july 17th

exoplanet classification

1. new data set received

- meeting on saturday, received a snapshot of the nasa data archive on **march 10, 2024** to better stay consistent with the rest of the HZ exoplanet classification paper

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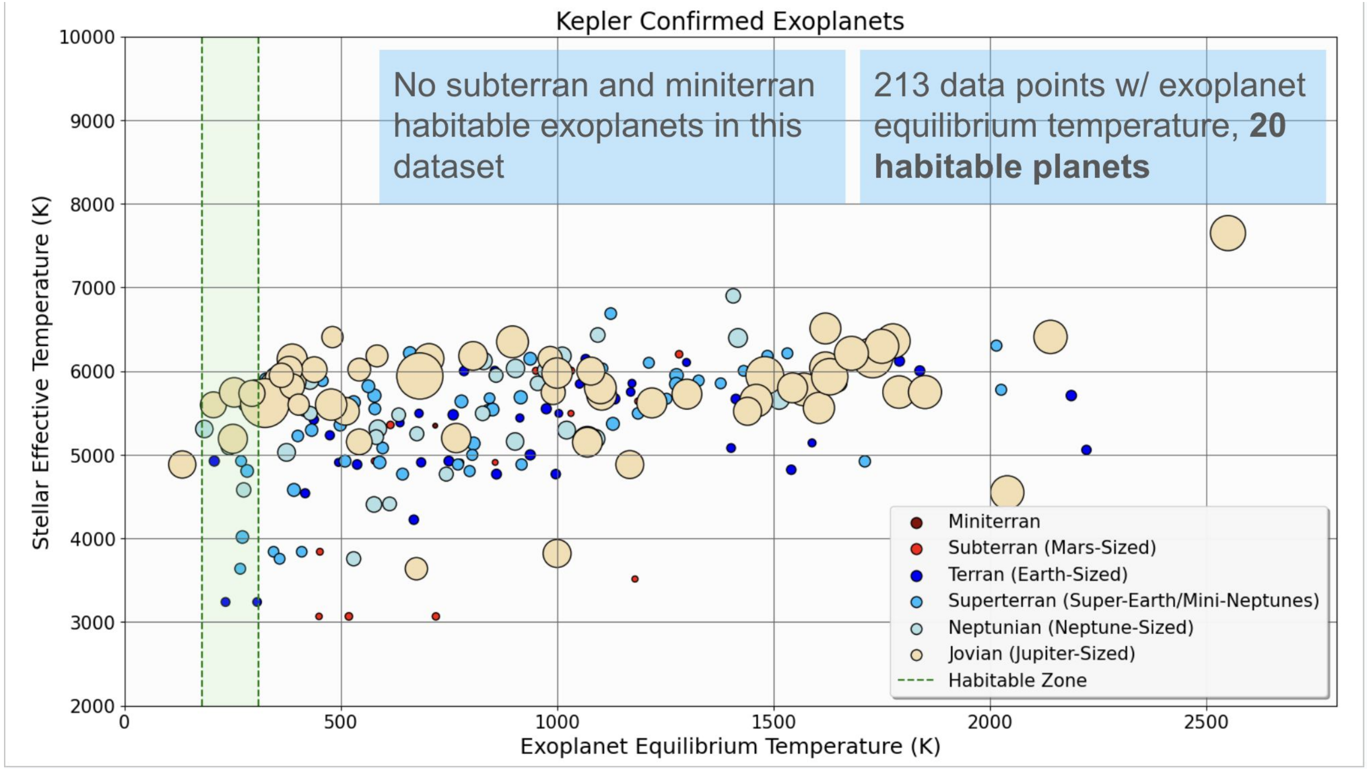
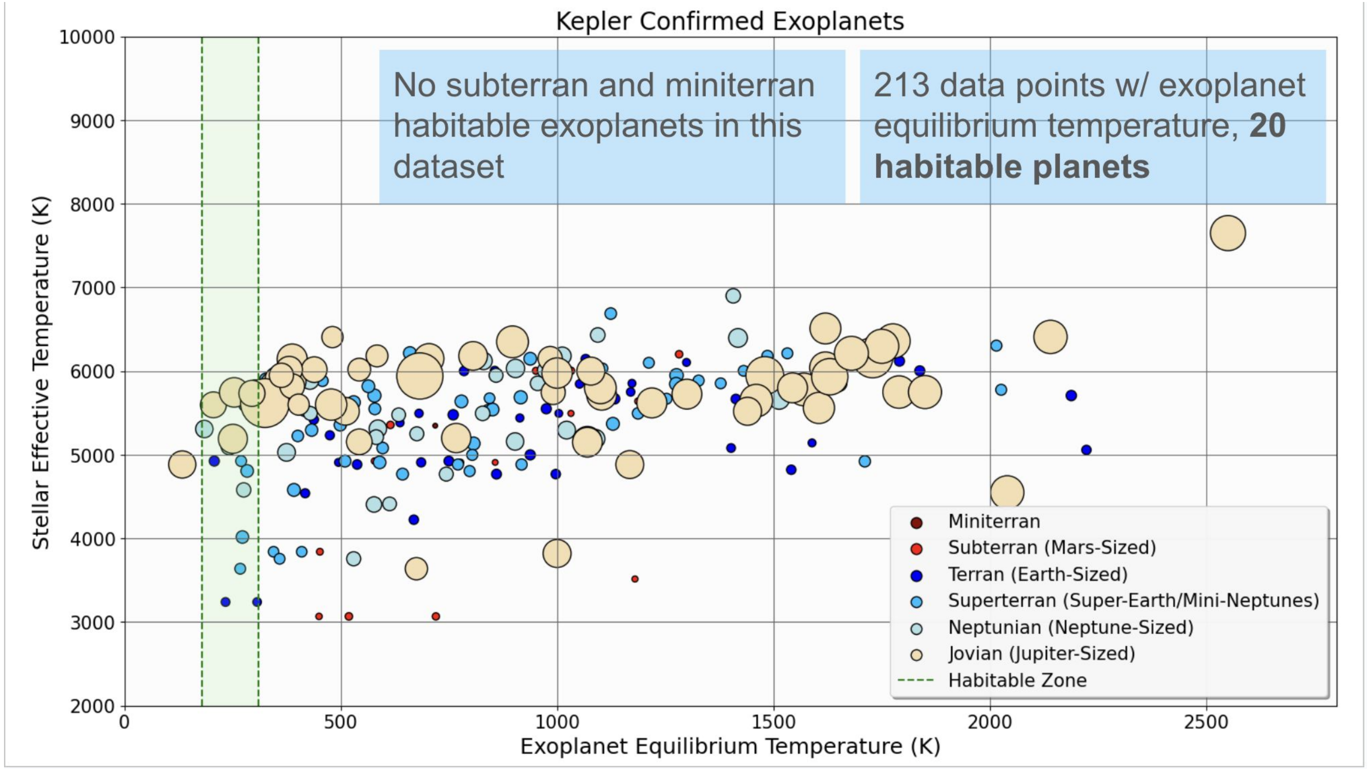
- also received a draft of the paper, which i was able to use to better arrange how i calculated habitability zones (which was always a constant struggle in the past)

