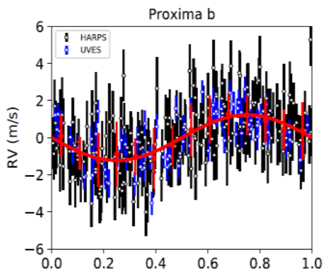
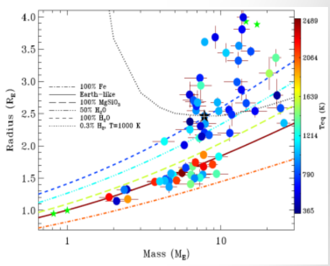
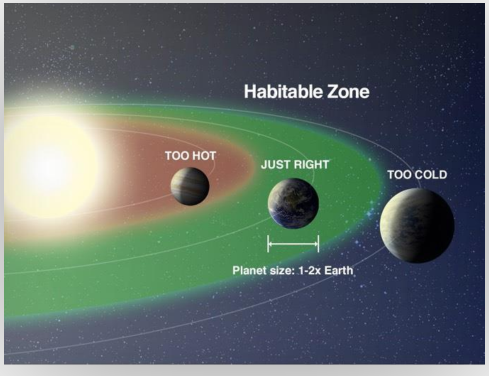
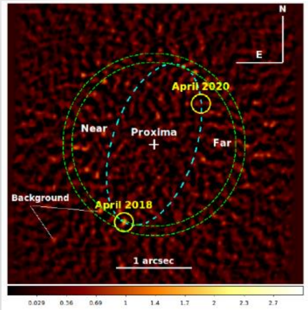
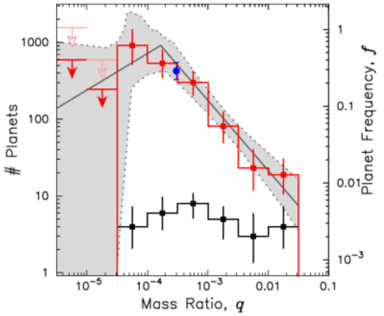










Architecture and Physical Properties of Planetary Systems

A. Sozzetti, K. Biazzo
(INAF – OATo, INAF - OARm)
+EXO-ARCH & EXO-STARS Teams

AUDIZIONE SCHEDE INAF CSN2 (ONLINE), 19/05/2021

AUDIZIONE SCHEDE INAF CSN2 (ONLINE), 19/05/2021

Architecture and Physical Properties

- Mass
- Radius
- Density/Composition
- Orbital Radius/Period
- Habitable Planets and eta-Earth
- Planet Multiplicity
- Eccentricity (& Inclination)
- Host Star Properties (Mass, Age, Composition, Binarity)

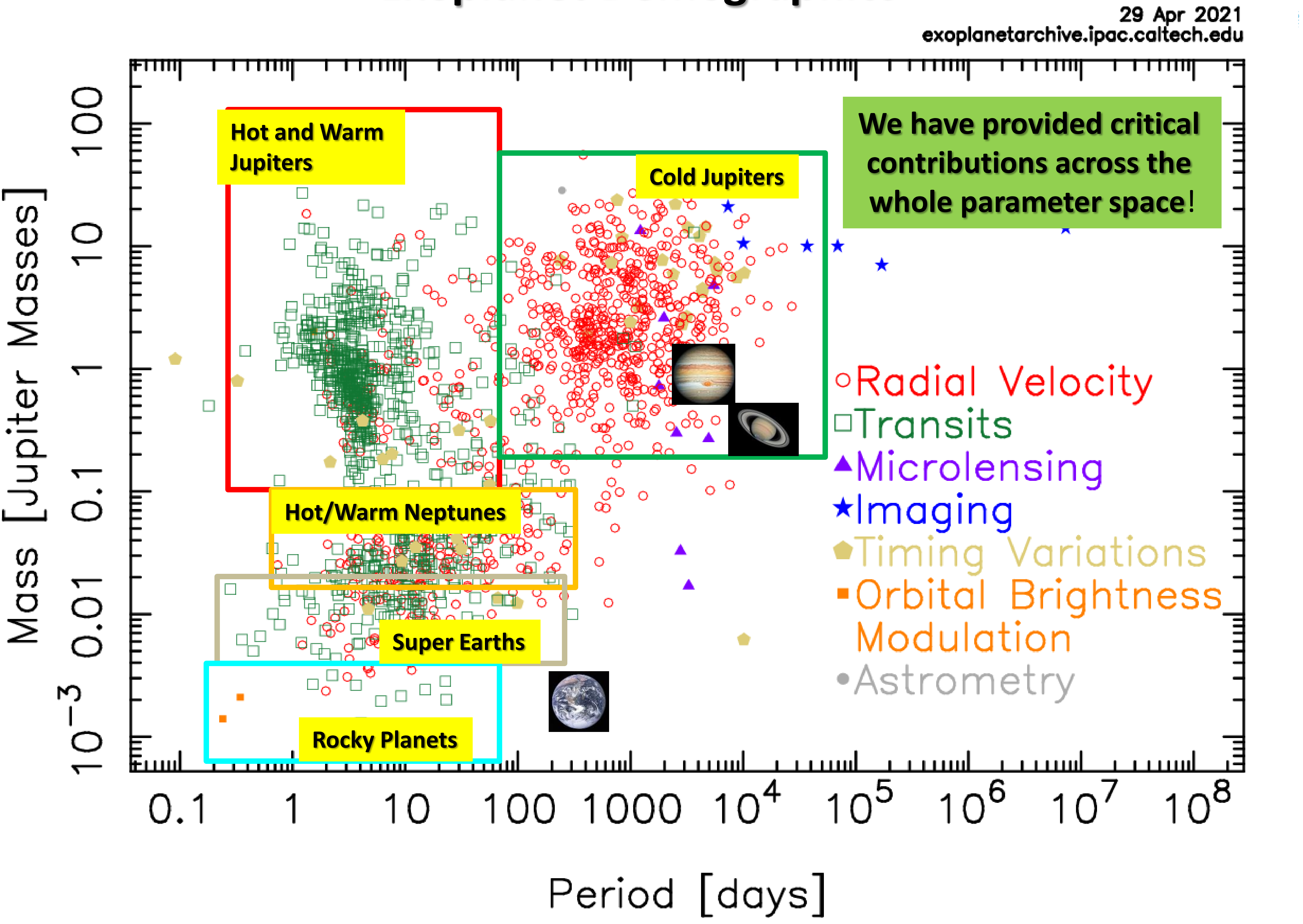
And ultimately answer the questions:
- Where are the true Earth-like planets?
- How common are Solar System analogs?

NOT TRIVIAL!

$$\frac{d^n N_{pl}}{dp_1 \ldots p_n} = A f(p_1) \ \ldots f(p_n) \quad \Rightarrow \quad \text{Occurrence Rate} = \frac{\#\,\text{planets}}{\#\,\text{stars}}$$

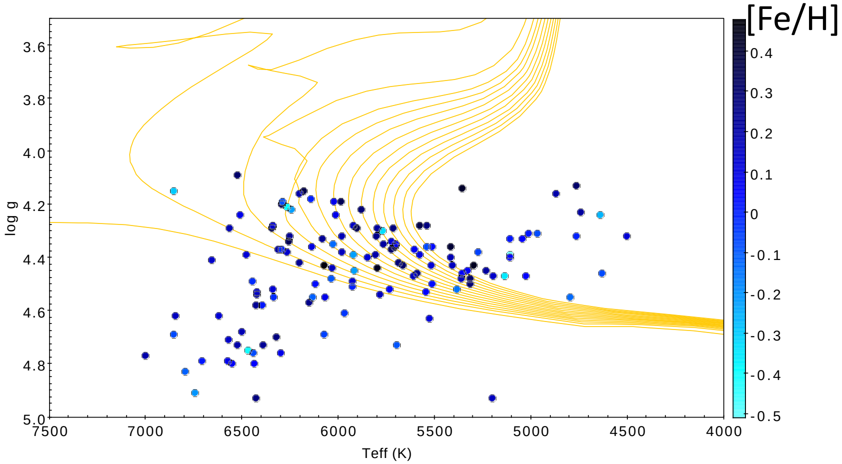
Distribution functions retain imprints of planet formation and evolution processes

Exoplanet Demographics



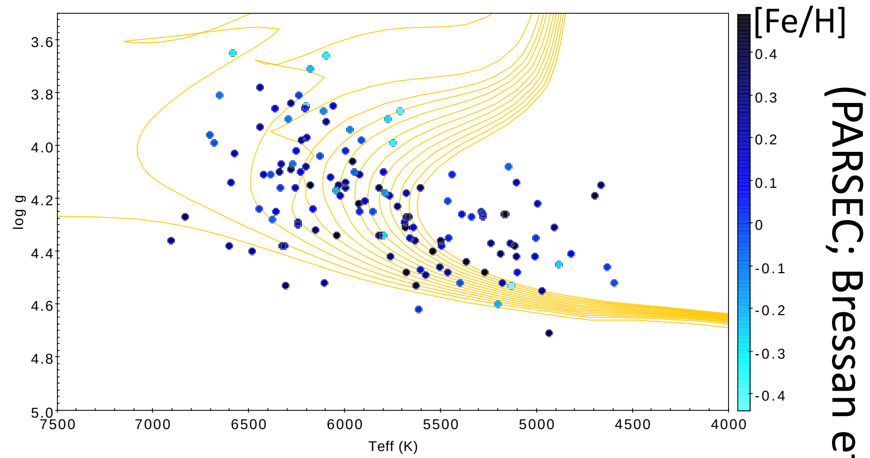
Know Thy Star…

I. Spectroscopic non homogeneous analysis



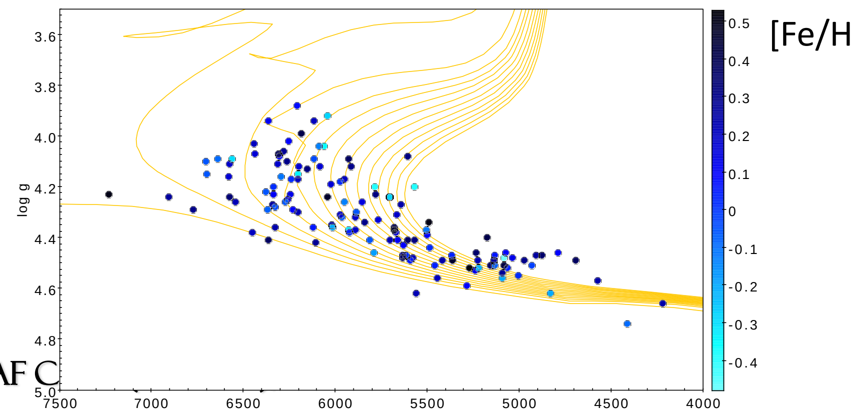
Biazzo et al. in prep.

