Progress report on PFI and potential synergies with Hi5

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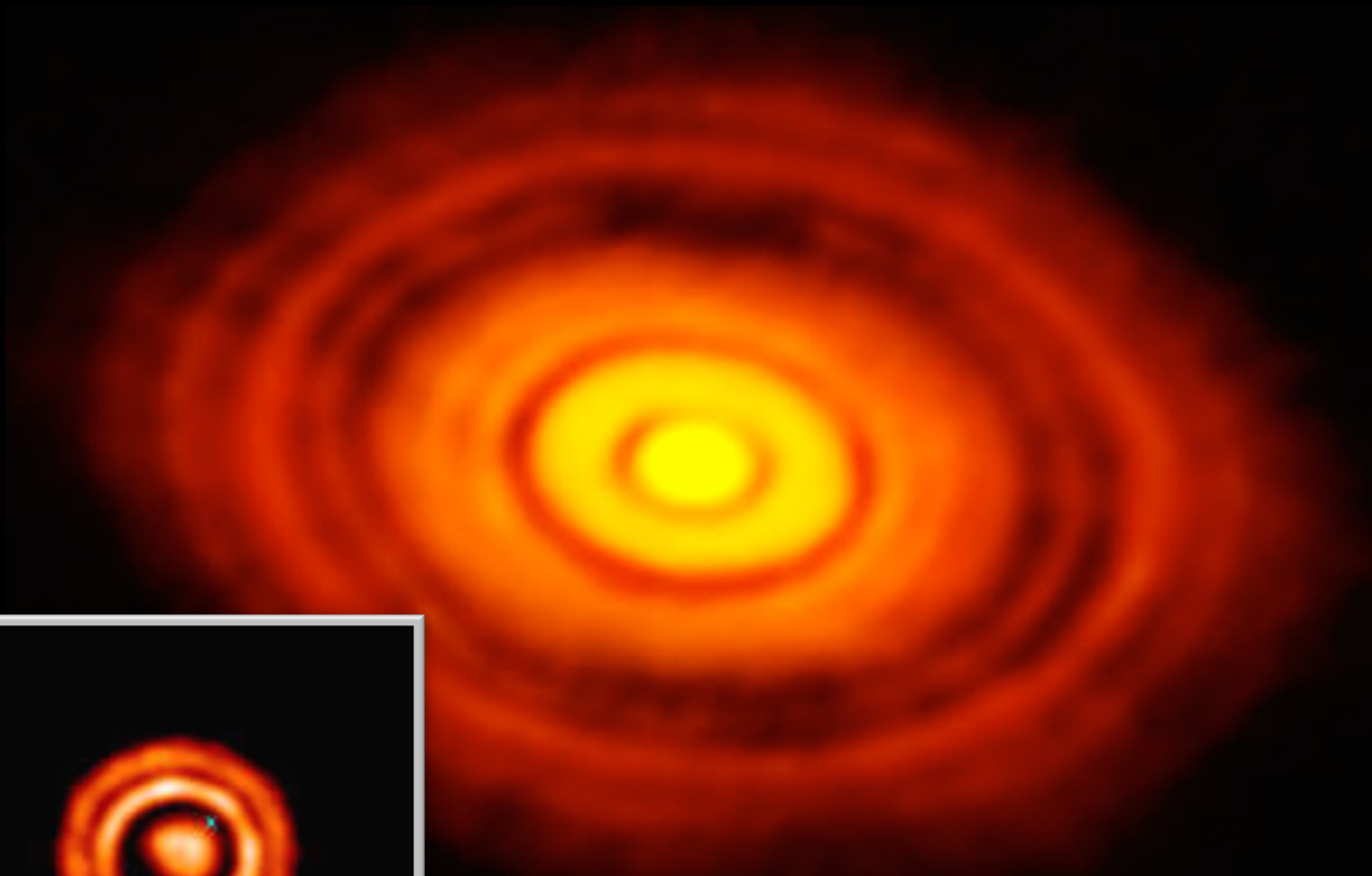
Science Case: Planet Formation

