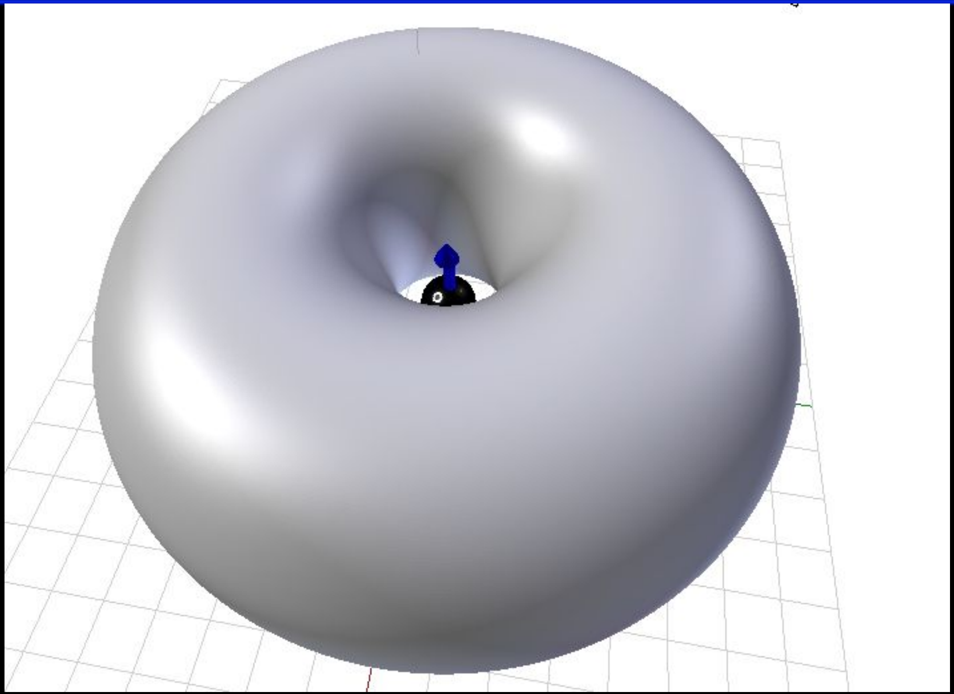
Probing ultralight bosons with gravitational waves

Nikhef seminar (26th of March, 2020)

Talk based on:

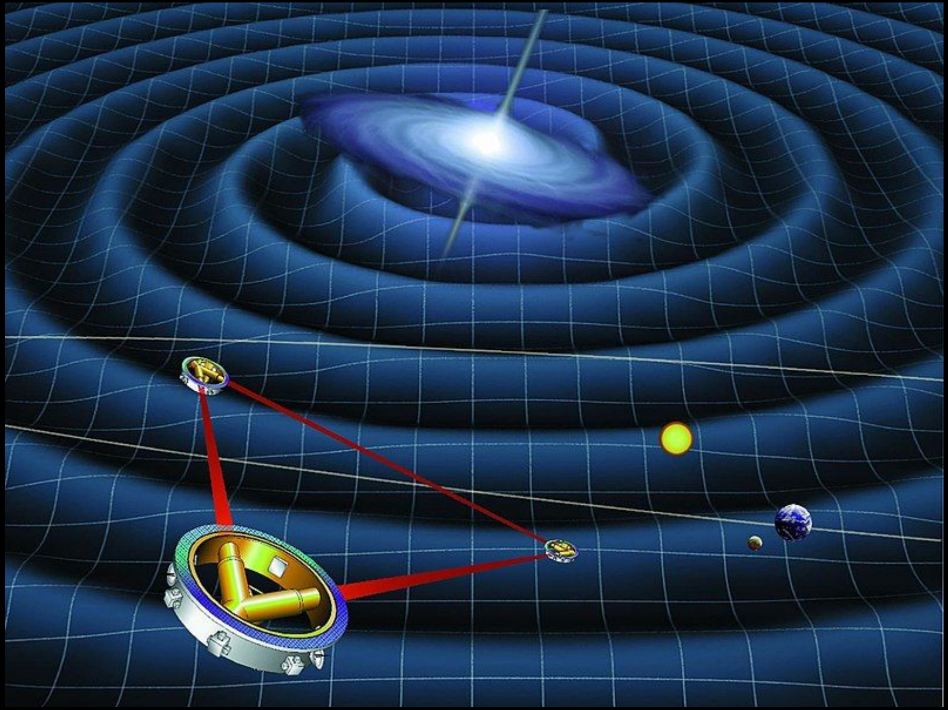
Arxiv:1804.09659
Arxiv:1908.02312

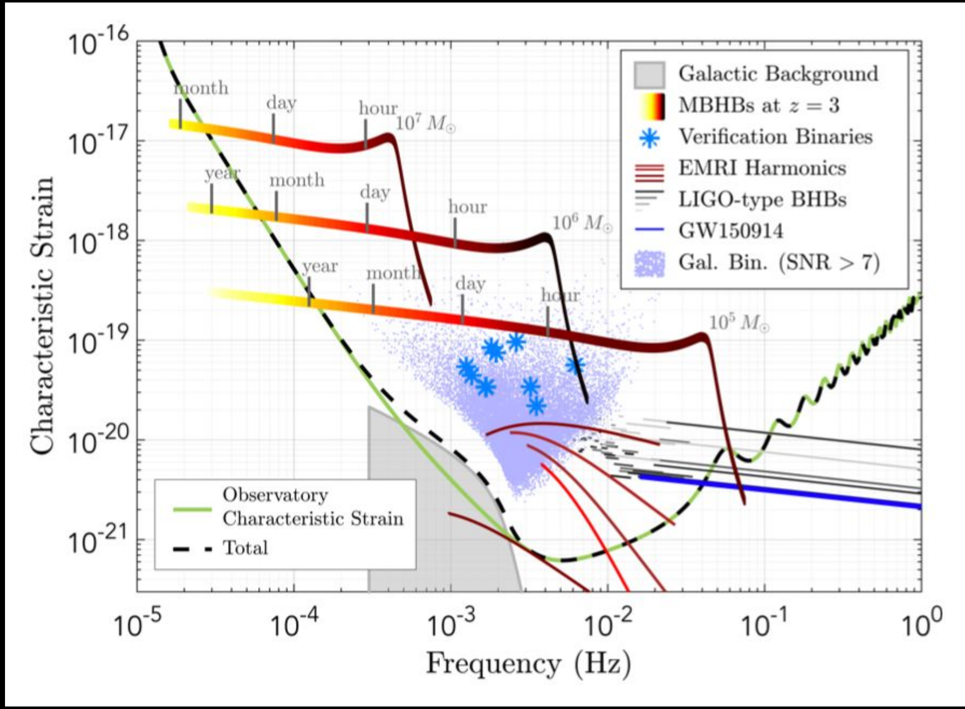


In collaboration with:
- Kaze Wong
- Richard Brito
- Emanuele Berti
- Tjonnie Li
- Ken Ng
- Salvatore Vitale

Otto Akseli Hannuksela
Nikhef

First part of the talk: LISA EMRI Measurements





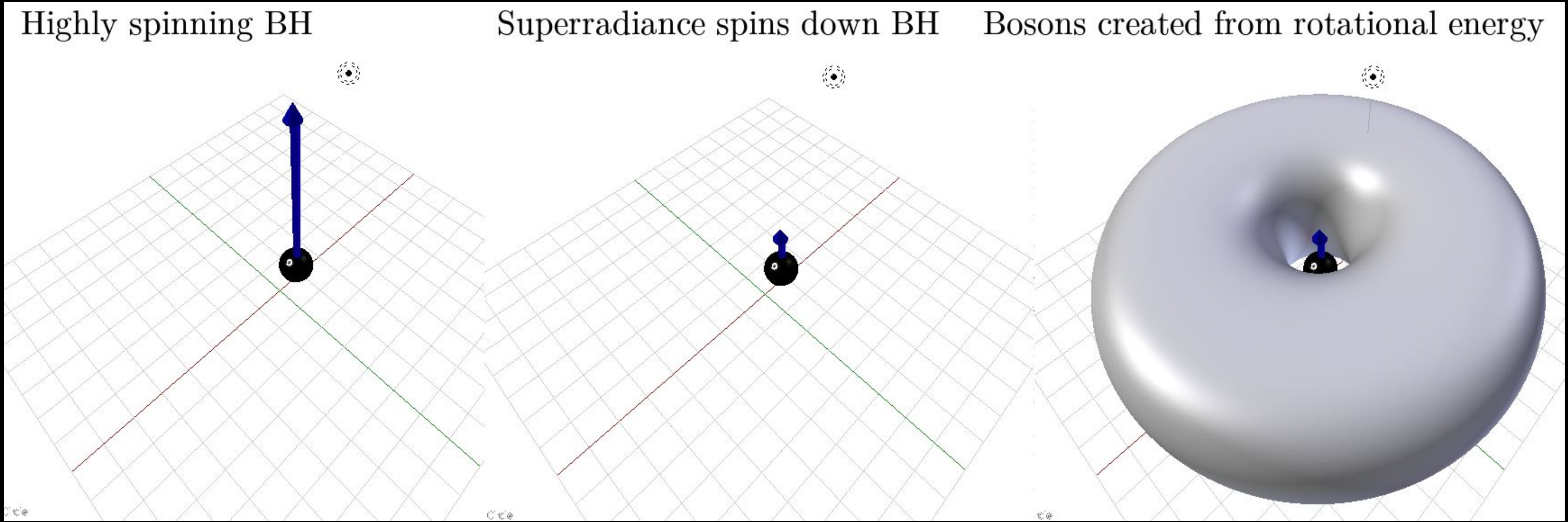
What are light bosons, what do we expect and who is interested?

- **Any** particle that is a boson and has a light mass (often <<10^(-5) eV)
- Range of particles fall into this category:
  - Light/ultralight axions
  - QCD Axion (upper end)
  - Wave dark matter
  - Dilatons
- These are a beyond-standard-model particles and hence not proven to exist

Depending on who you ask:

- A dark matter candidate
- Could solve cosmological and astrophysical problems, depending on its mass range
- Would give hints about physics beyond the standard model

Simplified overview



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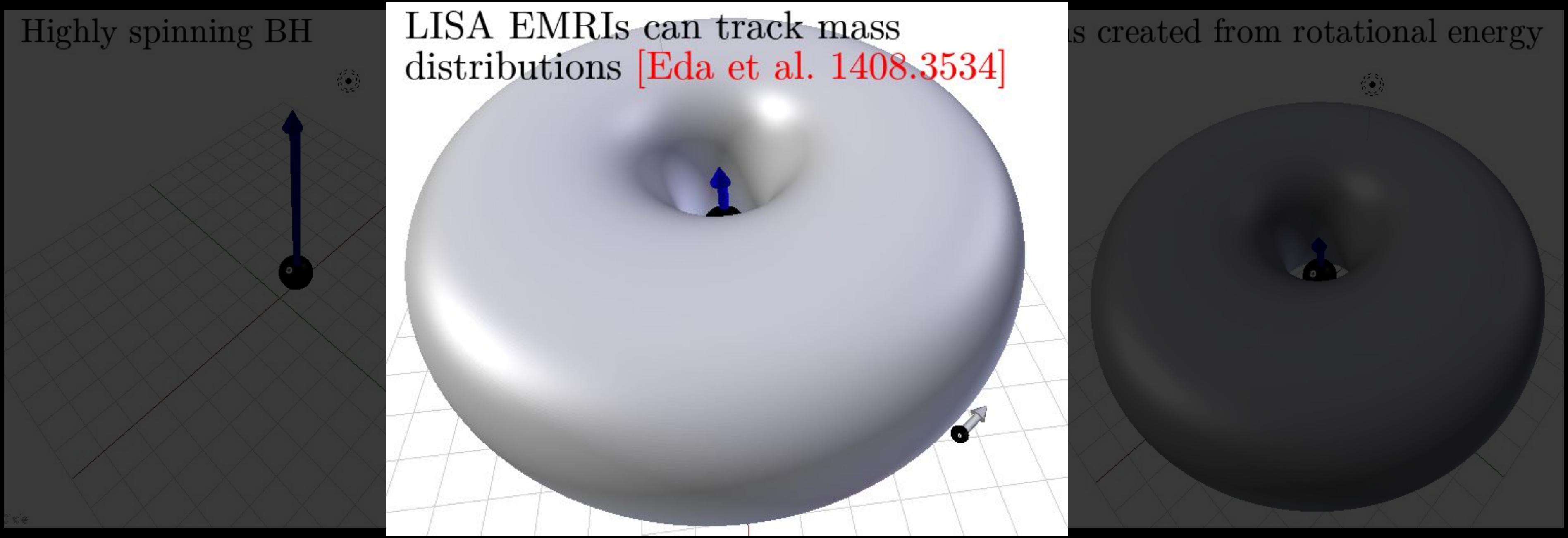

Black Hole & Boson Cloud: Theory

$$[\Box - \mu_S^2]\Psi = 0$$

$$\psi(\mu_S, a, M, r) \propto \tilde{r}^l e^{-\tilde{r}/2} L_n^{2l+1}(\tilde{r})$$

$$\tilde{r} = 2rM{\mu_S}^2/(l+n+1)$$

$$\Psi \sim e^{t/\tau}$$

$$\omega \sim \mu_S - \frac{\mu_S}{2}\left(\frac{M\mu_S}{l+n+1}\right)^2 + \frac{i}{\gamma_{nlm}}\left(\frac{am}{M} - 2\mu_S r_+\right)(M\mu_S)^{4l+5}$$

