An ancient extrasolar system with five sub-Earth-size planets

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September 18, 2014

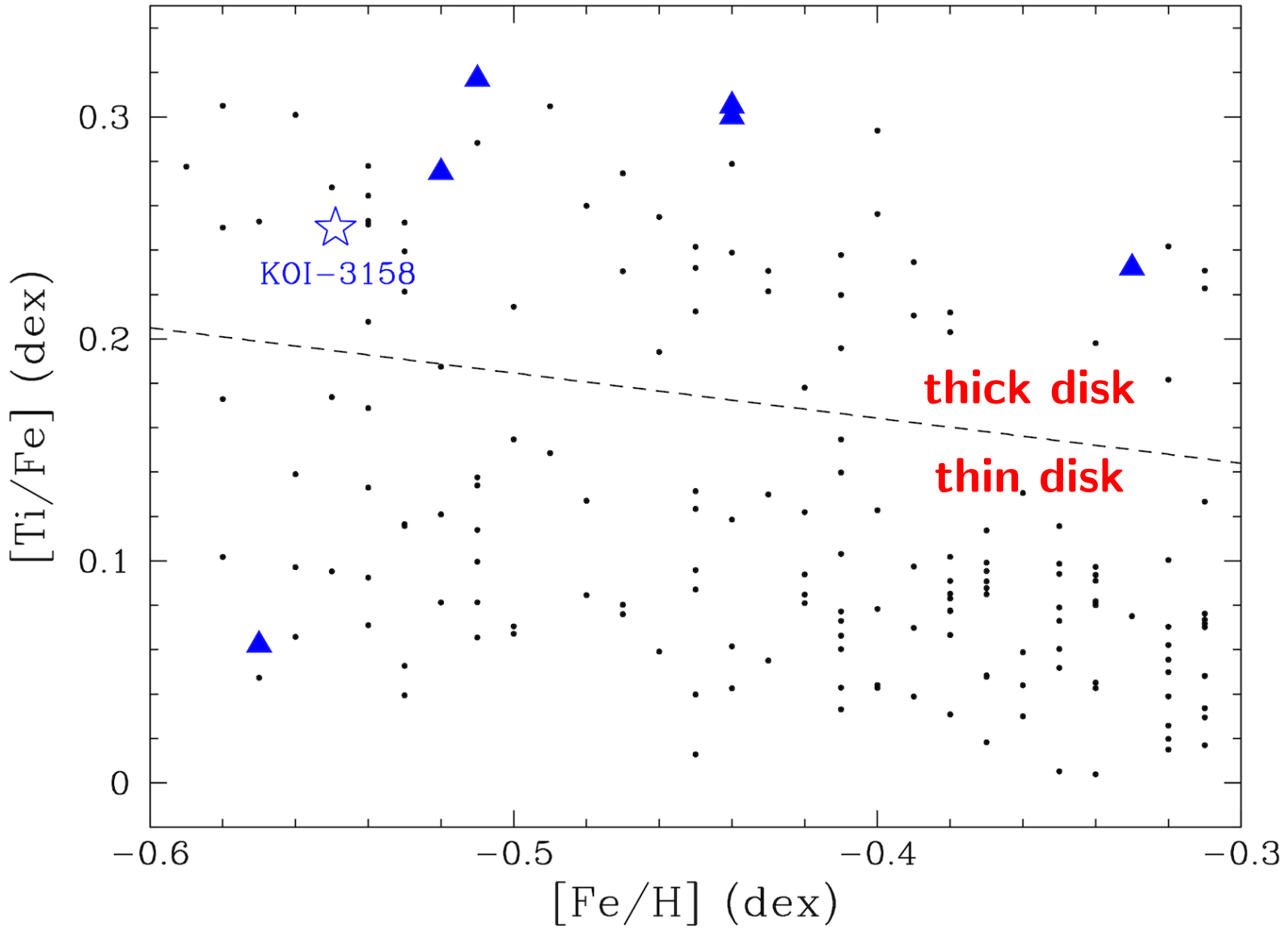
Introducing KOI-3158

- also KIC 6278762, HIP 94931
- spectral type K0V
- over 0.5 $\mathrm{arcsec\,yr^{-1}}$
- $V = 8.86$
- $d = 36\,\mathrm{pc}$
- iron-poor and overabundant in α elements (e.g., Si and Ti)

