The Alpha Centauri System, Towards New Worlds - Hotel Saint Paul, June 23rd, 2023

The Future of Ground-based Exoplanet Characterization at VLT/I & ELT

Gaël Chauvin
(Laboratoire Lagrange, Observatoire Côte d'Azur)

Outline

1. Context & science drivers

1. The VLT/I-2030 roadmap

   Toward exploring giant planet atmosphere demographics

1. The ELT one

   The long road toward characterizing super-Earths

1. Take away

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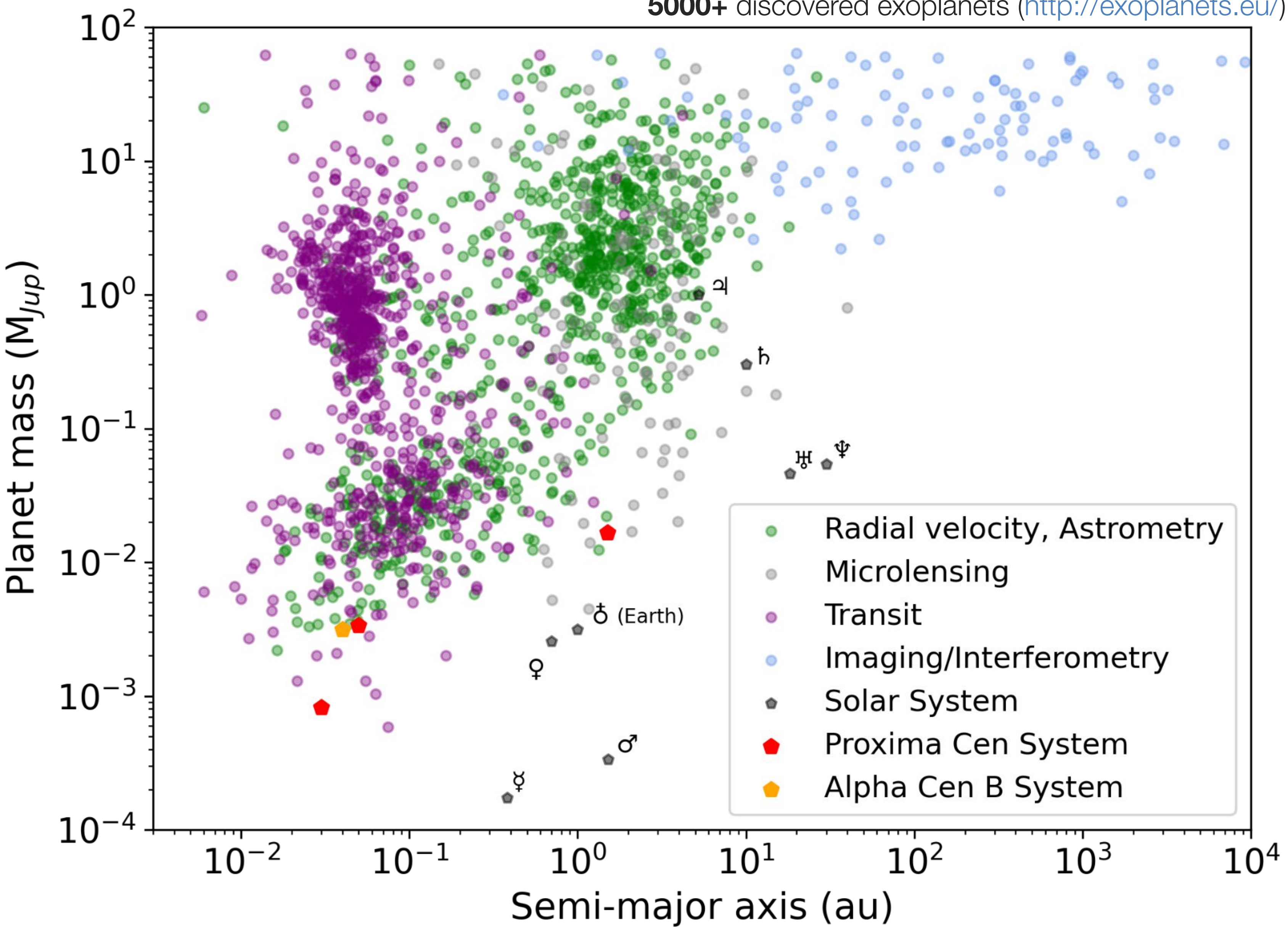
The Exoplanets Zoo

5000+ discovered exoplanets (http://exoplanets.eu/)



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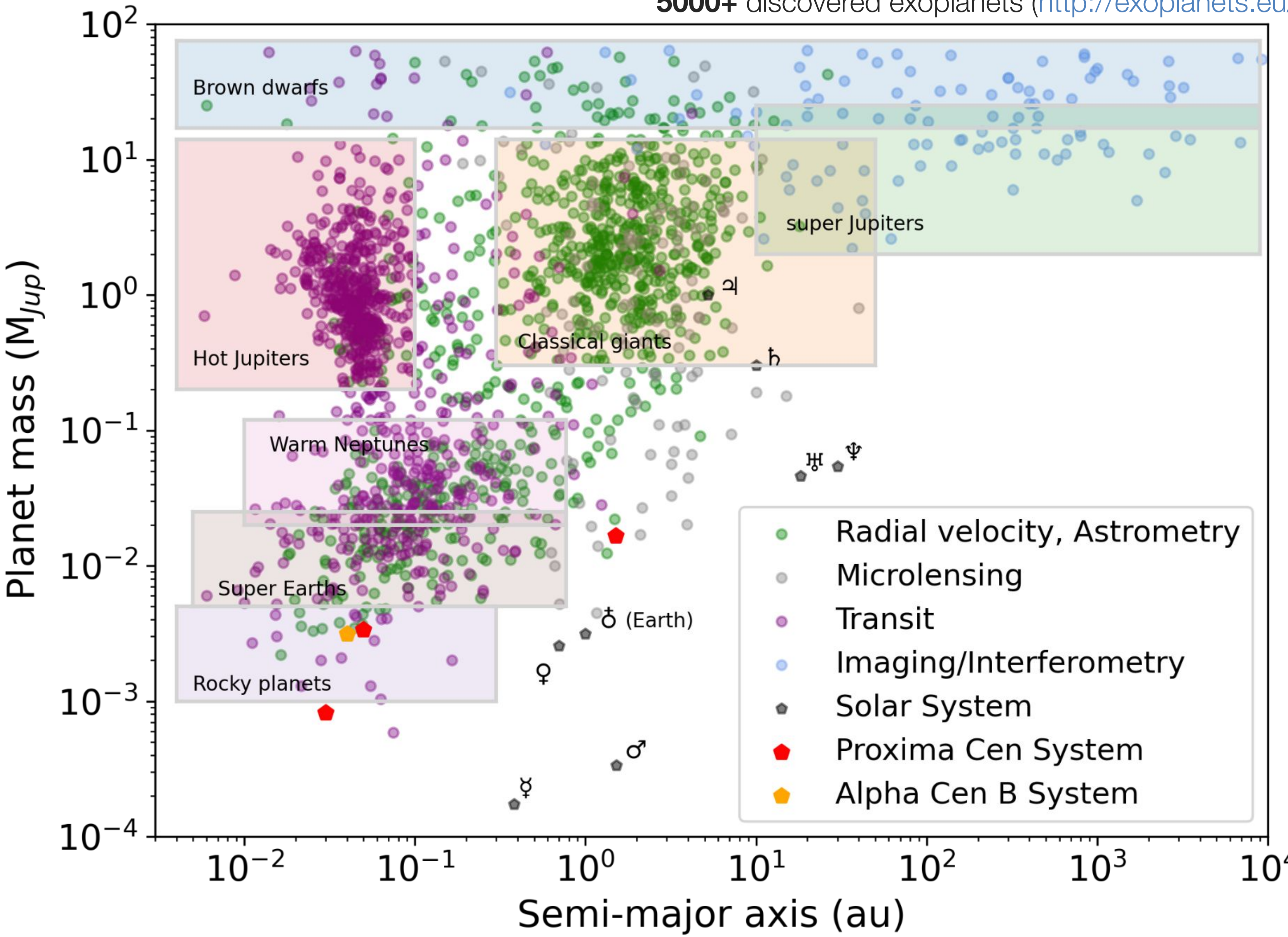

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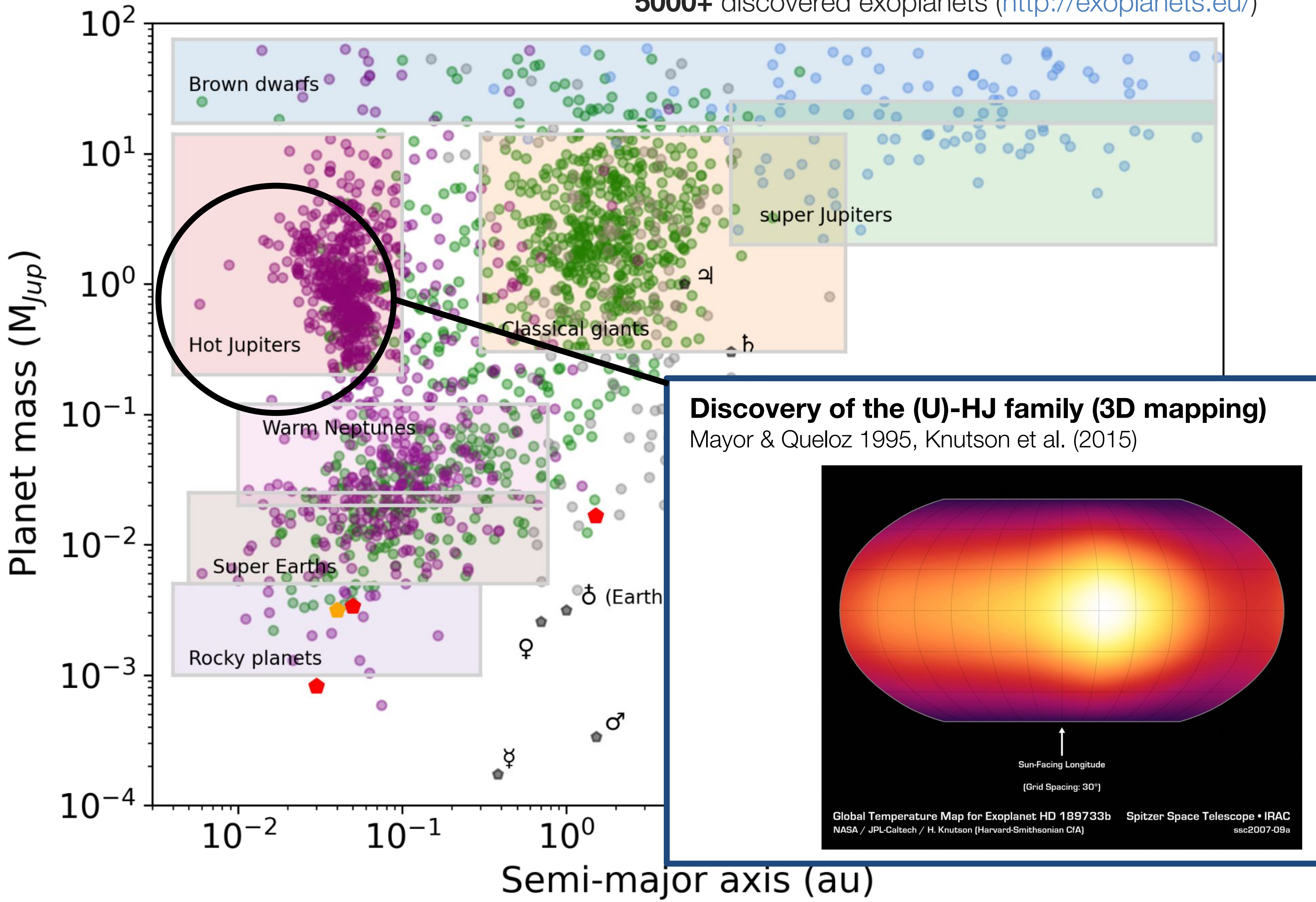

Discovery of the (U)-HJ family (3D mapping)

Mayor & Queloz 1995, Knutson et al. (2015)

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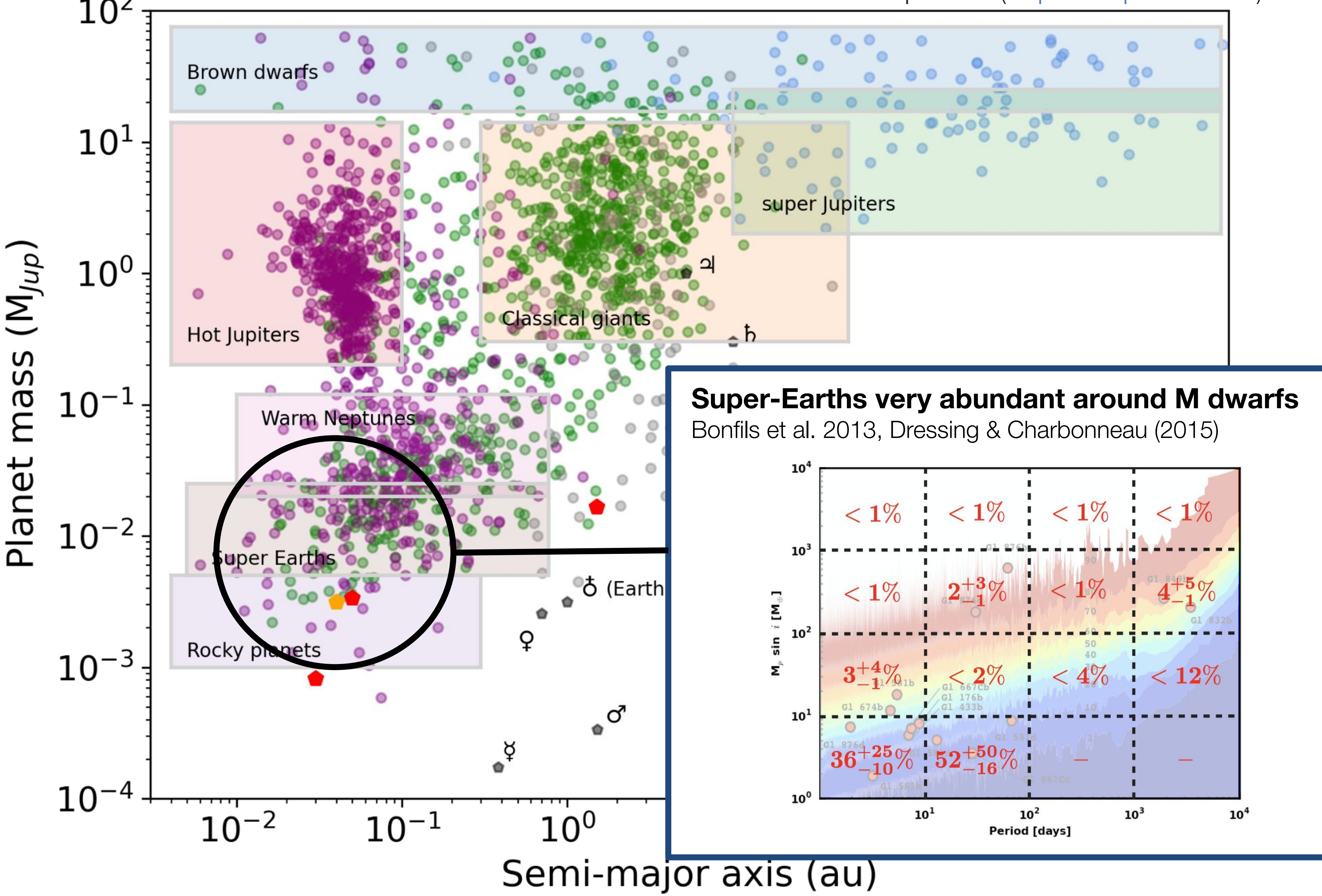

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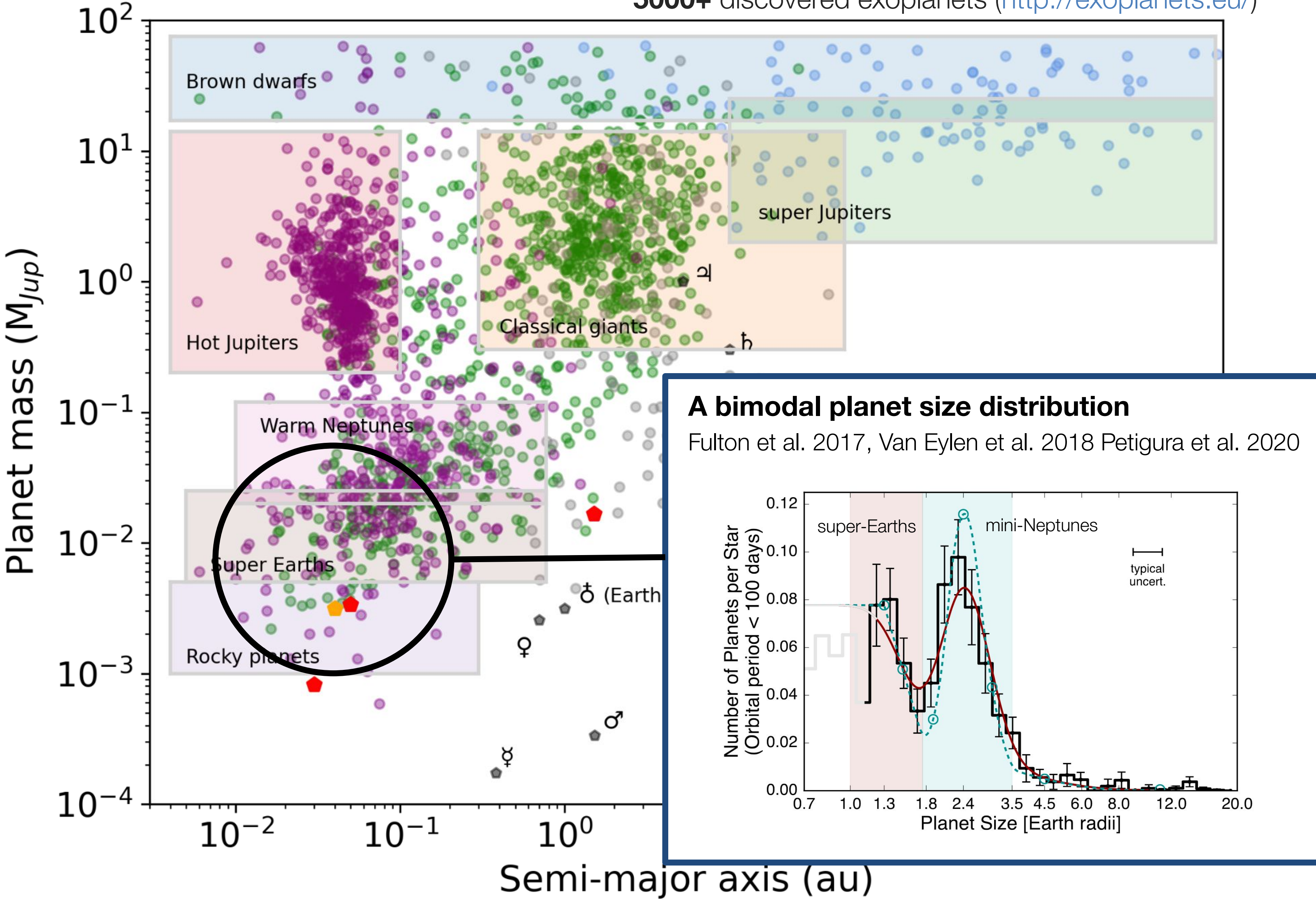

