Constraining spontaneous black hole scalarization with gravitational waves

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with C HERDEIRO and E RADU

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1. Hairy black holes

Any stationary, asymptotically flat solution that is not Kerr and has a nontrivial scalar-field profile

$$S = \frac{1}{16\pi} \int \sqrt{-g}\, \mathrm{d}^4x \left(R - 2(\partial\phi)^2 - V(\phi) \right)$$

The only suitably regular, stationary, asymptotically flat vacuum black hole solutions are those for which the metric is Kerr and the scalar is everywhere a constant.

[Hawking 1972; Sotiriou and Faraoni 2012]

$$\phi = \phi_0 : V'(\phi_0) = 0, \quad V''(\phi) \geq 0$$

Scalar–Gauss–Bonnet theories

$$S = \frac{1}{16\pi}\int \sqrt{-g}\, \mathrm{d}^4x \left(R - 2(\partial\phi)^2 + \lambda^2 f(\phi)\mathcal{G} \right)$$

$\mathcal{G} = R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$ is the Gauss–Bonnet invariant

λ is a coupling constant with dimensions of length

$$\nabla^{\mu}\nabla_{\mu}\phi = -\frac{1}{4}\lambda^2 f'(\phi)\mathcal{G}$$

I

All black holes have hair

$f'(\phi) \neq 0 \; \forall$ finite ϕ

E.g., $f(\phi) = \phi$ or $\frac{1}{\beta}e^{\beta\phi}$

$\lambda \lesssim 3.0 \, M_{\odot}$

[Lyu, Jiang and Yagi 2022]

II

$$\nabla^\mu \nabla_\mu \phi = -\frac{1}{4}\lambda^2 f'(\phi)\mathcal{G}$$

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[Lyu, Jiang and Yagi 2022]

II

$\exists \phi_0 : f'(\phi_0) = 0$

$$\nabla^\mu \nabla_\mu \phi = -\frac{1}{4}\lambda^2 f'(\phi)\mathcal{G}$$

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[Lyu, Jiang and Yagi 2022]

II

Spontaneous scalarization

$f'(0) = 0$

E.g., $f(\phi) = \frac{1}{2}\phi^2$ or $-\frac{1}{2\beta}e^{-\beta\phi^2}$

$(g_{\rm Kerr}, \phi = 0)$ not the unique solution

Some (M, S) tachyonically unstable

Second family of hairy, "spontaneously scalarized" black holes

$$\nabla^\mu \nabla_\mu \phi = -\frac{1}{4}\lambda^2 f'(\phi)\mathcal{G}$$

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All black holes have hair

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[Lyu, Jiang and Yagi 2022]

II

Spontaneous scalarization

$f'(0) = 0$

E.g., $f(\phi) = \frac{1}{2}\phi^2$ or $-\frac{1}{2\beta}e^{-\beta\phi^2}$

Fix $\beta = 6$

$(g_{\mathrm{Kerr}}, \phi = 0)$ not the unique solution

Some (M, S) tachyonically unstable

Second family of hairy,
“spontaneously scalarized” black holes

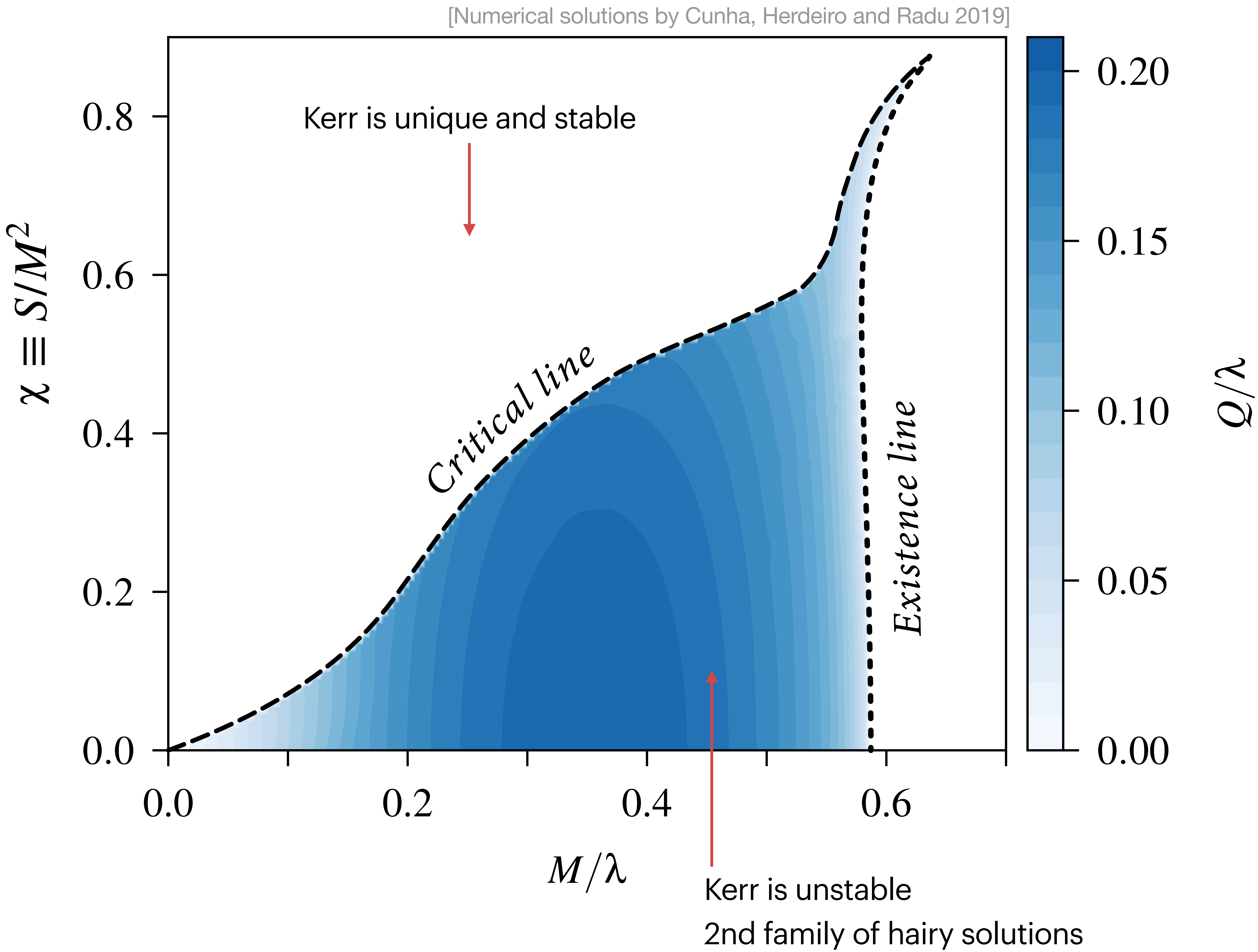
The *scalar charge* Q is read off from the asymptotic expansion

