Searching for ultralight bosons with black holes and gravitational waves

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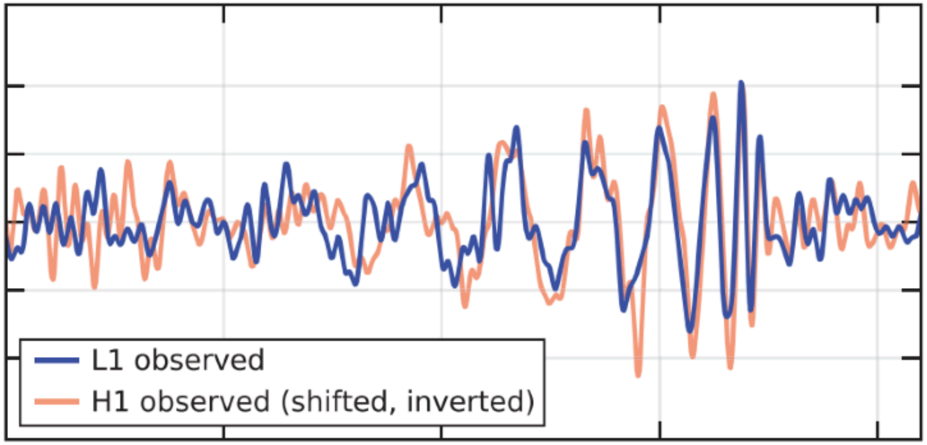
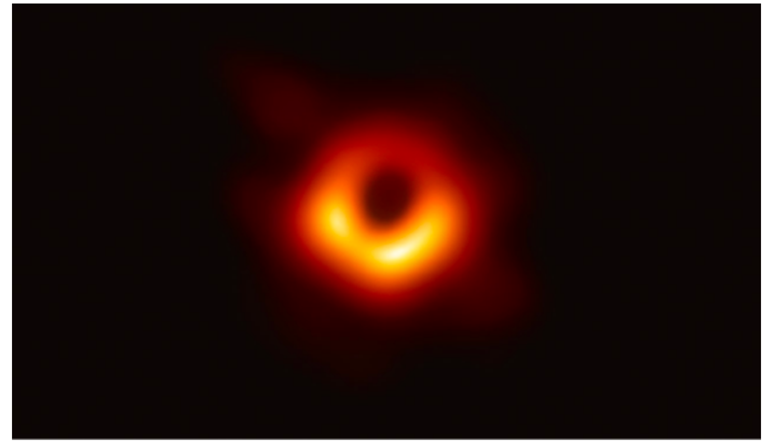
A new golden age for gravitation



Credit: (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. 116, 061102



Credit: Event Horizon Telescope collaboration

- Gravitational physics is entering a **new golden age**.
- A wealth of data, from **gravitational waves** to **EHT observations**, is opening new doors for potential discoveries.
- In the coming years, especially with **LISA** and **3G** detectors, we will be doing "**precision** gravitational-wave physics".
- Plenty of room for **unexpected** discoveries.

Ultralight bosons

- **Ultralight bosons** (masses < 1 eV) are ubiquitous in extensions of the Standard Model: QCD axion, string axiverse, string photiverse, dark photons, …
- Natural **weak coupling** to Standard Model particles: compelling **dark-matter** candidates alternative to WIMPs.
- Important note: during the talk I will **neglect** self-interactions and non-gravitational interactions.

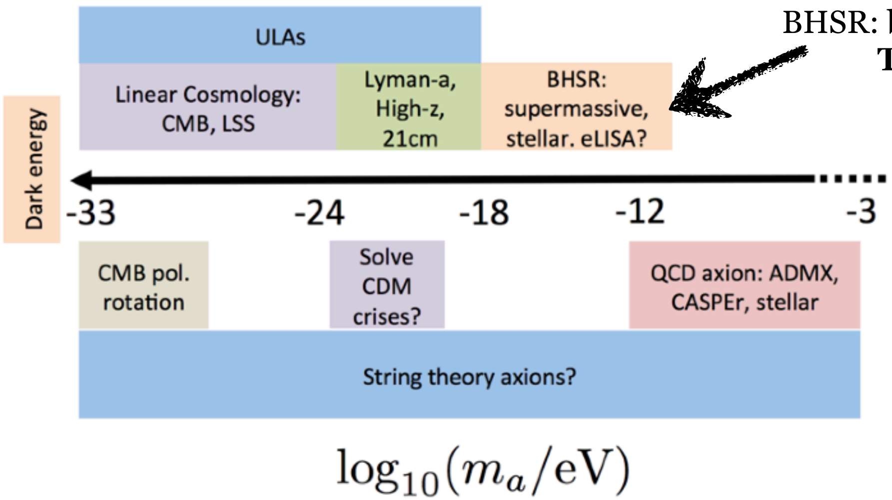


Figure 1: Summary of constraints and probes of axion cosmology.

BHSR: black hole superradiance
Topic of this talk

From: D. Marsh, Phys. Rept. 643 (2016)

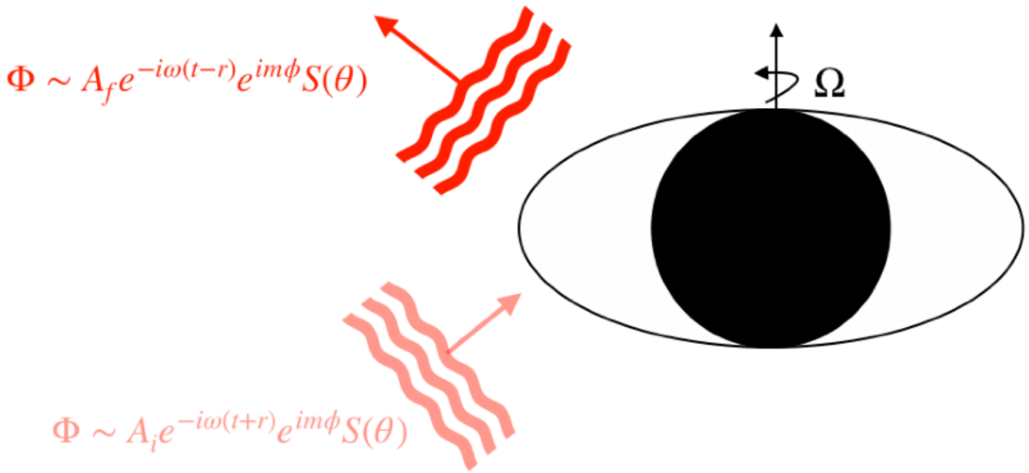
$$\mathscr{L} = \sqrt{-g}\left[\frac{R}{\kappa} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{2}\mu_V^2 - \frac{1}{2}\left(\partial_\mu\Phi\partial^\mu\Phi + \mu_S^2\Phi^2\right)\right]$$

Outline

- Black hole **superradiance**
- Physics of **ultralight bosons** in black hole spacetimes
- How to search for ultralight particles with **black holes** and **gravitational-wave** observations.
- Conclusions

BH Superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74;
Review: RB, Cardoso & Pani "Superradiance" arXiv:1501.06570



$$\omega/m < \Omega \implies |A_f|^2 > |A_i|^2$$

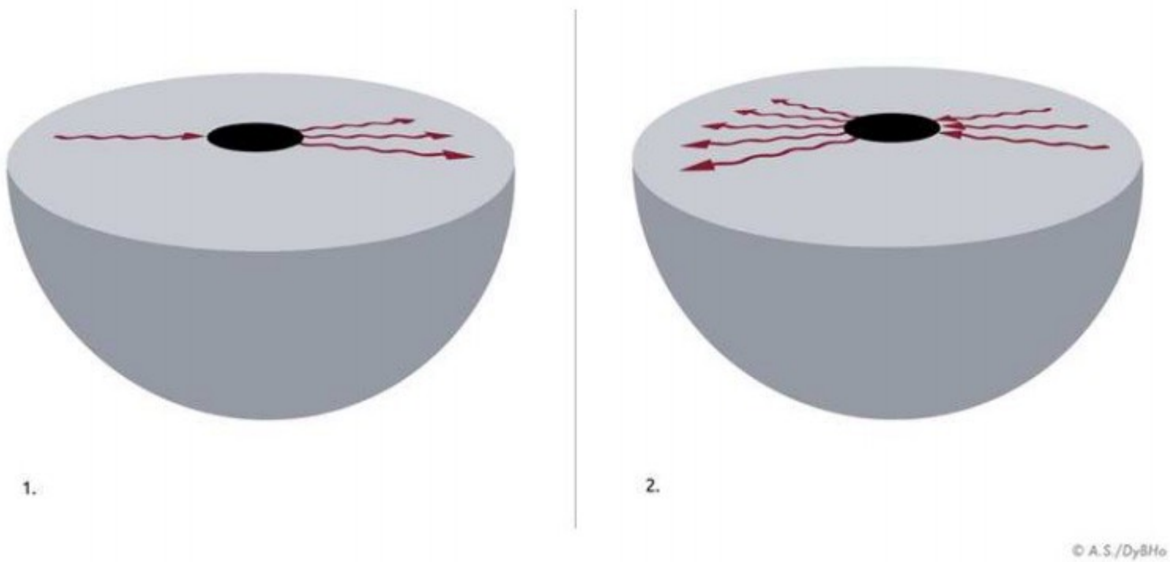
Superradiant scattering of classical **bosonic** waves $\Longrightarrow$ **Extraction** of energy and angular momentum from the black hole

Part of larger family of processes allowing for **energy extraction** from a spinning BH: Penrose process, Blandford-Znajek process.

Superradiant instability: black-hole bombs

Press & Teukolsky, ’72

Confinement + Superradiance $\longrightarrow$ Superradiant instability



Kerr black holes surrounded by a perfectly reflecting mirror are **unstable** against bosonic radiation with frequency:

$$\omega < m\Omega_H$$

Massive bosonic fields around Kerr BHs

Damour '76; Gaina '78; Zouros & Eardley '79; Detweiler '80; Dolan '07; Rosa & Dolan '12; Pani *et al* '12; Baryakthar, Lasenby & Teo '17; East '17; Cardoso *et al* '18; Frolov *et al* '18; Dolan '18; Baumann et al '19; RB, Grillo & Pani '20...

