

Matters of gravity: the interplay between environmental and beyond-GR effects in asymmetric binaries

@ 2nd New Horizons for Psi Workshop

International Centre for Theoretical Physics Asia-Pacific

August 24, 2026

In collaboration with Jack Purrant and Thomas Sotiriou, paper to appear



Andrea Maselli

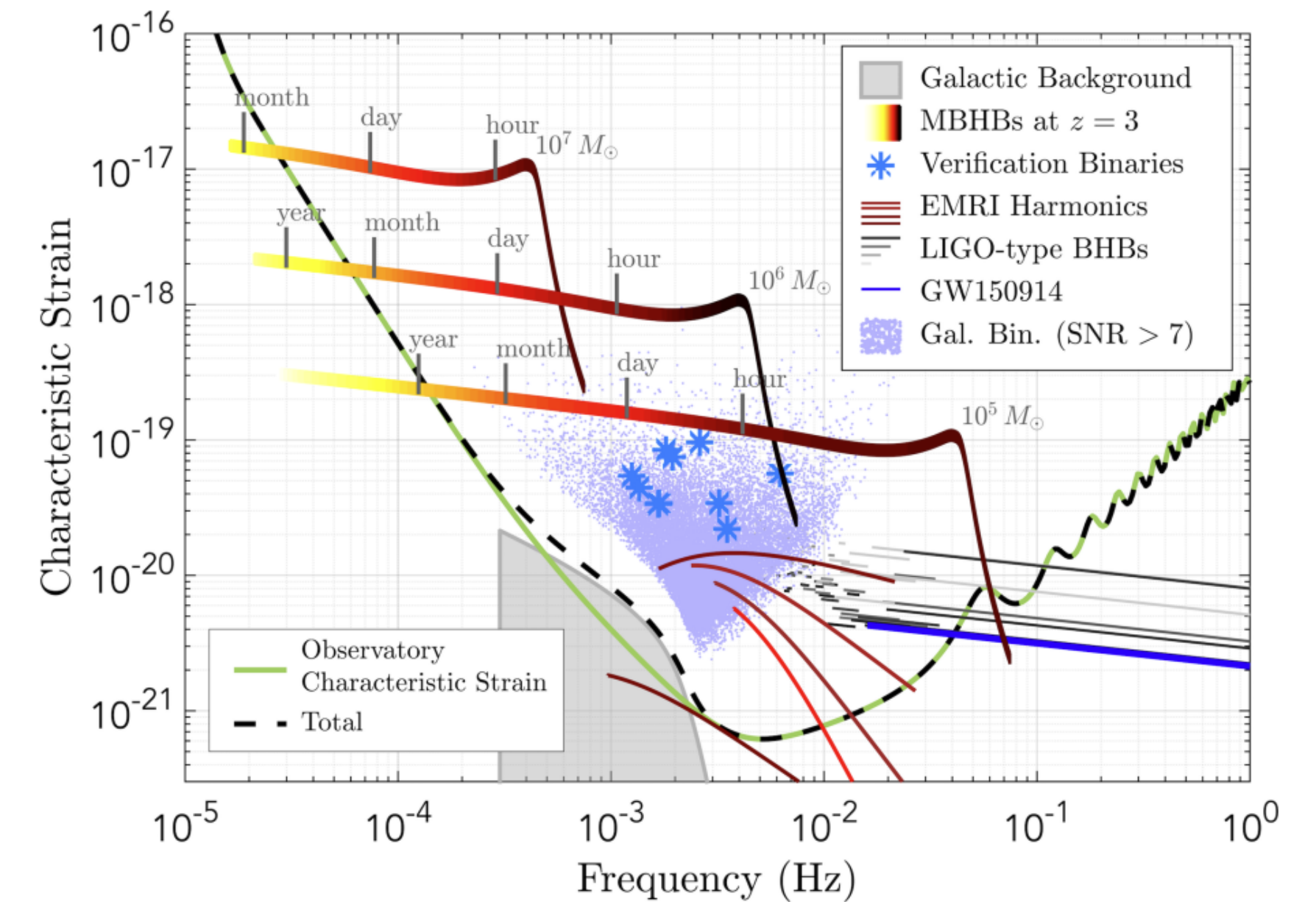
Asymmetric binaries

200+ events observed so far from LVK, spanning a relatively small interval of mass ratios $q \sim 1 : 30$

- Next- space/ground detectors expected to beat down such value by several orders of magnitudes

$$q \sim 10^{-7} - 10^{-2} \quad (10^6 - 10)M_{\odot}$$

- Duration of the inspiral & number of cycles growing as q decreases



Discovery potential

- Slow inspiral with $10^4 - 10^5$ **cycles**, which could allow to observe them for very long periods, from months to years
- Dynamical evolutions with an uncommon richness, with **resonances**, large **eccentricities** and **off-equatorial** orbits
- In principle, very accurate probes for testing deviations from vacuum and from General Relativity

Contaminations & biases: interplay

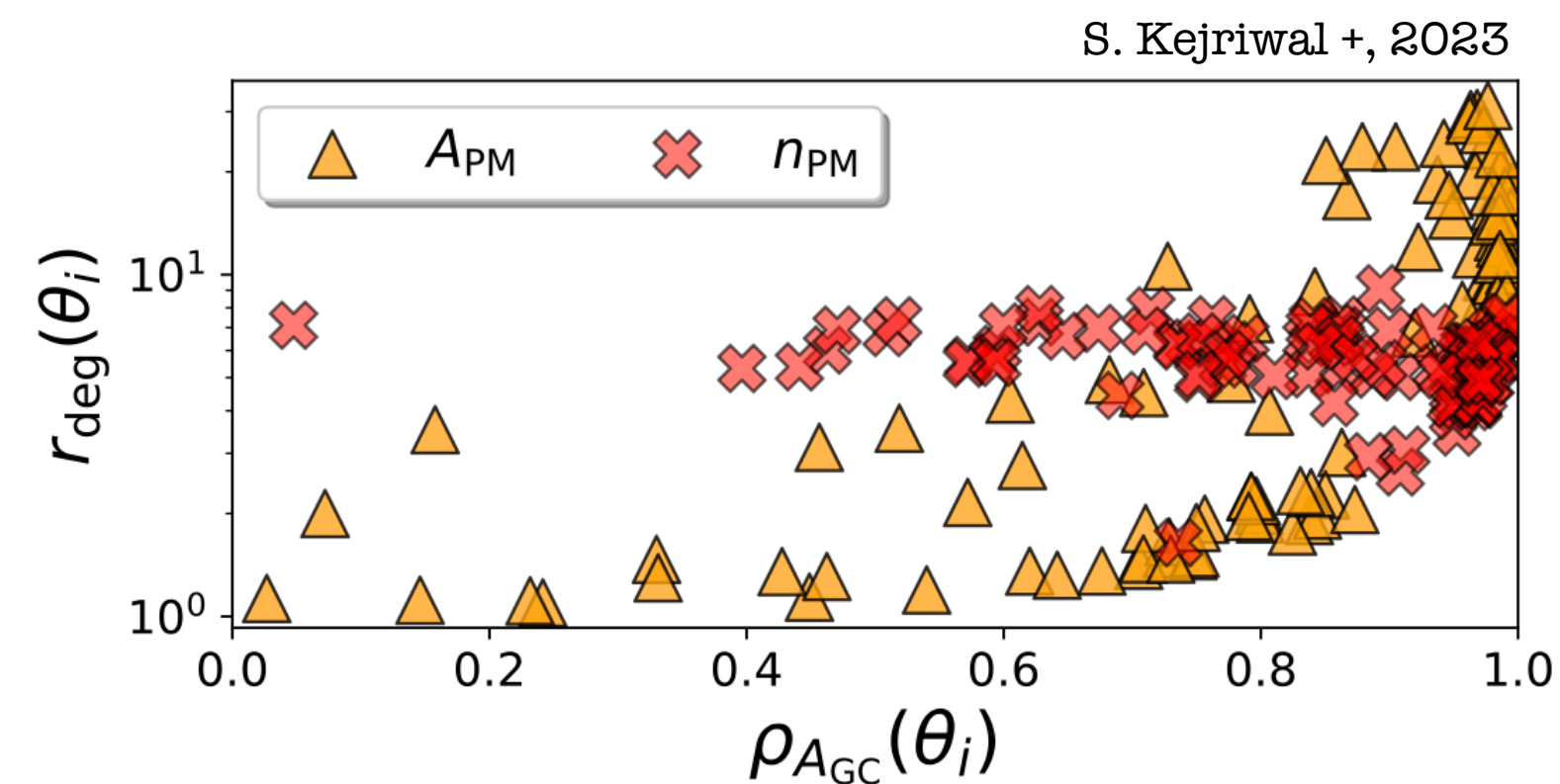
Does mismodeling, i.e. neglecting environmental or beyond GR corrections affect parameters reconstruction?

M. Garg +2024; L. Copparoni & E. Barausse 2026

- Bias in the source intrinsic parameters is small L. Speri +, 2023; L. Speri + inc. A. M., 2024
- Problematic for ‘small’ deviations, like beyond GR/environmental corrections
- What about the interplay of “small” effects?

$$r_{\text{deg}} = \sigma_{\theta_i} (\text{joint parameters}) / \sigma_{\theta_i} (\text{single parameter})$$

for amplitude of gas torque



correlation with beyond GR



Correlations between environmental and beyond-GR effects can severely degrade their own reconstruction

Contaminations & biases: interplay

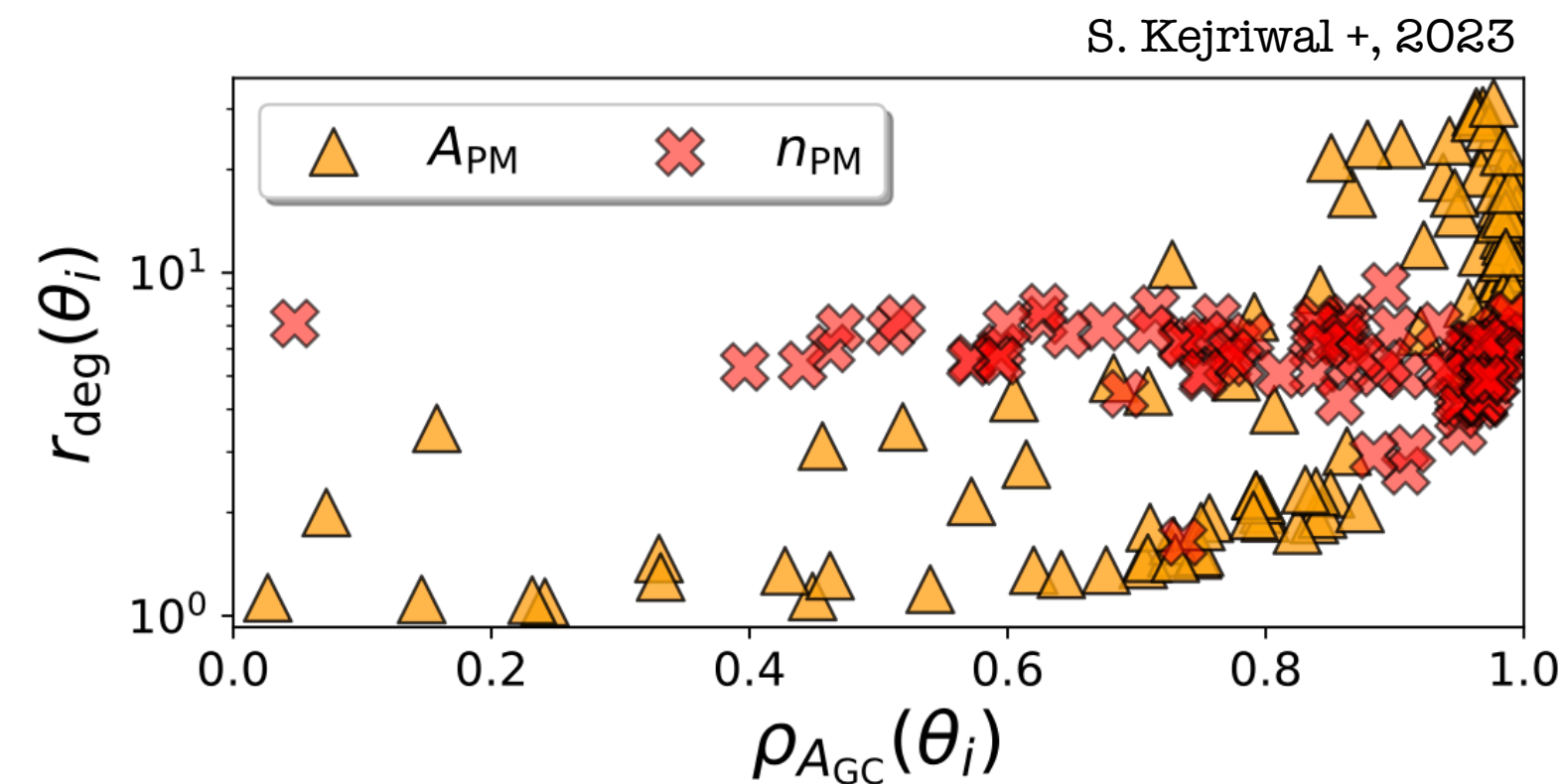
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Correlations between environmental and beyond-GR effects can severely degrade their own reconstruction

Can we study this problem from *first principles* and develop a perturbative framework suitable for observations?

E/IMRIs in GR

How do we study asymmetric binaries in GR? The *Self-Force* program A. Pound & B. Wardell, 2021

- ☉ The asymmetric character introduces a natural parameter to study the problem in perturbation theory, the mass ratio $q = m_p/M$

$$\mathbf{g}_{\alpha\beta} = g_{\alpha\beta}^{(0)} + qh_{\alpha\beta}^{(1)} + \dots$$

$$G_{\mu\nu} = T_{\mu\nu}^p = 8\pi m_p \int \frac{\delta^{(4)}(x - y_p(\lambda))}{\sqrt{-g}} \frac{dy_p^\alpha}{d\lambda} \frac{dy_p^\beta}{d\lambda} d\lambda$$

leading
adiabatic

Regge-Wheeler-Zerilli
(Schwarzschild)

Teukolsky
(Kerr)

- ☉ The solution determines the phase evolution

$$\phi(t) = \overset{\text{adiabatic}}{\phi_{\text{diss-1}}} + \overset{\text{first post-adiabatic}}{\dots}$$



$\mathcal{O}(1/q)$



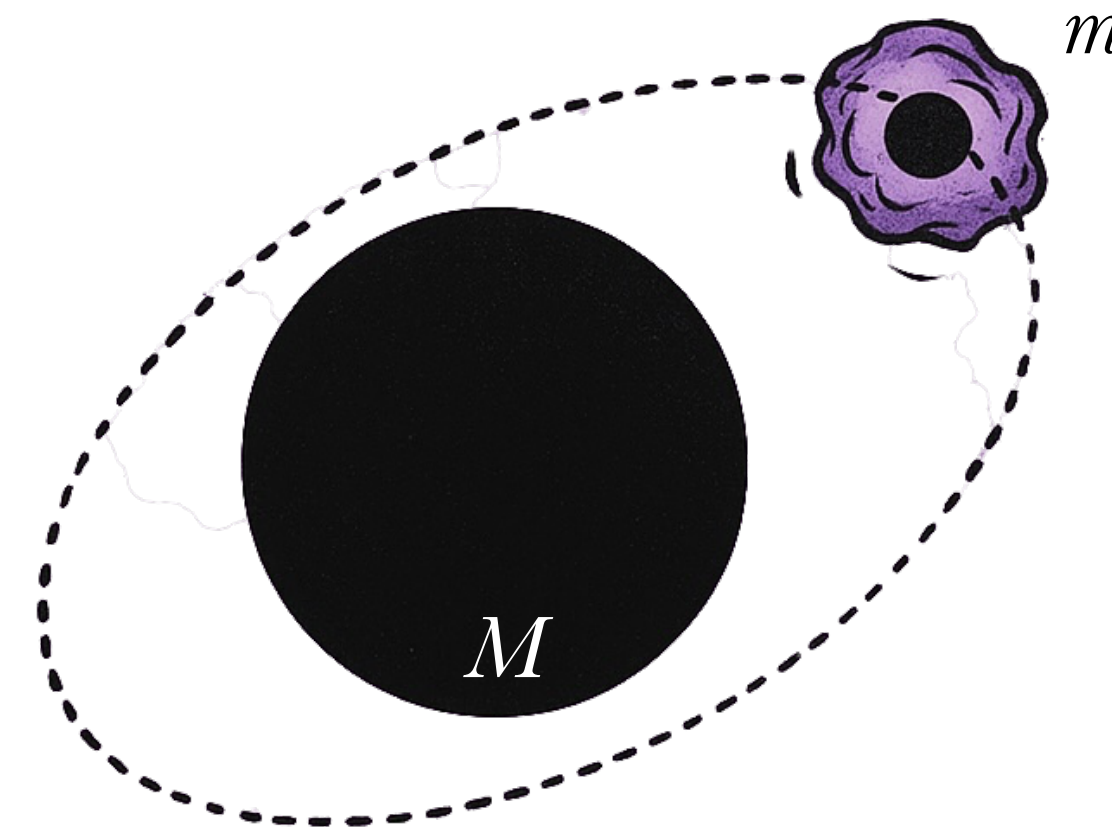
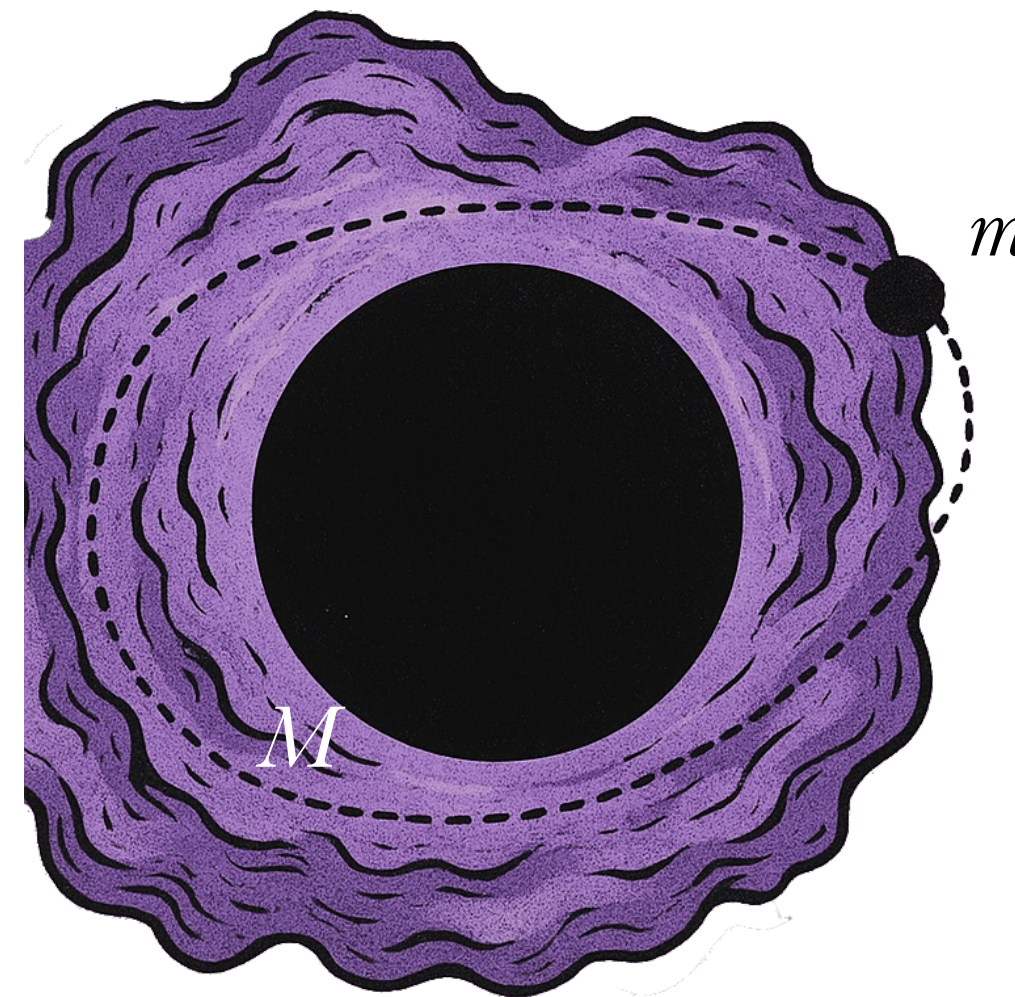
$\mathcal{O}(1)$

A tale of two sides

A. Avendano & C. Sopuerta, 2024

EMRI conventionally thought as probes of the massive BH spacetime

- Fundamental physics will come from testing deviations induced by the primary (new fields, matter components, Kerr hypothesis...)
- Highly non-trivial task (perturbations on non-Kerr background) A. Chung & N. Yunes, 2024



- What about the secondary? Does it play any role for testing gravity ?

