Black-hole spin alignment and disk breaking: consequences for LISA

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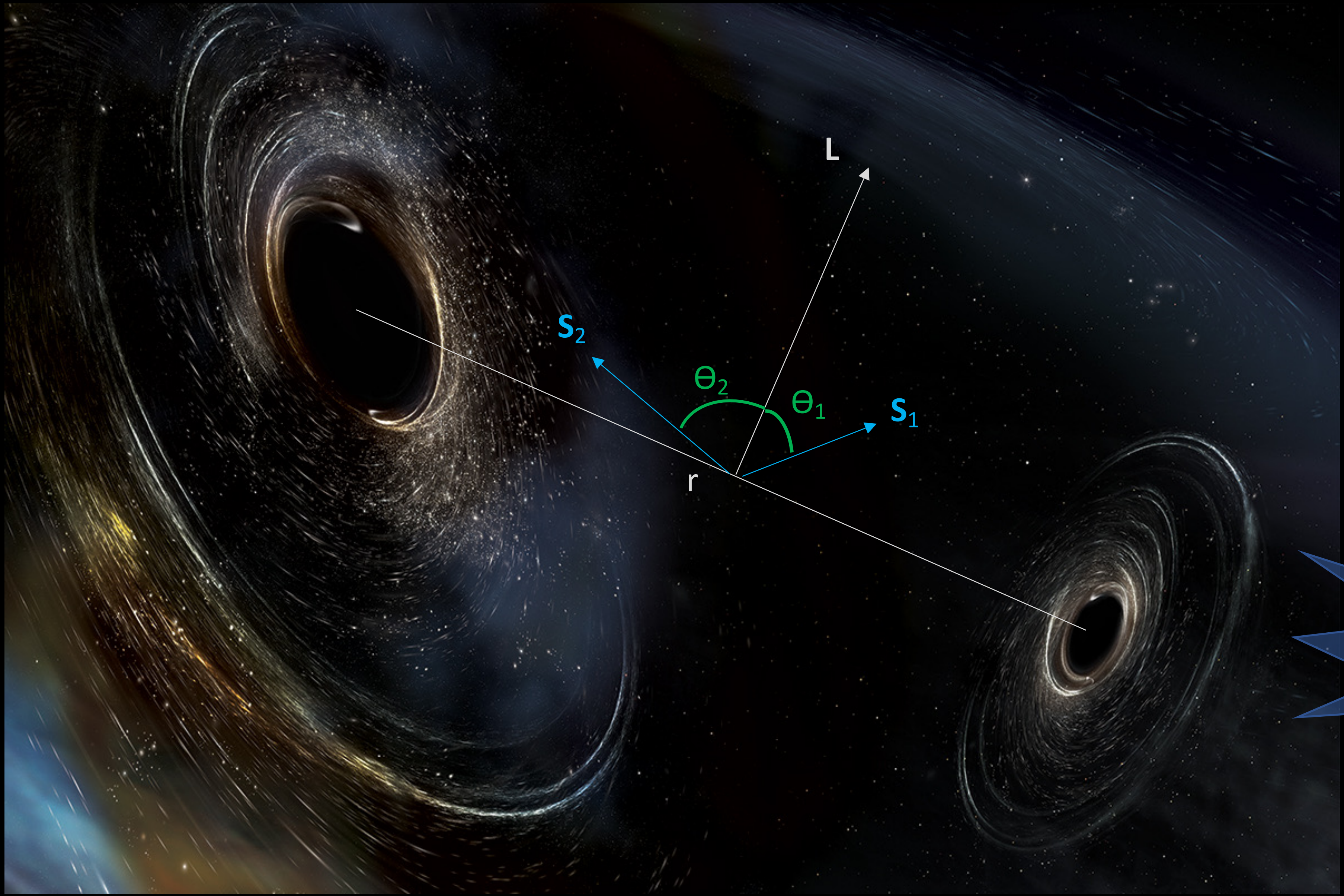
https://www.ligo.caltech.edu/mit/image/ligo20170601b



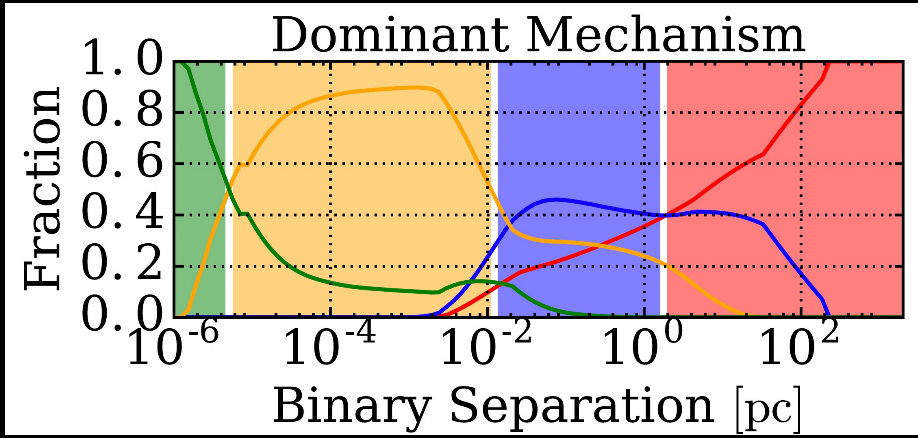
$$\chi = \frac{c|\mathbf{S}|}{Gm^2}$$

$$\cos\theta = \hat{\mathbf{S}} \cdot \hat{\mathbf{L}}$$

Binary Black-Hole (BBH)

Supermassive BBHs evolve in **gas-poor** or **gas-rich** galactic hosts.

LISA may discriminate these formation channels
[Bogdanovic *et al.*, 2007; Berti *et al.*, 2008; Sesana *et al.*, 2014; Gerosa *et al.*, 2015; Sayeb *et al.*, 2021].



Kelley *et al.*, 2017

Various processes drive the inspiral:

dynamical friction,

loss-cone scattering of individual stars,

viscous drag from disk migration **if in a gas-rich environment**,

and GW emission until merger [Begelman *et al.*, 1980].

If BBHs form with isotropic spin directions θ_1 and θ_2, i.e., no alignment during dynamical friction phase, then…

… in **gas-poor hosts** they remain roughly isotropic [Bogdanovic *et al.*, 2007; Barausse, 2012] and through GW emission [Bogdanovic *et al.*, 2007; Gerosa *et al.*, 2015]

- ➢ spin precession is generic, i.e., precession and nutation of **L**.

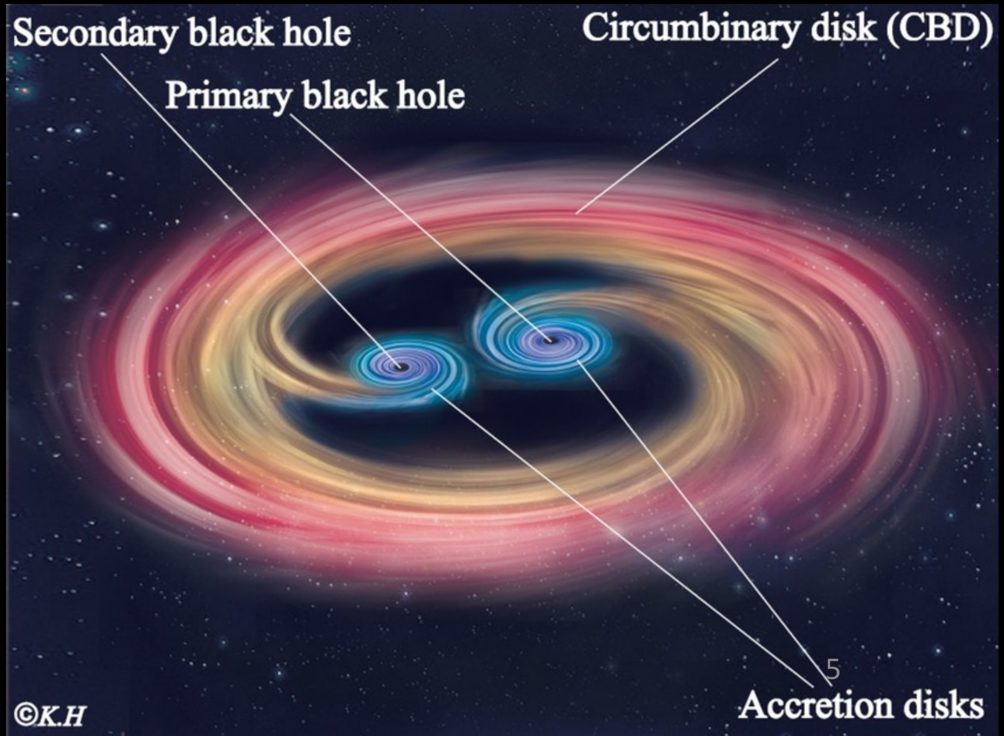
In **gas-rich hosts,** the Bardeen-Petterson effect can align the spins during disk migration.

