Circumstellar disks

The MIDI view

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Overview

Circumstellar disks: Potential of IR long-baseline interferometry

MIDI: Exemplary studies

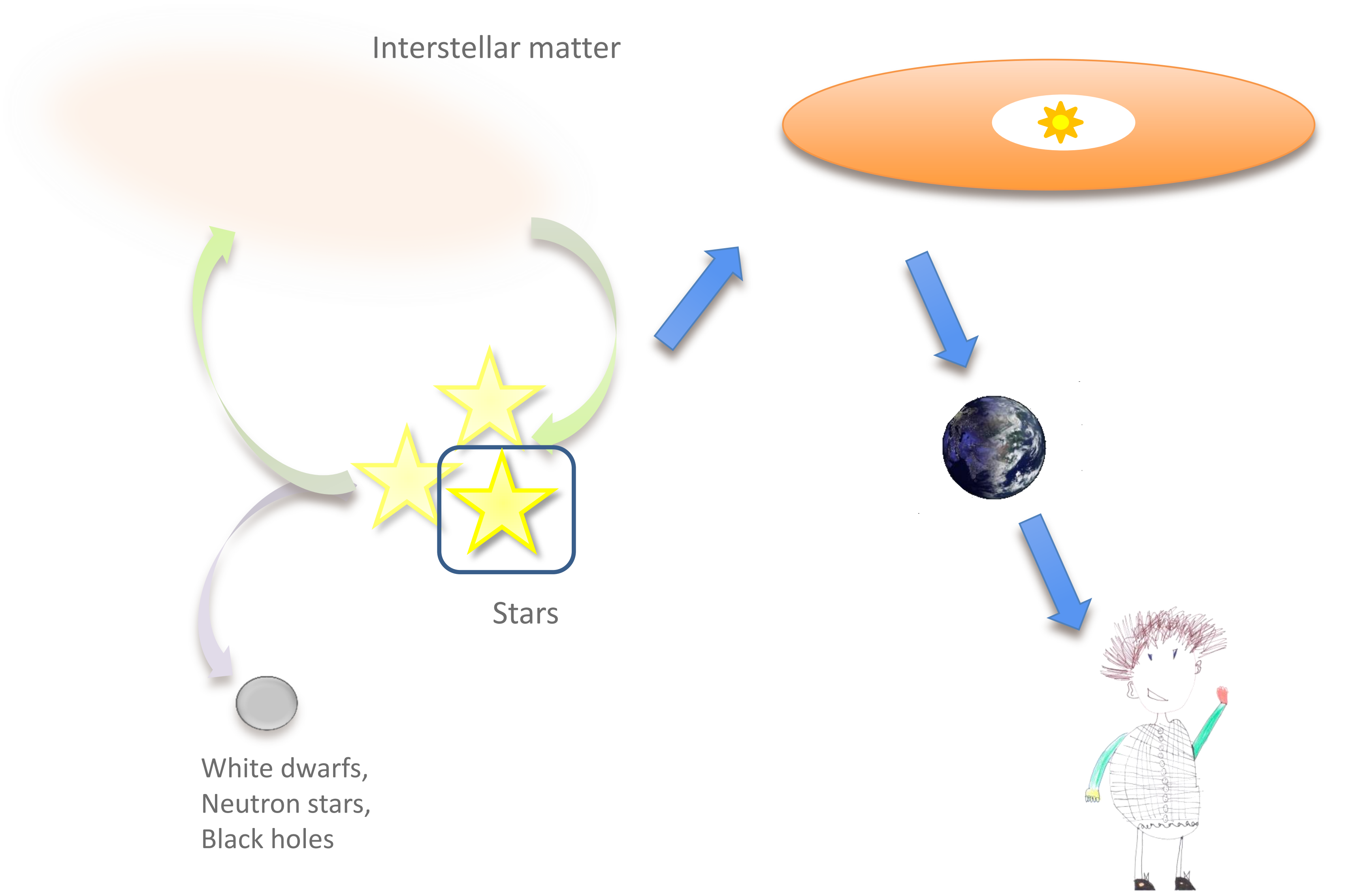
Limitations of MIDI – Prospects of MATISSE

Circumstellar disks

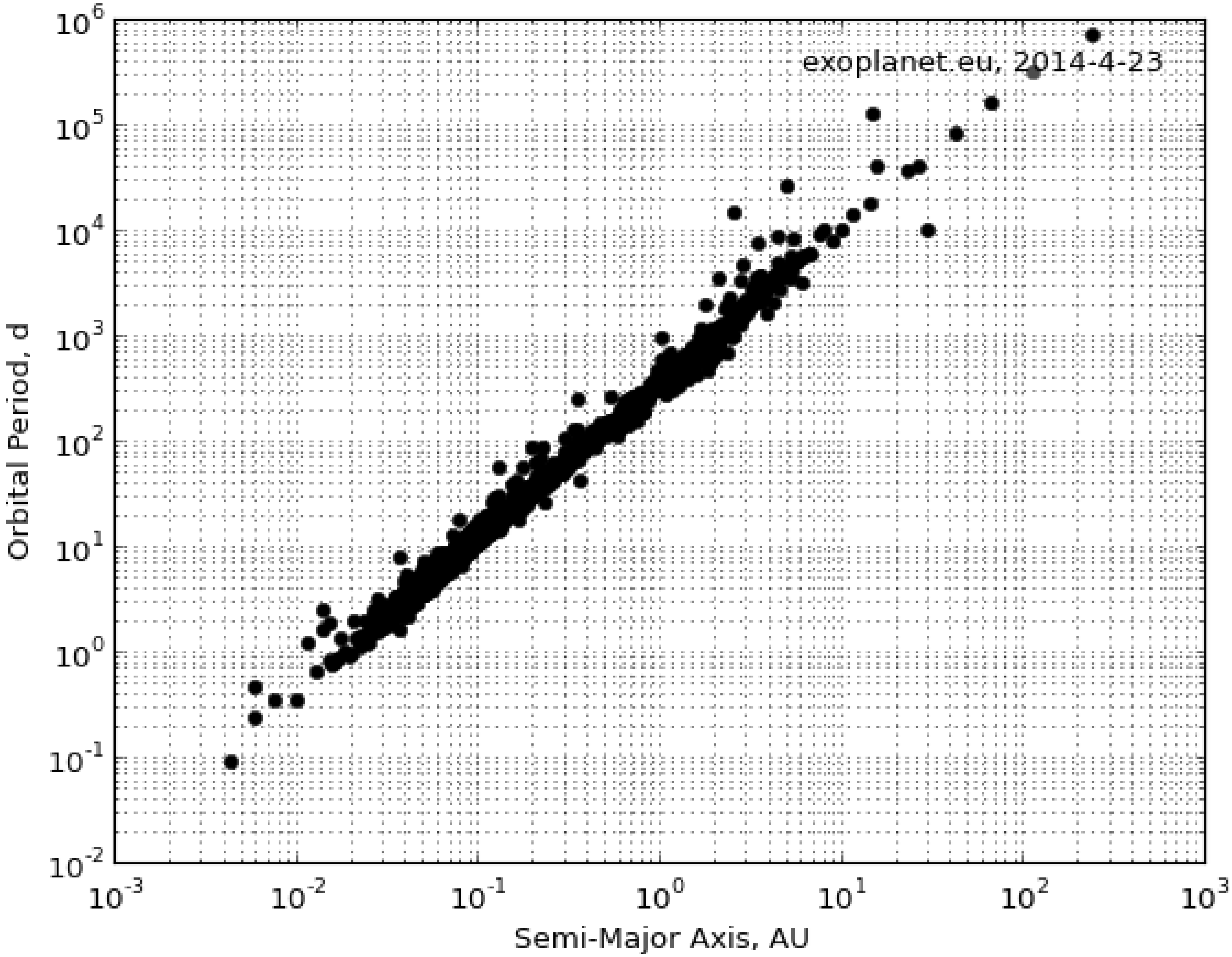
Potential of IR long-baseline interferometry

Circumstellar disks

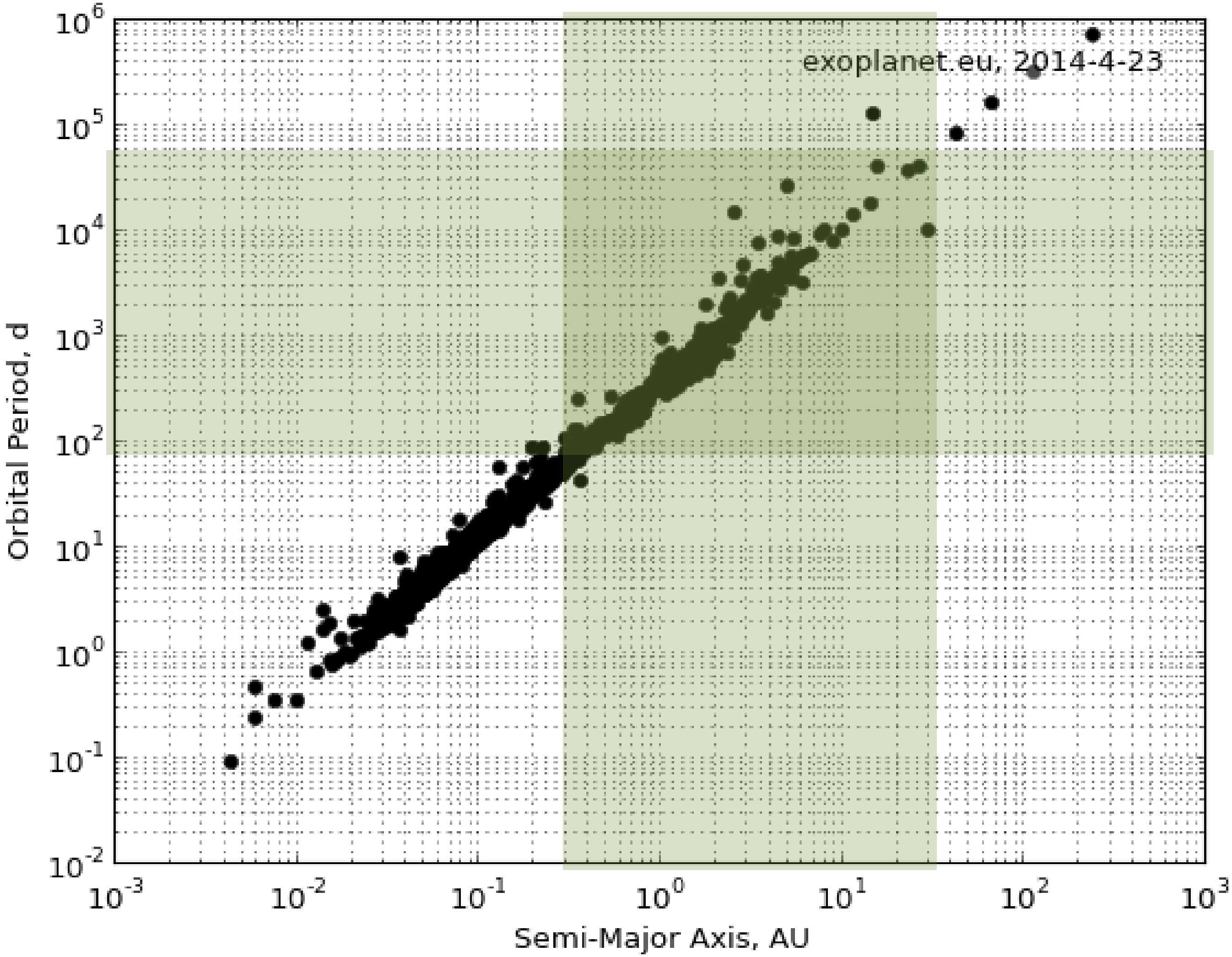
Circumstellar disks



Planets

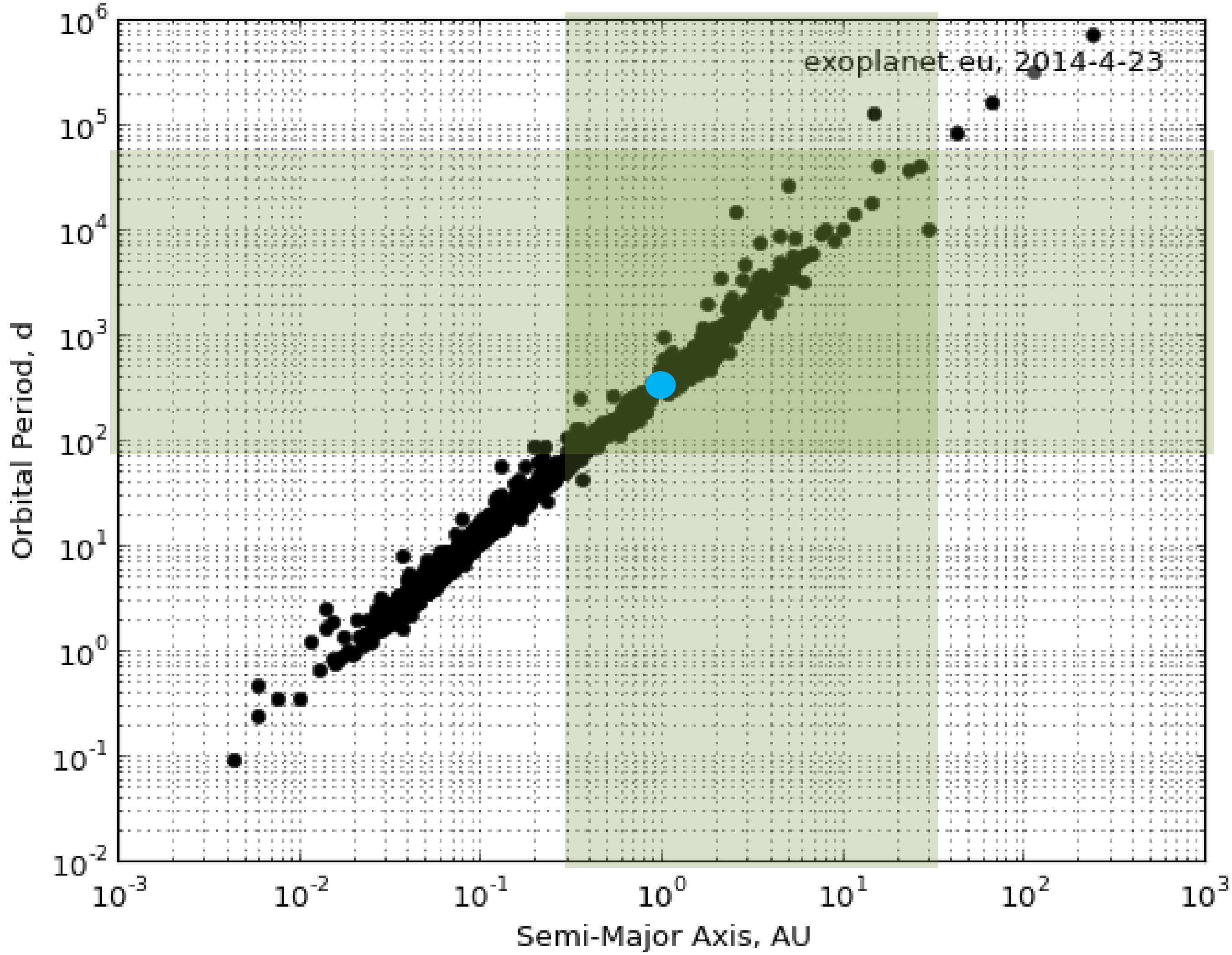

exoplanet.eu, 2014-4-23
Orbital Period, d
Semi-Major Axis, AU
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}

