

Genesis of Trojans in PDS 70 b

potentially hunted with ALMA

Olga **Balsalobre-Ruza**

PhD Supervisors:

Jorge **Lillo-Box** & Nuria **Huélamo**

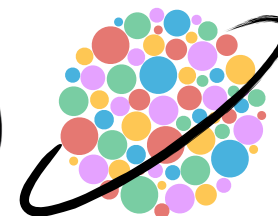
Centro de Astrobiología (CAB), Madrid, Spain



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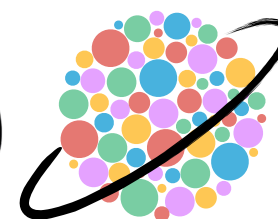
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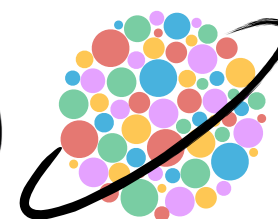
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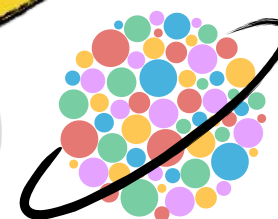
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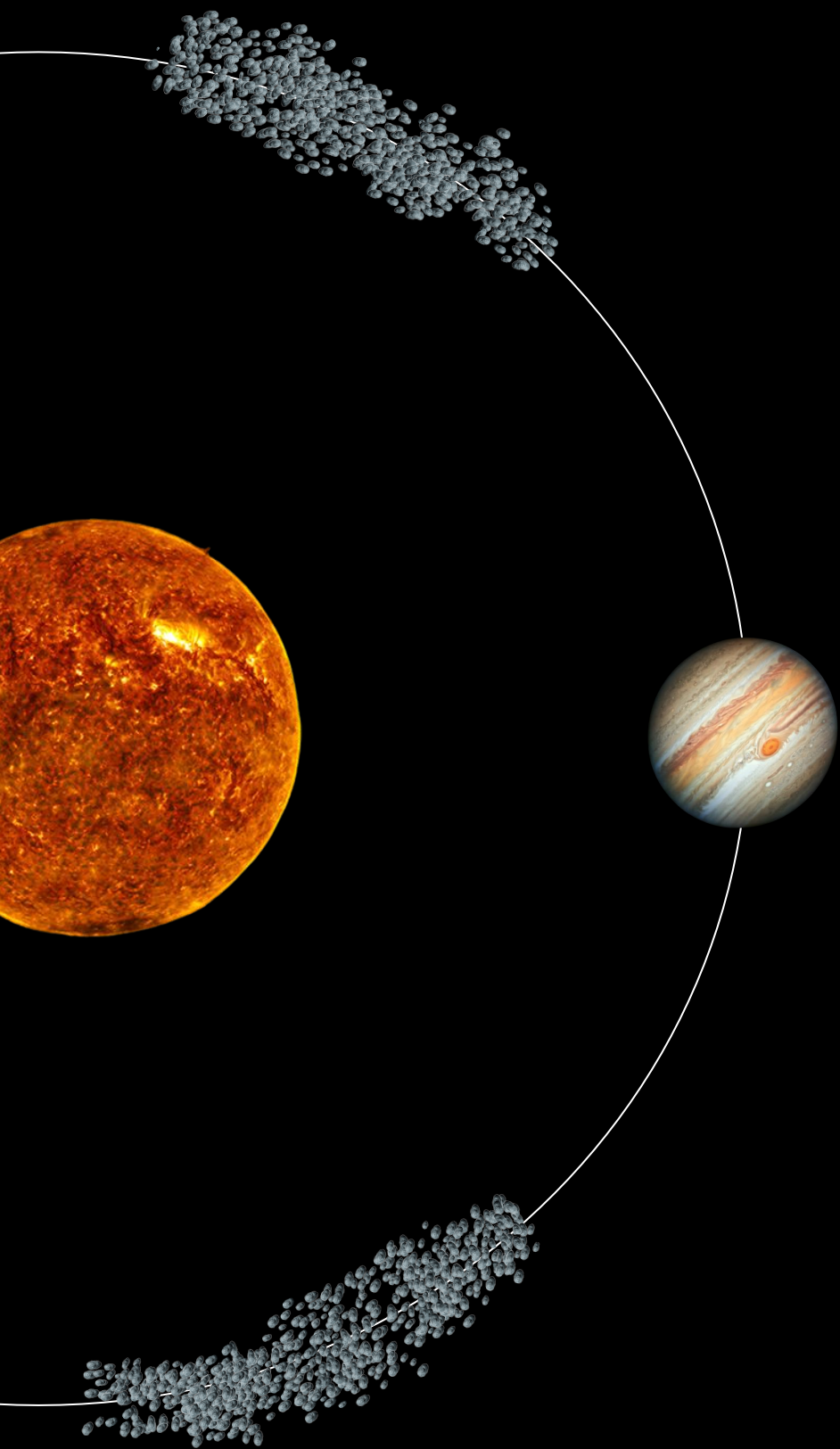
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Trojans are bodies co-orbiting with a planet

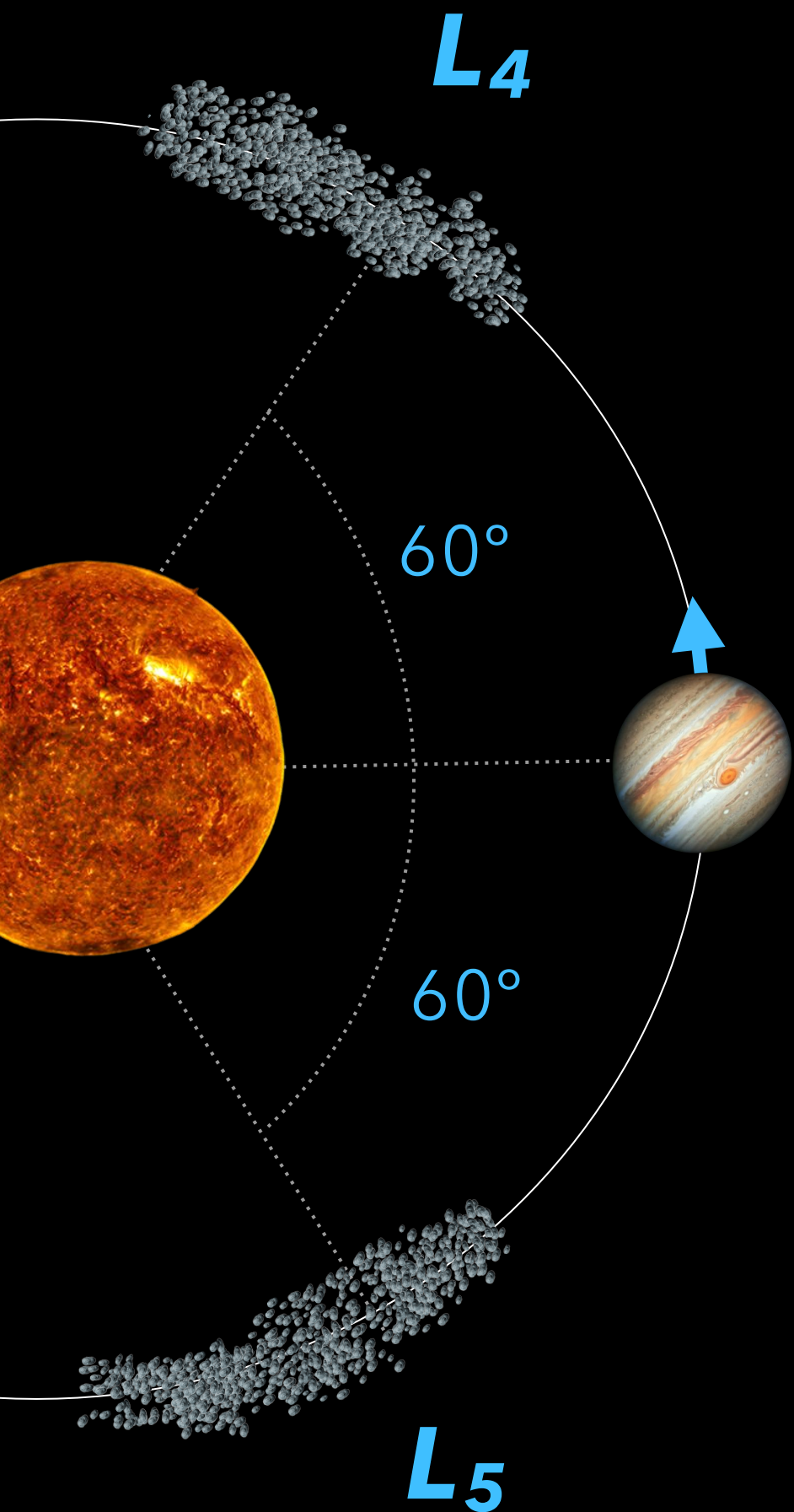
Trojans are bodies co-orbiting with a planet



In the **Solar System**
they are small rocky bodies.

Jupiter harbors more than
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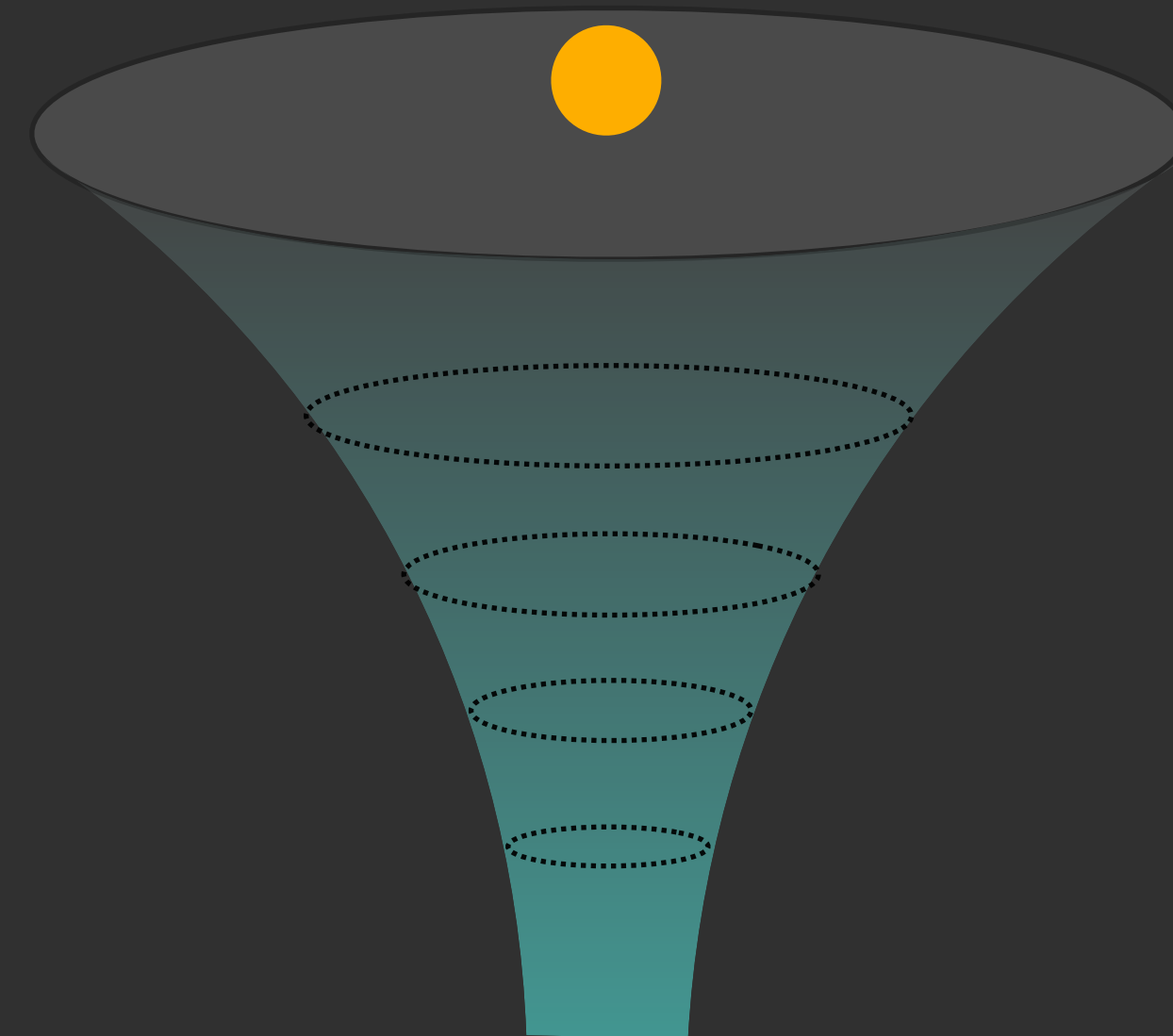
They reside in the
Lagrangian points
Solutions of the three-body problem

Lagrangian points are the home of Trojans

Bird view (Face-on)



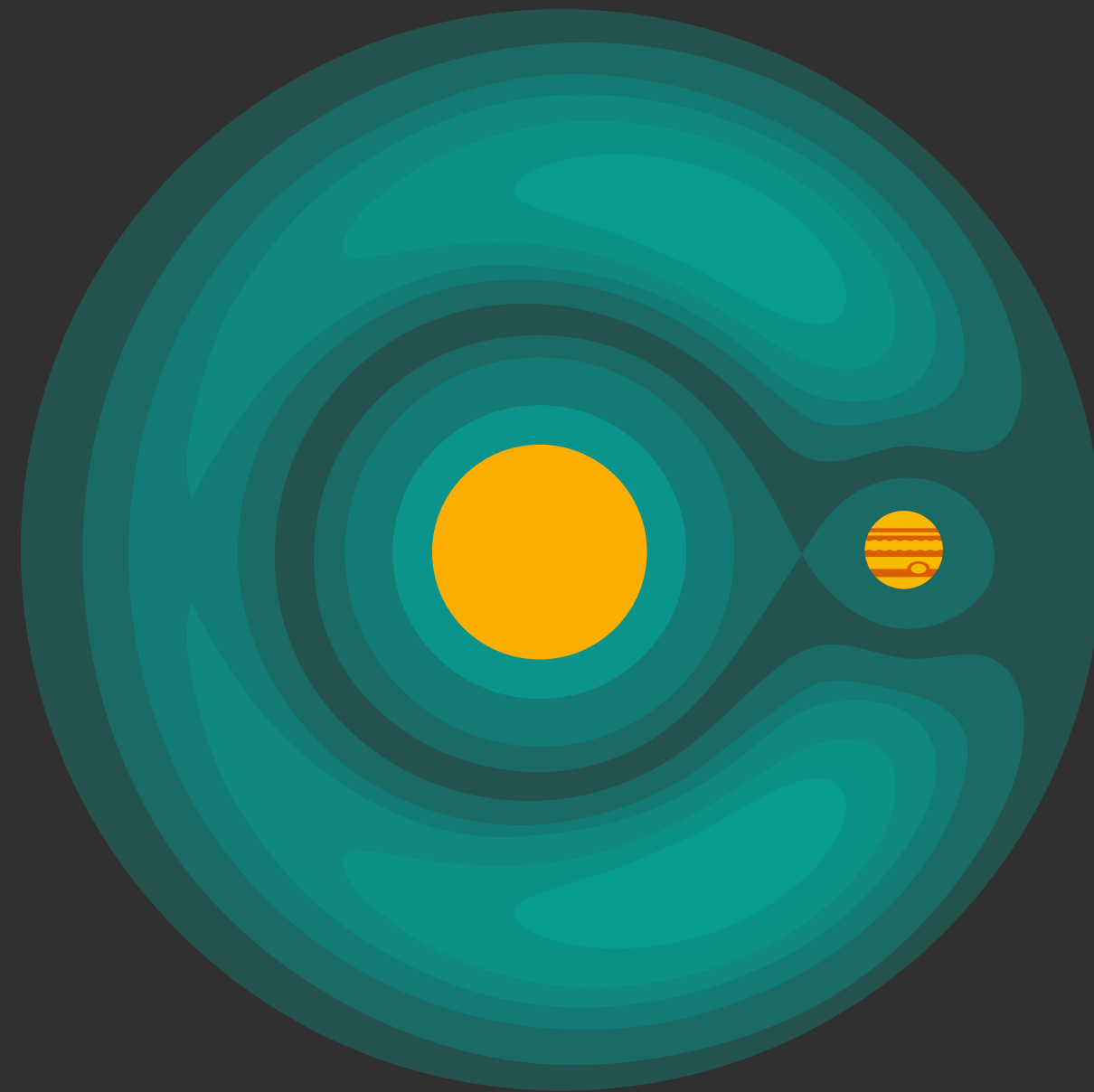
3D view (Edge-on)



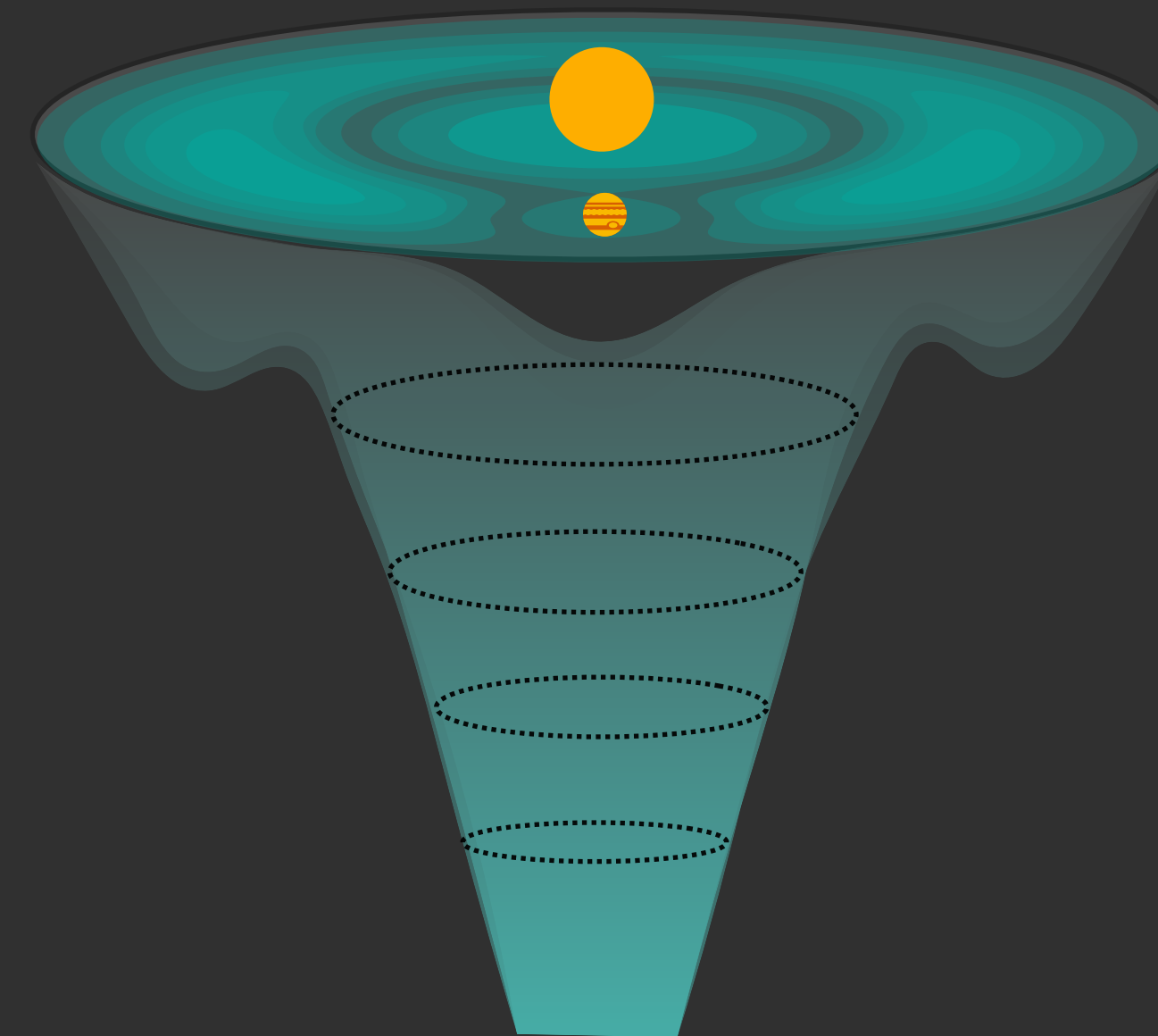
Credits: Jorge **Lillo-Box**

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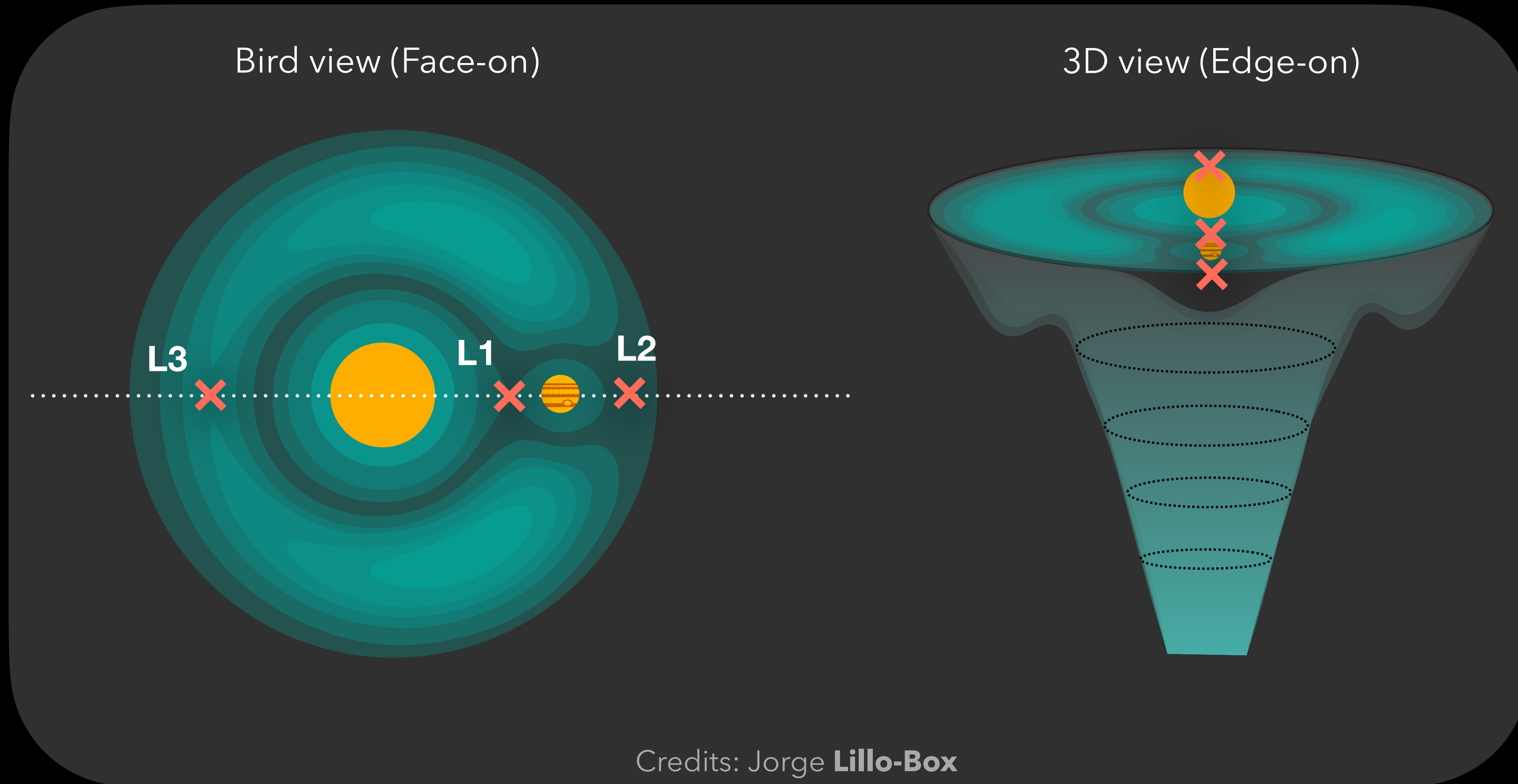


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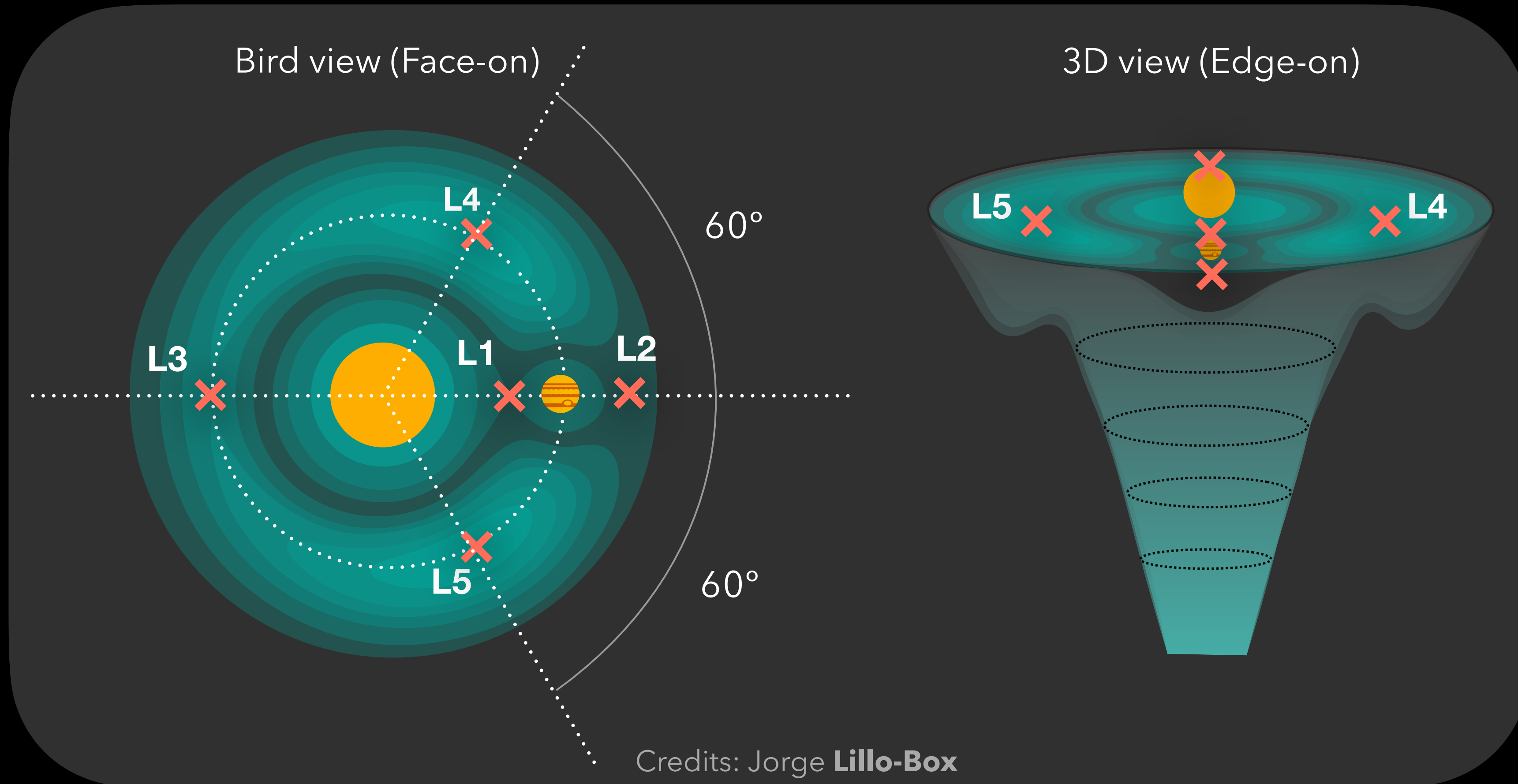


