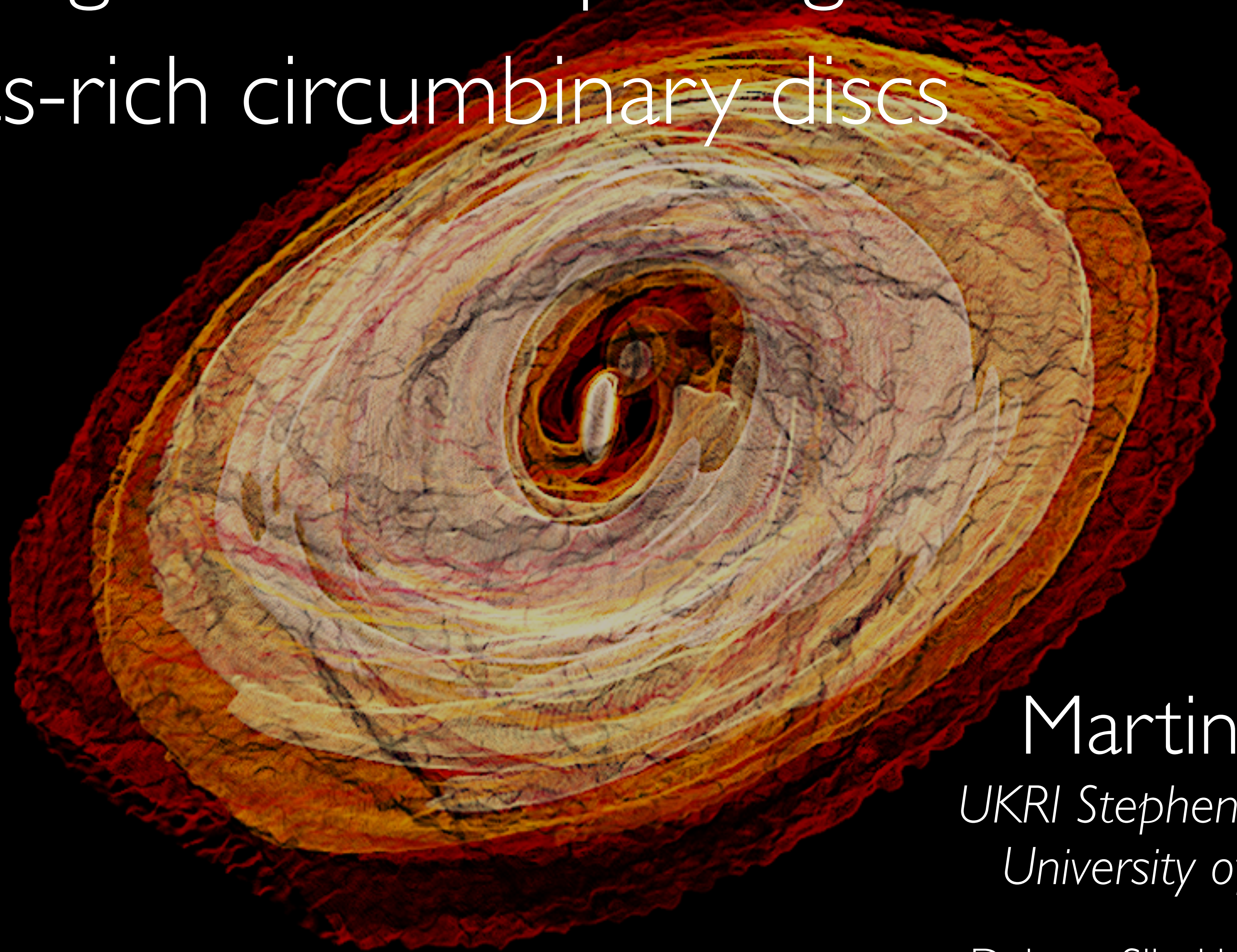
# Supermassive black hole binary dynamics, growth and spin alignment in gas-rich circumbinary discs



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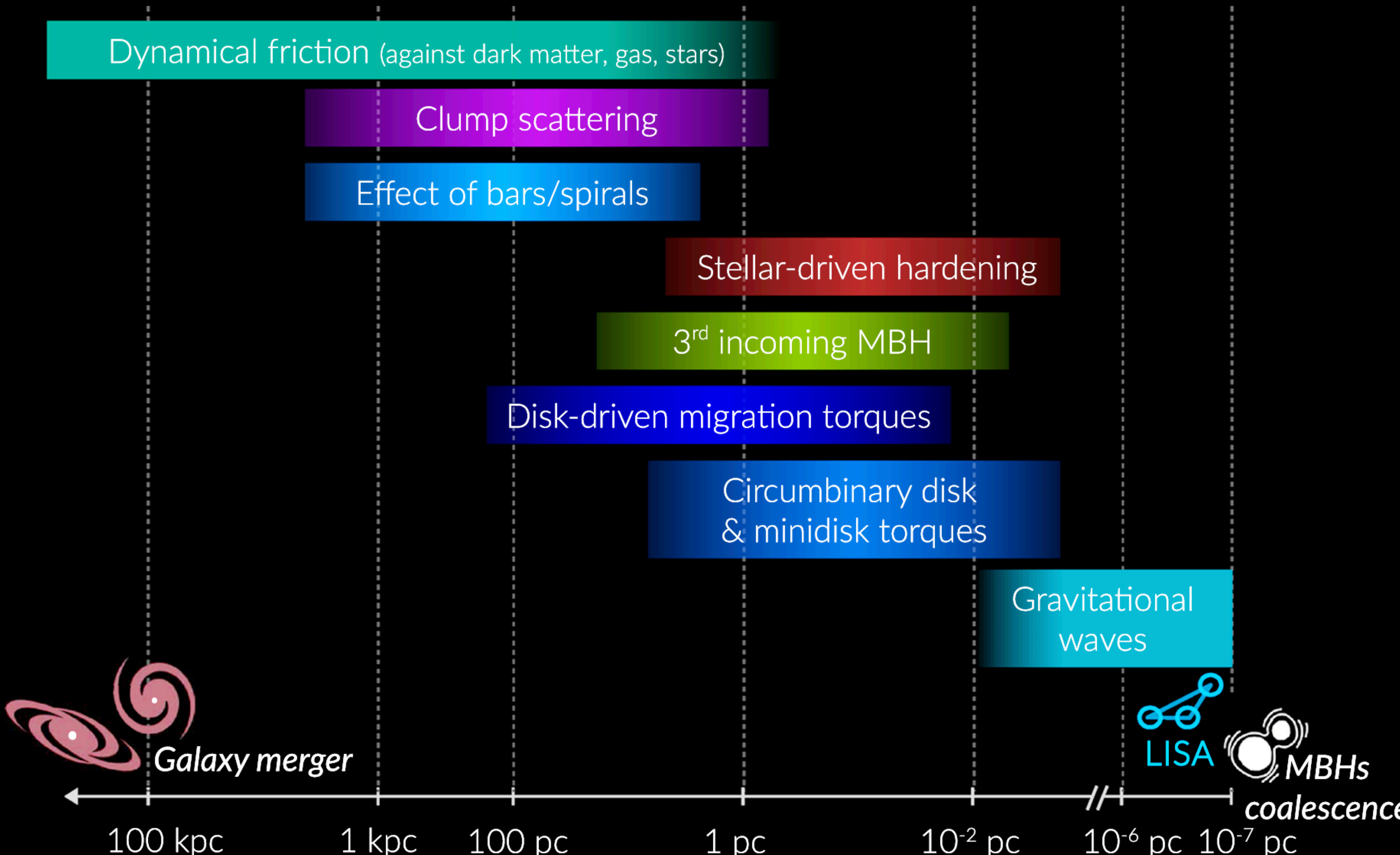
UK Research and Innovation

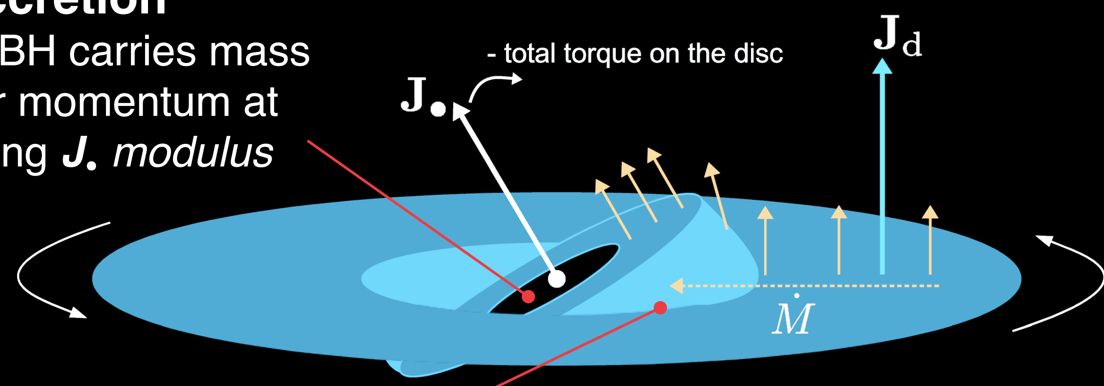
https://tinyurl.com/mab-cbd-spin




From "Astrophysics with the Laser Interferometer Space Antenna"

# SPIN EVOLUTION

**Mass accretion**
Gas falling on to BH carries mass specific angular momentum at $R_{ISCO}$, changing ***J*** ***modulus***