Planets



Parameter space covered by solar system planets

Planets



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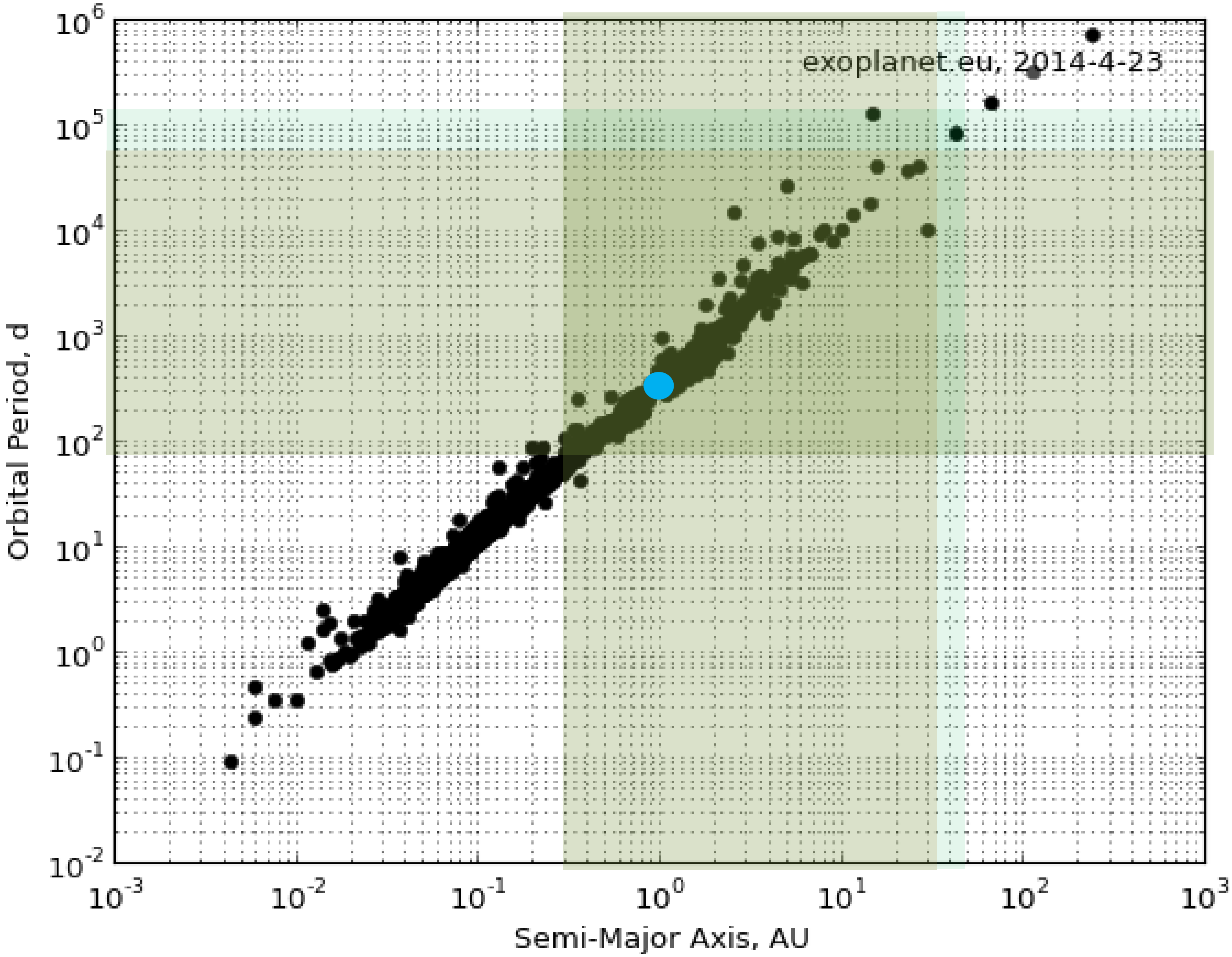
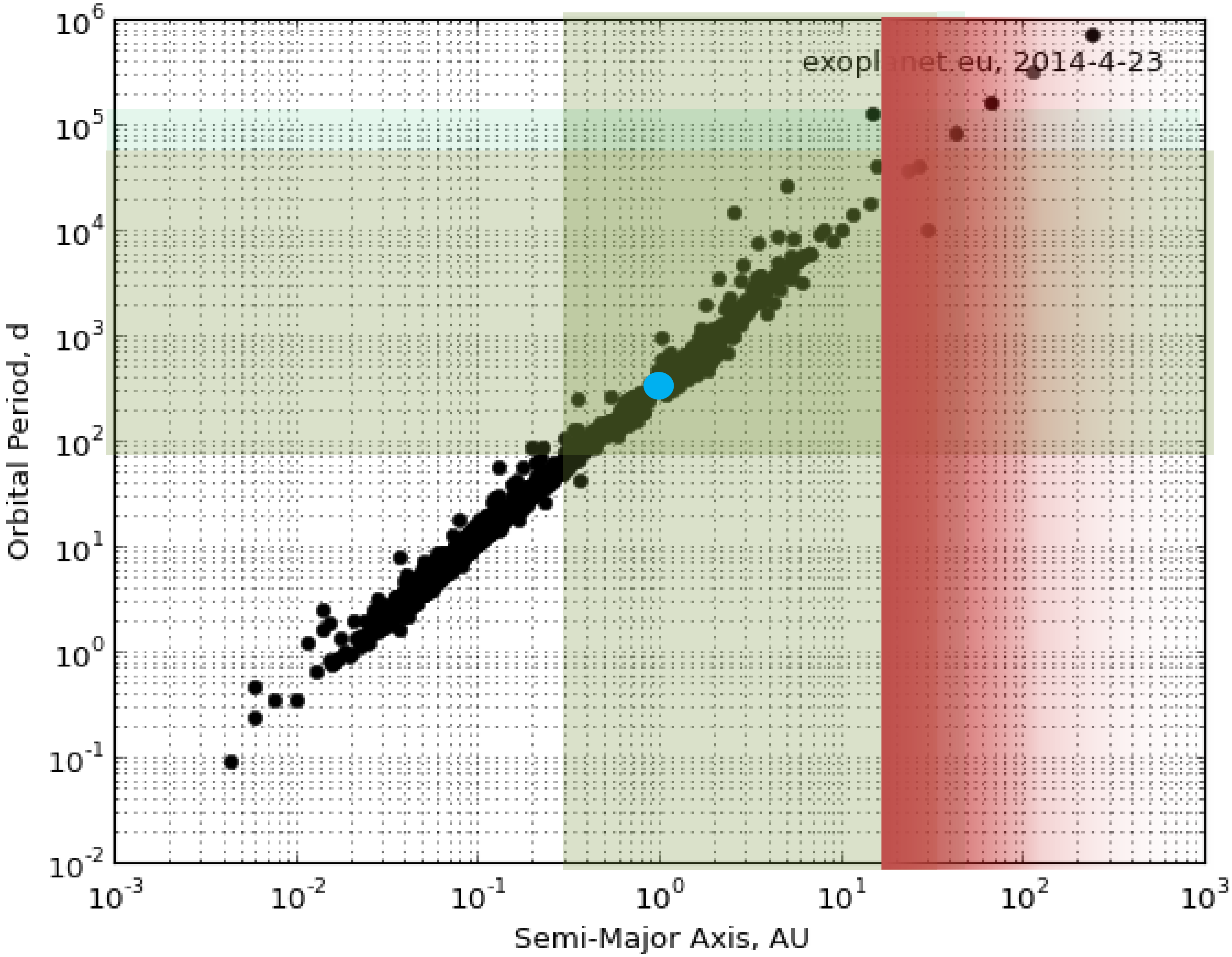


Parameter space covered by solar system planets

Kuiper Belt (without highly eccentric objects)

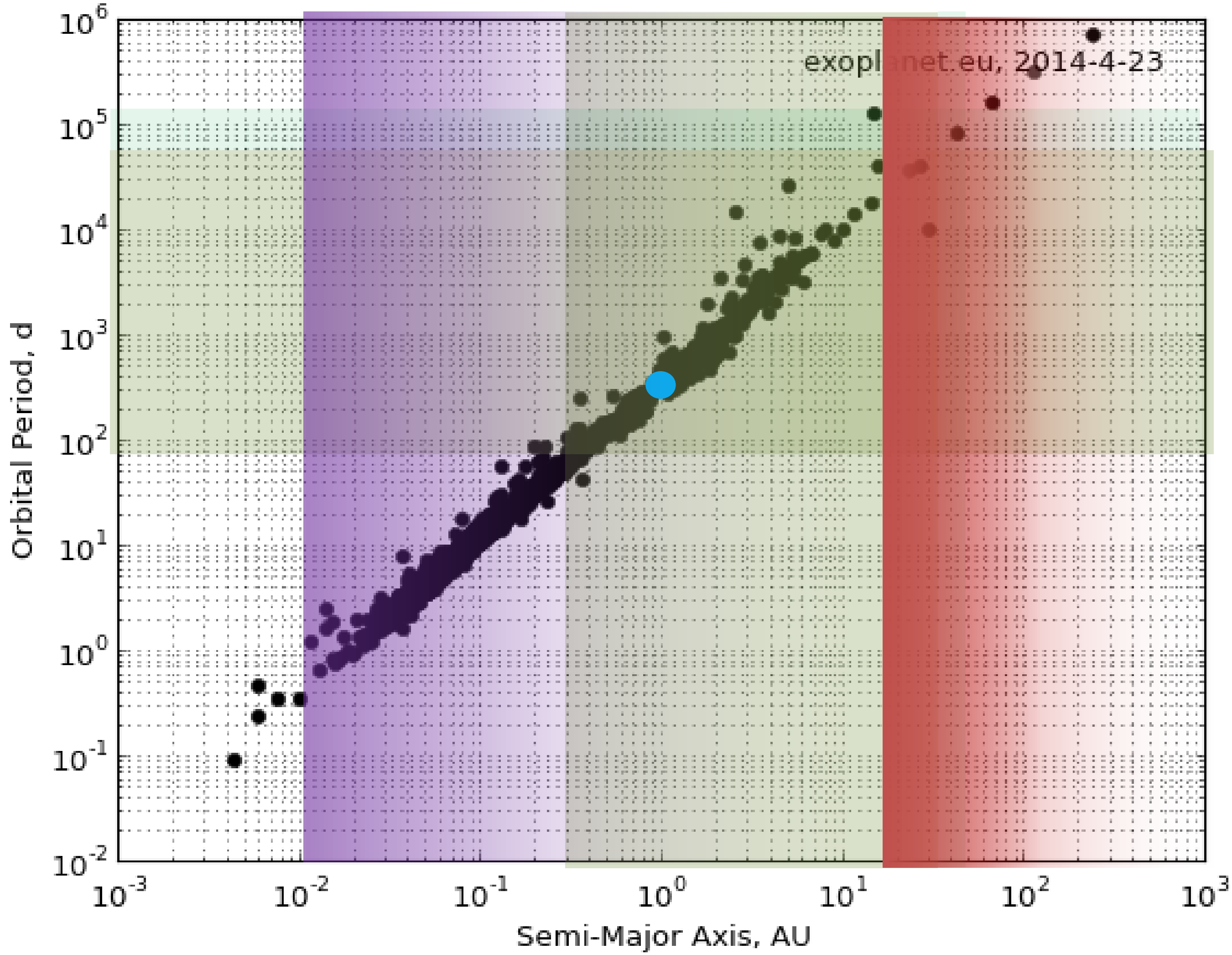
Disks @ 140pc: Techniques & Potential



~ 0.1“

(e.g. HST, VLT: Differential polarimetry, ALMA cycle 2)

Disks @ 140pc: Techniques & Potential



~ 0.1“

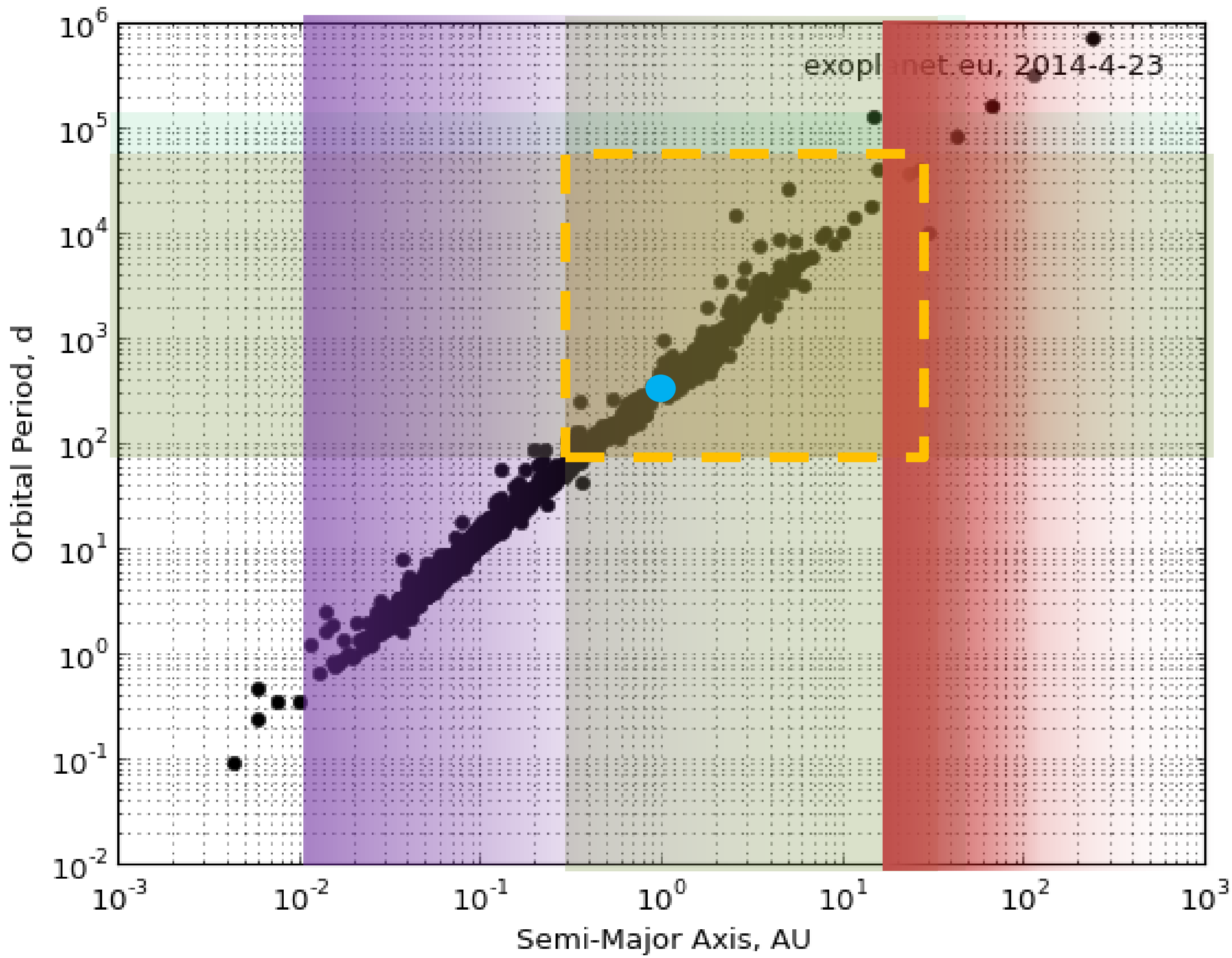
(e.g. HST, VLT: Differential polarimetry, ALMA cycle 2)

~ 10^{-4}“

Spectro-astrometry (Gas!): Constraints on disk dynamics

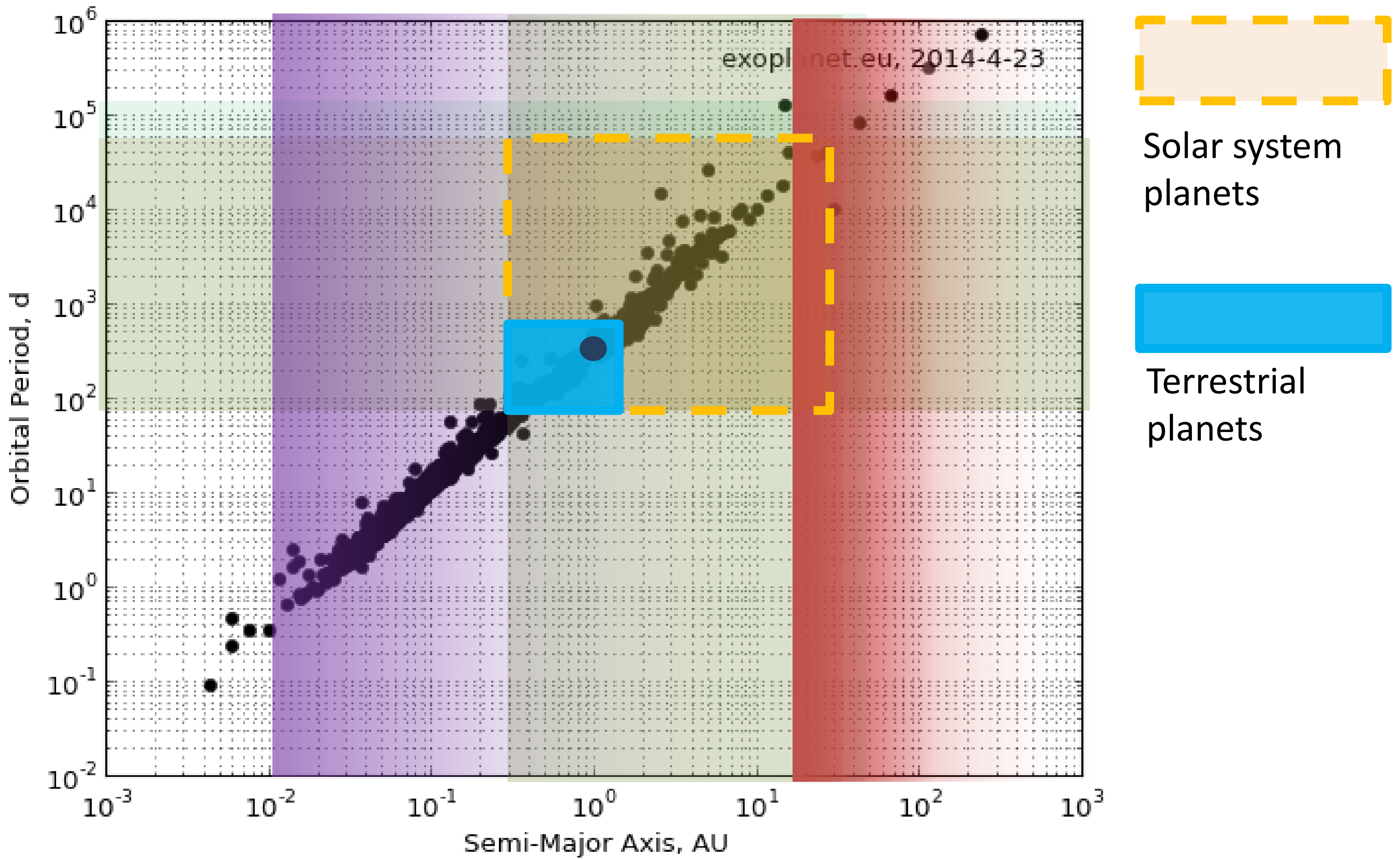
(e.g. SINFONI; TW Hya: Goto et al. 2012)

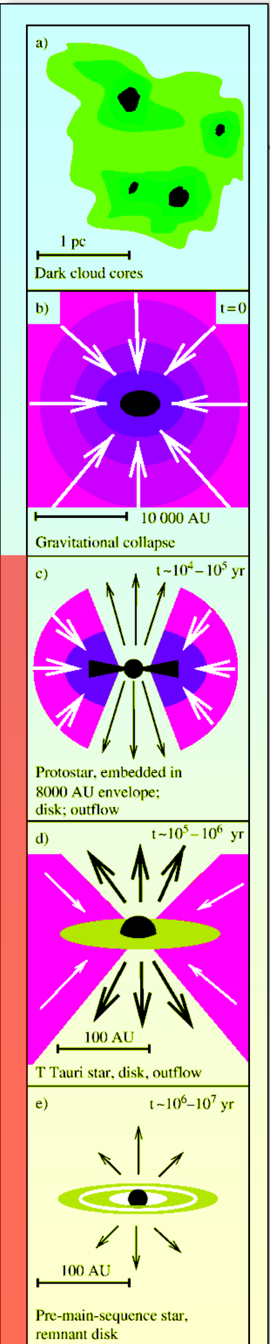
Disks @ 140pc: Techniques & Potential



Solar system planets

Disks @ 140pc: Techniques & Potential





(Waelkens 2001)

