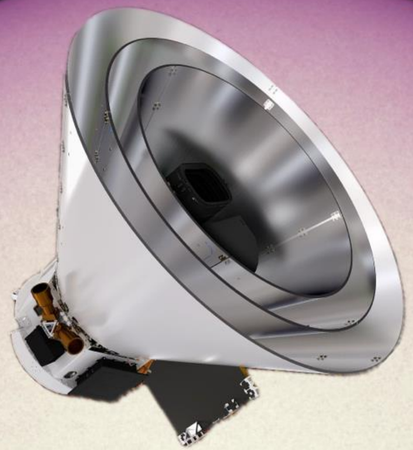
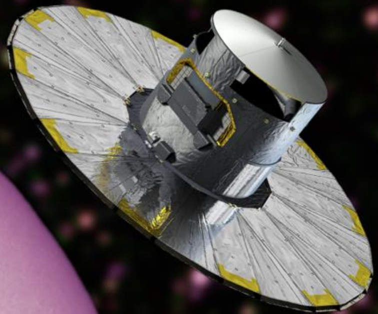
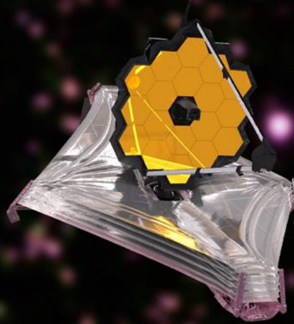
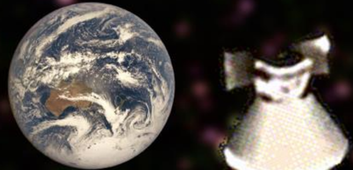
Precision Transit Host Characterization with SPHEREx, Gaia, & JWST



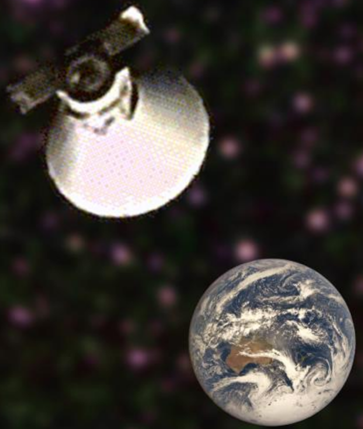






Zafar Rustamkulov
Rachel Akeson
Davy Kirkpatrick

Table of Contents



Spectro-

Photometer for the

History of the Universe,

- The Stellar Legacy Catalog

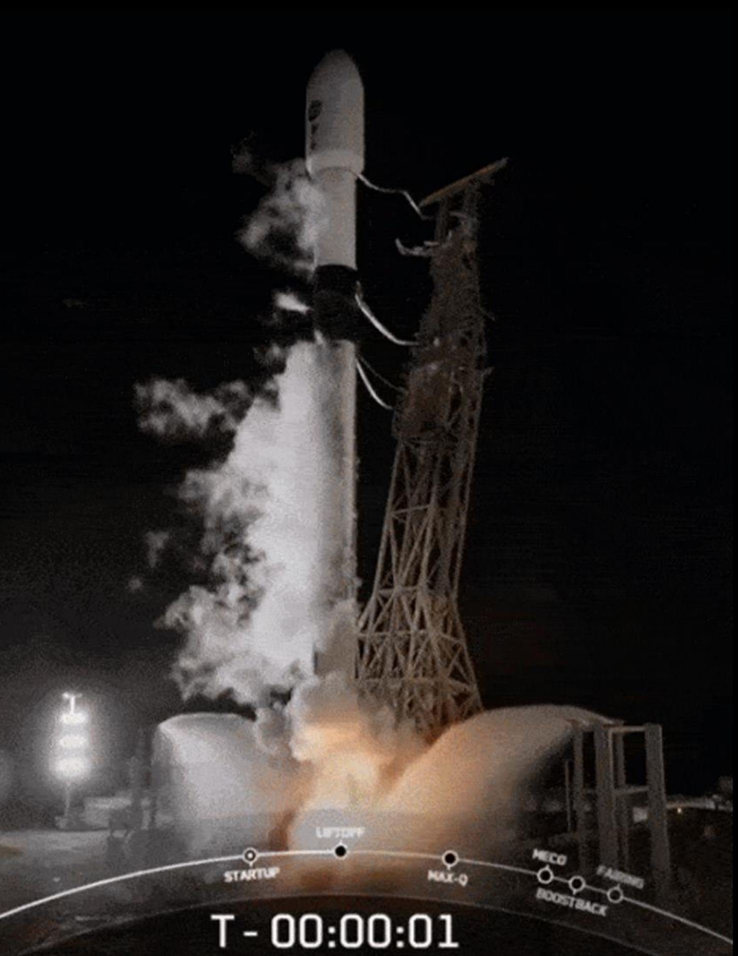
Epoch of

  - JWST

Reionization

E

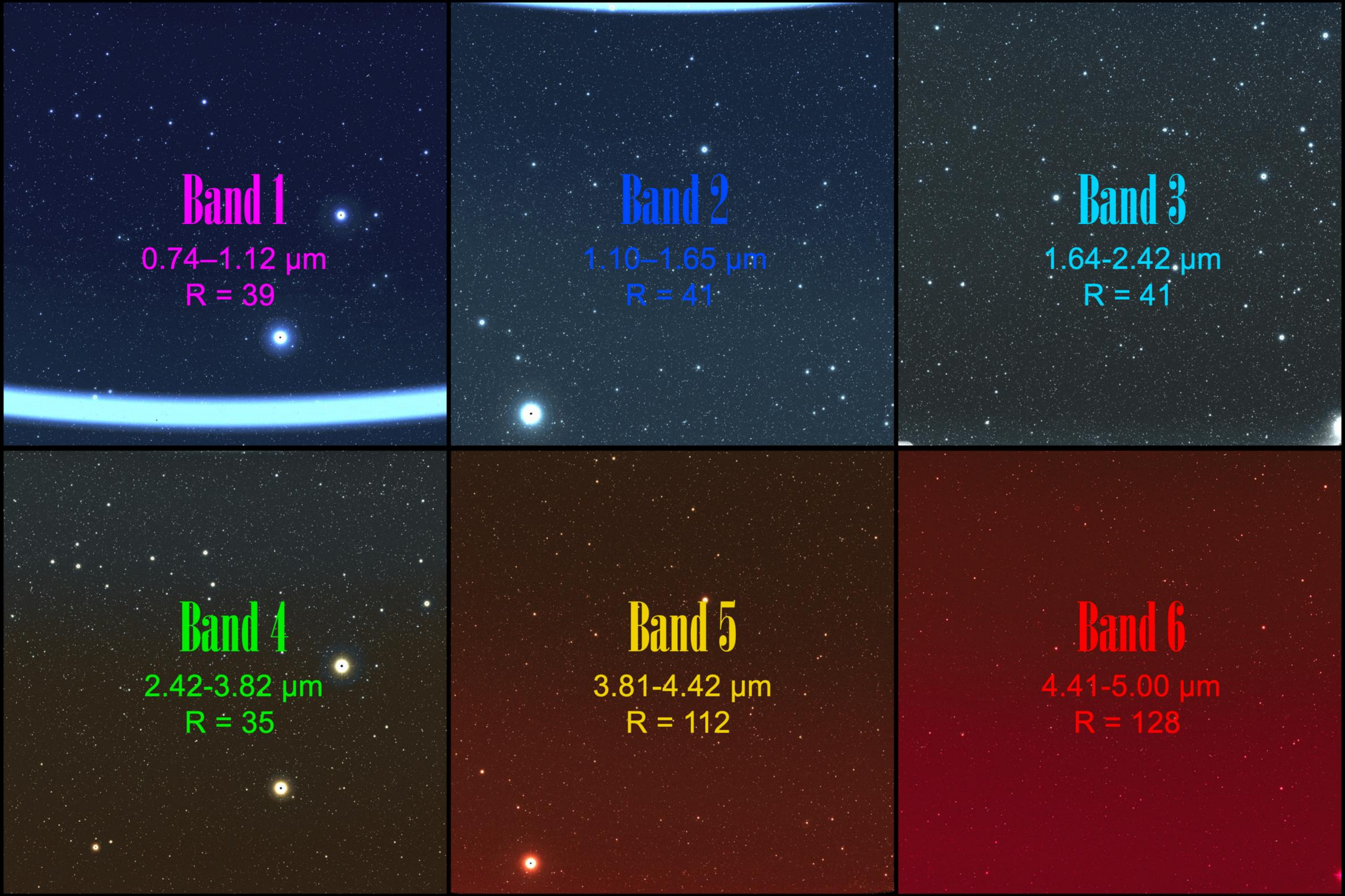
xplorer



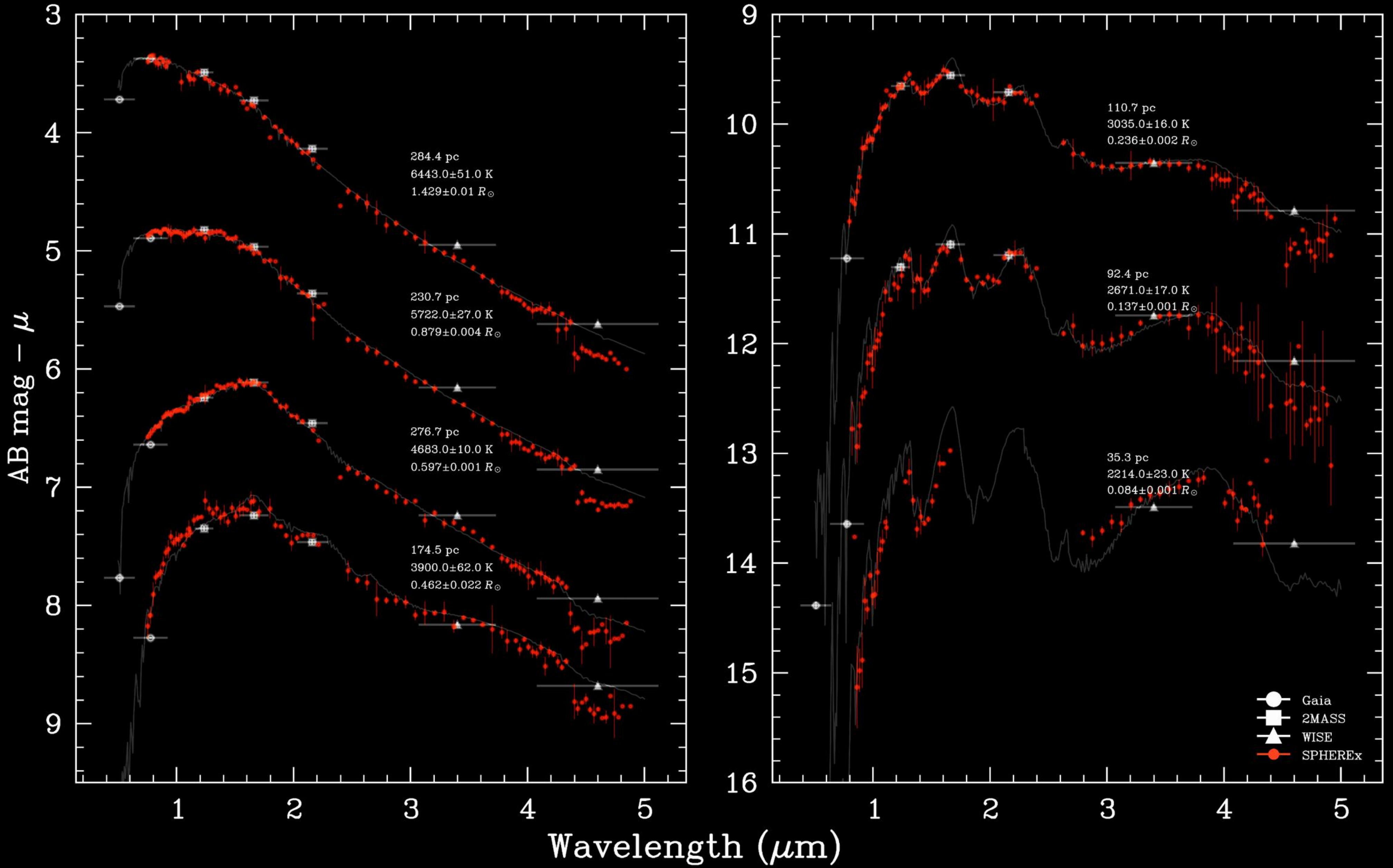
March 12, 2025:
Launched & deployed

May 1, 2025:
Science survey begins

Last week:
99.99% of sky covered

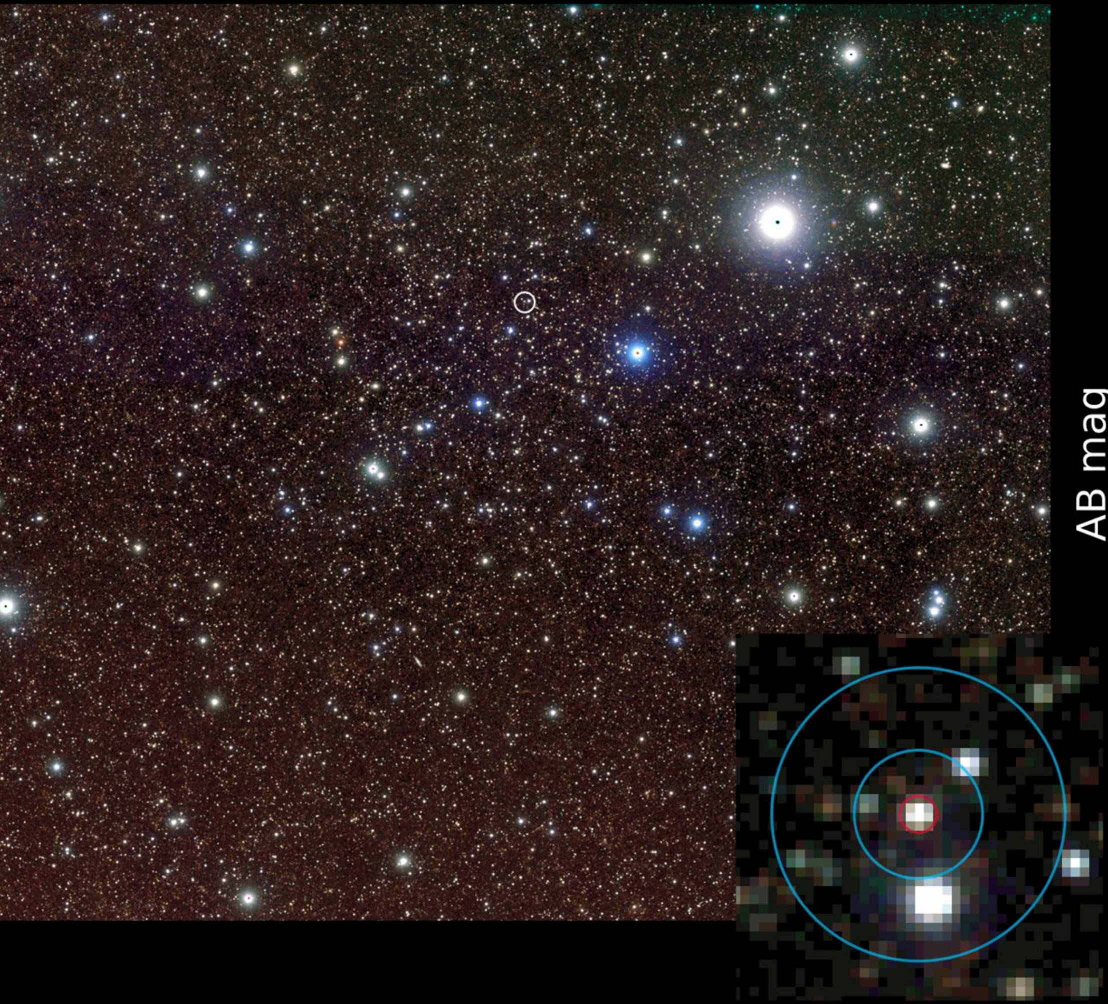

Band 1
0.74–1.12 μm
R = 39
Band 2
1.10–1.65 μm
R = 41
Band 3
1.64-2.42 μm
R = 41
Band 4
2.42-3.82 μm
R = 35
Band 5
3.81-4.42 μm
R = 112
Band 6
4.41-5.00 μm
R = 128