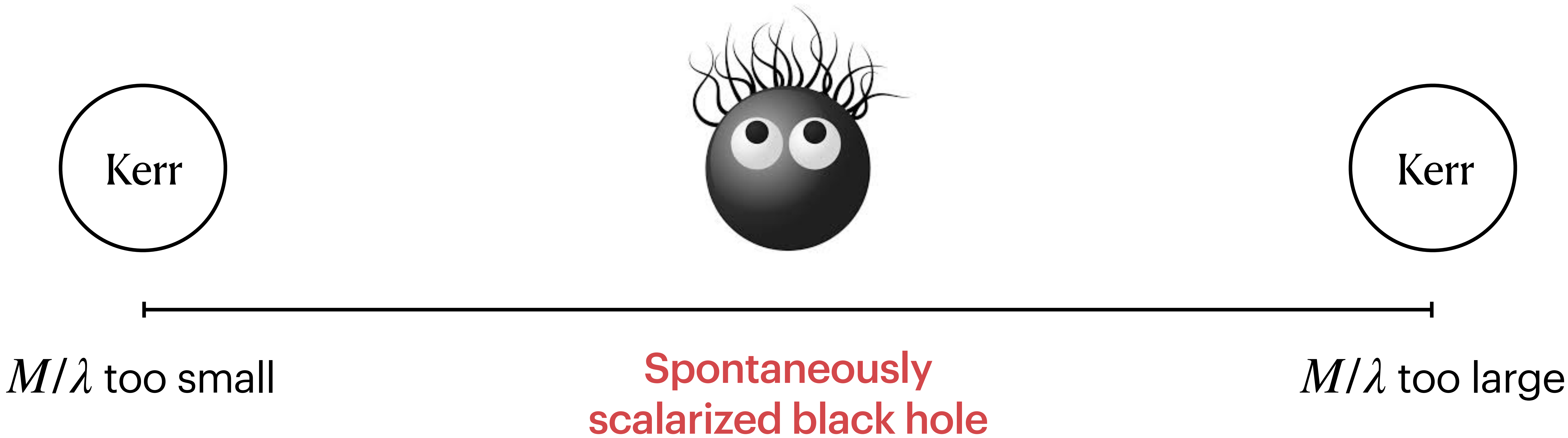
$$\phi = -\frac{Q}{r} + O(r^{-2})$$

From dimensional analysis,

$$Q = \lambda \times F\left(\frac{M}{\lambda}, \frac{S}{M^2}\right)$$

Scalar hair is of *secondary* type [Coleman, Preskill and Wilczek 1992]


[Numerical solutions by Cunha, Herdeiro and Radu 2019]
Kerr is unique and stable
Critical line
Existence line
Kerr is unstable
2nd family of hairy solutions
$\chi \equiv S/M^2$
M/λ
Q/λ
0.0
0.2
0.4
0.6
0.8
0.00
0.05
0.10
0.15
0.20



A black hole of mass M probes a certain range of values of λ

2. Gravitational-wave constraints

Hairy black holes = scalar waves

$$p(\lambda \mid d)$$

$$p(\lambda \,|\, d) = \int \mathrm{d}\theta \; p(\lambda, \theta \,|\, d)$$

$$p(\lambda, \theta \,|\, d) \propto p(d \,|\, \lambda, \theta)\, \pi(\lambda, \theta)$$

Posterior — Likelihood — Prior

Assume detector noise is stationary, Gaussian, and uncorrelated

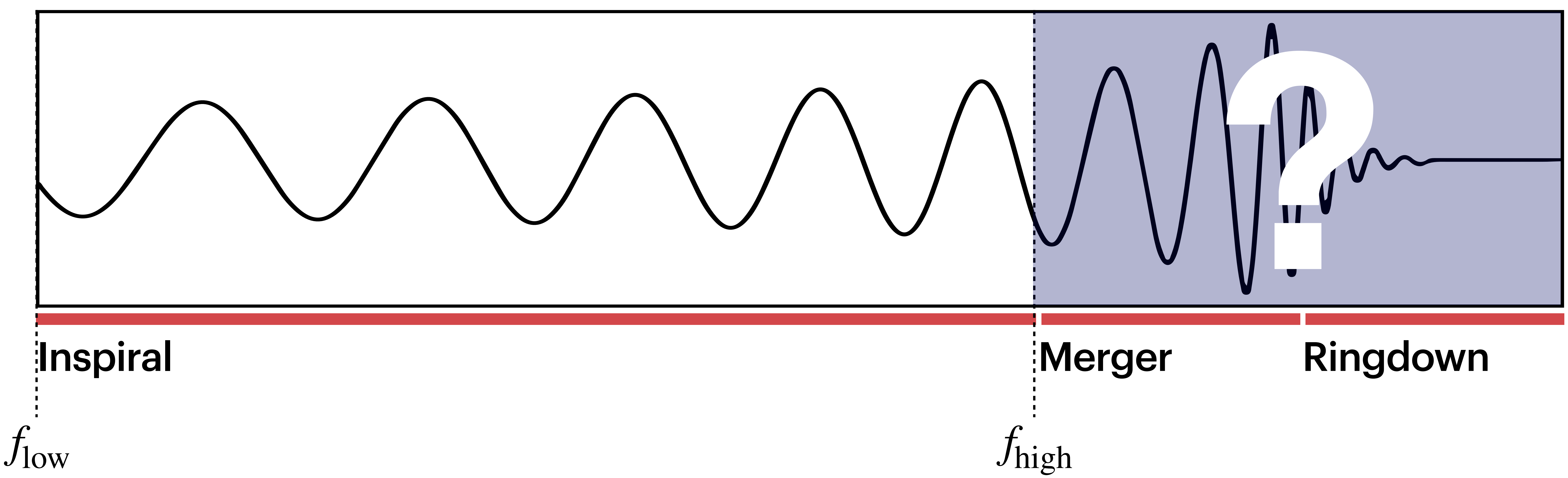
[Cutler and Flanagan 1994]

$$p(d\,|\,\lambda,\theta) \sim \prod_{a\in\{\text{detectors}\}} \exp\left(-2\int_{f_{\text{low},a}}^{f_{\text{high},a}} \mathrm{d}f\, \frac{|\tilde{d}_a(f) - \tilde{h}_a(f;\lambda,\theta)|^2}{S_{n,a}(f)}\right)$$

Signal: $\tilde{d}_a(f)$

Waveform: $\tilde{h}_a(f;\lambda,\theta)$

Noise PSD: $S_{n,a}(f)$



Decompose the waveform into spherical harmonics

$$\tilde{h}_{\ell m}(f) = \mathscr{A}_{\ell m}(f)\, e^{i\Psi_{\ell m}(f)}$$

Phase: $\Psi_{\ell m} = \Psi^{(\mathrm{GR})}_{\ell m} + \delta\Psi_{\ell m}$

$Q_A \equiv Q_A(M_A, S_A, \lambda)$

$$\delta\Psi_{\ell m} = \underbrace{\frac{5m}{14\,336\,\nu}\left(\frac{Q_1}{M_1} - \frac{Q_2}{M_2}\right)^2 \left(\frac{2\pi M f}{m}\right)^{-7/3}}_{}$$

–1PN scalar dipole radiation

[Sennett, Marsat and Buonanno 2016]

Amplitude: $\mathscr{A}_{\ell m} = \mathscr{A}^{(\mathrm{GR})}_{\ell m}$

Log uniform

(Restricted to $\lambda \in [1, 10^3]\ M_\odot$)

$$p(\lambda, \theta \,|\, d) \propto p(d \,|\, \lambda, \theta)\, \pi(\lambda, \theta)$$

?

