WHY TRIPLICITY MATTERS

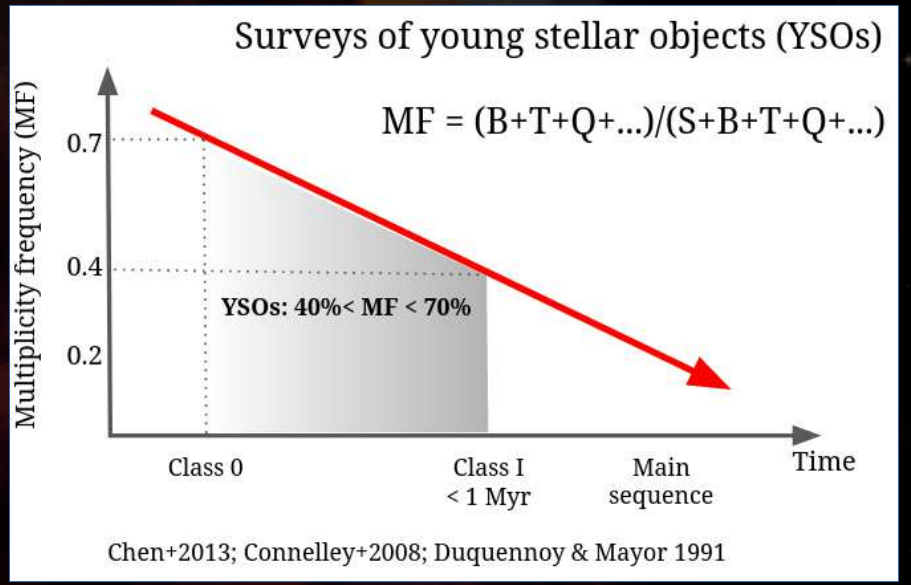
Polar alignment in triple systems and the role of (high-order) multiple stellar systems in stellar populations

SIMONE CEPPI

COLLABORATORS: GIUSEPPE LODATO, NICOLÁS CUELLO, CRISTIANO LONGARINI, CLAUDIA TOCI, CATHIE CLARKE, DANIEL PRICE, STEPHEN LUBOW

MULTIPLICITY IN YOUNG STELLAR OBJECTS

- **Less than 1 Myr: 0.4 < MF < 0.7**
- **MF decreasing with time**



- Higher-order multiples are common

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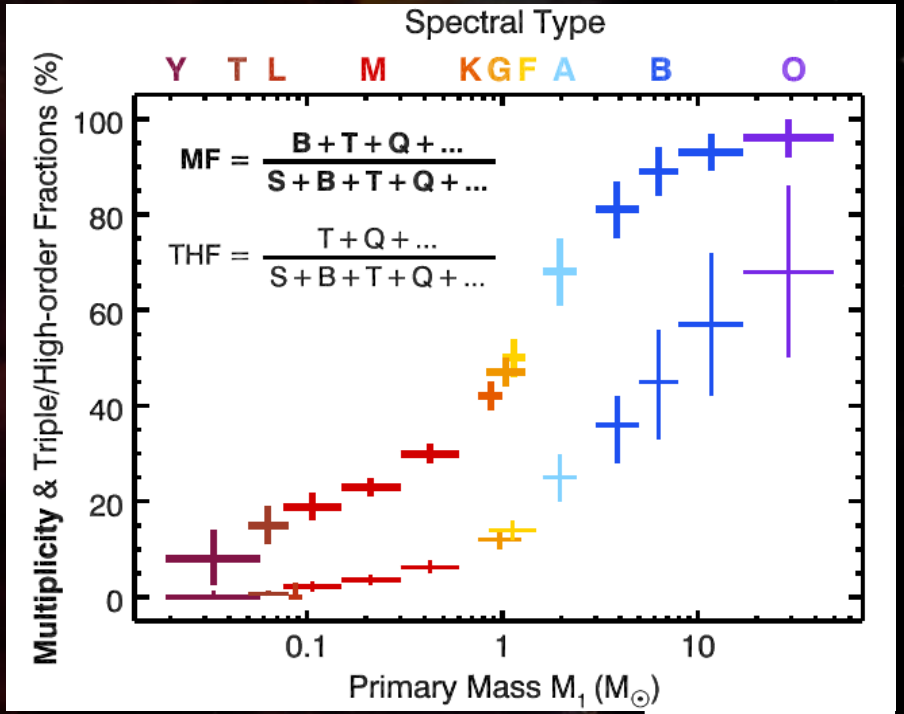

Offner+ PPVII

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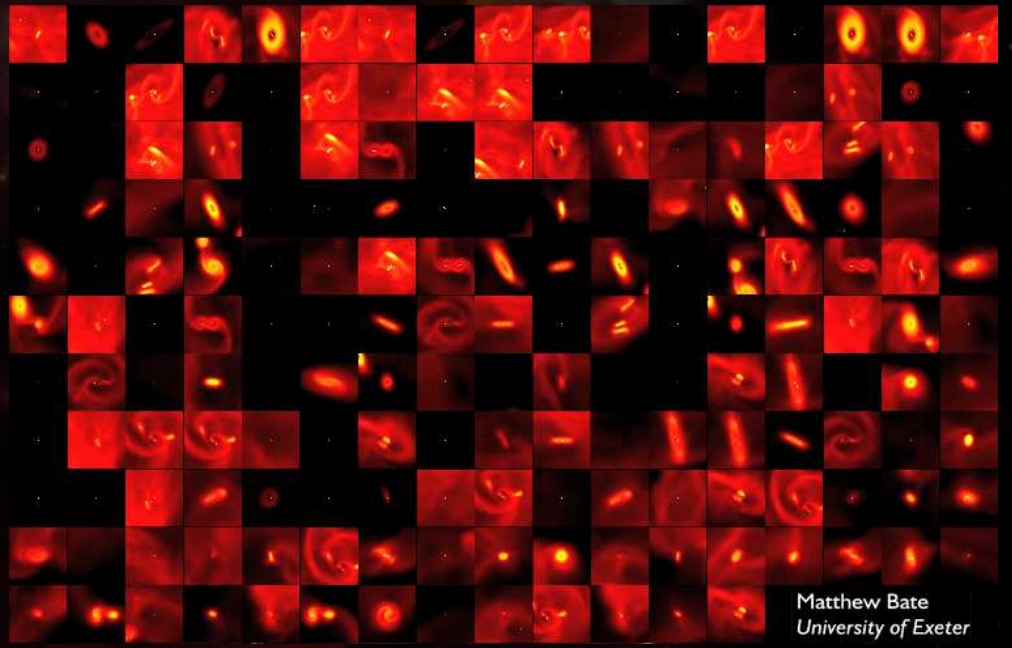
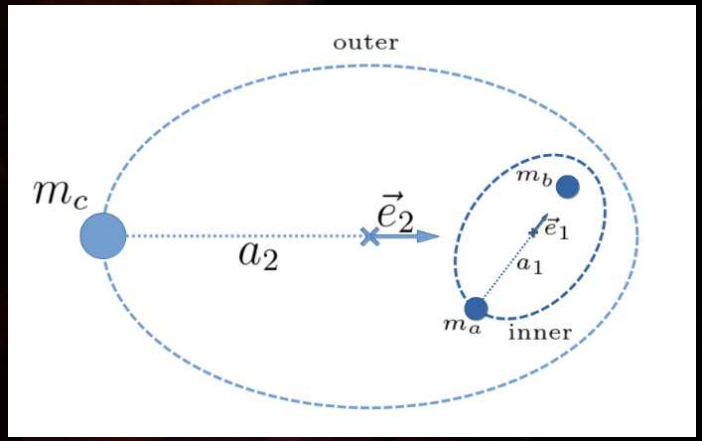


NOT ONLY BINARIES – TAKING INTO ACCOUNT MORE THAN TWO STARS

- Stability of > 2 stars systems
- Only observed configurations are hierarchical (nested binary orbits)
  - Mimic binaries at zeroth order: each hierarchical level instantaneously follows a binary orbit



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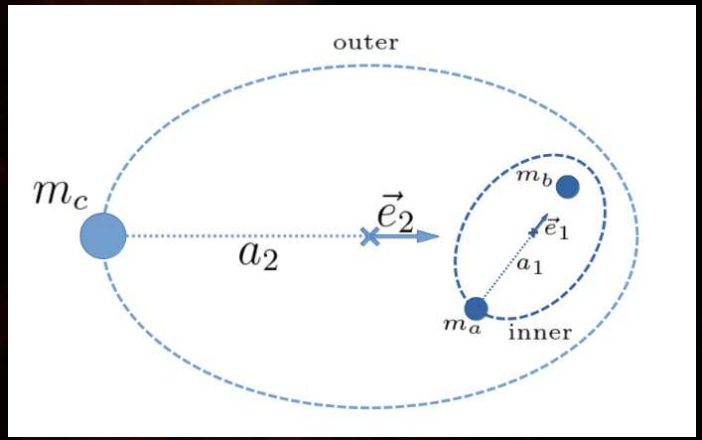
- Stability of > 2 stars systems
- Only observed configurations are hierarchical (nested binary orbits)
  - Mimic binaries at zeroth order: each hierarchical level instantaneously follows a binary orbit
- Evolve very differently from binaries on secular timescales
  - Evolution of orbital parameter (e_1, e_2, ...)
    - **Precession of the eccentricity vector**
    - Kozai-Lidov oscillations

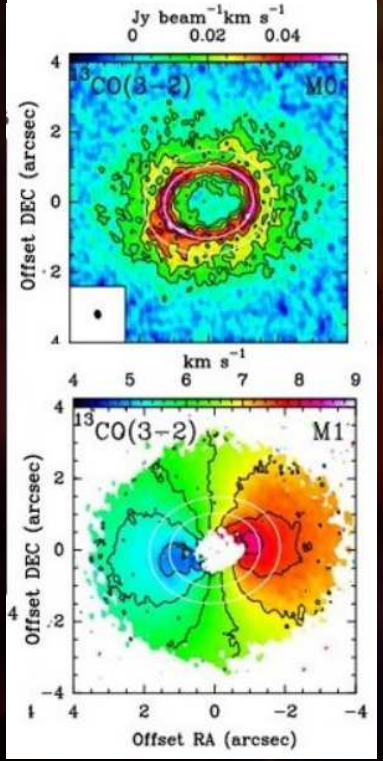


WHAT YOUNG SYSTEMS LOOK LIKE

- GG Tauri A
  - Hierarchical triple system (part of a quintuple) in Taurus-Auriga
  - Bright well studied circum-triple disc, orbit not constrained
  - Working on constraining the orbit

