Stochastic gravitational-waves from boson clouds

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Superradiant instability in a nutshell

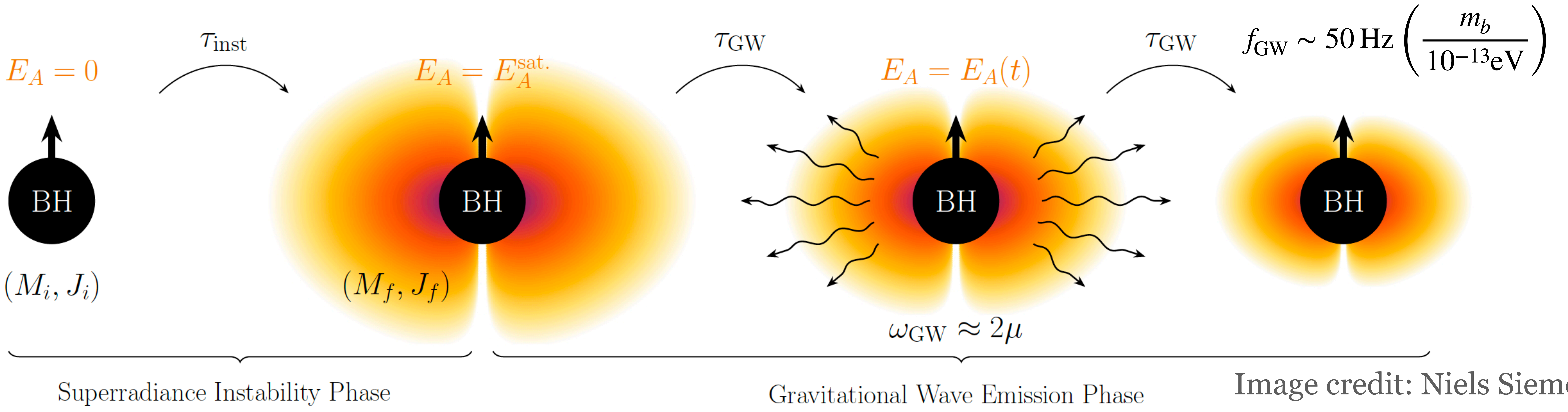
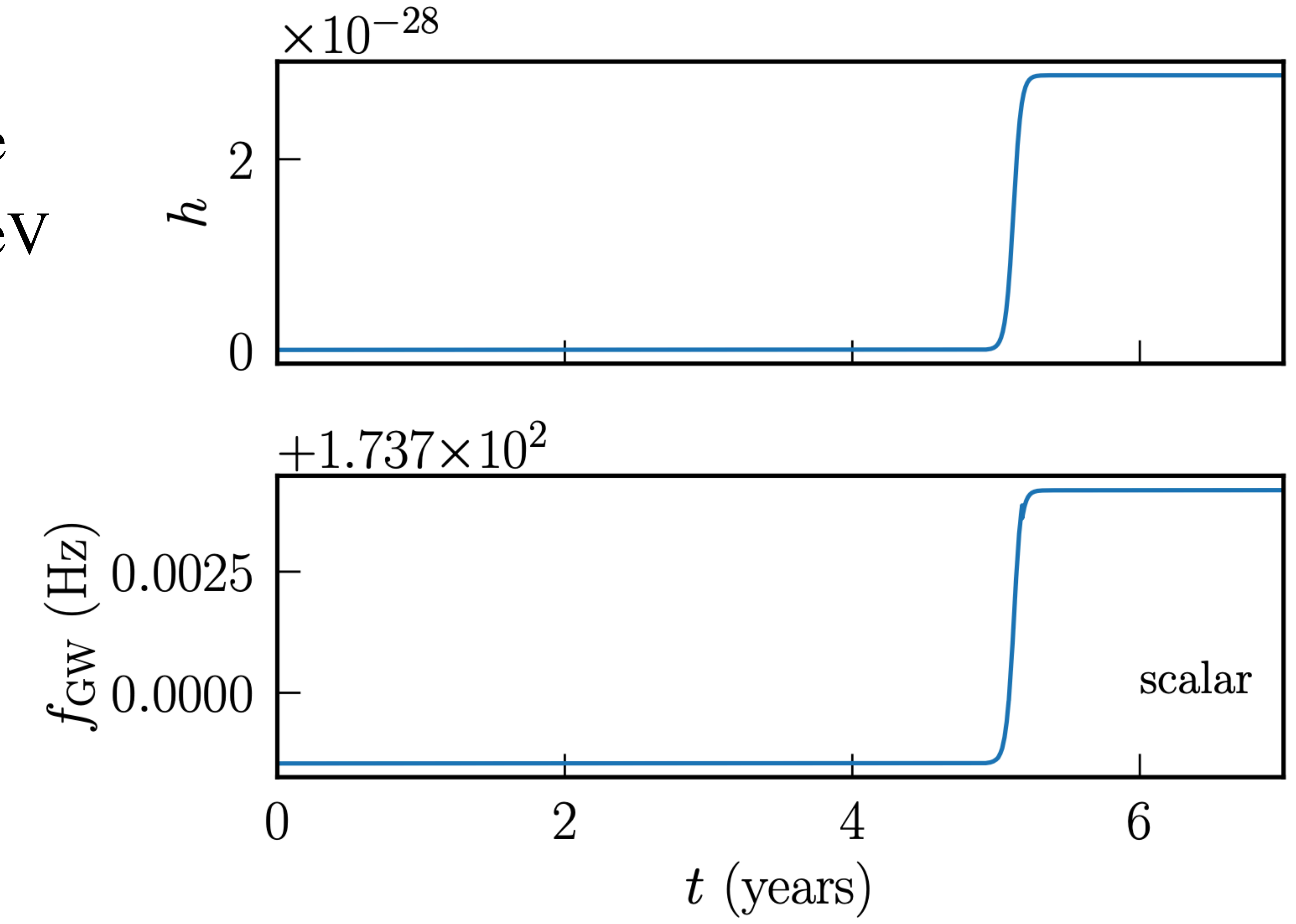
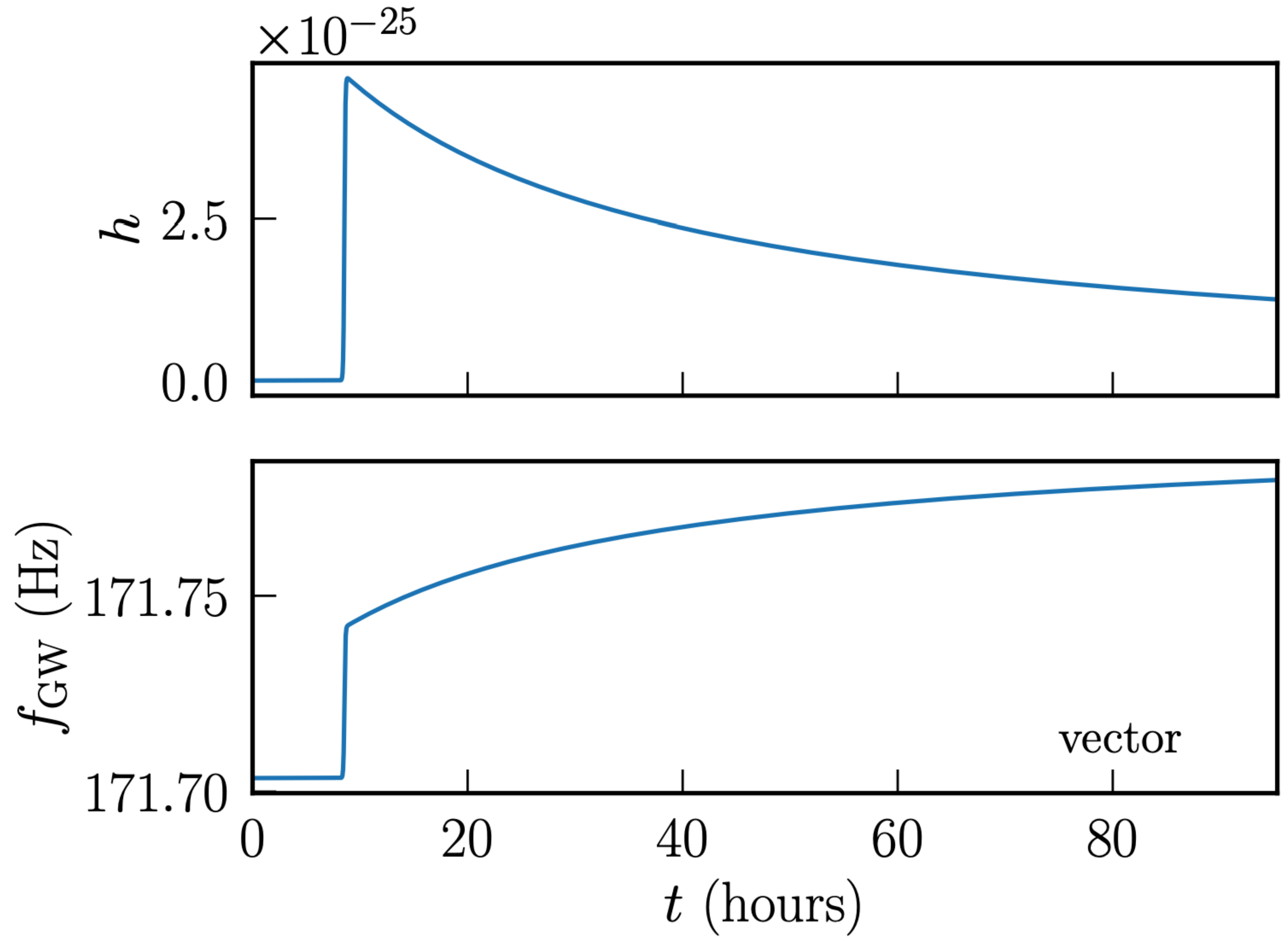


