Observational Prospects of Self-Interacting Scalar Superradiance with Next-Generation Gravitational-Wave Detectors

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On behalf of:
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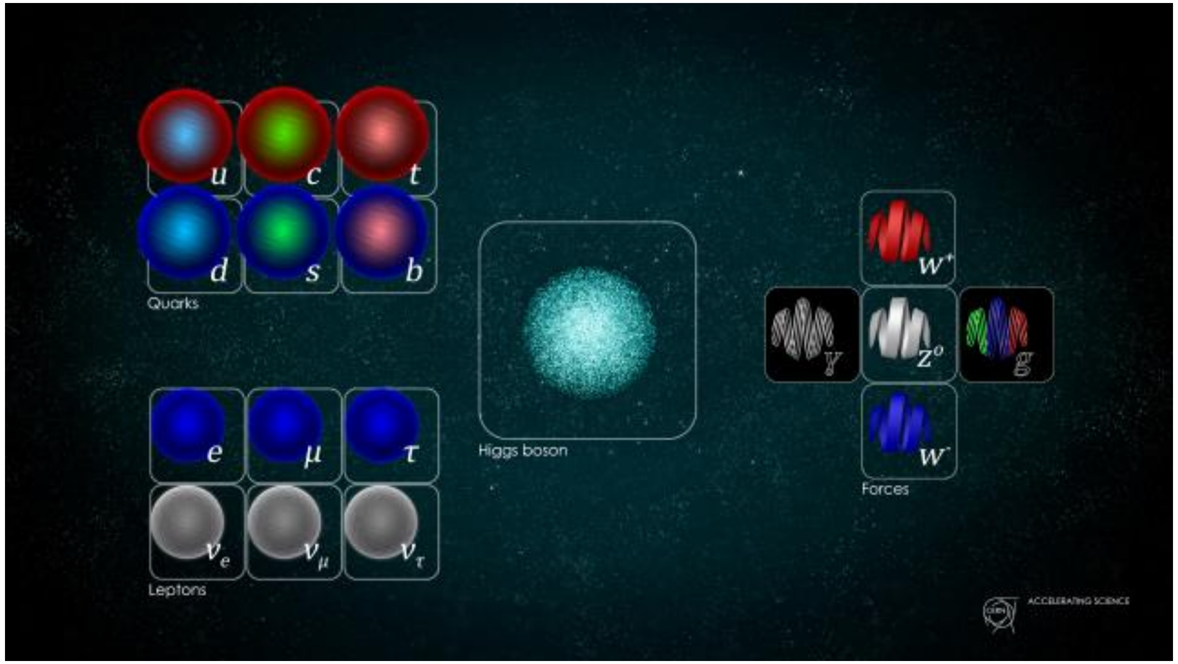
Presentation Outline

- Motivation for ultralight scalar searches
- Theoretical foundations
  - How do ultralight particles produce gravitational waves?
  - What is self-interaction and what is its relevance?
- Observational Prospects
  - The gravitational wave signatures
  - Comparison to current and next-generation detector sensitivities

Motivation for Ultralight Scalar Searches

Motivation for Ultralight Scalar Searches

- Ultralight ($\sim 10^{-12}$ eV$/c^2$) scalars do not appear in the Standard Model
- However, several well-motivated candidates. E.g.:
  - QCD axion
  - String axions
- Gravitational-wave (GW) searches provide a model-independent search mechanism