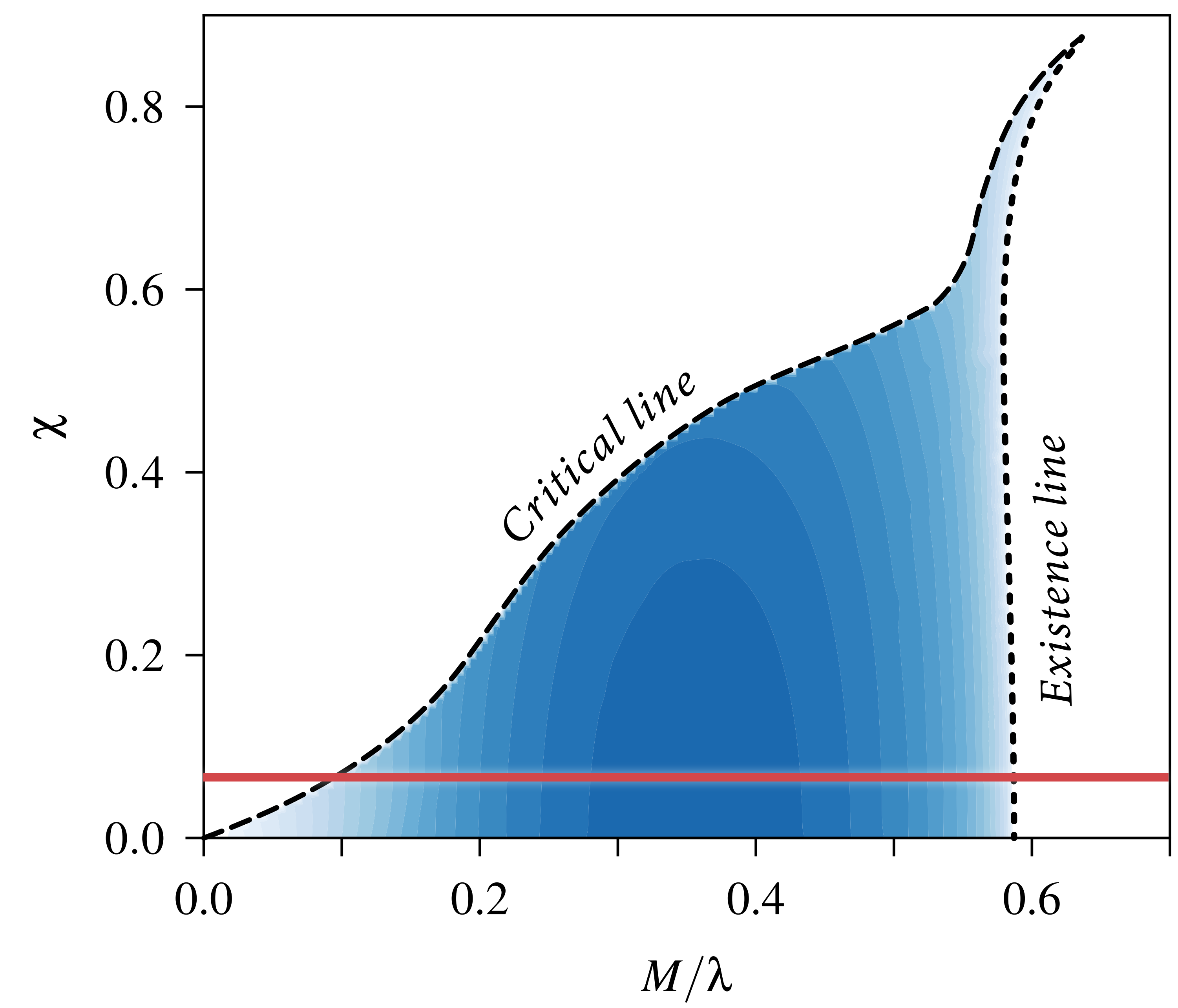
Same as in GR

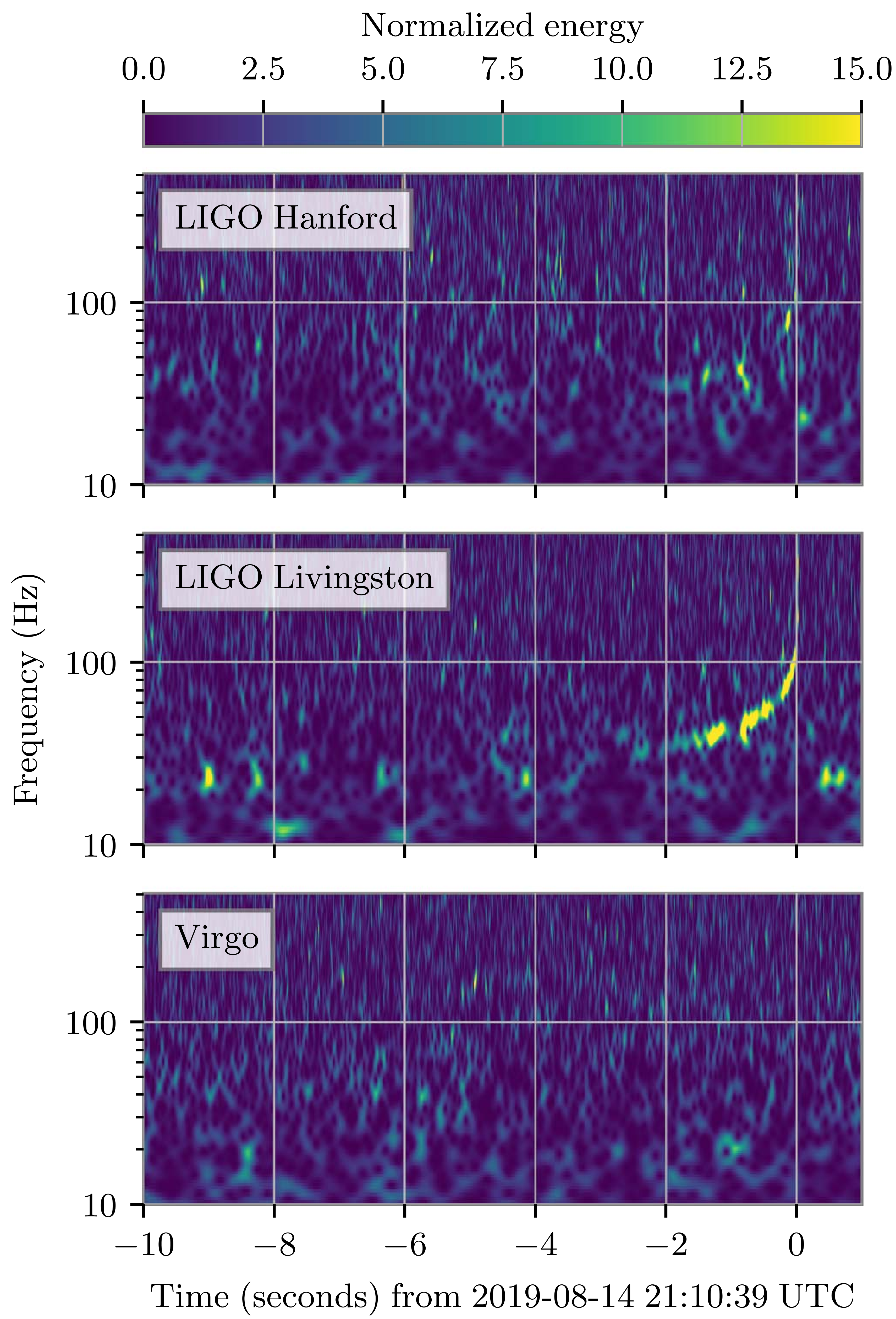
$\theta = \{M_1, M_2, \chi_1, \chi_2, \ldots\}$

- Need to know spins to confidently rule out a range of λ
- Individual spins are harder to measure than

$$\chi_{\rm eff} = \frac{(M_1\boldsymbol{\chi}_1 + M_2\boldsymbol{\chi}_2)\cdot\hat{\mathbf{L}}}{M_1 + M_2}$$