Image credit: Niels Siemonsen

GW150914 – like

$m_b \sim 3.6 \times 10^{-13}$ eV





From: Siemonsen, May & East, PRD107, 104003 (2023)

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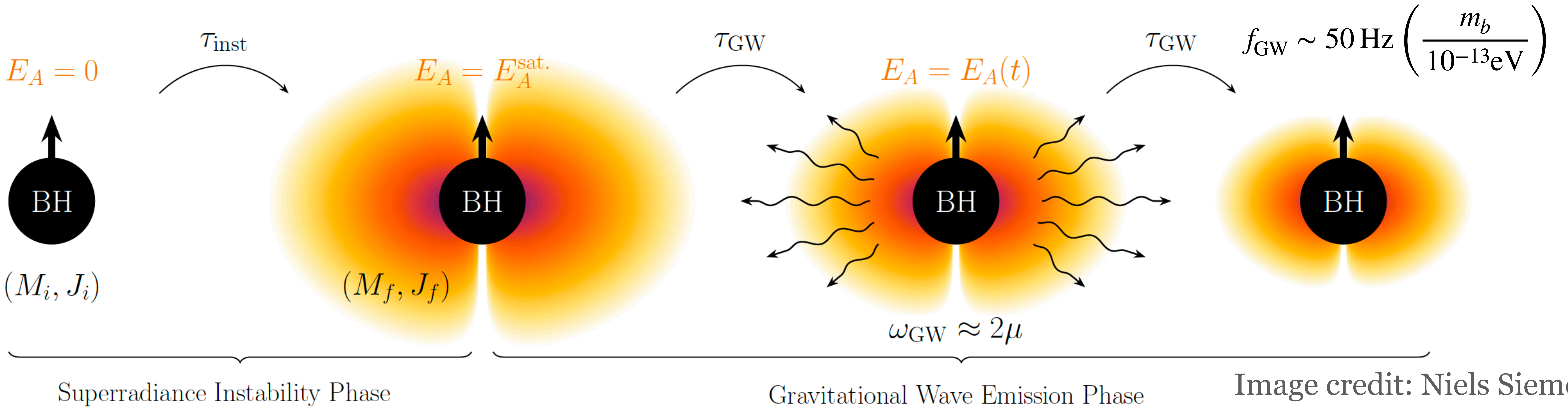


Image credit: Niels Siemonsen

For most unstable mode:

$t < t_{\rm sat.}, \quad M_{\rm cloud}(t) = e^{t/\tau_{\rm inst}}$

$\tau_{\rm inst}^{\rm scalar} \approx 15\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^9\left(\frac{0.9}{\chi_i}\right), \quad \tau_{\rm inst}^{\rm vector} \approx 140\,{\rm s}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^7\left(\frac{0.9}{\chi_i}\right)$

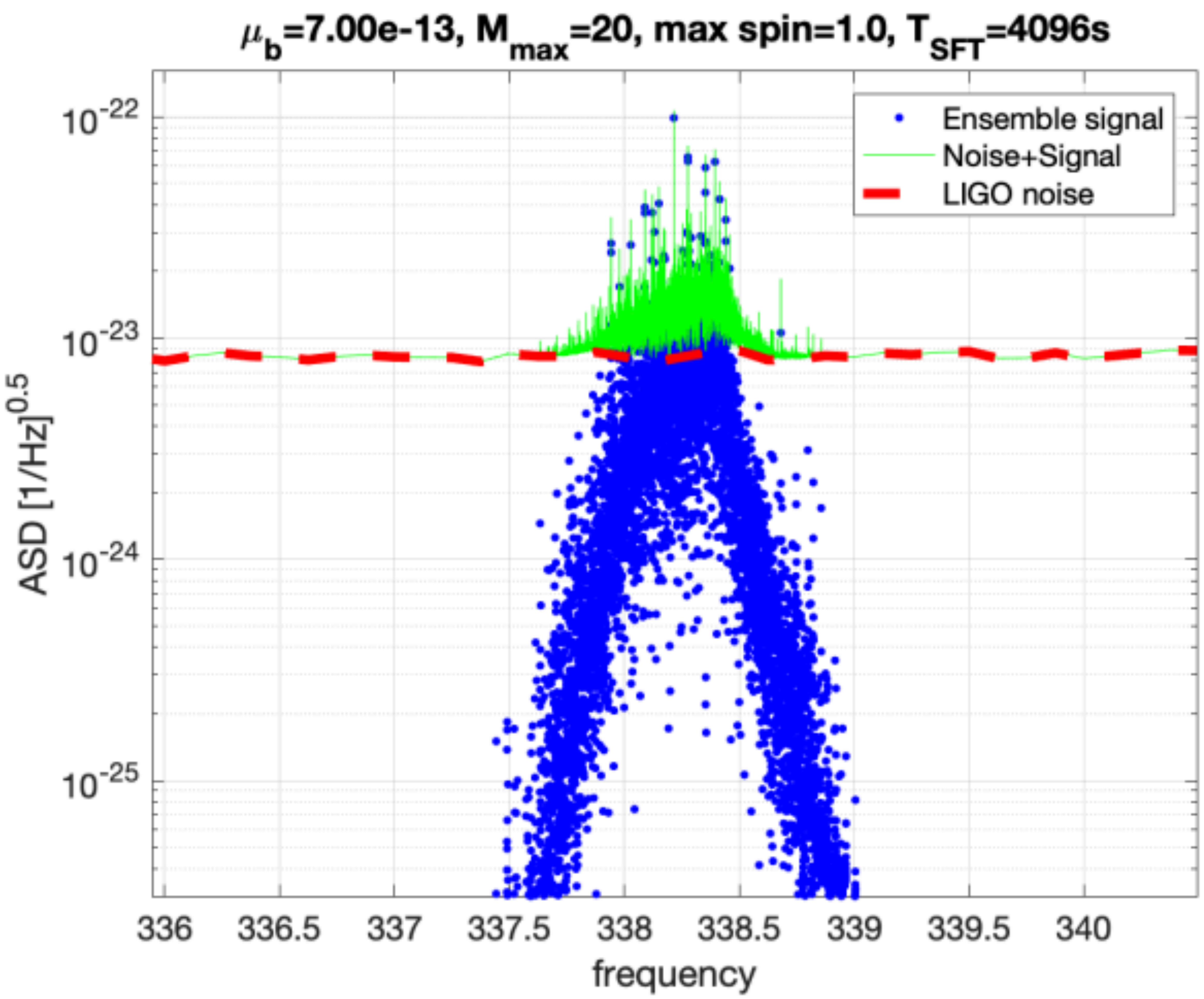
$t > t_{\rm sat.}, \quad M_{\rm cloud}(t) = \frac{M_{\rm cloud}^{\rm sat.}}{1 + t/\tau_{\rm GW}}$

$\tau_{\rm GW}^{\rm scalar} \approx 10^5\,{\rm yr}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{15}\left(\frac{0.5}{\chi_i - \chi_f}\right), \quad \tau_{\rm GW}^{\rm vector} \approx 2\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{11}\left(\frac{0.5}{\chi_i - \chi_f}\right)$

$\chi = J/M^2$ – dimensionless parameter

$\alpha := M m_b / M_{\rm Pl}^2 \sim 0.1\left(\frac{M}{15 M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}{\rm eV}}\right)$ – "fine-structure constant"

Galactic stochastic GW background



From: Zhu+ PRD102, 063020 (2020)

