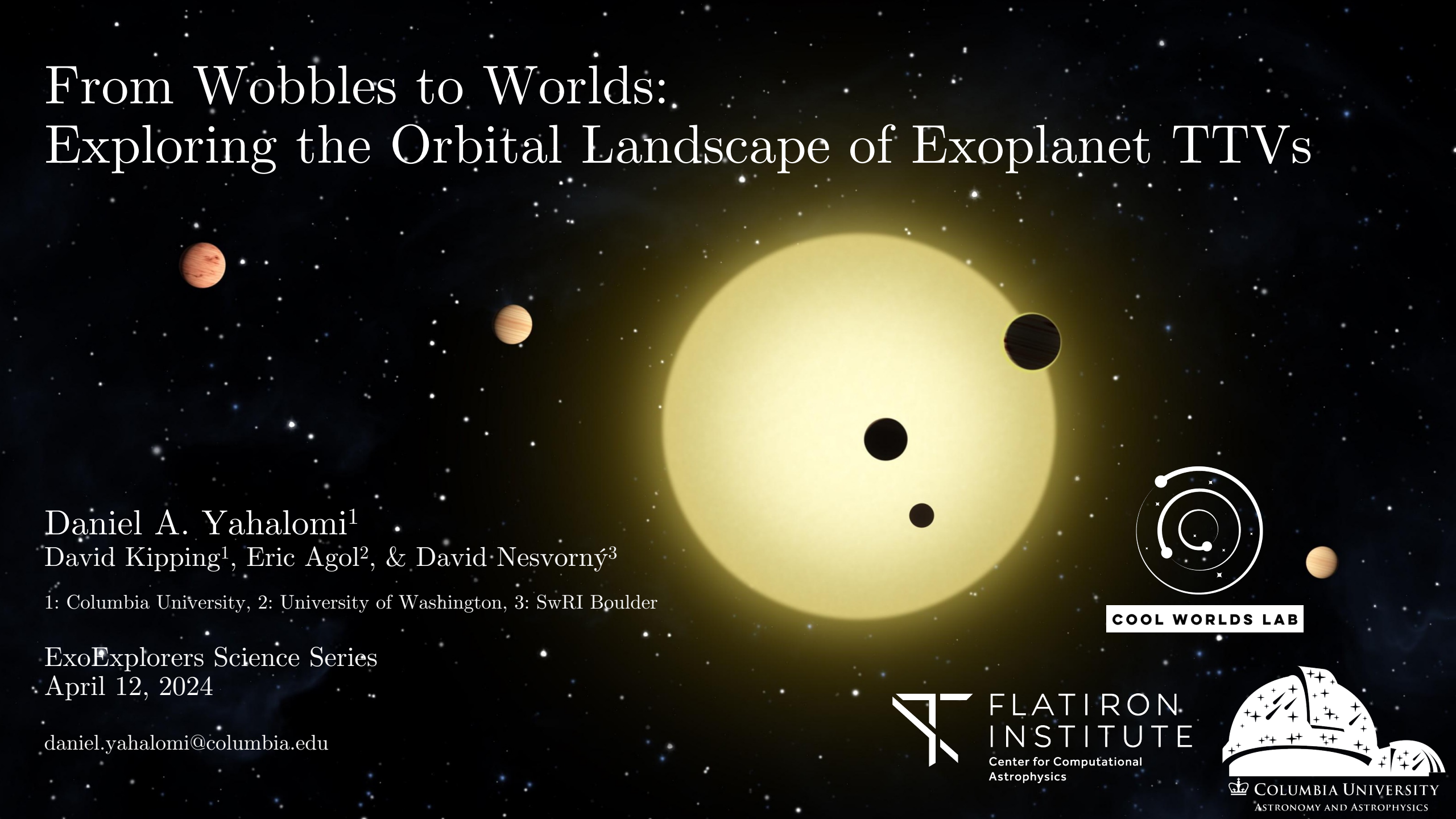
From Wobbles to Worlds: Exploring the Orbital Landscape of Exoplanet TTVs



Daniel A. Yahalomi[1]
David Kipping[1], Eric Agol[2], & David Nesvorný[3]

1: Columbia University, 2: University of Washington, 3: SwRI Boulder

ExoExplorers Science Series
April 12, 2024

daniel.yahalomi@columbia.edu

COOL WORLDS LAB

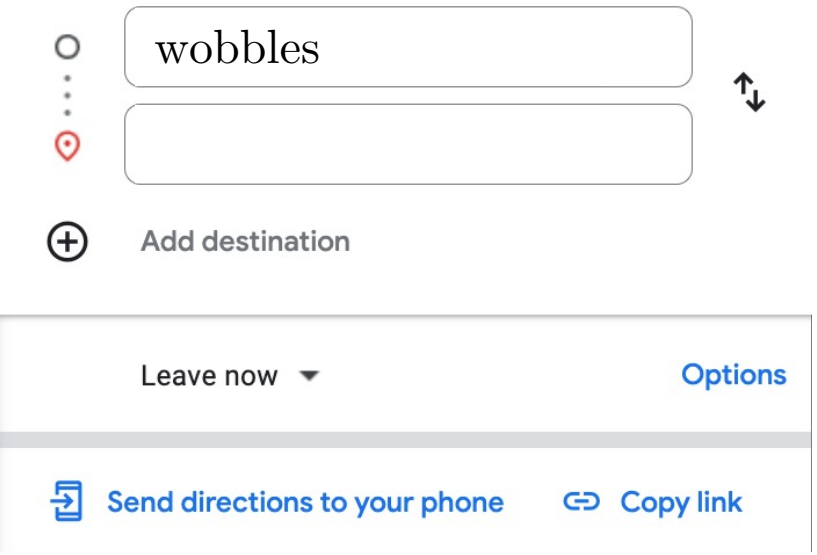
FLATIRON INSTITUTE
Center for Computational Astrophysics

COLUMBIA UNIVERSITY
ASTRONOMY AND ASTROPHYSICS

roadmap

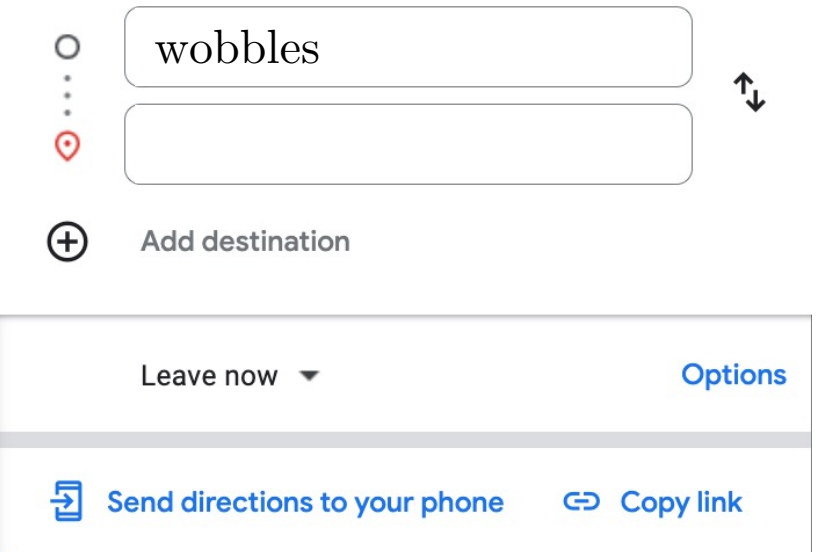
daniel.yahalomi@columbia.edu

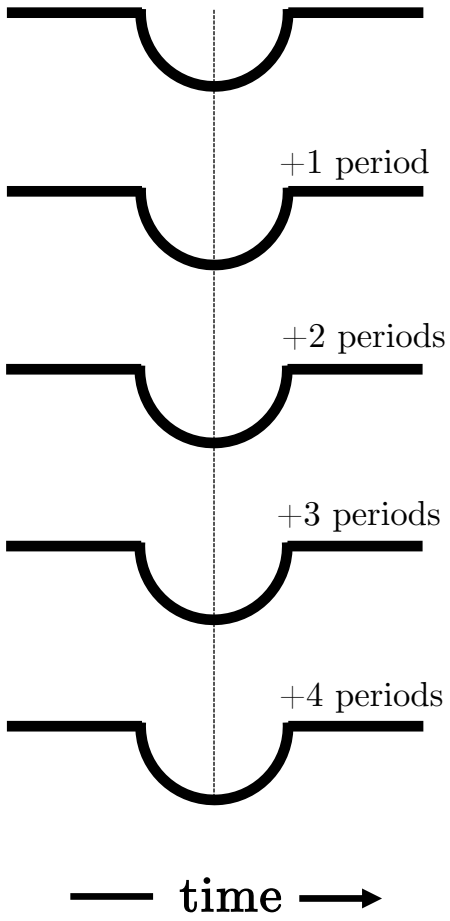
roadmap



daniel.yahalomi@columbia.edu

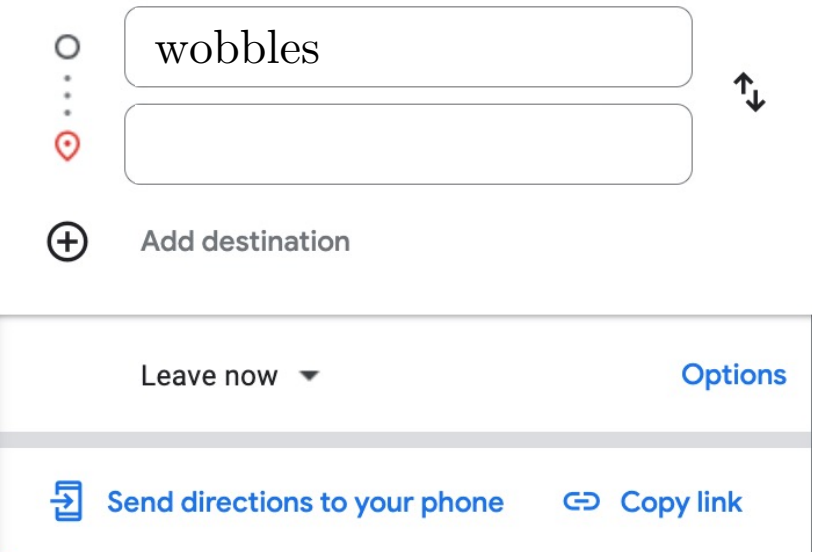
roadmap

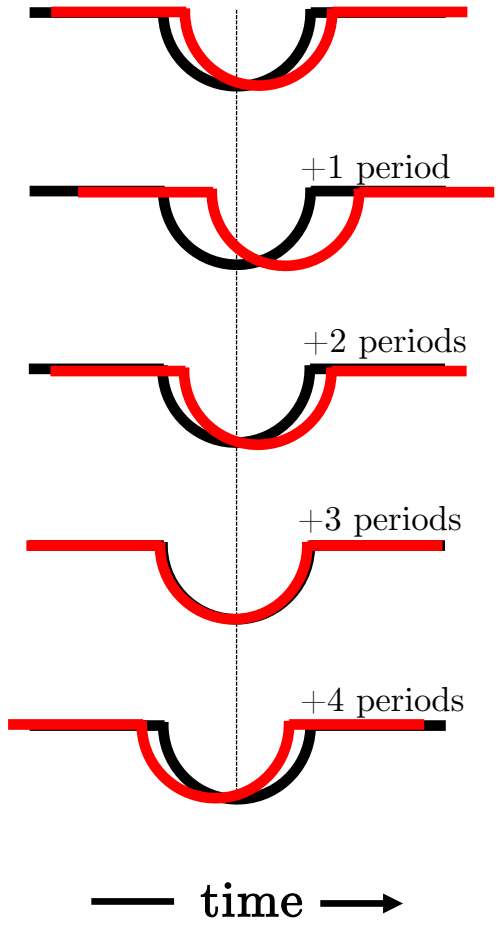




daniel.yahalomi@columbia.edu

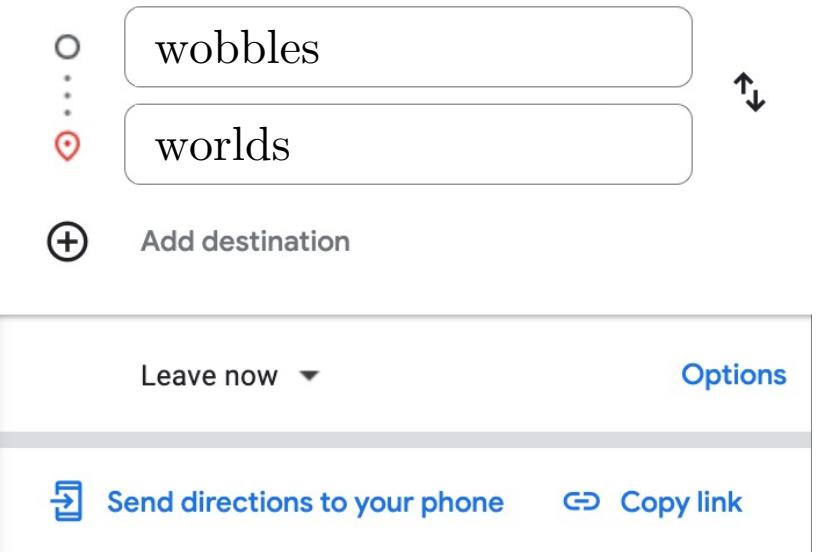
roadmap

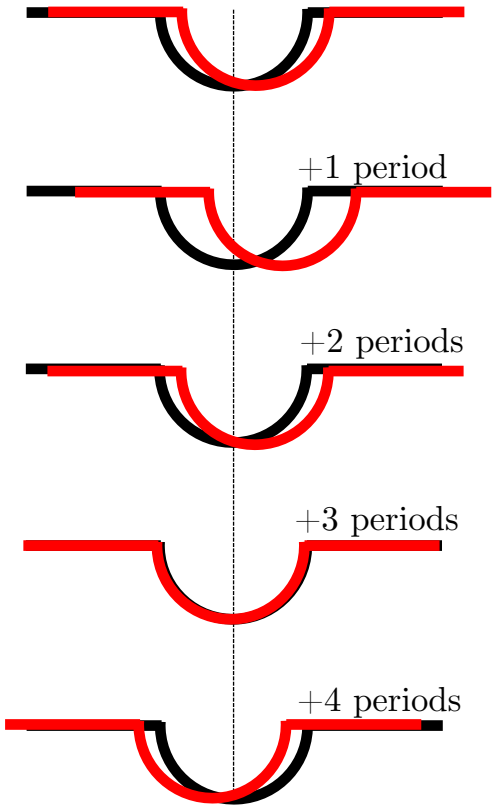


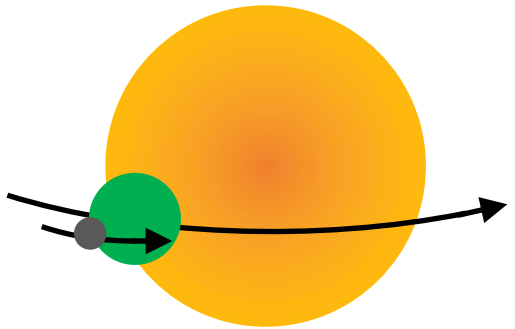


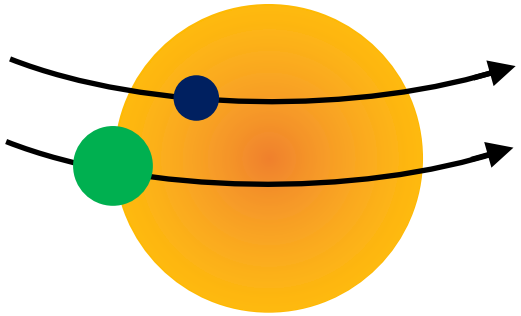
daniel.yahalomi@columbia.edu

roadmap









daniel.yahalomi@columbia.edu

roadmap

wobbles

worlds

Add destination

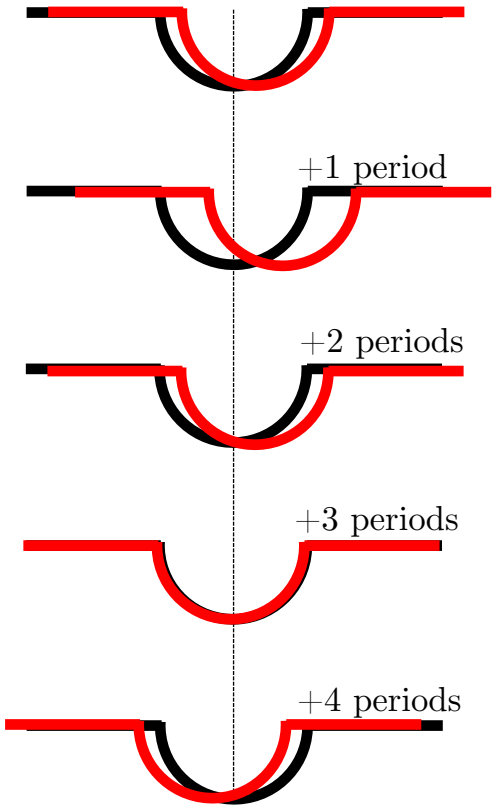
Leave now

Options

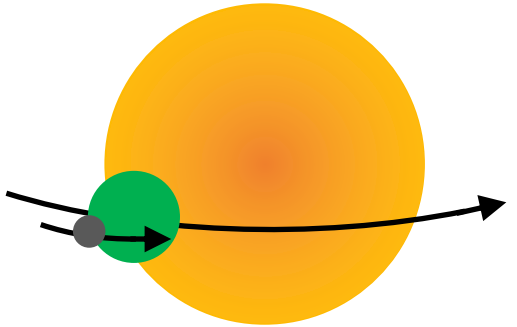
Send directions to your phone

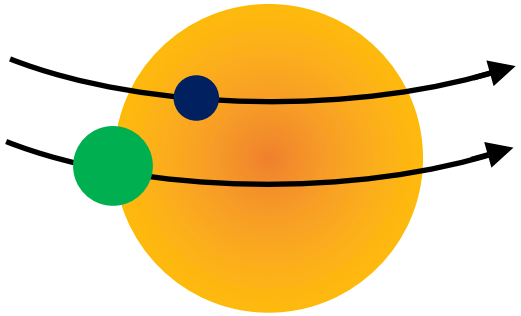
Copy link

via exomoon corridor



exomoon corridor





daniel.yahalomi@columbia.edu

roadmap

wobbles

worlds

Add destination

Leave now

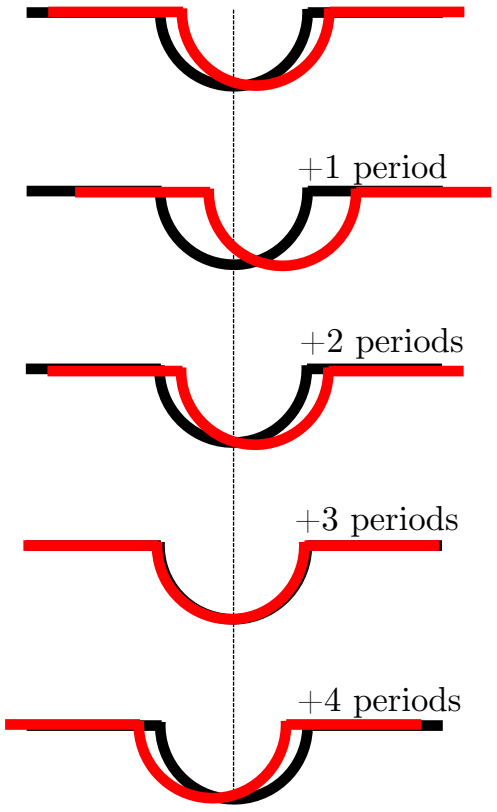
Options

Send directions to your phone

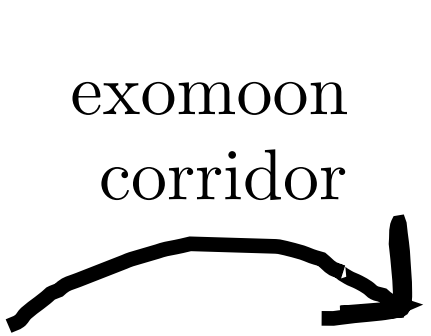
Copy link

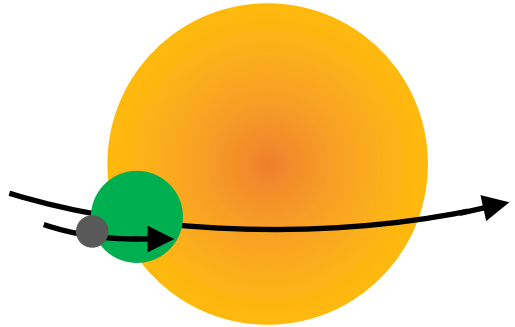
via exomoon corridor

via exoplanet edge

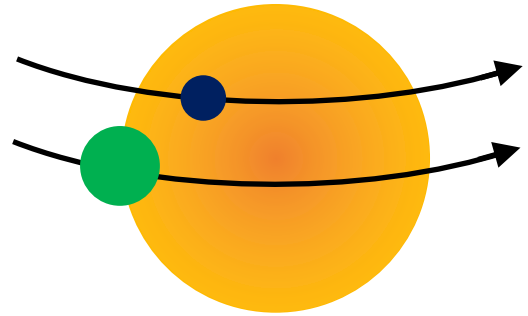


exomoon corridor





exoplanet edge



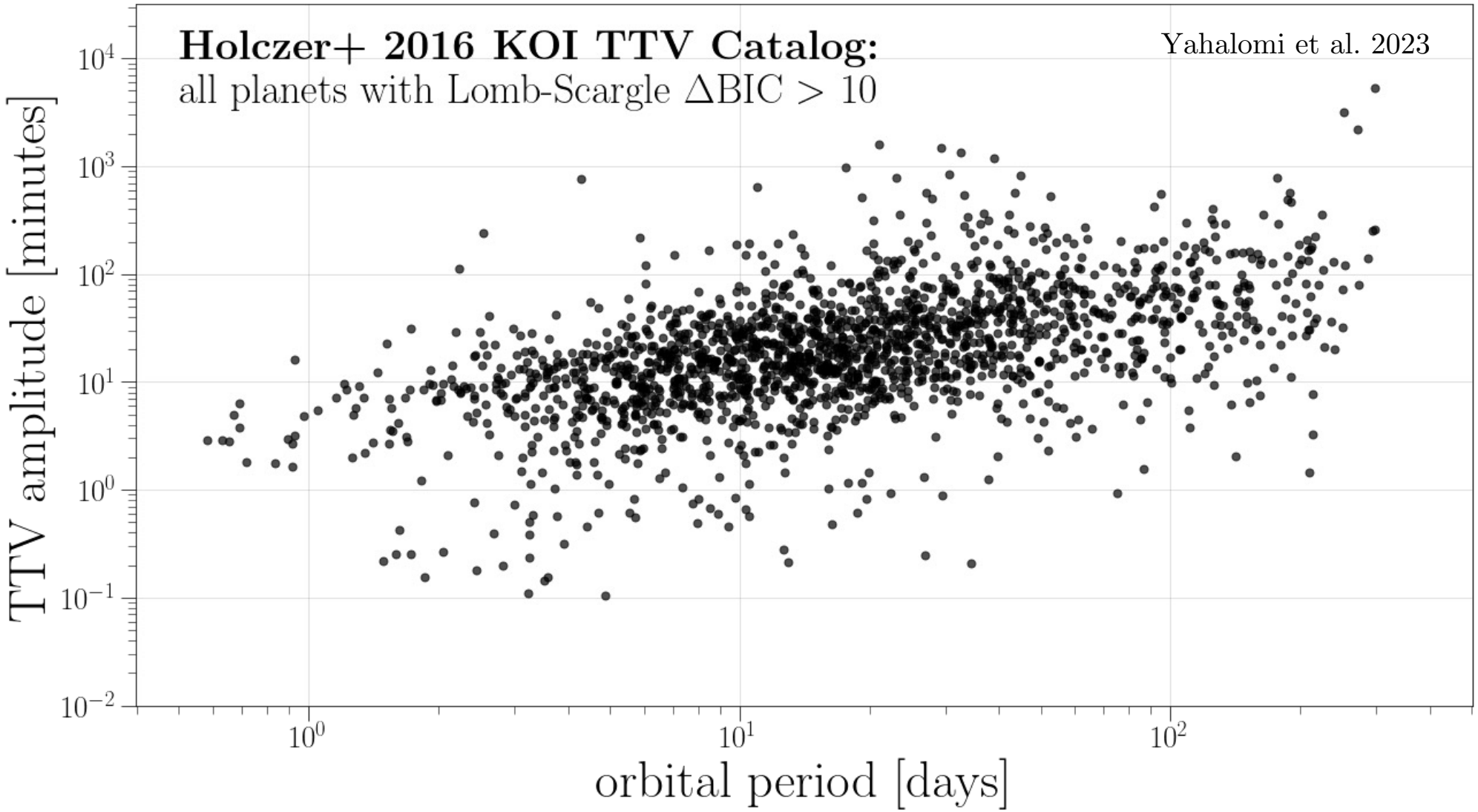
daniel.yahalomi@columbia.edu

daniel.yahalomi@columbia.edu

TTVs are ubiquitous!

