Project 1

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Motivation

- The motivation for this project is to explore exoplanet data, understand the distribution of exoplanets, and examine the detection limits of different techniques used to find them. The project aims to help understand the biases involved in detecting exoplanets. Specifically, the project's motivation can be broken down into the following goals:
- **Using the NASA Exoplanet Archive (NEA):** To learn how to use the NEA to check and download exoplanet data.
- **Understanding Exoplanet Distribution:** To gain insights into the distribution of exoplanets in different parameter spaces. This involves plotting exoplanet data in various ways, such as mass vs. period, mass vs. semi-major axis, radius vs. period, and radius vs. semi-major axis.
- **Detection Limits:** To understand the detection limits of different detection techniques and the biases that these limits introduce in our understanding of exoplanets. This includes researching the state-of-the-art performance of different exoplanet detection techniques and plotting their sensitivity limits.
- **Detection Signals:** To understand the detection signal of representative cases such as a temperate Earth-like planet around a Sun-like star, a Jupiter-like planet around a Sun-like star, or a temperate Earth-like planet around an M-type star. The project compares these signals to the state-of-the-art performance in detecting exoplanets.
- In essence, the project is motivated by the desire to learn about exoplanets and the methods used to discover them, as well as to gain an understanding of the limitations and biases involved in exoplanet detection.

Methods

- The project utilizes several methods to explore exoplanet data and detection techniques.
- **Data Acquisition:** The project begins by using the NASA Exoplanet Archive (NEA) to download exoplanet data. The specific data file used is 'PS_2025.01.16_06.39.23.csv'. The data includes various parameters like planet mass ('pl_bmassj'), radius ('pl_radj'), orbital period ('pl_orbper'), and semi-major axis ('pl_orbsmax'), as well as the discovery method used.
- **Data Exploration and Visualization**:
    - The project uses the astropy.io.ascii library to read the data file. The column names are printed to understand the available data.
    - The data is visualized using matplotlib.pyplot. The project generates plots of:
        - Mass vs. Orbital Period
        - Mass vs. Semi-Major Axis
        - Radius vs. Orbital Period
        - Radius vs. Semi-Major Axis
        - Semi-Major Axis vs. Orbital Period
    - These plots use a log scale for both x and y axes.
- **Overplotting Solar System Planets**: The project includes data for the planets in our solar system (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune) including their orbital period, radius, mass and color. This data is used to overplot the solar system planets on the exoplanet plots, providing a familiar reference.

Methods

- **Calculating and Plotting Detection Sensitivity Limits**:
  - The project researches the state-of-the-art performance of different exoplanet detection techniques.
  - Sensitivity limits are calculated for various detection methods and are plotted against the exoplanet data. These include:
    - Transit method
    - Radial Velocity (RV) method
    - Microlensing
    - Direct Imaging
    - Astrometry
    - Disk Kinematics
    - Eclipsing Time Variations
    - Orbital Brightness Modulation
    - Pulsar Timing
    - Transit Timing Variations
  - The sensitivity is calculated using different equations for each method and is plotted as a line on the mass vs semi-major axis plots.
  - The sensitivity line represents a threshold: anything above the line is detectable using the corresponding method.

Methods

- **Calculating Detection Signal for a Representative Case**:
  - The project calculates the detection signal for a temperate Earth-like planet around a Sun-like star for each of the detection methods and overplots it on the mass vs semi-major axis plots
- **Python Libraries**: The project uses the following Python libraries:
  - numpy for numerical operations
  - matplotlib.pyplot for plotting
  - astropy.io.ascii for reading data files
  - astropy.units for handling physical units
  - astropy.constants for physical constants
  - google.colab for accessing Google Drive
- In summary, the methods involve downloading and exploring data, creating visualizations, and calculating the detection limits for different methods and comparing to the location of a temperate earth-like planet around a sun-like star, all of which is done using Python.

Equations

- The project uses several equations to calculate the sensitivity limits of different exoplanet detection methods. Here's a breakdown of each equation and its purpose, along with explanations of the variables used:
- **Astrometry Sensitivity**: This equation calculates the mass sensitivity for the astrometry method.
  - Equation: **M_p = (delta_theta * distance * M_star / sma_arr).decompose()**
    - M_p: Mass sensitivity of the planet.
    - delta_theta: Angular displacement (1 microarcsecond).
    - distance: Distance to the star (10 parsecs).
    - M_star: Stellar mass (0.5 solar mass).
    - sma_arr: Array of semi-major axes.
  - m_p_a_arr = M_p converted to earth masses with equivalencies for dimensionless angles
  - Explanation: This equation calculates the minimum planetary mass that can be detected via astrometry, based on the angular displacement, distance to the star, stellar mass and the semi-major axis.

Equations

- **Microlensing Sensitivity**: This equation calculates the mass sensitivity for the microlensing method.
    - Equation: **m_p_ml_arr = 1 * u.earthMass / sma_arr.value**
        - m_p_ml_arr: Mass sensitivity of the planet in Earth masses.
        - sma_arr: Array of semi-major axes.
    - Explanation: This equation determines the minimum planetary mass that can be detected via microlensing, based on the semi-major axis.
- **Radial Velocity (RV) Sensitivity**: This equation calculates the mass sensitivity for the radial velocity method.
    - Equation: **m_p_arr = 0.5 * u.meter / u.second * 0.5 * u.solMass * np.sqrt(sma_arr / ac.G / (0.5 * u.solMass))**
        - m_p_arr: Mass sensitivity of the planet in kg, converted to Earth masses in the plot.
        - sma_arr: Array of semi-major axes.
        - ac.G: Gravitational constant.
    - Explanation: This equation estimates the minimum planetary mass that can be detected via the radial velocity method, based on the semi-major axis, stellar mass and the velocity sensitivity.

Equations

- **Direct Imaging Sensitivity**: This equation calculates the mass sensitivity for the direct imaging method.
    - Equation: m_p_di_arr = (sma_arr / (10 * u.AU))**2 * u.jupiterMass**
        - m_p_di_arr: Mass sensitivity of the planet in Jupiter masses, converted to earth masses in the plot.
        - sma_arr: Array of semi-major axes.
    - Explanation: This equation estimates the minimum planetary mass that can be detected through direct imaging based on the semi-major axis and assuming a sensitivity of 10 AU.
- **Disk Kinematics Sensitivity**: This equation calculates the mass sensitivity for the disk kinematics method.
    - Equation: **M_p = delta_v * M_star * np.sqrt(sma_arr / (ac.G * M_star)).decompose()**
        - M_p: Mass sensitivity of the planet.
        - delta_v: Velocity sensitivity (1 m/s).
        - M_star: Stellar mass (0.5 solar mass).
        - sma_arr: Array of semi-major axes.
        - m_p_dk_arr: M_p converted to Earth masses.
    - Explanation: This equation calculates the minimum planetary mass detectable using disk kinematics based on the velocity sensitivity, stellar mass, and semi-major axis.

