TOI-5344 b

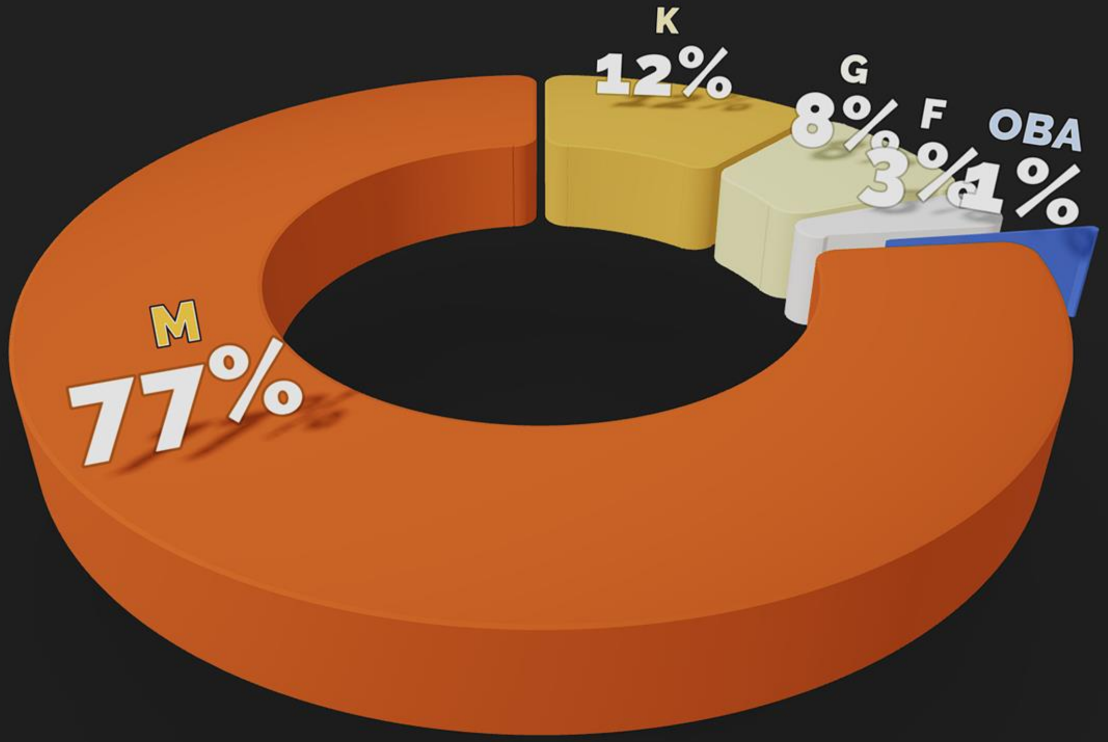
as a new Giant Exoplanets around M-dwarf Stars (GEMS)

- **Te Han** (University of California, Irvine)

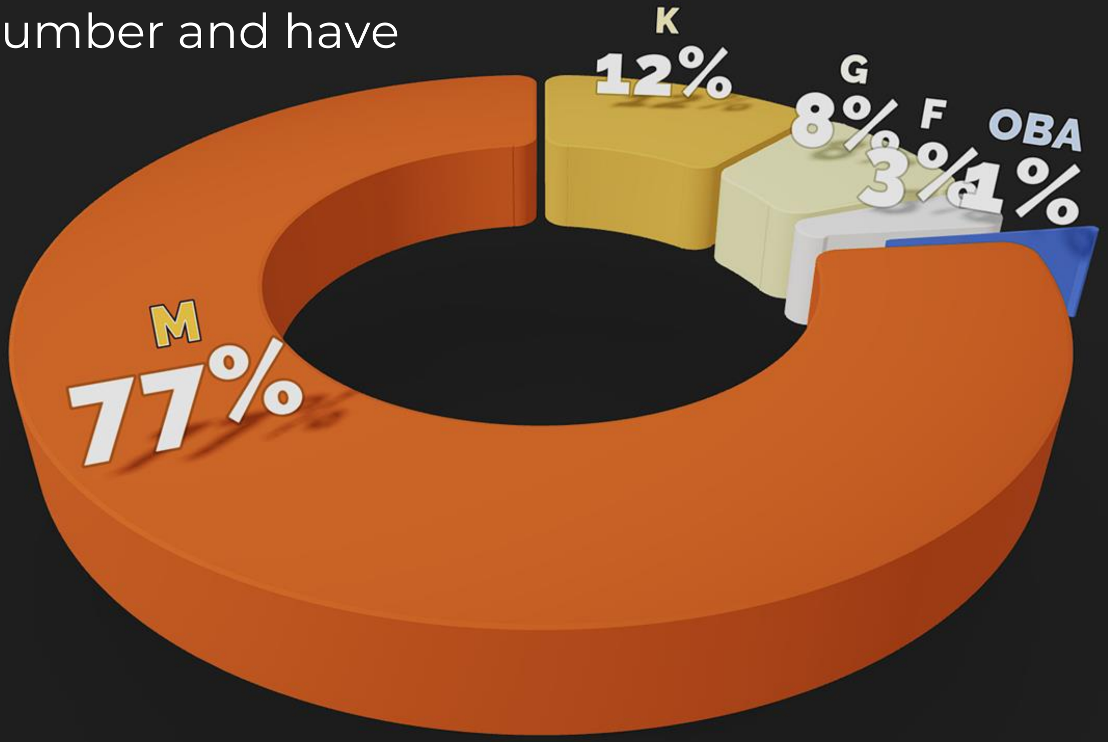
Exsocal 2023, Dec. 11, Caltech

I. What are GEMS?

GIANT
EXOPLANETS AROUND
GEMS
M-DWARF STARS

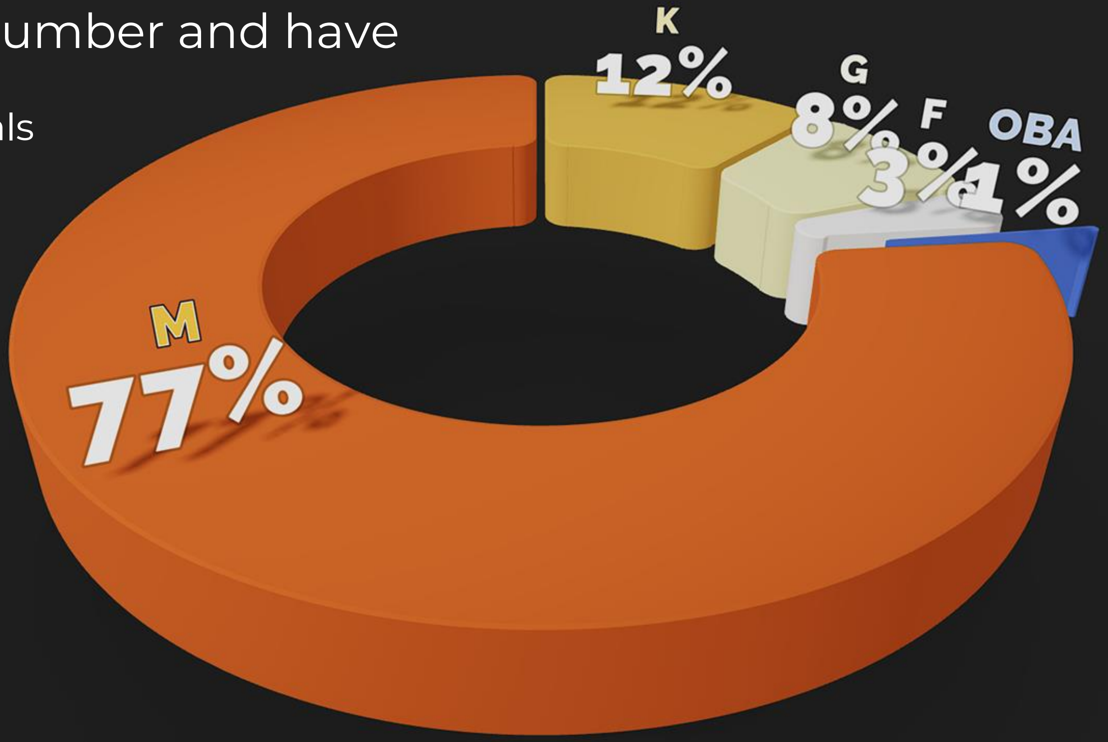

K
12%
G
8%
F
3%
OBA
1%
M
77%

M-dwarfs dominate in number and have



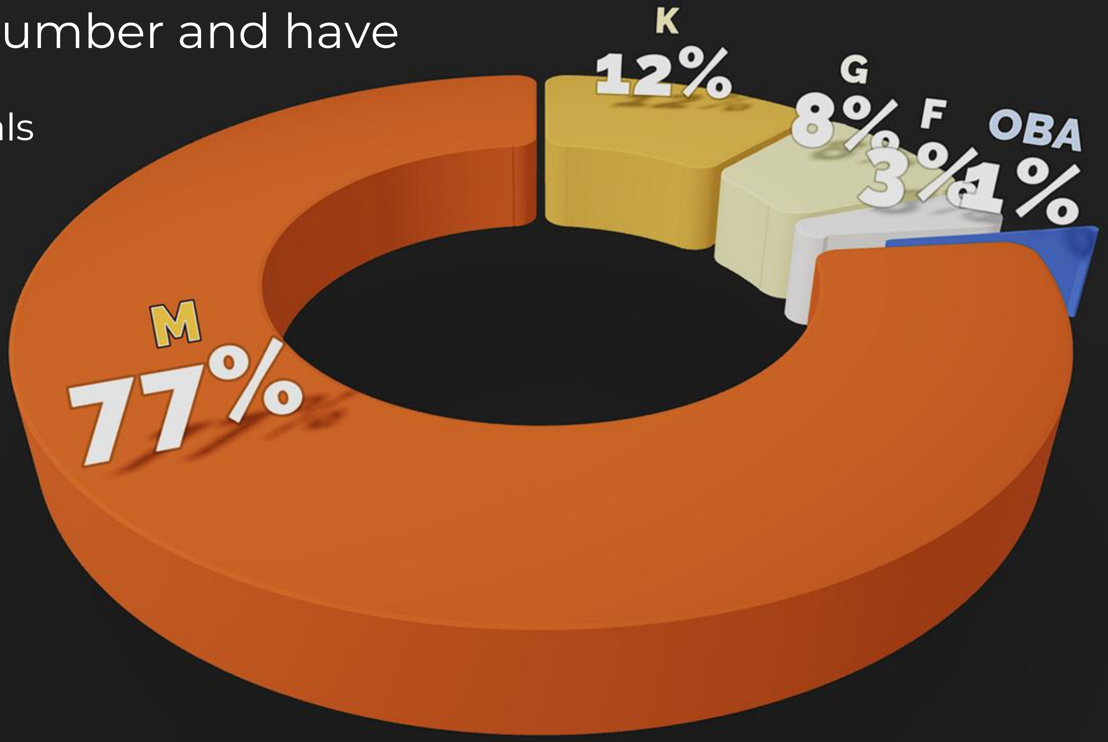
M-dwarfs dominate in number and have

★ larger radial velocity signals



M-dwarfs dominate in number and have

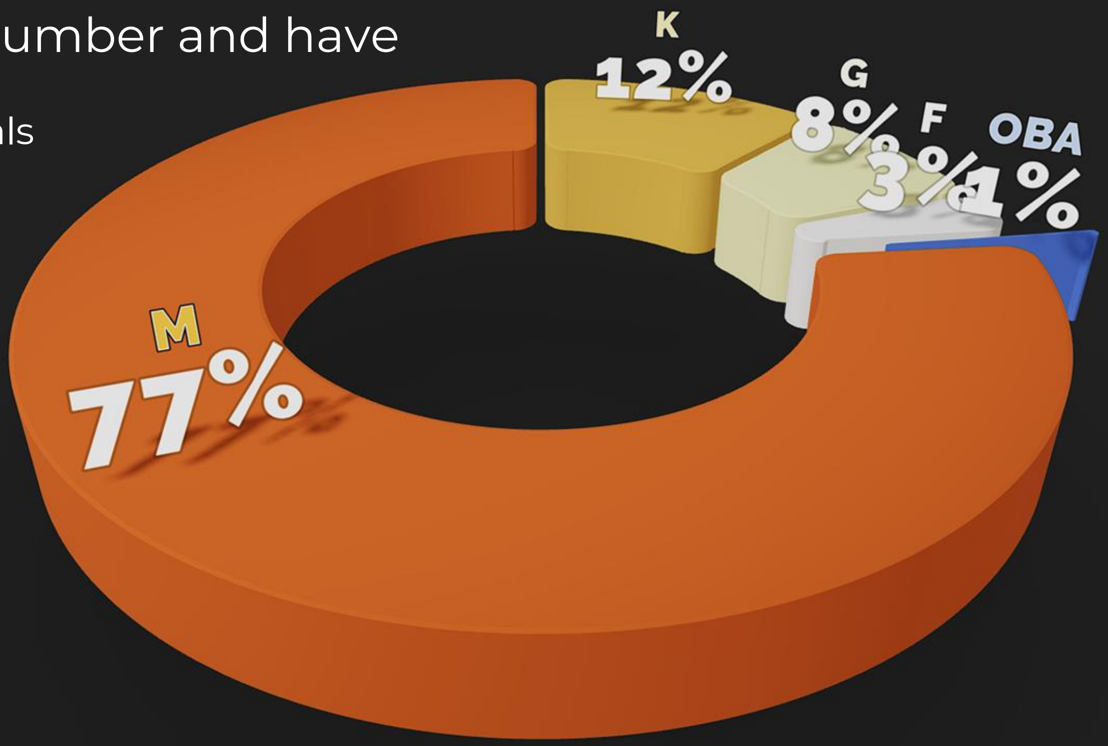
- ★ larger radial velocity signals
- ★ deeper transits



M-dwarfs dominate in number and have

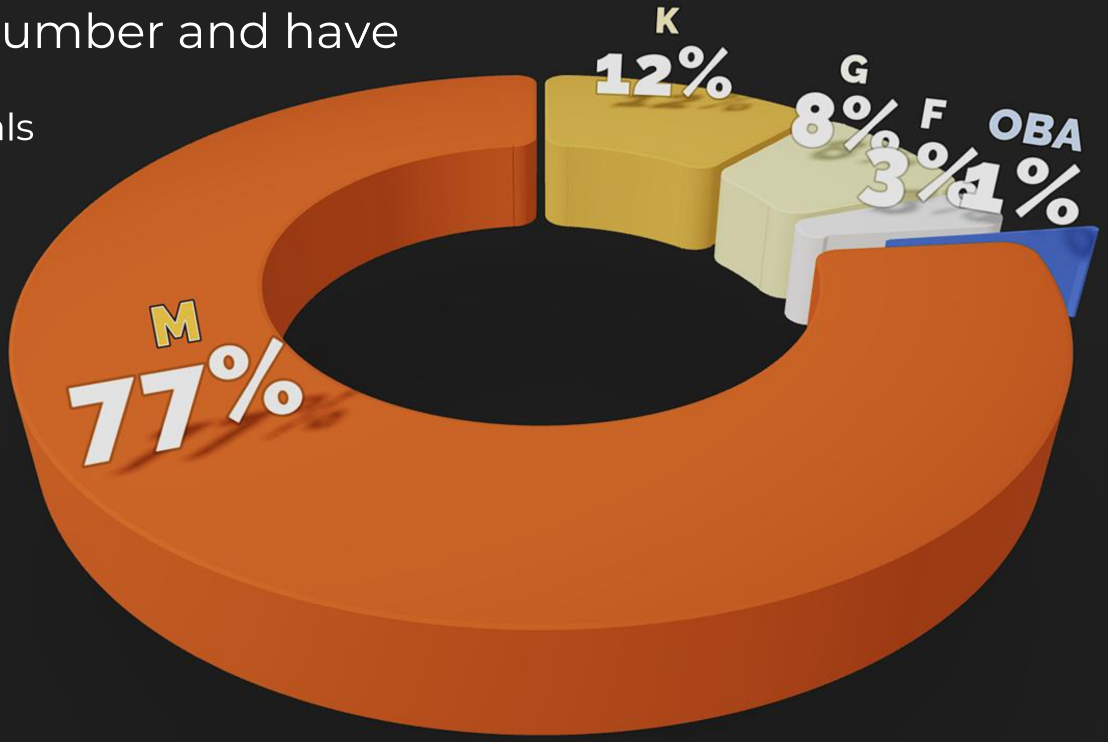
- ★ larger radial velocity signals
- ★ deeper transits