Decoupling of scales

Shift-symmetric theories with massless scalar field(s) φ **non-minimally** coupled to gravity

$$S[\mathbf{g}_{ab}, \varphi, \Psi] = S_0[\mathbf{g}_{ab}, \varphi] + \alpha S_c[\mathbf{g}_{ab}, \varphi] + S_m[\mathbf{g}_{ab}, \varphi, \Psi]$$

$$S_0[\mathbf{g}_{ab}, \varphi] = \int \frac{\sqrt{-\mathbf{g}}}{16\pi} \left(R - \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi \right) d^4x$$

non-minimal
coupling

matter fields

$$d_2 \sim \frac{\alpha}{m_p^n} \sim O(1)$$

☉ α has dimensions $[\text{length}]^n$ $n \geq 2$ (negative energy dimensions)

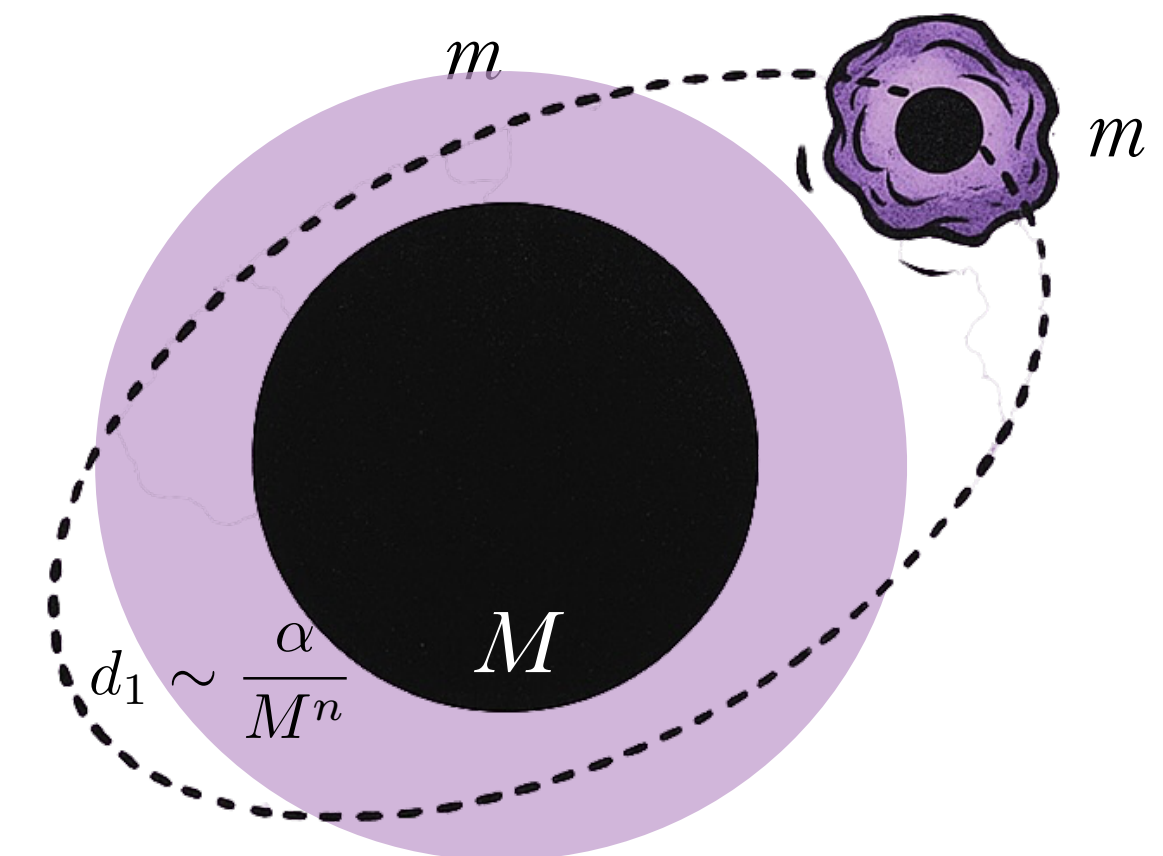
☉ Hairs have to be introduced by S_c

☉ Assuming BH solutions are continuously connected to GR as $\alpha \rightarrow 0$

☉ black holes have “charges” $d_1 \sim \alpha/M^n$ and $d_2 \sim \alpha/m_p^n$

[Notable example: linear Gauss-Bonnet gravity $d_1 \sim \alpha_{\text{GB}}/M^2$ and $d_2 \sim \alpha_{\text{GB}}/m_p^2$]

☉ deviations from GR scale as $\alpha/(\text{mass})^n \longrightarrow \sim \alpha/M^n = \alpha/m_p^n q^n$ and $\sim \alpha/m_p^n$



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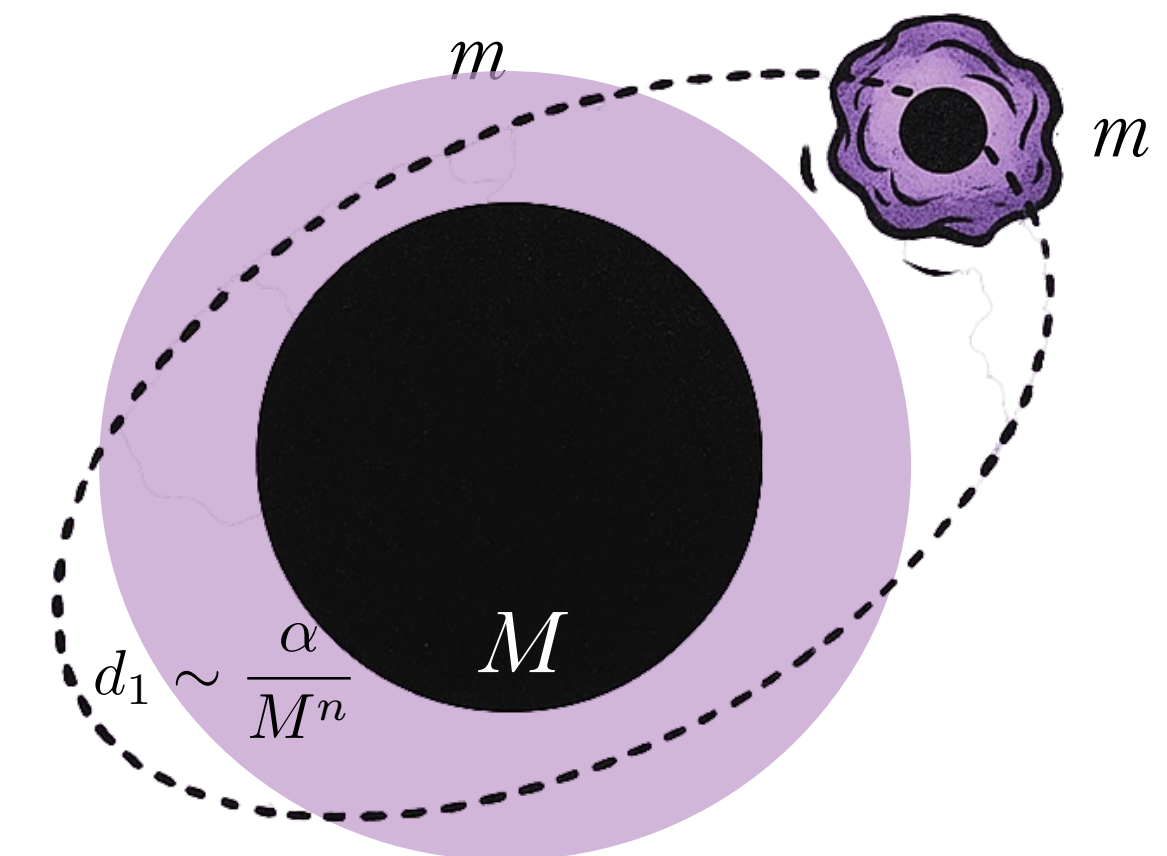
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EMRI decoupling



*MBH described
by Kerr*

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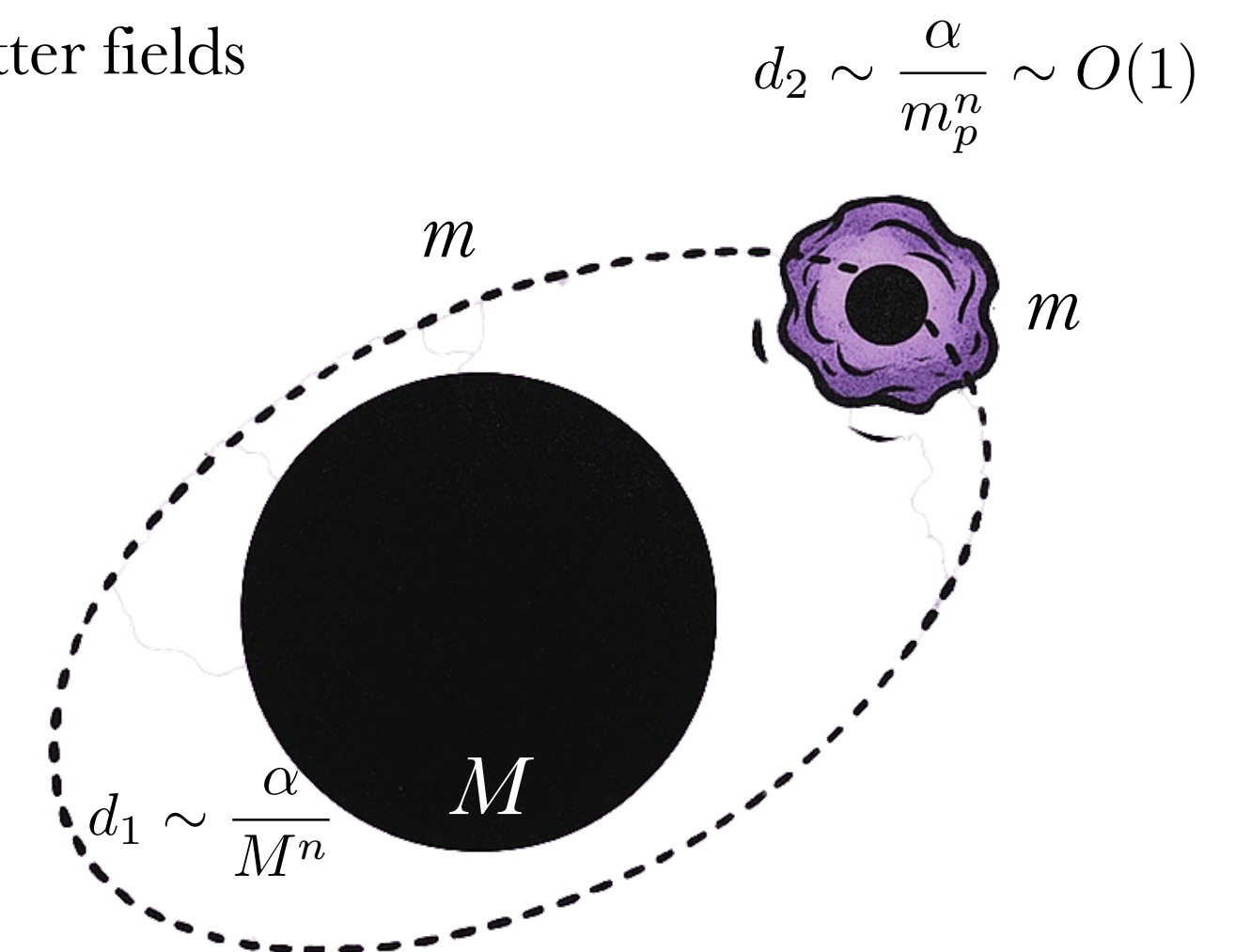
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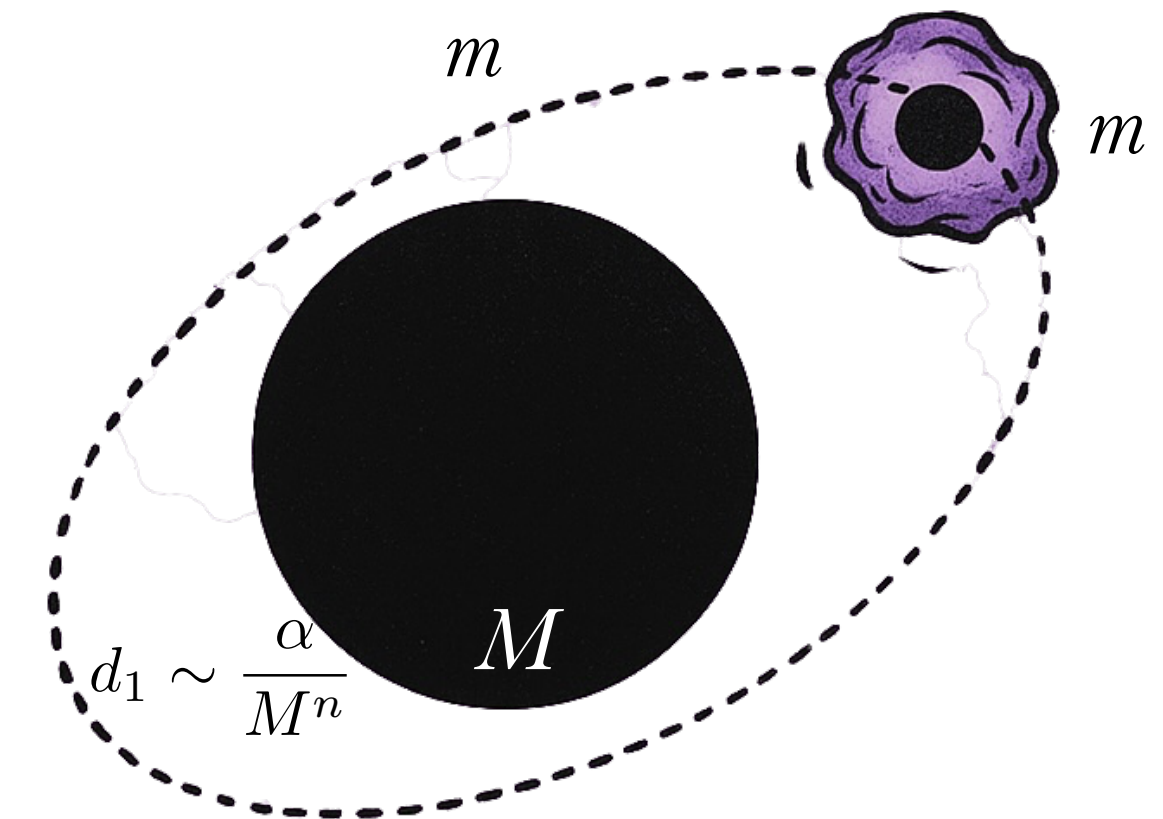
$$d_2 \sim \frac{\alpha}{m_p^n} \sim O(1)$$

☉ The secondary can be treated with a *skeletonized* approach

Eardley, ApJ 196 L59-62 (1975); Damour & EF, CGQ 9, 9 (1992)

$$S_p = - \int_{\gamma} m[\varphi] ds = - \int_{\gamma} m[\varphi] \sqrt{\mathbf{g}_{ab} \mathbf{u}^a \mathbf{u}^b} d\tau \longrightarrow \square_{\mathbf{g}} \varphi = 16\pi \int_{\gamma} m'[\varphi] \frac{\delta^4[x^\mu - z_p^\mu[\tau]]}{\sqrt{-\mathbf{g}}} d\tau$$

$$m'(\varphi) \sim m_p d_2$$



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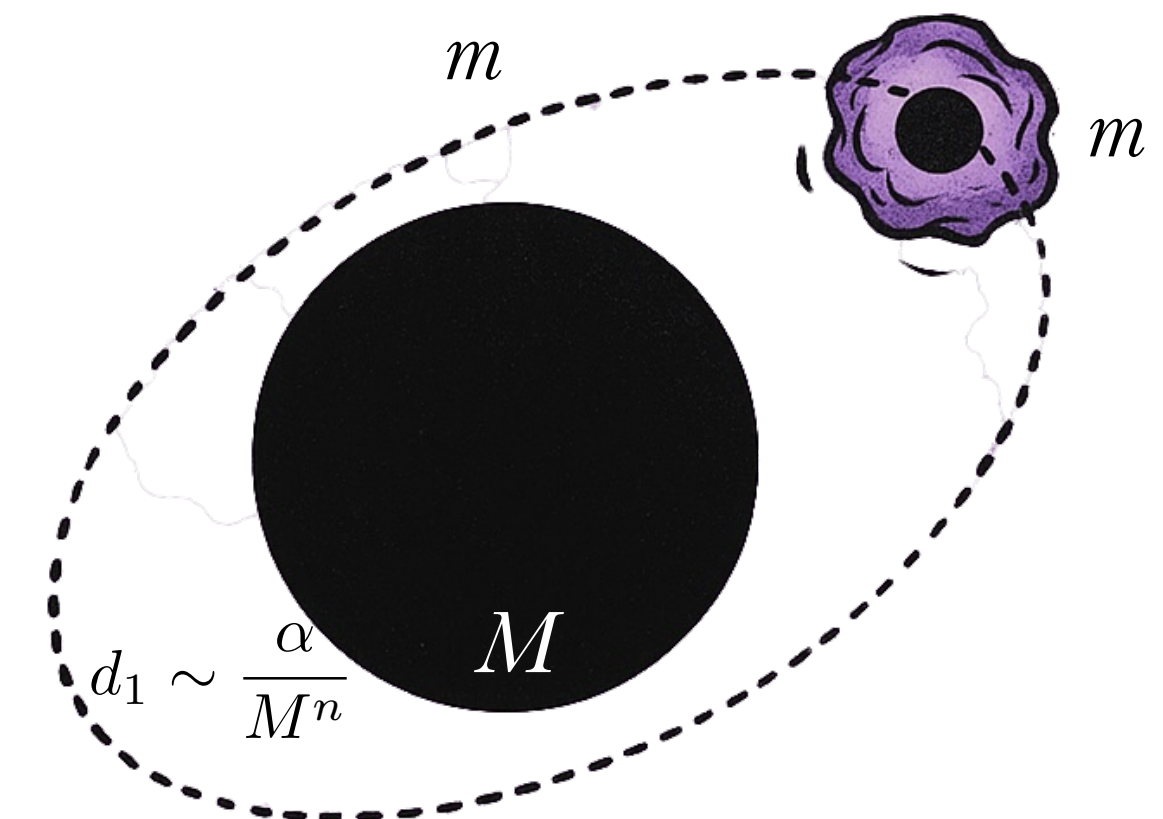
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Bonus: QNMs based tests of GR for LISA-like questiona A. M. +, 2023

A. M. +, 2020
A. Spiers, A. M., T. Sotiriou, 2024

Decoupling of scales

A. Spiers, A.M., T. Sotiriou, 2024

Consistent expansion within the SF approach, since $\alpha/M^n = q^n(\alpha/m_p^n)$

🕒 Mass ratio q as single expansion parameter $g_{\mu\nu} = g_{\mu\nu}^{(0)} + qh_{\mu\nu}^{(1)} + \dots$ $\varphi = \varphi^{(0)} + q\varphi^{(1)} + \dots$

🕒 Modularity with Self-Foce calculations in GR

🕒 Field's equations at the linear order

$$G_{ab}^{(1)} = 8\pi m_p \int_{\gamma} \frac{\delta^4[x_p^m - z_p^\mu[\tau]]}{\sqrt{-g}} u_a u_b d\tau \quad \square \varphi^{(1)} = -4\pi \textcolor{red}{d}m_p \int_{\gamma} \frac{\delta^{(4)}[x^\mu - z_p^\mu[\tau]]}{\sqrt{-g}} d\tau$$



Teukolsky equation as in GR



Scalar wave equation on a Kerr background

The solution can be used to compute the full scalar first order SF piece $f_{1,scal}^\mu$

🕒 At 0PA-adiabatic order $\text{GSF}^{(1)} + \textcolor{red}{\text{SSF}}^{(1)} \longrightarrow f_1^\alpha = f_{1,\text{grav}}^\alpha + f_{1,\text{scal}}^\alpha$

Universal family of waveforms

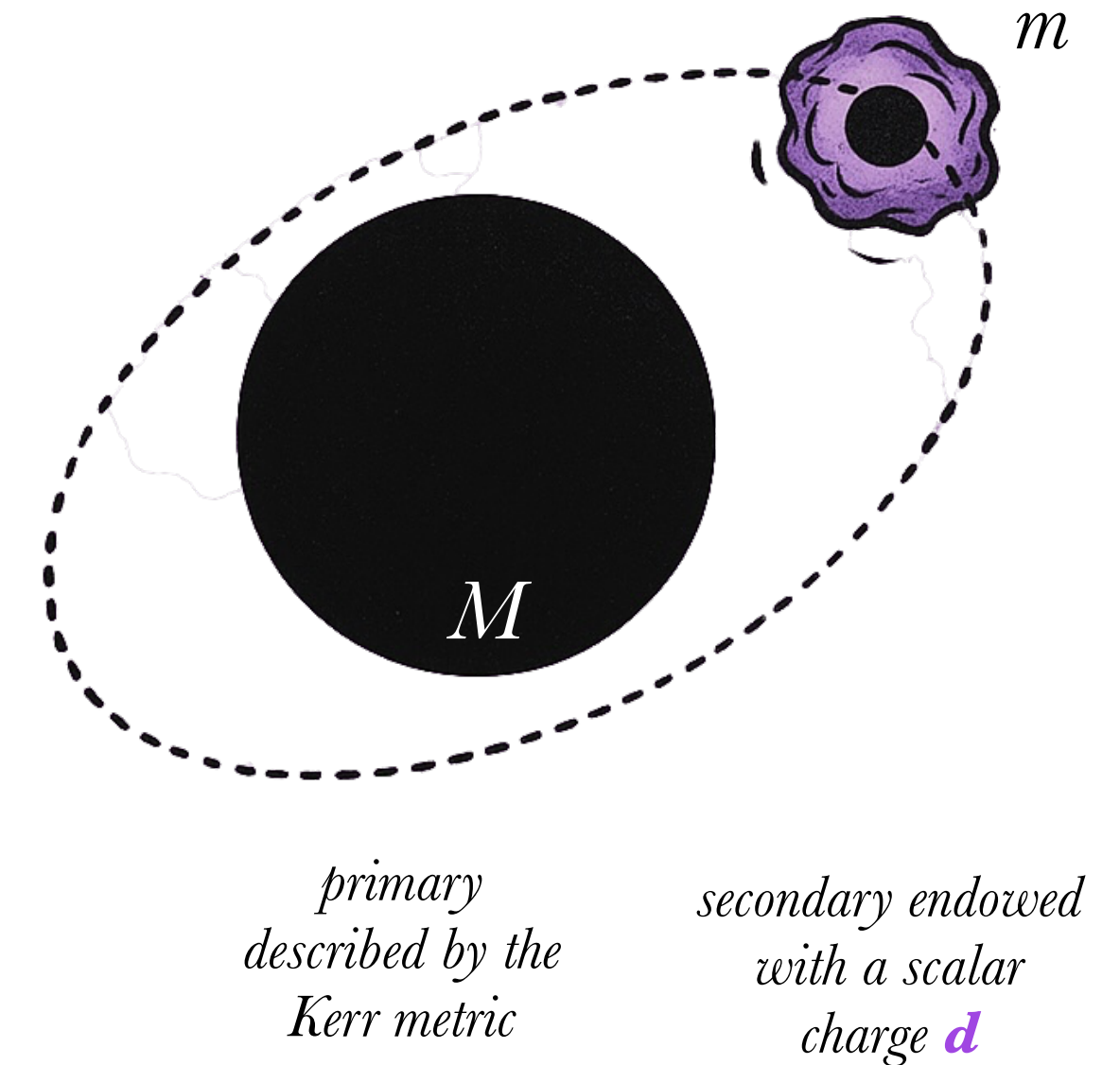
The recipe to generate *agnostic* waveforms

1. Compute the scal/grav energy fluxes $\dot{E}_{\text{GR}} \propto |h_{\mu\nu}^{(1)}|^2$ $\delta\dot{E} \propto |\varphi^{(1)}|^2$

2. Compute the total luminosity $\dot{E} = \dot{E}_{\text{GR}} + d^2\delta\dot{E}$

3. Determine the dynamics $\frac{dr(t)}{dt} = -\dot{E} \frac{dr}{dE_{\text{orb}}}$ $\frac{d\phi(t)}{dt} = \frac{M^{1/2}}{r^{3/2} + M^{3/2}\chi}$

4. Build the GW waveform with $h_+[r(t), \Phi(t)]$, $h_\times[r(t), \Phi(t)]$



Everything as in GR but $d^2\delta\dot{E}$, which depends **only** on the scalar charge

🔄 Waveforms already implemented within LISA pipelines

S. Gliorio incl. A. M +, 2026; S. Barsanti + incl. A. M., 2026



MEW
Modified **EMRI**
Waveforms

The interplay with the environmental field

$$S = \int \sqrt{-\mathbf{g}} \left(\frac{R}{\kappa} - \frac{1}{2} \partial_a \varphi \partial^a \varphi \right) d^4x + \alpha S_c[\mathbf{g}_{ab}, \varphi] + S_m[\mathbf{g}_{ab}, \varphi, \Psi] + \int \sqrt{-\mathbf{g}} [-\partial_a \psi \partial^a \psi^* - \mu^2 |\psi|^2] d^4x$$

Generalizing to a multi-field/parameter approach would require 3 parameters: (q, α, ξ)

 environment amplitude

☉ Neglecting post-adiabatic orders $\mathcal{O}(q^2)$, and Given GR corrections to the primary scale as $\alpha/M^n = q^n(\alpha/m_p^n)$ ($n > 2$)

☉ The perturbative framework therefore involves only two independent parameters (ξ, q)

$$\begin{aligned} h_{\mu\nu} &= \xi h_{\mu\nu}^{(1,0)} + q h_{\mu\nu}^{(0,1)} + \xi^2 h_{\mu\nu}^{(2,0)} + \xi q h_{\mu\nu}^{(1,1)} + \dots \\ \varphi &= \bar{\varphi} + q \varphi^{(0,1)} + \xi \varphi^{(1,0)} + \xi q \varphi^{(1,1)} + \dots \\ \psi &= \xi \psi^{(1,0)} + q \psi^{(0,1)} + \xi q \psi^{(1,1)} + \dots \end{aligned}$$

