Exoplanets in the Gaia era : **Searching nearby exoplanets for direct imaging & more**

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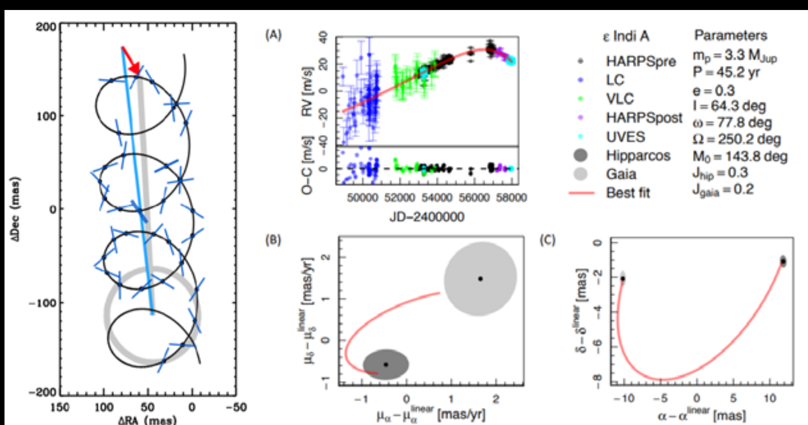
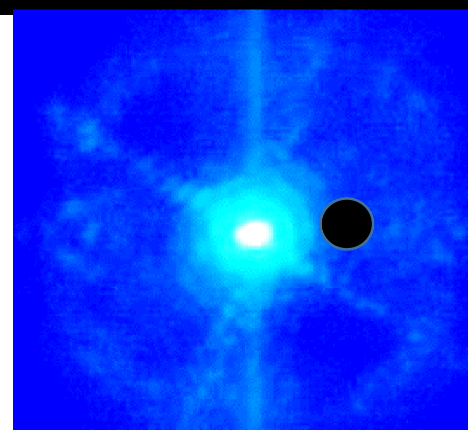
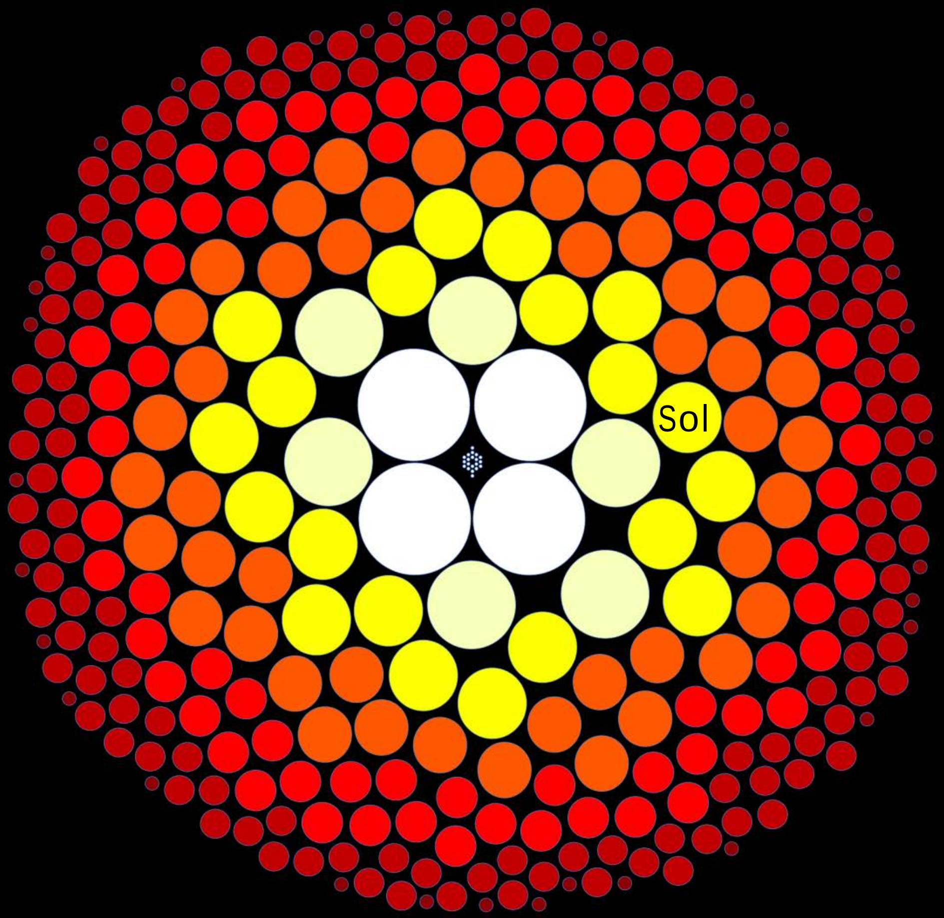




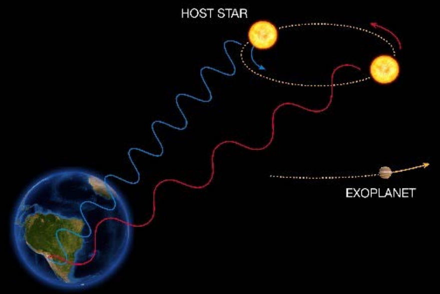
Nearest stars

10 pc sample

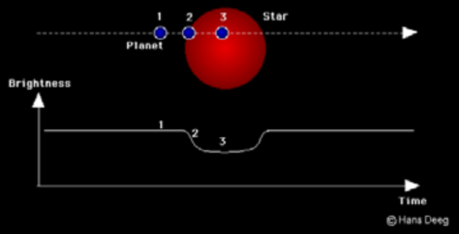


Credits : Todd Henry, RECONS group
www.recons.org

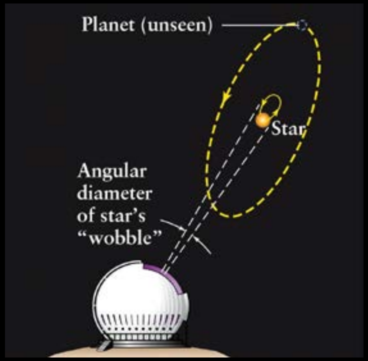
How we find exoplanets?



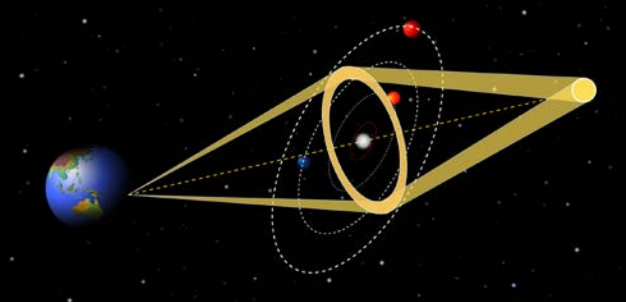
Radial velocity



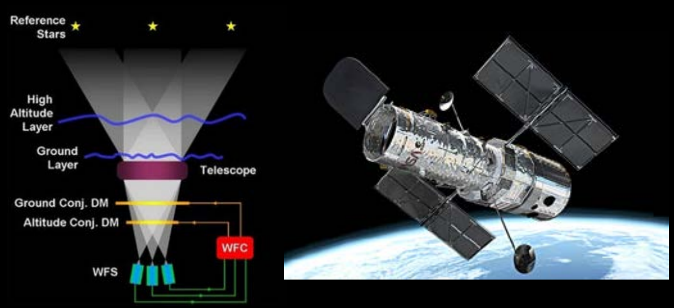
Transits



Astrometry

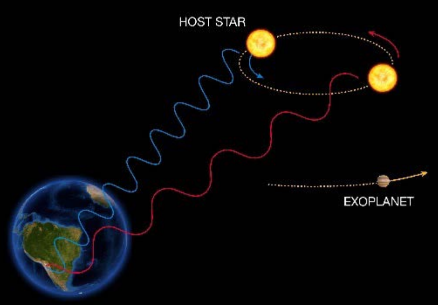


Microlensing

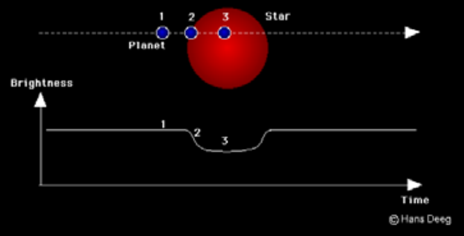


Direct imaging

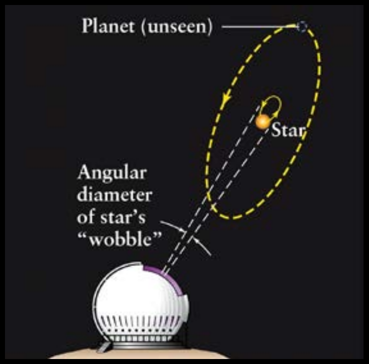
How we find exoplanets?