2. the original graph



< my **june 19th** presentation, with data from Confirmed Planets Discovered by Kepler (2774 entries)

2. the original graph



< my **june 19th** presentation, with data from [Confirmed Planets Discovered by Kepler]() (2774 entries)

ONLY 213 ENTRIES

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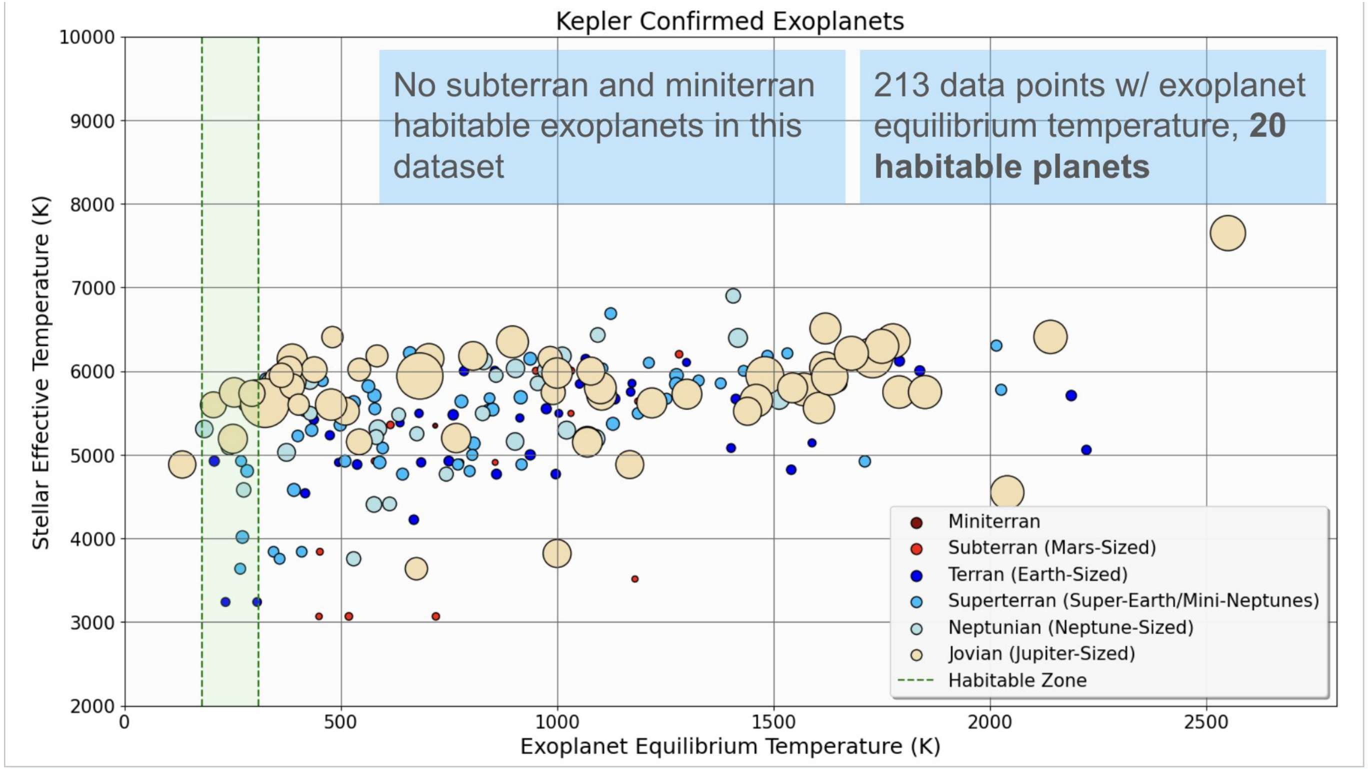

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ONLY 213 ENTRIES

ONLY TEMP. CONSIDERED

3. defining the habitable zone

one of my biggest frustrations in past graph-making endeavors … finally fixed!!

2.2 Habitability Zone Determination

The habitable zone of a given exoplanet was determined based on its calculated average surface temperature, denoted as $T_{surf,\ ave}$, a critical indicator of potential liquid water presence. We categorized exoplanets as "Too Hot" ($T_{surf,\ ave} > 100^{o}C$), "Too Cold" ($T_{surf,\ ave} < 0^{o}C$) or within the habitable zone (“In HZ”) for $T_{surf,\ ave}$ between the benchmark temperature range of 0 to 100ºC. This classification was vital to identifying exoplanets that could potentially support life under the assumed necessary precursor of liquid phase H_2O. Utilizing the basic Radiative Equilibrium equation as derived from first principles of radiative heat transfer, the exoplanet average surface temperature calculation considered several characterizing factors. These include the exoplanet's distance from its host star (d), the host's effective surface temperature ($T_{☼}$) and radius ($R_{☼}$), exoplanet albedo (A) and an additional scaler to account for bulk atmospheric greenhouse gas effect (k):

$$T_{surf,\ ave} = kT_{☼}(1 - A)^{0.25}(R_{☼}/(2d))^{0.5} \qquad \text{Eq 2.2-1}$$

Applying equation 2.2-1 to each listing in the NASA Exoplanet Archive enabled selective sifting of the database to produce quantified results based on the aforementioned exoplanet HZ status categories. Additionally, where the Archive had no entry for the observable parameters $T_{☼}$ and/or $R_{☼}$ and/or d, a designation of “N/A” was made for the associated exoplanet to denote insufficient information for determining HZ status in those cases.