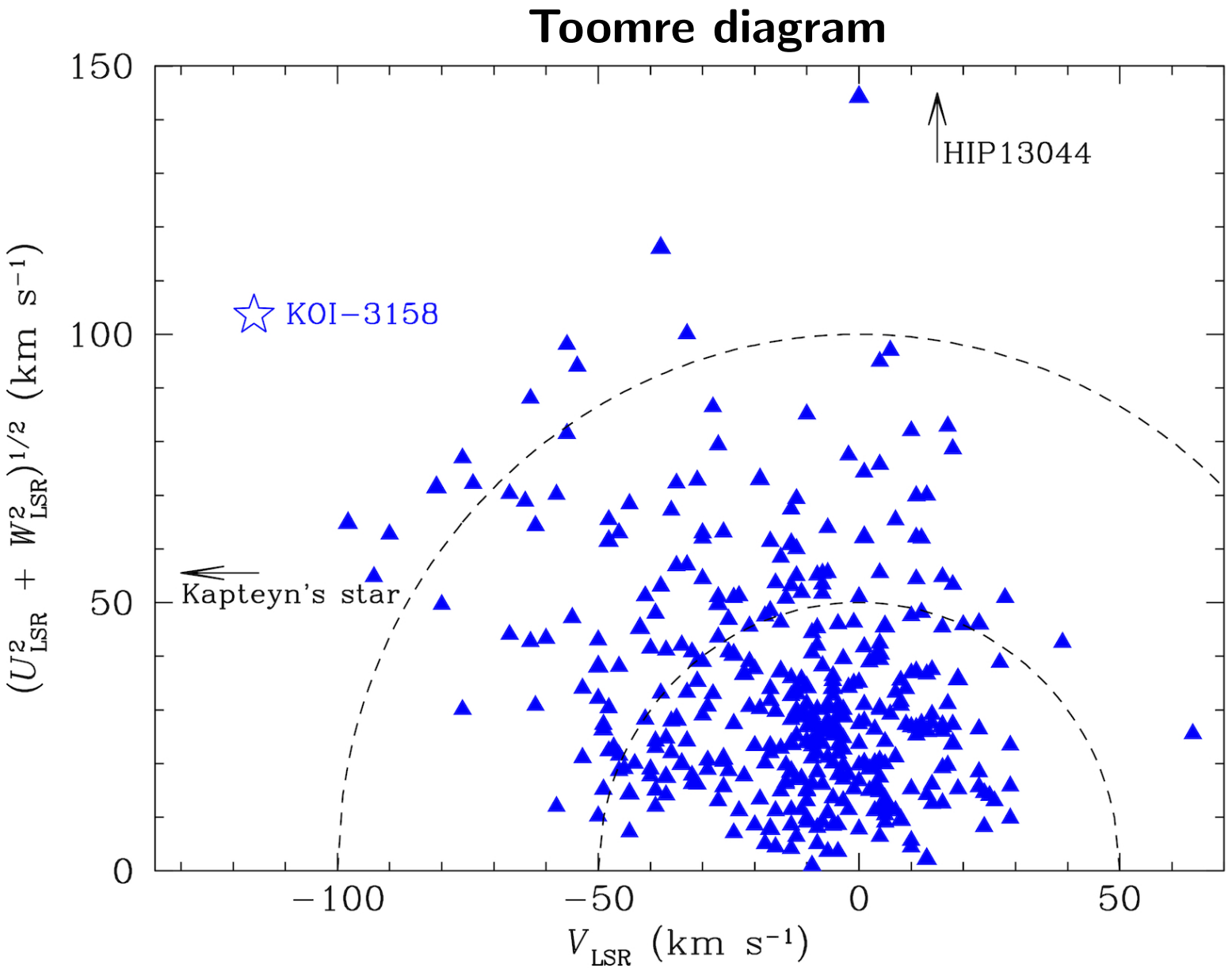
Atmospheric parameters

Parameter	Value
T_{eff} (K)	$5046 \pm 74\,(44)$
$\log g_{\mathrm{spec}}$ (dex)	4.595 ± 0.060
[Fe/H] (dex)	$-0.55 \pm 0.07\,(0.03)$
[Si/H] (dex)	-0.28 ± 0.02
[Ti/H] (dex)	-0.30 ± 0.05