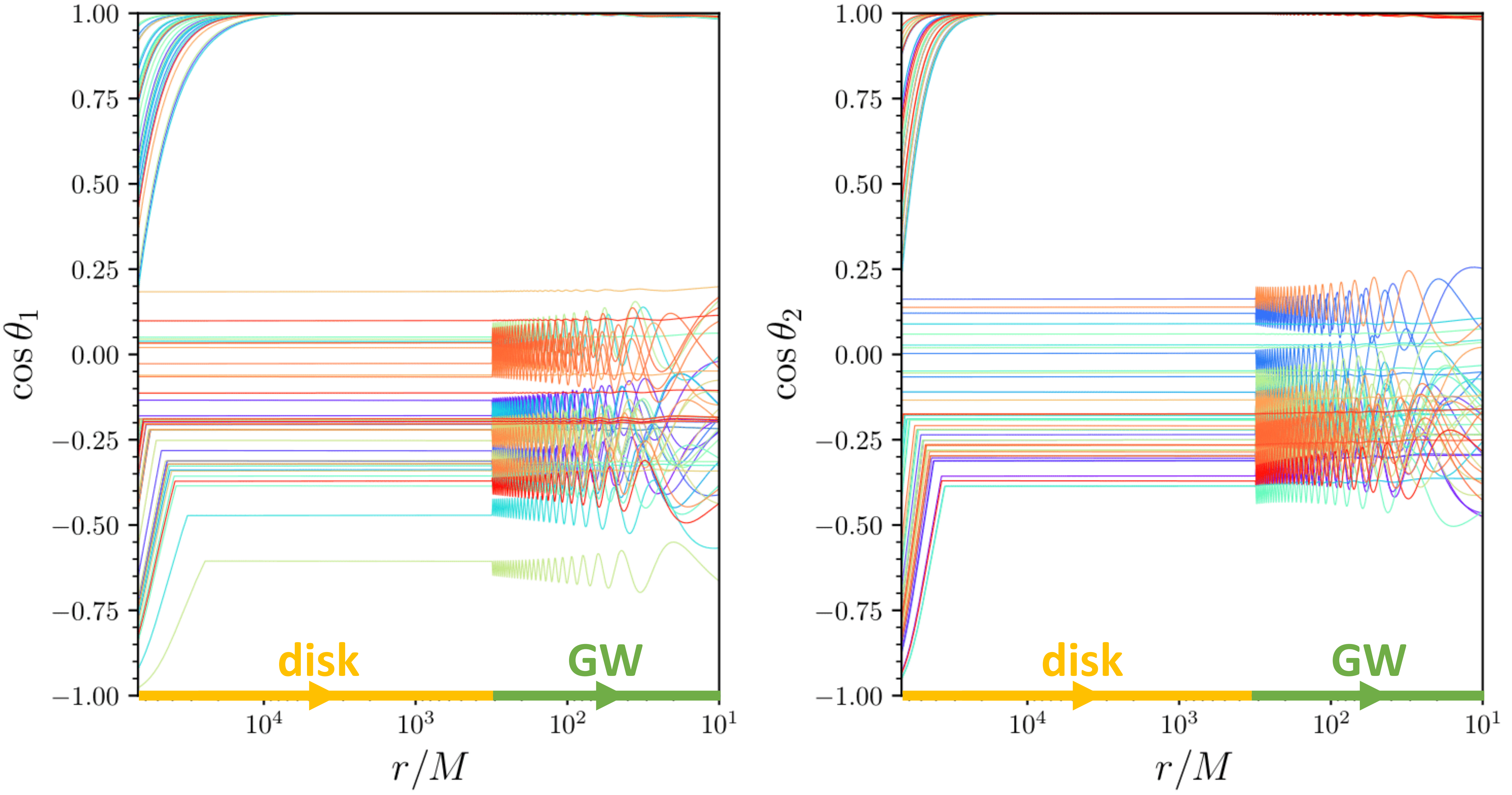
- ➢ but this is uncertain!

We examine circumbinary disk migration of BBHs with a systematic approach to the Bardeen-Petterson effect [Gerosa *et al.*, 2020; etc.]:

- accretion from minidisks can align the (initially isotropic) spins

- disk breaks at a critical angle $\theta_{crit} \sim {}^{\pi}/_{2}$ where alignment ceases
[Nixon *et al.*, 2012; Tremaine & Davis, 2014; Nealon *et al.*, 2015; Nealon *et al.*, 2022]





1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
$\cos\theta_1$
10^4
10^3
10^2
10^1
r/M
disk
GW
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
$\cos\theta_2$
10^4
10^3
10^2
10^1
r/M
disk
GW

1. κ governs the effect of the companion:
   - κ_i (initial κ) determines if spin begins at θ_{crit}

2. ω governs the relative contributions of inspiral and alignment:
   - Large $\omega \sim t_{inspiral}/t_{align}$ implies fast alignment

3. ω and κ depend on m_1 and m_2 so generally a binary has two of each
   - $\omega_1 \neq \omega_2$, and $\kappa_1 \neq \kappa_2$, i.e., equal masses imply $\omega_1 = \omega_2$, and $\kappa_1 = \kappa_2$