Importance of continuum observations / The role of **dust** in planet formation

Star Formation Process → Circumstellar Disks → Planets

Possible scenario: Core Accretion – Gas Capture

(sub)µm particles

↓

cm/dm grains

↓

Planetesimales

↓

Planets (cores)

Brownian Motion, Sedimentation, Drift → Inelastic Collision → Coagulation

Agglomeration vs. Fragmentation

Gravitational Interaction: Oligarchic Growth

Gas Accretion

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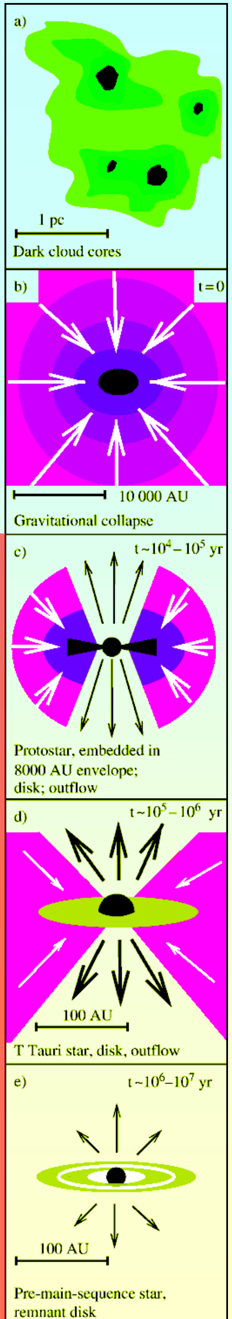

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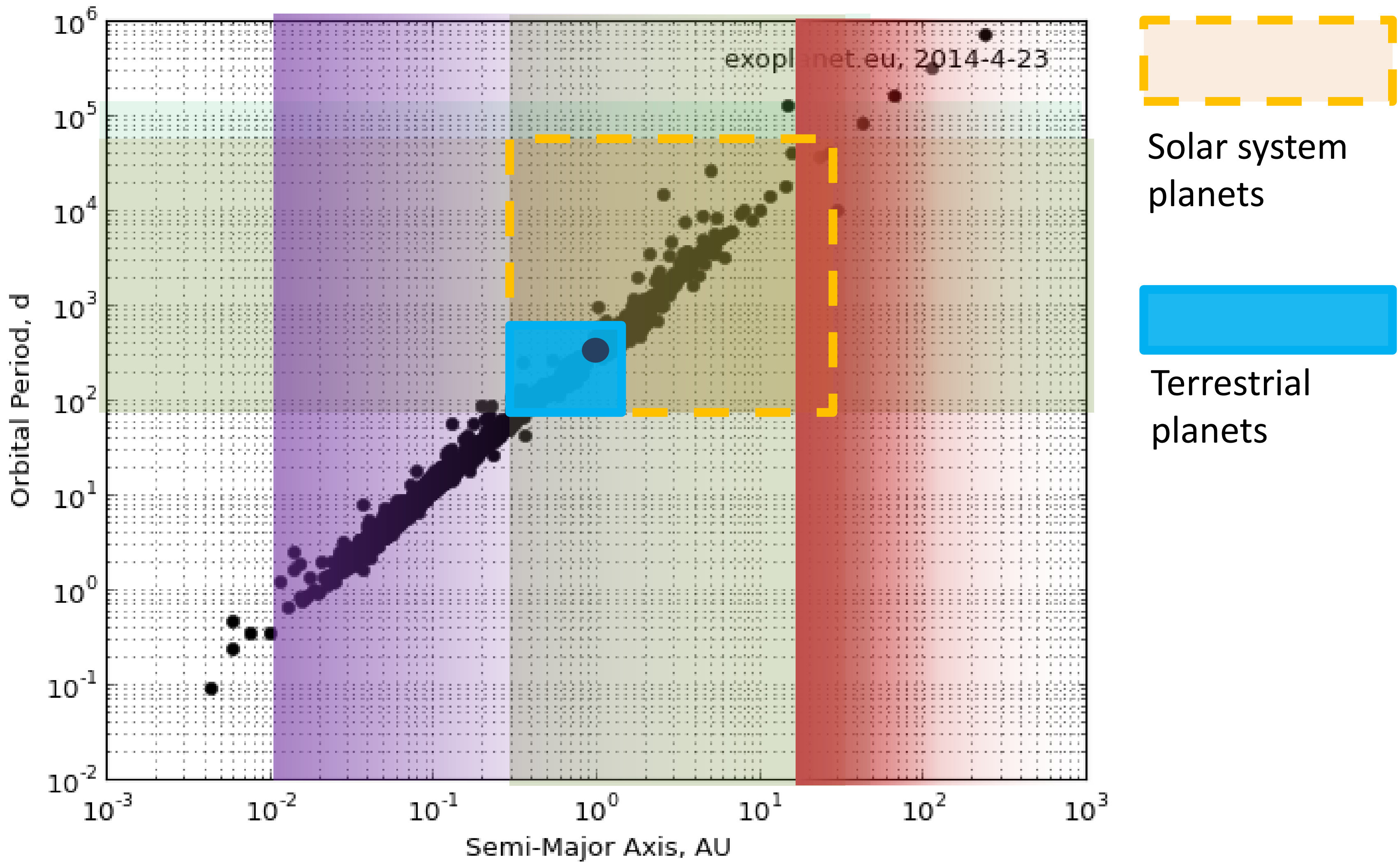

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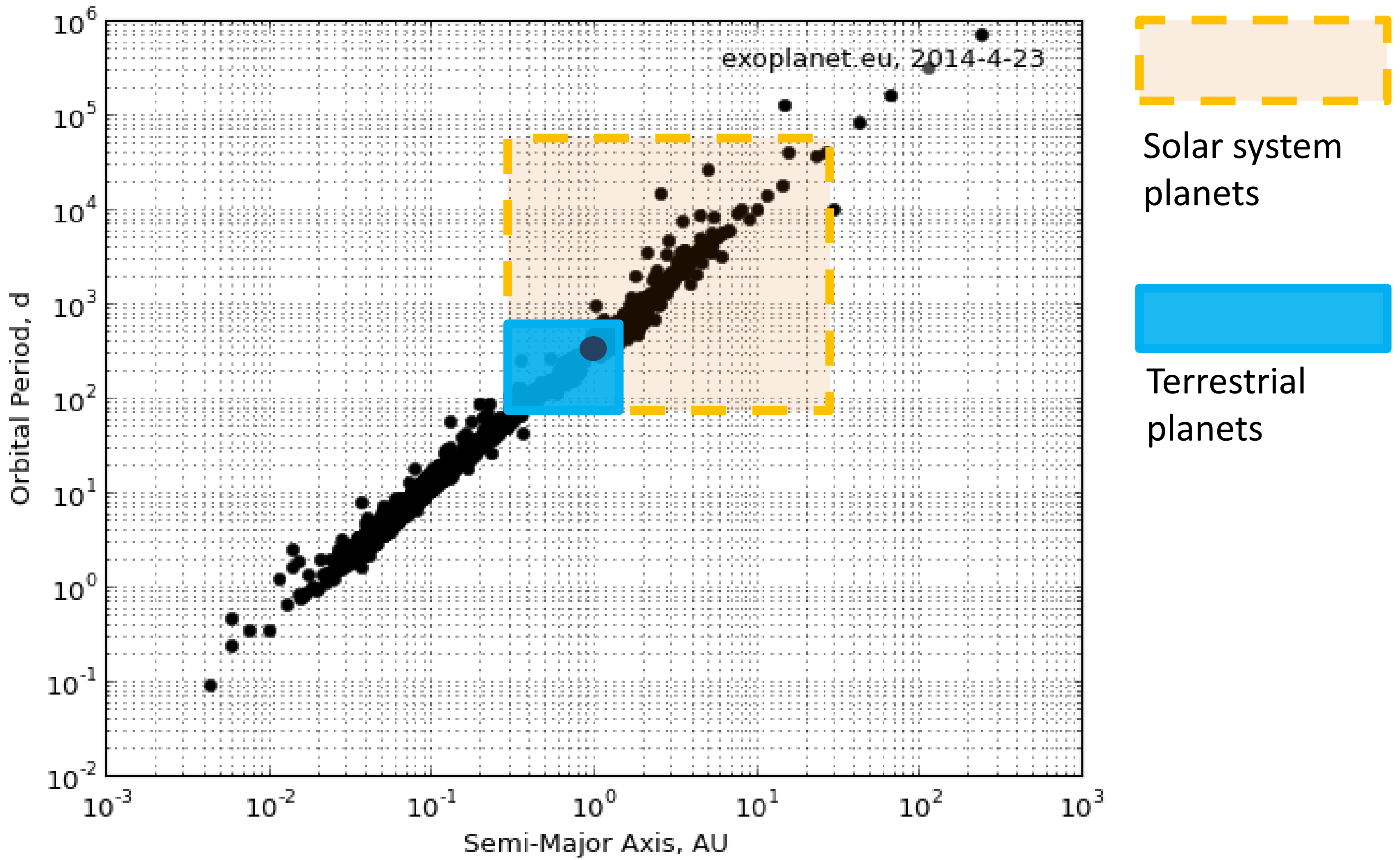

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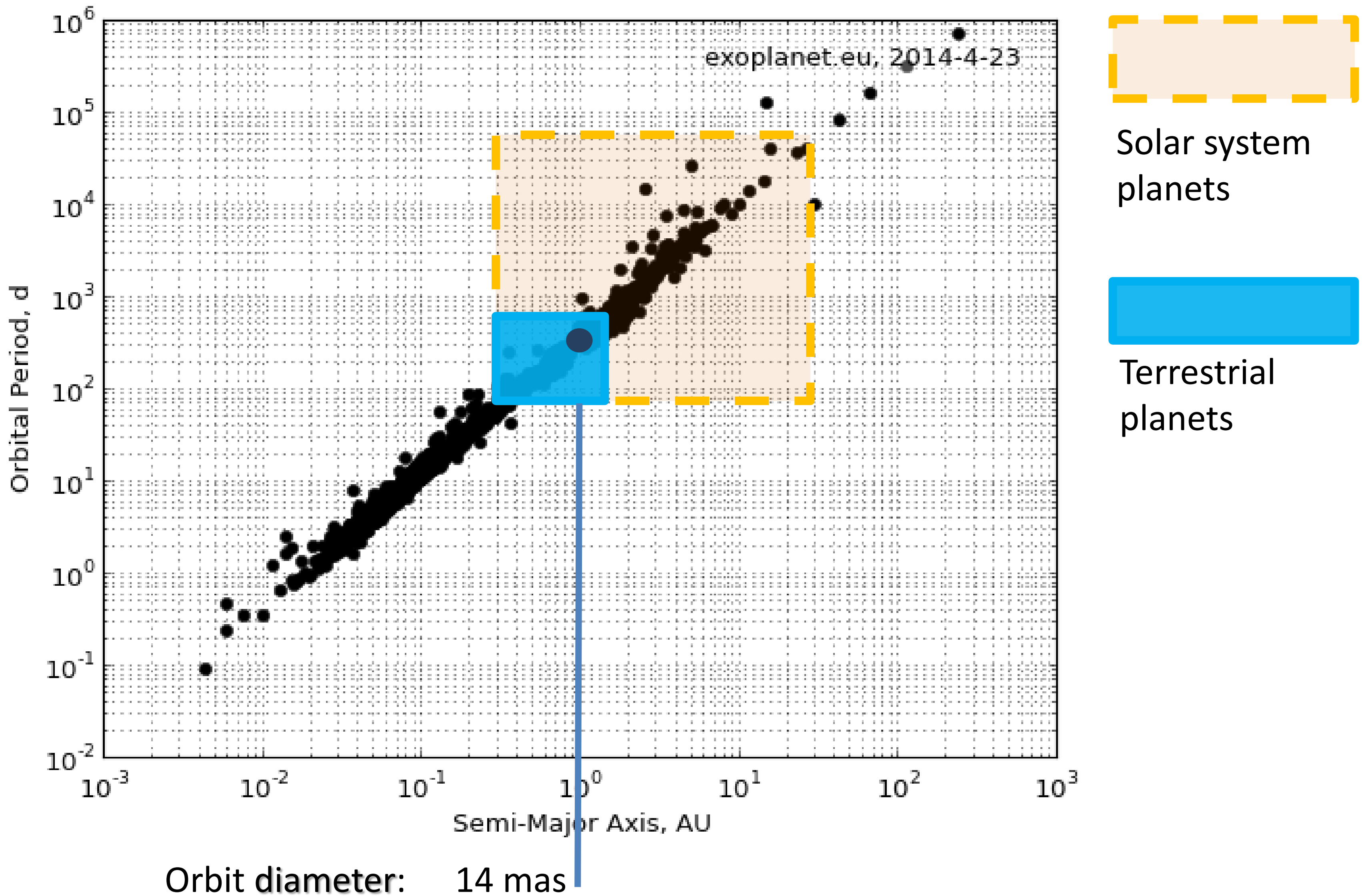

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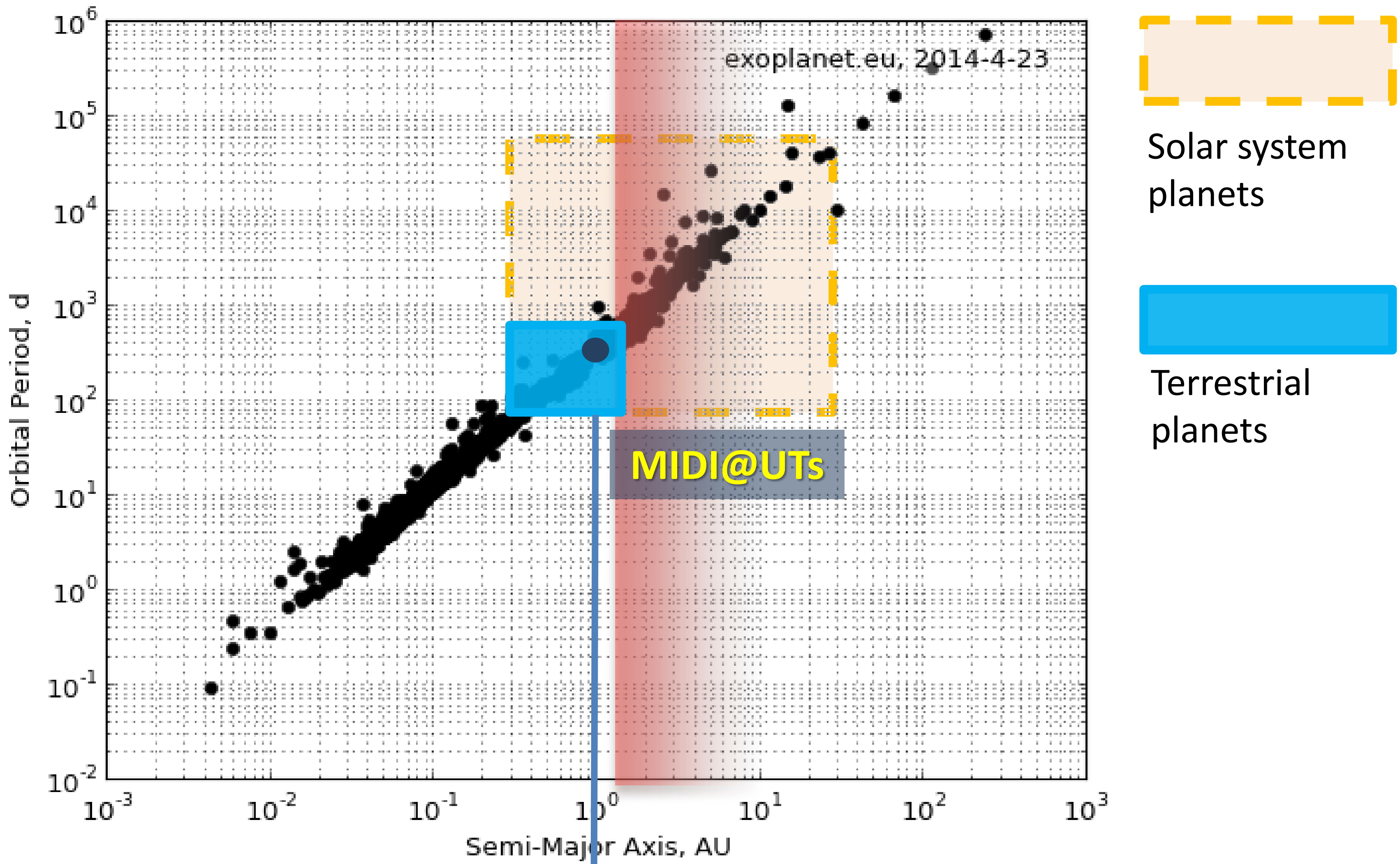

Orbit diameter: 14 mas

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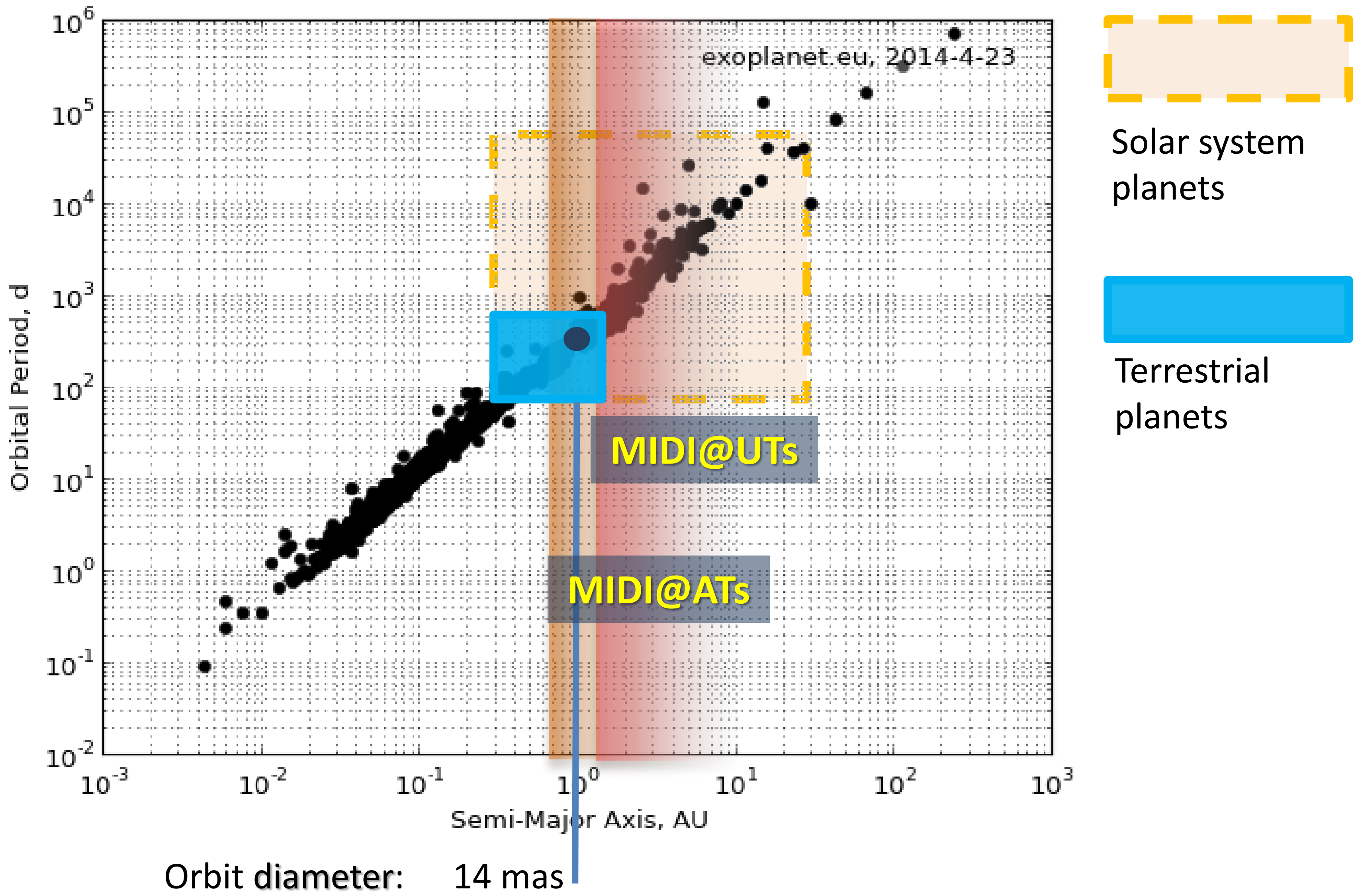


Next *minimum* criterion

- Angular resolution ✓

- Net flux?