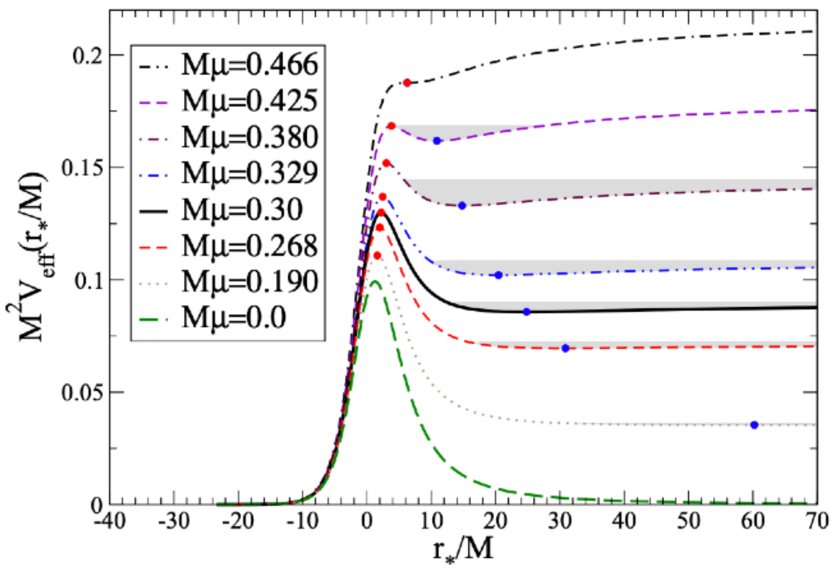
Massive bosonic fields naturally confines waves with frequency $\omega < \mu$.

$$\nabla_\mu \nabla^\mu \Phi = \mu^2 \Phi \qquad (\mu \equiv m_b c/\hbar)$$

$$\Phi = \frac{\Psi(r)}{r} S_{\ell m \omega}(\theta) e^{-i\omega t + i m \varphi}$$

$$\frac{d\Psi}{dr_*^2} + (\omega^2 - V_{\rm eff})\Psi = 0\,, \qquad V_{\rm eff}(r \to \infty) = \mu^2$$

$$M\mu \equiv \frac{M m_b}{M_{\rm Pl}^2} = R_G/\lambda_C$$



From: Barranco *et al*' 11, PRD84, 083008 (2011)

Kerr black holes can be **unstable** in the presence of massive bosons.

Strongest instability rates for

$$\left(\frac{M}{70 M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}{\rm eV}}\right) \sim \mathcal{O}\left(M_{\rm Pl}^2\right)$$

“Gravitational atom”

A (macroscopic) **“gravitational atom”** but with some big differences when compared to the hydrogen atom:

i) **boundary conditions** at the horizon;

ii) **no Pauli exclusion principle** for bosons.

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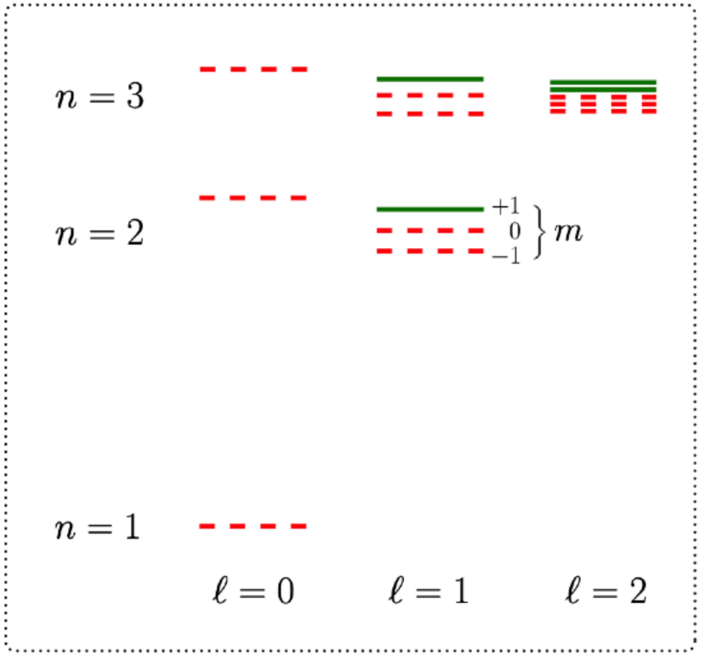
In the non-relativistic limit $\alpha \equiv M\mu \ll 1$:
(*can be generalized to vectors or tensor fields)

$$\omega_{nlm} \simeq \mu \left(1 - \frac{\alpha^2}{2n^2}\right) + \Delta\omega_{nlm}$$

$$\Delta\omega_{n\ell m} = \mu\left(-\frac{\alpha^4}{8n^4} + \frac{(2\ell - 3n + 1)\,\alpha^4}{n^4(\ell+1/2)} + \frac{2\tilde{a}m\alpha^5}{n^3\ell(\ell+1/2)(\ell+1)}\right)$$

See Baumann, Chia & Porto, PRD99, 044001 (2019) & Baumann, Chia, Stout & Haar, JCAP12, 006 (2019)



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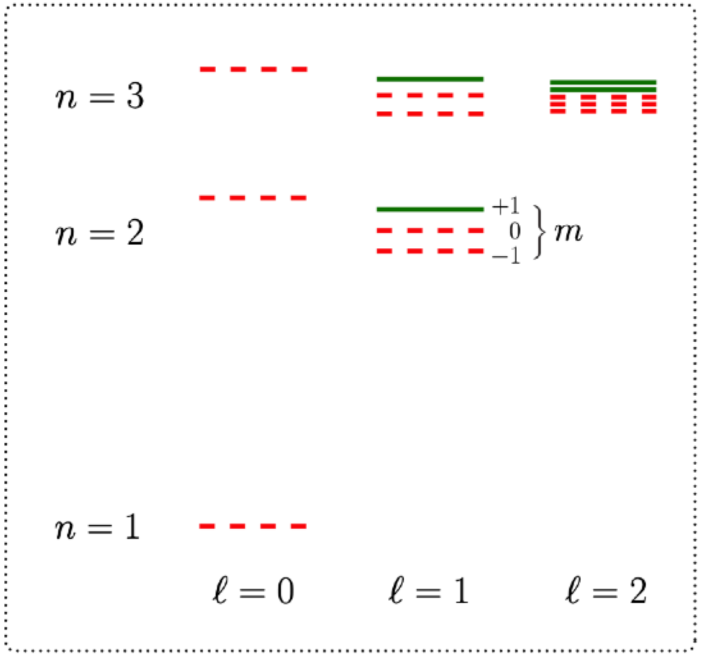

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Boundary conditions at the horizon

$$\omega_{n\ell m} \to \omega_{n\ell m} + i\Gamma_{n\ell m}$$

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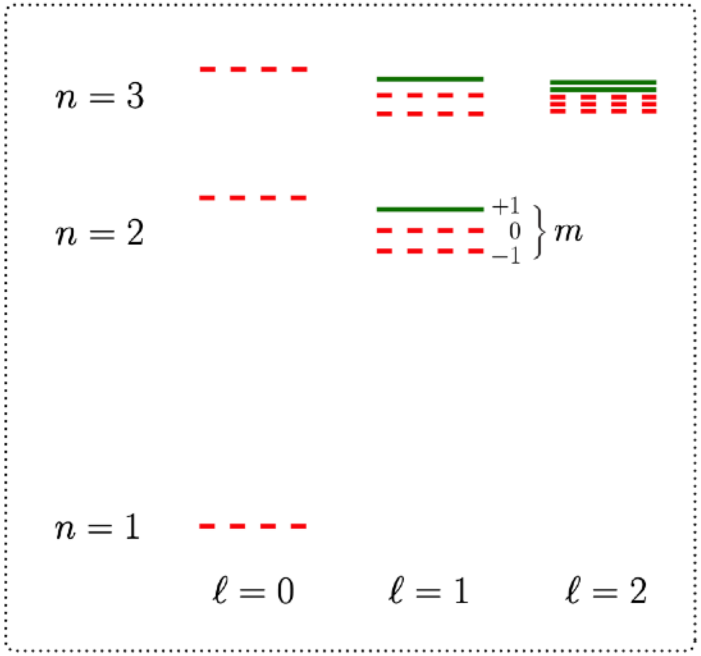

From: Baumann, Chia & Porto, PRD99, 044001 (2019)

Boundary conditions at the horizon

$$\Gamma_{n\ell m} = \frac{2r_+}{M} C_{n\ell m}(\alpha)\,(m\Omega_{\rm H} - \omega)\,\alpha^{4\ell+5}$$

If $\omega < m\Omega_H$: growing mode

If $\omega > m\Omega_H$: decaying mode

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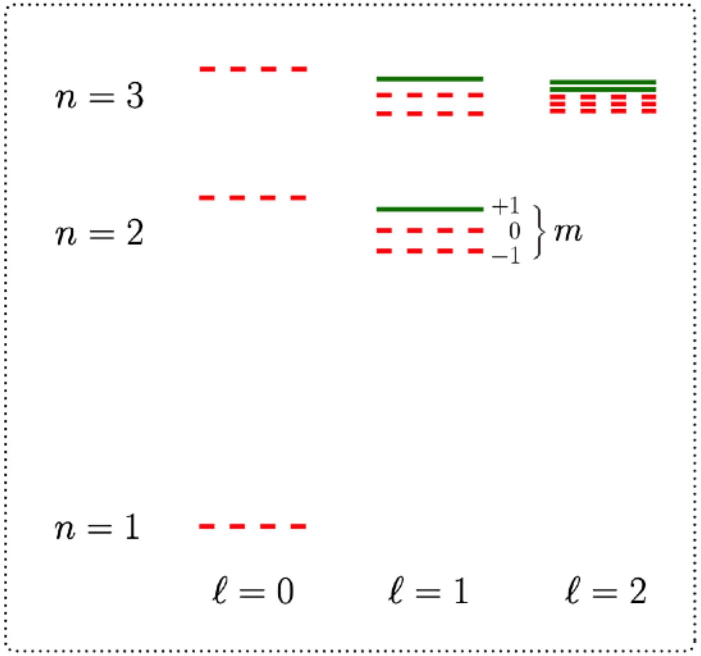


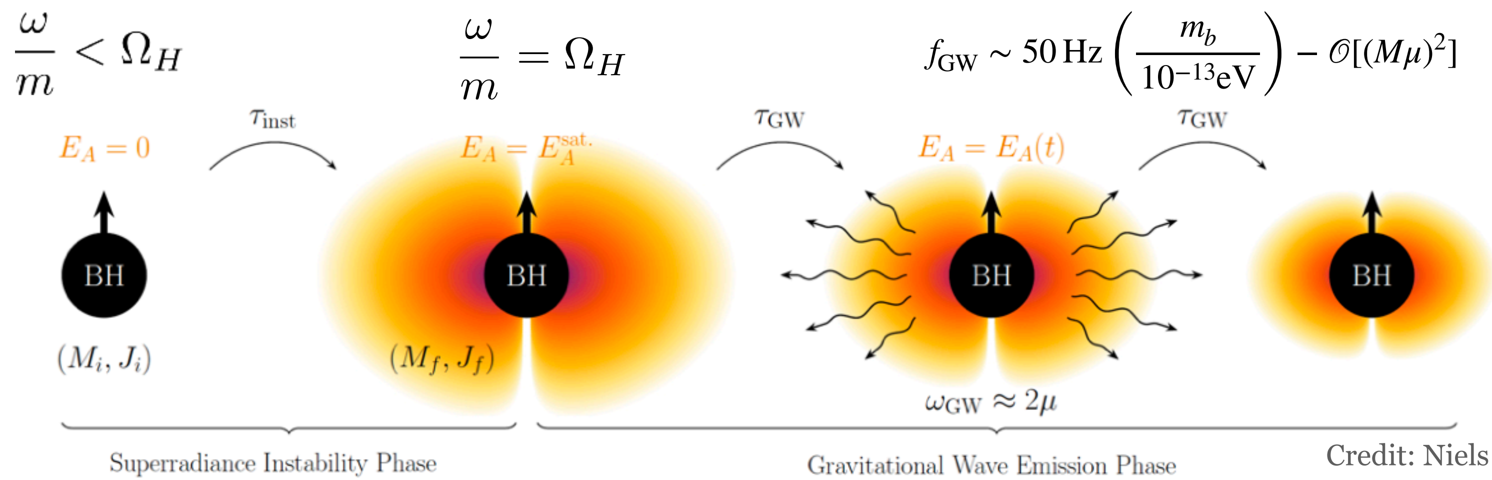
From: Baumann, Chia & Porto, PRD99, 044001 (2019)