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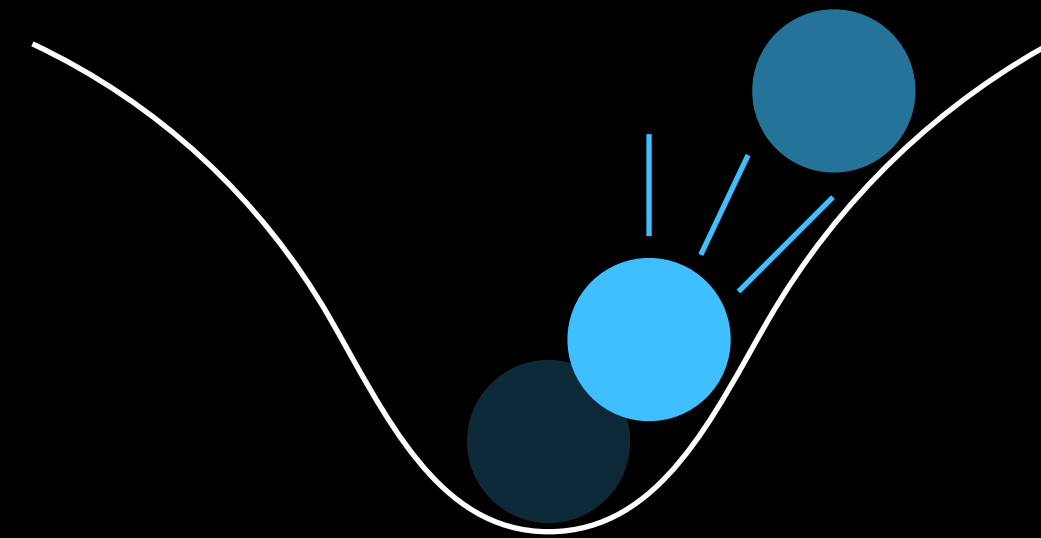
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Lagrangian points are the home of Trojans

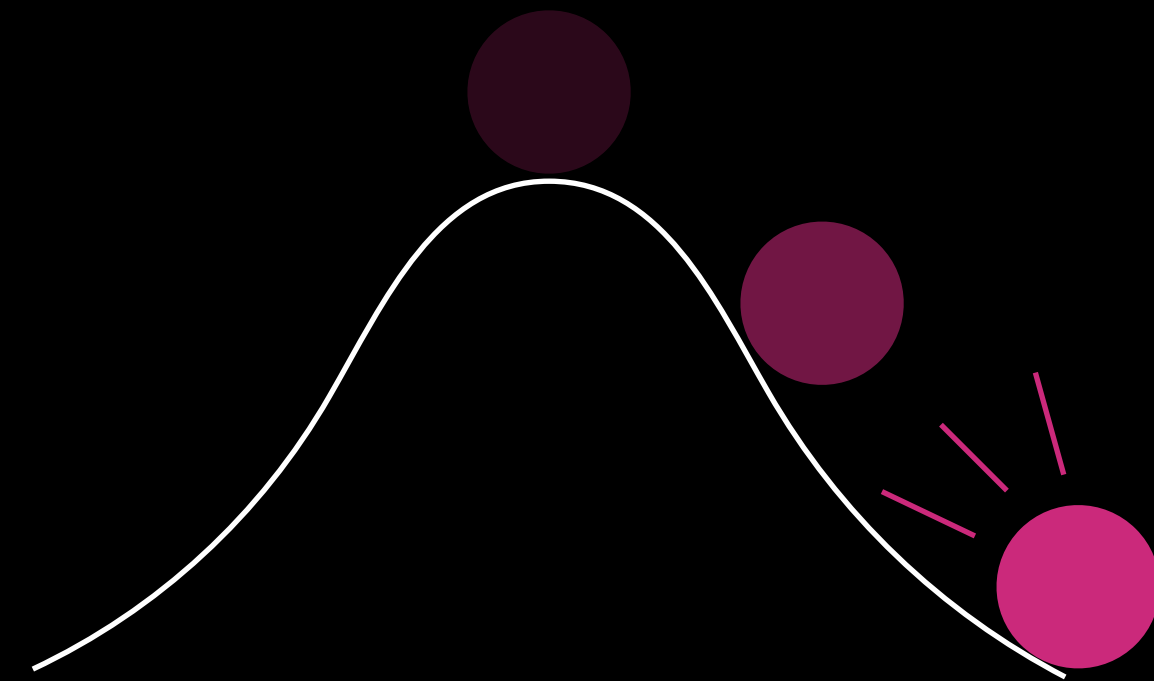


Indeed, **L_4 & L_5** are the home of Trojans

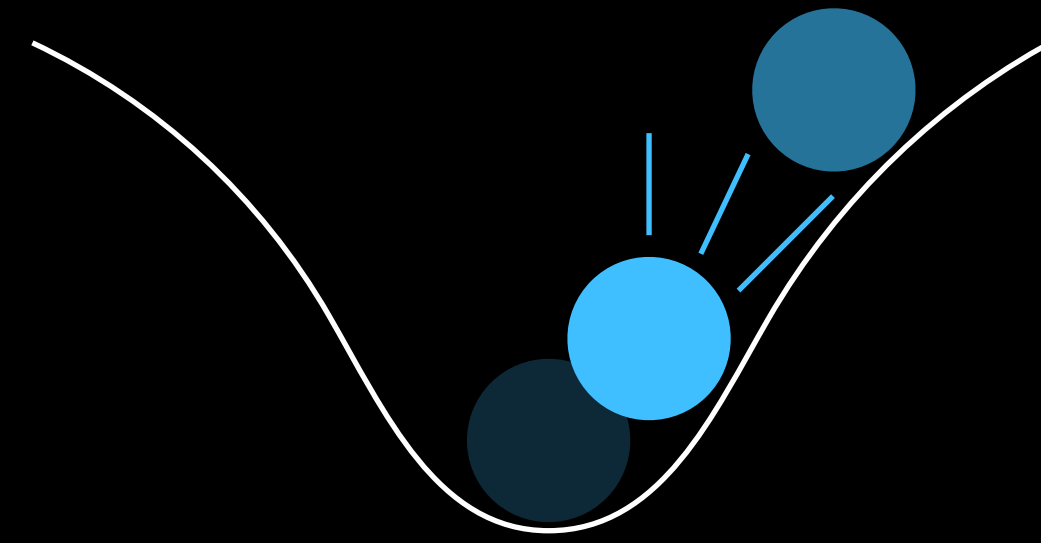


L_4 & L_5
are **stable**

Indeed, **L_4 & L_5** are the home of Trojans



L_1, L_2 & L_3
are **un**stable

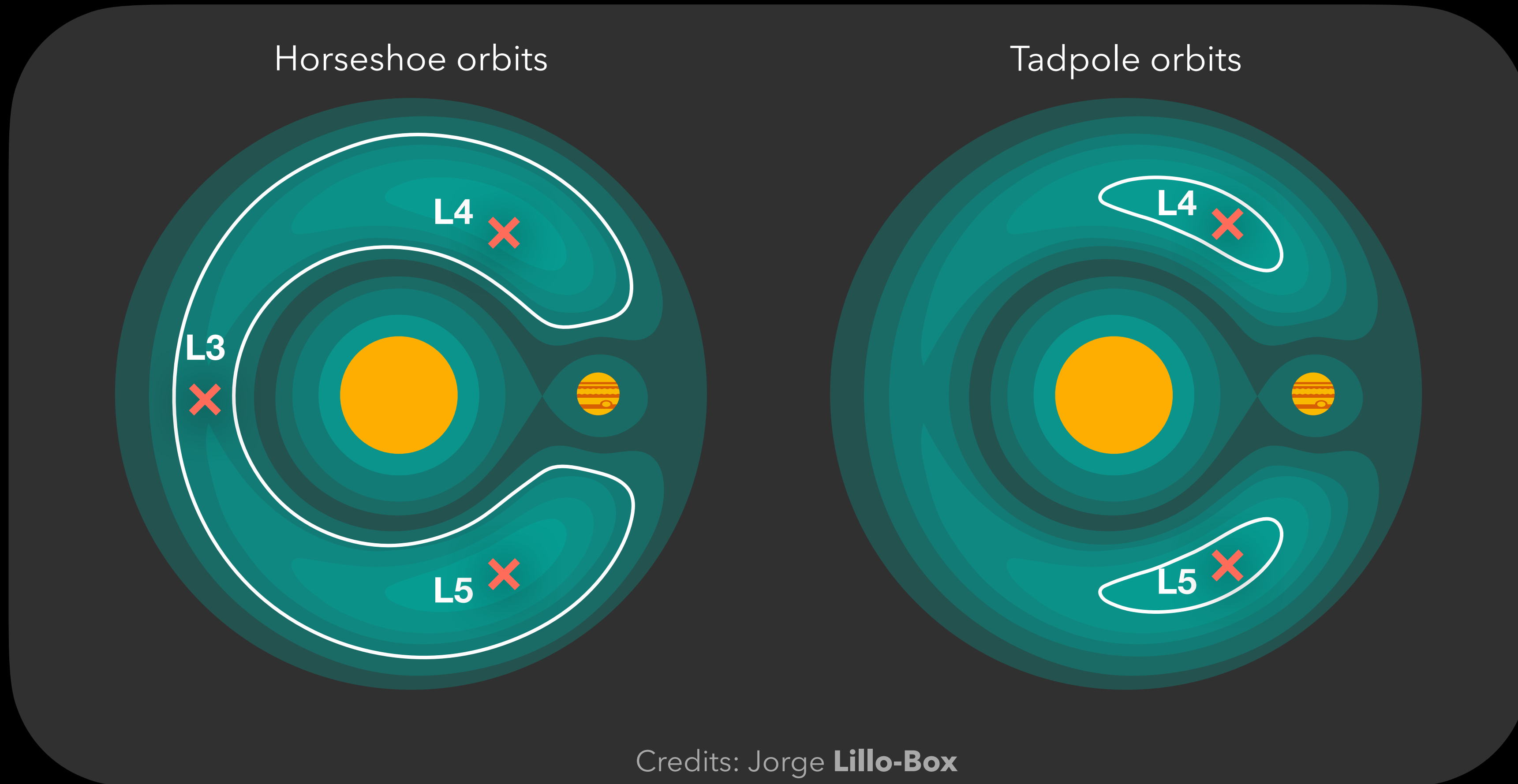


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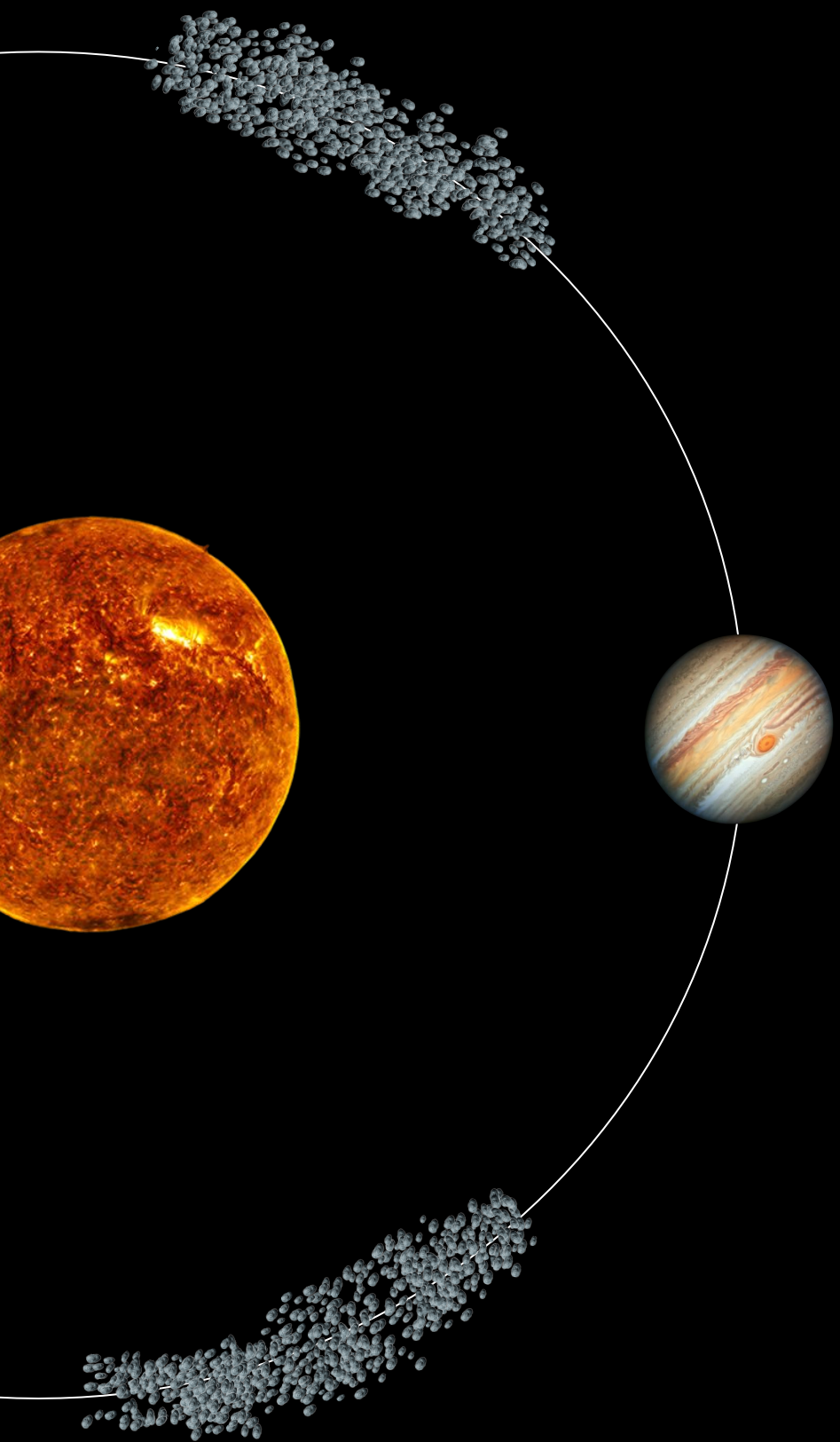
Indeed, **L_4 & L_5** are the home of Trojans
They can move in different configurations



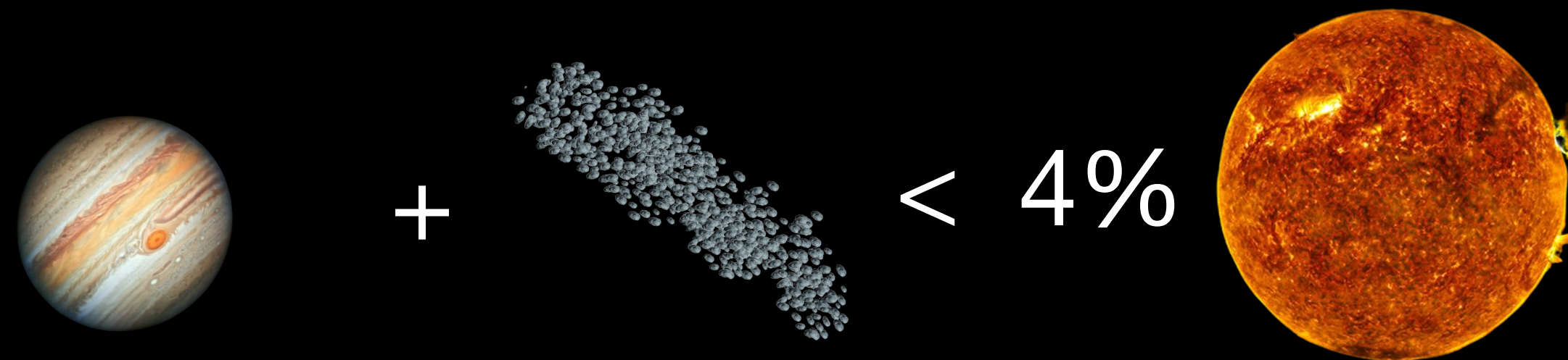
Indeed, **L_4 & L_5** are the home of Trojans
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Trojans are bodies co-orbiting with a planet

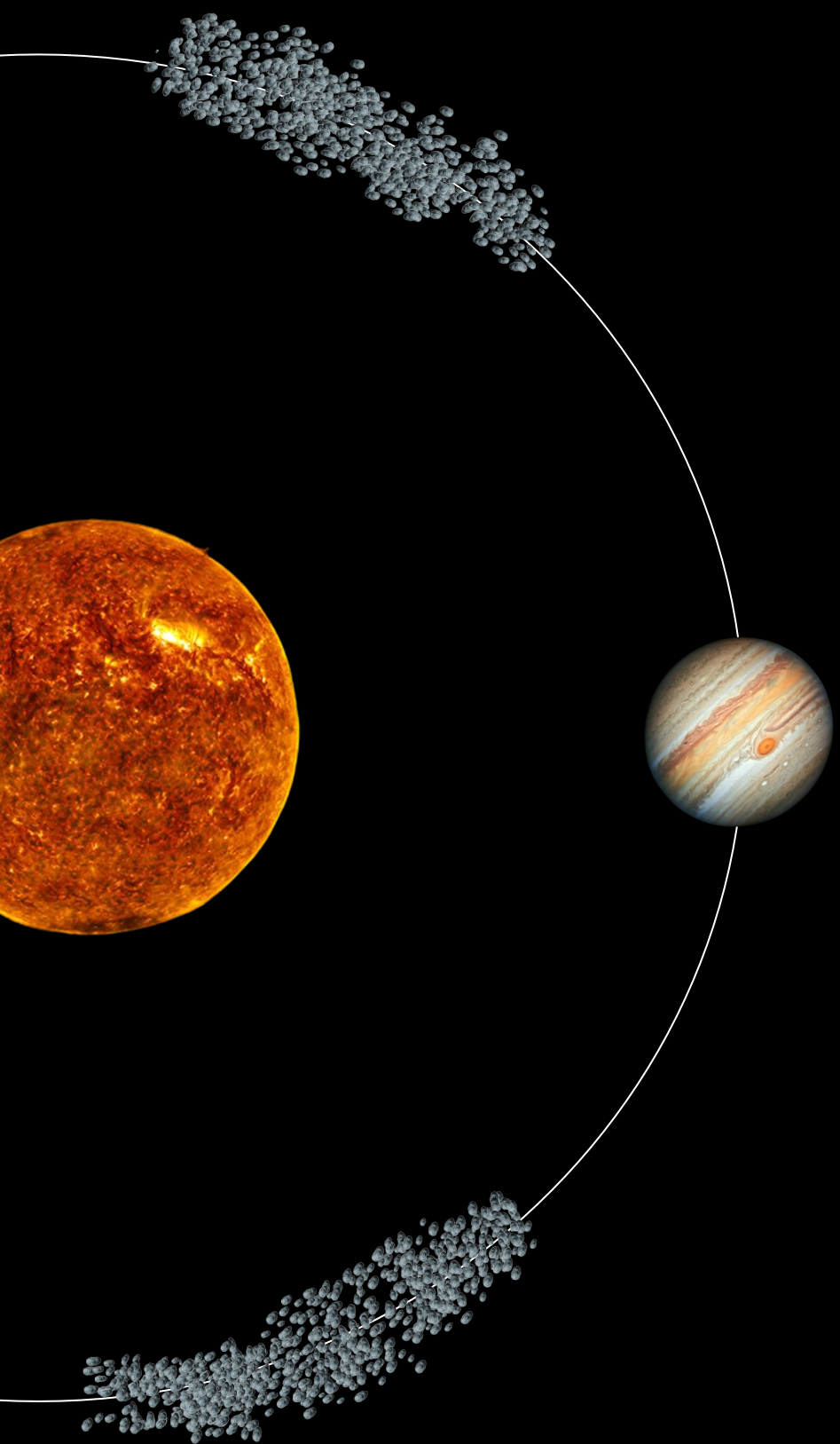


Stability condition




Laughlin & Chambers (2002)

Trojans could be planets co-orbiting with a planet



Stability condition

 $+$  $< 4\%$ 

Laughlin & Chambers (2002)

Trojans could be planets co-orbiting with a planet

In the **Solar System**
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Jupiter harbors more than
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~ 220 km

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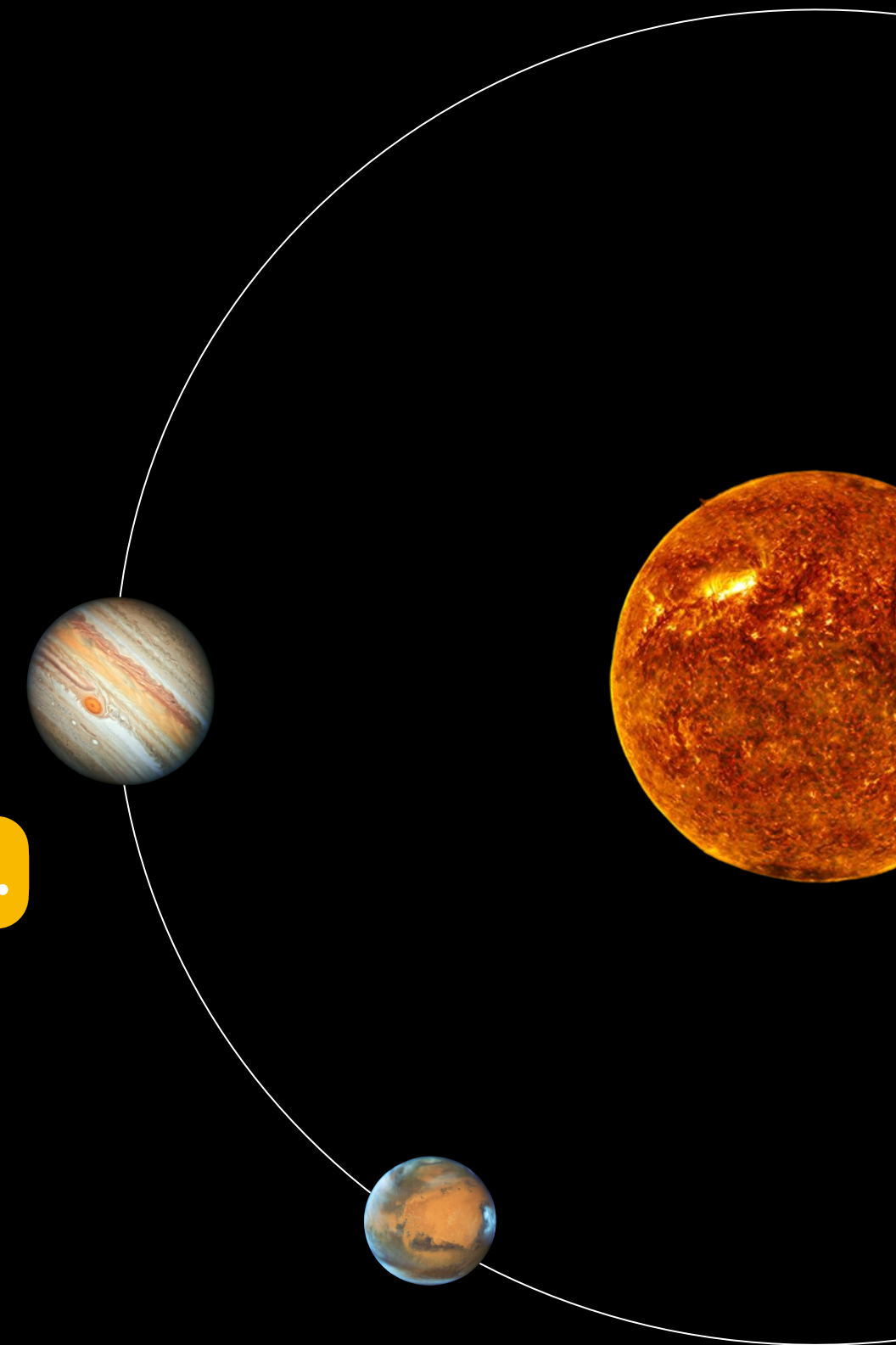
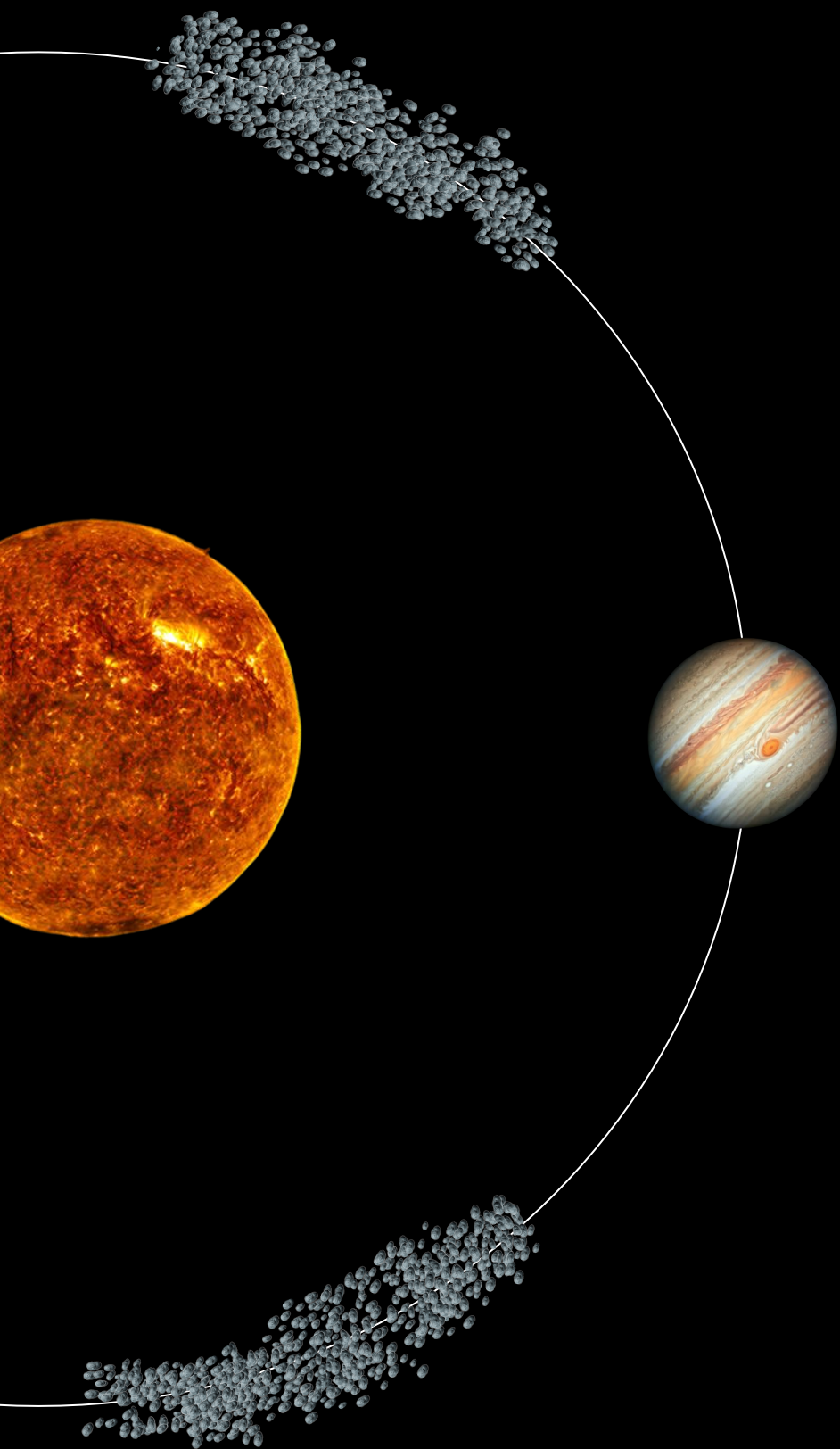
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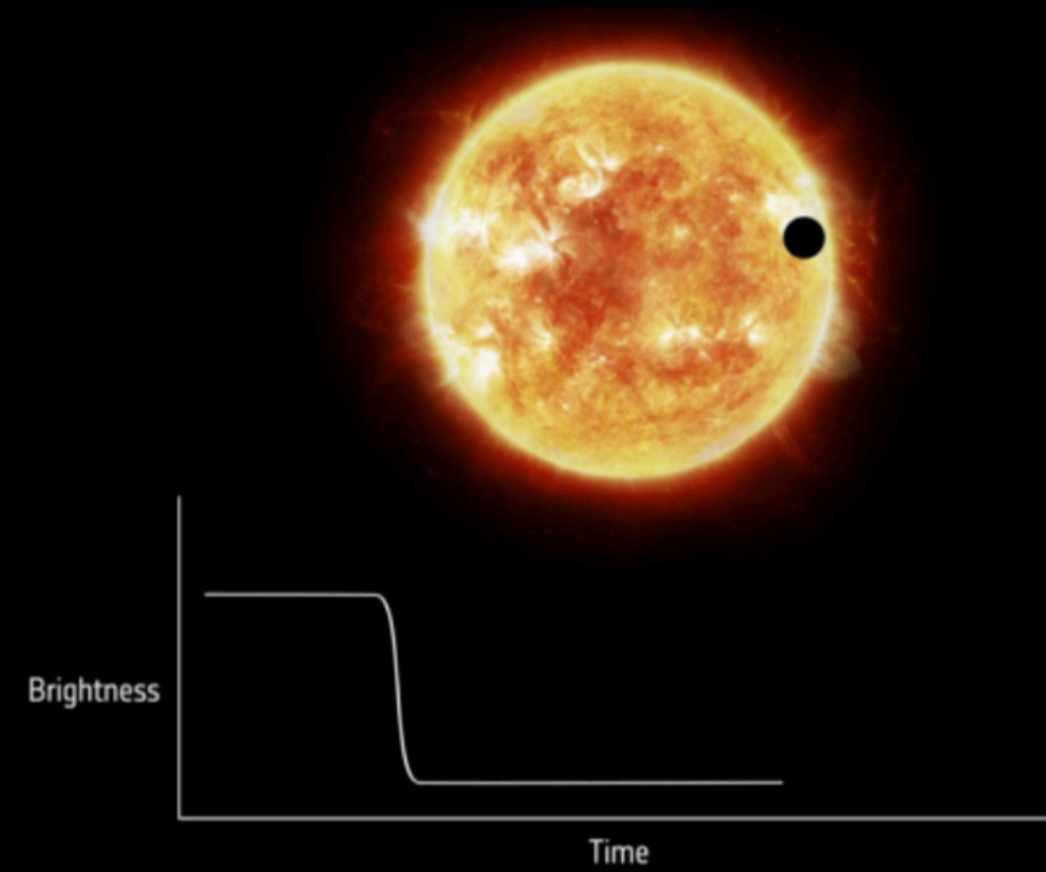
But theoretically, Trojans
could be of **planetary masses.**

