Viktória Fröhlich, PhD student, Sup.: Martin Jutzi, Fikut Nextgen, 2026. 11. 06.

Background: ChatGPT



From the death of stars to the dawn of life

Dynamical effects of mass loss around high-mass stars

From the death of stars to the dawn of life

How stable are planetary orbits around a supernova?

Are rogue planet moons retained, can they have subsurface oceans?

How to form a wide binary with a mass-gap black hole?

Can subsequent supernovae explain double neutron stars?

Is the exceptionally high eccentricity of Wolf-Rayet binaries primordial?



Shutterstock/van van

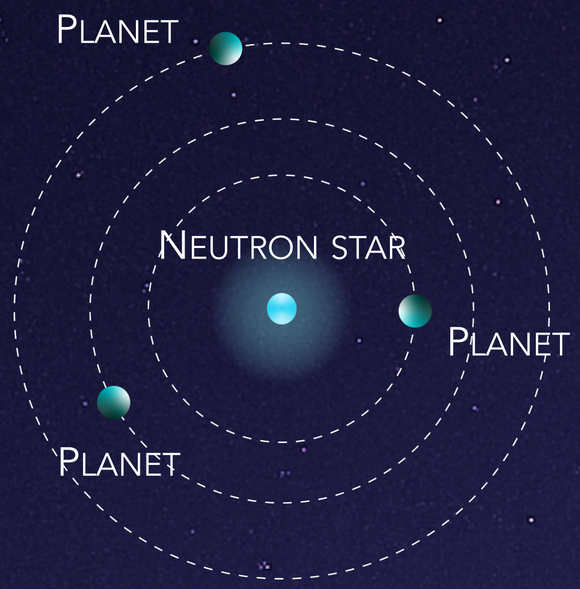


Vecteezy/Emiilia Bielkina

Exotic planet and star systems

PULSAR PLANETS

Wolszczan & Frail (1992)



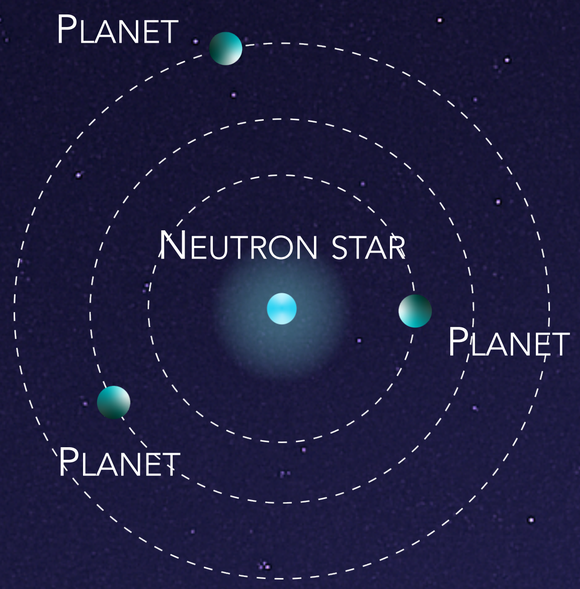
Regály et al. (2022)

Fröhlich & Regály (2025)

Exotic planet and star systems

Pulsar planets

Wolszczan & Frail (1992)



Regály et al. (2022)
Fröhlich & Regály (2025)

Double NS-systems

Hulse & Taylor (1975)

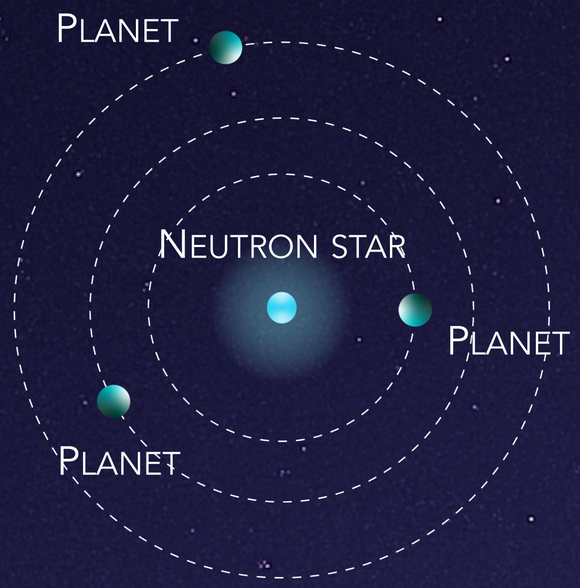


Fröhlich et al. (2023)

Exotic planet and star systems

pulsar planets

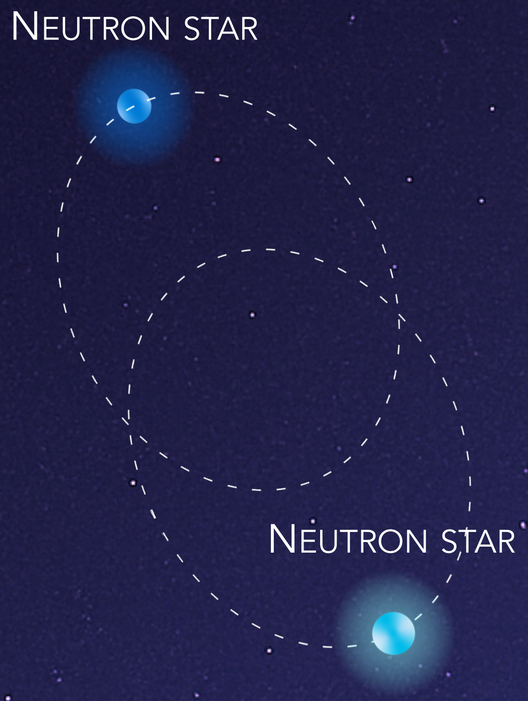
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Fröhlich & Regály (2025)

double NS-systems

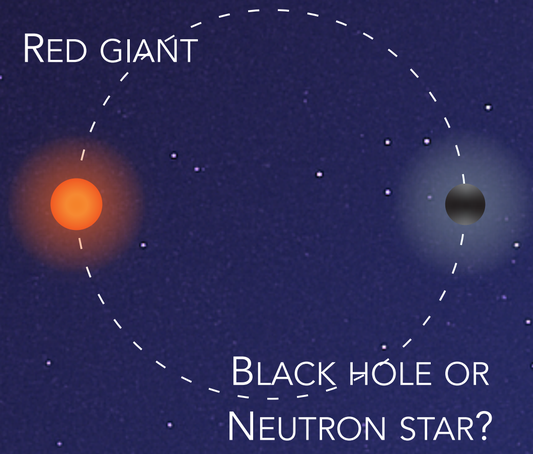
Hulse & Taylor (1975)



Fröhlich et al. (2023)

remnant + RG star

Wang et al. (2024)

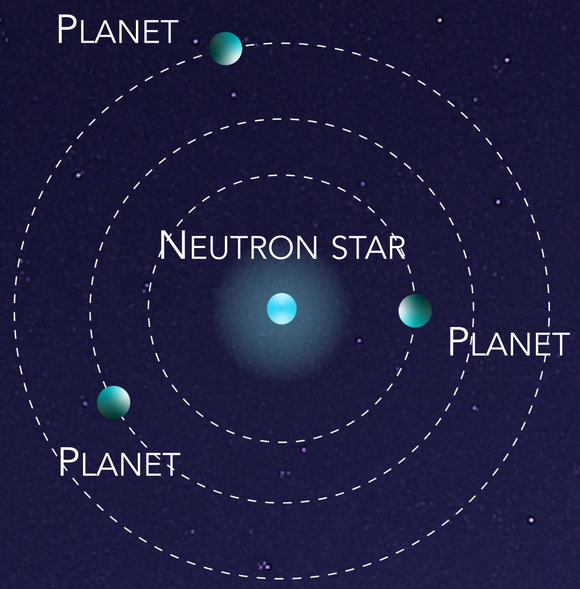


Regály et al. (2025)

Exotic planet and star systems

pulsar planets

Wolszczan & Frail (1992)



Regály et al. (2022)
Fröhlich & Regály (2025)

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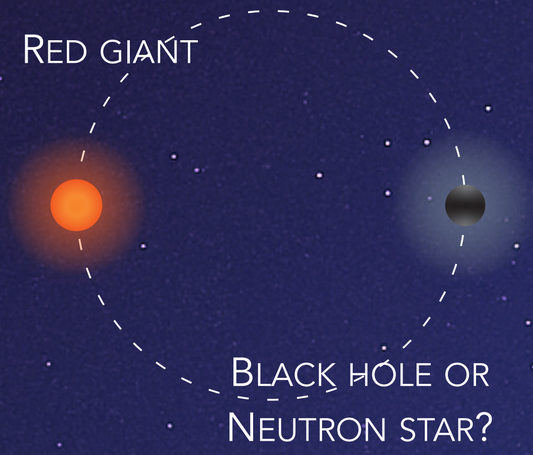
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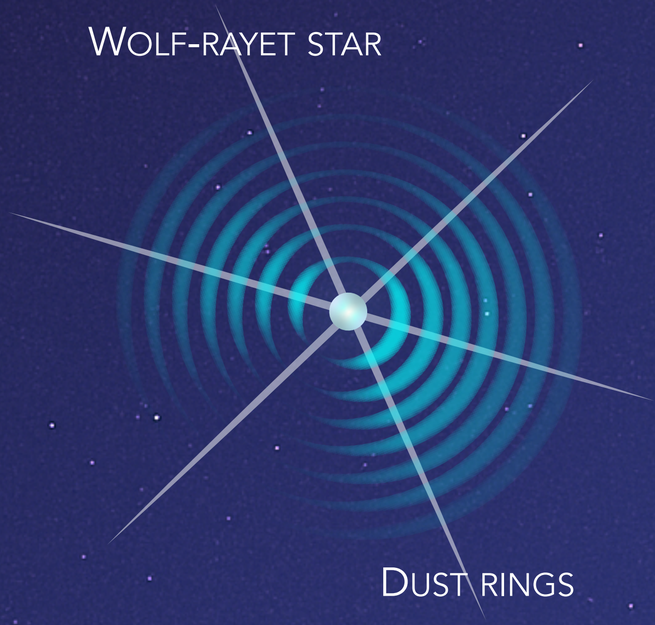
Wang et al. (2024)



Regály et al. (2025)

Eccentric WR binaries

Lieb et al. (2025)



Fröhlich & Regály (2026)

Roamers of the Galaxy - Rogue planets

Starless planets on the roads of the Milky Way

Hundreds discovered

Pearson & McCaughrean (2023)

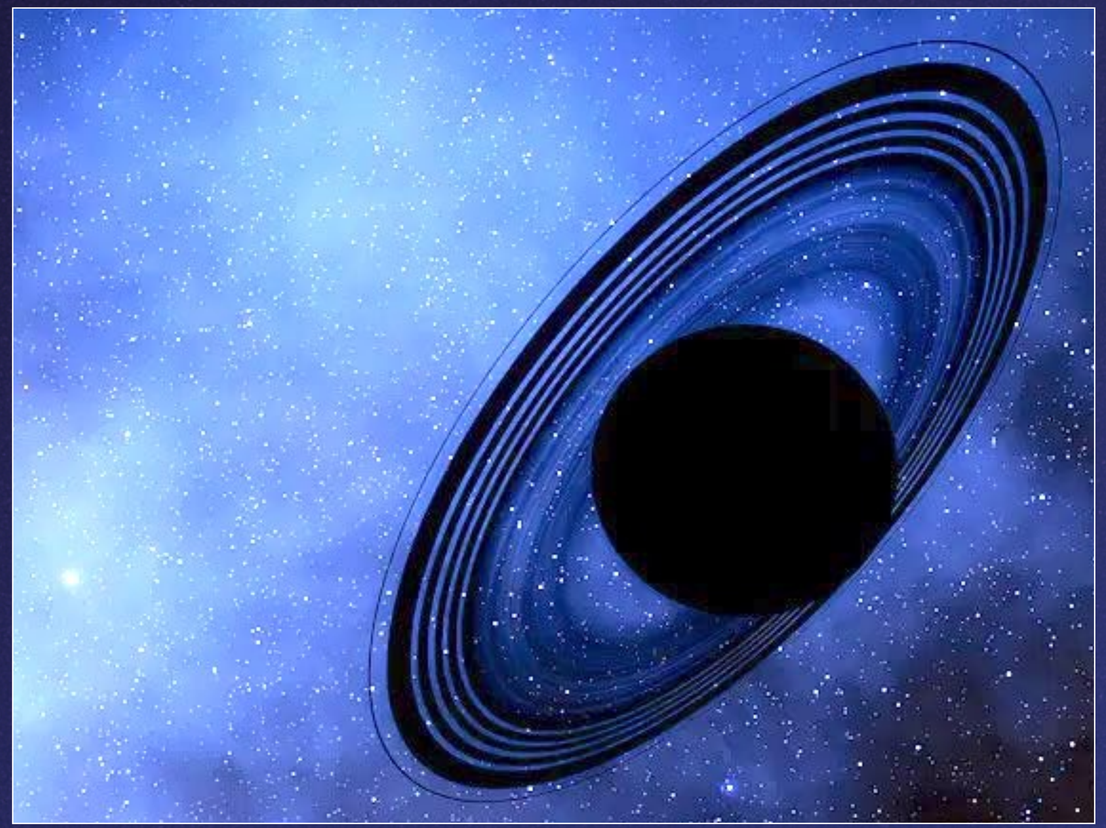
Causes for ejection:

1) Early dynamical instabilities

Holman & Wiegert (1999) , Ford & Rasio (2008)

