Architecture of planetary systems

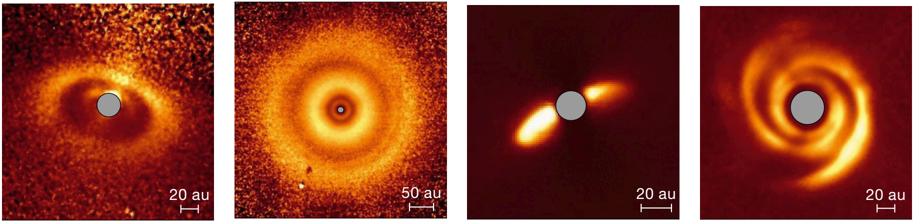
How do the planets form?

Célia DESGRANGE

Supervisors: Gaël Chauvin, Julien Milli, and Thomas Henning

Wide diversity of architectures of planetary systems

Protoplanetary disks (1–6 Myr)



LkCa15 | TW Hya | T Cha | HD 135344B

Garufi et al. (2017)

Early stage of formation: observation of cavity, rings, spirals...
In older systems: still observe diverse architectures e.g. presence of belts, different types of planets, some with circumplanetary disk.

To what extent the architecture of a system can help us to learn how do planets form?

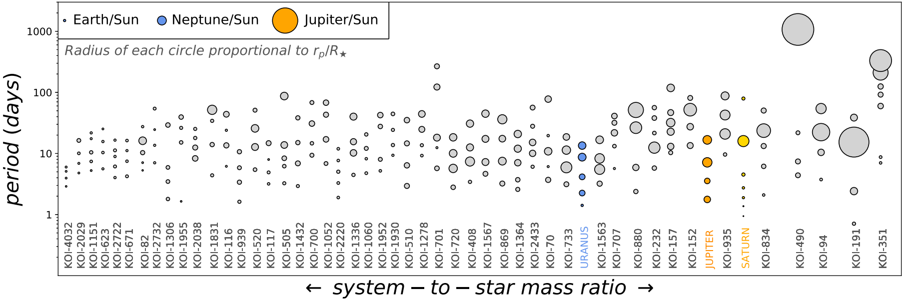
Do planets in a given system share similar properties?

"Peas in a pod" model

Intra-system uniformity:

From Kepler observations, pairs of exoplanets are similar in size and mass, and evenly spaced orbits (caused by accretion/migration competition?)

e.g. Millholland+2017; Weiss+2018; Gilbert & Fabrycky 2020



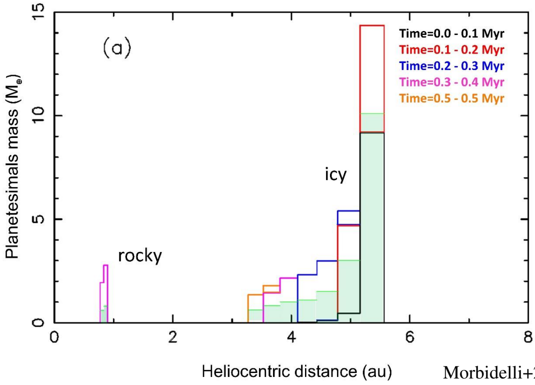
Gilbert & Fabrycky 2020

Where do the planets form?

A favorable place to form planetesimals is expected to be the **snow line** (accumulation of materials). (e.g. Ida+2016, Schoonenberg+2017, Drazkowska+2018)

Problem: formation of inner rocky planetesimals (and planets)

Recently, Morbidelli et al. 2022 (Nature Astronomy) shed light on another favorable region: the **silicate sublimation line**.



Morbidelli+2022 (Nature Astronomy)

Can we predict what are the planets in a system based on an a priori knowledge?