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3. defining the habitable zone

$$T_{surf,\ ave} = kT_{\odot}(1 - A)^{0.25}(R_{\odot}/(2d))^{0.5}$$

^^ redefining the habitable zone based on this formula

```
[11] exoplanets_data['pl_tsurf_k'] = 1.13 * exoplanets_data['st_teff'] * ((1 - 0.306) ** 0.25) * (((exoplanets_data['st_rad'] * 696000) / (2 * exoplanets_data[pl_orbsmax'] * 149598023)) ** 0.5)
     exoplanets_data['pl_tsurf_c'] = exoplanets_data['pl_tsurf_k'] - 273.15
```

```
[14] exoplanets_data.loc[(np.isnan(exoplanets_data['pl_tsurf_c'])), 'pl_hz_status'] = 'N/A'
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_tsurf_c'])) & (exoplanets_data['pl_tsurf_c'] >= 0) & (exoplanets_data['pl_rade'] <= 100)), 'pl_hz_status'] = 'In
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_tsurf_c'])) & (exoplanets_data['pl_tsurf_c'] > 100)), 'pl_hz_status'] = 'Too Hot'
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_tsurf_c'])) & (exoplanets_data['pl_tsurf_c'] < 0)), 'pl_hz_status'] = 'Too Cold'
```

categorized exoplanets as "Too Hot" ($T_{surf,\ ave}$ >100ºC), "Too Cold" ($T_{surf,\ ave}$ <0ºC) or within the habitable zone ("In HZ") for $T_{surf,\ ave}$ between the benchmark temperature range of 0 to 100ºC. This

4. exoplanet proposed classification

based on nasa's classification using **radius** located at

`https://science.nasa.gov/exoplanets/planet-types /`

Types of exoplanets

Each planet type varies in interior and exterior appearance depending on composition.

Gas giants are planets the size of Saturn or Jupiter, the largest planet in our solar system, or much, much larger.

More variety is hidden within these broad categories. Hot Jupiters, for instance, were among the first planet types found – gas giants orbiting so closely to their stars that their temperatures soar into the thousands of degrees (Fahrenheit or Celsius).

Neptunian planets are similar in size to Neptune or Uranus in our solar system. They likely have a mixture of interior compositions, but all will have hydrogen and helium-dominated outer atmospheres and rocky cores. We're also discovering mini-Neptunes, planets smaller than Neptune and bigger than Earth. No planets of this size or type exist in our solar system.

Super-Earths are typically terrestrial planets that may or may not have atmospheres. They are more massive than Earth, but lighter than Neptune.

Terrestrial planets are Earth sized and smaller, composed of rock, silicate, water or carbon. Further investigation will determine whether some of them possess atmospheres, oceans or other signs of habitability.

4. exoplanet proposed classification

```
[18] # Determine exoplanet types based on radius
     # Type classification is based on https://science.nasa.gov/exoplanets/planet-types/
     exoplanets_data.loc[(np.isnan(exoplanets_data['pl_rade'])), 'pl_type'] = 'N/A'
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_rade'])) & (exoplanets_data['pl_rade'] <= 1)), 'pl_type'] = 'Terrestrial-Panets'
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_rade'])) & (exoplanets_data['pl_rade'] > 1) & (exoplanets_data['pl_rade'] < 3.88)), 'pl_type'] = 'Super-Earths'
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_rade'])) & (exoplanets_data['pl_rade'] >= 3.88) & (exoplanets_data['pl_rade'] < 9.5)), 'pl_type'] = 'Neptunian-Planets'
     exoplanets_data.loc[((~np.isnan(exoplanets_data['pl_rade'])) & (exoplanets_data['pl_rade'] > 9.5)), 'pl_type'] = 'Gas-Giants'
```

terrestrial planets:

- ≤ 1 times the radius of the Earth

super-earths:

- 1 < *r* < 3.88, where the radius of the exopl. is *r* times as big as that of Earth

neptunian planets:

- 3.88 ≤ *r* < 9.5

gas giants:

- >= 9.5 times the radius of the Earth

5. single-host systems

- cleaned data for the following graphs to just include **single host star systems** (to match with the rest of the paper)

