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Departamento de Astronomia
Universidad de Chile

Talk Layout

- ***What is an exo-Earth in the context of planet searches?***
  - ***Key criteria we must adhere to***
  - ***Where should we be looking?***

- ***Challenges to overcome in the detection of exo-Earths orbiting the nearest stars***
  - ***Radial velocity noise sources***
  - ***Instrumental issues***
  - ***Observational bands***

- ***Potential for exo-Earth characterisation***

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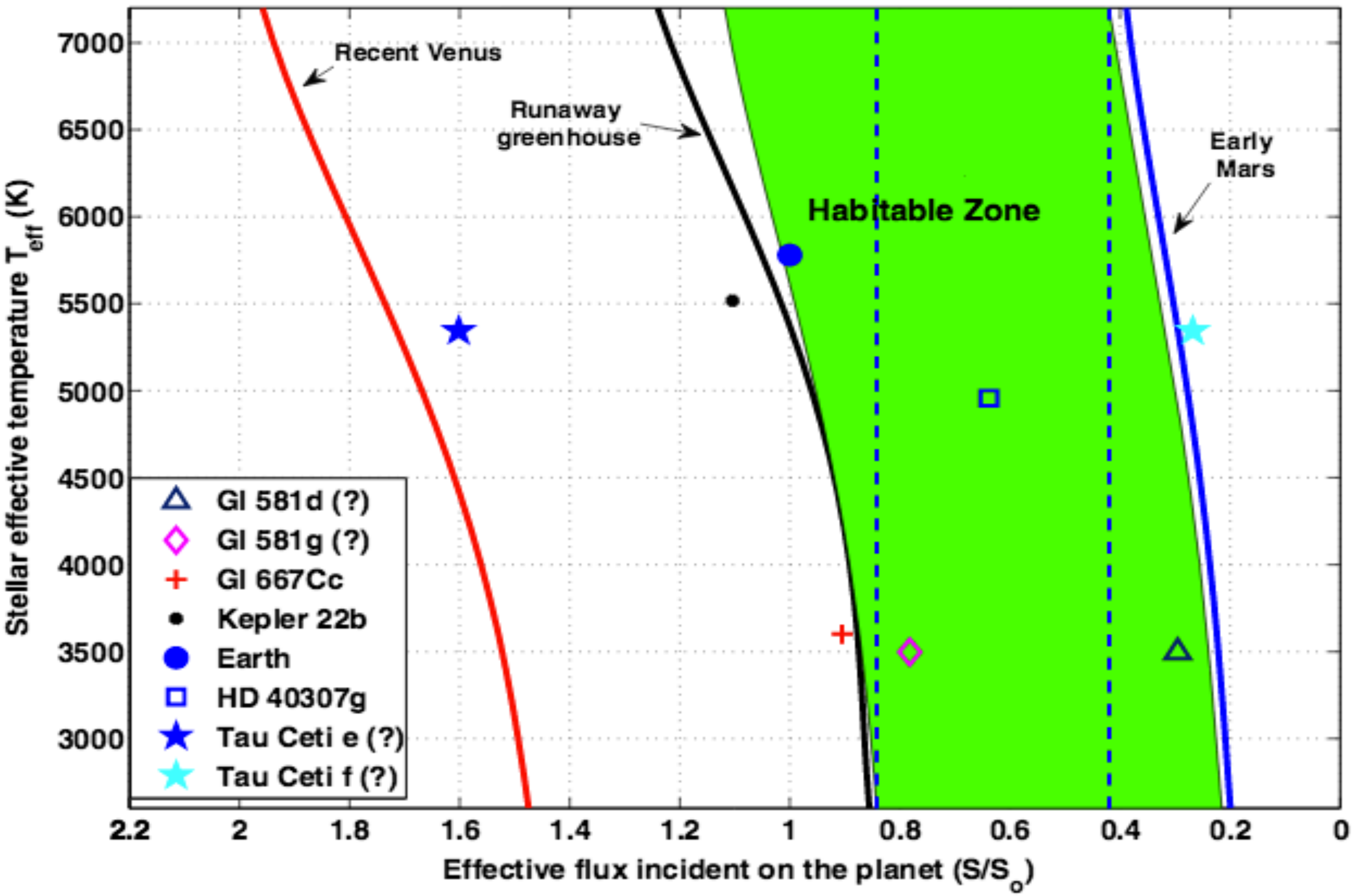
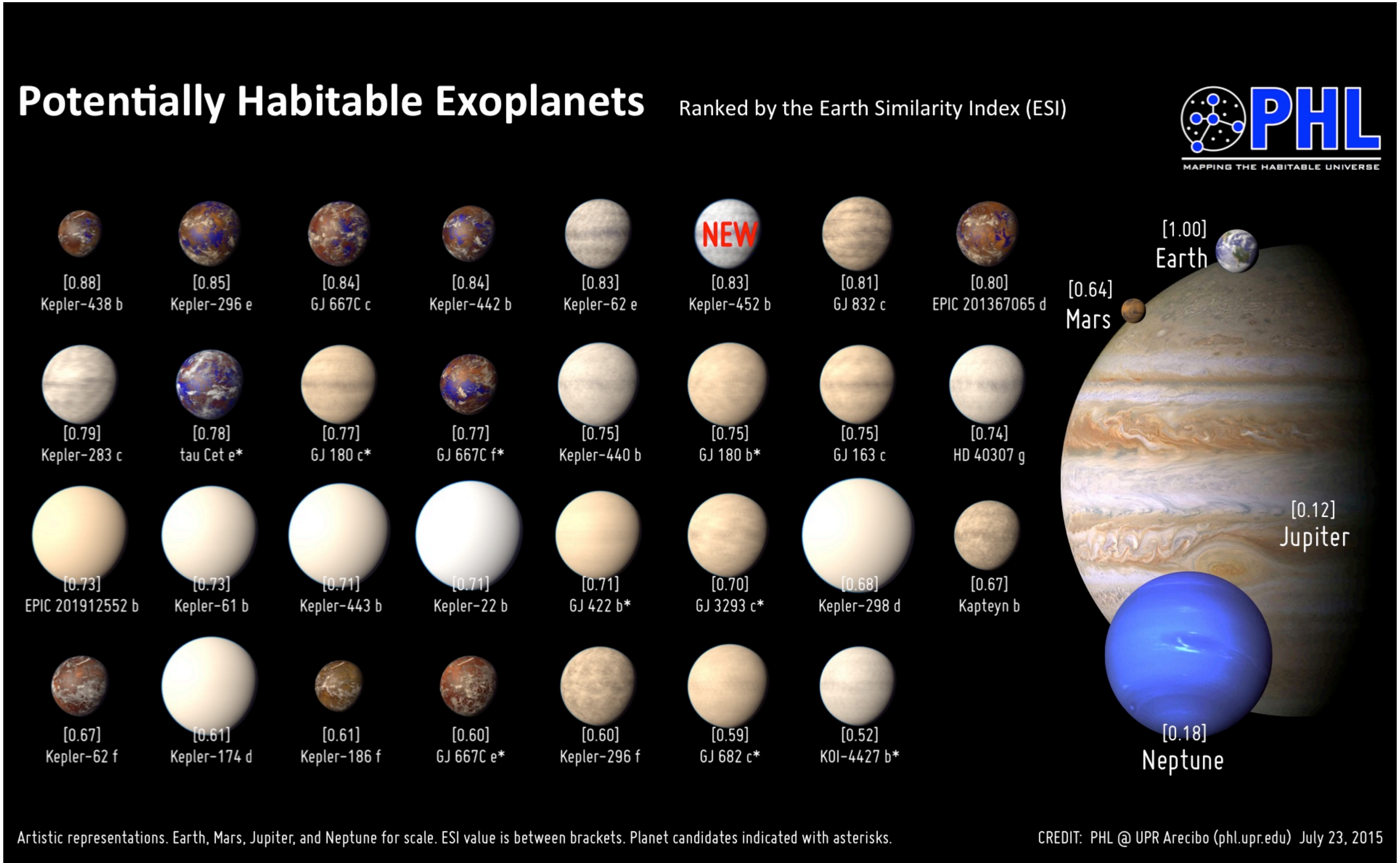
Updated Habitable Zones



Kopparapu et al. 2013, ApJ, 765, 131



Earth Similarity Index:

$$ESI = \prod_{i=1}^{n} \left(1 - \left|\frac{x_i - x_{io}}{x_i + x_{io}}\right|\right)^{\frac{w_i}{n}}$$

SPACE

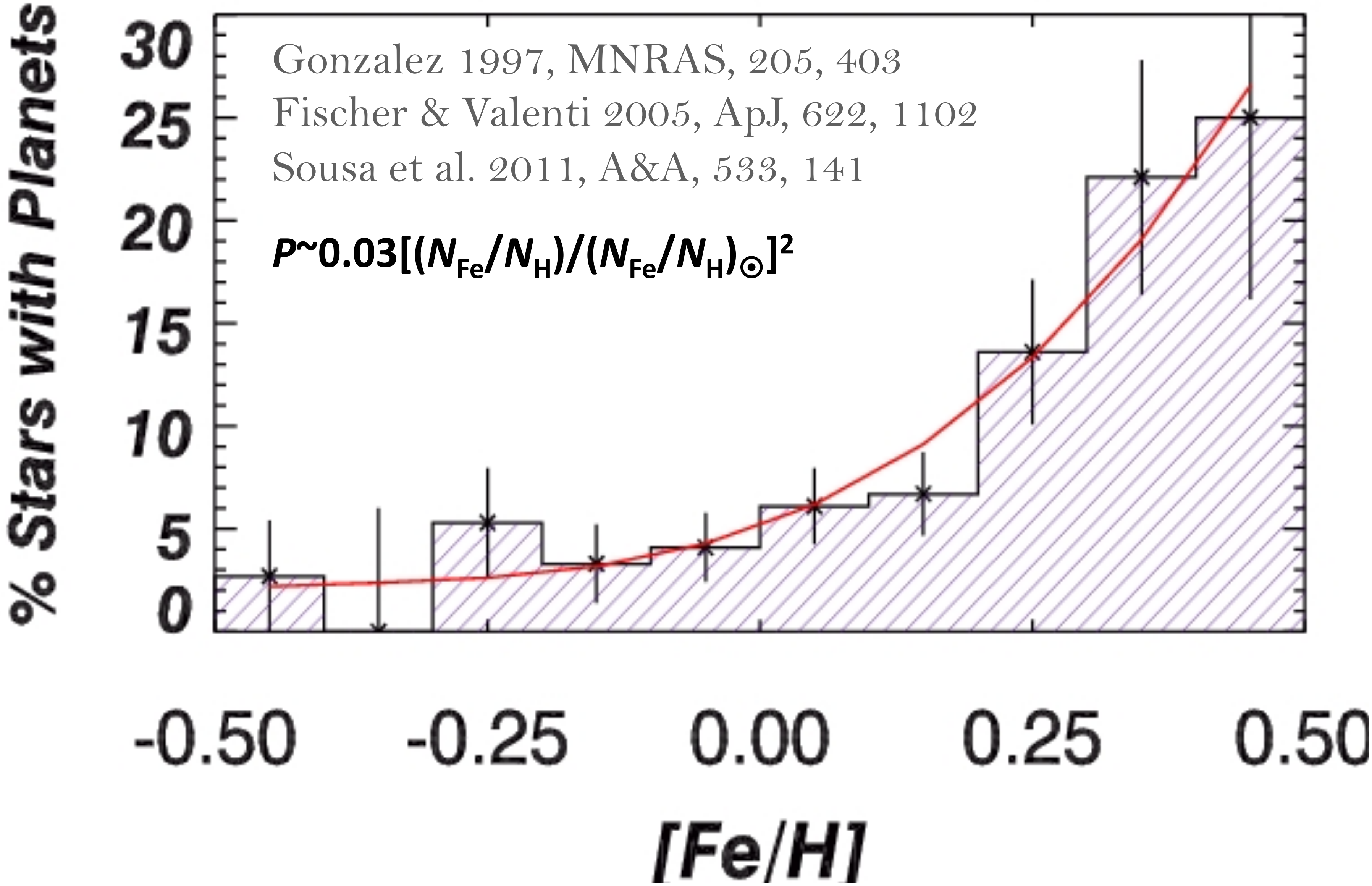
Earth 2.0: NASA finds planet that matches our own

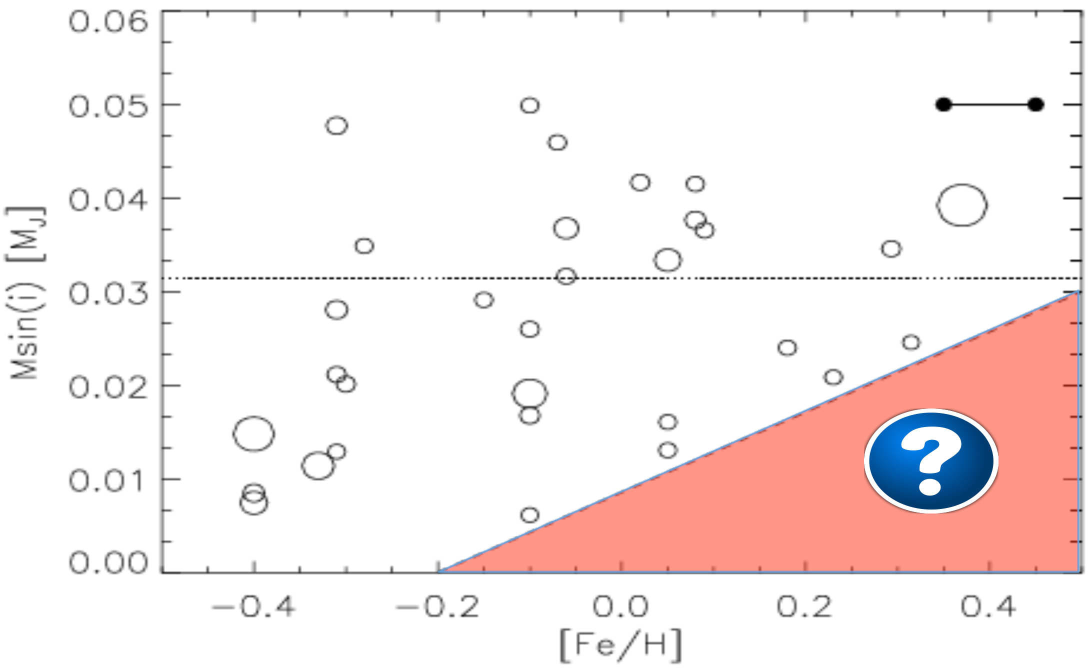
Space agency's Kepler mission finds planet outside solar system that may have volcanoes, oceans and sunshine like Earth.

Earth 2.0: What we know about Kepler 452b, the most Earth-like planet ever discovered

Could Human Beings Ever Reach 'Earth 2.0'?

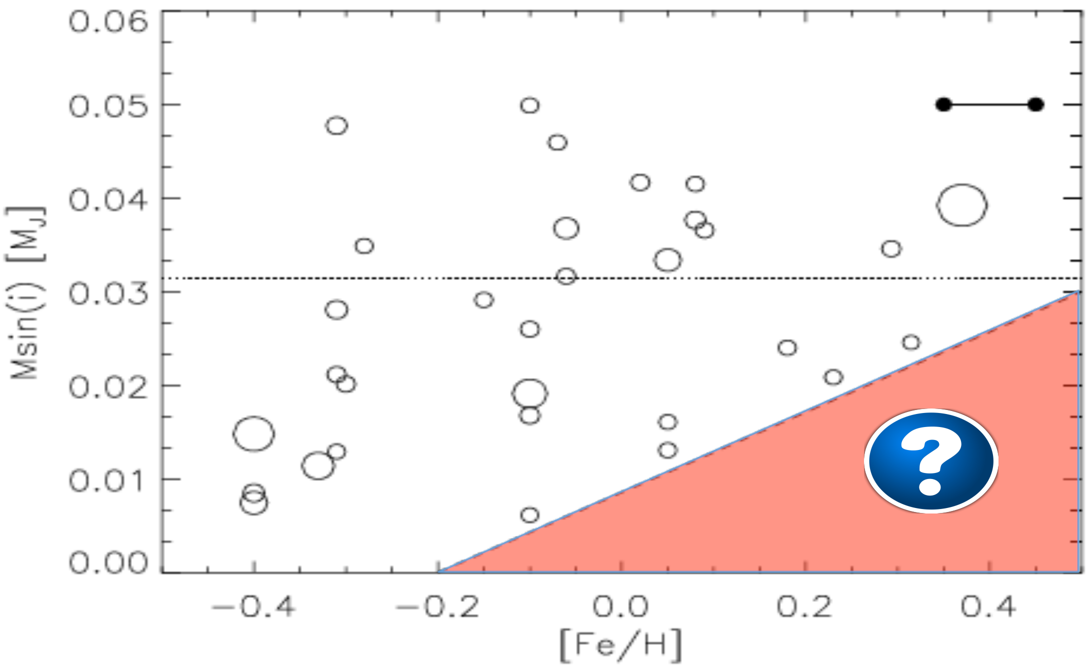
Are metal-rich stars good places to hunt?





Jenkins et al. 2013, ApJ, 766, 67

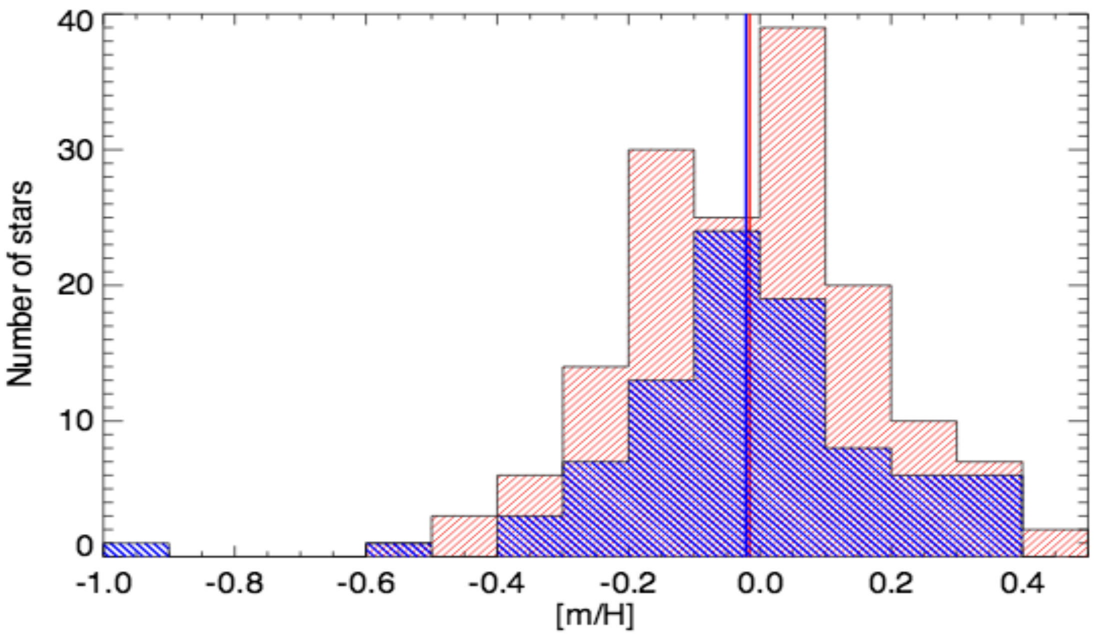
Gap region is statistically significant at the 4.5σ level



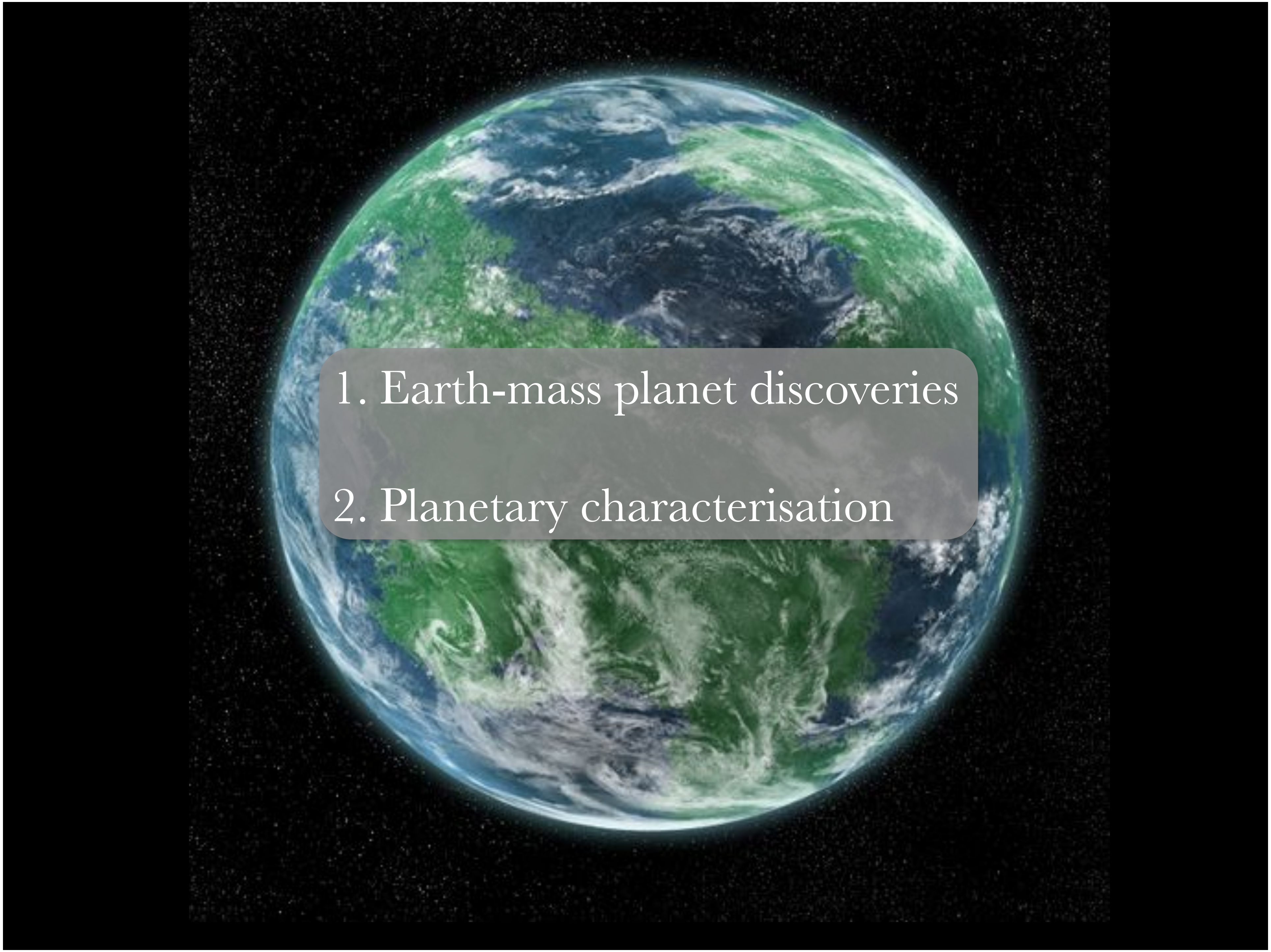
Jenkins et al. 2013, ApJ, 766, 67

Gap region is statistically significant at the 4.5σ level

Buchhave & Latham 2015, ApJ, 808, 187



Metallicity distribution of dwarfs with and without small planets are statistically similar