A member of the thick disk (I)

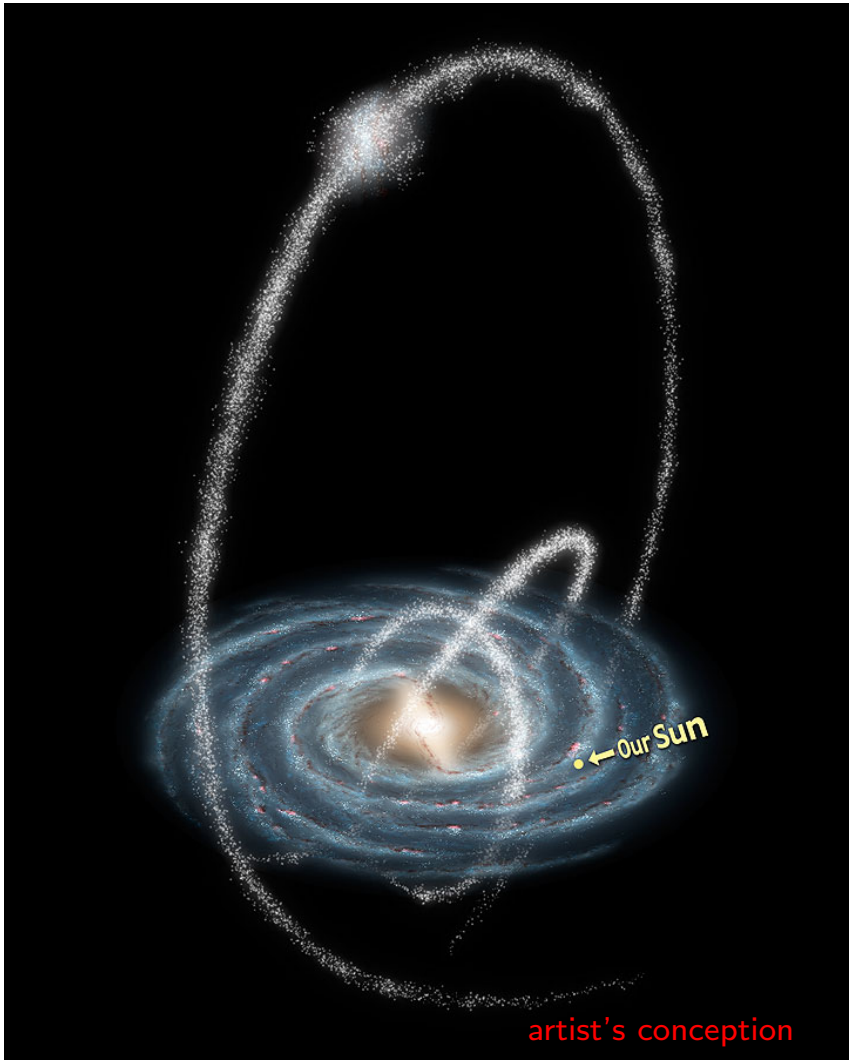


A member of the thick disk (II)