If $\omega = m\Omega_H \implies \Gamma_{n\ell m} = 0$:

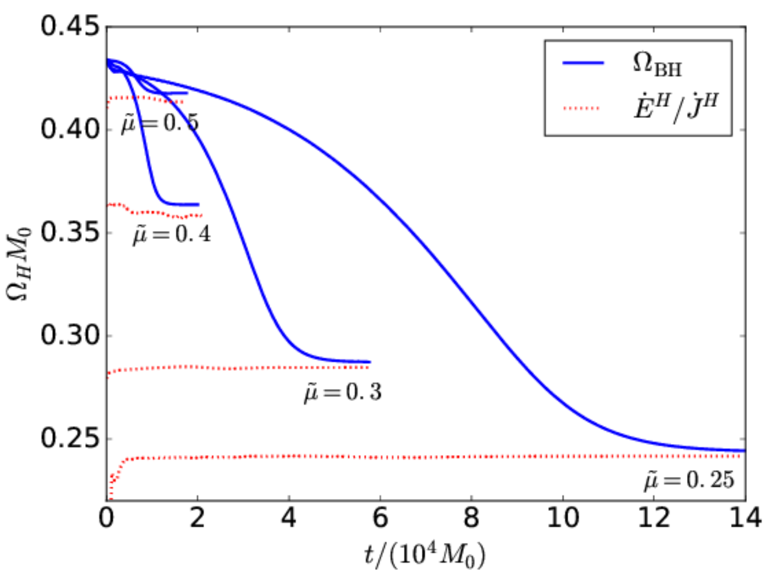
Exact bound states.

At the full non-linear level lead to "Kerr BHs with scalar/Proca hair" for complex fields (Herdeiro & Radu '14; Herdeiro, Radu & Rúnarsson '16)

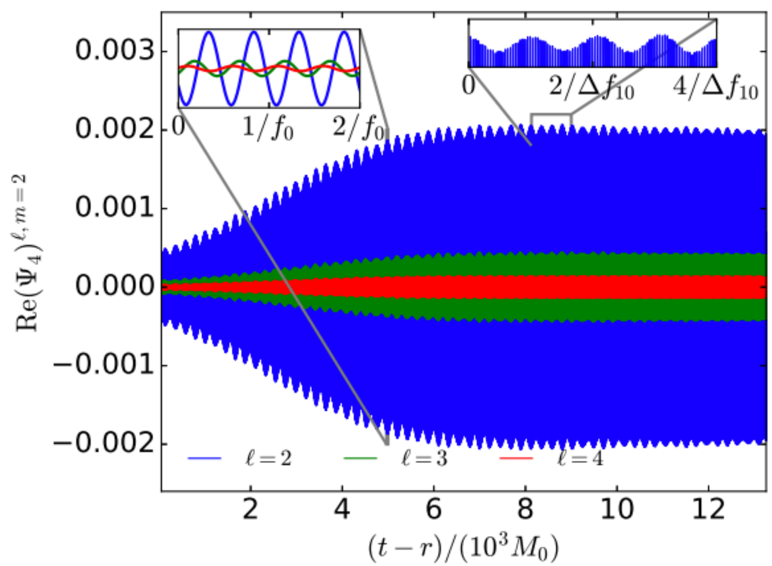
Evolution of the superradiant instability



Credit: Niels Siemonsen



From: East & Pretorius, PRL119, 041101 (2017)



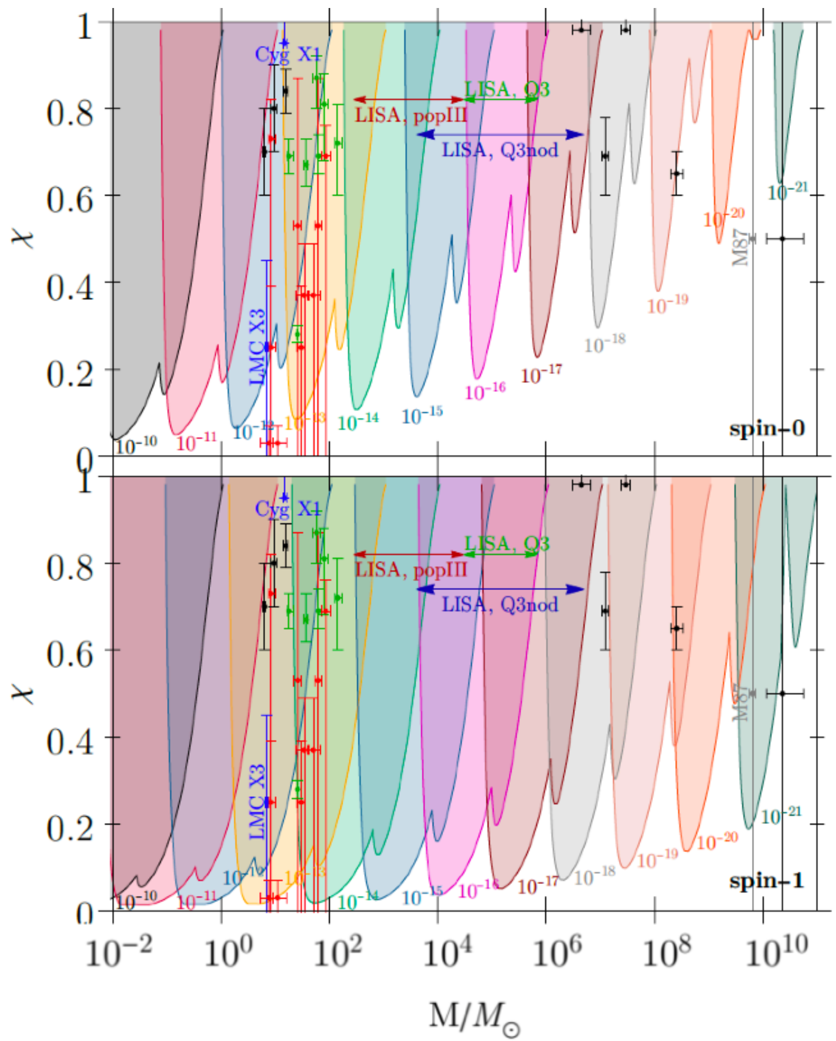
From: East, PRL121, 131104 (2018)

*end-state solutions well described by Kerr BHs with Proca hair (Herdeiro & Radu ‘17)

Useful scales and observables

Instability timescale:

$$\tau_{\rm inst}^{\rm scalar} \approx 30\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{\chi}\right)\,,\quad \tau_{\rm inst}^{\rm vector} \approx 280\,{\rm s}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{\chi}\right)$$



Precise measurements of **mass** and **spin** of **astrophysical BHs** can be used to constrain (or find evidence for) ultralight bosons.

Arvanitaki *et al* '09;
Arvanitaki & Dubovsky, '10

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GW emission timescale:

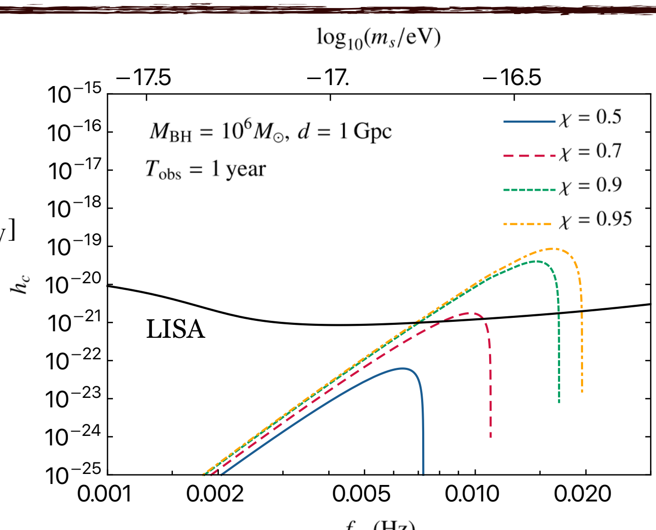
$$\tau_{\rm GW}^{\rm scalar} \approx 10^5\,{\rm yr}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\chi_i-\chi_f}\right), \qquad \tau_{\rm GW}^{\rm vector} \approx 2\ {\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{11}\left(\frac{0.5}{\chi_i-\chi_f}\right)$$

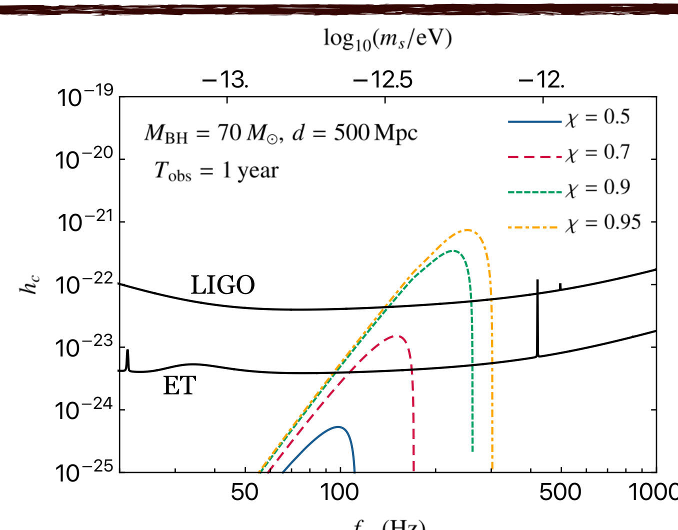
GW strain:

$$h_0^{\rm scalar} \approx 5\times 10^{-27}\left(\frac{M}{10M_\odot}\right)\left(\frac{M\mu}{0.1}\right)^7\left(\frac{\rm Mpc}{d}\right)\left(\frac{\chi_i-\chi_f}{0.5}\right), \quad h_0^{\rm vector} \approx 10^{-23}\left(\frac{M}{10M_\odot}\right)\left(\frac{M\mu}{0.1}\right)^5\left(\frac{\rm Mpc}{d}\right)\left(\frac{\chi_i-\chi_f}{0.5}\right)$$