1. Earth-mass planet discoveries
2. Planetary characterisation

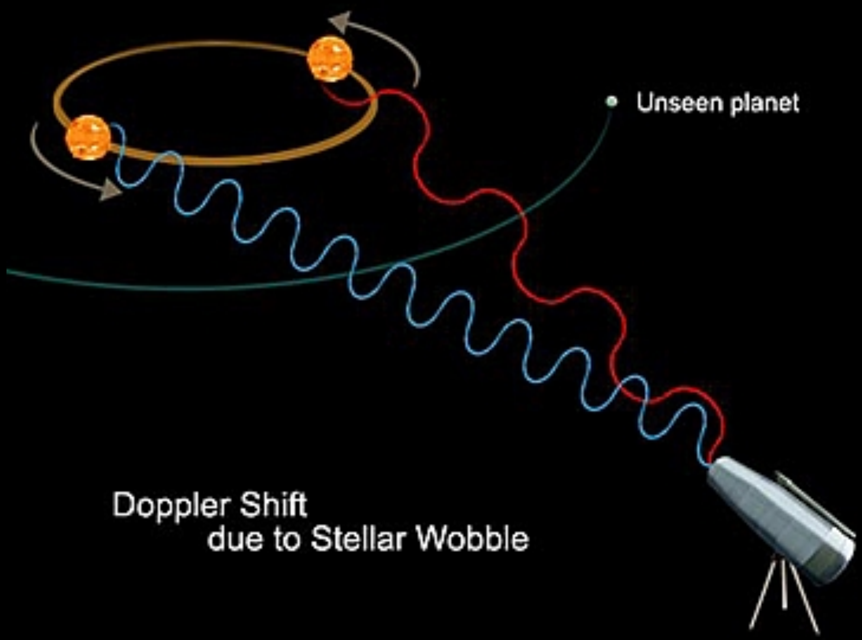
Talk Layout

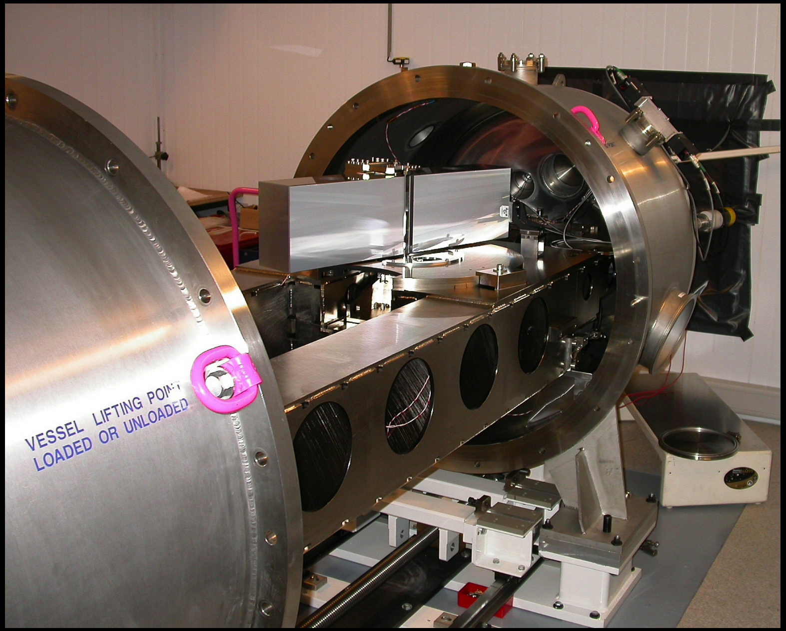
- *What is an exo-Earth in the context of planet searches?*
  - *Key criteria we must adhere to*
  - *What evidence is necessary for such a claim?*
  - *Where should we be looking?*

- *Challenges to overcome in the detection of exo-Earths orbiting the nearest stars*
  - *Radial velocity noise sources*
  - *Instrumental issues*
  - *Observational bands*

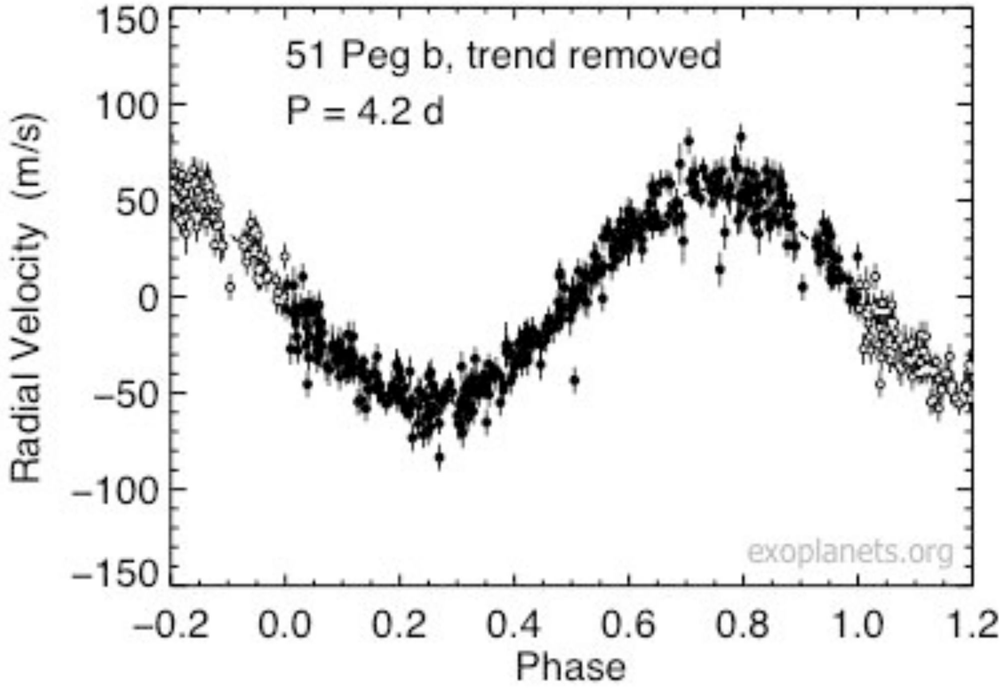
- *Potential for exo-Earth characterisation*

Radial Velocities



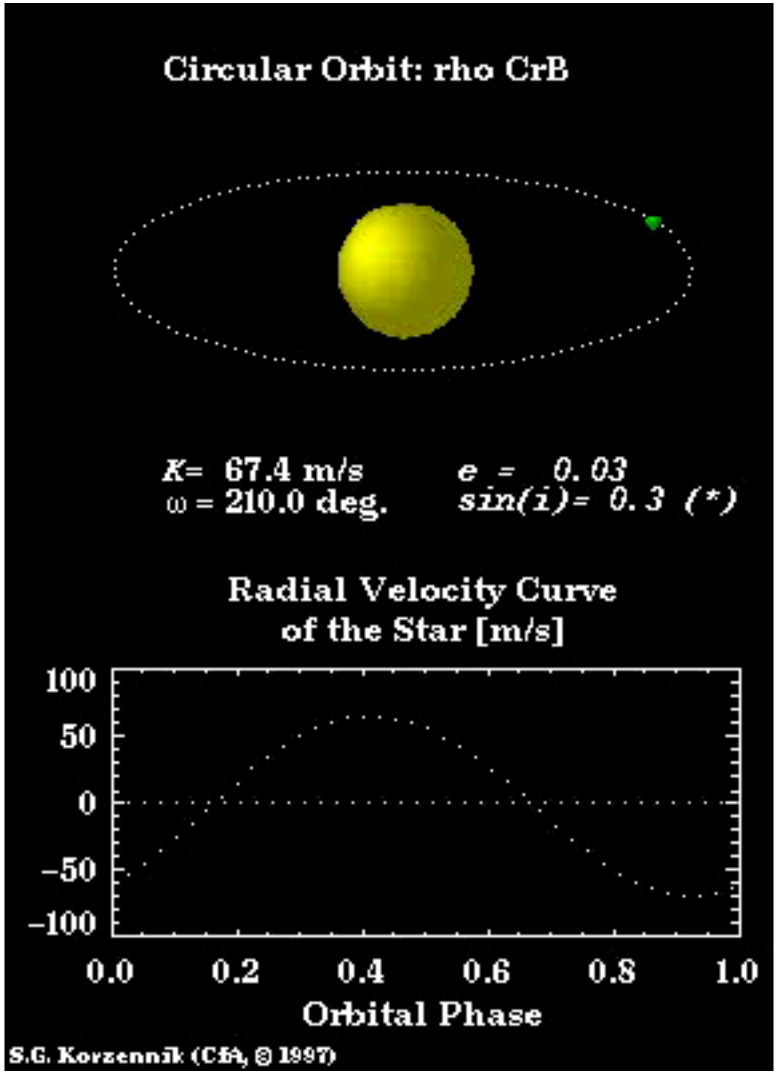


Optical Radial Velocities



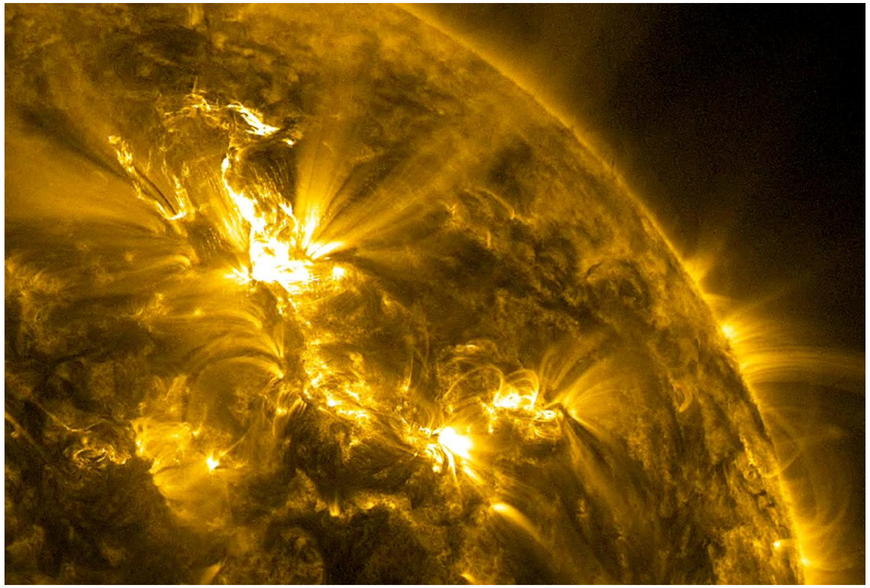
51 Pegasi b

Mayor & Queloz 1995, Nature, 378, 355

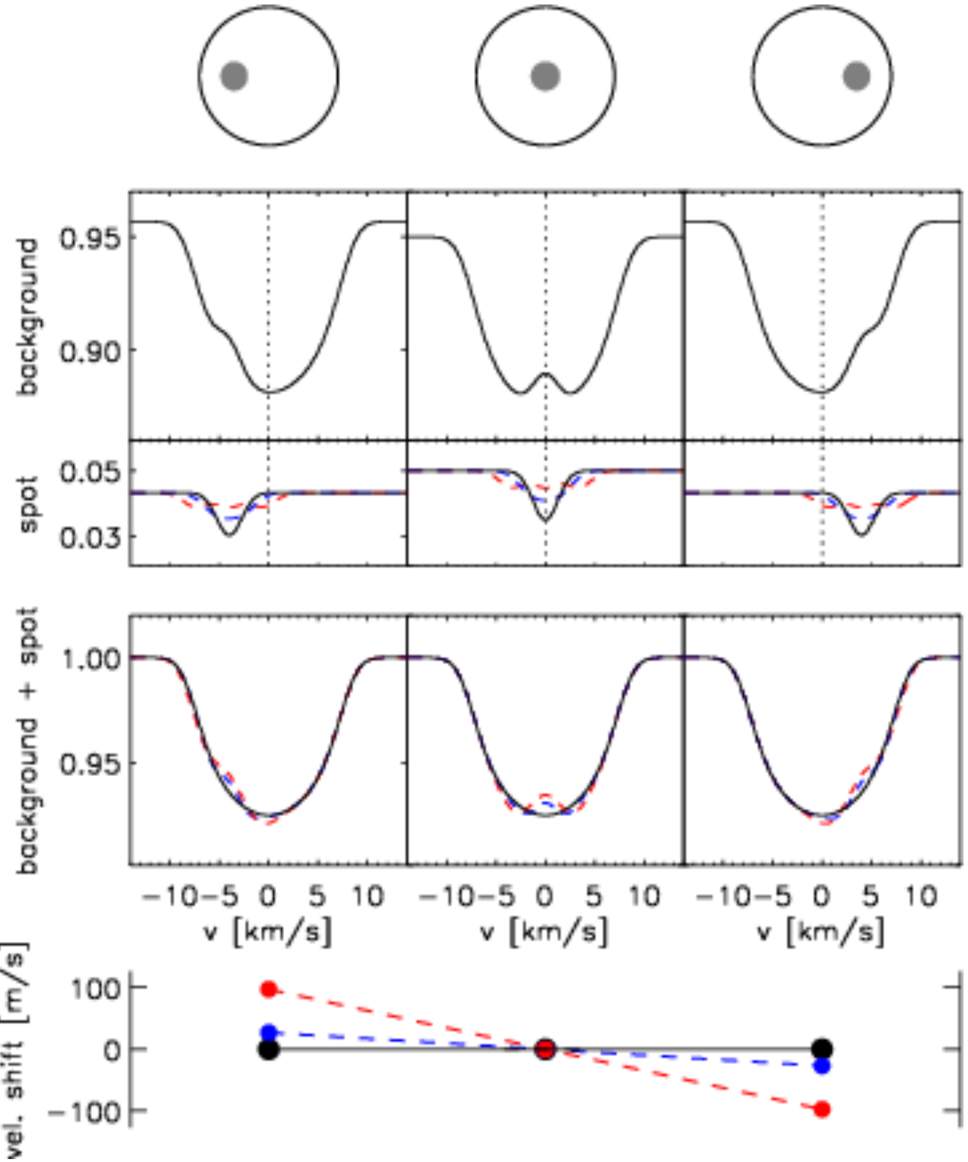


exo-Earth orbiting a solar-mass star exhibits a RV amplitude ~9cm/s!!

Radial Velocities & Magnetic Activity

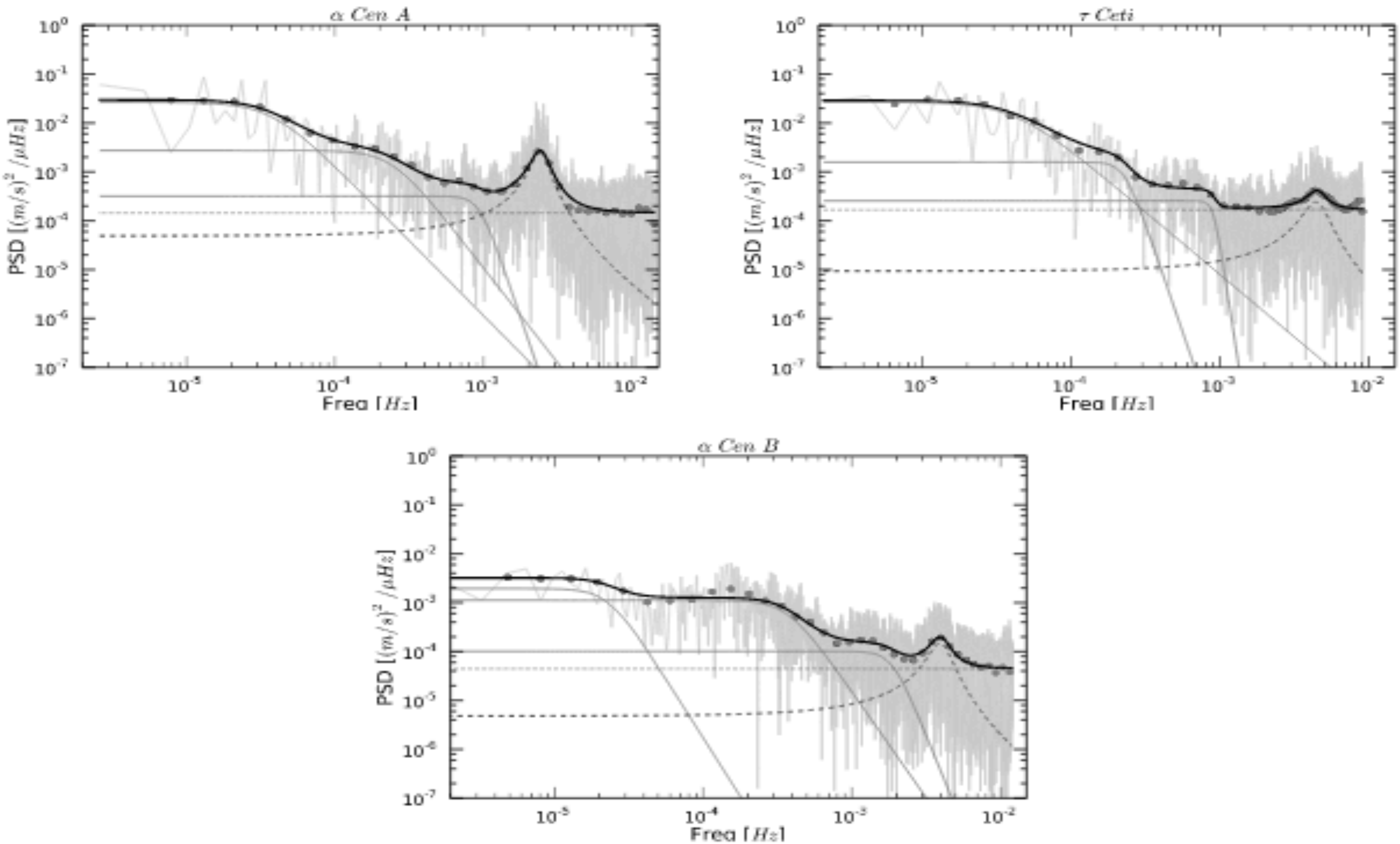


NASA – Solar Dynamics Observatory (SDO)



Reiners et al. 2013, A&A, 552, 103

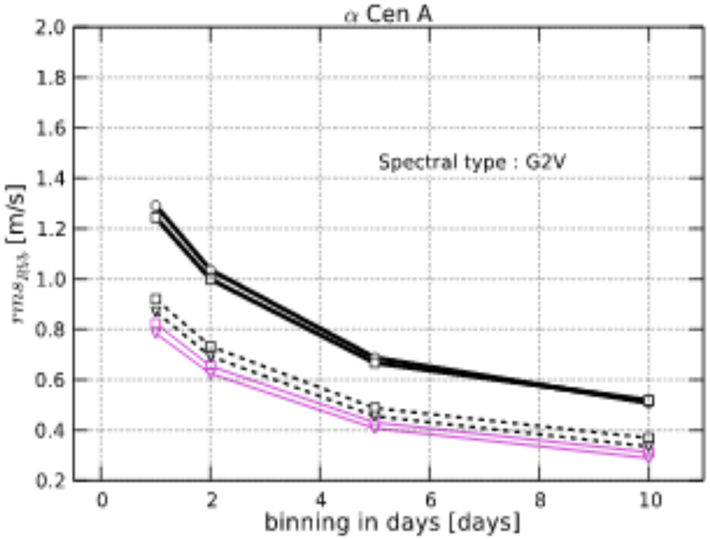
Convective Noise

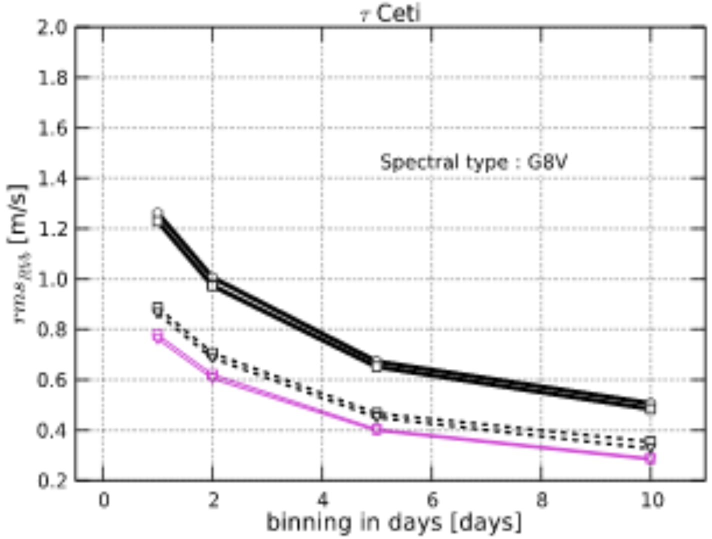


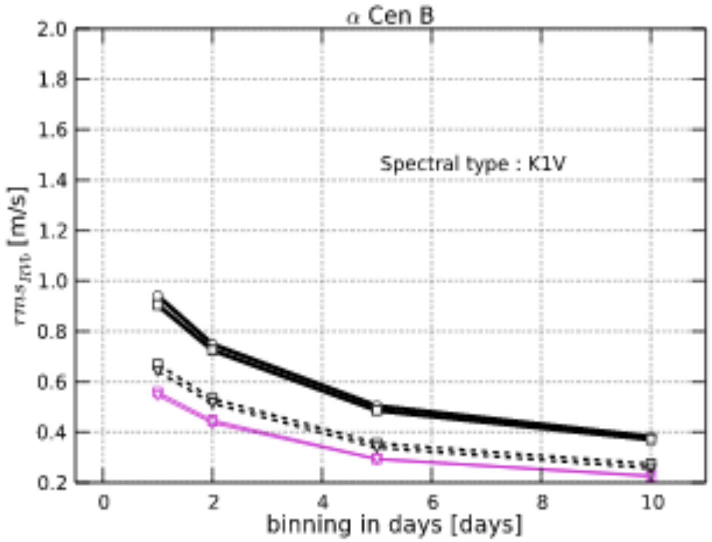
Granulation: 25 minutes   Mesogranulation: few hours   Supergranulation: ~1-1.5 days