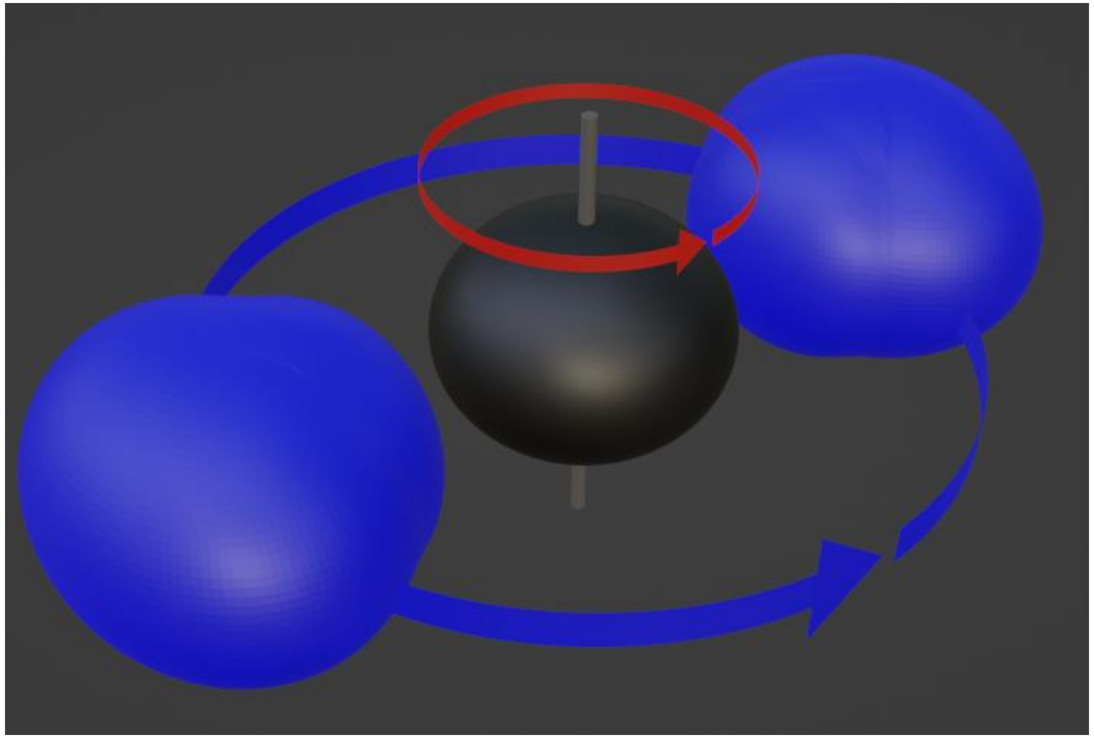


Theoretical Foundations

GWs from ultralight particles

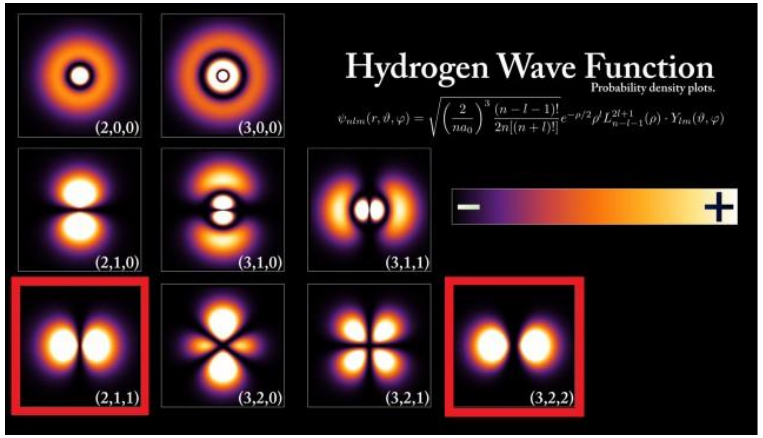
GWs from Ultralight Particles

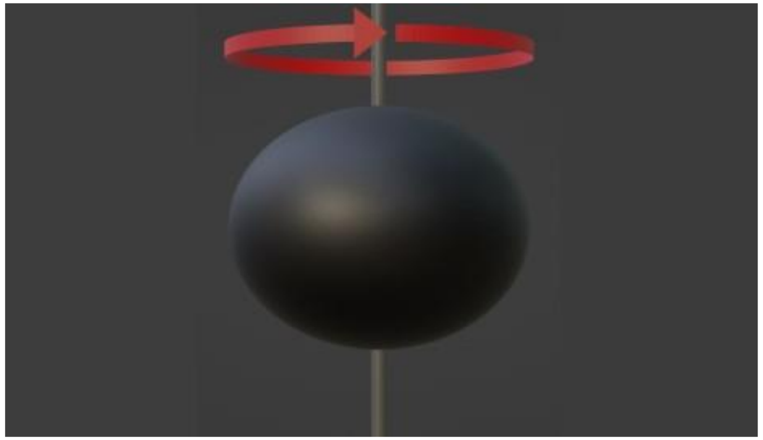
- Like all massive objects, ultralight particles produce GWs when they accelerate
- Yet, (obviously) the GWs from a single scalar are very weak
- The key is black holes:
  - Bind ultralight scalars in rotating orbitals
  - Superradiantly multiply bound scalars to a total mass $> 1\ M_{\odot}$ ($\sim 10^{78}$ particles)



Gravitational Binding of Ultralight Scalars

- Ultralight scalars bind to black holes analogously to the electrons in a hydrogen atom
- The binding is driven by:
  - An attractive potential (gravity)
  - Wave-like properties of particles (Compton wavelength)
- In practice, a two-level system is formed:
  - n=2,l=m=1 (211)
  - n=3,l=m=2 (322)



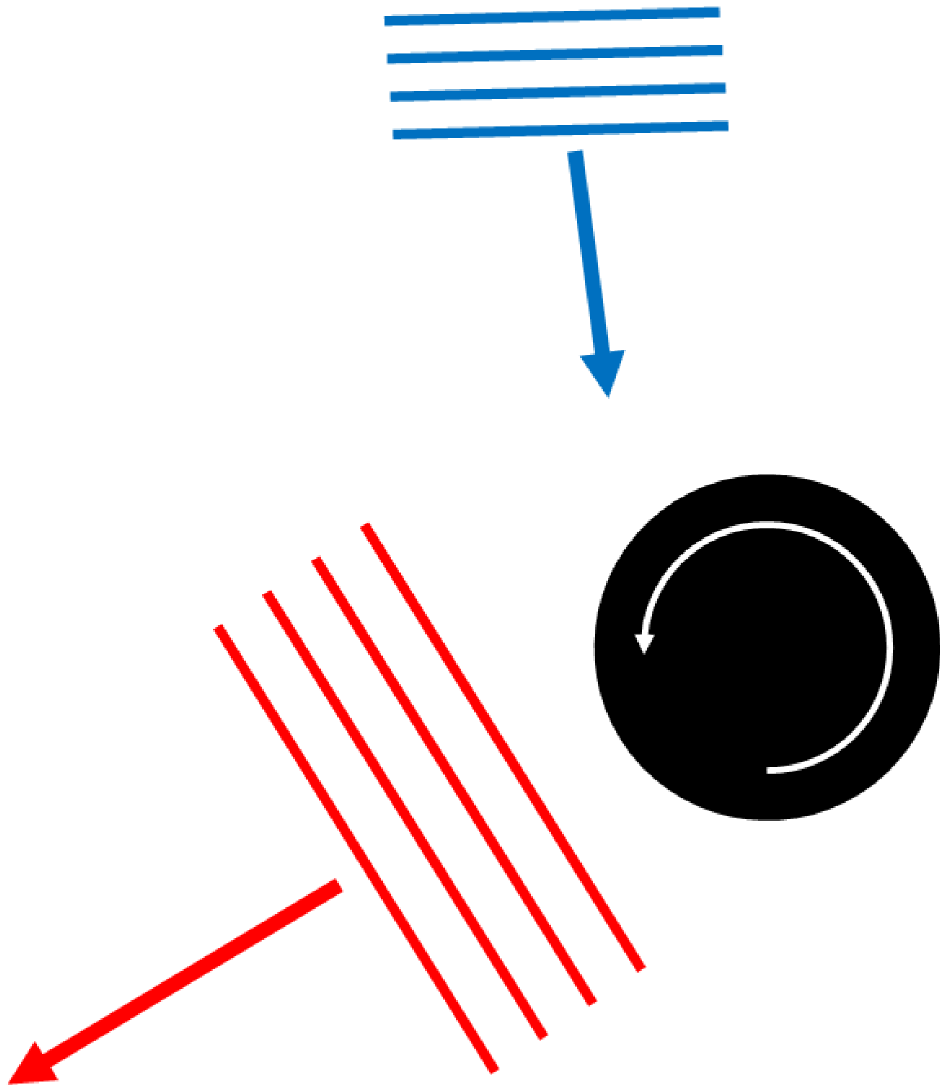


Black Hole Superradiance

- We cannot extract information from a black hole.
- We *can* extract energy from a black hole (Hawking radiation, Penrose process, …)
- The extraction of the rotational energy from a black hole by a wave is termed black hole superradiance
  - → Proceeds from vacuum minima until the rotational energy of the black hole is depleted (up to 29% of the total mass energy)
  - → Drives the exponential growth of ultralight scalars