II. Spectroscopic homogeneous analysis



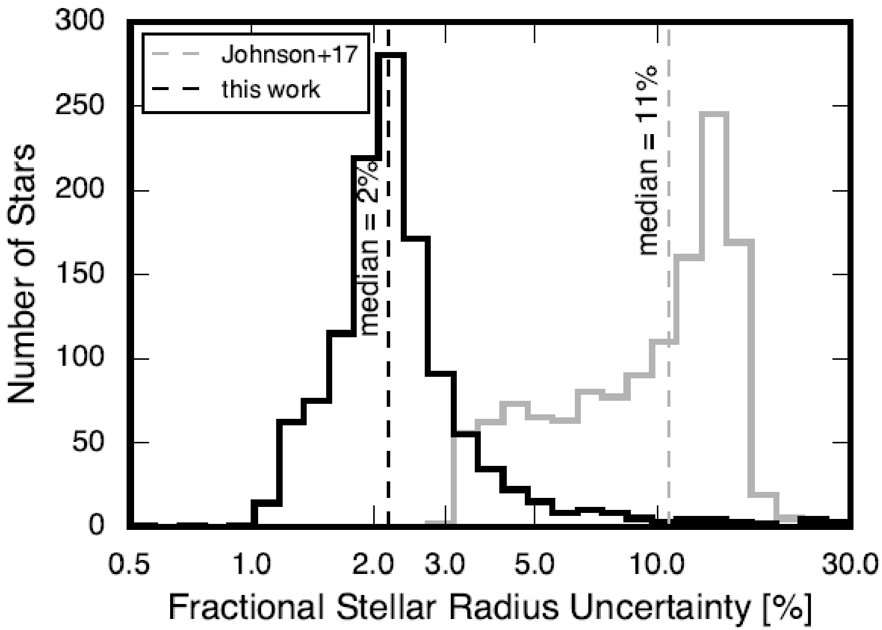
Isochrones at $Z_{\odot}$: 0.5-13.5 Gyr (PARSEC; Bressan et al. 2012)

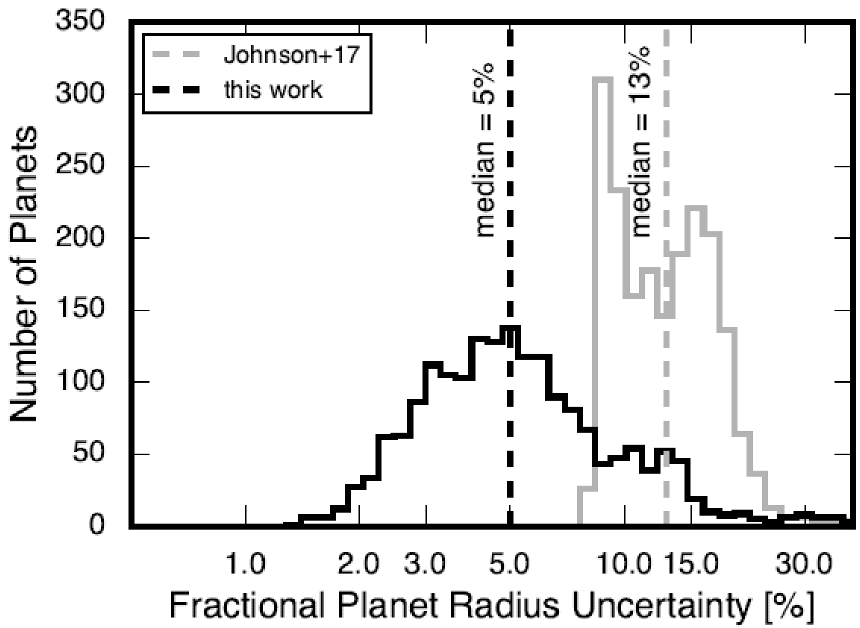
III. Spectro-photometric homogeneous analysis



- I. logg,T_{eff} from different analysis based on similar methods
- II. logg,T_{eff} from homogeneous automatic spectroscopic tool
- III. logg from Gaia (masses from PARAM), T_{eff} from automatic spectroscopic tool

....Know thy planet!





Team

- 71 INAF members (60% TI)
- 38 Associates at > 20 Institutes

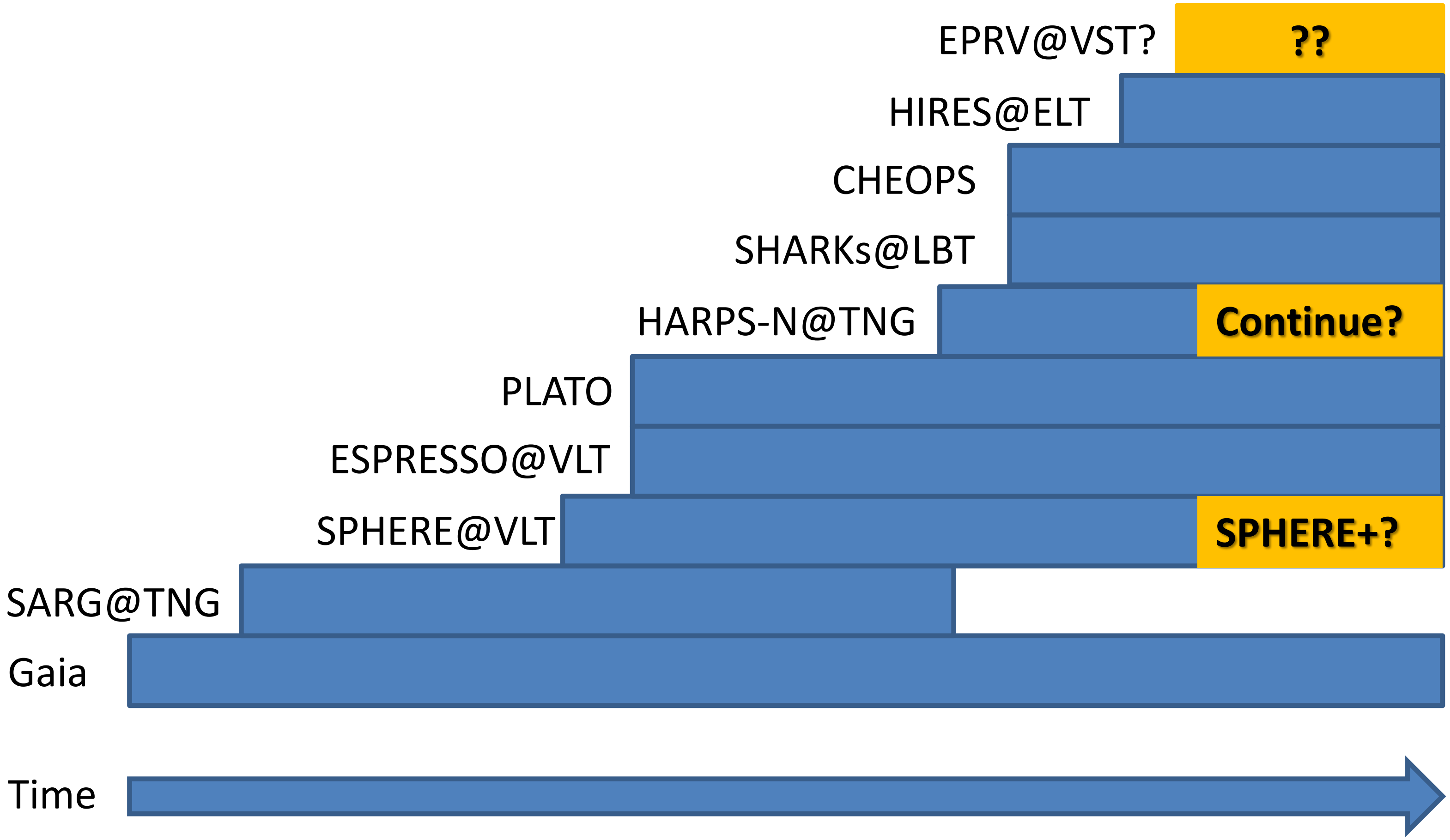
1) Over the 2021-2022-2023 period:

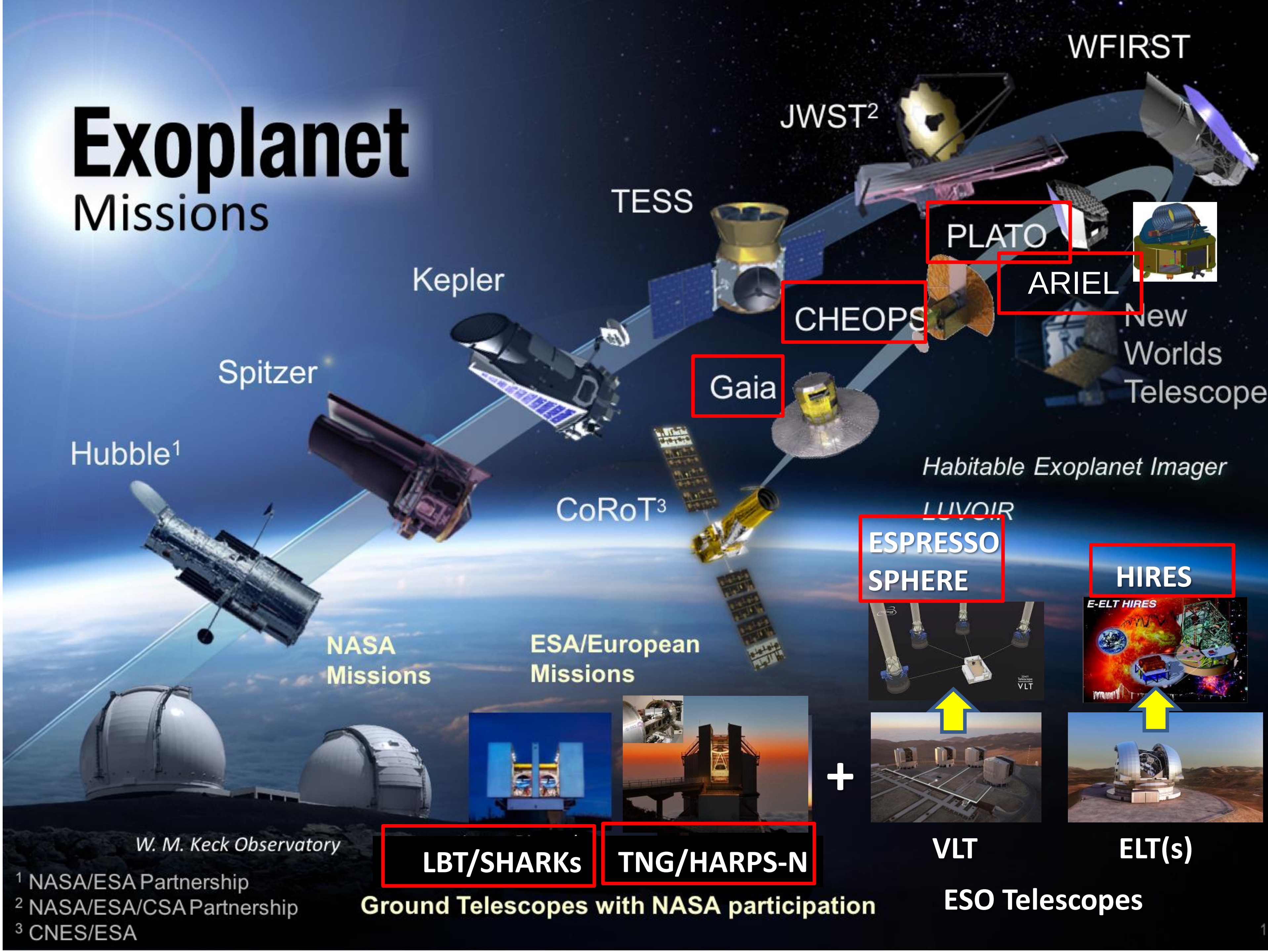
- 31 FTE [25(15 TI) INAF, 6 Associates]

2) Over the 2000-2030 period:

- 280 FTE [204(124 TI) INAF, 76 Associates]

Program Development: Facility Use




Exoplanet
Missions
WFIRST
JWST[2]
TESS
PLATO
ARIEL
CHEOPS
New Worlds Telescope
Kepler
Spitzer
Gaia
Hubble[1]
Habitable Exoplanet Imager
CoRoT[3]
LUVOIR
ESPRESSO
SPHERE
HIRES
E-ELT HIRES
NASA Missions
ESA/European Missions
VLT
+
W. M. Keck Observatory
LBT/SHARKs
TNG/HARPS-N
ELT(s)
[1] NASA/ESA Partnership
[2] NASA/ESA/CSA Partnership
[3] CNES/ESA
Ground Telescopes with NASA participation
ESO Telescopes

Connected Projects

- GaiaUniverse: M.G. Lattanzi
- PLATO: I. Pagano
- CHEOPS: I. Pagano
- TASSEL: A. Sozzetti
- EXO-DEMO: A. Sozzetti
- EPRVVST: A. Sozzetti
- EXO-FAMILIES: R. Gratton
- GAPS2: E: Covino
- HADES: L. Affer
- PLATEA: S. Desidera
- SPHERE-GTO: D. Mesa
- SPHERE+: R. Gratton
- Ecube: G. Micela (EXO-STARS)
- THE-Stellar-Path: A. Maggio (EXO-STARS)
- ERIS: A. Riccardi
- SHARK-VIS: F. Pedichini
- SHARK-NIR: M. Bergomi
- LOCNES: R. Claudi
- SLN: G. Leto
- SRT: E. Molinari
- REM: E. Molinari
- HARPS-N/GTO: A. Bonomo
- HARPNSUN: J. Maldonado
- Exo-MerCat: A. Bignamini
- EXO-SELENE: V. D'Orazi
- HIRES: A. Marconi
- NLMSTARS: J. Maldonado (EXO-STARS)
- PETS: V. Nascimbeni (EXO-STARS)

- **Ongoing (space)**
- **Ongoing (ground-based)**
- **Unfunded (ground-based)**

Scientific & Technical Aspects

The various program ramifications implement a variety of detection technique-dependent approaches including:

1) fully Bayesian frameworks for the modeling of planetary RV signals in presence of stellar correlated noise;
2) combined RVs + light-curve analysis of transiting systems, including self-consistent dynamical models of RVs and transit timing variations;
3) high-contrast imaging detection of sub-stellar companions;
4) combination of RVs with absolute and relative (imaging) astrometry.
5) determination of key planet parameters based on the precise and accurate knowledge of the fundamental properties of the host stars (age, mass, radius, chemical composition).
6) derivation of occurrence rate estimates of planets of given properties.

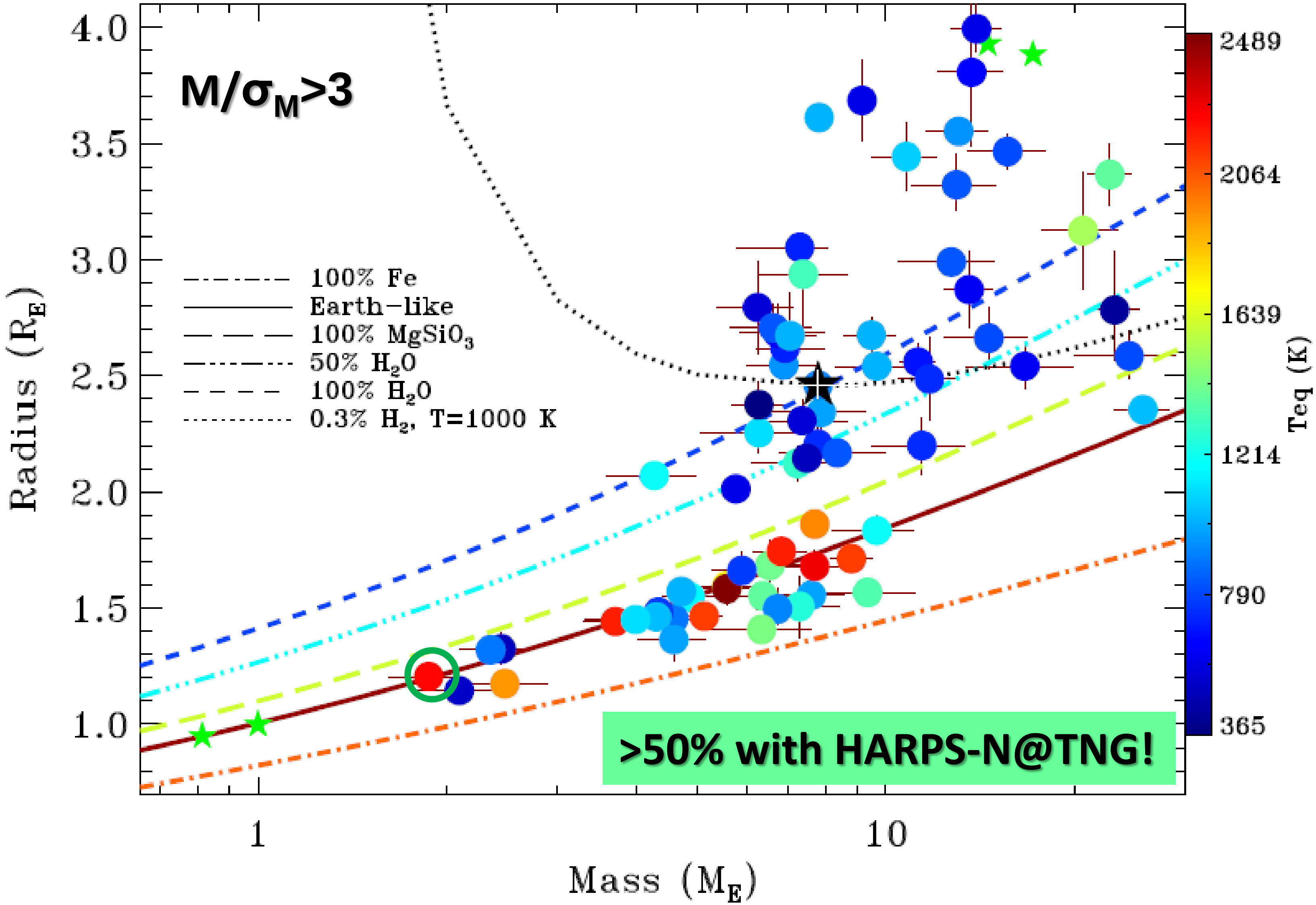
- Support facilities (star, further system characterization): SLN, REM, HARPNSUN, LOCNES, SRT

The various program ramifications also take advantage of the team's direct contributions to the design and development of ground-based instruments (e.g., LOCNES, SPHERE, SHARKs, ERIS, HIRES) and space missions (e.g., Gaia, CHEOPS, PLATO).