6. general data + results

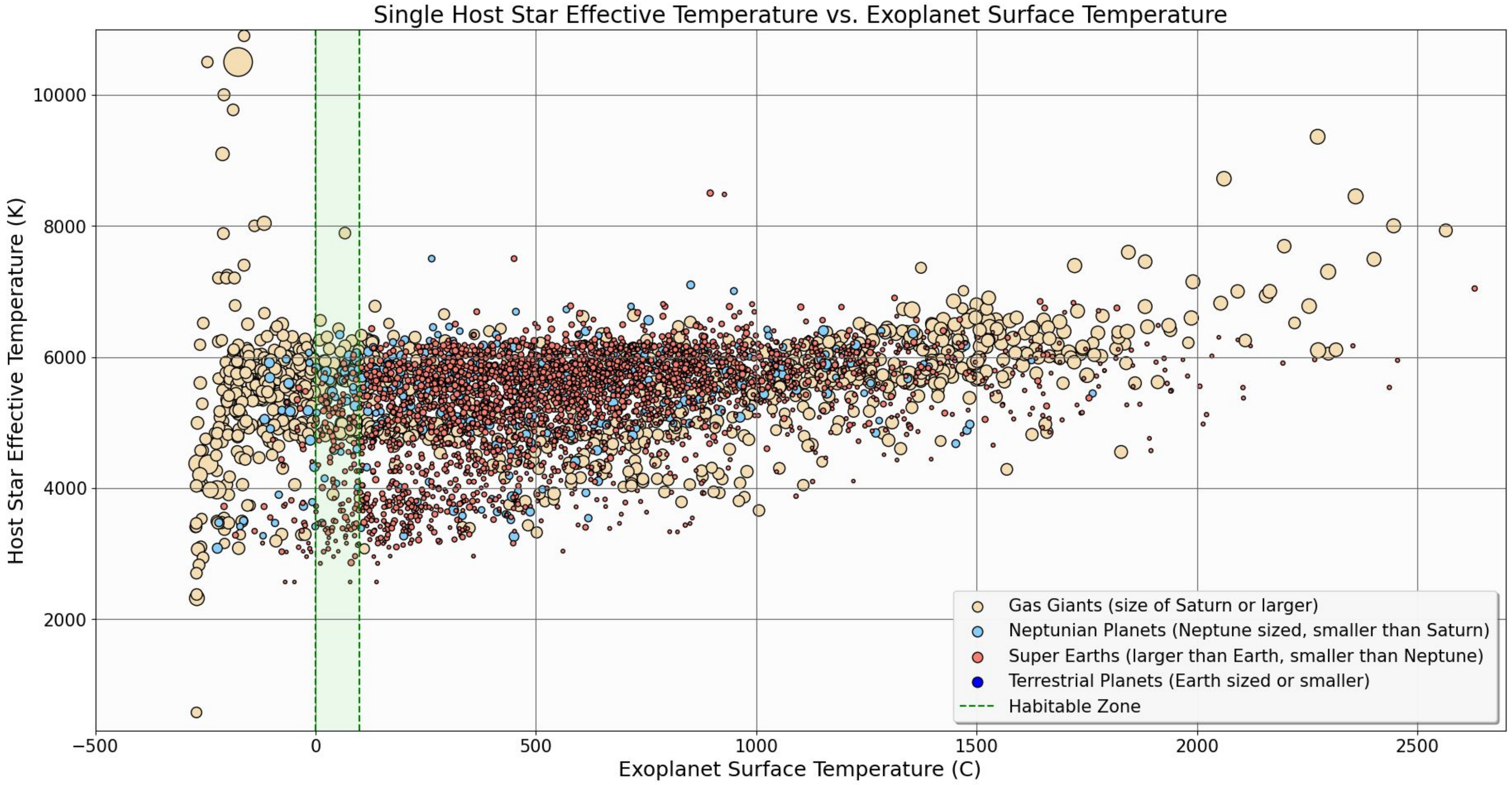
```
[16] exoplanets_data['pl_hz_status'].value_counts()
```

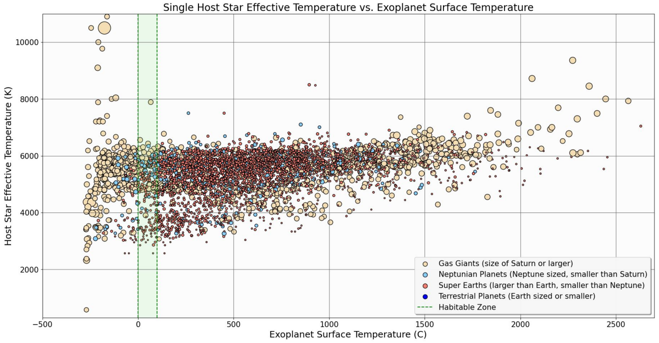
```
pl_hz_status
Too Hot      4310
N/A           536
Too Cold      490
In HZ         258
Name: count, dtype: int64
```

```
[19] exoplanets_data['pl_type'].value_counts()
```

```
pl_type
Super-Earths           3255
Gas-Giants             1598
Neptunian-Planets       509
Terrestrial-Panets      214
N/A                      19
Name: count, dtype: int64
```

6. the newer graphs (with the new 3.10 data)





