for raw material (diameter 0.5m, wall thickness 30mm)

Architecture 2:
Heterodyne Interferometry

- Star light is mixed with laser at telescope, digitalised, and then combined in electronic correlator
- Charlie Townes' Infrared Spatial Interferometer (ISI) is a mid-IR interferometer
  - Limiting magnitude too low to observe YSOs
  - BUT… this is largely due to tiny ISI bandwidth ($\lambda/\Delta\lambda$ = 10,000)

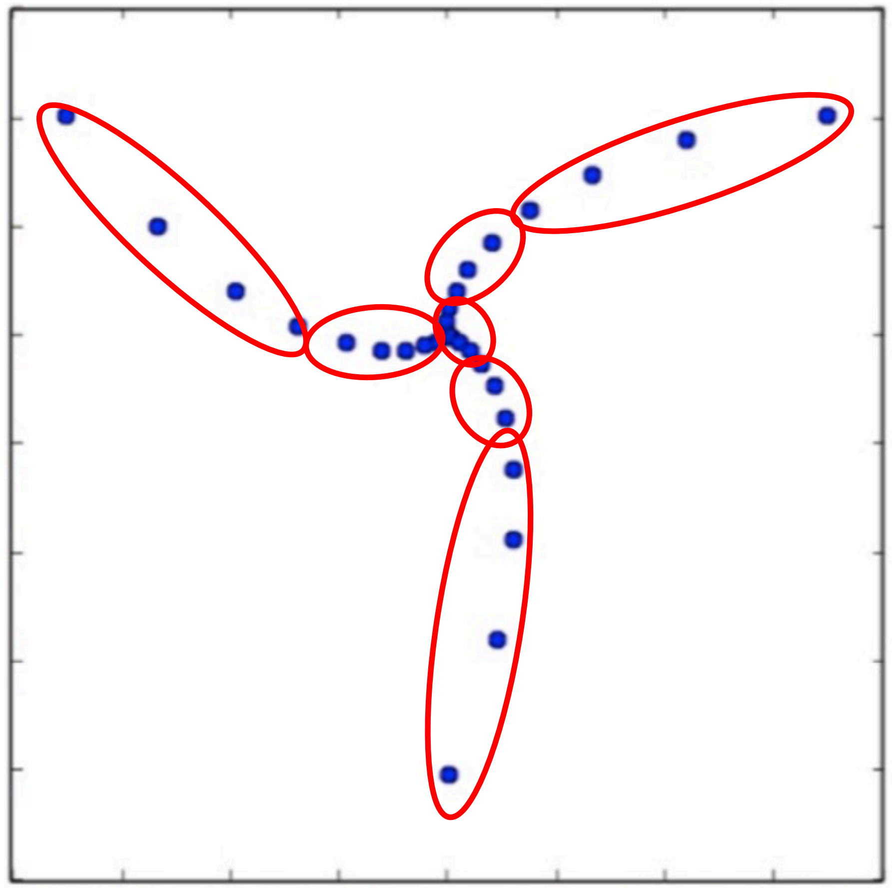


Architecture 2:
Heterodyne Interferometry

- 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 ➔ $\mathrm{SNR} \propto \sqrt{N}$ (Ireland et al. 2014, SPIE)
- Advantages
  - Higher throughput to detection
  - Ideal beam combination which is crucial for complex imaging

Architecture 2: Heterodyne Interferometry

- Must still phase up MIR using NIR fringe tracking
  - However, it is sufficient to phase up 4-5 nearest neighbors



The PFI Technical Working Group (TWG)

