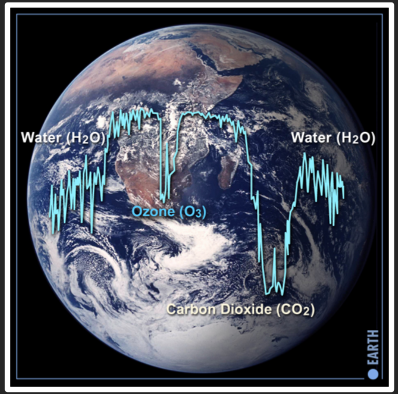
Results of LBTI's HOSTS survey and prospects

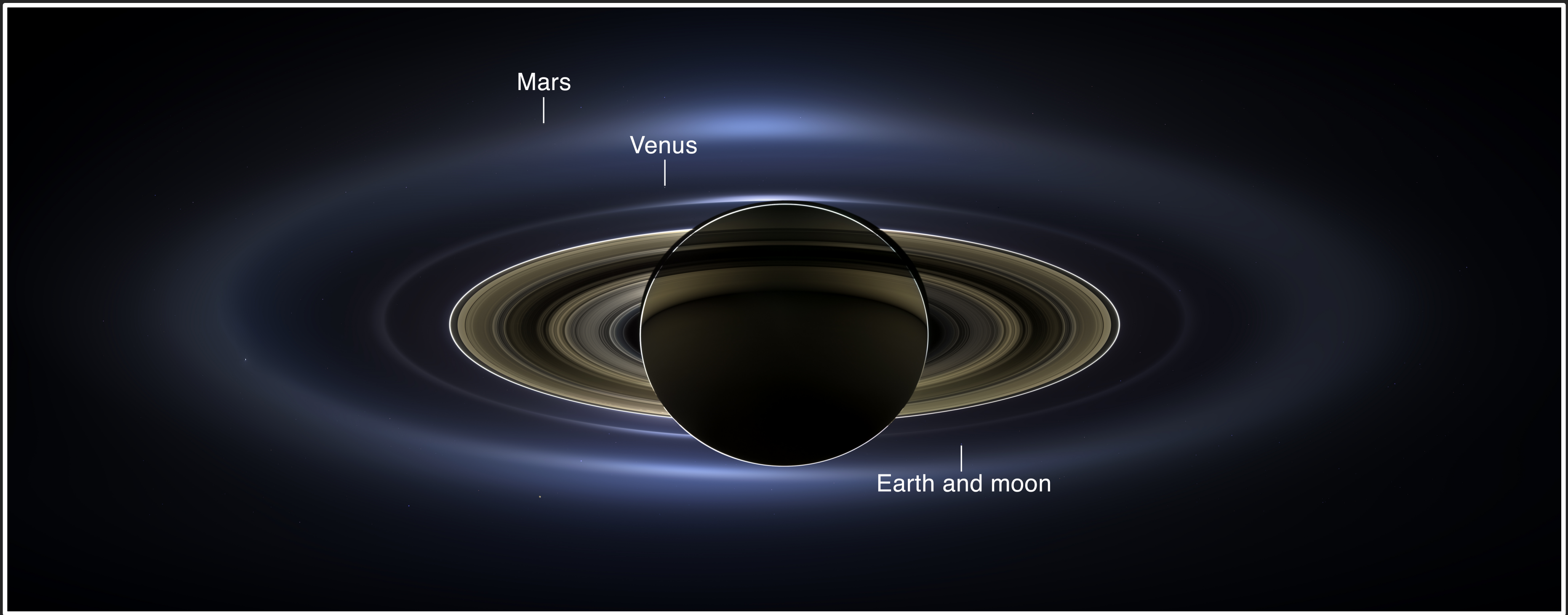


Denis Defrère
University of Liège

Thanks to P. Hinz and S. Ertel

Steward internal symposium – Tucson (September 21, 2018)

The long term goal



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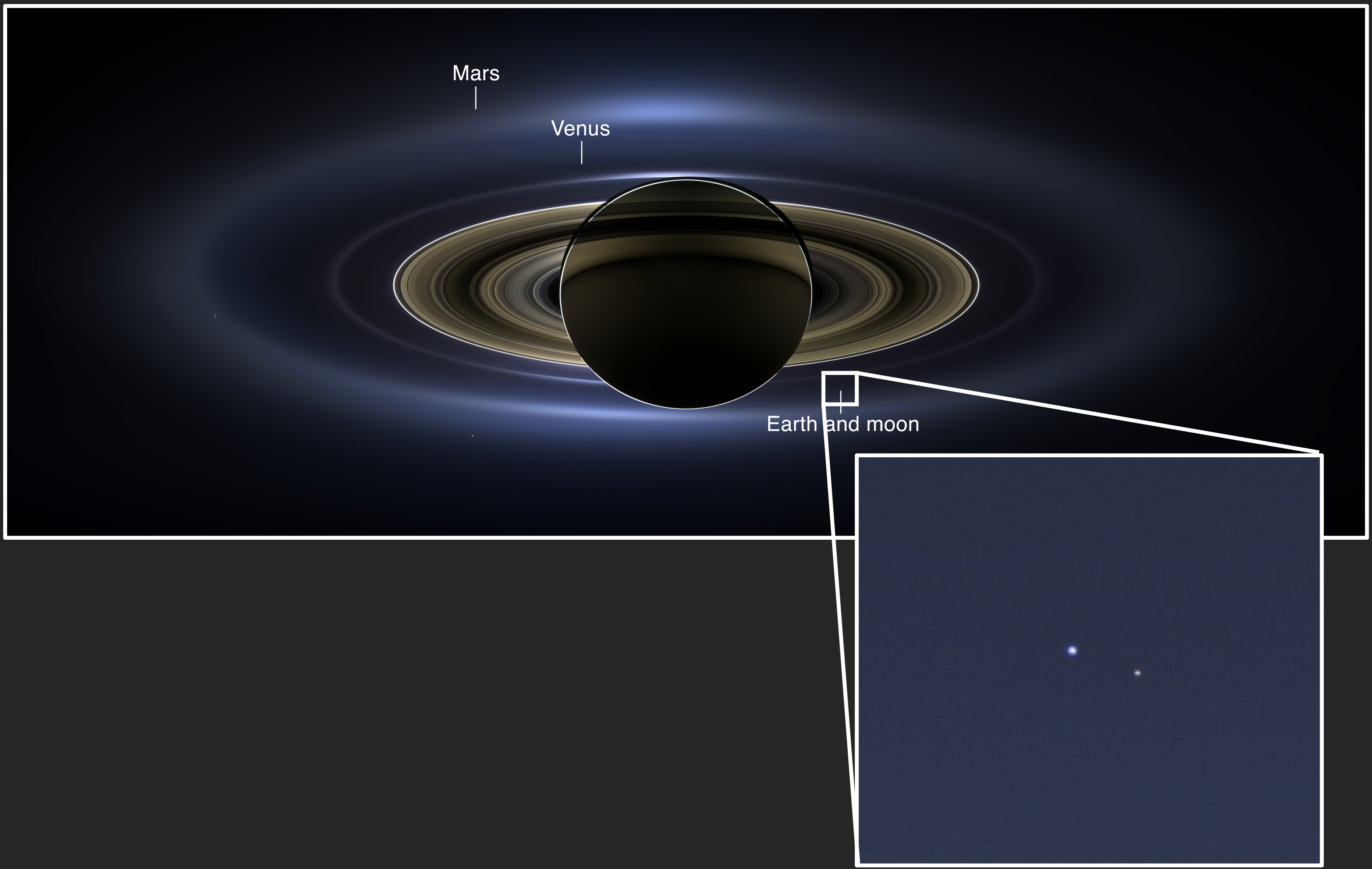

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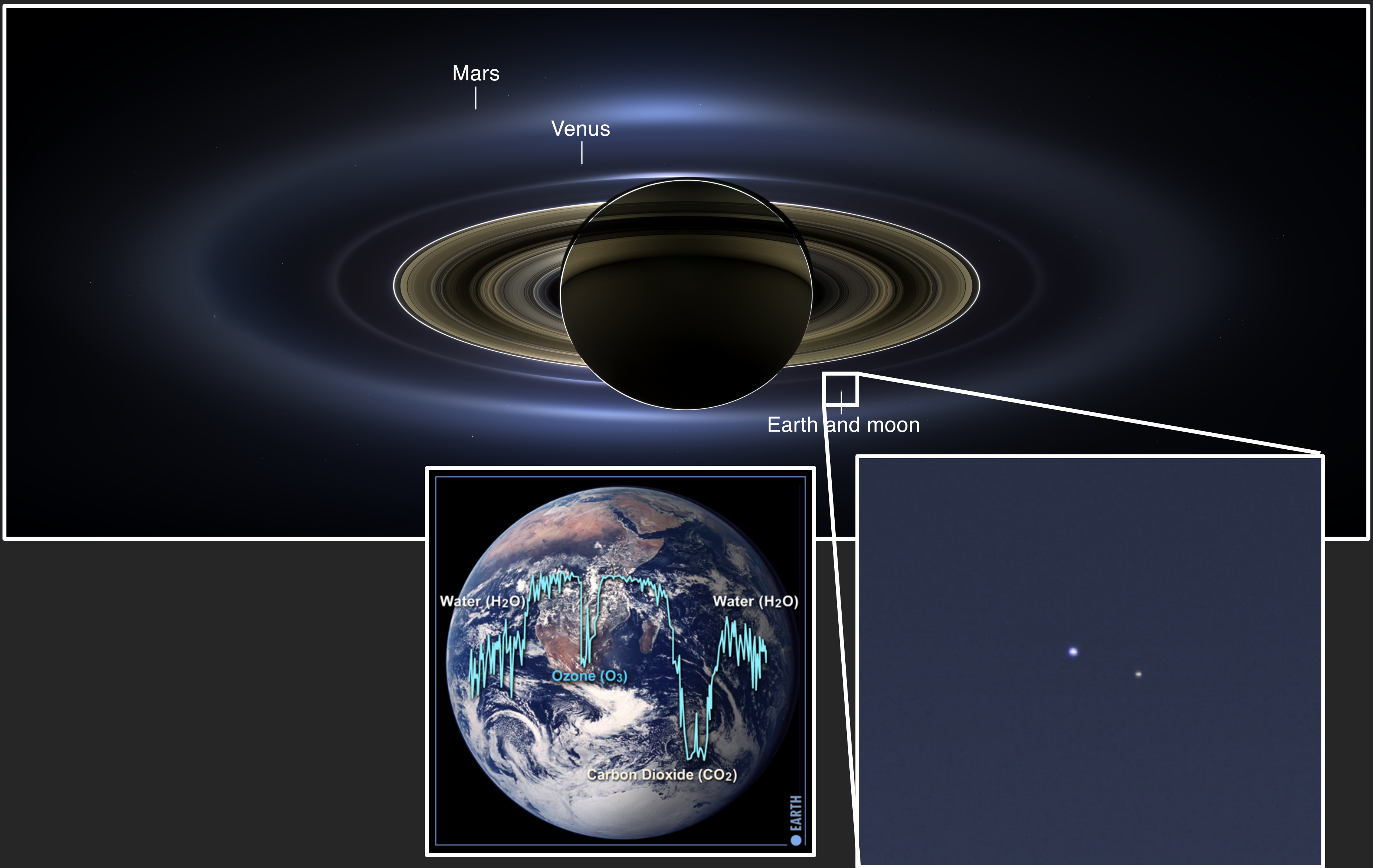

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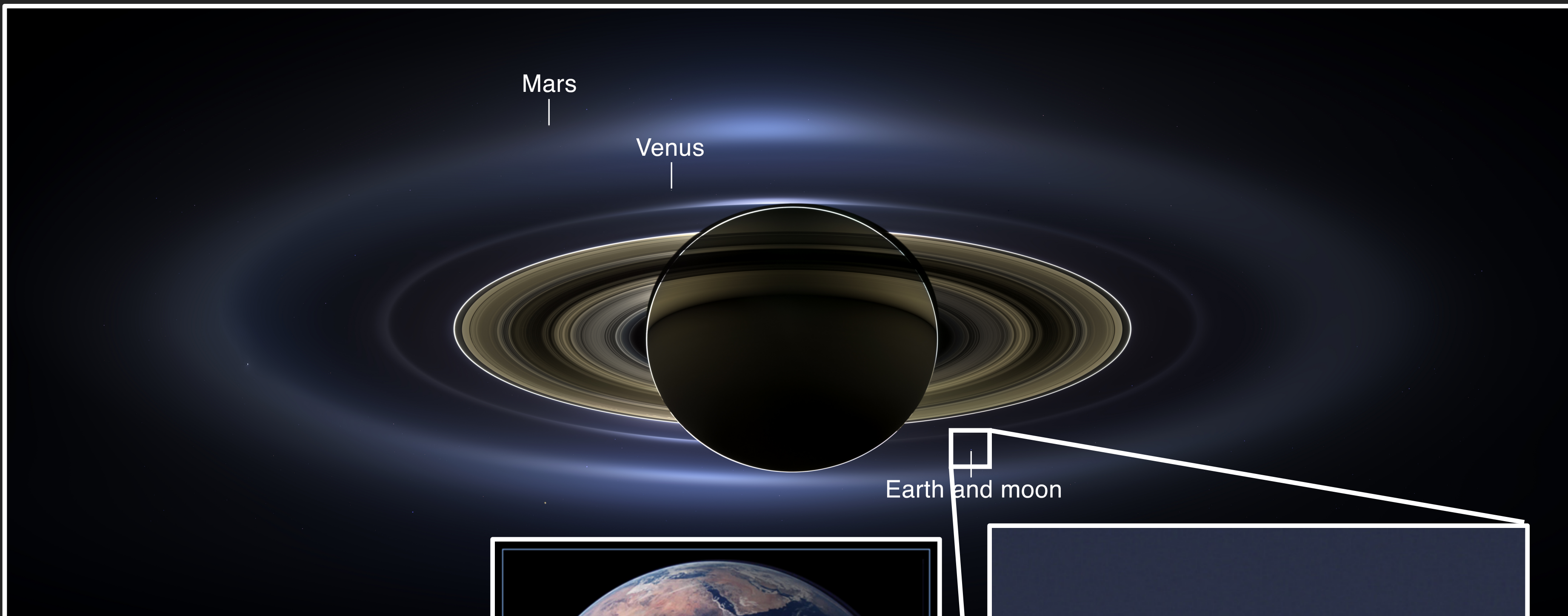
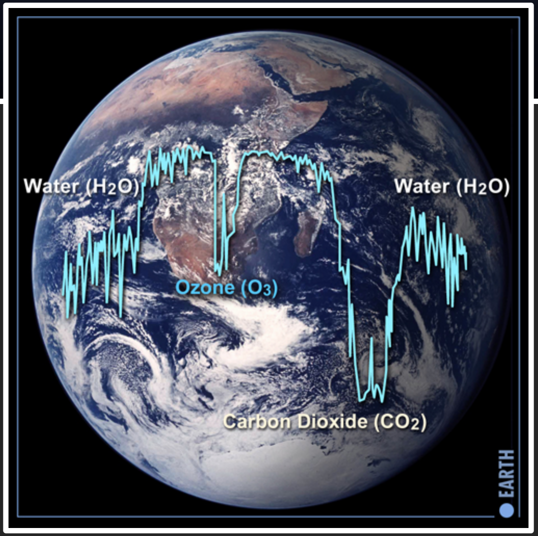
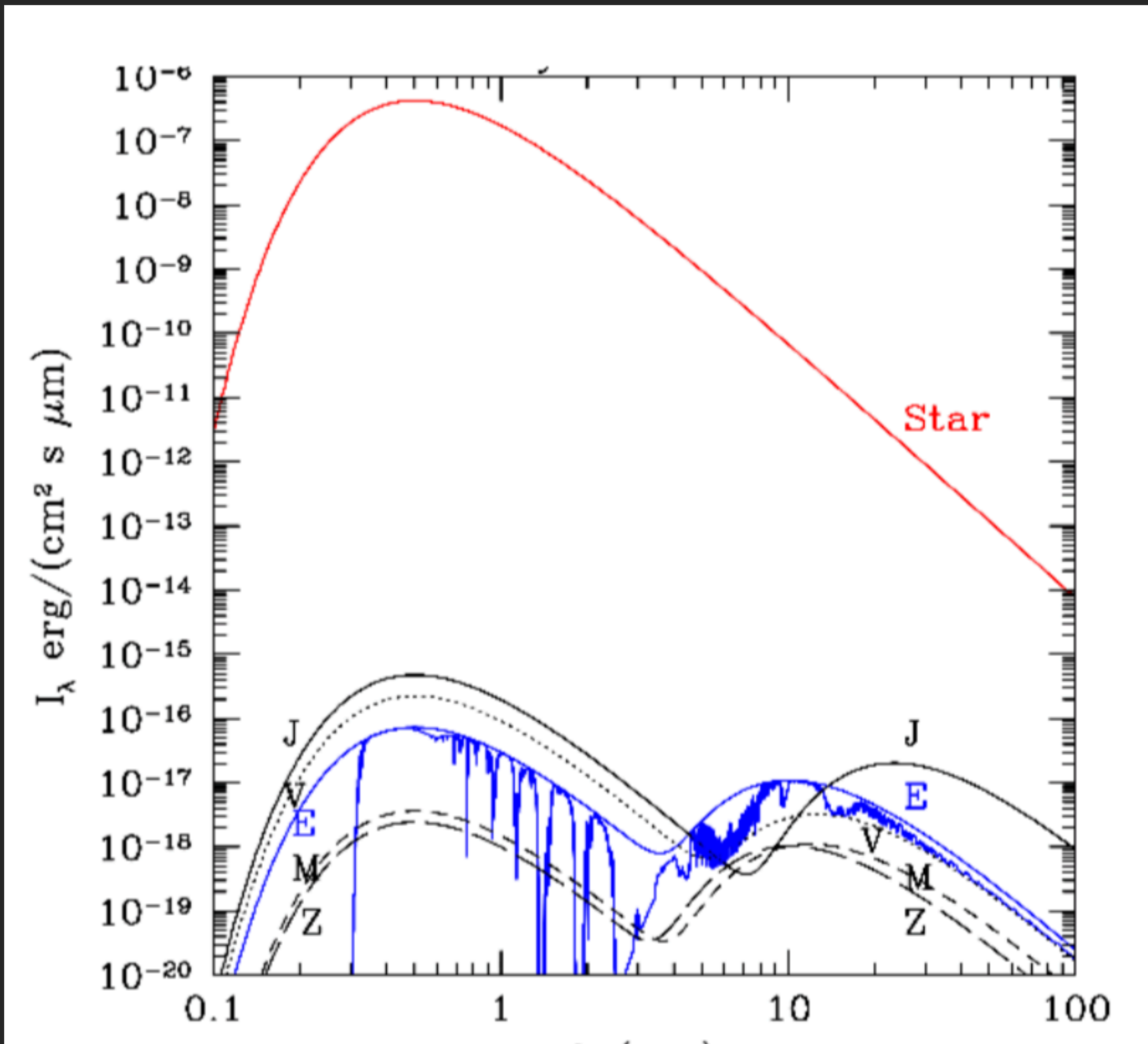




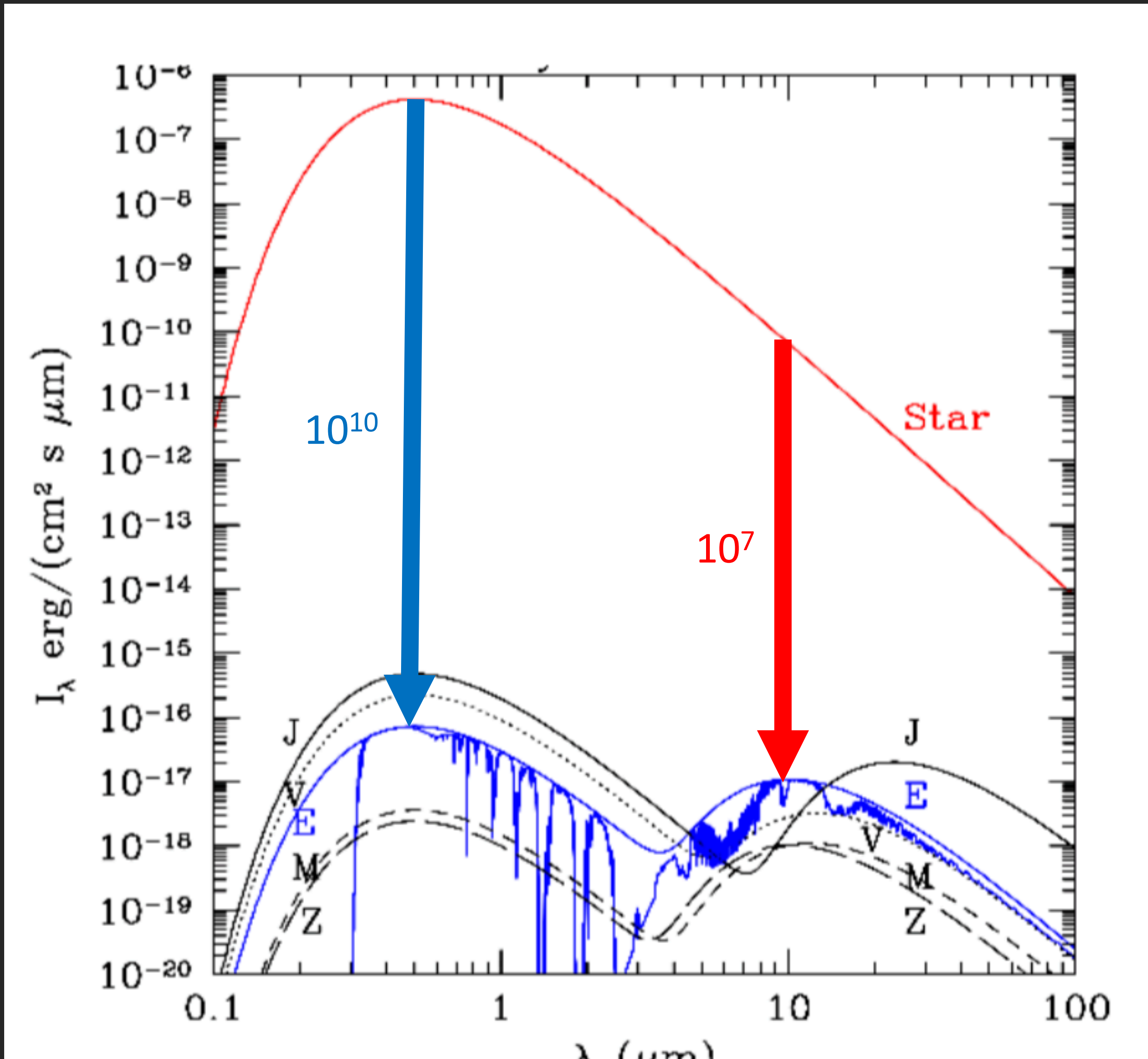
The observing challenge



Kaltenneger et al. 2009

1. Contrast:
   - Visible: 10^{-10} fainter
   - IR: 10^{-7} fainter

The observing challenge



Kaltenneger et al. 2009

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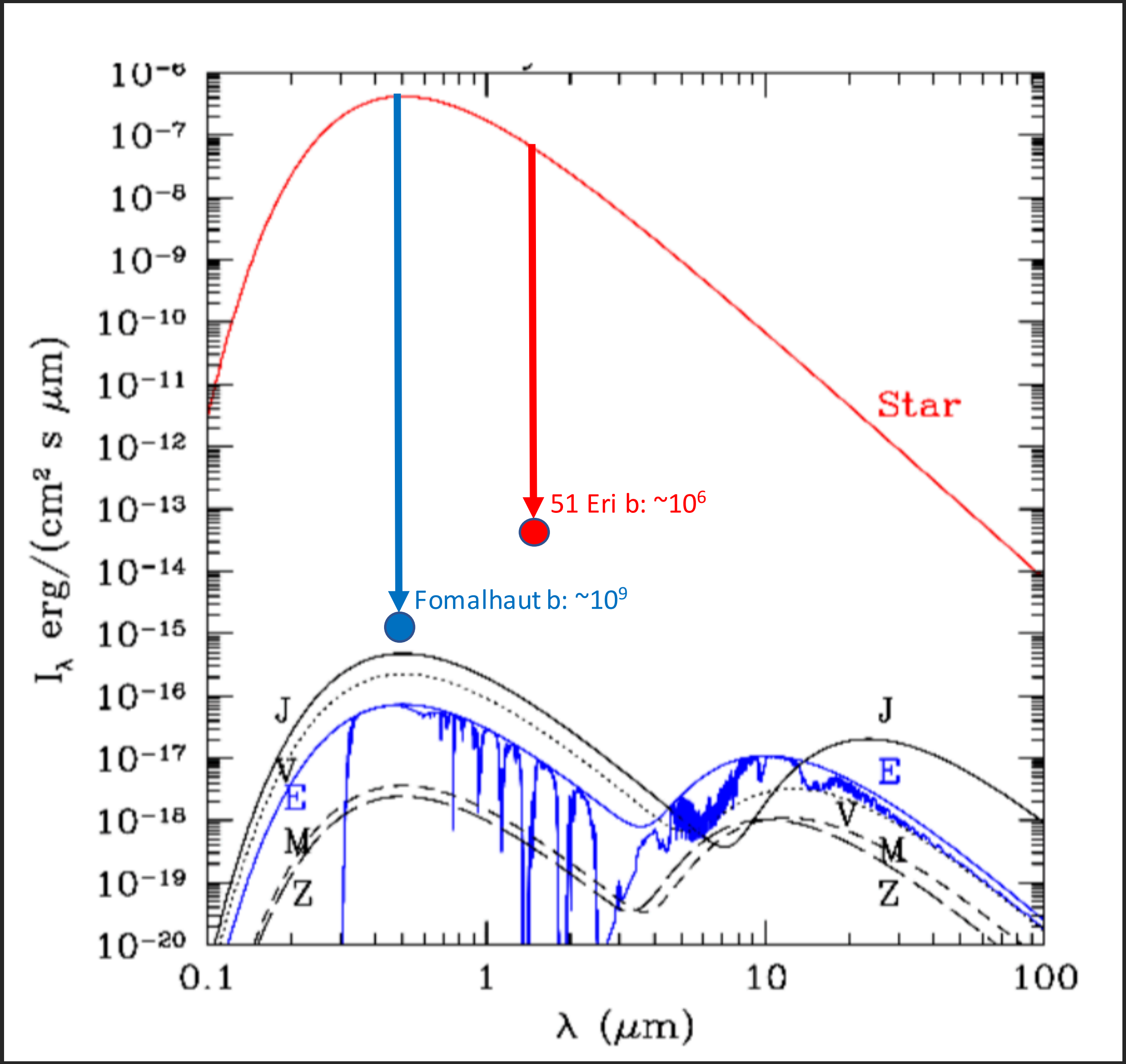