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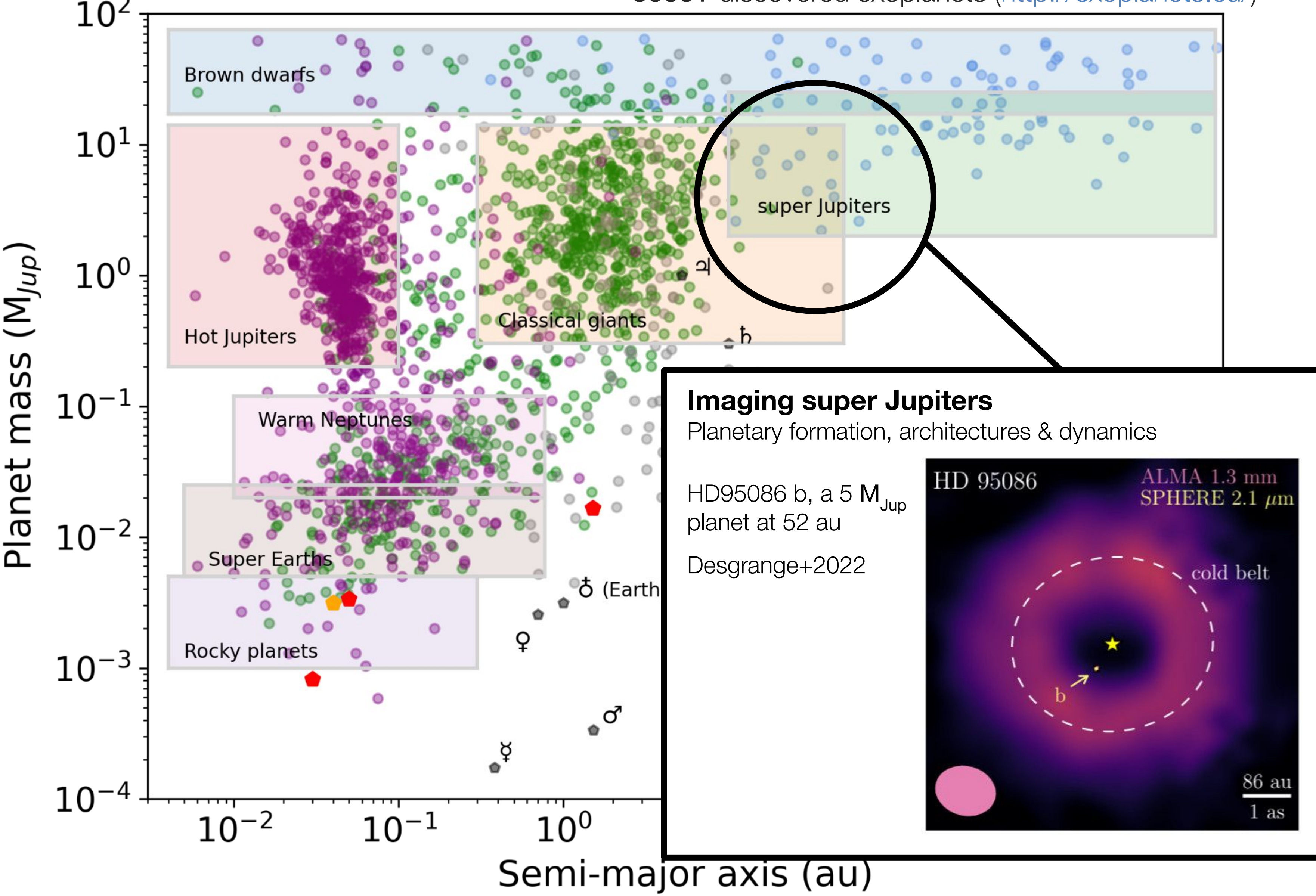
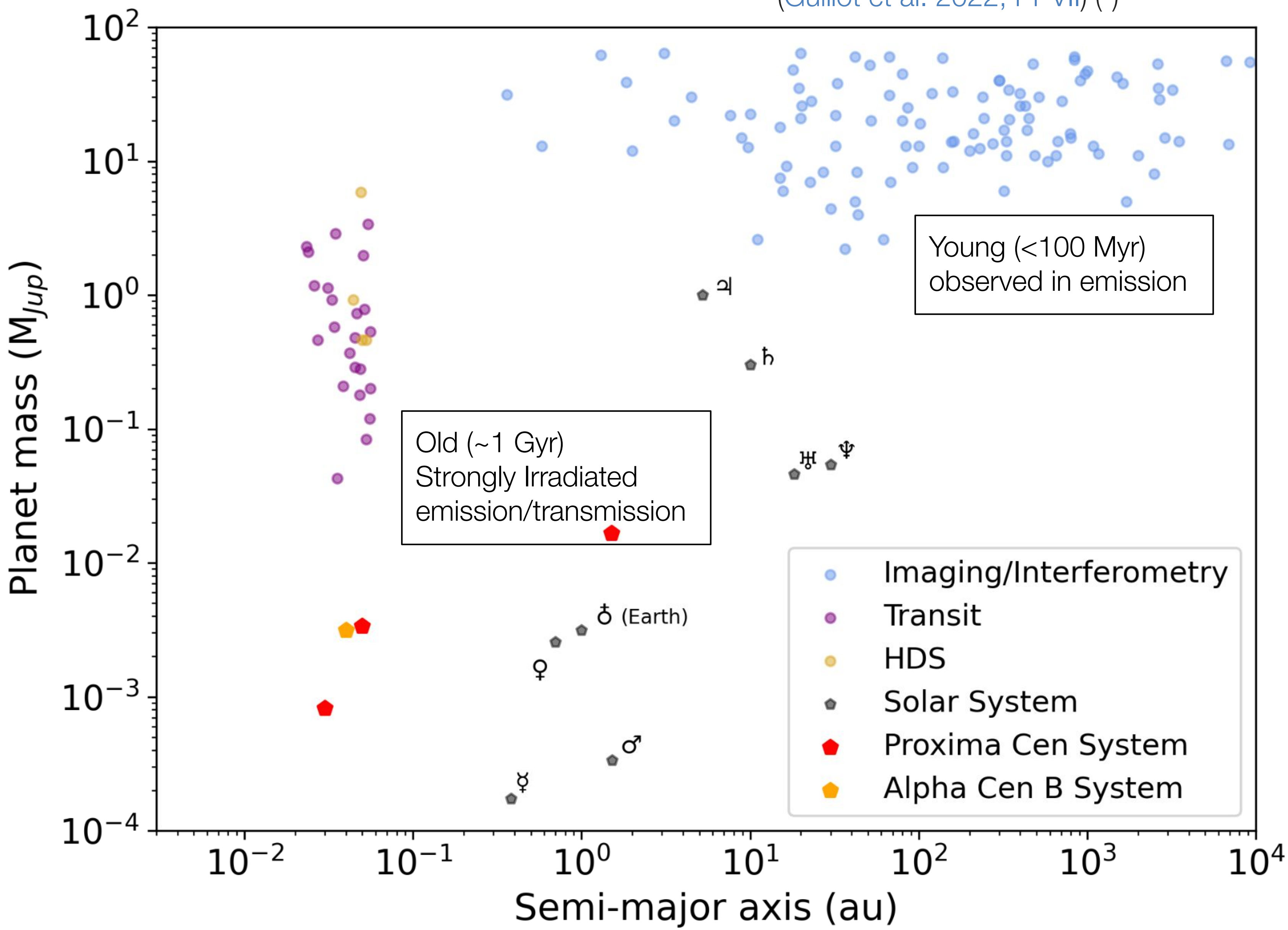


(*): We included only planets where more than 2 species have been detected and species that have been detected in at least two planets.

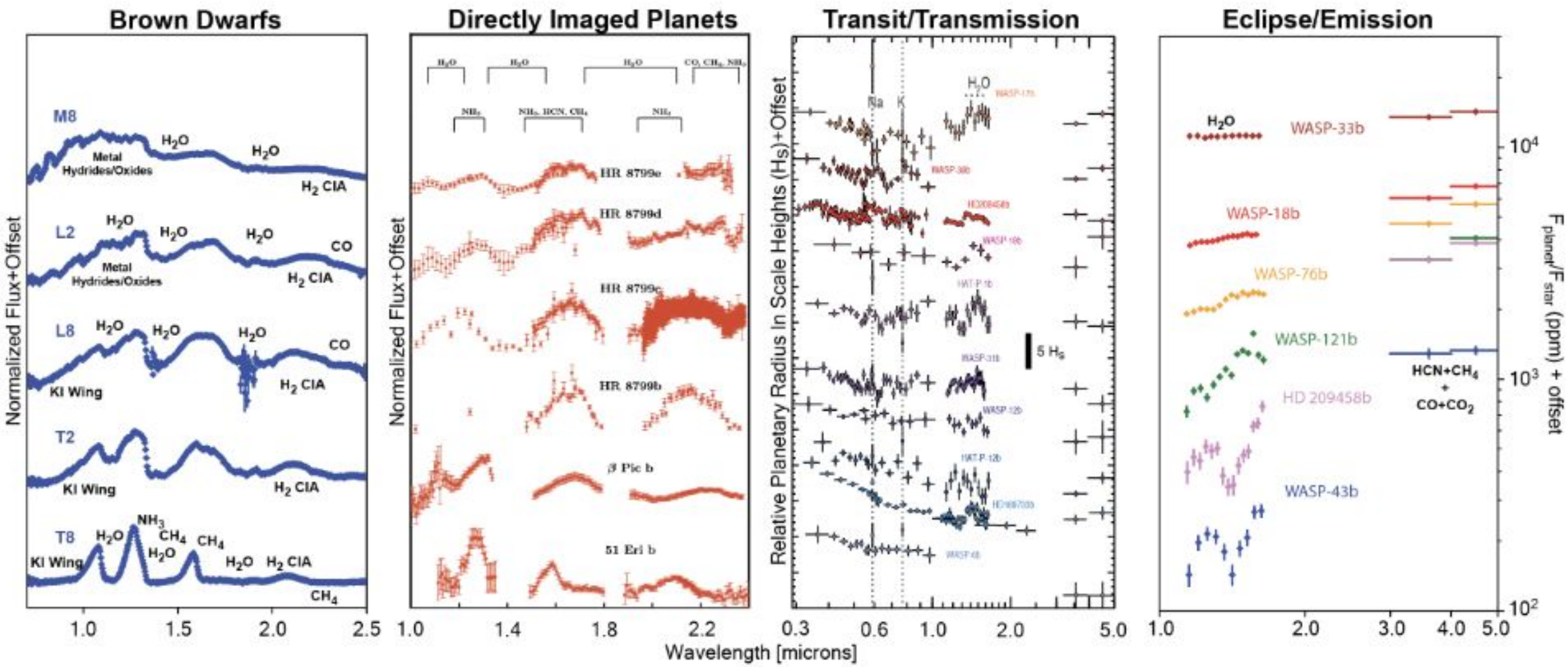
Exo-Atmospheres

50+ spectrally characterized exoplanets (Guillot et al. 2022, PPVII) (*)



Exoplanetary atmospheres

Diversity from various techniques & systems!

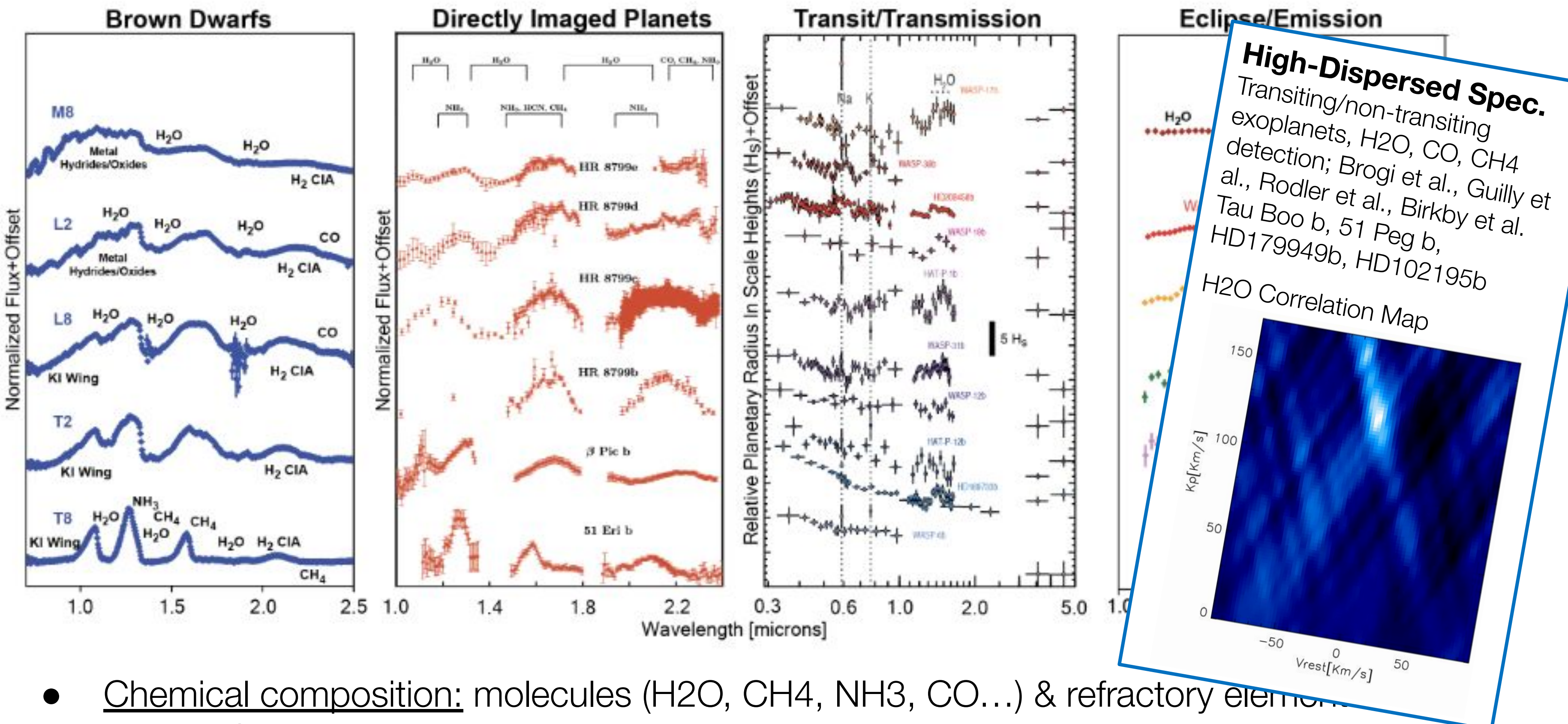


- Chemical composition: molecules (H2O, CH4, NH3, CO…) & refractory elements
- Haze & Clouds properties: variability, albedos, silicate signatures
- Global atmospheric circulation: winds, jets, vertical mixing
- Mass-loss and outflows: lines variability with orbital phase,

e.g. Madhusudhan (2019), Sing et al. (2016), Chauvin (2018), Mansfield et al. (2021), Pelletier et al. (2023)

Exoplanetary atmospheres

Diversity from various techniques & systems!



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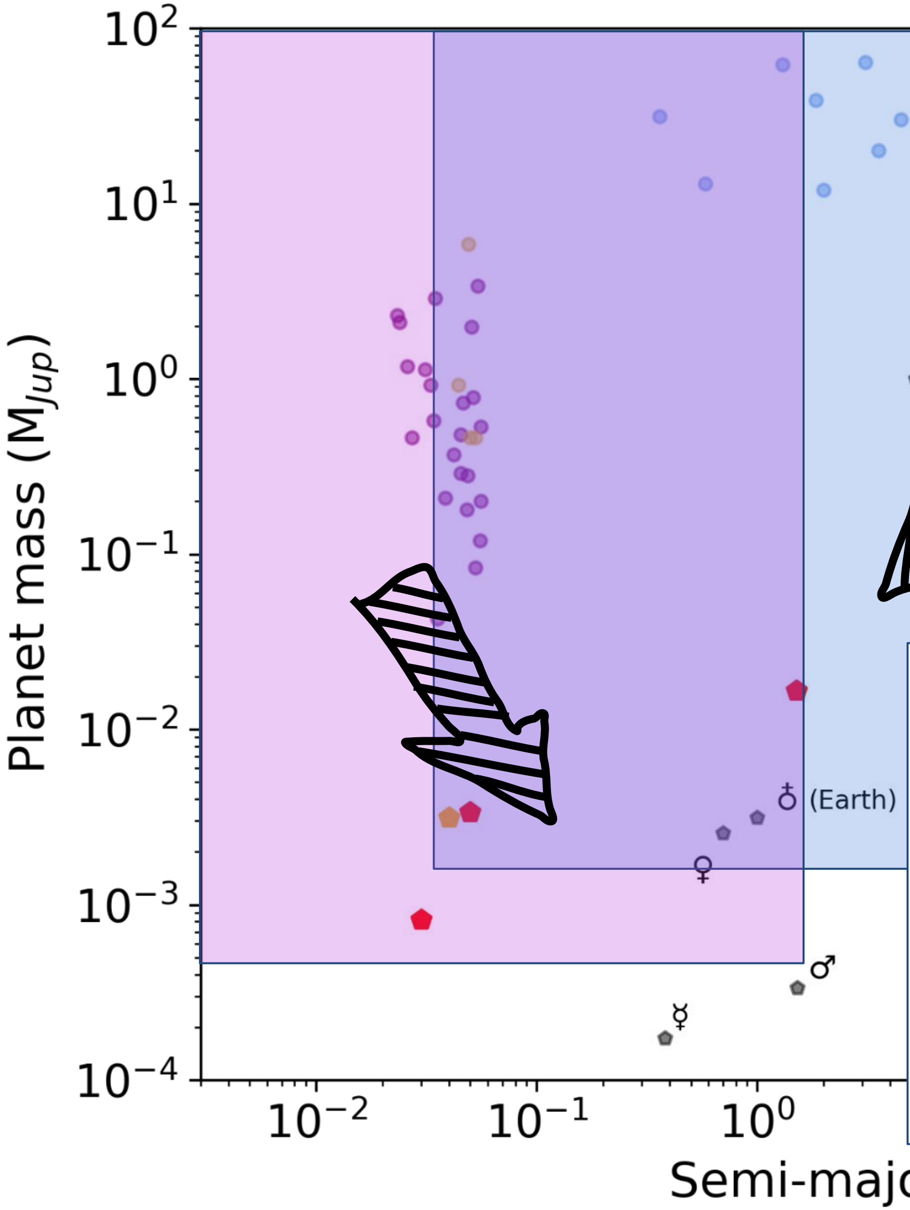
Fundamental questions *still* unanswered

- Planet Formation: How do planets and planetary systems form?
- Discoveries & Demographics: What is the diversity of planets and planetary system architectures?
- How does the Solar System fit in?
- Planet Characterization: What are planets made of?
- Can we understand the atmospheric and geological processes?
- Can we find evidence for biological activity?
- Evolution and fate: What is the evolution and ultimate fate of planetary systems?

See ASTRONET Science Vision & Infrastructures: Roadmap for 2022 - 2025 report on line

Long-term Grail (2050)

50+ spectrally characterized exoplanets (Guillot et al. 2022, PPVII) (*)



What's next?

- Demographics of exoplanetary atmospheres,
- Connection with planet formation/evolution history,
- 1D to 3D revolution in the making,
- Clouds properties, spatial distribution,
- Young Saturns to primitive Earths (?),
- Mature UHJs to rocky worlds,
- Discovery of the first signs of bio-signatures,

BUT, how do we do that?