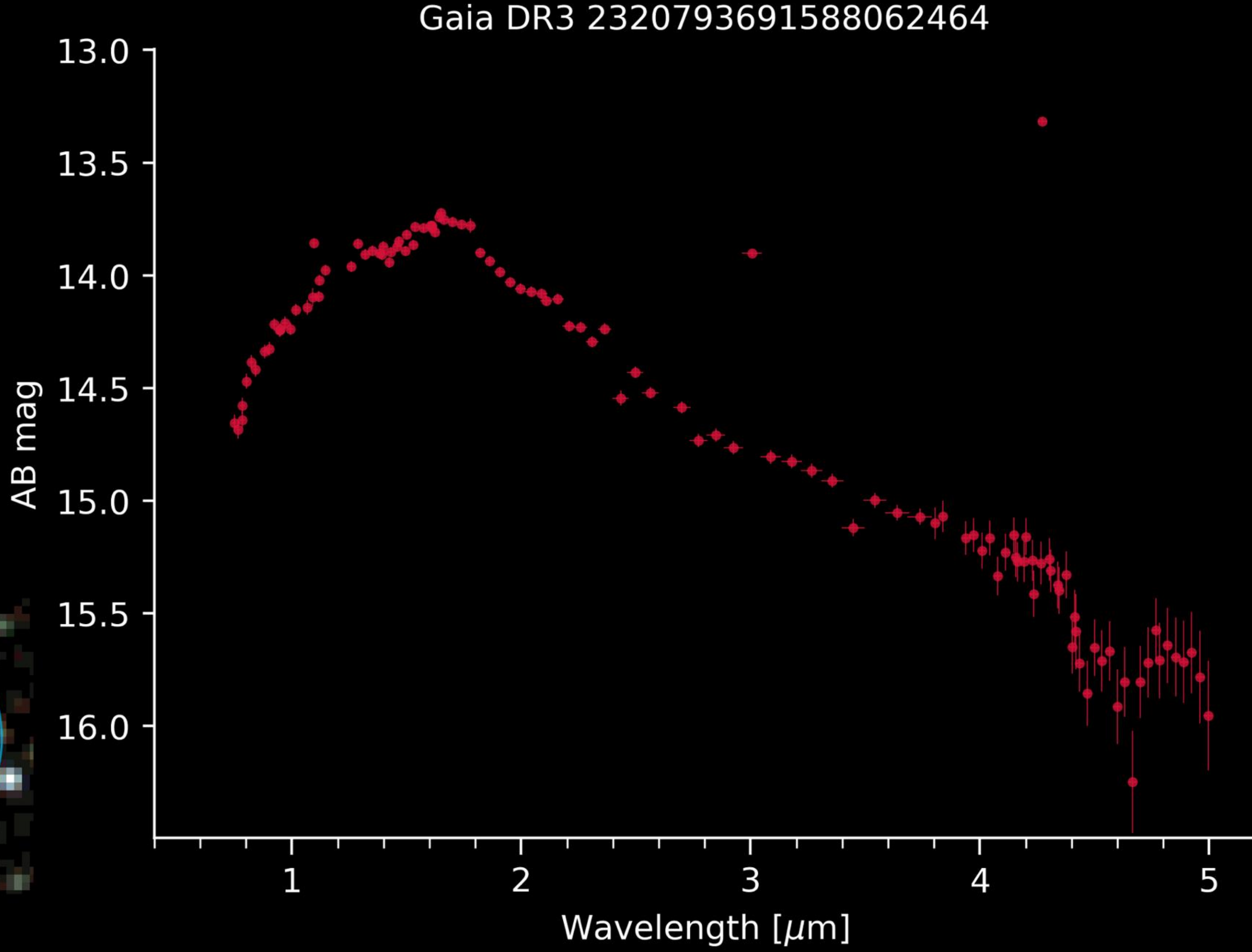
Spectral maps every 6 months
Data public almost instantly

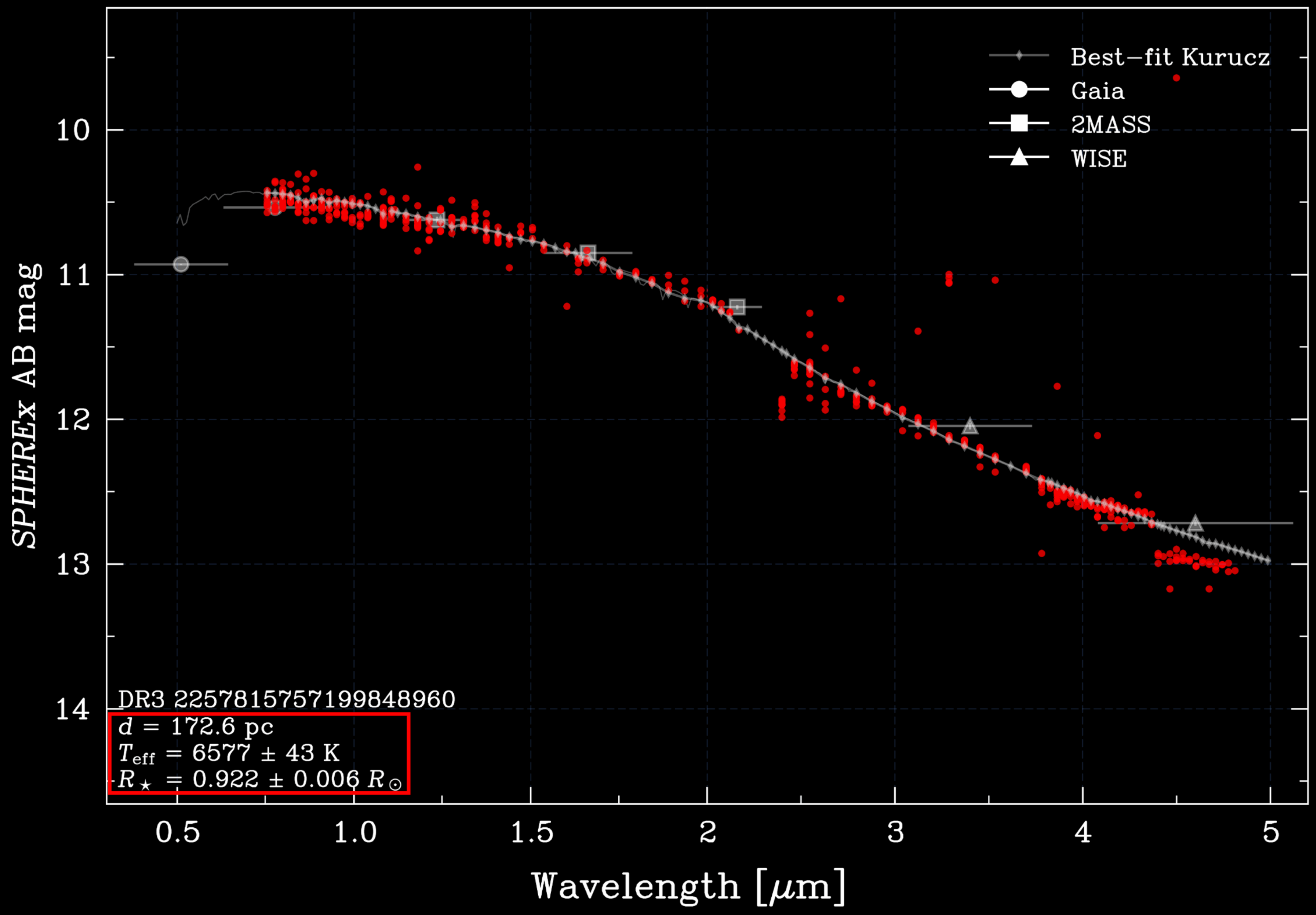


284.4 pc
6443.0±51.0 K
1.429±0.01 $R_\odot$
230.7 pc
5722.0±27.0 K
0.879±0.004 $R_\odot$
276.7 pc
4683.0±10.0 K
0.597±0.001 $R_\odot$
174.5 pc
3900.0±62.0 K
0.462±0.022 $R_\odot$
110.7 pc
3035.0±16.0 K
0.236±0.002 $R_\odot$
92.4 pc
2671.0±17.0 K
0.137±0.001 $R_\odot$
35.3 pc
2214.0±23.0 K
0.084±0.001 $R_\odot$
Gaia
2MASS
WISE
SPHEREx
AB mag − μ
Wavelength (μm)

Spectra of cluster members

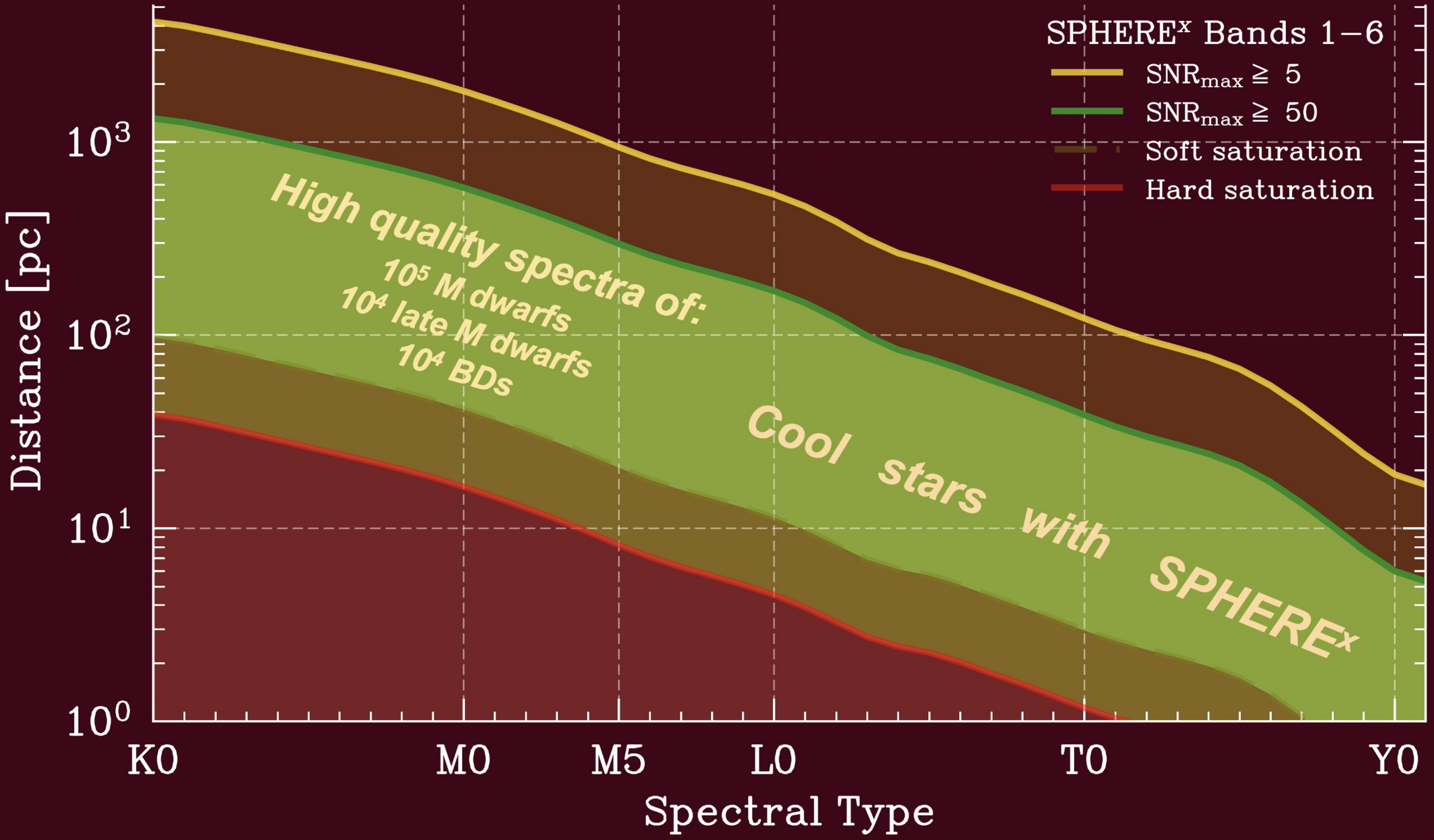




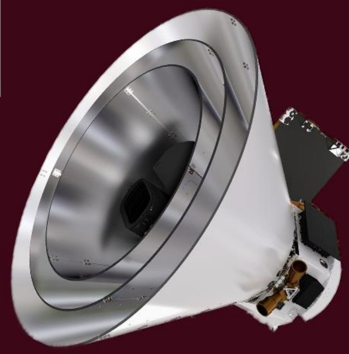

Best−fit Kurucz
Gaia
2MASS
WISE
10
11
12
13
14
SPHEREx AB mag
0.5
1.0
1.5
2
3
4
5
Wavelength [μm]
DR3 2257815757199848960
d = 172.6 pc
T_eff = 6577 ± 43 K
R⋆ = 0.922 ± 0.006 R⊙

SPHEREx Fast Facts

- Passively cooled via *Cone of Shade*
- **First all-sky IR spectral survey (!)**
- No consumables
- Takes ~600 114s exposures/day
- Effective mirror diameter = 8”
- **Surveys entire sky every 6 months**
- Per-channel sensitivity comparable to **WISE**



SPHERE^x Bands 1–6
$SNR_{max} \geqq 5$
$SNR_{max} \geqq 50$
Soft saturation
Hard saturation
High quality spectra of:
10^5 M dwarfs
10^4 late M dwarfs
10^4 BDs
Cool stars with SPHERE^x
Distance [pc]
10^0
10^1
10^2
10^3
K0
M0
M5
L0
T0
Y0
Spectral Type



