

Direct imaging of exoplanets in the context of PLATO

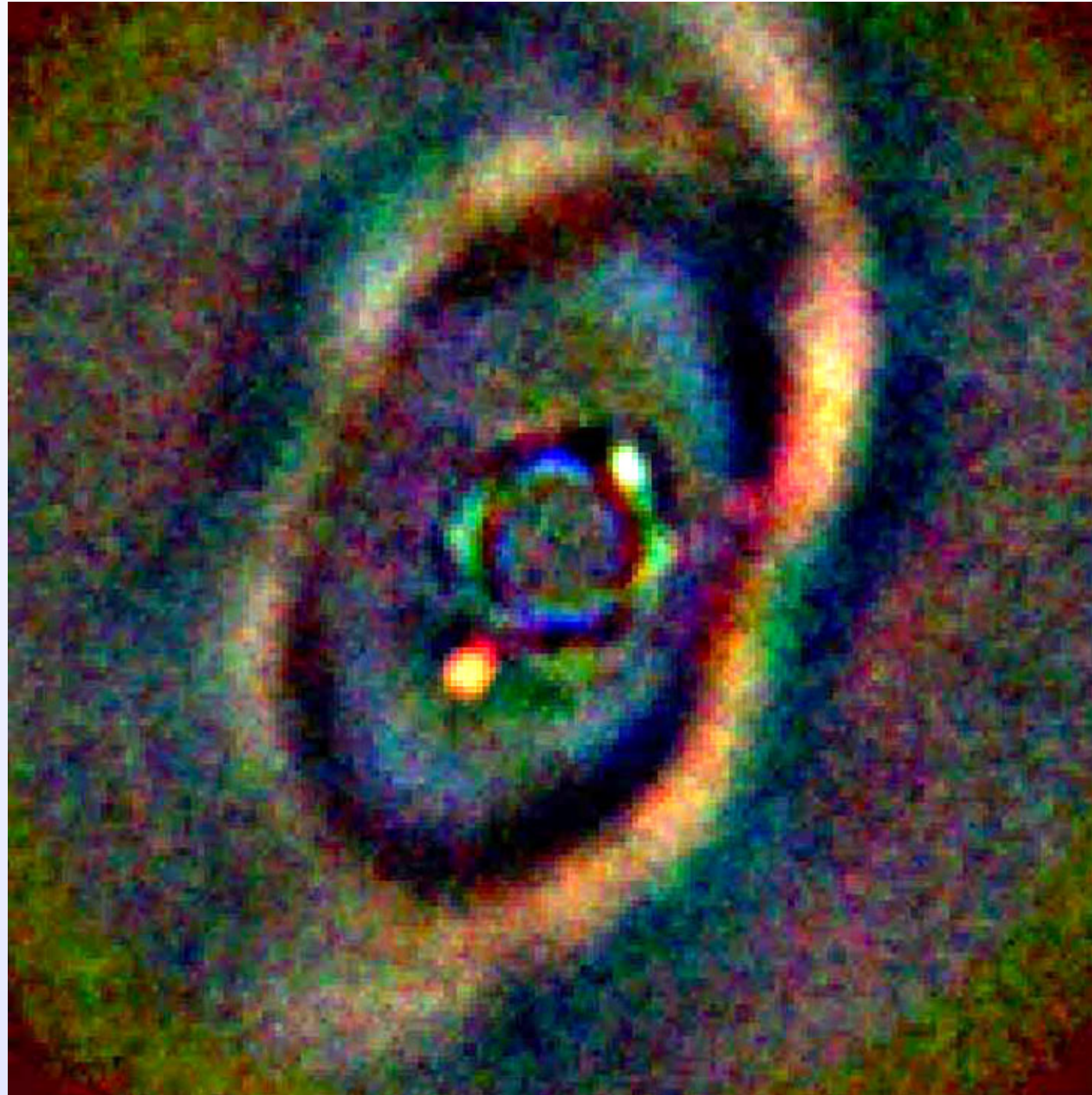
From validation of candidates to the direct detection of Earth analogs

Arthur Vigan

Laboratoire d'Astrophysique de Marseille / CNRS

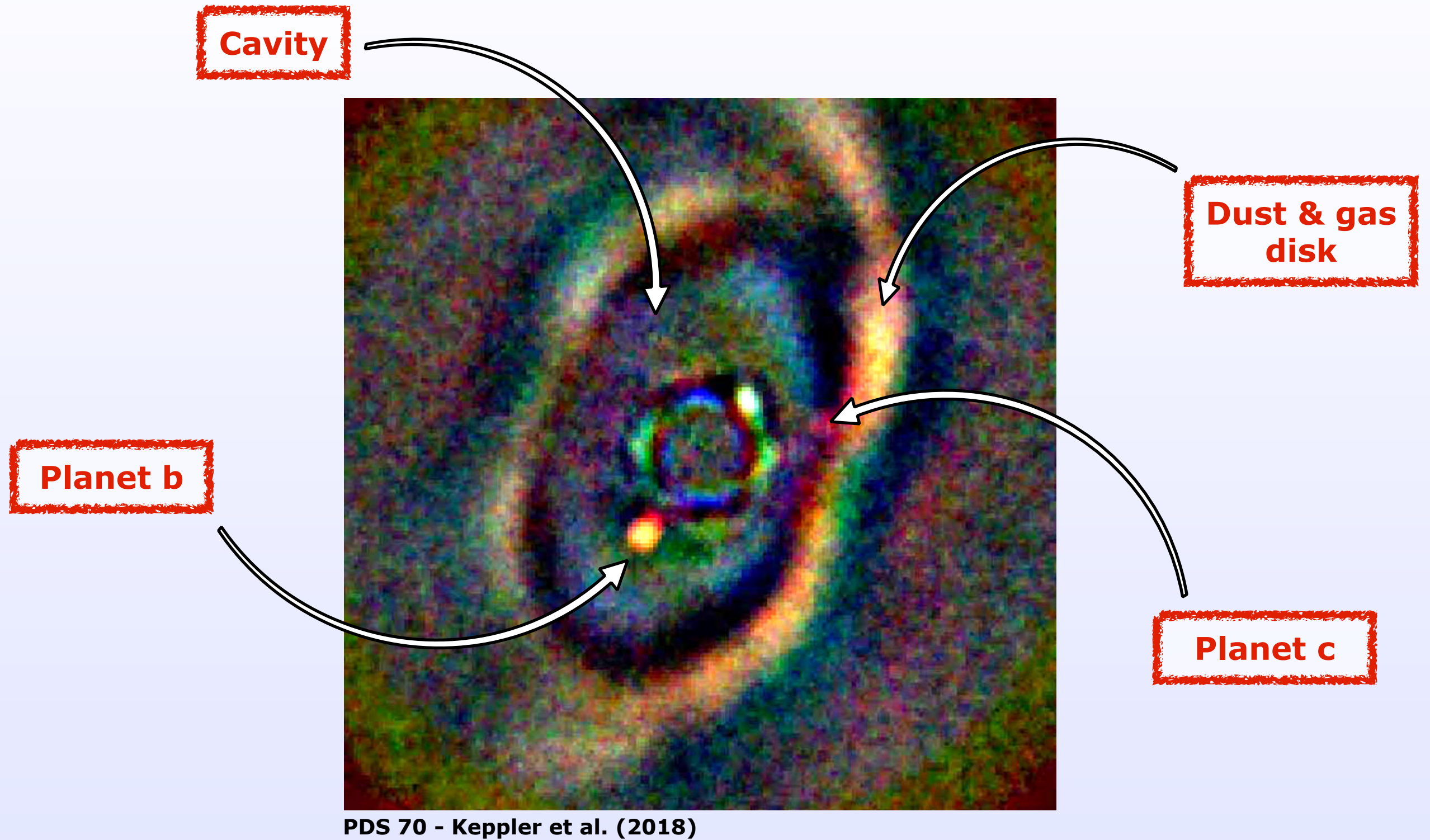


Direct imaging of exoplanetary systems



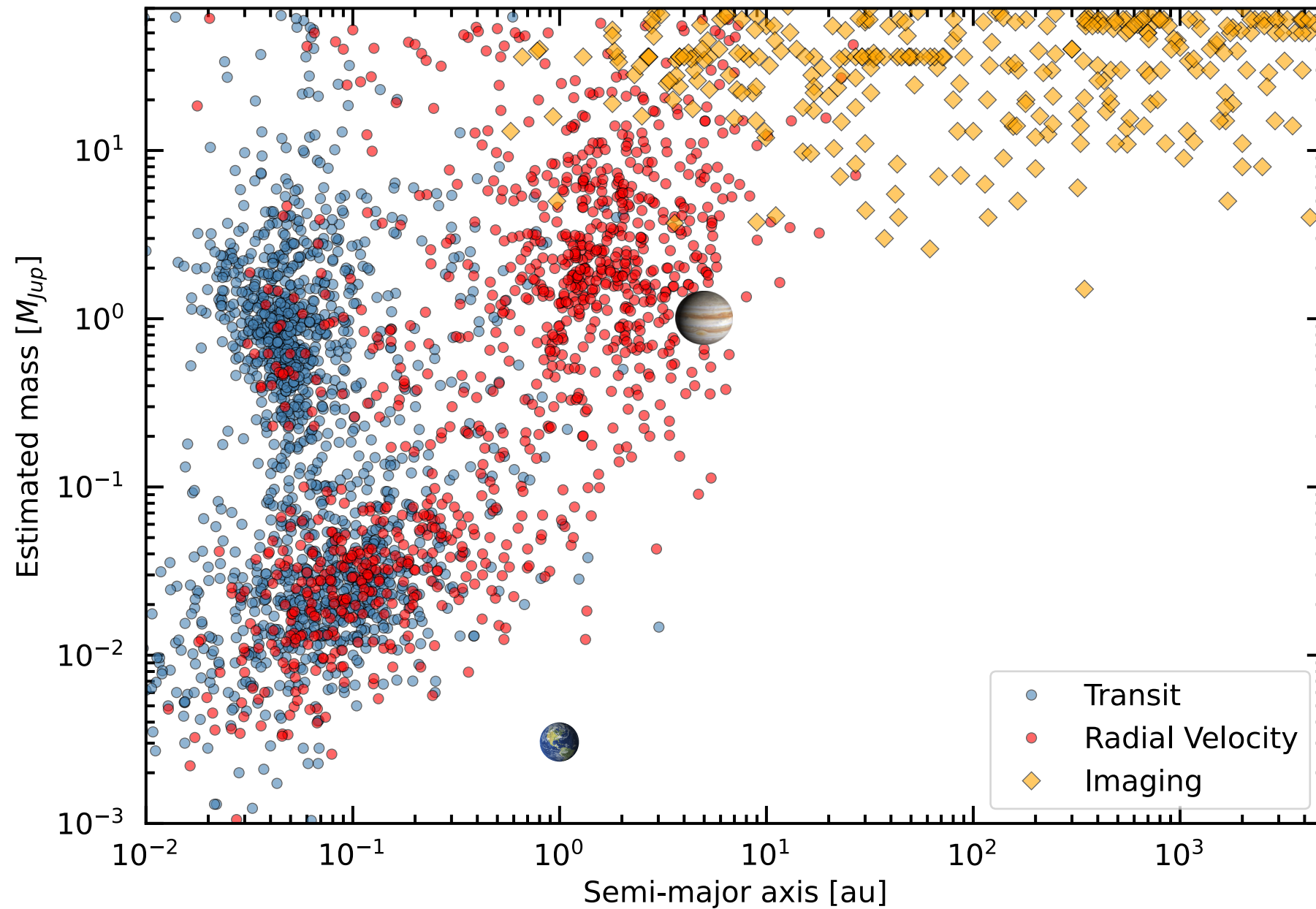
PDS 70 - Keppler et al. (2018)

Direct imaging of exoplanetary systems



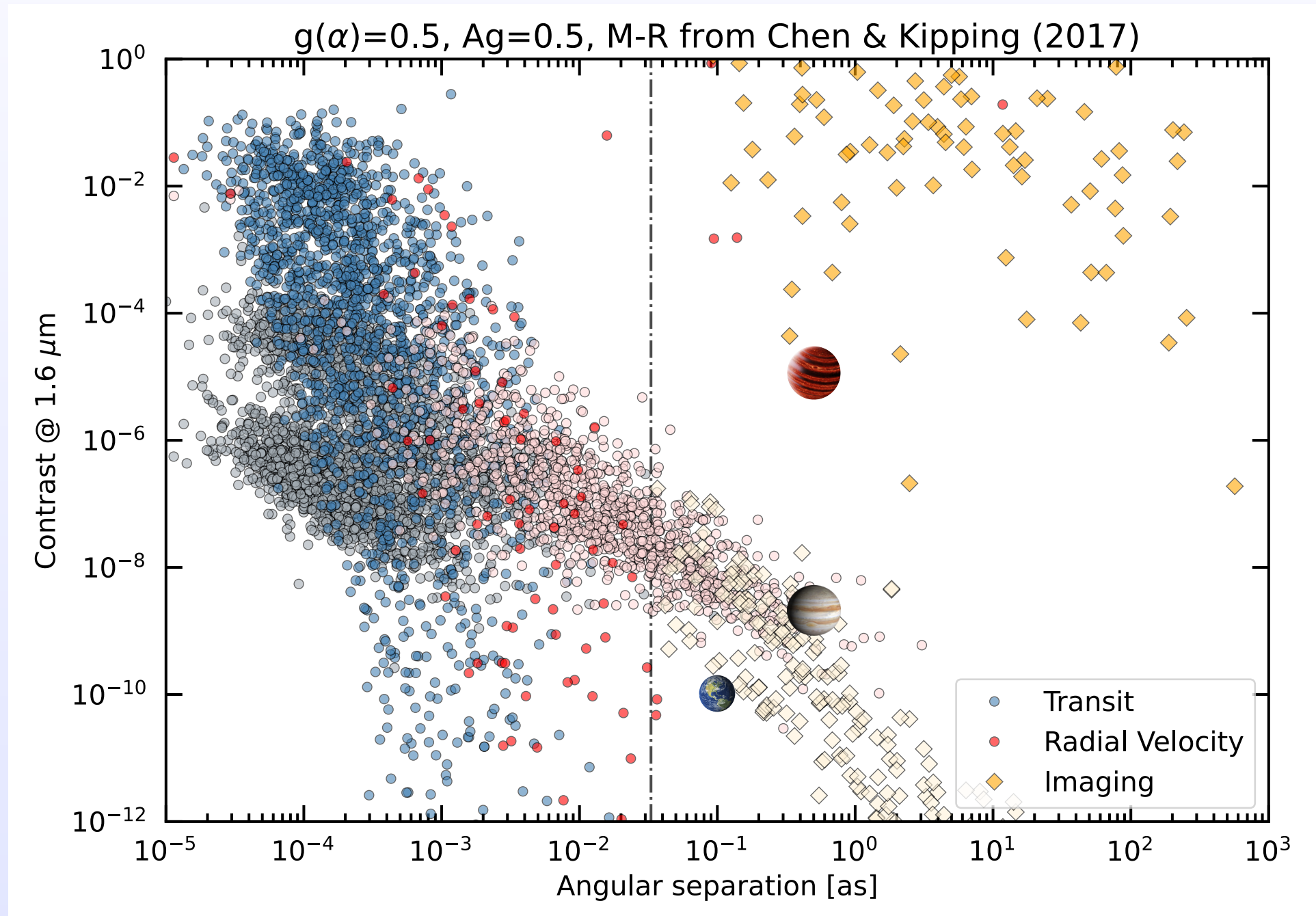
Direct imaging: the challenge

Physical units



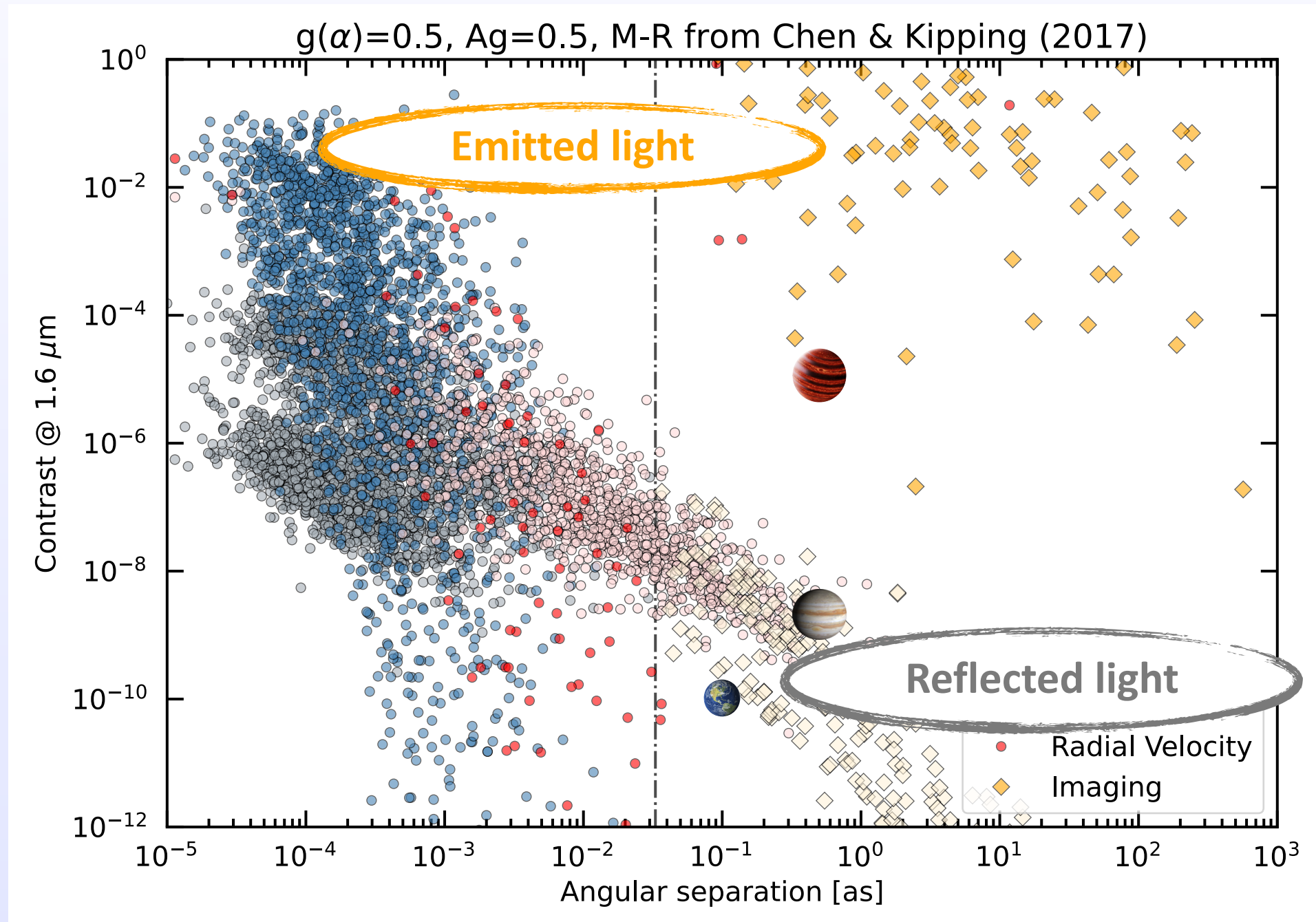
Direct imaging: the challenge

Observables



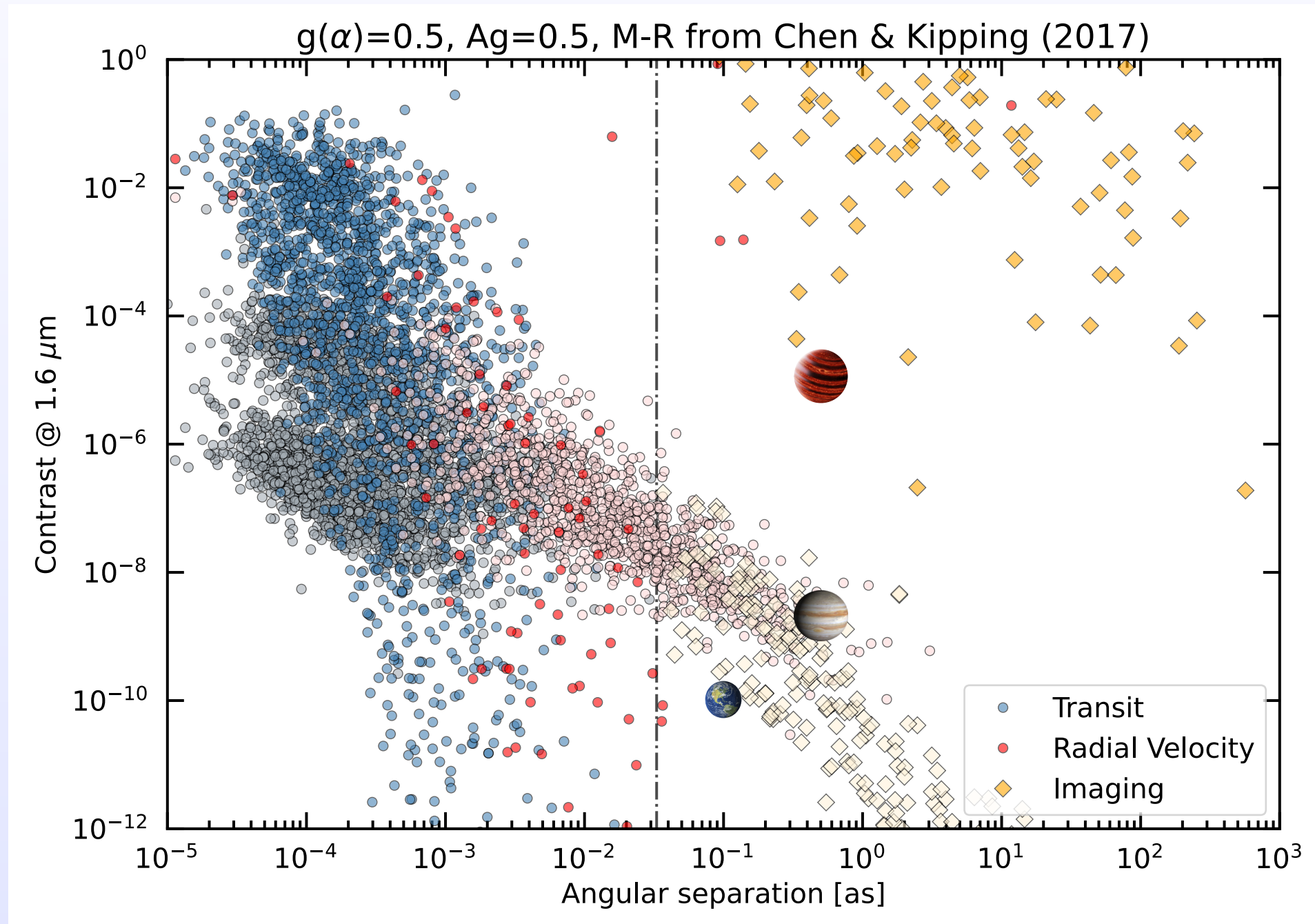
Direct imaging: the challenge

Observables



Direct imaging: the challenge

High-angular resolution



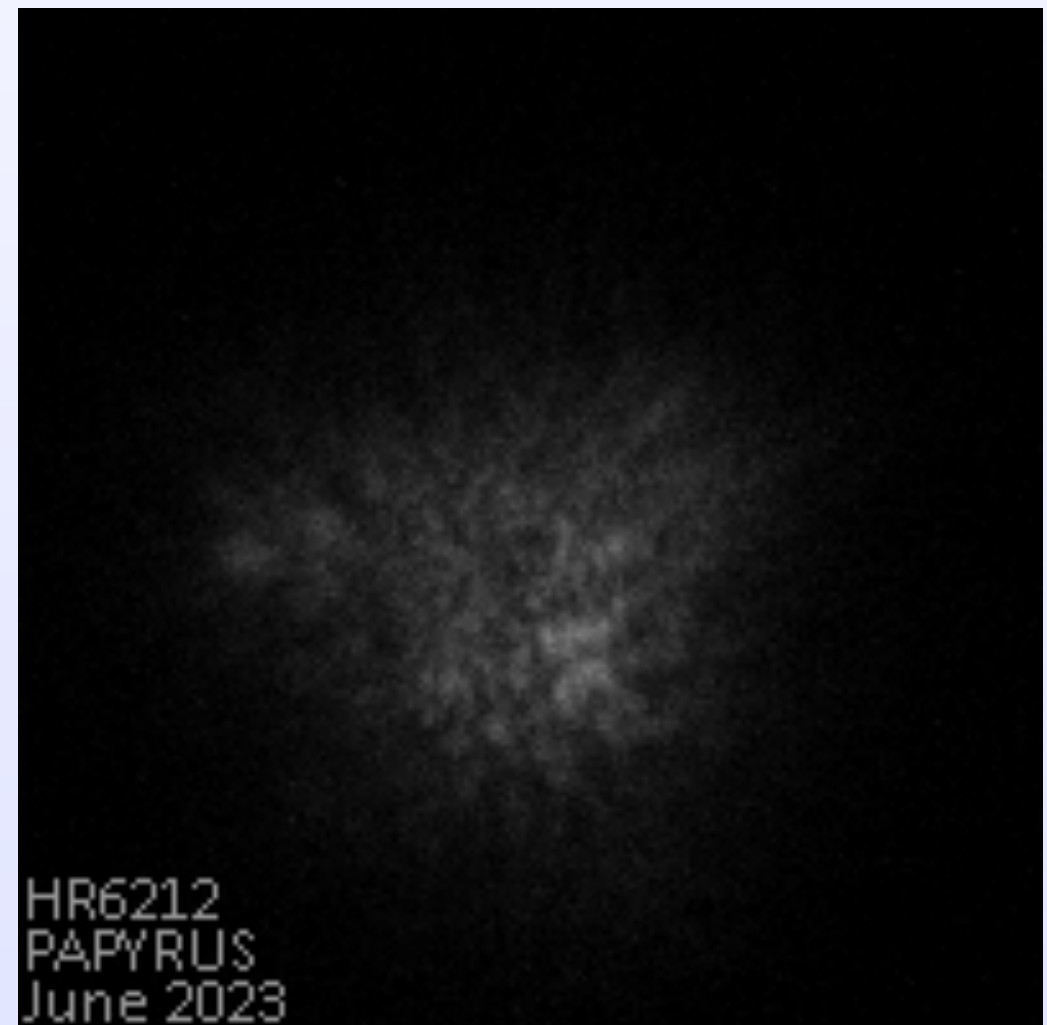
High-contrast

The key combo for direct imaging



Large telescopes

Adaptive optics

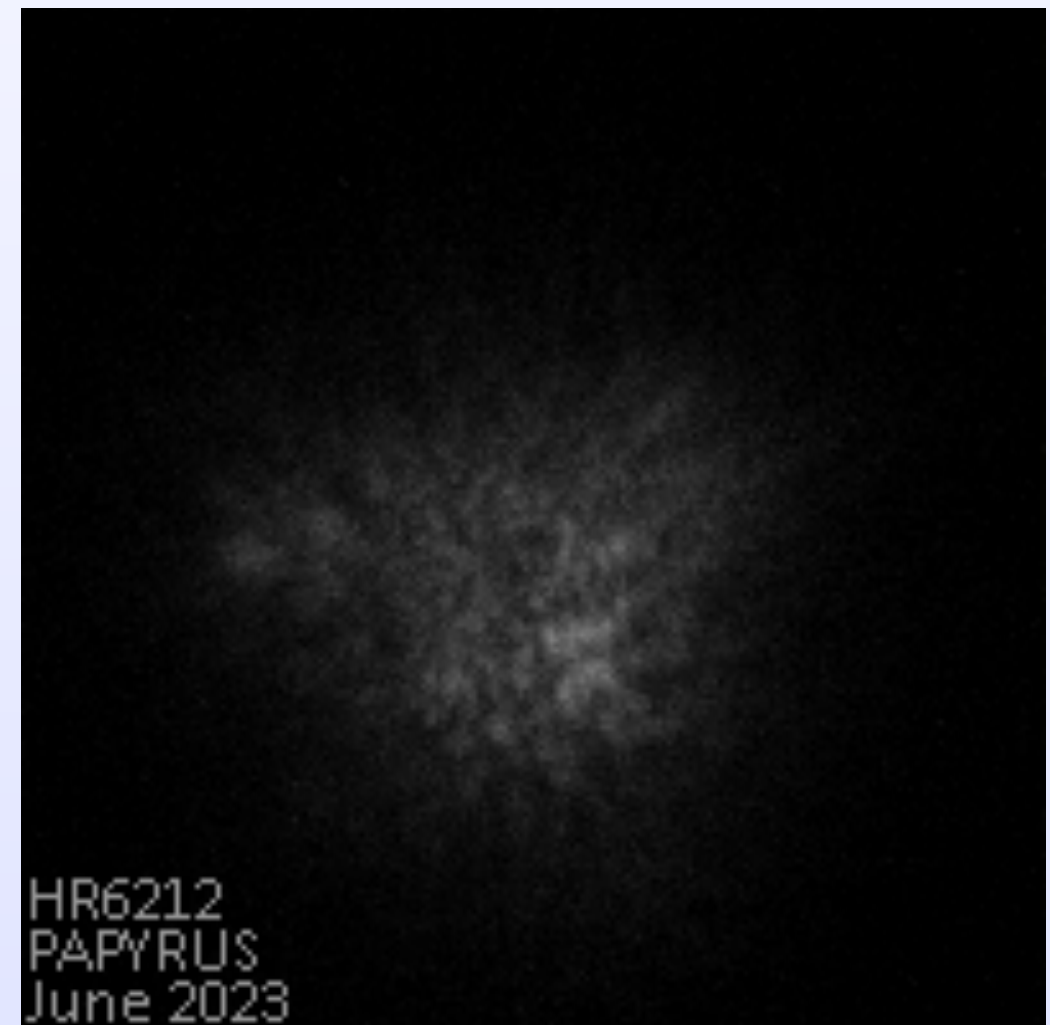


The key combo for direct imaging



Large telescopes

Adaptive optics



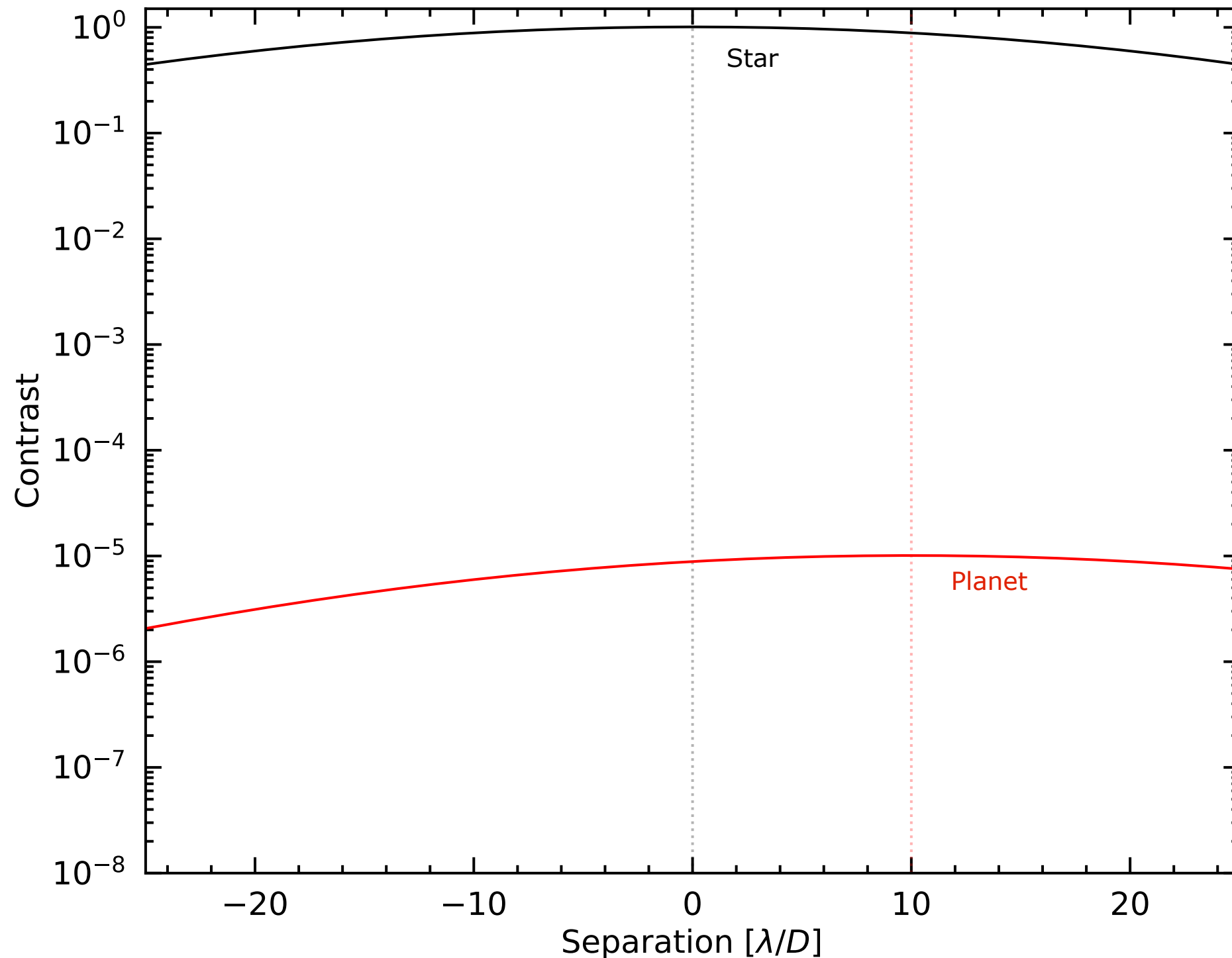
Progress in adaptive optics & coronagraphy

Seeing-limited

Since 1998

Large ground-based
telescopes
8-10 m diameter

VLT, Keck, Subaru
Gemini N & S



Progress in adaptive optics & coronagraphy

Low-order AO

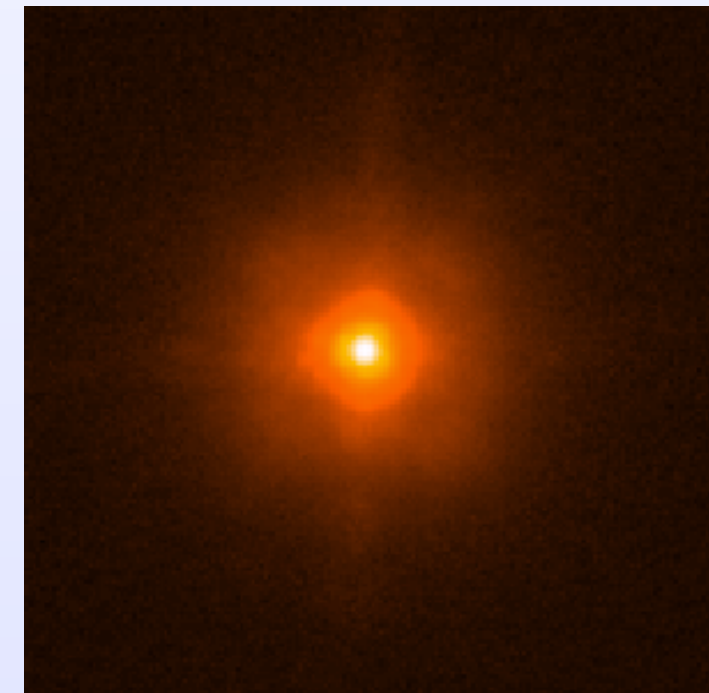
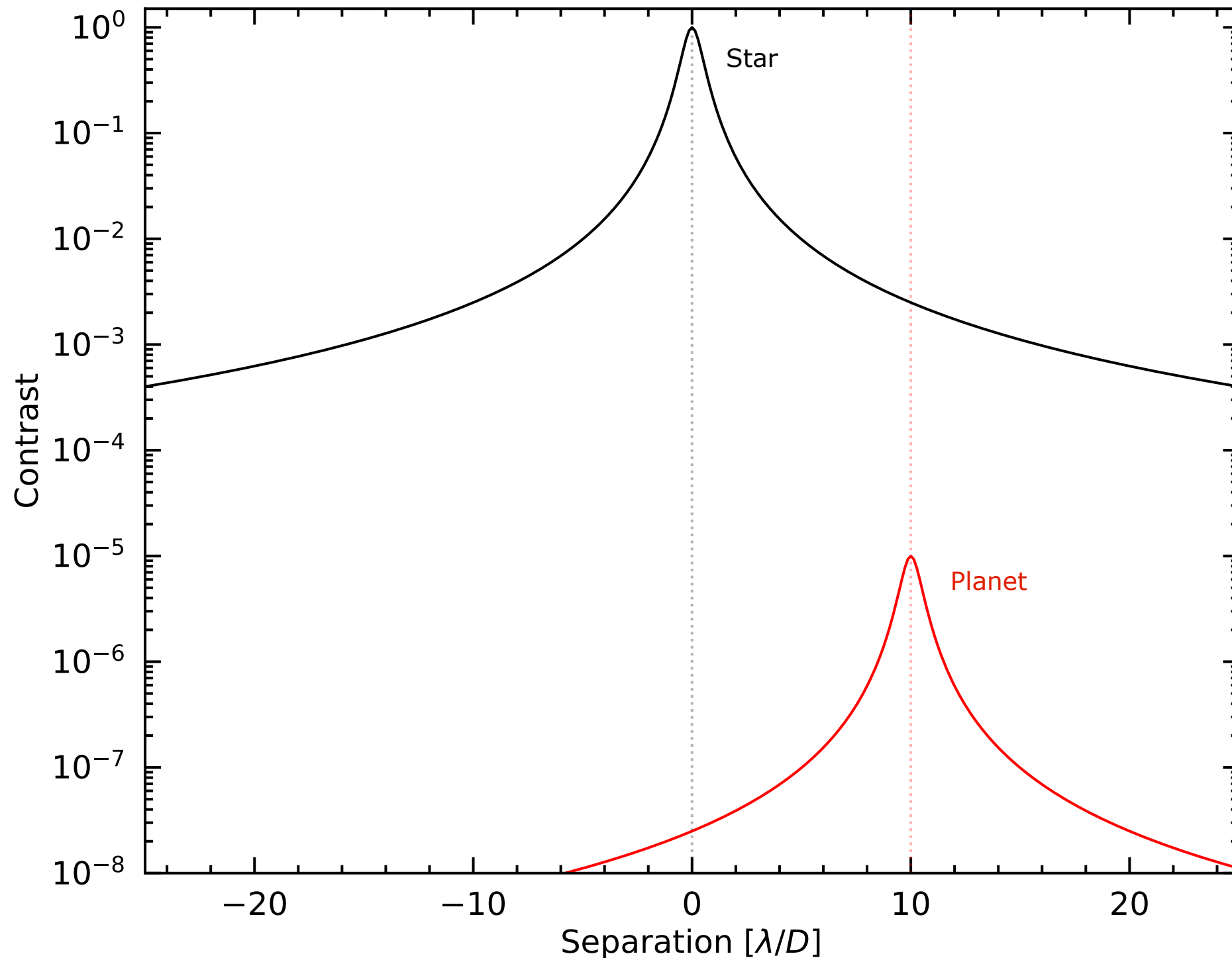
2000s

Shack-Hartmann WFS

~150 actuators

Sr = 40-50% (H)

NaCo, CRIRES,
SINFONI, OSIRIS

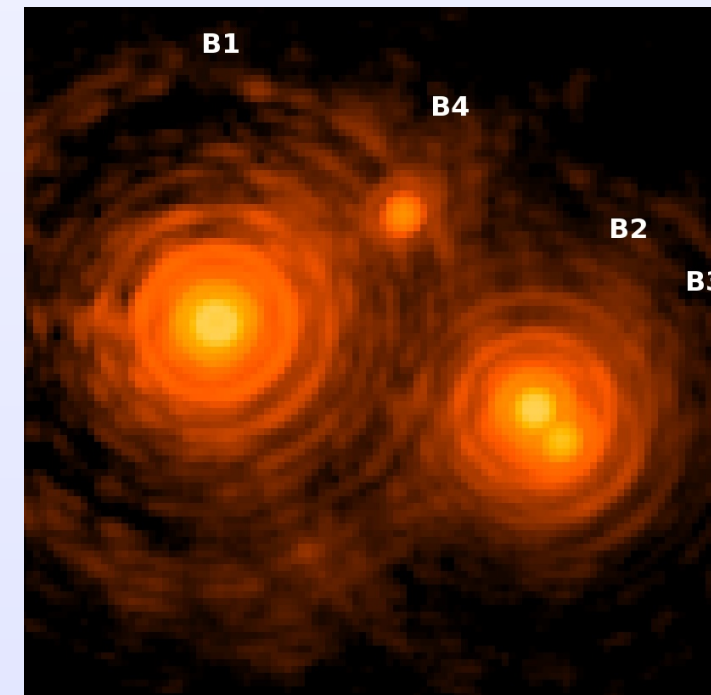
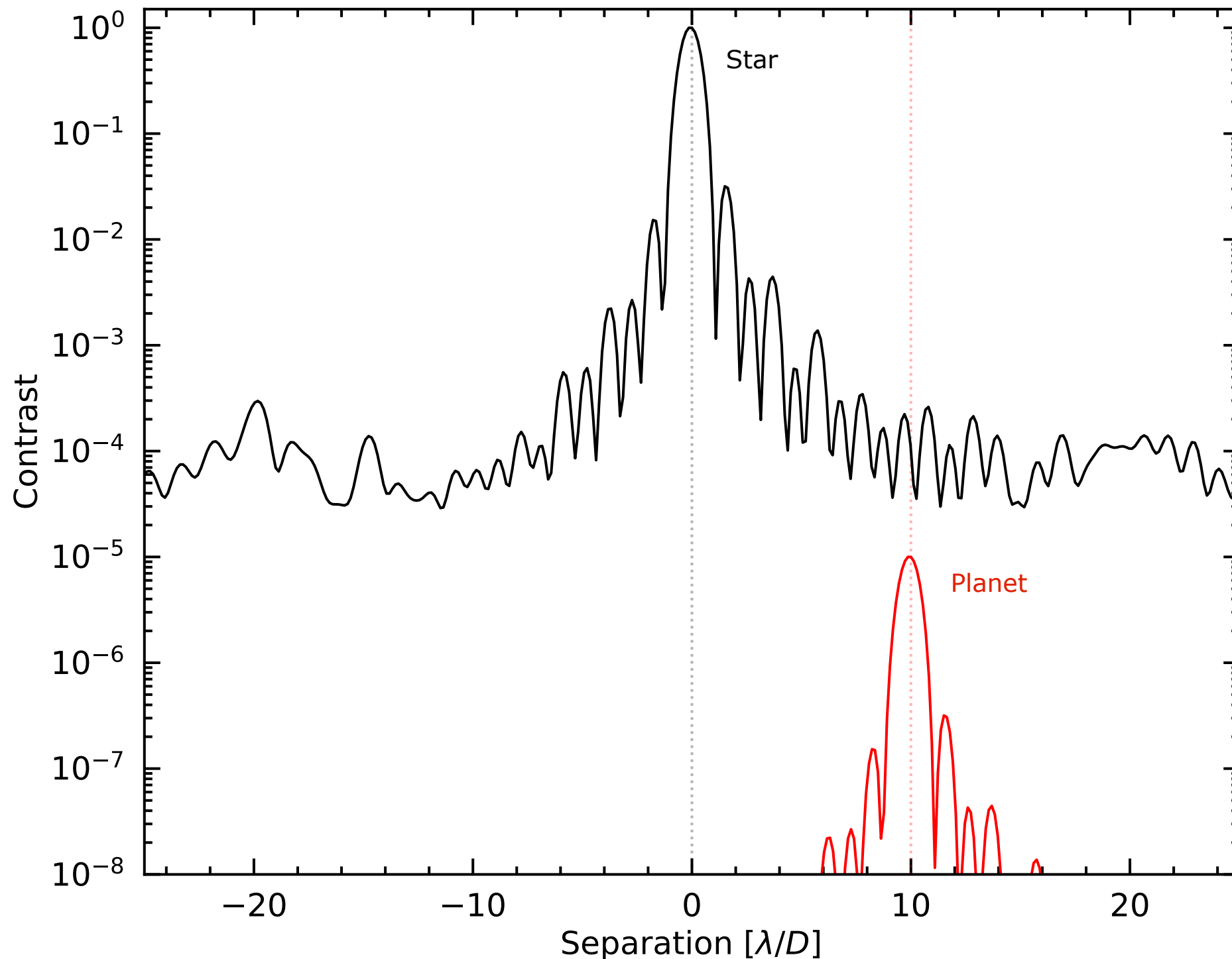


