Characterizing Exoplanets with Nulling: Surveying Unseen Systems (aka *CENSUS*)

A near-term 3-8 μm thermal-IR interferometer as a complement to HWO and a bridge toward LIFE

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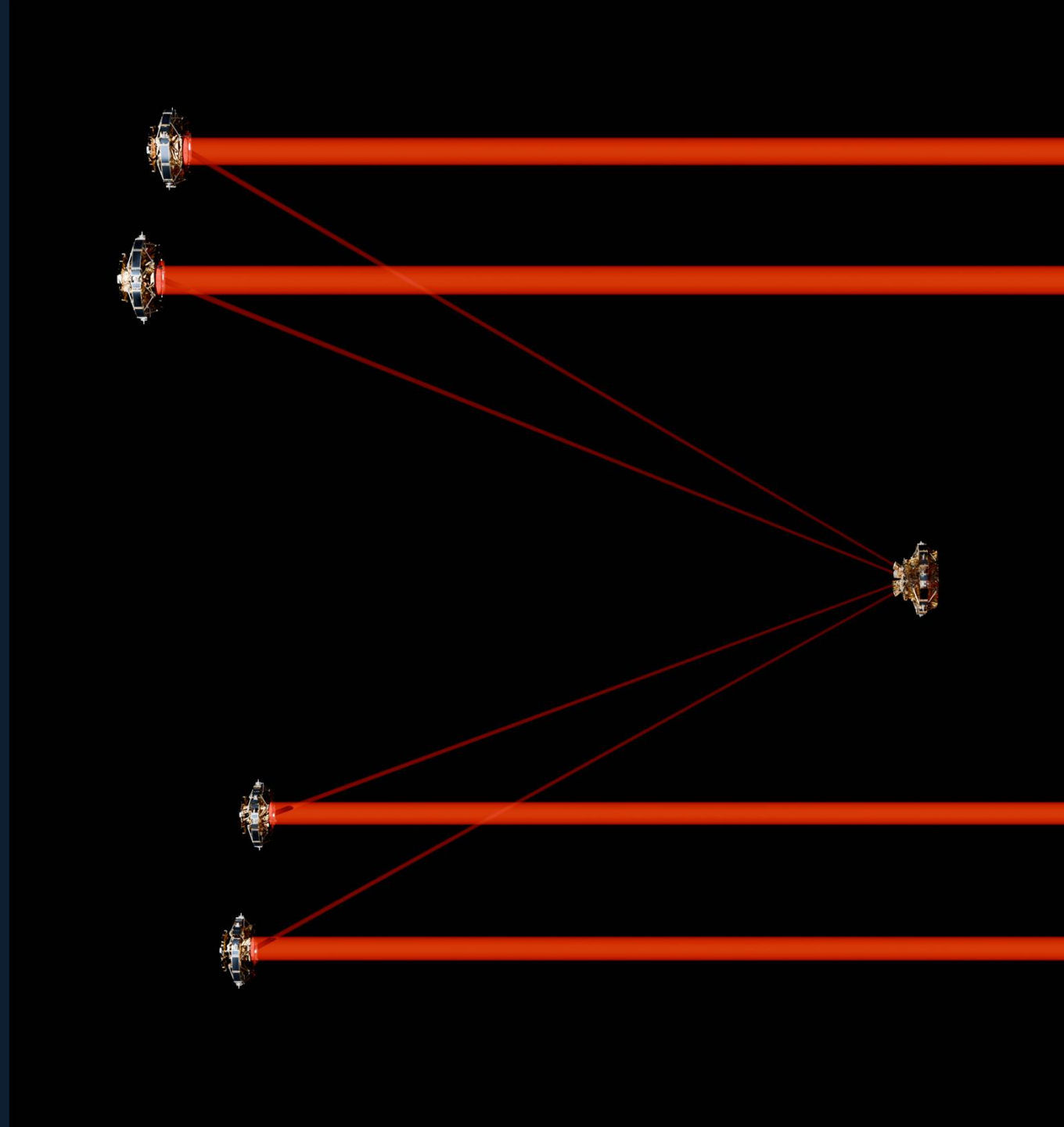
for John D. Monnier, Oscar Carrión-González, Felix Dannert, Seongbong Han, Jonah Hansen, Jens Kammerer, Sascha Quanz, and the CENSUS Team (+Claude)

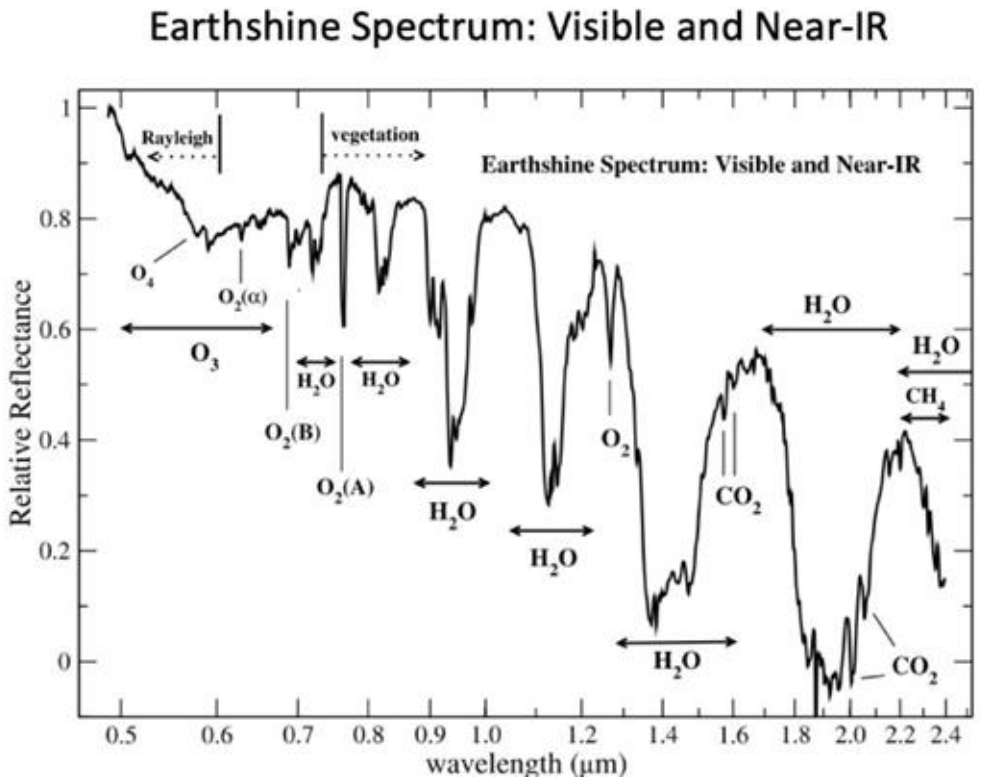


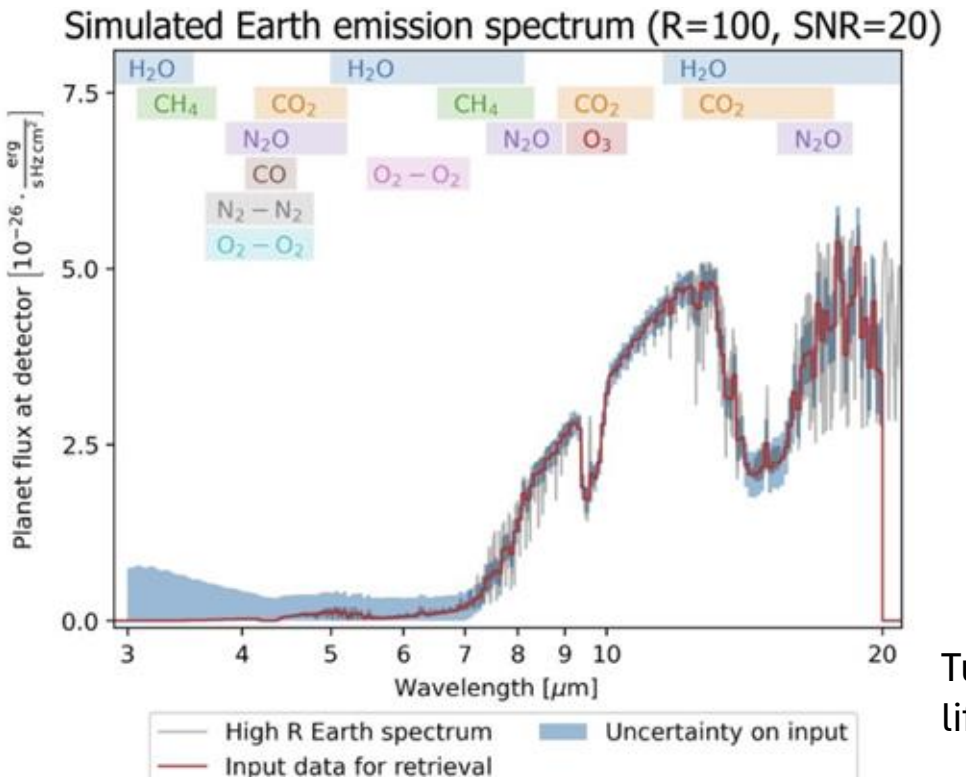
Background: LIFE mission artist impression, credit: LIFE mission; Quanz et al. 2022 / Glauser et al. 2024 slide context.

Characterizing Small Exoplanets:

Reflected light or thermal emission? Yes!