$$h_c \propto h_0\sqrt{N_{\rm cycles}}$$

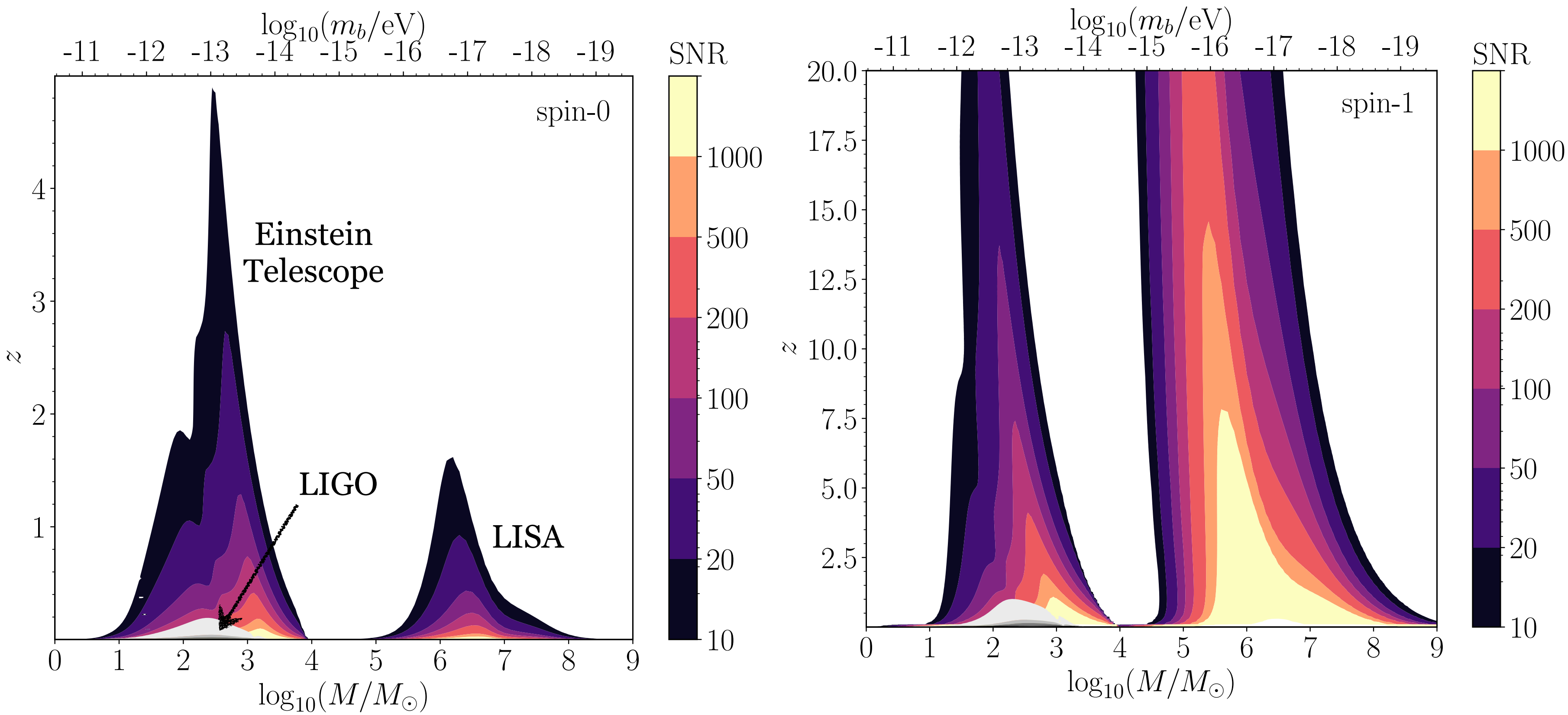
$$N_{\rm cycles} \approx \min[f\,T_{\rm obs}, f\,t_{\rm GW}]$$





Gravitational-wave searches

$$\chi_i = 0.9\,, \quad M\mu = 0.2\,, \quad T_{\rm obs} = 4\,\text{years}$$



$$\text{SNR} \propto \sqrt{\frac{h_0^2 N_{\rm cycles}}{f S_n(f)}}\,, \quad N_{\rm cycles} \approx \min[f T_{\rm obs}, f t_{\rm GW}]$$

Detection horizons

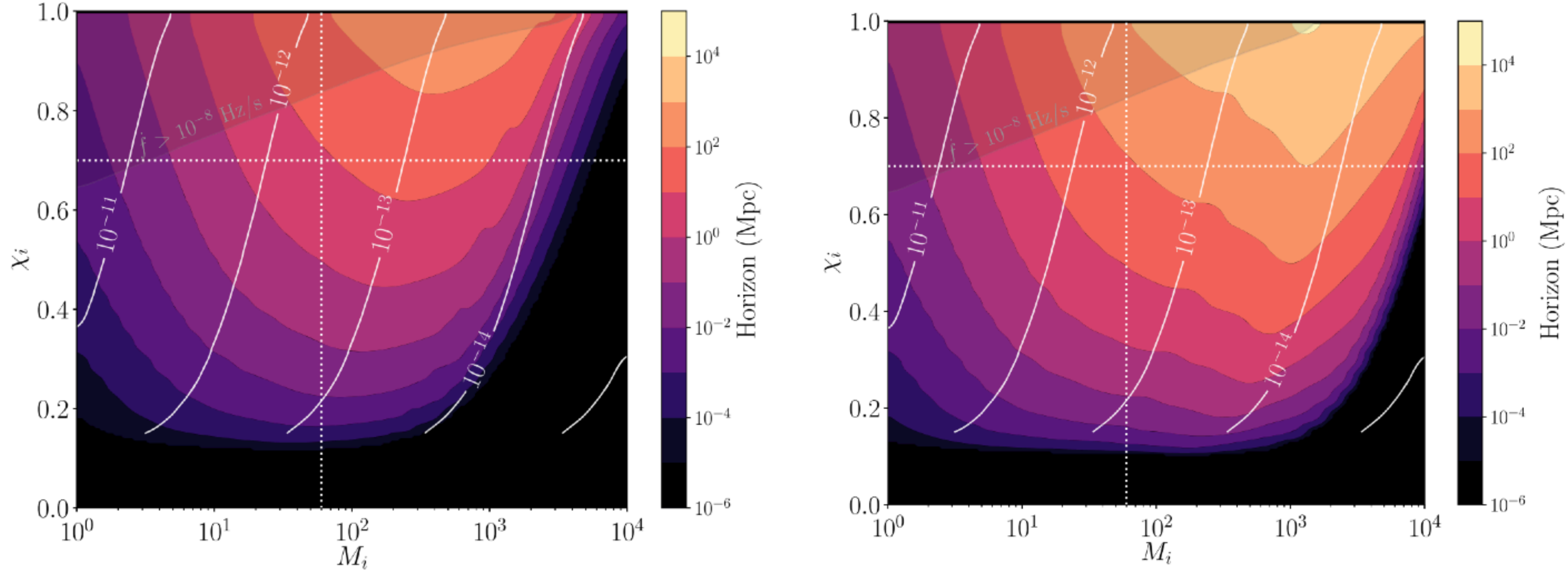
M. Isi, L. Sun, RB, A. Melatos, '19

Most searches for continuous GWs use **semi-coherent** methods.

$$h_0^{95\%}(f) \propto N_{\rm ifo}^{-1/2} S_h(f)^{1/2} (T_{\rm coh} T_{\rm obs})^{-1/4}$$

$N_{\rm ifo} = 1\,, \quad T_{\rm obs} = 1$ year

*numbers are for the $\ell = m = 1$ mode of a scalar field



(a) aLIGO design

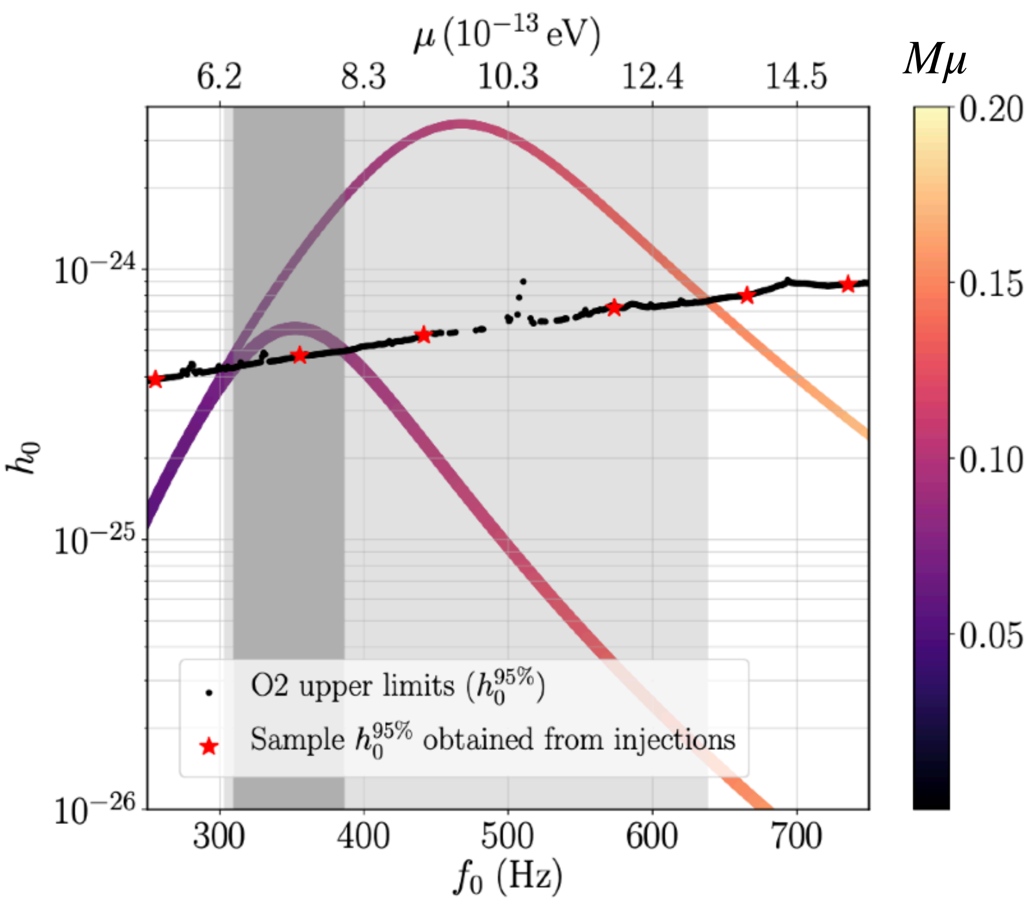
(d) Einstein Telescope

- LIGO still mostly sensitive to potential **galactic sources** (known BBHs remnants too far).
- Current continuous GW search methods **not (yet) adapted** to search for shorter lived GWs from vector clouds.

Directed searches at Cygnus X-1

L. Sun, RB & M. Isi '19

Cygnus X-1 harbours a black hole candidate at ~ 1.86 kpc with mass $\sim 15 M_{\odot}$.