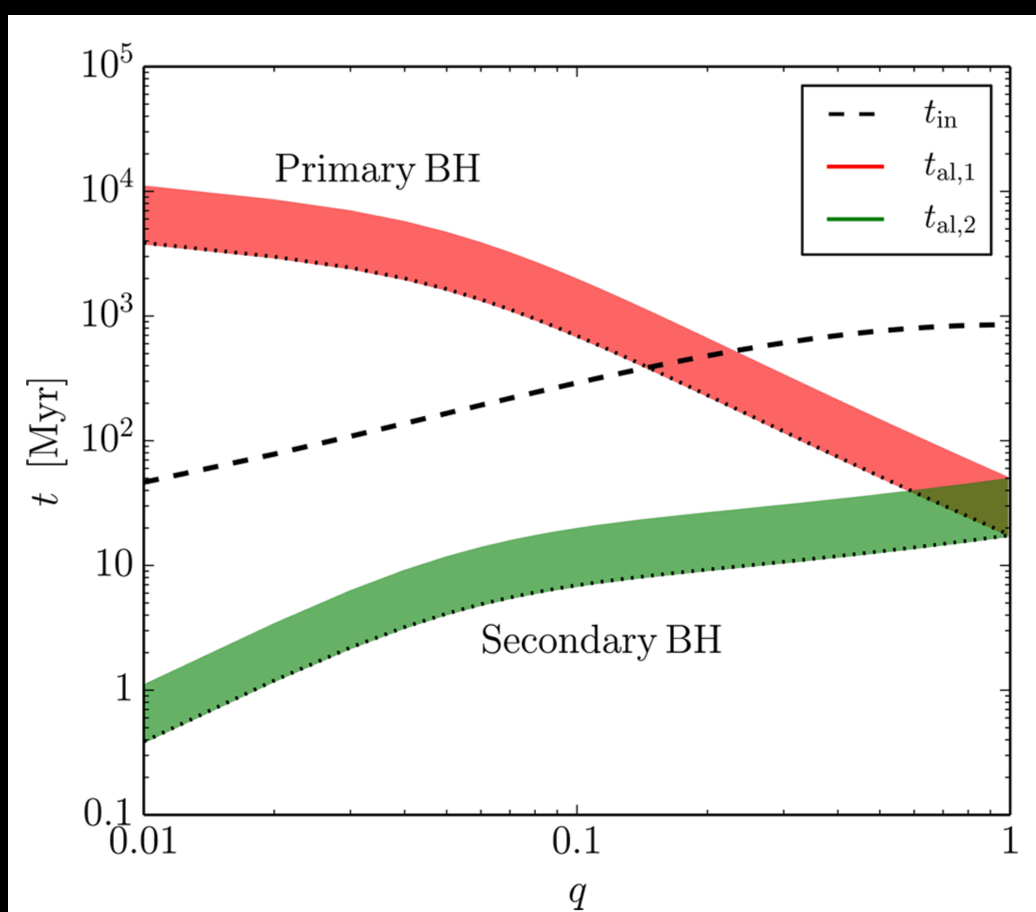

**Bardeen-Petterson effect**
The disc attains a steady warp because of Lense-Thirring precession and viscosity; gas flowing through the warp gets torqued, as does the BH to conserve total AM; the torque induces precession and (counter)alignment, changing ***J*** ***direction***

Accretion and torquing of BH via the Bardeen-Petterson (75) effect drive spin evolution (e.g. King et al. 2005, Lodato & Pringle 2006).

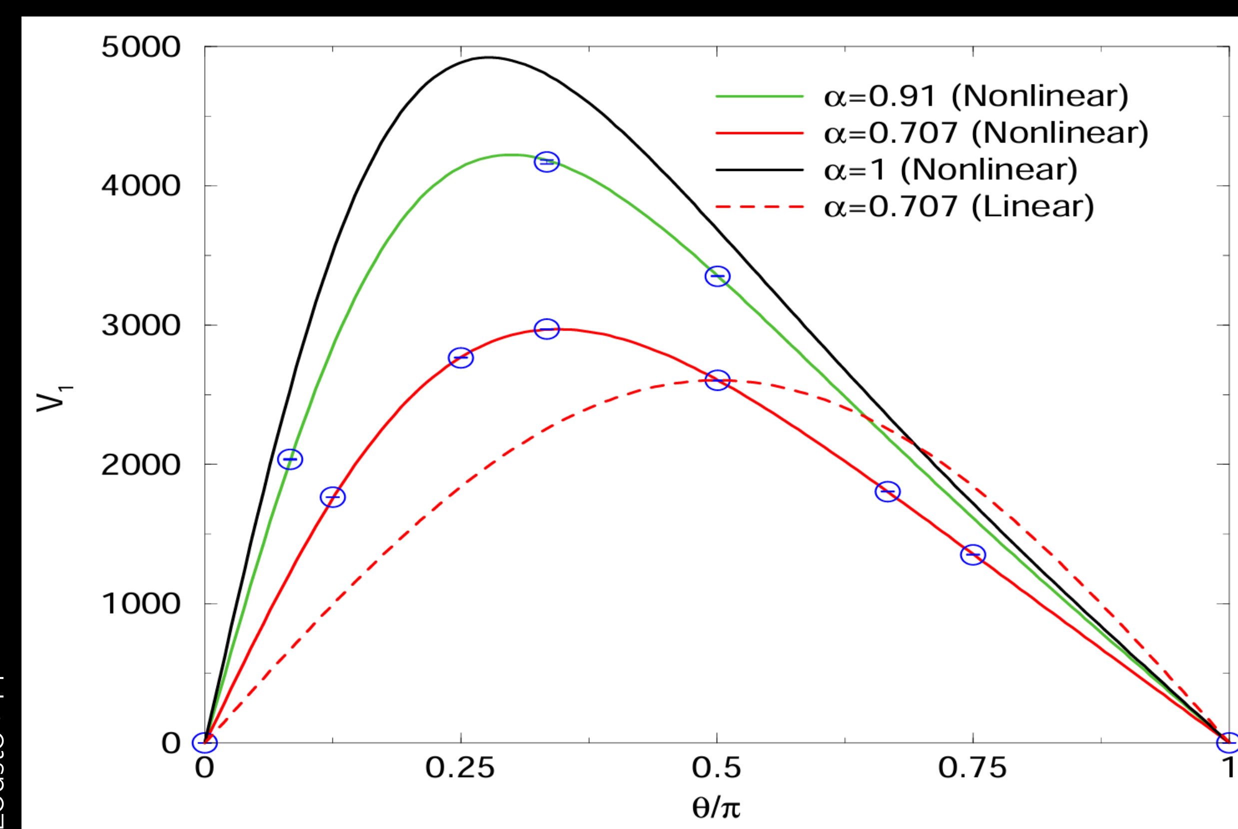
BH Spin plays an important role in feedback processes (e.g. set radiative efficiency, jet direction and efficiency). (e.g., Tchekhovskoy et al. 11, Yuan & Narayan 14, Liska+17, Beckmann+22, Talbot+21,22)

Spin alignment has implications for GW emission and recoil velocities (e.g. Campanelli+07, Gonzalez+07, Lousto+11,13,19)

When spins align or not depends on circumbinary disc properties, q and $\lambda$.
(e.g. Miller & Krolik 13, Gerosa+15)




Gerosa+15




Lousto+11

# MODELLING ACCRETION & SPIN EVOLUTION

Fiacconi+ 2018, MNRAS, 477, 3807

Model mass and angular momentum transfer onto a sub-grid Shakura-Sunyaev accretion disc.

Subsequently track the mass and angular momentum evolution of the disc and black hole assuming the Bardeen-Petterson effect (King et al. 2005, Lodato & Pringle 2006).

**DISC MASS $M_d$ AND BH MASS $M_{BH}$ EVOLUTION:**

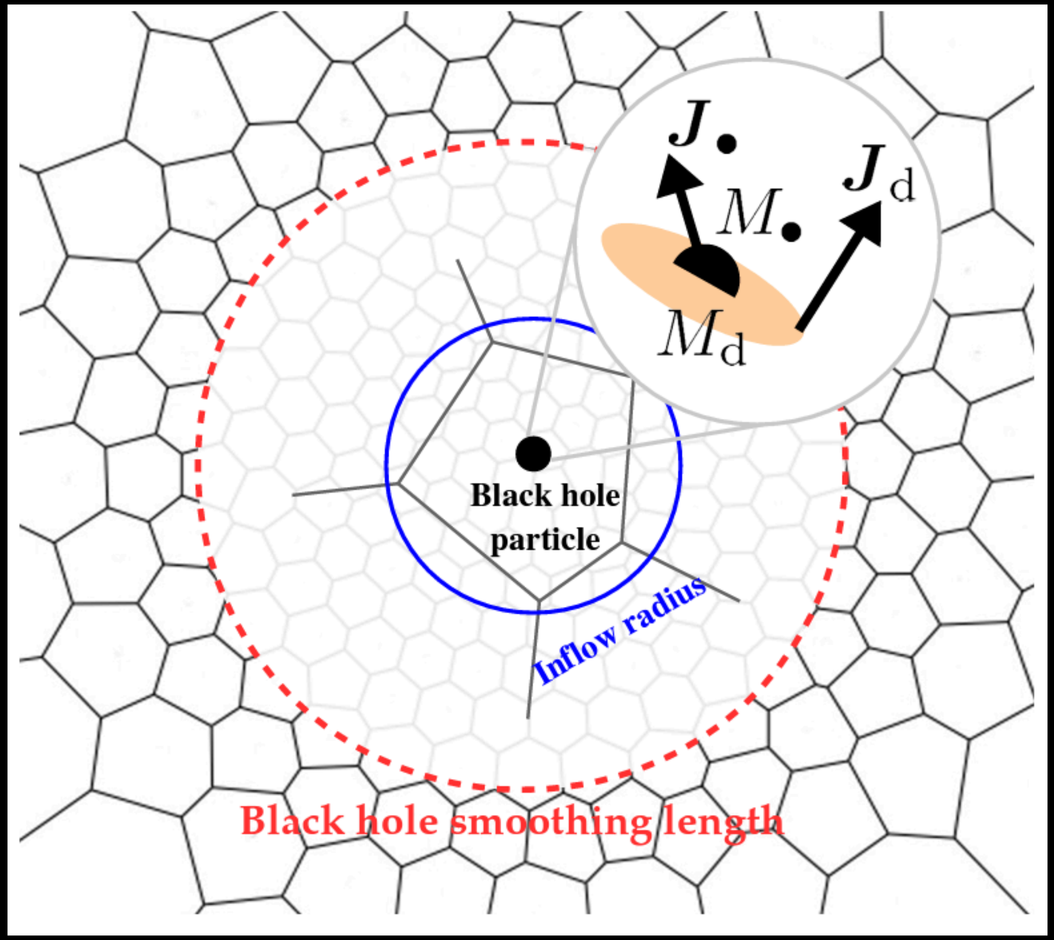
$$\frac{dM_d}{dt} = -\dot{M} + \dot{M}_{in}$$