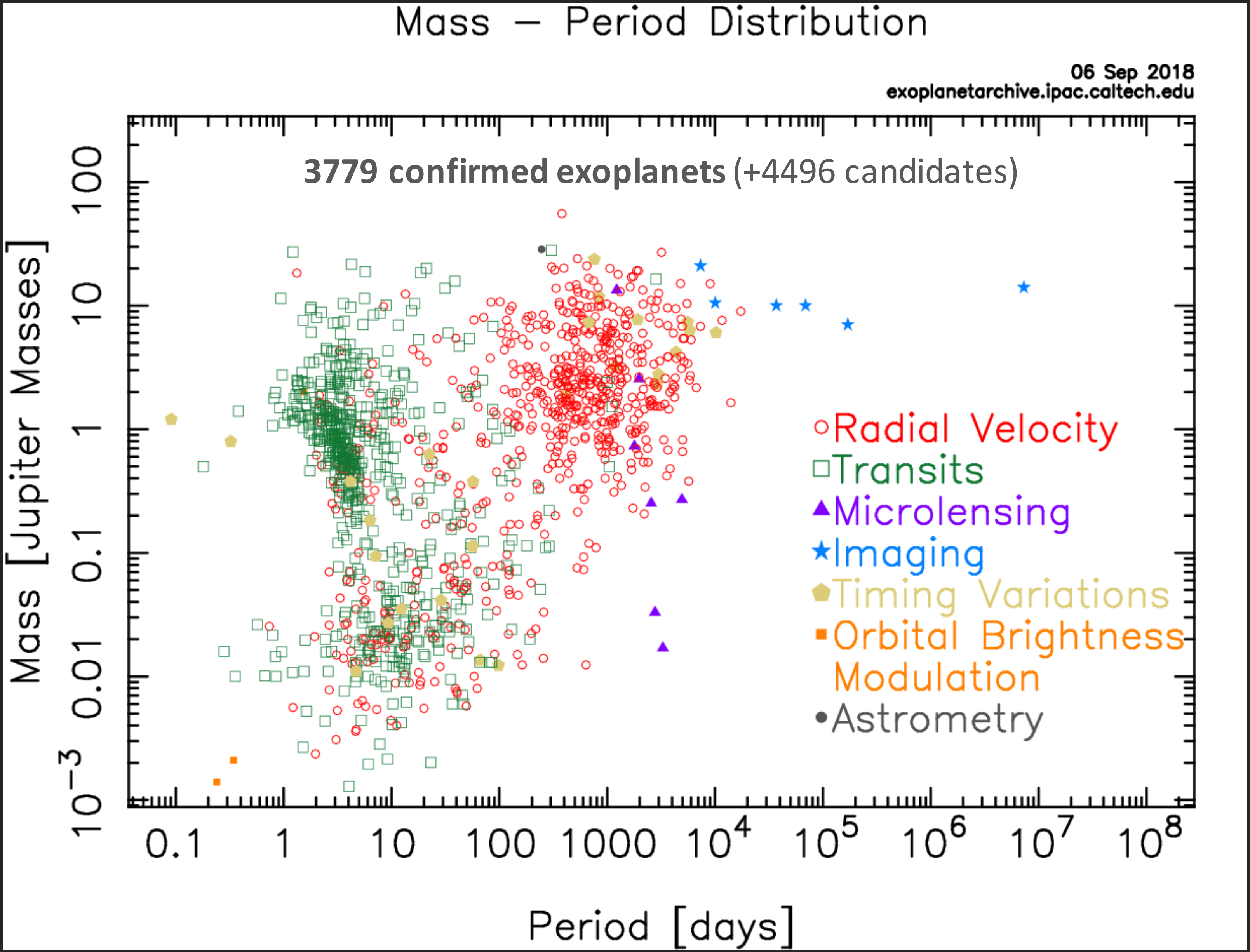
Visible: ~10^9

Fomalhaut b but 150x sep

Infrared: ~10^6

51 Eri but 13x sep

Exoplanet status



The observing challenge

The observing challenge

The observing challenge


1

Talk overview

1. What is an exozodi? Why do we care?

2. What do we know?

3. The HOSTS survey

4. Beyond the HOSTS survey

Talk overview

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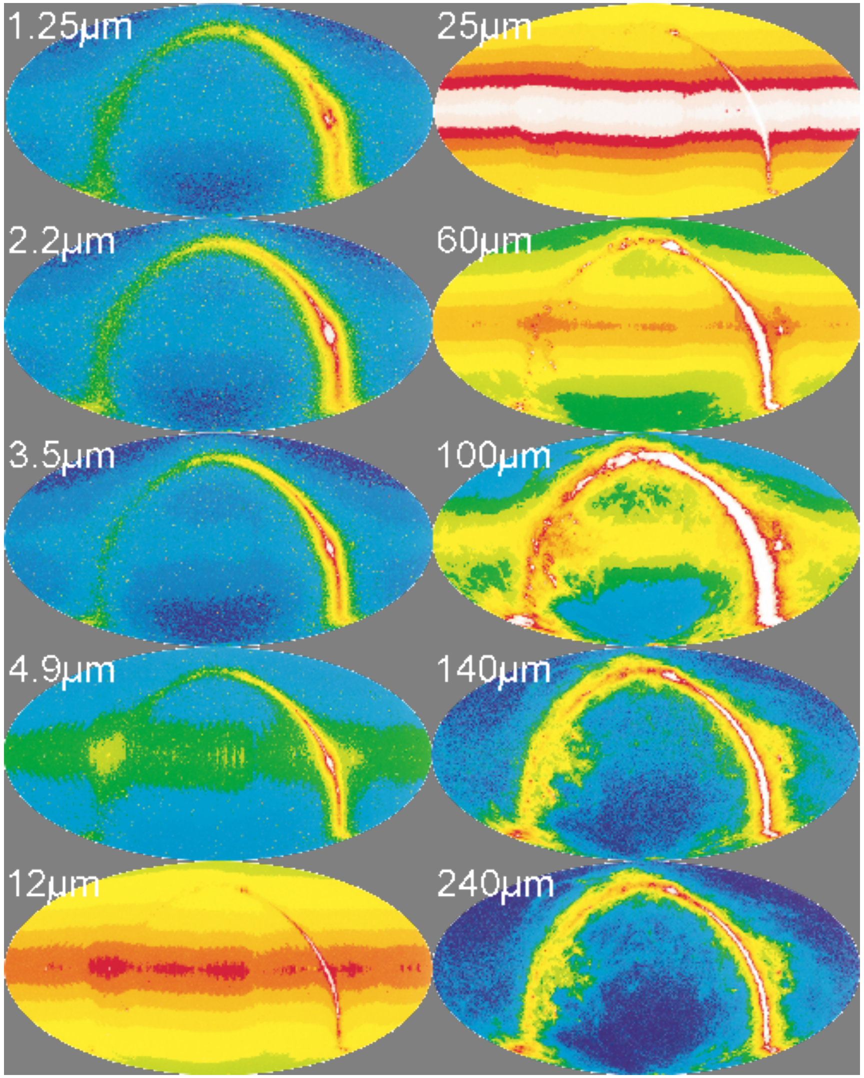
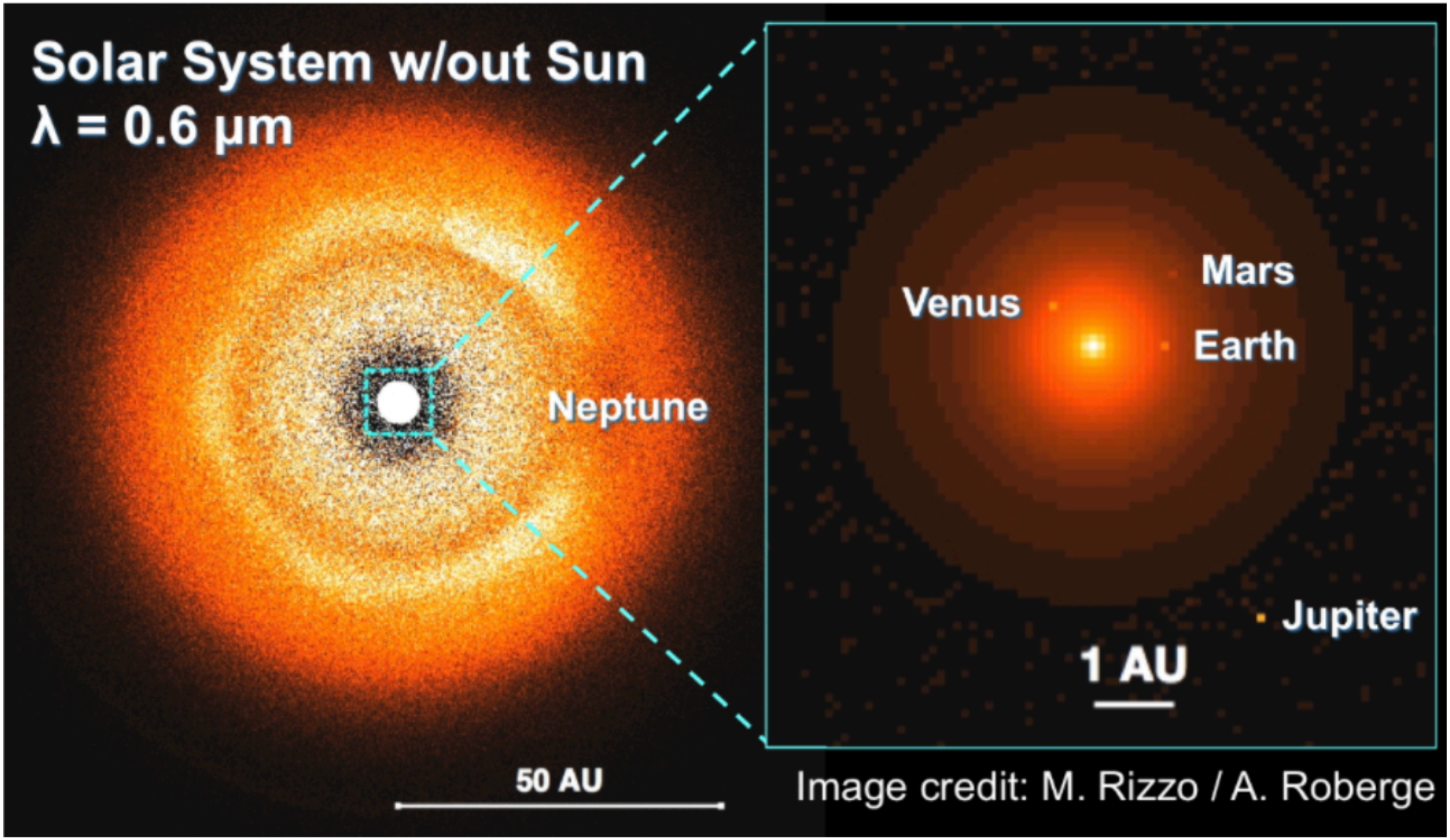
Zodiacal dust



COBE/DIRBE (Kelsall et al. 1998)

- Dust inside a few AU
- Power law surface density (α ~ -0.5, Kimura & Mann 1998, Hahn et al. 2002)
- T: few 100K to 2000K (Kimura & Mann 1998, Hahn et al. 2002)
- Comet evaporation (Nesvorny et al. 2010)
- Asteroid collision & P-R drag (Dermott et al. 2002)
- Complex local structure (planetary interaction, local dust creation)

Zodiacal dust



Exozodiacal dust

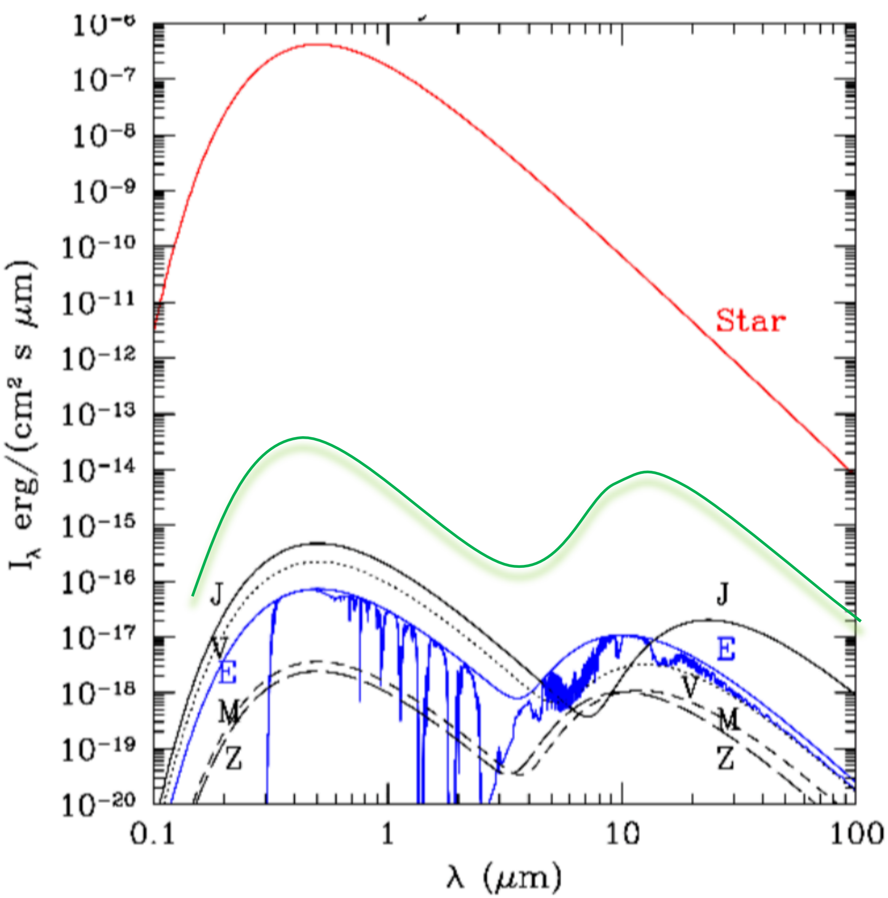
Kral et al. 2018, Astronomical Review

The term exozodiacal dust (short exozodi) is used here to refer to warm or hot dust (with $T > 300$K) orbiting around a main sequence star. The zodiacal dust in our Solar System is part of this category. However, exozodis can be much brighter and located at different radial locations than the zodiacal dust. Exozodis are to be distinguished from their colder counterparts, called debris discs, for which the observed dust is produced by quasi steady state collisions in belts (similar to the Kuiper belt) composed of planetesimals and large rocky bodies orbiting at tens of au [77, 160].

- **Warm dust:** Near the habitable zone (HZ, T ~ 300K), observed in the mid-IR
- **Hot dust:** Very close to the star, near sublimation distance, observed in the near-Ir
- Common physics: **No equilibrium collisional cascade** from large bodies over age of the star

Why do we care?

- Most luminous component of planetary systems (after star)
- Gives insight into architecture and dynamics in the innermost regions (near habitable zone)

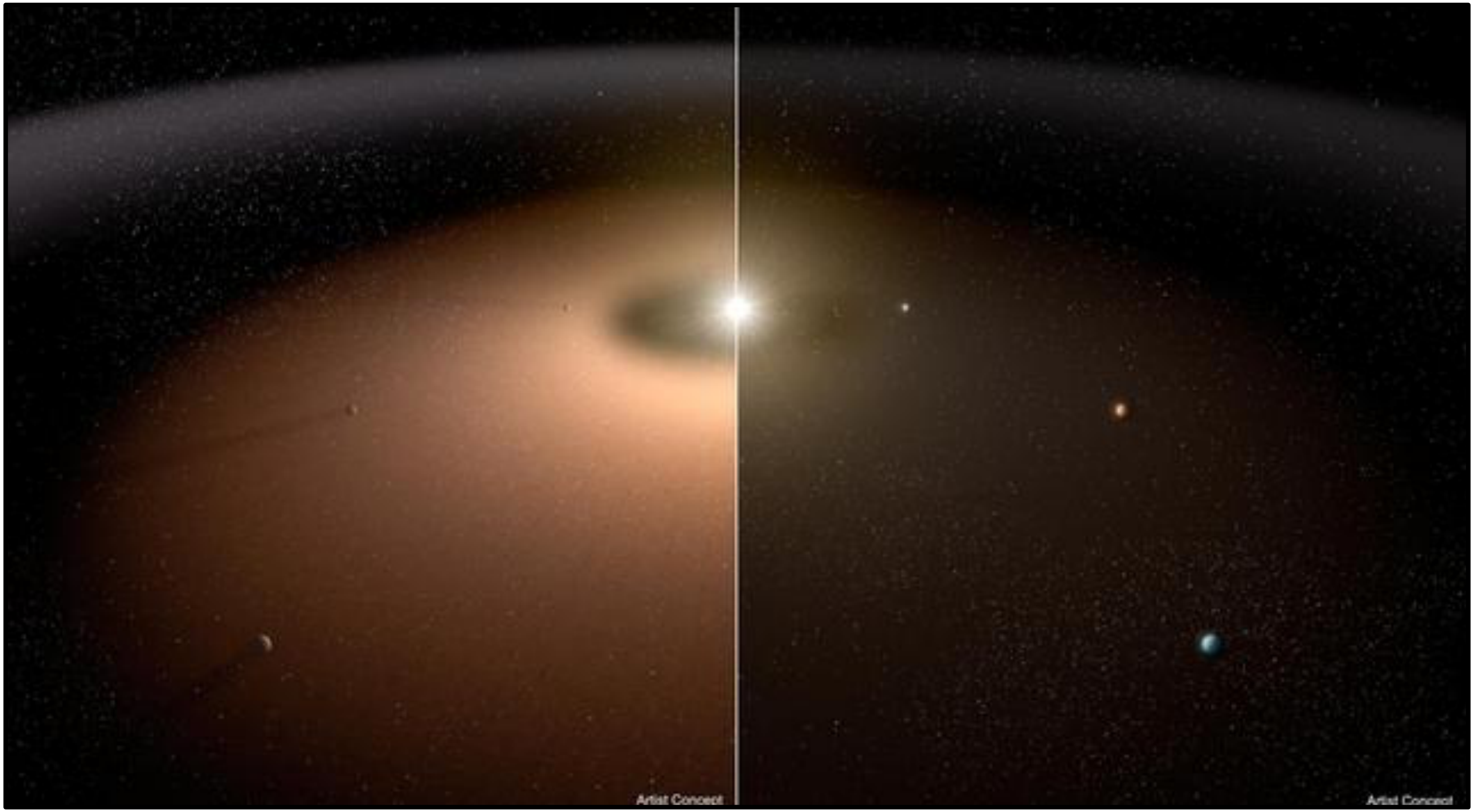


<u>1. Source of noise</u>

1 zodi = ~300x Earth at 550 nm and 10 μm.

Why do we care?

- Source of noise and confusion for future direct imaging missions



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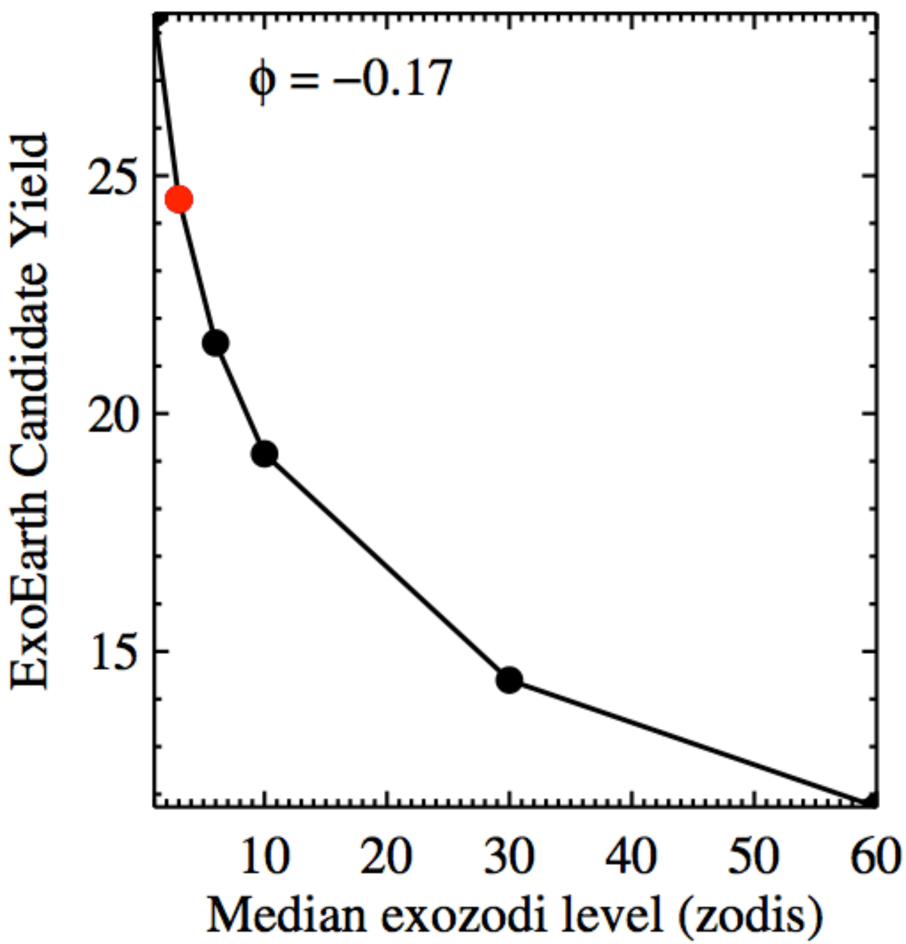


Reduce exozodi by 10x, increase yield by ~ 2x

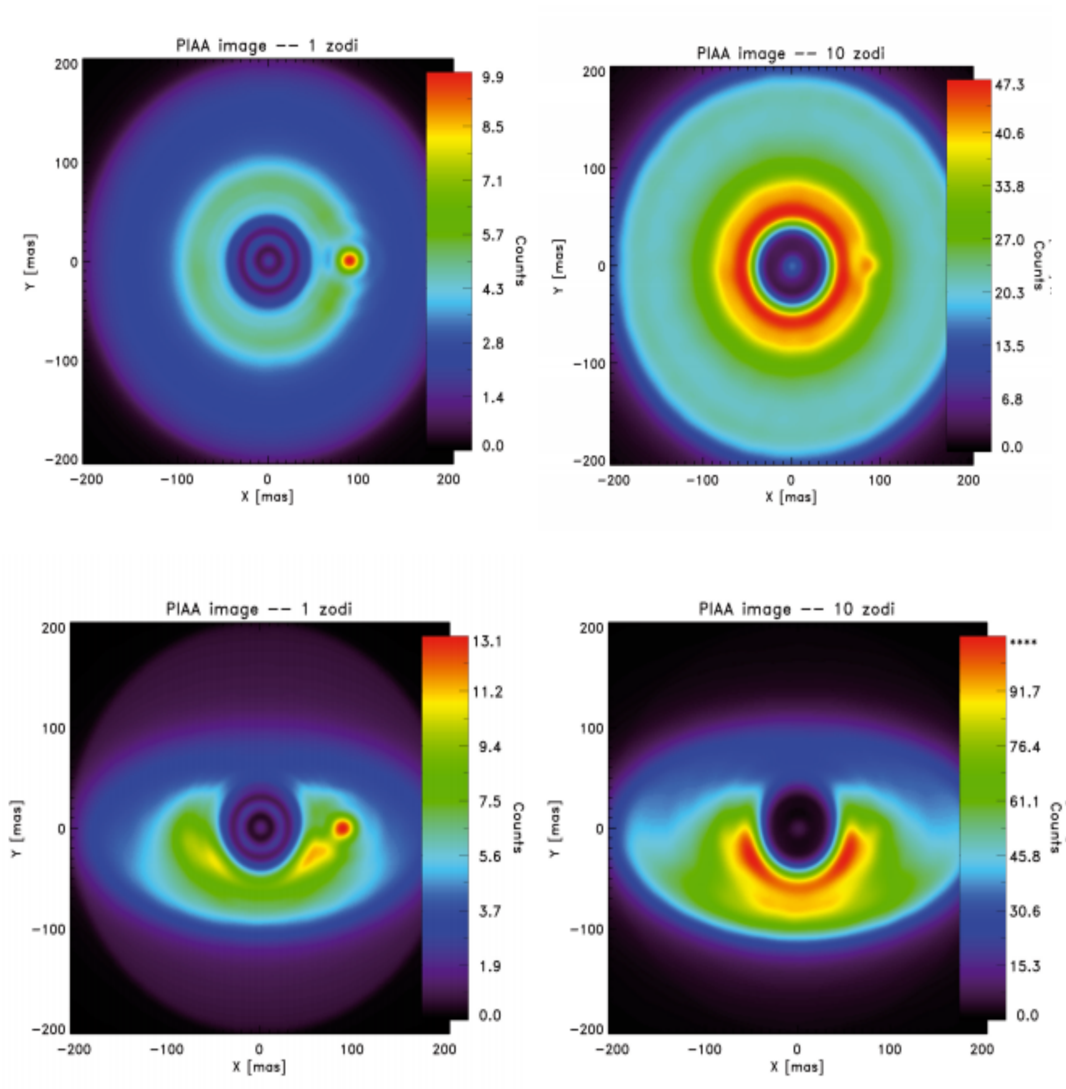
Stark et al., 2014, 2015

Tolerable dust density is ~15 zodis for IR imagers

Defrère et al. 2010

Why do we care?

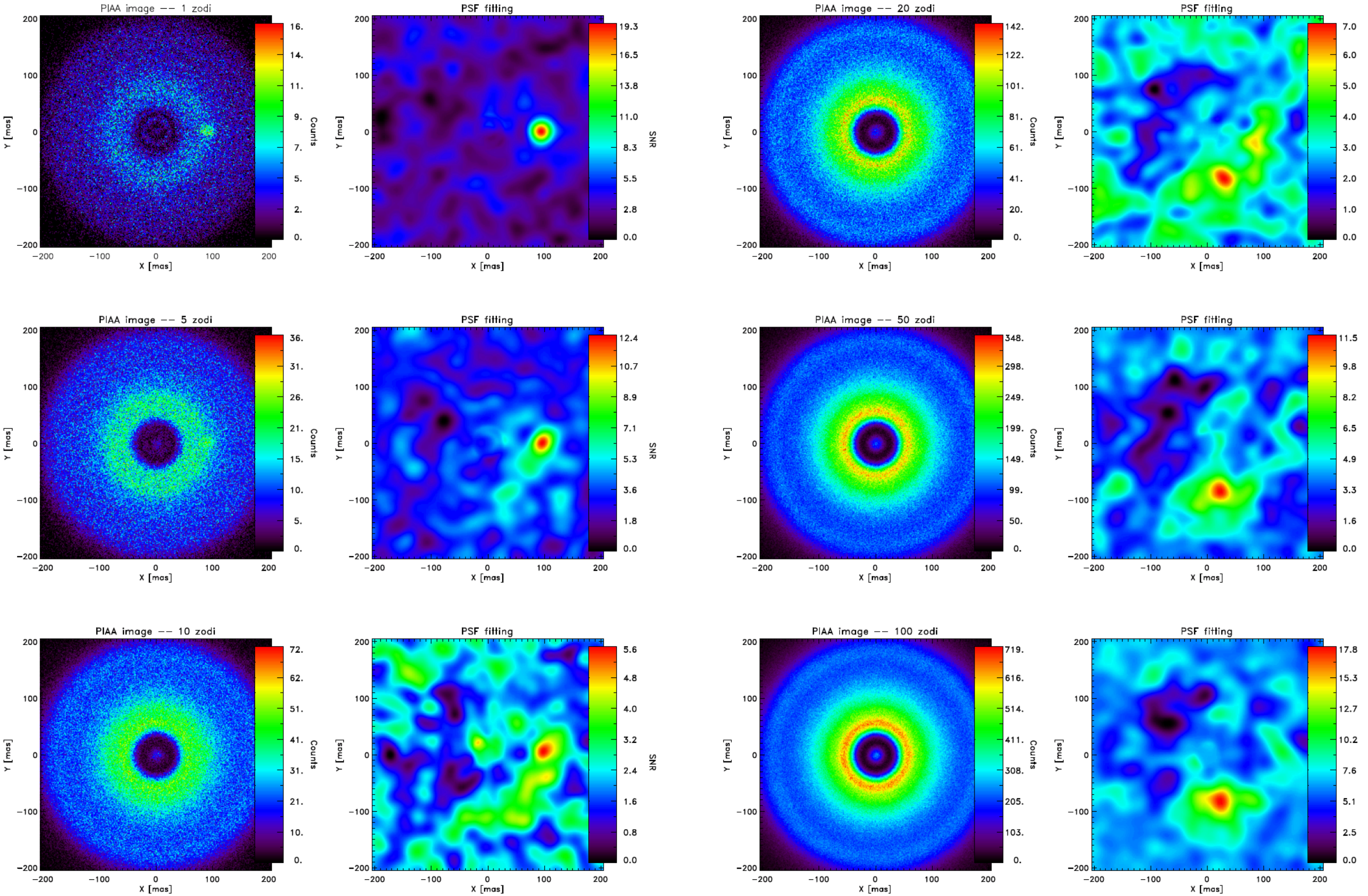
Defrère et al. 2012



2. Source of confusion

Why do we care?