Typical flux of T Tauri stars *) @ 10μm : ~ 1 Jy
Herbig Ae/Be stars *) : > 1 Jy

Objects sufficiently bright ✓

- Remaining risk: Radial brightness distribution
  - Objects spatially resolved?
  - Objects spatially over-resolved @ VLTI baselines?

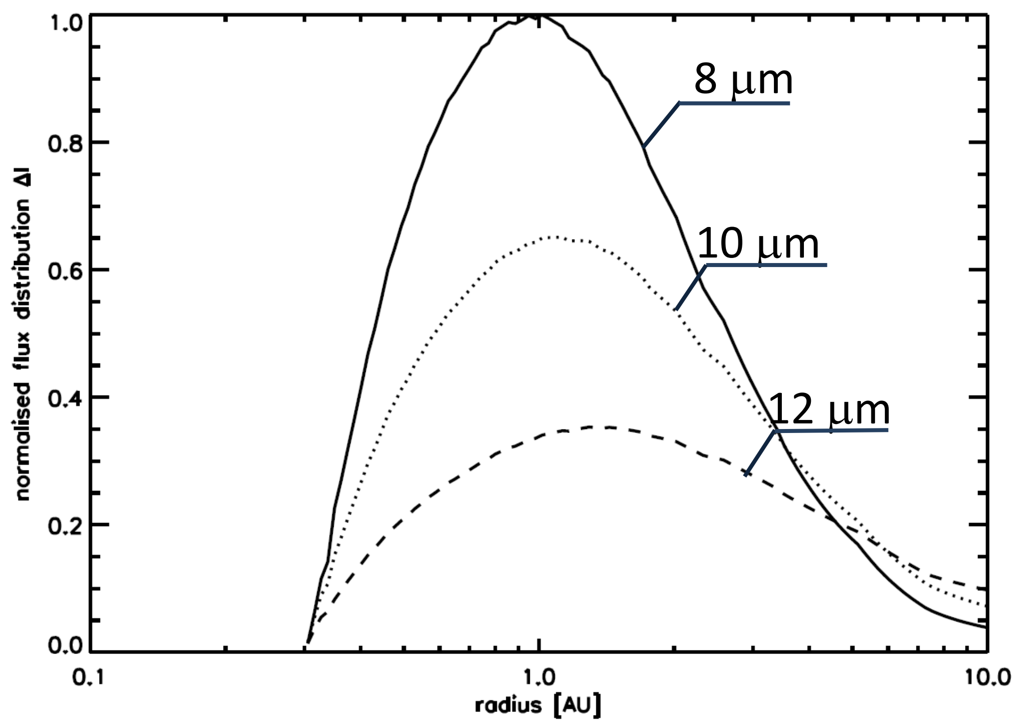
*) *If inclined face-on*

Next *minimum* criterion

- Radial brightness distribution:

Example:

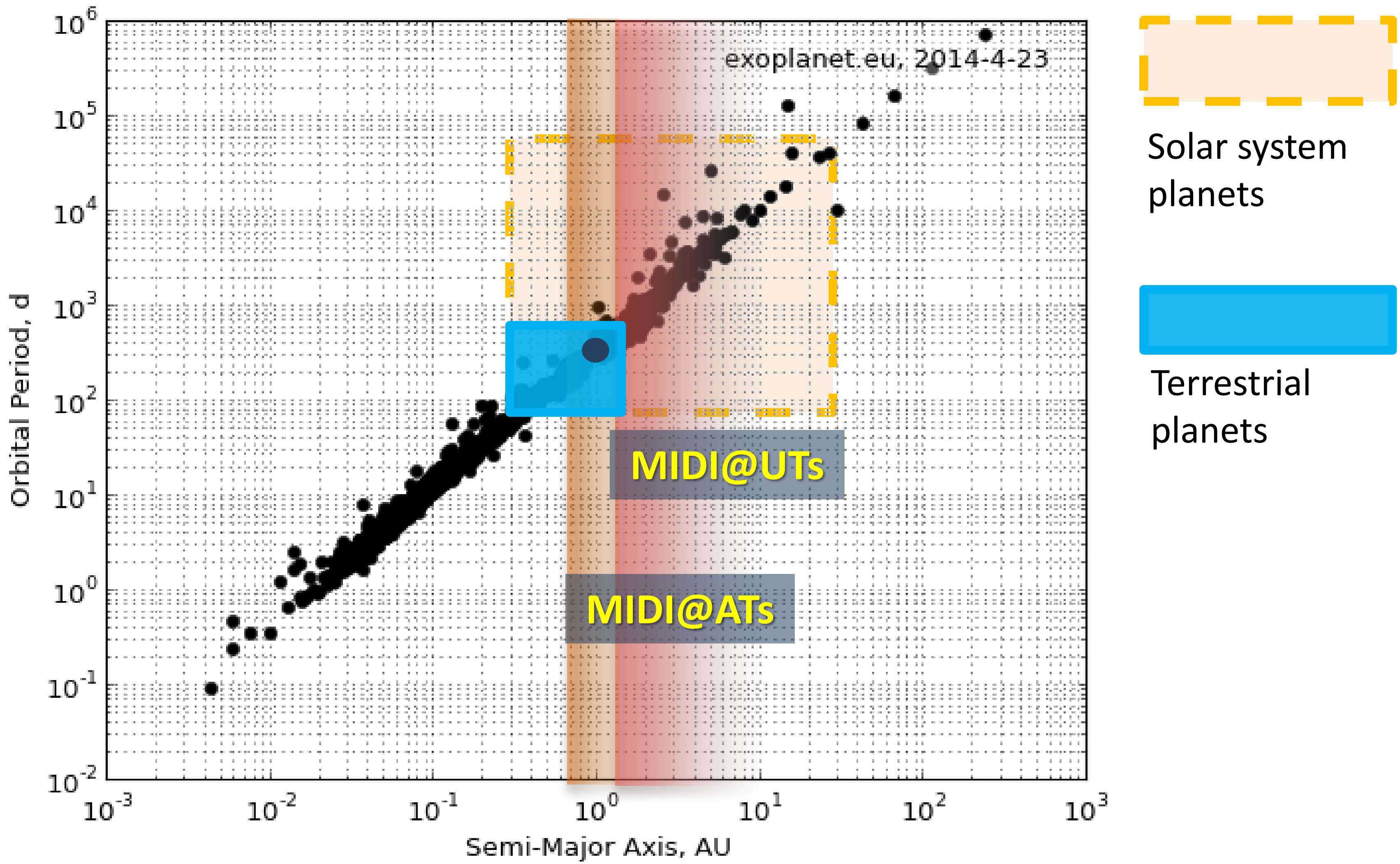
RY Tau	
Distance	134^{+54}_{-31} pc
Luminosity	$23.8 L_{sun}$
SpT	F8 III
Accr. rate	$7.8 \times 10^{-8}\ M_{sun}/yr$
Age	6.5 +/- 0.9 Myr



Radial flux distribution for a wavelength of **8 µm (solid), 10 µm (dotted), 12 µm (dashed curve)**. *The mean flux I, emitted at a radius r, is multiplied with r and normalized.*

[Schegerer et al. 2008]

Disks @ 140pc: Techniques & Potential



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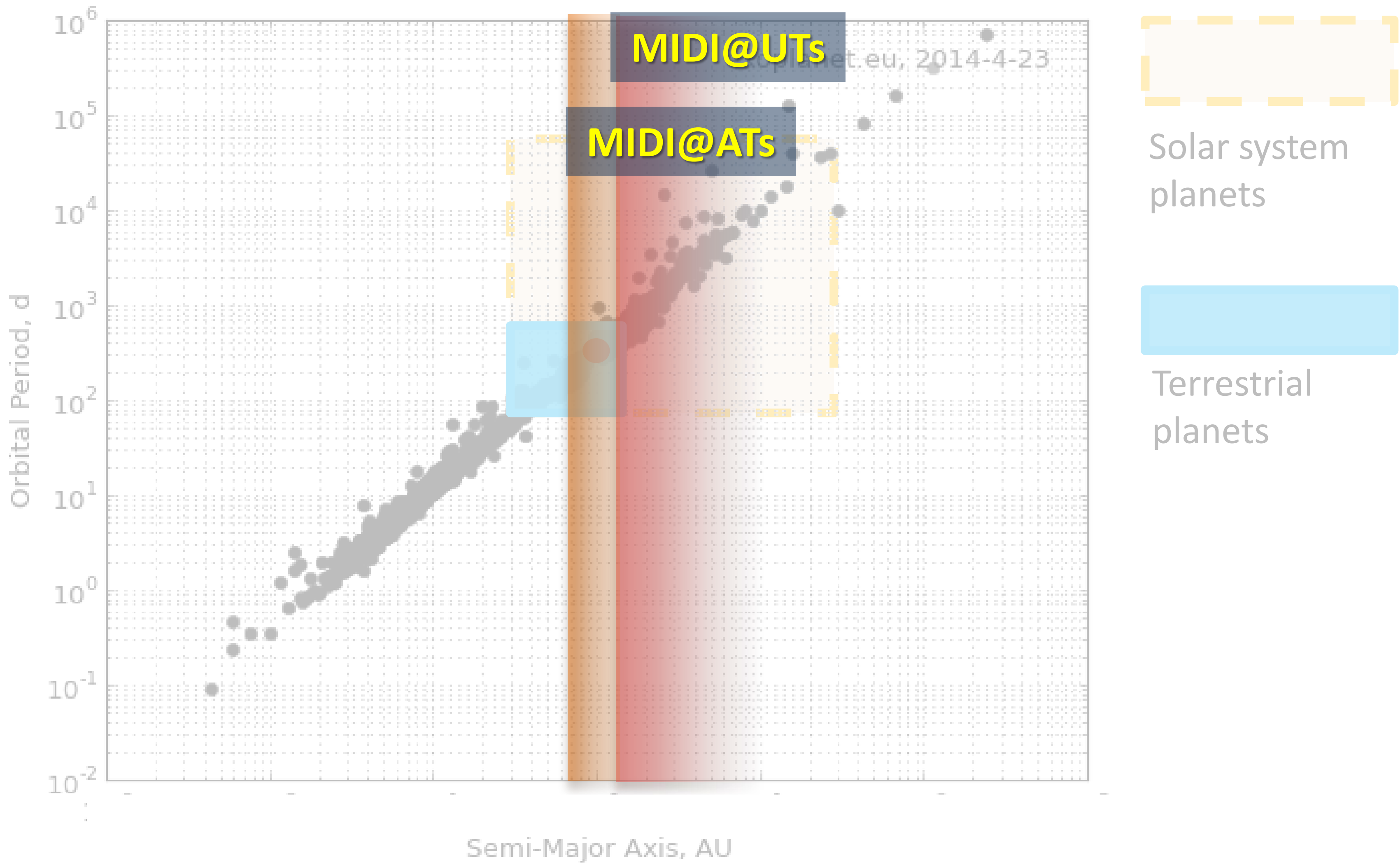

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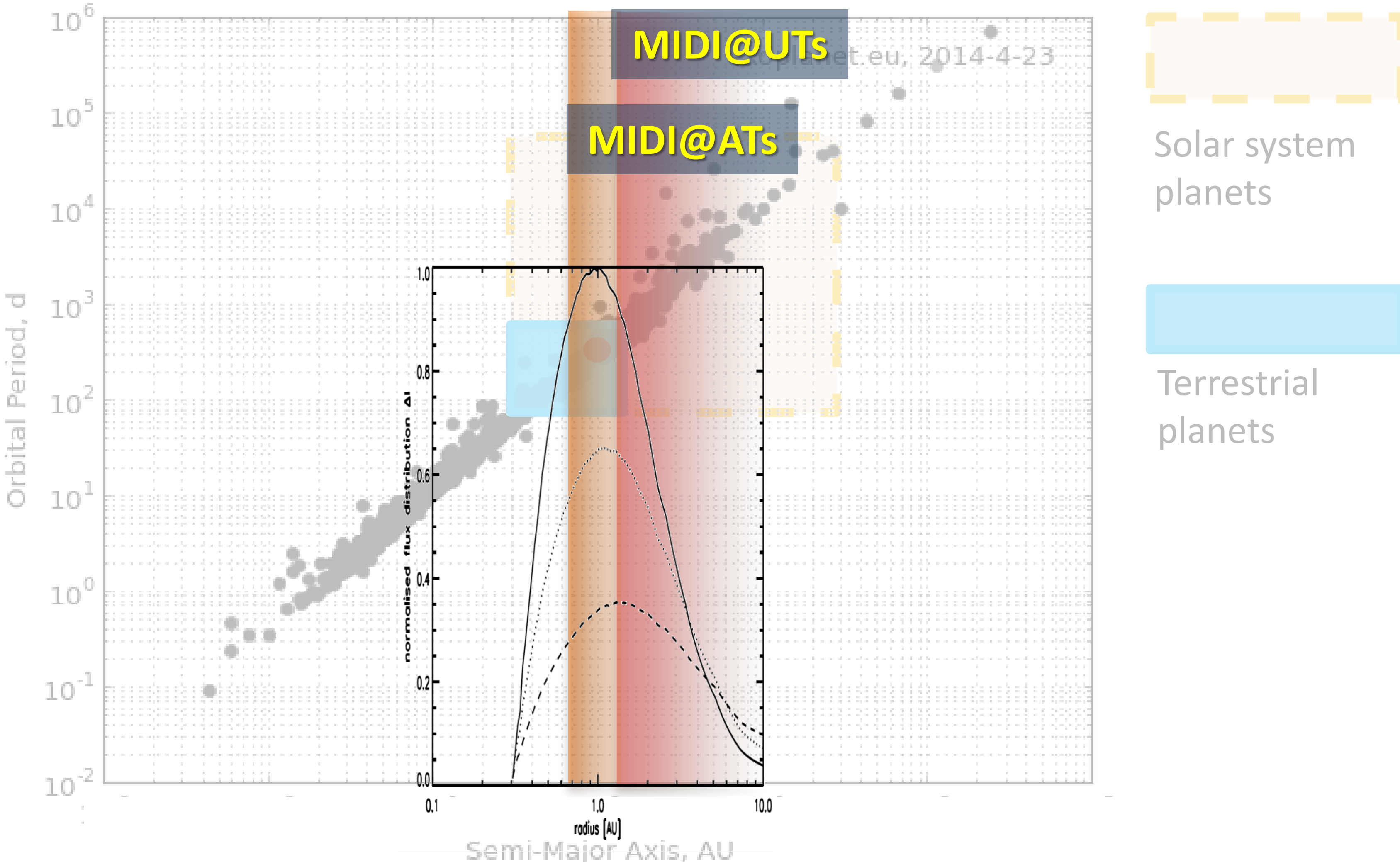


General success

- Perfect combination of

  Observing wavelength (~10μm) and
  Angular resolution (VLTI baselines ~ 10-20mas)

  => Regions with hot dust can be spatially resolved

- Observations of the hot dust in
  - Circumstellar disks
  - AGB stars
  - Winds of hot stars
  - Massive star forming regions
  - Tori of AGNs
  - Debris disks
  - Solar system objects

General success

- Perfect combination of

  Observing wavelength (~10μm) and
  Angular resolution (VLTI baselines ~ 10-20mas)

  => Regions with hot dust can be spatially resolved

- Moreover:
  Very successful in **high-angular resolution spectroscopy**

  => Chemical composition of dust on various spatial scales

General success

- Perfect combination of

  Observing wavelength (~10μm) and

  Angular resolution (VLTI baselines ~ 10-20mas)