Equations

- **Pulsation Timing Variations Sensitivity:** This equation calculates the mass sensitivity for the Pulsation Timing Variation method.
  - Equation: **m_p_ptv_arr = ((delta_t / P_pulse * M_star * (sma_arr / u.AU)) * u.dimensionless_unscaled).decompose().to(u.earthMass)**.
    - m_p_ptv_arr: This represents the array of planet masses that can be detected using the Pulsation Timing Variations method. The unit is in Earth masses.
    - delta_t: This is the pulse period variation, or the change in the timing of the star's pulsations. It is given as 1e-6 seconds.
    - P_pulse: This is the period of the star's pulsation. It is given as 1 second.
    - M_star: Represents the mass of the star. In this case, it appears to be 0.5 or 1 solar mass depending on where it is being used in the code.
    - sma_arr: This is the array of semi-major axes, which is the average distance between the planet and the star. The unit is in AU.
  - Explanation: This equation estimates the mass of a planet that could cause a detectable variation in a star's pulsation period, based on the timing precision, pulsation period of the star, stellar mass and semi-major axis of the planet.
- **Eclipsing Time Variations Sensitivity**: This equation calculates the mass sensitivity for the eclipsing time variations method.
  - Equation: **m_p_etv_arr = (delta_t / P_binary * M_star * (sma_arr / (1*u.AU))**(3/2)).decompose().to(u.earthMass)**
    - m_p_etv_arr: Mass sensitivity of the planet, in Earth masses.
    - delta_t: Timing precision (1 second).
    - P_binary: Binary period (10 days).
    - M_star: Stellar mass (0.5 solar mass).
    - sma_arr: Array of semi-major axes.
  - Explanation: This equation calculates the minimum planetary mass detectable using eclipsing time variations based on timing precision, binary period, stellar mass and semi-major axis.

Equations

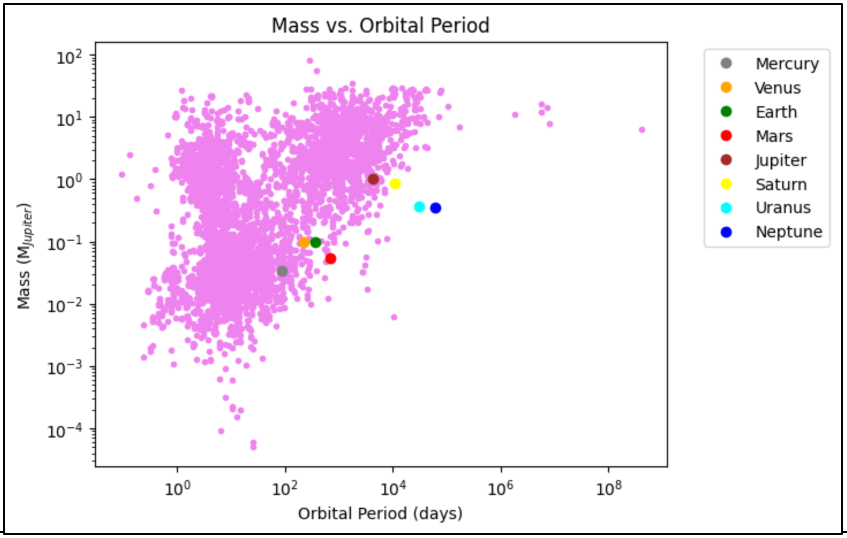
- **Orbital Brightness Modulation Sensitivity**: This equation calculates the mass sensitivity for the orbital brightness modulation method.
  - Equation: **m_p_obm_arr = (F_obs * M_star * sma_arr / u.AU).decompose().to(u.earthMass)**
    - m_p_obm_arr: Mass sensitivity of the planet, in Earth masses.
    - F_obs: Observed flux variation (1e-6).
    - M_star: Stellar mass (0.5 solar mass).
    - sma_arr: Array of semi-major axes.
  - Explanation: This equation calculates the minimum planetary mass detectable using orbital brightness modulation, based on the observed flux variation, stellar mass and semi-major axis.
- **Pulsar Timing Sensitivity**: This equation calculates the mass sensitivity for the pulsar timing method.
  - Equation: **m_p_pt_arr = (delta_t / P_pulse * M_star * (sma_arr / (1 * u.AU))**(3/2)).decompose().to(u.earthMass)**
    - m_p_pt_arr: Mass sensitivity of the planet, in Earth masses.
    - delta_t: Timing precision (1 microsecond).
    - P_pulse: Pulsar period (1 second).
    - M_star: Stellar mass (0.5 solar mass).
    - sma_arr: Array of semi-major axes.
  - Explanation: This equation calculates the minimum planetary mass detectable using pulsar timing, based on the timing precision, pulsar period, stellar mass and semi-major axis.

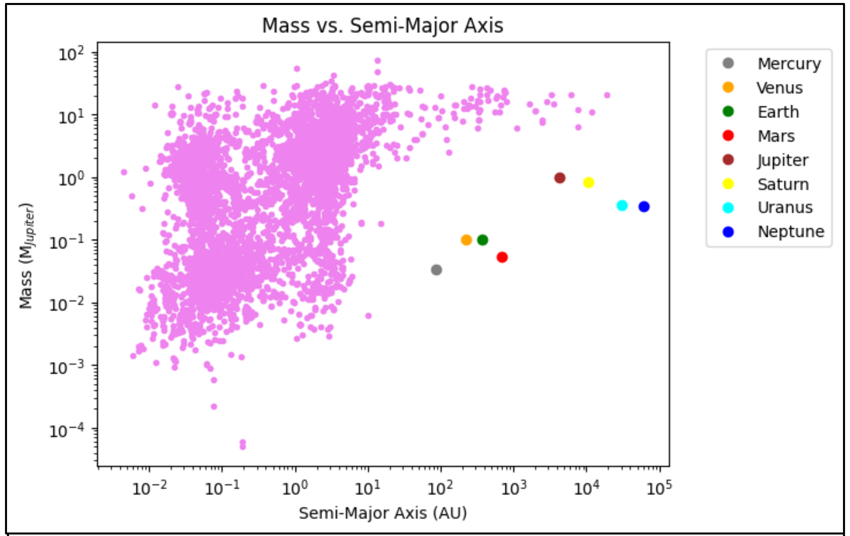
Equations

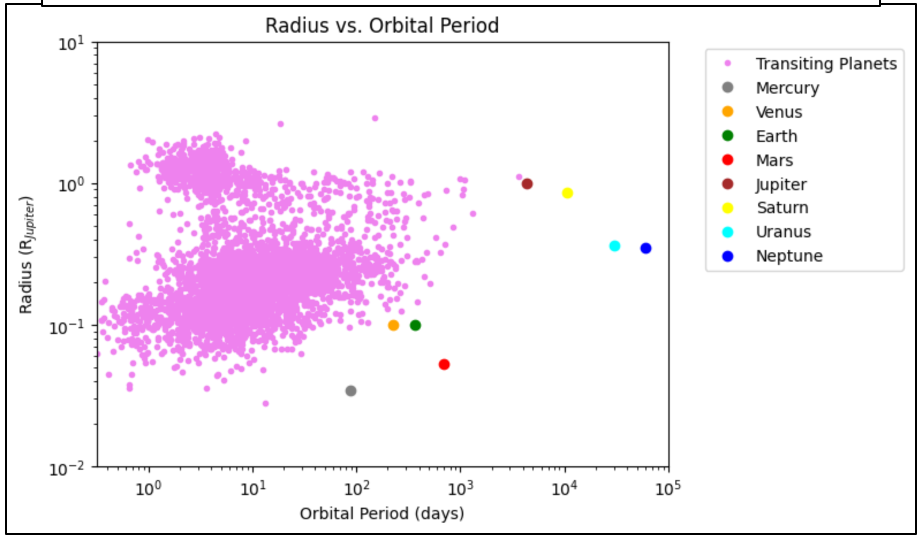
- **Transit Sensitivity**: This equation determines the radius sensitivity for the transit method.
  - Equation: **r_p_arr = np.sqrt(3 * np.sqrt(p_arr / T)) * u.earthRad**
    - r_p_arr: Radius sensitivity of the planet, in Earth radii.
    - p_arr: Array of orbital periods.
    - T: Total observation time (1 year).
  - Explanation: This equation calculates the minimum planetary radius that can be detected via the transit method for a given orbital period, based on the total observation time.
- **Transit Timing Variations Sensitivity**: This equation calculates the mass sensitivity for the transit timing variations method.
  - Equation: **P_transit = np.sqrt((4 * np.pi**2 * sma_arr**3) / (G * M_star))** and **m_p_ttv_arr = (delta_t / P_transit * M_star).to(u.earthMass)**
    - m_p_ttv_arr: Mass sensitivity of the planet, in Earth masses.
    - delta_t: Transit timing deviation (1 second).
    - P_transit: Orbital period in seconds.
    - M_star: Stellar mass (0.5 solar mass).
    - sma_arr: Array of semi-major axes.
    - G: Gravitational constant
  - Explanation: This equation calculates the minimum planetary mass detectable using transit timing variations based on the timing deviation, the orbital period, and the stellar mass.
- These equations are used to generate the sensitivity curves plotted on the various graphs, which are compared to the location of discovered exoplanets, and a temperate earth-like planet orbiting a sun-like star. The sensitivity lines show the theoretical limits of each detection method.