Thus, we could detect them
using current detection
techniques and instruments
in **exoplanetary systems.**

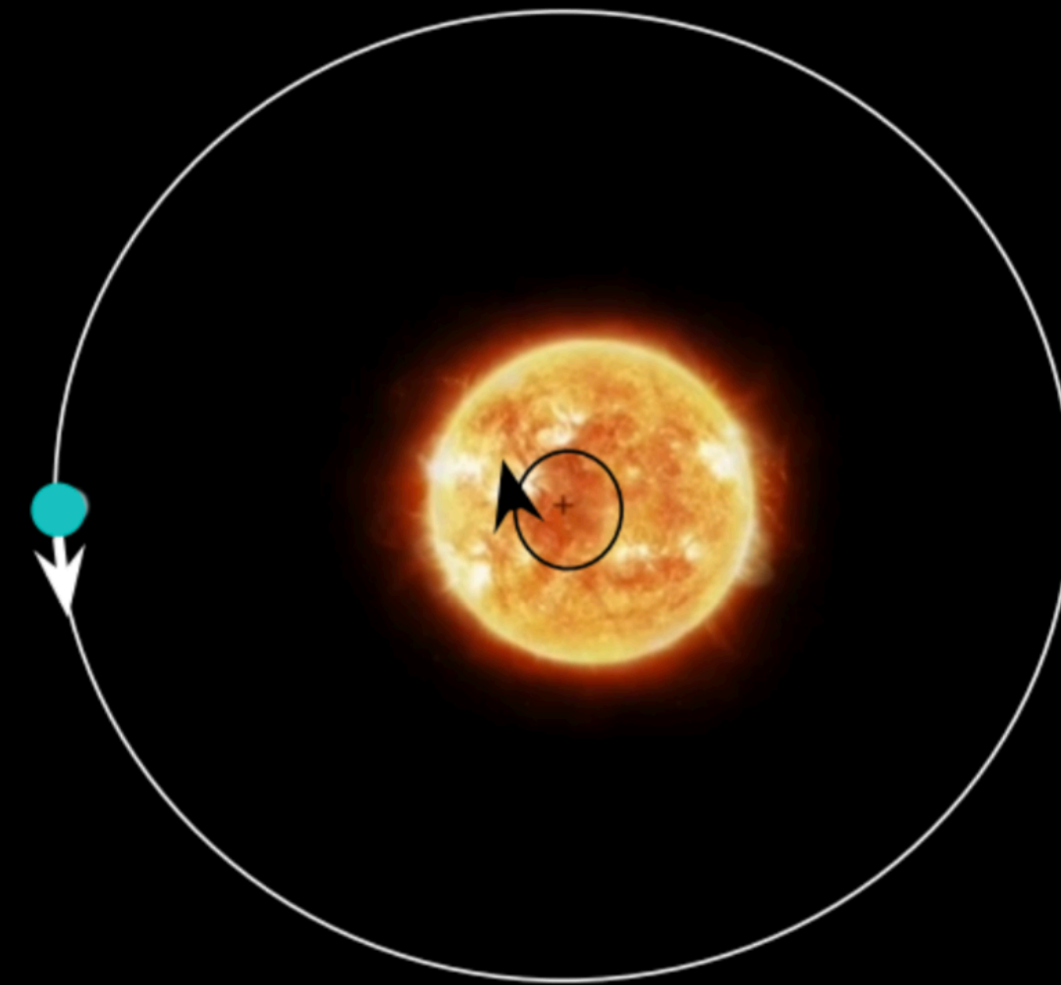


Trojans could be planets co-orbiting with a planet

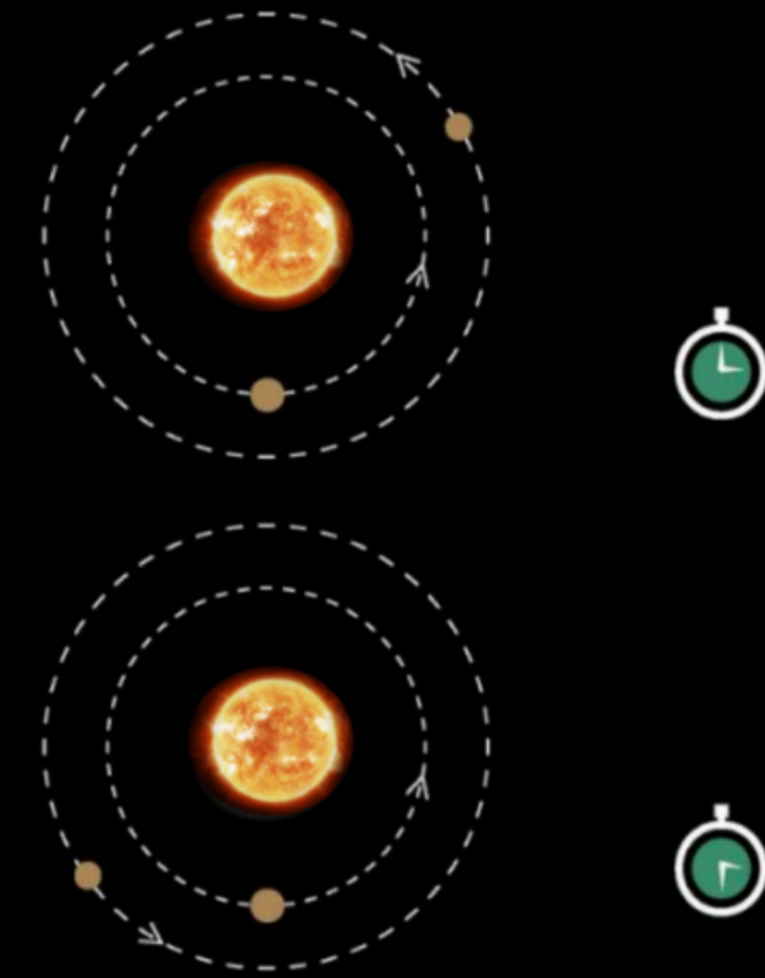
But we have not detected any so far...



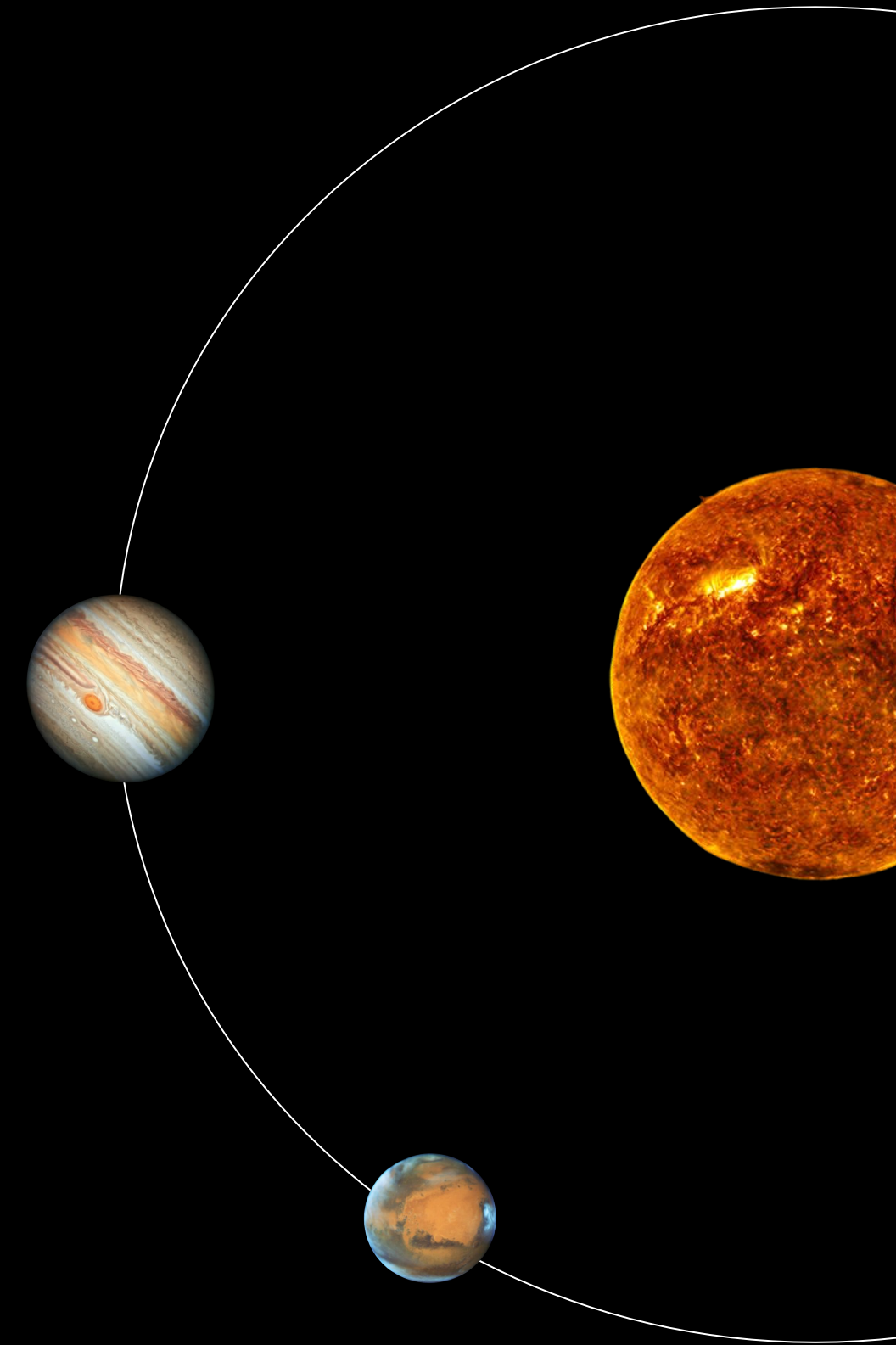
Transits



Radial Velocities



Transit Timing Variations (TTVs)



A few unconfirmed candidates

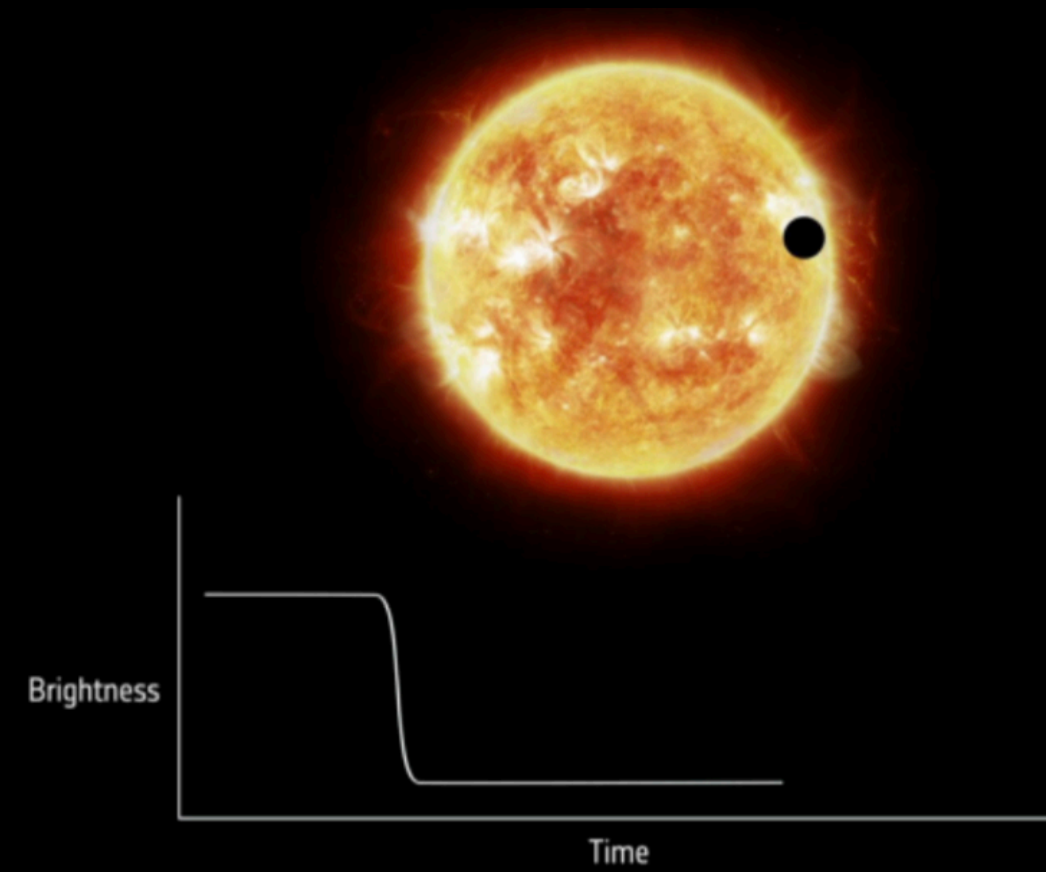
Lillo-Box et al. (2014)

Hippke & Angerhausen (2015)

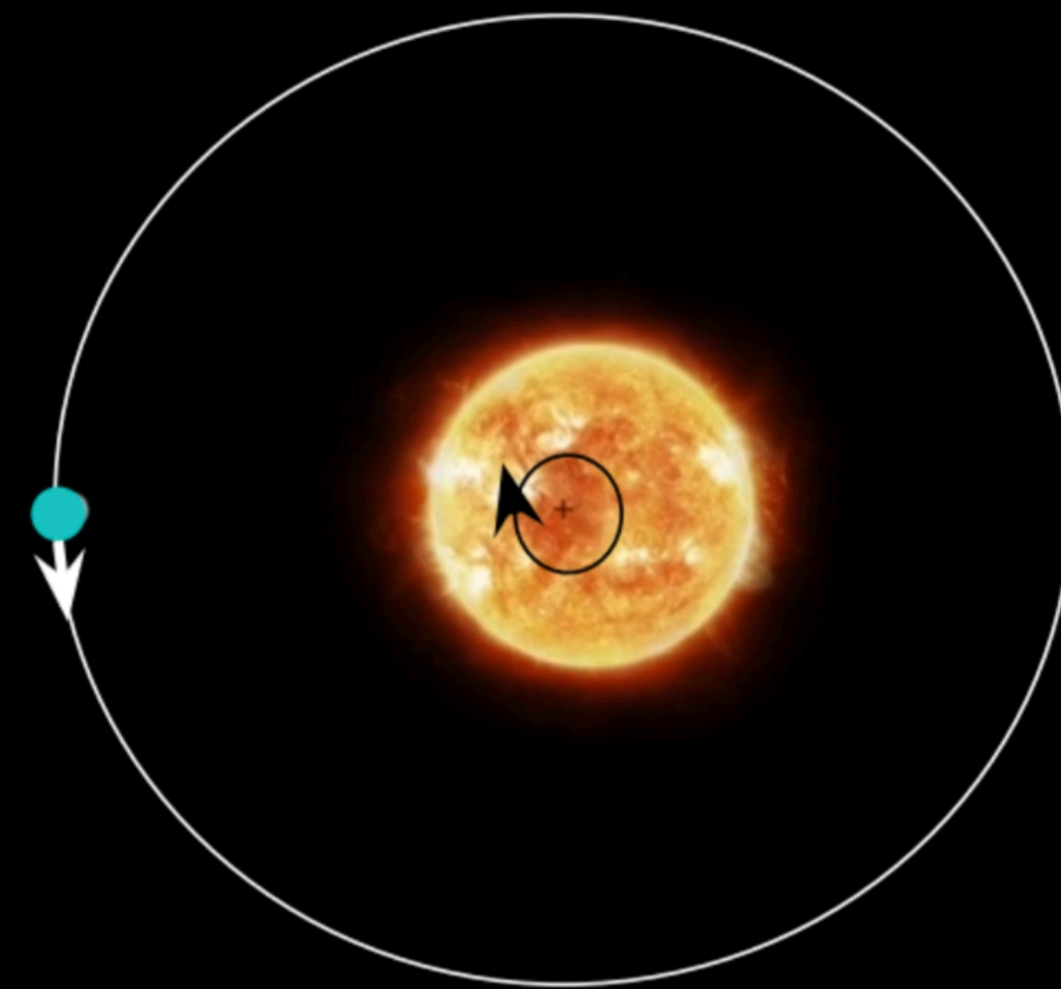
Leleu et al. (2015) & **Lillo-Box** et al. (2018)

Trojans could be planets co-orbiting with a planet

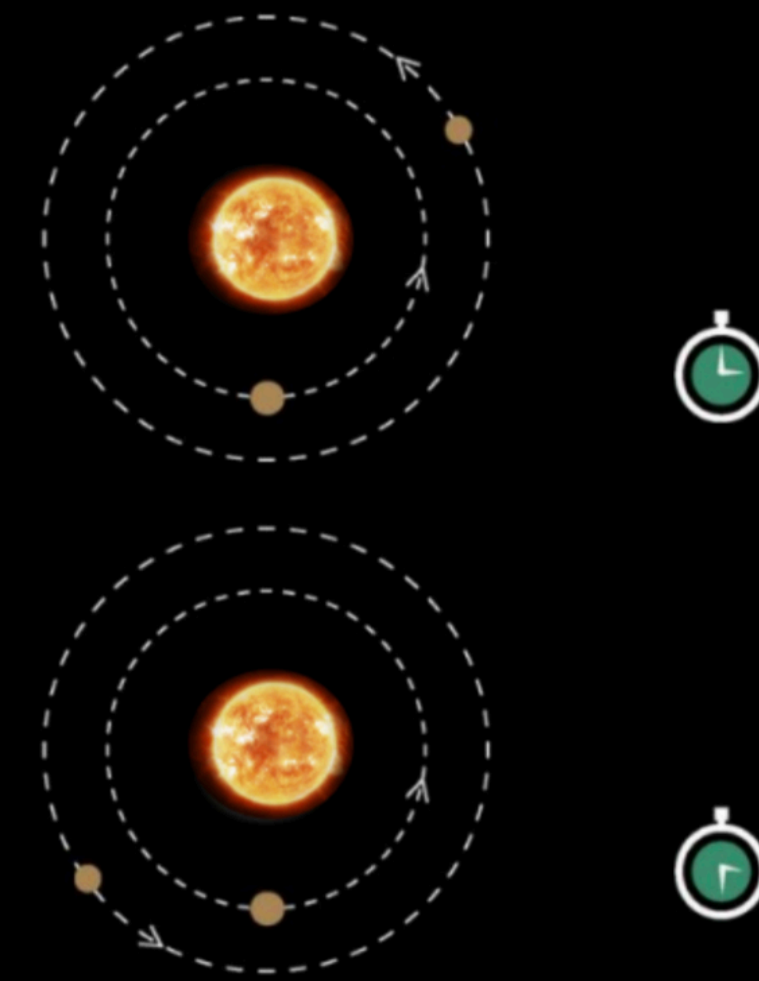
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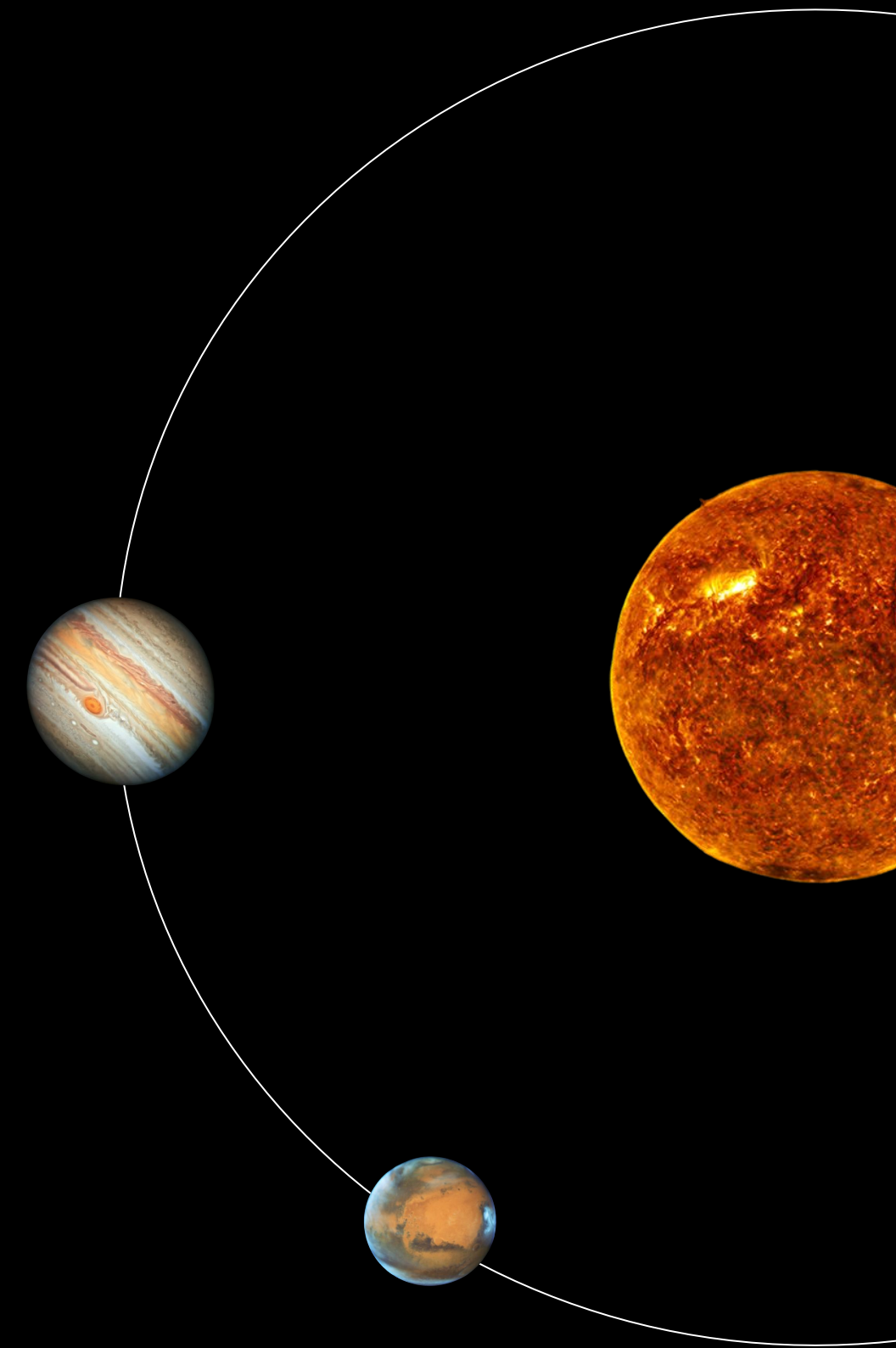
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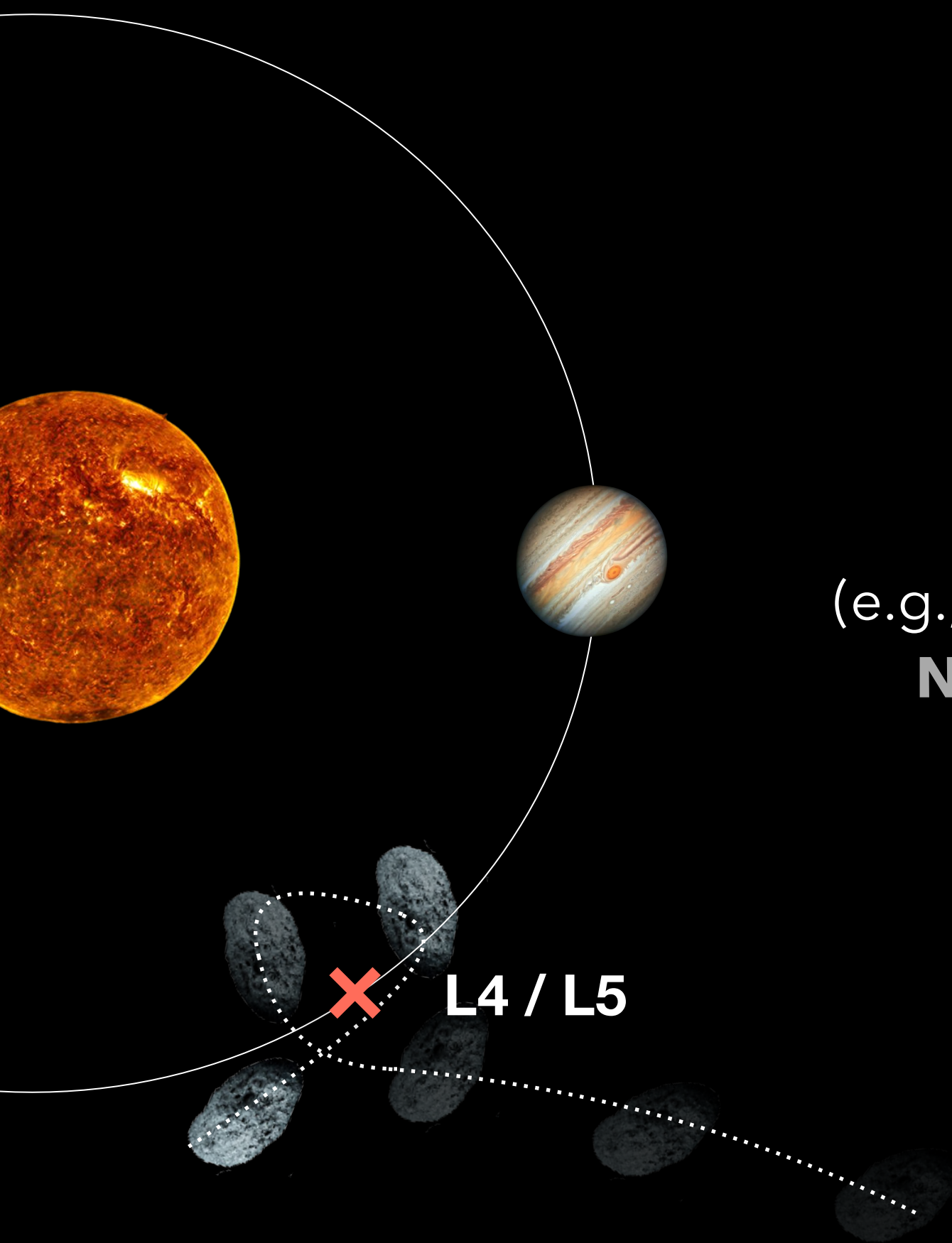


Formation mechanisms of Trojans

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Captures

From close encounters
(e.g., during planetary migration
Namouni & Morais 2017)