SPHEREx Precision Stellar Properties Legacy Catalog

Objectives *of the* ***SPHEREx Precision Stellar Properties Legacy Catalog***

- Stellar SED fits + ℝefined T_{eff} / $R_{\star}$ / Z for:

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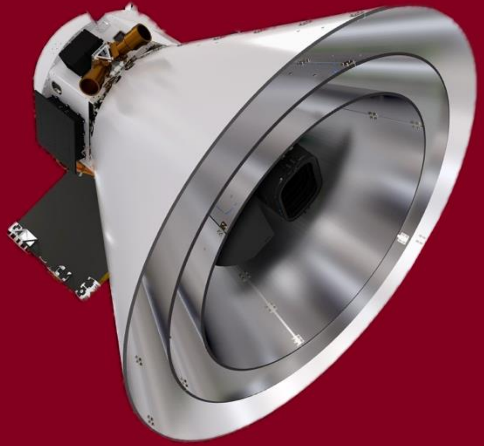
- Stellar SED fits + ℝefined T_{eff} / $R_{\star}$ / Z for:

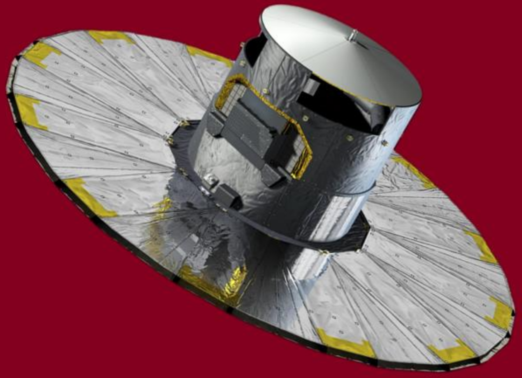
  - **600k** nearby main sequence stars from exoplanet surveys *(Kepler, K2, TESS, Plato)*
  - **2.4M** **FGK** dwarfs/subgiants
  - **300k** early **M** dwarfs
  - **10k** nearby late **M** dwarfs; 582 **L**, **T**, **Y** dwarfs < 20 pc

2.99M

SPHERE^x Precision Stellar Properties Legacy Catalog



2.99M



In order to…

1. Shrink **FGK** $R_\star$ to <1%, Refining exoplanet a, R_p

2. Measure **MLTY** L_{bol} to study IMF cutoff

3. Do Ancillary Science!

$$F_{\mathrm{bol}} = \sigma T_{\mathrm{eff}}^{4} \left(\frac{R_{\star}}{d} \right)^{2}$$