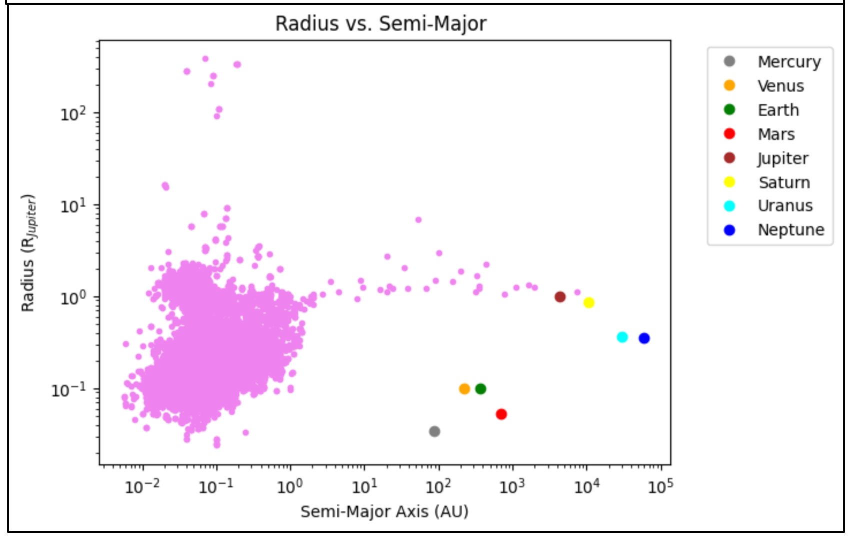
Results

Distribution of Exoplanets in Different Parameter Spaces with Solar System Overplot