Dumusque et al. 2011, A&A, 525, 140

Noise Suppression by Binning

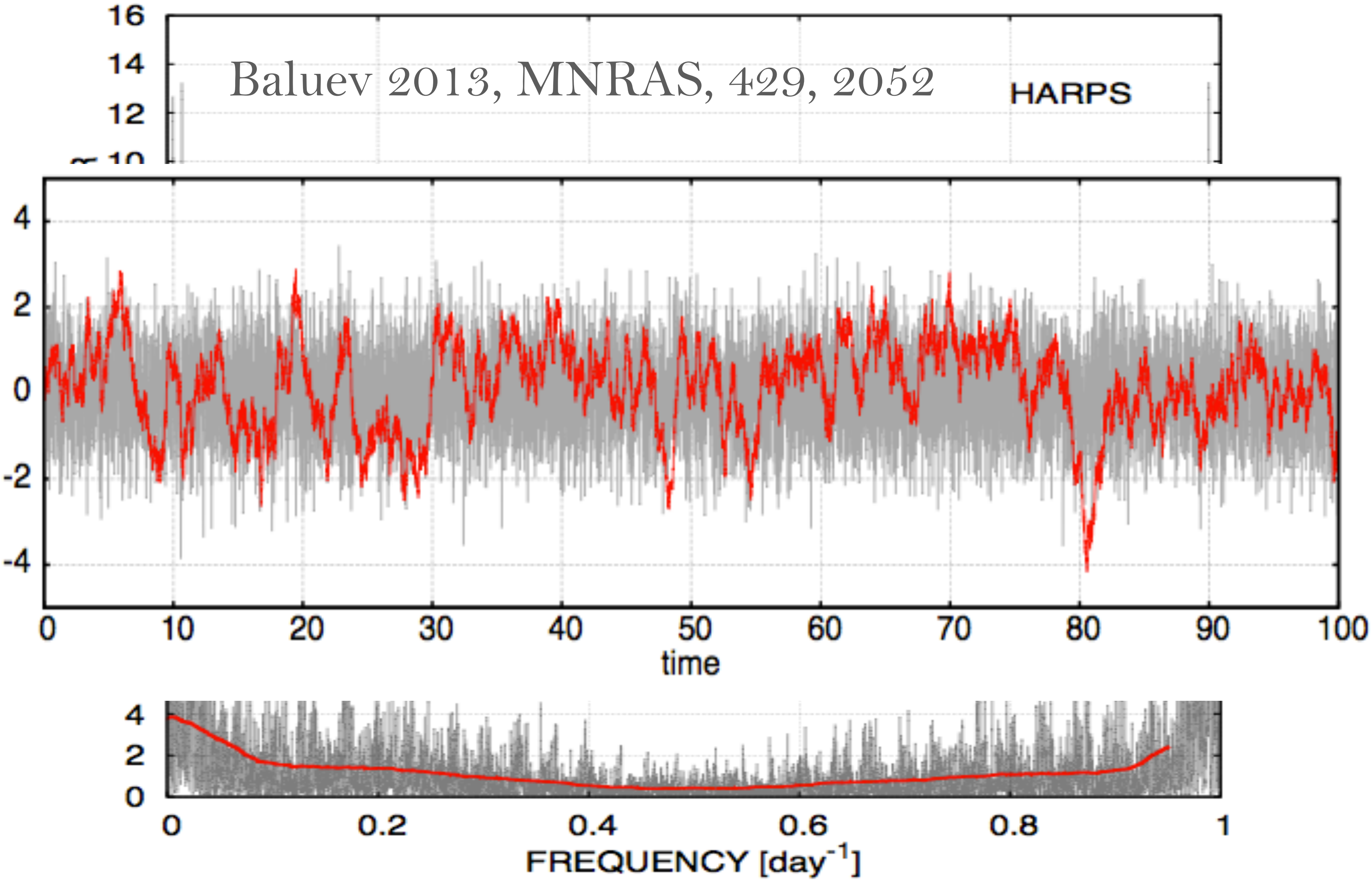




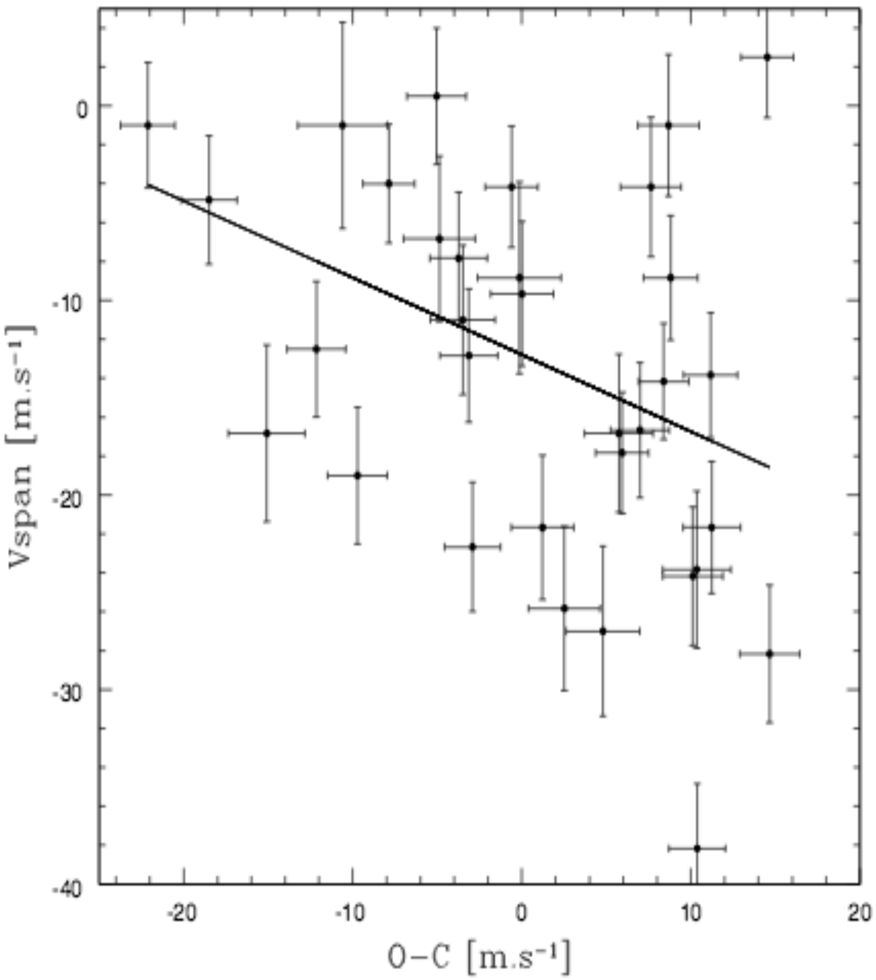


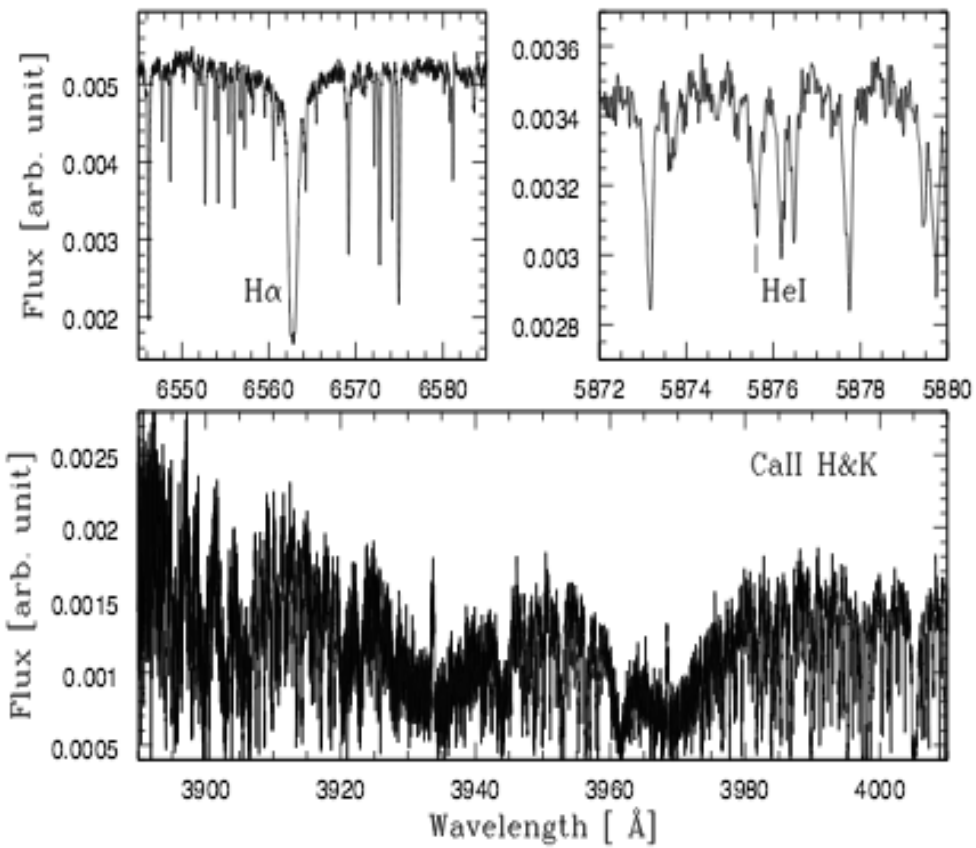
Averaging nightly Doppler velocities is the best strategy?

Impact of Correlated Noise on RVs



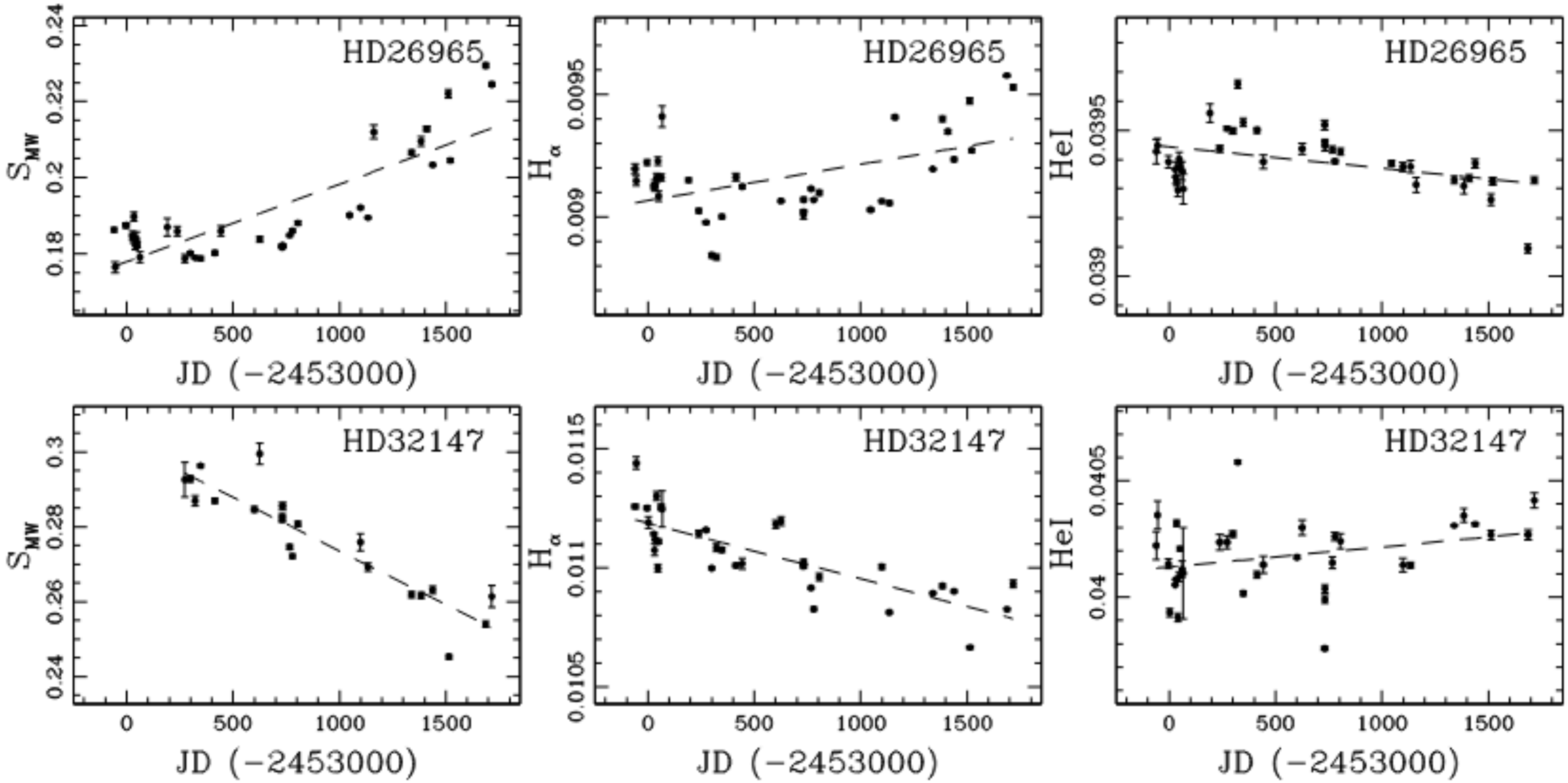
Activity Diagnostics





Boisse et al. 2009, A&A, 495, 959

Activity Cycles



Santos et al. 2010, A&A, 511, A54

Global+Correlated Noise Modeling

Keplerian models

Systemic offset

Linear activity correlations

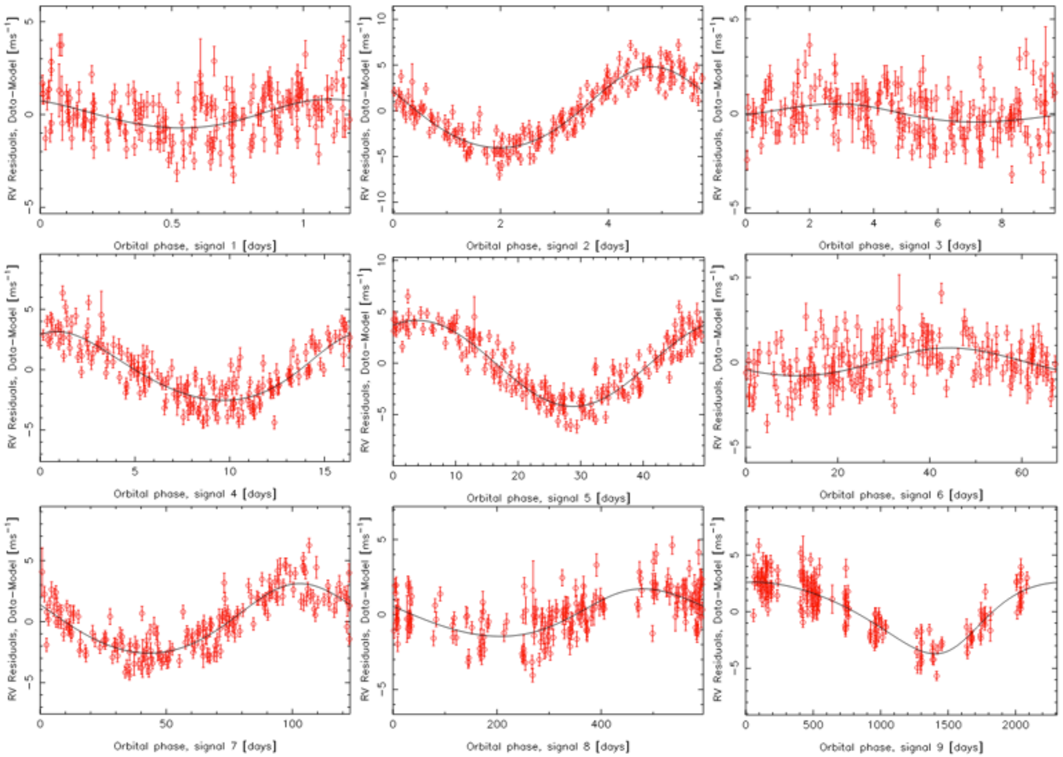
$$m_i = \gamma + \dot{\gamma} t_i + f_k(t_i) + \varepsilon_i + \sum_{j=1}^{p} \phi_j \exp\left\{ \frac{t_{i-j} - t_i}{\tau} \right\} \varepsilon_j + \sum_{j=1}^{q} c_j \xi_{j,i}$$

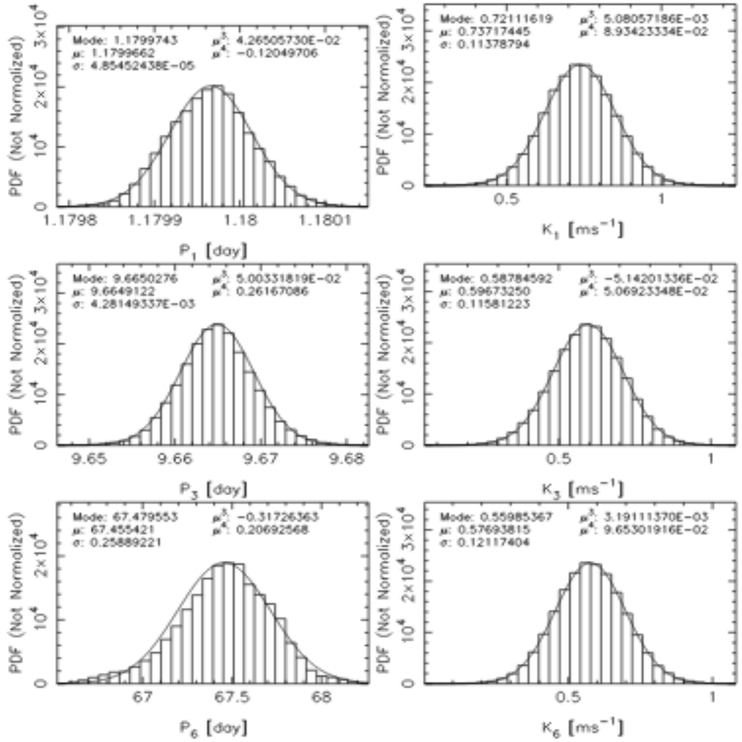
Acceleration term

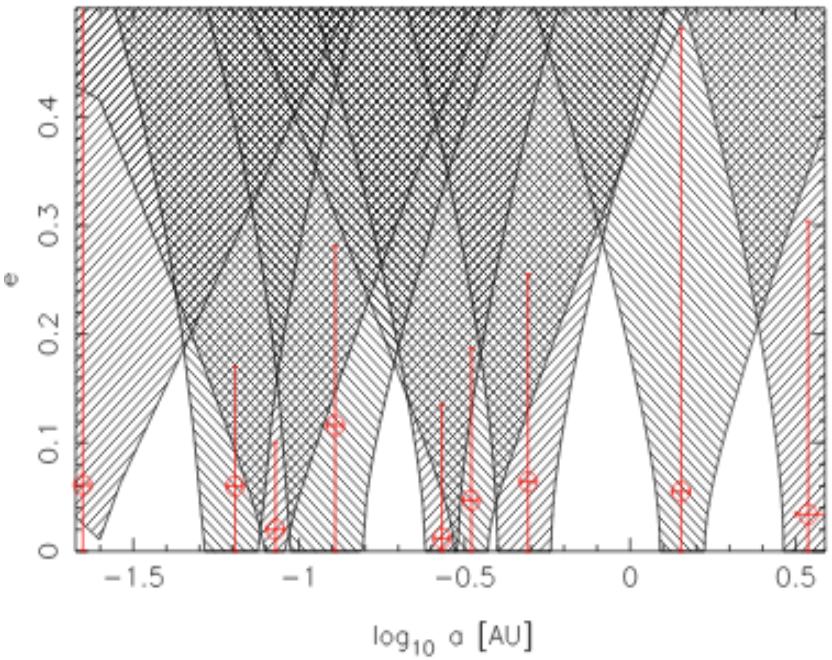
Moving Average model

Gaussian noise model

Nine Planets Orbiting HD10180?



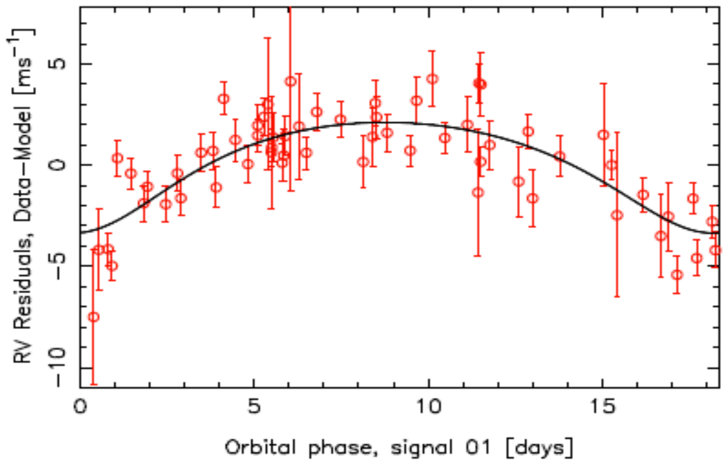


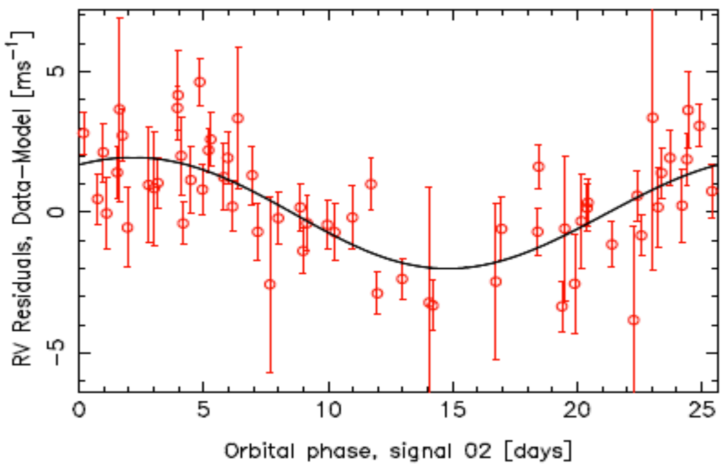


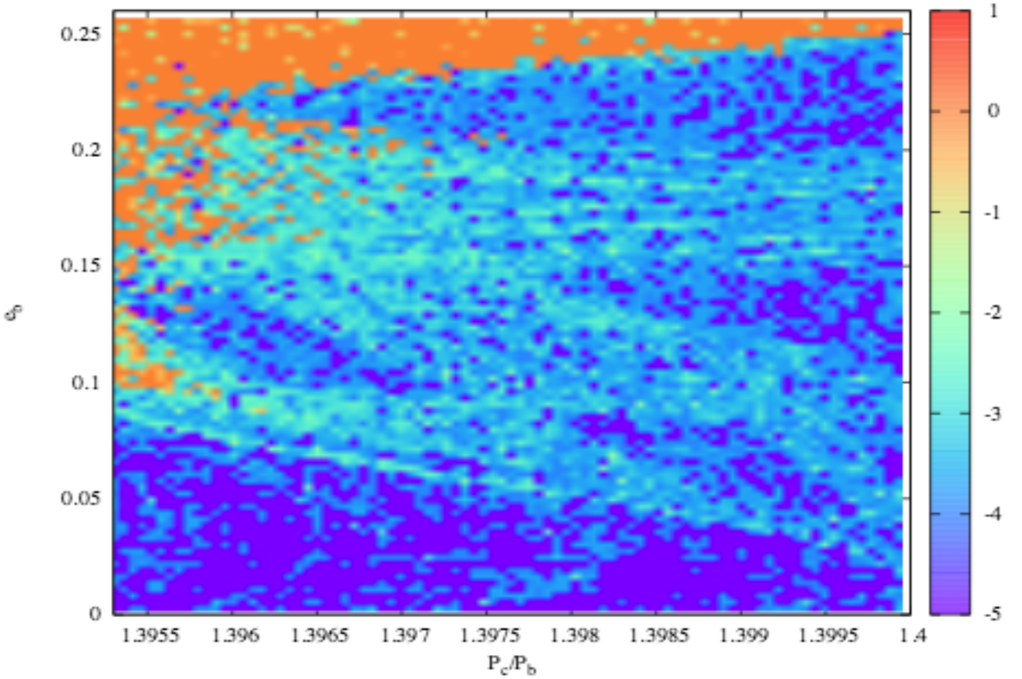
Would be a solar analogue with more planets than the solar system

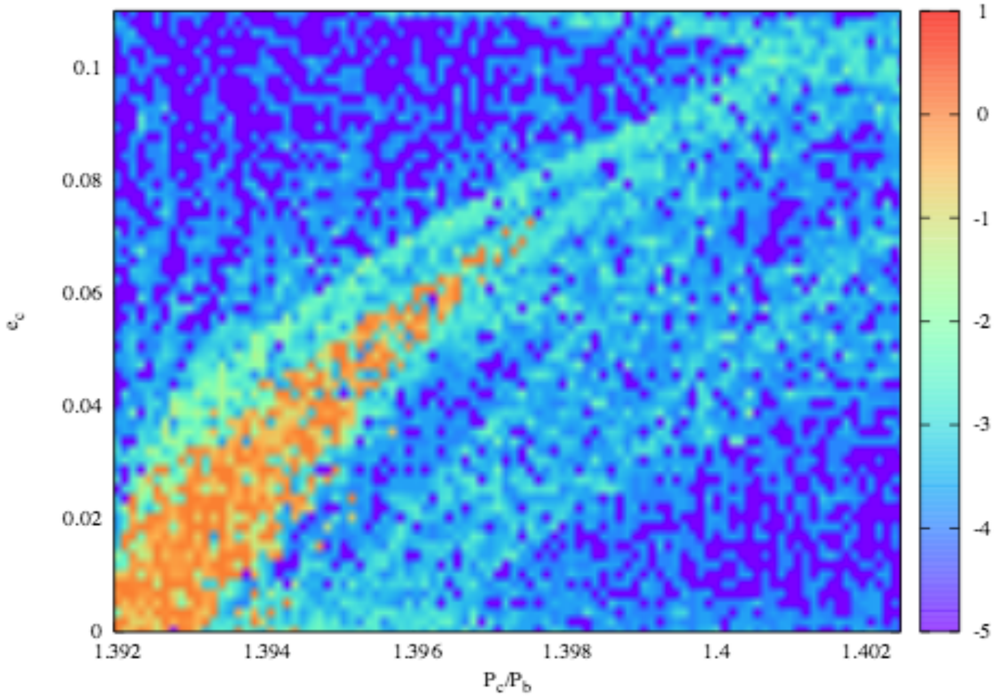
Tuomi 2012, A&A, 771, 41

HD41248 Signals
7:5 MMR?



