Exoplanet Characterization with the VLTI

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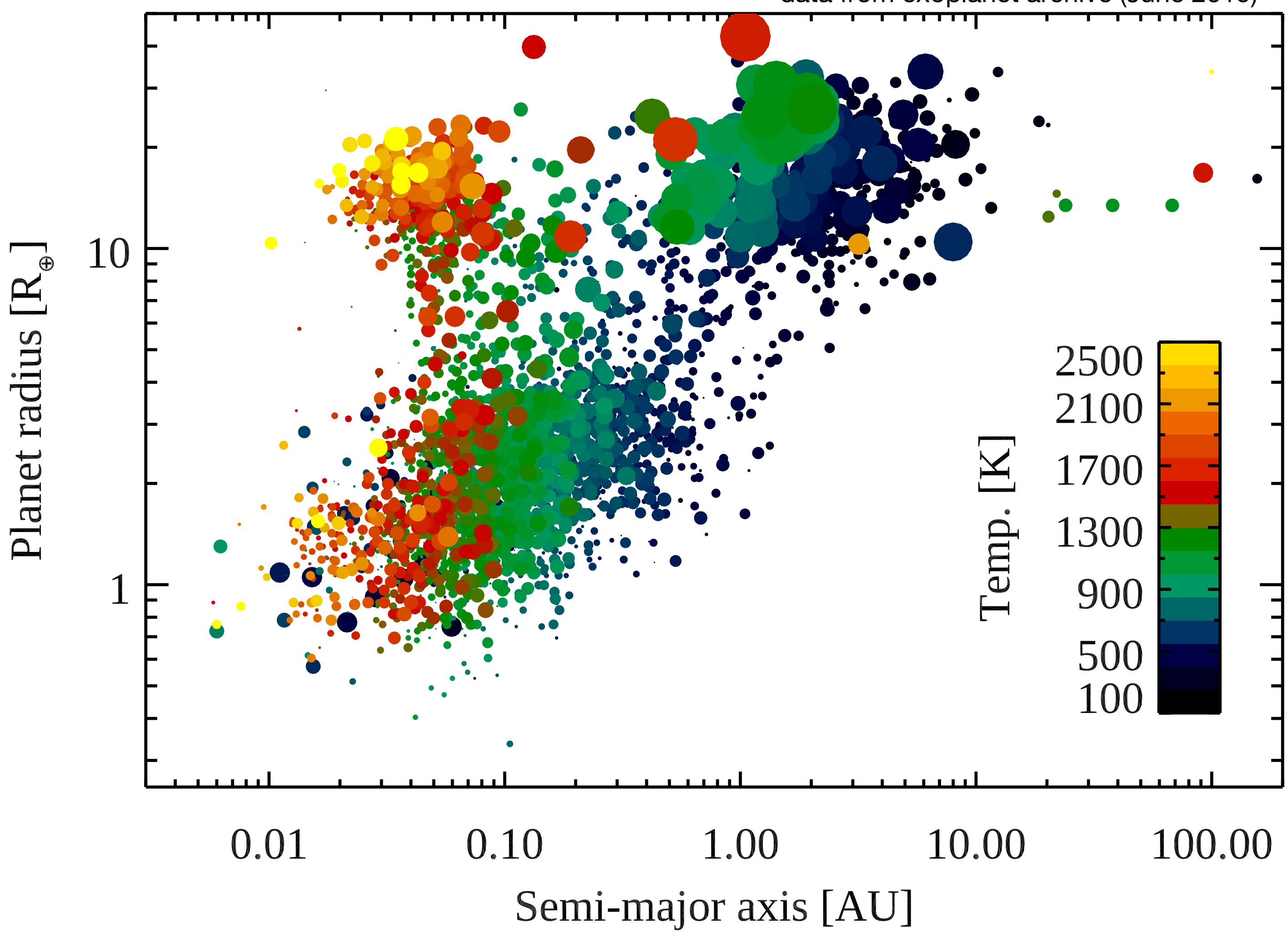
June 20th 2019 – Munich

Exoplanet today: huge diversity

- 3900+ planets, 2700 planetary systems known in our galaxy

*data from exoplanet archive (June 2019)



Key Exoplanet Questions

1. What is the **chemical composition of exoplanets**? How do the solar system planets fit in the big picture?

2. **How do exoplanets form and evolve?** (migration, interaction with star, …). Correlation between formation and chemical composition?

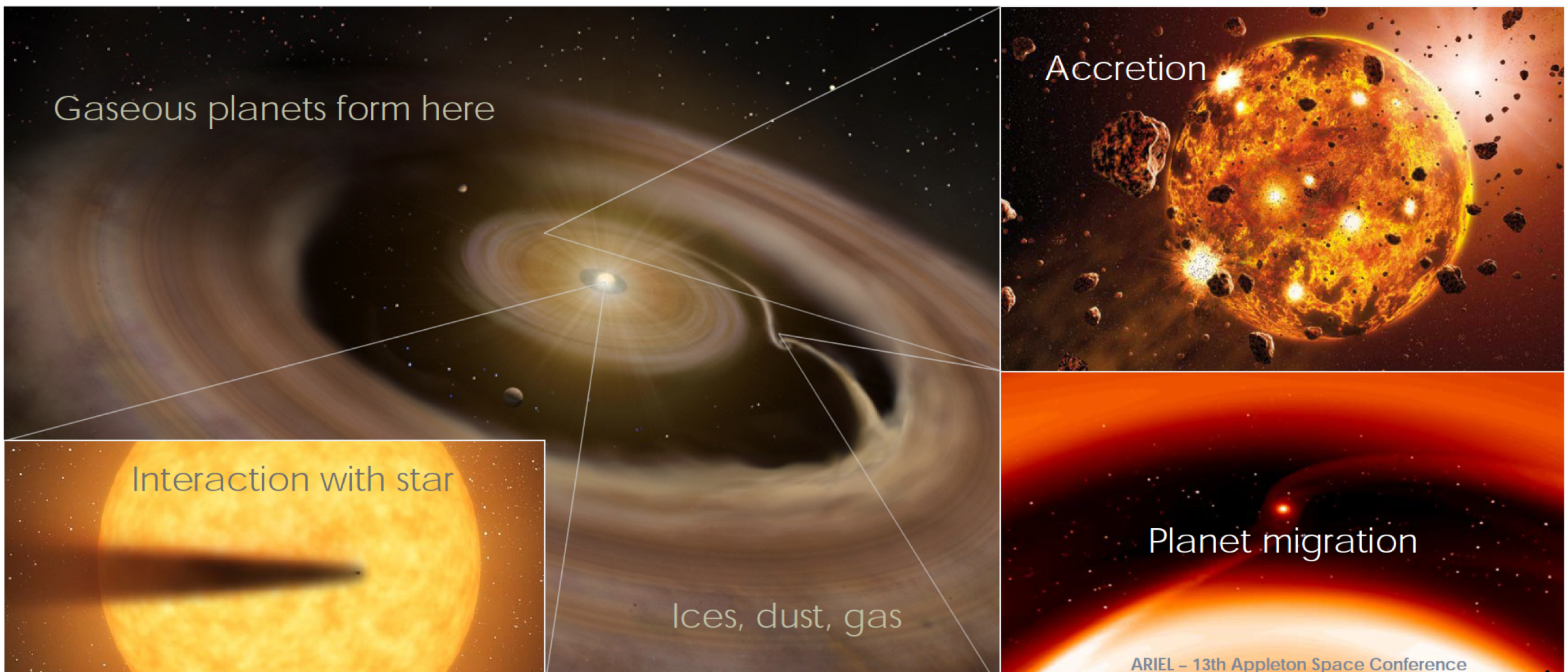
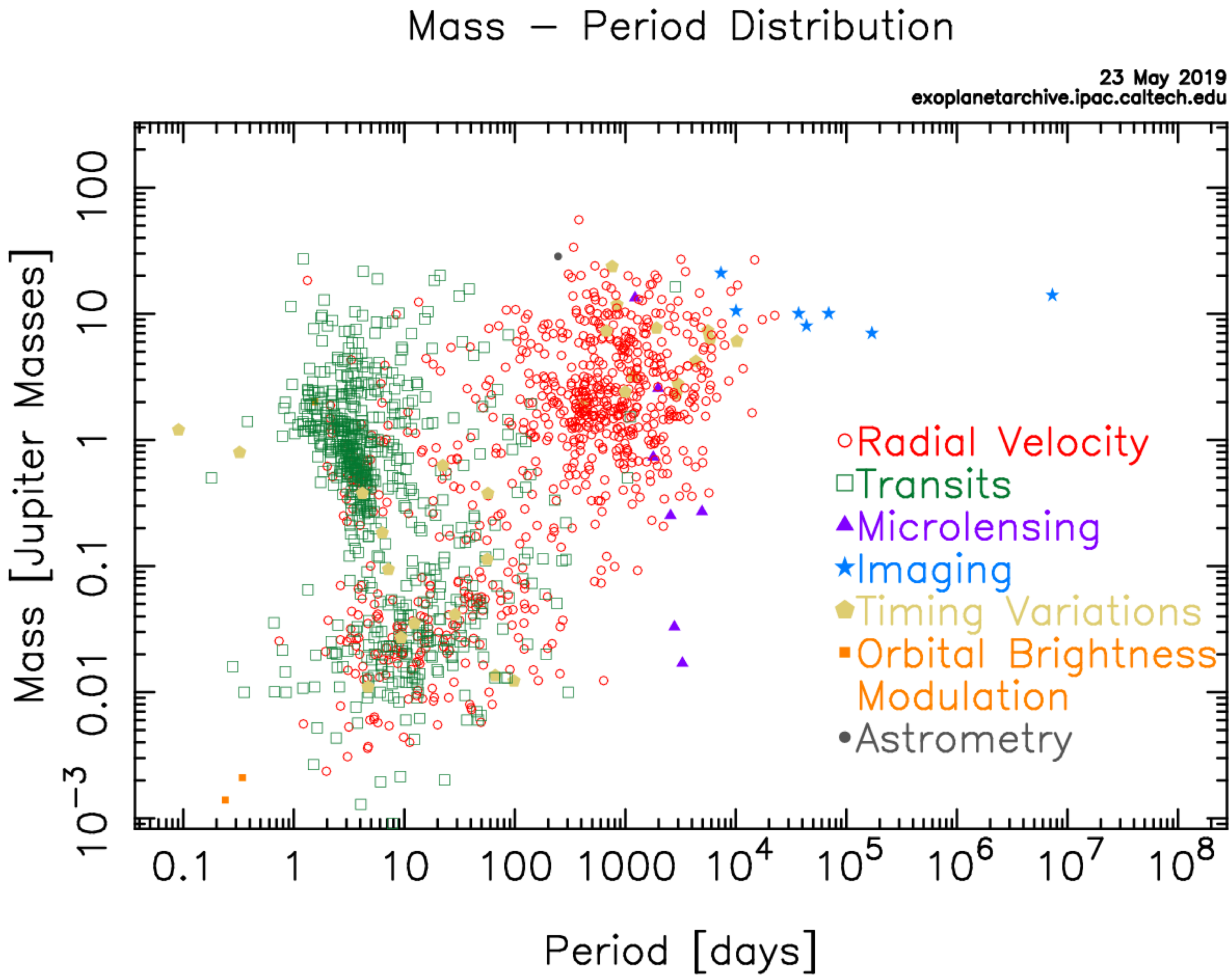


Image credit: G. Tinetti (ARIEL)

