Probing ultralight bosons with black holes and gravitational waves

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ANU CENTRE FOR GRAVITATIONAL ASTROPHYSICS

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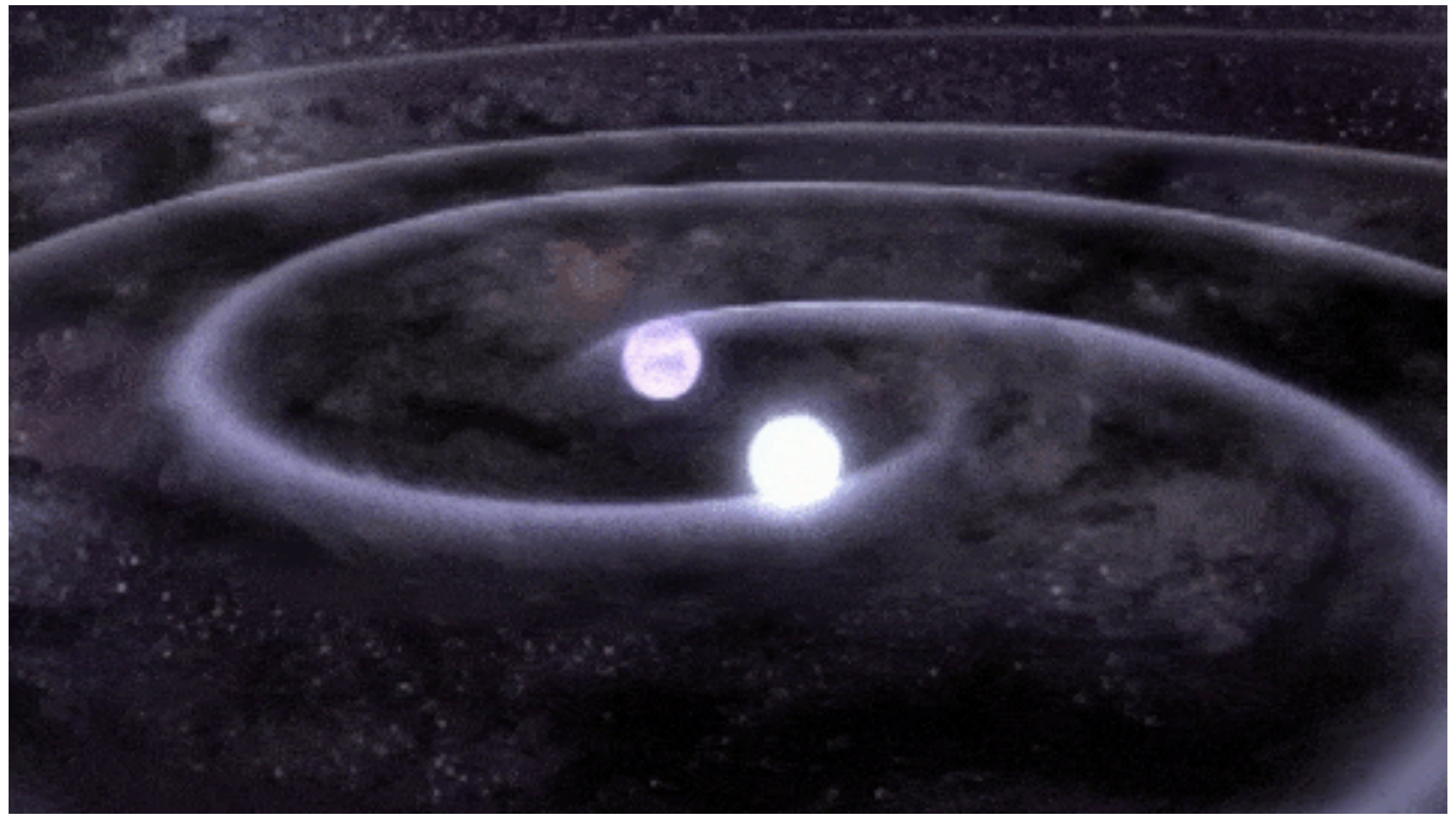
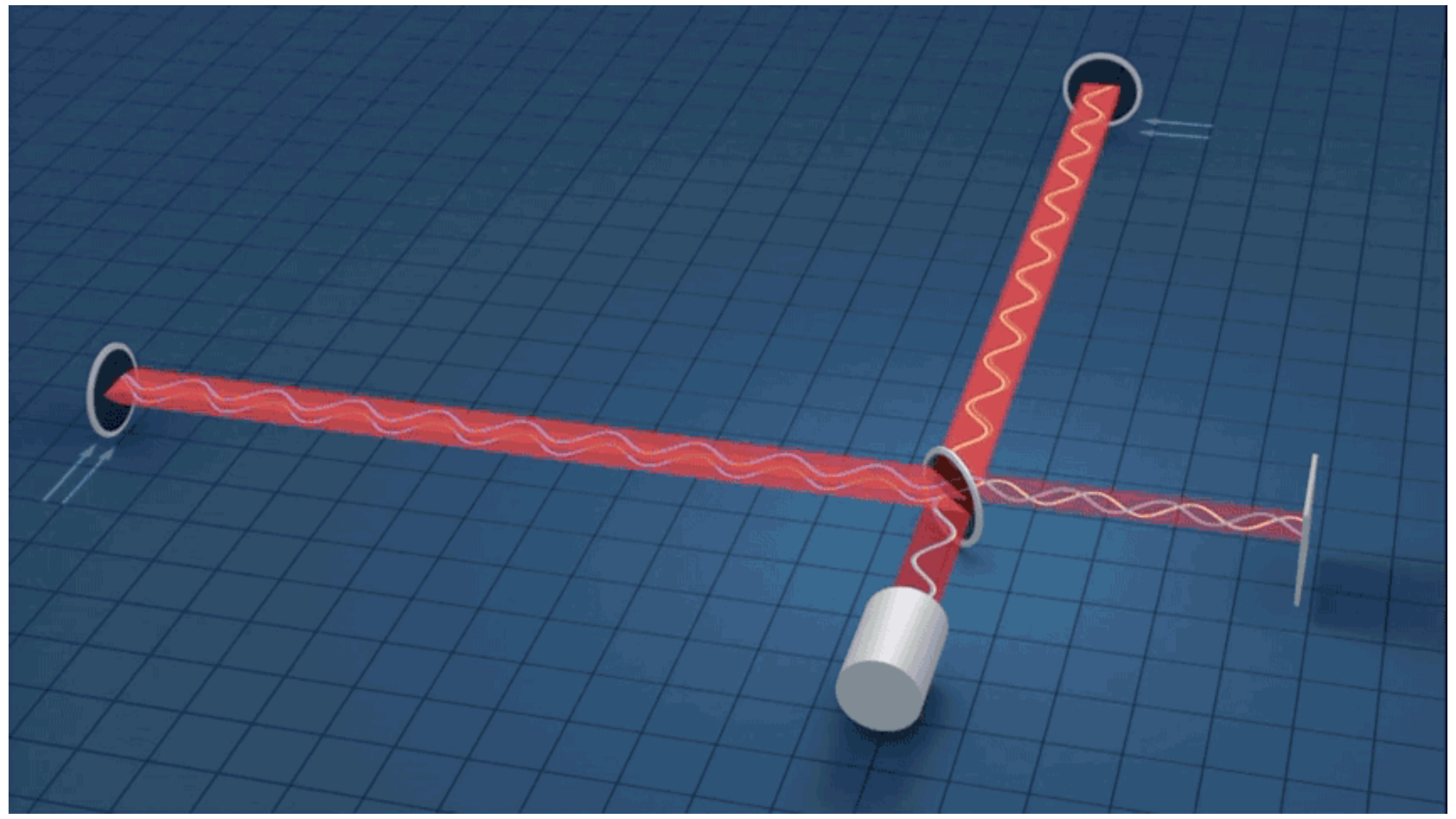
Detection of gravitational waves