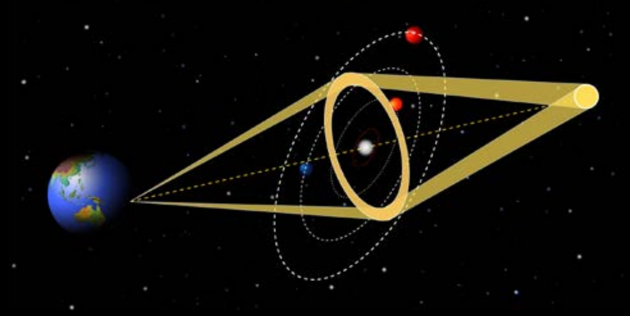
Radial velocity



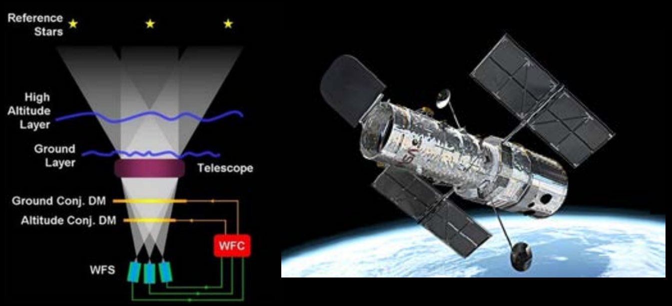
Transits



Astrometry

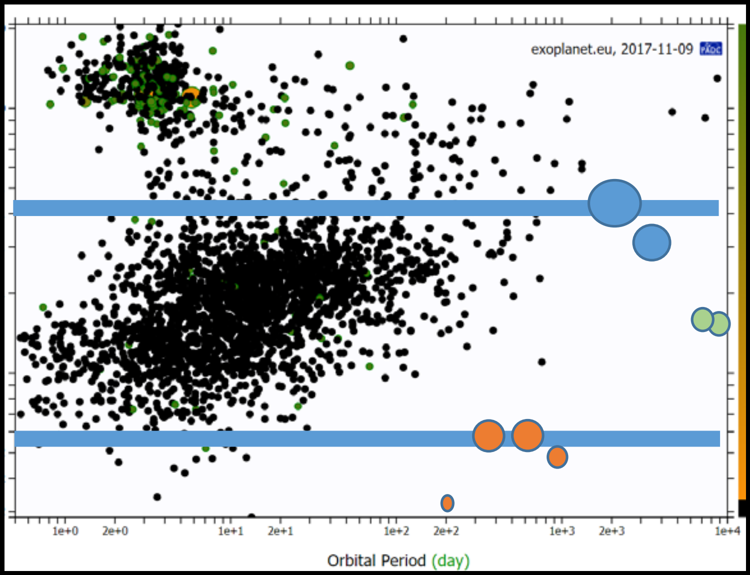


Microlensing

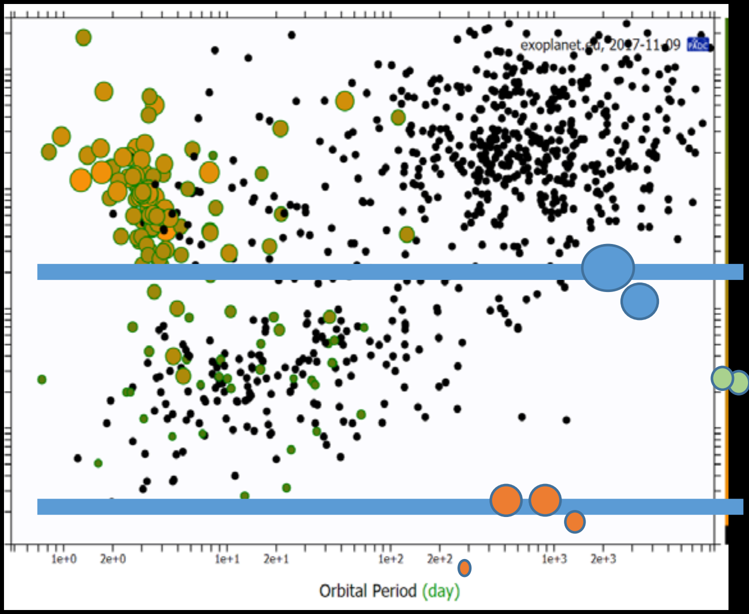


Direct imaging

The exoplanet zoo today

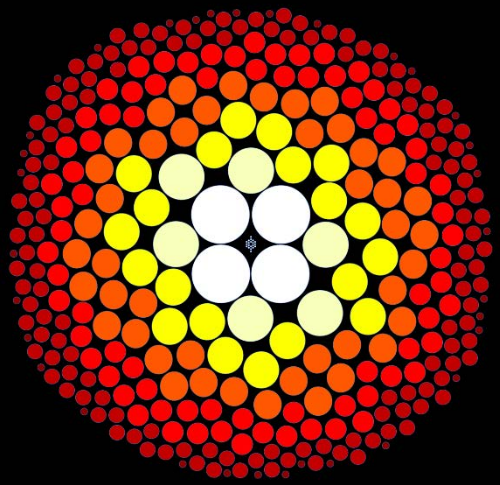


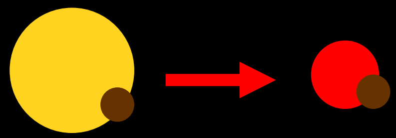
Transit method
Radius

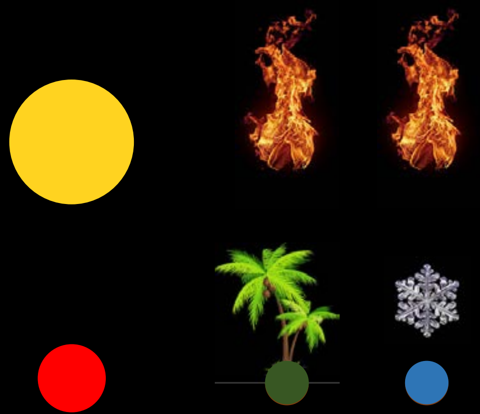


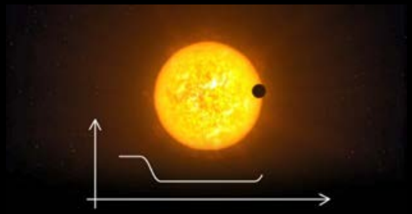
Radial velocity method
Mass

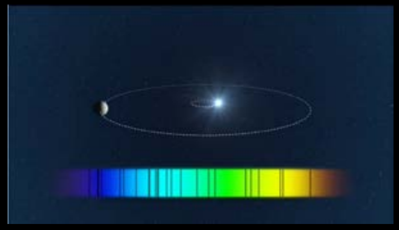
The red dwarf advantage











The 5pc sample

1 A 1 F 3 G 7 K 46 M 6 BD 5 wd

#	Name	ID		Sp.type	Radius	Teff	L/L_{Sun}	Center HZ [AU]	Distance [pc]	$Mass/M_{Sun}$
0	**Sol**	**Sun**		**G2.0V**	**1.00**	**5800**	**1.000000**	1.225	**0.000**	**1.00**
1	Proxima Centauri	GJ 551	C	M5.5V	0.17	2700	0.001328	0.046	1.301	0.11
1	Alpha Centauri A	GJ 559	A	G2.0V	0.88	6700	1.411351	1.491	1.339	1.14
	Alpha Centauri B		B	K0.0V	0.77	5400	0.456550	0.848	1.339	0.92
2	Barnard's Star	GJ 699		M4.0V	0.20	3100	0.003245	0.072	1.833	0.16
3	Luhmann 16 A	WISE 1049		L7.5V	0.05	1350	0.000006	0.003	1.998	0.05
	Luhmann 16 B			T0.5	0.04	1250	0.000003	0.002	1.998	0.05
4	Wolf 359	GJ 406		M6.0V	0.16	2500	0.000919	0.038	2.386	0.09
5	Lalande 21185	GJ 411		M2.0V	0.34	3700	0.019190	0.174	2.543	0.46
6	Sirius	GJ 244	A	A1.0V	1.65	10000	24.252863	6.181	2.632	1.99
	Sirius B		B	WD/DA2	0.01	20000	0.014340	0.002	2.632	1.00
7	BL Ceti	GJ 65	A	M5.5V	0.25	2600	0.002519	0.063	2.674	0.11
	UV Ceti		B	M6.0V	0.23	2700	0.002411	0.062	2.674	0.10
8	Ross 154	GJ 729		M3.5V	0.21	3100	0.003791	0.077	2.965	0.17
8	Ross 248	GJ 905		M5.5V	0.22	2700	0.002222	0.059	3.161	0.12
9	epsilon Eridani	GJ 144		K2.0V	0.63	5400	0.302474	0.690	3.213	0.85
10	Lacaille 9352	GJ 887		M1.5V	0.41	3800	0.032031	0.225	3.278	0.53
11	Ross 128	GJ 447		M4.0V	0.21	3000	0.003294	0.072	3.354	0.16
12	EZ Aquarii A	GJ 886	A	M5V	0.16	3000	0.001858		3.454	
	EZ Aquarii C		C	M6V	0.15	2700	0.001072		3.454	
	EZ Aquarii B		B	M5V	0.22	2700	0.002202	0.059	3.448	0.08
13	61 Cygni A	GJ 820	A	K5.0V	0.71	4000	0.115336	0.427	3.497	0.70
	61 Cygni B		B	K7.0V	0.53	4300	0.086071	0.369	3.497	0.63
14	Procyon	GJ 280	A	F5.0IV-V	1.91	6700	6.561093	3.215	3.509	1.57
	Procyon B		B	WD/DQZ					3.507	0.50
15	LHS 58	GJ 725	A	M3.0V	0.34	3400	0.014173	0.150	3.521	0.35
	LHS 59		B	M3.5V	0.28	3300	0.008038	0.113	3.521	0.26
16	GX Andromedae	GJ 15	A	M1.5V	0.32	3800	0.019497	0.176	3.571	0.49
	GQ Andromedae		B	M3.5V	0.20	3200	0.003647	0.076	3.571	0.16
17	Epsilon Indi A	GJ 845	A	K5.0V	0.61	4900	0.190995	0.549	3.623	0.77
	Epsilon Indi B		B	T1.0V	0.08	1300	0.000016	0.005	3.623	0.07
	Epsilon Indi C		C	T6.0V	0.08	900	0.000004	0.002	3.623	0.05
18	DX Cancri	GJ 1111		M6.0V	0.16	2400	0.000780	0.035	3.626	0.09
19	Tau Ceti	GJ 71		G8.0V	0.70	5700	0.463582	0.855	3.650	0.92
20	GJ 1061	GJ 1061		M5.0V	0.18	2700	0.001509	0.049	3.676	0.11

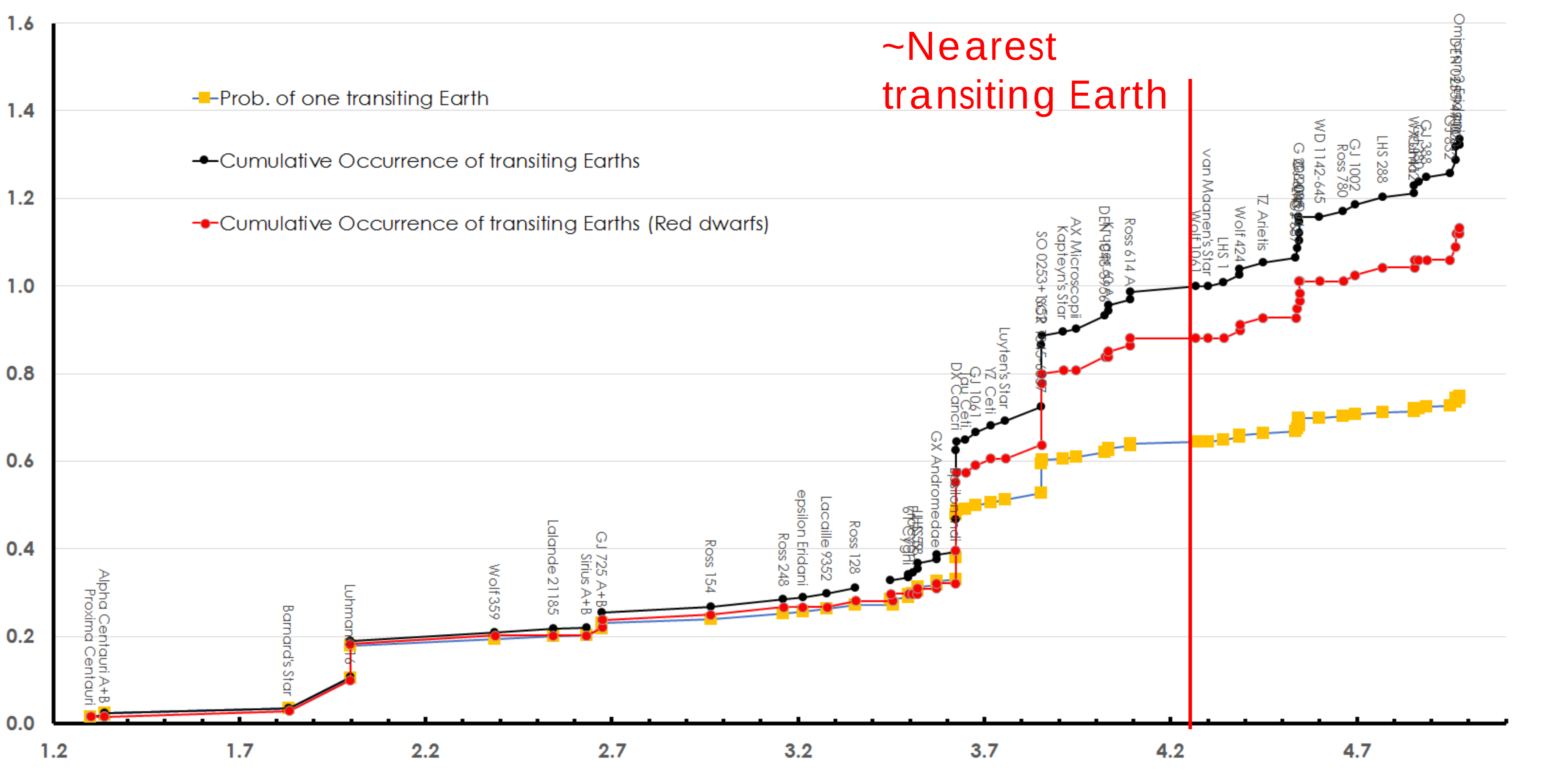
#	Name	ID		Sp.type	Radius	Teff	L/L_{Sun}	Center HZ [AU]	Distance [pc]	$Mass/M_{Sun}$
21	YZ Ceti	GJ 54.1		M4.5V	0.18	2900	0.002077	0.057	3.716	0.13
22	Luyten's Star	GJ 273		M3.5V	0.32	3200	0.009384	0.121	3.756	0.26
23	SCR 1845-6357 A	SCR 1845	A	M8.5V	0.13	2000	0.000239	0.019	3.854	0.07
	SCR 1845-6357 B	SCR 1845	B	T5V	0.08	950	0.000005	0.003	3.854	0.03
24	SO 0253+1652	SO 0253		M7.0V	0.16	2400	0.000724	0.034	3.855	0.08
25	Kapteyn's Star	GJ 191		M1.5VI	0.24	3800	0.010764	0.130	3.911	0.39
26	AX Microscopii	GJ 825		M0.0V	0.52	4100	0.067432	0.326	3.946	0.60
27	DEN 1048-3956	DEN 1048		M8.5V	0.13	2000	0.000257	0.020	4.024	0.07
28	Kruger 60 A	GJ 860	A	M3.0V	0.33	3300	0.011435	0.134	4.032	0.28
	Kruger 60 B		B	M4.0V	0.19	3200	0.003537	0.075	4.032	0.16
29	Ross 614 A	GJ 234	A	M4.0V	0.29	3000	0.005980	0.097	4.092	0.17
	Ross 614 B		B	M5.5V	0.16	2700	0.001144	0.043	4.092	0.10
30	Wolf 1061	GJ 628		M3.0V	0.32	3200	0.009684	0.124	4.267	0.26
31	van Maanen's Star	GJ 35		WD/DZ7.5	0.01					0.50
32	LHS 1	GJ 1		M1.5V	0.35	3700	0.020459	0.179	4.342	0.48
33	Wolf 424	GJ 473	A	M5.0V	0.21	2700	0.002141	0.058	4.386	0.12
	Wolf 424		B	M7.0V	0.18	2900	0.001986	0.056	4.386	0.12
34	TZ Arietis	GJ 83.1		M4.5V	0.20	2900	0.002410	0.062	4.448	0.14
35	GJ 687	GJ 687		M3.0V	0.41	3400	0.019742	0.176	4.536	0.39
36	LHS 292	LHS 292		M6.5V	0.15	2400	0.000634	0.032	4.539	0.08
37	G 208-044	GJ 1245	A	M5.5V	0.19	2700	0.001793	0.053	4.545	0.11
			B	M6.0V	0.15	2700	0.001072	0.041	4.545	0.07
	G 208-045		C	M7.0V	0.17	2100	0.000510	0.029	4.545	0.10
38	GJ 674	GJ 674		M2.5V	0.36	3400	0.015094	0.154	4.543	0.36
39	WD 1142-645	GJ440		WD/DQ D						0.50
40	Ross 780	GJ 876		M4.0V	0.39	3100	0.012589	0.141	4.663	0.27
41	GJ 1002	GJ 1002		M5.0V	0.14	2900	0.001278	0.045	4.695	0.11
42	LHS 288	LHS 288		M5.5V	0.15	2700	0.001072	0.041	4.769	0.11
43	GJ 412	GJ 412	A	M1.0V	0.35	3700	0.020931	0.182	4.854	0.48
	WX Uma		B	M5.5V	0.15	2600	0.000946	0.039	4.854	0.10
44	GJ 380	GJ 380		K7.0V	0.65	4100	0.106345	0.410	4.865	0.64
45	GJ 388	GJ 388		M3.0V	0.45	3300	0.021715	0.185	4.888	0.39
46	GJ 832	GJ 832		M1.5V	0.42	3600	0.026935	0.206	4.950	0.50
47	LP 944-020	LP 944-020		M9.0V	0.09	2000	0.000119	0.014	4.965	0.07
48	DEN 0255-4700	DEN 0255		L7.5V	0.09	1300	0.000021		4.966	0.05
49	Omicron 2 Eridani	GJ 166	A	K0.5V	0.74	5200	0.354013	0.747	4.975	0.89
			B	WD/DA4					4.975	0.50
			C	M4.5V	0.25	3200	0.005827	0.096	4.975	