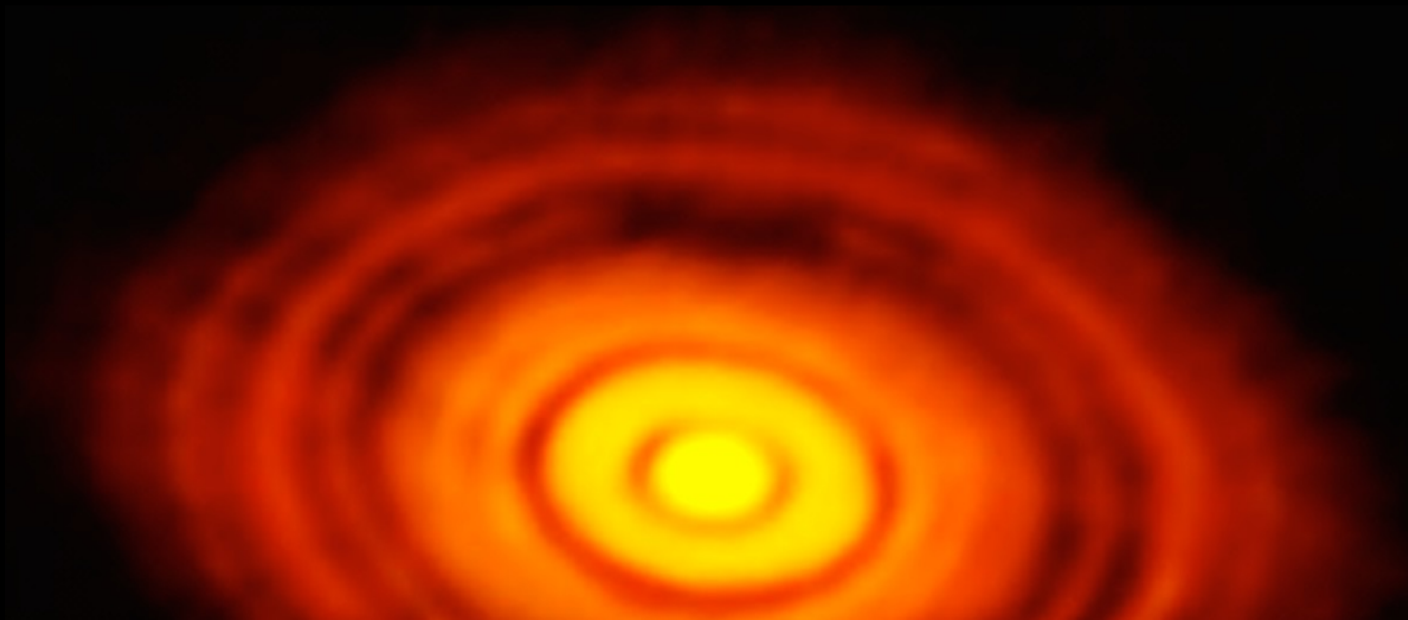


HL Tau image
ALMA 15km data

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

ALMA alone does not
provide the answers

Science Case: Planet Formation



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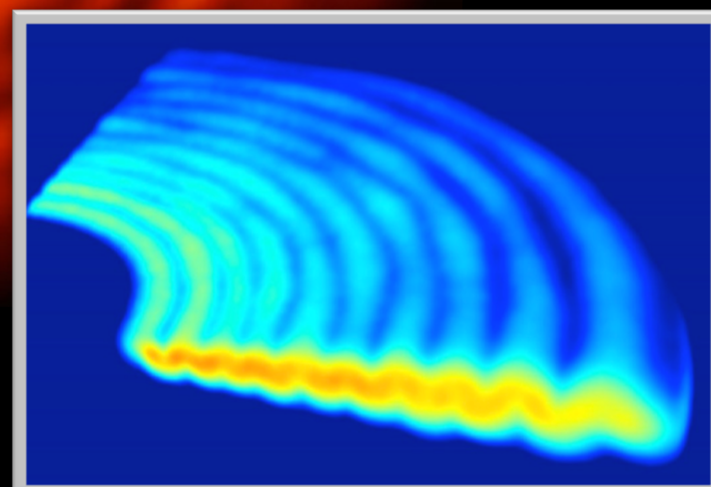
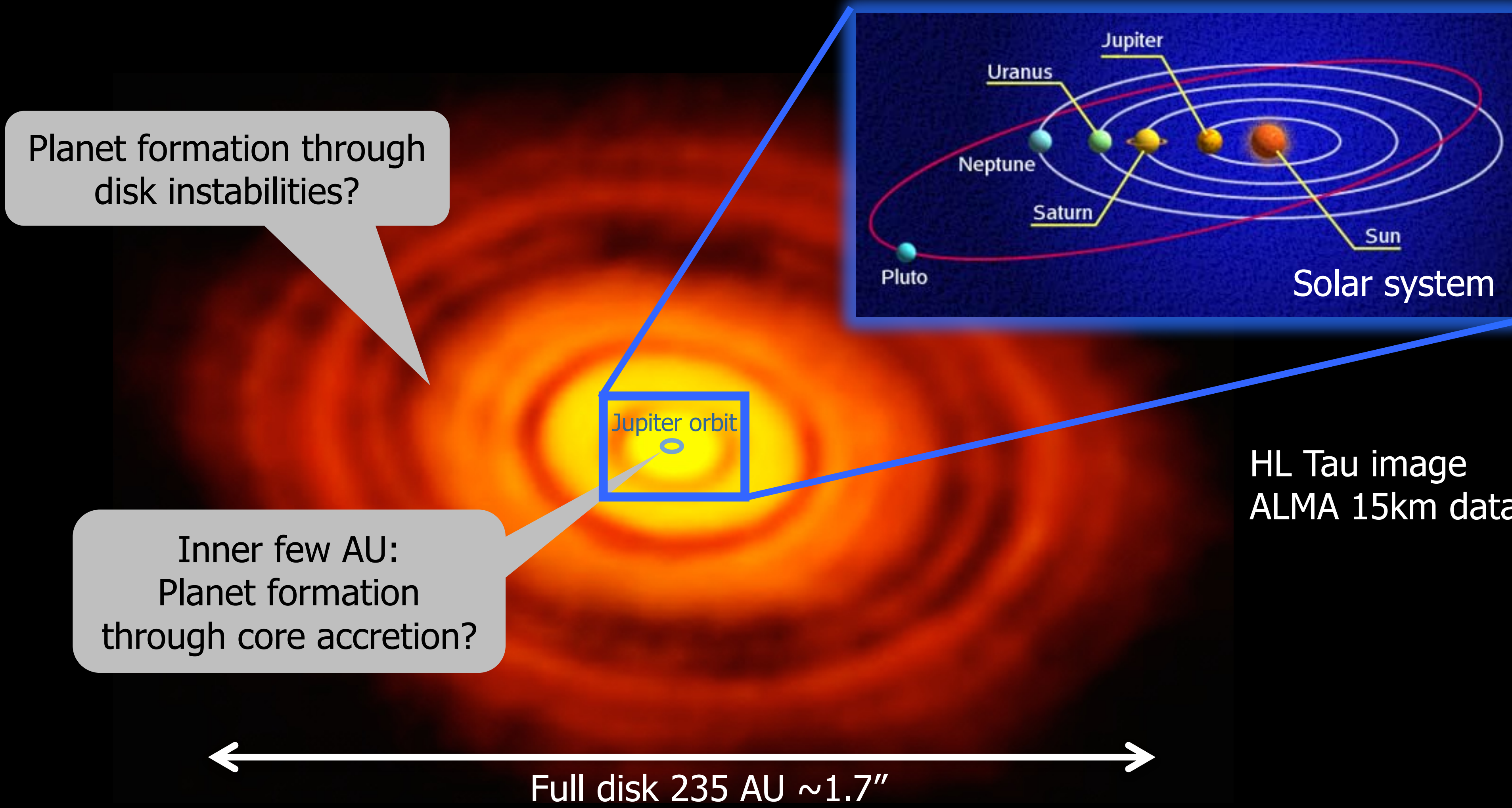