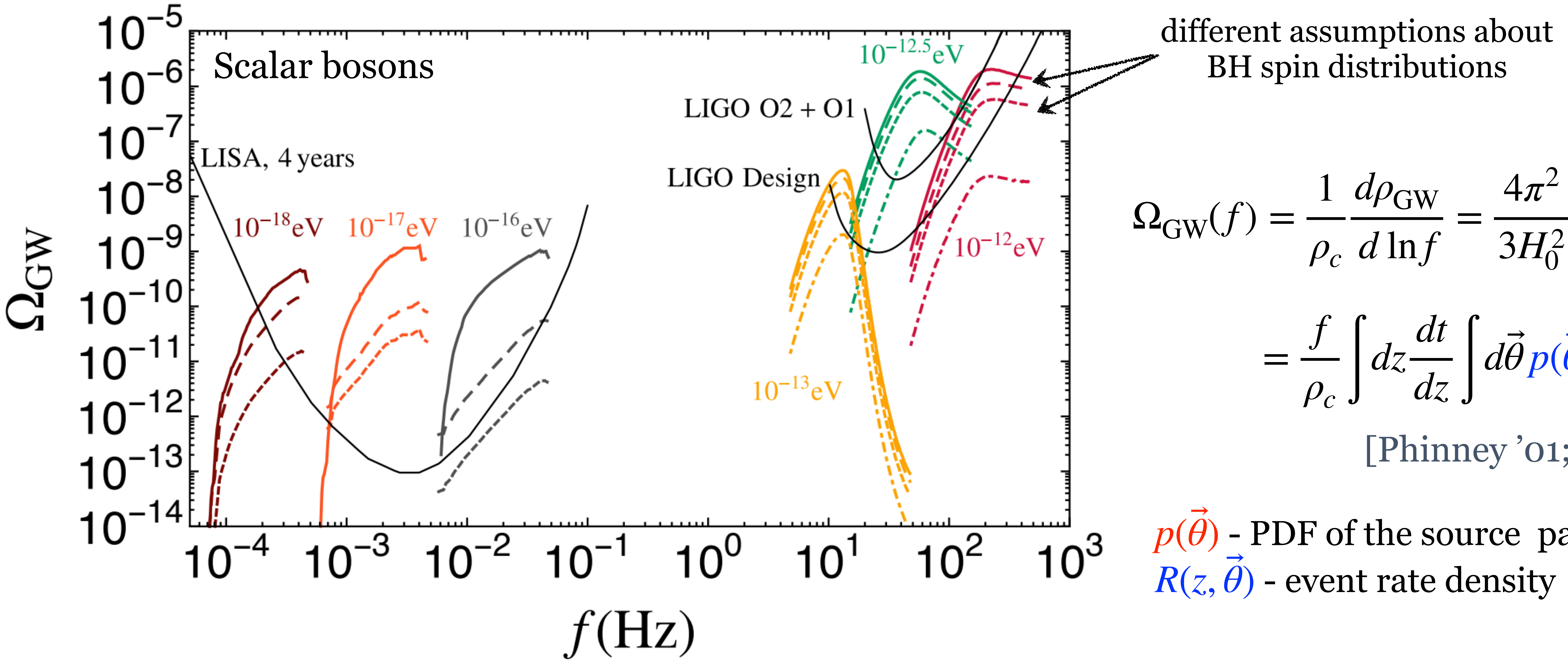
Galactic sources should contribute to a GW background in a **narrow frequency band**.

Small spread in frequency due to spread in BH masses and line-of-sight BH velocity.

Galactic signals **not uniformly distributed** in the sky (mainly located in galactic disk).

Extra-galactic stochastic GW Background

RB+ ’17; Tsukada+ ’18; Tsukada, RB, East & Siemonsen, ’20; Yuan, RB, Cardoso ’21; Yuan, Jiang & Huang ‘22



$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f} = \frac{4\pi^2}{3H_0^2} f^3 S_h(f)$$

$$= \frac{f}{\rho_c}\int dz \frac{dt}{dz}\int d\vec{\theta}\, p(\vec{\theta}) R(z;\vec{\theta})\, \frac{dE_{\rm GW}}{df_s}(\vec{\theta})$$

[Phinney ’01; Rosado 11]

$p(\vec{\theta})$ - PDF of the source parameters

$R(z,\vec{\theta})$ - event rate density

$$\frac{dE_{\rm GW}}{df_s} \approx E_{\rm GW}\delta(f(1+z)-f_s)$$

$$E_{\rm GW} = \int_{t=0}^{\Delta t} dt\, \dot{E}_{\rm GW} = \frac{M_{cloud}^{sat.}\Delta t}{\Delta t + \tau_{\rm GW}}$$

Δt - signal duration

Modeling the (extra-galactic) GW background

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- $\Omega^{\rm iso}_{\rm GW}(f) = \frac{f}{\rho_c}\int dz \frac{dt}{dz}\int d\chi_i dM_i\, p(\chi_i)\frac{d\dot{n}}{dM_i}\frac{dE_{\rm GW}}{df_s}$ — "**isolated**" black-holes channel $M_i \in [3M_\odot, 50]M_\odot$

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$\frac{d\dot{n}}{dM} = \psi(z_f)\phi(\mathscr{M}_*)\frac{d\mathscr{M}_*}{dM}$, $\psi(z_f)$ – star formation rate, $\phi(\mathscr{M}_*) \propto \mathscr{M}_*^{-2.35}$ – Salpeter initial mass function

$d\mathscr{M}_*/dM = \left(dg/d\mathscr{M}_*\right)^{-1}$, where $M = g(\mathscr{M}_*, Z)$ relates BH mass M to its progenitor star $\mathscr{M}_*$. Implicitly depends on redshift via stellar metallicity Z dependence.

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Note: Distribution of BH spins for isolated BHs at birth **largely unknown**.
We will assume $p(\chi_i)$ uniform.

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Merger rate density $R(z; M_1, M_2)$ and $P(M_{1/2})$ follows what is used by LVK.

Modeling the (extra-galactic) GW background

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$$\frac{d\dot{n}}{dM} = \psi(z_f)\phi(\mathscr{M}_*)\frac{d\mathscr{M}_*}{dM}\,,\qquad \psi(z_f) - \text{star formation rate}\,,\qquad \phi(\mathscr{M}_*) \propto \mathscr{M}_*^{-2.35} - \text{Salpeter initial mass function}$$

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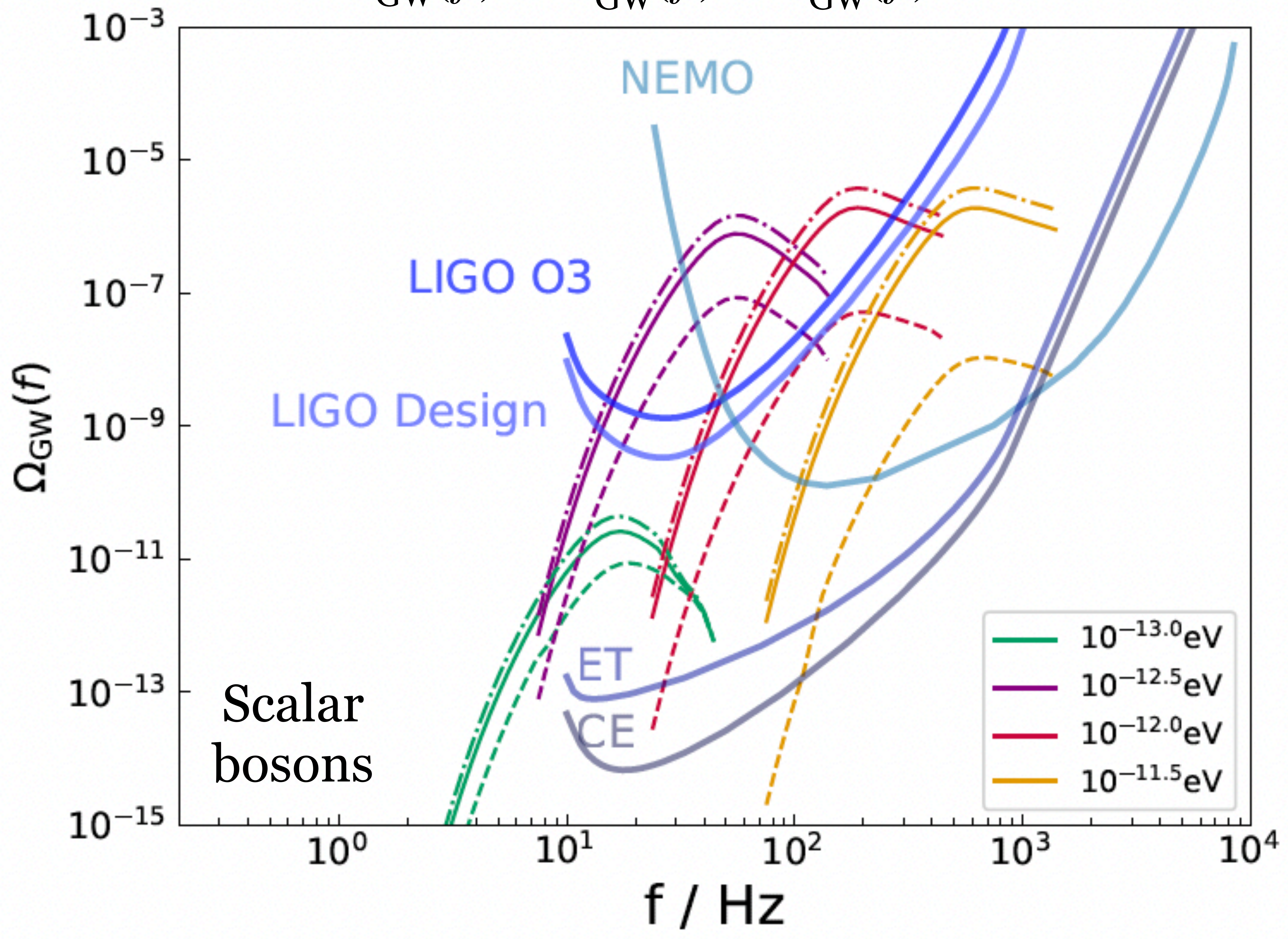
Merger rate density $R(z; M_1, M_2)$ and $P(M_{1/2})$ follows what is used by LVK.