2) Heavy mass loss at stellar death

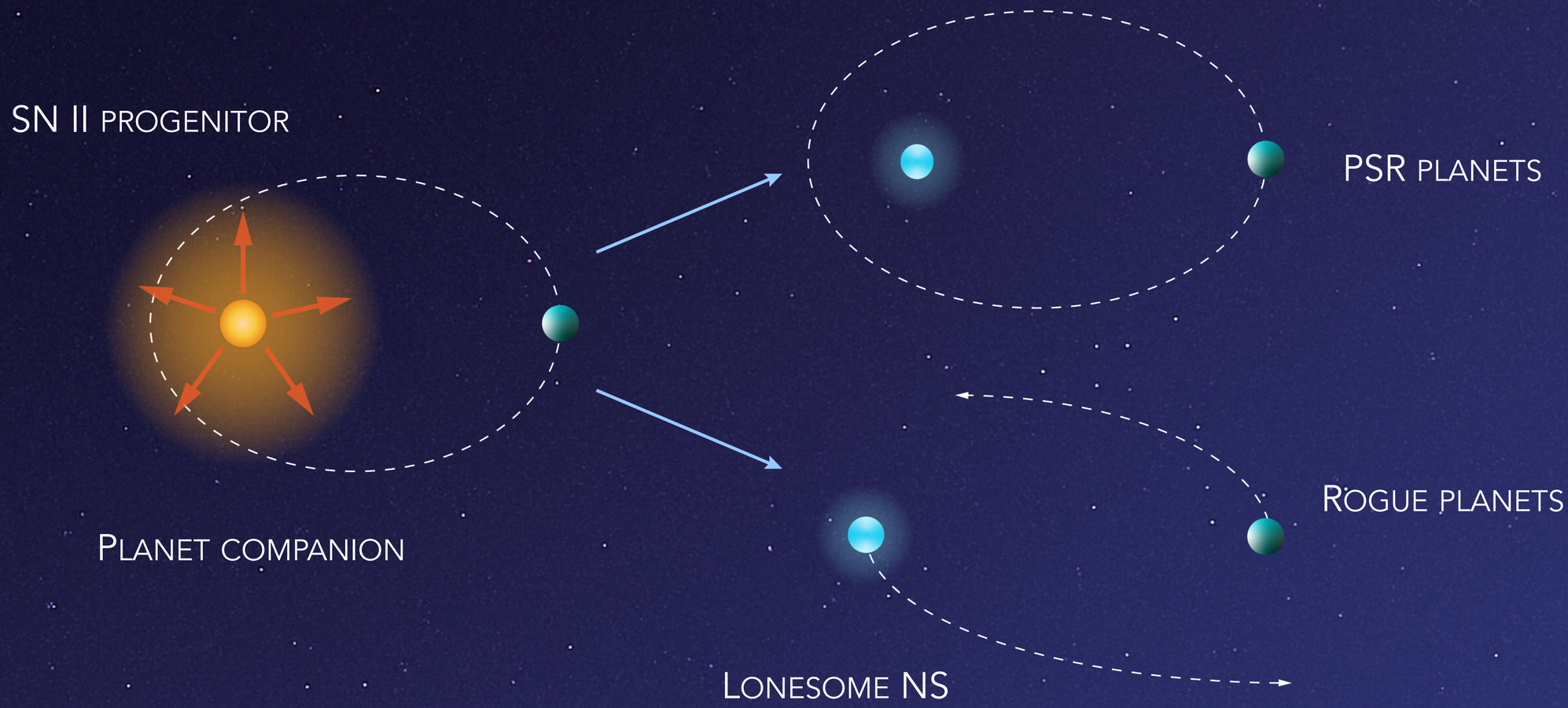
Regály, Fröhlich & Vinkó (2022), Fröhlich, Regály & Vinkó (2023), Regály, Fröhlich & Vinkó (2025), Fröhlich & Regály (2025)



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Pulsar planets

Regály, Fröhlich & Vinkó (2022)



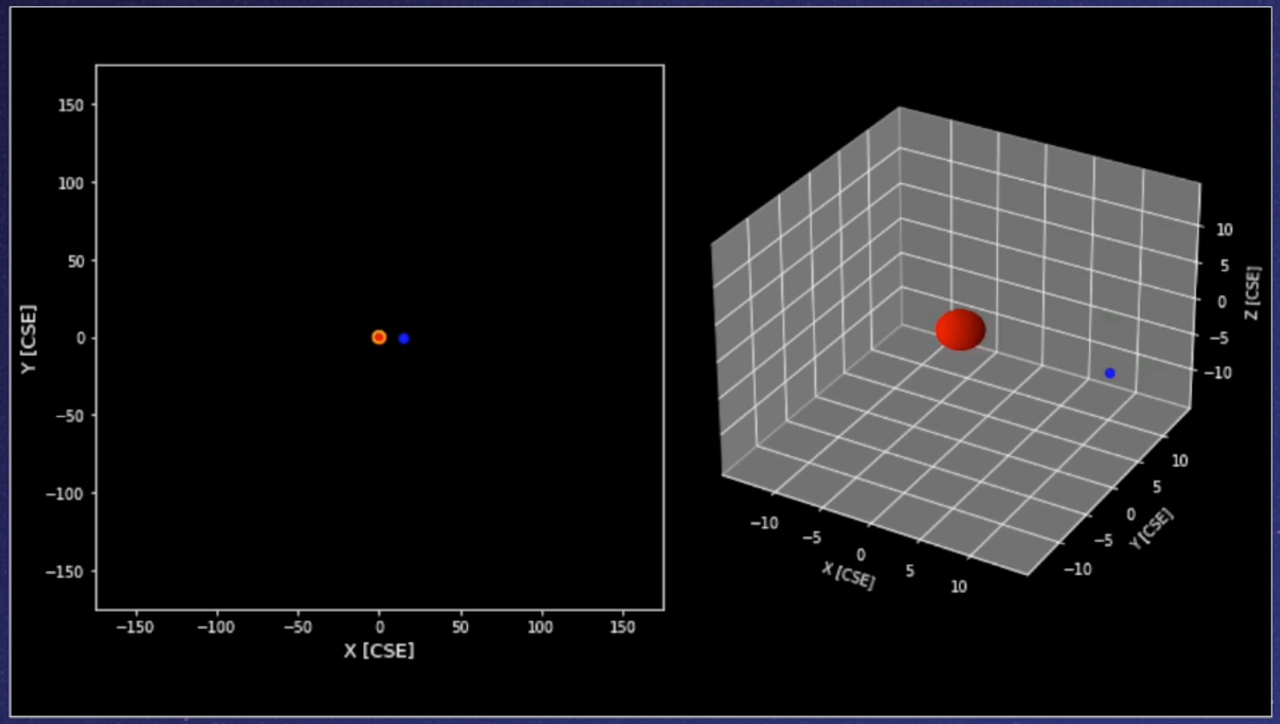
Variable mass few-body problem

Numerical simulations

- Self-written n-body code
- 8th order Runge–Kutta integrator
- Homologous, spherically symmetric envelope expansion
- Variable central mass: $M_{\mathrm{in,i}}(t)$

$$\ddot{\mathrm{r}}_{\mathrm{i}} = -GM_{\mathrm{in,i}}(t)\frac{\mathrm{r_i}-\mathrm{r_0}}{|r_{\mathrm{i}}-r_0|^3} - G\sum_{j=1}^{N-2} M_{\mathrm{j}}\frac{\mathrm{r_i}-\mathrm{r_j}}{|r_{\mathrm{i}}-r_{\mathrm{j}}|^3}$$

Example simulation:



Analysis

- Initial conditions:
  - orbital elements, masses, ejecta speed
- Post-explosion parameters:
  - new orbital elements: a, e
  - component velocities

Variable mass few-body problem

Numerical simulations

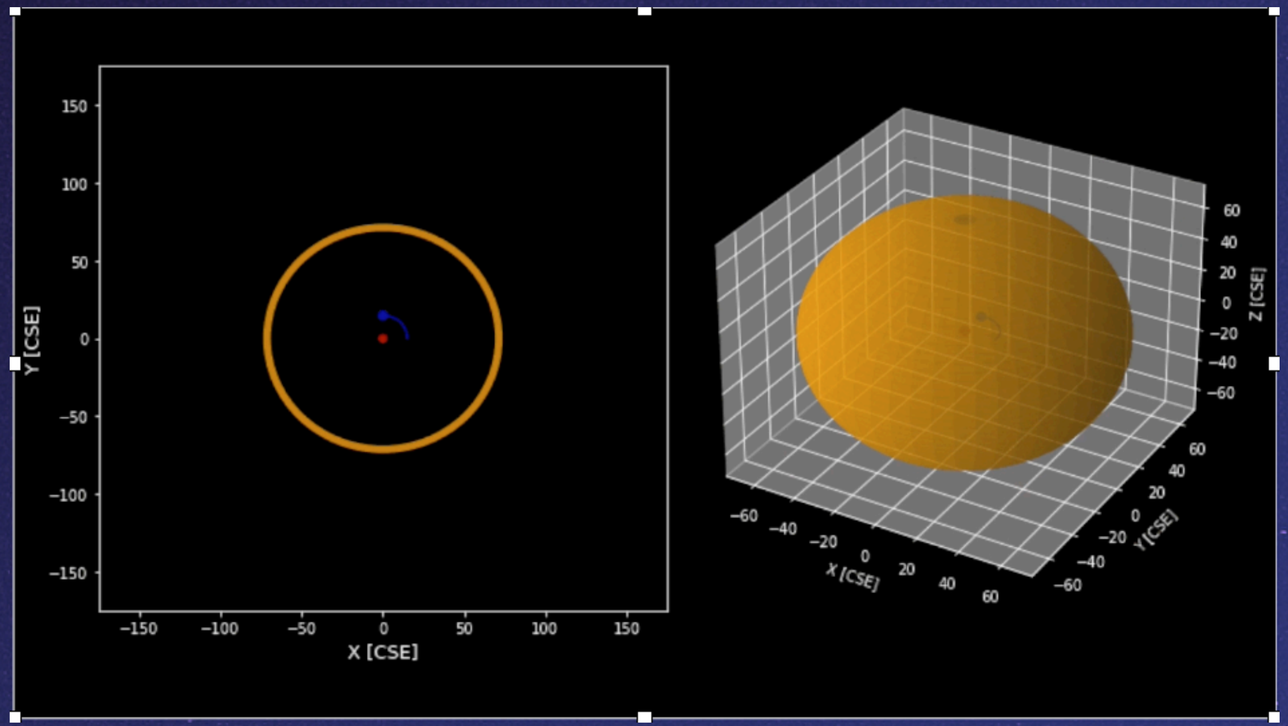
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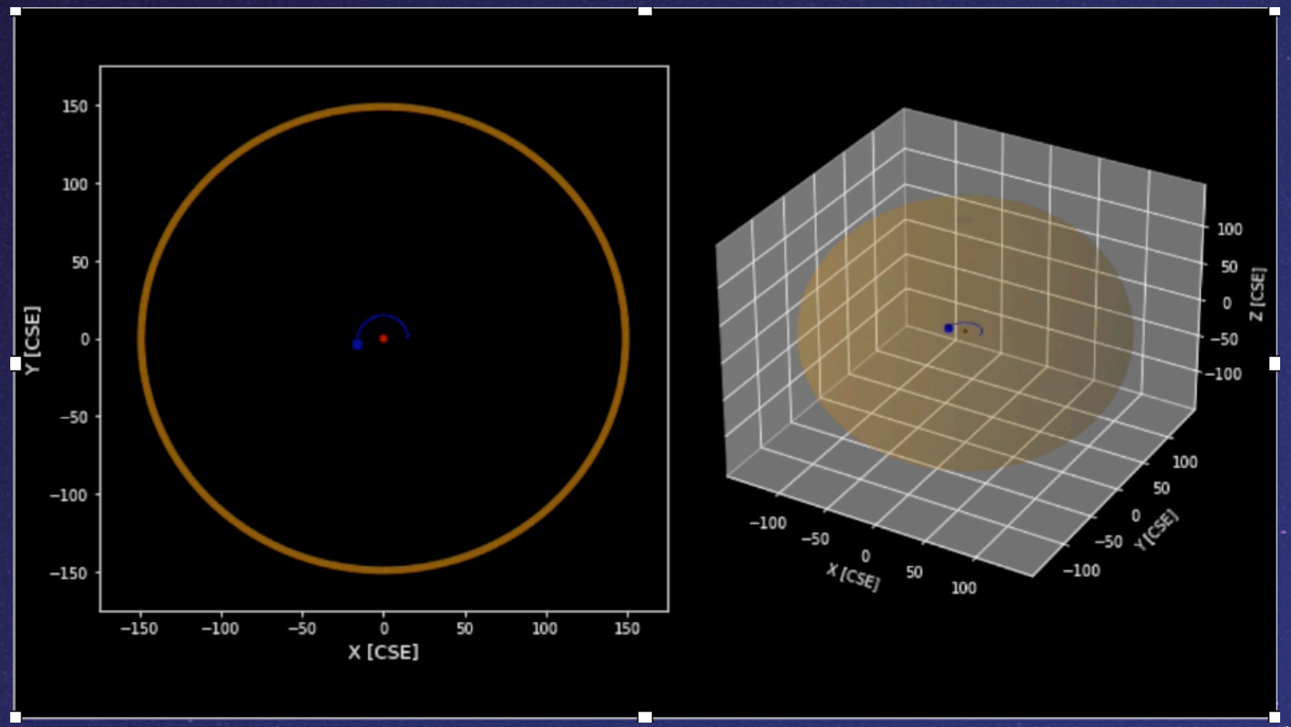
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Variable mass few-body problem