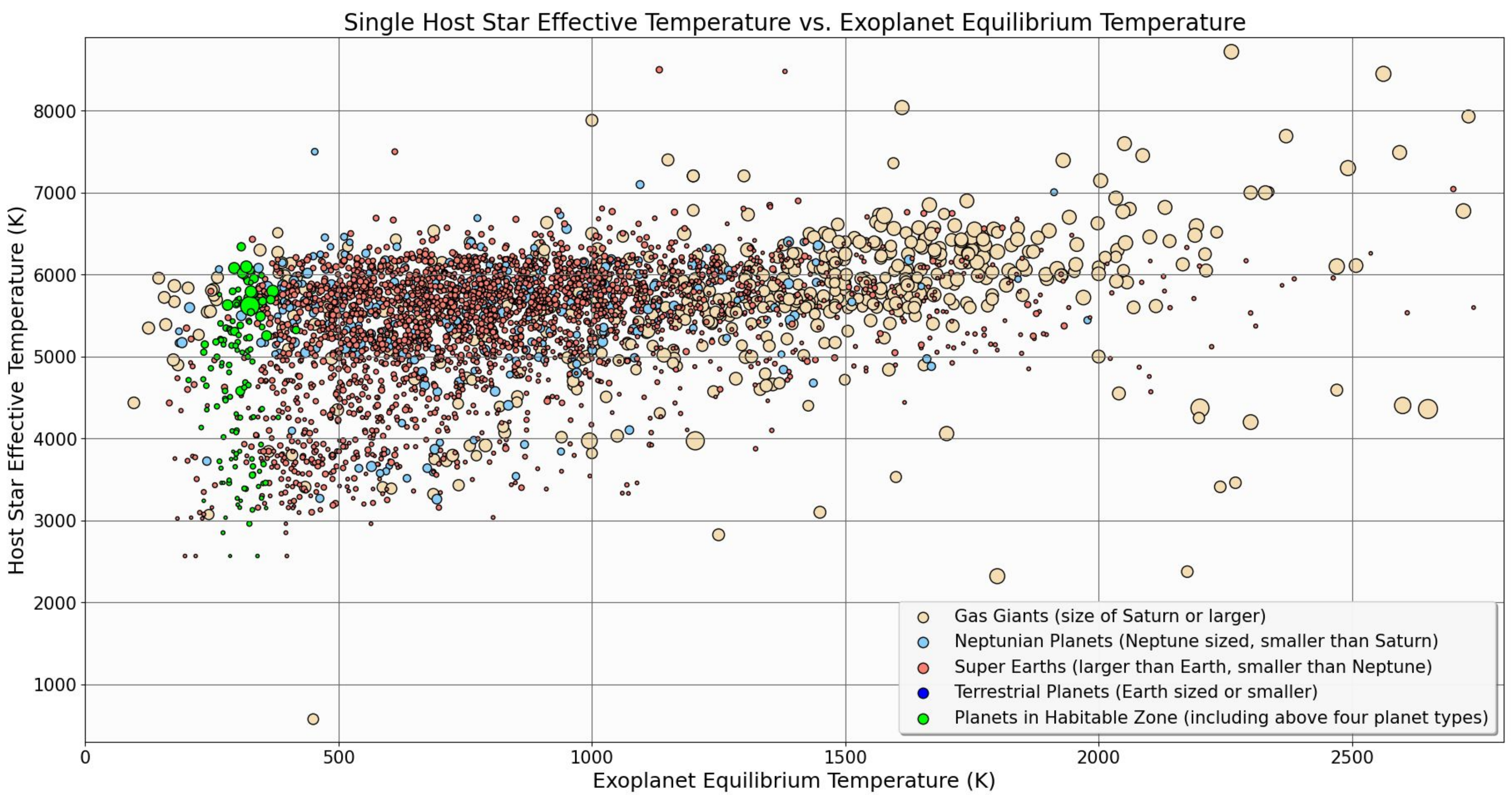
4583 total planets

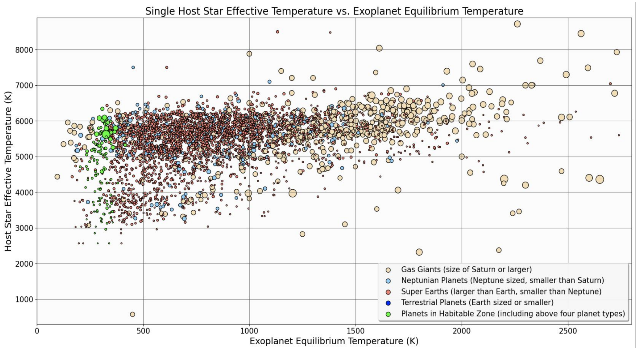
```
[22] st_teff_vs_pl_tsurf_plot_data['pl_hz_status'].value_counts()
```

```
pl_hz_status
Too Hot     3953
Too Cold     403
In HZ        227
Name: count, dtype: int64
```

```
st_teff_vs_pl_tsurf_plot_data['pl_type'].value_counts()
```

```
pl_type
Super-Earths           2868
Gas-Giants             1146
Neptunian-Planets       387
Terrestrial-Panets      182
Name: count, dtype: int64
```

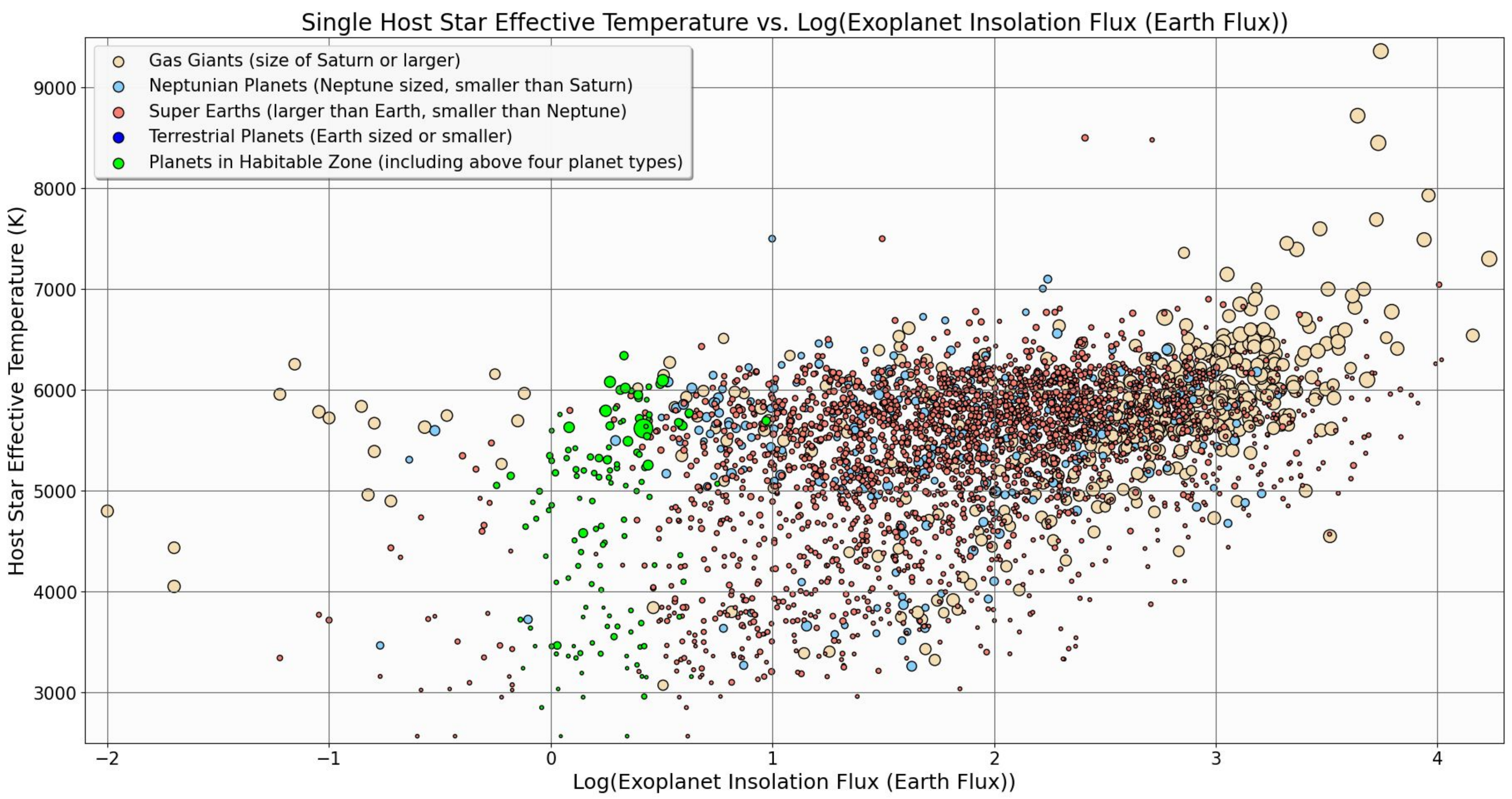

Single Host Star Effective Temperature vs. Exoplanet Equilibrium Temperature
Host Star Effective Temperature (K)
Exoplanet Equilibrium Temperature (K)
8000
7000
6000
5000
4000
3000
2000
1000
0
500
1000
1500
2000
2500
Gas Giants (size of Saturn or larger)
Neptunian Planets (Neptune sized, smaller than Saturn)
Super Earths (larger than Earth, smaller than Neptune)
Terrestrial Planets (Earth sized or smaller)
Planets in Habitable Zone (including above four planet types)