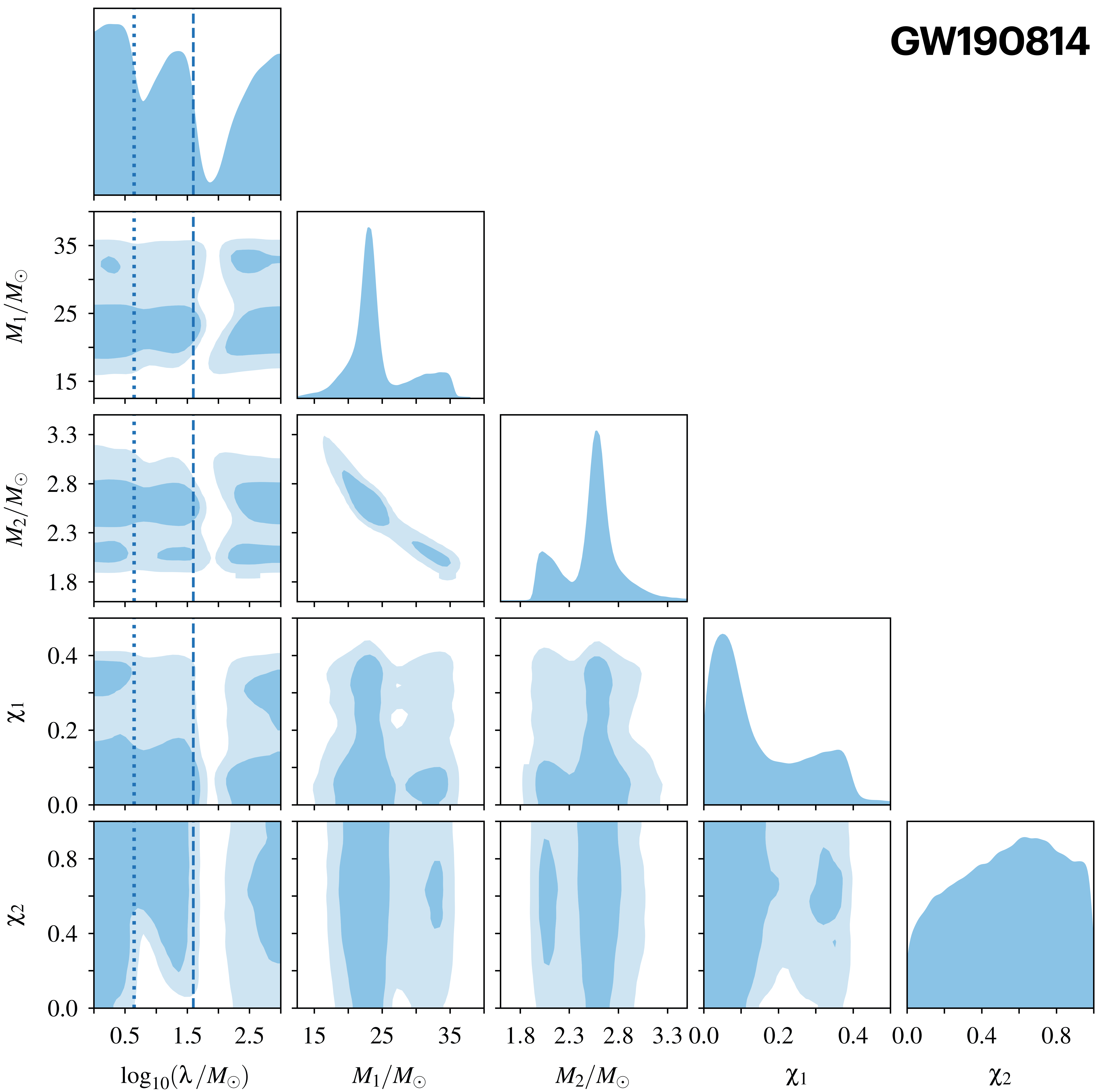
- $\chi_{\rm eff} \sim \chi_1$ when $M_1 \gg M_2$