Getting Exoplanet Spectra



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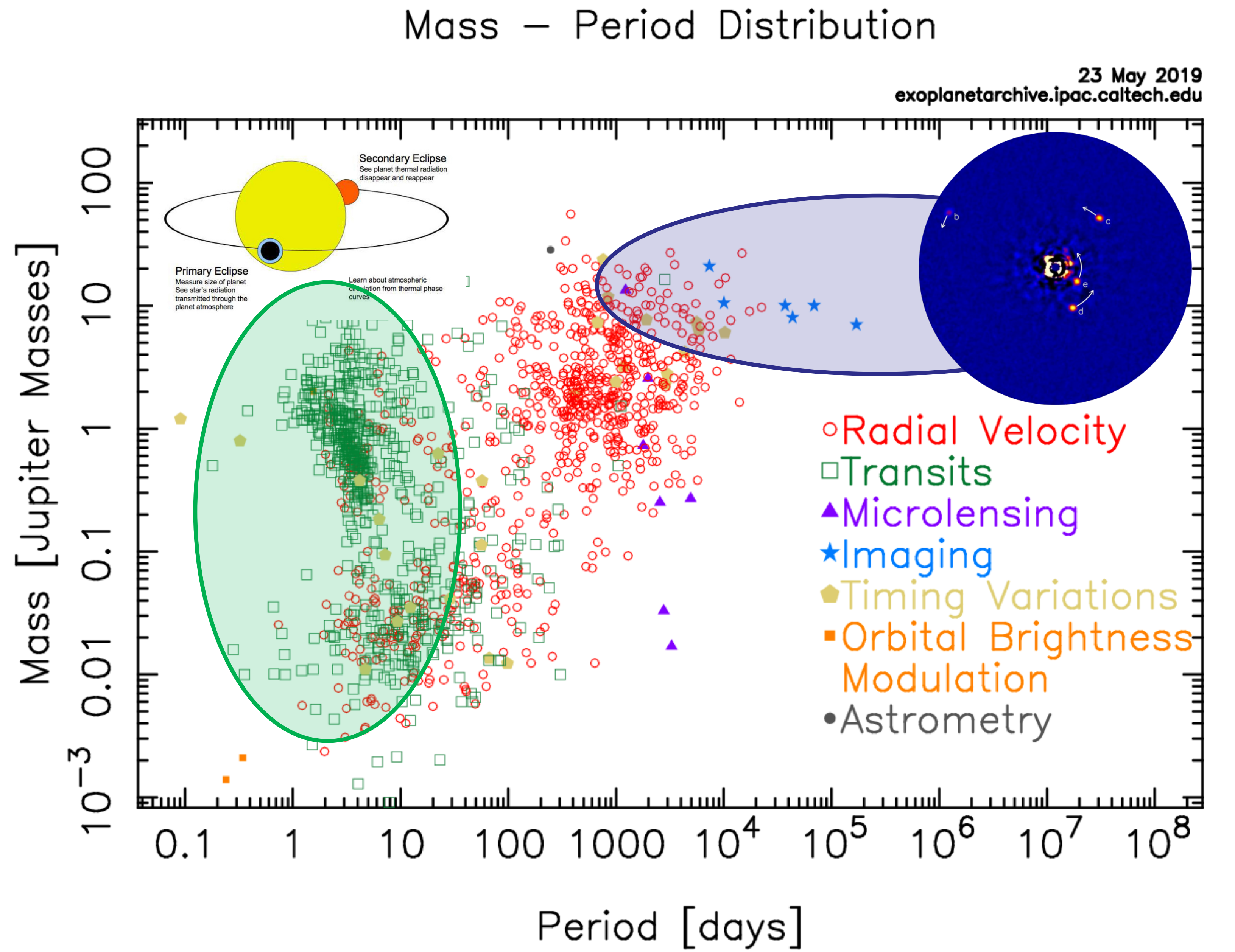

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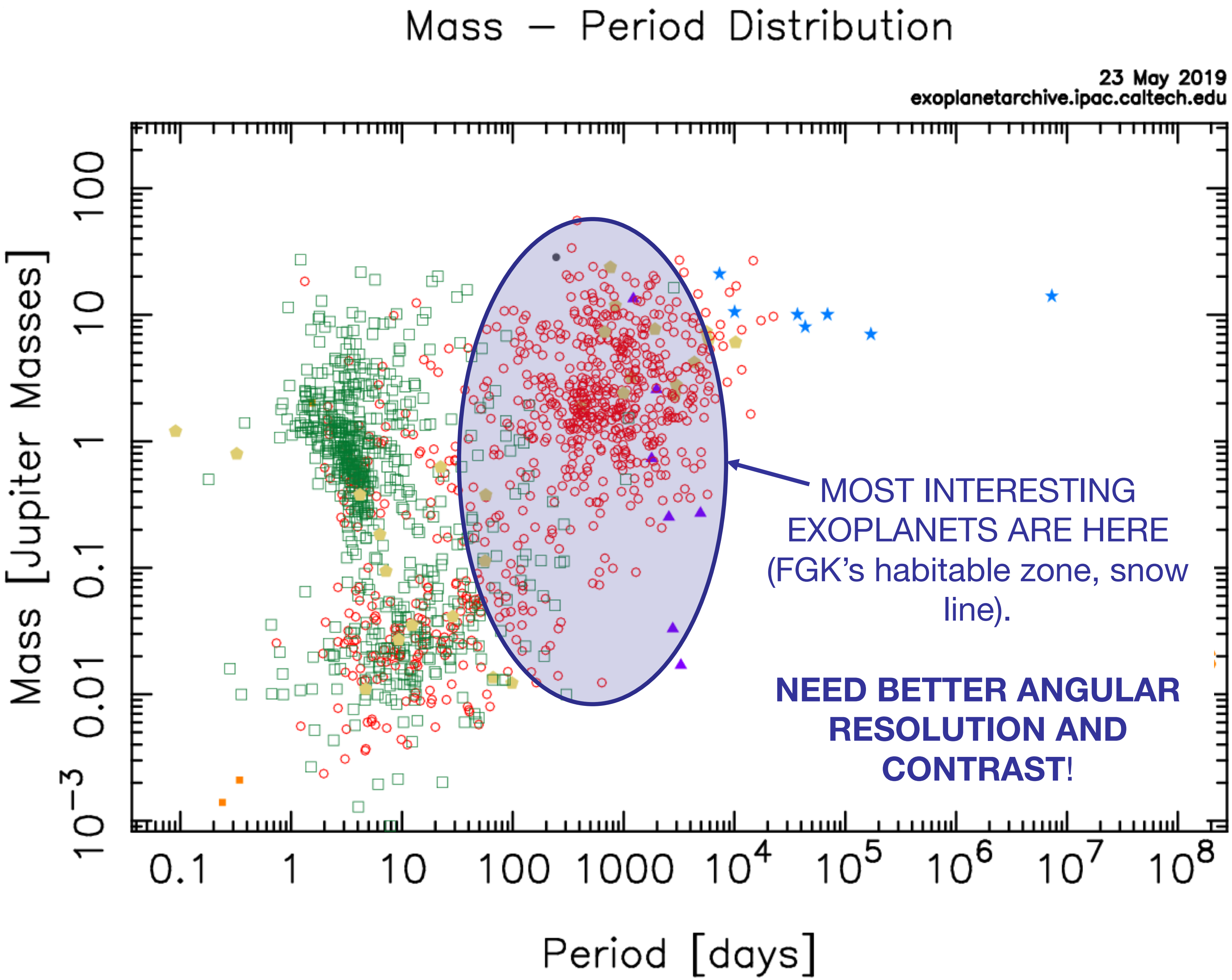
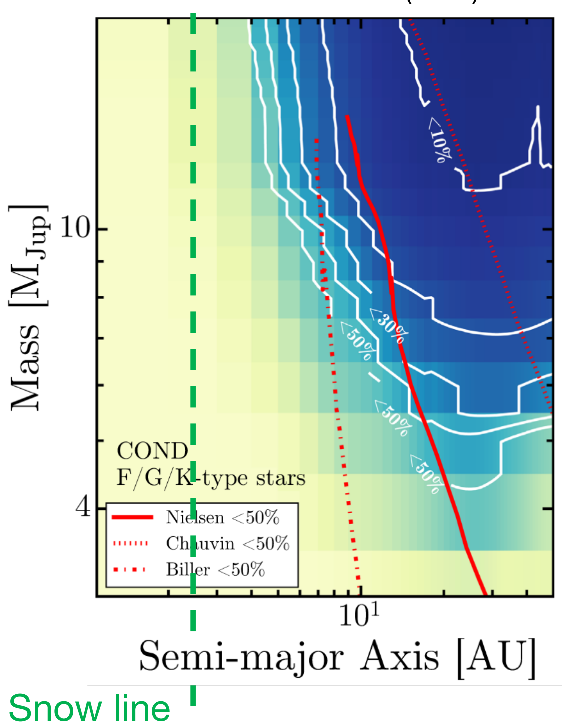


Direct imaging status

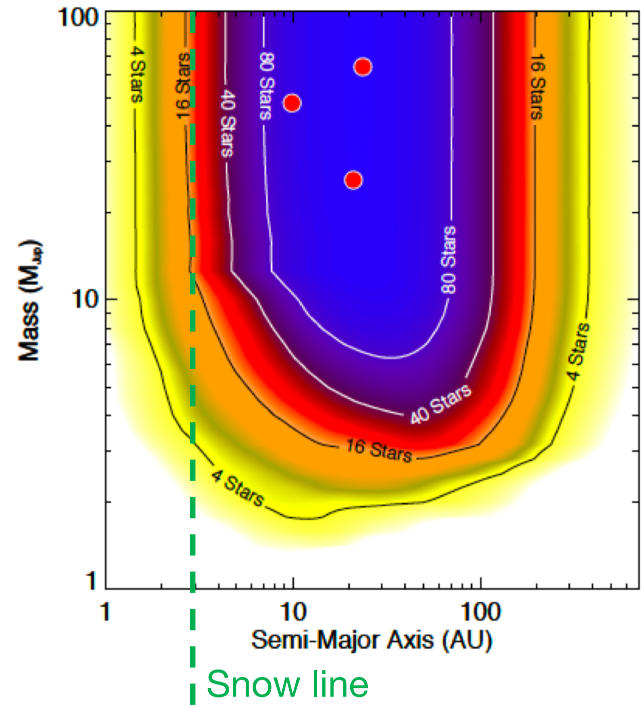
- Small sample to characterize (updated from Bowler 2016)
  - **~10 planetary-mass close-in companions (<100 AU)**
  - ~10 planetary-mass companions on wide orbit (>100 AU)
  - ~30 near the deuterium burning limit

- Current imaging surveys (SPHERE, GPI, LBTI) mostly sensitive to giant exoplanets beyond the snow line

Stone et al. 2019 (LBTI)



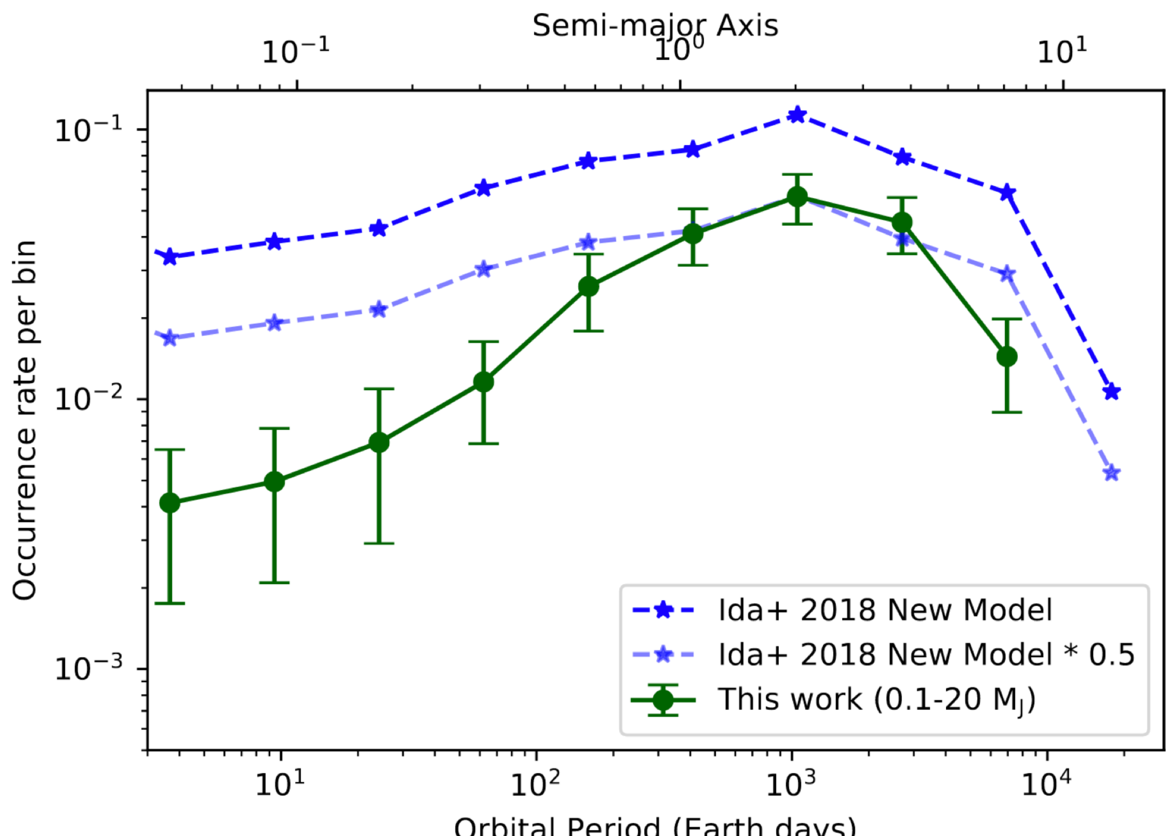
Nielsen et al. 2019 (GPI)



Occurrence turnover at the snow line?