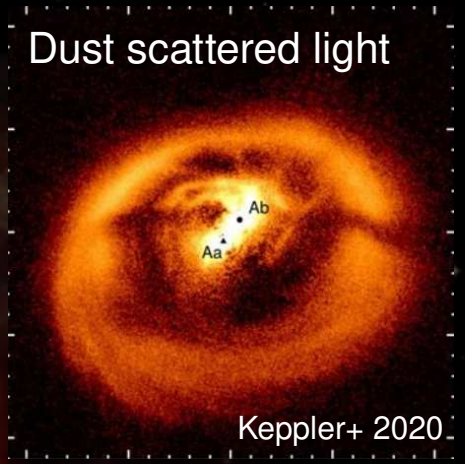
  (**Toci**, Ceppi et al, in prep, Yesterday Claudia's talk)

Gas kinematics



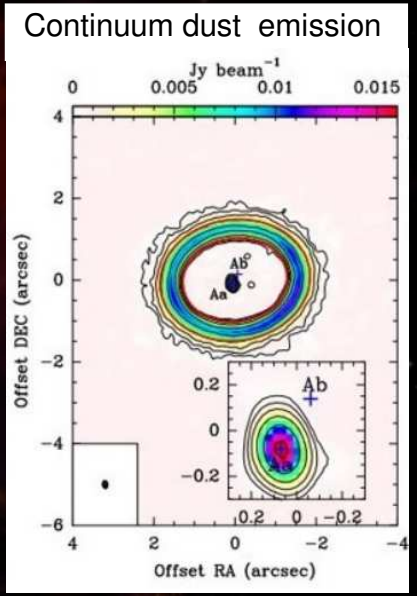
Phuong+ 2020

Dust scattered light



Keppler+ 2020

Continuum dust emission



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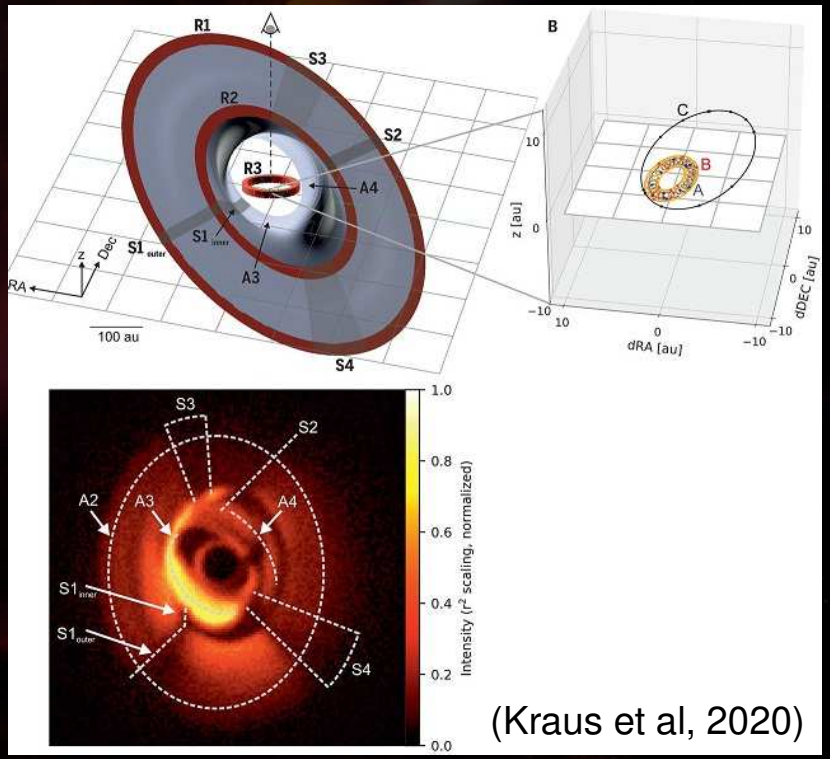
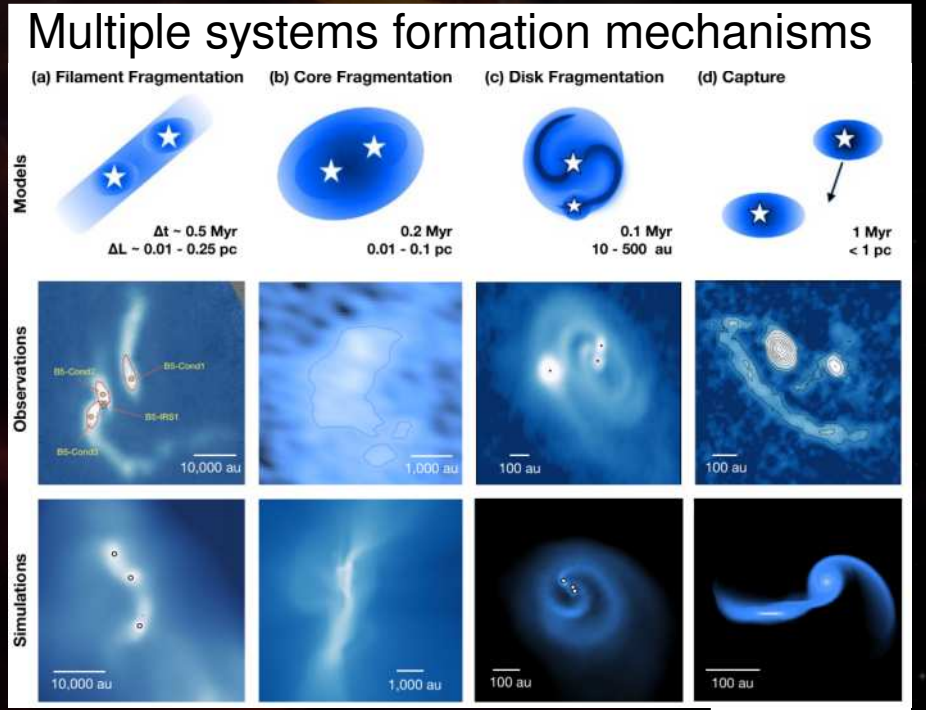
  - Working on constraining the orbit (Toci, Ceppi et al, in prep)
- GW Orionis
  - Hierarchical triple system
  - Well constrained properties of:
    - Orbital parameters
    - Circum-inner binary disc and broken circum-triple disc



(Kraus et al, 2020)

MULTIPLICITY AS A PROBE FOR MOLECULAR CLOUD INITIAL CONDITIONS

- Distinct signatures on systems
  - Spatial scale, mass ratios, disc properties
- Distinct efficiency
- Dependency on initial molecular cloud properties
  - Turbulence
  - Magnetic fields
  - Metallicity
  - Gas and stellar density
  - …
- Theoretical and observational efforts to retrieve initial conditions



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MUTUAL INCLINATION DISTRIBUTION

- Inclined circum-binary disc undergoes:
  - **Alignment to orbital plane**, $\beta \rightarrow 0°$, Ω prec. (~ 10^6 years)

    (Papaloizou+ 1995)
    - Low initial misalignment ($\beta_{init} < \beta_{crit}$)
    - Circular stellar system orbit
  - **Polar alignment**, $\beta \rightarrow$ ~ 90°, Ω librates

    (Farago+10, Aly+15, Martin+ 2017, 18)
    - Highly misaligned ($\beta_{init} > \beta_{crit}$) discs around eccentric orbits

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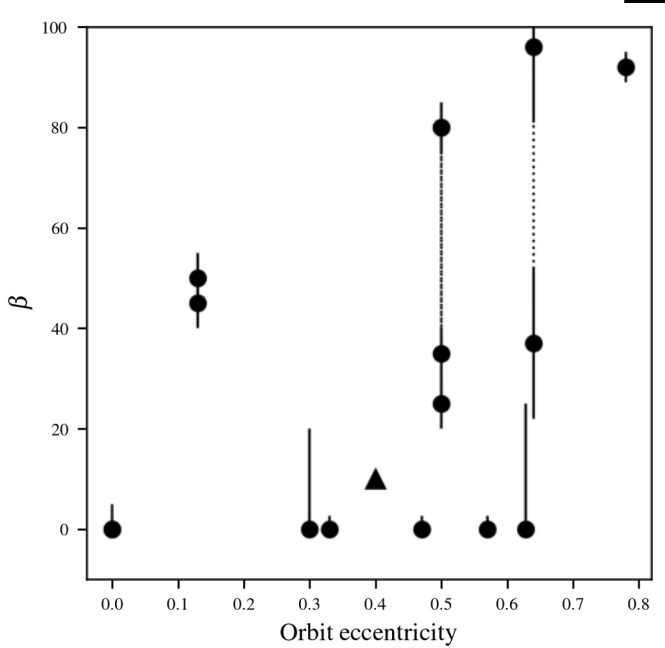
Ceppi+ 2023 (from Czekala+ 2019)