RECONS : list of nearest stars
+ a few more

1 Earth-size planet in the HZ of the star

The 5 pc sample by transits

Chance of one transiting : ~75%
Expected number ~1.2

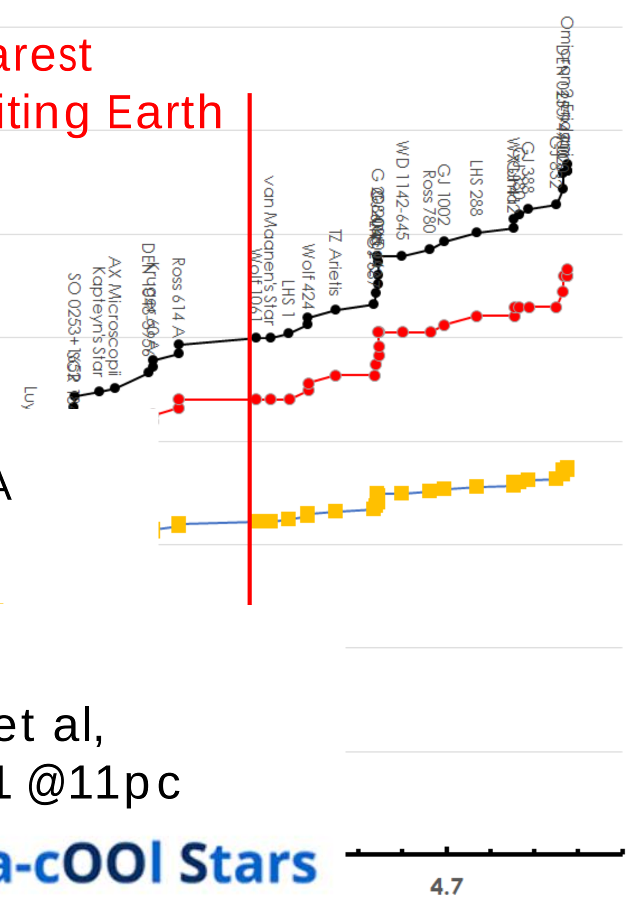


1 Earth-size planet in the HZ of the star

The 5 pc sample by transits

Chance of one transiting : ~75%
Expected number : 1.1 & 1.3

~Nearest transiting Earth



TESS Transiting Exoplanet Survey Satellite

THE MEARTH PROJECT
WELCOME SCIENCE TEAM TELESCOPES DISCOVERIES DATA

Charbonneau et al. CfA
LHS 1140b @11pc

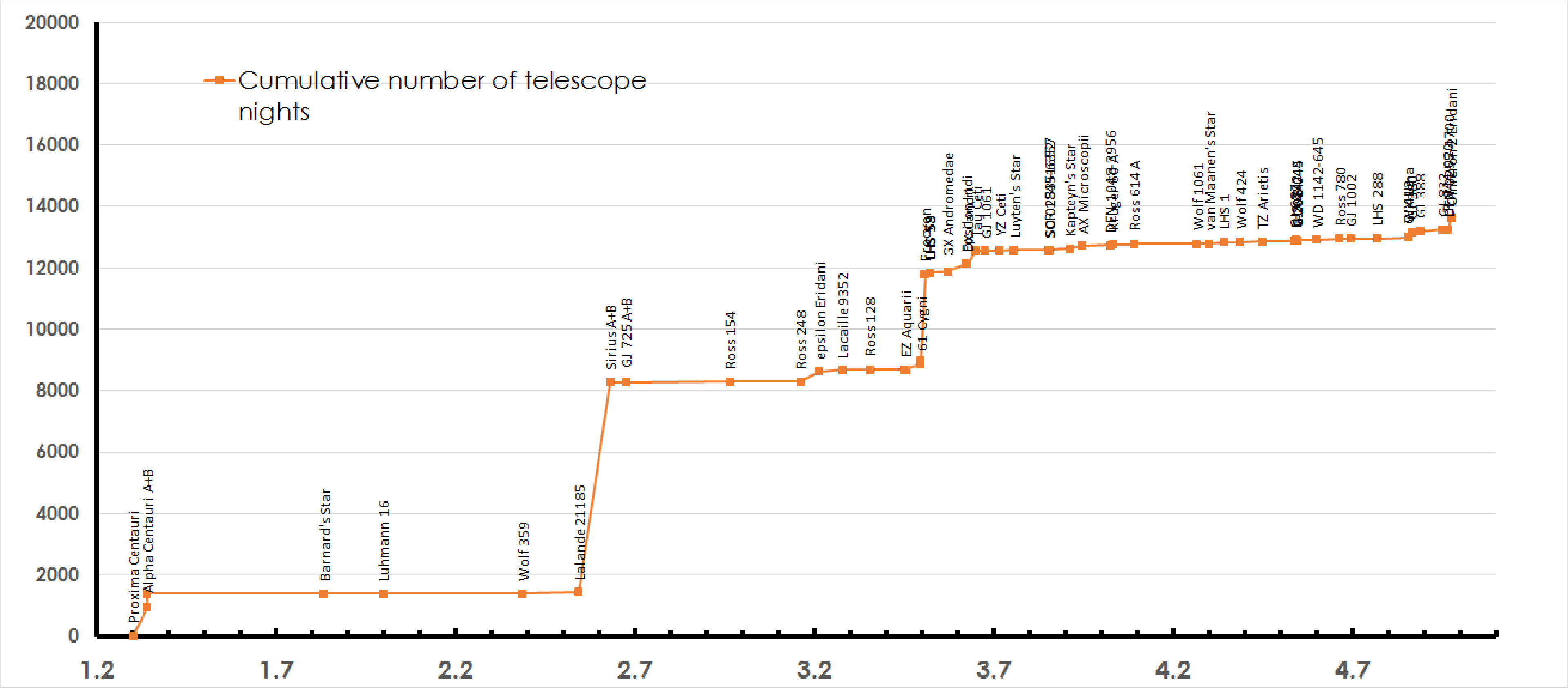
SPECULOOS
Search for habitable Planets EClipsing ULtra-cOOl Stars

M. Gillon et al,
TRAPPIST-1 @11pc

1 Earth-sized planet in the HZ of the star

The 5 pc sample by Doppler

One epoch precision of 1 m/s
S/N > 5



The 5 pc sample by Doppler

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One epoch precision of 1 m/s
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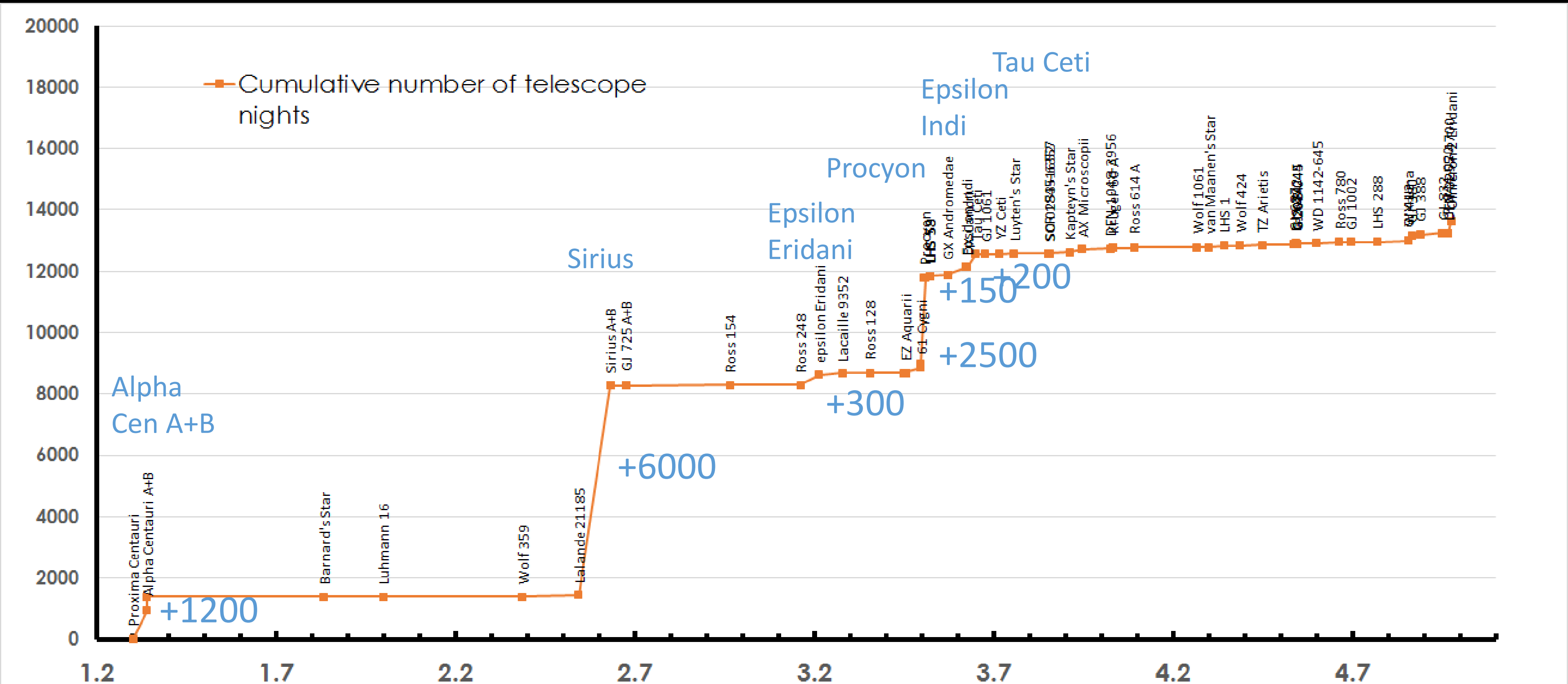
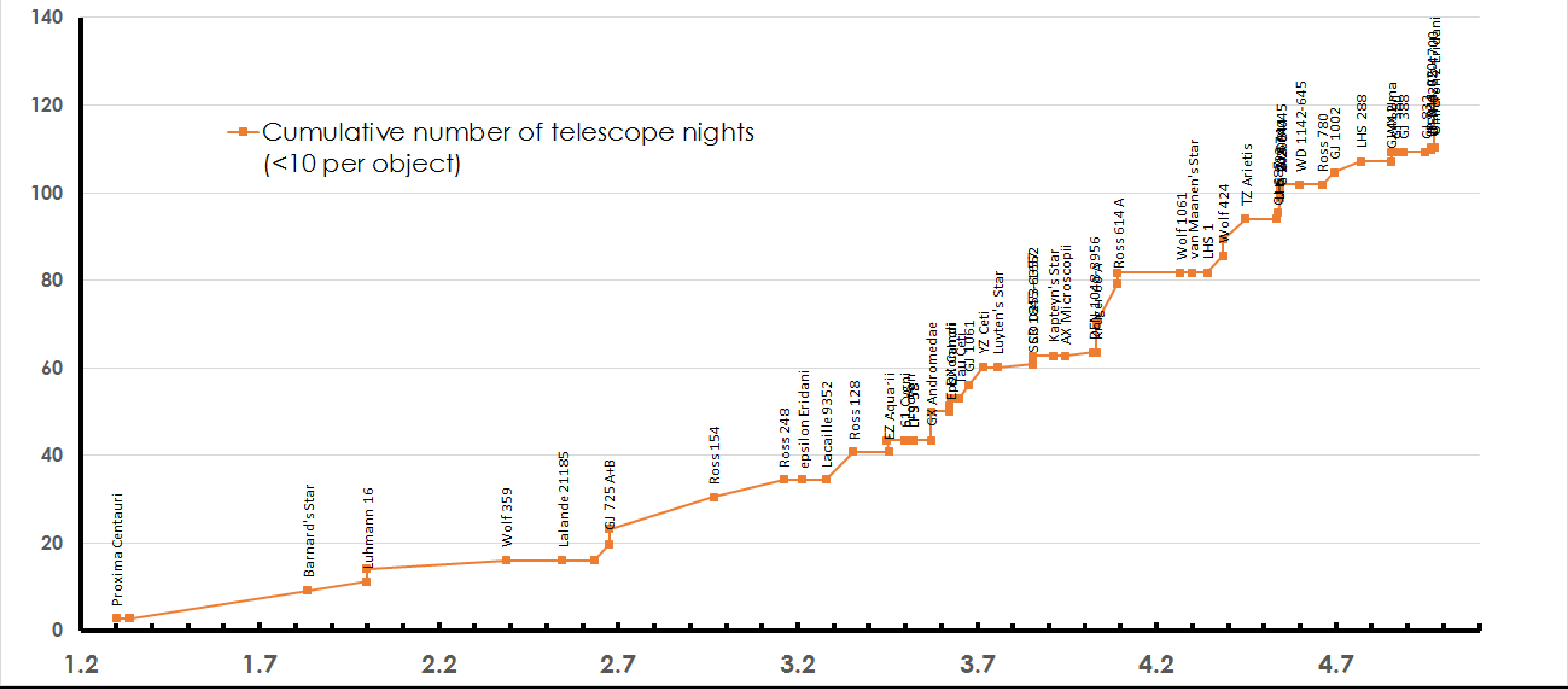