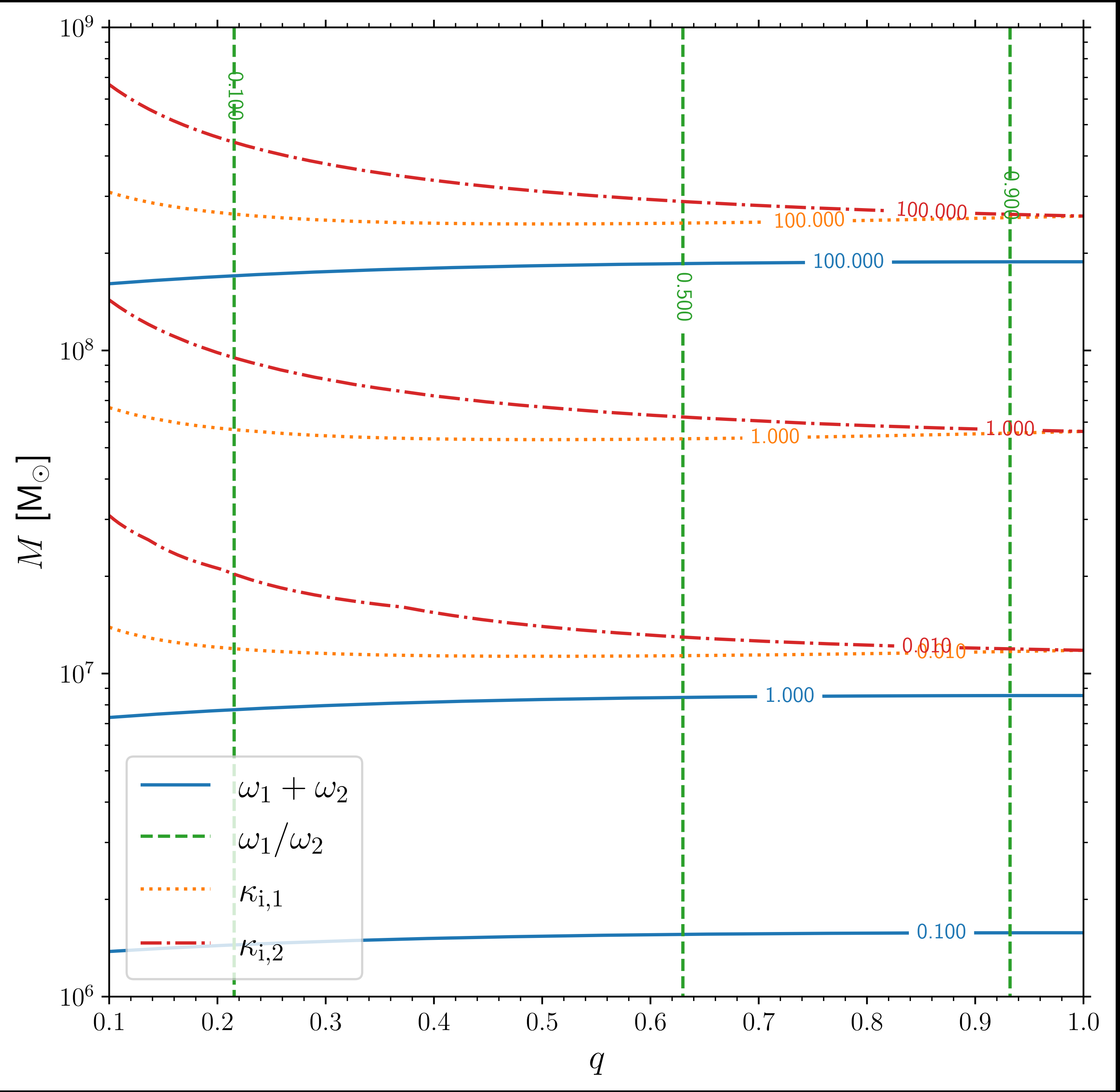
4. Reduce the full parameter space to 5 parameters: $\omega_1,\ \kappa_1,\ \omega_2,\ \kappa_2,\ \alpha$, then relate them to the BH masses and spins.

The dimensionless viscosity

It's more helpful to look at $\omega_1 + \omega_2$ and $\frac{\omega_1}{\omega_2}$

For larger total mass M, $\kappa_{i,1}$, $\kappa_{i,2}$ and $\omega_1 + \omega_2$ increase, implying more binaries reach critical angle and align quickly

As q → 1, $\kappa_{i,1} = \kappa_{i,2}$ and $\frac{\omega_1}{\omega_2} \to 1$ implying both black holes align quickly if $\omega_1 + \omega_2 \gtrsim 1$



For simplicity, assume here that $\kappa_{i,1} = \kappa_{i,2}$, and $\omega_1 = \omega_2 = 1$.

Larger κ_i increases the area of the black box

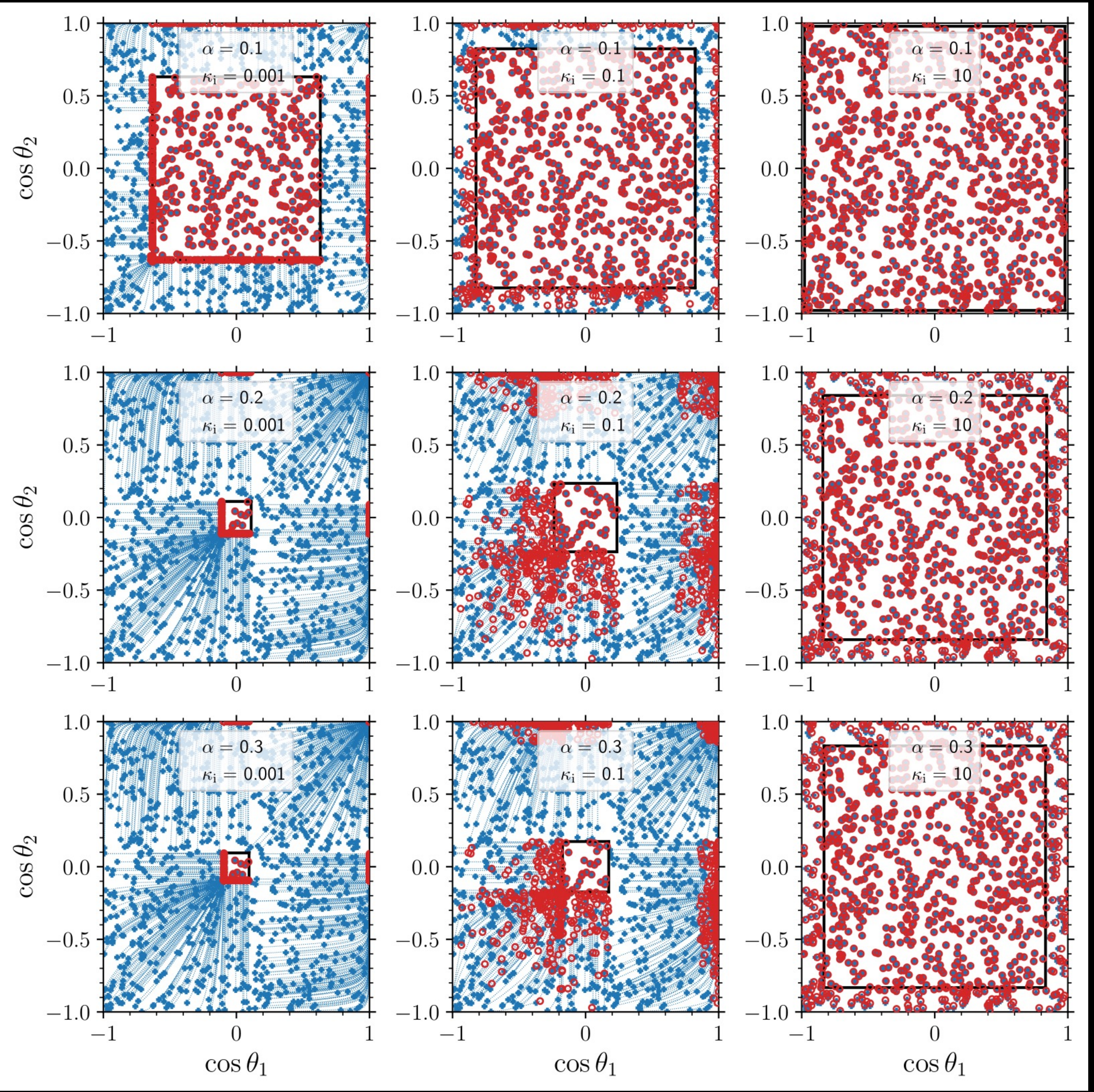
Small α is indistinguishable from gas-poor formation channel due to critical angle