$$\frac{dM_{BH}}{dt} = (1-\eta)\,\dot{M}_{BH,0}$$

**DISC ANGULAR MOMENTUM $J_d$ AND BH SPIN $J_{BH}$ EVOLUTION:**

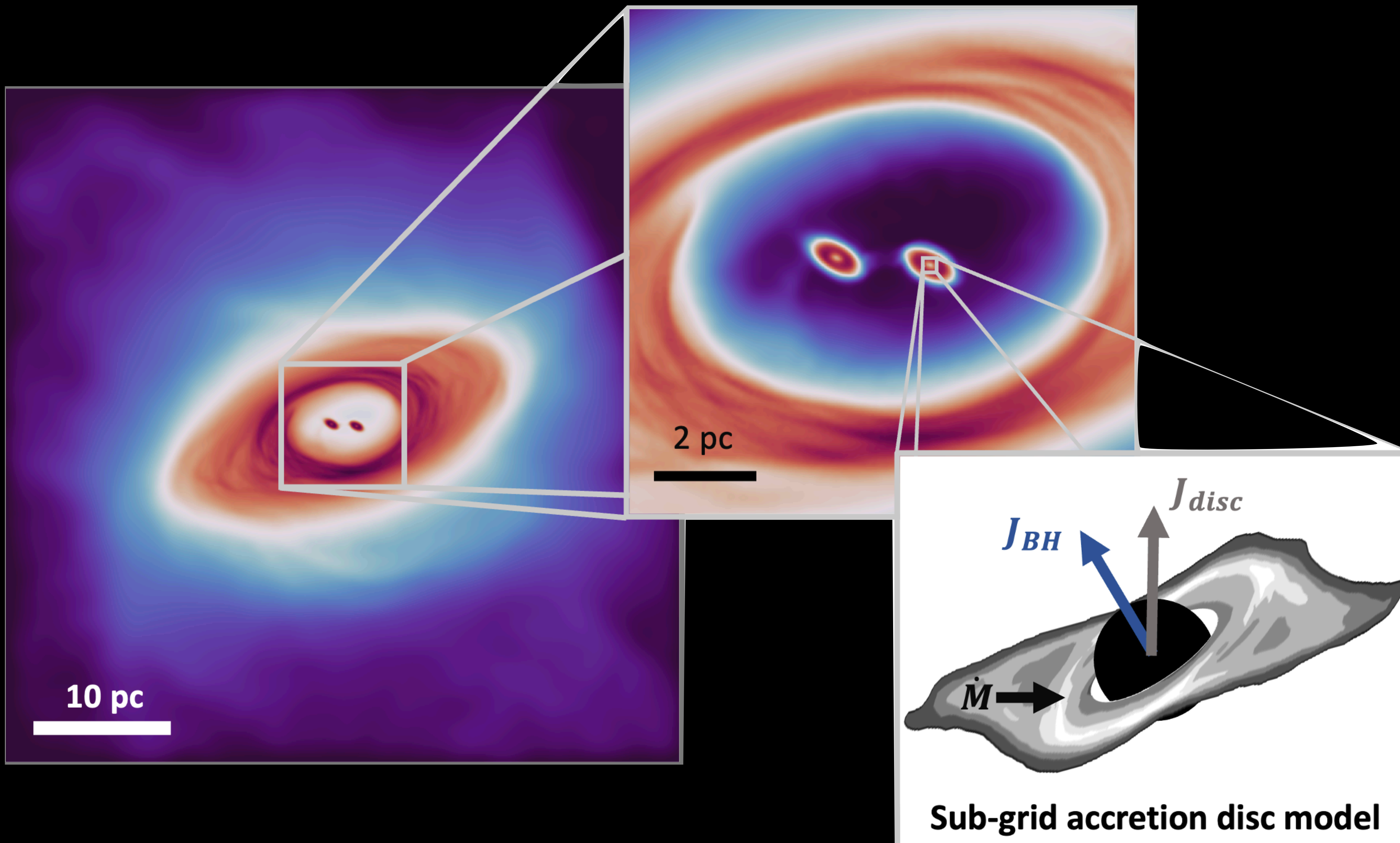
$$\frac{d\mathbf{J}_d}{dt} = -\dot{M}\,L_{ISCO}\,\mathrm{sign}(\mathbf{j}_{BH}\cdot\mathbf{j}_d)\,\mathbf{j}_{BH} - \left.\frac{d\mathbf{J}_{BH}}{dt}\right|_{LT} + \dot{\mathbf{J}}_{in}$$

$$\frac{d\mathbf{J}_{BH}}{dt} = \dot{M}_{BH,0}\,L_{ISCO}\,\mathrm{sign}(\mathbf{j}_{BH}\cdot\mathbf{j}_d)\,\mathbf{j}_{BH} + \left.\frac{d\mathbf{J}_{BH}}{dt}\right|_{LT}$$




(See also e.g., Dubois+14, Bustmante+19, Cenci+21, Husko+22, **Koudmani+24**)

# SMBH BINARIES IN GAS RICH CIRCUMBINARY DISCS



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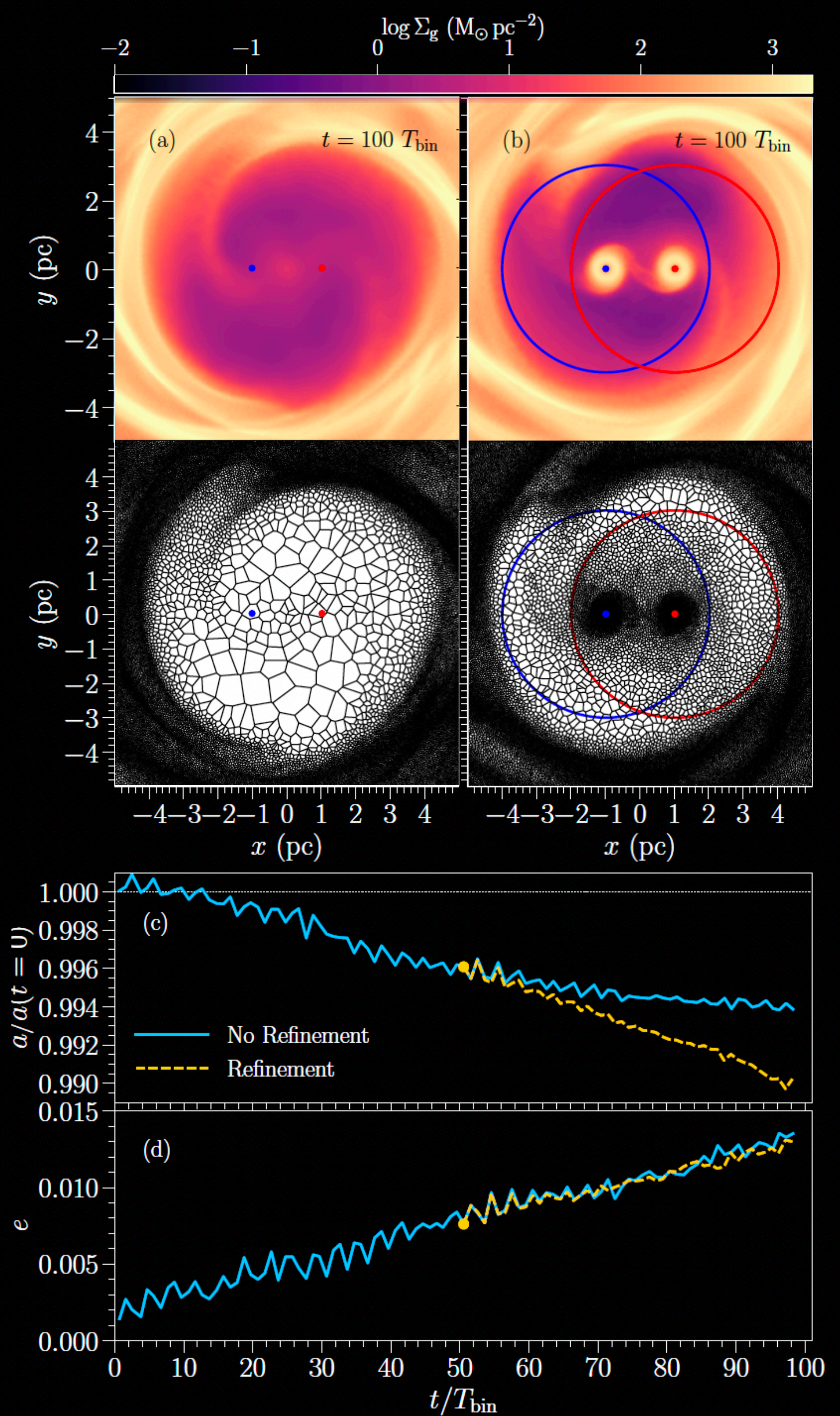



Perform simulations for a range of binary parameters using moving mesh code Arepo (Springel 10, Pakmor+16)

$M_{\rm bin} = M_{\bullet 1} + M_{\bullet 2} = 2 \times 10^6 M_\odot$ $\quad e = 0$ or $0.5$