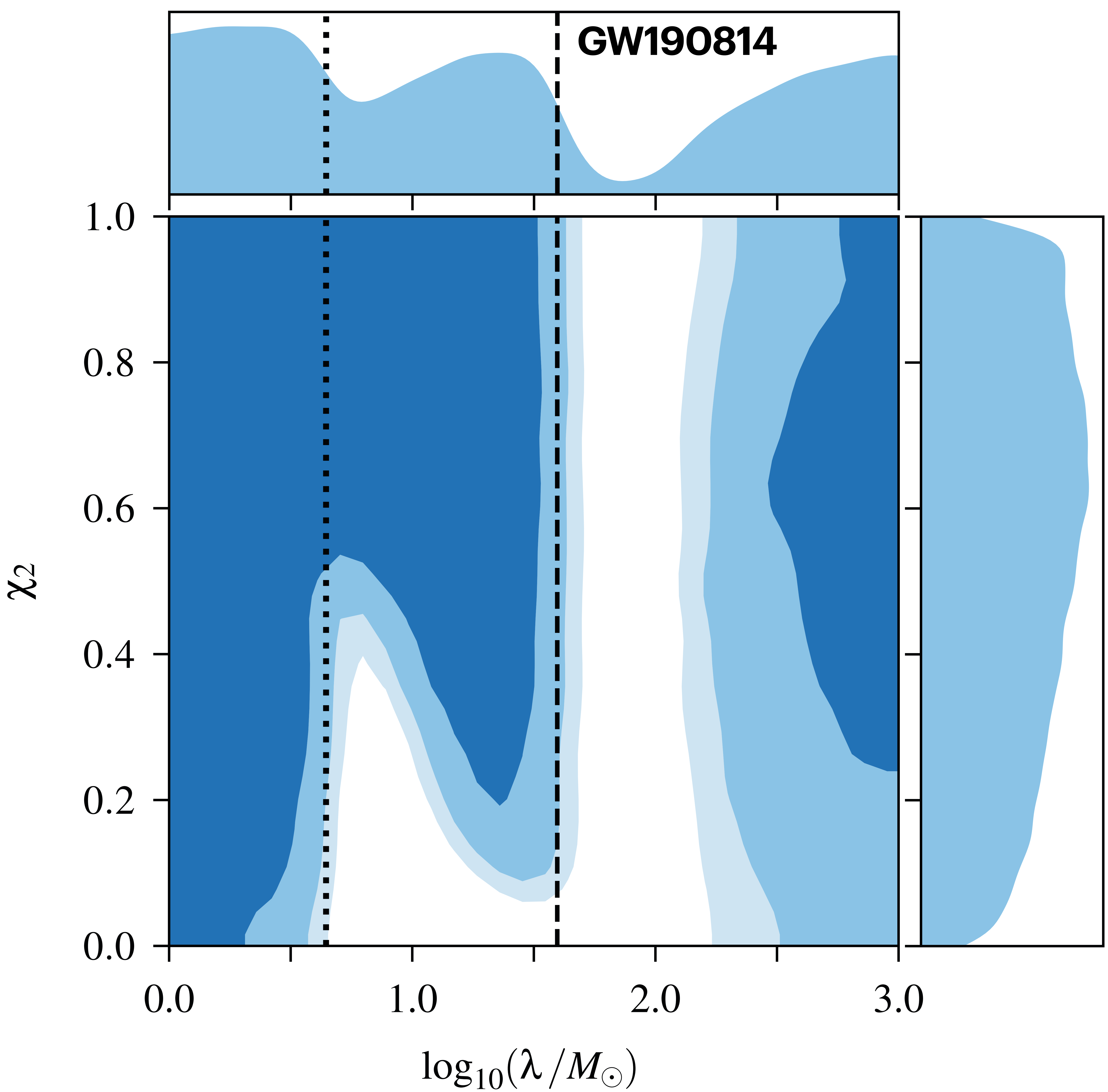


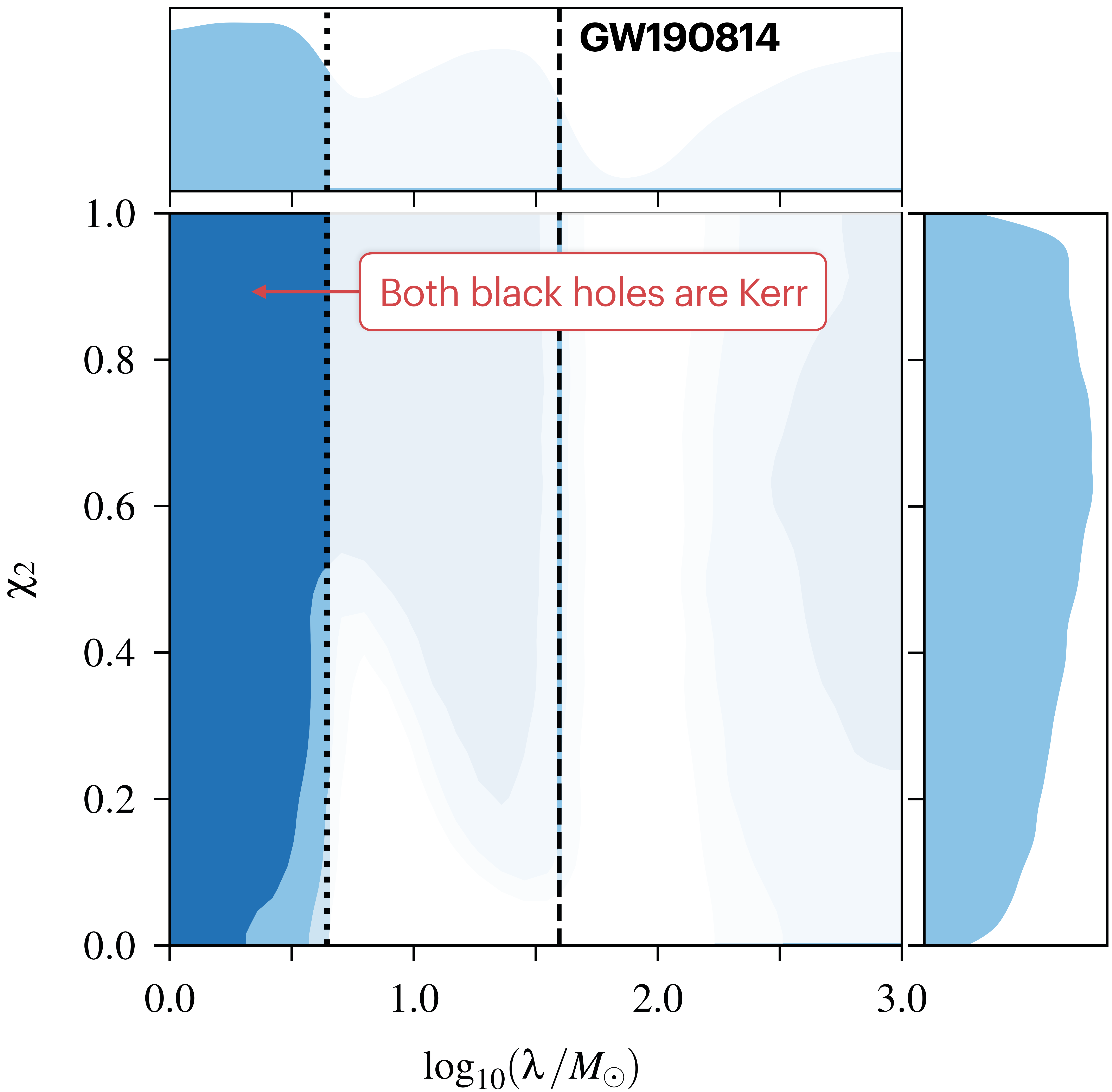


GW190814

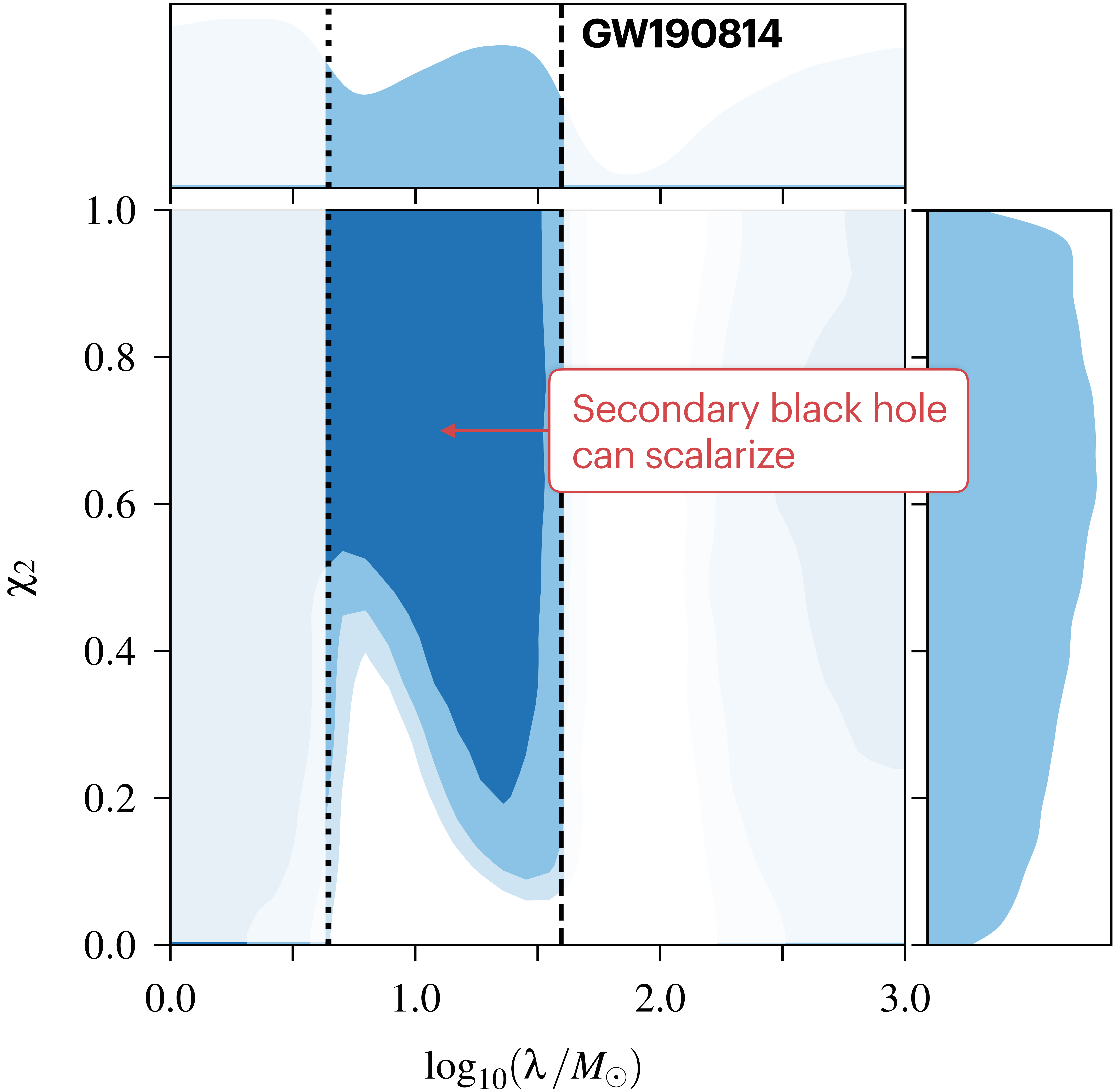
$\chi_1 < 0.07$

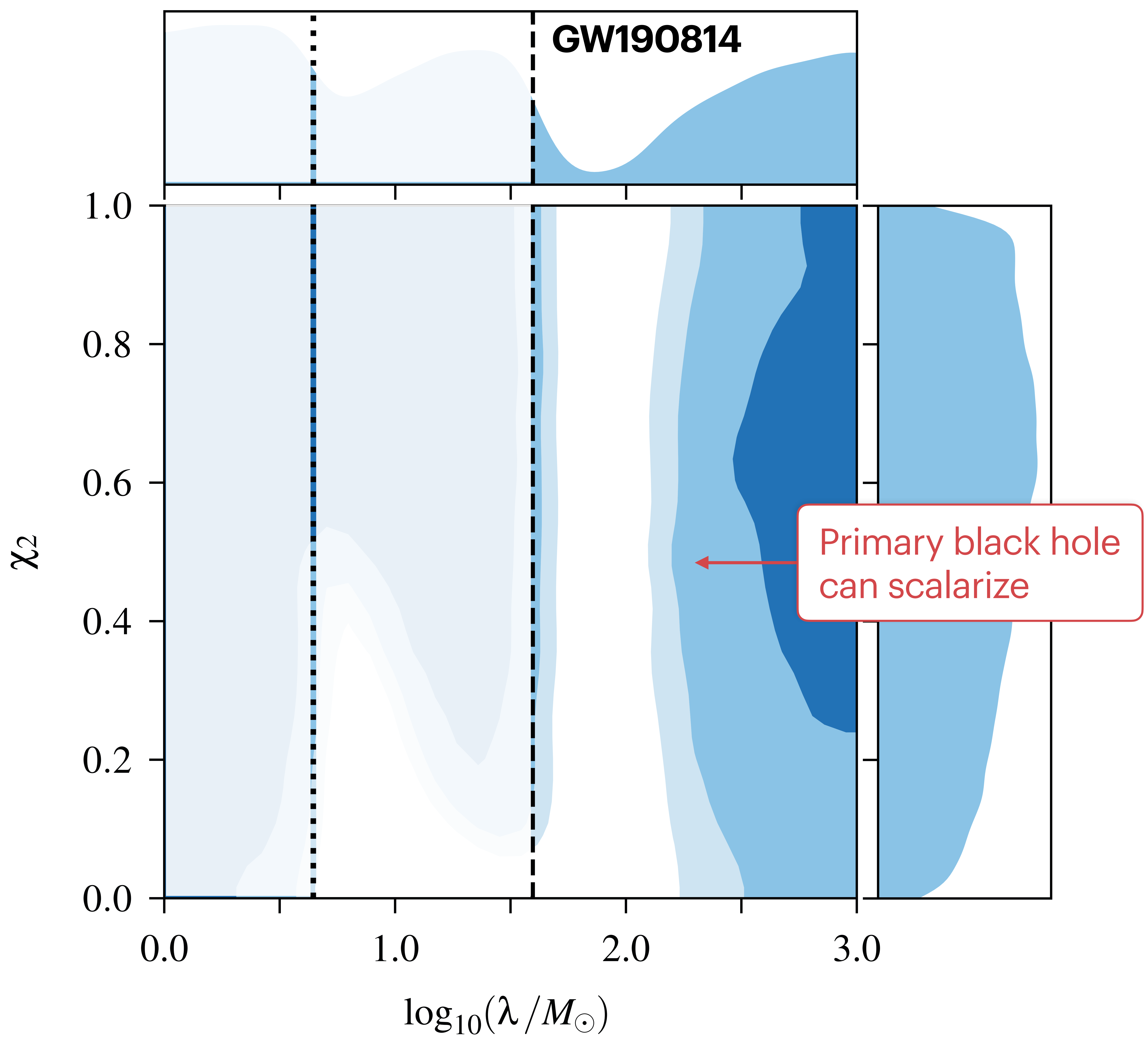

GW190814
$M_1/M_\odot$