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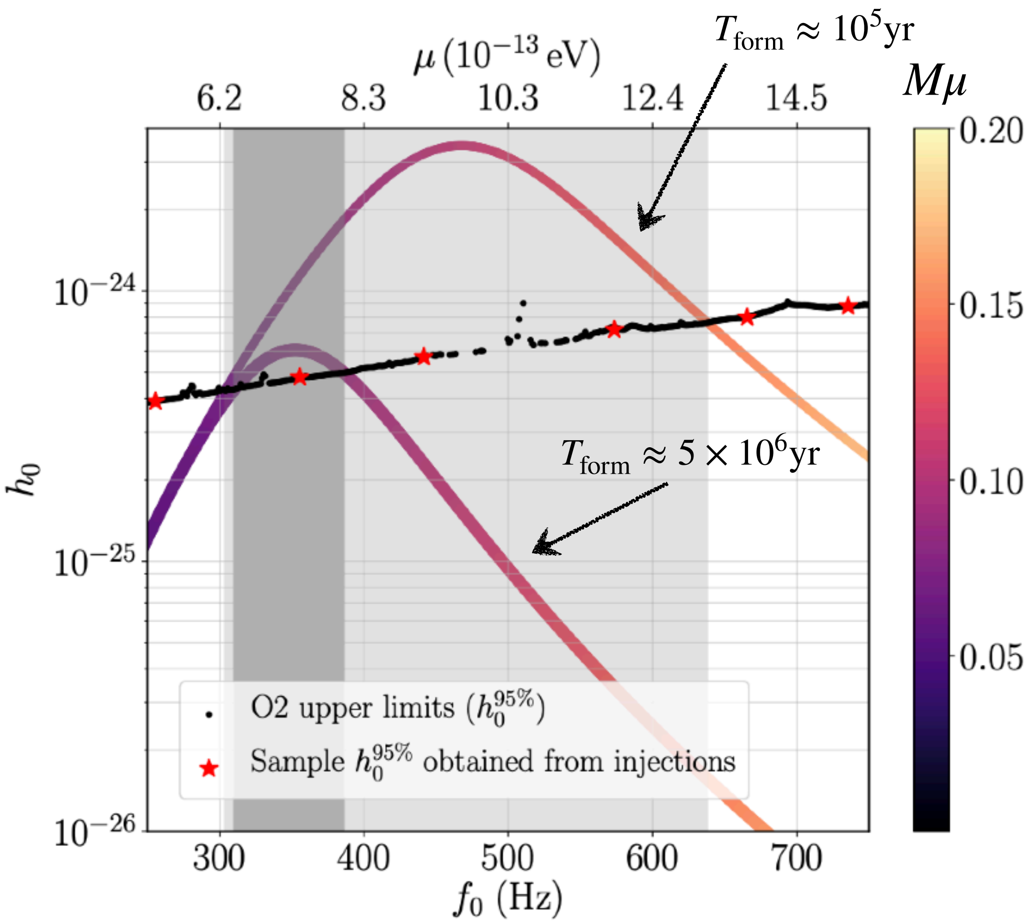

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- Large uncertainties in formation age;

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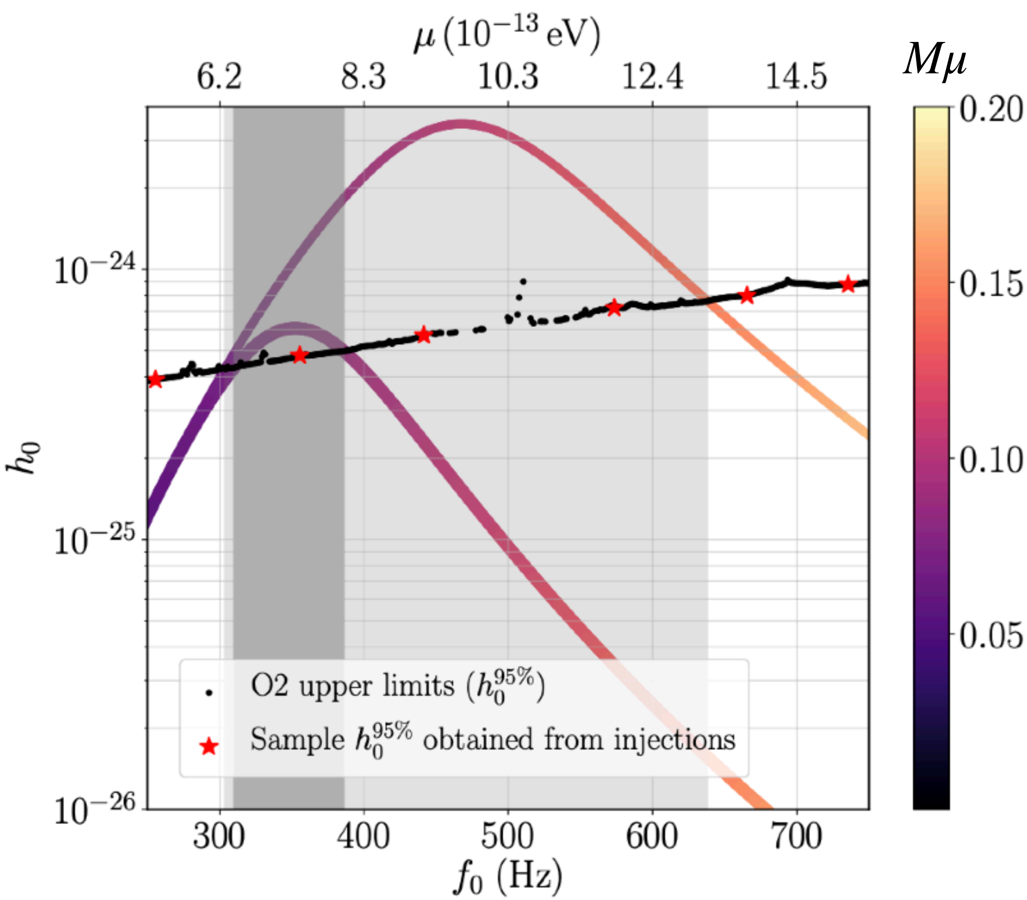
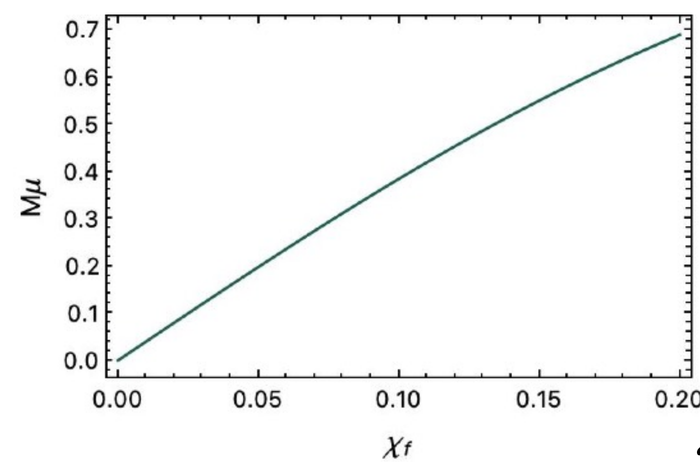


- Assuming BH was born with high spin $\chi_i = 0.99$ search can constrain a range of masses. However…
- Current best spin measurements indicate that this BH has $\chi \geq 0.95$ (there are modelling uncertainties in this measurement but there seems to be consensus among different methods).



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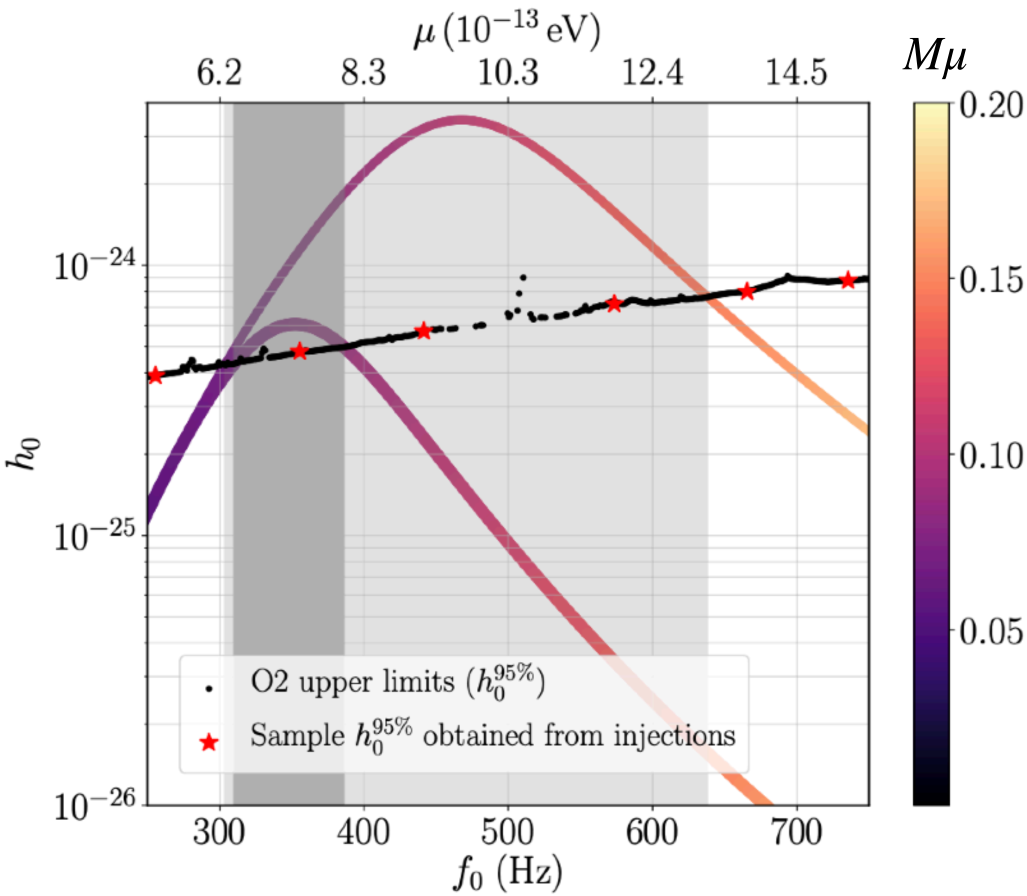


Directed searches at the **remnants** of binary black hole mergers (almost) free from uncertainties on BH spin and formation age.

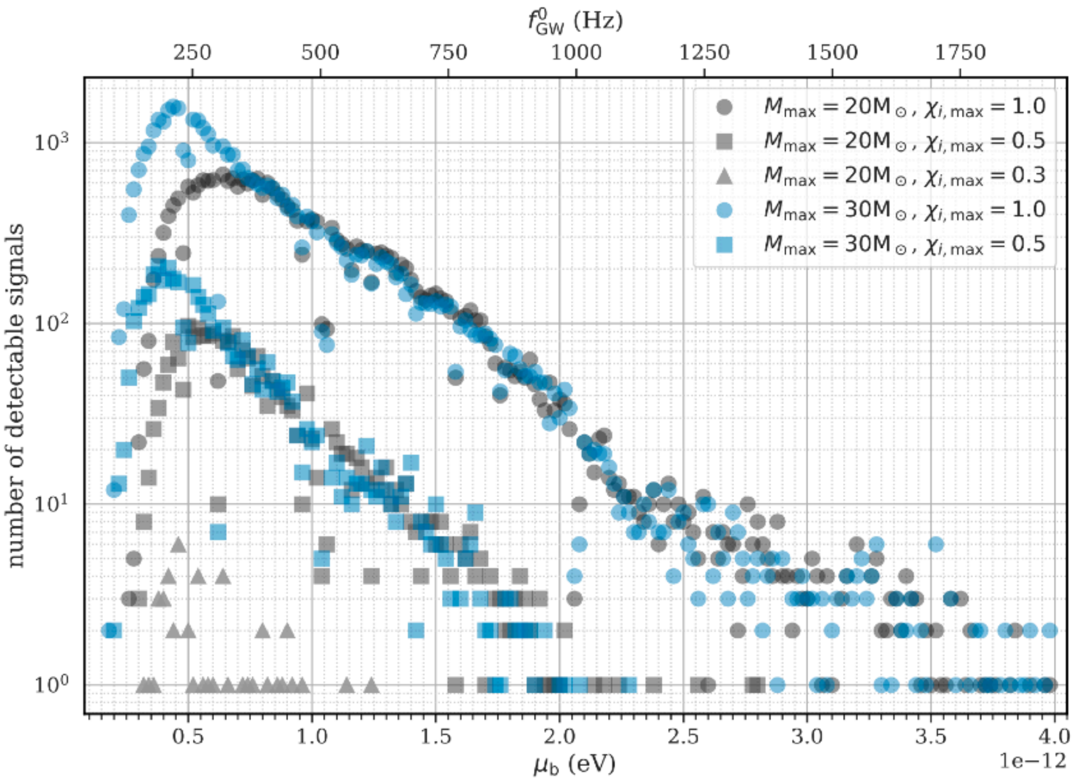
But likely only feasible with **3G detectors** (at least for scalar fields).