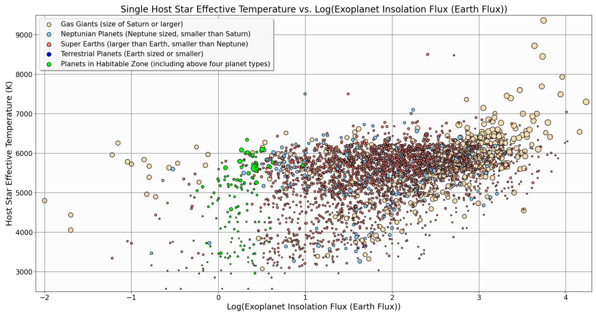


3725 total planets

```
[28] st_teff_vs_pl_eqt_plot_data['pl_hz_status'].value_counts()
```

```
pl_hz_status
Too Hot     3503
In HZ        132
Too Cold      90
Name: count, dtype: int64
```


Single Host Star Effective Temperature vs. Log(Exoplanet Insolation Flux (Earth Flux))
Gas Giants (size of Saturn or larger)
Neptunian Planets (Neptune sized, smaller than Saturn)
Super Earths (larger than Earth, smaller than Neptune)
Terrestrial Planets (Earth sized or smaller)
Planets in Habitable Zone (including above four planet types)
Host Star Effective Temperature (K)
Log(Exoplanet Insolation Flux (Earth Flux))
9000
8000
7000
6000
5000
4000
3000
−2
−1
0
1
2
3
4



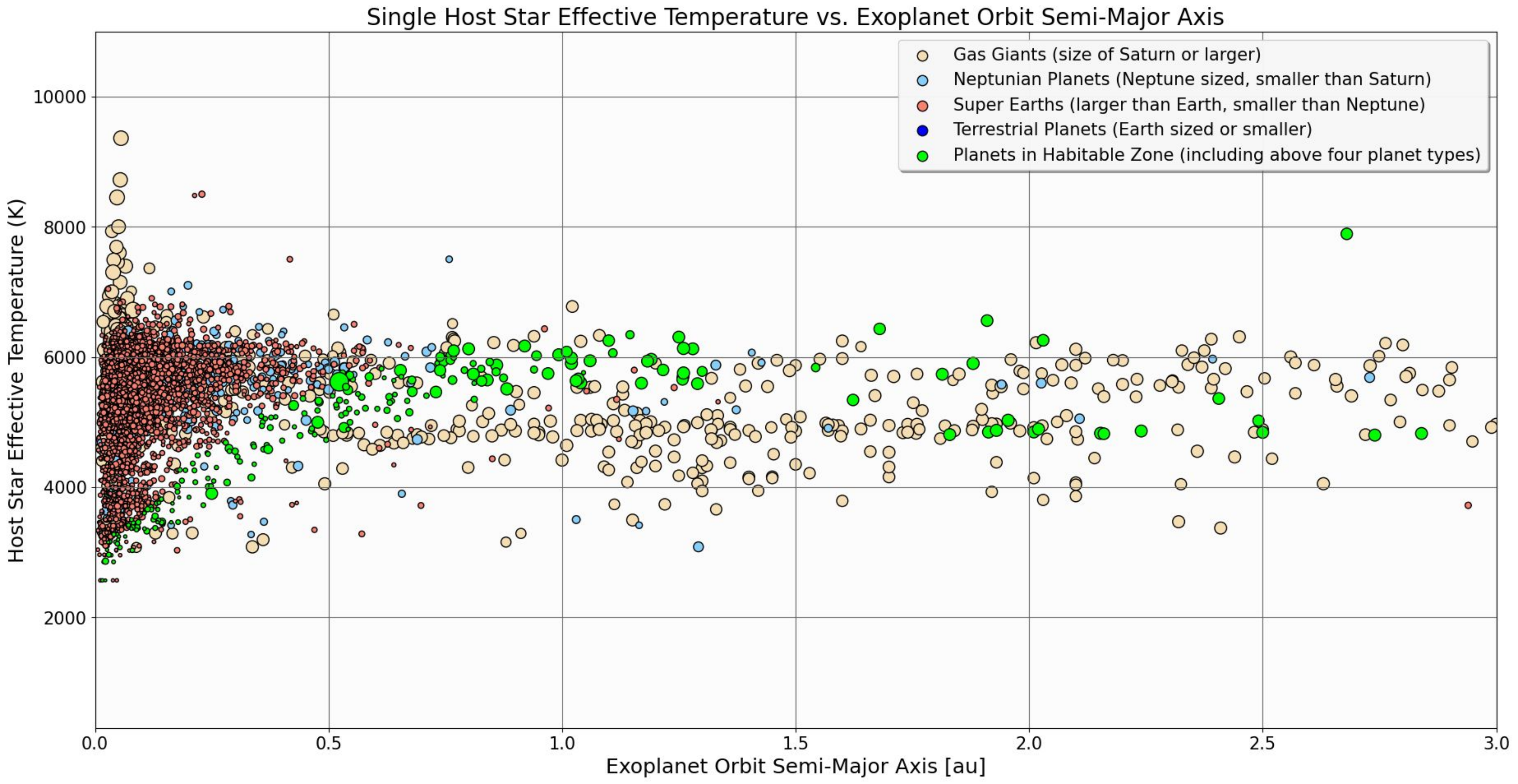
3563 total planets

```
[36] st_teff_vs_pl_insol_plot_data['pl_hz_status'].value_counts()
```