Defrère et al. 2012



Talk overview

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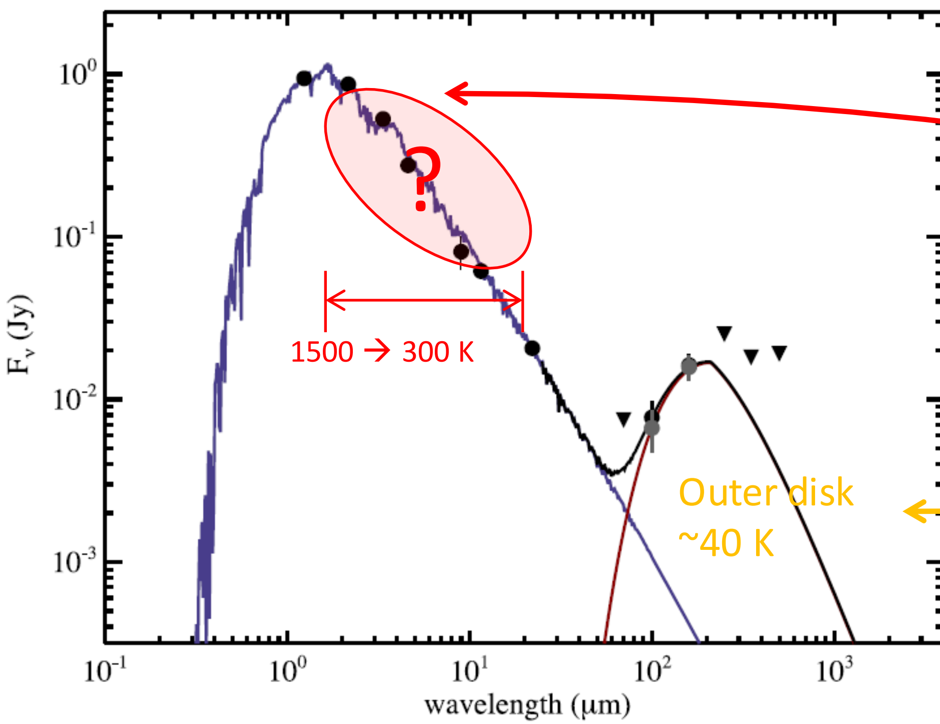
The need for infrared interferometry

- High contrast (≥ 1:100), zodi levels < 1000 x Solar system not detectable with photometry or spectroscopy
- Small angular separation:
  - ✓ Inner disc: a few 10 mas
  - ✓ Requires high-precision IR interferometry



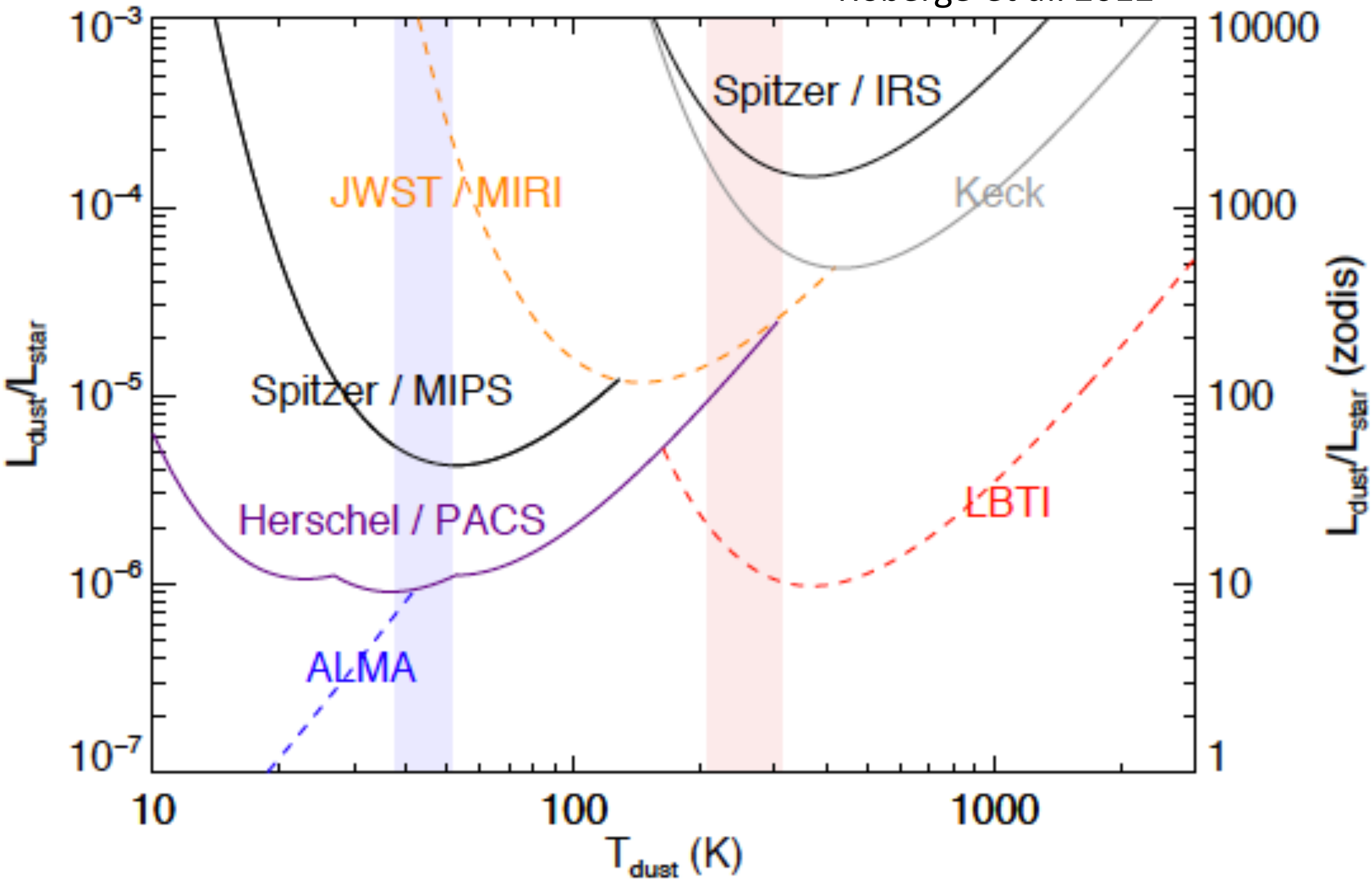
What do we know?

- Single-dish photometry
  - Spitzer: ~1% of 152 main-sequence stars (Lawler et al., 2009)
  - WISE: ~0.09% of 22000 main-sequence stars (Kennedy et al. 2012)
  - Sensitivity threshold **~1000 zodis**

- Infrared interferometry
  - Keck nuller: ~10 detections out of 41 main-sequence stars (sensitivity threshold **~250 zodis,** Mennesson et al. 2014).
  - **Median level** of exozodiacal dust **< 60 zodis** high confidence (95%, assuming a log-normal luminosity distribution).

What do we know?

Roberge et al. 2012



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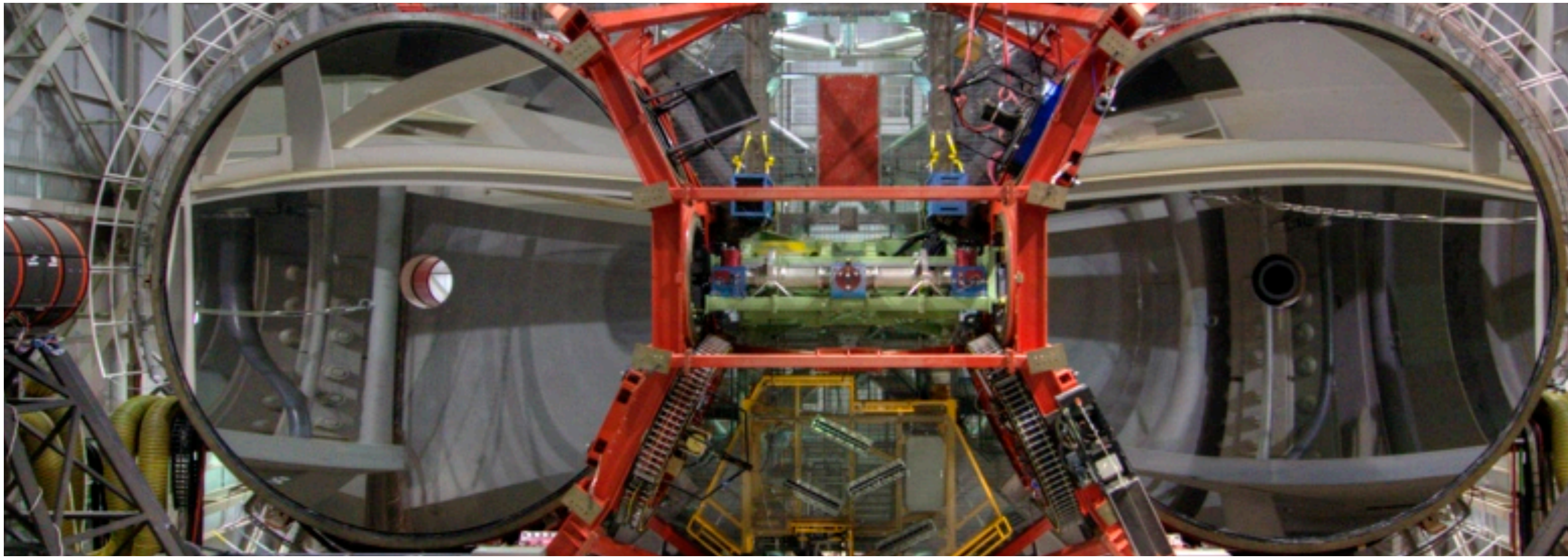
Enters the LBTI

Large Binocular Telescope (LBT) on Mt Graham, Arizona

And the HOSTS team

HOSTS team: <u>P. Hinz</u> (PI), <u>S. Ertel</u>, G. Bryden, A. Weinberger, W.C. Danchi, A. Roberge, A. Gaspar, B. Mennesson, G. Serabyn, G. Kennedy, J. Stone, M. Wyatt, P. Willems, K. Stapeldfeldt, A. Skemer

The Large Binocular Telescope

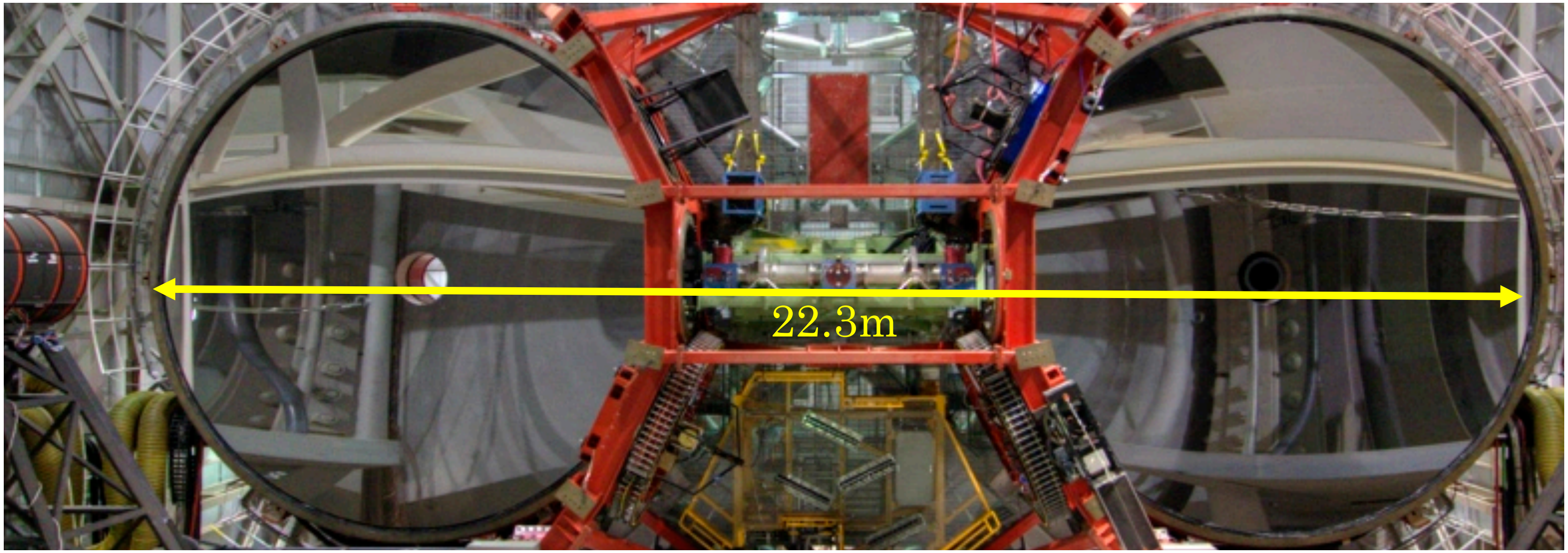


Resolution
Beam combination provides the equivalent resolution of a 22.7-m telescope.

High Contrast
The AO system creates an image with a Strehl of >90% at 3.8 μm.

Sensitivity
LBT has two 8.4-m mirrors mounted on a single structure (collecting area of a single 11.8-m aperture)

The Large Binocular Telescope



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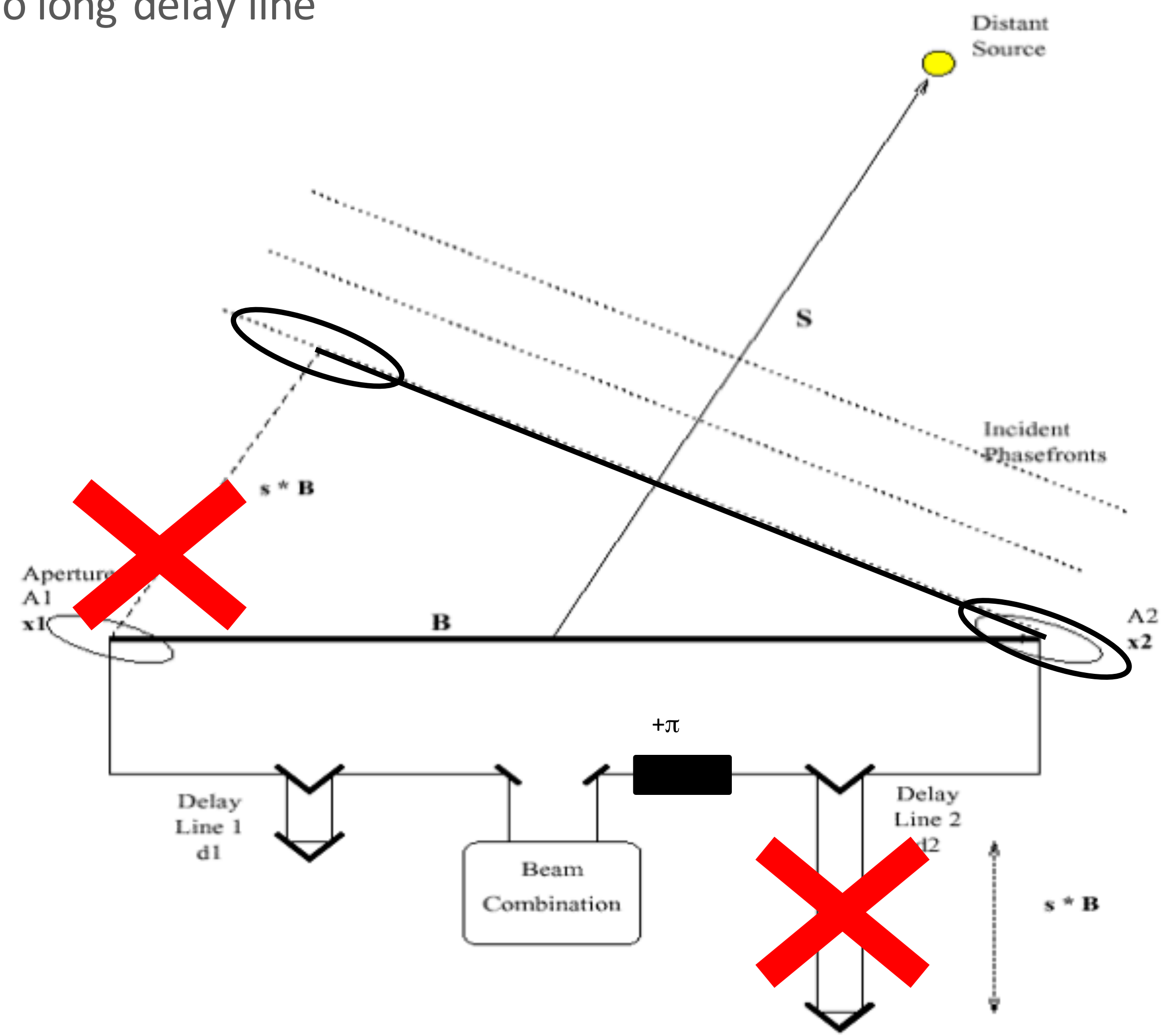
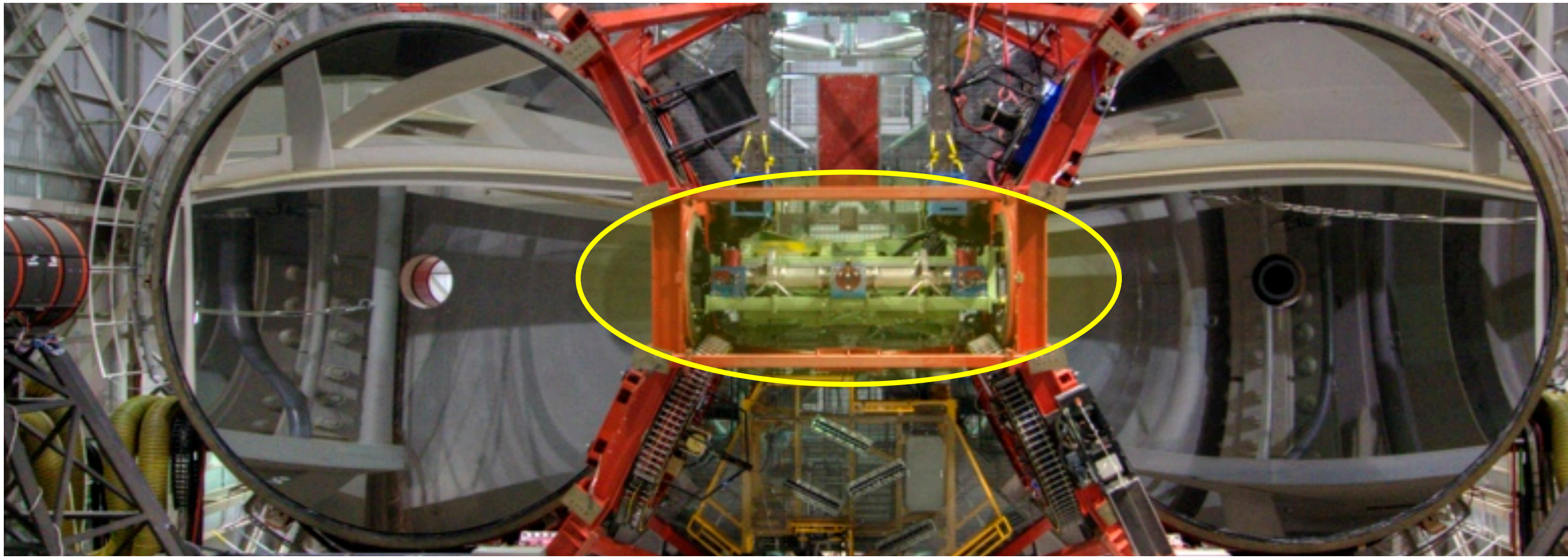
Key specifities

1. Common mount interferometer
   ⇒ No geometric delay
   ⇒ No long delay line



The LBT interferometer (LBTI)



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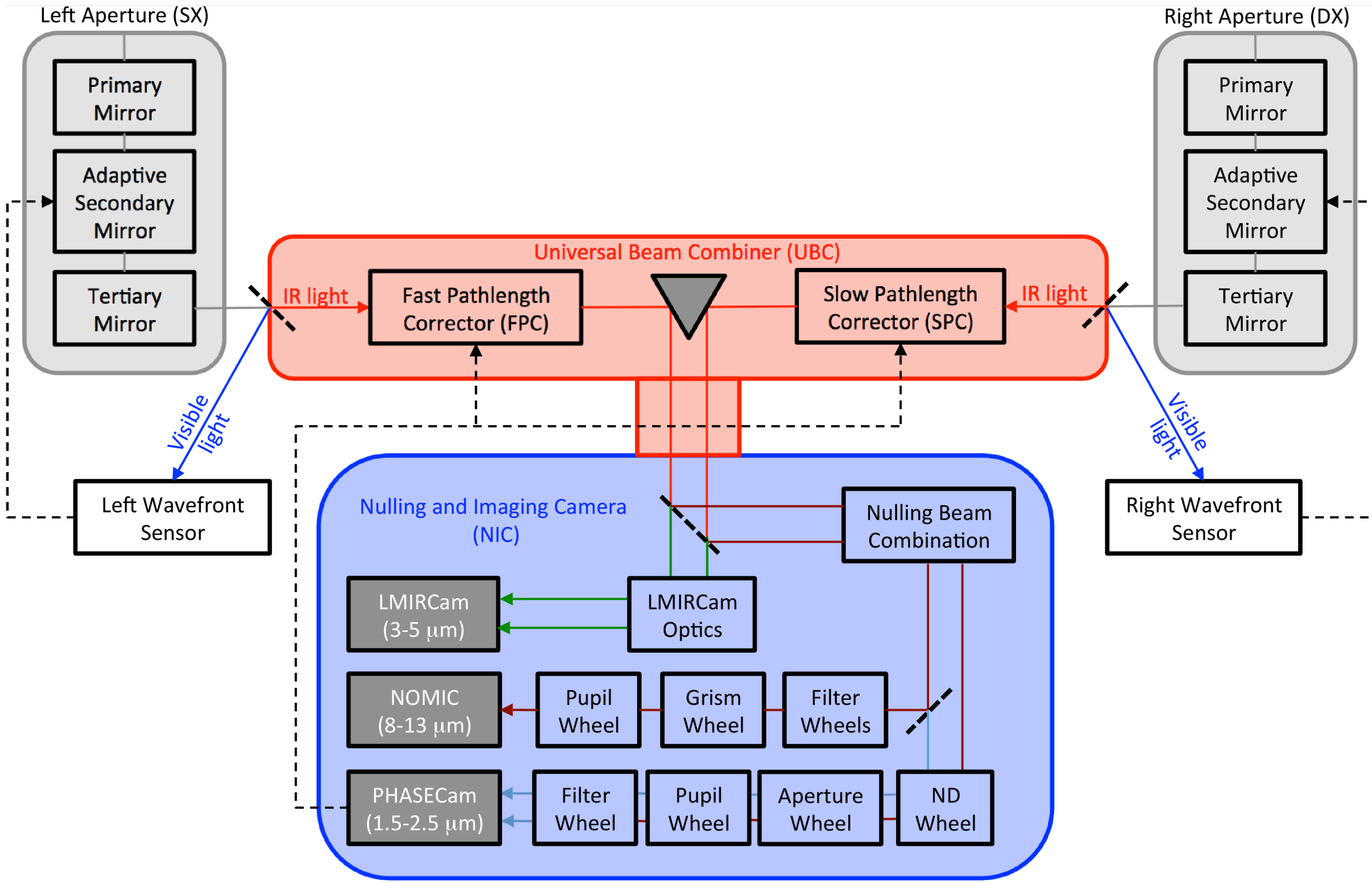
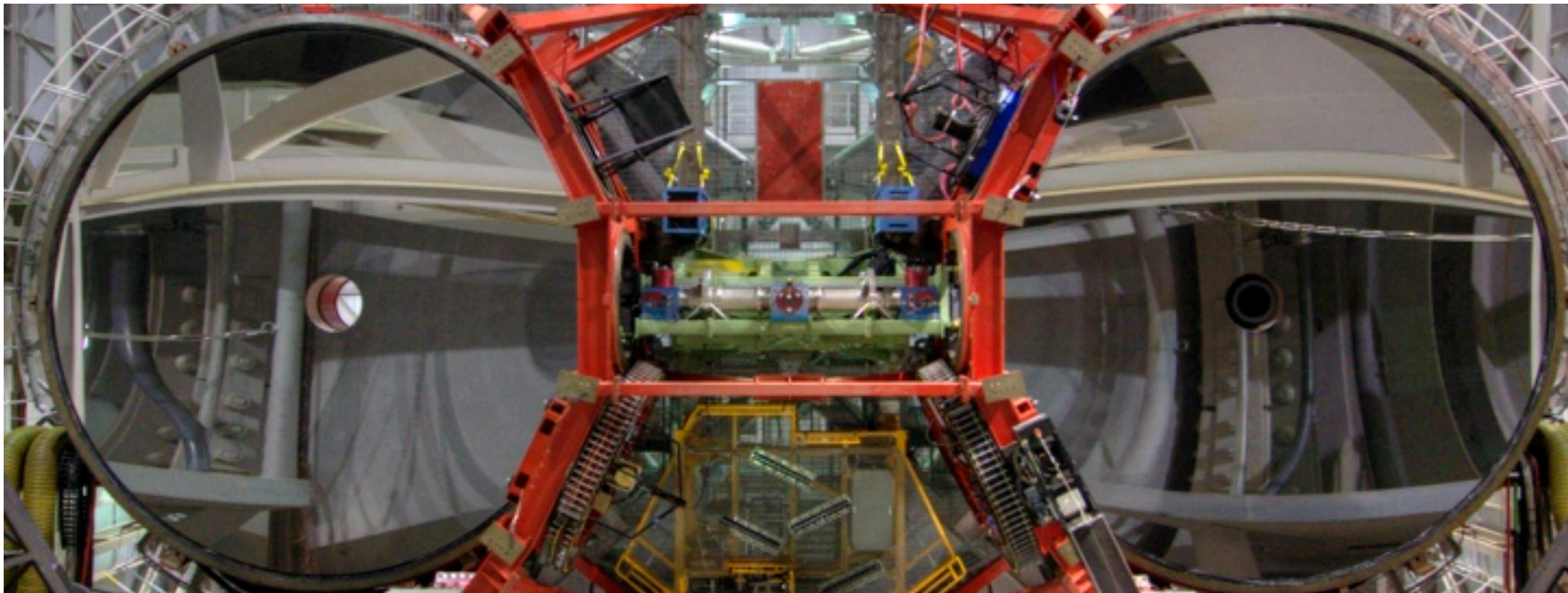
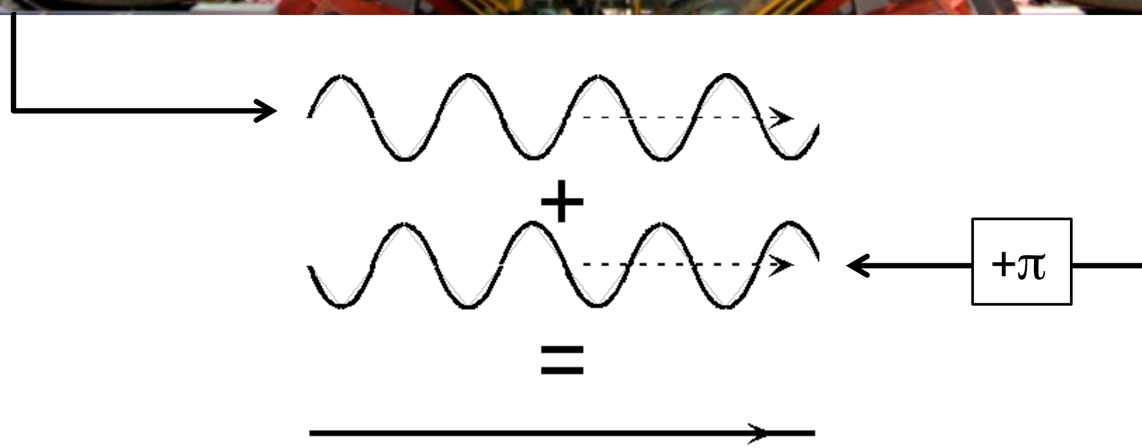
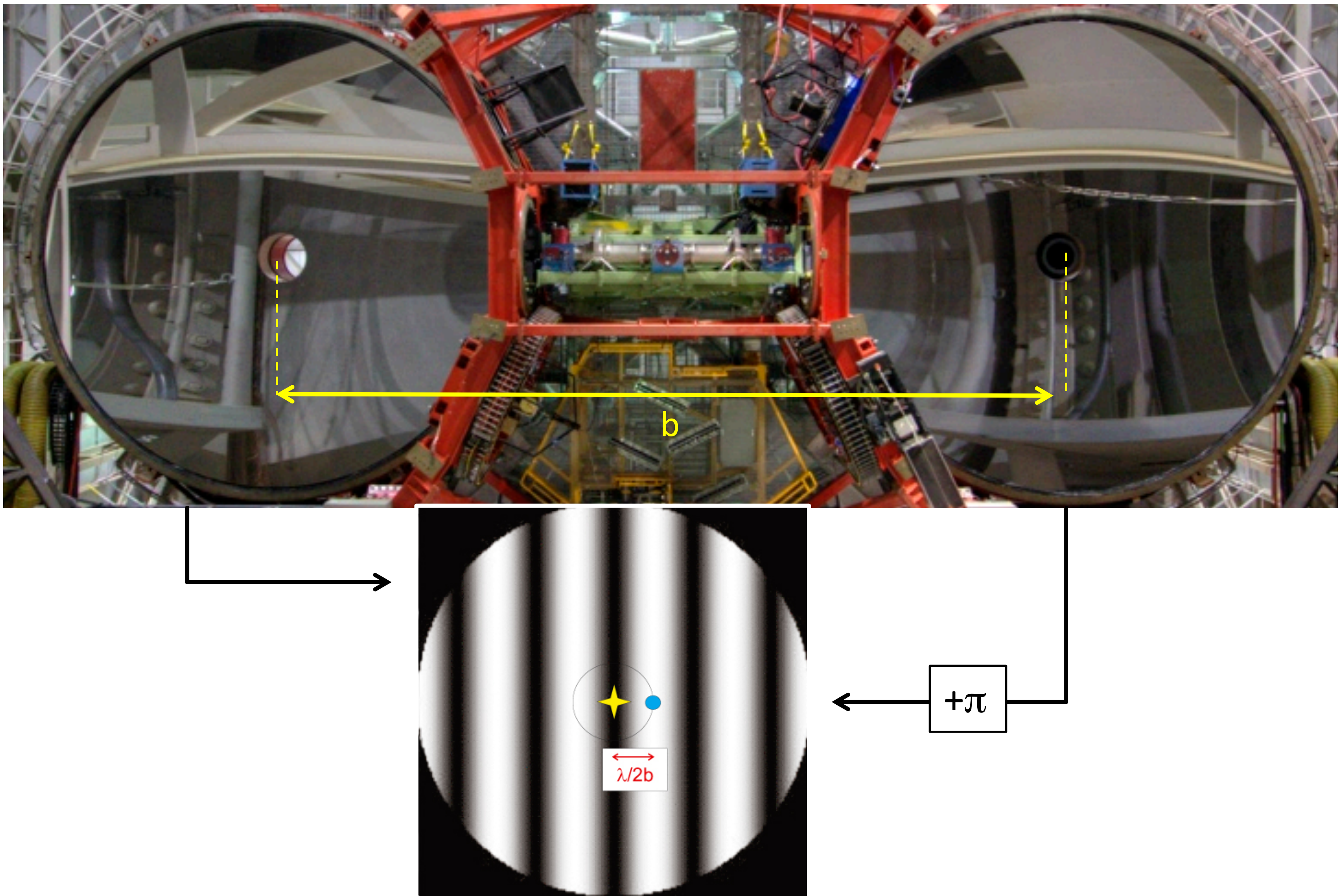