Progress in adaptive optics & coronagraphy

High-order AO

Since 2015s
SHWFS or PyWFS
> 1000 actuators
 $Sr > 80\%$ (H)

LBT, SPHERE, GPI,
SCExAO



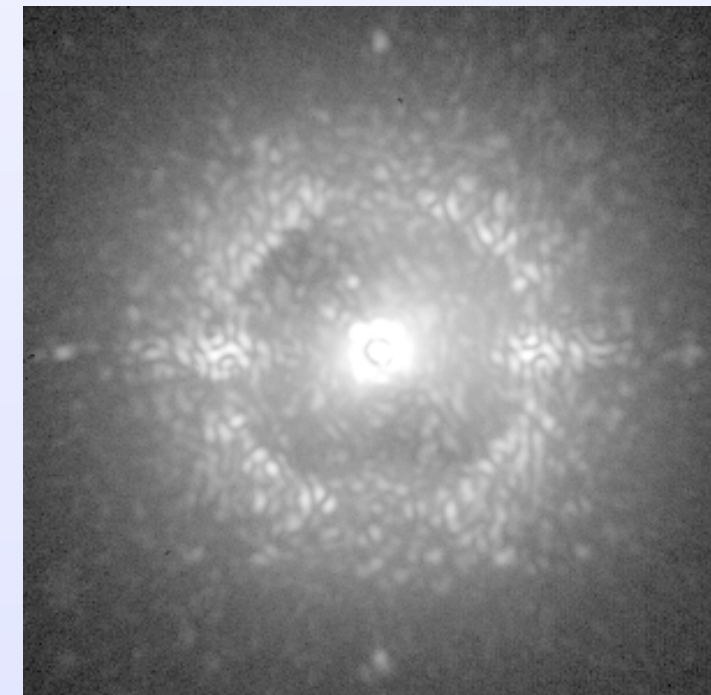
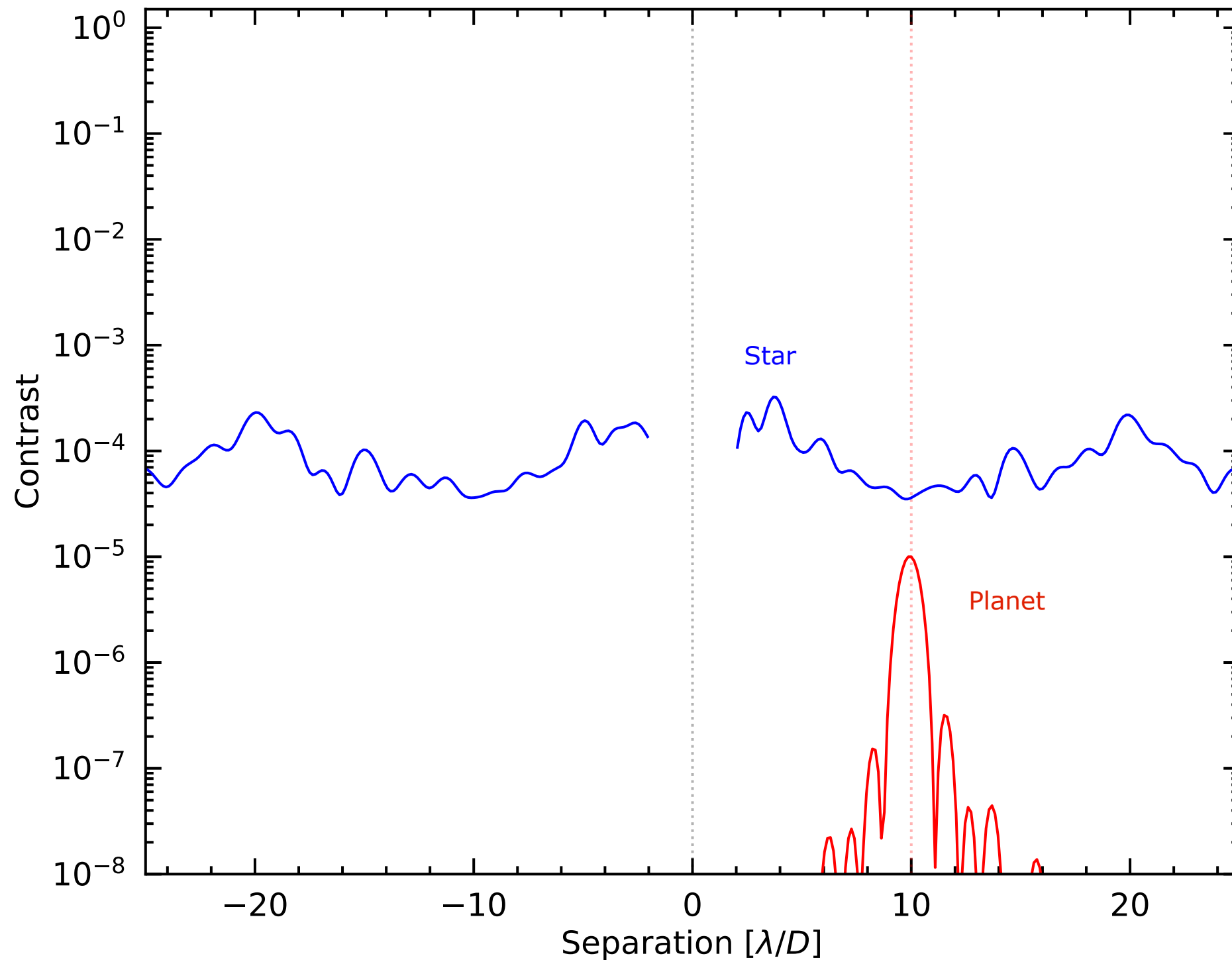
And more recently: KPIC, MagAO-X, ...

Progress in adaptive optics & coronagraphy

High-order AO

Since 2010s
SHWFS or PyWFS
> 1000 actuators
 $S_r > 80\%$ (H)
+ coronagraphy !

LBT, SPHERE, GPI,
SCExAO



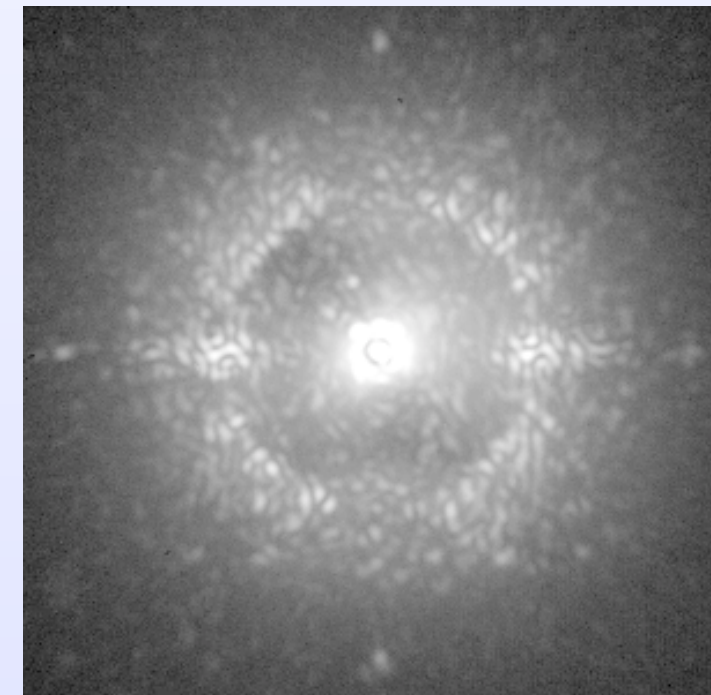
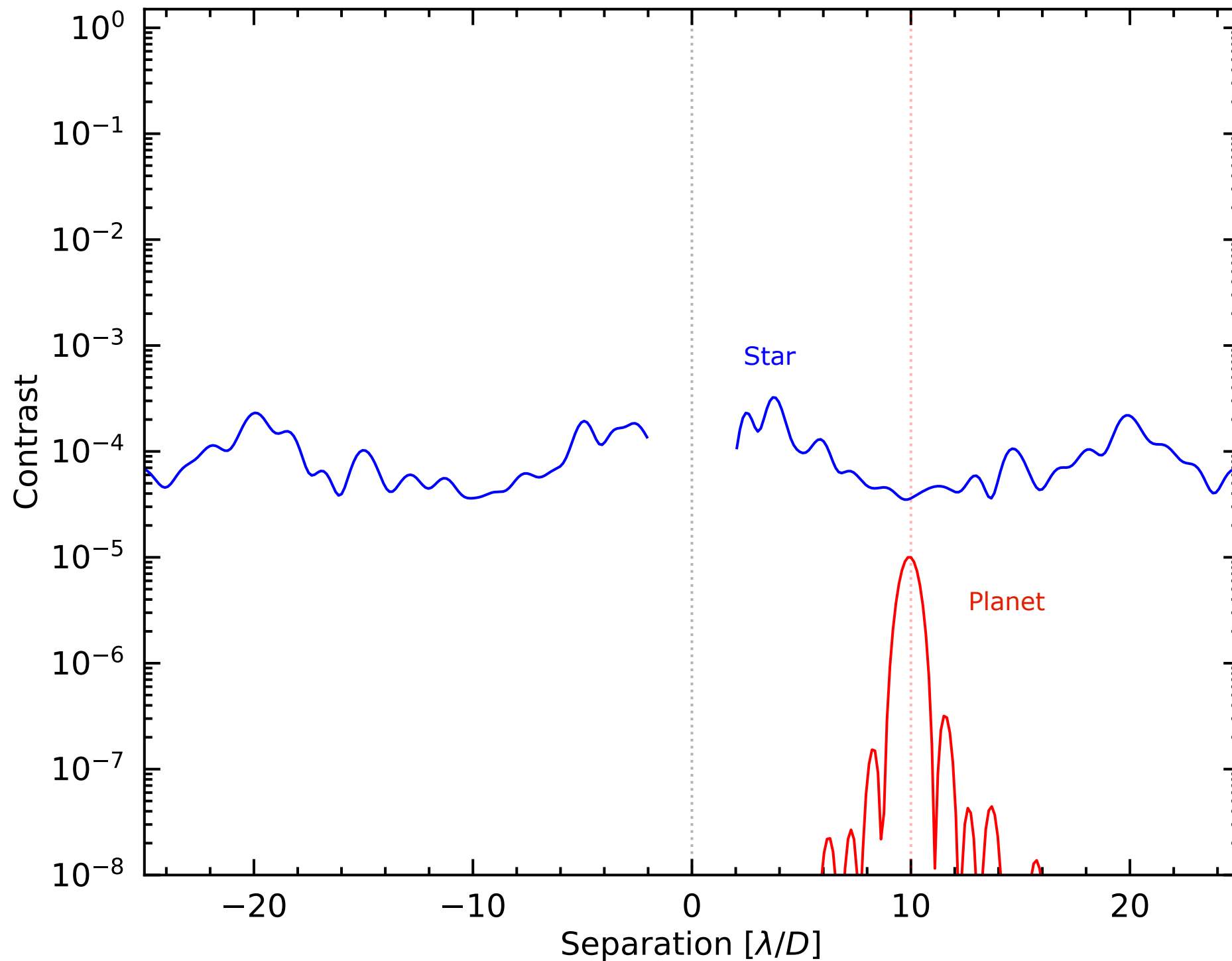
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Progress in adaptive optics & coronagraphy

High-order AO

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SHWFS or PyWFS
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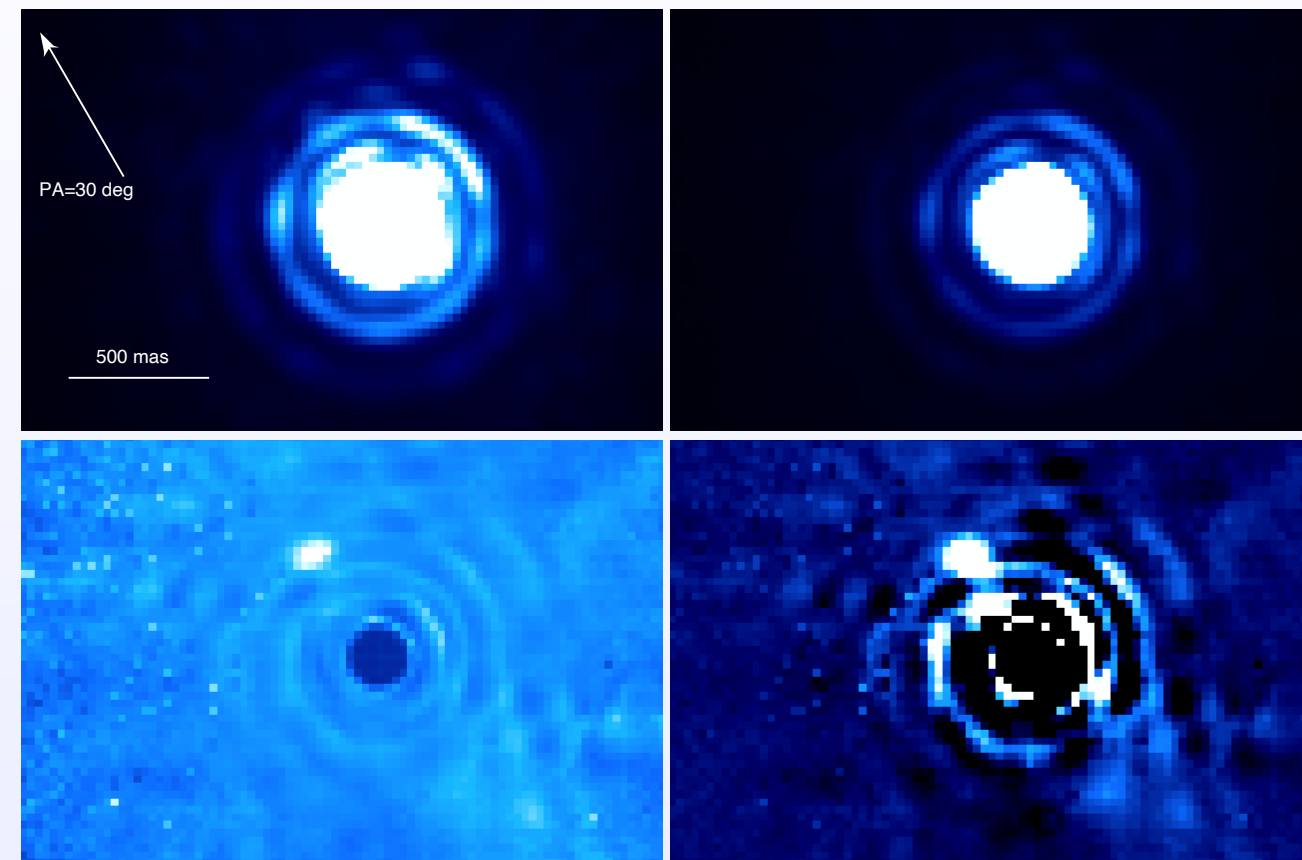
LBT, SPHERE, GPI,
SCEXAO



And more recently: KPIC, MagAO-X, ...

And progress on data processing

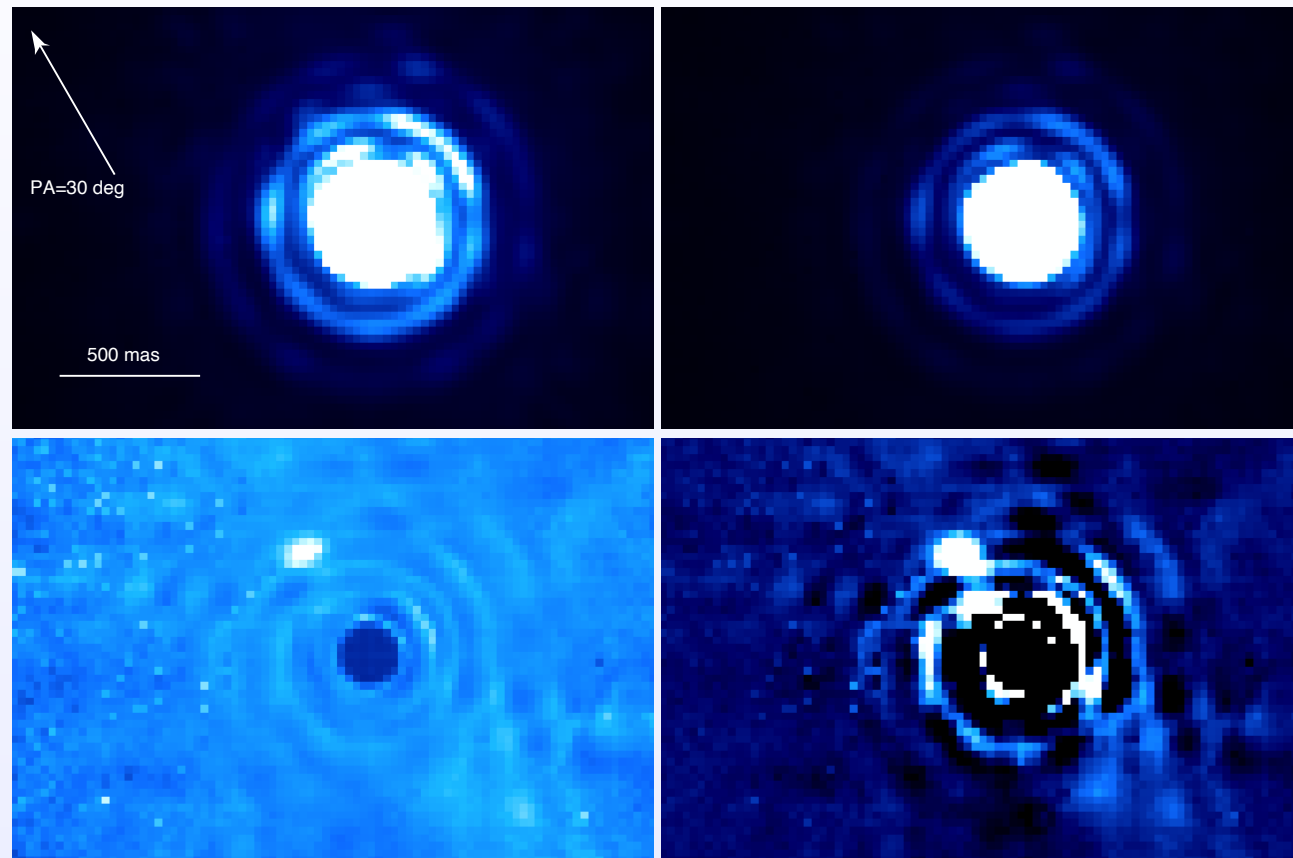
Reference differential imaging



Lagrange et al. (2008)

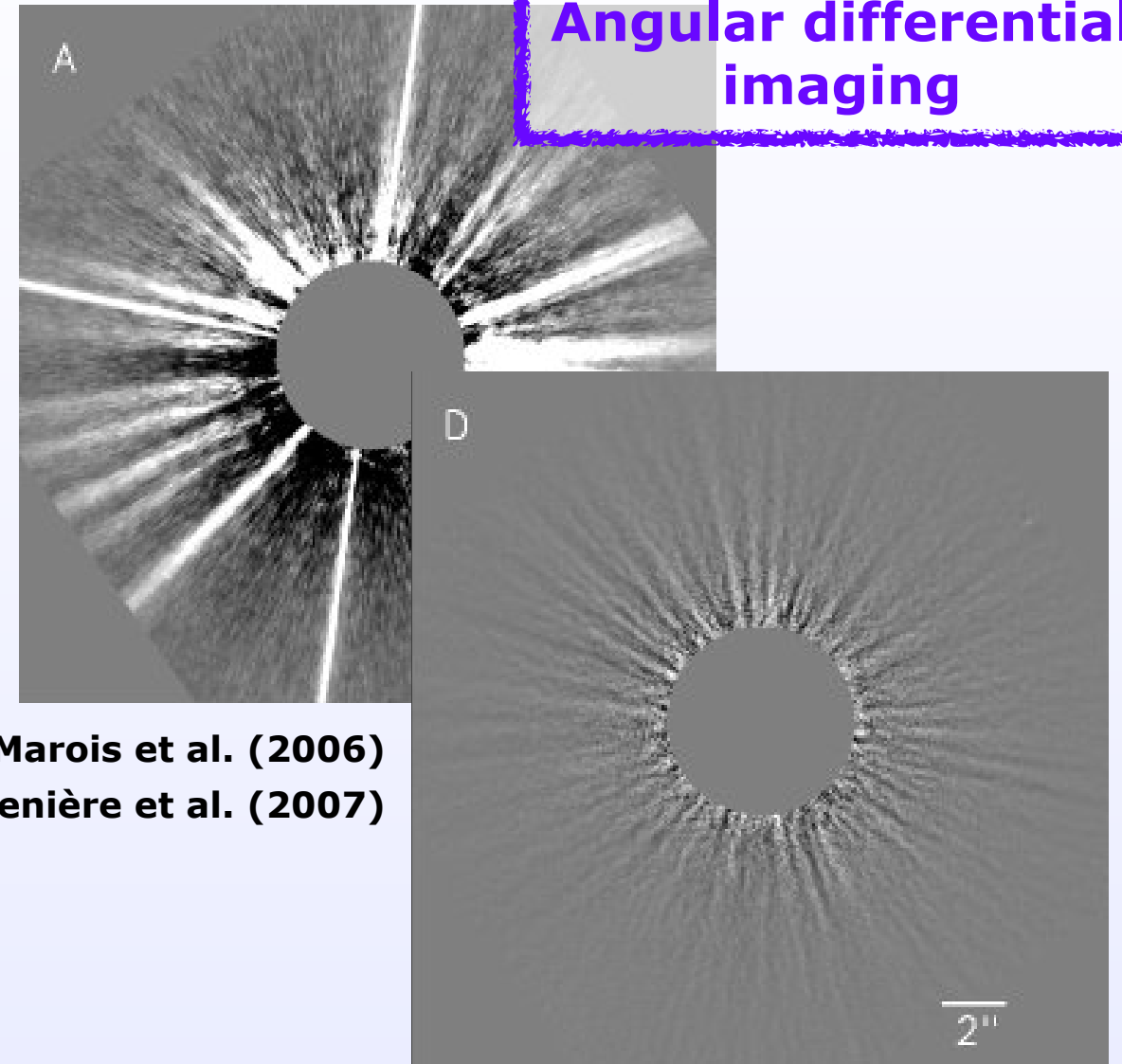
And progress on data processing

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Lagrange et al. (2008)

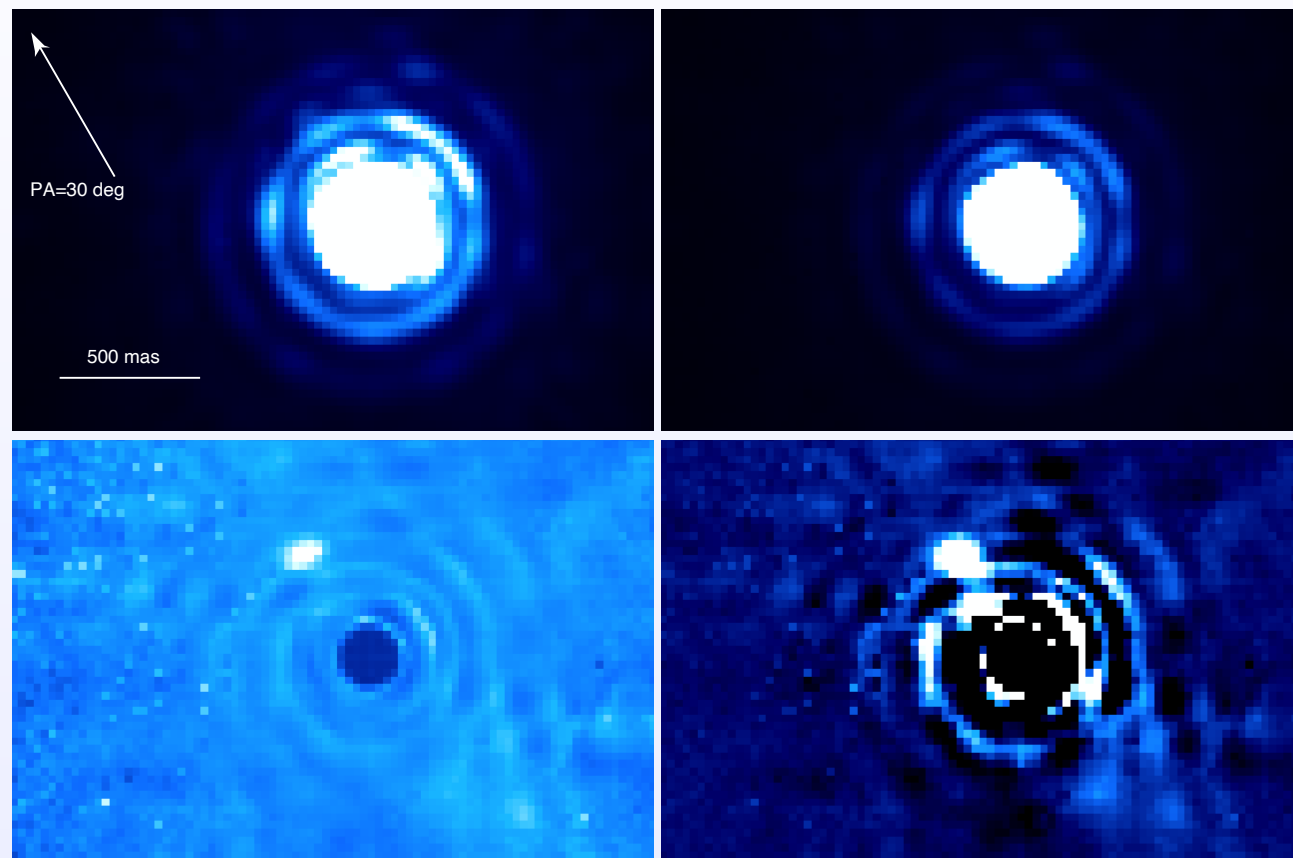
Angular differential imaging



Marois et al. (2006)
Lafrenière et al. (2007)

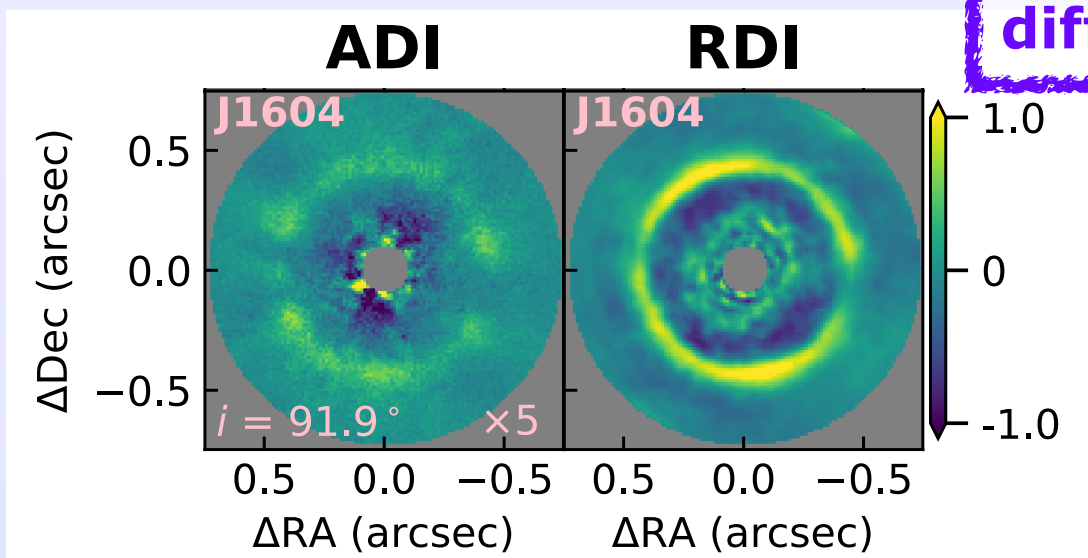
And progress on data processing

Reference differential imaging

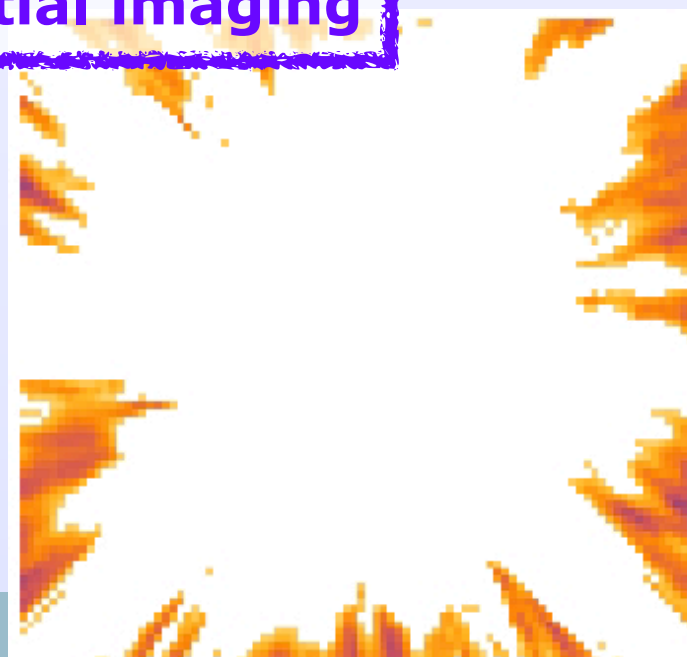


Lagrange et al. (2008)

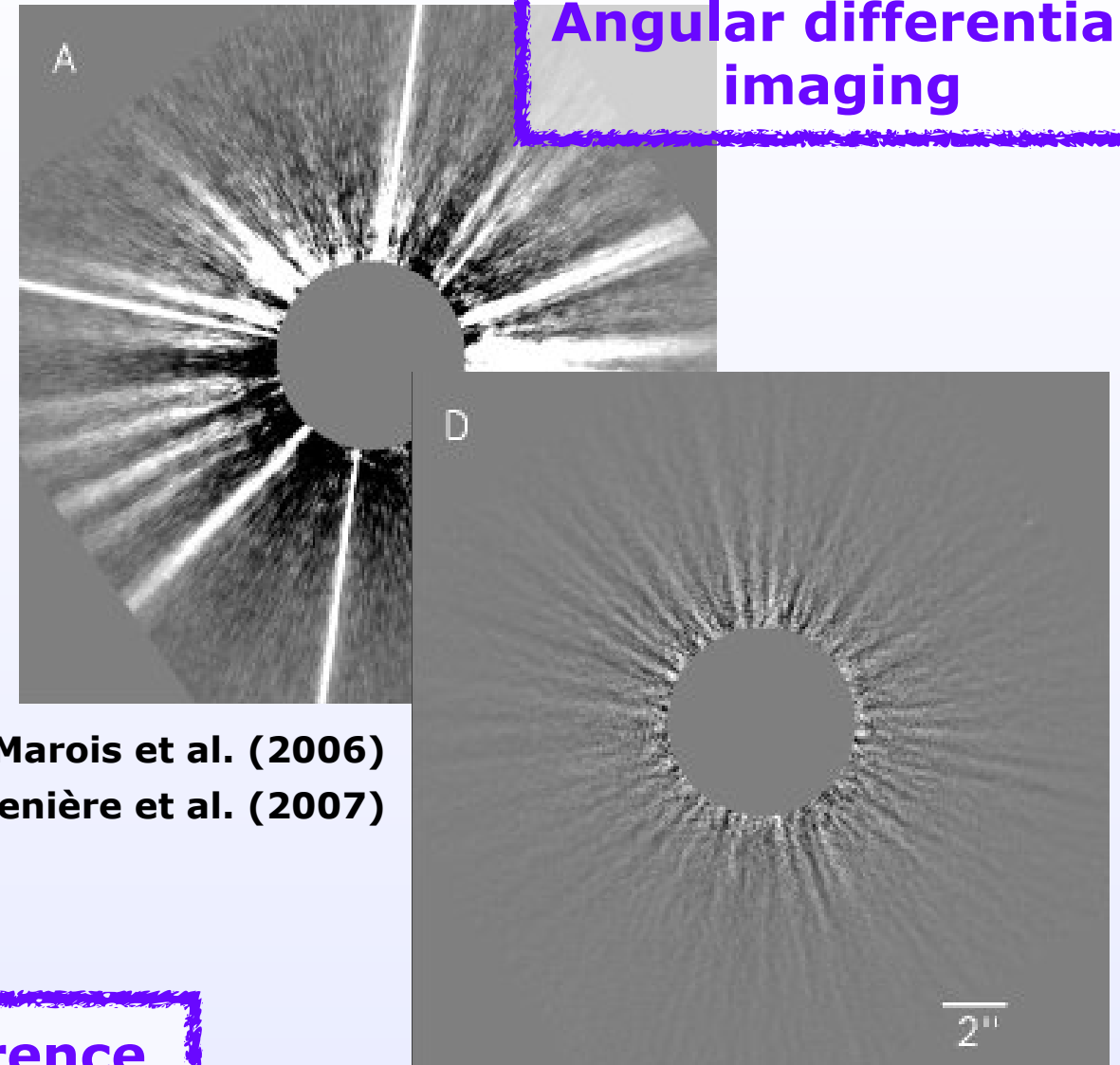
Xie et al. (2022)



Archival reference differential imaging

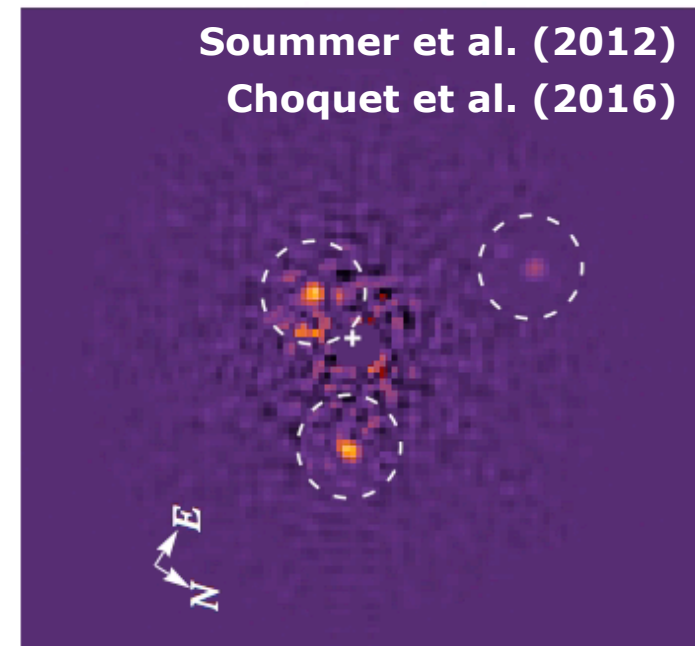


Angular differential imaging

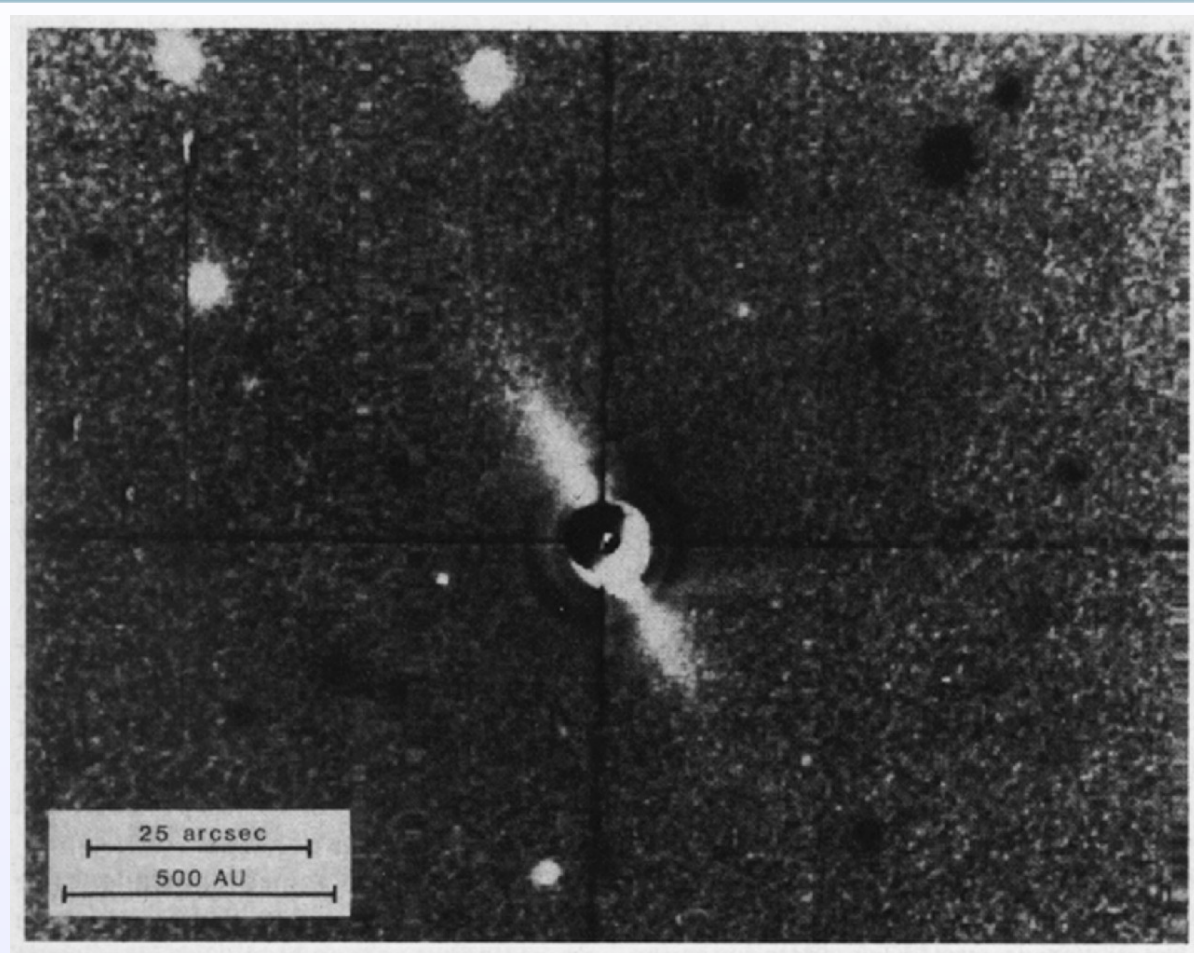


Marois et al. (2006)
Lafrenière et al. (2007)

Soummer et al. (2012)
Choquet et al. (2016)

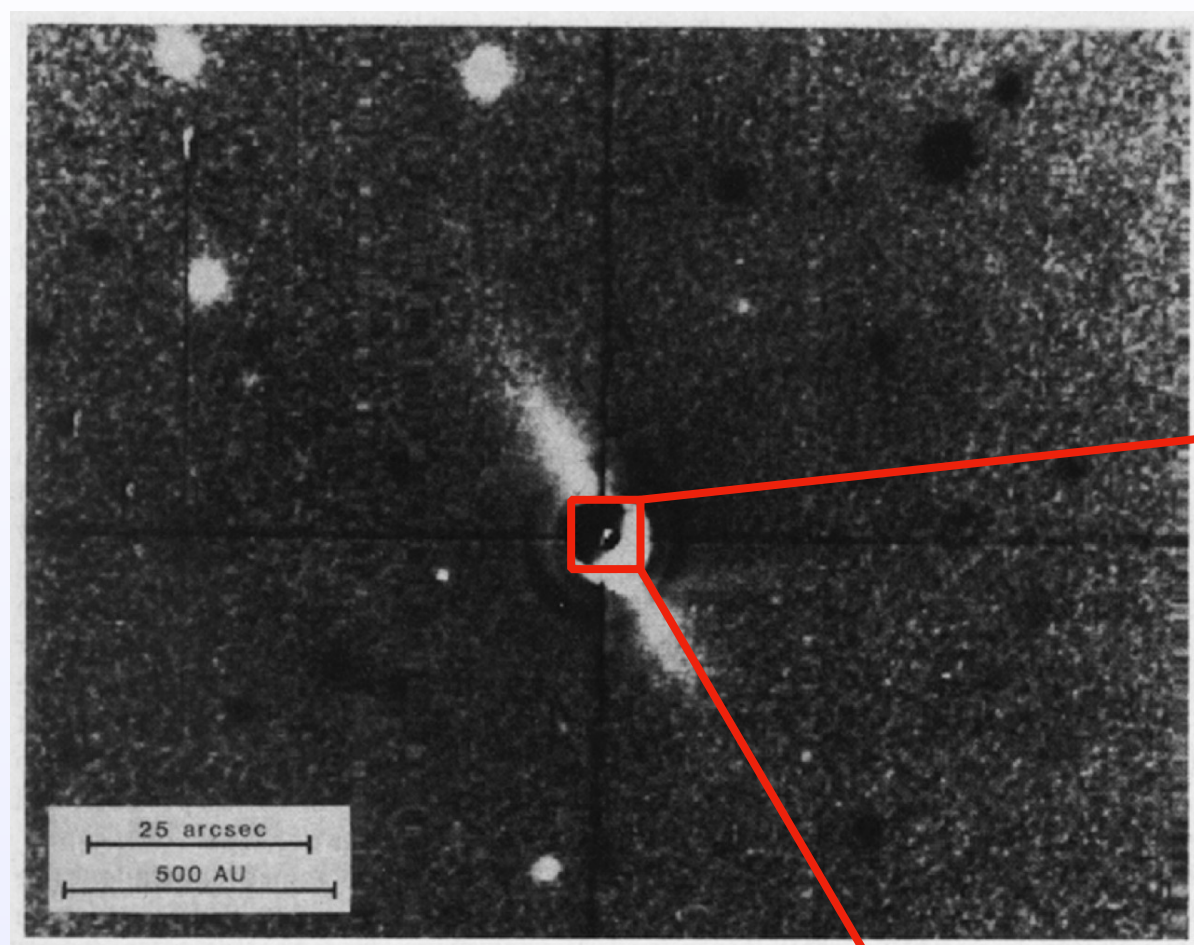


High-contrast imaging: from the 1980s to now



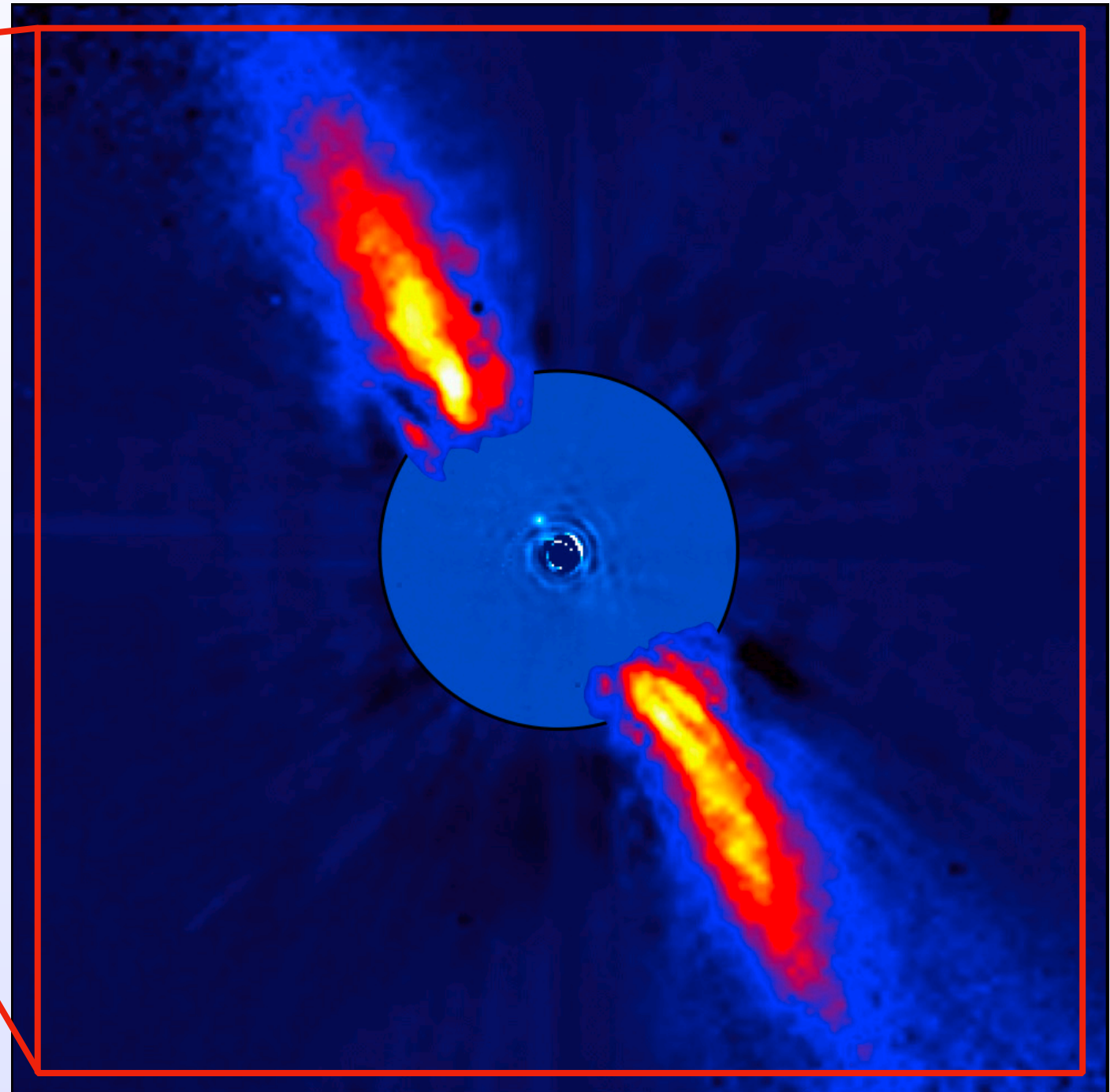
Smith & Terrile (1984)