Constraints from all-sky searches

Arvanitaki, Baryakhtar & Huang, '15; RB *et al* '17; Baryakthar, Lasenby & Teo '17
Palomba '19; Zhu *et al* '20

- Aside from known black holes there are **many more** in the Universe that we do not see. Estimated 10^8 black holes just in the Milky Way.

- **All-sky "blind" searches** could reveal the presence of a boson cloud around a black hole emitting gravitational waves.



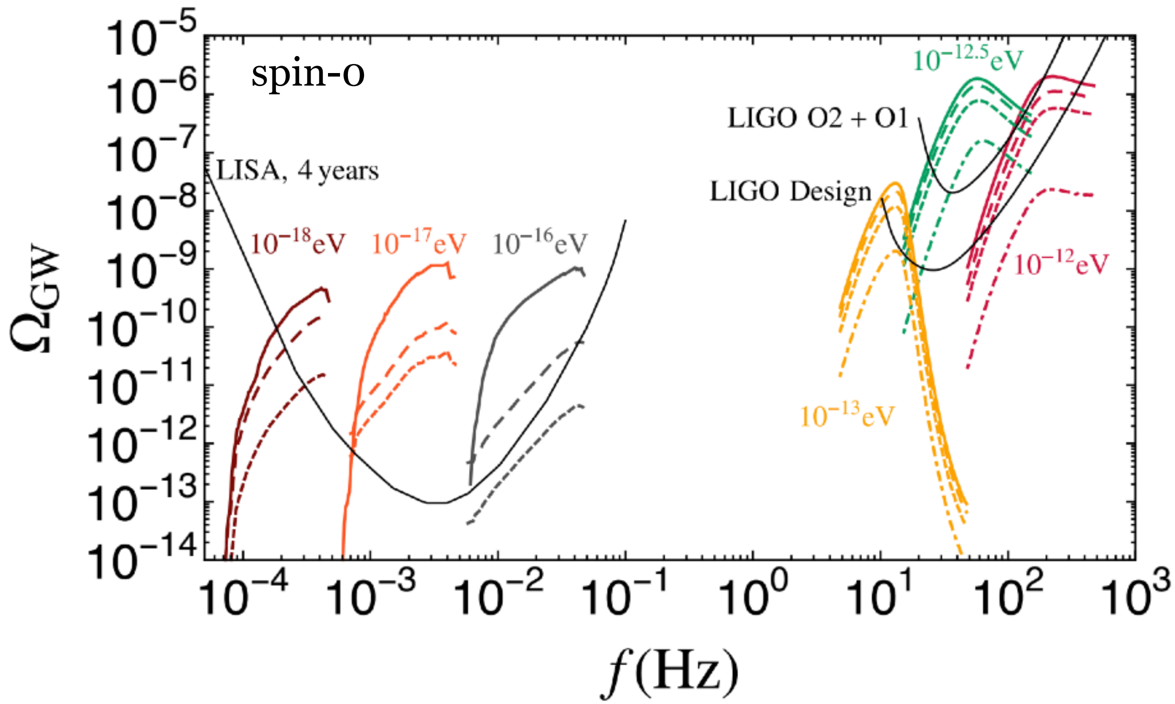
From: Zhu *et al* ' PRD102, 063020 (2020)

Lack of detections can, in principle, be used to constrain scalar fields in range (with large astrophysical uncertainties on BH population):

$$[2 \times 10^{-13}\text{eV}, 2.5 \times 10^{-12}]\,\text{eV}$$

Stochastic Background

RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, '17



Large uncertainty

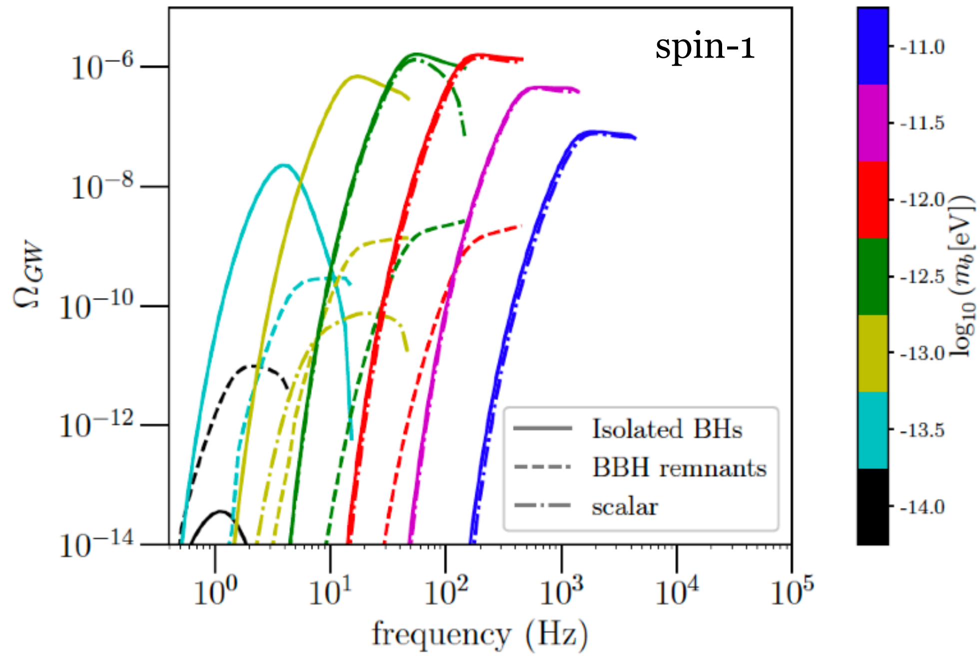
$$\Omega_{\rm GW}^{\rm iso}(f) = \frac{f}{\rho_c}\int {\rm d}z \frac{{\rm d}t}{{\rm d}z}\int {\rm d}M\, {\rm d}\chi p(\chi)\frac{{\rm d}\dot{n}}{{\rm d}M}\frac{{\rm d}E_s}{{\rm d}f_s}$$

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

The existence of many unresolved sources can produce a **large stochastic background** but large uncertainties in the exact BH population.

Stochastic Background

Tsukada, RB, East & Siemonsen, ’20



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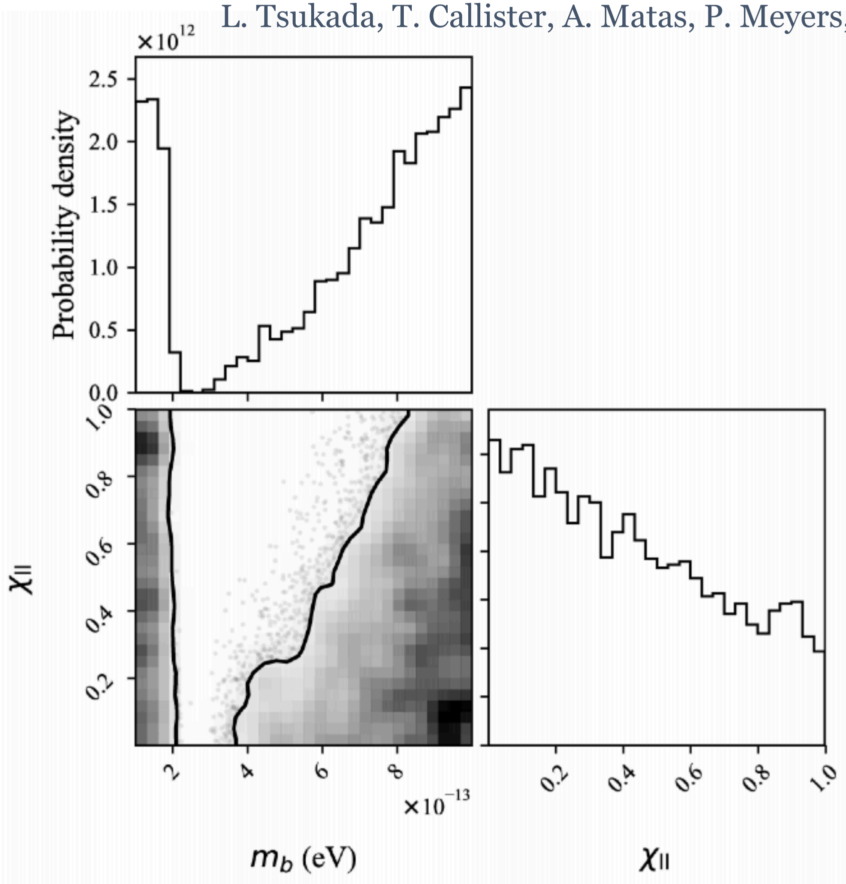
Constraints from using LIGO data

Searches in LIGO data **did not find** any background yet.
Null-searches can be used to constrain model.

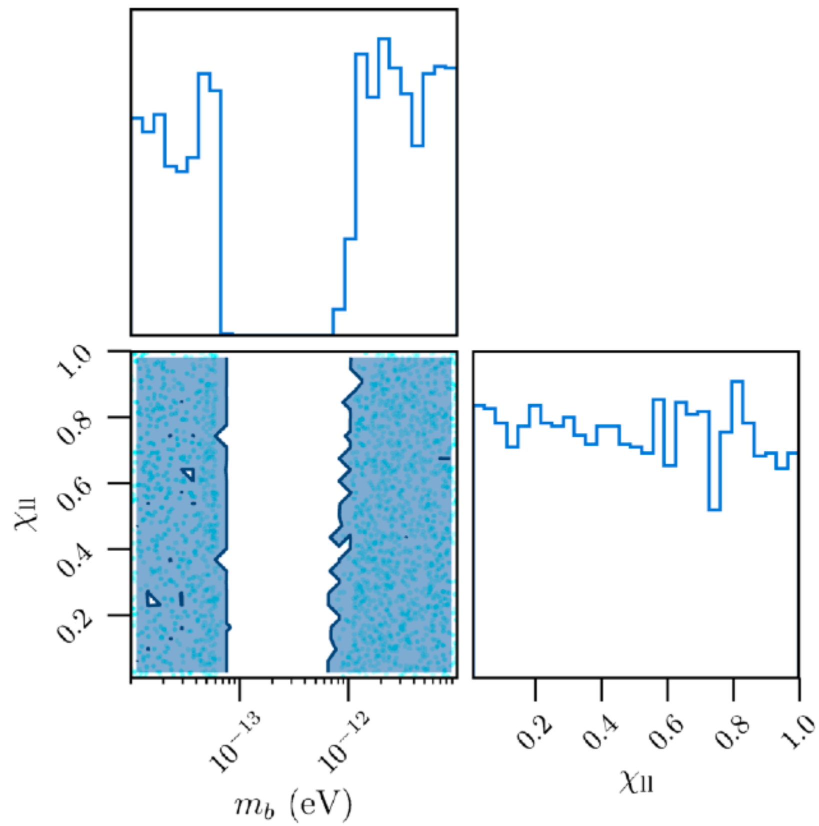
Scalar fields (only used O1)