$M_{\rm cbd}/M_{\rm bin} = 0.1$ $\quad i = 0^\circ,\ 45^\circ$ *or* $180^\circ$

$0.1 \lesssim q \equiv M_{\bullet 2}/M_{\bullet 1} \lesssim 1$

We include self-gravity and employ $\beta$-cooling such that

$$t_{\rm cool}(R) = \beta/\Omega_{\rm K}(R)$$

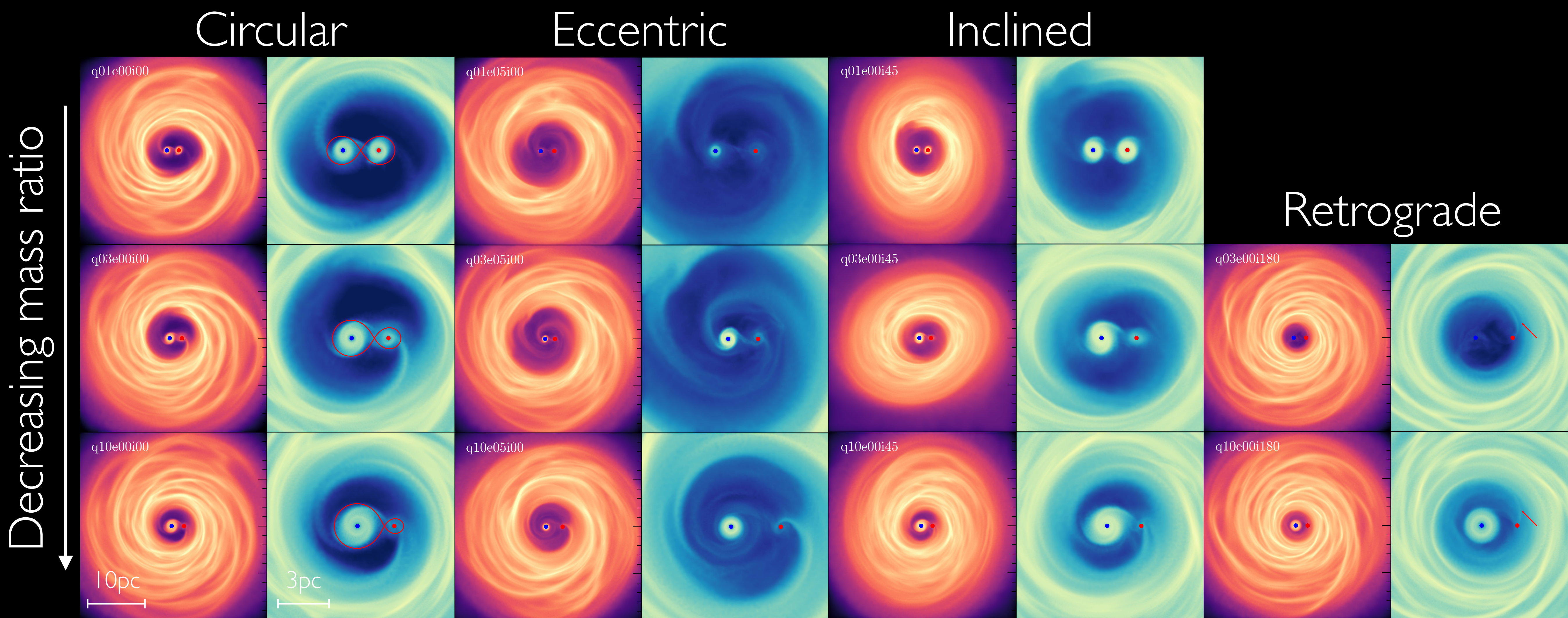
With $\beta = 10$ chosen to maintain disc in marginally stable configuration.

Can capture streams a mini-discs thanks to super-Lagrangian refinement technique (Curtis & Sijacki 15, 16)

(See also ***Cuadra+09, Roedig+2012***, Farris+14, Duffell+20, Munoz+20, D'Orazio+21, ***Franchini+21***, Siwek+23, Tiede+23)

Bourne et al. 2024 MNRAS

# GENERAL PROPERTIES




Minidiscs typically size of Roche-Lobe (see Artymowicz+1994), although high eccentricities lead to truncated minidiscs.

Cavities are typically larger for high eccentricity and high q binaries.

Retrograde orbits unable to prevent mass inflow and``clear'' cavity.
(See Lodato+2009, Nixon+2011, Roedig & Sesana 14, Tiede & D'Orazio 23)

Limited formation of minidiscs in retrograde cases.

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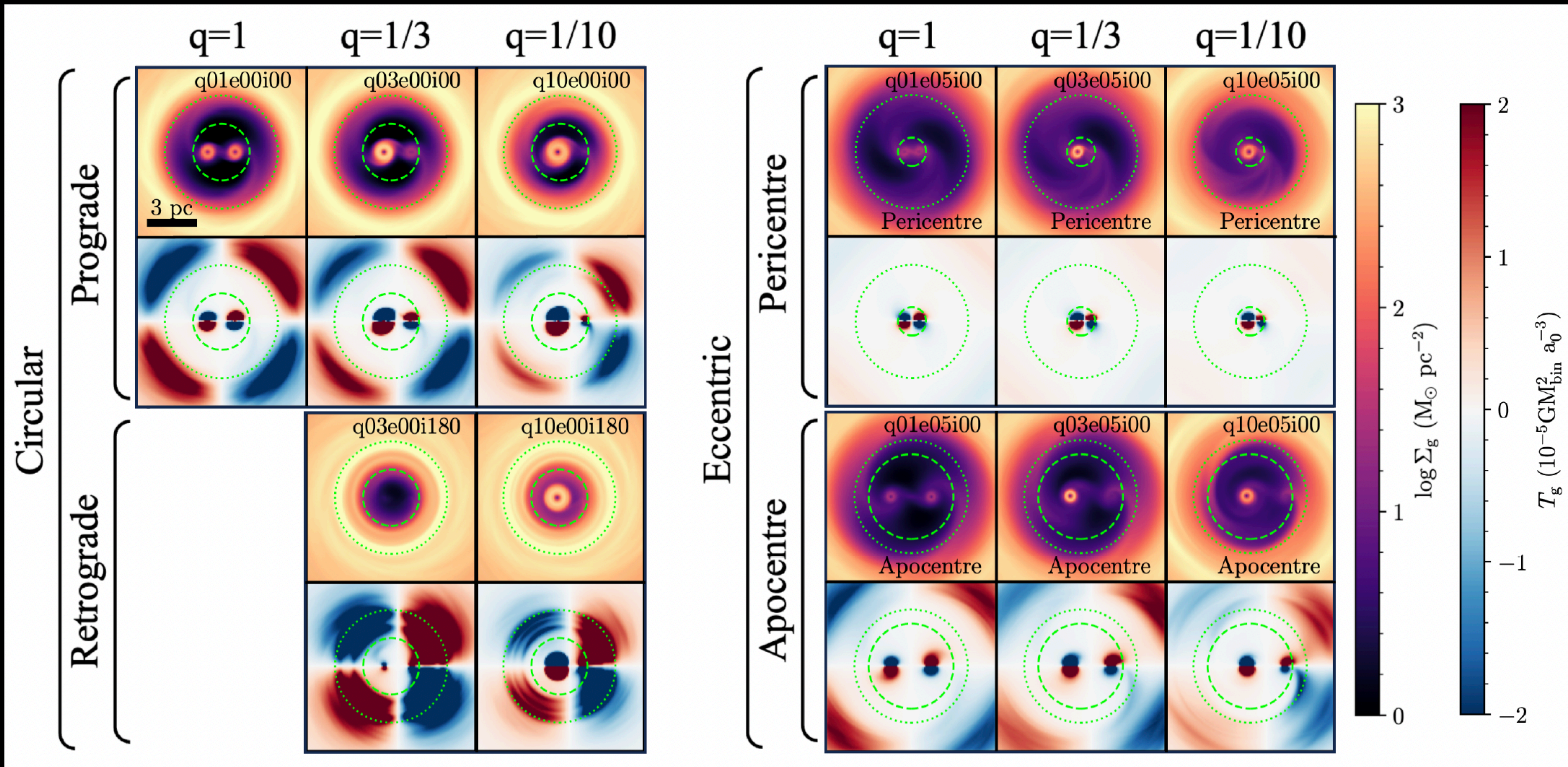
# GRAVITATIONAL TORQUES




**Prograde:** strong net torques from minidisc region (+ve) and streams/inner disc edge (-ve).
(See also Roedig+12, Tang+17, Munoz+19, Tiede+20)

**Retrograde:** strong net torques from minidisc region only (-ve)
(See also Tiede & D'Orazio 23)

In all cases net gravitational torque is negative and dominates over accretion torques.

These results likely sensitive to thermodynamics
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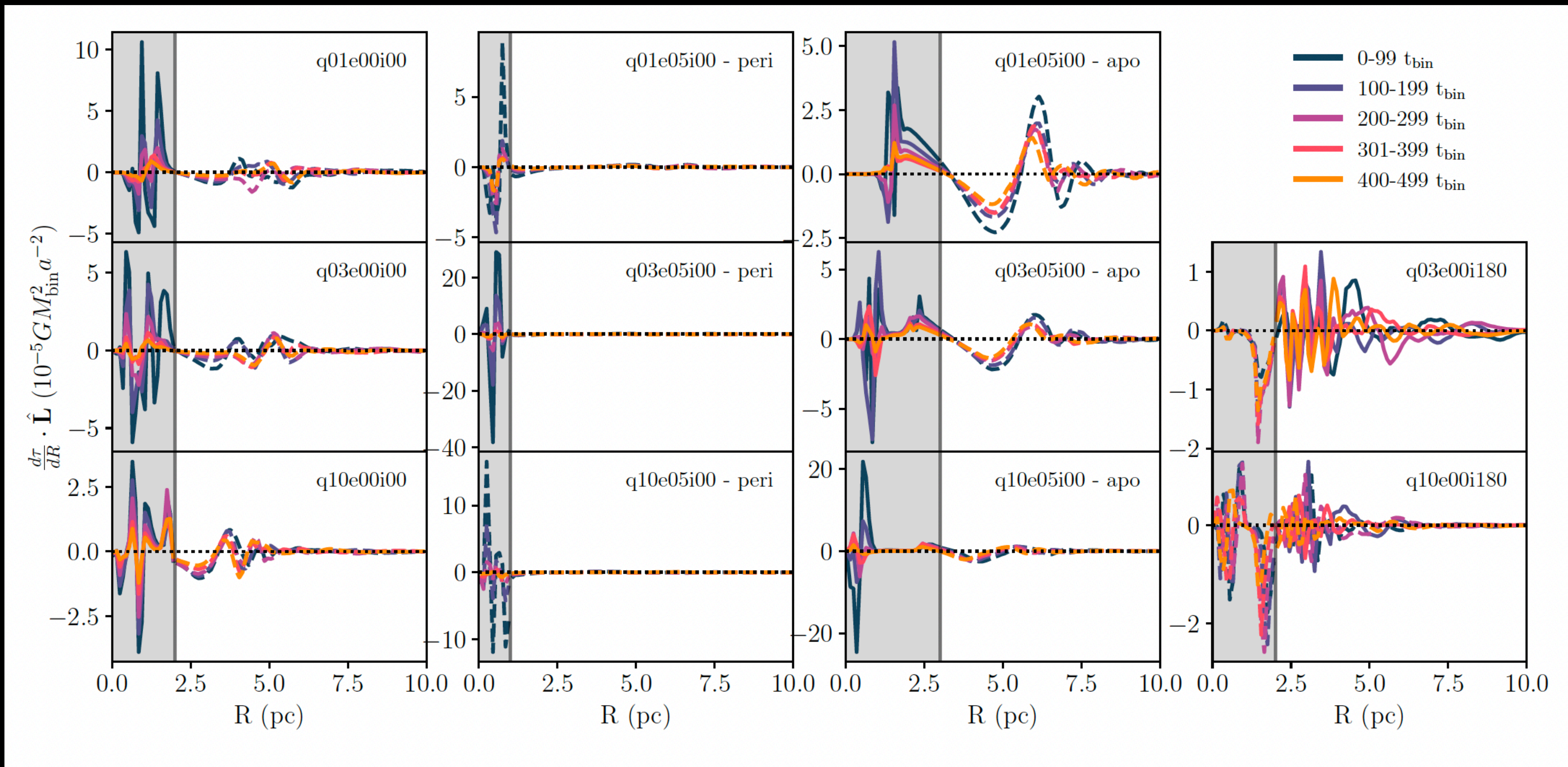


