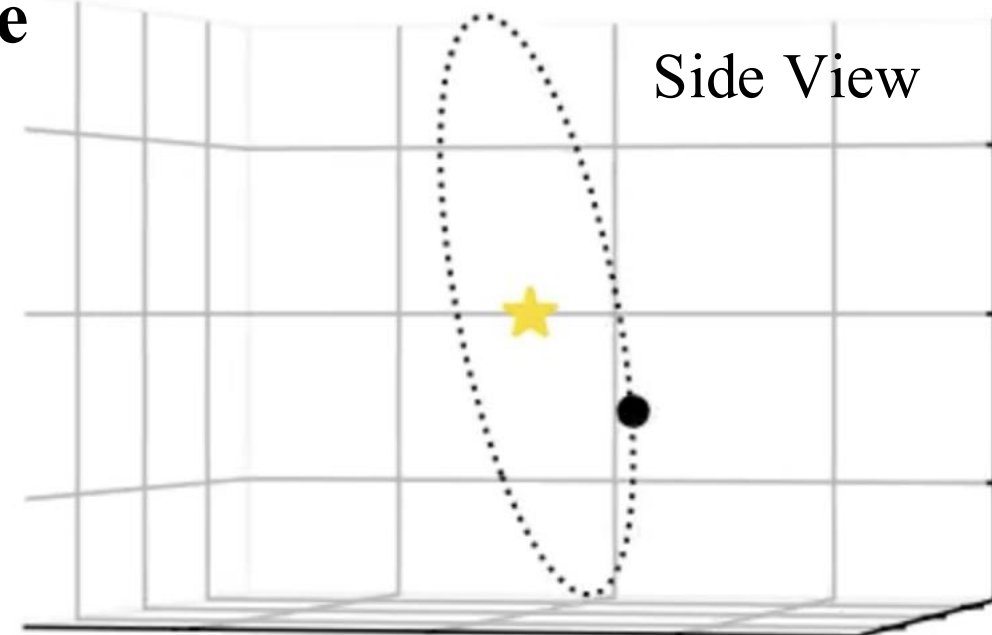
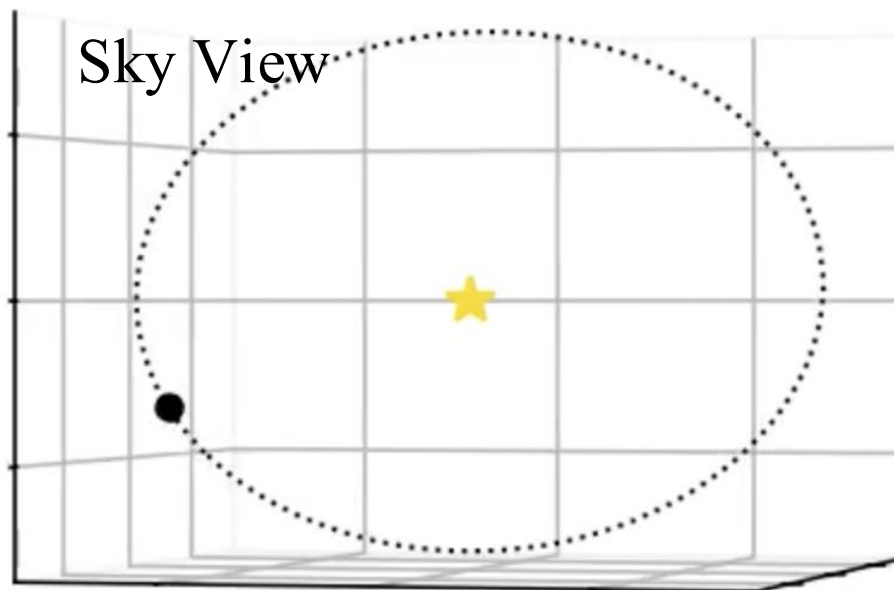




University of
Southern
Queensland

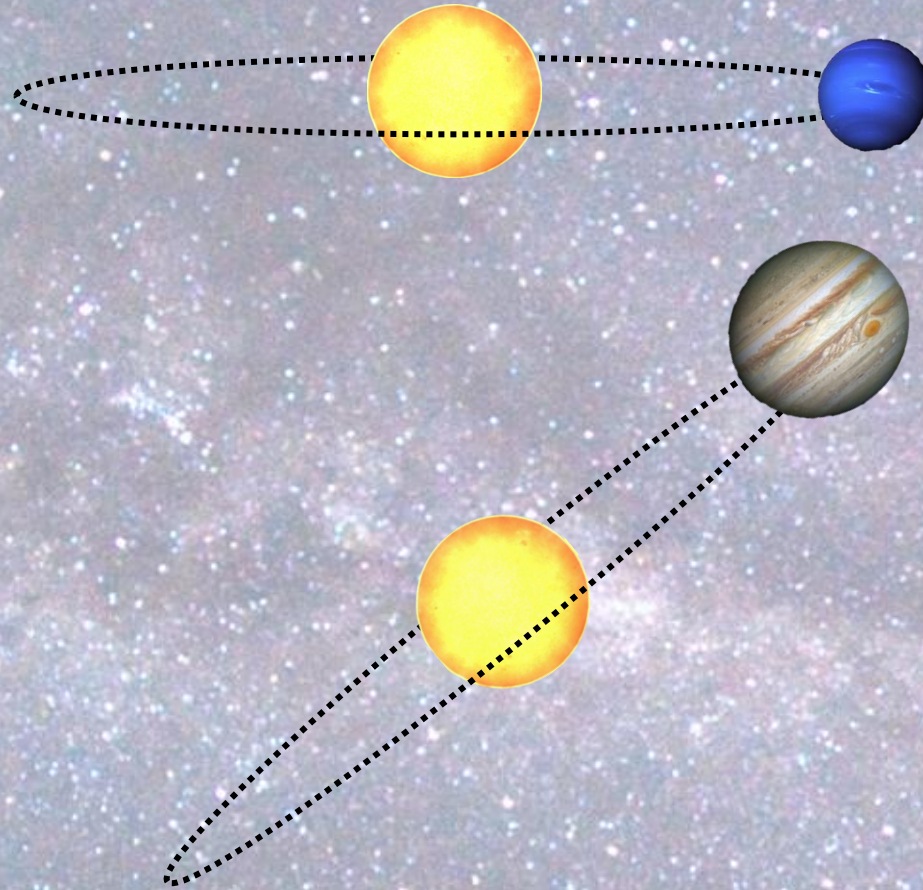
Characterising Planetary Systems in 3-D

Alex Wallace

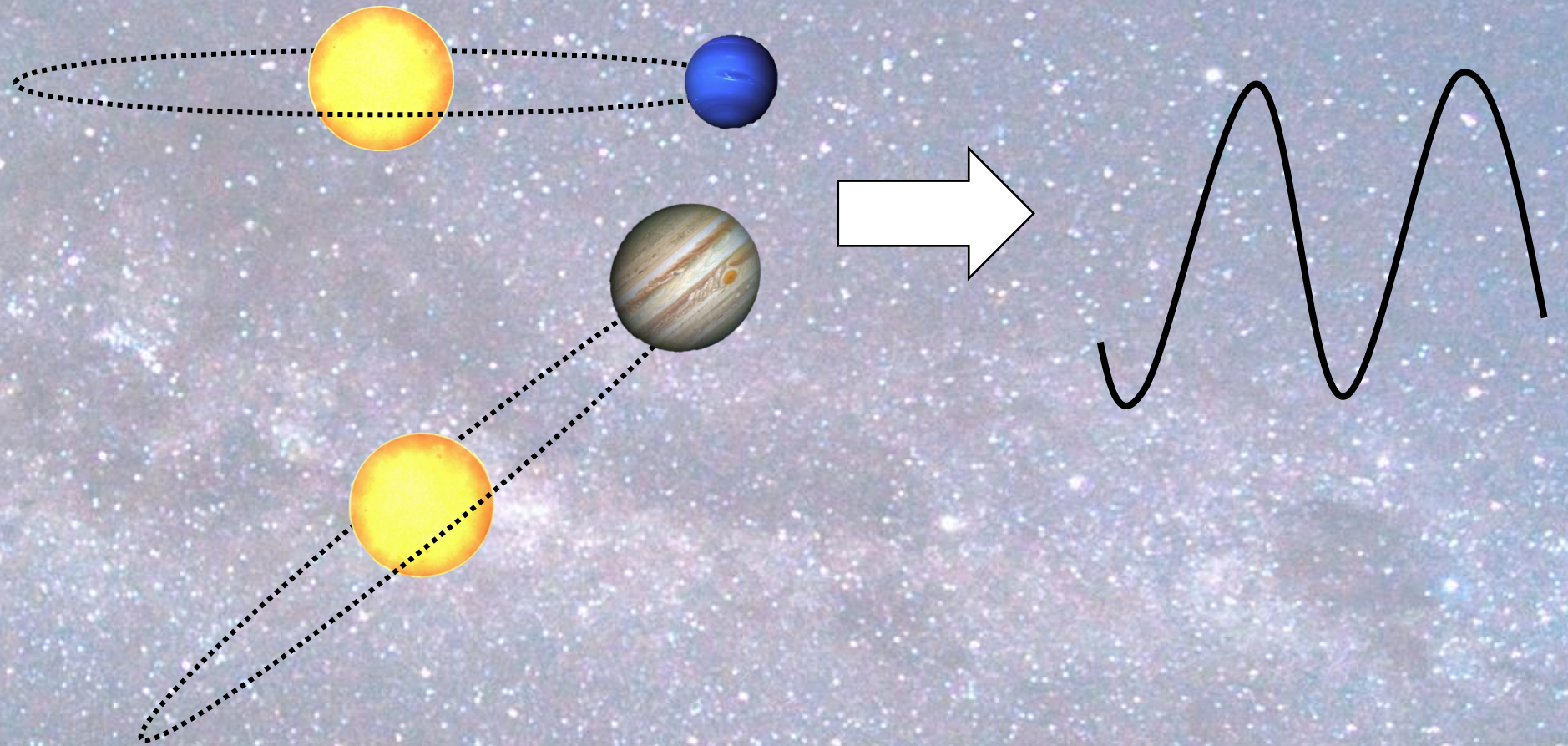


with Rob Wittenmyer & Jonti Horner

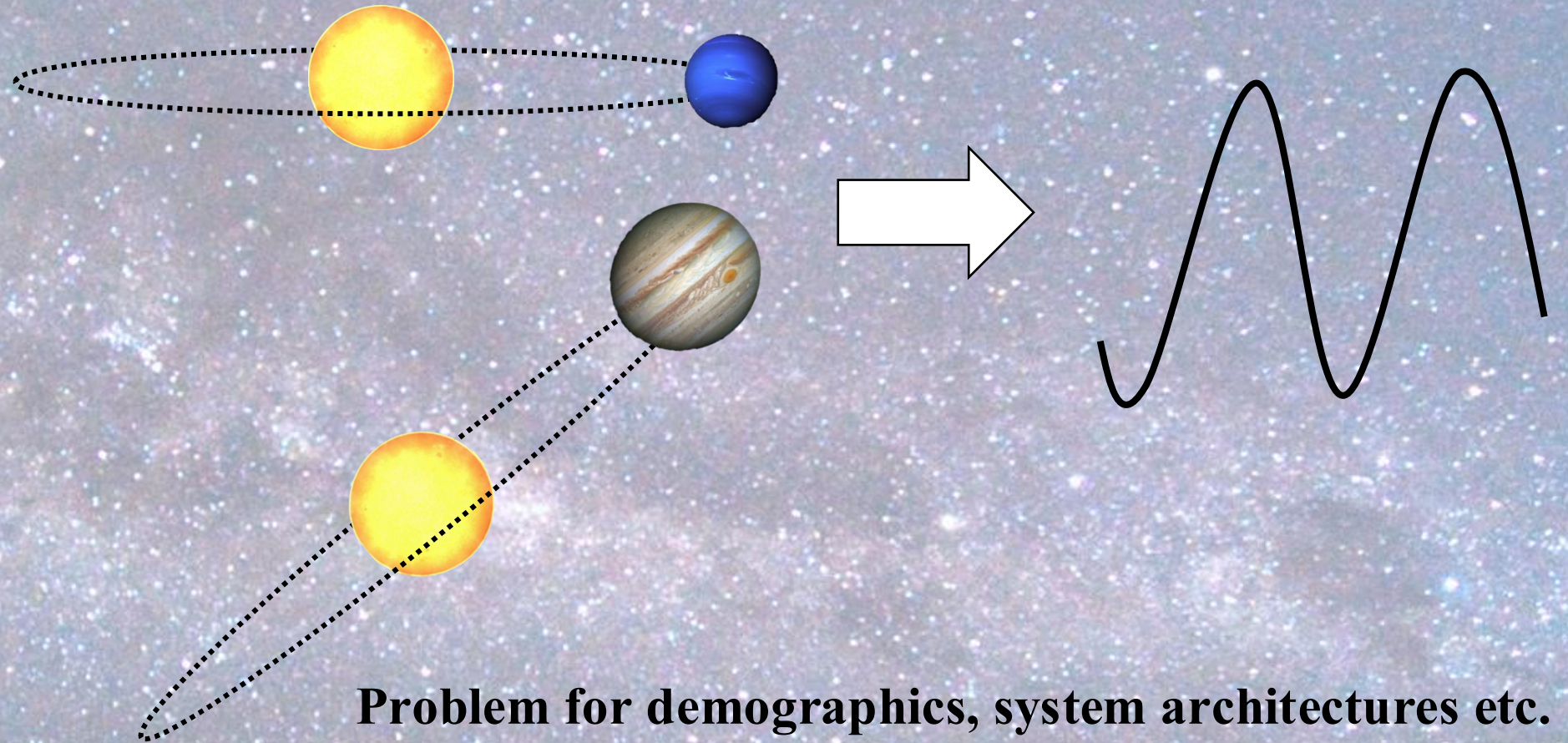
Mass-Inclination Problem



Mass-Inclination Problem



Mass-Inclination Problem



Our Goals

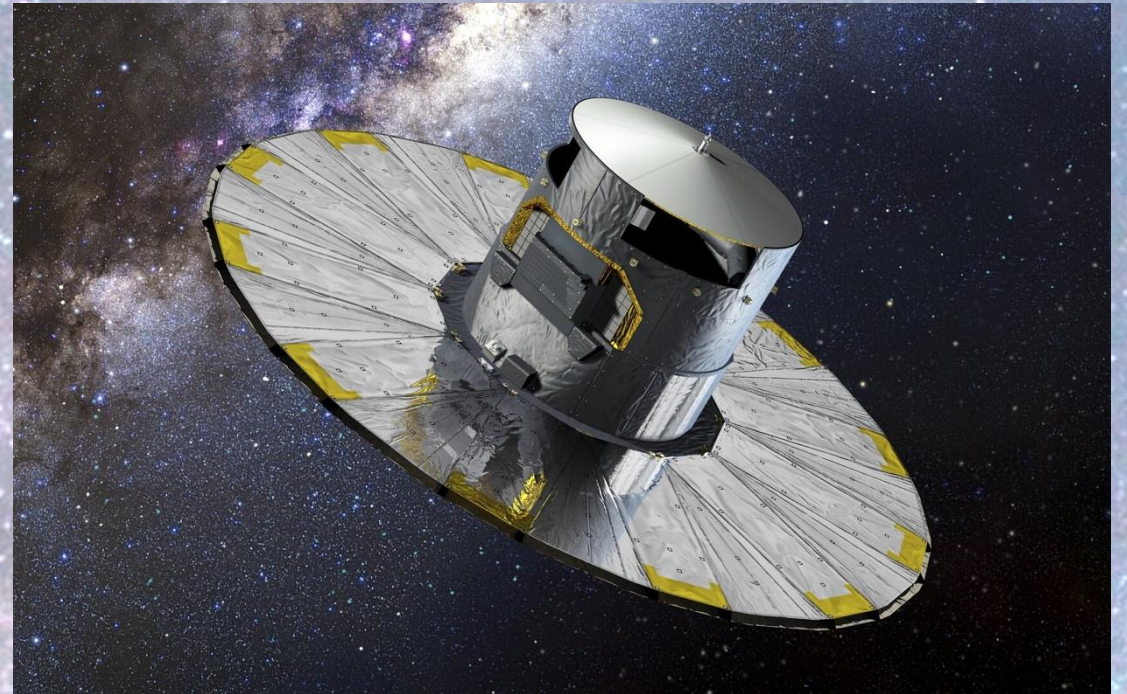
RV

Anglo-Australian Planet Search

~long term RV Study
(Wittenmyer et al.)



Astrometry



What We Can Do Now



What We Can Do Now

Gaia DR3

Renormalised Unit Weight Error:

$$\text{RUWE} = \sqrt{\sum \frac{(x_{AL} - x_0)^2}{\sigma^2 (N - 5)}}$$

Difference between data and fit

Astrometric uncertainty

Number of observations

Sensitive to Gaia's Baseline

What We Can Do Now

Gaia DR3

Renormalised Unit Weight Error:

$$\text{RUWE} = \sqrt{\sum \frac{(x_{AL} - x_0)^2}{\sigma^2 (N-5)}}$$

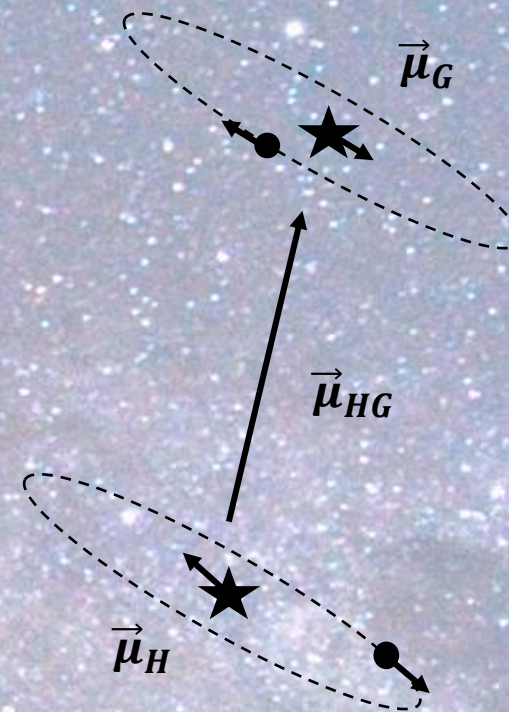
Difference between data and fit

Astrometric uncertainty

Number of observations

Sensitive to Gaia's Baseline

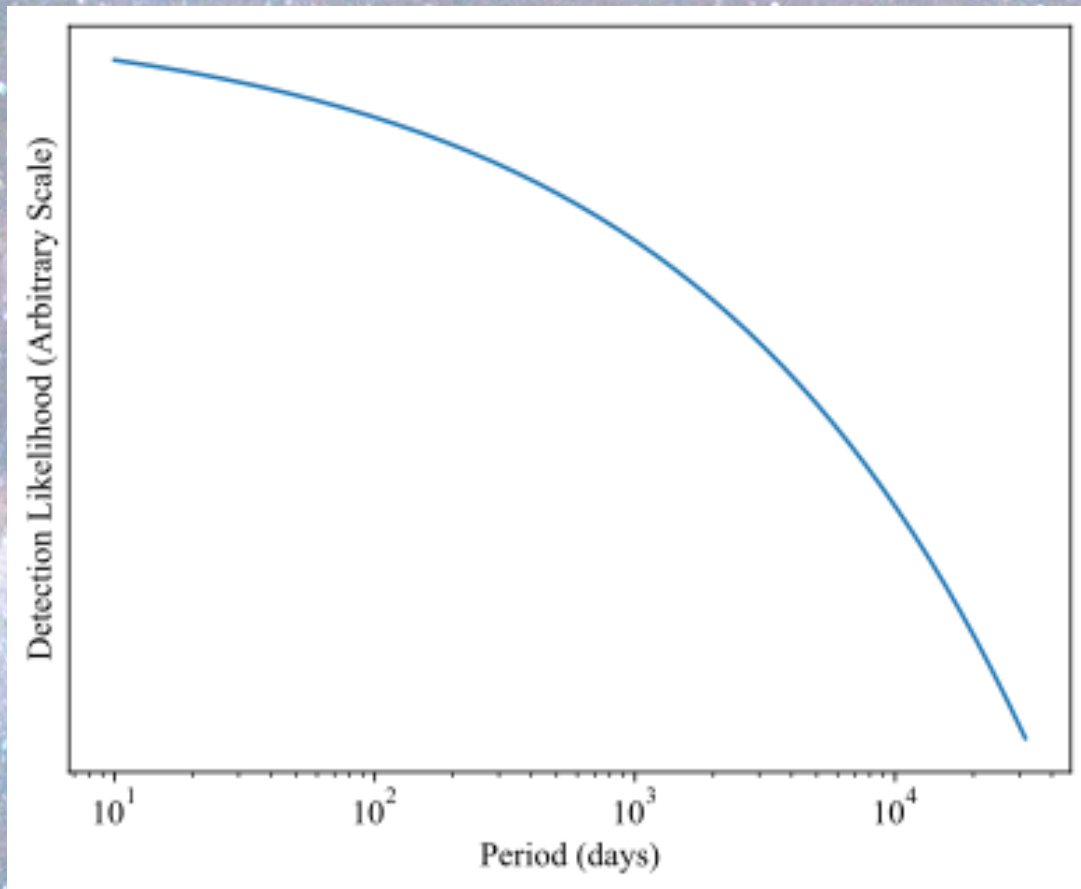
Proper Motion Anomaly (Hipparcos-Gaia)