- Evidence for a **break in the exoplanet occurrence rate near the snow line** based on RV and Kepler data (Fernandes et al. 2019)

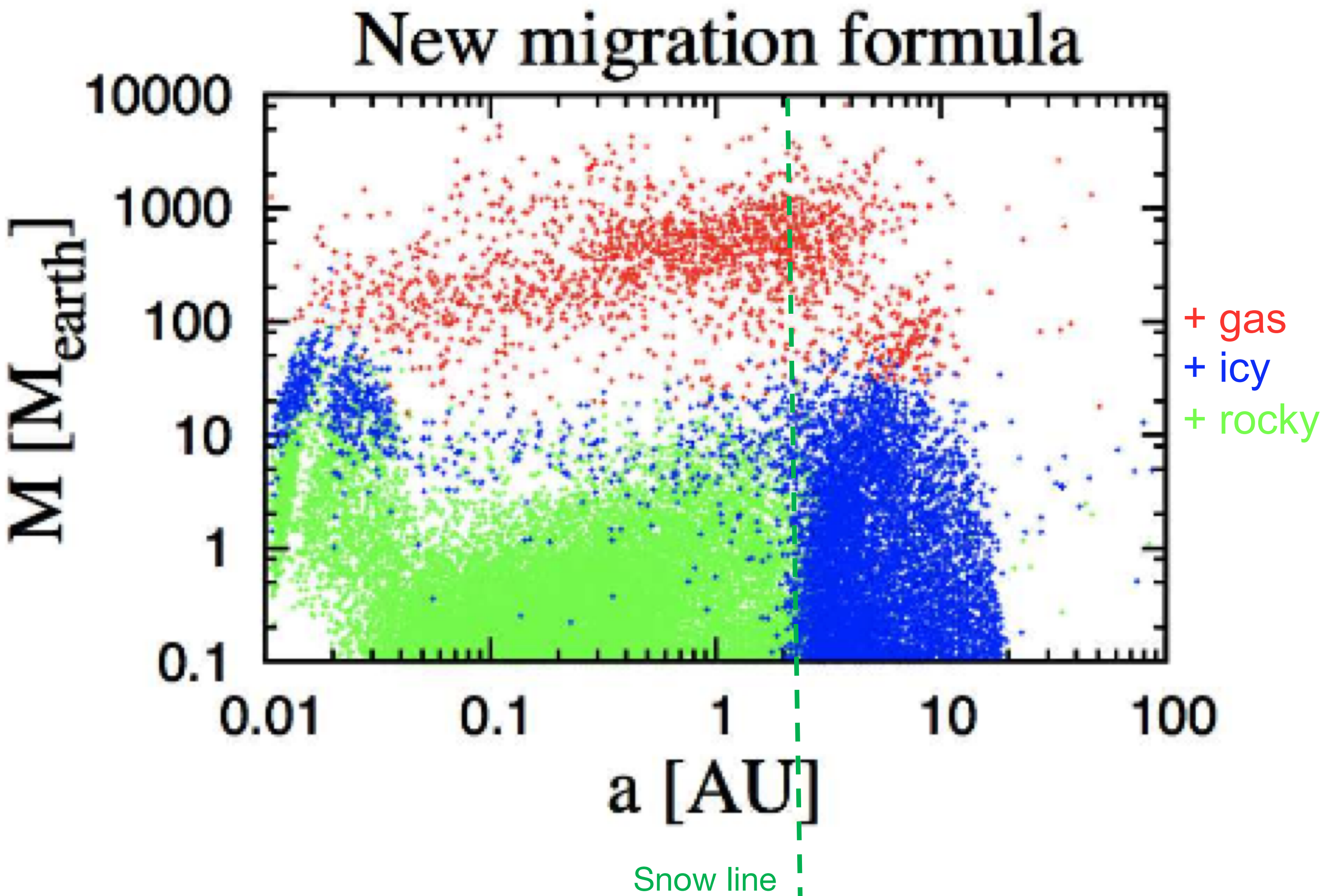
- ~1% of Jupiter—mass exoplanets can be detected by current imaging surveys (consistent with results)



Fernandes et al. 2019

Occurrence turnover at the snow line?

- Consistent with planet formation/migration models (Ida et al. 2018)



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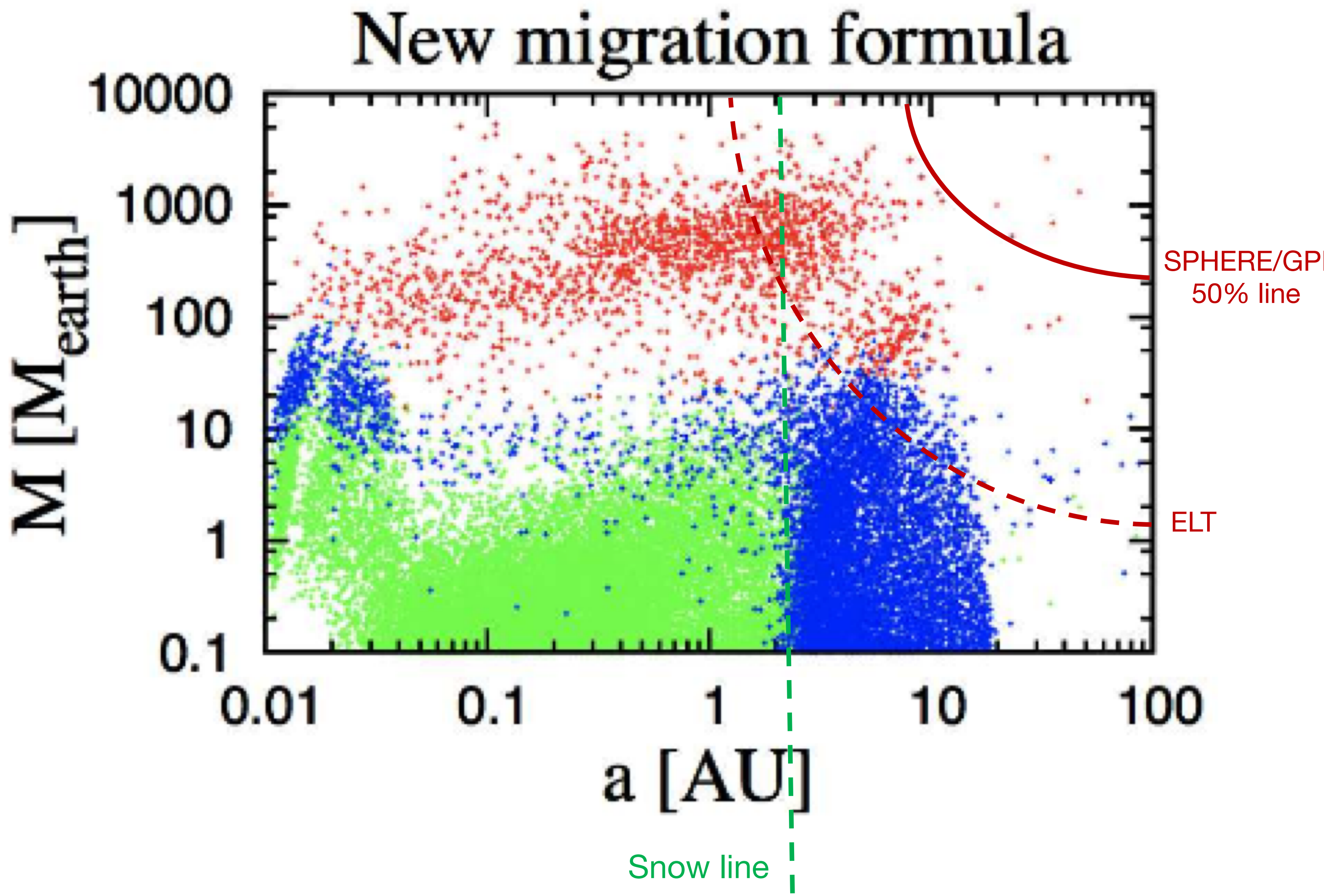

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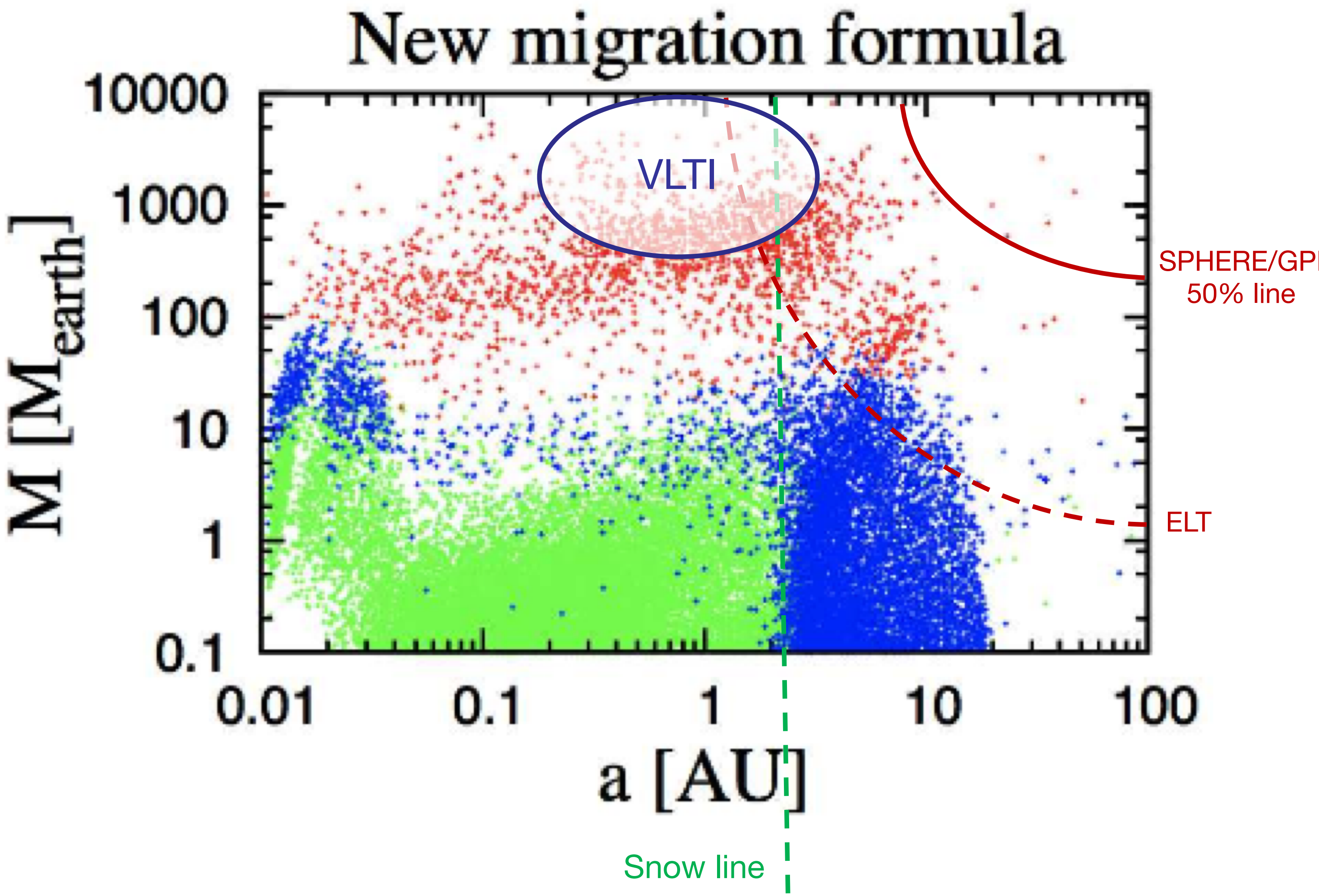
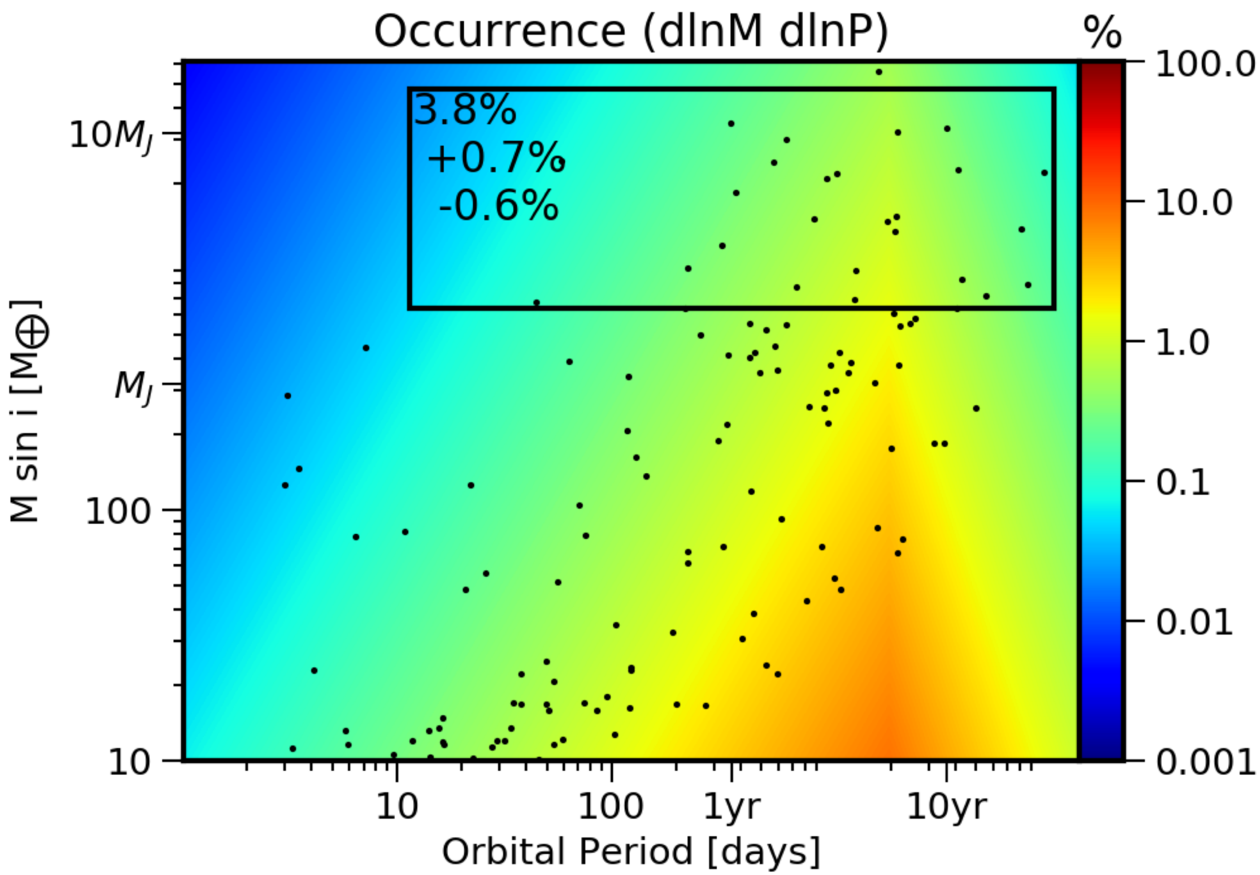