1 Earth-size planet in the HZ of the star

The 5 pc sample by Doppler

Easy ones : less than 1 year
37 systems (~60%)



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The 5 pc sample by Doppler

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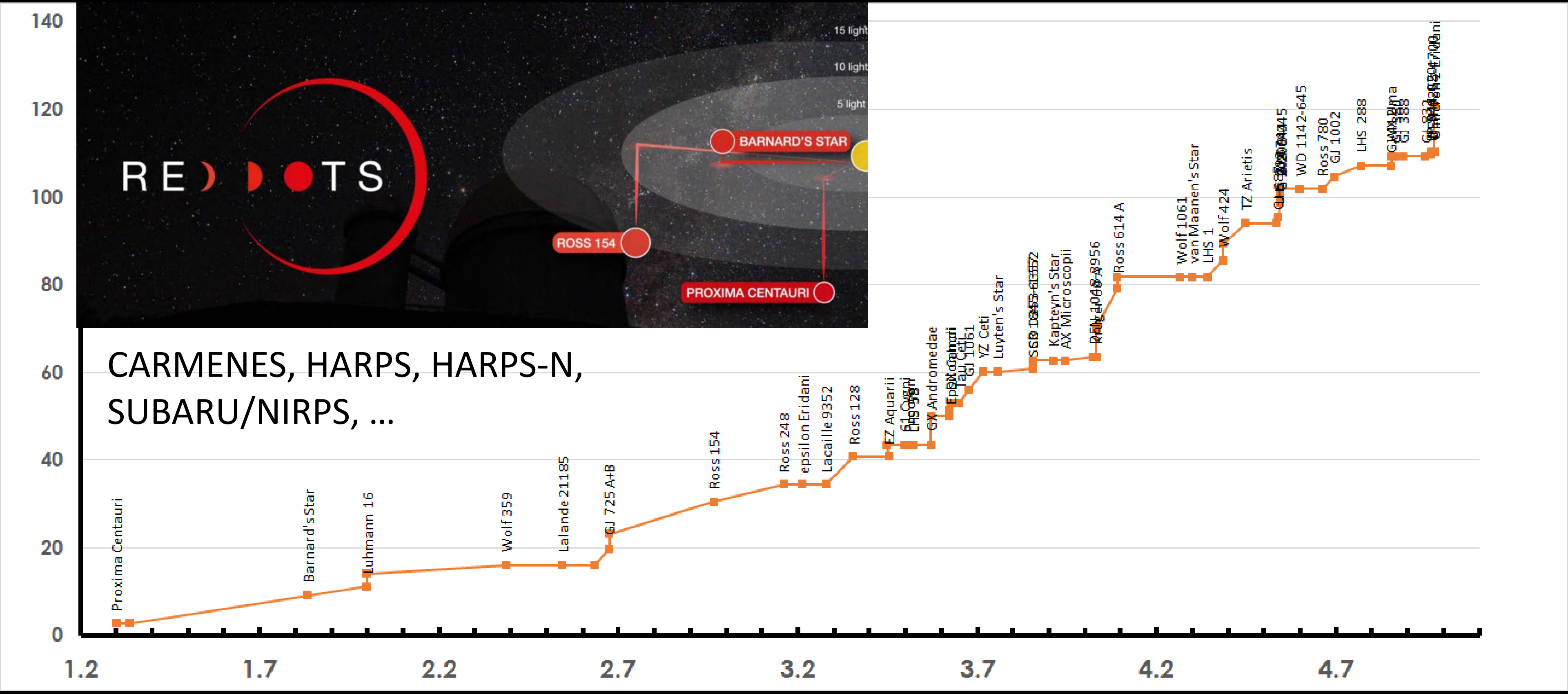
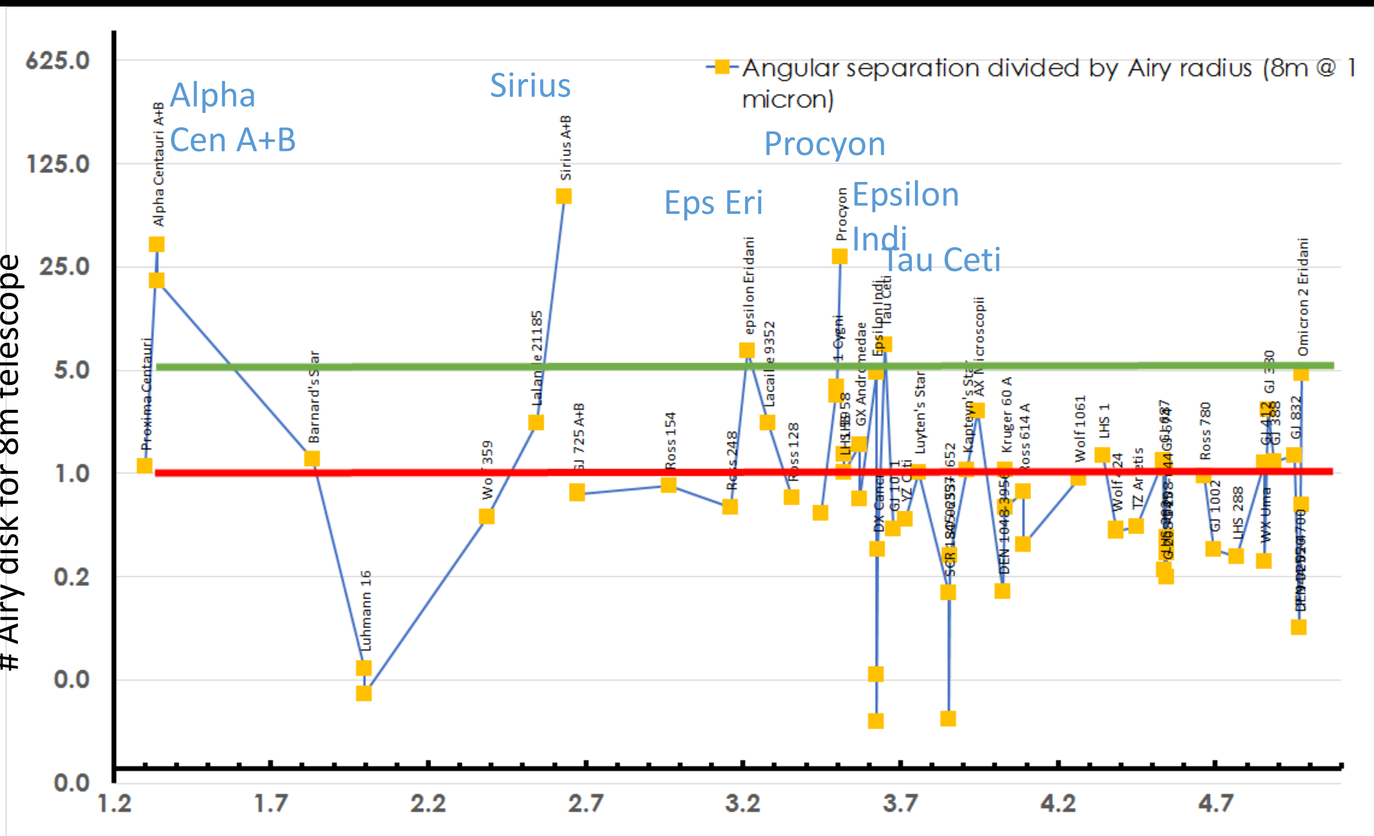


1 Earth-size planet in the HZ of the star

The 5 pc sample by Imaging



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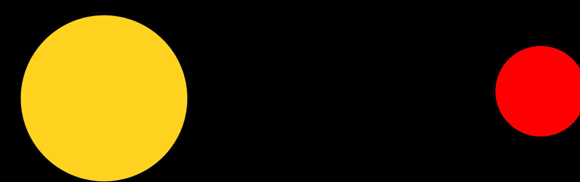
Transits (if any)

The 5 pc sample in millimetric/radio?

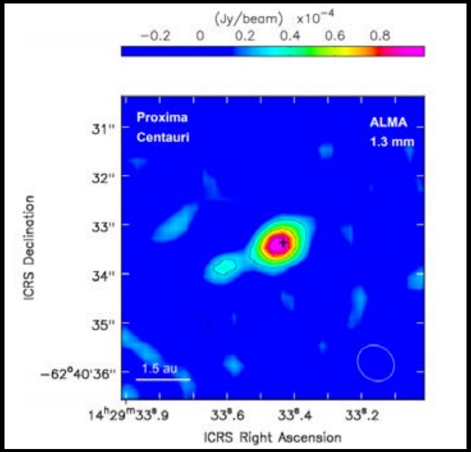


5×10^{-6} 1×10^{-3}

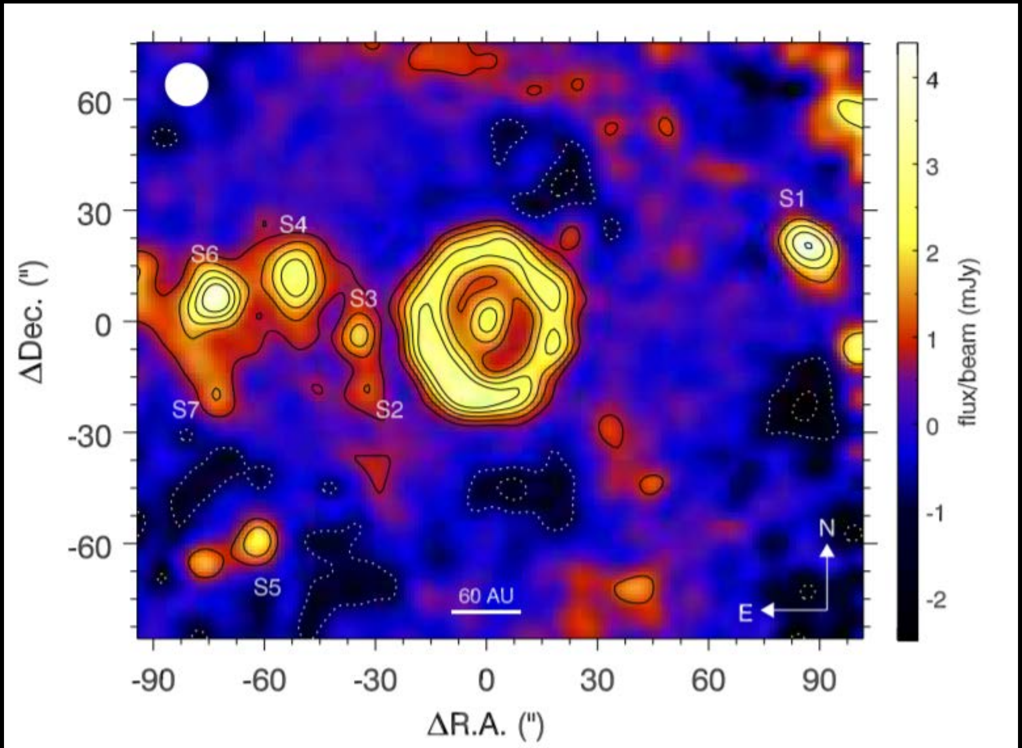
$$C = \frac{T_p}{T_*} \frac{R_p^2}{R_*^2}$$

+ non-thermal processes...?