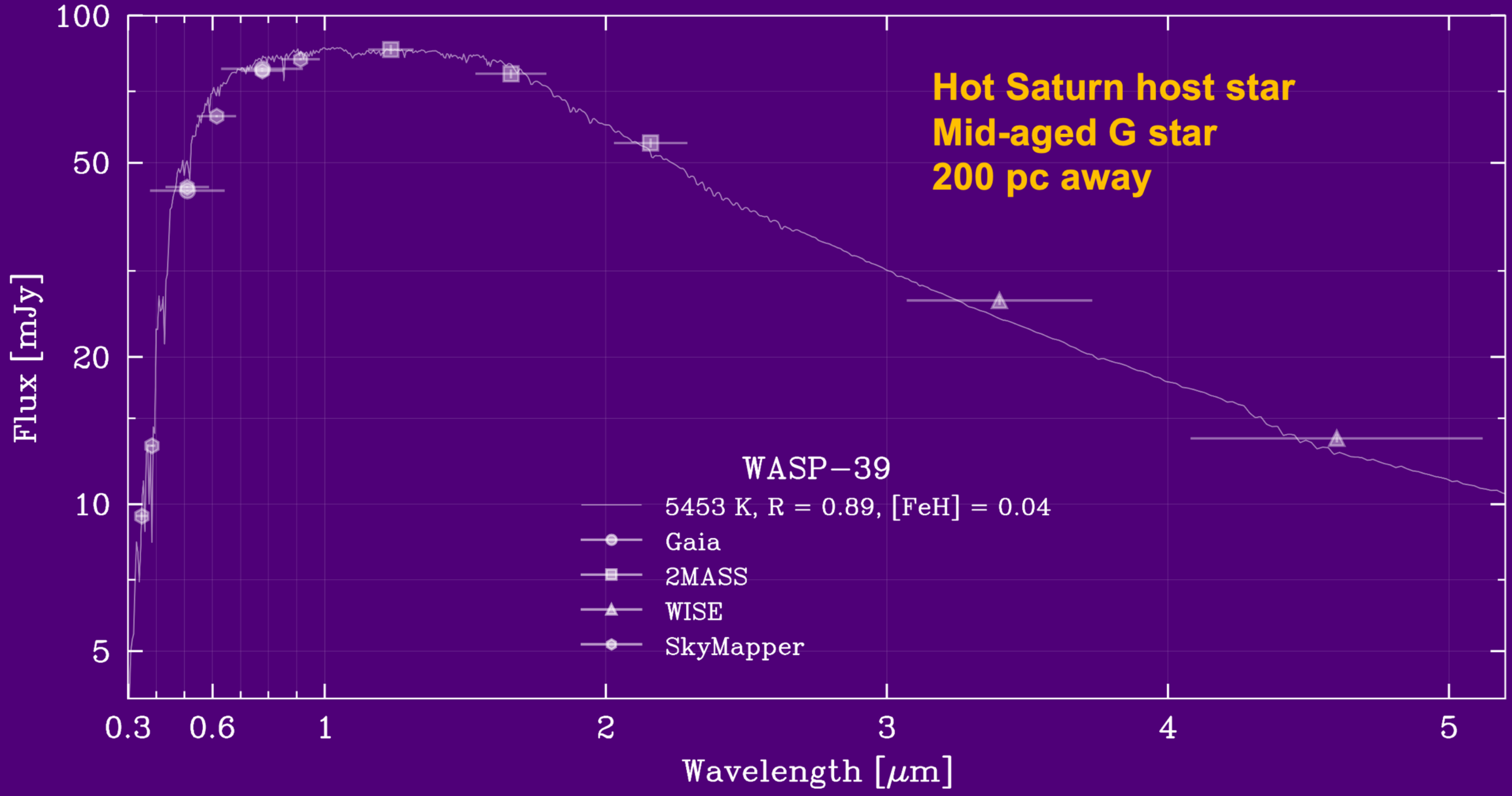
solve for R_*

$$F_{\text{bol}} = \sigma T_{\text{eff}}^4 \left(\frac{R_\star}{d}\right)^2$$

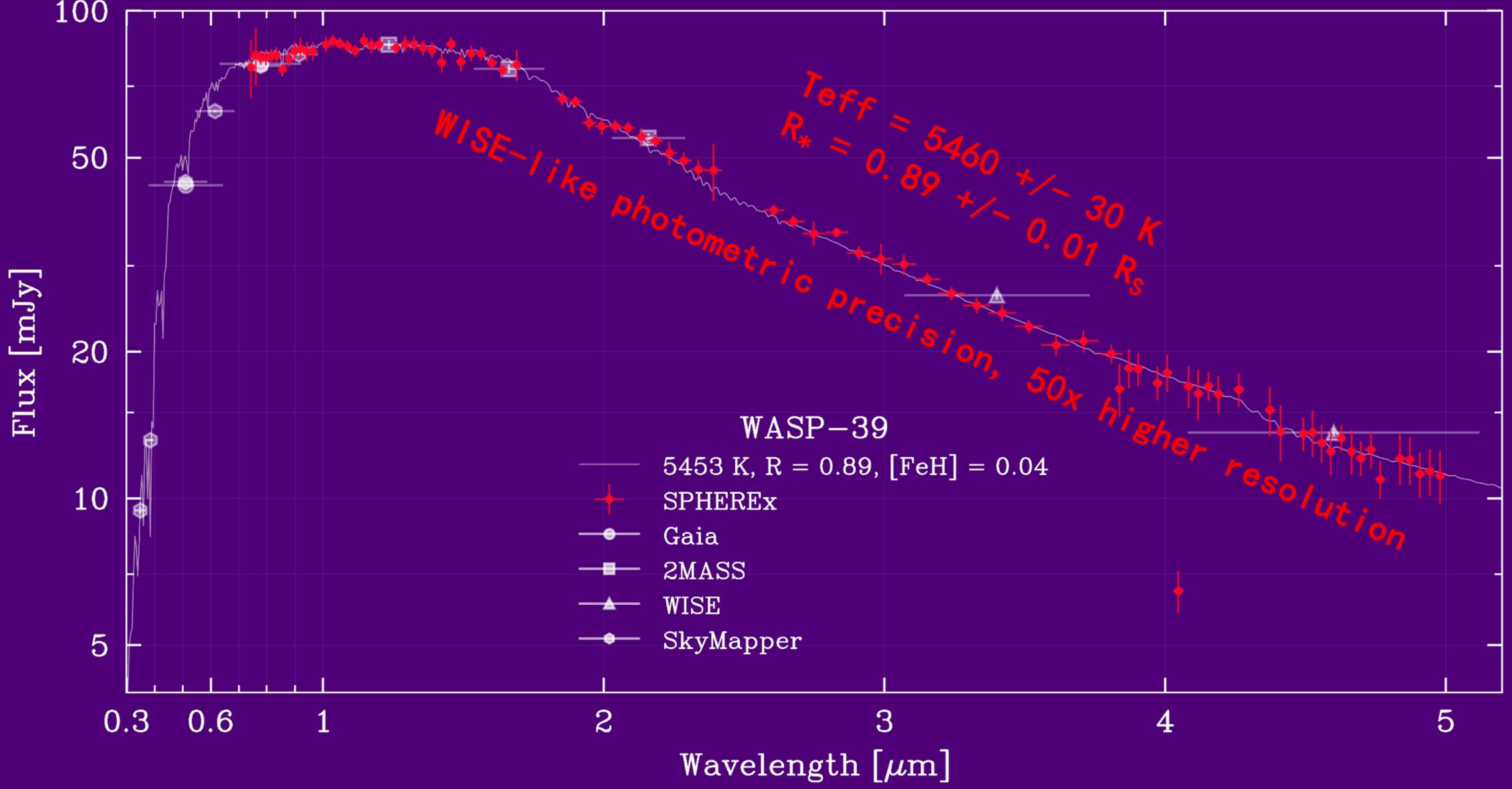
Gaia

SPHEREx

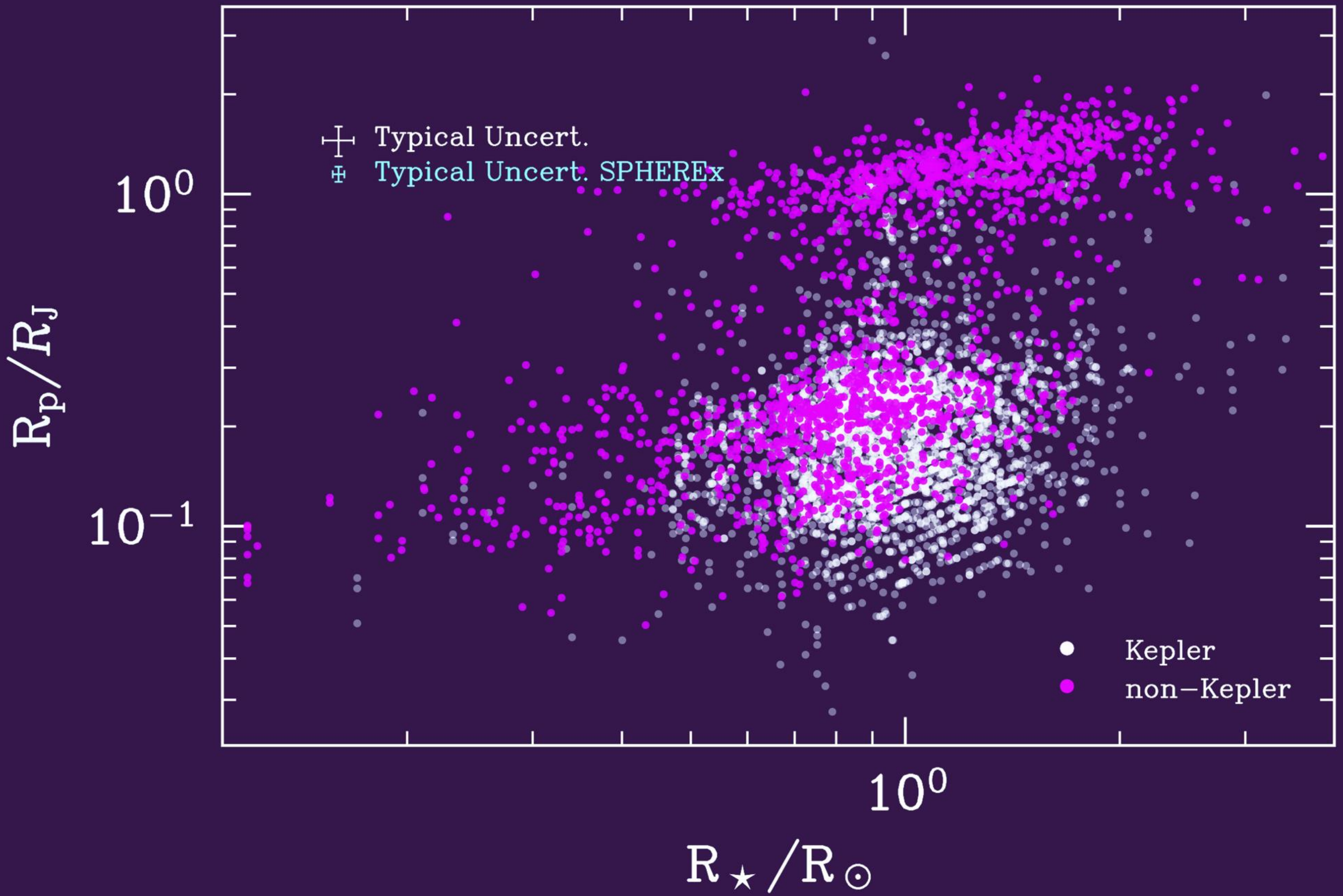
Exoplanet host: WASP-39



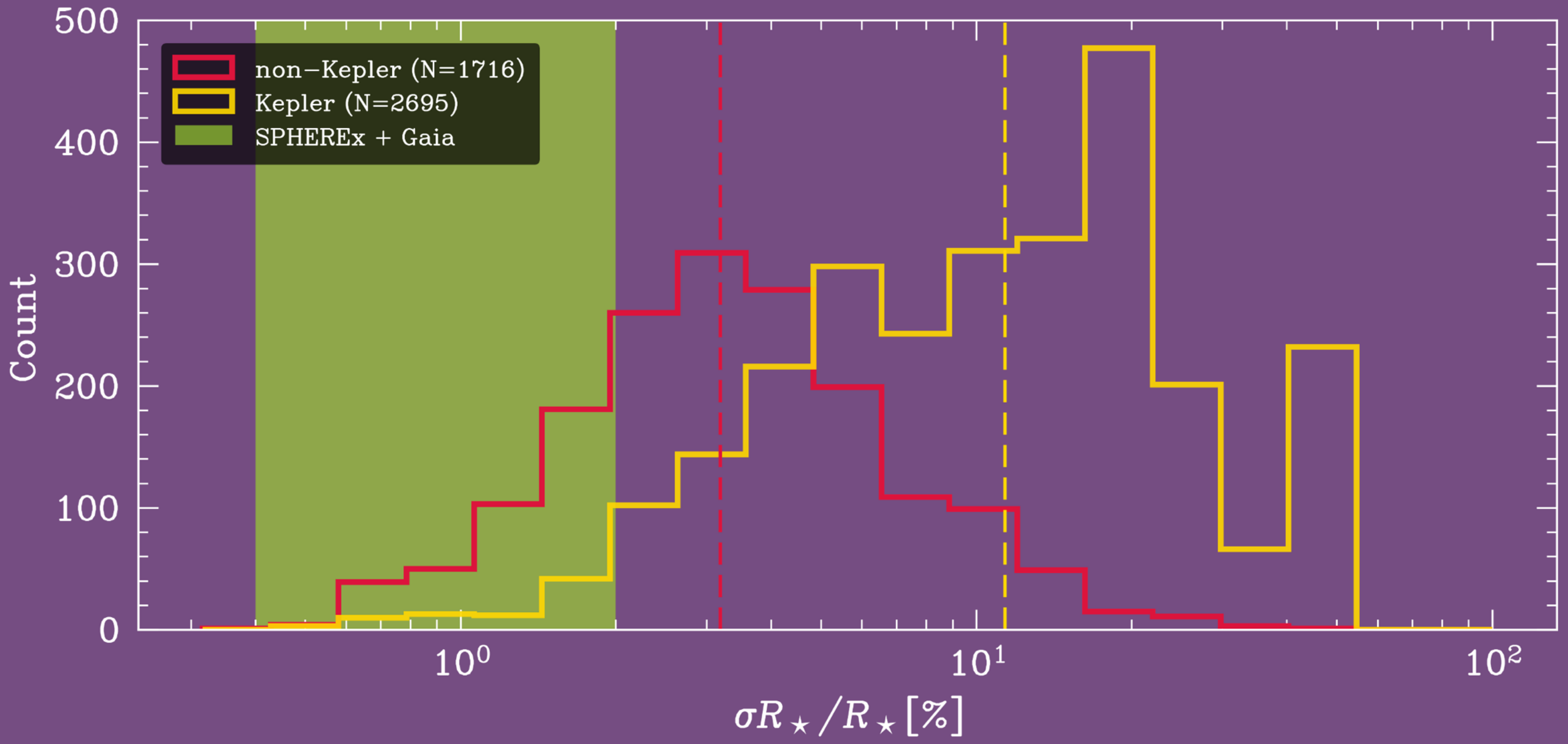
Exoplanet host: WASP-39



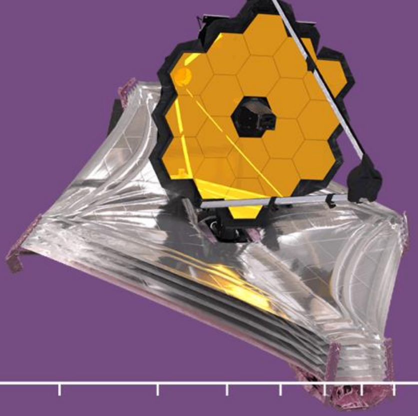
Exoplanet hosts

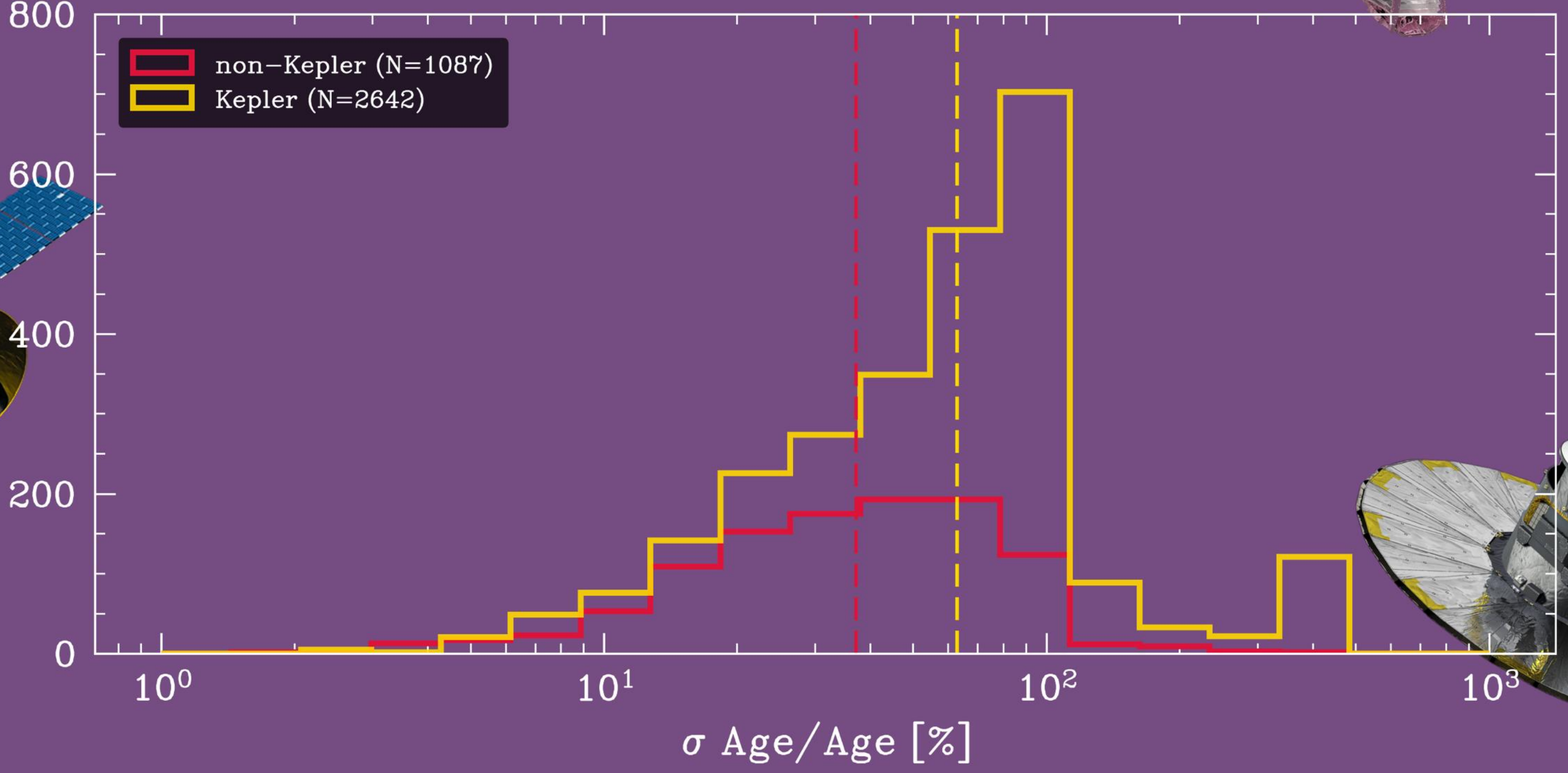


Exoplanet hosts



Exoplanet hosts





Topics of interest in exoplanets

- Thermal evolution processes
- Mass loss mechanisms
- Composition demographics
- Tidal interactions with star
- Orbital migration trends

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This science requires precise system ages!

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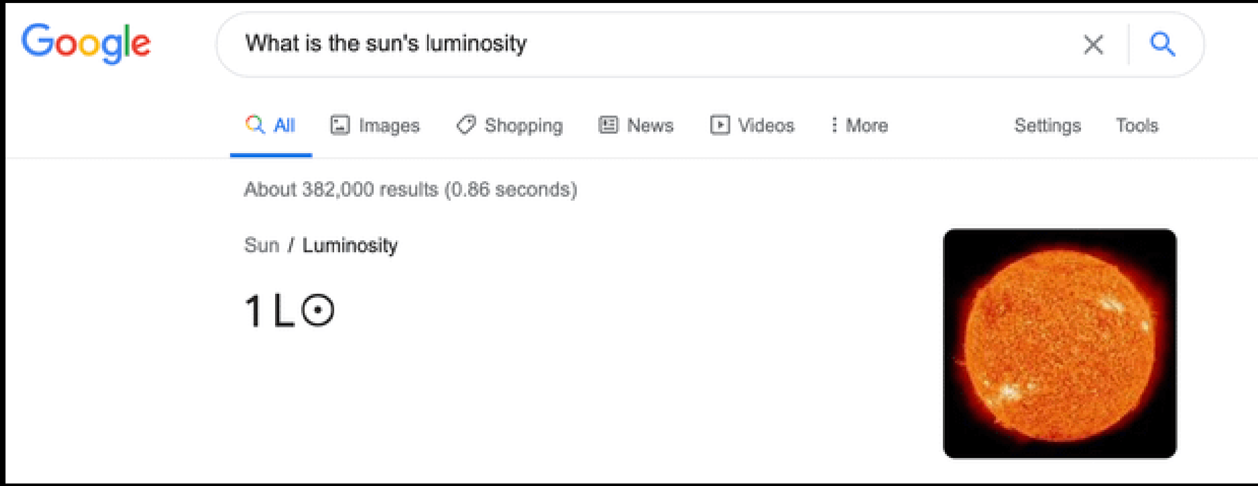
This science requires precise system ages!

HOW THO?!

$$\tau_\star \propto \frac{M_\star}{L_\star}$$

$$\tau_\star \propto \frac{M_\star}{L_\star}$$ need.



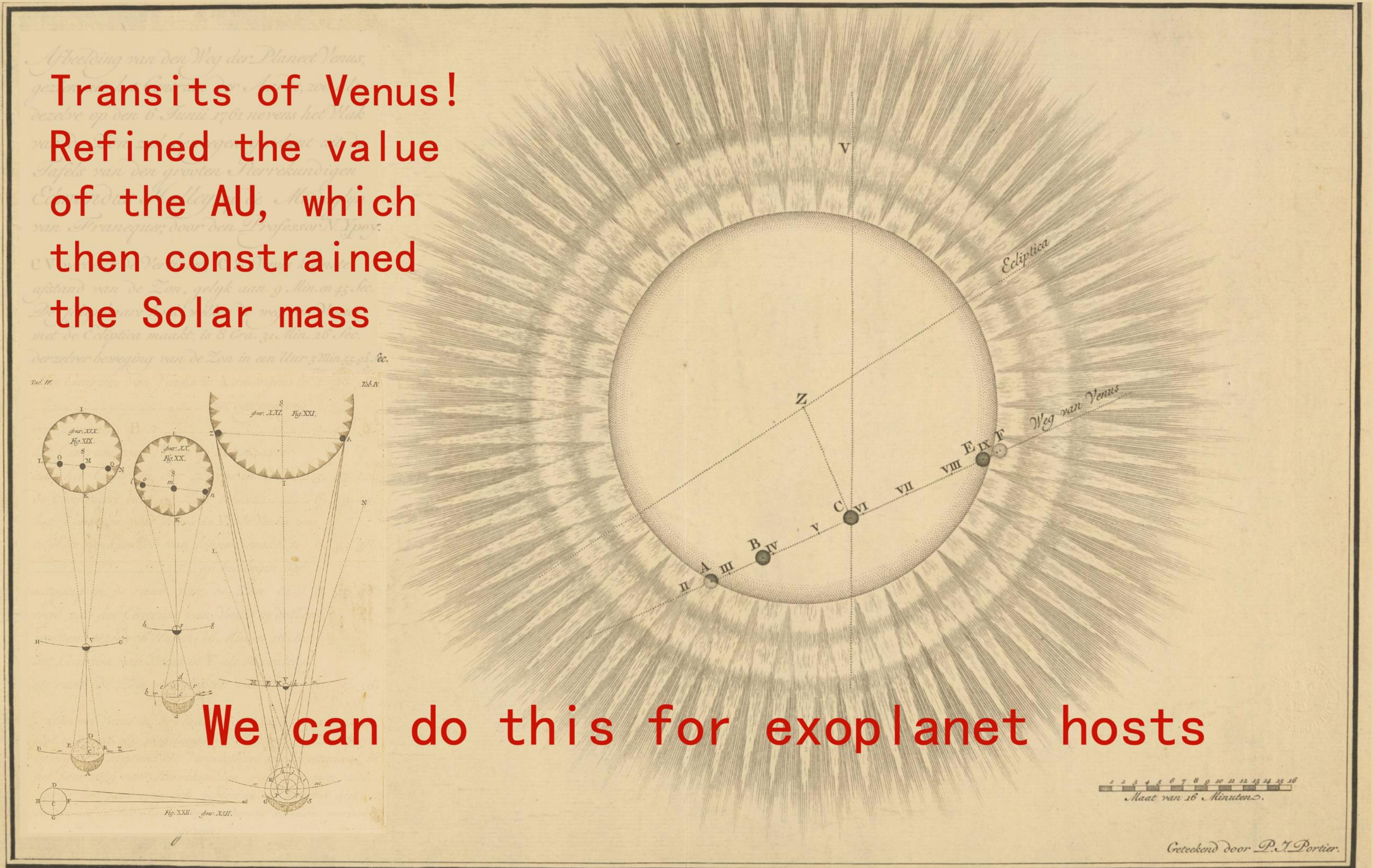
$$\frac{M_\star}{L_\star}$$

need

Wait…

How did we even measure the *Sun's* mass?