High-contrast imaging: from the 1980s to now

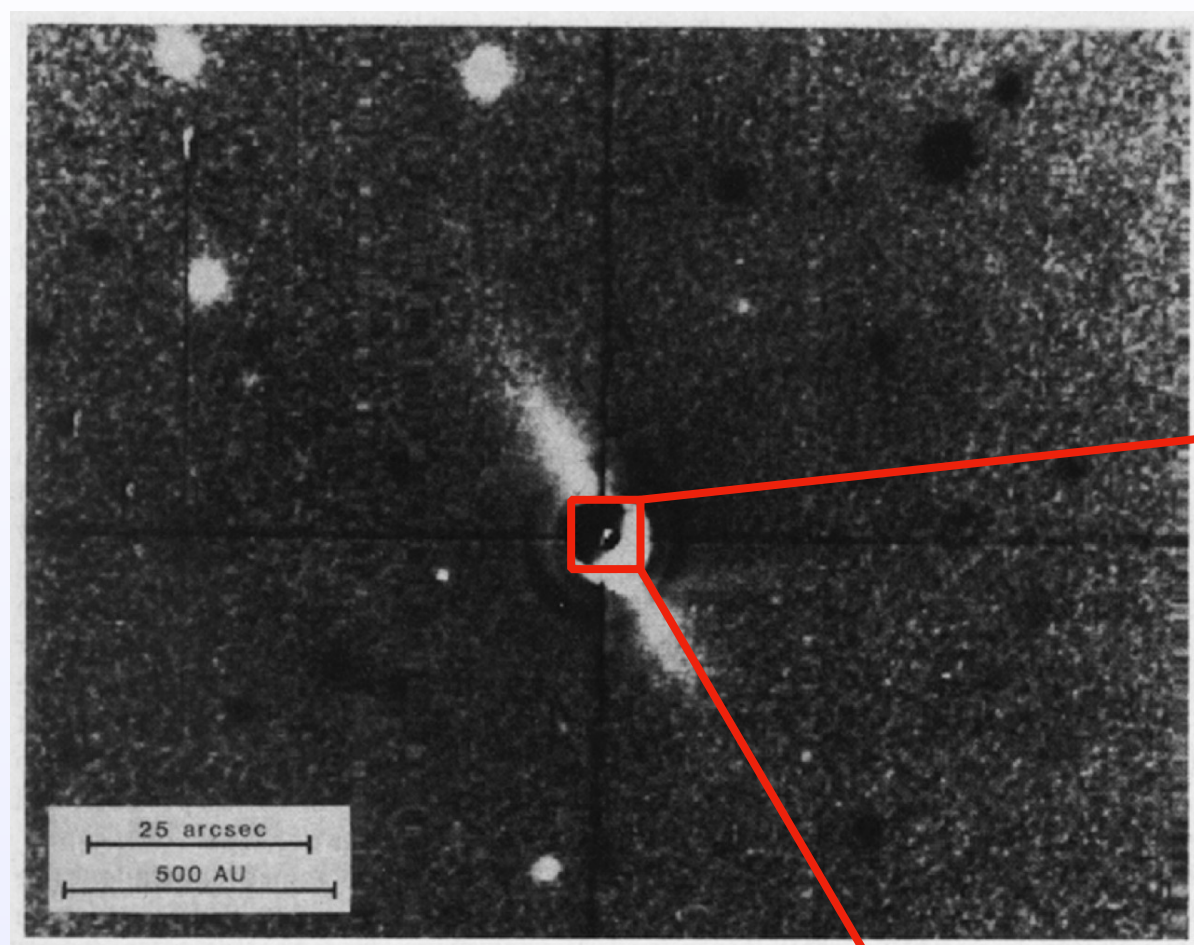


Smith & Terrile (1984)

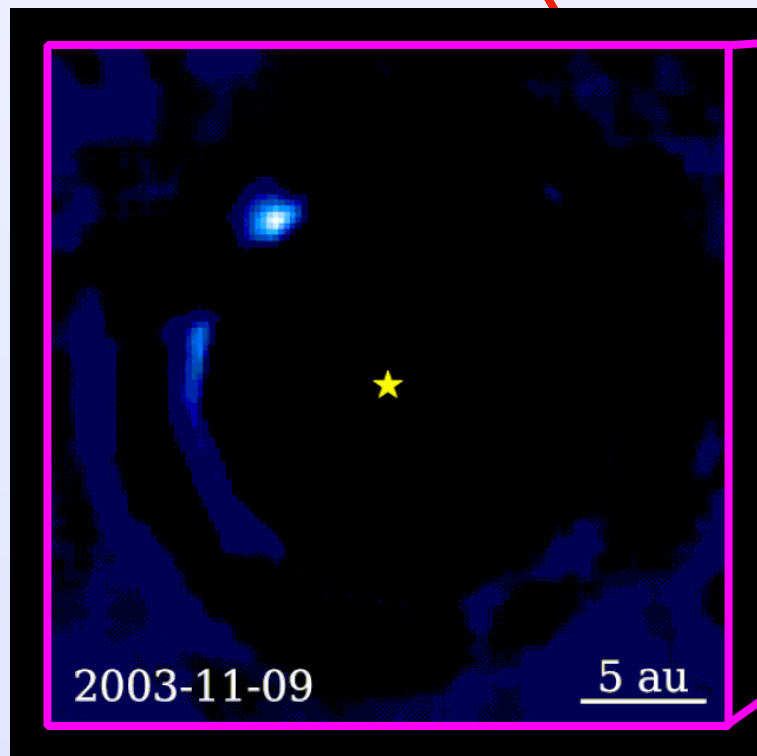
Lagrange et al. (2010)



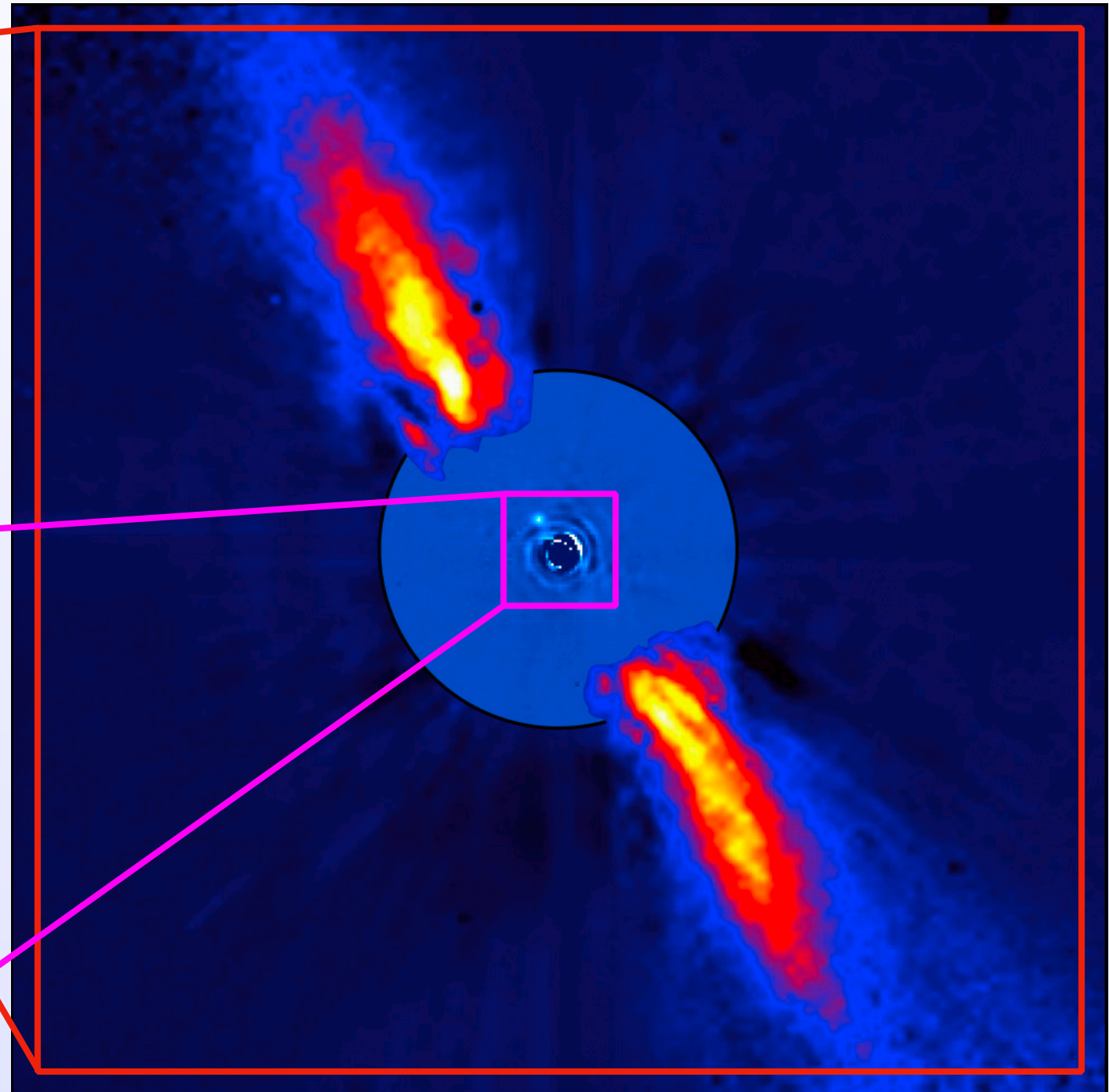
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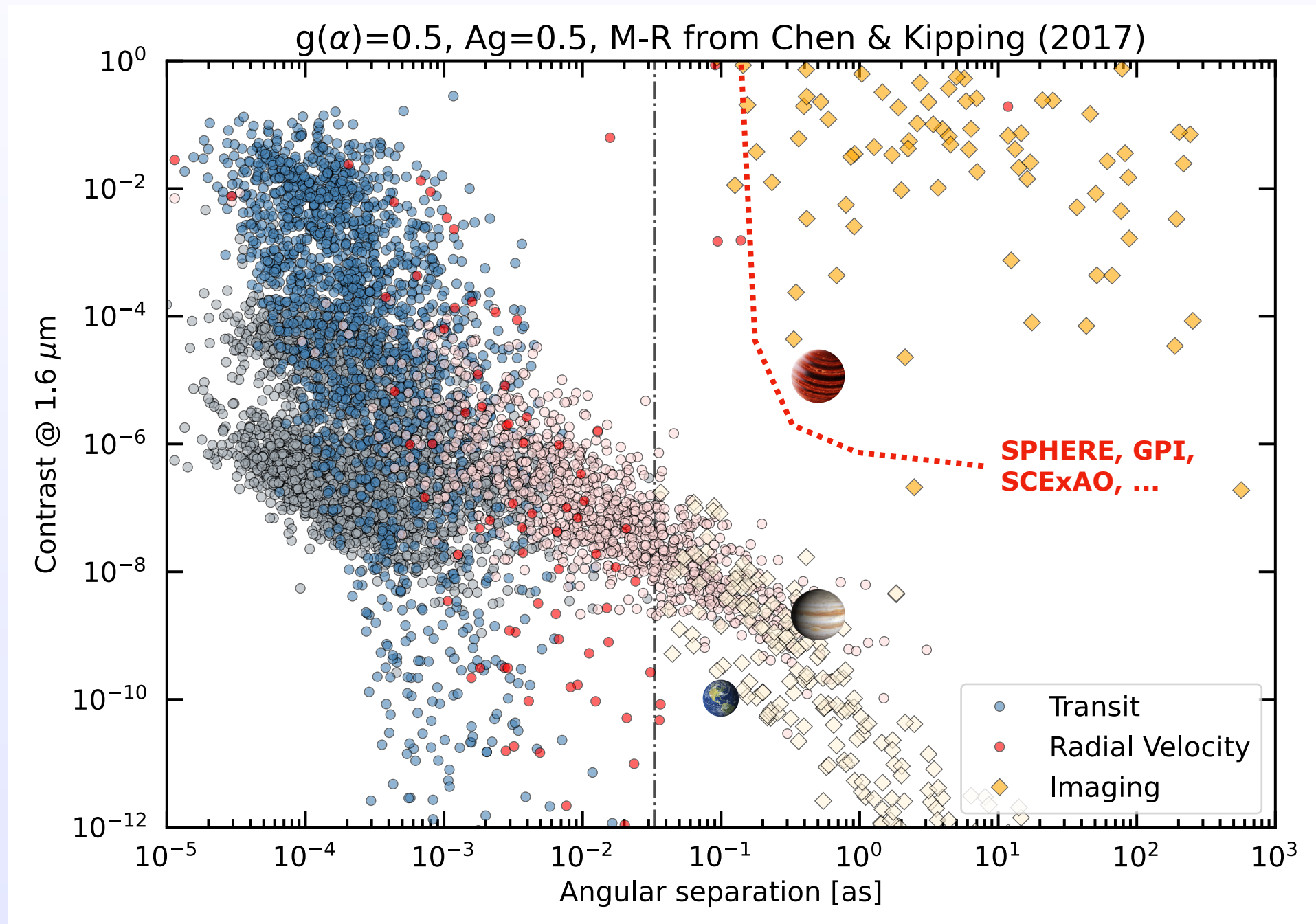
Smith & Terrile (1984)



Lagrange et al. (2010)



Where do we end up now in terms of contrast?

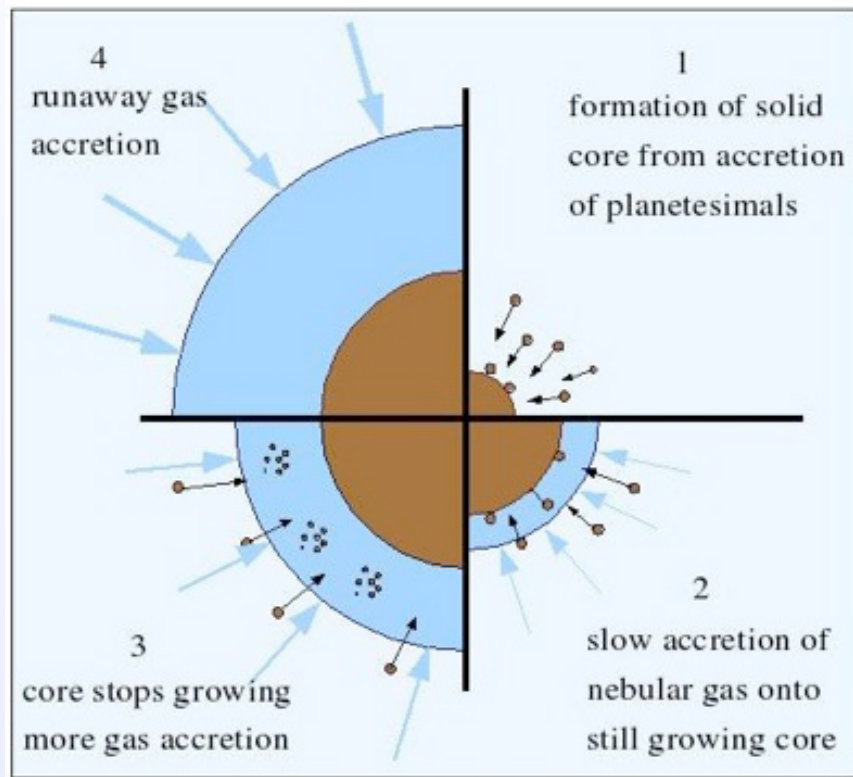


Can we constrain giant planet formation from imaging?

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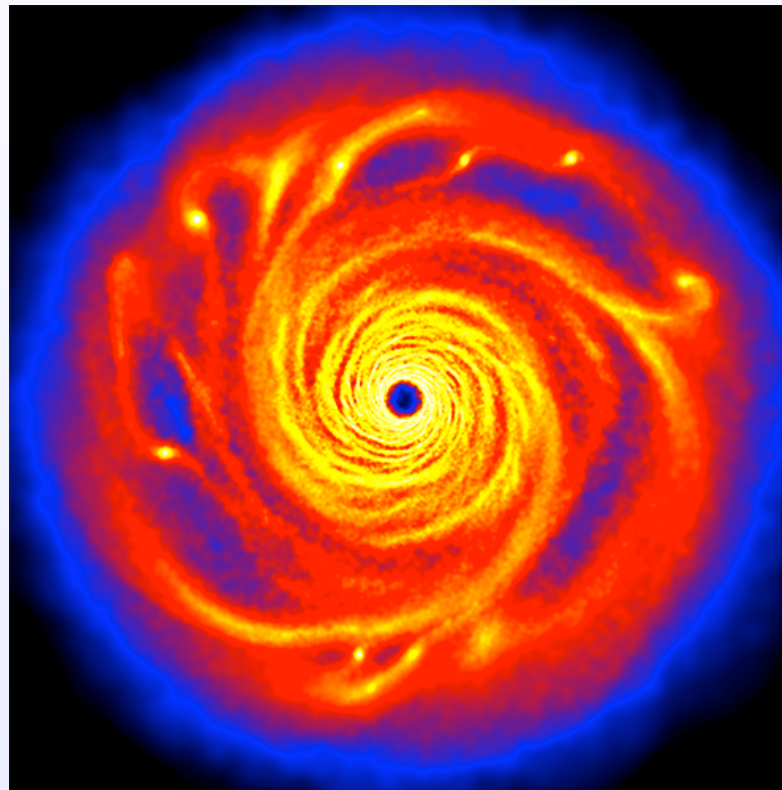
Core Accretion

Pollack et al. 1994



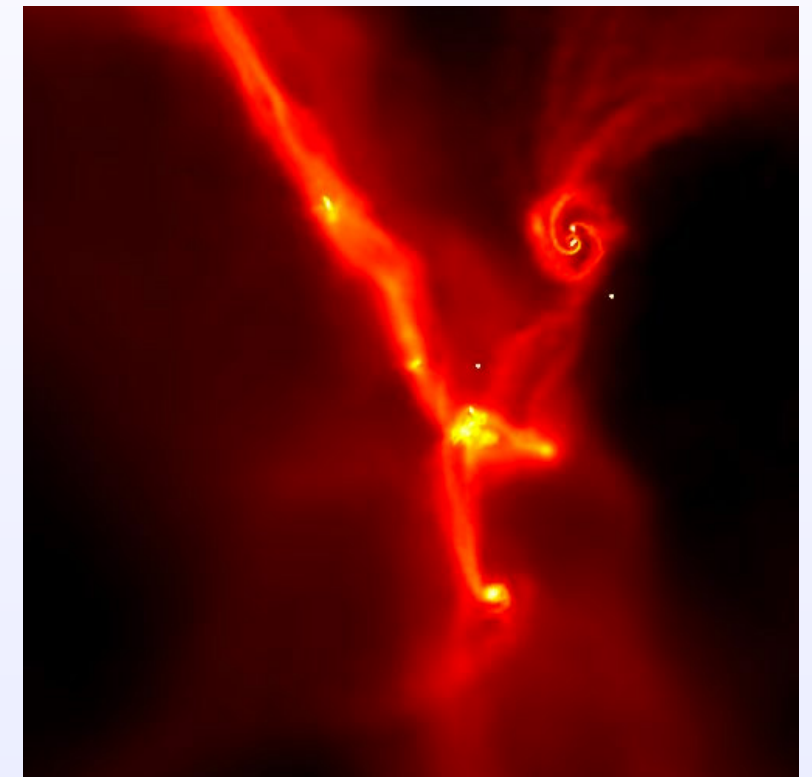
Gravitational Instability

Cameron 1978



Gravo-turbulent fragmentation

Hennebelle & Chabrier 2011



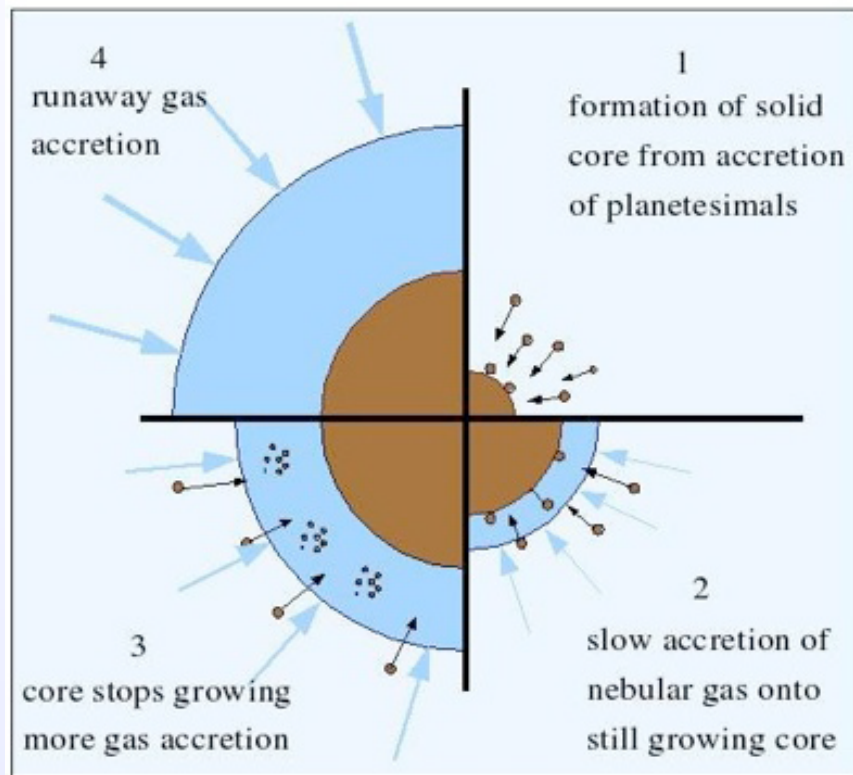
For planets formed differently we expect:

- Differences in composition
- Differences in population statistics (mass, semi-major axis, spectral type, ...)

Can we constrain giant planet formation from imaging?

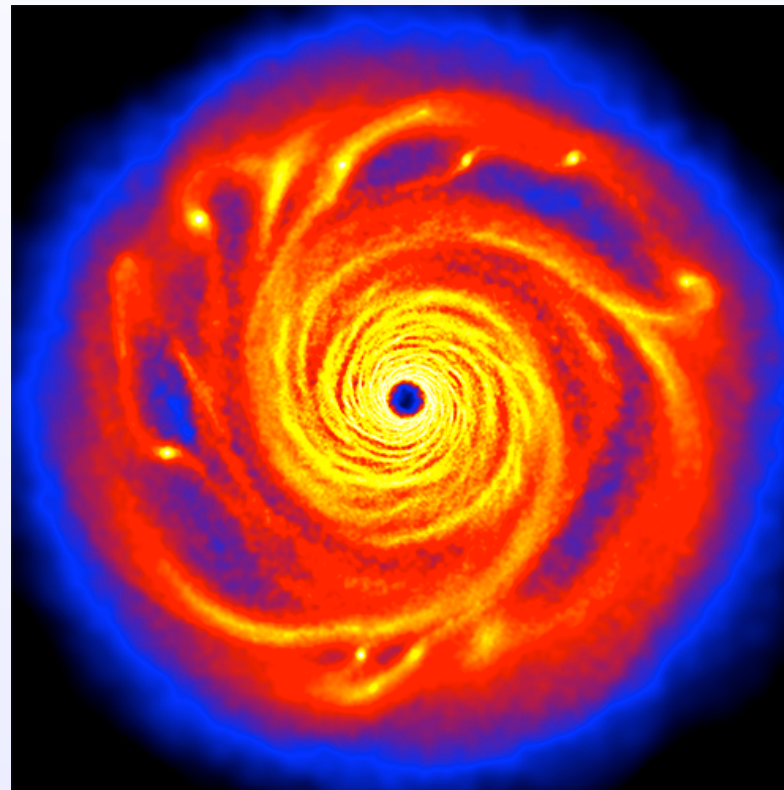
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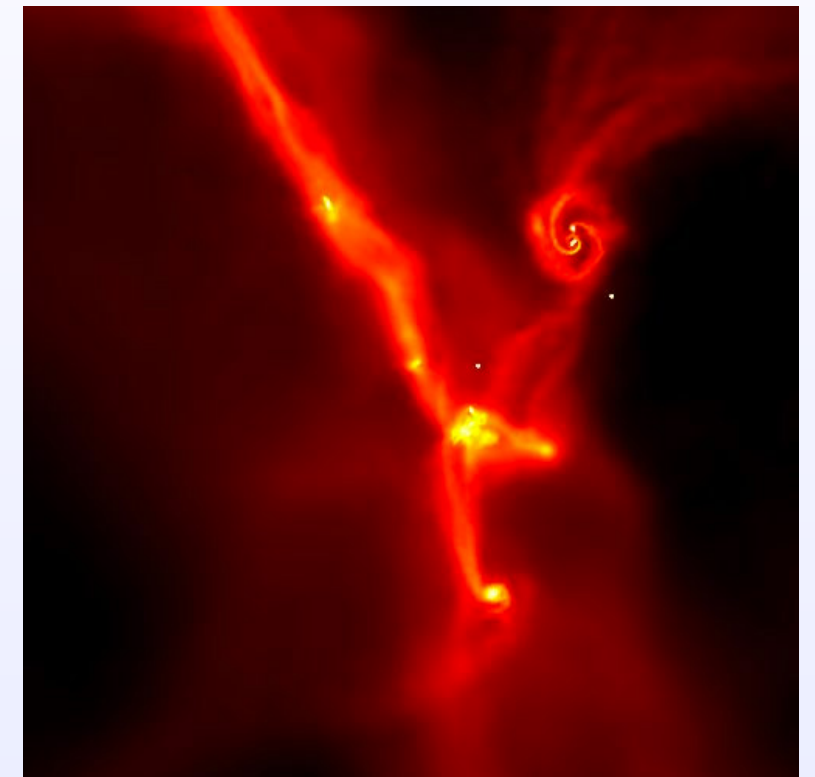
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- Differences in composition
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**Need for large surveys
to look for companions!**

Large imaging surveys

Reference	Telescope	Instr.	Mode	Filter	FoV ("×")	#	SpT	Age (Myr)
Chauvin et al. (2003)	ESO3.6m	ADONIS	Cor-I	<i>H, K</i>	13 × 13	29	GKM	≤50
Neuhäuser et al. (2003)	NTT	Sharp	Sat-I	<i>K</i>	11 × 11	23	AFGKM	≤50
	NTT	Sofi	Sat-I	<i>H</i>	13 × 13	10	AFGKM	≤50
Lowrance et al. (2005)	HST	NICMOS	Cor-I	<i>H</i>	19 × 19	45	AFGKM	10–600
Masciadri et al. (2005)	VLT	NaCo	Sat-I	<i>H, K</i>	14 × 14	28	KM	≤200
Biller et al. (2007)	VLT	NaCo	SDI	<i>H</i>	5 × 5	45	GKM	≤300
	MMT		SDI	<i>H</i>	5 × 5	–	–	–
Kasper et al. (2007)	VLT	NaCo	Sat-I	<i>L'</i>	28 × 28	22	GKM	≤50
Lafrenière et al. (2007)	Gemini-N	NIRI	ADI	<i>H</i>	22 × 22	85		10–5000
Apai et al. (2008) ^a	VLT	NaCo	SDI	<i>H</i>	3 × 3	8	FG	12–500
Chauvin et al. (2010)	VLT	NaCo	Cor-I	<i>H, K</i>	28 × 28	88	BAFGKM	≤100
Heinze et al. (2010a,b)	MMT	Clio	ADI	<i>L', M</i>	15.5 × 12.4	54	FGK	100–5000
Janson et al. (2011)	Gemini-N	NIRI	ADI	<i>H, K</i>	22 × 22	15	BA	20–700
Vigan et al. (2012)	Gemini-N	NIRI	ADI	<i>H, K</i>	22 × 22	42	AF	10–400
	VLT	NaCo	ADI	<i>H, K</i>	14 × 14	–	–	–
Delorme et al. (2012)	VLT	NaCo	ADI	<i>L'</i>	28 × 28	16	M	≤200
Rameau et al. (2013c)	VLT	NaCo	ADI	<i>L'</i>	28 × 28	59	AF	≤200
Yamamoto et al. (2013)	Subaru	HiCIAO	ADI	<i>H, K</i>	20 × 20	20	FG	125 ± 8
Biller et al. (2013)	Gemini-S	NICI	Cor-ASDI	<i>H</i>	18 × 18	80	BAFGKM	≤200
Brandt et al. (2013)	Subaru	HiCIAO	ADI	<i>H</i>	20 × 20	63	AFGKM	≤500
Nielsen et al. (2013)	Gemini-S	NICI	Cor-ASDI	<i>H</i>	18 × 18	70	BA	50–500
Wahhaj et al. (2013) ^a	Gemini-S	NICI	Cor-ASDI	<i>H</i>	18 × 18	57	AFGKM	~100
Janson et al. (2013) ^a	Subaru	HiCIAO	ADI	<i>H</i>	20 × 20	50	AFGKM	≤1000

Before 2015

>25 AO-assisted surveys since 2003

~20 known companions

Large imaging surveys

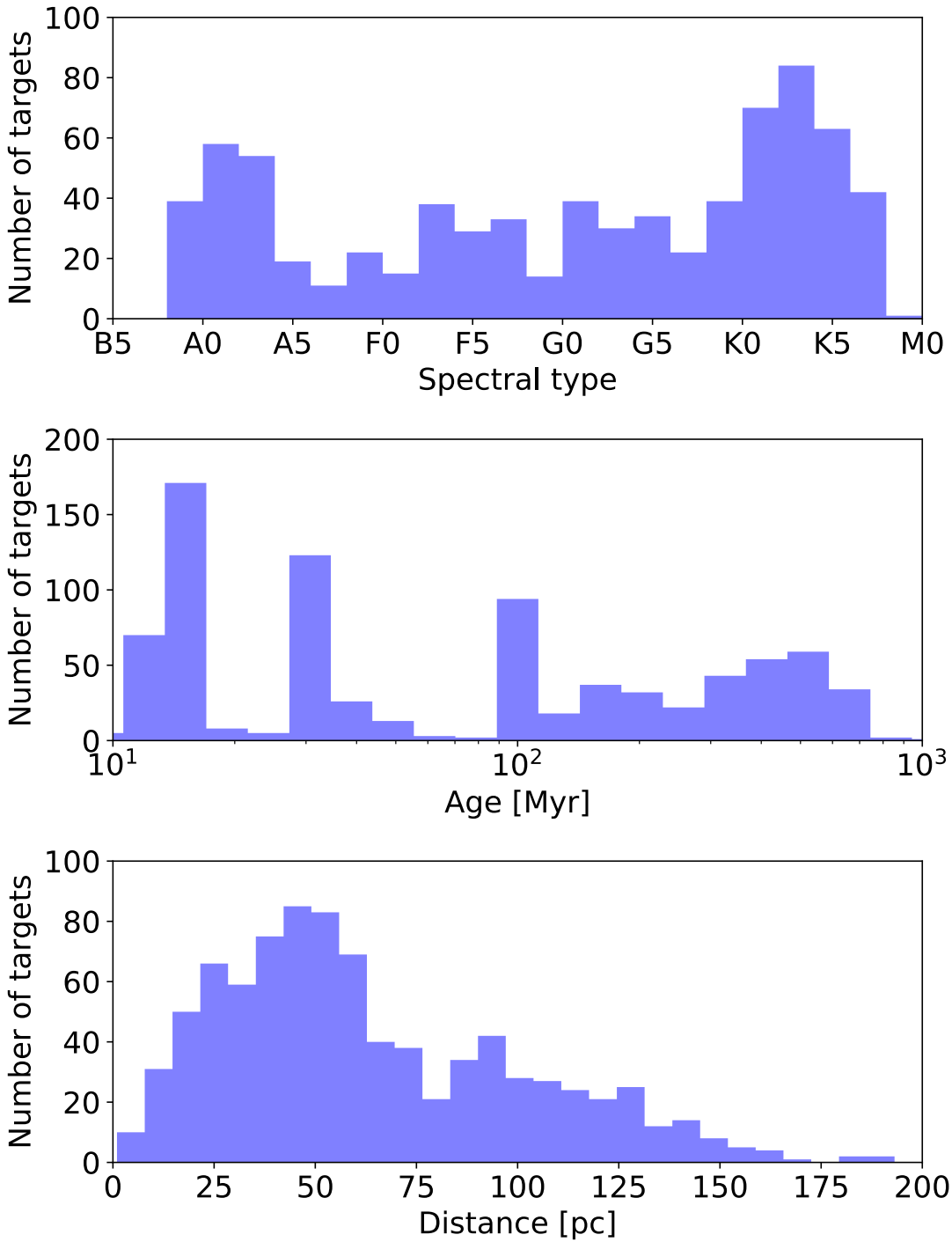
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+Galicher et al. (2016), Vigan et al. (2017), Meshkat et al. (2016, 2017), Durkan et al. (2016), Nielsen et al. (2019), Vigan et al. (2021), Bonavita et al. (2022), Delorme et al. (2024), Squicciarini et al. (2025), Chomez et al. (2025), ...

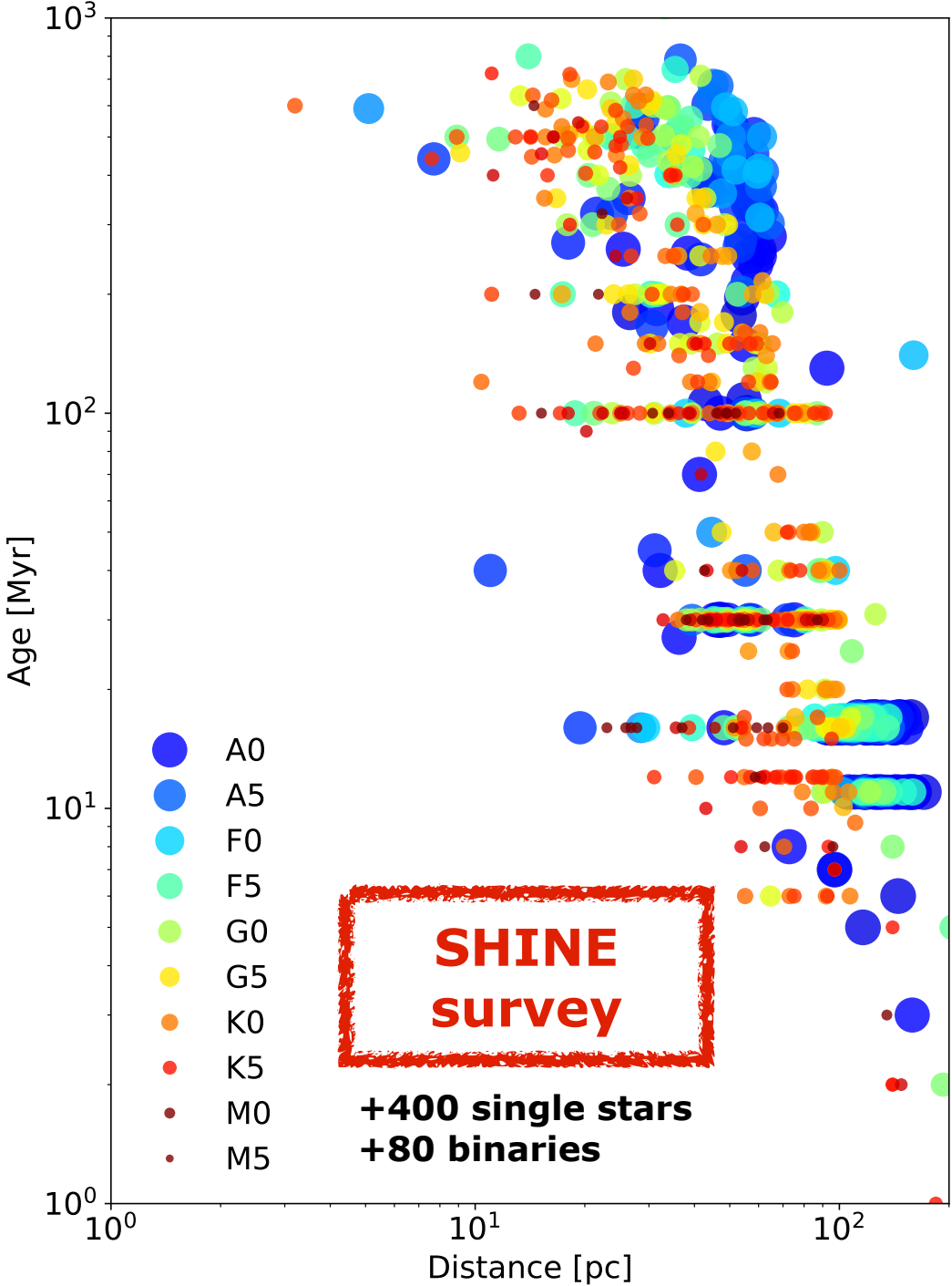
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Masciadri et al. (2005)	V							
Biller et al. (2007)	V							
	V							
Kasper et al. (2007)	V							
Lafrenière et al. (2007)	C							
Apai et al. (2008) ^a	V							
Chauvin et al. (2010)	V							
Heinze et al. (2010a,b)	M							
Janson et al. (2011)	C							
Vigan et al. (2012)	C							
	V							
Delorme et al. (2012)	V							
Rameau et al. (2013c)	V							
Yamamoto et al. (2013)	S							
Biller et al. (2013)	C							
Brandt et al. (2013)	S							
Nielsen et al. (2013)	C							
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Janson et al. (2013) ^a	S							

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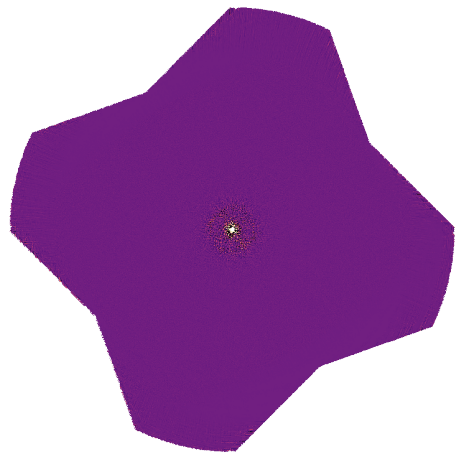
+ GPIES
survey



Population analysis from large imaging surveys

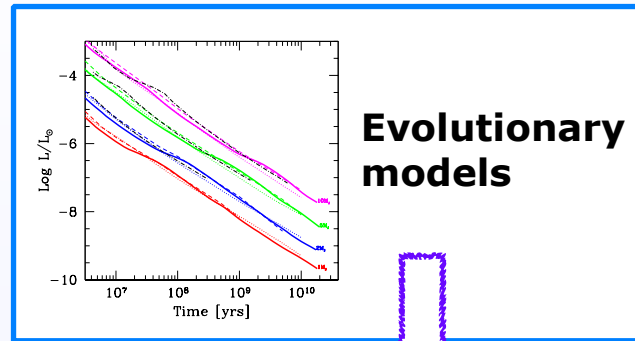
Population analysis from large imaging surveys

Images [ADU]

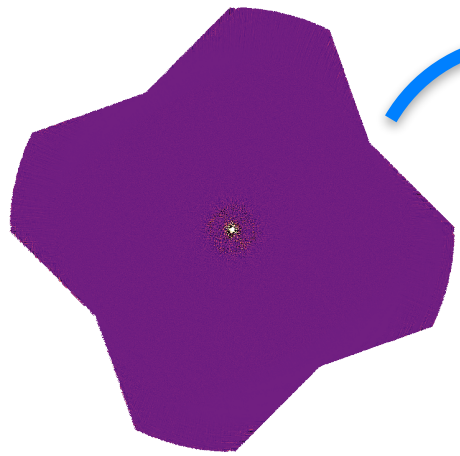


Targets with
non-detections

Population analysis from large imaging surveys

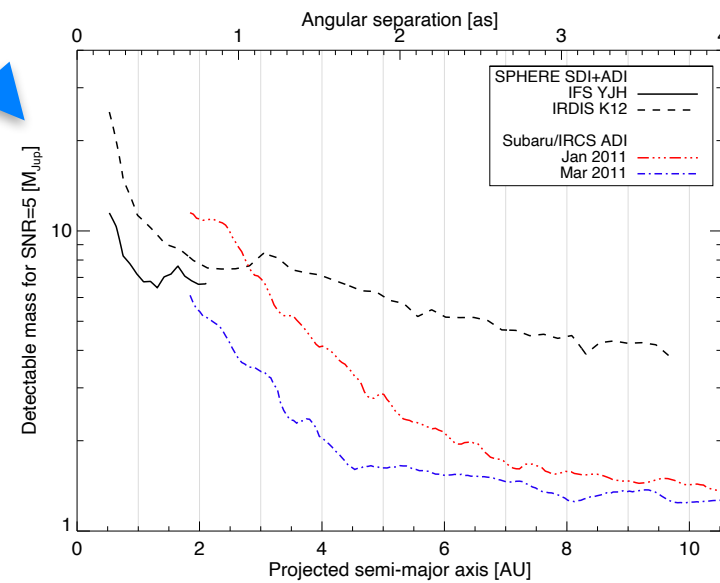


Images [ADU]