The interplay with the environmental field

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$$\varphi = \bar{\varphi} + q \varphi^{(0,1)} + \xi \varphi^{(1,0)} + \xi q \varphi^{(1,1)} + \dots$$

$$\psi = \xi \psi^{(1,0)} + q \psi^{(0,1)} + \xi q \psi^{(1,1)} + \dots$$

 depends on the scalar charge of the secondary

Multi-parameter expansion

The full solution can be obtained order by order as a 2-parameter expansion

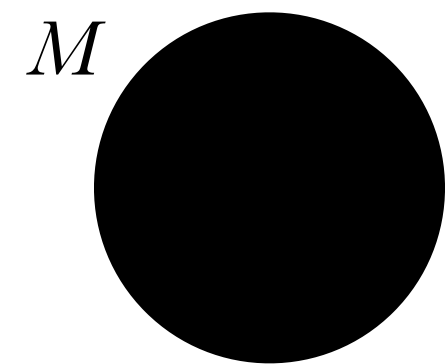
R. Brito & S. Shah, 2024

C. Dyson +, 2025

S. Datta & A. M., 2025

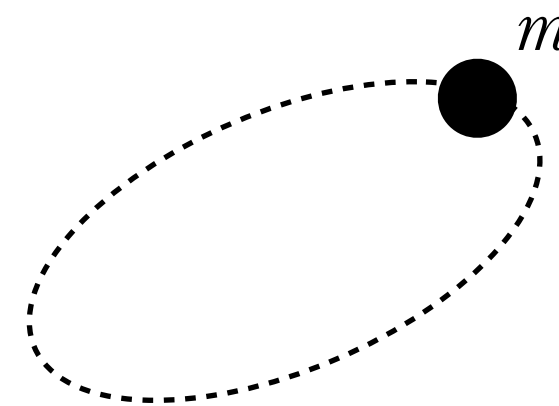
☉ At linear order $\mathcal{O}(q, \xi)$

Kerr



$$G_{ab}[\bar{g}_{cd}] = 0$$

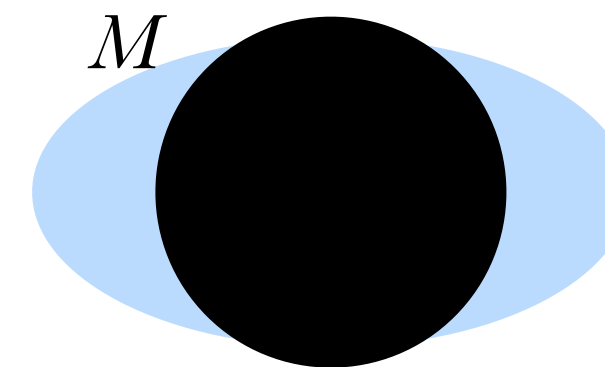
$$q = m_p/M$$



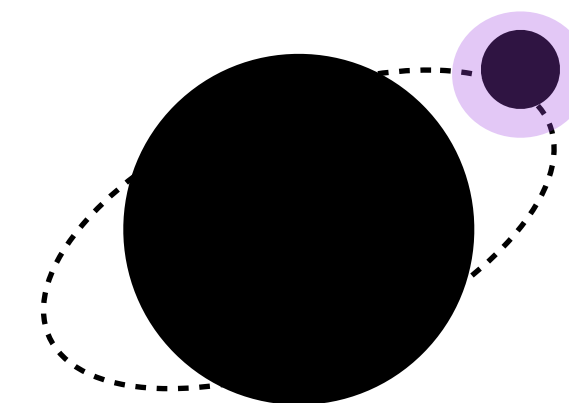
$$G_{ab}^{[1]}[h_{cd}^{(1,0)}] = 8\pi m_p \int \frac{\delta^4[x - y_p(\tau)]}{\sqrt{-\bar{g}}} u_a^p u_b^p d\tau$$

Teukolsky equations

Cloud



$$(\square - \mu^2) \psi^{(1,0)} = 0$$



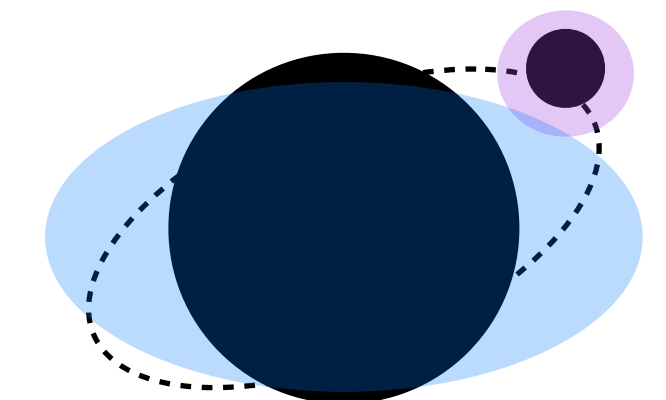
$$\square \varphi^{(0,1)} = 4\pi d m_p \int \frac{\delta^4[x - y_p(\tau)]}{\sqrt{-\bar{g}}} d\tau$$

☉ At quadratic order $\mathcal{O}(q\xi, \xi^2)$

$$(\square - \mu^2) \psi^{(1,1)} = h^{(0,1)ab} \nabla_a \nabla_b \psi^{(1,0)} + \nabla^a \psi^{(1,0)} \nabla_b h_a^{(0,1)} - \frac{1}{2} \nabla_a h^{(0,1)} \nabla^a \psi^{(1,0)}$$

$$G_{ab}^{[1]}[h_{cd}^{(2,0)}] = 8\pi \partial_{(a} \psi^{*(1,0)} \partial_{b)} \psi^{(1,0)} - 4\pi g_{ab} [\partial_c \psi^{*(1,0)} \partial^c \psi^{(1,0)} + \mu^2 |\psi^{(1,0)}|^2]$$

=



Conservative corrections

The cloud backreaction on the background geometry at order order $\mathcal{O}(\xi^2)$ induces conservative corrections to the orbital dynamics

$$G_{ab}^{[1]}[h_{cd}^{(2,0)}] = 8\pi\partial_{(a}\psi^{*(1,0)}\partial_{b)}\psi^{(1,0)} - 4\pi g_{ab}[\partial_c\psi^{*(1,0)}\partial^c\psi^{(1,0)} + \mu^2|\psi^{(1,0)}|^2]$$

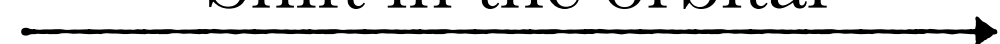
☉ The problem reduces to find a solution for the shifts $\delta M(r)$ and $\delta\lambda(r)$

$$ds^2 = -F(r) e^{2\xi^2\delta\lambda(r)} dv^2 + 2e^{\xi^2\delta\lambda(r)} dv dr + r^2 d\Omega^2 \quad F(r) = f(r) - 2\xi^2\delta M(r)/r$$

$$\partial_r\delta M = r^2 \left[f(r) |\partial_r\tilde{R}_{00}|^2 + \mu^2 |\tilde{R}_{00}|^2 \right]$$

$$\partial_r\delta\lambda = 2r |\tilde{R}_{00}(r)|^2$$

 *cloud radial
function*

Shift in the orbital
energy and frequency 

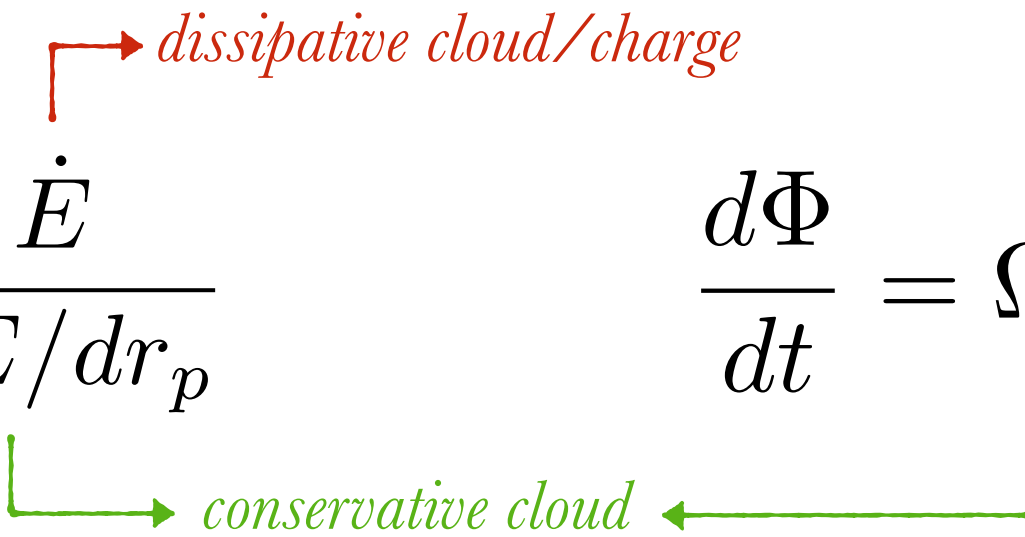
$$E(r_p) = E_{\text{vac}}(r_p) + \xi^2 \delta E(r_p)$$

$$\Omega(r_p) = \Omega_p(r_p) + \xi^2 \delta\Omega(r_p)$$

Phenomenology and metrics

Charge and cloud effects included within Fast EMRI Waveforms using  + a dedicated infrastructure we built for the cloud

$$\frac{dr_p}{dt} = \frac{\dot{E}}{dE/dr_p} \quad \frac{d\Phi}{dt} = \Omega_p$$



To assess relevance and interplay of the effects, we focused on 2 metrics

- ☉ GW dephasing, i.e. difference in phase evolution with respect to vacuum-GR
- ☉ Statistical and systematic uncertainties using Fisher matrix and Cutler-Vallisneri approach on the parameters

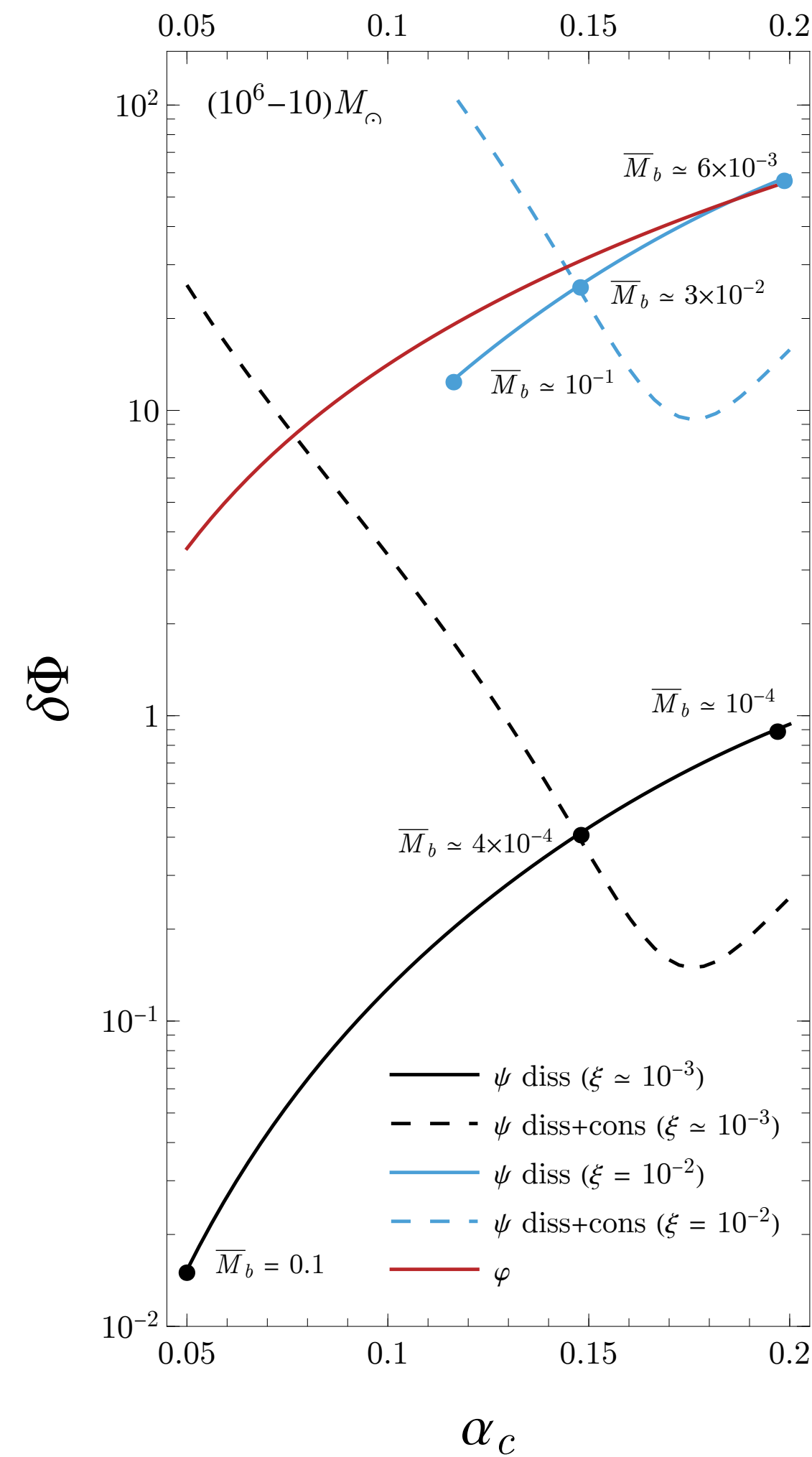
$$\vec{\theta} = \{M, m_2, d^2, \xi^2, d_L, \theta_s, \phi_s, \theta_k, \phi_k, p_0, \phi_0\}$$



- ☉ Binaries evolving on circular orbits for $T_{\text{obs}} = 1\text{yr}$ up to the plunge, with $M_b = (10^6, 10^5)M_{\odot}$, $M_b = (0.1, 0.01)M$ and $d = (0.1, 0.025)$

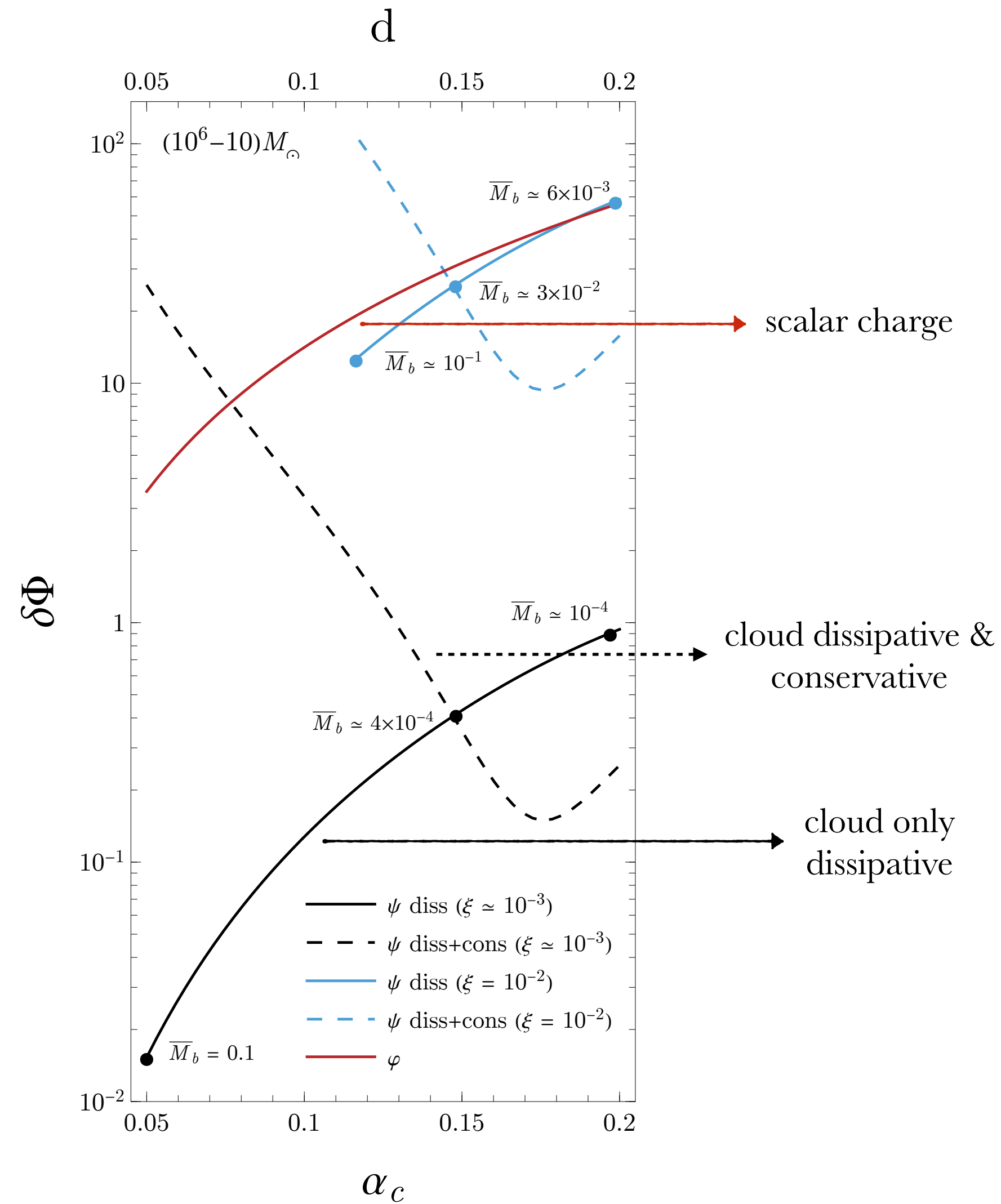
GW Dephasing: individual contributions

Difference in phase evolution of EMRI in vacuum - GR v.s. EMRI endowed by scalar fields $\frac{\Phi_{\text{vac}} - \Phi_{\text{pert}}}{\pi}$