Note: In this case $\chi_i := \chi_i(M_1, M_2)\,,\ M_i := M_i(M_1, M_2)$ (neglecting component spins)

Main uncertainty: BH spin distribution

$$\Omega_{\rm GW}(f) = \Omega_{\rm GW}^{\rm iso}(f) + \Omega_{\rm GW}^{\rm rem}(f)$$



From: Yuan, Jiang & Huang, PRD106, 023020

Amplitude of SGWB **largely dependent** on assumed $p(\chi_i)$ for isolated BH channel.

Dot-dashed lines: $\chi_i \in [0.5,1[$

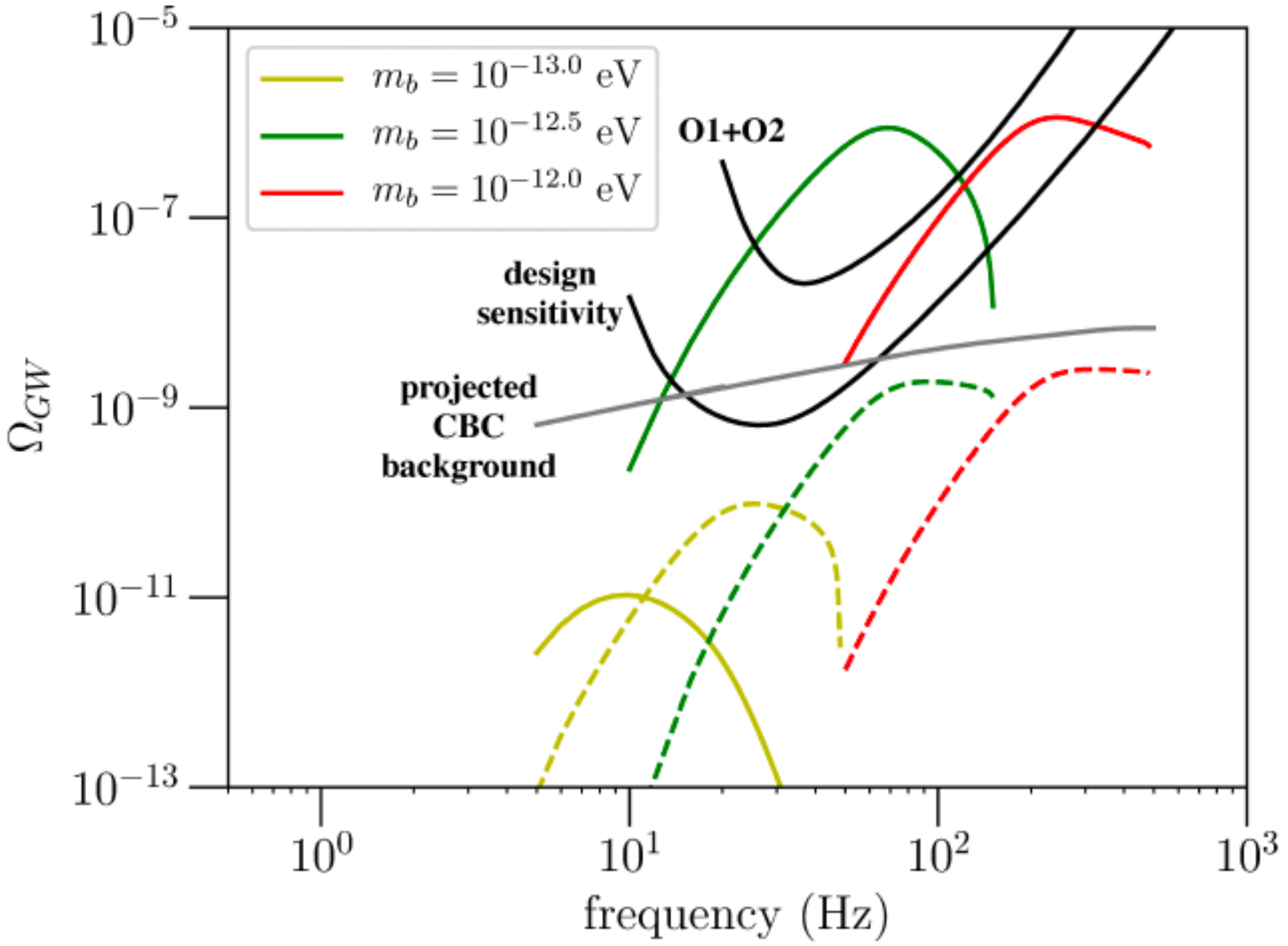
Solid lines: $\chi_i \in [0,1[$

Dashed lines: $\chi_i \in [0,0.5]$

Isolated BHs vs merger remnant BHs

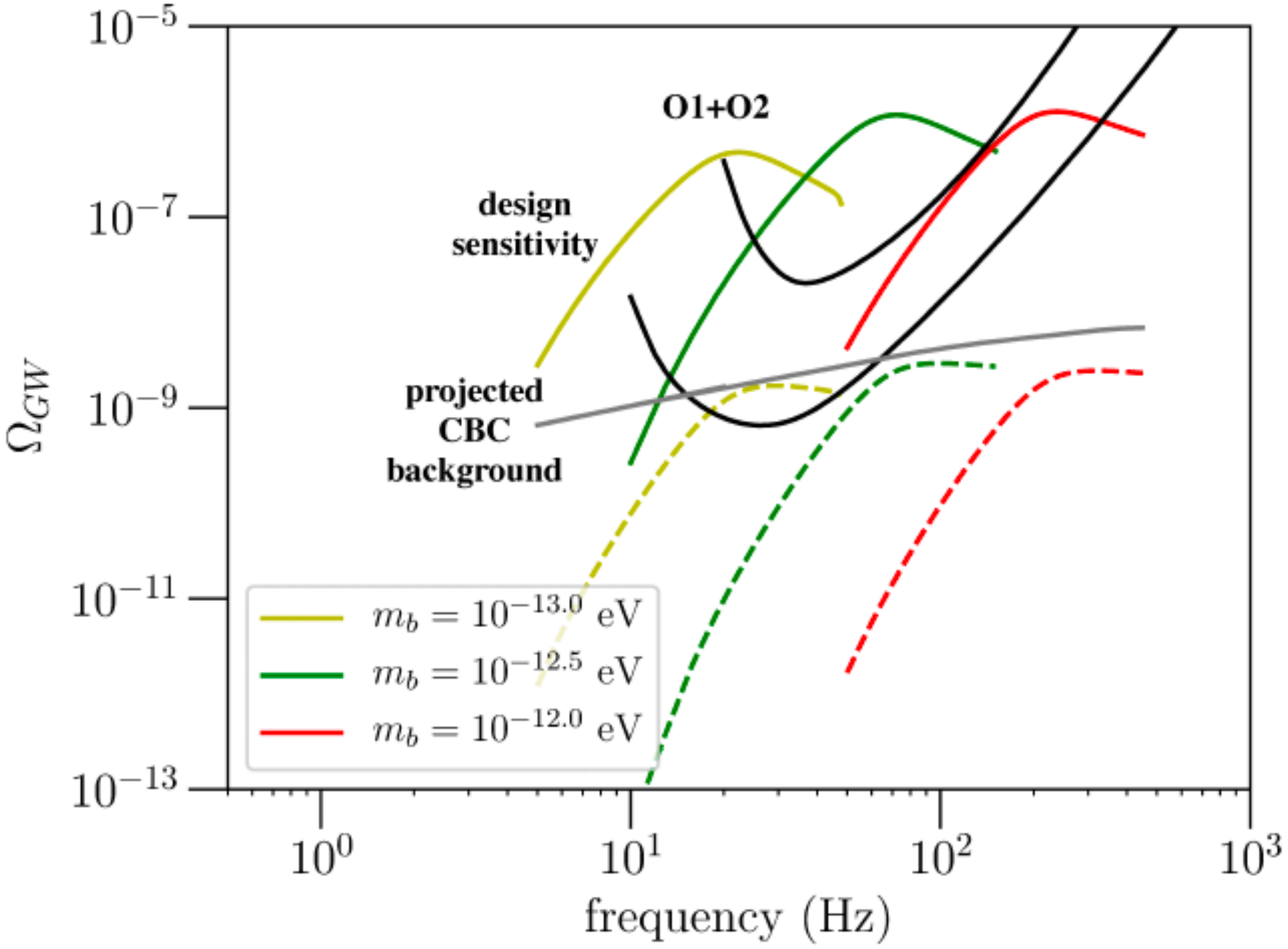