Ring structures in discs <u>without</u> planets
(Toroidal vortices; Loren-Aguilar & Bate 2015)

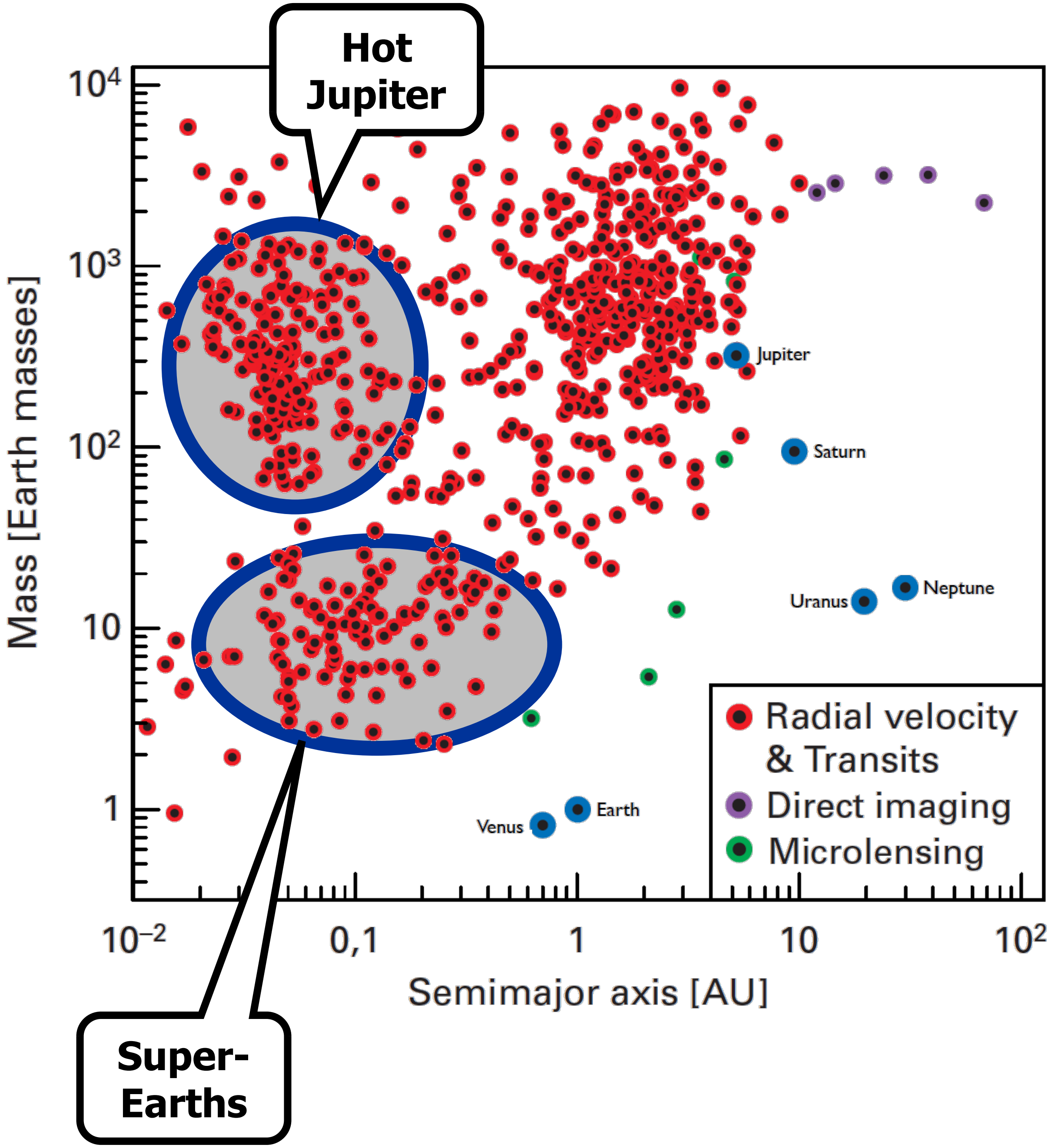
Science Case: Planet Formation