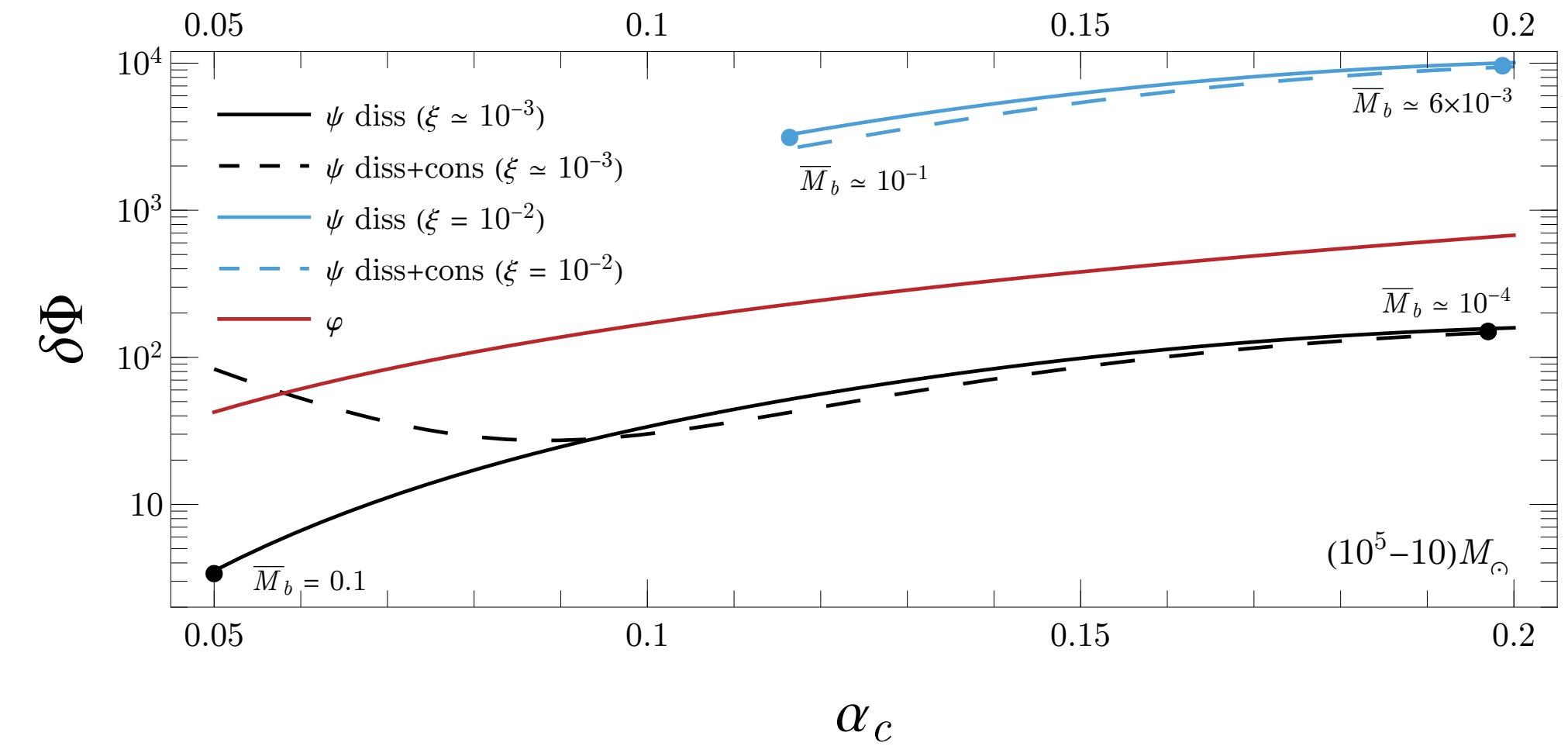
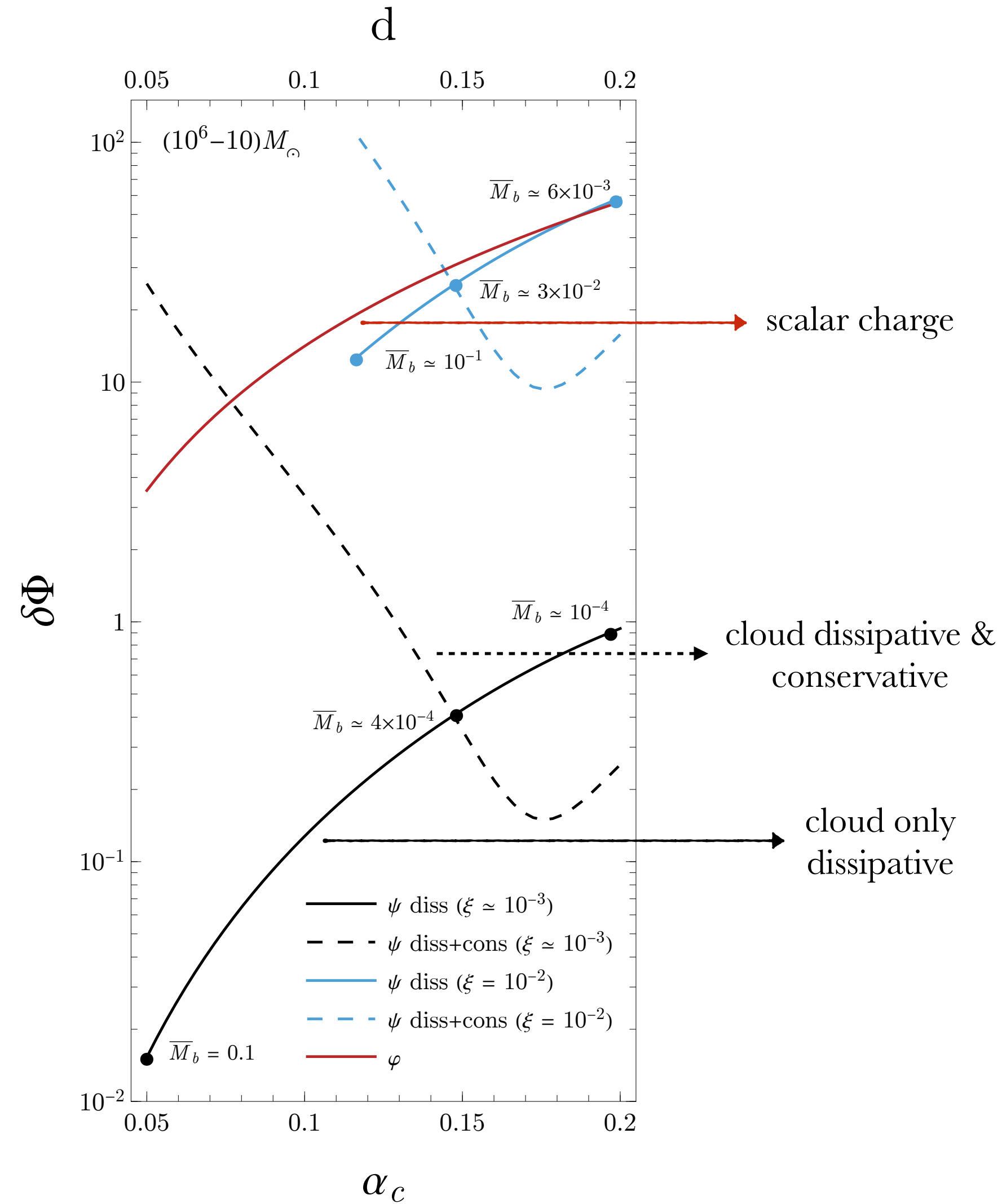
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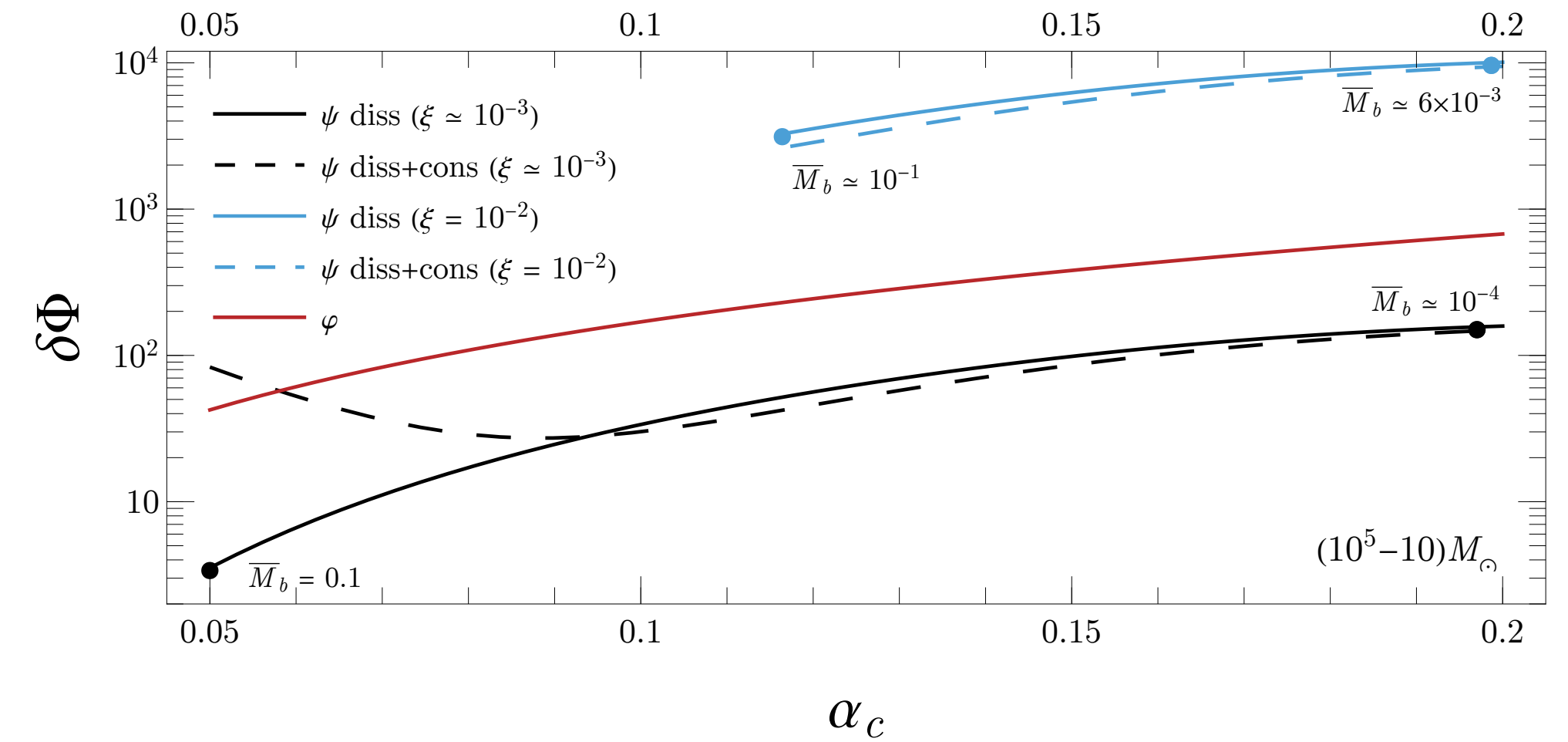
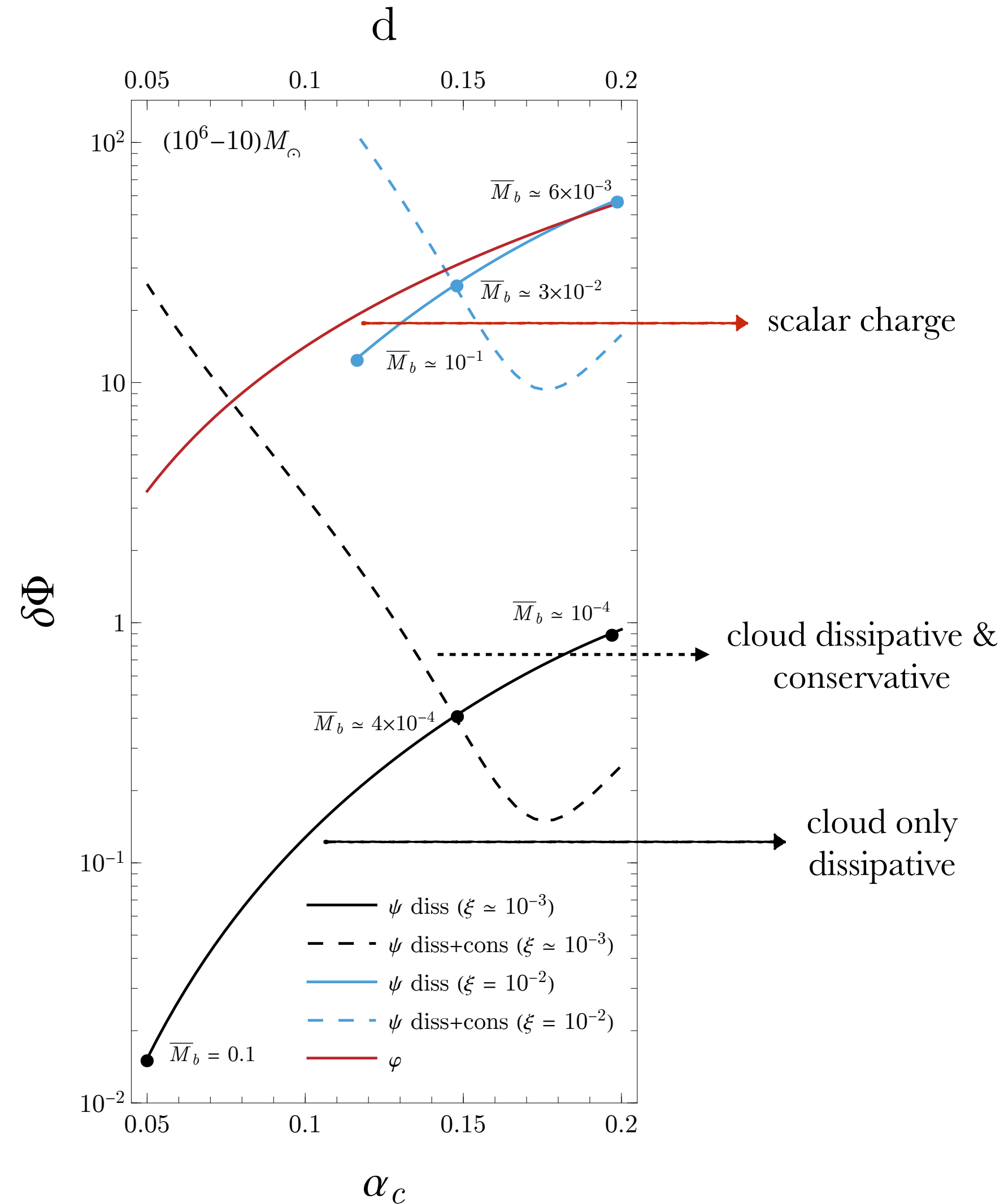
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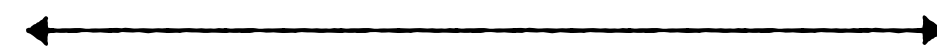
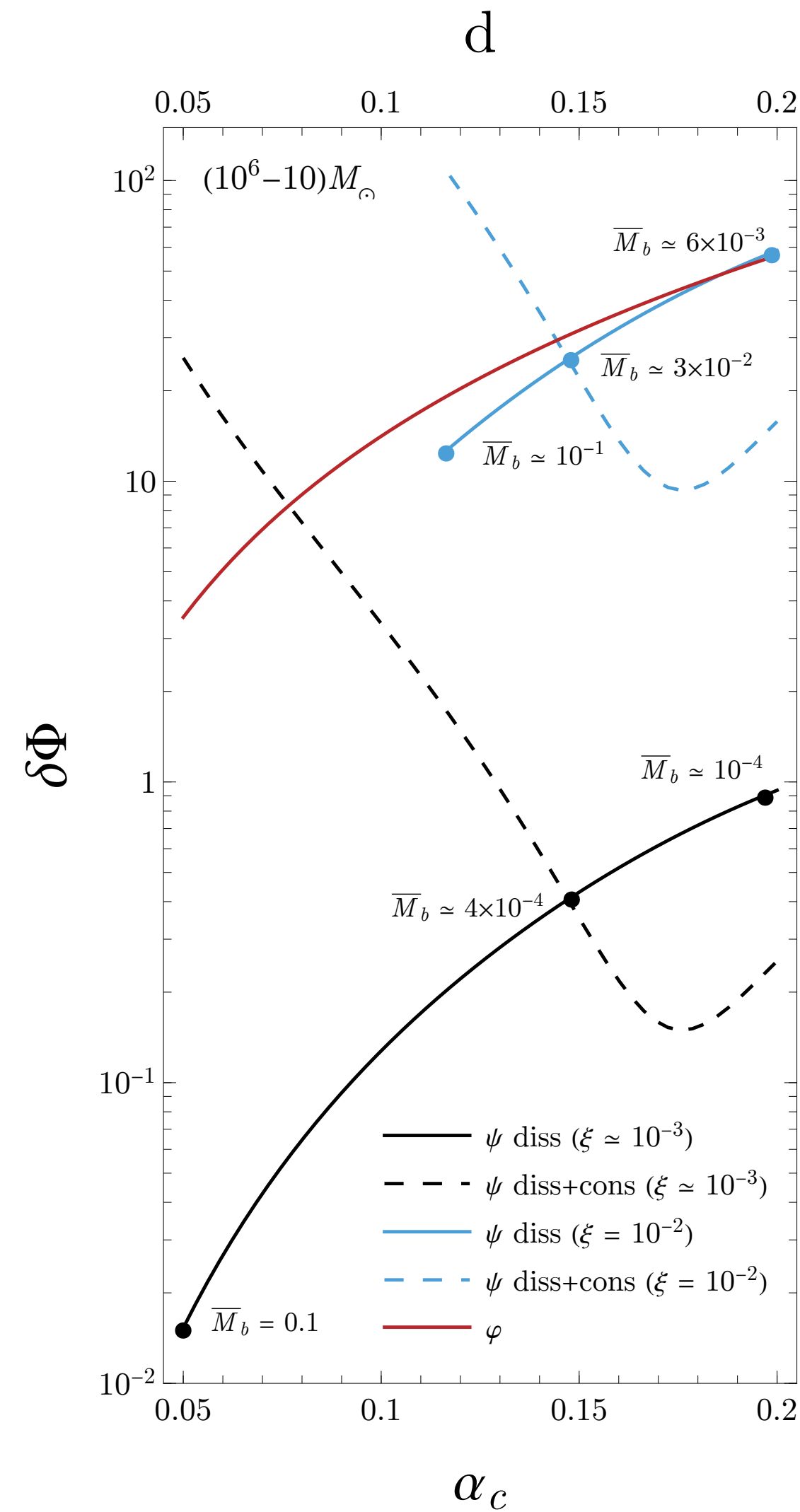
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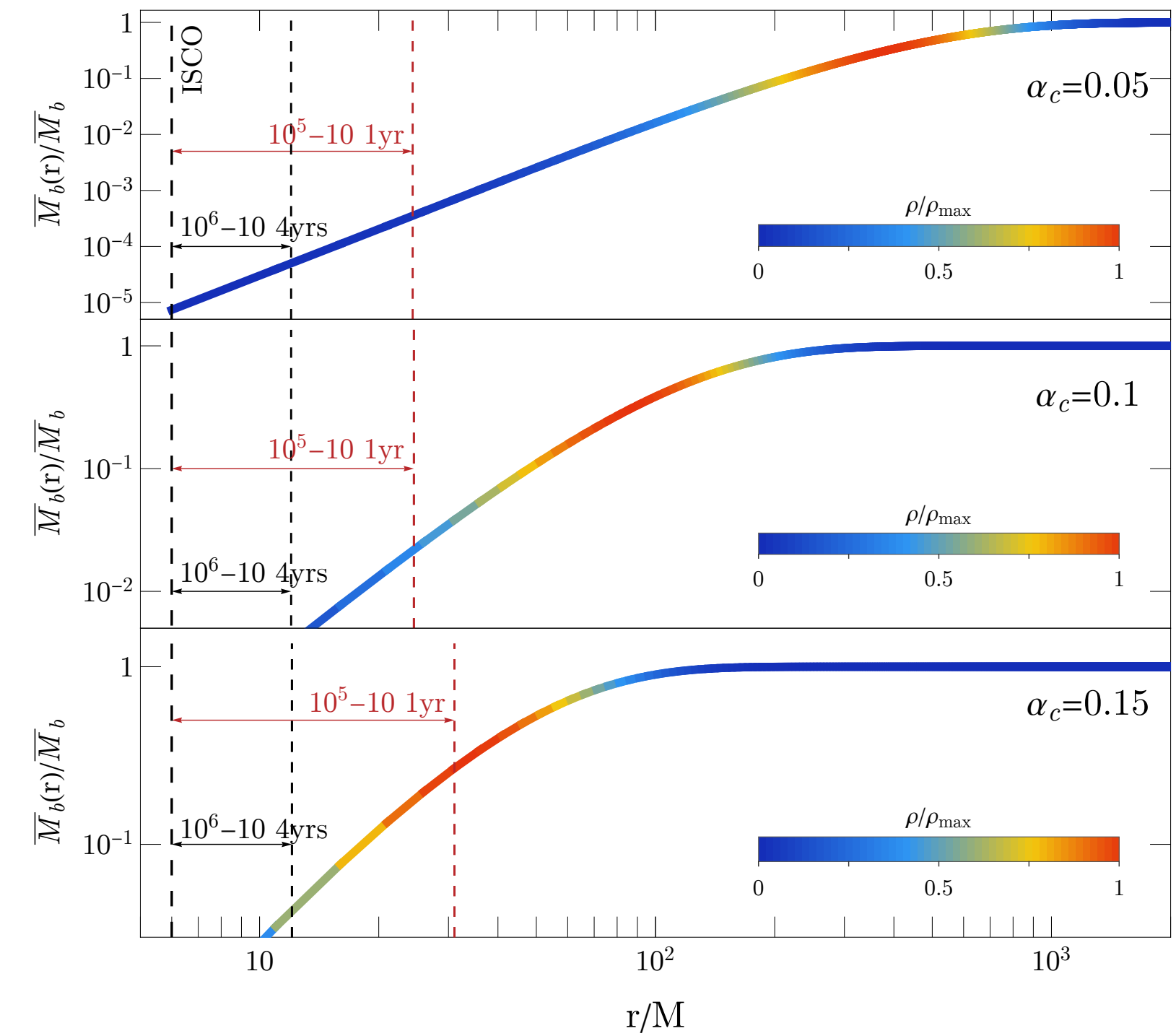
- ☉ The environmental cloud's imprint on the GW phase is dominated by its conservative correction at small coupling
- ☉ As α_c increases the conservative and dissipative contributions partially cancel: characteristic crossing at intermediate coupling
- ☉ Strong dependence on the primary mass

GW Dephasing: individual contributions

Difference in phase evolution of EMRI in vacuum - GR v.s. EMRI endowed by scalar fields



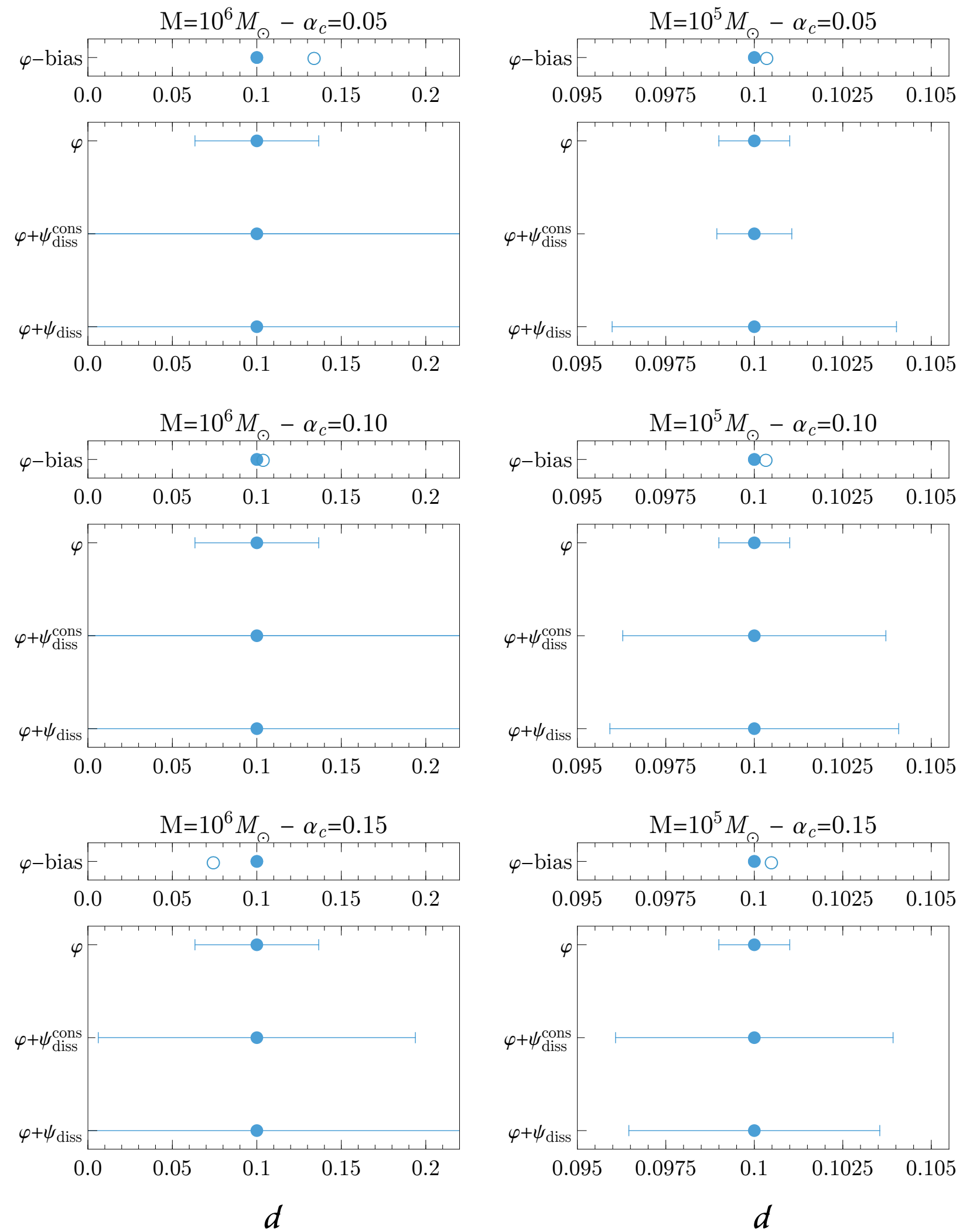
Cloud mass & density profiles



(picture worsens for dipolar clouds..)

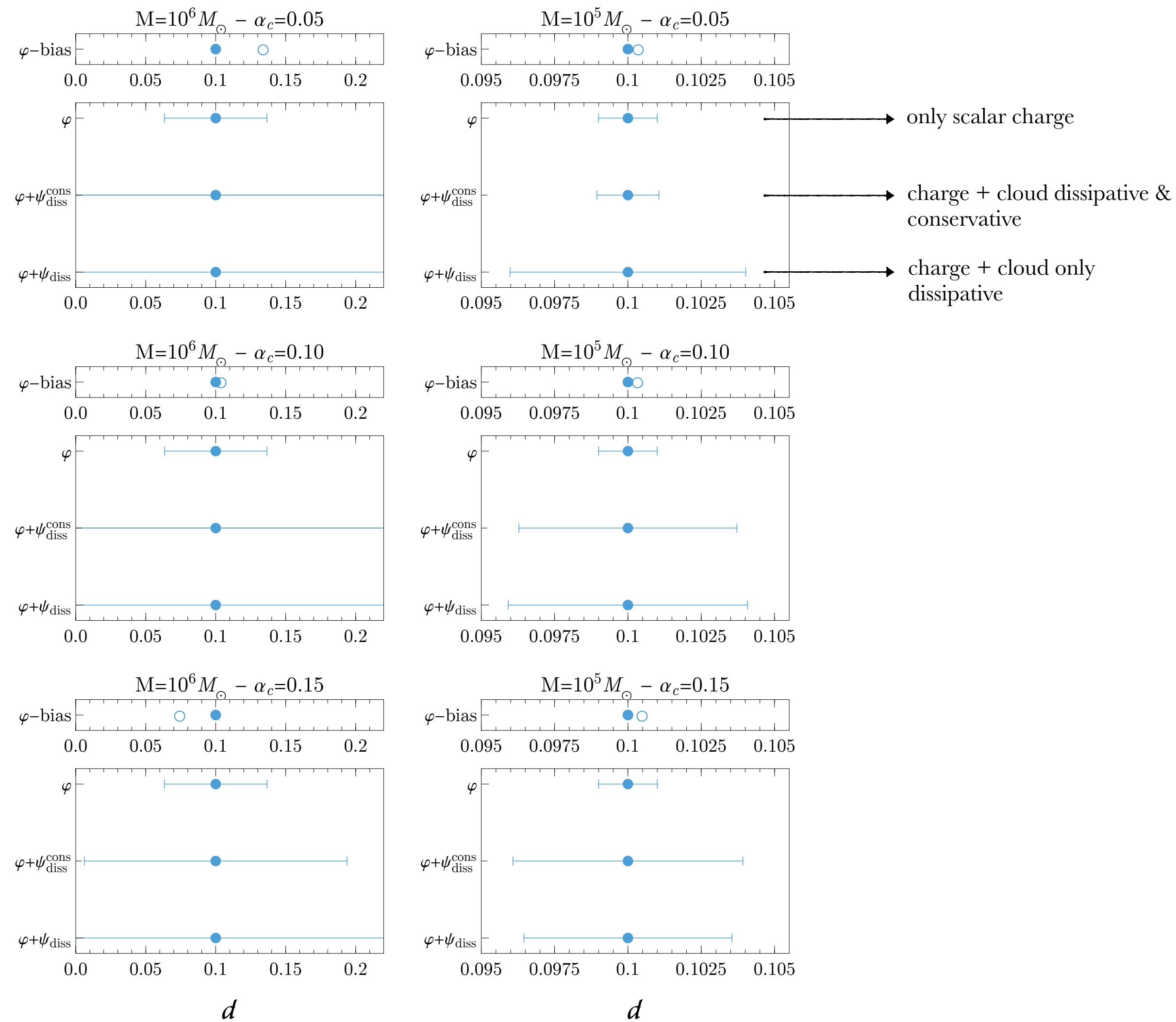
Interplay and Measurability

2σ uncertainties on the scalar charge ($d = 0.1$, $M_b = 0.1M$)



Interplay and Measurability

2σ uncertainties on the scalar charge ($d = 0.1$, $M_b = 0.1M$)