Numerical simulations

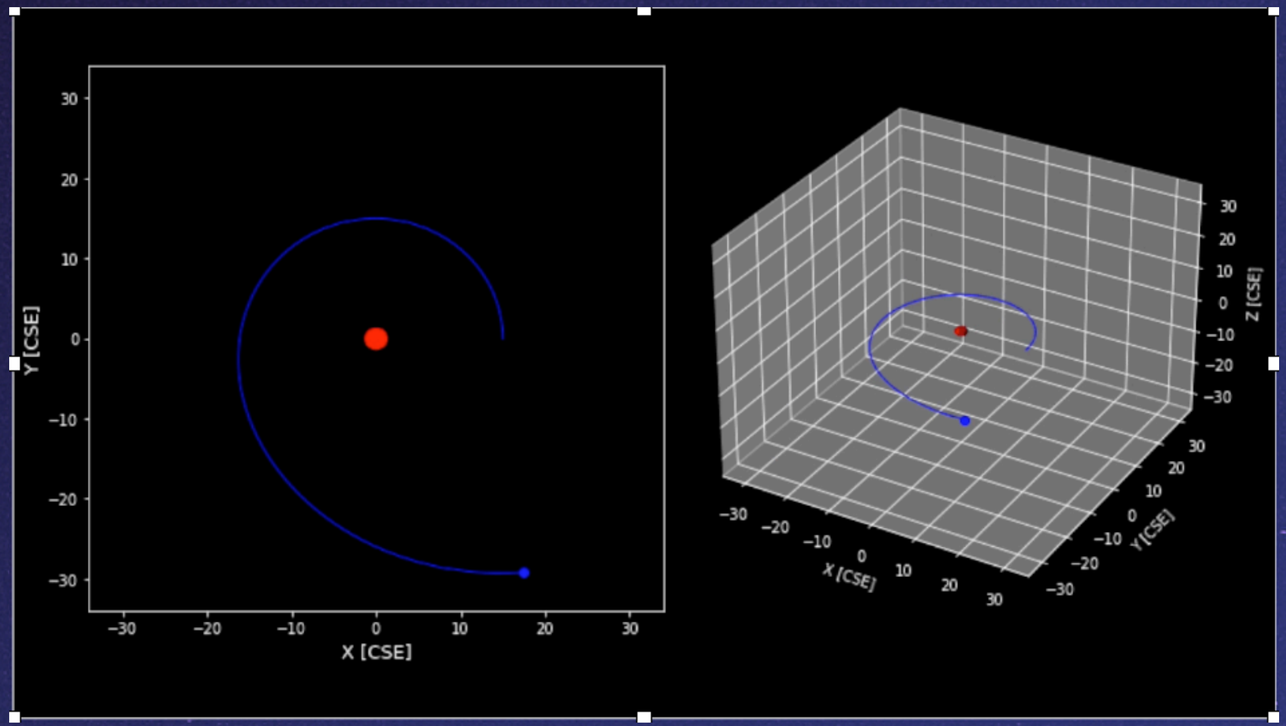
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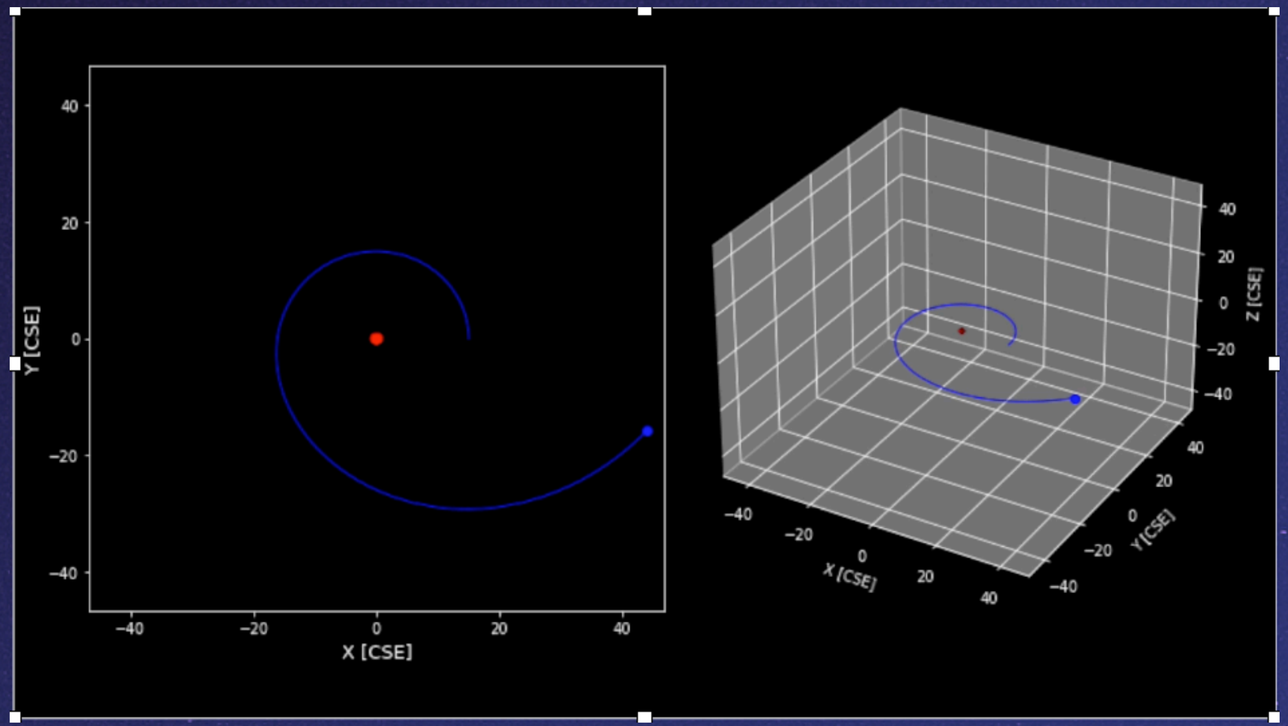
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Example simulation:



Analysis

- Initial conditions:
  - orbital elements, masses, ejecta speed
- Post-explosion parameters:
  - new orbital elements: a, e
  - component velocities

Pulsar planets

~9% chance for staying bound

Need eccentric (e > 0.4), near-apocentre explosion

Semi-major axis grows significantly (> 4 au)

observed PSR planets' orbits are tighter!

up to 275 km/s rogue planet velocity



DETLEV VAN RAVENSWAAY

Urability

Habitability (Lammer et al. 2008)

- Surface liquid water
- Sustainment of life

Urability (Deamer et al. 2022)

- Life sprouting capacity?
- Minimum for life to emerge (temperature, solvent, etc.)

Note: life as we know it!



Shutterstock/universal blackpink



Reddit/midjourney

Where to look?

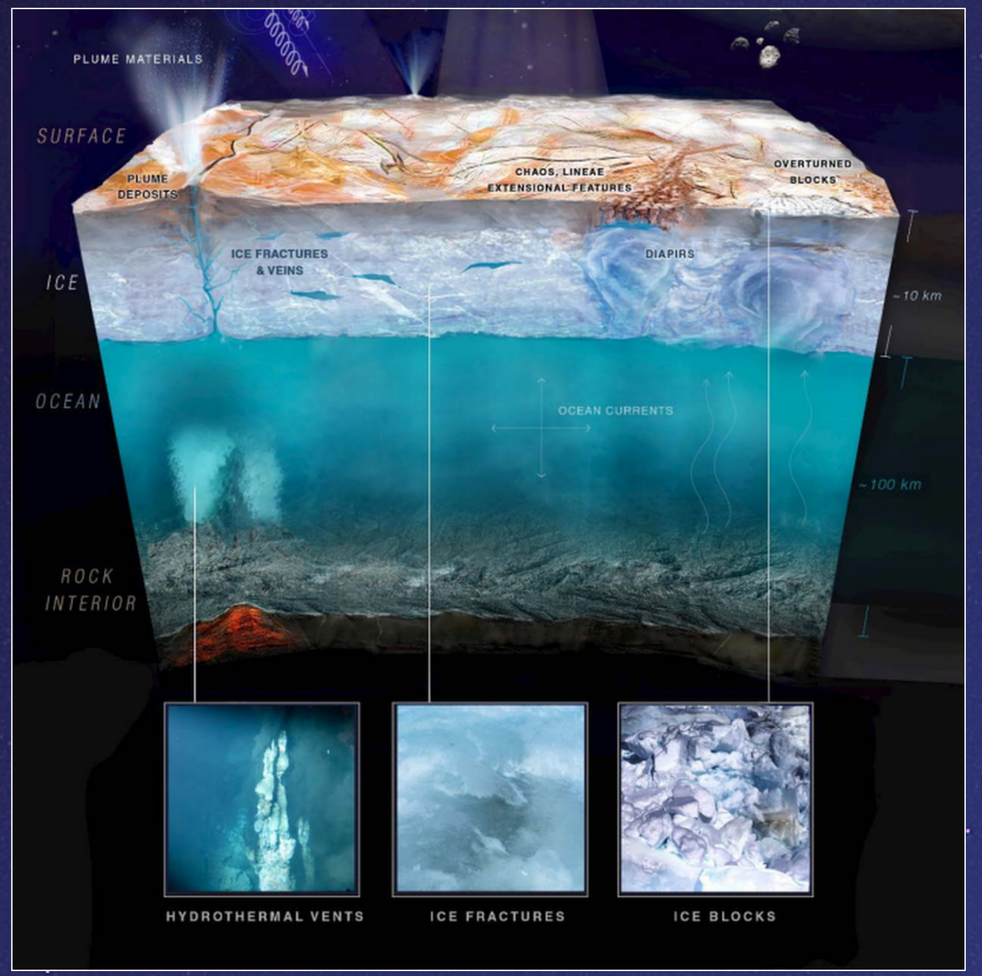
Elusive exomoons

- exoplanets and Solar System moons aplenty…
- Only false positive exomoons so far
  (Teachey & Kipping 2018, Fox & Wiegert 2021, Kipping et al. 2022)

Urability of moons

- tidal heating is a significant energy source
- Subsurface oceans of icy moons
- What about a moon of a rogue planet?

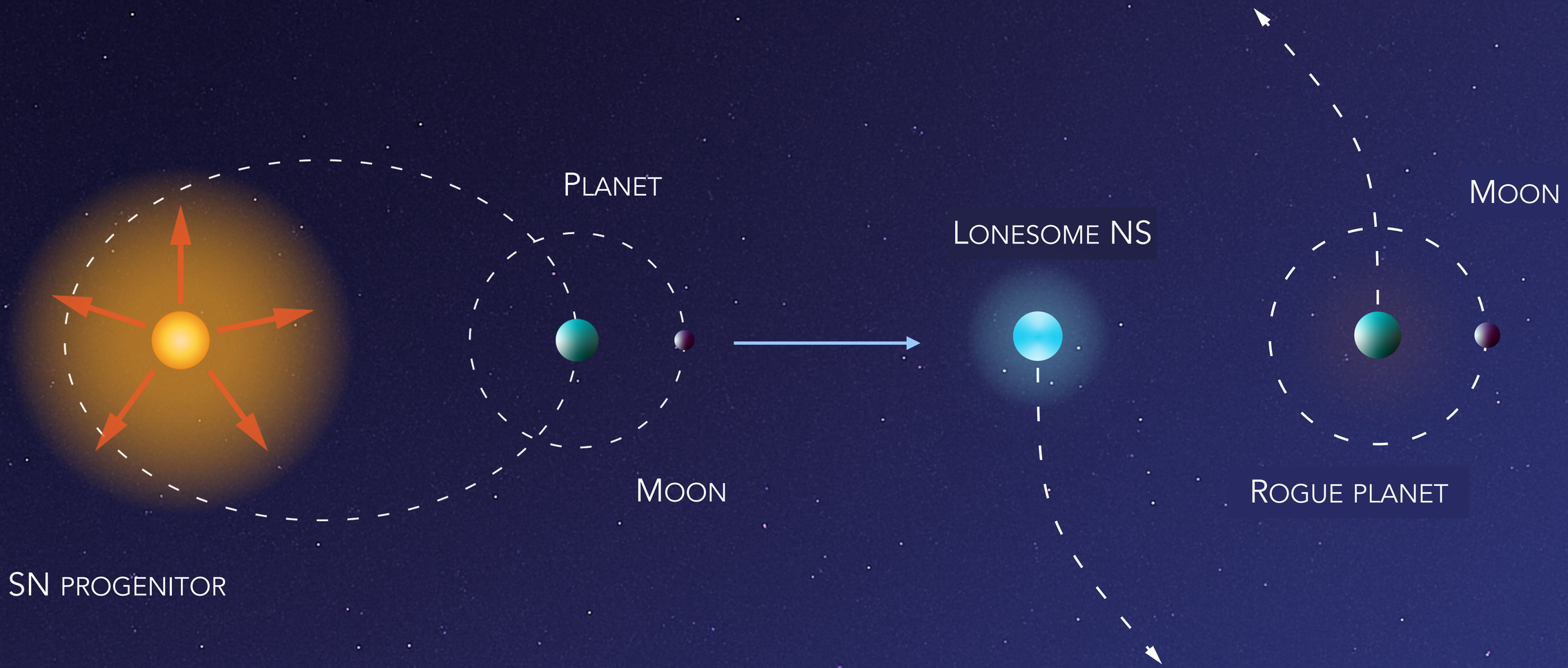
Interior cross-section of Europa



NASA JPL

Planet-moon systems

Fröhlich & Regály (2025)