Credit: NASA/Dana Berry, Sky Works Digital



Credit: LIGO/T. Pyle

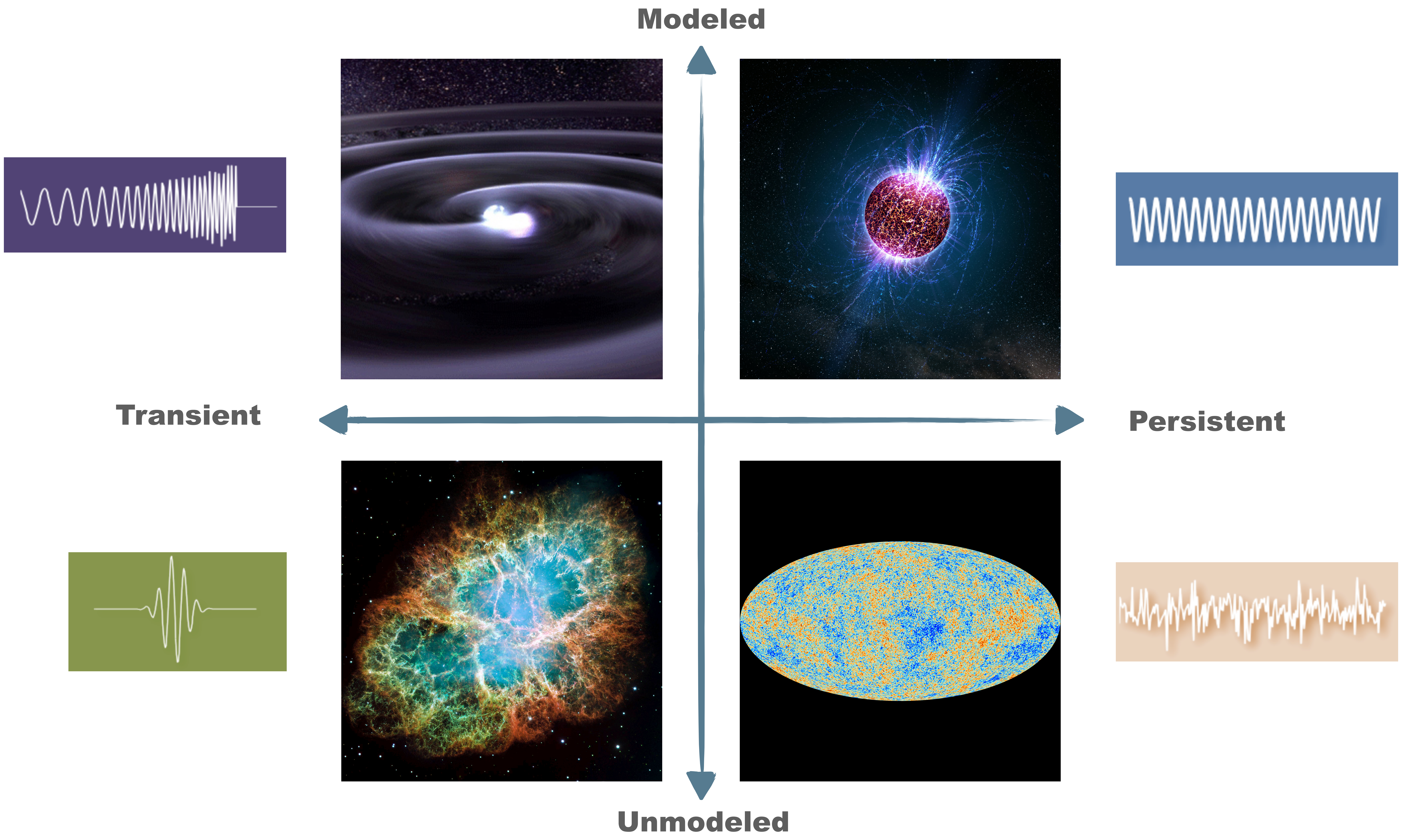
Credit: ICRR, Univ. of Tokyo/LIGO Lab/Caltech/MIT/Virgo Collaboration

** This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Masses in the Stellar Graveyard

DCC-G2102319; LVK, arXiv:2111.03606 (2021)

Other sources of gravitational waves



Probes of dark matter with GW detectors

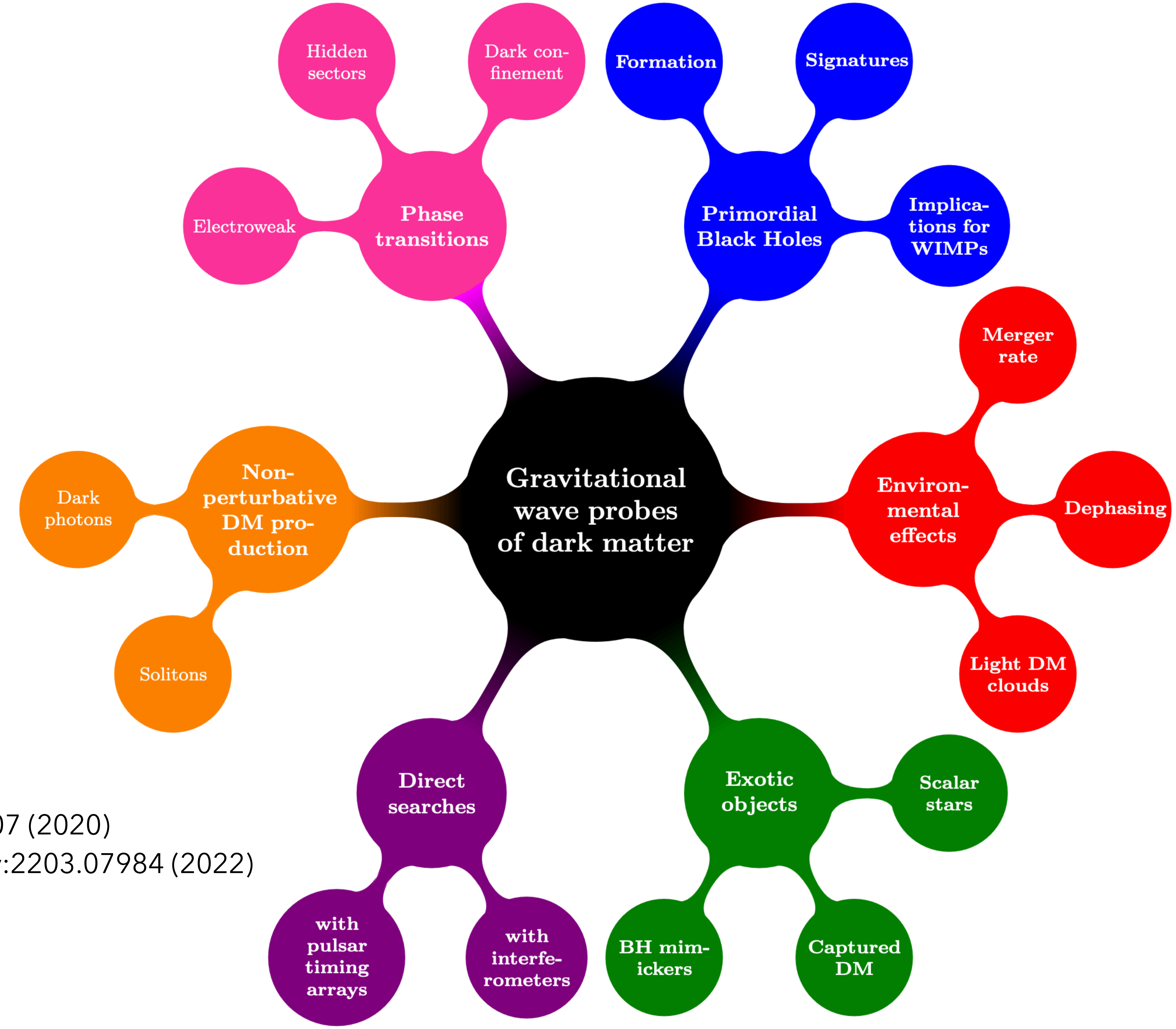
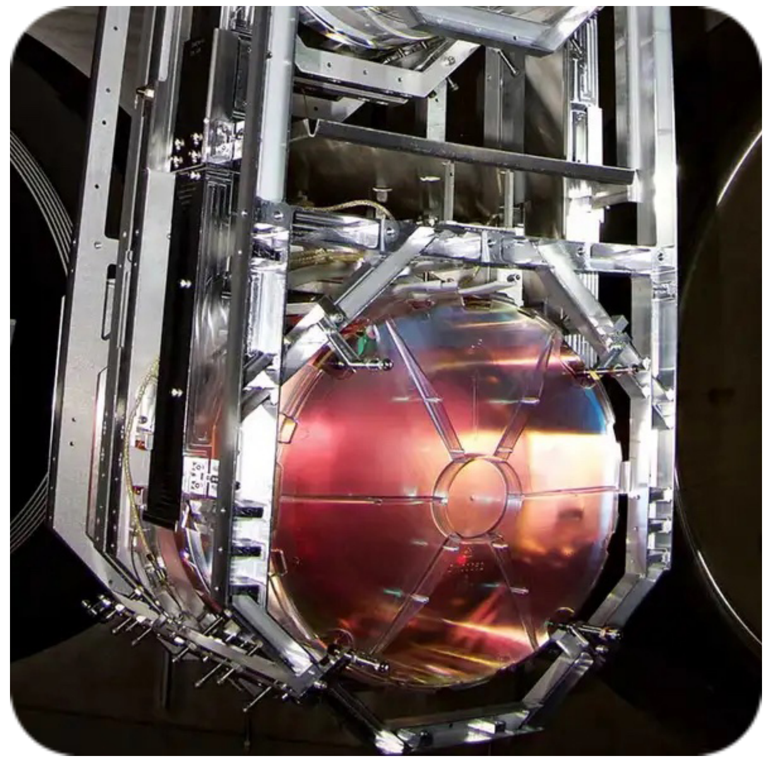