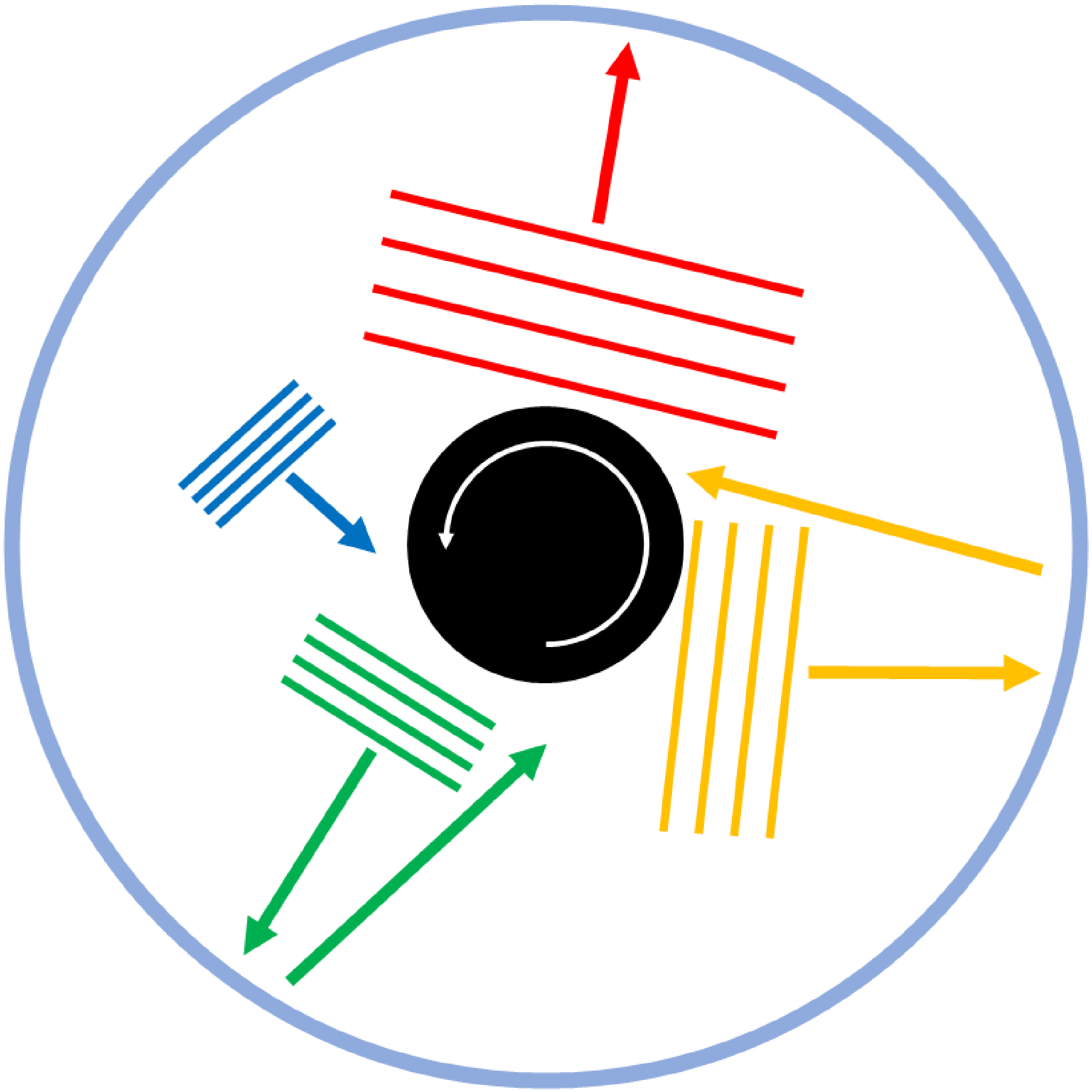
Superradiance

- Classical phenomenon where a wave is amplified by a rotating object
- This growth is fueled by the object’s rotational energy



Superradiance of a Bound State

- If the wave is bound near the rotating object, it is continually amplified
- This leads to exponential growth of the wave until the rotational energy is depleted



GWs from Ultralight Particles

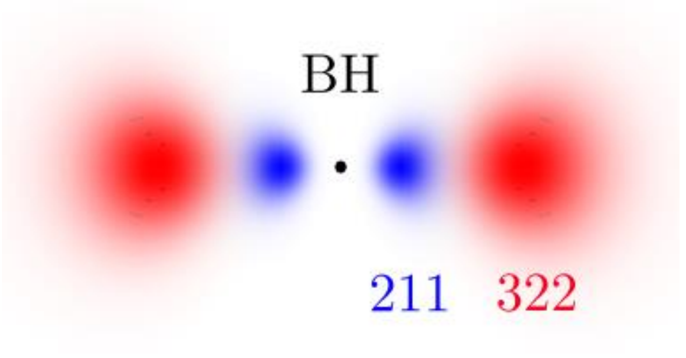
- We have bound energy levels, with rotation rates in the hundreds of Hz
- We have a mass of bosons up to 29% of a black hole's mass
- $\rightarrow$ Potential for appreciable gravitational waves

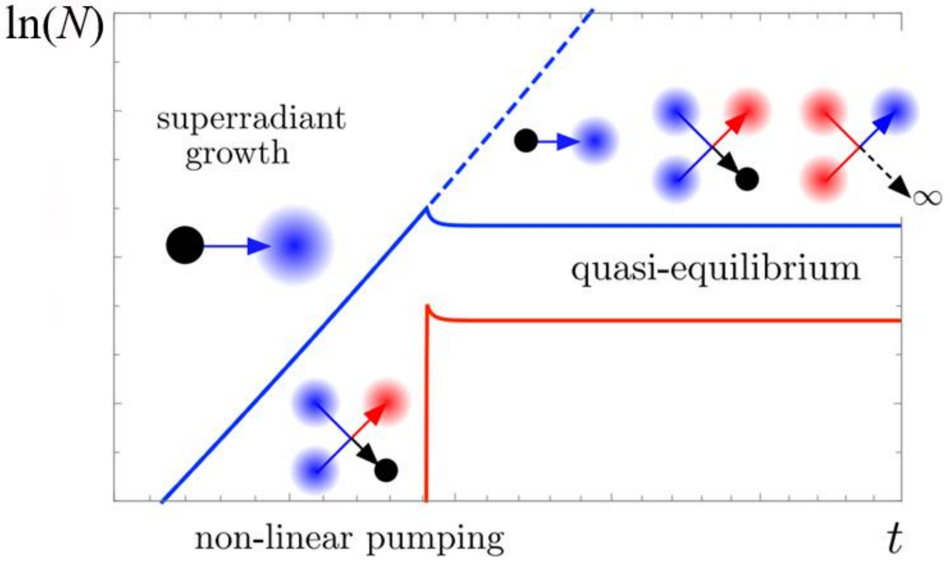
Non-Self-Interacting Model of Ultralight Scalars

- The processes we have described so far constitute the non-self-interacting model of ultralight scalars
- This model has been studied with:
  - GW searches
  - Black hole spindown searches
- Non-self-interacting ultralight scalars largely excluded
- The end?

Self-Interaction

- Ultralight scalars are (almost generically) expected to have a φ^4 term in the Lagrangian
- Induces coupling between the two-level bound system
  - → Reduction in black hole spindown
  - → Weaker gravitational waves
- Ultralight scalars may still have observational prospects