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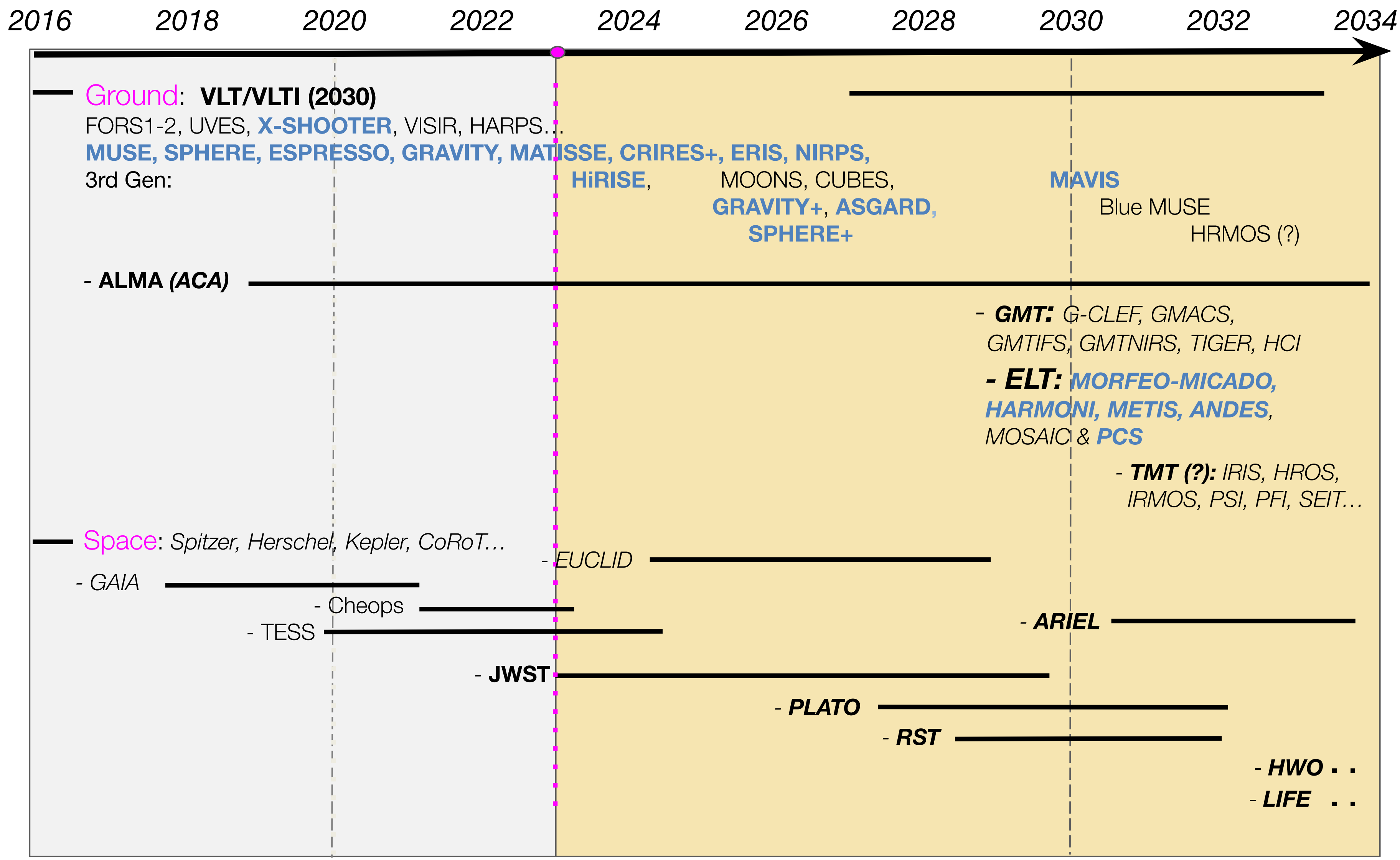
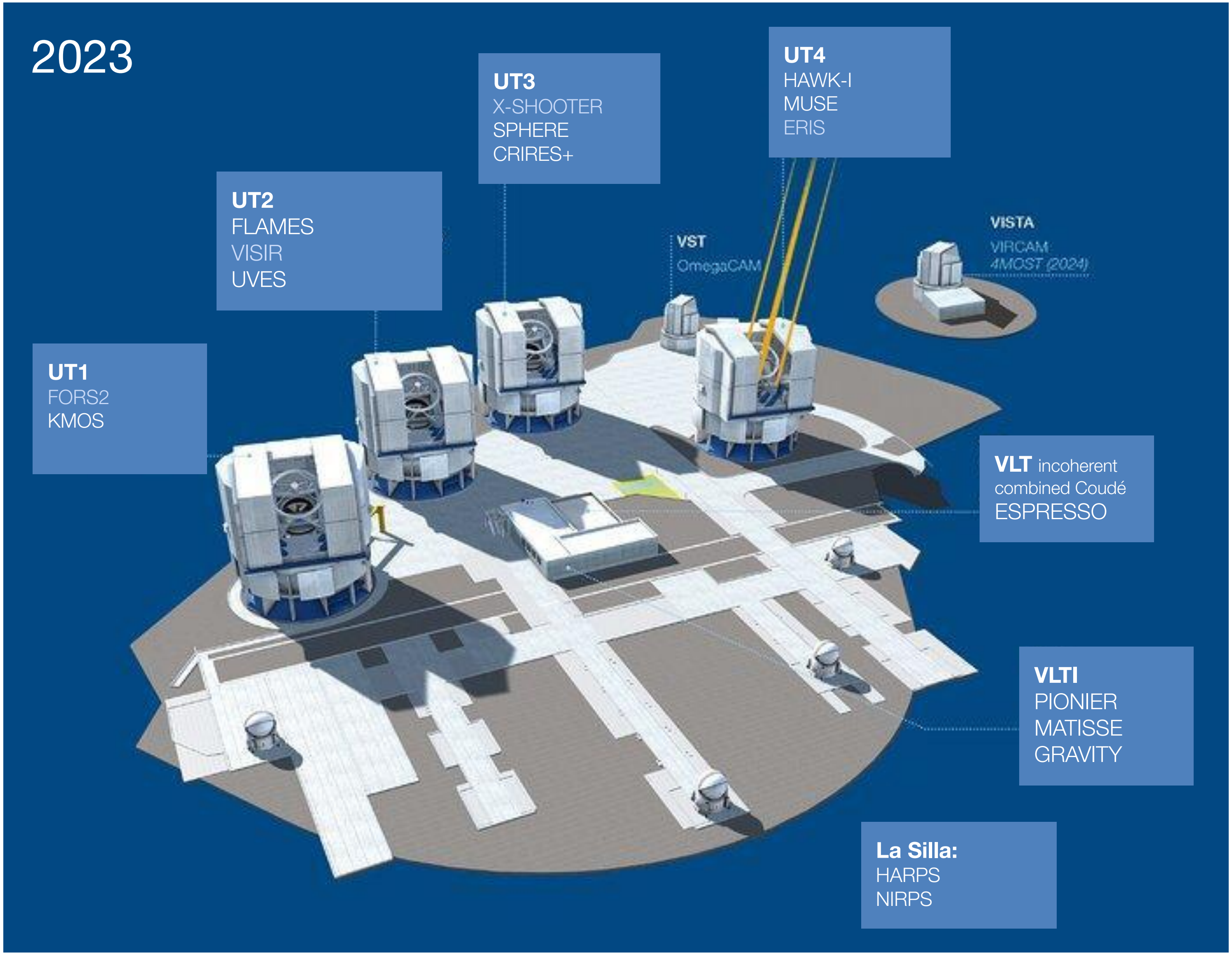
What's next?

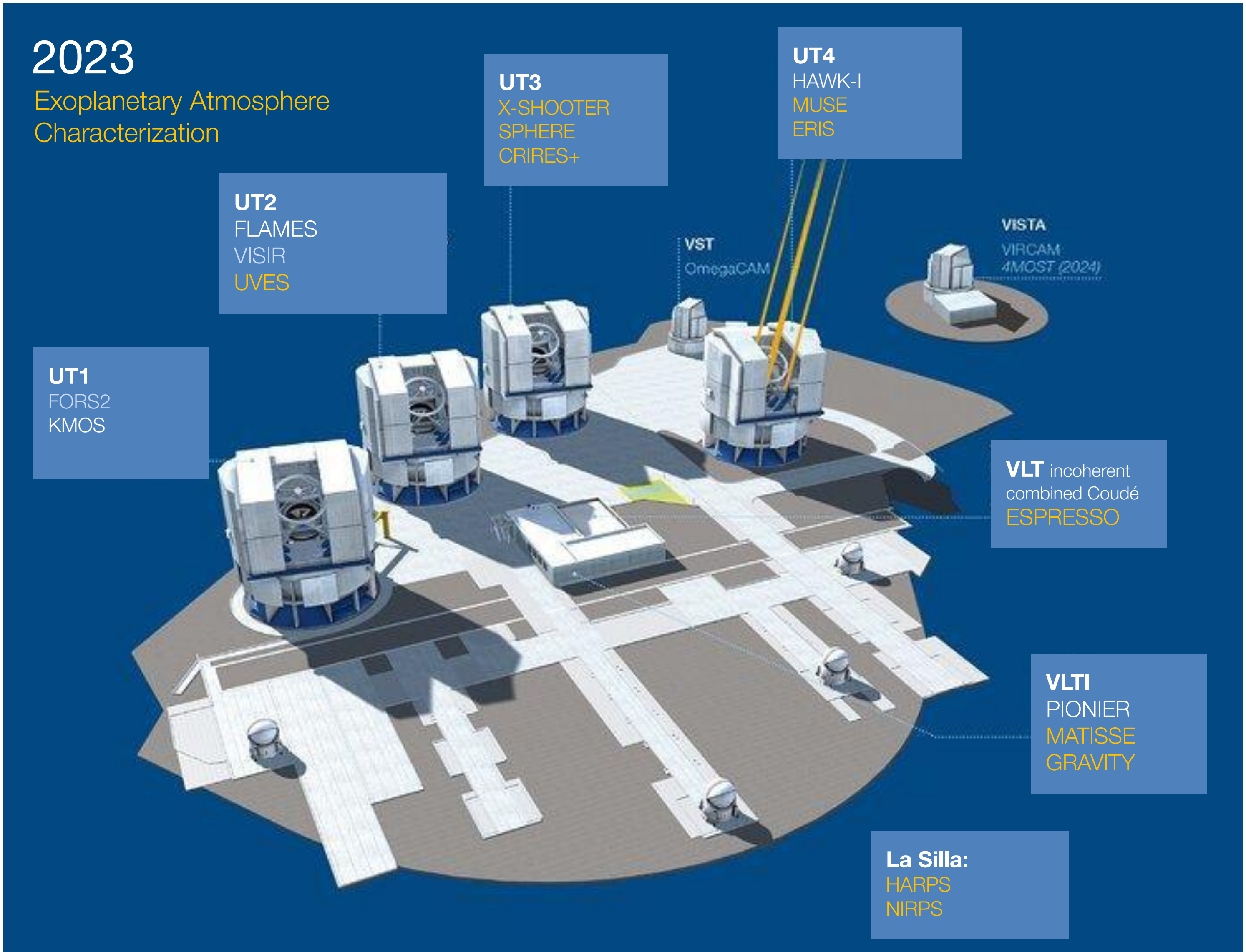
Space mission/Telescope timeline



The VLT/I
Today

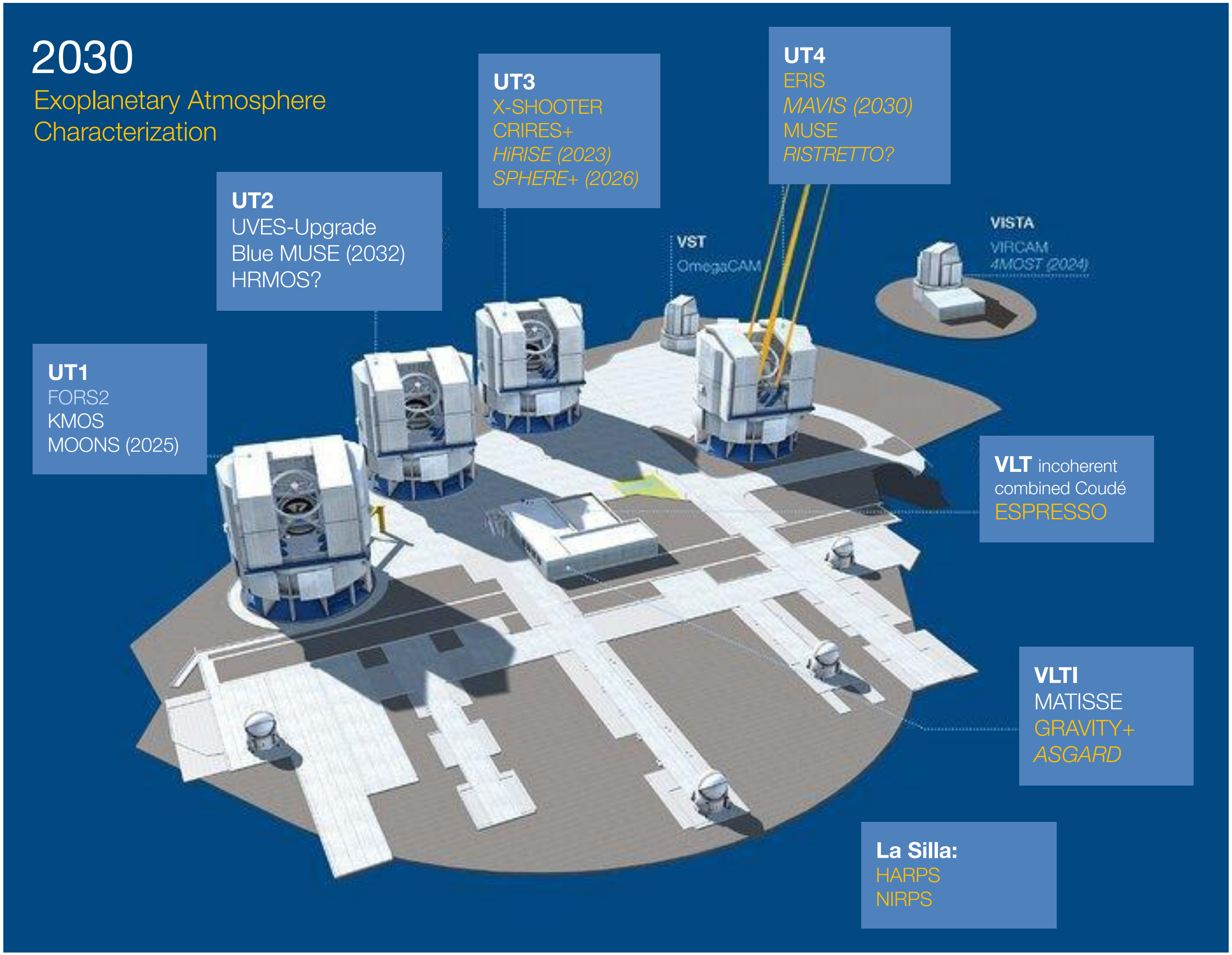


The VLT/I
Today



The VLT/I

A new 3rd generation of instruments



The VLT/I

Instruments

Generation (Exoplanet Characterization)

1st 2nd 3rd

Instruments - First Light	Description	AO	λ (μm)	Resolution	FoV	Add. Mode
SPHERE (2014)	Spectro-imager IFS, LSS	XAO	0.5 – 2.4	30 - 350	10.0” 1.8”	Coronography
MUSE-NFM (2014)	Spectro-imager IFS	AOF LGS-AO	0.46-0.93	1700-3400	60” 7.5”	NFM-mode
GRAVITY (2019)	Interferometer	-	2.0-2.4	20-500-4000	0.05”	dual-field on-axis
ERIS (2022)	Spectro-imager IFS, LSS	SCAO LG-AO	1.0-5.0 1.0-2.5	900 8000	26”, 56” 0.8”, 8”	Coronography
X-SHOOTER (2009)	X-Echelle Spec.	noAO	0.3-2.5	4000-17000	0.4-5.0”	
HARPS (2003)	X-Echelle Spec.	noAO	0.38-0.69	120 000	1.0”	
NIRPS (2022)	X-Echelle Spec.	SCAO	0.95-1.80	100 000	0.4-0.9”	
ESPRESSO (2017)	X-Echelle Spec.	noAO	0.38-0.69	70000-190000	1.0” (x4)	
CRIRES+ (2021)	X-Echelle Spec.	SCAO	1.0-5.0	50000-100000	0.2”, 0.4”	

The VLT/I

Instruments in 2030

Generation (Exoplanet Characterization)