But they also have



M-dwarfs dominate in number and have

- ★ larger radial velocity signals
- ★ deeper transits



But they also have

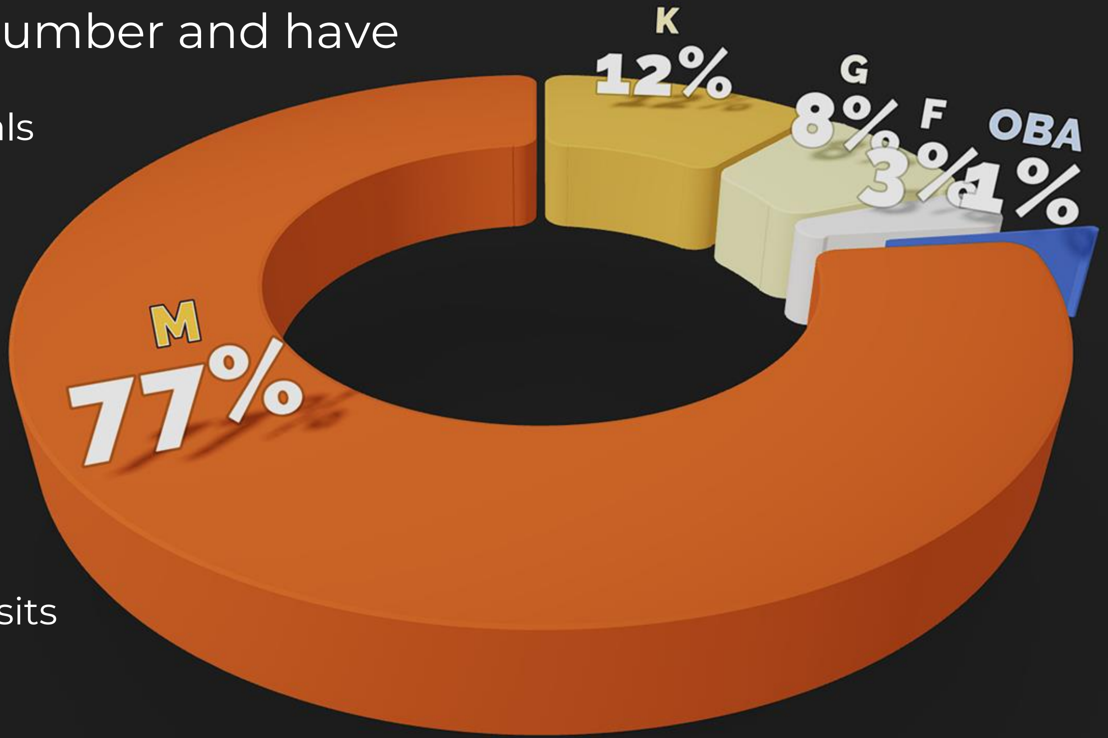
- ✕ lower luminosity

M-dwarfs dominate in number and have

- ★ larger radial velocity signals
- ★ deeper transits

But they also have

- ✕ lower luminosity
- ✕ spots contaminating transits

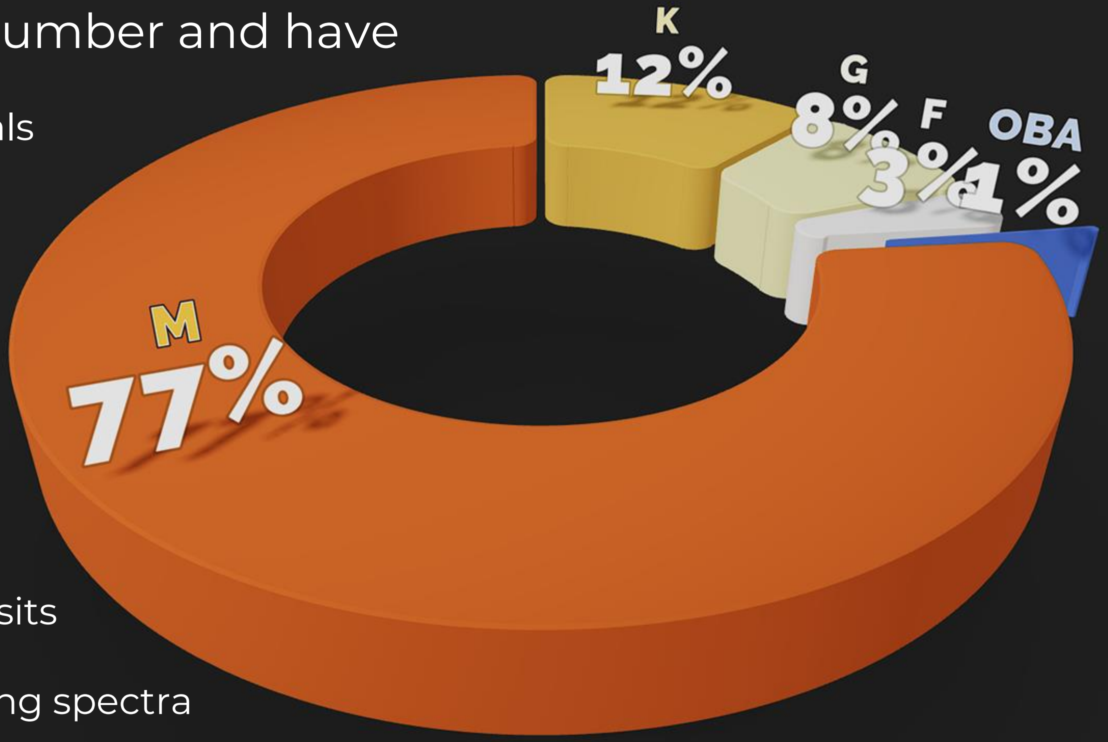


M-dwarfs dominate in number and have

- ★ larger radial velocity signals
- ★ deeper transits

But they also have

- ✕ lower luminosity
- ✕ spots contaminating transits
- ✕ molecular line complicating spectra



Defining GEMS: A rare class of Exoplanets

Defining GEMS: A rare class of Exoplanets

Stellar T_{eff}

2600 K — 4000 K

5780 K

Defining GEMS: A rare class of Exoplanets

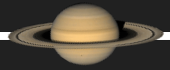
Stellar T_{eff}

2600 K — 4000 K

5780 K

Planet R_p

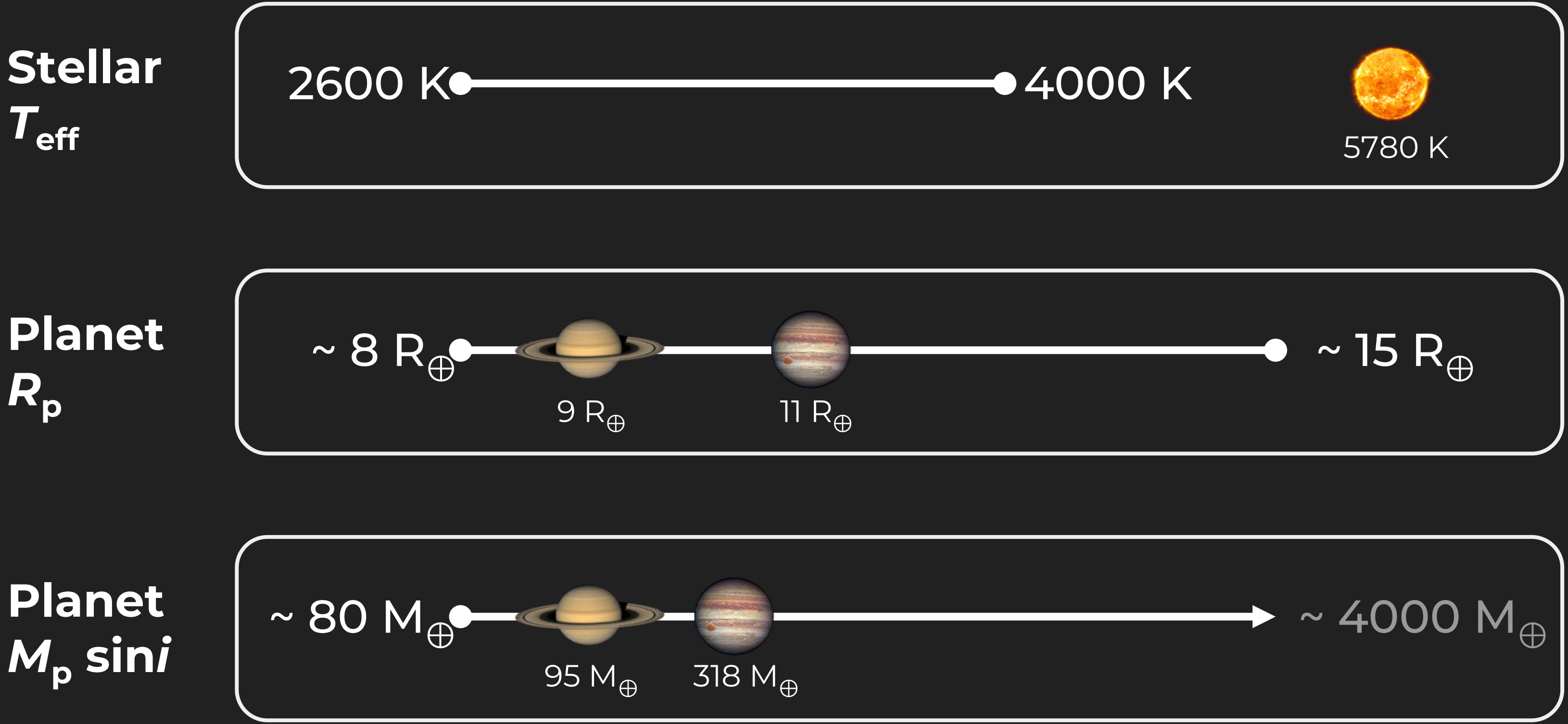
~ 8 $R_\oplus$ — ~ 15 $R_\oplus$



9 $R_\oplus$

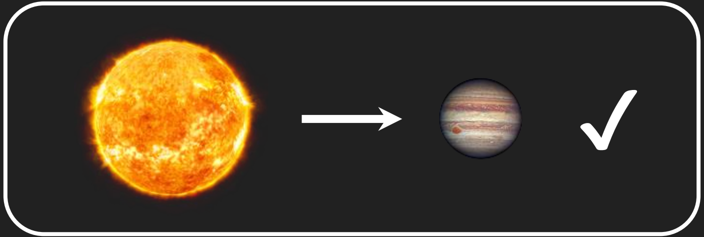
11 $R_\oplus$

Defining GEMS: A rare class of Exoplanets

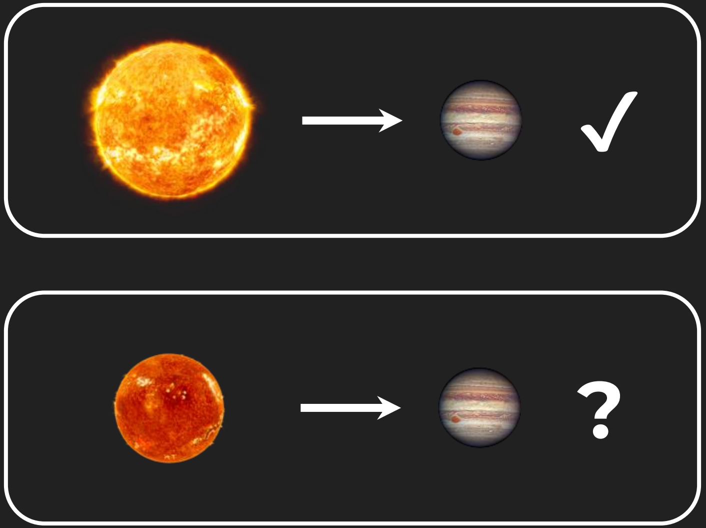


GEMS are rare in theory

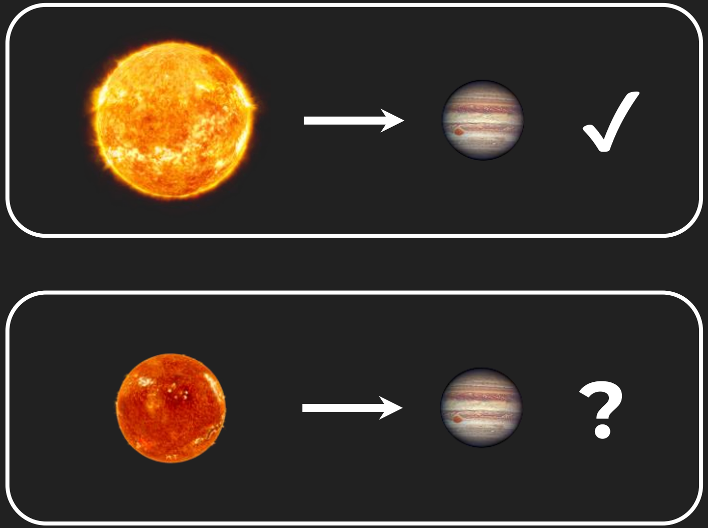
GEMS are rare in theory



GEMS are rare in theory

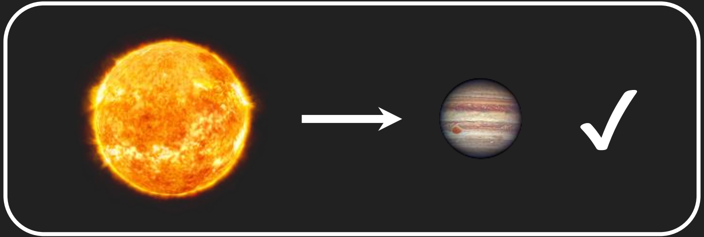


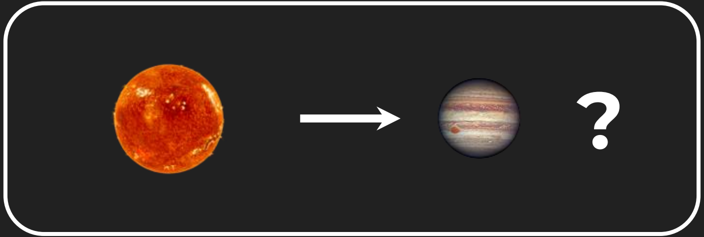
GEMS are rare in theory



Are M dwarfs too small to form giant planets?

GEMS are rare in theory

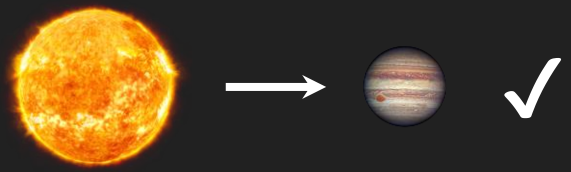


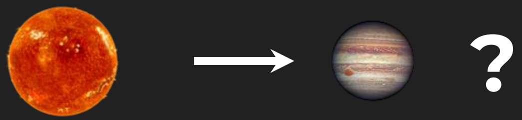


Are M dwarfs too small to form giant planets?

… and in practice

GEMS are rare in theory



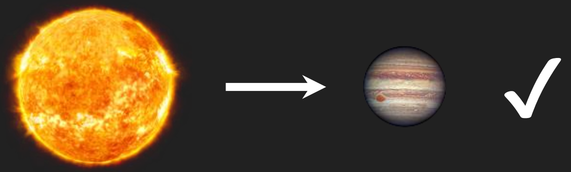


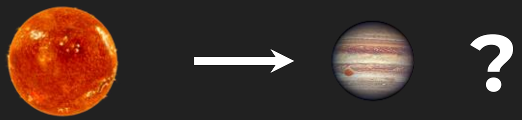
Are M dwarfs too small to form giant planets?

… and in practice

We have only confirmed
~ 30 GEMS, with 17 transiting.

GEMS are rare in theory





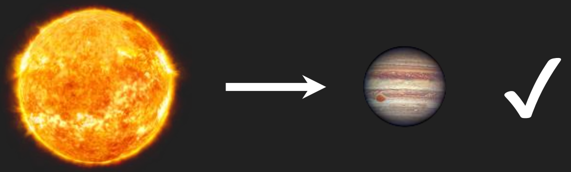
Are M dwarfs too small to form giant planets?

