

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

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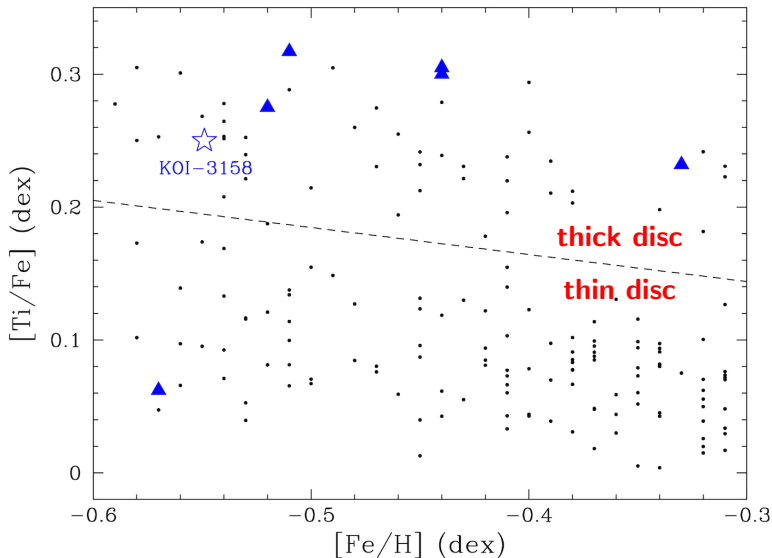
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- also KIC 6278762, HIP 94931
- spectral type K0V
- over  $0.5 \text{ arcsec yr}^{-1}$
- $V = 8.86$
- $d = 36 \text{ pc}$
- iron-poor and overabundant in  $\alpha$  elements (e.g., Si and Ti)

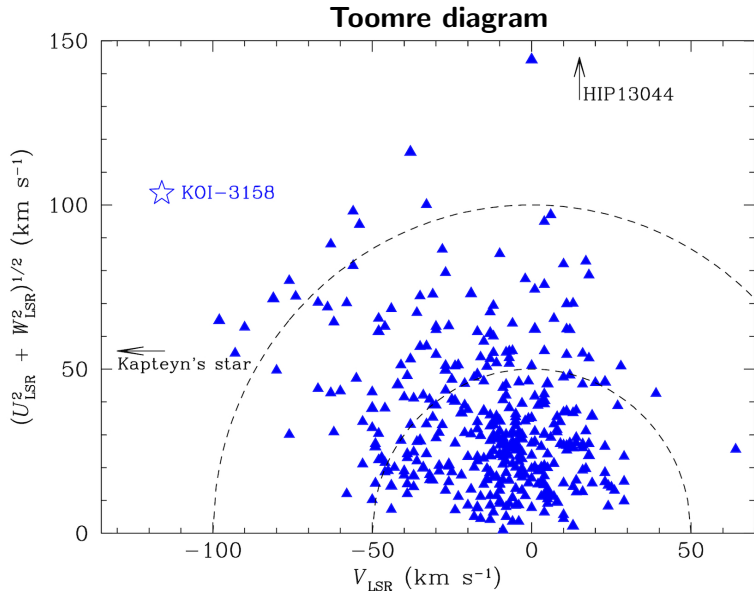
## Atmospheric parameters

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

# A member of the thick disc (I)

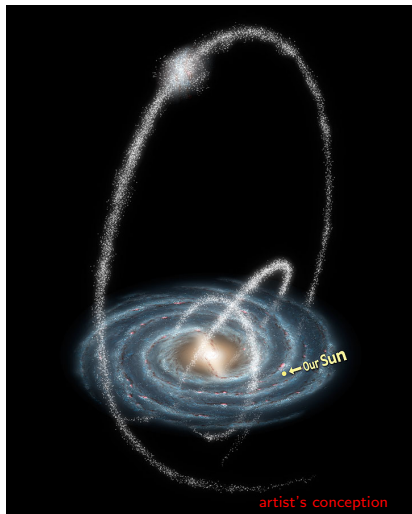


# A member of the thick disc (II)



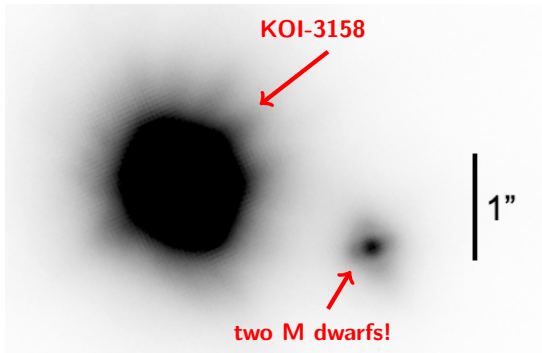
# Possible extragalactic origin?