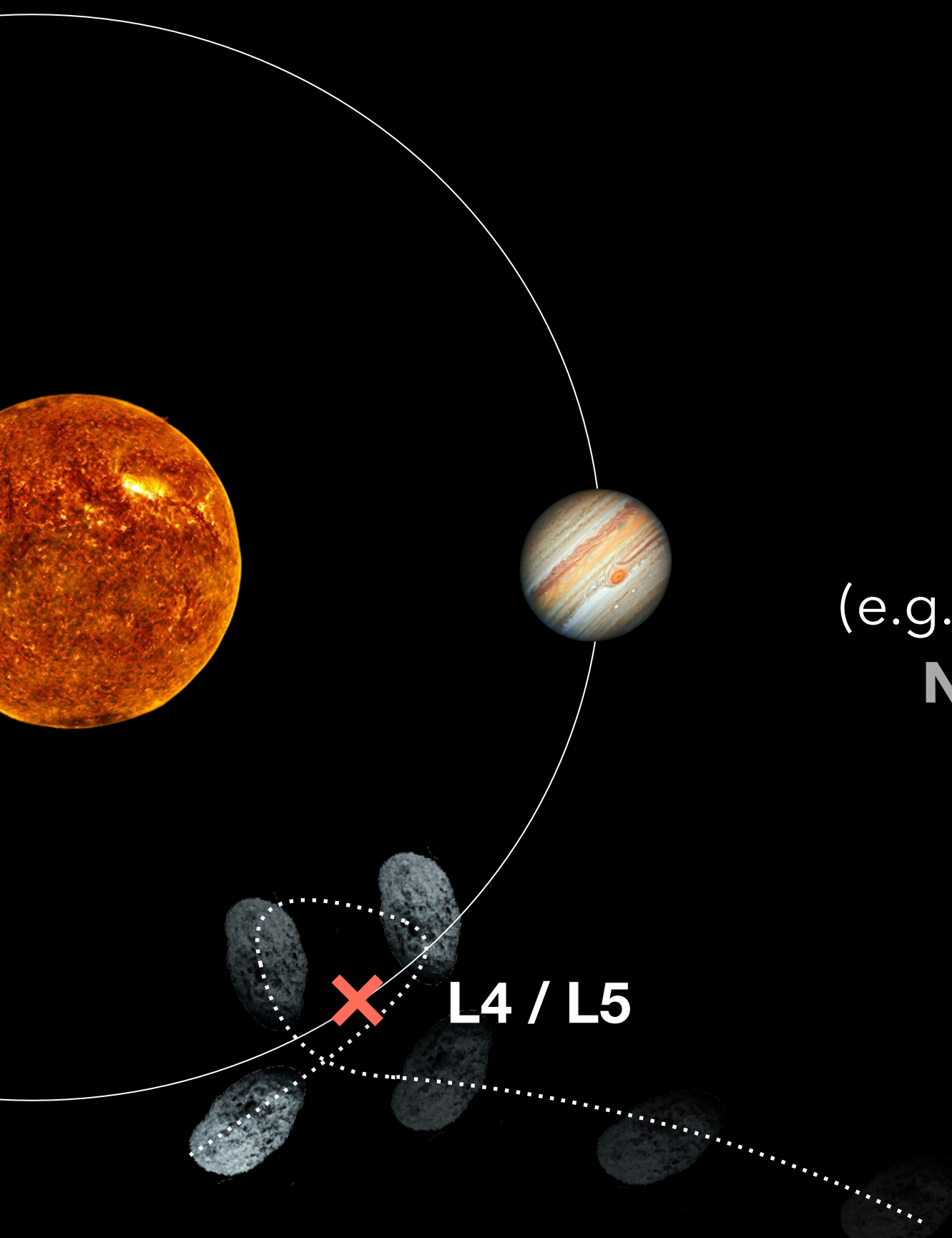


L4 / L5

Formation mechanisms of Trojans

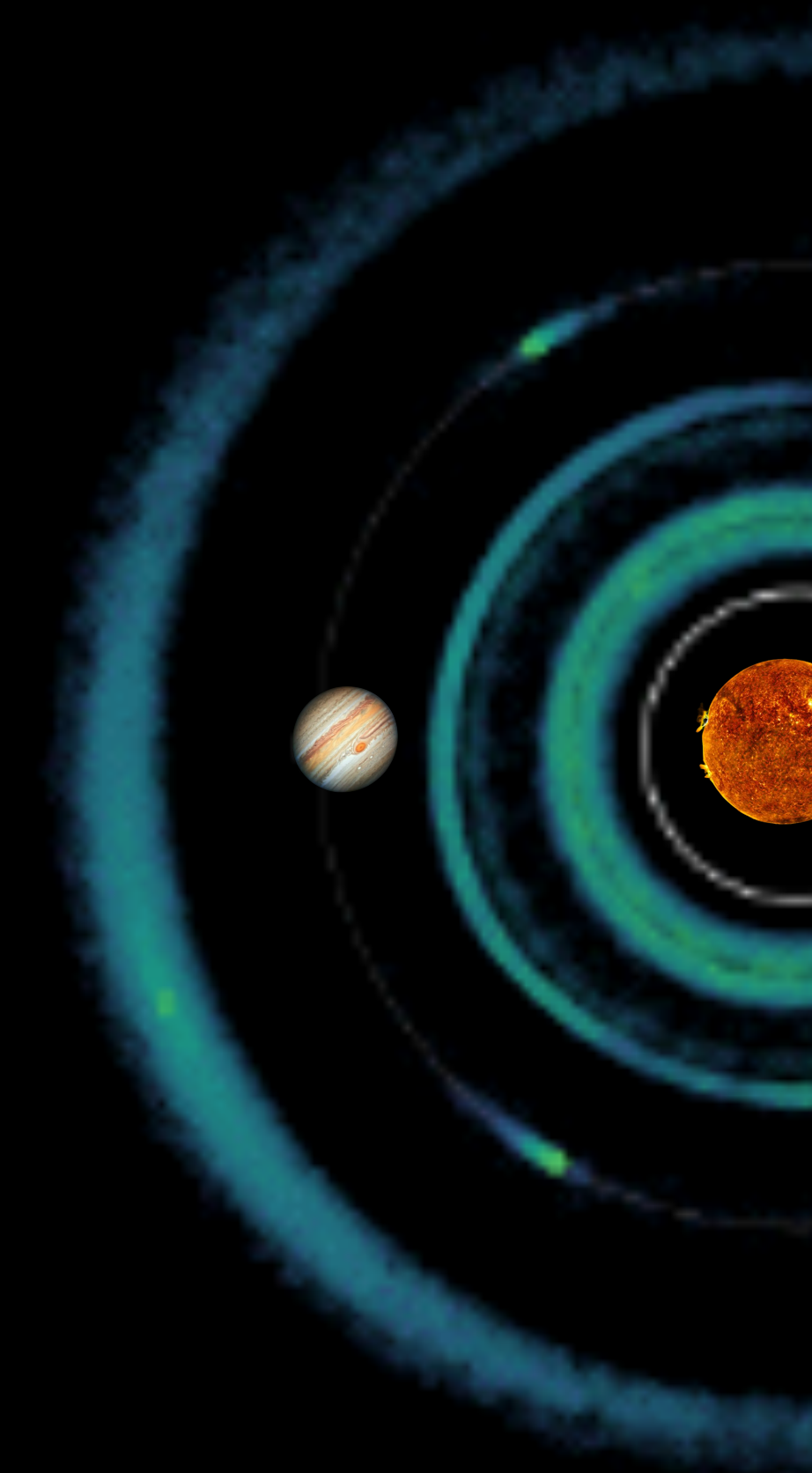
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In-situ

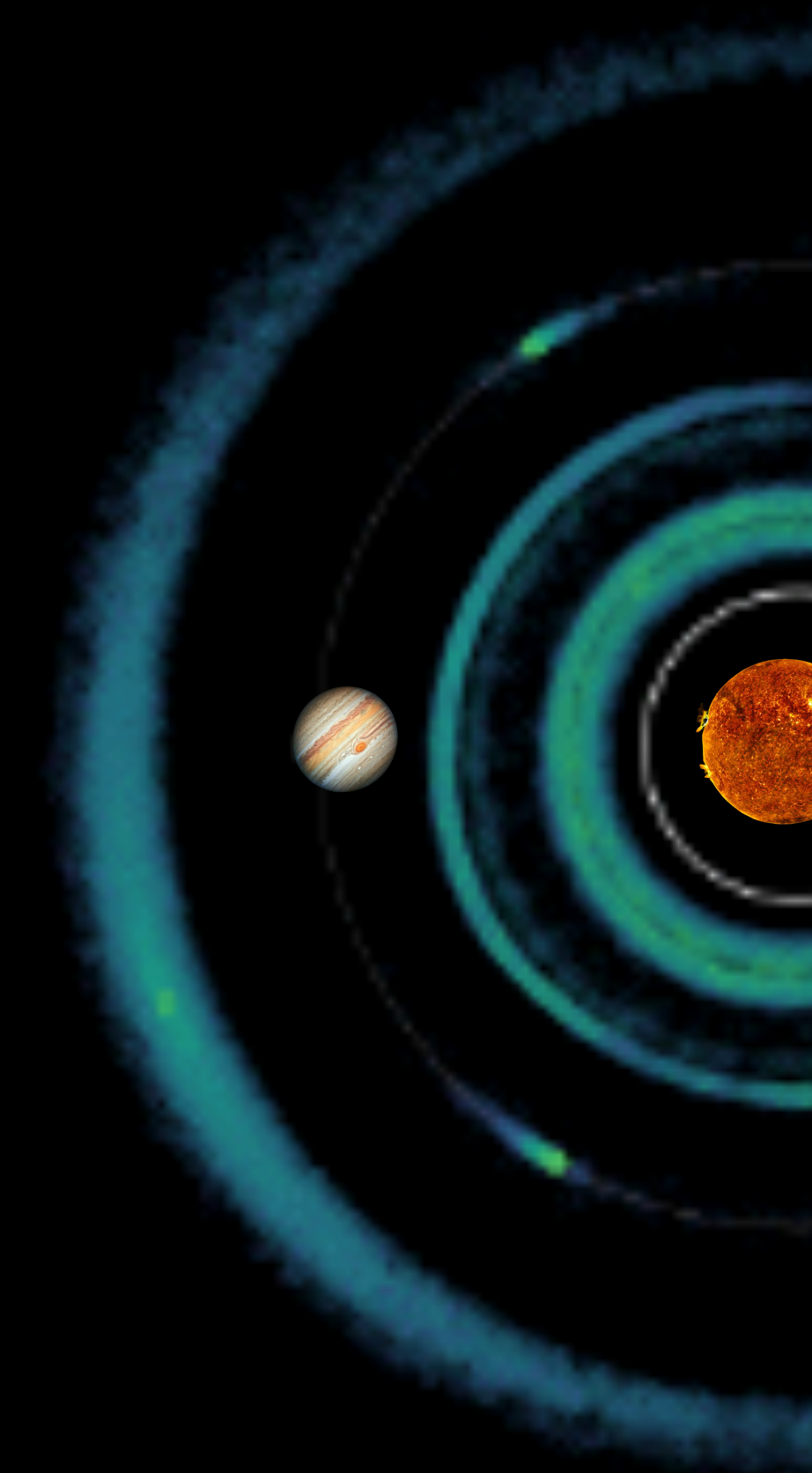
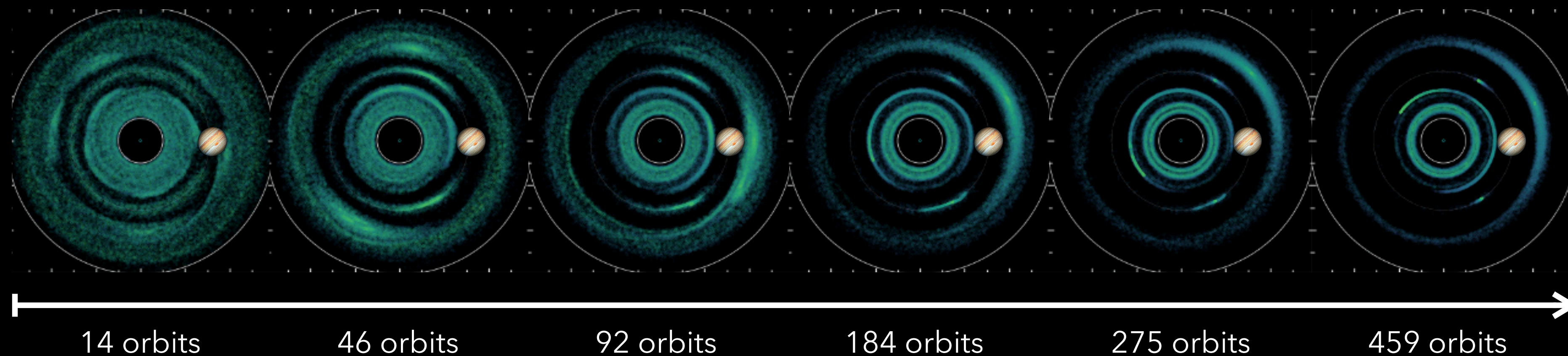
Assembling from the planetesimals
during planetary formation
(e.g., **Beaugé** et al., 2007;
Lyra et al. 2009;
Montesinos et al., 2020)



Trojans might be a **natural by-product** of planetary formation

Hydrodynamical simulations from different authors agree that
dust accumulation in the Lagrangian points of protoplanets
is a natural fate, that eventually, can form planetary mass bodies.

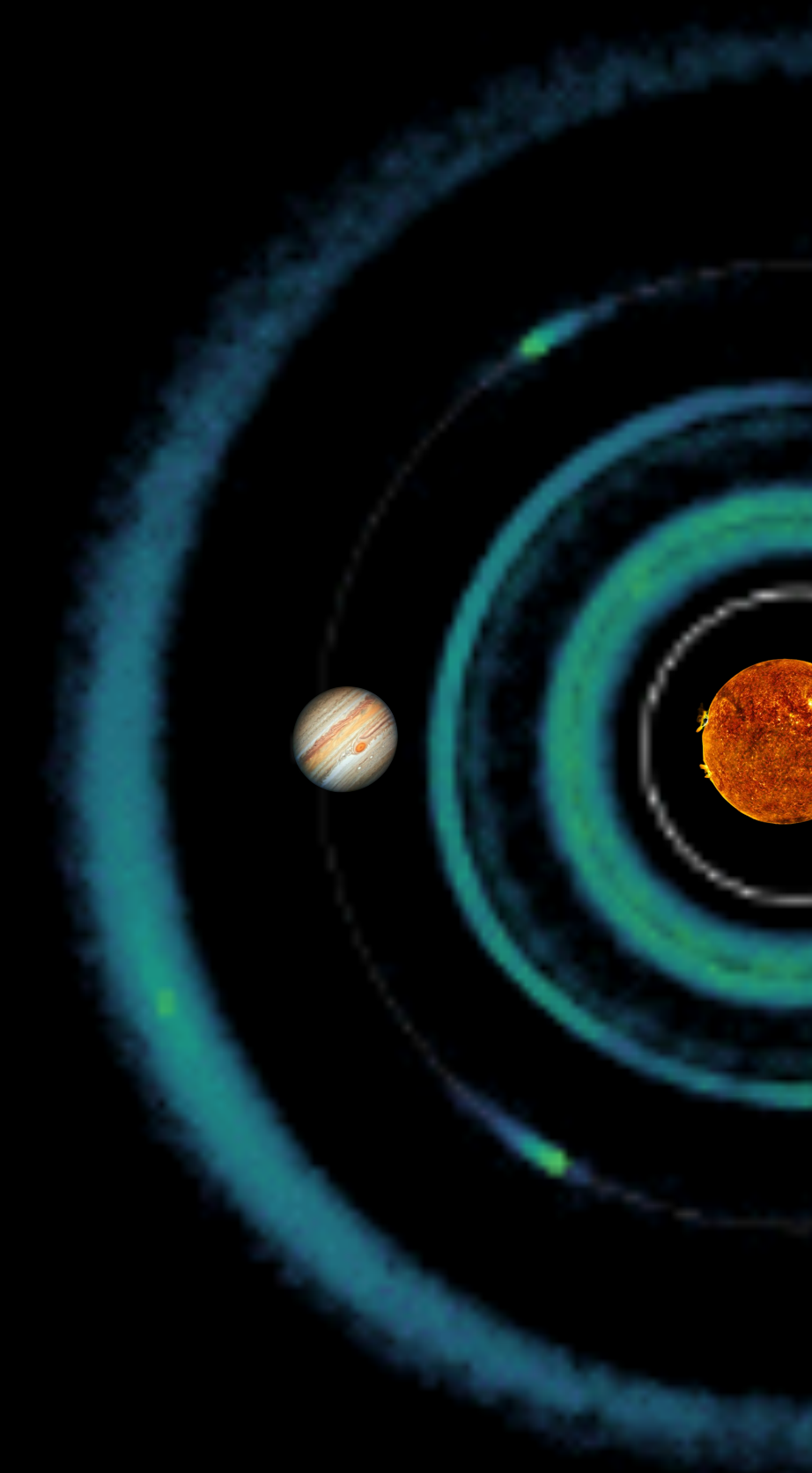
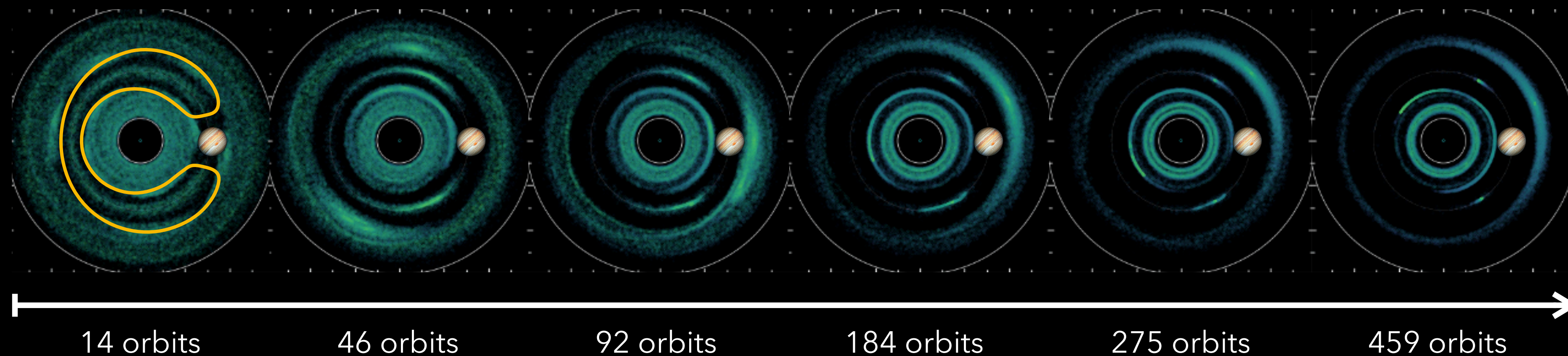
Dust evolution since planet formation (**Montesinos** et al. 2020):



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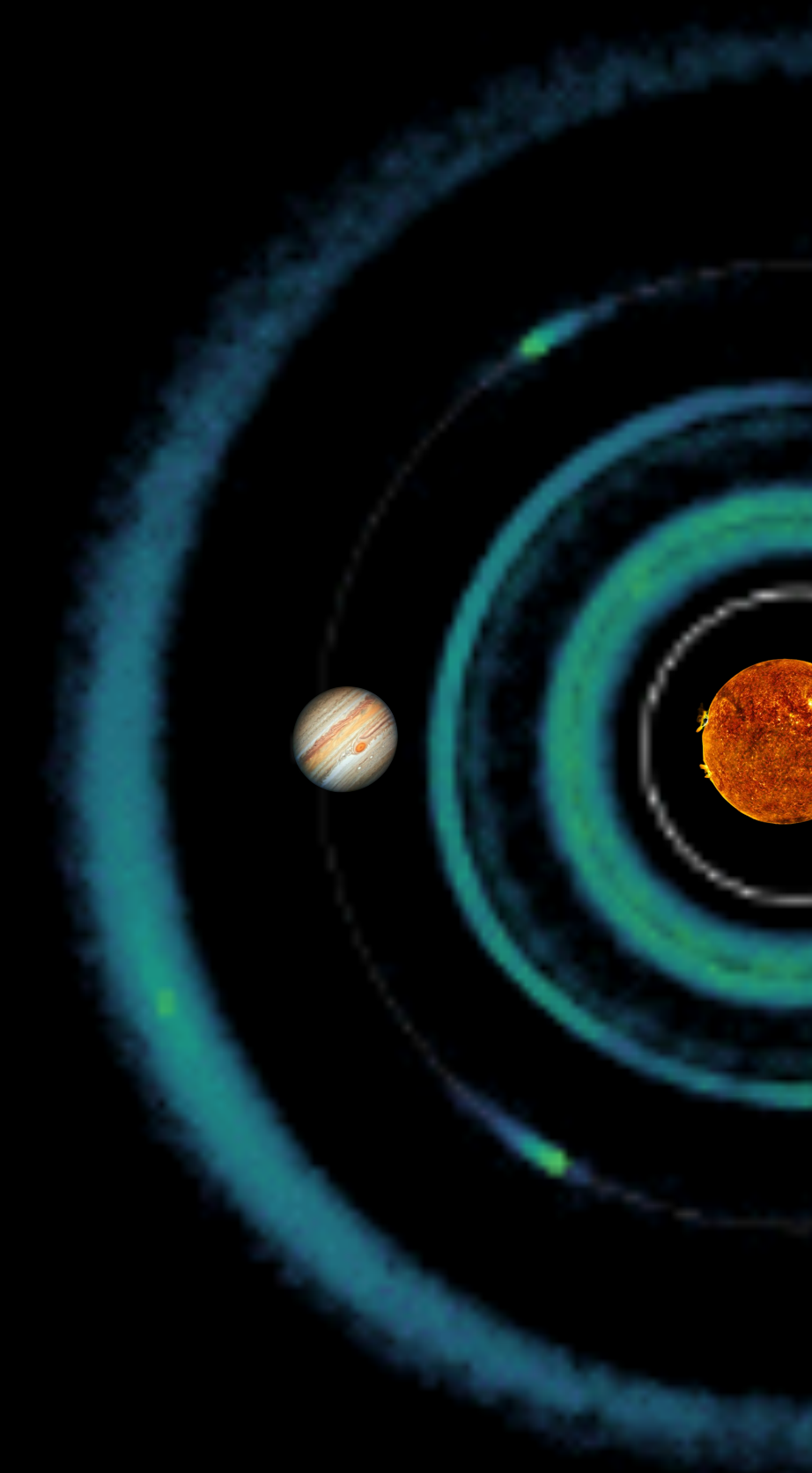
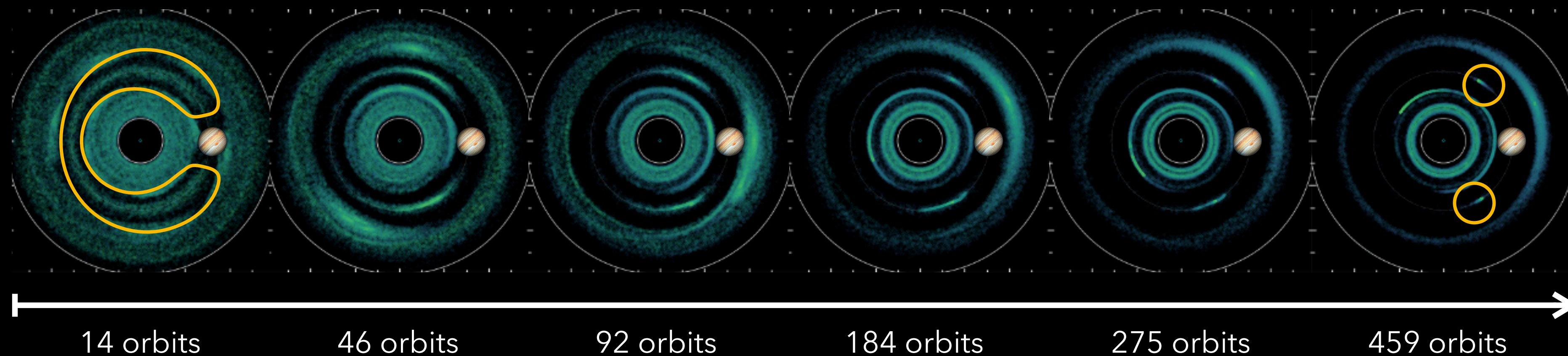
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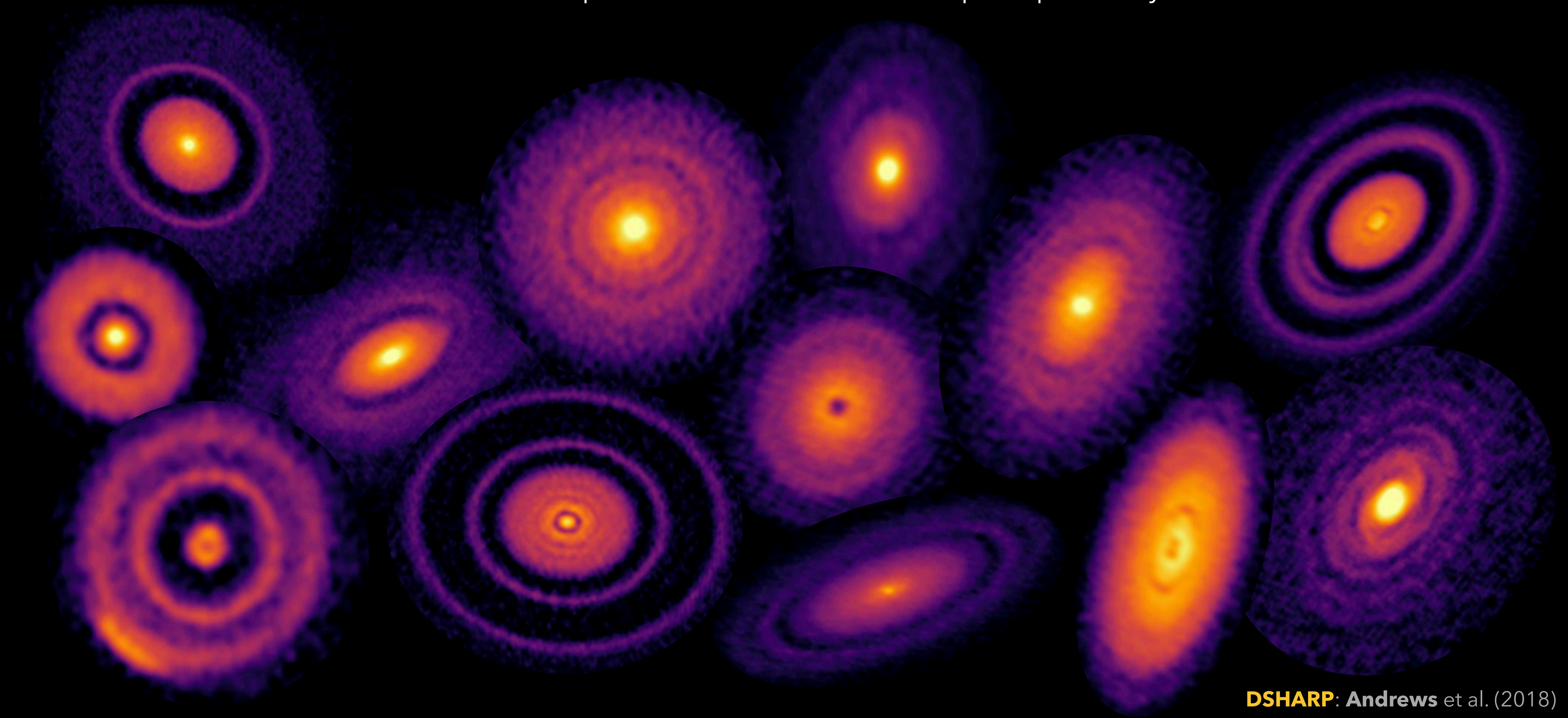
Dust evolution since planet formation (**Montesinos** et al. 2020):



ALMA is key to study young systems



ALMA shows a plethora of substructures in protoplanetary disks



DSHARP: Andrews et al. (2018)