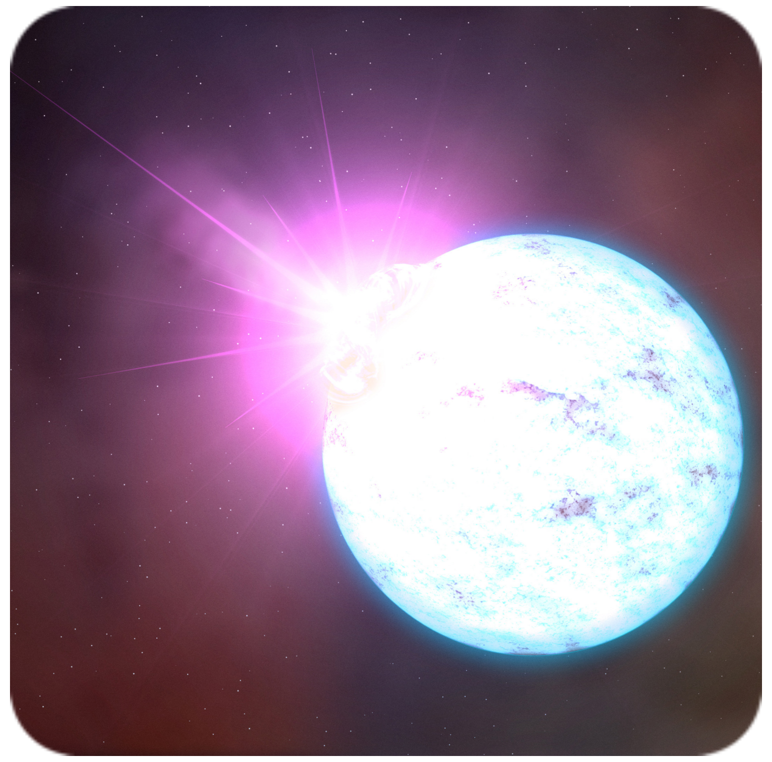
Figure from Bertone et al., SciPost Phys. Core 3, 007 (2020)
Also see Snowmass review: Baryakhtar et al., arXiv:2203.07984 (2022)

Probes of dark matter with GW detectors

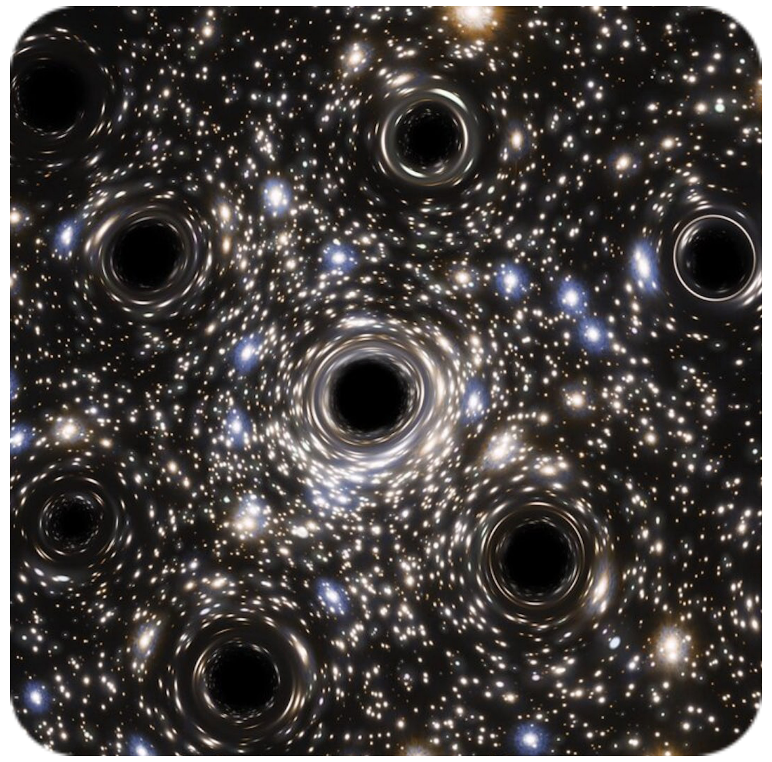
- *GW detectors are extremely sensitive to displacements —— can also be used as direct dark matter detectors through the field's weak coupling to normal matter.*
- *If neutron stars were to contain dark matter, there would be imprints in the star's tidal deformability, which may be accessible to GW observation.*
- *Primordial black holes are also dark matter candidates. Sub-solar-mass black hole inspirals are continuous GW sources.*
- *Astrophysical probes of ultralight boson condensates around black holes become possible via GW observation, by only assuming a coupling through gravity.*



Caltech/MIT/LIGO Lab



Goddard Space Flight Center/NASA



ESA/Hubble, N. Bartmann

Superradiance: Brito, Cardoso, Pani

Ultralight bosons

- *The **Standard Model** of particle physics has been tremendously successful but still **incomplete**, e.g., it is irreconcilable with General Relativity and does not contain any viable dark matter particle.*

- *Alternative beyond Standard Model theoretical frameworks predict the existence of **new ultralight boson particles**, including scalar (spin 0), vector (spin 1), and tensor (spin 2) fields.*

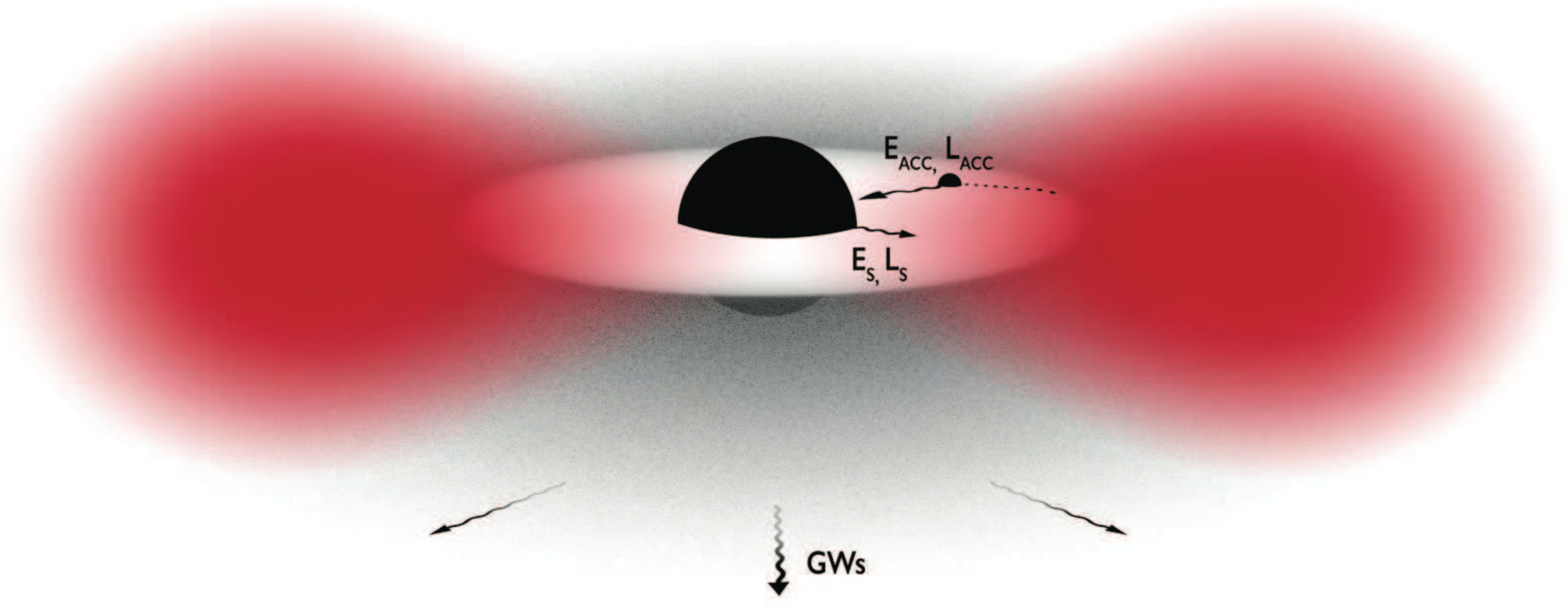
- *QCD axion (well motivated to solve the strong-CP problem), string axion, dark photon, etc. —— They are also **dark matter candidates**.*