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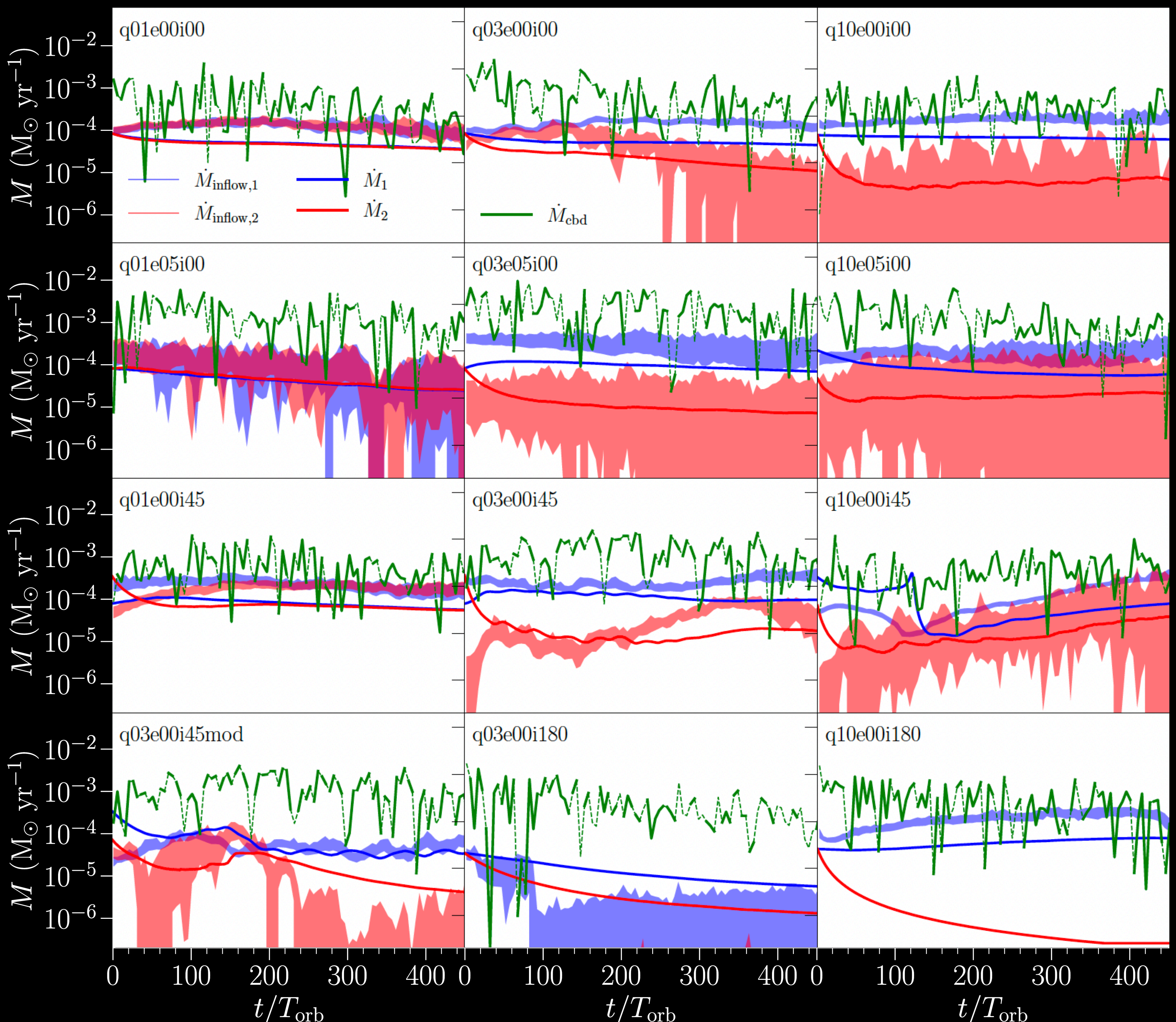
# BLACK HOLE GROWTH




Secondaries accrete more slowly than primaries - i.e. we don't find preferential accretion onto secondary. (contrary to e.g. Farris+2014, Munoz+2020, Siwek+2023)

Likely due to thermodynamics and viscosity. (see e.g. Ochi+05, Hanawa+10, Young+15, Dittman+24)

Inflow onto secondary typically fluctuates more than onto primary.

Final masses and mass ratios can have important impact on gravitational waves. (see e.g. Rajagopal & Romani 1995, Phinney 2001, Siwek+2020)

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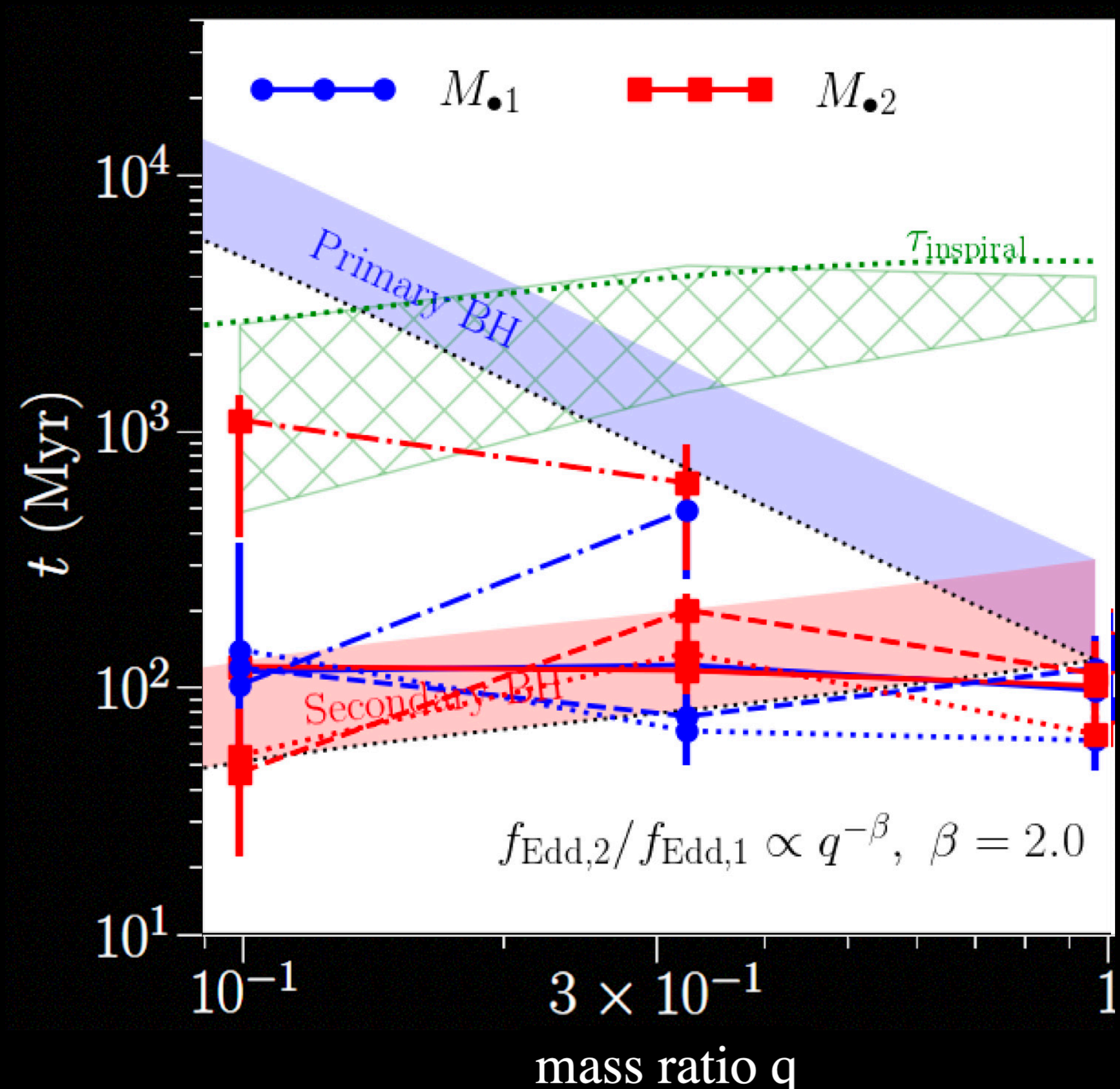
# SPIN ALIGNMENT

$$\tau_{\rm align} \approx 0.17 \left(\frac{M_\bullet}{10^6 M_\odot}\right)^{-2/35} \left(\frac{f_{\rm Edd}}{\eta_{0.1}}\right)^{-32/35} a_\bullet^{5/7} {\rm Myr}$$




Analytical curves from: Gerosa+2015

Inspiral times typically $\lesssim$ analytic expectation of Gerosa+15. Retrograde binaries shrink more quickly due to stronger negative torques.

Timescale on which we expect BH spin to align with accretion disc angular momentum typically much shorter than inspiral timescale.