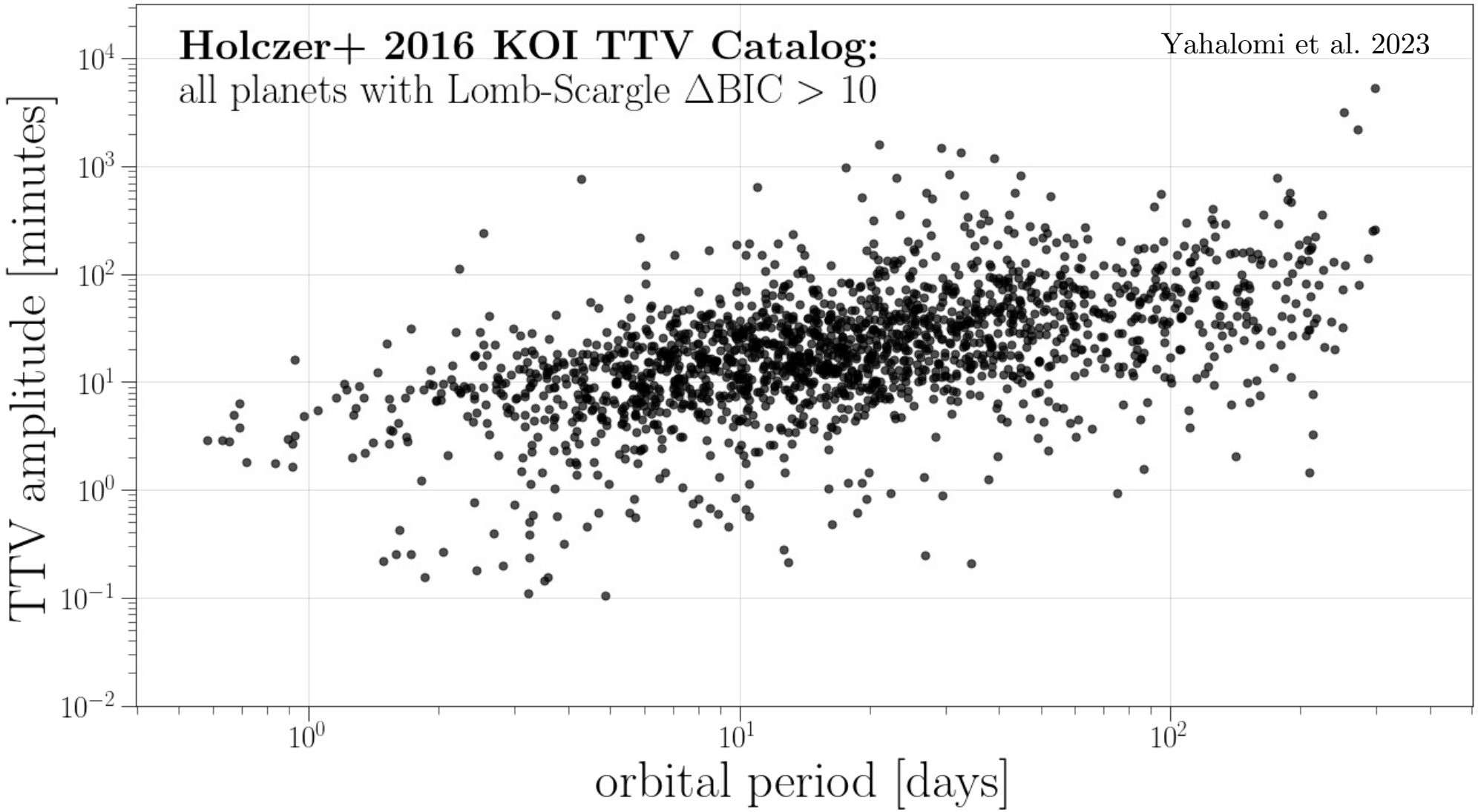
daniel.yahalomi@columbia.edu

TTVs are ubiquitous!



daniel.yahalomi@columbia.edu

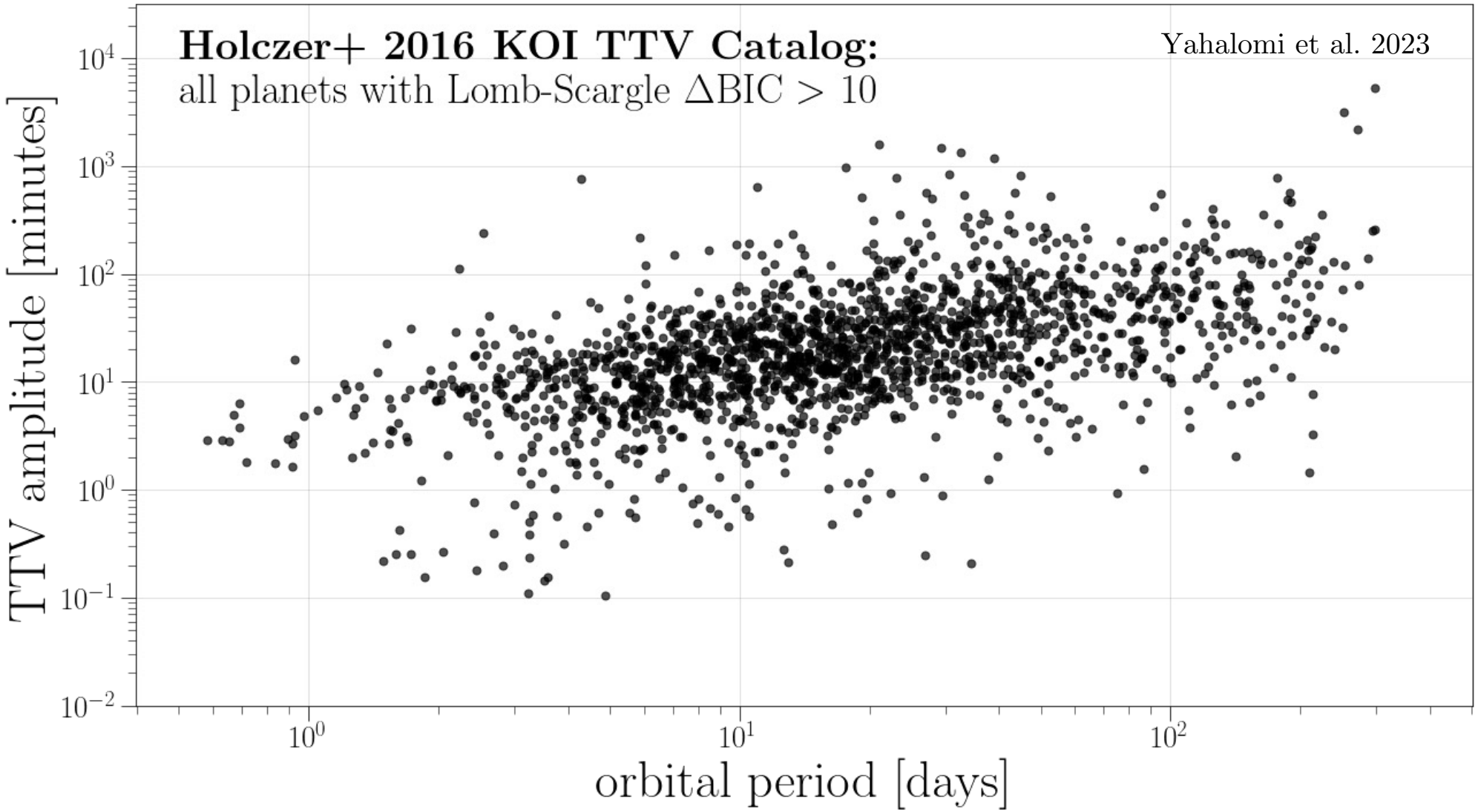
1889 KOIs "strongly favor" (ΔBIC > 10) sinusoidal TTV model over linear ephemeris



daniel.yahalomi@columbia.edu

(nearly 75% of the systems in Holczer+ 2016 catalog)

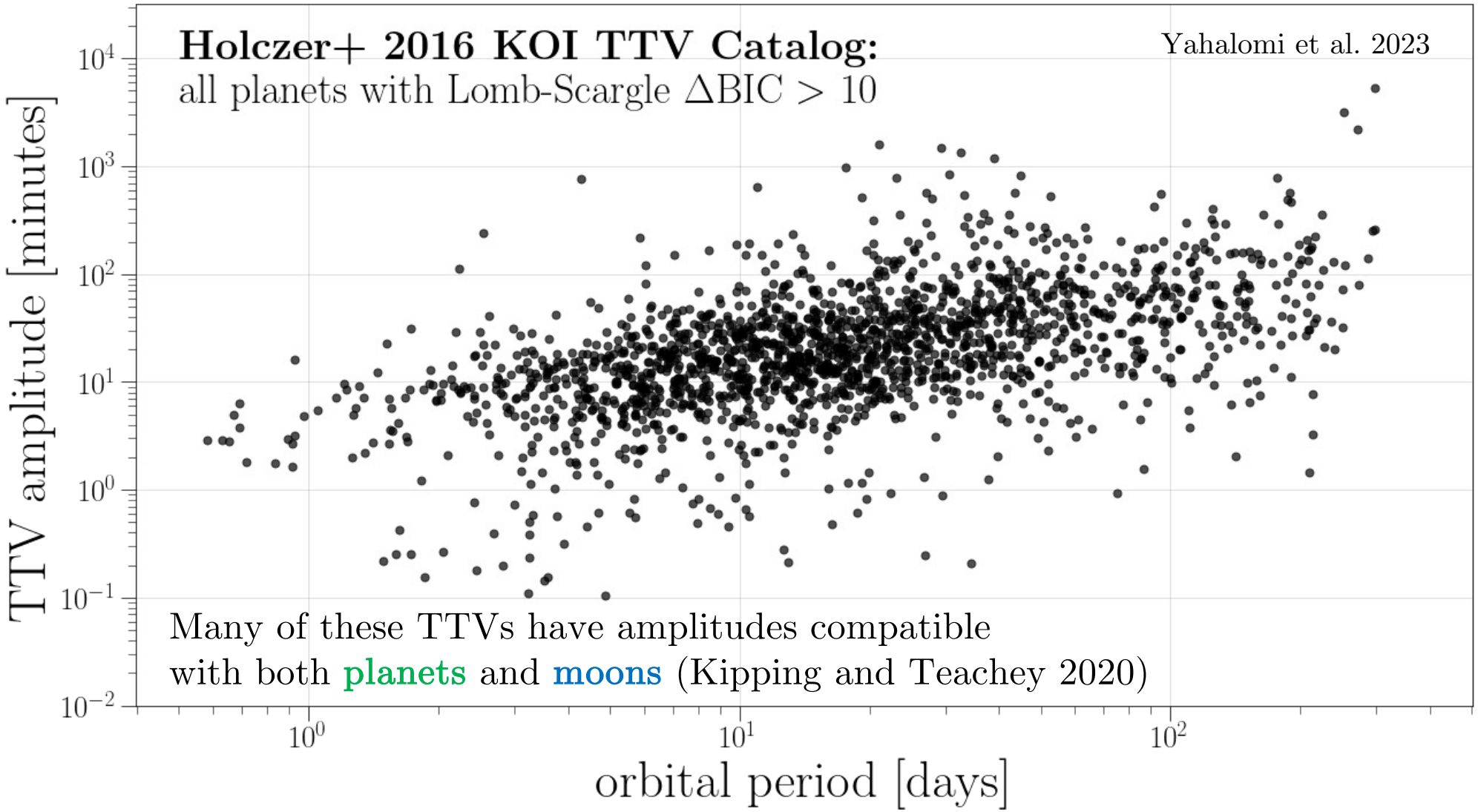
1889 KOIs "strongly favor" (ΔBIC > 10) sinusoidal TTV model over linear ephemeris



daniel.yahalomi@columbia.edu

(nearly 75% of the systems in Holczer+ 2016 catalog)

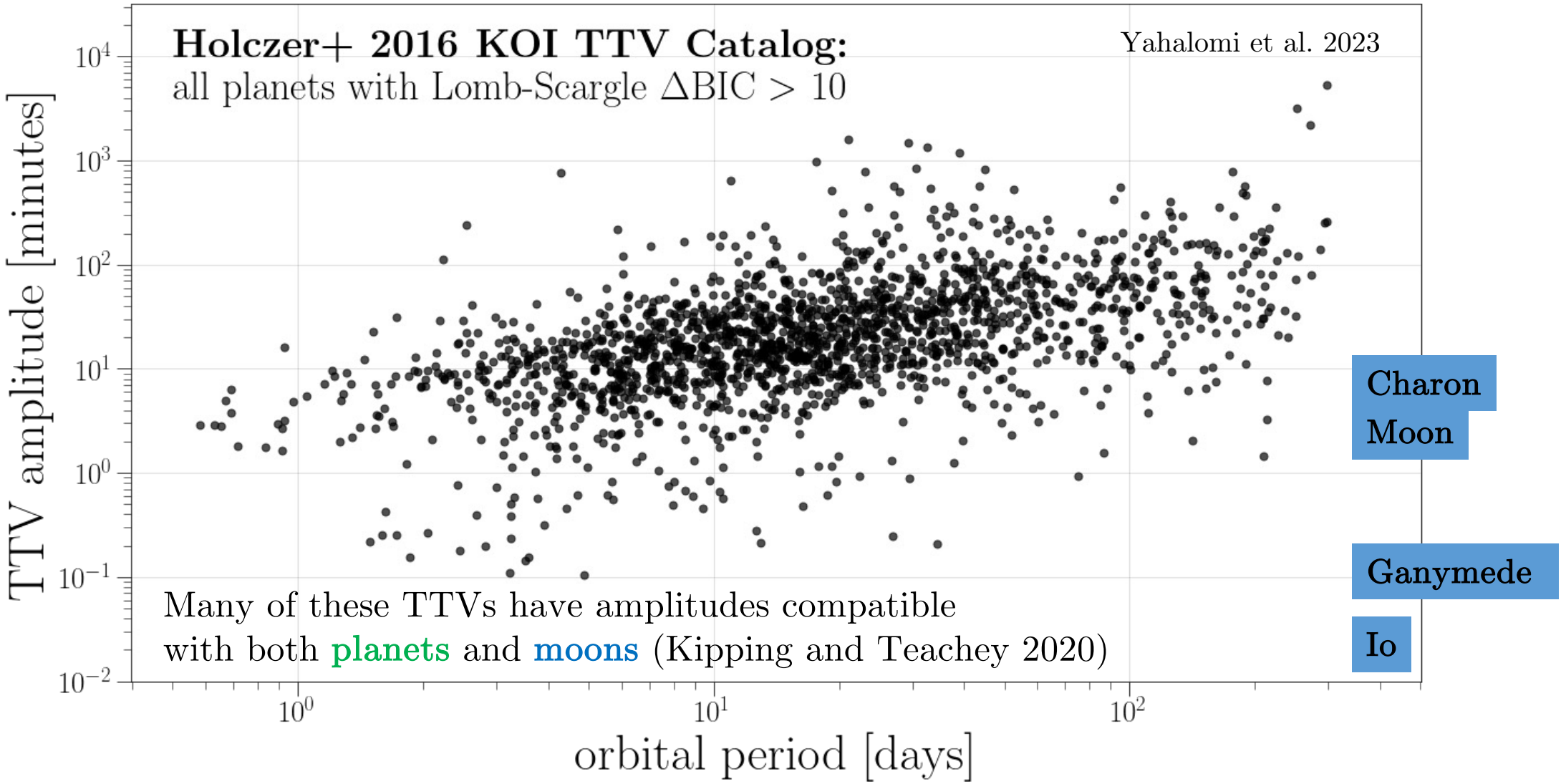
1889 KOIs "strongly favor" (ΔBIC > 10) sinusoidal TTV model over linear ephemeris



daniel.yahalomi@columbia.edu

(nearly 75% of the systems in Holczer+ 2016 catalog)

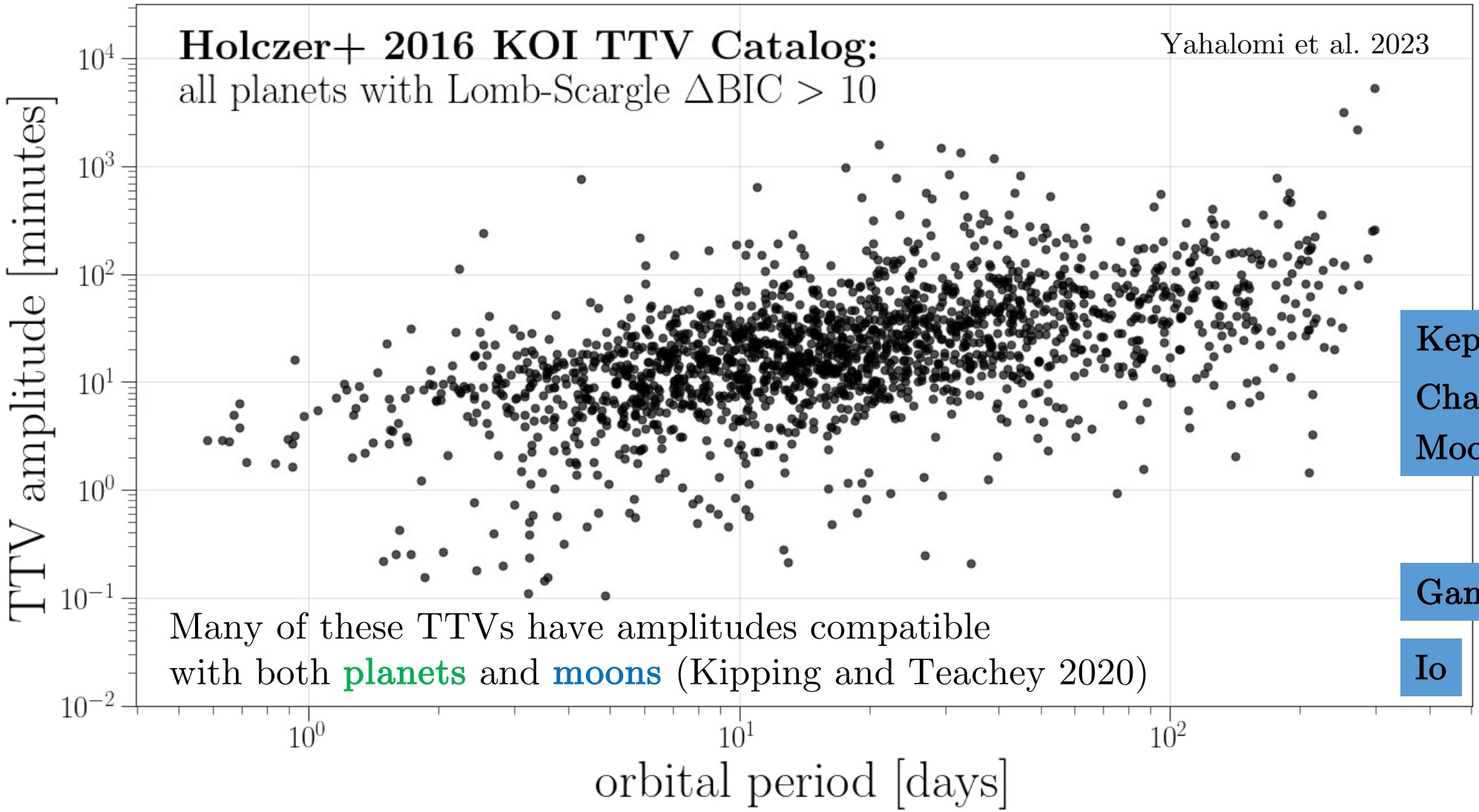
1889 KOIs "strongly favor" (ΔBIC > 10) sinusoidal TTV model over linear ephemeris



daniel.yahalomi@columbia.edu

(nearly 75% of the systems in Holczer+ 2016 catalog)

1889 KOIs "strongly favor" (ΔBIC > 10) sinusoidal TTV model over linear ephemeris

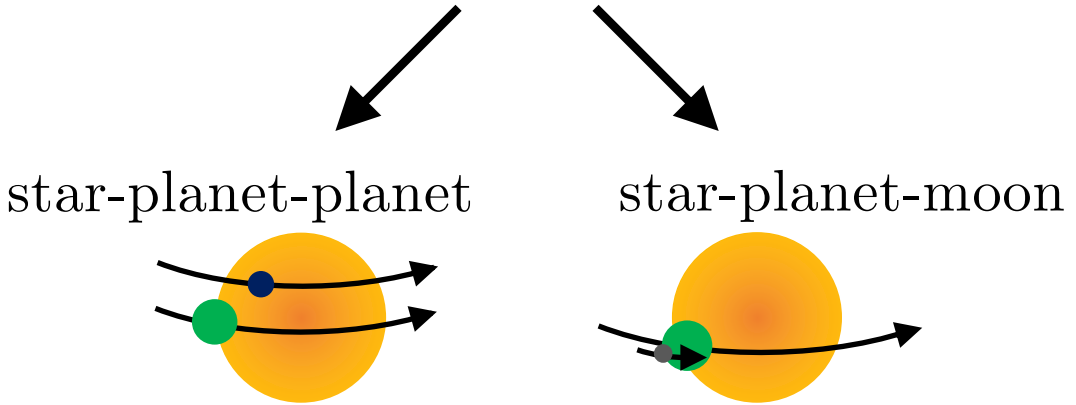


daniel.yahalomi@columbia.edu

TTVs alone are **ambiguous**

daniel.yahalomi@columbia.edu

TTVs alone are **ambiguous**

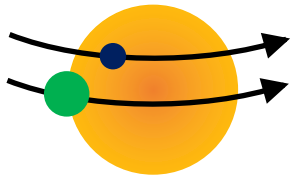


daniel.yahalomi@columbia.edu

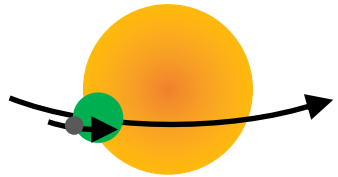
Early days of planet hunting, a transit alone was **ambiguous**

TTVs alone are **ambiguous**

star-planet-planet



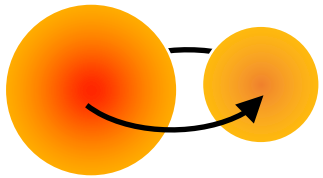
star-planet-moon



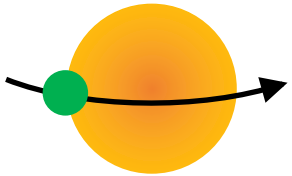
daniel.yahalomi@columbia.edu

Early days of planet hunting, a transit alone was **ambiguous**

star-star

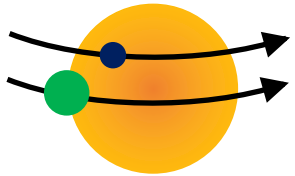


star-planet

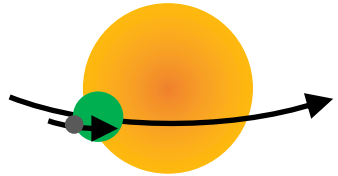


TTVs alone are **ambiguous**

star-planet-planet

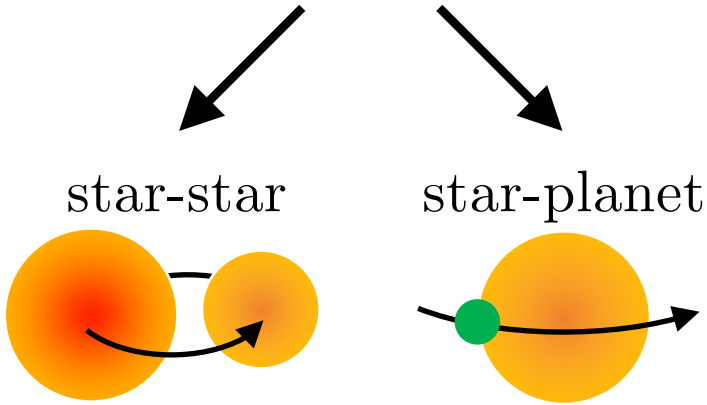


star-planet-moon

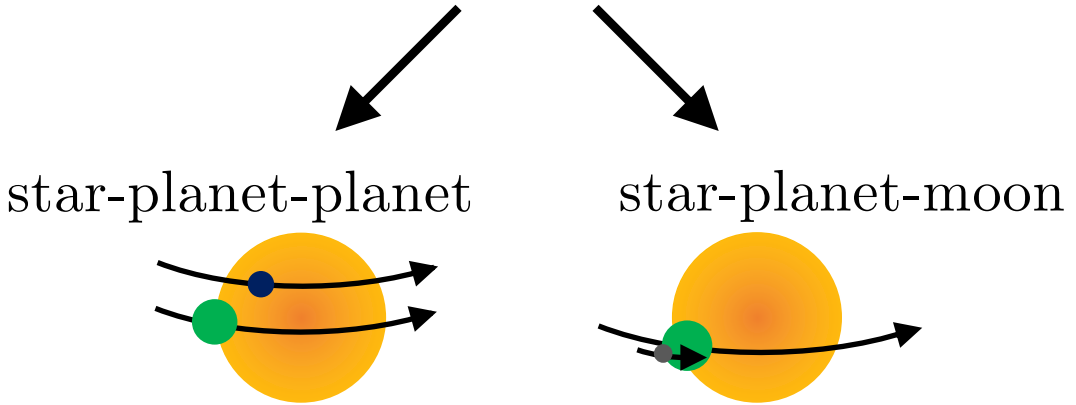


daniel.yahalomi@columbia.edu

Early days of planet hunting, a transit alone was **ambiguous**



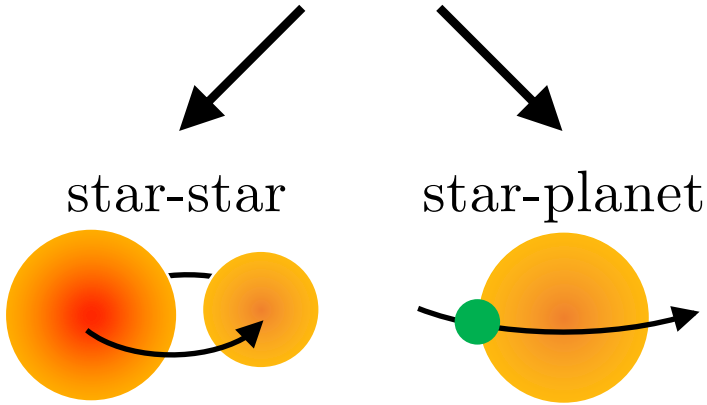
TTVs alone are **ambiguous**



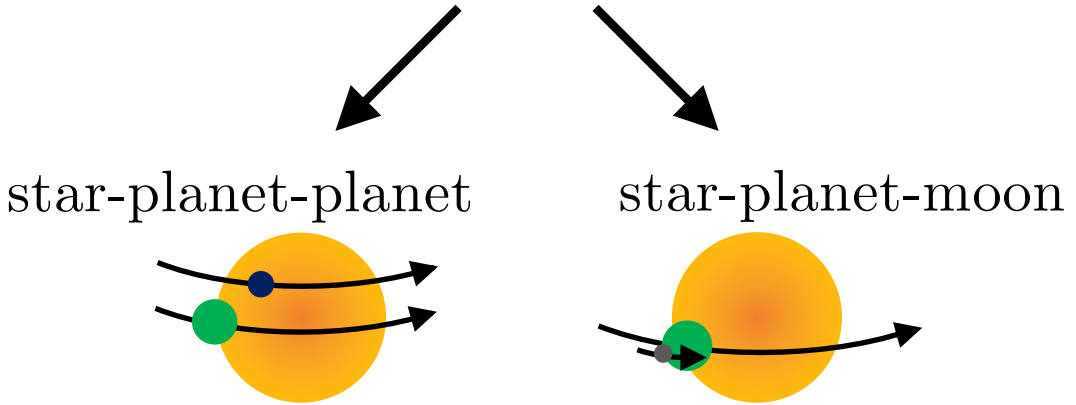
Statistical validation techniques that analyze properties of the transit shape now allow for **transit model selection:**
(BLENDER: Torres et al. 2004, 2011)
(Vespa: Morton et al. 2016)

daniel.yahalomi@columbia.edu

Early days of planet hunting, a transit alone was **ambiguous**



TTVs alone are **ambiguous**



Statistical validation techniques that analyze properties of the transit shape now allow for **transit model selection:**
(BLENDER: Torres et al. 2004, 2011)
(Vespa: Morton et al. 2016)

We are developing similar tools for **TTV model selection** by analyzing the orbital landscape of exoplanet TTVs

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

- Sartoretti and Schneider (1999) were the first to suggest looking for satellites via transit timing variations.

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

- Sartoretti and Schneider (1999) were the first to suggest looking for satellites via transit timing variations.

- Moon-planet TTV amplitude is proportional to satellite-to-planet mass ratio multiplied by the moon's semi-major axis
  - TTV amplitude can be anywhere from less than a second to up to an hour (Kipping & Teachey 2020).