Scalar bosons

RB+ 17; Tsukada+ ’18; Yuan+ ’21
Tsukada Phd thesis ´21



Vector bosons

Tsukada, RB, East & Siemonsen, ’20;
Tsukada PhD thesis ‘21



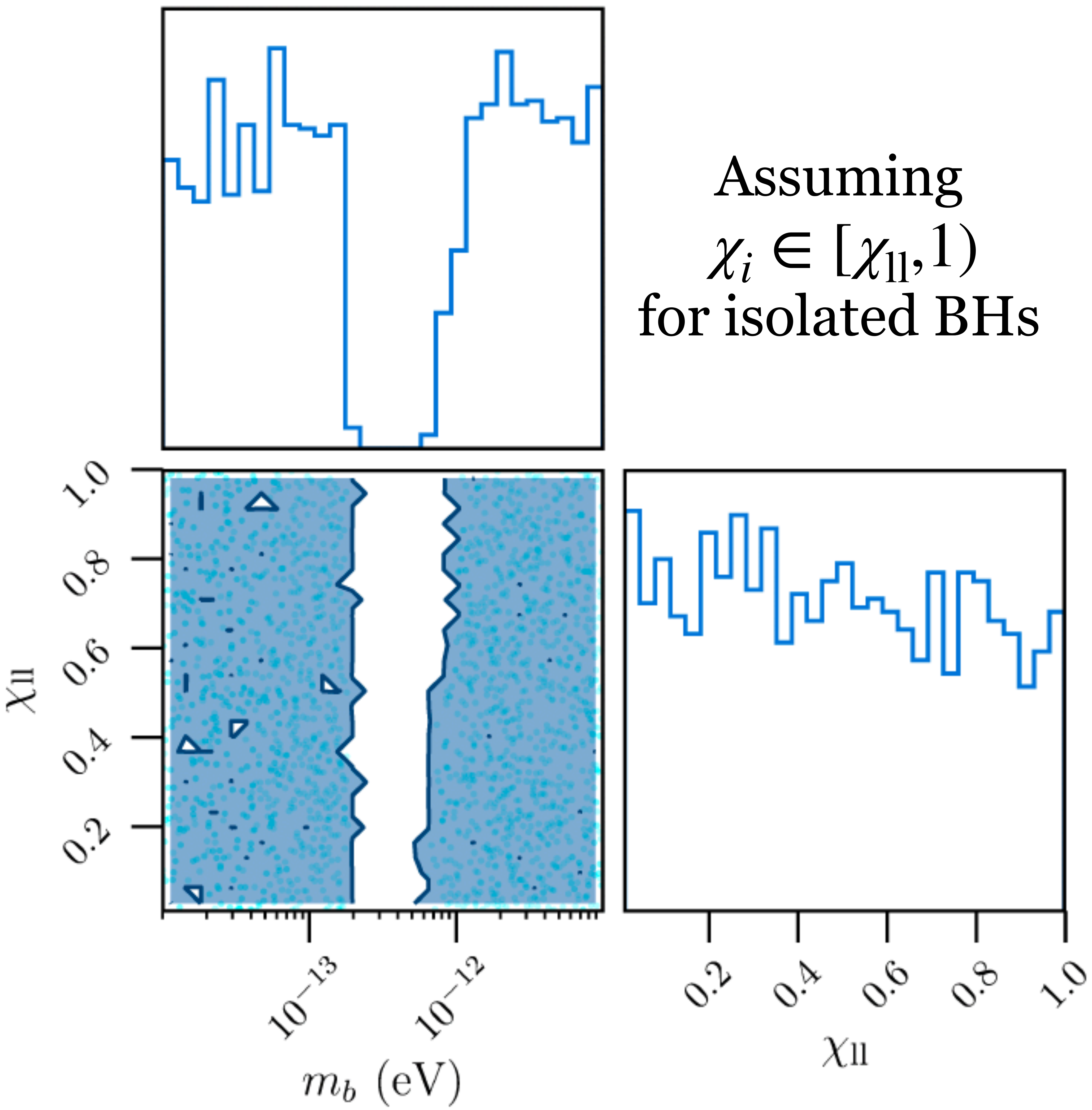
From: Leo Tsukada’s PhD thesis

Solid lines: isolated; **Dashed lines:** merger remnants

Constraints using LIGO O1+O2 data

Scalar bosons

Tsukada, T. Callister, A. Matas, P. Meyers, '18
Tsukada Phd thesis ´21



Assuming
$\chi_i \in [\chi_{ll}, 1)$
for isolated BHs

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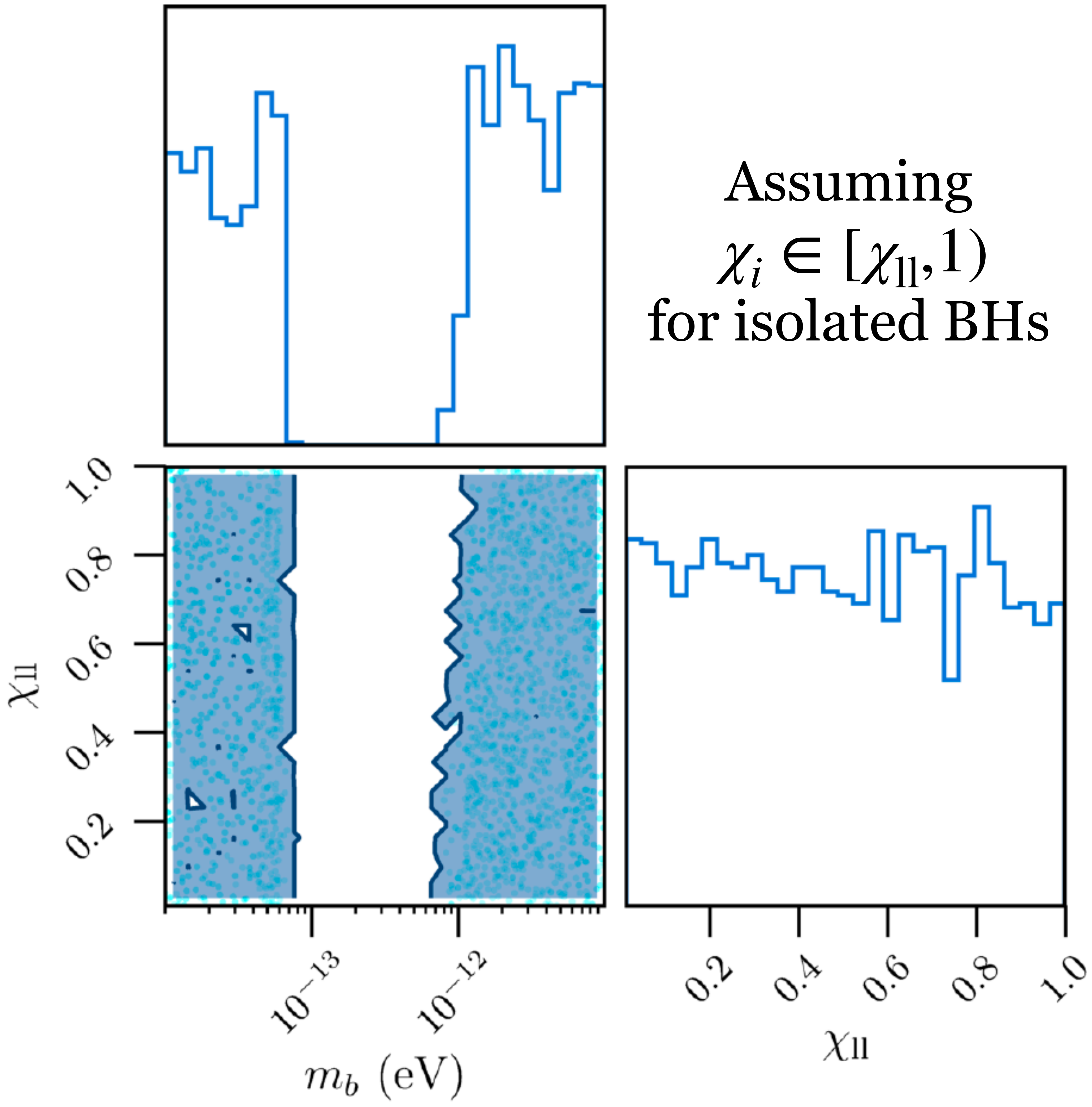