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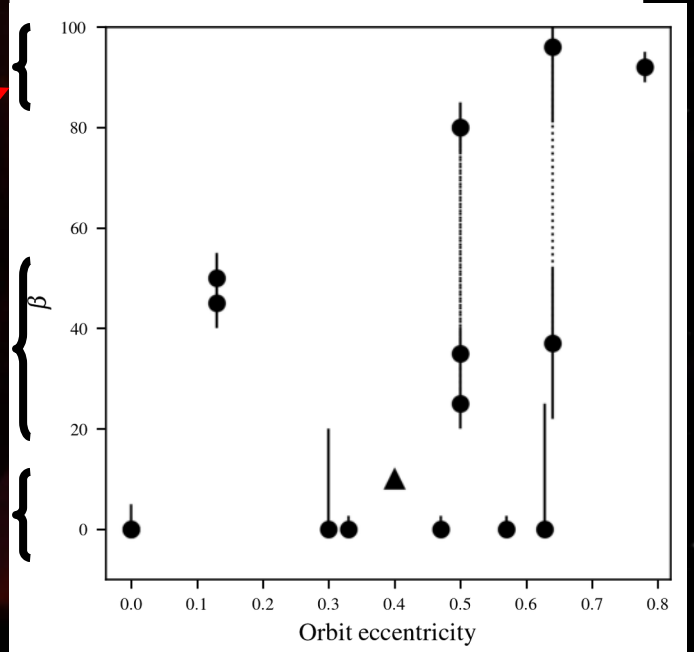
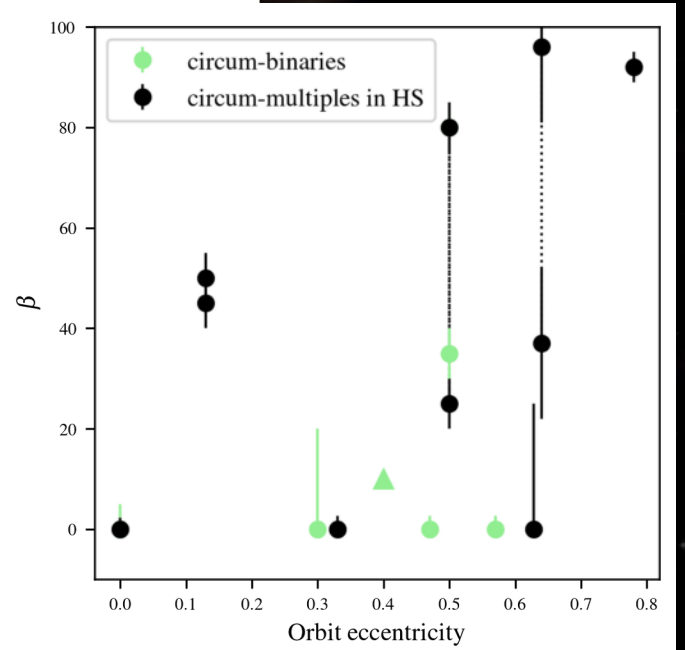


MUTUAL INCLINATION DISTRIBUTION – LOOKING CLOSELY...

- Two distinct populations
  - Pure binaries mostly coplanar
  - > 2 stars systems mostly misaligned
- Highly misaligned systems have > 2 stars
- Only known polarly aligned disc resides in an hierarchical quadruple (HD98800)

Ceppi+ 2023



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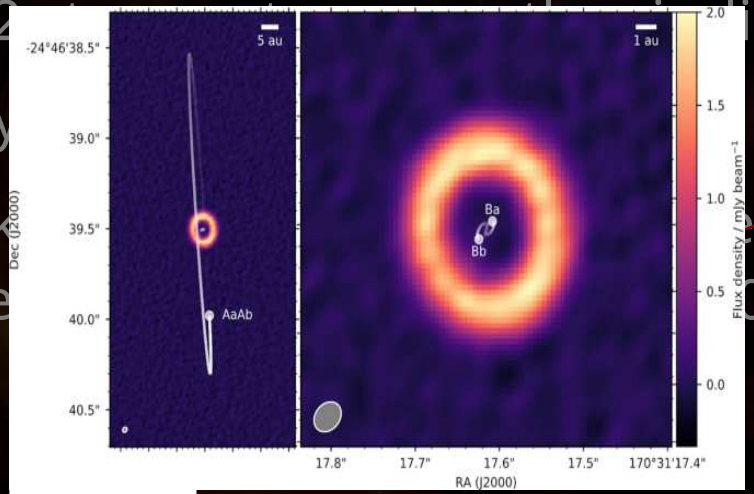
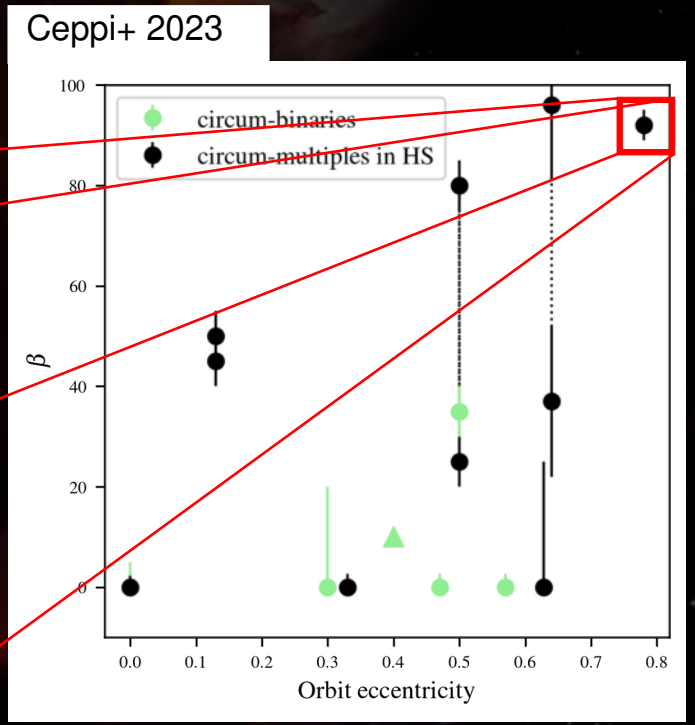
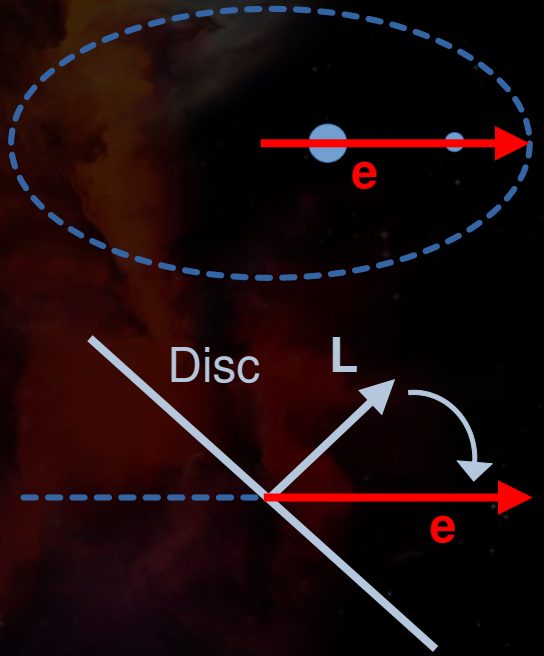




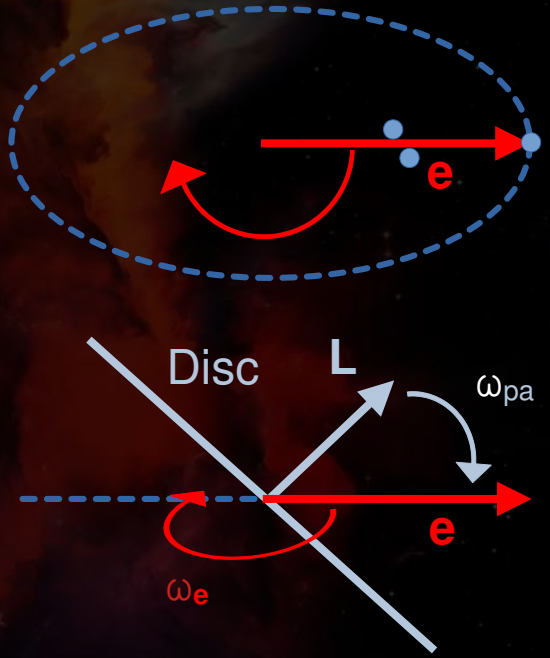
POLAR ALIGNMENT IN TRIPLES – THE PROBLEM WITH TRIPLES

- Angular momentum vector of the disc aligns to the eccentricity vector of the binary ($\beta \to 90°$)



POLAR ALIGNMENT IN TRIPLES – THE PROBLEM WITH TRIPLES

- Angular momentum vector of the disc aligns to the eccentricity vector of the binary ($\beta \to 90°$)
- Triple eccentricity vector precesses
- **L** chases **e**
  - **L** aligns with ω_{pa}
  - **e** precesses with ω_{e}



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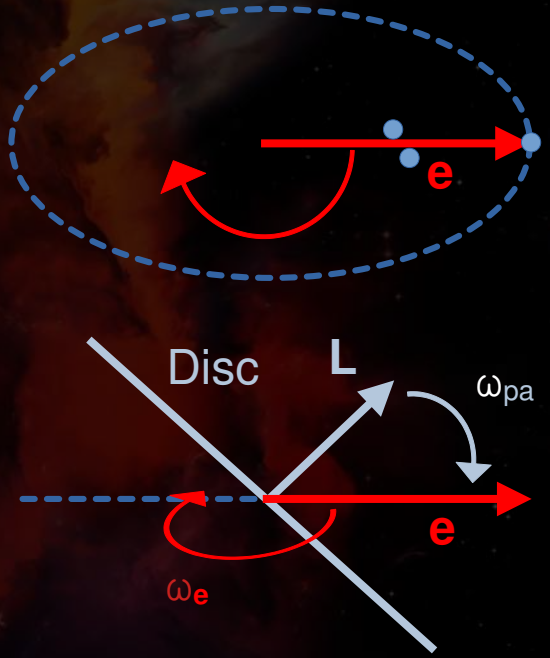
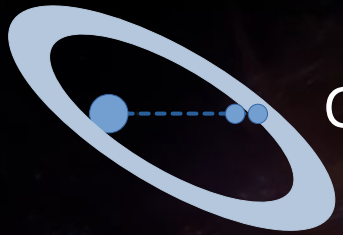
$$T = \frac{\omega_e}{\omega_{\rm pa}}$$