Nulling interferometry

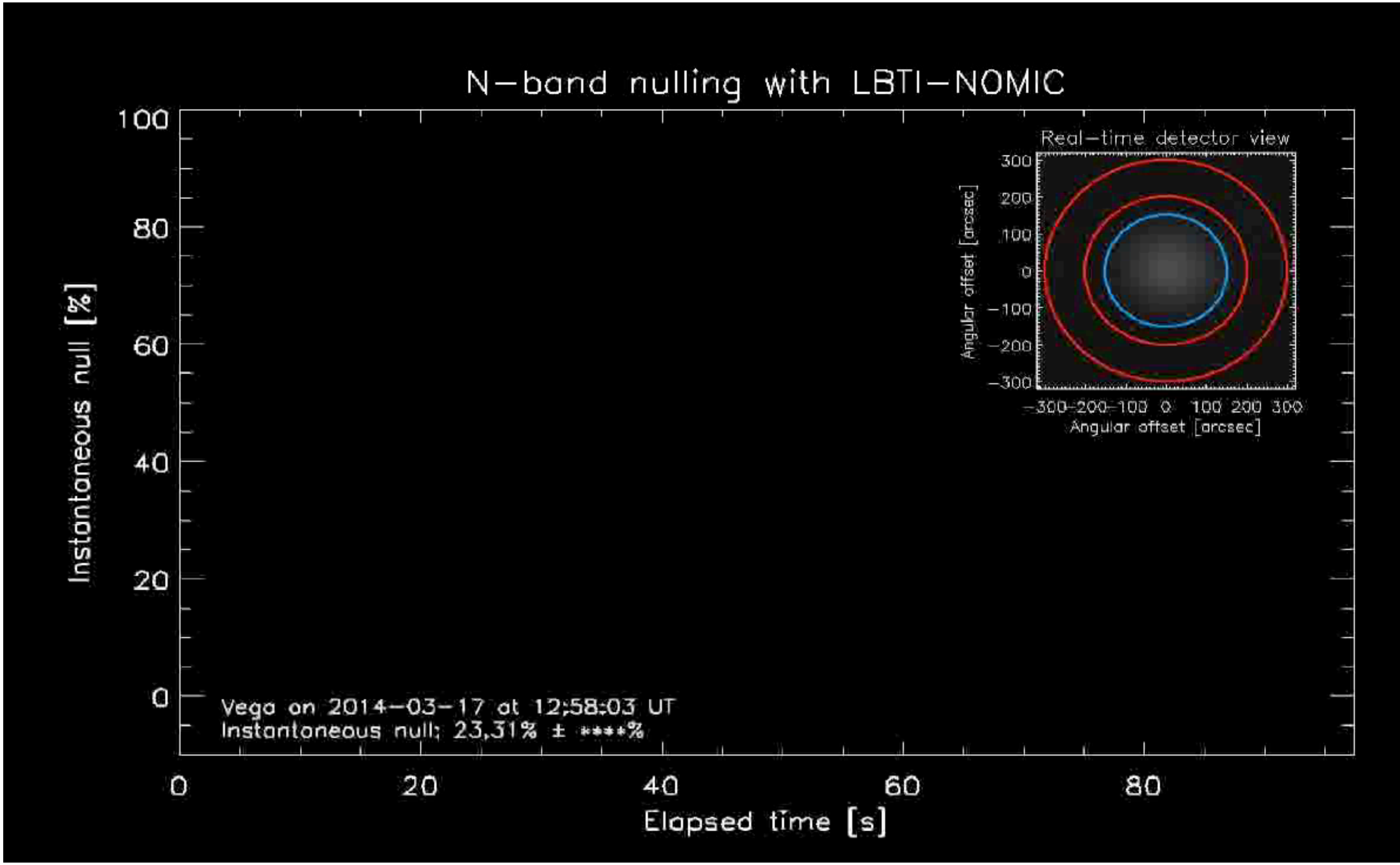




Nulling interferometry

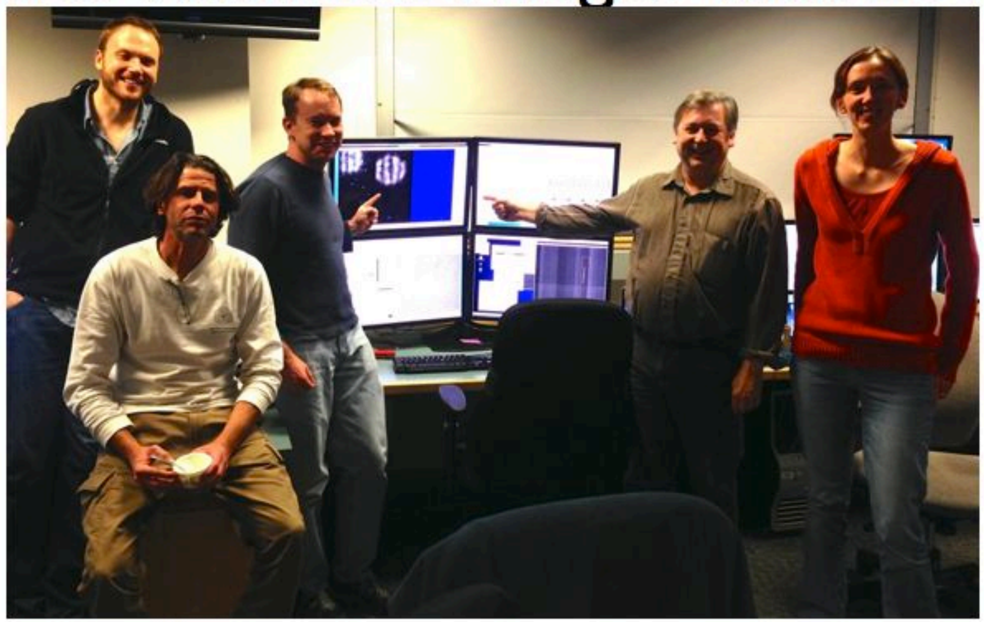


Example of observation

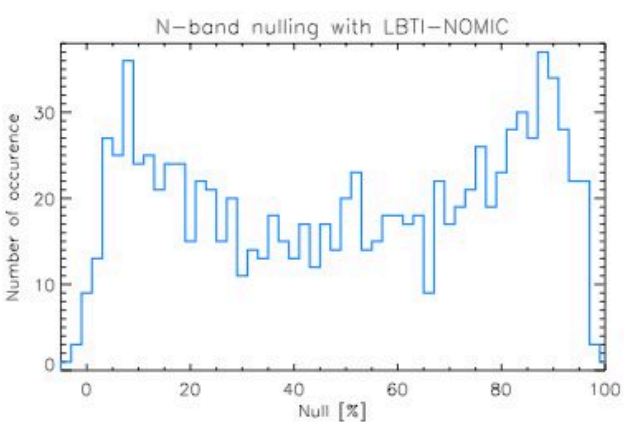


Example of observation (2013)

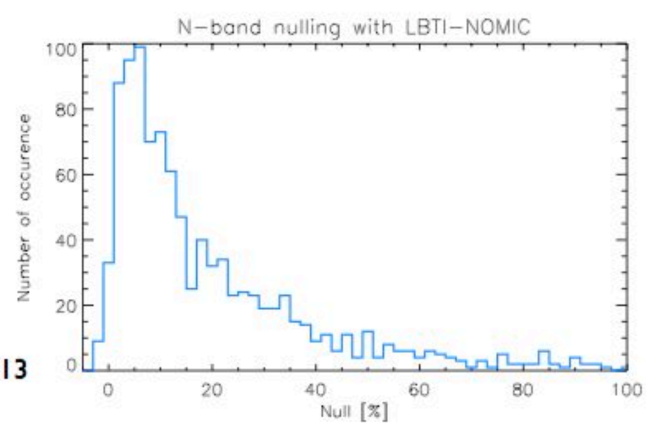
First Stabilized Fringes with LBTI



Open Phase Loop

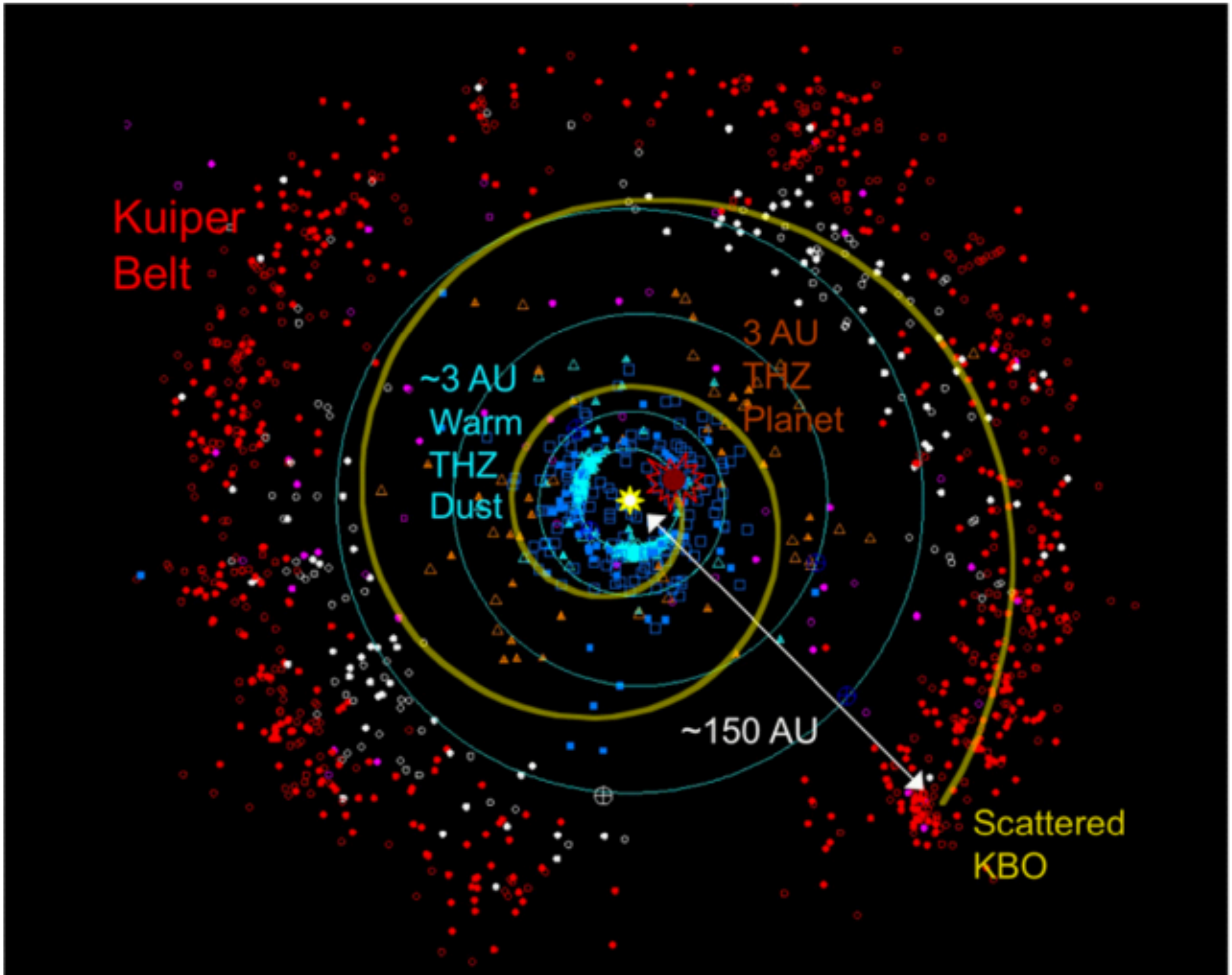


Closed Phase Loop



Dec. 30, 2013

First-light results: η Crv (2014)



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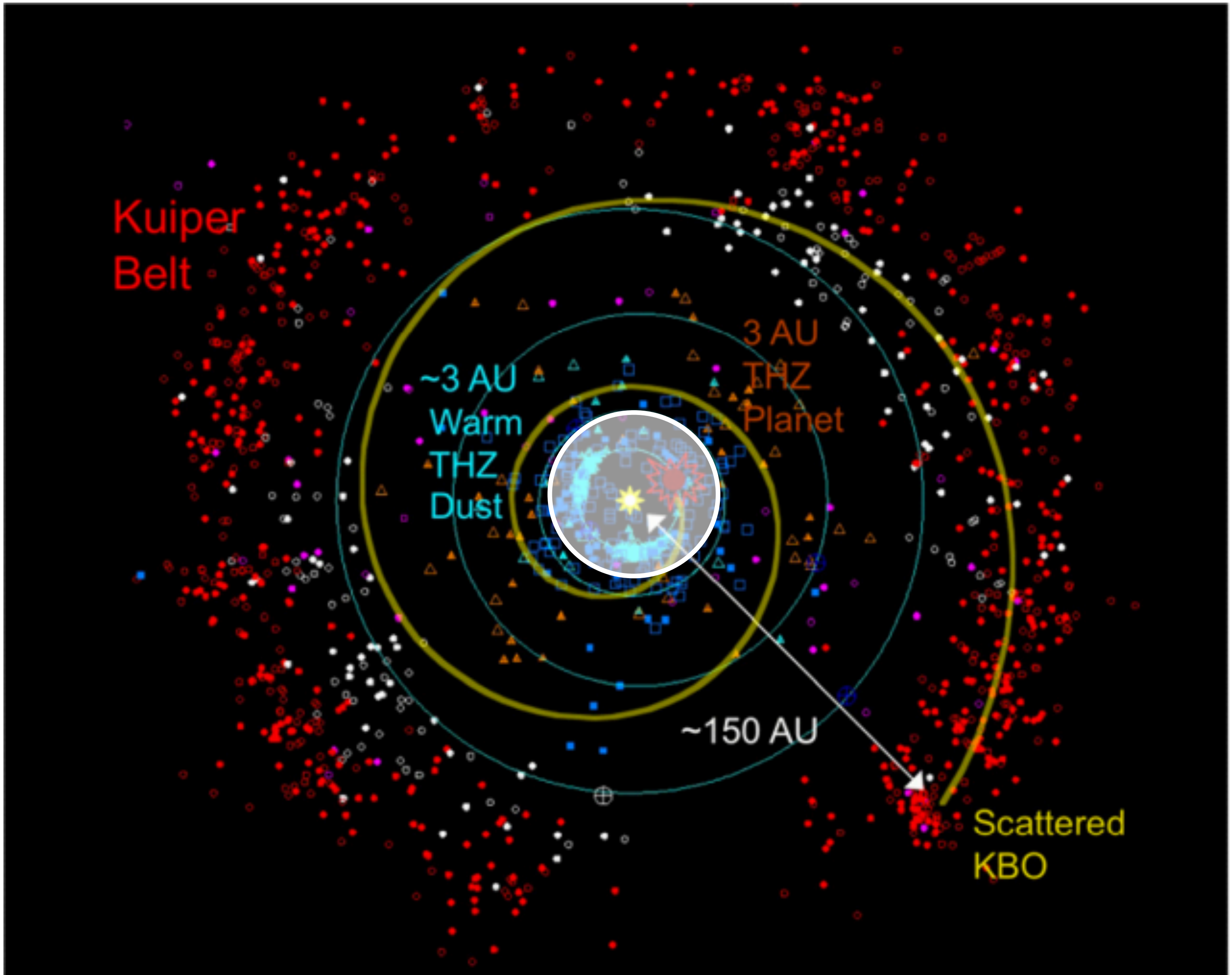

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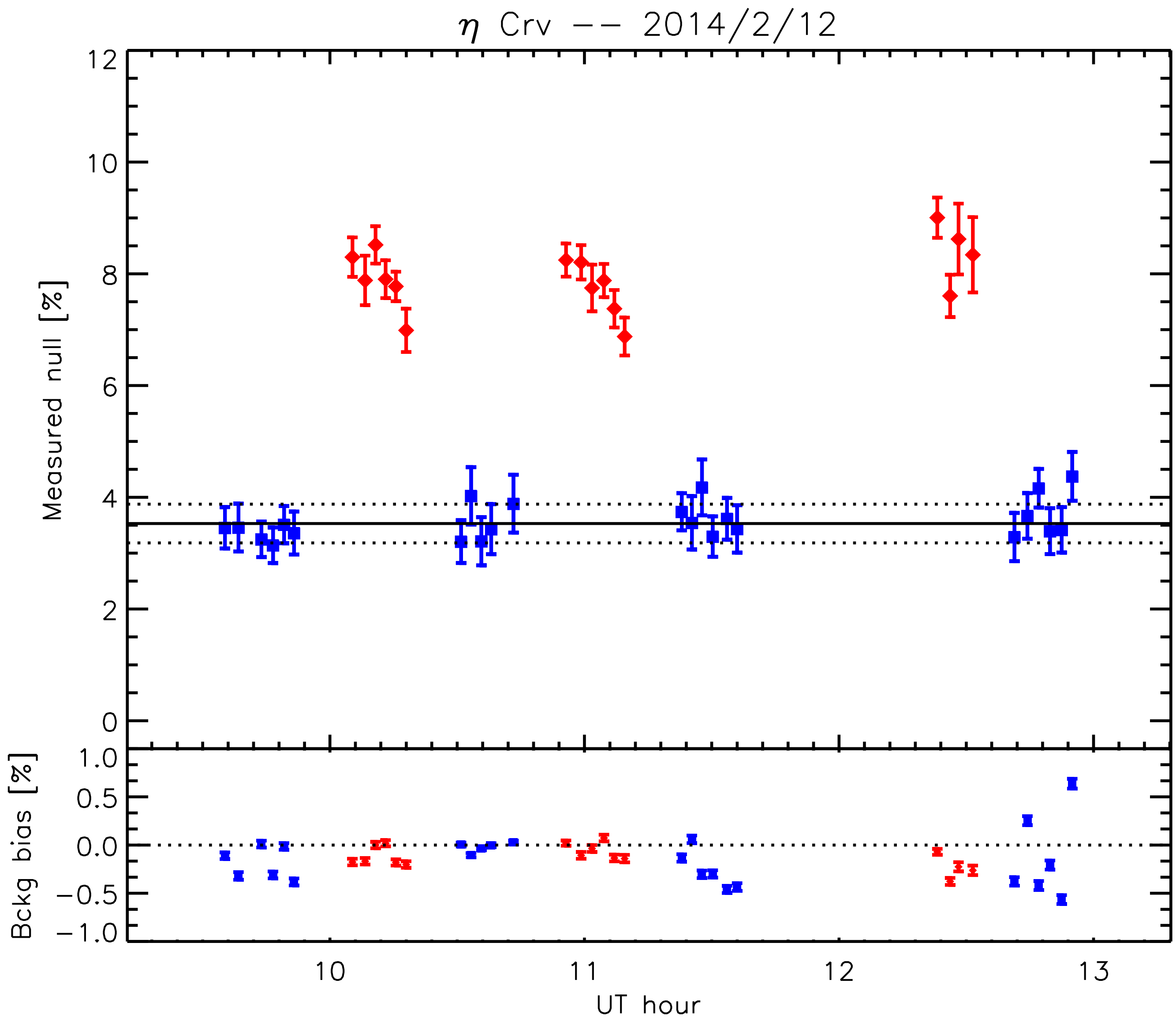
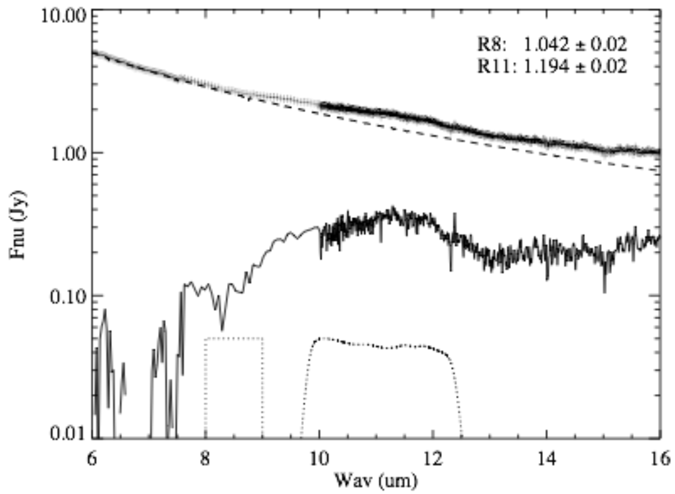


Defrère et al. 2015

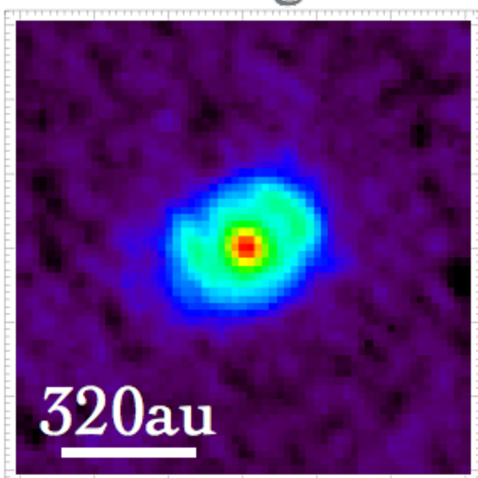
First-light results: η Crv (2014)