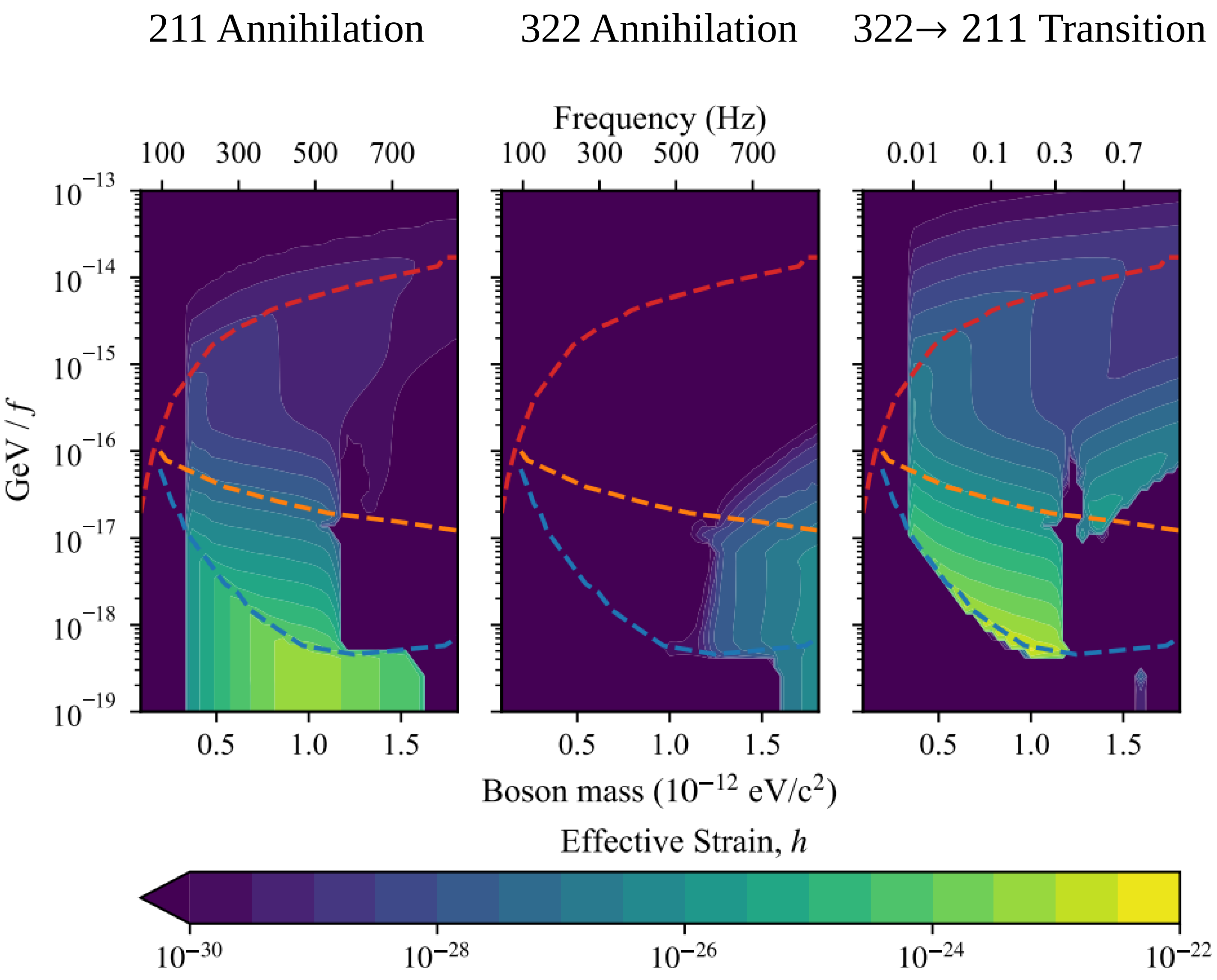
Baryakhtar *et al.;* Phys. Rev. D 103, 095019 (2021)

Observational Prospects

GW Signatures

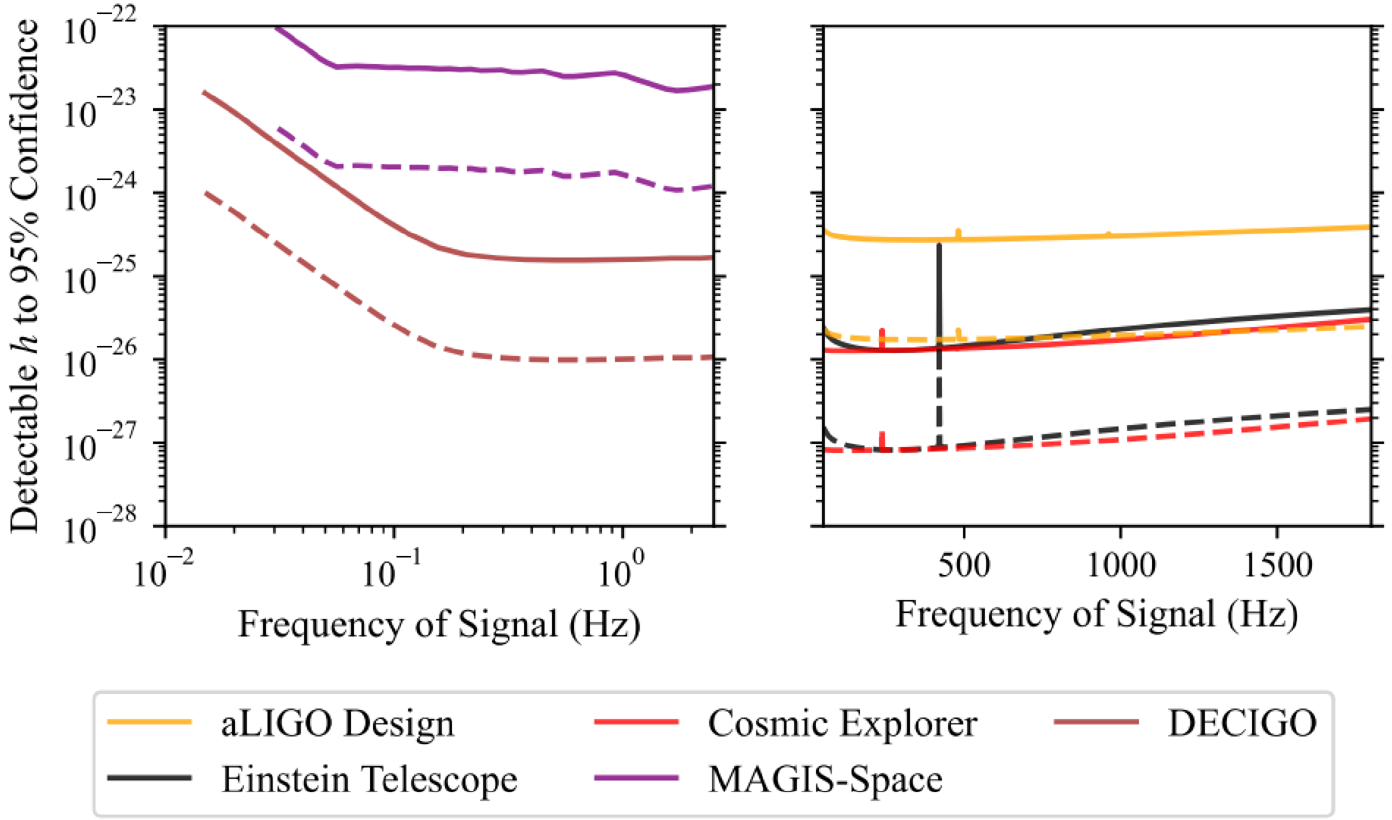
Right: the expected GW signatures of ultralight scalars around Cygnus X-1 with the following parameters:

Property	Value
Mass ($M_\odot$)	14.8
Initial spin (dimensionless)	0.99
Inclination (°)	27.1°
Distance (kpc)	1.86
Age (yr)	1.0×10^5