- Described by Klein-Gordon equation in Kerr metric [Press & Teukolsky (1972) 10.1038/238211a0]
- Simplifying assumption: Newtonian potential, small coupling [Detweiler (1980) 10.1103/PhysRevD.22.2323]

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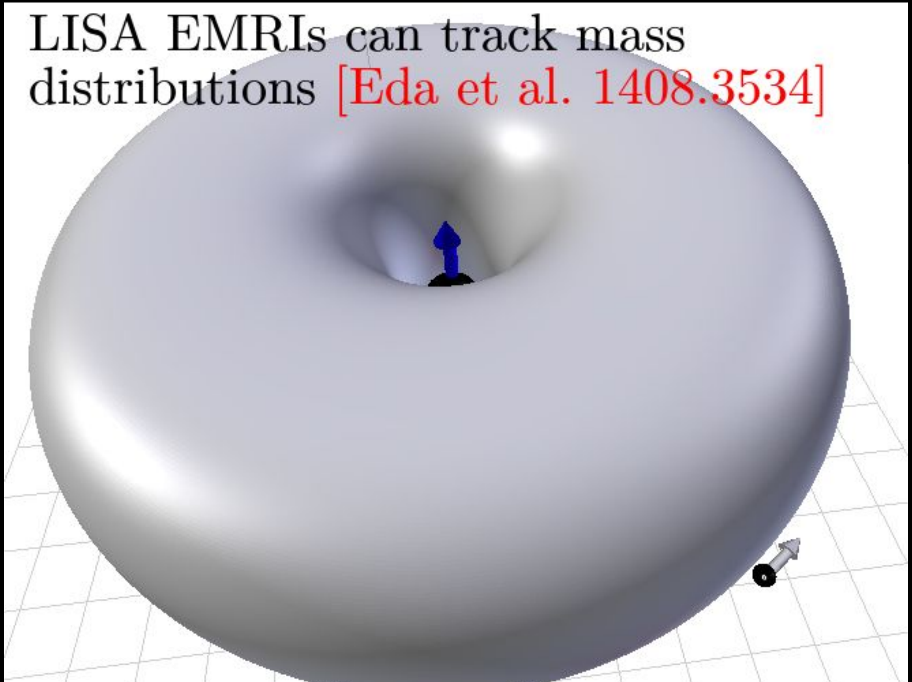

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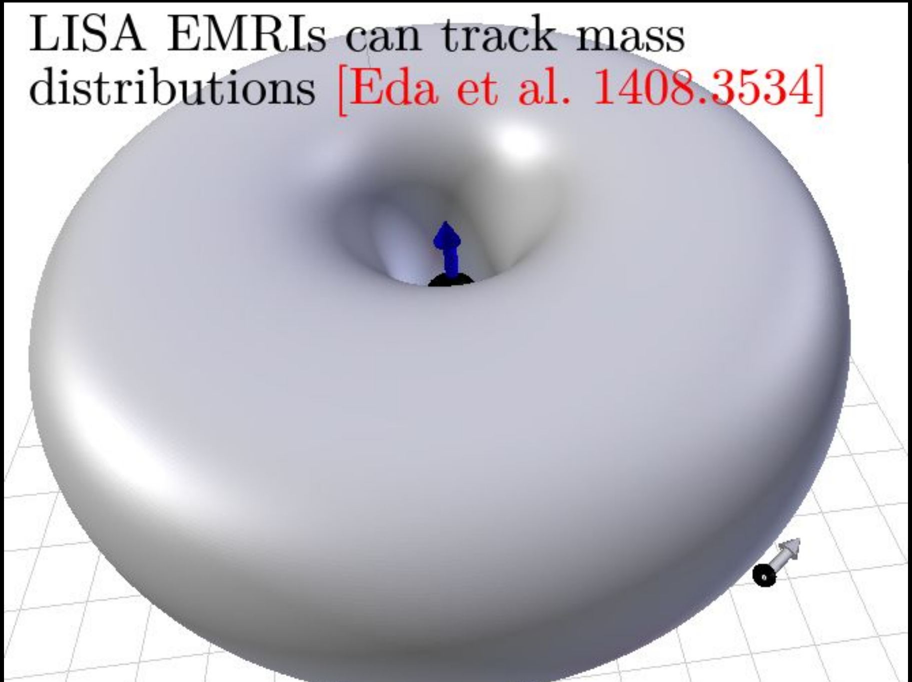

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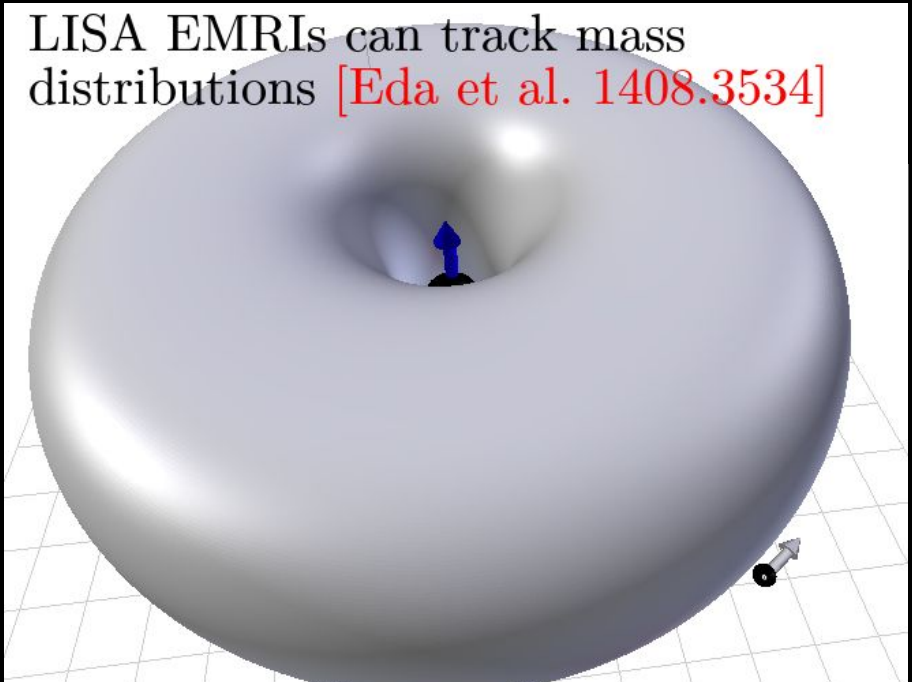

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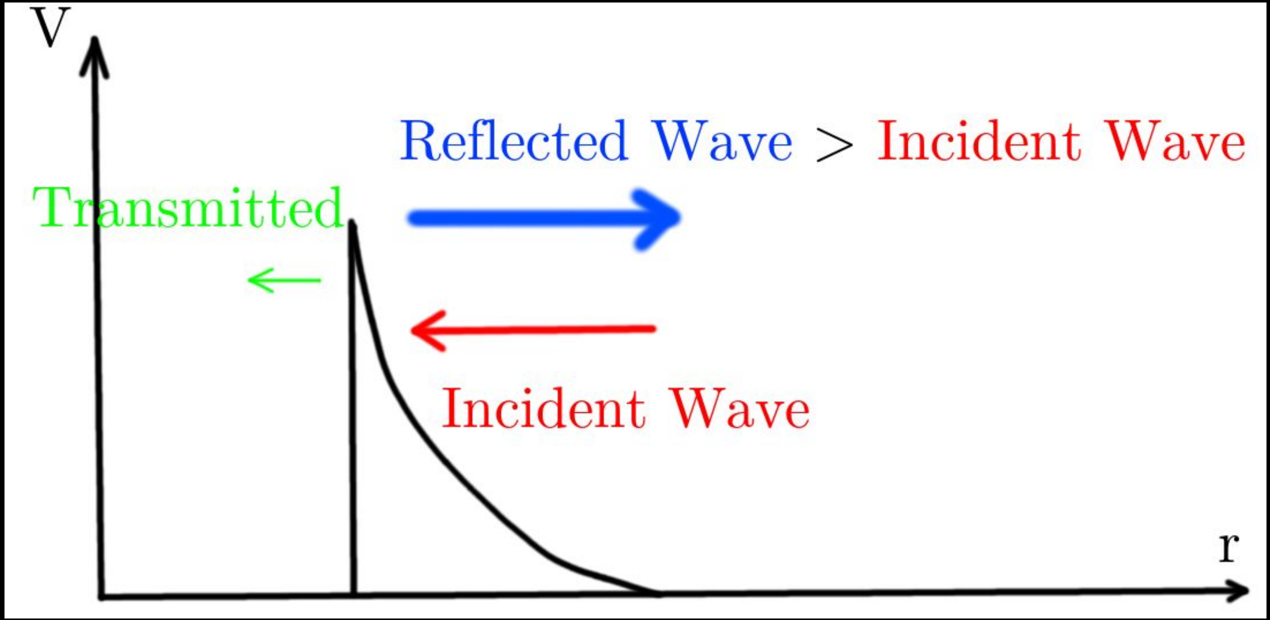
Spontaneous Cloud Formation: Superradiant Scattering & instability

$$[\Box - \mu_S^2]\Psi = 0$$



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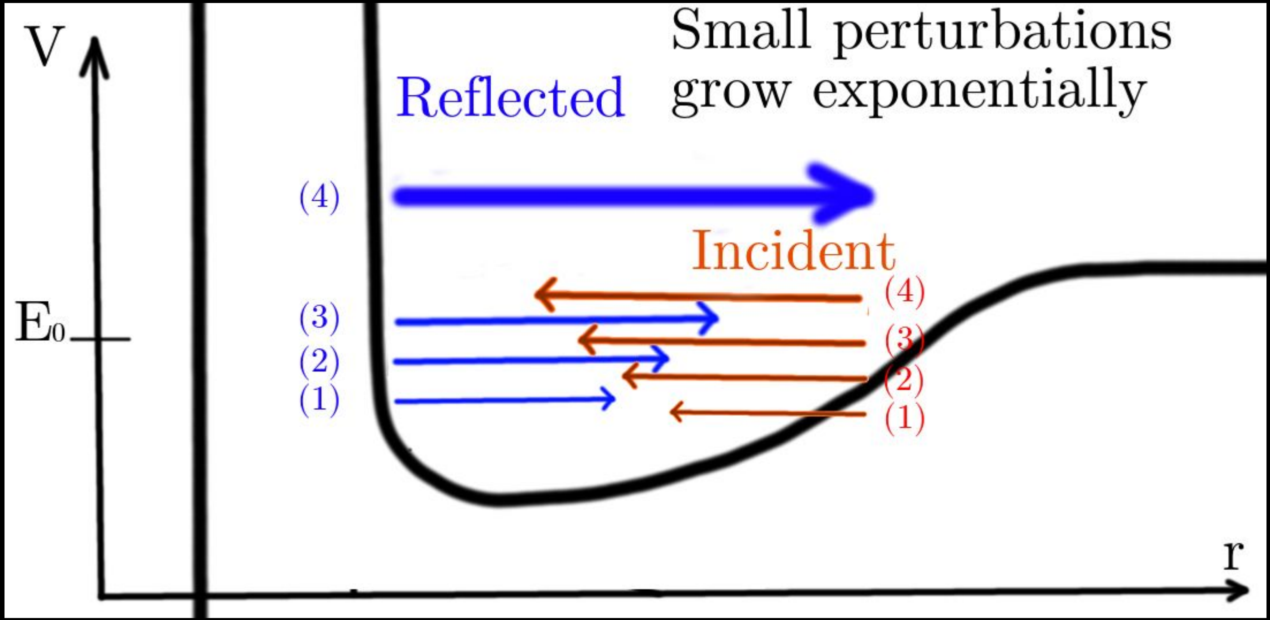

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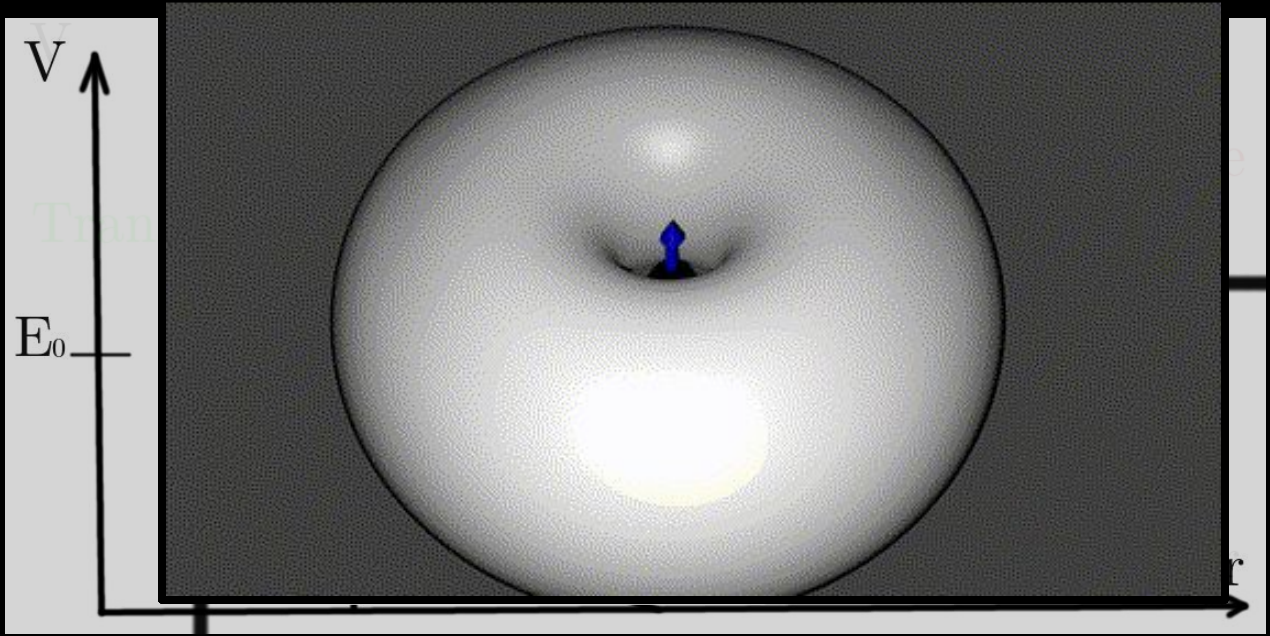