- Solve the radius-albedo ambiguity.
- Calculate planetary energy budget & greenhouse effect.



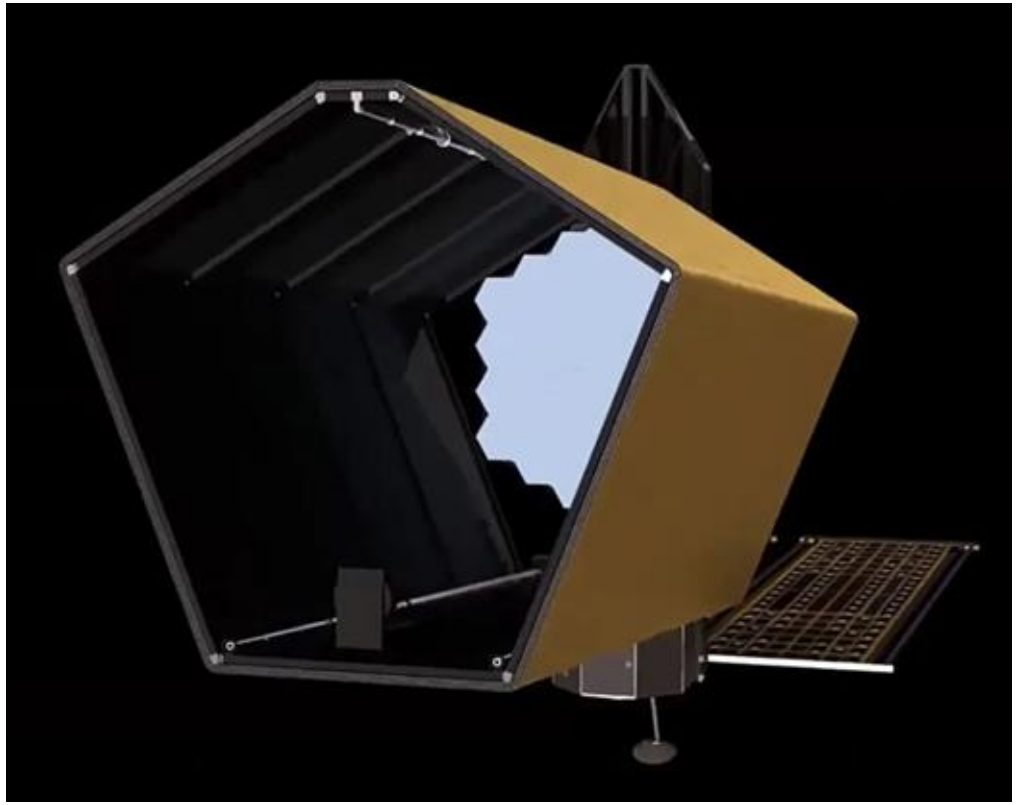


Turnbull et al. 2006; life-mission website

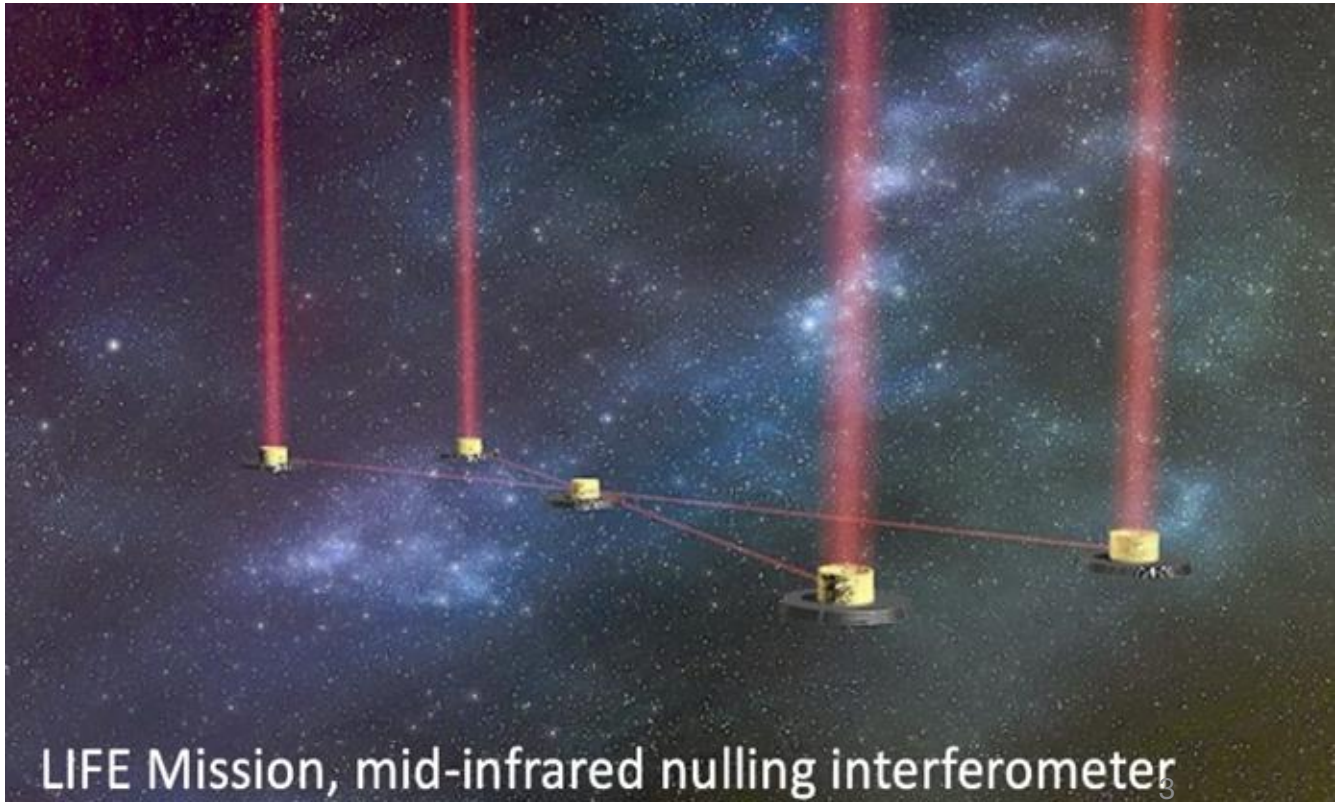
Characterizing Exoplanets

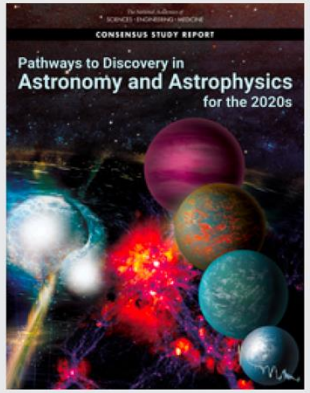
- To see faint planet emission, we need to block the starlight!

Reflected light (coro): Roman, ELT, & HWO



Thermal emission: ELT (coro) & LIFE (nulling).





Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2023)

TABLE E.2 Capabilities, Facilities, and Future Needs to Address the Science Questions and Discovery Area

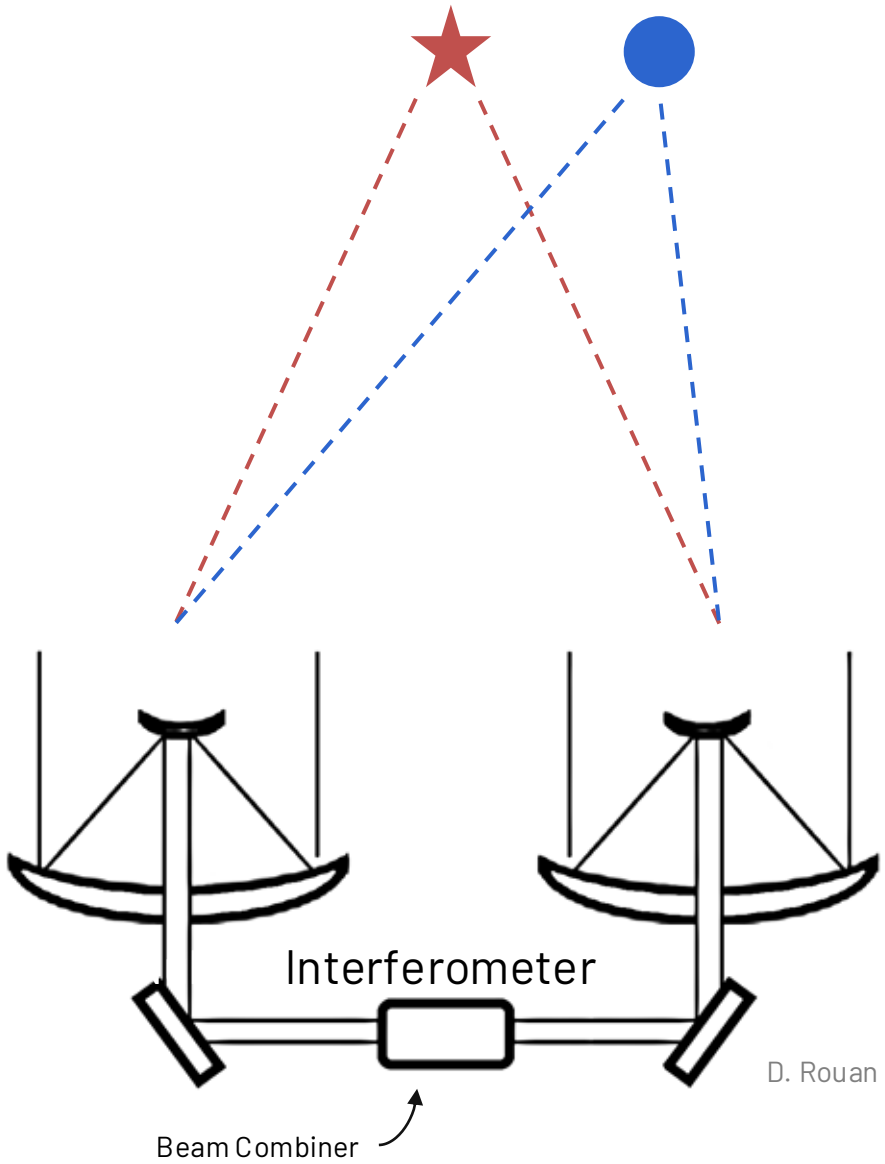
Capability	Science Enabled	Current/Expected Facilities	Future Needs
Mid-IR direct imaging	E-Q2a, E-Q2b, E-Q2c, E-Q2e, E-DA	ELTs: 10 micron high-contrast imaging from ground for a few stars to measure radii and temperatures of few planets	Mid-IR interferometry: measure temperature, radii, and atmospheric features of planets around FGKM stars, including Earth-size HZ planets (5–18 microns)