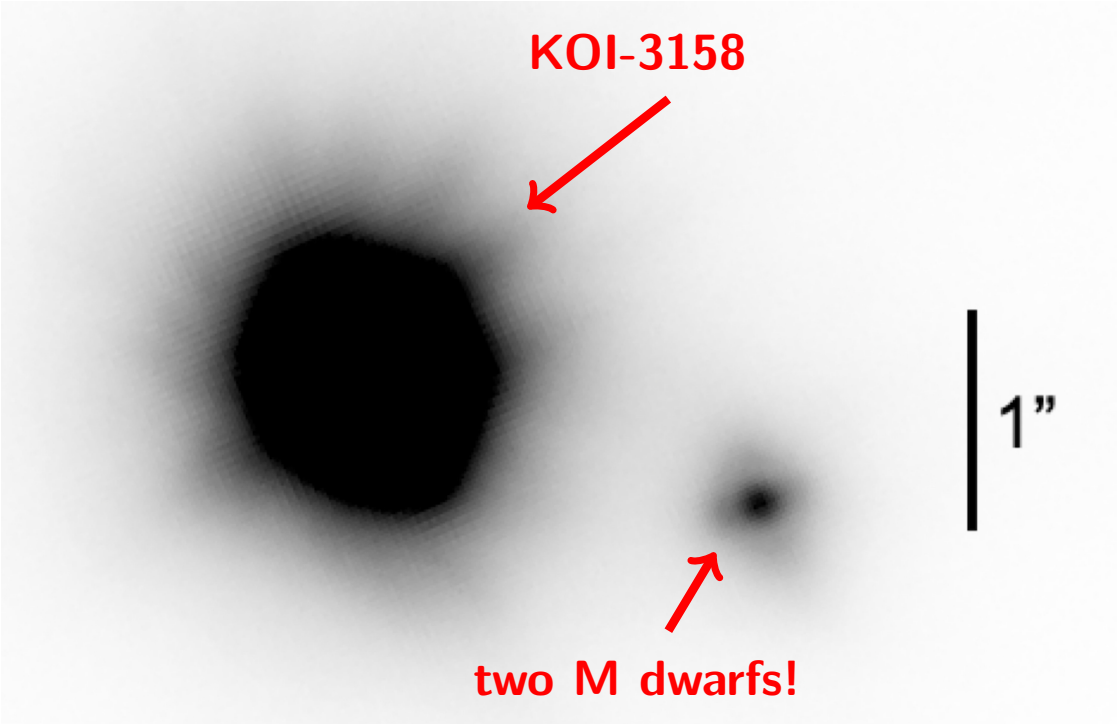
Possible extragalactic origin?

- member of the Arcturus stream
- named after Arcturus (brightest star in northern celestial hemisphere)
- these stars travel $2\,\mathrm{kpc}$ above Galactic plane
- extragalactic origin vs. dynamical origin within Galaxy



Hierarchical triple system

- fainter companion at 1.8 arcsec
- high-resolution imaging with Robo-AO
- 3.94 % dilution
- the two components are co-moving
- secondary comprises two M dwarfs!



Asteroseismic analysis (I)

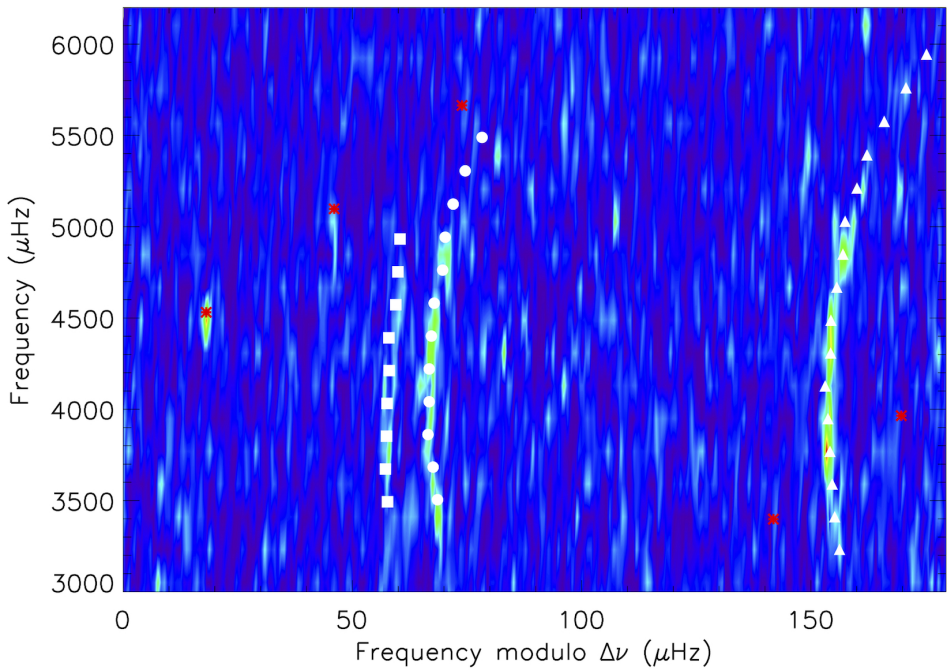
- short cadence: Q4.2, Q6, Q15–17
- record-breaking $\Delta\nu$ at 180 μHz
- stellar properties from grid-based modeling
- 1.9 % relative precision on R and 1.1 % on $\langle\rho\rangle$