Spin alignment when merging can impact recoil velocities, and hence gravitational wave detection rates
(e.g., Gonzalez+2007, Lousto+2011, Sperehake+2020)

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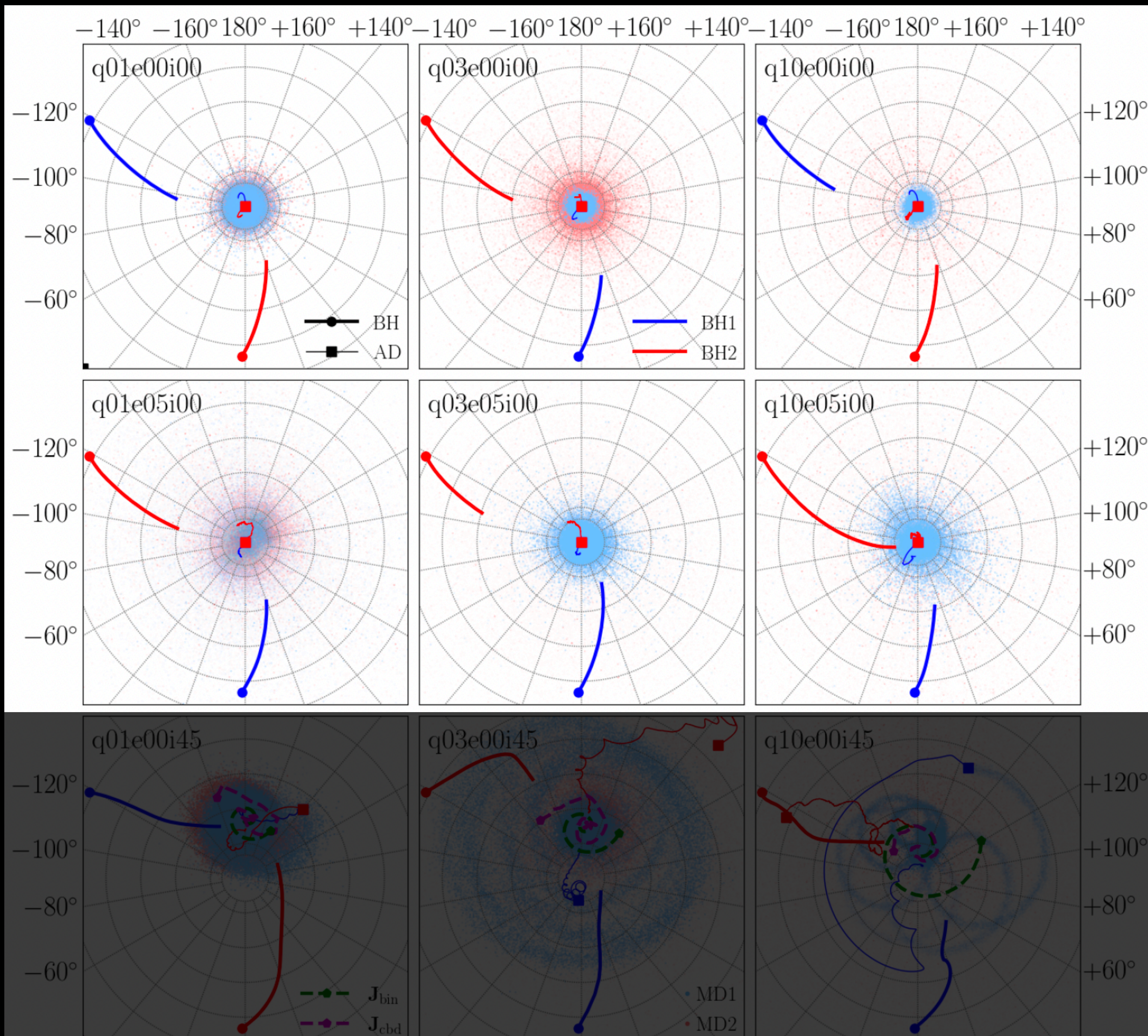
# SPIN EVOLUTION




Typically spin vectors move towards the CBD angular momentum vector.

More complex for inclined binary, the CBD warps with the CBD & binary angular momentum tending toward each other

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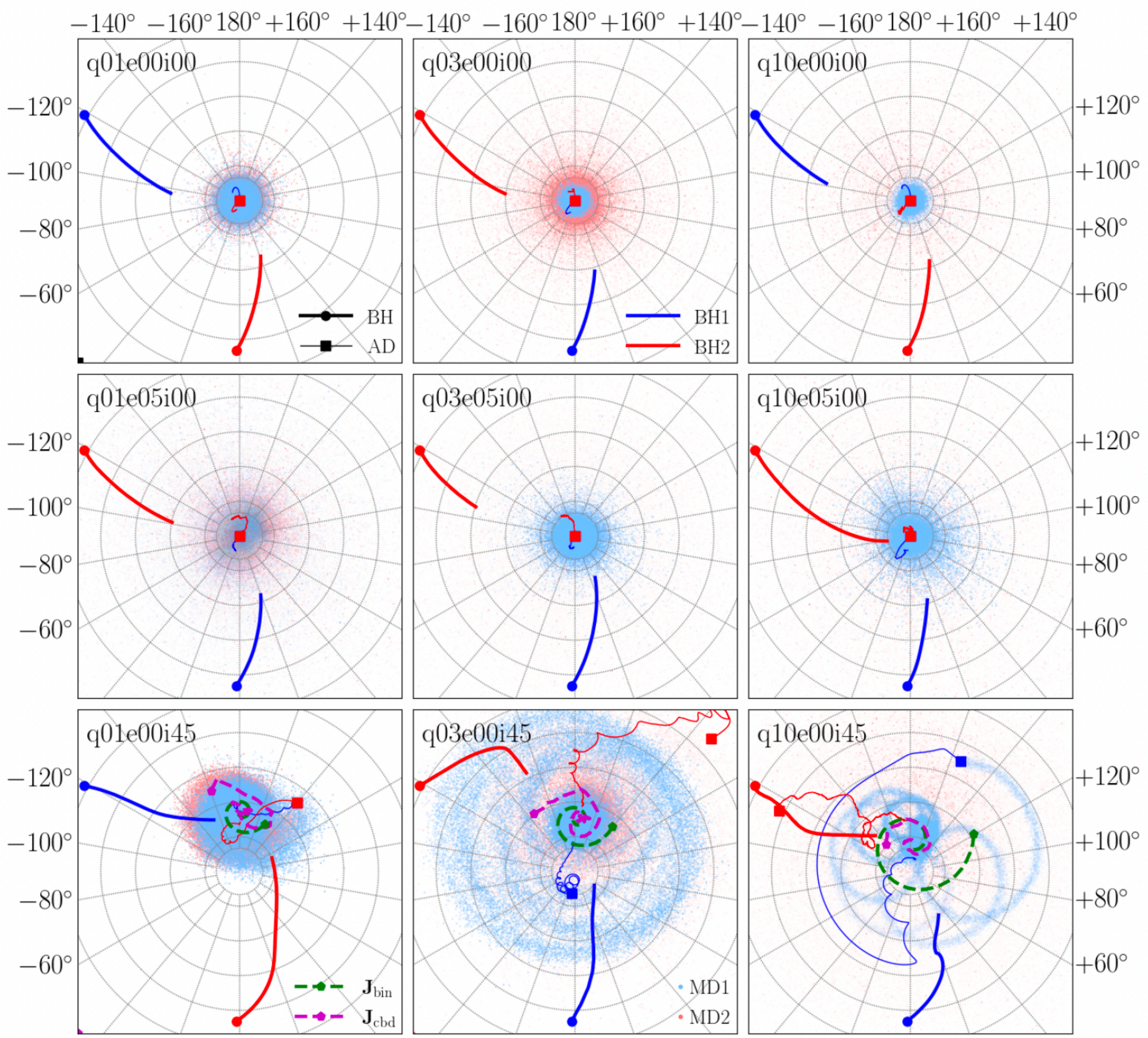


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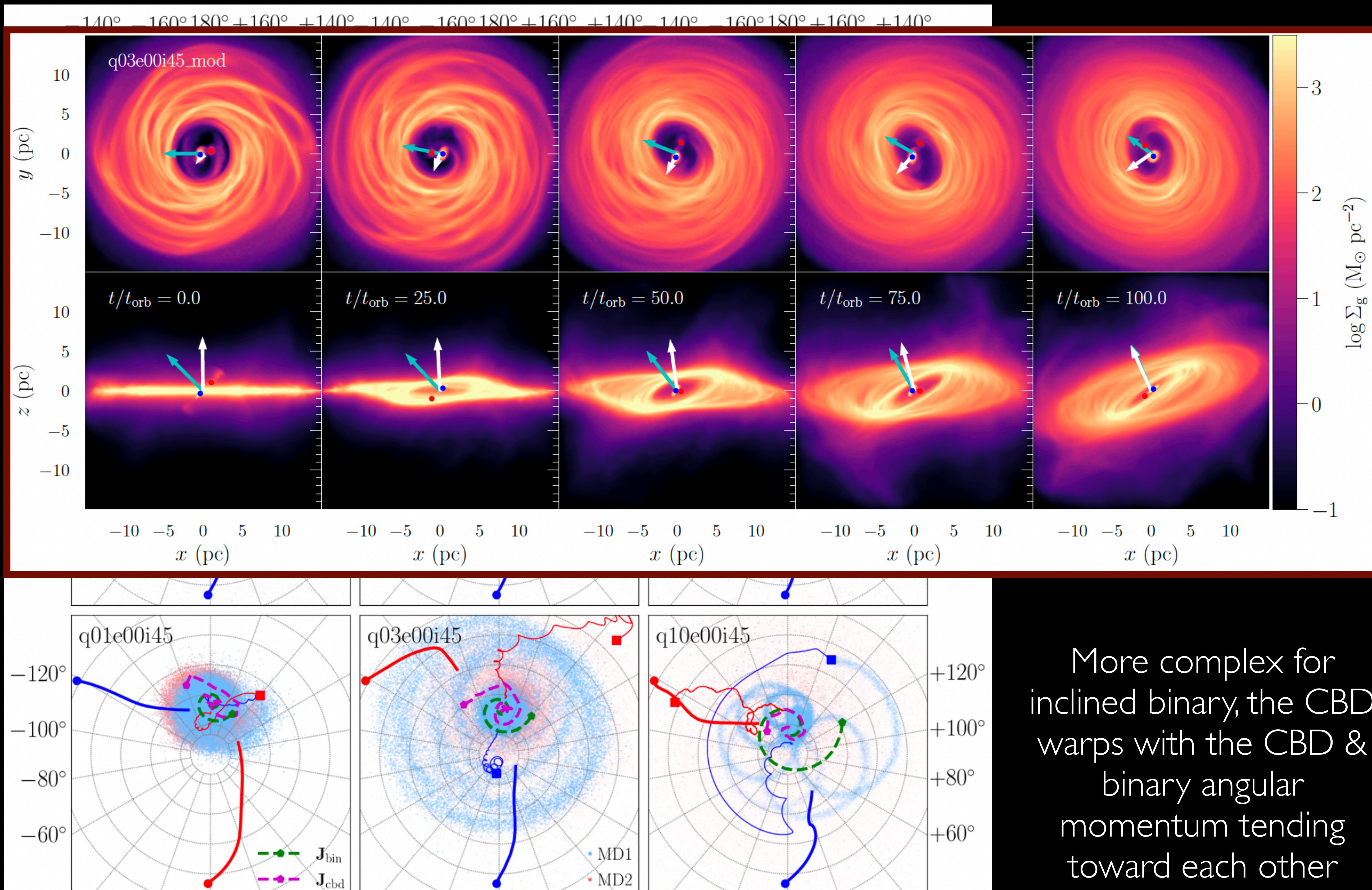