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

- It can be difficult to detect moon-planet TTVs for 2 main reasons:

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

- It can be difficult to detect moon-planet TTVs for 2 main reasons:

1. It is difficult to assess whether TTV is truly caused by a moon

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

- It can be difficult to detect moon-planet TTVs for 2 main reasons:

1. It is difficult to assess whether TTV is truly caused by a moon

2. Any moon (within the Hill sphere) will have an orbital period much shorter than the planetary period so always undersampled...
    - sampling rate = planetary period

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

- It can be difficult to detect moon-planet TTVs for 2 main reasons:

1. It is difficult to assess whether TTV is truly caused by a moon

2. Any moon (within the Hill sphere) will have an orbital period much shorter than the planetary period so always undersampled...
    - sampling rate = planetary period

- Therefore, we expect the TTV period = aliasing of moon period

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs

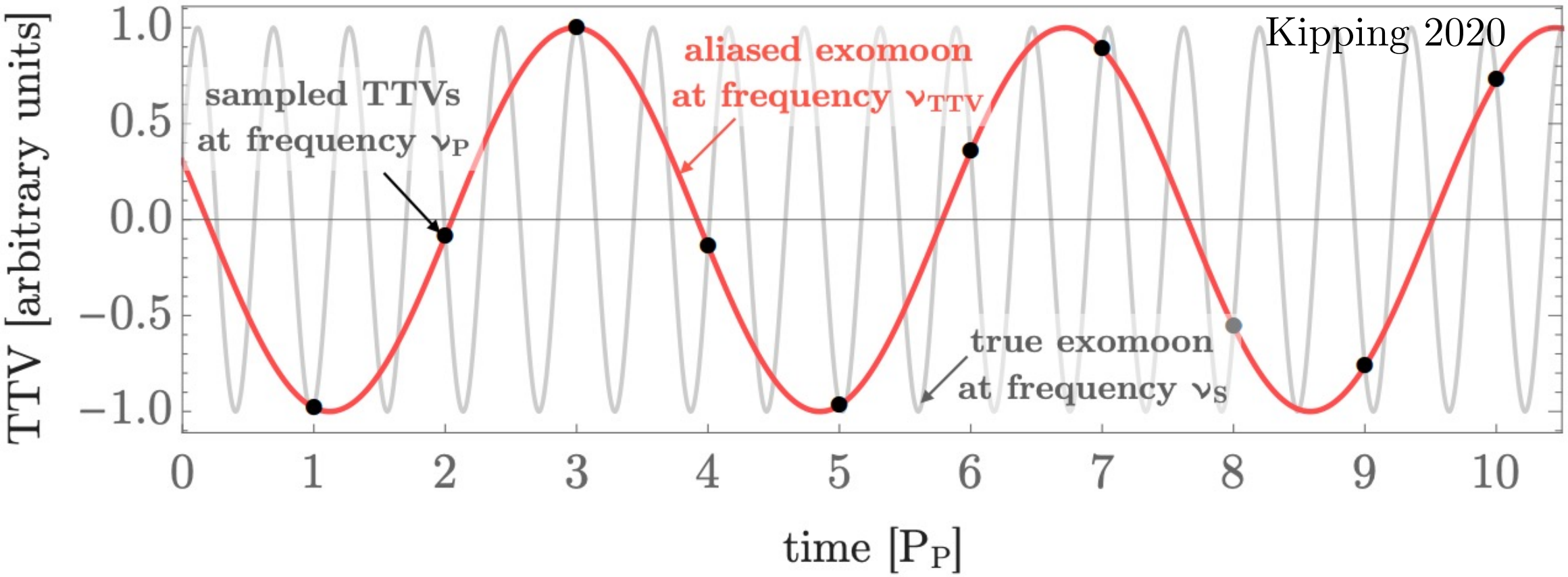
- It ca s:

1. It i
2. An uch
   sho
   -

- The

daniel.yahalomi@columbia.edu

a (brief) history of planet-moon TTVs



daniel.yahalomi@columbia.edu

aliased TTV period of the Earth-Moon system

daniel.yahalomi@columbia.edu

aliased TTV period of the Earth-Moon system

$$P_{\rm TTV} = \frac{1}{\frac{1}{P_S} - \mathrm{round}\left[\frac{P_P}{P_S}\right]\frac{1}{P_P}}.$$

Kipping 2020

daniel.yahalomi@columbia.edu

aliased TTV period of the Earth-Moon system

$$P_{\rm TTV} = \frac{1}{\frac{1}{P_S} - \mathbf{round}\left[\frac{P_P}{P_S}\right]\frac{1}{P_P}}.$$

Kipping 2020

- Moon period = 27.3 days
- Earth period = 365.25 days

daniel.yahalomi@columbia.edu

aliased TTV period of the Earth-Moon system

$$P_{\rm TTV} = \frac{1}{\frac{1}{P_S} - \mathbf{round}\left[\frac{P_P}{P_S}\right]\frac{1}{P_P}}.$$

Kipping 2020

- Moon period = 27.3 days
- Earth period = 365.25 days

- True Earth-Moon induced TTV period on = 27.3 days
- Observable (aliased) Earth-Moon induced TTV period = 963.41 days
- Observable (aliased) Earth-Moon induced TTV period = 2.64 $P_{\rm Earth}$

daniel.yahalomi@columbia.edu

- These aliases are more likely to manifest near the Nyquist rate
  - $f_{Nyquist} = 1/2\ f_{sampling} = 1/2\ f_{transit}$
  - $P_{Nyquist} = 2P_{sampling} = 2P_{transit}$

daniel.yahalomi@columbia.edu

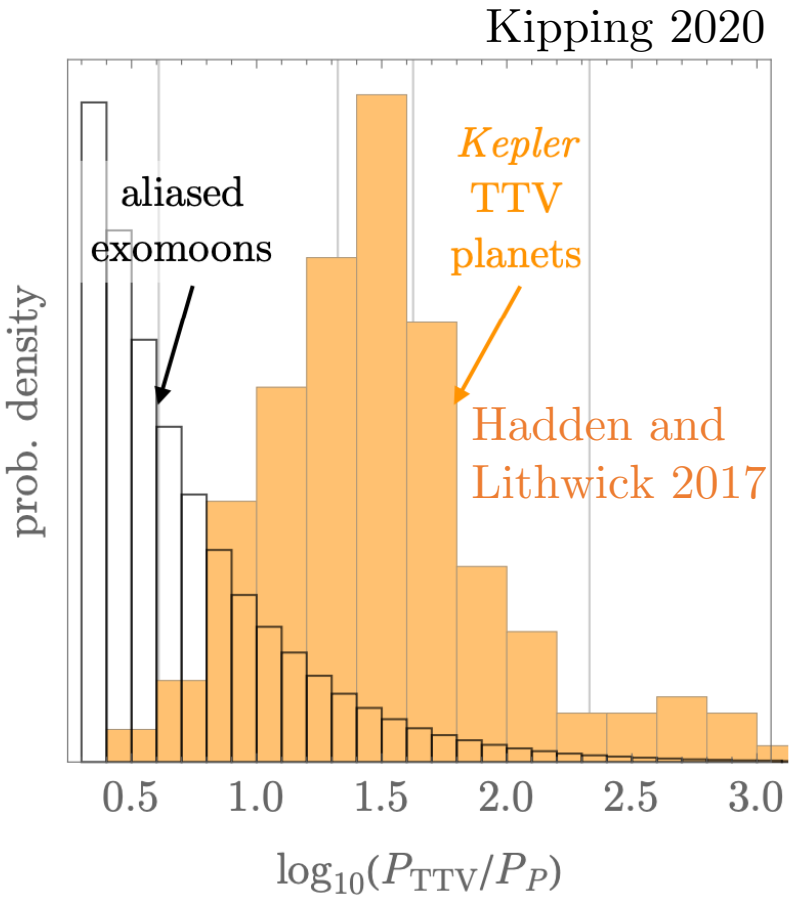
- These aliases are more likely to manifest near the Nyquist rate
  - $f_{Nyquist} = 1/2\ f_{sampling} = 1/2\ f_{transit}$
  - $P_{Nyquist} = 2P_{sampling} = 2P_{transit}$

- Kipping 2020: 50% of all exomoon induced TTVs would have an observed period equal to 2-4 times the period of the transiting planet

daniel.yahalomi@columbia.edu

- These aliases are more likely to manifest near the Nyquist rate
  - $f_{Nyquist} = 1/2\ f_{sampling} = 1/2\ f_{transit}$
  - $P_{Nyquist} = 2P_{sampling} = 2P_{transit}$

- Kipping 2020: 50% of all exomoon induced TTVs would have an observed period equal to 2-4 times the period of the transiting planet

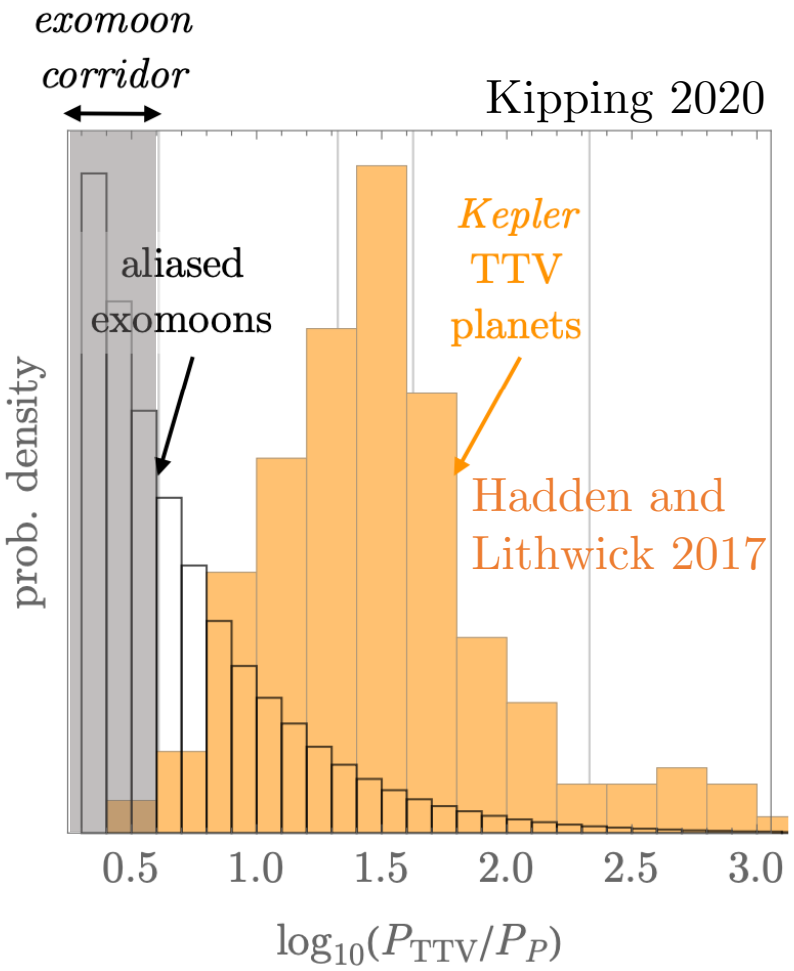


daniel.yahalomi@columbia.edu

The Exomoon Corridor

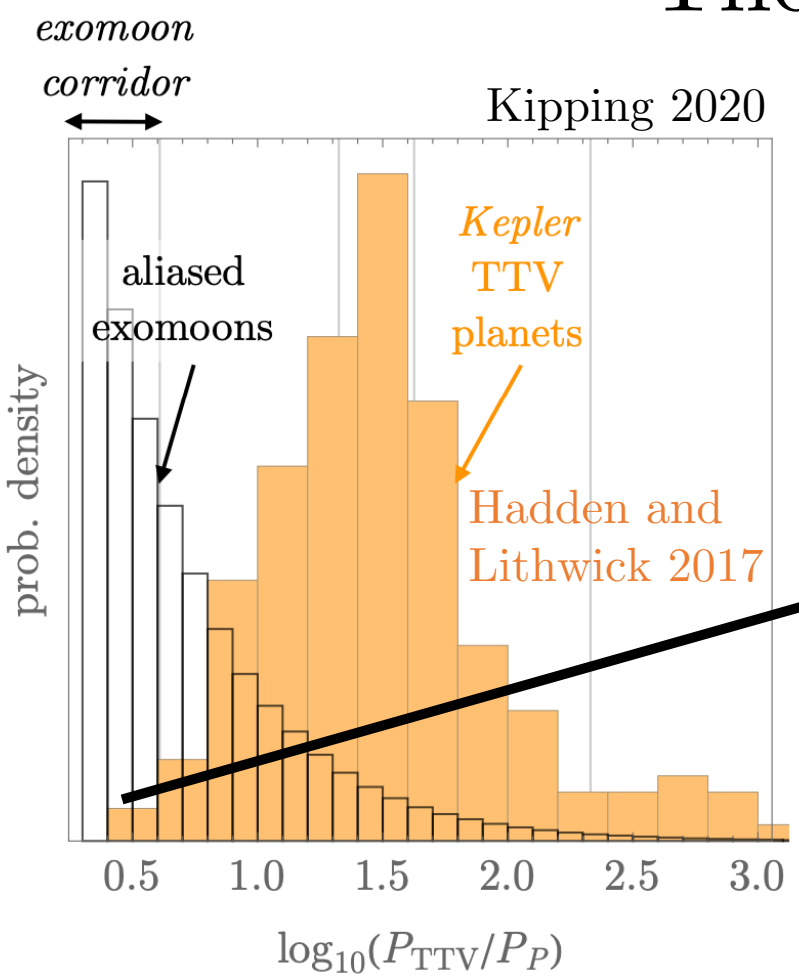
- These aliases are more likely to manifest near the Nyquist rate
  - $f_{Nyquist} = 1/2\ f_{sampling} = 1/2\ f_{transit}$
  - $P_{Nyquist} = 2P_{sampling} = 2P_{transit}$

- Kipping 2020: 50% of all exomoon induced TTVs would have an observed period equal to 2-4 times the period of the transiting planet



daniel.yahalomi@columbia.edu

The Exomoon Corridor



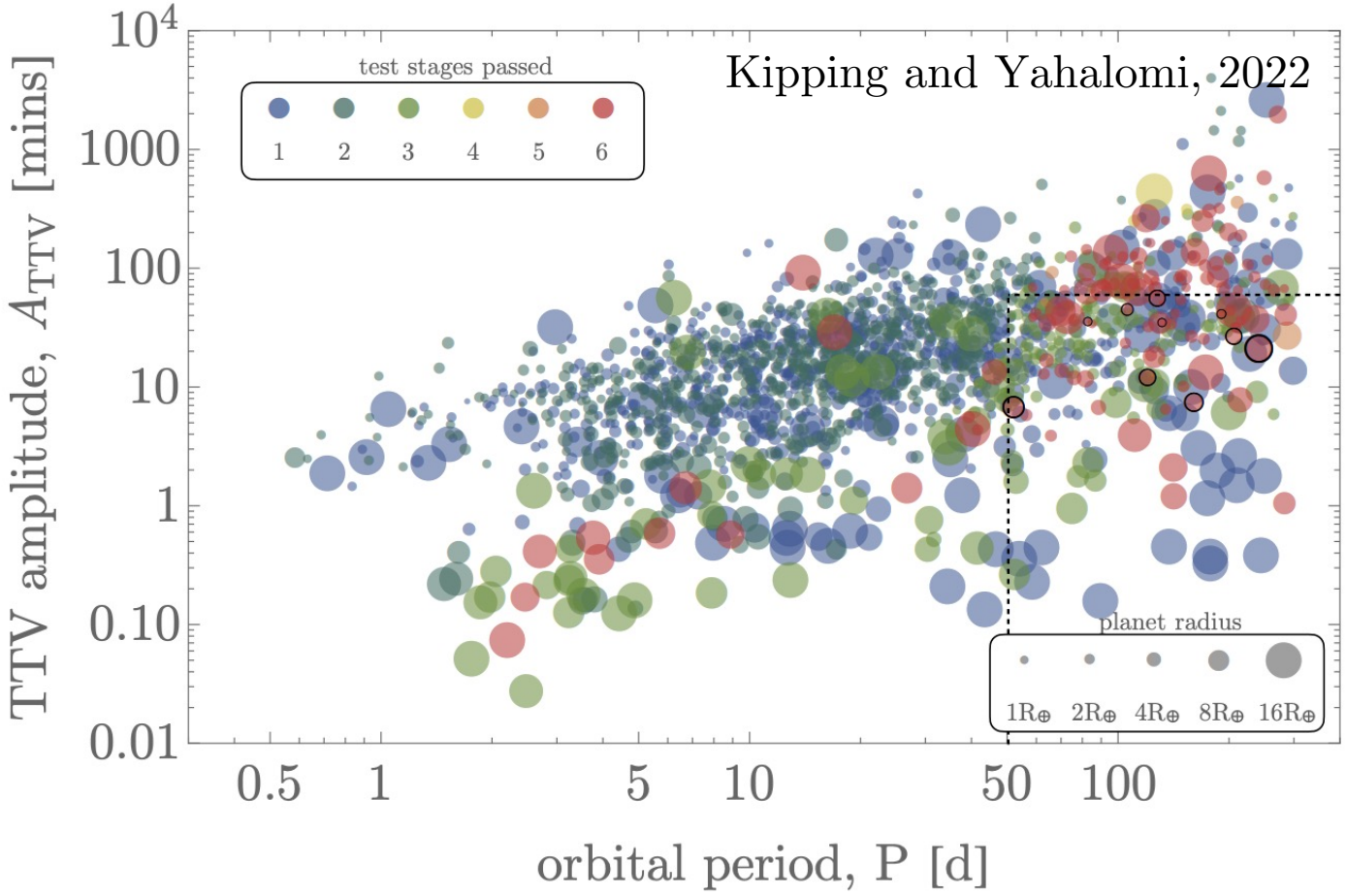
let's search the exomoon corridor of Kepler data for possible new moons!

(Kipping and Yahalomi, 2022)

daniel.yahalomi@columbia.edu

A search for transit timing variations within the exomoon corridor using *Kepler* data

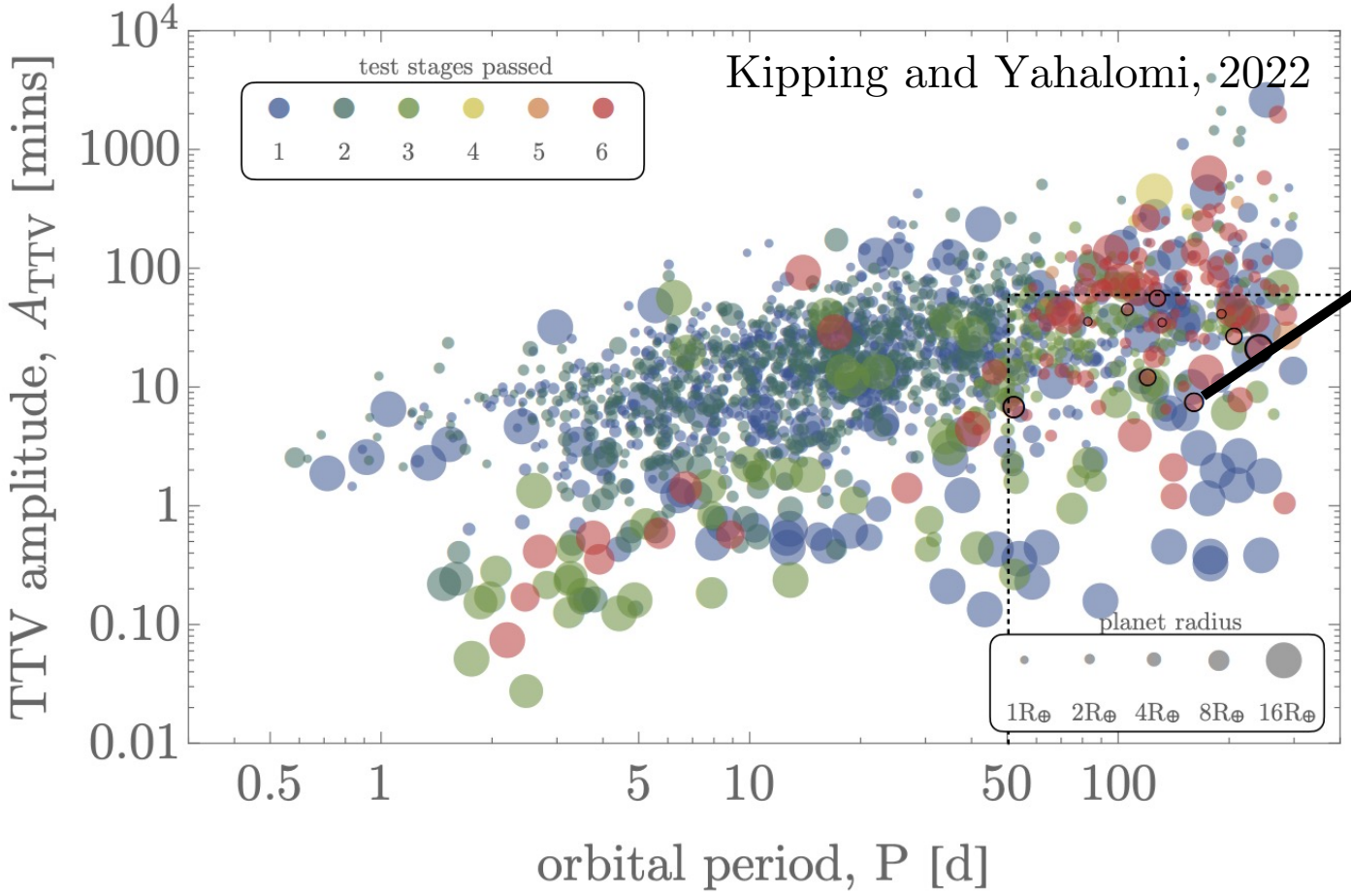
David Kipping[1]* and Daniel A.. Yahalomi[1]
[1]*Dept. of Astronomy, Columbia University, 550 W 120th Street, New York NY 10027*



daniel.yahalomi@columbia.edu

A search for transit timing variations within the exomoon corridor using *Kepler* data

David Kipping[1]* and Daniel A.. Yahalomi[1]
[1]*Dept. of Astronomy, Columbia University, 550 W 120th Street, New York NY 10027*



one system survives all our testing:

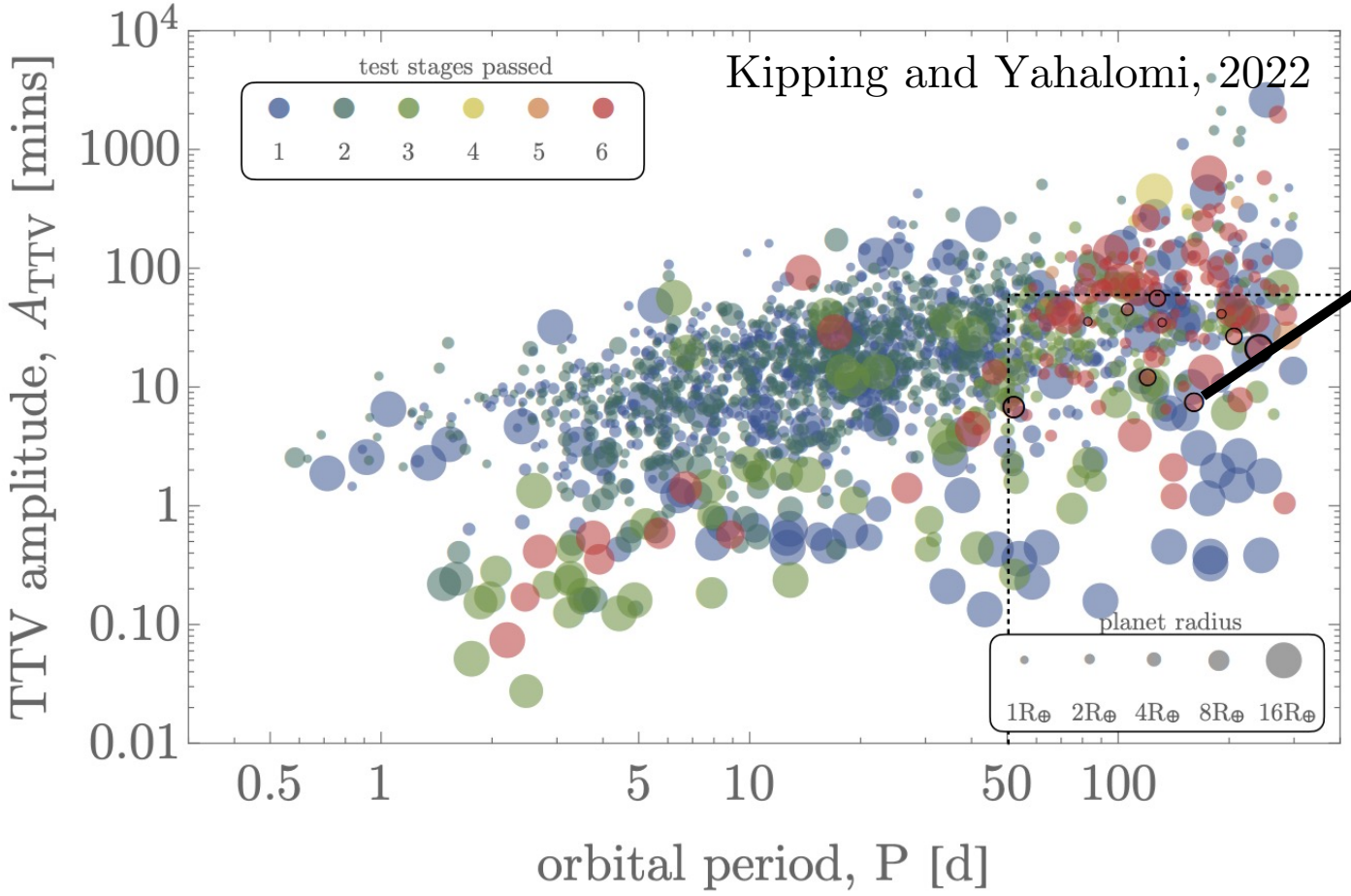
Kepler-1513b

(a gas giant on ~160-day orbit)

daniel.yahalomi@columbia.edu

A search for transit timing variations within the exomoon corridor using *Kepler* data

David Kipping[1]* and Daniel A.. Yahalomi[1]
[1]*Dept. of Astronomy, Columbia University, 550 W 120th Street, New York NY 10027*



one system survives all our testing:

Kepler-1513b

(a gas giant on ~160-day orbit)

is the unseen companion to
Kepler-1513b
a **planet** or a **moon**?

(Yahalomi et al. 2023)

daniel.yahalomi@columbia.edu

Kepler-1513b

daniel.yahalomi@columbia.edu

Kepler-1513b

- Critical step in transit analysis is removal of systematics in time-series photometry.

daniel.yahalomi@columbia.edu

Kepler-1513b

- Critical step in transit analysis is removal of systematics in time-series photometry.
- There is no community-wide consensus regarding the “best” detrending method.

daniel.yahalomi@columbia.edu

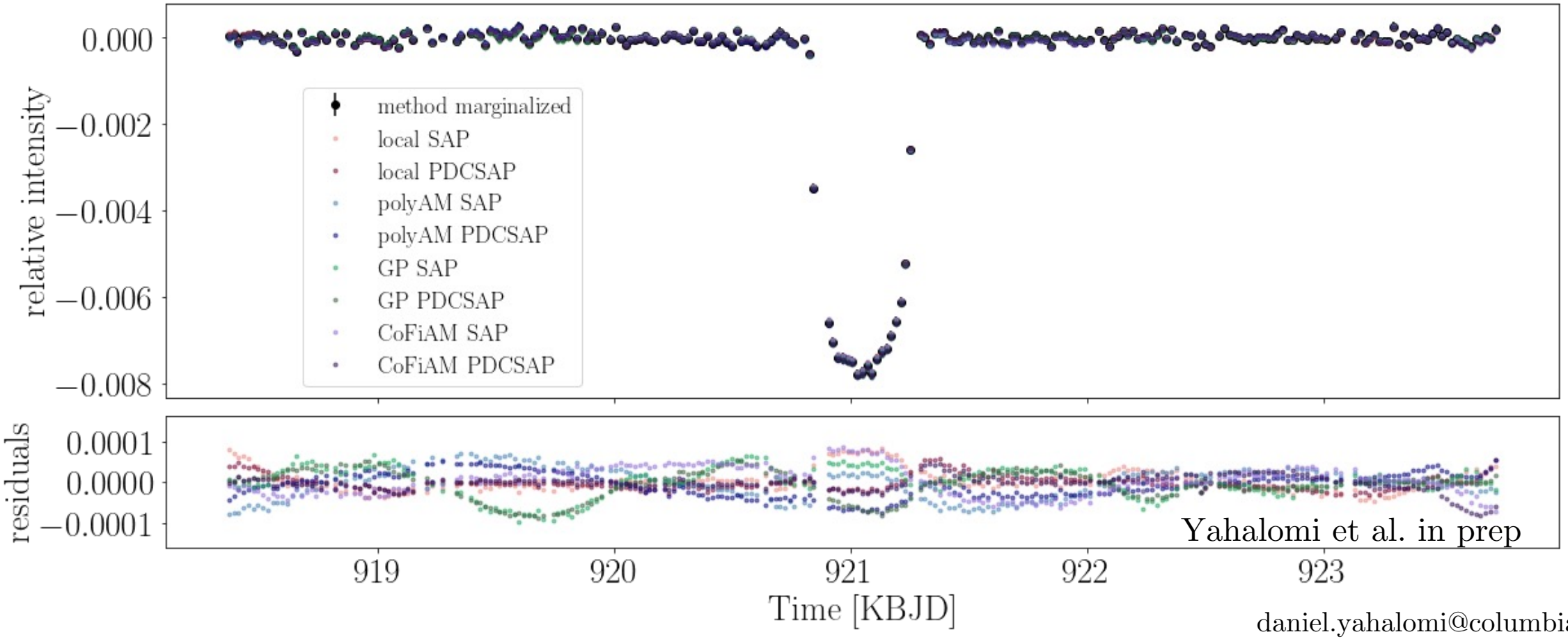
Kepler-1513b

- Critical step in transit analysis is removal of systematics in time-series photometry.
- There is no community-wide consensus regarding the “best” detrending method.
- The *democratic detrender* is open-source code for “method marginalized” detrending.

daniel.yahalomi@columbia.edu

Kepler-1513b

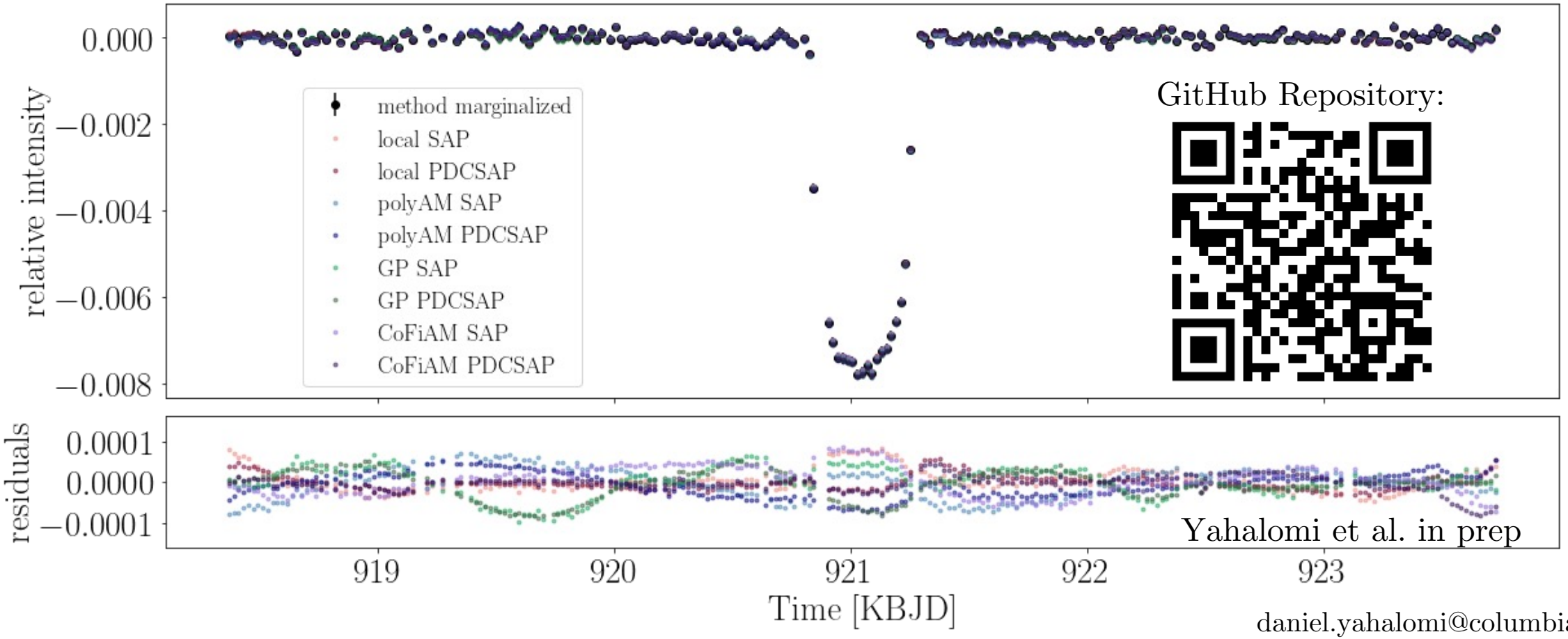
- Critical step in transit analysis is removal of systematics in time-series photometry.
- There is no community-wide consensus regarding the "best" detrending method.
- The *democratic detrender* is open-source code for "method marginalized" detrending.