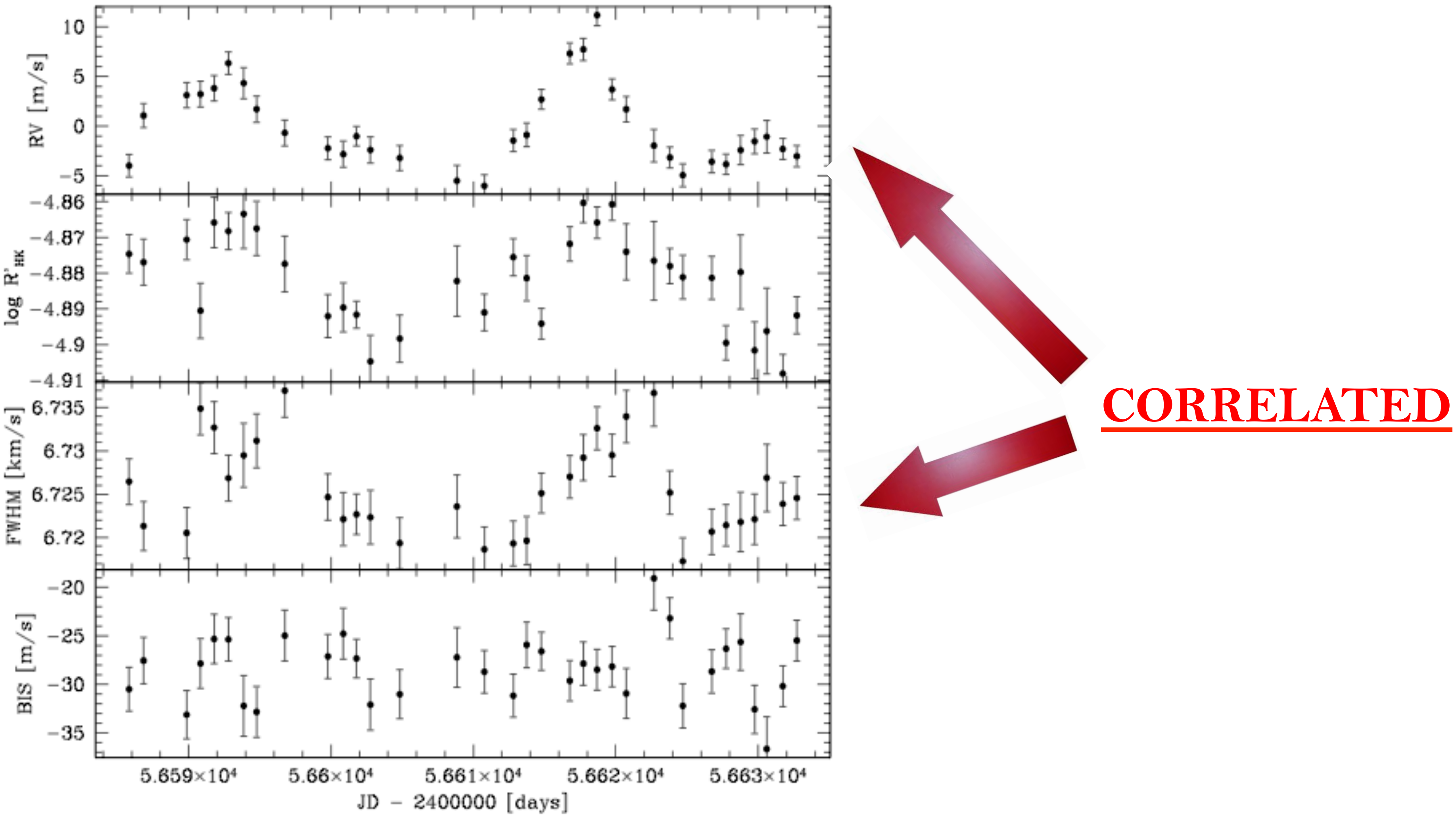






Jenkins et al. 2013, ApJ, 771, 41

Reanalysis of HD41248



Santos et al. 2014, A&A, 556, 35

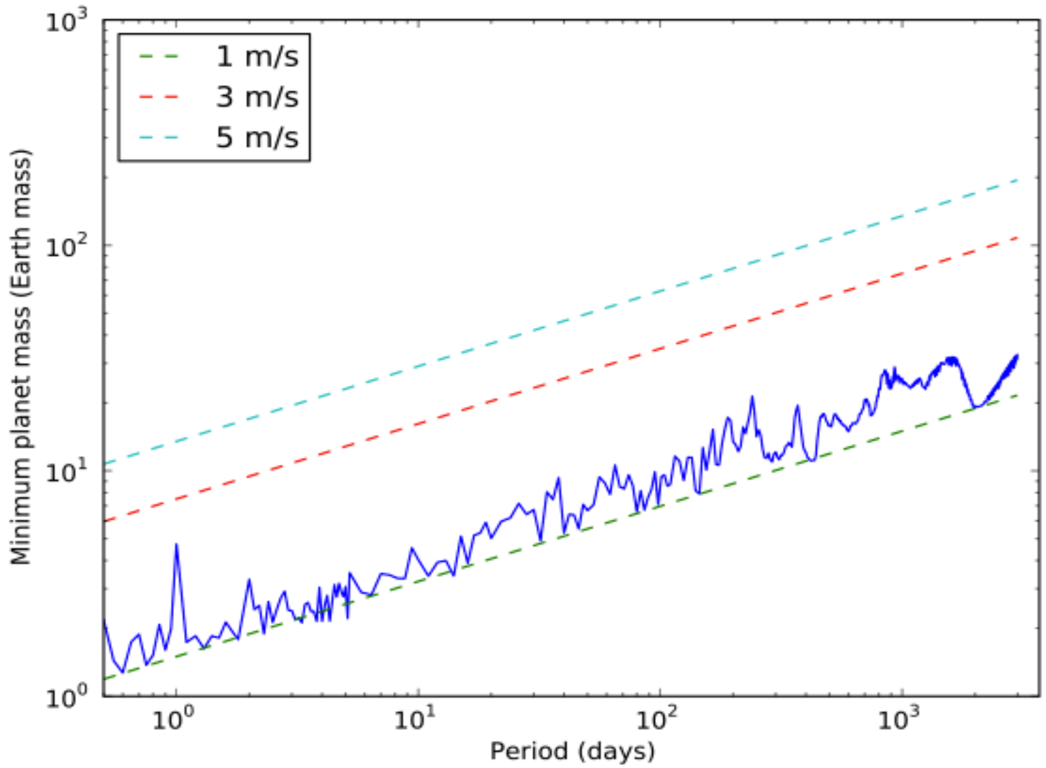
Reanalysis of HD41248

Conclusion

One signal at 25 days

Signal evolves with time

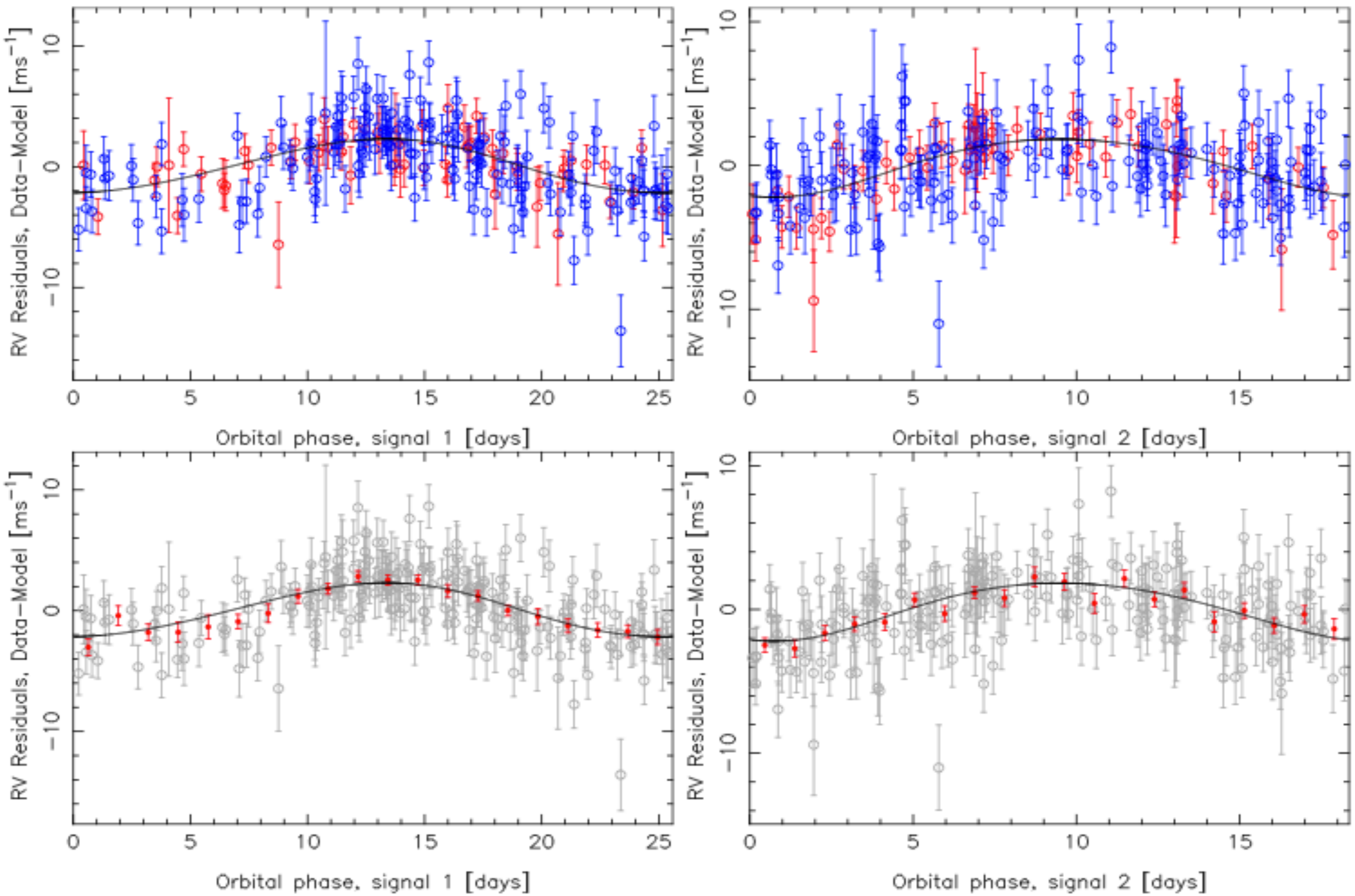
Due to an Active Longitude



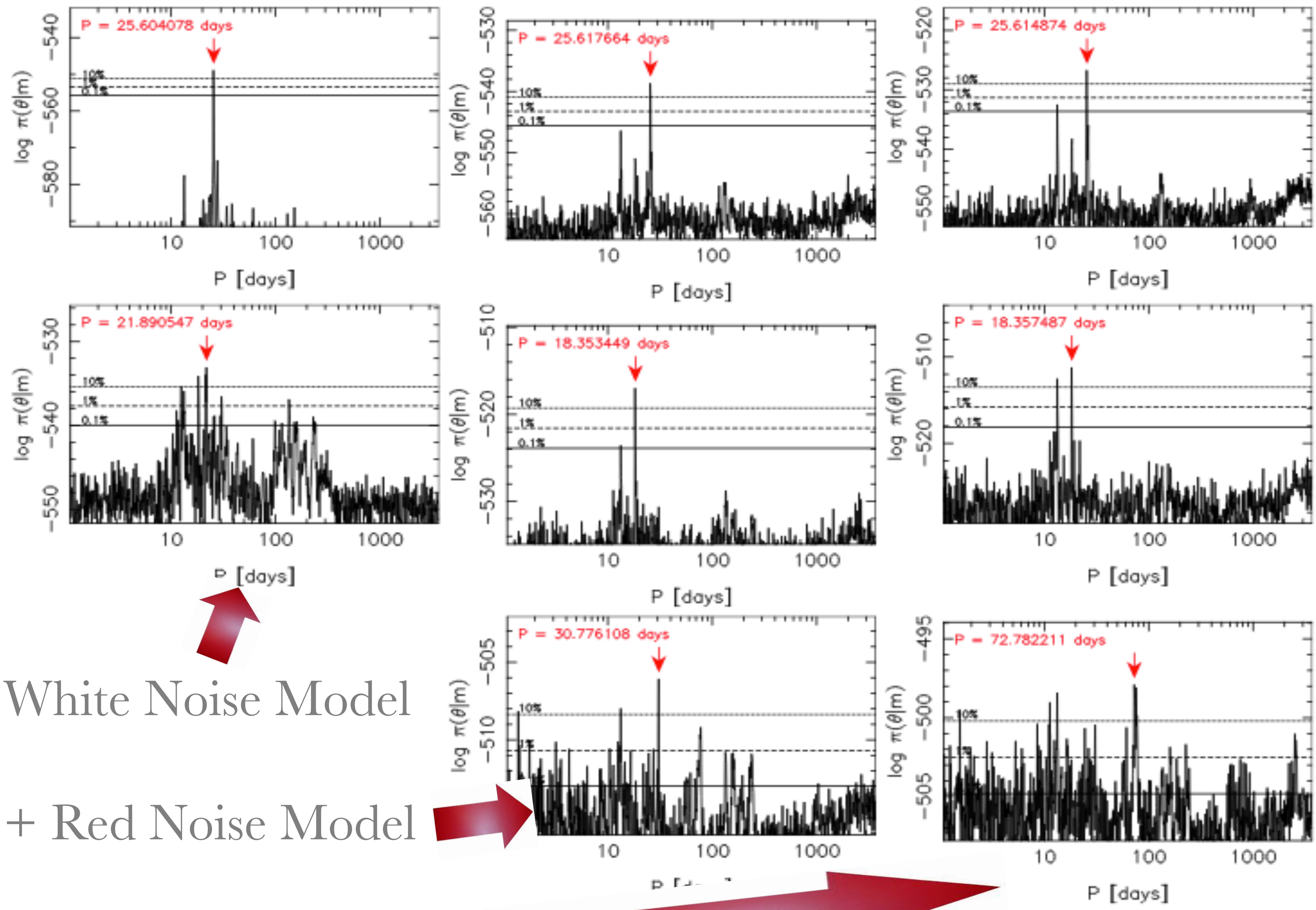
Weakness?

Simple modeling approach!!

Re-reanalysis of HD41248



Jenkins & Tuomi 2014, ApJ, 794, 110



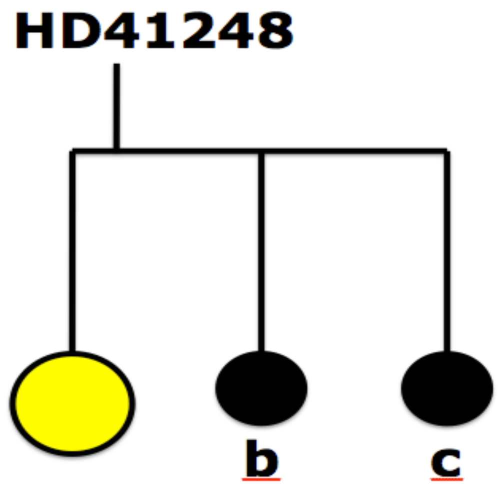
White Noise Model

+ Red Noise Model

+ Linear Correlations

Re-reanalysis of HD41248

- There are both red noise correlations and linear correlations
- Correlations are not constant with time
- Amplitude variations are not statistically significant … correlated noise?
- Two signals are still present and significant
- *Correlated noise modeling and global modeling can not be ignored if we want to discover the lowest-mass planets!!*

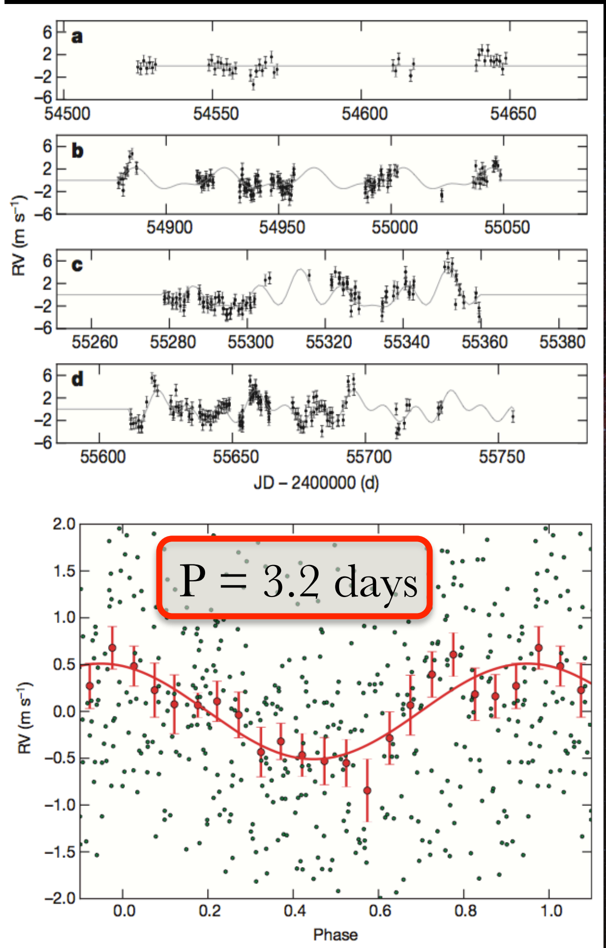


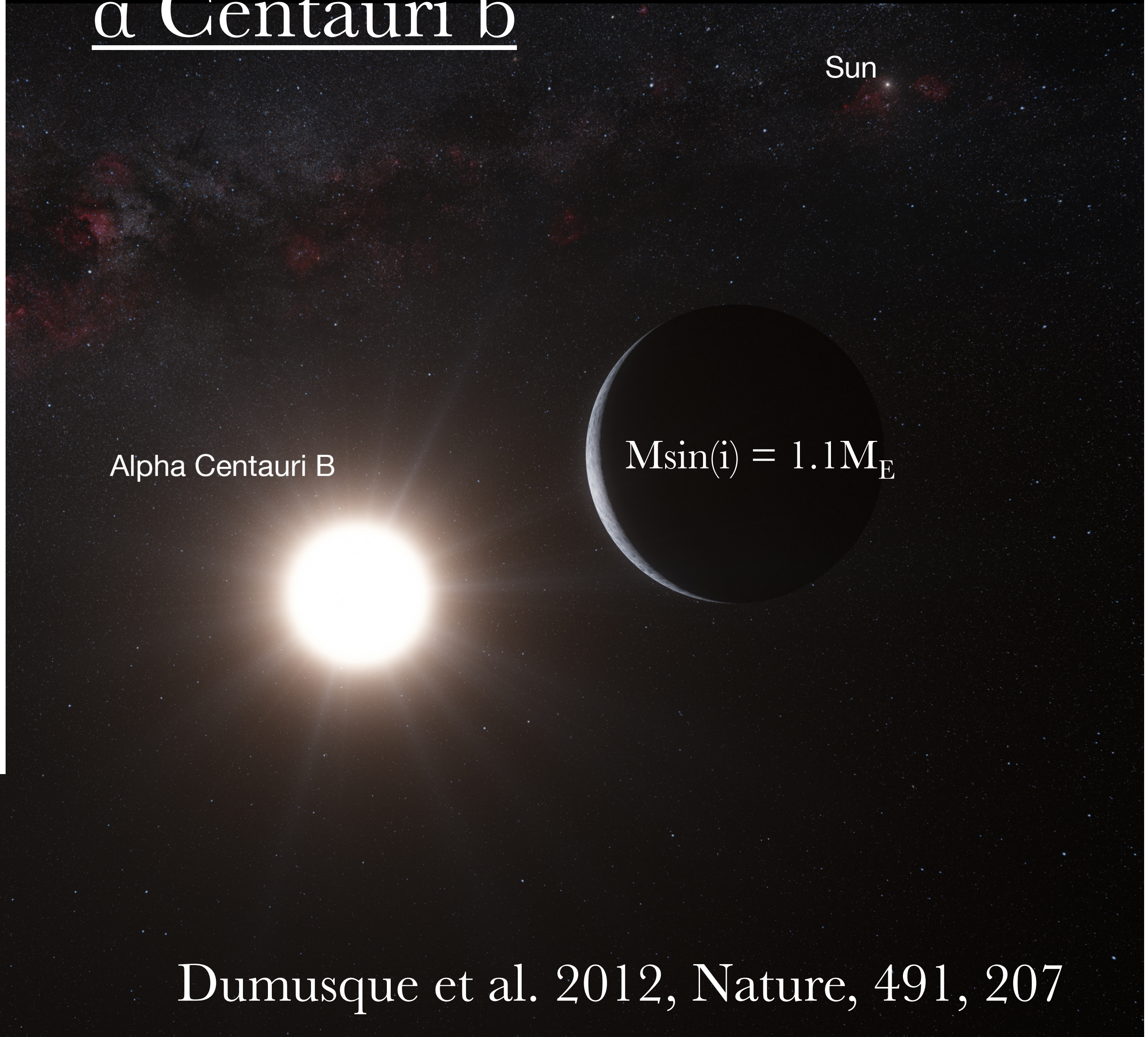
Planetary signals Recovery

https://rv-challenge.wikispaces.com/

Planets with K > 1 m/s	52/57 (91%)	50/57 (88%)
Planets with K < 1 m/s	4/35 (11%) (K=0.34, 0.6, 0.7, 0.8)	1/35 (3%) (K=0.6)
Mistake with K > 1 m/s	2 (1 because wrong Prot)	4
Mistake with K < 1 m/s	2	3