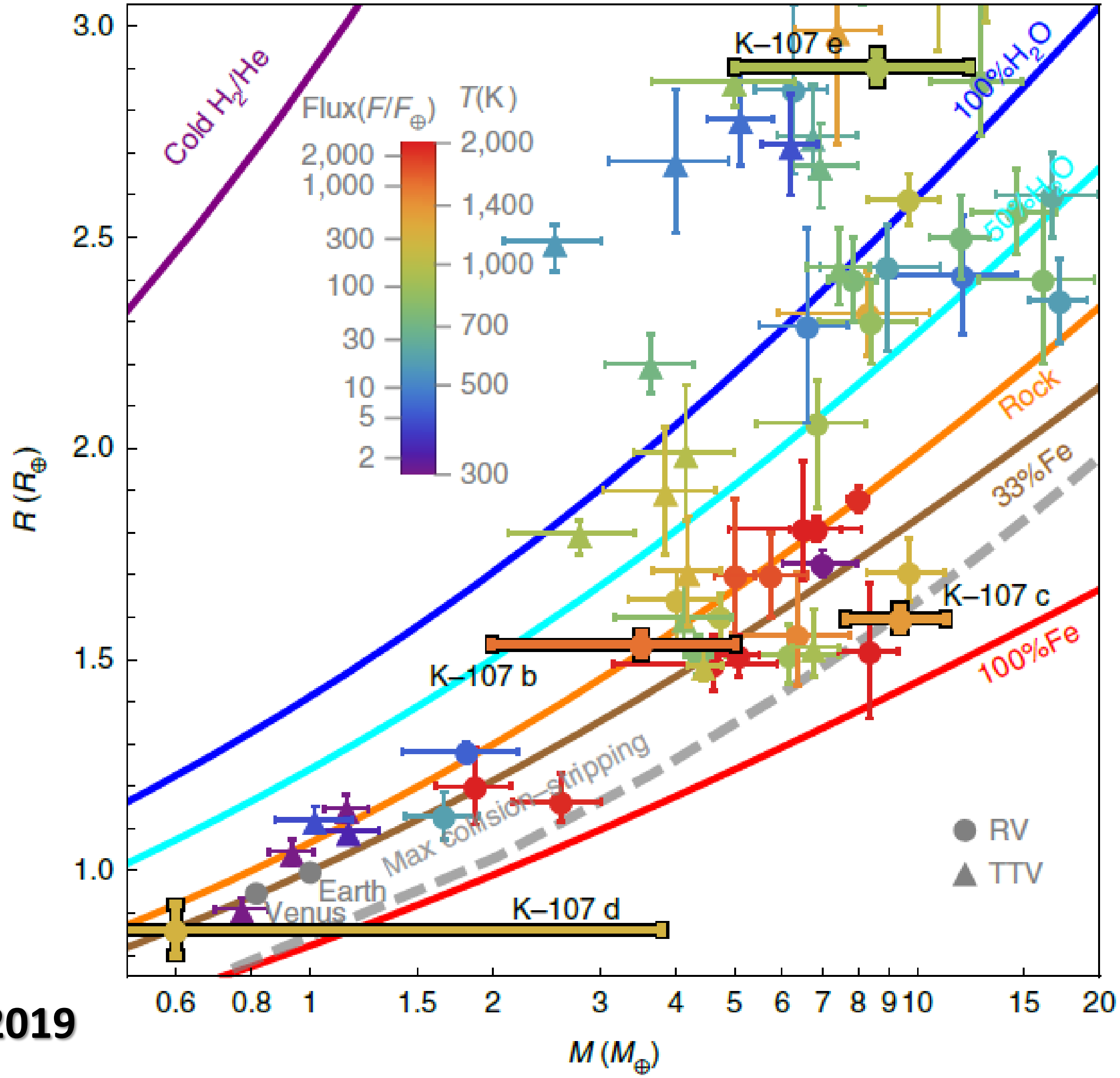
Architecture and Physical Properties of Planetary Systems

Main Research Line	Projects/Programs	Main Infrastructures
Architecture, physical properties and occurrence rates of short- and intermediate-separation planetary systems	**Funded:** GaiaUniverse, CHEOPS, PLATO, TASSEL, ESPRESSO, TESS, HADES, HARPS-N/GTO, GAPS2, LOCNES, HARPNSUN, HIRES **Proposals:** EXO-DEMO, EPRVVST	TNG, VST, SRT, TESS, CHEOPS, PLATO, Gaia, SLN, REM
Architecture, physical properties and occurrence rates of wide-separation planetary systems	**Funded:** SPHERE-GTO, SHARK-VIS, SHARK-NIR, ERIS, GaiaUniverse-0, PLATEA. **Proposals**: EXO-FAMILIES, EXO-SELENE, SPHERE+, EXO-DEMO	VLT, LBT, ESO, Gaia