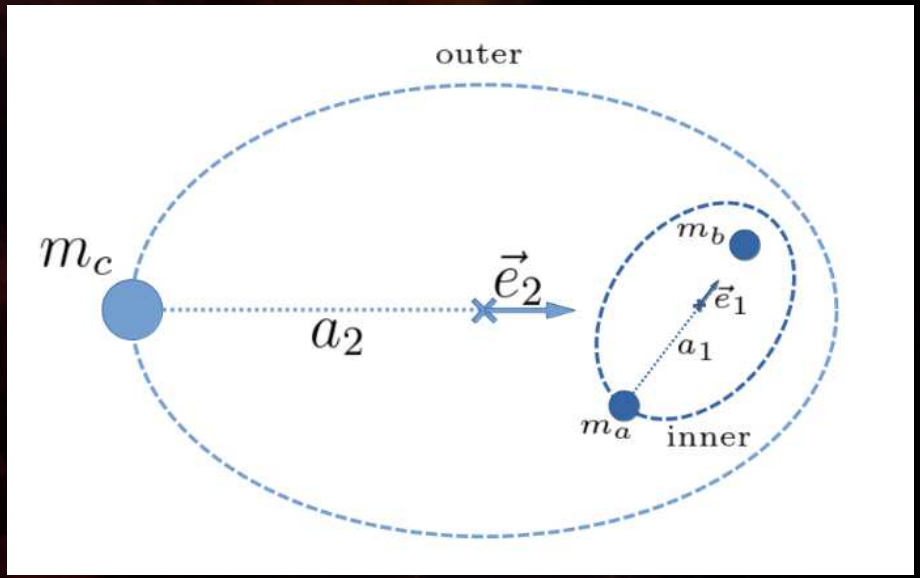


POLAR ALIGNMENT IN TRIPLES – OUTER AND INNER ORBIT



Circum-outer orbit disc

Circum-inner orbit disc



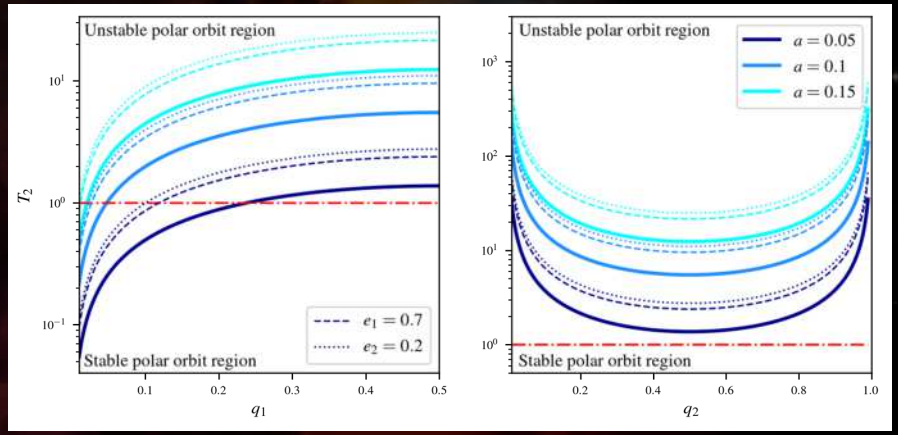
POLAR ALIGNMENT IN TRIPLES – OUTER AND INNER ORBIT

$a = a_{in}/a_{out}$
$q_1 = m_b / (m_a+m_b)$
$q_2 = m_c/(m_a+m_b+m_c)$

Circum-outer orbit disc

$$T_2 = \frac{\omega_{e_2}}{\omega_{\mathrm{pa},2}}$$

$$T_2 = \frac{4}{3\sqrt{5}} a^2 \left(\frac{R_{\mathrm{in}}}{a_2}\right)^{\frac{7}{2}} \frac{x_o^{3/2} - 1}{1 - x_o^{-2}} \frac{q_1(1-q_1)}{q_2(1-q_2)} \frac{1 + \frac{3}{2}e_1^2}{(1-e_2^2)^2 e_2 \sqrt{1+4e_2^2}}$$



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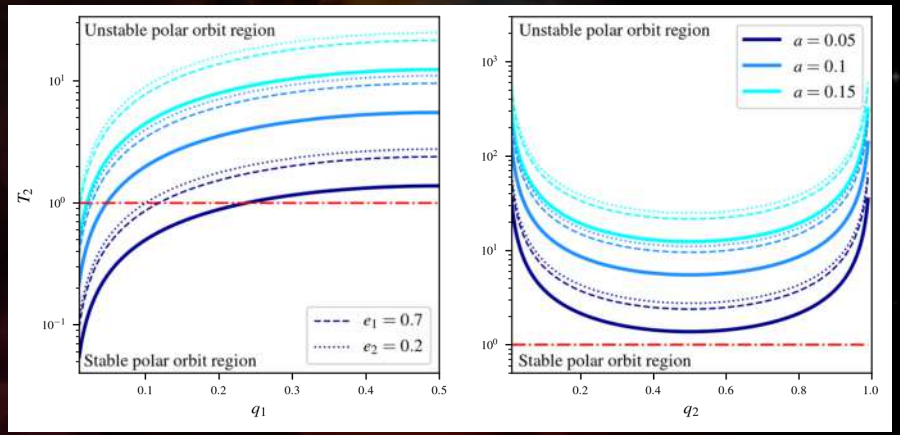
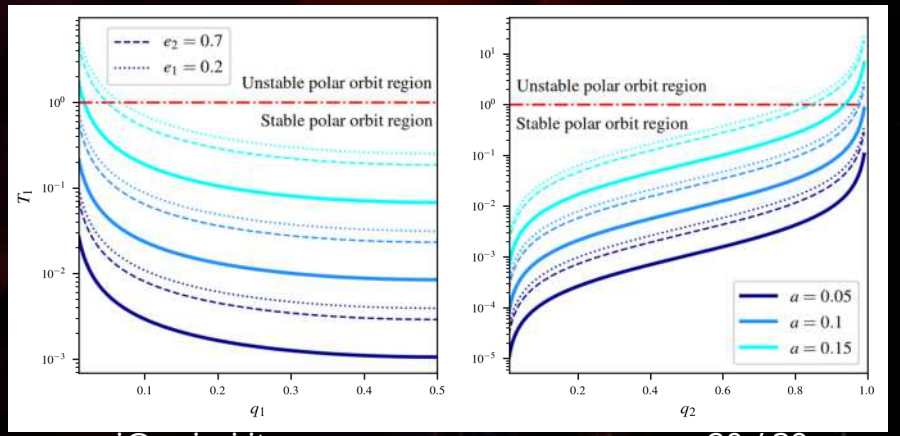


Circum-inner orbit disc $T_1 = \frac{\omega_{e_1}}{\omega_{\rm pa,1}}$

$$T_1 = \frac{4}{3\sqrt{5}} a^3 \left(\frac{R_{\rm in}}{a_1}\right)^{\frac{7}{2}} \frac{x_o^{3/2}-1}{1-x_o^{-2}} \frac{q_2/q_1}{(1-q_1)(1-q_2)} \sqrt{\frac{1-e_1^2}{(1-e_2^2)^3}} \frac{1}{e_1\sqrt{1+4e_1^2}}$$

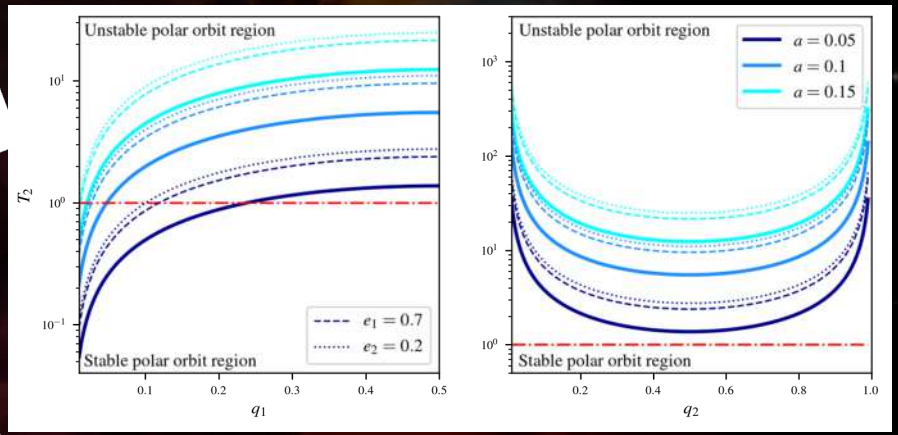


POLAR ALIGNMENT IN TRIPLES – OUTER AND INNER ORBIT

Circum-outer orbit disc T_2

$$T_2 = \frac{4}{3\sqrt{5}} a^2 \left(\frac{R_{\rm in}}{a_2}\right)^{\frac{7}{2}} \frac{x_o^{3/2} - 1}{(1-e_2^2)^2 e_2 \sqrt{1+4e_2^2}}$$