Star properties:

Mass ⇒ disk mass ⇒ quantity of materials available (e.g. Schlecker+2021)

Metallicity

Planet properties:

Eccentric small planet ⇒ may expect an eccentric giant planet

Eccentric giant planet ⇒ likely no inner small planet (e.g. Baruteau+2020, Bitsch+2020, Schlecker+2021)

Inner Super-Earth ⇒ favorable to the presence of outer giant planets? (e.g. Zhu&Wu2018, Schlecker+2021)
→ **Super-Earth project**

Belt properties:

Is there a **cavity** or a **wide gap** between two belts?
→ **HD 95086 project**

Plan

Super-Earth project: Objective

How do the Super-Earths form ?

Super-Earth $\simeq$ 1–2 $R_{\mathrm{Earth}} \simeq$ 1–20 M_{Earth}

$\Rightarrow$ most abundant type of exoplanets, but their location close to their host star raises questions on their formation...

Super-Earth project: Objective

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2 possibilities:

Could close-in Super-Earths have formed in-situ at typically less than 1 au?

or,

Did they form further out in the planet-forming disk and migrated inwards?

and thus,

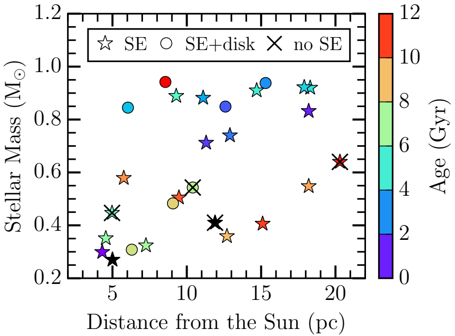
Could there be a correlation between the presence of Super-Earths and outer giant planets ?

Super-Earths: Sample

Sample = 23 systems hosting at least one Super-Earth already detected by radial velocities (over a sample of 27 systems)

- Spectral type: MKG
- Close (< 20 pc)
- Old (100 Myr – 10 Gyr)
- Six systems have a debris disk already discovered

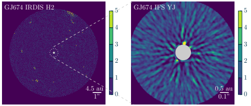
$\Rightarrow$ we look for giant planets or brown dwarfs located at > 1 au from their star



Desgrange, Milli, Chauvin et al. (in prep); same for next Figures

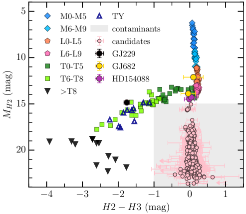
Big picture: data processing and analysis

50 Observations



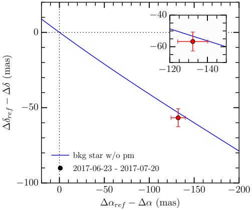
⇒

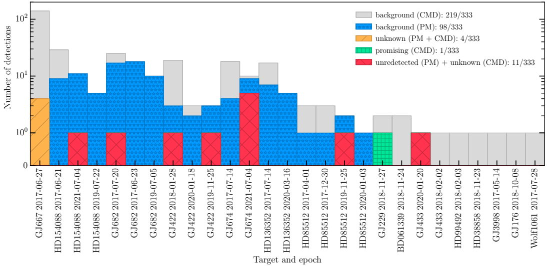
Criterion CMD



and/or

Criterion PMD





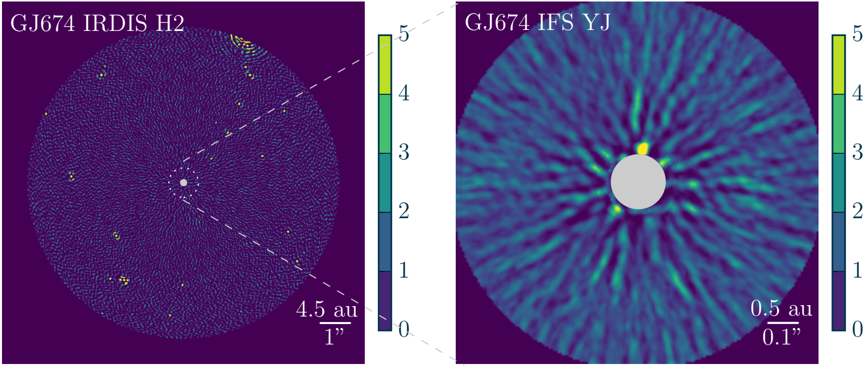
Detection status

- companion bound ?
- background star?
- instrumental artefact?