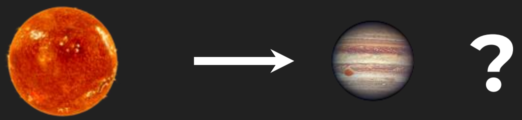
… and in practice

We have only confirmed ~ 30 GEMS, with 17 transiting.

TESS has been discovering many transiting GEMS.

GEMS are rare in theory





Are M dwarfs too small to form giant planets?

… and in practice

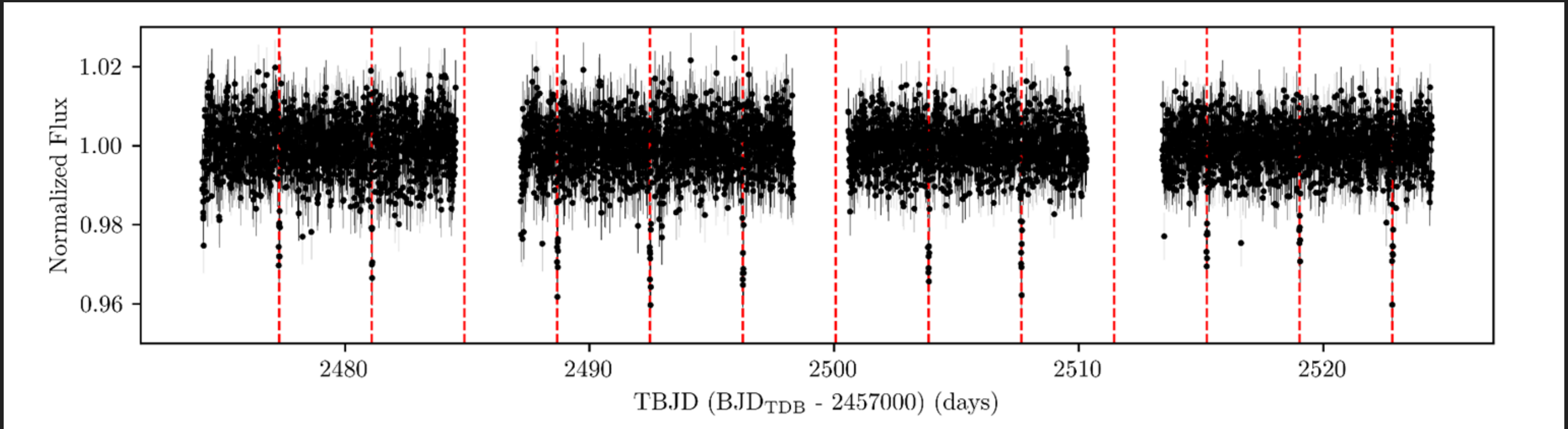
We have only confirmed ~ 30 GEMS, with 17 transiting.

TESS has been discovering many transiting GEMS.

Will GEMS keep being rare?

II. TOI-5344 b as a new GEMS

TESS observed ten transits of ~3% depth



★ TOI-5344 b was identified as a planet candidate in the QLP Faint Star Search (Huang et al. 2020; Kunimoto et al. 2022).

Ruling out False-Positives:

Ruling out False-Positives:

1. No stellar companion

Ruling out False-Positives:

1. No stellar companion
   a. Gaia RUWE = 1.035

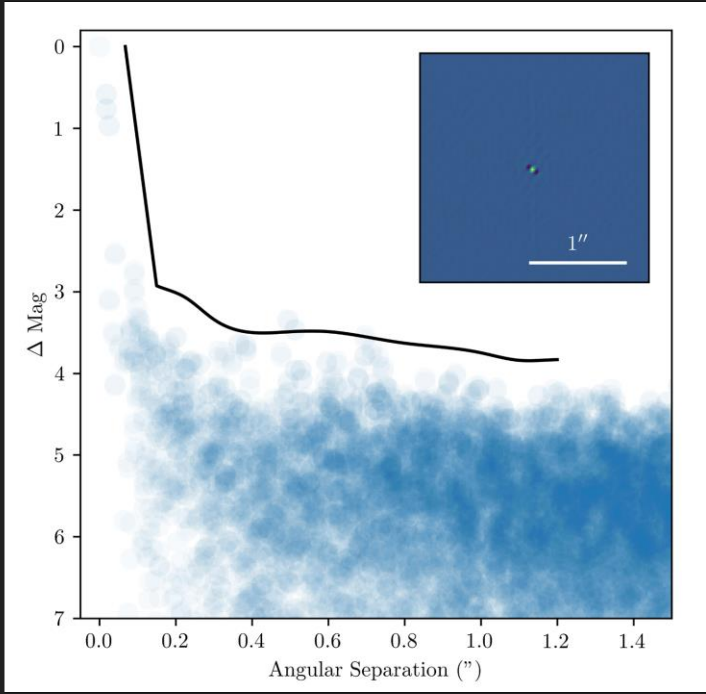
Ruling out False-Positives:

1. No stellar companion
    a. Gaia RUWE = 1.035
    b. NESSI Speckle imaging

Ruling out False-Positives:

1. No stellar companion
   a. Gaia RUWE = 1.035
   b. NESSI Speckle imaging

No bright companions with Δ z < 3.0 are observed between 0.2” and 1.2” of the target.



GIANT EXOPLANETS AROUND GEMS M-DWARF STARS

Ruling out False-Positives:

1. No stellar companion
   a. Gaia RUWE = 1.035
   b. NESSI Speckle imaging

No bright companions with Δ z < 3.0 are observed between 0.2” and 1.2” of the target.

Ruling out False-Positives:

1. No stellar companion
   a. Gaia RUWE = 1.035
   b. NESSI Speckle imaging

   No bright companions with $\Delta z < 3.0$ are observed between 0.2” and 1.2” of the target.

2. No Detectable Stellar Rotation Signal

Ruling out False-Positives:

1. No stellar companion
    a. Gaia RUWE = 1.035
    b. NESSI Speckle imaging

    No bright companions with $\Delta z < 3.0$ are observed between 0.2'' and 1.2'' of the target.

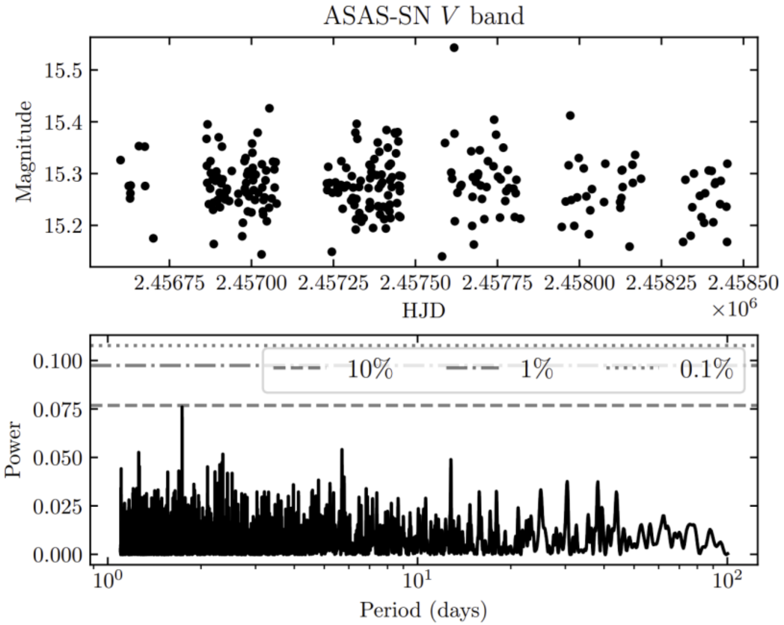
2. No Detectable Stellar Rotation Signal
    a. TESS GLS periodogram

Ruling out False-Positives:

1. No stellar companion
    a. Gaia RUWE = 1.035
    b. NESSI Speckle imaging

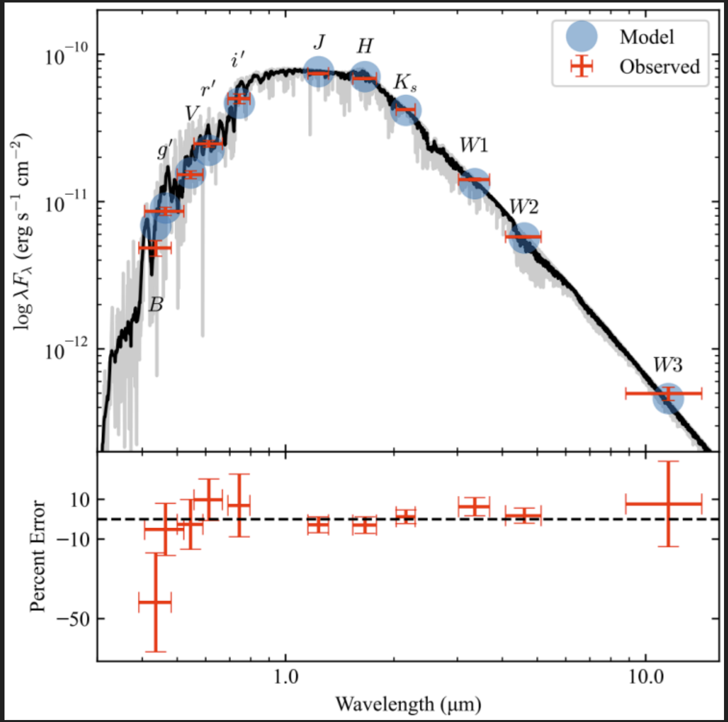
No bright companions with Δ z < 3.0 are observed between 0.2” and 1.2” of the target.

2. No Detectable Stellar Rotation Signal
    a. TESS GLS periodogram
    b. ZTF* & ASAS-SN† GLS periodogram



*Zwicky Transient Facility. †All-Sky Automated Survey for Supernovae.

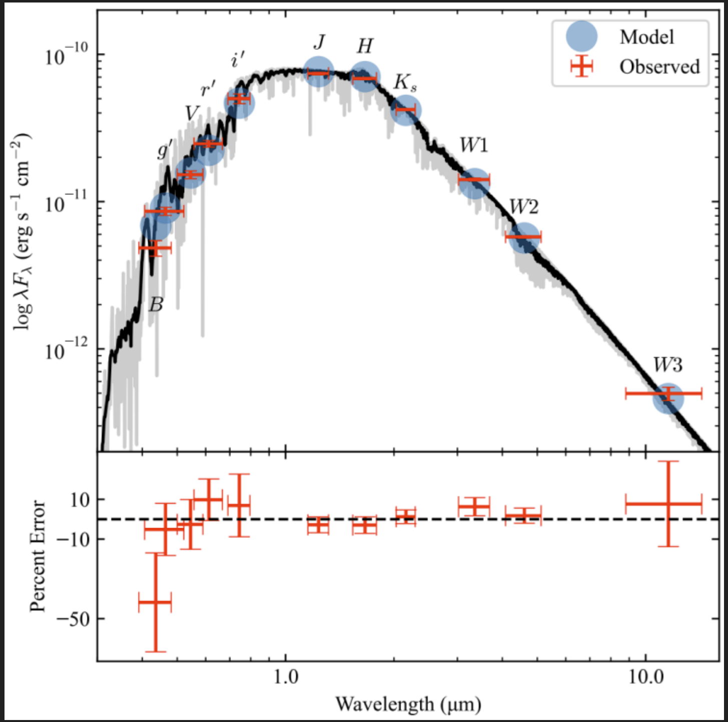
Spectral Energy Distribution (SED)



GIANT EXOPLANETS AROUND M-DWARF STARS GEMS

Spectral Energy Distribution (SED)

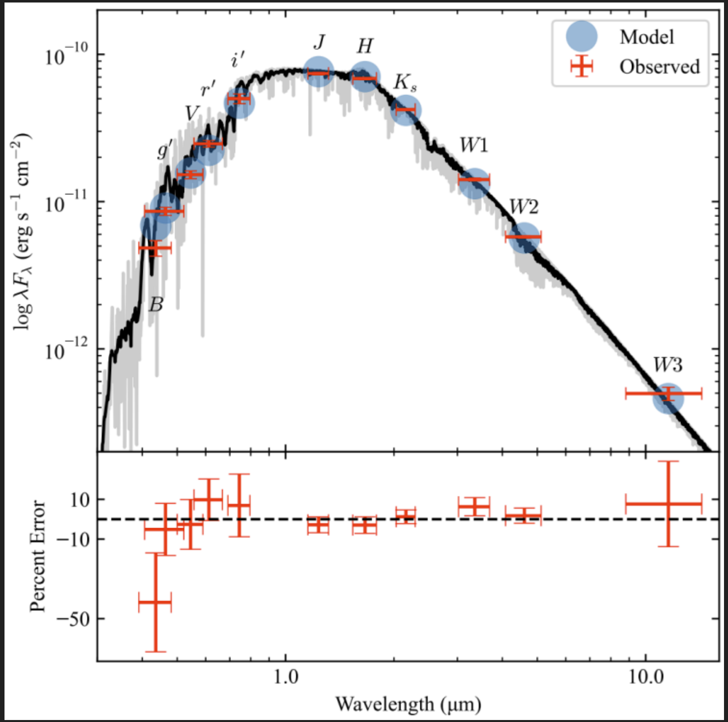
$M_{\star} = 0.59^{+0.02}_{-0.03}\ M_{\odot}$



Spectral Energy Distribution (SED)

$M_{\star} = 0.59^{+0.02}_{-0.03}\ M_{\odot}$

$R_{\star} = 0.563 \pm 0.016\ R_{\odot}$

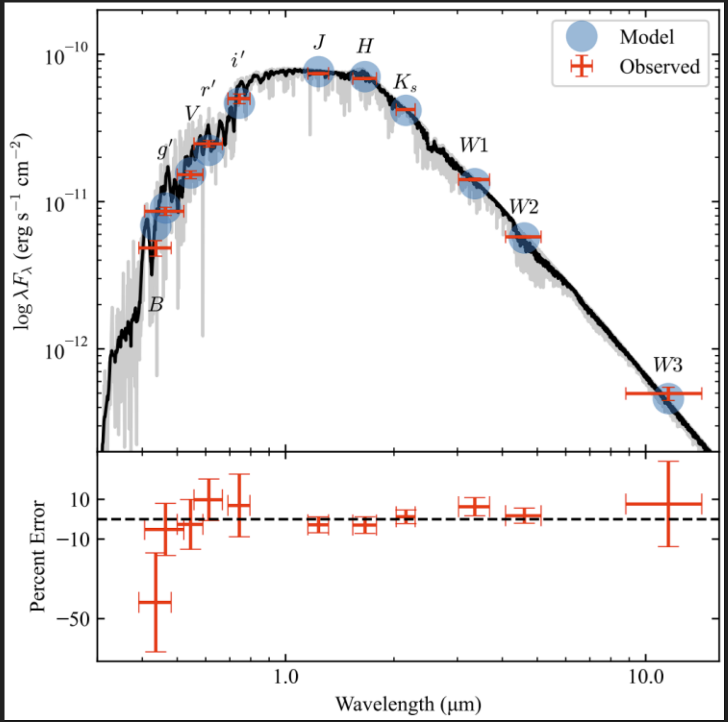


Spectral Energy Distribution (SED)

$M_\star = 0.59^{+0.02}_{-0.03}\ M_\odot$

$R_\star = 0.563 \pm 0.016\ R_\odot$

⇒ TOI-5344 is a M0 dwarf

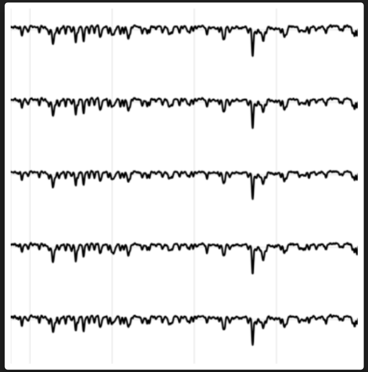


HPF*-SpecMatch†

*Habitable-zone Planet Finder (HPF). †Stefansson et al. 2020.

HPF*-SpecMatch†

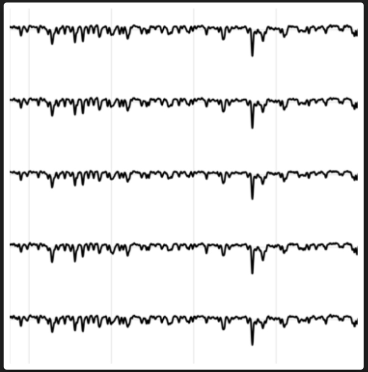
Observe M-dwarfs with known stellar properties



*Habitable-zone Planet Finder (HPF). †Stefansson et al. 2020.