Expected exoplanet yield

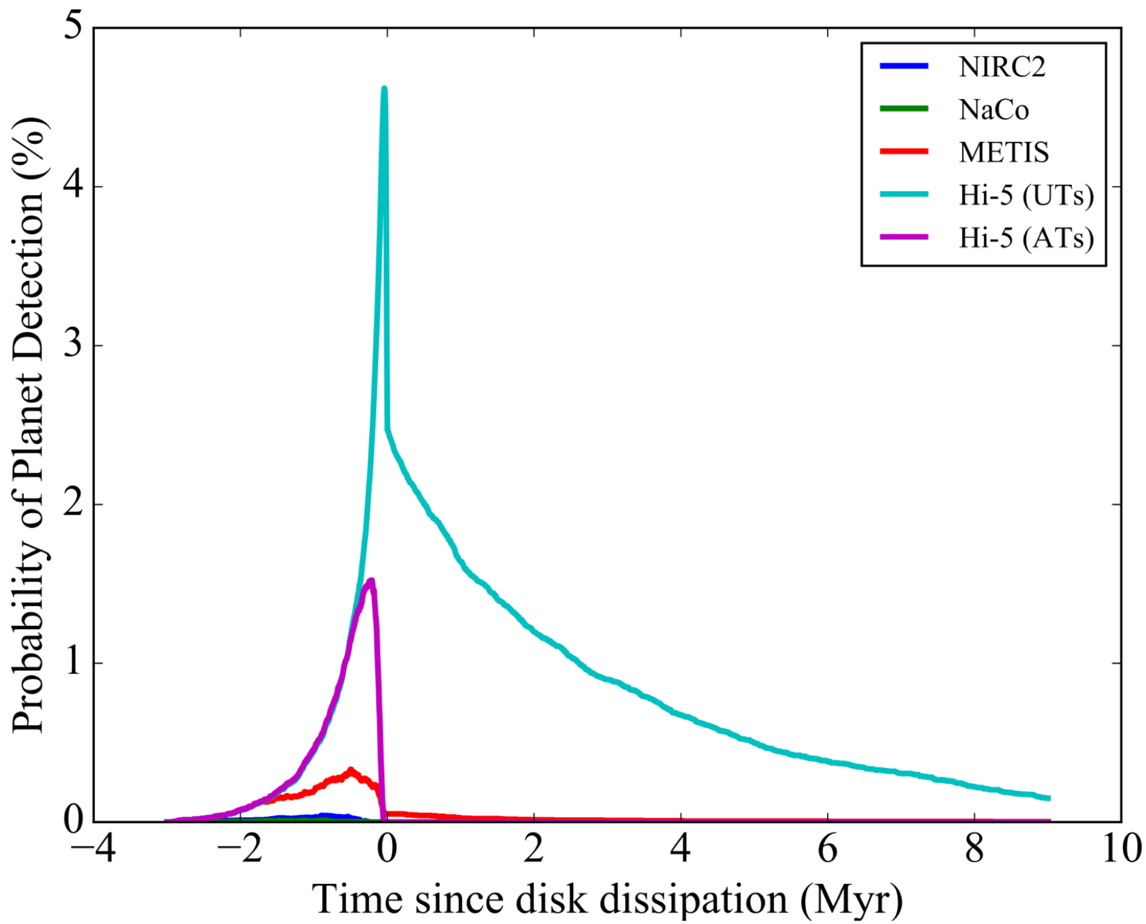
- Monte-carlo simulations based on Kepler and RV data with EPOS software (Fernandes et al. 2019)

- Expected survey completeness: ~4% (assuming mean distance of 40pc and age of 100Myr)



Expected exoplanet yield

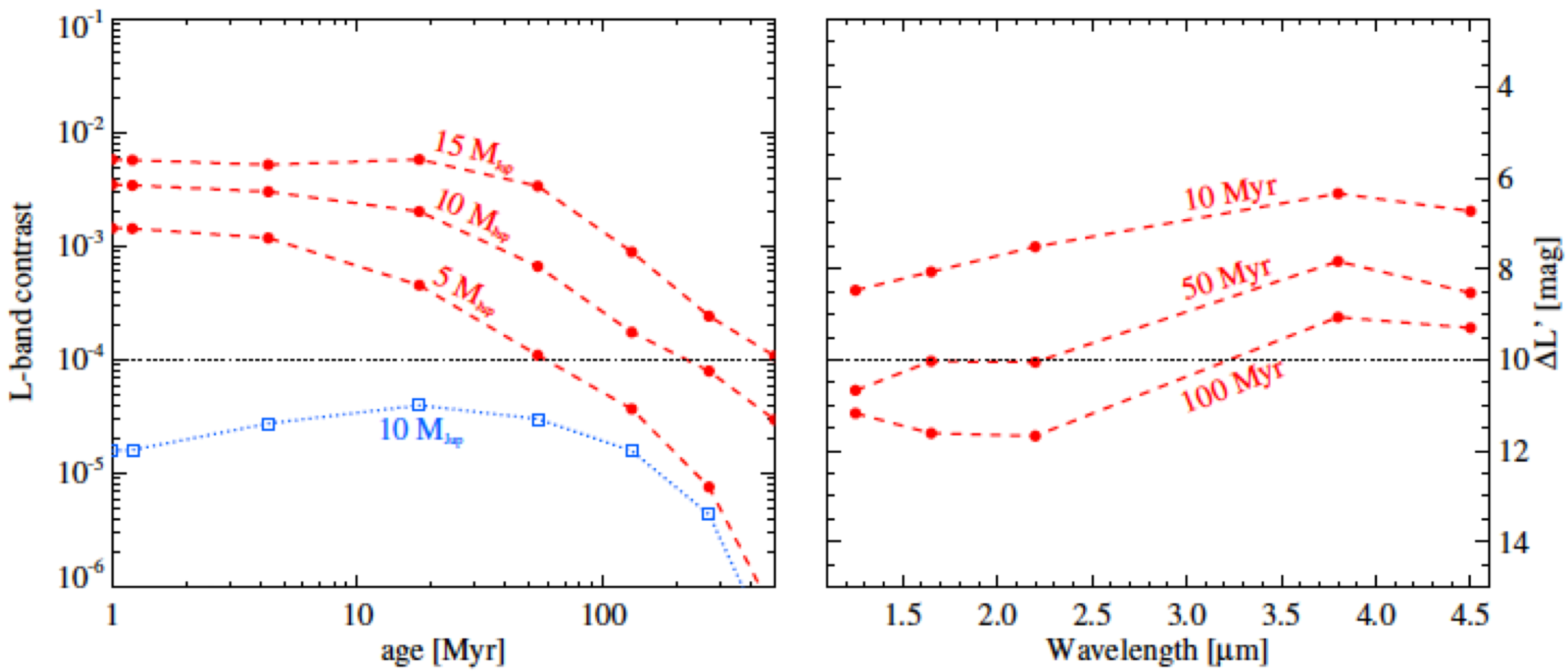
- VLTI is the best machine to detect forming exoplanets in nearby star forming region
- See M. Ireland talk and also Wallace's poster