  => Regions with hot dust can be spatially resolved

Concept of mid-infrared long-baseline interferometry proven to work

Specific questions in the field of star and planet formation

Low-mass Star and Planet Formation

- Mineralogy of proto-planetary disks, dust grain growth and sedimentation
- Transitional objects: Status of inner disk clearing
- Nature of outbursting young stellar objects
- Binary mode of star formation:
  Inner structure and conditions for planet formation in circumbinary vs. circumstellar disks. Disk alignment.
- *Characteristic structures in disks: Tracing giant proto-planets*

Late stage of planet formation - Debris disks

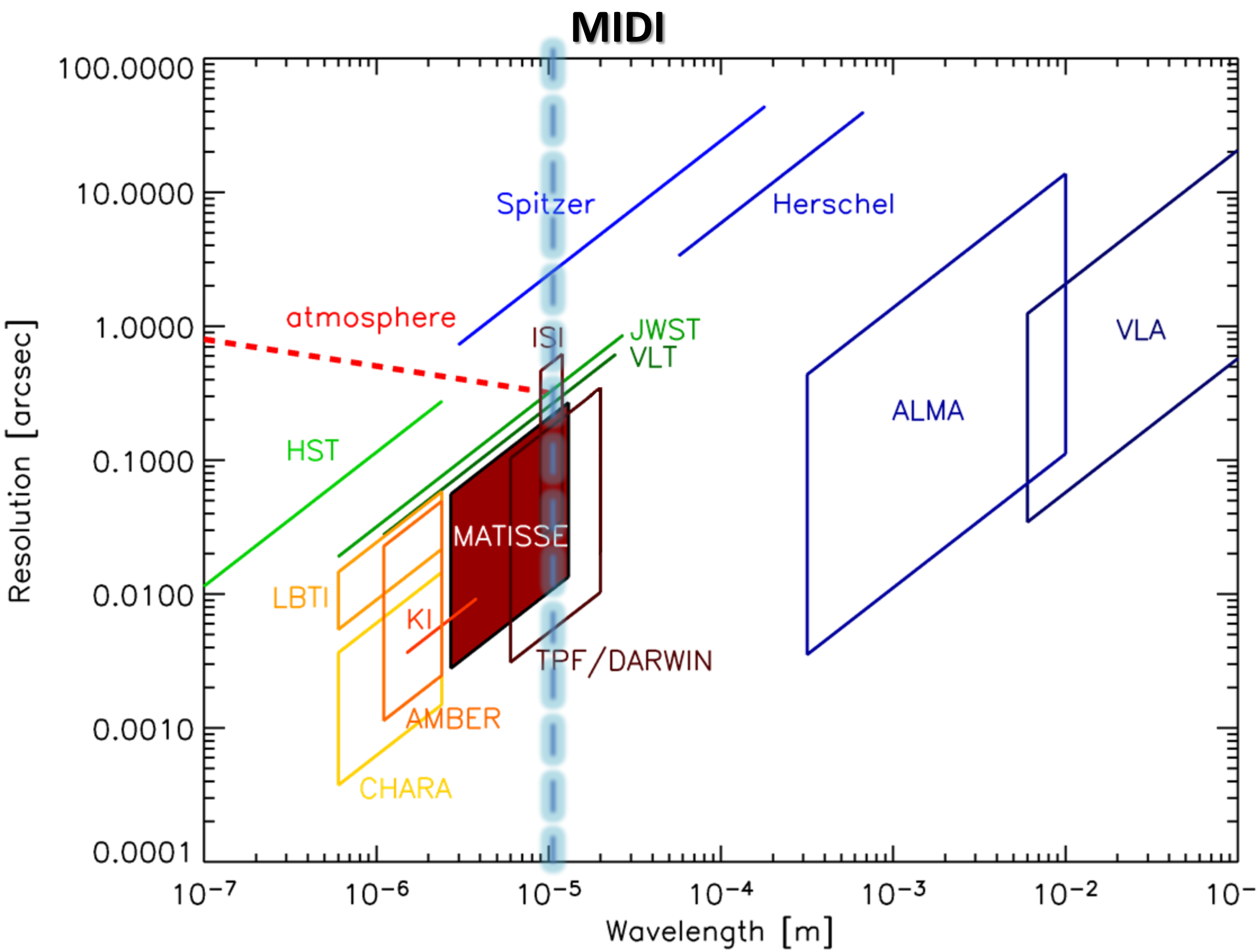
- Planetesimal collisions and exo-comets evaporation, grain properties and disk geometry
- *Complex spatial inner disk structure – direct indicators for the presence of planets*

Required

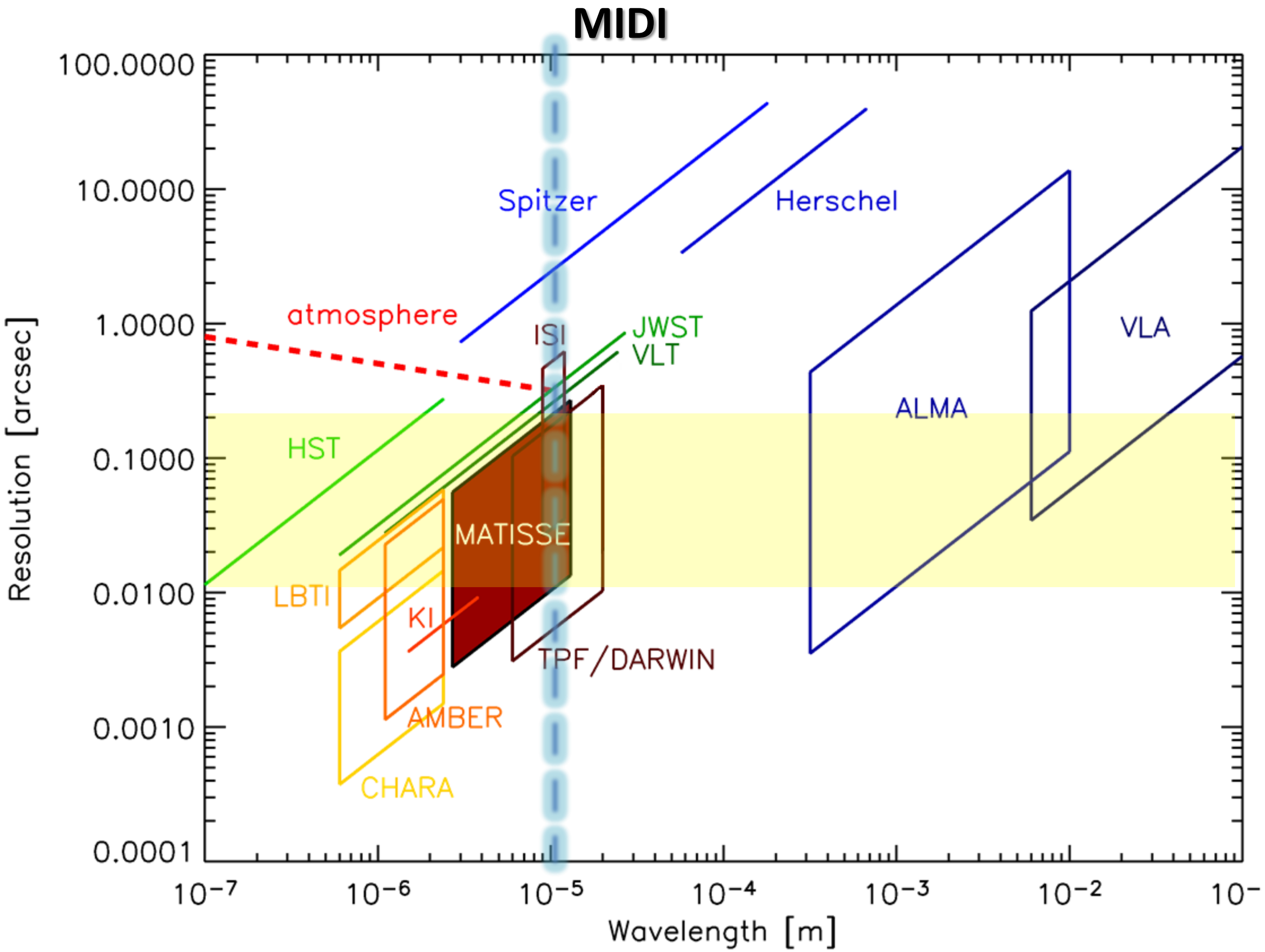
Empirically-based input to improve our general understanding and thus to better constrain planet formation / disk evolution models

Making best use of MIDI data

(1) Complementary observations



(1) Complementary observations



(2) The need for – sophisticated – modeling

(2) The potential of – sophisticated – modeling

(2) The potential of – sophisticated – modeling

Goal

Self-consistent disk model with the least number of parameters

i.e.

Constraints:

Structure, composition, and physical conditions of circumstellar disks

Theoretical picture of planet formation process

(2) The potential of – sophisticated – modeling

- Two-element interferometer (far field):
  - Radiation sampled at different locations $(\overrightarrow{r_1}, \overrightarrow{r_2})$ and times (t_1, t_2):
  - ?: Correlation between the two measurements: $\langle \boldsymbol{E}^*(\overrightarrow{\boldsymbol{r_1}}, \boldsymbol{t_1}) \times \boldsymbol{E}\ (\overrightarrow{\boldsymbol{r_2}}, \boldsymbol{t_2})\rangle$
  - $\langle \ldots \rangle$: time average over period $\gg$ oscillation time of electric field

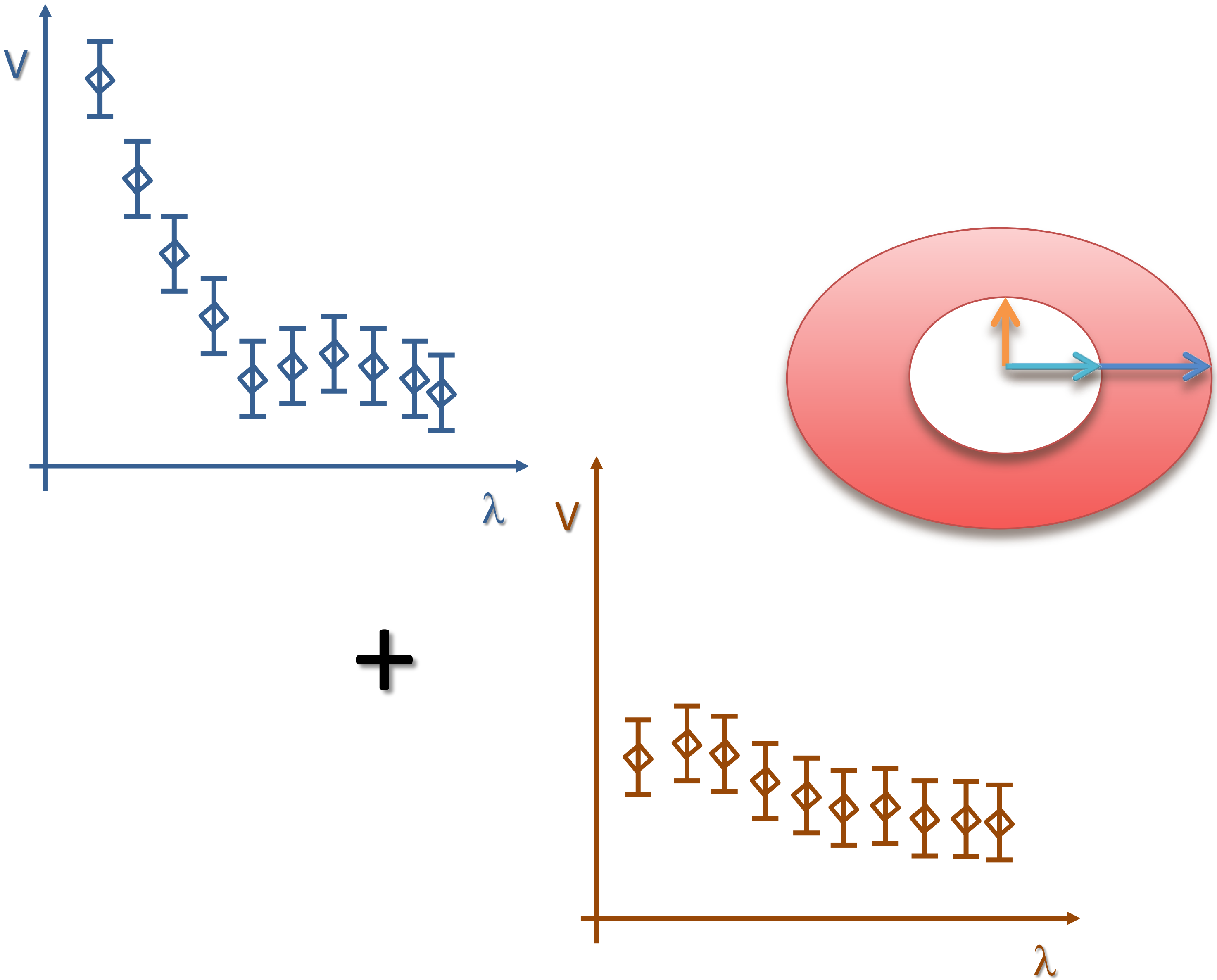
- Spatial coherence (i.e., $t_1 = t_2$):
  - $\langle E^*(\overrightarrow{r_1}, t_1) \times E\ (\overrightarrow{r_2}, t_2)\rangle = \mathrm{V}(\overrightarrow{r_1} - \overrightarrow{r_2}, t_1 - t_2) = \mathbf{V}(\vec{\boldsymbol{\rho}}, \mathbf{0})$ (Spatial coherence function)
  - Van Citter-Zernike theorem:

    For farfield sources:

    Normalized value of the **spatial coherence function**

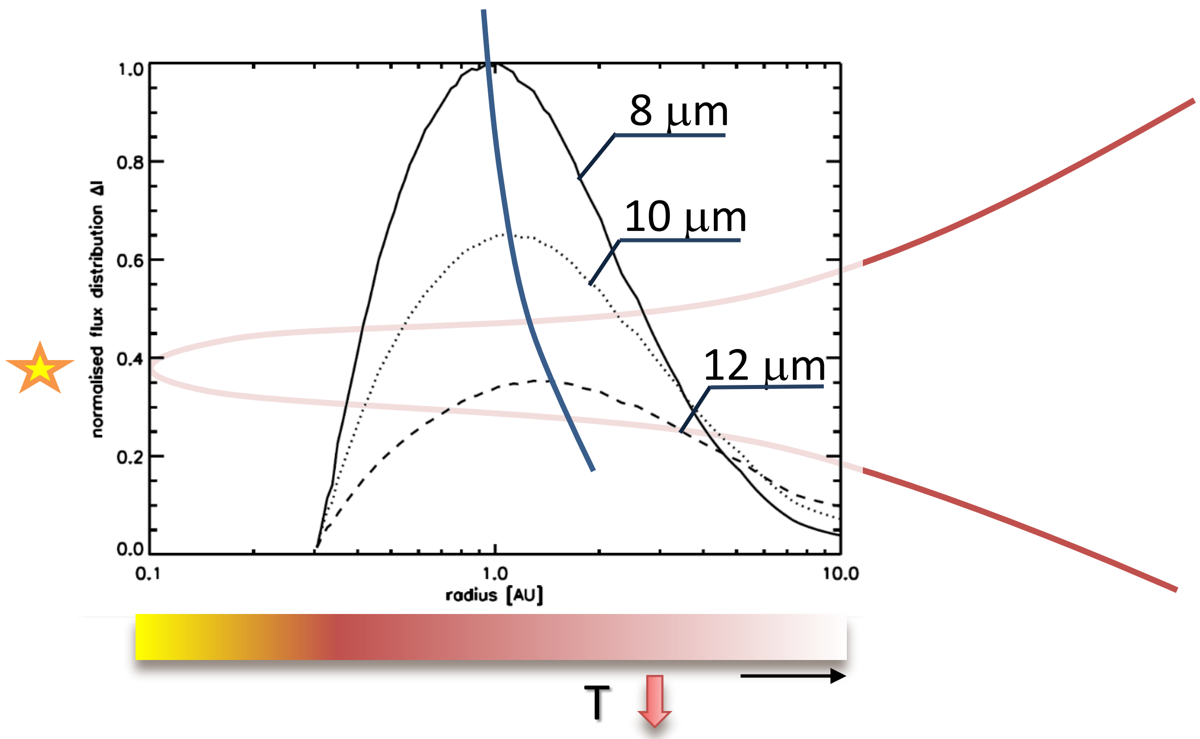
    = Fourier transform of the normalized **sky brightness distribution**