HPF*-SpecMatch†

Observe M-dwarfs with known stellar properties



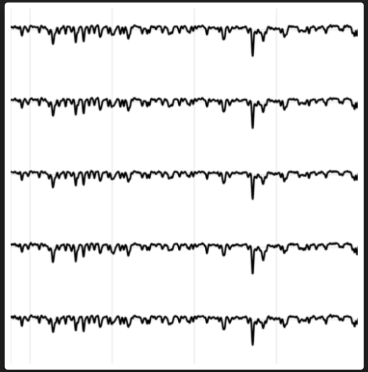
→

Fit a Composite Spectrum for the target star

*Habitable-zone Planet Finder (HPF). †Stefansson et al. 2020.

HPF*-SpecMatch†

Observe M-dwarfs with known stellar properties



→

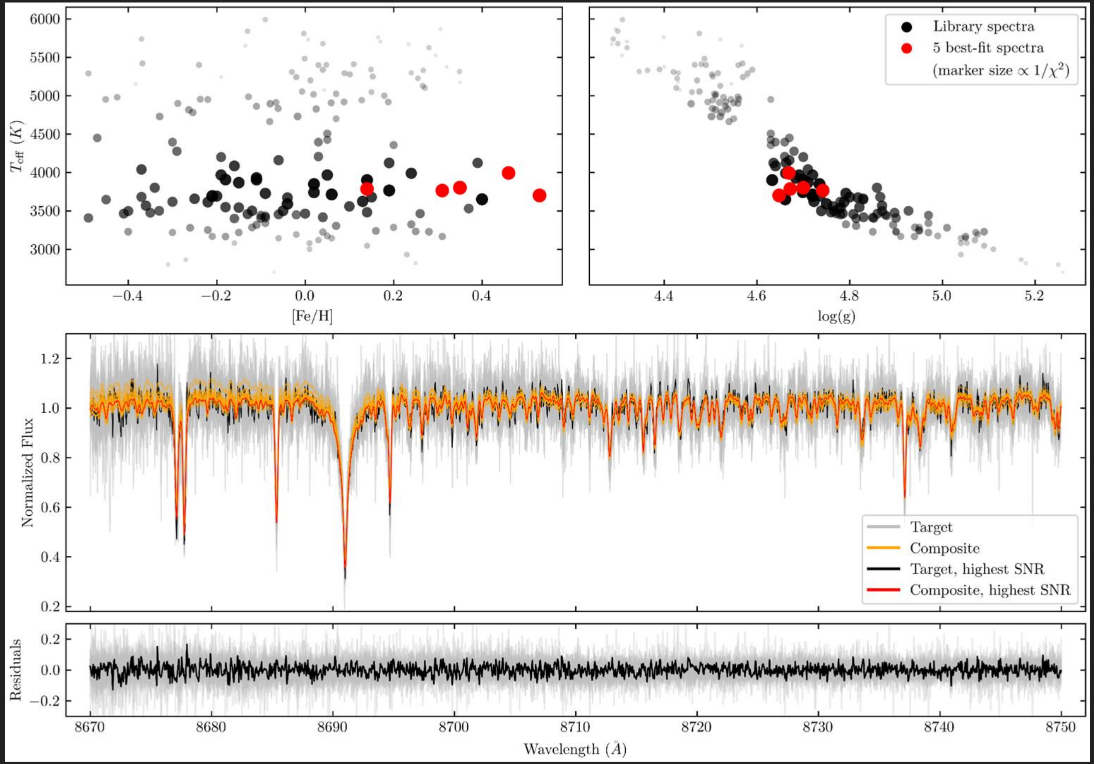
Fit a Composite Spectrum for the <u>target star</u>

→

Minimize the residual & get stellar parameters for the <u>target star</u>

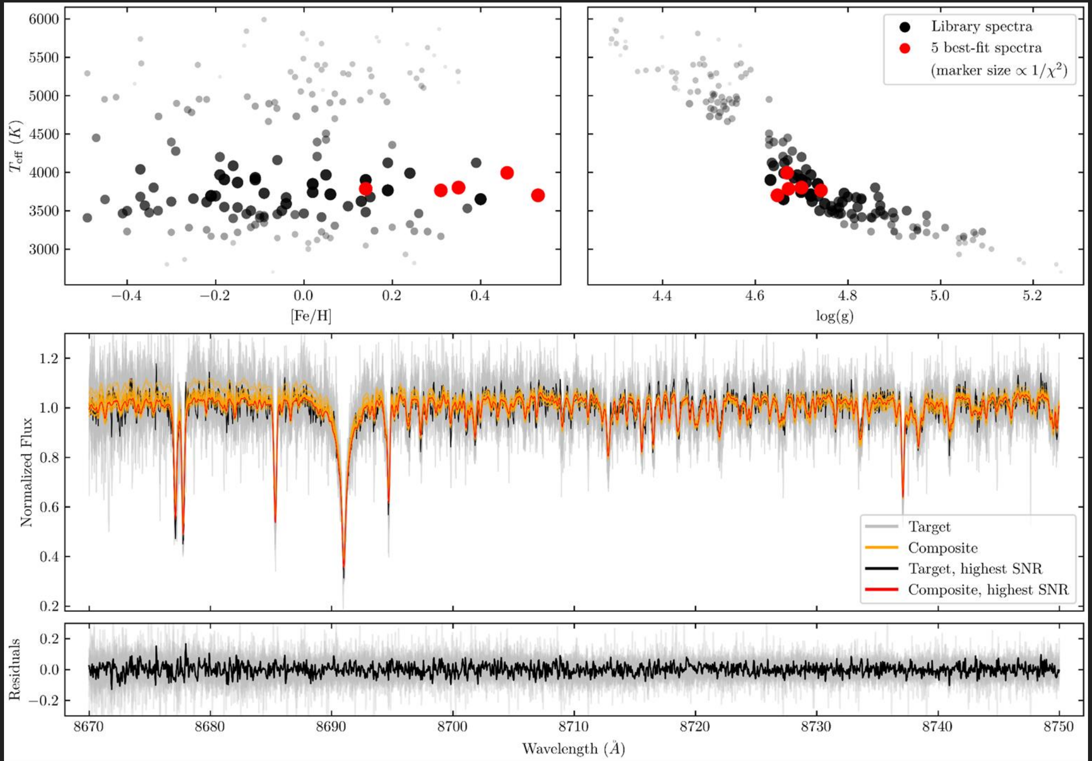
*Habitable-zone Planet Finder (HPF). †Stefansson et al. 2020.