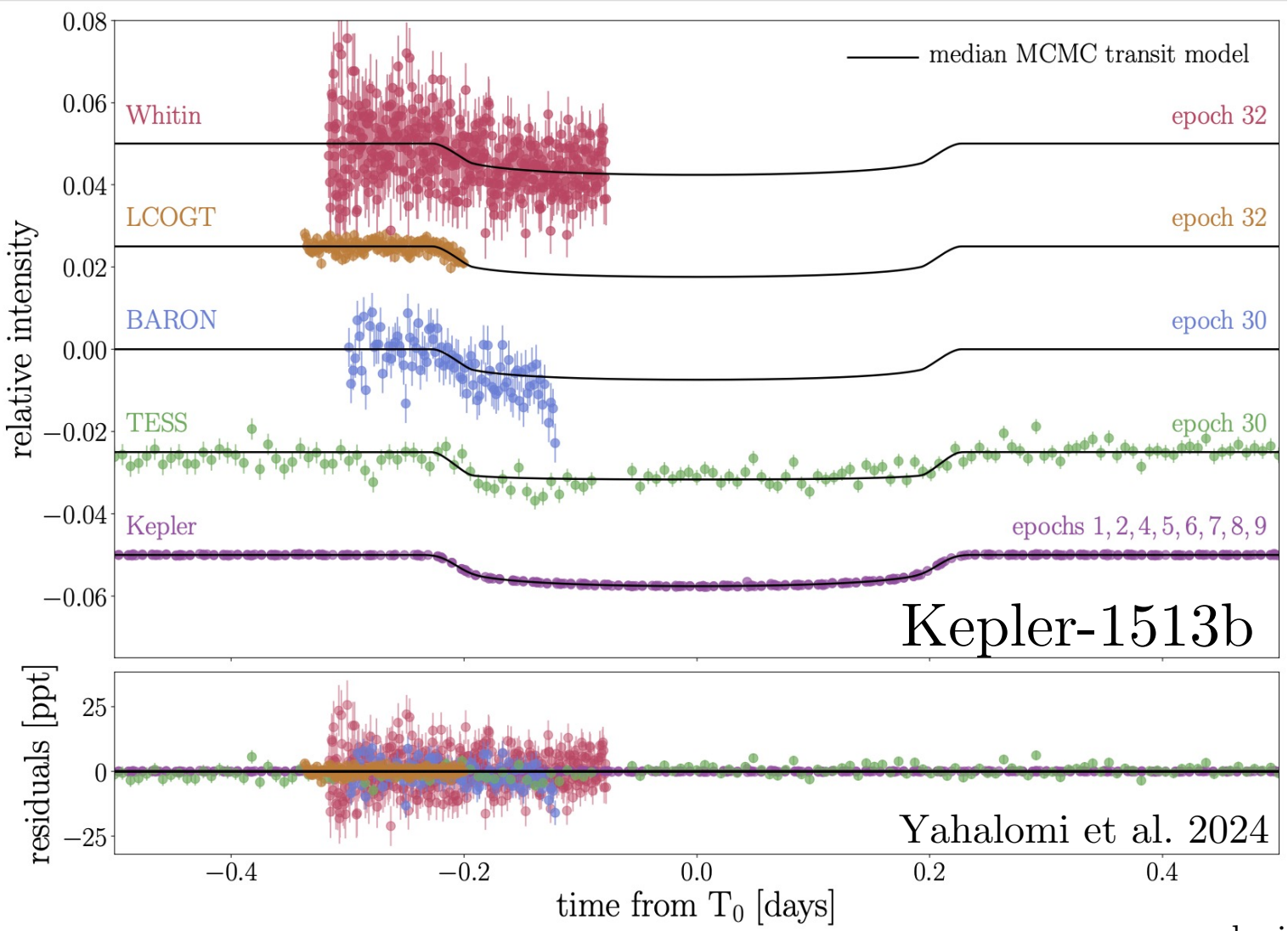
daniel.yahalomi@columbia.edu

Kepler-1513b

- Critical step in transit analysis is removal of systematics in time-series photometry.
- There is no community-wide consensus regarding the “best” detrending method.
- The *democratic detrender* is open-source code for “method marginalized” detrending.

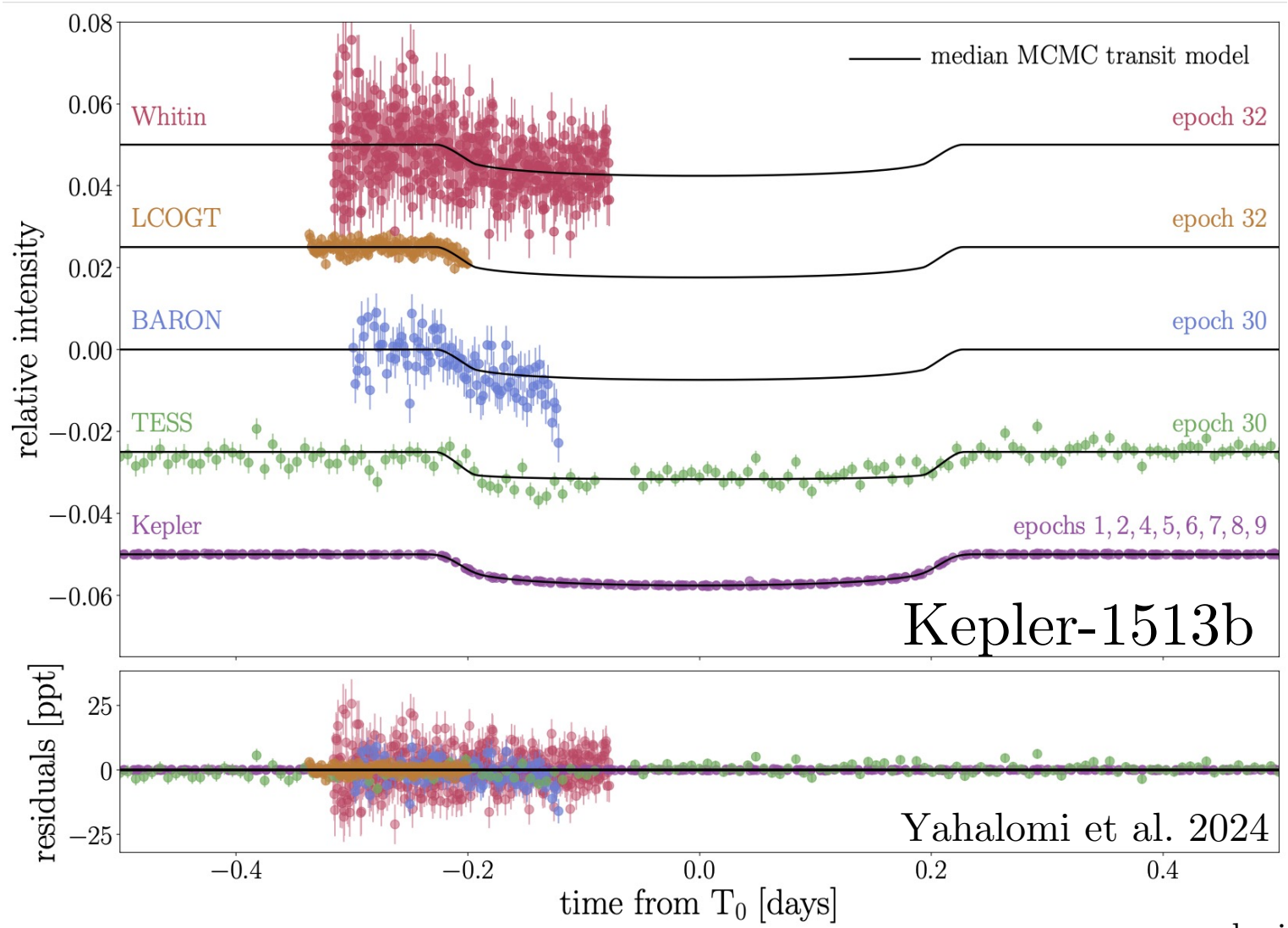


daniel.yahalomi@columbia.edu



daniel.yahalomi@columbia.edu

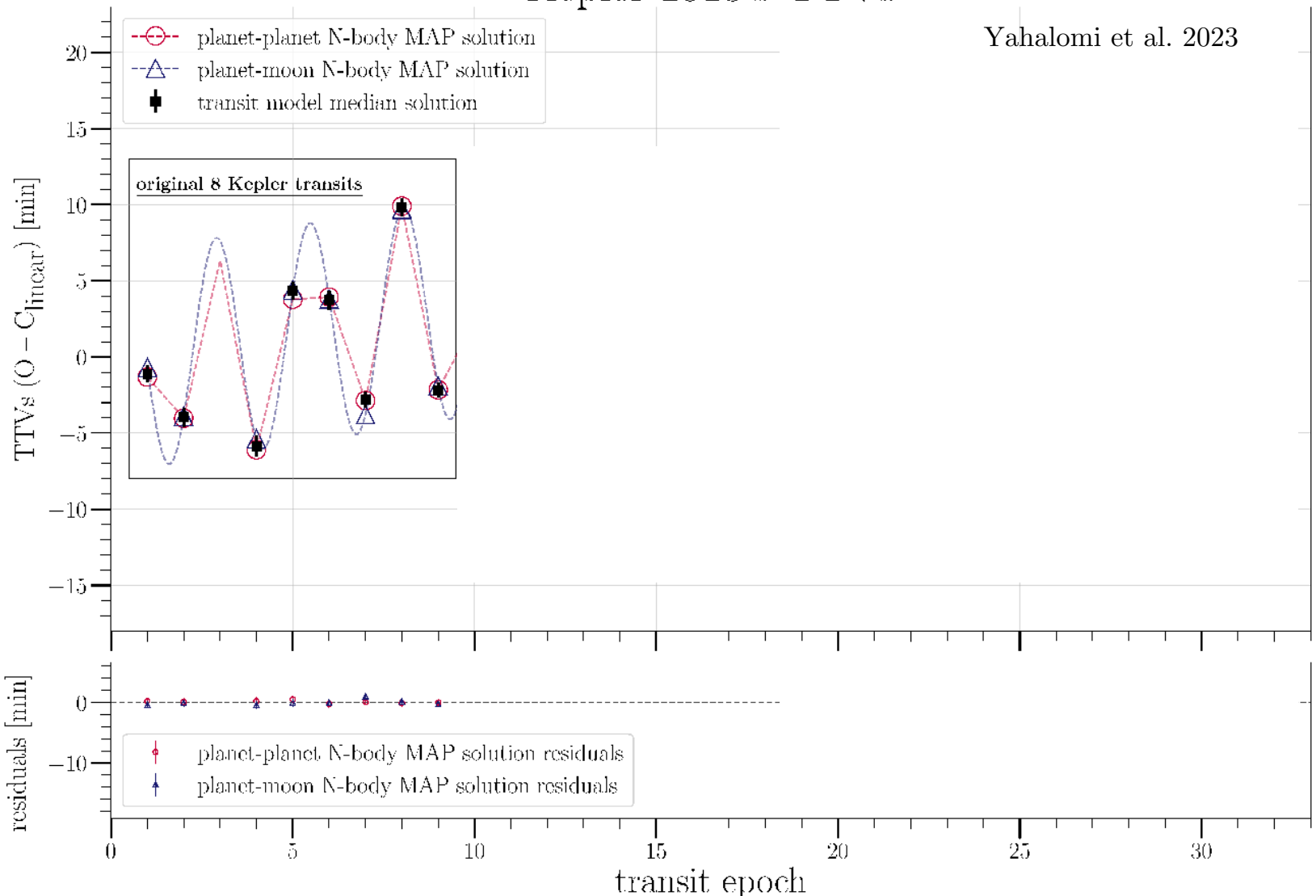
we observed 2 additional transits ~9 years after the last Kepler transit



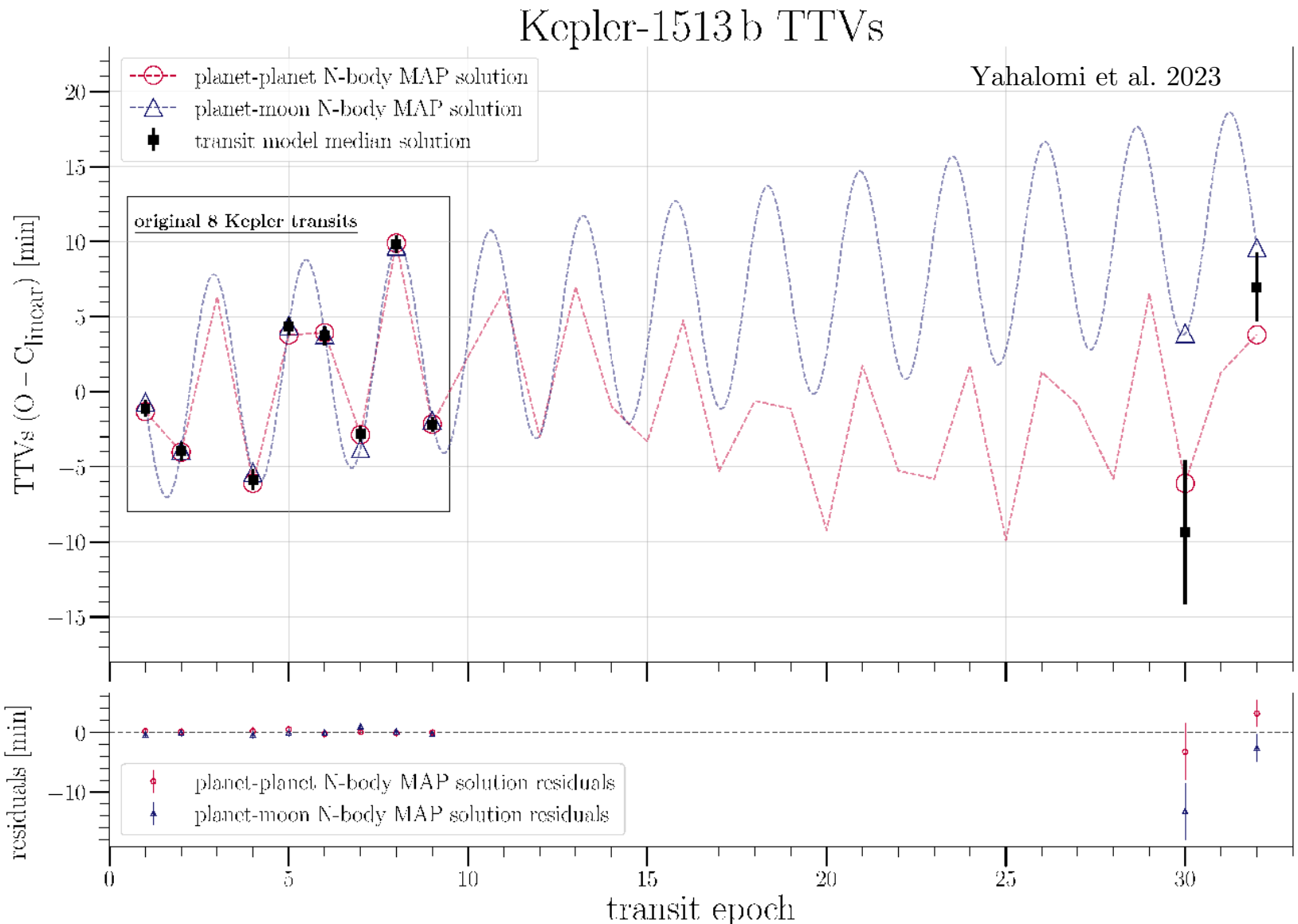
daniel.yahalomi@columbia.edu

Kepler-1513 b TTVs

Yahalomi et al. 2023

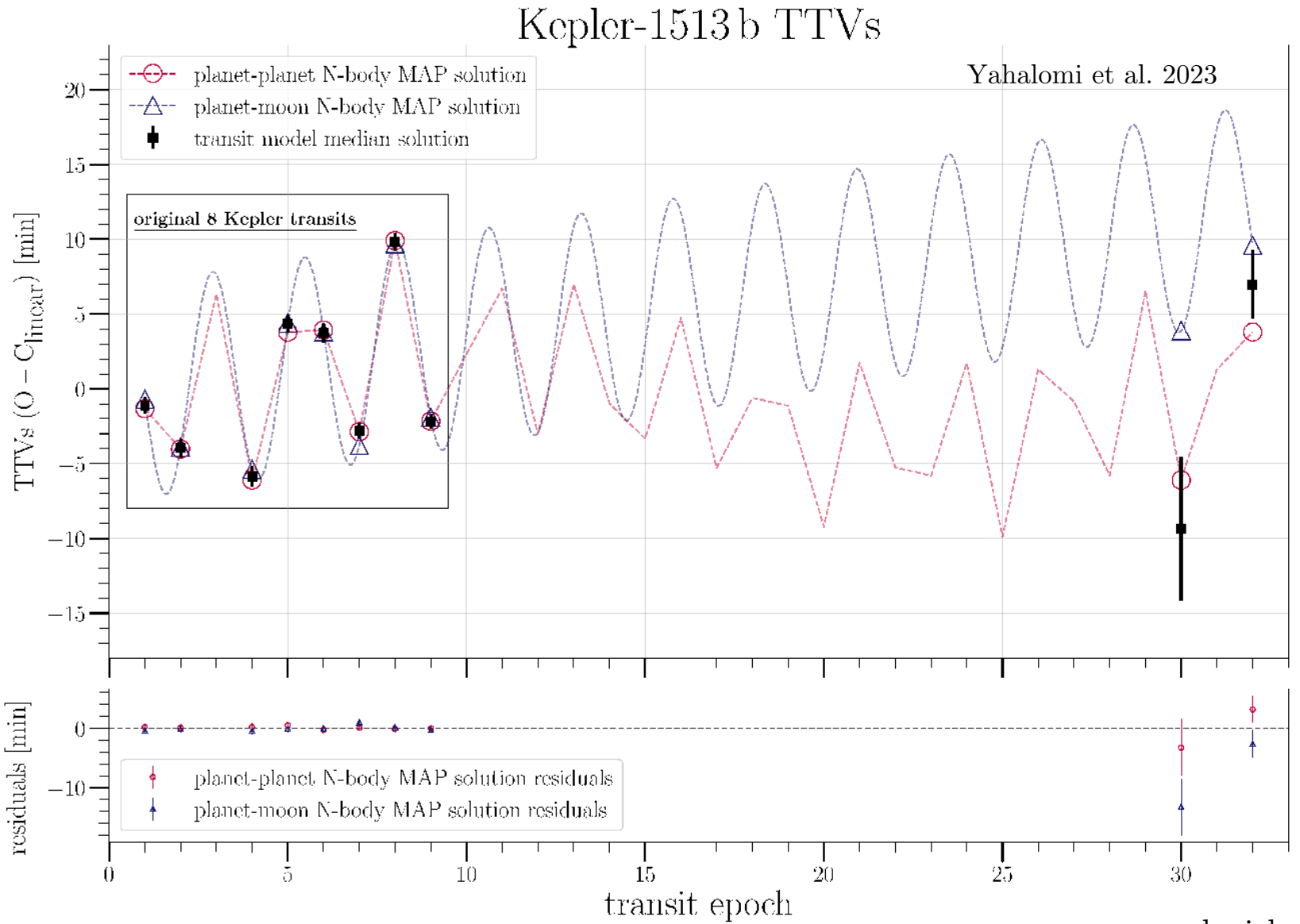


daniel.yahalomi@columbia.edu



daniel.yahalomi@columbia.edu

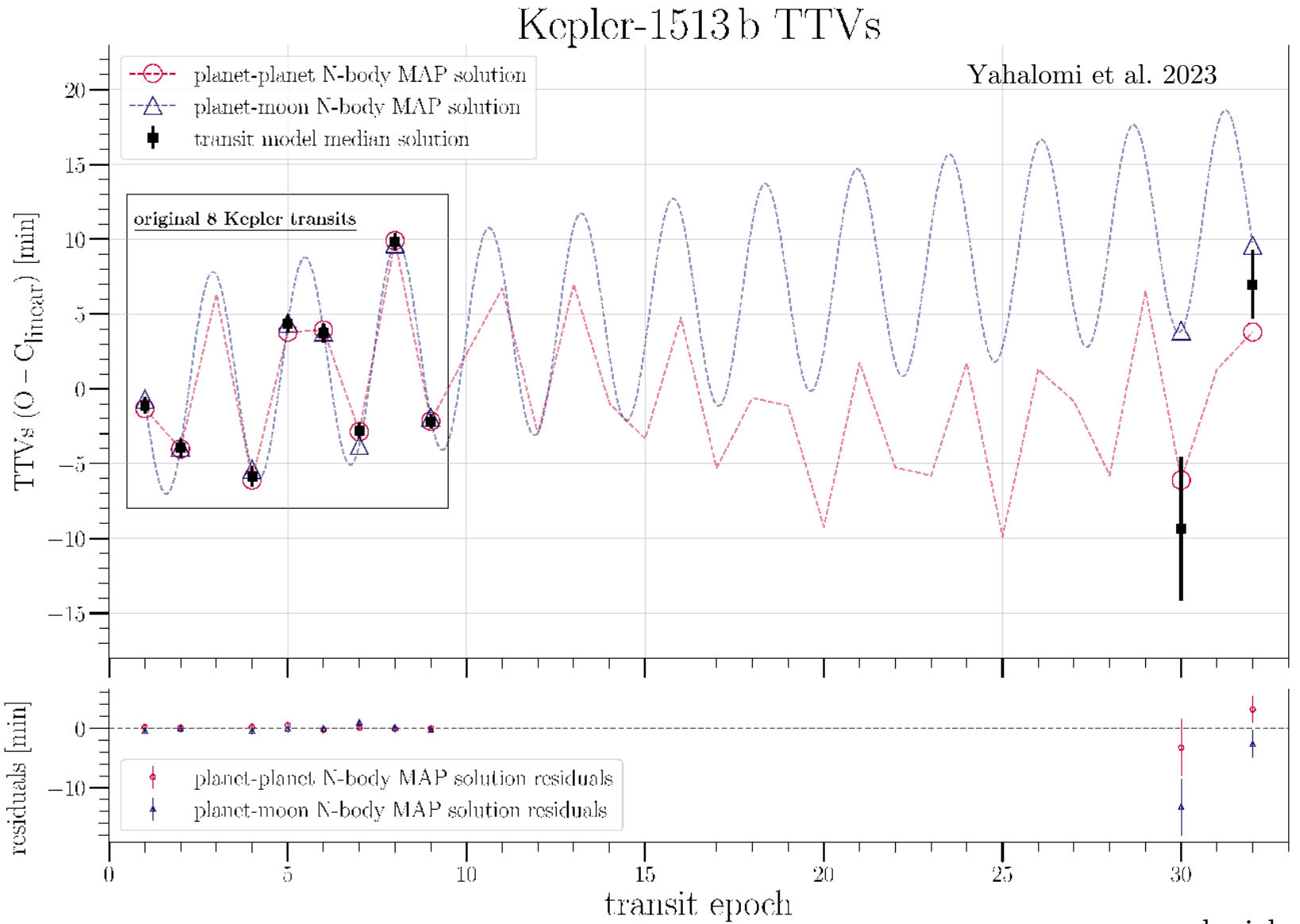
follow-up transit observations reveal second, slow-period TTV...



daniel.yahalomi@columbia.edu


That's no moon.

Kepler-1513c is most likely a Saturn that is ~5% outside a 5:1 period ratio



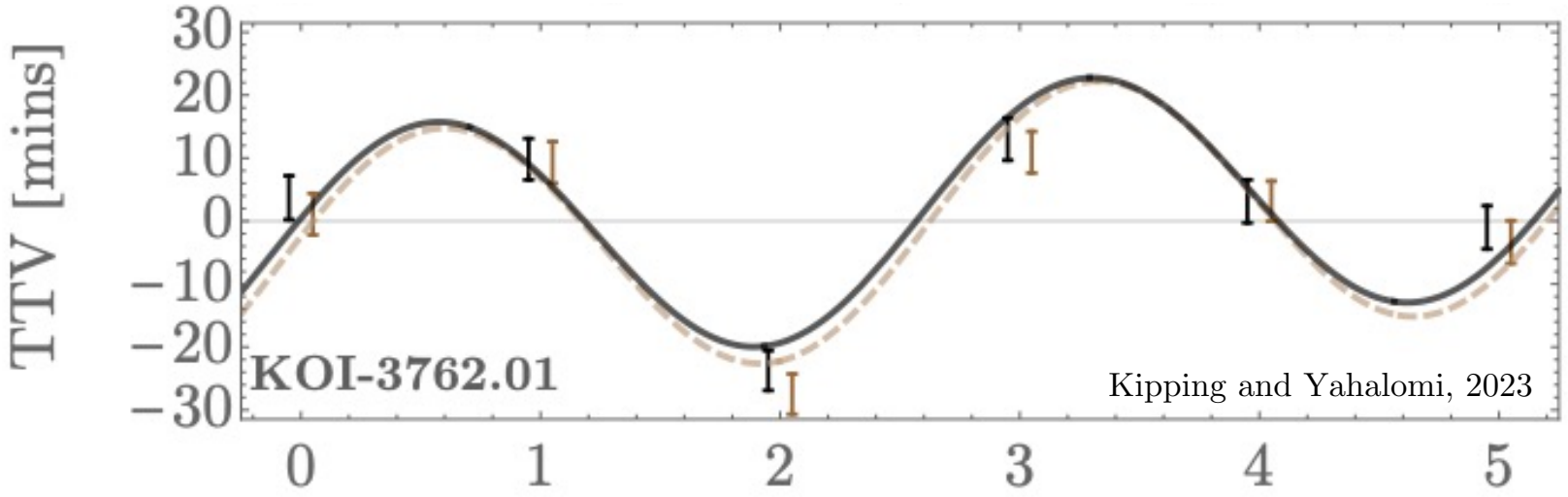
daniel.yahalomi@columbia.edu

Additional targets in the exomoon corridor:

daniel.yahalomi@columbia.edu

Additional targets in the exomoon corridor:

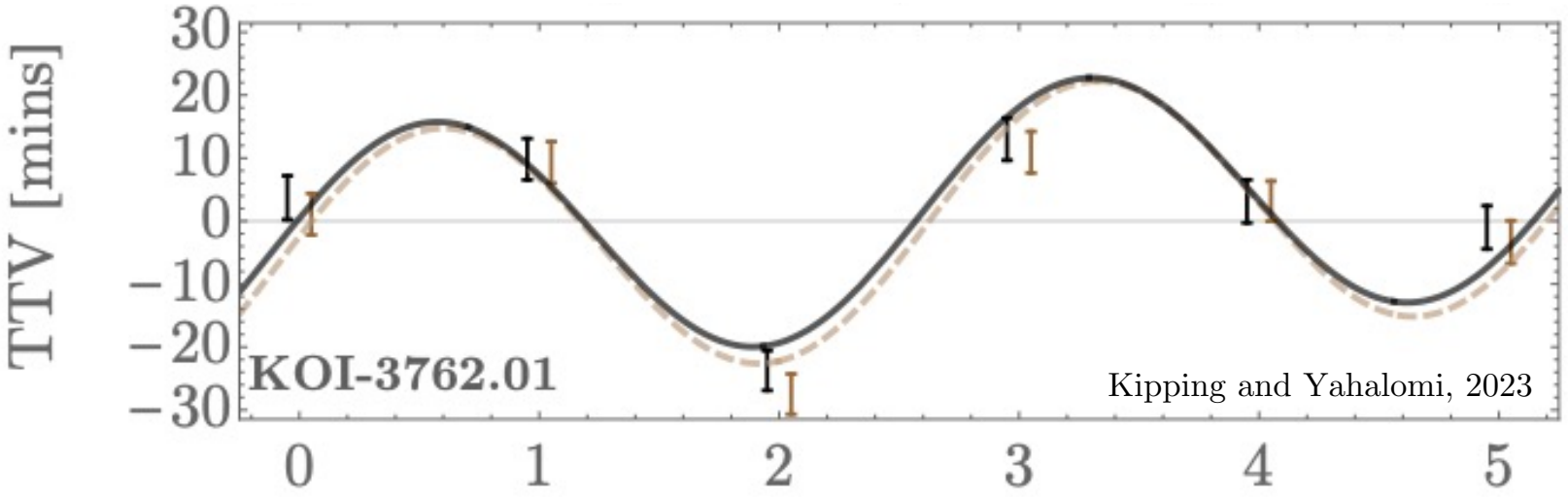
- KOI-3762b is a ~10 R_{Earth} gas giant at ~241 days.