Transits of Venus!
Refined the value of the AU, which then constrained the Solar mass



We can do this for exoplanet hosts

Kepler's 3rd

$$\frac{P^2}{4\pi^2} \simeq \frac{a^3}{GM_\star}$$

Kepler's 3rd

$$\frac{P^2}{4\pi^2} \simeq \frac{a^3}{GM_\star}$$

Density of Sphere

$$\rho_\star = \frac{M_\star}{\frac{4}{3}\pi R_\star^3}$$

Kepler's 3rd

$$\frac{P^2}{4\pi^2} \simeq \frac{a^3}{GM_\star}$$

Density of Sphere

$$\rho_\star = \frac{M_\star}{\frac{4}{3}\pi R_\star^3}$$

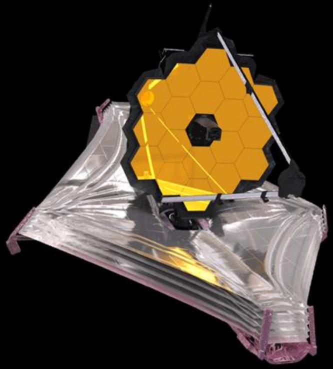
$$\rho_\star = \frac{3\pi}{GP^2}\frac{a^3}{R_\star^3}$$

needed

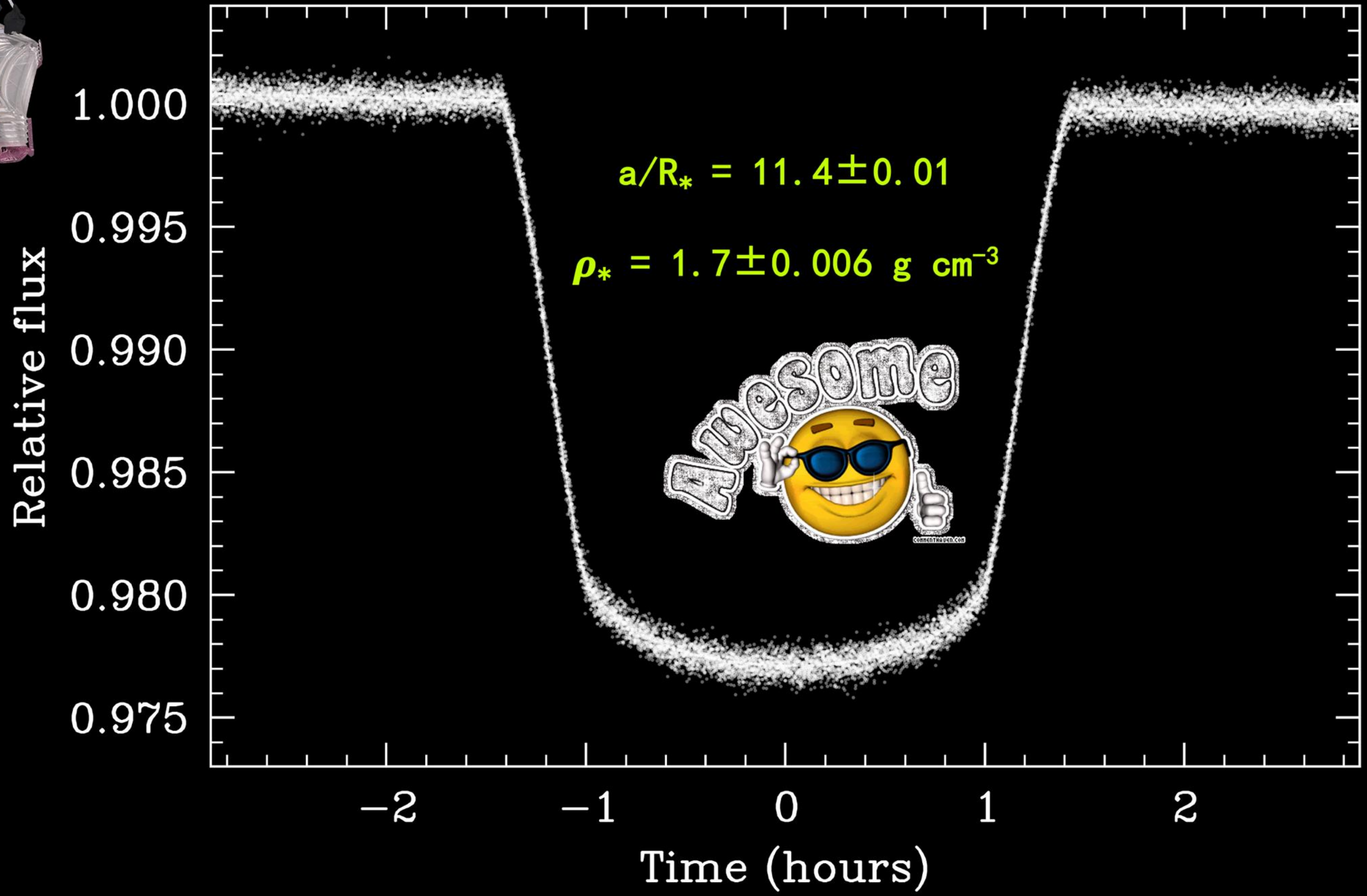
$$\rho_\star = \frac{3\pi}{G\underbrace{P^2}_{\text{known}}} \frac{a^3}{\underbrace{R_\star^3}_{\text{known}}}$$

$$\rho_\star = \frac{3\pi}{G\underbrace{P^2}_{\text{known}}} \frac{a^3}{\underbrace{R_\star^3}_{\text{known}}}$$

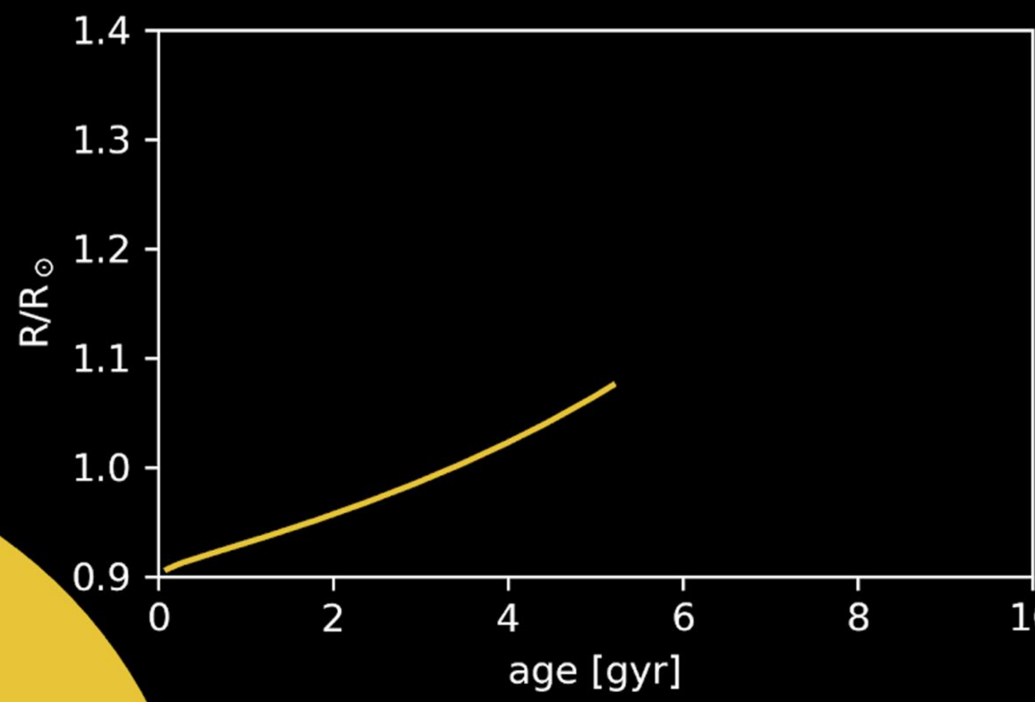
$$\frac{a}{R_\star} \sim \frac{P}{\pi \underbrace{T}_{\text{Transit duration}}}$$