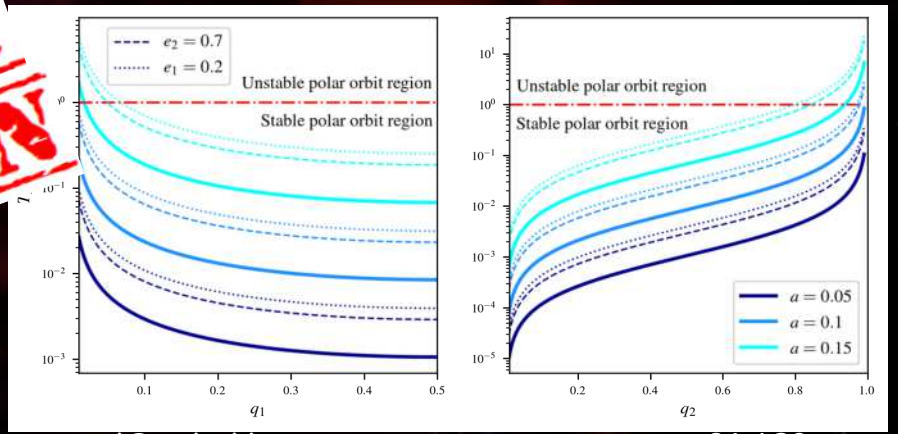
UNSTABLE POLAR CONFIGURATION



Circum-inner orbit disc T_1

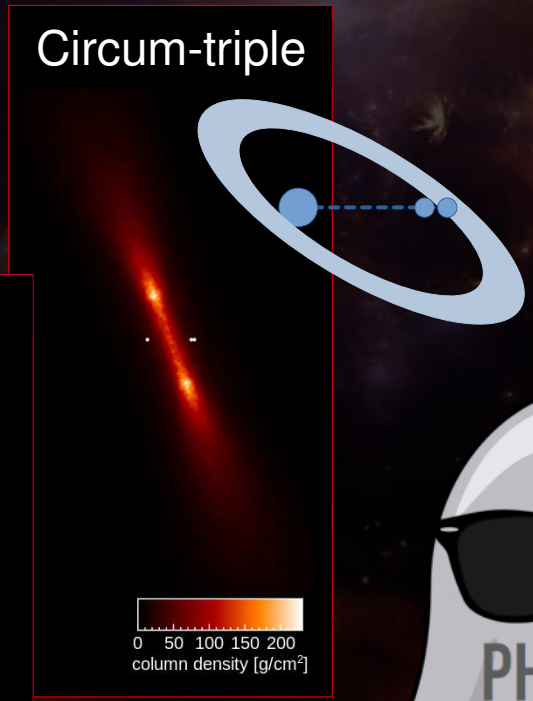
$$T_1 = \frac{4}{3\sqrt{5}} a^3 \left(\frac{R_{\rm in}}{a_1}\right)^{\frac{7}{2}} \frac{x_o^{3/2} - 1}{e_1 \sqrt{1+4e_1^2}}$$

STABLE POLAR CONFIGURATION

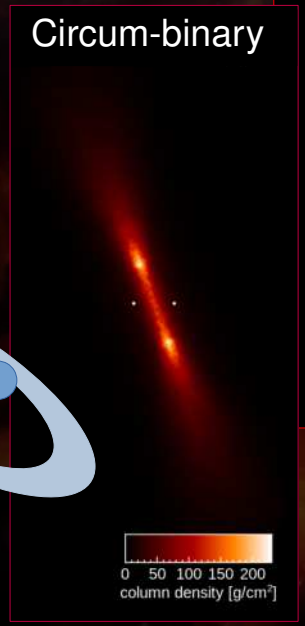


SO WE NUMERICALLY TESTED THIS...

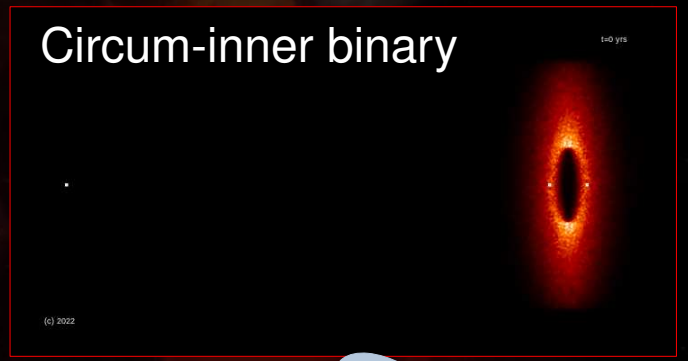
Circum-triple



Circum-binary



Circum-inner binary



Hierarchical systems setup:
Ceppi+ 2022

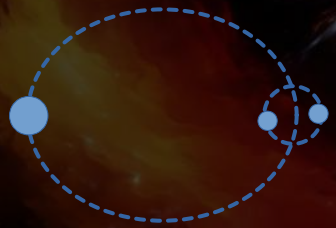
Discs in HTS setup
(not public yet):
Ceppi+ 2023

CIRCUM-TRIPLE DISC

Stellar systems

$a_b = 10$ au
$e_b = 0.5$
$q_b = 0.5$

$a_1, a_2 = 1, 10$ au
$e_1, e_2 = 0, 0.5$
$q_1, q_2 = 0.5, 0.5$



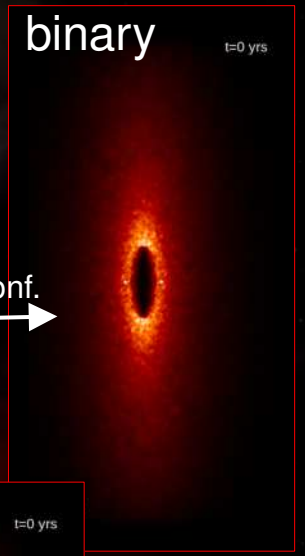
Disc

$R_{in} = 15$ au
$R_{out} = 100$ au

$\beta_{init} = 70° > \beta_{crit}$
$\Omega_{init} = 90°$

$T_2 \sim 6 > 1$

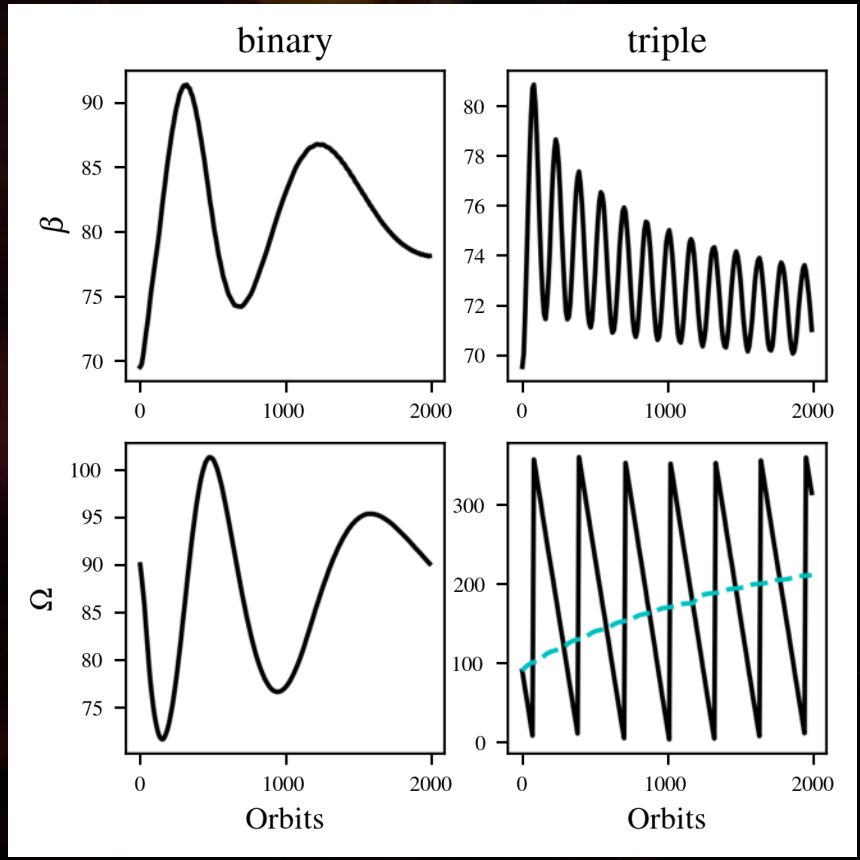
Stable polar conf.



Unstable polar conf.

CIRCUM-TRIPLE DISC

- Circum-binary disc polarly align
  - Oscillating tilt and twist
- Same disc orbiting the triple (T_2>1)
  - Tilt exponentially decays (+ oscill.)
  - Twist precesses



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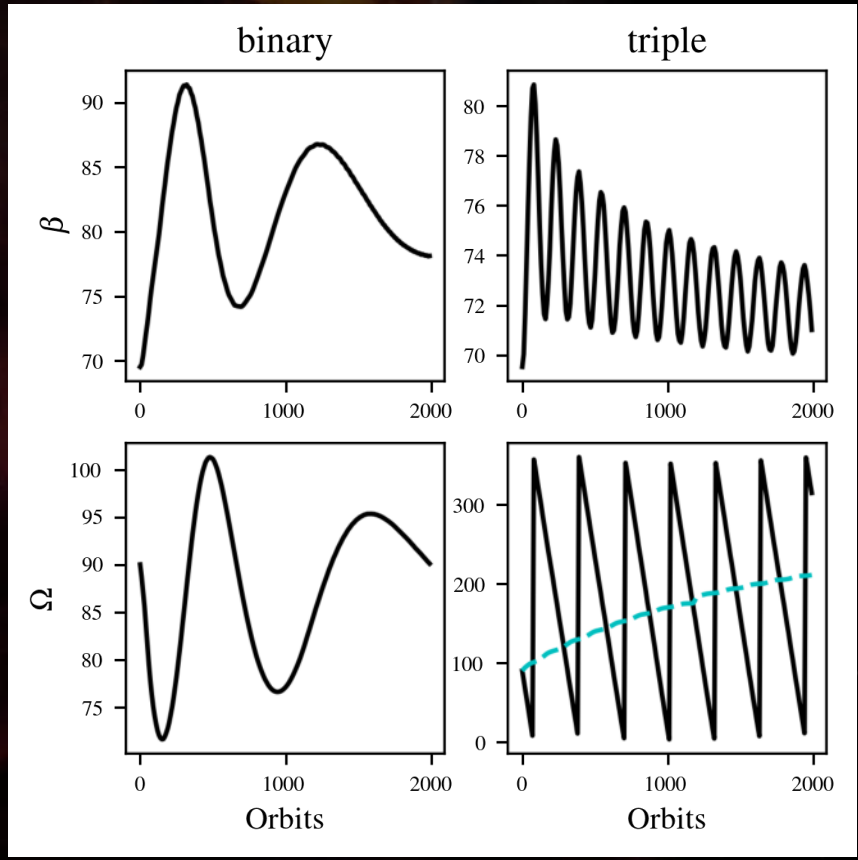
Circum-triple behaves as orbiting circular binary!