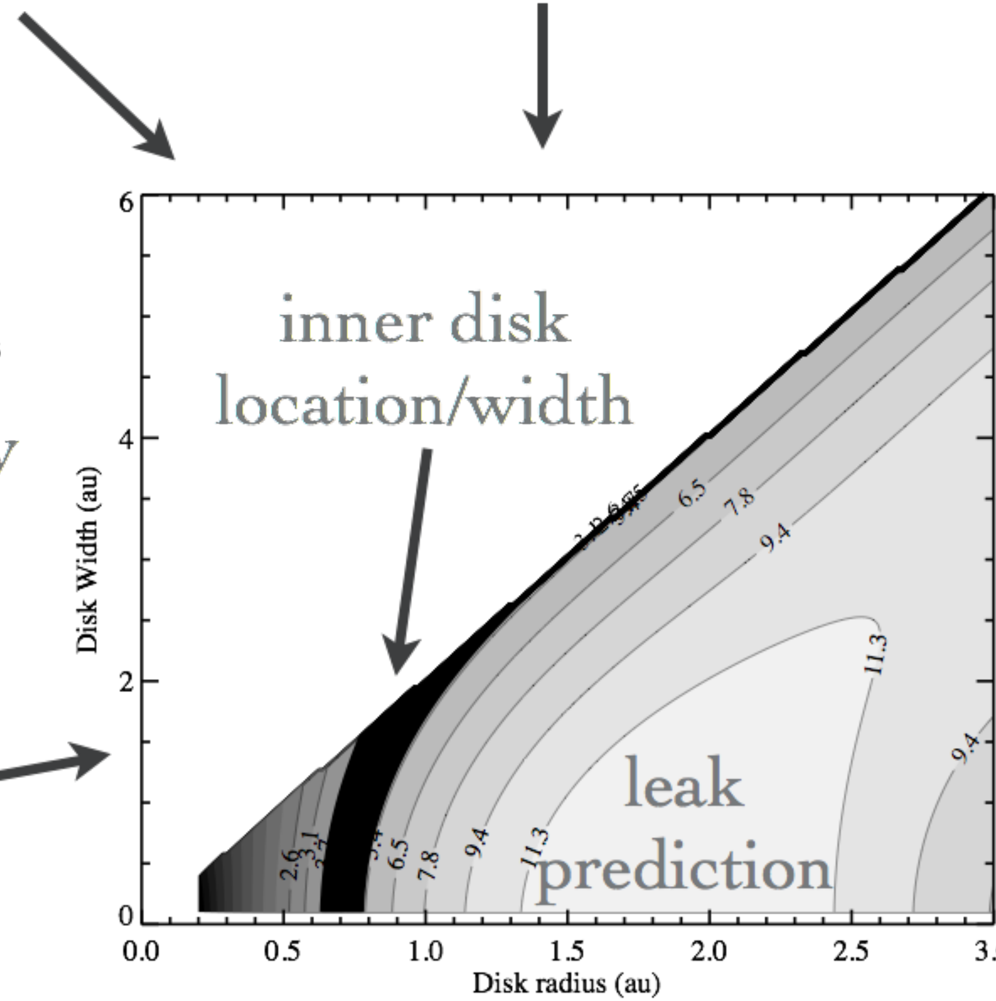
Disk/star flux ratio ~20%



4.5% LBTI leak

Outer disk geometry





Defrère et al. 2015

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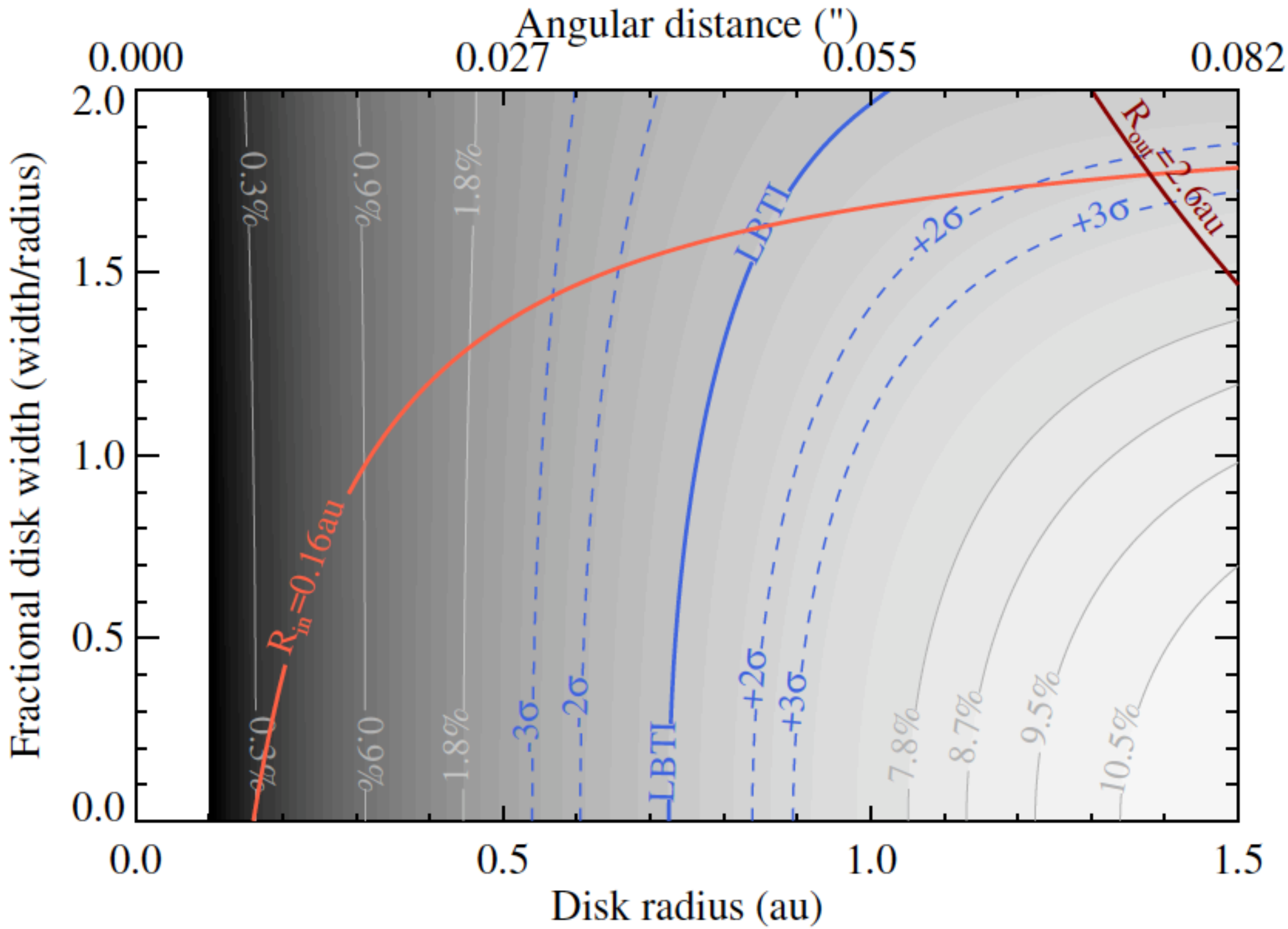
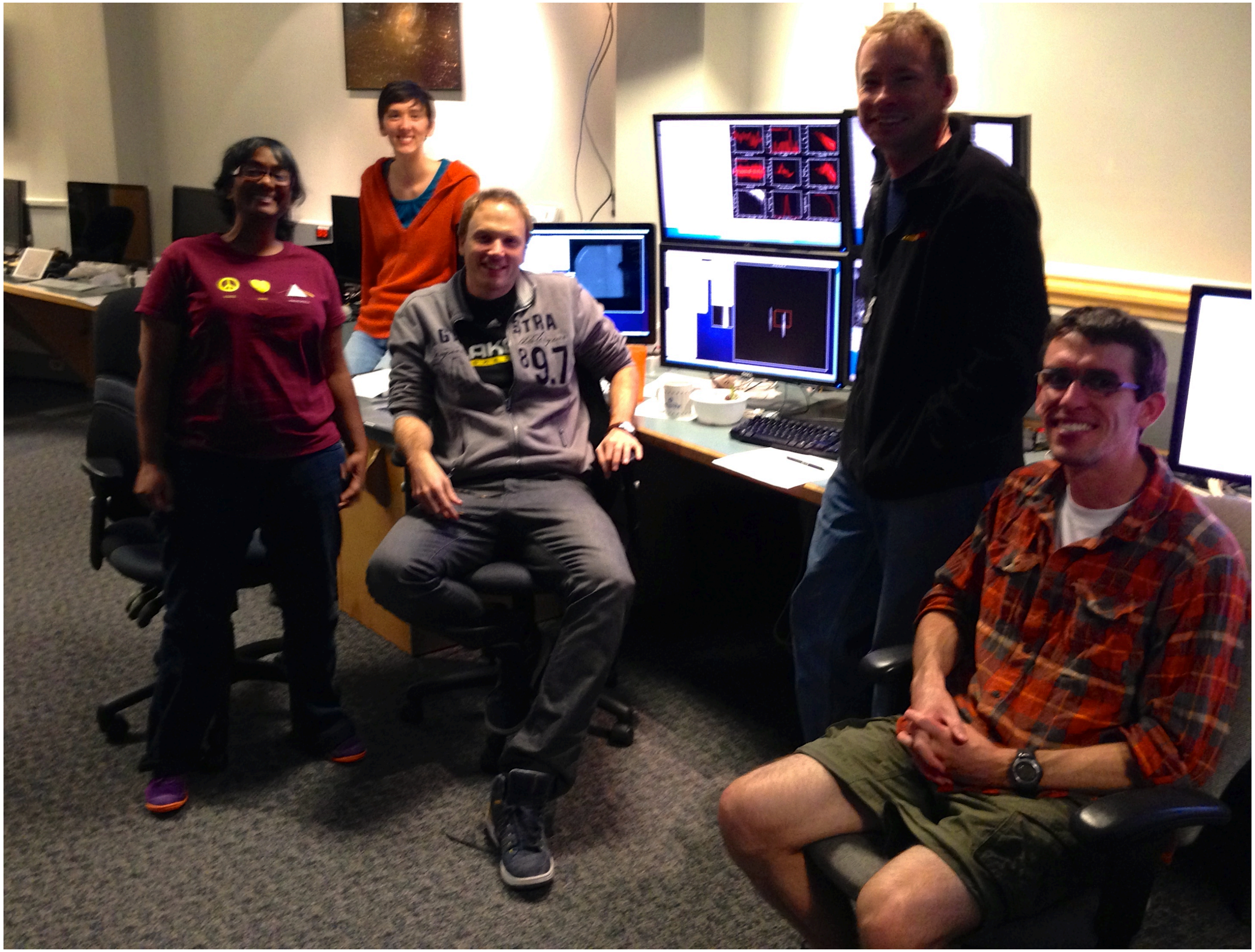


Defrère et al. 2015

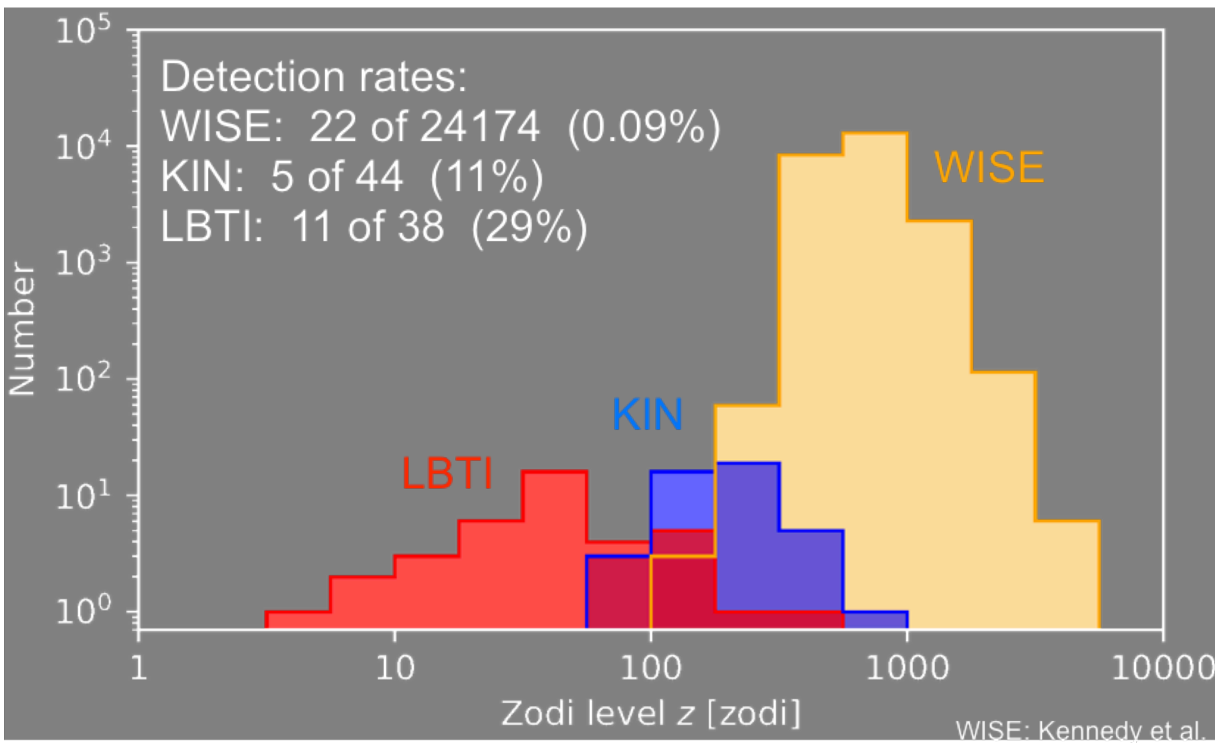
First observations with closed phase loop



From presentation at internal symposium **2014**

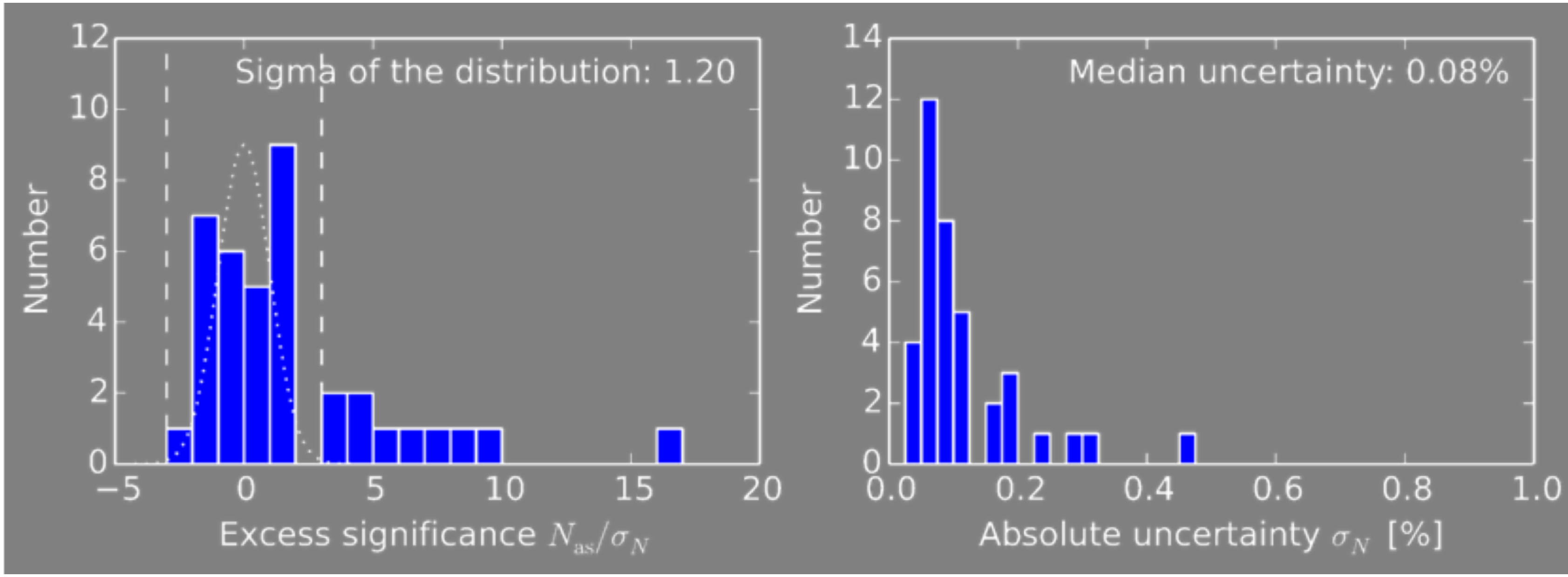
HOSTS survey results

- Hunt for Observable Signatures of Terrestrial planetary Systems
- NASA funded, managed by JPL: build the LBTI, execute survey
- Carried out at 11 microns (N band)
- Most sensitive exozodi survey!
- 38 stars observed, 11 detections



WISE: Kennedy et al. (2013)
KIN: Mennesson et al. (2014)
LBTI: Ertel et al. (2018)

HOSTS survey results



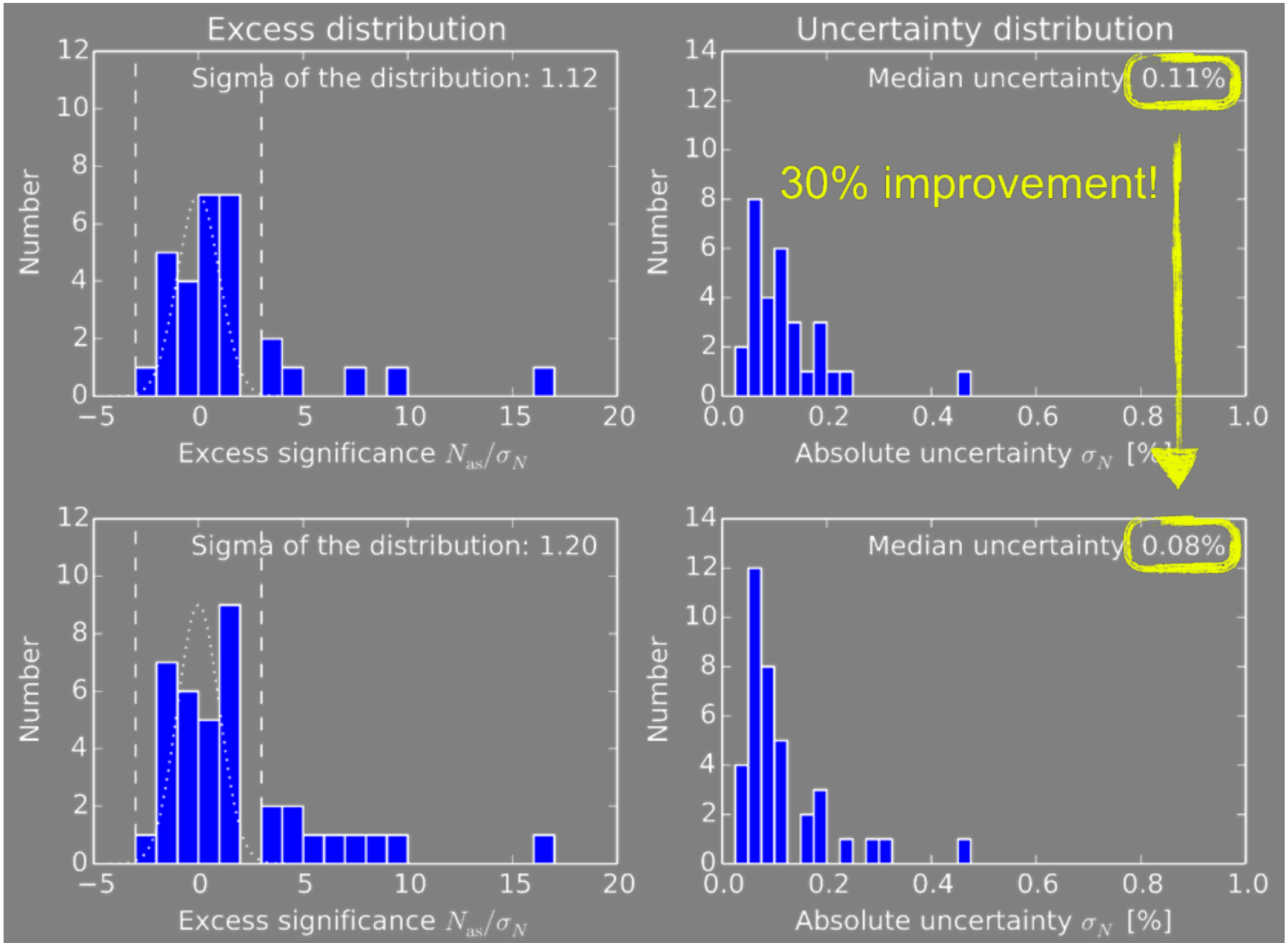
Ertel et al. (2018)

- Measurements & errors well behaved
- 8 new detections (+3 KIN excesses confirmed at high SNR)

HOSTS survey results

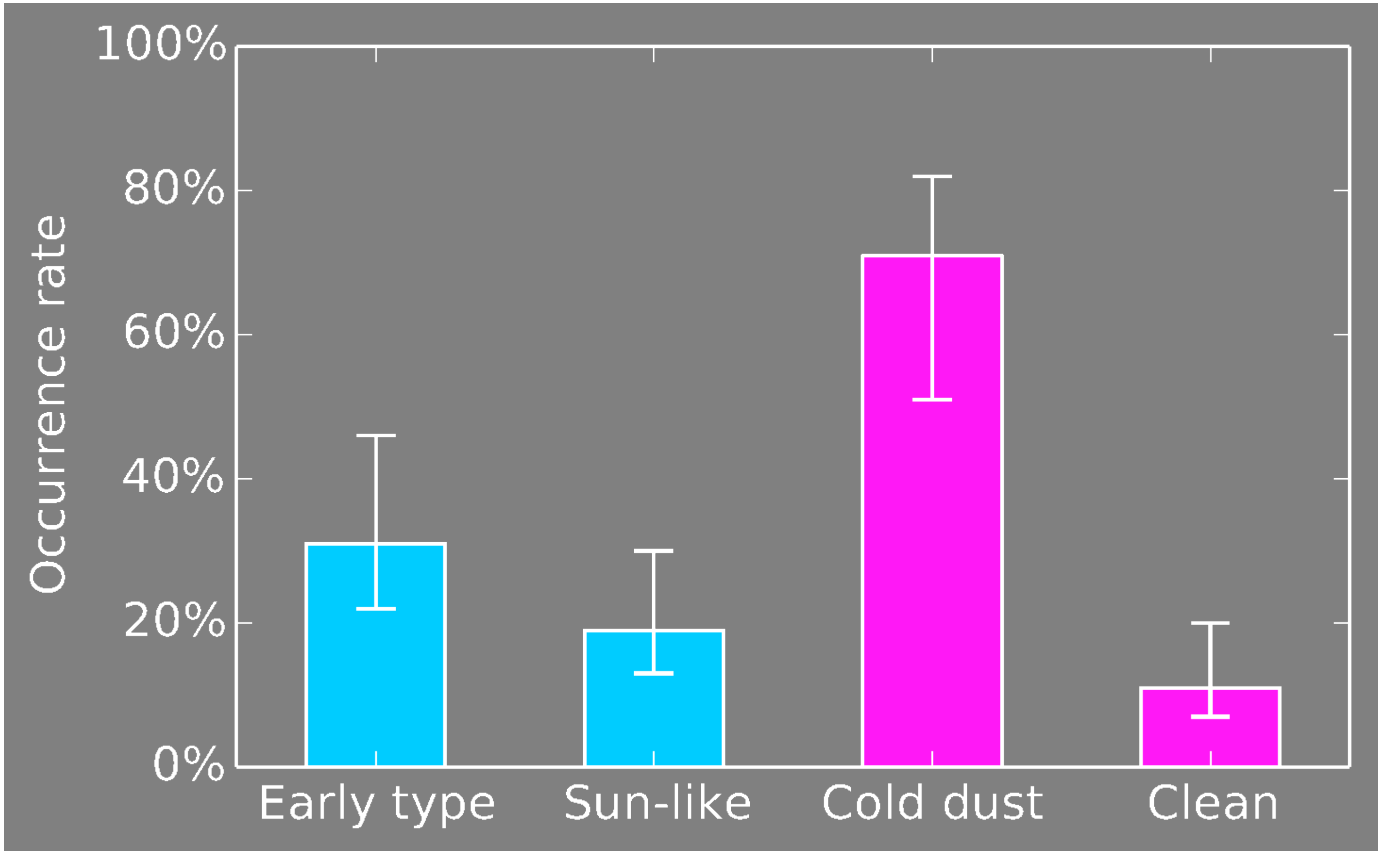
Interim paper

Final survey



HOSTS survey results

Ertel et al. in prep

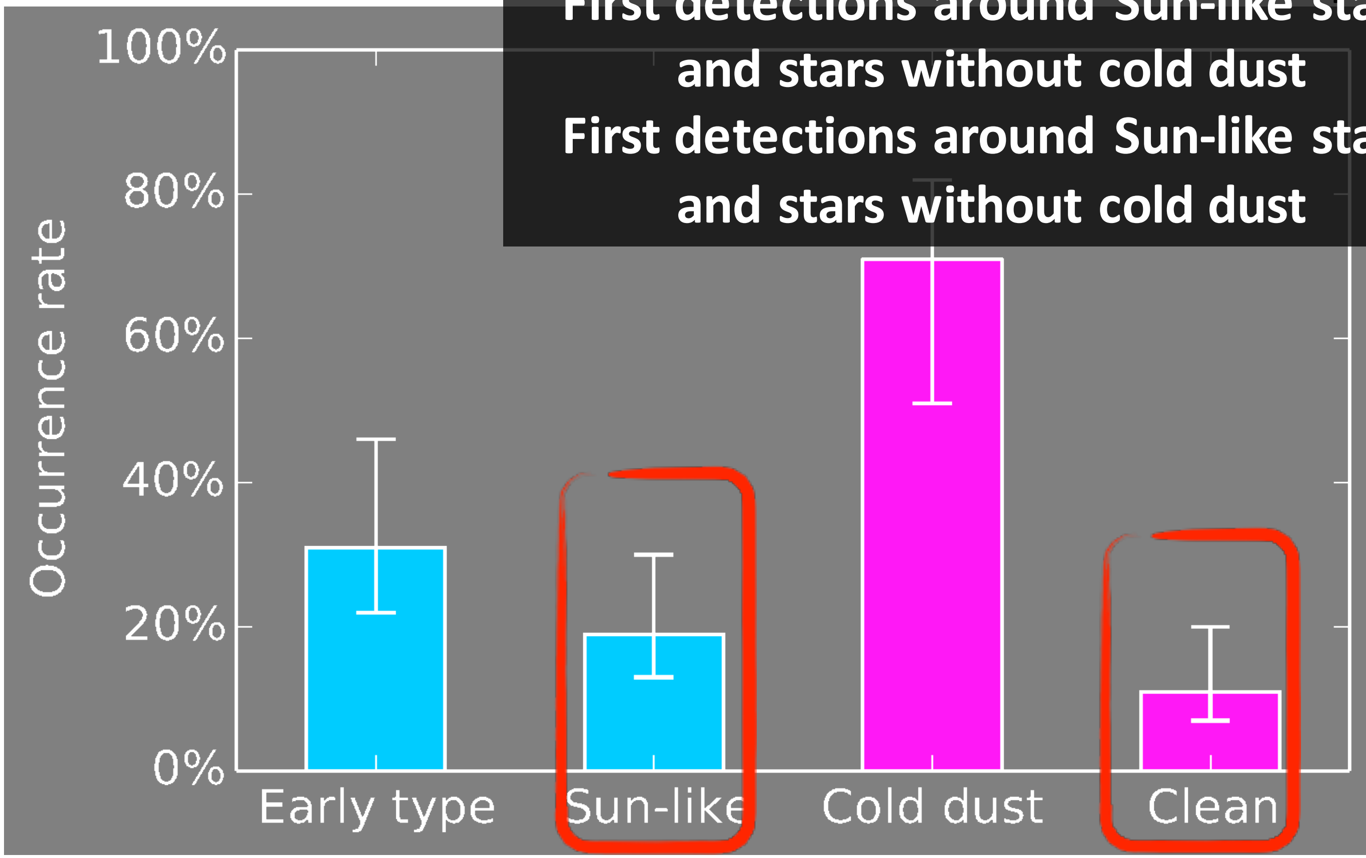


- Probability that stars **with and without cold dust** have the **same occurrence rate: $p = 0.003$**
- Similar incidence rate for **Sun-like and early type stars** comes at **~4x lower sensitivity around Sun-like stars**

HOSTS survey results

Ertel et al. in prep

First detections around Sun-like stars and stars without cold dust
First detections around Sun-like stars and stars without cold dust



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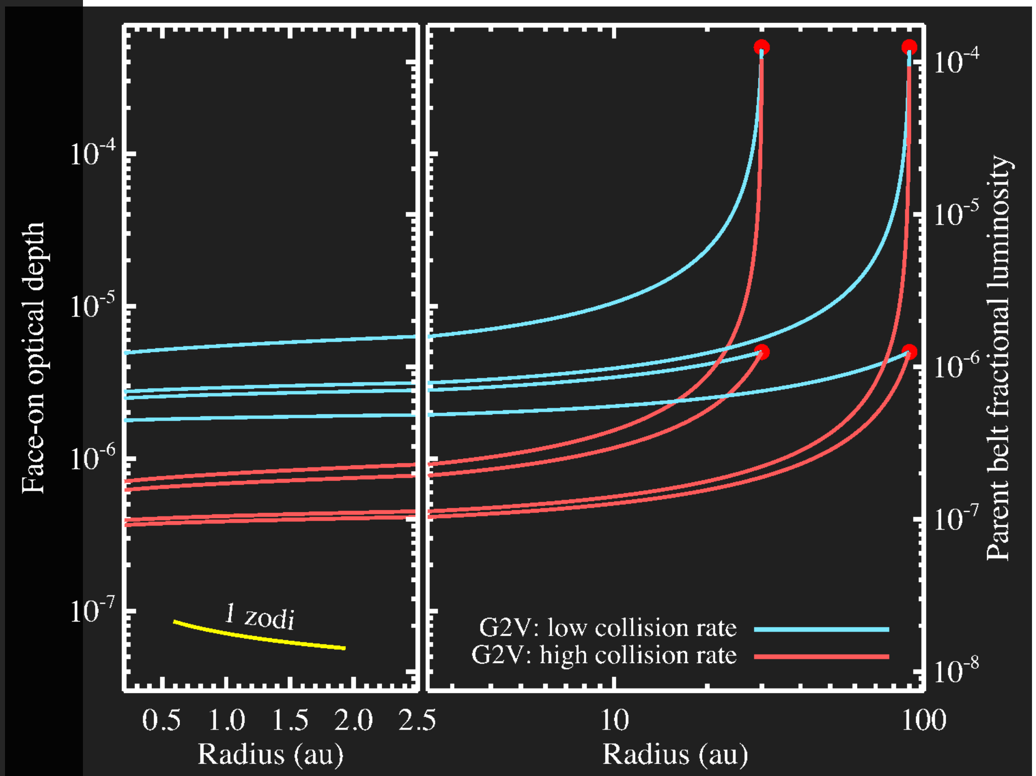
HOSTS survey results