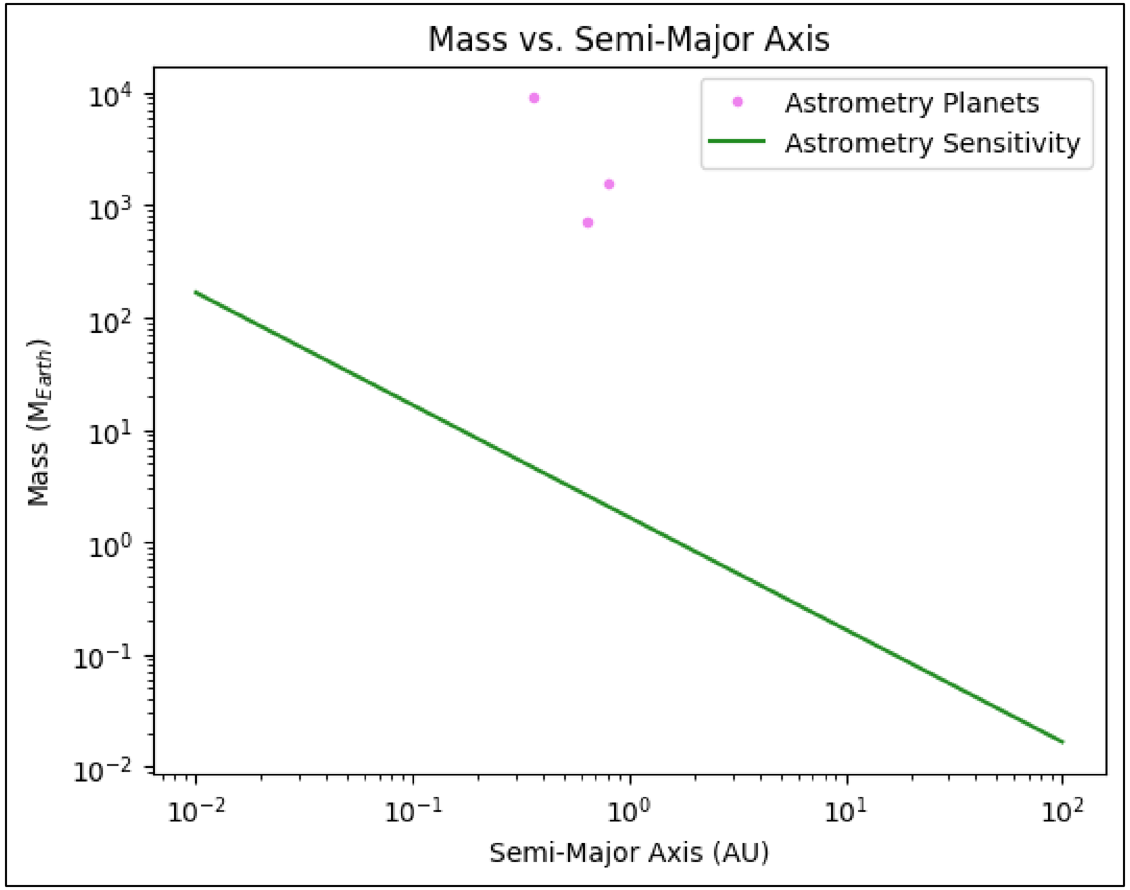




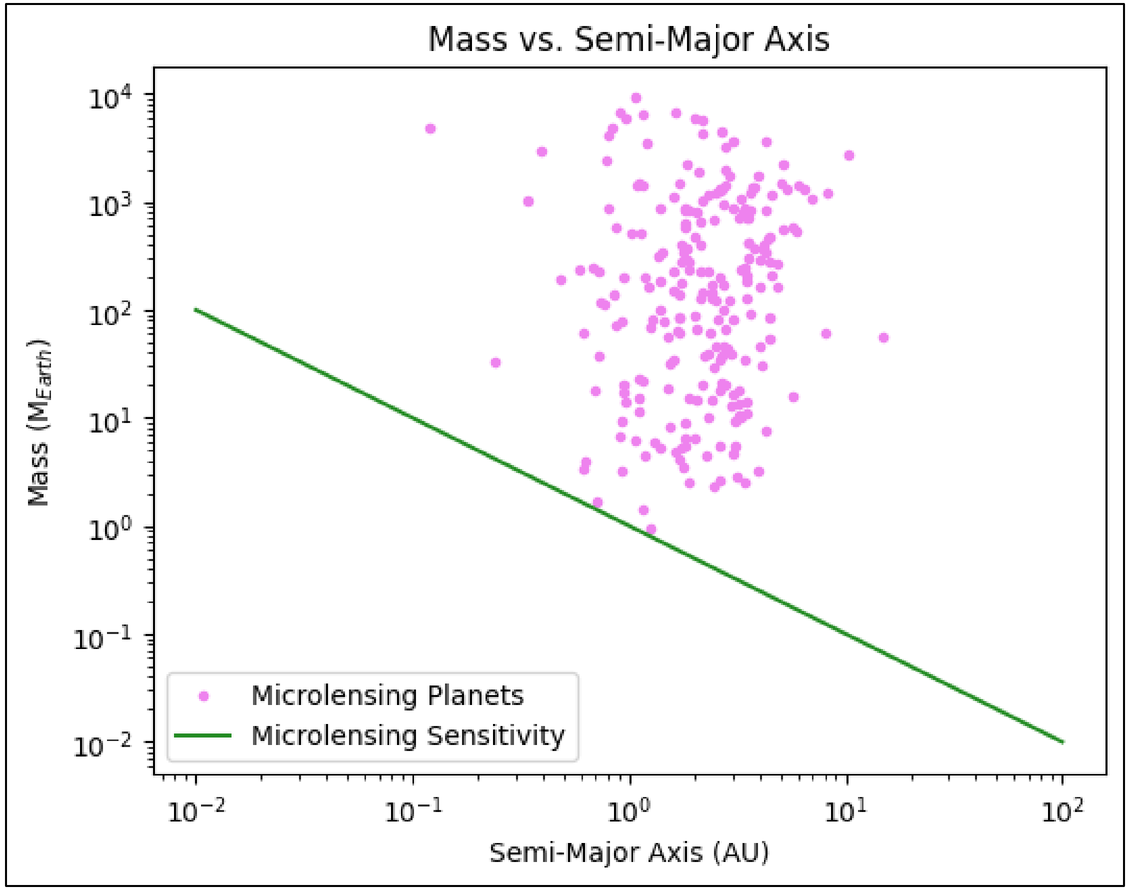
Results

Performance of Different Exoplanet Detection Techniques and their Sensitivity Limit

Astrometry



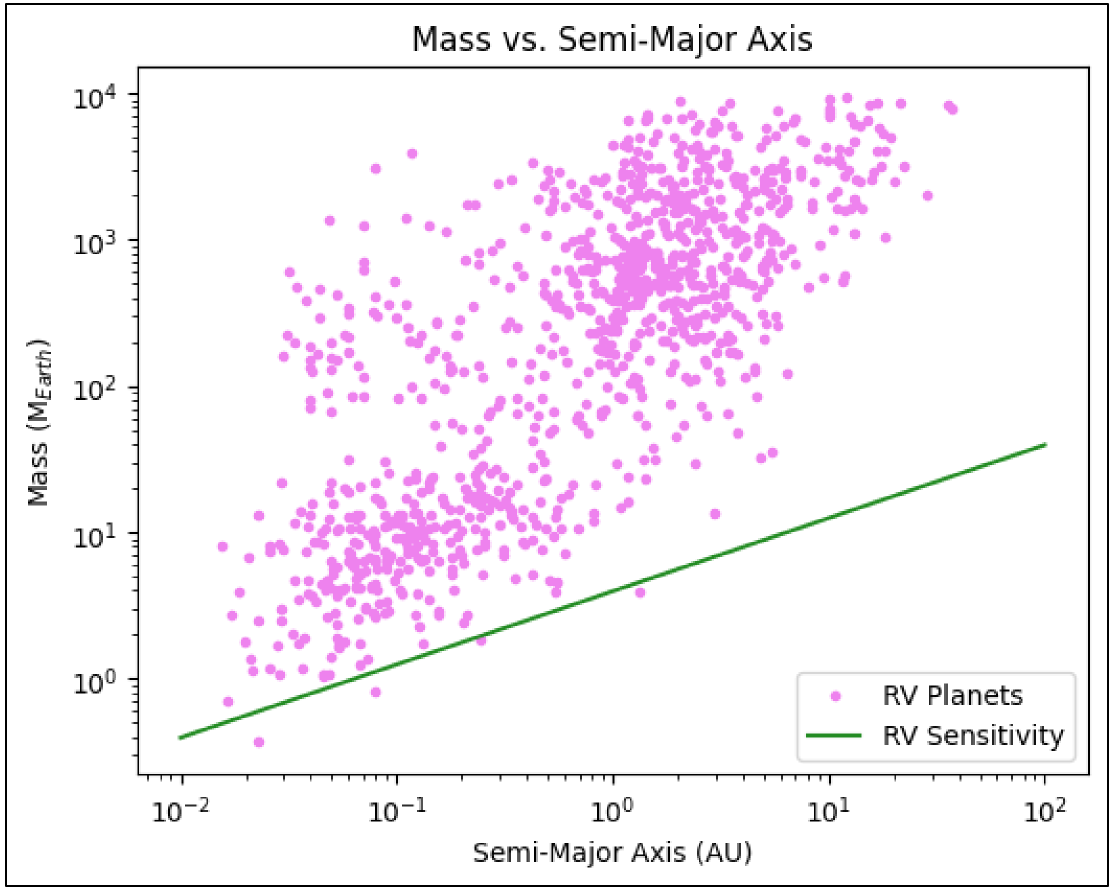
Microlensing



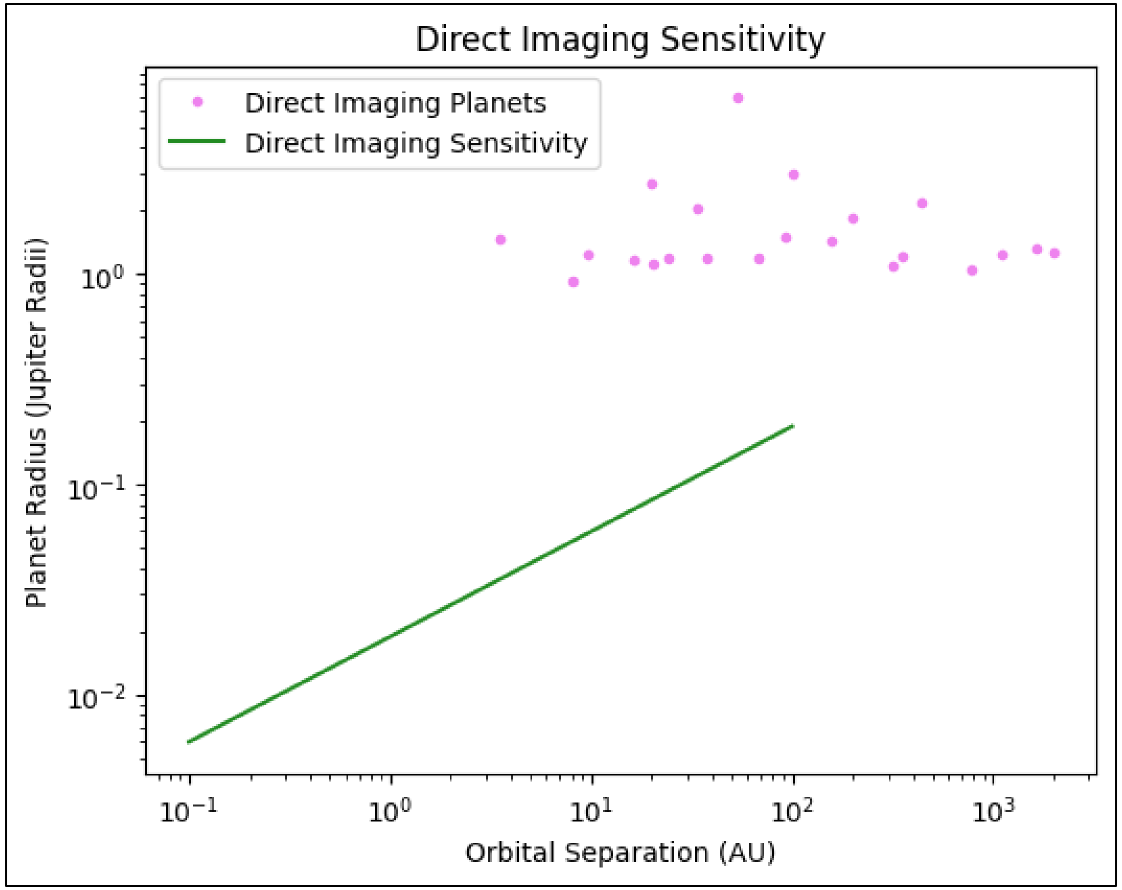
Results

Performance of Different Exoplanet Detection Techniques and their Sensitivity Limit