Expected exoplanet yield

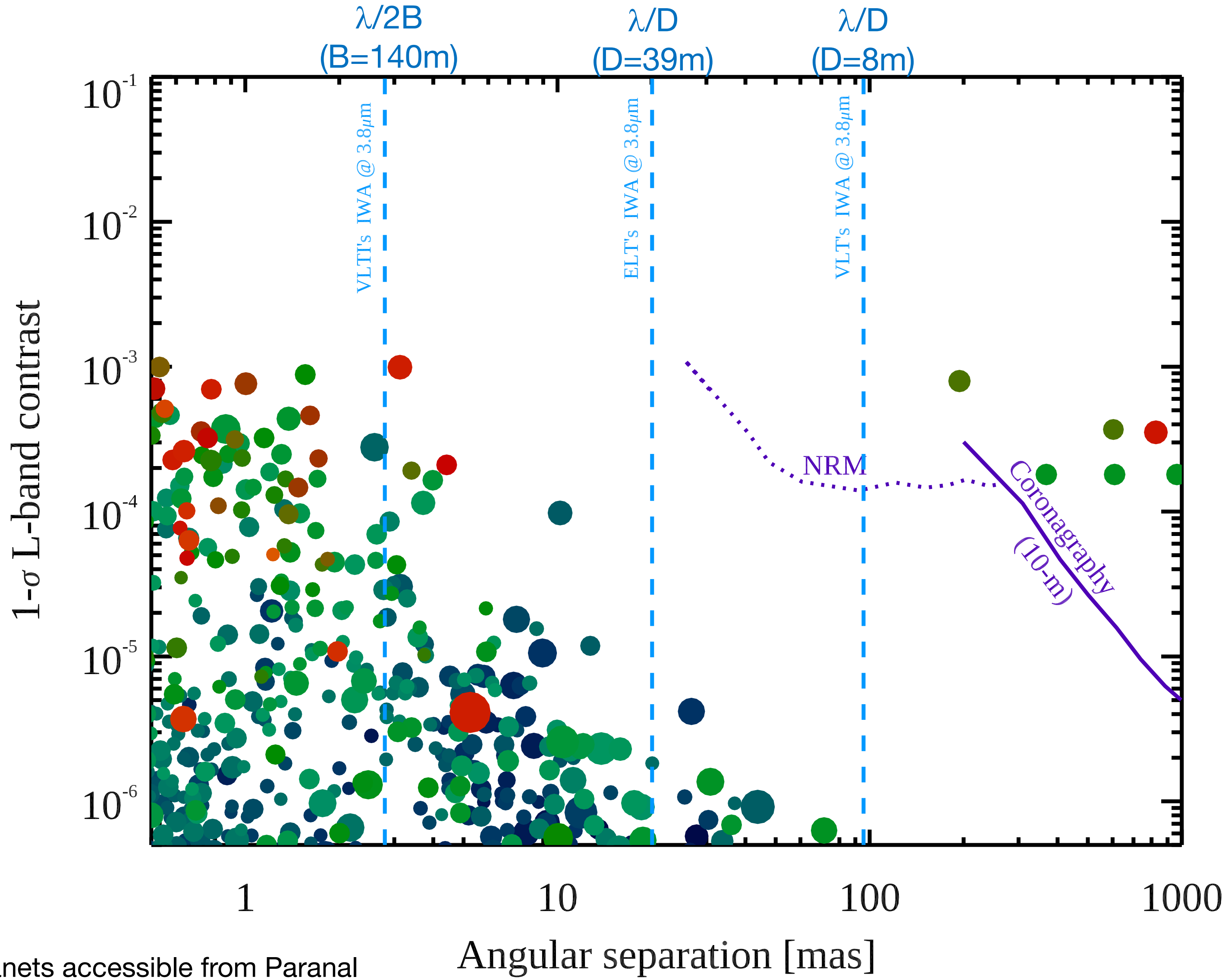
- L and M- bands: sweet spot for imaging young planetary systems
- 10 mag contrast enough for dedicated (sub)AU-scale survey in moving groups (~250 targets K<10)

Defrère et al. 2018 (based on BT-Settl models)



What about known exoplanets?

- Most known exoplanets too close for the ELT at 3.8 μm



*only exoplanets accessible from Paranal

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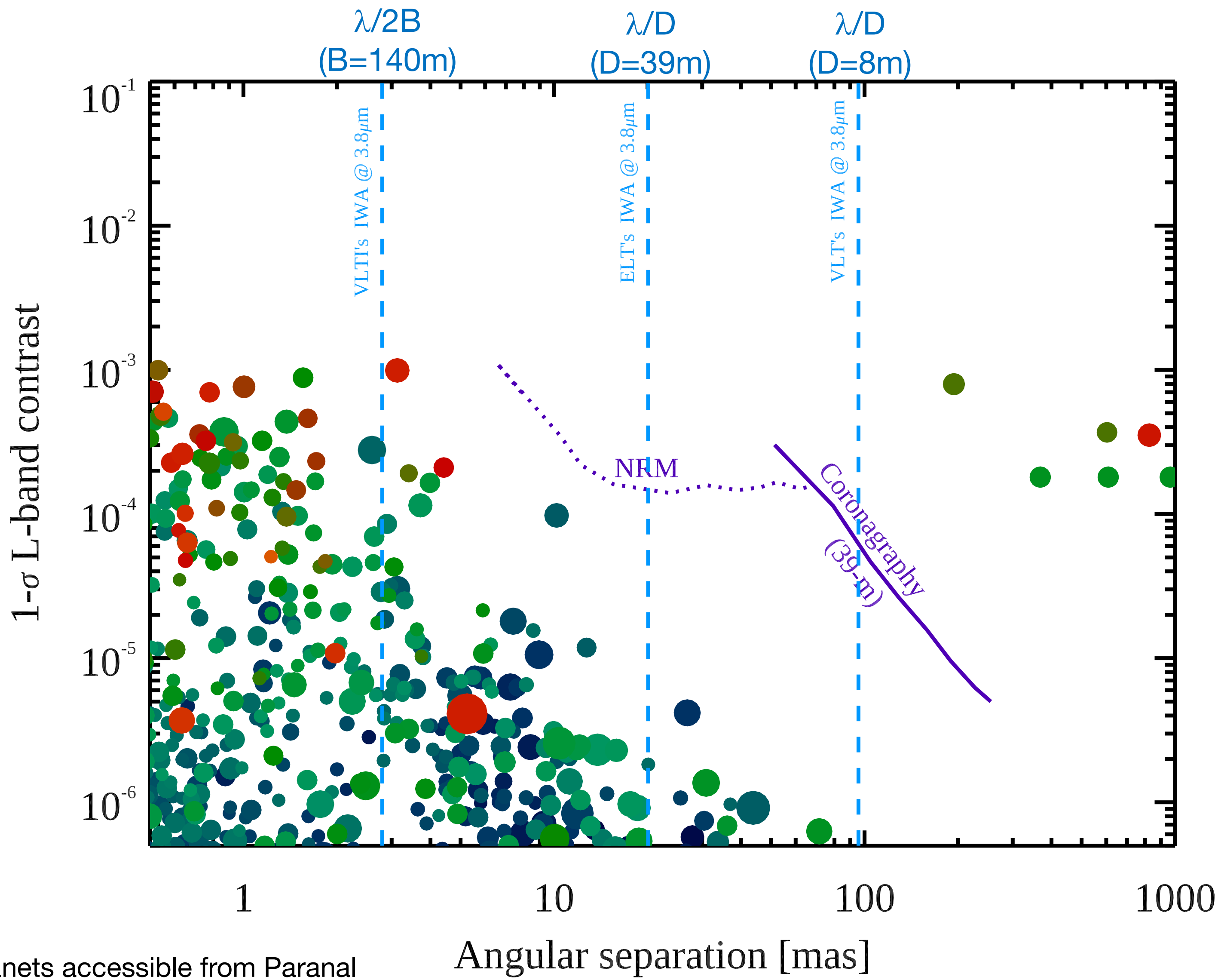

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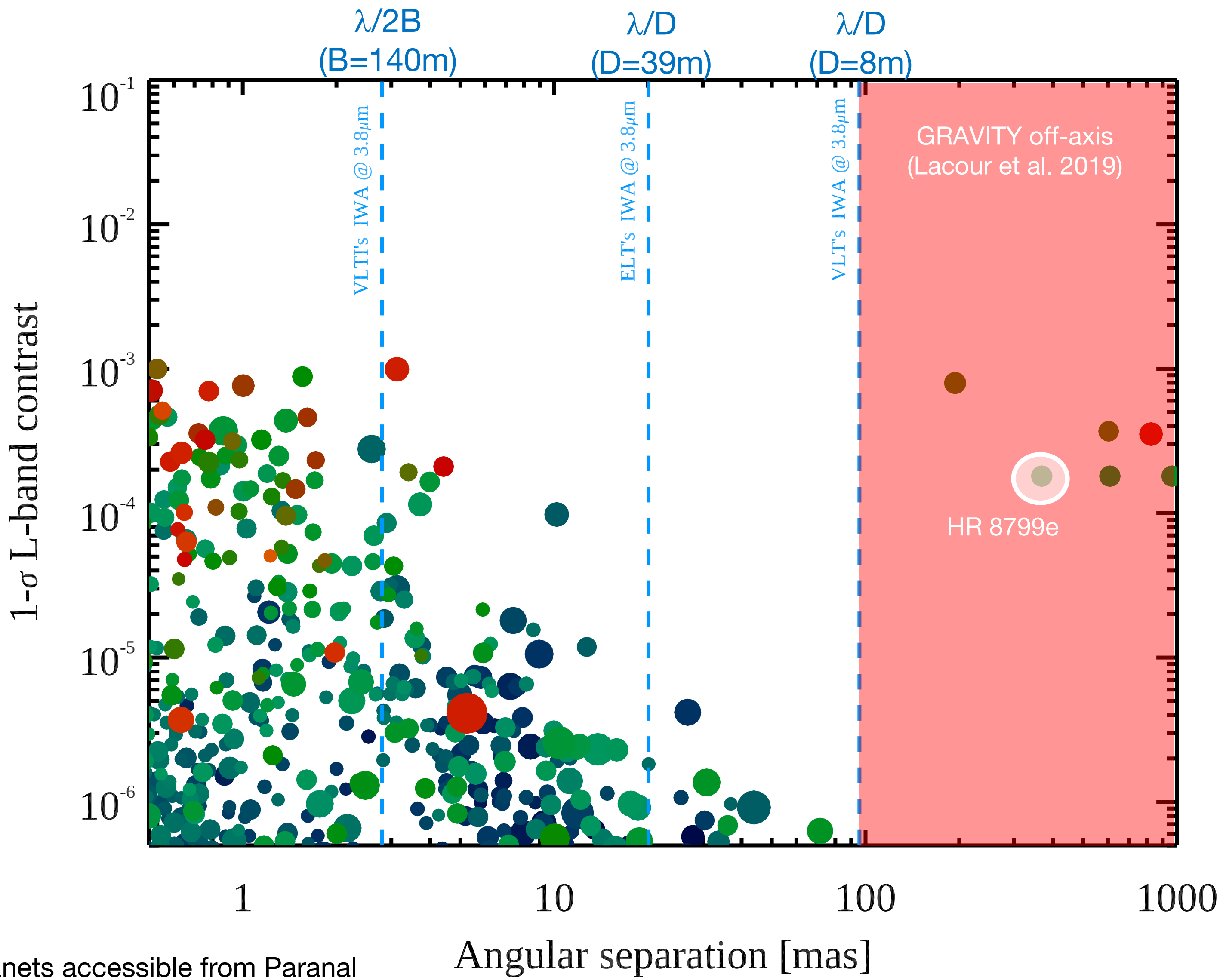

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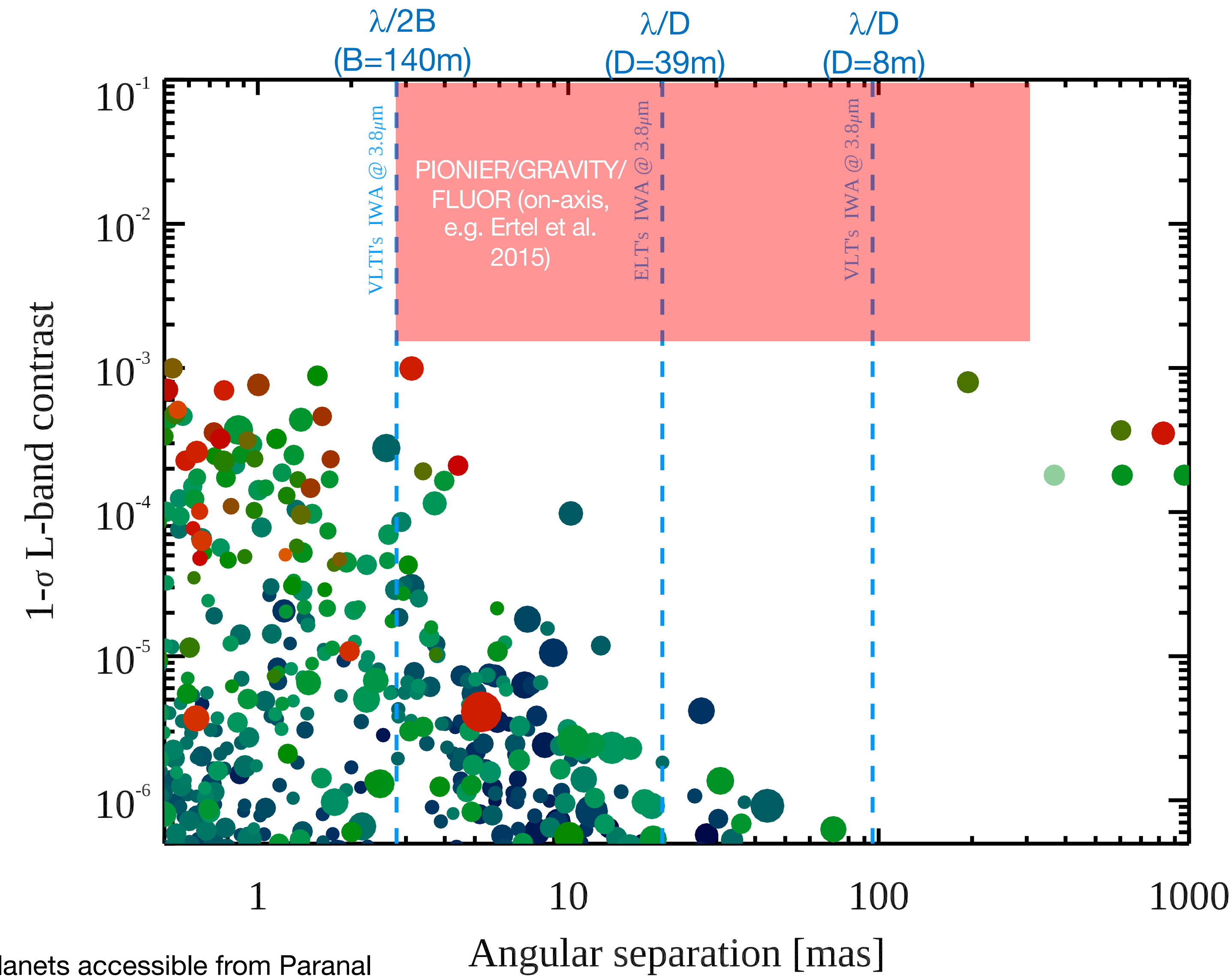