Observation SPHERE-IRDIS and SPHERE-IFS

Example with GJ 674 system

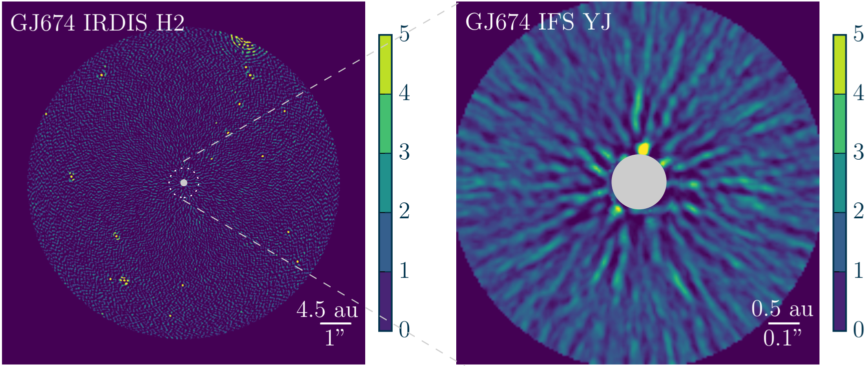
1 among the 50 observations of the Super-Earths survey
(image post-processing with ANDROMEDA, Cantalloube+2015)



H2 = 1.59 μm　　　　YJ = 0.96–1.34 μm

A point source in an image can have different origins...

On the image, **a point source** can be =
- (1) giant planet, brown dwarf
- (2) background star
- (3) instrumental artefact



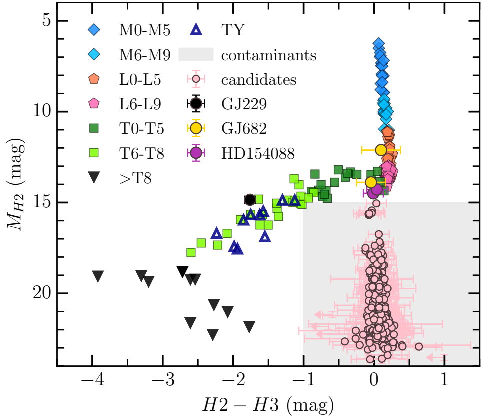
H2 = 1.59 μm

YJ = 0.96–1.34 μm

Criterion #1: bound companions or background stars?

Color Magnitude Diagrams in H23

vs empirical sequence of known substellar objects



CMD = easiest criterion to disentangle between bound companions and background stars, but only indicative.

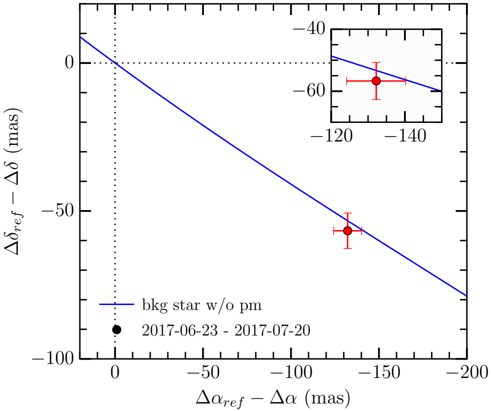
Promising detections but most of them are consistent with background contaminants.

Plot Color Magnitude Diagram: tool from Arthur Vigan, Mickaël Bonnefoy

Criterion #2: bound companions or background stars?