$M_2/M_\odot$
χ_1
χ_2
$\log_{10}(\lambda/M_\odot)$
35
25
15
3.3
2.8
2.3
1.8
0.4
0.2
0.0
0.8
0.5
1.5
2.5

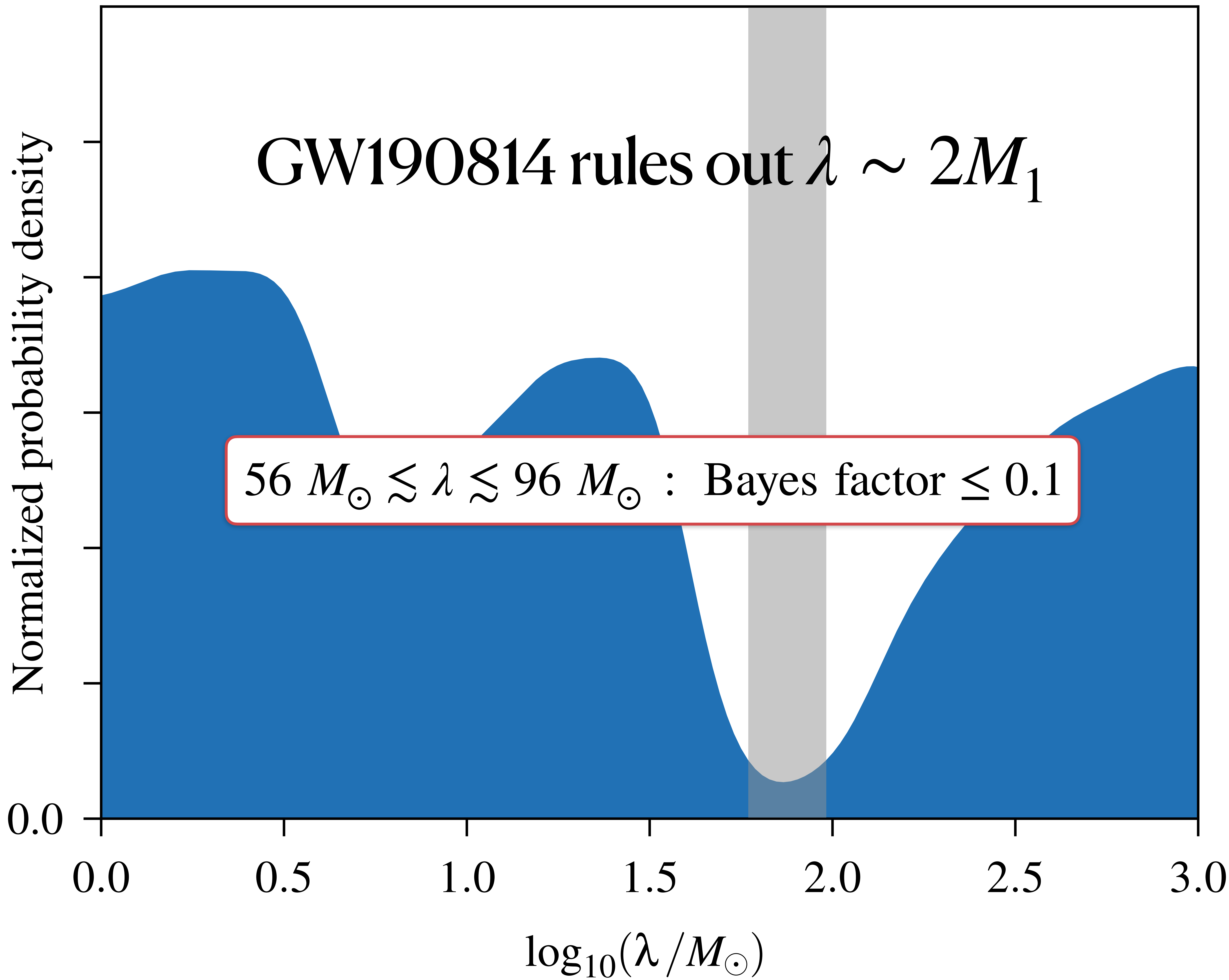

GW190814
1.0
0.8
0.6
0.4
0.2
0.0
χ_2
0.0
1.0
2.0
3.0
$\log_{10}(\lambda/M_\odot)$