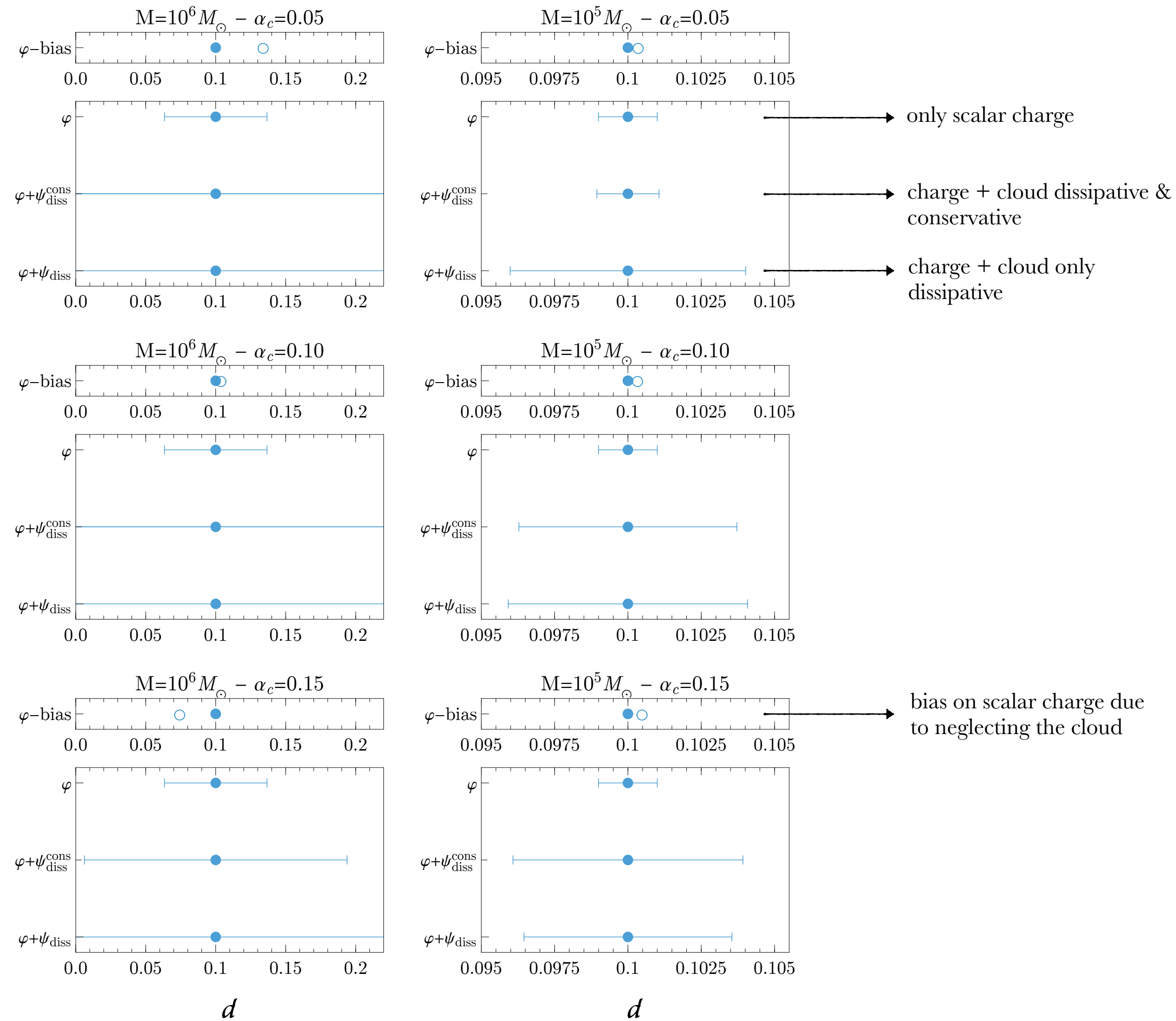
Including the cloud contribution degrades the detectability of the scalar charge

More severe for more massive binaries

Including conservative cloud corrections in general slightly improves the charge measurability

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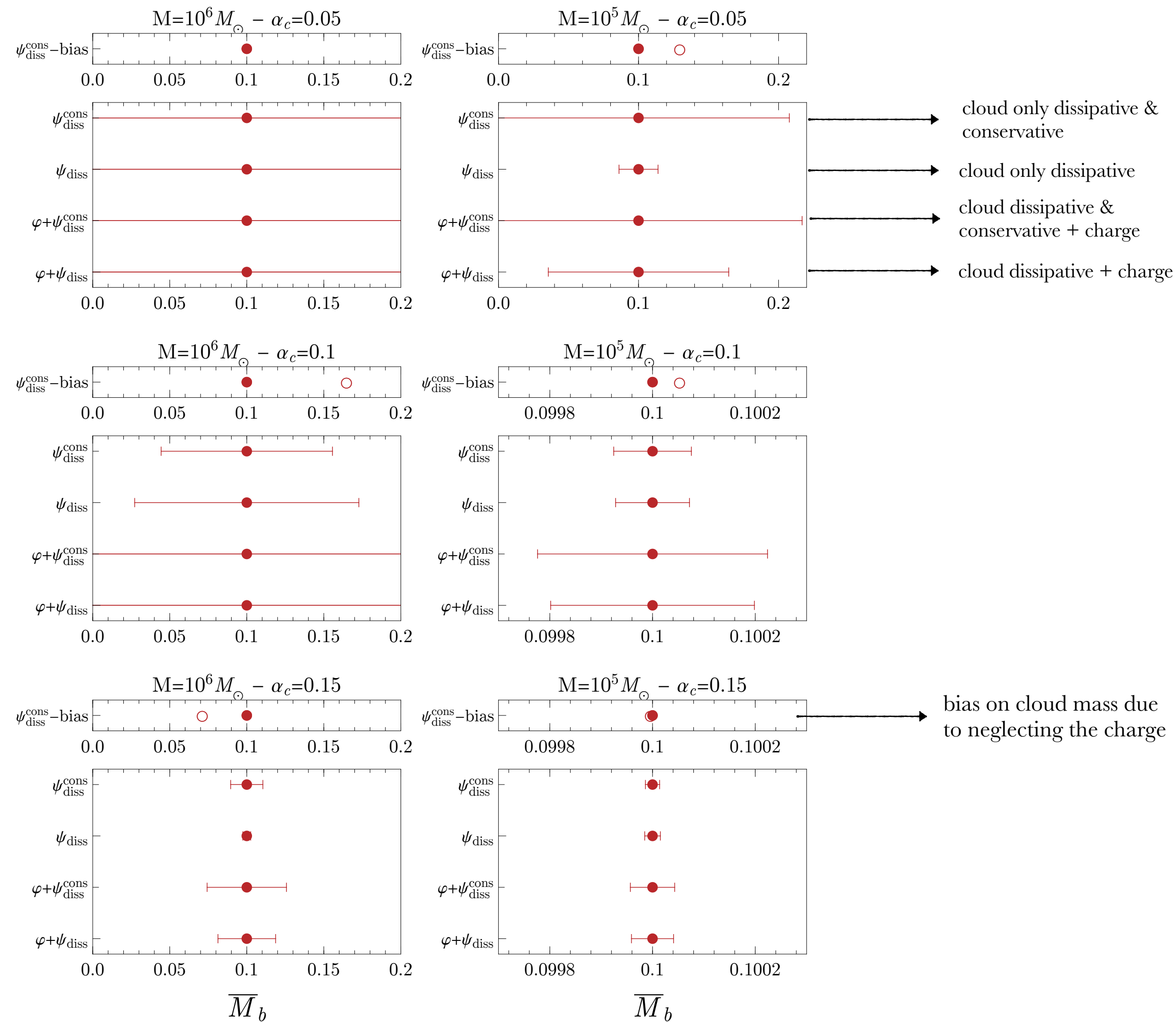
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The bias is larger for more massive primaries and becomes subdominant as M decreases

Interplay and Uncertainties

2σ uncertainties on the cloud mass ($d = 0.1$, $M_b = 0.1M$)

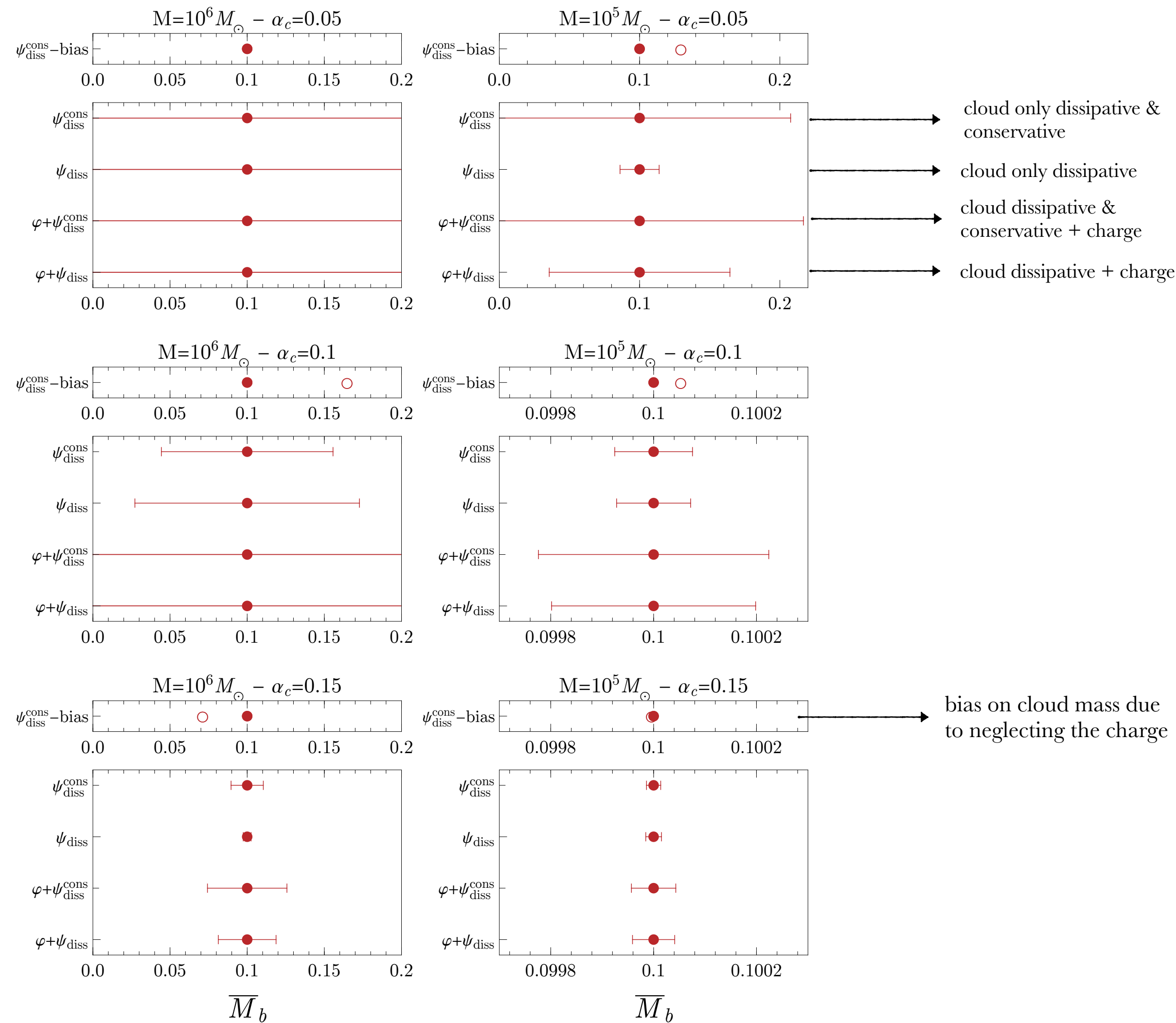


For binaries evolving in the high density region bounds become particularly narrow

Dissipative contributions alone lead, in general, to artificially stronger constraints

Interplay and Uncertainties

2σ uncertainties on the cloud mass ($d = 0.1$, $M_b = 0.1M$)



Including the charge degrades the measurement of the cloud mass

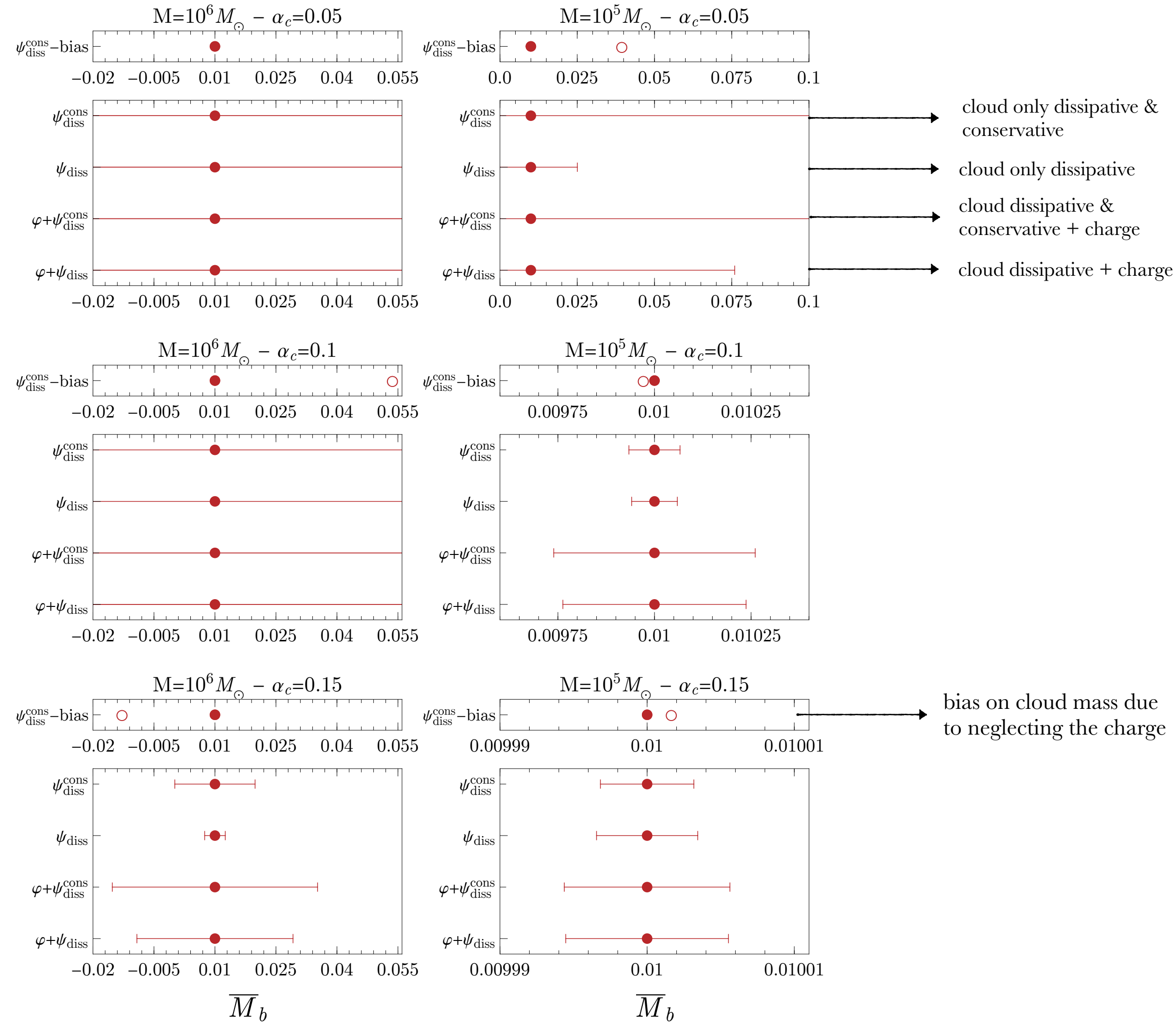
For $M = 10^6 M_\odot$ ($M = 10^5 M_\odot$) it requires $\alpha_c = 0.15$ ($\alpha_c = 0.1$)

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Interplay and Uncertainties

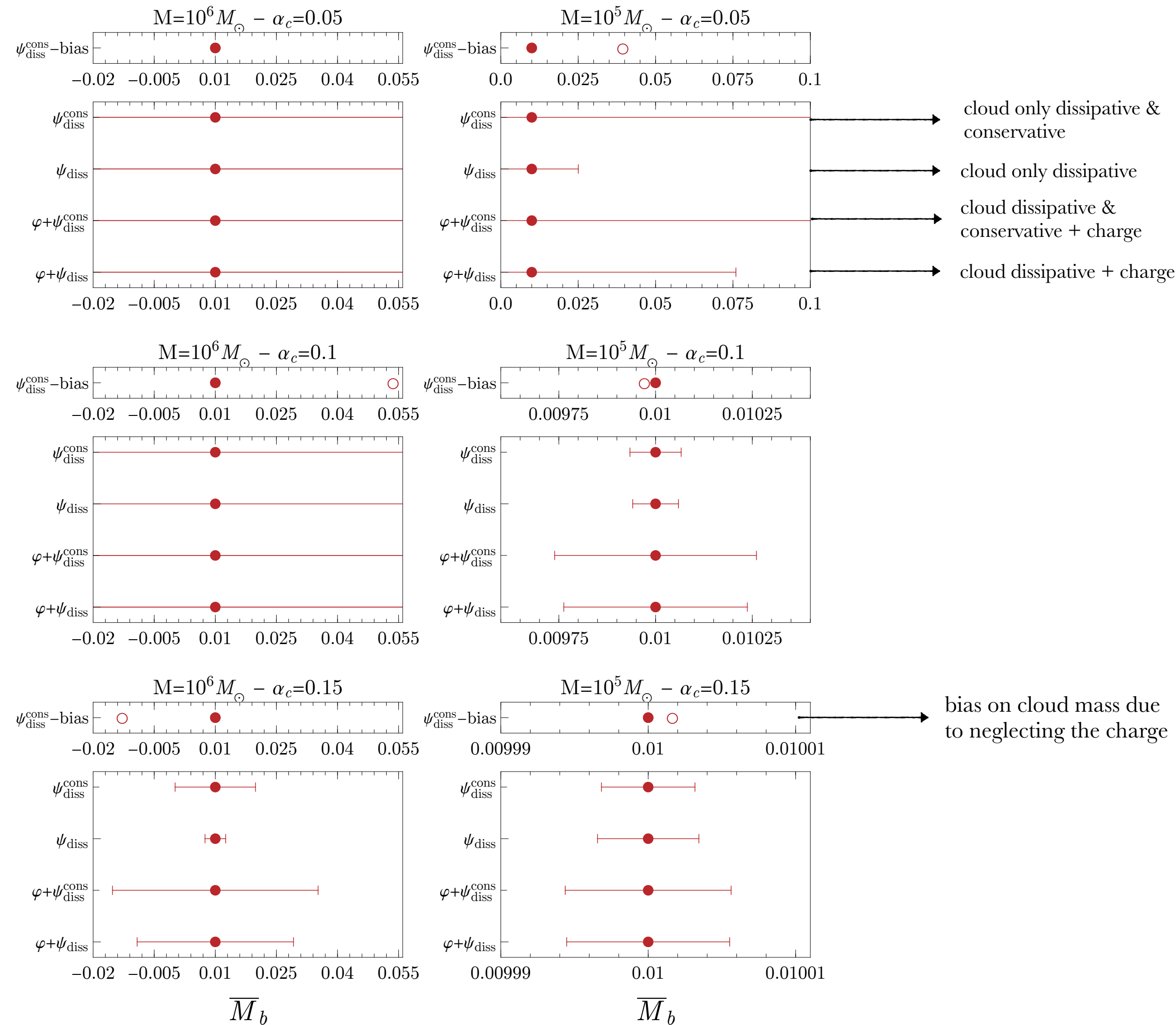
2σ uncertainties on the cloud mass ($d = 0.1$, $M_b = 0.01M$)



- For binaries evolving in the high density region bounds become particularly narrow
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Interplay and Uncertainties

2σ uncertainties on the cloud mass ($d = 0.1$, $M_b = 0.01M$)



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For $M = 10^6 M_\odot$ ($M = 10^5 M_\odot$) it requires $\alpha_c = 0.15$ ($\alpha_c = 0.1$)

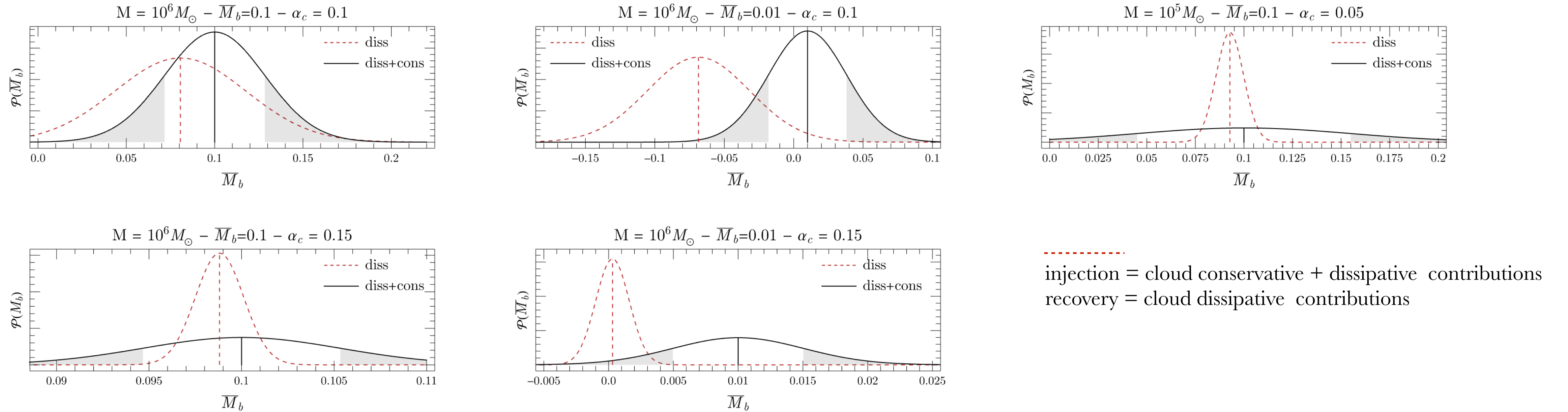
For binaries evolving in the high density region bounds become particularly narrow

Dissipative contributions alone lead, in general, to artificially stronger constraints

For lighter clouds bounds are compatible with vacuum, except for $M = 10^5 M_\odot$ and $\alpha_c \gtrsim 0.1$

Conservative vs dissipative cloud contributions

The impact of conservative corrections for the cloud mass reconstruction (no charge)



- As the cloud mass decreases, the bias becomes more severe
- Neglecting the conservative correction systematically shifts the peak of the recovered posterior toward lower values of M_b/M
- Neglecting the conservative correction tends to artificially narrow the posterior

Summary

Multi-field approach as model for the interplay between matter & GR modifications