CIRCUM-INNER BINARY DISC

Stellar systems

$a_1, a_2 = 1, 20$ au

$e_1, e_2 = 0.5, 0$

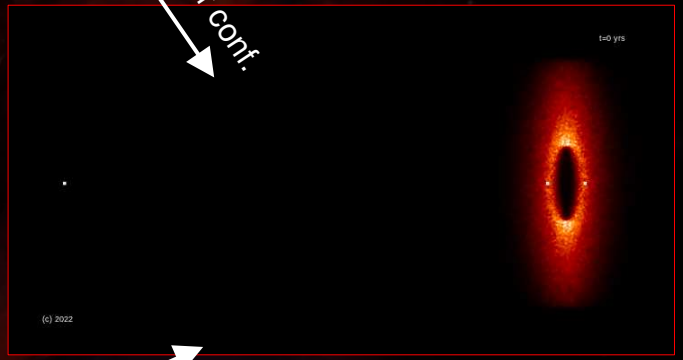
$q_1, q_2 = 0.5, 0.5$

Disc

$R_{in} = 1.5$ au $\beta_{init} = 70° > \beta_{crit}$

$R_{out} = 5$ au $\Omega_{init} = 90°$

Stable polar conf.

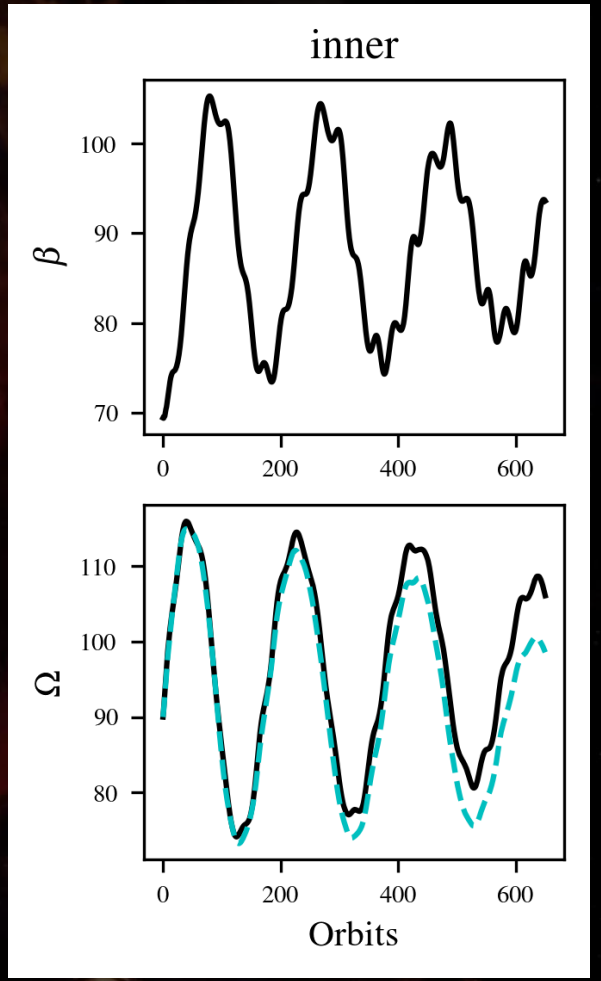


$T_1 \sim 0.008 < 1$

Stable polar conf.

CIRCUM-INNER BINARY DISC

- Circum-inner binary disc polarly align (T_1<1)
  - Oscillating tilt and twist



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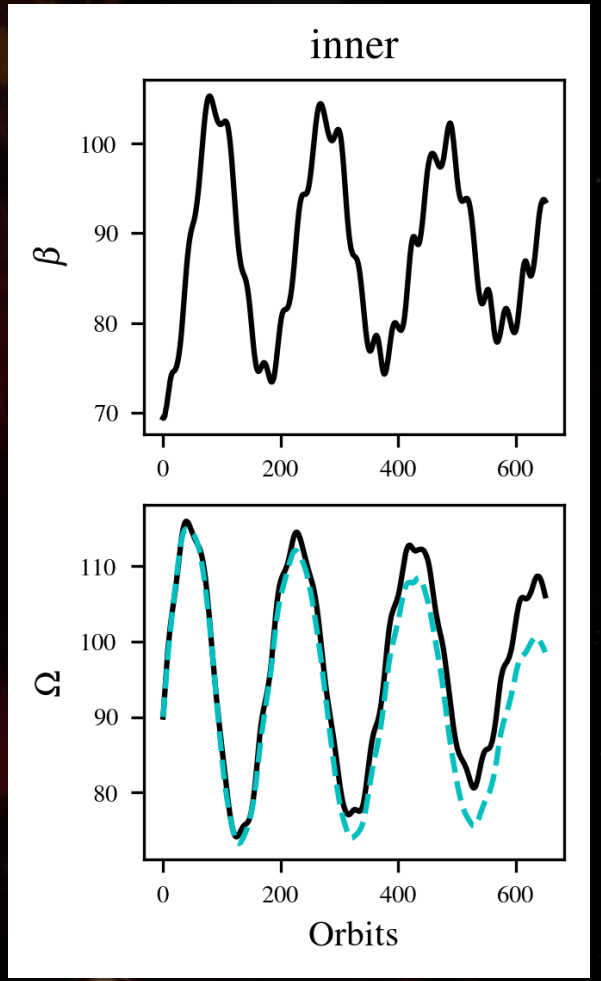
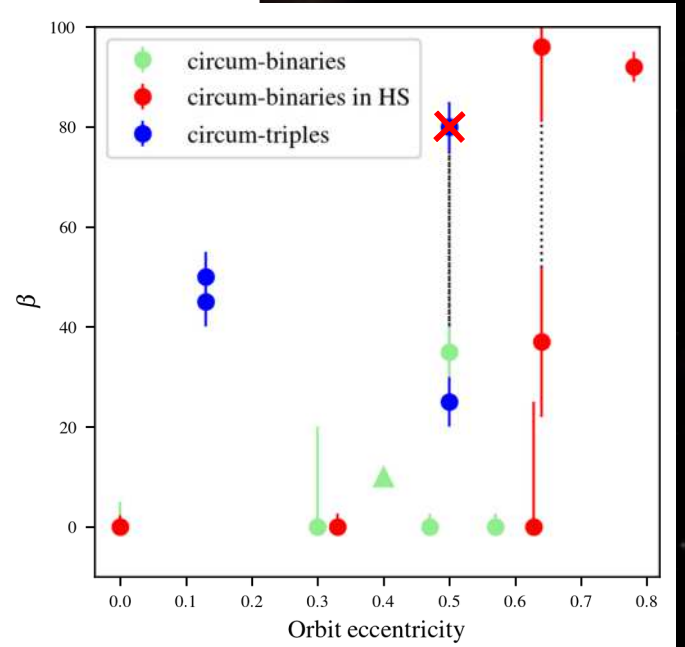
We confirmed both our analytical findings!



MUTUAL INCLINATION DISTRIBUTION – LOOKING CLOSELY...

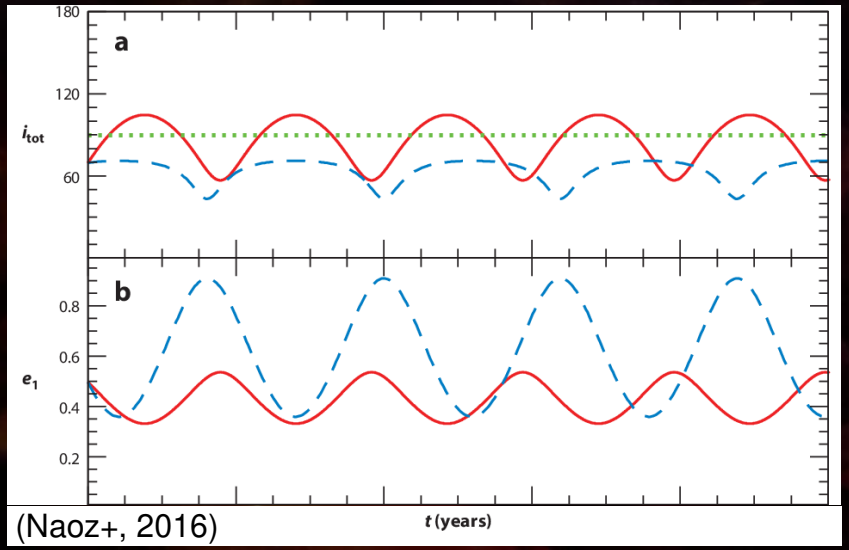
- Polar discs discs are orbiting
  - Hierarchical systems inner orbits
  - Binaries (no clear detection)
- No highly misaligned discs orbiting hierarchical systems outer orbits
- Circum-triple ≠ circum-binary

Ceppi+ 2023



HIERARCHICAL SYSTEMS VS PURE BINARY POPULATIONS

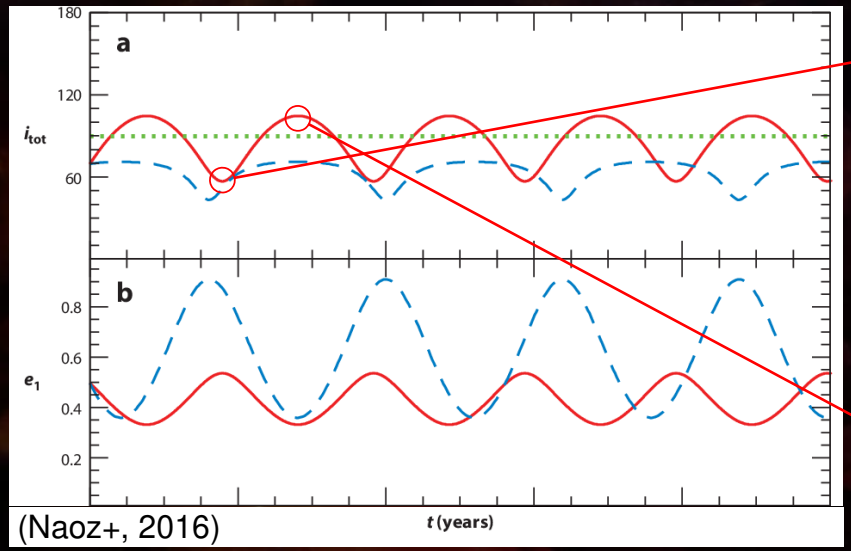
- It's not the disc that misaligns wrt the stars (viscous evolution)
- It's the system that misaligns wrt to the disc (Kozai-Lidov oscillations)



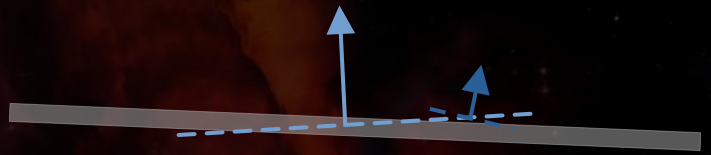
(Naoz+, 2016)

HIERARCHICAL SYSTEMS VS PURE BINARY POPULATIONS

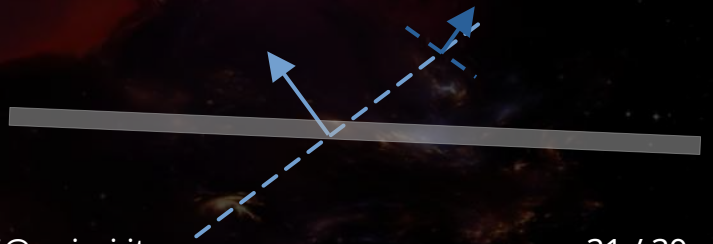
- It's not the disc that misaligns wrt the stars (viscous evolution)
- It's the system that misaligns wrt to the disc (Kozai-Lidov oscillations)



(Naoz+, 2016)



β oscillates due to N-body dynamics!