1st 2nd 3rd

Instruments - First Light	**Description**	**AO**	**λ (µm)**	**Resolution**	**FoV**	**Add. Mode**
SPHERE+ (2026?)	Spectro-imager IFS, LSS	XAO	0.5 – 2.4 1.2-1.8	30 - 350 3000	10.0” 0.6”	Coronography *MEDRES*
MUSE-NFM (2014)	Spectro-imager IFS	AOF LGS-AO	0.46-0.93	1700-3400	60” 7.5”	NFM-mode
GRAVITY+ (2025?)	Interferometer	GPAO	2.0-2.4 1.0-1.8	20-500-4000 1000-25000	0.05”	dual-field on-axis *ASGARD/BIFROST*
ERIS (2022)	Spectro-imager IFS, LSS	SCAO LG-AO	1.0-5.0 1.0-2.5	900 8000	26”, 56” 0.8”, 8”	Coronography *ERIS-SOM?*
X-SHOOTER (2009)	X-Echelle Spec.	noAO	0.3-2.5	4000-17000	0.4-5.0”	
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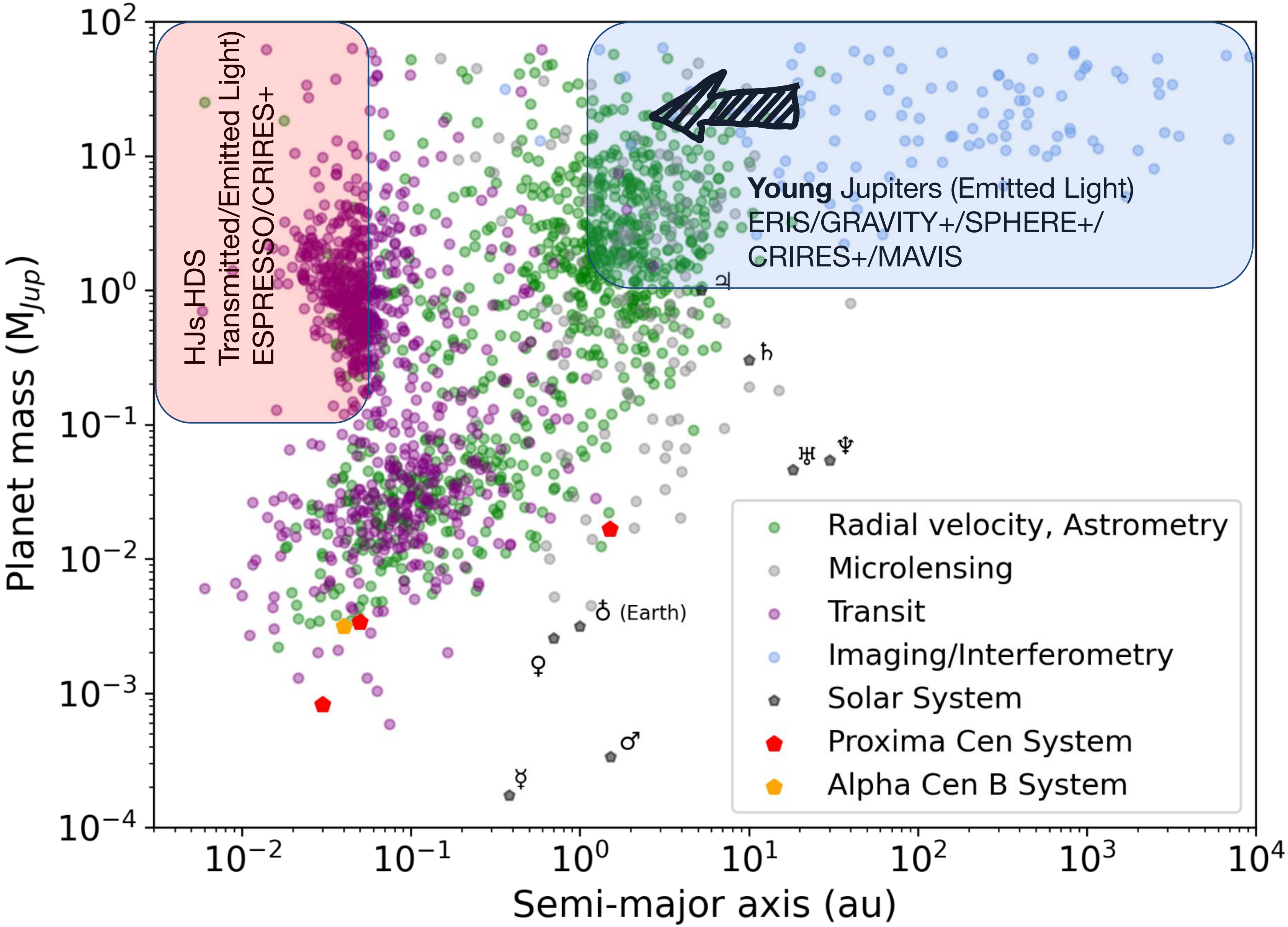
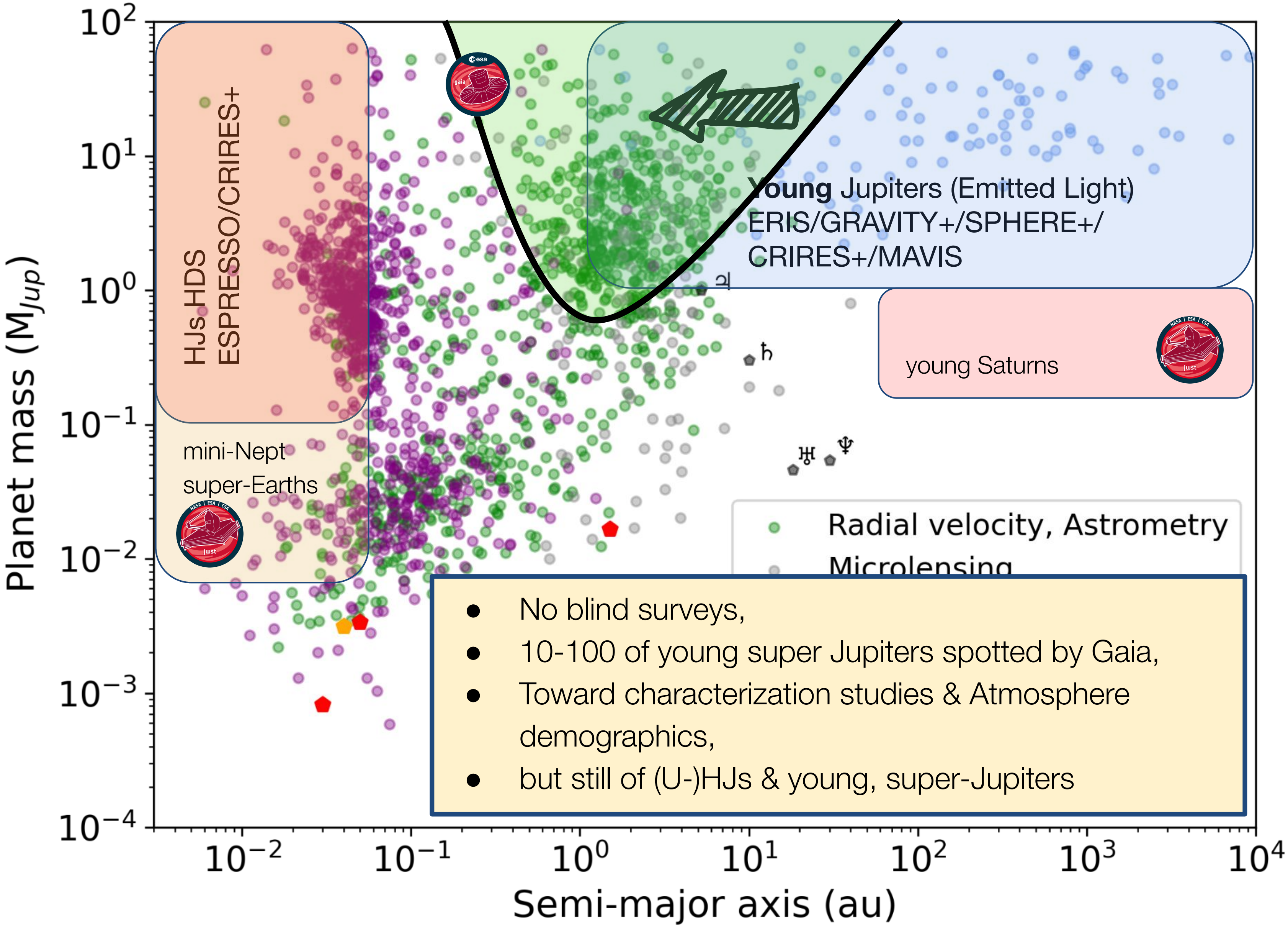
CRIRES+ (2023)	X-Echelle Spec.	SCAO XAO	1.0-5.0 1.4-1.8	50000-100000 50000-100000	0.2”, 0.4”	HiRISE, coupling with SPHERE
MAVIS (2030)	Spectro-imager IFS	MCAO	0.37-1.0	6000-15000	30”	Protoplanets, acccretion

Extending the characterization space



Important synergies with Gaia/JWST



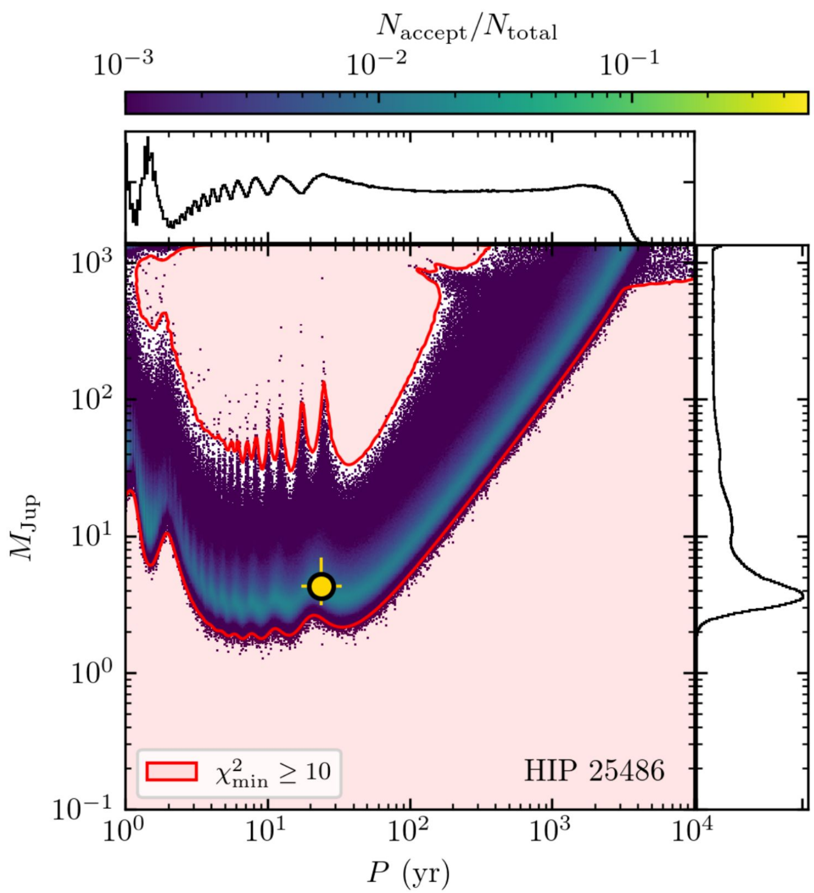
- No blind surveys,
- 10-100 of young super Jupiters spotted by Gaia,
- Toward characterization studies & Atmosphere demographics,
- but still of (U-)HJs & young, super-Jupiters

Gaia-ground synergy

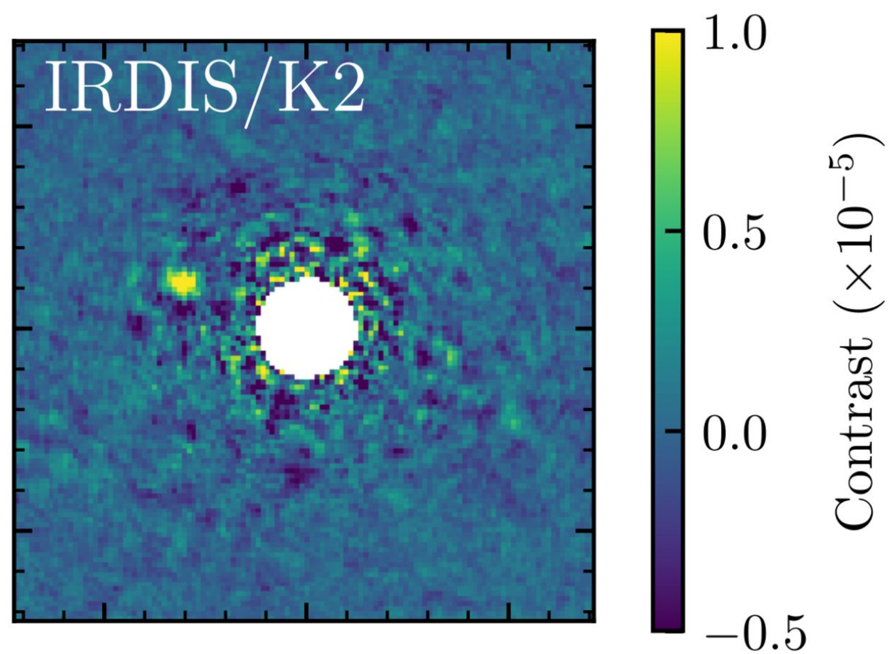
Hunting for planets around accelerating young, nearby stars

- AF Lep, 24 Myr-old F8V star at 26.8 pc with a 4-6 M_{Jup} giant planet at 9 au (330mas)

HIPPARCOS - GAIA Proper motion anomaly



VLT/SPHERE targeted search



Rosa et al. (2023)

ERIS/GRAVITY+/SPHERE+

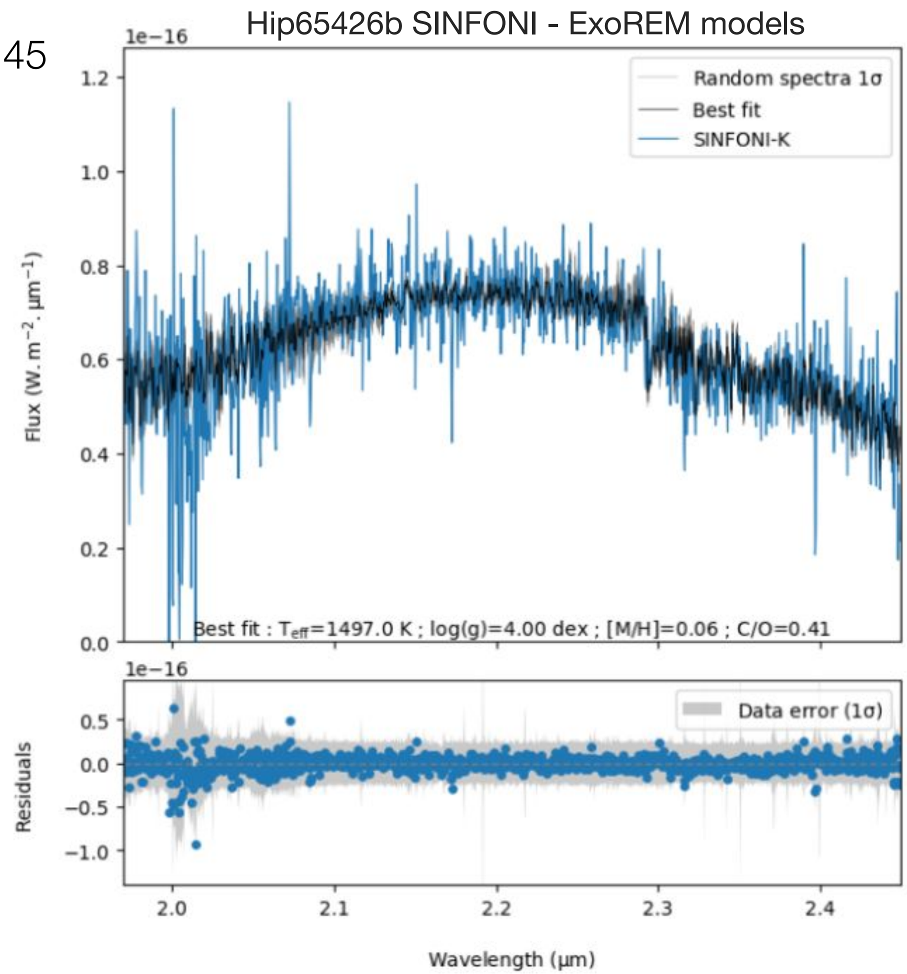
Atmospheric diversity of young Jupiters

down to the snowline (3-30 au)

Accessing chemical abundances & isotopologues

- HIP65426 b: 8 M_{Jup} **at 92 au**, L5-type,
  Teff = 1497 ± 80 K, log(g) < 4.20,
  clouds (Si), Fe/H = 0.05 ± 0.20, C/O < 0.45
  RV, v.sin(i), *ecc*~0.35, C-isotopologues
  SINFONI > ERIS
  Petrus et al. (2021)

  Fe/H, C/O, isotopes:
  Atmosphere Demographics of
  young super-Jupiters



GRAVITY+/SPHERE+
Larger wavelength coverage: 1.0-2.5
Increased spectral resolution: ~5000
Increased stability for temporal studies

ERIS/GRAVITY+/SPHERE+

Atmospheric diversity of young Jupiters

down to the snowline (3-30 au)

Accessing chemical abundances & isotopologues

- Bpic b: 13 M_{Jup} **at 9 au**, L1-type,
  Teff = 1747K, log(g) = 4.35,
  fsed=2.5, Fe/H = 0.66, C/O = 0.44
  RV, v.sin(i), *ecc*~0, C-isotopologues
  GPI (SPHERE)-ERIS & GRAVITY
  Nowak et al. (2020)

  Fe/H, C/O, isotopes:
  Atmosphere Demographics of
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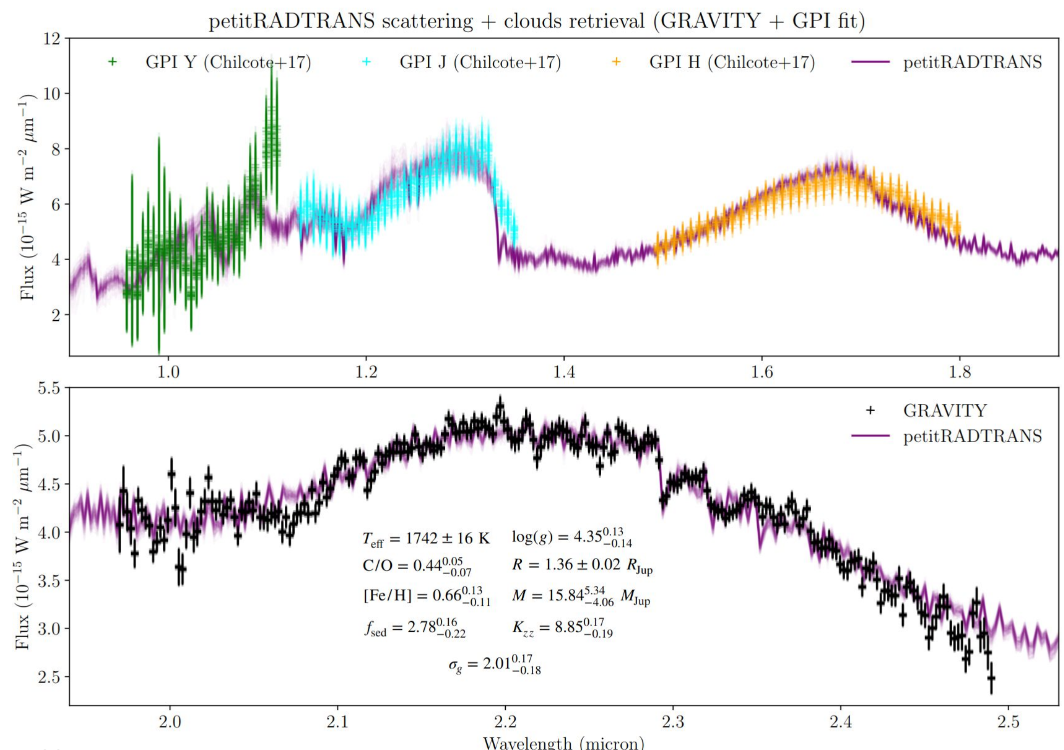
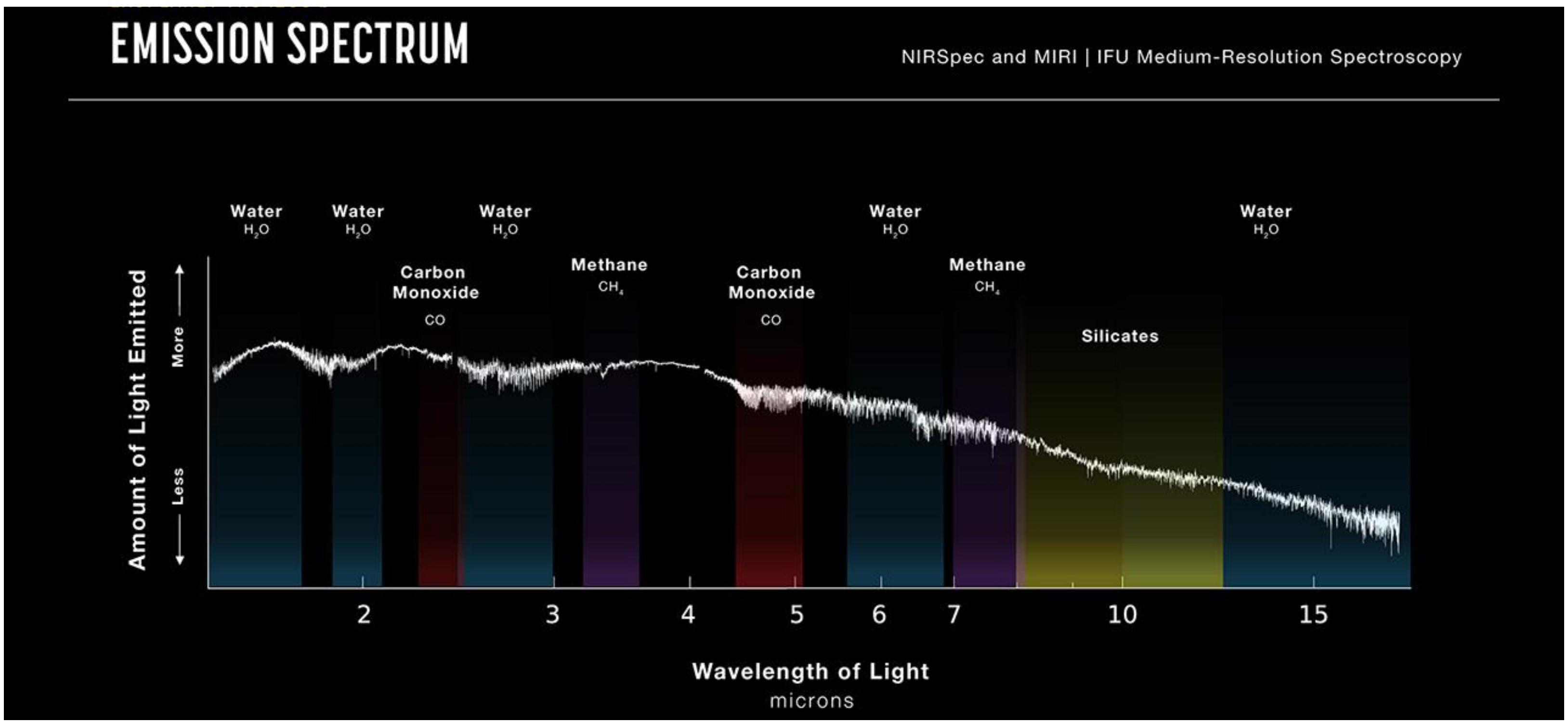


GRAVITY+/SPHERE+
Larger wavelength coverage: 1.0-2.5 µm
Increased spectral resolution: ~5000
Increased stability for temporal studies

JWST: Atmospheres of young Jupiters

Med-resolution spectrum from 1.0 to 20 microns (ERS results)!