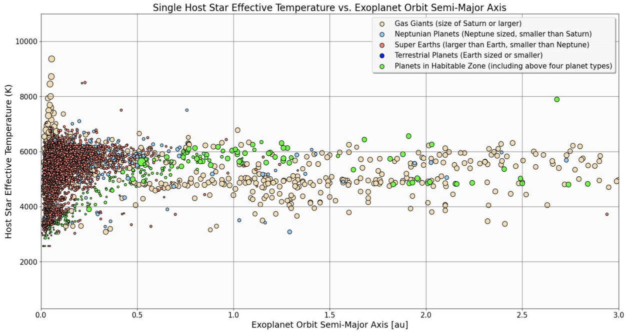
```
pl_hz_status
Too Hot      3373
In HZ         131
Too Cold       59
Name: count, dtype: int64
```

```
st_teff_vs_pl_insol_plot_data['pl_type'].value_counts()
```

```
pl_type
Super-Earths               2523
Gas-Giants                  469
Neptunian-Planets           270
Terrestrial-Panets          170
HabitableZone-Planets       131
Name: count, dtype: int64
```



Single Host Star Effective Temperature vs. Exoplanet Orbit Semi-Major Axis
Gas Giants (size of Saturn or larger)
Neptunian Planets (Neptune sized, smaller than Saturn)
Super Earths (larger than Earth, smaller than Neptune)
Terrestrial Planets (Earth sized or smaller)
Planets in Habitable Zone (including above four planet types)
Host Star Effective Temperature (K)
10000
8000
6000
4000
2000
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Exoplanet Orbit Semi-Major Axis [au]