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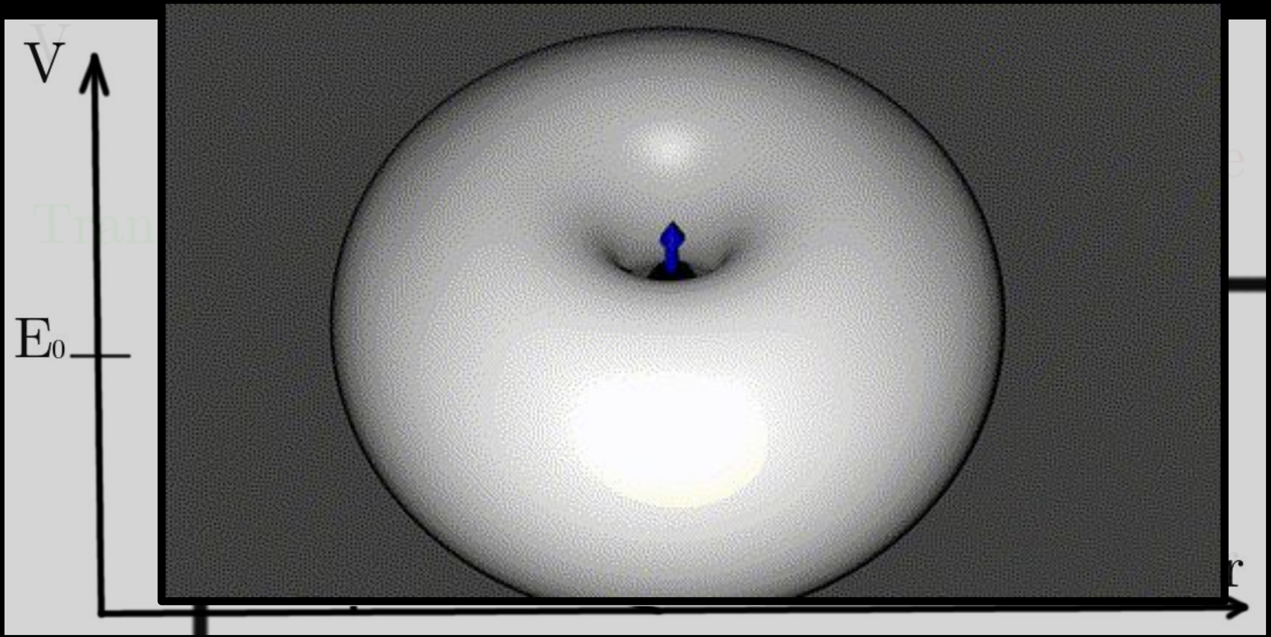

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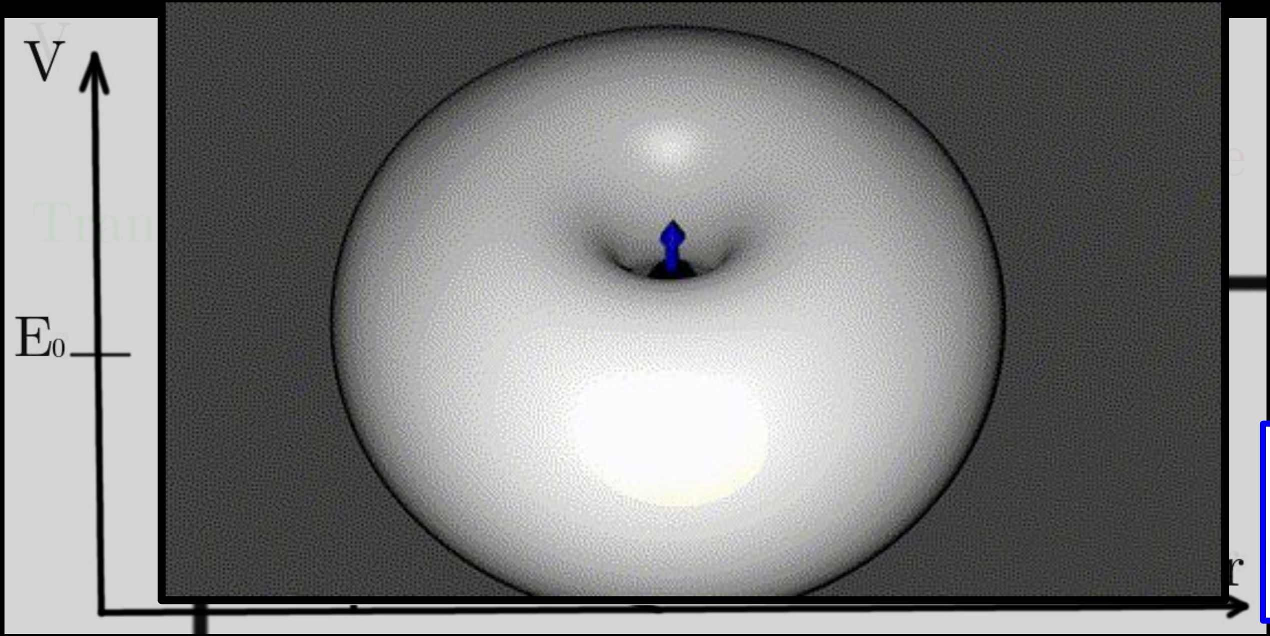

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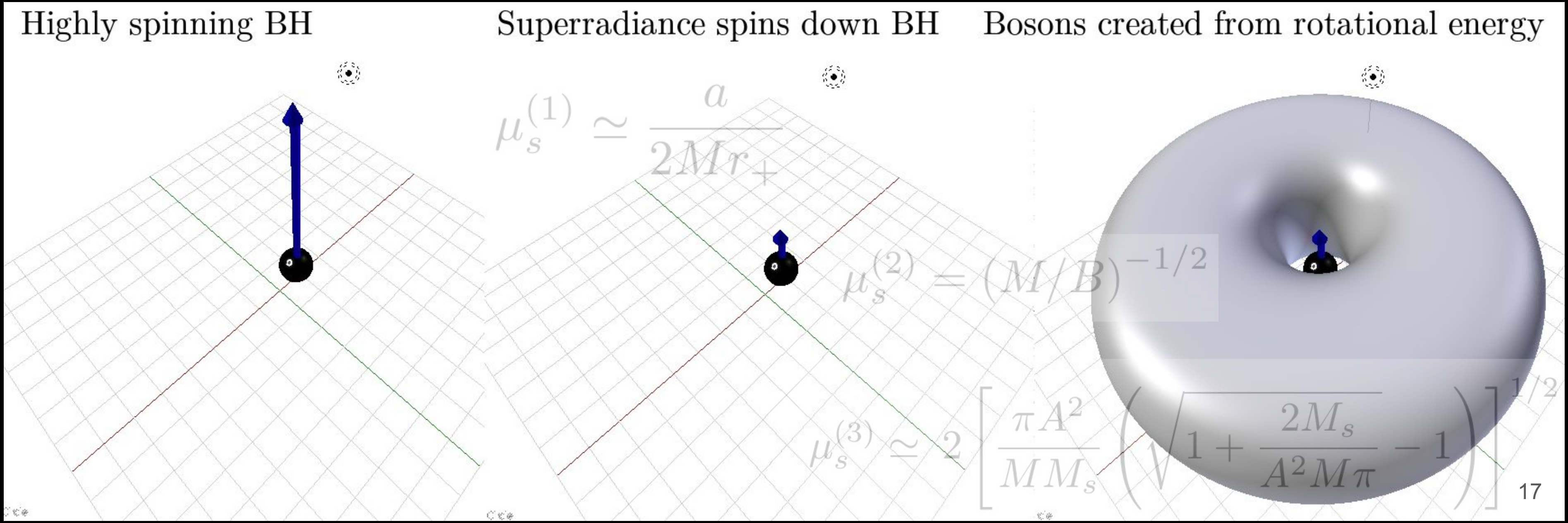
Superradiance Summary



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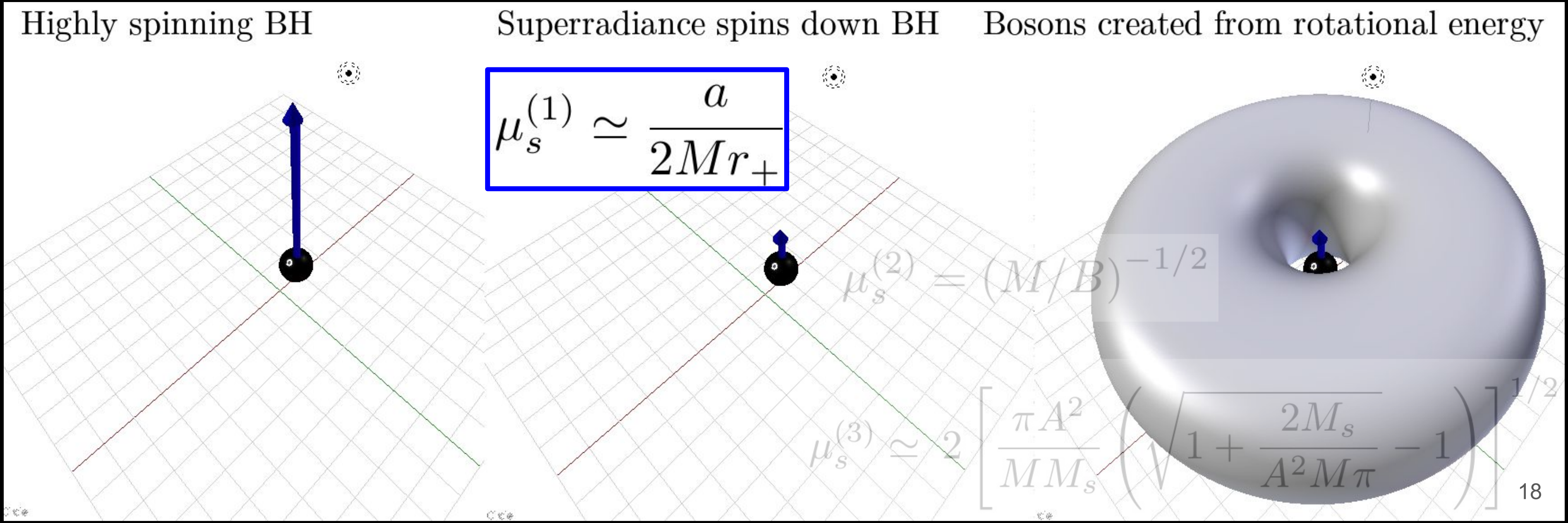

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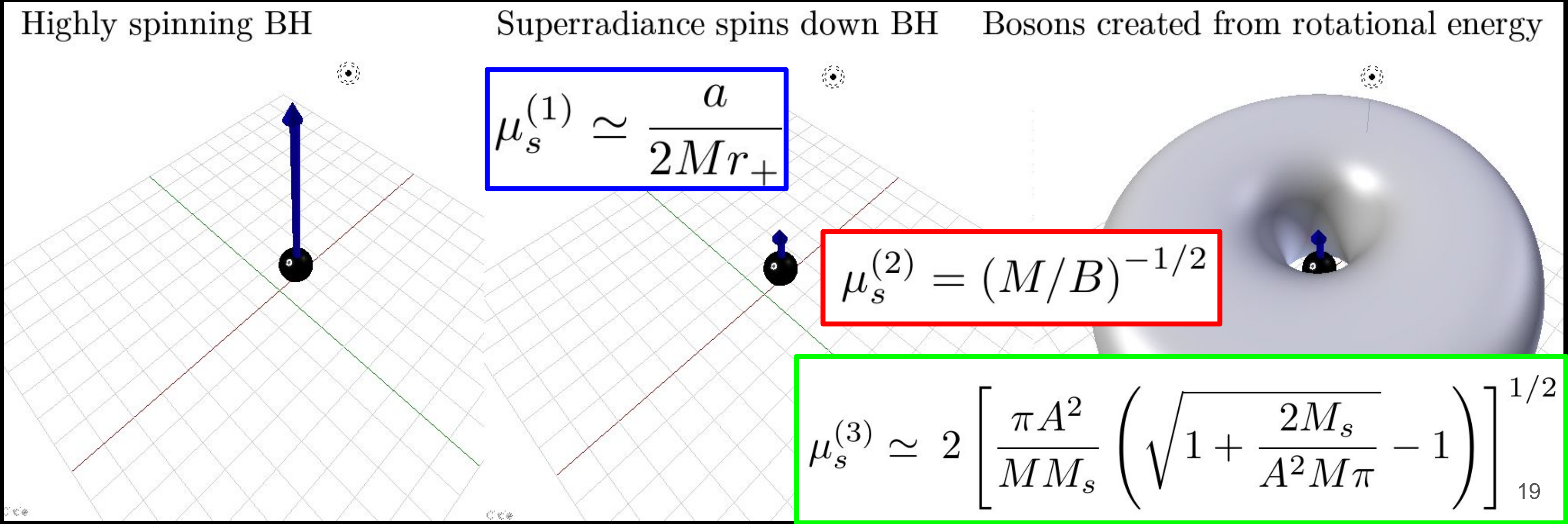