κ_i = 0.001 κ_i = 0.1 κ_i = 10

α = 0.1

α = 0.2

α = 0.3



Assume $\alpha = 0.2$ and $\kappa_i = 0.1$

For $\omega_1 + \omega_2 < 1$ binaries don't align

For $\omega_1 + \omega_2 \gtrsim 1$ binaries can align quickly

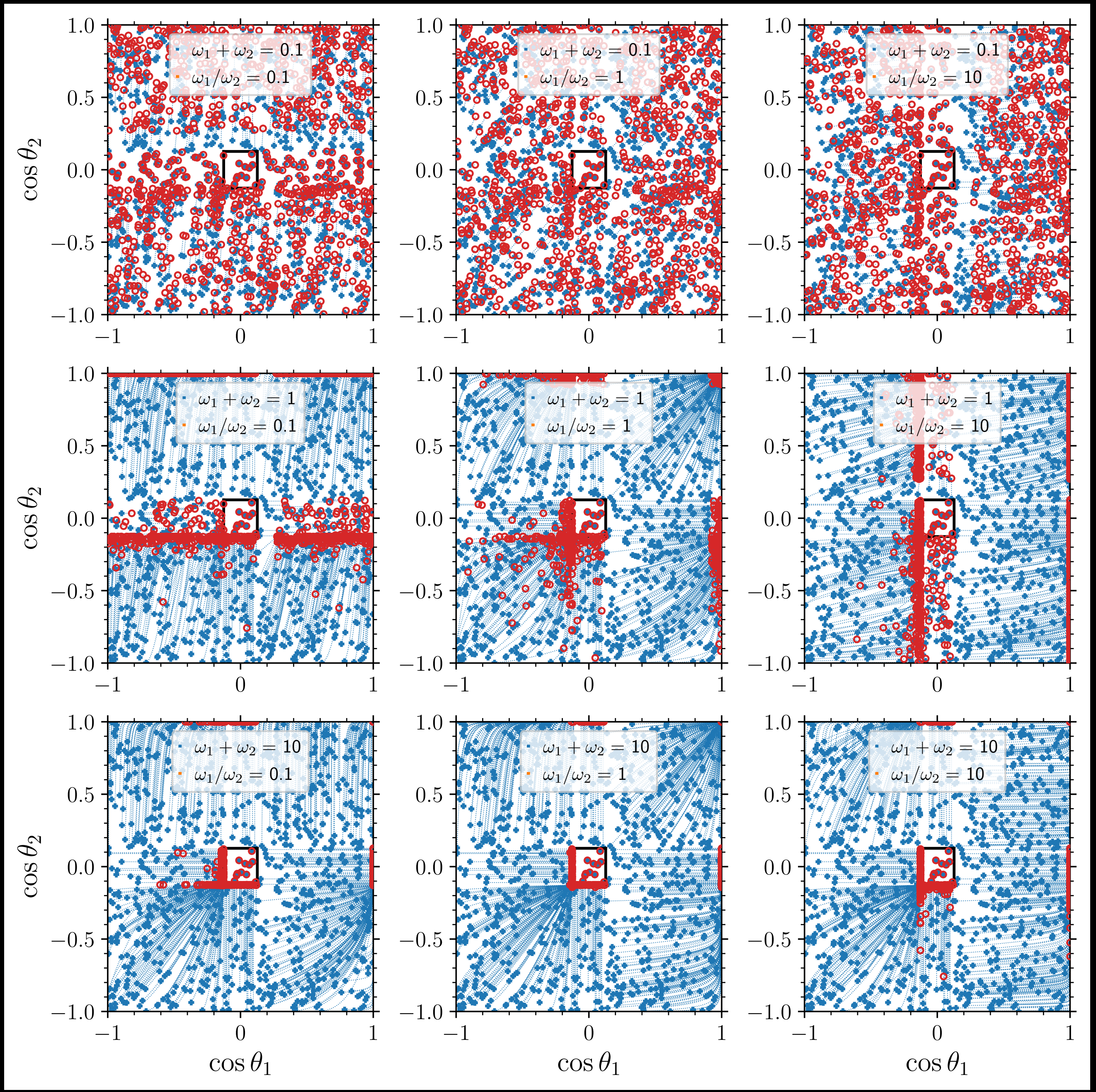
$\frac{\omega_1}{\omega_2} < 1$ $\left(\frac{\omega_1}{\omega_2} > 1\right)$ causes secondary (primary) to align quicker