Radial Velocity



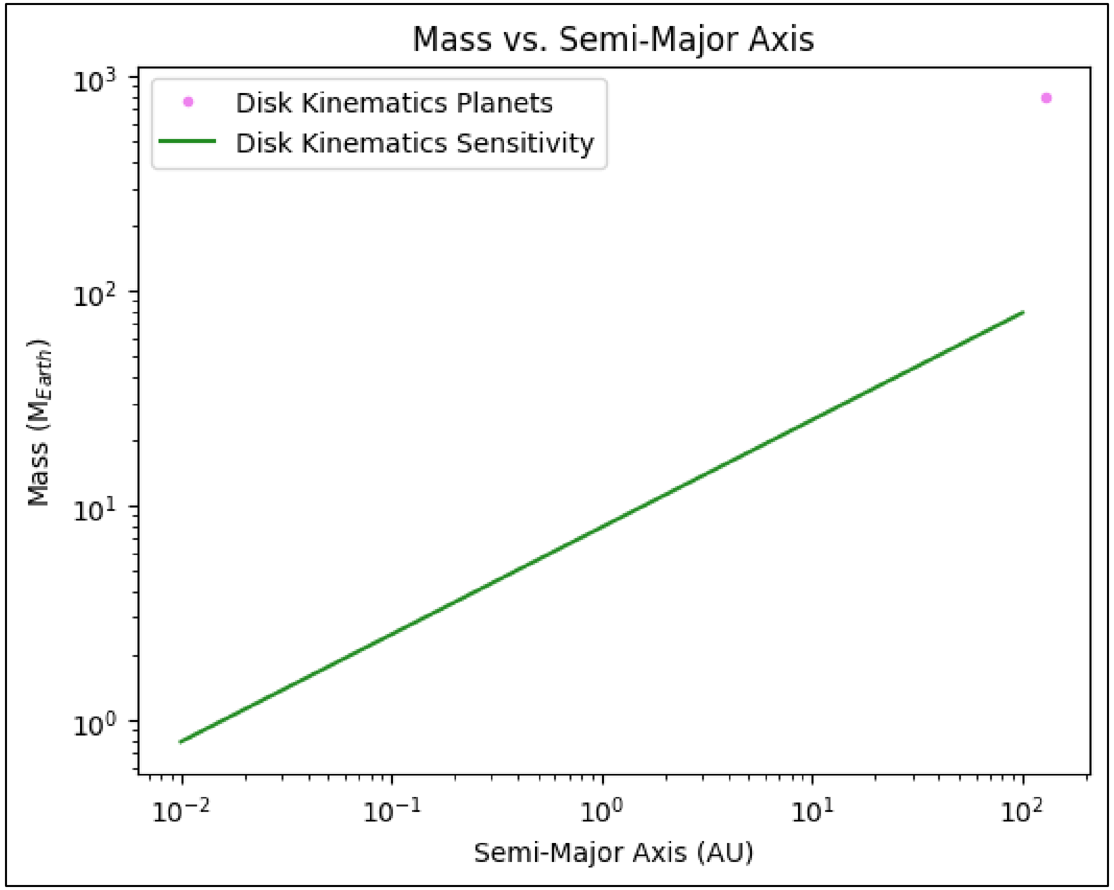
Direct Imaging



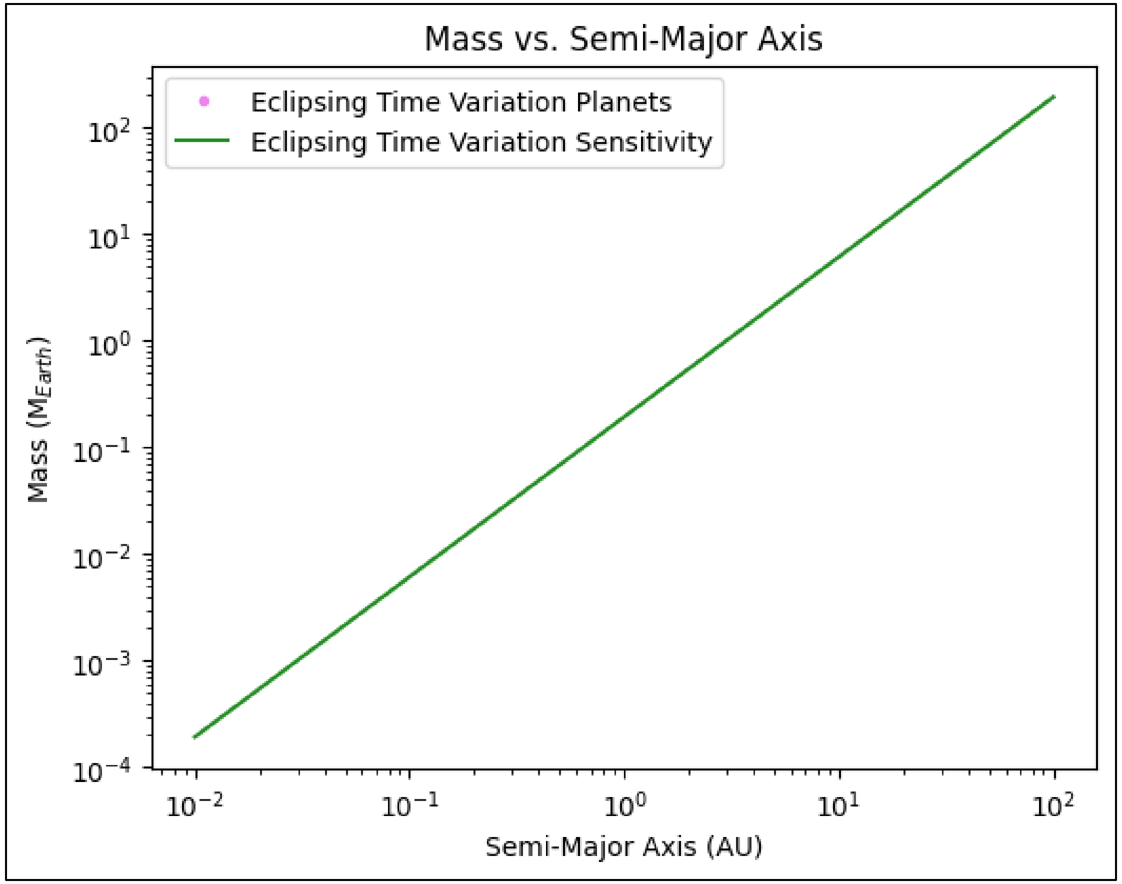
Results

Performance of Different Exoplanet Detection Techniques and their Sensitivity Limit