Stellar properties

Parameter	Value
$M/\mathrm{M}_\odot$	0.758 ± 0.043
$R/\mathrm{R}_\odot$	0.752 ± 0.014
$\log g_{\mathrm{seis}}$ (dex)	4.5625 ± 0.0095
$\langle\rho\rangle$ (g cm^{-3})	2.493 ± 0.028
[redacted]	

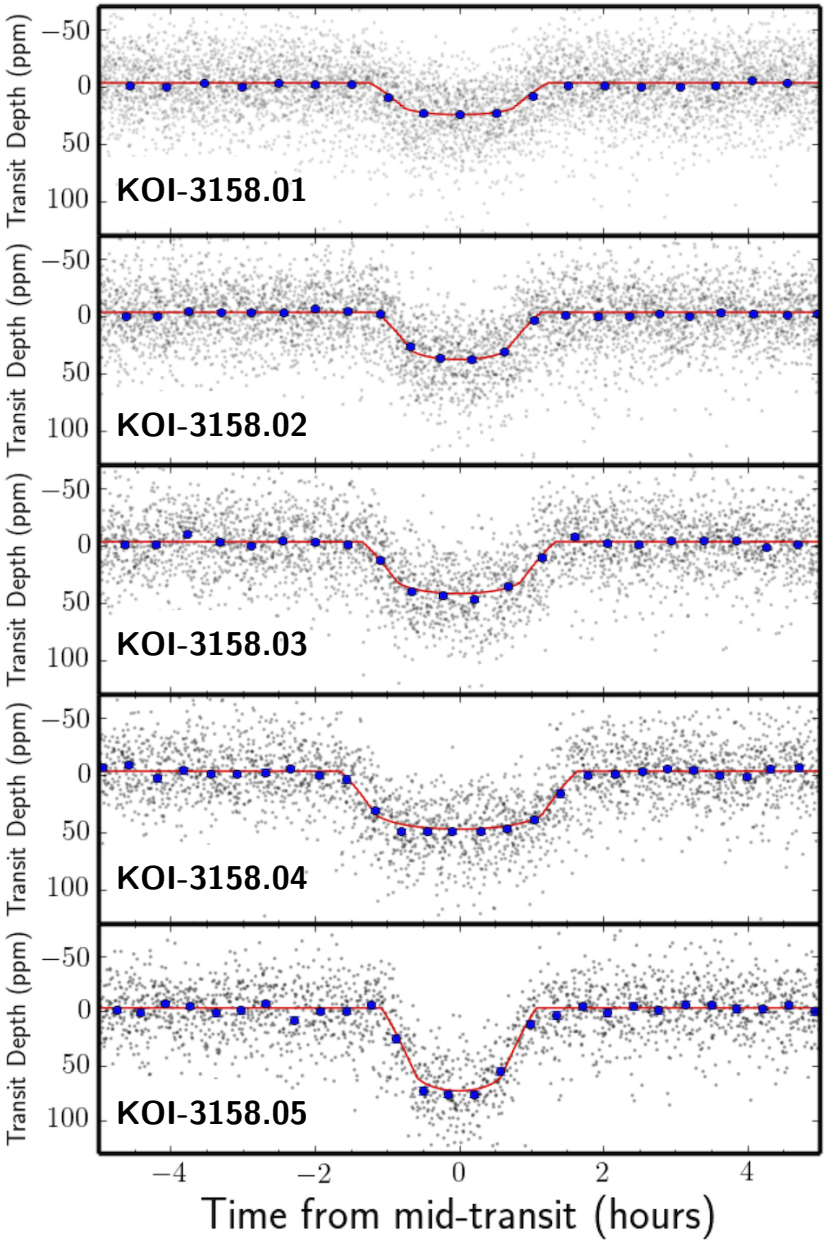
Asteroseismic analysis (II)