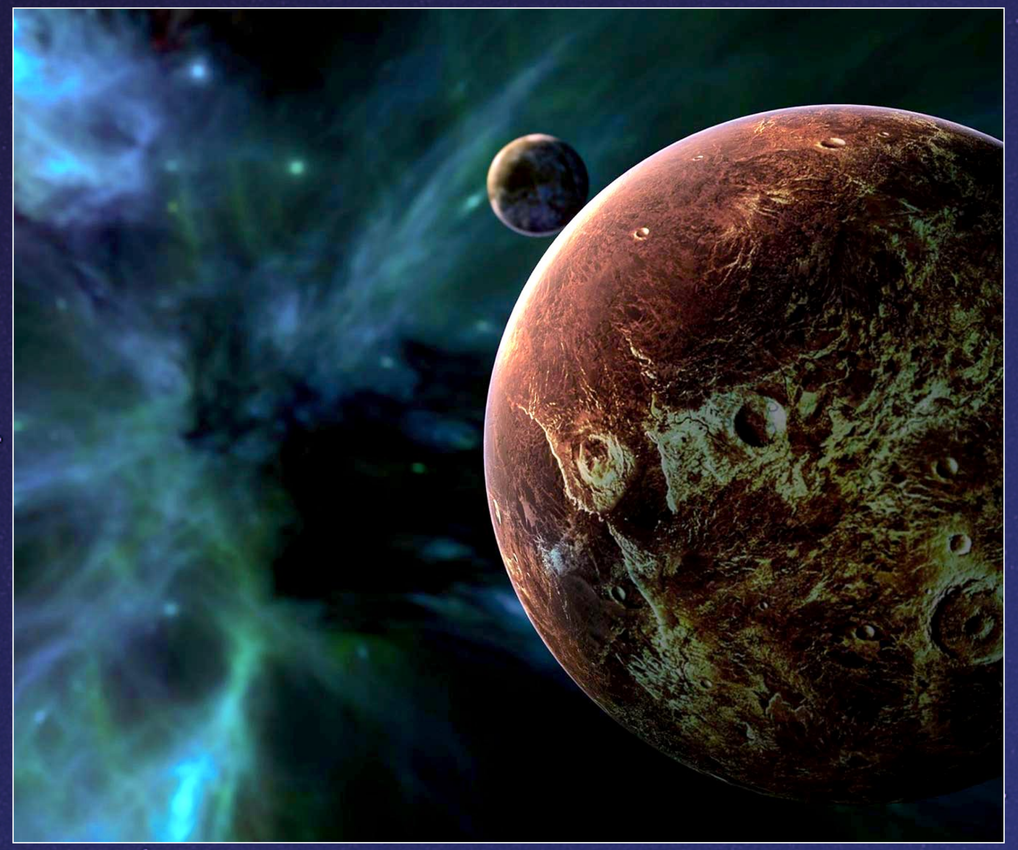
Planet-moon systems

Almost always ejected

Moons stay bound and can become eccentric

Tidal heating is similar to Europa or Enceladus in up to 15% of models

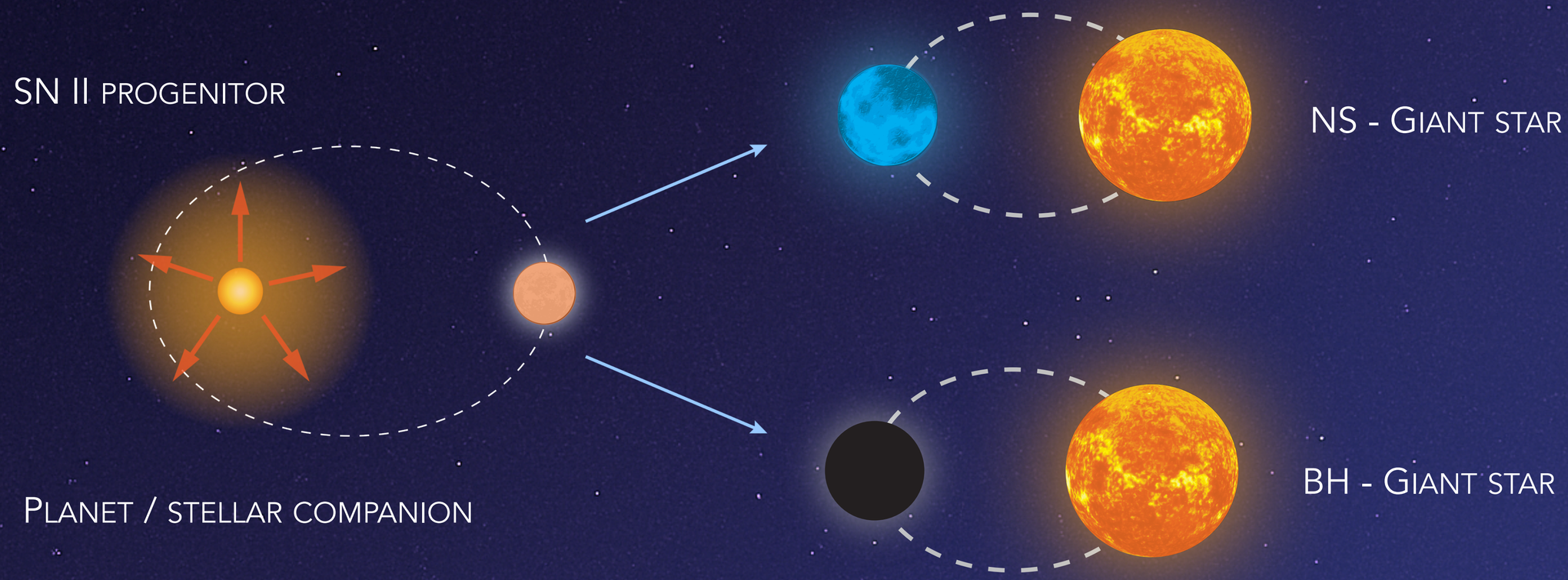
Eccentricity can last for billions of years



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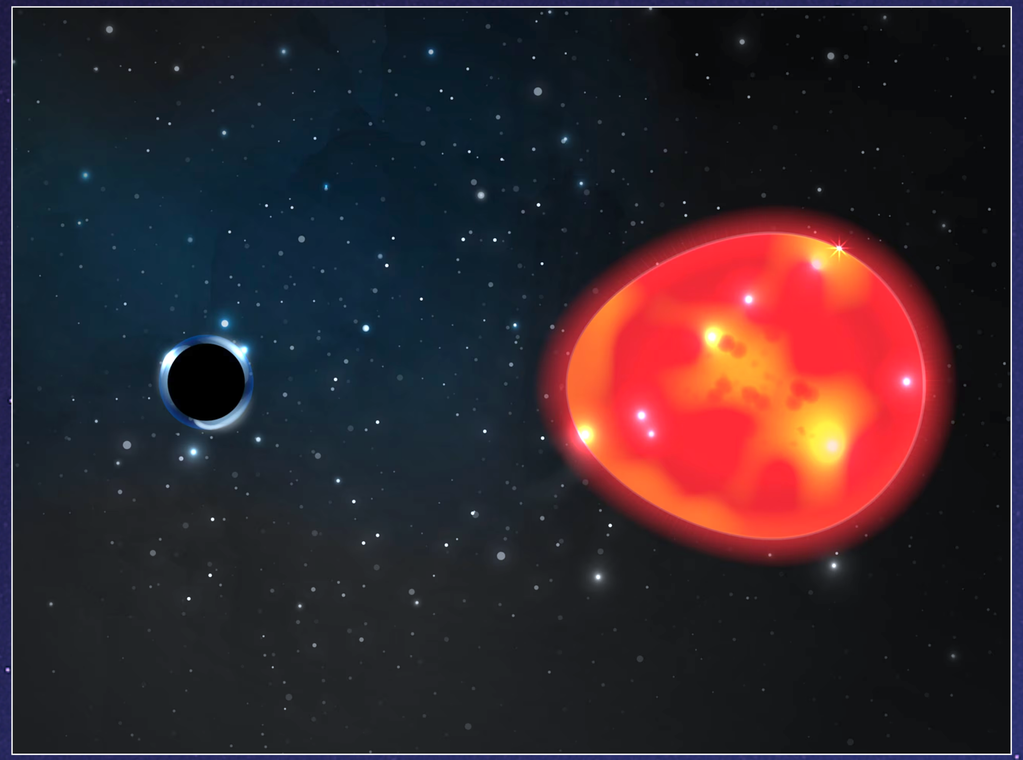
Black hole sun, i.e. Gaia 3425

Regály, Fröhlich & Vinkó (2025)



Black hole sun, i.e. Gaia 3425

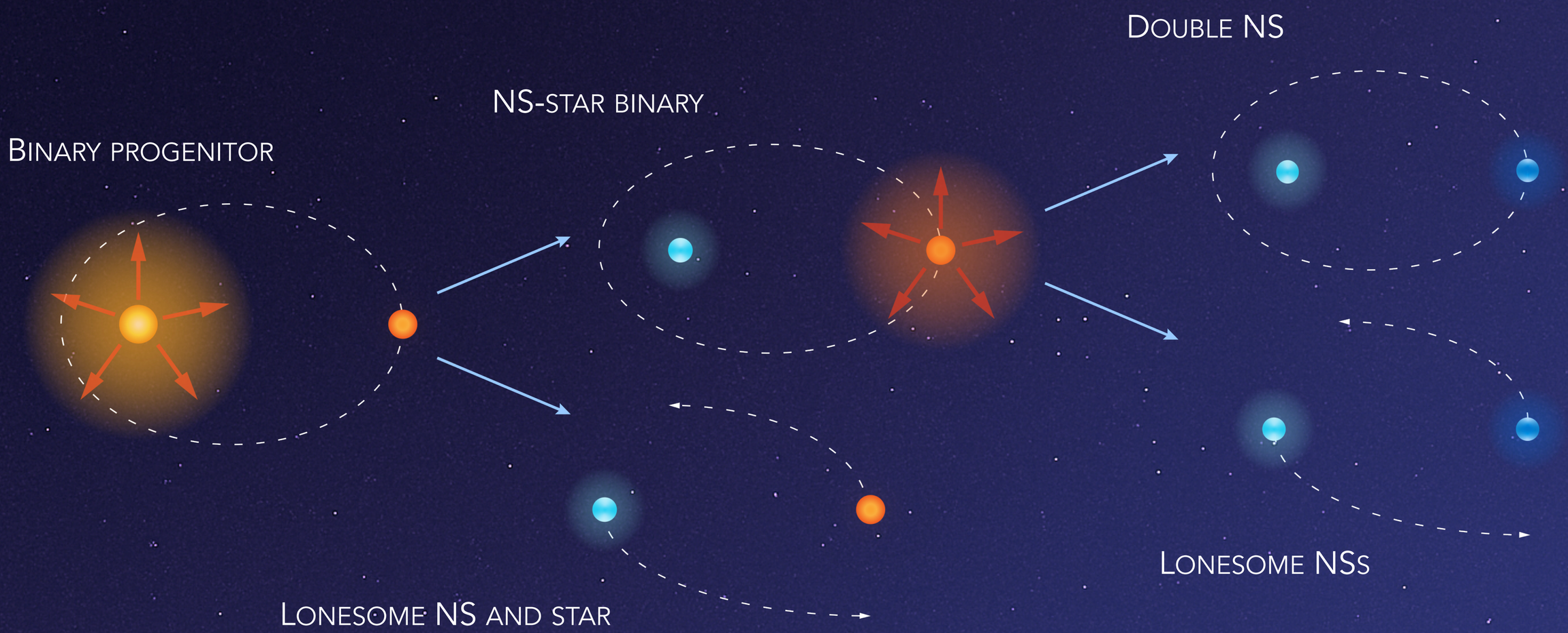
- orbit too wide for binary interaction
- SN II would've engulfed the companion
- SN Ib/c (high e, apocentre) or failed SN reproduce orbit
- Unseen component is more likely a BH



Shutterstock

Double SN II explosions

Fröhlich, Regály & Vinkó (2023)