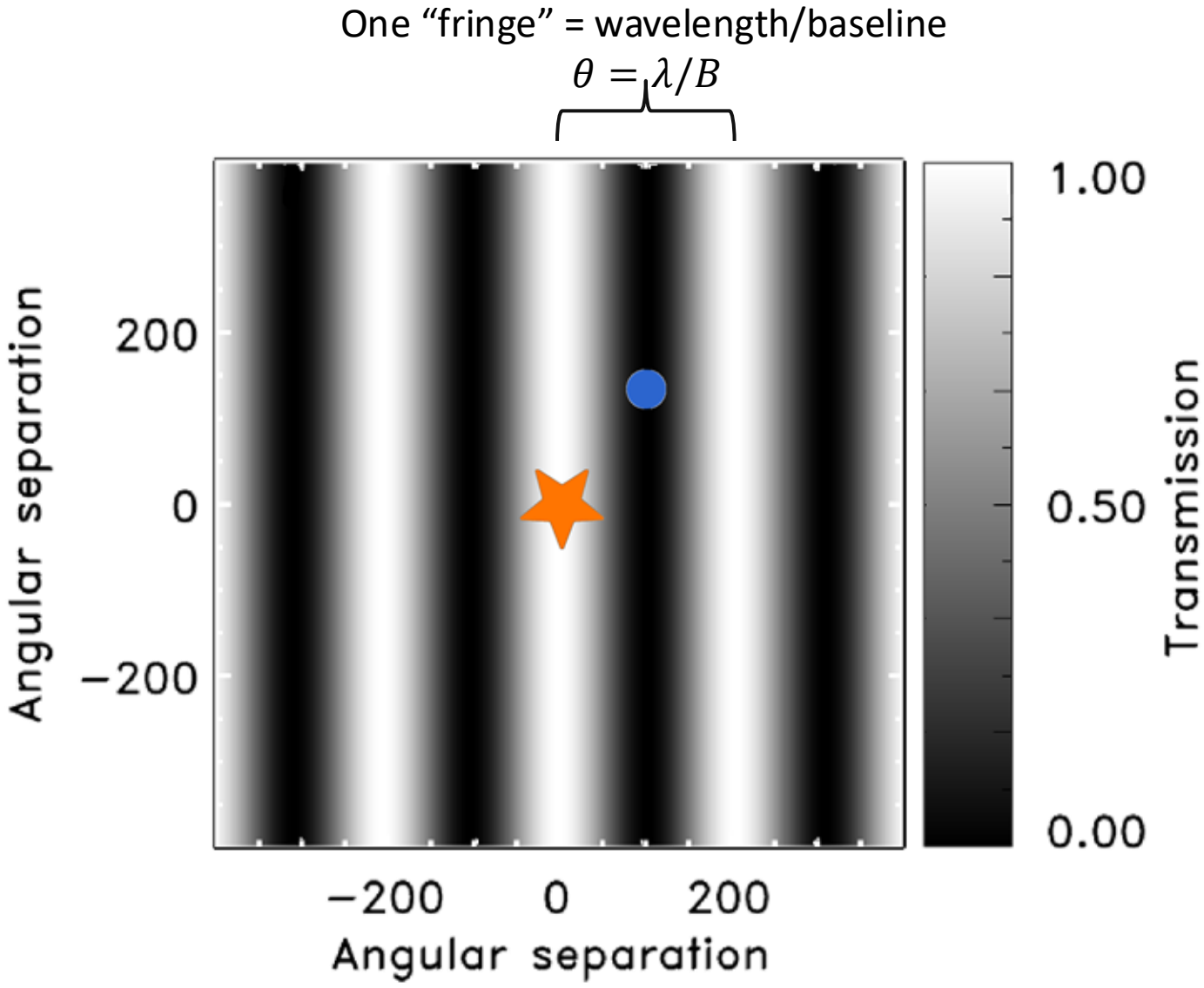
TABLE E.1 Science Questions and Discovery Area

Questions	Subquestions
E-Q1: What is the range of planetary system architectures, and is the configuration of the solar system common?	E-Q1a: What are the demographics of planets beyond the reach of current surveys? E-Q1b: What are the typical architectures of planetary systems? E-Q1c: How common is planetary migration, how does it affect the rest of the planetary system, and what are the observable signatures? E-Q1d: How does the distribution of dust and small bodies in mature systems connect to the current and past dynamical states within planetary systems? E-Q1e: Where are the nearby potentially habitable planets, and what are the characteristics of their planetary systems?
E-Q2: What are the properties of individual planets, and which processes lead to planetary diversity?	E-Q2a: Which physical processes govern a planet's interior structure? E-Q2b: How does a planet's interior structure and composition connect to its surface and atmosphere? E-Q2c: What fundamental planetary parameters and processes determine the complexity of planetary atmospheres? E-Q2d: How does a planet's interaction with its host star and planetary system influence its atmospheric properties over all time scales? E-Q2e: How do giant planets fit within a continuum of our understanding of all substellar objects?
E-Q3: How do habitable environments arise and evolve within the context of their planetary systems?	E-Q3a: How are potentially habitable environments formed? E-Q3b: What processes influence the habitability of environments? E-Q3c: What is the range of potentially habitable environments around different types of stars? E-Q3d: What are the key observable characteristics of habitable planets?
E-Q4: How can signs of life be identified and interpreted in the context of their planetary environments?	E-Q4a: What biosignatures should we look for? E-Q4b: How will we interpret the biosignatures that we see? E-Q4c: Do any nearby planets exhibit biosignatures?
E-DA Discovery Area: The search for life on exoplanets.	