(2) The potential of – sophisticated – modeling



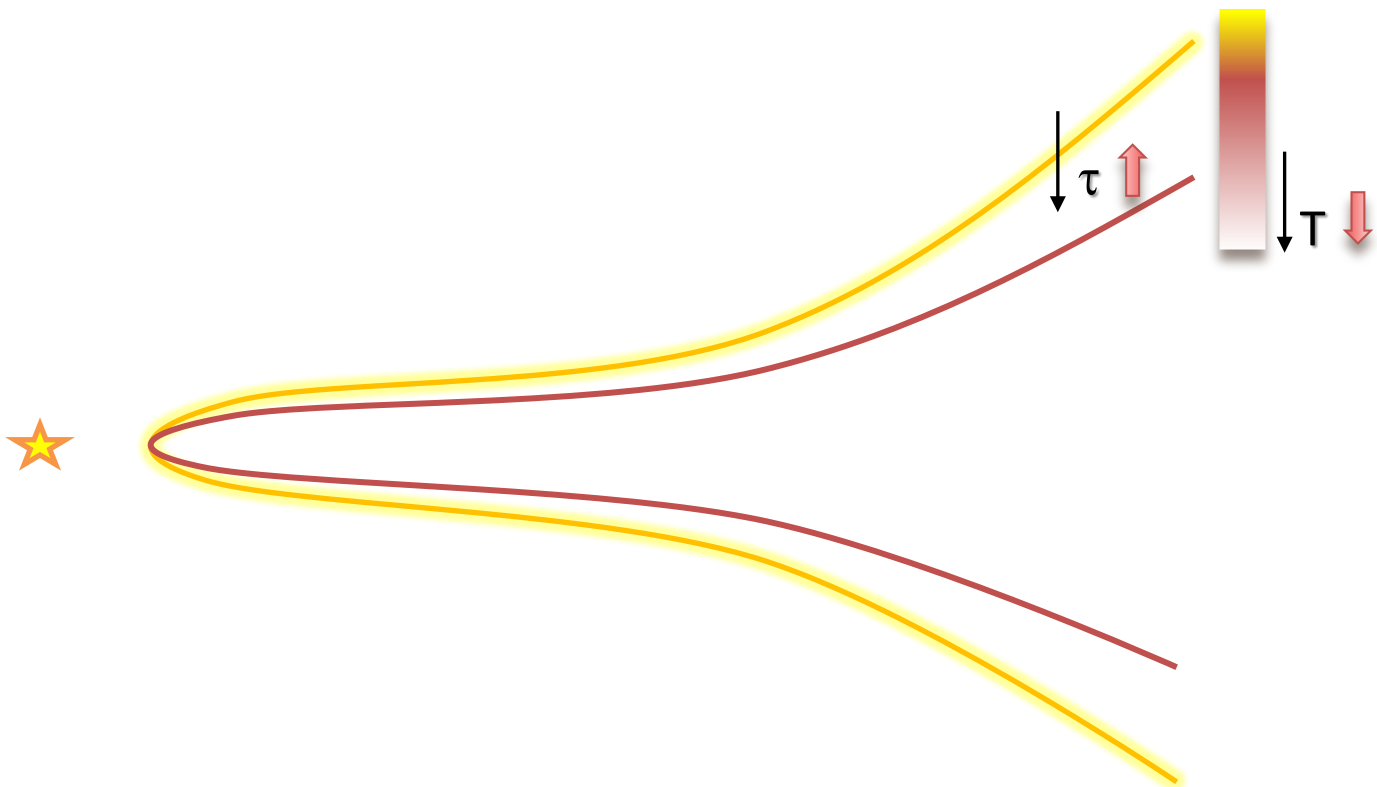
(2) The potential of – sophisticated – modeling

- Multiwavelength observations: Trace partially different disk regions
  - In **radial** direction



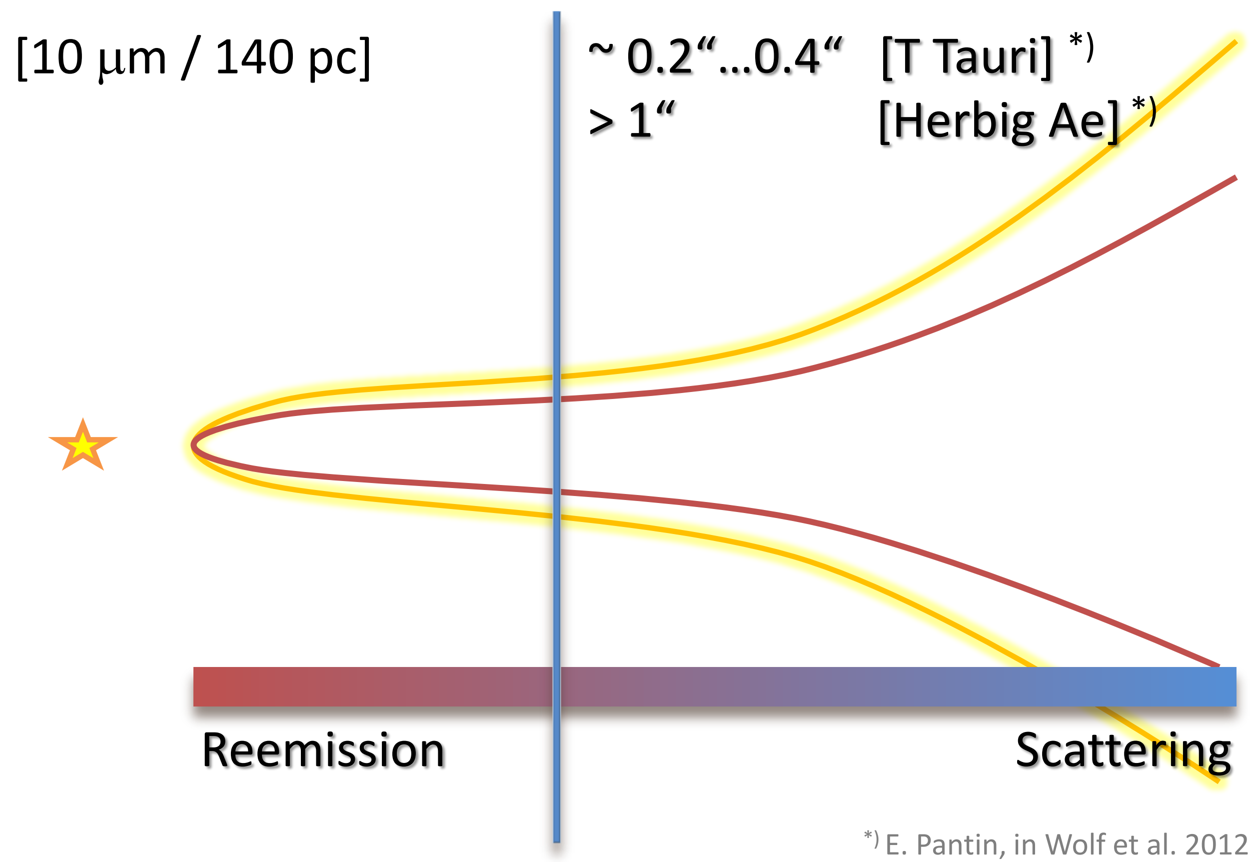
(2) The potential of – sophisticated – modeling

- Multiwavelength observations: Trace partially different disk regions
  - In radial + vertical direction



(2) The potential of – sophisticated – modeling

- Multiwavelength observations: Trace partially different disk regions
  - In radial + vertical direction
  - Radiation resulting from different physical processes:
    Scattered light vs. Reemission radiation (= f(disk structure, dust properties))



*) E. Pantin, in Wolf et al. 2012

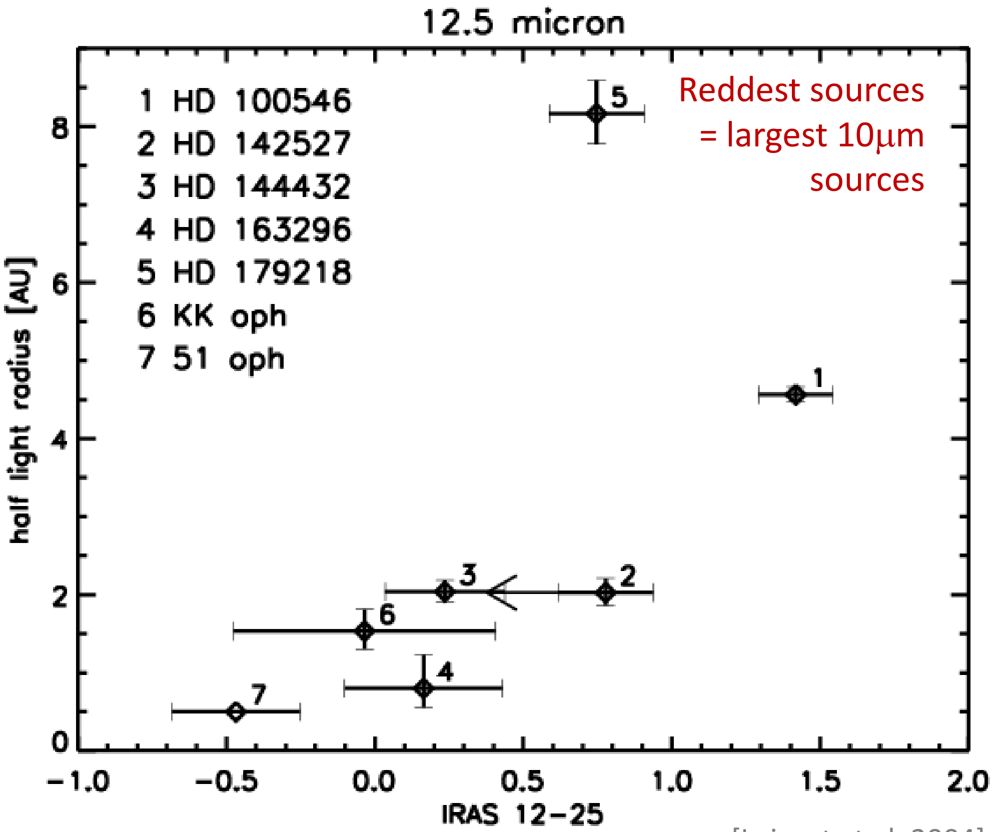
MIDI

Exemplary studies

(1) Radial / Vertical disk structure

Leinert et al. 2004: First long baseline mid-infrared interferometric observations of the circumstellar disks surrounding Herbig Ae/Be stars

- 7 nearby HAe/Be stars, all spatially resolved
- Characteristic emission region: 1 AU – 10 AU
- Correlation: Size of emission region – Slope of 10-25μm spectrum



[Leinert et al. 2004]

(1) Radial / Vertical disk structure

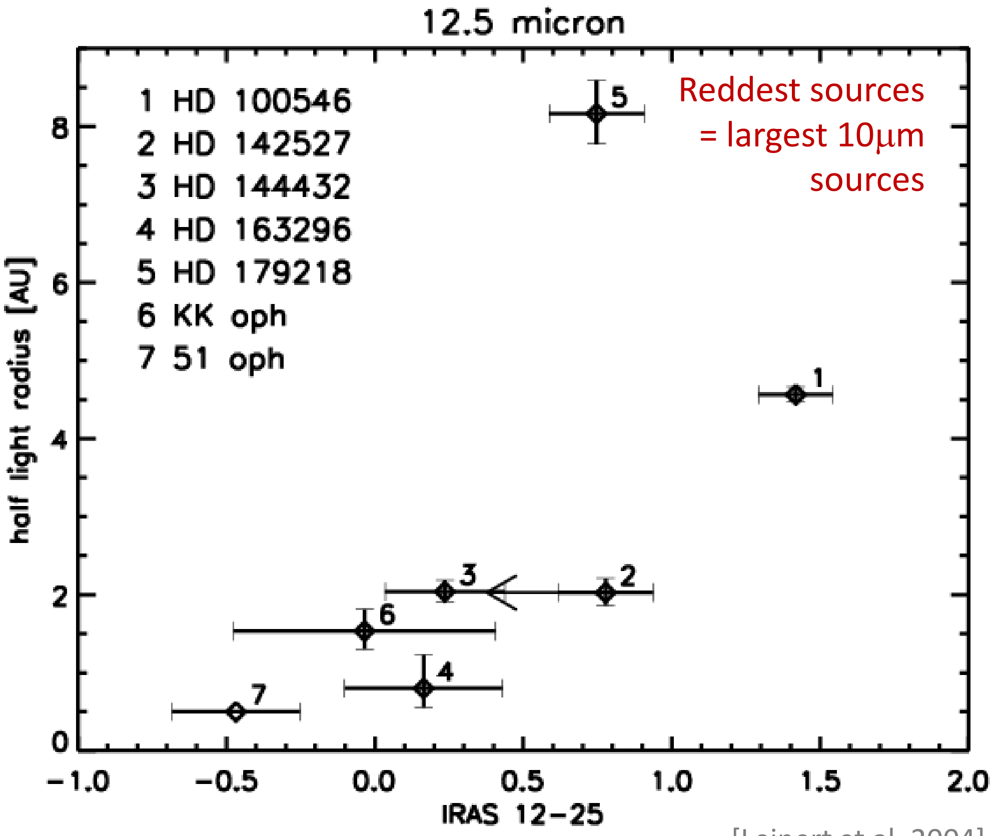
Leinert et al. 2004: First long baseline mid-infrared interferometric observations of the circumstellar disks surrounding Herbig Ae/Be stars

- Qualitative agreement with Meeus (2001) classification scheme:
  - Group I:

    Flared, redder,

    Large mid-IR emission
  - Group II:

    Flat, self-shadowed, More compact mid-IR emission

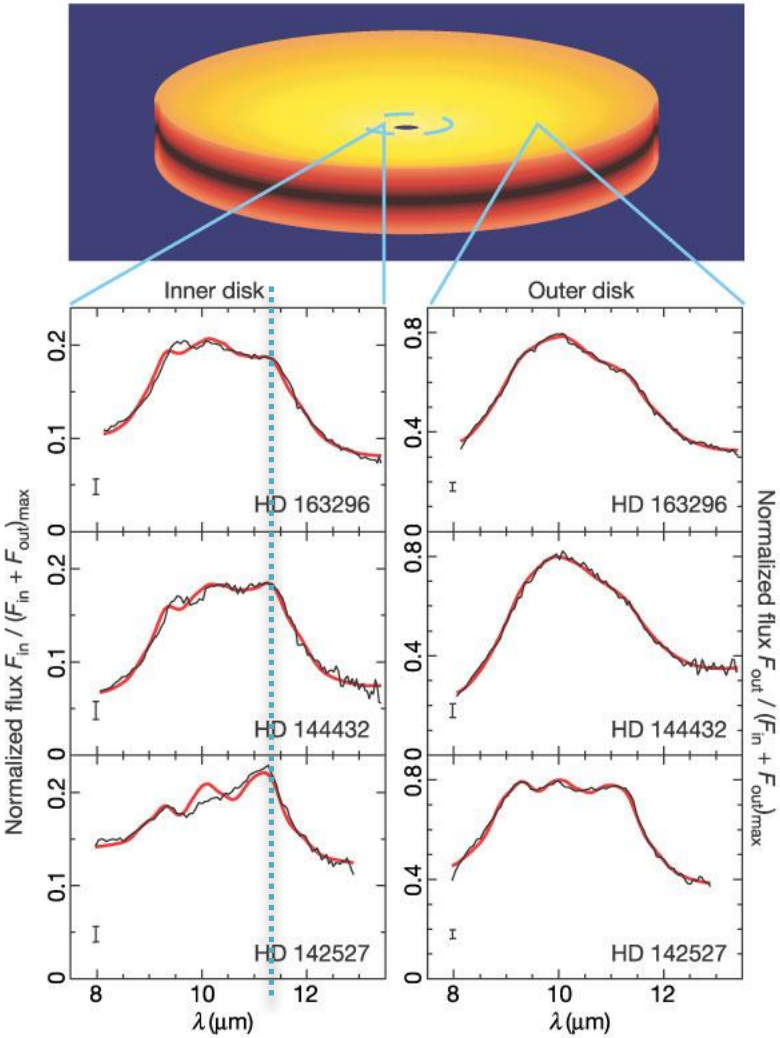


[Leinert et al. 2004]

(2) Radial gradient in disk mineralogy

- SED (outer disk) = SED (net) – SED (correlated flux)
- Difference in shape of Silicate feature = Difference in dust mineralogy as function of radial position

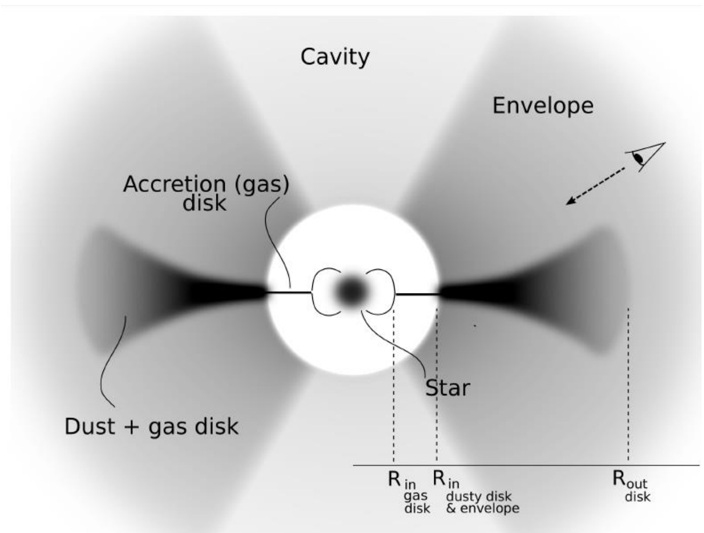
- Inner region:
  - Broad feature:
    Large grains (growth?)
  - Prominent resonance at 11.3μm:
    Crystalline silicate (e.g., annealing)
- Outer region:
  - Crystalline silicate abundance exceeds limits derived for ISM



Infrared spectra of the inner (1–2 AU) and outer (2–20 AU) disk regions of three Herbig Ae stars

[van Boekel et al. 2004]

(3) Temporal variability on ~ few AU scale



[Mosoni et al. 2013]

- Observations: MIDI, Spitzer, various optical/near-IR lightcurves

Parameters	2004		2005		2003/06
	Mar	Oct	Mar	Sept	quiescent
$\dot{M}$ ($M_{\odot} yr^{-1} \times 10^{-6}$)	7.0	5.5	3.5	1.6	0.3
$R_{\rm in,disk}$ (AU)	0.7	0.7	0.7	0.7	0.5
$R_{\rm in,env}$ (AU)	0.7	0.7	0.7	3.0	0.5
$A_{\rm V}$ (mag)	18.9	18.9	18.9	11.5	23.4

Varied model parameters for different epochs

Mosoni et al. (2013):

Young eruptive star V1647Ori

(2003-2006 outburst)

- Disk and the envelope: similar to those of non-eruptive young stars
- Accretion rate varied during the outburst
- Increase of the inner radii of the circumstellar disk and envelope at the beginning of the outburst
- Change of the interferometric visibilities: Indications for structural changes in the circumstellar material

(4) Connection: Inner / outer disk region

- Approach:
  - Combination of **MIDI observations***) (inner disk regions, thermal re-emission)
    with **SED** (flux from entire disk @ optical…mm) and
    IOTA / AMBER data (inner disk region, scattered light)
  - Targets: 11 young, low-mass stars with CS disks
    for various T Tauri disks
  - Model: Parameterized disk model (parameter fitting)