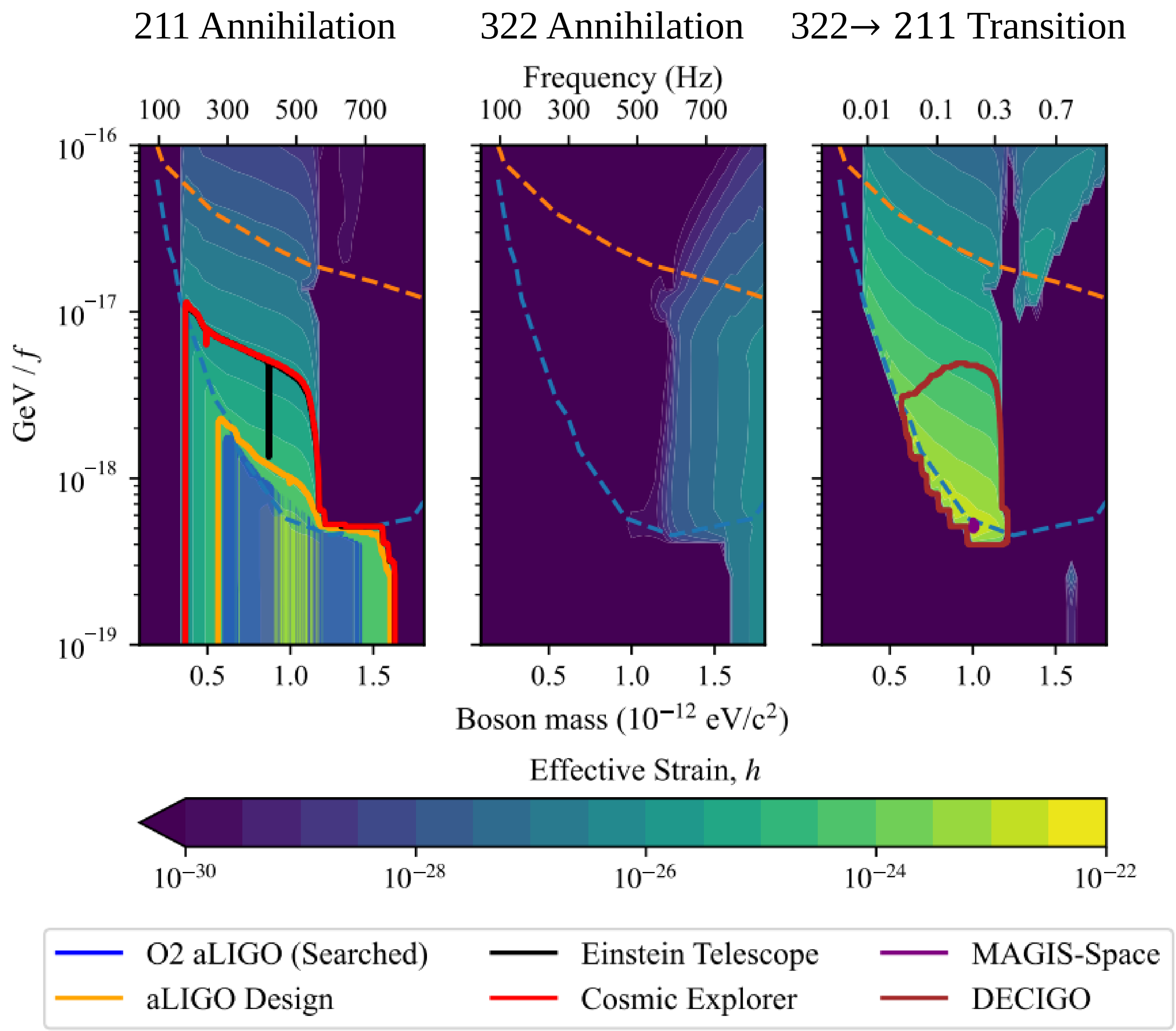
Detector Sensitivities

- The detectable GW strain scales linearly with the amplitude spectral density (ASD):
  $$h(\nu) \propto S_h^{1/2}(\nu)$$
- We use the ASD from next-generation detectors to scale the sensitivity from past results
- Generically, isolated systems (dashed line) show improved sensitivity over binary systems (solid line)



Observational Prospects

- We have presented:
  - GW strains and frequencies expected for each ultralight scalar mass and self-interaction strength
  - Sensitivity of GW detectors to each frequency
- A simple comparison yields the observational prospects



*For Cygnus X-1 assuming an age of 10^5 yr

Conclusion

Conclusion

- GW searches provide a model-independent probe of ultralight scalars
- Self-interactions weaken the GW and black hole spin-down signals expected, and allow ultralight scalars to have escaped past searches
- There exist observational prospects for self-interacting ultralight scalars with next-generation gravitational wave detectors

Additional Material

Self-Interacting Model

- We adopt the self-interacting model of Baryakhtar *et al.* 2021.
- This is described by the differential equation:

$$\dot{\varepsilon}_{211} = \gamma_{\mathrm{BH}}^{211}\varepsilon_{211} - 2\gamma_{211\times211}^{\mathrm{GW}}\varepsilon_{211}^{2} + \gamma_{322}^{211\times\mathrm{GW}}\varepsilon_{211}\varepsilon_{322} - 2\gamma_{211\times211}^{322\times\mathrm{BH}}\varepsilon_{2111}^{2}\varepsilon_{322} + \gamma_{322\times322}^{211\times\infty}\varepsilon_{211}\varepsilon_{322}^{2}$$

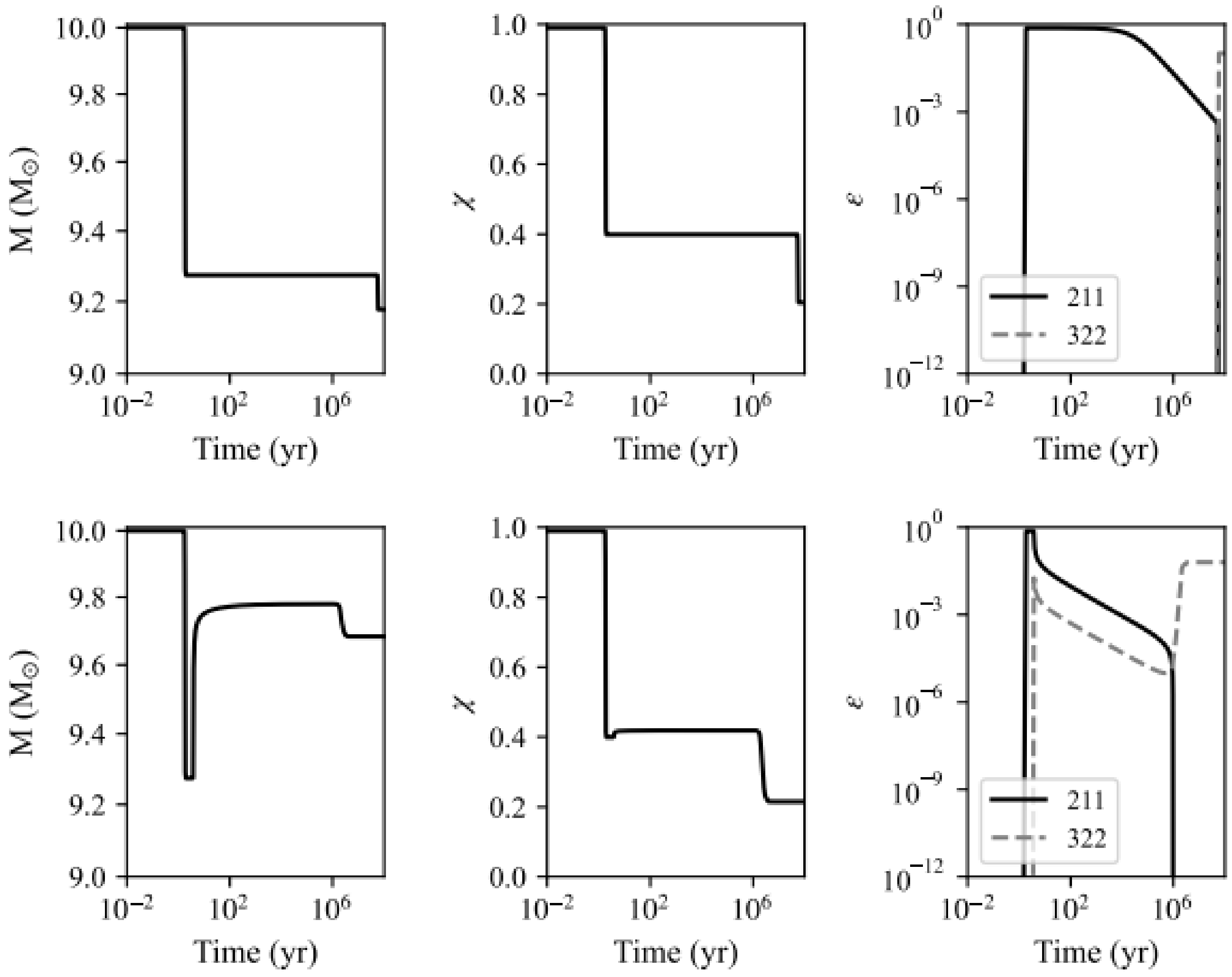
$$\dot{\varepsilon}_{322} = \gamma_{\mathrm{BH}}^{322}\varepsilon_{322} - 2\gamma_{322\times322}^{\mathrm{GW}}\varepsilon_{322}^{2} - \gamma_{322}^{211\times\mathrm{GW}}\varepsilon_{211}\varepsilon_{322} + \gamma_{211\times211}^{322\times\mathrm{BH}}\varepsilon_{211}^{2}\varepsilon_{322} - 2\gamma_{322\times322}^{211\times\infty}\varepsilon_{211}\varepsilon_{322}^{2}$$