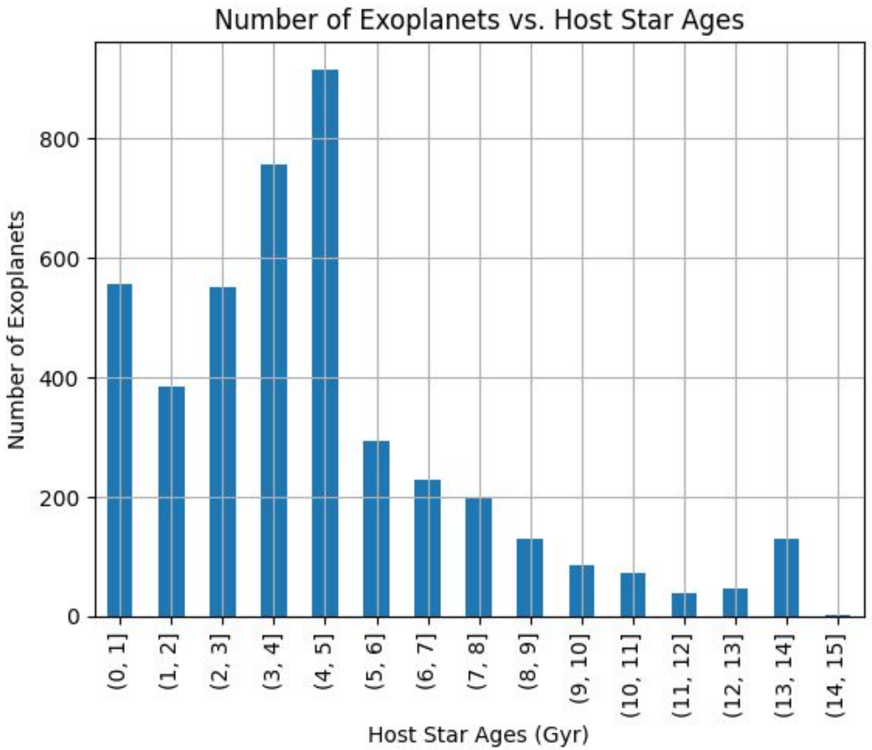


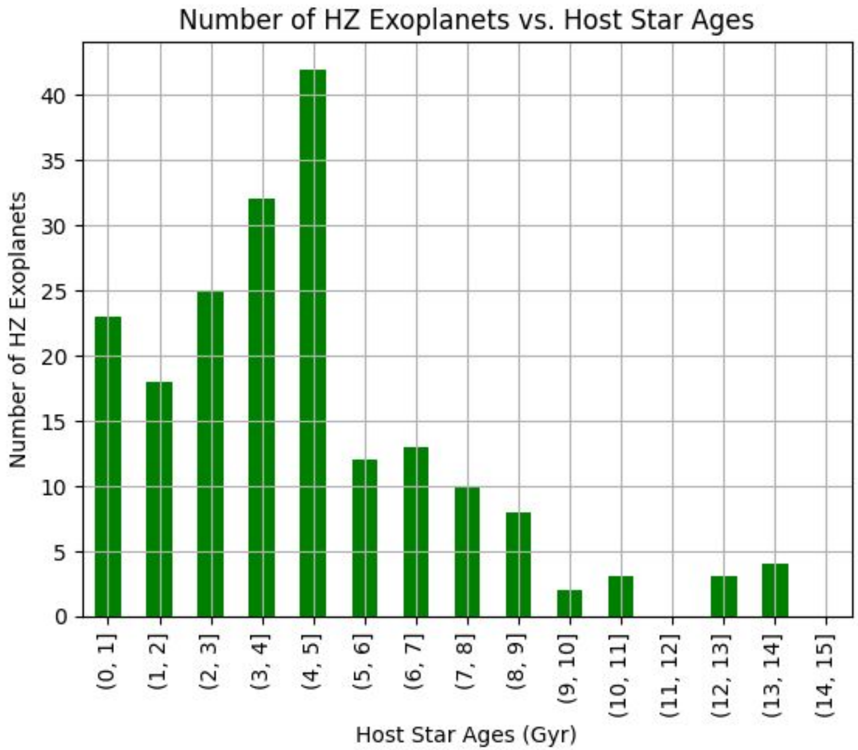
4583 total planets

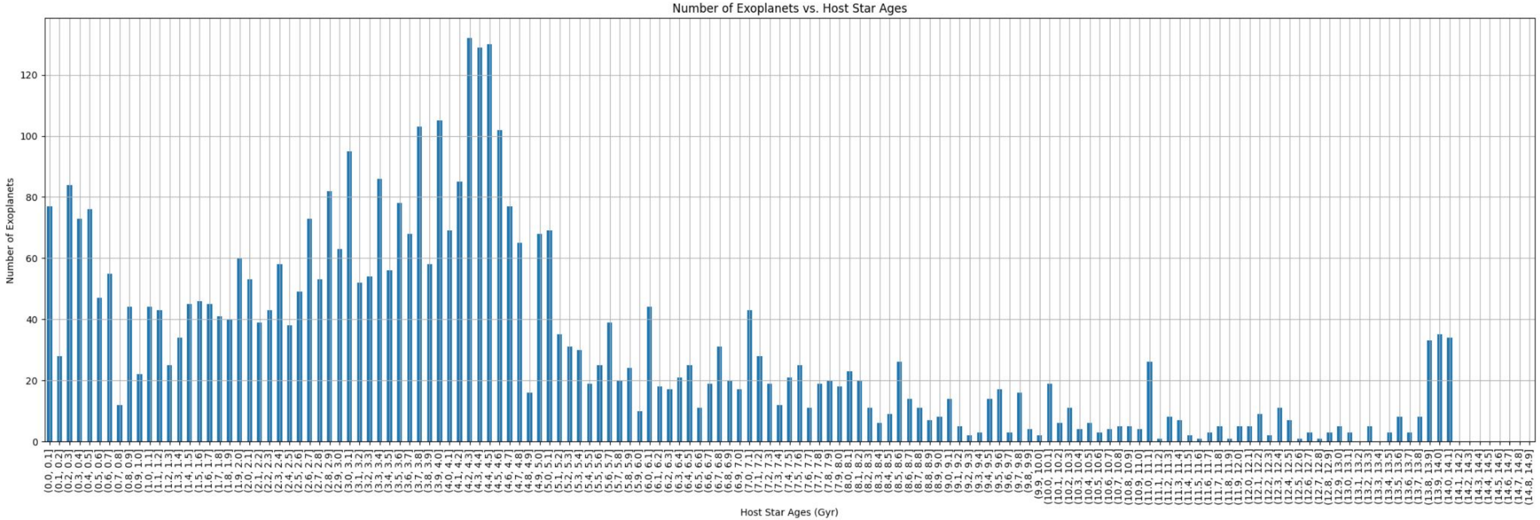
```
[44] st_teff_vs_pl_orb_plot_data['pl_hz_status'].value_counts()

pl_hz_status
Too Hot      3953
Too Cold      403
In HZ         227
Name: count, dtype: int64
```

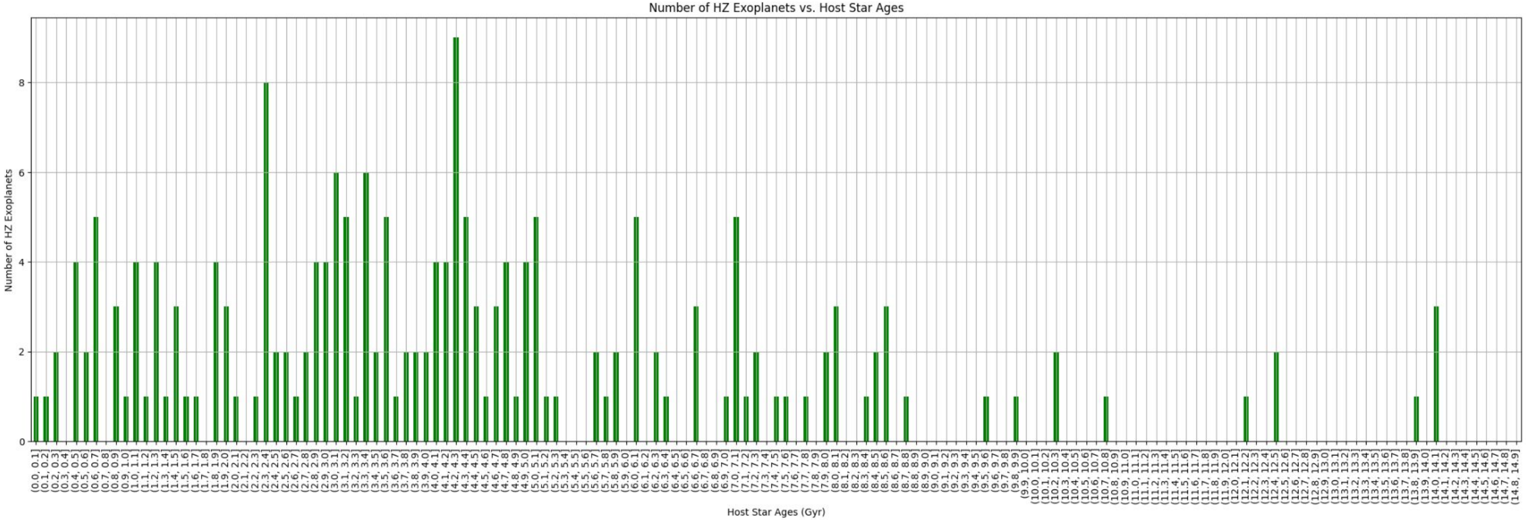
```
[46] st_teff_vs_pl_orb_plot_data['pl_type'].value_counts()

pl_type
Super-Earths                2744
Gas-Giants                  1080
Neptunian-Planets            353
HabitableZone-Planets        227
Terrestrial-Panets           179
Name: count, dtype: int64
```

number of exoplanets or HZ exoplanets vs. host star ages






Number of Exoplanets vs. Host Star Ages
Number of Exoplanets
0
20
40
60
80
100
120
Host Star Ages (Gyr)


Number of HZ Exoplanets vs. Host Star Ages
Number of HZ Exoplanets
0
2
4
6
8
Host Star Ages (Gyr)

other graphs

at this link:
https://github.com/christinaxliu/research/blob/main/Caltech-JPL-Intern/HZExoplanetsExploration/PlanetarySystemsCompositeData/HZExoplanetsExploration_PlanetarySystemsCompositeData.ipynb