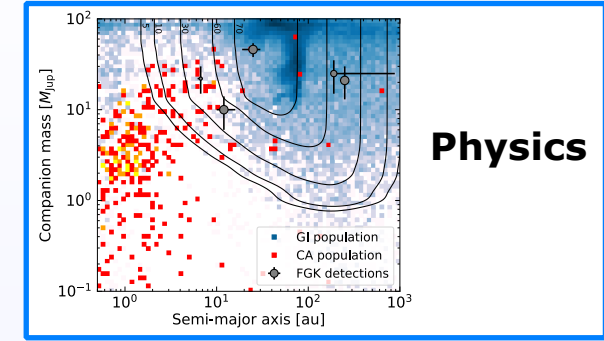
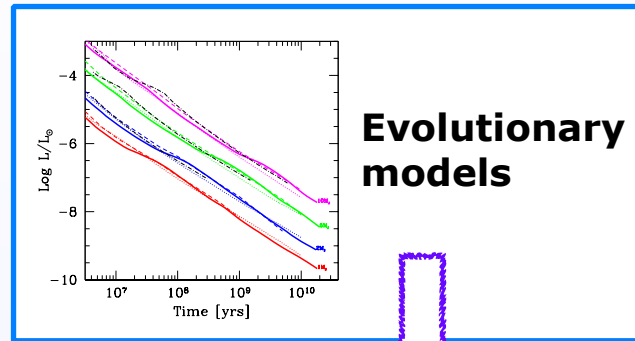


Targets with non-detections

Detection limits (mass vs. sma)



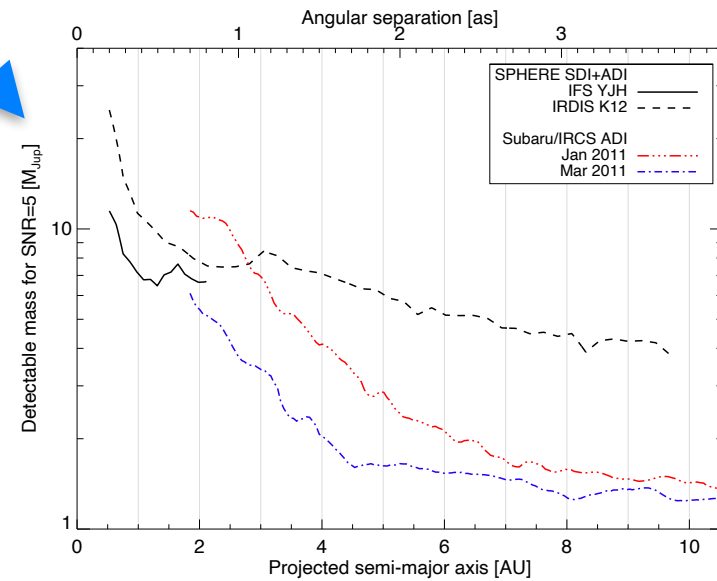
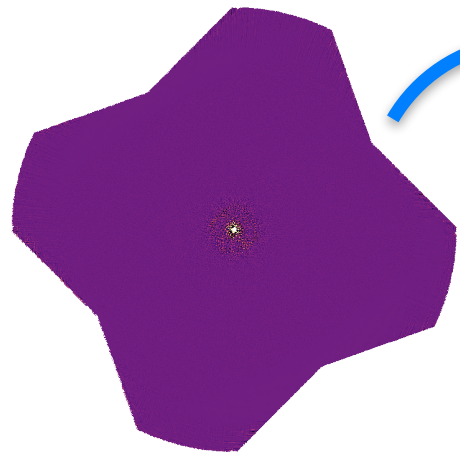
Population analysis from large imaging surveys



MC
sims

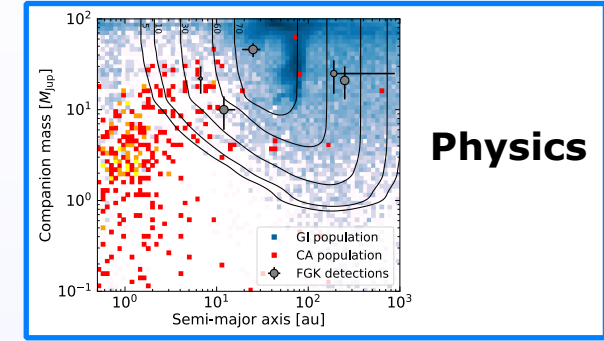
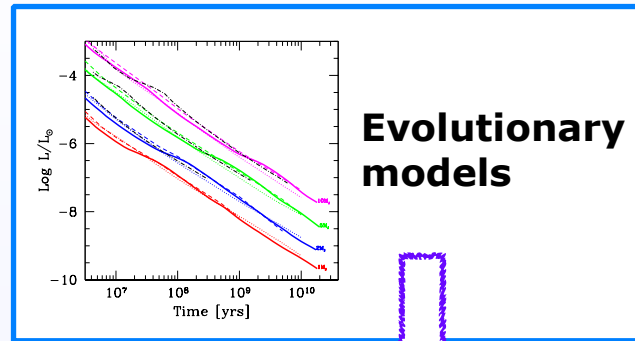
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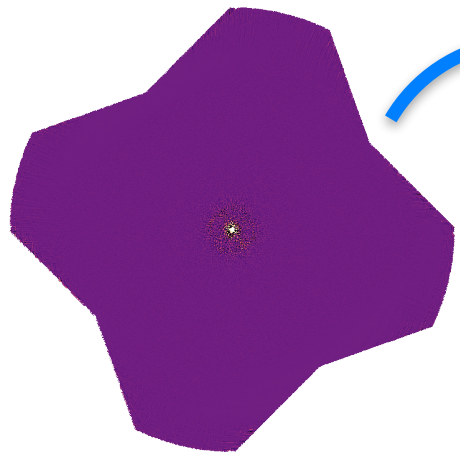
Targets with
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Population analysis from large imaging surveys



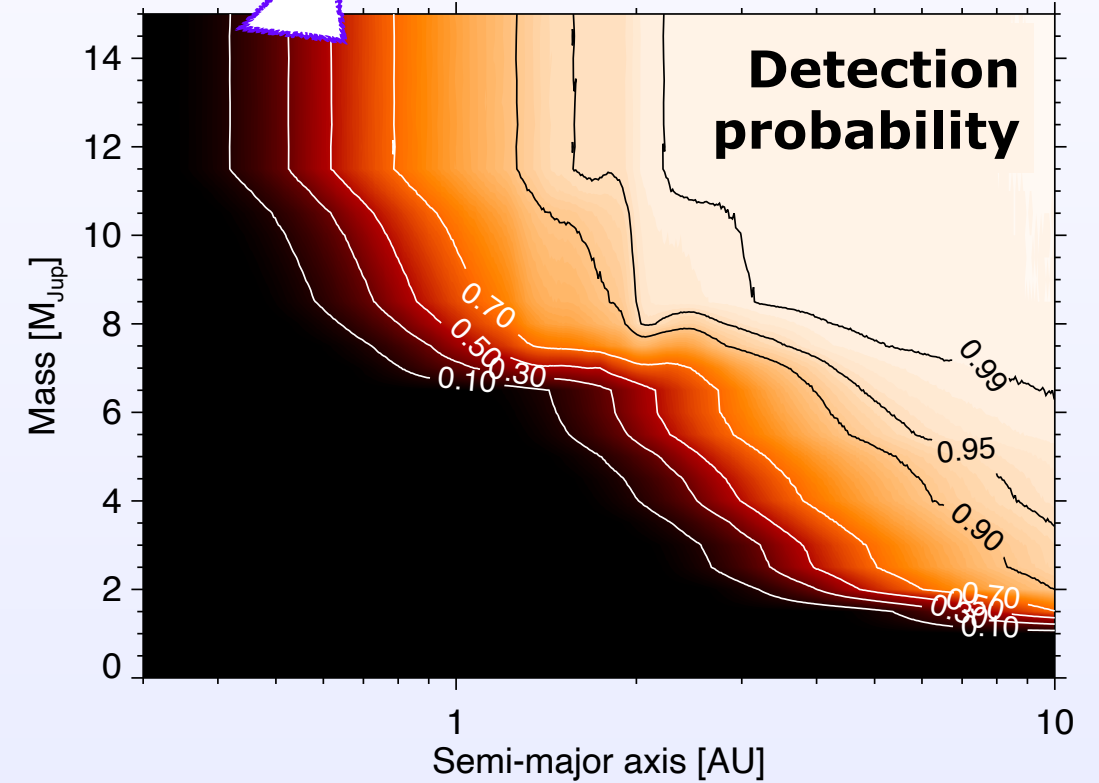
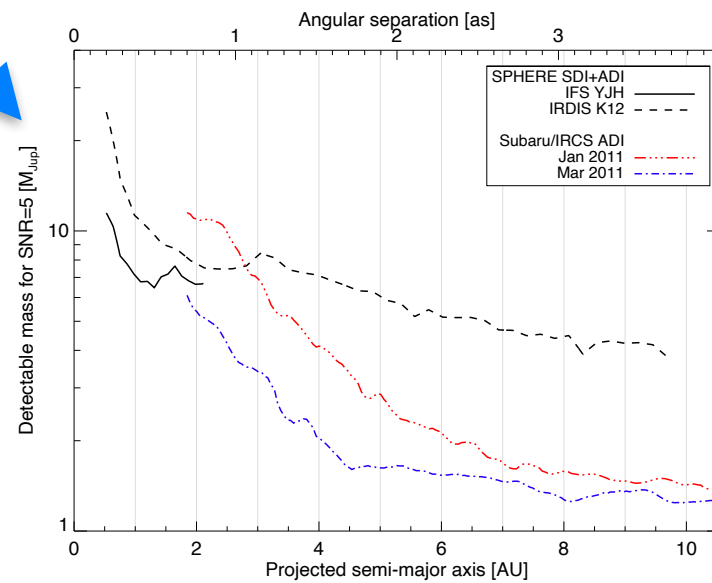
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sims

Images [ADU]

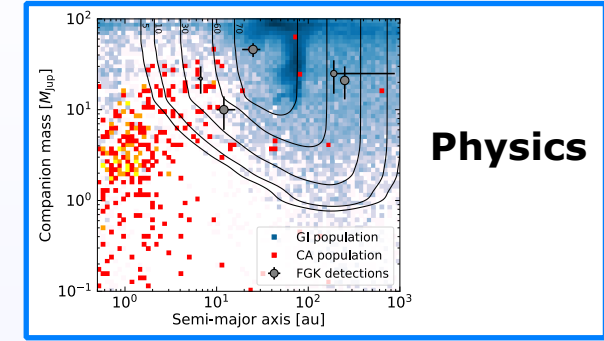
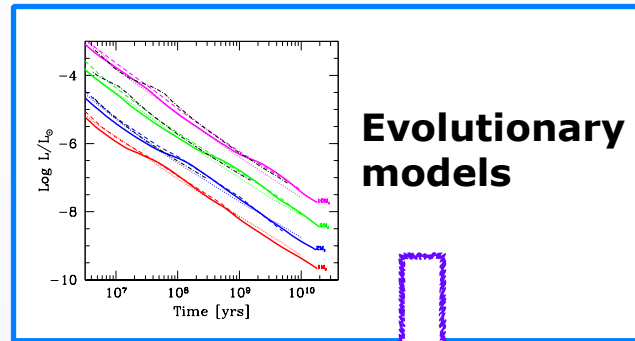


Targets with
non-detections

Detection limits (mass vs. sma)

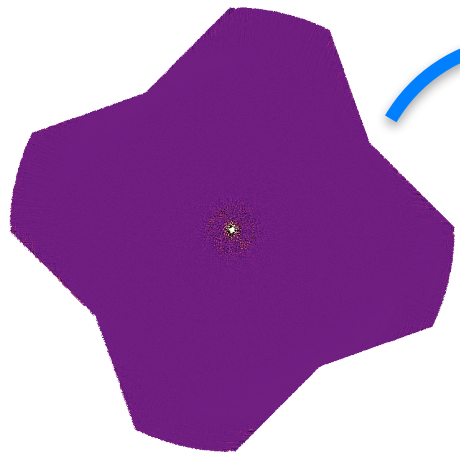


Population analysis from large imaging surveys

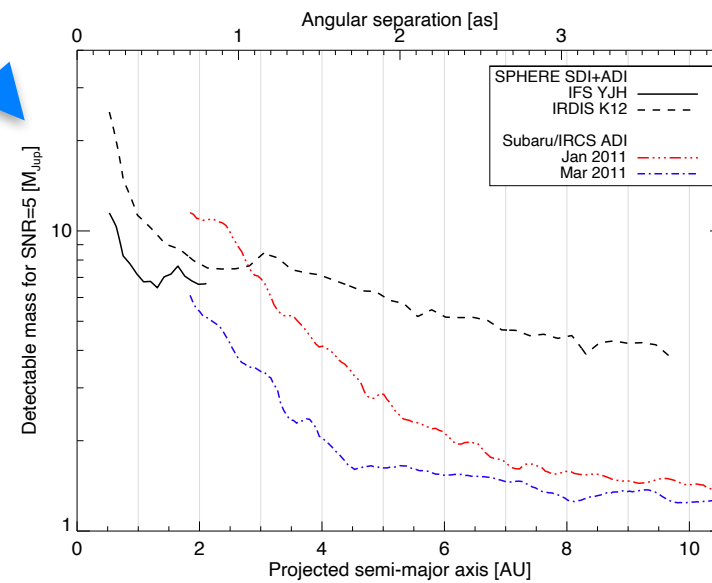


**MC
sims**

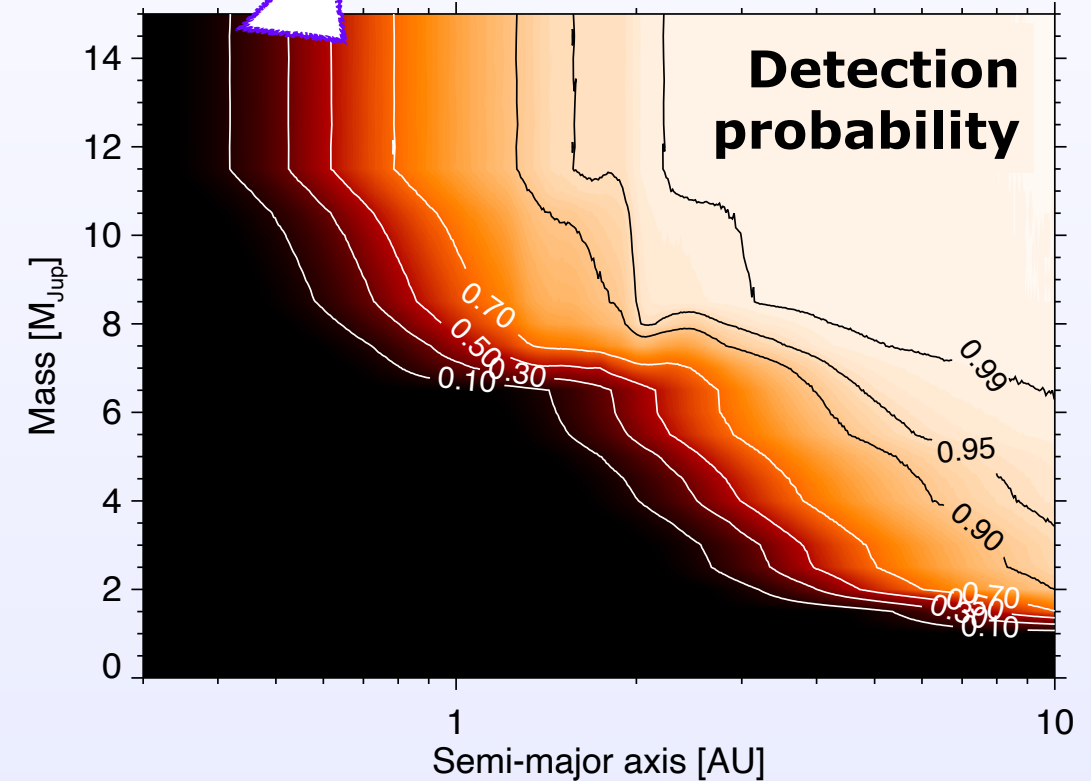
Images [ADU]



Detection limits (mass vs. sma)

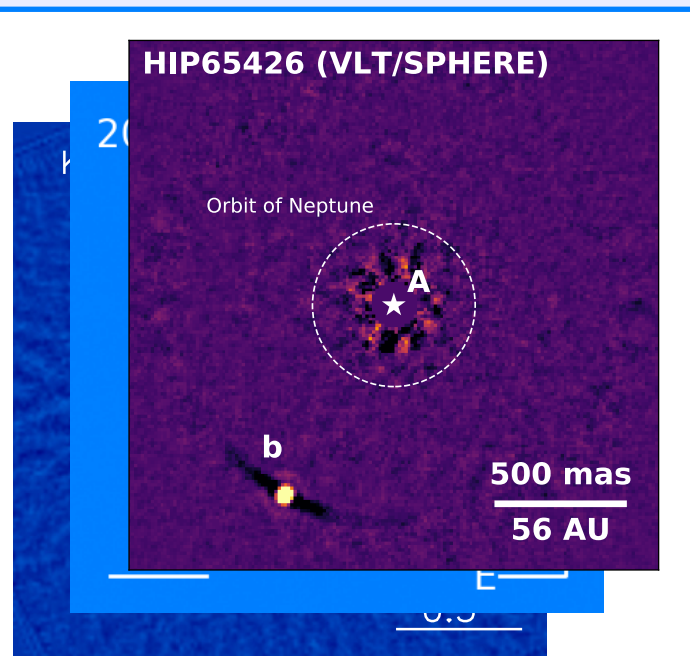


**Detection
probability**

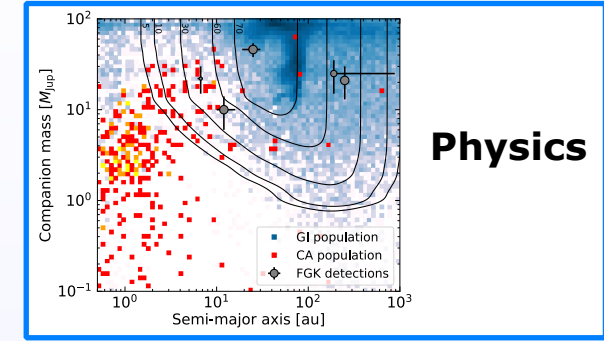
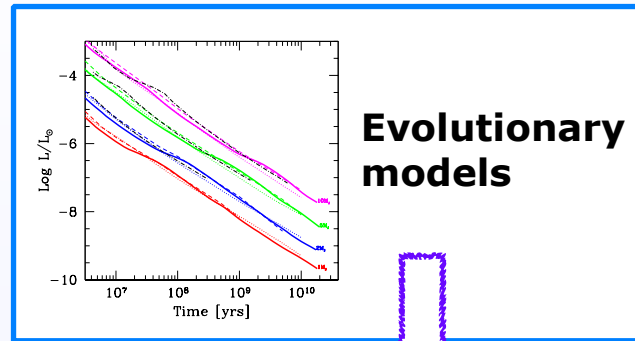


**Targets with
non-detections**

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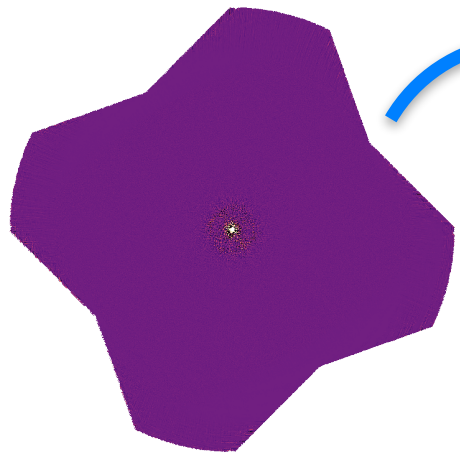


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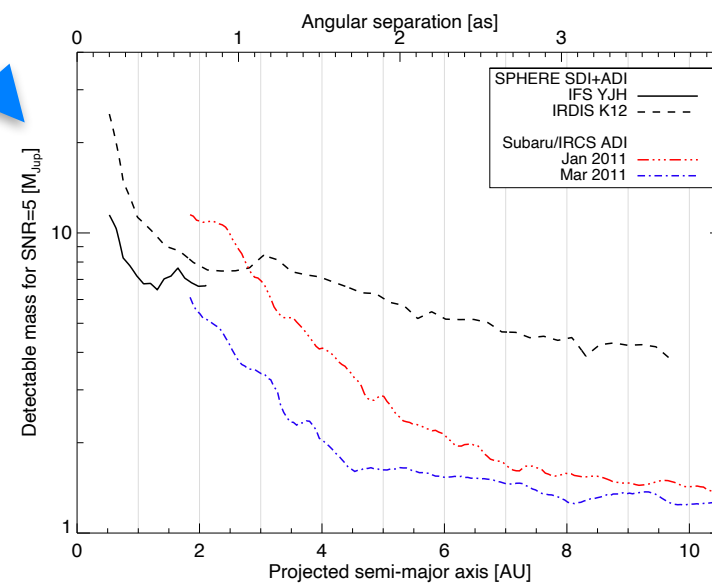


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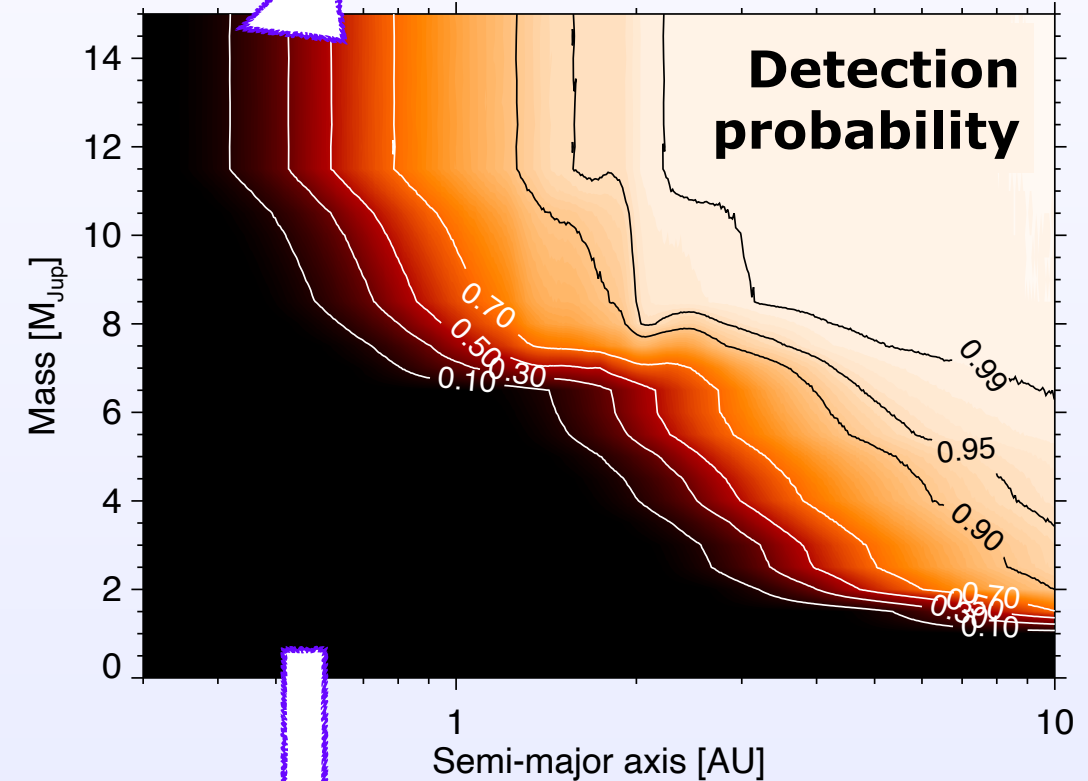
Images [ADU]



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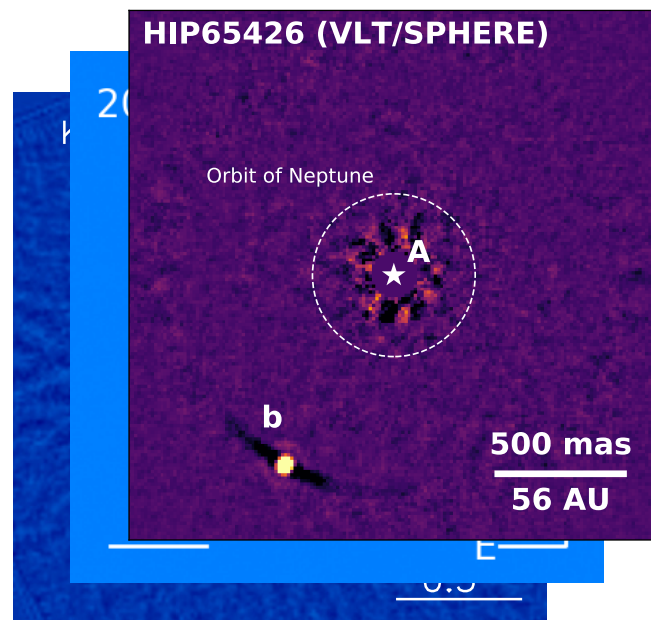


**Detection
probability**



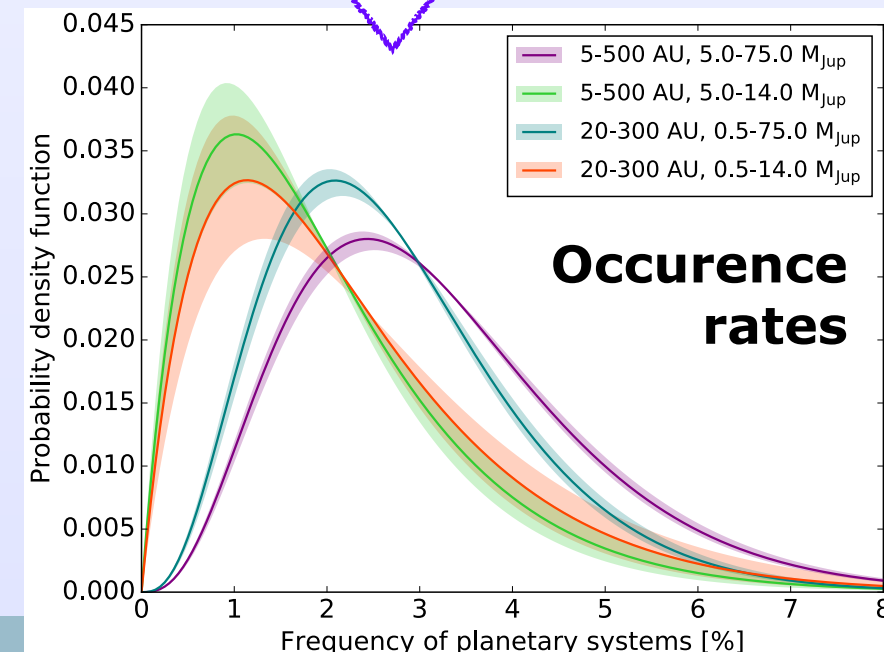
**Targets with
non-detections**

HIP65426 (VLT/SPHERE)