- *Their model-dependent weak couplings to the Standard Model (if at all) and the vanishingly small mass make them **extremely difficult to detect by conventional lab experiments**.*

Bosons, black holes, GWs

- *Now we can appeal to the new experimental field and use* ***GW detectors*** *to search for them, taking advantage of their universal character of* ***gravitational*** *couplings.*

- *The ultralight boson field around a rapidly rotating BH can grow exponentially due to a phenomenon called "****superradiance****." A macroscopic cloud can form around the BH and generate* ***gravitational waves*** *that could be detected by GW detectors.*



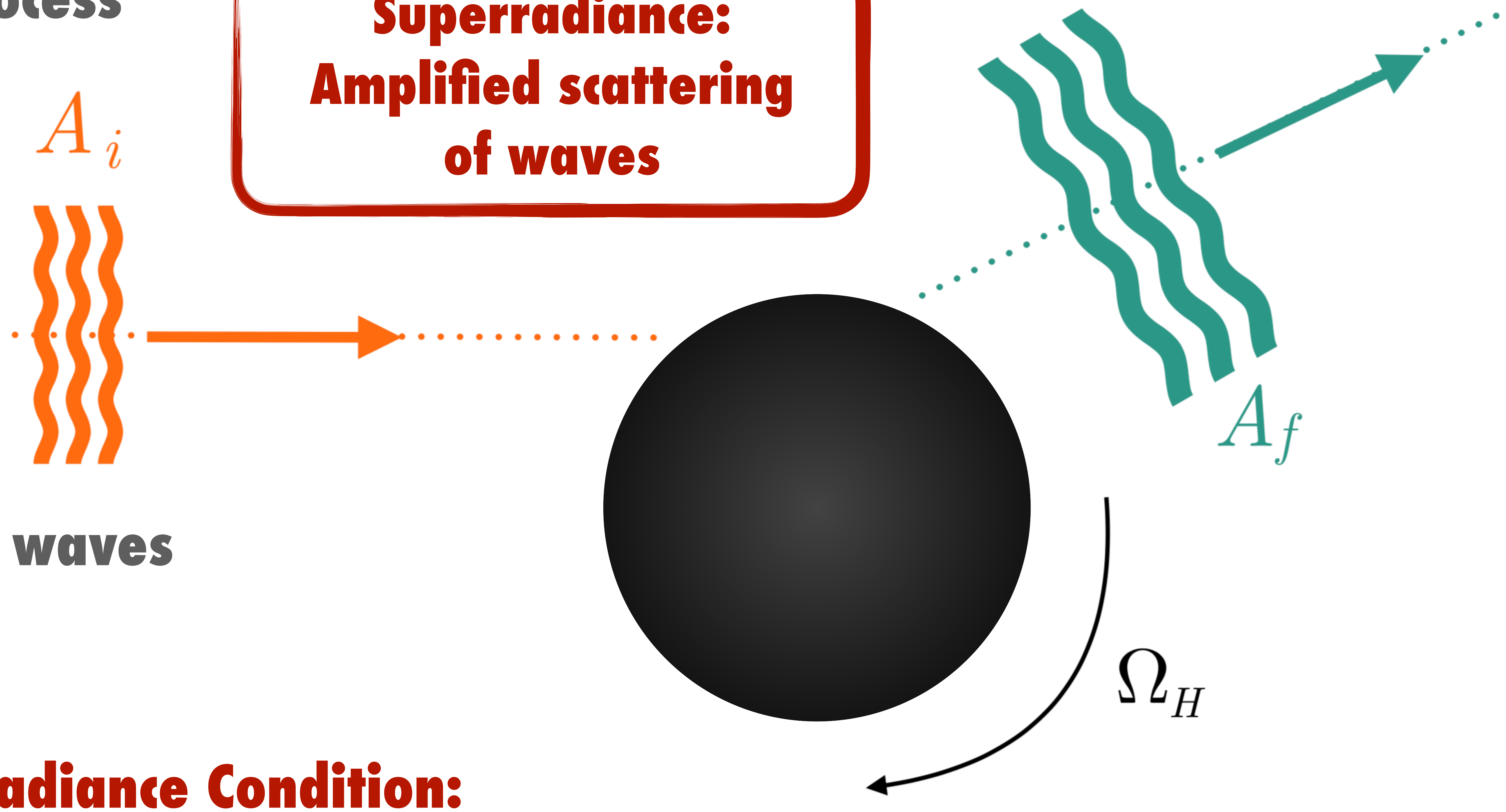
Brito, Cardoso, Pani (2015)

- *Even without detection, limits on gravitational-wave strain can be translated into interesting* ***constraints on boson properties****.*

Black hole superradiance

Penrose process

Superradiance: Amplified scattering of waves



Bosonic waves

Superradiance Condition:

$$\boxed{\omega \ /m < \Omega_H} \Longrightarrow \ A_i < A_f$$

wave frequency, ω ; azimuthal quantum number, m

Image credit: Isi

Superradiant instability

BH bomb (Press and Teukolsky)