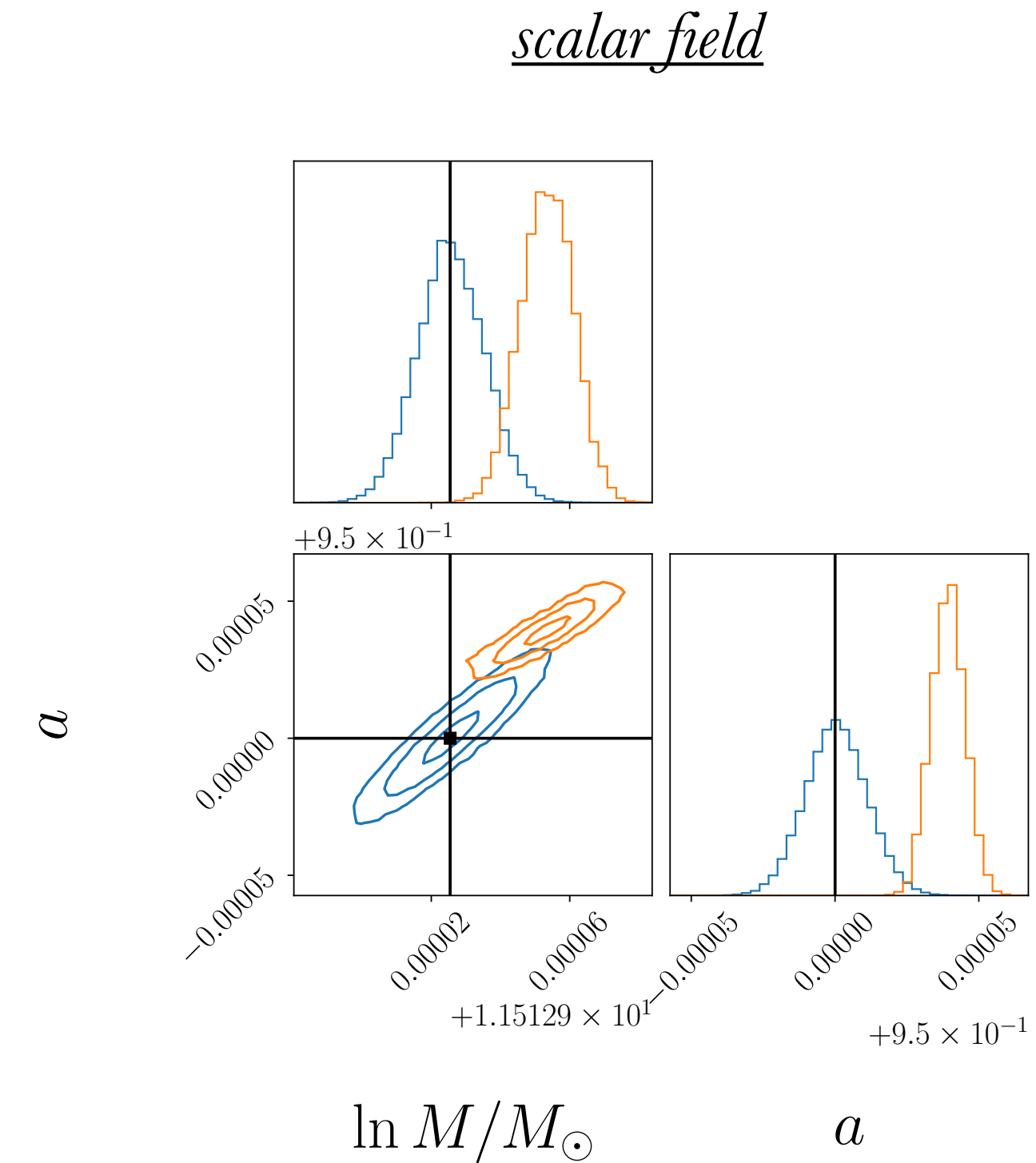
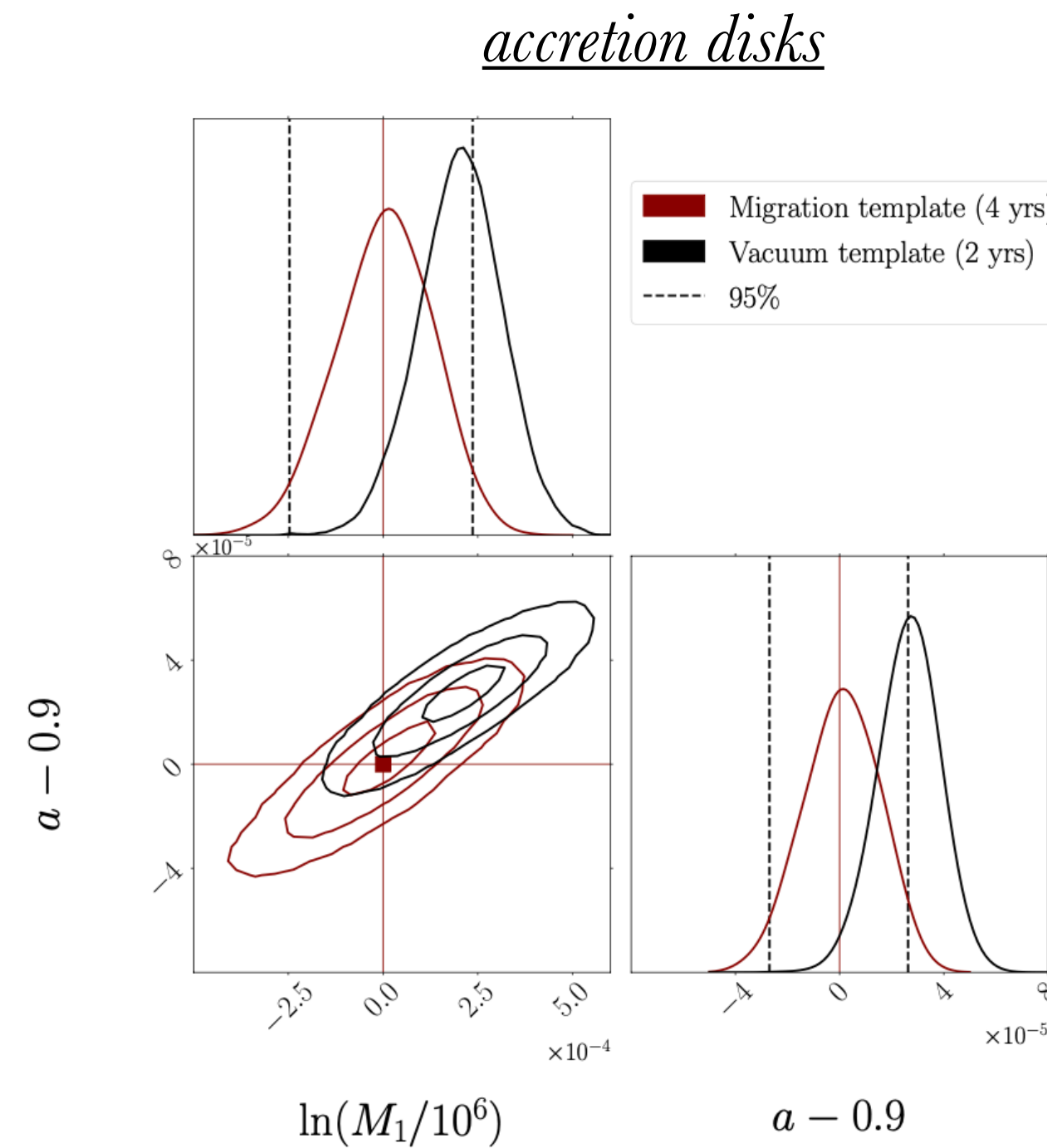
- Key simplifications occur due to mass asymmetry
- (leading) GR deviations are **universal** and only controlled by the scalar **charge** of the **lighter** component
- Inclusion of charge/cloud can degrade even significantly the measurement
- Conservative effects dominate dissipative terms for small couplings α_c .
 - At intermediate regimes of α_c partial cancellations between conservative and dissipative terms occur
 - Neglecting conservative correction can lead to systematic bias, and to artificially strong constraints on the cloud parameters
- Environmental effects from the cloud around the primary and a scalar charge on the secondary are unlikely to be mutually misinterpreted as a genuine deviation from GR

Back up

Contaminations & biases: one at a time

Does mismodeling affect parameters reconstruction, and other tests of fundamental physics (tests of GR)?

L. Speri +, 2023; L. Speri + inc. A. M., 2024



🟢 Bias in the source intrinsic parameters is small

🔴 Problematic for ‘small’ deviations, like beyond GR/environmental corrections

E/IMRIs in GR

$$\mathbf{g}_{\alpha\beta} = g_{\alpha\beta} + qh_{\alpha\beta} + q^2 h_{\alpha\beta}^{(2)} + \mathcal{O}(q^3)$$

Contributions to the orbital trajectory

$$\frac{D^2 z^\alpha}{d\tau^2} = qf_1^\alpha + q^2 f_2^\alpha + \mathcal{O}(q^3)$$

Inspiral evolution on radiation-reaction time t_{rr}

$$t_{rr} = \mathcal{E}/\dot{\mathcal{E}} \sim M/q \quad \xrightarrow[\text{of second order SF}]{\text{cumulative shift}} \quad \delta z^\alpha \sim q^2 f_2^\alpha t_{rr}^2 \sim q^0$$

Match filtering require error in phase < 1 radian: f_2^α ✓ f_3^α ✗

$$\Phi(t) = \frac{1}{q} [\Phi_0(t) + q\Phi_1(t) + \mathcal{O}(q^3)]$$

$f_{1,\text{diss}}^\alpha$

$f_{1,\text{cons}}^\alpha$
 $f_{2,\text{diss}}^\alpha$

How do we go beyond GR, including new fundamental fields?

Multi-parameter expansion

Full set of the equations for the scalar cloud - scalar charge system

☉ At linear order $\mathcal{O}(q, \xi)$

$$G_{ab}^{[1]}[h_{cd}^{(1,0)}] = 8\pi m_p \int \frac{\delta^4[x - y_p(\tau)]}{\sqrt{-\bar{g}}} u_a^p u_b^p d\tau$$

$$\square \varphi^{(0,1)} = 4\pi d m_p \int \frac{\delta^4[x - y_p(\tau)]}{\sqrt{-\bar{g}}} d\tau \quad (\square - \mu^2) \psi^{(1,0)} = 0$$

☉ At quadratic order $\mathcal{O}(q\xi, \xi^2)$

$$(\square - \mu^2) \psi^{(1,1)} = h^{(0,1)ab} \nabla_a \nabla_b \psi^{(1,0)} + \nabla^a \psi^{(1,0)} \nabla_b h_a^{b(0,1)} - \frac{1}{2} \nabla_a h^{(0,1)} \nabla^a \psi^{(1,0)}$$

$$G_{ab}^{[1]}[h_{cd}^{(2,0)}] = 8\pi \partial_{(a} \psi^{*(1,0)} \partial_{b)} \psi^{(1,0)} - 4\pi g_{ab} [\partial_c \psi^{*(1,0)} \partial^c \psi^{(1,0)} + \mu^2 |\psi^{(1,0)}|^2]$$

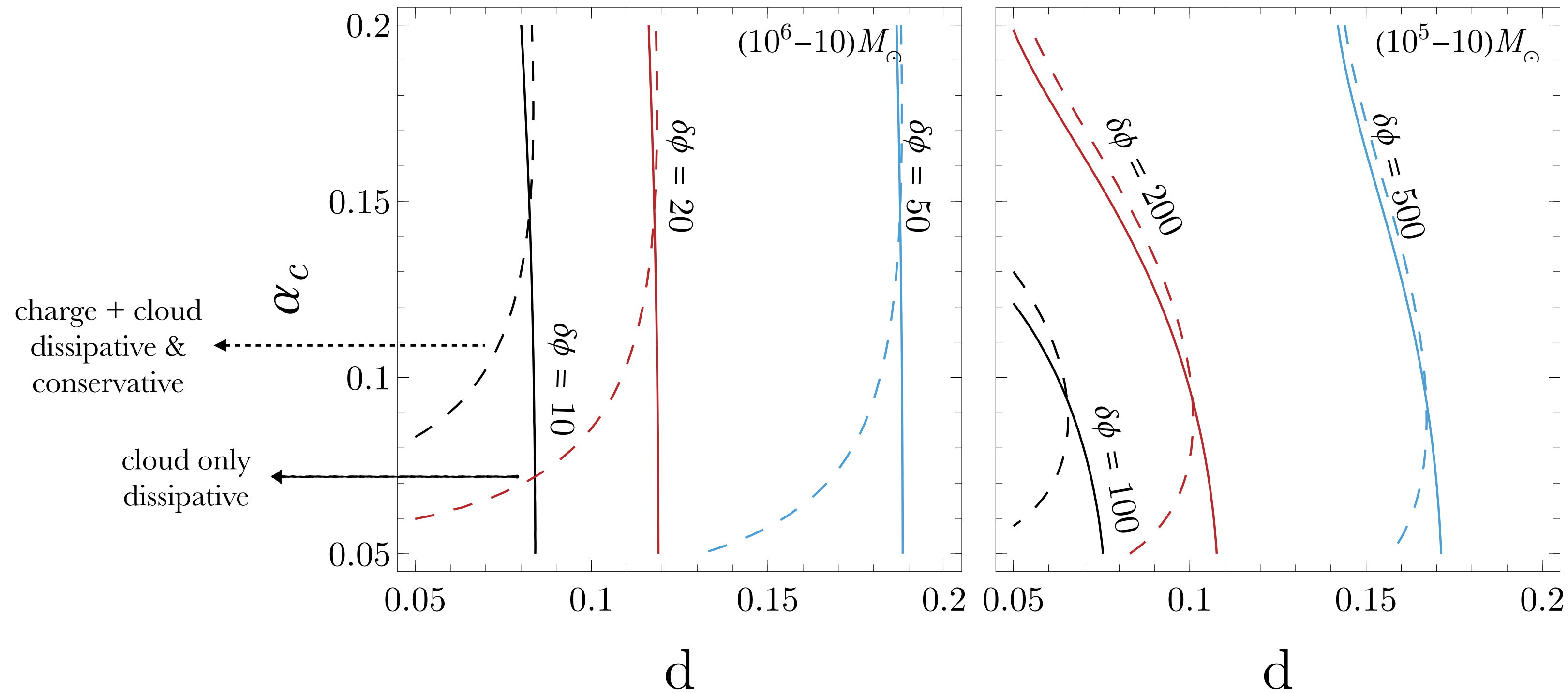
☉ At cubic order $\mathcal{O}(q\xi^2)$

$$\square \varphi^{(2,1)} = 3 \left[h^{(2,0)ab} \nabla_a \nabla_b \varphi^{(0,1)} + \left(\nabla^b h_{ab}^{(2,0)} - \frac{1}{2} \nabla_a h^{(2,0)} \right) \nabla^a \varphi^{(0,1)} \right]$$

$$G_{ab}^{[1]}[h_{cd}^{(2,1)}] = G_{ab}^{[2]}[h_{cd}^{(2,0)}, h_{cd}^{(0,1)}] + S_{ab}^{(2,1)}$$

GW Dephasing: interplay

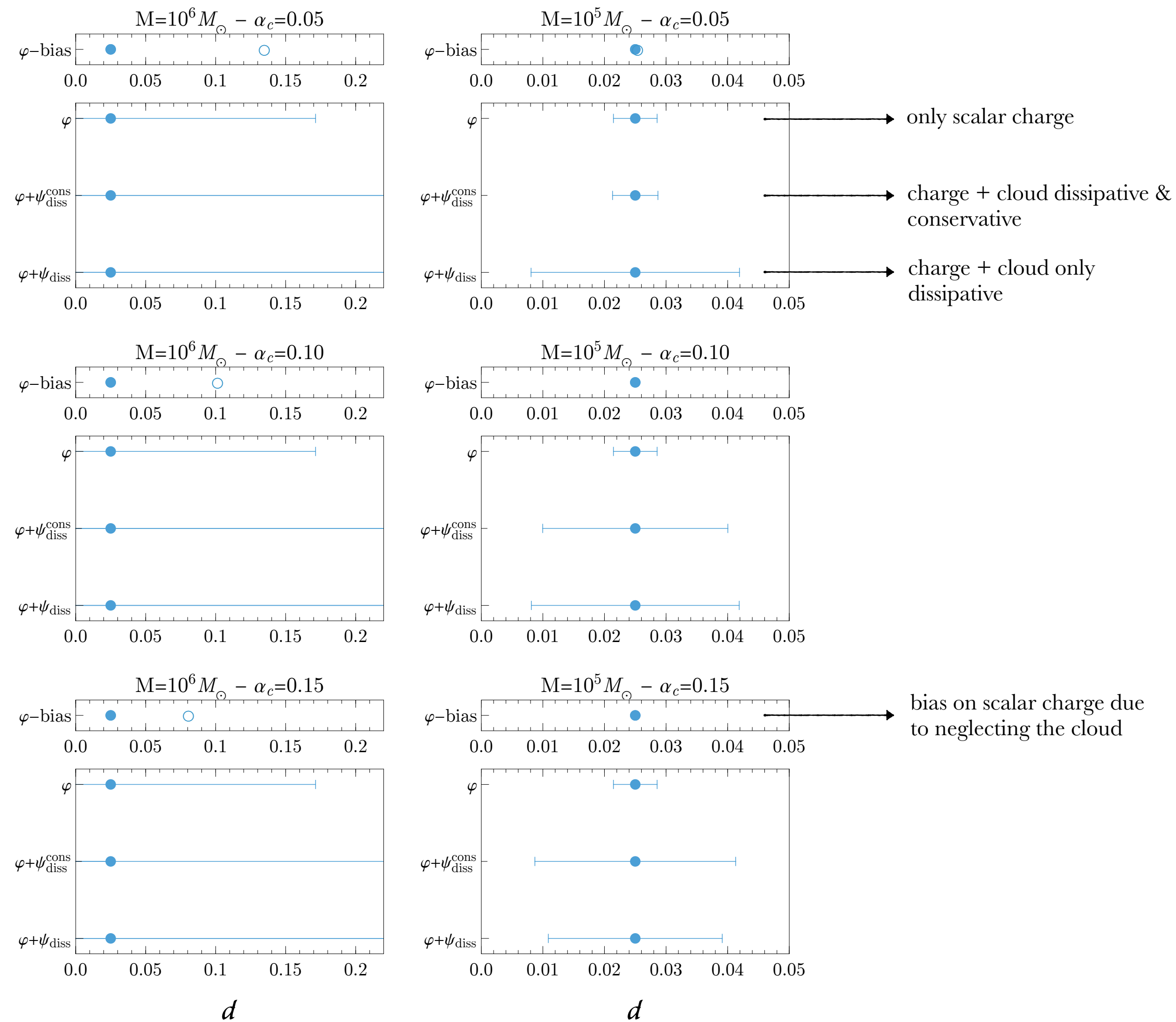
Joint contribution charge-cloud to the total dephasing



- At small α_c and d dephasing tends to be dominated by conservative corrections
- The combined dephasing is approximated by the sum of the individual contributions from each sector, with a mild degeneracy

Interplay and Measurability

2σ uncertainties on the scalar charge ($d = 0.025$, $M_b = 0.1M$)

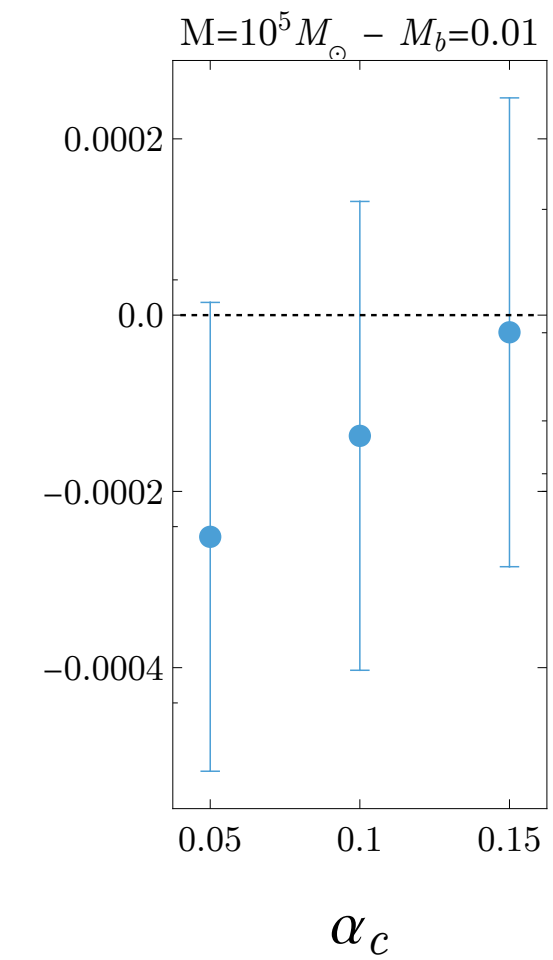
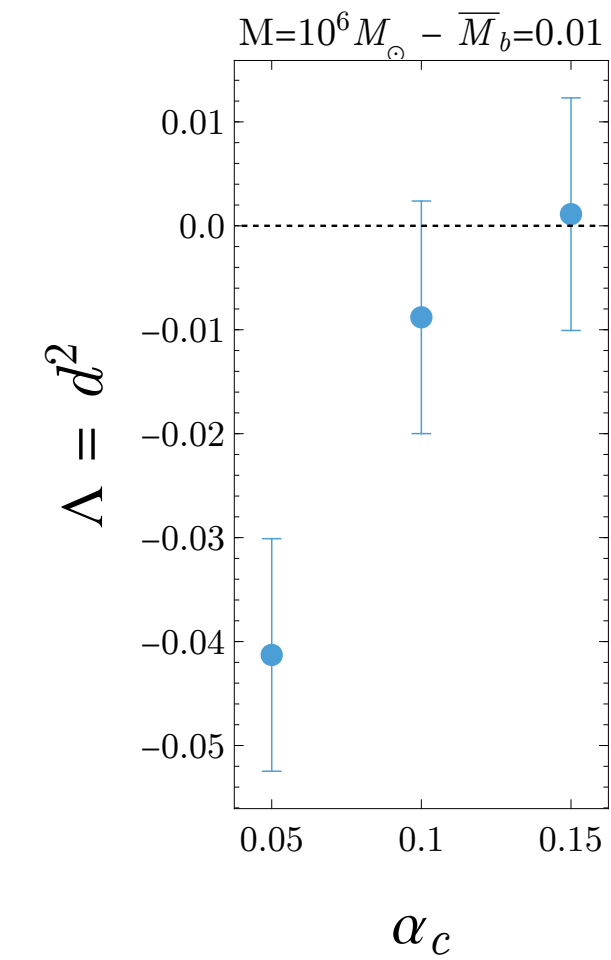
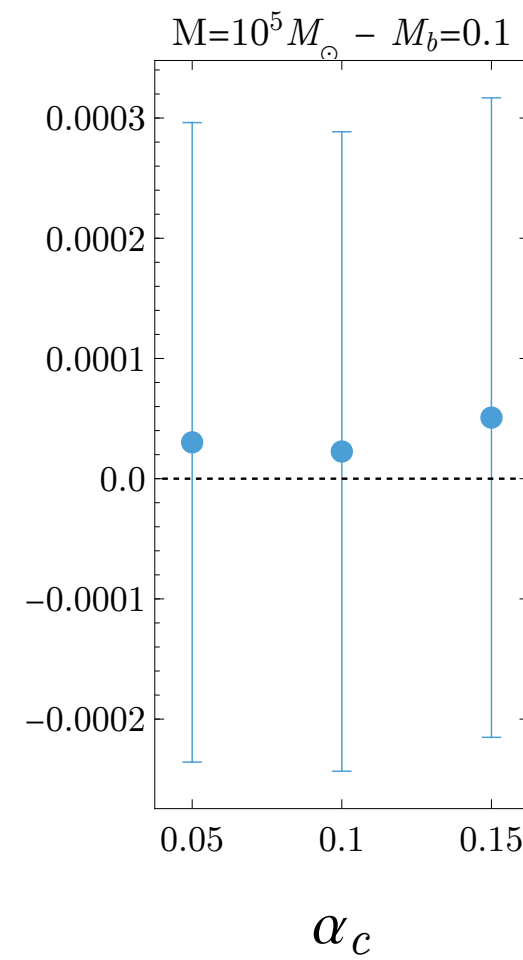
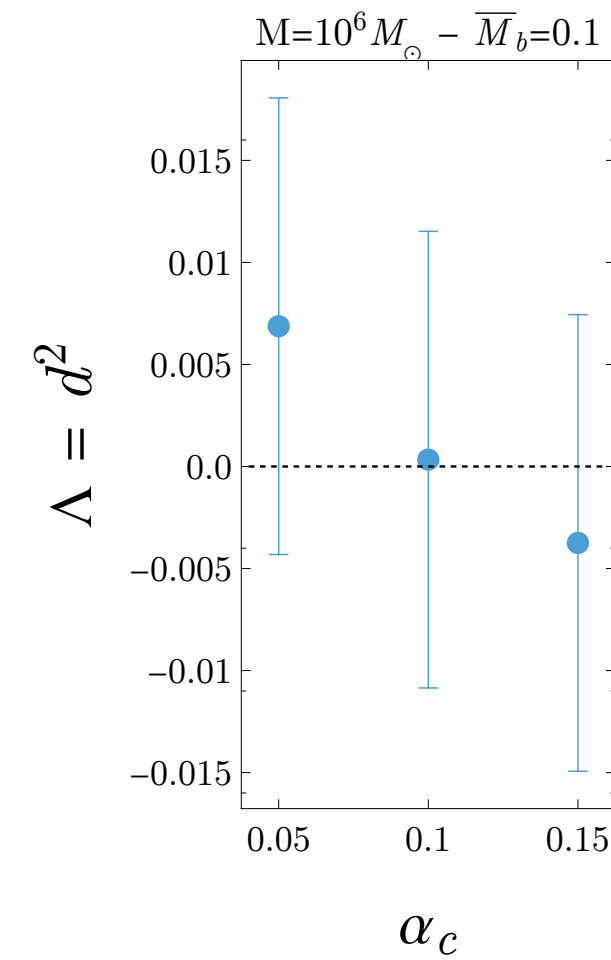