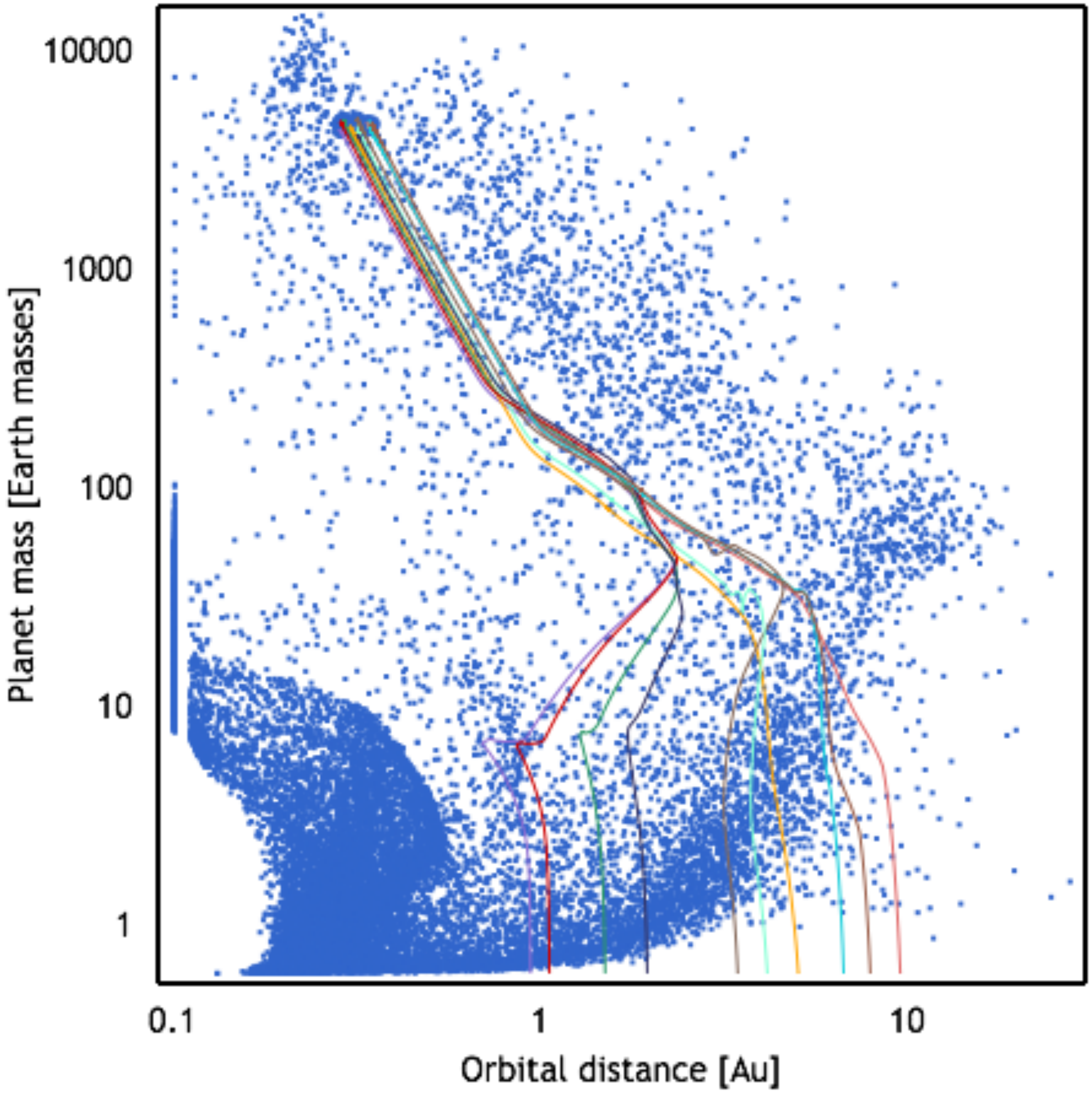
HL Tau image
ALMA 15km data

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

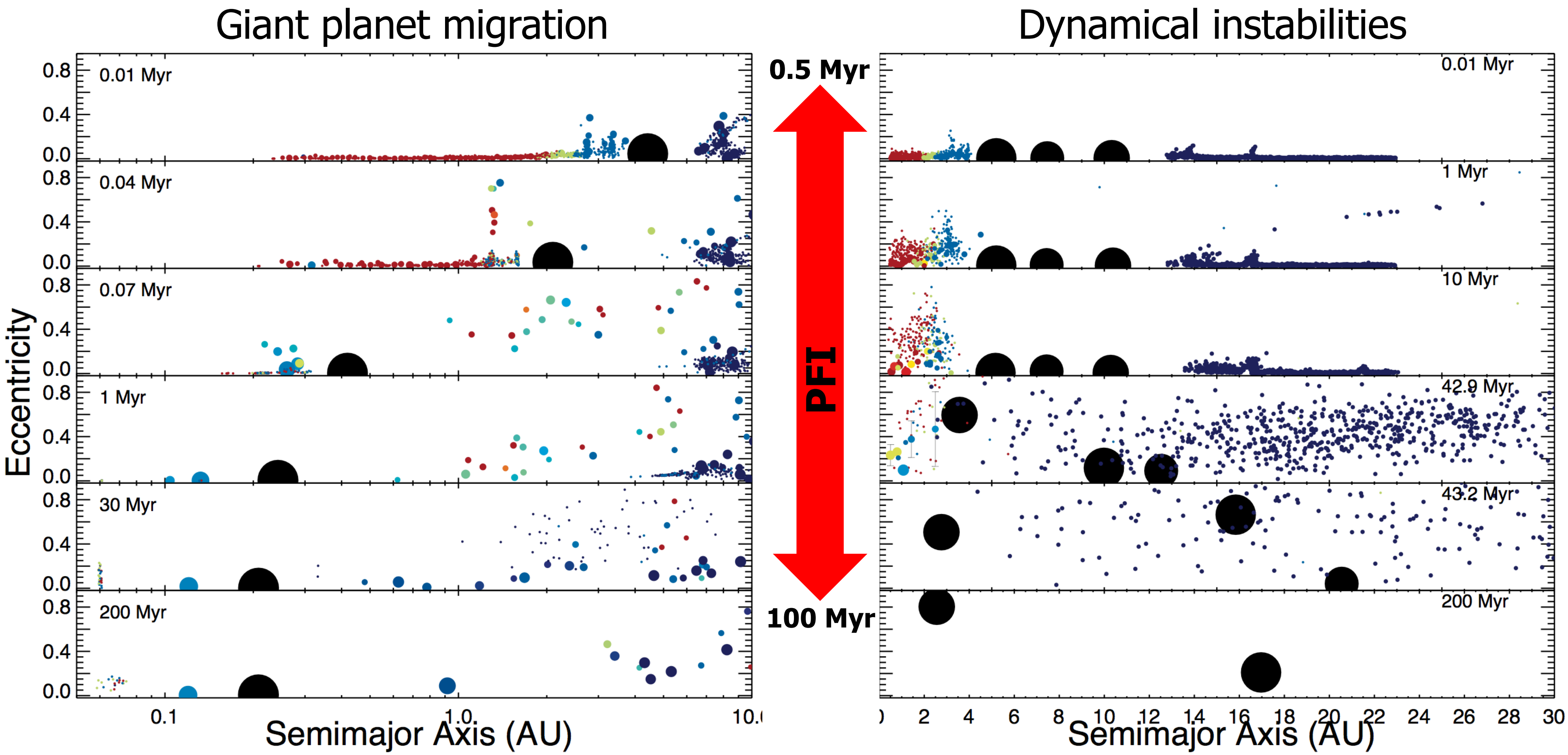


Architecture of planetary systems determined by…