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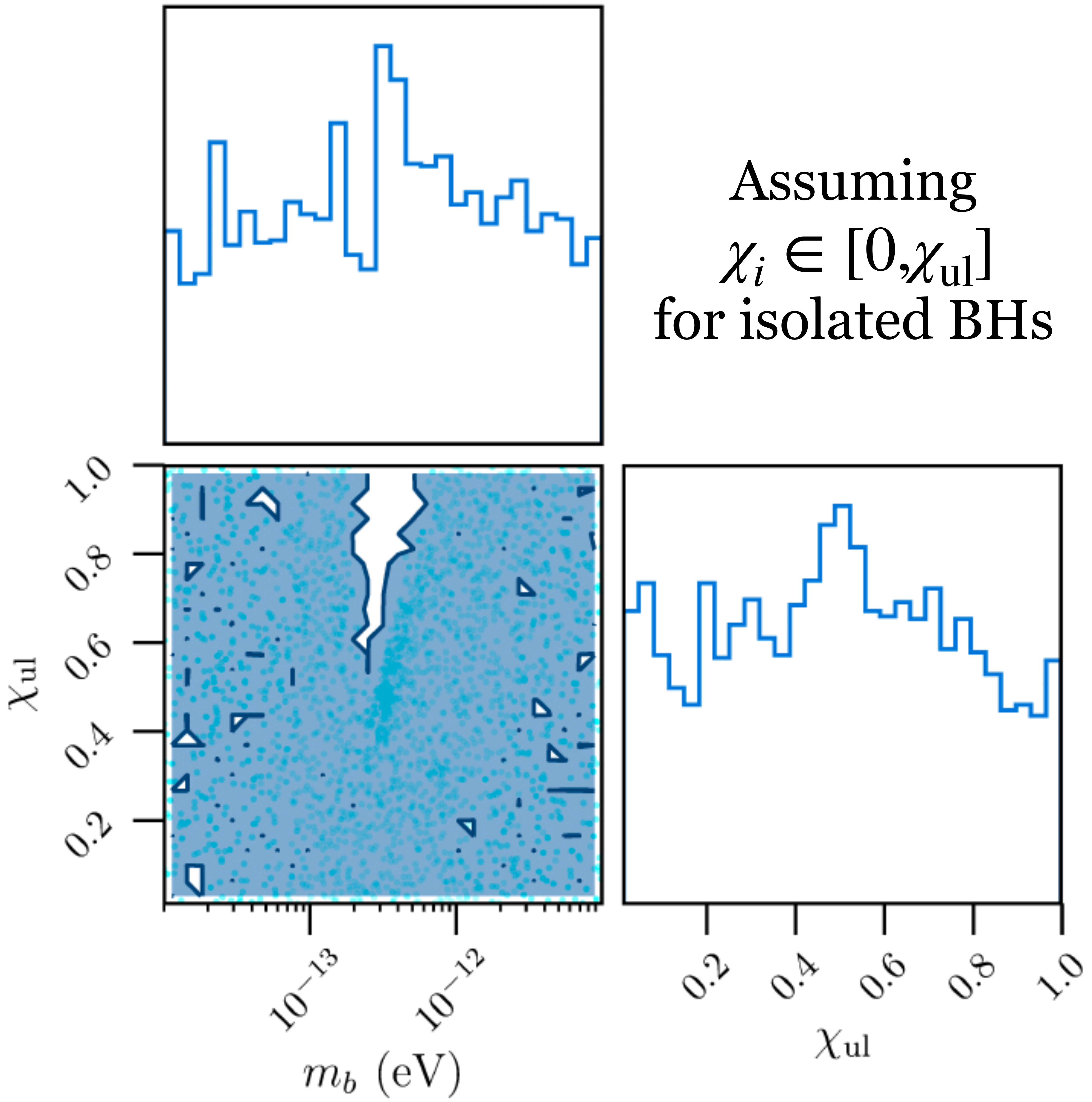

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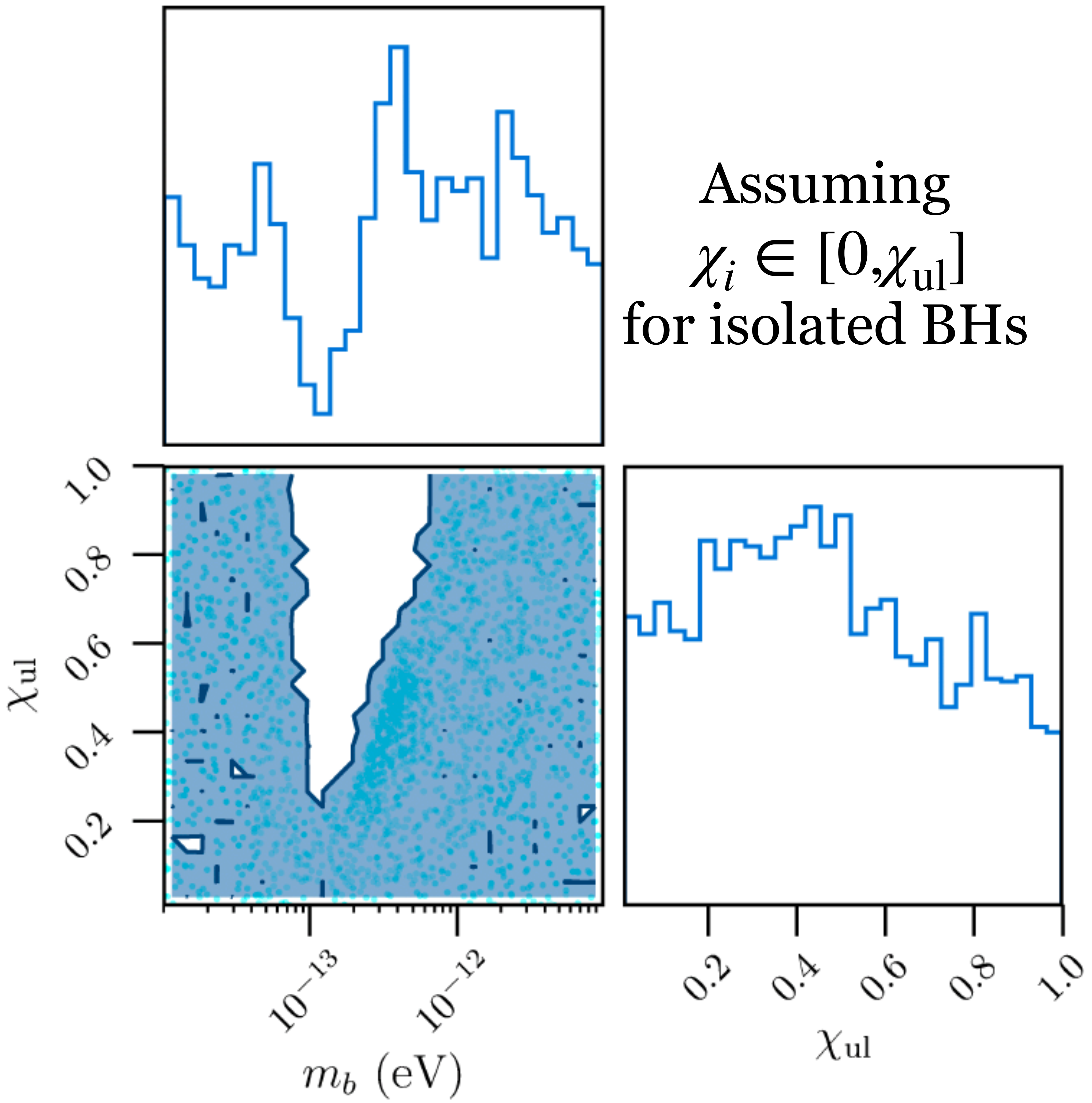