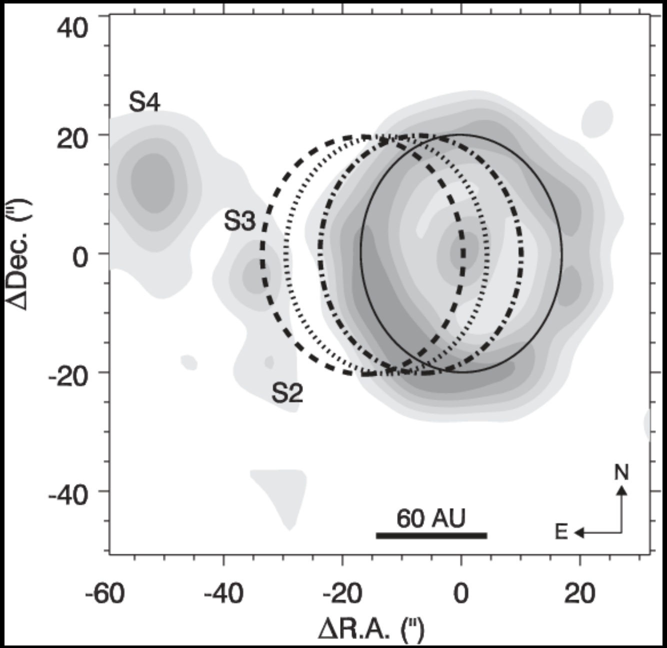
The 5 pc sample in millimetric/radio?



Proxima Cen,
Anglada et al. 2018 w/ALMA

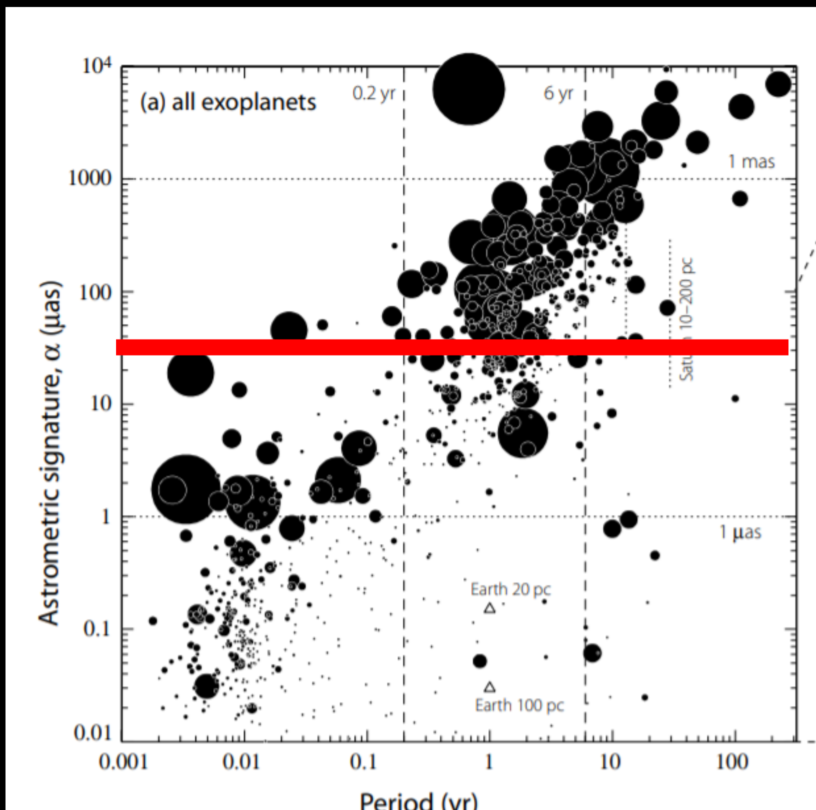


Epsilon Eridani, Chavez et al. 2016 w/LMT



~~1 Earth-size planet in the HZ of the star~~

The ~~5 pc~~ sample by Astrometry



Perryman et al. 2014 ApJ

Expected yields

1000 – few tens of thousands

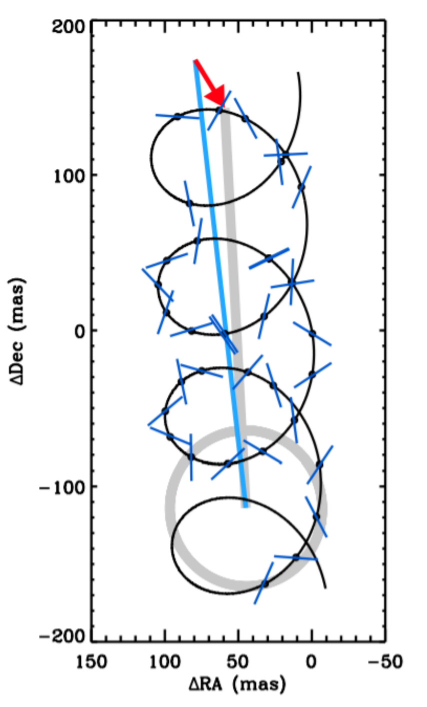
We have an basic idea of the occurrence rates, -> #detections strongly depends on Gaia performance

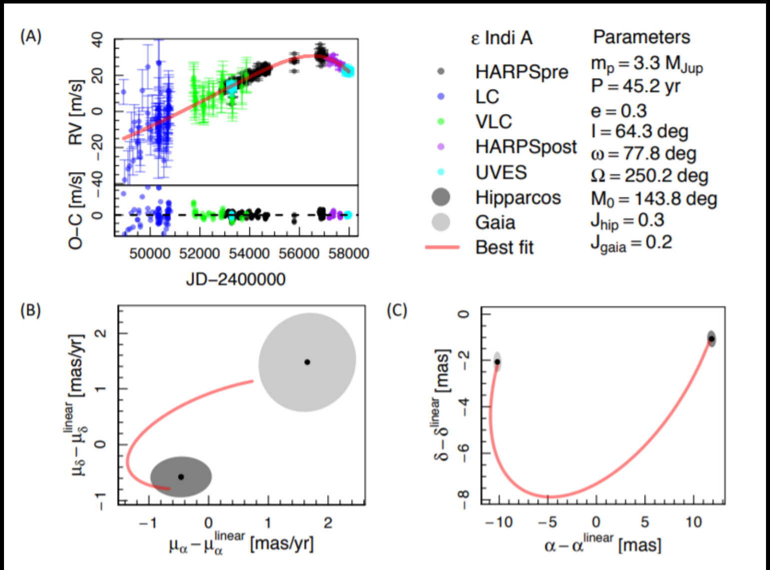
Ground Infrastructure required
Large aperture with adaptive optics in optical, NIR or thermal IR

~~1 Earth-size planet in the HZ of the star~~

The ~~5 pc~~ sample by Astrometry

Snellen & Brown
Nat. 2018
HIPPARCOS + Gaia
DR2 joint fit





Epsilon Indi
RV + HIP + Gaia DR2
Feng et al. 2019, ApJ

Ground Infrastructure required
RV spectrometer (CARMENES, HARPS, etc.)

~~1 Earth-size planet in the HZ of the star~~

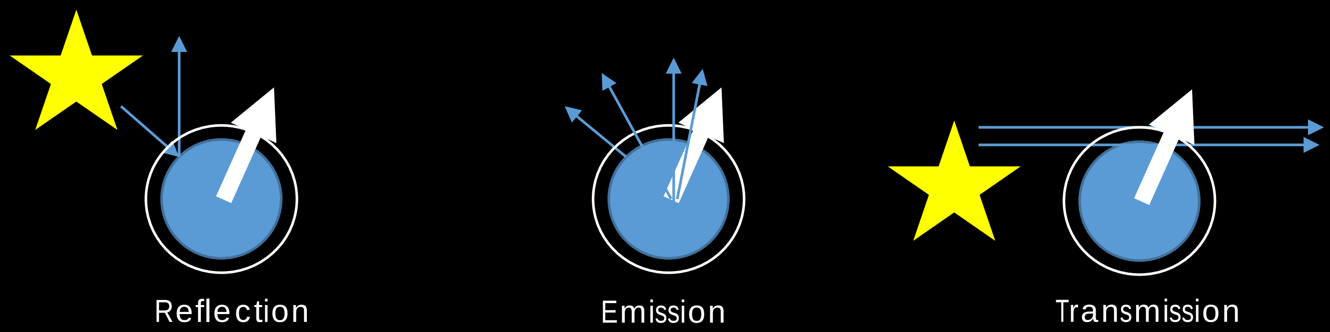
The ~~5 pc~~ sample by Astrometry

- Precision **not** achievable for terrestrials : with Gaia or Ground
- Gaia : **distances to all exoplanet hosts**. DR2 ok, but more precision need for distant targets (Kepler, PLATO)
- Link exoplanet to galactic pop. : Thick disk, thin disk, halo, etc.
- Gaia : **Gas giant population statistics within 50-100pc**
- **Gaia + ground : possible direct detection and/or associated structures : optical/NIR, thermal IR, submm/radio**

Ground Infrastructure required
Large aperture with adaptive optics in optical, NIR or thermal IR

Characterization

How to learn more?

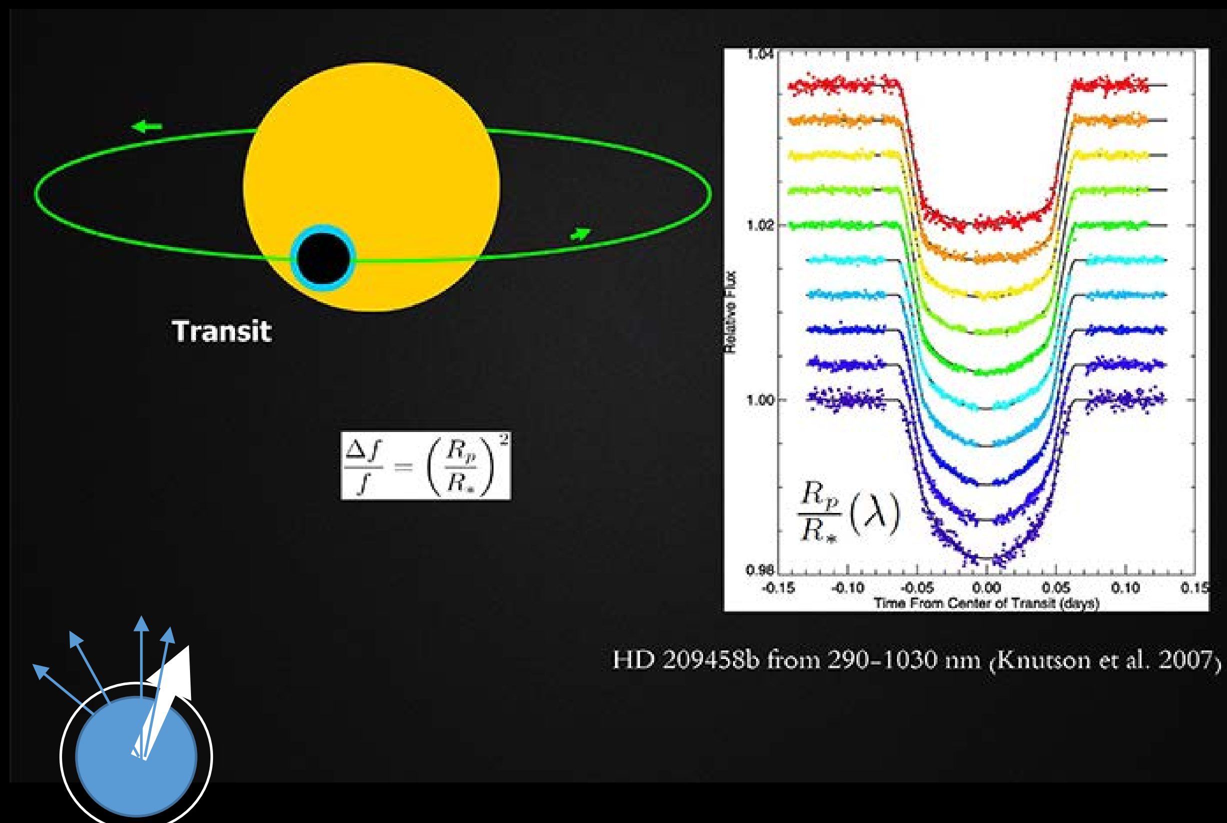


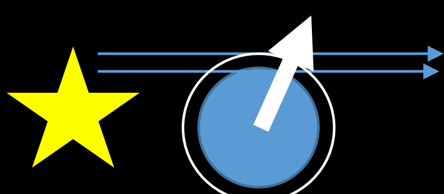
Transit & phase spectroscopy in lowres
Transit & phase spectroscopy in hires

High contrast imaging
High contrast imaging + lowres
High contrast imaging + hires

How to learn more?