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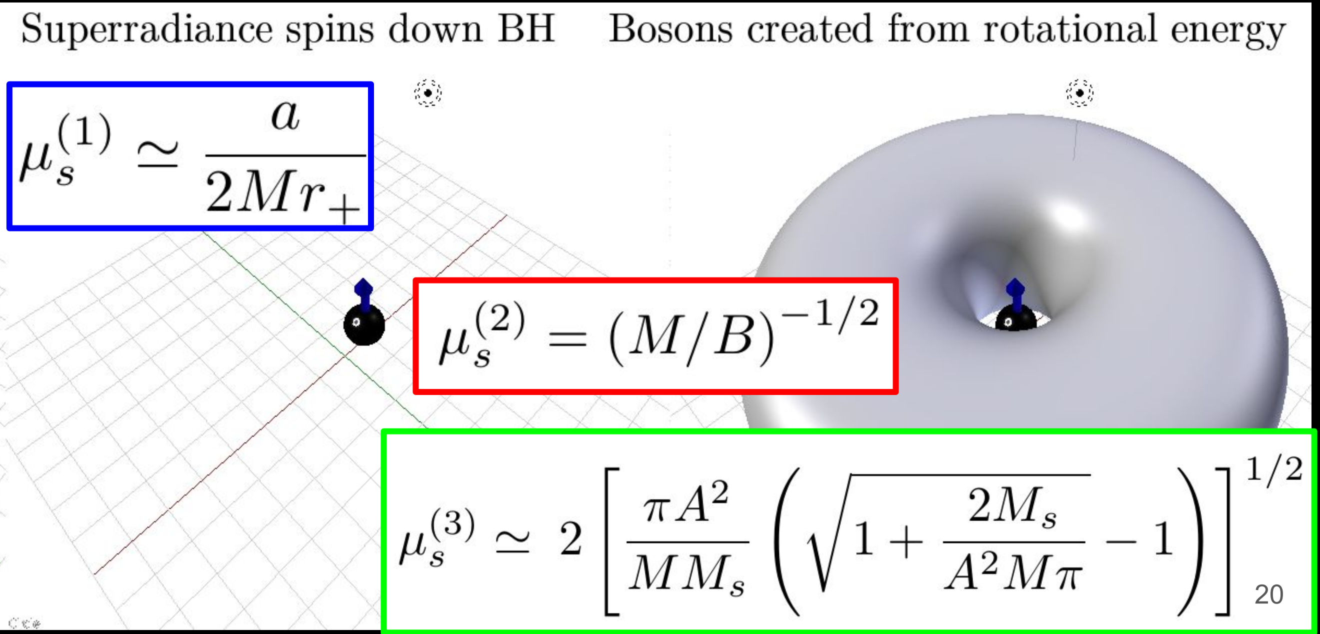
Superradiance Summary

- Mass and spin measured to better than **1%** accuracy with **LISA**
- Matter effects resolvable even at lower than boson cloud densities [Eda et al. (2014) 1408.3534]



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EMRI Measurements

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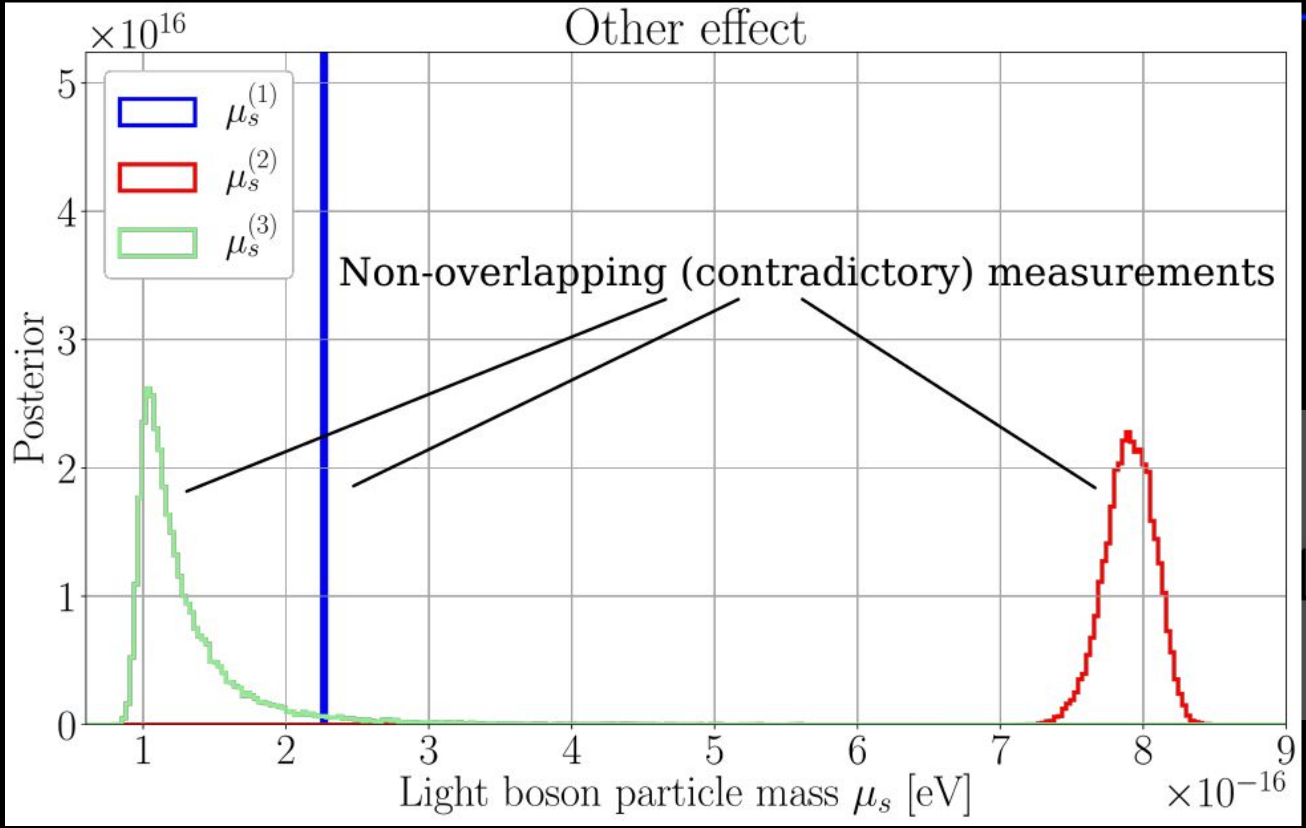
$$\varphi(t,r,\theta,\phi) = ABre^{-Br/2}\cos(\phi-\omega_R t)\sin\theta$$

- Critical spin: Spin-down by superradiance
- Characteristic scale of cloud: BH geometry
- Amplitude: Accretion and BH geometry

Verifying ultralight bosons

Nikhef



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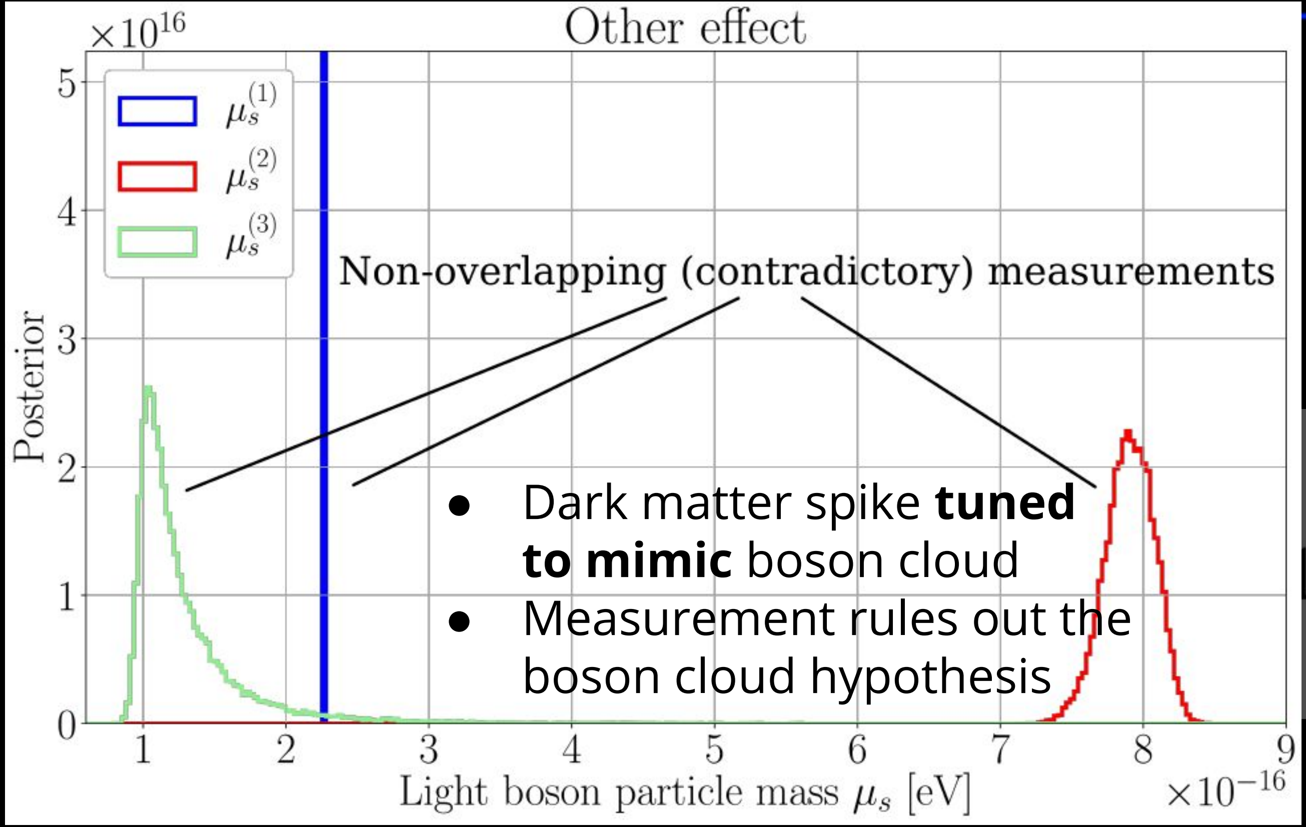

- Dark matter spike **tuned to mimic** boson cloud
- Measurement rules out the boson cloud hypothesis

- Critical spin: Spin-down by superradiance
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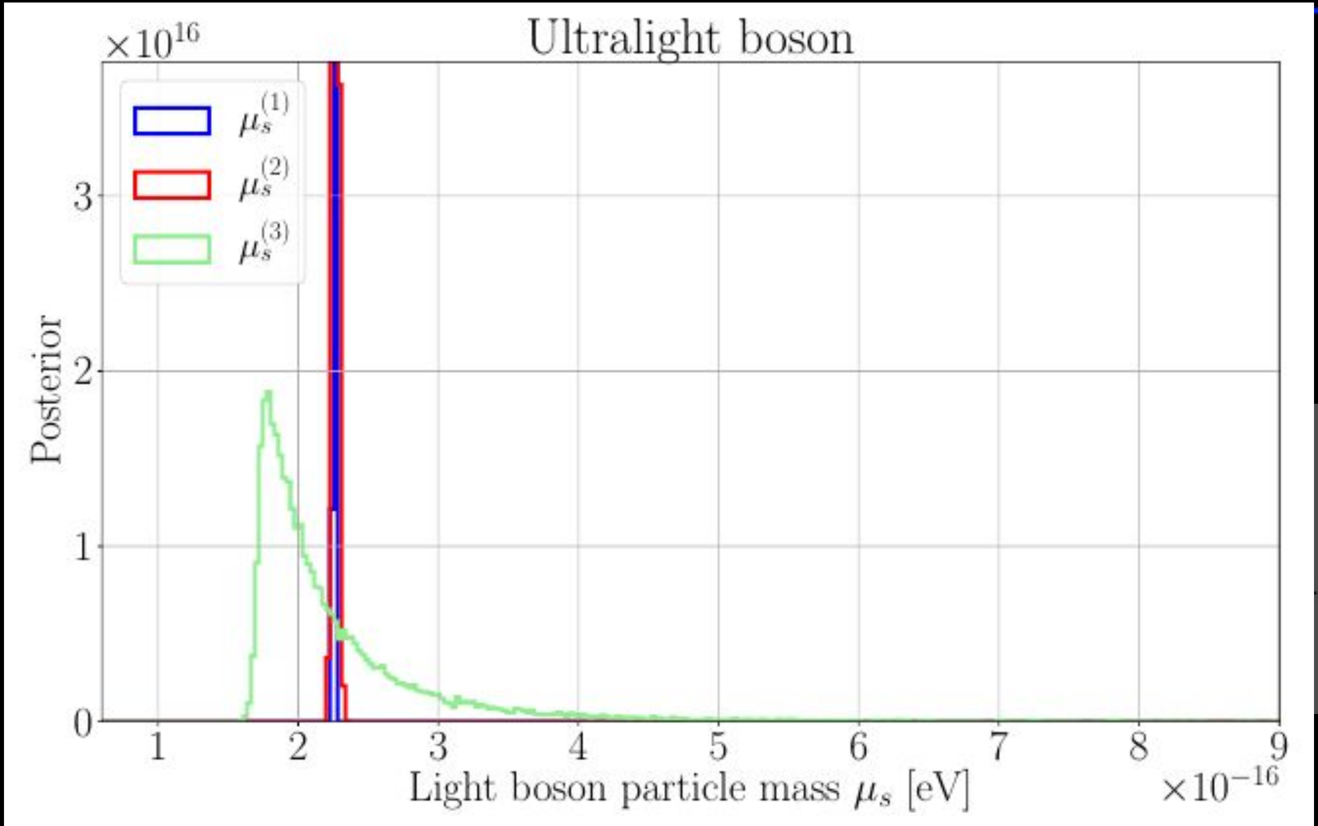
Verifying ultralight bosons