- Including the cloud contribution degrades the detectability of the scalar charge
- More severe for more massive binaries
- Including conservative cloud corrections in general slightly improves the charge measurability
- The bias is larger for more massive primaries and becomes subdominant as M decreases
- For smaller charges and heavier binaries we can only set upper bounds on the charge, and bias increases

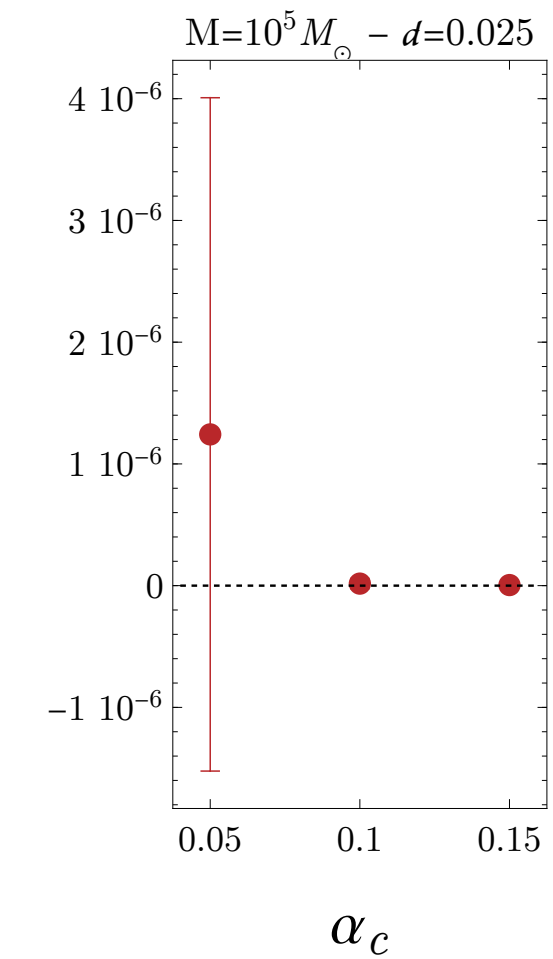
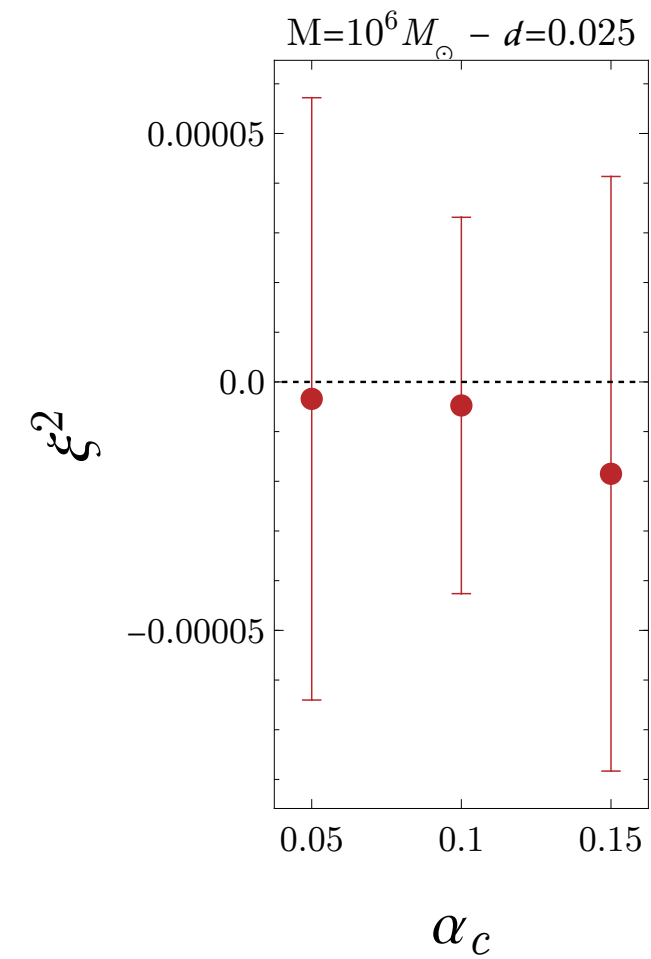
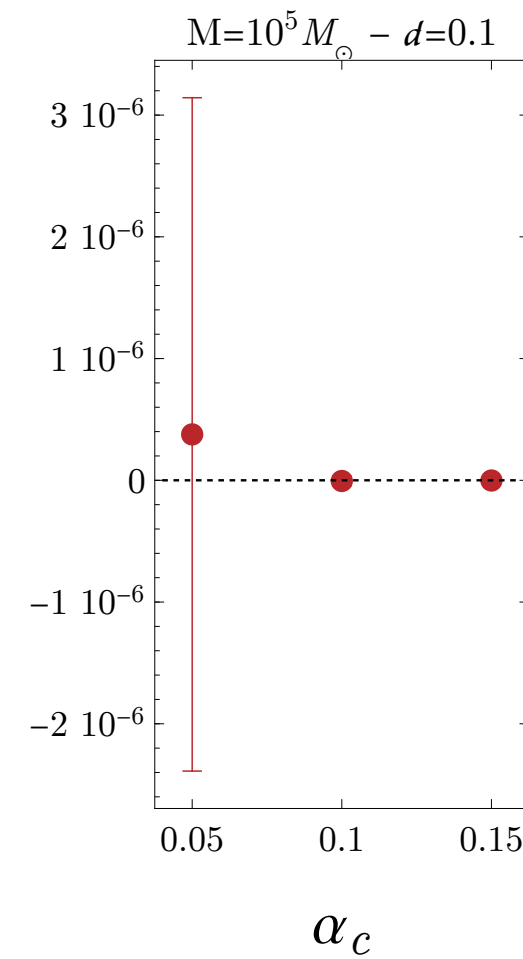
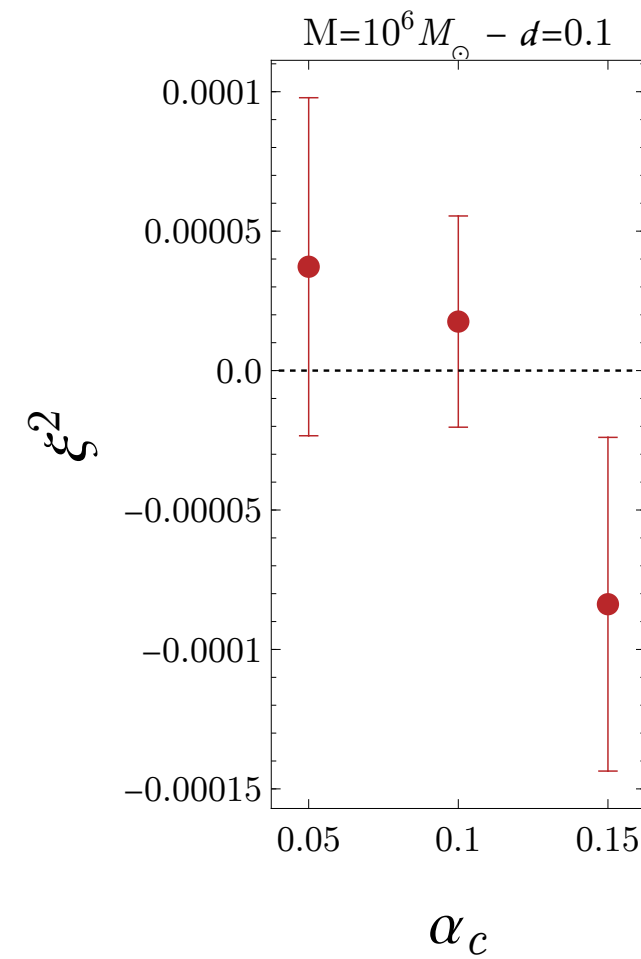
False deviations of vacuum-GR

Can we interpret cloud effect as GR modifications, and viceversa?

injection = cloud
recovery = charge



injection = charge
recovery = cloud

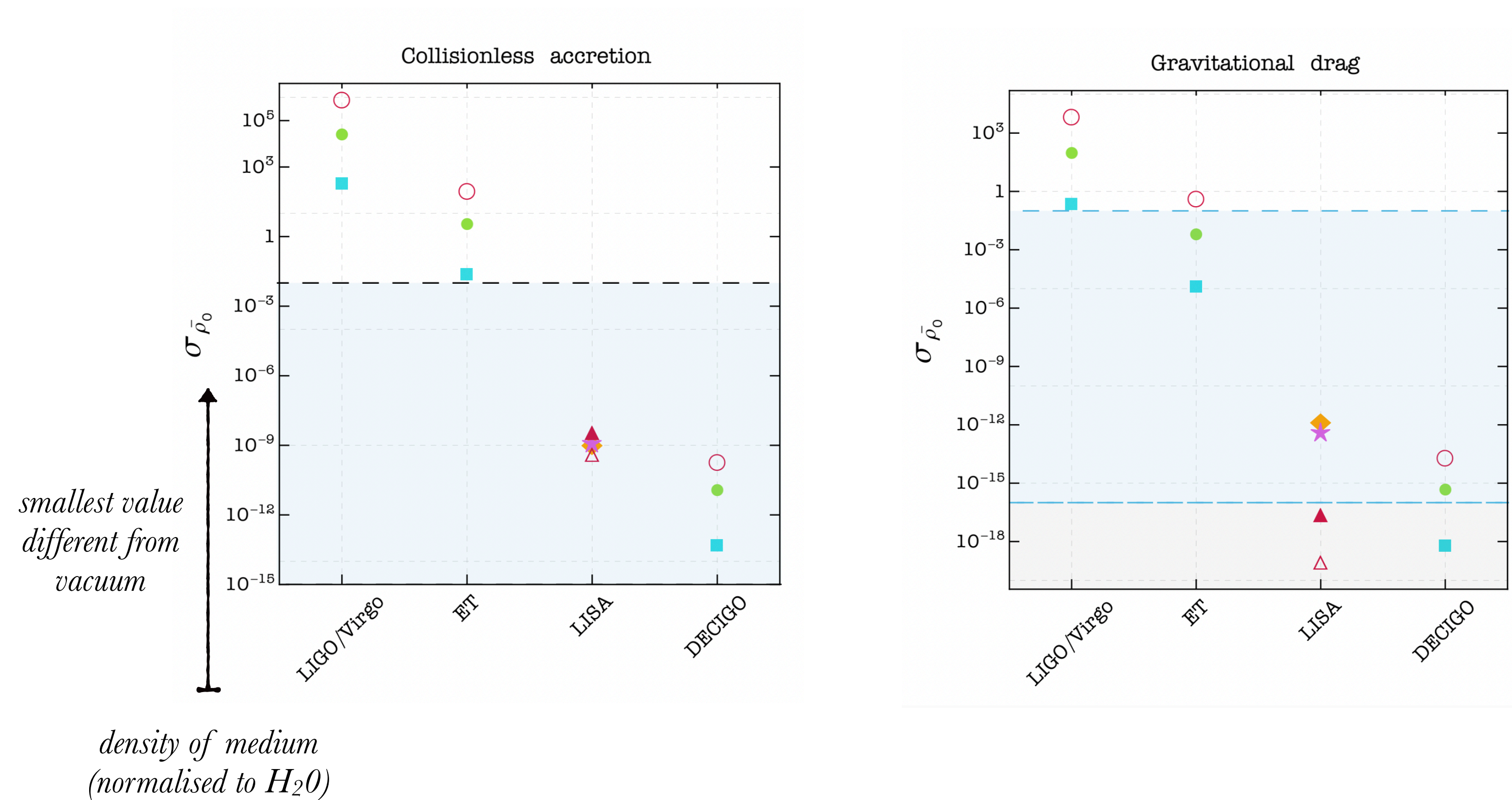


Where do we look for environmental signatures

Constraints on the environment's density from different effects & sources & detectors

V. Cardoso & A. M. 2020

Environmental effects *typically* accumulate at low frequencies and long timescales

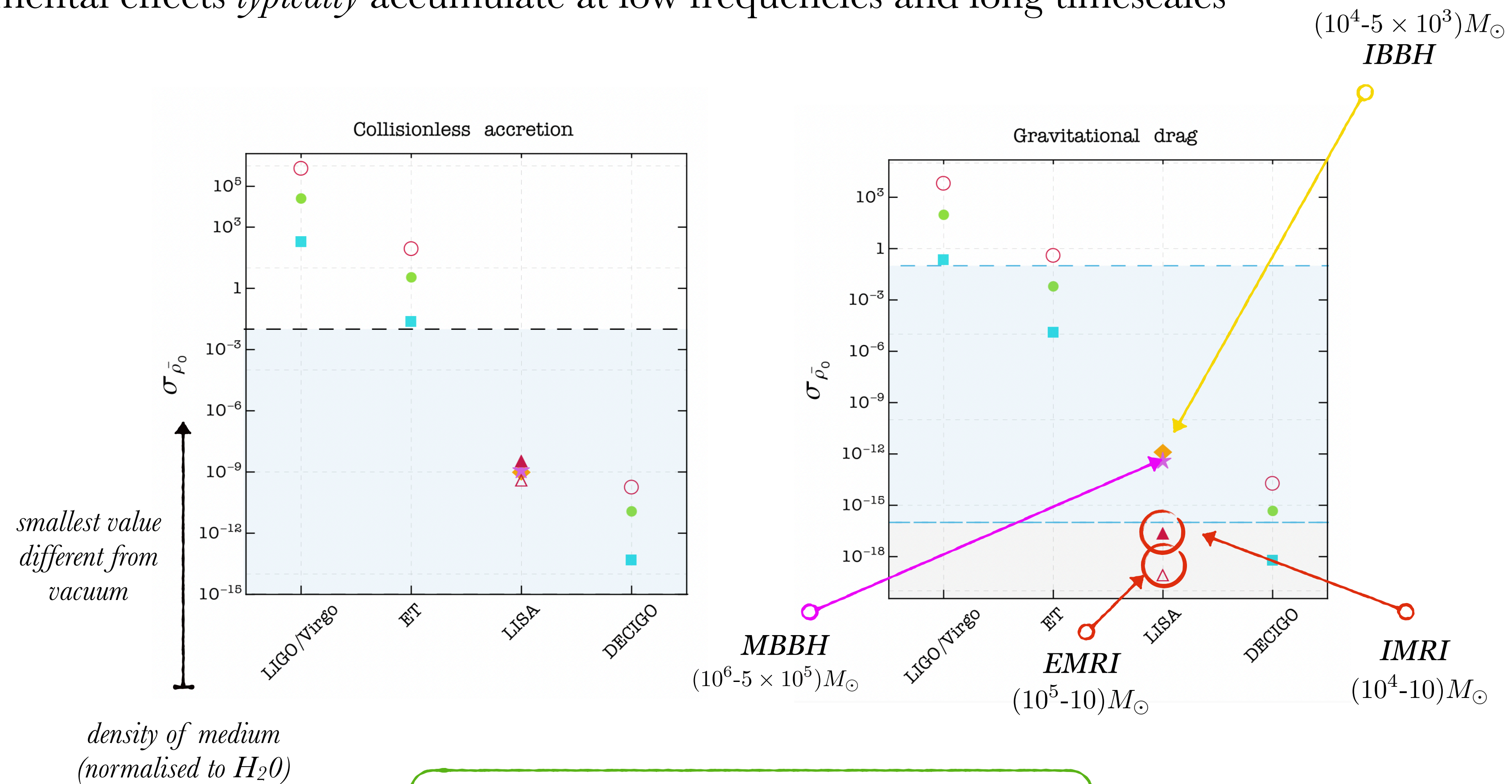


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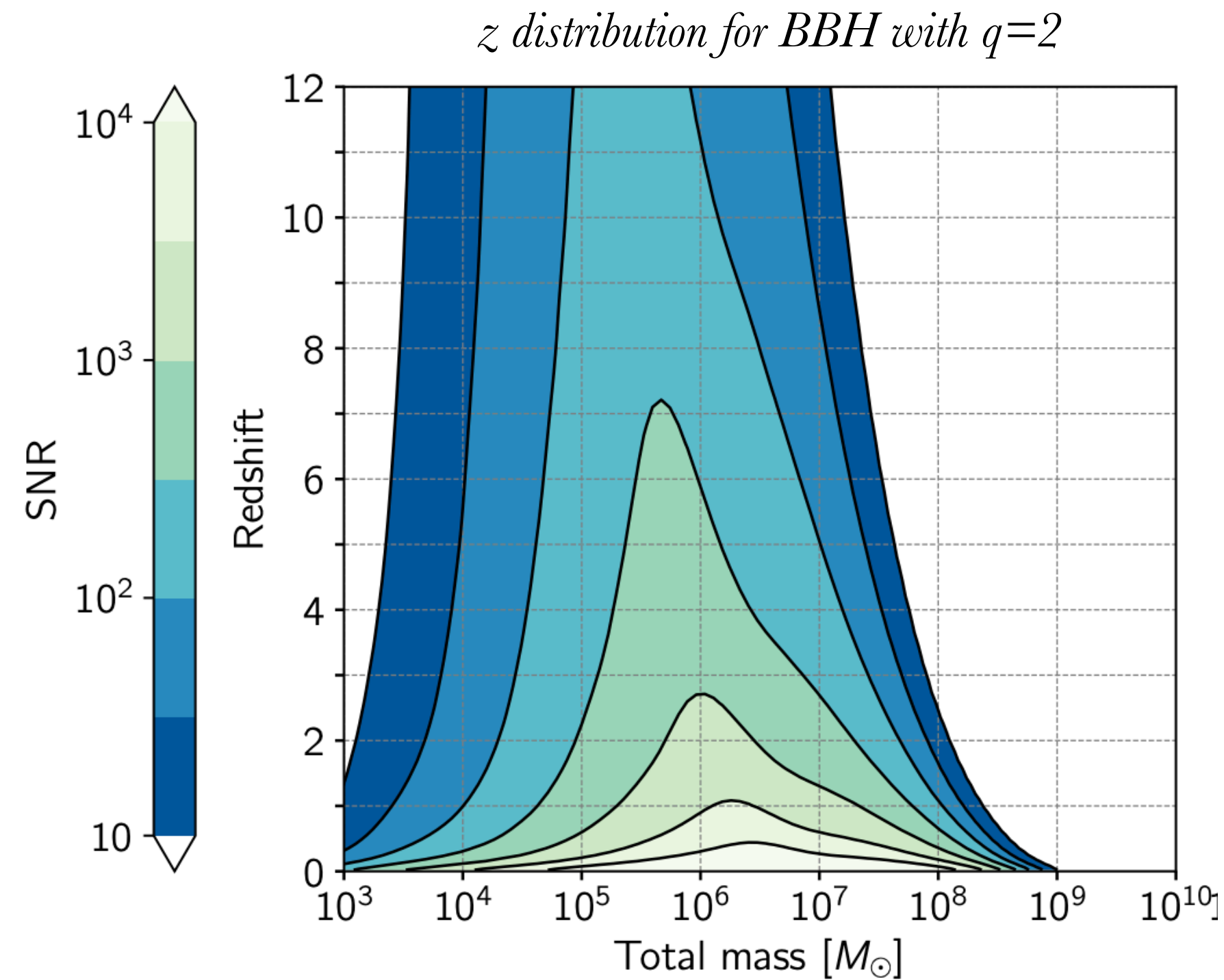


EMRI/IMRIs work really well

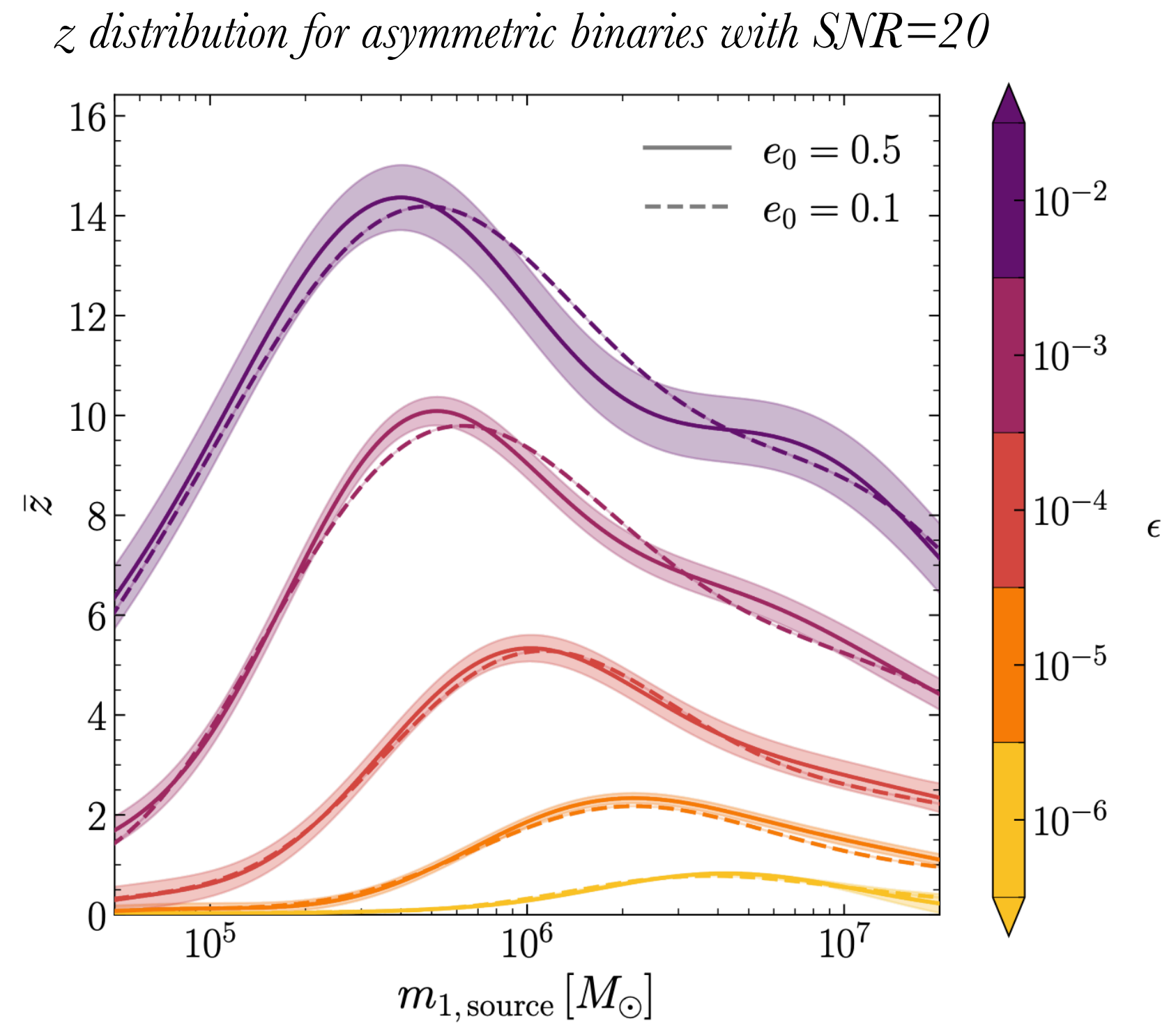
Decoupling of scales and SNRs

Massive comparable-mass binaries are not (always) the best target due to mass suppression, despite their large signal-to-noise ratios