$\omega_1/\omega_2 = 0.1$ | $\omega_1/\omega_2 = 1$ | $\omega_1/\omega_2 = 10$

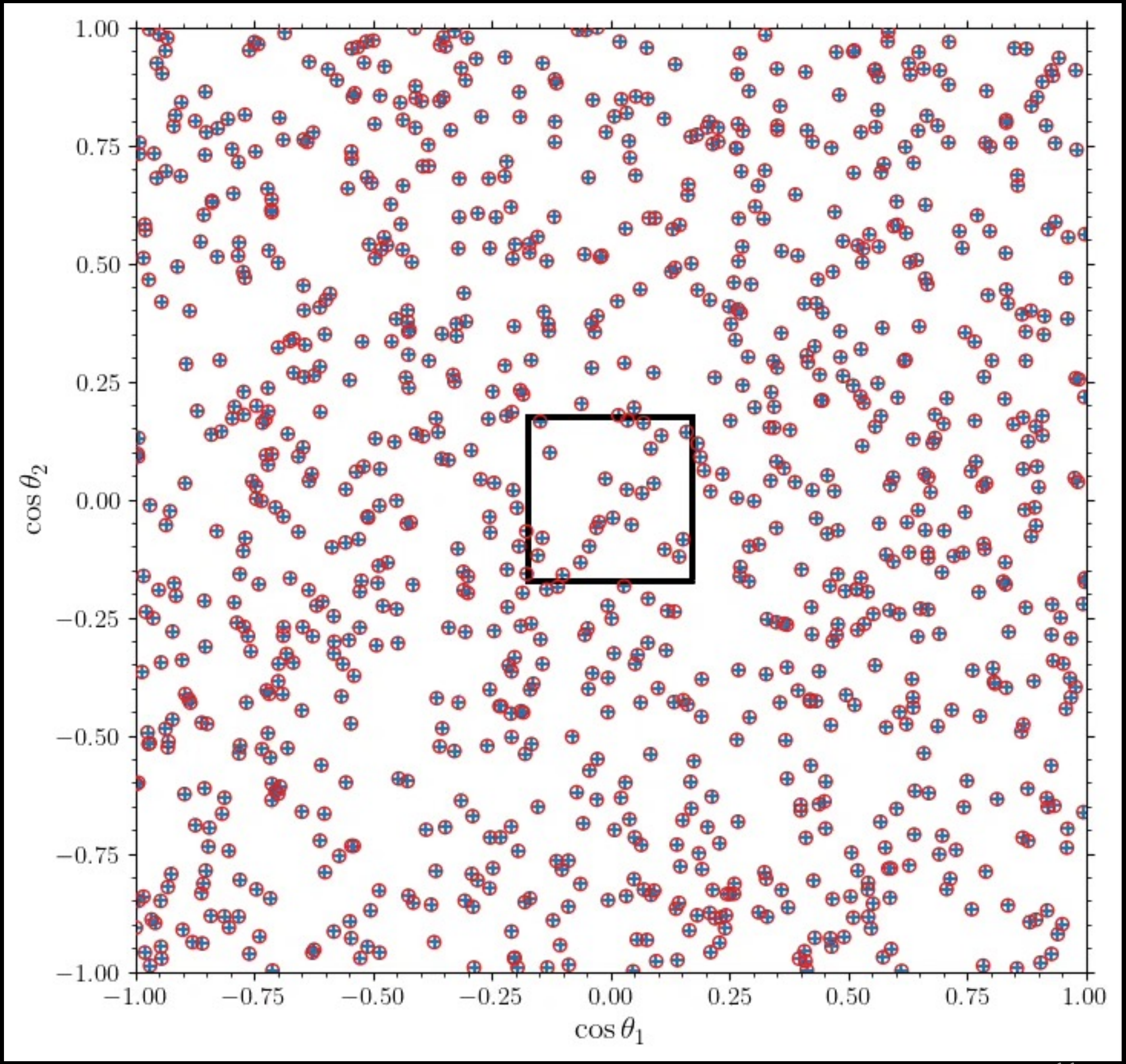
$\omega_1 + \omega_2 = 0.1$

$\omega_1 + \omega_2 = 1$

$\omega_1 + \omega_2 = 10$



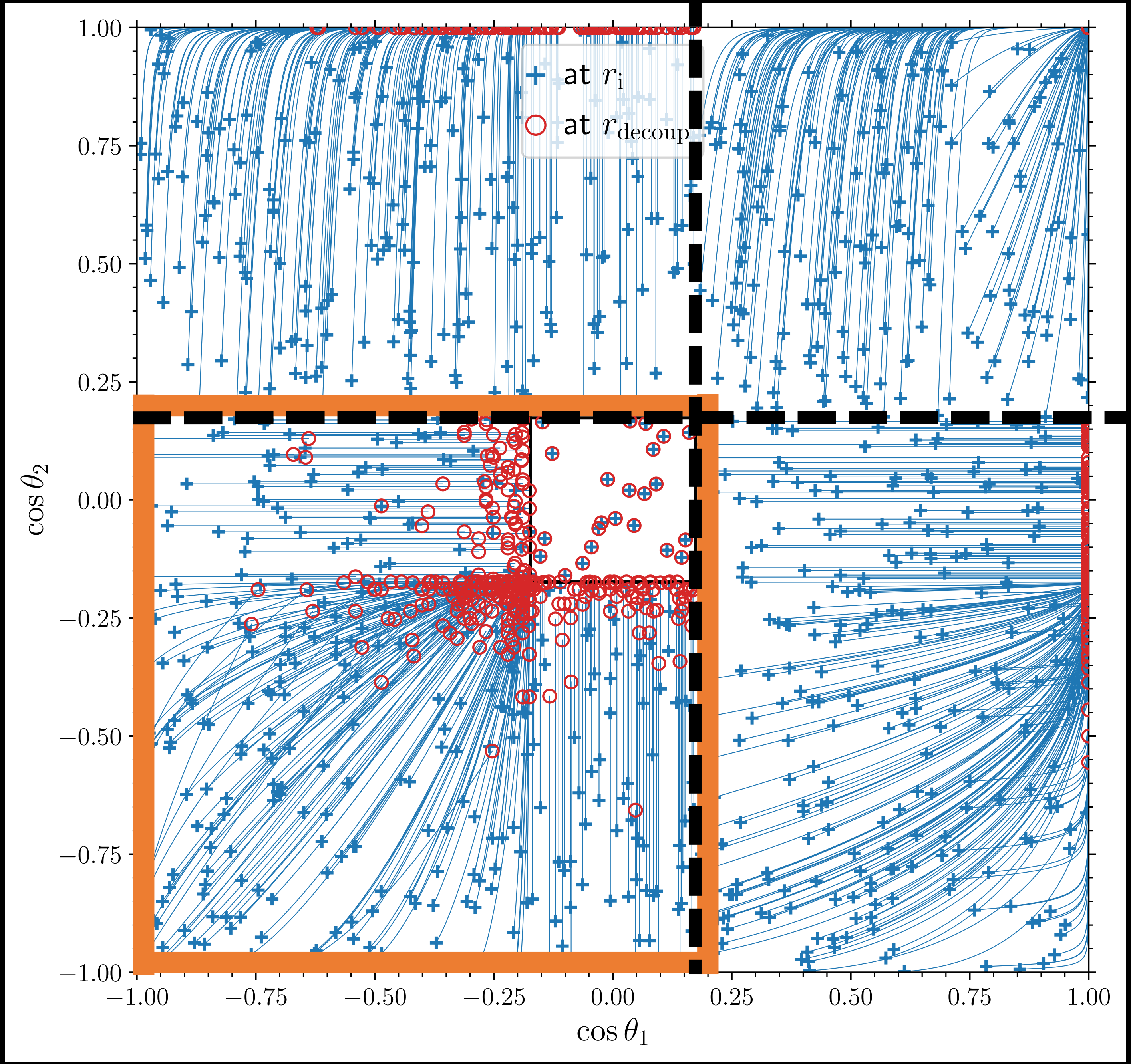
$M = 2{\times}10^7\ \mathrm{M}_\odot$,
$q = 0.8$,
$\chi_1 = \chi_2 = 0.1$,
$\alpha = 0.2$



$M = 2{\times}10^7\ \mathrm{M}_\odot$,
$q = 0.8$,
$\chi_1 = \chi_2 = 0.1$,
$\alpha = 0.2$

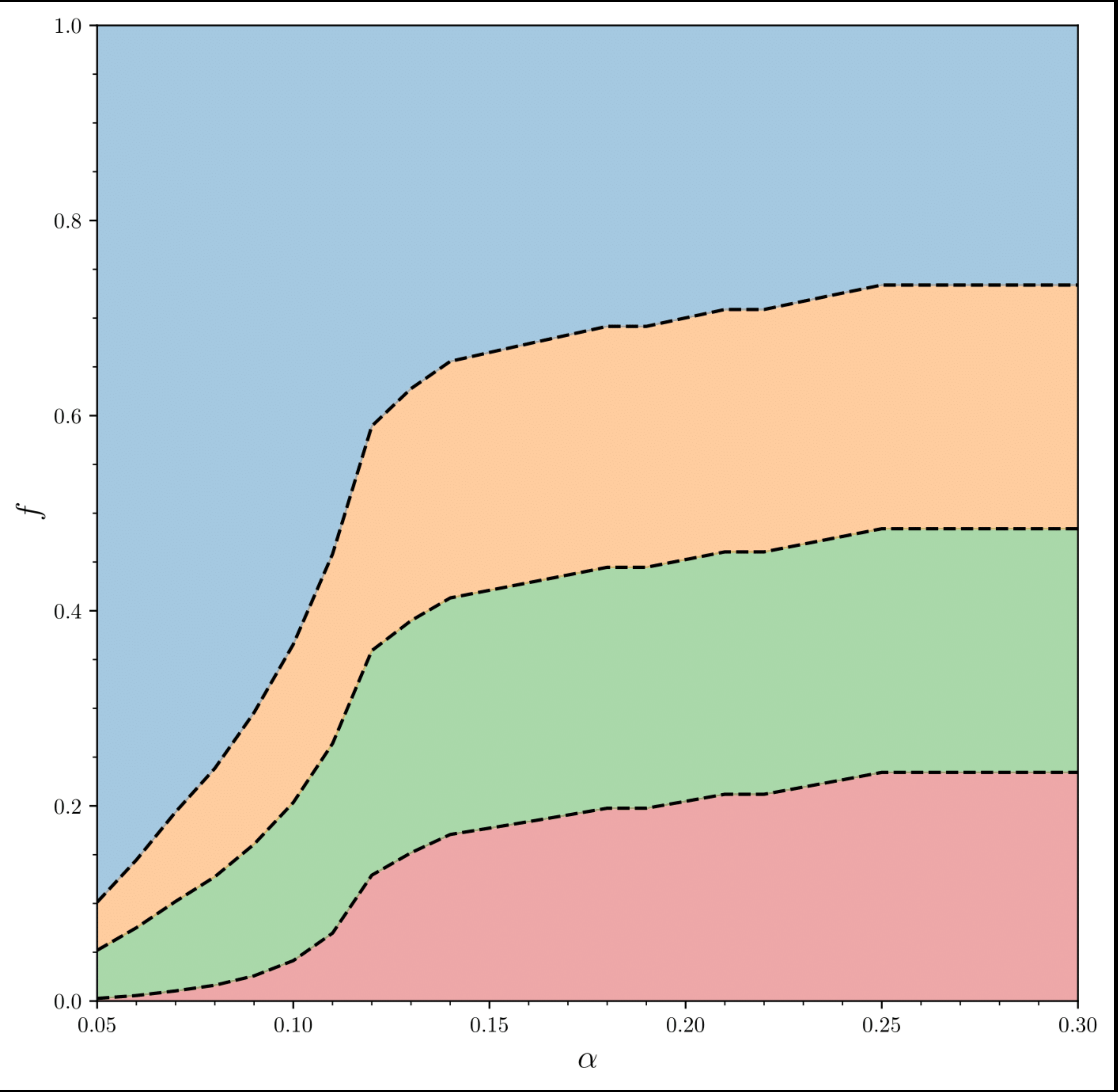
~ 35% **avoid alignment** of both spins:

→ these will exhibit **generic** precession



All else held constant, vary the viscosity α:

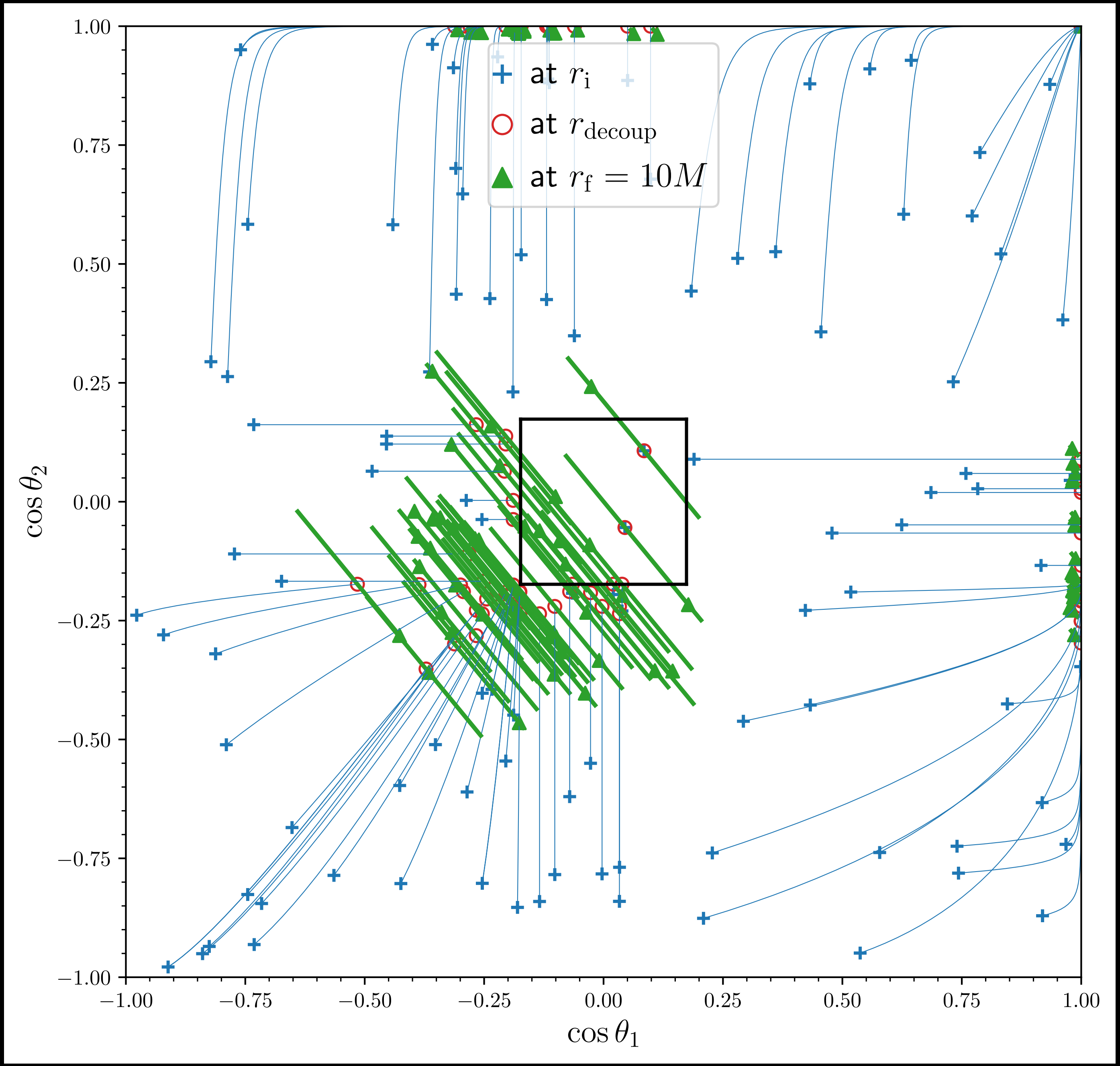
- Most binaries have both spins misaligned for small α
- The four fractions converge to ~0.25 in large-α limit



In the GW-driven phase, the aligned effective spin $\chi_{eff}(q, \chi_1, \chi_2, \cos\theta_1, \cos\theta_2)$ is conserved.

q, χ_1, χ_2 are constant, $\cos\theta_1, \cos\theta_2$ evolve.

BBHs that avoid alignment evolve on lines of constant χ_{eff} and exhibit generic spin precession.



The Bardeen-Petterson effect and its consequences for LISA observations of supermassive black-hole binary spin orientations

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ABSTRACT
Supermassive black holes can be driven to merger by many processes: dynamical

... Will publish soon!

If binaries begin with initially isotropic spin directions:

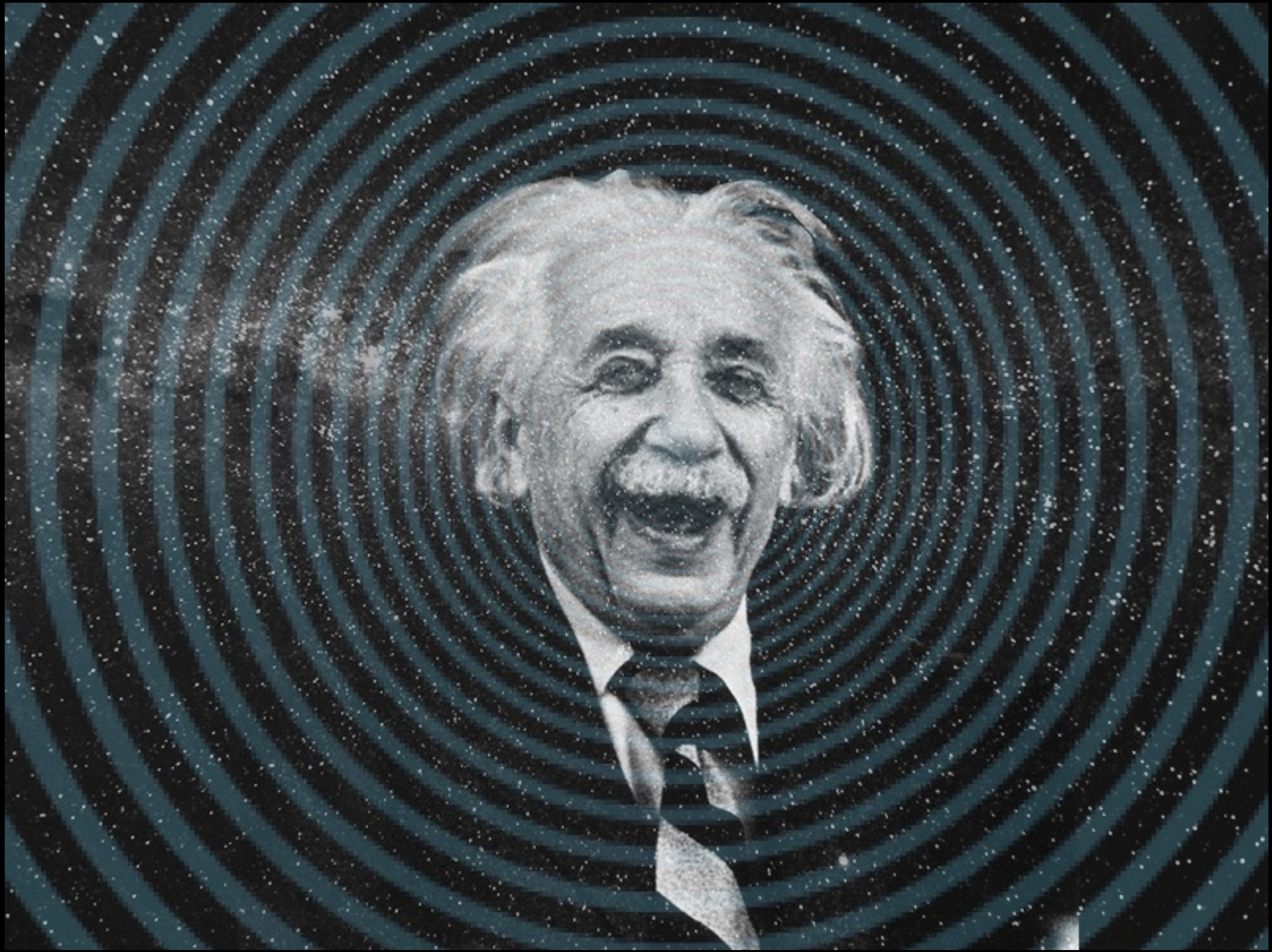
✓A degeneracy exists between the spin orientations of BBHs in gas-poor hosts and of BBHs in gas-rich hosts with low viscosity α b/c of critical obliquity.