- detailed frequency modeling
- GARSTEC, ASTEC, YREC, MESA, and AMP codes used
- 11.2 billion years old!
- 9 % precision on age estimate
- oldest known system of terrestrial-size planets



Transit analysis

- 4 years of long-cadence data
- five-planet transit model
- affine-invariant MCMC algorithm
- took into account dilution

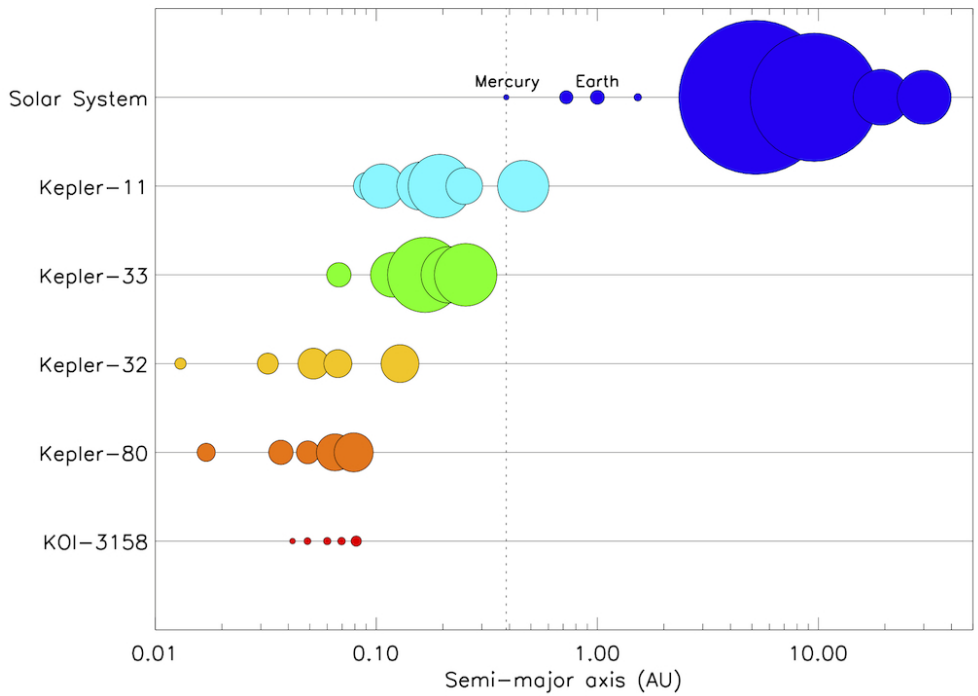


A system of terrestrial-size planets

- KOI-3158.01 is Mercury-sized
- intermediate planets are Mars-sized
- KOI-3158.05 smaller than Venus
- from the mini-Neptunes around Kapteyn's star and Kepler-10's super-Earths to the terrestrial-size regime

Highly-compact system

- orbital periods under 10 days
- . . . or within 0.08 AU
- period ratios close to strong 5 : 4, 4 : 3, 5 : 4, and 5 : 4 first-order MMRs
- system fits within orbit of Kepler-11's innermost planet
- compact systems make up $\sim$1 % of *Kepler* candidate hosts