Sensitive to Longer Periods

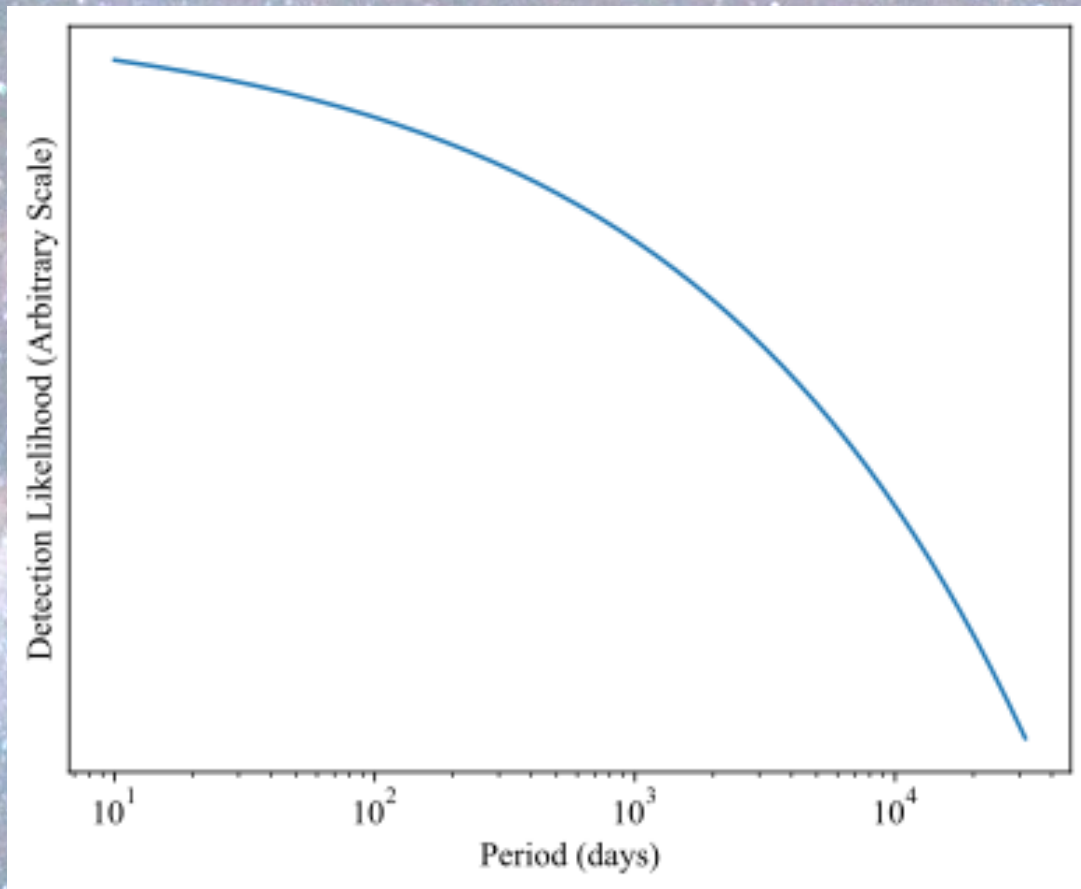
Types of Planets

Radial Velocity



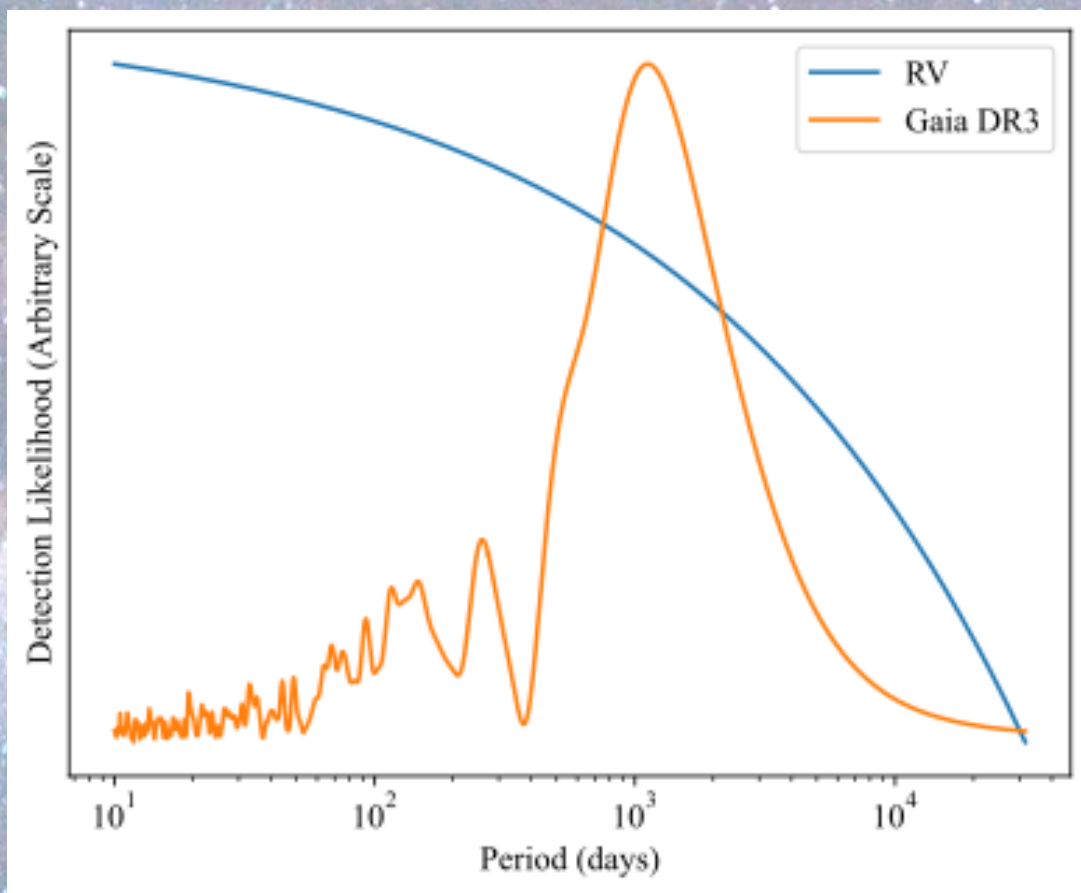
Types of Planets

Radial Velocity



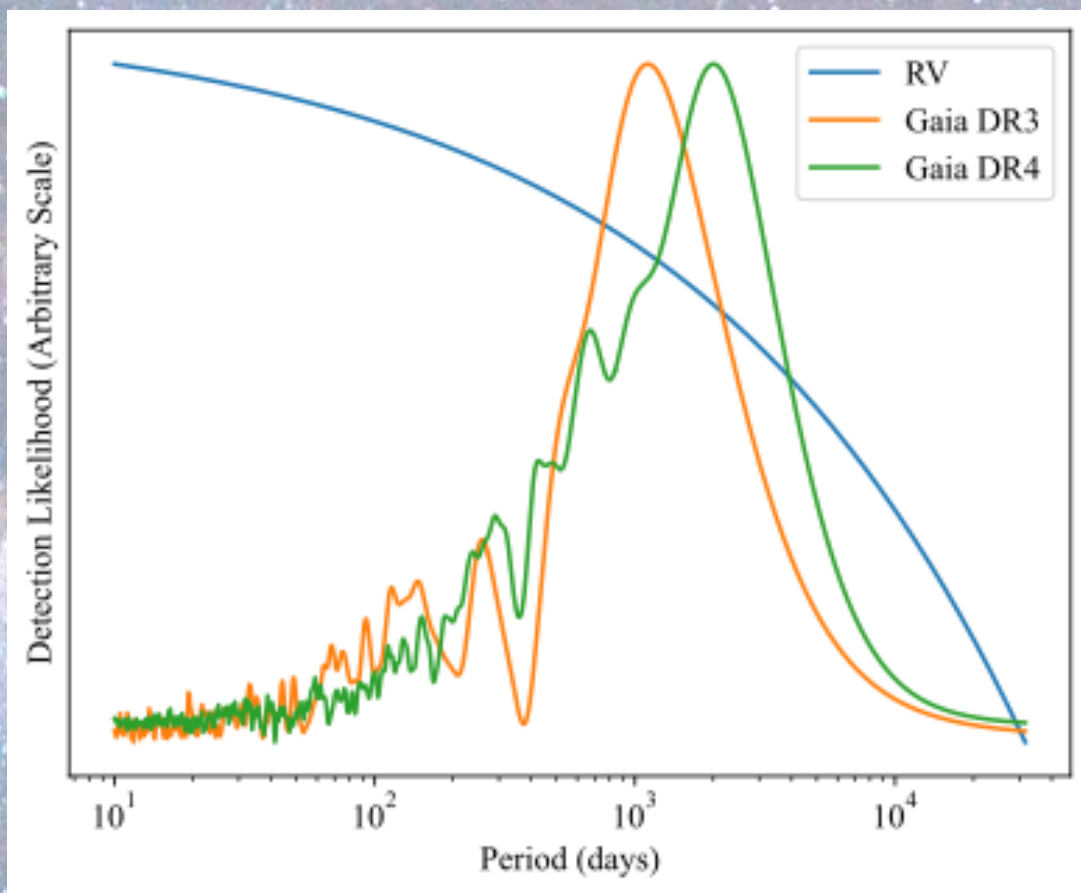
Types of Planets

Gaia



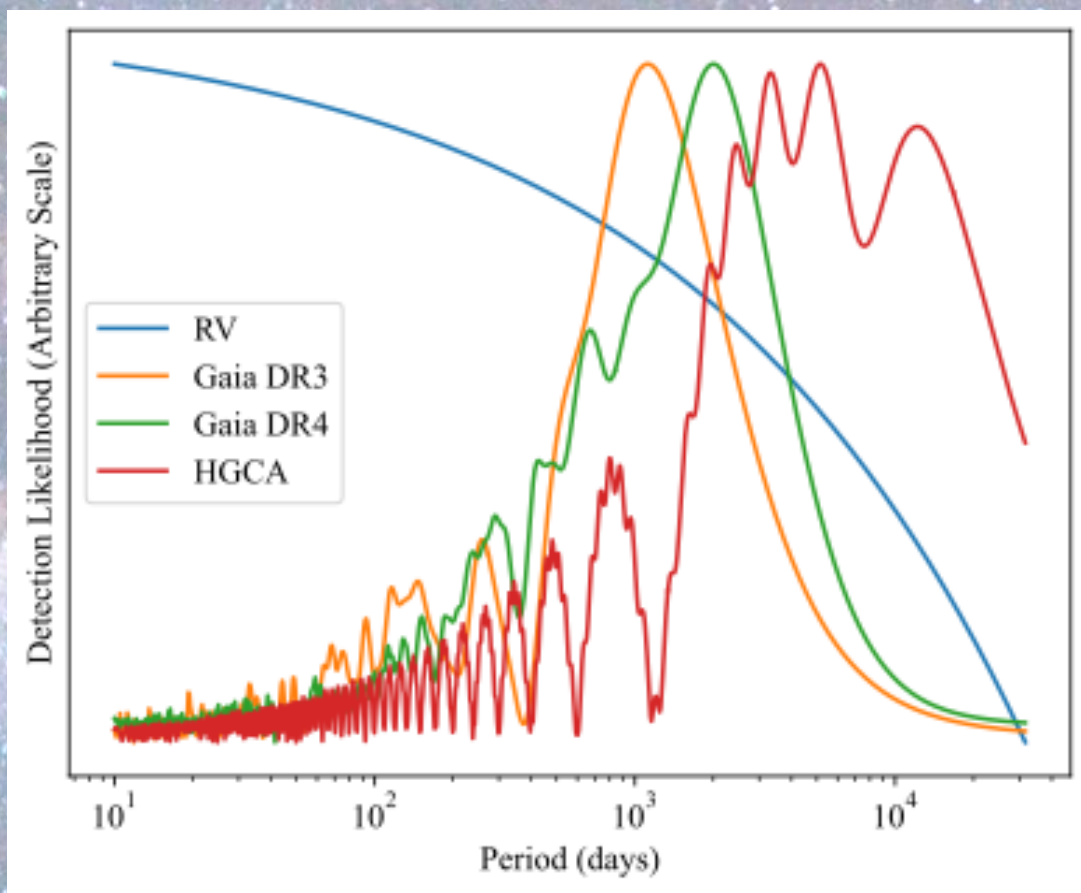
Types of Planets

Gaia



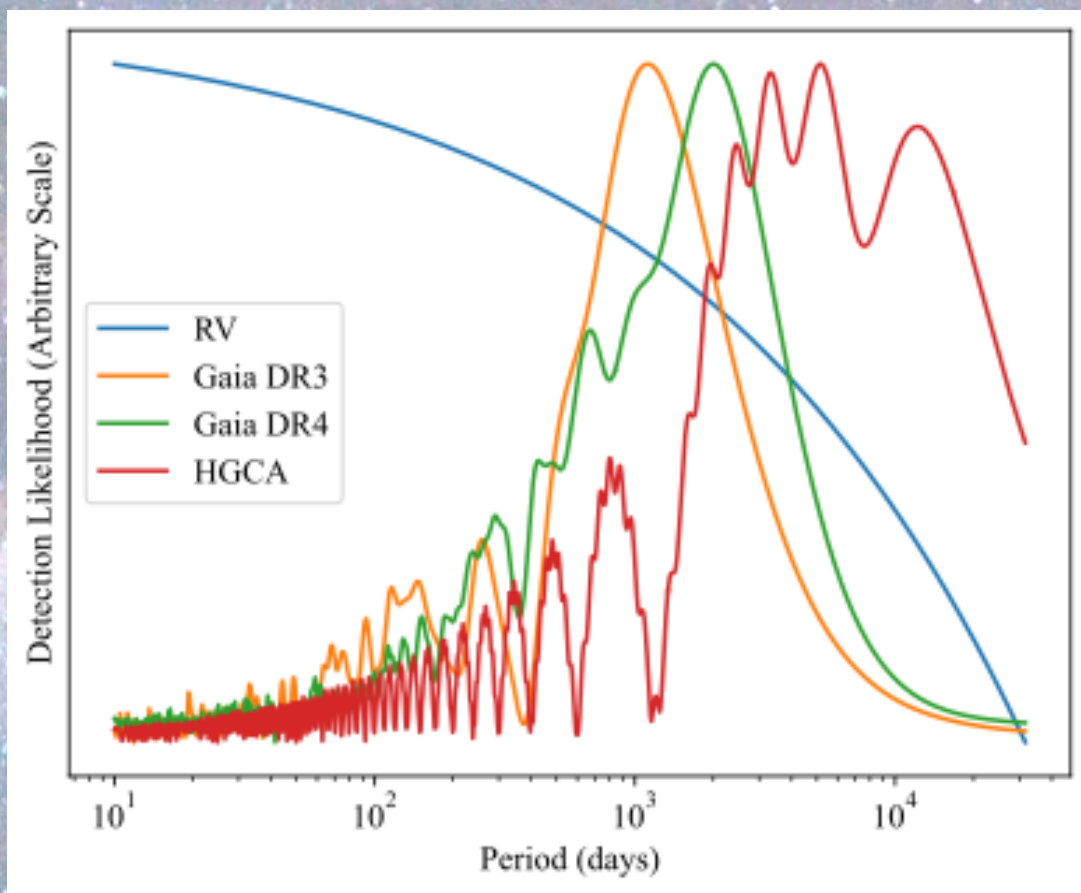
Types of Planets

Hipparcos-Gaia



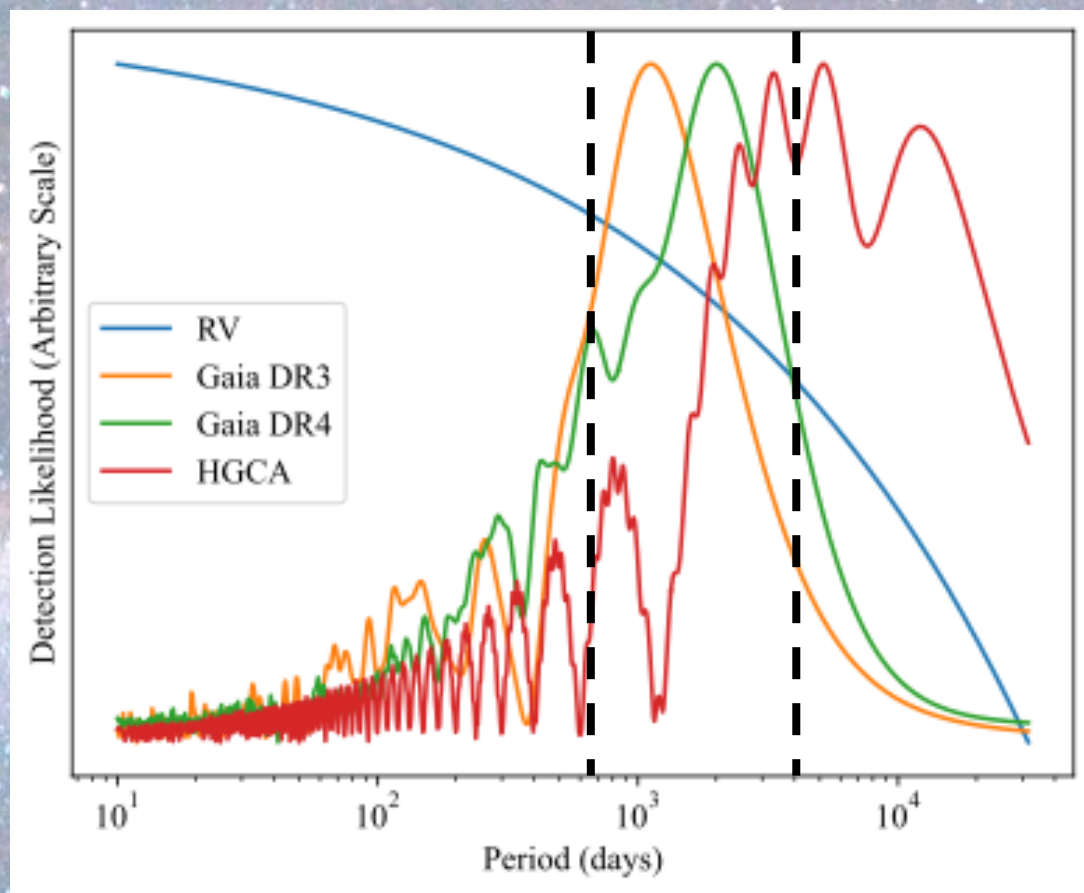
Types of Planets

Hipparcos-Gaia

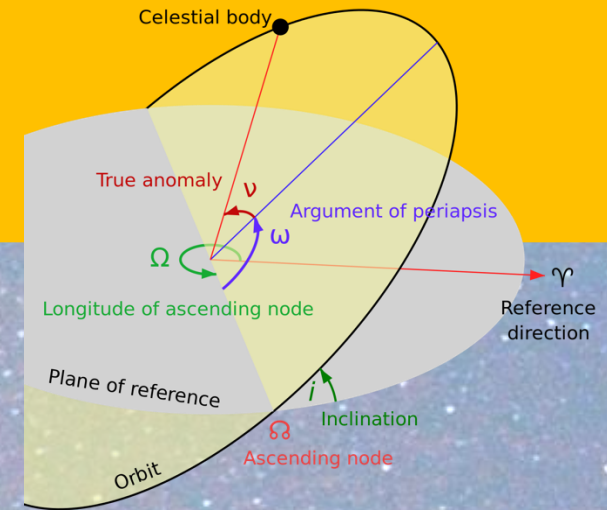


Types of Planets

Hipparcos-Gaia



Finding Orbital Parameters



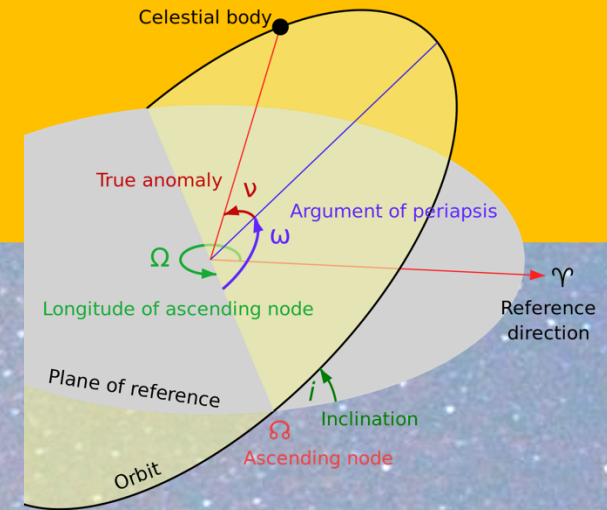
Finding Orbital Parameters

JAX/numpyro sampling

RUWE

$\varpi, \vec{\mu}$

Gaia DR3

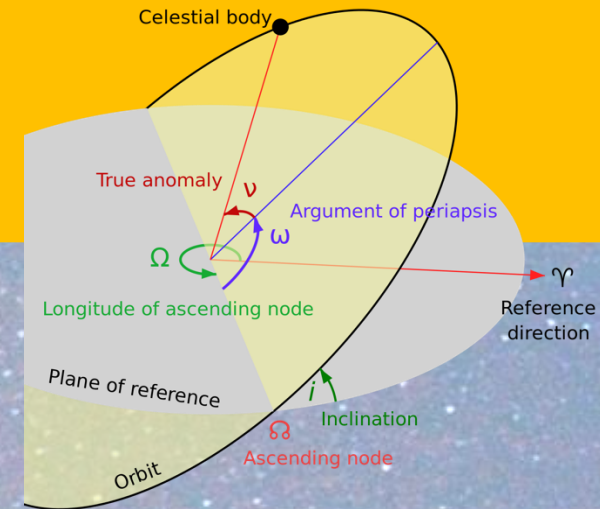


Finding Orbital Parameters

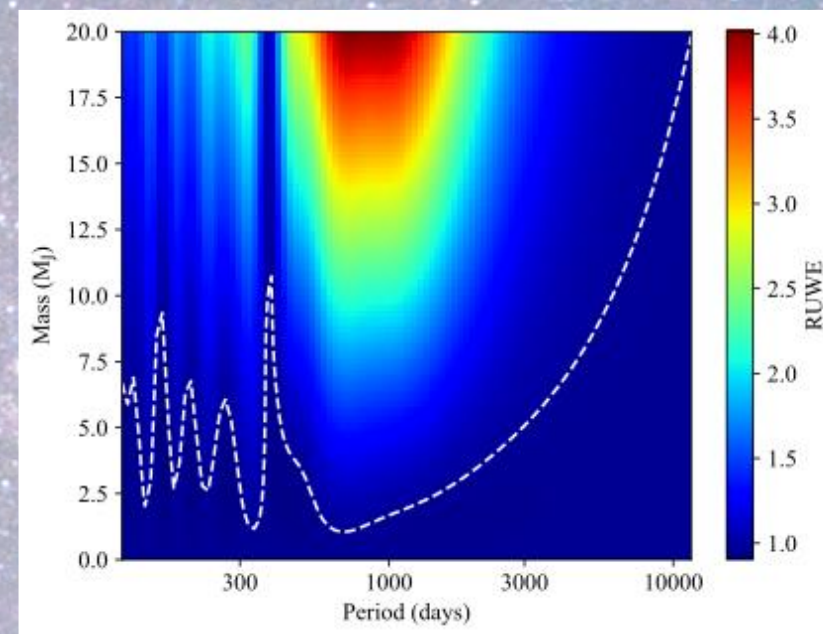
JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