- VHS1256b: a wide (102 au), planetary-mass companion, 19±5 M_{Jup} and Teff of 1240±50K
- Forest of atomic (KI, NaI) and molecular (FeH, H2O, CO, CH4..) lines
- First direct detection of silicate feature absorption



Miles et al. (2022)

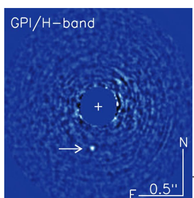
ERIS/GRAVITY+/SPHERE+

Atmospheric diversity of young Jupiters

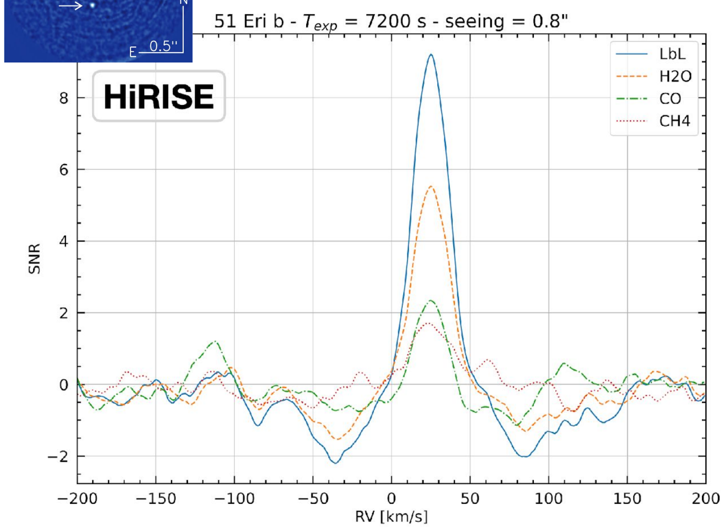
down to the snowline (3-30 au)

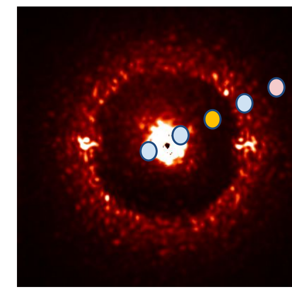
Accessing high-res ($R_\lambda > 35\,000$) spectra

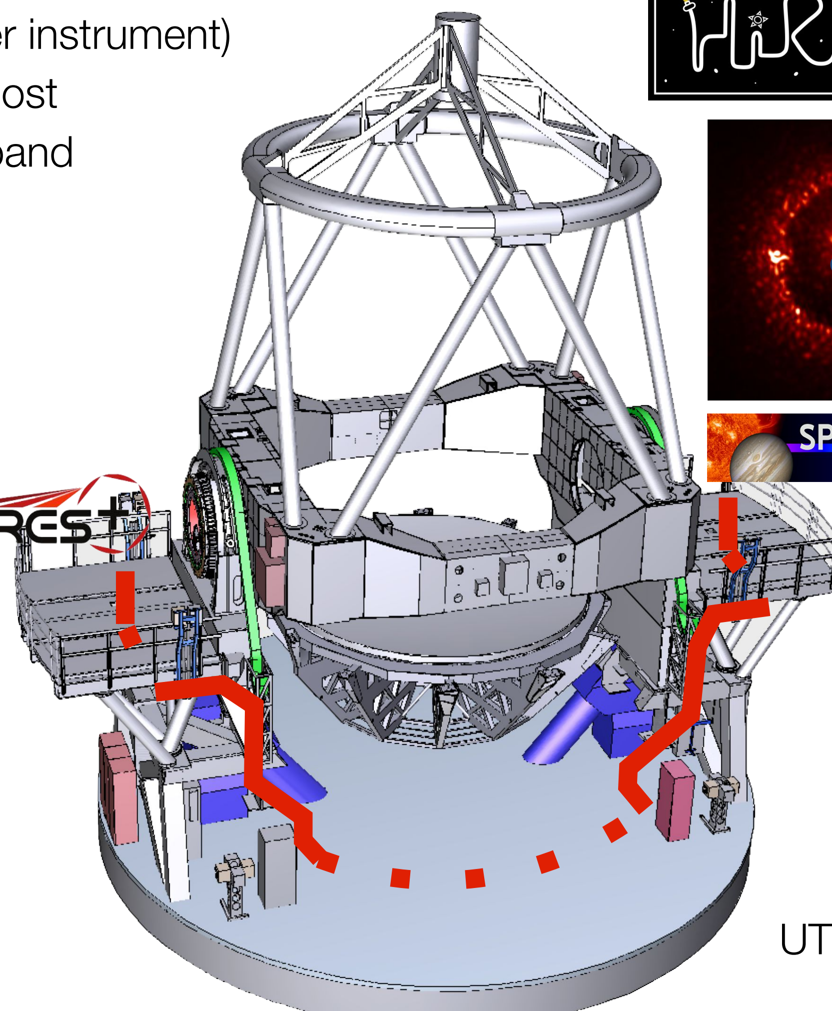
- HiRISE, Coupling SPHERE and CRIRES+
  PI: A. Vigan (following Keck/KPIC pionier instrument)
  Improved characterization, detection boost
  New opportunities for exoplanets in H-band
  On sky in June 2023!



51 Eri b: 2-3 M_{Jup} at 11 au, T3-type, 700K
Macintosh et al. (2015)







UT3

Atmospheric diversity of young Jupiters

down to the snowline (3-30 au)

Accessing high-res (R_λ> 35 000) spectra

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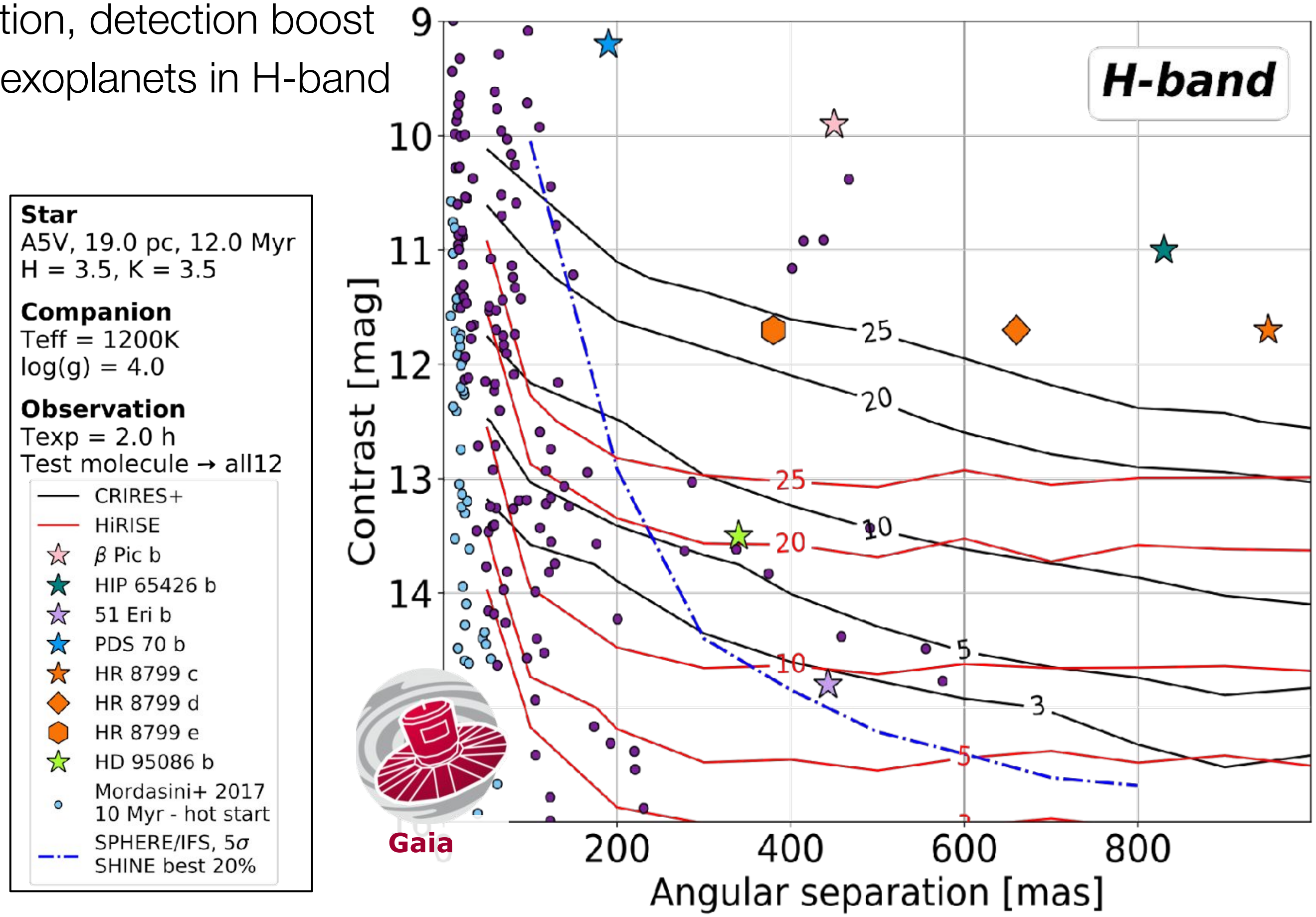
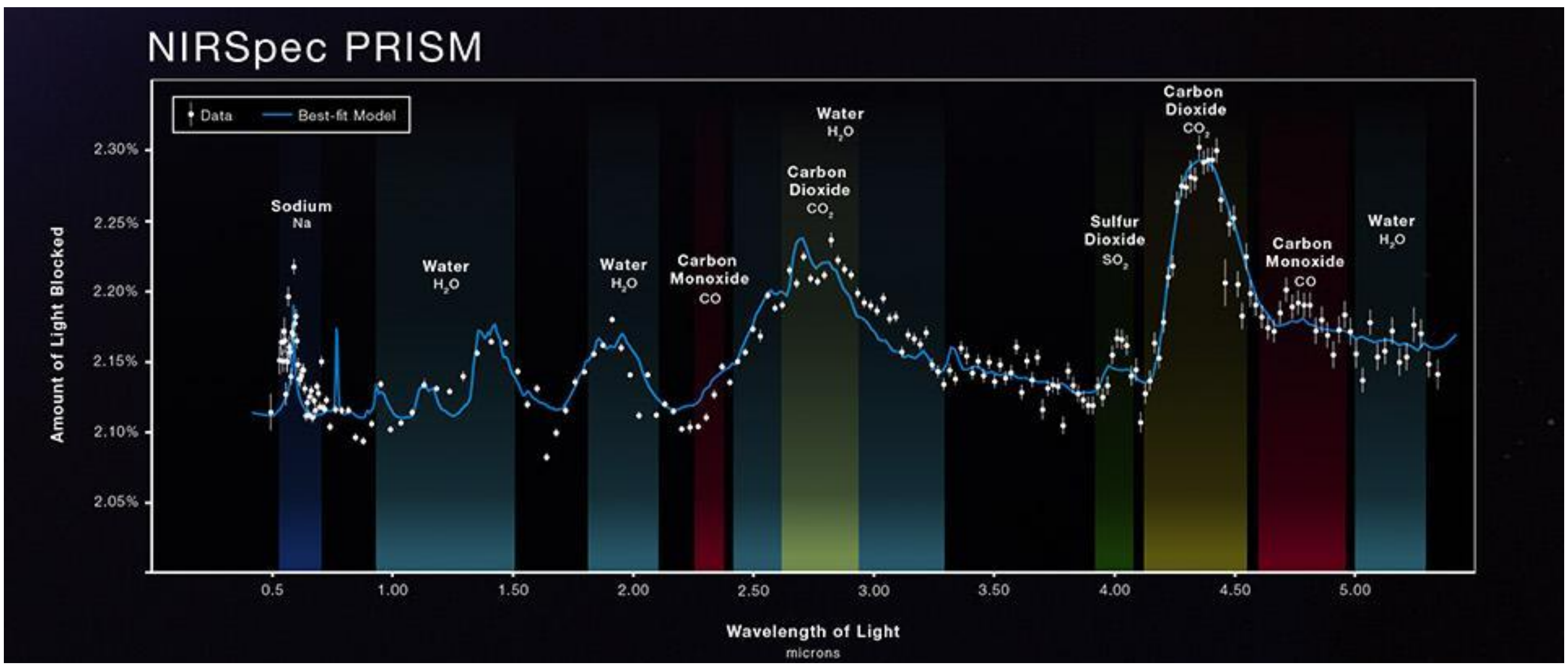


JWST: Atmospheres of Ultra-Hot Jupiters

Photochemistry in action in Wasp 39b's atmospheres

- Chemical species: Na (19σ), H_2O (33σ), CO_2 (28σ) and CO (7σ). Non-detection of CH_4, & strong CO_2 feature, favours super-solar atmospheric metallicity.
- An unanticipated absorption feature at 4 μm is best explained by SO_2 (2.7σ), which could be a tracer of atmospheric photochemistry.

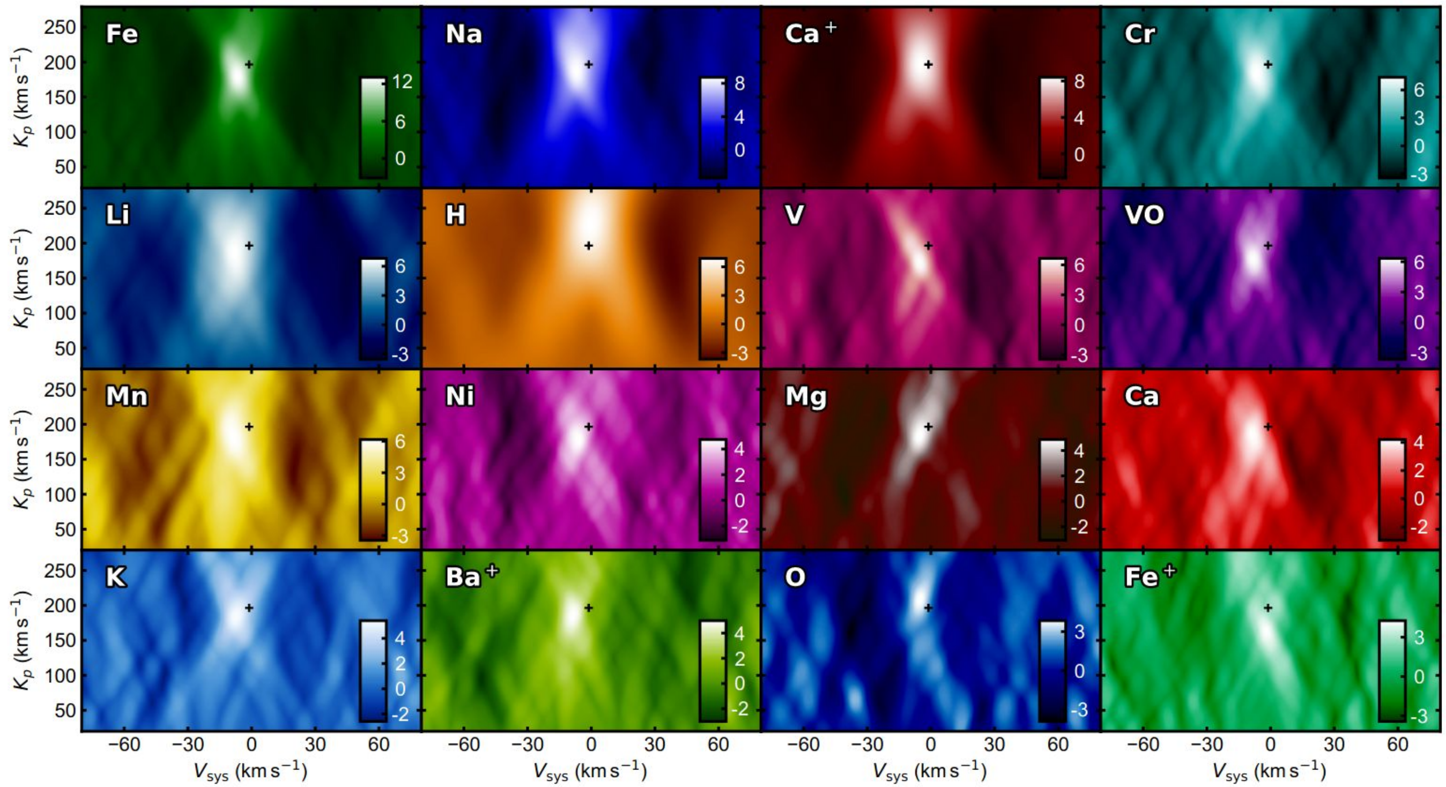


Rustamkulov et al. (2023)

General circulation & clouds in UHJs

Refractory elements in WASP-76b's atmosphere

- Gemini-North/MAROON-X (R_λ> 85 000) visible HDS, revealing various species, Precise abundance constraints of 14 major refractory elements including VO potentially responsible for the atmospheric thermal inversion (Pelletier et al. (2023)



ESPRESSO/CRIRES+

General circulation & clouds in UHJs

Decomposing the iron cross-correlation signal of WASP-76b

ESPRESSO (R_λ=120 000) Observations
Iron lines in the transmission spectrum blueshifting during the transit (from ingress to egress).
Ehrenreich et al. (2020)

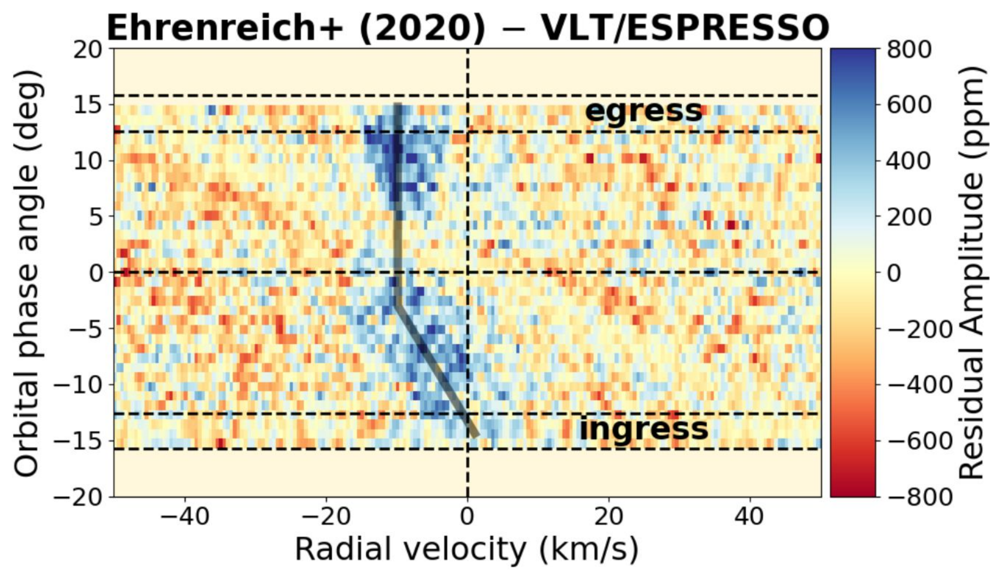
Possible interpretations:

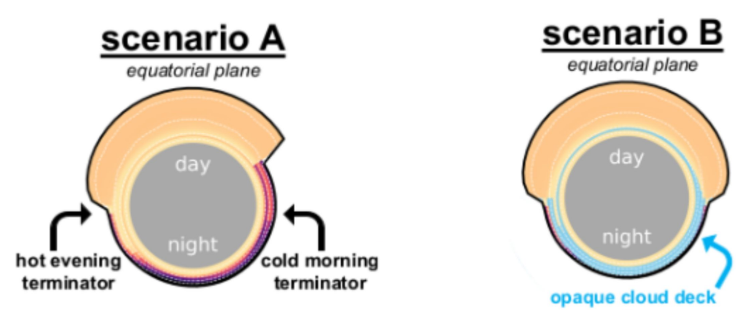
A/ **Evening terminator is hotter more extended, more iron-rich** than the cooler morning terminator.