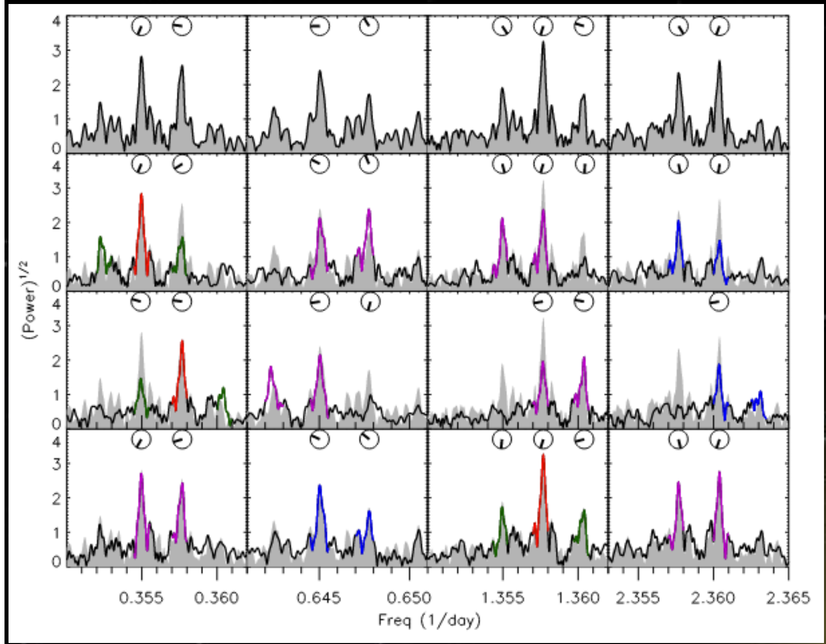
α Centauri b





Dumusque et al. 2012, Nature, 491, 207

55 Cancri e



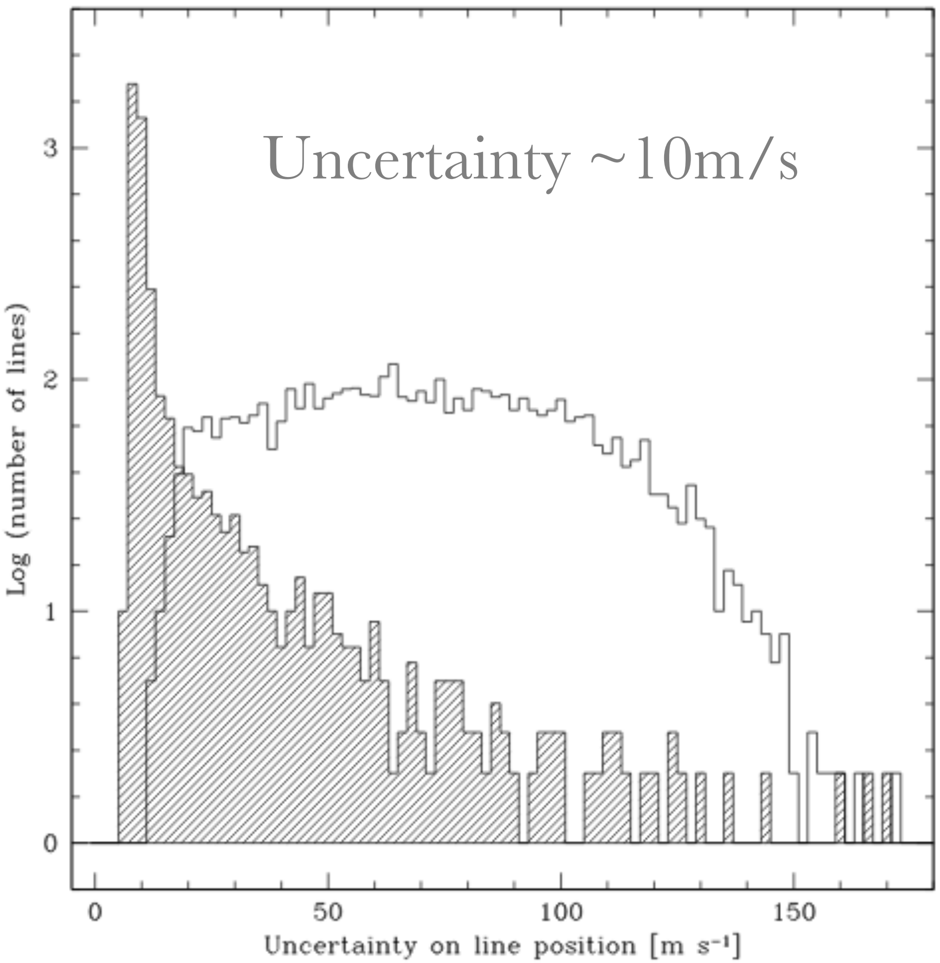
P = 0.7 days

Msin(i) = 8.6M_E

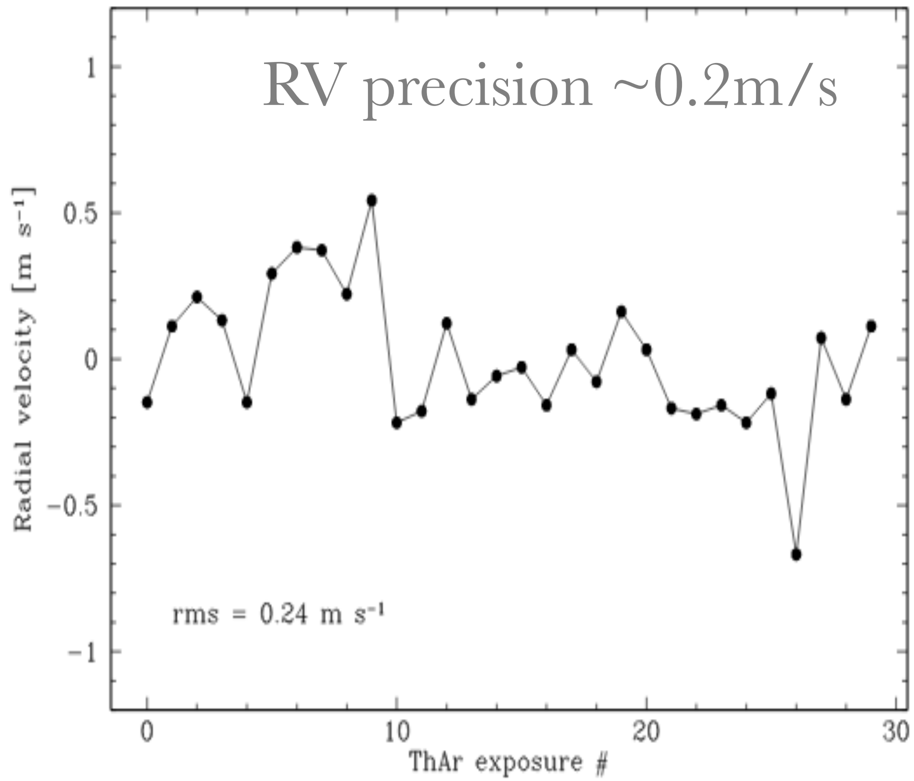
McArthur et al. 2004, ApJ, 614, L81

Dawson & Fabrycky 2010, ApJ, 722, 937

Current HARPS Precision

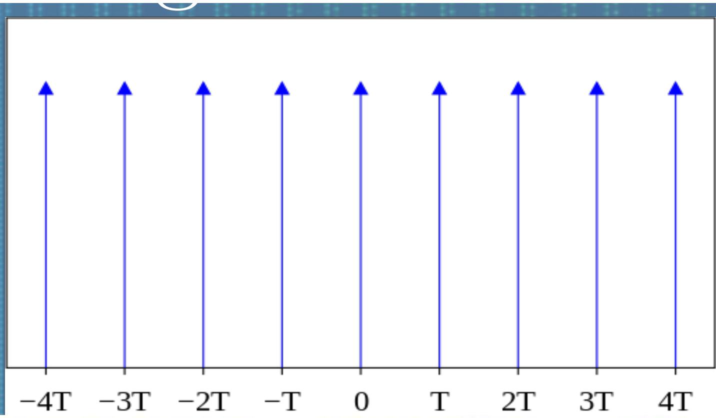


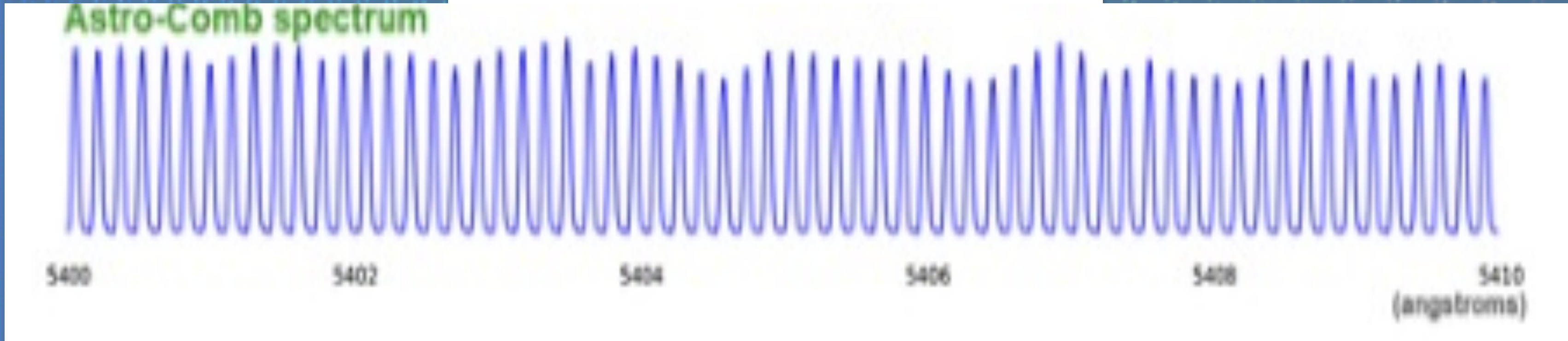
Lovis & Pepe 2007, A&A, 468, 1121



Remember: RV amplitude of an exo-Earth orbiting a solar-mass star is only 9cm/s!!

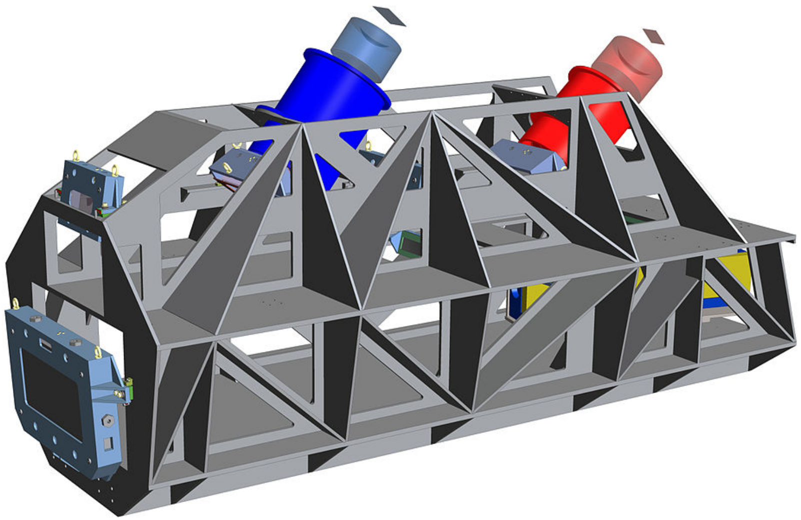
Reaching 1cm/s Precision



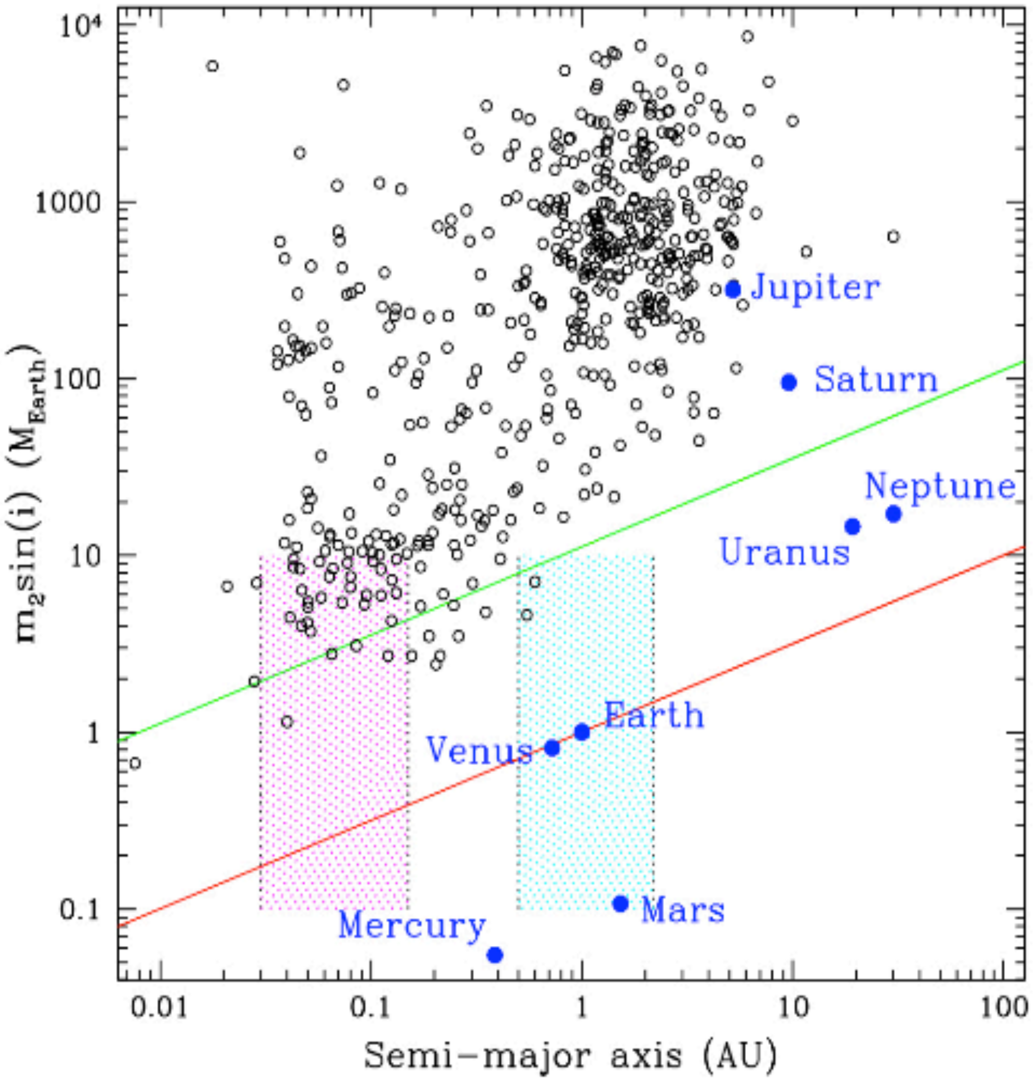


Mode-locked laser comb – Dirac delta functions separated by the repetition rate

HARPS results reveal 2cm/s precision!!



ESPRESSO



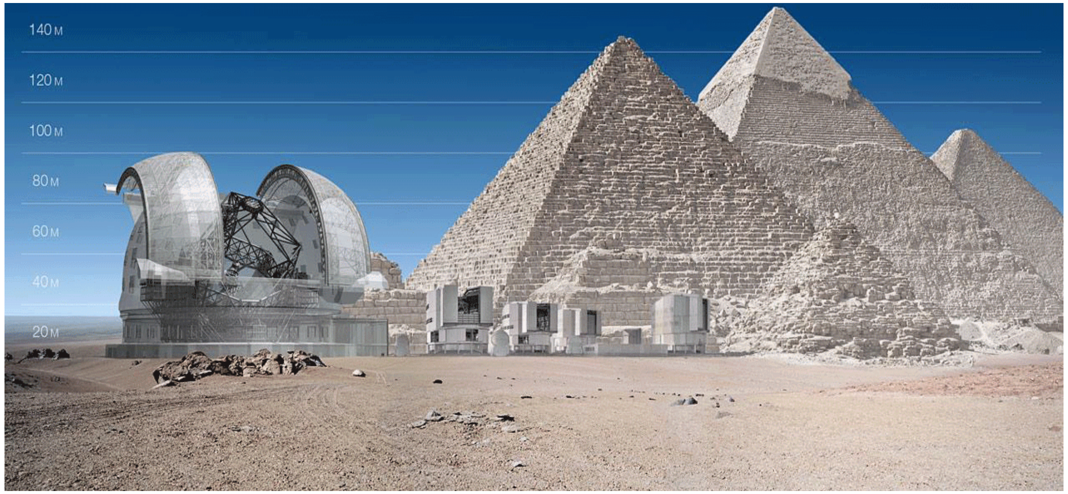
Gains compared to HARPS

2 - 3.5 magnitudes in depth

4 telescope flexibility

~order of magnitude in RV precision ~0.1m/s (10cm/s)

Pepe et al. 2014, AN, 335, 10



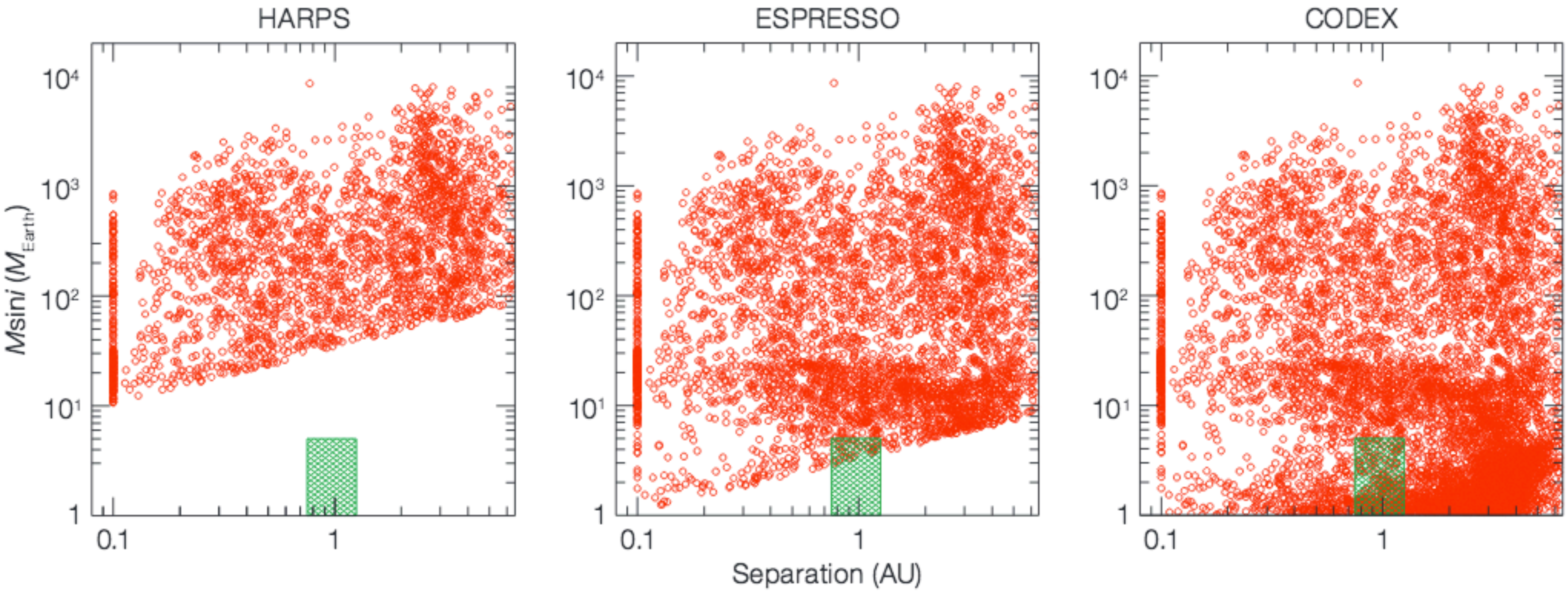
ELT - CODEX

Gains over ESPRESSO

Factor of 6 increase in collecting area ~10^9 objects

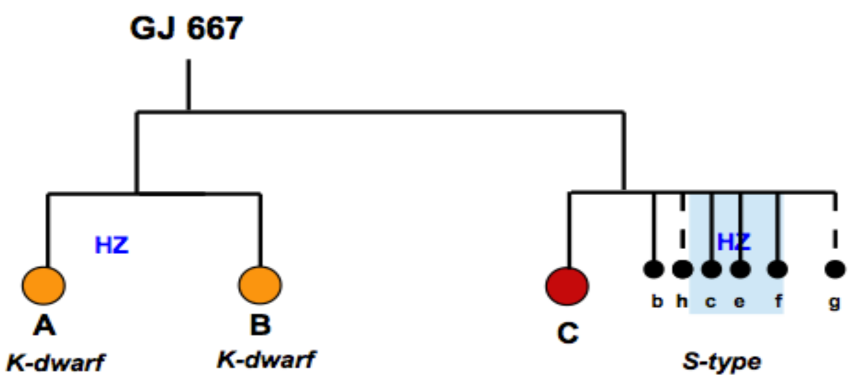
Pasquini et al. 2010, Msngr, 140, 20

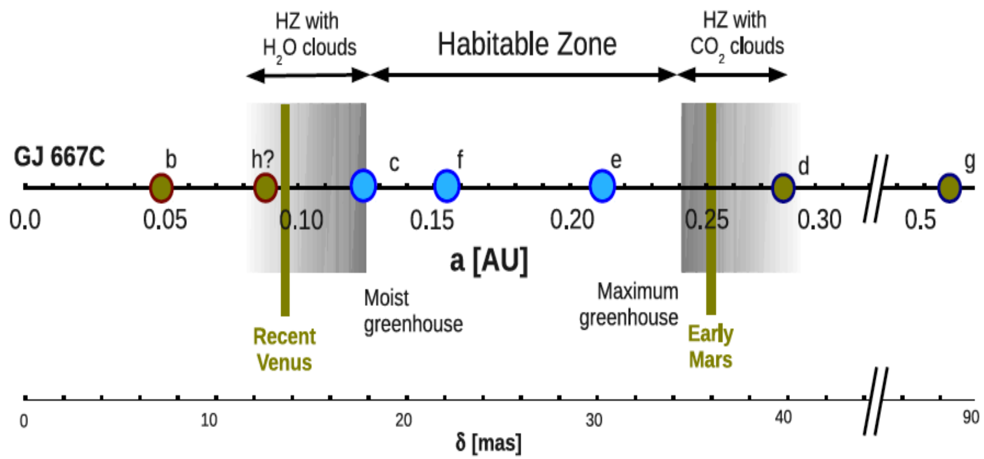
~order of magnitude in RV precision ~0.01m/s (1cm/s)



Near-IR….The Worlds of GJ667C

Possible 7 planet system with 4 rocky planets in the Habitable Zone!