- member of the Arcturus stream
- named after Arcturus (brightest star in northern celestial hemisphere)
- these stars travel 2 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)

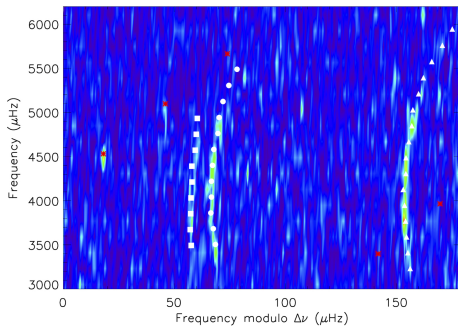
- short cadence: Q4.2, Q6, Q15–17
- record-breaking  $\Delta\nu$  at  $180 \mu\text{Hz}$
- stellar properties from grid-based modelling
- 1.9 % relative precision on  $R$  and 1.1 % on  $\langle\rho\rangle$

## Stellar properties

Parameter	Value
$M/M_{\odot}$	$0.758 \pm 0.043$
$R/R_{\odot}$	$0.752 \pm 0.014$
$\log g_{\text{seis}}$ (dex)	$4.5625 \pm 0.0095$
$\langle\rho\rangle$ ( $\text{g cm}^{-3}$ )	$2.493 \pm 0.028$

# Asteroseismic analysis (II)

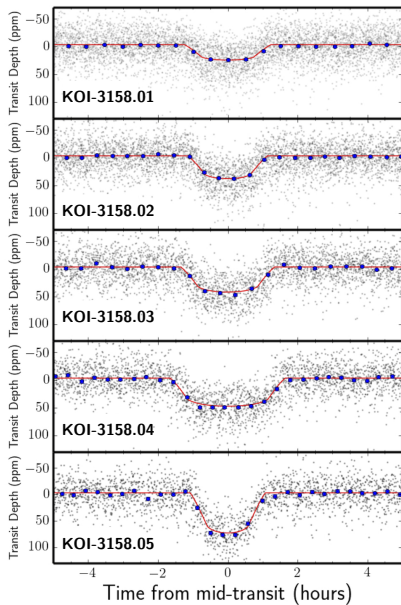
- detailed frequency modeling
- GARSTEC, ASTEC, YREC, MESA, and AMP codes used
- frequencies corrected for Doppler shift (Guy R. Davies et al., submitted)
- 11.2 billion years old!
- oldest known system of terrestrial-size planets





# Transit analysis

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



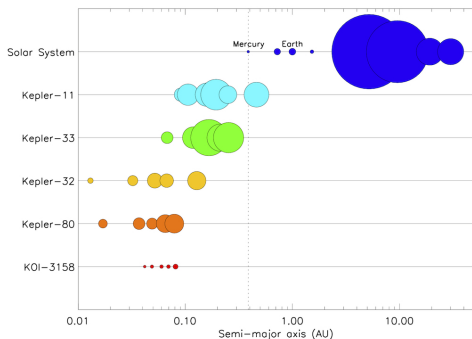
# A system of terrestrial-size planets

- monotonically increasing radii with orbital distance
- 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 to the terrestrial-size regime



# Highly-compact system

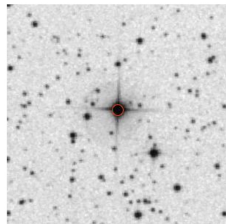
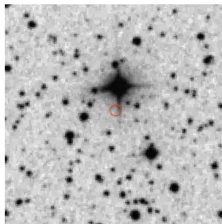
- orbital periods under 10 days
- ... or within 0.08 AU
- period ratios close to strong 5:4, 4:3, 5:4, and 5:4 first-order MMRs
- system fits within orbit of Kepler-11's innermost planet
- compact systems make up  $\sim 1\%$  of *Kepler* candidate hosts



- proximity to strong resonances points to dynamical evolution
- planetary masses increase outward and
- ... migration rate scales as planet mass
- $\Rightarrow$  convergent inward migration is a 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

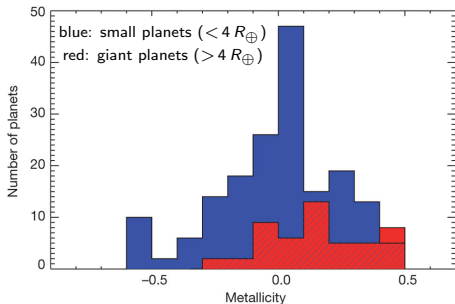


DSS POSS-I (epoch 1945-58) DSS POSS-II (epoch 1984-99)

# Implications (I)

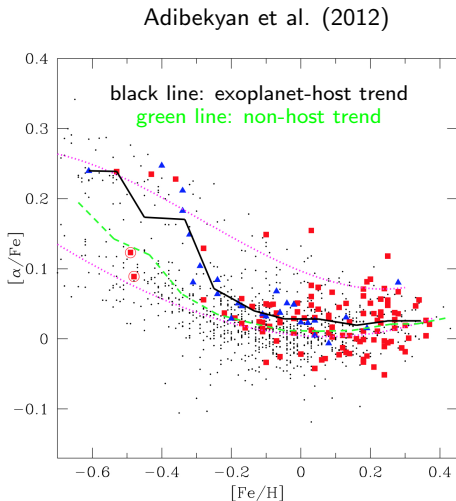
- giant-planet hosts: metal-rich
- small-planet hosts: more diverse composition
- $\Rightarrow$  Earth-size planets may have started to form earlier
- **Earth-size planets have formed throughout most of Universe's history**
- **ancient life in the Galaxy?**

Buchhave et al. (2012)



# Implications (II)

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



# Acknowledgements

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