Motion Diagram for GJ 682

Compare the motion of the detection between two epochs

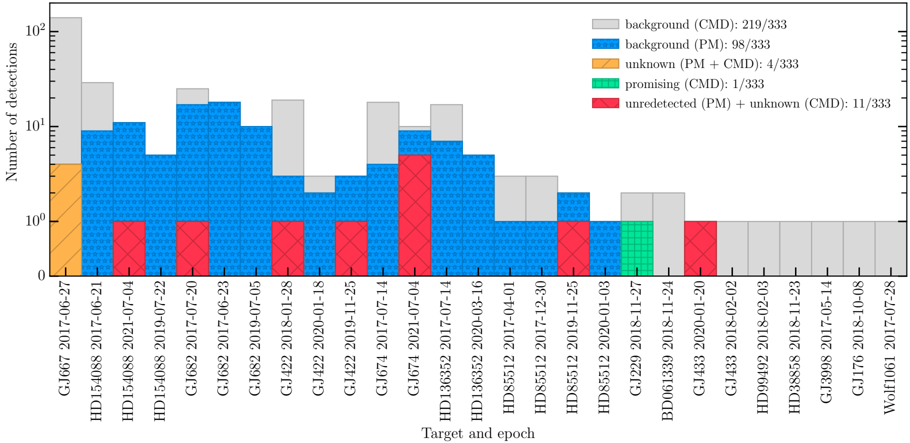


PMD = an absolute criterion to disentangle between bound companion and background star.

Detection consistent with a background star.

Derived expected background motion: tool from Arthur Vigan

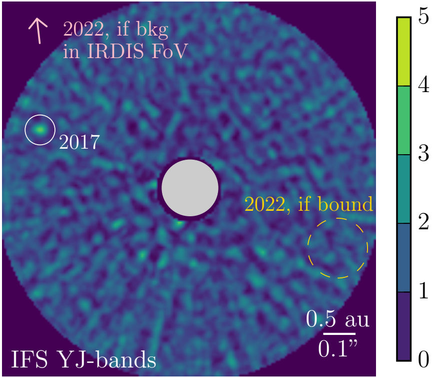
Results: Status of the detections from SPHERE-IRDIS



The only promising detection is the already known brown dwarf in the GJ 229 system. All other detections from IRDIS are likely to be background stars.

A direct detection of the exoplanet GJ 832 b ?

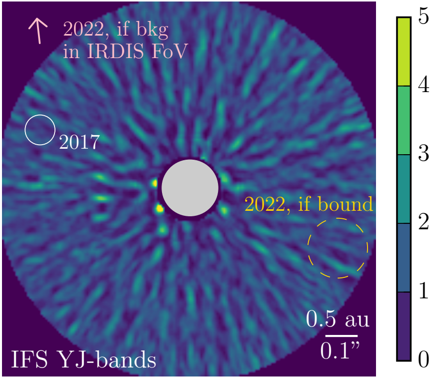
Observation 2017-05-27 (SPHERE-IFS)



- **Discovery:** RV (Bailey+2009)
- **Orbital parameters:** (Gorrini+2022)
  Mass: 0.74 ± 0.06 M_{Jup}
  Period: 3838 ± 49 days
  (i.e. a semi-major axis of ~ 3.8 au)
  Low eccentricity: 0.02–0.06
- **Significant proper motion anomaly** (Gaia/Hipparcos)
  i.e. S/N ~ 14.1 (Kervella+2022)
- **Gaia/Hipp signal consistent with the RV measurements** assuming a circular orbit and an inclination of 60° (Kervella+2019)

A direct detection of the exoplanet GJ 832 b ?

Observation 2022-07-29 (SPHERE-IFS)



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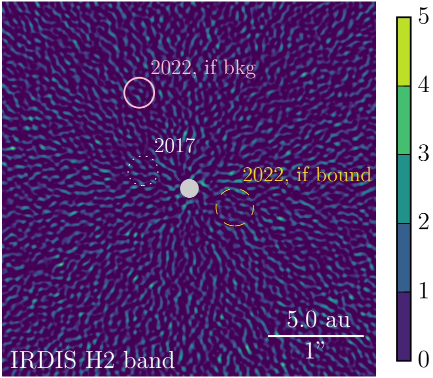

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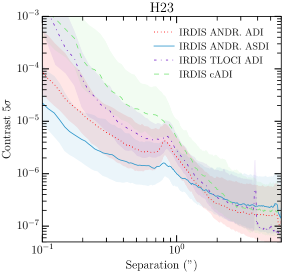
No detection do *not* mean no planet! Survey sensitivity.