HPF-SpecMatch on TOI-5344



HPF-SpecMatch on TOI-5344

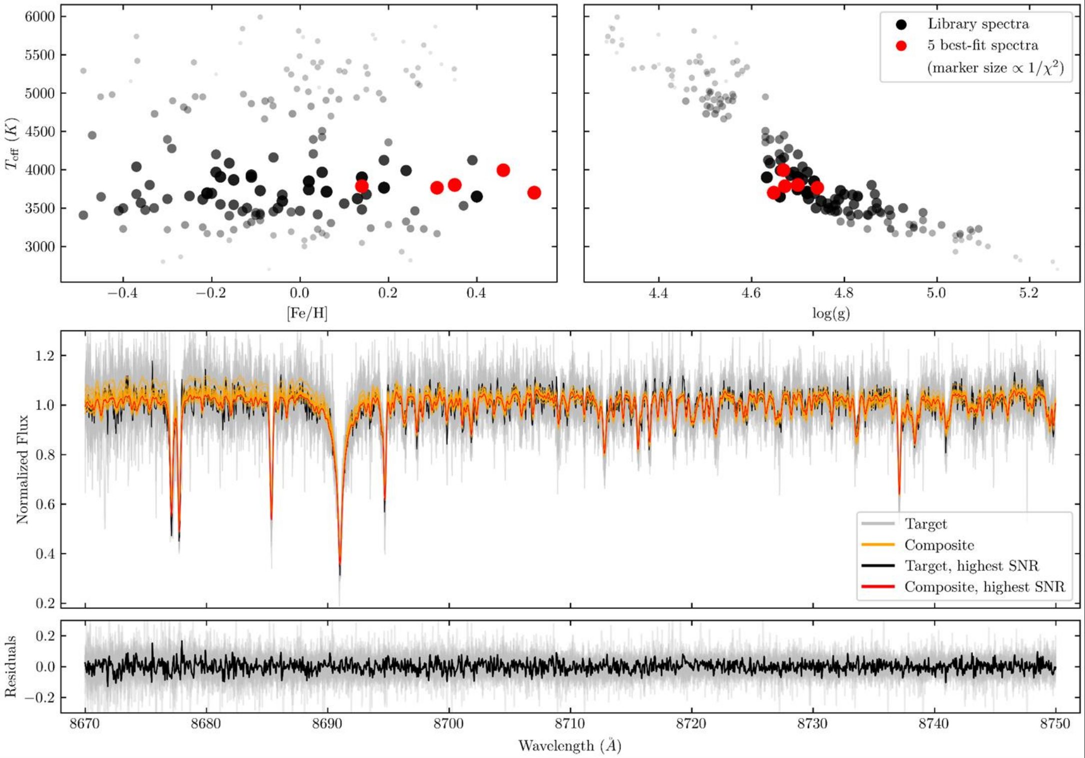
T_{eff} = 3770 ± 88 K



HPF-SpecMatch on TOI-5344

T_{eff}= 3770 ± 88 K

[Fe/H] = 0.48 ± 0.12

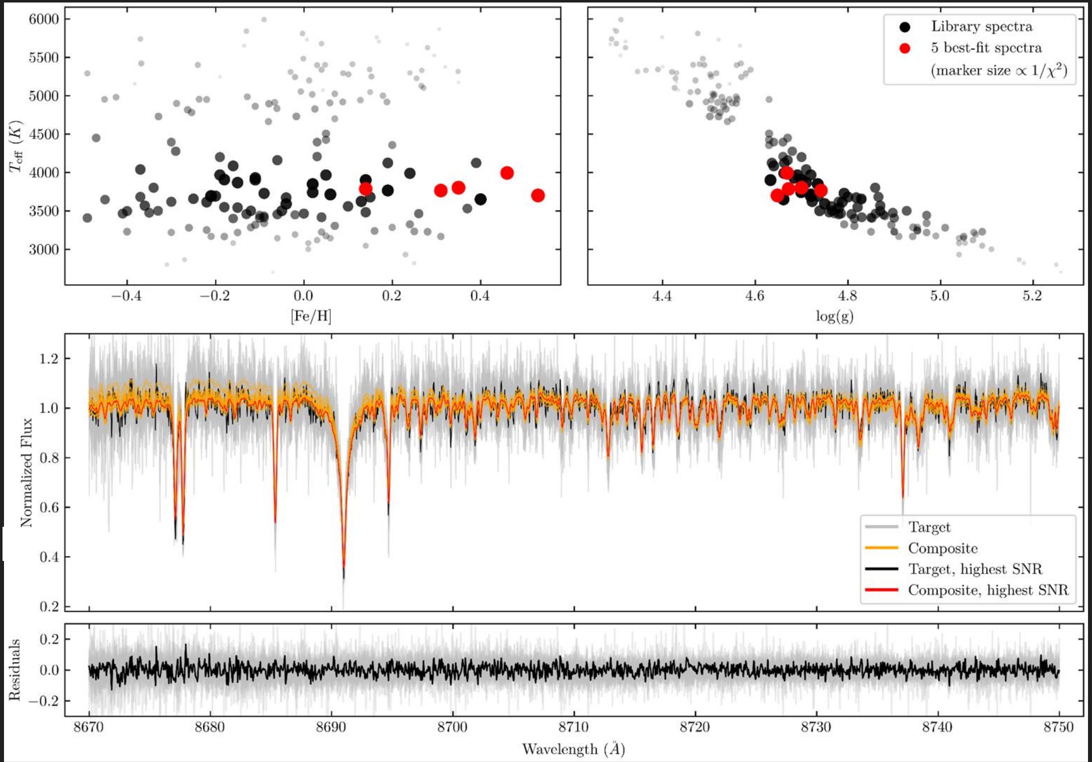


HPF-SpecMatch on TOI-5344

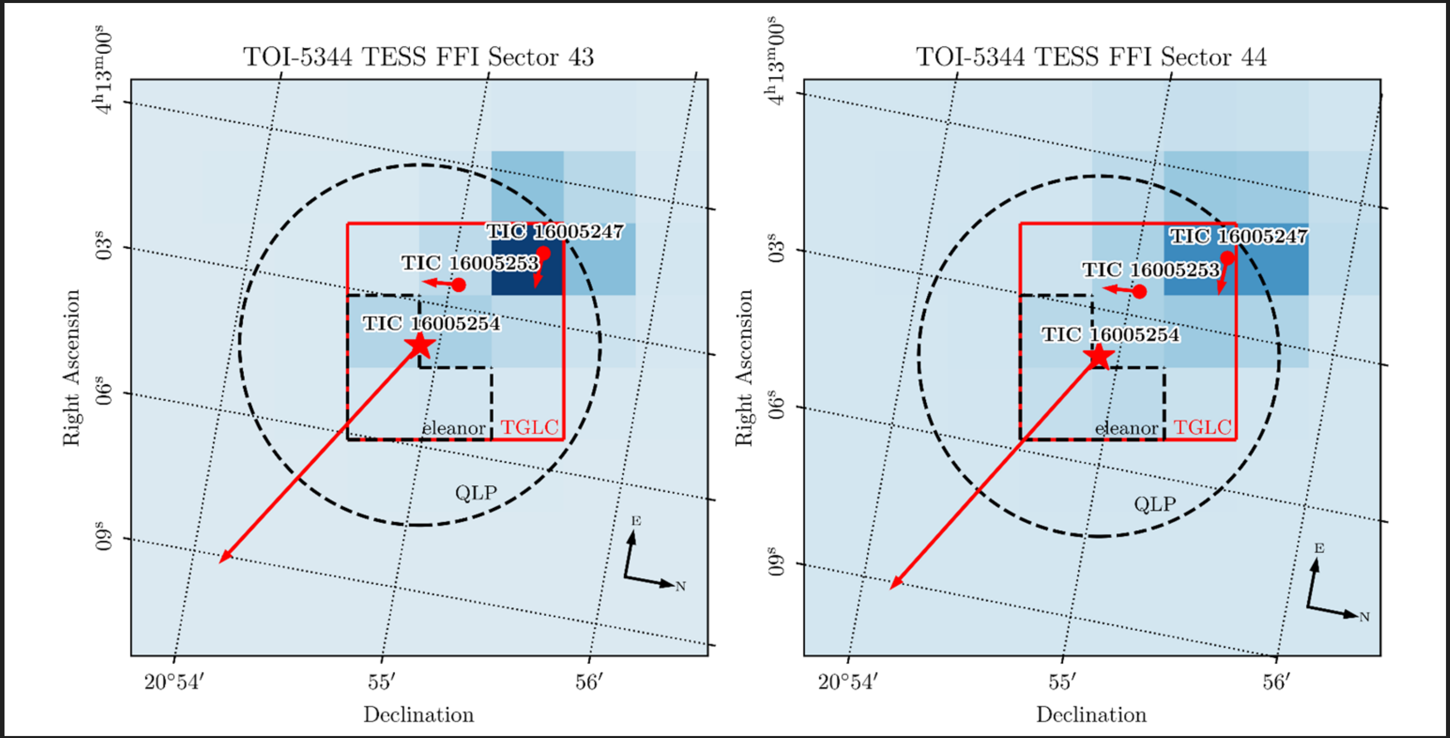
T_{eff}= 3770 ± 88 K

[Fe/H] = 0.48 ± 0.12

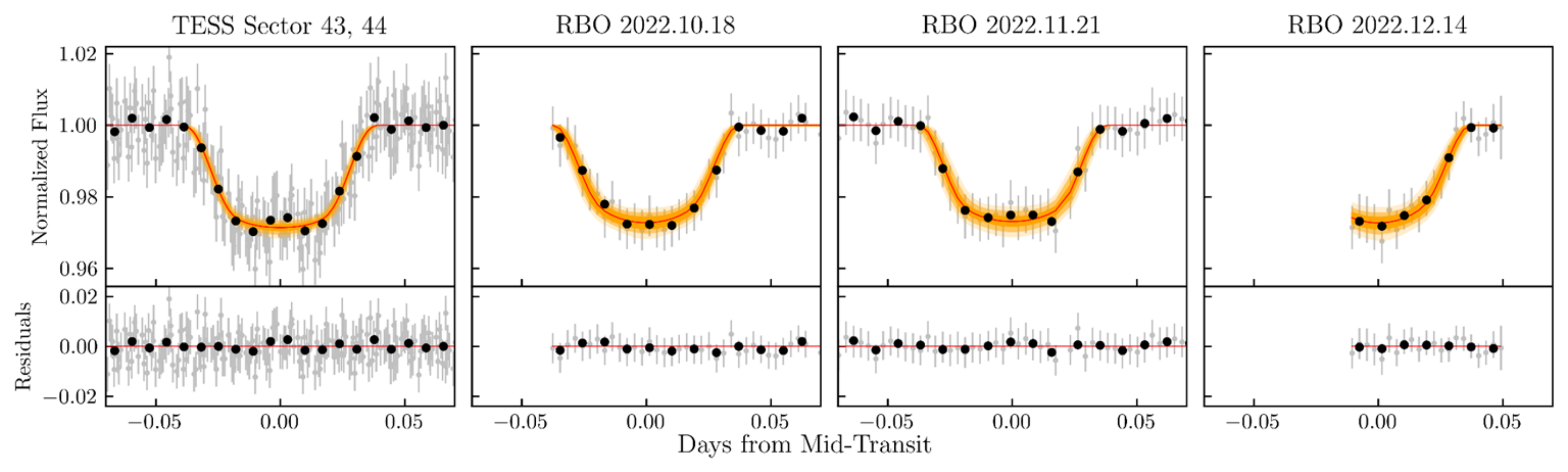
⇒ TOI-5344 has Super-sol
Metallicity



Comparing TESS FFI light curves

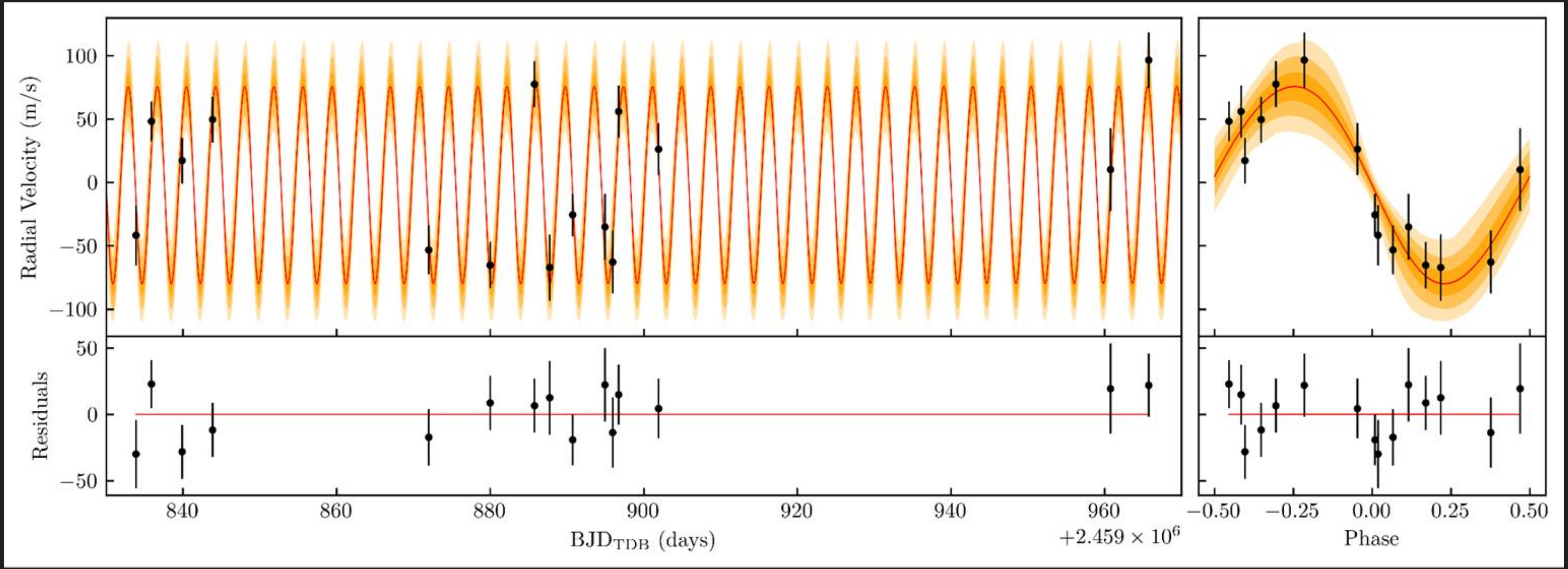


Ground-based photometry: the Red Buttes Observatory



P = 3.792622 ± 0.000010 days

HPF Radial Velocity



GIANT EXOPLANETS AROUND GEMS M-DWARF STARS

Planetary Parameters†

$M_p = 135^{+17}_{-18}\ M_\oplus$
$= 0.42^{+0.05}_{-0.06}\ M_J$

$R_p = 9.7 \pm 0.5\ R_\oplus$
$= 0.87 \pm 0.04\ R_J$

$T_{eq} = 679 \pm 14$ K

†from photometry & RV joint fit.

Planetary Parameters†

$M_p = 135^{+17}_{-18}\ M_\oplus$
$= 0.42^{+0.05}_{-0.06}\ M_J$

$R_p = 9.7 \pm 0.5\ R_\oplus$
$= 0.87 \pm 0.04\ R_J$

$T_{eq} = 679 \pm 14$ K

Stellar Parameters

$M_\star = 0.59^{+0.02}_{-0.03}\ M_\odot$

$R_\star = 0.563 \pm 0.016\ R_\odot$

$T_{eff} = 3770 \pm 88$ K

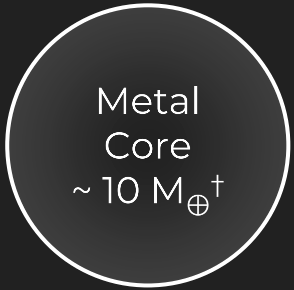
[Fe/H] = 0.48 ± 0.12

†from photometry & RV joint fit.

III. GEMS Formation

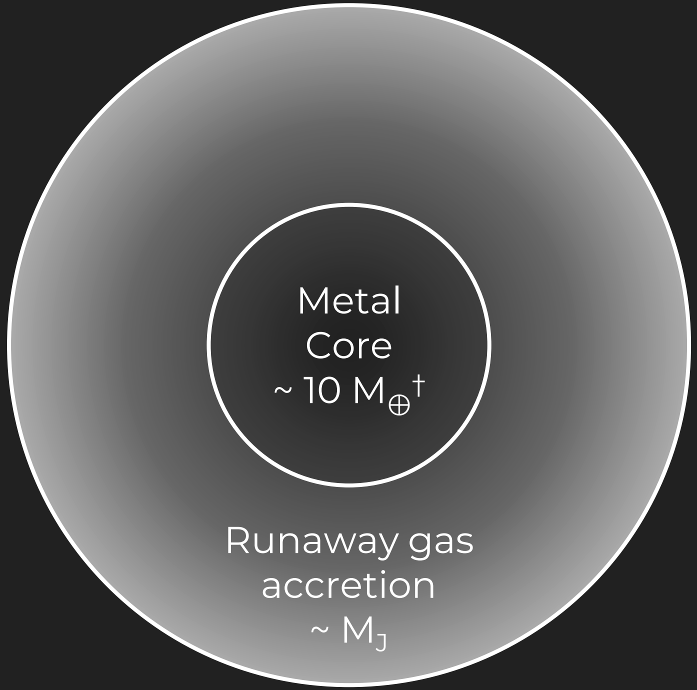
The (simple) core accretion theory

The (simple) core accretion theory



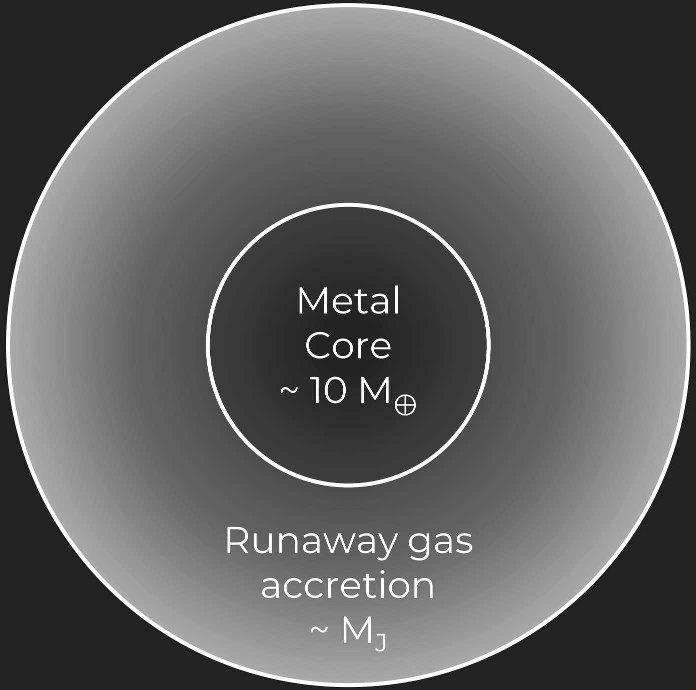
†Pollack et al. 1996

The (simple) core accretion theory



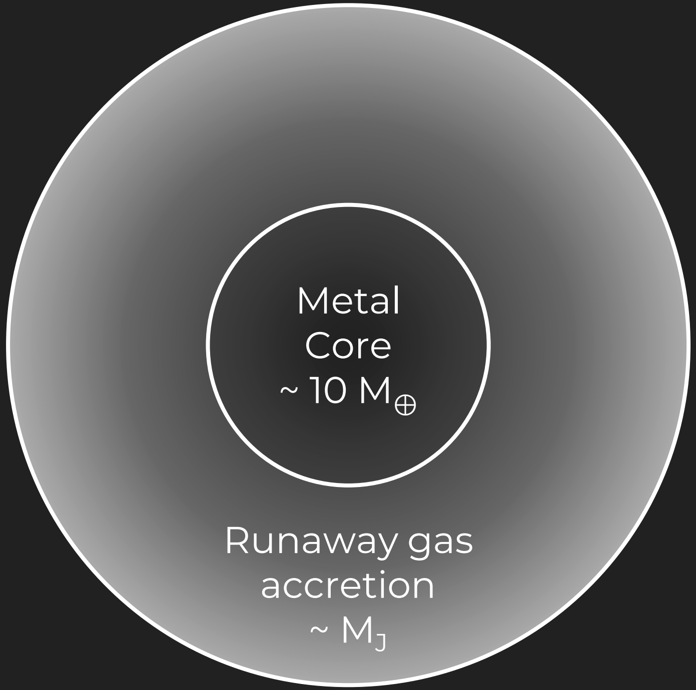
†Pollack et al. 1996

Why M dwarfs might struggle to form giants?



Why M dwarfs might struggle to form giants?

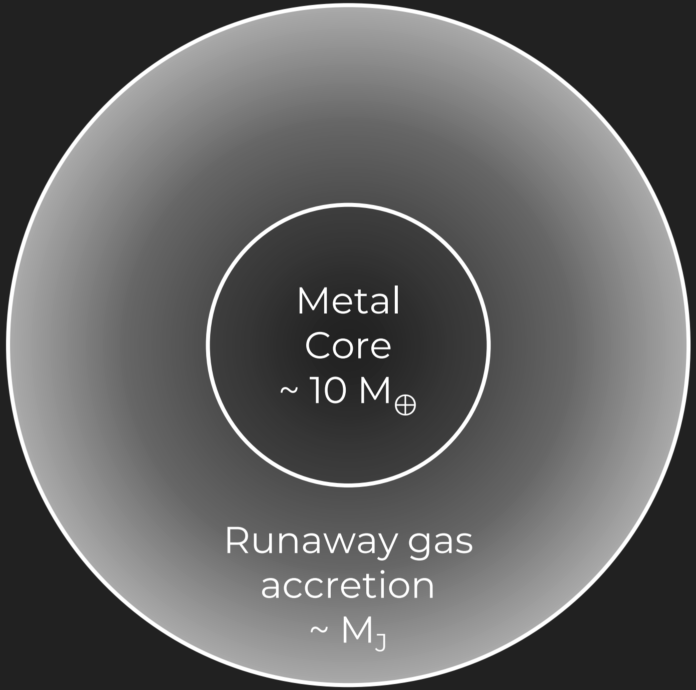
1. M-dwarf planetary disk might not have <u>enough metal</u> to form core



Why M dwarfs might struggle to form giants?

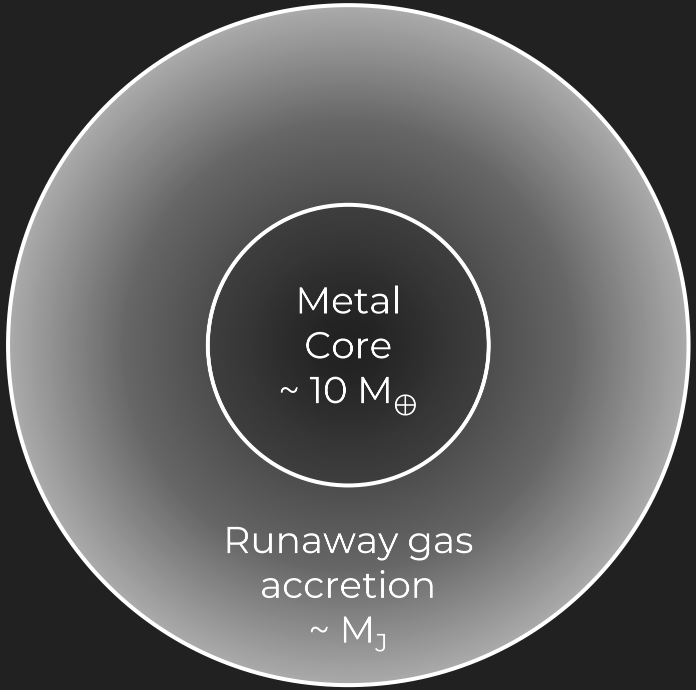
1. M-dwarf planetary disk might not have <u>enough metal</u> to form core

    - Kanodia 2023 (in prep) shows ~ 100 $M_\oplus$ metal mass in the disk might be needed to form ~ 10 $M_\oplus$ core.



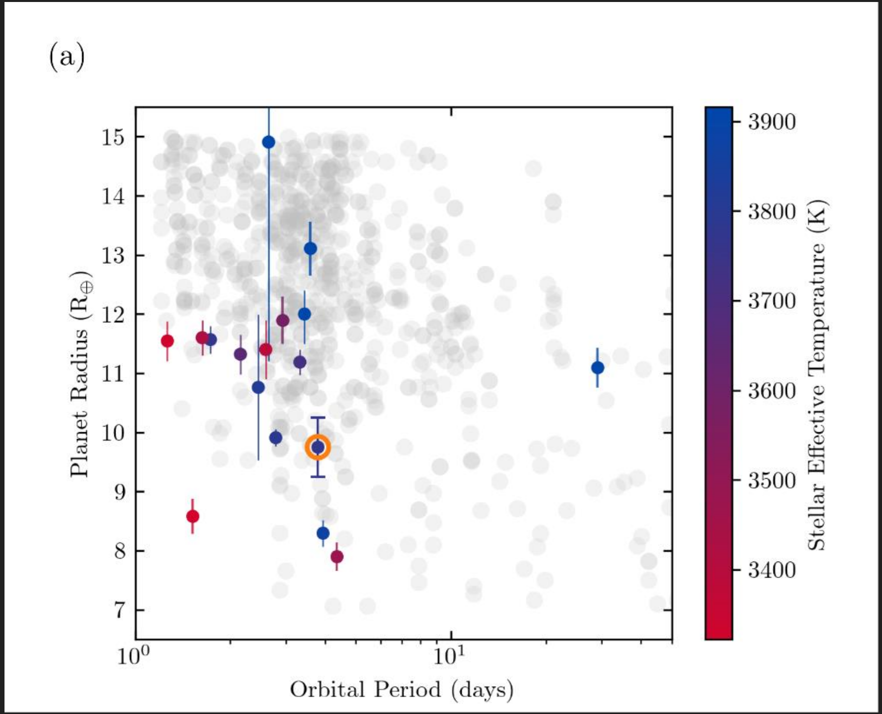
Why M dwarfs might struggle to form giants?