MUTUAL INCLINATION DISTRIBUTION – LOOKING CLOSELY...

- Polar discs discs are orbiting
  - Hierarchical systems inner orbits
  - Binaries (no clear detection)
- No highly misaligned discs orbiting hierarchical systems outer orbits
- Circum-triple ≠ circum-binary

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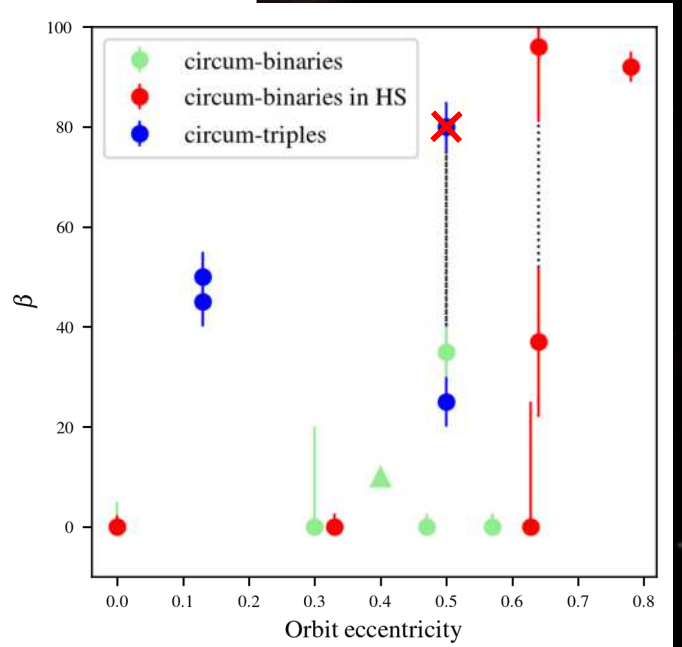
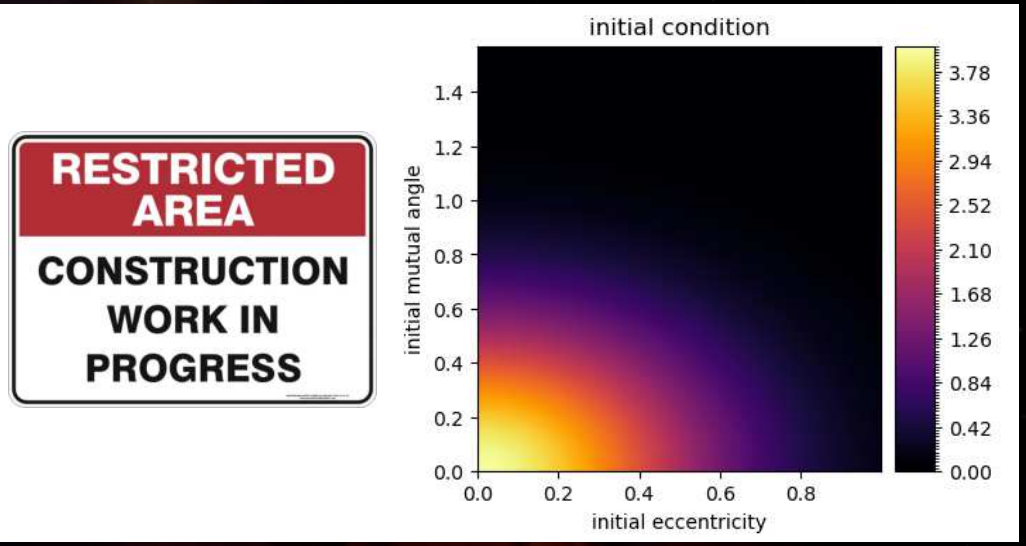


WHAT COULD WE DO WITH HIGHER STATISTIC ON POLAR DISCS?

- Ingredients 
  - Evolution of mutual misalignment
  - Orbital eccentricity initial distribution
  - Mutual misalignment initial distribution
- Result 
  - Fraction of polar discs in evolved population
  - Distribution of polar discs wrt orbital eccentricity

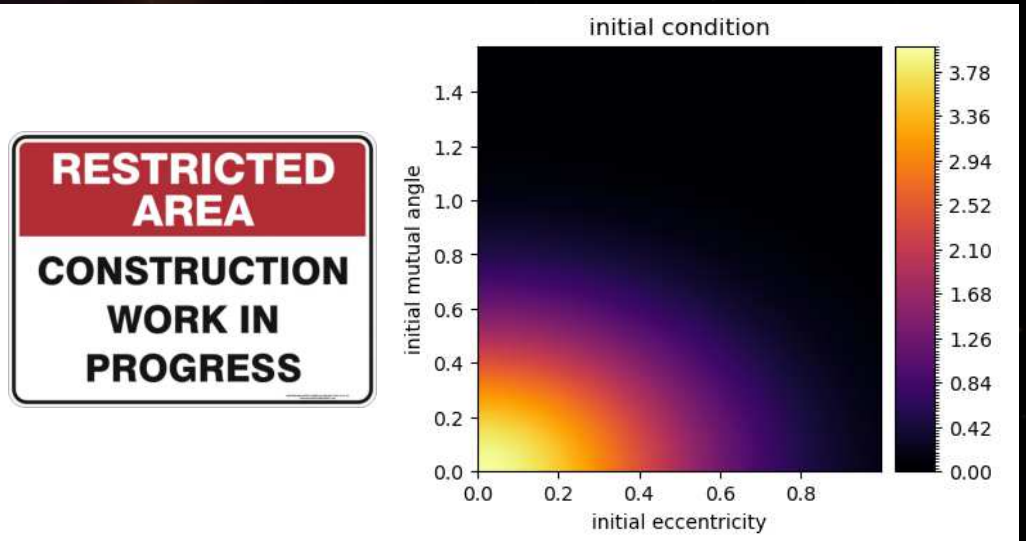
FRACTION OF POLAR DISCS

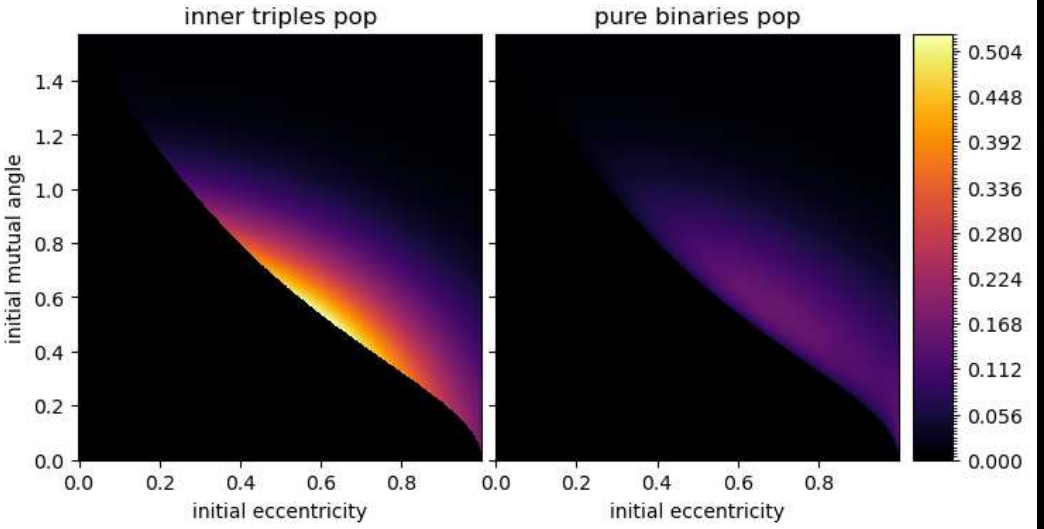
- Let’s compute initial condition from MC collapse simulations (Bate 2018)



FRACTION OF POLAR DISCS

- Let’s compute initial condition from MC collapse simulations (Bate 2018)
- Compute the pdf of polar discs
- Integrate to obtain fraction of polar discs
  - Triples: ~ 7%
  - Binaries: ~ 3,5%

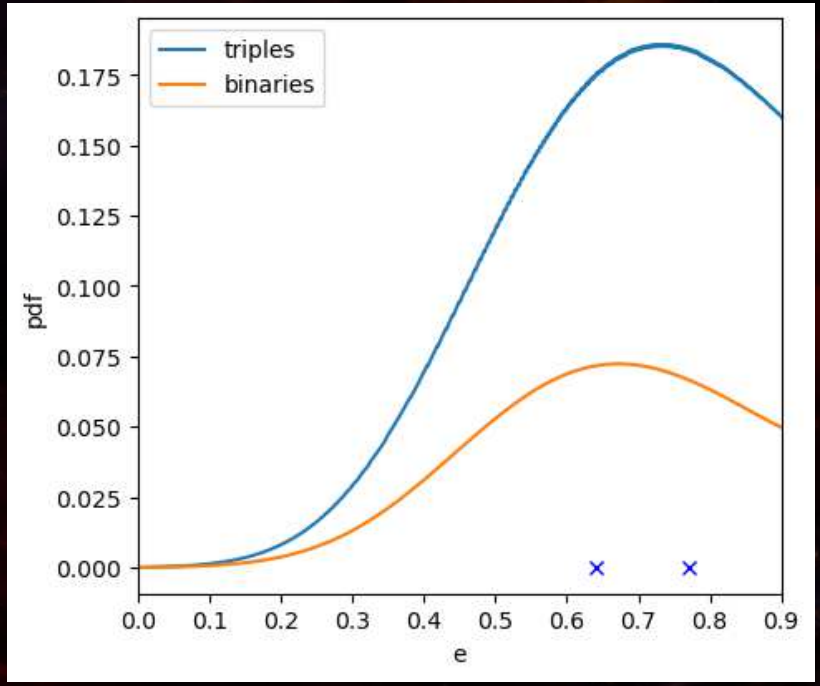




HOW POLAR DISCS WOULD DISTRIBUTE WRT ECCENTRICITY?