Ad ASTRA

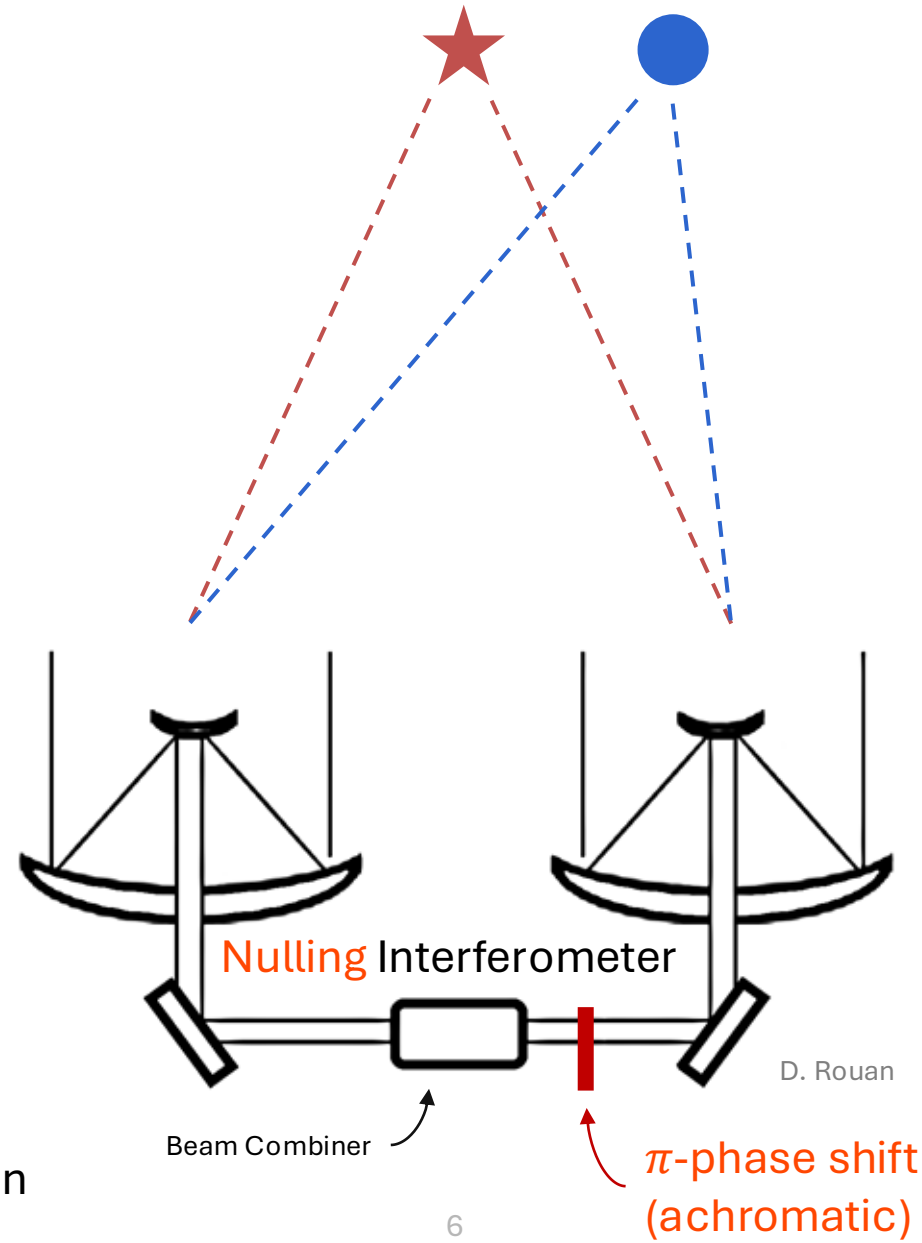
Nulling Interferometry in a nutshell

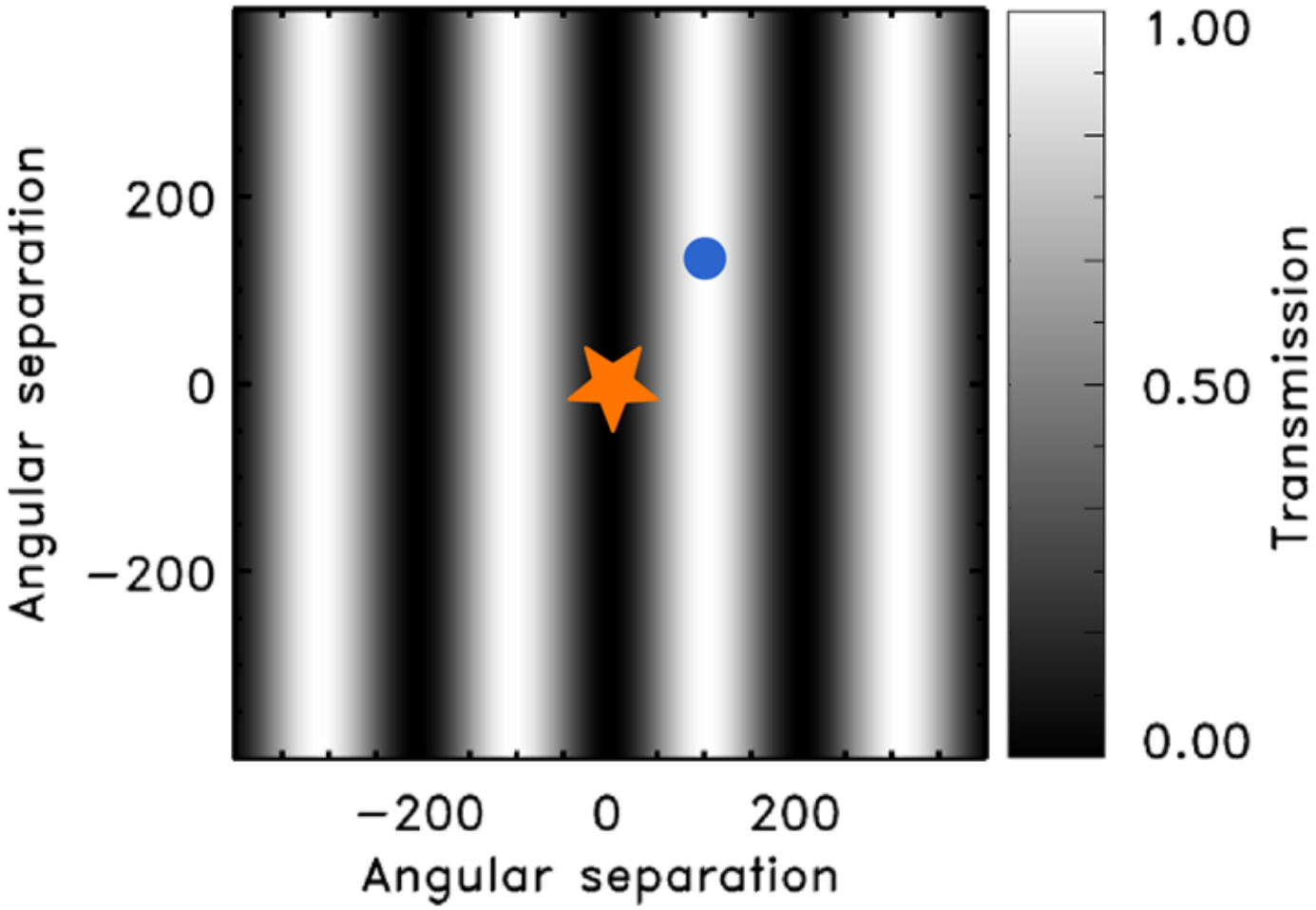




Hansen

Nulling Interferometry in a nutshell





Hansen

3-8 μm CENSUS is a near-term science opportunity!

SCIENCE OPPORTUNITY:

*Physical characterization of **known** planets:*

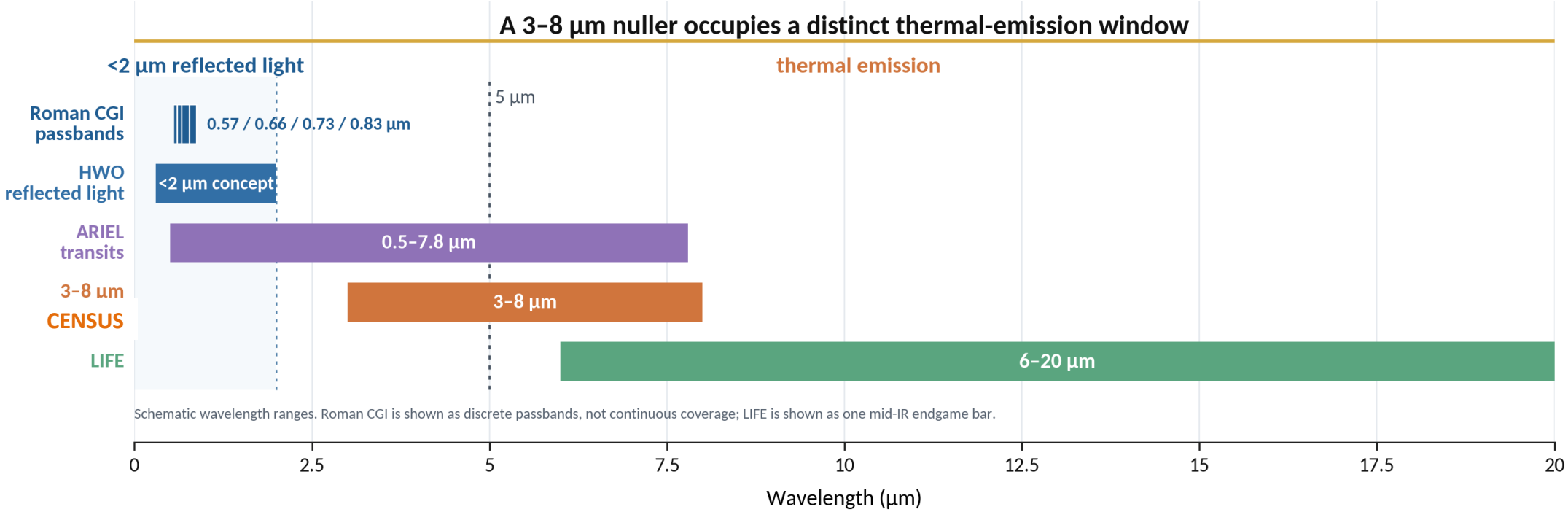
- Within 0.1 AU to beyond 2 AU.
- Very warm Earths to temperate giants.

Breaks the M sini degeneracy for hundreds of RV planets, provides radii [sqrt(L/T^4)] and characterization spectra!