daniel.yahalomi@columbia.edu

Additional targets in the exomoon corridor:

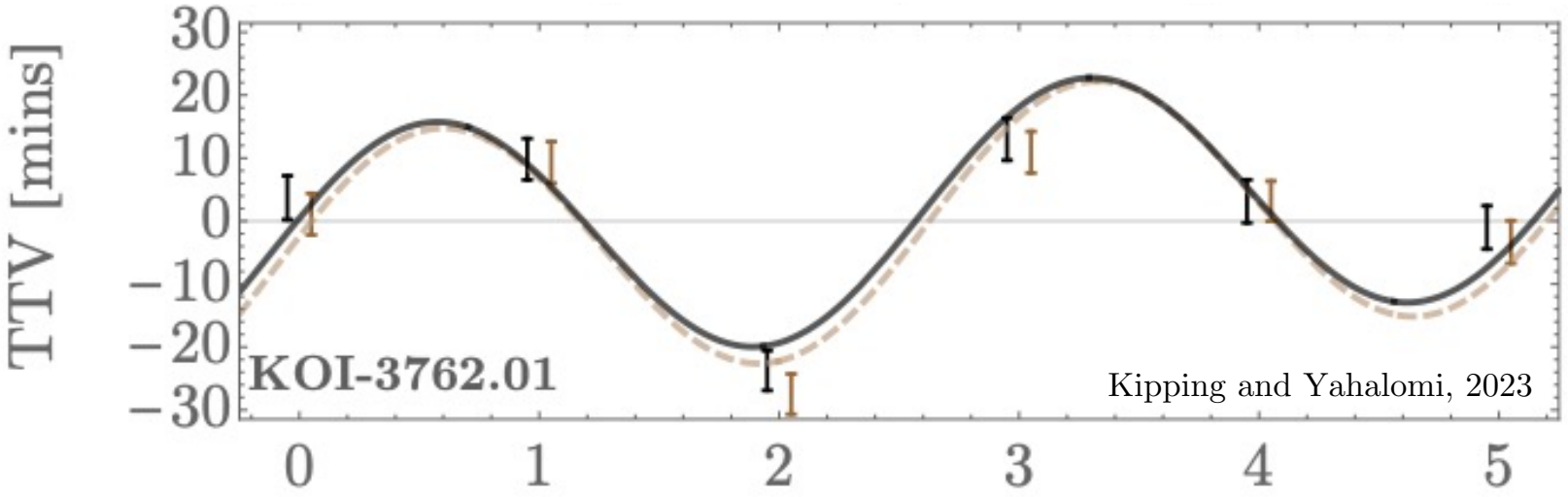
- KOI-3762b is a ~10 R_{Earth} gas giant at ~241 days.
- Currently, short-period TTV signal dominated by single epoch...



daniel.yahalomi@columbia.edu

Additional targets in the exomoon corridor:

- KOI-3762b is a ~10 R_{Earth} gas giant at ~241 days.
- Currently, short-period TTV signal dominated by single epoch...
- Transit opportunity in June!



daniel.yahalomi@columbia.edu

roadmap

wobbles

worlds

Add destination

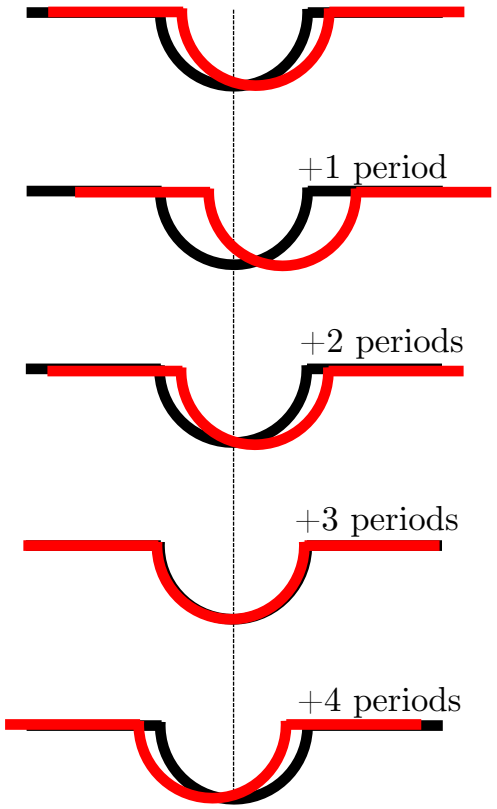
Leave now

Options

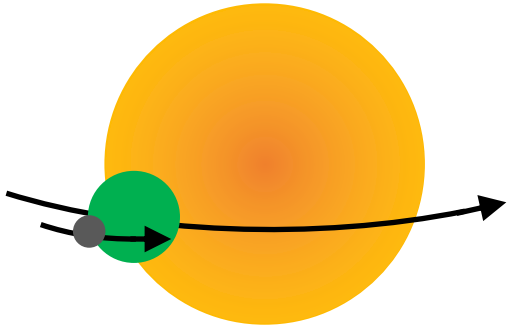
Send directions to your phone

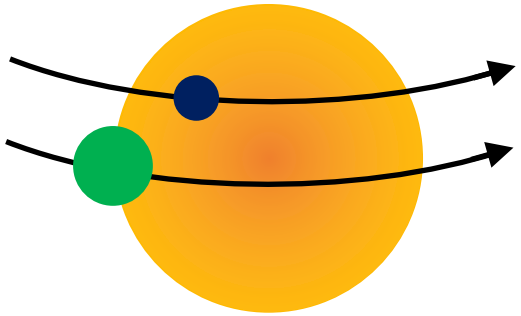
Copy link

via exomoon corridor



exomoon corridor





daniel.yahalomi@columbia.edu

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

near MMR induced TTVs

$$P_{sup} = \frac{1}{|j/P_1 - k/P_2|}.$$

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

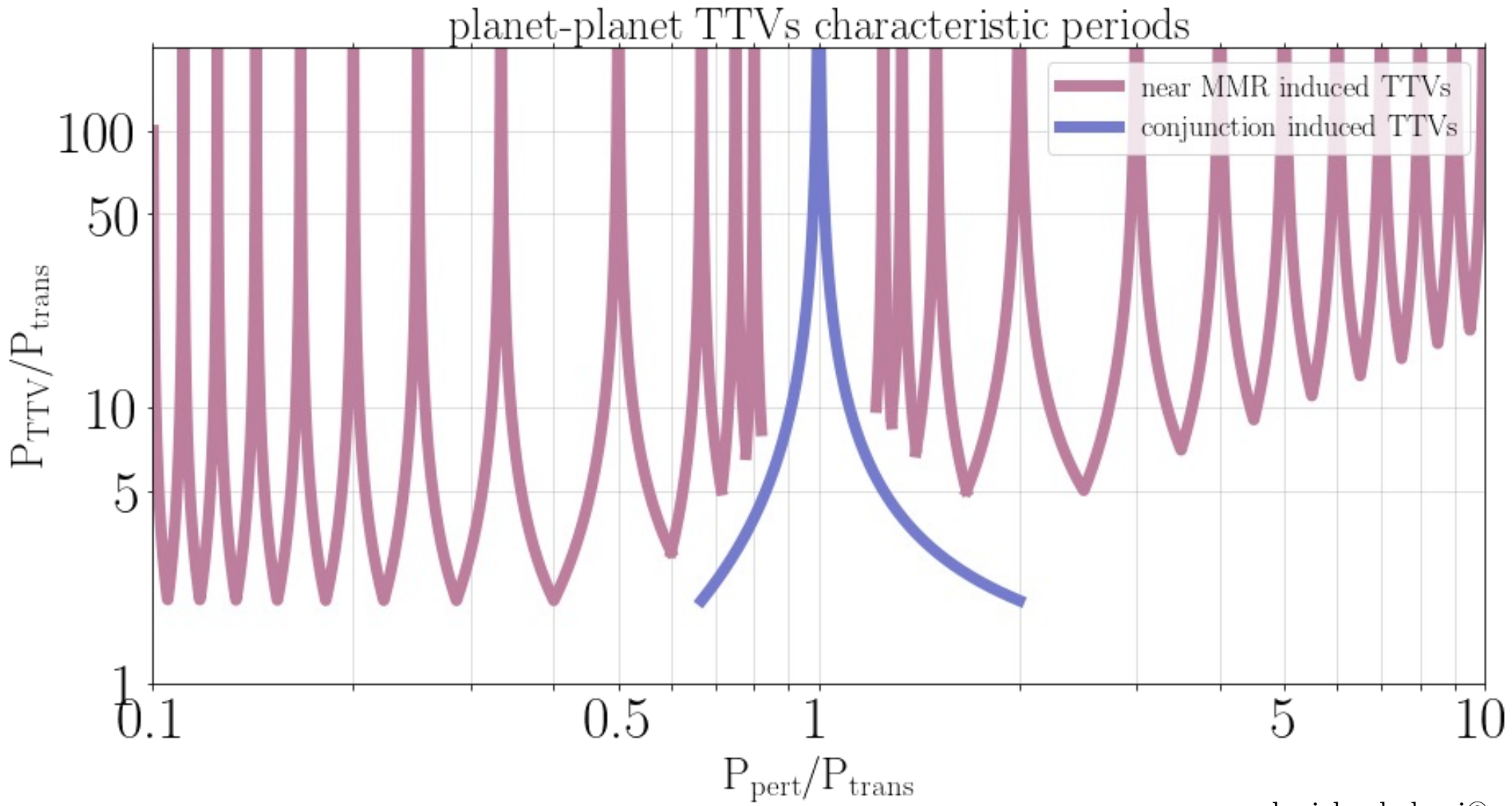
near MMR induced TTVs

$$P_{sup} = \frac{1}{|j/P_1 - k/P_2|}.$$

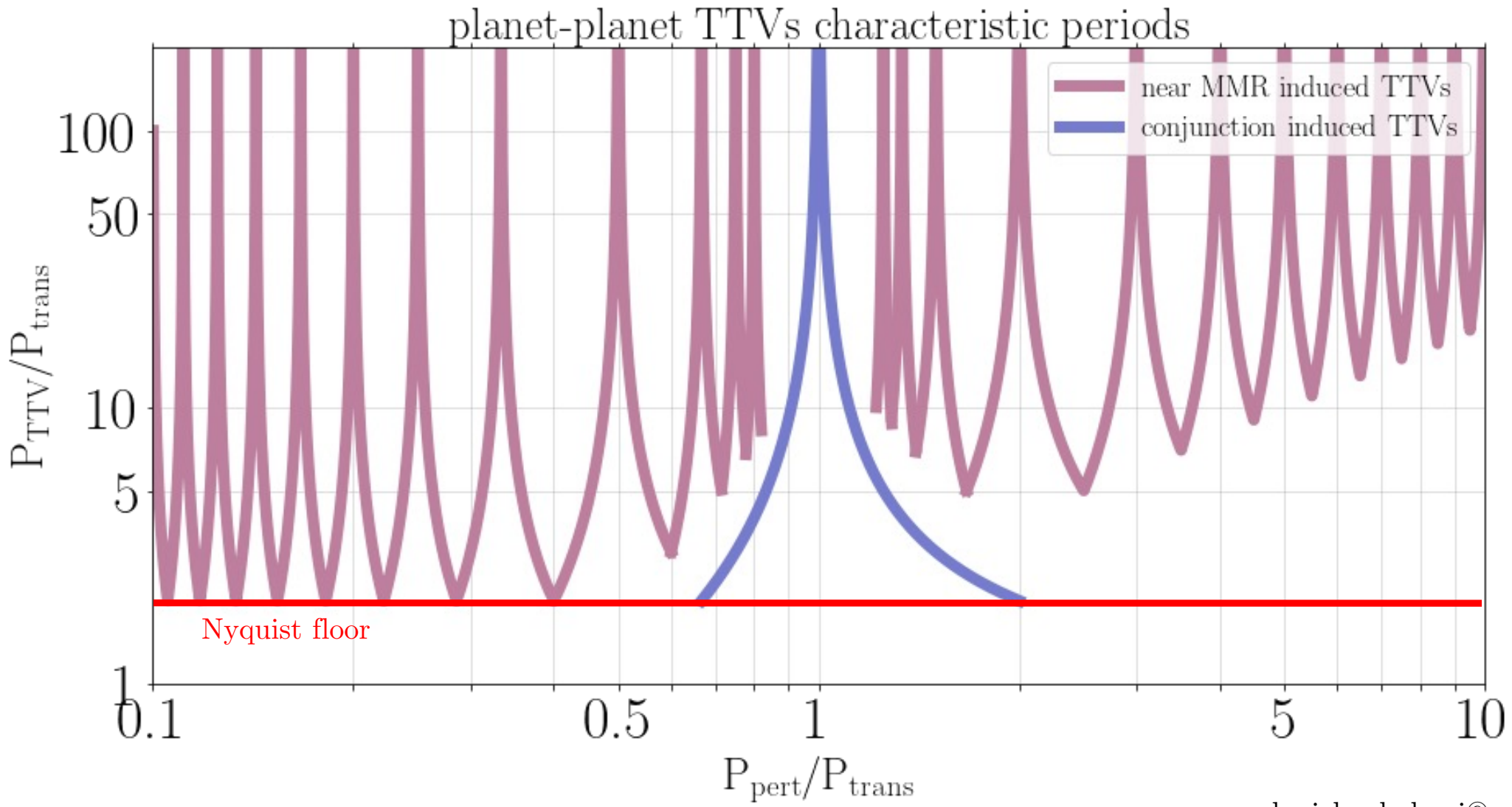
conjunction induced TTVs

$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

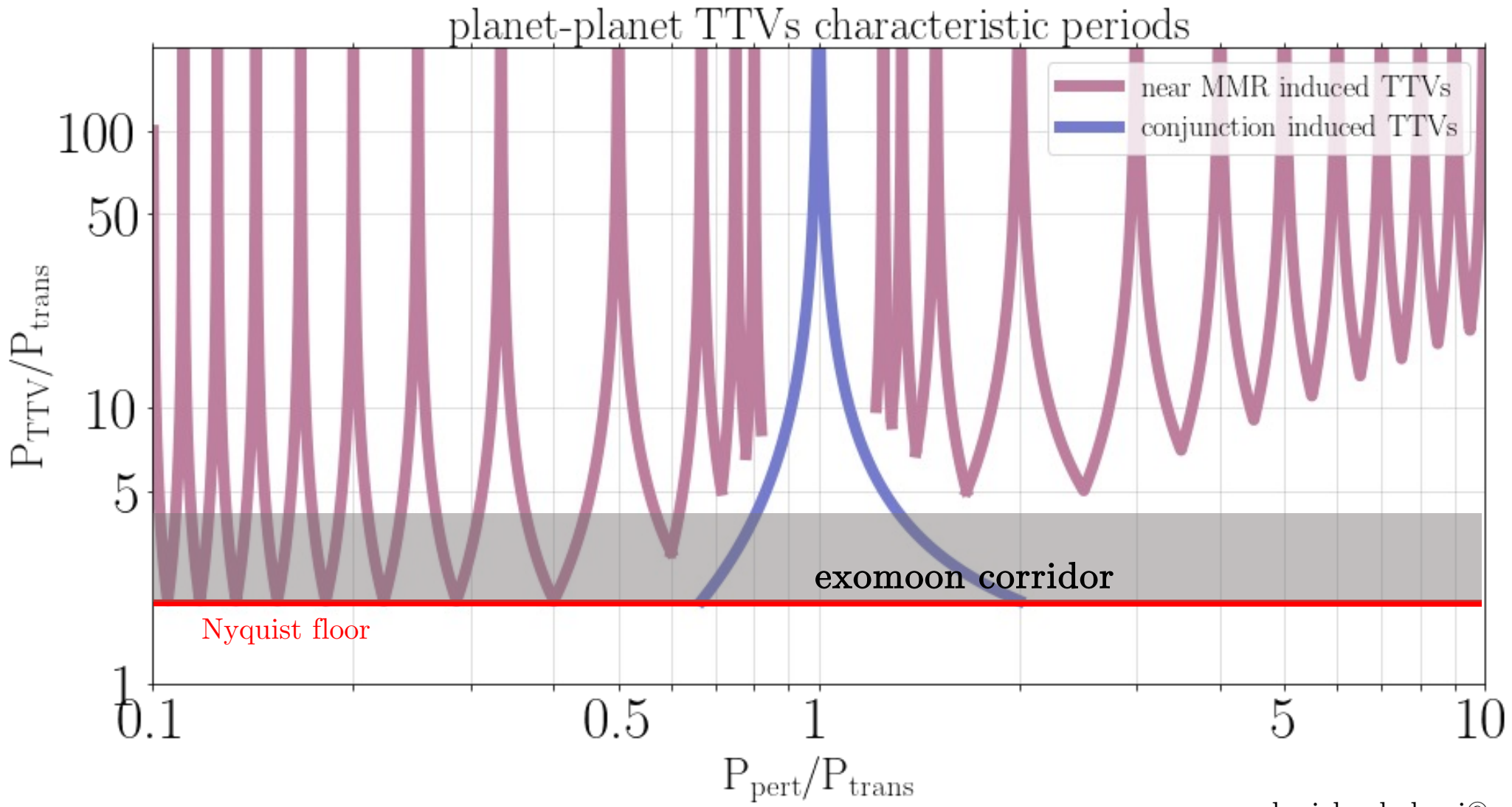
daniel.yahalomi@columbia.edu



daniel.yahalomi@columbia.edu

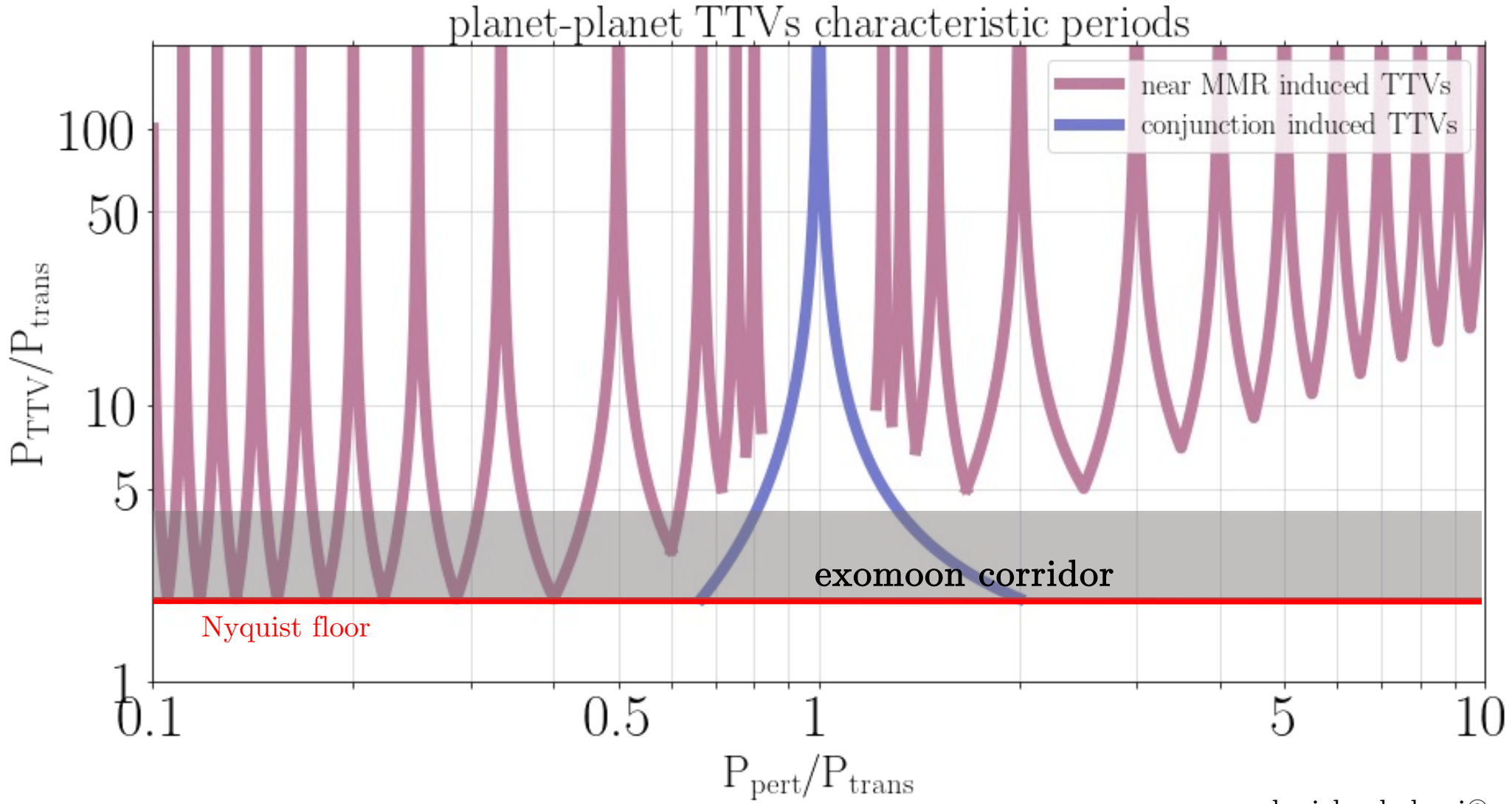


daniel.yahalomi@columbia.edu



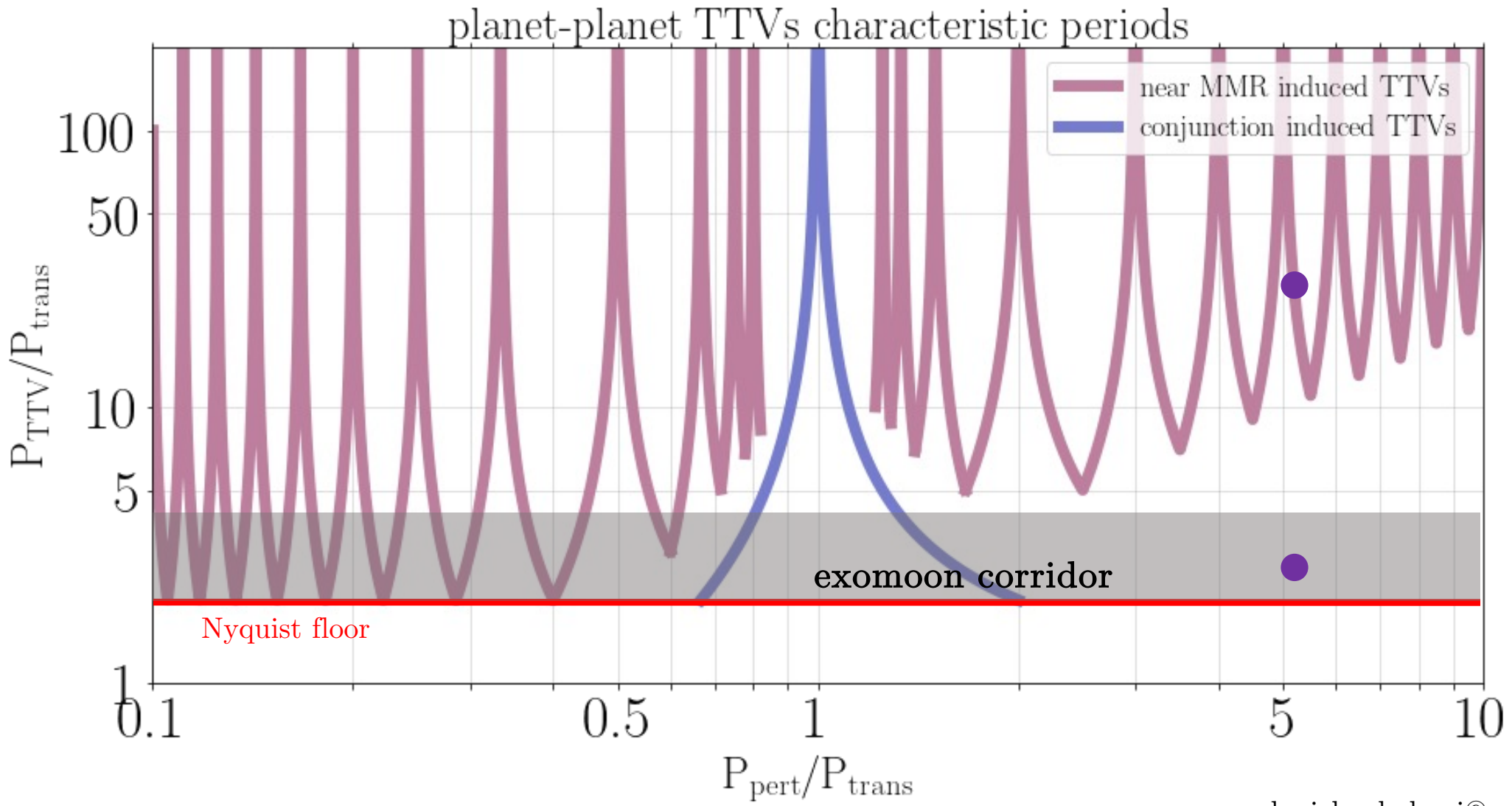
daniel.yahalomi@columbia.edu

Where do Kepler-1513 b and c live on this diagram?



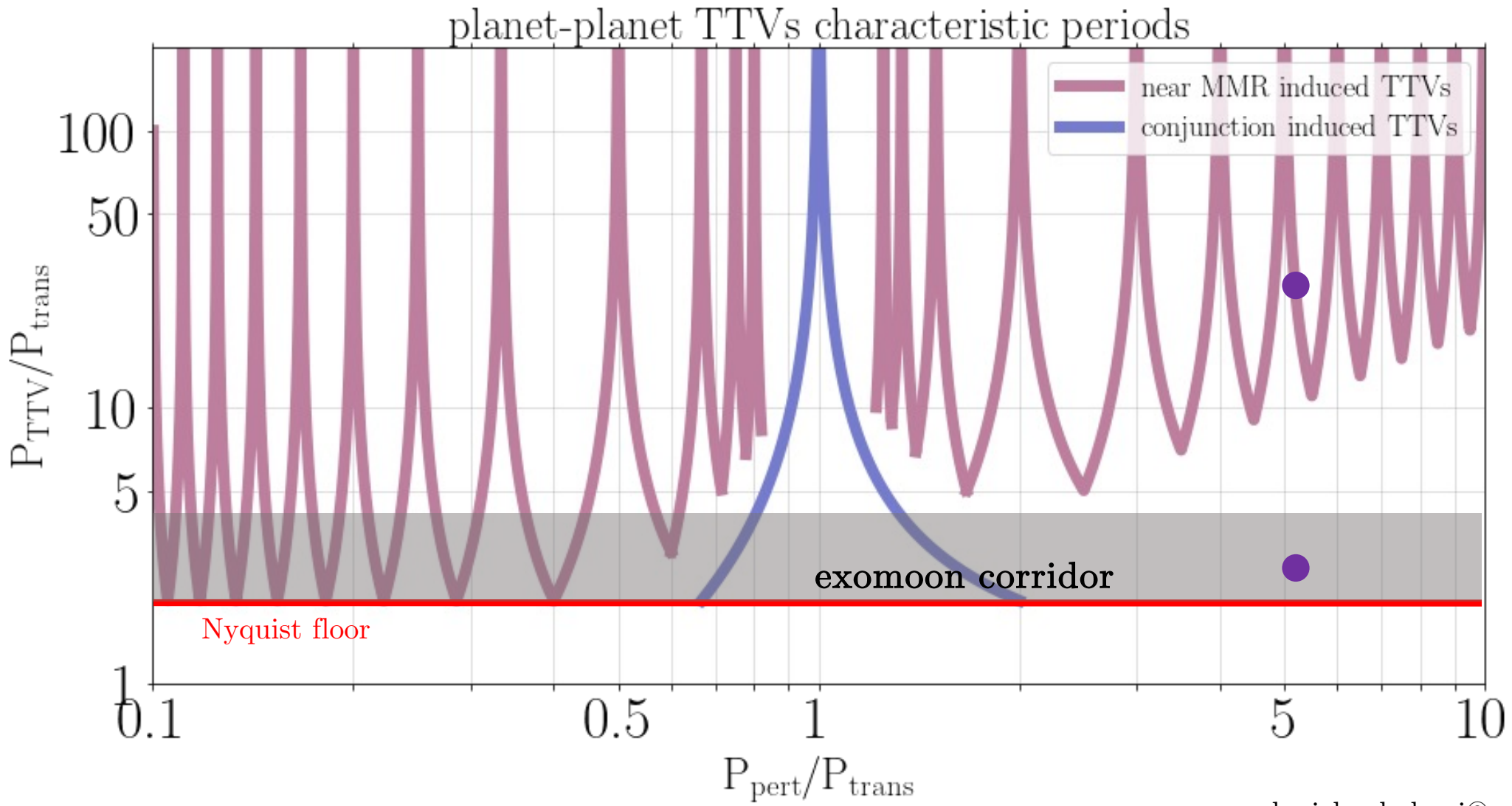
daniel.yahalomi@columbia.edu

Where do Kepler-1513 b and c live on this diagram?