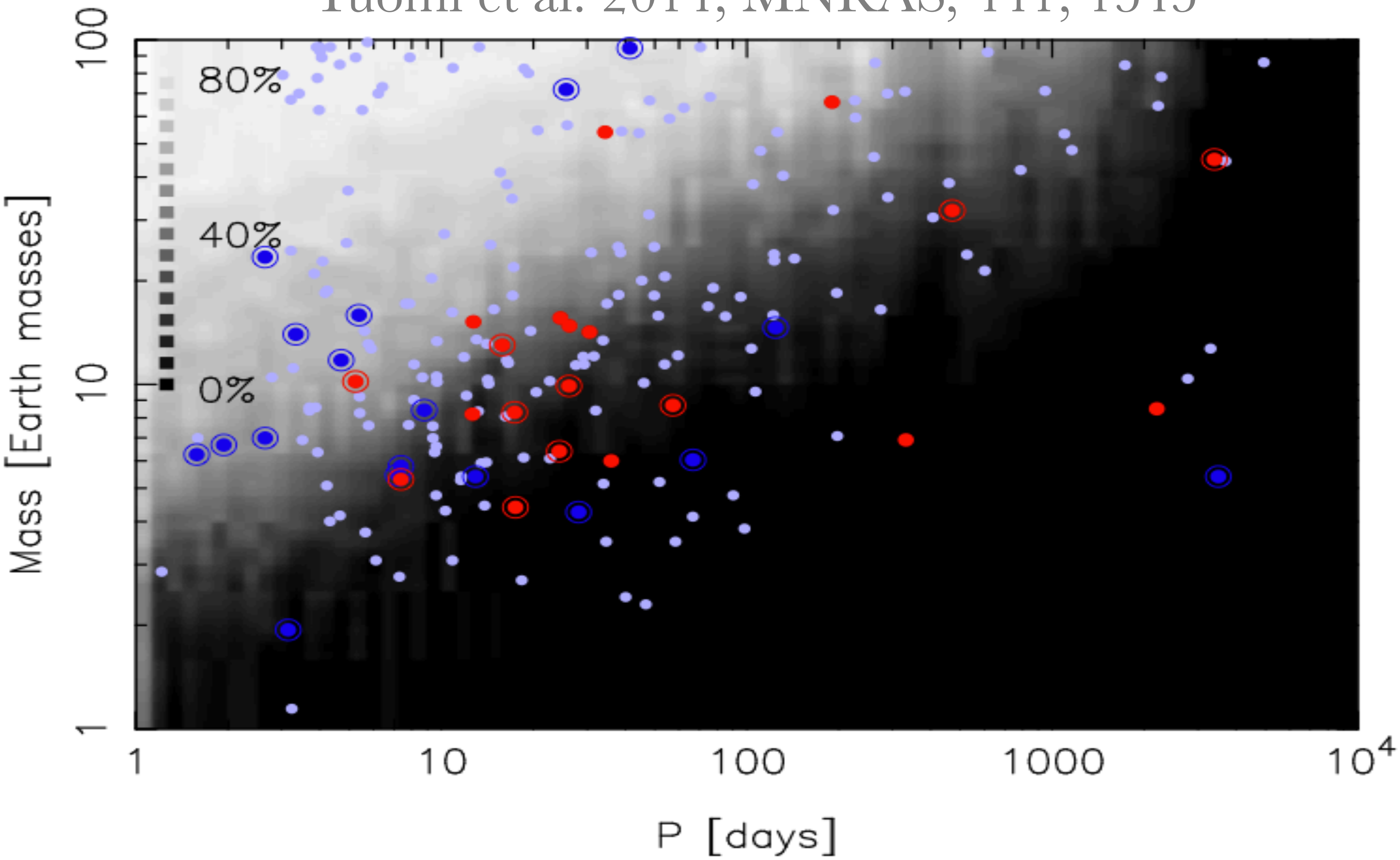




Anglada-Escude et al. 2013, A&A, 556, 126

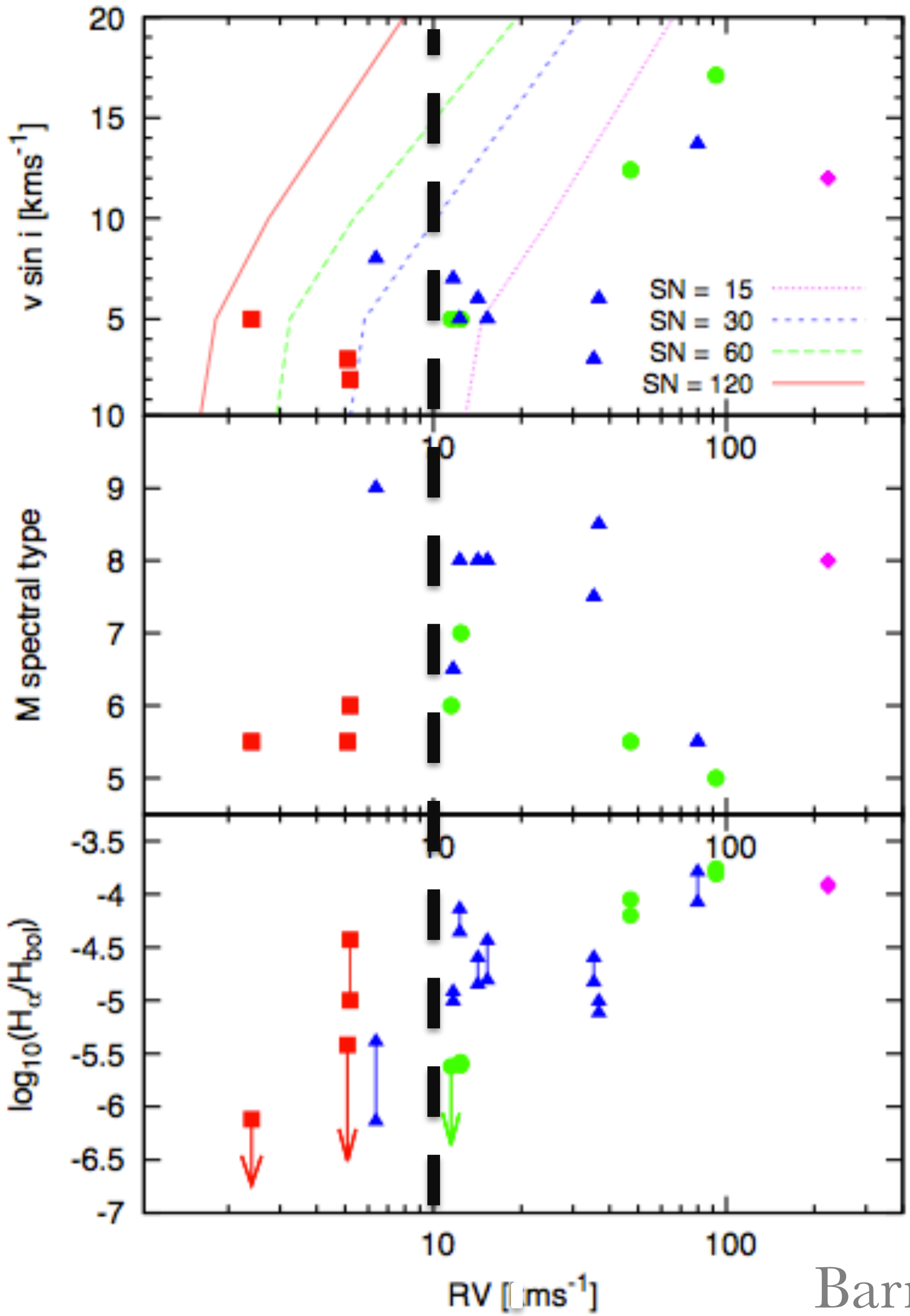
Fraction of Planets Orbiting M-dwarfs

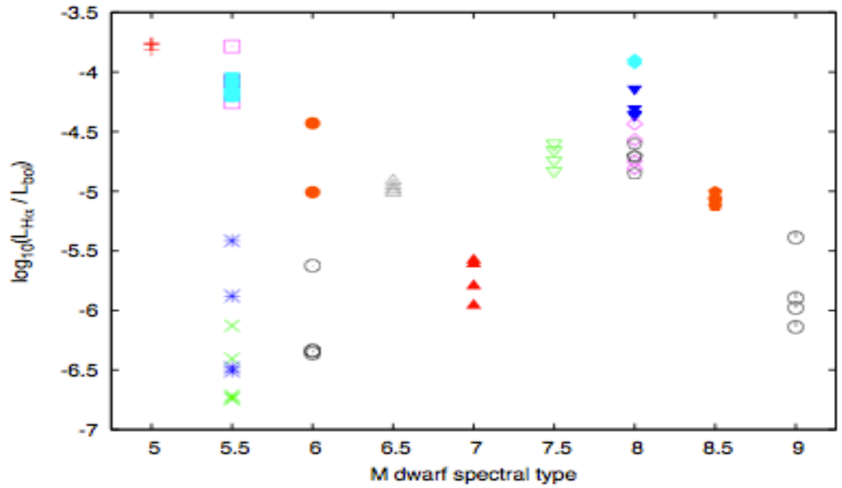
Tuomi et al. 2014, MNRAS, 441, 1545

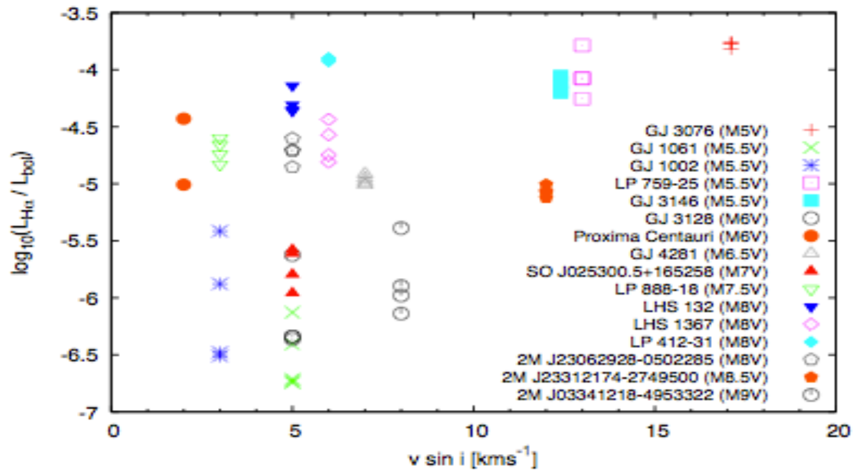


3-10M_E & 10-100 d = 1.02 (0.69-1.48)

3-10M_E in the HZ = 0.21 (0.18-0.26)



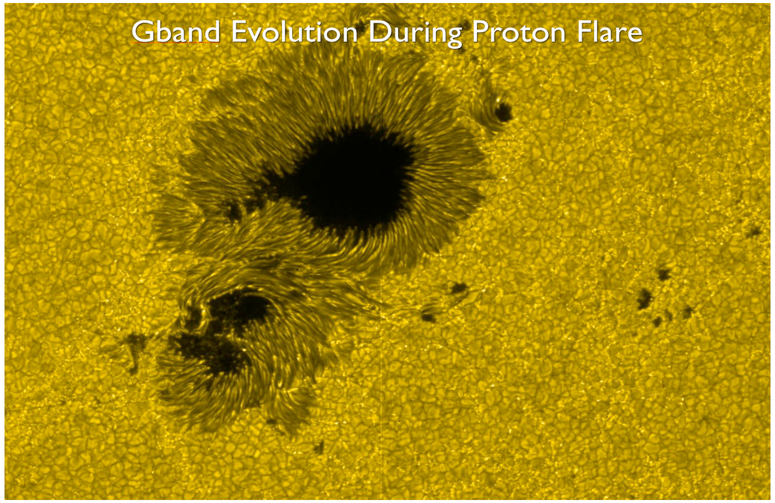


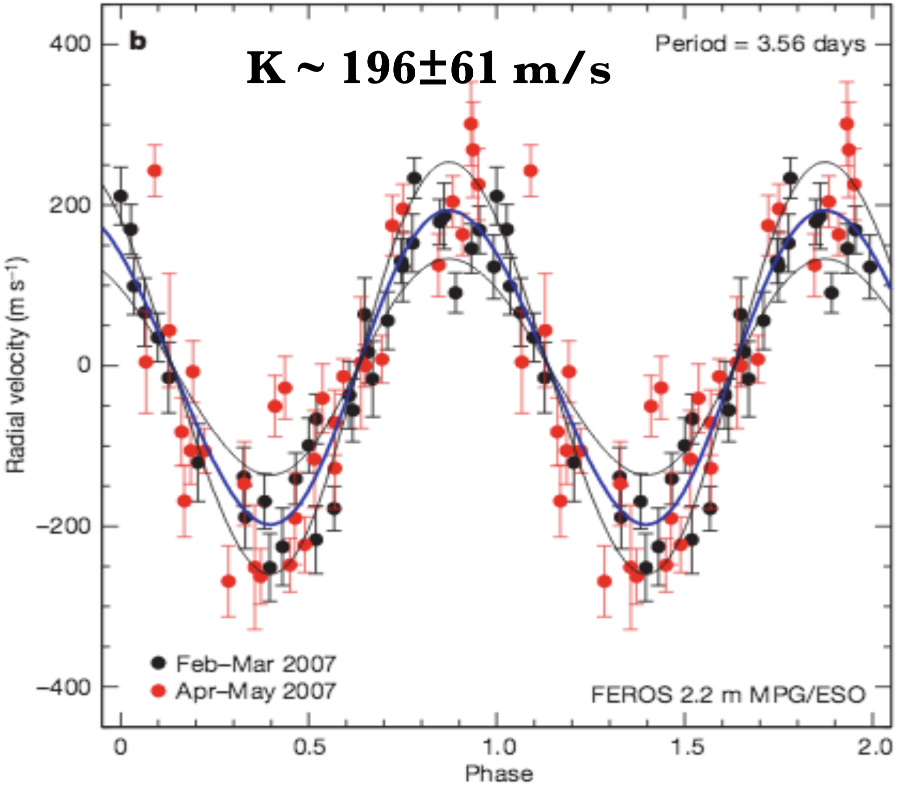


Late Ms tend to exhibit RV scatter in excess of 10m/s!!

Barnes et al. 2014, MNRAS, 439, 3094

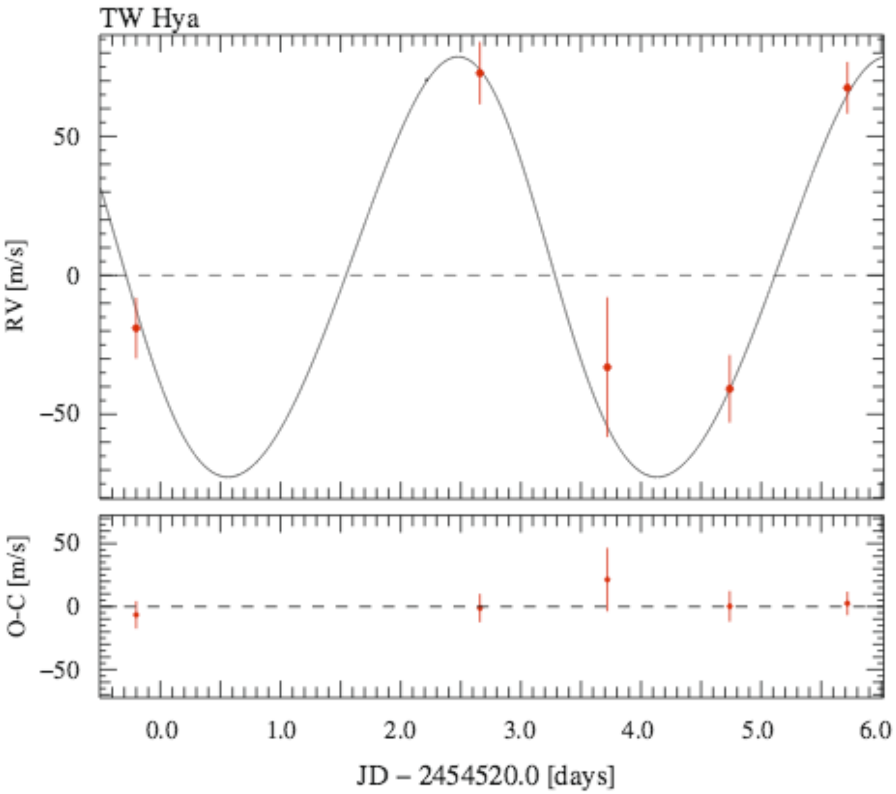
Optical+Near IR



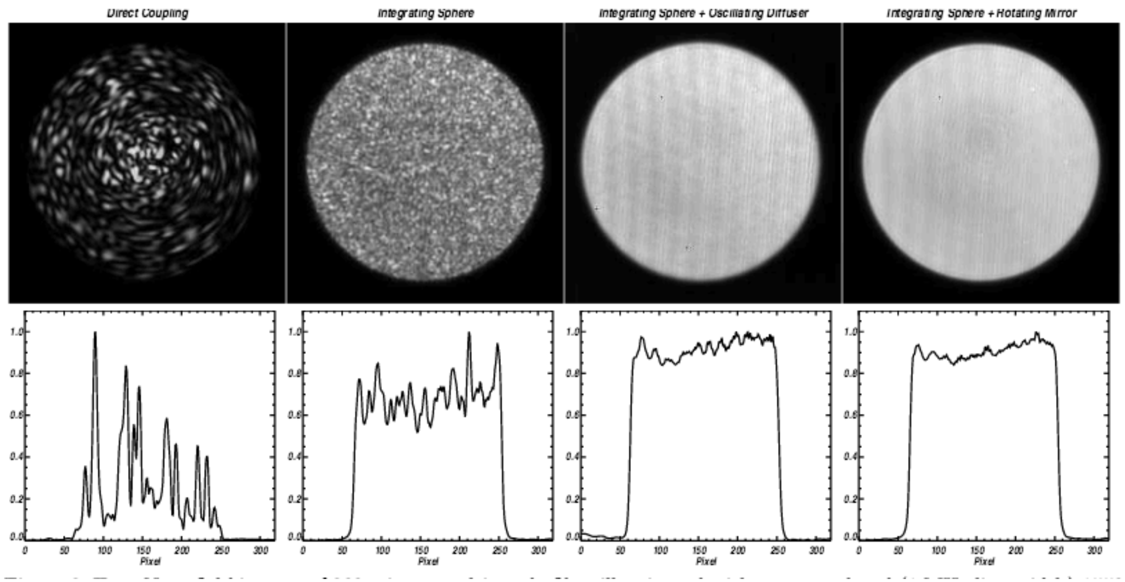


Setiawan et al. 2008, Nature, 451, 3

K ~ 80.50±6.83 m/s



Figueira et al. 2010, A&A, 511, 55

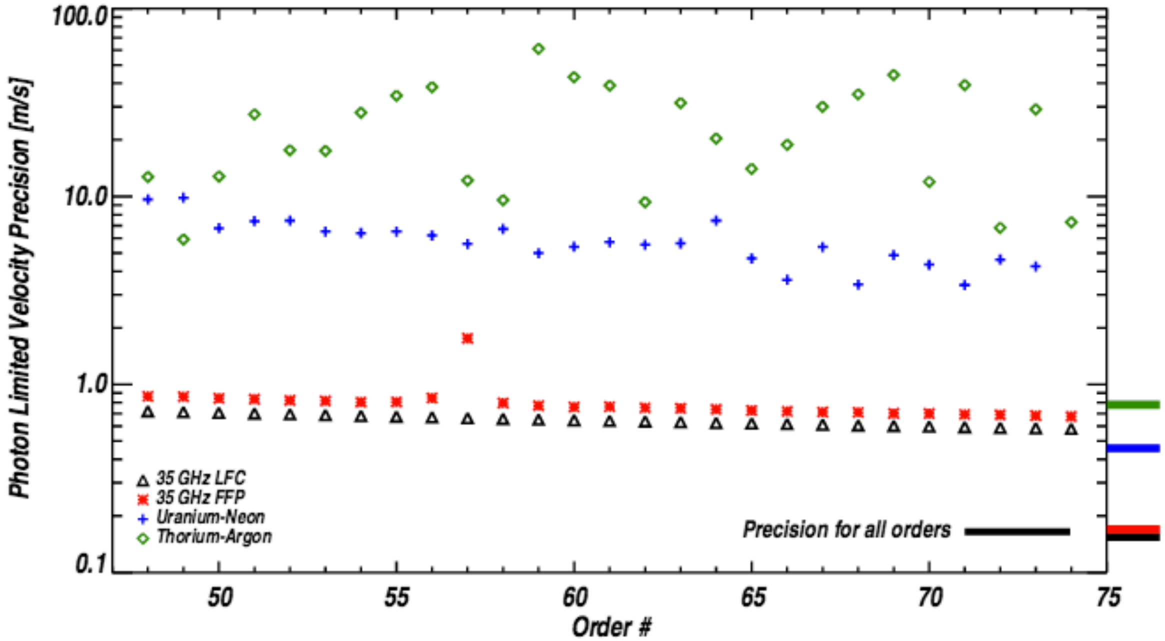


Habitable Planet Finder

Near-IR modal noise reduction

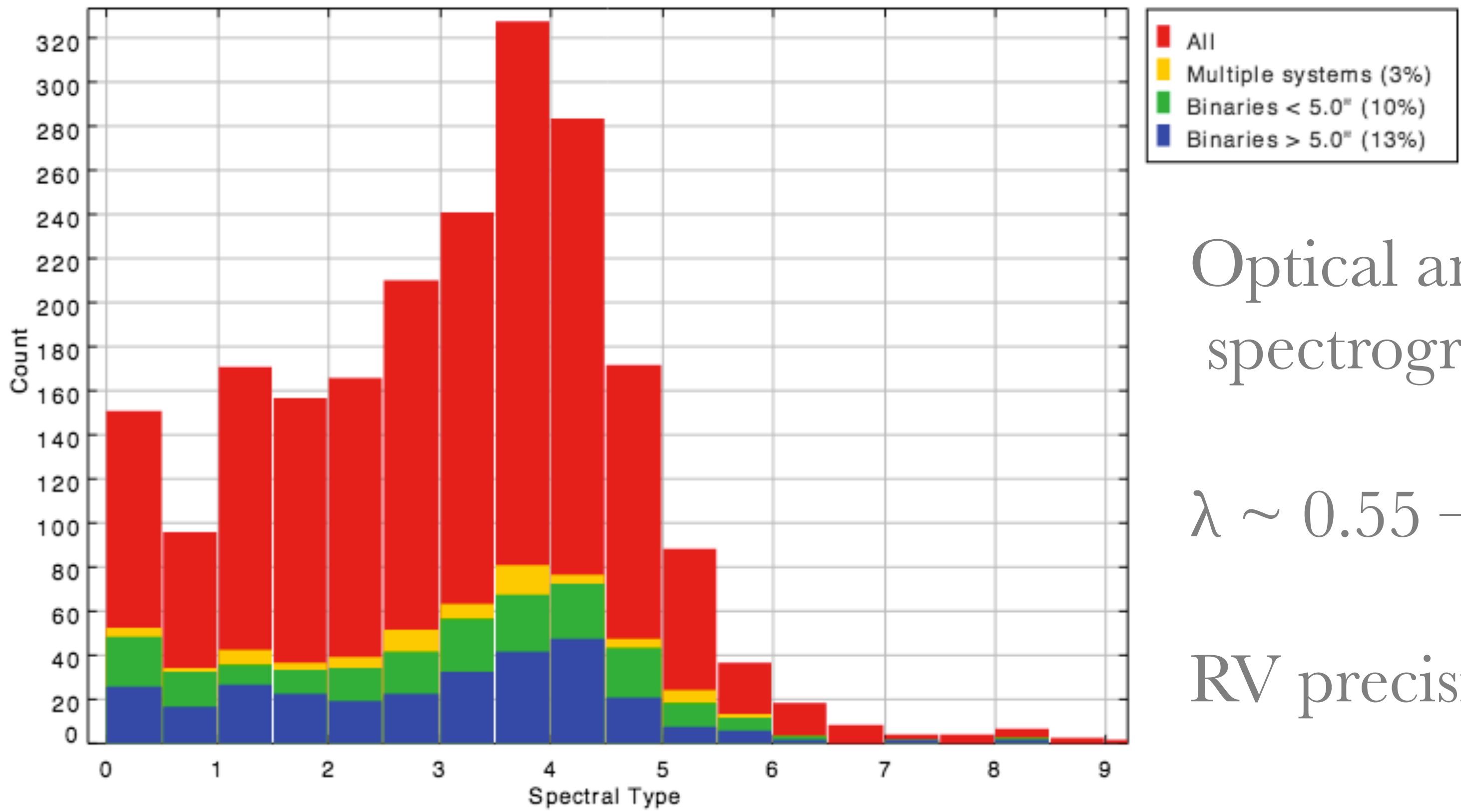
Multiple wavelength calibration units

~1m/s RV precision expected



Halverson et al. 2014, SPIE, 9147, 7

carmenes



Optical and near-IR spectrograph

λ ~ 0.55 – 1.7μm

RV precision ~1m/s

Quirrenbach et al. 2014, SPIE, 9147, 1

RV Summary

- *Stars seem to the limiting factor for detecting exo-Earths*
- *Radial velocity surveys are now detecting rocky planets*
- *Pathways towards the stability level necessary to reach exo-Earths orbiting Sun's are in place*
- *Optical and near-IR spectrographs can be used in conjunction to help alleviate false-positives*

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- ❑ *What is an exo-Earth in the context of planet searches?*
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  - *Where should we be looking?*

- ❑ *Challenges to overcome in the detection of exo-Earths orbiting the nearest stars*
  - *Radial velocity noise sources*
  - *Instrumental issues*
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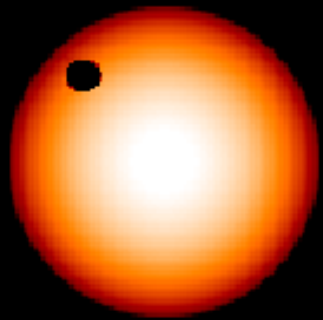
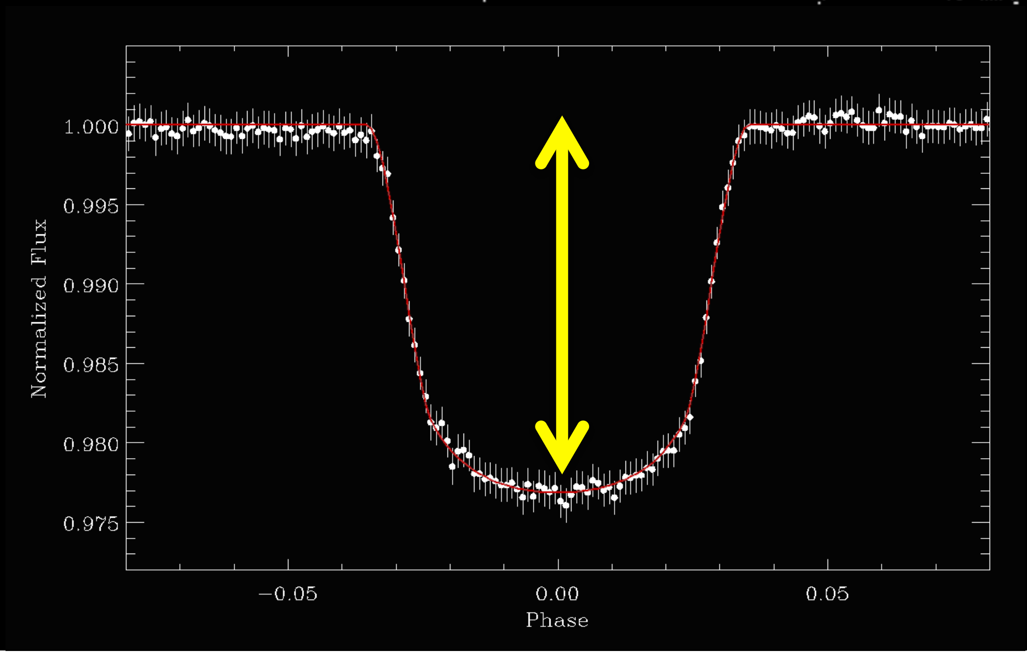
- ❑ *Potential for exo-Earth characterisation*