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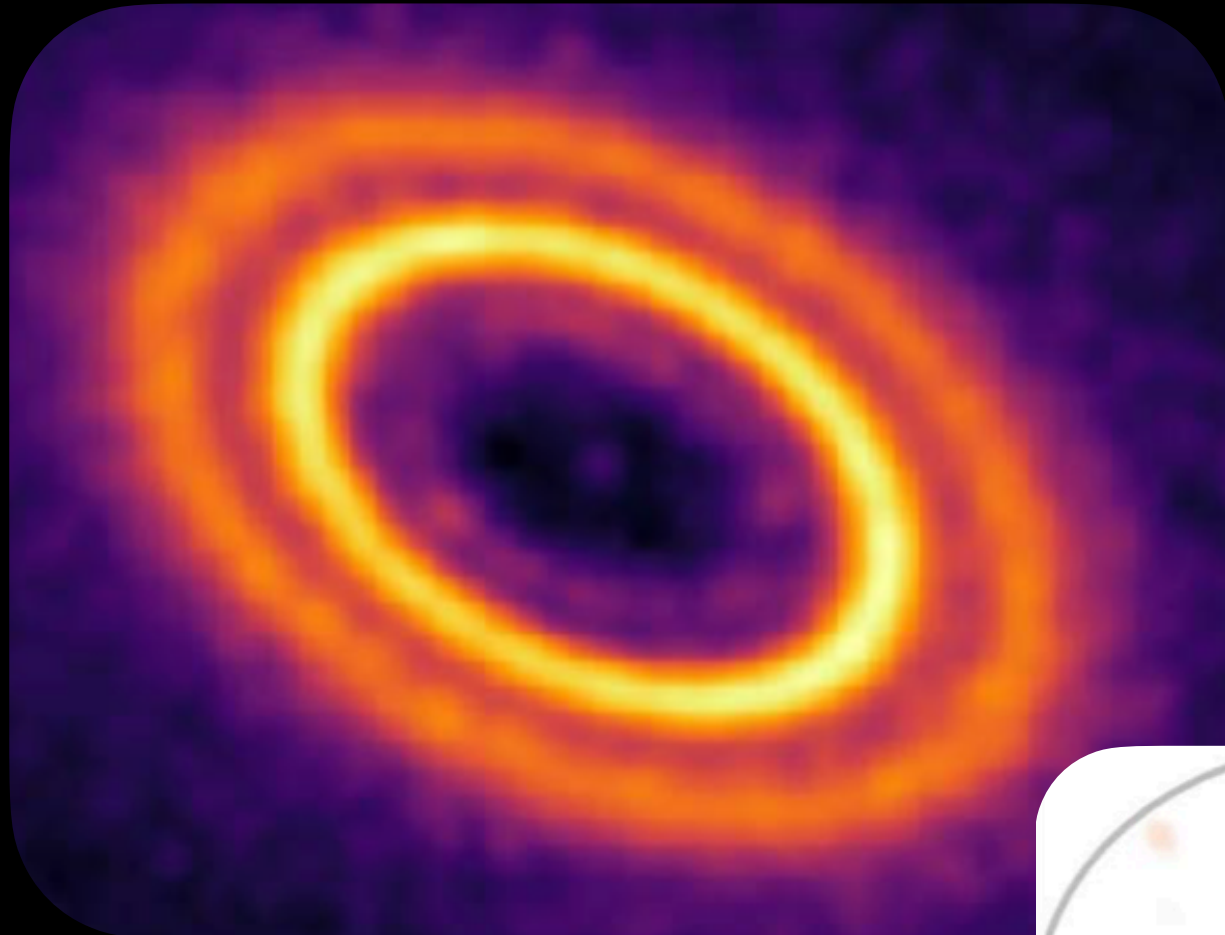
Dust in the Lagrangian regions L₄/L₅ of protoplanets

Candidates for **dust** trapping around **Lagrangian** points

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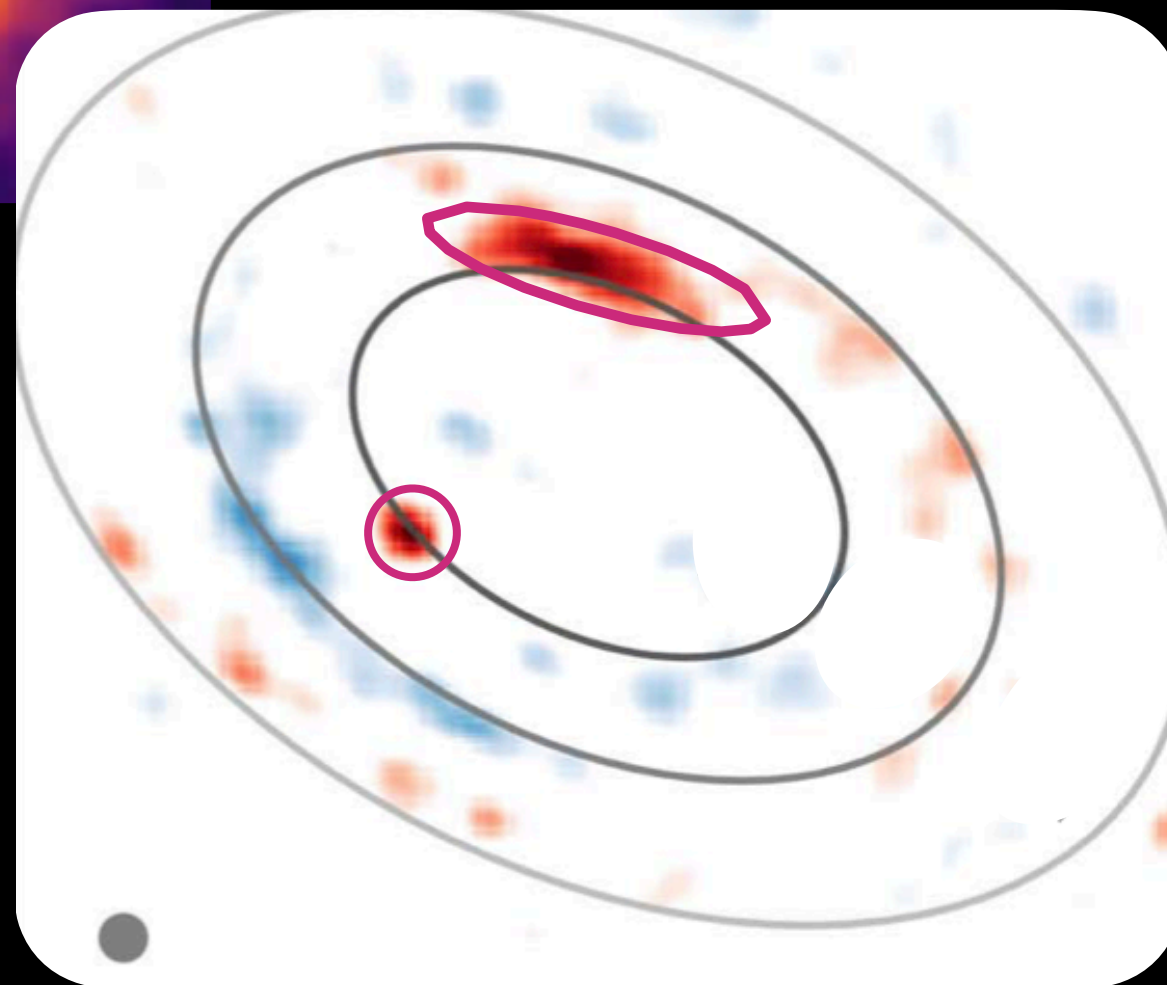
LkCa 15

ALMA Band 6



Long et al. (2022)

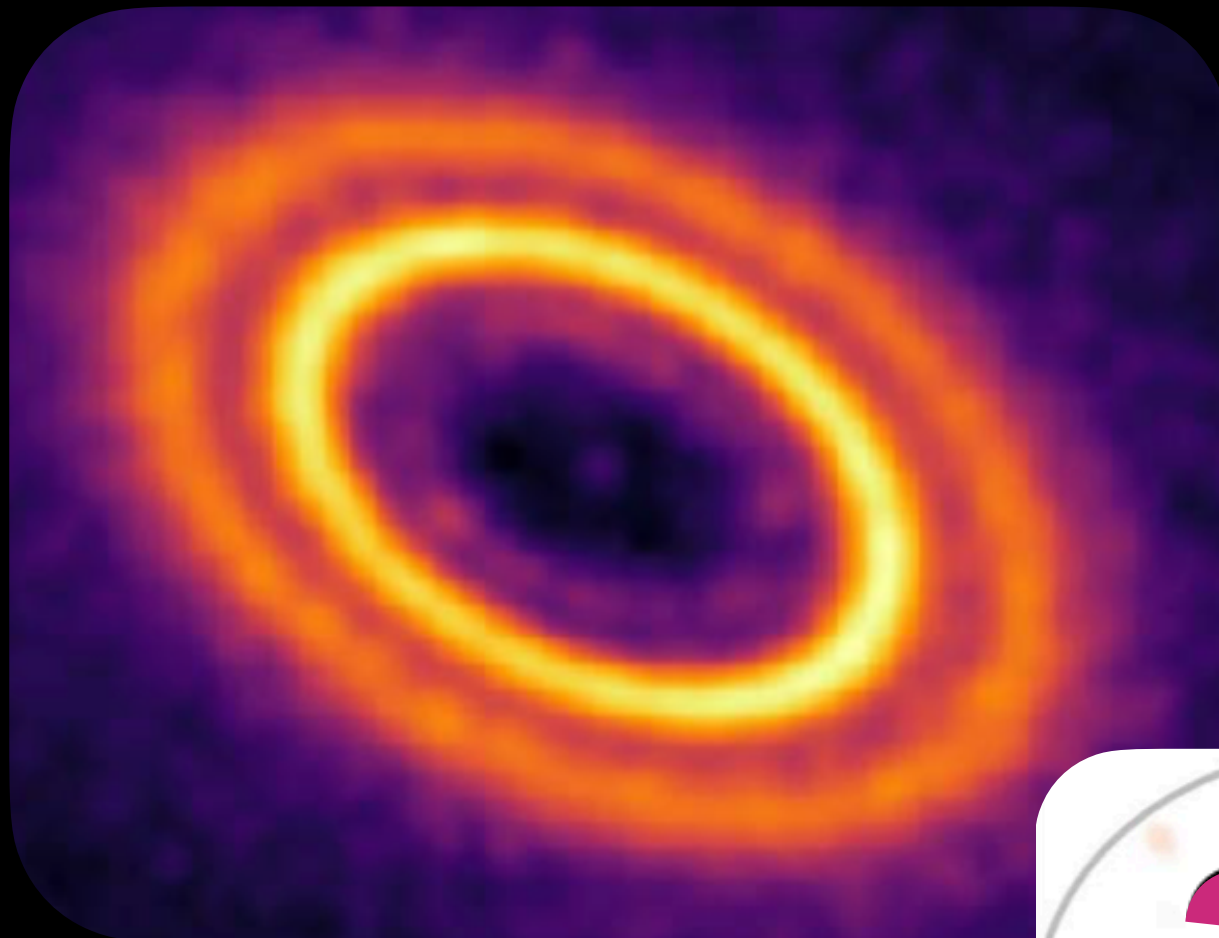
Residuals



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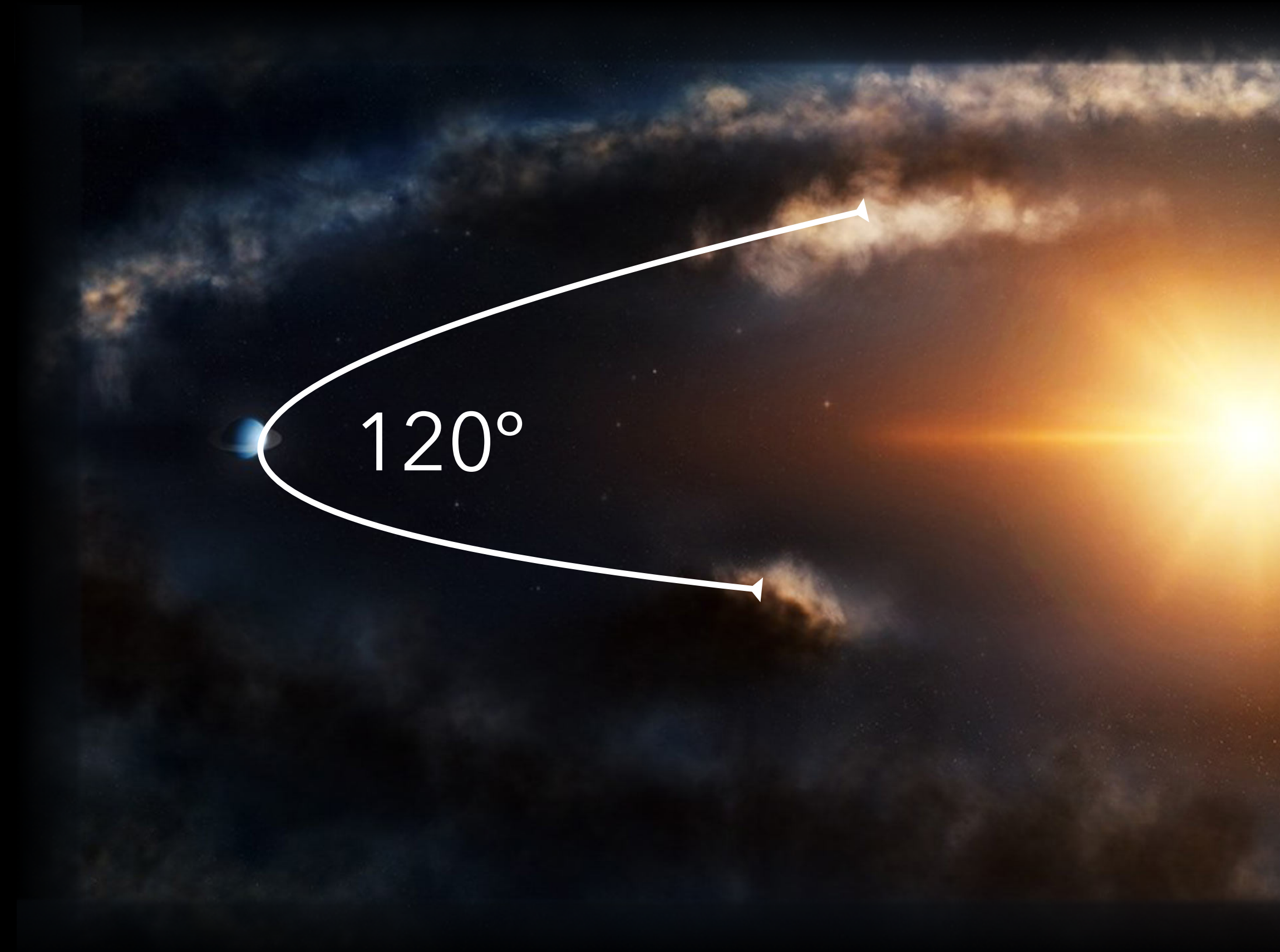
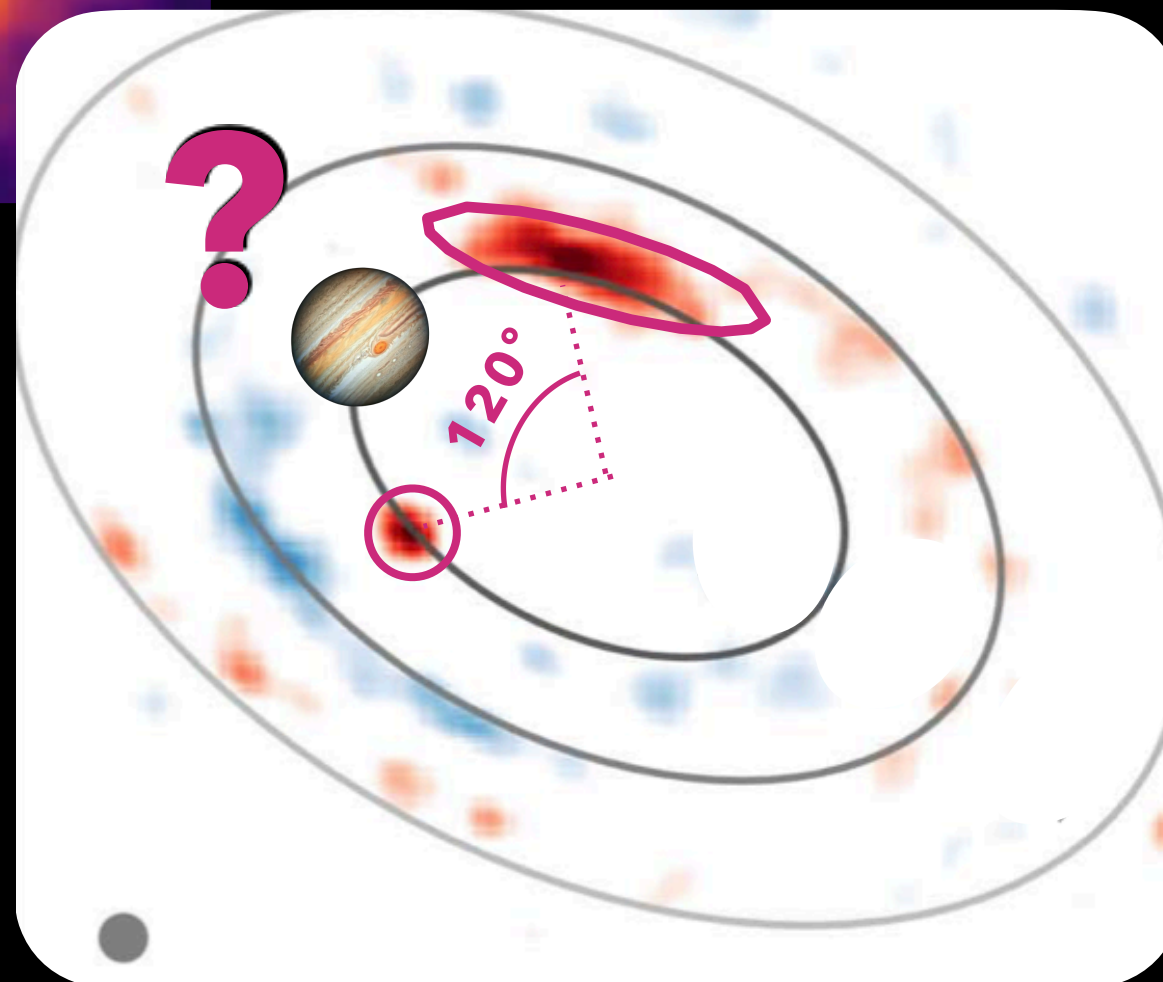
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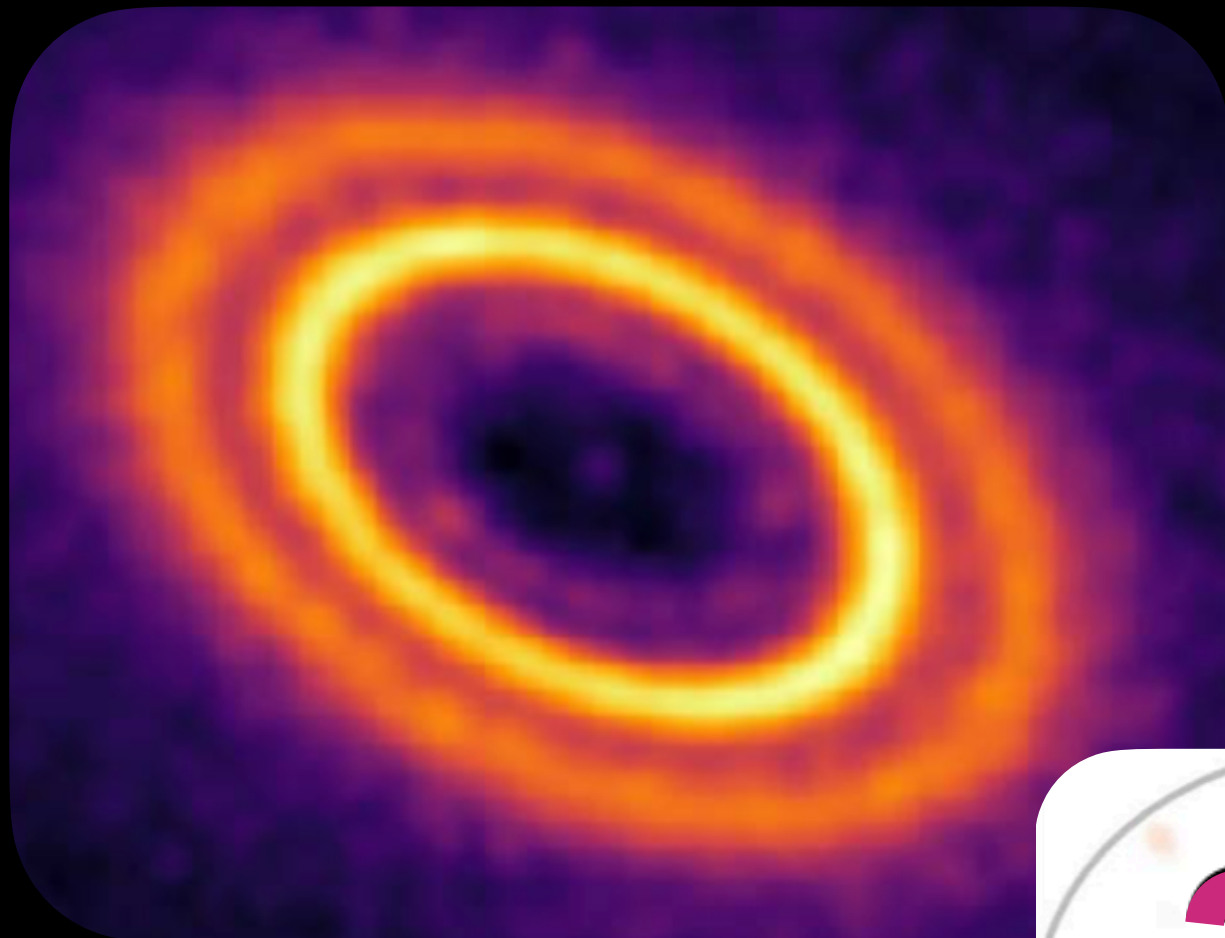
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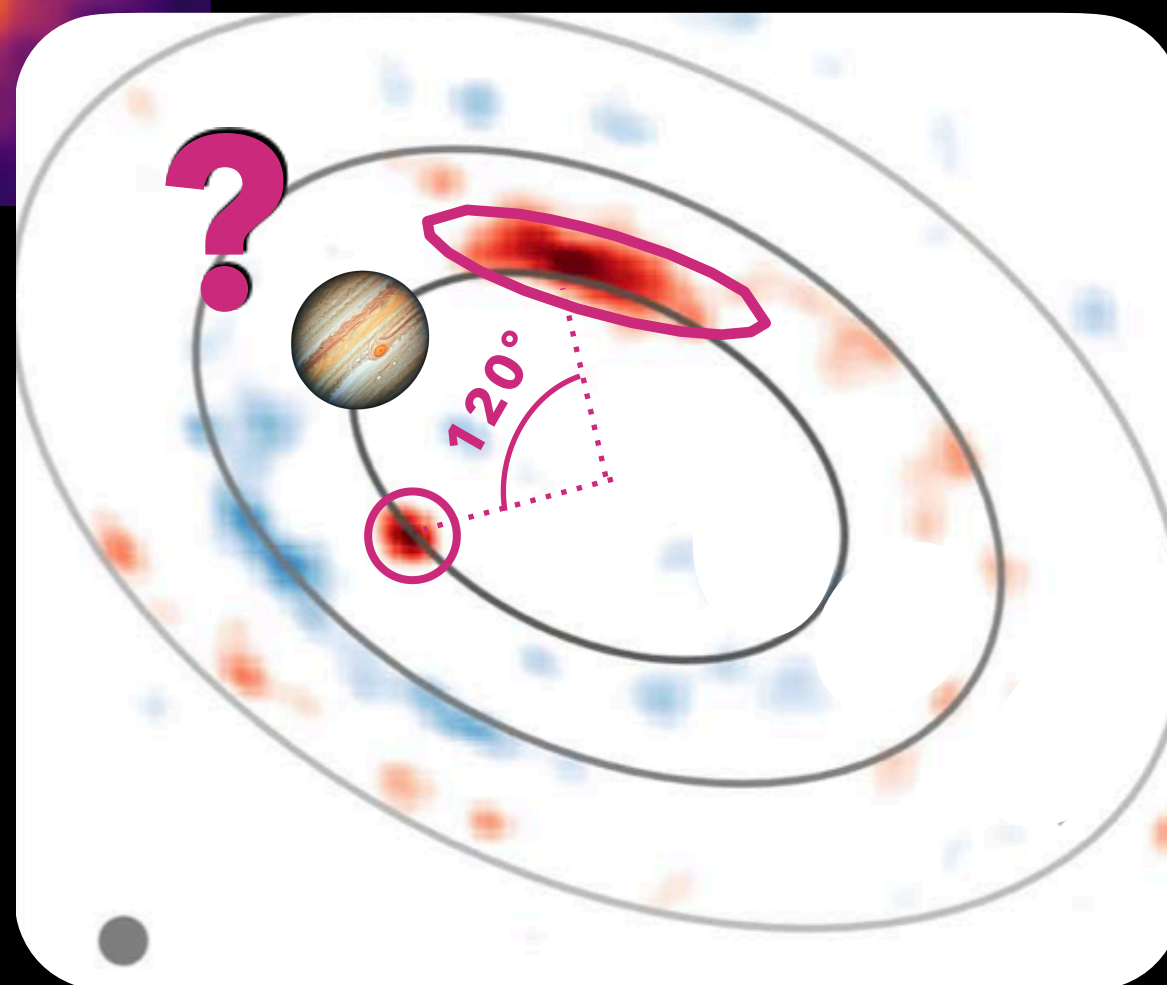
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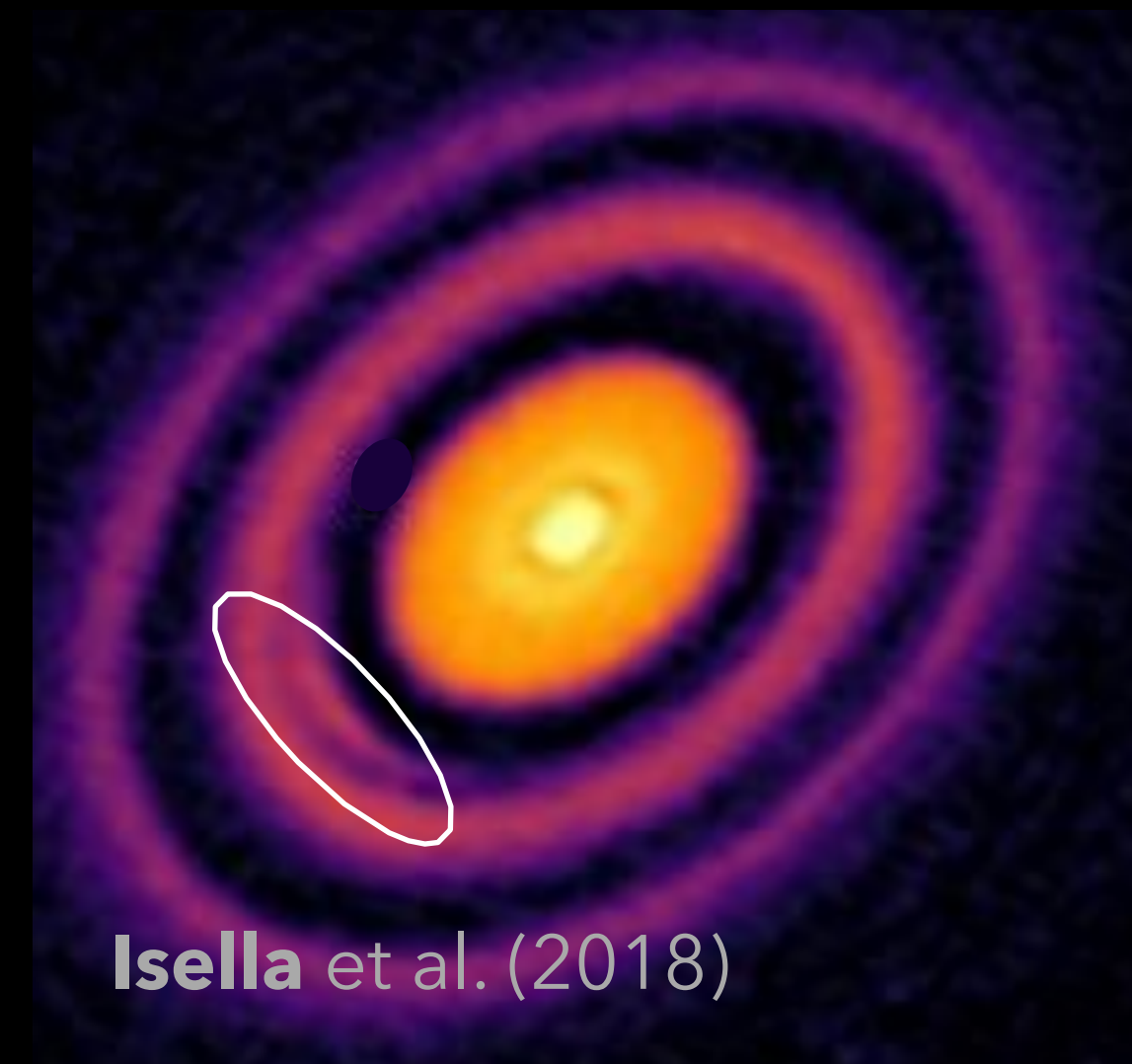
Long et al. (2022)