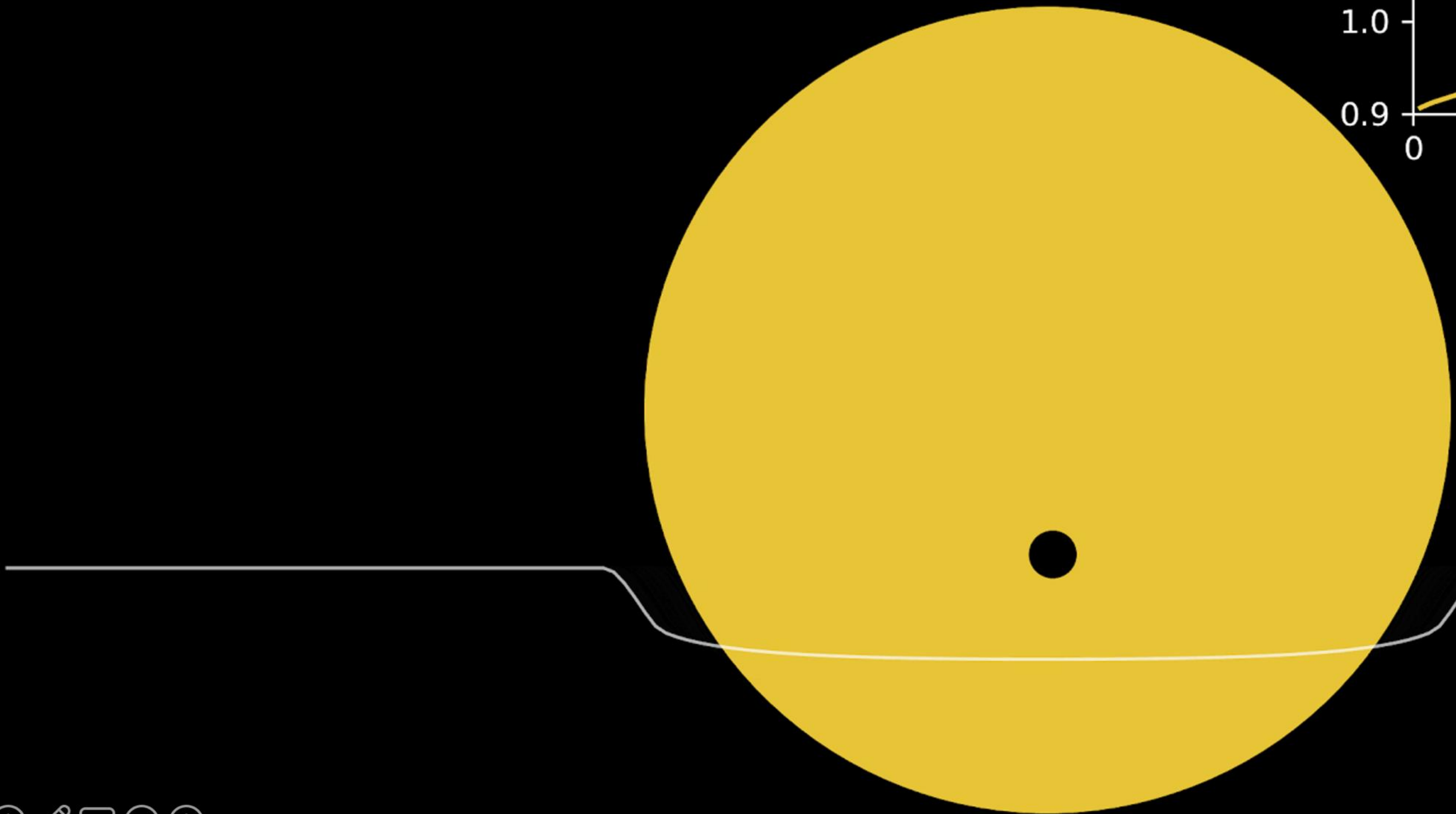


JWST transit of WASP-39 b gives precise stellar density

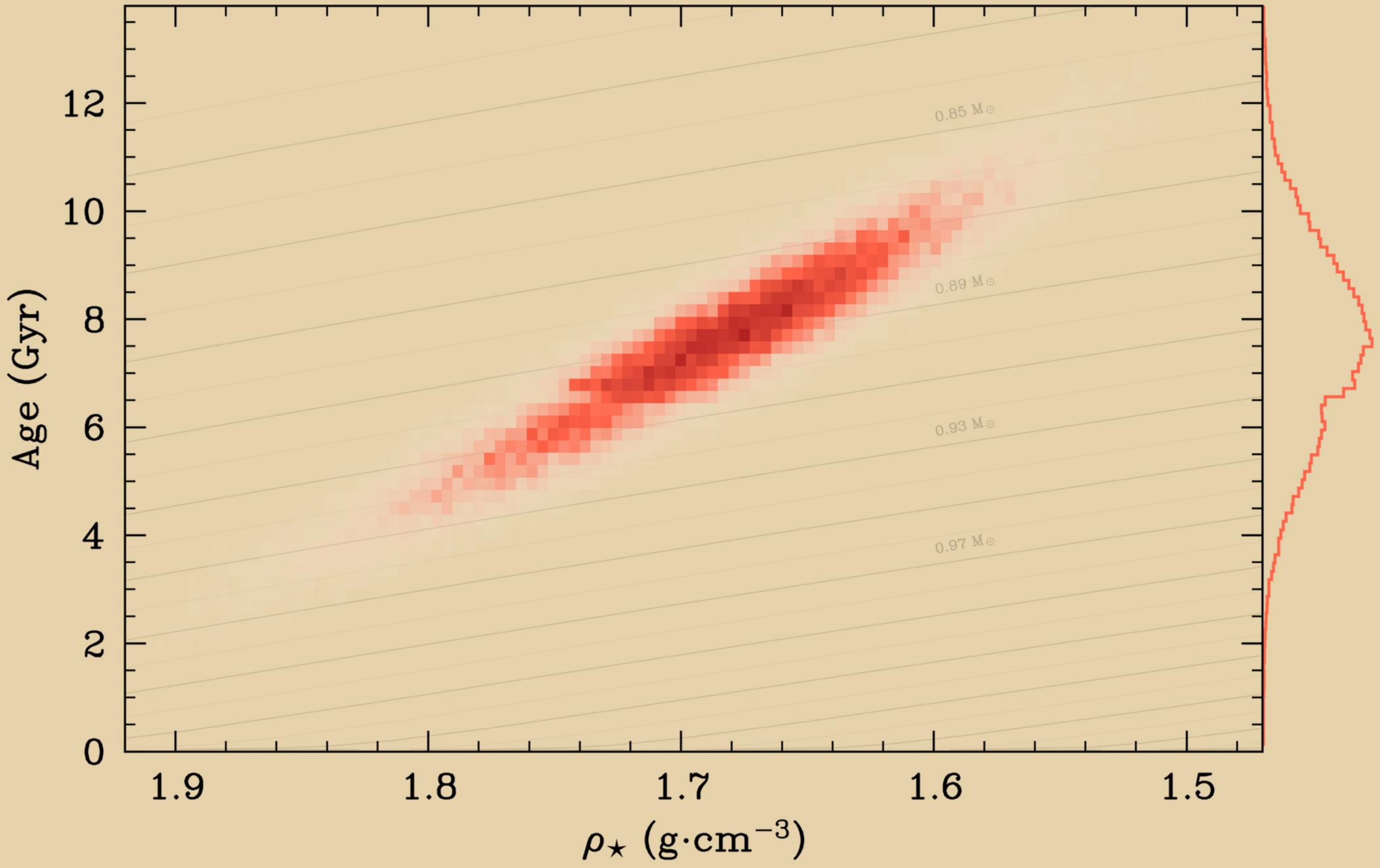


Aging shapes the transit light curve

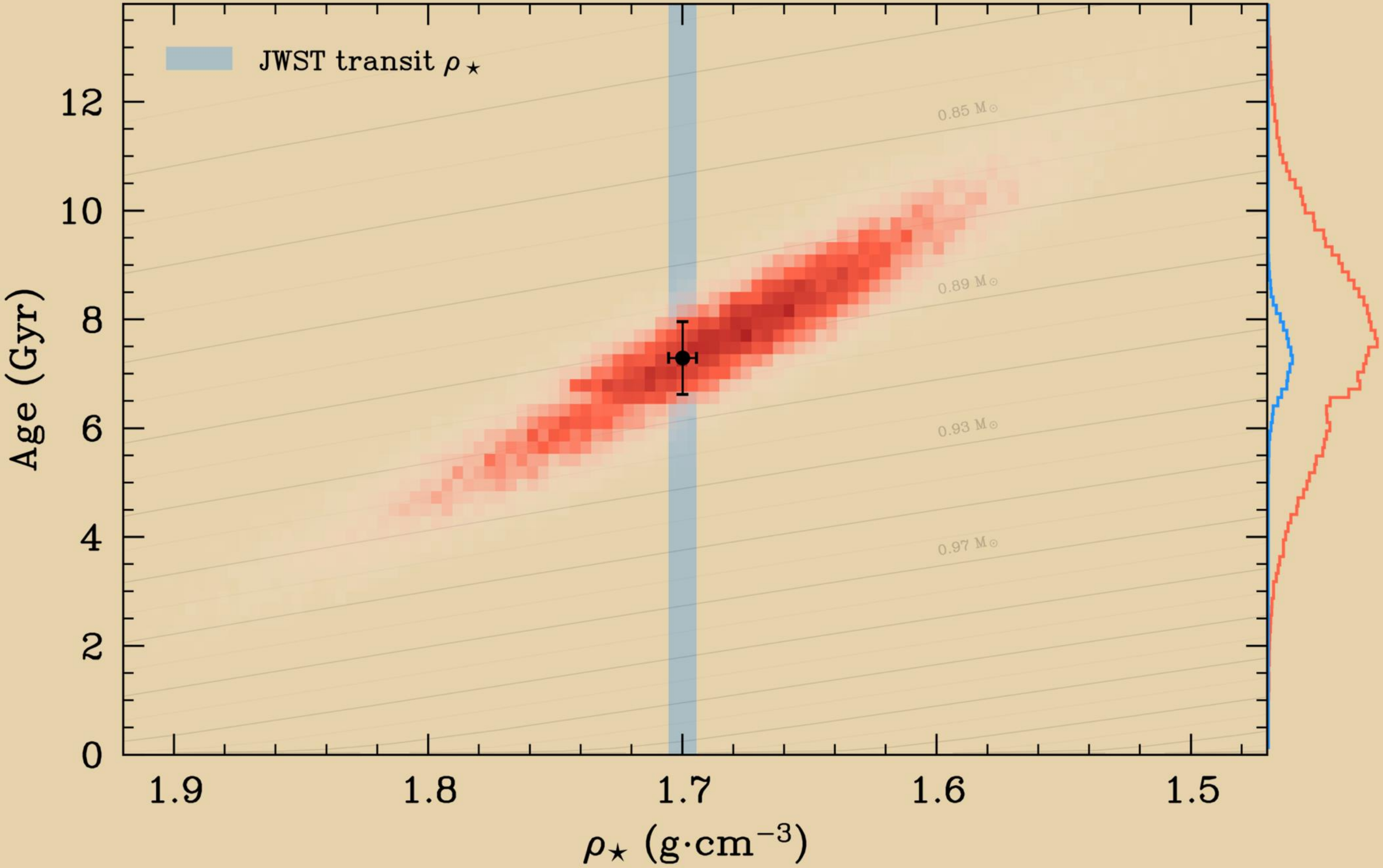


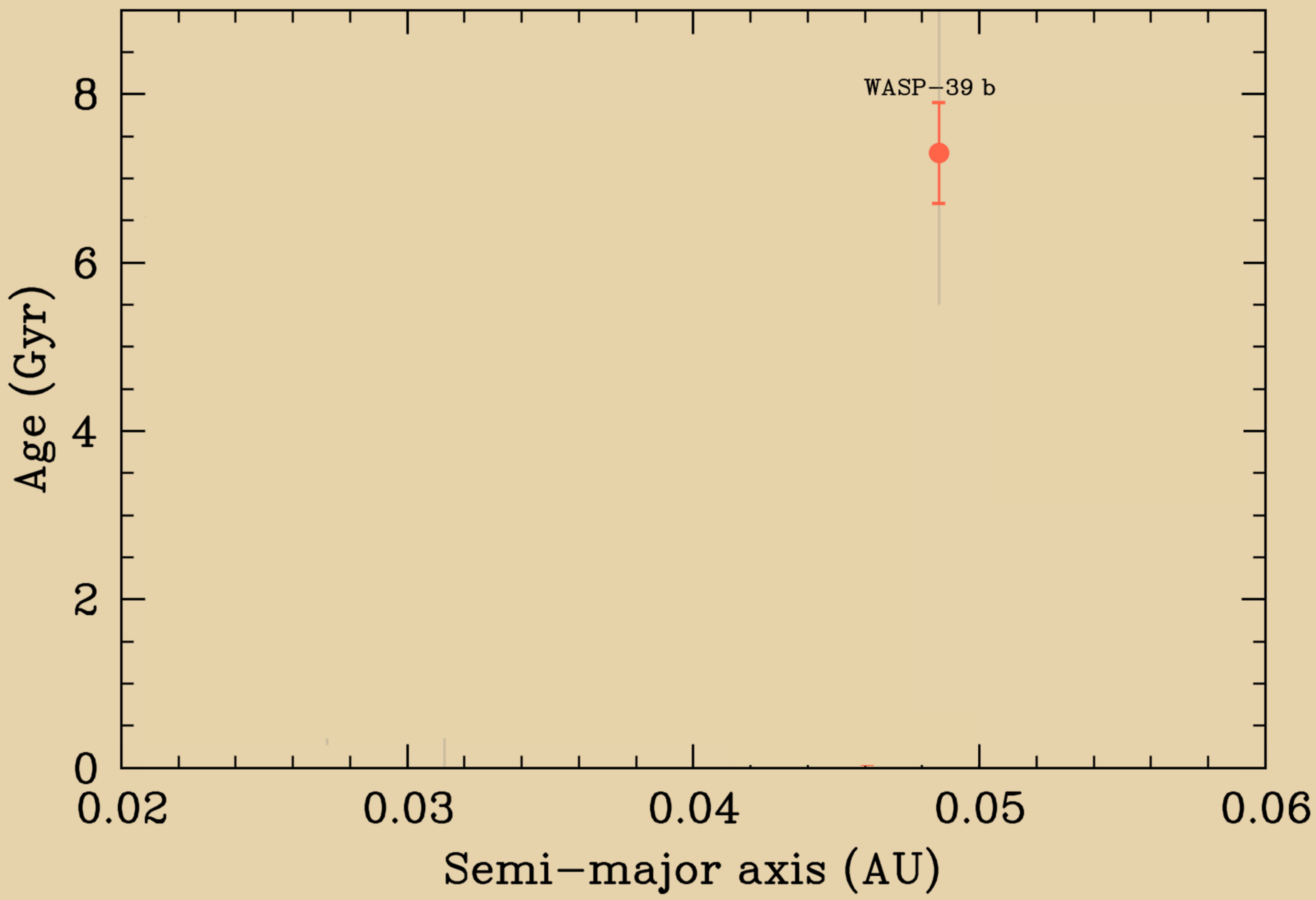


WASP-39 isochrones package fit posterior:

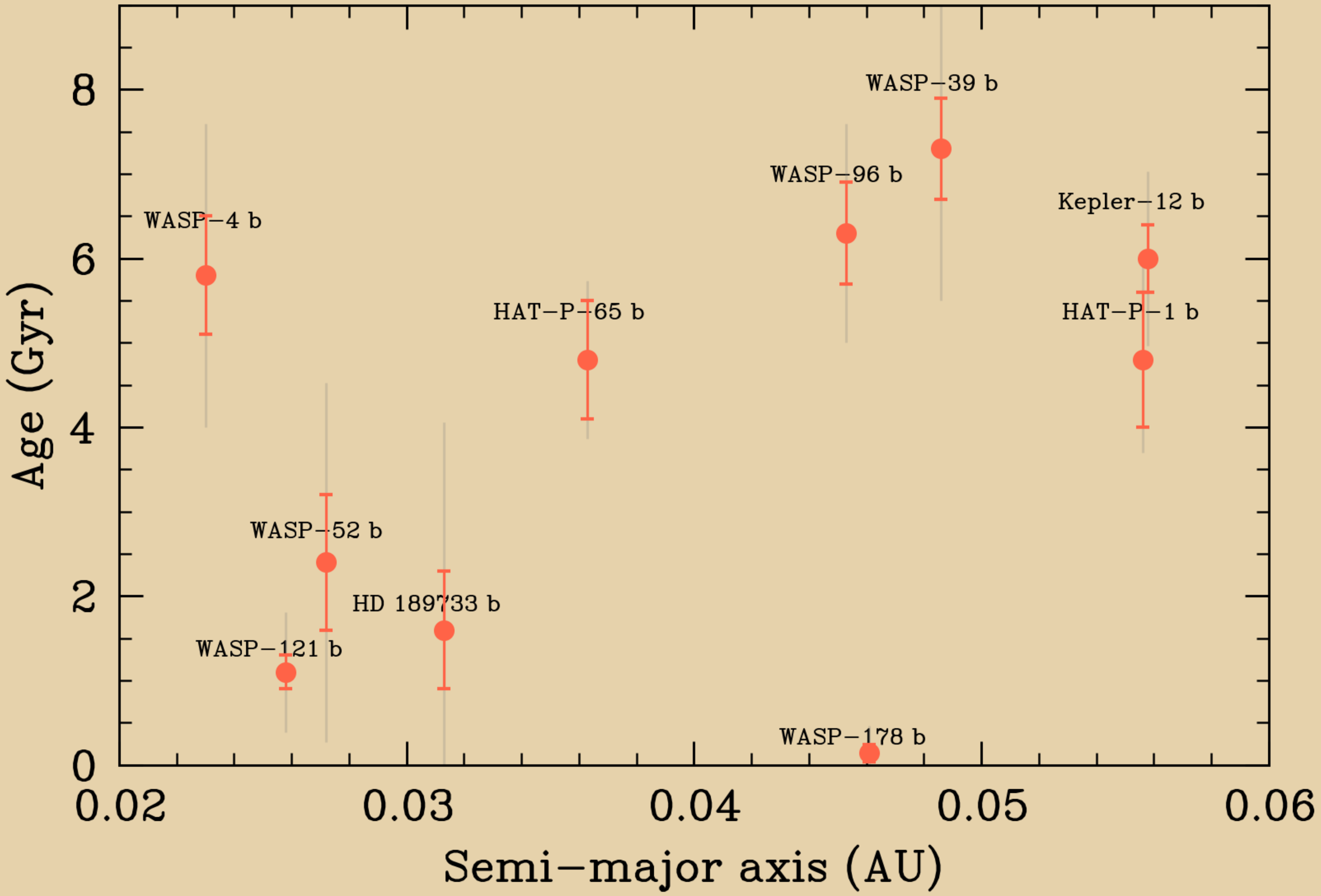


Apply JWST density cut to localize mass/age!

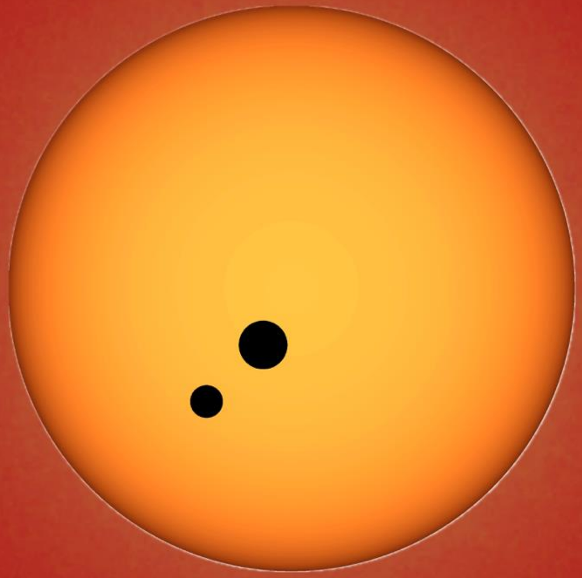




WASP−39 b
8
6
4
2
0
Age (Gyr)
0.02
0.03
0.04
0.05
0.06
Semi−major axis (AU)

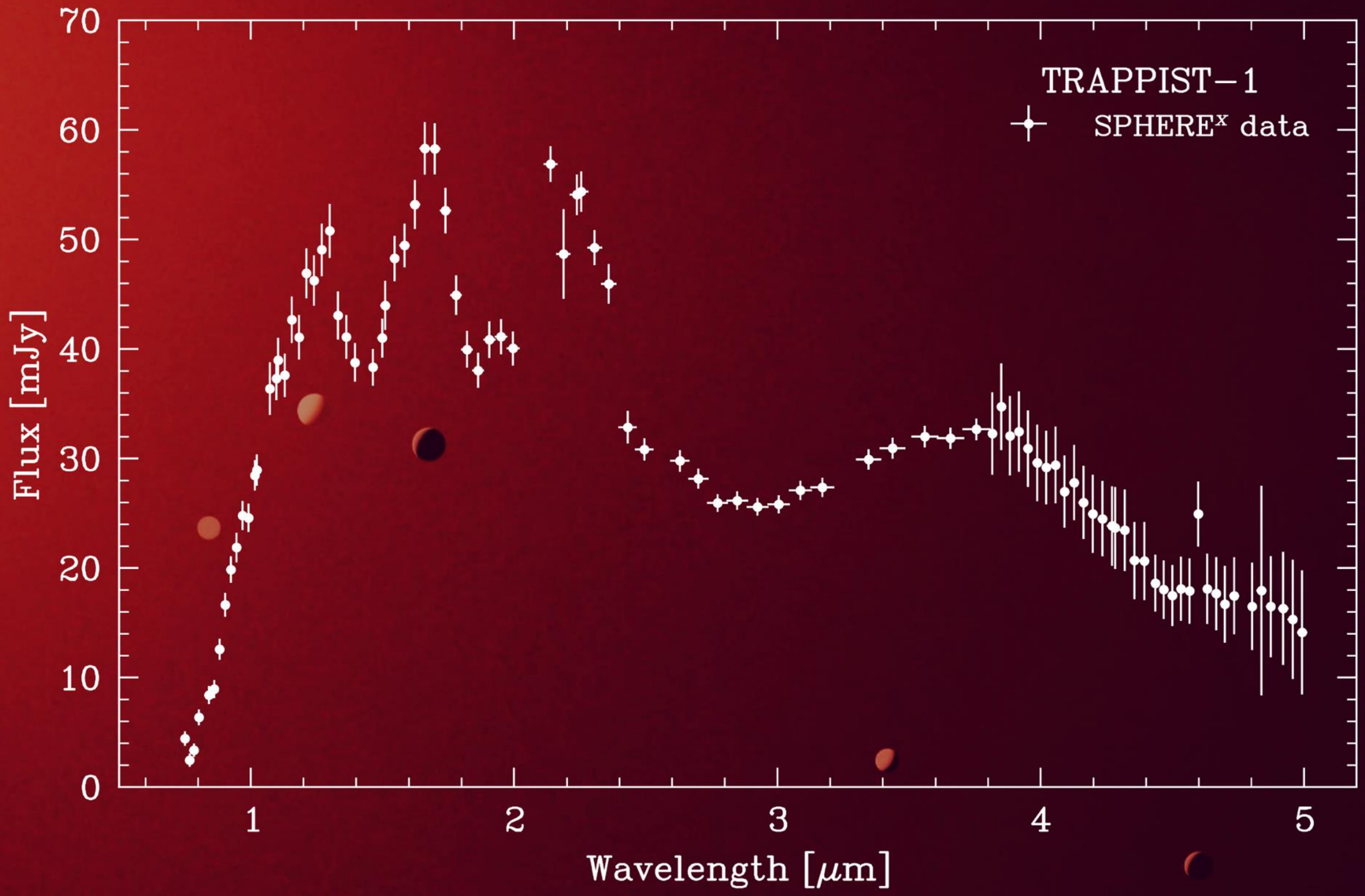


WASP−4 b
WASP−121 b
WASP−52 b
HD 189733 b
HAT−P−65 b
WASP−96 b
WASP−39 b
WASP−178 b
Kepler−12 b
HAT−P−1 b
Age (Gyr)
Semi−major axis (AU)
0
2
4
6
8
0.02
0.03
0.04
0.05
0.06