✓If α is sufficiently high, the Bardeen-Petterson effect can align the spins to create subpopulations defined by alignment of one or both spins.

✓These subpopulations will exhibit different spin precession in LISA band.

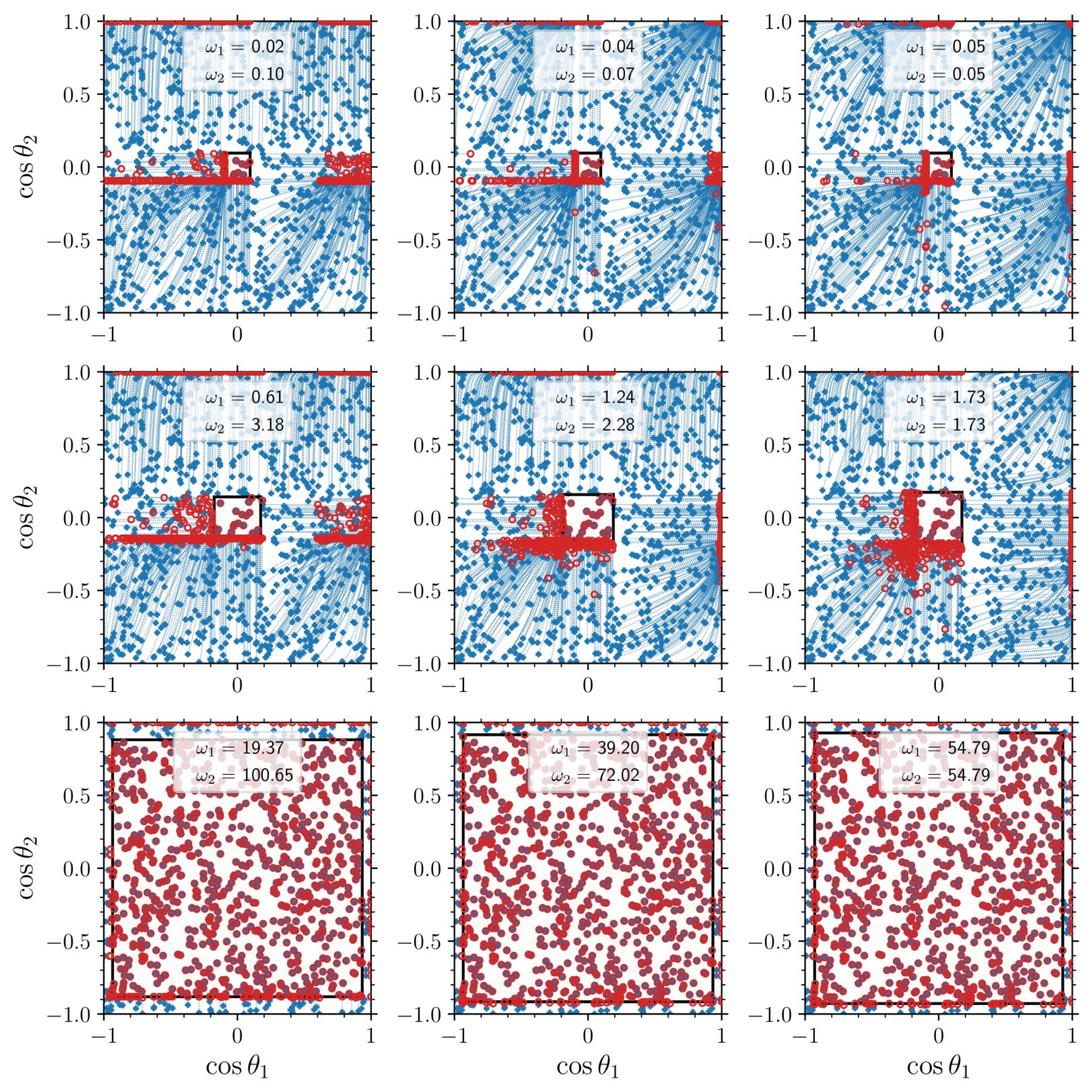
✓If LISA measures BBHs with predominantly aligned spins,

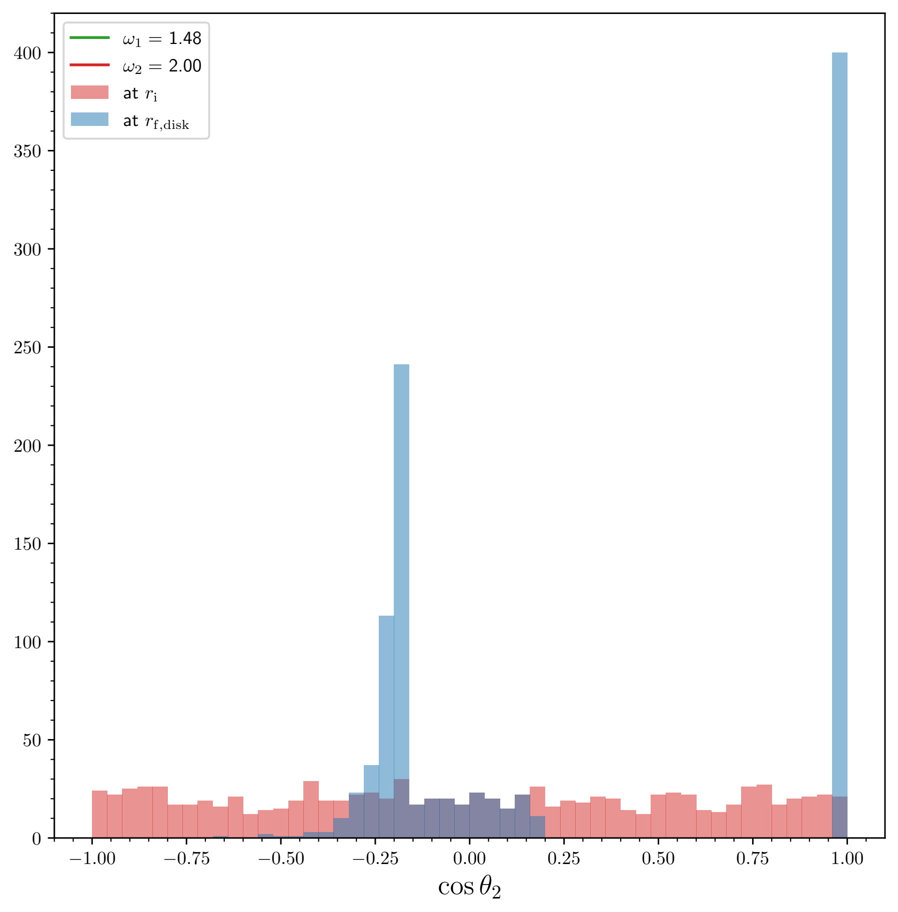
then this implies formation in a <u>high viscosity gas-rich host</u>!