M-R Relation of Small Planets



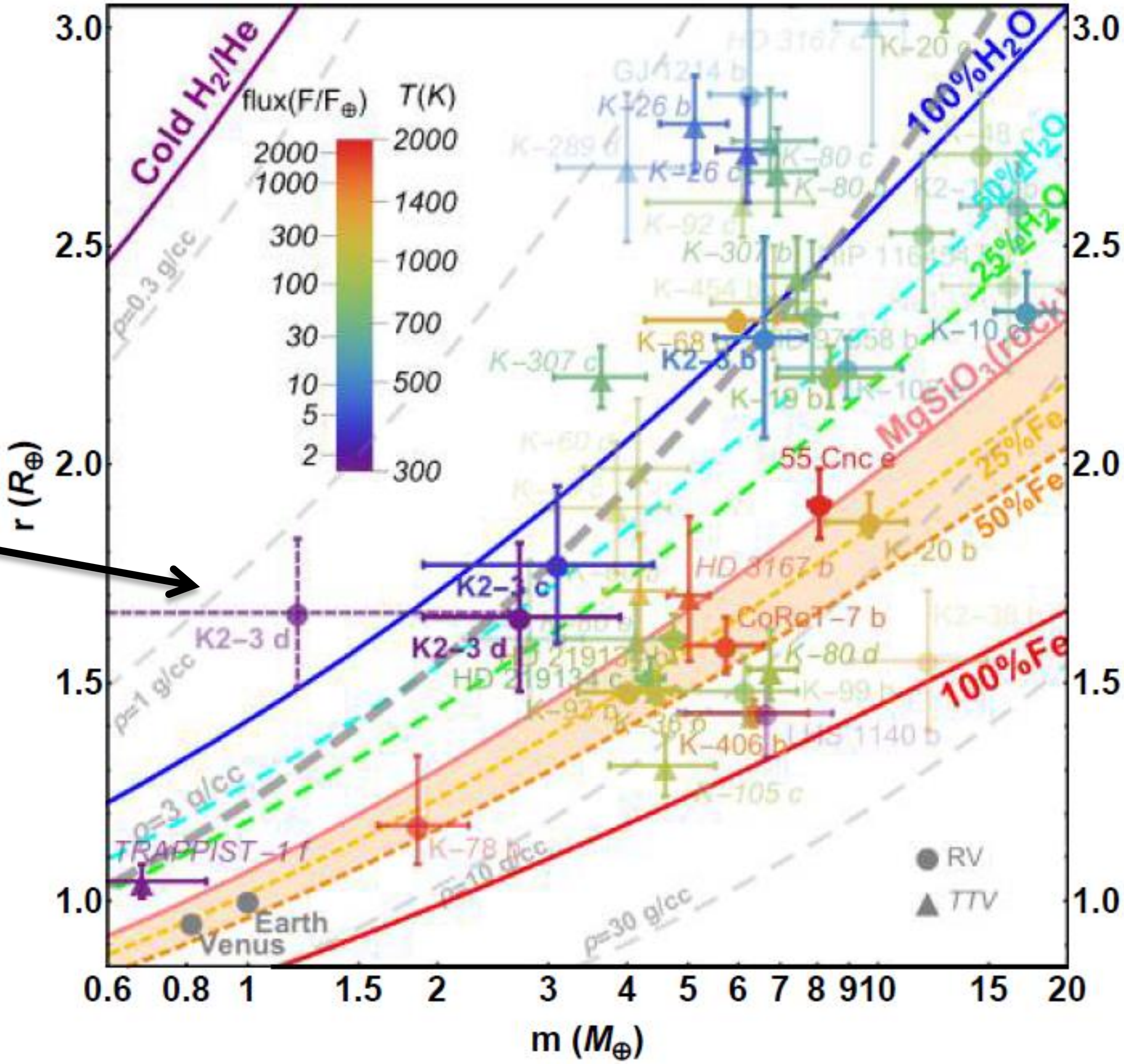
Cosmic Collisions



Bonomo et al. 2019

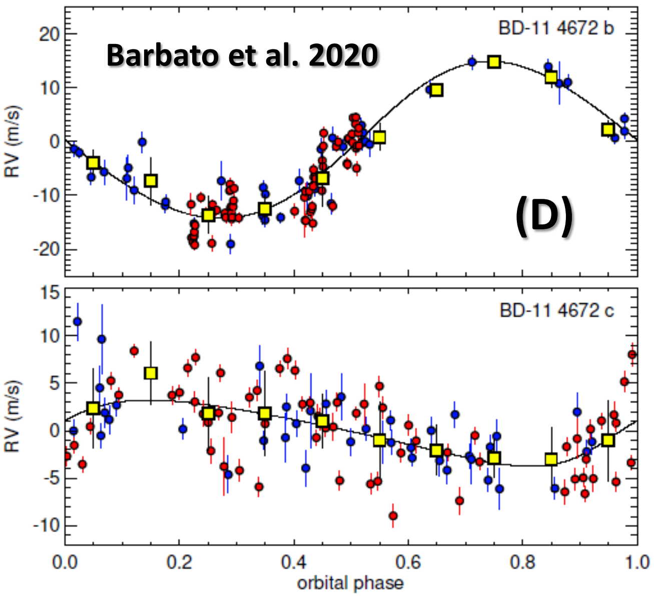
Habitable-zone Planets

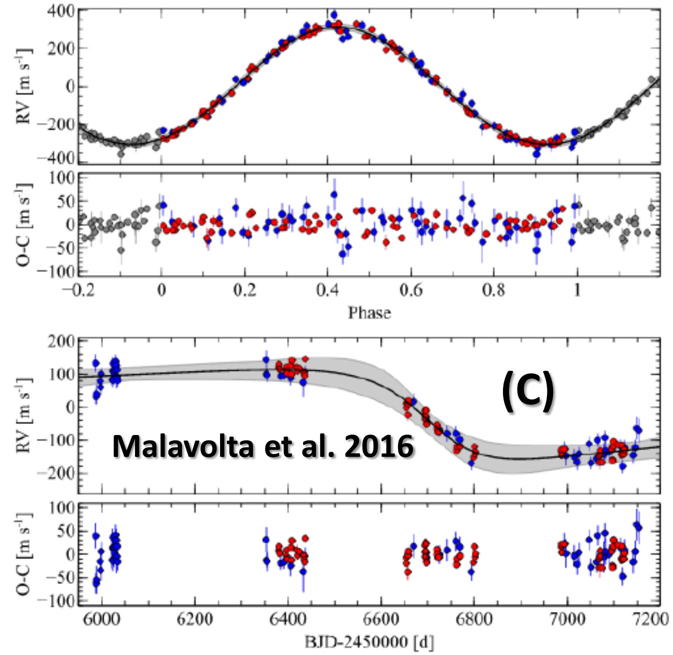
In the HZ of a M0 dwarf



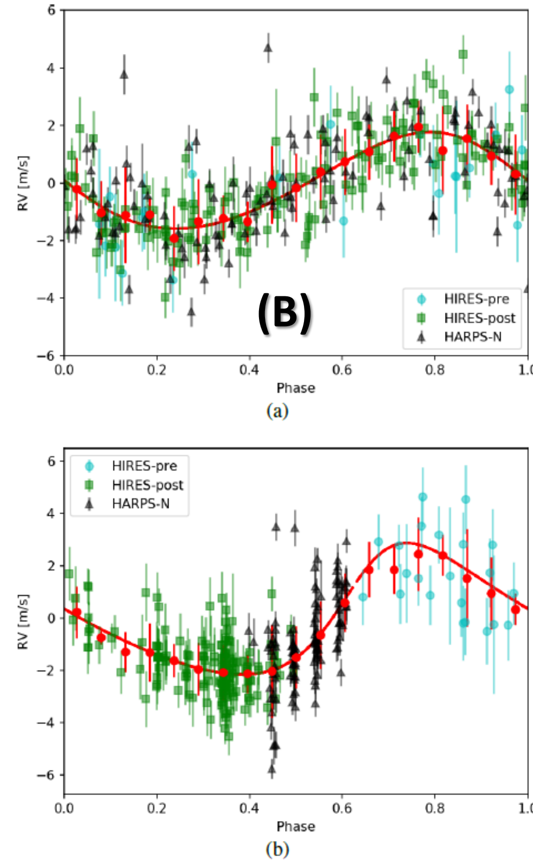
Damasso et al. A&A 2018

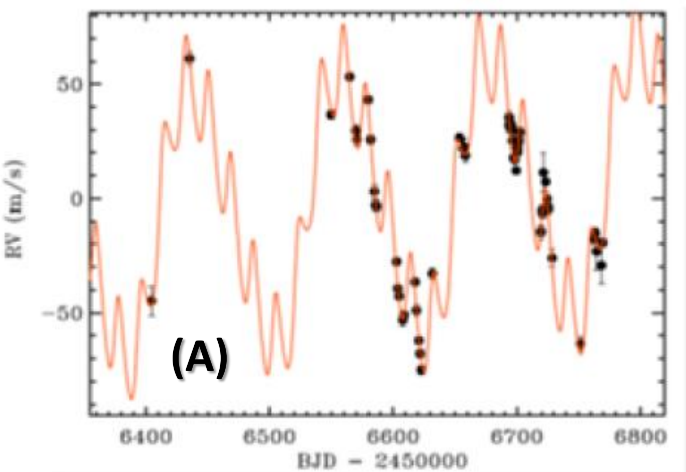
Architectures



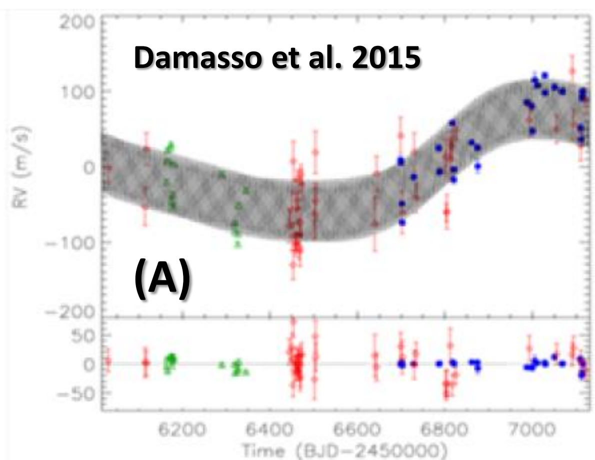


Pinamonti et al. 2018





Desidera et al. 2014



A selection of Multis:

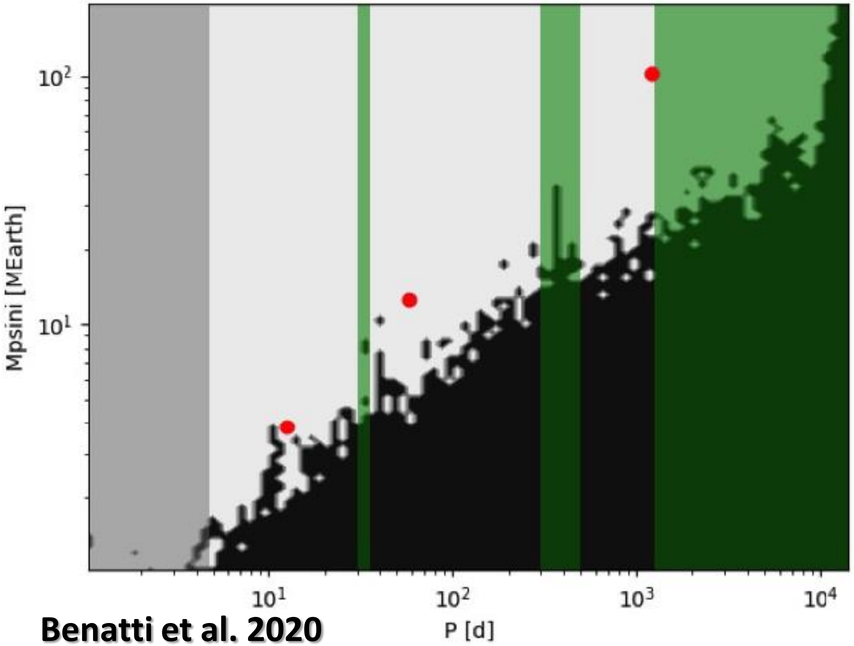
(A) In binaries

(B) around M dwarfs

(C) in open clusters

(D) around G-K dwarfs

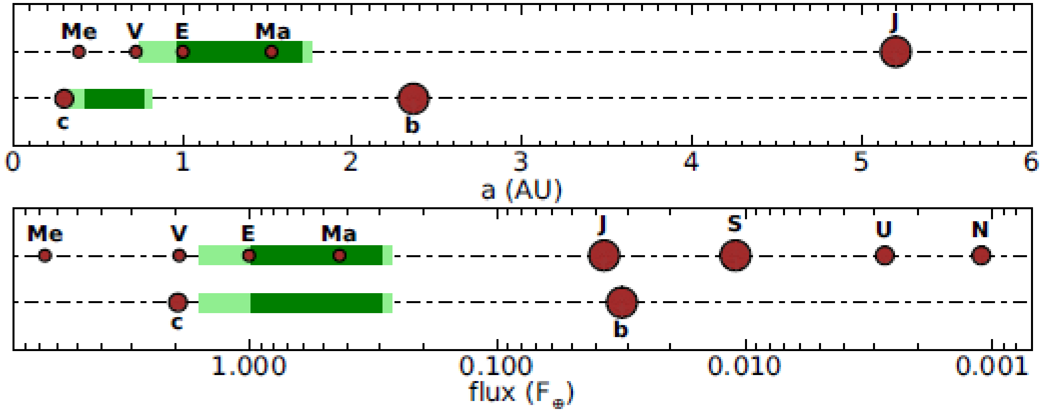
Quasi-Solar-System-types



Benatti et al. 2020

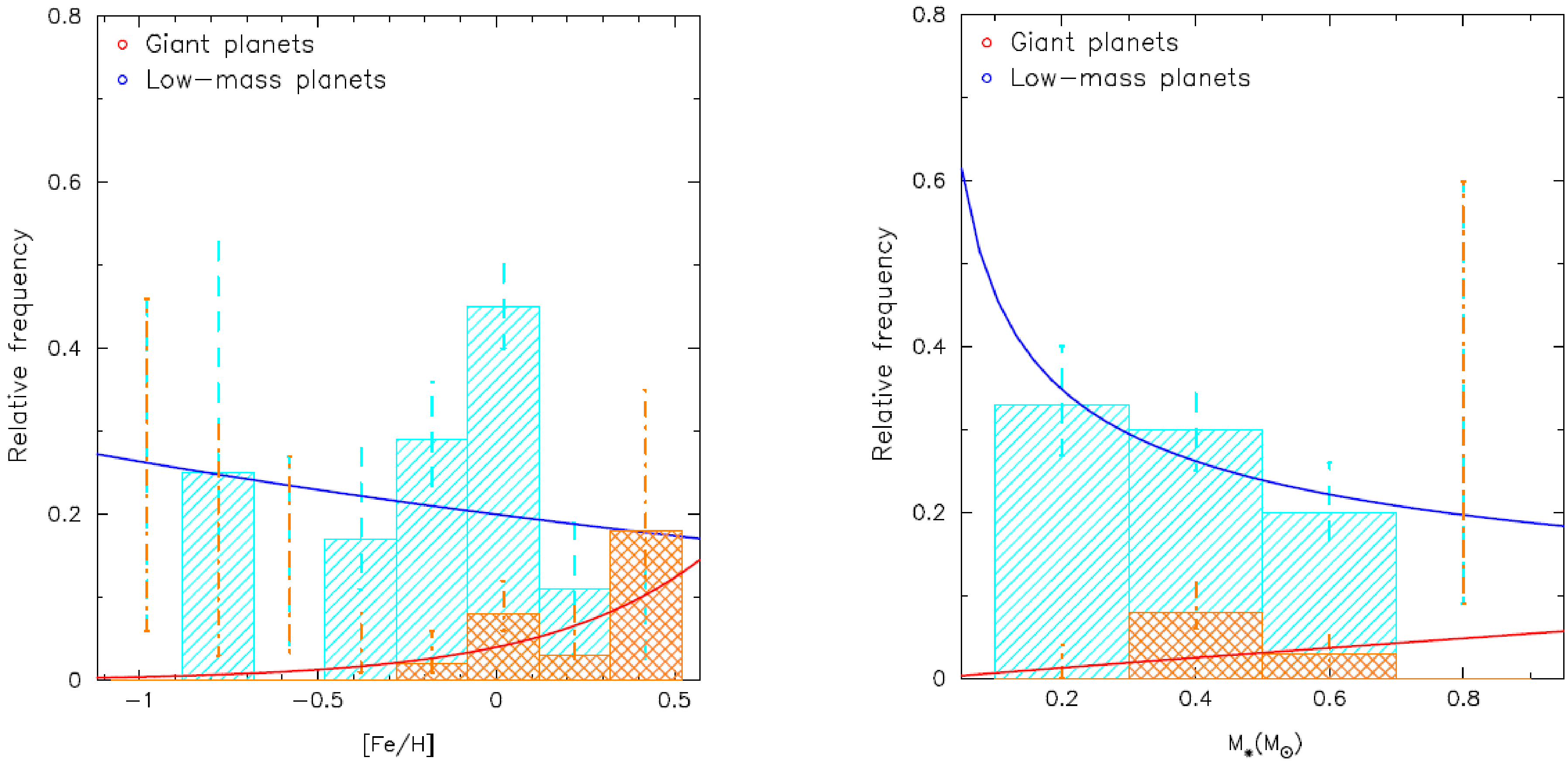
- 'Scaled' versions
- Mass hierarchy only rough