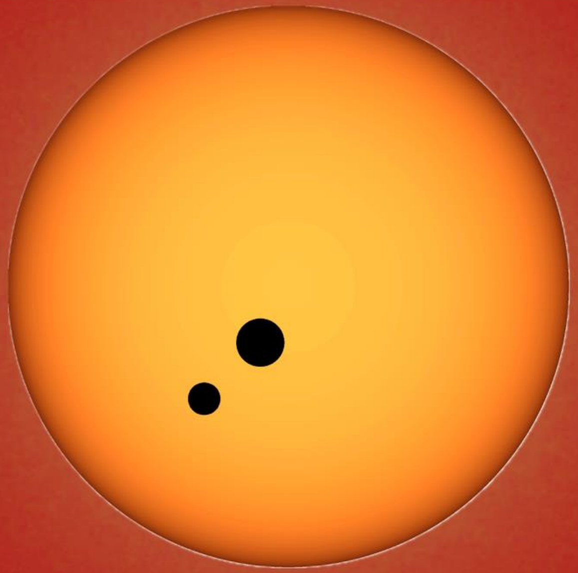


M dwarfs are the most common type of star…

TRAPPIST-1

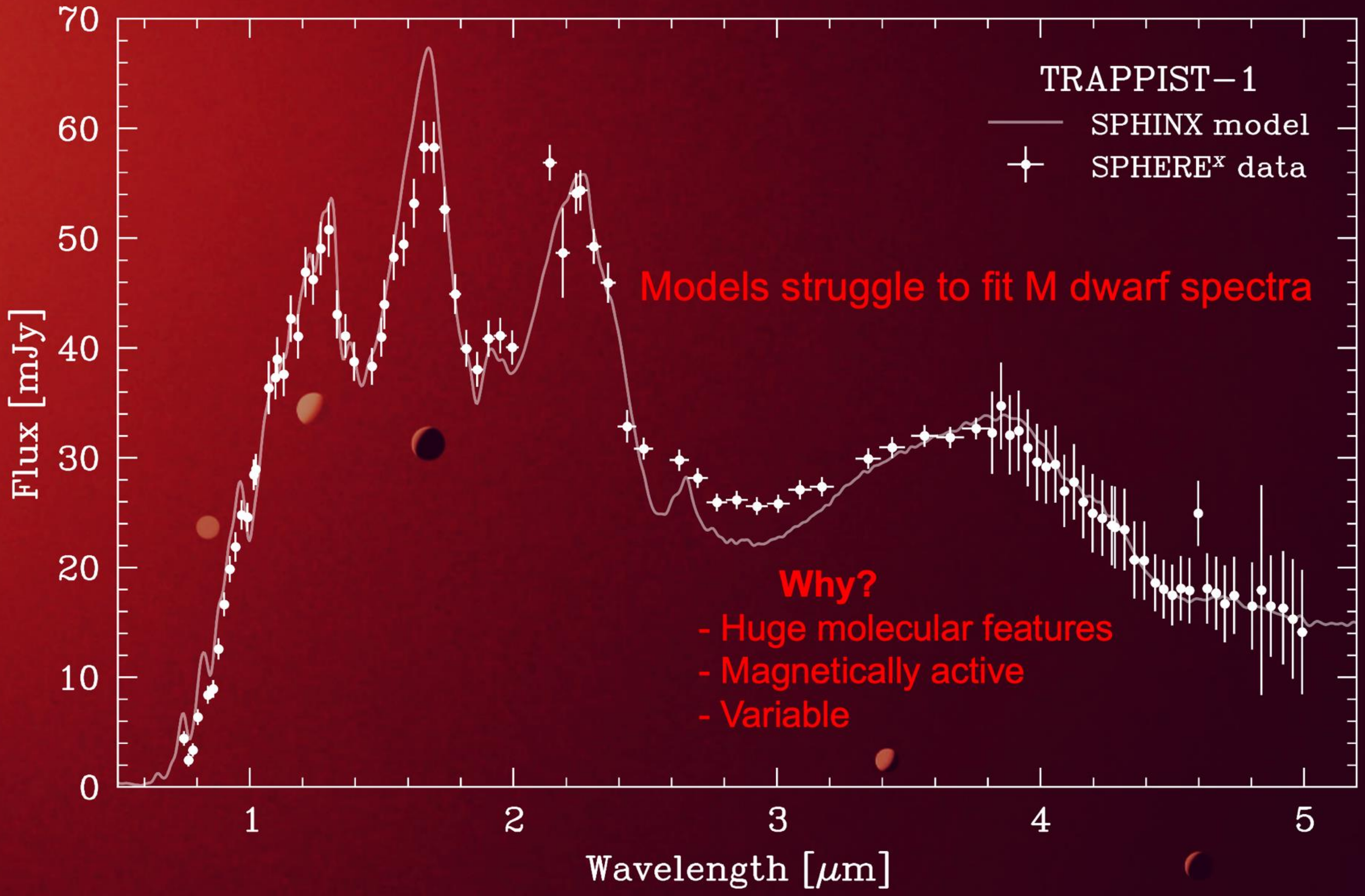


TRAPPIST-1



M dwarfs are the most common type of star…

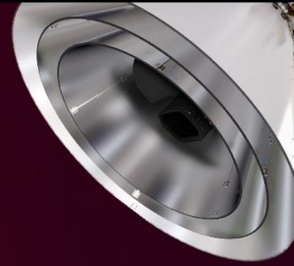
…but notoriously the most poorly understood



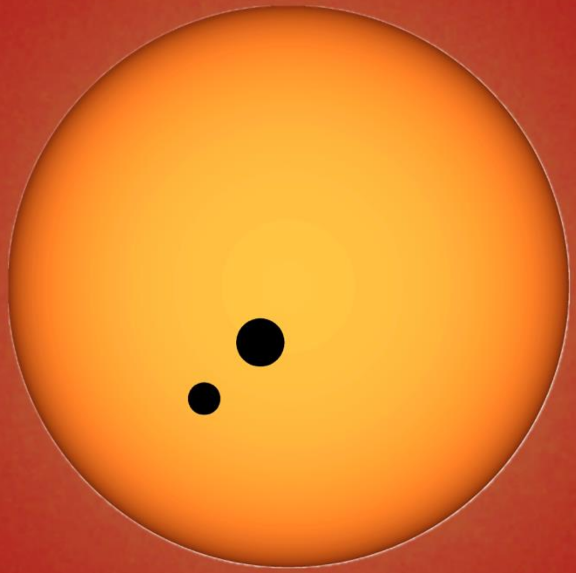
Models struggle to fit M dwarf spectra

Why?