Disk Kinematics



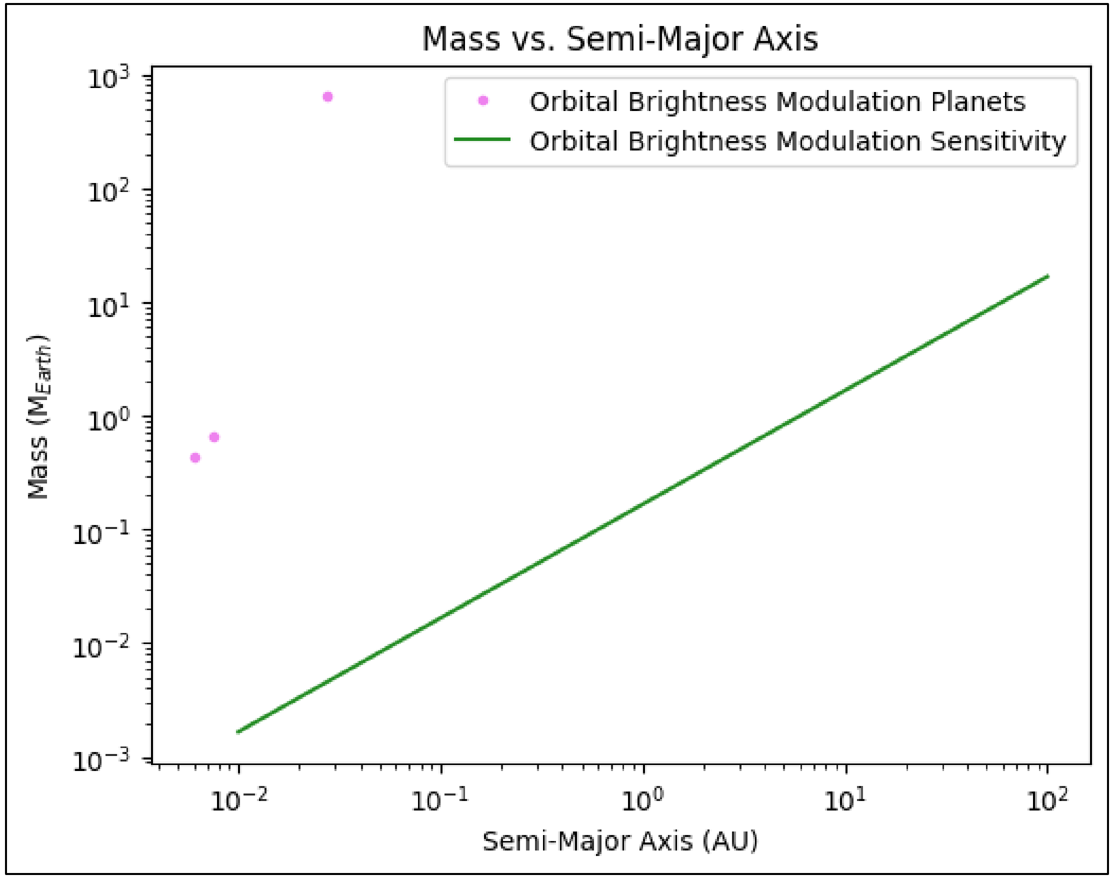
Eclipsing Time Variations



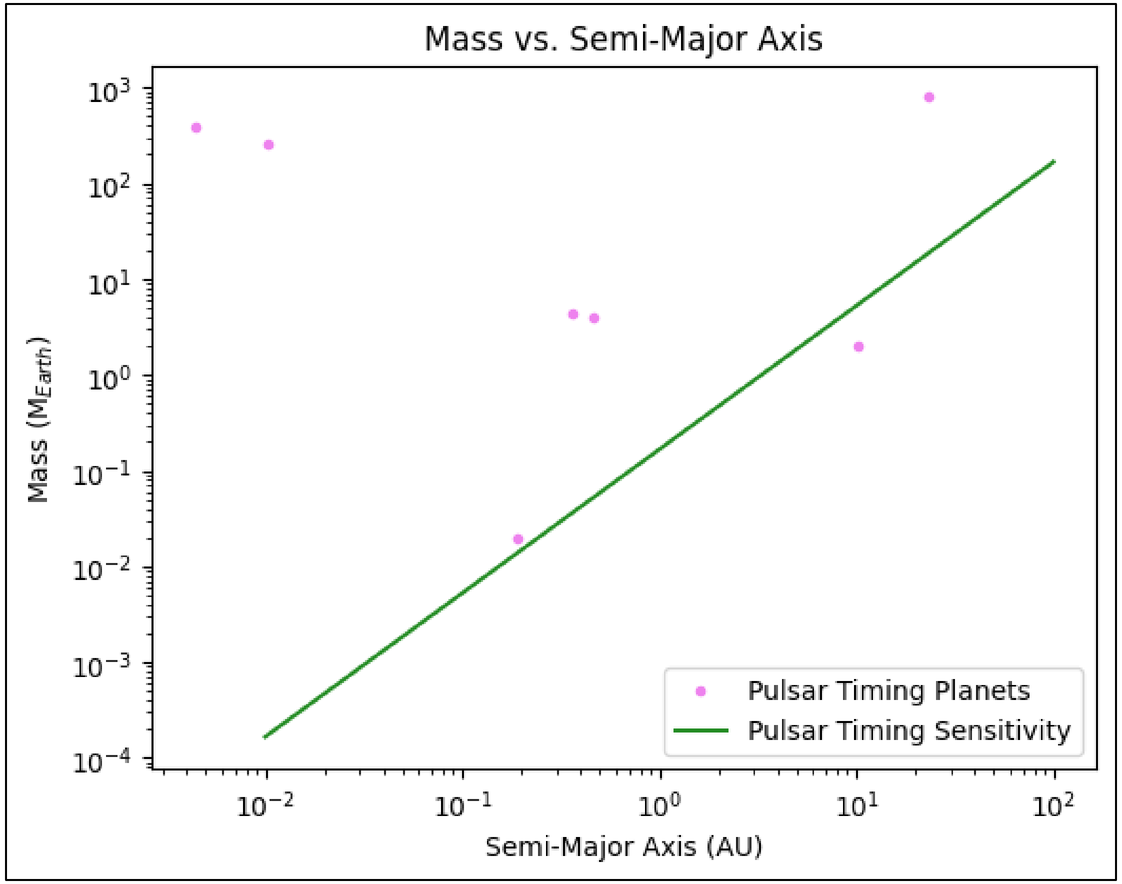
Results

Performance of Different Exoplanet Detection Techniques and their Sensitivity Limit