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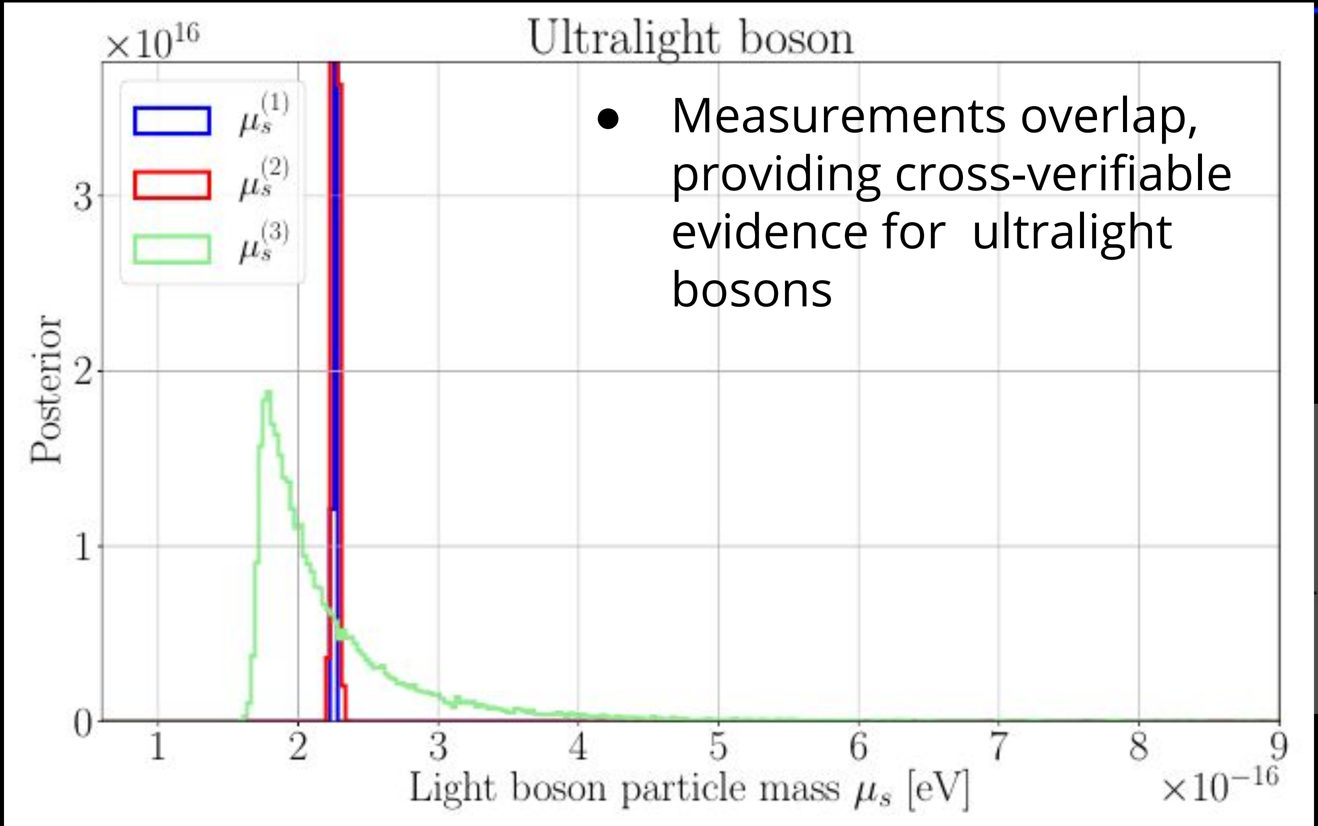

- Measurements overlap, providing cross-verifiable evidence for ultralight bosons

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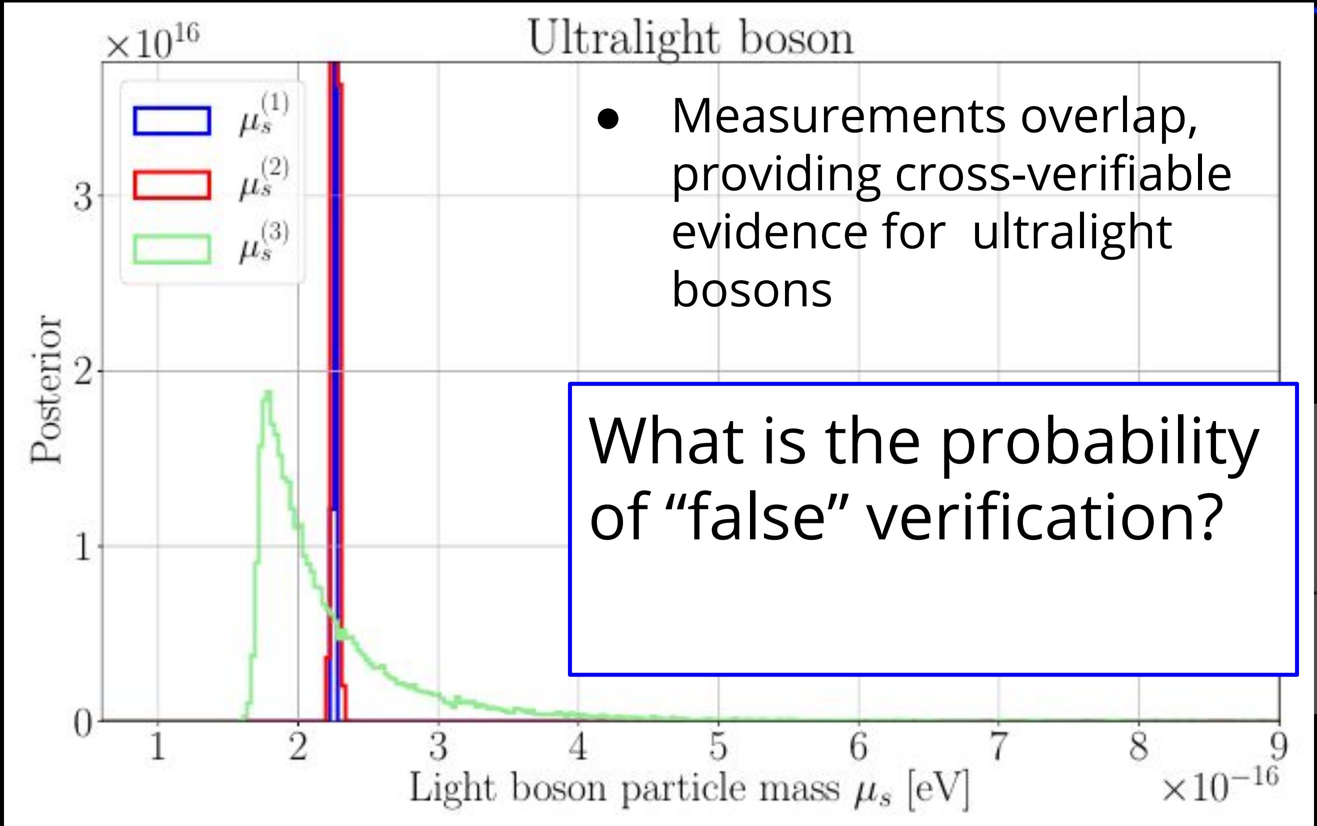

- Measurements overlap, providing cross-verifiable evidence for ultralight bosons

What is the probability of "false" verification?

- Critical spin: Spin-down by superradiance
- Characteristic scale of cloud: BH geometry
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$\Big)\Big]^{1/2}$

Detections Across LISA Range

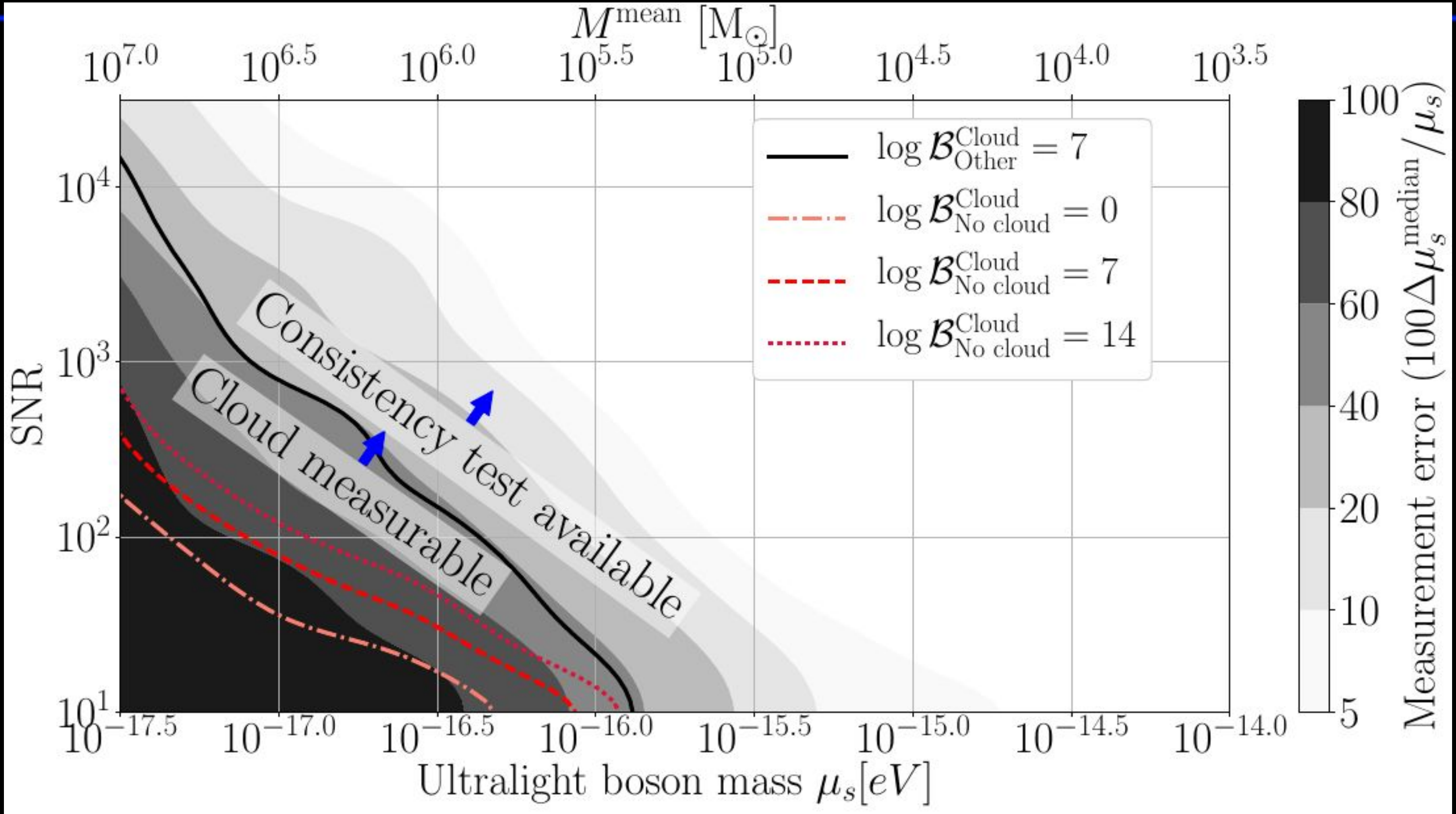
- Inject several GWs from various black hole/cloud systems
- Distribute spin linearly
- Distribute mass & mass ratio logarithmically