Transit spectroscopy



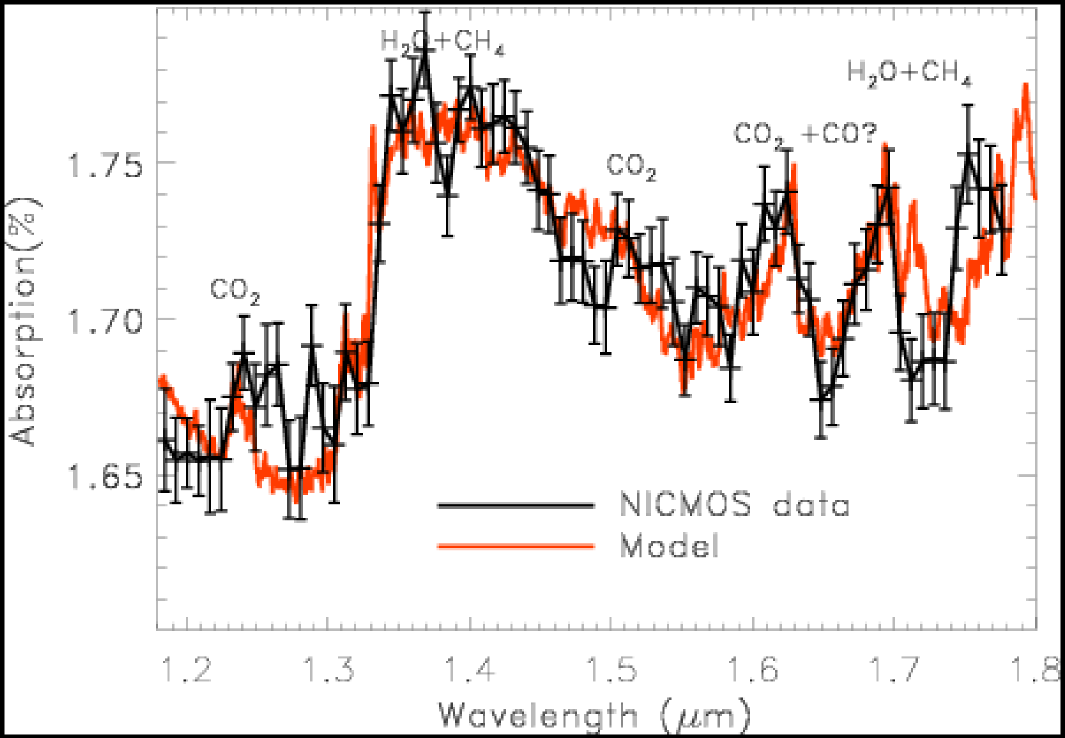


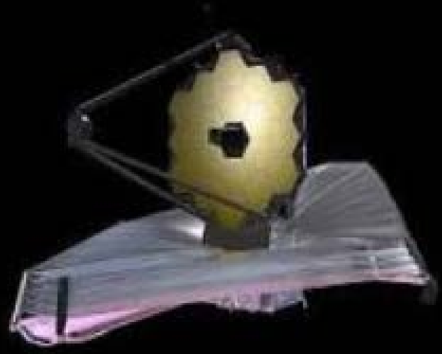
Transmission
(transit)

Emission
(eclipses)

How to learn more?

Transit spectroscopy



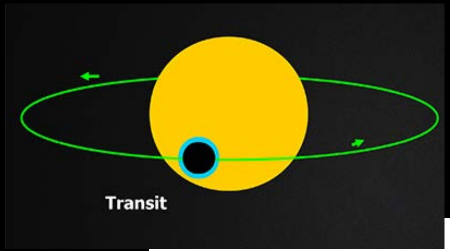


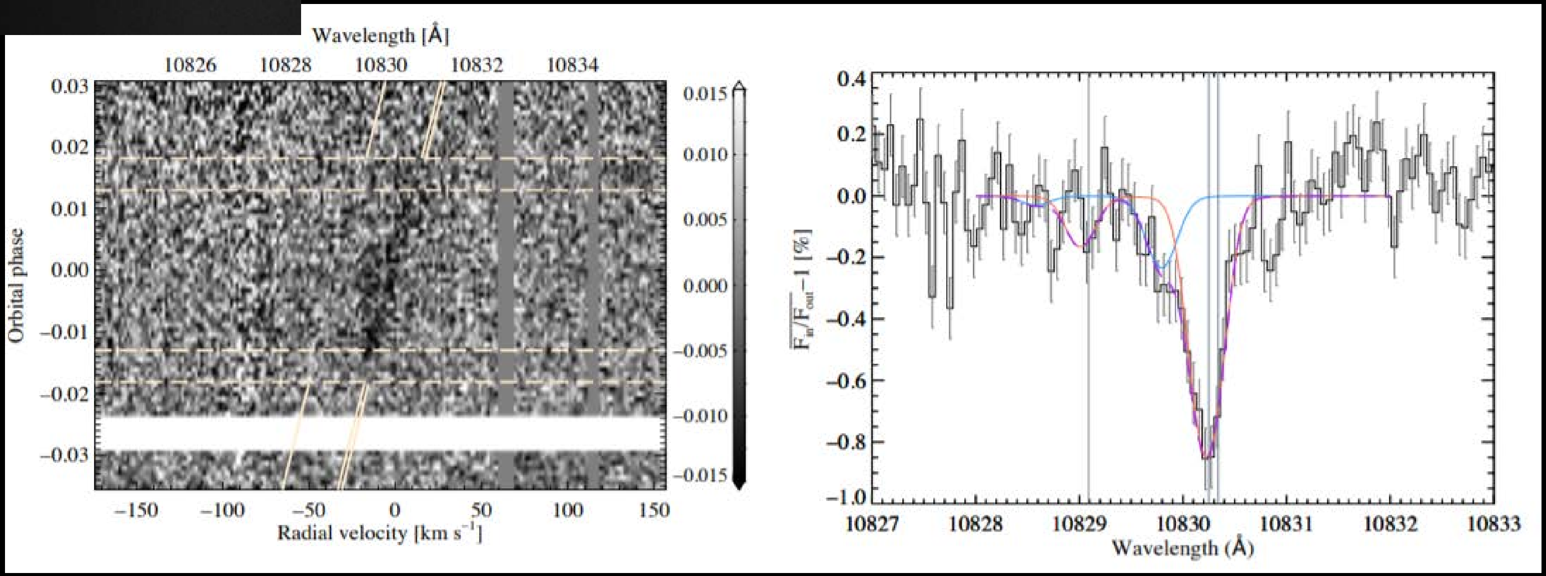
Tinnetti et al. 2010 ApJ
XO-1

Ground Infrastructure required
Simultaneous follow-up small telescopes (photometry)
High precision low-res spectrometry feasible? (GTC)

How to learn more?

Transit & phase hires spectroscopy





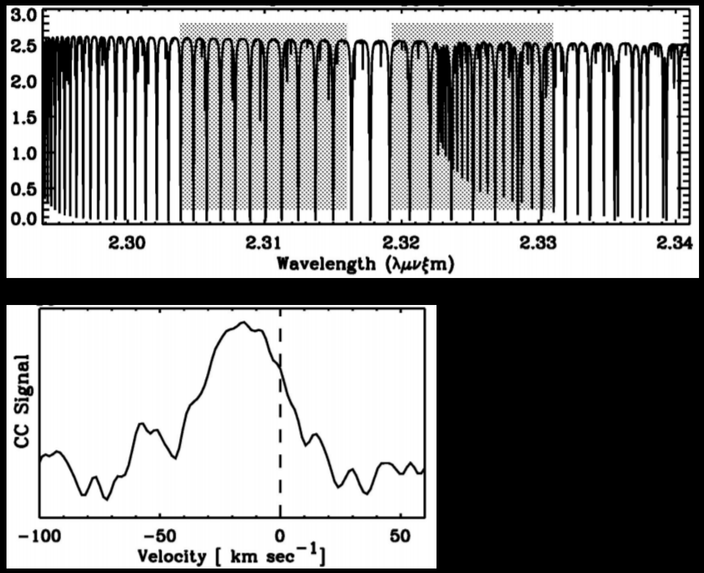
He i λ 10830 Å in the transmission spectrum of HD 209458 b
Alonso-Floriano et al. A&A 2019
w/ CARMENES

~1 micron
(Y band)

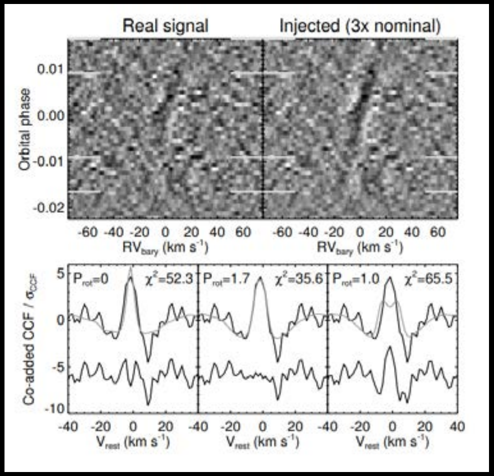
Ground Infrastructure required
High precision high-res spectrometry in moderate/large telescope

How to learn more?

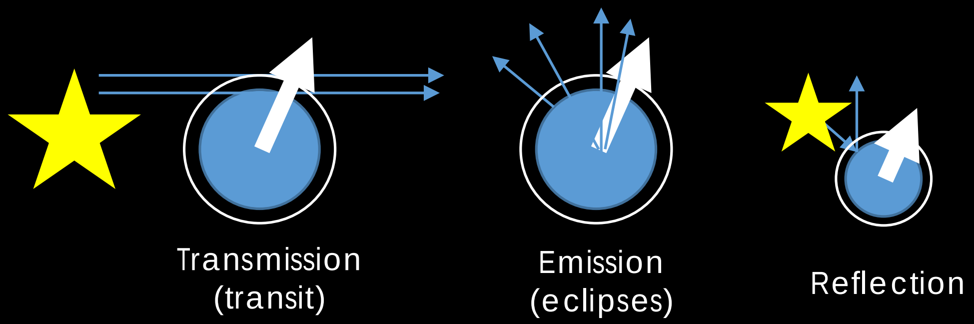
Transit & phase hires spectroscopy



HD 189733 – during transit



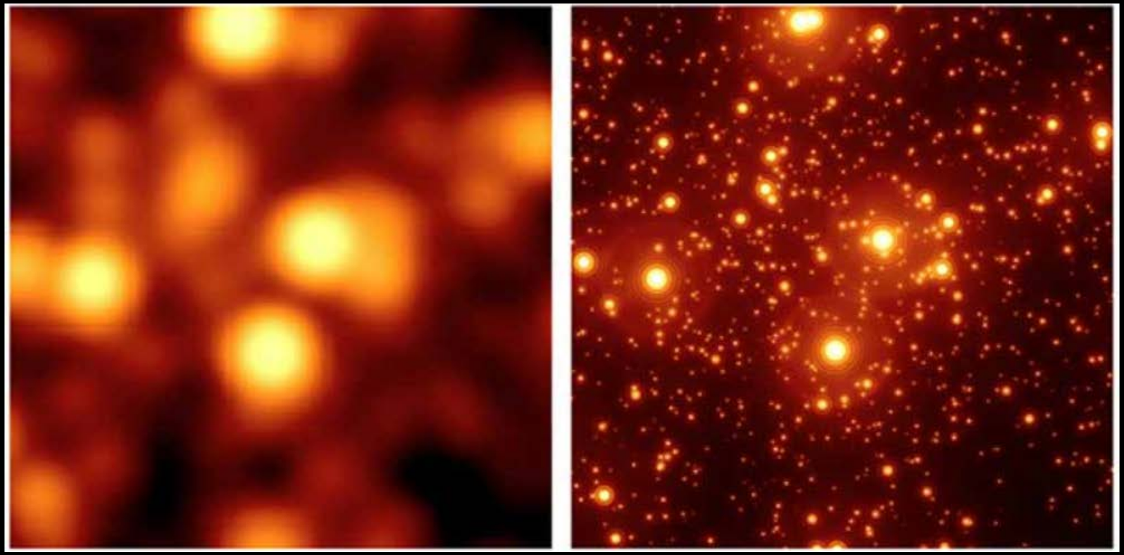
Brogi et al. 2016, ApJ



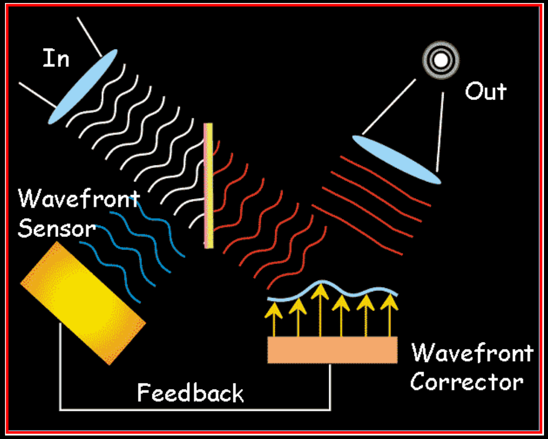
Ground Infrastructure required
High precision high-res spectrometry in moderate/large telescope

How to learn more?