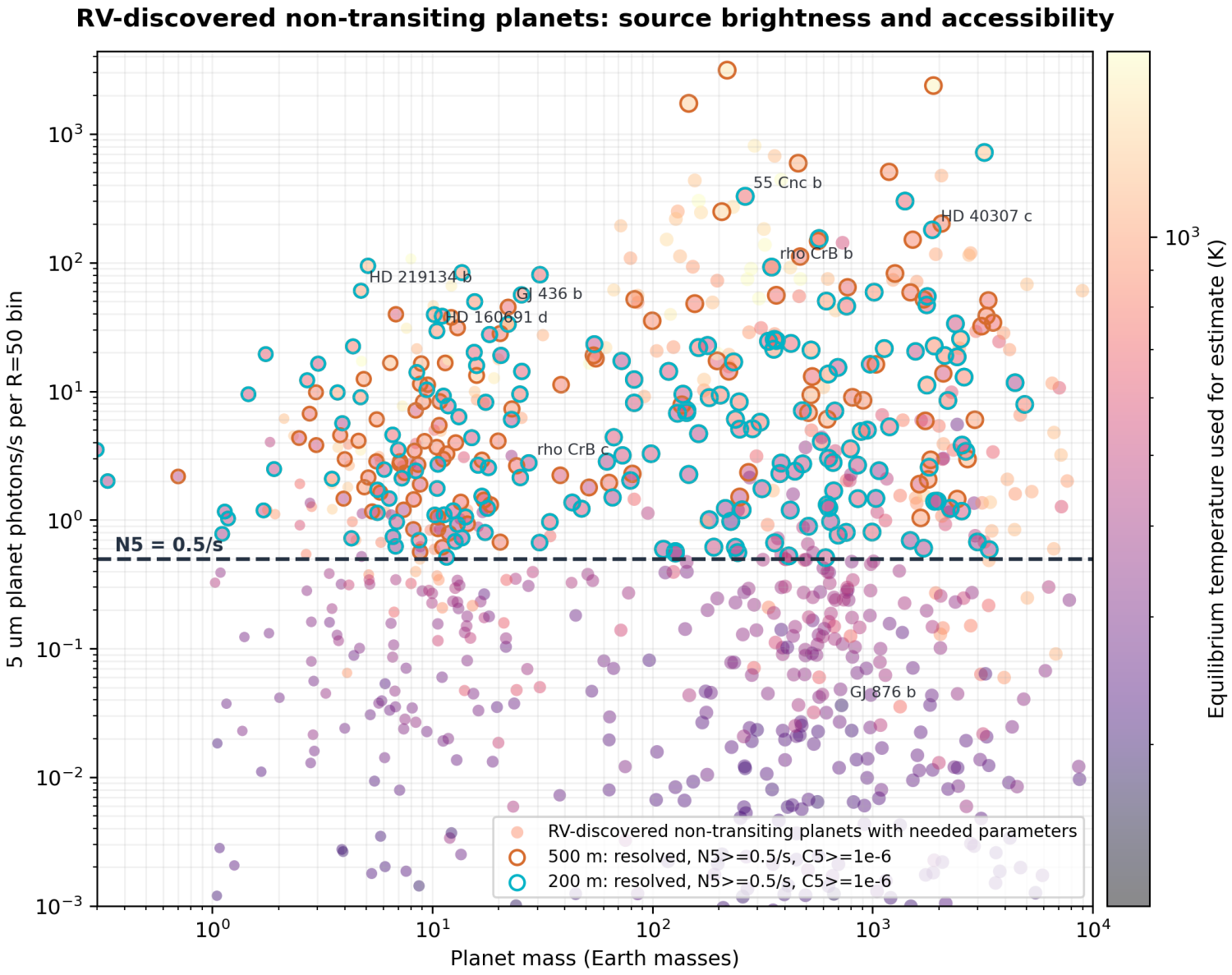
DISCOVERY SPACE:

- JWST: farther out than transit, closer in that imaging!
- Complements Roman+ELT/METIS Coronagraphy.
- Colder planets than ARIEL.
- Thermal emission first for many HWO targets.

Transformative science, not just a LIFE tech demo!



CENSUS (4 x 2-meter space nulling interferometer) nets hundreds of RV planets



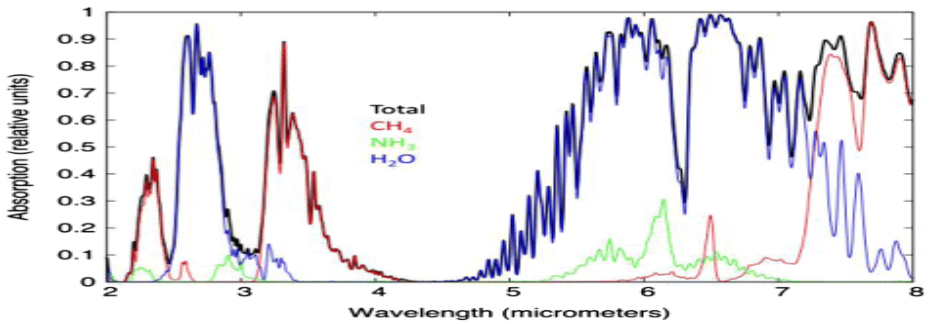
Nets 25 % of RV Planets (~ 200 planets).

Breaks the $M \sin i$ degeneracy.
Provides Thermal emission (radii).
And 3-8 μm R ~ 50 spectra.

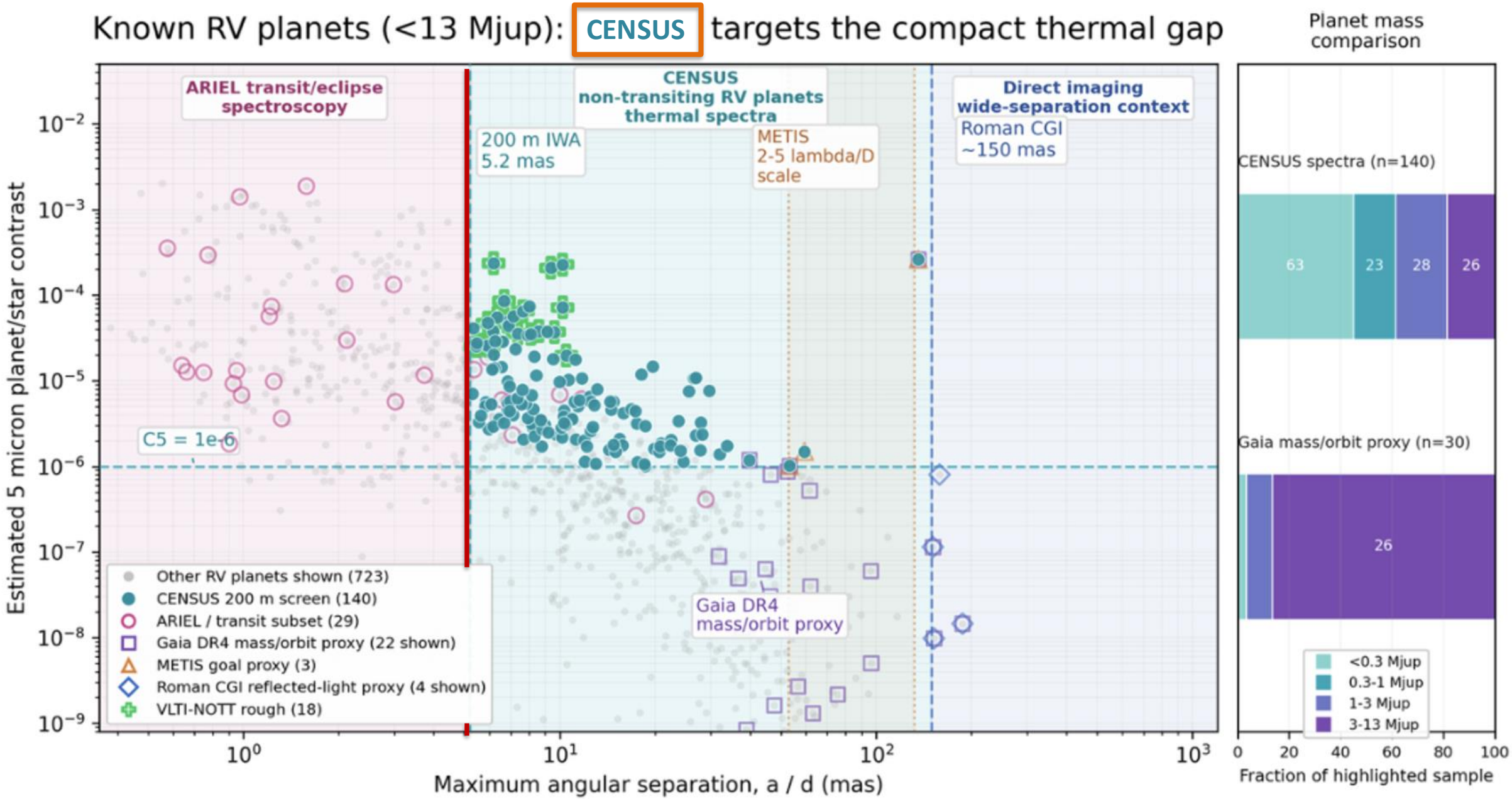
Around diverse stellar hosts:

- 14% M stars
- 35% K stars
- 43% G stars
- 7% F stars

Encrenaz et al. (2018)



NASA Exoplanet Archive planets discovered by radial velocity. Radii measured where available; otherwise smooth mass-radius estimate. Detection guide only: no stellar leakage, background, or calibration model.


Known RV planets (<13 Mjup): CENSUS targets the compact thermal gap
ARIEL transit/eclipse spectroscopy
CENSUS non-transiting RV planets thermal spectra
Direct imaging wide-separation context
200 m IWA 5.2 mas
METIS 2-5 lambda/D scale
Roman CGI ~150 mas
C5 = 1e-6
Gaia DR4 mass/orbit proxy
Other RV planets shown (723)
CENSUS 200 m screen (140)
ARIEL / transit subset (29)
Gaia DR4 mass/orbit proxy (22 shown)
METIS goal proxy (3)
Roman CGI reflected-light proxy (4 shown)
VLTI-NOTT rough (18)
Estimated 5 micron planet/star contrast
Maximum angular separation, a / d (mas)
Planet mass comparison
CENSUS spectra (n=140)
63
23
28
26
Gaia mass/orbit proxy (n=30)
26
<0.3 Mjup
0.3-1 Mjup
1-3 Mjup
3-13 Mjup
Fraction of highlighted sample

(> 0.1 AU @ 20 pc)

Mid-IR interferometry is moving from component demos to systems:

For Ad ASTRA, the development story is convergence: nulling performance + distributed spacecraft + an integrated 3–8 µm science case.