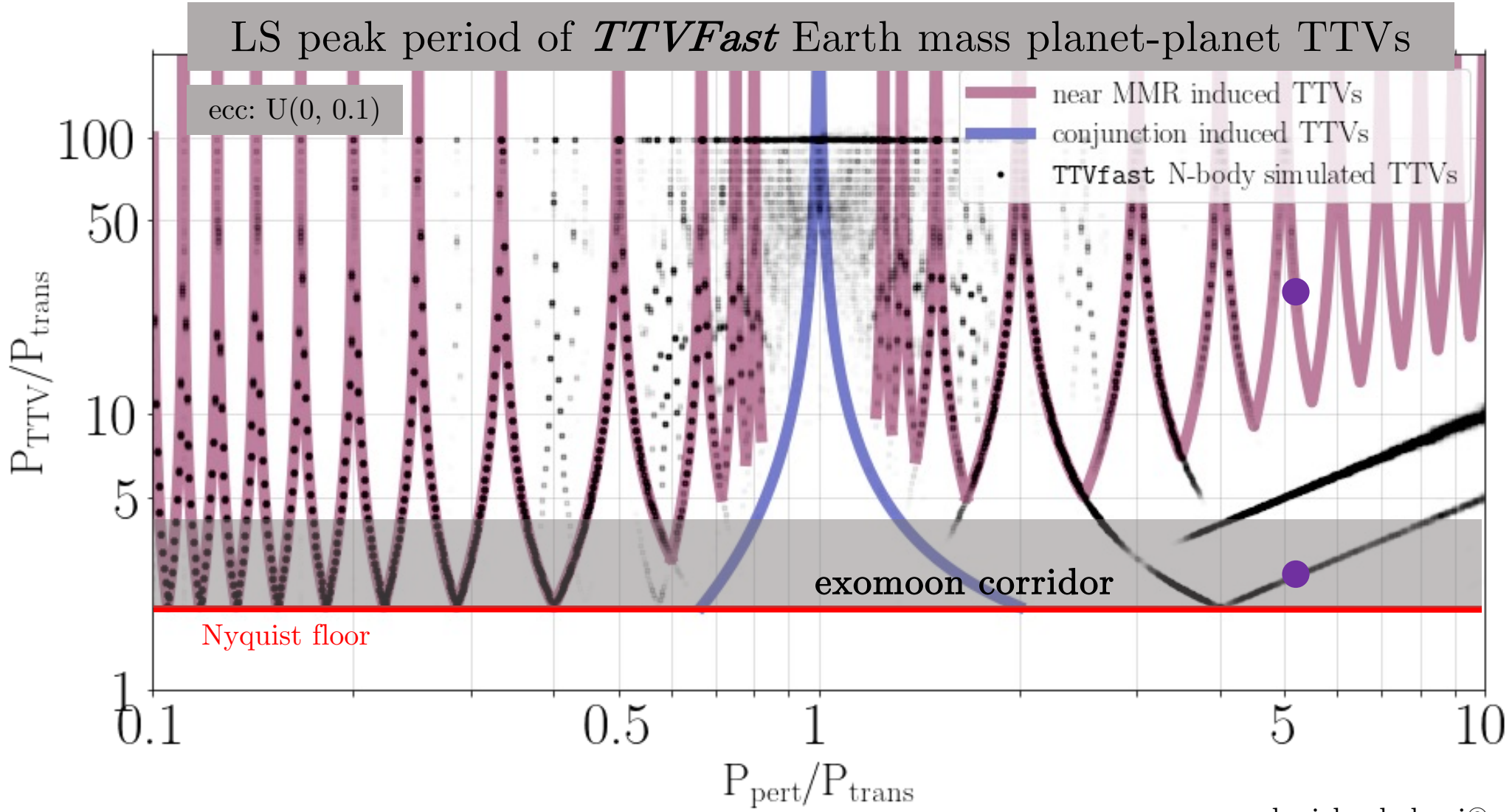


daniel.yahalomi@columbia.edu

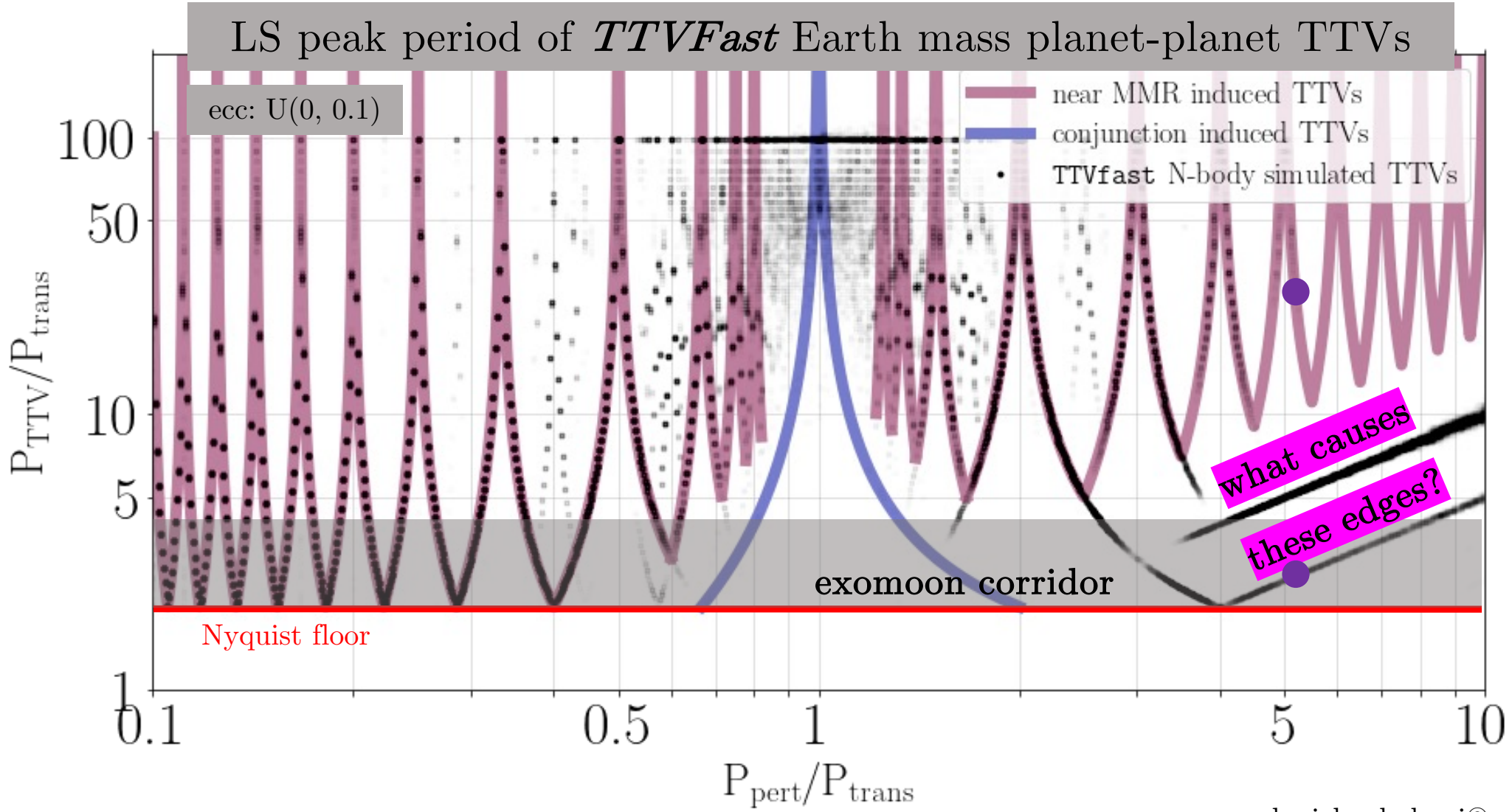
We can test these characteristic TTV periods via N-body simulations with ***TTVfast*** (Deck et al. 2014) and peak period determination with LS periodograms



daniel.yahalomi@columbia.edu

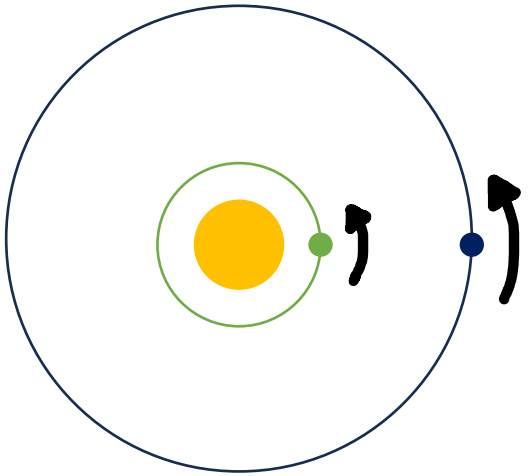


daniel.yahalomi@columbia.edu



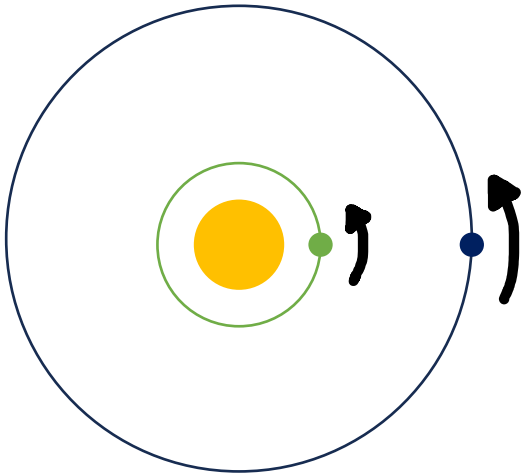
daniel.yahalomi@columbia.edu

conjunction induced TTVs



daniel.yahalomi@columbia.edu

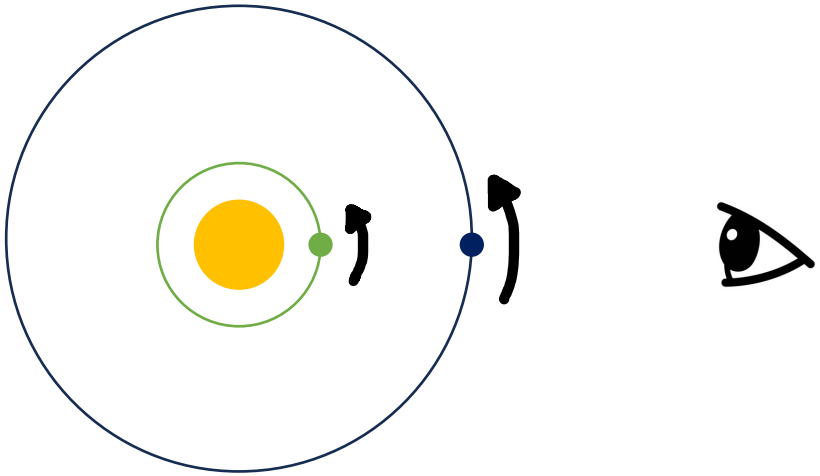
conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

daniel.yahalomi@columbia.edu

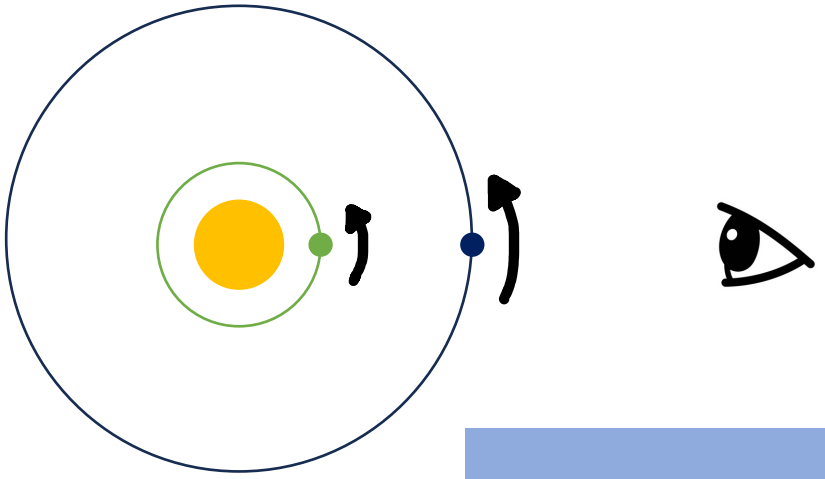
conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

daniel.yahalomi@columbia.edu

conjunction induced TTVs

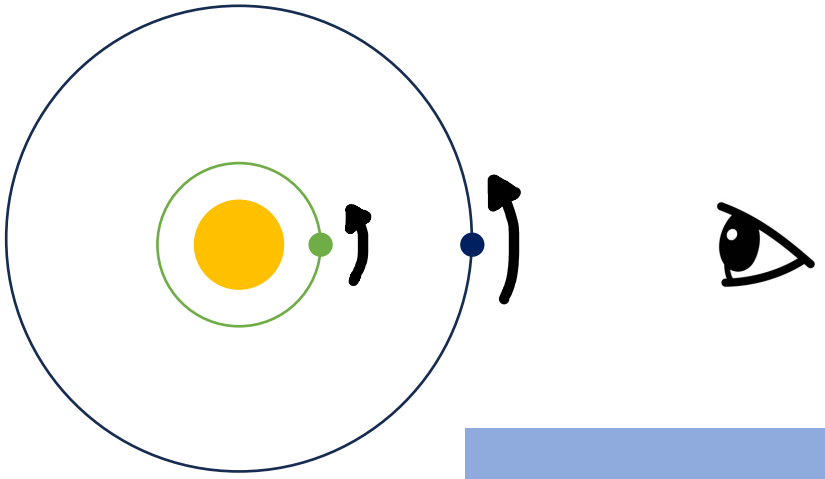


$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

we only observe **transits**

daniel.yahalomi@columbia.edu

conjunction induced TTVs



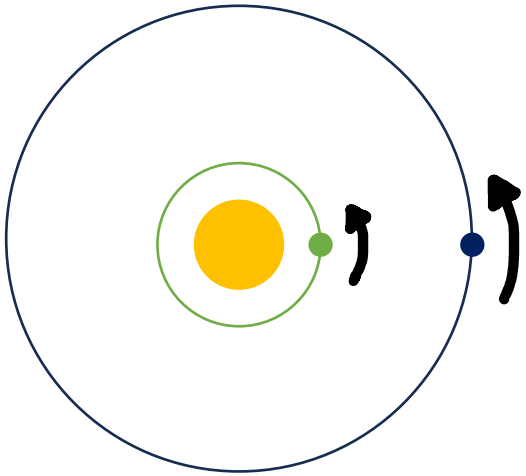
$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

we only observe **transits**

what do the **TTVs**
look like **during transits?**

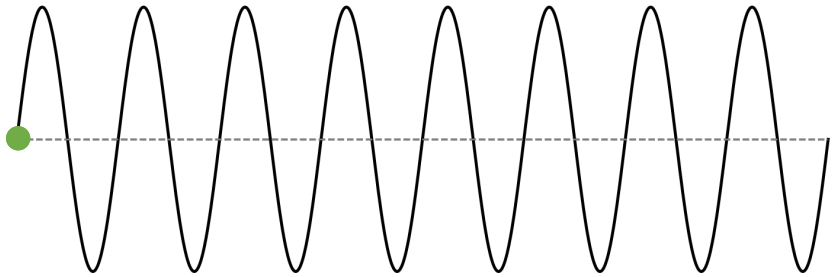
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

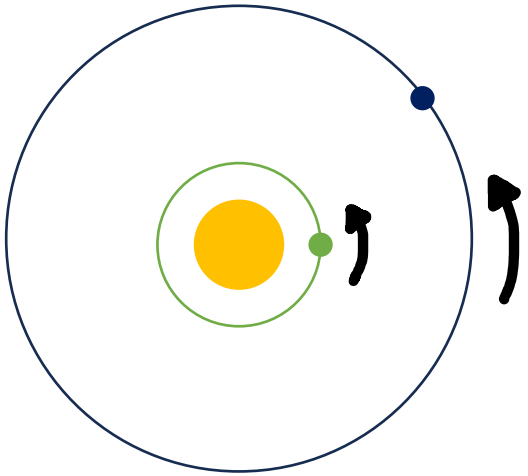
interior planet TTVs



time

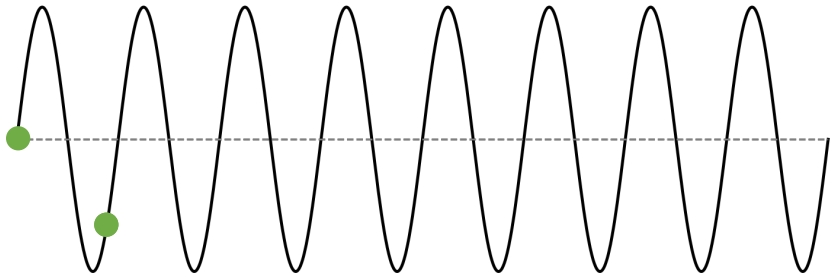
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

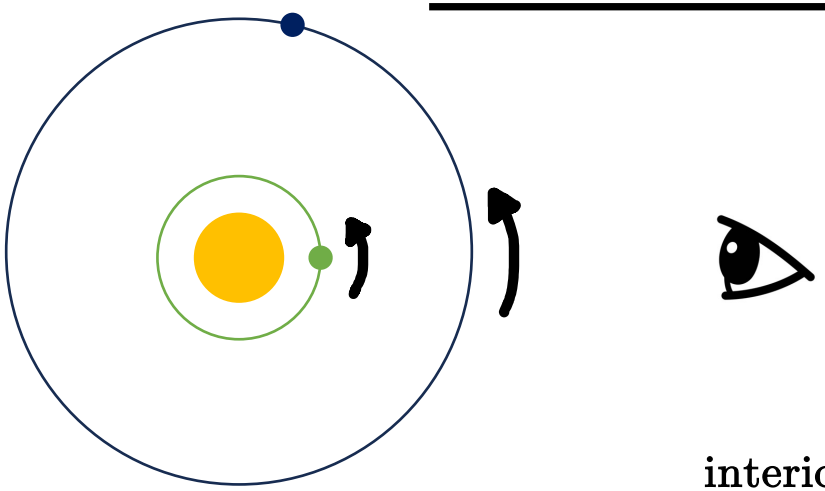
interior planet TTVs



time ⟶

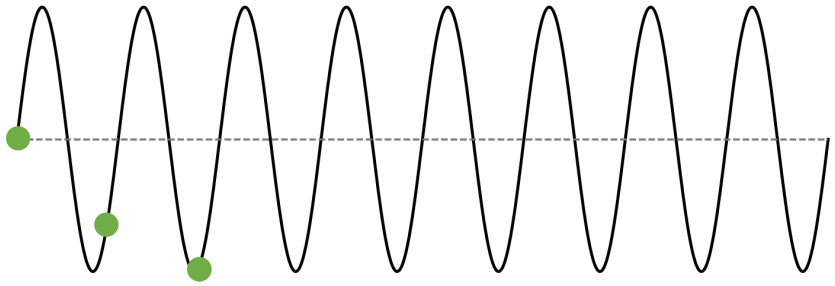
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

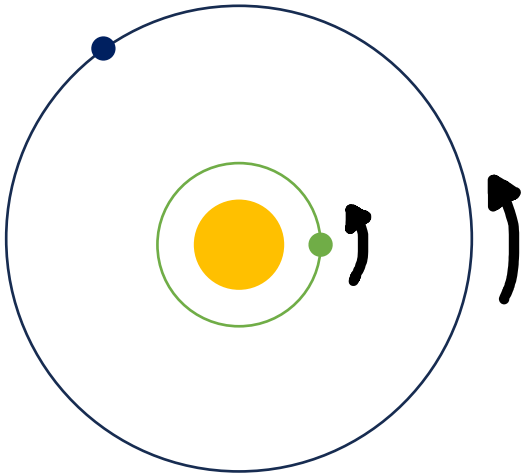
interior planet TTVs



time ⟶

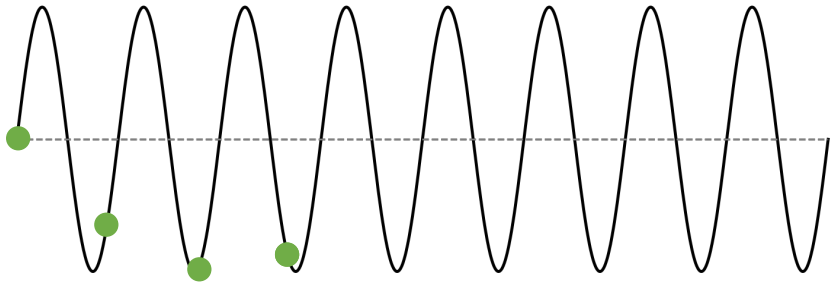
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

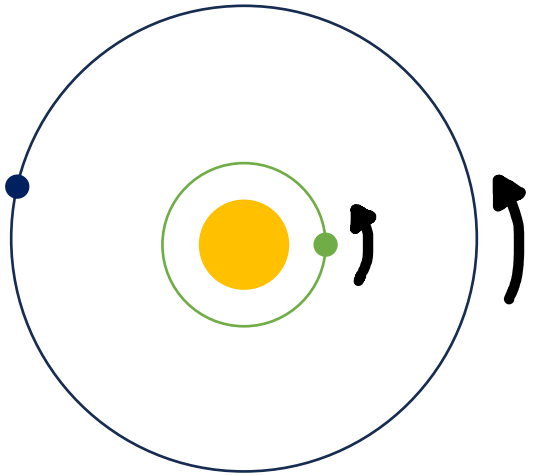
interior planet TTVs



time ⟶

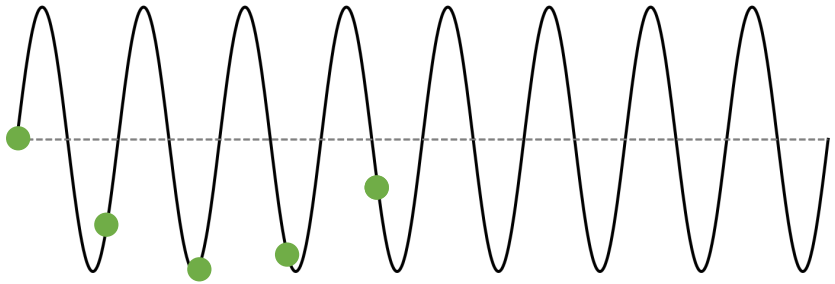
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

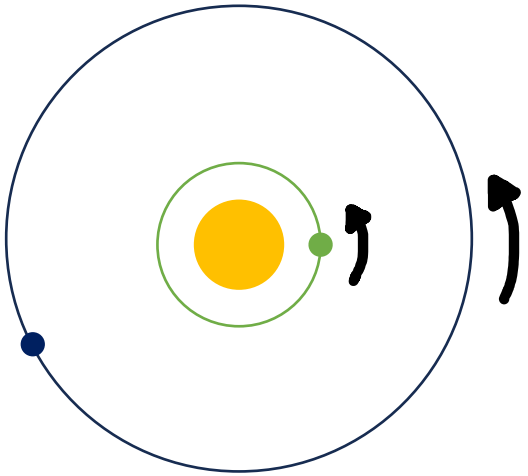
interior planet TTVs



time ⟶

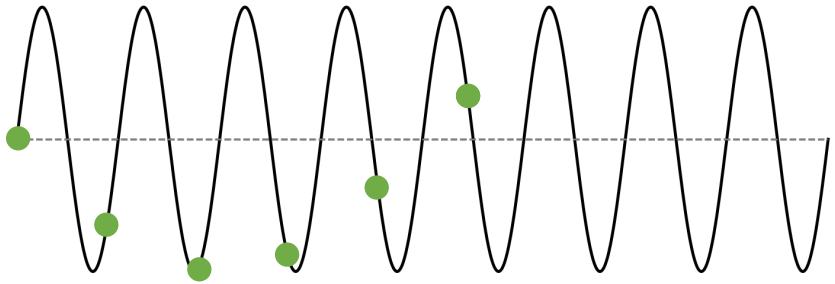
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

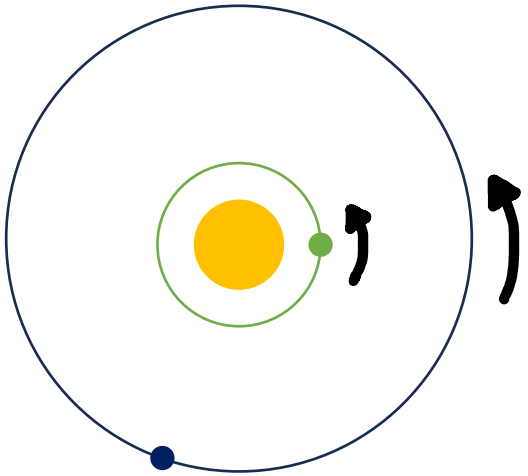
interior planet TTVs



time

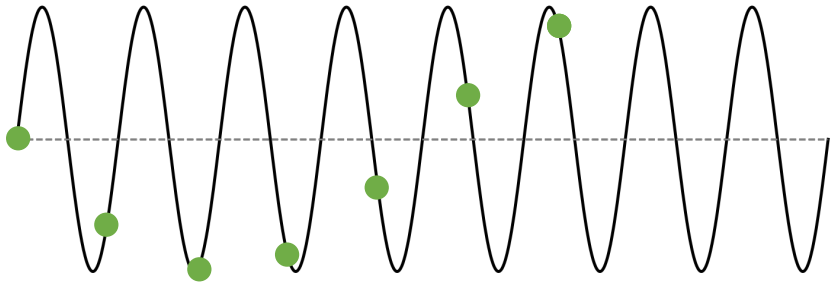
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

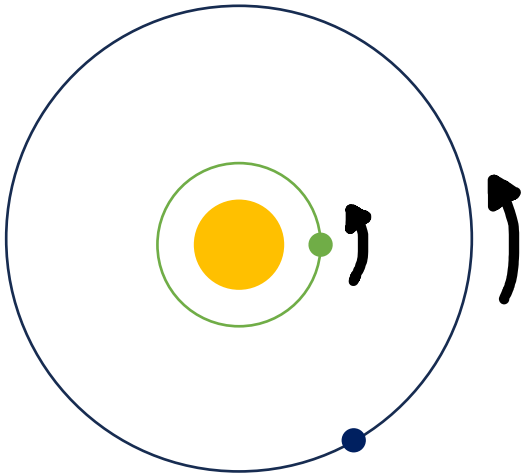
interior planet TTVs



time

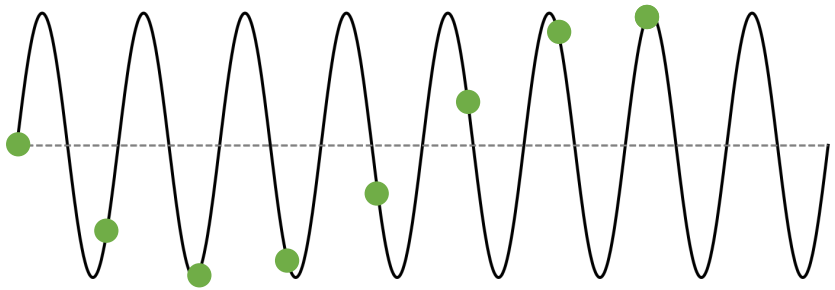
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