Identifies the key technologies and develops a technology roadmap

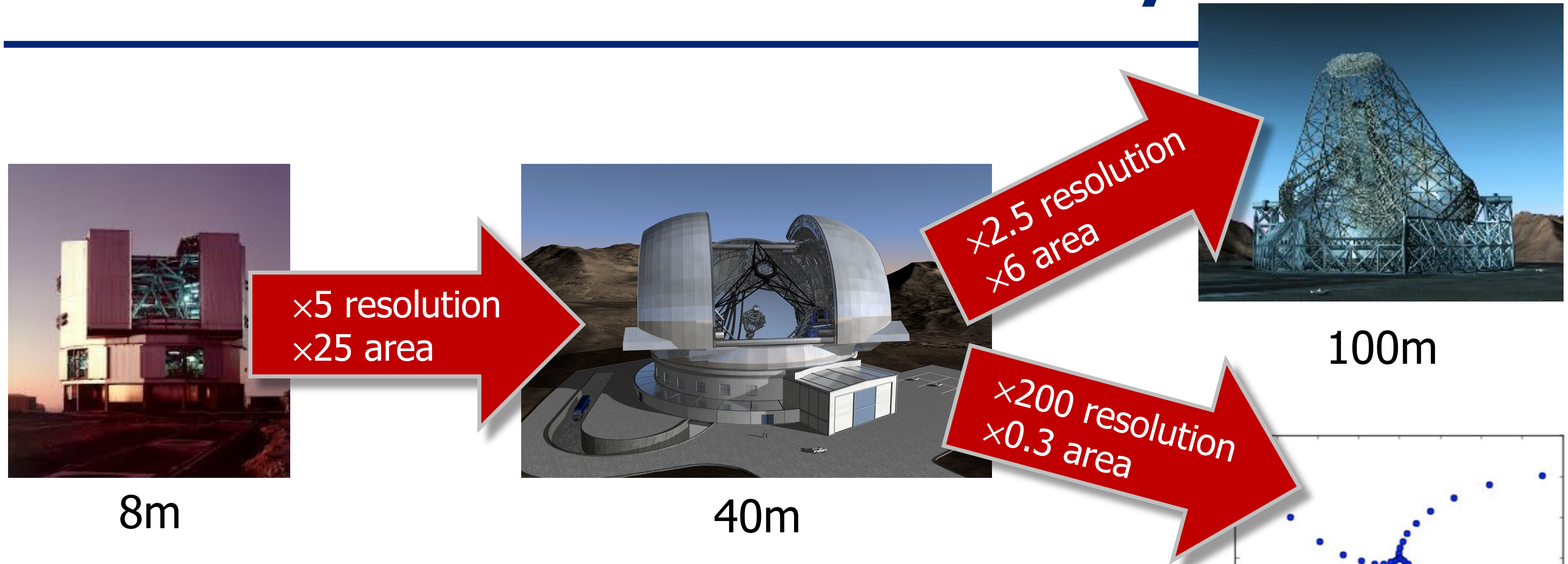
Concept architectures:

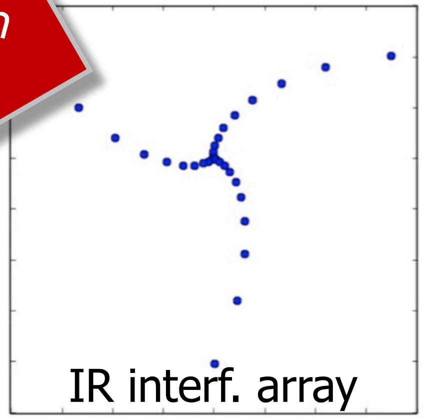
1. Visible and NIR interferometry (lead by Romain Petrov)
2. Mid-IR interferometry – direct detection (lead by David Buscher)
3. Mid-IR interferometry – heterodyne (lead by Michael Ireland)
4. Far-IR interferometry (lead by Stephen Rhinehard)
5. mm-wave interferometry (lead by Andrea Isella)
6. Non-interferometric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

Future of interferometry





IR interferometric array as post-ELT facility would…

…enter completely new regime of parameter space (0.2 mas at 10 μm)

…complement other major facilities of the 2030s
(sensitivity: ELTs/JWST, time-domain: LSST, wavelength: ALMA, SKA)

…gather support with unique new science cases

…drive technology innovation (astrophotonics, detectors, delay lines, laser-combs)

…generate industrial spin-off (cheap/light-weight telescopes)