Gaia DR3



HD 70642



Finding Orbital Parameters

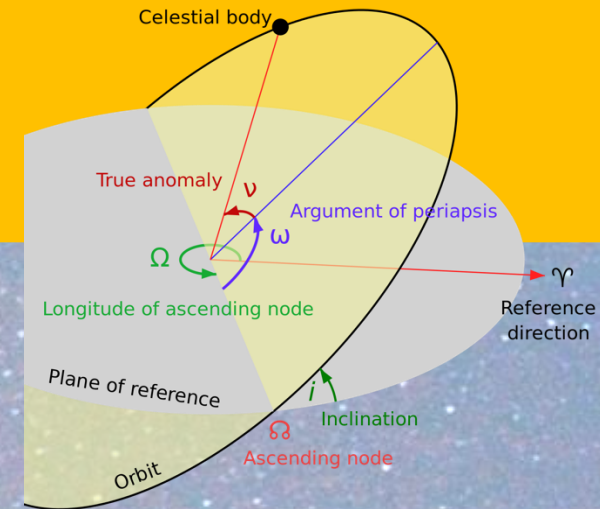
JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

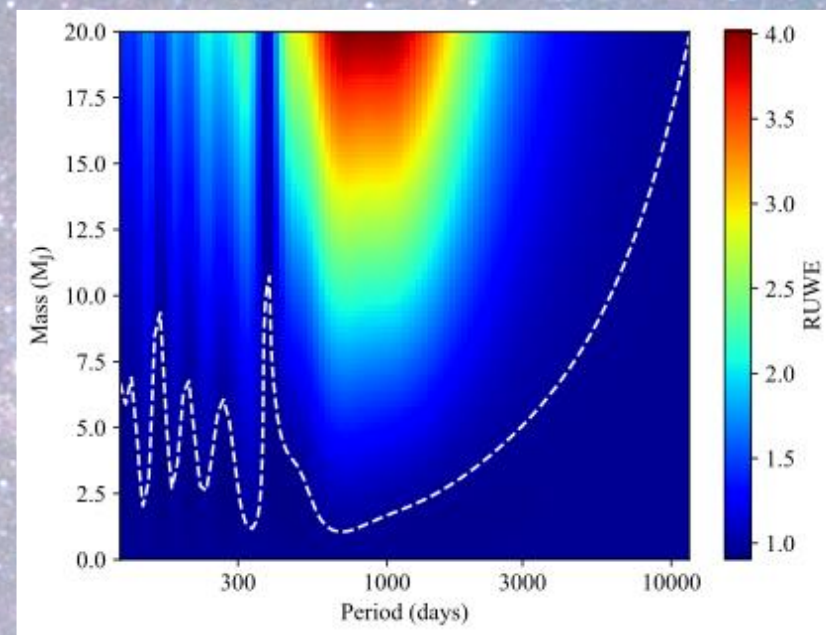
Gaia DR3



Maximum Mass
for range of
periods



HD 70642



Finding Orbital Parameters

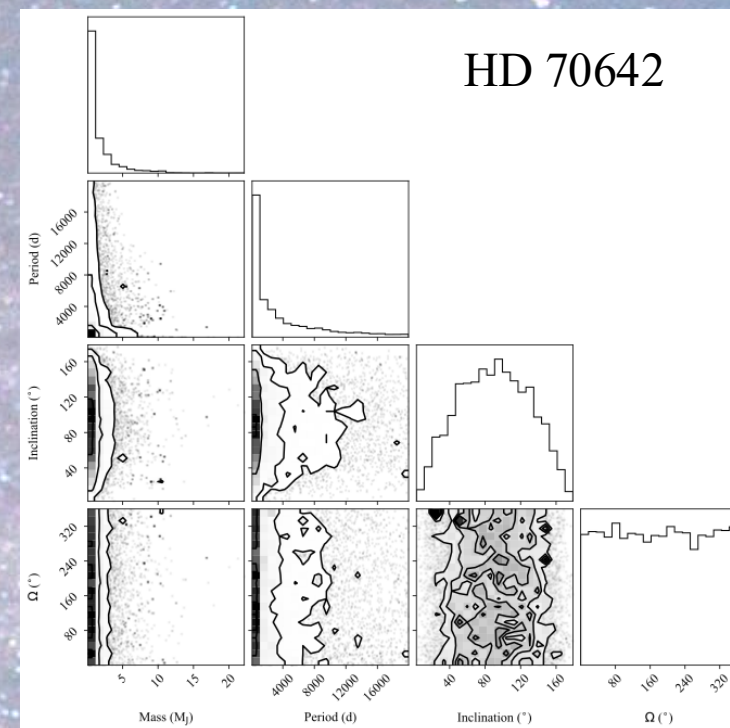
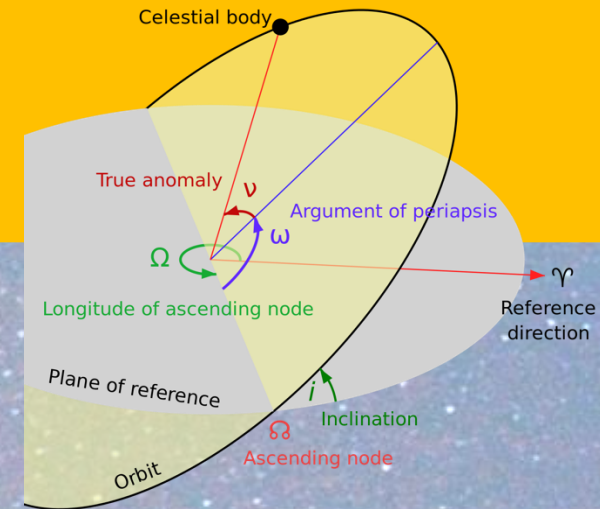
JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

Gaia DR3



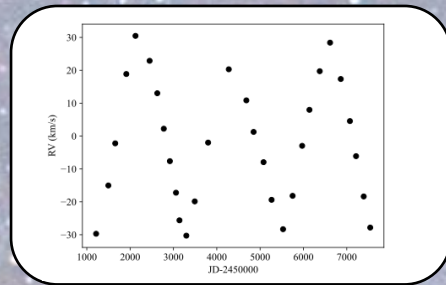
Maximum Mass
for range of
periods



Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

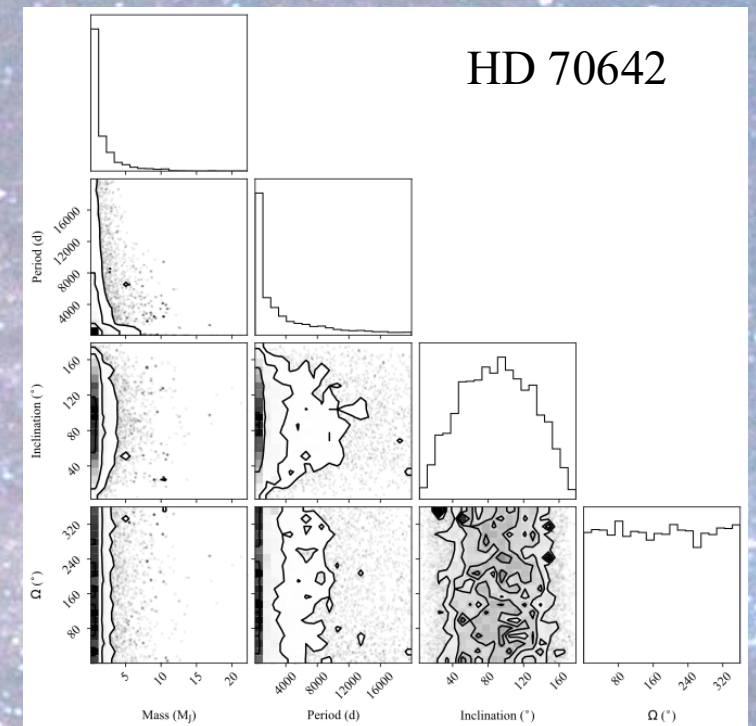
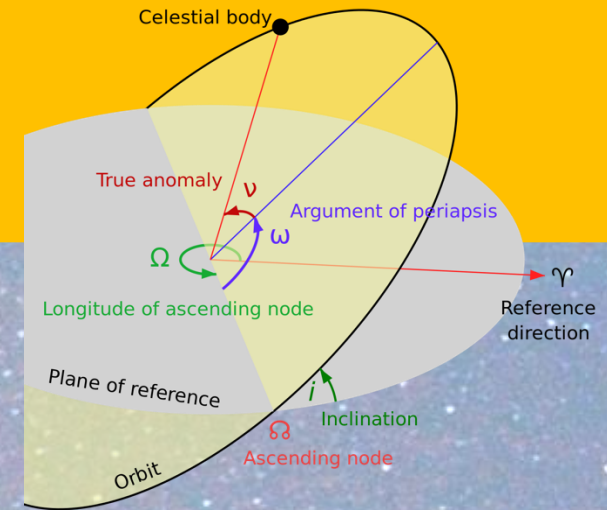


Gaia DR3

RV Data

Maximum Mass
for range of
periods

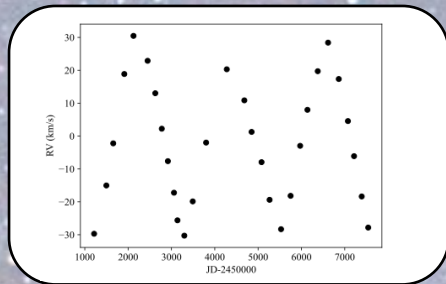
Minimum Mass
Period
 e, ω, T_P



Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

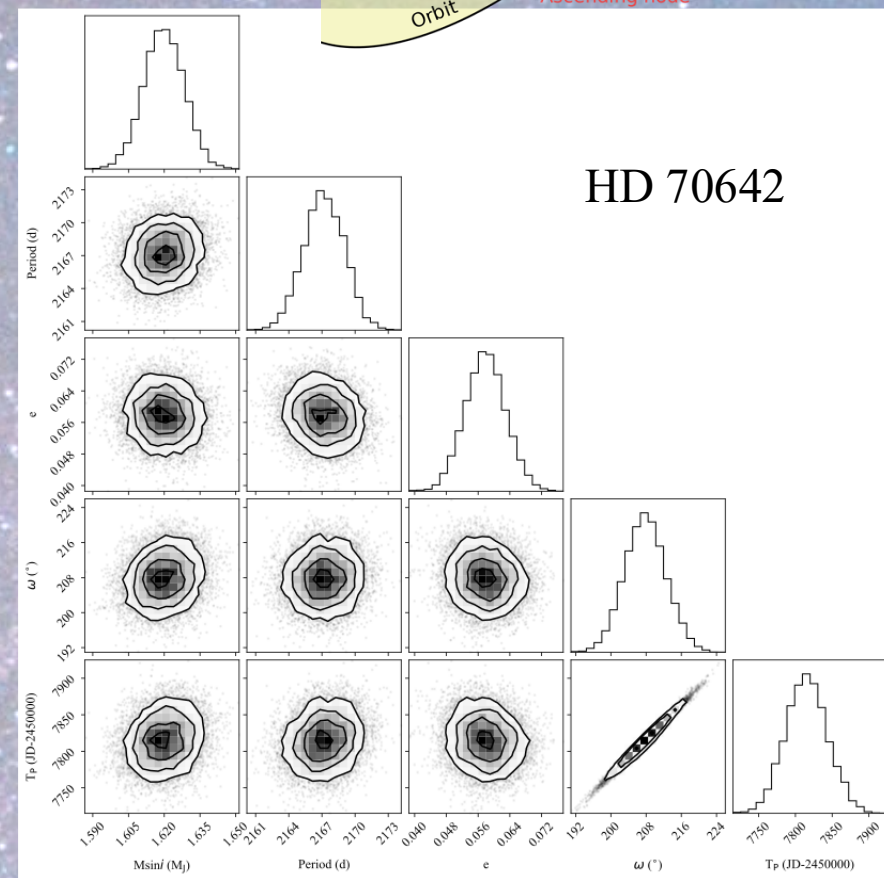
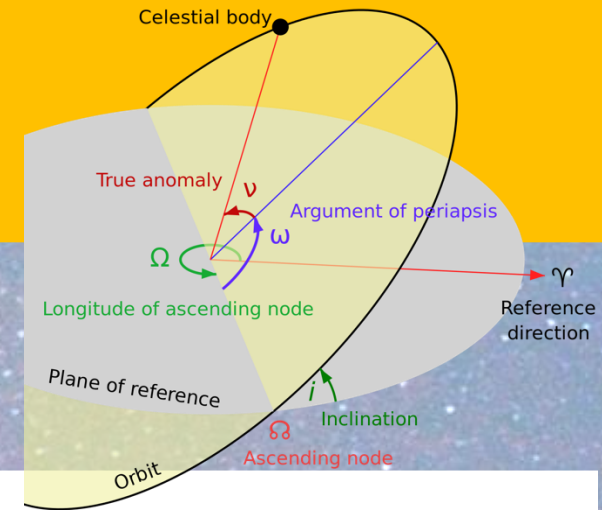


Gaia DR3

RV Data

Maximum Mass
for range of
periods

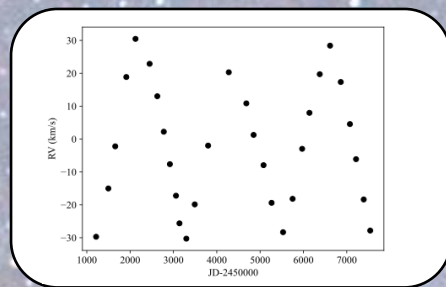
Minimum Mass
Period
 e, ω, T_P



Finding Orbital Parameters

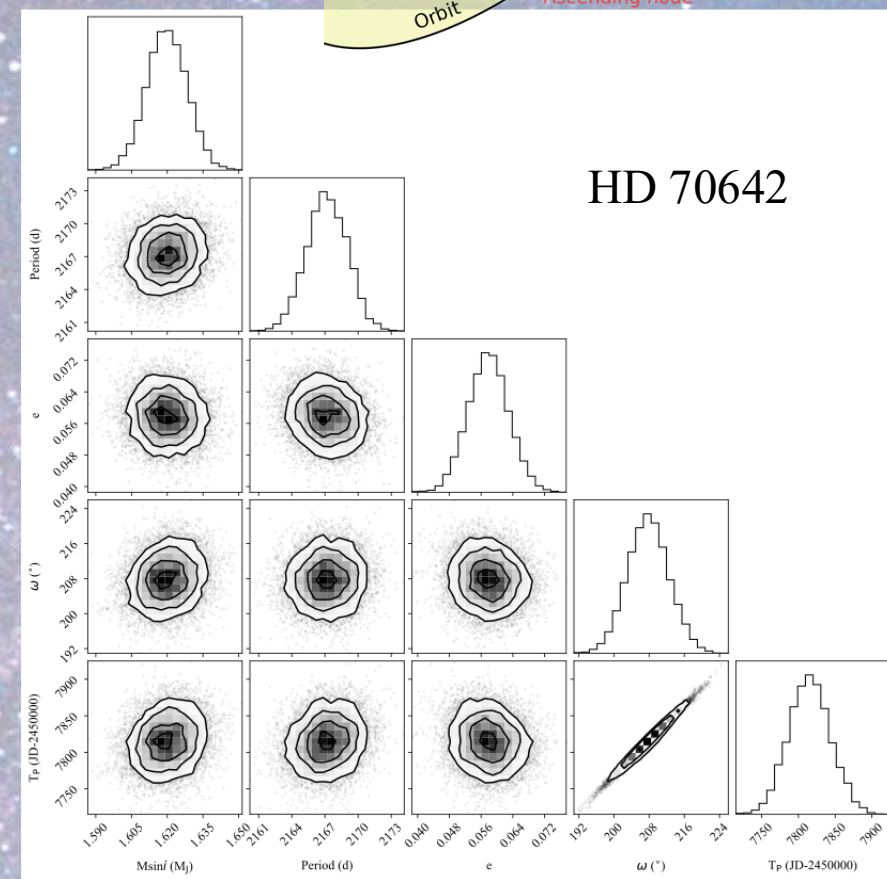
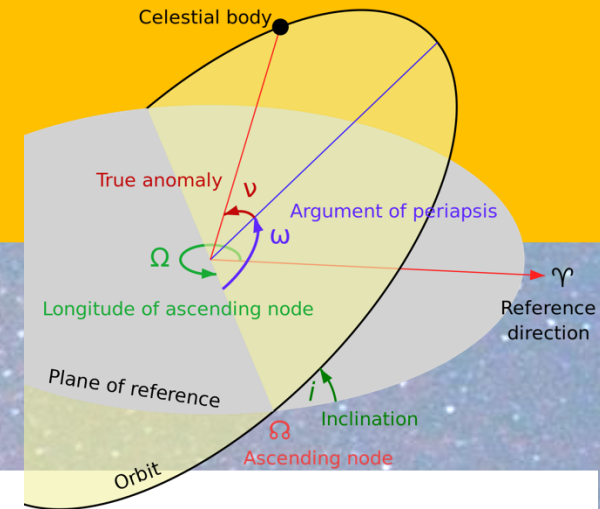
JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$



Gaia DR3

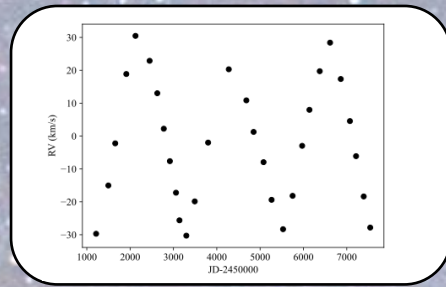
RV Data



Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

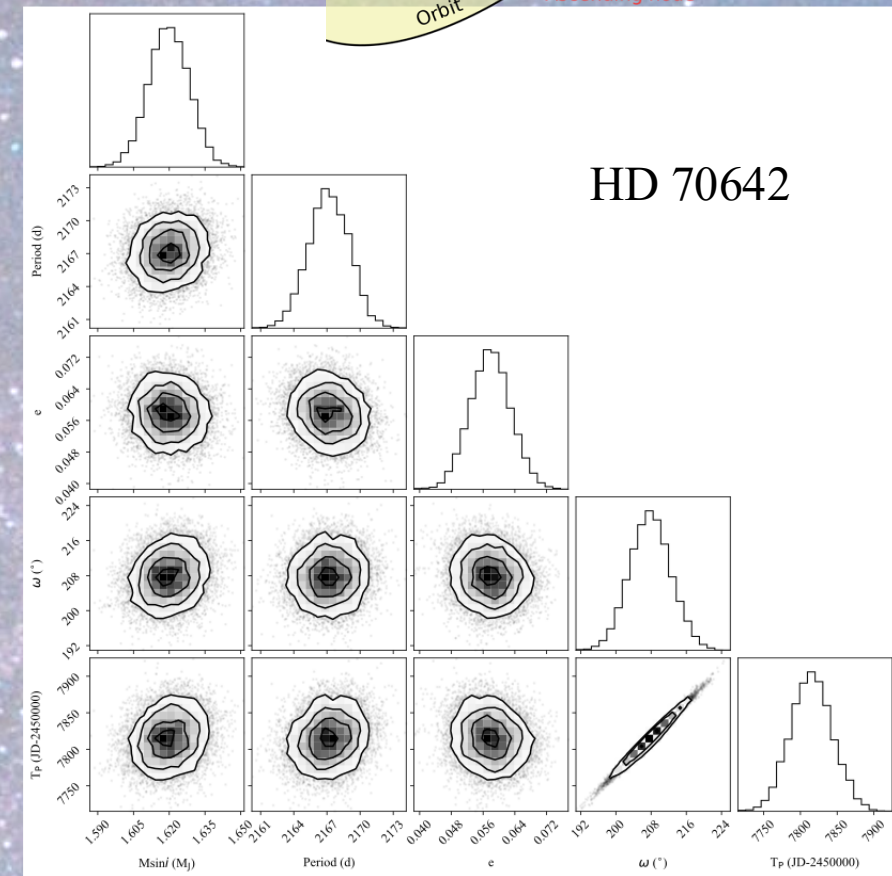
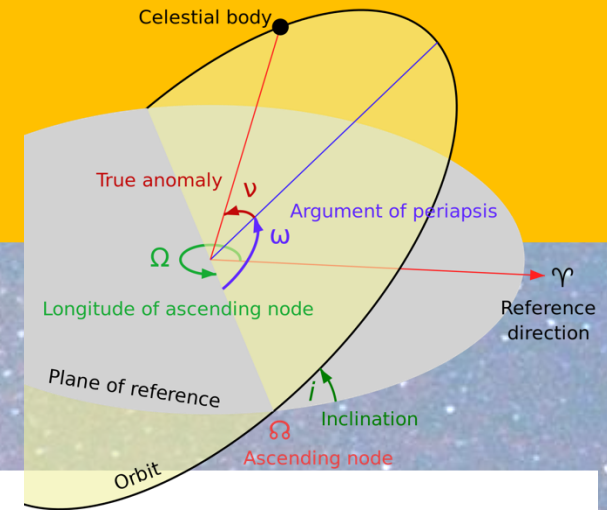