$$\boxed{\omega\ /m < \Omega_H}$$

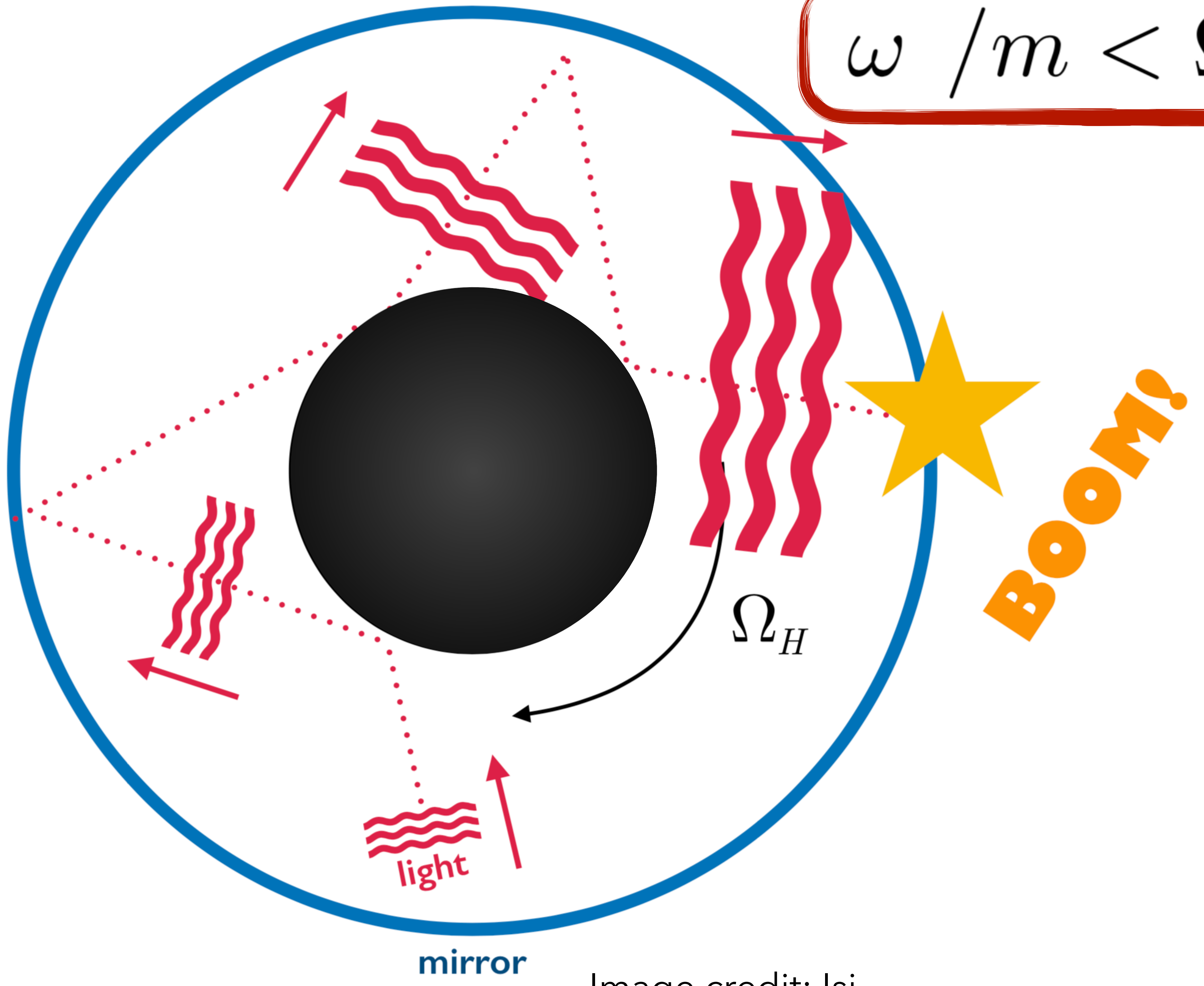


Image credit: Isi

- *With astrophysical BHs, we can probe boson mass (rest energy) range:* $\mu \equiv m_b c^2$

$$\mu \sim 10^{-20} - 10^{-9}\,\mathrm{eV}$$

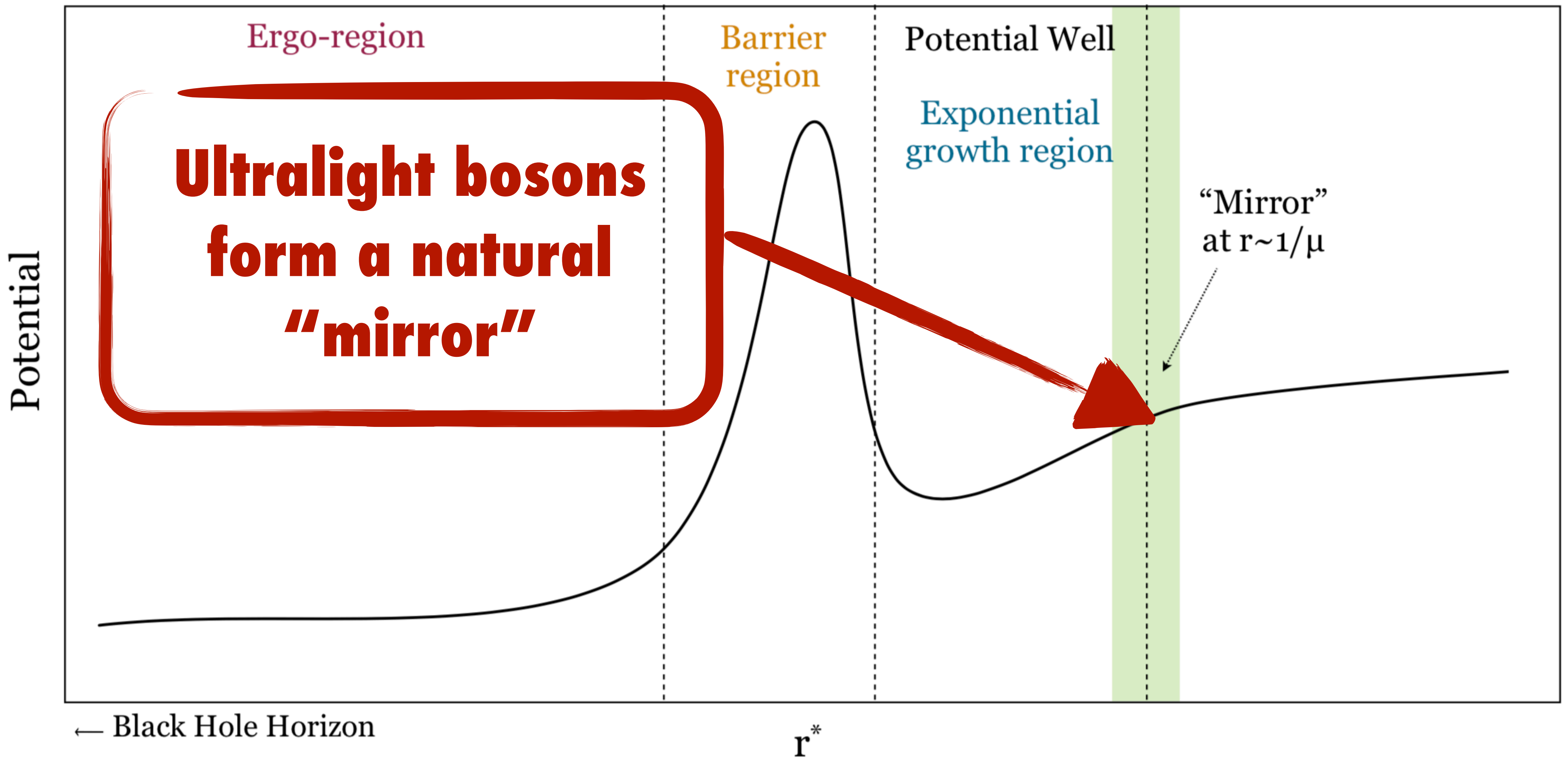
- **Confinement condition:**

  Compton wavelength ~ BH characteristic length

$$\boxed{\lambda_\mu \sim r_g}$$

$$\lambda_\mu \equiv 2\pi \lambda\!\!\!^{-}_\mu \equiv h/(m_b c) \qquad r_g \equiv GM/c^2$$

Arvanitaki & Dubovsky, 2011



Superradiance + Confinement = Instability

Mechanisms of gravitational radiation

- ***Annihilation*** – *two bosons annihilate into a graviton (cf. an electron and a positron annihilate into a photon)*

Promising continuous/long-lasting sources

- ***Level transition*** – *boson transitions between energy levels (cf. electrons jump in the hydrogen atom)*

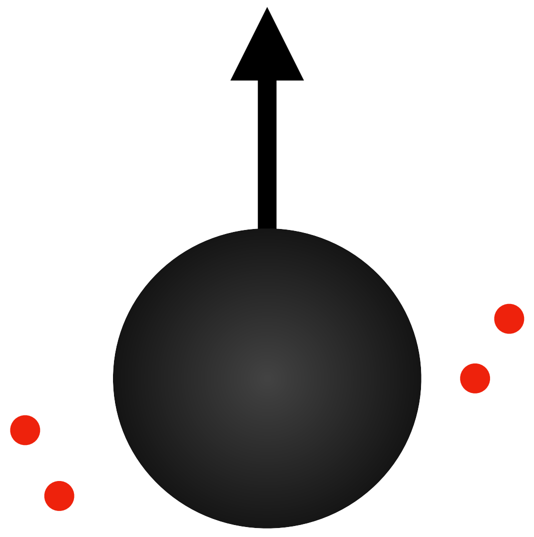
Need more than one level occupied with considerable numbers
Too weak for young BHs (scalar); short observational window; frequency not preferred

- ***"Bosenova"*** – *(in some cases) abrupt collapse of the cloud due to particle self-interactions* **Too short (burst-like)**

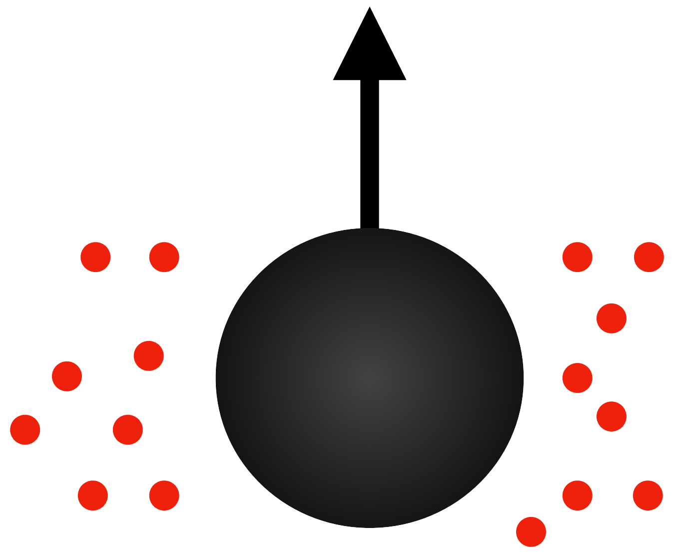
More interested in fastest growing level
Scalar field: j = l = m =1, s = n = 0
Vector field: j = s = m =1, l = n = 0

j – total angular momentum; l – orbital azimuthal; m – (magnetic) azimuthal
s – spin angular momentum; n – radial; n+l+1 – principal