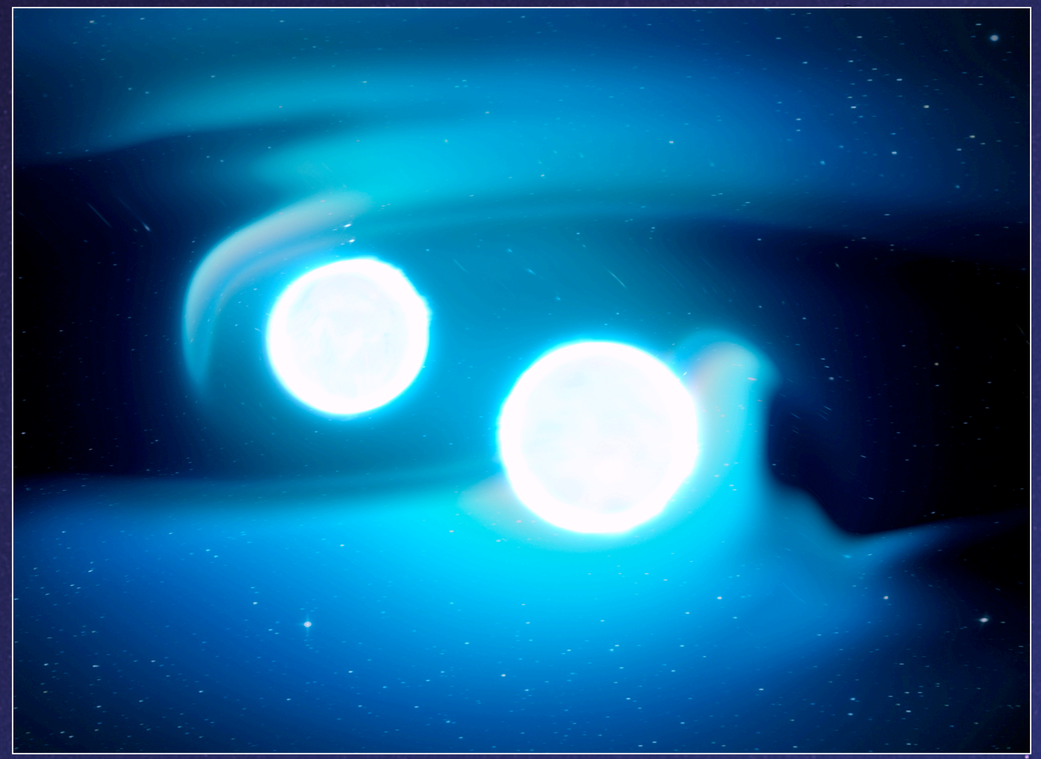
Double SN II explosions

~4.5% form double neutron star systems

Require eccentric, near-apocentre explosions

Orbit circularisation is possible

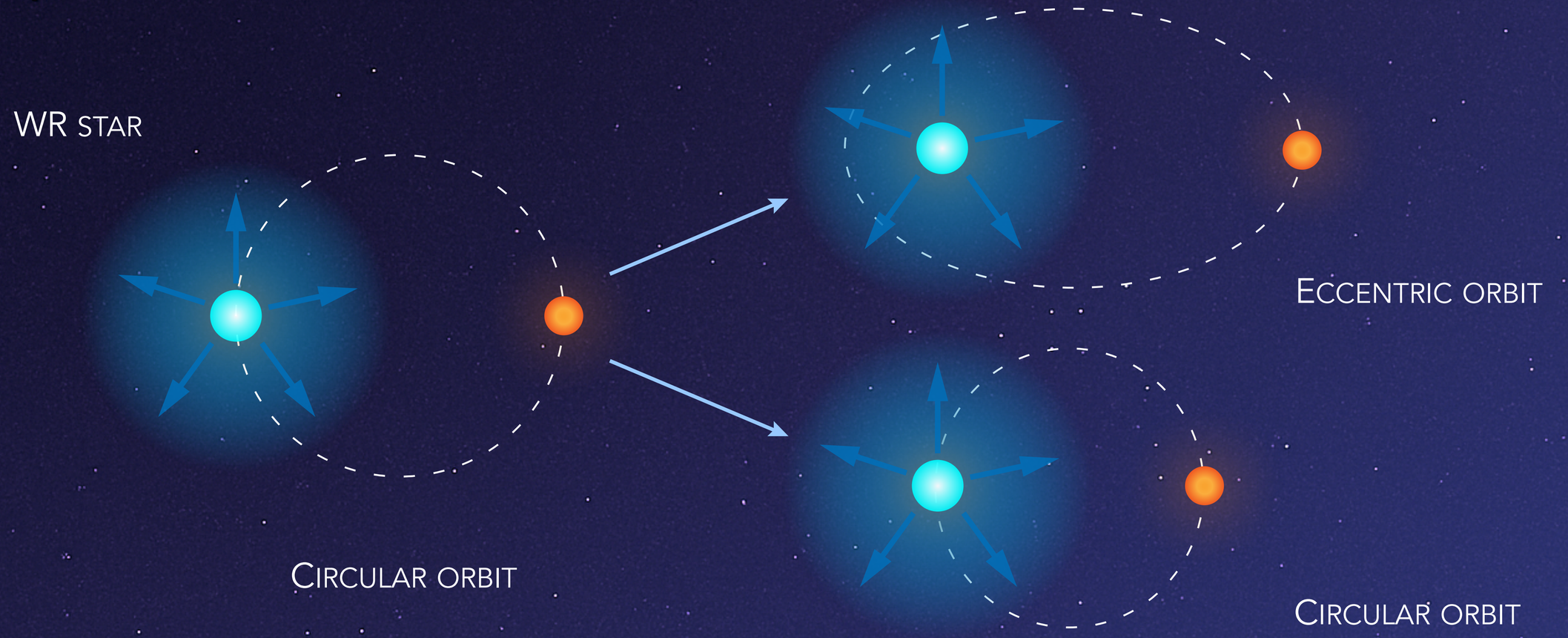
But: need orbit-shrinking mechanism!



NASA

Eccentricity in WR binaries

Fröhlich & Regály (2026)



Eccentricity in WR binaries

Significantly higher e than field binaries

Neither continuous, slow mass loss or Tidally-enhanced mass loss can drive observed e

Eccentricities are primordial



Lieb et al (2025)

Look up!



Numerical simulations on fly-by response, composition, collisional history @ UniBern with Martin Jutzi

Closest encounter 2029.04.13 (Friday) - Apophis seen as a 3mag star crossing the sky in a few hours

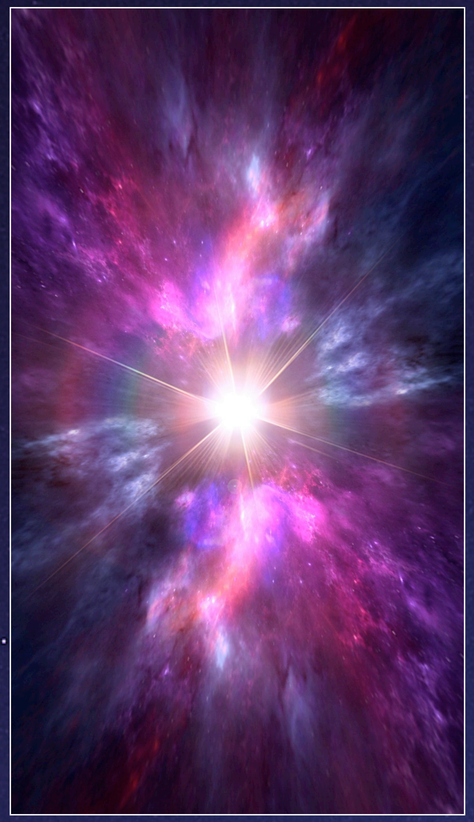
Take-aways…

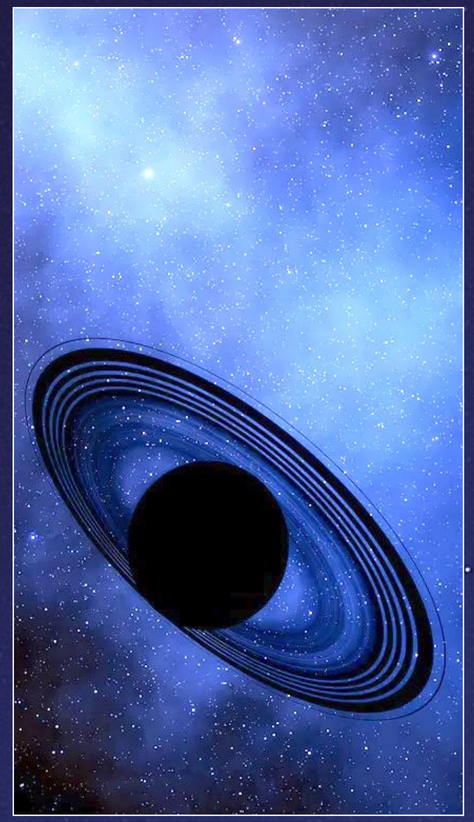
SN II are an effective formation channel of rogue planets

Urability describes the minimal conditions for life to emerge

Moons of rogue planets might be abundant and urable

WR eccentricities are primordial







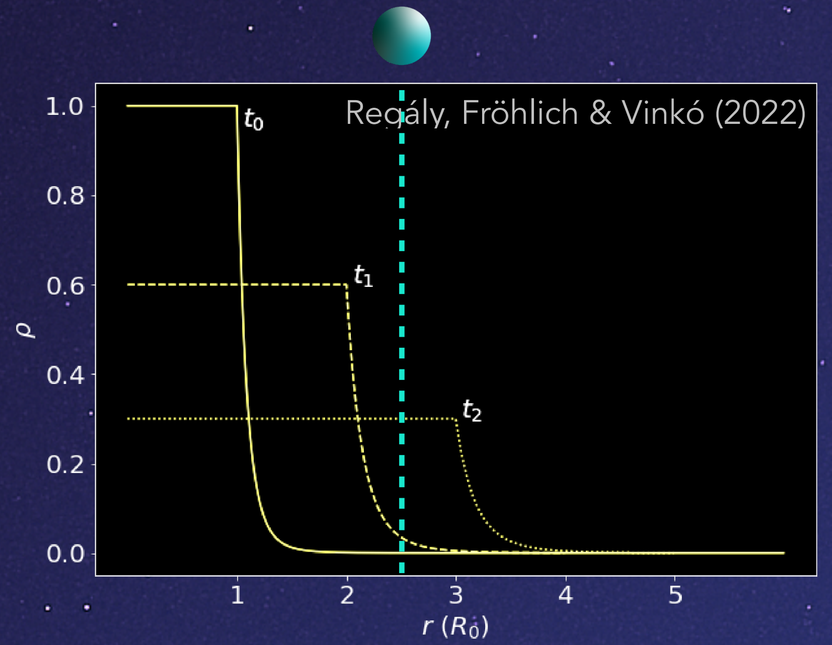
Homologous expansion

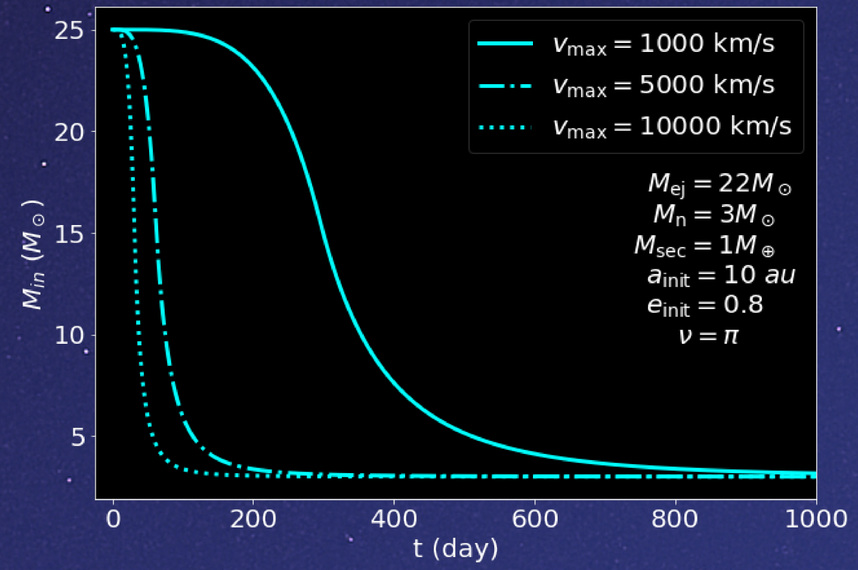
Homologous means that…

- Speed of layers is a linear function of distance from star, $v \sim r$
- Outermost layer travels with a constant speed, $v_{\max}$
- Envelope density profile doesn't change with time

Variable central mass

- T_0 – All mass within companion orbit
- T_1 – Envelope core within companion orbit
- T_2 – Envelope core partially/fully outside companion orbit





PSR PLANETS AND ROGUE PLANETS

Regály, Fröhlich & Vinkó (2022)

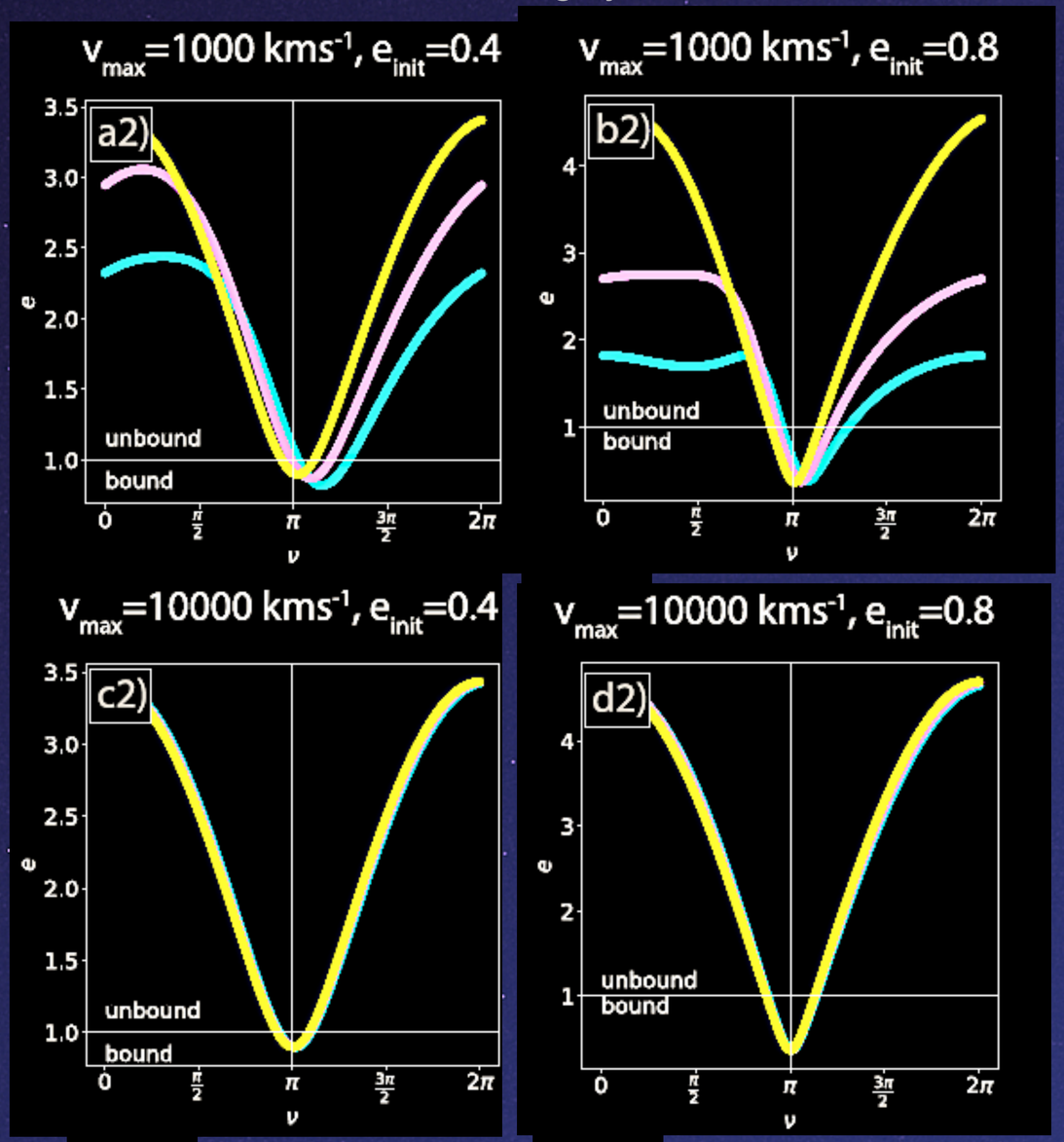
BOUND PSR PLANETS:

- REQUIRES INITIAL ECCENTRICITY >0,4 + A NEAR-APOCENTRE EXPLOSION
- ORBIT SEMI-MAJOR AXIS AT LEAST DOUBLES
- ONLY PSR PLANETS WITH $a > 4$ AU ARE EXPLAINED (OUCH!)