High contrast imaging

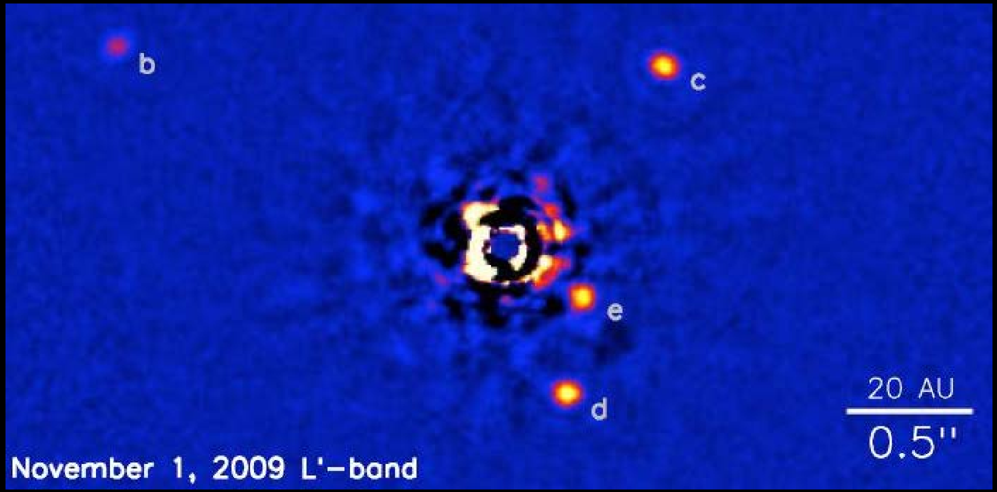


Adaptive optics

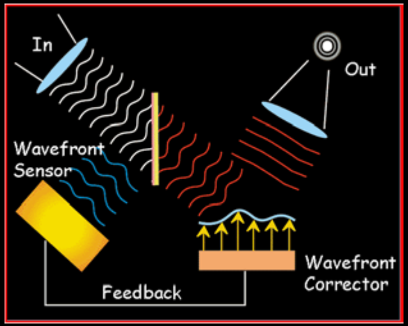


How to learn more?

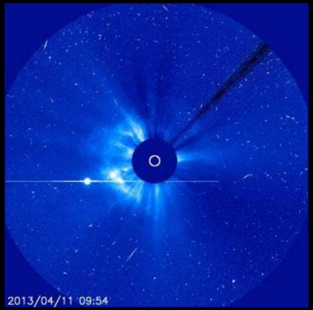
High contrast imaging

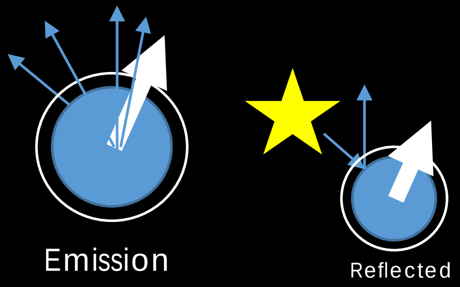


Adaptive optics



Coronograph



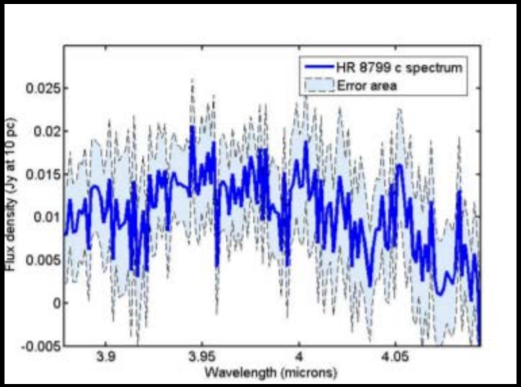


Ground Infrastructure required

Adaptive optics in moderate sized telescope coupled with coronograph

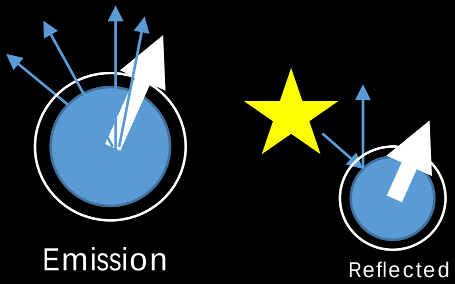
How to learn more?

High contrast imaging+low res



NACO @ VLT, press release image ESO
Spatially resolved spectroscopy of the exoplanet HR 8799 c", by M. Janson et al. 2010 ApJL

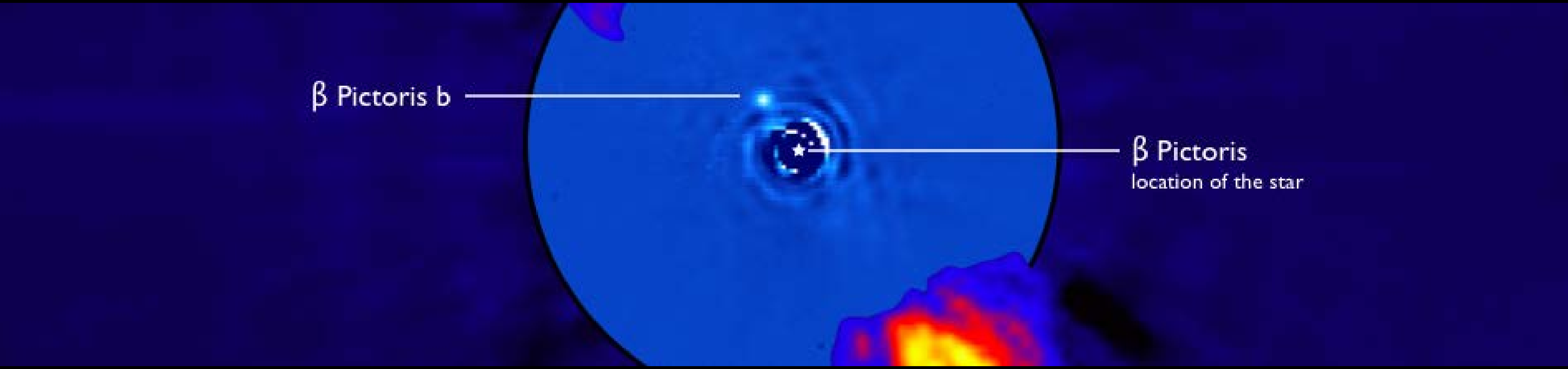
Enough for young gas giants
...not enough for terrestrial planets

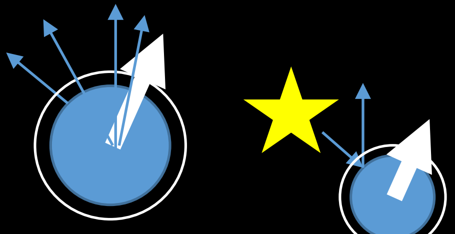


Ground Infrastructure required
Adaptive optics coupled with coronograph and low res spec

How to learn more?

High contrast imaging with
high resolution spectrometer



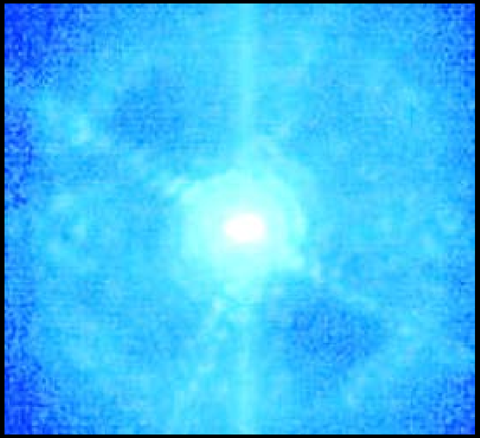


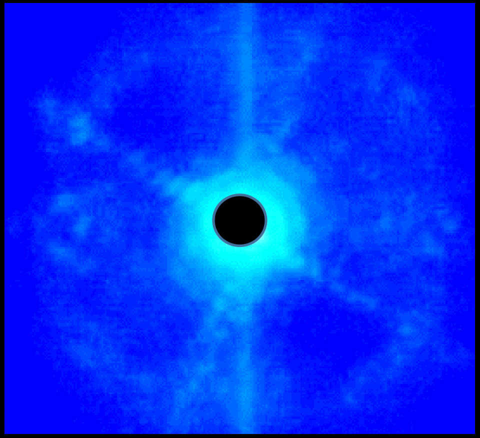
Snellen et al. 2014, Nature
CRIRES, CO bands at 2.3 microns

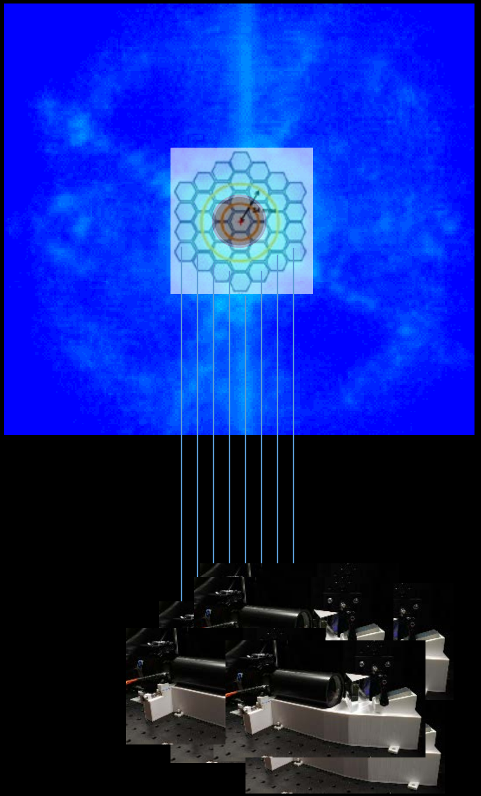
Ground Infrastructure required
Adaptive optics coupled to highres spec & tech testbeds to E-ELT instrument

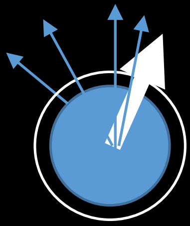
How to learn more?

Direct imaging with adaptive optics,
a coronograph,
and a high resolution spectrometer <u>array</u>

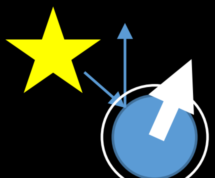








Emission



Reflected

Clark Baker, QMUL

How to learn more?

NEREA a high resolution spectrometer for the GTC.

LoI submitted
Paper SPIE in prep

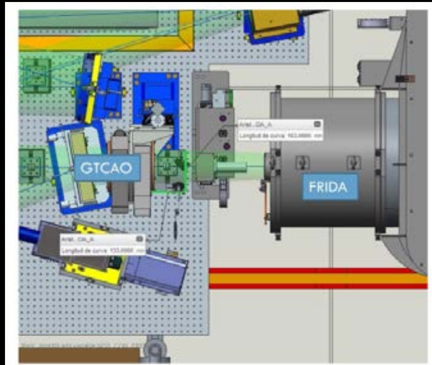
IAC, ICE/IEEC, CAB
(E. Palle, G. Anglada-Escude, I. Ribas, M. Zapatero-Osorio & more)

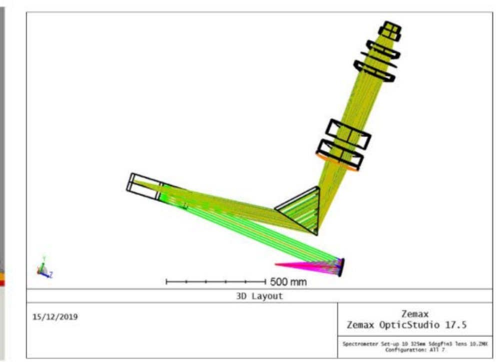
Immediate
- terrestrial planets around cool stars (TRAPPIST 1, Proxim)
- TESS follow-up of fa

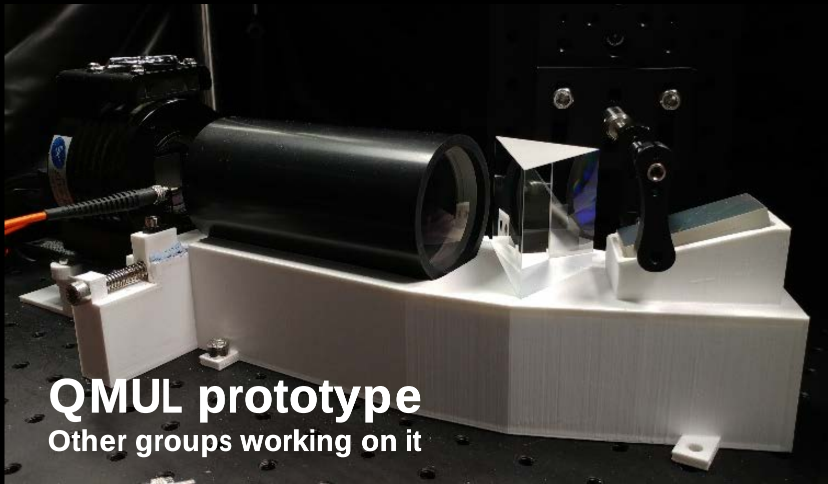
Technolog ation :
- Hir to AO system in d/nIR