- Huge molecular features
- Magnetically active
- Variable



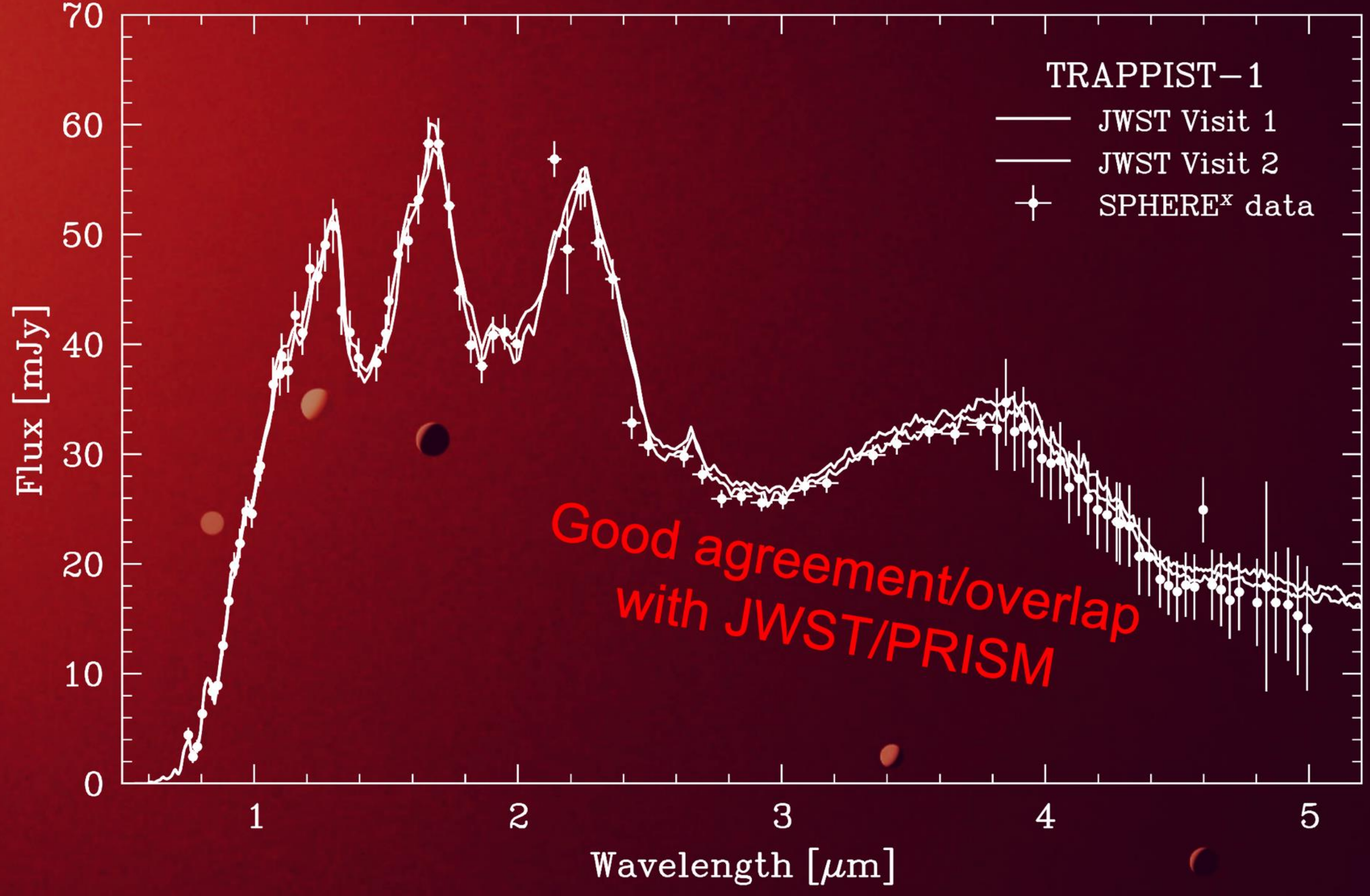
TRAPPIST-1

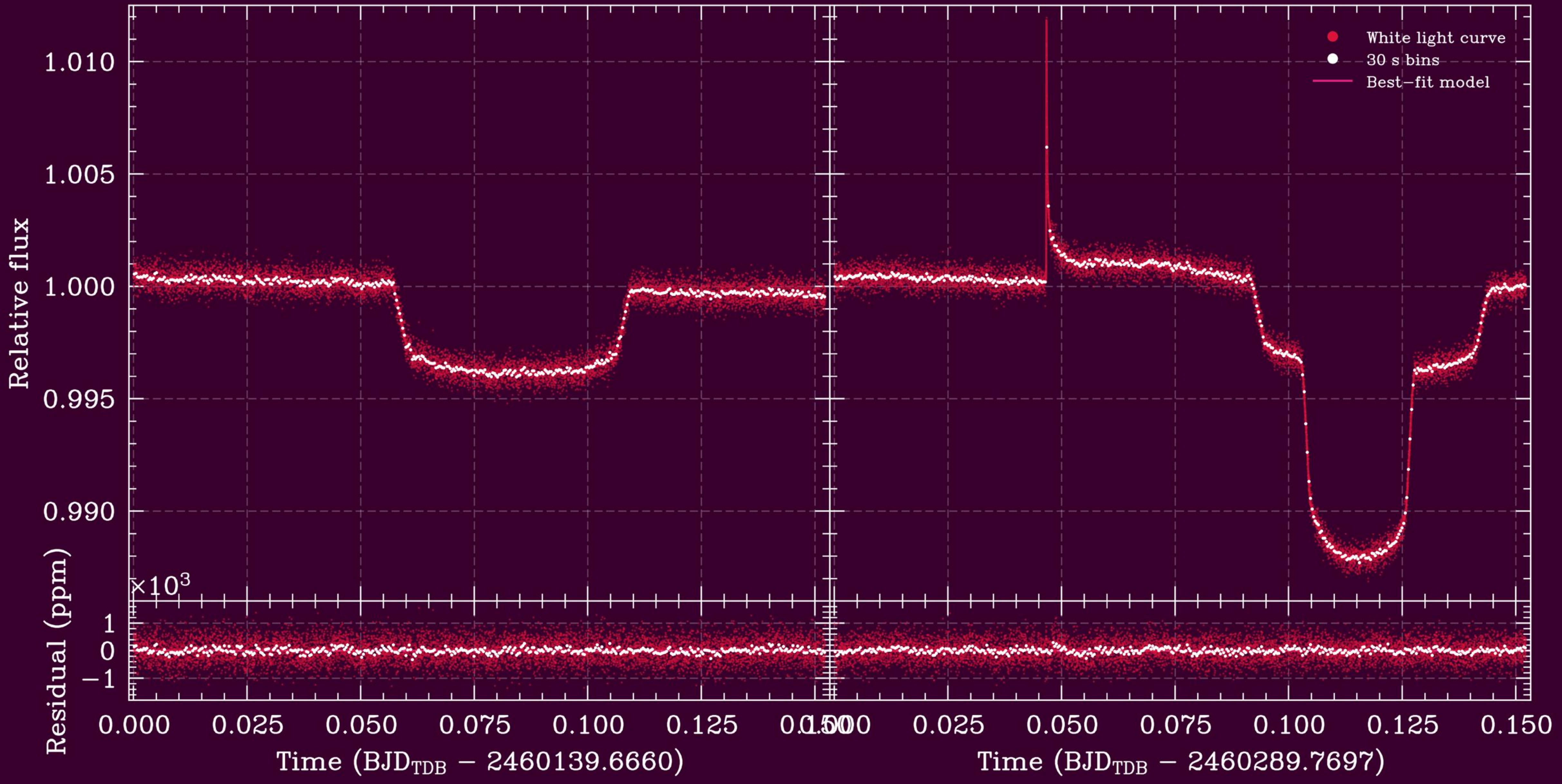


M dwarfs are the most common type of star…

…but notoriously the most poorly understood

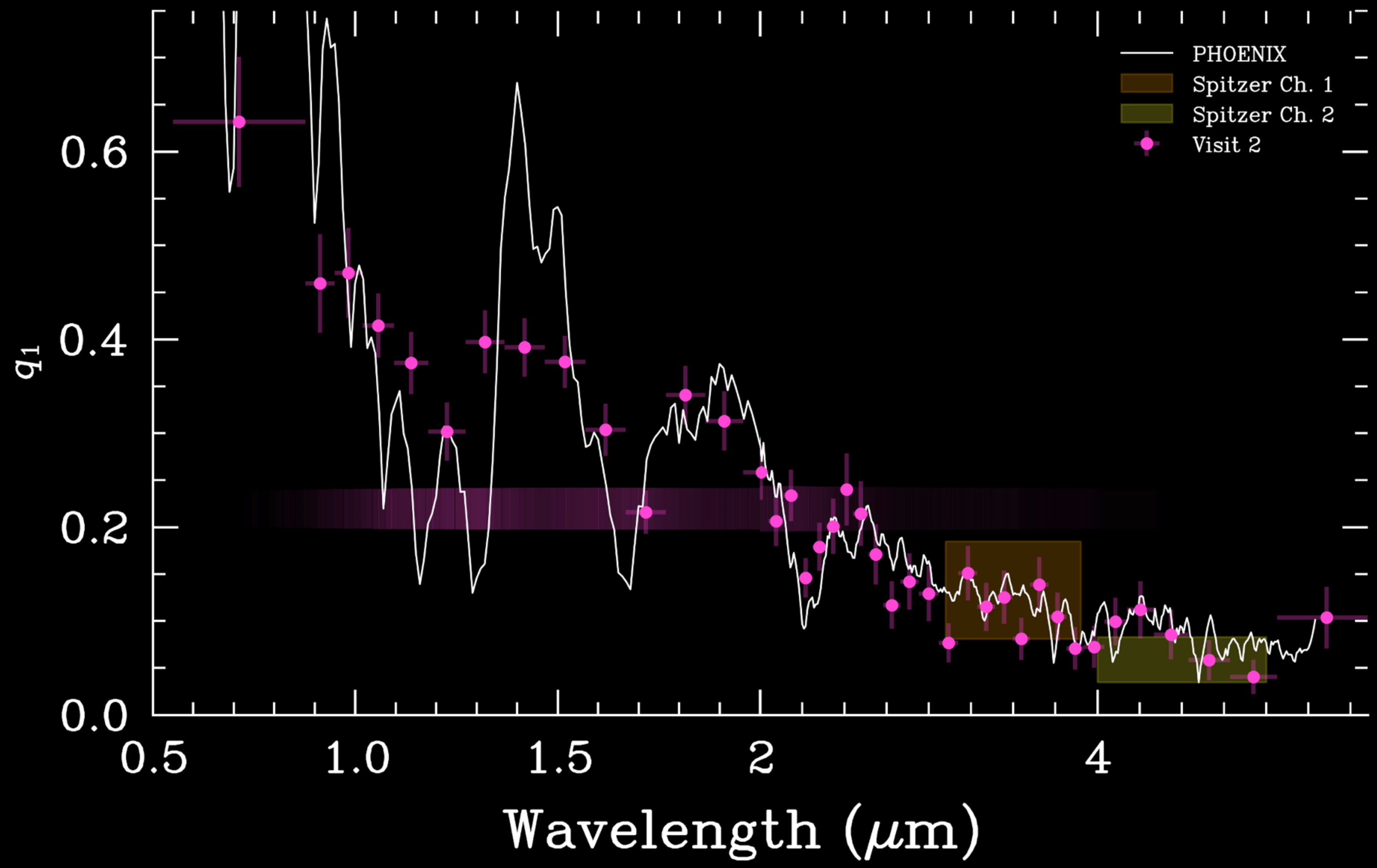
SPHEREx is gathering millions of M dwarf spectra!

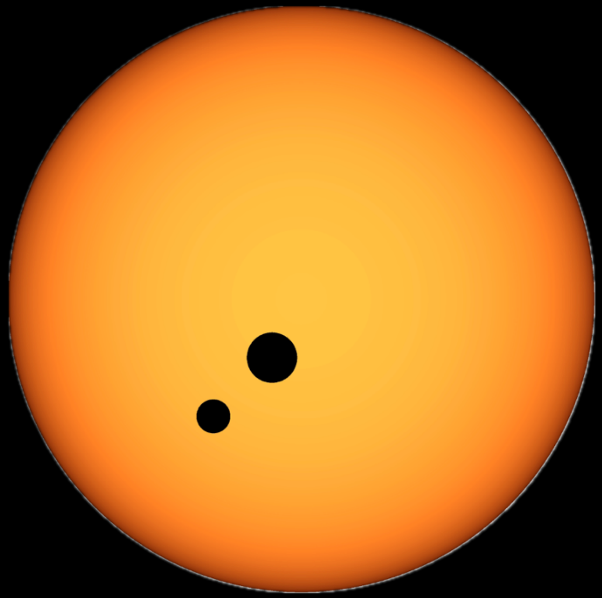




White light curve
30 s bins
Best−fit model
Relative flux
1.010
1.005
1.000
0.995
0.990
×10^3
Residual (ppm)
1
0
−1
0.000
0.025
0.050
0.075
0.100
0.125
0.150
Time (BJD_TDB − 2460139.6660)
Time (BJD_TDB − 2460289.7697)

JWST Limb darkening spectrum of TRAPPIST-1

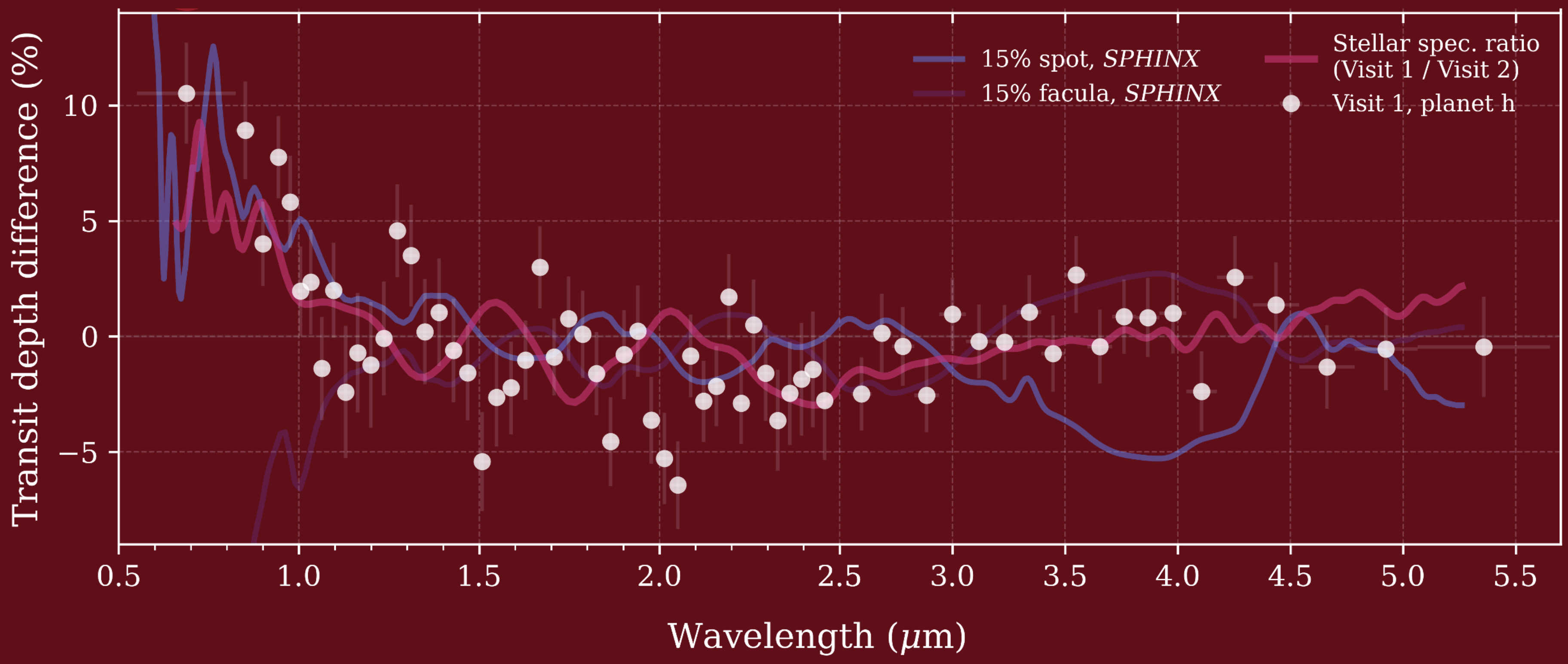


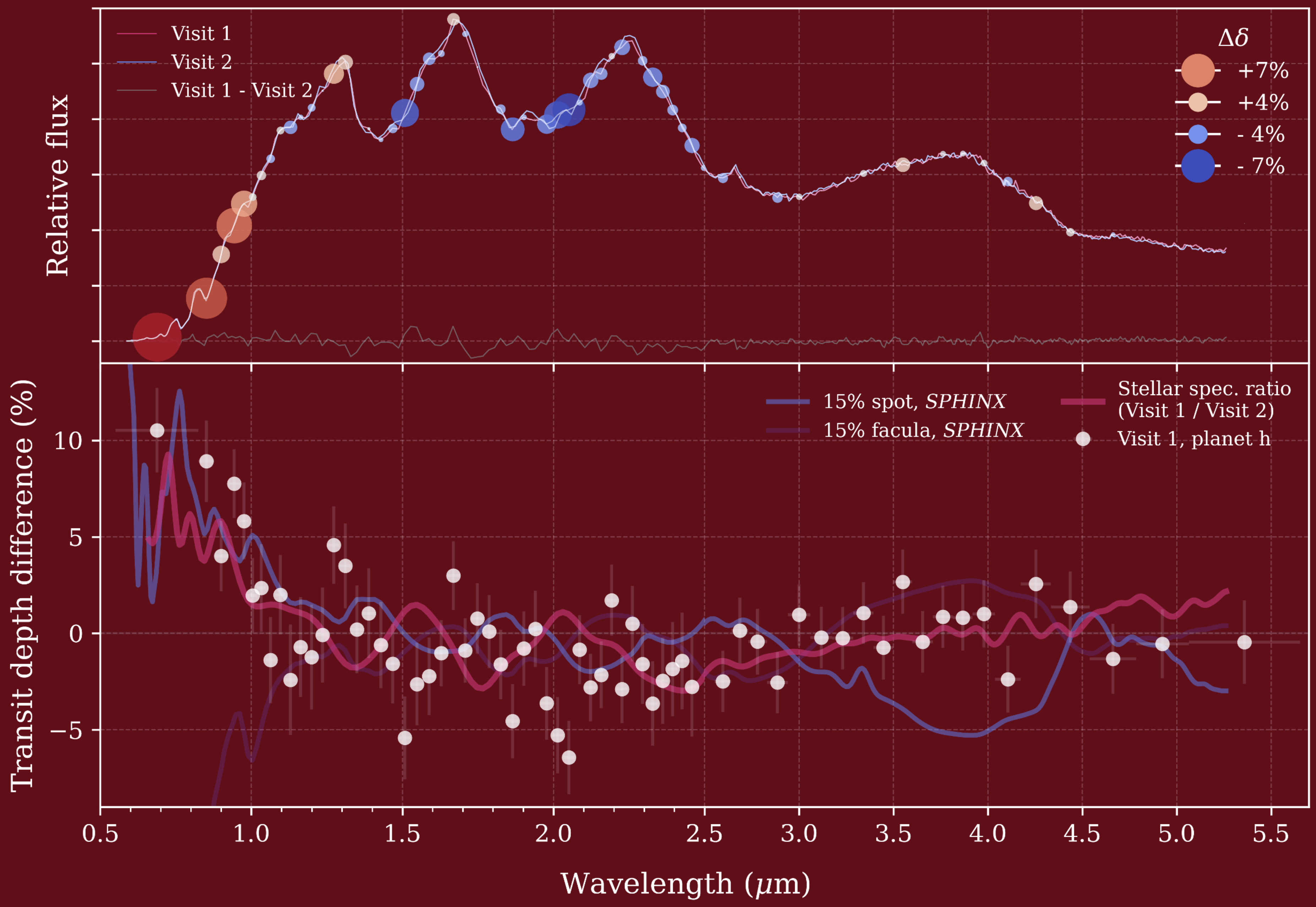


The center-to-limb spectrum of TRAPPIST-1 shows prominent water features, which probe thermal structure

The photosphere also shows thermal/compositional inhomogeneities

As probed via the Transit Light Source Effect

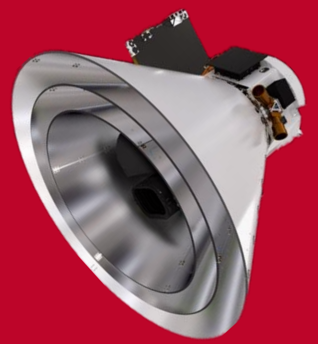




Inhomogeneities correlate with the water absorption features

What is the connection?

TAKEAWAYS:



- SPHEREx yields extremely precise stellar temperatures
- Combining SPHEREx Teffs with Gaia distances results in **R**efined radii
- Combining SPHEREx/Gaia with JWST transit density gives **R**efined **mass**, **age**
- Expanding this analysis to many planet hosts will allow us to test models of stellar and planetary coevolution across the Main Sequence
- JWST probes ultracool dwarf atmospheres with unprecedented detail thanks to their transiting planets
- SPHEREx will help us understand why our models struggle to fit red dwarf spectra