ORBIT CIRCULARISATION IS POSSIBLE FOR BINARY STARS

FOR A DNS: ECCENTRIC, NEAR-APOCENTRE TIMING FOR BOTH SN

GROWING SMA → KNOWN SYSTEMS WERE NOT FORMED THIS WAY!



Double Neutron Star systems

Semi-major axis grows during both SN

Second SN can circularise orbits

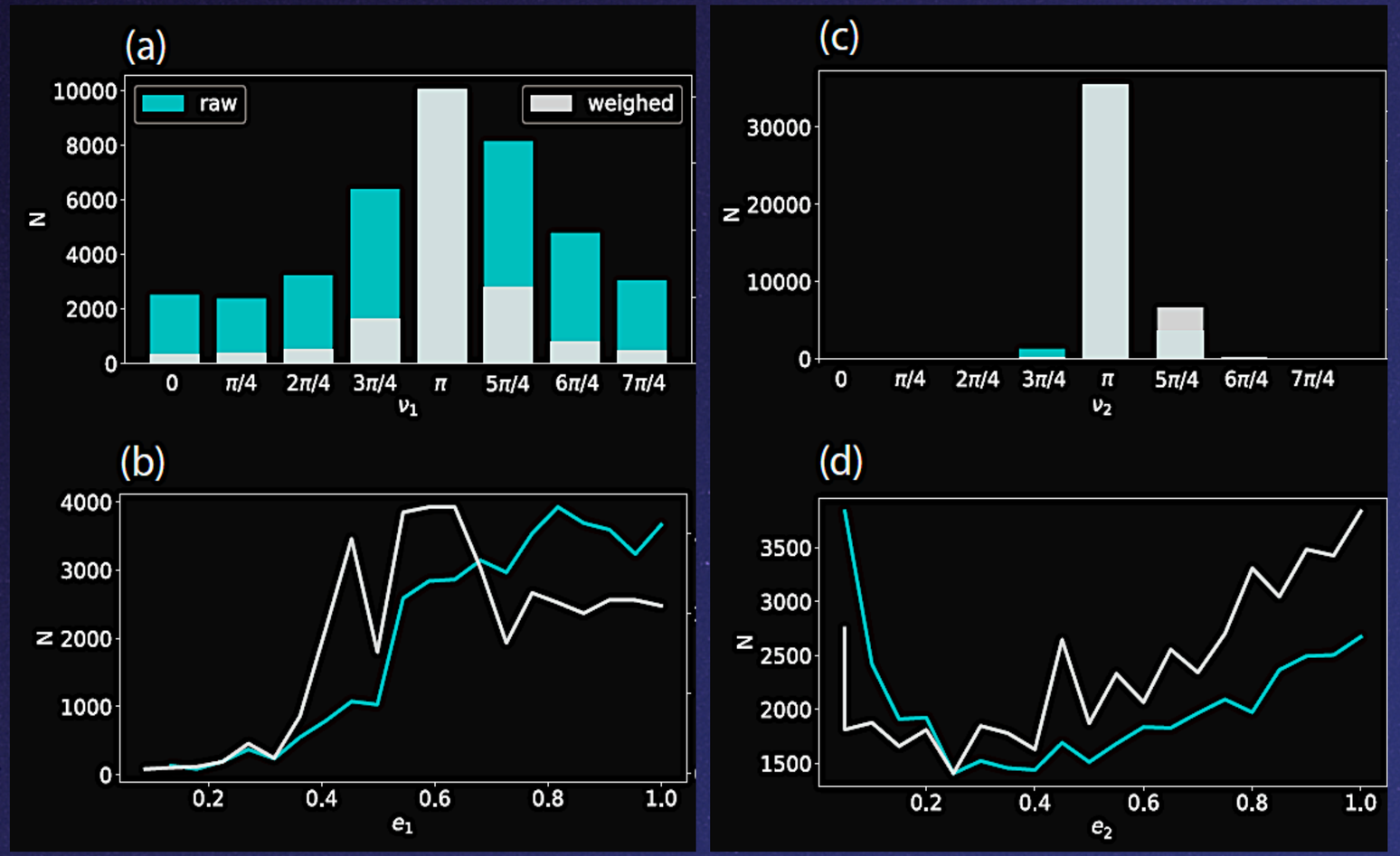
For a DNS: eccentric,

near-apocentre timing

Known systems were not formed this way!

Need a mechanism to shrink orbits
(i.e. binary interaction)

Fröhlich, Regály & Vinkó (2023)



Urability

- A set of conditions that create a window of opportunity for life to emerge
- Urable zones start small (e.g. hydrothermal vents)
- They expand + diversify as life becomes able to adapt to changing conditions
  - → There is a time-dependence
- Note: present understanding = subset of possible conditions
  We only know ourselves!
- Are there factors that are universal to all forms of life?



What makes a body urable?

- Geophysical factors

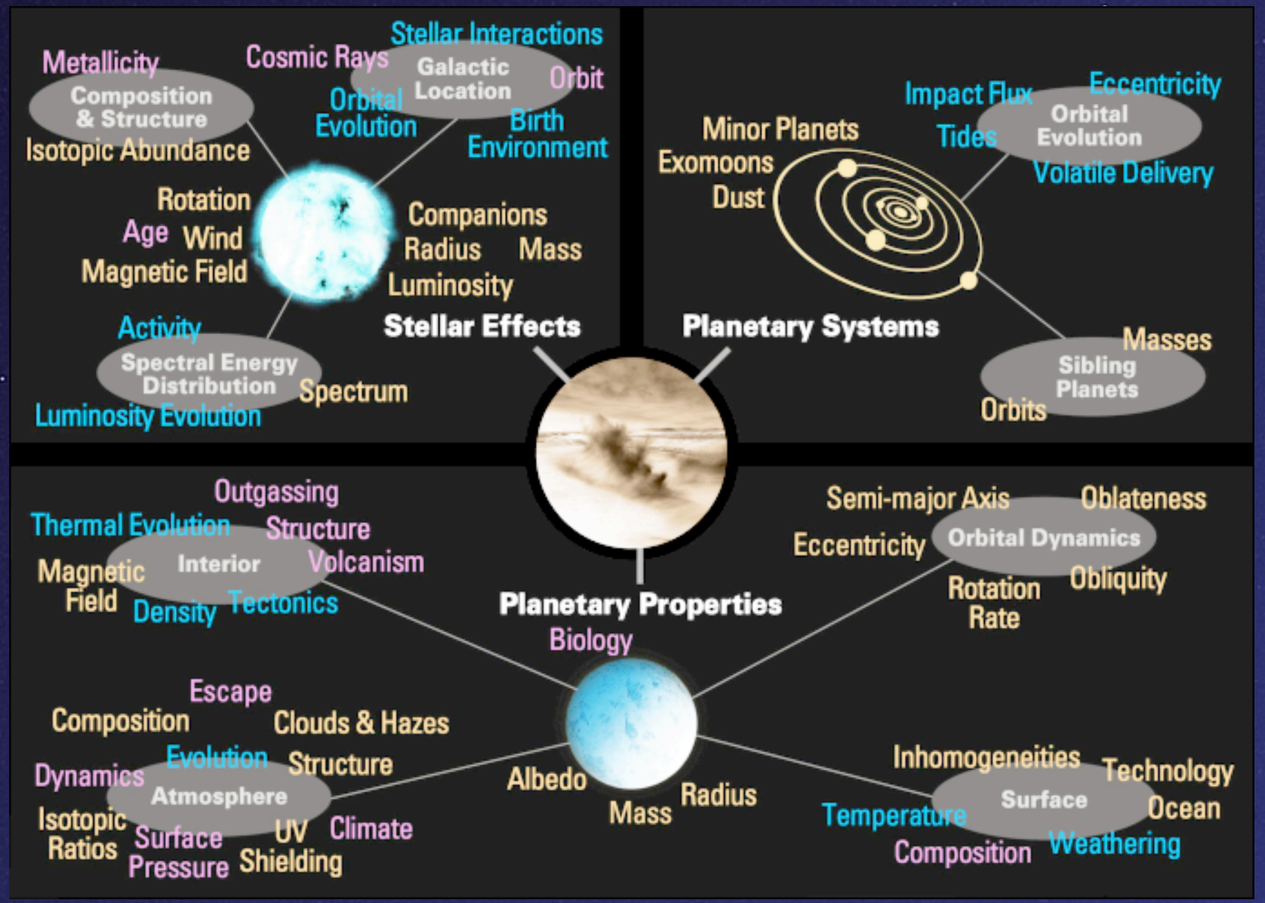
  Size, rotation, moon, planetary core, volcanism, hydrological cycles, light energy, magnetosphere, planet-star distance, stellar and tectonic activity, mineral inventories, hydrothermal activity

- Chemical factors

  Anoxic atmosphere, liquid water, ionic concentration, catalysts, acidity, sources of organics,
  synthesis of amino acids and nucleobases and phosphate, sources for membranes, energy types, concentration processes, storage of energy, organic compound mixtures, homochirality, encapsulation,

- Combinatorial factors

  Environmental stress to drive selection, capability to spread protocells, enough time



Tidal heating models

- Constant time lag
  - Tidal bulge follows the movement of bodies with a time delay
- Constant phase lag
  - The axis of the tidal bulge is not aligned with the planet-moon axis
- Analytical calculations:
  - Tidal luminosity
  - Moon effective temperatures from Stefan-Boltzmann law

$$L_{\text{tidal,CPL}} = \frac{21}{2} G \frac{k_{2,\text{m}}}{Q_{\text{m}}} M_{\text{p}}^{5/2} R_{\text{m}}^{5} \frac{e^2}{a^{15/2}}$$

$$L_{\text{tidal,CTL}} = \frac{Z}{\beta^{15}} \left(f_1 - \frac{f_2^2}{f_5} \right) \tau_{\text{m}}$$

$$\beta = \sqrt{1 - e^2}$$

$$Z = M_{\text{p}}^2 (M_{\text{p}} + M_{\text{m}}) R_{\text{m}}^5 a^{-9}$$

$$f_1 = 1 + \frac{255}{8} e^4 + \frac{188}{16} e^6 + \frac{25}{64} e^8$$

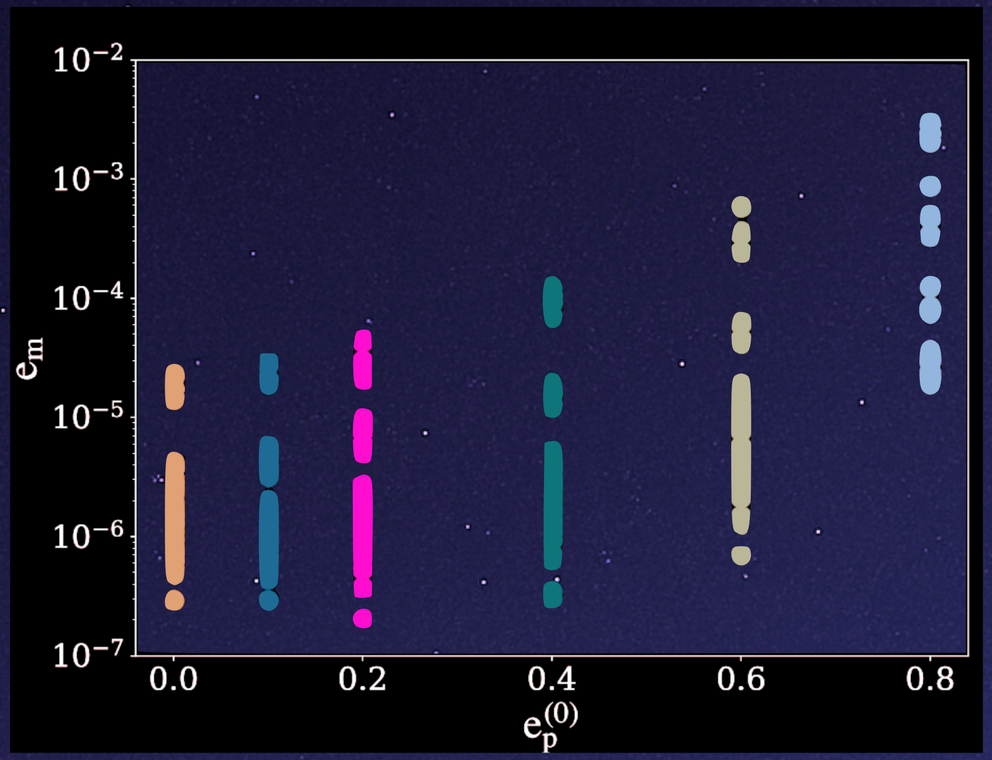
$$f_2 = 1 + \frac{15}{2} e^2 + \frac{45}{8} e^4 + \frac{5}{16} e^6$$