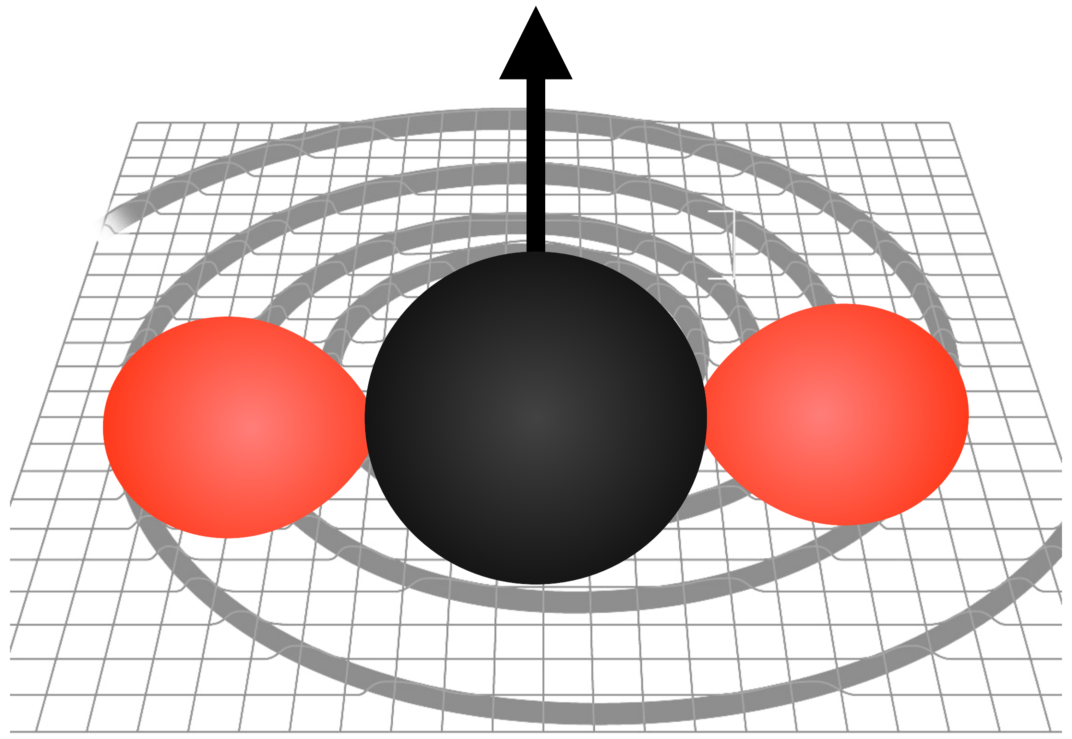
Superradiance, boson clouds, GWs



Quantum fluctuation

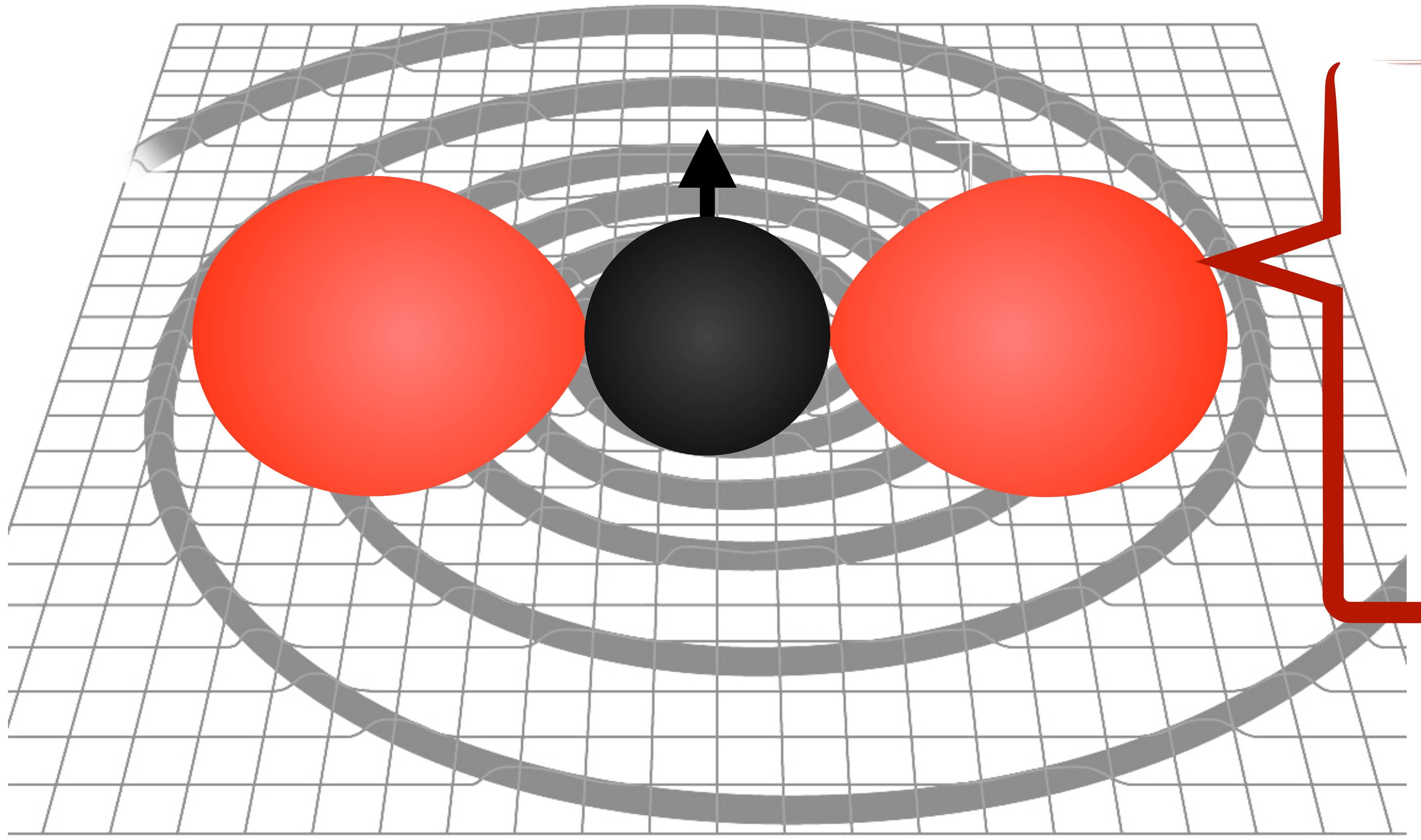


$$\omega_\mu / m < \Omega_{\rm BH}$$



Scalar cloud (l = m = 1)

$\lambda_\mu \sim r_g$ ***"resonate"***



$$\omega_{\rm GW} = 2\omega_{\bar{n}}$$

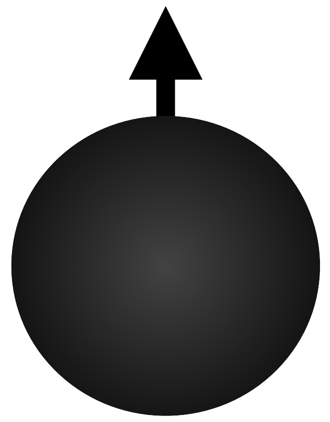
Continuous quasi-monochromatic signals (small positive $\dot{f}$)

$$r_c \sim \frac{\bar{n}^2}{\alpha^2}\frac{GM}{c^2}$$

Keep growing until $\omega_\mu / m < \Omega_{\rm BH}$ **is no longer satisfied**

Number of bosons occupying a level >10^{77}

Cloud mass may reach ~10% of the BH mass



Cloud dissipated
BH spun down
(on a very long timescale)

Parameter space

Ground-based detector

$$10^{-14} \lesssim \mu/\mathrm{eV} \lesssim 10^{-11}$$

Space-based detector

$$10^{-19} \lesssim \mu/\mathrm{eV} \lesssim 10^{-15}$$

Brito+ (2017)