L. Tsukada, T. Callister, A. Matas, P. Meyers, '18



Vector fields(O1+O2)

Tsukada, RB, East & Siemonsen, '20



assume $\chi_i \in [\chi_{ll}, 1)$

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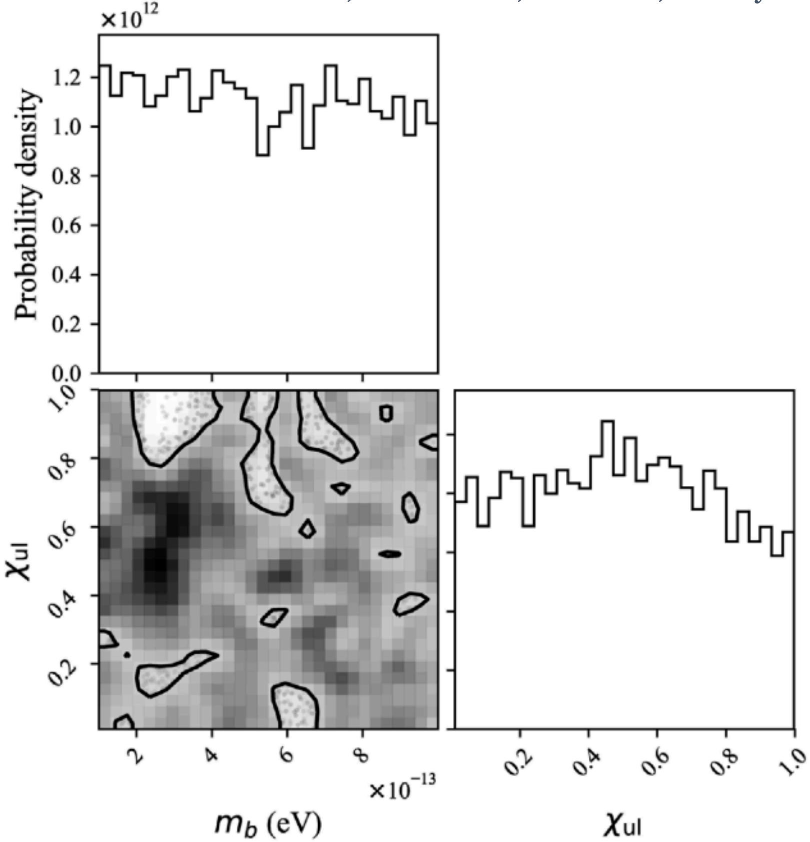

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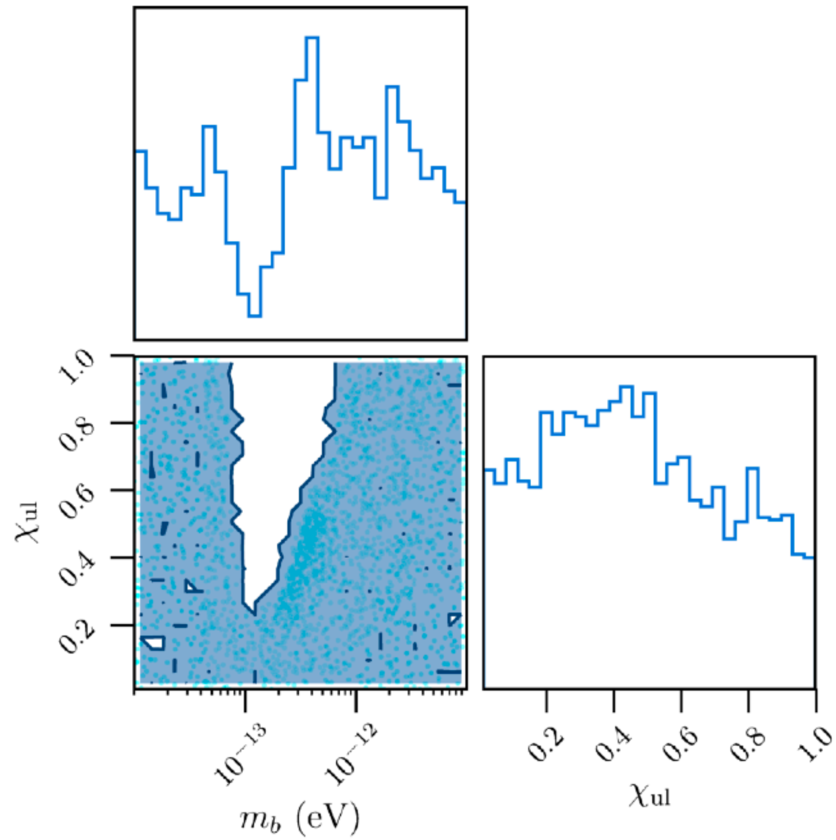


assume $\chi_i \in [0, \chi_{ul}]$

Final remarks

- Superradiant instabilities provide an interesting arena to use black holes as "**particle detectors**" and search for ultralight particles, especially in the range $m_b \in [10^{-20}, 10^{-10}]$ eV.

- **Gravitational-wave** signatures are among the most interesting observational channels but there are others: **black-hole spin measurements**; signatures in **black-hole binaries**; black-hole **shadow**...

- Here I neglected **self-interactions** and **couplings** to other particles. For **large interactions** picture would be different, although further work is needed to fully understand their impact and consequences for observations.

Thank you!

Backup slides

Computation of the GW signal in practice

Arvanitaki *et al*'09; Yoshino & Kodama '14; Arvanitaki, Baryakhtar & Huang, '15; RB *et al '17;* Baryakhtar, Lasenby & Teo '17; Siemonsen & East '20; RB, Grillo & Pani '20...

At any given time, backreaction of boson field on the geometry is **small**:

- Evolve system **adiabatically** (Brito, Cardoso & Pani '14);
- GW signal can estimated using **BH perturbation theory** (Yoshino & Kodama '14):

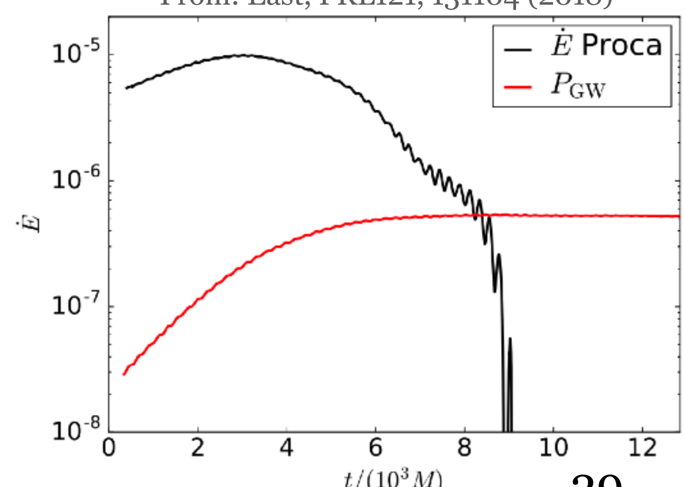
$$\Phi = \epsilon\,\Re\left(\phi_{lmn}(r)S_{lm}(\theta)e^{im\varphi}e^{i\omega_R t}\right) \qquad T_{\mu\nu} = -\frac{1}{2}g_{\mu\nu}\left(\Phi_{,\alpha}\Phi^{,\alpha} + \mu^2\Phi^2\right) + \Phi_{,\mu}\Phi_{,\nu}$$

$$\boxed{\mathcal{O}(\epsilon):\ \Box^{(0)}\Phi^{(1)} = \mu^2\Phi^{(1)}, \qquad \mathcal{O}(\epsilon^2):\ \mathcal{E}^{\rho\sigma}_{\mu\nu}h^{(2)}_{\rho\sigma} = T_{\mu\nu}[\Phi^{(1)},\Phi^{(1)}]}$$

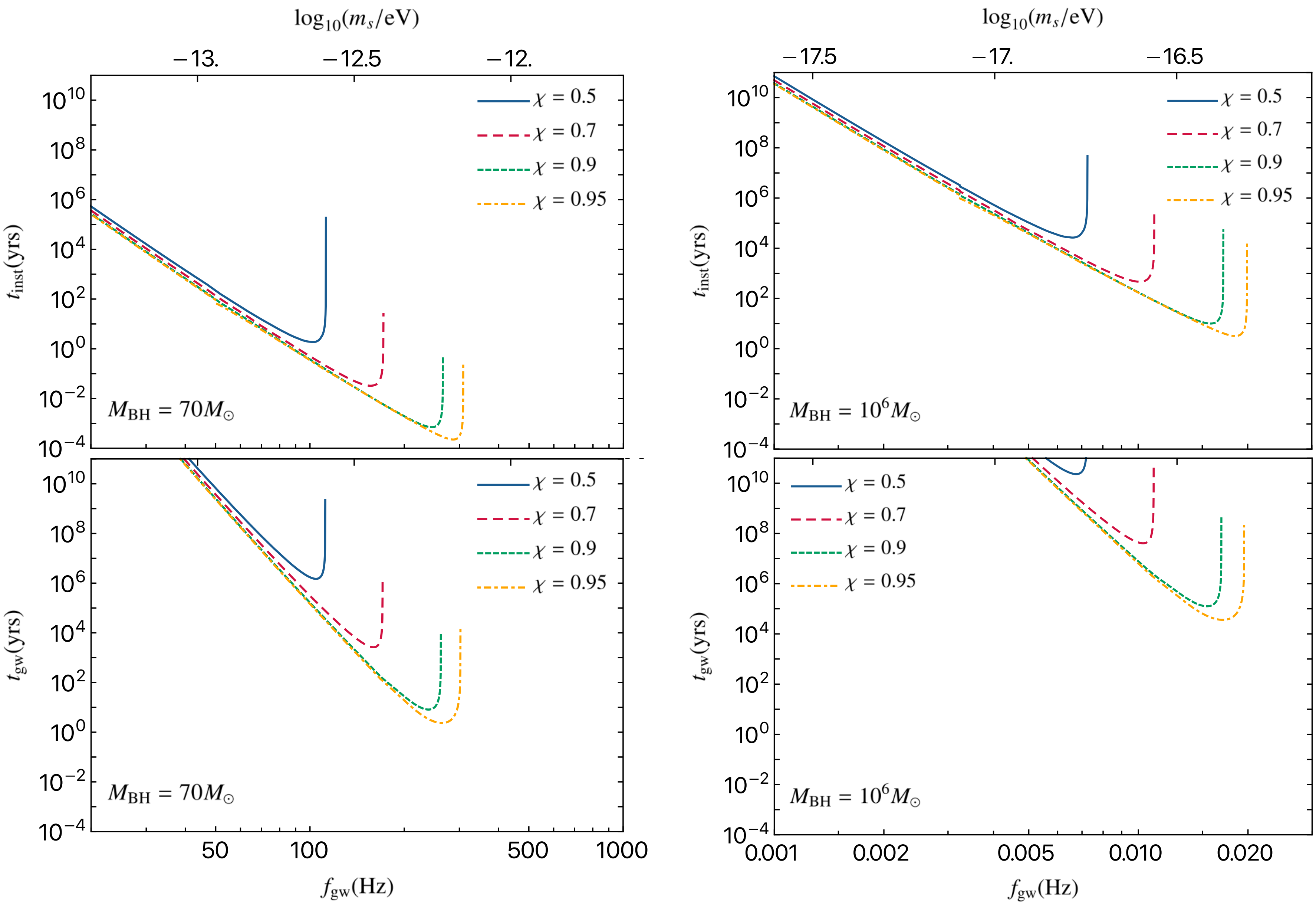
$$\omega_R < m\Omega_H:\quad \dot{E}_{\rm cloud} \approx 2\Gamma E_{\rm cloud} \implies E_{\rm cloud} \approx E_0 e^{2\Gamma t}$$

$$\omega_R = m\Omega_H:\ \dot{E}_{\rm cloud} \approx -P_{\rm GW} \implies E_{\rm cloud} = \frac{E^{\rm sat.}_{\rm cloud}}{1 + t/t_{\rm GW}}$$