Exoplanet Transits





Transit Depths

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$$

F = flux

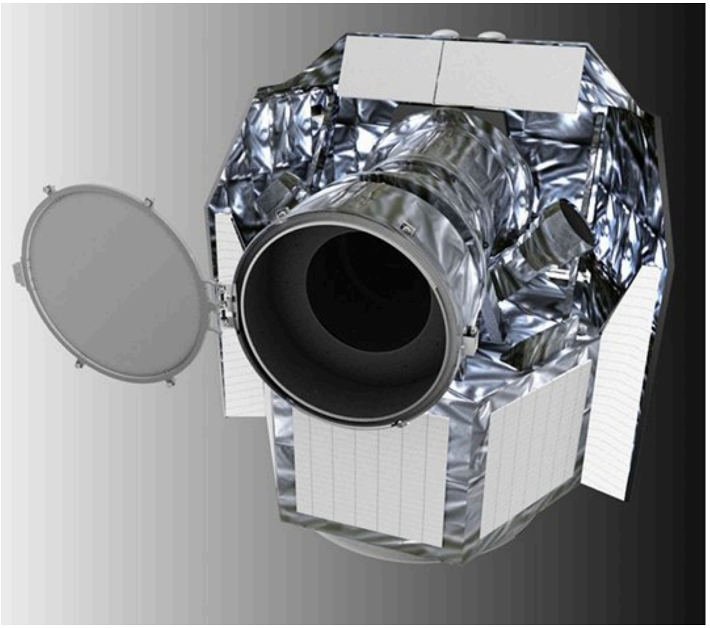
ΔF = Flux difference

R_p = Planet radius

R_* = Star radius

Earth-sized transiting planet depth ~0.1% level

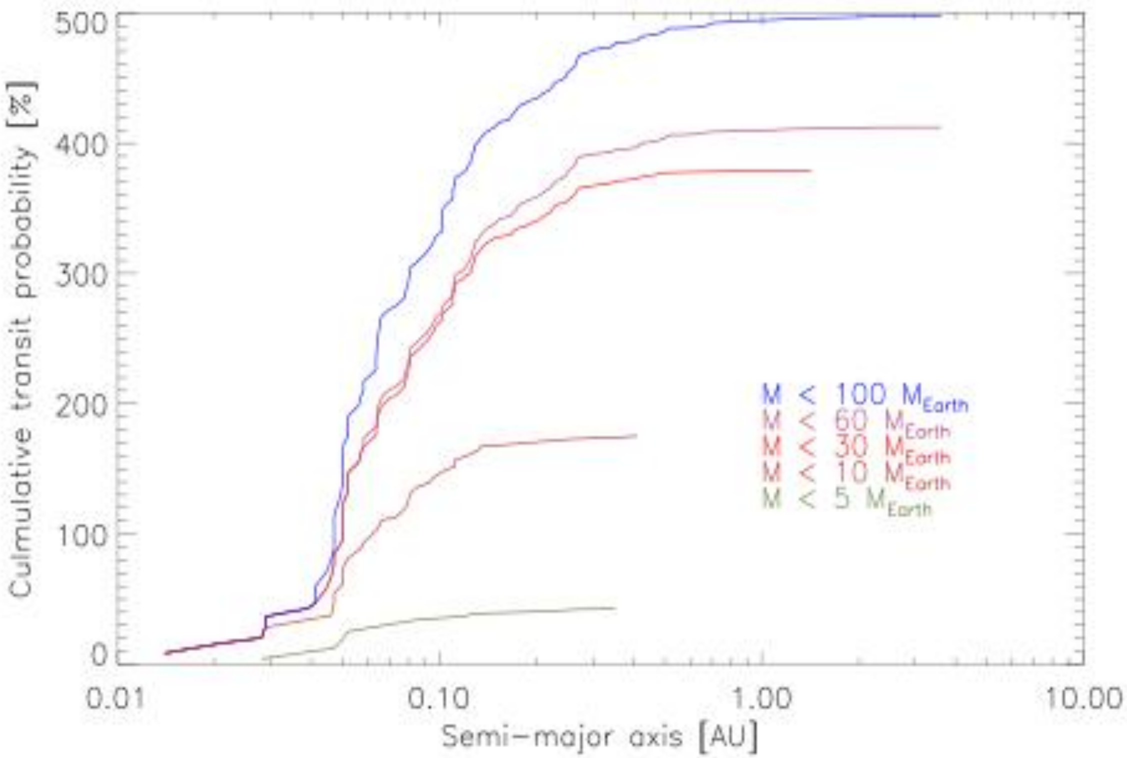
Duration ~ 13hrs



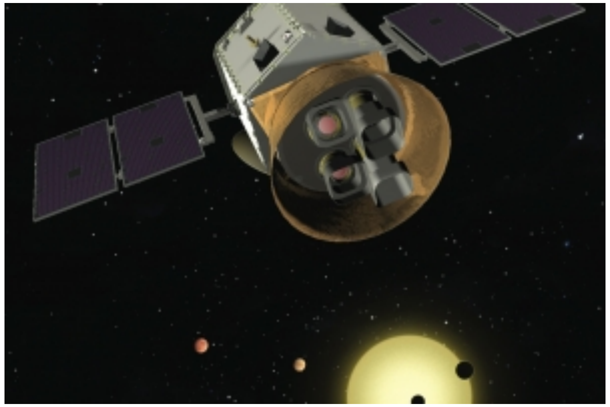
CHEOPS

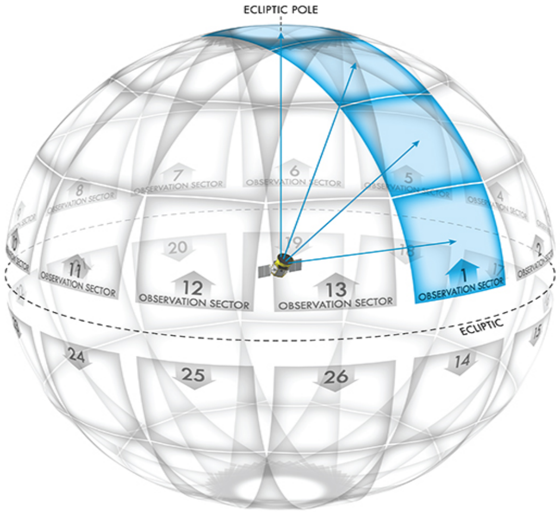
CHARACTERISING EXOPLANET SATELLITE

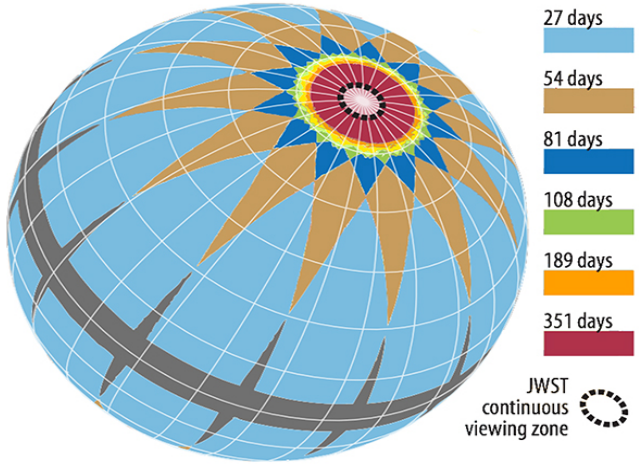
Mission to directly follow-up radial velocity detections to search for transits



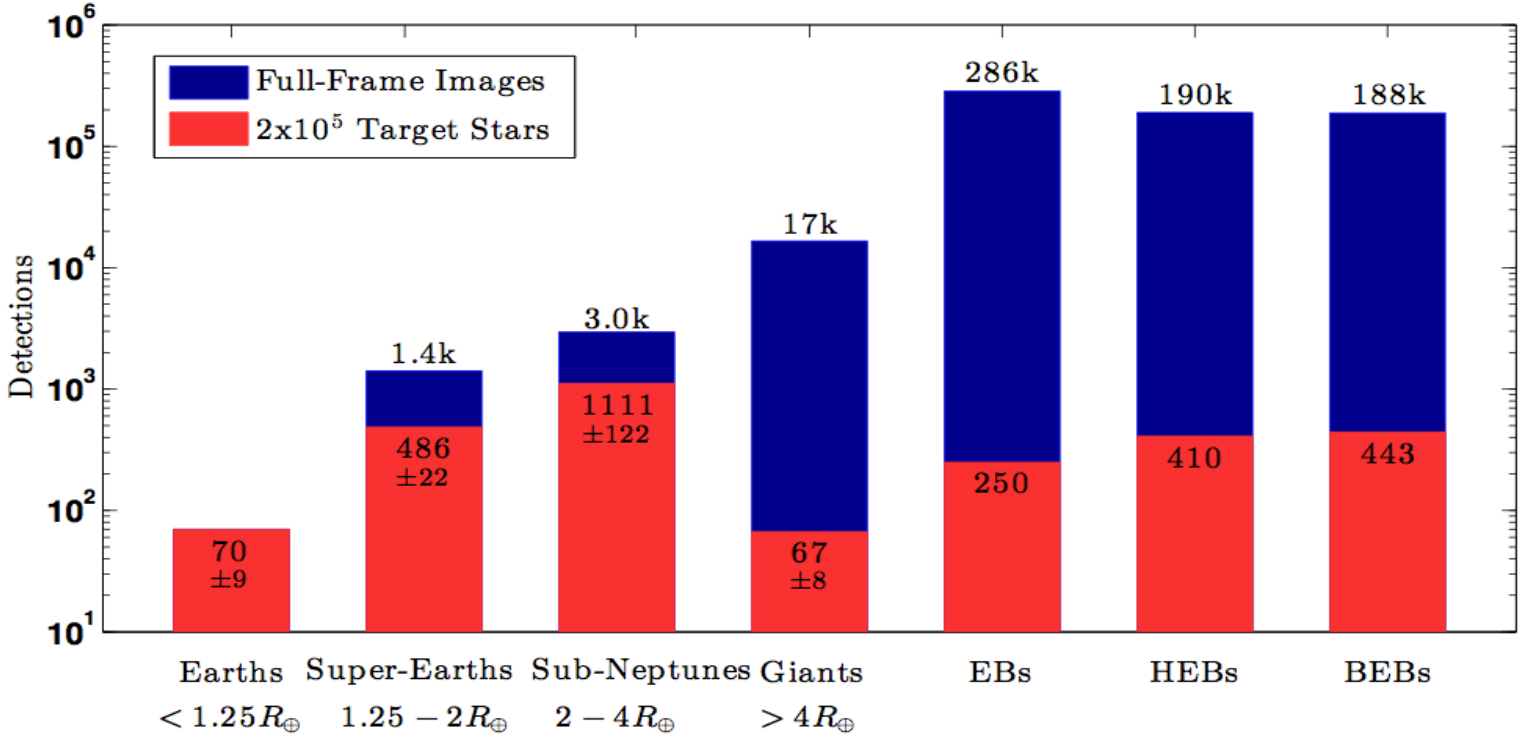
Fortier et al. 2014, SPIE, 9143, 2



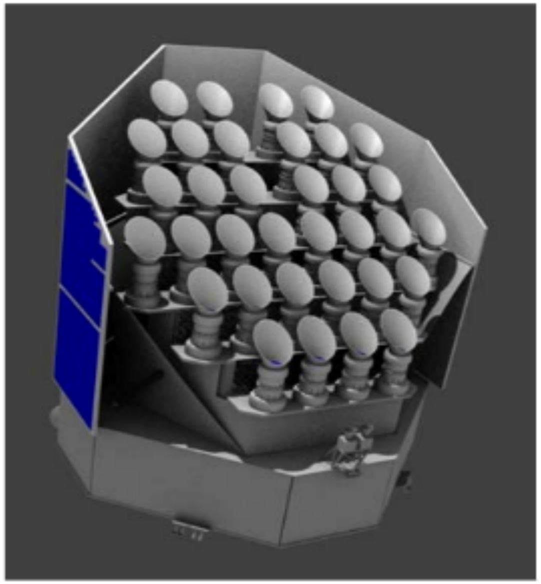


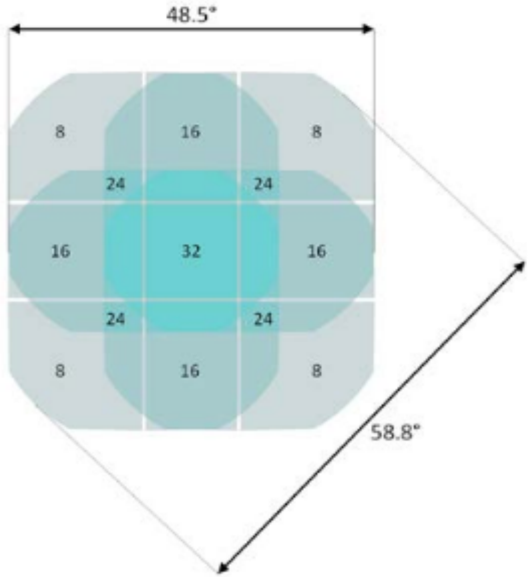


TESS Expected Yield



Sullivan et al. 2015, ApJ, 809, 77





PLATO2.0

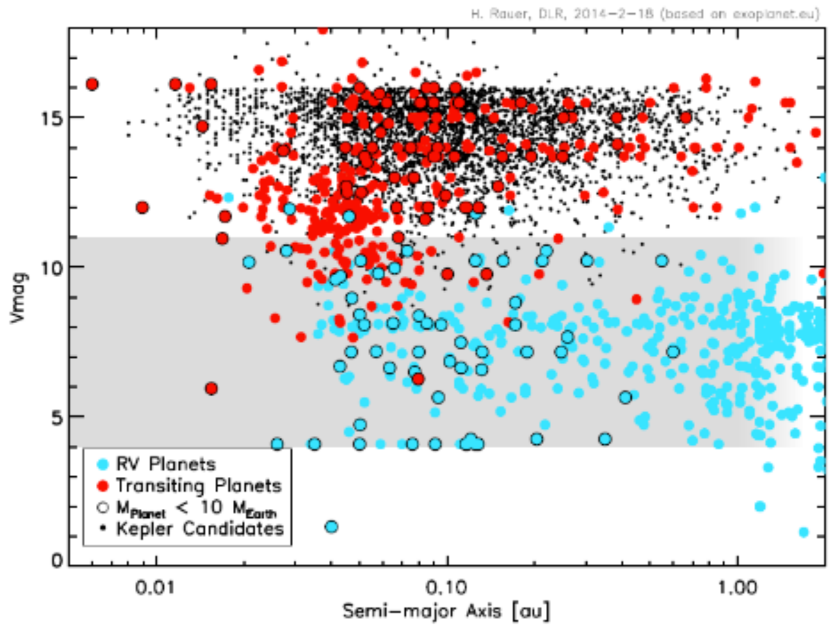
10^9 stars surveyed in the mission

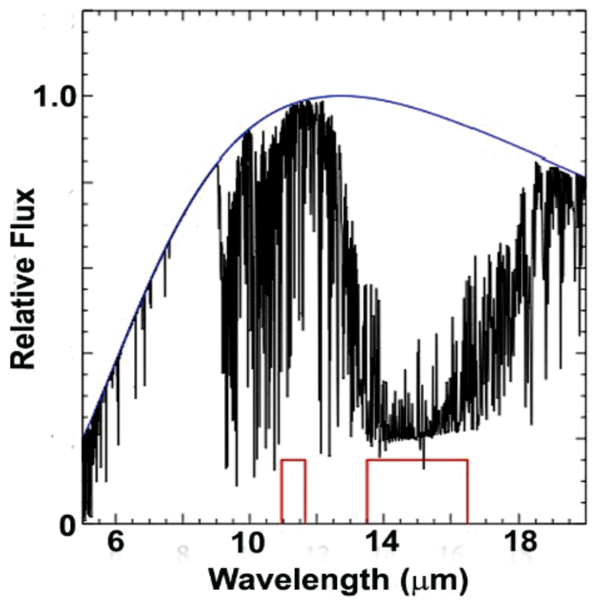
80’000 masses and ages for stars – asteroseismology

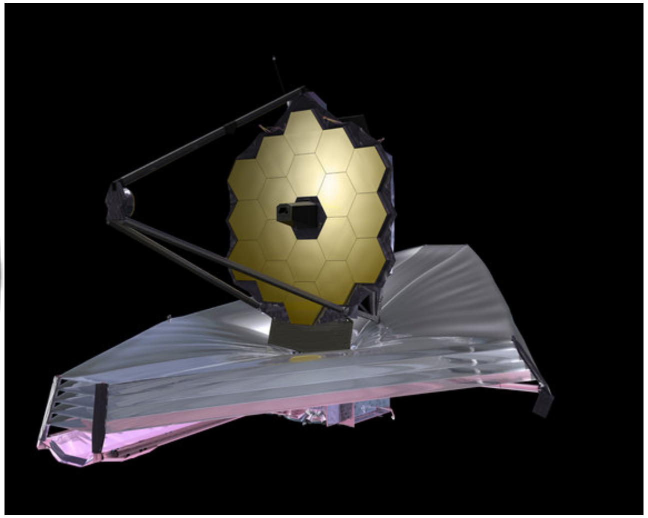
4 ≤ V ≤ 11 magnitudes for exo-Earths

3 year mission

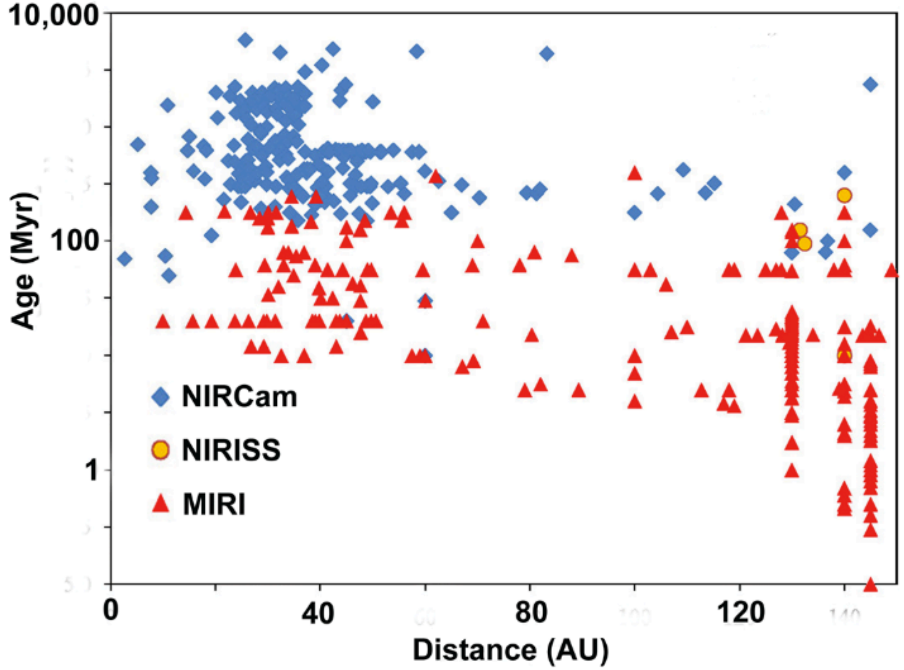
Rauer et al. 2014, ExA, 38, 249





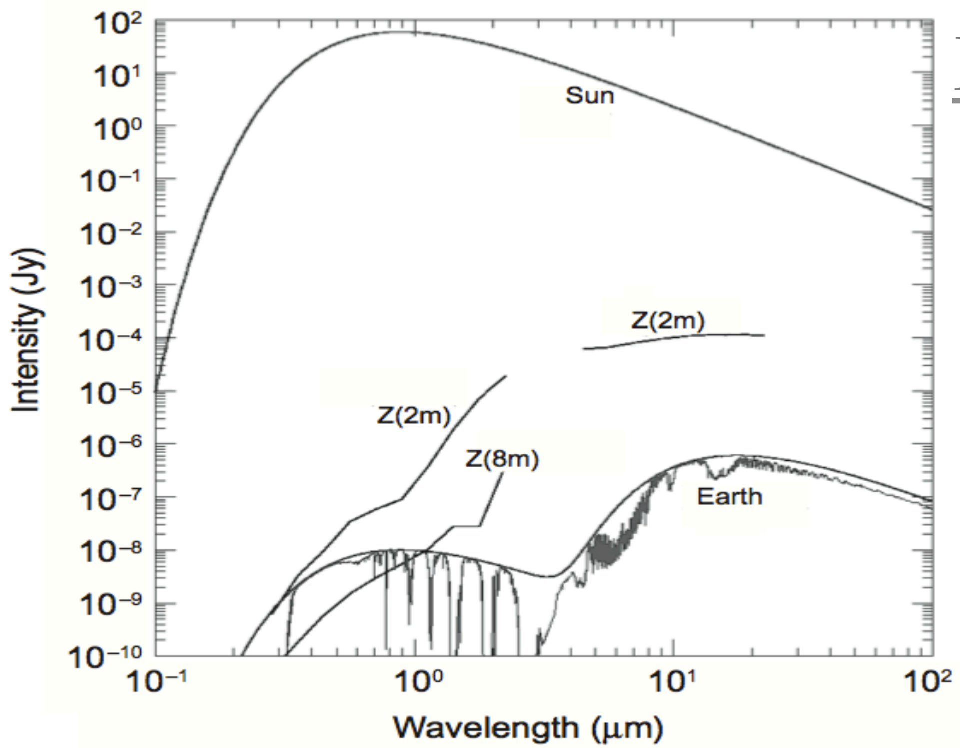


- Transmission spectral characterisation of super-Earths
- Direct imaging of giant planets ~few x mass of Saturn
- MIRI λ/D ~ 5AU @ 10pc



Rieke et al. 2015, PASP, 127, 584

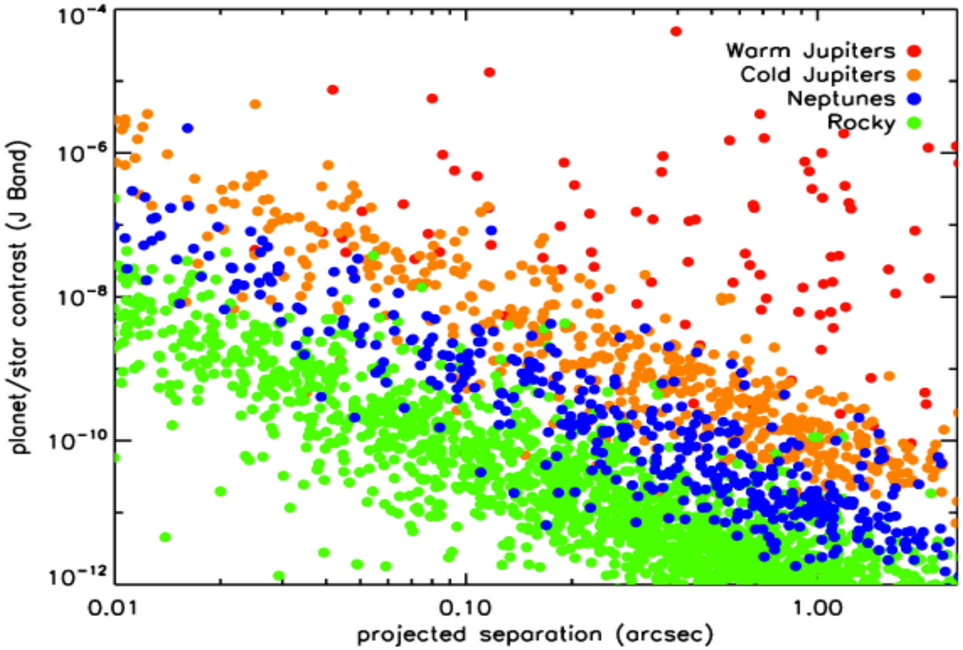
Beichman et al. 2010, lyot.confE, 47



Expected exo-Earth Contrast

- Simulated Earth-Sun system @13pc
- Contrasts ~10^{-10} in near-IR intensity
- exo-Zodis shown for different telescope diameters