- 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

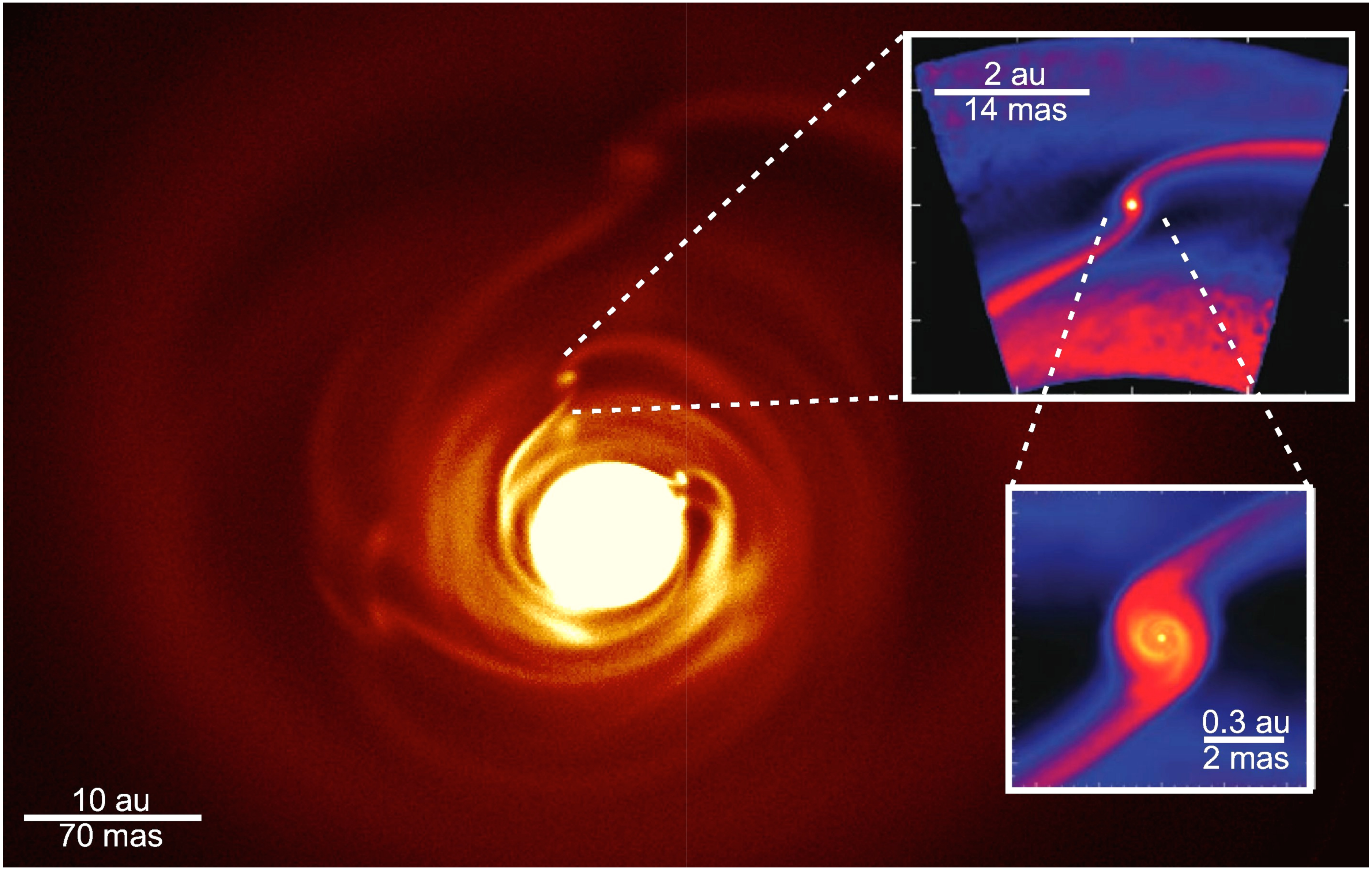
PFI: Exoplanetary systems



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