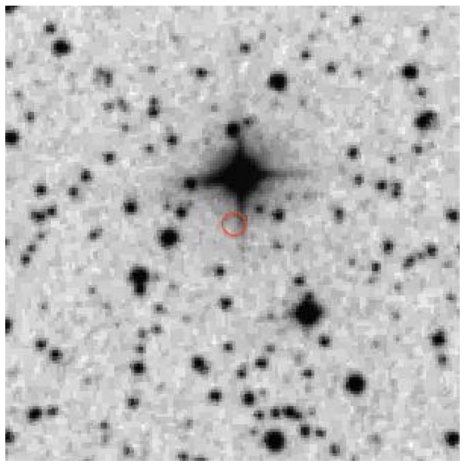


Dynamical evolution

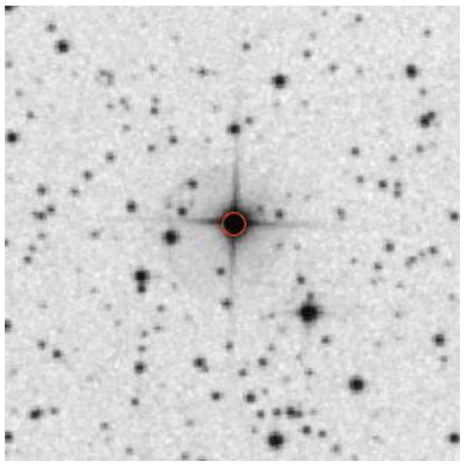
- proximity to strong resonances points to dynamical evolution
- convergent inward migration is likely mechanism
- tides then push planets wide of exact commensurability
- will make an interesting case study!

System validation

- only plausible FP of 4 planets + 1 background EB rejected at 99.9 % level
- no background stars in DSS archival data
- non-randomness of observed multi-resonant chain
- dynamical instability if planets were to orbit M-dwarf companion



DSS POSS-I (epoch 1945-58)

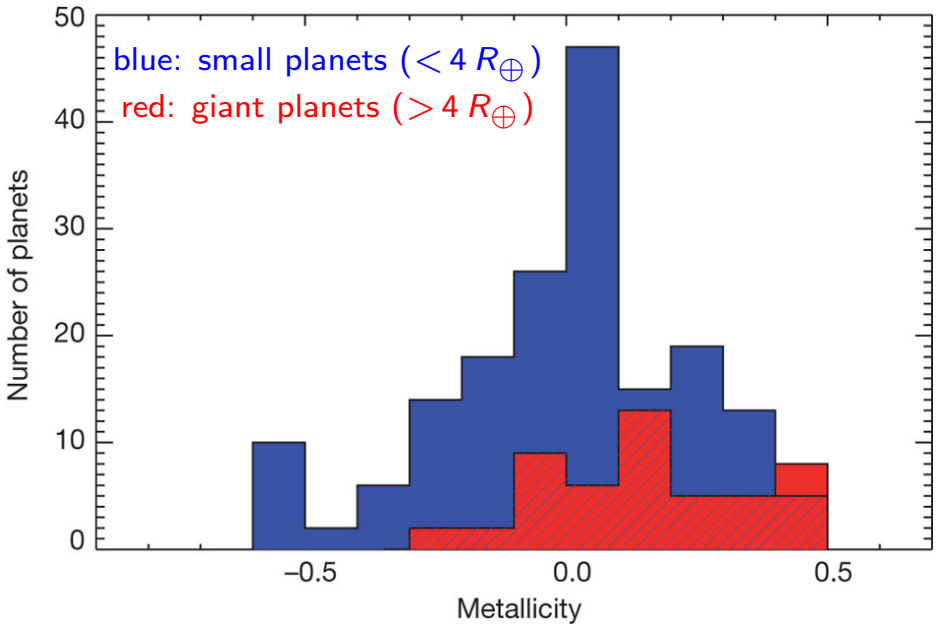


DSS POSS-II (epoch 1984-99)

Implications (I)

- giant-planet hosts: metal-rich
- small-planet hosts: more diverse composition
- $\Rightarrow$ terrestrial-size planets may have started to form earlier
- **(sub-)Earth-size planets have formed throughout most of Universe's history**
- **ancient life in the Galaxy?**