But that's where the frontier is shifting…



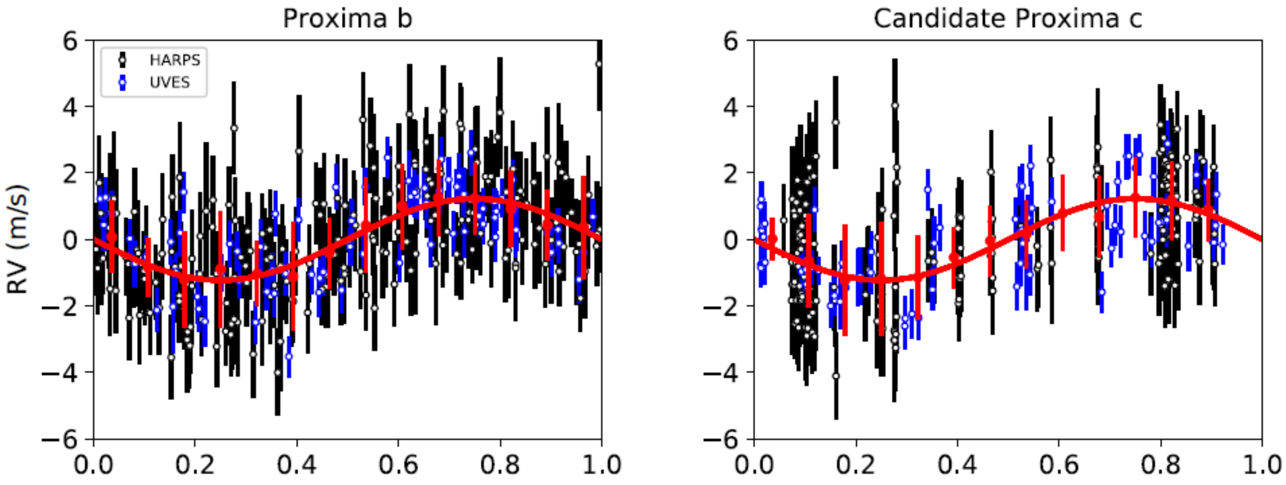
Barbato et al. 2020

Frequencies



Maldonado et al. 2020

The Proxima System



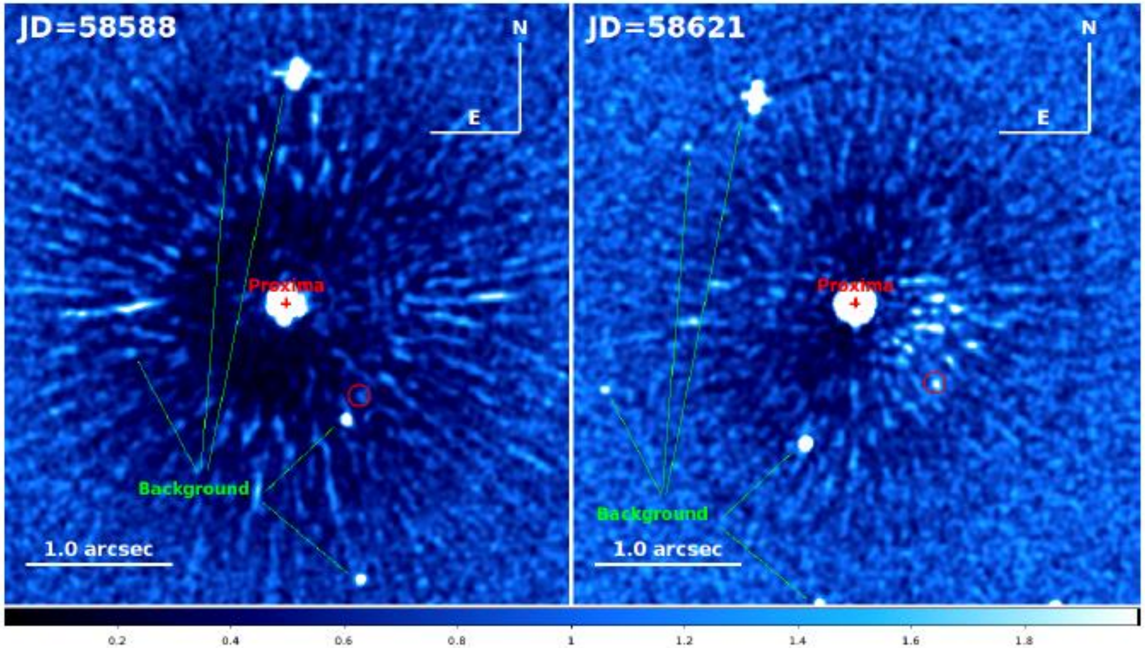
A cold super Earth @ 1.5 au

Damasso et al. 2020

Proxima c image only tentative

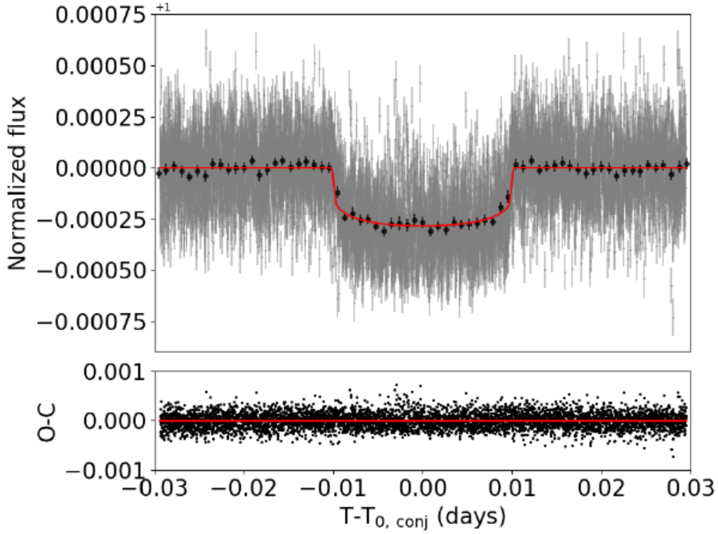
But if you know where to look…

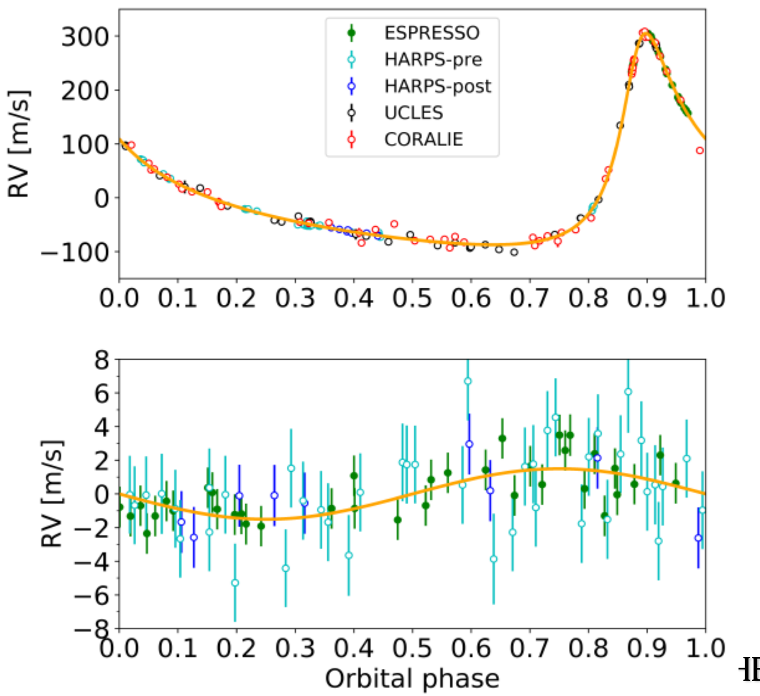
Gratton et al. 2020

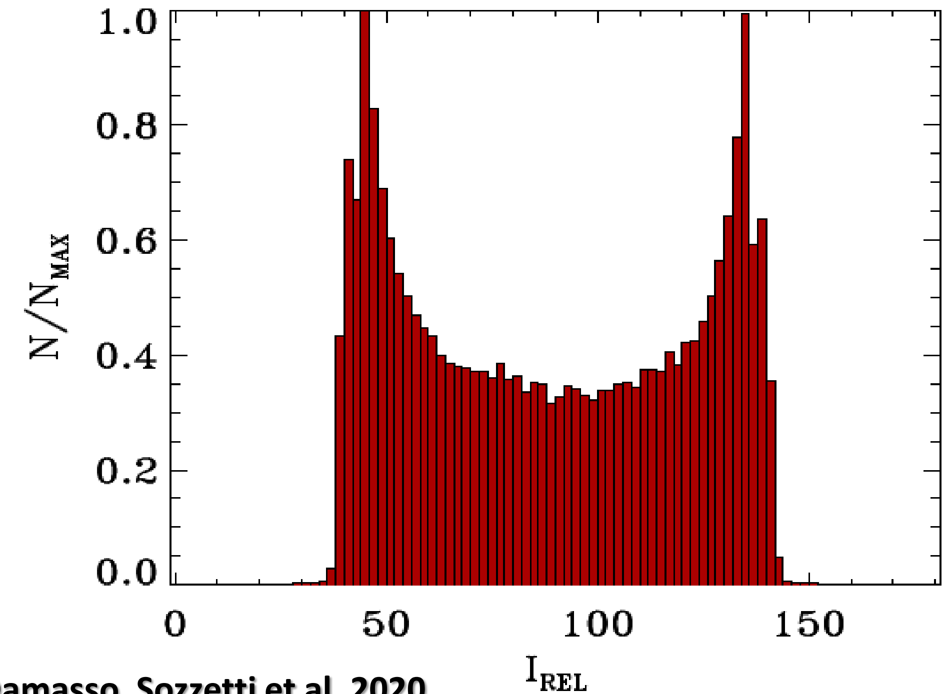


AUDIZIONE

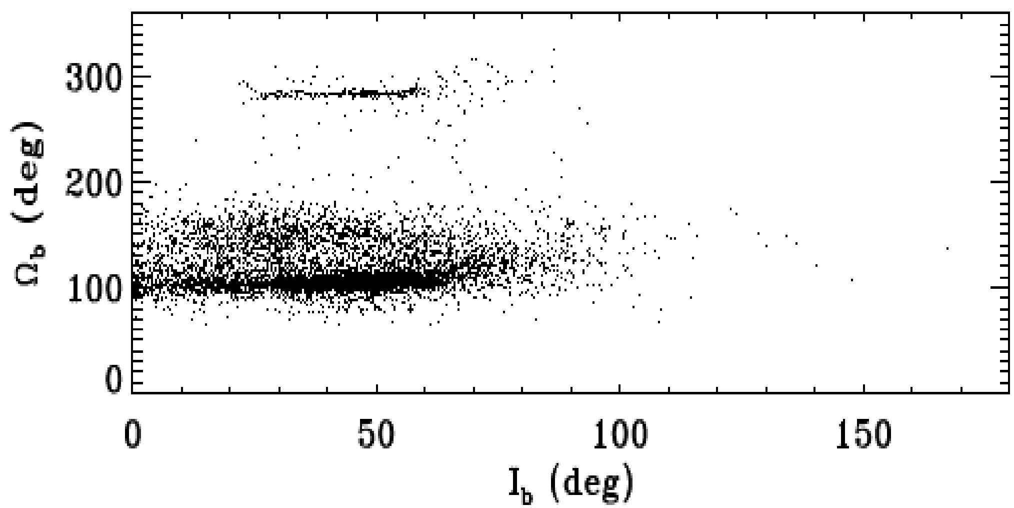
The π Mensae System







Damasso, Sozzetti et al. 2020



Communication & Outreach

- Examples of successful communication and outreach programs:

1) Over 30 PRs, radio and TV interviews stemming from the HARPS-N/GTO discoveries

2) TG2 dossier in October 2017 (end of 5-yr HARPS-N/GAPS project)

3) 25 Media INAF PRs (more than 30 on other media), blogs, a web communication channel, development of specific products for public engagement (e.g., interactive educational units) to broadcast the HARPS-N/GAPS project research outputs

Higher Education & Training

- Advanced School on Exoplanetary Science (three editions so far, two on detection techniques and demographics)
- 15 PhD theses with primary focus on architecture and physical properties of exoplanets

A research program with a natural, strong connection to INAF's third mission

Programmatics

- Increased degree of coordination of science sub-programs over the last decade

- Existing and new ground-based ramifications: positive feedback from space missions

- A two-fold path forward:

1) WITHIN THE PTA TIMEFRAME:

Capitalize on the skills and expertise developed, and successes obtained in the field thus far to further strengthen our roles within the major project Consortia we are members of (HARPS-N, ESPRESSO, CHEOPS, Gaia, PLATO, SPHERE, ERIS, SHARKs, HIRES), and prepare the exploitation of the wealth of data from future endeavors in exoplanetary science both from the ground (ESO ELT) and in space (PLATO, Ariel) in which INAF plays leading roles;