Gaia DR3

RV Data



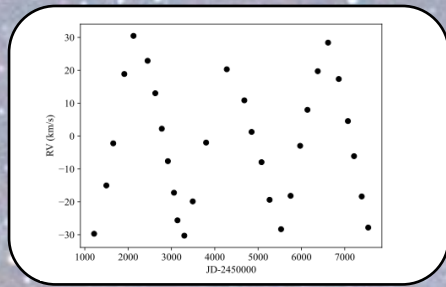
Maximum Mass
Minimum $\sin i$
Period
 e, ω, T_P



Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

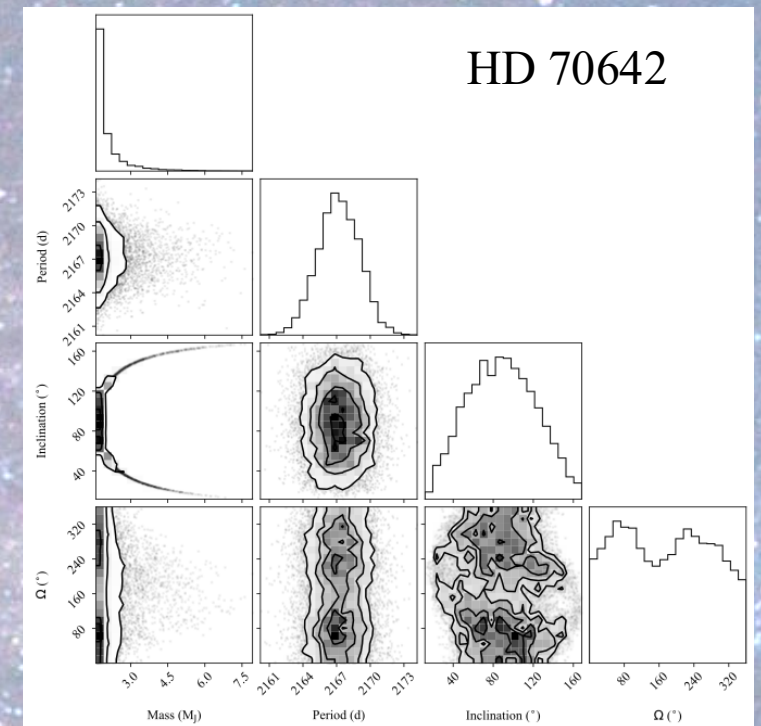
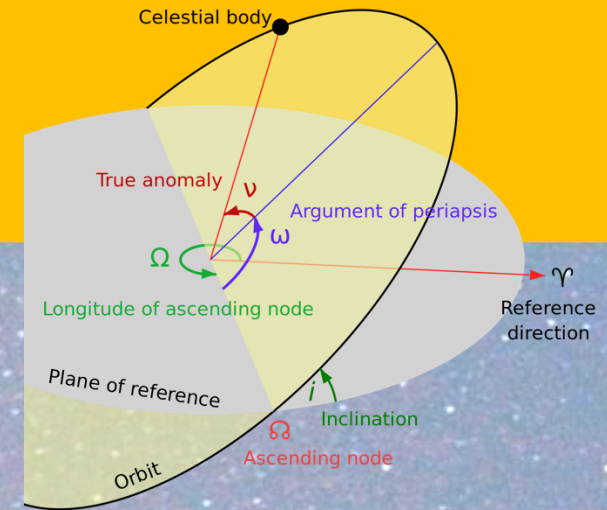


Gaia DR3

RV Data



Maximum Mass
Minimum $\sin i$
Period
 e, ω, T_P

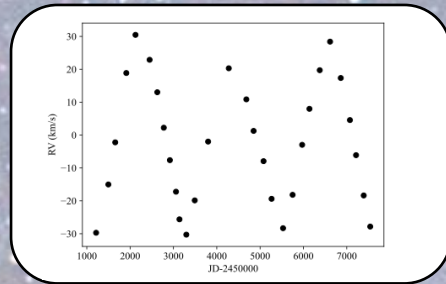


Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

Gaia DR3



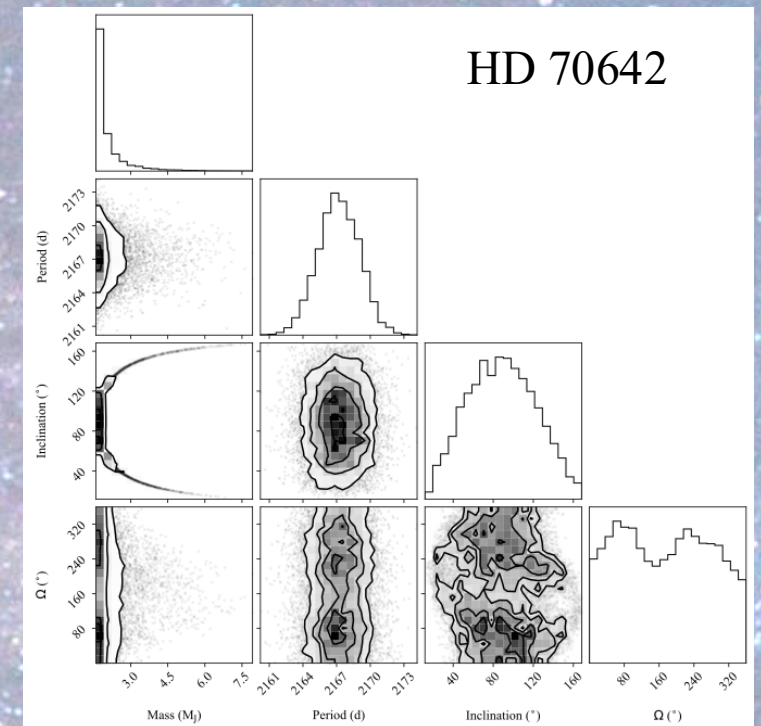
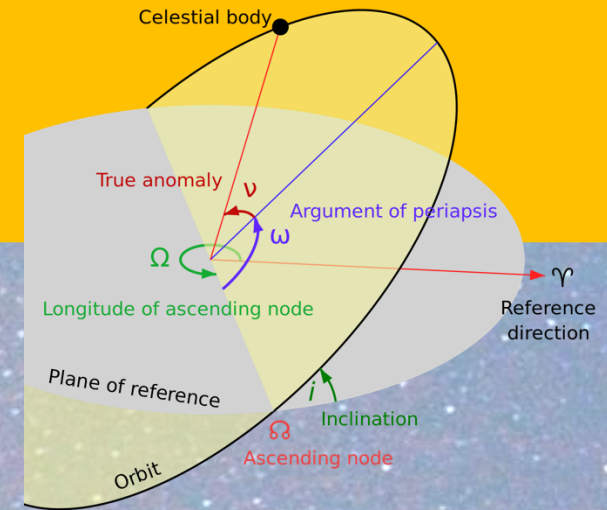
RV Data

$\vec{\mu}_G, \vec{\mu}_{HG}$

HGCA



Maximum Mass
Minimum $\sin i$
Period
 e, ω, T_P

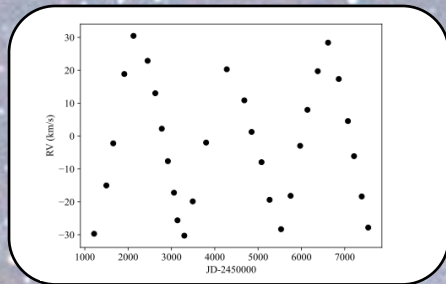


Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$

Gaia DR3



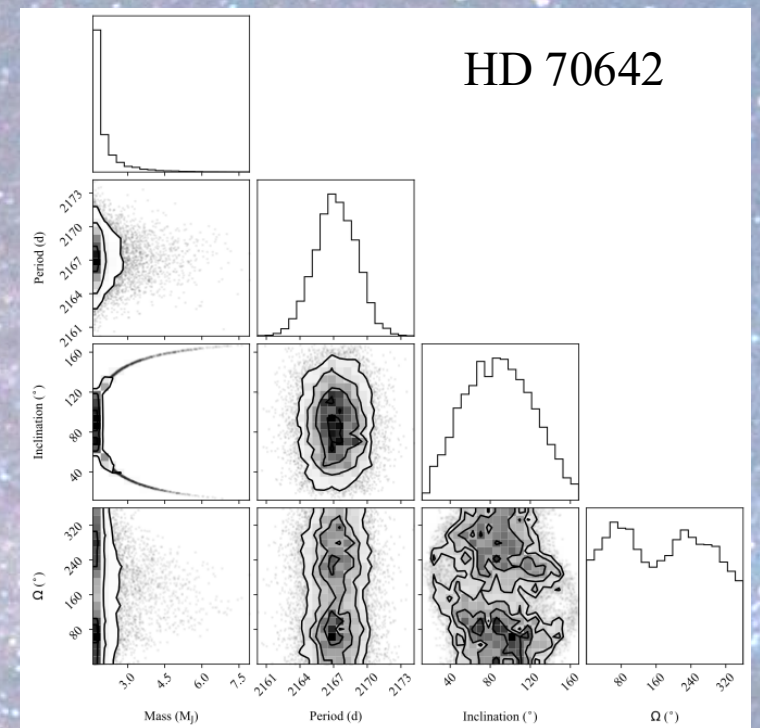
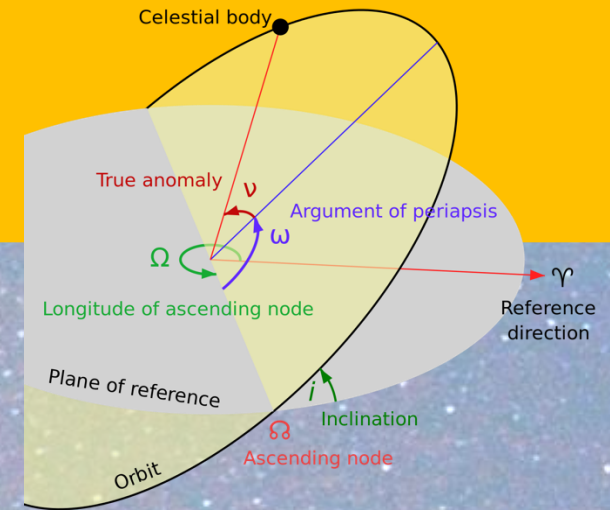
RV Data

$\vec{\mu}_G, \vec{\mu}_{HG}$

HGCA



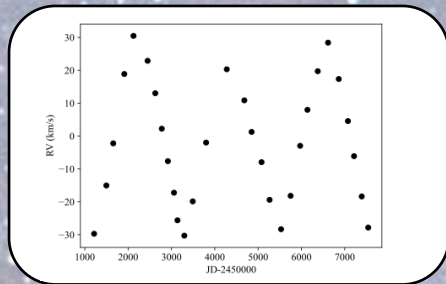
Maximum Mass
Minimum $\sin i$
Period
 e, ω, Ω, T_P



Finding Orbital Parameters

JAX/numpyro sampling

RUWE
 $\varpi, \vec{\mu}$



$\vec{\mu}_G, \vec{\mu}_{HG}$

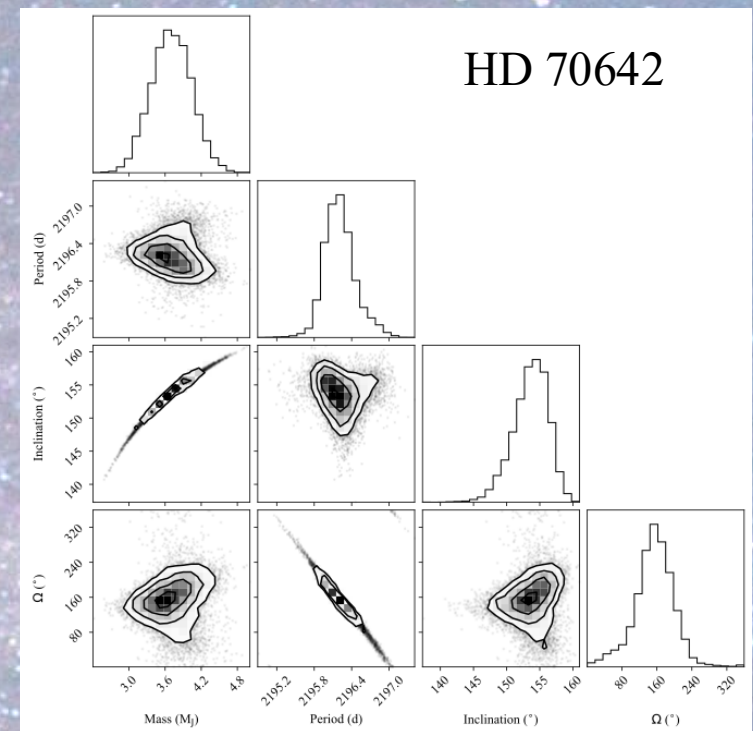
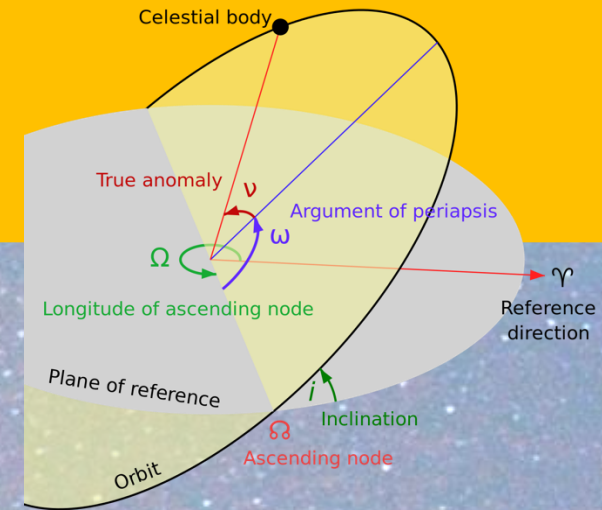
Gaia DR3