$$f_5 = 1 + 3e^2 + \frac{3}{8} e^4$$

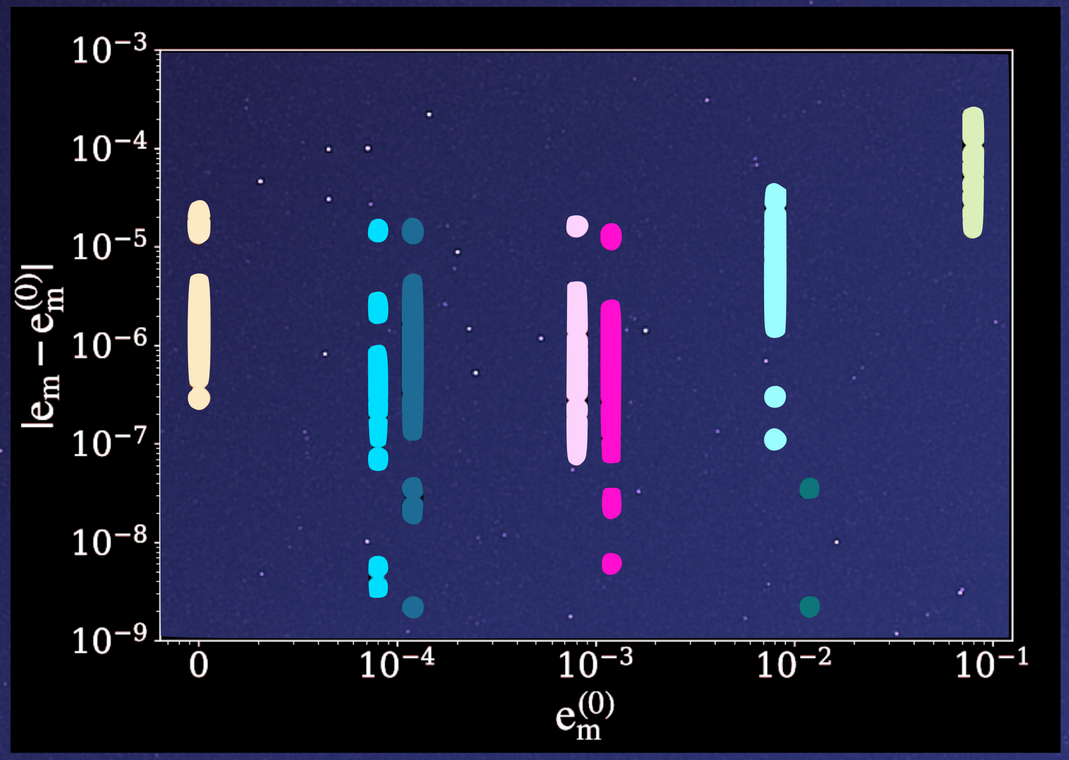
$$T_{\text{tidal}} = \left(\frac{L_{\text{tidal}}}{4\pi\sigma R_{\text{m}}^2} \right)^{1/4}$$

Eccentric planets and moons

- **Eccentric planets**
  - Moon eccentricity grows with planet ecentricity
  - $e_m \leq 3 \times 10^{-3}$



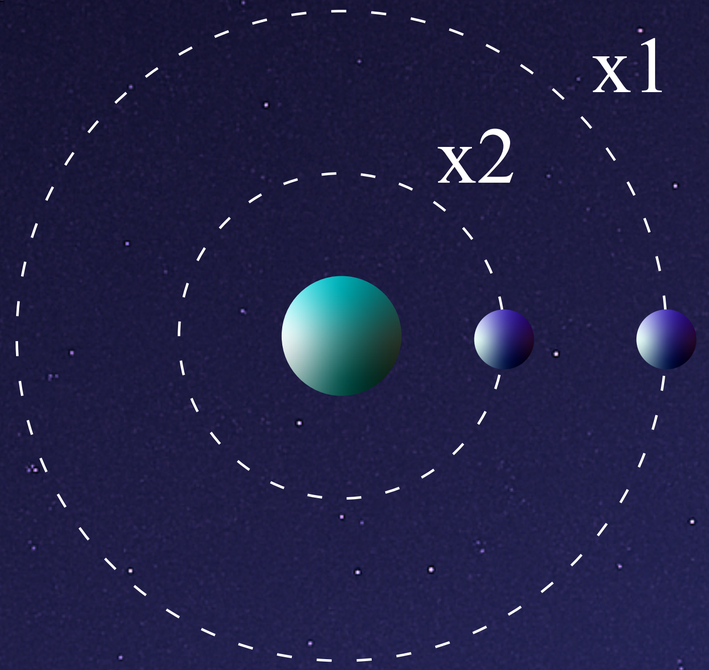
- **Eccentric moons**
  - $\Delta e_m \lesssim 10^{-4}$
  - Moon eccentricity unchanged after SN

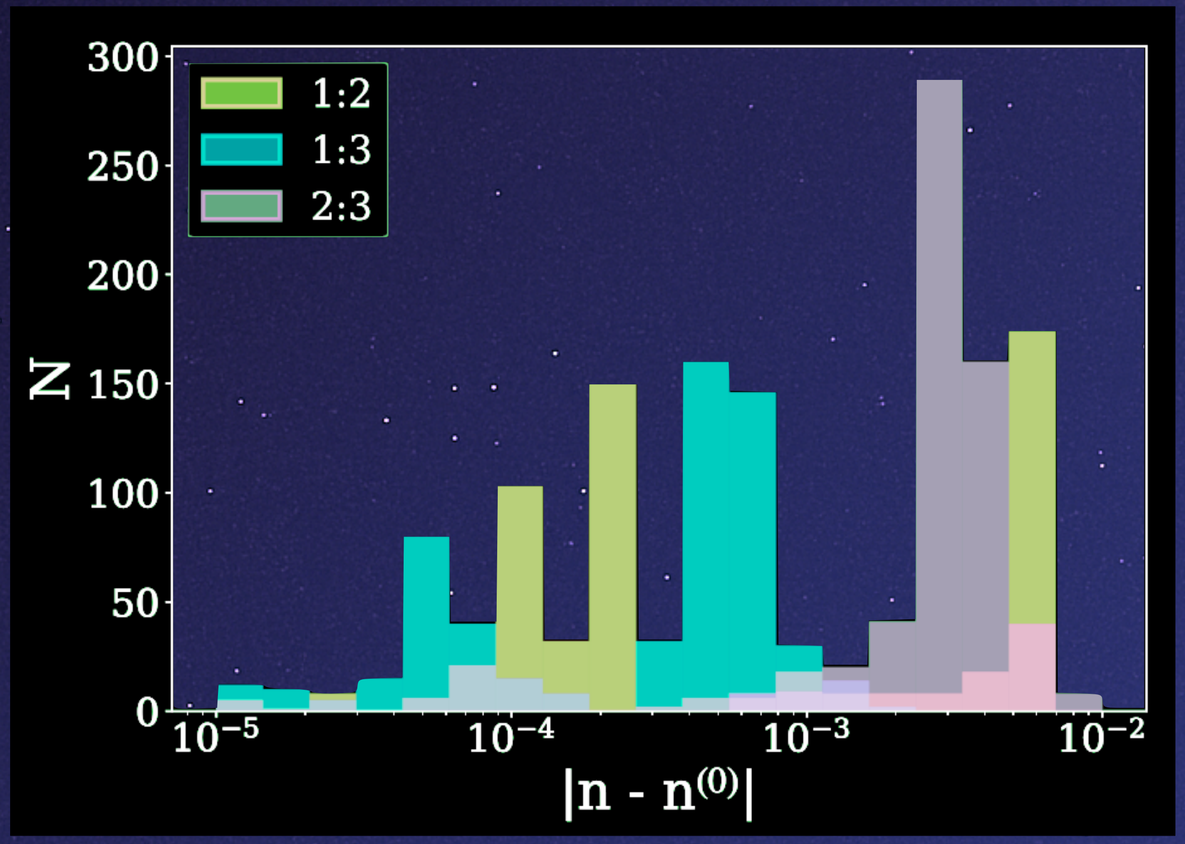


Resonant Systems

- 2:1, 3:1, 3:2 mean motion resonances
- Resonant configuration persists after SN
- $e_m \leq 4 \times 10^{-2}$

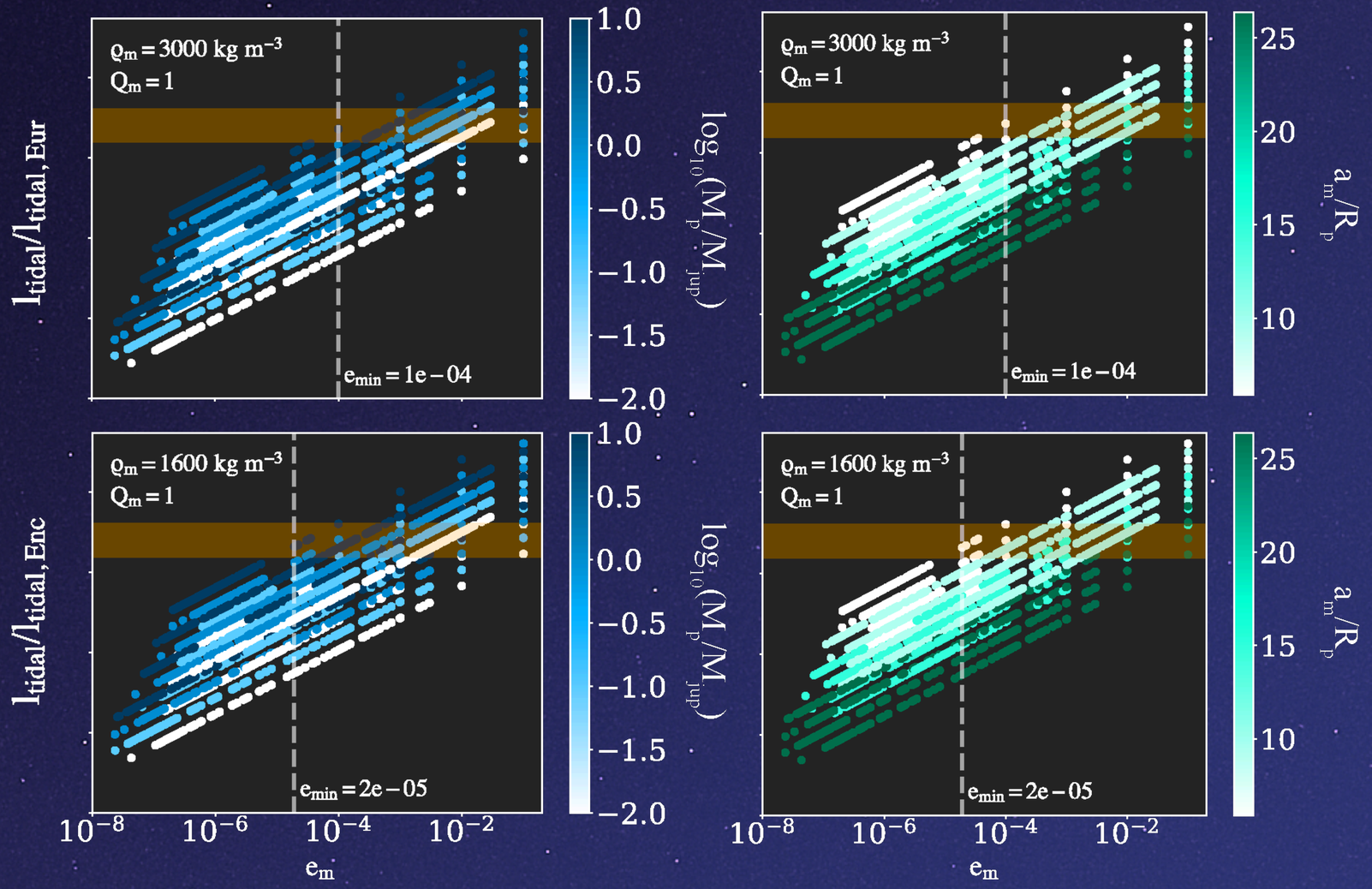
E.g.:





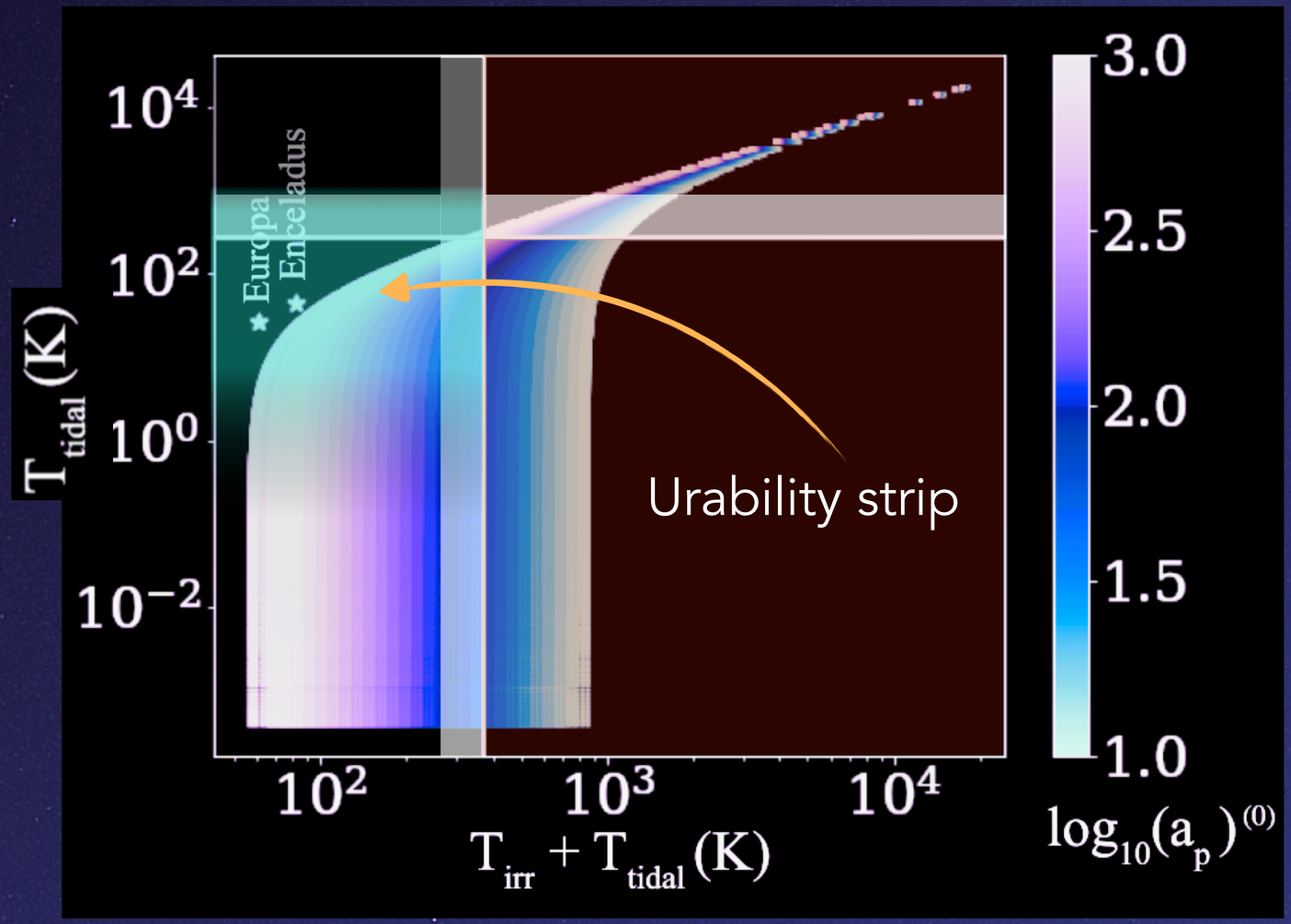
Specific tidal luminosity as a urability proxy