$$j \in [0.4, 0.98]$$

$$M \in [10^3, 10^7]\mathrm{M}_\odot$$

$$q \in [10^{-3}, 10^{-2}]$$

Detections Across LISA Range



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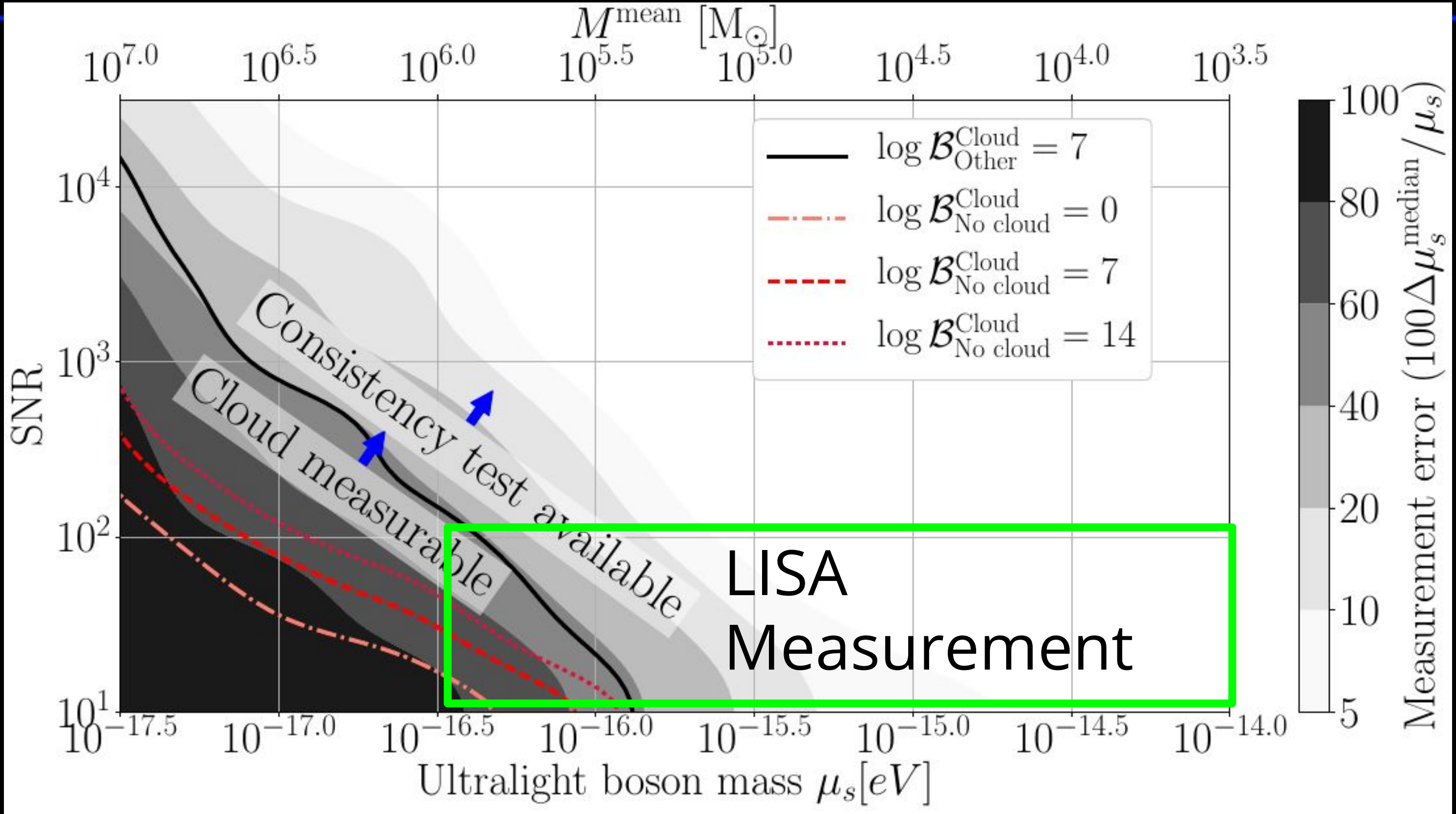

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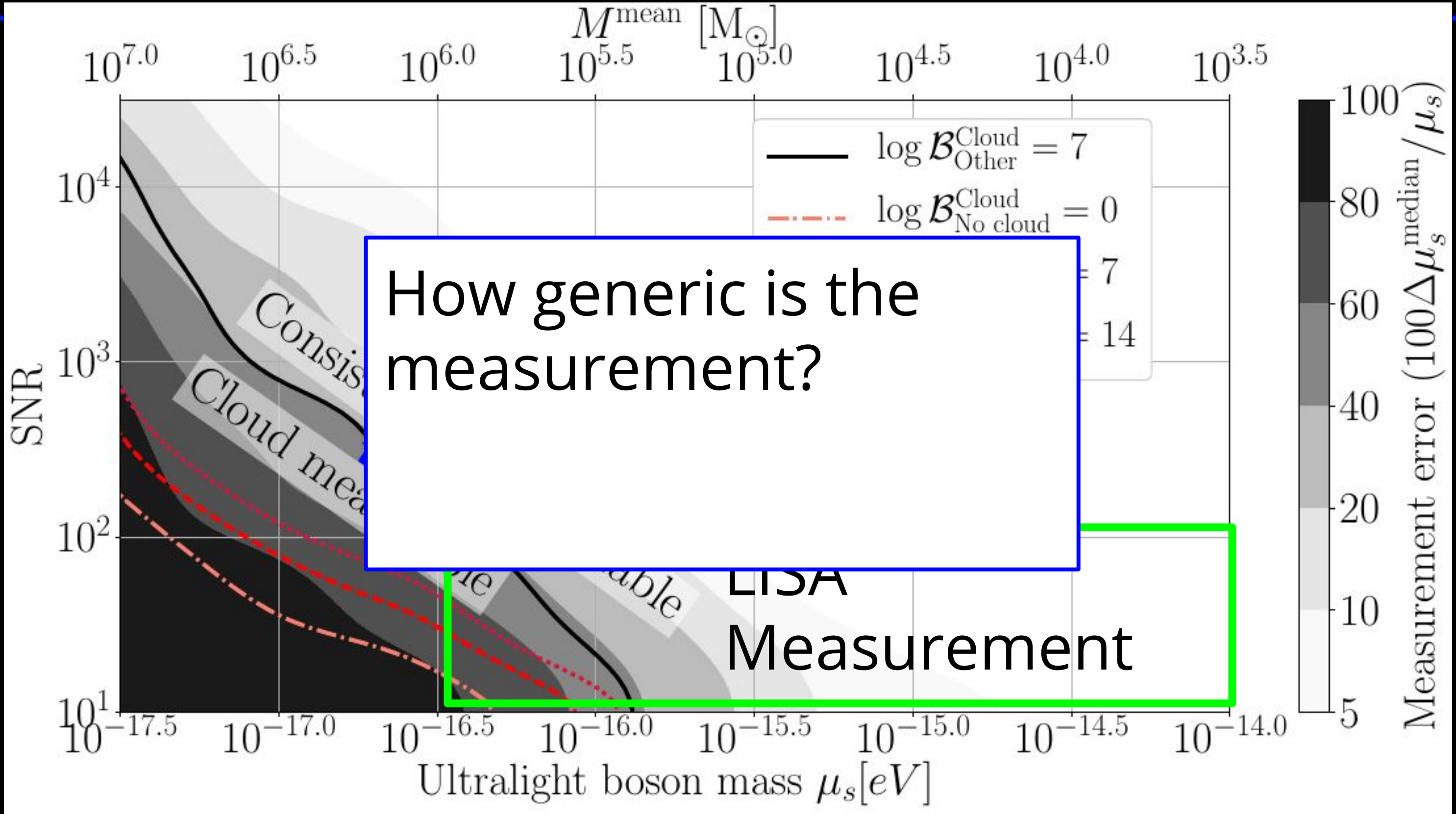


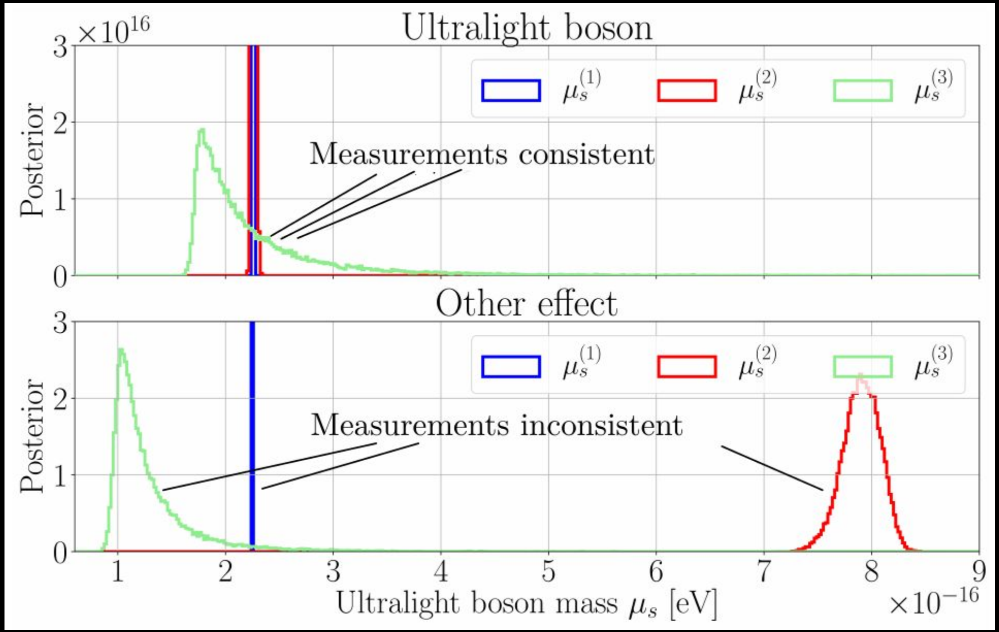
How generic is the measurement?

LISA Measurement

LISA Summary

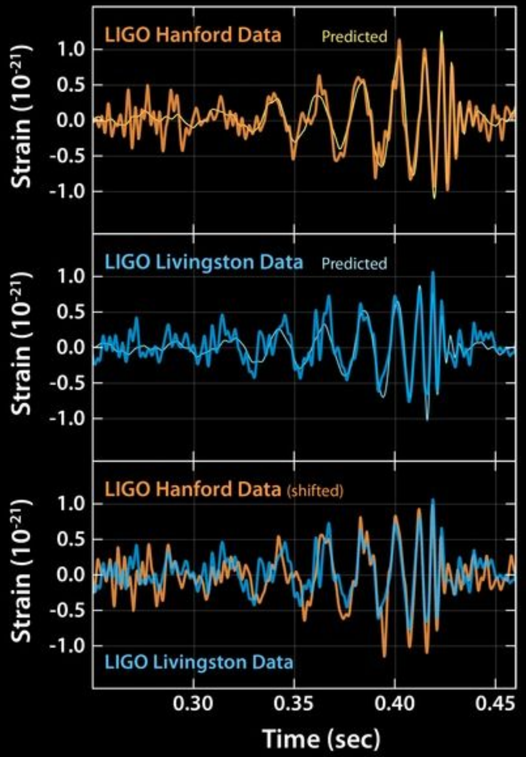
With continued progress:

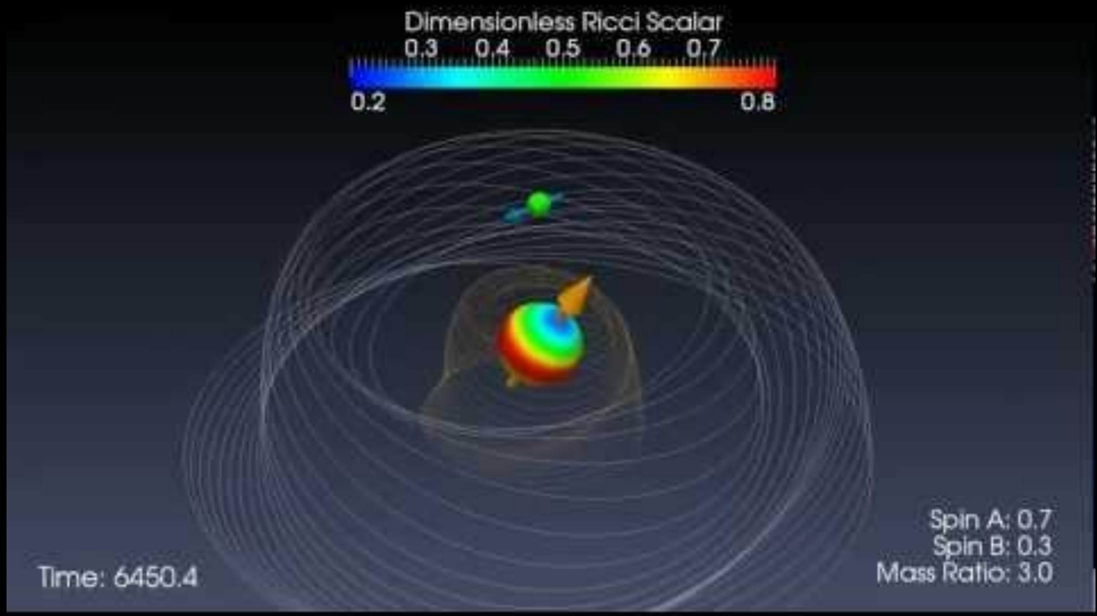
- Ultralight bosons could be tested for across a wide mass range with LISA EMRIs using “consistency tests” that make use of the fact that black hole/cloud systems are over-determined