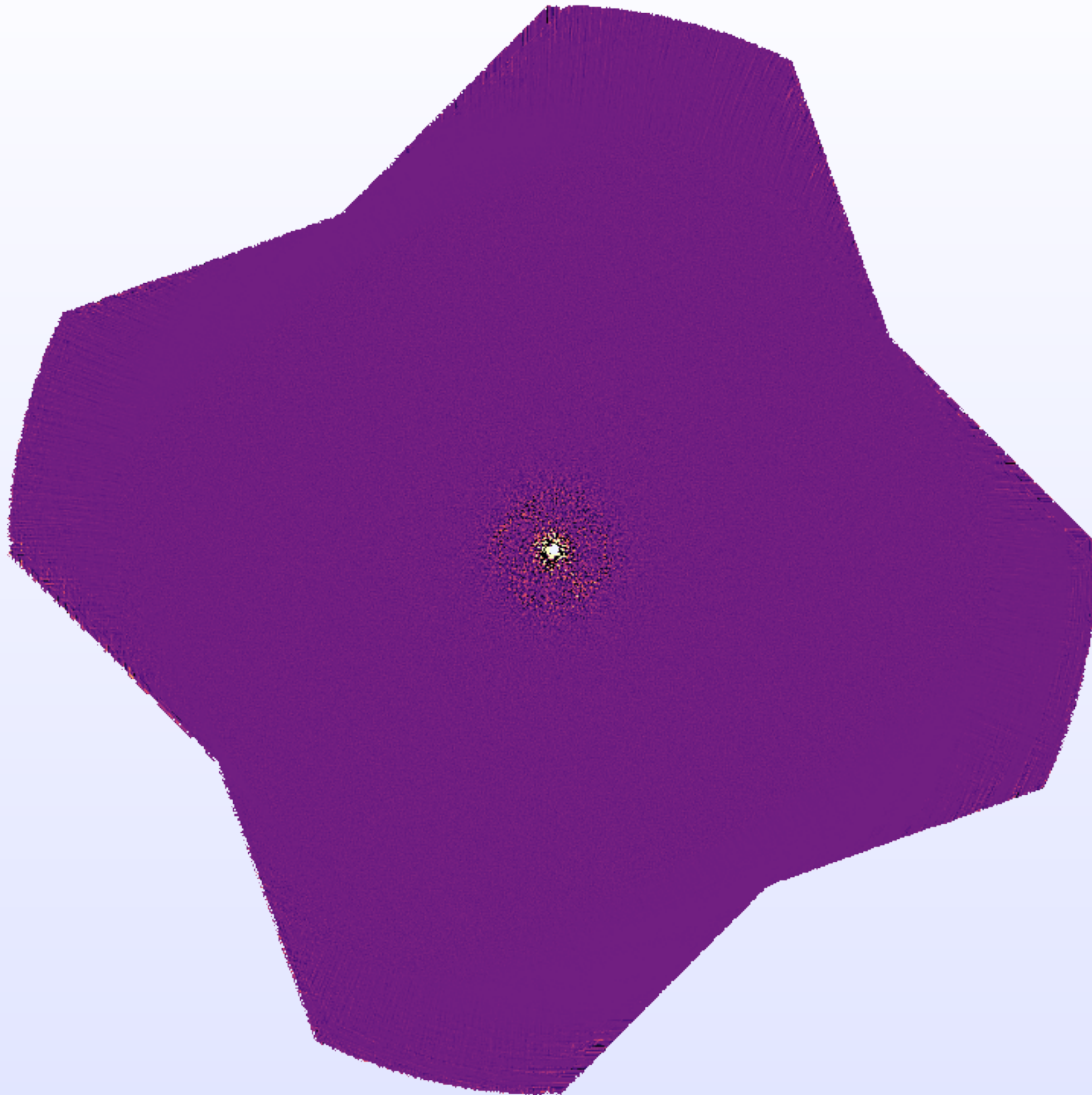


**Targets with
detections**

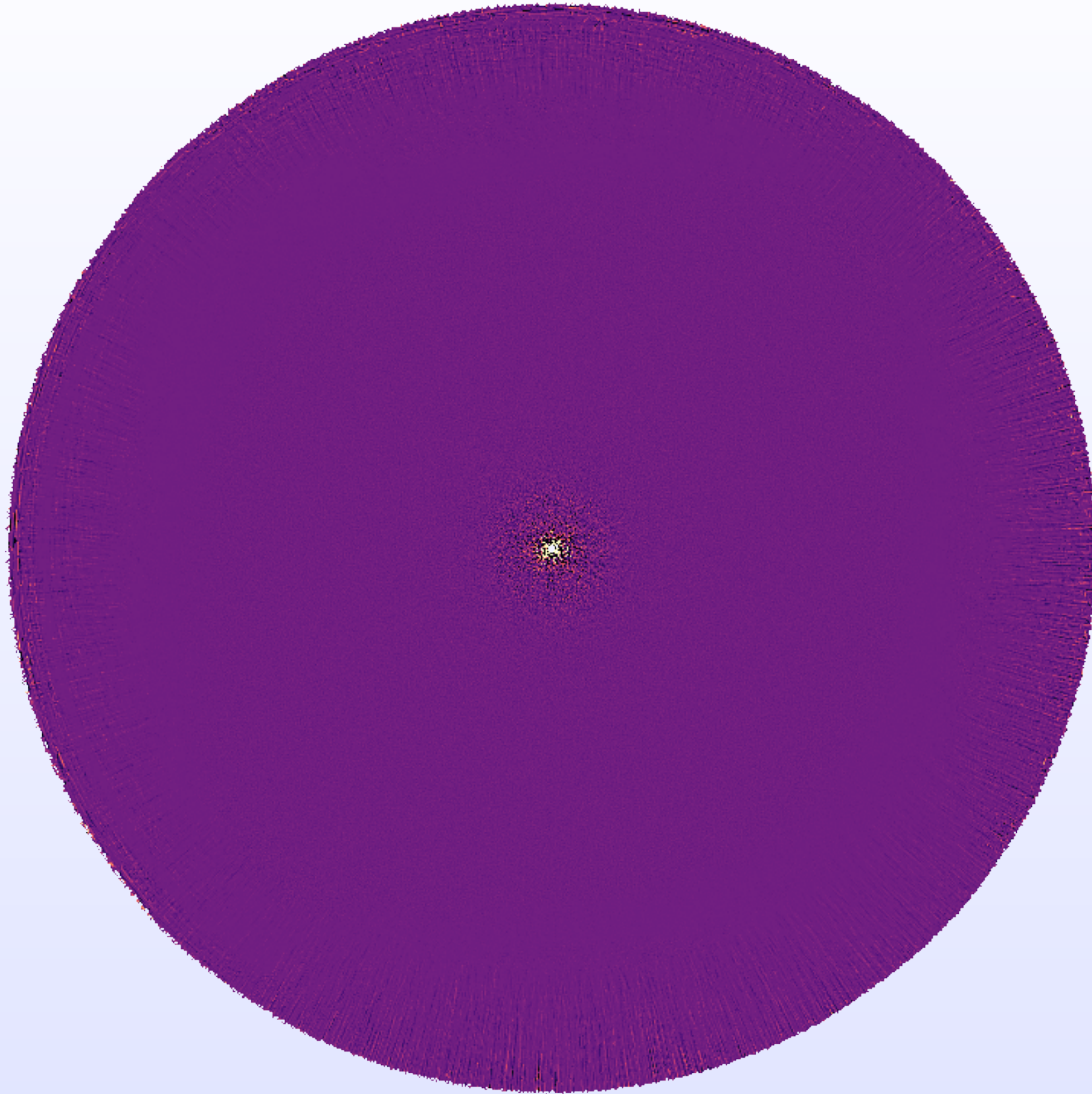
**Occurrence
rates**



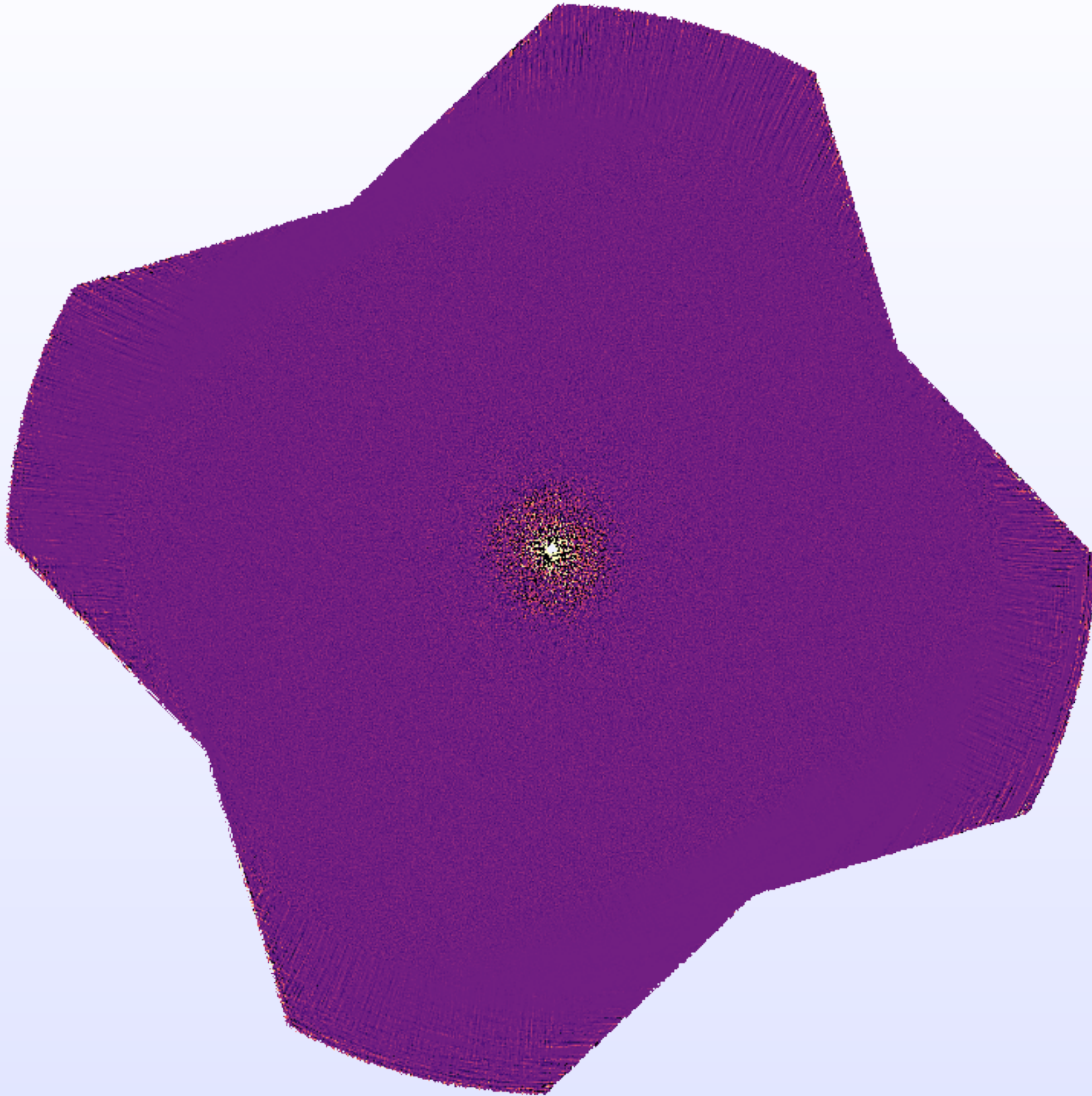
The search for planets



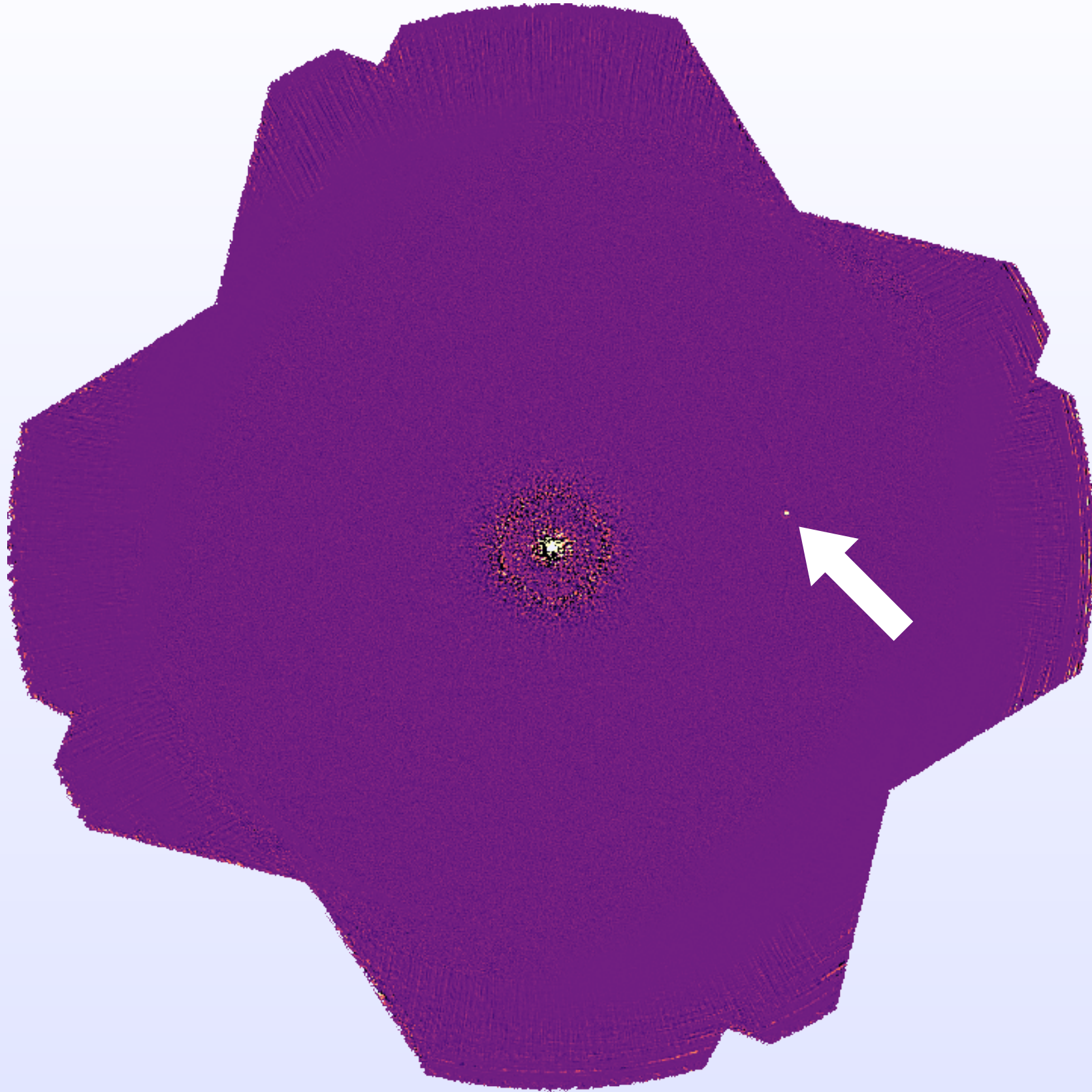
The search for planets



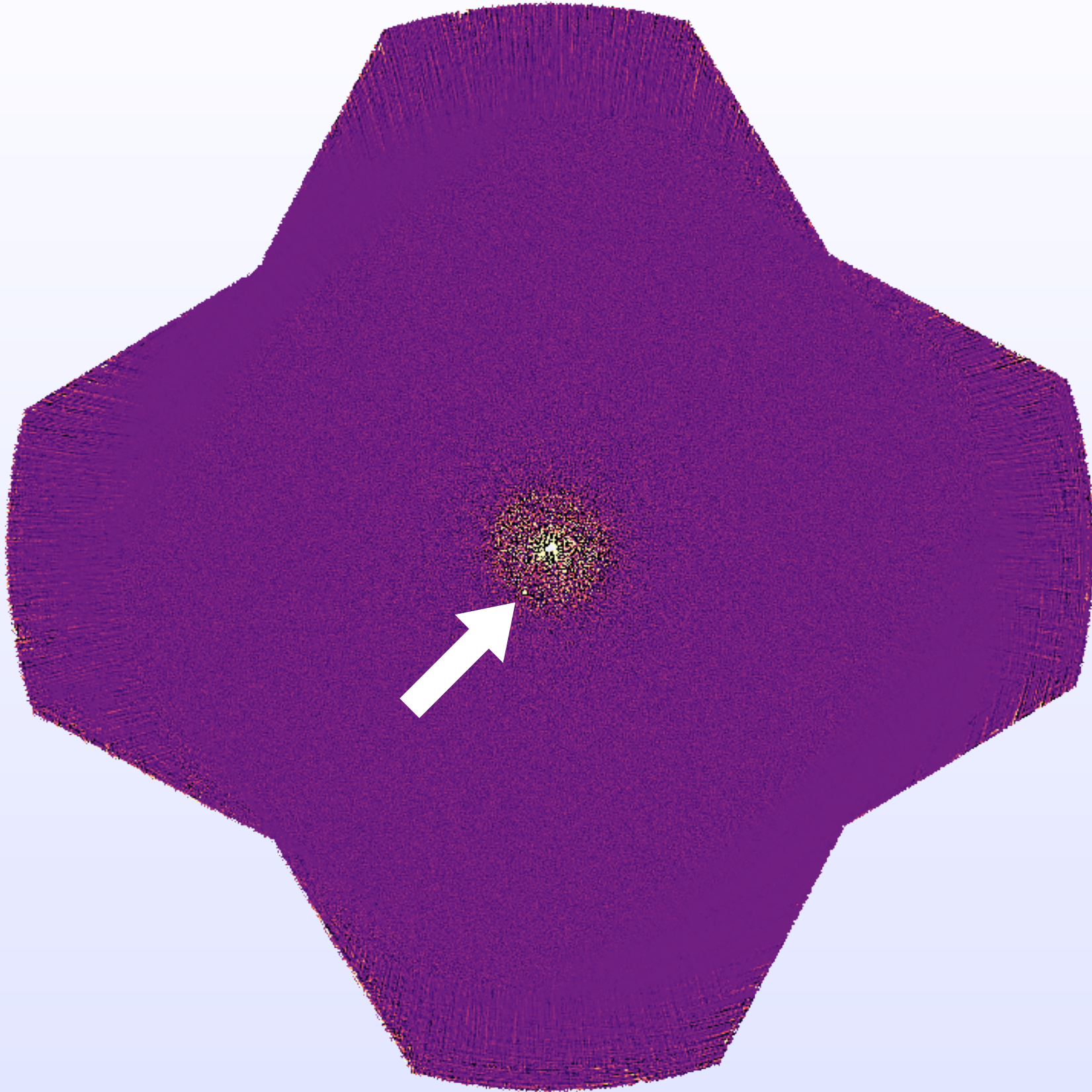
The search for planets



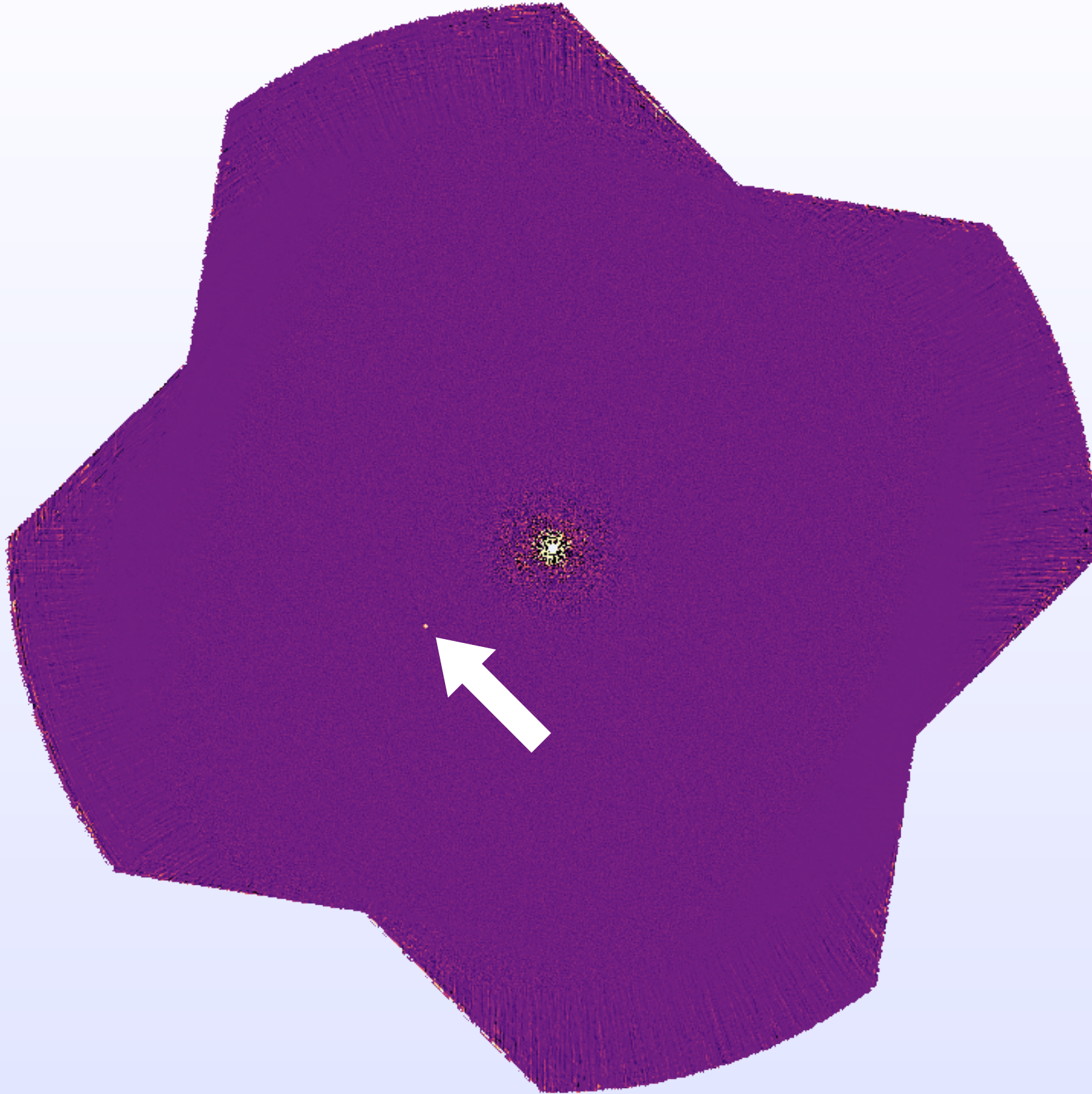
The search for planets



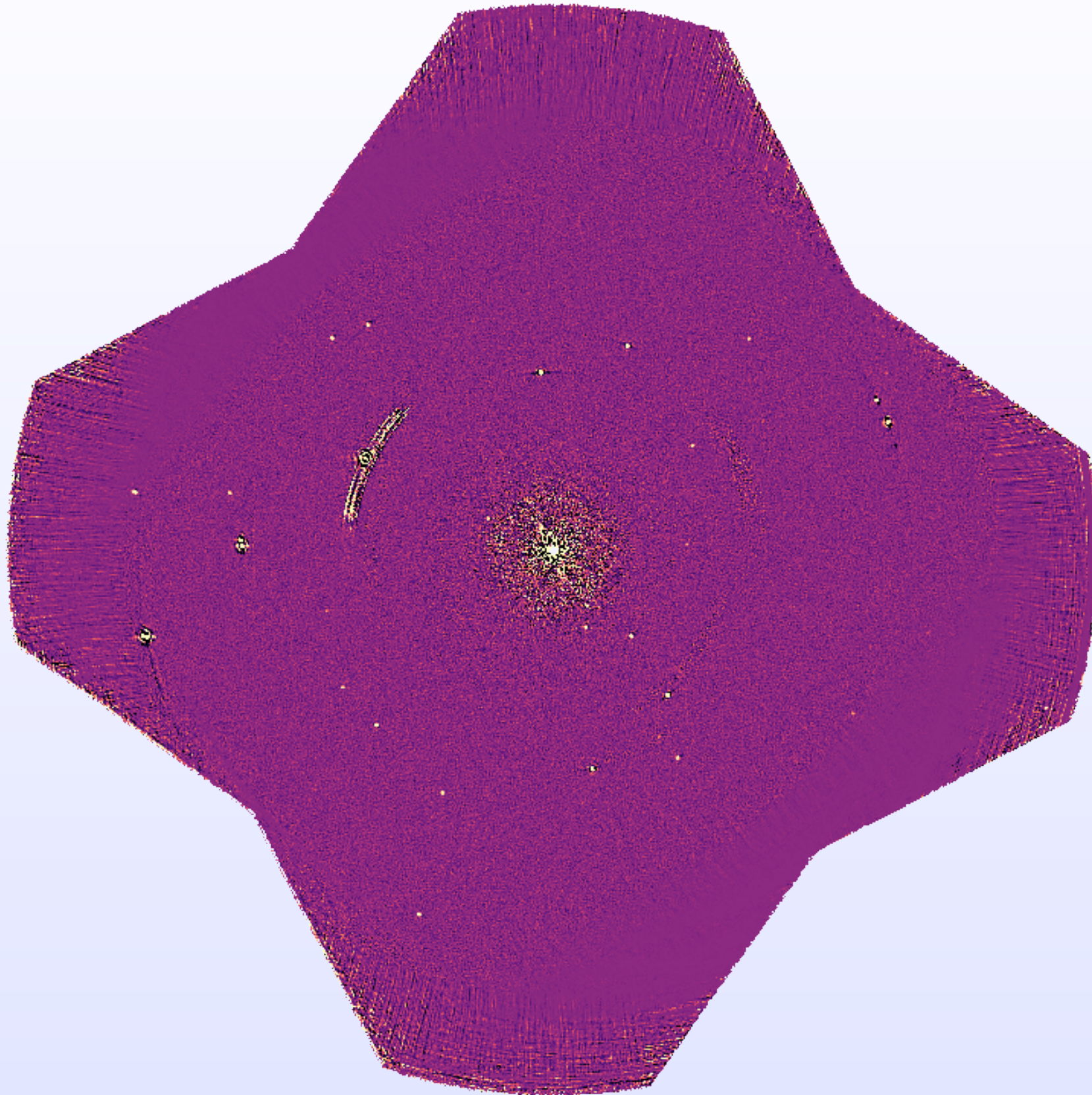
The search for planets



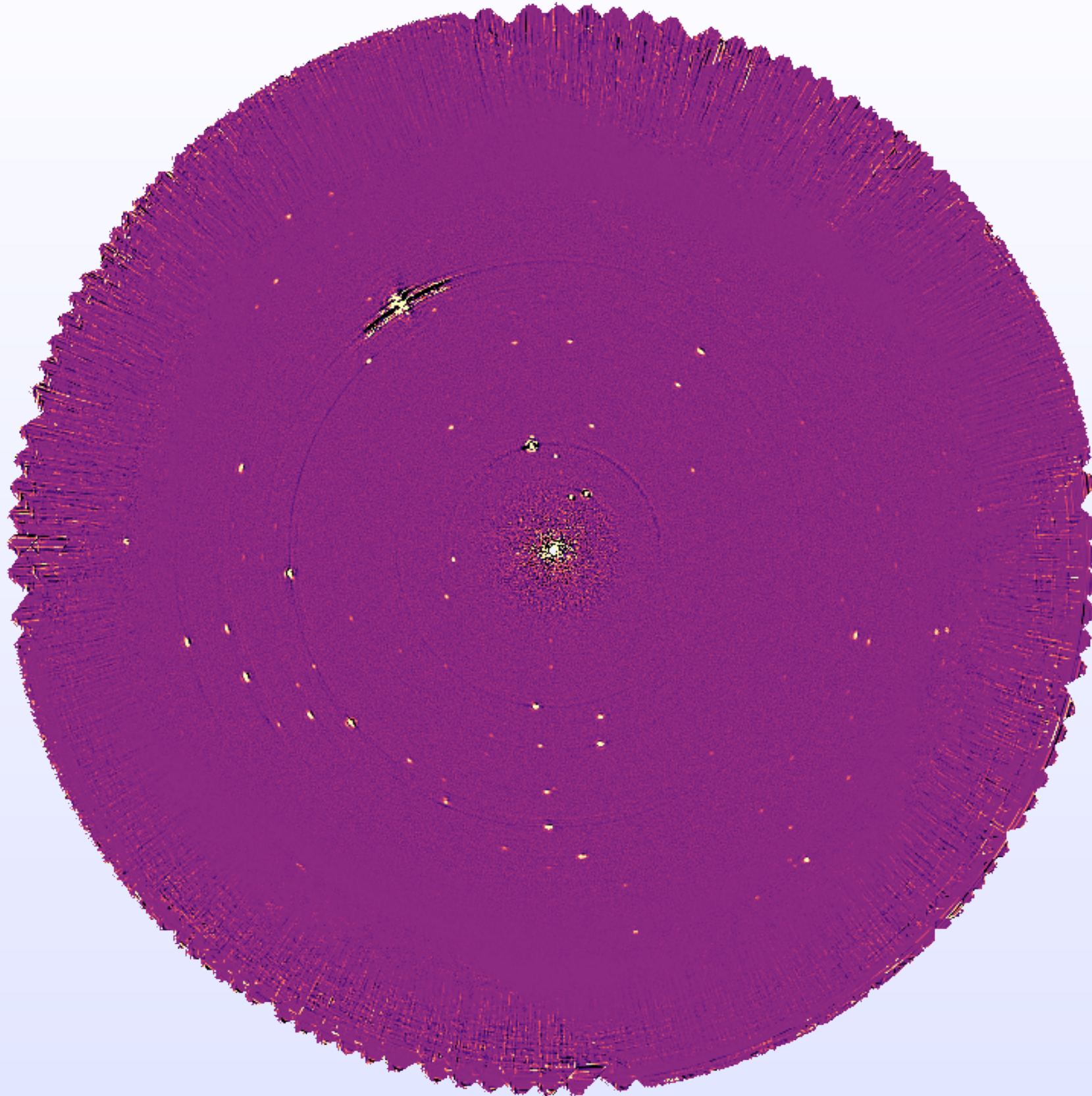
The search for planets



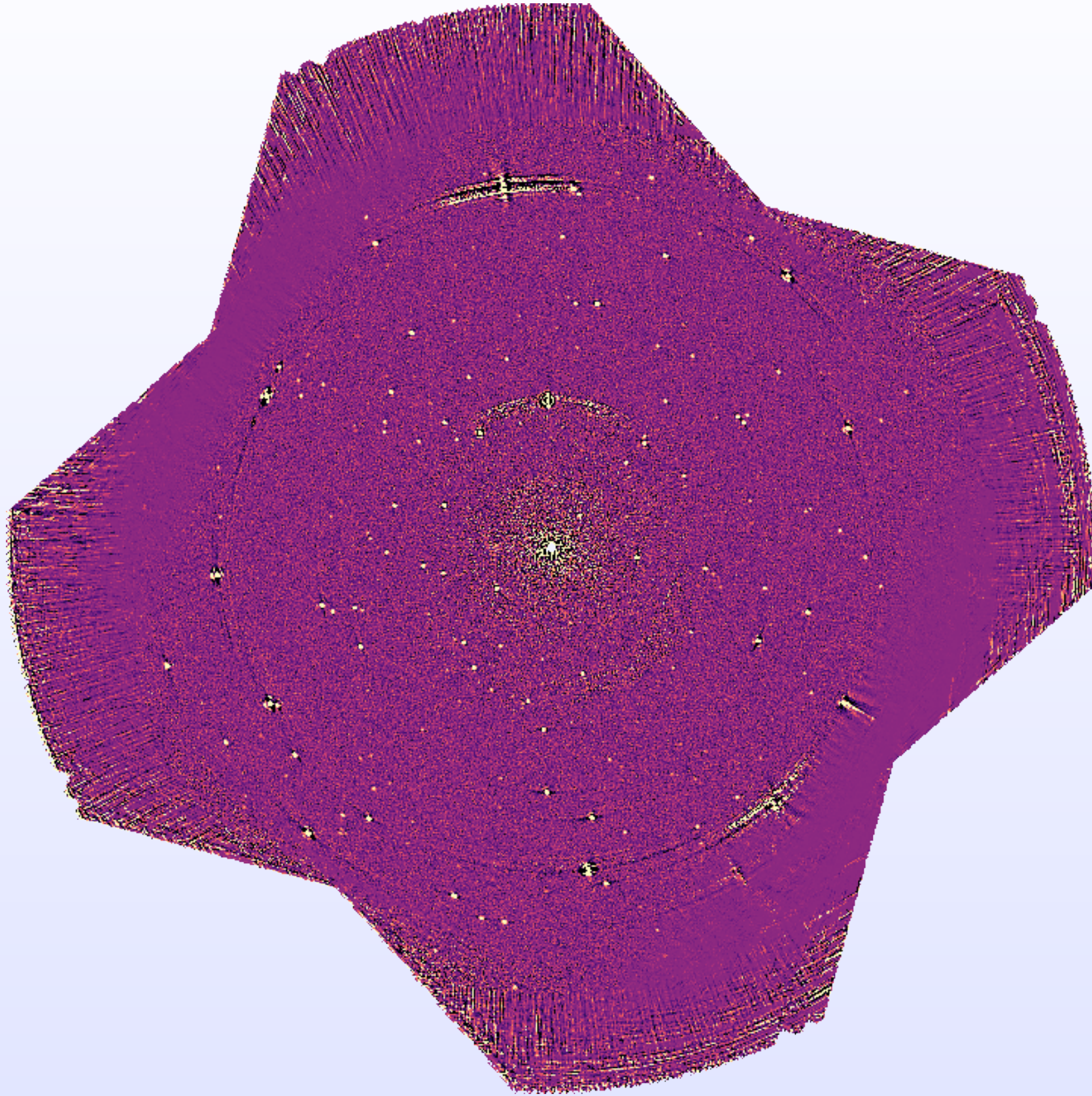
The search for planets



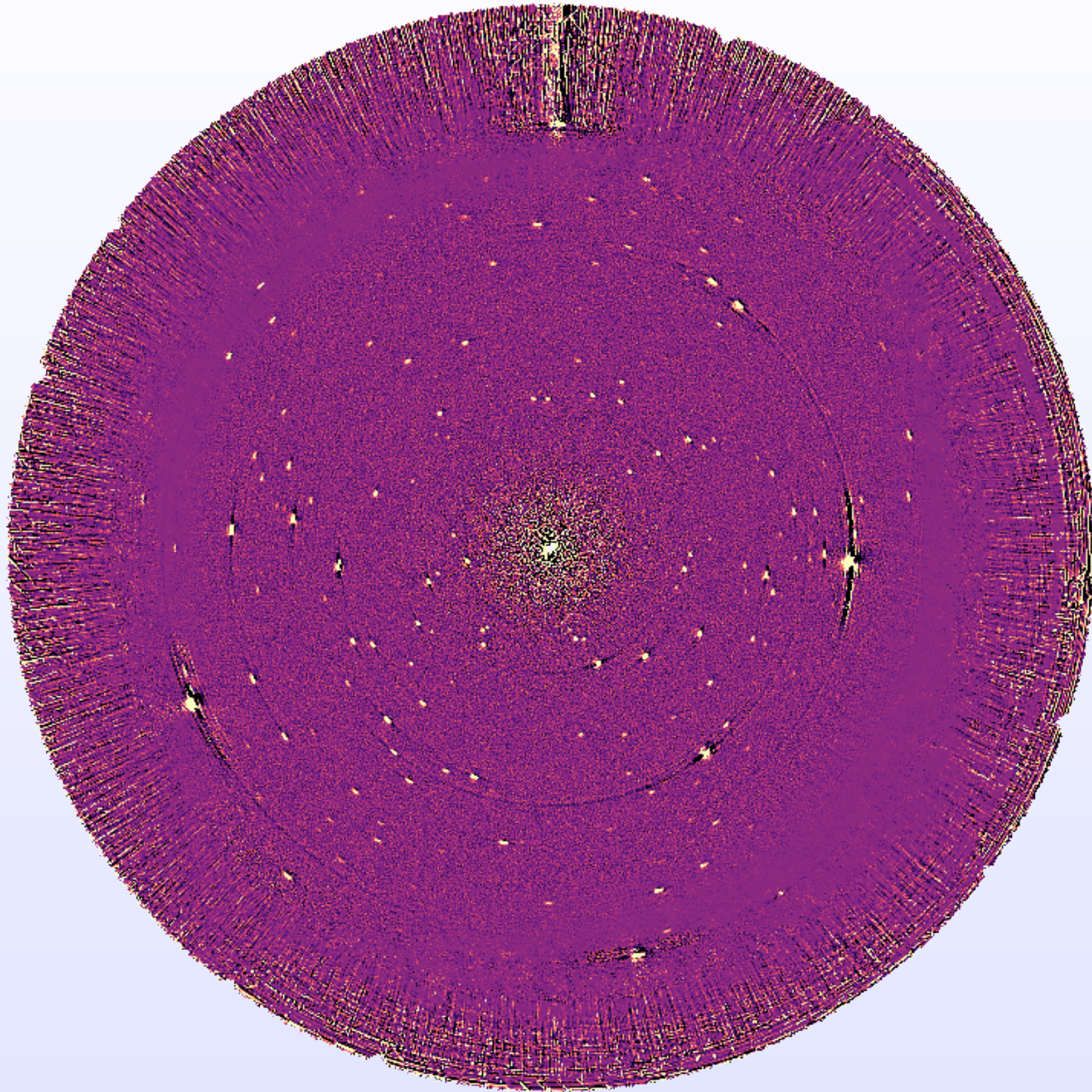
The search for planets



The search for planets

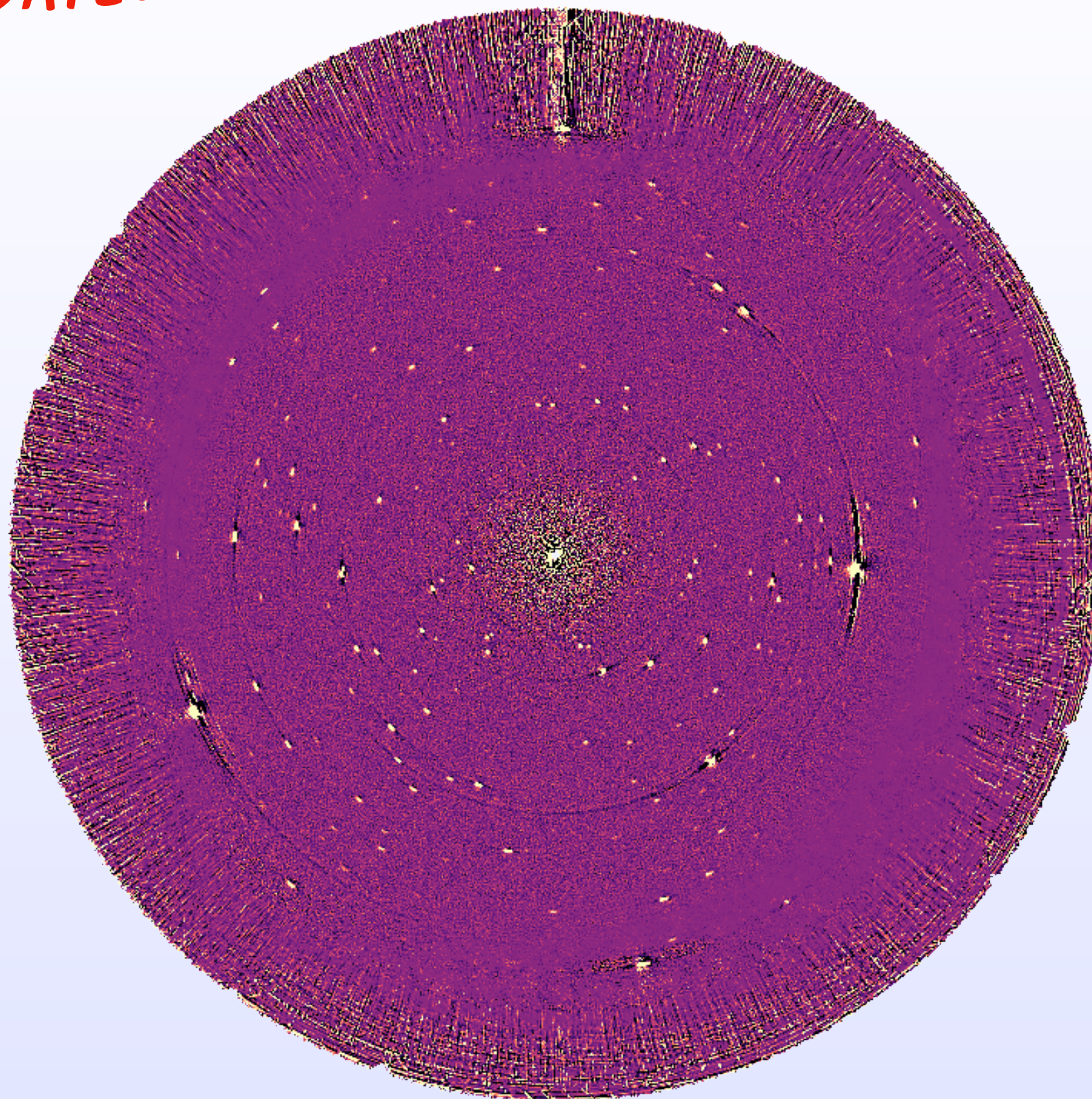


The search for planets



~~The search for planets~~

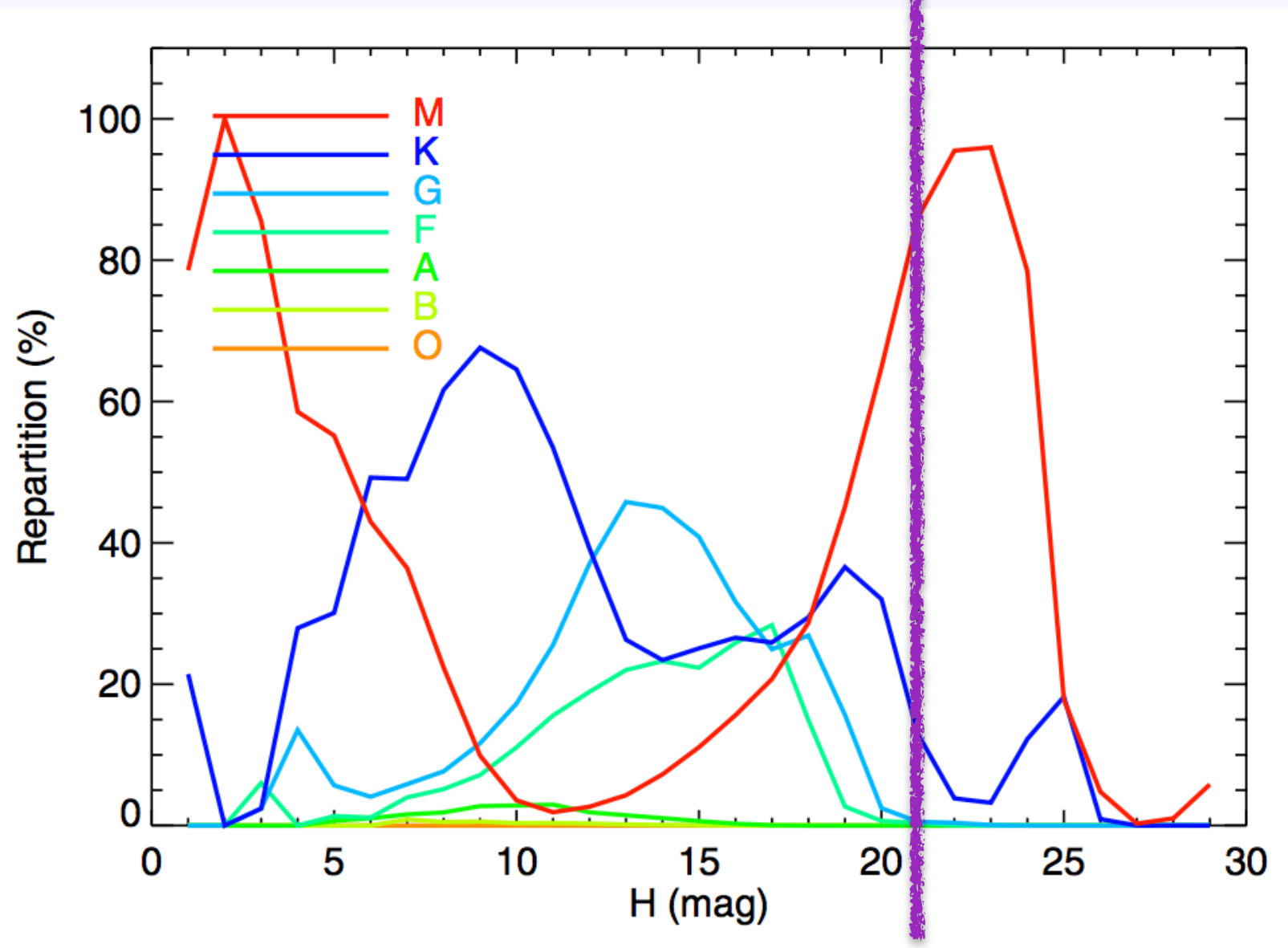
THE CANDIDATES NIGHTMARE



The search for planets

THE CANDIDATES NIGHTMARE

Typical SPHERE
detection limit



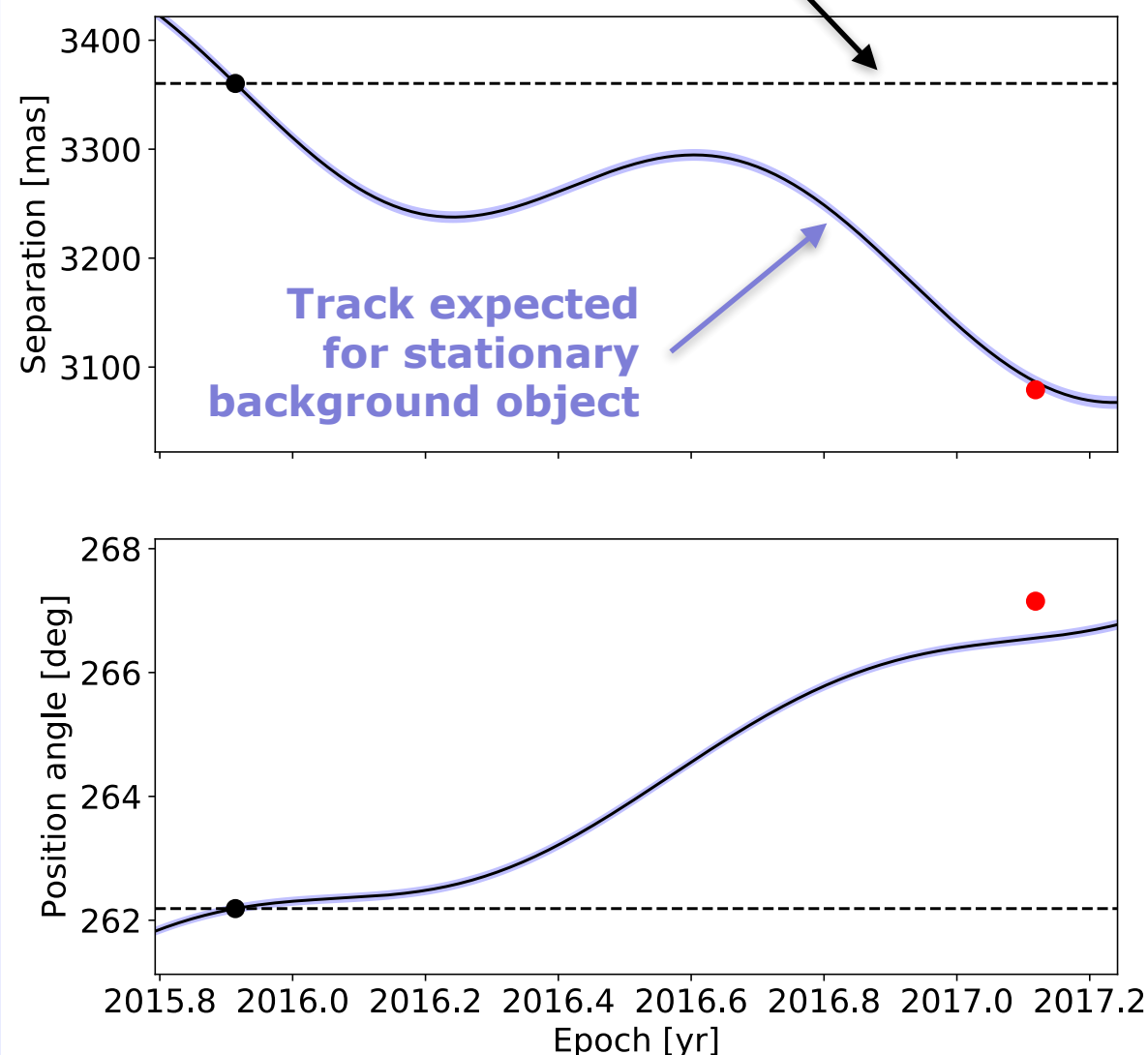
Besançon models, 10" FoV, H-band (Chauvin et al. 2015)

- contamination by remote background stars
- probability increases with FoV²
 - SPHERE/IFS: 1.8x1.8" → 5%
 - SPHERE/IRDIS: 10x10" → 40-50%

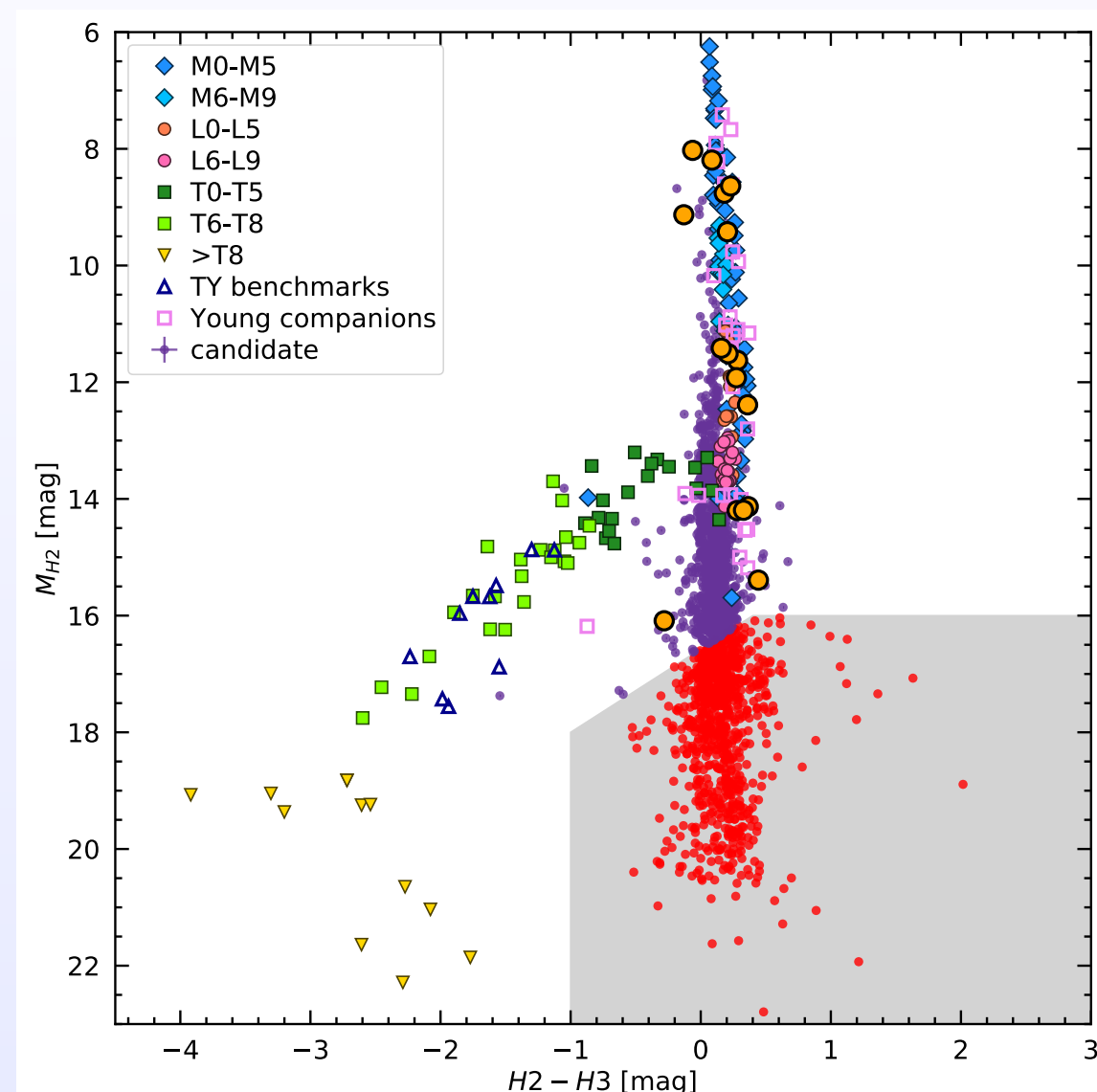
~~The search for planets~~

THE CANDIDATES NIGHTMARE

Track expected for a real companion



Second epoch astrometry

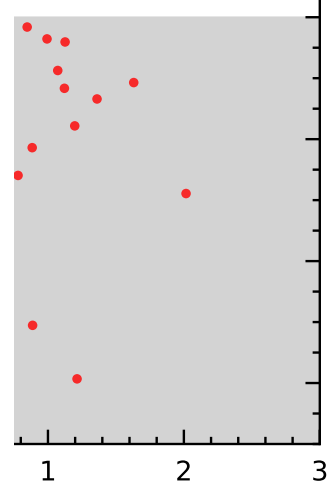
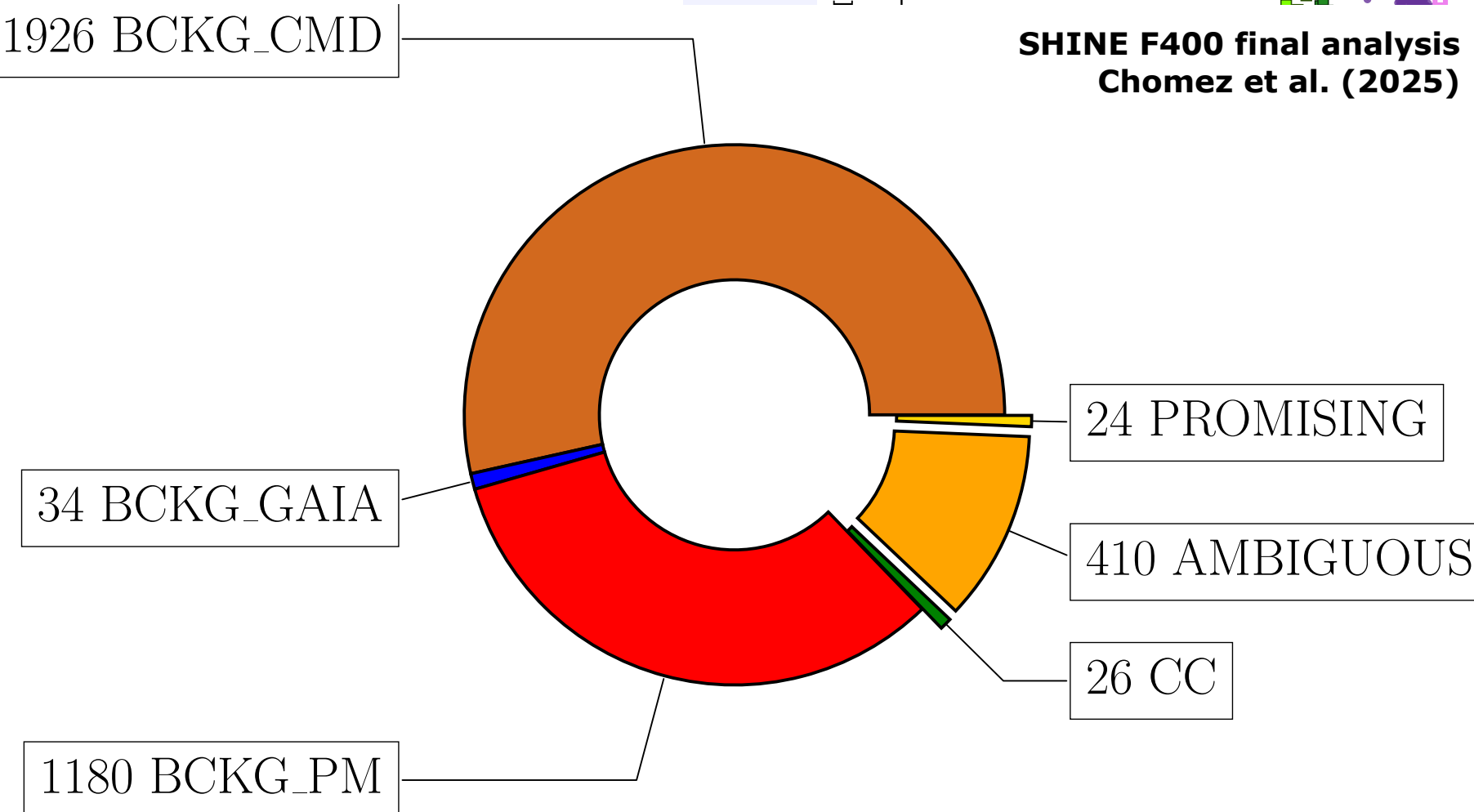
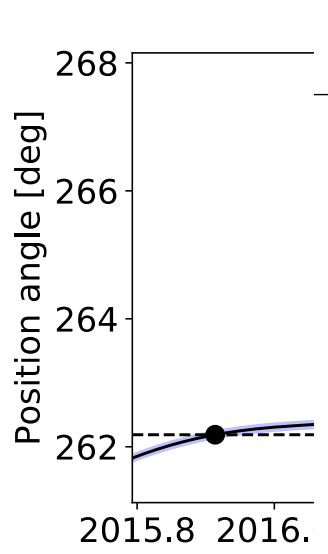
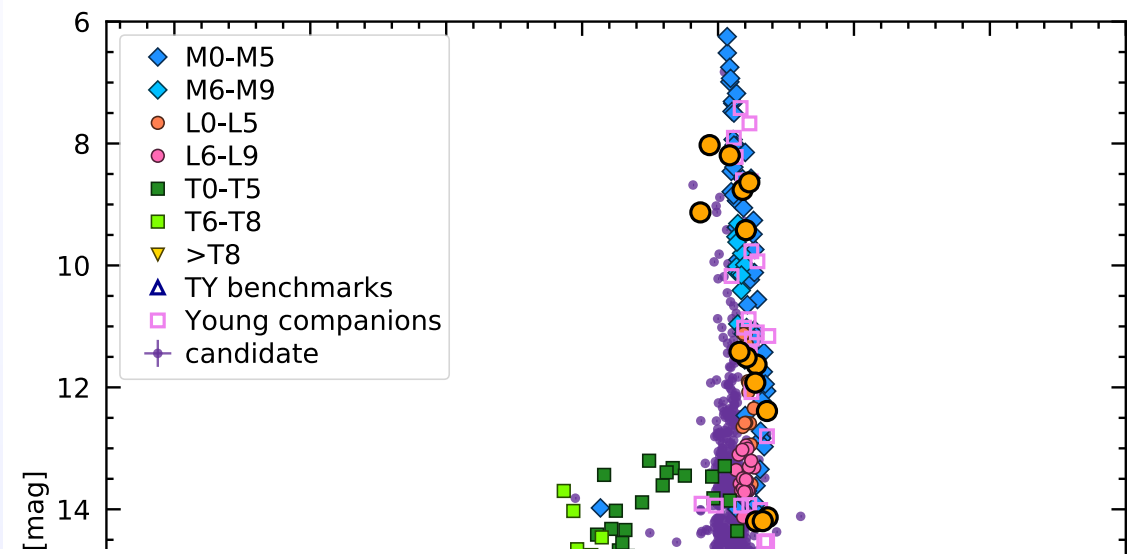
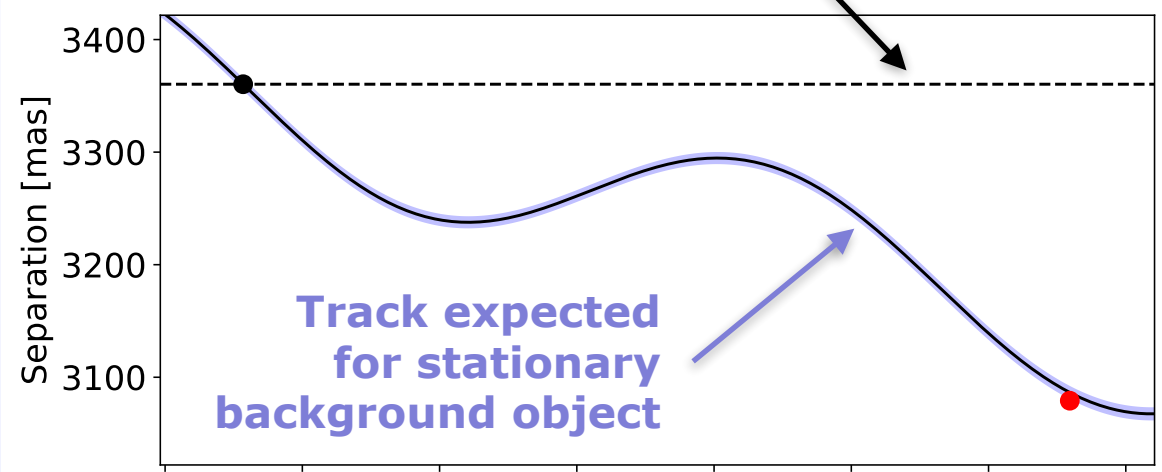