GW190814
Both black holes are Kerr
1.0
0.8
0.6
0.4
0.2
0.0
χ_2
0.0
1.0
2.0
3.0
$\log_{10}(\lambda/M_\odot)$

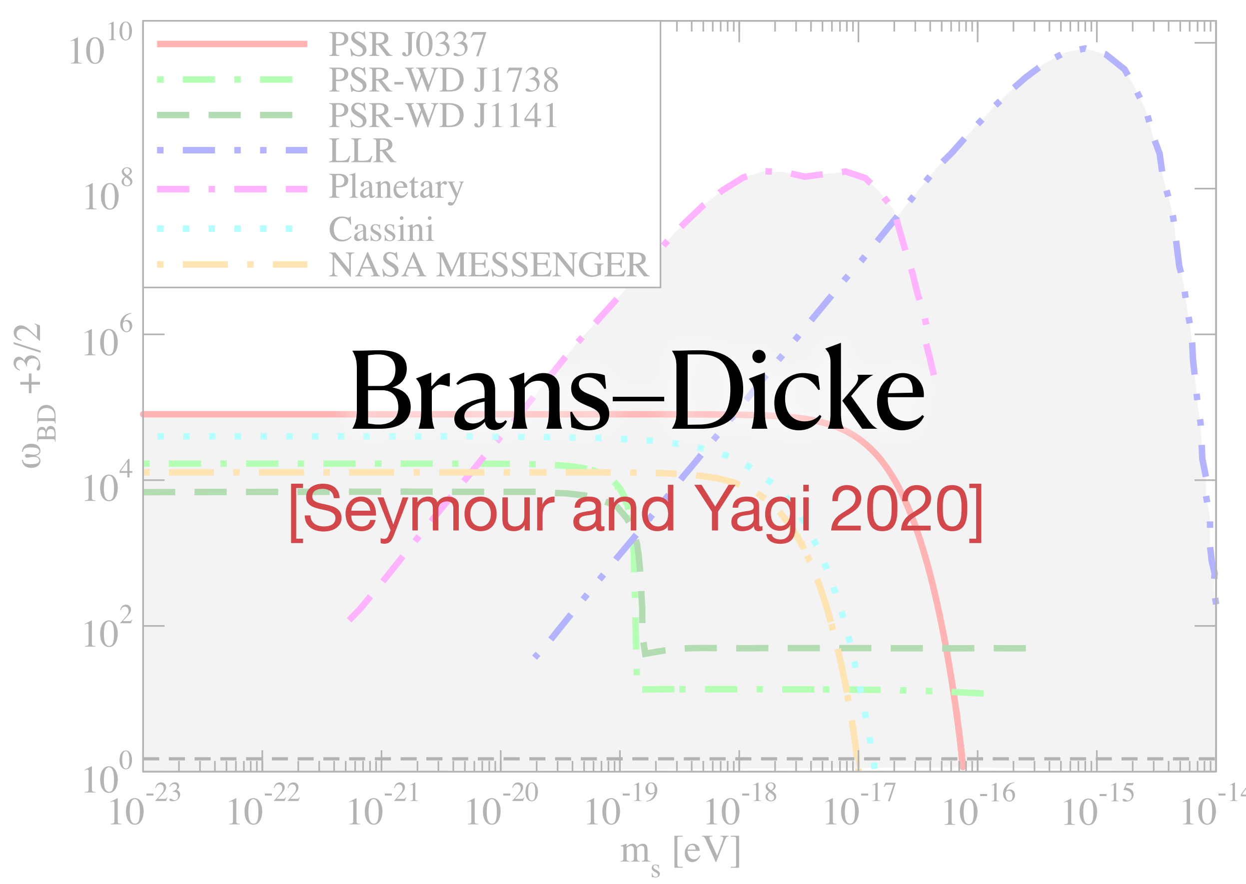

GW190814
Secondary black hole can scalarize
1.0
0.8
0.6
0.4
0.2
0.0
χ_2
0.0
1.0
2.0
3.0
$\log_{10}(\lambda/M_\odot)$


GW190814
1.0
0.8
0.6
0.4
0.2
0.0
χ_2
0.0
1.0
2.0
3.0
$\log_{10}(\lambda/M_\odot)$
Primary black hole
can scalarize


GW190814 rules out $\lambda \sim 2M_1$
$56\ M_\odot \lesssim \lambda \lesssim 96\ M_\odot$: Bayes factor ≤ 0.1
Normalized probability density
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\log_{10}(\lambda/M_\odot)$