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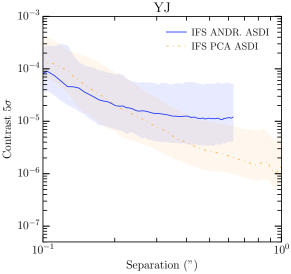


+

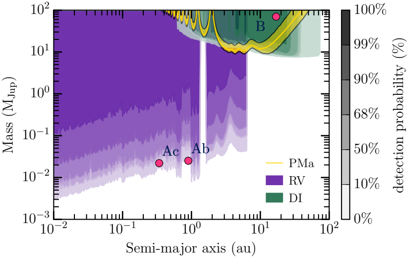
evolutive models COND2003

Conversion :

Detection limit in terms of **contrast**
$\Rightarrow$ in terms of **mass** (tool: `pyMESS2`, priv. comm. Anne-Marie Lagrange)

Coupling detection methods:

RV & DI & PMa



and what about work from the literature?

Observational results in literature

Positive correlation between Super-Earths and Cold Jupiters

- **Zhu&Wu (2018)**:
  31 systems harboring Super-Earths (RV)
  $P(CJ|SE) = 29 \pm 18\%$ while $P(CJ) = 10\%$ $(CJ \geq 1$ au, $0.3\,M_{Jup})$
- **Bryan+ (2019)**:
  65 systems harboring Super-Earths (RV+Transit)
  $P(CJ|SE) = 32 \pm 7\%$ while $P(CJ) = 7 \pm 3\%$ (CJ 1–20 au, 0.5–20 M_{Jup})
- Herman+ (2019):
  12 systems harboring Super-Earths (Transit)
  $P(CJ|SE) = 42\%$ $(CJ \geq 1.6$ au, $0.3\,M_{Jup})$
- **Rosenthal+ 2021**
  28 systems harboring super-Earths (among a survey of 719 FGKM stars) (RV+Transit)
  $P(CJ|SE) = 13 \pm 9\%$ while $P(CJ) = 7 \pm 1\%$ (CJ 3–7 au, 0.3–13 M_{Jup})

vs Super-Earth project: G, K, M-stars.

Theoretical numerical predictions from Bern models

Regarding solar-like stars (1 $M_\odot$)**:**

Weak positive correlation but which depends on the mass and period limits of each planet category.

Influence from cold Jupiters on the **composition of inner super-Earth** (which are drier).

Driver of Super-Earths and cold Jupiter formation: **disk mass**, with formation of both of them in an intermediate mass disk.

(Schlecker+2021)

disk mass $\Longleftrightarrow$ **stellar type**

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As for lower mass stars (M-stars):

No giants are expected around 0.3 $M_\odot$-stars, p = 0.02 around 0.5 $M_\odot$-stars and p = 0.09 around 0.7$M_\odot$-stars. (Burn+2021)

Role of giant planets

Giant planets at large distances could:

(Positive correlation case)

- scatter Super-Earths inside their orbit
- trap Super-Earth in secular resonances
- increase eccentricity of Super-Earth cores via Kozai interactions, before orbit circularization at ≤ 1 au

(Negative correlation case)

- halt migration of Super-Earths formed at larger distances
- cut off the flow of solids to the inner disk
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No correlation case:

- independent formation processes between outer giant planets and Super-Earths (which formed in-situ)
- or a mix of everything

$\rightarrow$ **What is the timescale to form a planet ?**
$\rightarrow$ **Do Super-Earths form contemporary/before/after giant planets?**

Conclusion on the project super-Earths

The **SPHERE Super-Earths project** demonstrates particularly relevant synergy to offer **a global view of planetary systems**, especially the ones hosting super-Earths.