Color-magnitude diagram rejection

The search for planets

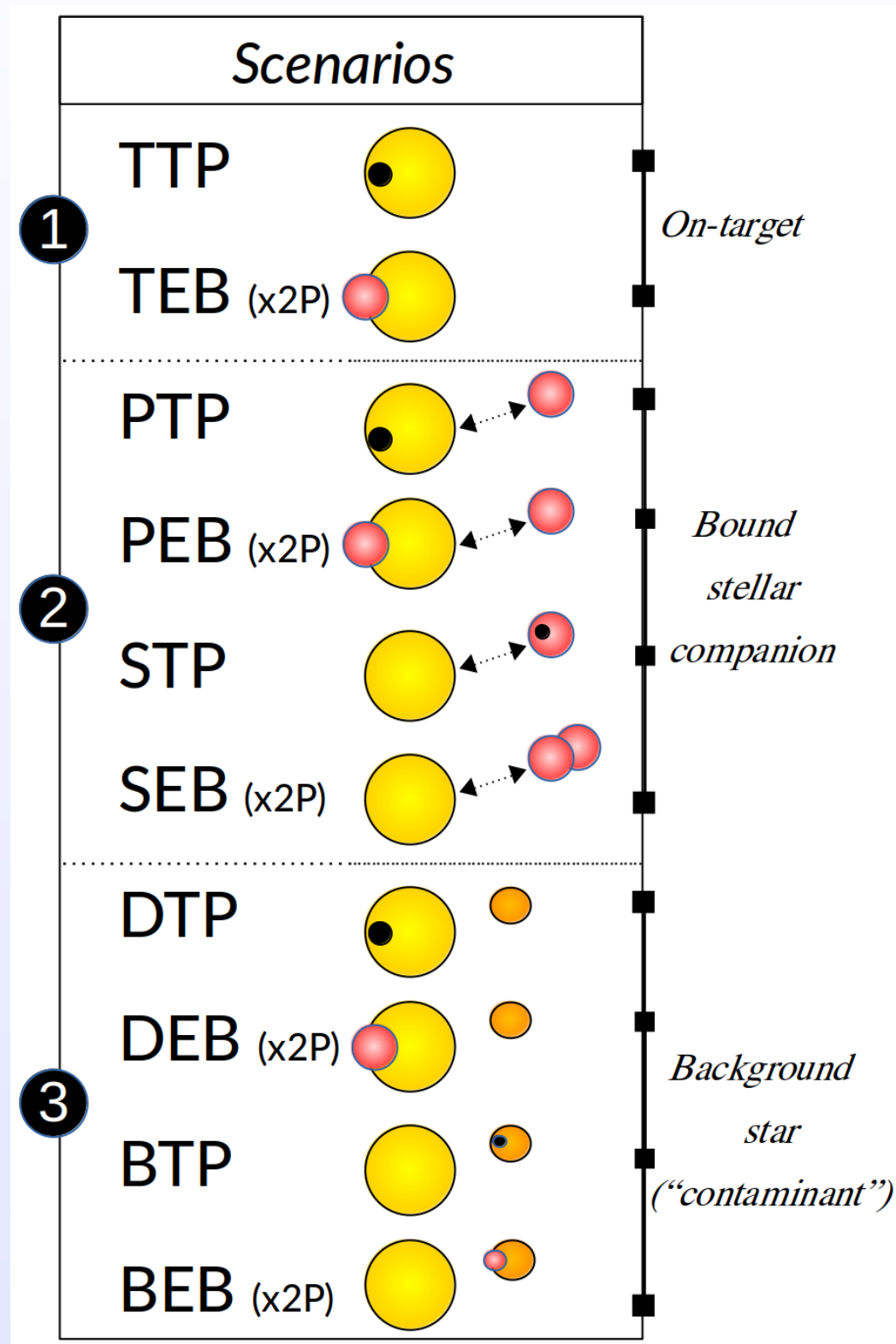
THE CANDIDATES NIGHTMARE

Track expected for a real companion

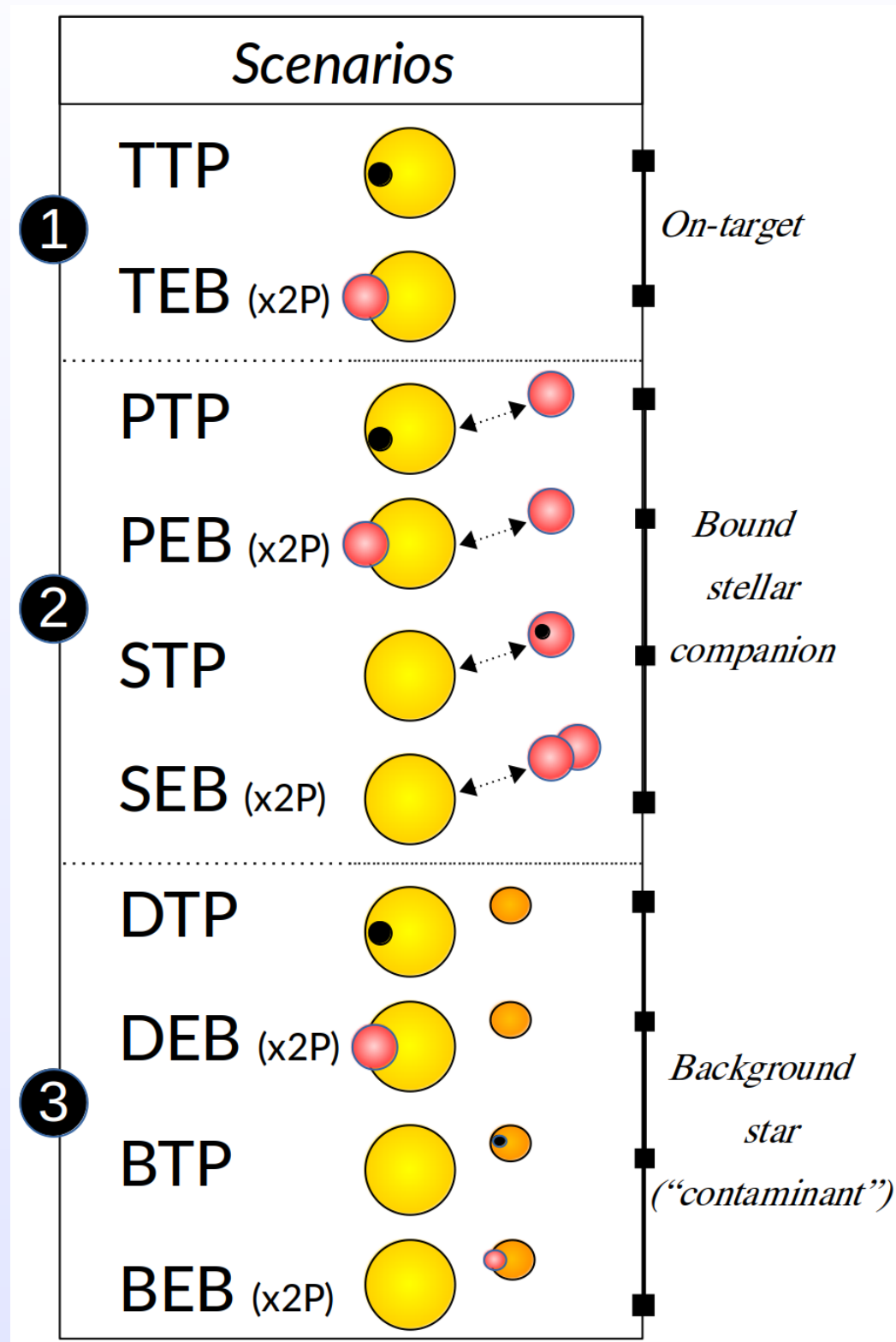


rejection

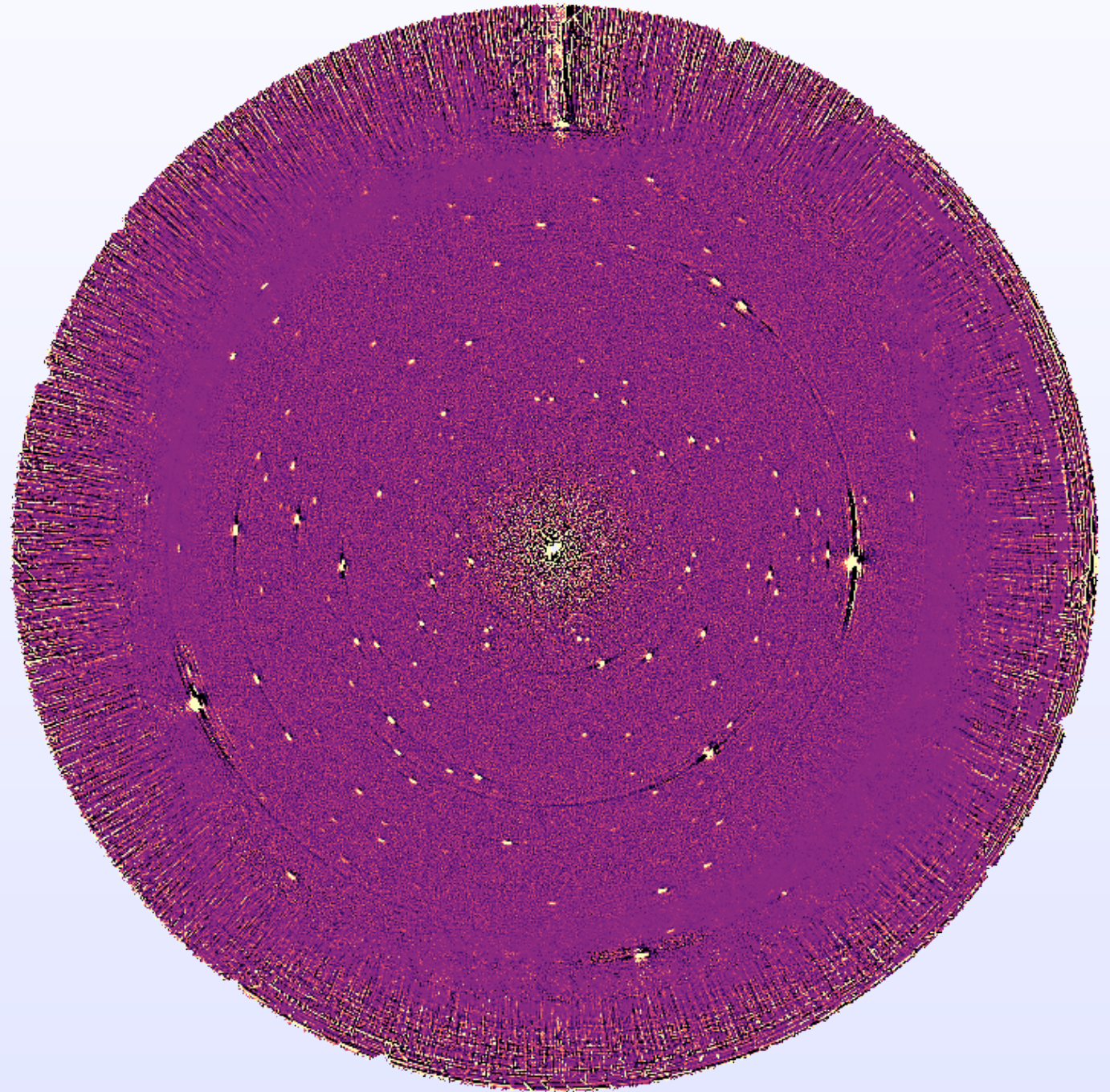
Contamination in transit observations



Contamination in transit observations

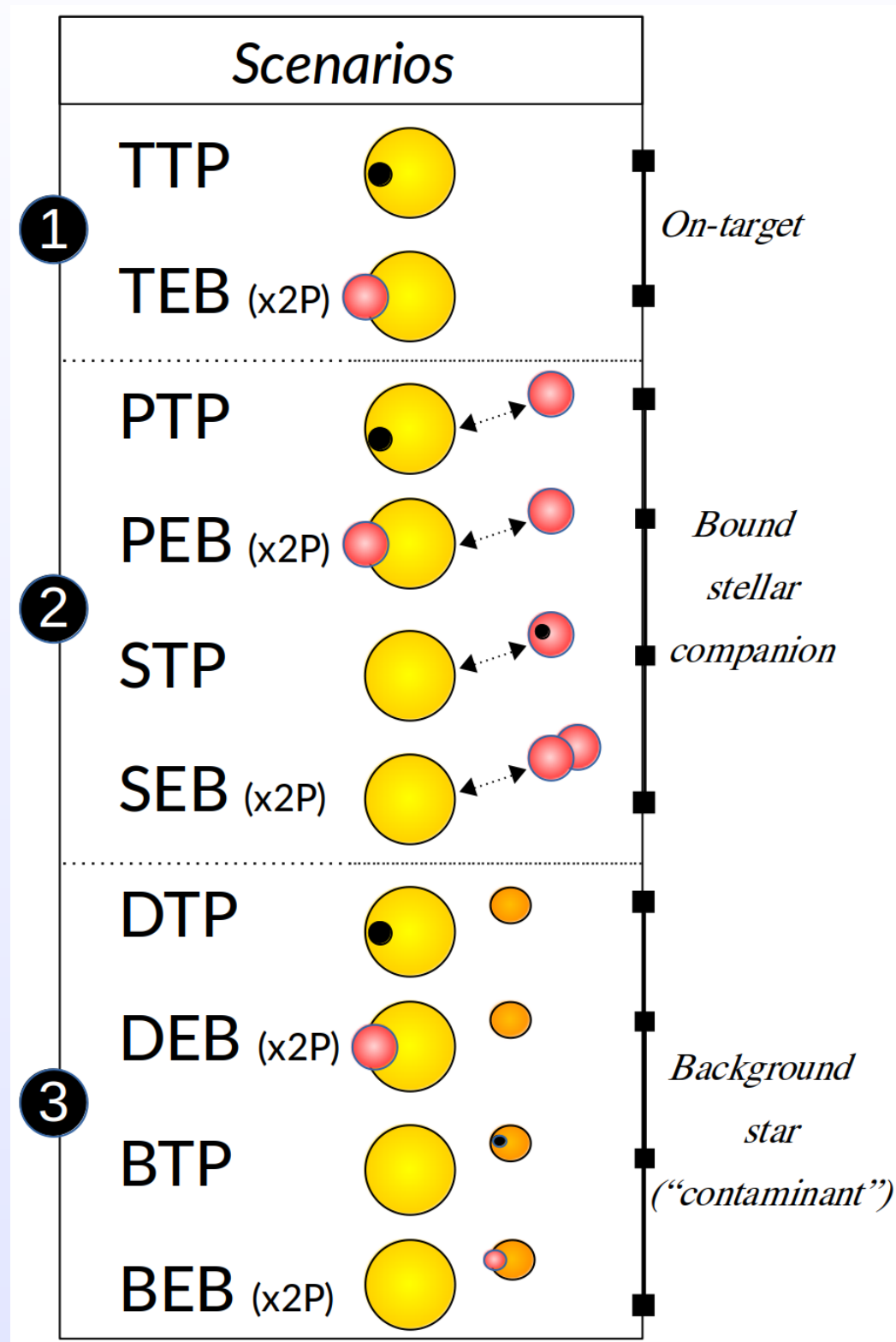


- Earth analogue around a solar-type star:
 - 85 ppm transit depth

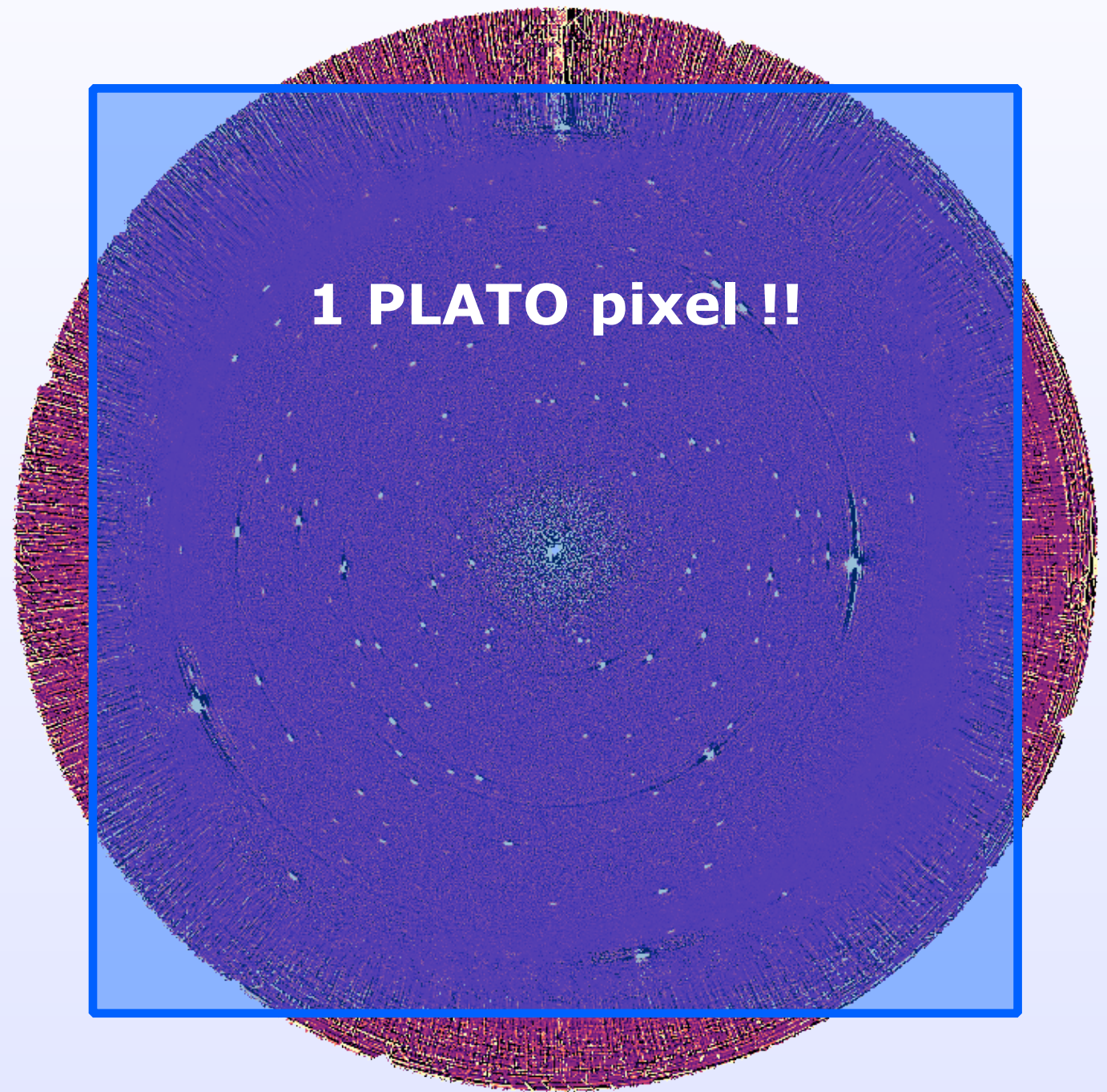


How many of these background stars can create a 85 ppm variation?

Contamination in transit observations



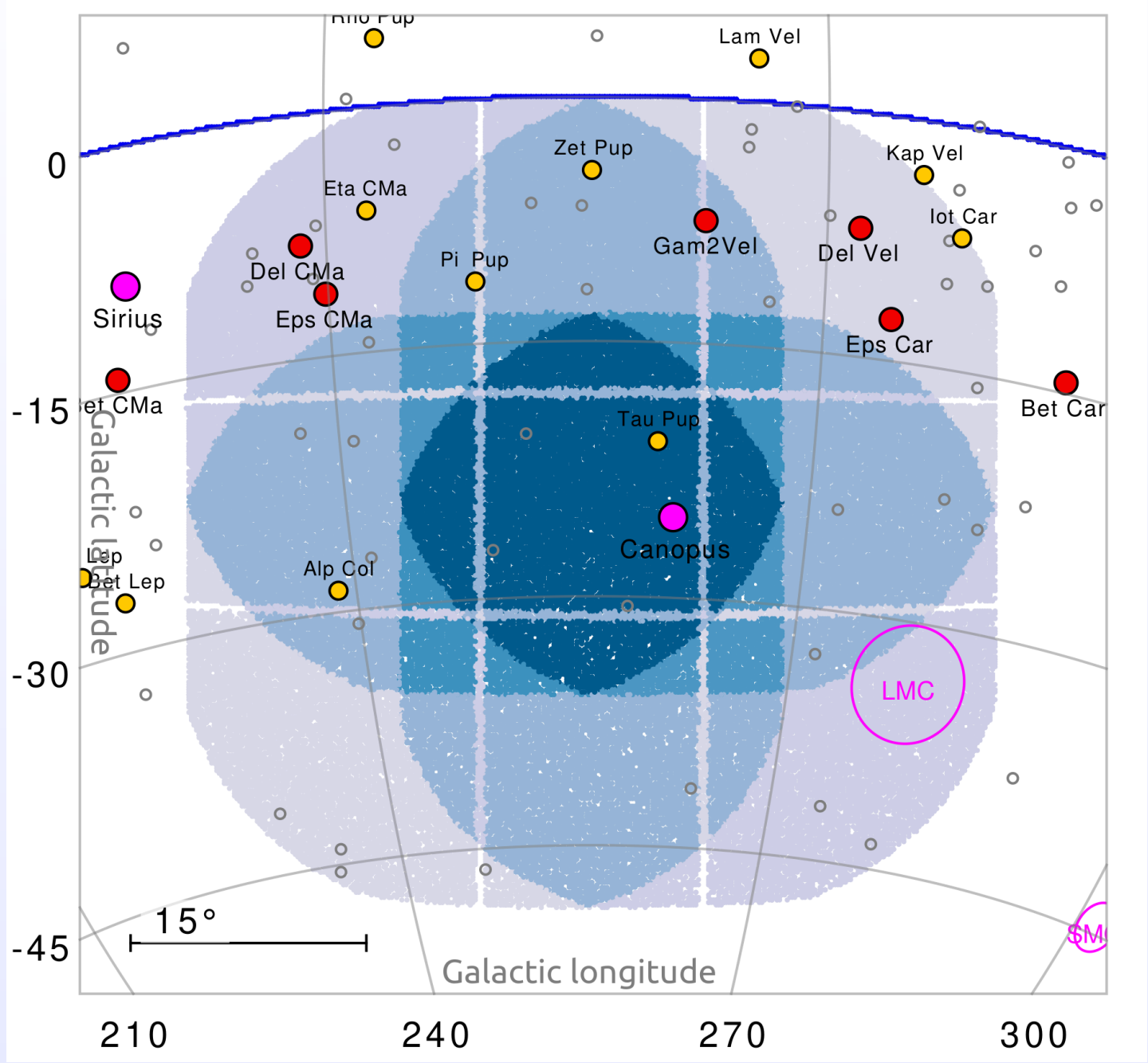
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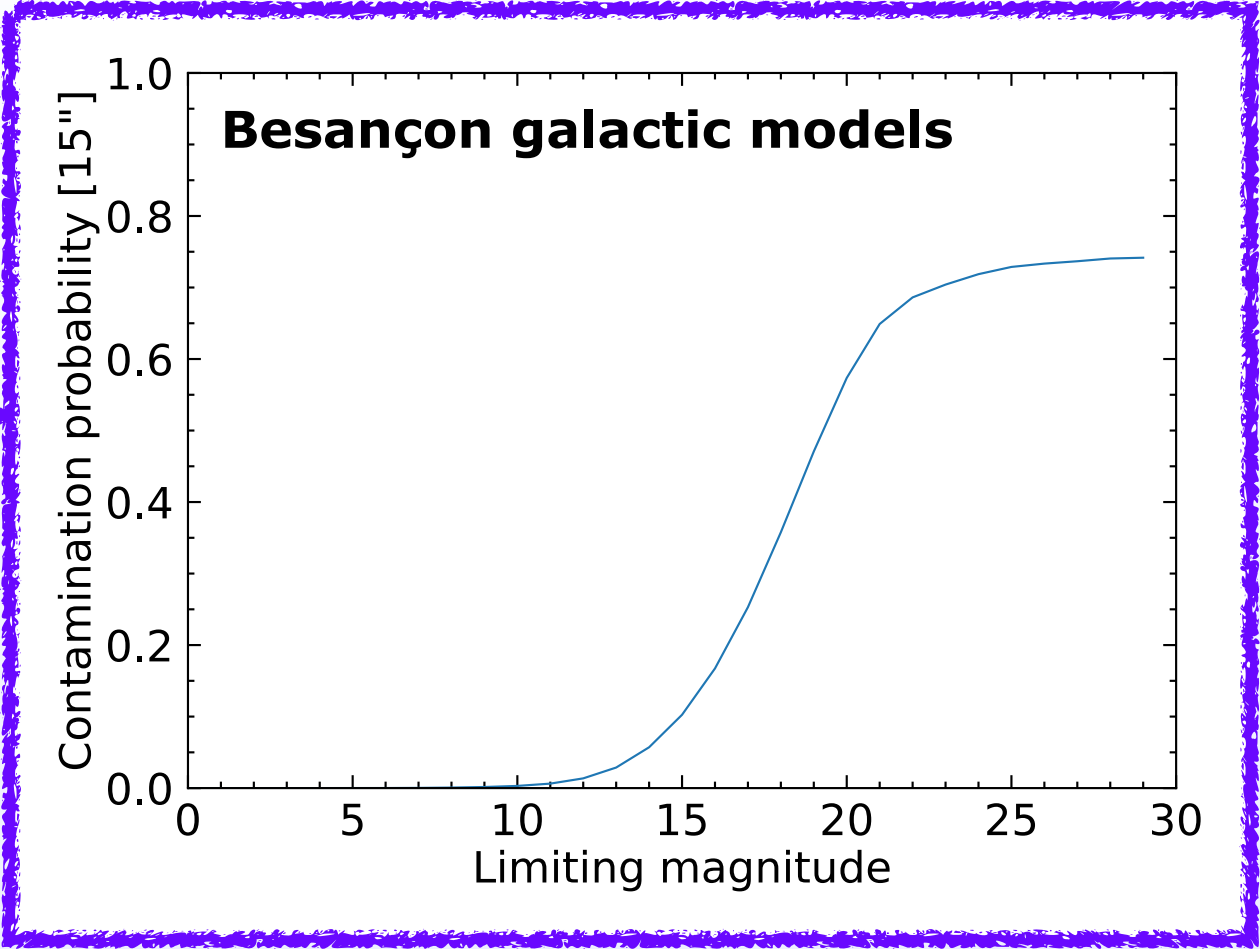
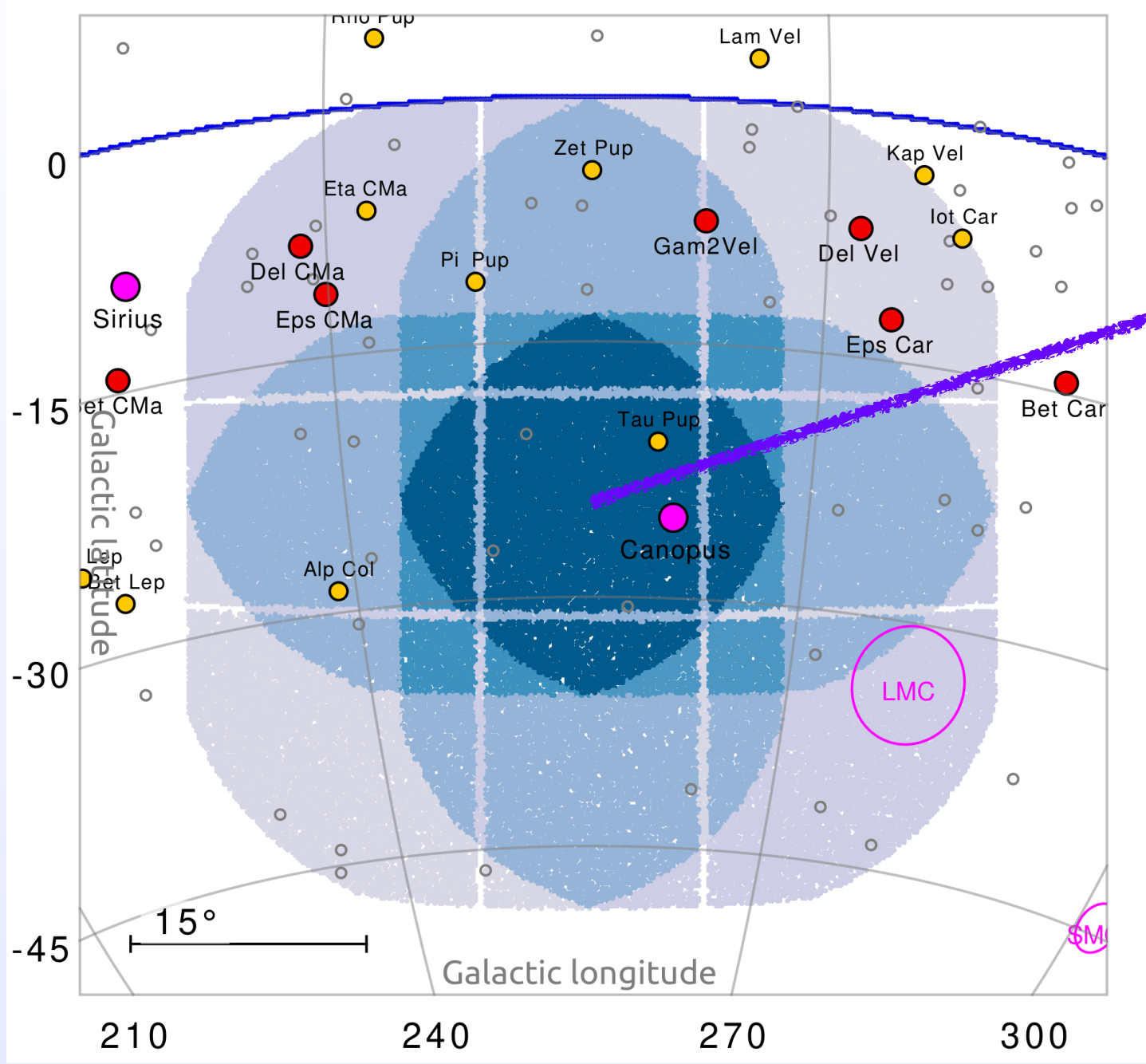
Comparison with LOPS2

Nascimbeni et al. (2025)



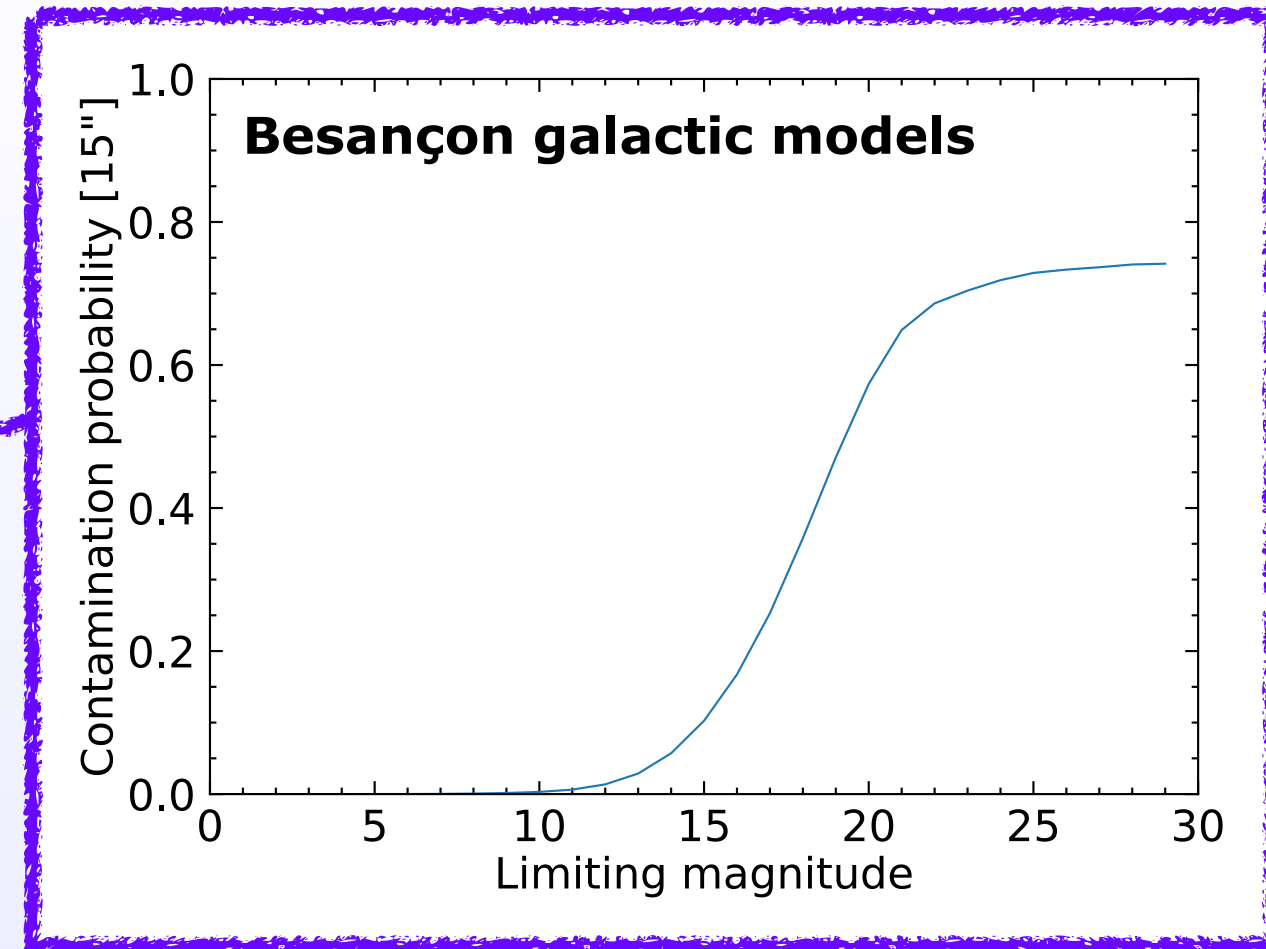
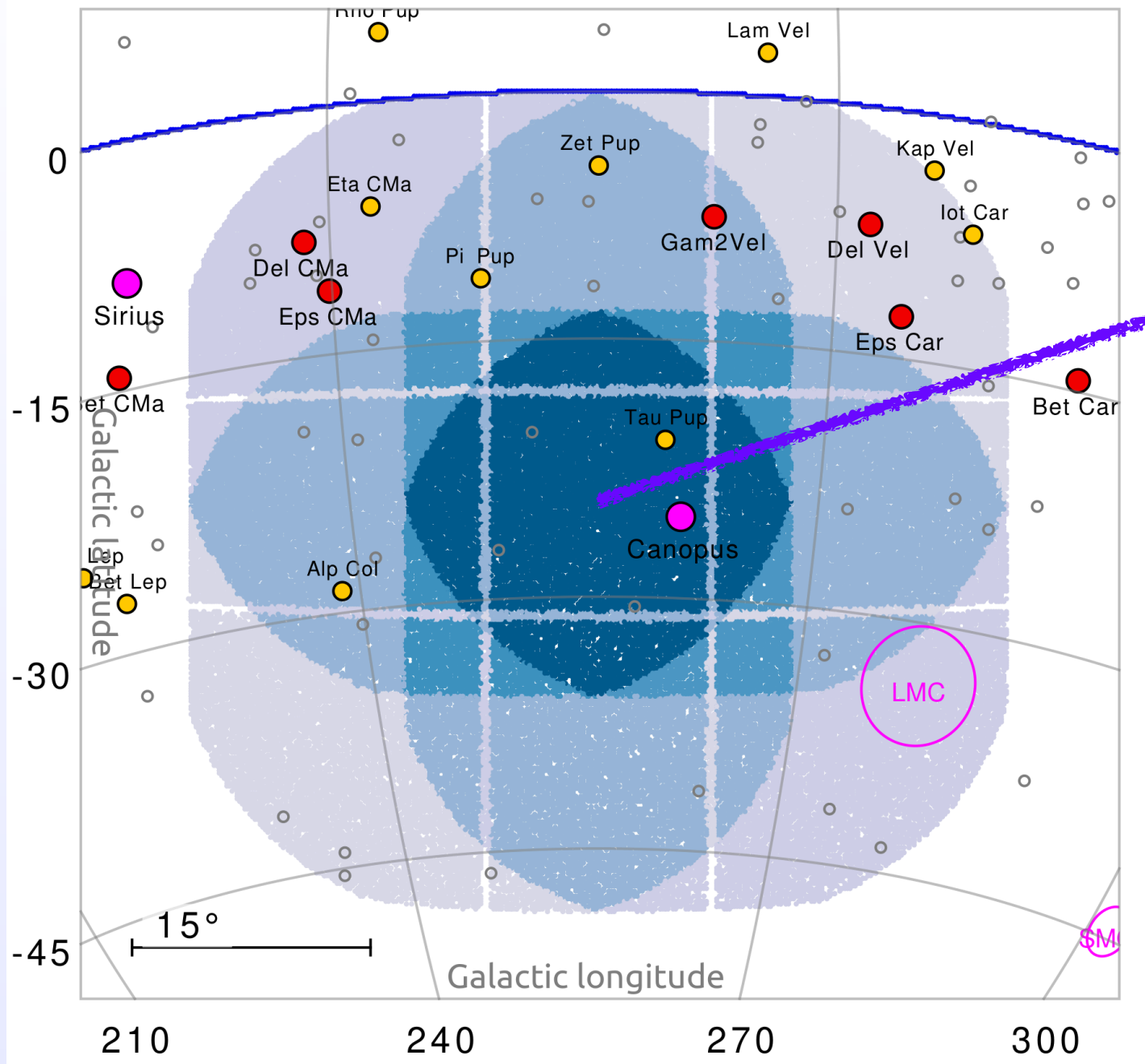
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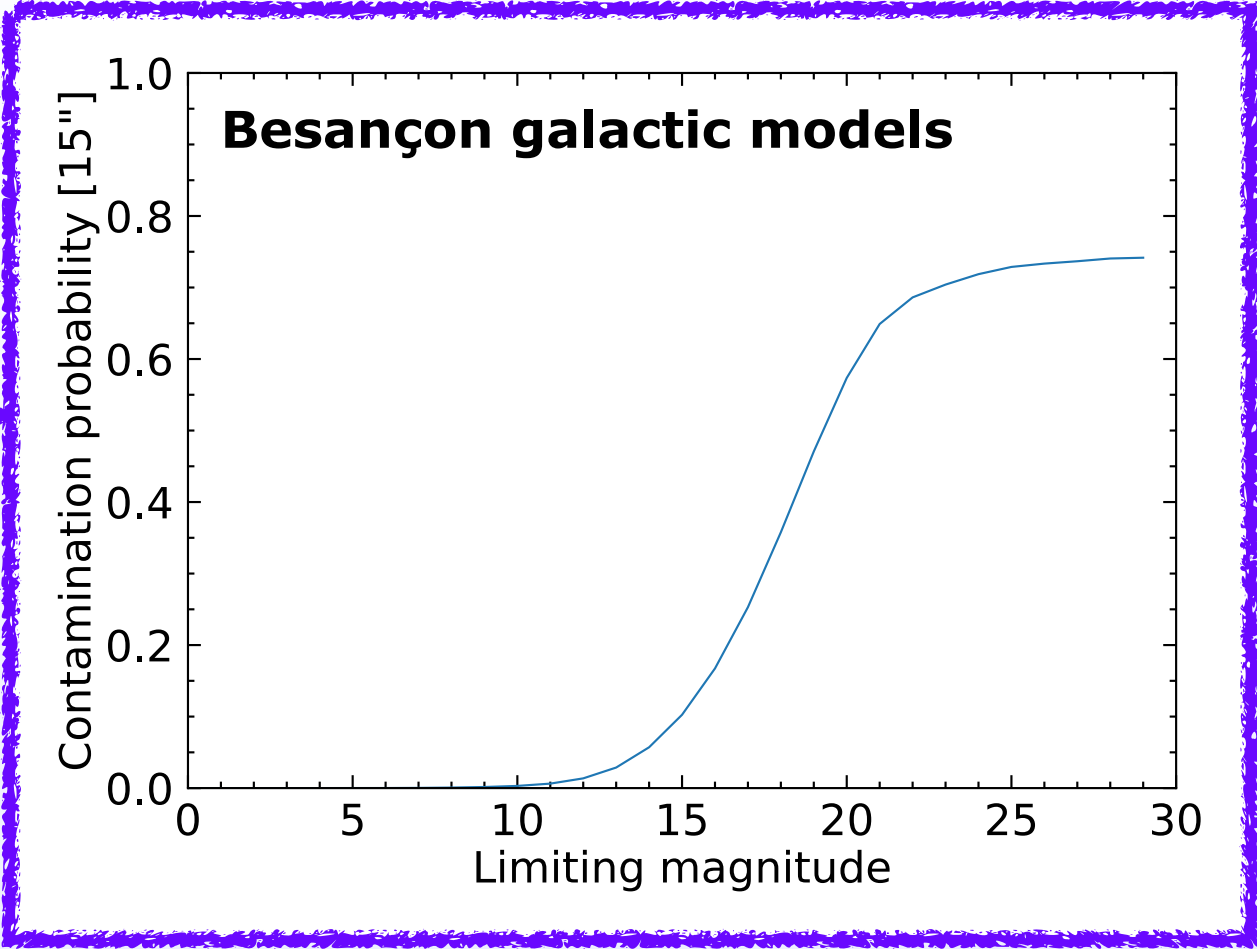
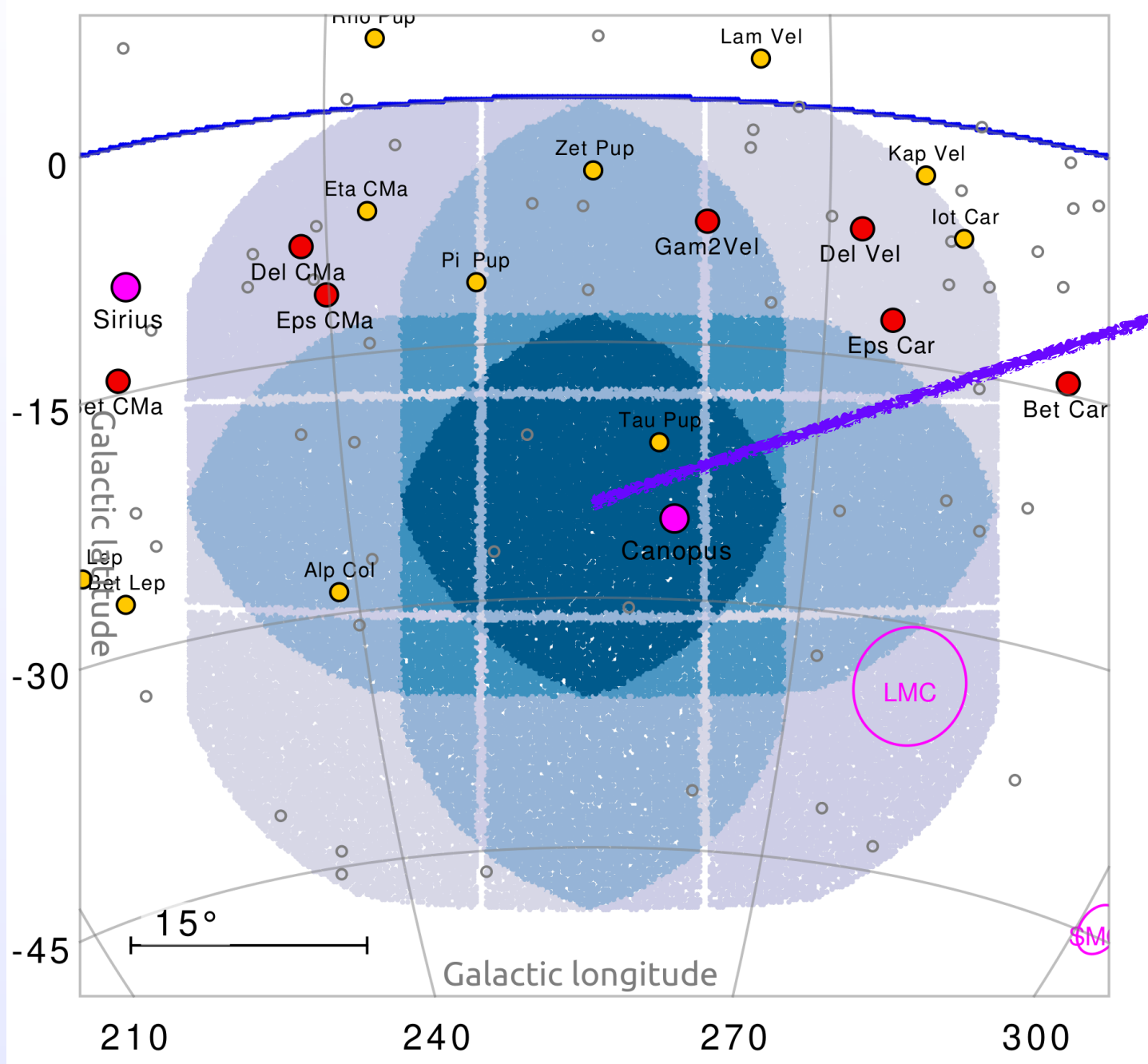
Nascimbeni et al. (2025)



High-contrast imaging will be essential for follow-up!