Residuals



HD 163296

ALMA Band 6

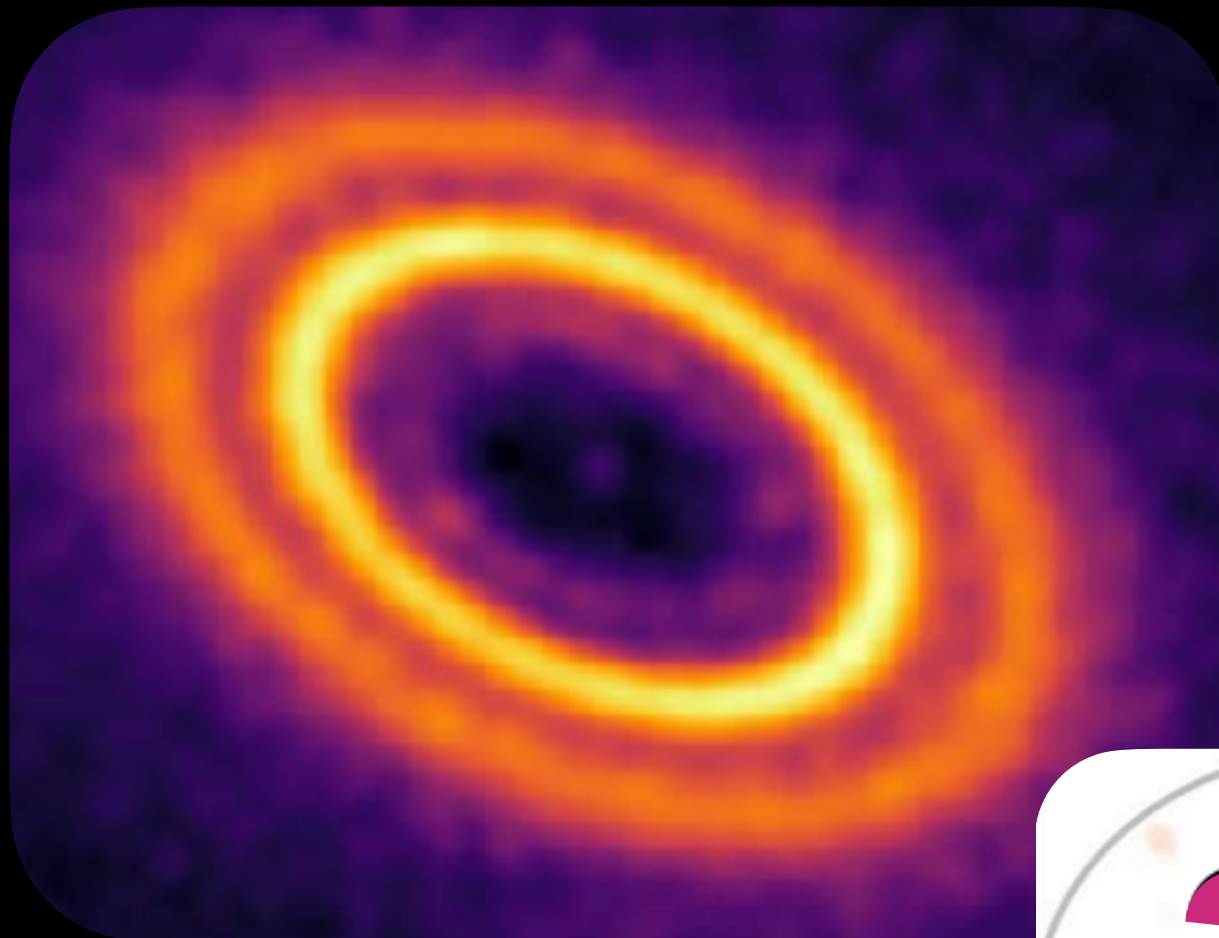


Isella et al. (2018)

Candidates for **dust** trapping around **Lagrangian** points

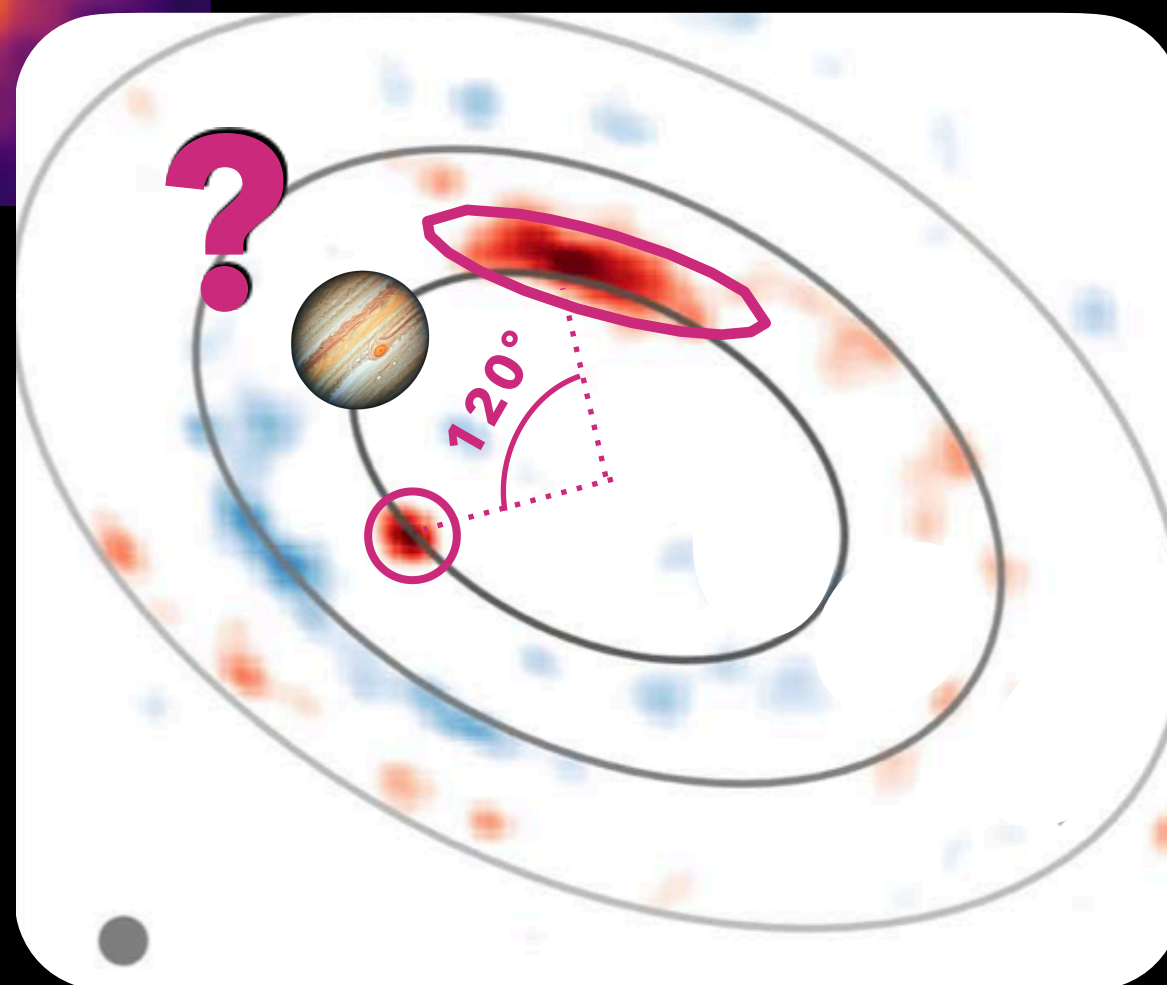
LkCa 15

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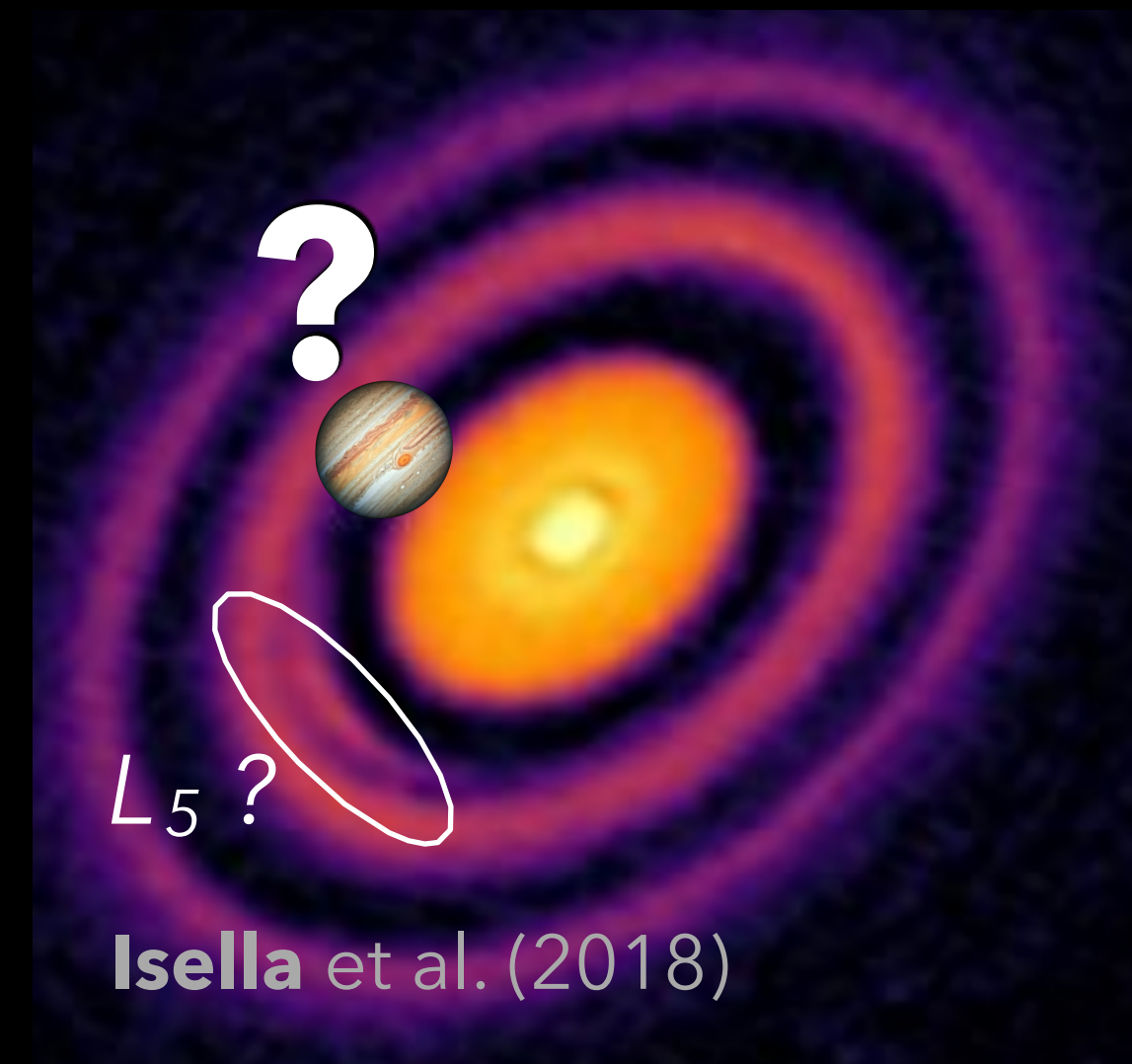
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Residuals



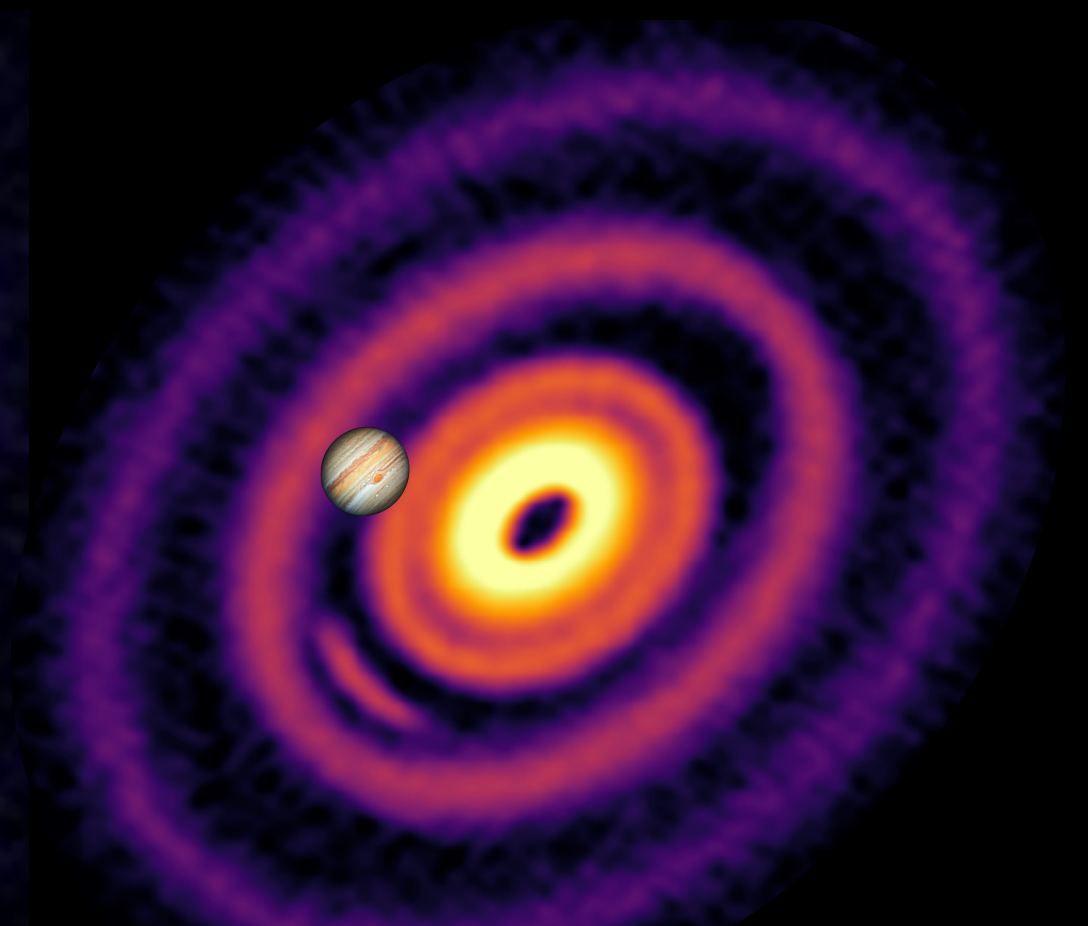
HD 163296

ALMA Band 6



Isella et al. (2018)

Model



Rodenkirch et al. (2021)

Garrido-Deutelmose
et al. (2023)

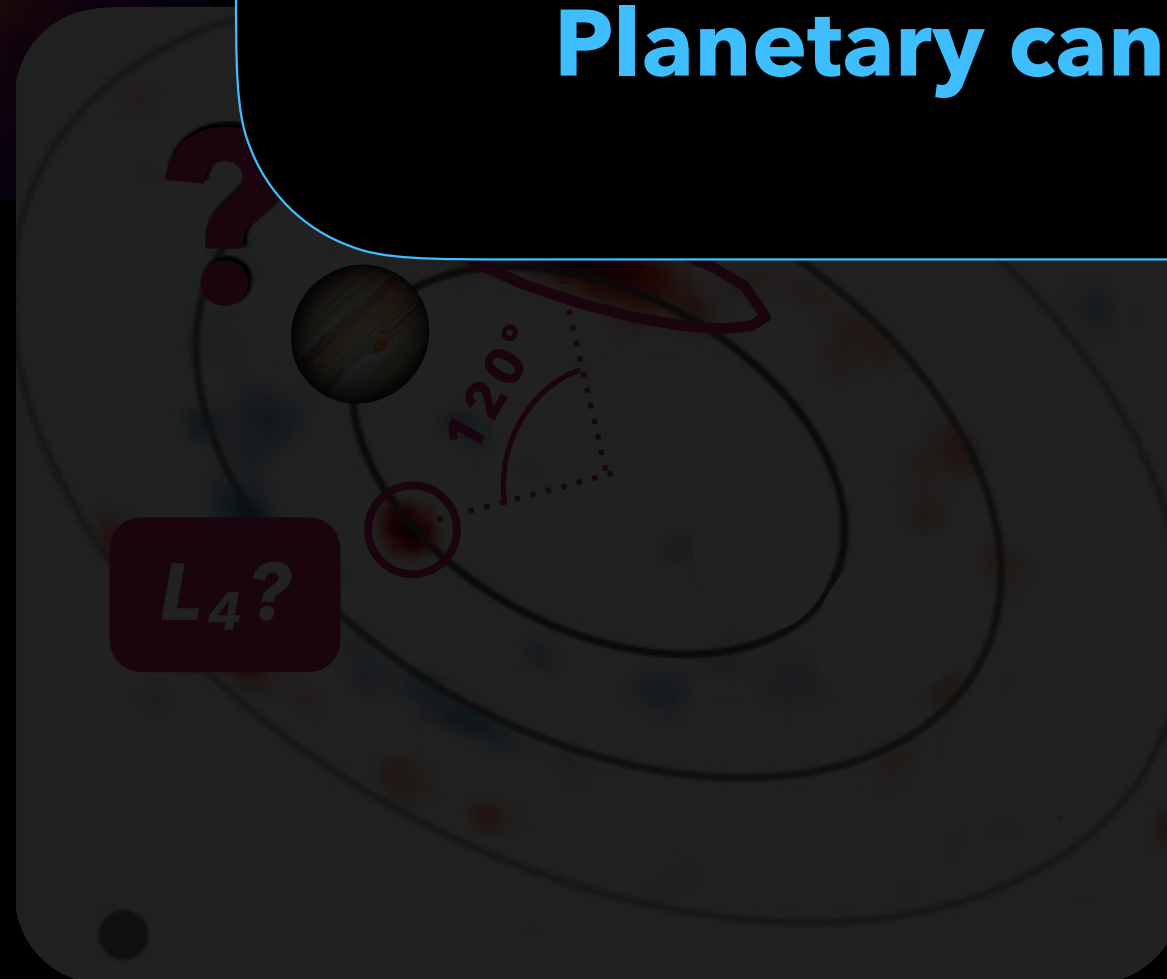
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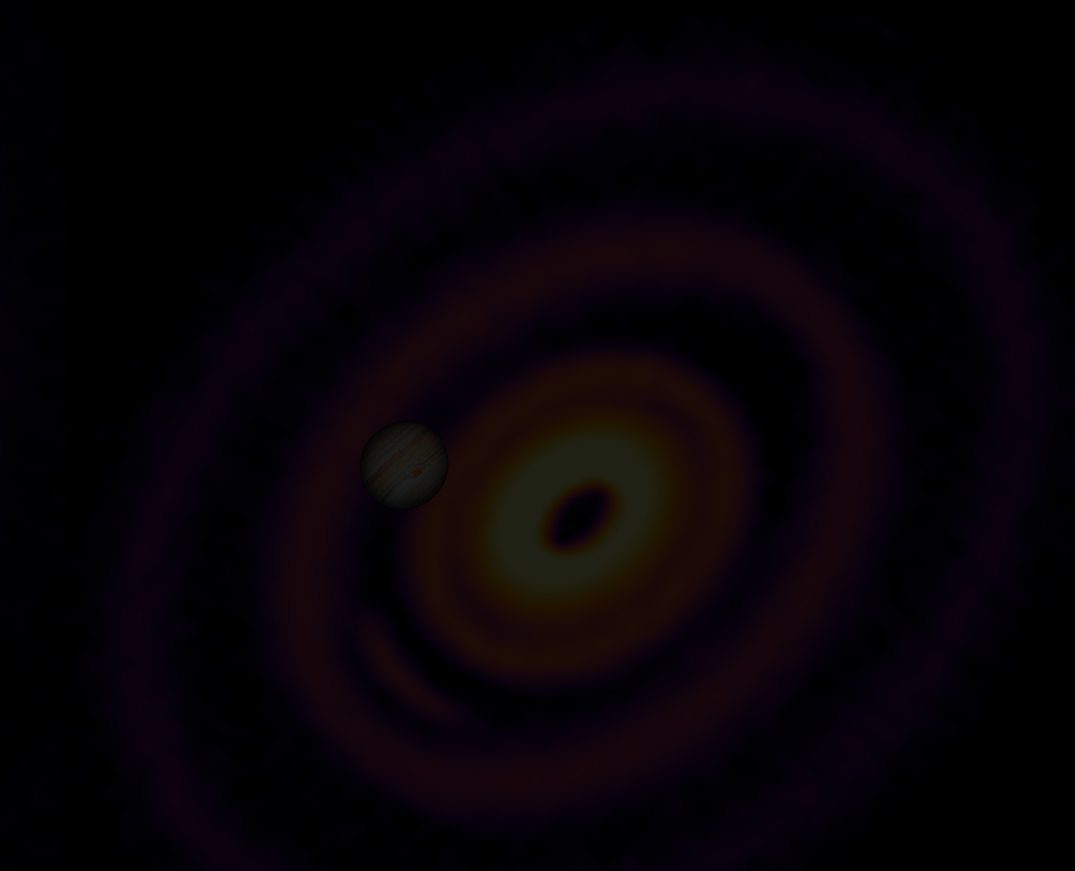


Long et al. (2022)



HD 163296

Model



Rodenkirch et al. (2021)

Garrido-Deutelmoser
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L5 ?
Isella et al. (2018)

Dust in gaps suggests
the presence of protoplanets
but
Planetary candidates remain undetected

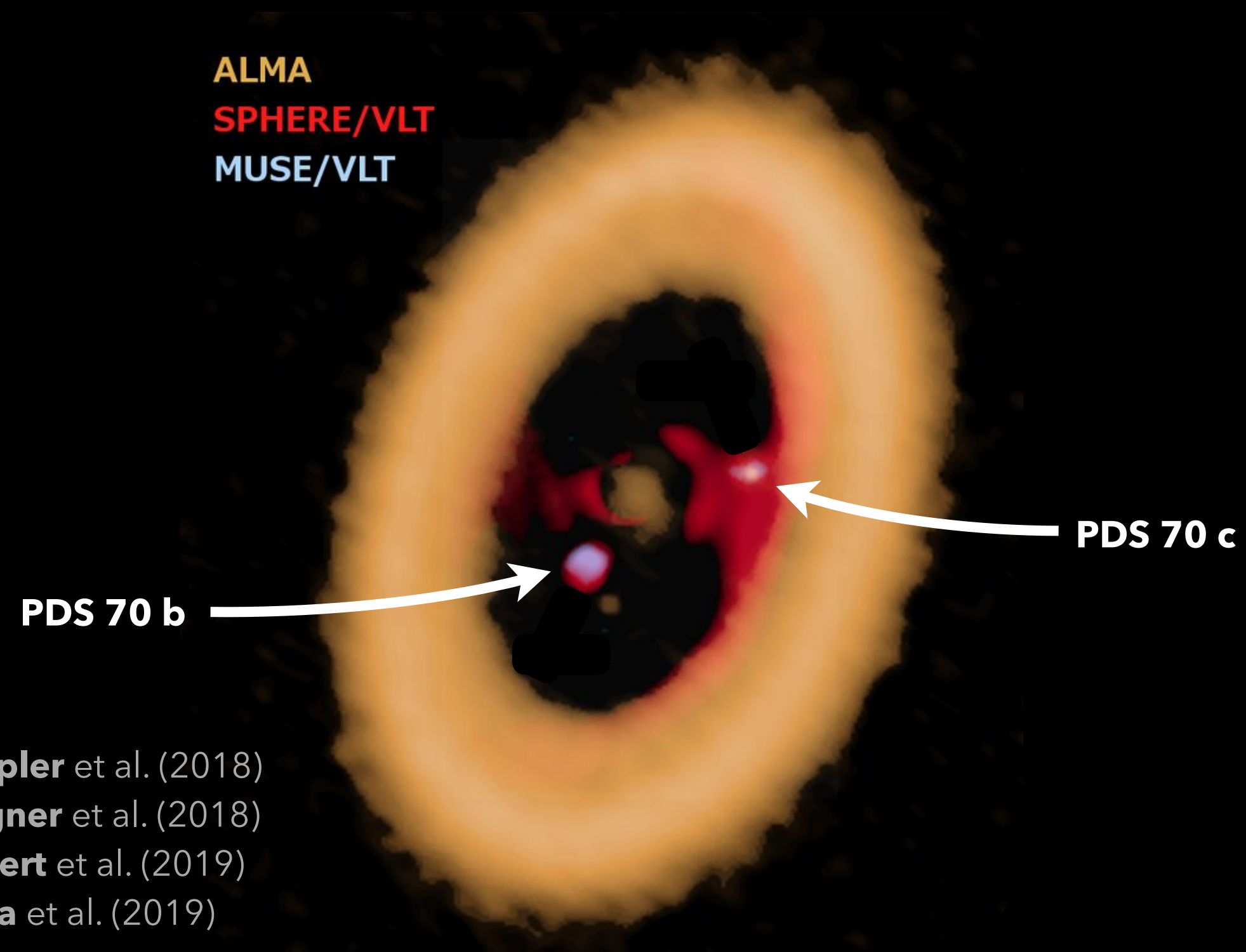
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PDS 70 is a privileged place