$$\dot{\chi} = -\gamma_{\mathrm{BH}}^{211}\varepsilon_{211} - 2\gamma_{\mathrm{BH}}^{322}\varepsilon_{322}$$

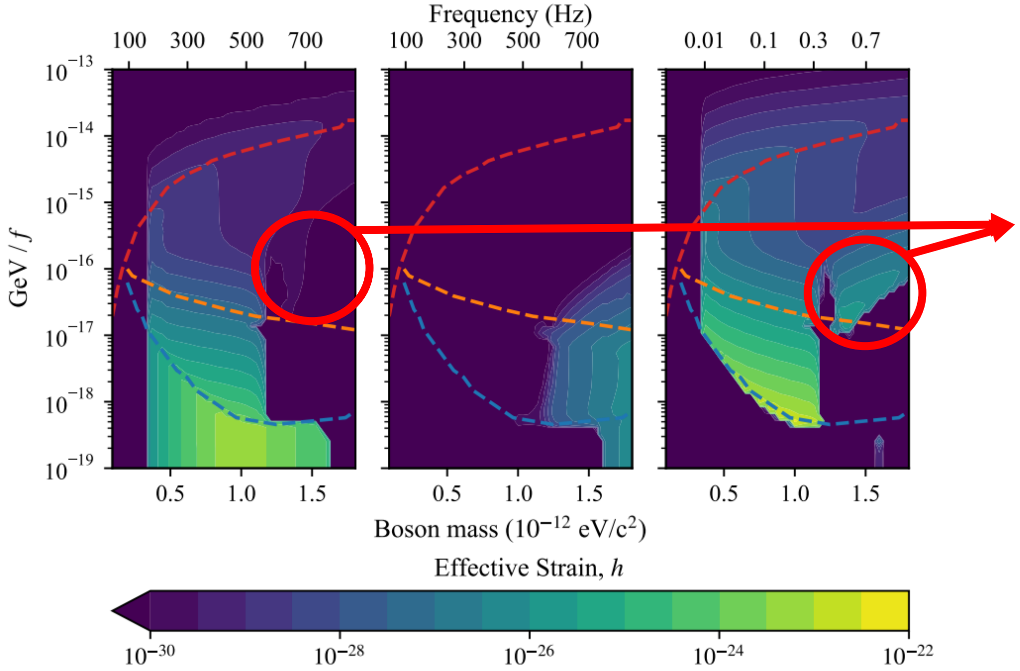
$$\dot{M} = \frac{GM^{2}m_{b}}{\hbar c}\left(-\gamma_{\mathrm{BH}}^{211}\varepsilon_{211} - \gamma_{\mathrm{BH}}^{322}\varepsilon_{322} + \gamma_{211\times211}^{322\times\mathrm{BH}}\varepsilon_{211}^{2}\varepsilon_{322}\right)$$