- Let's define urability as:
- specific tidal luminosity is similar to that on Europa or Enceladus
- This is achieved if
  - $e_m \gtrsim 10^{-3}$
- 12-15% of models are urable



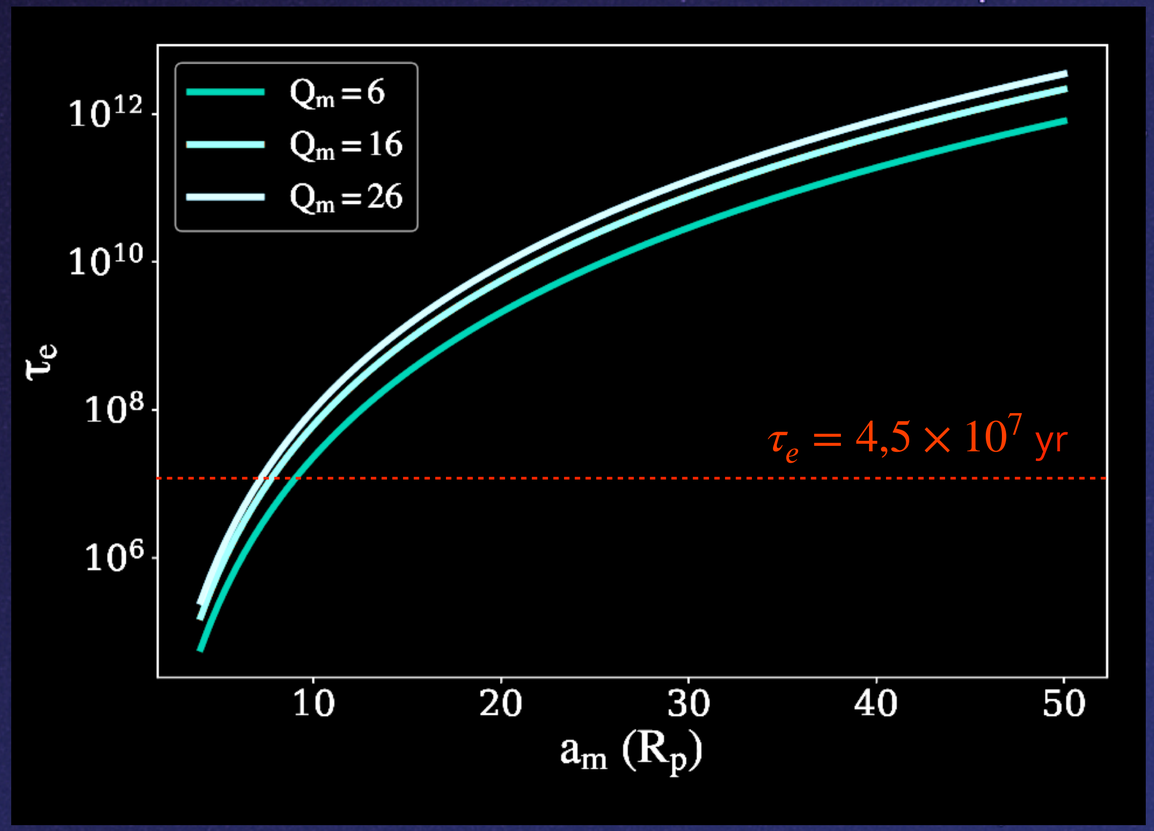
Urability based on temperature

- Expanded parameter space
  PARSEC stellar evolution models
- Urability requires
  - Pre-SN: T(irr+tidal) $\lesssim$ 373 K
  - Post-SN: T(tidal) > 273 K
- Achieved if
  - $e_m \geq 0{,}1$
- Note: urability depends on composition!



Timescale of urability

- Equals to the eccentricity damping timescale
  - In the constant phase lag model
  - $$\tau_{\mathrm{e}} = \frac{4}{63}\frac{M_{\mathrm{m}}}{M_{\mathrm{p}}}\left(\frac{a_{\mathrm{m}}}{R_{\mathrm{m}}}\right)^{5}\frac{\widetilde{\mu}_{\mathrm{m}}Q_{\mathrm{m}}}{n}$$
  - Depends heavilty on planet-moon separation, $\propto a_{\mathrm{m}}^{6.5}$
- Surpasses the age of the Solar System if $a_m \gtrsim 10R_p$



Black hole sun, i.e. Gaia 3425

Red giant star + "unseen component"

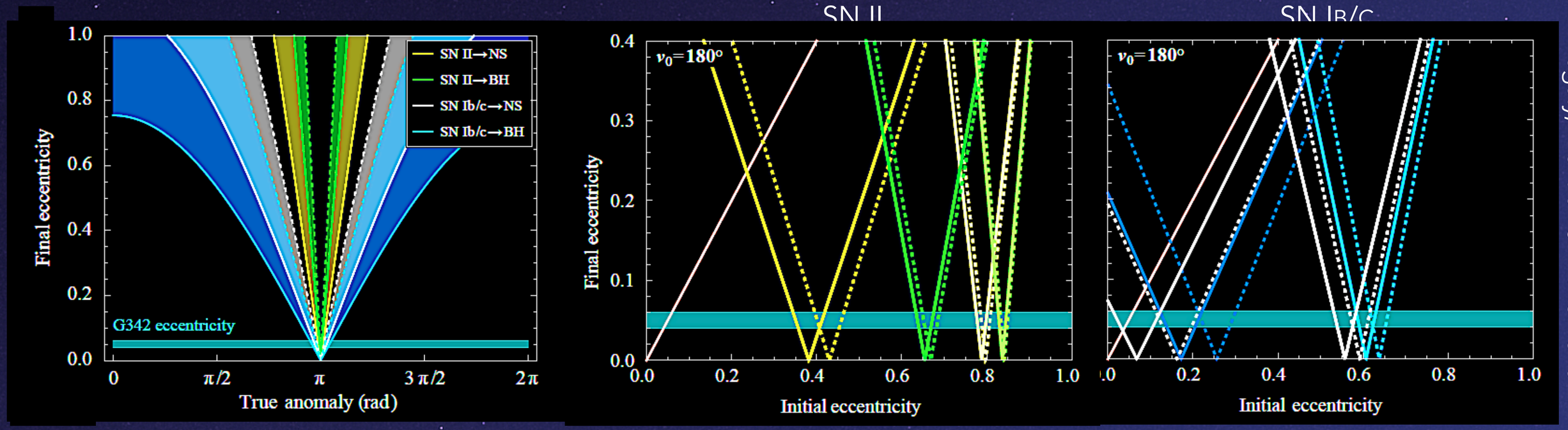
Orbit is circular, but wide for binary interaction

What was the progenitor system like?

SN II would've engulfed the companion

SN Ib/c (high e, apocentre) or failed SN reproduce orbit

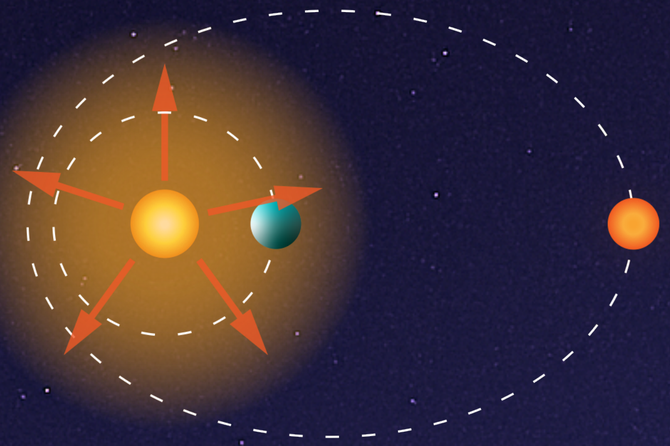
Unseen component is more likely a BH



Regály, Fröhlich & Vinkó 2025

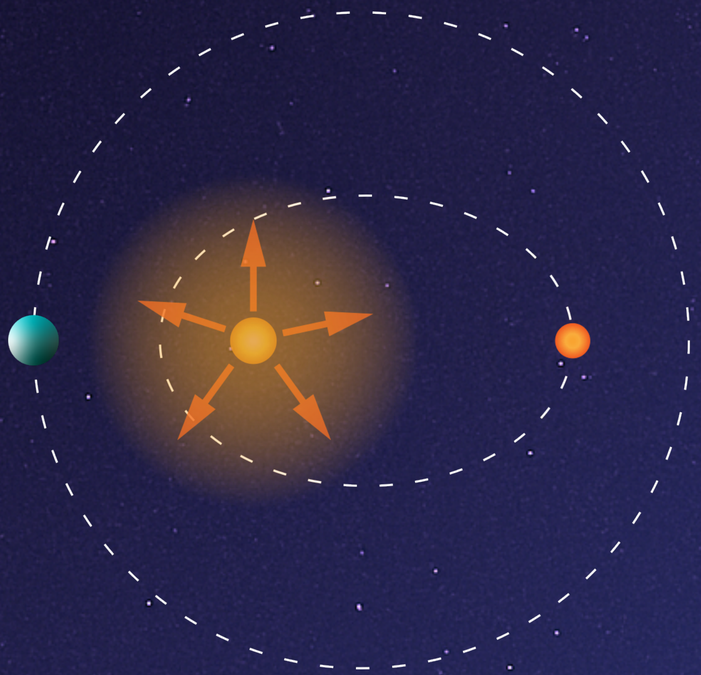
Future: SN in triple systems

A) Circumprimary planets



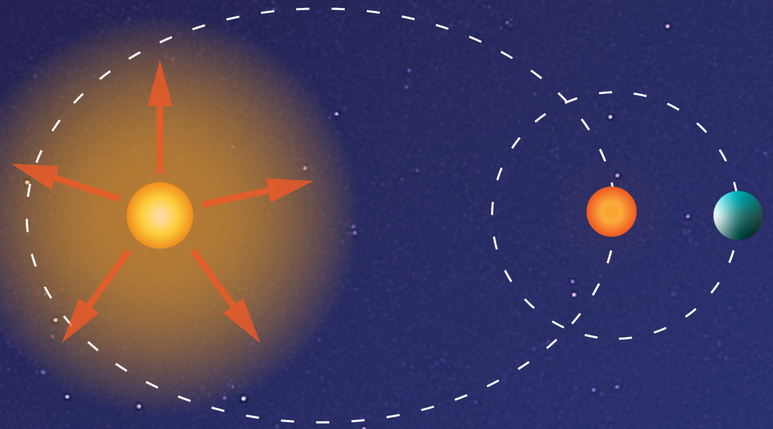
No stable planetary orbits!

B) Circumbinary planets



Stars can trap planets in single-star orbits!

C) Circumsecondary planets



Running… want to join?

PLANET TRAPS

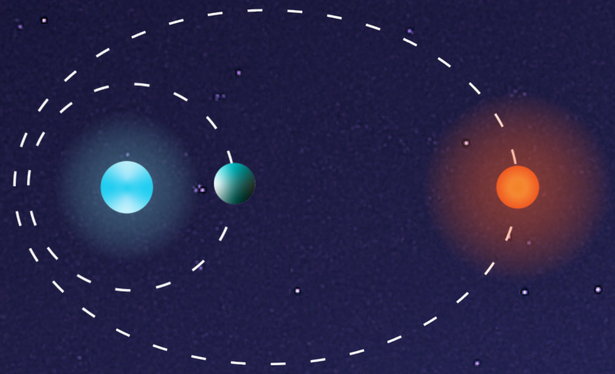
MAIN COMPONENT CAPTURES PLANET

NEW ORBIT:

- $e_b > 0{,}3$
- $a_b = 10^4 - 10^5 \mathrm{CSE}$

REQUIREMENTS:

- $M_{sec} \geq 4M_{\odot}$
- $e_{bin} \geq 0{,}4$
- PLANET ~ $1M_{Jup}$
- $v_{max} > 5000 \mathrm{km/s}$



SECONDARY CAPTURES PLANET

NEW ORBIT:

- $e_b > 0{,}3$
- $a_b = 10^4 - 10^5 \mathrm{CSE}$

REQUIREMENTS:

- $M_{sec} \geq 2M_{\odot}$
- $e_{bin} \geq 0{,}6$
- PLANET ~ $1M_{Earth}$
- $v_{max} < 5000 \mathrm{km/s}$