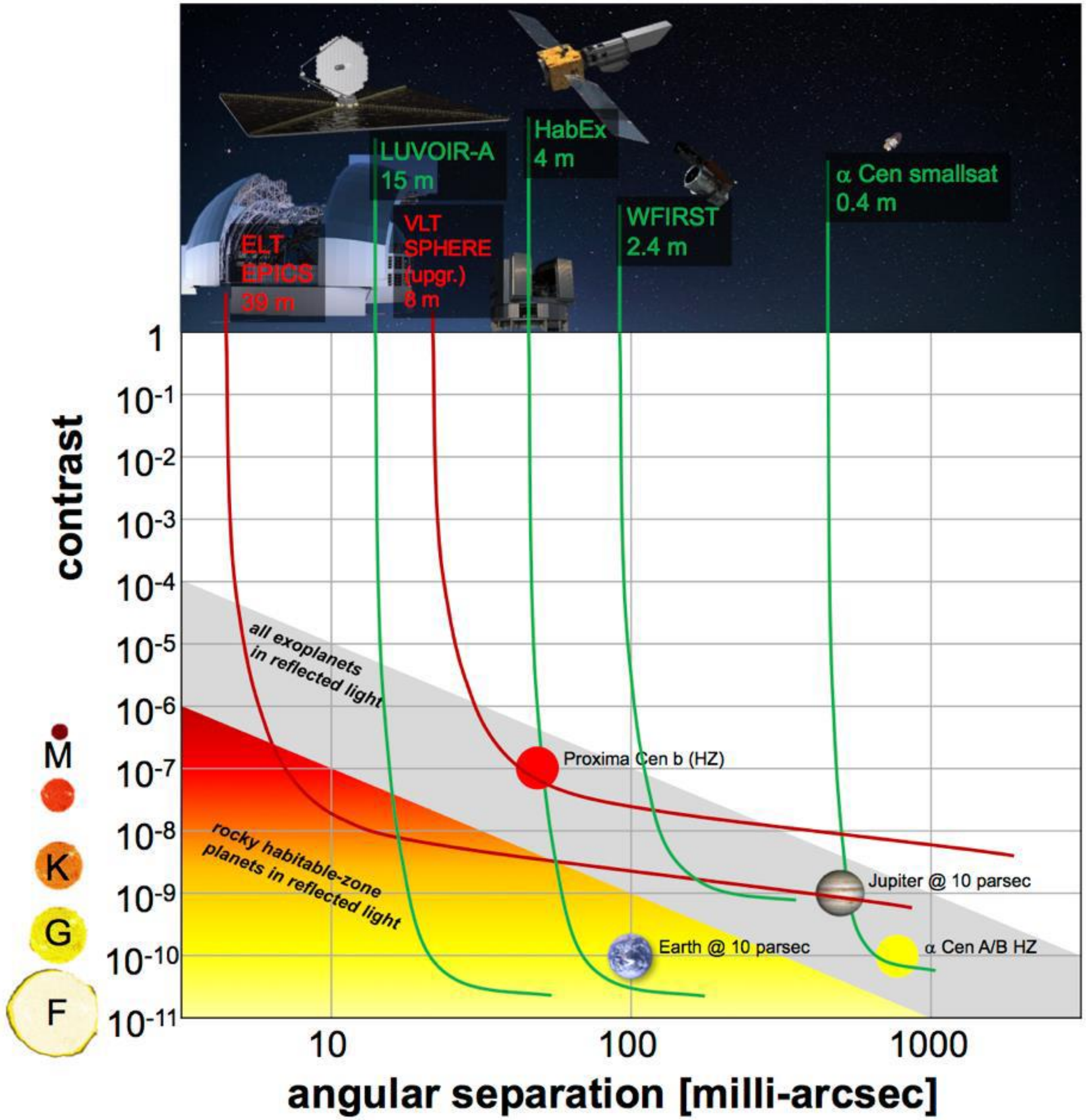
2) BEYOND THE PTA TIMEFRAME:

Exploit the know-how acquired and catch the opportunity to lead new frontier projects (e.g., EPRV@VST) that will eventually bring us ever closer to reaching the overarching scientific goal of this program, i.e. the identification of Solar-System-like planetary systems architectures around the nearest stars to the Sun, with terrestrial-mass companions in the habitable zone that would be amenable to spectroscopic characterization measurements of their atmospheres, searching for the presence of biosignature gases with future facilities from the ground, such as ELT/HIRES, and in space, such as LUVOIR and HabEx.

The Frontier

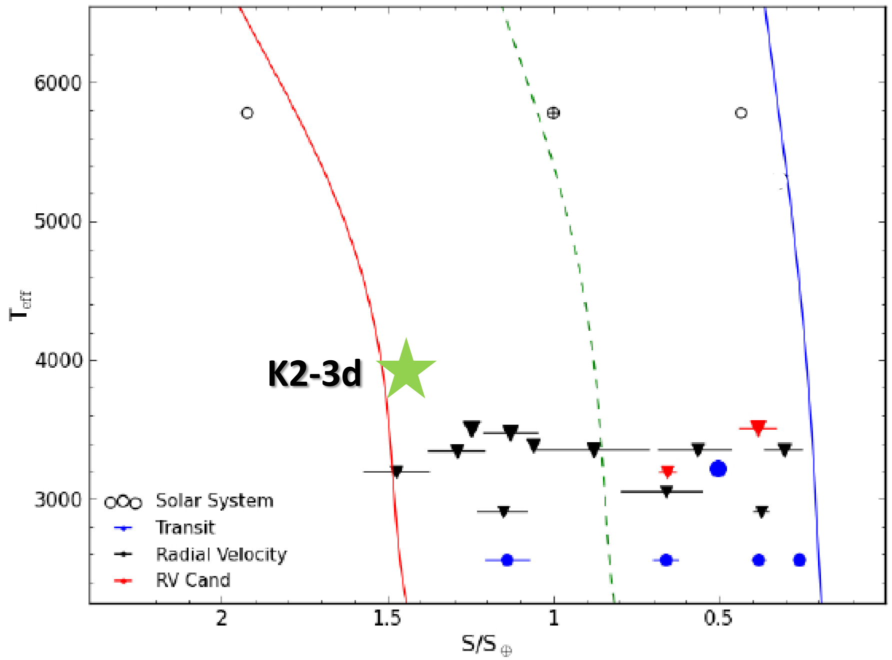
Habitability and atmospheric biosignatures of terrestrial exoplanets around the nearest stars

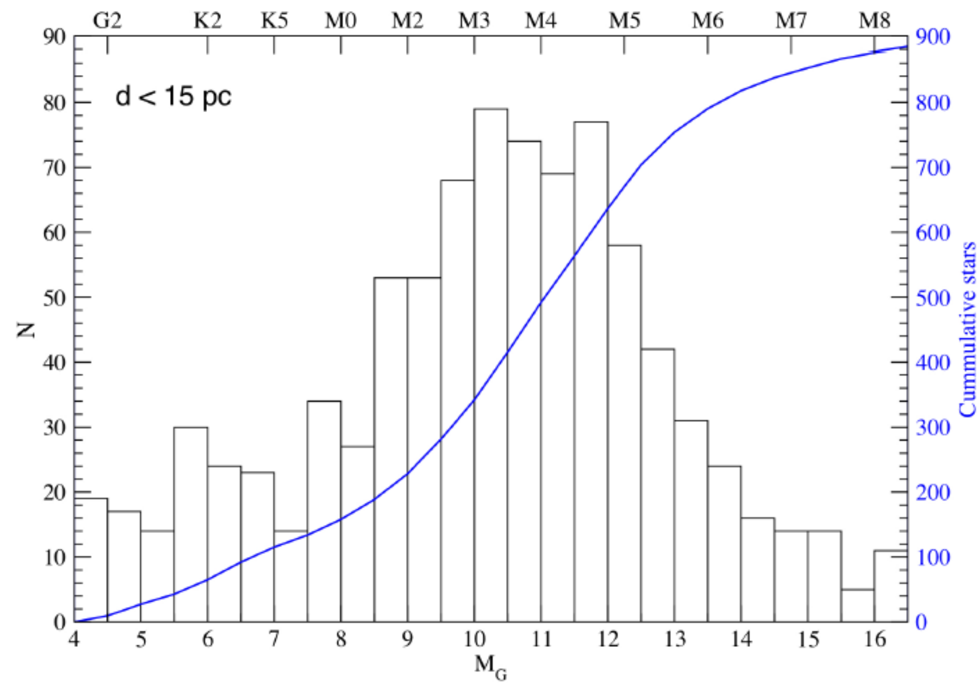
Finding the targets FIRST is <u>mandatory</u> in order to maximize science return



AUDIZION

The Opportunity





"A long-term extreme-precision RV monitoring campaign for the most nearby G-K-type stars is therefore highly recommendable" (Snellen et al. 2019, ESA Voyage 2050 WP)

Same recommendations from the ASTRONET panel on planet formation

Funding

- INAF-wide team with 20 yr of collaborative research, and >200 years of involvement in exoplanet detection and characterization programs and instrument development;
- Many important roles in the existing, upcoming, and planned planet detection programs.
- 100s of publications in high-impact factor Journals

- The achievements have been possible due to:

a) Strategic choices made by INAF, such as joining the HARPS-N Consortium that brought the state-of-the-art spectrograph for high-precision RVs at the TNG;

b) A series of successful bids for significant injection of funding resources in our research lines competitively obtained both at the national (Progetti Premiali WOW (PI: GMi) & FRONTIERA (PI: IPa) 2013-2018, PRIN INAF 2008 (PI: NLa), 2010 (PI: SDe), 2019 (PI: SDe), ASI-INAF (PI: ASo) 2018), and European level (FP7-SPACE ETAEARTH (PI: ASo) 2013-2017);

c) The ability to attract and prepare bright students and young researchers to exploit the wealth of high-quality data, that has further materialized in a number (4) of permanent positions exoplanet research at INAF institutes over the last decade.

Total funding until 2020: 3.6 M€ (2.7 M€ for ground-based programs)

Critical Issues

1) **SCIENTIFIC:**

- Improved (institutional) coordination across projects desirable as more programs come online
- Expertise to be acquired/developed for more complex multi-technique analyses
- Expertise to be acquired/developed for multi-technique analyses with large datasets
- HTC/MTC might be needed in the short/medium term

2) **STRATEGIC:**

- Ratio of fixed-term to permanent FTEs (0.35) still too high
- Few junior permanent staff with leading roles
- Continuity (and increase) of leading roles requires investiments
- Existing and planned ground-based projects under-funded: only 40% of minimum required funding is certain in the 2021-2022-2023 timeframe [15 ‘Potential’ FTEs]
- INAF support critical for continued exploitation of cutting-edge instruments presently at INAF-owned facilities (e.g., renewal of HARPS-N agreement at TNG), and highly desirable for future plans of development at other INAF-owned facilities (EPRV@VST)