PDS 70: A unique planetary formation laboratory

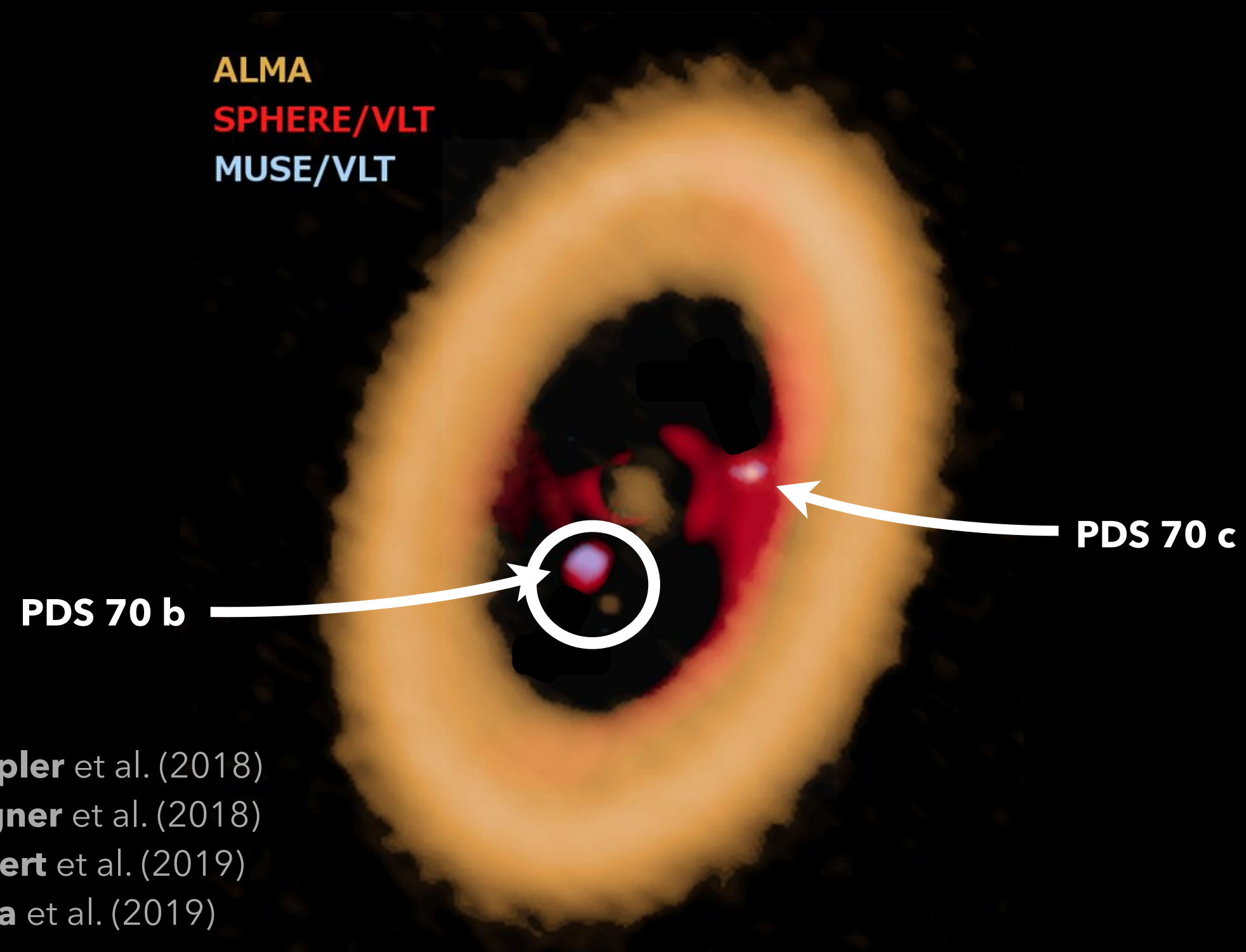
- 1 *This is the only star with confirmed **protoplanets**: PDS 70 b & c.*



Keppler et al. (2018)
Wagner et al. (2018)
Haffert et al. (2019)
Isella et al. (2019)

PDS 70: A unique planetary formation laboratory

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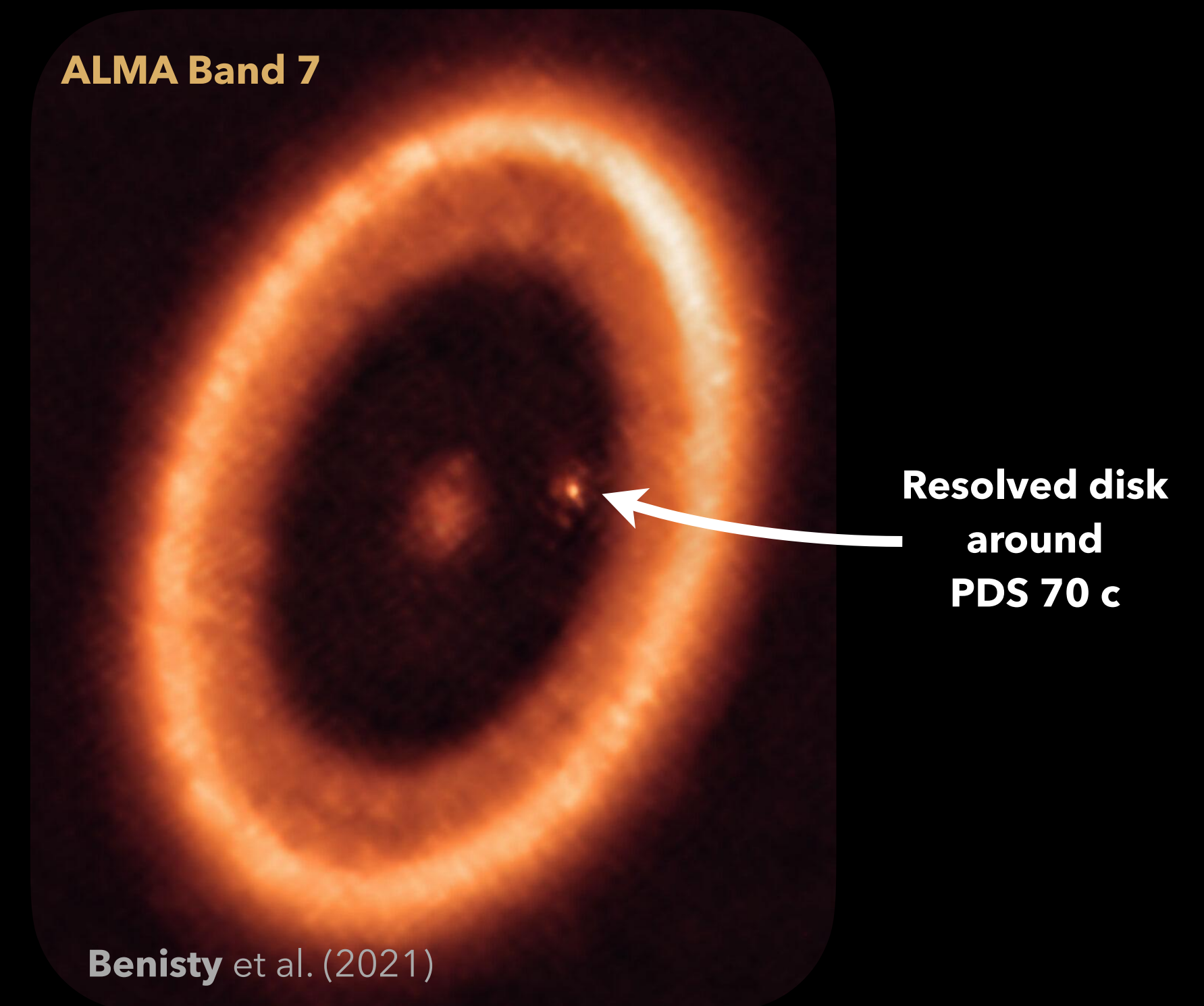
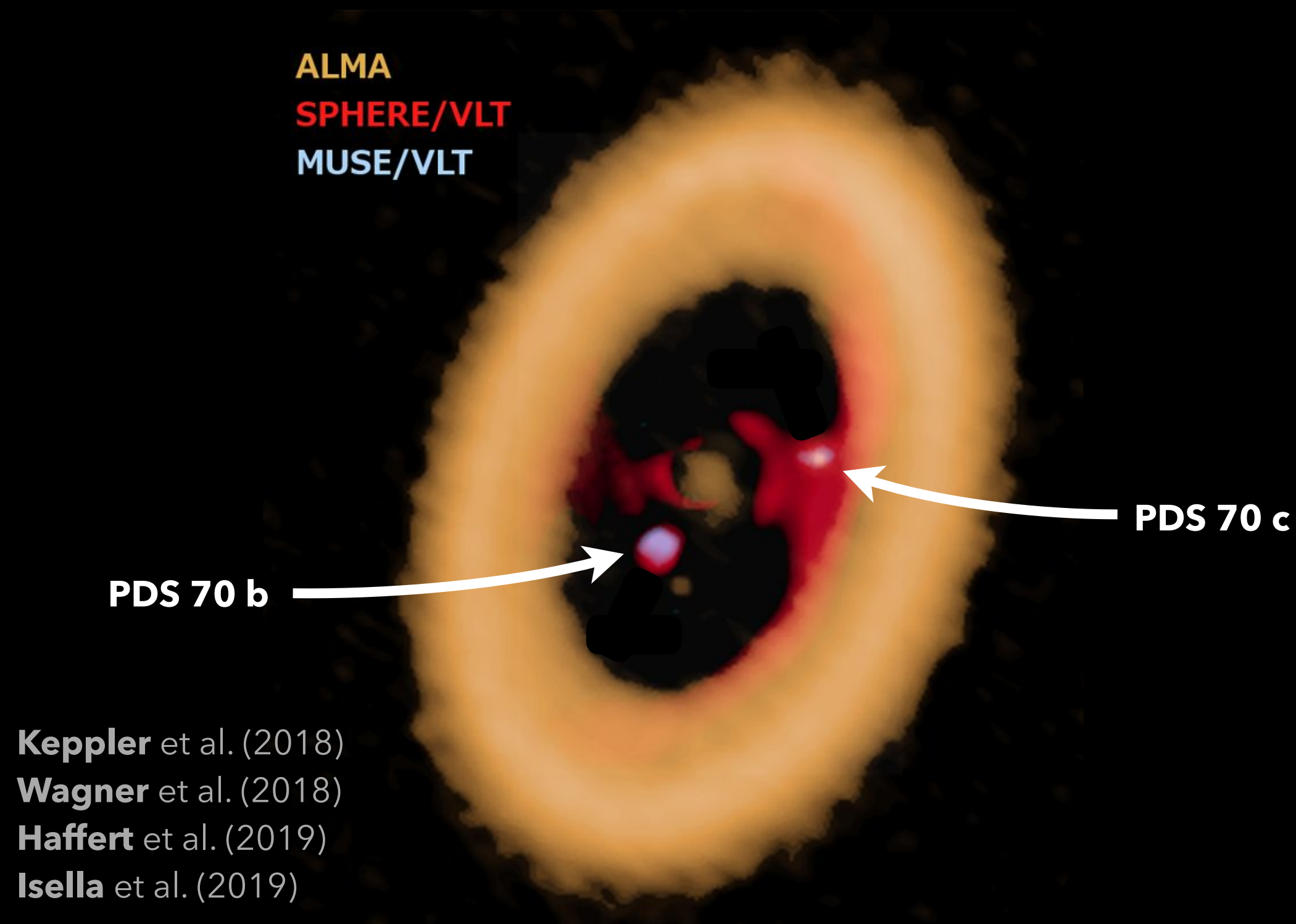


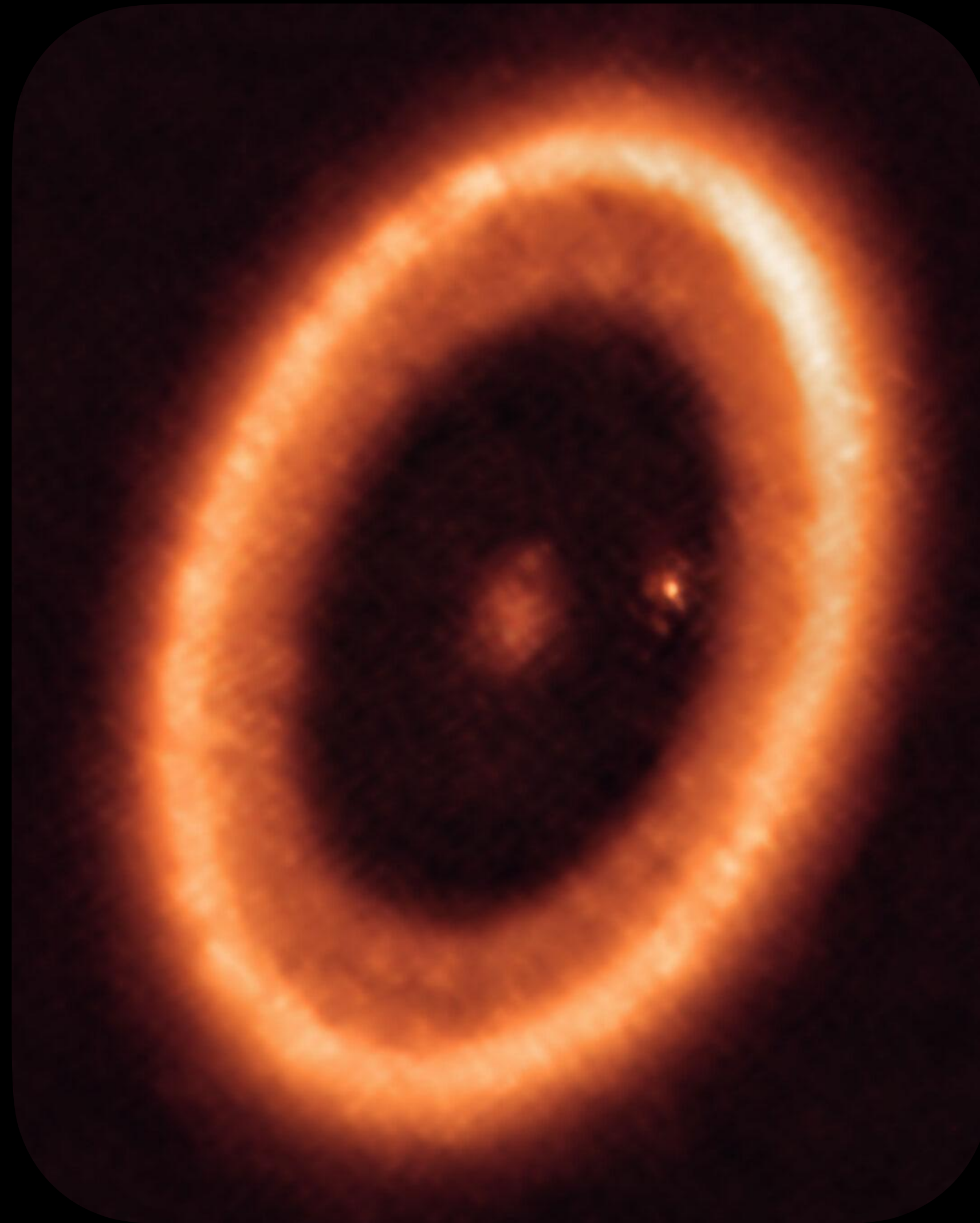
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PDS 70: A unique planetary formation laboratory

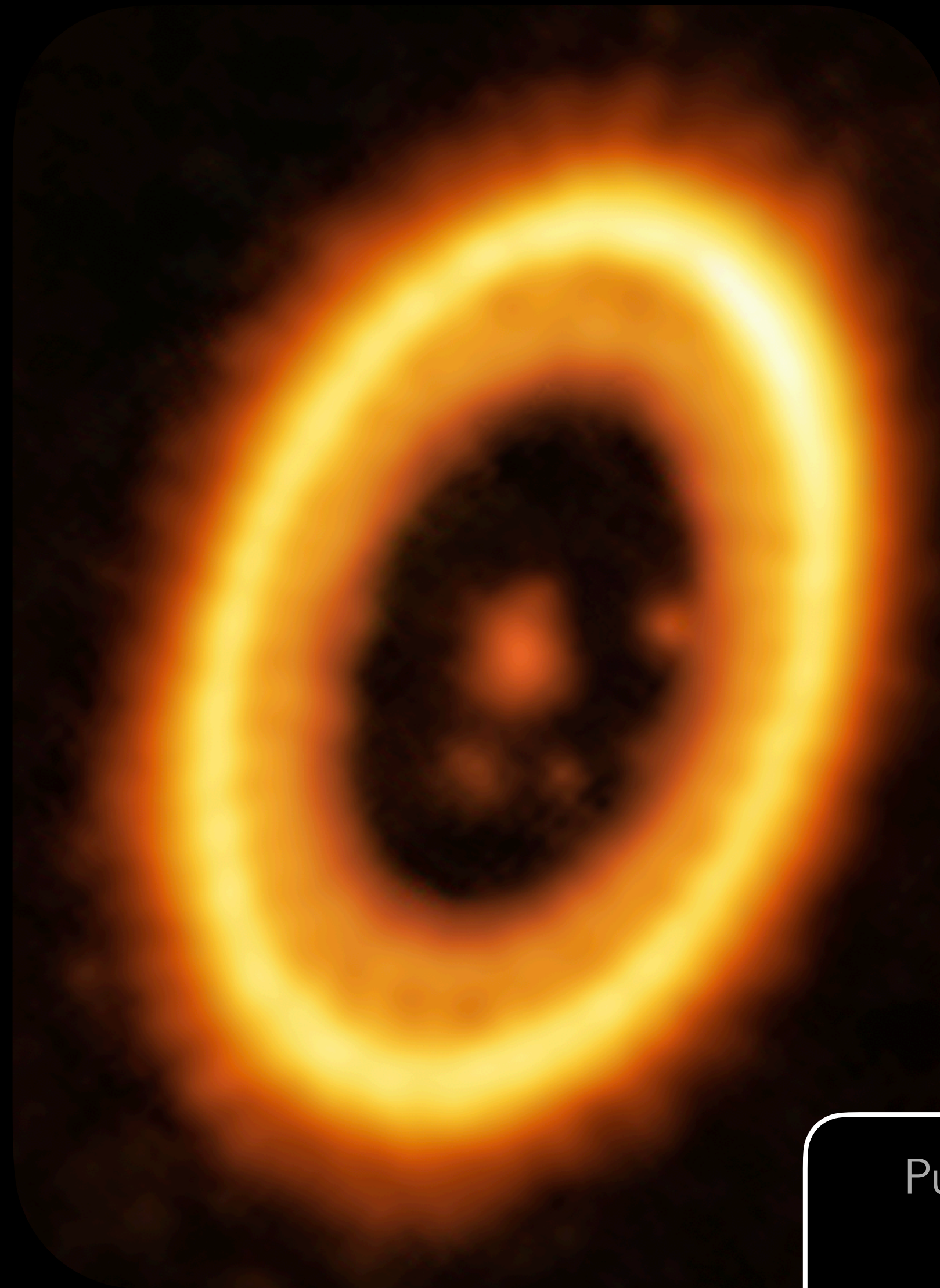
- 1 This is the only star with confirmed **protoplanets**: PDS 70 b & c.

- 2 PDS 70 c is the only planet with a **Circumplanetary Disk (CPD)**: site where moons could form.





Benisty et al. (2021)



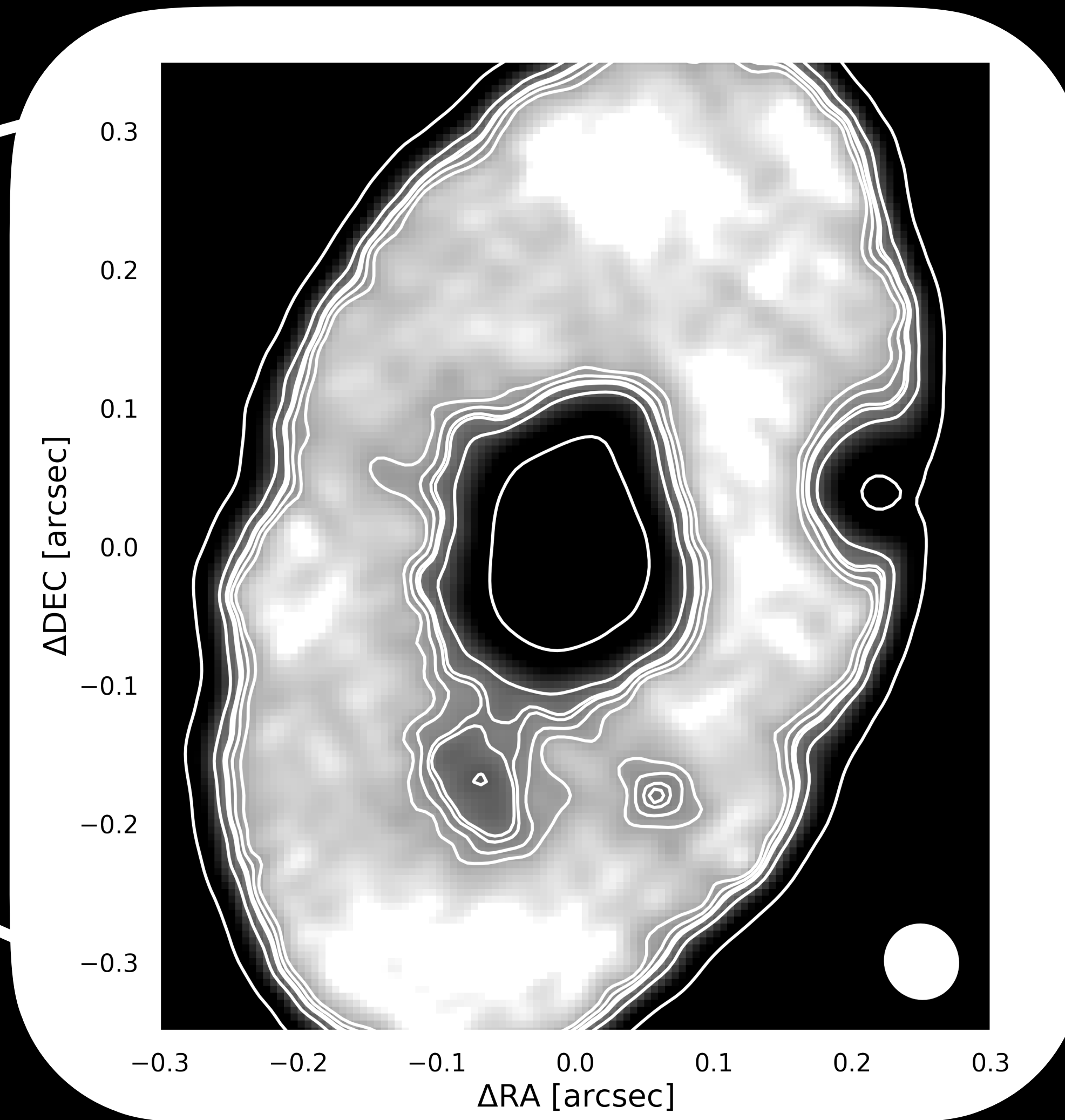
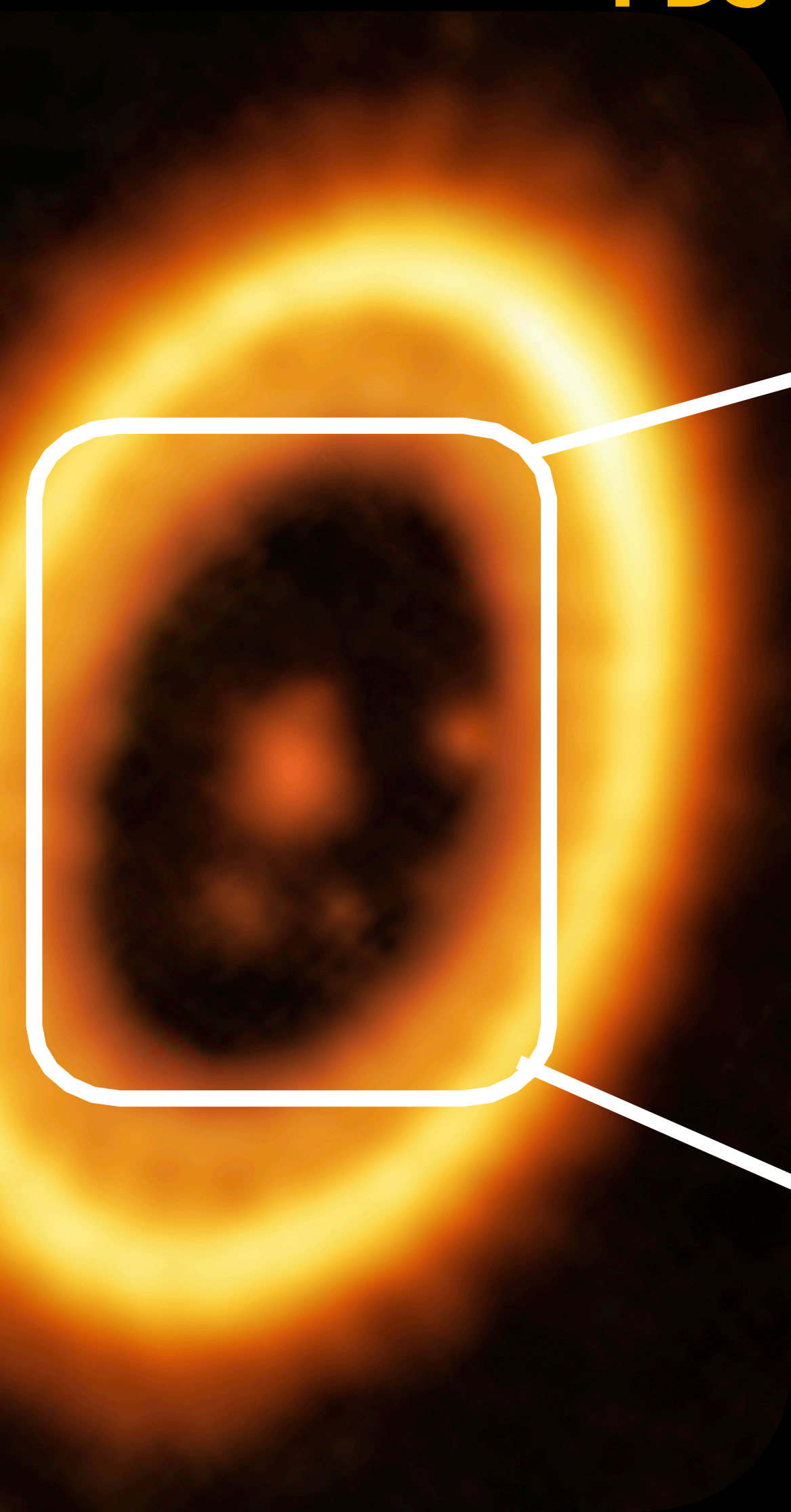
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Balsalobre-Ruza et al. (2023)