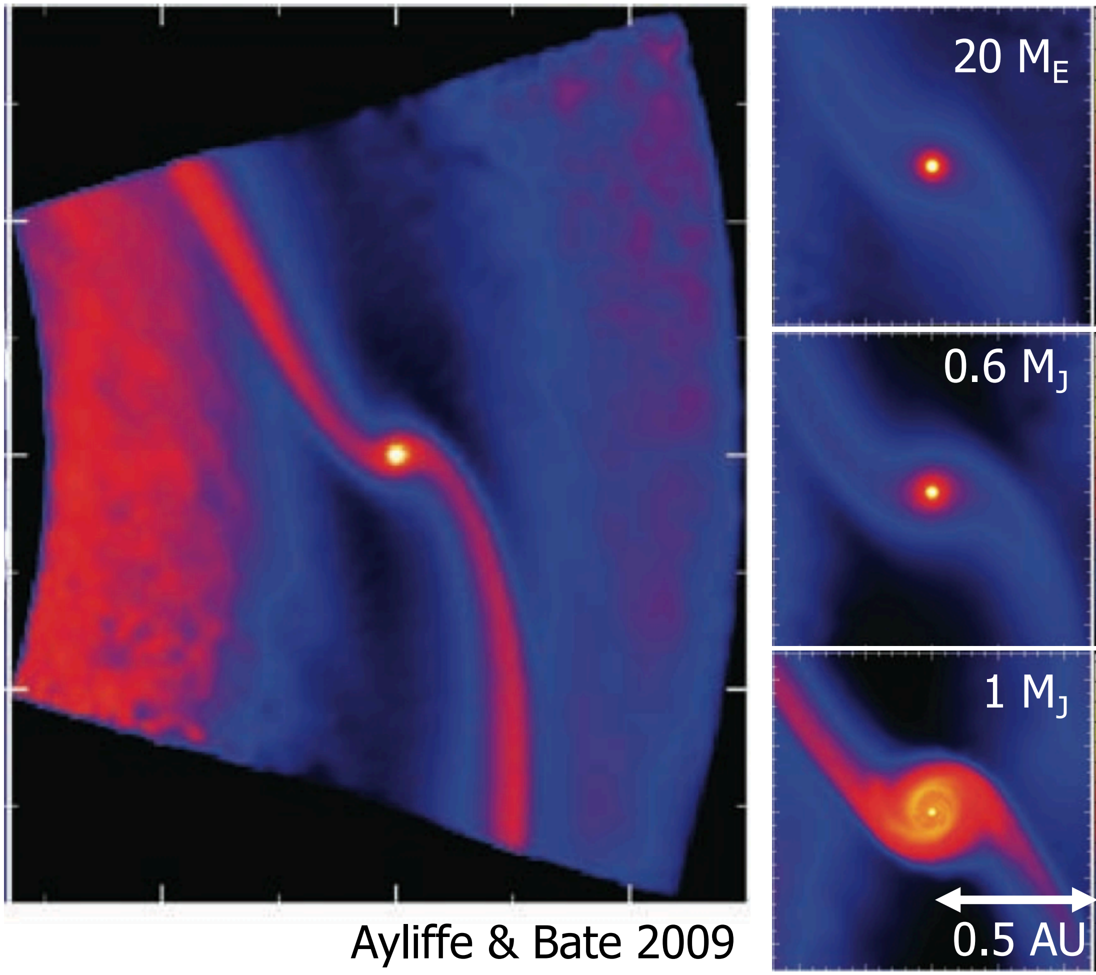
Raymond et al. 2006

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**

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.)