Orbital Brightness Modulation



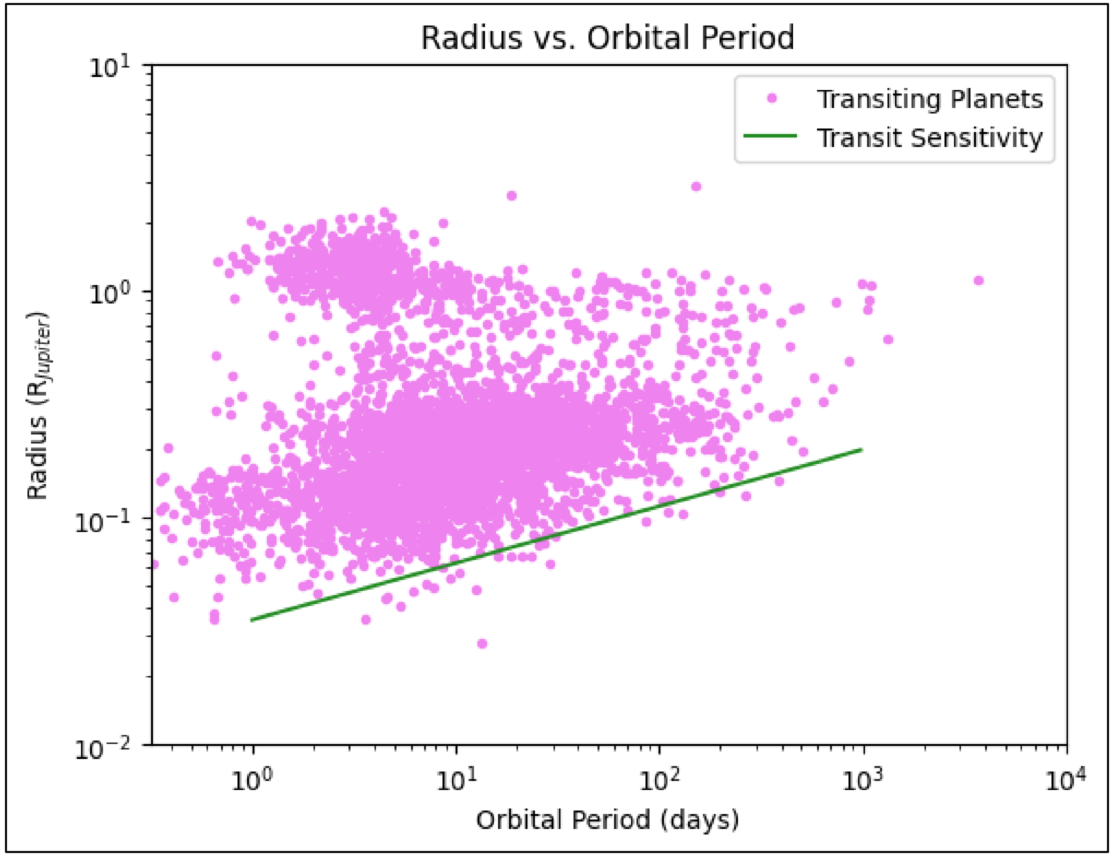
Pulsar Timing



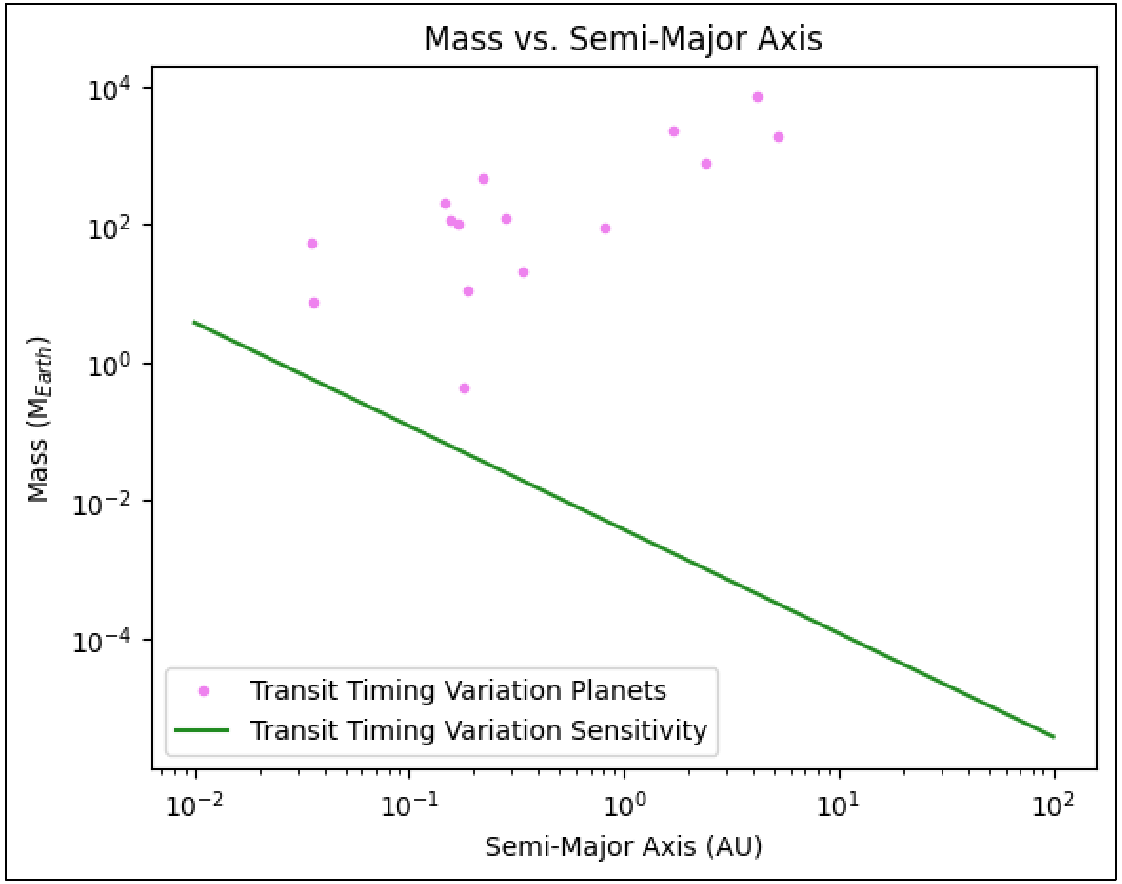
Results

Performance of Different Exoplanet Detection Techniques and their Sensitivity Limit