RV Data

HGCA

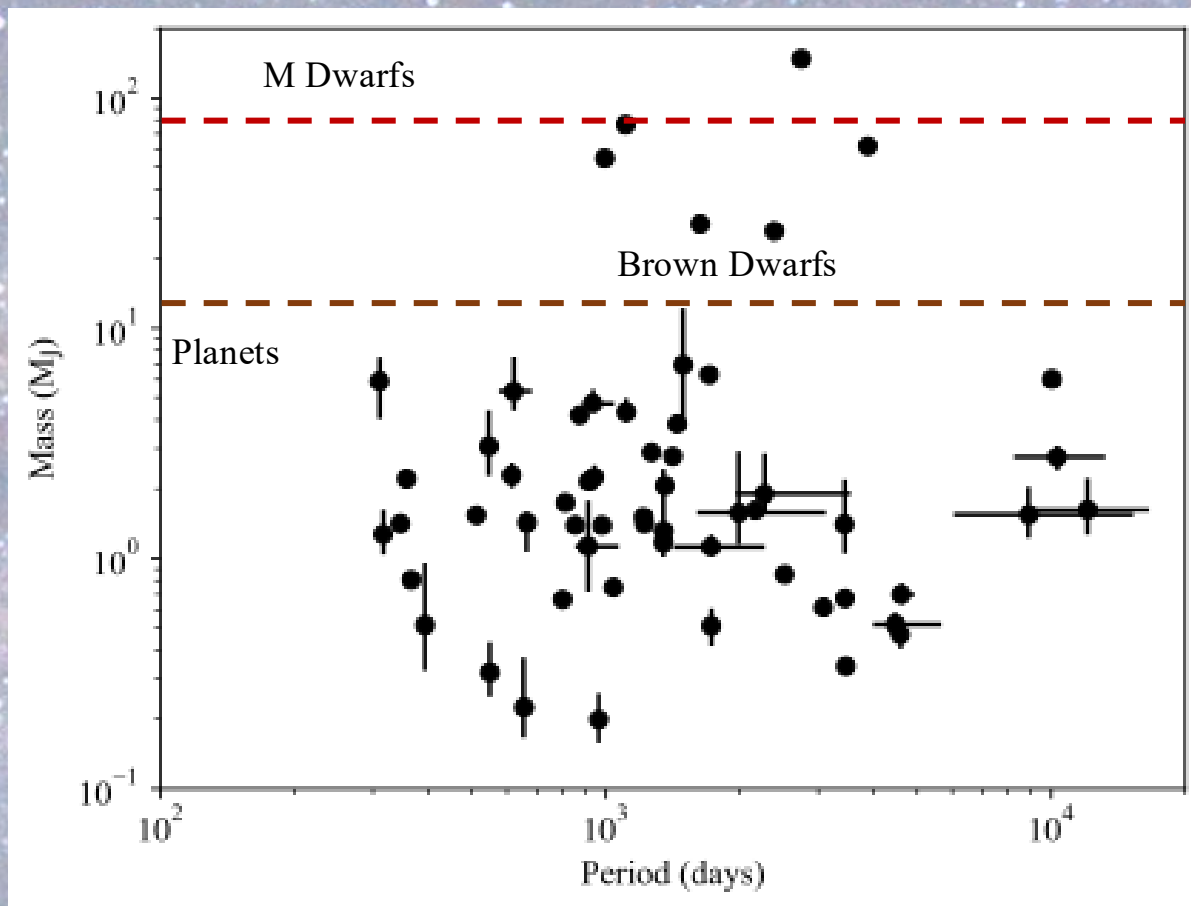


Maximum Mass
Minimum $\sin i$
Period
 e, ω, Ω, T_P



Some Results

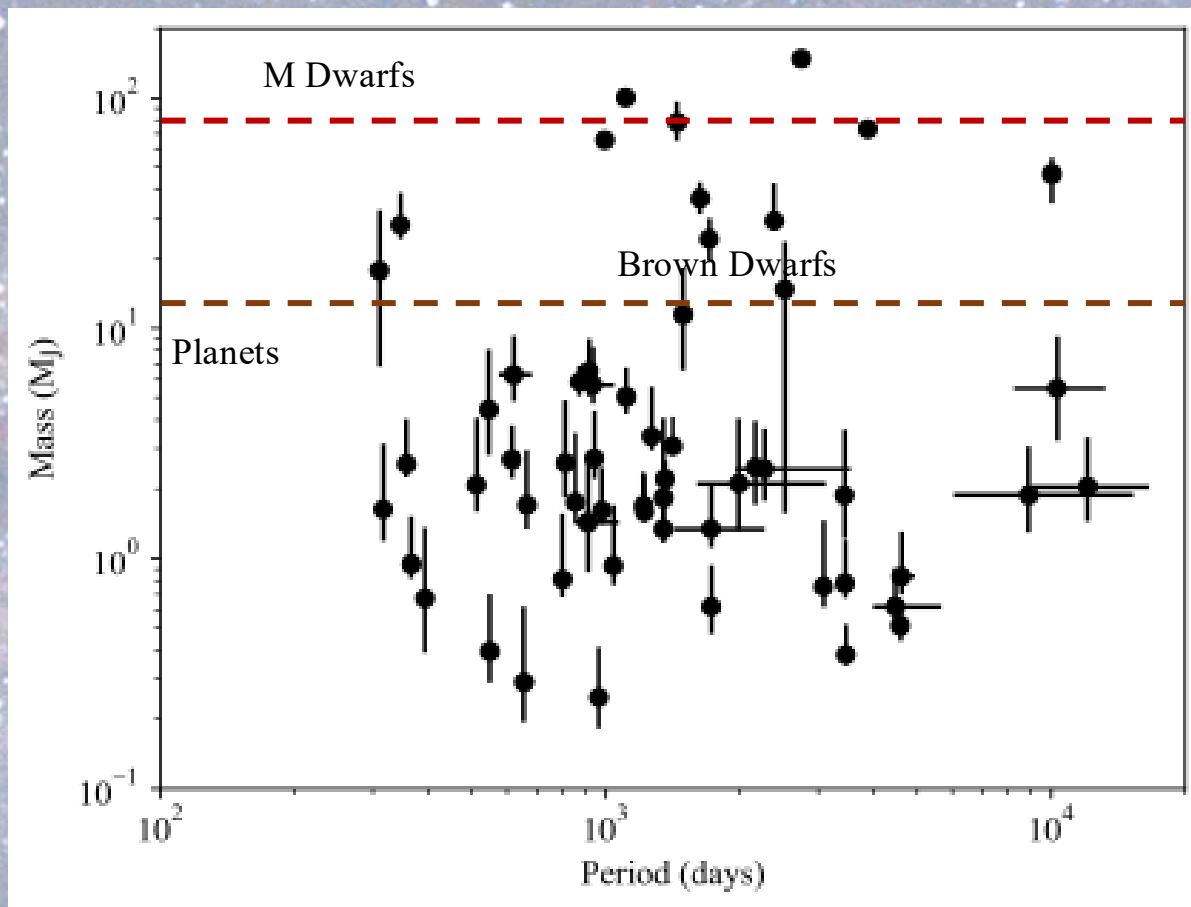
Minimum Mass



Using Only RV

Some Results

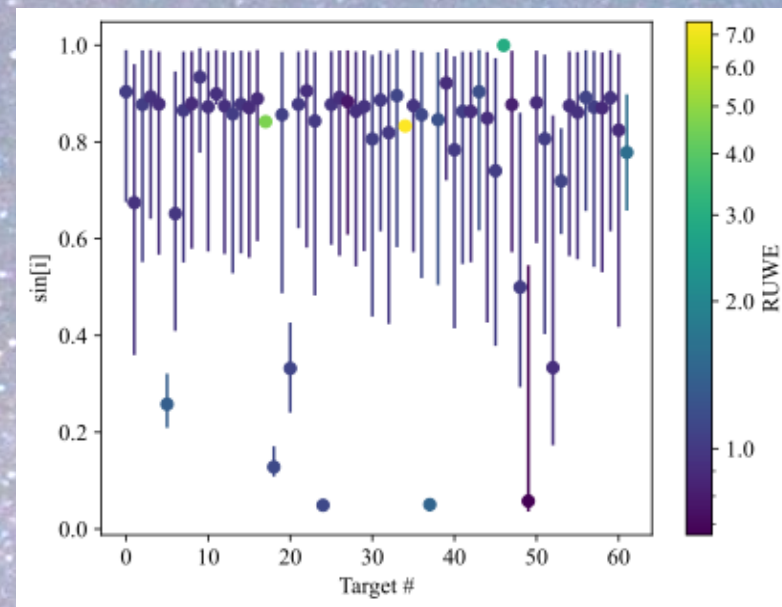
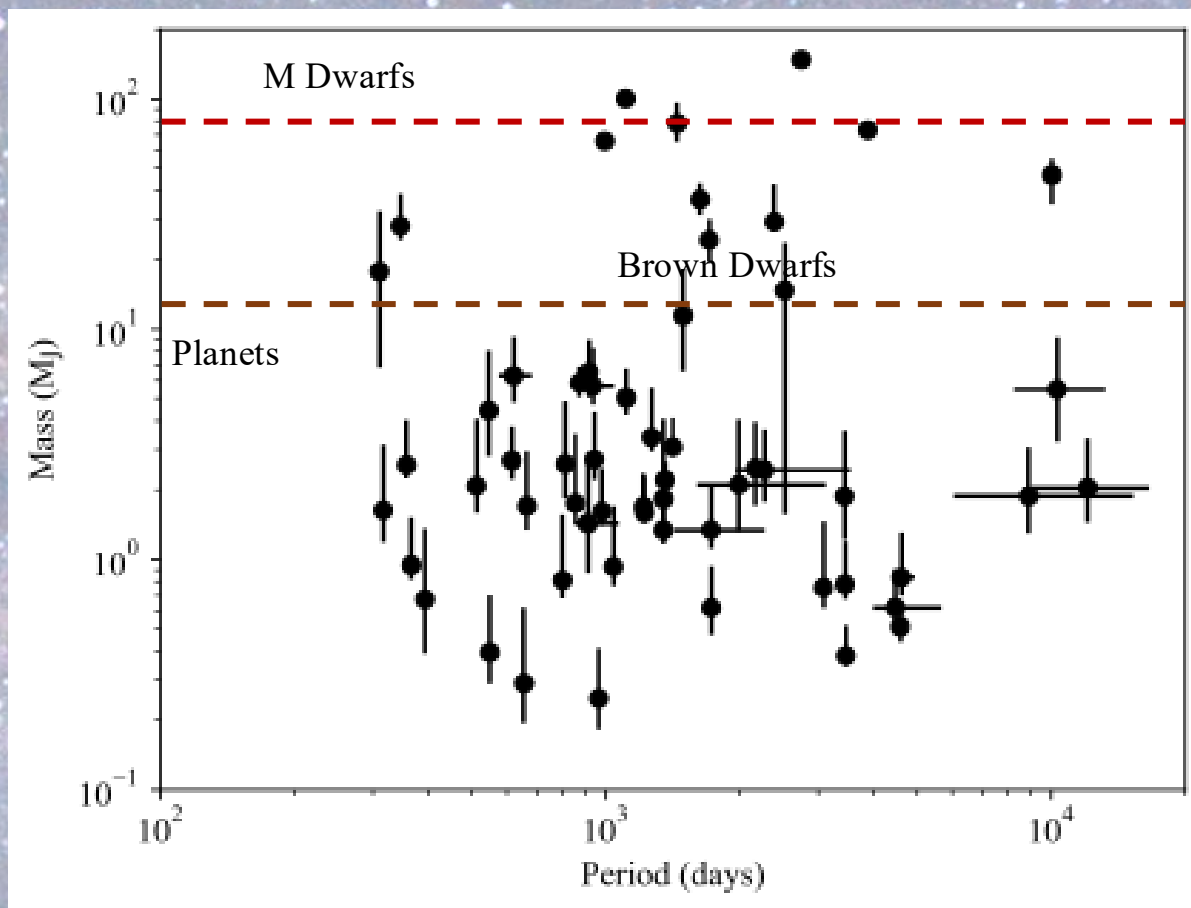
Maximum Mass



RV and RUWE Combined

Some Results

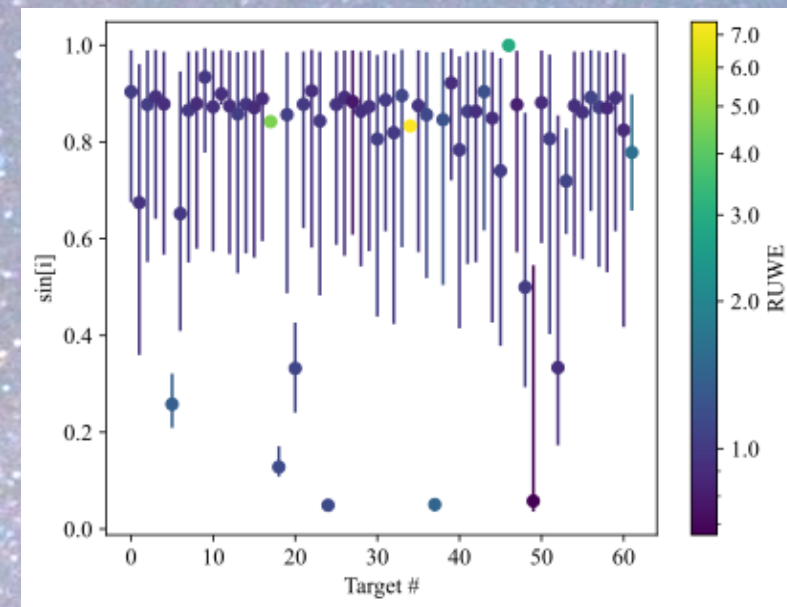
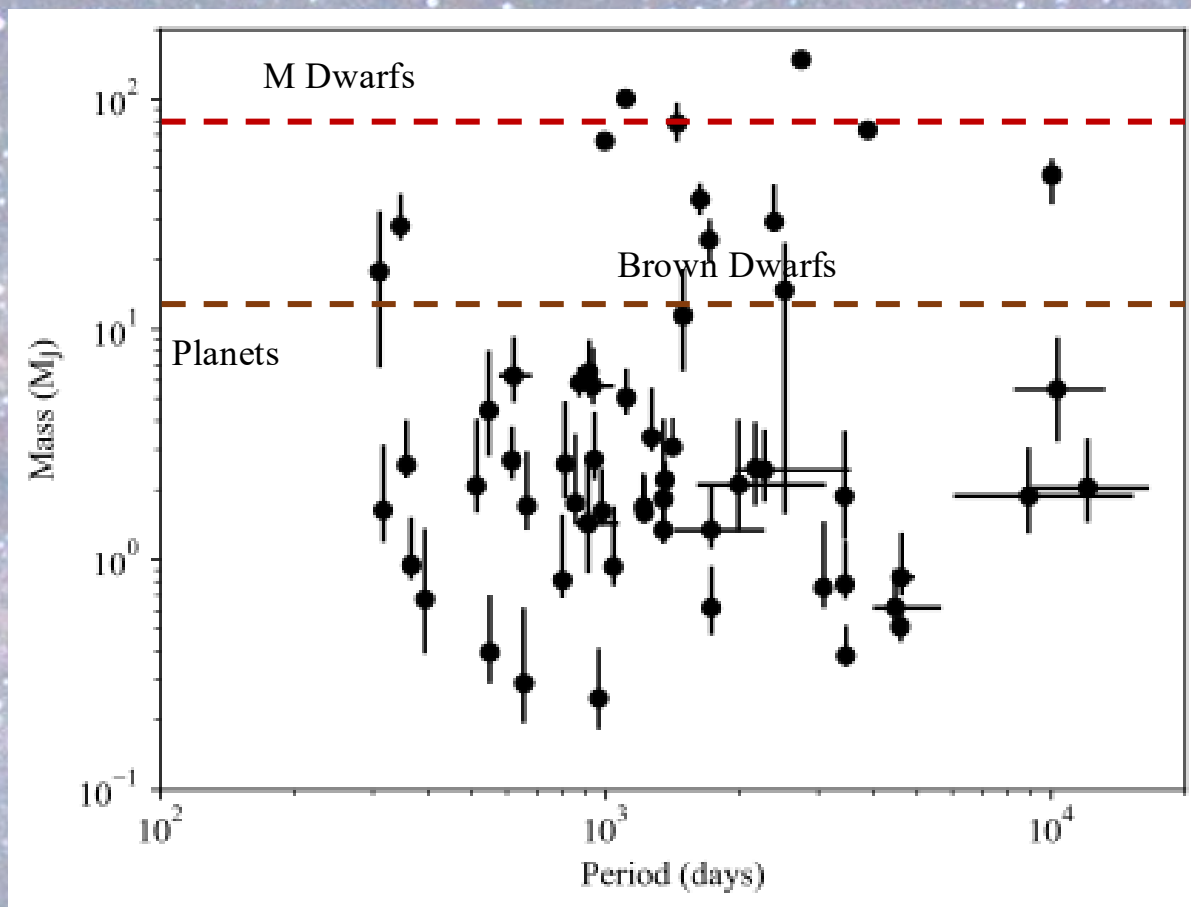
Maximum Mass