Planet Formation Imager (PFI) project

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)

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, …

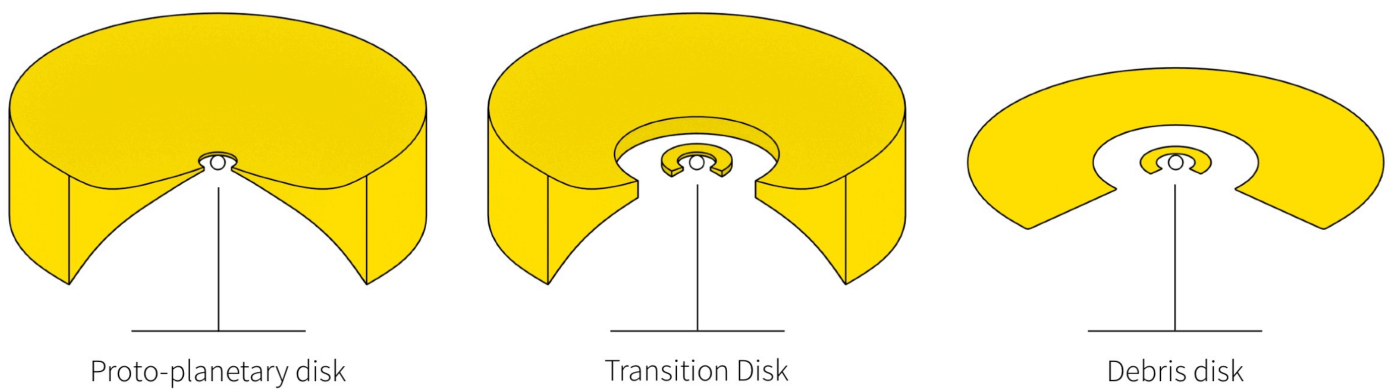
Technology Roadmap Team:

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)

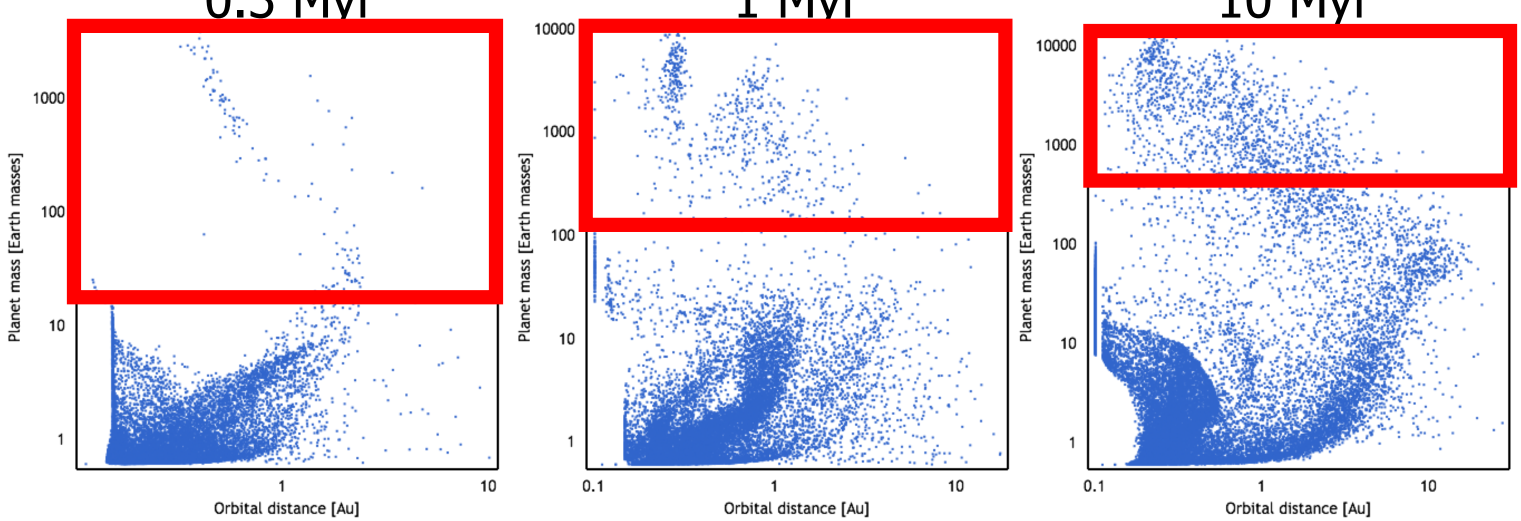
Architecture of planetary systems

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

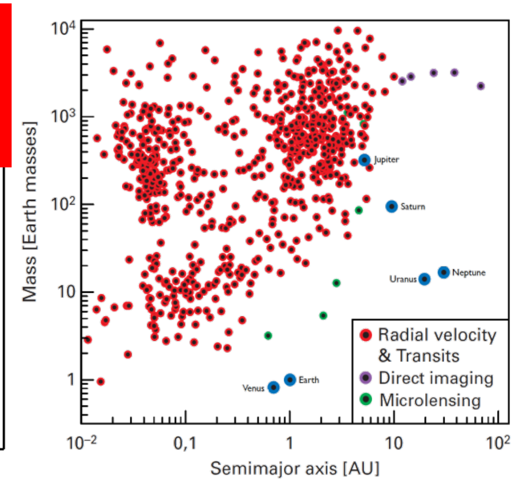
>100 systems @ 0.5 Myr | **>100 systems @ 5 Myr** | **>100 systems @ 50 Myr**