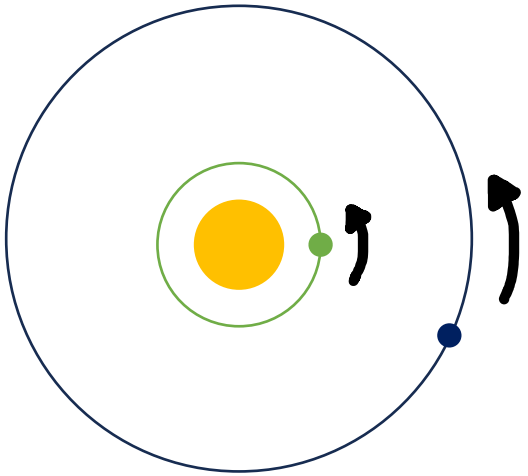
interior planet TTVs



time ⟶

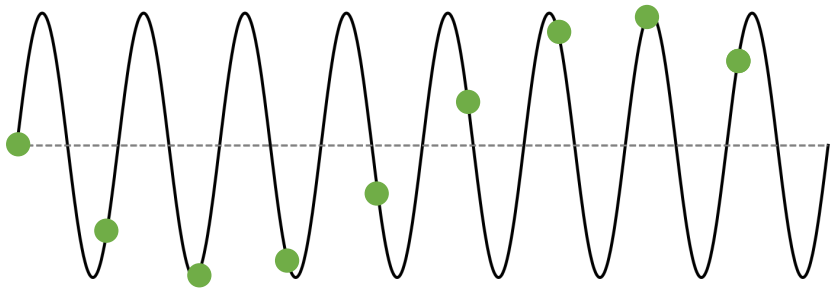
daniel.yahalomi@columbia.edu

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

interior planet TTVs

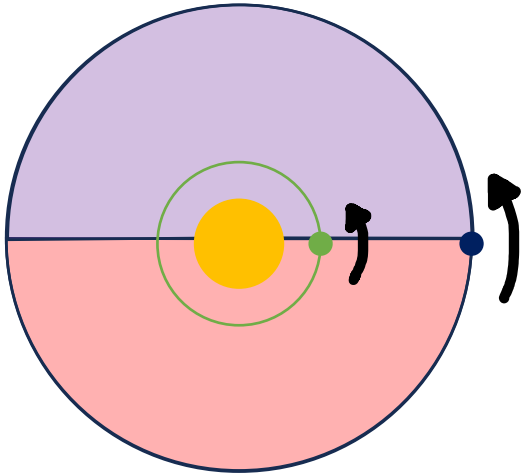


time

daniel.yahalomi@columbia.edu

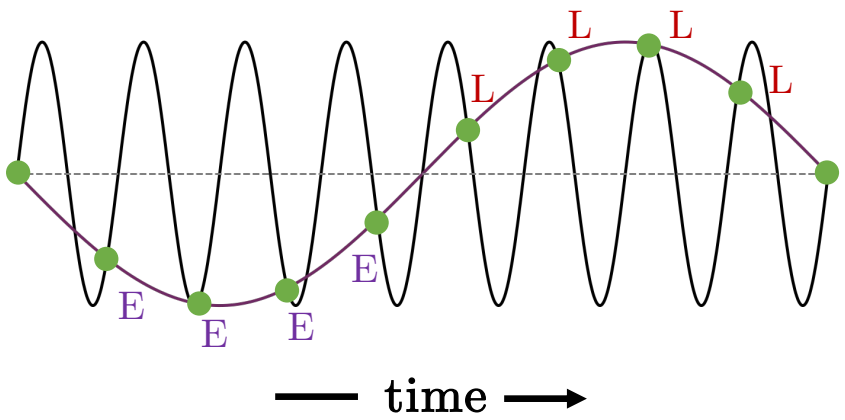
E = early TTV
L = late TTV

conjunction induced TTVs



$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

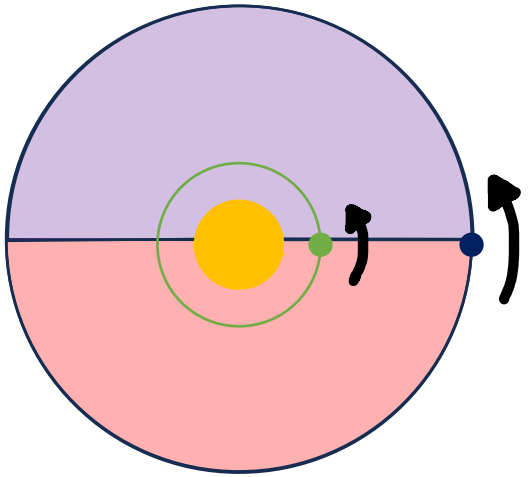
interior planet TTVs



daniel.yahalomi@columbia.edu

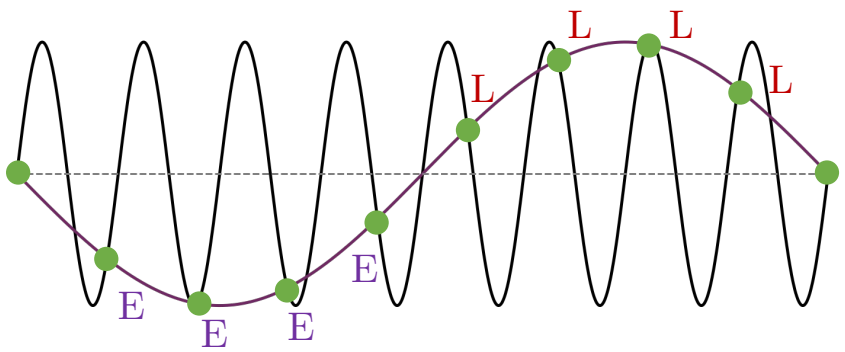
E = early TTV
L = late TTV

conjunction induced TTVs



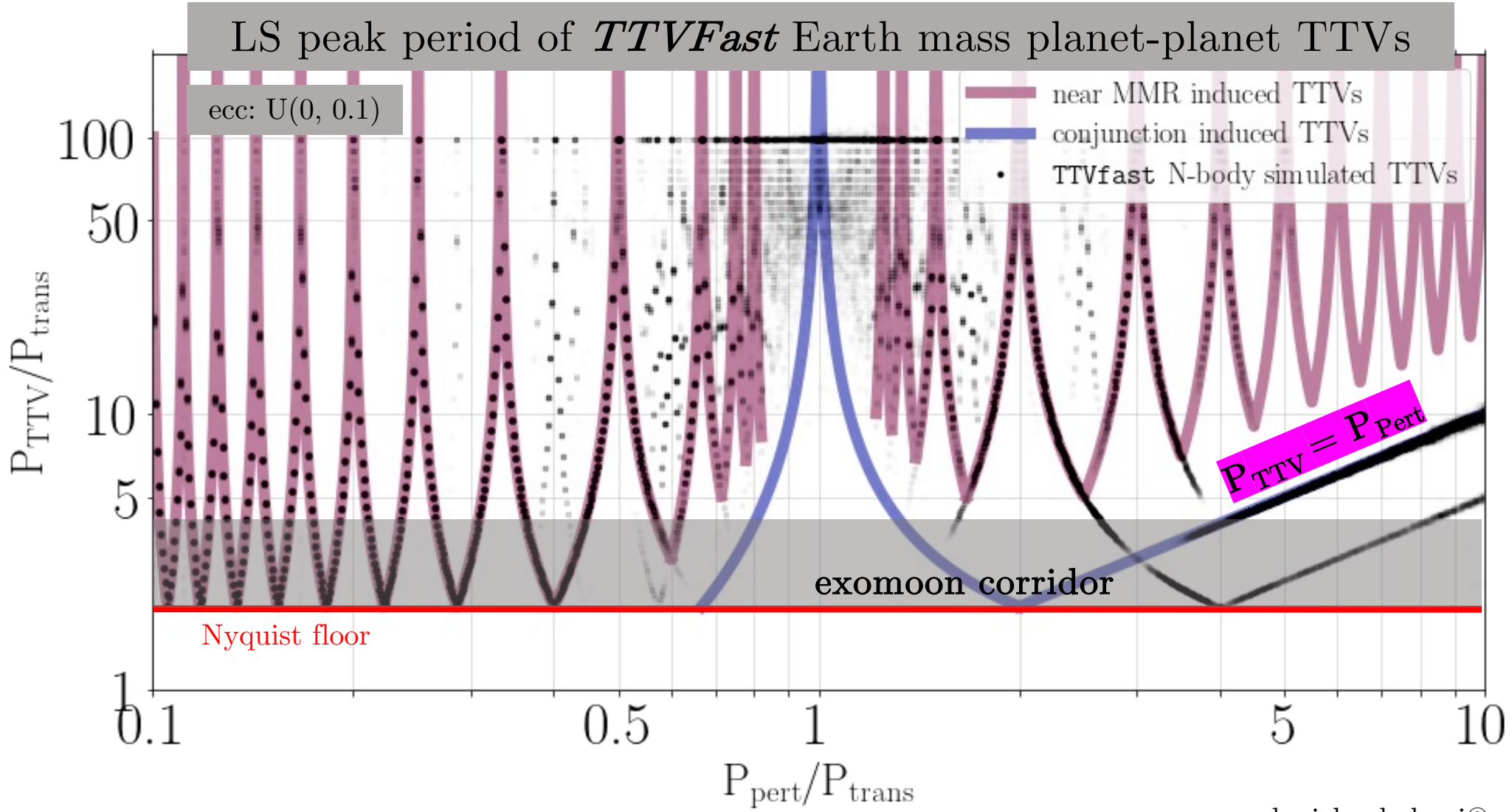
$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

interior planet TTVs

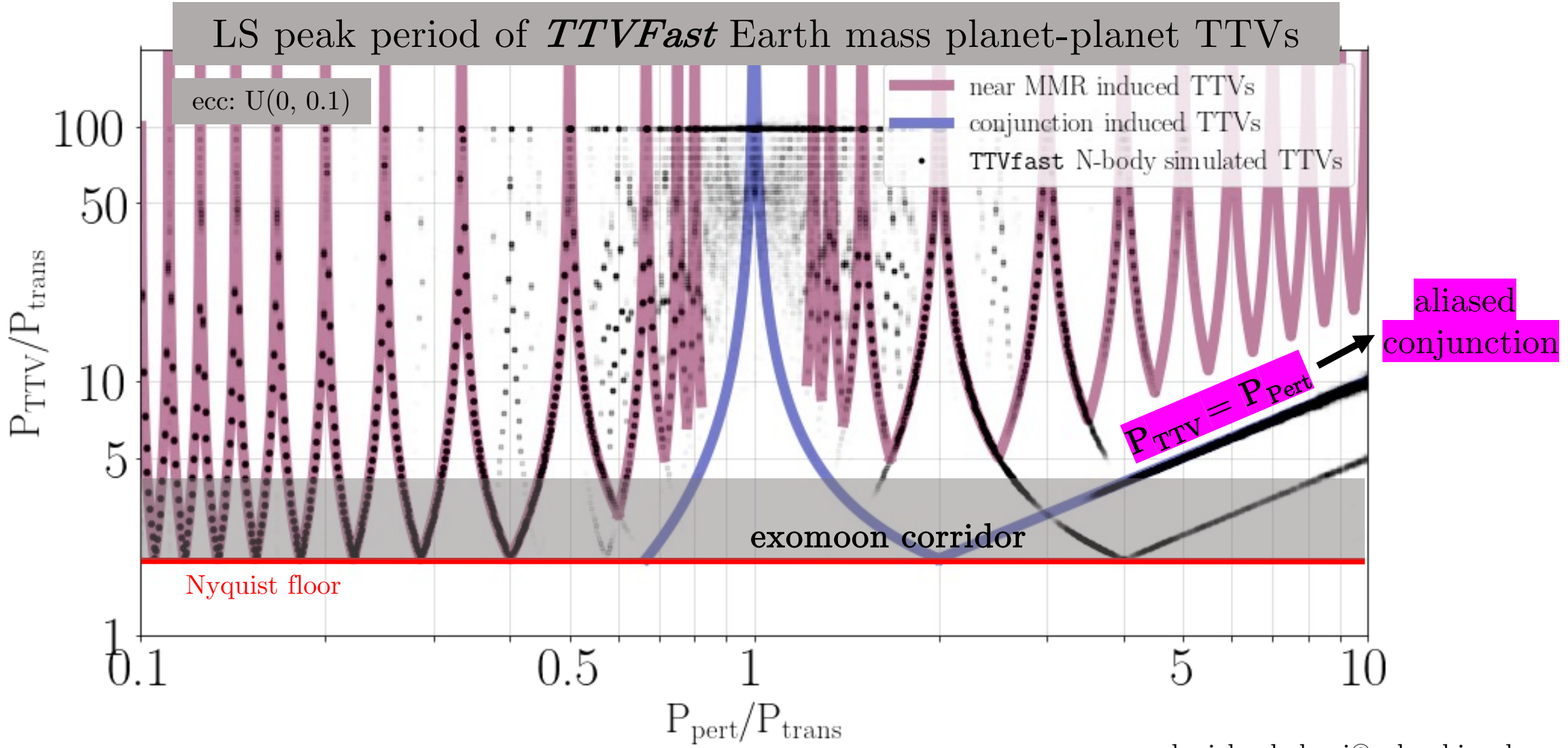


$P_{\text{TTV alias}} = P_{\text{exterior planet}}$

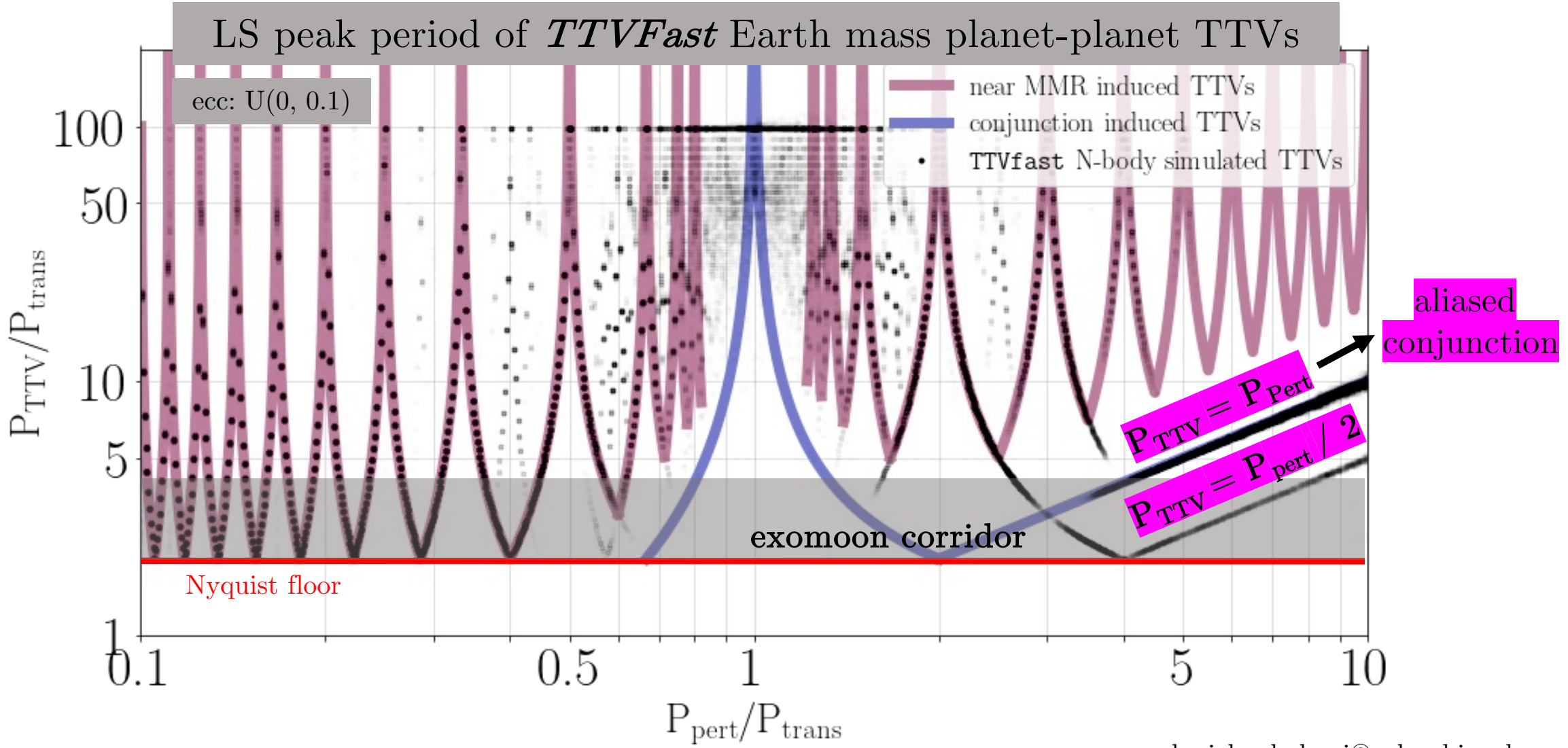
daniel.yahalomi@columbia.edu



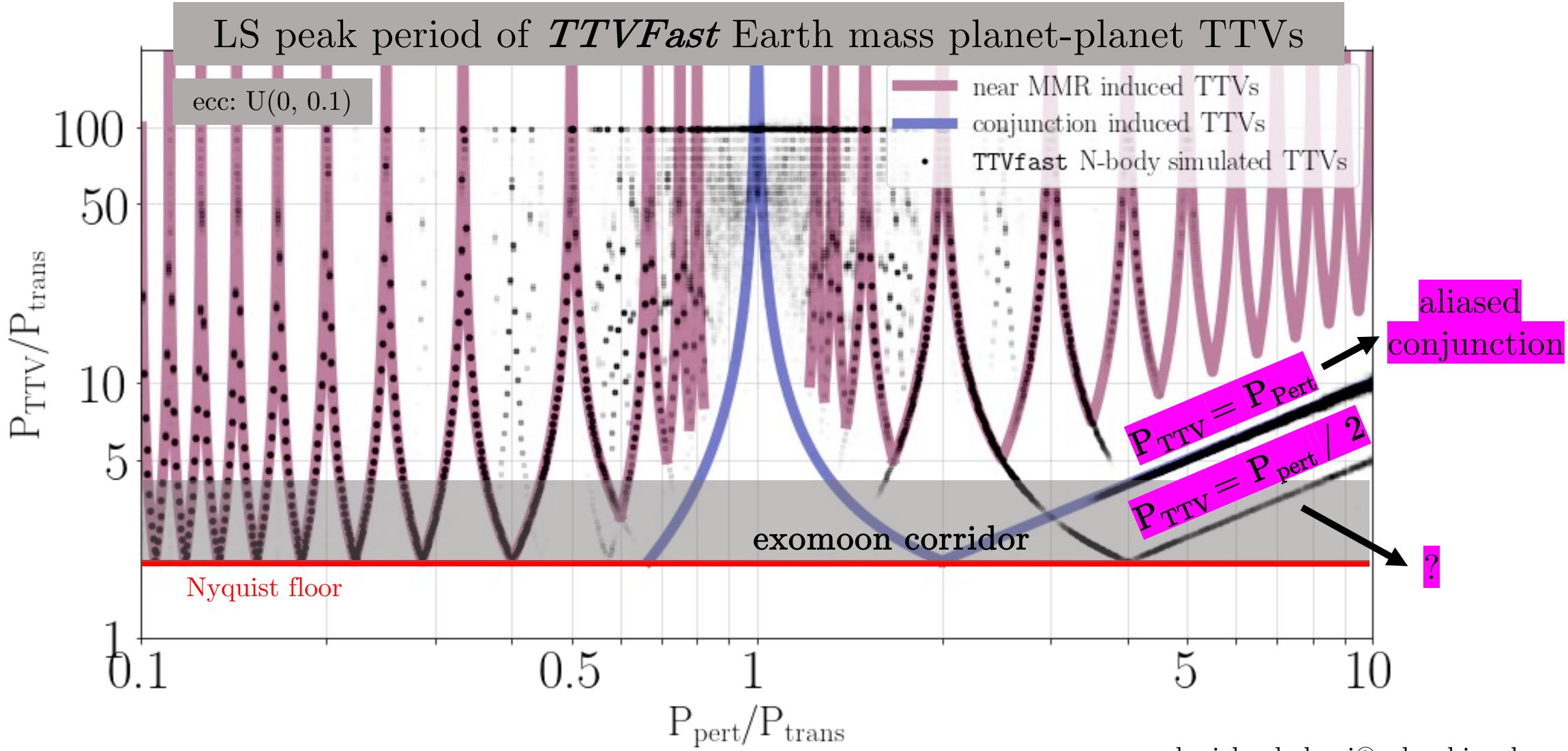
daniel.yahalomi@columbia.edu



daniel.yahalomi@columbia.edu



daniel.yahalomi@columbia.edu



daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

conjunction induced TTVs

$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

near MMR induced TTVs

$$P_{sup} = \frac{1}{|j/P_1 - k/P_2|}.$$

~~conjunction induced TTVs~~

$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

near MMR induced TTVs

$$P_{sup} = \frac{1}{|j/P_1 - k/P_2|}.$$

~~conjunction induced TTVs~~

$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

$$P_{sup} = \frac{1/j}{|1/P_1 - 1/[(\frac{j}{k})\,P_2]|}.$$

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

near MMR induced TTVs

$$P_{sup} = \frac{1}{|j/P_1 - k/P_2|}.$$

~~conjunction induced TTVs~~

$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

$$P_{sup} = \frac{1/j}{|1/P_1 - 1/[(\frac{j}{k})\,P_2]|}.$$

super-period for 1:k MMR
with P_1 and P_2
=
synodic period
with periods P_1 and P_2/k.

daniel.yahalomi@columbia.edu

planet-planet TTVs characteristic periods

near MMR induced TTVs

~~conjunction induced TTVs~~

$$P_{sup} = \frac{1}{|j/P_1 - k/P_2|}.$$

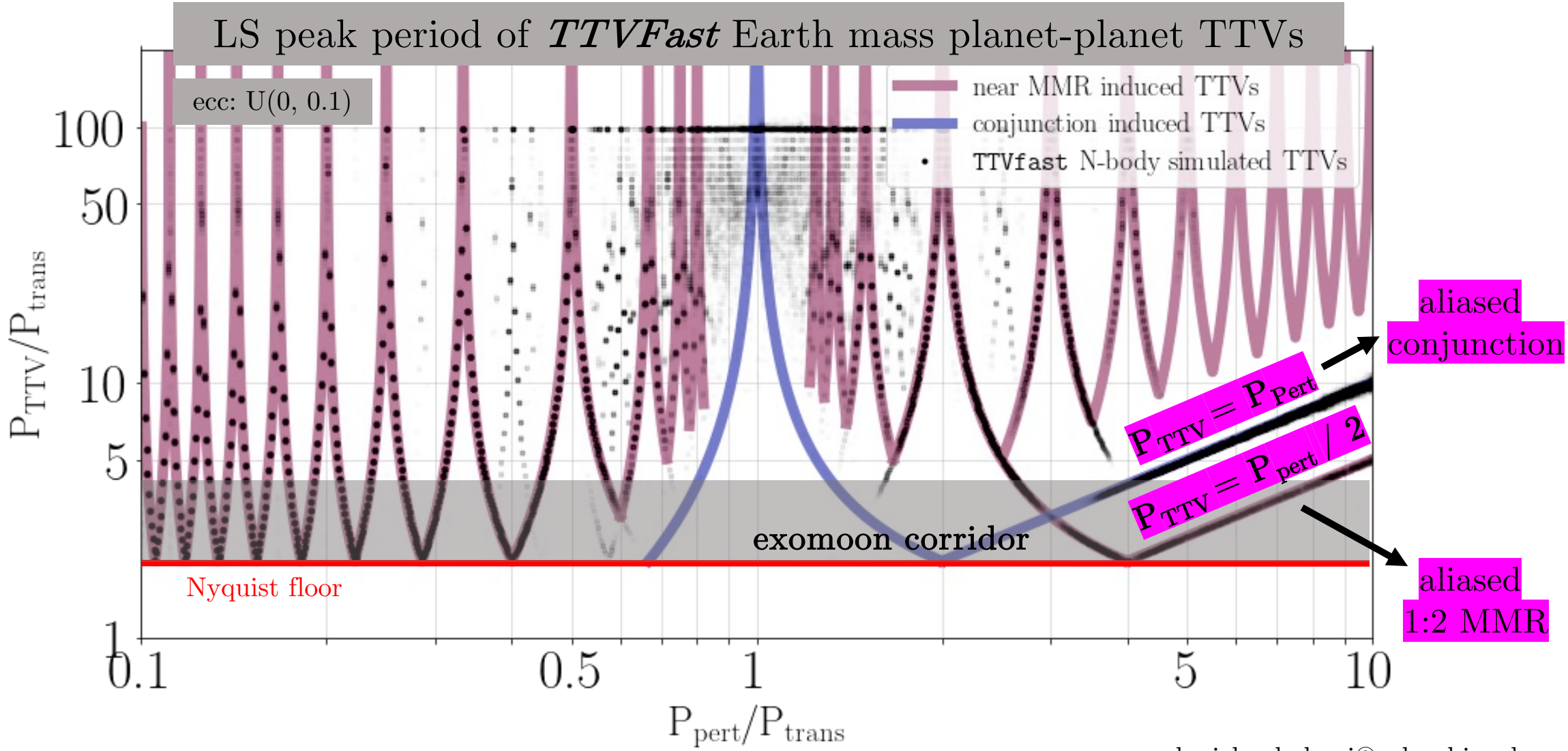
$$P_{syn} = \frac{1}{|1/P_1 - 1/P_2|}.$$

$$P_{sup} = \frac{1/j}{|1/P_1 - 1/[(\frac{j}{k})\,P_2]|}.$$

super-period for 1:k MMR
with P_1 and P_2
=
synodic period
with periods P_1 and P_2/k.

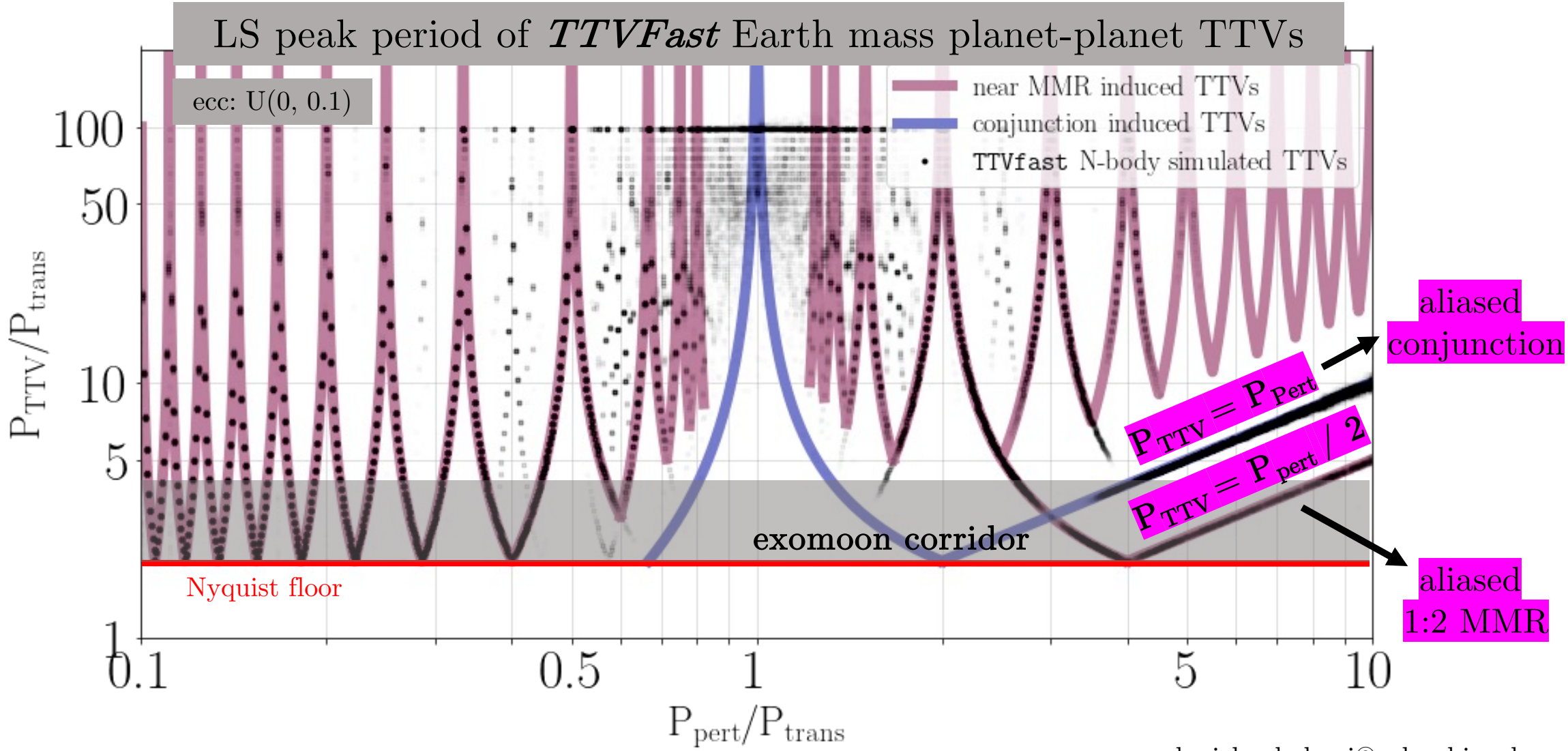
therefore, a 1:2 MMR TTV has an aliased period of $P_2/2$

daniel.yahalomi@columbia.edu



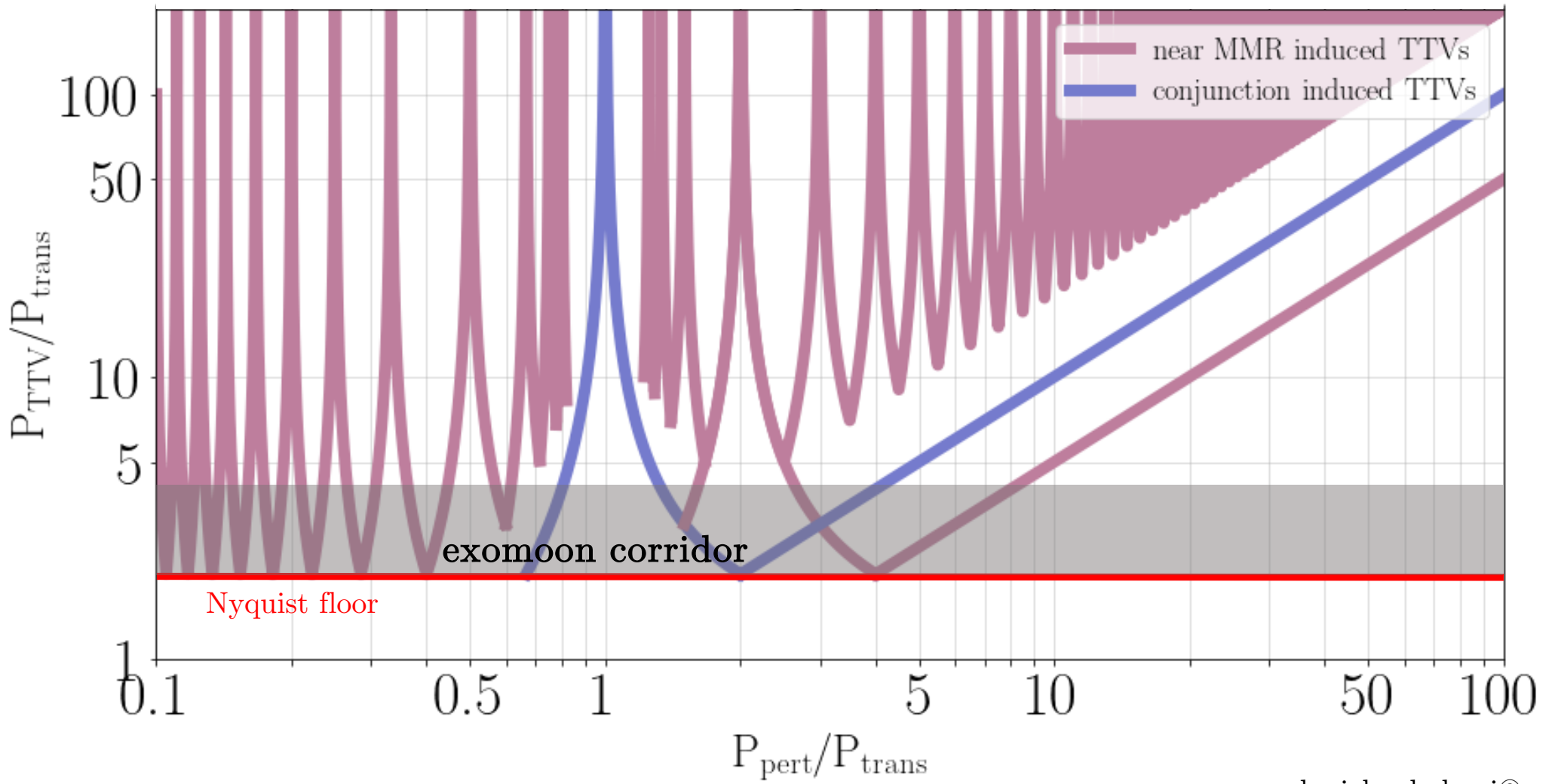
daniel.yahalomi@columbia.edu

Let's change our x-axis to include period ratios up to 100x...