1. M-dwarf planetary disk might not have <u>enough metal</u> to form core
    - Kanodia 2023 (in prep) shows ~ 100 $M_\oplus$ metal mass in the disk might be needed to form ~ 10 $M_\oplus$ core.
2. The <u>time-scale</u> of forming such core might be longer than the gas depletion time



More Saturns, less Jupiters

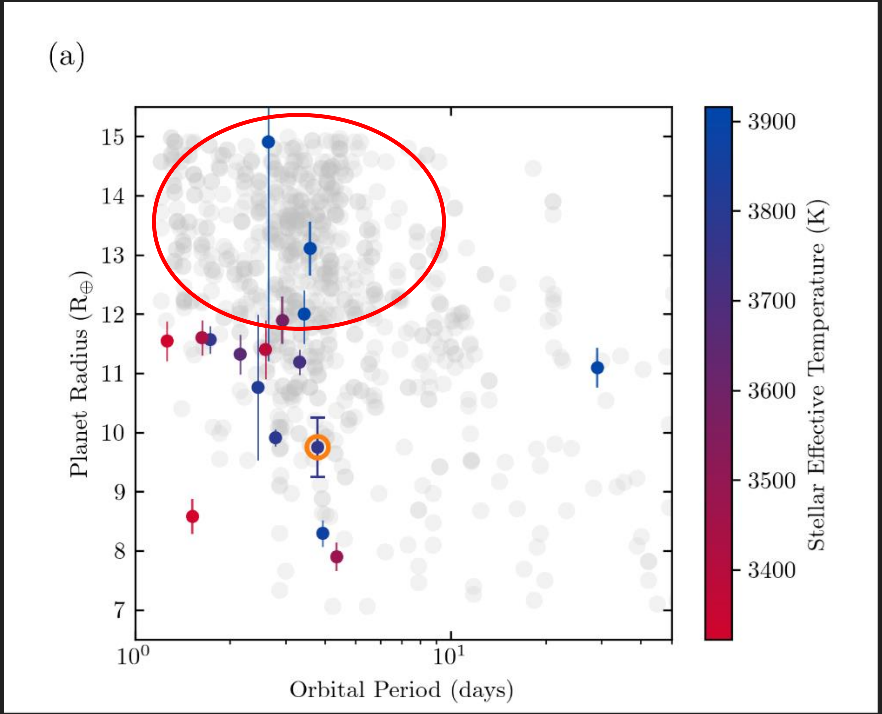
Compared to Giants around FGK dwarfs (gray points), GEMS† seems to be smaller:



† The sample consists of 17 Transiting GEMS.

More Saturns, less Jupiters

Compared to Giants around FGK dwarfs (gray points), GEMS† seems to be smaller:

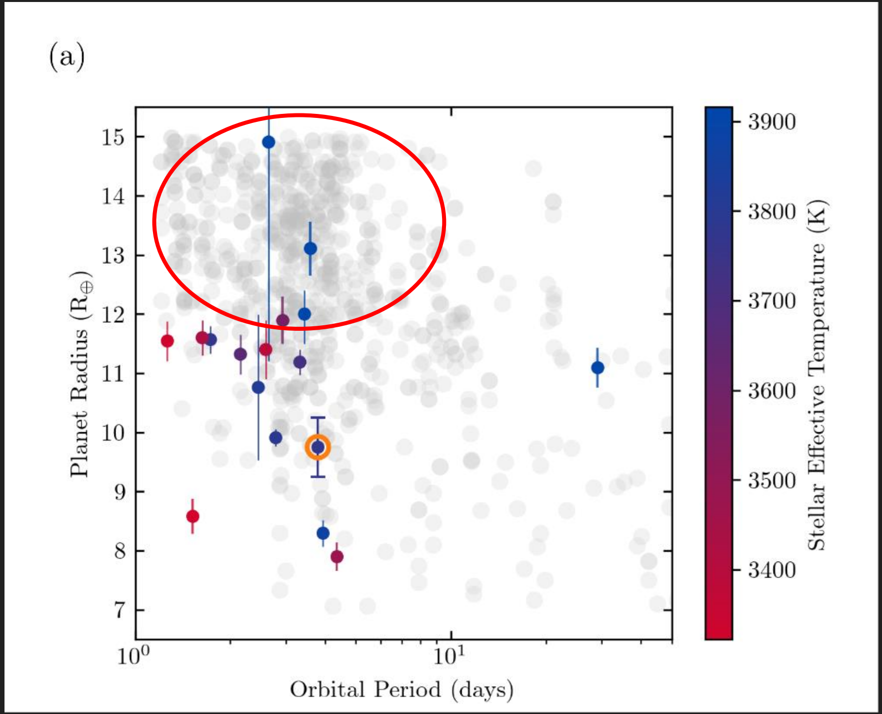


† The sample consists of 17 Transiting GEMS.

More Saturns, less Jupiters

Compared to Giants around FGK dwarfs (gray points), GEMS† seems to be smaller:

FGK: $N_{Saturns} / N_{Jupiters} = 0.12$



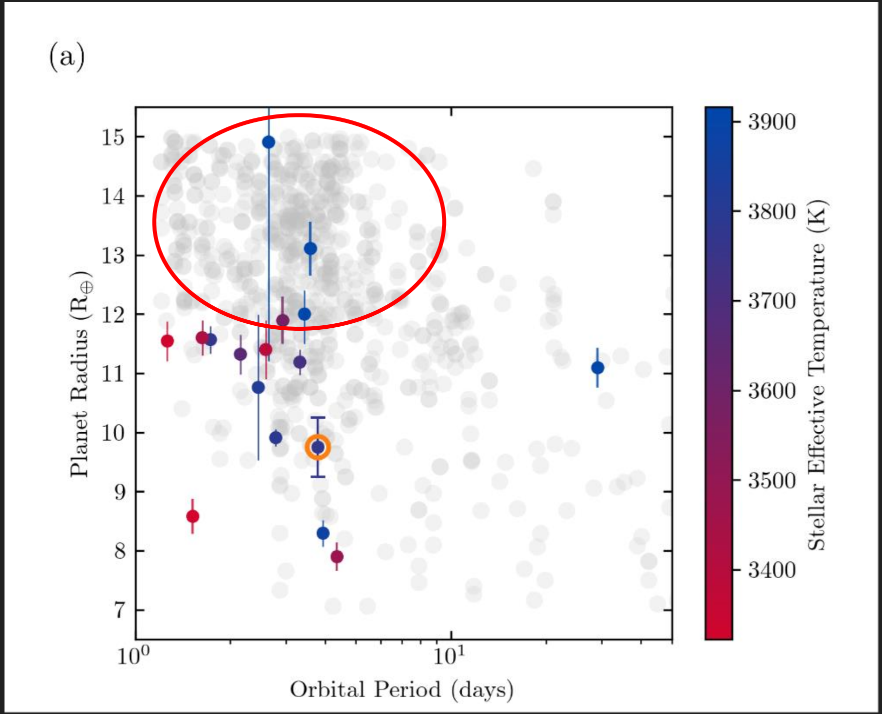
† The sample consists of 17 Transiting GEMS.

More Saturns, less Jupiters

Compared to Giants around FGK dwarfs (gray points), GEMS† seems to be smaller:

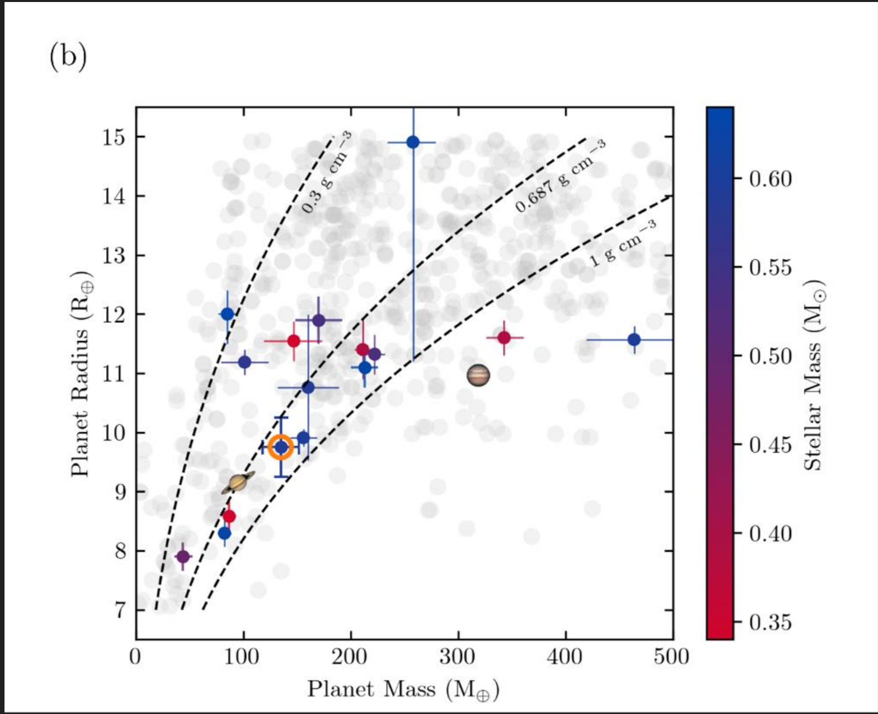
FGK: $N_{Saturns} / N_{Jupiters} = 0.12$

M: $N_{Saturns} / N_{Jupiters} = 0.42$

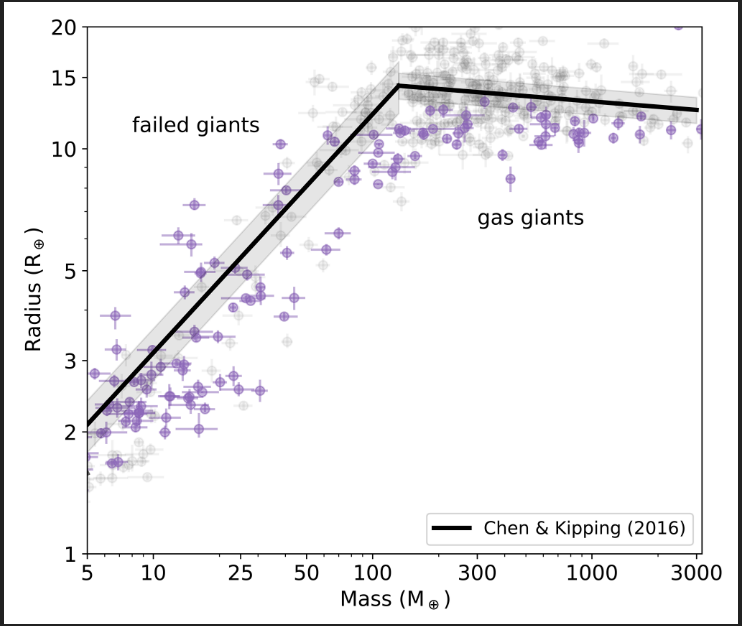


† The sample consists of 17 Transiting GEMS.

More Saturns, less Jupiters



More Saturns, less Jupiters



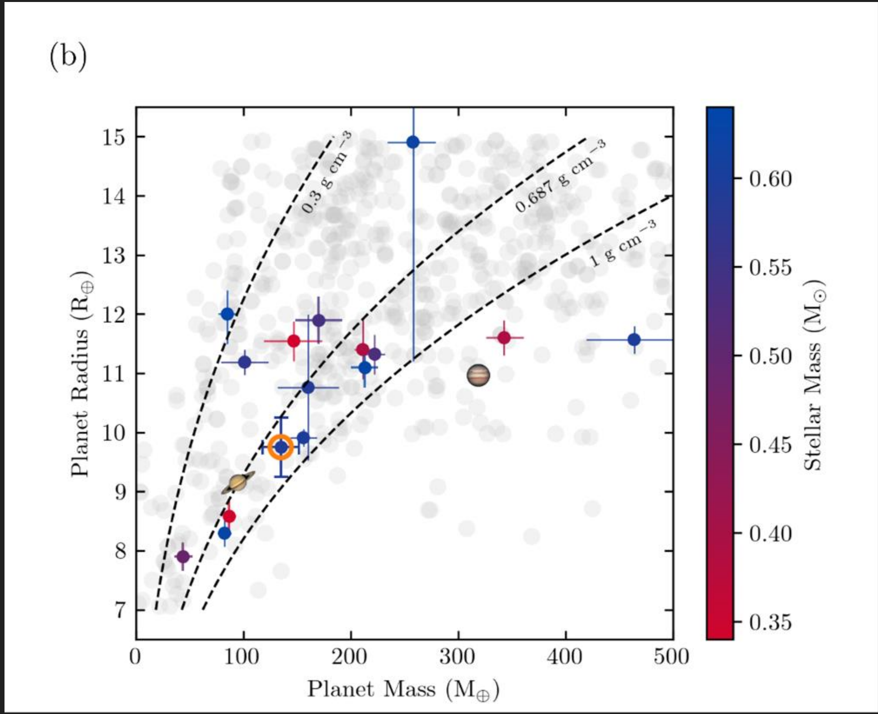
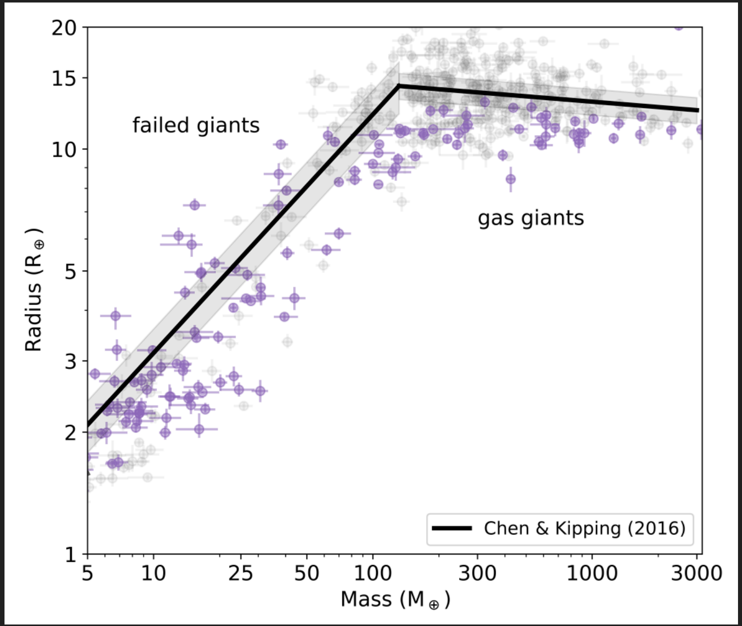