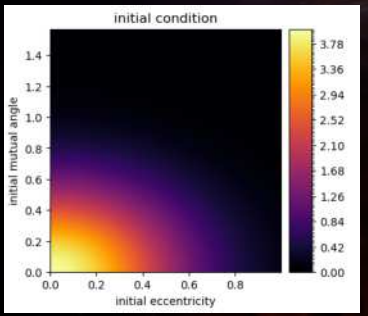
- Integrating over the initial mutual inclination

  → Distribution of polar discs wrt eccentricity

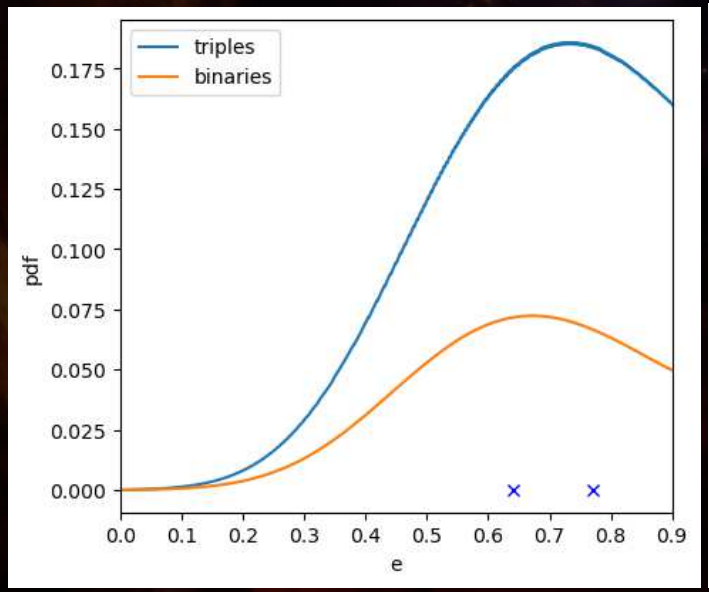


WHAT COULD WE DO WITH HIGHER STATISTIC ON POLAR DISCS?

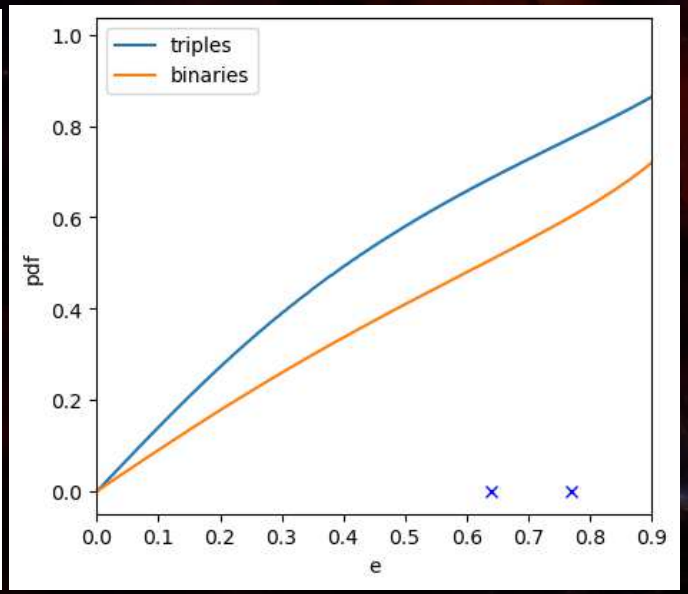
Shape of distribution constrains initial conditions!

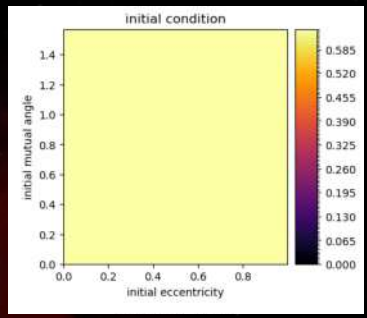


Bate init. distribution



Random init. distribution



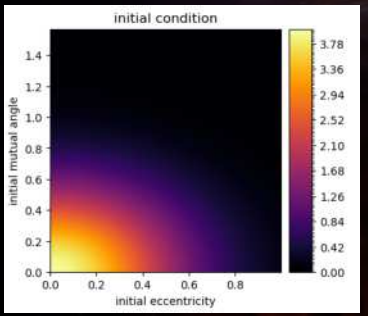


Tri: ~ 7 %
Bin: ~ 3,5%

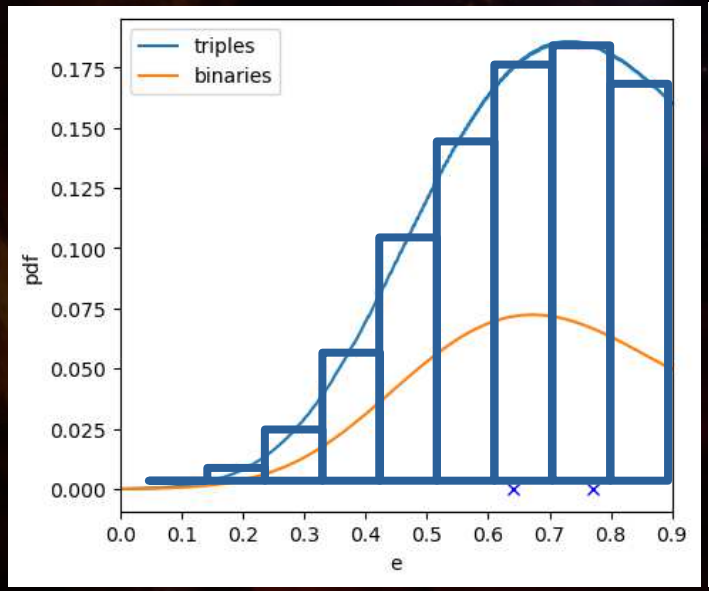
Tri: ~ 50%
Bin: ~ 40%

WHAT COULD WE DO WITH HIGHER STATISTIC ON POLAR DISCS?

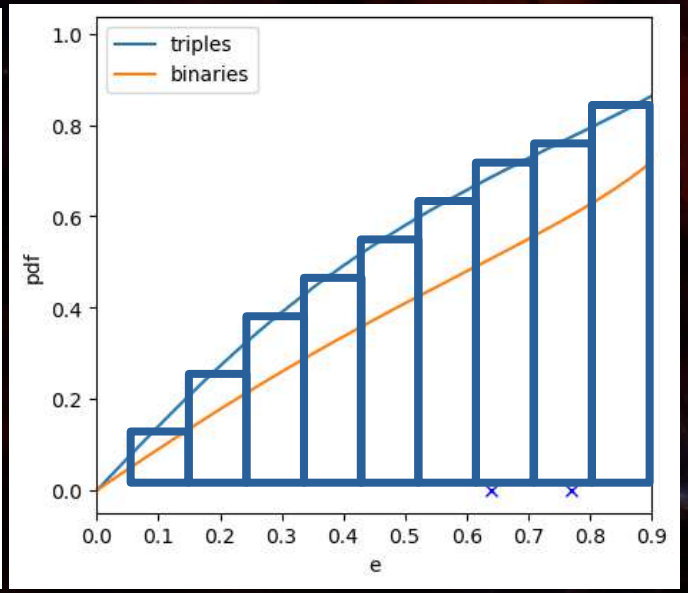
Shape of distribution constrains initial conditions!

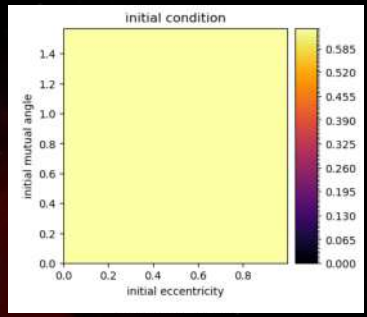


Bate init. distribution



Random init. distribution





Tri: ~ 7 %
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Tri: ~ 50%
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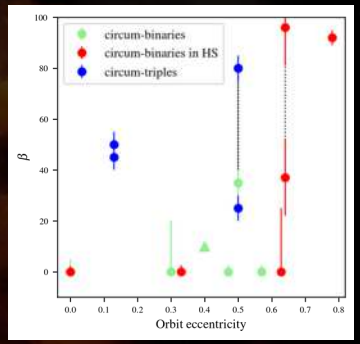
CONCLUSIONS – WHY MULTIPLICITY MATTERS

"Do not underestimate the **power** of *multiplicity*"

- Secular evolution matters
  - Binaries mostly coplanar: where's the initial misalignment?
  - Polar alignment differs in > 2 stars systems
    - Outer discs do not polarly align 
    - Inner discs do, possibly more likely than bins 
  - Tilt distribution in circum-triple talks about KL oscillations



"With great **power** comes great *possibility*"

- Correlation in angular momenta direction is needed
- Greater statistic constrains initial conditions