RV and RUWE Combined

Some Results

Maximum Mass

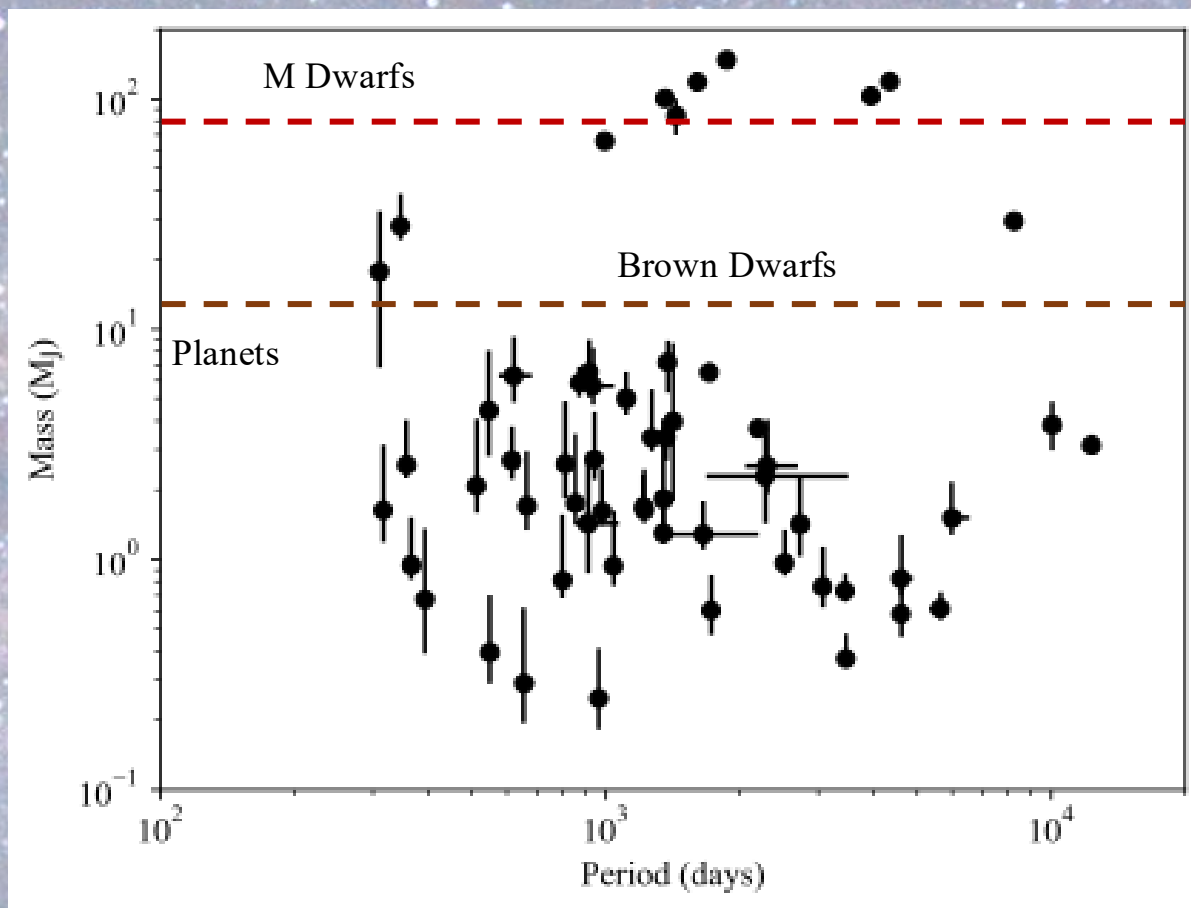


High RUWE constrains inclination

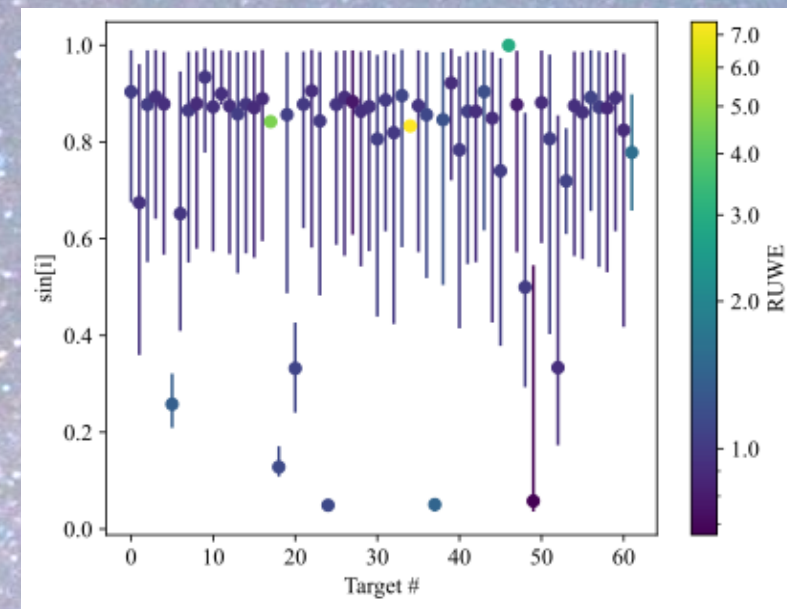
RV and RUWE Combined

Some Results

Maximum Mass

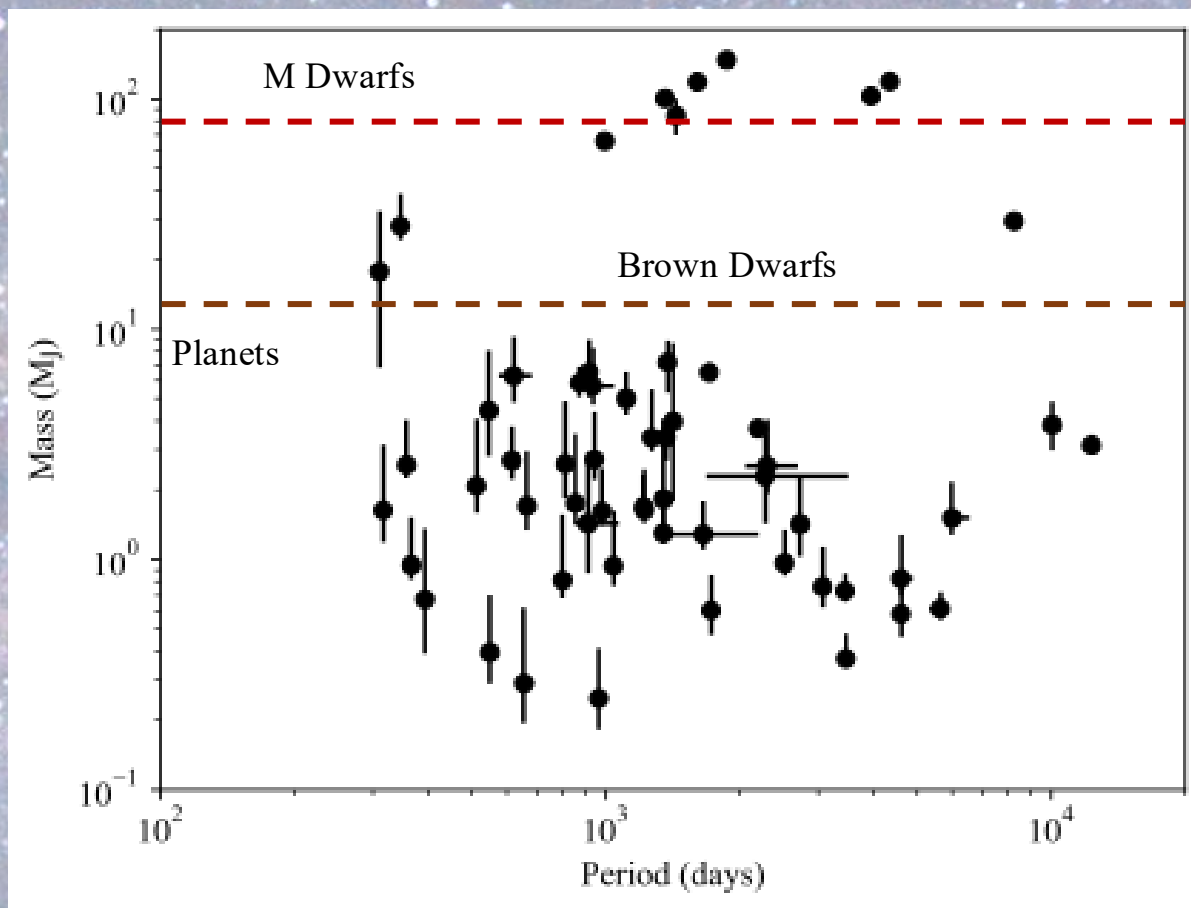


Hipparcos-Gaia

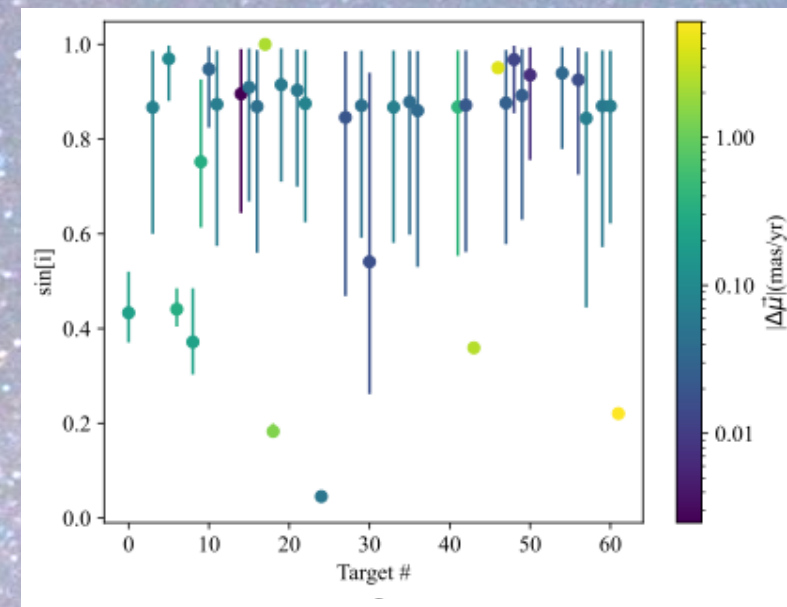


Some Results

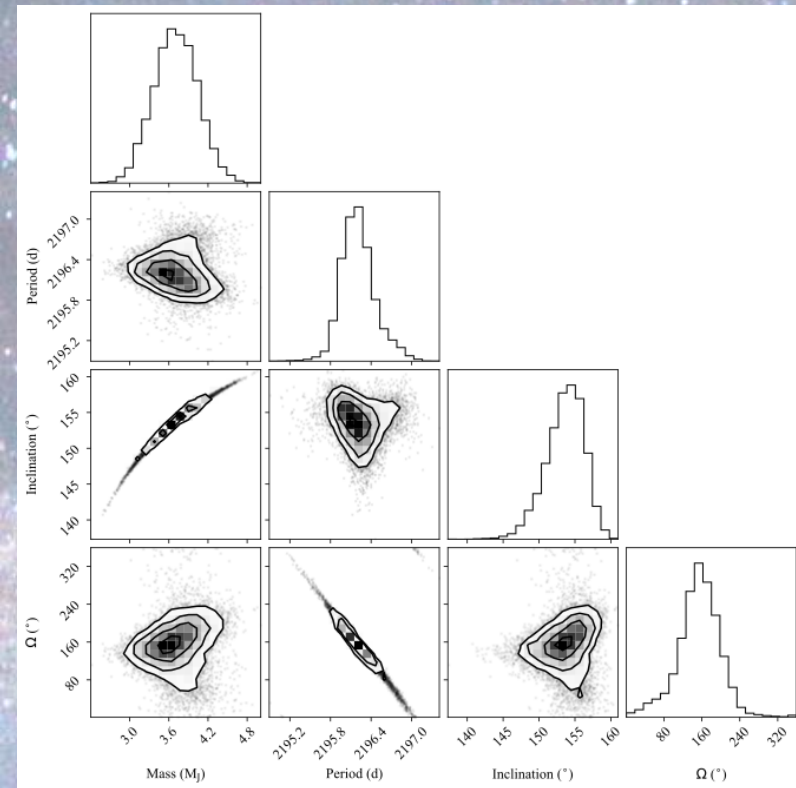
Maximum Mass



Hipparcos-Gaia



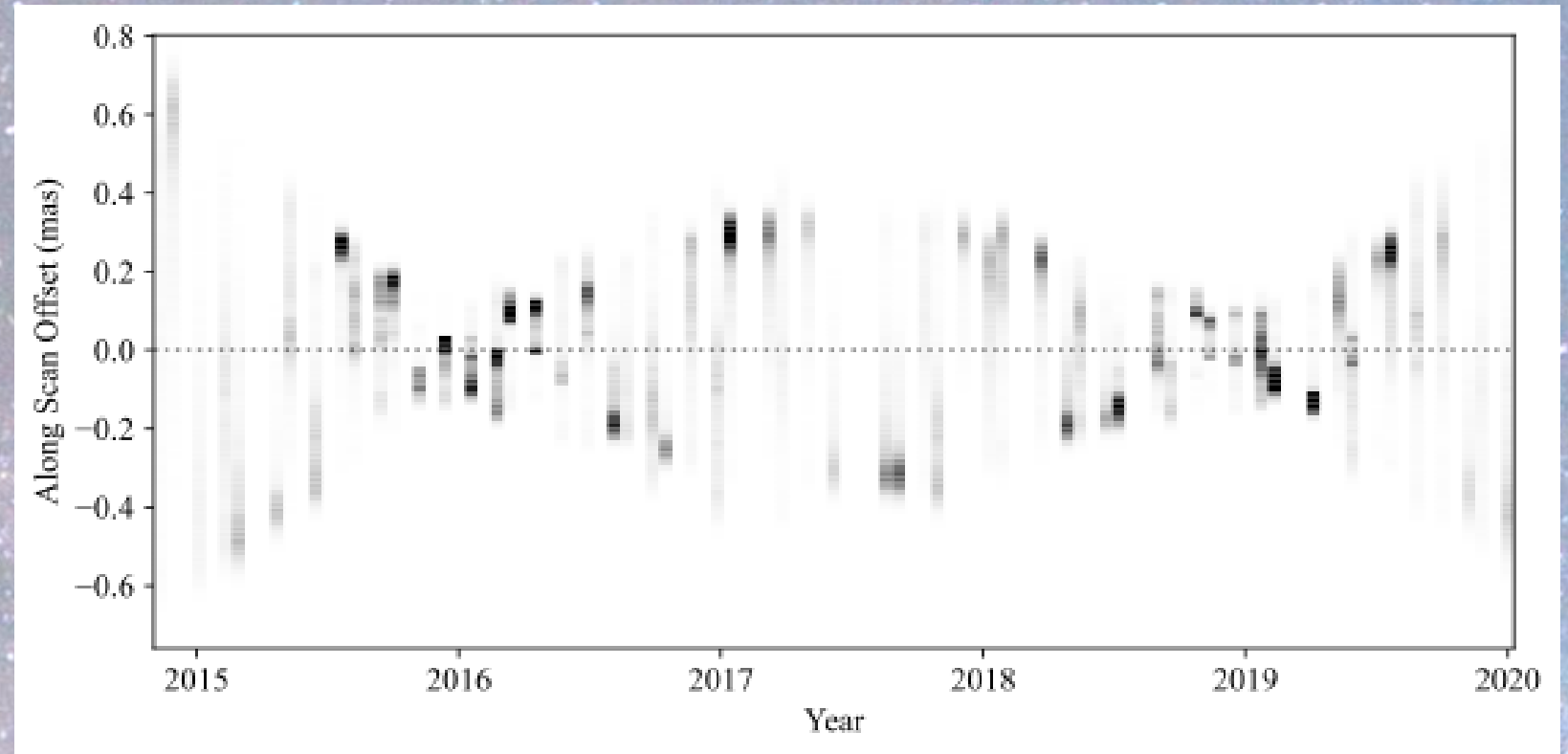
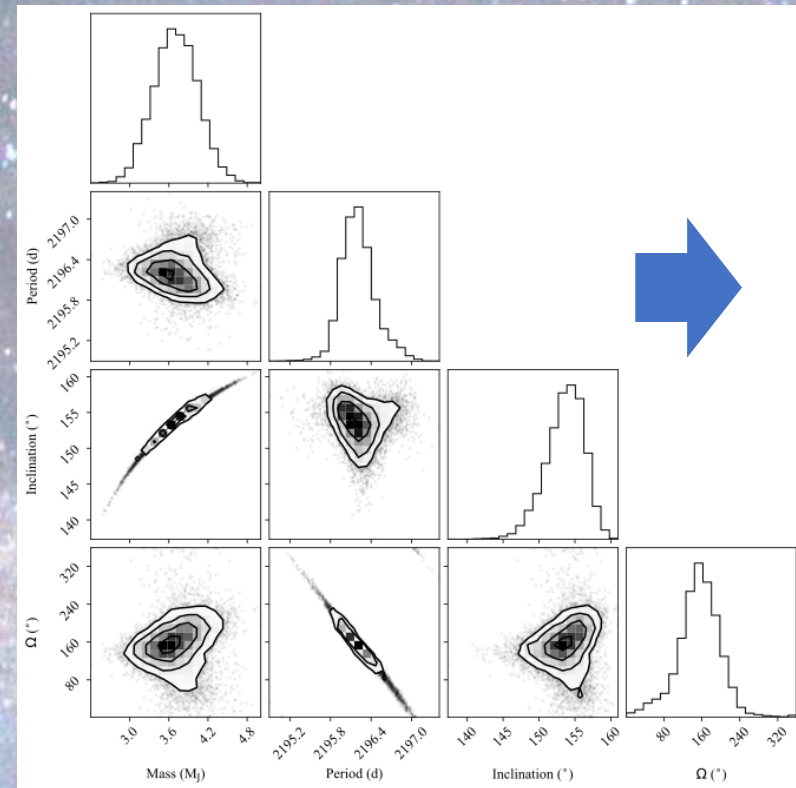
Epoch Data (DR4)



Hipparcos-Gaia Fit

Epoch Data (DR4)

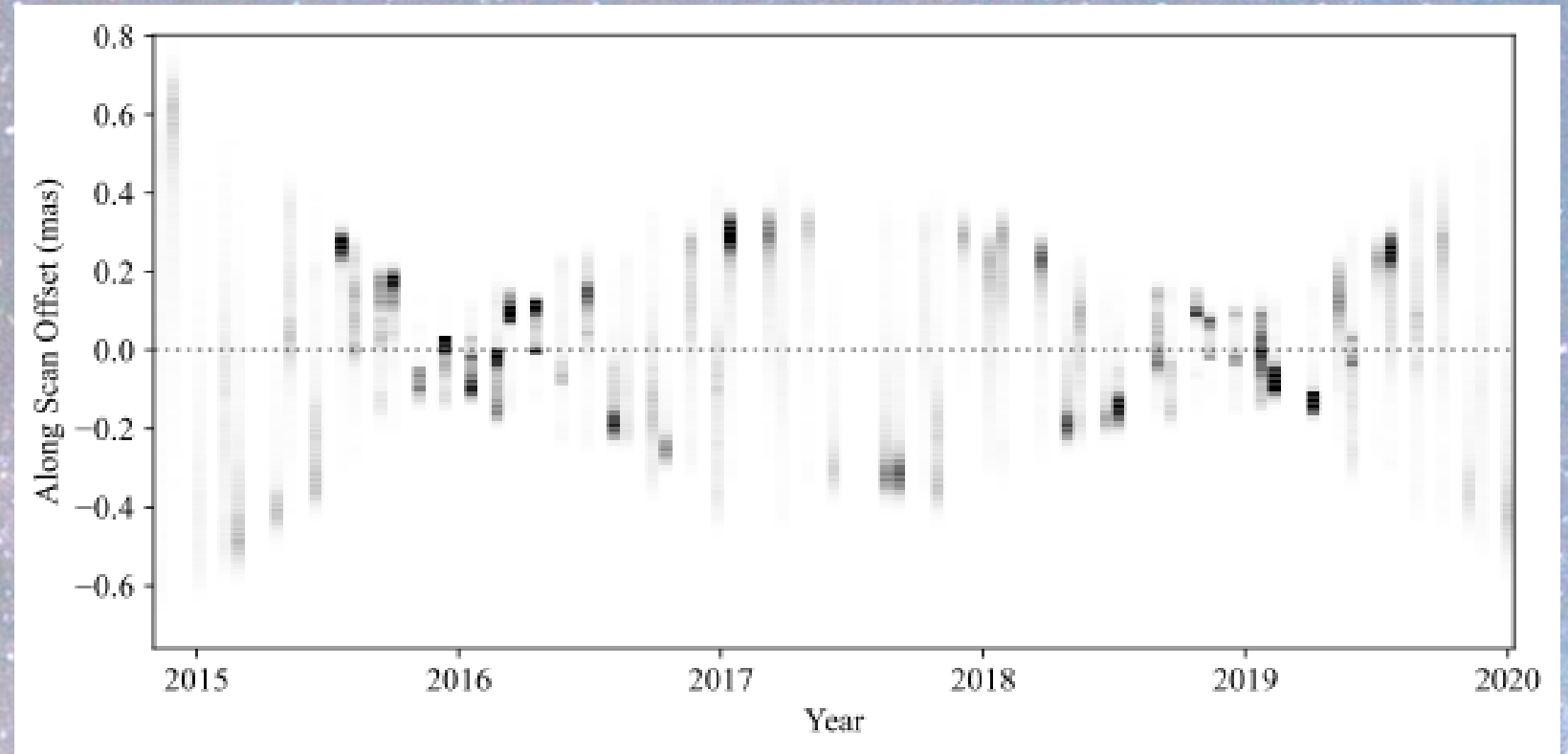
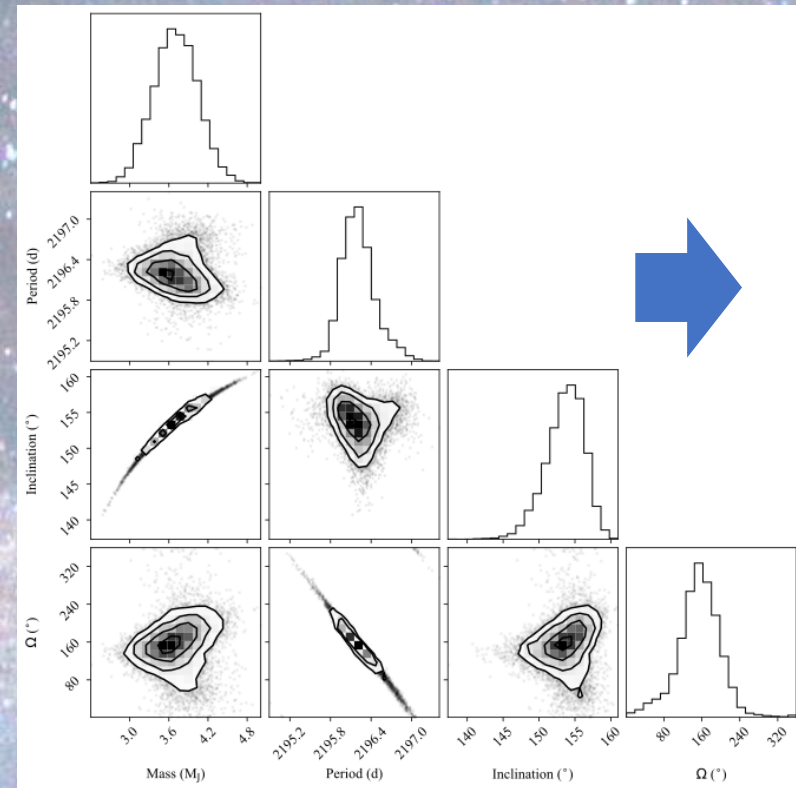
$$x_{AL} - x_0$$



Hipparcos-Gaia Fit

Epoch Data (DR4)

$$x_{AL} - x_0$$

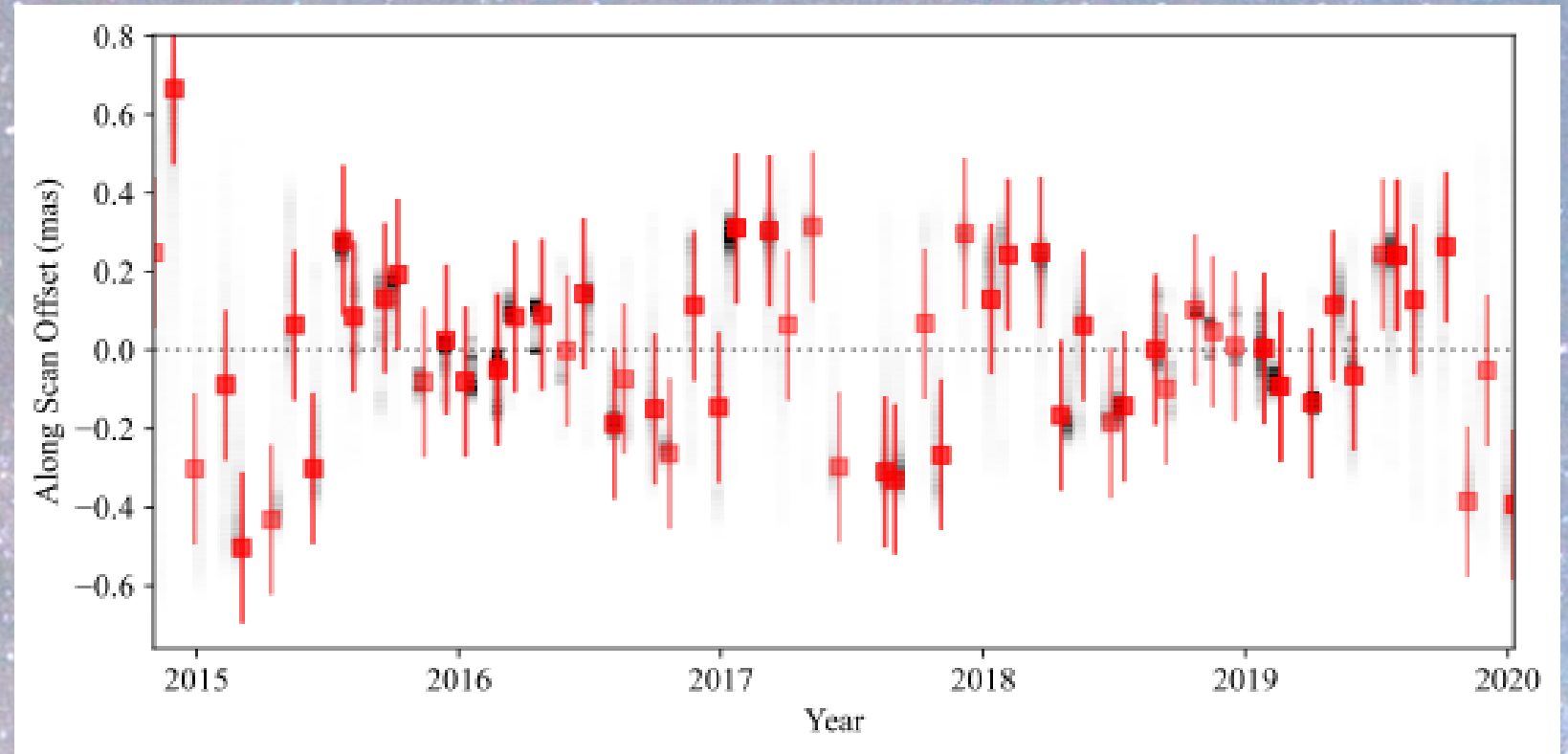
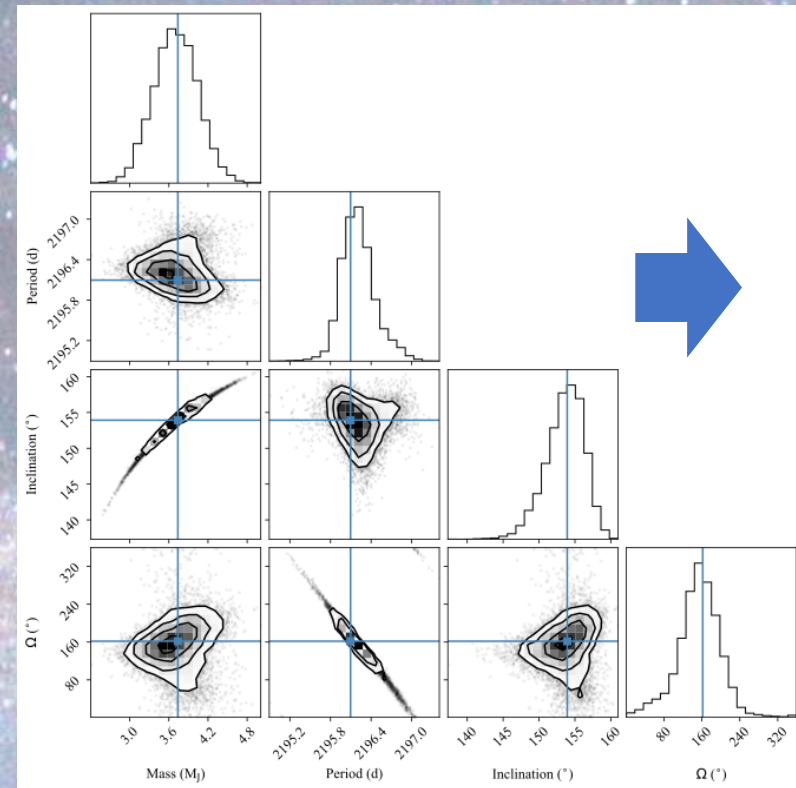


Hipparcos-Gaia Fit

Epoch Data can narrow this down

Epoch Data (DR4)

$$x_{AL} - x_0$$



Hipparcos-Gaia Fit

Epoch Data can narrow this down

Epoch Data (DR4)

Example: HD 70642

$$M_P = 3.74 M_J$$

$$P = 2196 \text{ days}$$

$$e = 0.045$$

$$i = 154^\circ$$

$$\Omega = 162^\circ$$

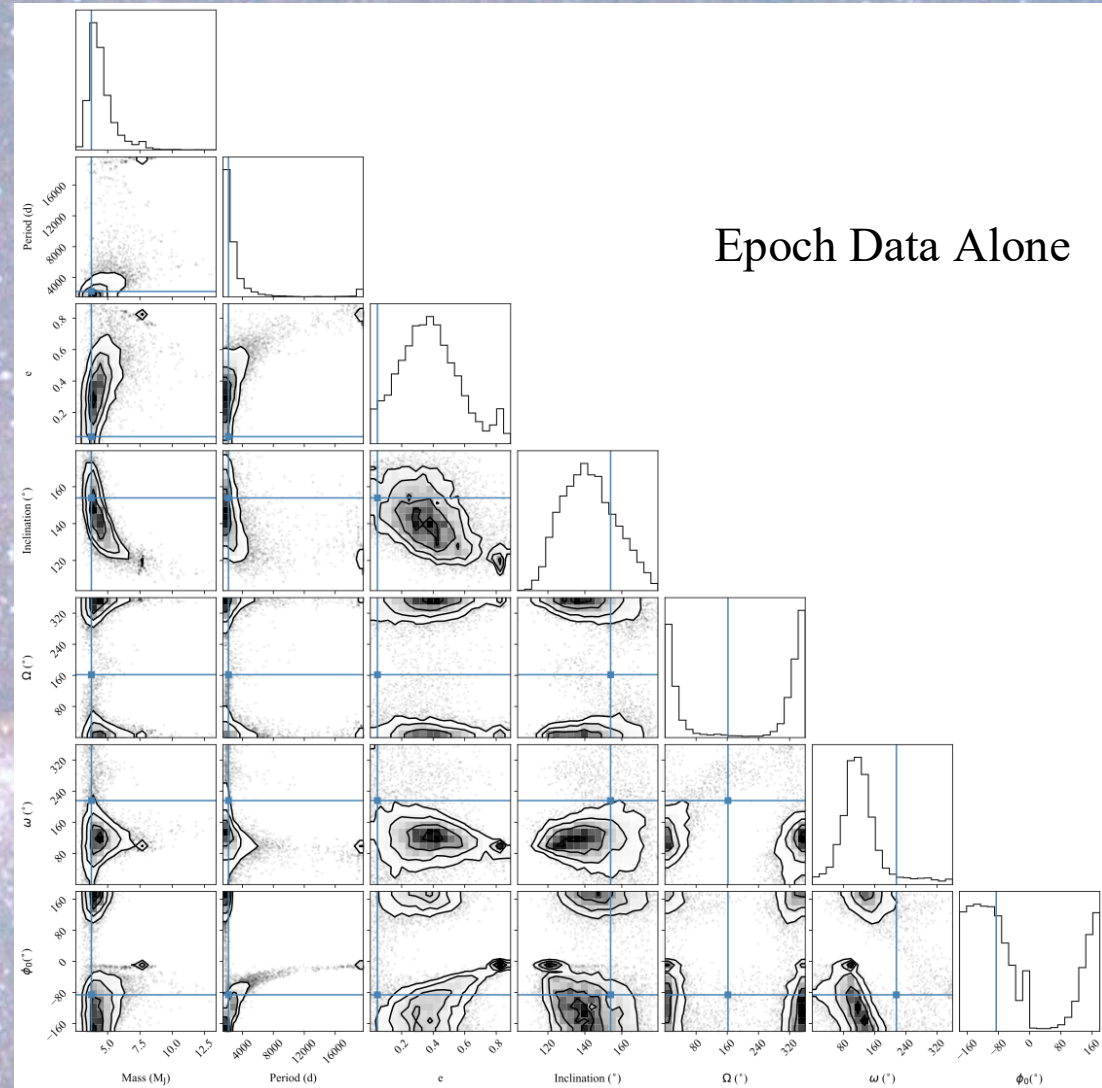
$$\omega = 216^\circ$$

$$\phi_0 = -85.9^\circ$$

Epoch Data (DR4)