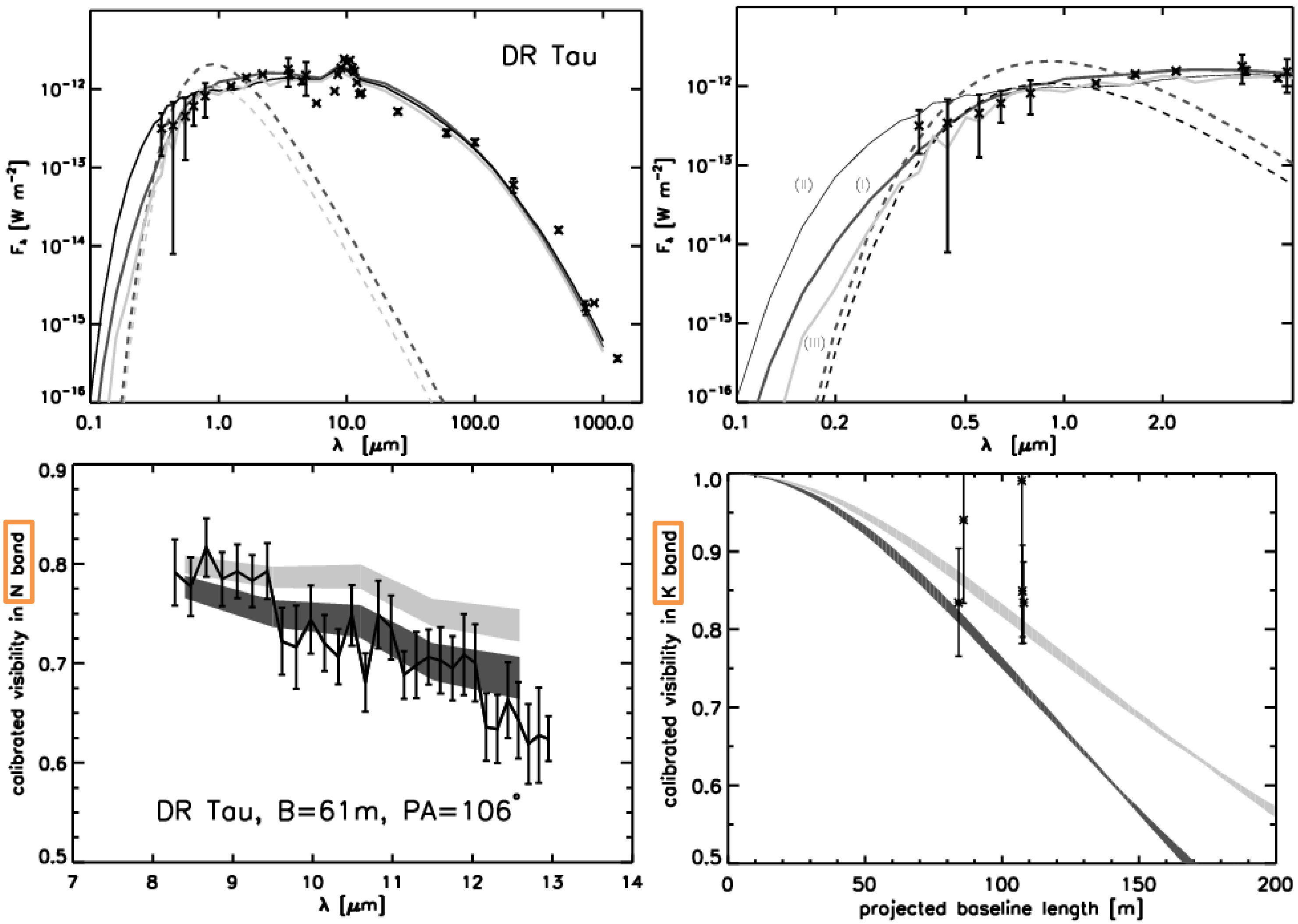
$$\rho(r,z) = \rho_0 \left(\frac{R_\star}{r}\right)^{\alpha} \exp\left[-\frac{1}{2}\left(\frac{z}{h(r)}\right)^2\right] \qquad h(r) = h_{100}\left(\frac{r}{100\ \mathrm{AU}}\right)^{\beta}$$

- Question:

  Does a simple disk model allow fitting the entire data set, with constraints on the global disk structure, as well as on the potential planet-forming region?

*) Spectrally resolved (R=30) N band visibilities

(4) Connection: Inner / outer disk region



[Schegerer et al. 2009]

(4) Connection: Inner / outer disk region

- Results
  - **SED** (global appearance of the disk) + spectrally resolved **visibilities** could be fitted **simultaneously** in 9 (out of 11) sources
  - Best-fit achieved in most cases with an **active accretion disk and/or envelope**
  - Decompositional analysis of the 10μm feature confirms effect of **Silicate Annealing** in the inner disk (~ few AU)
  - Individual constraints on inner holes (e.g., HD142666: R_{in} = 0.3AU < d*λ/B)

- *References*

  - *Schegerer, et al. 2008, A&A, 478, 779 „The T Tauri star RY Tauri as a case study of the inner regions of circumstellar dust disks "*
  - *Schegerer, et al. 2009, A&A, 502, 367 „Tracing the potential planet-forming region around seven pre-main sequence stars"*
  - *Schegerer et al. 2013, A&A, 555, 103 „Multiwavelength interferometric observations and modeling"*

Limitations of MIDI
-
Prospects of MATISSE

Inner disks – Open questions

Hypotheses / Theoretical model to be tested

- Surface density distribution
- Accretion: Viscosity, Angular momentum transfer, Accretion geometry on star(s)
- Snow-line (location / surface density profile)
- Planets: Luminosity, induced gaps
- Puffed-up inner rim and associated shadowed region
- Gas within the inner rim
- Gas-to-dust mass ratio; Empty(?) holes in transition disks

The general context (exemplary questions):

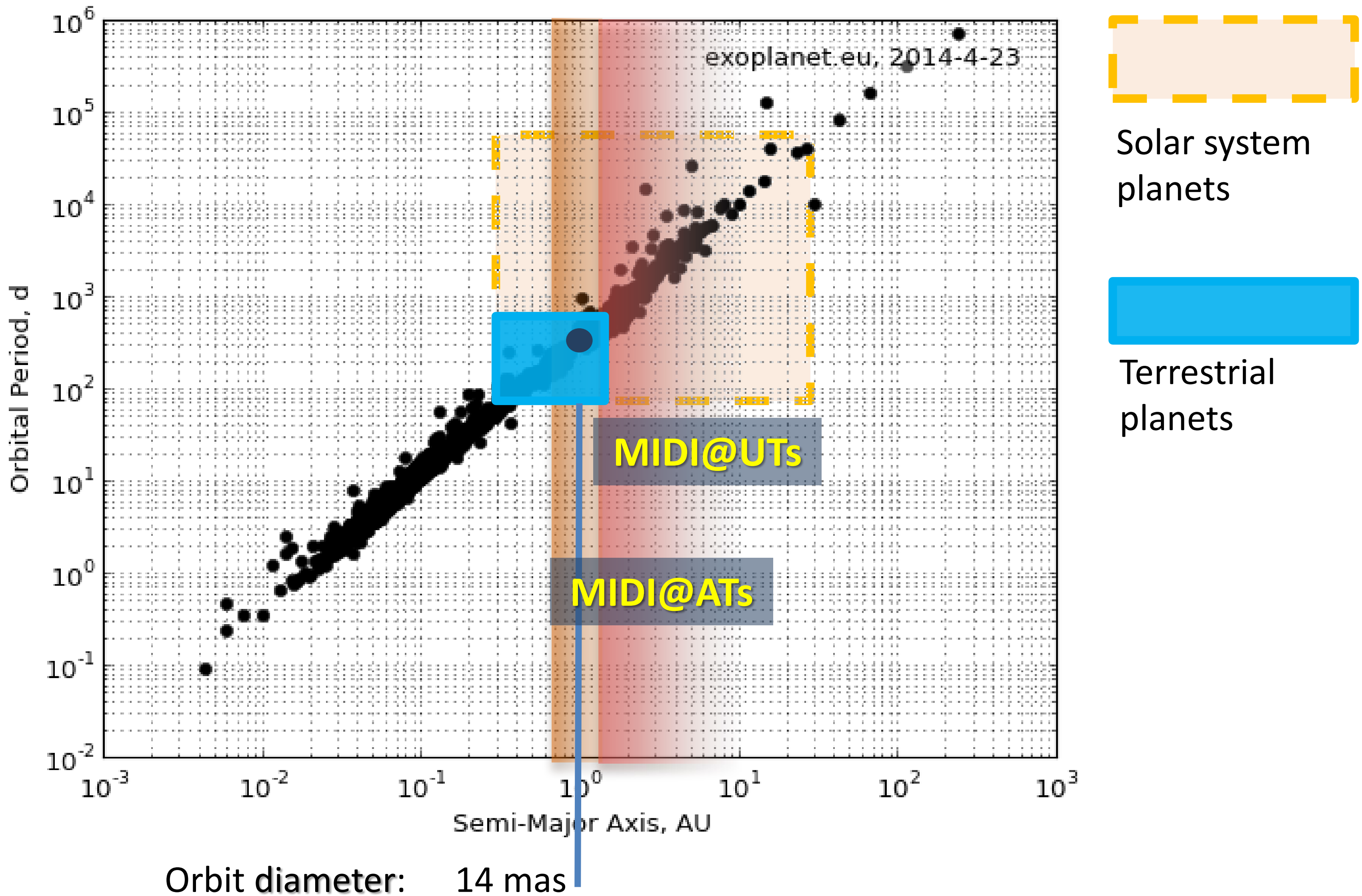
- How do inner and outer disk relate to each other?
- Where and when do planets form?

Approach

Constraints on brightness distribution of the inner disk;

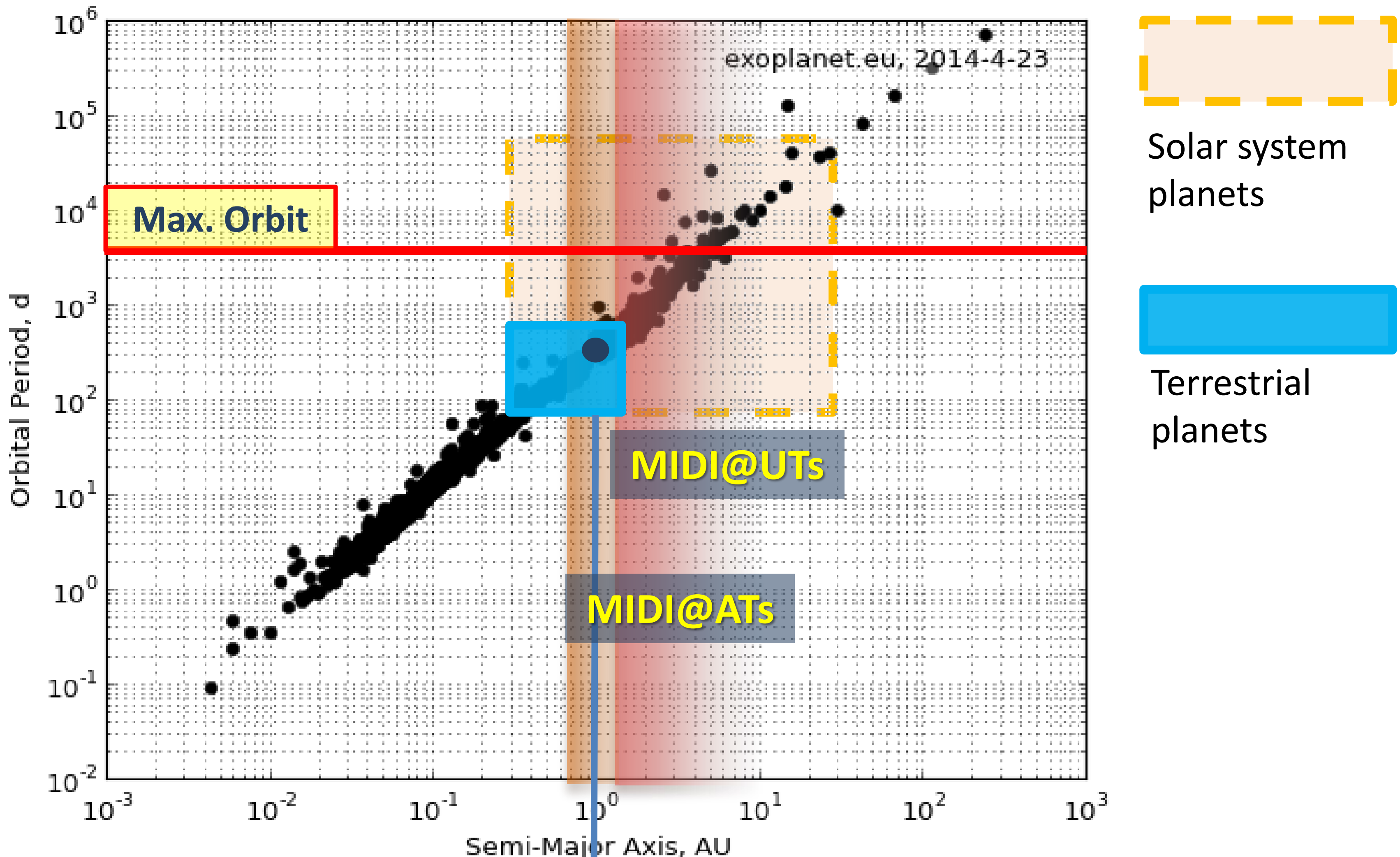
Goal: Multi-wavelength imaging

Disks @ 140pc: Techniques & Potential



Orbit diameter: 14 mas

Disks @ 140pc: Techniques & Potential



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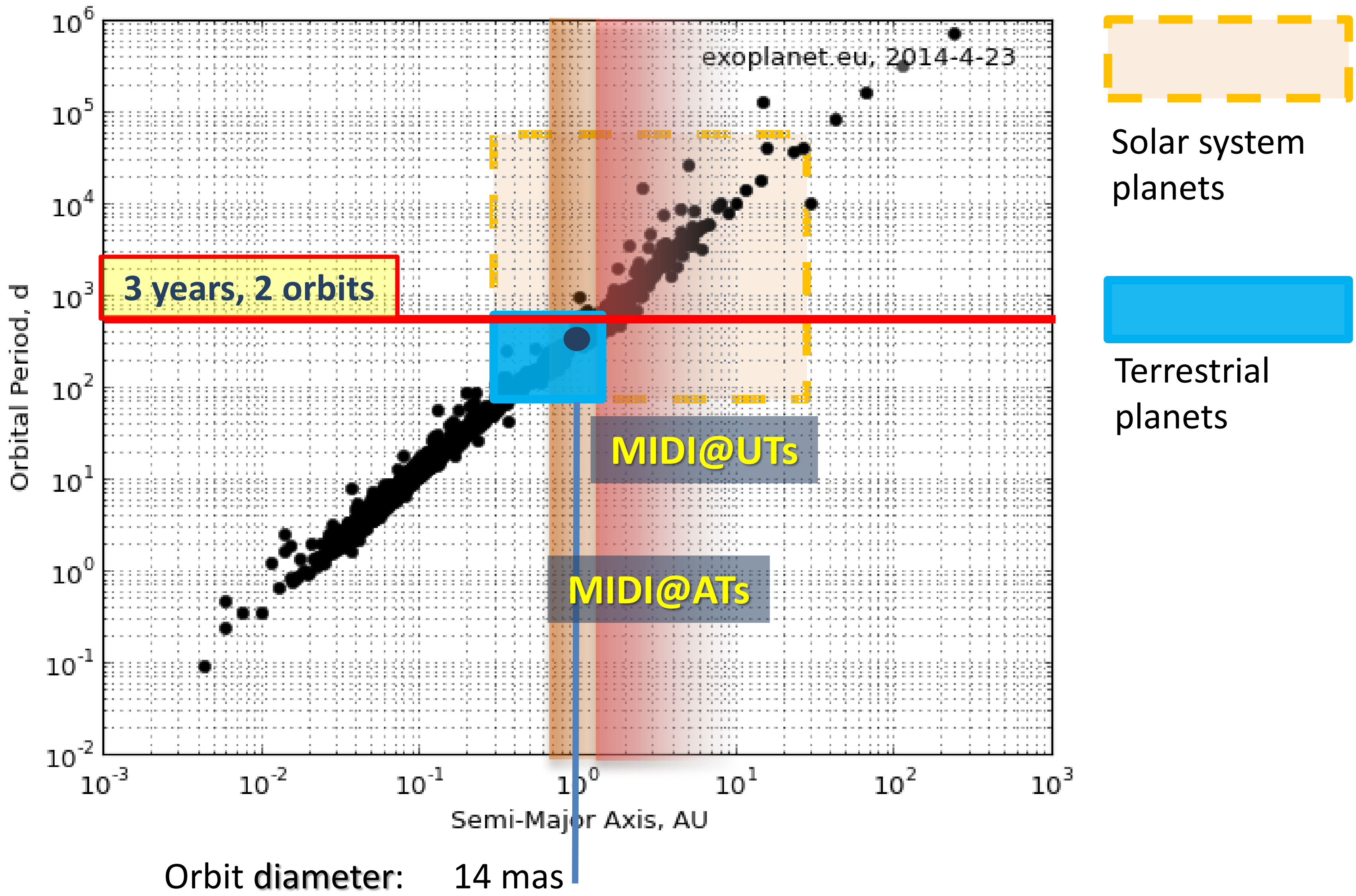


Limitation #1: Availability / Source variability

- MIDI scientific operation:
  - Begin : 2002
  - End : 2014(?)