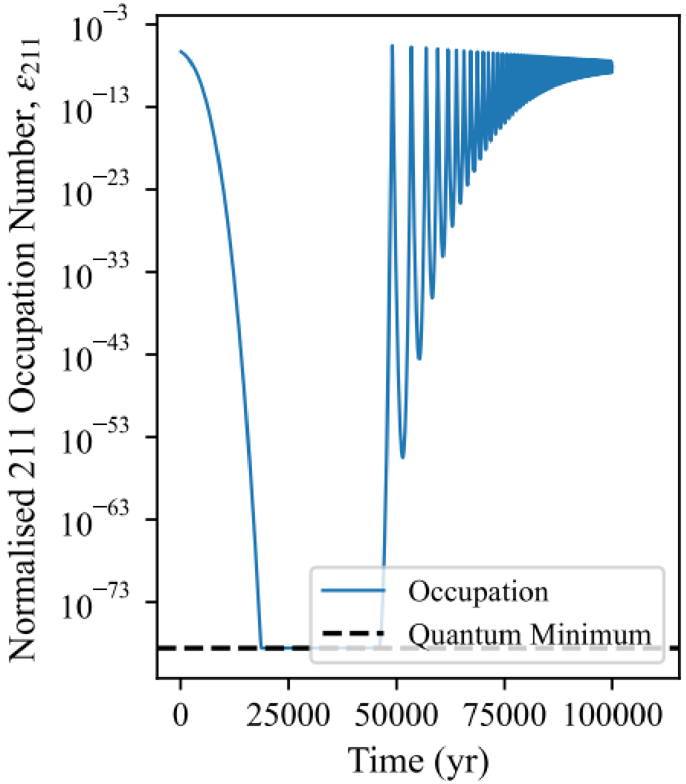
Cloud Evolution

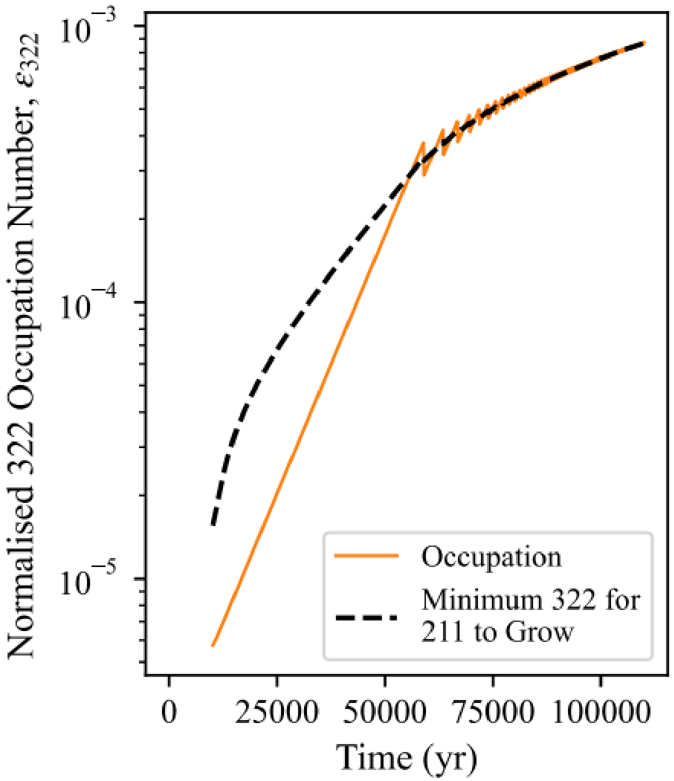
- Three competing rates drive the evolution of ultralight scalar clouds:
  1. Superradiant growth rate
  2. Gravitational wave decay rate
  3. Self-interactive coupling rate
- The interplay of these three rates leads to four (main) regimes of cloud evolution dynamics
  - Top: Gravitational (negligible self-interaction) regime
  - Bottom: Moderate self-interaction regime



Harmonic Equilibrium

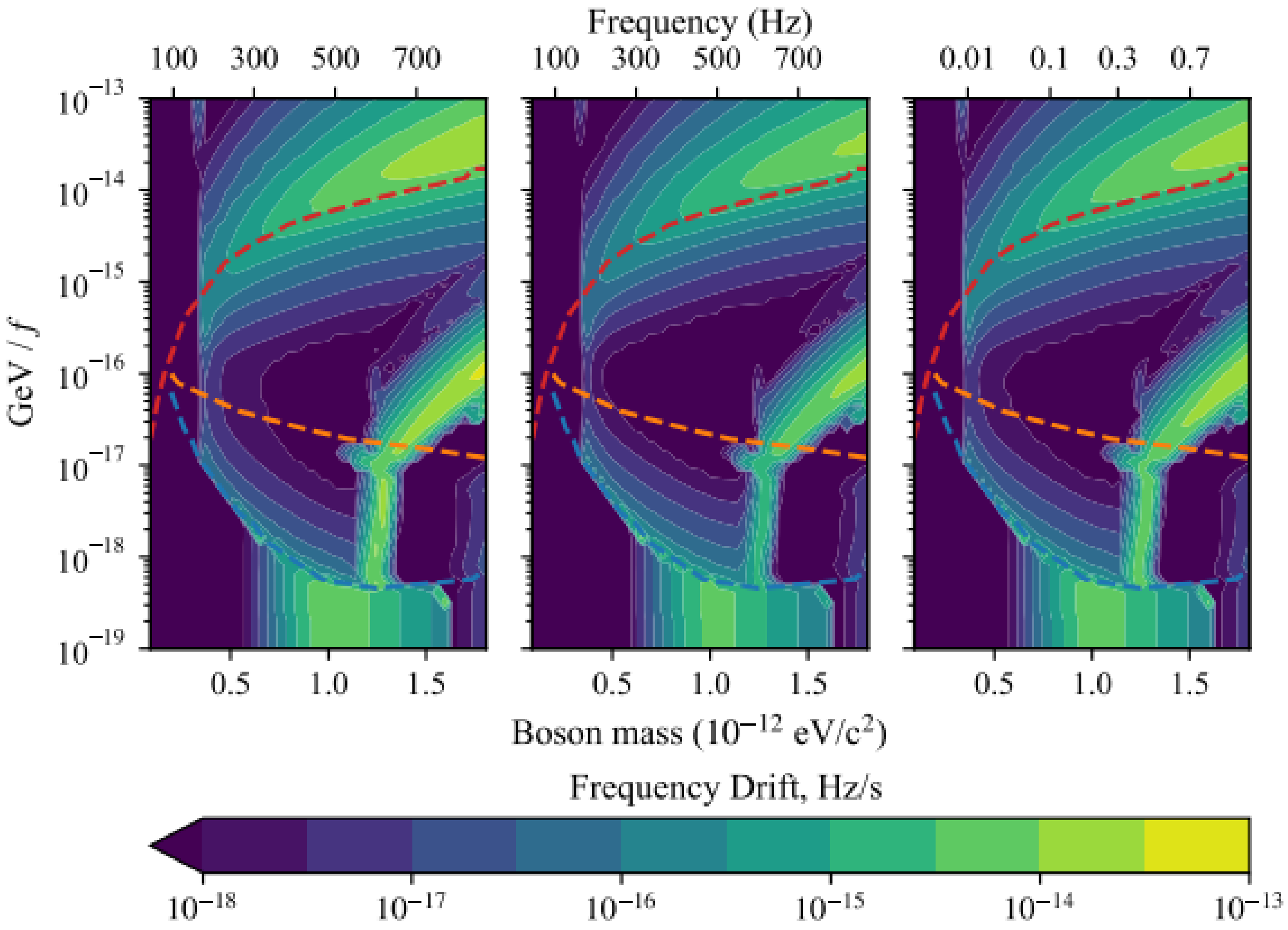






Frequency Drift

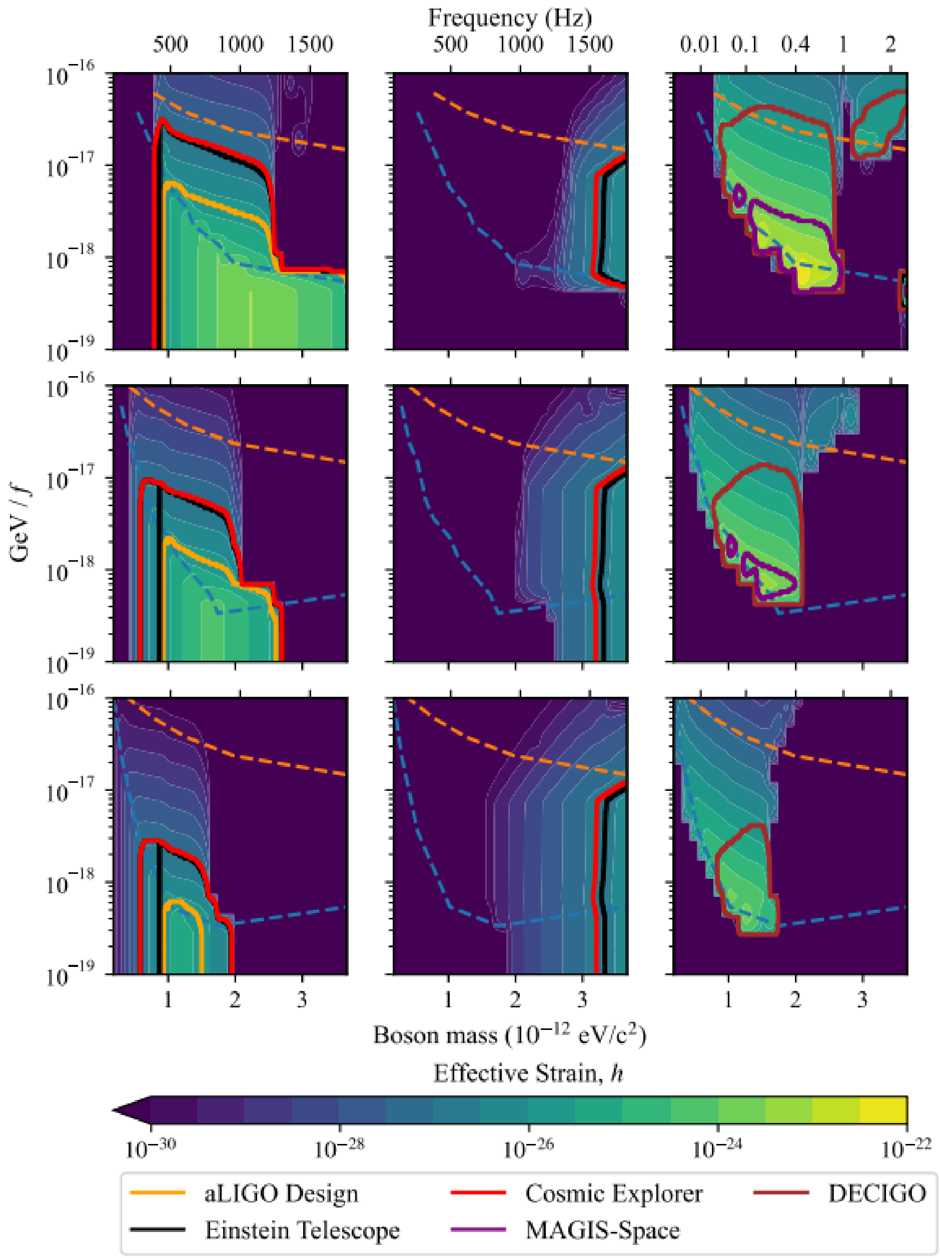
- GWs from ultralight scalars are only quasi-monochromatic
- Frequency drift is induced by:
  - Evolution of the black hole mass
  - Higher-order corrections to the hydrogenic energy levels (self-gravity, self-interaction)
- Frequency drift has consequences for sensitivity
- Drift in self-interactive regimes is comparable to gravitational regime