Poynting-Robertson drag from outside



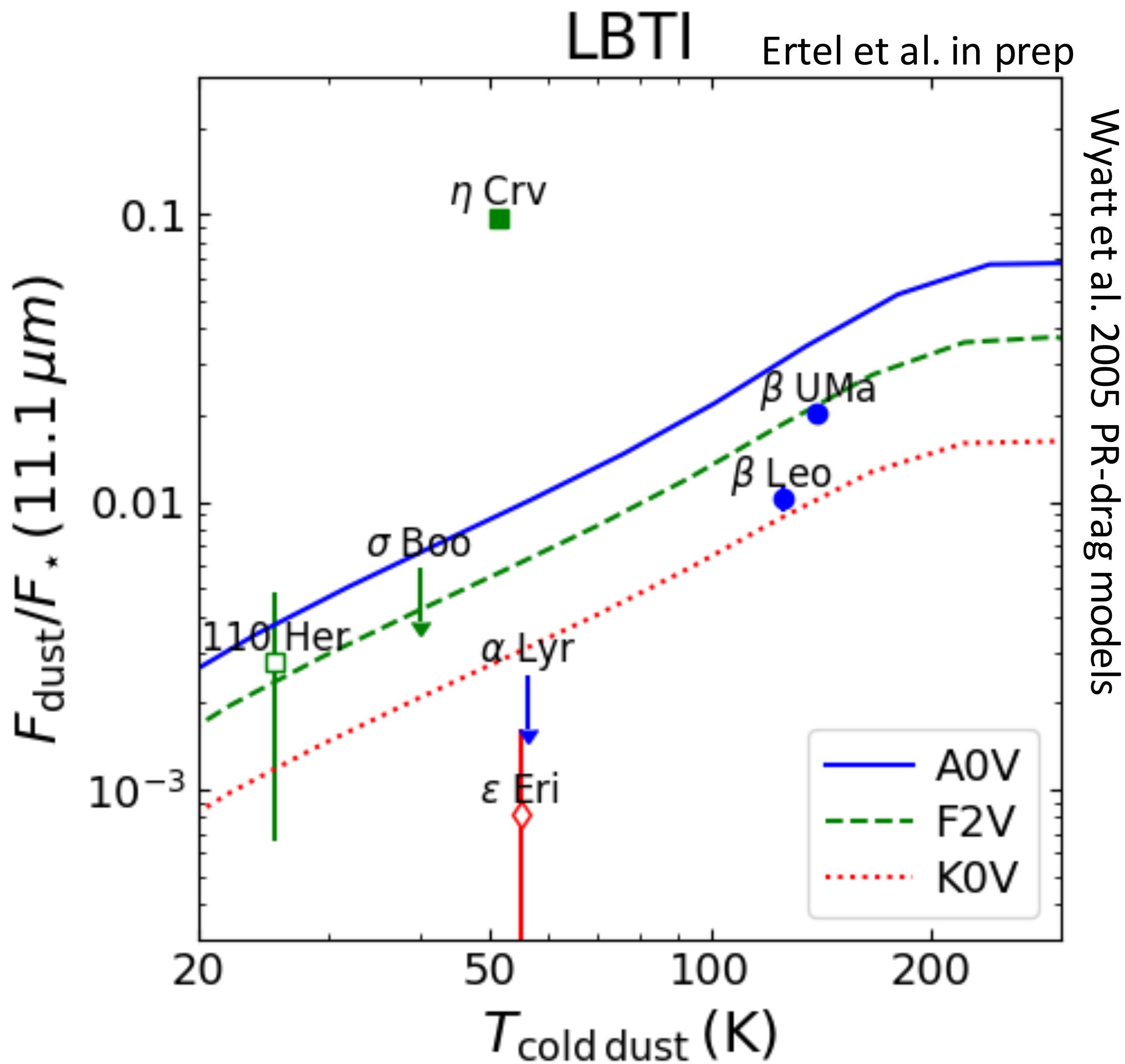
Kennedy & Piette (2015)

- Offers sufficient explanation
  (Kennedy & Piette, 2015)
- Confirmed in detailed modeling
  (β Leo, Hinz et al., in prep.)
- Some (extreme) systems need other explanation
  (e.g., η Crv, Defrère et al. 2015)
- Also works for faint outer belts?

Still, better understanding is critical:

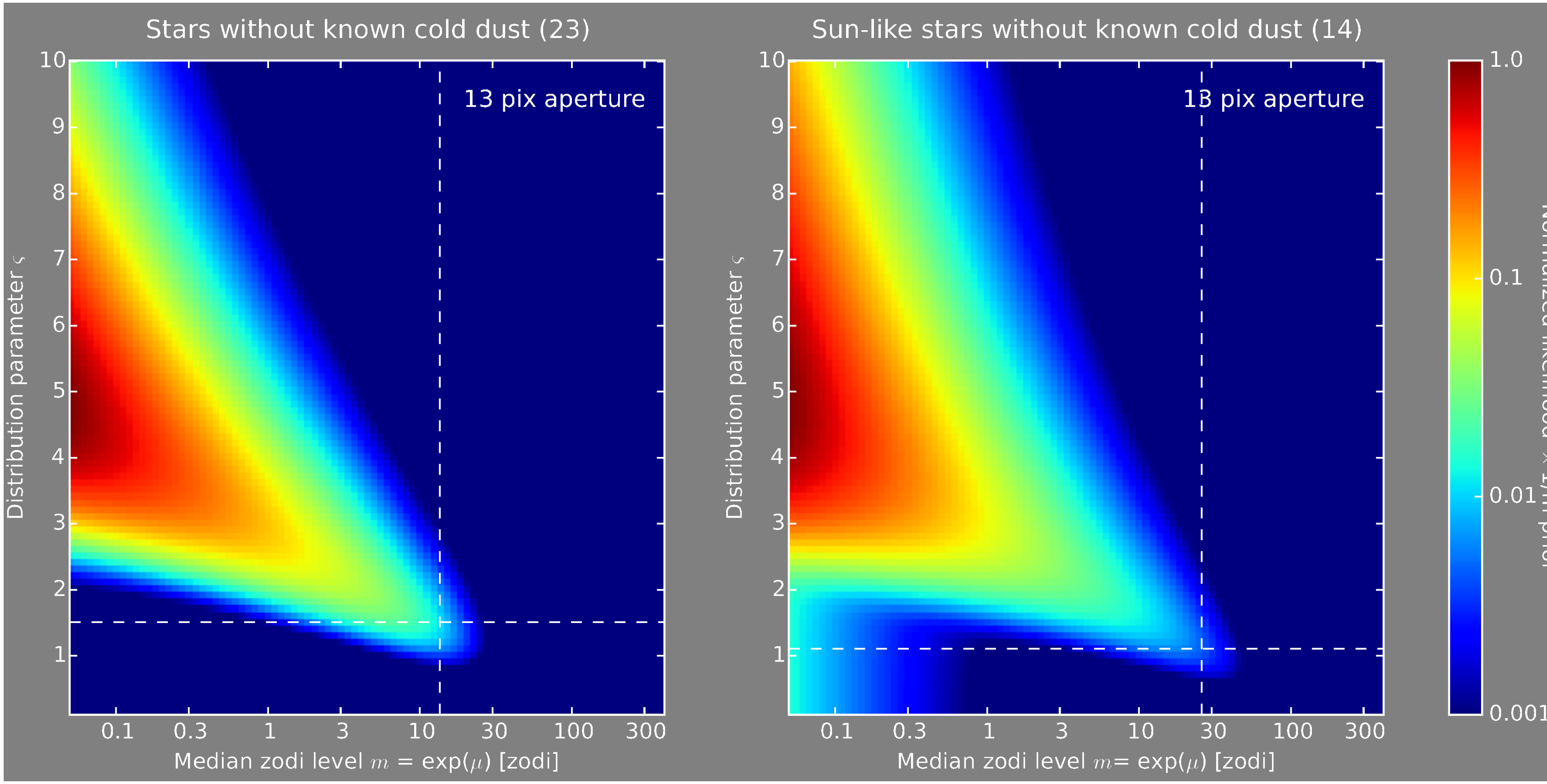
- Where is the source (Kuiper belts vs. Asteroid belts)?
- Contribution from other mechanisms, like comet evaporation?

HOSTS survey results



Median zodi level

Ertel et al. (2018)



Upper limits on median zodi level on stars without cold dust (95% confidence, assuming lognormal distribution):

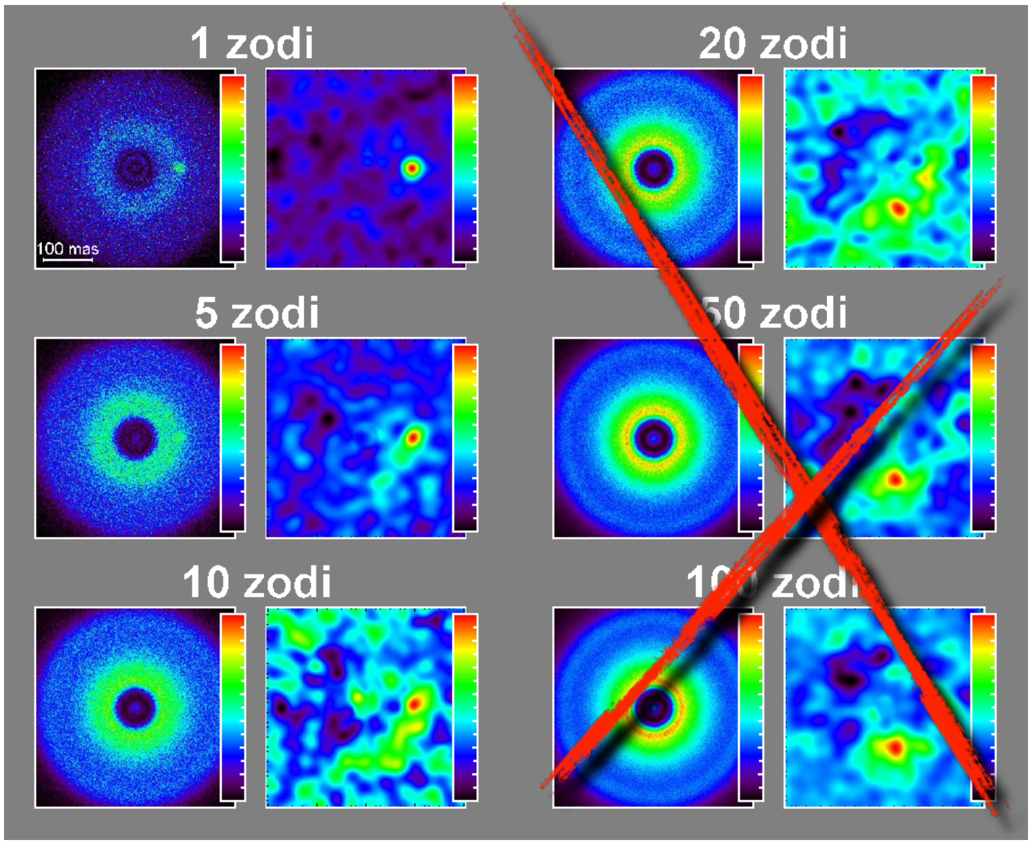
- 12 zodis for all clean stars!

Median zodi level

Upper limits on median zodi level
(95% confidence, assuming lognormal distribution):

- 12 zodis for all stars
- 16 zodis for Sun-like stars

For stars without known cold dust



Exo-Earth imaging generally possible!

Main conclusions from HOSTS

- HOSTS survey completed (38 total stars observed, Ertel et al. in prep)
- Many papers to write on existing HOSTS data!
- Exozodi delivered from outer Kuiper/Asteroid belt by **PR drag**
- Upper limit on median exozodi level 12 zodi
- Exo-Earth imaging generally possible!

Talk overview

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HOSTS prospects

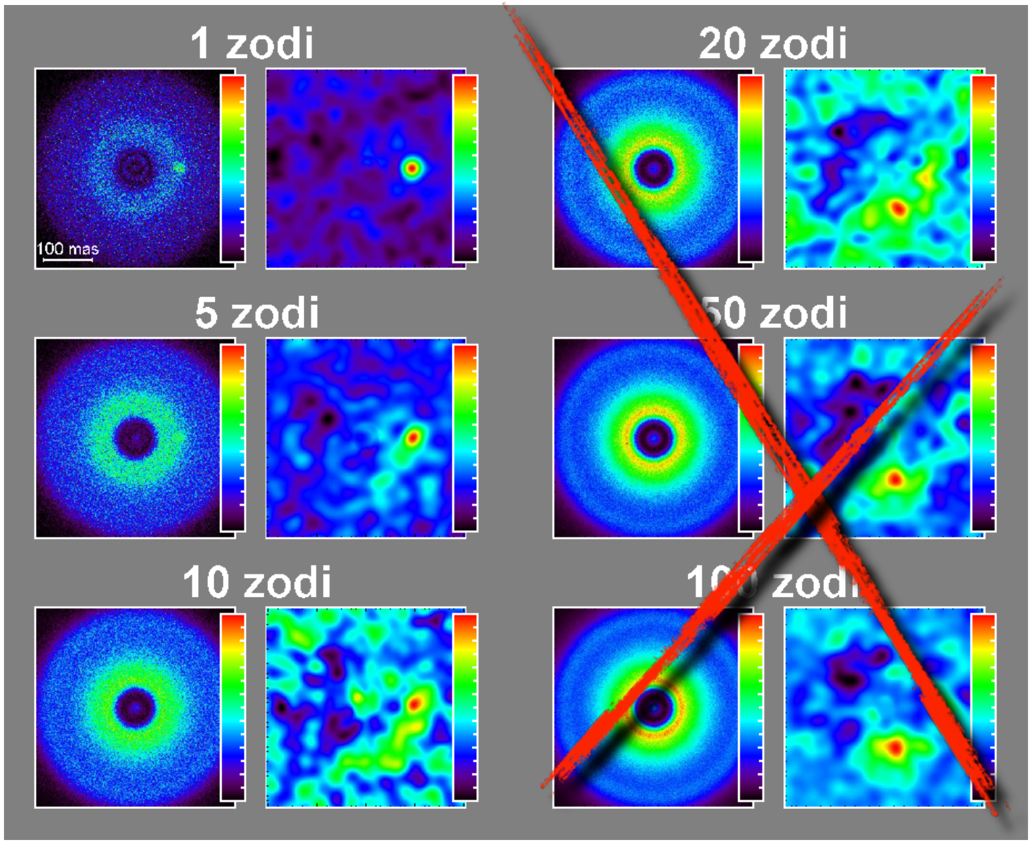
- More observations required:
  - Characterize detected systems (disk geometry, different P.A. and wavelength)
  - Exozodi still major uncertainty in exoplanet yield predictions
  - Some high priority targets (i.e. nearest stars) not observed during baseline survey
  - To tie the phenomenon of zodiacal dust to physical models and proxy markers

- System performance and robustness will improve in the future:
  - Better AO (fainter and more southern stars accessible)
  - New detector (better sensitivity),
  - New optimized data acquisition approach (better sensitivity)

Target vetting for exo-Earth imaging

Upper limits on median zodi level
(95% confidence, assuming lognormal distribution):

- 11.5 zodis for all stars
- 16 zodis for Sun-like stars
- 7.5 for Sun-like stars without LBTI detection!



Still for stars without known cold dust

Exo-Earth imaging generally possible!

Target vetting for exo-Earth imaging

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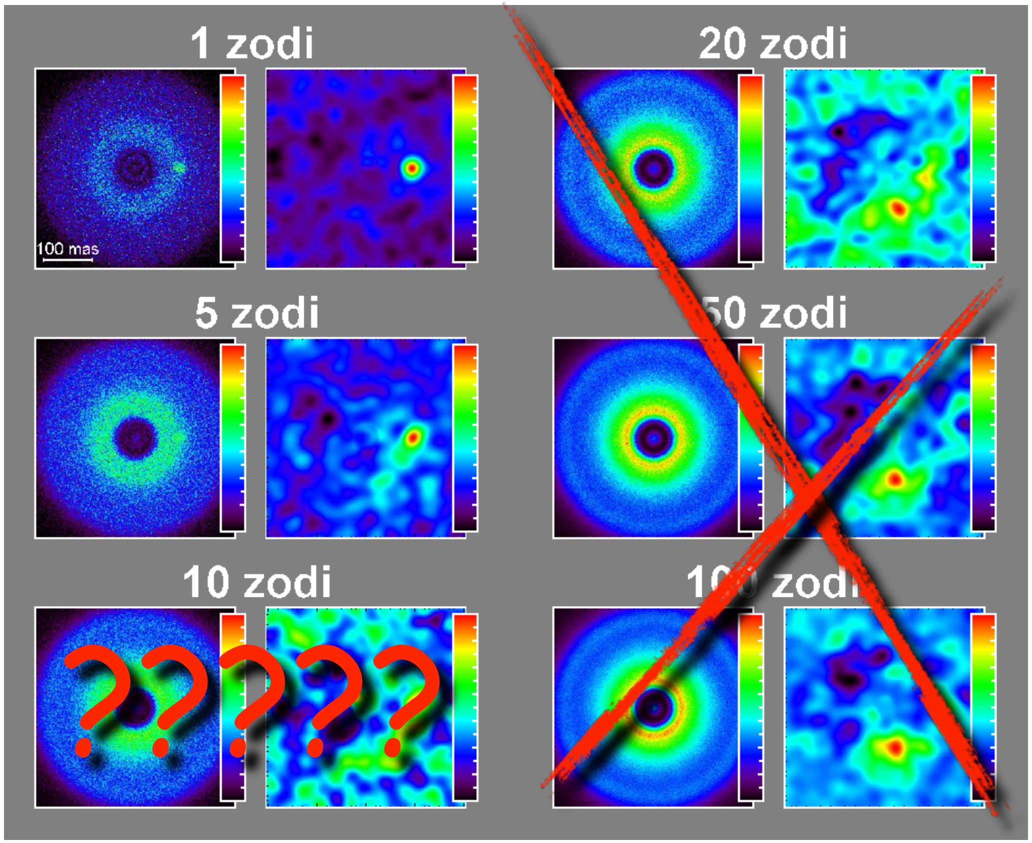
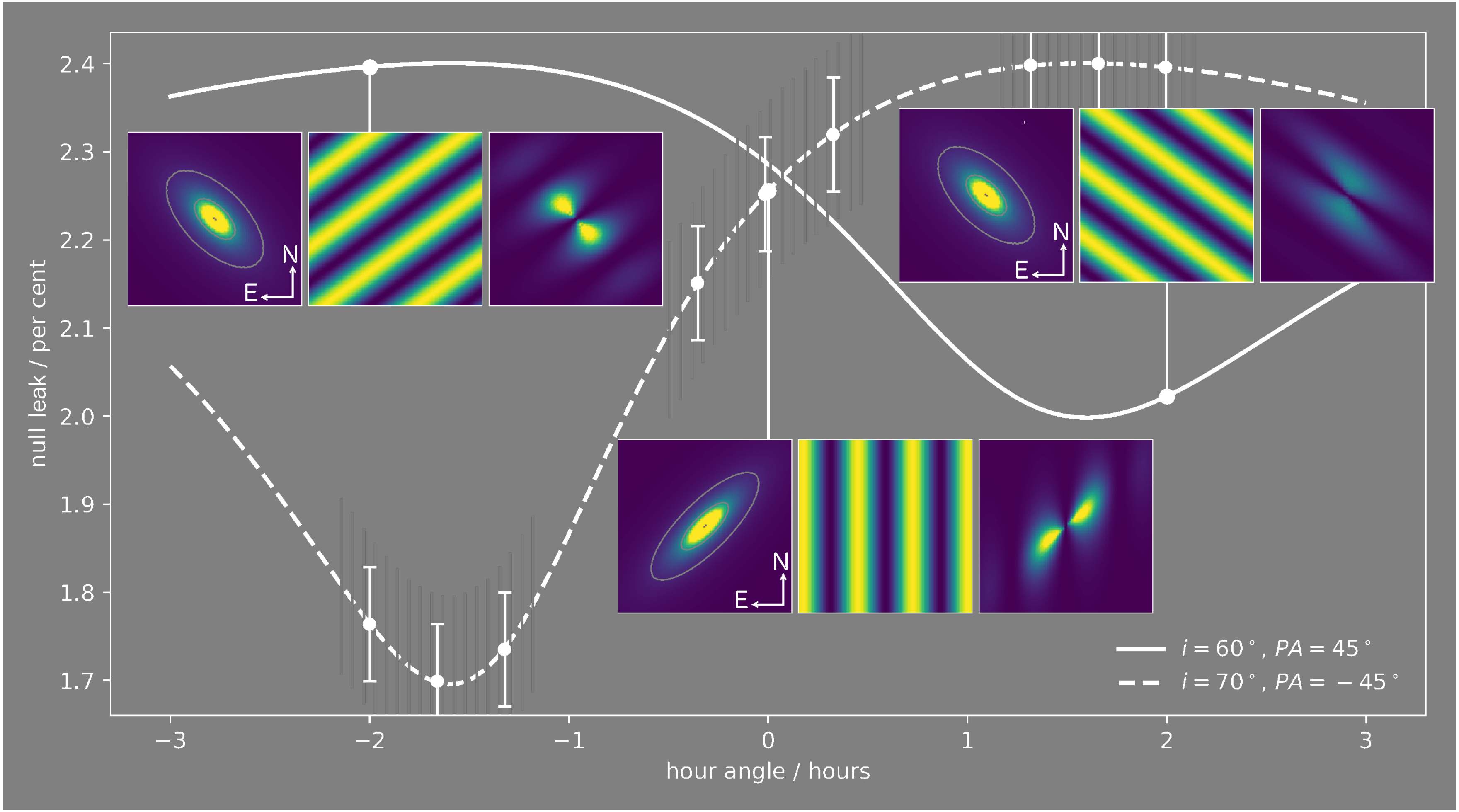
- 7.5 for Sun-like stars without LBTI detection!



Still for stars without known cold dust

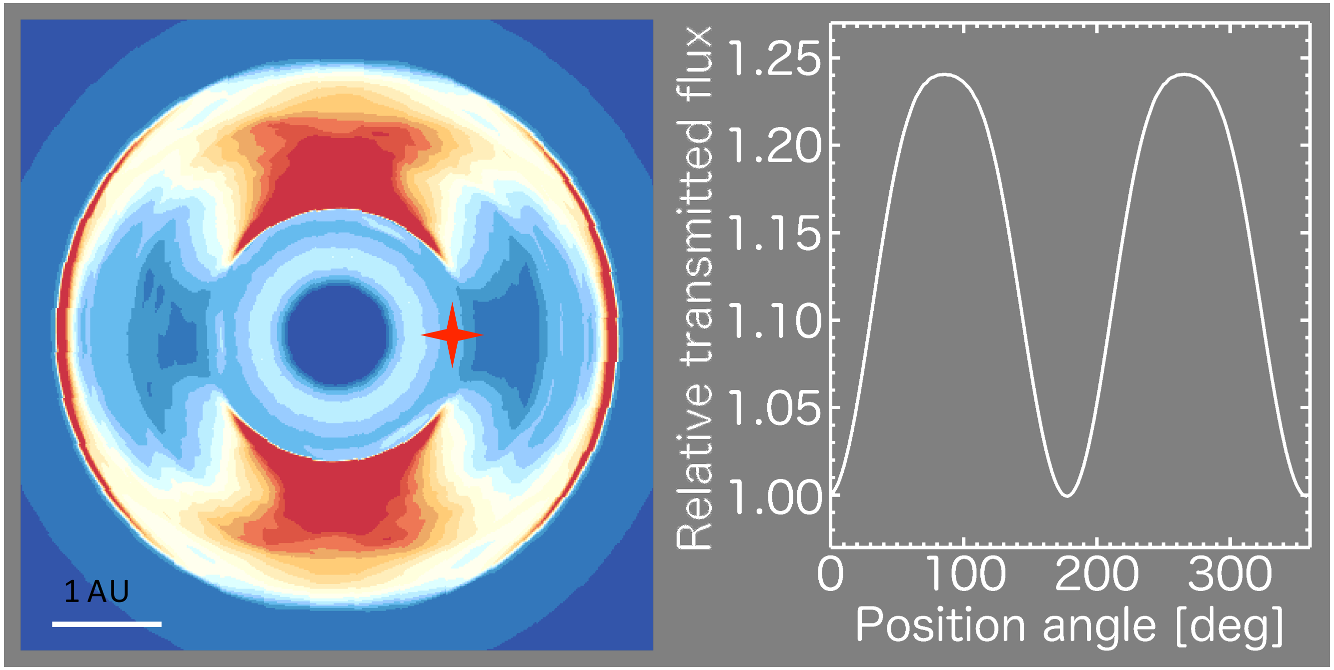
Exo-Earth imaging generally possible!

Characterization of detected systems



Disk geometry and exact excess from field rotation

Characterization of detected systems

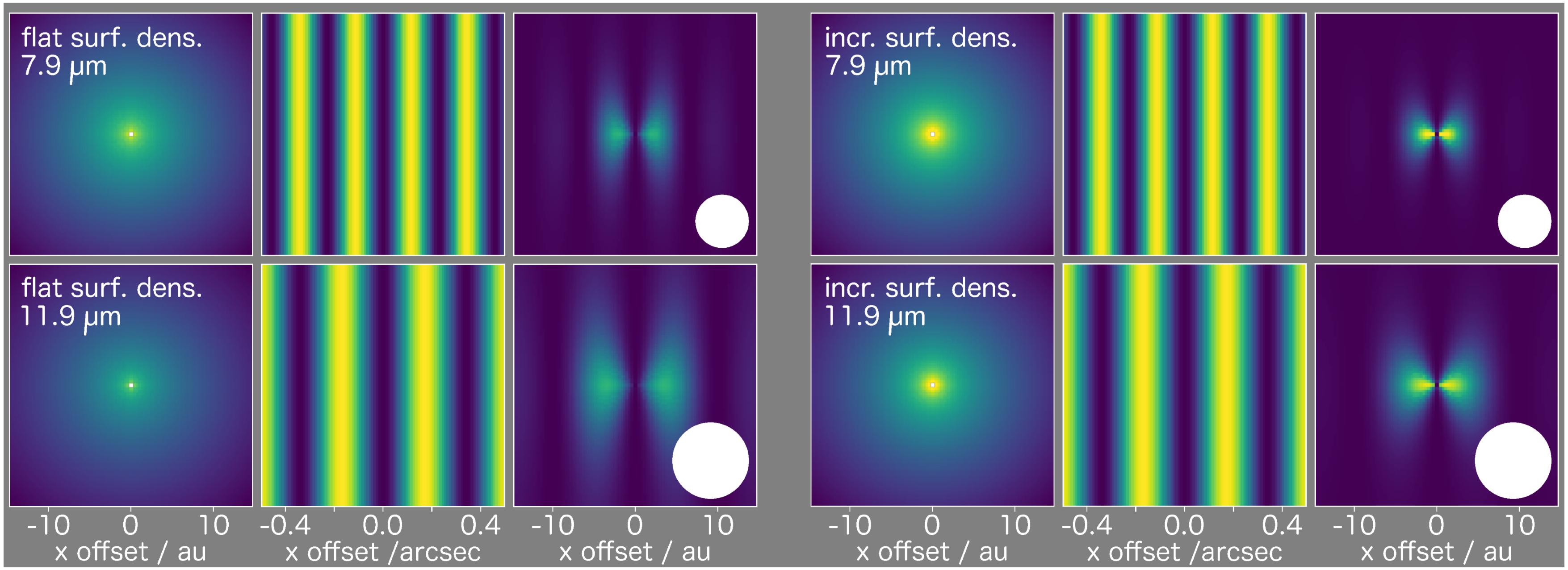


20 MEarth, 1 AU, Sun-like star @ 10pc
following Shannon et al. (2015) & Kennedy et al. (2015)

- Search for & characterize structures in dust distribution due to planets
- Rotate on time scale of planetary orbit
- Characterize architectures of habitable zones (presence of planets, mass, orbits)

(e.g., Ertel et al. 2012, Shannon et al. 2015, Bonsor et al. in prep.)