3-5 µm NULLING IS BECOMING OBSERVATIONAL

NICE / ETH lab work

10^{-5} nulls; next steps are broadband, polarization, throughput, and cryogenic operation.

NOTT @ VLTI

Nulling at 3.5–4.0 µm brings the technique onto sky for young planets and exozodi (2026-2027)

FORMATION FLYING IS GAINING FLIGHT HERITAGE

UM

PROBA-3

Millimeter-scale autonomous alignment demonstrated in orbit.

SunRISE

Six-spacecraft radio interferometer pathfinder; launch in 2026.

UM

STARI + SEIRIOS

Starlight handoff and stellar-fringe demonstrations 2029-2031.

COLD STABLE COLLECTORS AND IR DETECTORS ARE HERITAGE

Herschel 3.5 m passively cooled telescope at L2 (80 K); WISE (74K) at LEO.
Low background MCT detectors are ready (NEOCAM).

Open Questions for an ASTRA Study

Yield: how many planets?

Architecture: aperture, baseline range, combiner, orbit, cost?

Noise floor: stellar leakage, zodi, exozodi, telescope background?

Stability: pathlength, phase, polarization, formation control?

Calibration: can leakage be subtracted in flight?

Program value: diverse goals. what LIFE-relevant risks are retired by **CENSUS**?

Source line to adapt: ETH/NICE; Defrère et al. / Asgard-NOTT; ESA PROBA-3; NASA/JPL SunRISE; STARI; SEIRIOS/SILVIA.

The nulling field is moving from component demos to systems

For ASTRA, the readiness story is convergence: nulling performance + distributed spacecraft + an integrated 3–8 µm science case.

Ad ASTRA concept study needed for Cross-PAG Probe-class 3-8 µm CENSUS!

- Spectra of 100s of known RV planets as well as new discoveries.
- Spatially-resolved chemistry of planet-forming disks.
- Dust forming shells around evolved stars.
- Galactic center, local starbursts, and AGN accretion disks.
- Little red dot analogues ($0.4 < z < 4.5$) to resolve size scale > 30 pc.

Expect strong interest from international partners.

3-5 µ

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NEOCAM using low background MCT detectors working over this wavelength range

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RV planets ?

erture, baseline orbit, cost?

ar leakage, zodi, e background?

gth, phase, nation control?

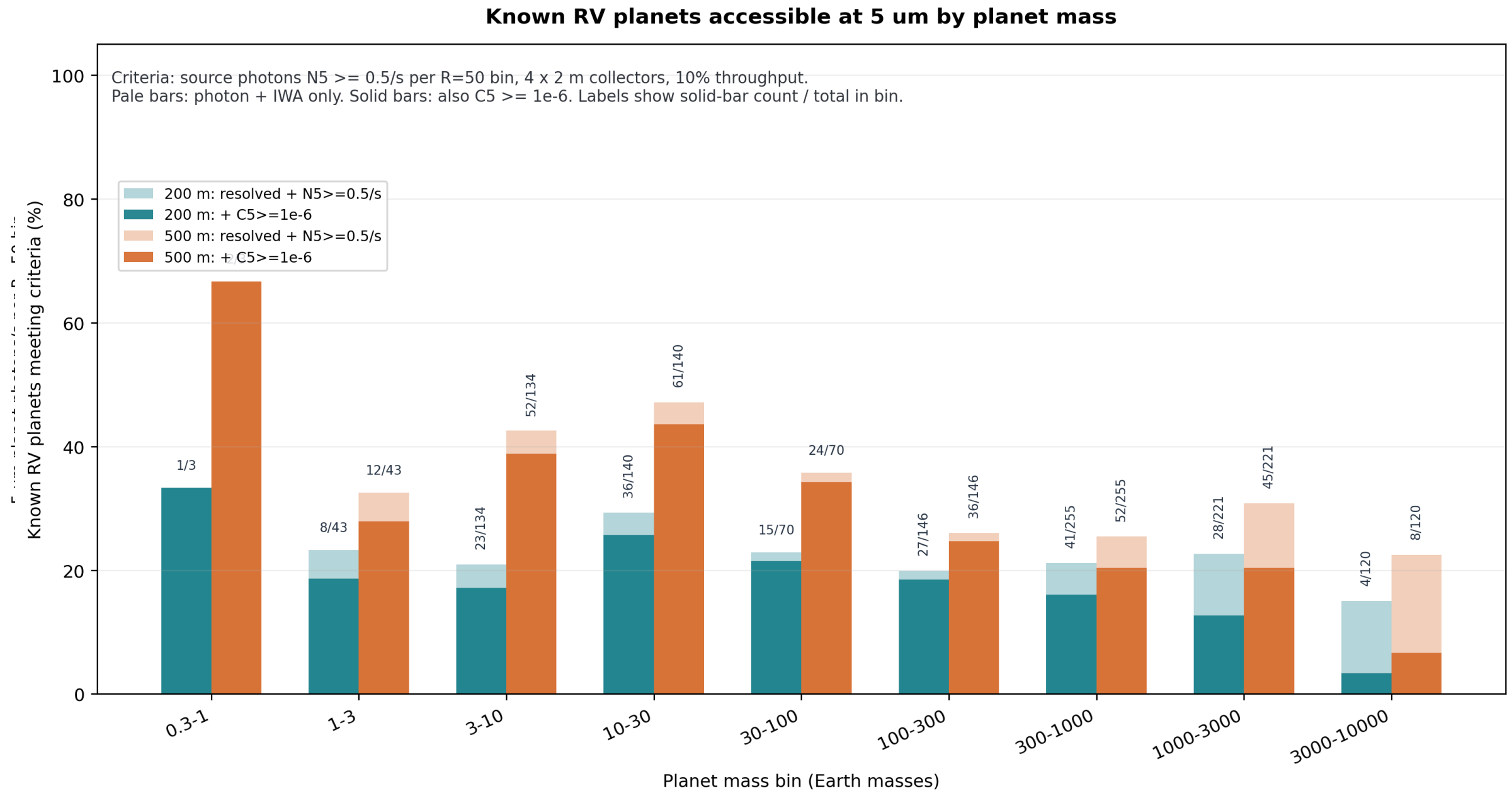
leakage be btracted in

ey non- e goals? what LIFE-relevant risks are retired by a science mission?

Source line to adapt: ETH/NICE; Defrère et al. / Asgard-NOTT; ESA PROBA-3; NASA/JPL SunRISE; STARI; SEIRIOS/SILVIA.

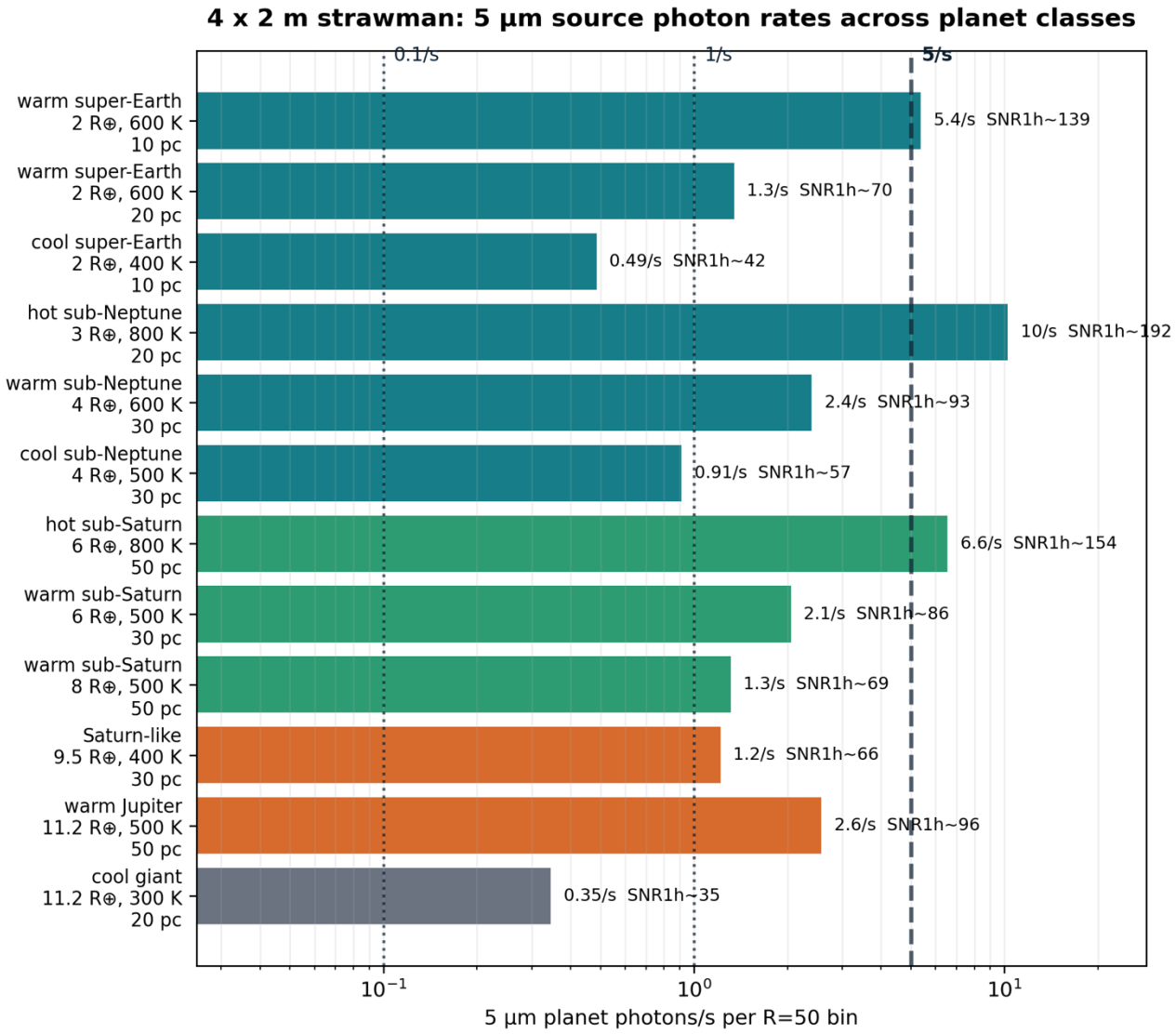
Backups

… and these planets span a wide range of masses and temperatures (400-1000K)



Photon-rate scale for a 4 x 2 m strawman

The 3-8 um case is not only hot giants, but the most robust margin is still warm/larger planets.