B/ **Opaque cloud deck on the nightside** blocking most of the iron absorption on the morning terminator.

Wardenier et al. (2021); Savel et al. (2022)

Wealth of information related to their thermal, chemical, aerosol & dynamical (i.e., wind) structures and properties.





Take away 1 for Alpha Cen

- New/next generation of VLT/I instruments will mostly allow to confirm the current discoveries in the system and push for new detection(s):
    - Alpha Cen:
        - Follow-up on the VLT/NEAR candidate (K. Wagner), and our current best option is SPHERE-ZIMPOL (H.-M. Schmid) to search for a reflected light signature,
    - Proxima:
        - Refine/Confirm the existence of current planets: b, c & d, from new RV EXPRESSO & NIRPS Radial Velocity campaigns (J. Faria)
        - Follow-up of directly imaged candidate(s) with ERIS/SPHERE+ based on the work of Gratton et al. (2020) - (M. Damasso)
    - Prepare the mid-2028 conjunction event, probably not accessible by the ELT as first light currently foreseen in mid-2028 (P. Kervella)
- But, not sensitive enough to initiate the atmospheric characterization…

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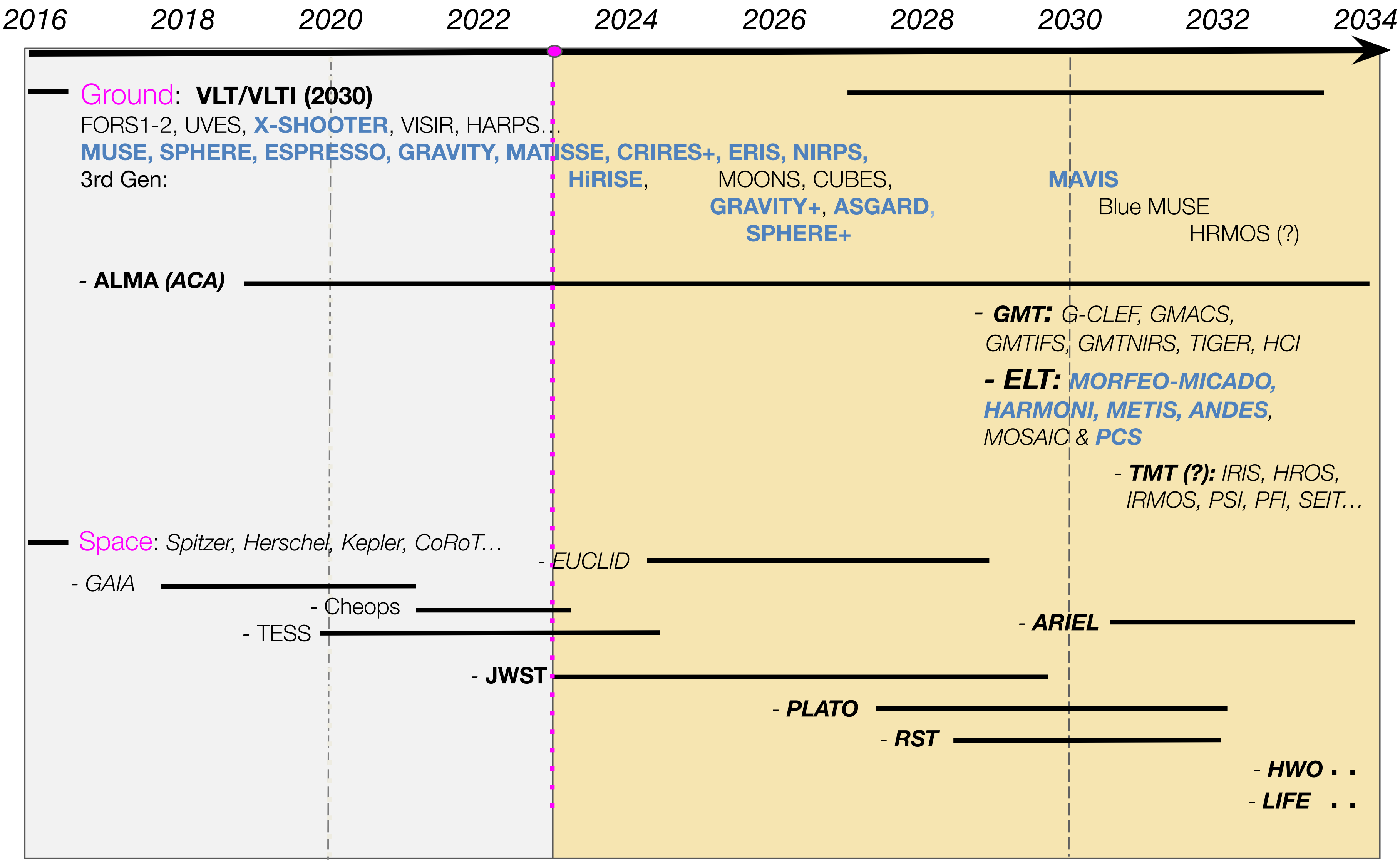
1. The ELT one

   The long road toward characterizing super-Earths

1. Take away

What's next?

Space mission/Telescope timeline



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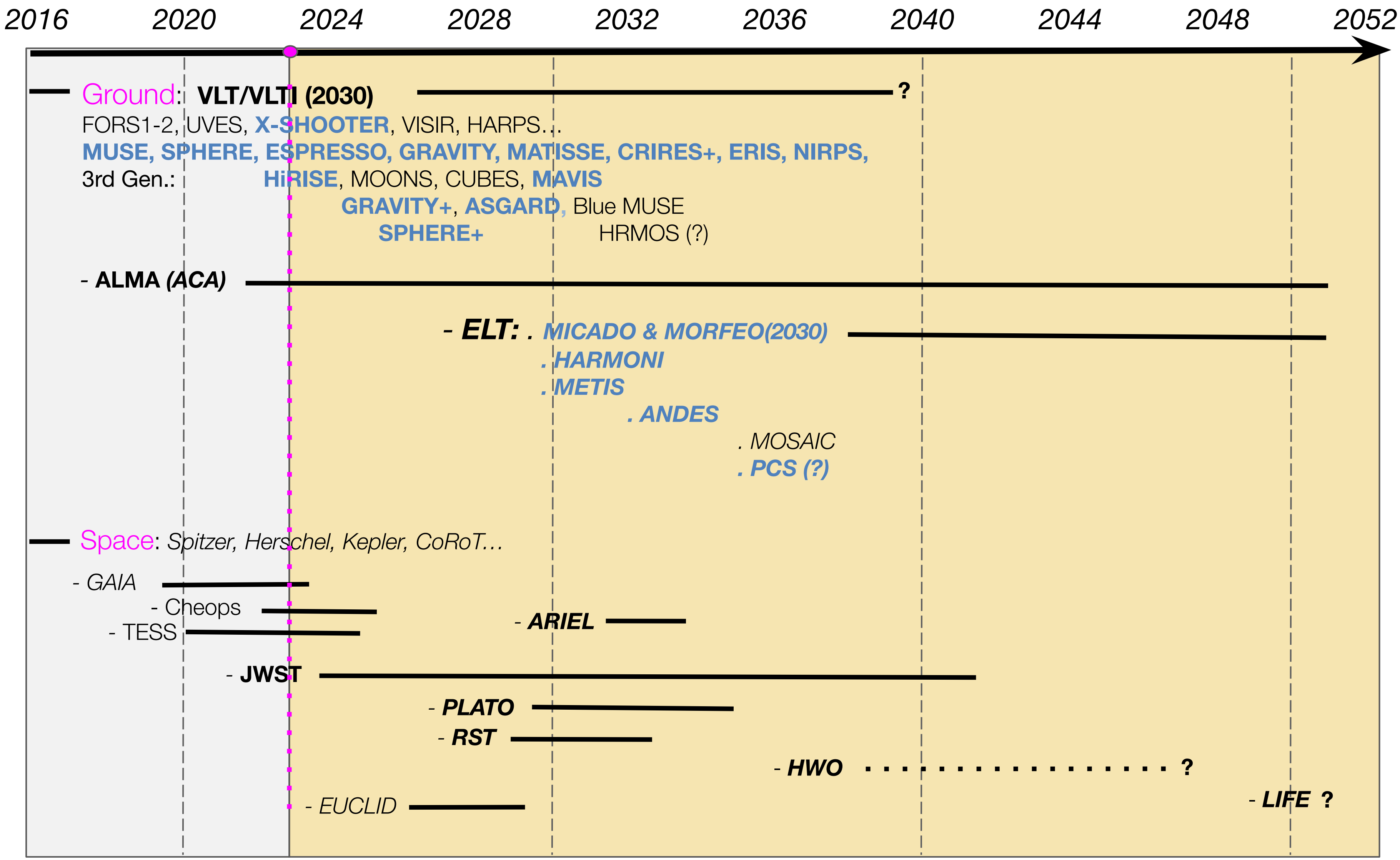


Era of Giants

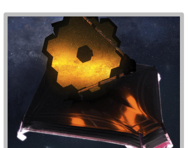
Extremely Large Telescopes (ELTs)

Opening a new Horizon

- Increased Sensitivity
- Improved Spatial Resolution (10 mas scale)

  10 mas > 0.5 au for a star @50pc
- Instrumentation Versatility (access high-R_λ), over at least 30-40 years of operation...

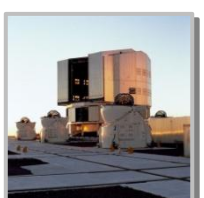
JWST



6.2m, 25m2

2 µm 68mas

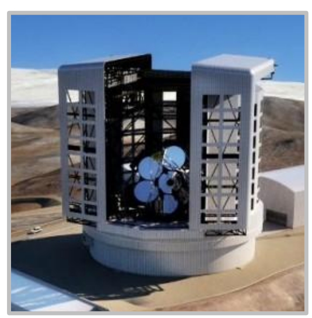
VLT



8.2m, 50m2

50mas

GMT



25m, 400m2

18mas

TMT

30m, 600m2

14mas

E-ELT

39m, 1200m2

10mas

The ELT
Instrumentation roadmap

Phasing

1st Generation   2nd Generation

Instruments - First Light	Description	AO	λ (µm)	Resolution	FoV	Add. Mode
MORFEO/MICADO (PdR/FdR completed) (2028-2030)	Spectro-imager	SCAO, MCAO	0.8 – 2.4	3000 - 20 000	53.0" 19.0" 6.0"	Astrometry 40µas Coronography Long-Slit Spectro
HARMONI (FdR completed) (2029)	IFU Spectrograph	SCAO, LTAO	0.5 – 2.4	3500 7000 18 000	1.0" 10.0"	Coronography
METIS (FdR completed) (2030)	IFU & Spectro-Imager	SCAO	3 – 20 3 - 5	5000 100 000	18" 0.4"×1.5"	Coronography Long-Slit Spectro IFU mode
ANDES (HIRES) (PdR started) (2032+)	Optical and NIR High-Resolution Spectrograph	SCAO	0.37 – 1.38 (2.4)	100 000 (150 000)	0.82" 0.5"	IFU mode
MOSAIC (Phase A completed) (2032+)	Optical and NIR Wide/Narrow field Multi Object Spectrograph	-	0.37 – 1.4 0.37 – 1.4	300- 2500 5000 – 30 000	6.8" 420'	Multiplex ~ 400 Multiplex ~100 Imaging?
PCS (2035+)	Optical and NIR High Contrast IFU Spectrograph & imager	XAO	0.6 – 0.9 0.95 – 1.65	125 – 20 000 100 000?	2.0" 0.8"	Coronography Polarimetry

The ELT

Instrumentation roadmap

Priority (Exoplanet Characterization)

Low | Medium | High

Instruments - First Light	Description	AO	λ (µm)	Resolution	FoV	Add. Mode
MORFEO/MICADO (PdR/FdR completed) (2028-2030)	Spectro-imager	SCAO, MCAO	0.8 – 2.4	3000 - 20 000	53.0” 19.0” 6.0”	Astrometry 40µas Coronography Long-Slit Spectro
HARMONI (FdR completed) (2029)	IFU Spectrograph	SCAO, LTAO	0.5 – 2.4	3500 7000 18 000	1.0” 10.0”	Coronography
METIS (FdR completed) (2030)	IFU & Spectro-Imager	SCAO	3 – 20 3 - 5	5000 100 000	18” 0.4”×1.5”	Coronography Long-Slit Spectro IFU mode
ANDES (HIRES) (PdR started) (2032+)	Optical and NIR High-Resolution Spectrograph	SCAO	0.37 – 1.38 (2.4)	100 000 (150 000)	0.82” 0.5”	IFU mode
MOSAIC (Phase A completed) (2032+)	Optical and NIR Wide/Narrow field Multi Object Spectrograph	-	0.37 – 1.4 0.37 – 1.4	300- 2500 5000 – 30 000	6.8” 420’	Multiplex ~ 400 Multiplex ~100 Imaging?
PCS (2035+)	Optical and NIR High Contrast IFU Spectrograph & imager	XAO	0.6 – 0.9 0.95 – 1.65	125 – 20 000 100 000?	2.0” 0.8“	Coronography Polarimetry

MICADO Direct Imaging performances

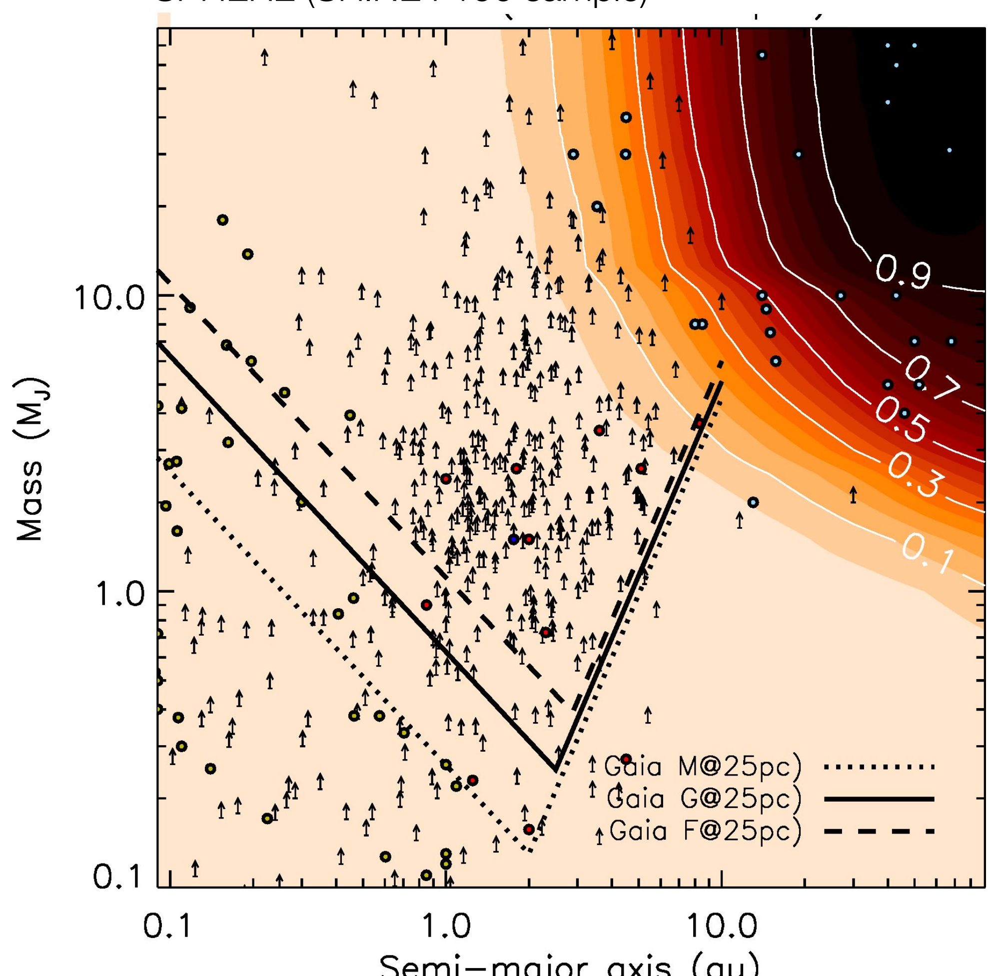
Global content of the young Jupiter population

SPHERE - SHINE completeness

F150 - 152 stars (50 pc, 100 Myr)

Chauvin et al. (2017), Vigan et al. (2021)

SPHERE (SHINE F150 sample)



MICADO Direct Imaging performances

Global content of the young Jupiter population

MICADO - SHINE completeness

F150 - 152 stars (50 pc, 100 Myr)