Preliminary results:

- Can go down to 3-30 M_{Jup} planets, brown dwarfs at $\gtrsim$ 1 au (even Y-spectral type!).
- Several candidates identified ($\geq$ 330), likely background. Not a surprise based on our survey sensitivity coupled to planetary population synthesis from Bern models.

Limitations:

- Constrain the presence of outer giant planets remain limited to massive objects
  $\rightarrow$ interesting prospects for future studies (e.g.: smaller mass: JWST; closer: ELTs METIS/PCS).
- Age of the systems (poorly constrained and old, $\sim$ Gyrs)

Conclusion on the project super-Earths

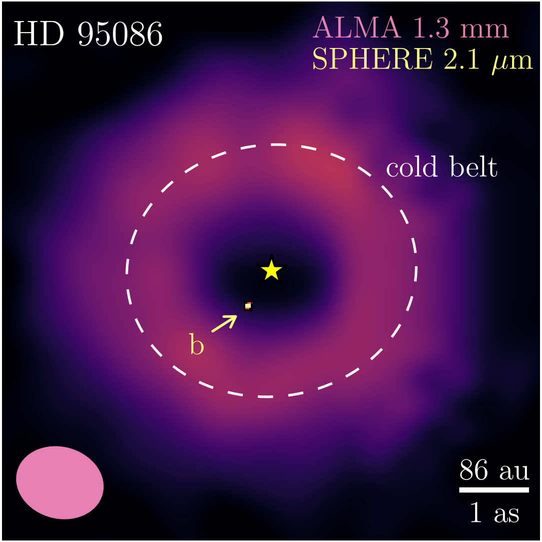
- **Initial question: is there a correlation between super-Earth(s) and outer giant planet(s) ?**

  $\rightarrow$ our survey is not sensitive enough for giant planet in most systems, but in the case of outer brown dwarfs ($\gtrsim$ 13 M_{Jup}, $\gtrsim$ 3 au): no robust detections.

- **Other tracers of the presence of outer giant planets:**

  $\rightarrow$ stellar metallicity and eccentricity of the super-Earths already discovered or the presence of debris disks.

The exoplanetary system HD 95086



Courtesy of Kate Su (ALMA image) and Gaël Chauvin (SPHERE image)

– star –

A-type
1.6 $M_\odot$
$13.3^{+1.1}_{-0.6}$ Myr
86.2 pc in Carina

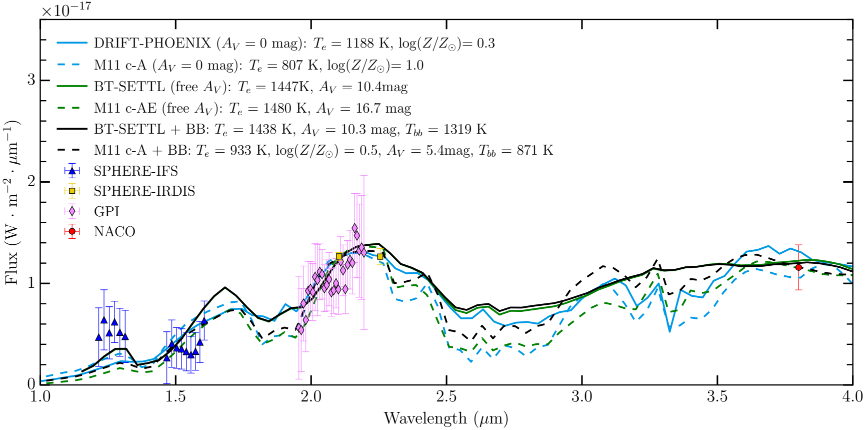
– belts –

warm belt
(7–10 au, $\simeq$ 190 K)
cold belt
(106–320 au, $\simeq$ 57 K)

– exoplanet(s) –

HD 95086 b
4–5 M_{Jup}
52 au ($\simeq$ 620 mas)
L6-type
+ 1, 2 giants ?