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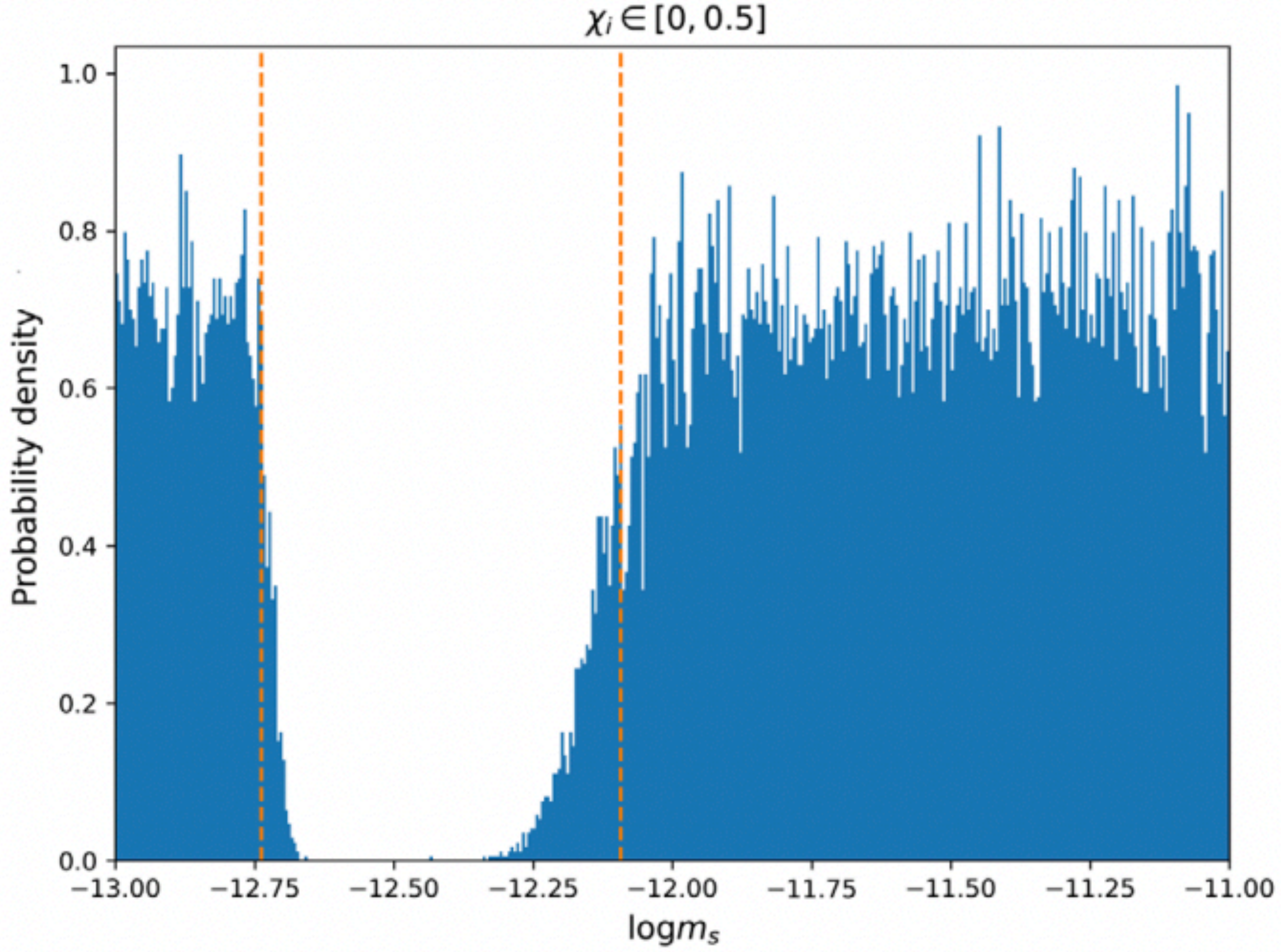
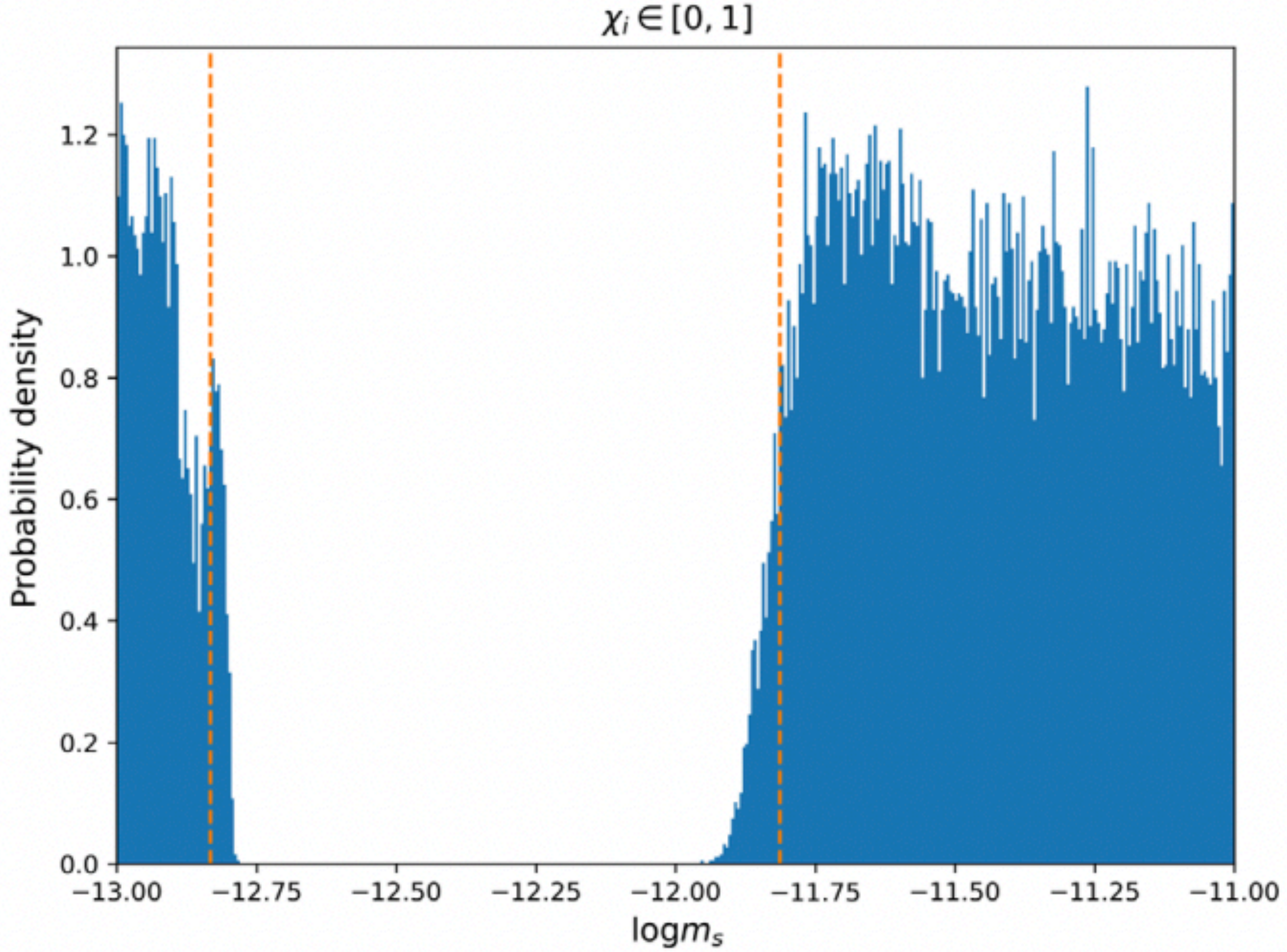
Constraints with O3 data for scalar bosons

From: Yuan, Jiang & Huang, PRD106, 023020





	$m = 1$		All m-modes	
χ_i (Uniform)	$\log \mathcal{B}$	m_s (eV)	$\log \mathcal{B}$	m_s (eV)
[0,1]	−0.26	$[1.4, 13] \times 10^{-13}$	−0.27	$[1.5, 15] \times 10^{-13}$
[0,0.5]	−0.15	$[1.9, 8.1] \times 10^{-13}$	−0.15	$[1.8, 8.1] \times 10^{-13}$
[0.5,1]	−0.29	$[1.3, 14] \times 10^{-13}$	−0.30	$[1.3, 17] \times 10^{-13}$

Final Remarks

- Include **non-gravitational interactions** (self-interactions, couplings to photons, etc…) in the calculation.

- **Combine** constraints coming from continuous GW + stochastic background searches (+ BH spin distributions).

- Robust predictions for stochastic GW background in **LISA** (and PTA?) probably requires including superradiant instability in models that follow the formation and evolution of supermassive black holes.

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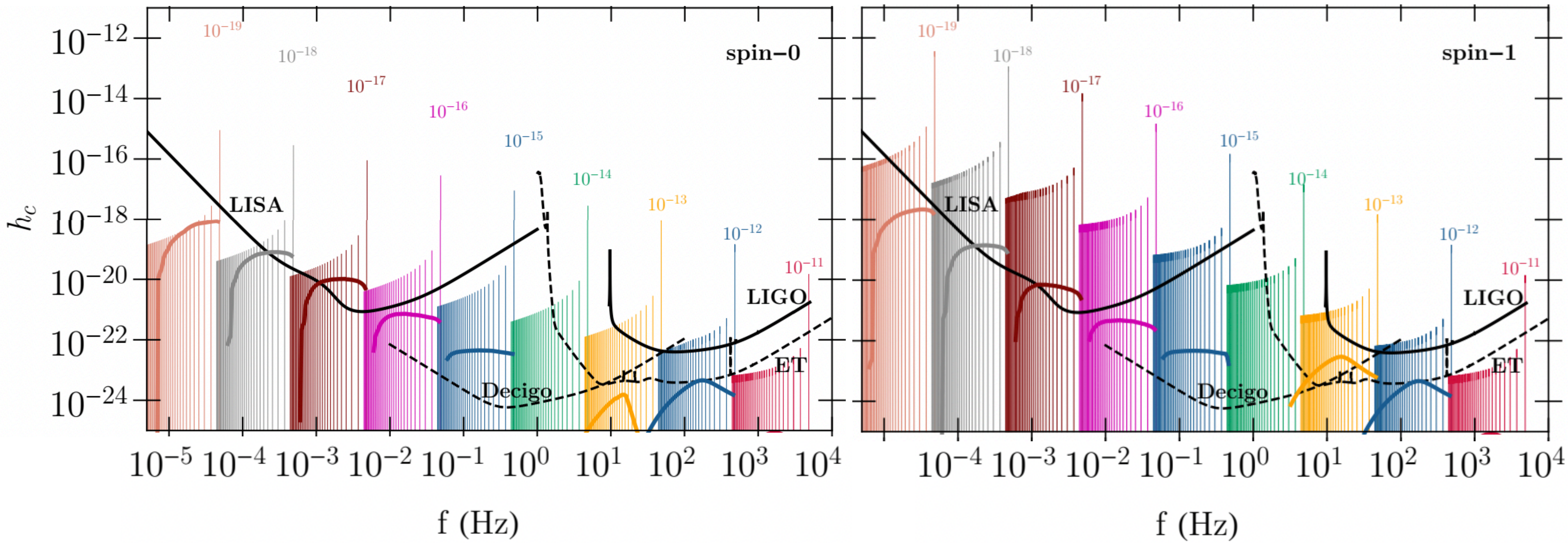
Thank you!