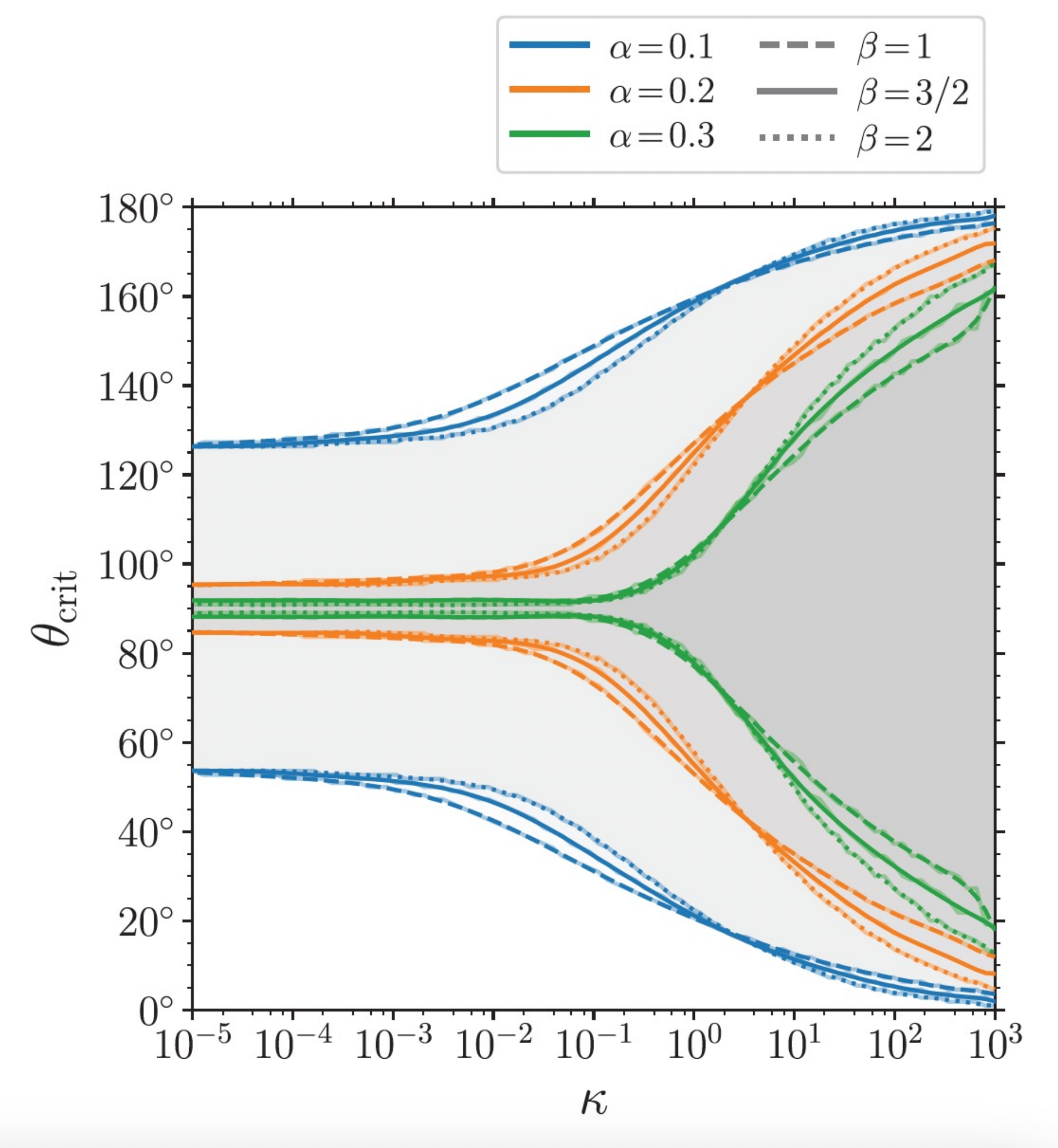
Thank you for listening!

Vary mtotal and q

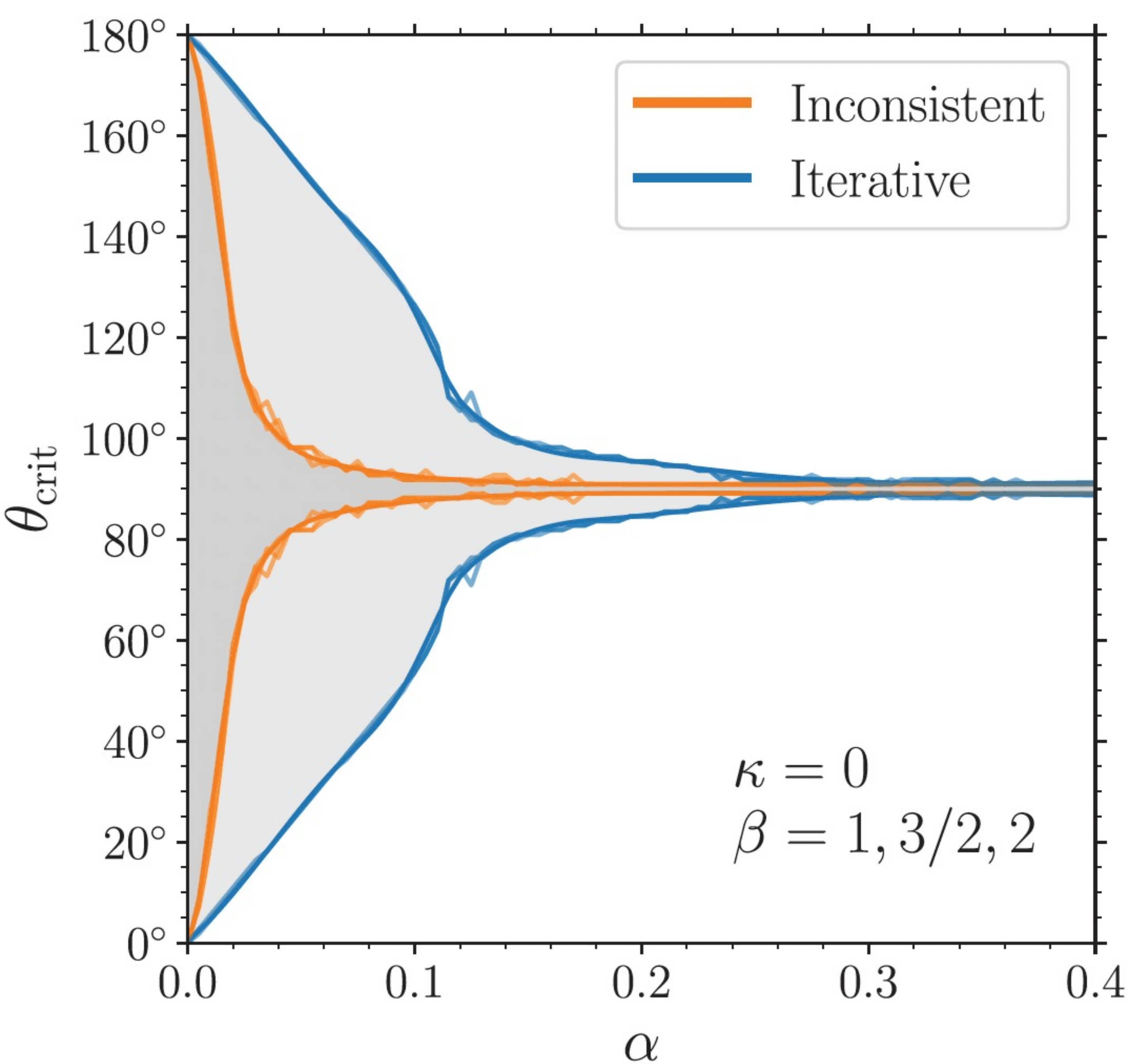




ω_1 = 1.48
ω_2 = 2.00
at r_i
at $r_\mathrm{f,disk}$
400
350
300
250
200
150
100
50
0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
$\cos\theta_2$



$\alpha = 0.1$
$\alpha = 0.2$
$\alpha = 0.3$
$\beta = 1$
$\beta = 3/2$
$\beta = 2$
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
θ_{crit}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
κ


Inconsistent
Iterative
$\kappa = 0$
$\beta = 1, 3/2, 2$
θ_{crit}
α
180°
160°
140°
120°
100°
80°
60°
40°
20°
0°
0.0
0.1
0.2
0.3
0.4