MOA-2011

Right: the expected GW signatures of ultralight scalars around MOA-2011 with the following parameters:

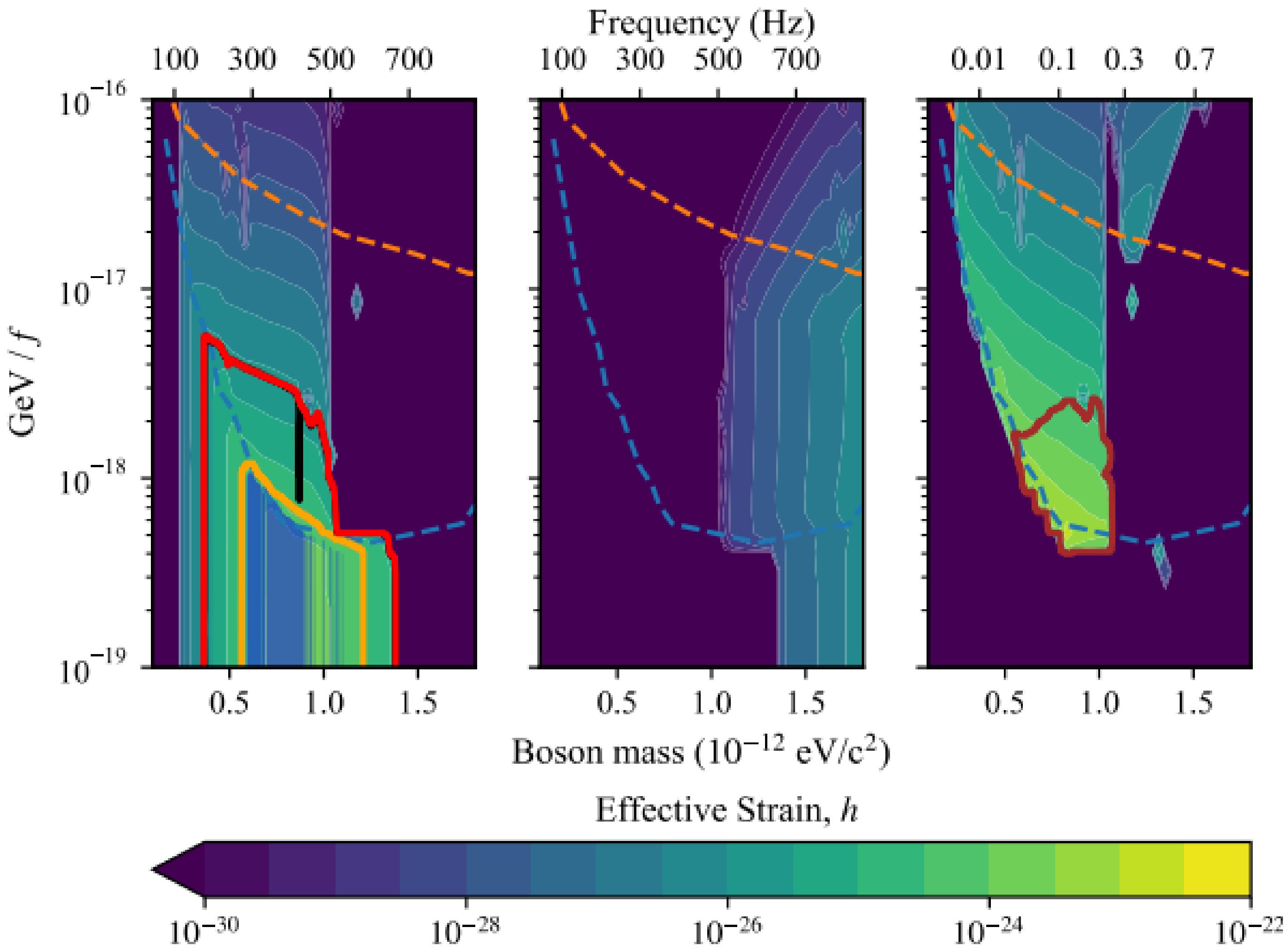
Property	Value
Mass ($M_\odot$)	7.3
Initial spin (dimensionless)	0.99
Inclination (°)	90.0°
Distance (kpc)	1.58
Ages Considered (yr)	$\{10^4, 10^6, 10^8\}$



Cygnus X-1 (10^6 yr)

Right: the expected GW signatures of ultralight scalars around Cygnus X-1 with the following parameters:

Property	Value
Mass ($M_\odot$)	14.8
Initial spin (dimensionless)	0.99
Inclination (°)	27.1°
Distance (kpc)	1.86
Age (yr)	1.0×10^6



Angular Dependence

- The characteristic strain of a gravitational-wave mode is:

$$h_{0,\,\mathrm{mode}} = \left(\frac{10 G P_{\mathrm{mode}}}{c^3 r^2 \omega_{\mathrm{mode}}^2} \right)^{1/2}$$

- The *effective* (measurable) strain at a given inclination, ι, is:

$$h_{\mathrm{mode}}(\iota) = \sqrt{\frac{8\pi}{5}}\, h_{0,\,\mathrm{mode}} \left[\frac{\left(\frac{dP}{d\Omega}\right)_{\mathrm{mode}}(\iota)}{P_{\mathrm{mode}}} \right]^{1/2}$$

- → Angular dependencies