Example: HD 70642

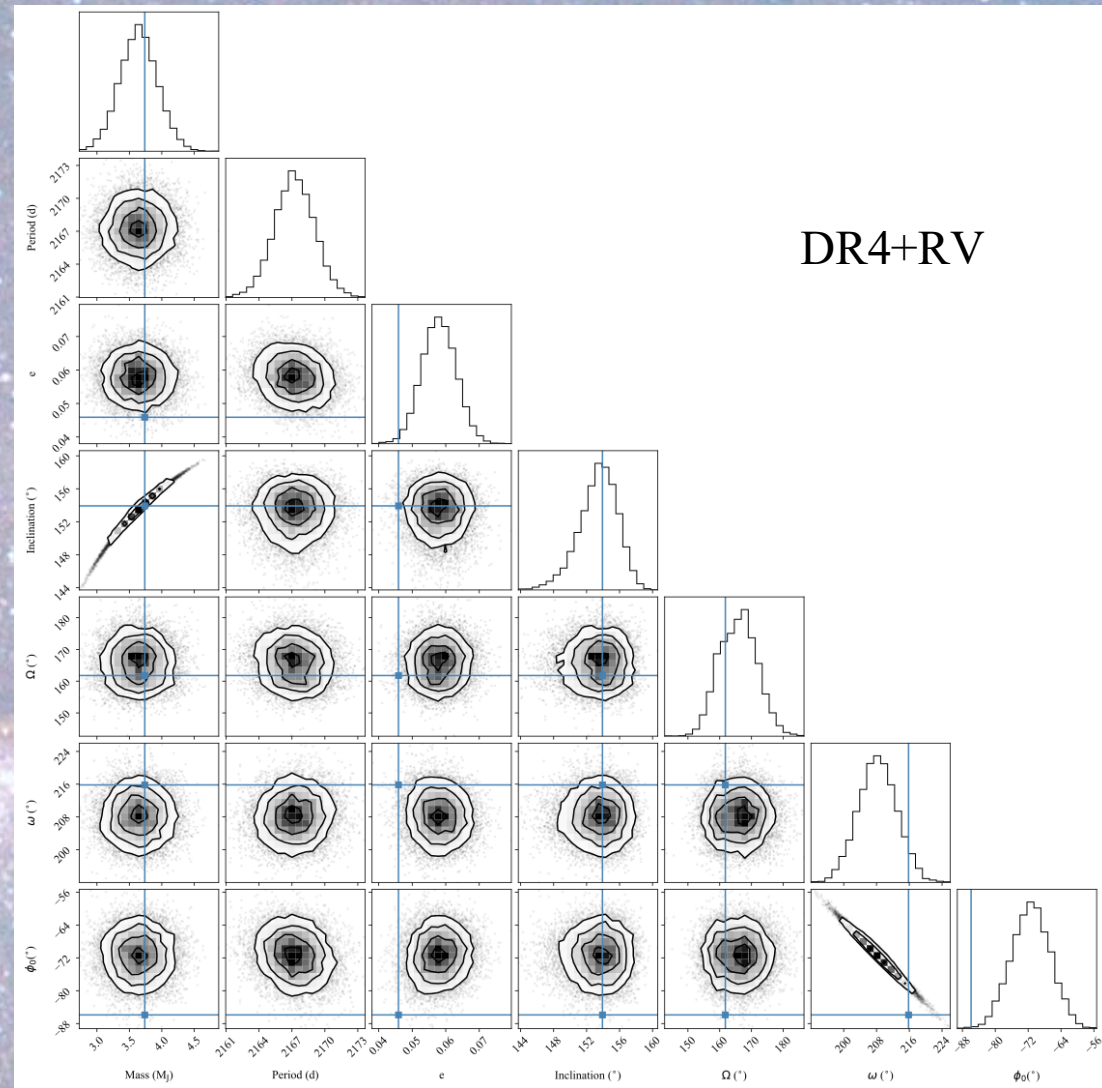
$M_P = 3.74 M_J$
 $P = 2196$ days
 $e = 0.045$
 $i = 154^\circ$
 $\Omega = 162^\circ$
 $\omega = 216^\circ$
 $\phi_0 = -85.9^\circ$



Epoch Data (DR4)

Example: HD 70642

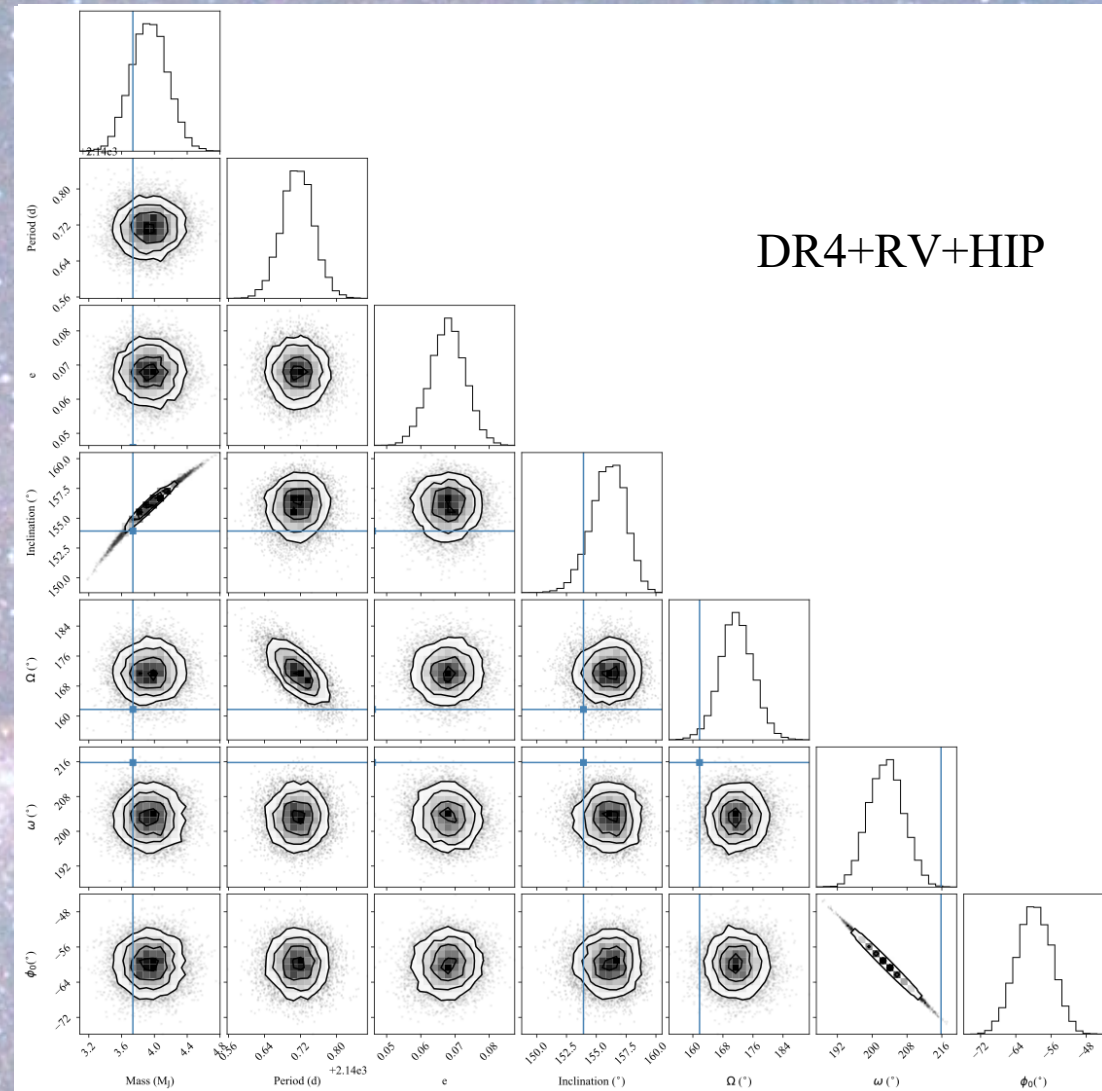
$M_P = 3.74 M_J$
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Epoch Data (DR4)

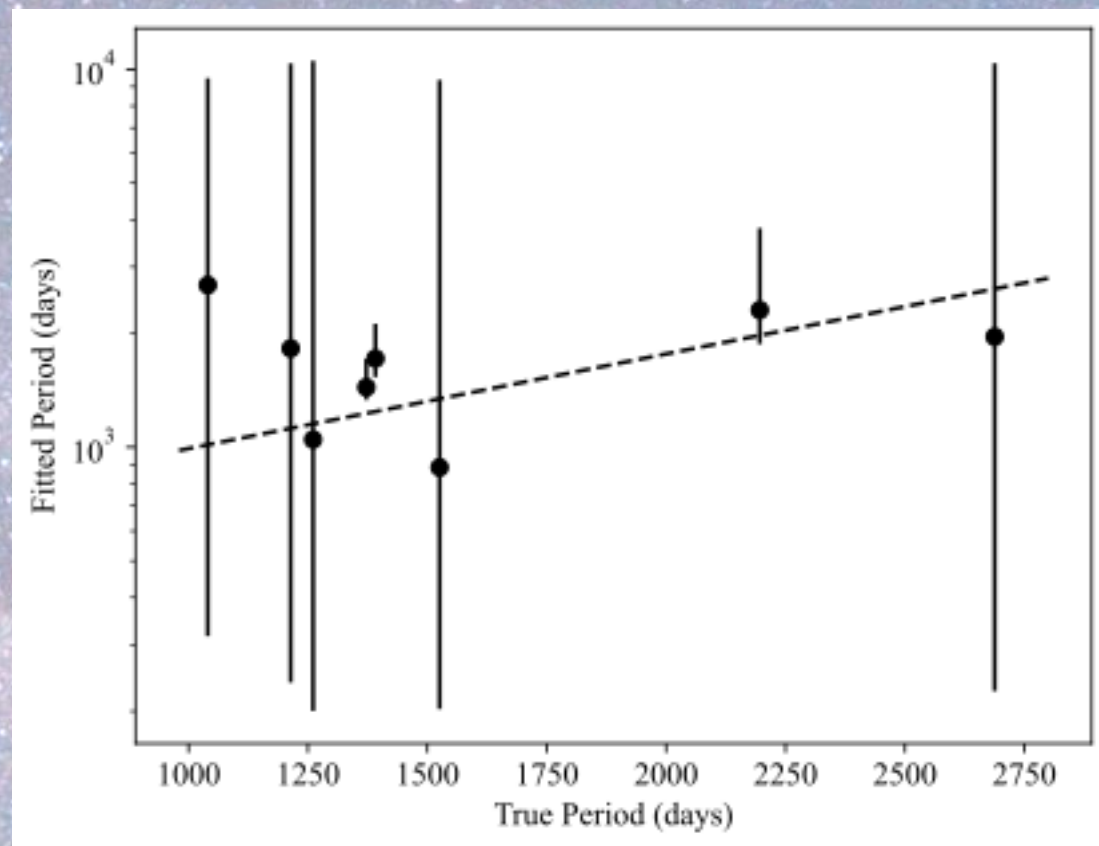
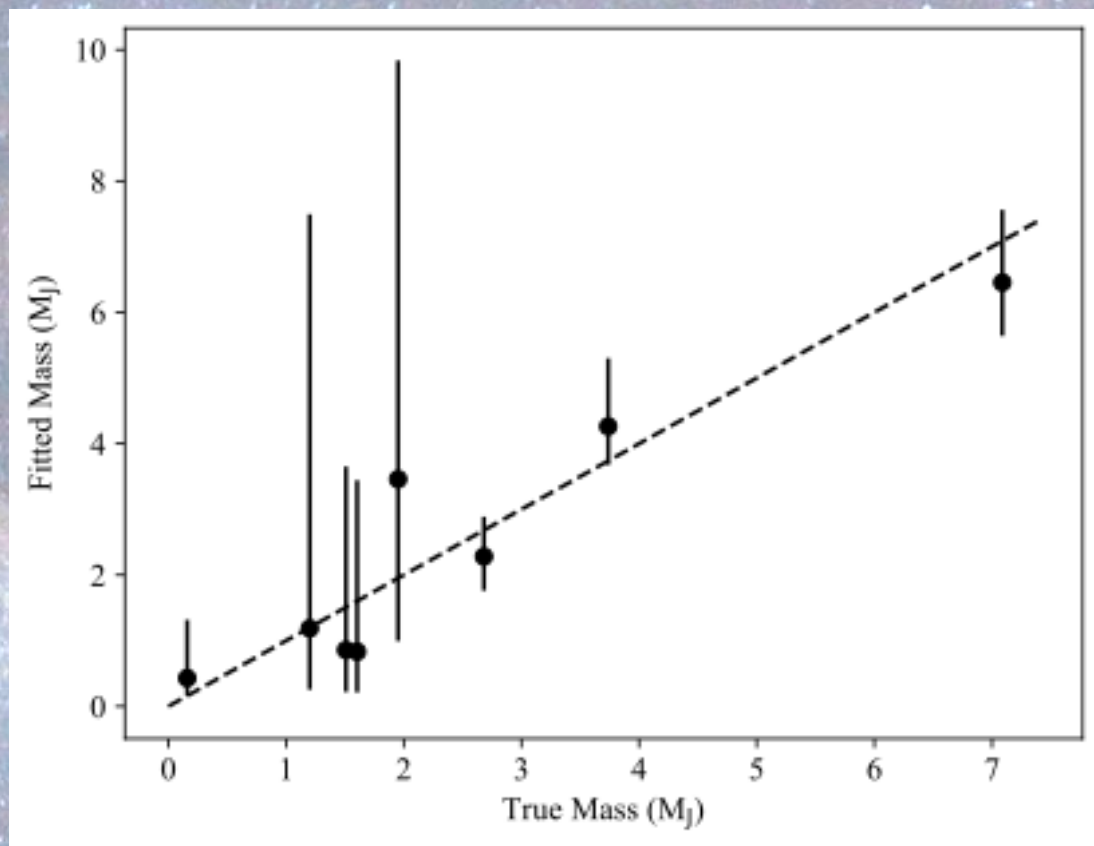
Example: HD 70642

$M_P = 3.74 M_J$
 $P = 2196$ days
 $e = 0.045$
 $i = 154^\circ$
 $\Omega = 162^\circ$
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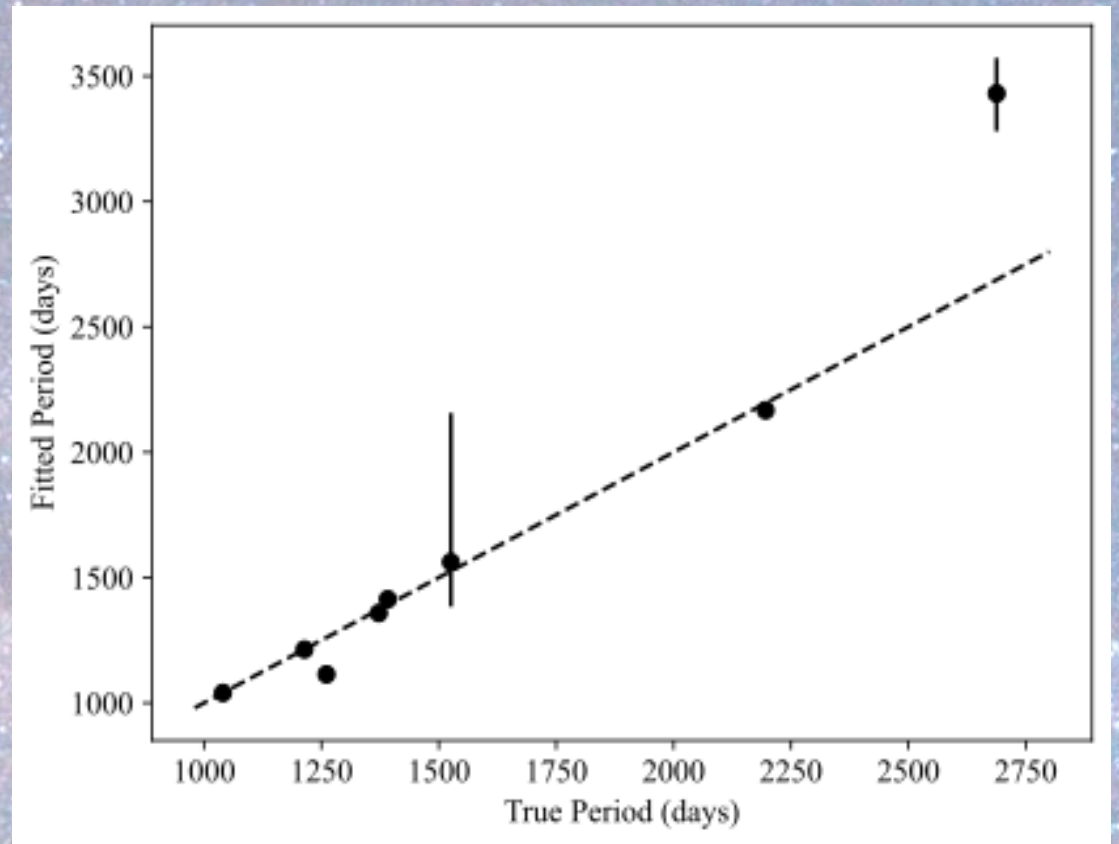
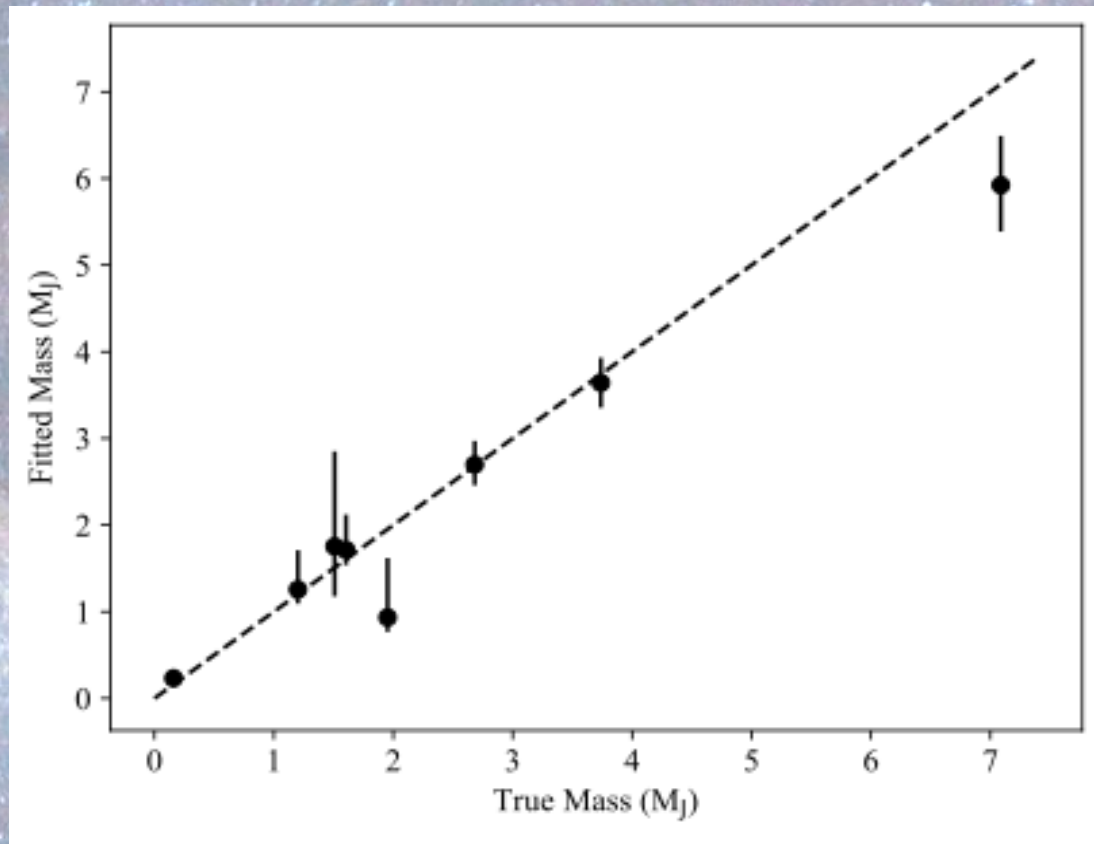
Epoch Data (DR4)