Transit



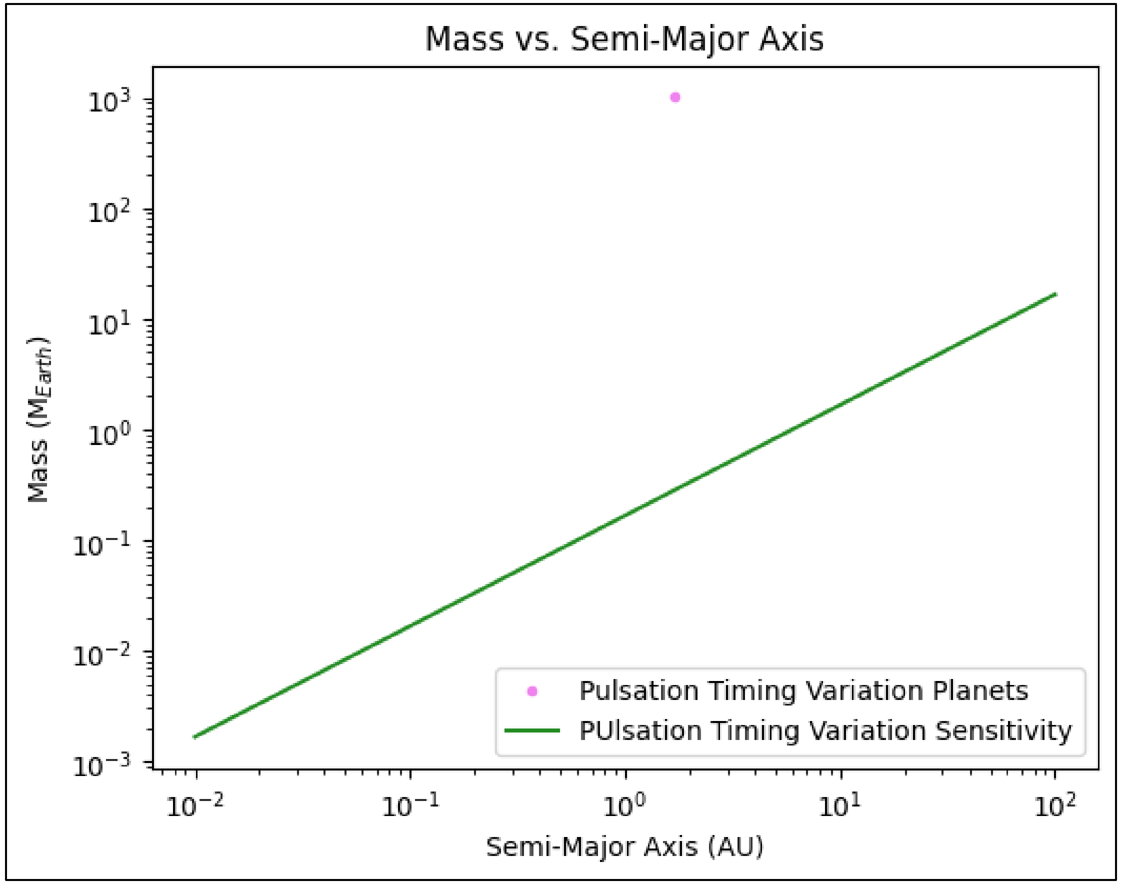
Transit Timing Variations



Results

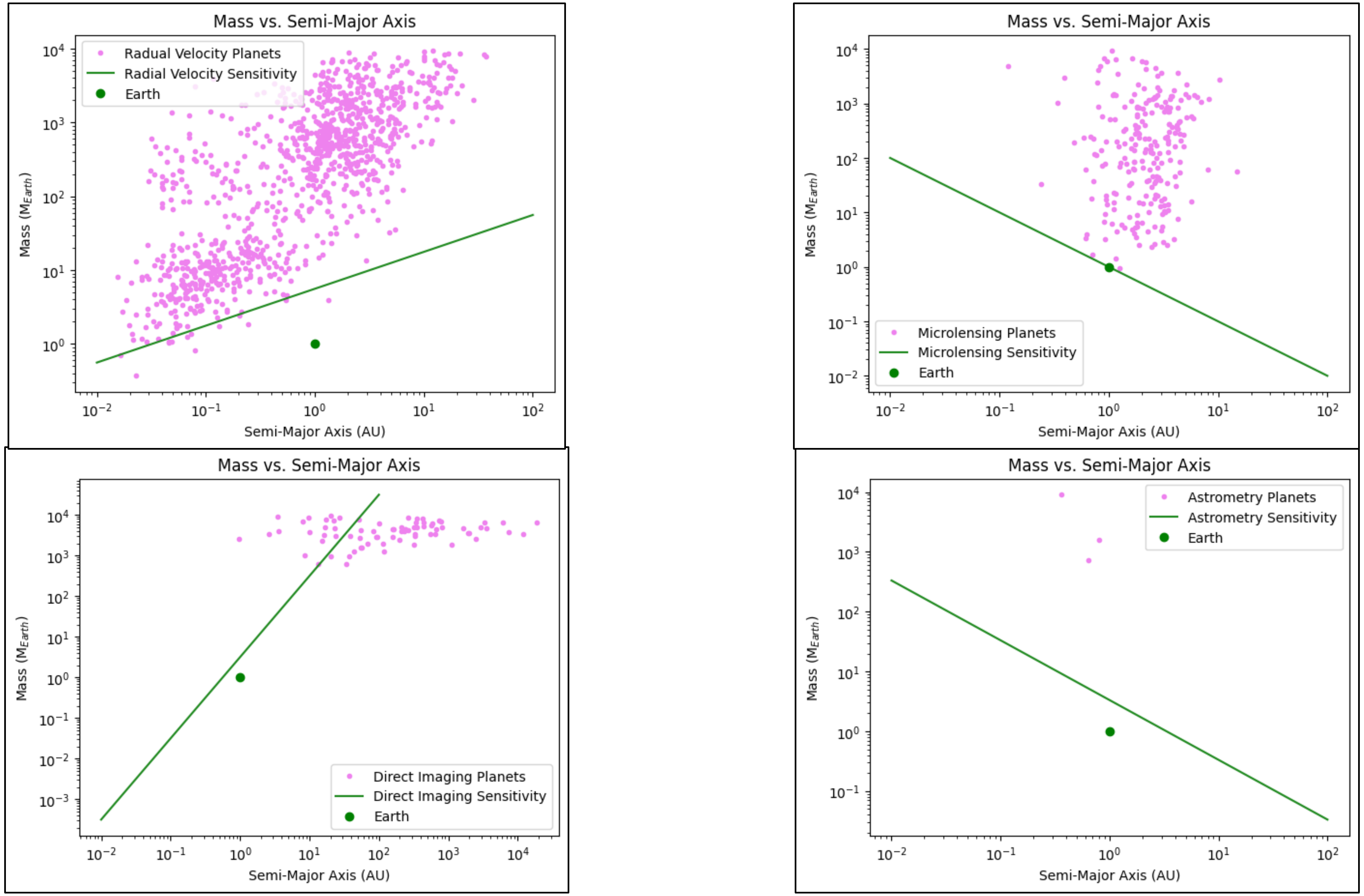
Performance of Different Exoplanet Detection Techniques and their Sensitivity Limit

Pulsation Timing Variations



Results

Detection signal of a Representative Case for a Temperate Earth-like Planet Around a Sun-like Star



Conclusion

Summary of Key Findings

- **Exoplanet Distributions:** The mass vs. period, mass vs. semi-major axis, radius vs. period, and radius vs. semi-major axis plots revealed clustering in specific regions, highlighting observational biases and the prevalence of certain types of exoplanets.
- **Correlation Between Semi-Major Axis and Orbital Period:** The strong correlation between these parameters was evident in the similarities between their respective plots, confirming expectations based on Kepler's laws.
- **Detection Sensitivity Limits and Selection Bias:** Sensitivity lines for various detection techniques (transit, radial velocity, microlensing, direct imaging, and others) demonstrated the threshold above which exoplanets can be detected. These limits reinforce that our current technology is biased toward detecting large, short-period planets while missing many smaller, long-period planets.
- **Solar System Comparison:** When we overplotted the solar system planets on the exoplanet distributions, they barely appeared near the rest of the data points. This highlights the extent of selection bias in our detection methods. We have barely begun to discover exoplanets like those in our own solar system. The fact that our planetary system does not align well with the detected exoplanet population suggests that there may be many more undiscovered exoplanets that our current methods are unable to detect.
- **Representative Case Analysis – Earth-like Planet Detection:** When we plotted an Earth-like planet around a Sun-like star against different detection methods, it fell below the sensitivity limits for almost all of them. This means that, with current technology, Earth-like planets are largely undetectable. This finding strongly suggests that there could be a vast number of terrestrial, potentially habitable planets that remain undiscovered simply because our detection methods are not yet sensitive enough to find them.

Conclusion

Implications and Conclusions

- The fact that the solar system planets and Earth-like planets are mostly below detection limits reinforces the idea that our exoplanet discoveries are heavily shaped by technological limitations. Current detection methods favor the discovery of large, short-period planets, leaving many smaller, potentially habitable planets undetected.
- Future improvements in detection methods, such as more sensitive telescopes and longer observation periods, will be necessary to detect Earth-like planets more effectively. Missions like the James Webb Space Telescope (JWST) and next-generation observatories will help address these limitations.
- This project has provided a deeper understanding of exoplanet data, detection techniques, and the challenges of exoplanet discovery. It underscores the fact that our current exoplanet catalog represents only a fraction of the total exoplanet population that exists in the universe.

By exploring exoplanet distributions, detection sensitivities, and observational biases, this project has provided valuable insights into how we discover and study worlds beyond our solar system. The fact that Earth-like planets remain largely undetectable due to selection bias highlights a major frontier in exoplanet research. As technology advances, we will gain a clearer picture of the diversity of planetary systems and move closer to answering fundamental questions about habitability and the potential for life beyond Earth.