Spectrum and atmospheric fitting of HD 95086 b

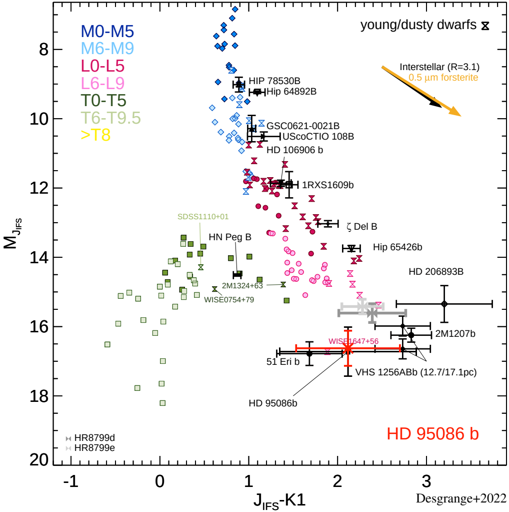


atmosphere fitting solutions = { (1) hot ($\geq$ 1400 K) + high extinction ($A_V > 10$ mag)
(2) colder (800–1200 K) + extra-solar metallicity } $\Rightarrow$ dust!

Atmosphere fitting: `special` package from Valentin Christiaens (open access: `vip_hci` library)

Desgrange, Chauvin, Christiaens et al. 2022; same for next Figures

The exoplanet HD 95086 b is red and under-luminous

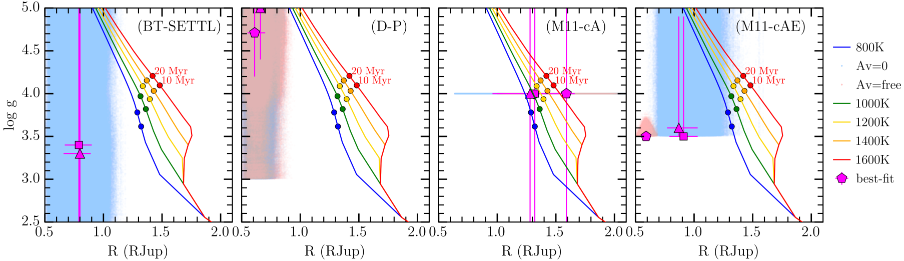


Desgrange+2022

- falls at the **late-L to L/T transition**
- **under-luminous** compared to the field dwarves of similar spectral types.
- **red** companion

(from Galicher+2014, De Rosa+2016, and Chauvin+2018)

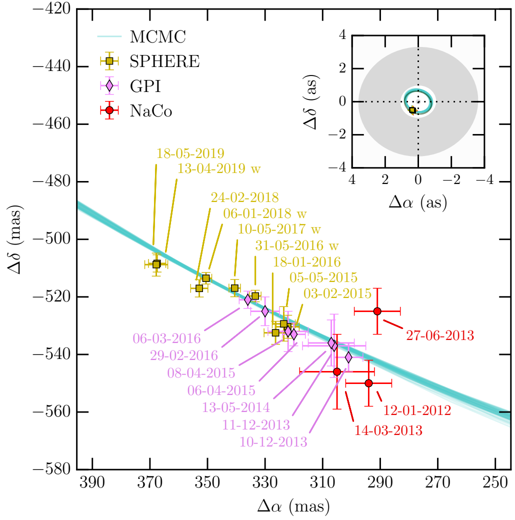
Atmospheric *versus* internal models



Best atmospheric solutions (e.g. from BT-Settl, Drift-Phoenix, Madhusudhan+11 cloud AE i.e. localized forsterite clouds grids) **often incompatible with internal models** (here: BEX-Hot).

Madhusudhan et al. 2011 cloud A (extended forsterite clouds) grids are compatible with BEX-Hot grids.