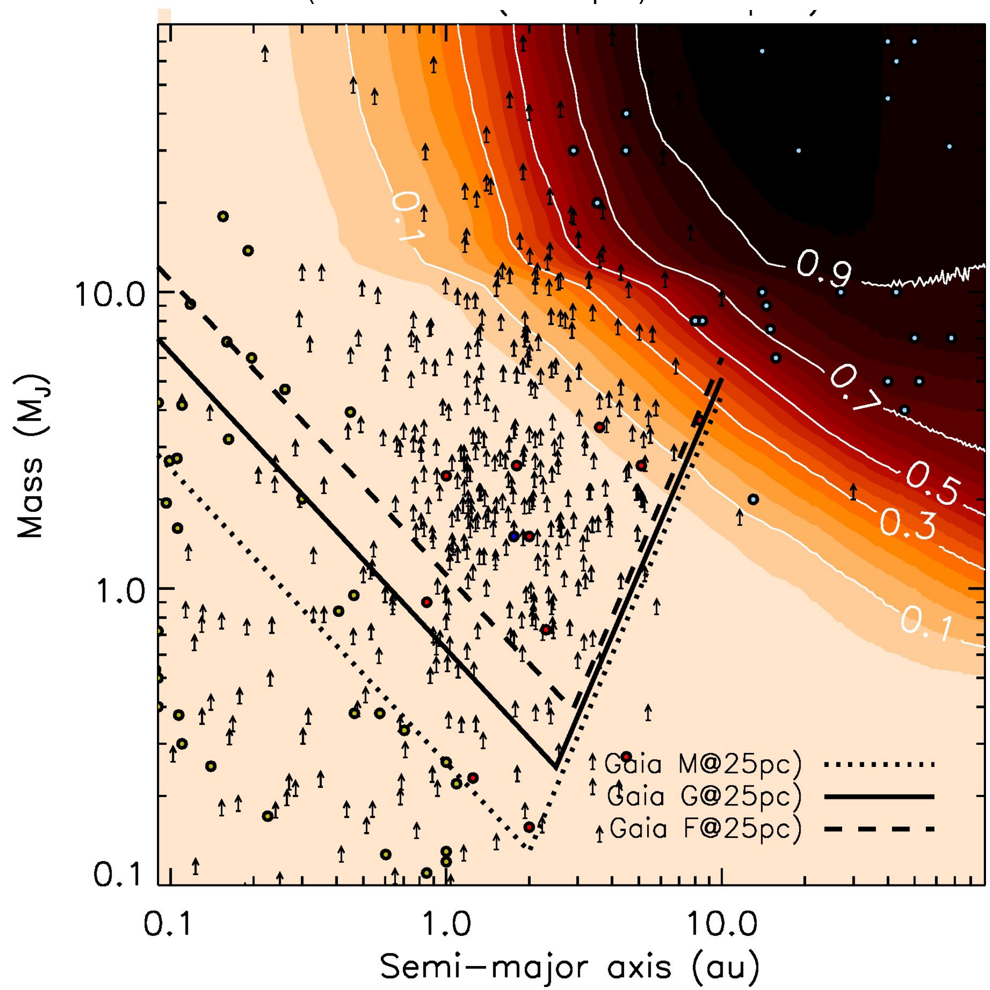
COMPASS/MISTHIC (Baudoz/Huby)

MESS/Pop. (Chauvin)

Contrast: 10^{-6} (50mas)

(SPHERE gets to 10^{-6} at 300mas)

MICADO (SHINE F150 sample)



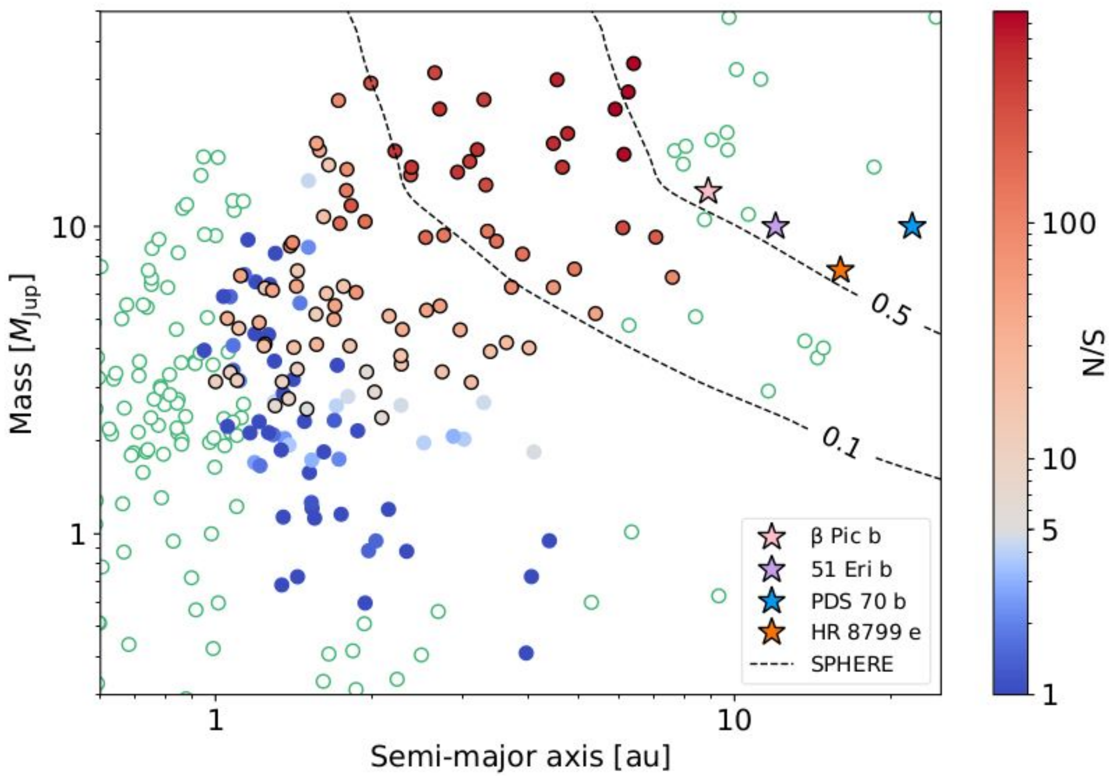
HARMONI Direct Imaging performances

Global content of the young Jupiter population

HARMONI - SHINE completeness
F150 - 152 stars (50 pc, 100 Myr)
OMAO/HDC, Pop. synthesis
Houllé et al. (2021)

Contrast: 10^{-6} (50mas)
(SPHERE gets to 10^{-6} at 300mas)

Consistent results btw
MICADO/HARMONI completeness



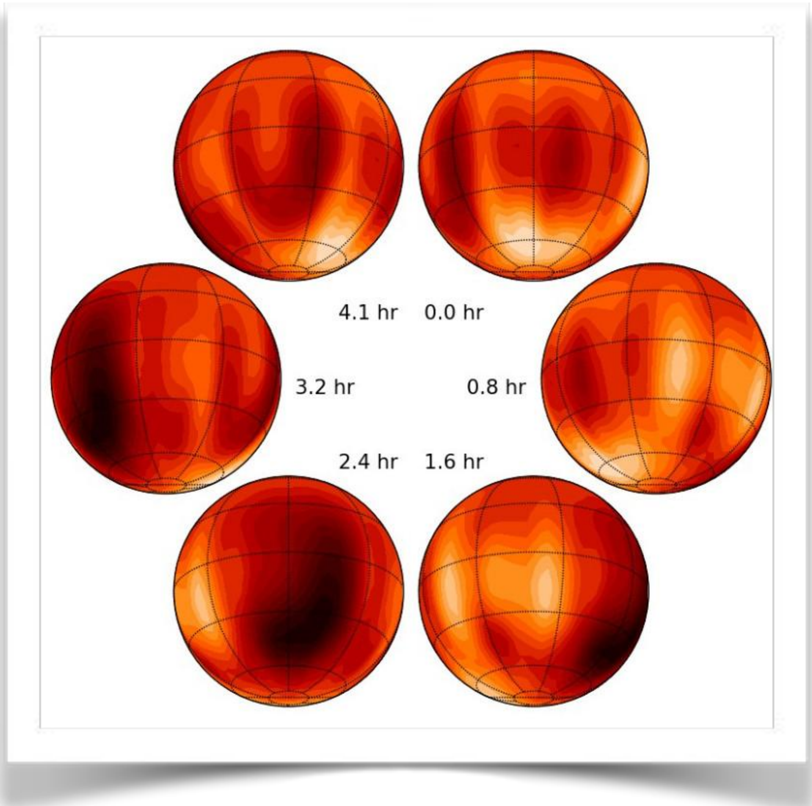
First Light Instruments will image
& characterize young, giant (> 0.1-1.0 MJup) planets beyond 1 au

METIS/ANDES exciting prospects!

3D Chemical/cloud exploration of young Jupiter atmospheres at high spectral resolution

- Broad molecular absorptions (H2O, CO, CH4, CO2) & refractory elements
- Temporal variation, doppler imaging & atmospheric circulation,
- Already observed in BD/UHJs, applied to directly imaged planets,
- Patchy clouds?
- Combination of surface brightness & chemical abundance variations?

METIS : IFU, R_λ = 100 000, [3 - 5] µm
ANDES: R_λ = 100 000, [0.4 - 2.5] µm



Luhman 16 B, 2 pc, Rotation 4.9hrs, CRIRES spectroscopic variability (Crossfield et al. 14)

METIS/ANDES exciting prospects!?

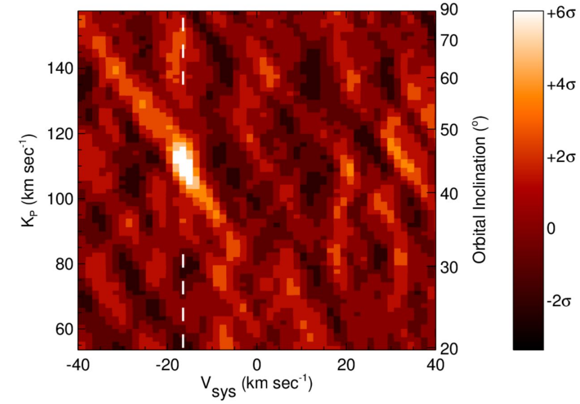
Atmospheres of (non-)transiting exoplanets

- From Hot Jupiters around Bright Nearby stars!

  Optical/IR: Rayleigh scattering, metals, molecules like H_2O, CH_4, CO, CO_2, isotopes ($^{13}C^{16}O$, HDO, and CH3D), Direct exploration of 3D effects (winds, clouds) in synergy with JWST,

  Potentially 40+ (non-)transiting (U-)HJs accessible with ELT
  Strong synergies with JWST
  Mollière & Snellen (2019)

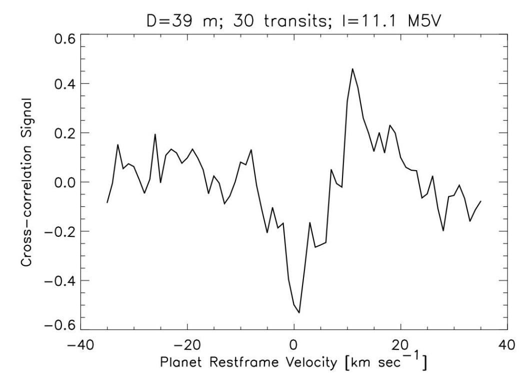
Detection of CO absorption in the thermal day-side spectrum of τ Boötis b with CRIRES
Brogi et al. (2012)



- To super-Earths around very, nearby M dwarfs?

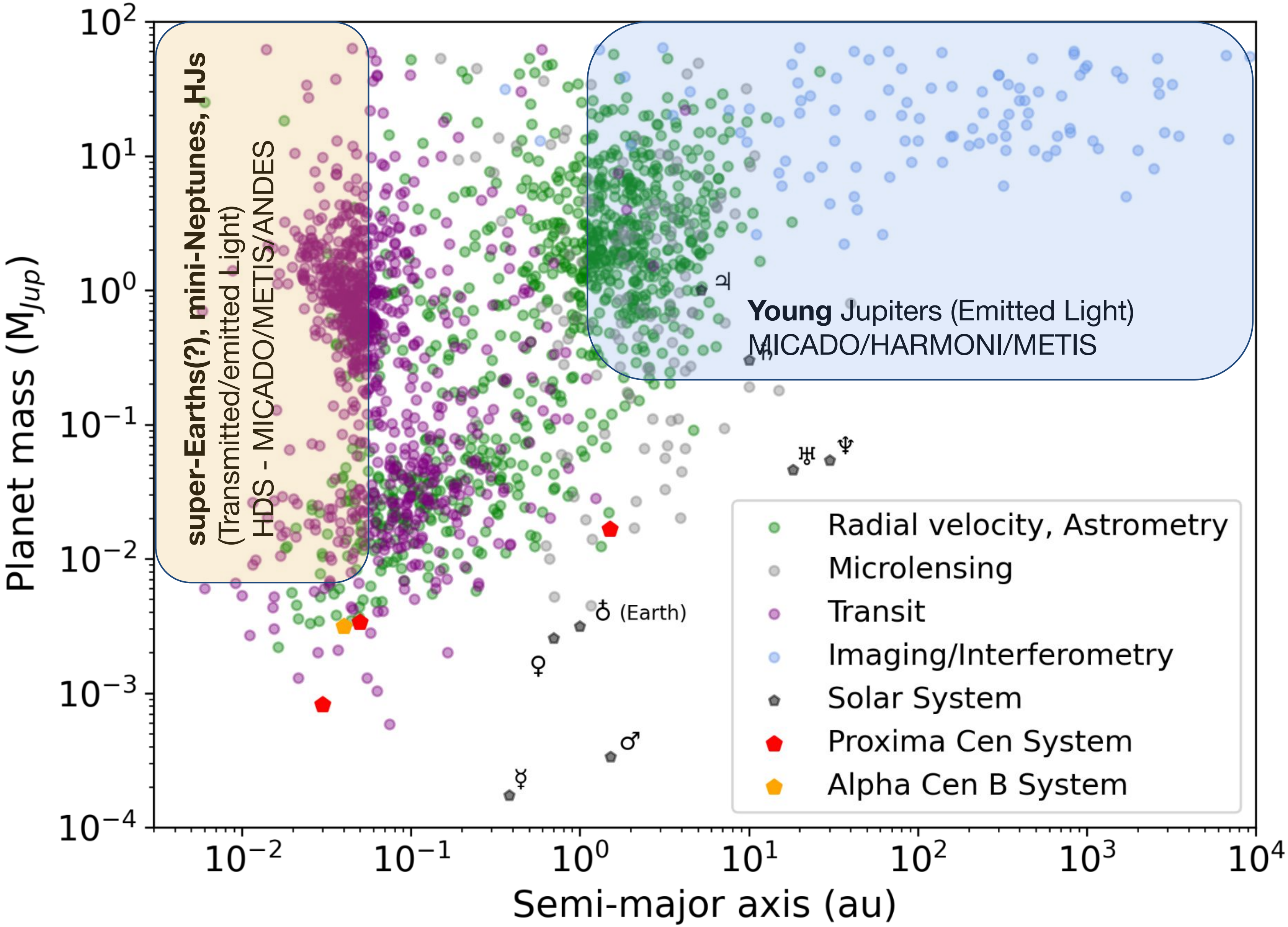
  Using multiple transit in HDS to detect O_2 in Super-Earths?
  Snellen et al. (2013), Lopez-Morales et al. (2019)
  Wunderlich et al. (2020)

  Extremely challenging! Calling for realistic simulations considering observing constraints, HZ planet transit probability, Earth's atmosphere, telescope & instrumental limitations…

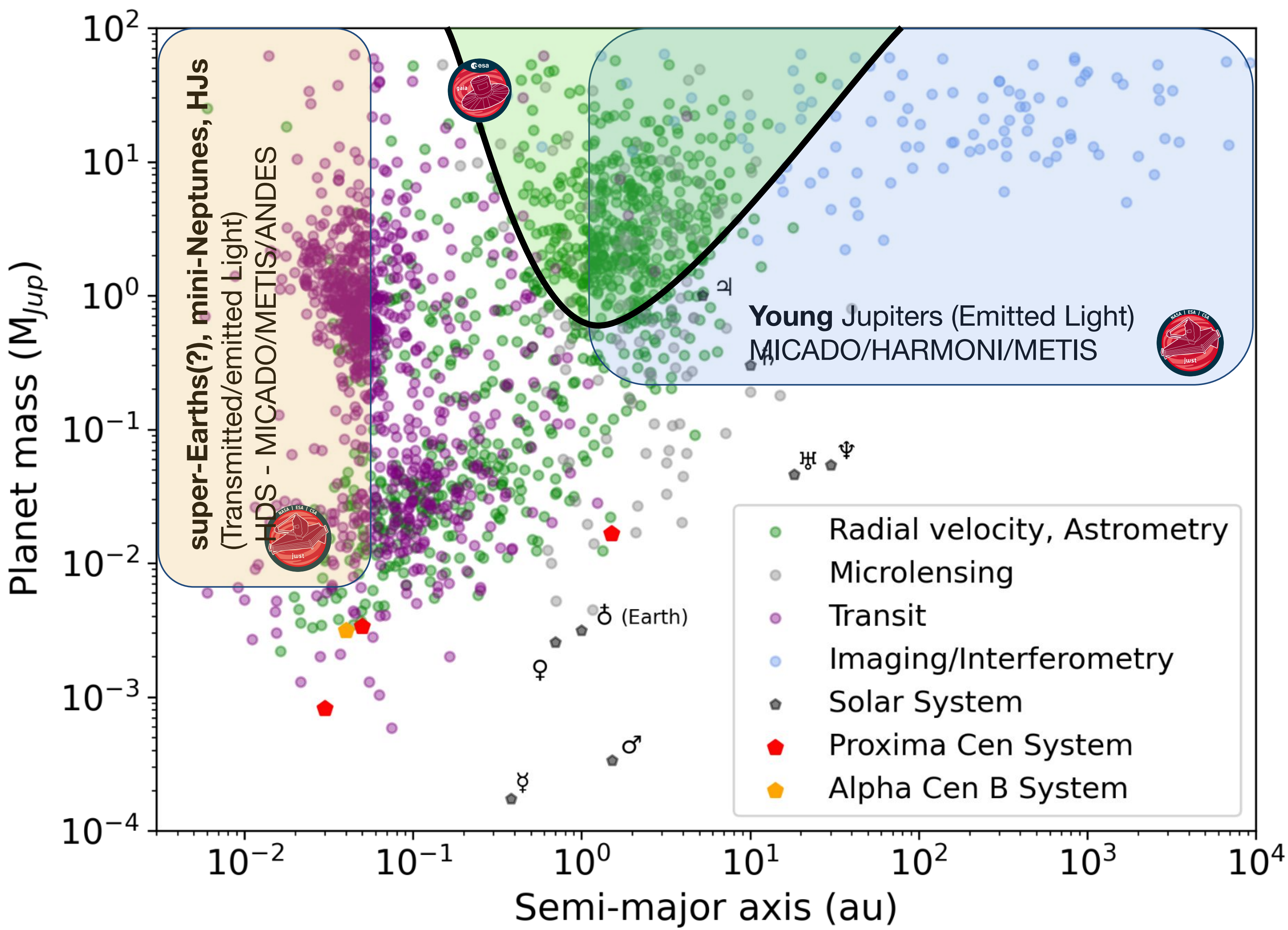


Simulated O2 signal from an Earth-twin in the GJ1214 system

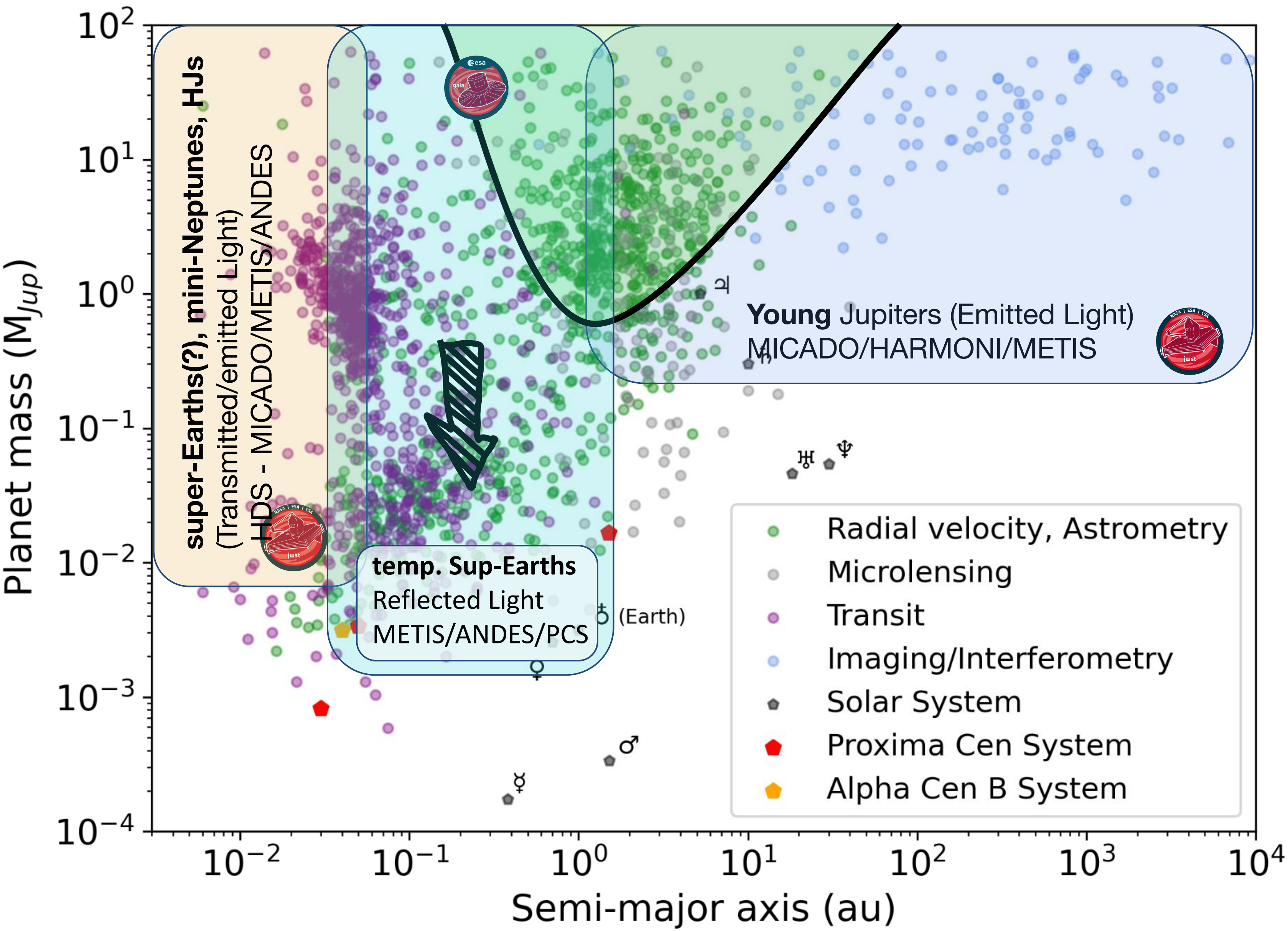
Discovery/characterization space



Discovery/characterization space



Our “rendez-vous” point for Alpha Cen!