- Orbital timescale / radius in gravitational field around solar-mass star:

Orbit [yr]	Radius [AU]
5	3
10	5
20	7

- „o.k.“: for 1-2 epochs of observations of the 10μm bright regions
- not „o.k.“: for studying the temporal variability
  (as indicators of inhomogeneities / substructures
  in the potential planet-forming region)

Limitation #2: uv coverage / phases

a. Small number of visibility points

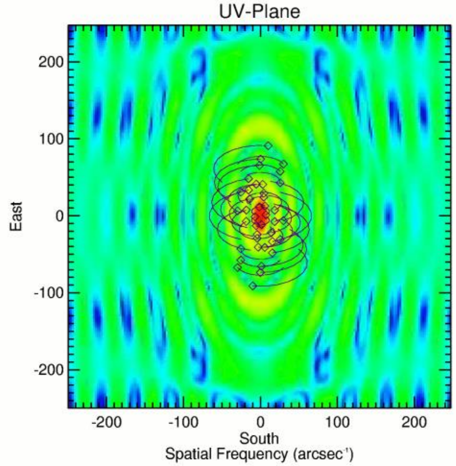
b. Lack of Phase Information

   Investigation of small-scale structures and
   quantitative analysis of spectroscopic observation strongly limited

Limitation #2: uv coverage / phases

MATISSE / Circumstellar disks

Configuration: 7 Nights × 3 ATs
Baselines: B5-J6-J1, B5-D0-J3, B5-B1-D1, B5-M0-G2, J6-A0-J2, J1-D1-G2, J6-A0-M0
Number of Visibilities: 210, Number of Closure Phase Relations: 70



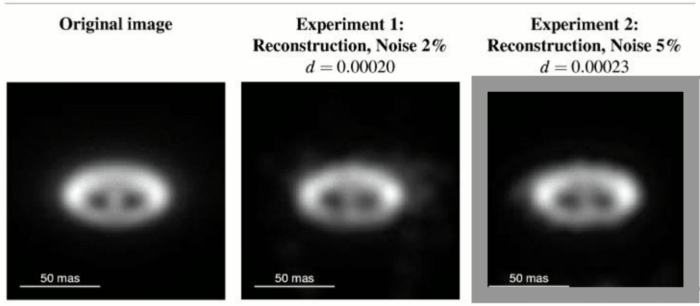
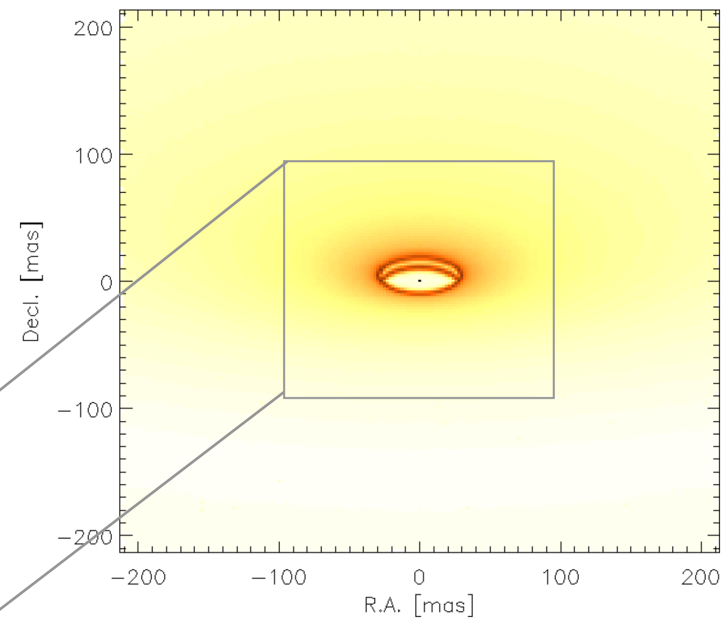


Figure 22: Image reconstruction experiments. *Top*: uv-coverage of the two reconstruction experiments; *Bottom left*: original image (see Fig. 21, right) convolved with a PSF corresponding to a 202 m aperture; *Bottom center and right*: images reconstructed from two data sets with 2% and 5% noise of the squared visibilities (4% and 10% for the simulated closure phases). The reconstruction errors are 0.00020 (2% noise) and 0.00023 (5% noise) using the distance measure d by Lawson et al. (2004).

[K.-H- Hofmann in Wolf et al. 2007]



10μm image of a circumstellar disk with an inner hole; radius 4AU (inclination: 60°; distance 140pc; inner 60AU x 60AU)

Limitation #2: uv coverage / phases

MATISSE / Circumstellar disks

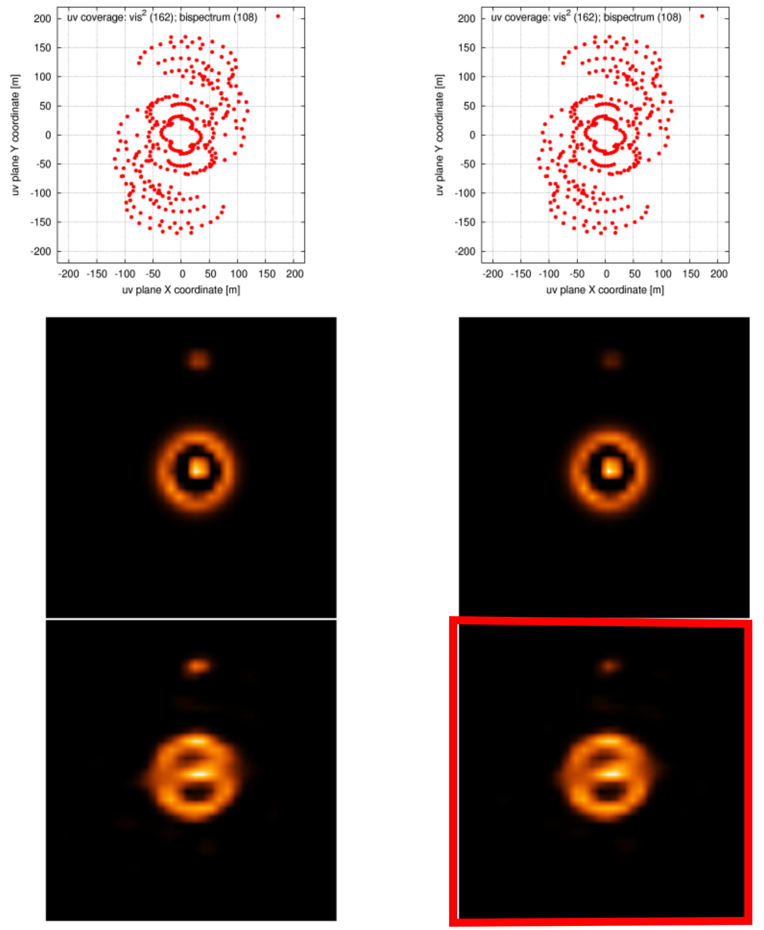
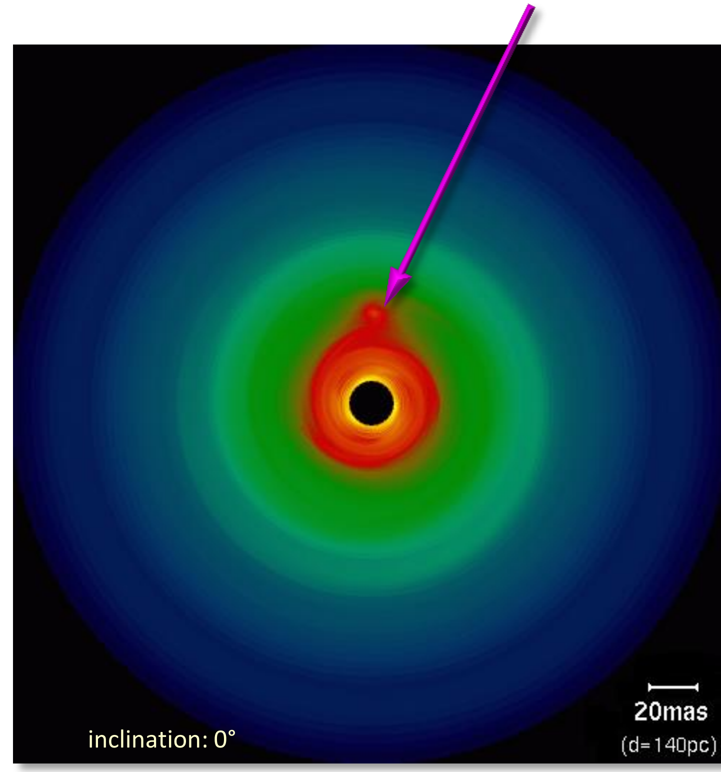


Figure 6: Reconstructed N band images (3x4ATs; ~ 150 m) of a protoplanetary disk with an embedded planet (see Fig. 5[right]). Left: Brighter planet: intensity ratio star/planet=100/1; Right: Fainter planet: intensity ratio star/planet=200/1. First row: uv coverages Second and third row: originals and reconstructions, respectively. The images are not convolved (2x super resolution). Simulation parameter: modelled YSO with planet (declination -30°; observing wavelength 9.5 μm; FOV = 104 mas; 1000 simulated interferograms per snap shot with photon and 10 μm sky background noise (average SNR of visibilities: 20). See Doc. No. VLT-TRE-MAT-15860-5001 for details.

[K.-H- Hofmann in Wolf et al. 2007]

Hot Accretion Region
around Proto-Planet



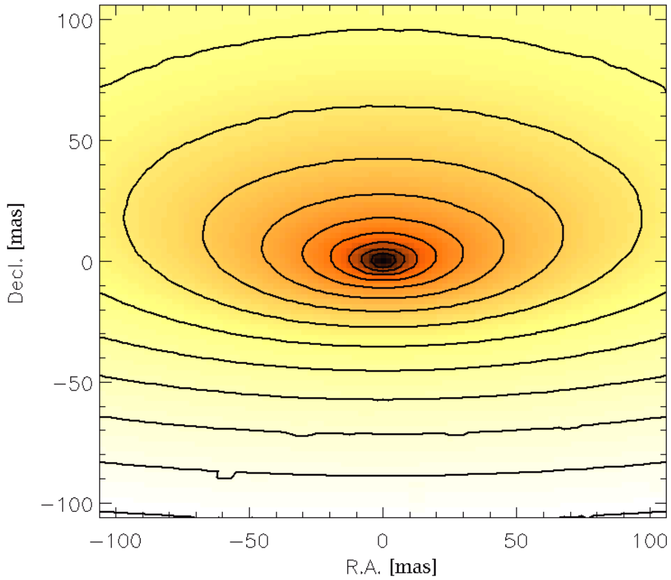
Limitation #2: uv coverage / phases

- Interpretation of MIDI data:
  - Comparison between modeled and observed visibility points, using 2D models with point-symmetry (usually even rotation symmetry)
  - Approach justified only by large-scale (if at all existing) symmetries, but expected to be strongly misleading or simply wrong

Problem

Two-telescope interferometers: “Mean” disk size & approximate disk inclination

Assumption: Iso-brightness contours are centered on the location of the central star



Simulated 10µm intensity map of the inner 30AU×30AU region of a circum-stellar T Tauri disk at an assumed distance of 140 pc; inclination: 60°.

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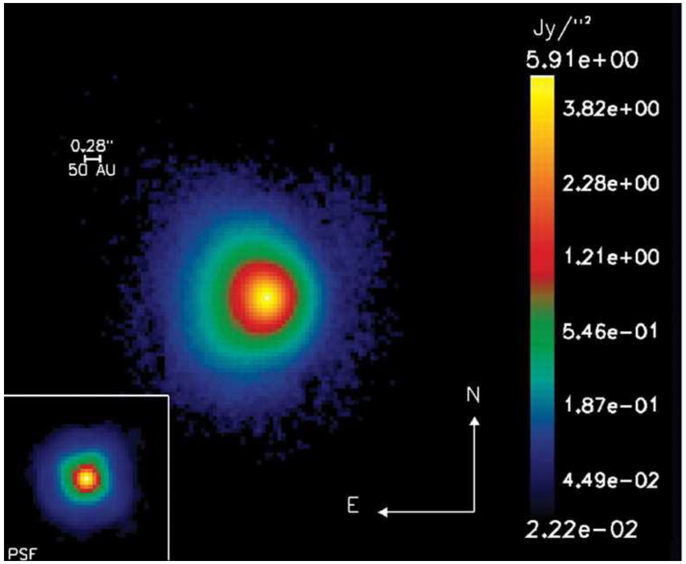
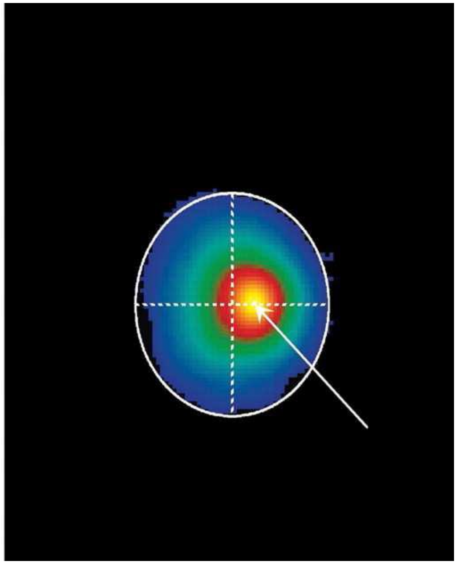




Left: VISIR false-color image of the emission from the circumstellar material surrounding the HAe star HD97048. The emission is widely extended, as compared with the point spread function (inset) obtained from the observation of a pointlike reference star.

Right: Same image as in the middle, but with a cut at the brightness level and a fit of the edge of the image by an ellipse (Lagage et al. 2006).

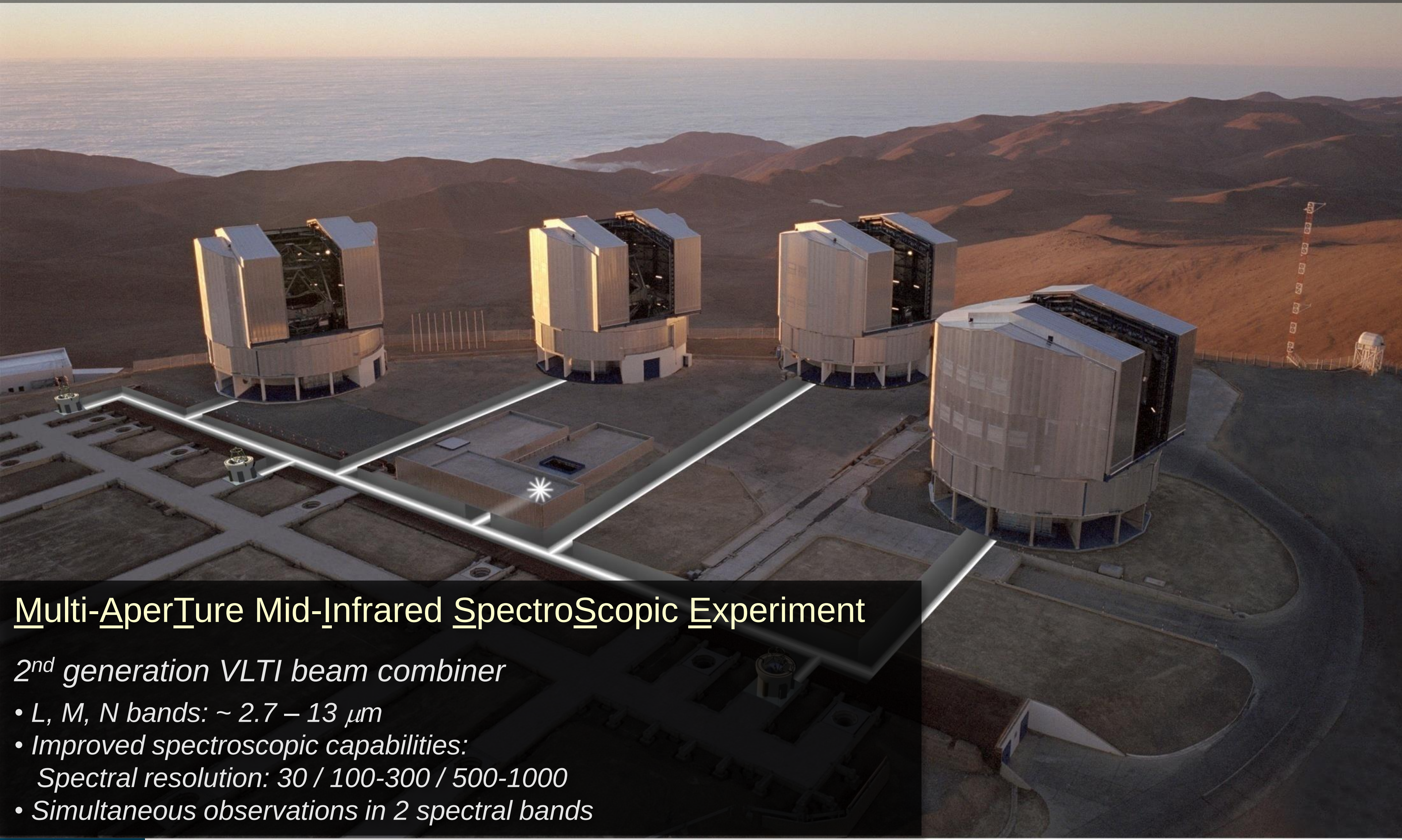
MATISSE: Further prospects

- Wavelength coverage
  - L (~3.0-4.1μm), M (~4.6-4.8μm), N
  - *Impact:*
    - *Regions with higher characteristic temperatures*
    - *Higher angular resolution (~ 2-3)*
    - *Scattered light*
    - *High sensitity (reduced background noise)*

- Spectral resolution
  - Low 20 < R < 40 (3.5μm, 10.5μm)
  - Medium 350 < R < 550 (3.5μm), 150 < R < 250 (10.5μm)
  - High 800 < R < 1000 (3.5μm)
  - *Impact:*
    - *Molecular bands; selected atomic lines*

      e.g., H_2O, PAHs, CO fundamental transition series, CO ice features, Pf β (4.65μm)

MATISSE @ Very Large Telescope Interferometer



Multi-AperTure Mid-Infrared SpectroScopic Experiment

2nd generation VLTI beam combiner

- *L, M, N bands: ~ 2.7 – 13 μm*
- *Improved spectroscopic capabilities:*
  Spectral resolution: 30 / 100-300 / 500-1000
- *Simultaneous observations in 2 spectral bands*

Goal: Thermal reemission/scattered light images with an angular resolution of 0.003“