Characterization of detected systems



- Multi-wavelength data trace spectral shape of the emission (grain size) and radial dust distribution
- Constrain dust properties and origin
- Better predict scattered light brightness

Talk overview

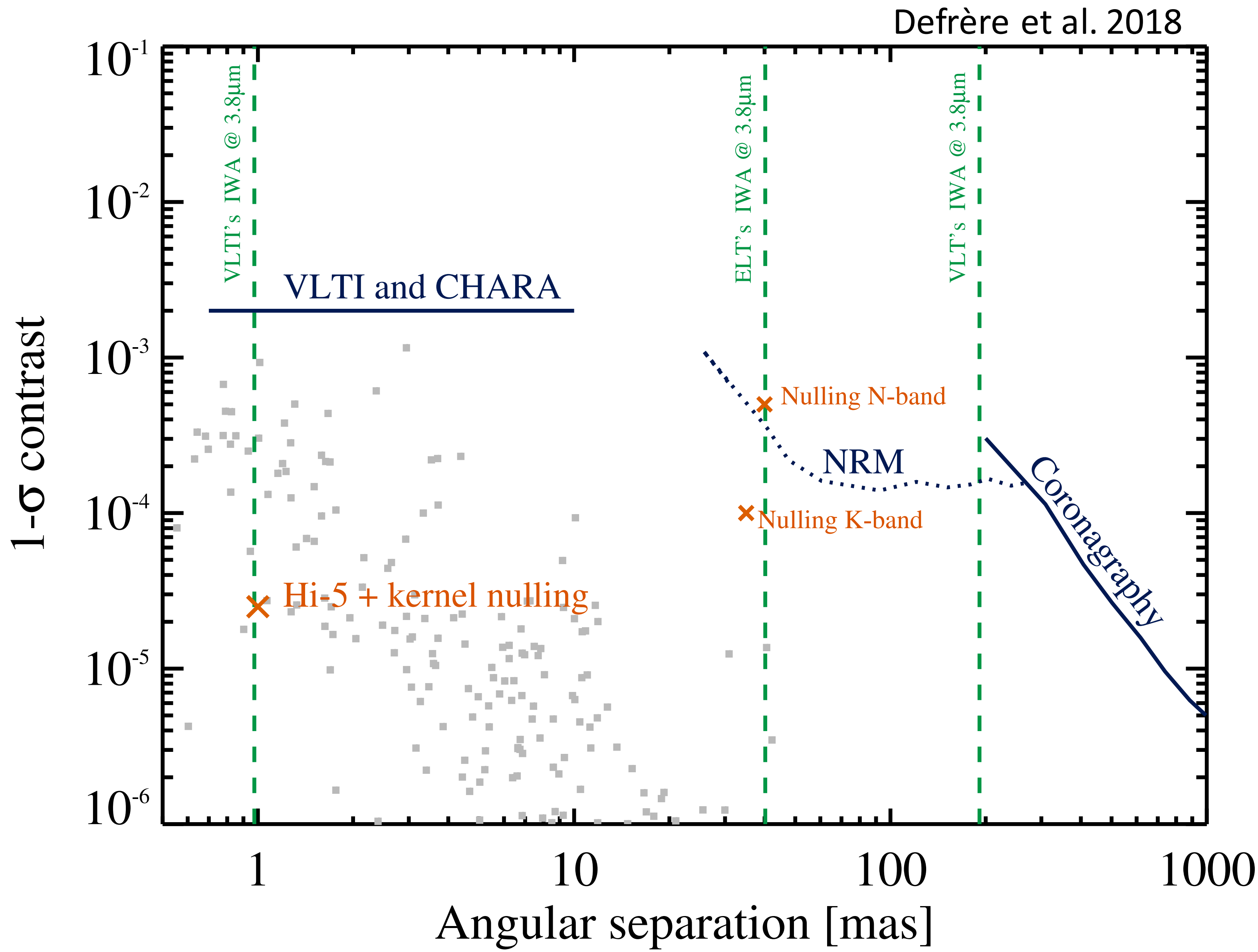
1. What is an exozodi? Why do we care?
2. What do we know?
3. The HOSTS survey
4. Beyond the HOSTS survey

Hi-5: a potential high-contrast thermal near-infrared imager for the VLTI

D. Defrère , M. Ireland
University of Liège, Australian National University

<u>Hi-5 team</u>: Absil, O., Berger, J.-P., Boulet, T., Danchi, W. C., Ertel, S., Gallenne, A., Hénault, F., Hinz, P., Huby, E., Kraus, S., Labadie, L., Le Bouquin, J.-B., Martin, G., Matter, A., Mérand, A., Mennesson, B., Minardi, S., Monnier, J., Norris, B., Orban De Xivry, G., Pedretti, E., Pott, J.-U., Reggiani, M., Serabyn, E., Surdej, J., Tristram, K. R. W., and Woillez J.

High-contrast interferometry status



New project: Hi-5

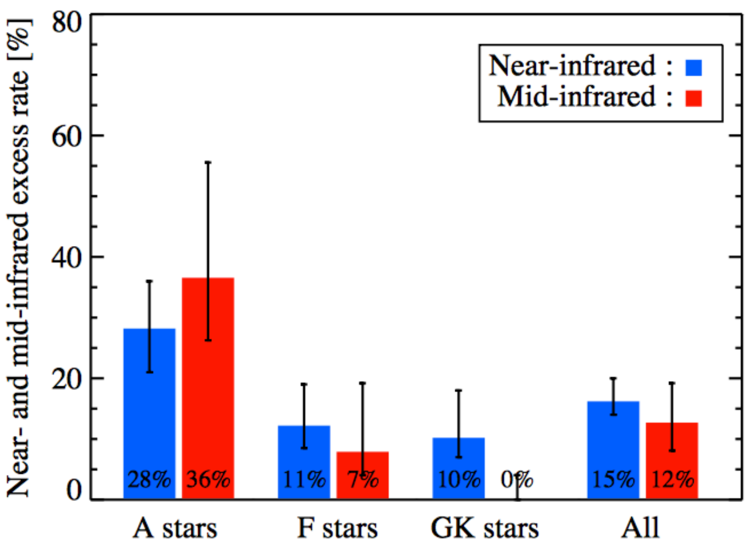
Hi-5
High-contrast Interferometry up to 5 microns

- L/M-band high-contrast interferometry on the VLTI (Defrère et al. 2018)
- Leverage the angular resolution of the VLTI and nulling interferometry
- EU-funded for a design study led by the University of Liege

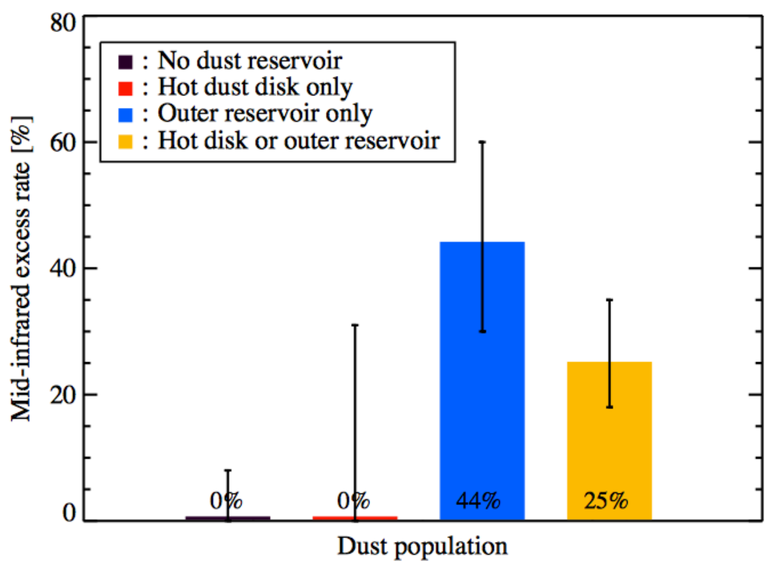
VLTI (Cerro Paranal, Chile)

Science case 1: exozodiacal disks

- Thermal near-IR = 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)



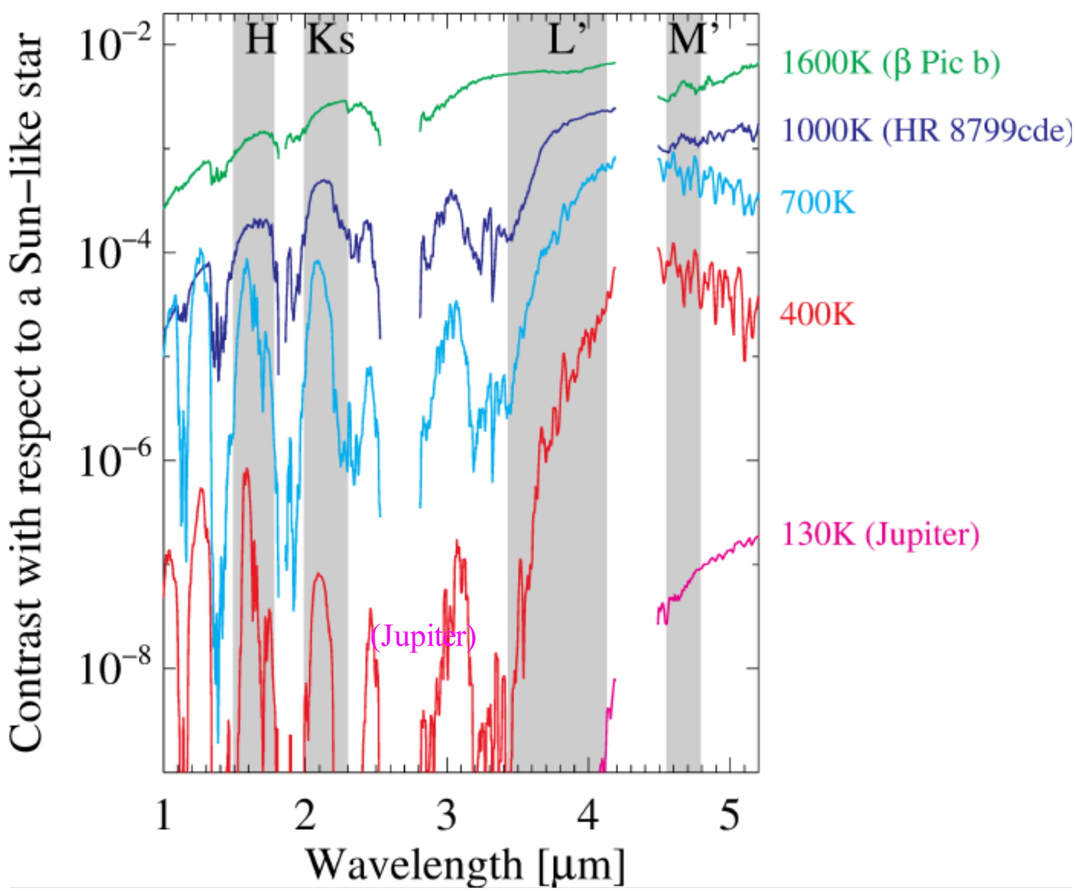
Kral et al. 2018



Science case 2: exoplanets

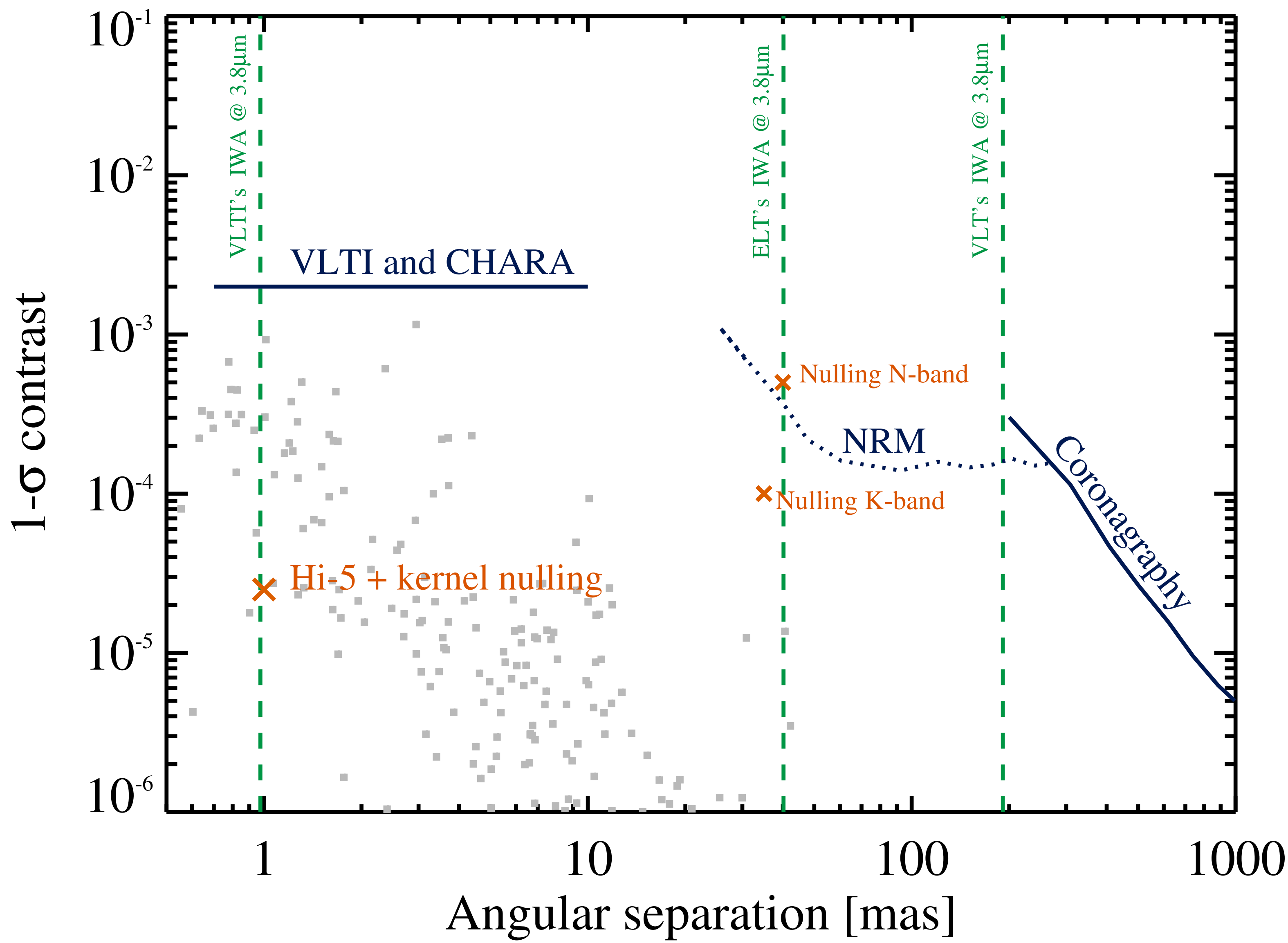
- L/M-band = sweet spot for direct exoplanet imaging
  - Favorable star/planet contrast
  - Access to planet radius and temperature
  - Molecular bands / nonequilibrium chemistry

Skemer et al. 2014



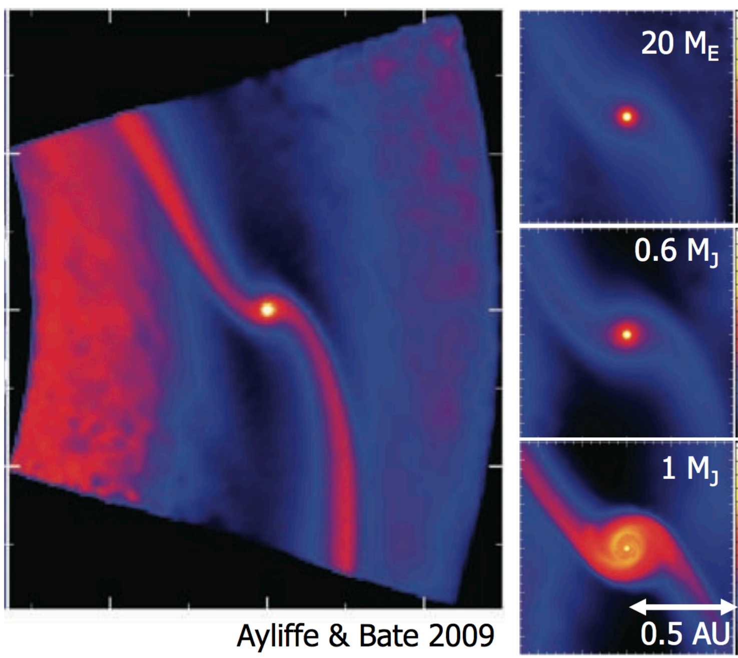
Hi-5

Science case 2: exoplanets

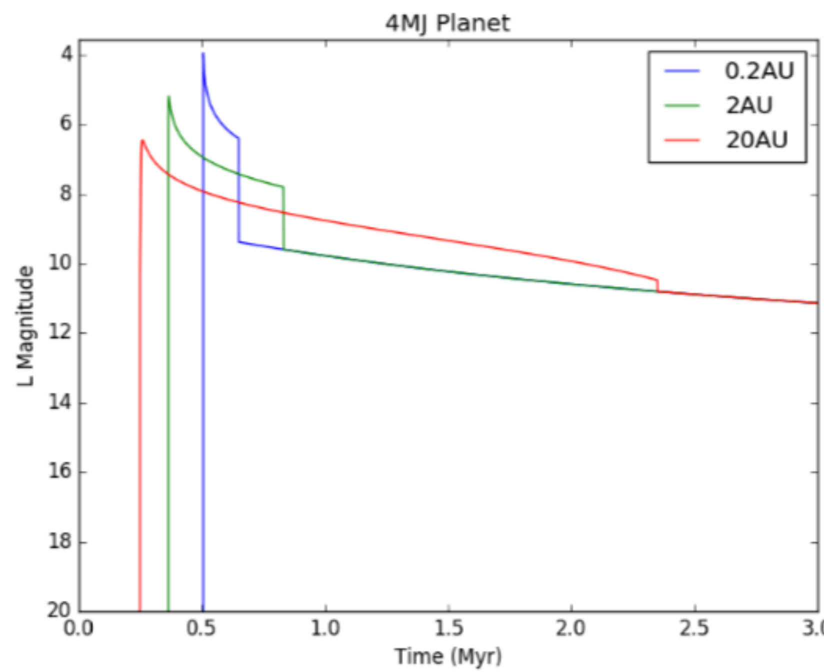


Science case 3: planet formation

- Imaging young stars in nearby star forming regions
  - Search for young, forming planets (e.g., explore the cavities of transitions disks)
  - Need good imaging capabilities in addition to high contrast
  - Prepare for PFI science

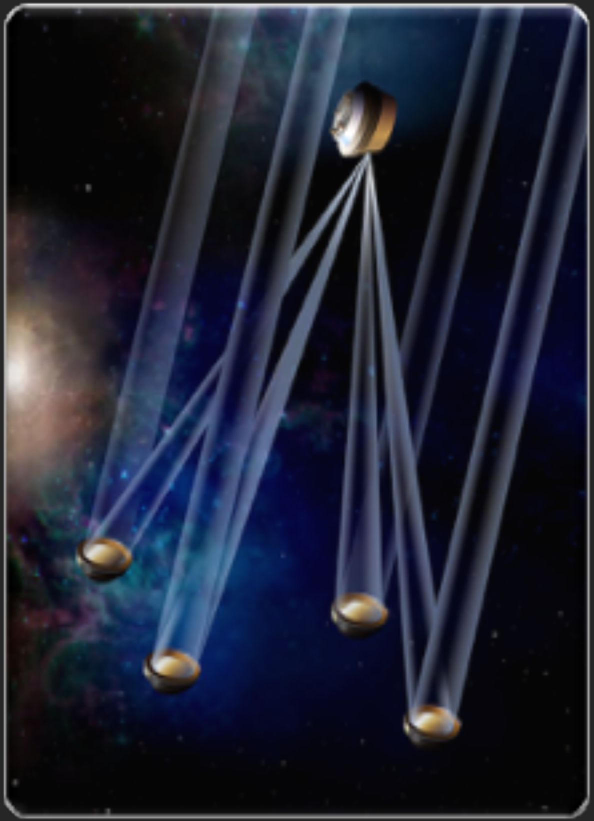


Ayliffe & Bate 2009

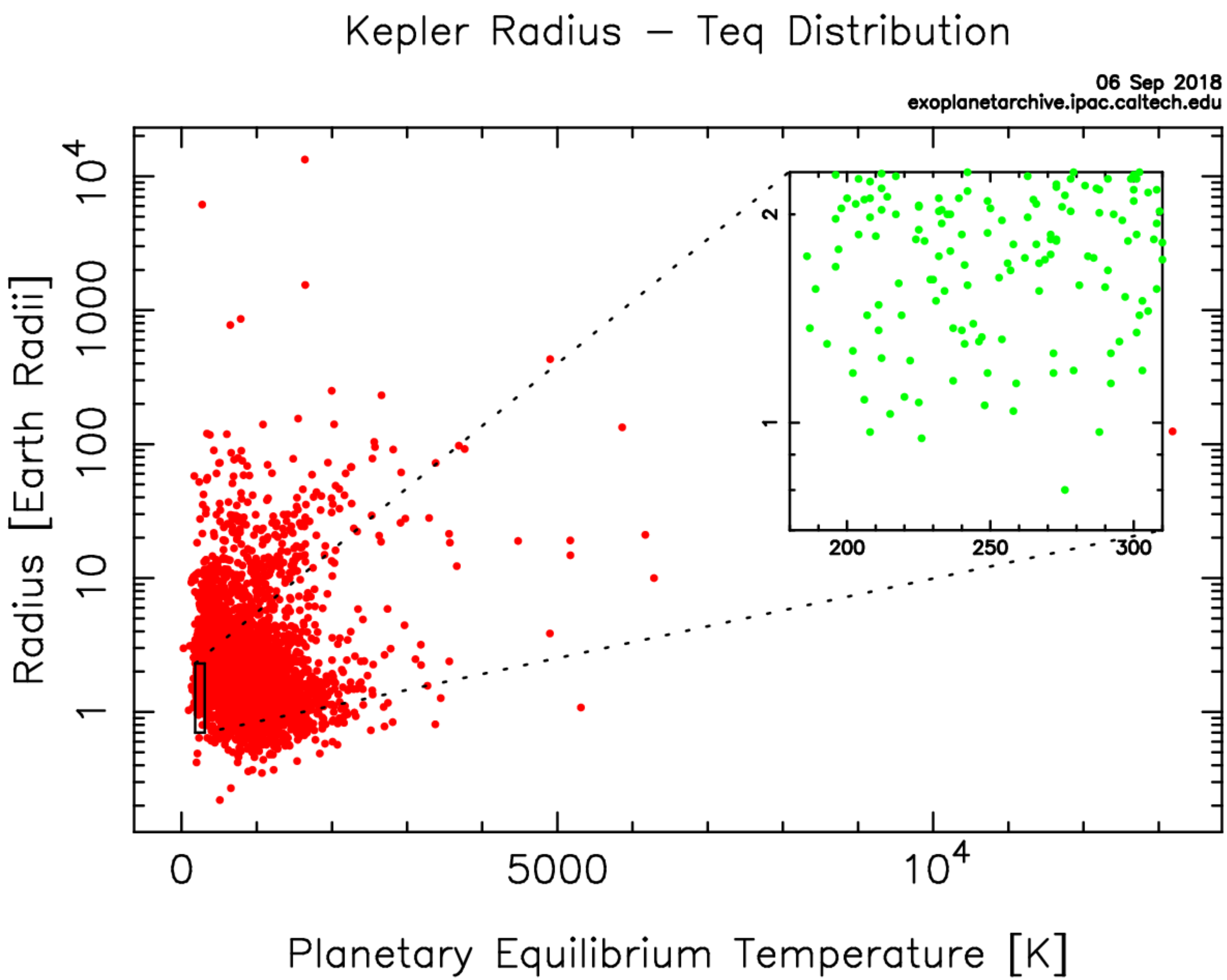


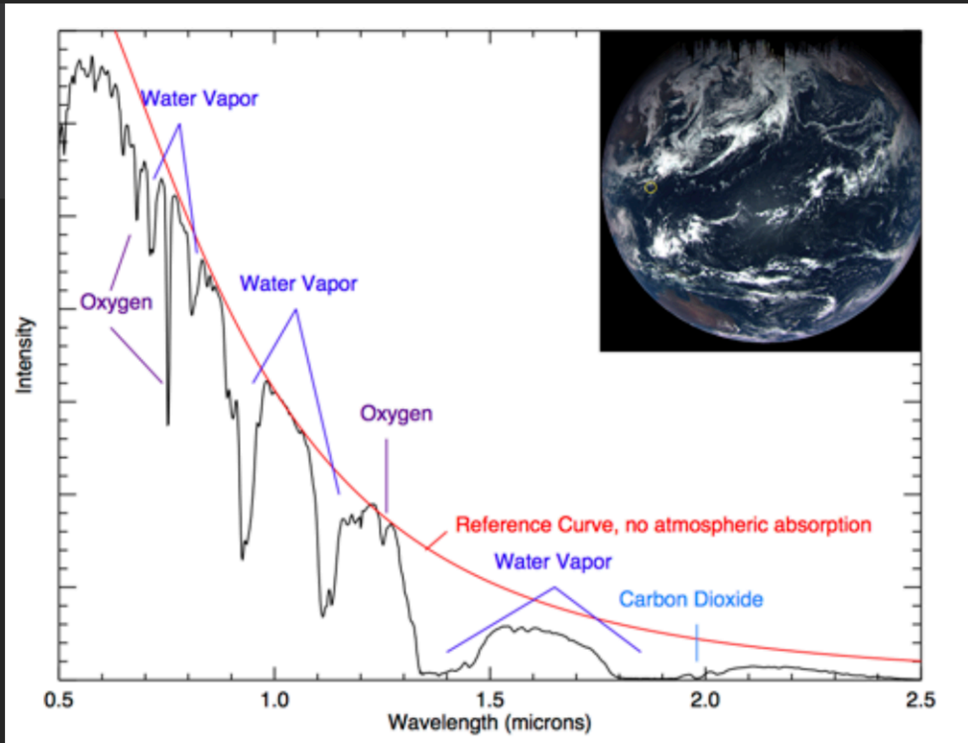
Wallace (in prep)