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High-contrast imaging will be essential for follow-up!

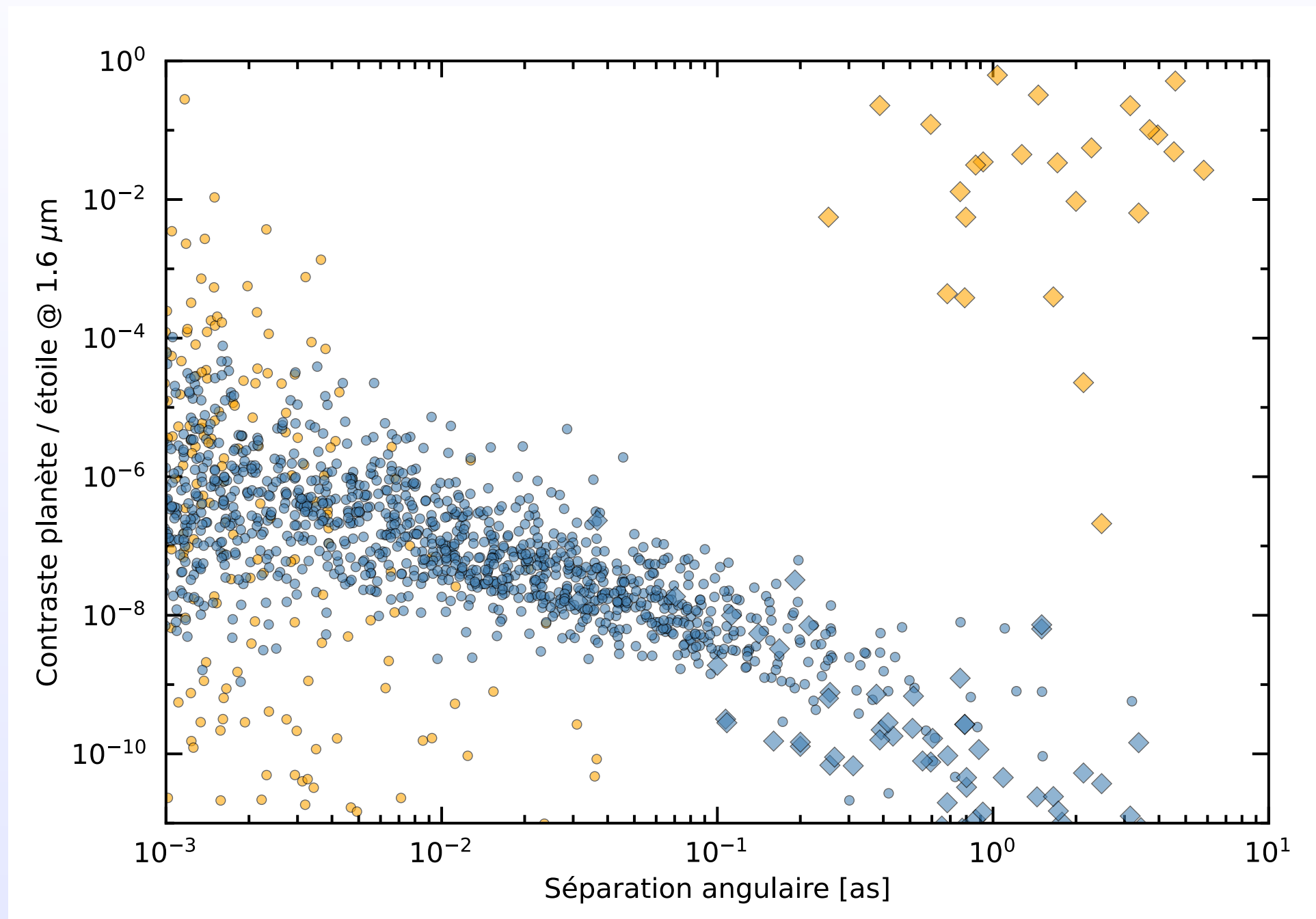
140 000

Ground-based
Observation
Programme
S. Udry

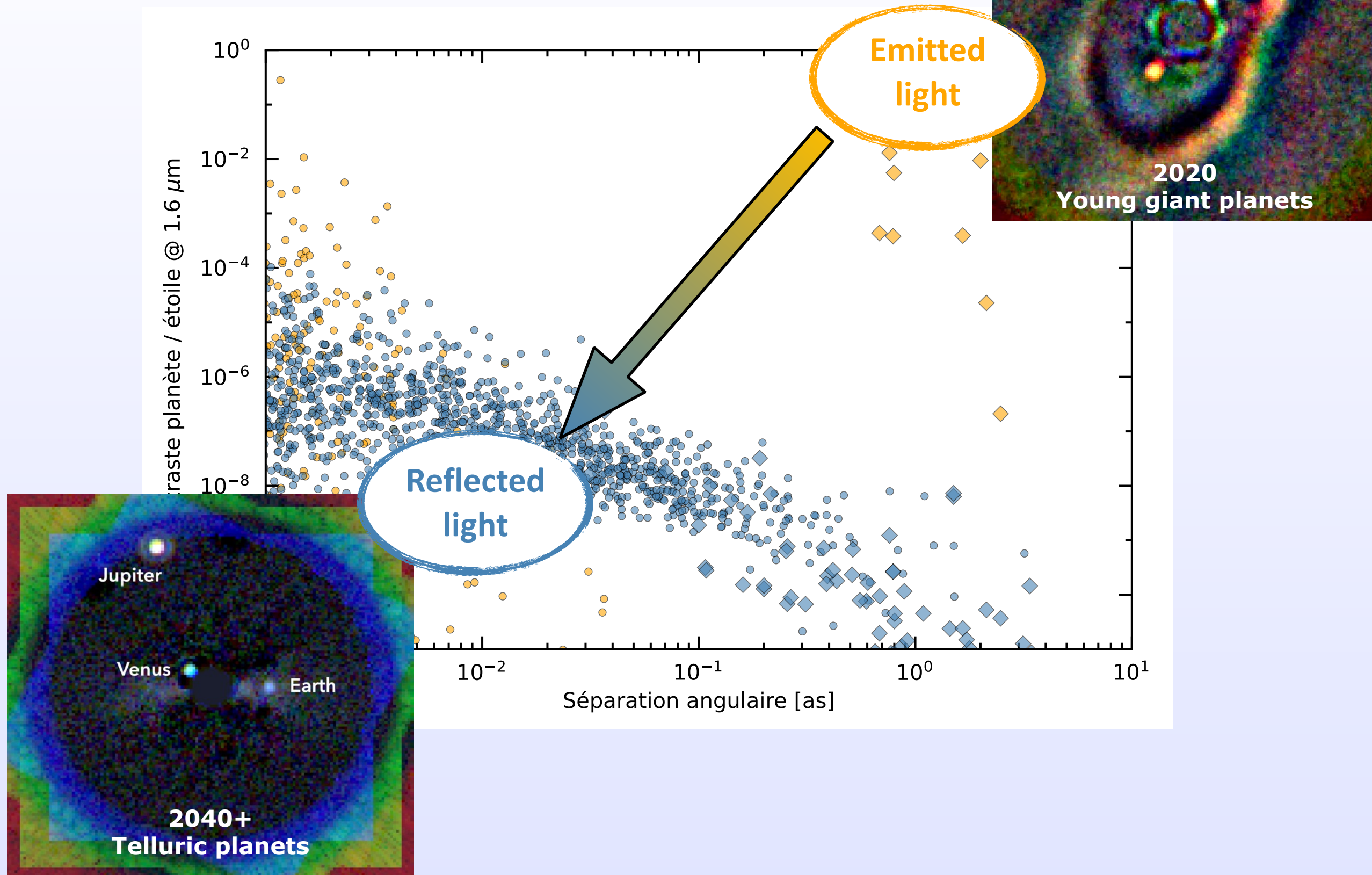


Thank GOP, we have a plan!
(sorry for the pun)

Where is imaging going?



Where is imaging going?



Where is imaging going?



**Extremely large
telescopes**

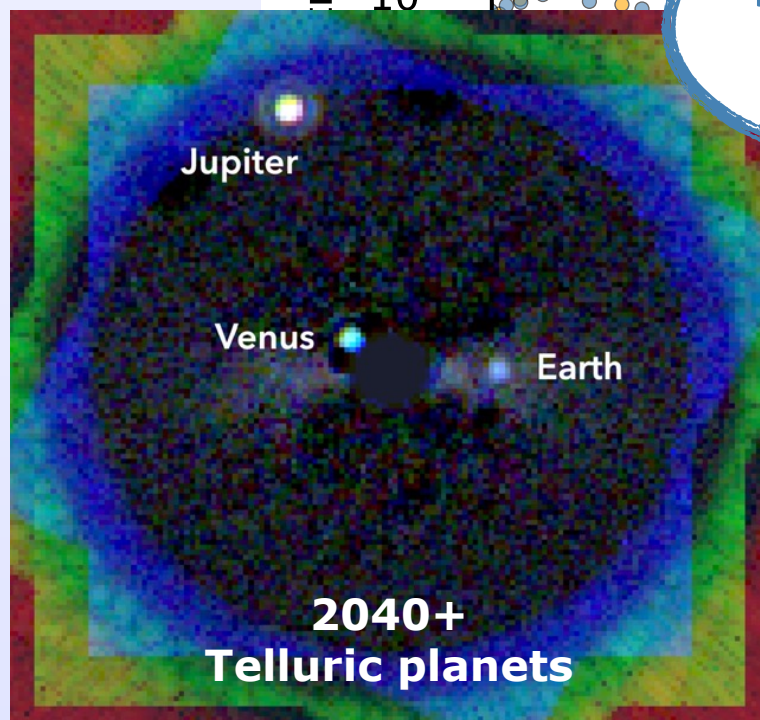
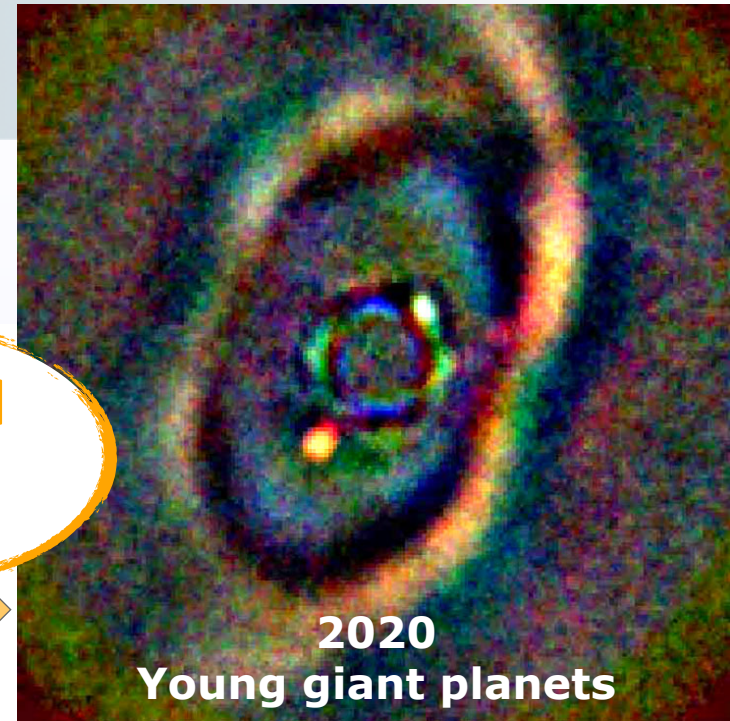
Contraste planète / étoile @ 1.6μ

10^{-4}
 10^{-6}
 10^{-8}

**Reflected
light**

**Emitted
light**

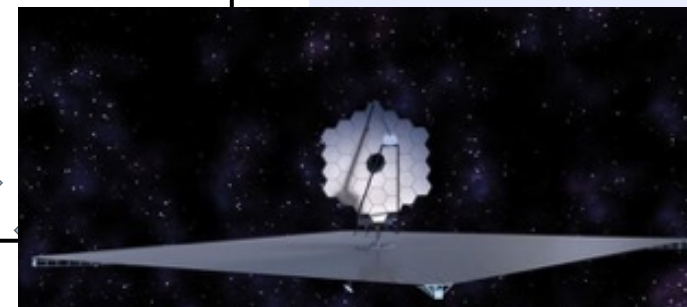
**2020
Young giant planets**



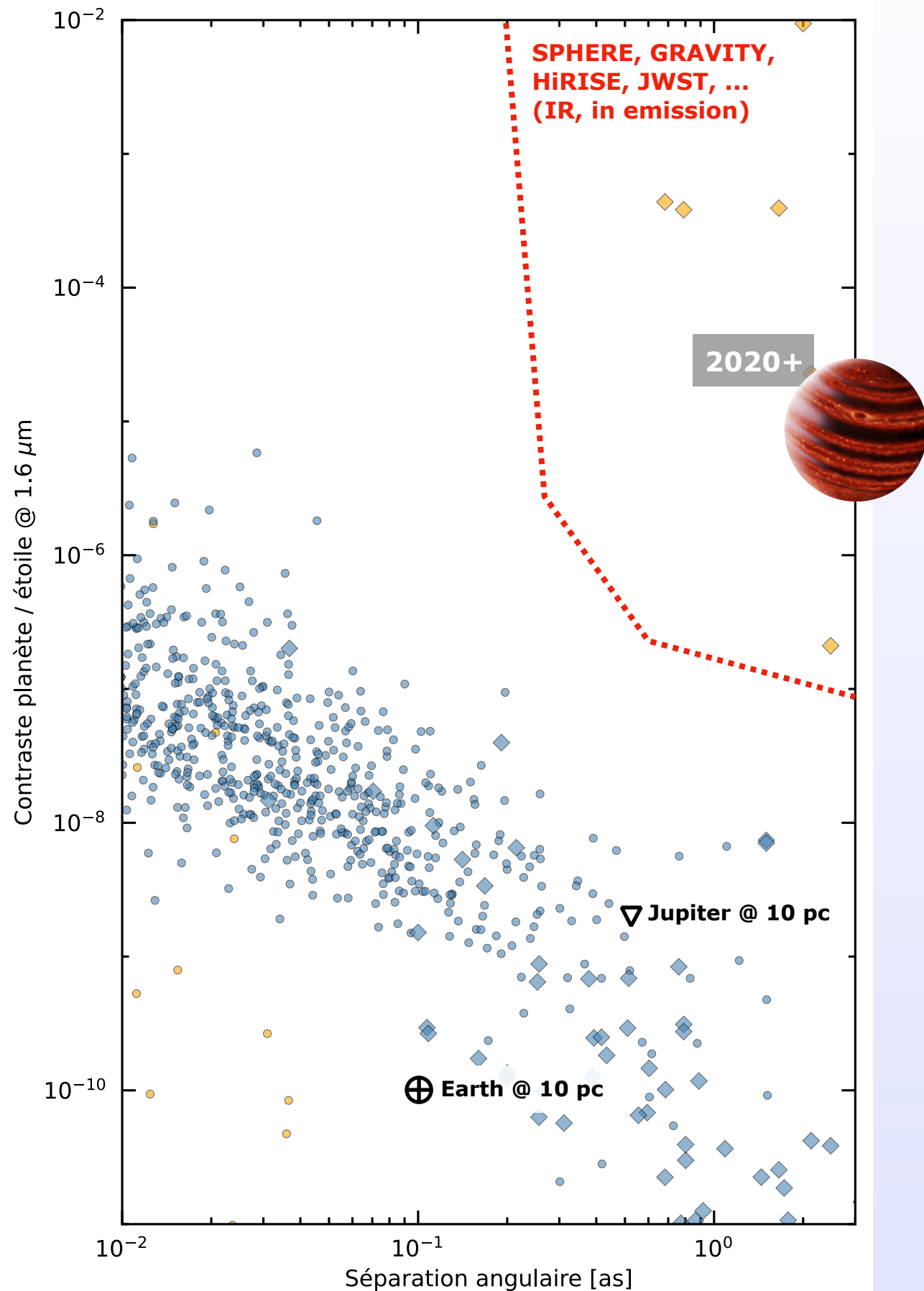
Séparation angulaire



**Space
missions**

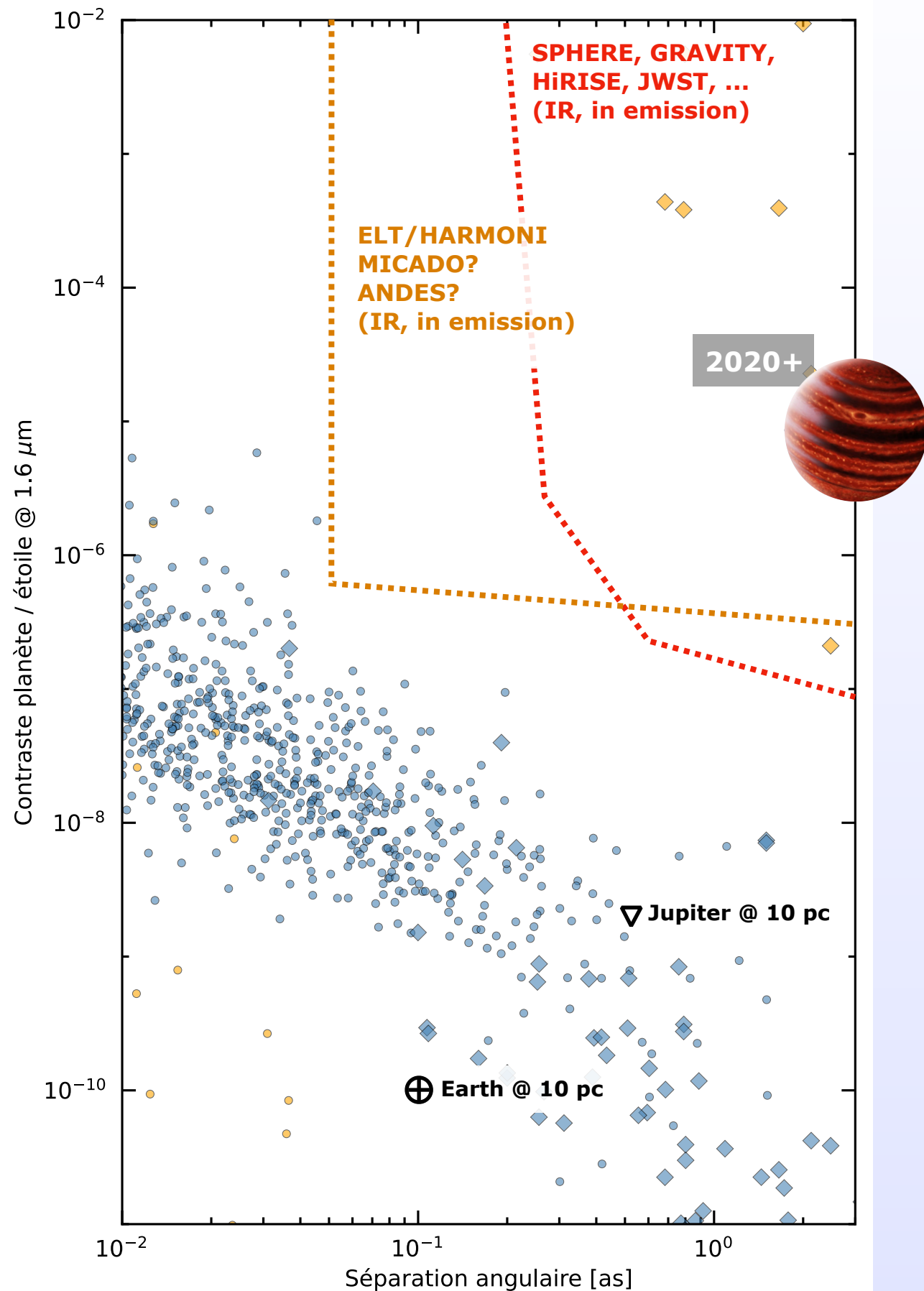


Towards imaging Earth analogues



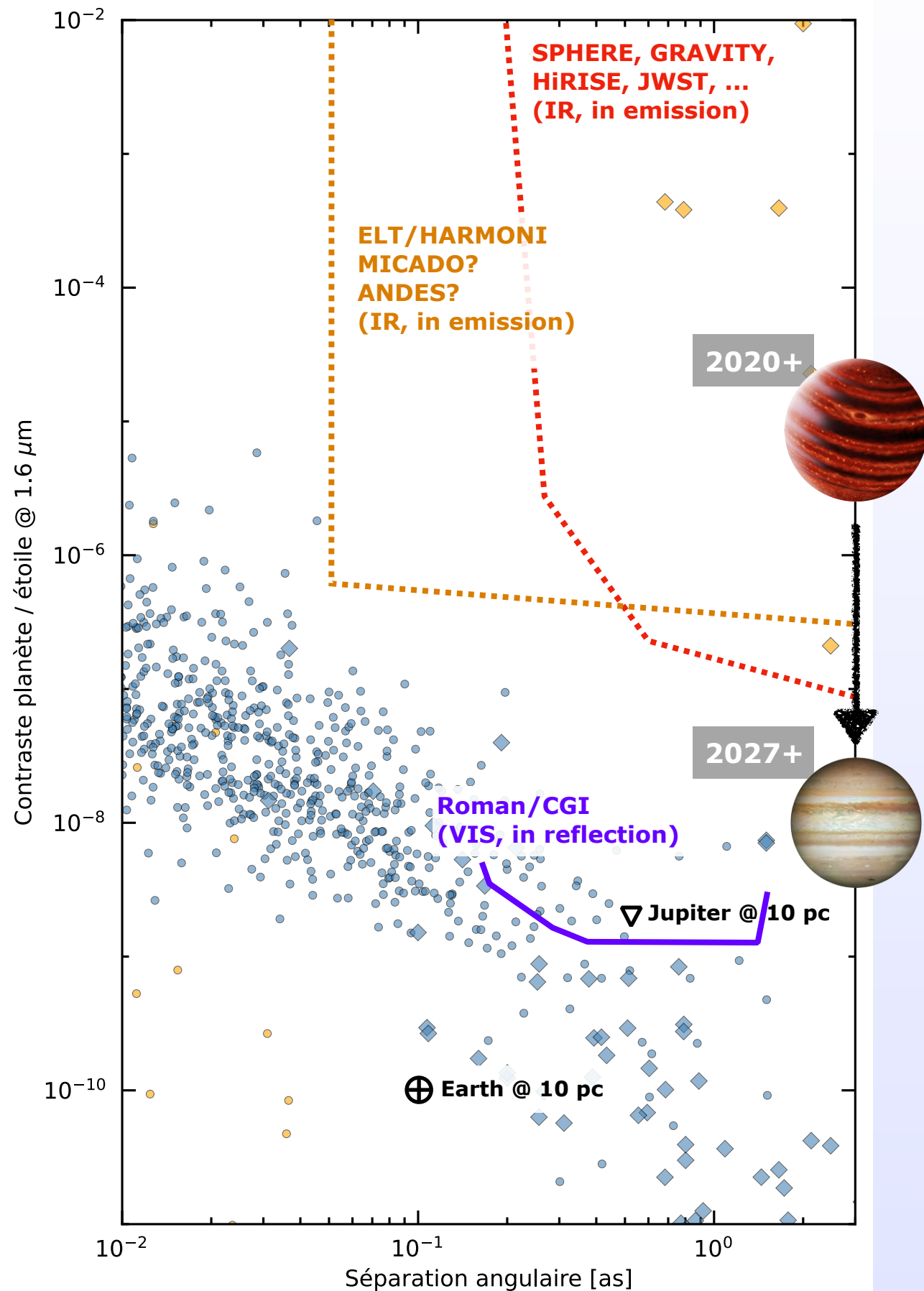
- Many steps along the way:
 - ELT first-light instruments (2028+)
 - NASA Roman Coronagraph (2027+)
- Imaging Earth analogues in the 2040s:
 - PCS on the ELT
 - Habitable Worlds Observatory (HWO)

Towards imaging Earth analogues



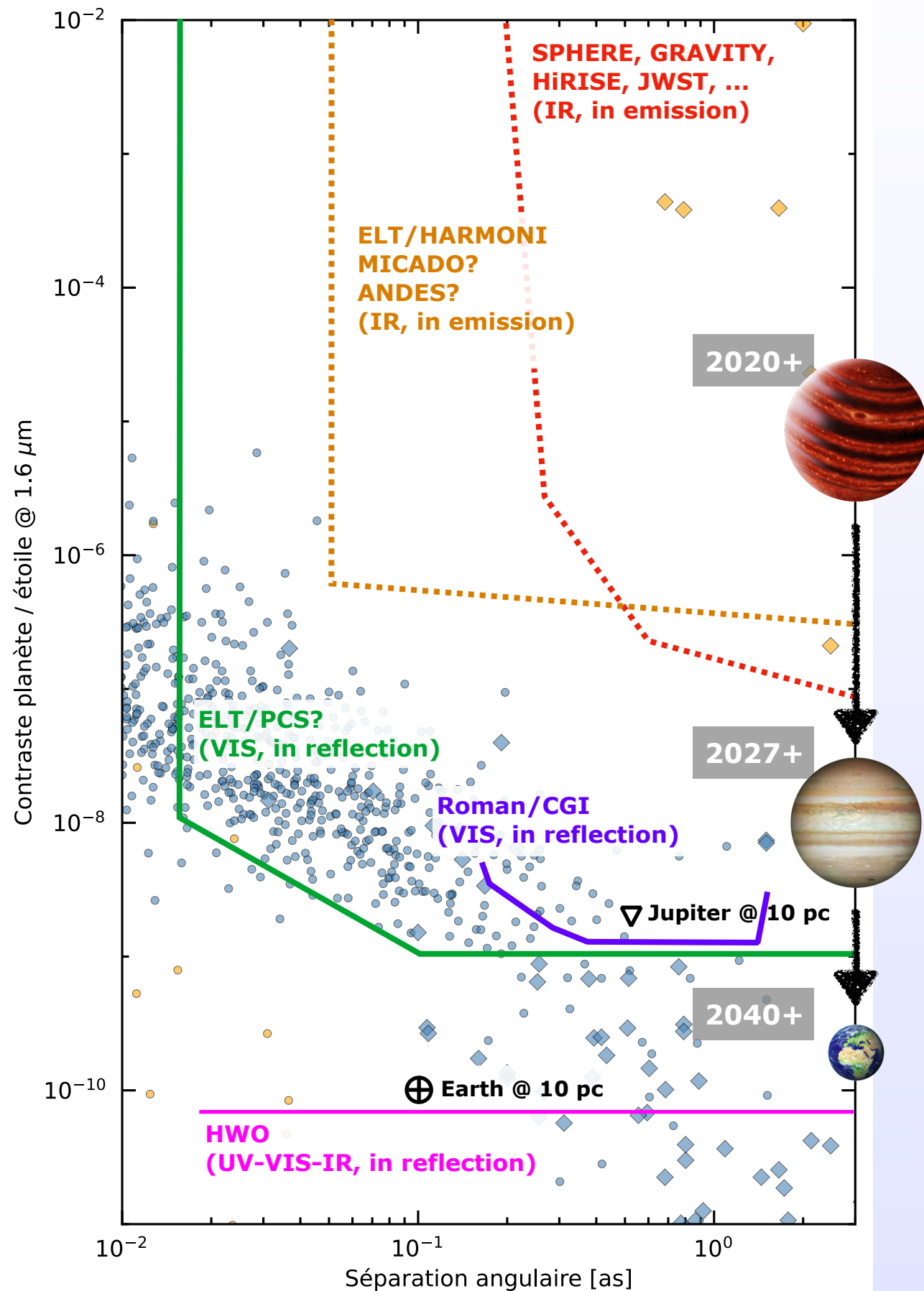
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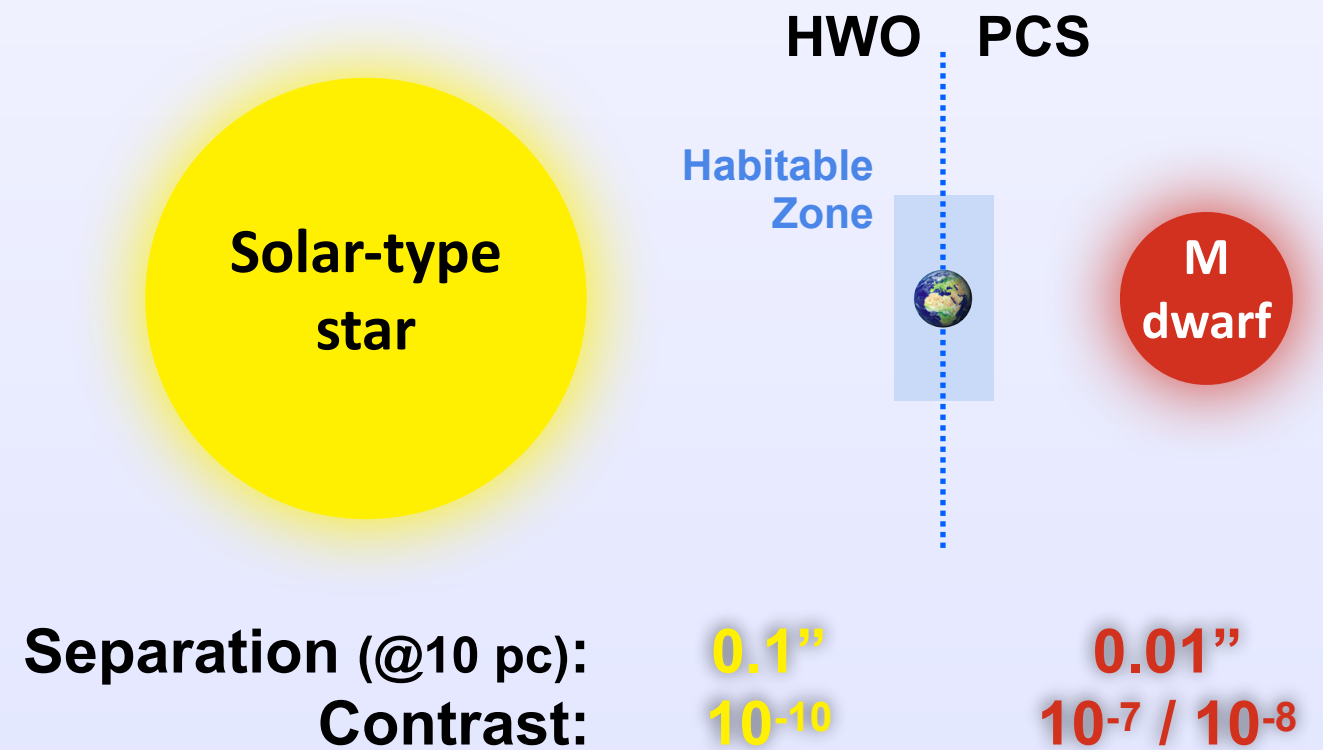


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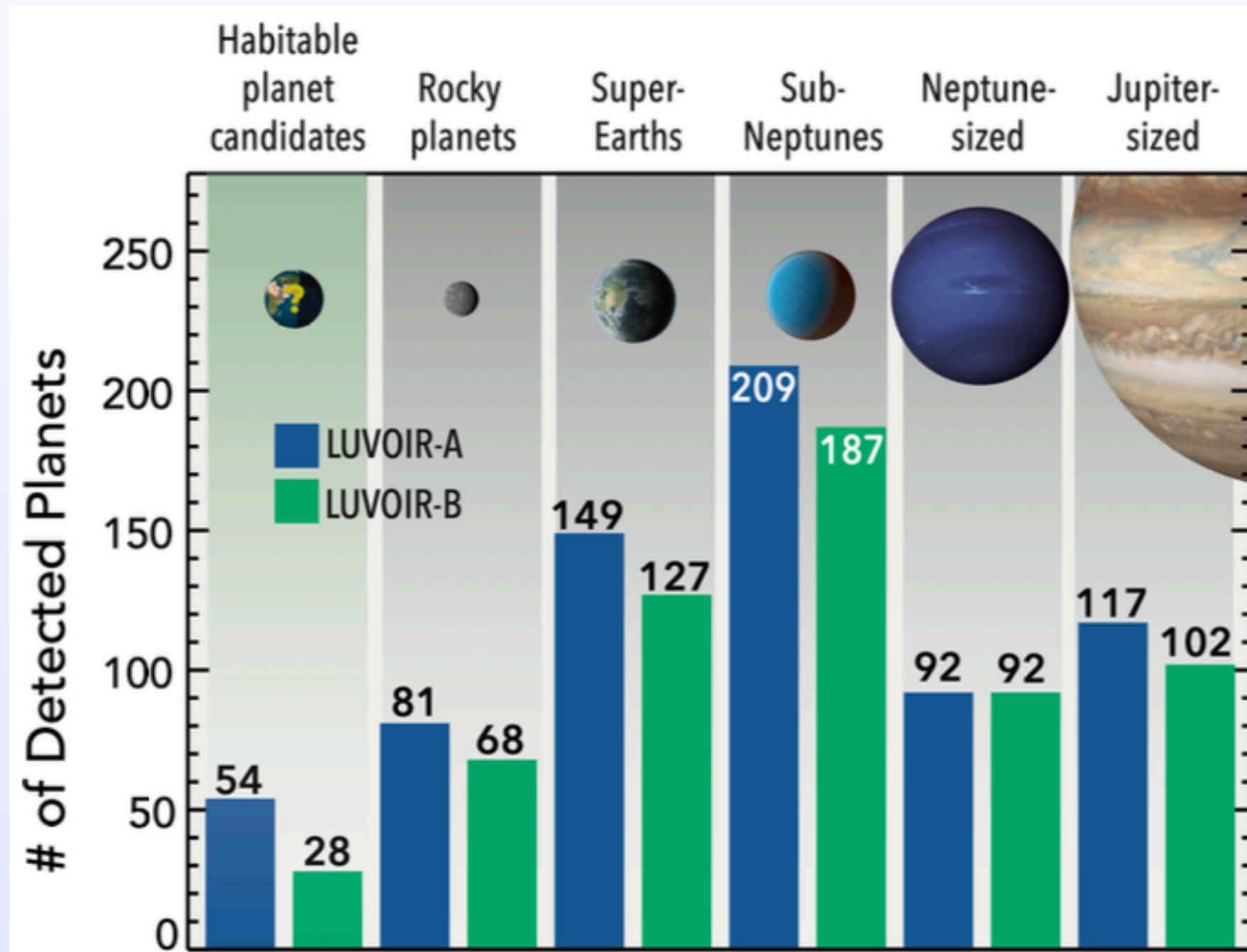


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HWO & PCS: transformational science...