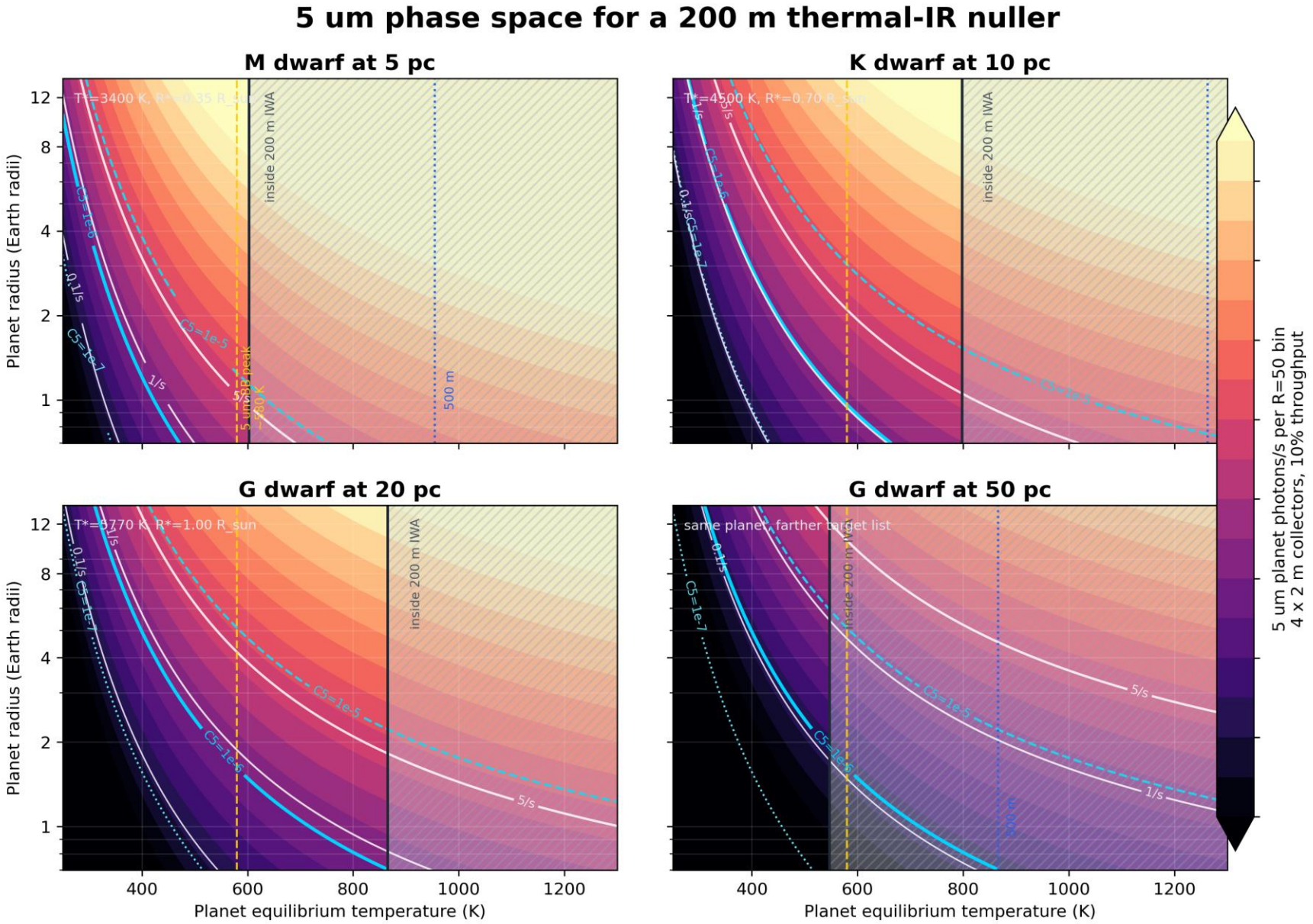
Warm super-Earths can be bright if very nearby; farther or cooler examples quickly move below a few photons/s.

Sub-Neptunes, sub-Saturns, and giants remain viable at larger distances in source-photon terms.

These are source-only rates; they should motivate a proper SNR model, not replace one.

Blackbody guide using NASA Exoplanet Archive pscomppars; source photons only.

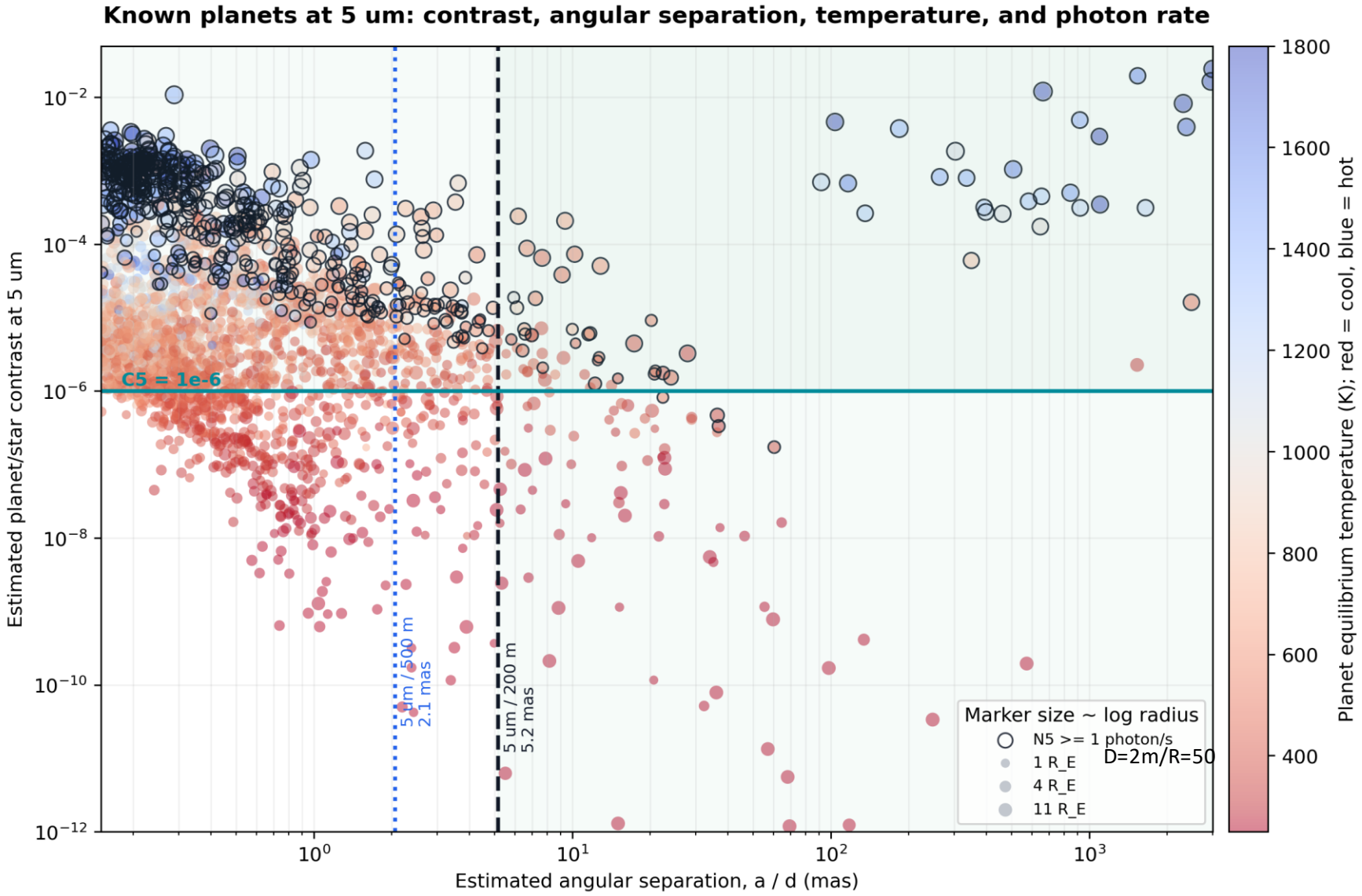
Host type and distance set contrast and photon-rate reach



Background = 5 um source photons/s. Cyan = 5 um planet/star contrast contours. White = photon-rate contours. Gray hatch = inside 200 m IWA; blue dotted = 500 m.

Known planets: contrast, angular separation, and photon rate

A 200 m baseline opens warm-planet space at small angular separations; photon rate still matters.