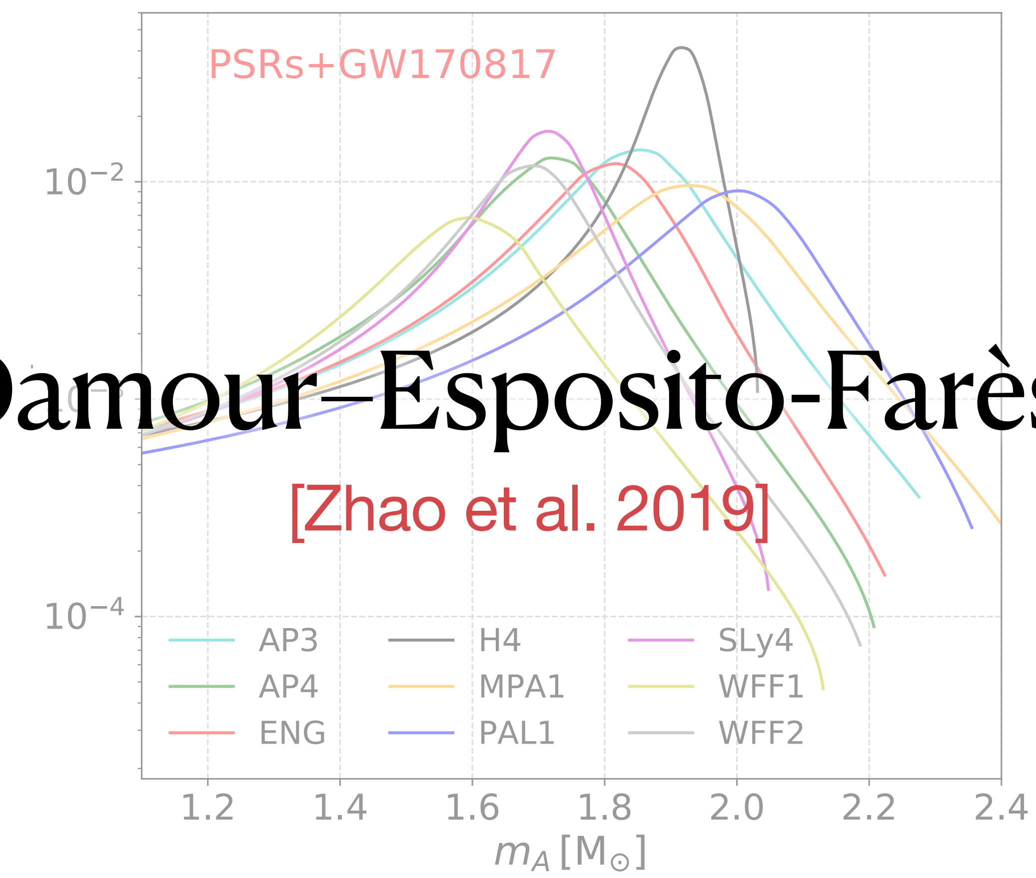
Massless scalar-tensor theories

No hairy black holes



Brans–Dicke

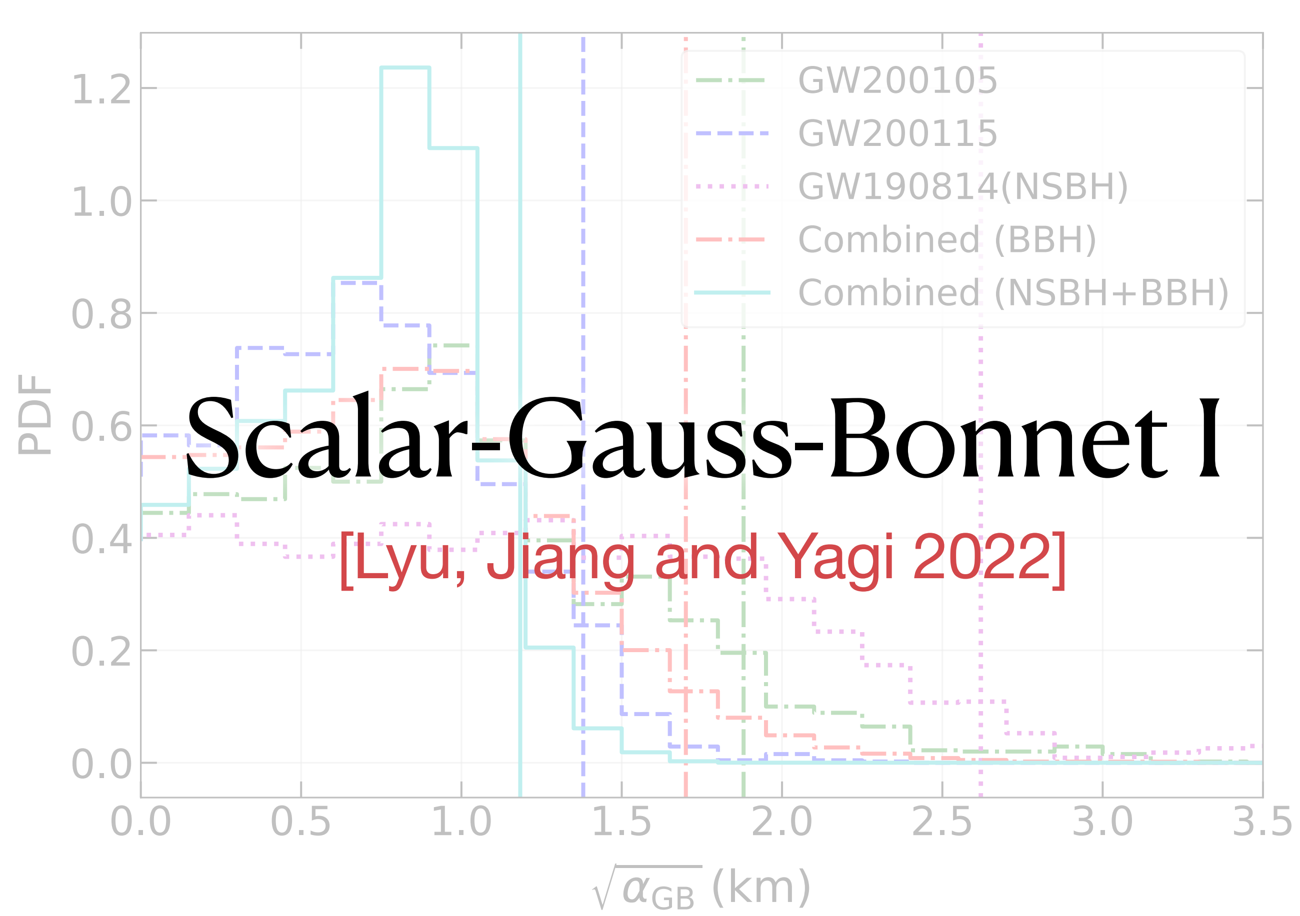
[Seymour and Yagi 2020]



Damour–Esposito-Farèse

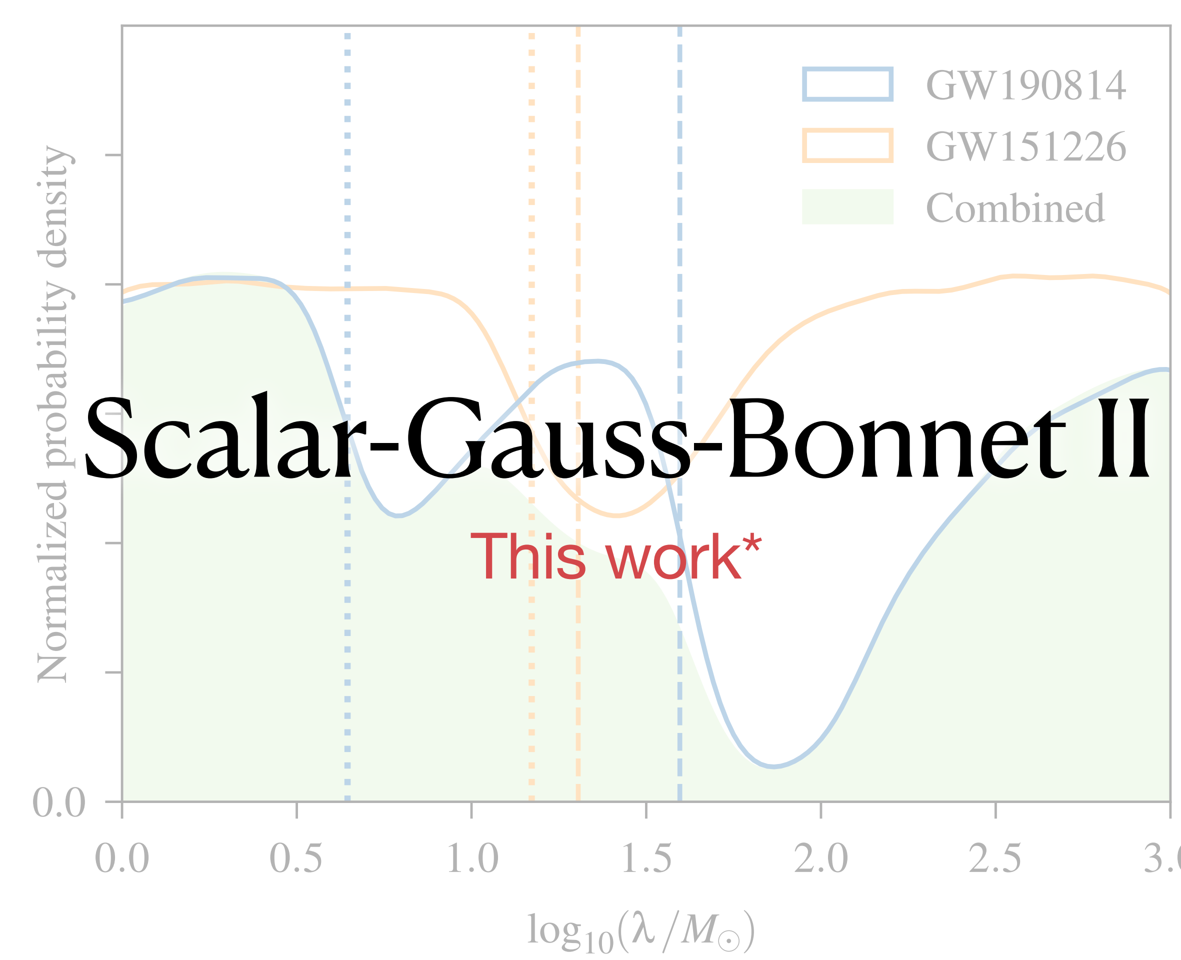
[Zhao et al. 2019]

Hairy black holes



Scalar-Gauss-Bonnet I

[Lyu, Jiang and Yagi 2022]



Scalar-Gauss-Bonnet II

This work*

All objects have scalar charges | Spontaneous scalarization

*See also [Danchev, Doneva and Yazadjiev 2022] for binary pulsar constraints