Revival of space interferometry in Europe



Temperate Rocky planets are ubiquitous



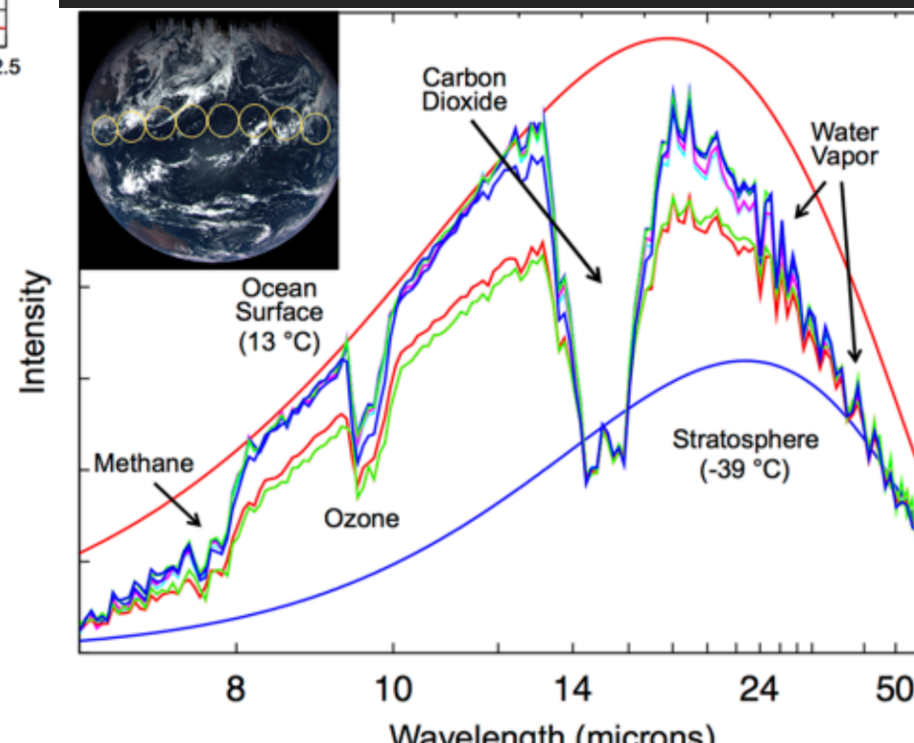


OSIRIS-Rex **optical** spectrum

- Evidence of gas-phase H_2O over the entire planet.
- Substantial concentration of O_2

OSIRIS-Rex **infrared** spectrum

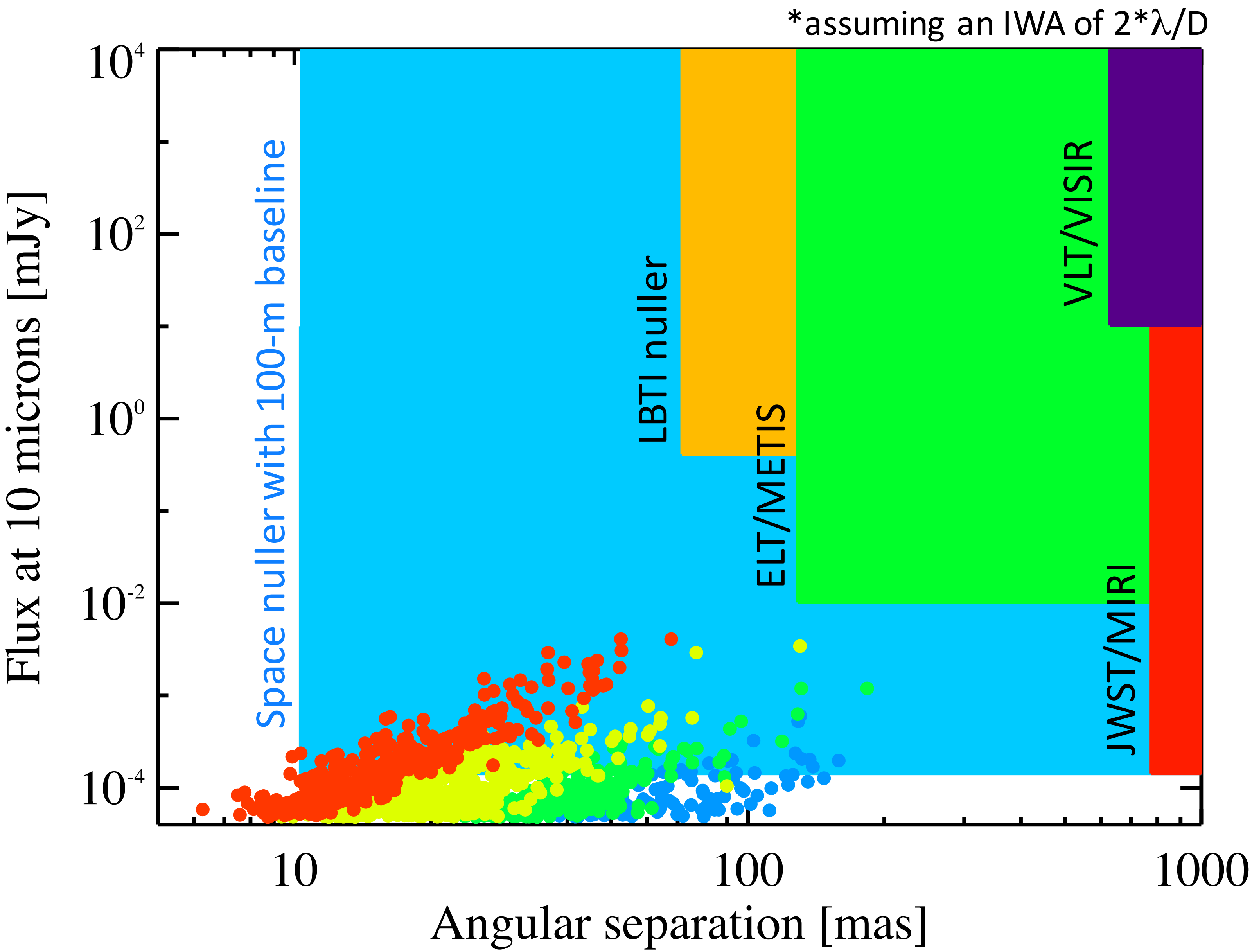
- Evidence of CO_2, O_3 , CH_4, and H_2O
- Atmosphere transparent between 8.3 and 12.5 µm (probe of surface temperatures)



Lauretta et al. 2018

Credit: NASA/Goddard/University of Arizona/Arizona State

Direct detection: context



Hi-5

https://www.life-space-mission.com/

LIFE

Large Interferometer For Exoplanets

A SPACE MISSION DESIGNED TO CHARACTERIZE TERRESTRIAL EXOPLANET ATMOSPHERES

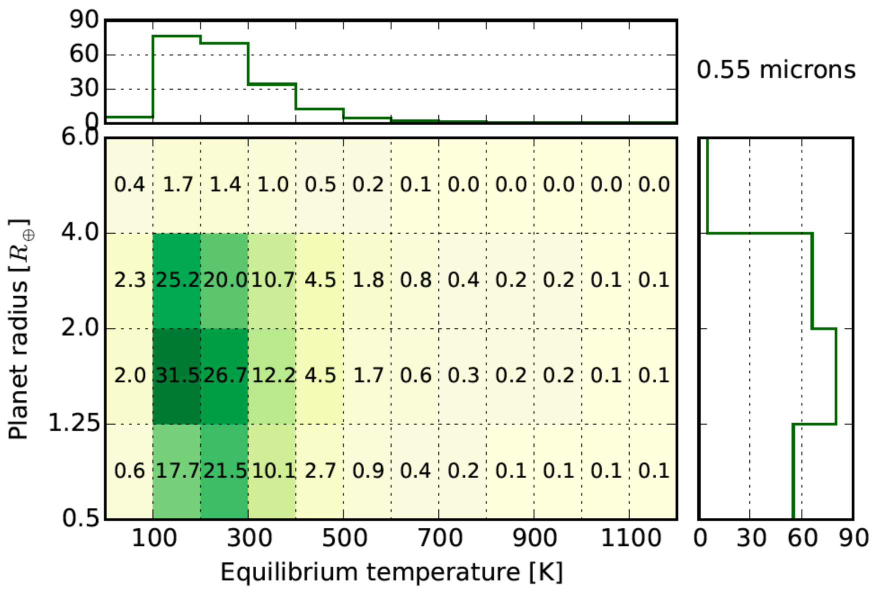
At the moment the LIFE core team consists of

- Sascha P. Quanz (ETH Zurich, Switzerland; Project Coordinator and Science Lead)
- Denis Defrere (University of Liege, Belgium; Technical Lead)
- Olivier Absil (University of Liege, Belgium)
- Adrian Glauser (ETH Zurich, Switzerland)
- Kate Isaak (ESA/ESTEC, The Netherlands)
- Jens Kammerer (Australian National University Canberra, Australia)
- Lucas Labadie (University of Cologne, Germany)
- Sylvestre Lacour (Paris Observatory, France)
- Yamila Miguel (Leiden Observatory, The Netherlands)
- Heike Rauer (DLR, Germany)
- Sarah Rugheimer (University of St. Andrews, Scotland UK)

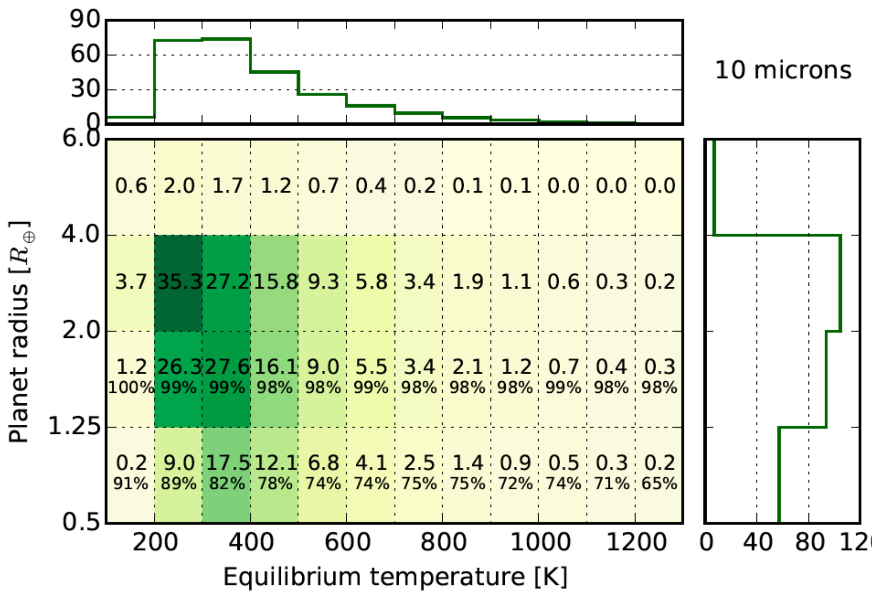
Comparison with LUVOIR

- Revised exoplanet yield of space nuller (4x 2-m, with 5 mas IWA) based on Kepler stats (Kammerer and Quanz 2018)
- Similar results as LUVOIR (12m) for 200 and 450 K and radii between 0.5 and 1.75 R_{Earth} : **63 (LUVOIR) vs 85 (LIFE) detections**.
- For mid-IR nuller, 50% of observed planets are **around M stars**

LUVOIR



LIFE



Kammerer and Quanz 2018a, Quanz et al. 2018

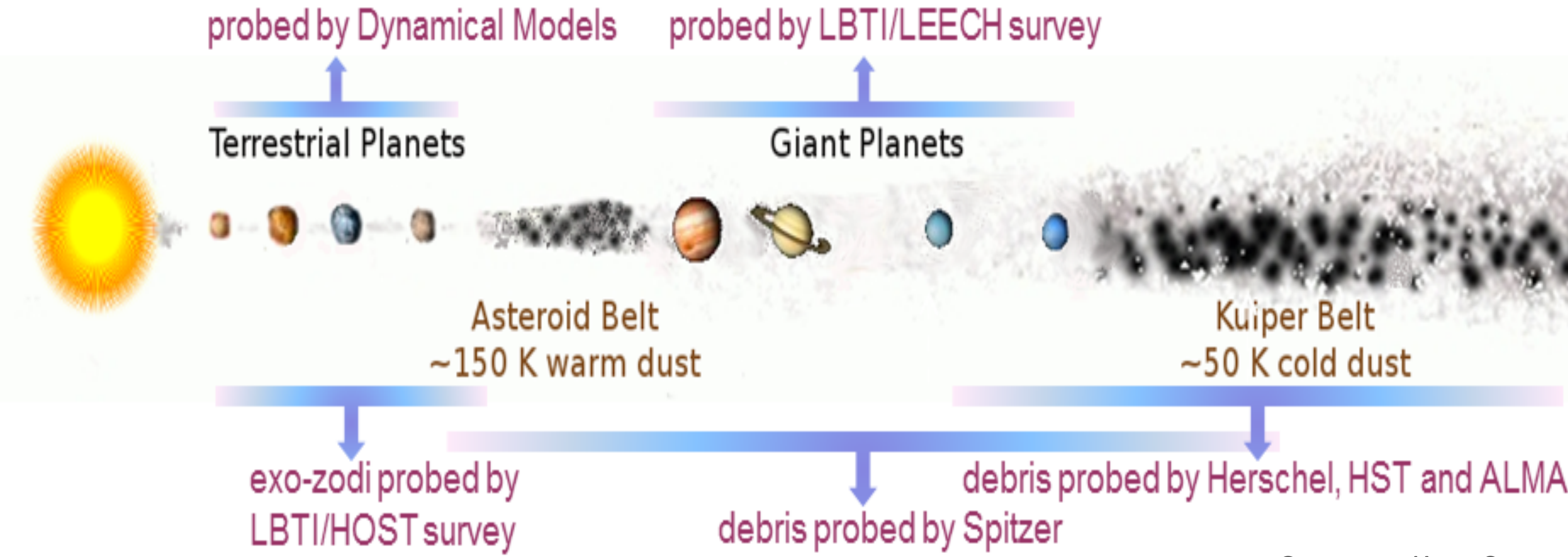
Take away messages

- HOSTS is successful!
- Many detections to study, much to learn
- Exo-Earth imaging possible! … but:
  - Still a major uncertainty in exoplanet yield computation
  - Many prime targets not yet observed
- A new VLTI project (Hi-5)
  - No high-precision/nulling interferometer in the South
  - Near-IR/mid-IR gap in high-contrast interferometric observations
  - Strong exoplanet science case (~40 better IWA than ELT)
- Revival of space inteferometry in Europe (LIFE project)

Thank you very much!

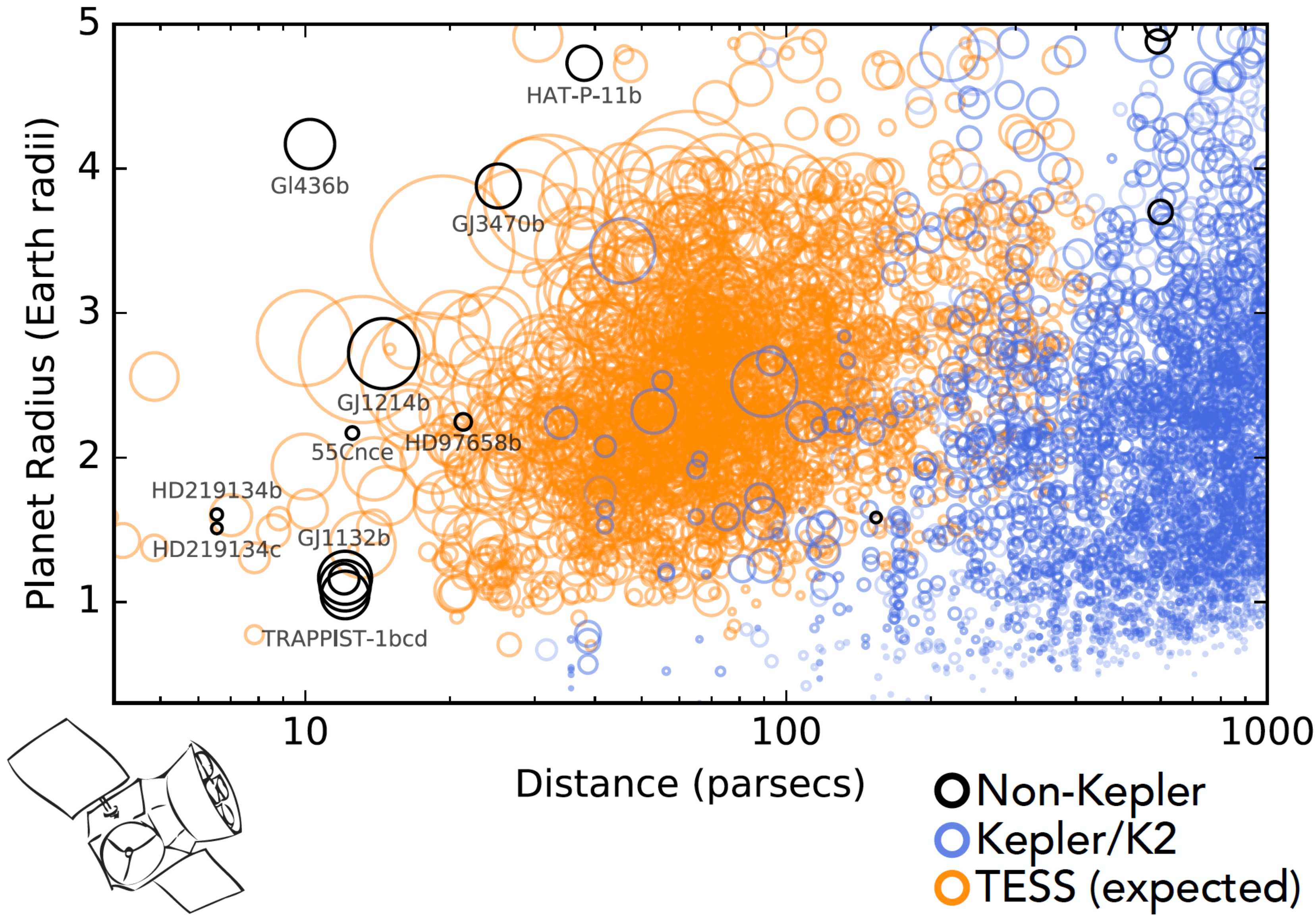
Context

see Stone et al. submitted



Courtesy Kate Su

Context



Planet Radius (Earth radii)
Distance (parsecs)
HAT-P-11b
Gl436b
GJ3470b
GJ1214b
55Cnce
HD97658b
HD219134b
HD219134c
GJ1132b
TRAPPIST-1bcd
5
4
3
2
1
10
100
1000
Non-Kepler
Kepler/K2
TESS (expected)

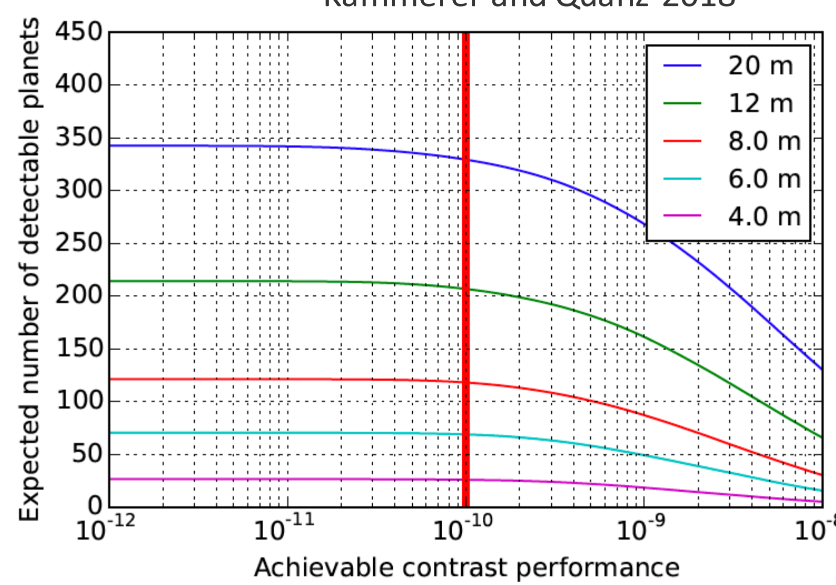
LIFE: exoplanet yield

- Exoplanet yield based on Kepler stats:
  - 207 ($R < 6R_E$) planets observable (V band), 70 (J band), and 38 (H band)
  - No significant improvement with contrasts better than 10^{-10}
  - Improving IWA more important at this point

Table 5. Instrumental parameters for our baseline scenario for HabEx/LUVOIR.

Parameter	Value	Description
D	12 m	Aperture size
IWA	$2\,\lambda_{\mathrm{eff}}/D$	Inner working angle
C_{ref}	1e−10	Achievable contrast performance
$\lambda_{\mathrm{cen},\,V}$	554 nm	Central wavelength of V-band filter
$\lambda_{\mathrm{cen},\,J}$	1245 nm	Central wavelength of J-band filter
$\lambda_{\mathrm{cen},\,H}$	1625 nm	Central wavelength of H-band filter
$F_{\mathrm{lim},\,V}$	3.31e−10 Jy	Sensitivity limit (V-band)[a]
$F_{\mathrm{lim},\,J}$	9.12e−10 Jy	Sensitivity limit (J-band)[a]
$F_{\mathrm{lim},\,H}$	8.32e−10 Jy	Sensitivity limit (H-band)[a]

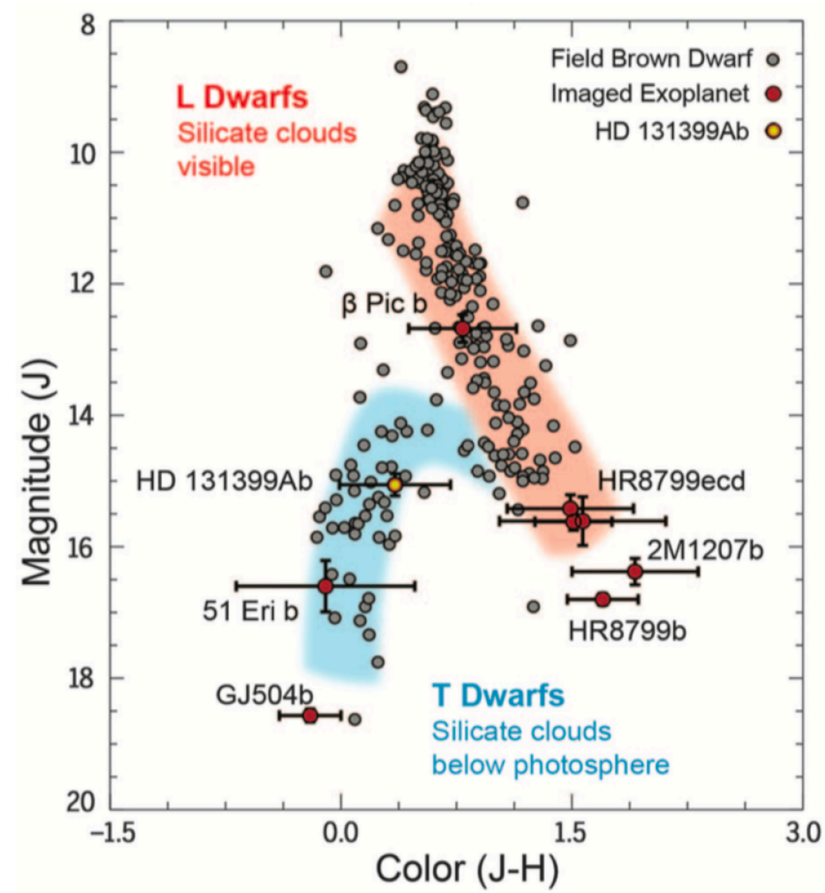
Kammerer and Quanz 2018



And then? How to identify life?

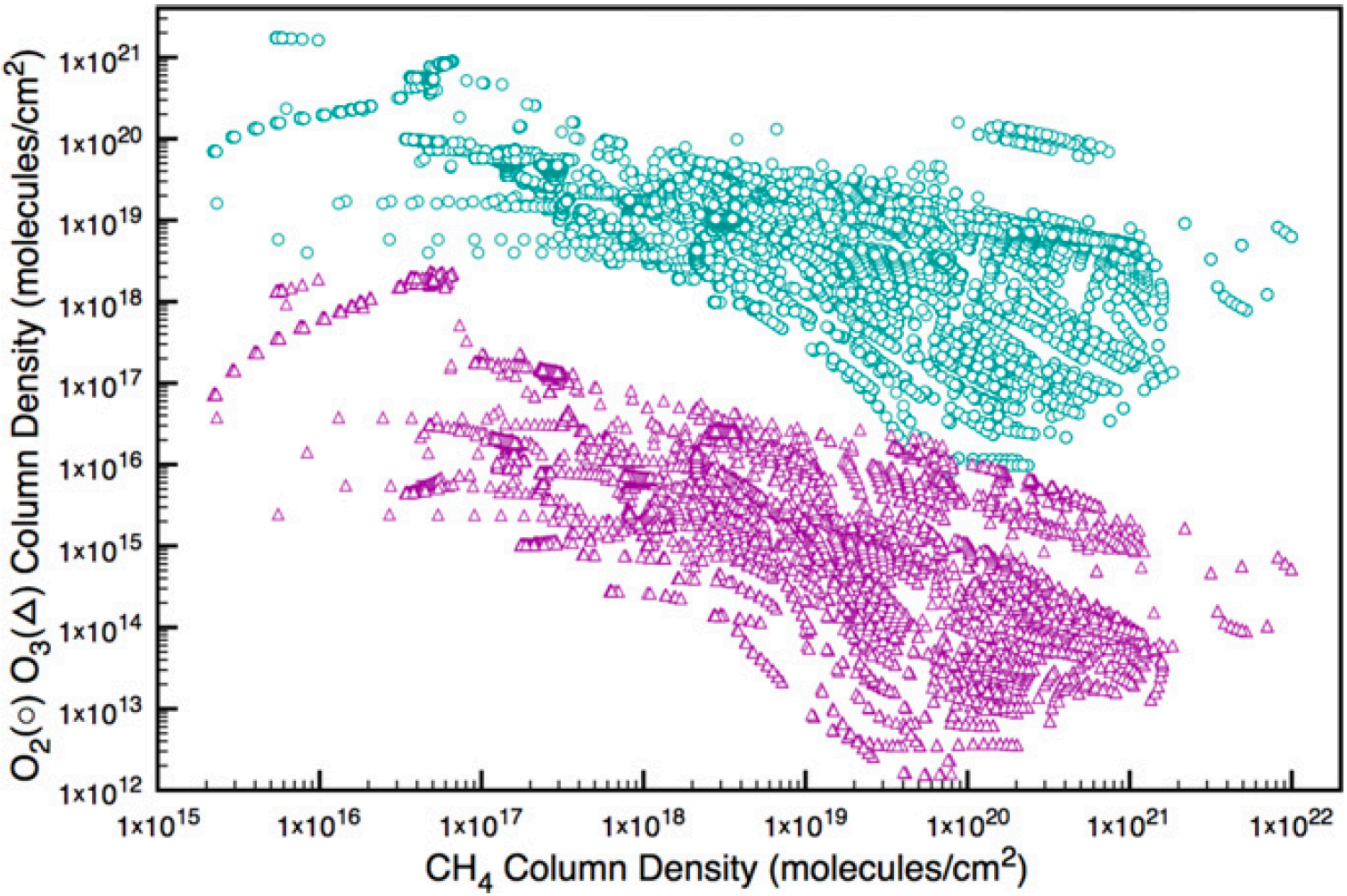
- Several important molecules to look for (ex: O_2, O_3, CH_4) but no clear/unambiguous biosignatures (false positives!)
- Necessary to better planet atmospheric processes and their evolutionary histories
- **Large sample is required**
- Population analysis:

Colour-colour or $CH_4/O_2/H_2O$ diagrams will allow to identify **families of planets** and maybe some **anomaly**



Wagner et al. 2016

And then? How to identify life?



Domagal-Goldman et al. 2014

Take away messages

<u>Want to know more?</u>

Weinberger et al. (2015): Sample selection
Kennedy et al. (2015): Modeling
Defrère et al. (2015): η Crv
<u>Ertel et al. (2018): First survey results</u>
<u>Ertel et al. (in prep.): Full survey results</u>
Hinz et al. (in prep): β Leo
More to come!