- *GW emission frequency is determined by the particle's energy (mass)* $\omega_{\mathrm{GW}} = 2\omega_{\bar{n}}$
- *Can estimate the emission frequency for a given BH!*

$$f = \frac{\omega_\mu}{\pi} \approx \frac{\alpha}{\pi r_g} \approx 645\,\mathrm{Hz}\left(\frac{10 M_\odot}{M_i}\right)\left(\frac{\alpha}{0.1}\right)$$

Fine structure constant $\alpha \equiv \frac{GM}{c}\frac{m_b}{\hbar}$

- *Emission timescale*

Scalar $\tau_{\mathrm{GW}}^{(\mathrm{s})} \approx 6.5 \times 10^4\ \mathrm{yr}\left(\frac{M}{10\ M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{15}\frac{1}{\chi_i}$

Vector $\tau_{\mathrm{GW}}^{(\mathrm{v})} \approx 33\ \mathrm{days}\left(\frac{M}{10 M_\odot}\right)\left(\frac{0.1}{\alpha}\right)^{11}\left(\frac{0.1}{\chi_i - \chi_f}\right)$

A given BH could "resonate" with bosons in a narrow mass range, and hence emit GWs at frequencies in a limited band on a predictable timescale

Population and stochastic background studies

- ***Constraints obtained from black hole spin measurements***

  e.g. [Arvanitaki et al. 2017, Brito et al. 2017, Baryakhtar et al. 2017, Cardoso et al. 2018, Ng et al., PRD 2021, Ng et al. PRL 2021]

- ***Constraints from searches for stochastic GW background***

  e.g. [Tsukada et al. 2019, Tsukada et al. 2021]

There are systematics and uncertainties associated with spin measurements and assumptions are made for BH populations

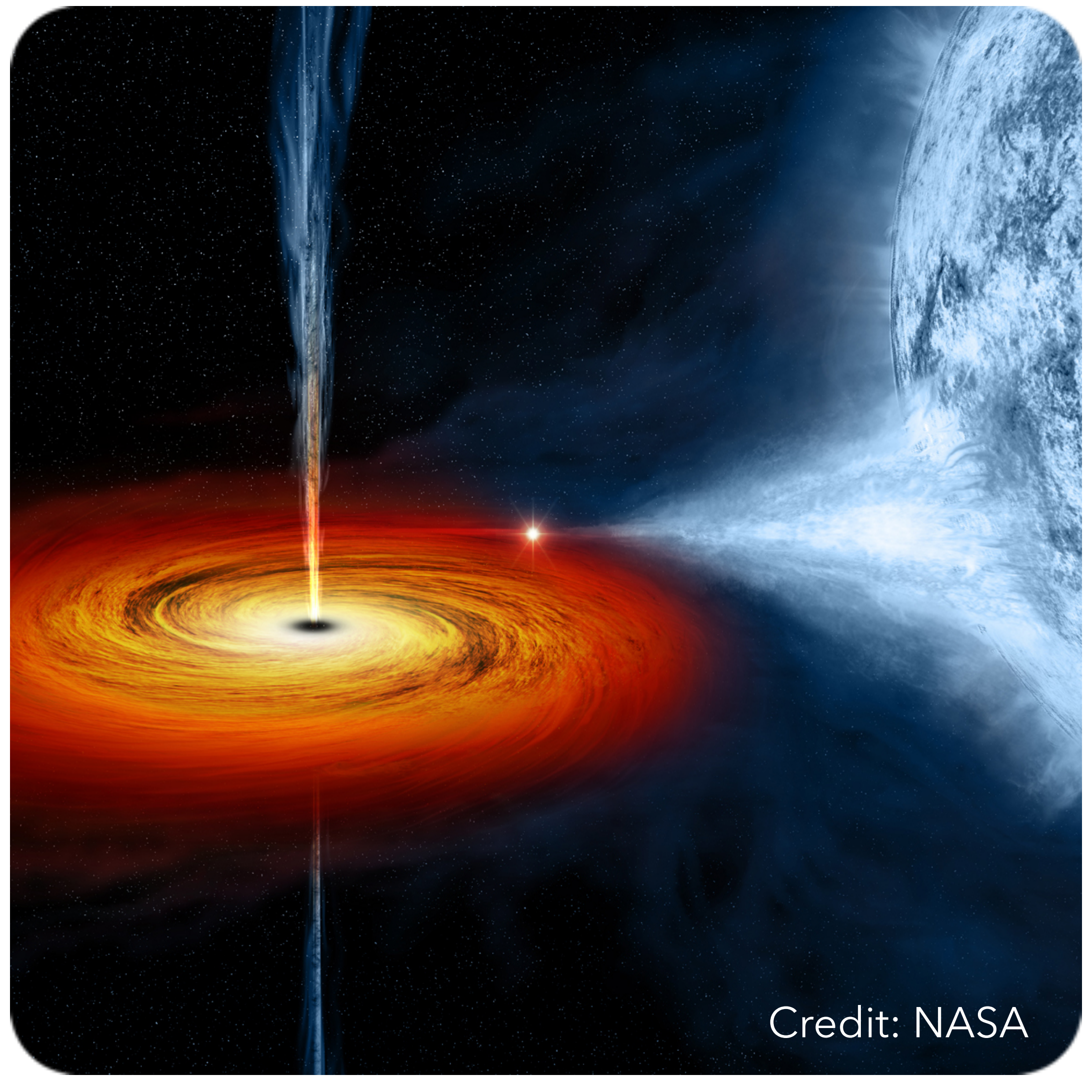
Searches for individual galactic sources (examples)

- ***An all-sky search for scalar clouds around unknown BHs in O3***

  [Abbott+ PRD 105, 102001 (2022)]

  - *Semiquantitative constraints on the possible presence of emitting boson clouds in our Galaxy*
  - *E.g., systems **younger than** $\sim 10^3$ **yrs** are disfavored in the whole Galaxy for **boson masses** $\sim [2.5,\ 10] \times 10^{-13}\,\mathrm{eV}$ for a maximum BH mass of $50 M_\odot$ and $\sim [1.2,\ 10] \times 10^{-13}\,\mathrm{eV}$ for a maximum BH mass of $100 M_\odot$ (using Kroupa mass distribution with PDF $\propto m^{-2.3}$)*

Credit: NASA



Credit: NASA

- ***A dedicated search for scalars targeting Cygnus X-1 in O2***

  [Sun+ PRD 101, 063020 (2020)]

  - *E.g., **boson masses** $[6.4,\ 8.0] \times 10^{-13}\,\mathrm{eV}$ are disfavored assuming a BH age of 5×10^6 **yrs** and $[6.3,\ 13.2] \times 10^{-13}\,\mathrm{eV}$ assuming a BH age of 10^5 **yrs***

Unknown black holes or black holes with unknown history are not ideal in order to obtain robust constraints