Kasting et al. 2009, arxiv:0911.2936

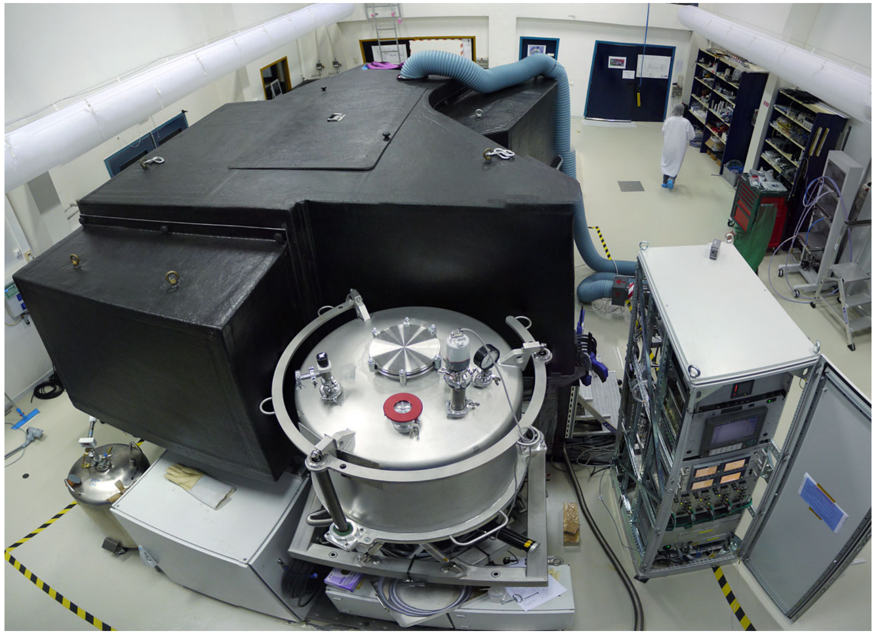


Population Simulations

- Simulated population of planets
- Contrasts ~10^{-10} in J-band with typical on-sky separations ~0.1”

Bonavita et al. 2012, A&A, 537, 67

Science Verification SPHERE

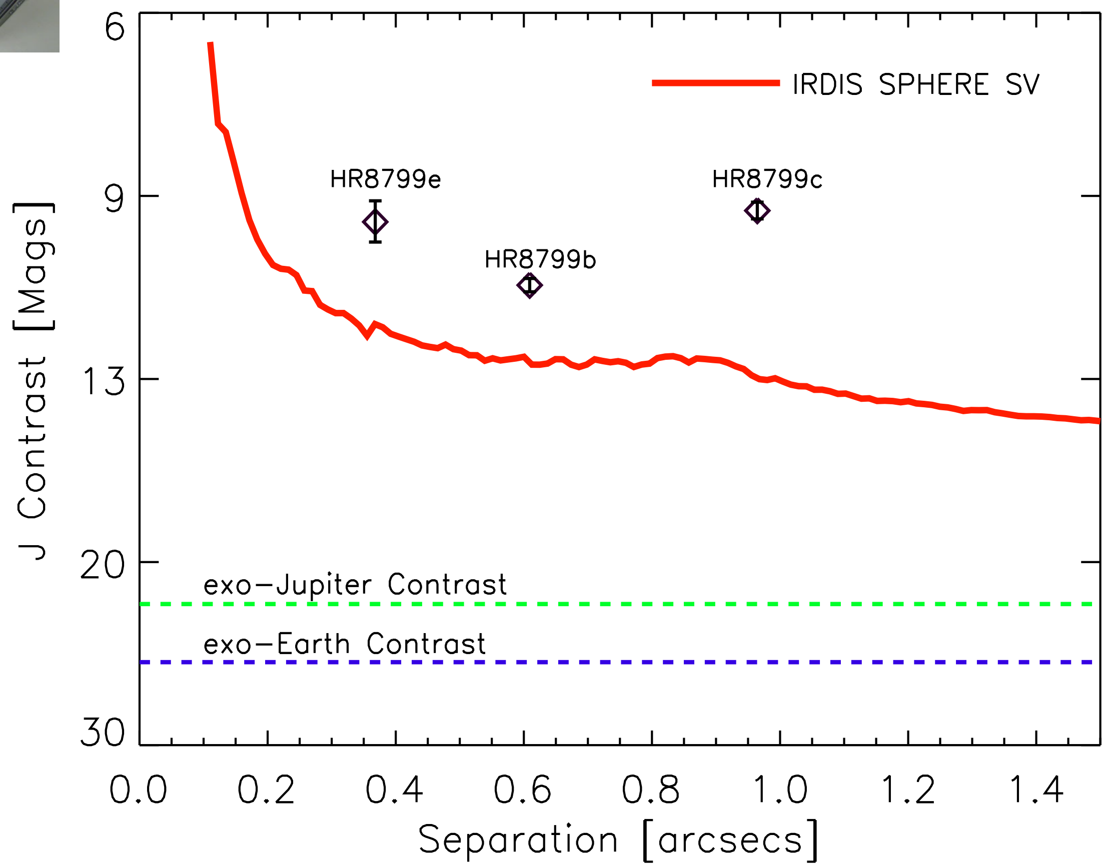


- ESO-VLT UT3
- Instruments – IRDIS, IFS, ZIMPOL
- Good AO Strehls in H ~ 75%

- ~13 magnitudes @ 0.5”
- Active correction ≤ 1”
- Young massive planets imaged

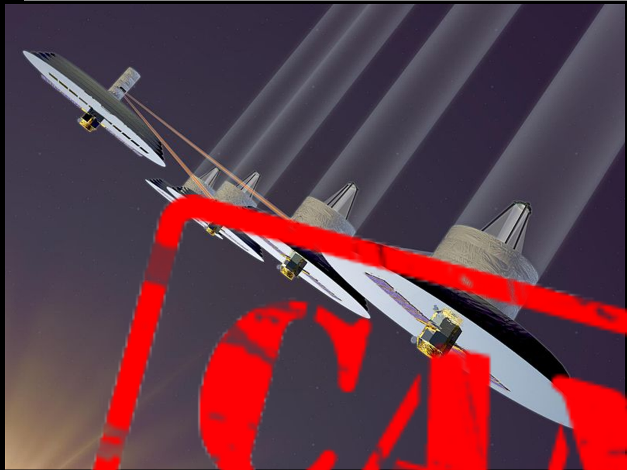
~4 more magnitudes of contrast are required for exo-Earths!!

see Pantoja presentation



Interferometry from Space

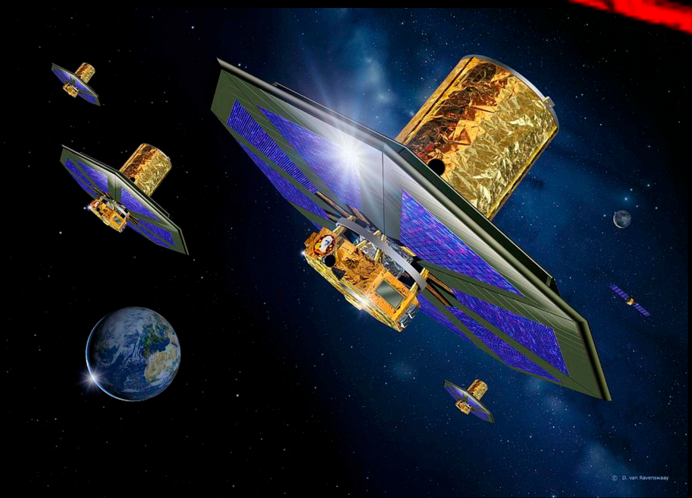
Terrestrial Planet Finder



- NASA led initiative
- Multiple tethered spacecraft
- Nulling interferometry
- Mission goal – imaging and spectroscopy of the nearest Earth-like planets

CANCELLED

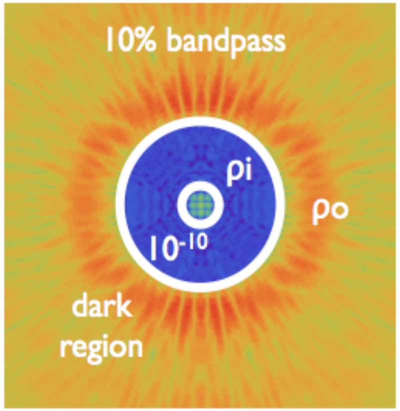
Darwin

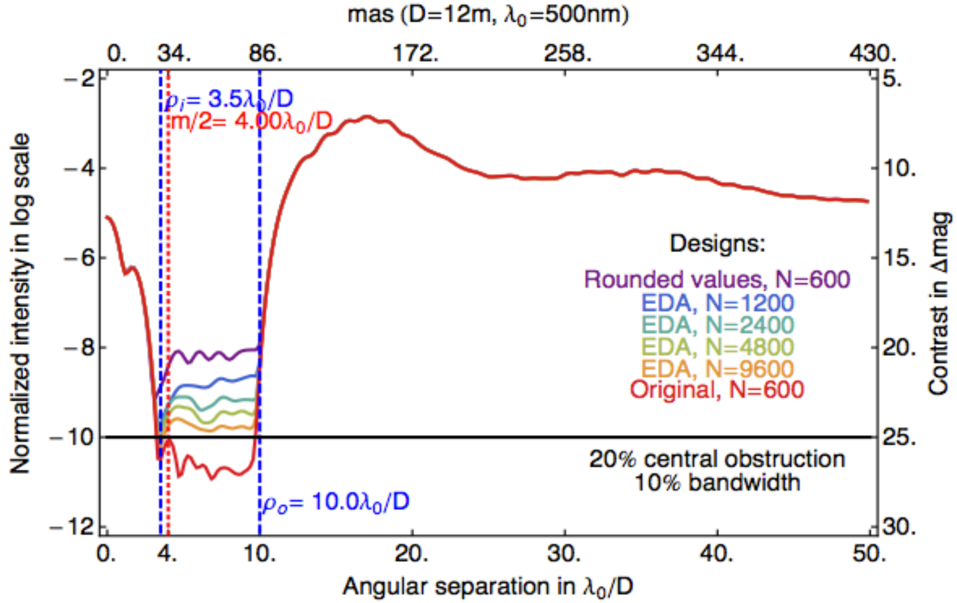


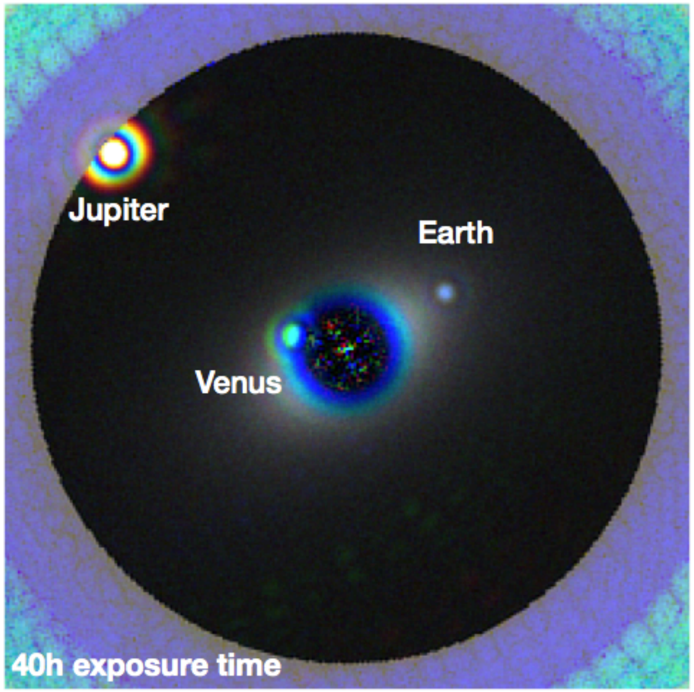
- ESA led initiative
- Multiple formation flying spacecraft
- Nulling interferometry
- Mission goal – imaging and spectroscopy of the nearest Earth-like planets

Apodization

Broadband coronagraphic image







Simulation by L. Pueyo

Apodized Pupil Lyot Coronographs
Shaped Pupil Designs

Possibilities to reach 10^{-10} contrasts at low inner working angles

Proposed design for a 12m space telescope

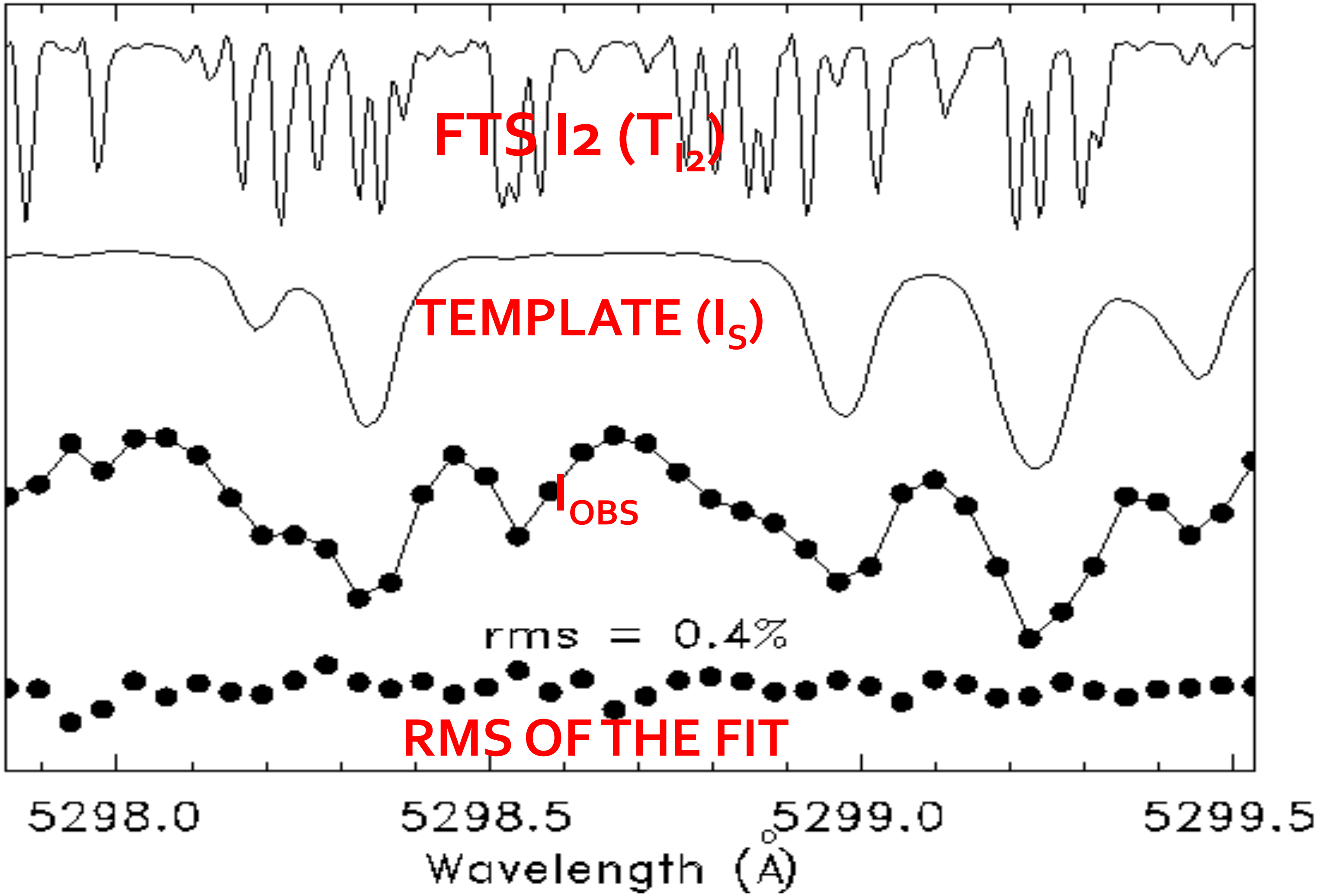
Simulations suggest 13 detectable exo-Earths

Mamadou N'Diaye 2015 (STScI), priv. comm.


Am I an exo-Earth?
You better hope you are not an exo-Earth!!

Absorption Cell RVs

$$I_{obs}(\lambda) = k[T_{\mathrm{I2}}(\lambda) I_s(\lambda + \Delta\lambda)] * \mathrm{PSF}$$



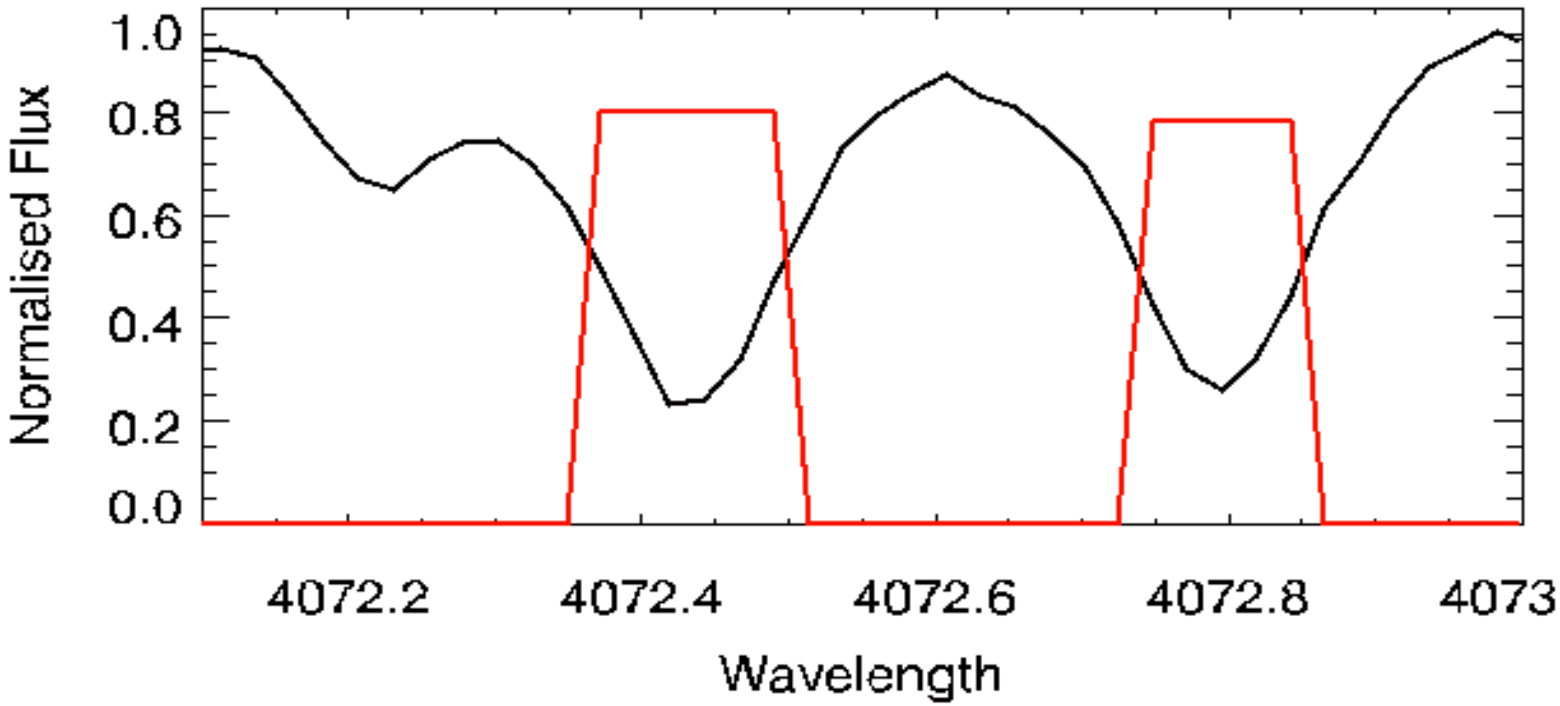
Butler et al. 1996, PASP, 108, 500

Cross-Correlation RVs

$$CCF(v_R) = \int S(\lambda) \cdot M(\lambda_{v_R})\, d\lambda$$
$$= \int S(\lambda) \cdot \sum_i M_i(\lambda_{v_R})\, d\lambda$$
$$= \sum_i \int S(\lambda) M_i(\lambda_{v_R})\, d\lambda = \sum_i CCF_i(v_R)$$

where

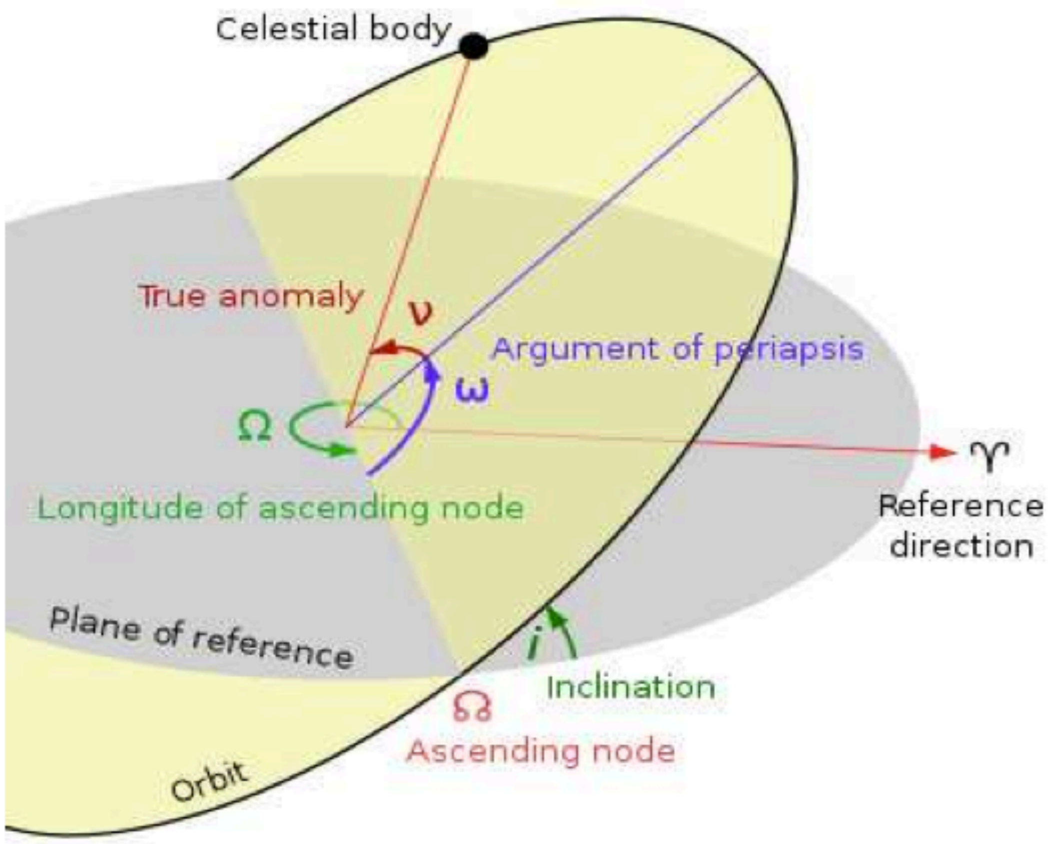
$$\lambda_{v_R} = \lambda \sqrt{\frac{1 - \frac{v_R}{c}}{1 + \frac{v_R}{c}}}.$$



Baranne et al. 1996, A&AS, 119, 373

Radial Velocities

$$V_r(\nu) = K\left(cos(\nu+\omega) + e\,cos(\omega)\right)$$



$$K = \frac{28.4}{\sqrt{1-e^2}}\left(\frac{M_p \sin i}{M_J}\right)\left(\frac{M_\star}{M_\odot}\right)^{-1/2}\left(\frac{a}{AU}\right)^{-1/2}$$