Epoch Data Alone



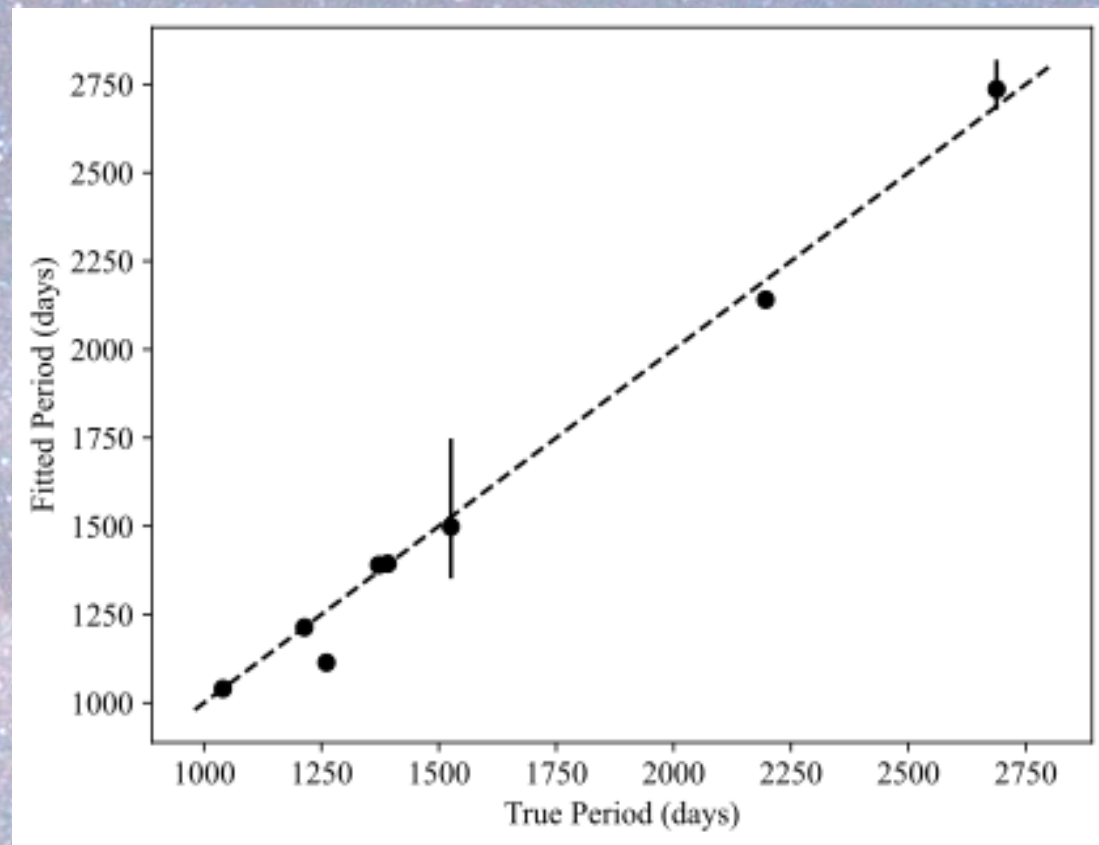
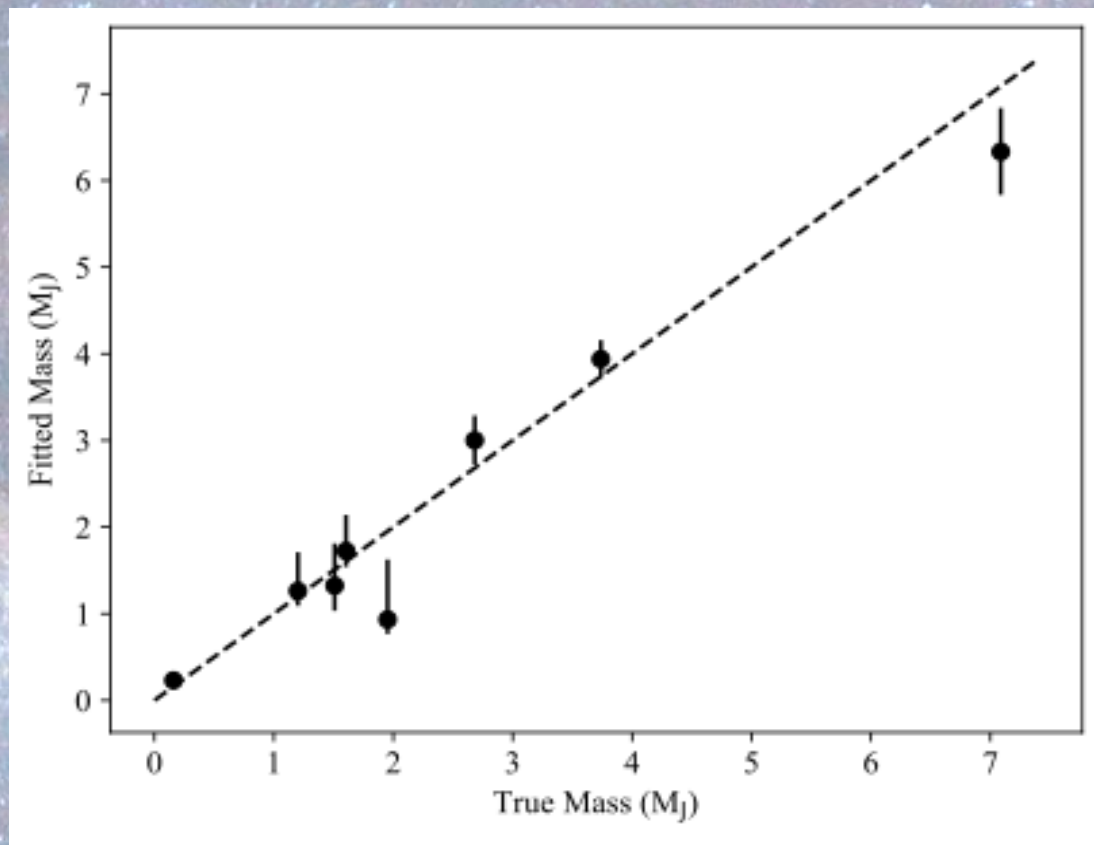
Epoch Data (DR4)

DR4+RV

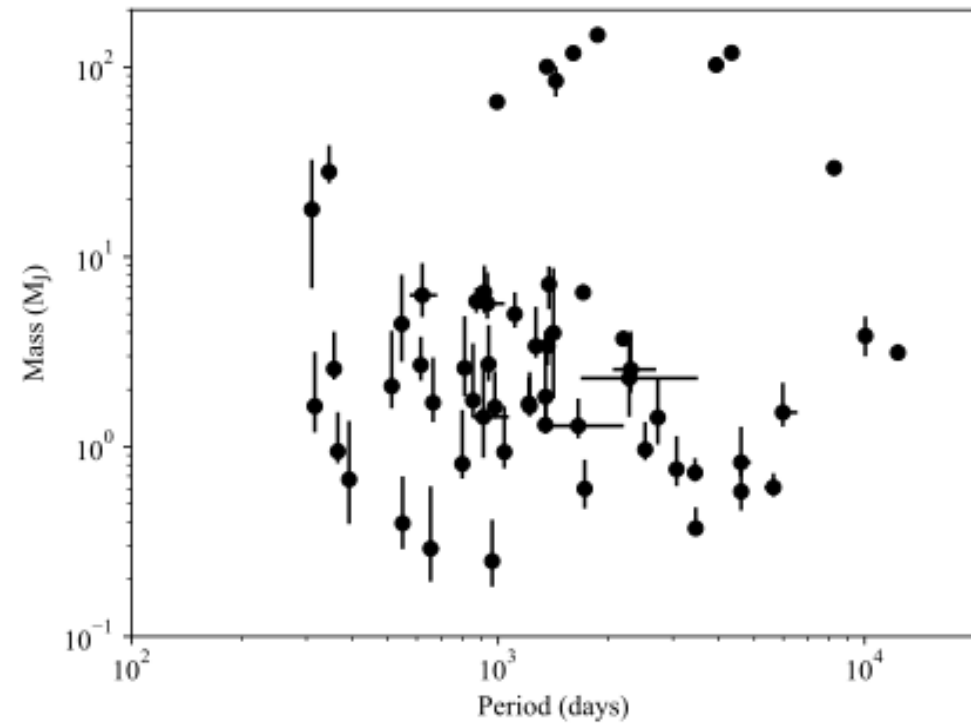


Epoch Data (DR4)

DR4+RV+HIP

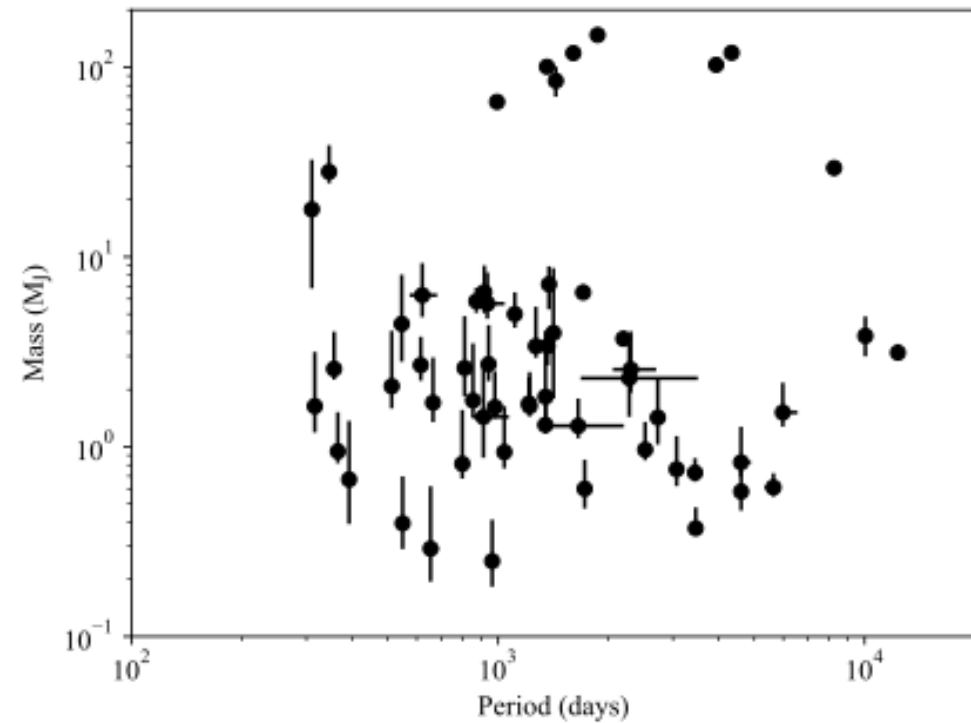


Summary & Future



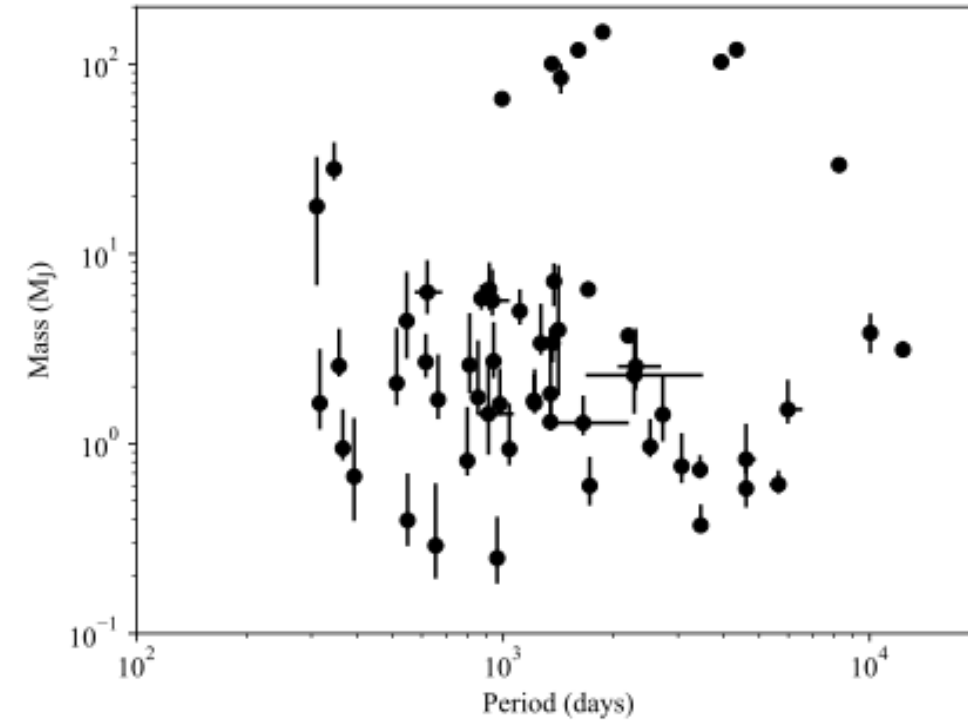
Summary & Future

- RV/Gaia place lower/upper limits on mass



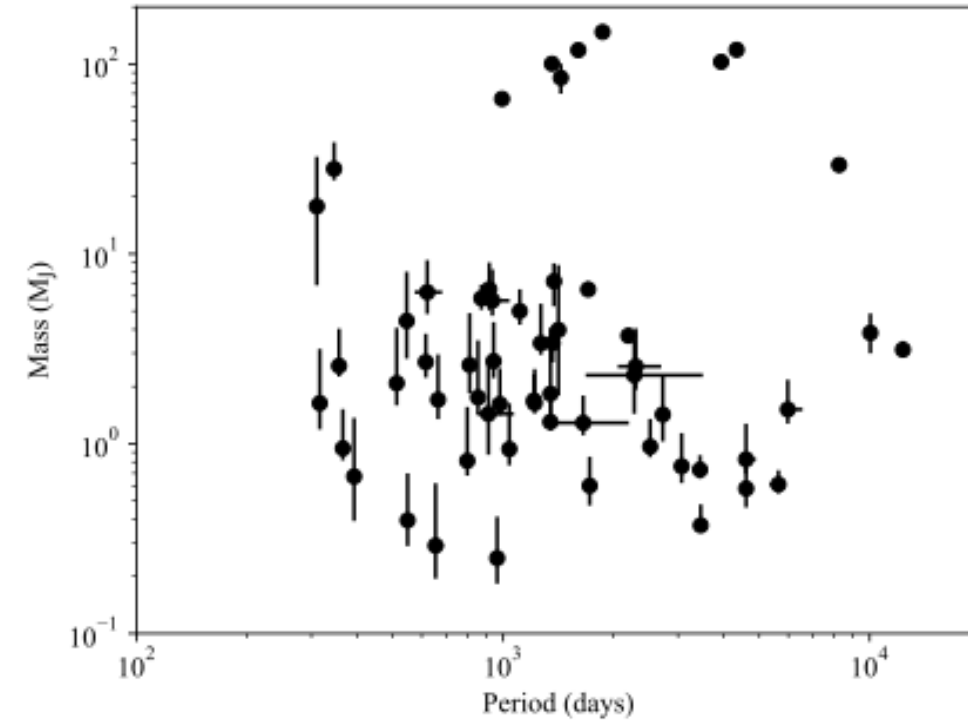
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- RV/Gaia place lower/upper limits on mass
- Combine to resolve mass-inclination degeneracy



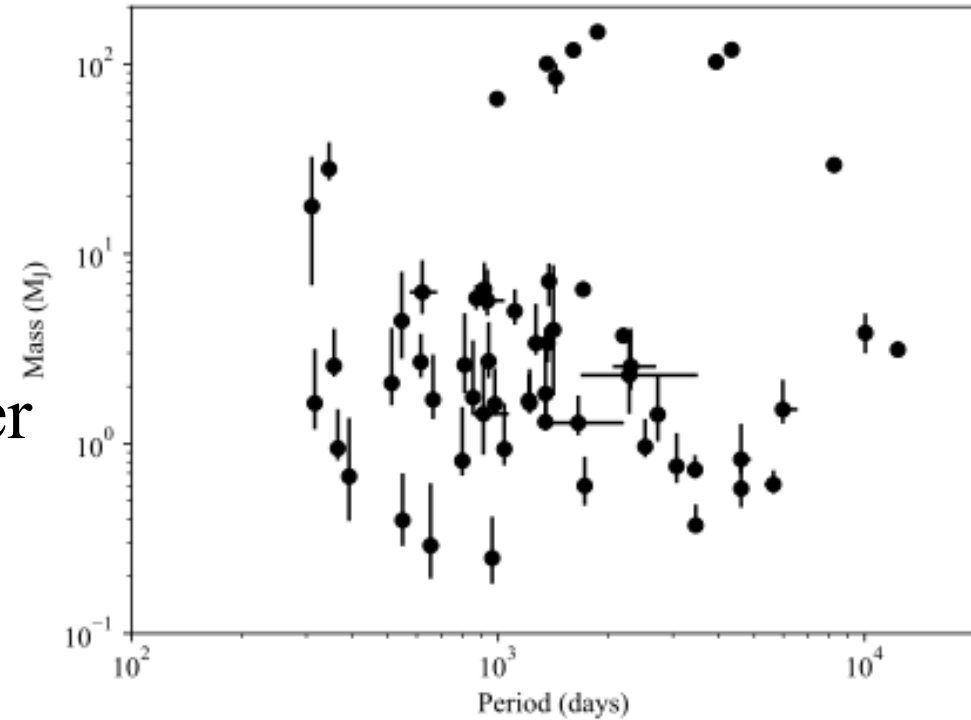
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- Hipparcos is needed for longer periods



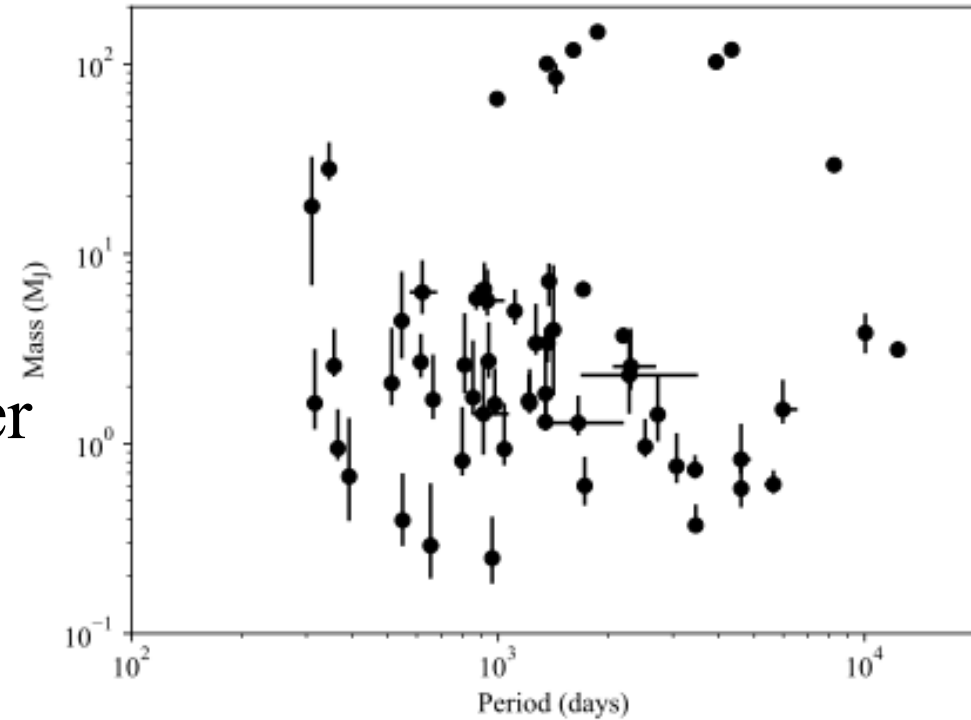
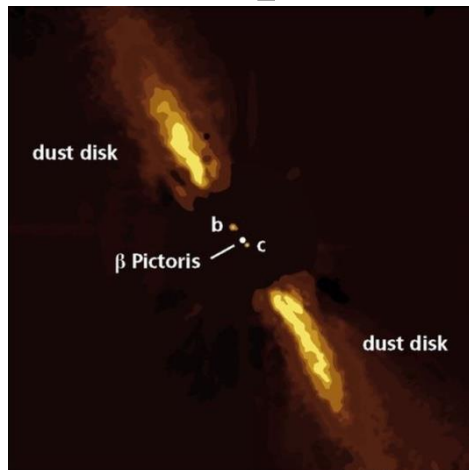
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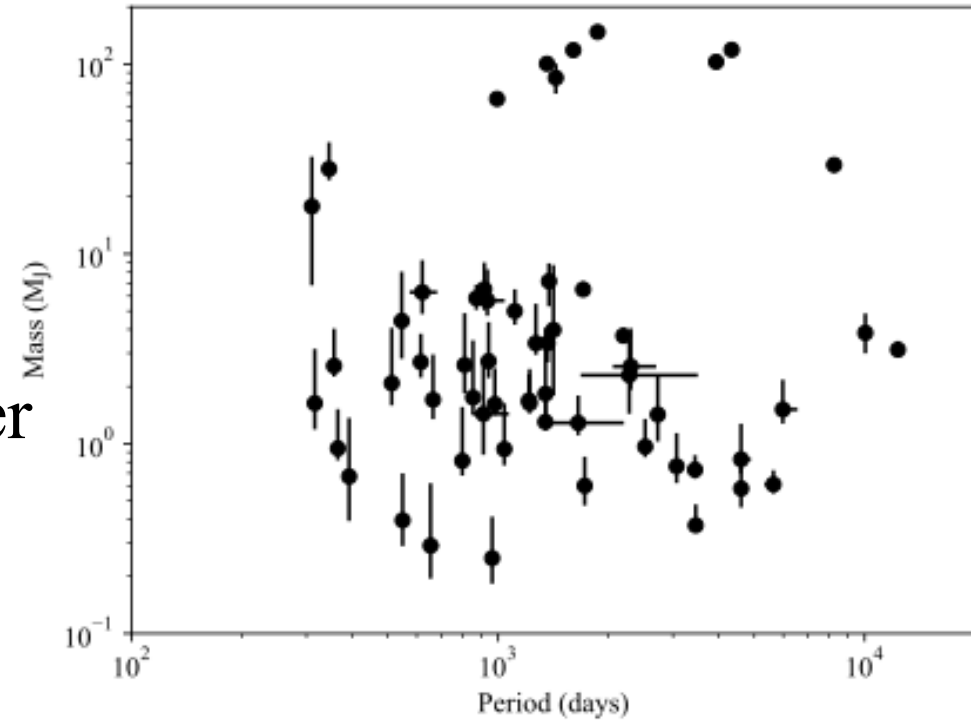
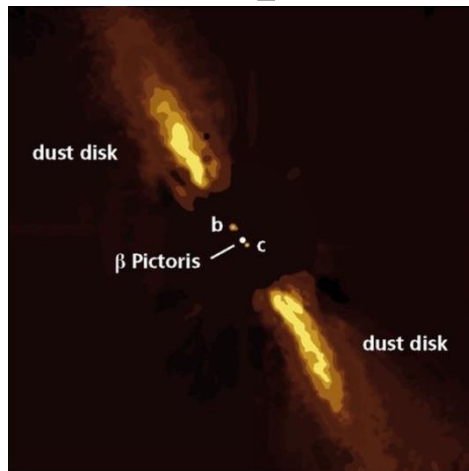
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More results to come