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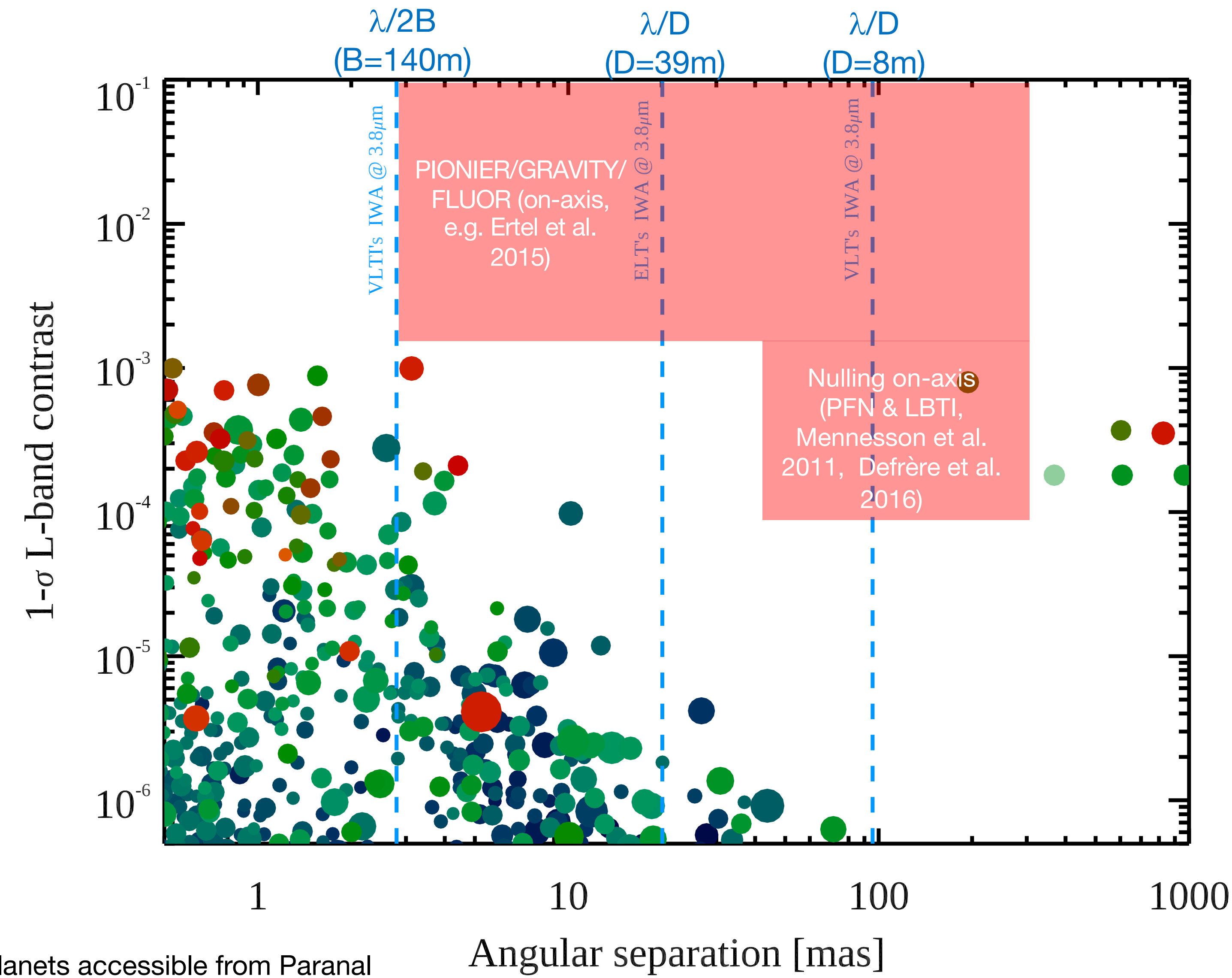

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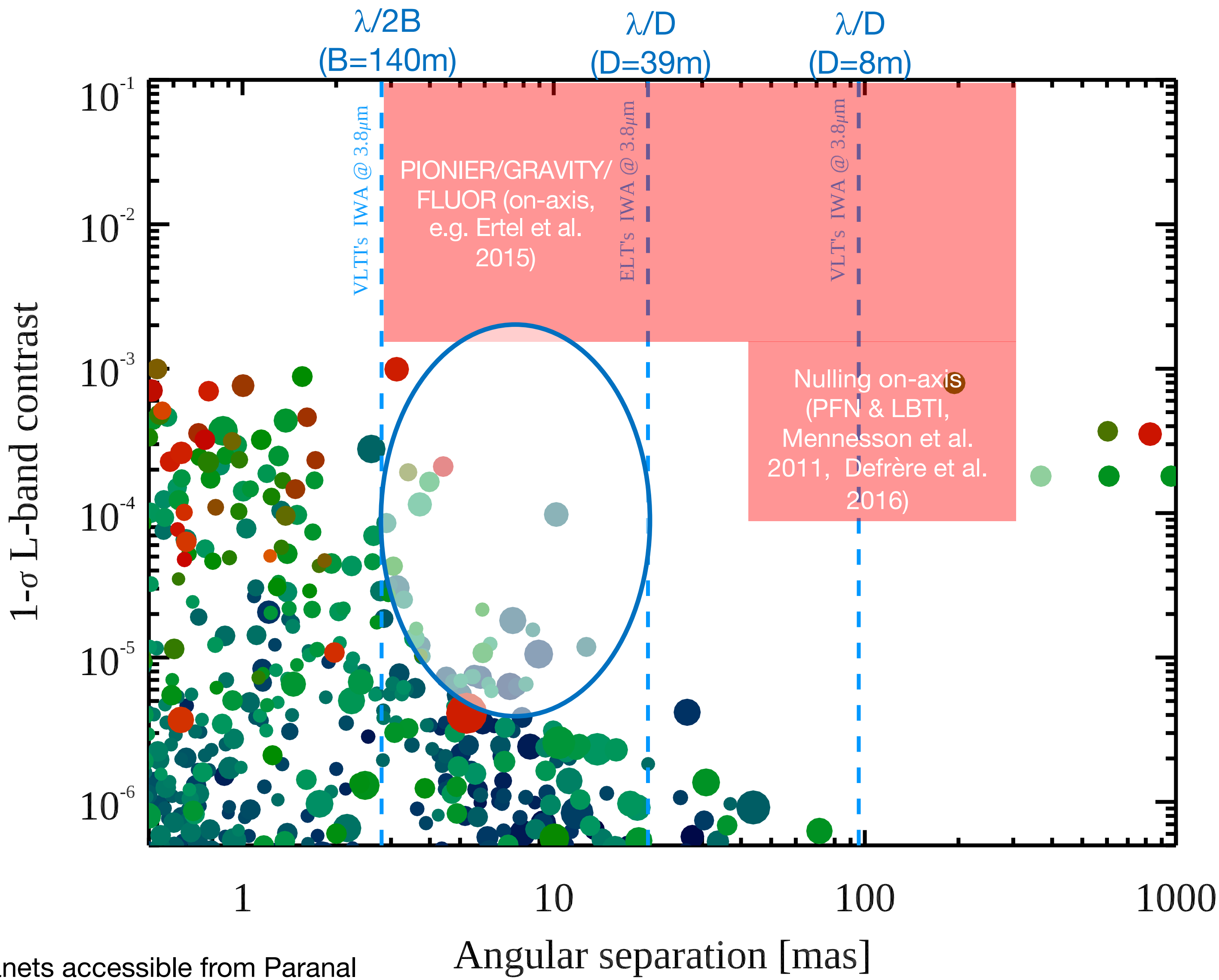

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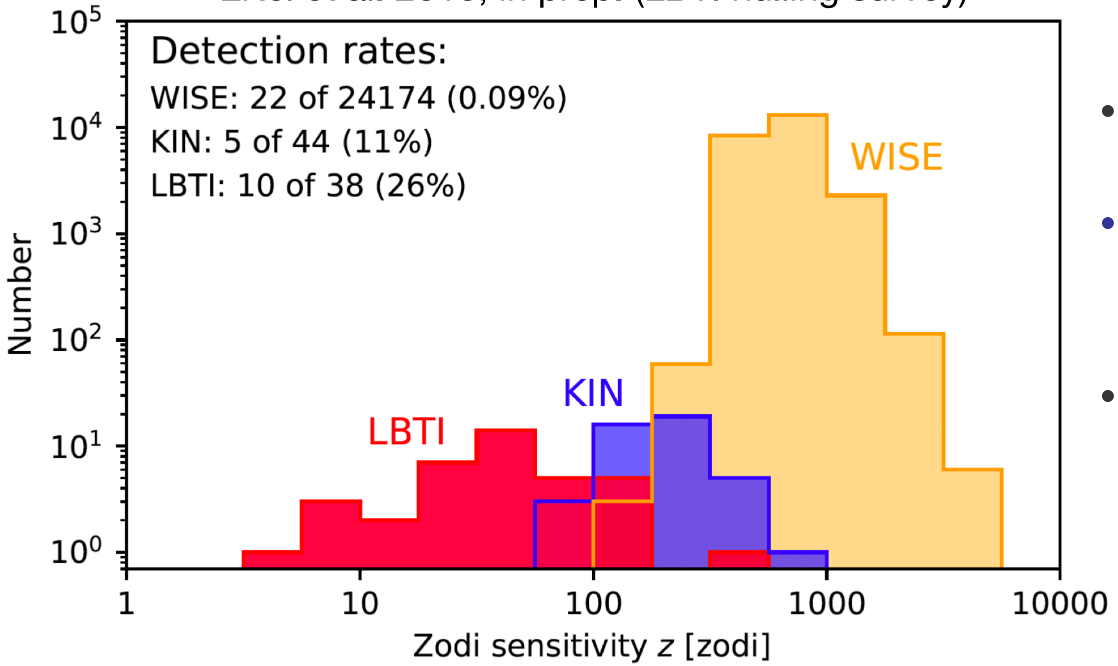
Can the VLTI do this?