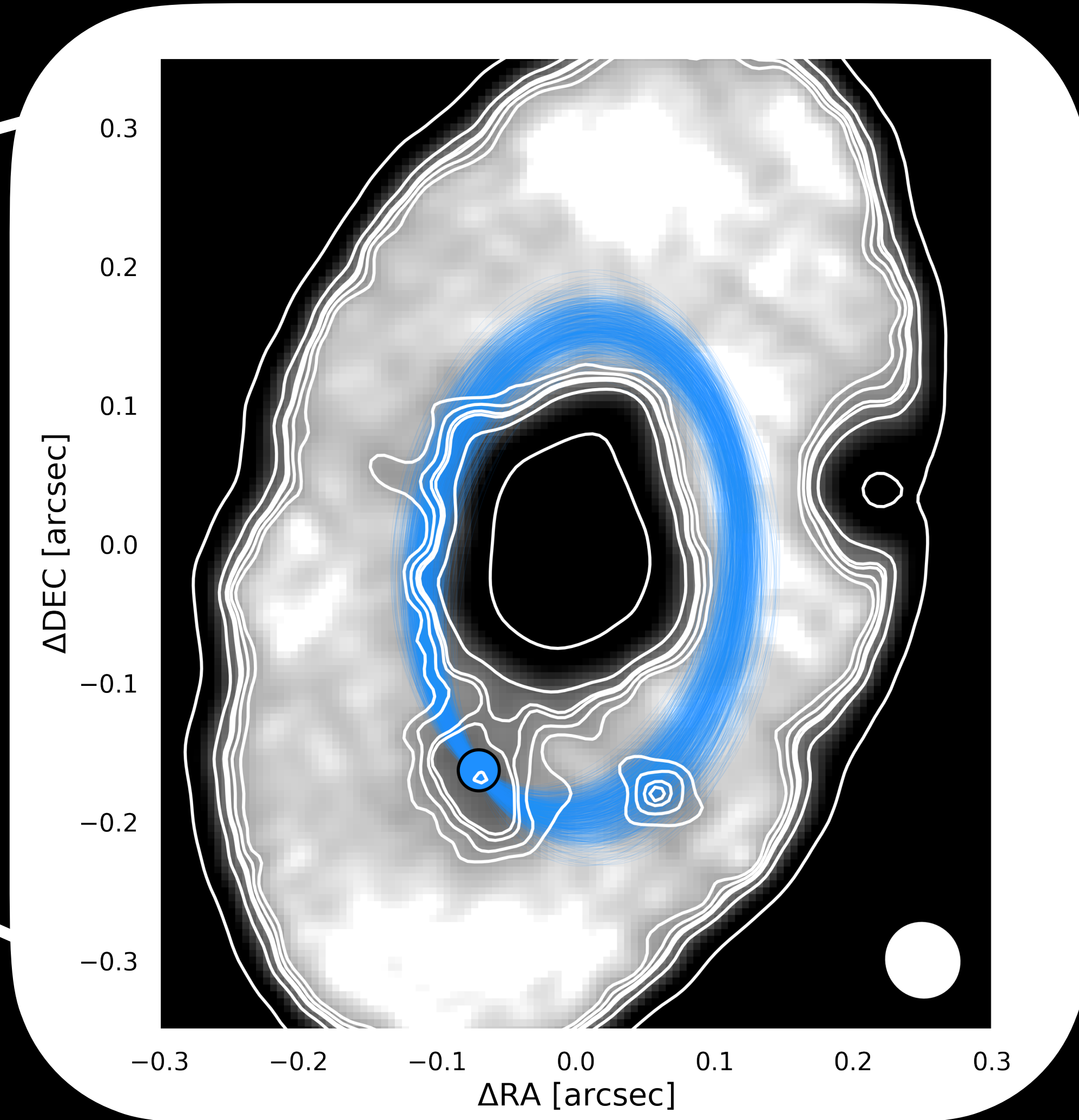
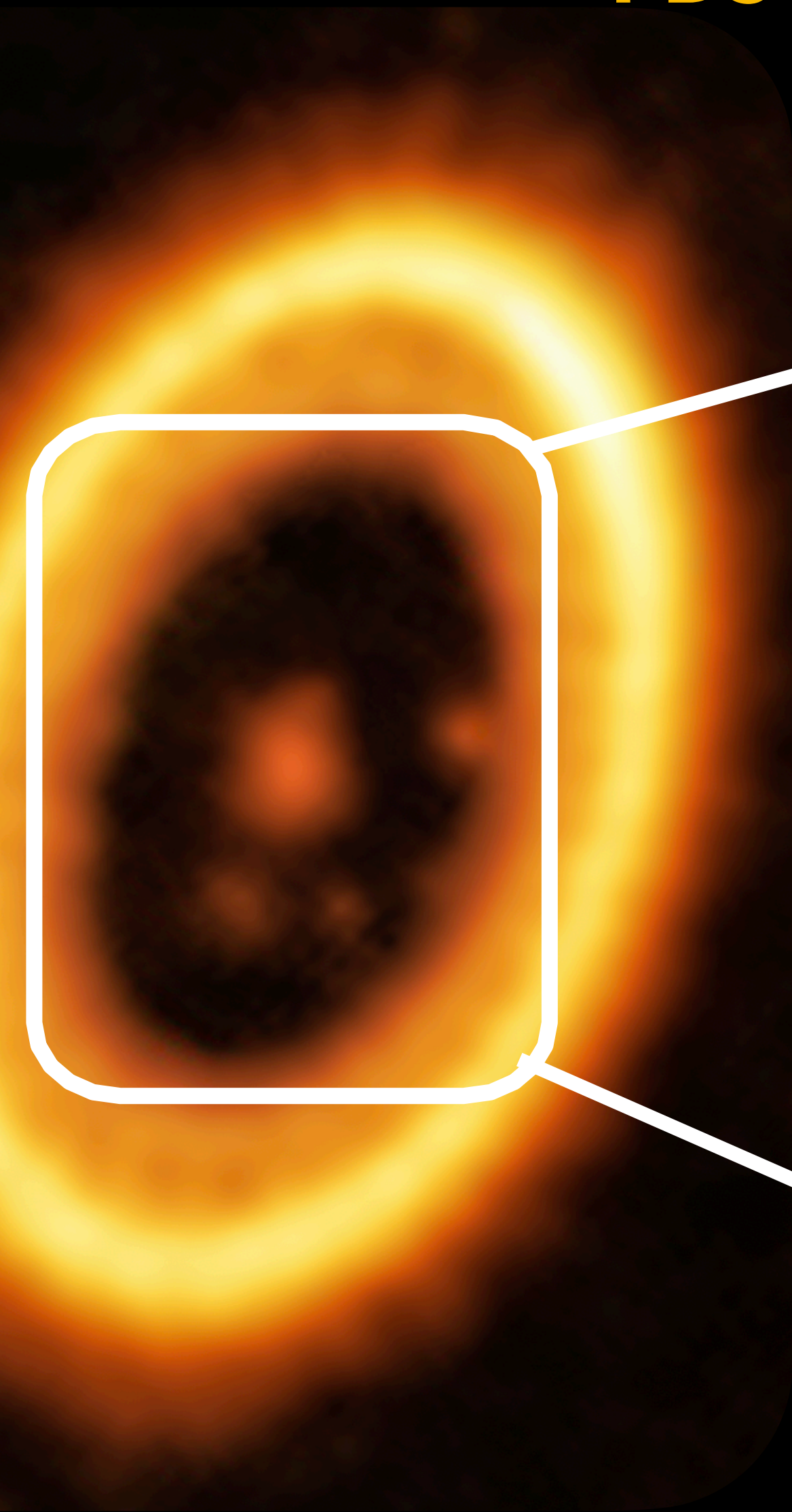
PDS 70 L₅ b: First cloud of Trojan dust associated with a confirmed planet?



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Astronomy
&
Astrophysics

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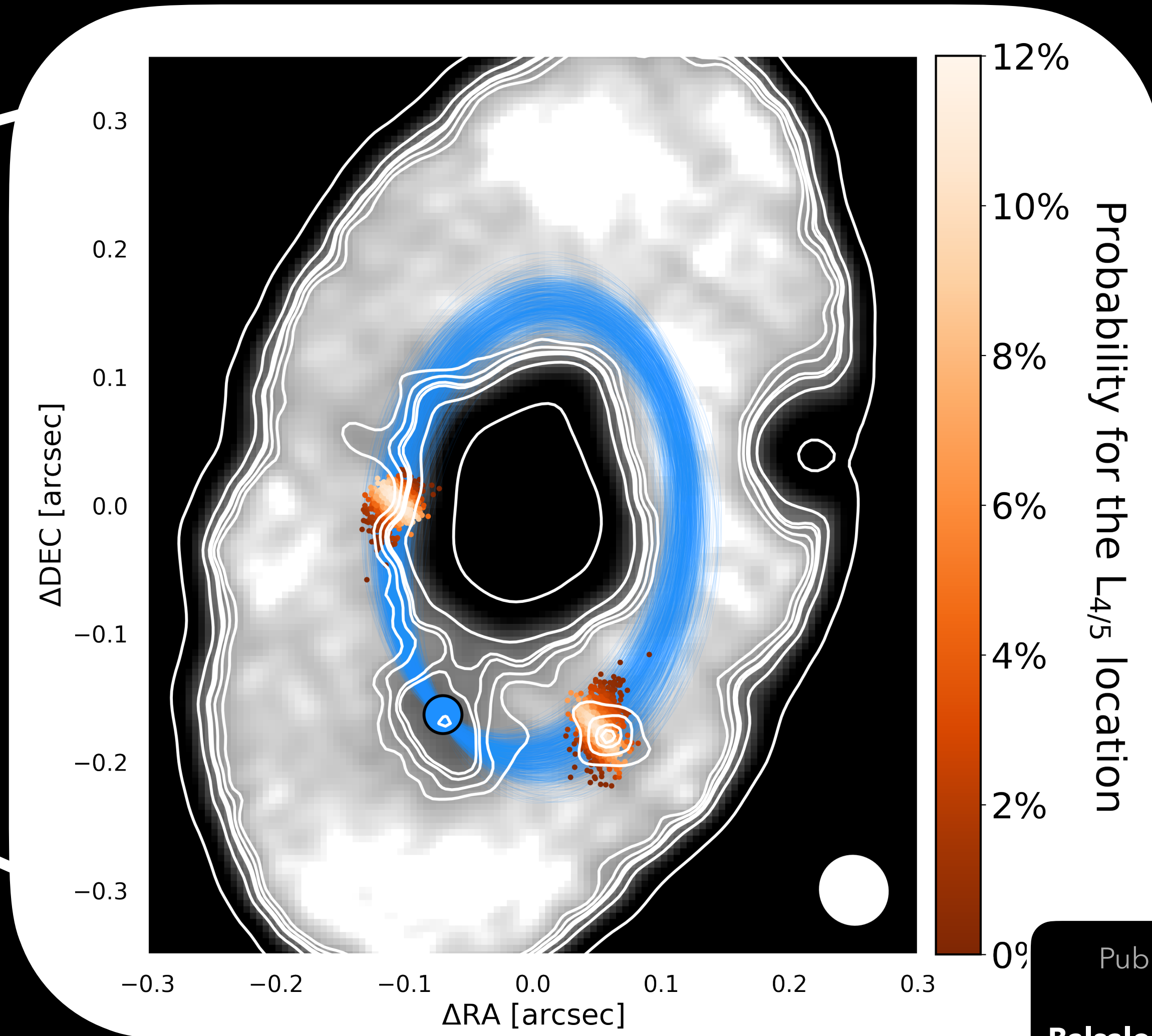
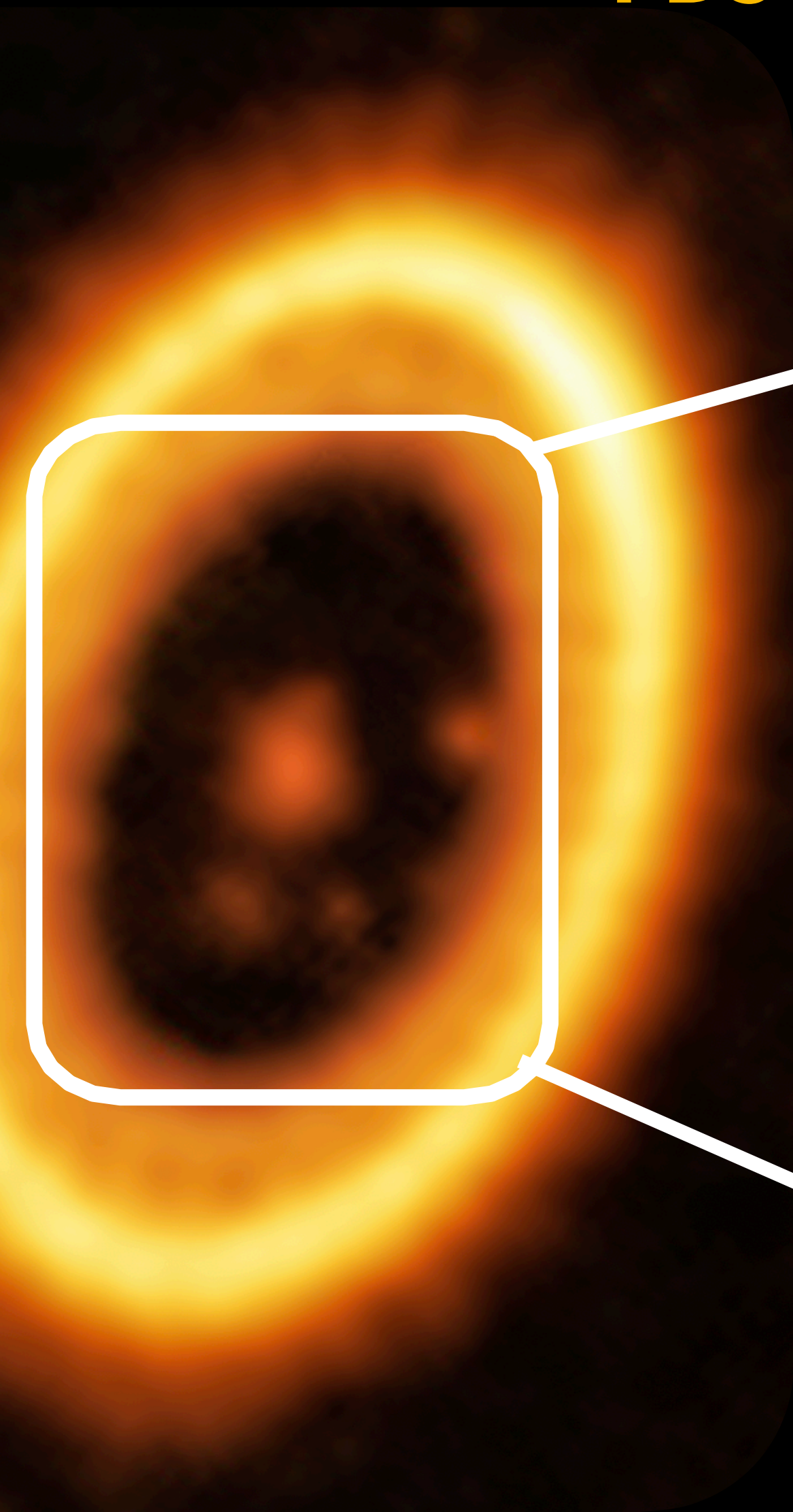


Orbits characterized with
astrometry from IR observations
VLTI/GRAVITY
Wang et al. (2021)

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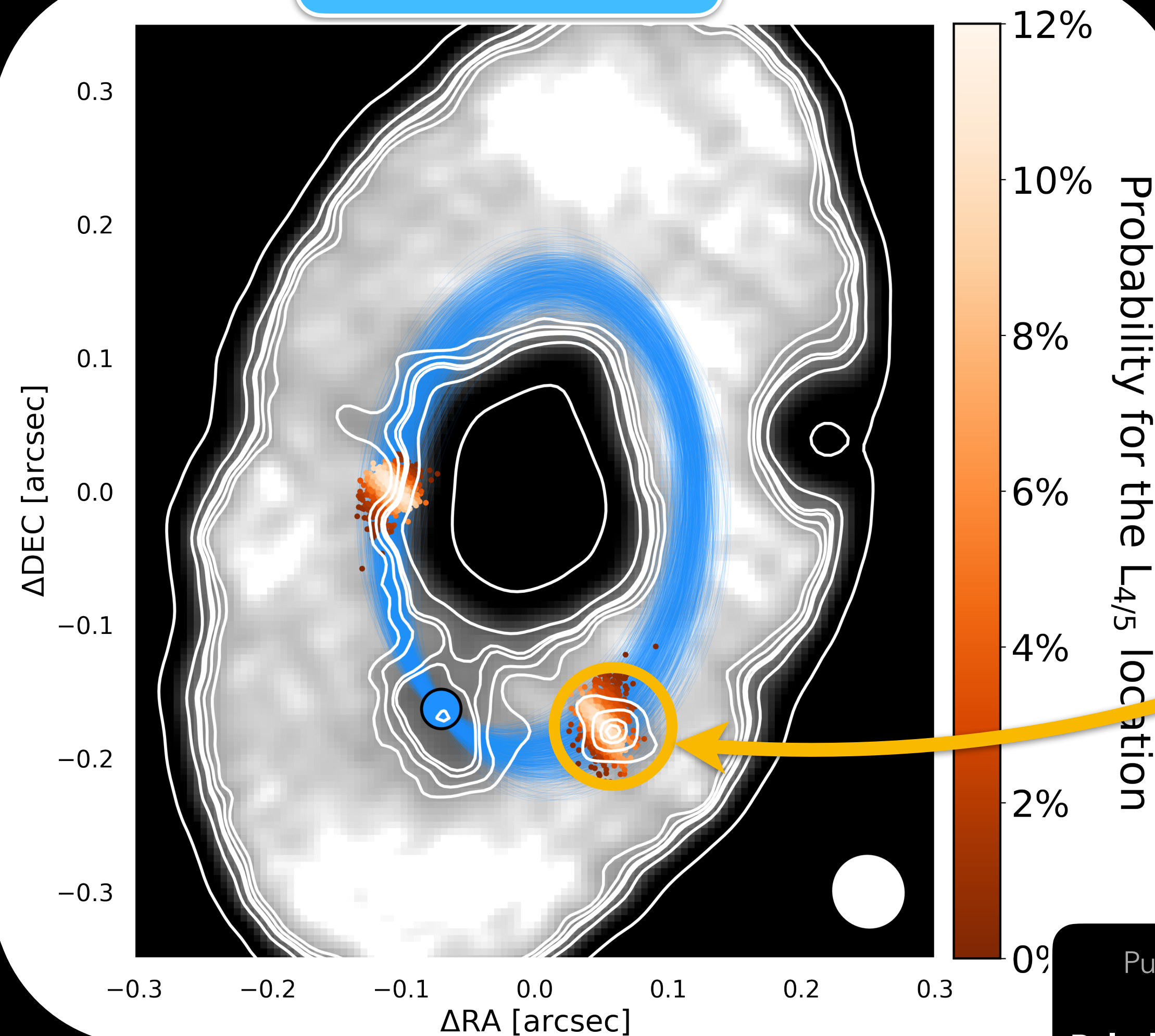
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Astrophysics

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6- σ detection



Orbits characterized with
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VLTI/GRAVITY
Wang et al. (2021)

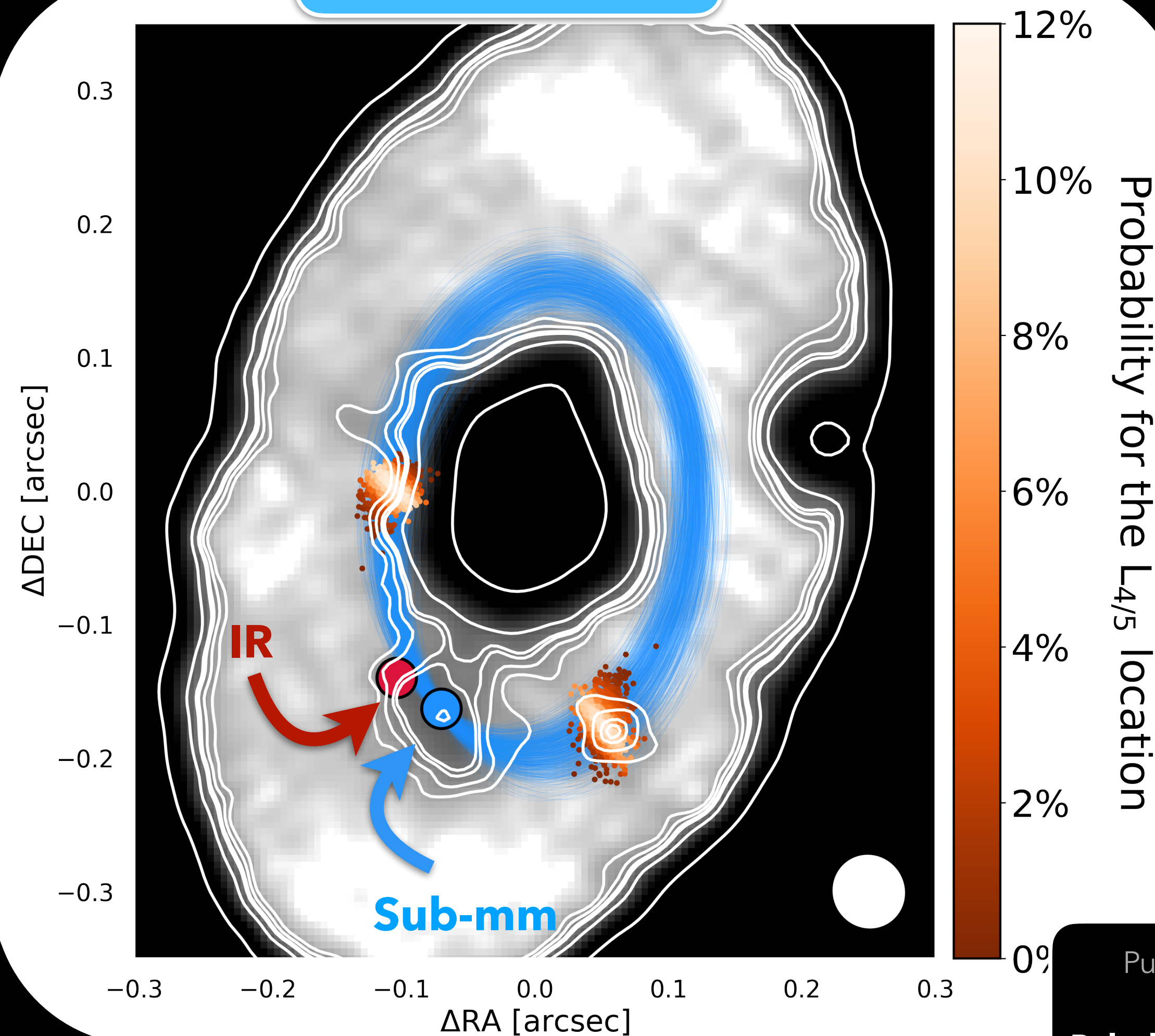
Exactly at the
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6- σ detection



Orbits characterized with
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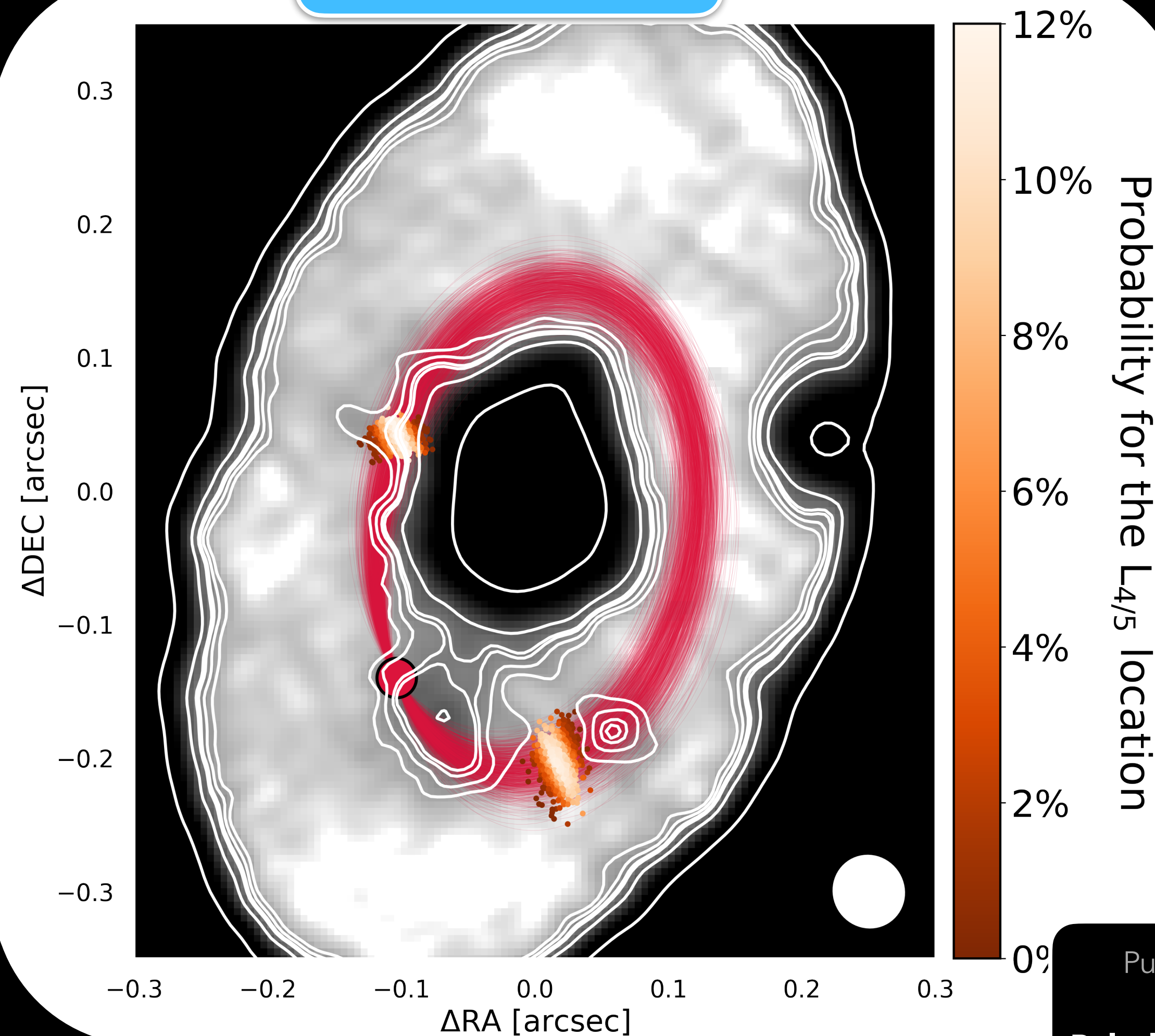
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~5° shifted from the **L5 point** of the **IR** planet emission

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What it is

0.03 - 2 M_{Moon} of **~1 mm-sized dust particles** located within the **L₅ region** of PDS 70 b.

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What it **could be**

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- **Debris particles** that eventually **could form** a planet.

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How can we **confirm** it

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What it could be

How can we **confirm** it

Why is this **exciting**

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Revisiting PDS 70 not sooner than **2026**.

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If confirmed, PDS 70 L₅ b will be the **strongest evidence** in favor of the precursors of **Trojan planets**. These objects, might shed new light into the formation and evolution of planetary systems.

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Thank you!

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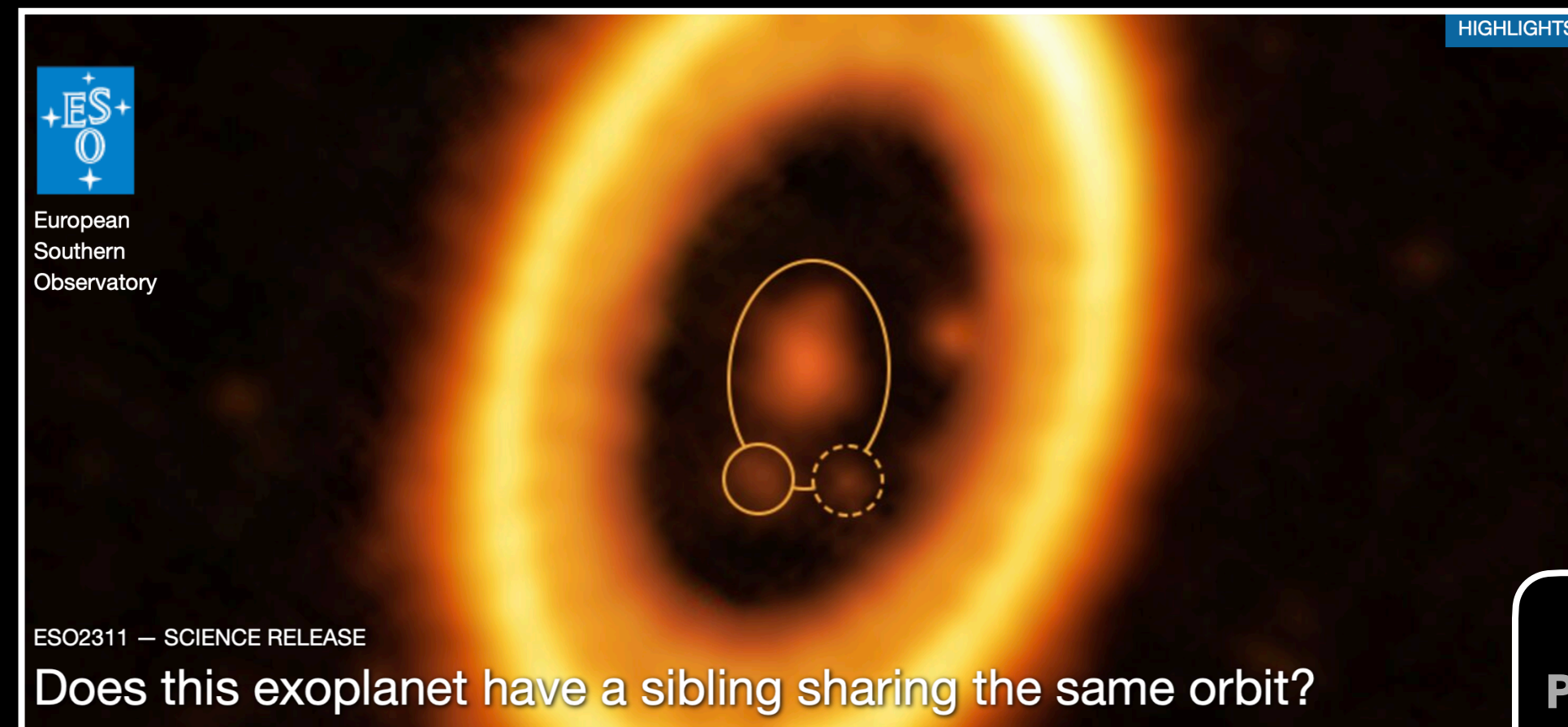
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Tentative co-orbital submillimeter emission within the Lagrangian region L_5 of the protoplanet PDS 70 b

O. Balsalobre-Ruza¹ , I. de Gregorio-Monsalvo² , J. Lillo-Box¹ , N. Huélamo¹, Á. Ribas³ ,
M. Benisty^{4,5}, J. Bae⁶ , S. Facchini⁷ , and R. Teague⁸ 



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