From: East, PRL121, 131104 (2018)



Timescales



*numbers are for the dominant unstable mode of a scalar field ($\ell = m = 1$)

Useful scales

Instability timescale:

$$\tau_{\rm inst}^{\rm scalar} \approx 30\,{\rm days} \left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{\chi}\right)\,, \quad \tau_{\rm inst}^{\rm vector} \approx 280\,{\rm s} \left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^7\left(\frac{0.9}{\chi}\right)$$

GW emission timescale:

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

GW strain:

$$h_+(t) \approx \frac{1}{2(1+t/t_{\rm GW})}h_0(1+\cos^2\iota)\cos\left(2\pi f_{\rm GW}t+\phi\right)\,, \quad h_\times(t) \approx \frac{1}{1+t/t_{\rm GW}}h_0\cos\iota\sin\left(2\pi f_{\rm GW}t+\phi\right)$$

$$h_0^{\rm scalar} \approx 5\times 10^{-27}\left(\frac{M}{10M_\odot}\right)\left(\frac{M\mu}{0.1}\right)^7\left(\frac{\rm Mpc}{d}\right)\left(\frac{\chi_i-\chi_f}{0.5}\right)\,, \quad h_0^{\rm vector} \approx 10^{-23}\left(\frac{M}{10M_\odot}\right)\left(\frac{M\mu}{0.1}\right)^5\left(\frac{\rm Mpc}{d}\right)\left(\frac{\chi_i-\chi_f}{0.5}\right)$$

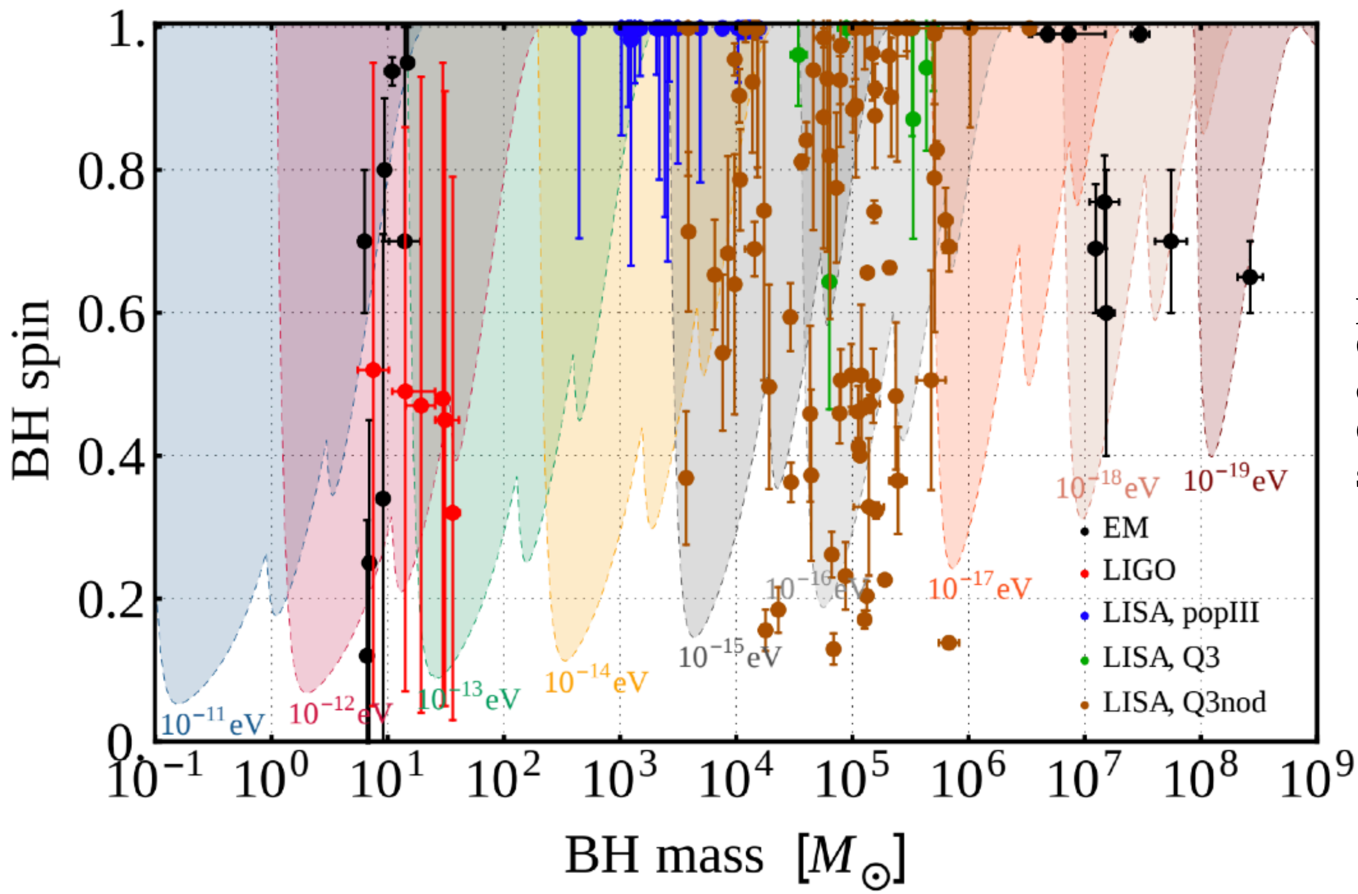
Frequency derivative:

$$\dot f_{\rm GW}^{\rm scalar}(t) \approx 5\times 10^{-15}\,{\rm Hz/s}\left(\frac{M\mu}{0.1}\right)^{19}\left(\frac{10M_\odot}{M}\right)^2\left(\frac{\chi_i-\chi_f}{0.5}\right)^2\left(\frac{M_{\rm cloud}(t)}{M_{\rm cloud}^{\rm sat}}\right)^2$$

$$\dot f_{\rm GW}^{\rm vector}(t) \approx 10^{-7}\,{\rm Hz/s}\left(\frac{M\mu}{0.1}\right)^{15}\left(\frac{10M_\odot}{M}\right)^2\left(\frac{\chi_i-\chi_f}{0.5}\right)^2\left(\frac{M_{\rm cloud}(t)}{M_{\rm cloud}^{\rm sat}}\right)^2$$

Gaps in the mass vs spin plane

RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, ‘17

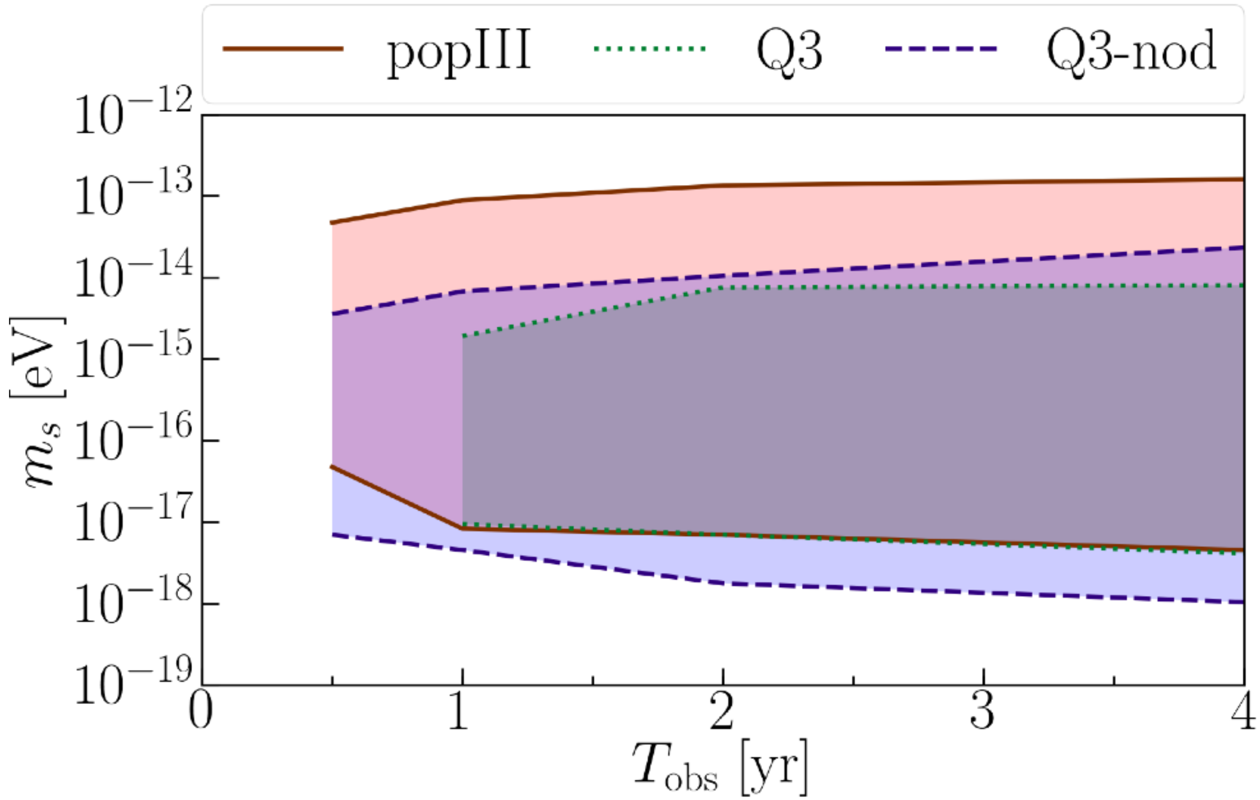


popIII=light seeds
Q3-d=heavy seeds, delays
Q3-nod=heavy seeds, no delays

❖ LISA will be able to measure black hole masses and spins with very good precision therefore providing a unique opportunity to detect or constrain ultralight bosons.

Constraining ultralight bosons with BH spin measurements

RB, Ghosh, Barausse, Berti, Cardoso, Dvorkin, Klein, Pani, '17



❖ LISA could rule out/detect scalar fields in the mass range $\sim [10^{-13}, 10^{-18}]\,\mathrm{eV}$