M. Colpi +, 2024
C. Chapman-Bird +, 2025



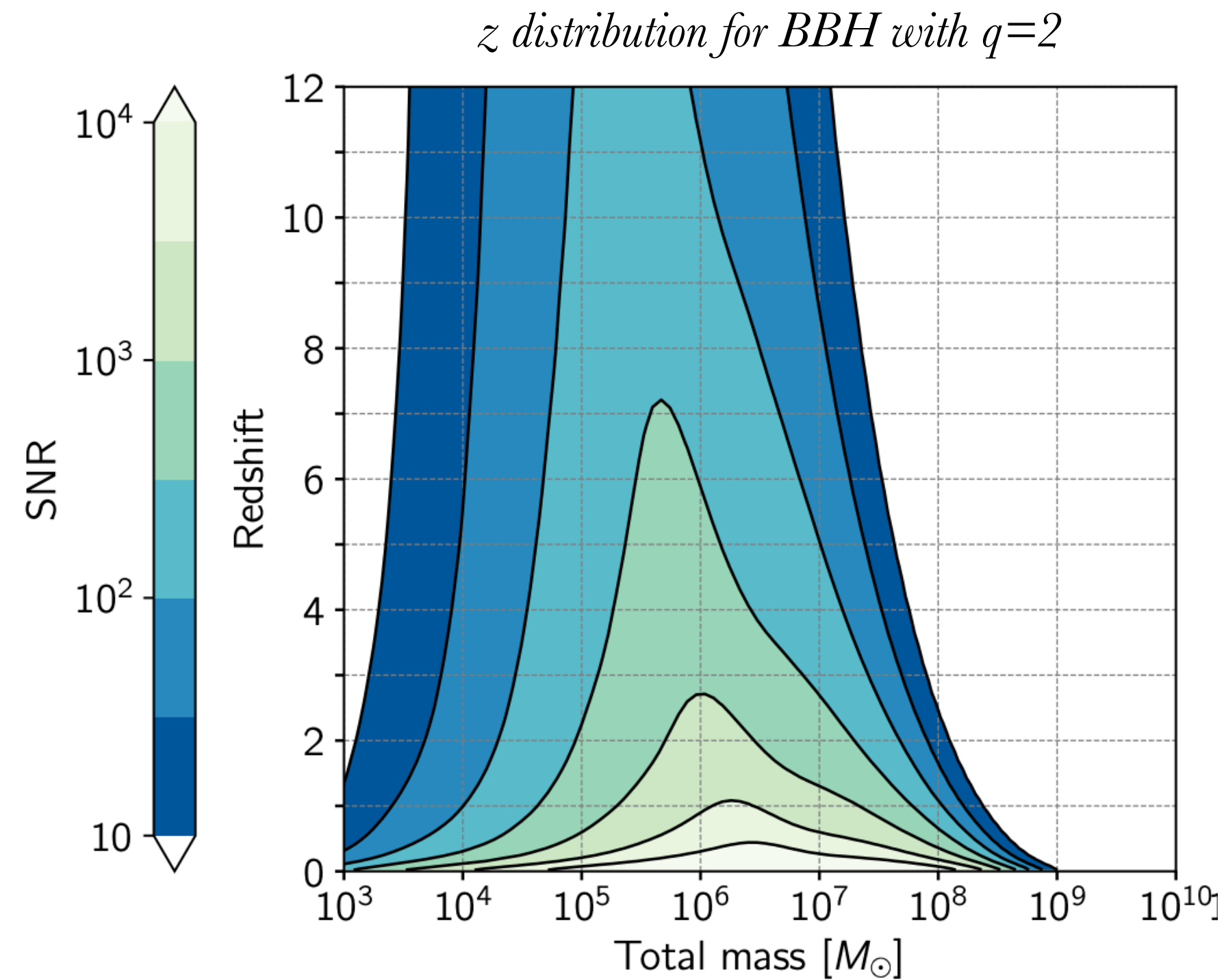
*among the loudest sources in the
Universe*



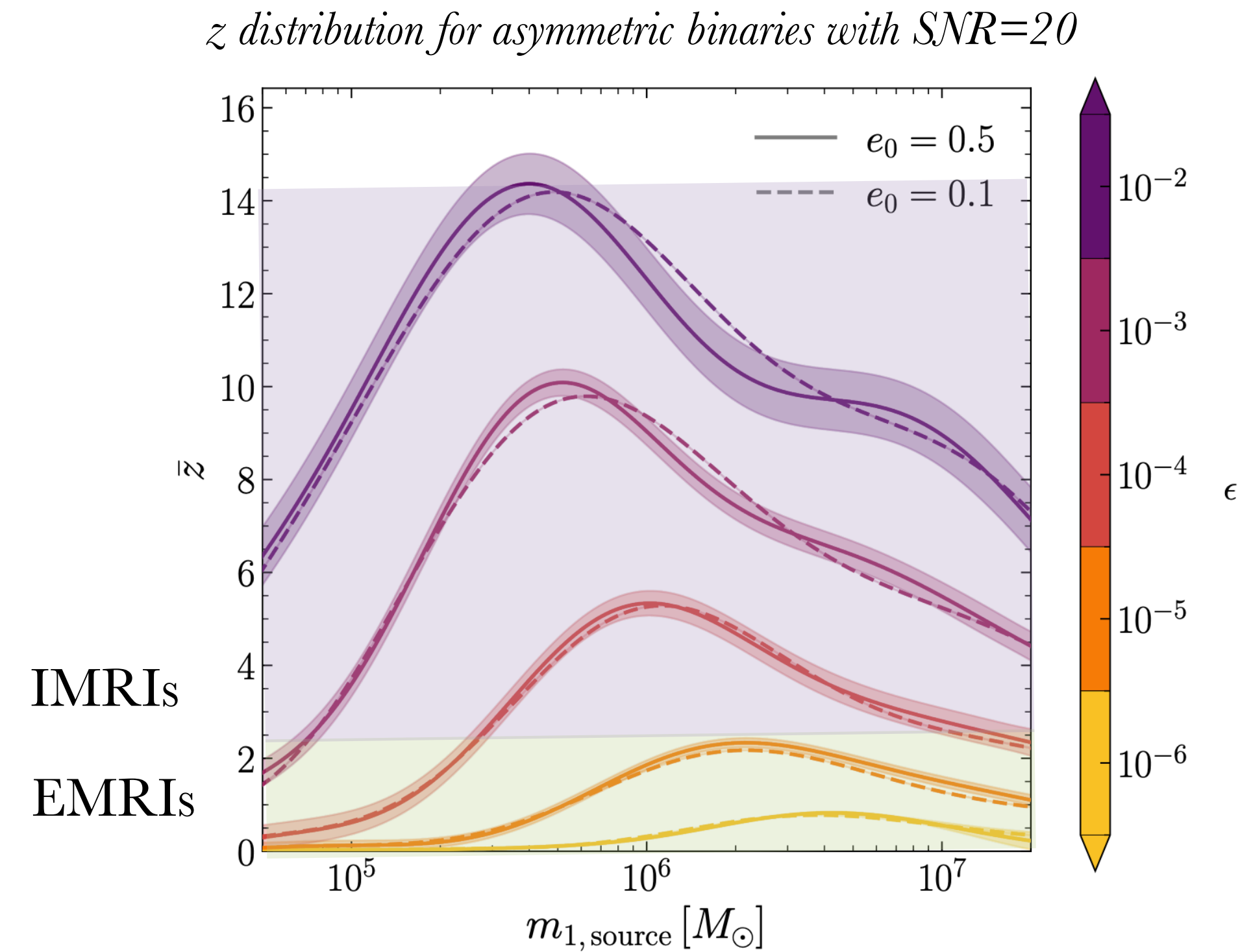
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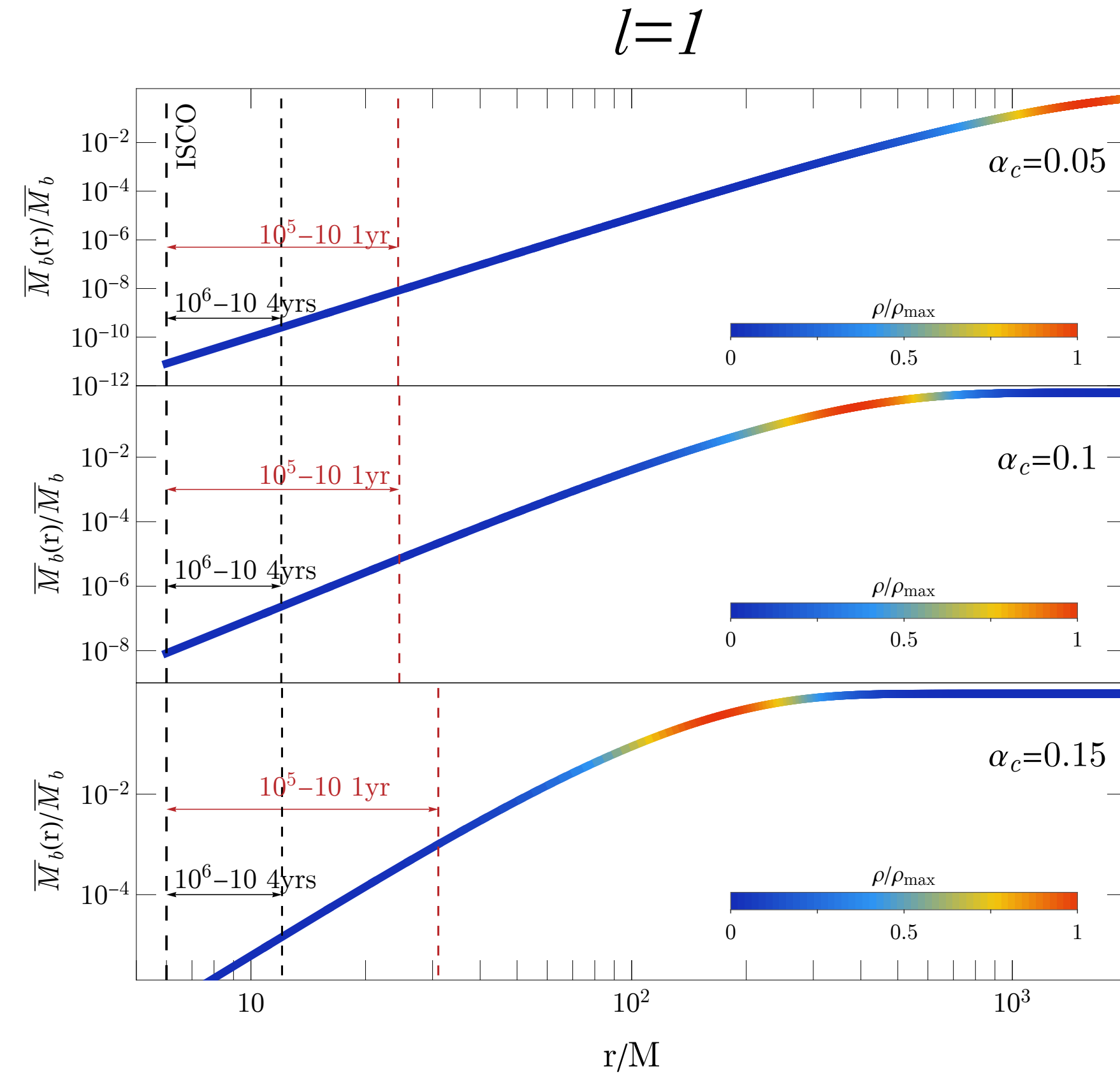
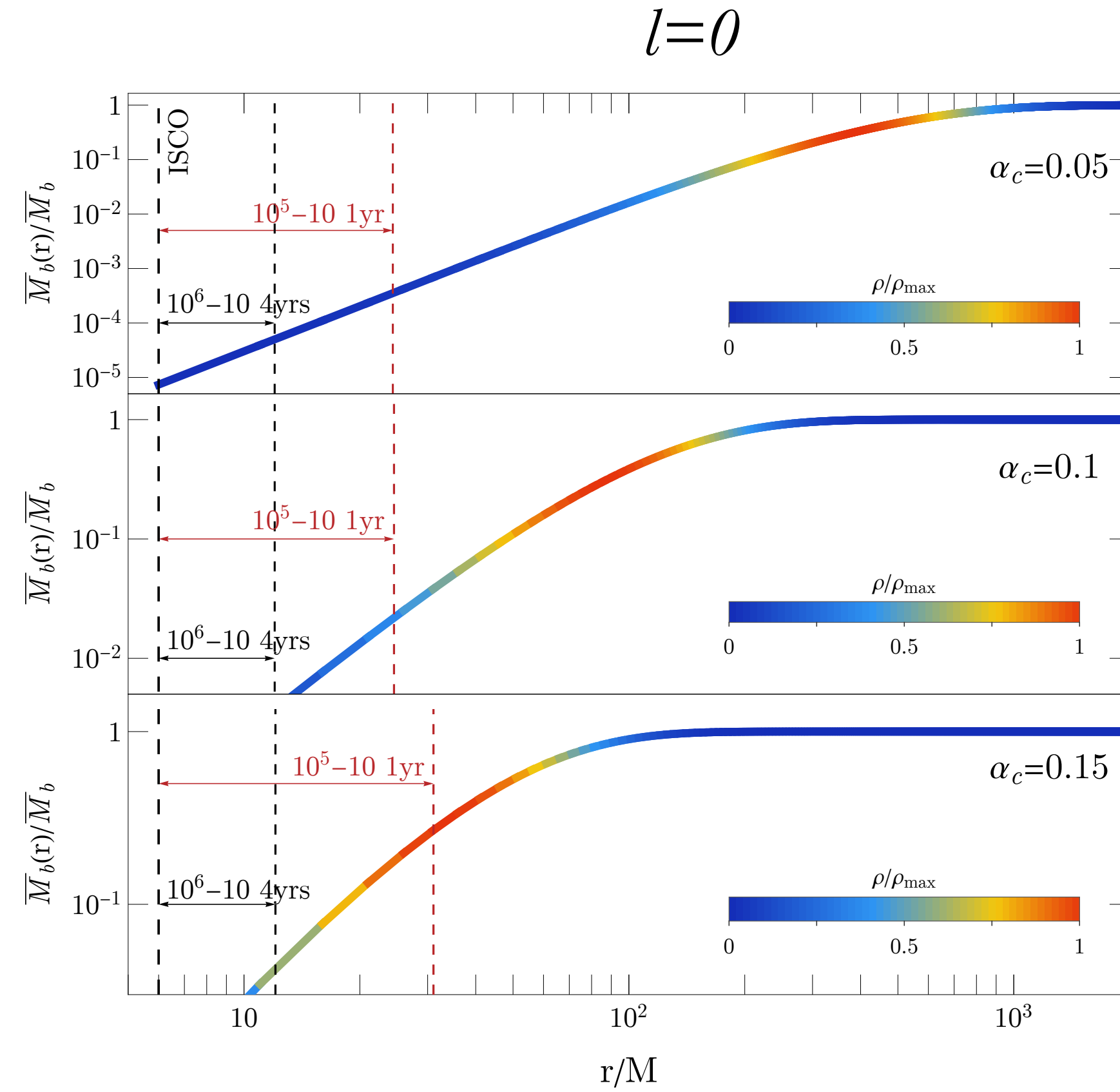
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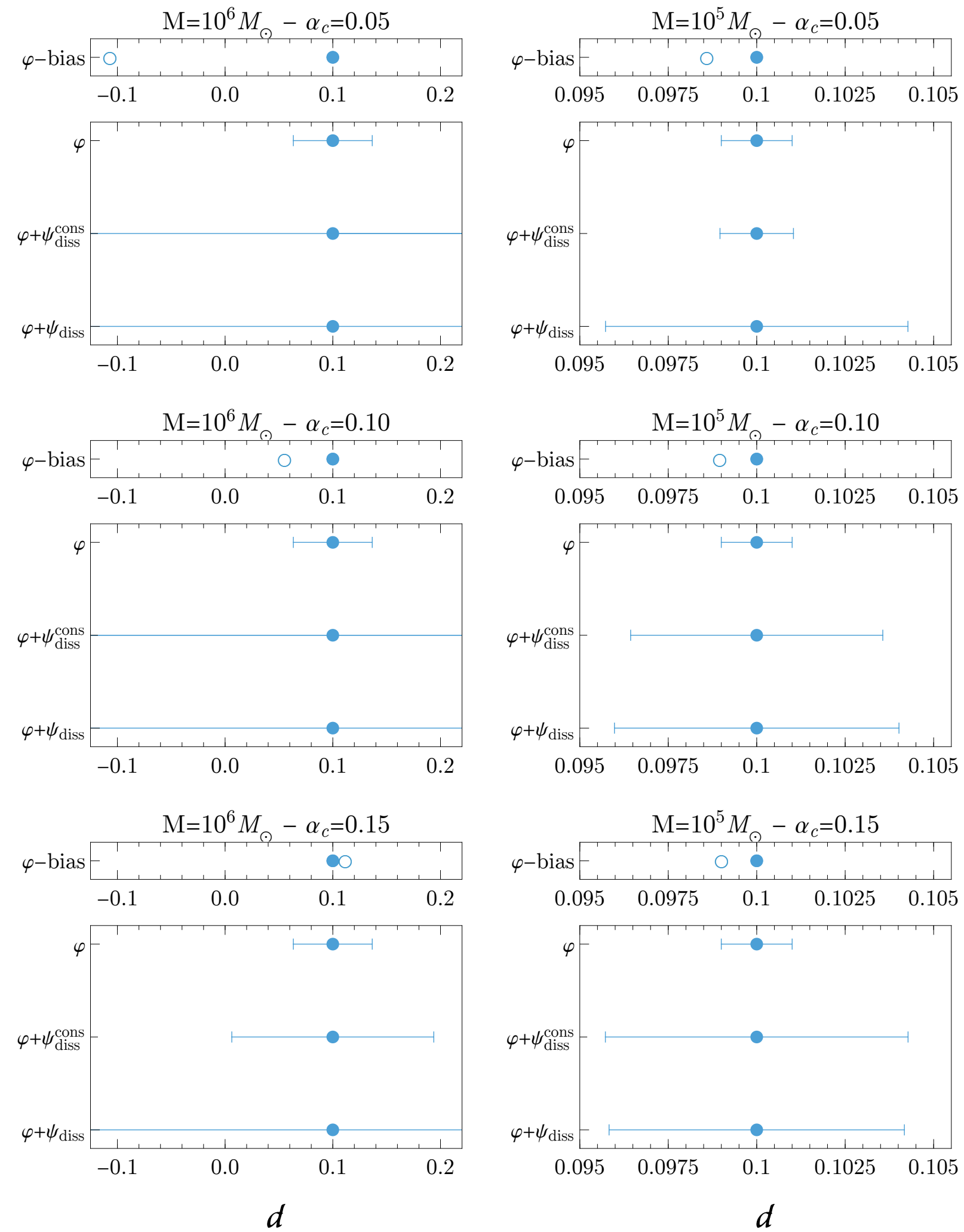


Cloud mass & density profiles

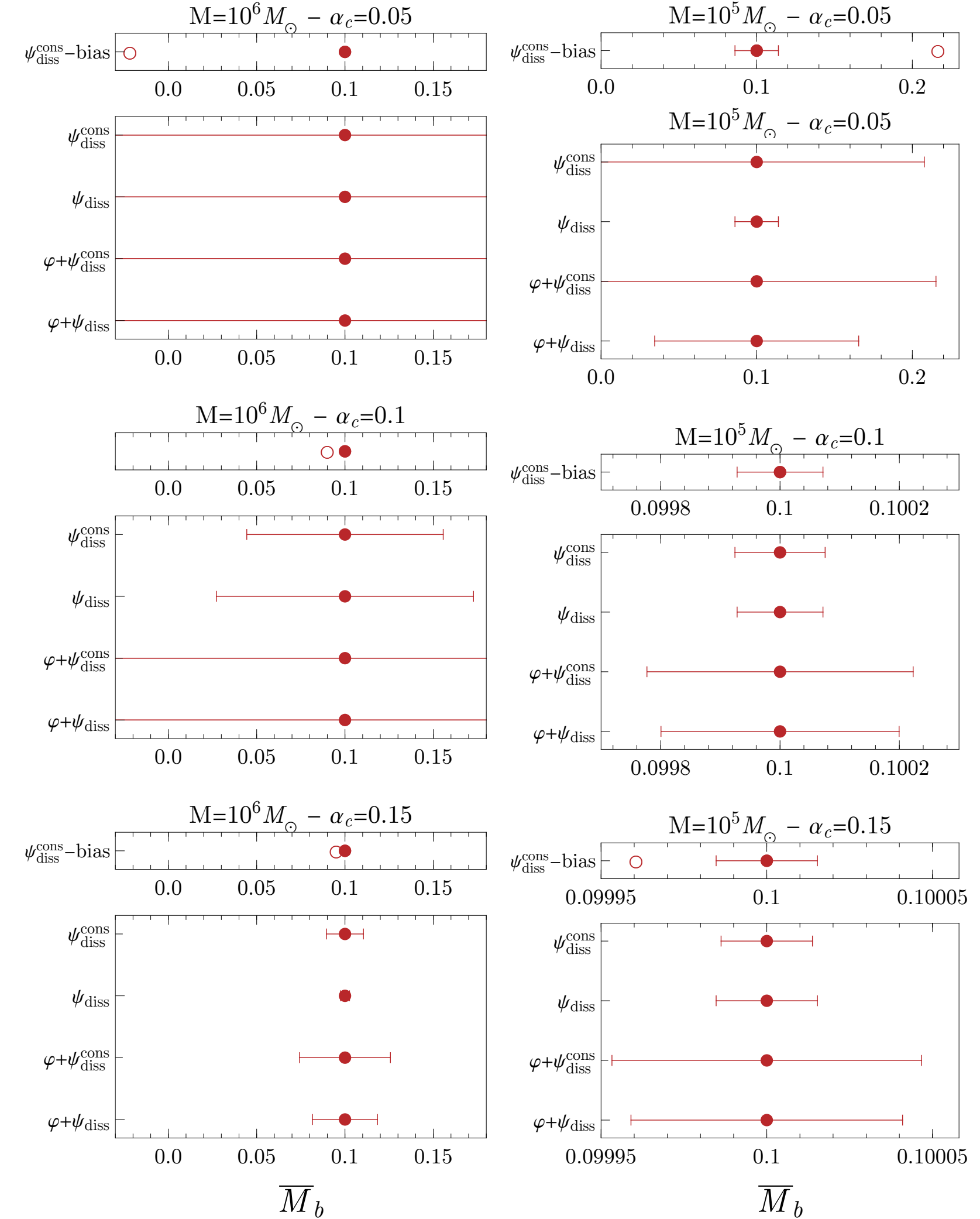


Charge/Cloud uncertainties

2σ uncertainties on the scalar charge ($d = 0.1$, $M_b = 0.01M$)



2σ uncertainties on the cloud mass ($d = 0.025$, $M_b = 0.1M$)



Tracing back the couplings

F. Julié & E. Berti, 2019

Constraints are so far agnostic: they can be mapped to couplings of a specific theory

☉ Scalar Gauss-Bonnet (sGB) gravity $\alpha S_c = \frac{\alpha}{4} \int d^4x \frac{\sqrt{-g}}{16\pi} \varphi \mathcal{G}$ $\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$ $[\alpha] = [length^2]$

☉ Changes from Kerr scale as $\sim \alpha/mass^2 \rightarrow \alpha/M^2 = q^2\alpha/m_p^2$ ($n=2$)

☉ Charge proportional to the coupling constant $d = 2\alpha/m_p^2$