Figure: Chen & Kipping 2017; Helled 2023

More Saturns, less Jupiters



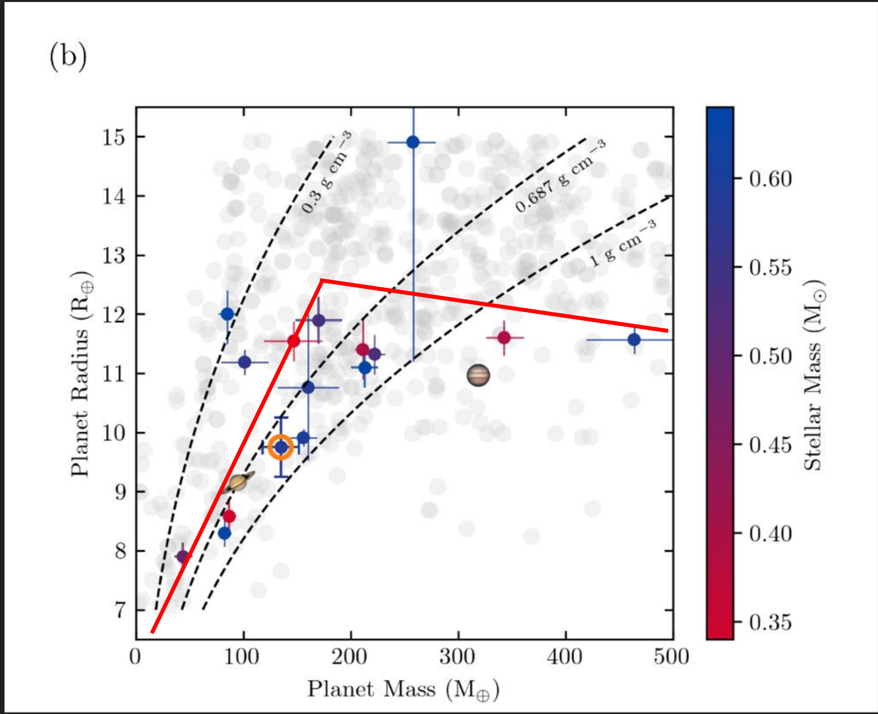
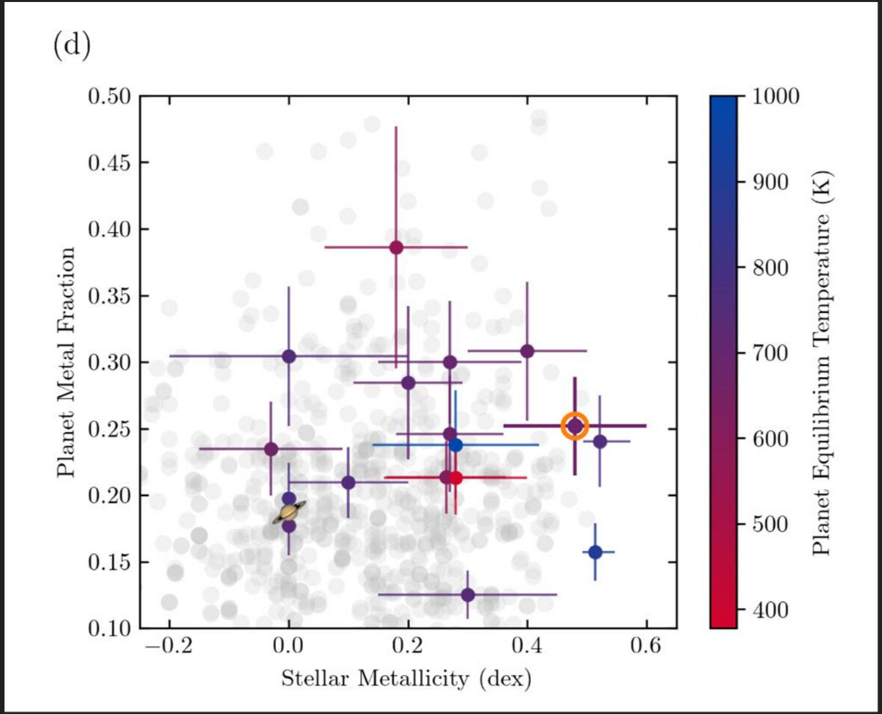


Figure: Chen & Kipping 2017; Helled 2023

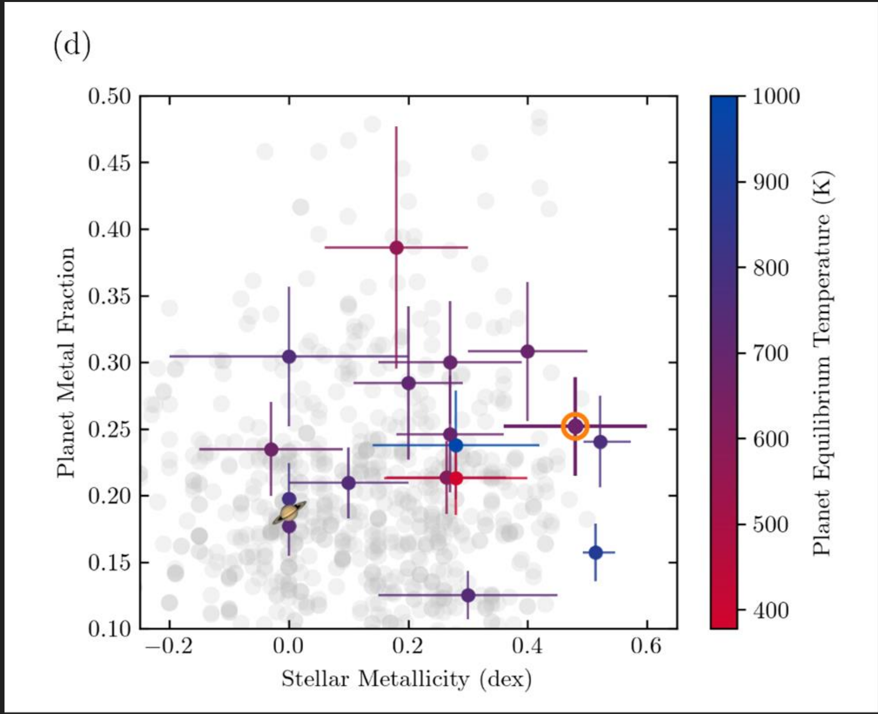
Planet Metal fraction† of GEMS are high



†Calculated following Thorngren et al. 2016

Planet Metal fraction† of GEMS are high

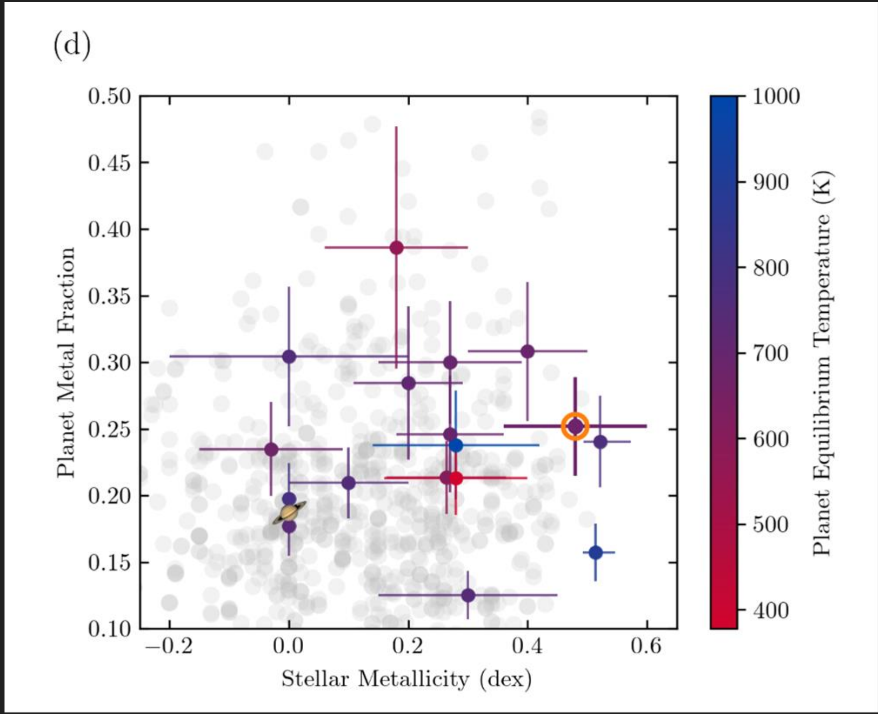
- Jupiter Metal fraction = 0.057–0.103



†Calculated following Thorngren et al. 2016

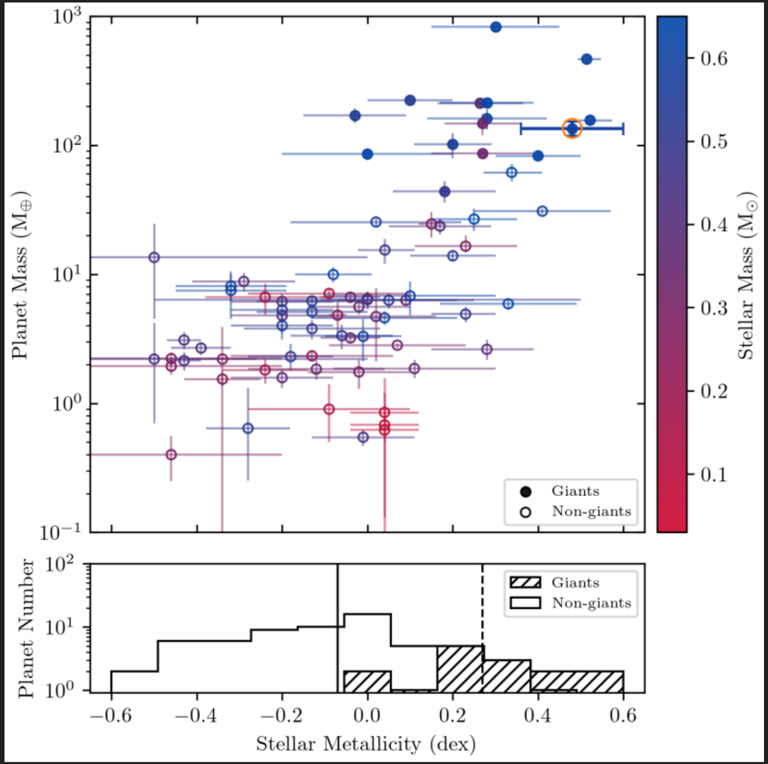
Planet Metal fraction† of GEMS are high

- Jupiter Metal fraction = 0.057–0.103
- The high metal fraction suggests GEMS accretes relatively less gas (like Saturn)



†Calculated following Thorngren et al. 2016

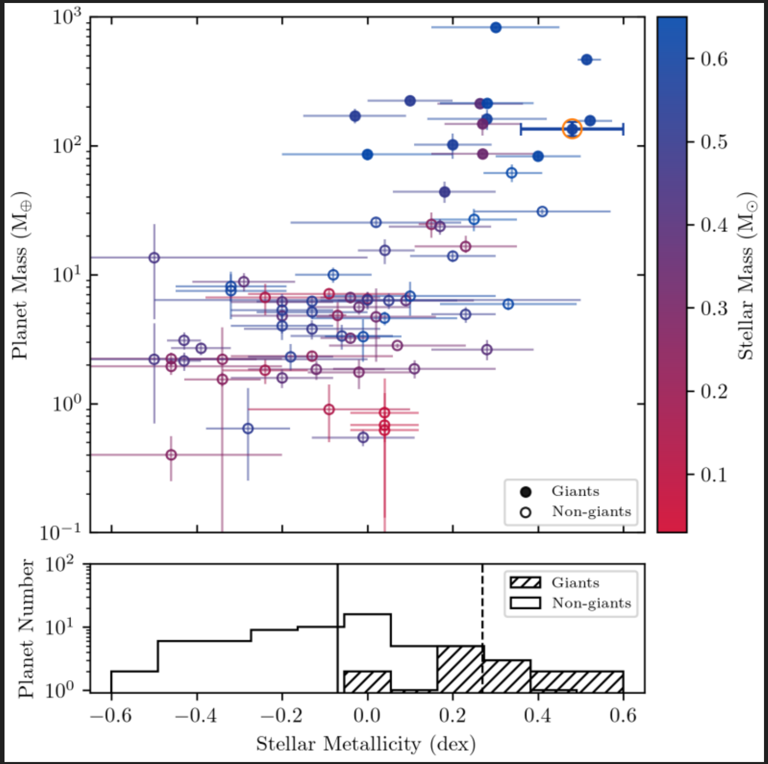
Planet-Metallicity Correlation for M dwarfs



Planet-Metallicity Correlation for M dwarfs

Giants $\equiv 8 \lesssim R_p \lesssim 15$

Non-giants $\equiv R_p \lesssim 8$

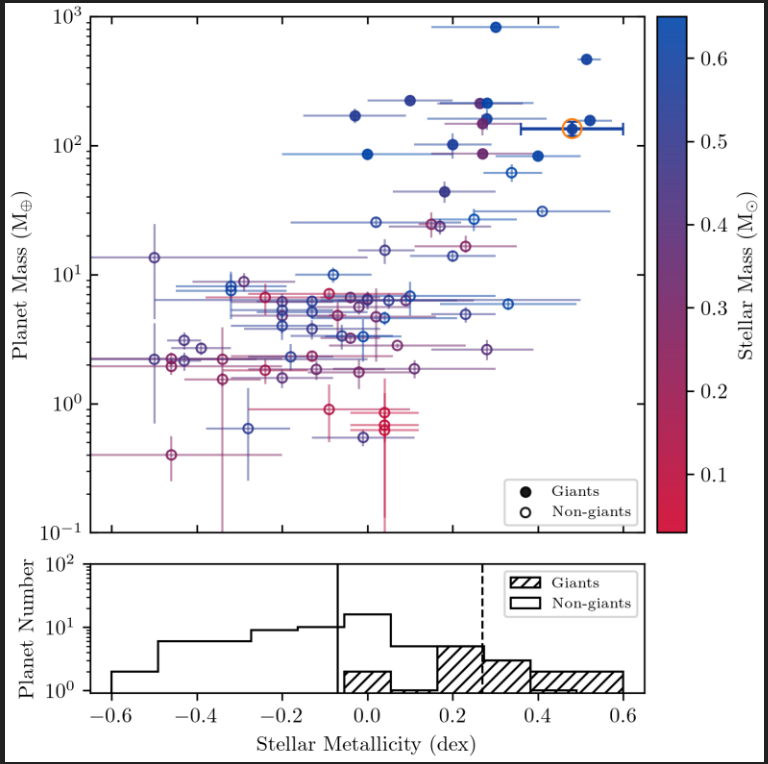


Planet-Metallicity Correlation for M dwarfs

Giants ≡ $8 \lesssim R_p \lesssim 15$

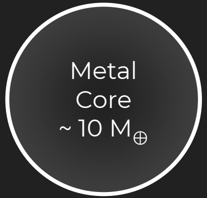
Non-giants ≡ $R_p \lesssim 8$

⇒ M dwarfs hosting giant planets appear to have higher metallicity than those hosting non-giants.



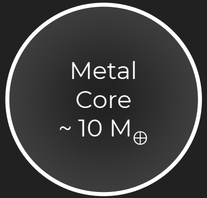
Two GEMS formation theories

If metal cores are formed in certain (high metallicity) disks before gas depletion

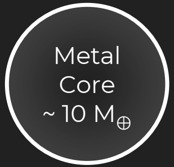


Two GEMS formation theories

If metal cores are formed in certain (high metallicity) disks before gas depletion

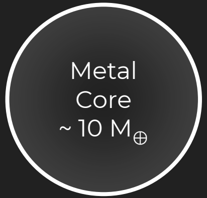


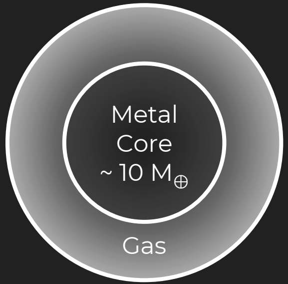
→



Two GEMS formation theories

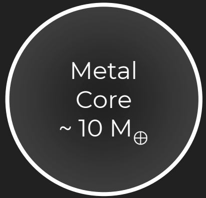
If metal cores are formed in certain (high metallicity) disks before gas depletion





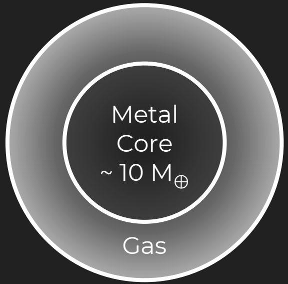
Two GEMS formation theories

If metal cores are formed in certain (high metallicity) disks before gas depletion



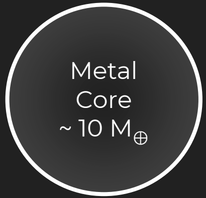
→

High metallicity disk



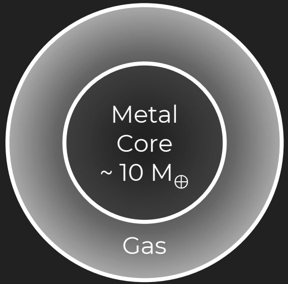
Two GEMS formation theories

If metal cores are formed in certain (high metallicity) disks before gas depletion



→

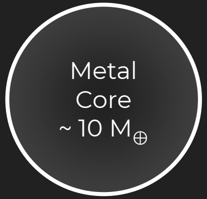
High metallicity disk
⇒ high opacity†



†Movshovitz et al. 2010

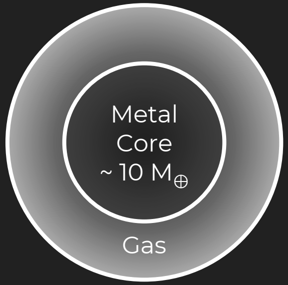
Two GEMS formation theories

If metal cores are formed in certain (high metallicity) disks before gas depletion



→

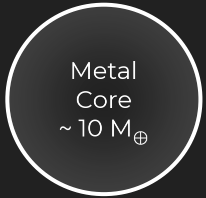
High metallicity disk
⇒ high opacity†
⇒ slow heat dissipation