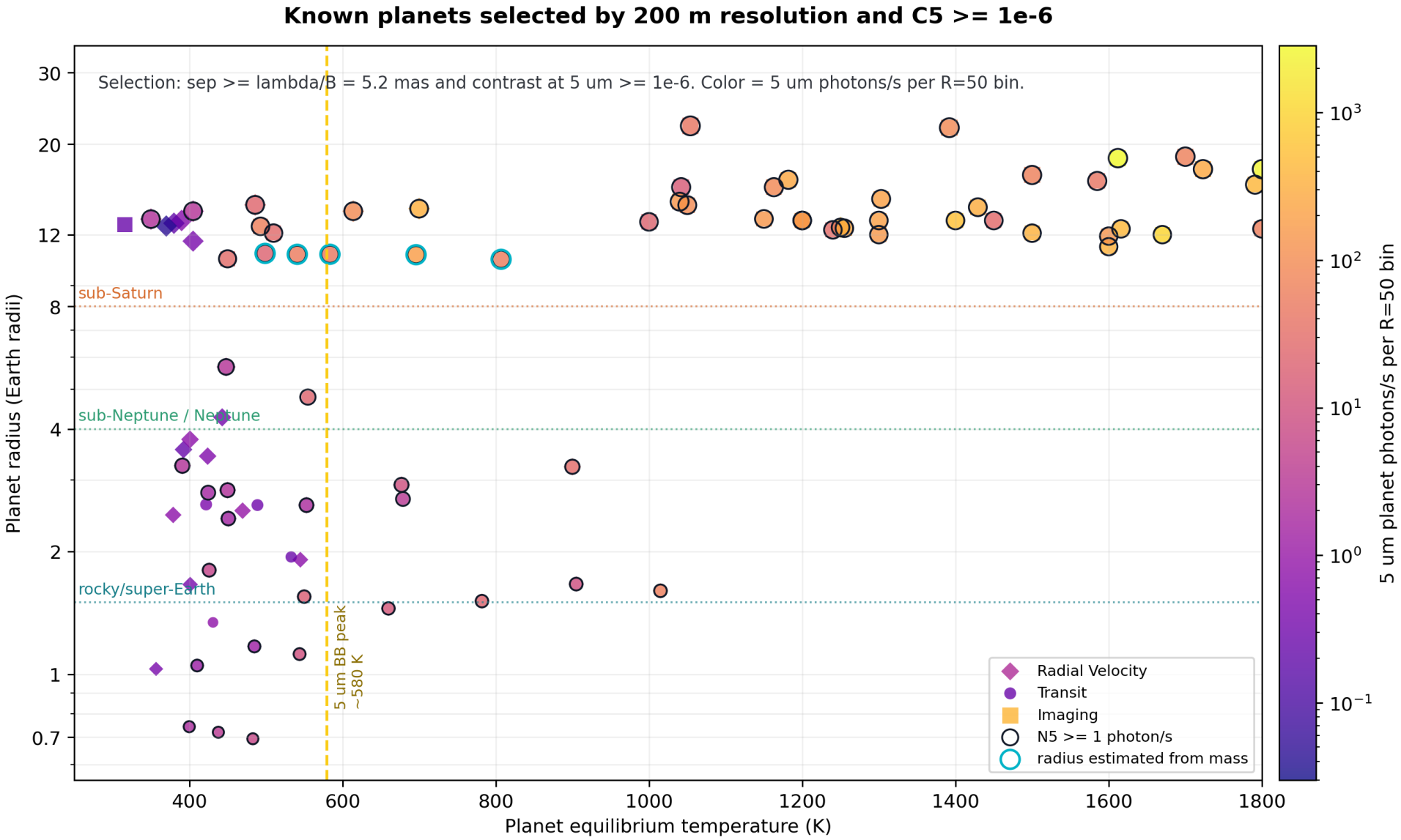
Circle outline indicates planets provides >1 photons/s per R=50 bin at 5 um for 4 x 2 m collectors and 10% throughput.

Real SNR performance needs stellar leakage, local/exozodi background, thermal background, calibration, and observing strategy.

NASA Exoplanet Archive pscomppars. Radii measured where available; mass-only planets use smooth mass-radius estimates. Blackbody guide only; no leakage/background/calibration model.

What lives in the upper-right discovery space?

Small planets enter mainly because the closest M/K systems convert tiny AU separations into resolvable angles.

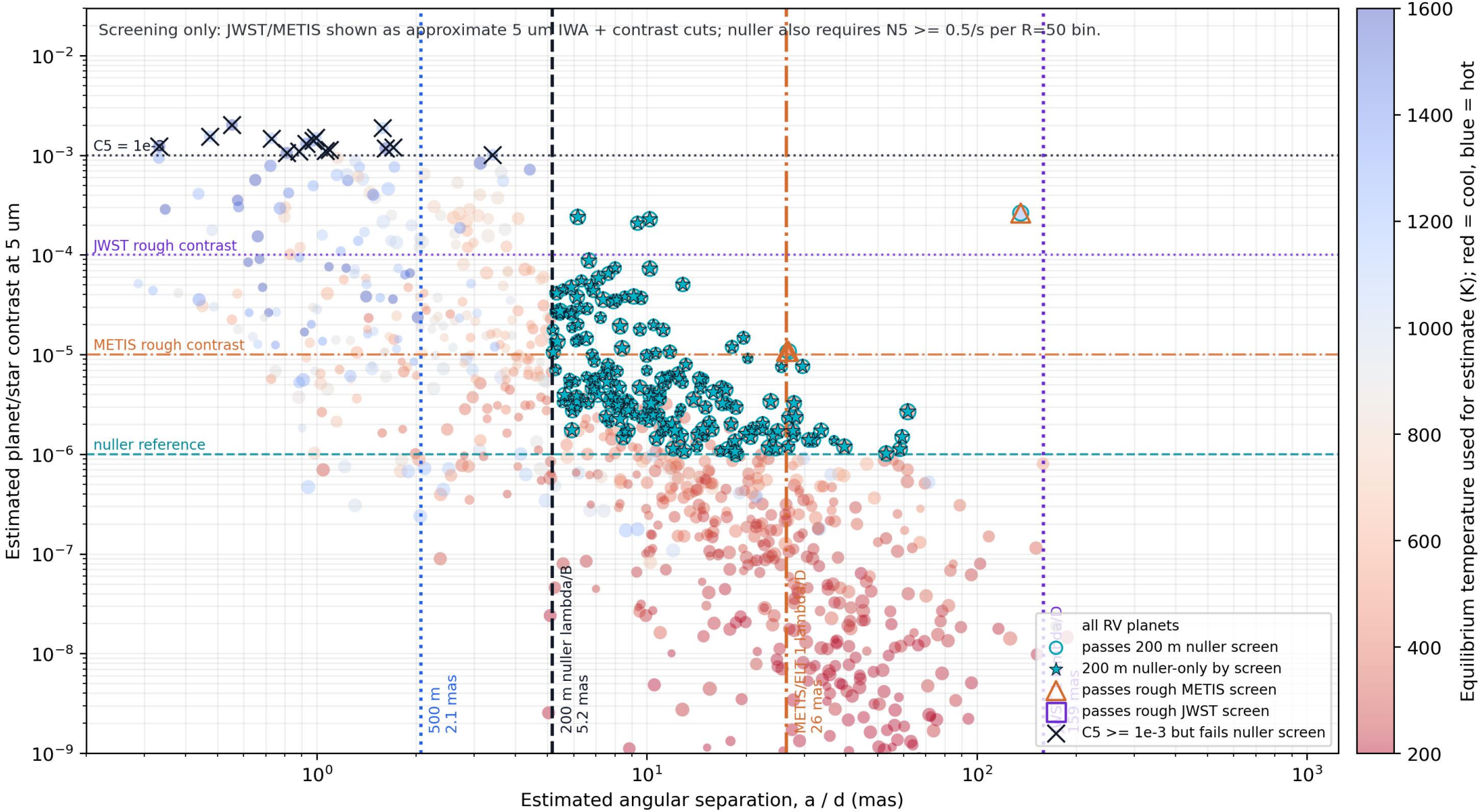


Selection here is C5 >= 1e-6 and angular separation >= lambda/B at 5 um and 200 m.

No photon-rate cut is applied on this slide; point size shows the source photon rate.

At 5 um and 200 m, lambda/B = 5.2 mas: 0.02 AU is resolvable only within about 4 pc; 0.05 AU within about 10 pc.

Same data/model as the contrast-separation plot. Estimated radii are flagged; this is a target-space guide, not a yield model.


Known RV planets: angular separation explains facility access
Screening only: JWST/METIS shown as approximate 5 um IWA + contrast cuts; nuller also requires N5 >= 0.5/s per R=50 bin.
C5 = 1e-3
JWST rough contrast
METIS rough contrast
nuller reference
500 m
2.1 mas
200 m nuller lambda/B
5.2 mas
METIS/ELT 1 lambda/D
26 mas
JWST 1 lambda/D
159 mas
all RV planets
passes 200 m nuller screen
200 m nuller-only by screen
passes rough METIS screen
passes rough JWST screen
C5 >= 1e-3 but fails nuller screen
Estimated planet/star contrast at 5 um
Estimated angular separation, a / d (mas)
Equilibrium temperature used for estimate (K); red = cool, blue = hot
NASA Exoplanet Archive RV planets. Blackbody guide only; no ETC/AO/leakage/background/calibration model.