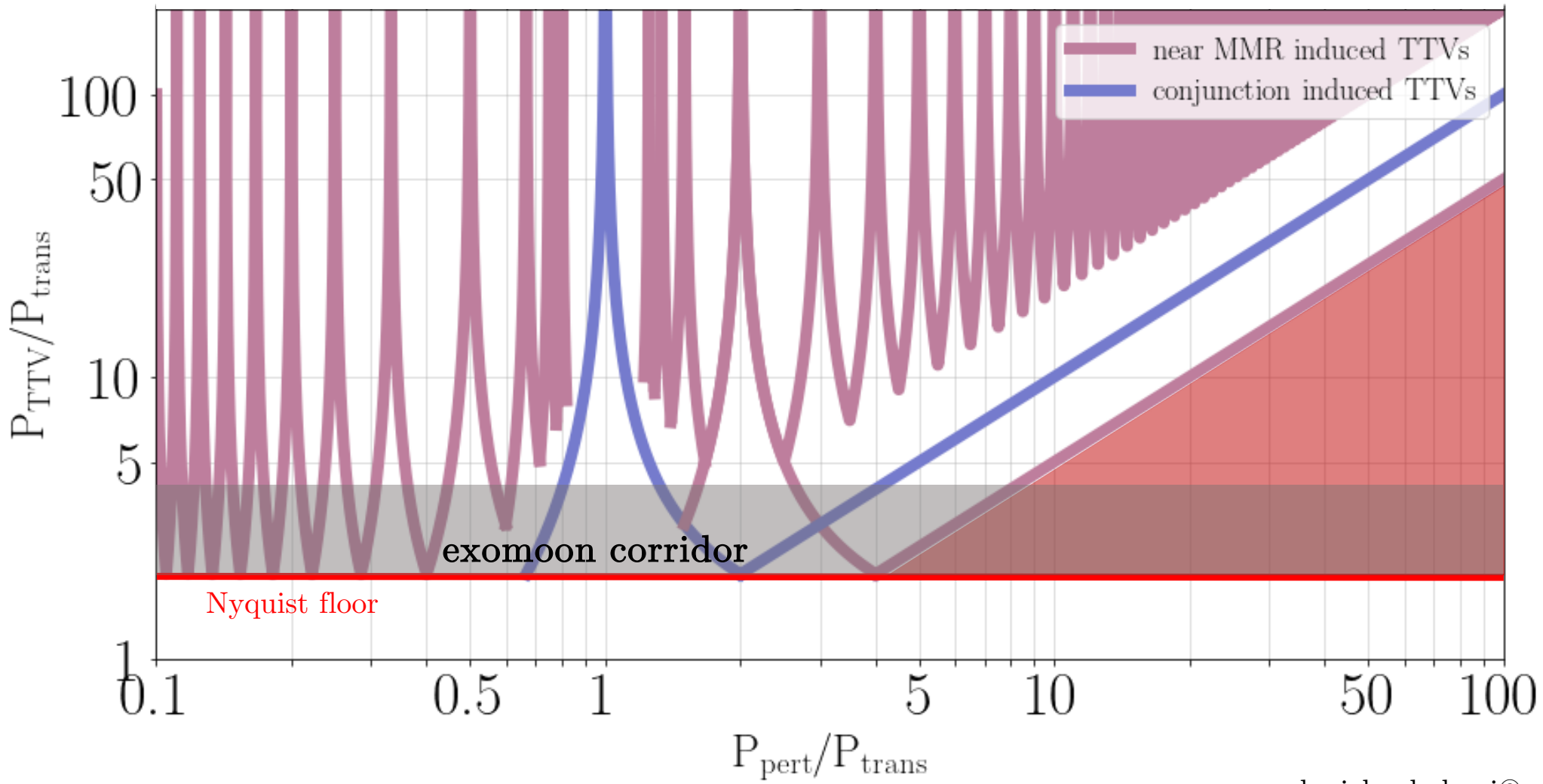
daniel.yahalomi@columbia.edu

Let's change our x-axis to include period ratios up to 100x...



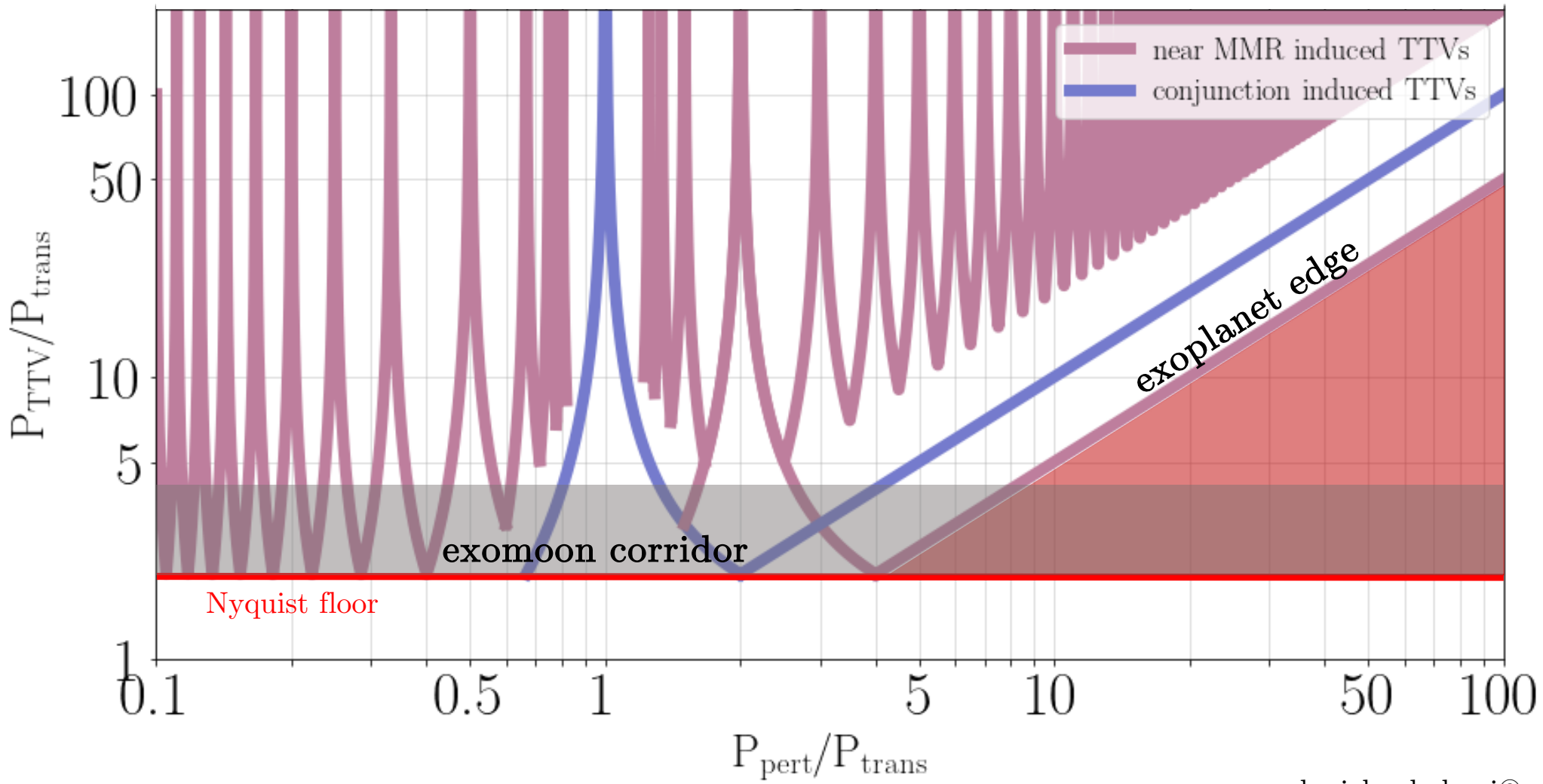
daniel.yahalomi@columbia.edu

planet-planet TTVs are not expected below this edge!



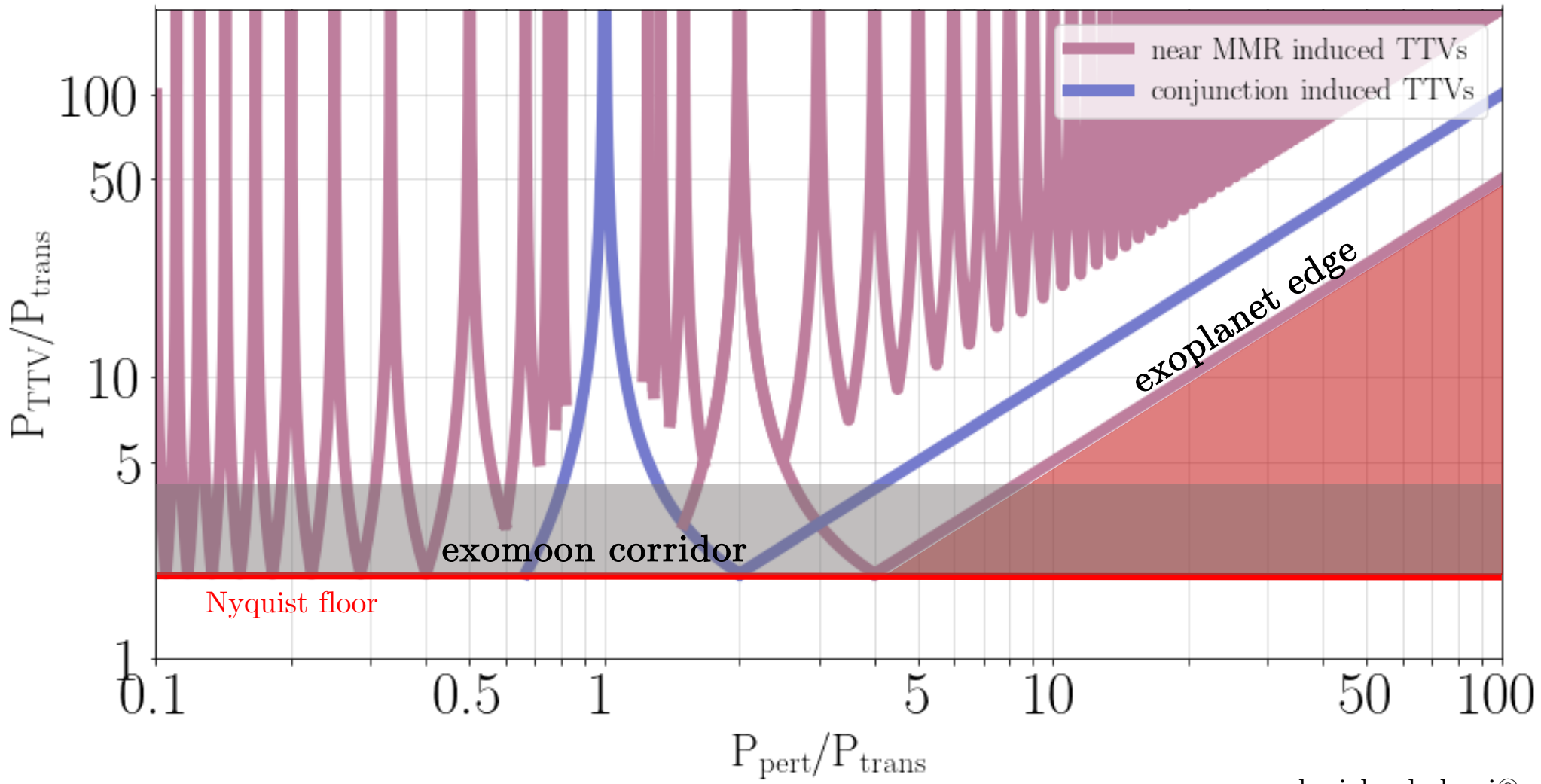
daniel.yahalomi@columbia.edu

planet-planet TTVs are not expected below this edge!



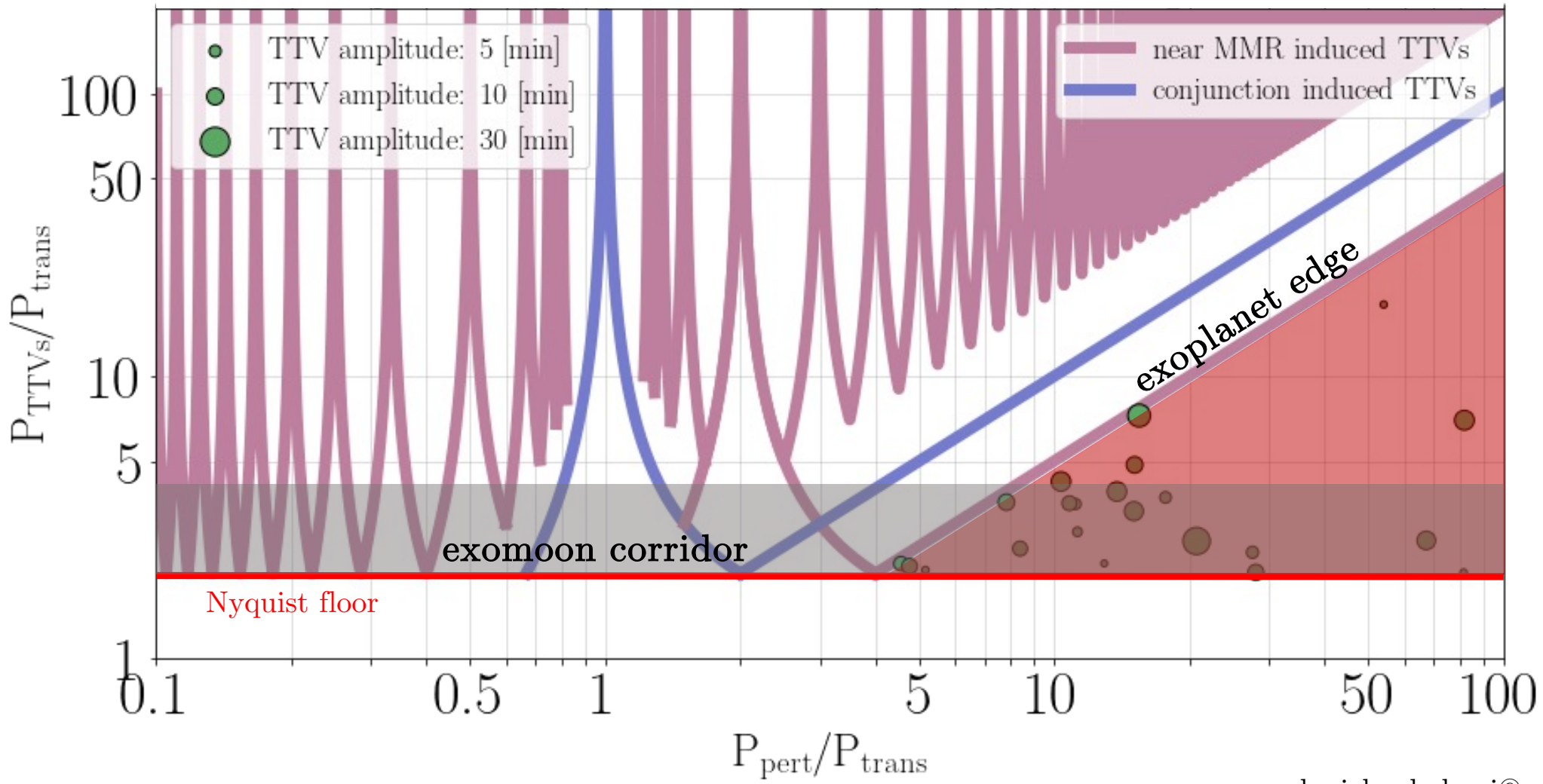
daniel.yahalomi@columbia.edu

Do any two-planets systems appear below the exoplanet edge?



daniel.yahalomi@columbia.edu

22 two-planet systems in Holczer+ 2016 are anomalous



daniel.yahalomi@columbia.edu

22 two-planet systems in Holczer+ 2016 are anomalous

daniel.yahalomi@columbia.edu

22 two-planet systems in Holczer+ 2016 are anomalous

- Possible exomoon corridor systems...

daniel.yahalomi@columbia.edu

22 two-planet systems in Holczer+ 2016 are anomalous

- Possible exomoon corridor systems...
  - Would've been eliminated from Kipping and Yahalomi, 2023

daniel.yahalomi@columbia.edu

22 two-planet systems in Holczer+ 2016 are anomalous

- Possible exomoon corridor systems...
  - Would've been eliminated from Kipping and Yahalomi, 2023
  - We are currently working on more rigorous analysis of these 22 systems to determine which systems to follow-up.

daniel.yahalomi@columbia.edu

What could cause anomalous TTV periods?

daniel.yahalomi@columbia.edu

What could cause anomalous TTV periods?

- Another (non-transiting) planet?

daniel.yahalomi@columbia.edu

What could cause anomalous TTV periods?

- Another (non-transiting) planet?
- A moon?

daniel.yahalomi@columbia.edu

What could cause anomalous TTV periods?

- Another (non-transiting) planet?
- A moon?
- Highly eccentric planets?

daniel.yahalomi@columbia.edu

What could cause anomalous TTV periods?

- Another (non-transiting) planet?
- A moon?
- Highly eccentric planets?

Stay tuned (and I am certainly excited to talk about ideas!)

daniel.yahalomi@columbia.edu

Takeaways

1. TTVs are ubiquitous and we must develop more efficient ways to analyze TTV datasets on a population level.

daniel.yahalomi@columbia.edu

Takeaways

1. TTVs are ubiquitous and we must develop more efficient ways to analyze TTV datasets on a population level.

2. We are developing analytic methods to differentiate between TTVs cause by moons, planets, and stellar-activity.
   - Analysis of TTV period space is particularly promising.

daniel.yahalomi@columbia.edu

Takeaways

1. TTVs are ubiquitous and we must develop more efficient ways to analyze TTV datasets on a population level.

2. We are developing analytic methods to differentiate between TTVs cause by moons, planets, and stellar-activity.
   - Analysis of TTV period space is particularly promising.

3. Using the **exomoon corridor** and **exoplanet edge** we can identify targets of interest and follow them up with ground-based facilities. This effort is underway and will continue.

daniel.yahalomi@columbia.edu

roadmap

wobbles

worlds

Add destination

Leave now

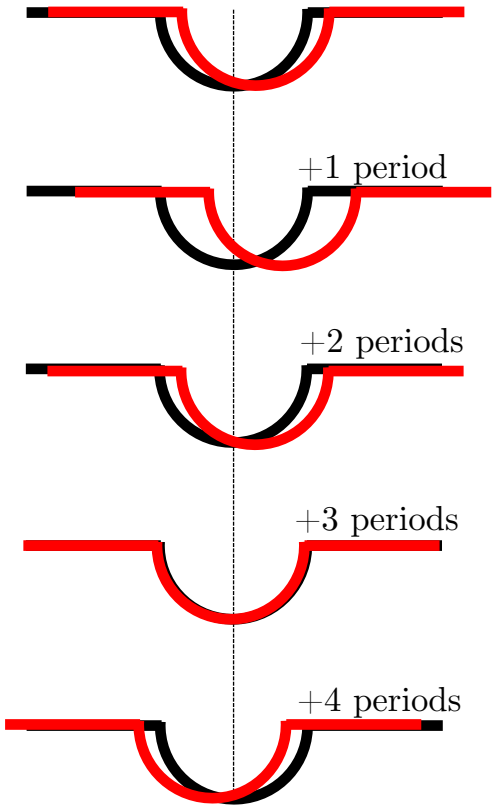
Options

Send directions to your phone

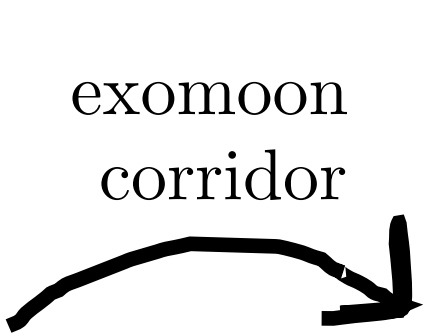
Copy link

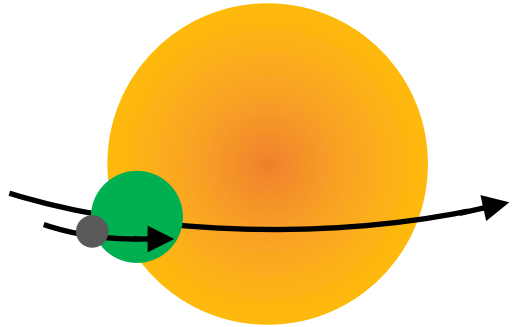
via exomoon corridor

via exoplanet edge

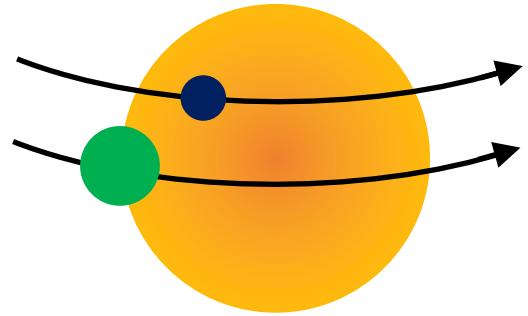


exomoon corridor



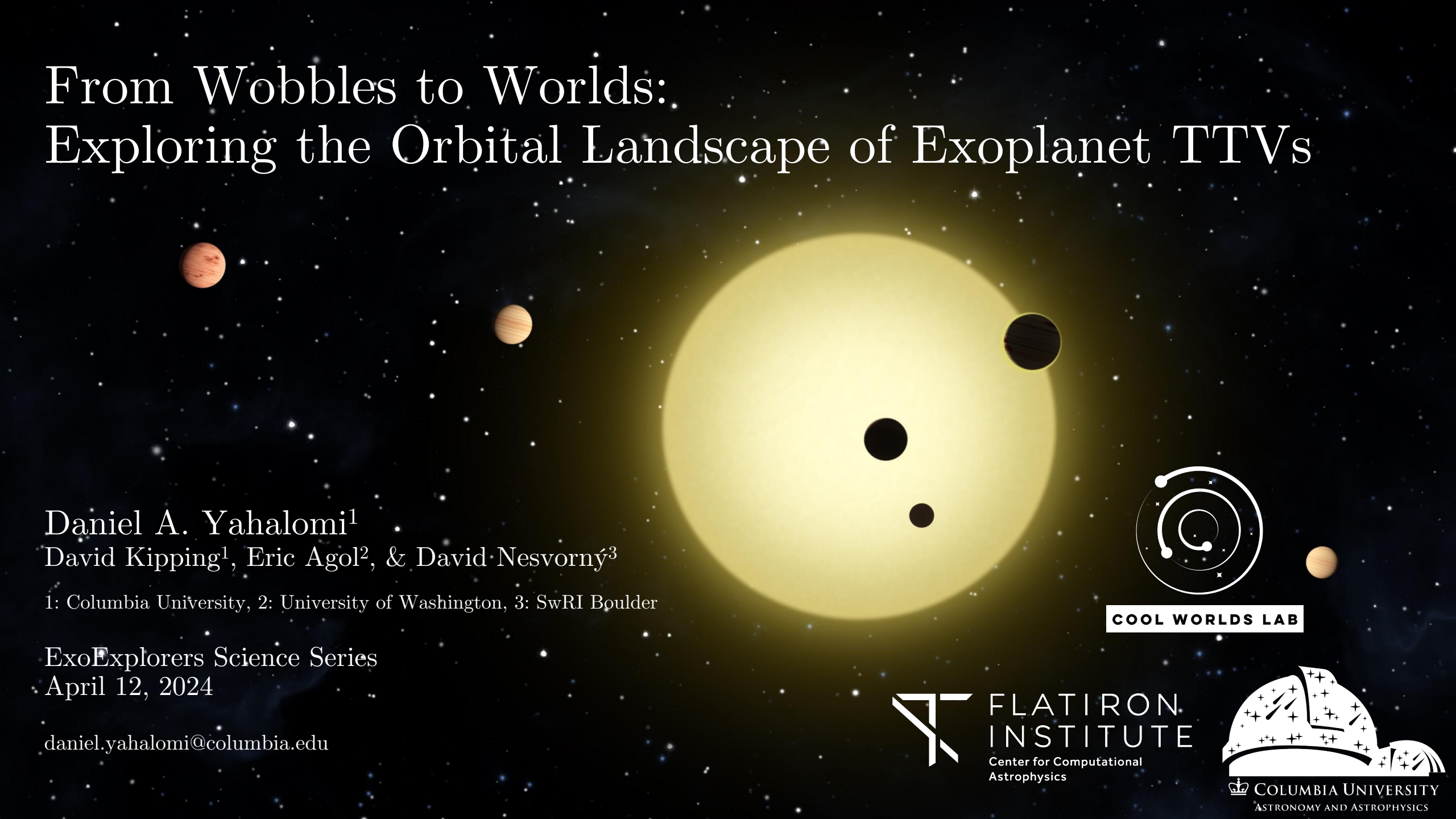


exoplanet edge



daniel.yahalomi@columbia.edu

From Wobbles to Worlds: Exploring the Orbital Landscape of Exoplanet TTVs



Daniel A. Yahalomi[1]
David Kipping[1], Eric Agol[2], & David Nesvorný[3]

1: Columbia University, 2: University of Washington, 3: SwRI Boulder

ExoExplorers Science Series
April 12, 2024

daniel.yahalomi@columbia.edu

COOL WORLDS LAB

FLATIRON INSTITUTE
Center for Computational Astrophysics

COLUMBIA UNIVERSITY
ASTRONOMY AND ASTROPHYSICS