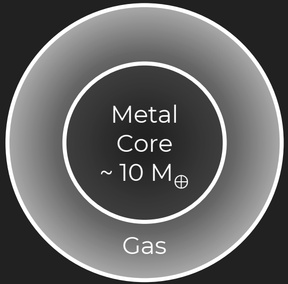
†Movshovitz et al. 2010

Two GEMS formation theories

If metal cores are formed in certain (high metallicity) disks before gas depletion



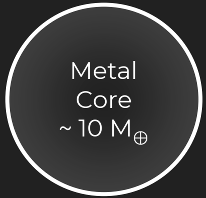
High metallicity disk
⇒ high opacity†
⇒ slow heat dissipation
⇒ slowed gas accretion



†Movshovitz et al. 2010

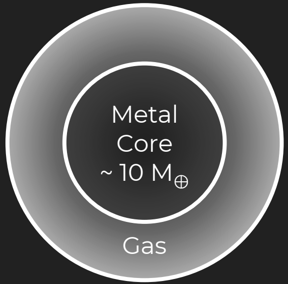
Two GEMS formation theories

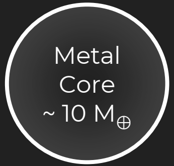
If metal cores are formed in certain (high metallicity) disks before gas depletion



High metallicity disk
⇒ high opacity†
⇒ slow heat dissipation
⇒ slowed gas accretion

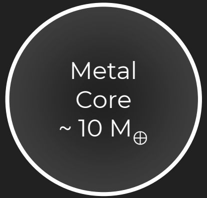
†Movshovitz et al. 2010





Two GEMS formation theories

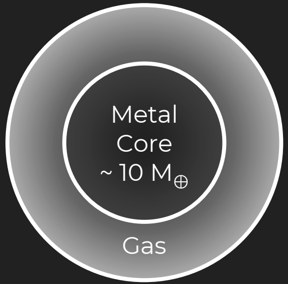
If metal cores are formed in certain (high metallicity) disks before gas depletion



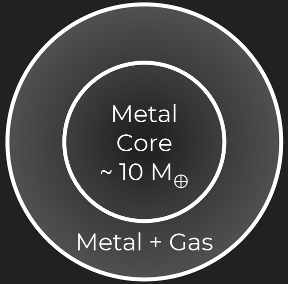
→

High metallicity disk
⇒ high opacity†
⇒ slow heat dissipation
⇒ slowed gas accretion

†Movshovitz et al. 2010

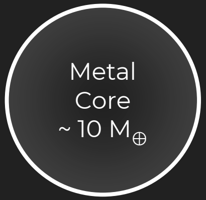


→



Two GEMS formation theories

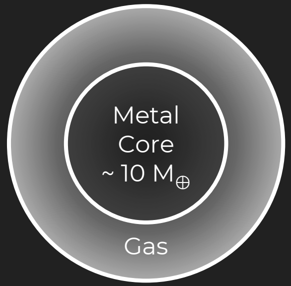
If metal cores are formed in certain (high metallicity) disks before gas depletion



→

High metallicity disk
⇒ high opacity†
⇒ slow heat dissipation
⇒ slowed gas accretion

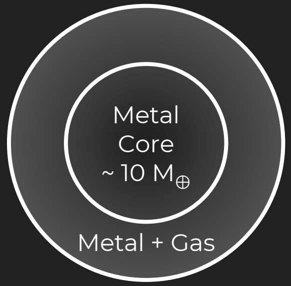
†Movshovitz et al. 2010



→

A prolonged intermediate stage of metal accretion offer energy to hinder rapid gas accretion.

Helled 2023




THE ASTRONOMICAL JOURNAL, 167:4 (14pp), 2024 January
https://doi.org/10.3847/1538-3881/ad09c2

TOI-5344 b: A Saturn-like Planet Orbiting a Super-solar Metallicity M0 Dwarf

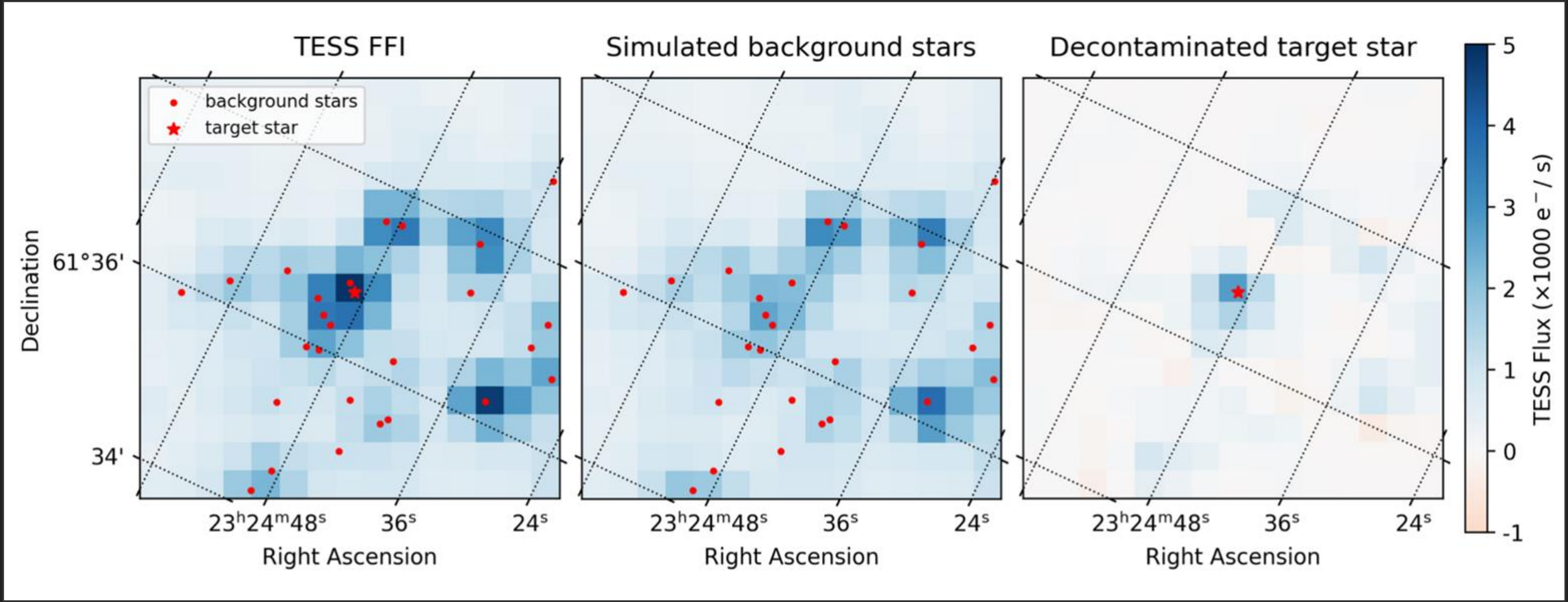
Te Han[1], Paul Robertson[1], Shubham Kanodia[2], Caleb Cañas[3,18], Andrea S. J. Lin[4,5], Gumundur Stefánsson[6,19], Jessica E. Libby-Roberts[4,5], Alexander Larsen[7], Henry A. Kobulnicky[7], Suvrath Mahadevan[4,5], Chad F. Bender[8], William D. Cochran[9], Michael Endl[10], Mark E. Everett[11], Arvind F. Gupta[4,5], Samuel Halverson[12], Fred Hearty[4,5], Andrew Monson[8], Joe P. Ninan[13], Arpita Roy[14,15], Christian Schwab[16], and Ryan C. Terrien[17]

[1] Department of Physics & Astronomy, The University of California, Irvine, CA 92697, USA
[2] Earth and Planets Laboratory, Carnegie Institution for Science, 5241 Broad Branch Road, NW, Washington, DC 20015, USA
[3] NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA
[4] Department of Astronomy & Astrophysics, 525 Davey Laboratory, The Pennsylvania State University, University Park, PA 16802, USA
[5] Center for Exoplanets and Habitable Worlds, 525 Davey Laboratory, The Pennsylvania State University, University Park, PA 16802, USA
[6] Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08540, USA
[7] Department of Physics & Astronomy, University of Wyoming, Laramie, WY 82070, USA
[8] Steward Observatory, University of Arizona, 933 N. Cherry Avenue, Tucson, AZ 85721, USA
[9] McDonald Observatory and Center for Planetary Systems Habitability, The University of Texas, Austin, TX 78712, USA
[10] Department of Astronomy and McDonald Observatory, University of Texas at Austin, 2515 Speedway, Austin, TX 78712, USA
[11] NSF's National Optical-Infrared Astronomy Research Laboratory, 950 N. Cherry Avenue, Tucson, AZ 85719, USA
[12] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[13] Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400005, India
[14] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[15] Department of Physics and Astronomy, Johns Hopkins University, 3400 N Charles Street, Baltimore, MD 21218, USA
[16] School of Mathematical and Physical Sciences, Macquarie University, Balaclava Road, North Ryde, NSW 2109, Australia
[17] Carleton College, One North College Street, Northfield, MN 55057, USA
Received 2023 September 12; revised 2023 October 24; accepted 2023 October 30; published 2023 December 4

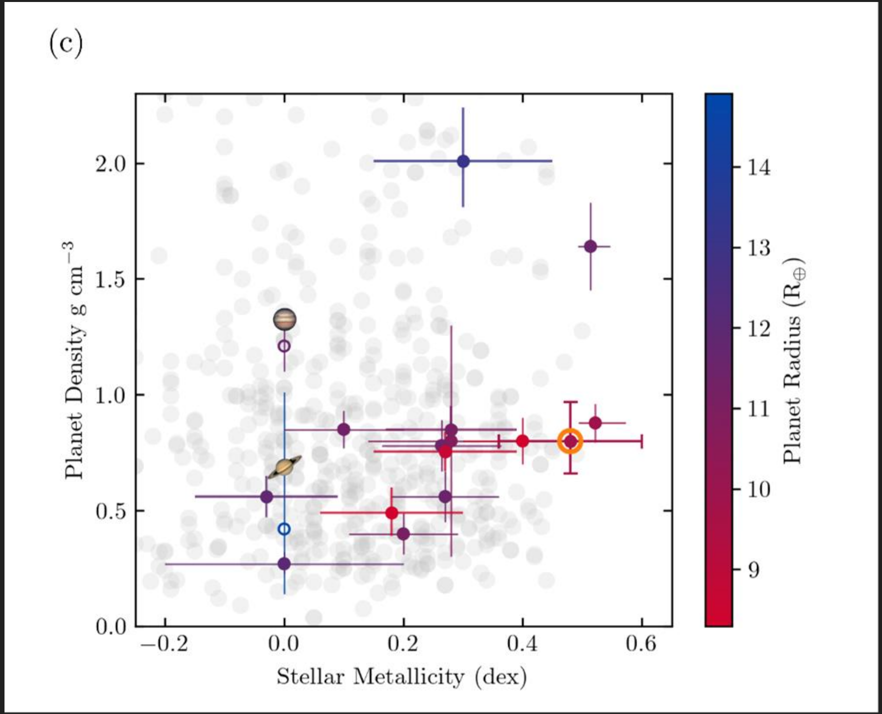
Read the paper:

Index

TESS-Gaia Light Curve (TGLC)



A correlation between [Fe/H] and Planet density?



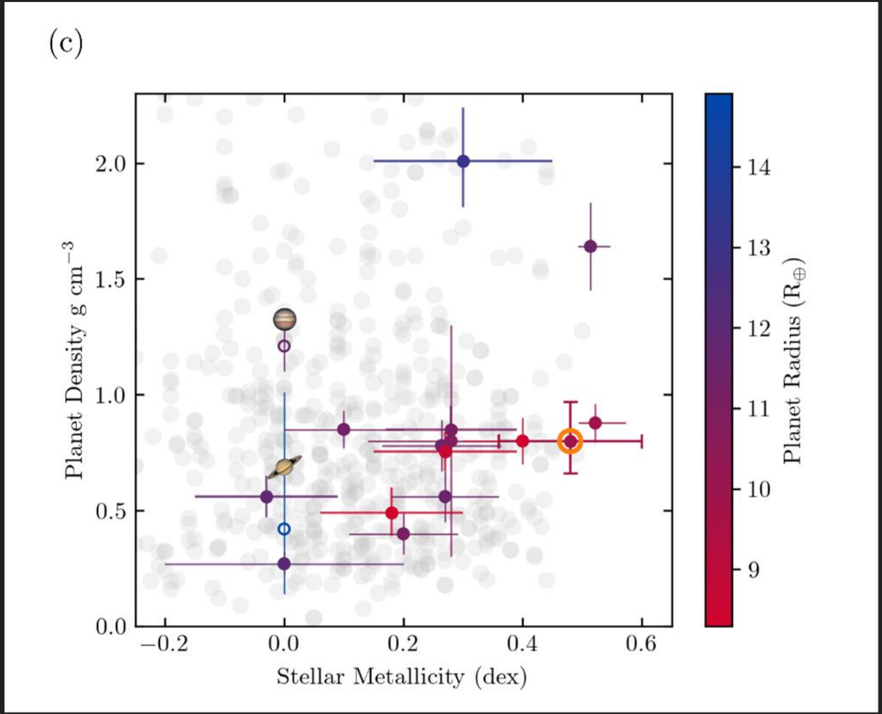
A correlation between [Fe/H] and Planet density?

Kendall's Tau test:

$\tau = 0.5268$

$p = 0.0072$

⇒ Suggesting a moderate correlation, but needs more data to confirm.



The good and bad of finding M-dwarf Exoplanets:

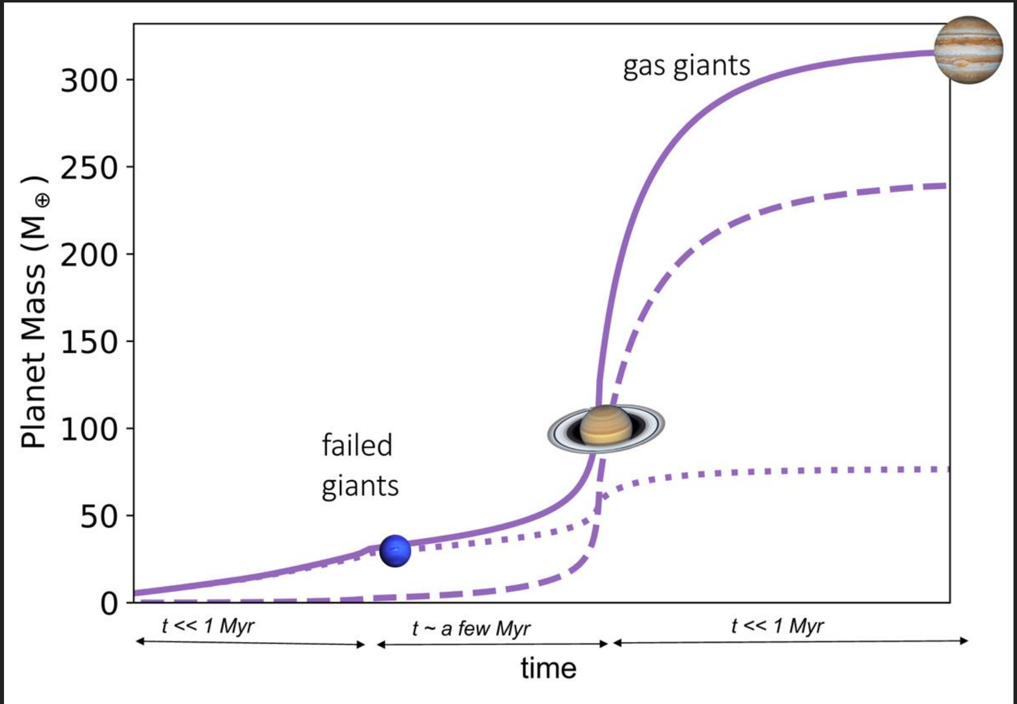
1. Deeper transits
2. Usually dimmer
3. We have more M-dwarfs
4. RV signal larger
5. , but noisier

Giant Exoplanets around M-dwarf Stars (GEMS) are rare in theory and observation.

How to further understand these systems

GEMS JWST

Helled 2023



Planet Mass ($M_\oplus$)
300
250
200
150
100
50
0
gas giants
failed giants
t << 1 Myr
t ~ a few Myr
t << 1 Myr
time