Imaging the reflected-light, a game changer

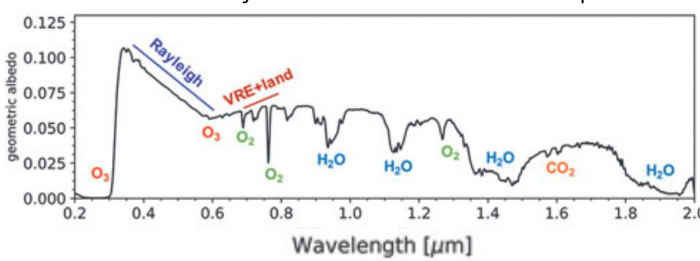
From young, giant planets to old, rocky worlds?

- Contrast: 10^{-6} (50mas) to 10^{-8} (20mas)
- Emitted (1st Gen) & Refl. (2nd Gen) light
- From Giant planets to super-Earths?
- around Young stars & Nearby stars

MICADO (2027)
HARMONI (2027)
METIS (2030)

METIS
ANDES (2032+)
PCS (2033+)

Synthetic Earth radiance spectrum



Schwieterman et al. (2018)

Ultimate Goal: Characterization of temperate rocky planets around nearby stars

A large sample of temperate exoplanets already known and to be discovered before METIS, and particularly ANDES/PCS First Light…

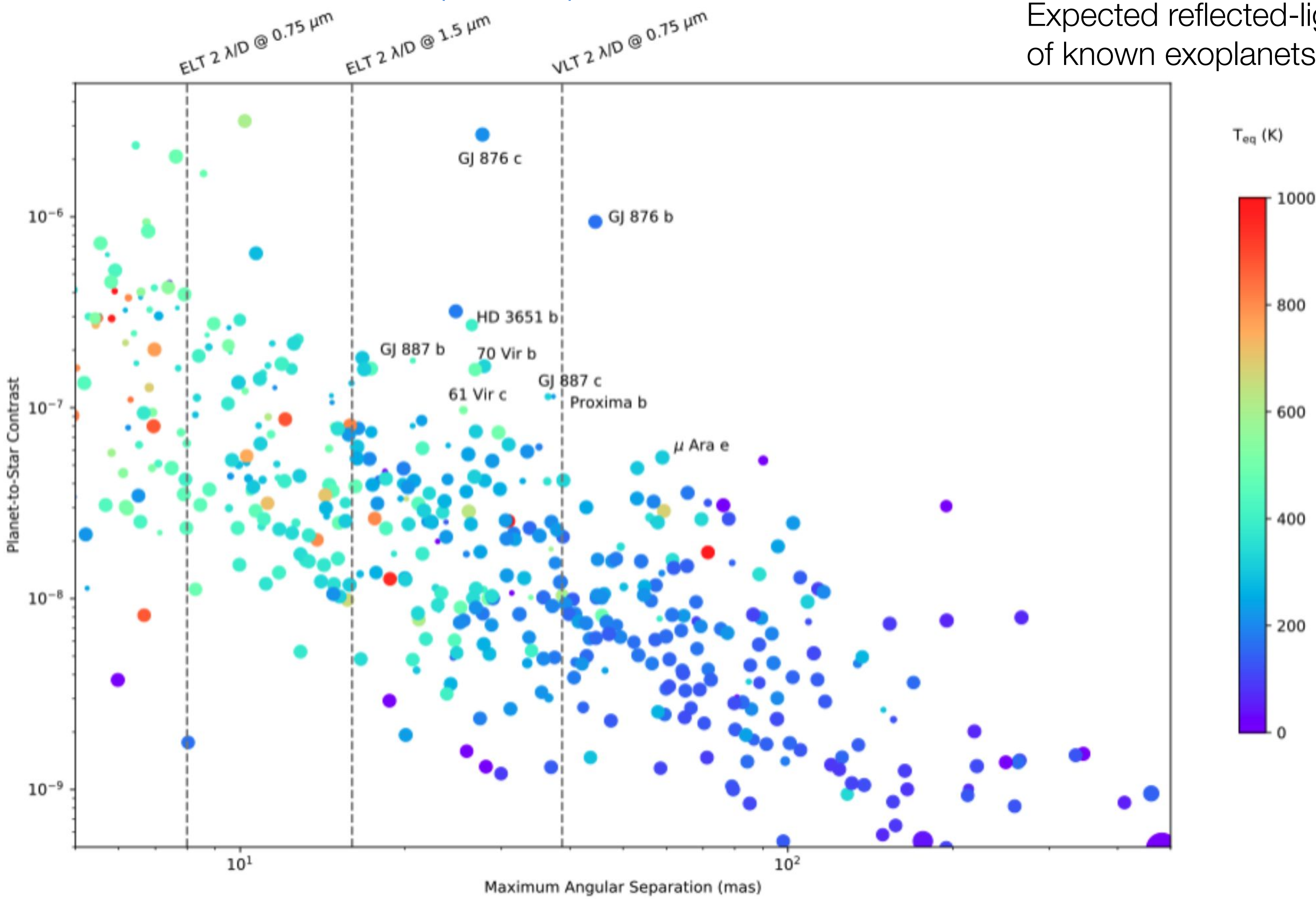
> Talks by K. Wagner & E. Bendek (space-CGI/HWO)

Imaging the reflected-light, a game changer

From young, giant planets to old, rocky worlds?

- TLR in Contrast: 10^{-8} (20mas)

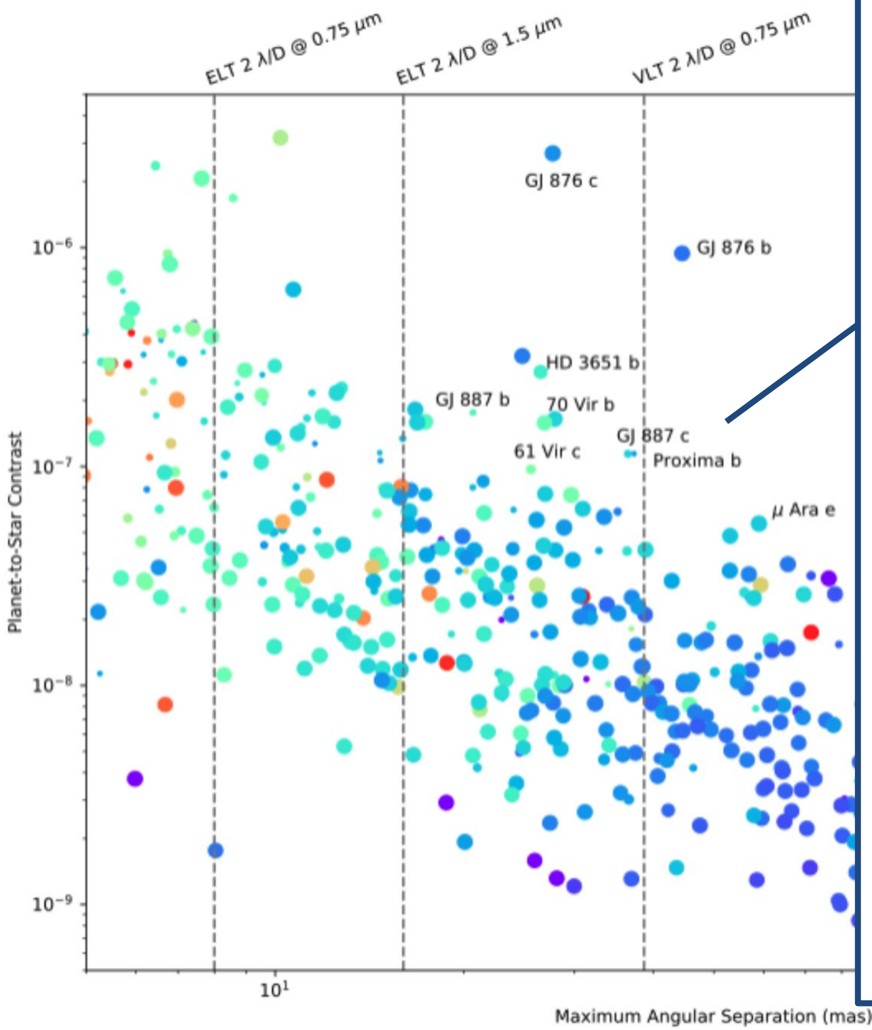
Expected reflected-light contrast of known exoplanets (Lovis et al. 2022))

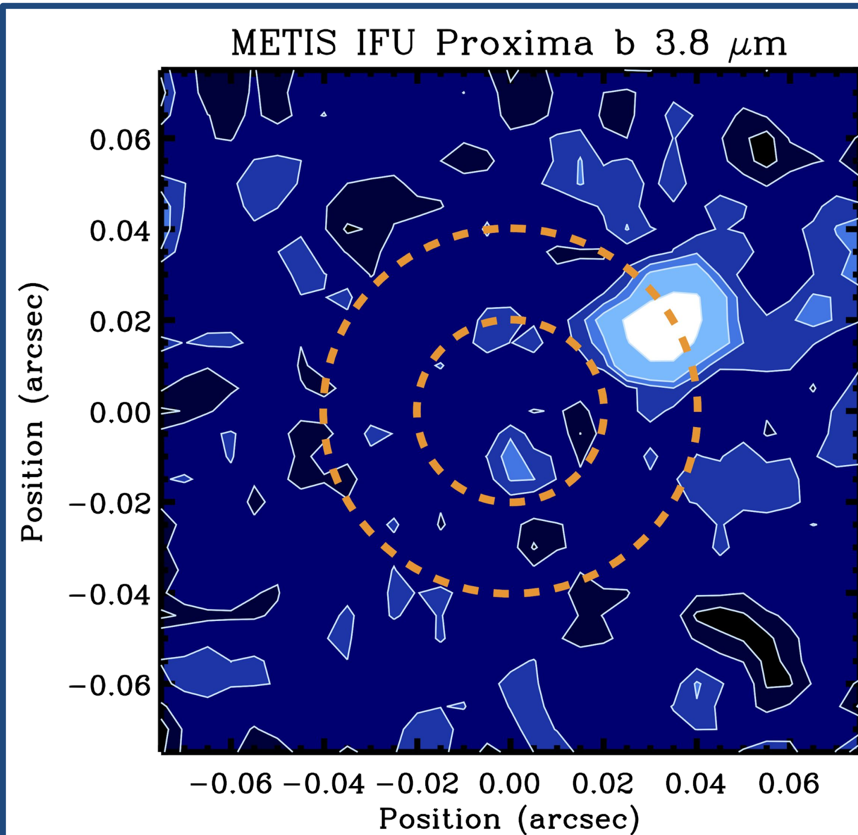


Imaging the reflected-light, a game changer

From young, giant planets to old, rocky worlds?

- TLR in Contrast: 10^{-8} (20mas)



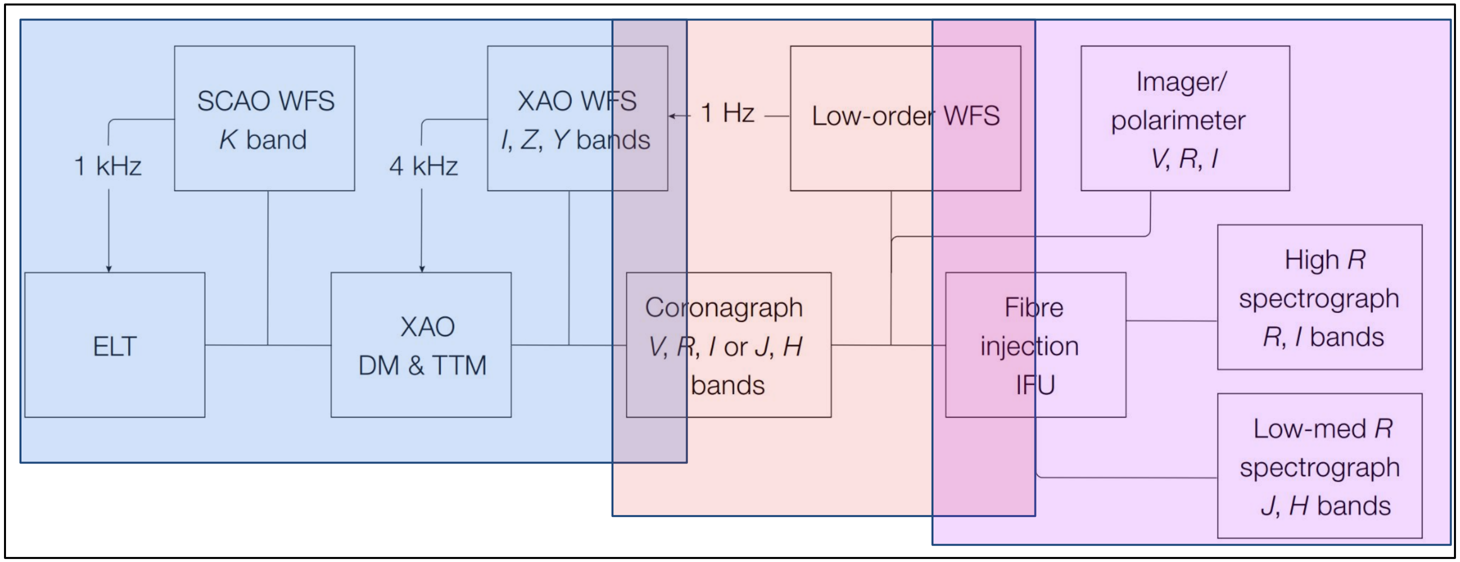


Proxima, 1.3 pc, 1.1 R_{Earth} planet radius (albedo 0.3, 50% illumination), CO, CH_4 & H_2O-rich planet. 10hr obs.

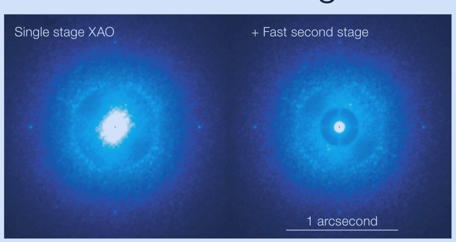
Imaging the reflected-light, a game changer

PCS (2036): a dedicated XAO imager for ELT (Kasper et al. 2021)

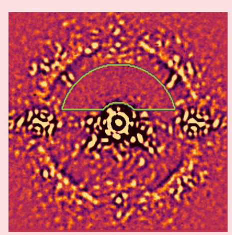
to search for and characterize rocky planets



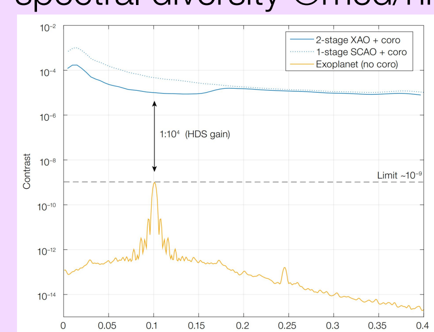
1/ XAO with 2nd stage



2/ Coronography & Low-order corrections



3/ spectral diversity @med/high-R



SPHERE+/HiRISE: no simulations but a VLT prototype!

Take away 2 for Alpha Cen

- ELT First Light Instruments (MORFEO-MICADO, HARMONI, METIS),
  - Not specialized instruments, limited AO or spectral resolution performances,
  - Will image & characterize young, giant (> 0.1-1.0 MJup) planets beyond 1 au! (Emitted light regime, except in the case of a few low-hanging fruits (and Alpha Cen belong to them!)

- Reflected light, a game changer,
  - Mandatory to image/characterize rocky planets from the ground,
  - Must target the close environment of very, nearby systems, with typical contrasts of 10^{-8} (20mas)!, constraints more relaxed for Alpha Cen / Proxima.
  - Will require a dedicated instrument combining XAO + coronography + FP-WFS-control + HDS as proposed for the ambitious PCS instrument at ELT (2036?)

Outline

1. Context & science drivers
1. The VLT/I-2030 roadmap
   Toward exploring giant planet atmosphere demographics
1. The ELT one
   The long road toward characterizing super-Earths
1. Take away

Take away

- Exoplanets: We are very far from being done!
  - Young Jupiters - Formation/evolution history,
  - Demographics of exoplanets & exoplanetary atmospheres,
  - Atmospheres: slowly fill the gap btw mature HJs/SEs & young super Jupiters,
  - HJs: 3D revolution in the making,
  - Discovery of the first signs of life,

- The VLT/VLT-I 2030 roadmap
  - Increased characterization capabilities (wavelength coverage, spatial/spectral res.)
  - Improve radial velocity discovery space (ESPRESSO, NIRPS),
  - Atmosphere dynamics of HJs (ESPRESSO/CRIRES+) - JWST
  - Young Jupiters down to the snowline (ERIS/GRAVITY+/SPHERE+) - Gaia/JWST
  - Push for HCI R&D in preparation for ELT/PCS!

- ELT (First Light: mid-2028),
  - Unique spatial resolution, sensitivity, versatility & lifetime
  - Will be undoubtedly a characterization machine!
  - 1st Gen (MICADO, HARMONI, METIS) will focus on mature & young, giant planets, but open new avenues on the 3D-ness of exoplanetary atmospheres,
  - 2nd Gen (METIS, ANDES & PCS), will open the path forward the characterization of super-Earths & first signs of Life (our “rendez-vous” point for the Alpha Cen & Proxima Cen rocky planets!),