Backup slides

Gravitational-waves from boson clouds



$$h_c = \sqrt{N_{\rm cycles}}\, h$$

$$N_{\rm cycles} \sim \min[f T_{\rm obs}, f\tau_{\rm GW}]$$

$$T_{\rm obs} = 4\ \text{years}$$

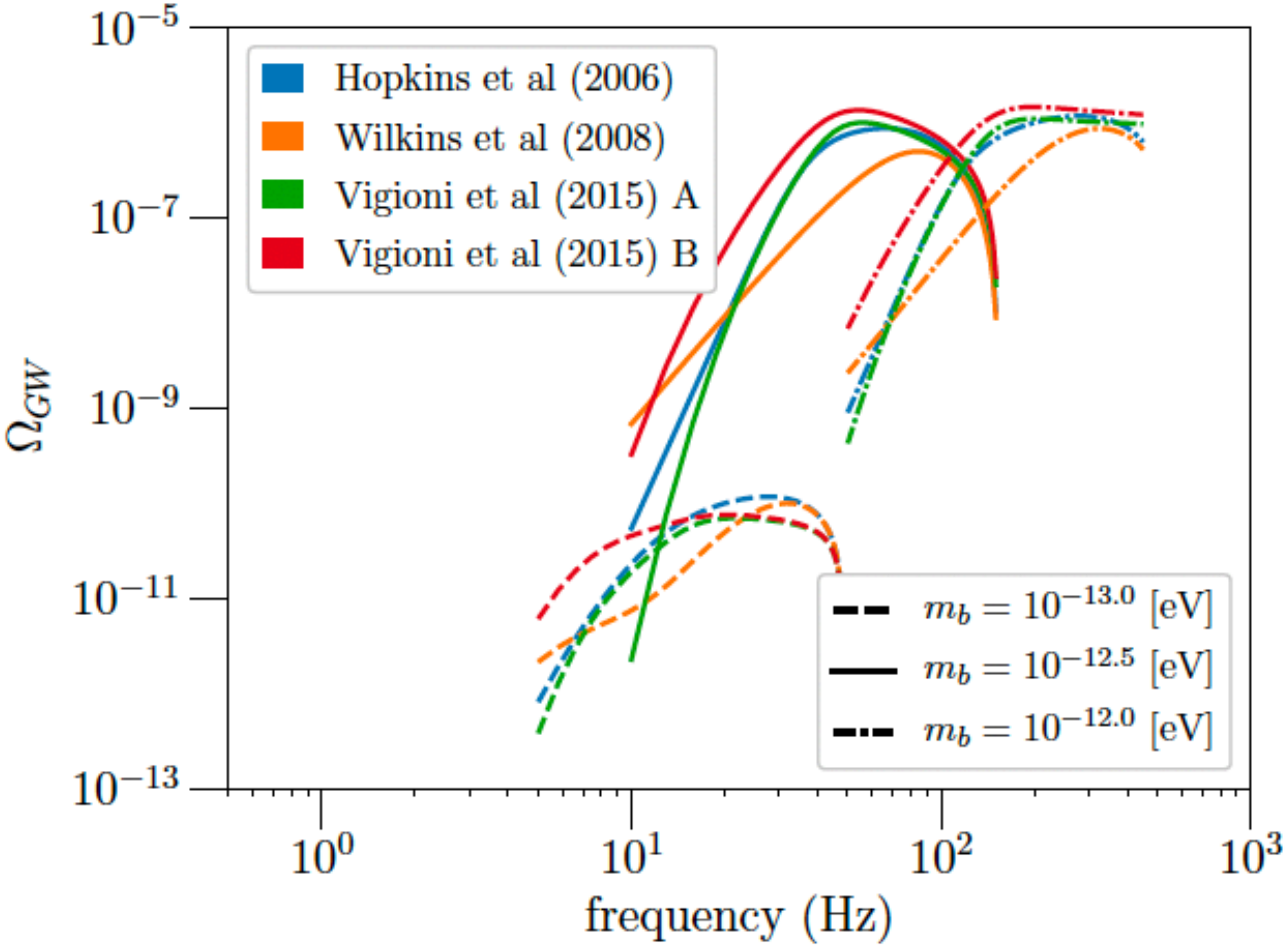
Vertical lines: $J/M^2 = 0.9$, $z = 0.001 - 10$ (right to left), M changes along vertical lines

Solid lines: (extragalactic) stochastic GW background under optimistic assumptions

Uncertainties: Choice of SFR

SFR = star formation rate

Scalar bosons



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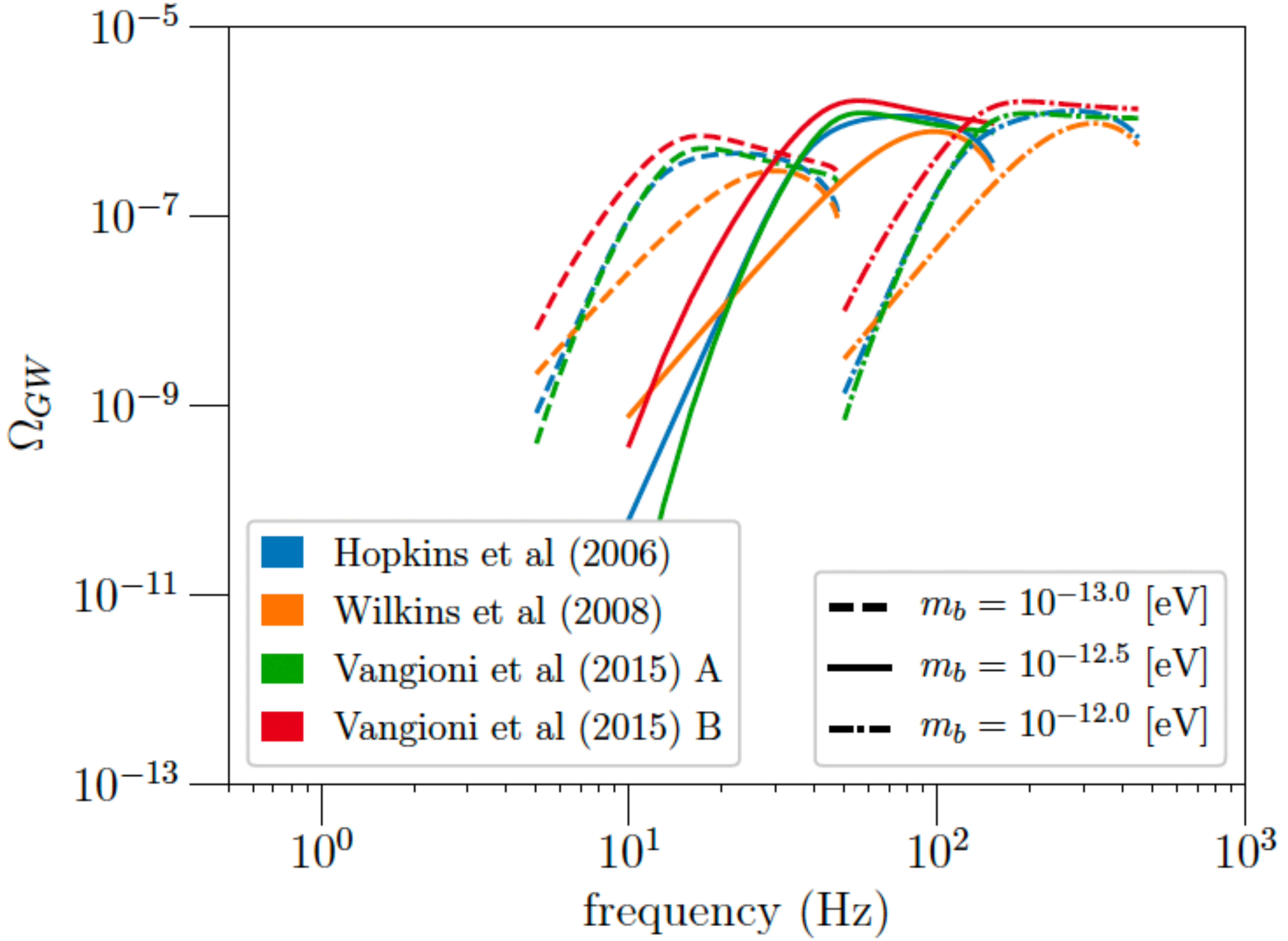

From: Tsukada, RB, East & Siemonsen, '20