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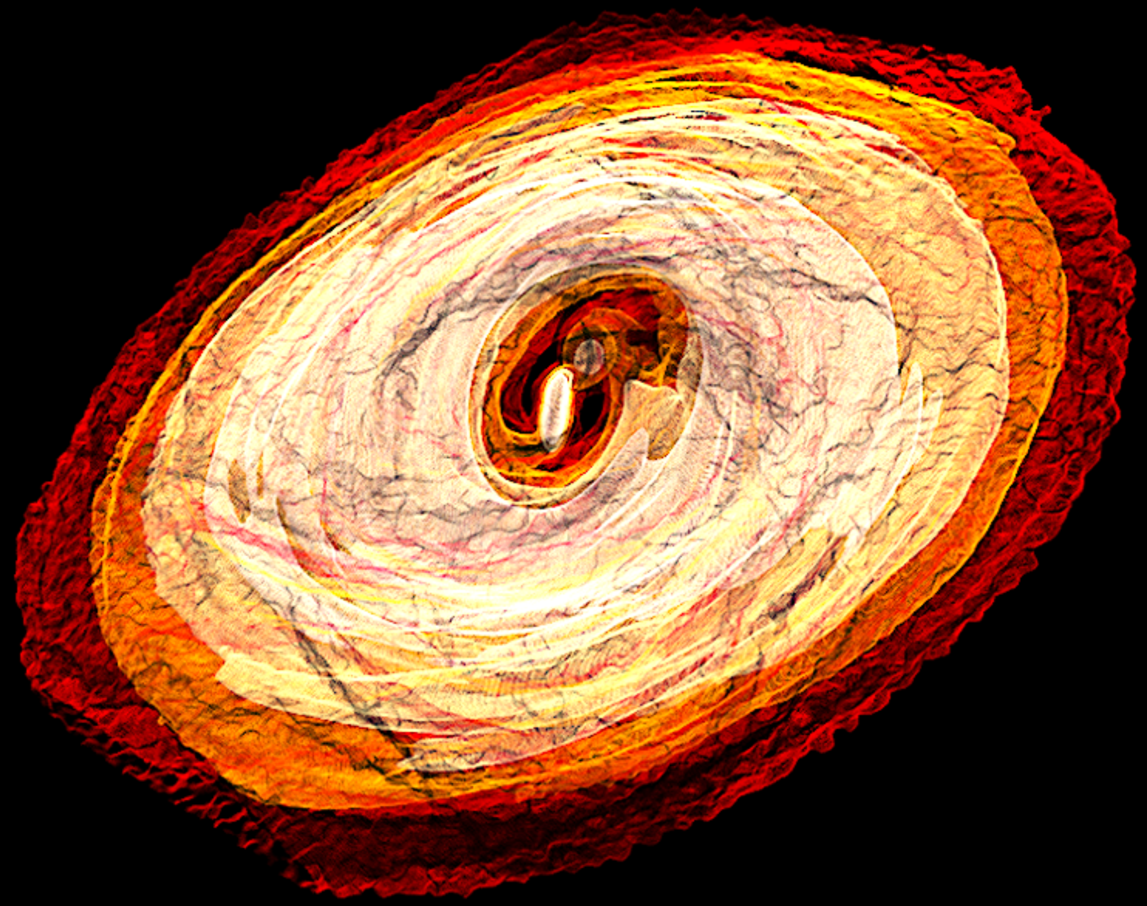
# SUMMARY

- New simulations of SMBH binaries in gas-rich CBDs use super-lagrangian refinement to capture mini-discs and streams in the cavity - which contribute to gravitational torques and binary evolution.

- For our setup, gravitational torques dominate the angular momentum evolution of the binaries, with accretion being sub-dominant - binaries shrink in all cases - retrograde binaries shink more rapidly.

- Unlike many previous works, we do not find preferential accretion onto the secondary, likely due to the gas thermodynamics and viscosity - further investigation is required.

- A subgrid accretion disc model allows us to track BH spin evolution - alignment timescales are typically shorter than the binary inspiral timescale - although initially misaligned CBDs may complicate the picture.



THANK YOU

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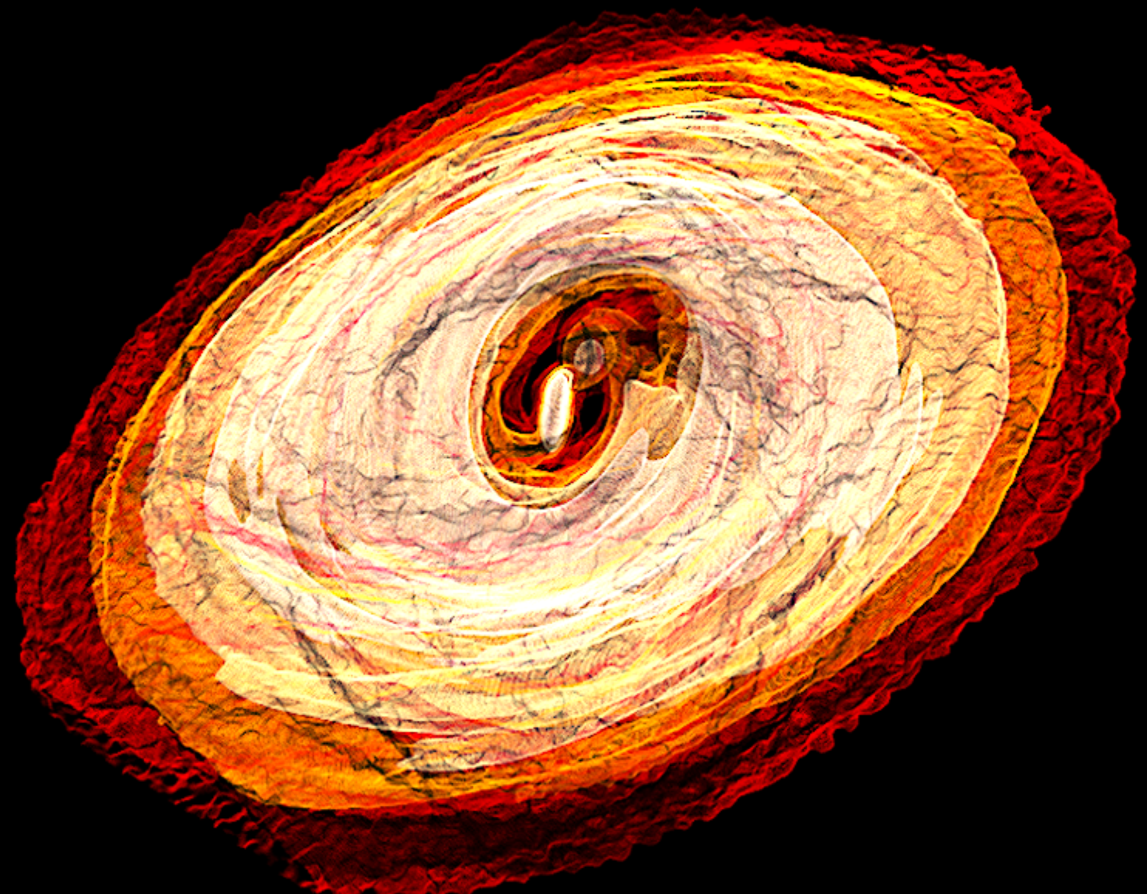