0.3 Myr | 1 Myr | 10 Myr



Exoplanet population > 1 Gyr



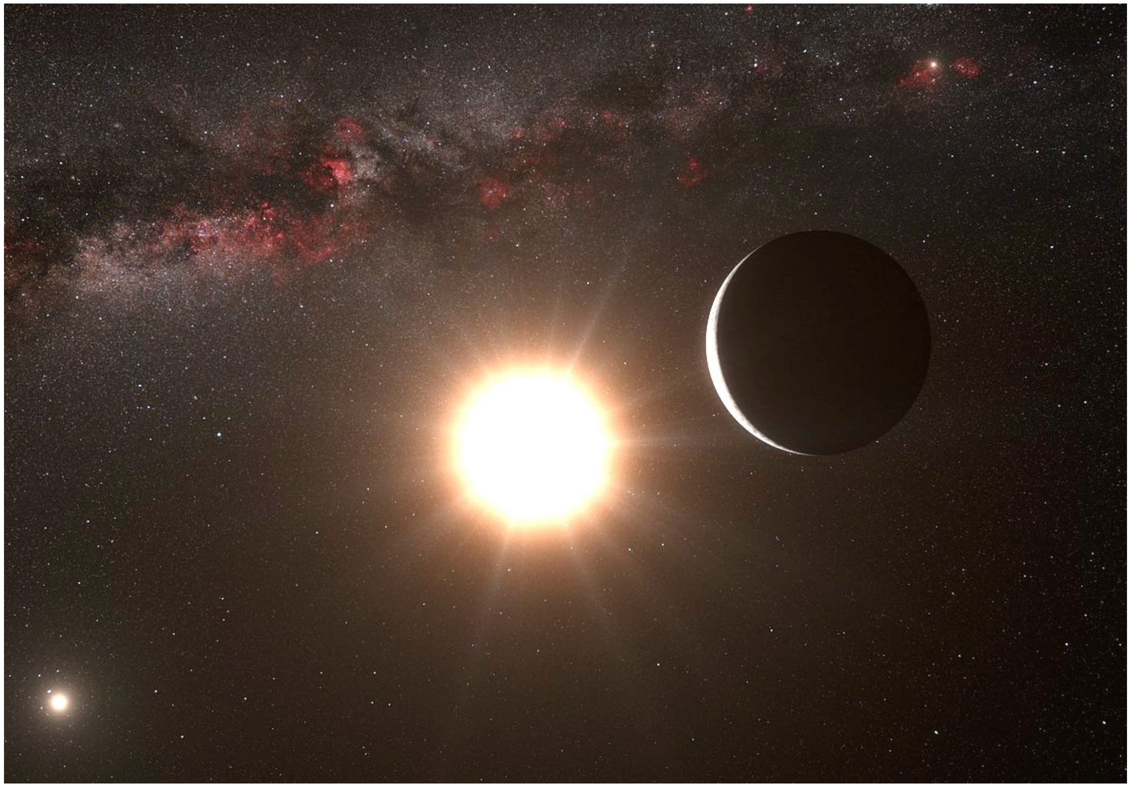
Simulation: DACE/Geneva; Illustration: Olofsson

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

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 ~$10^{6...7}$ (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*

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

FAVOURITE SCENARIO

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

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 **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

Publication strategy

- Series of SPIE papers published in 2014 (3 papers) and 2016 (7 papers)
- Series of 10 science-focussed papers + 1 technology paper in preparation
- **Peer-reviewed PASA journal agreed to publish 11 papers as special issue**

First funding successes

- **MIR laser-freq. comb heterodyne lab demonstrator**
  (Gautam Vasisht, JPL)

- **NIR heterodyne on-sky demonstrator**
  (Ernest Michael, U. Chile)

- **1 MEur "Nucleo Millenio"** 3-year grant to develop innovative **manufacturing techniques for producing cheap telescope mirror,** includes funding for 1m carbon-fibre prototype mirror
  (Amelia Bayo, Valparaiso, Chile)

PFi
Planet Formation Imager

Synergies with Hi5

Scientific:

- Hi5's mission would likely be "explorative", while PFI's mission is to provide a comprehensive picture of planet formation and characterisation (resolving circumplanetary disk)
- Hi5 discoveries could trigger interest in PFI science

Technological:

- Demonstrate achievability of contrast requirements on-sky
- Is Nulling needed (TWG concluded that nulling not needed to achieve 10^4 contrast)?
- Demonstrate achievability of sensitivity requirements on-sky