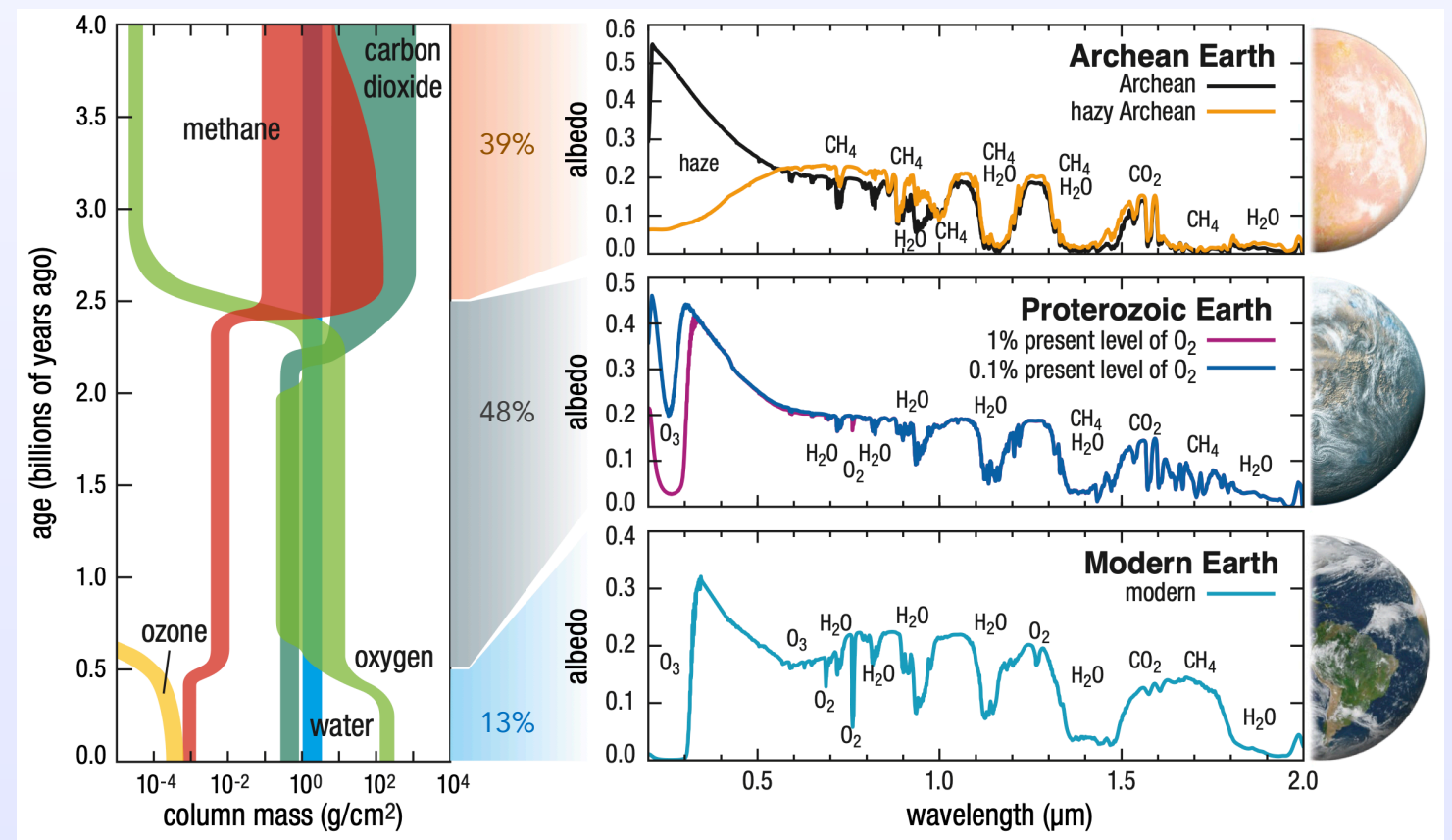
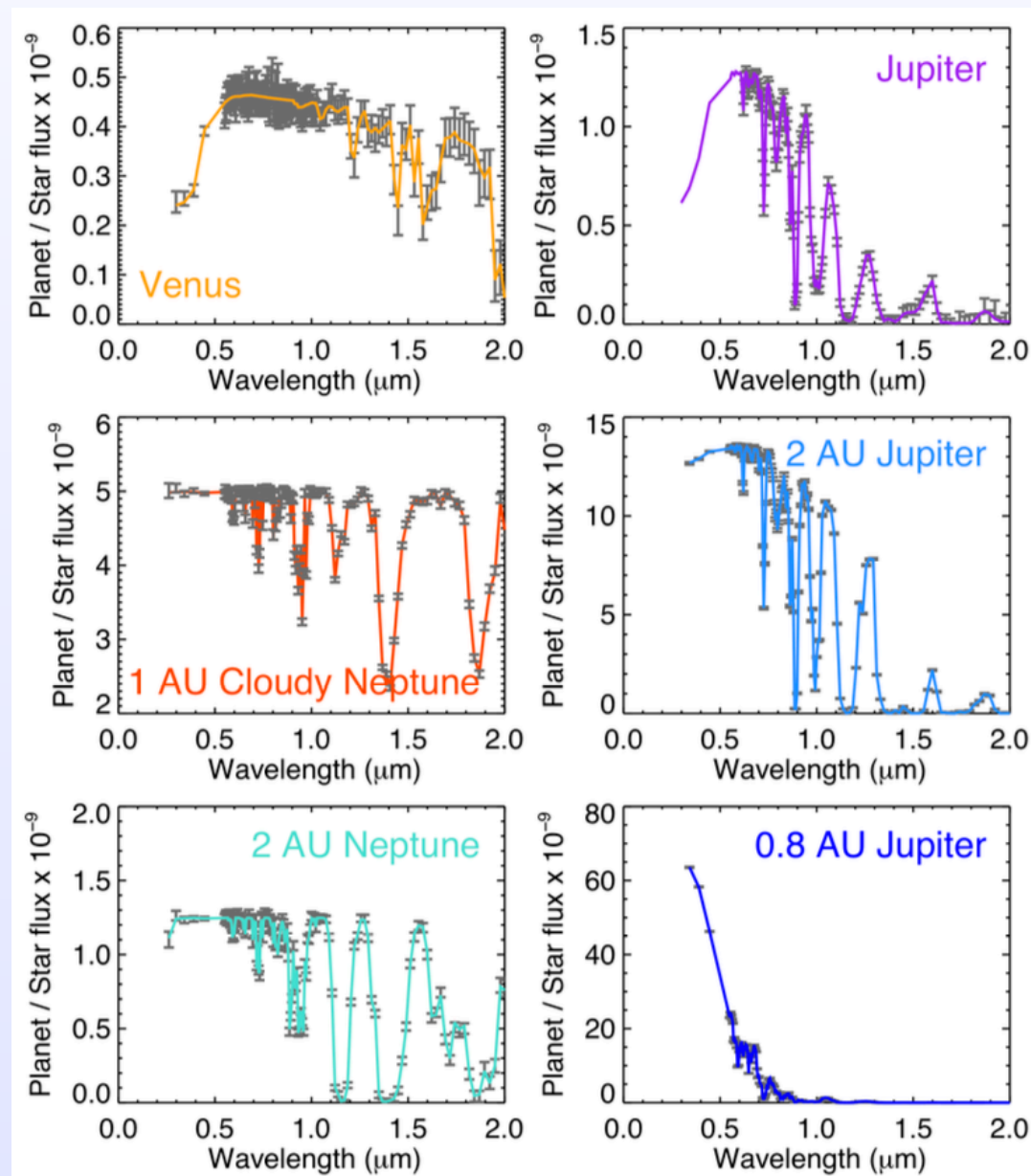
- Sensitive to all kinds of planets
 - From Jupiter-sized planets to small rocky planets



LUVOR & HabEx final reports (2020)

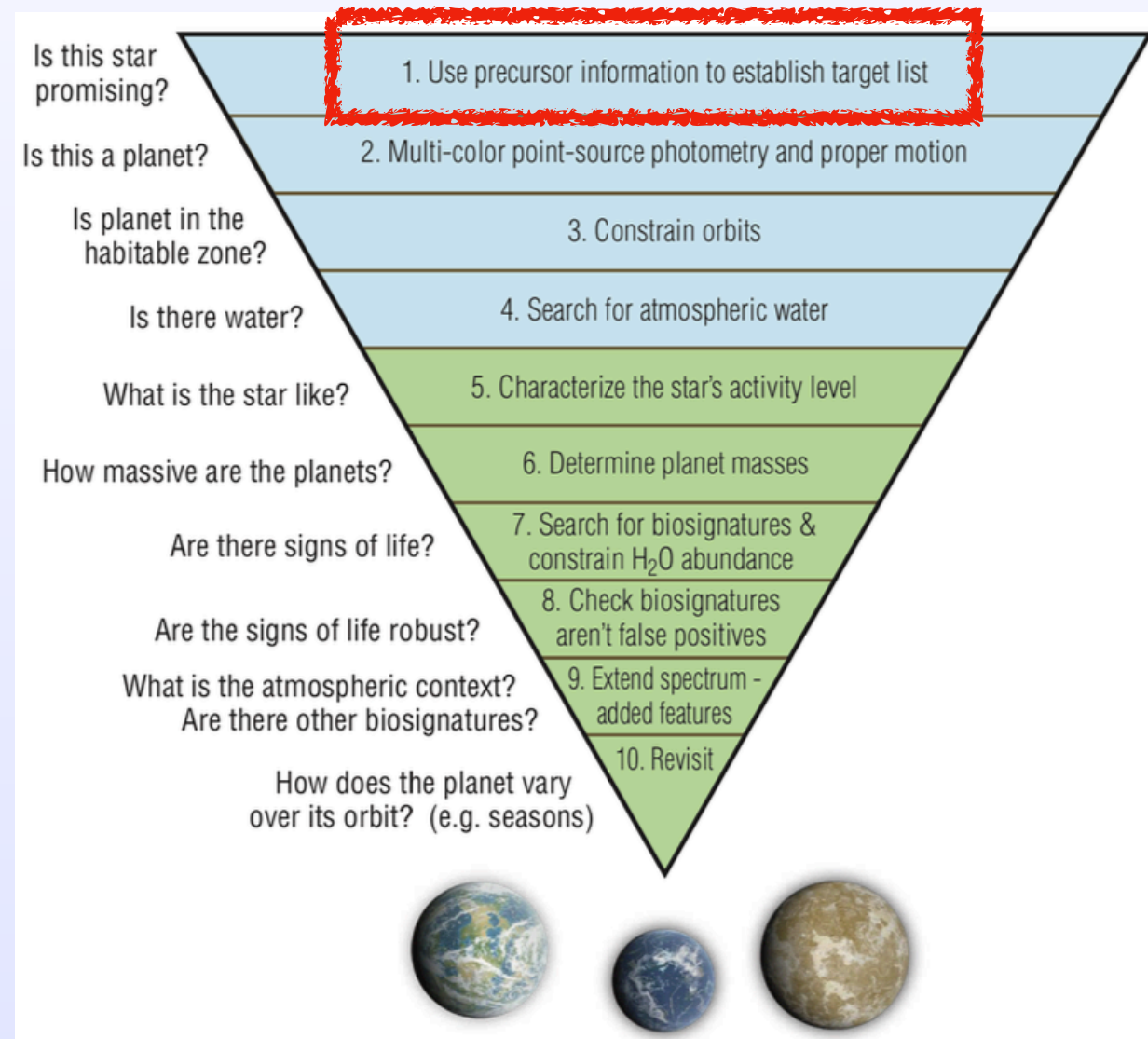
HWO & PCS: transformational science...

- Will be sensitive to all kinds of planets
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 - Characterisation of different evolutionary stages

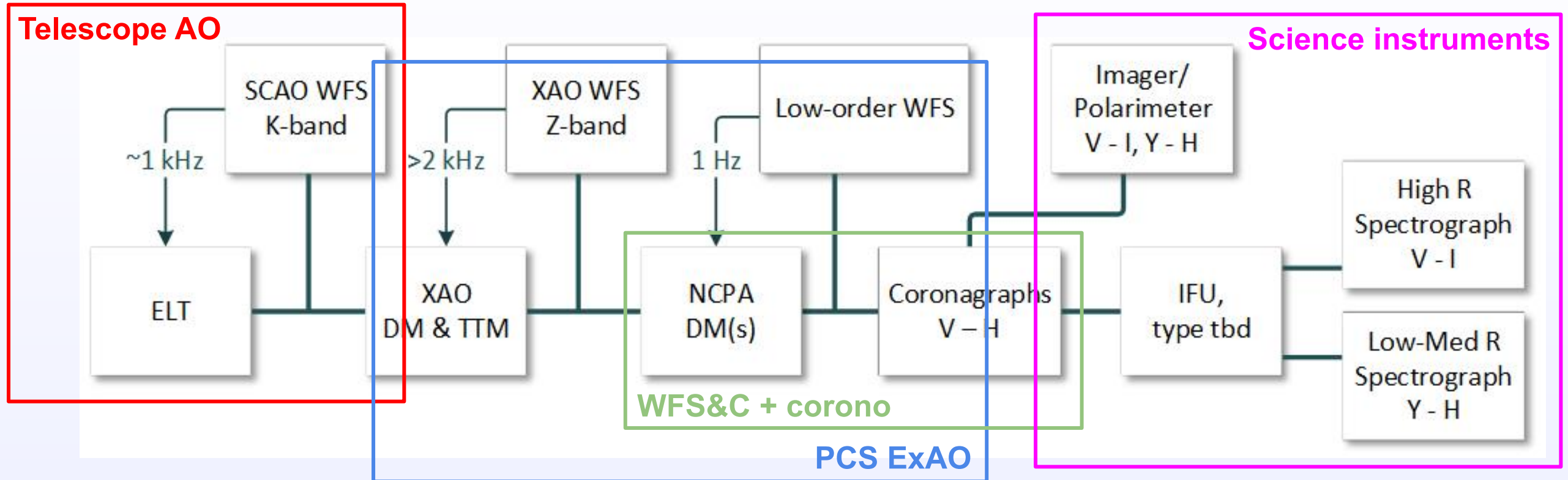


HWO & PCS: transformational science...

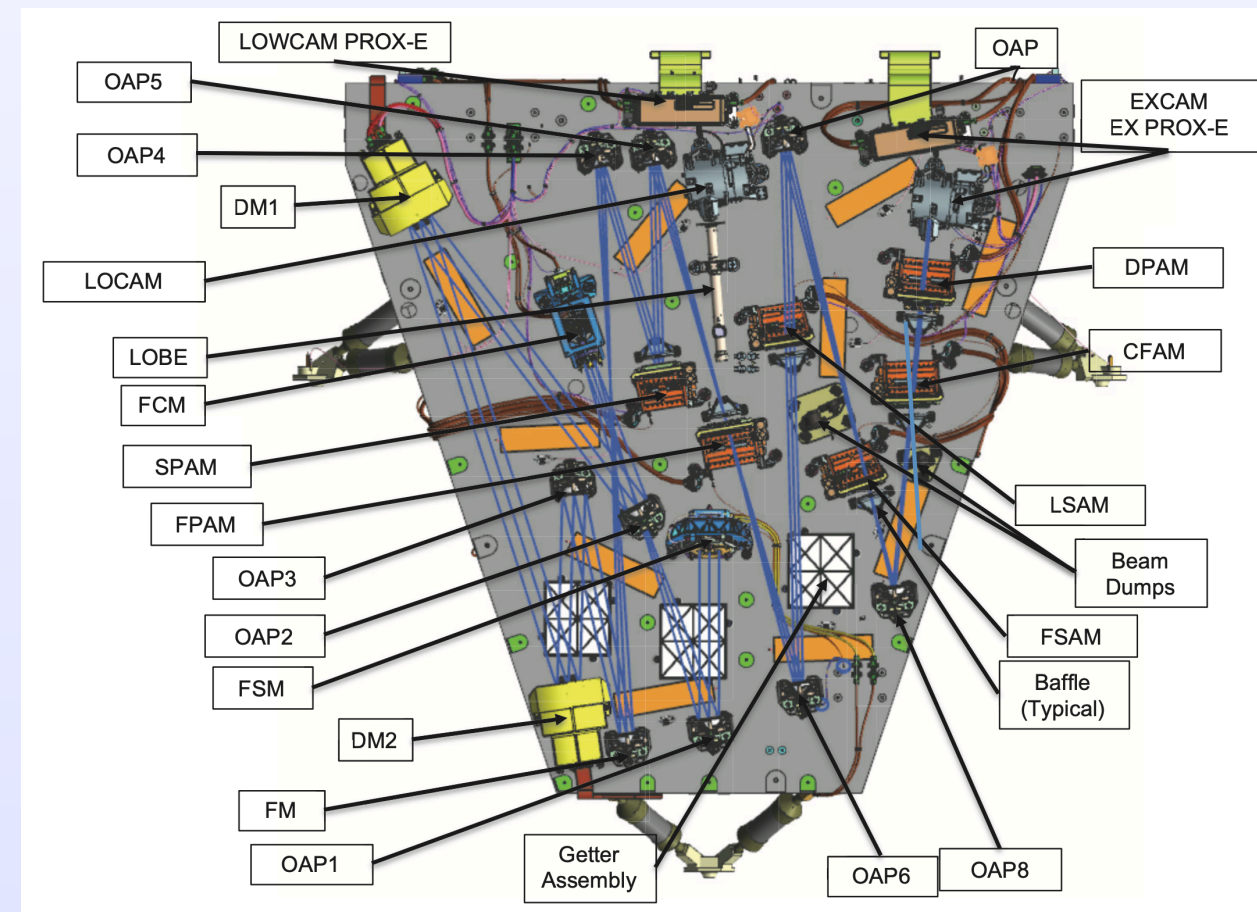
- Will be sensitive to all kinds of planets
 - From Jupiter-sized planets to small rocky planets
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- **Prior information will be key for selecting the best targets → RV, PLATO, ...**



... at the cost of a huge technological step...



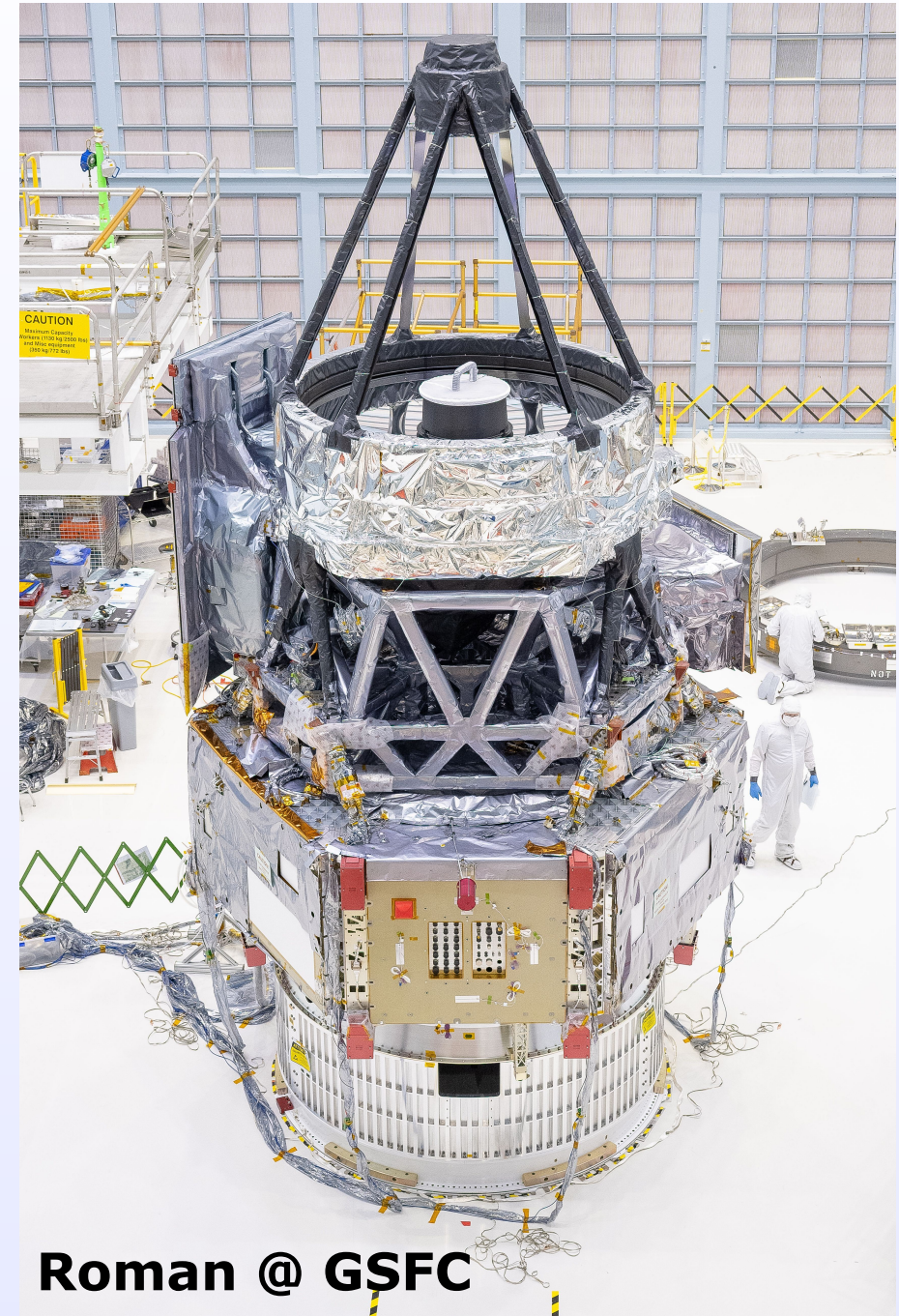
- Very complex (& yet unknown!) telescopes
- Very complex instruments:
 - Multiple AO systems
 - Wavefront sensing & control
 - Advanced coronagraphs
 - Multi-spectral instruments
- Massive R&D effort on-going in Europe and US:
 - SPHERE+, Roman/CGI, multiple testbeds, ...



... but we're already on the way!



ELT @ Armazones

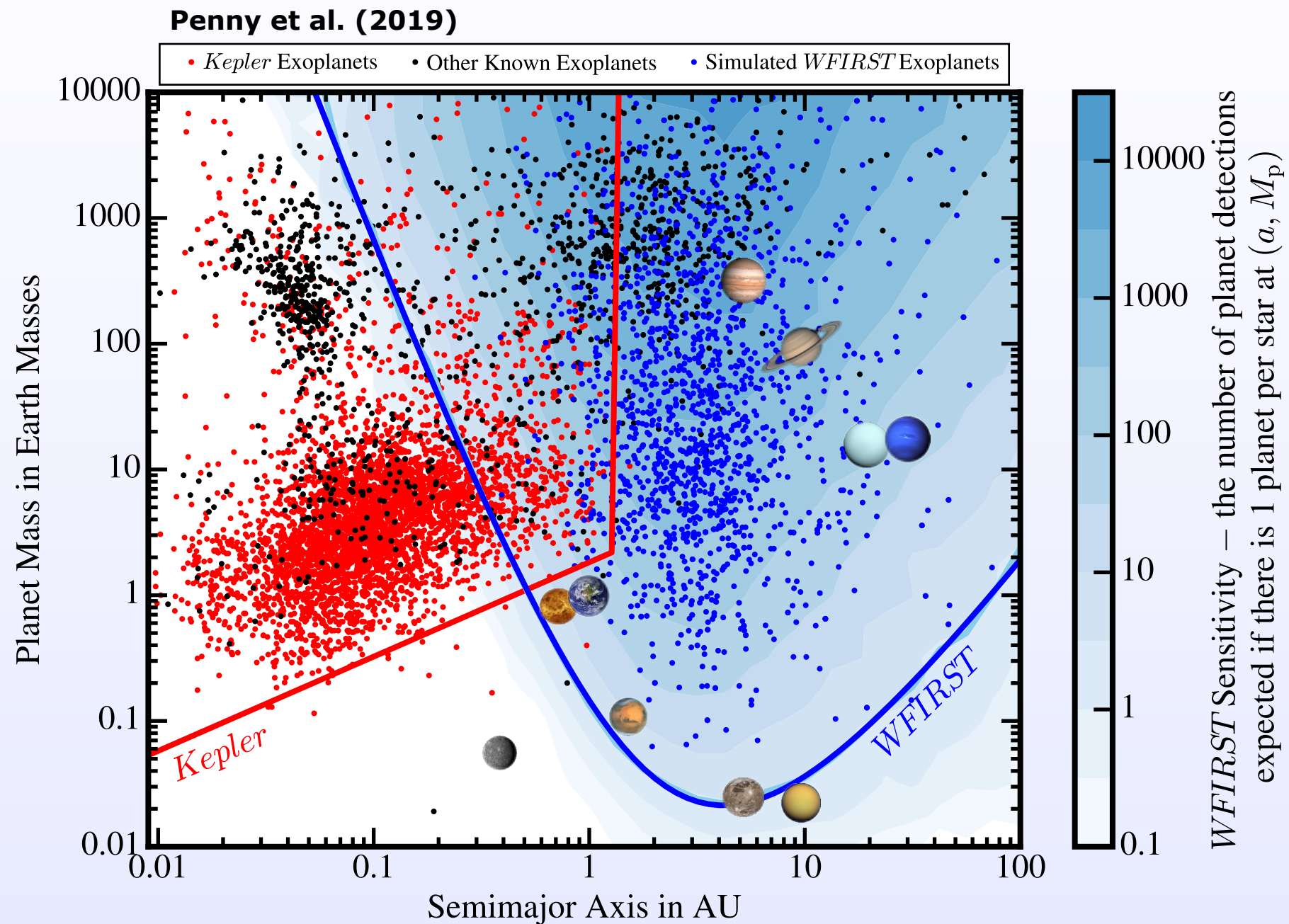


Roman @ GSFC

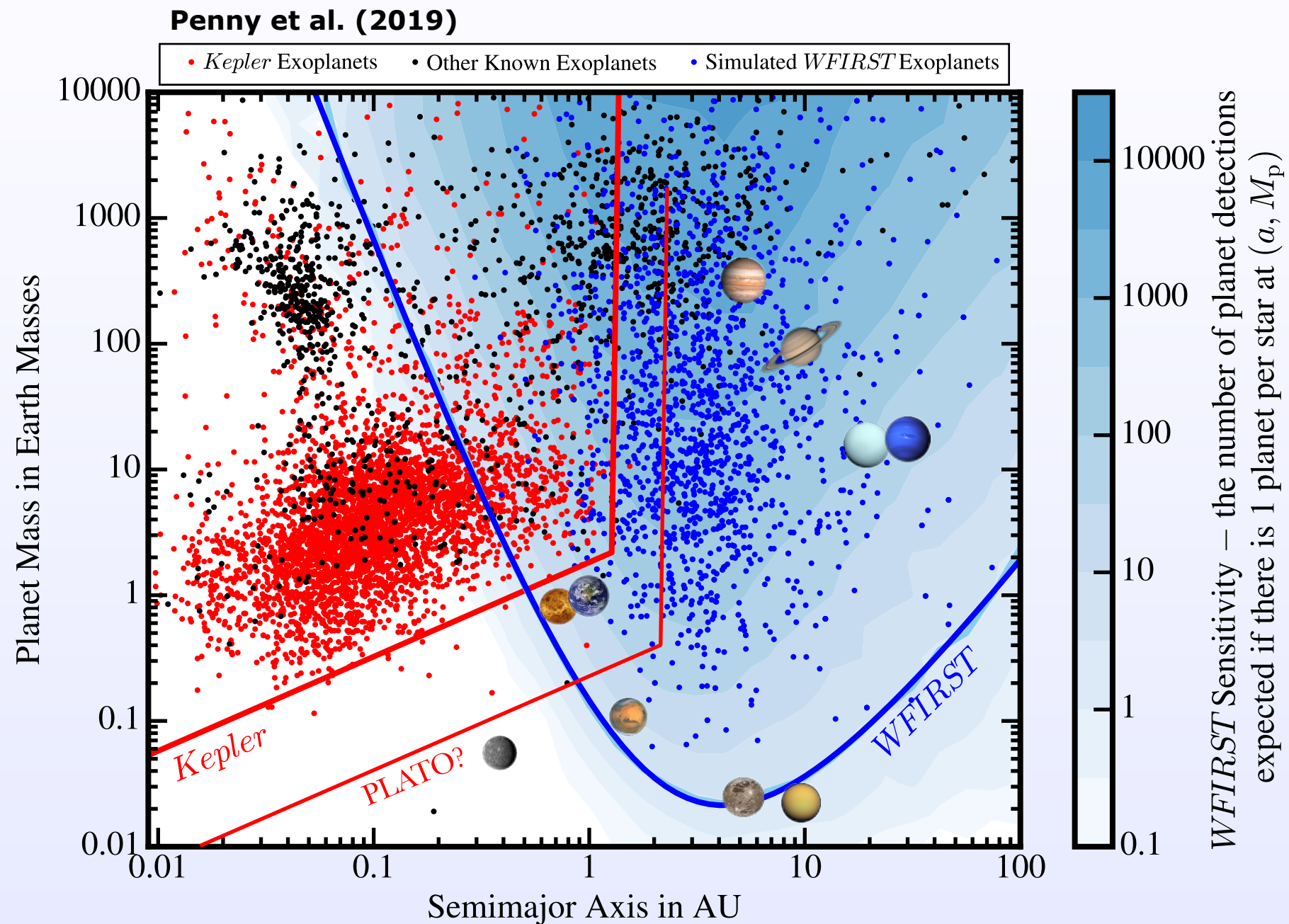
**+ HWO & PCS working groups
already hard at work**

Will we ever image PLATO Earth-like planets?

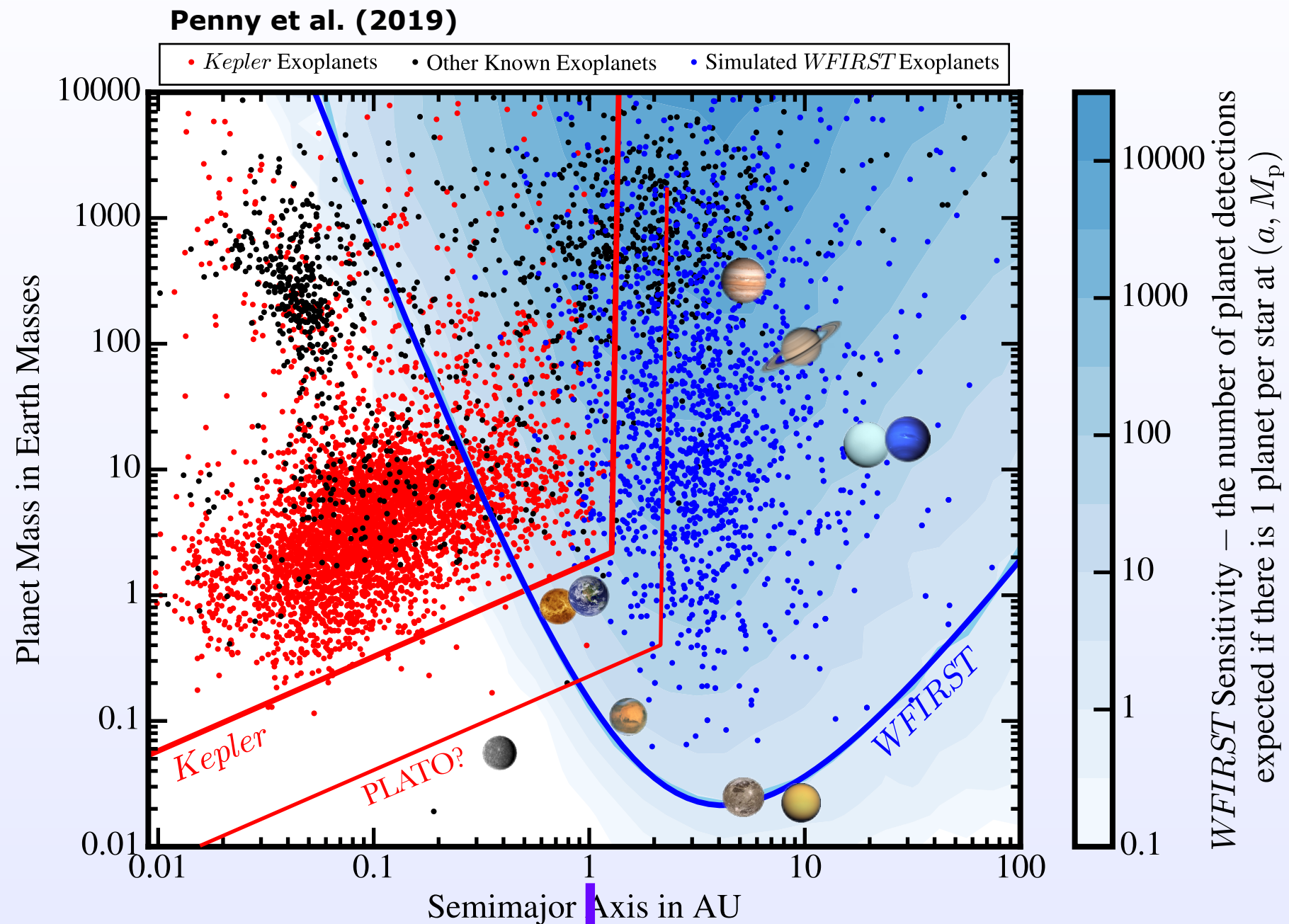
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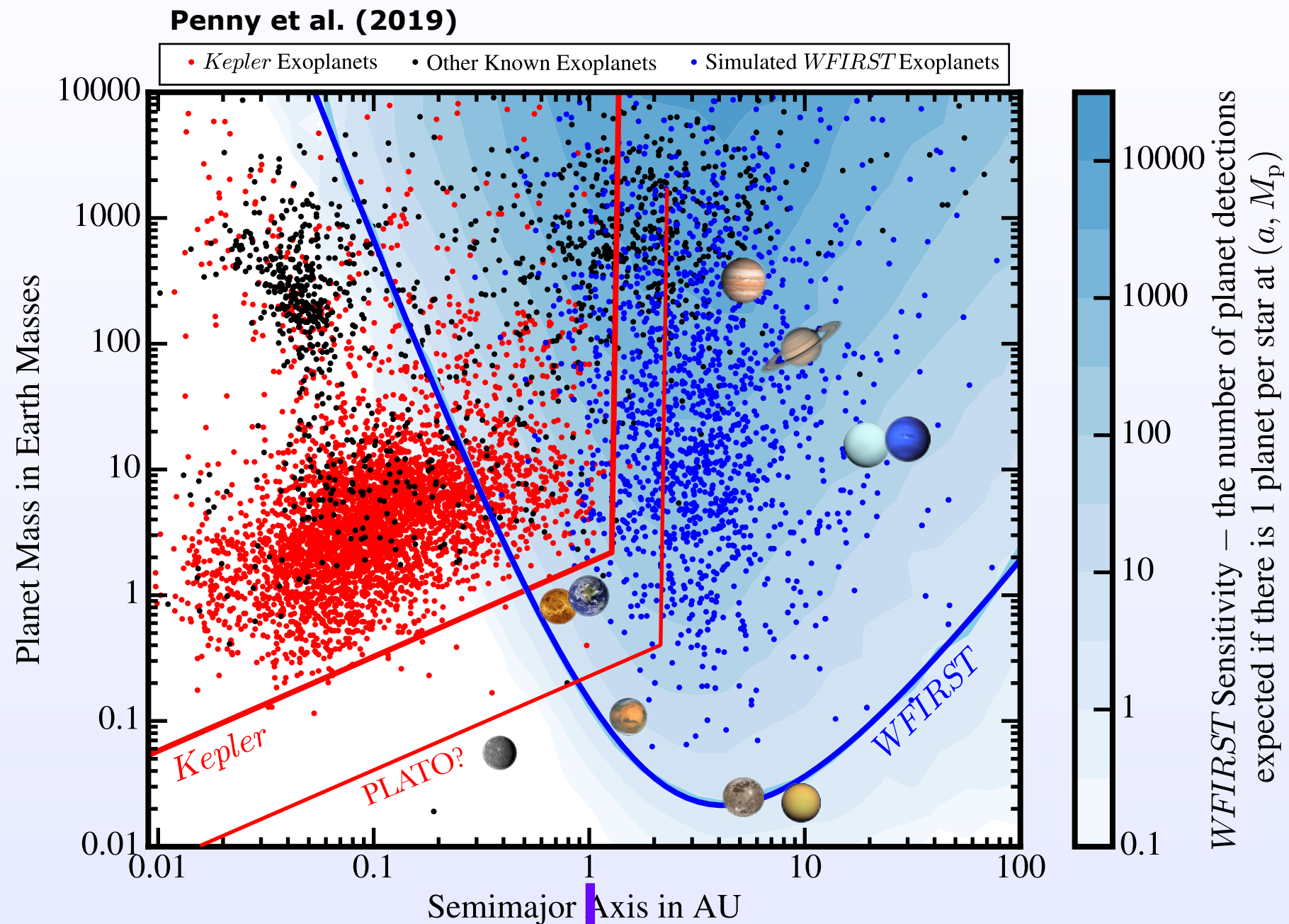


Will we ever image PLATO Earth-like planets?



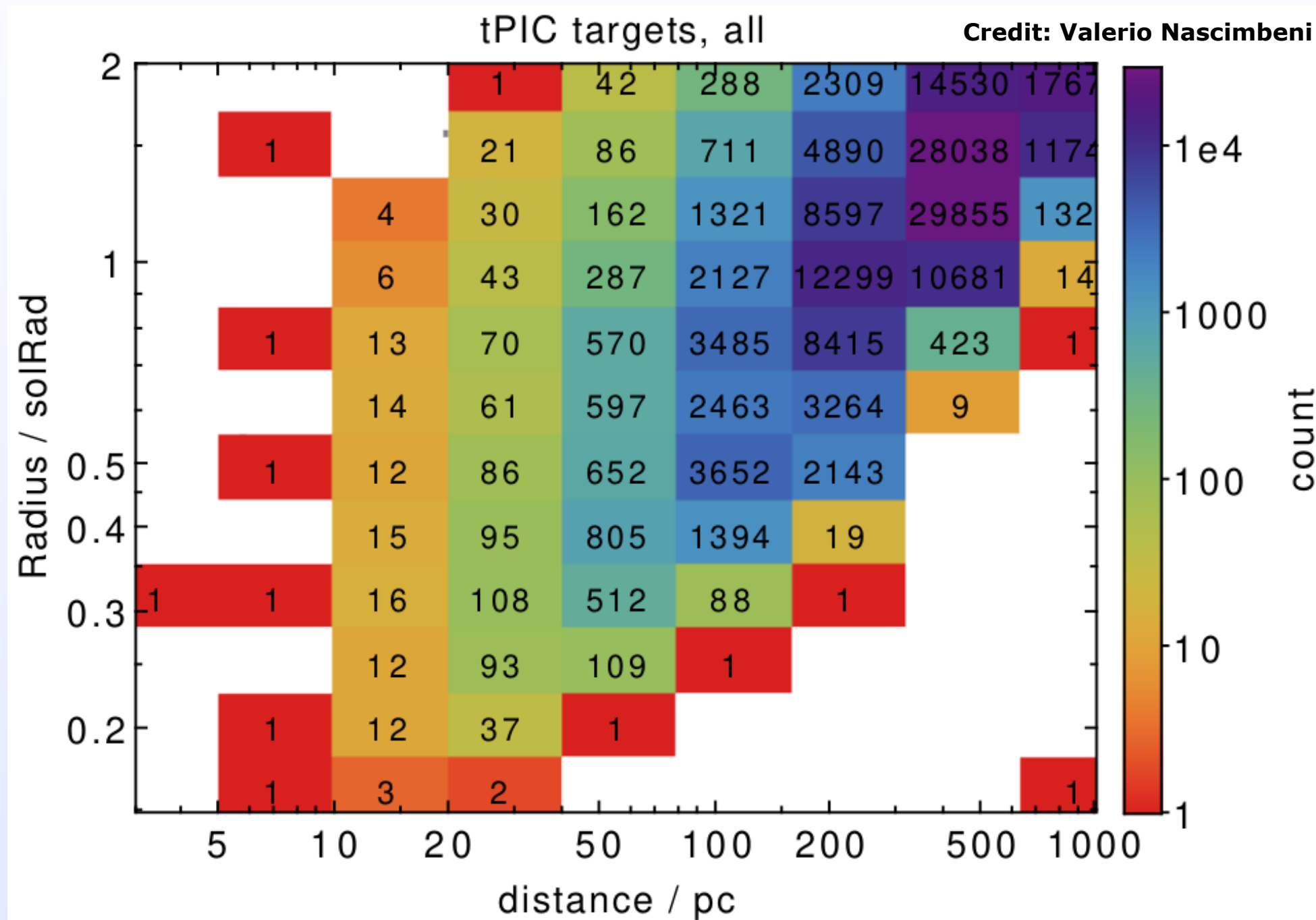
<i>5 pc</i>	<i>10 pc</i>	<i>30 pc</i>	<i>50 pc</i>	<i>100 pc</i>
<i>0.2''</i>	<i>0.1''</i>	<i>0.03''</i>	<i>0.02''</i>	<i>0.01''</i>

Will we ever image PLATO Earth-like planets?

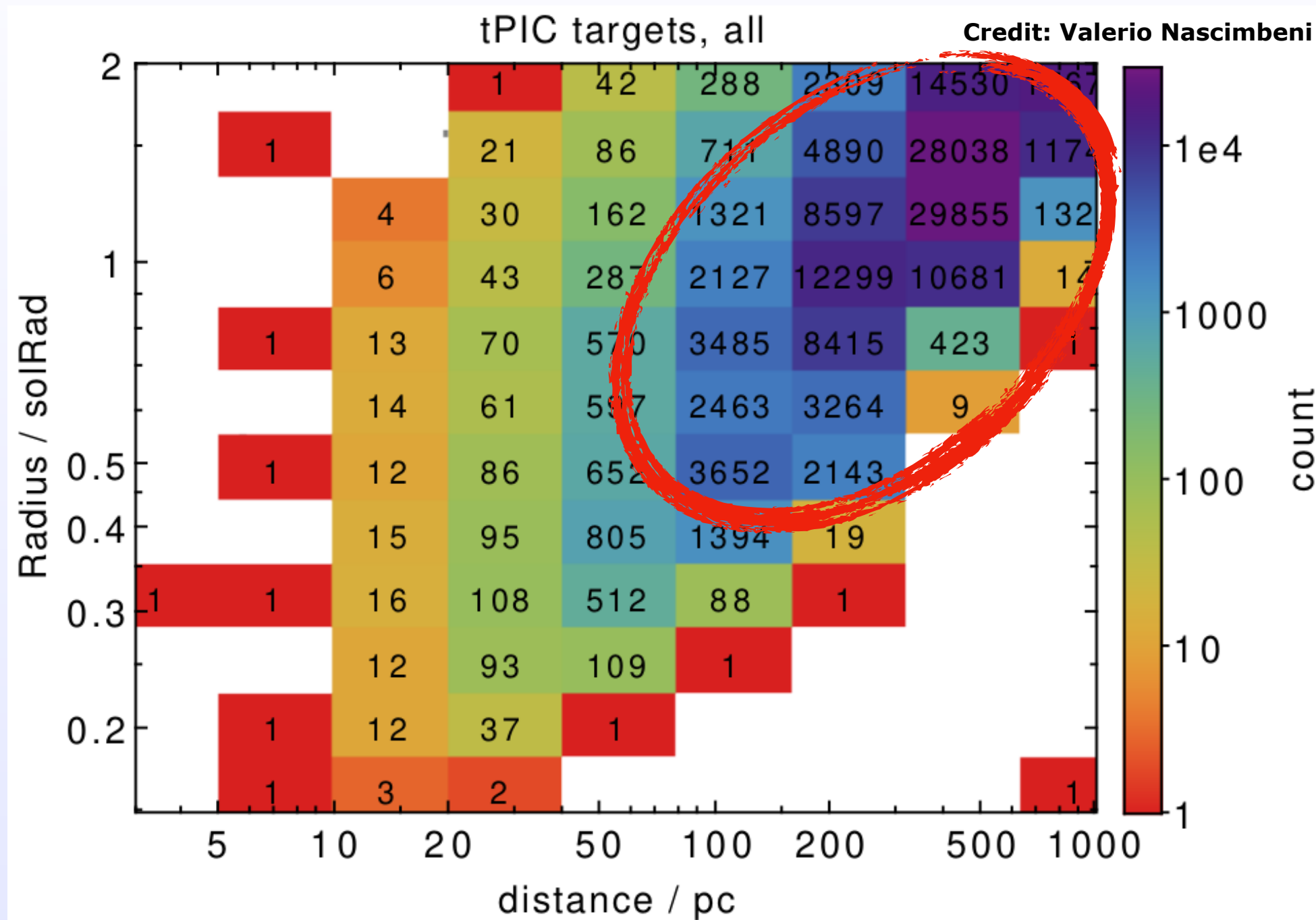


5 pc	10 pc	30 pc	50 pc	100 pc
0.2"	0.1"	0.03"	0.02"	0.01"

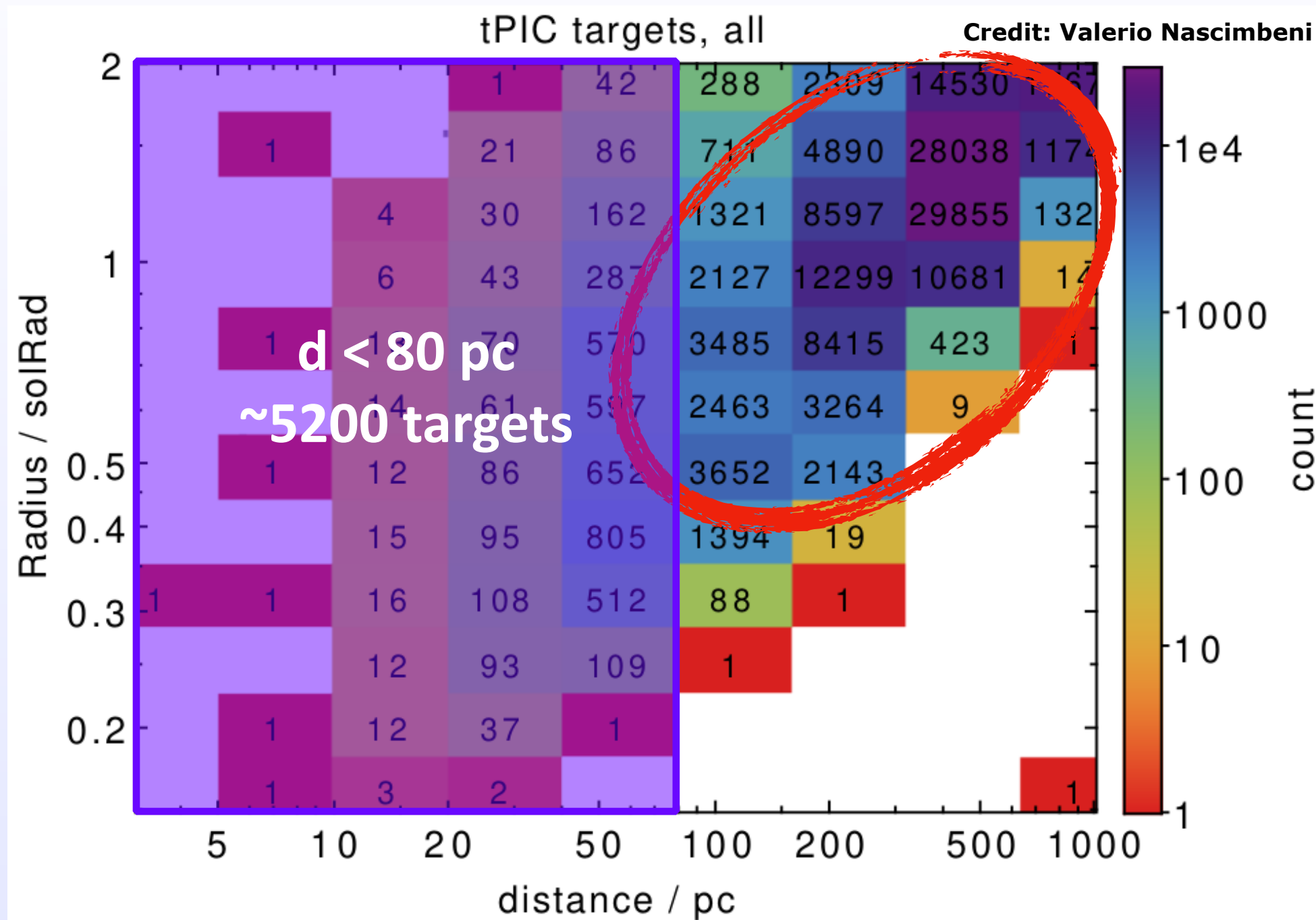
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 - **Byproduct: how many planets will HWO be able to detect and characterise?**

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Thank you!