- **On-axis contrast down to 10^{-4} demonstrated with nulling**
  - Near-infrared (K band) with PFN (Mennesson et al. 2011), limited by high-frequency phase jitter
  - Mid-infrared (N band) with LBTI (Defrère et al. 2016), limited by background and detector systematics

Ertel et al. 2018, in prep. (LBTI nulling survey)



- Deepest exozodi survey
- **Median zodi density $= 4.5 + 7.3 - 1.5$ zodis**
- ~50x deeper than space-based photometric surveys

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  - Near-infrared (K band) with PFN (Mennesson et al. 2011), limited by high-frequency phase jitter
  - Mid-infrared (N band) with LBTI (Defrère et al. 2016), limited by background and detector systematics
- **A few key technological components for a future instrument**
  - Modal filtering (PFN, 2μm) or extreme adaptive optics (LBTI, 10 μm)
  - Dedicated fringe tracker for PWV correction (turbulent component)
  - Real-time high-frequency vibrations monitoring and compensation
  - Advanced post-processing techniques (self-calibration, PFN: Mennesson et al. 2011, LBTI: Defrère et al. 2016)

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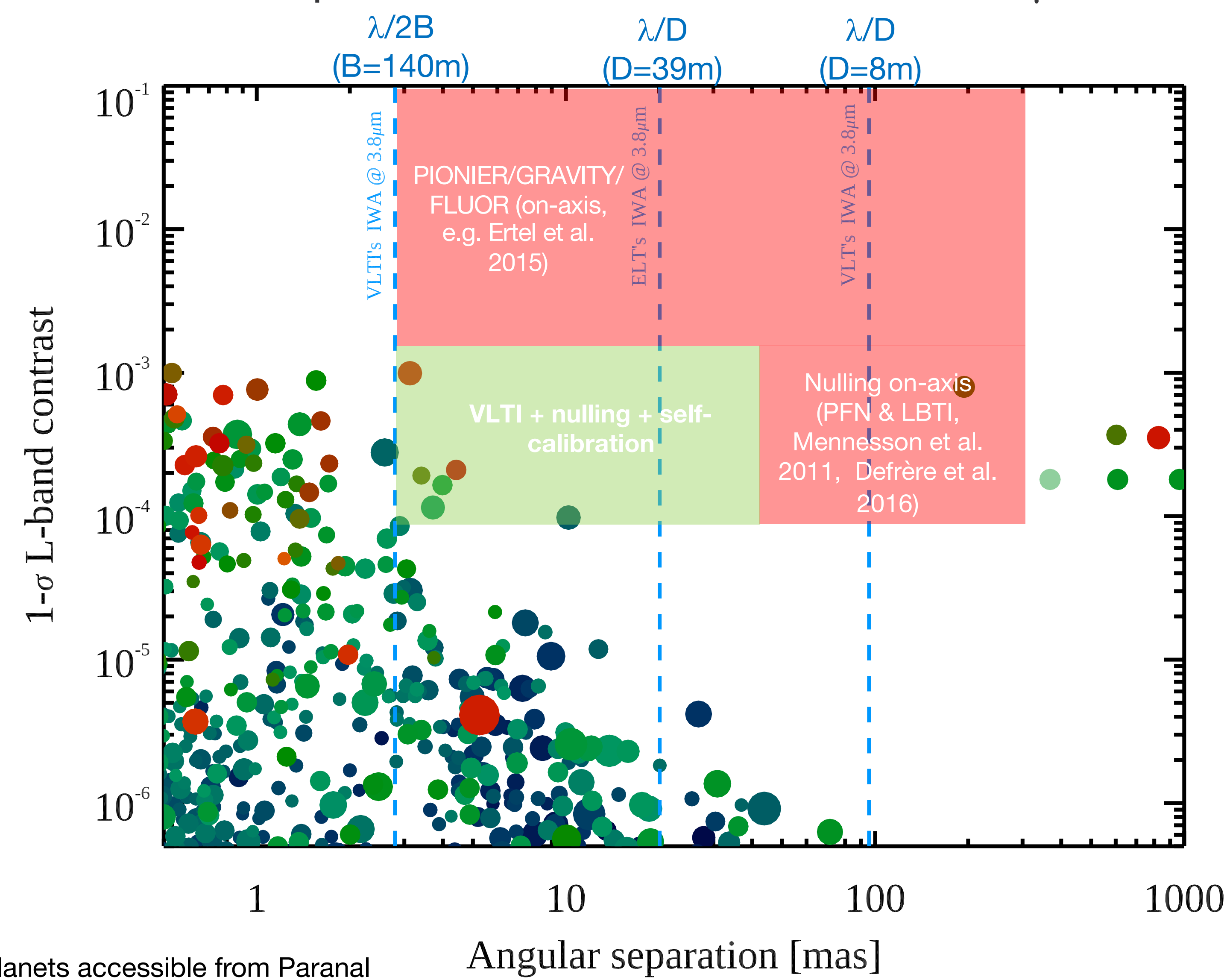

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How to go from 10^{-4} to 10^{-5}

- Thermal near-infrared **(3 - 5 µm) not addressed**
  - Less thermal background wrt KIN and LBTI
  - Less phase errors than PFN

    —> potential for higher accuracy

- OPTICON-funded Hi-5 study to **refine the science case** and **identify and understand contrast limitations at L band (Defrère et al. 2018a, 2018b)**

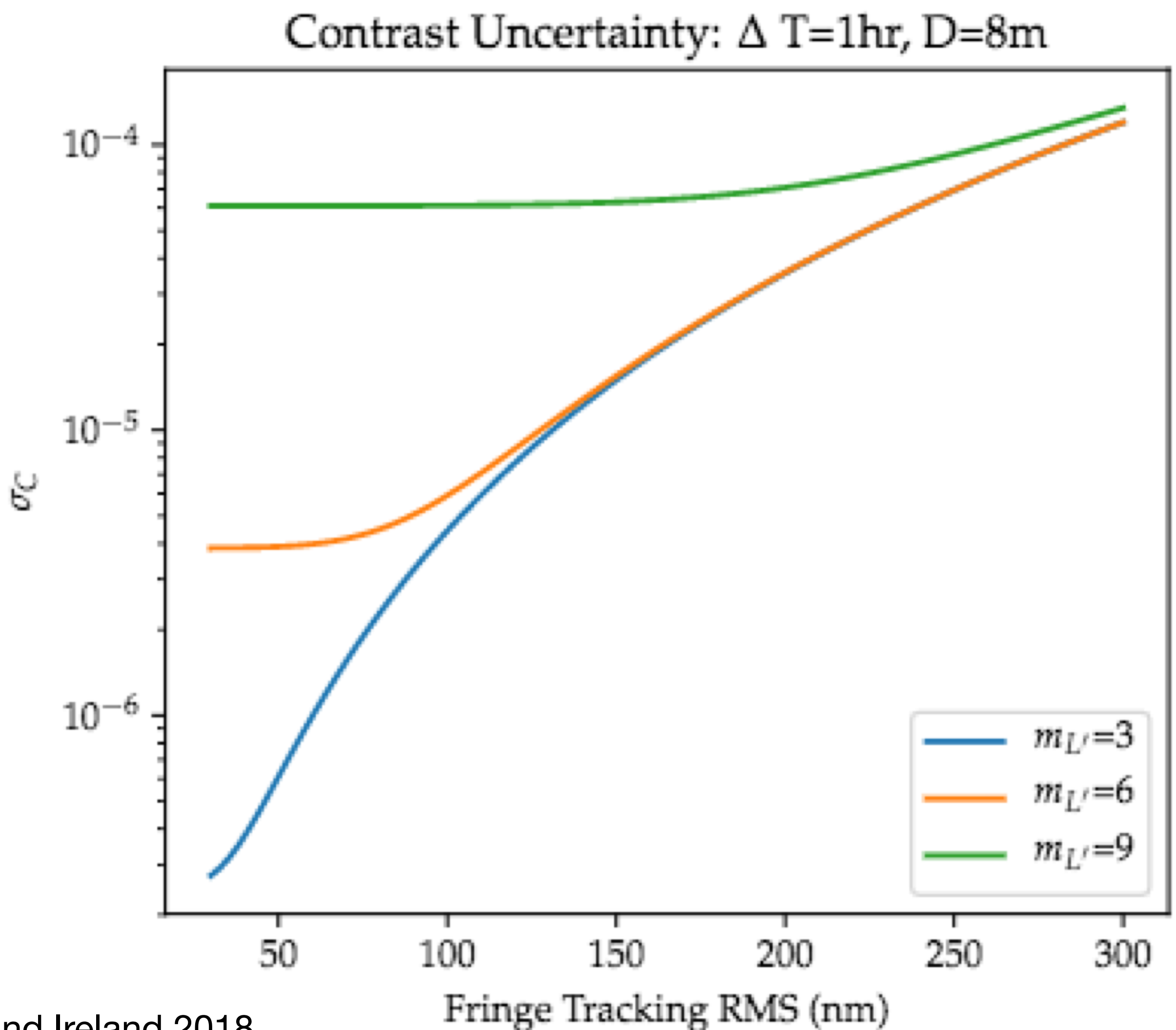
- Classical nulling combination with spectral self-calibration (post-processing, Hi-5 instrument)

- Kernel nulling implementation (pre-processing, **VIKING instrument of the ASGARD suite**, see Frantz's Martinache talk)

- Sensitive fringe tracker (HEIMDALRR)

How to go from 10^{-4} to 10^{-5}

- Contrast prediction for **Kernel nulling**



Martinache and Ireland 2018

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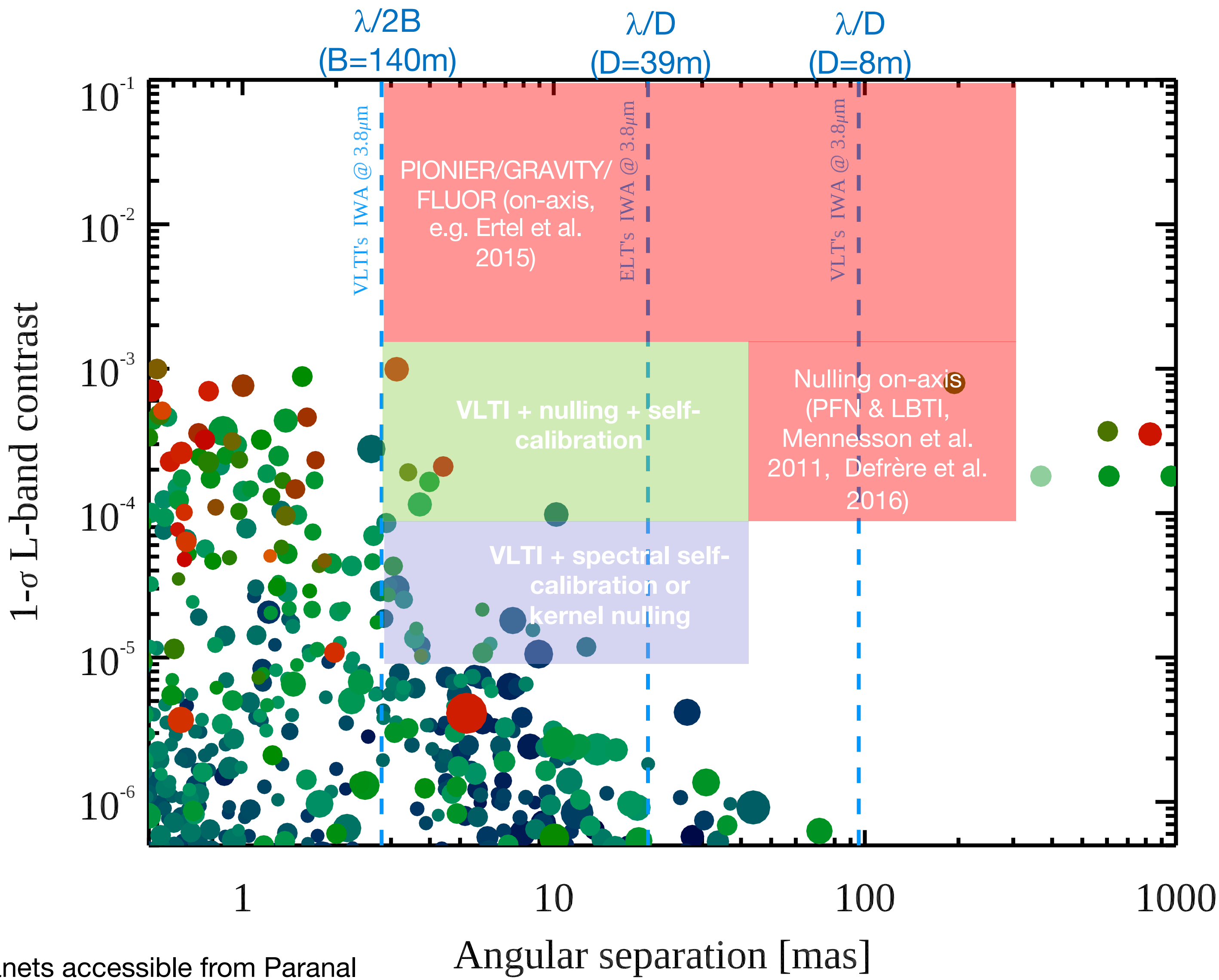