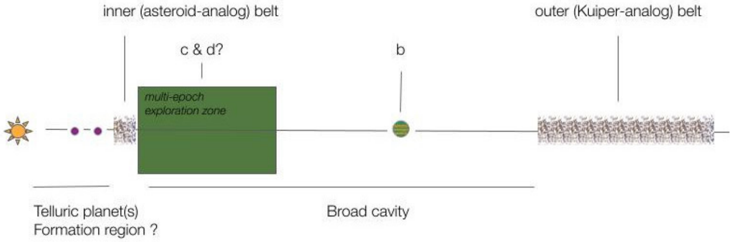
Astrometric positions and orbital fitting of HD 95086 b



Orbital fitting: MCMC tool from Hervé Beust

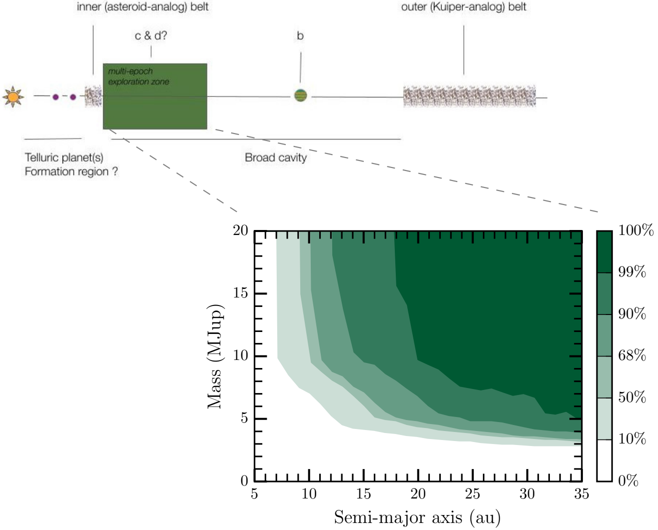
Additional exoplanet(s) ?

We look for at least one additional giant planet between $\sim$ 10 and 35 au.



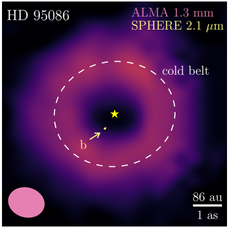
Crédits: Gaël Chauvin

Constraints on the researched planet c



Derivation detection limits: `pyMESS2` tool from Anne-Marie Lagrange

Conclusion on the planetary system HD 95086



- **Emblematic system (disk+planet)**, many observations from different telescopes/instruments, ongoing studies (e.g. GRAVITY, ALMA), and prime target for future observational facilities (JWST-GTO, ELTs..)
- **Reddeness of the exoplanet HD 95086 b: clouds or circumplanetary disk ?** the answer could be given by high spectral resolution? (HiRISE?)
- Still looking for the **exoplanet c**, my guess: interferometric observations from JWST-NIRISS may find it!

Global conclusion

Architecture of planetary systems
requires to have a
global picture on planetary systems

$\rightarrow$ coupling detection methods (DI, interferometry, RV, Gaia, Transit...) for a same system, and ideally for a same planet to get better constraints.

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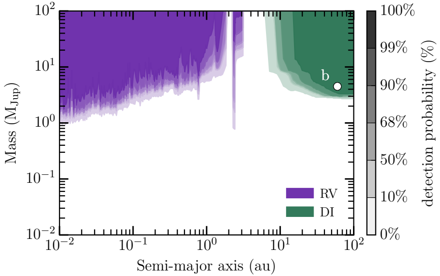
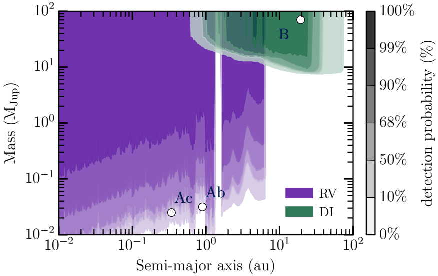
[HD 95086]
Young system (∼ 14 Myr)
86 pc, A-star



[GJ 229]
Old system (∼ 3 Gyr)
6 pc, M-star



Thank you for your attention!

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