$$\mu_s \in [10^{-17}, 10^{-14}]\,\mathrm{eV}$$

Second part of the talk: LIGO/Virgo spin measurements





Credits: SXS collaboration

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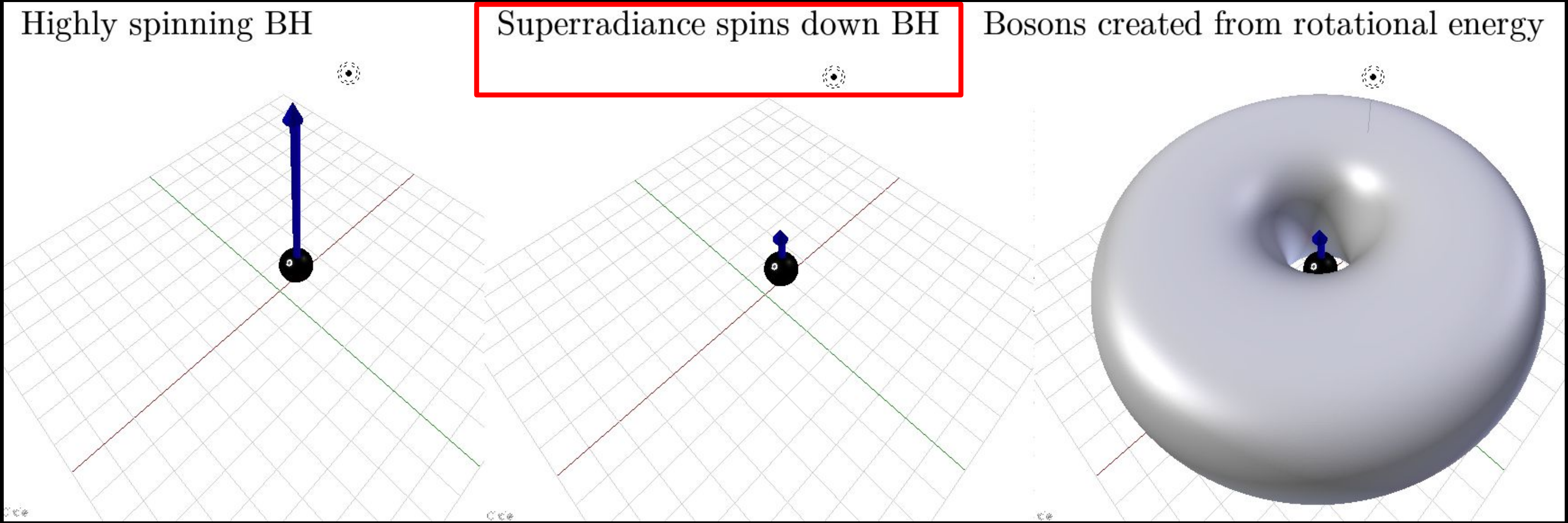
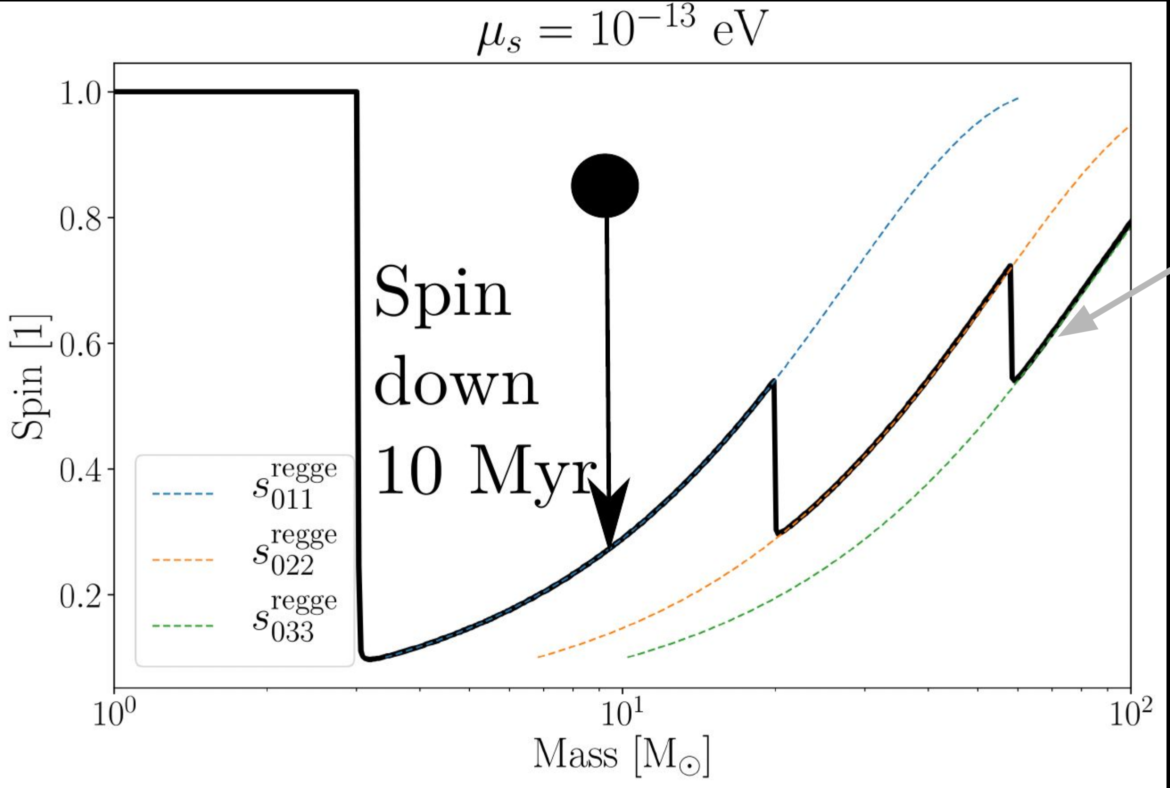


Regge trajectory



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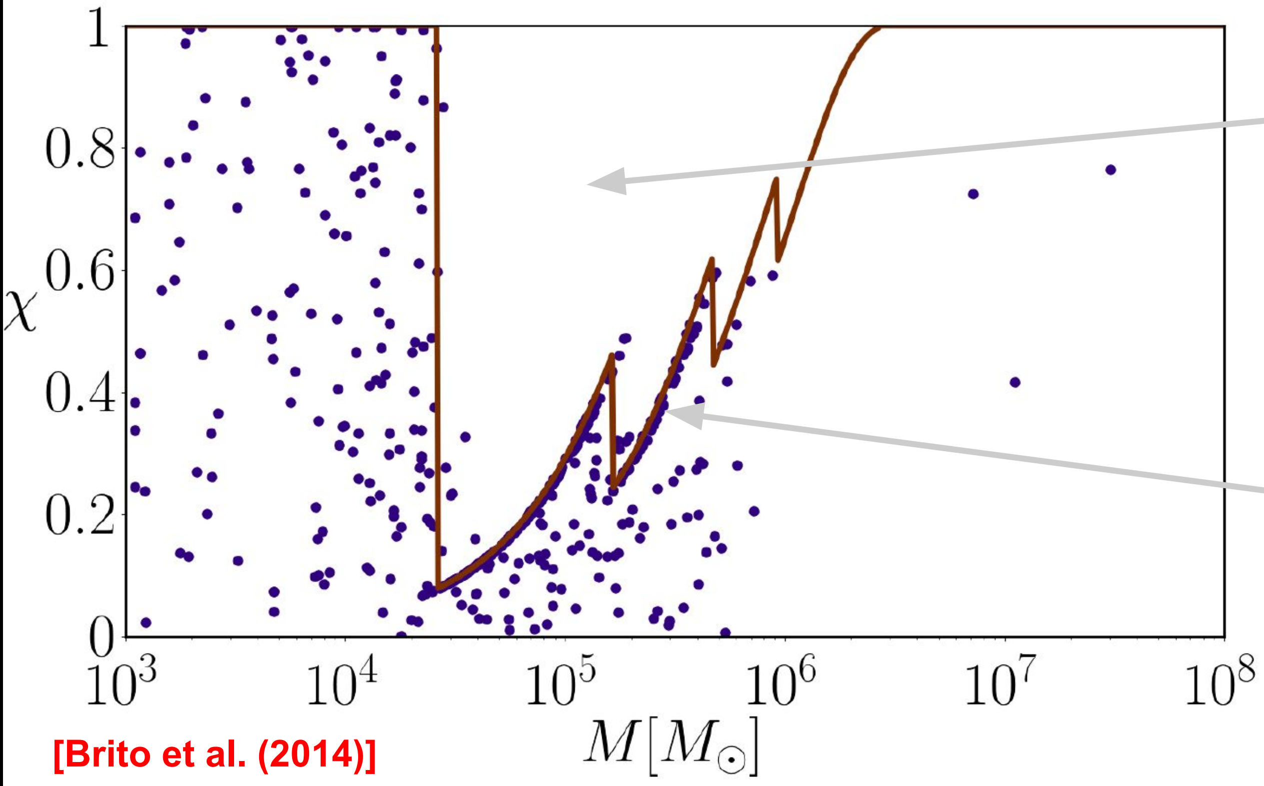


Regge gap (void of black holes at high spin)

Black holes accumulate around the Regge trajectory

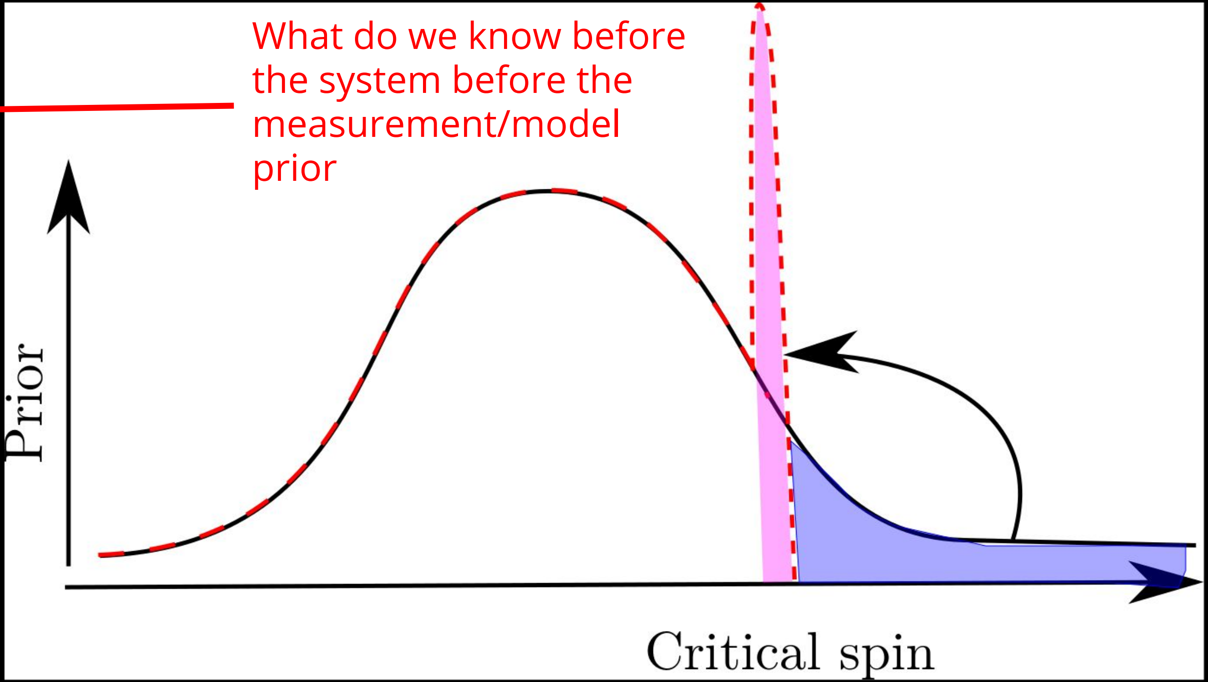
Incorporating the Regge trajectory to the GW analysis