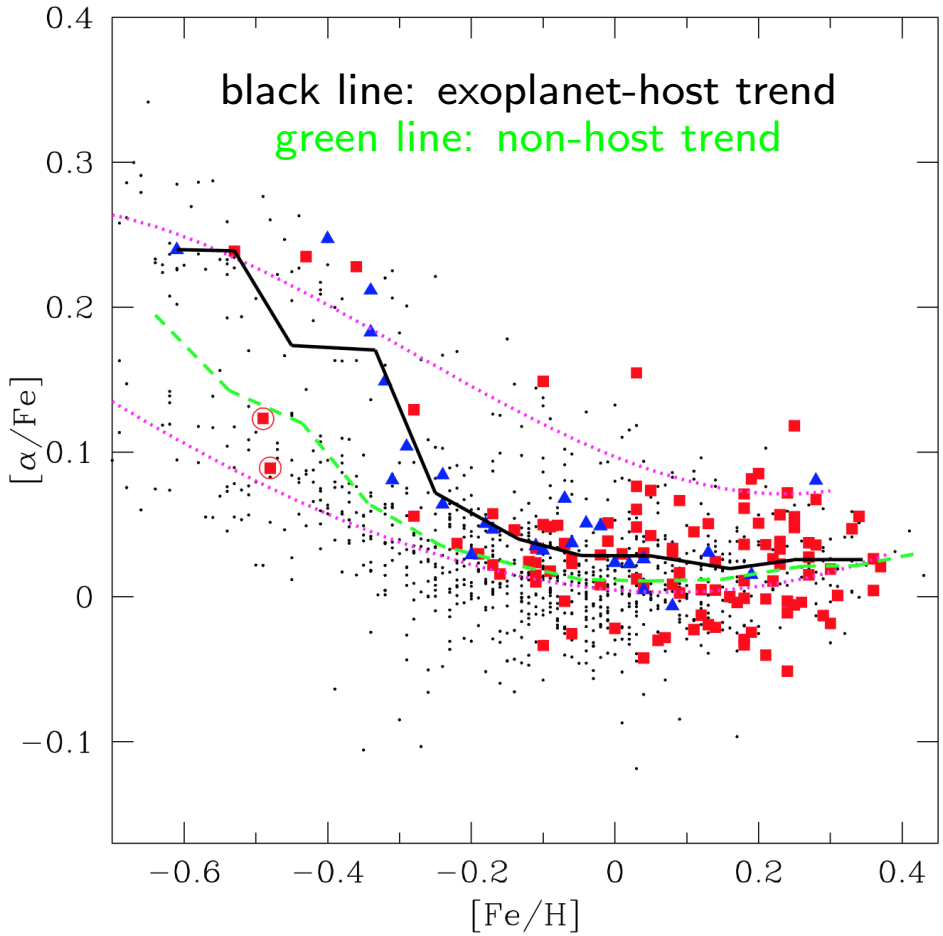
Buchhave et al. (2012)



Implications (II)

- α elements critical for planet formation in iron-poor environments
- thick-disk stars overabundant in α elements in low-metallicity regime
- $\Rightarrow$ thick-disk (and high-α halo) stars were likely hosts to first Galactic planets
- **ancient systems around KOI-3158 and Kepler-10 help pinpoint beginning of era of planet formation**

Adibekyan et al. (2012)



Acknowledgments

Tiago L. Campante[1,2], Thomas Barclay[3,4], Jonathan J. Swift[5], Daniel Huber[3,6], Vardan Zh. Adibekyan[7], William Cochran[8], Christopher J. Burke[6,3], Howard Isaacson[9], Elisa V. Quintana[6,3], Guy R. Davies[1,2], Víctor Silva Aguirre[2], Darin Ragozzine[10], Reed Riddle[11], Christoph Baranec[12], Sarbani Basu[13], William J. Chaplin[1,2], Jørgen Christensen-Dalsgaard[2], Travis S. Metcalfe[14,2], Timothy R. Bedding[15,2], Rasmus Handberg[1,2], Dennis Stello[15,2], John M. Brewer[16], Saskia Hekker[17,2], Christoffer Karoff[2,18], Rea Kolbl[9], Nicholas M. Law[19], Mia Lundkvist[2], Andrea Miglio[1,2], Jason F. Rowe[3,6], Nuno C. Santos[7,20], Christa Van Laerhoven[21], Torben Arentoft[2], Yvonne P. Elsworth[1,2], Debra A. Fischer[16], Steven D. Kawaler[22], Hans Kjeldsen[2], Mikkel N. Lund[2], Geoffrey W. Marcy[9], Sérgio G. Sousa[7,20], Alessandro Sozzetti[23] & Timothy R. White[24]