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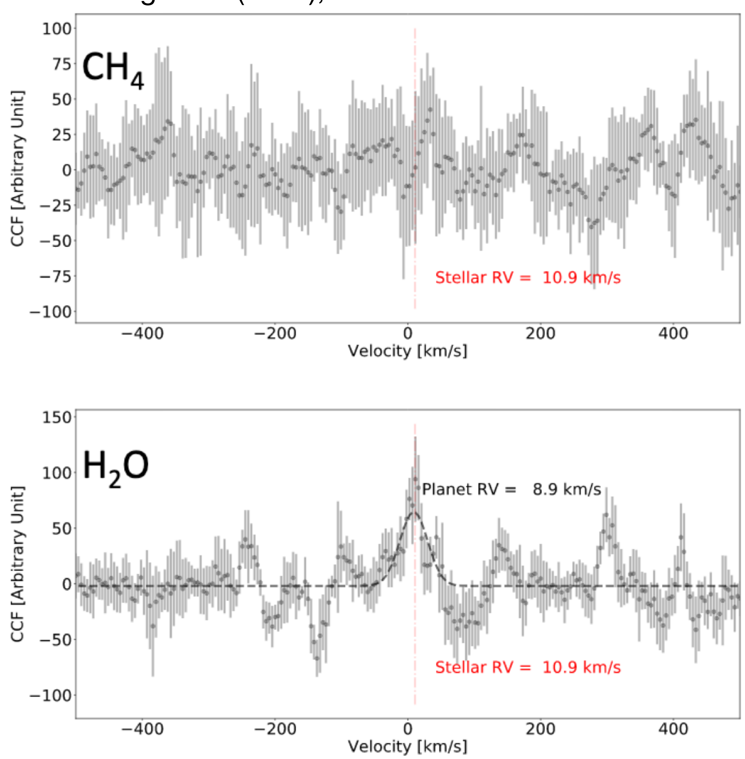
Thermal near-infrared (L and M bands)

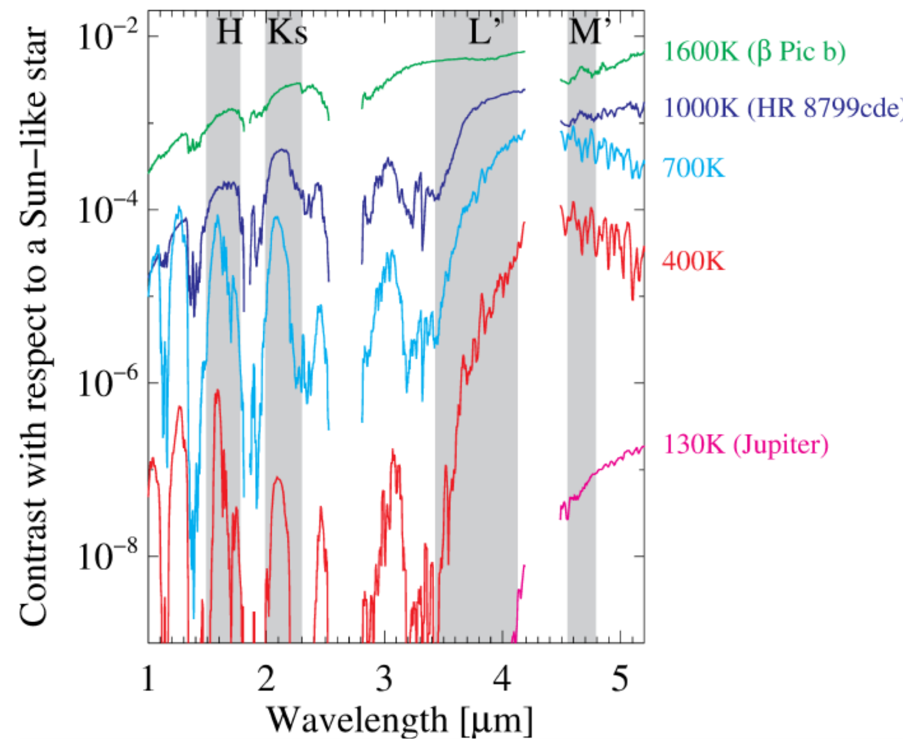
- **Physical properties** from low-resolution spectroscopy: temperature, metallicity, surface gravity (see HR8799, GJ504, … studies, e.g. Skemer et al. 2015)

- High-resolution spectroscopy (R>~1000): chemical composition (H_2O, CH_4, CO_2, C_2H_2, HCN, de Kok et al. 2014)

Wang et al. (2018), water detected on HR8799c



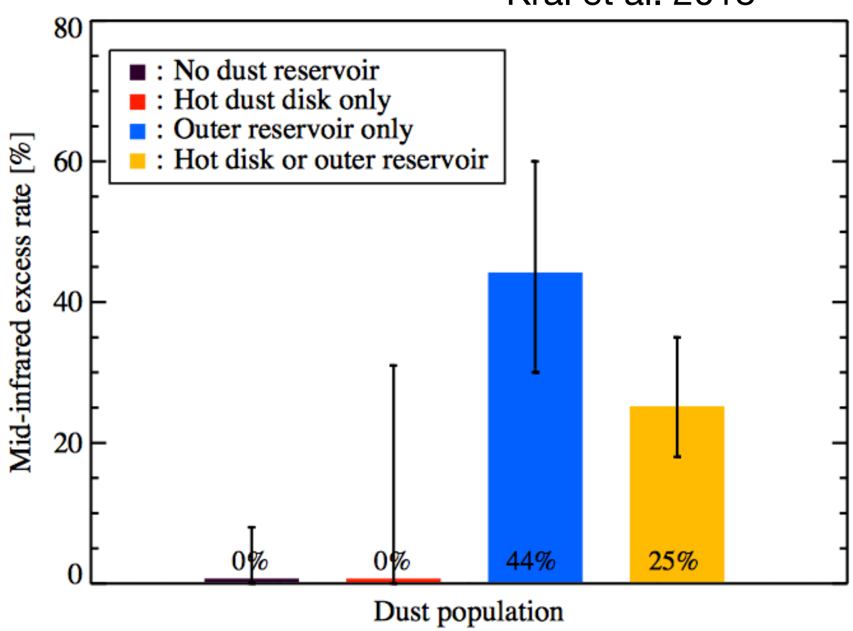
Skemer et al. (2015)



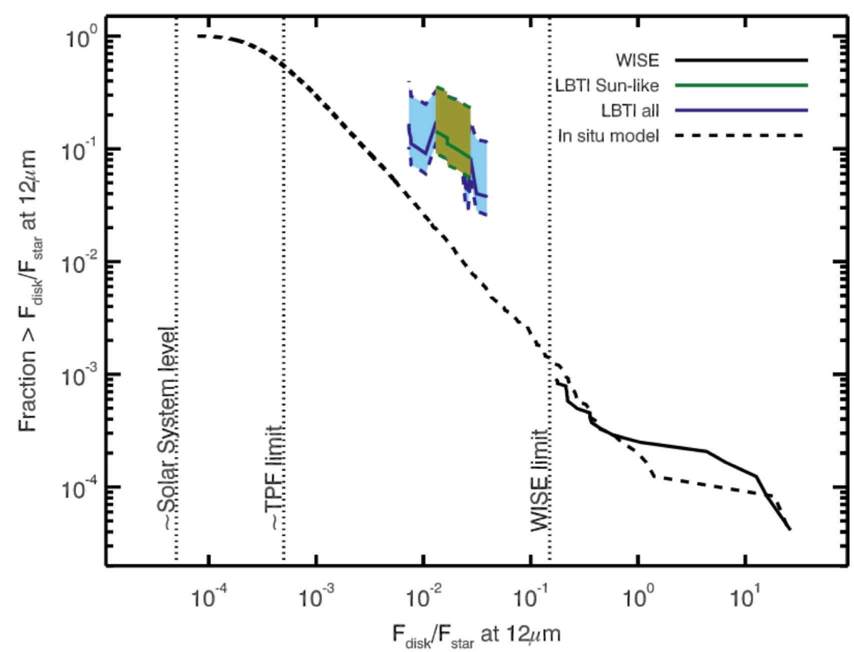
Other science case: exozodiacal disks

- L and M bands = missing link in current exozodiacal disk models (interactions between hot dust and asteroid belts)
- Measuring the faint end of the exozodi luminosity function (complementary with LBTI in northern hemisphere)

Kral et al. 2018



Ertel et al. 2018



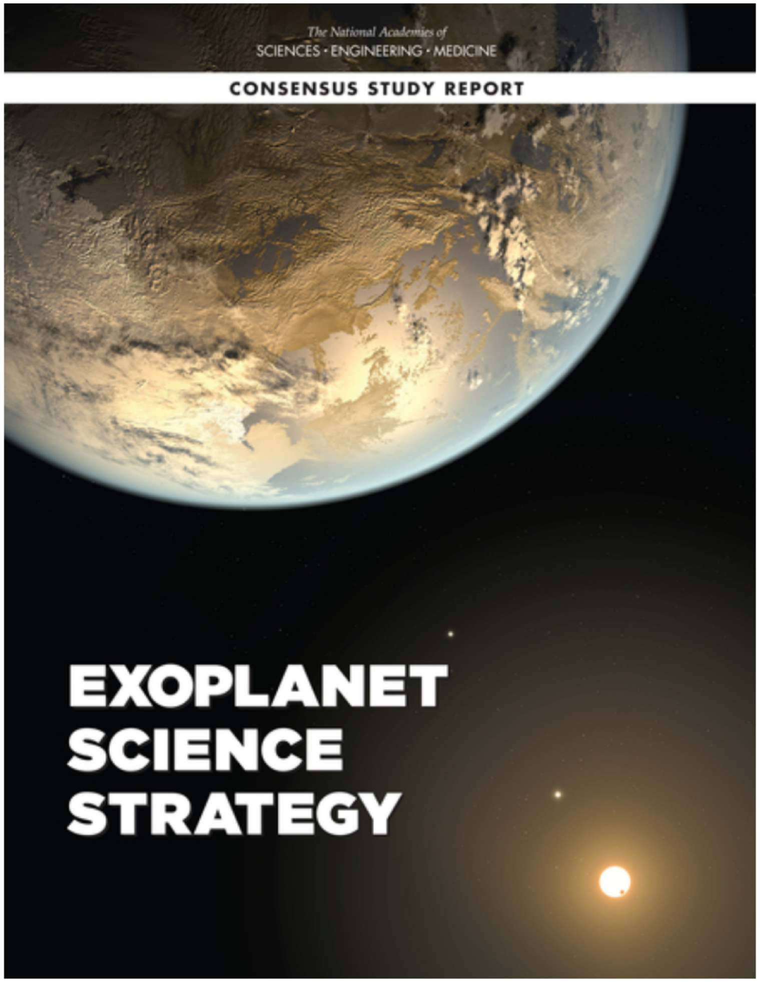
Summary of VLTI-enabled exoplanet science

1. **On-axis spectroscopy** of known RV exoplanets inaccessible with the ELT (L/M band)
    - **Physical properties**: temperature, metallicity, surface gravity
    - **Planet formation models** (access to the snow line)
    - **Chemical composition** (H_2O, CH_4, CO_2, C_2H_2, HCN)

2. **Off-axis spectroscopy** of known imaged exoplanets
    - **Interferometric astrometry** (and hence masses)
    - Unique characterization possibilities (e.g., V, J bands with **BIFROST**)
    - Number to grow with the ELT

3. **Prevalence and nature of exozodiacal disks**
    - Investigate the hot dust mystery
    - Prevalence of exozodi around southern stars

Long-term prospects



National Academy of Sciences (2018)

The report states: "**Technology development support in the next decade for future characterization concepts such as mid-infrared (MIR) interferometers […] will be needed to enable strategic exoplanet missions beyond 2040**."

Even more important is the following statement: "That said, the common (although often unspoken) belief is that **such a nulling, infrared interferometer would be a necessary follow-up to any reflected light direct imaging mission, as detecting the exoplanet in thermal emission is not only required to measure the temperature of the planet, but is also needed to measure its radius**, and so (with an astrometric or radial velocity detection of […] the mass of the planet) measure its density and thus determine if it is truly terrestrial."

Take away messages

- Characterizing exoplanet with long-baseline interferometry is possible (off-axis 10^{-5} contrast, see Lacour's talk)
- Progress on nulling interferometers in the North (10^{-4} contrast)
- No dedicated exoplanet/high-contrast VLTI instrument
- No dedicated high-contrast interferometric instrument in the South where most young planetary systems are located
- Exciting exoplanet science requires the VLTI baselines (access to the snow line, imaging of known RV exoplanets)