$$\mathcal{Z} = \int \mathcal{L}(\vec{\theta})p(\vec{\theta})d\vec{\theta}$$

What do we know before the system before the measurement/model prior

How likely the model is correct / model evidence

How the GW and detector noise look like



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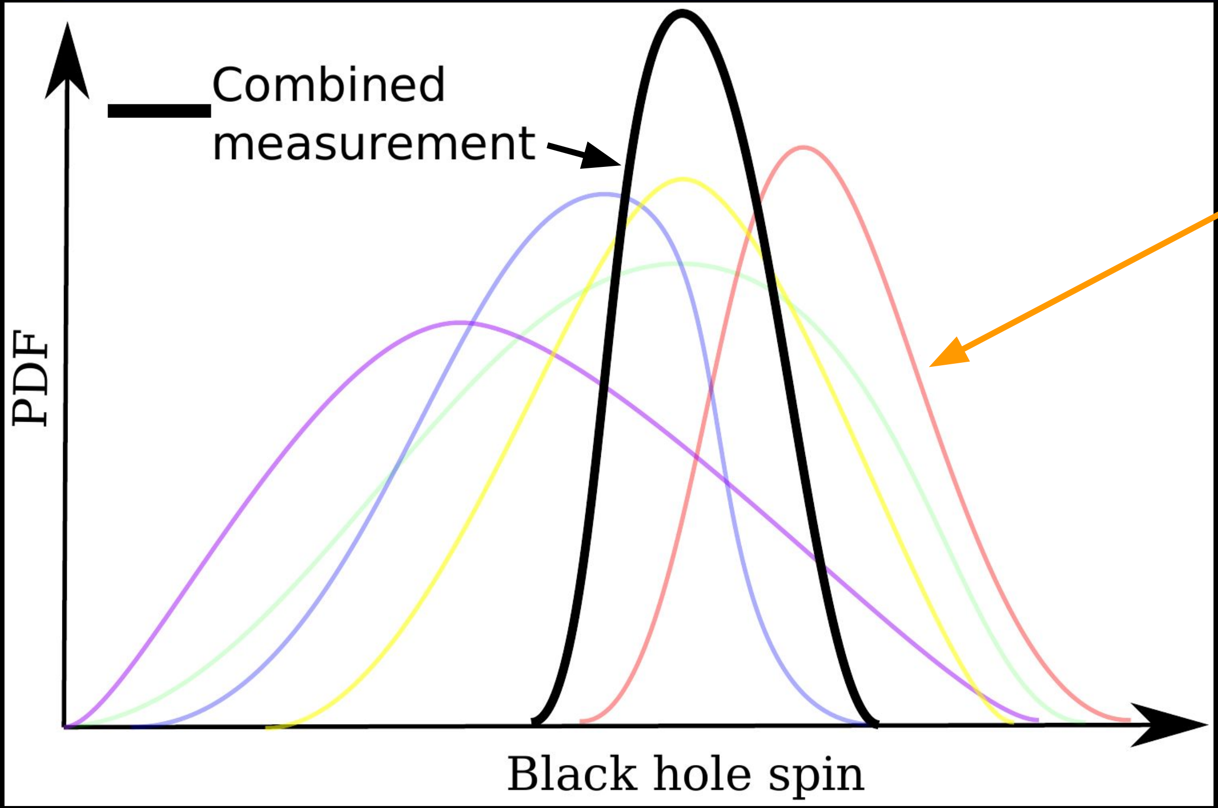
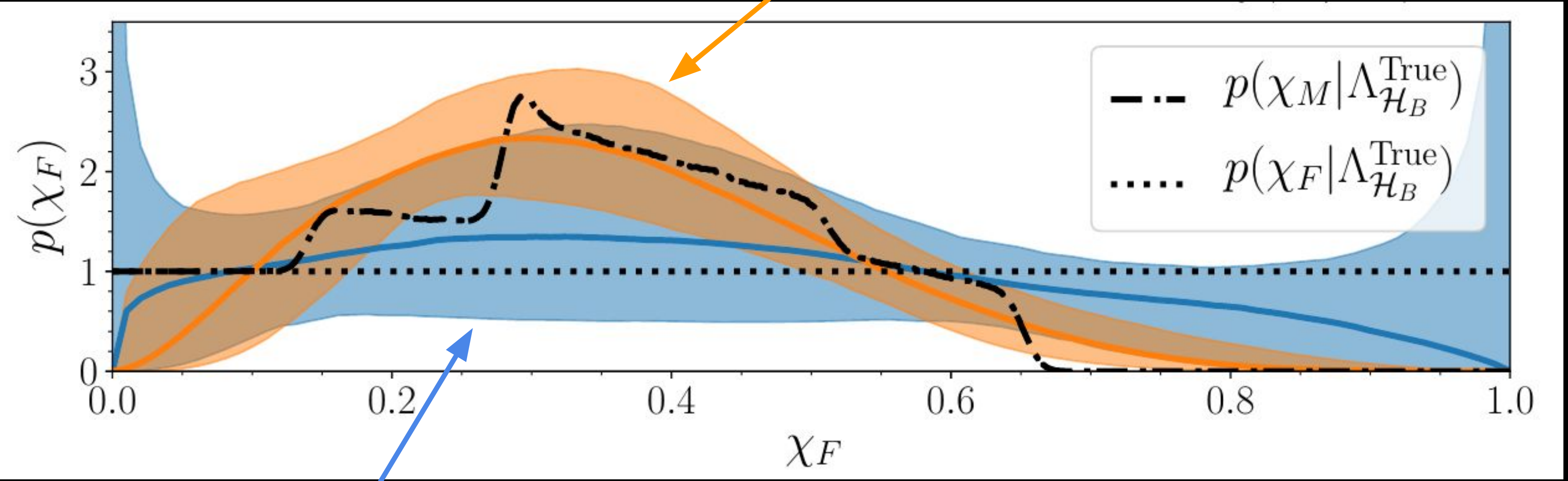


Individual measurements

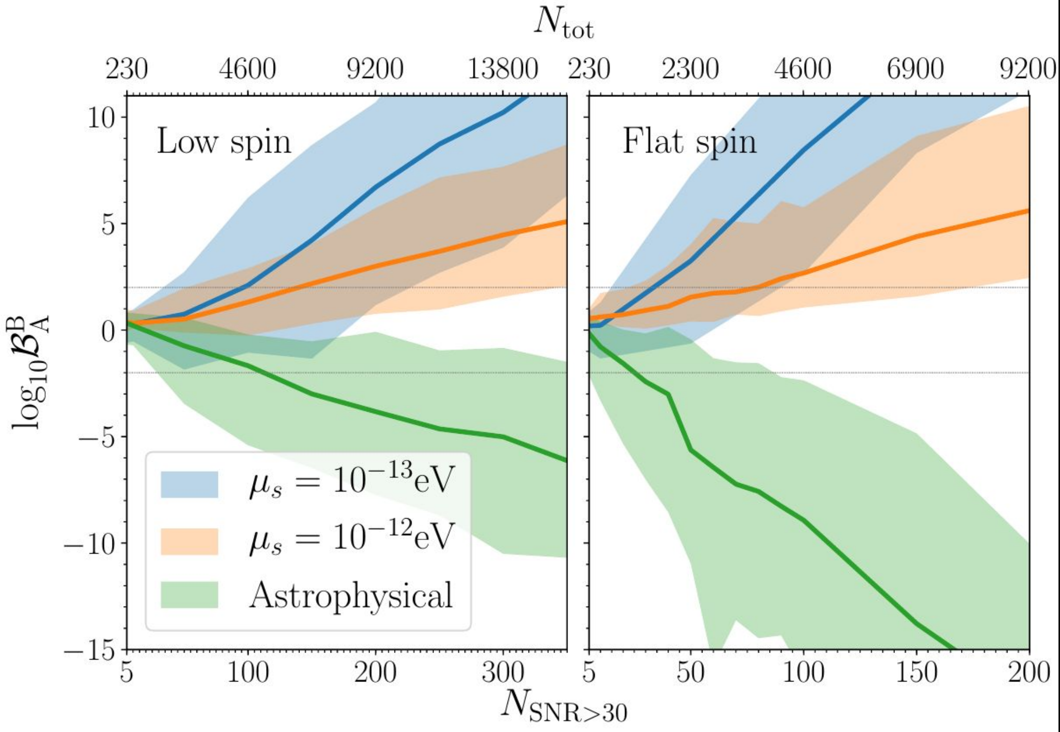
LIGO/Virgo spin measurements

Boson model tracks the Regge trajectory
(in this case dot-dashed black line)



Non-boson model consistent with the flat spin distribution
(dotted line) and doesn't capture the Regge trajectory with good precision

Model selection results

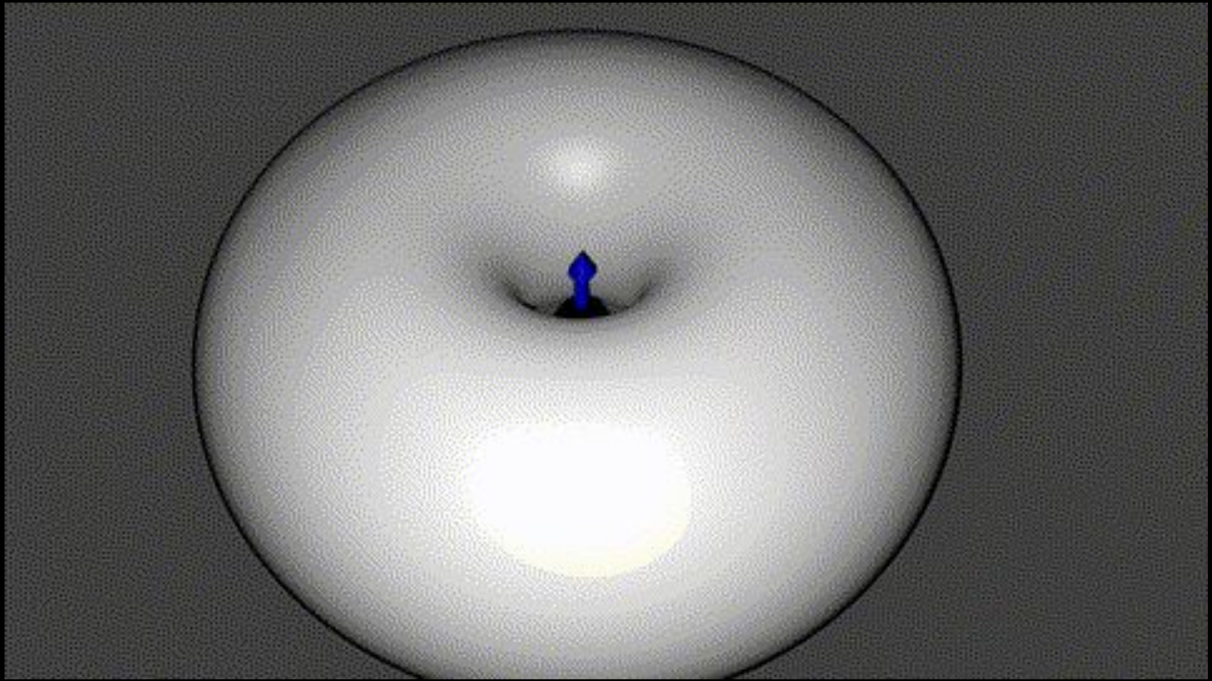


Population models	Flat spin	Low spin
Astrophysical	25^{+60}_{-20}	110^{+270}_{-80}
$\mu_s = 10^{-13}$ eV	35^{+55}_{-20}	95^{+130}_{-60}
$\mu_s = 10^{-12}$ eV	80^{+95}_{-55}	140^{+95}_{-85}

Forecast:

- LIGO/Virgo at design sensitivity: May rule out light bosons
- Einstein telescope: Might confirm the light bosons if they exist.
- Better models including selection effects and binary inspiral modeling could yield more stringent results

Summary



- Light bosons couple to black holes, spinning them down, and forming massive ‘clouds’.
- The clouds could be tested for across a wide mass range with LISA EMRIs using “consistency tests”
- LIGO/Virgo and future ground-based detectors might allow us to probe the bosons through black hole spins

Thank you

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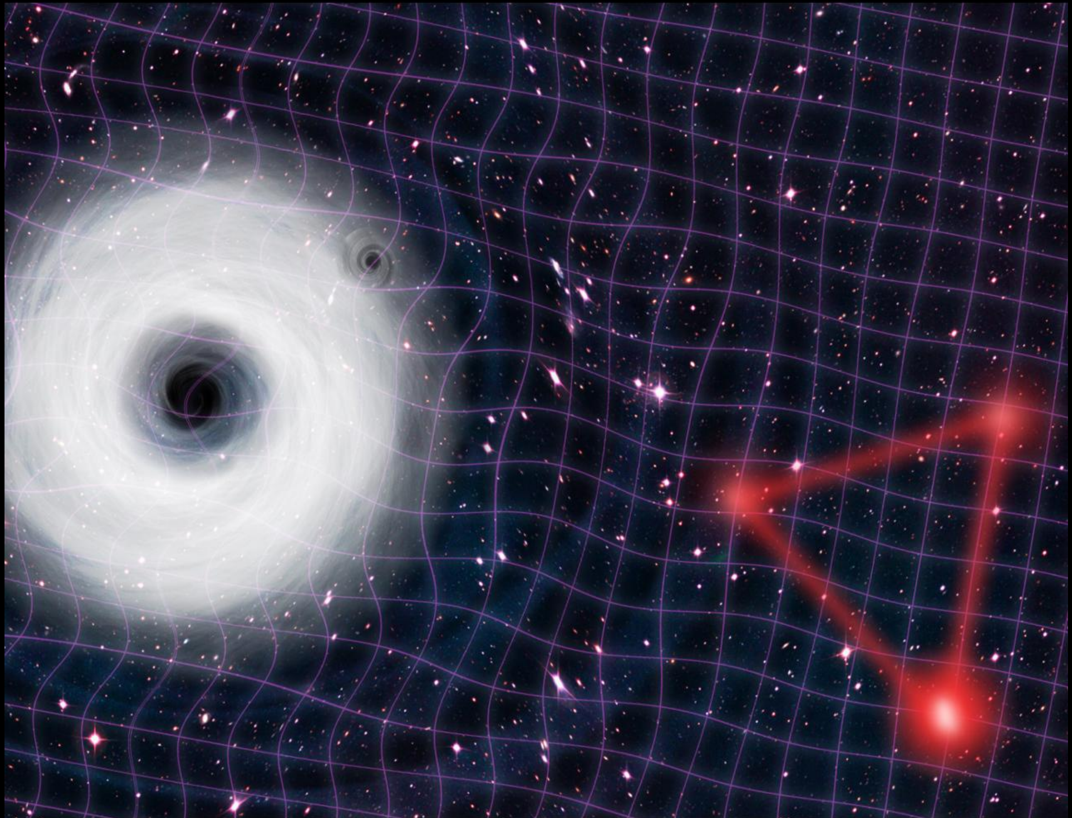

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