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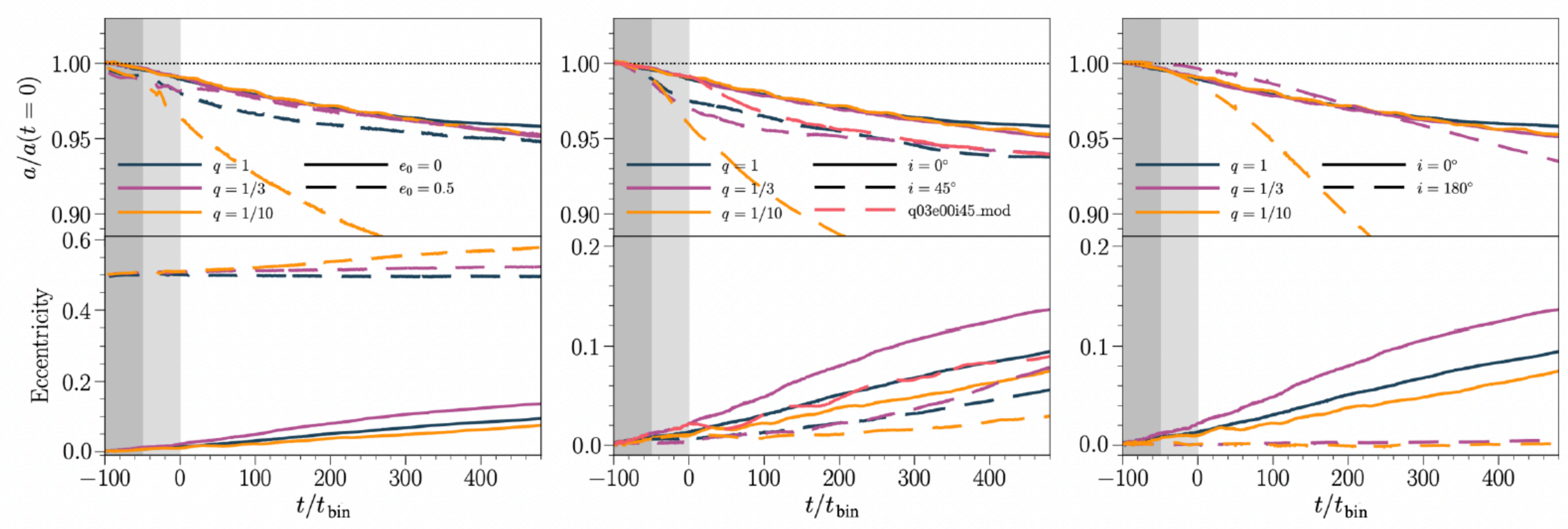
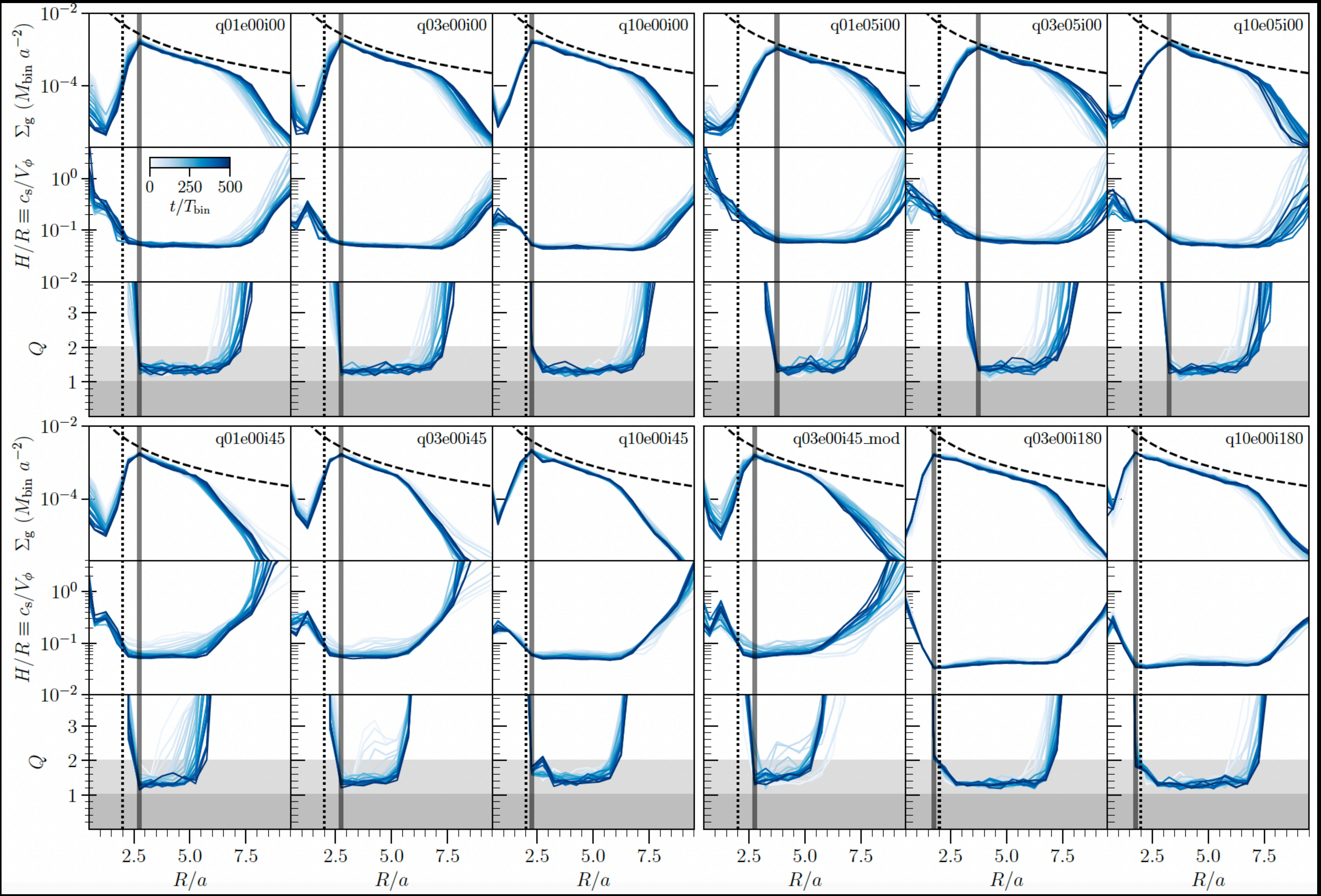
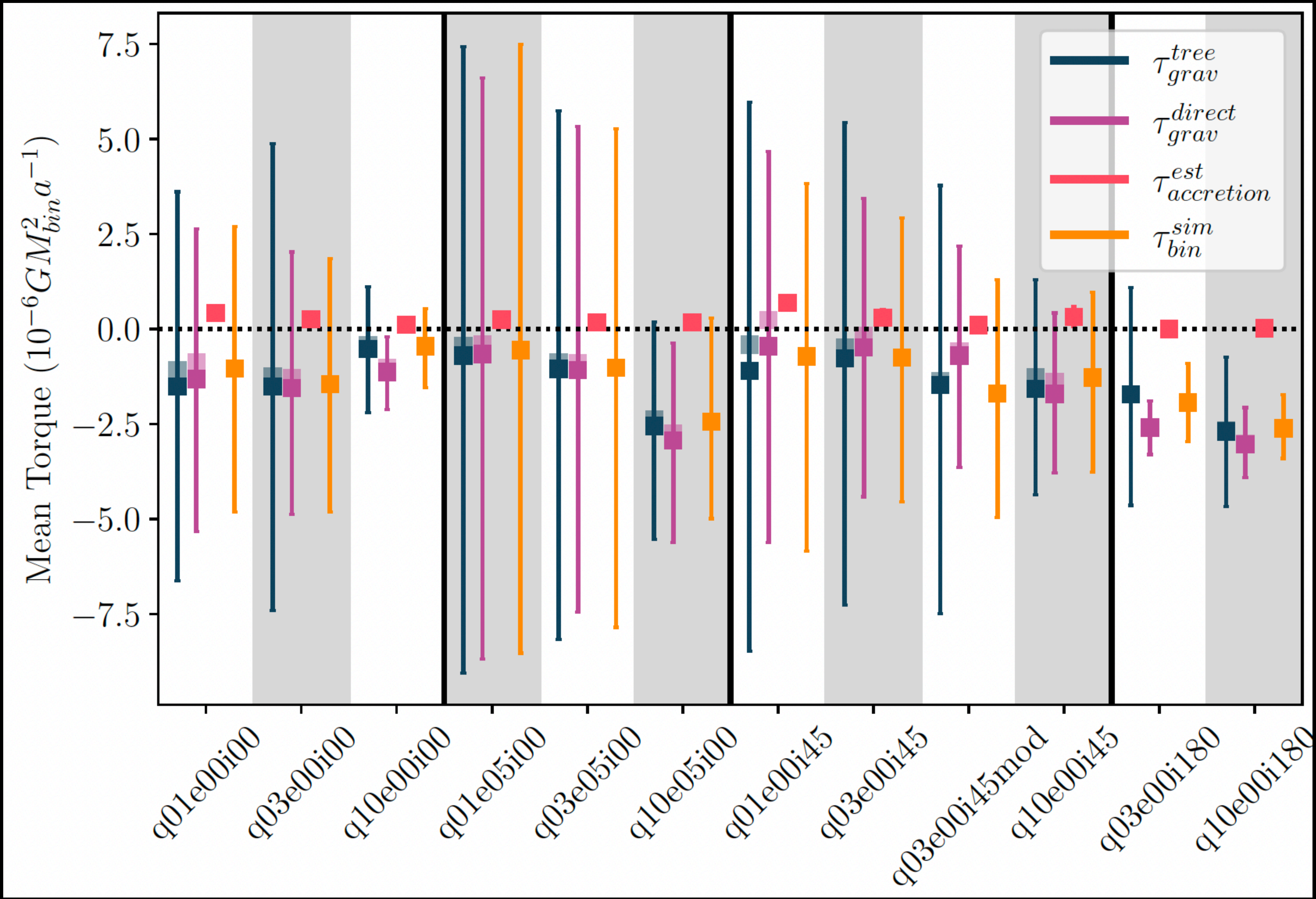


1.00
0.95
0.90
$a/a(t=0)$
$q=1$
$q=1/3$
$q=1/10$
$e_0=0$
$e_0=0.5$
0.6
0.4
0.2
0.0
Eccentricity
−100
0
100
200
300
400
$t/t_{\rm bin}$
$i=0°$
$i=45°$
q03e00i45_mod
$i=180°$
0.1


q01e00i00
q03e00i00
q10e00i00
q01e05i00
q03e05i00
q10e05i00
q01e00i45
q03e00i45
q10e00i45
q03e00i45_mod
q03e00i180
q10e00i180
$\Sigma_{\rm g}\ (M_{\rm bin}\ a^{-2})$
$H/R \equiv c_{\rm s}/V_\phi$
$Q$
$t/T_{\rm bin}$
0
250
500
$R/a$
2.5
5.0
7.5
$10^{-2}$
$10^{-4}$
$10^{0}$
$10^{-1}$
1
2
3



Mean Torque $(10^{-6} GM_{bin}^2 a^{-1})$
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
$\tau_{grav}^{tree}$
$\tau_{grav}^{direct}$
$\tau_{accretion}^{est}$
$\tau_{bin}^{sim}$
q01e00i00
q03e00i00
q10e00i00
q01e05i00
q03e05i00
q10e05i00
q01e00i45
q03e00i45
q03e00i45mod
q10e00i45
q03e00i180
q10e00i180