Ideal targets — remnant BHs formed in CBCs

Witnessed birth → When

Constrained position → Where

Measured BH mass/spin → What parameter space

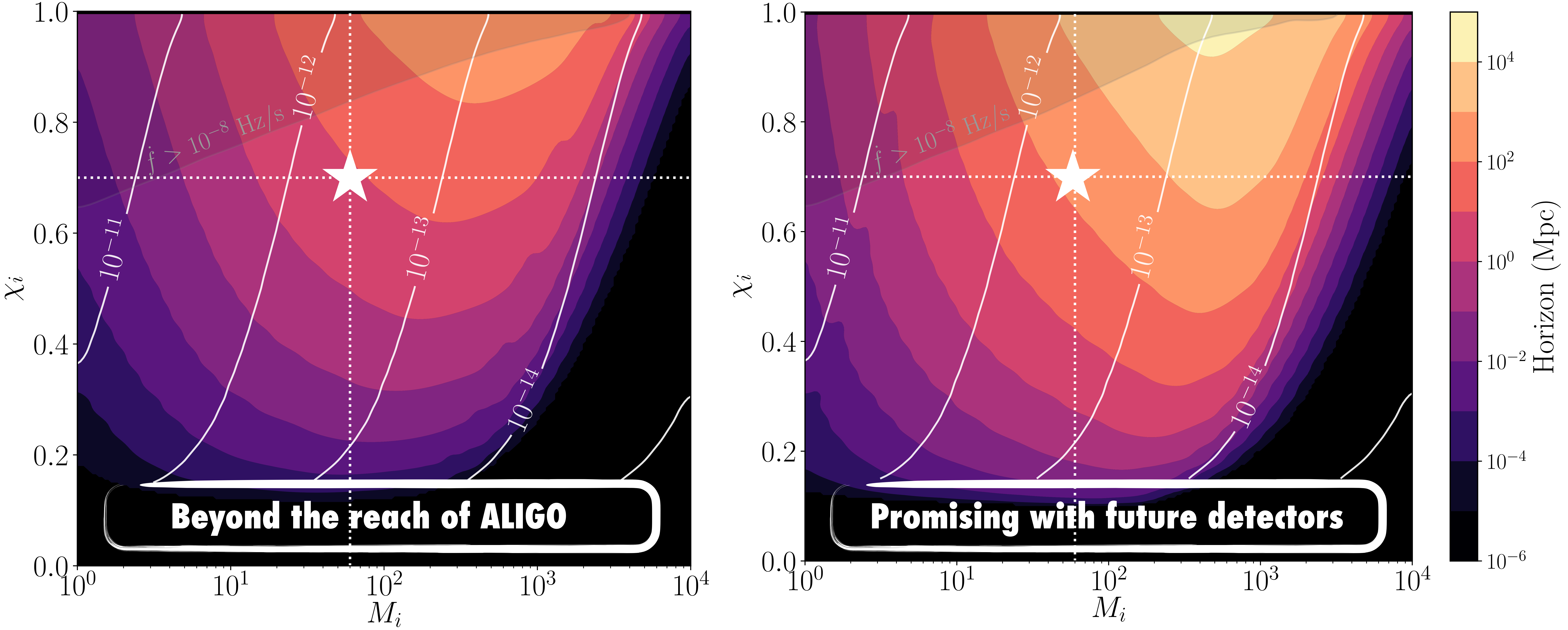
Measured luminosity distance, inclination, etc. → How far can we reach

Search methods are available, e.g., Sun+ 2018, D'Antonio+ 2018, Isi+ 2019, Jones+ 2023

Horizon distance (scalar)

1 detector, 1-year observation

Isi, Sun, Brito, Melatos (2019)



$M_i = 60\ M_\odot \quad \chi_i = 0.70$

[GW150914] can reach ~10 Mpc

$M_i = 60\ M_\odot \quad \chi_i = 0.70$

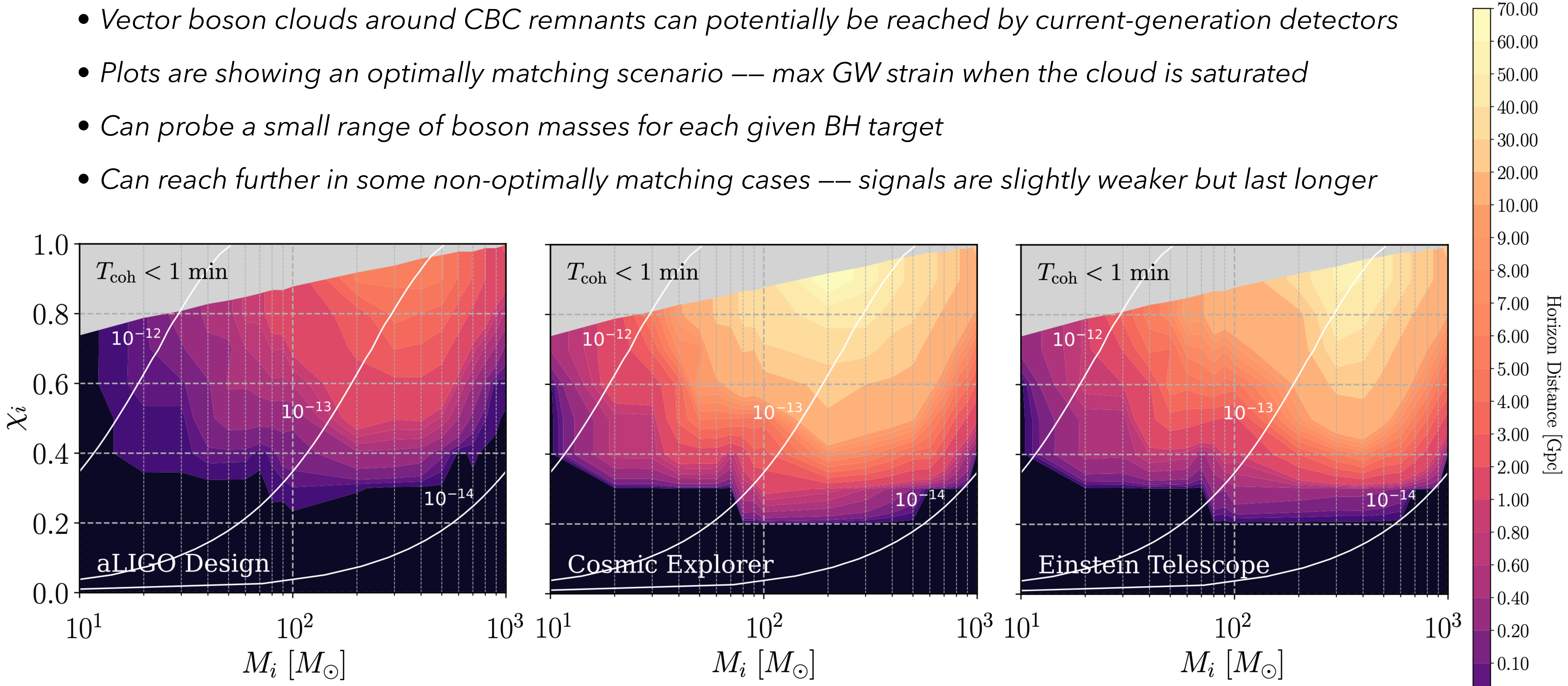
[GW150914] can reach ~160 Mpc

Prospect for vectors

- *Vector clouds have much stronger radiation power*
- *But meantime the signal is much shorter*
- *Do we have a better chance detecting vector signals?*

Horizon distance (vector)

- *Vector boson clouds around CBC remnants can potentially be reached by current-generation detectors*
- *Plots are showing an optimally matching scenario —— max GW strain when the cloud is saturated*
- *Can probe a small range of boson masses for each given BH target*
- *Can reach further in some non-optimally matching cases —— signals are slightly weaker but last longer*



2 aLIGO, 1 CE, 1ET, observation duration depends on emission timescale $\tau_{\rm GW}$

Jones, Sun, Siemonsen, East, Scott, Wette, arXiv:2305.00401 (2023)

Summary

- *GW detectors provide a new way to probe the dark sector in the universe, including yet-undiscovered* ***ultralight bosons****. Various studies have already been carried out.*

- ***Newly born BHs*** *formed in mergers are ideal target sources for directed searches. Observations for* ***scalars*** *will become promising with future detectors.* ***Vectors*** *are potentially at the reach of current-generation detectors; searches are being planned.*

- *Future studies may* ***combine*** *theoretical predictions, gravitational-wave search results, and constraints from other types of studies.*

Thanks!

Questions?

The gravitational "atom"

- *Solving the Schrödinger equation over a Kerr background, one gets:*

$$E_{\bar{n}} \approx \mu\left(1 - \frac{1}{2}\frac{\alpha^2}{\bar{n}^2} + \cdots\right)$$

Hydrogen atom!

Principal quantum number

$$\bar{n} = n + l + 1$$

Fine structure constant

$$\alpha \equiv \frac{r_g}{\lambda\!\!\!^{-}_\mu} = \frac{GM}{c}\frac{m_b}{\hbar}$$

- *BUT – it's different from a hydrogen atom*
  - *System is non-Hermitian (ingoing boundary condition at horizon)*
  - *Bosons rather than fermions*

- **Occupation number of a given quantum state grows exponentially!!**
- **One energy level dominates at a given time.**

Searches for individual galactic sources

BHs in galactic X-ray binaries e.g., [Sun+ PRD 101, 063020 (2020)]	• *Well-localized* • *Unknown age and history* • *Systematics affecting the spin measurements* • *Not well understood impact from the active environment* • *Relatively low BH mass* • *Search challenges due to the binary motion*
Isolated galactic BHs e.g., [Abbott+ PRD 105, 102001 (2022)]	• *Clean environment, no impact from binary motion* • *Unknown location (need an all-sky blind search)* • *Contingent on BH populations* • *Unknown age, spin, etc.*