PNAYA proposal

t the same time...
- Inexpensive echelle units







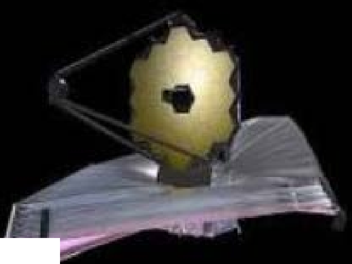
QMUL prototype
Other groups working on it

HST
2.5m class
NASA/ESA

SPITZER
1m, infrared, NASA

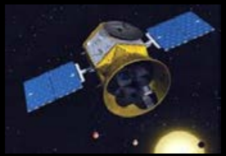
CHEOPS
(30cm, ESA)

JWST
6.5m, NASA/ESA

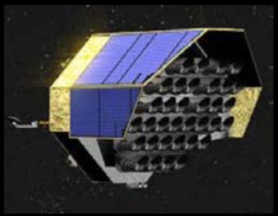


Kepler
NASA, 1m

TESS
10x20 cm, NASA)



PLATO
ESA, 50x10 cm



ARIEL
ESA, 1m, spectra

Space

Gaia
1m, astrometry, ESA

gaia

NOW ***2020*** ***2030***

Ground-based

Doppler spec.
2m class telescopes
HARPS (ESO)
CARMENES
HARPS-N
APF, PFS

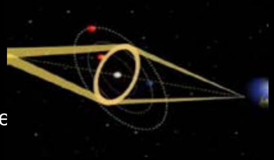
Networks
10cm-1.5m telescopes
NGTS, Mearth,
SPECULOOS, QATAR

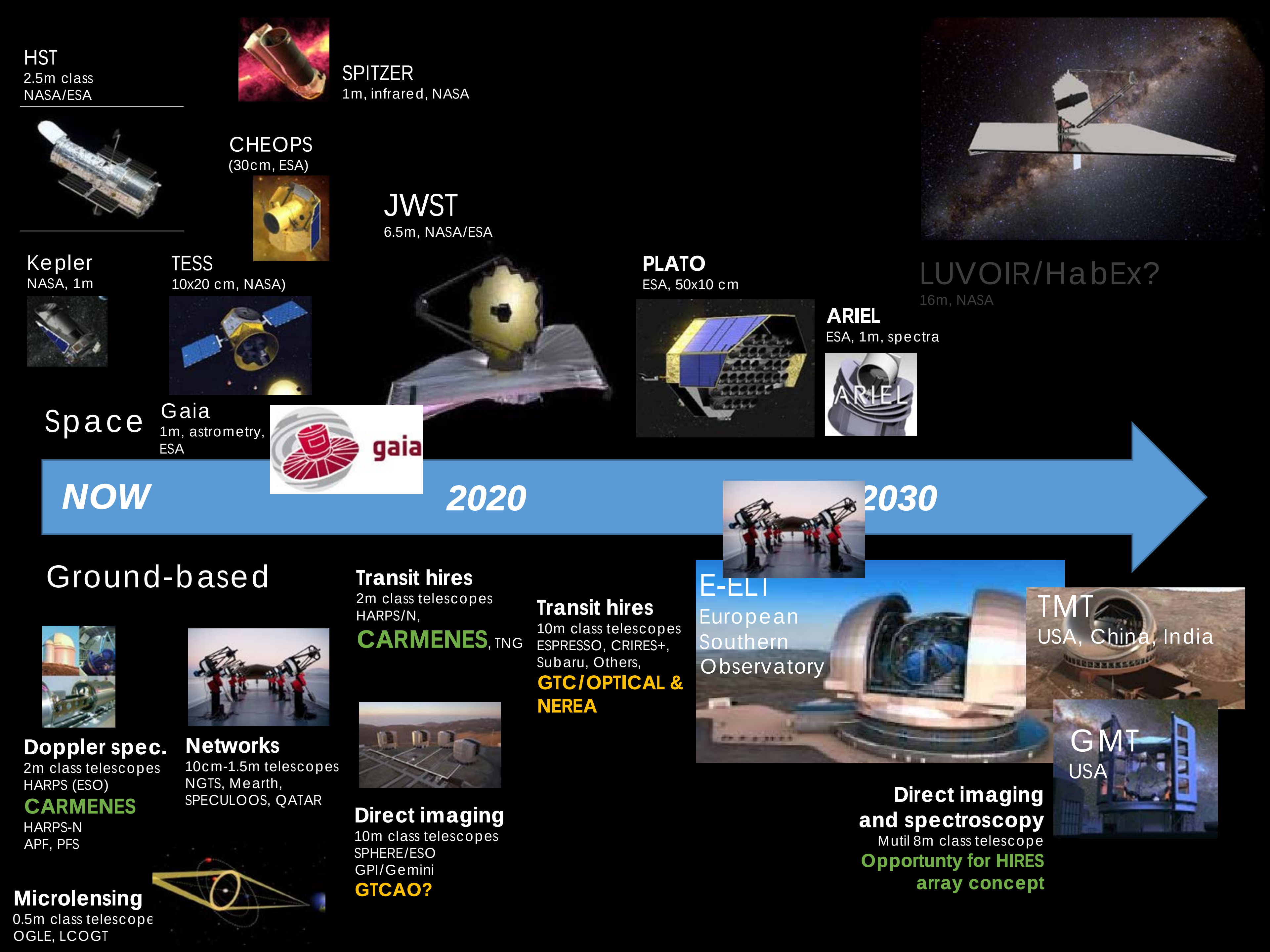
Transit hires
2m class telescopes
HARPS/N,
CARMENES, TNG

Direct imaging
10m class telescopes
SPHERE/ESO
GPI/Gemini
GTCAO?

Transit hires
10m class telescopes
ESPRESSO, CRIRES+,
Subaru, Others,
GTC/OPTICAL & NEREA

Microlensing
0.5m class telescope
OGLE, LCOGT




HST
2.5m class
NASA/ESA
SPITZER
1m, infrared, NASA
CHEOPS
(30cm, ESA)
JWST
6.5m, NASA/ESA
Kepler
NASA, 1m
TESS
10x20 cm, NASA)
PLATO
ESA, 50x10 cm
LUVOIR/HabEx?
16m, NASA
ARIEL
ESA, 1m, spectra
ARIEL
Space
Gaia
1m, astrometry, ESA
gaia
NOW
2020
2030
Ground-based
Transit hires
2m class telescopes
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CARMENES, TNG
Transit hires
10m class telescopes
ESPRESSO, CRIRES+,
Subaru, Others,
GTC/OPTICAL &
NEREA
E-ELT
European
Southern
Observatory
TMT
USA, China, India
Doppler spec.
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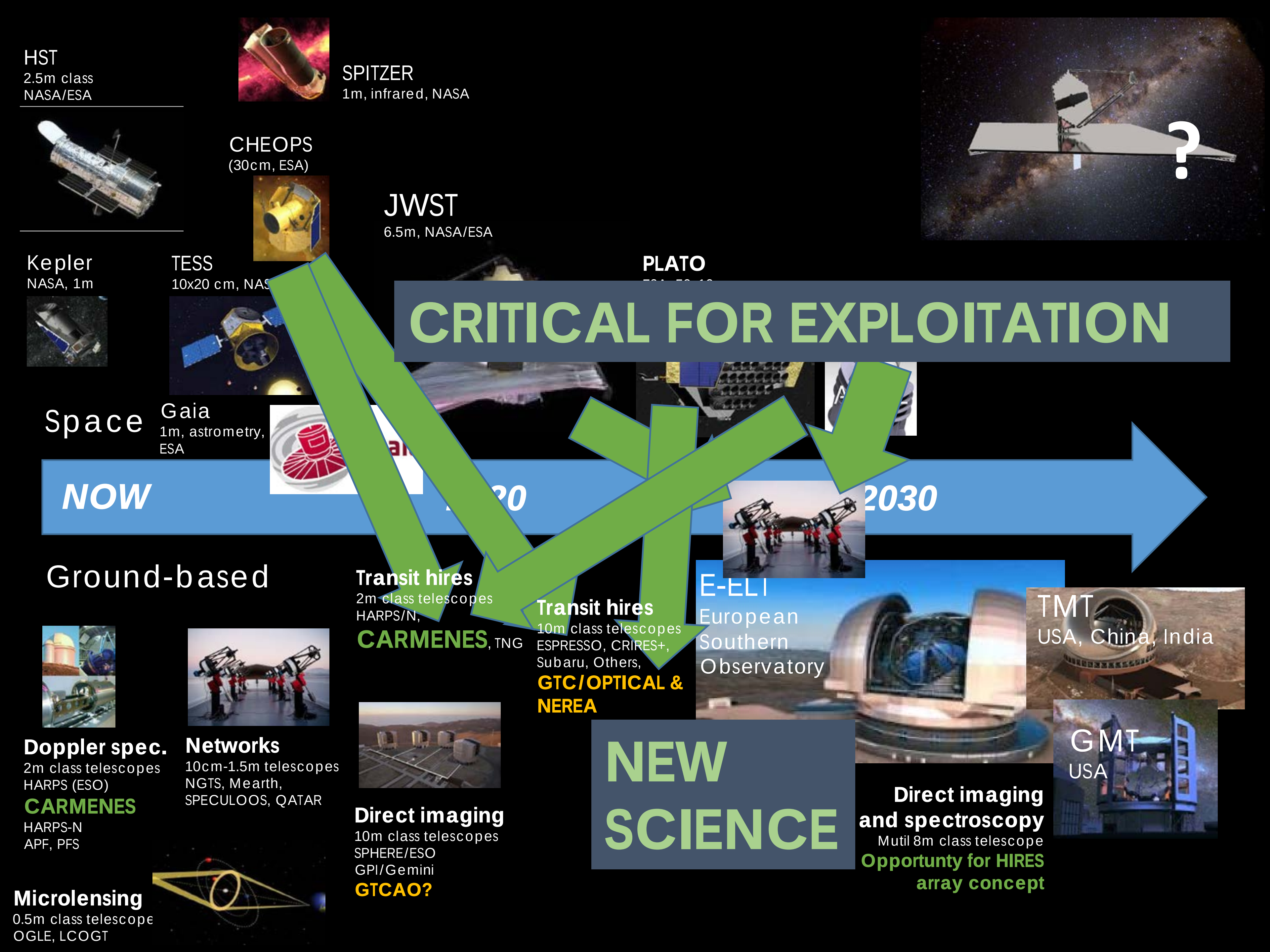
GMT
USA
Direct imaging
10m class telescopes
SPHERE/ESO
GPI/Gemini
GTCAO?
Direct imaging
and spectroscopy
Mutil 8m class telescope
Opportunity for HIRES
array concept
Microlensing
0.5m class telescope
OGLE, LCOGT


HST
2.5m class
NASA/ESA
SPITZER
1m, infrared, NASA
CHEOPS
(30cm, ESA)
JWST
6.5m, NASA/ESA
?
Kepler
NASA, 1m
TESS
10x20 cm, NAS
PLATO
CRITICAL FOR EXPLOITATION
Space
Gaia
1m, astrometry,
ESA
NOW
2030
Ground-based
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HARPS/N,
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NEREA
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USA, China, India
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GPI/Gemini
GTCAO?
NEW
SCIENCE
Direct imaging
and spectroscopy
Mutil 8m class telescope
Opportunity for HIRES
array concept
Microlensing
0.5m class telescope
OGLE, LCOGT

Current exoplanet science opportunities

- Nearby star deep RV surveys (CARMENES, others intl.)
- Transit spectroscopy in low resolution : space but also possible from ground (GTC, ESO, Keck… ask E. Pallé)
- Transit spectroscopy in higres : few dozen hot planets with CARMENES & ESO facilities (ESPRESSO, CRIRES+, HARPS,…)
- Complementary observations to surveys RV and transit surveys with small telescopes
- Precision population studies (Gaia DR2+, Kepler/TESS/CHEOPS, ground based hires spec)
- Gaia non-linear mover RV follow-up (and viceversa)

Exoplanet (ground) infrastructure based development opportunities

Robotic small telescope networks (low EUR) : support to space missions & surveys

2-4m class telescope with dedicated hires spectrometer : support to space missions (cutting edge, large consortium contrib).

Hires spectrometer in large aperture : GTC, NEREA concept, cutting edge experiments **(GTC LoI & PNAYA submitted)**

Technology testbeds and programmes for starlight suppression (AO+coronographs) + coupling to spectrometers (lowres and highres)

- 2-4m class telescopes : advanced suppression experiments
- 10m (GTC) : Direct detection (gas giants) and system testbed for E-ELT

Radio and submm single dish (eg. IRAM) (high risk, but low cost & high gain), and access to intl. radio networks and facilities for experimental programmes

Nano-sat follow-up services : super-stable space photometry (support to other space missions, cost comparable to 1m class ground) & Testbeds to ESA tech development... *build up ground antennae infrastructure? (...also business case)*