GRAVITATIONAL WAVES: FROM DETECTION TO NEW PHYSICS SEARCHES

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Lecture 1 June 29. 2020

Today

- Noise at LIGO (finishing yesterday's lecture)

- Pulsar Timing for Gravitational Waves and Dark Matter

- Introduction to Black hole superradiance

Gravitational Wave Signals

Gravitational wave strain $h = \left(\frac{4G_N P}{r^2\omega^2}\right)^{1/2} \sim \frac{\Delta L}{L}$

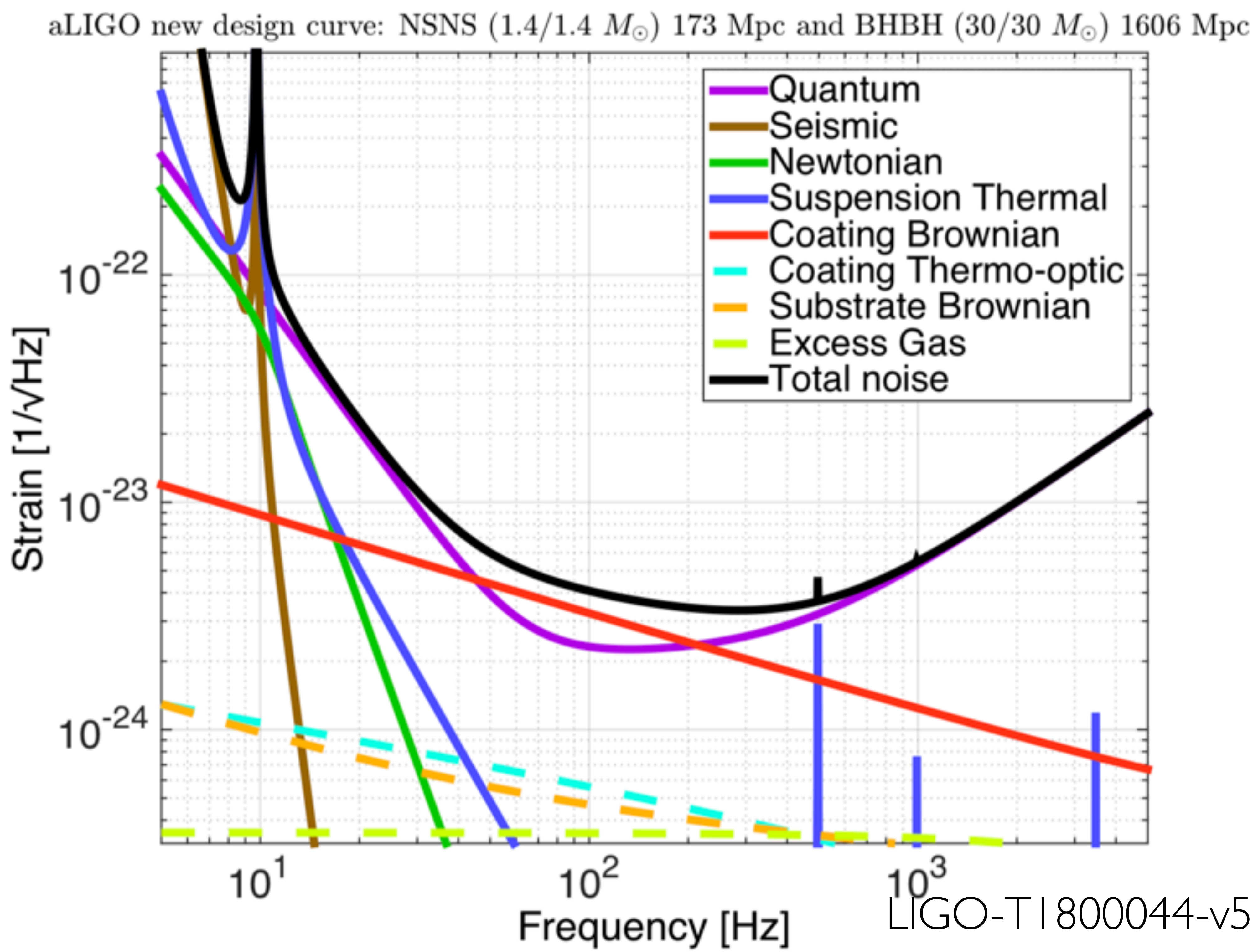
Advanced LIGO

Advanced VIRGO

Advanced LIGO and VIRGO already made several discoveries

Goal to reach target sensitivity in the next years

Gravitational Wave Noise



LIGO-T1800044-v5

Figure 1: Updated estimate of the Advanced LIGO design curve.

Noise in Interferometers

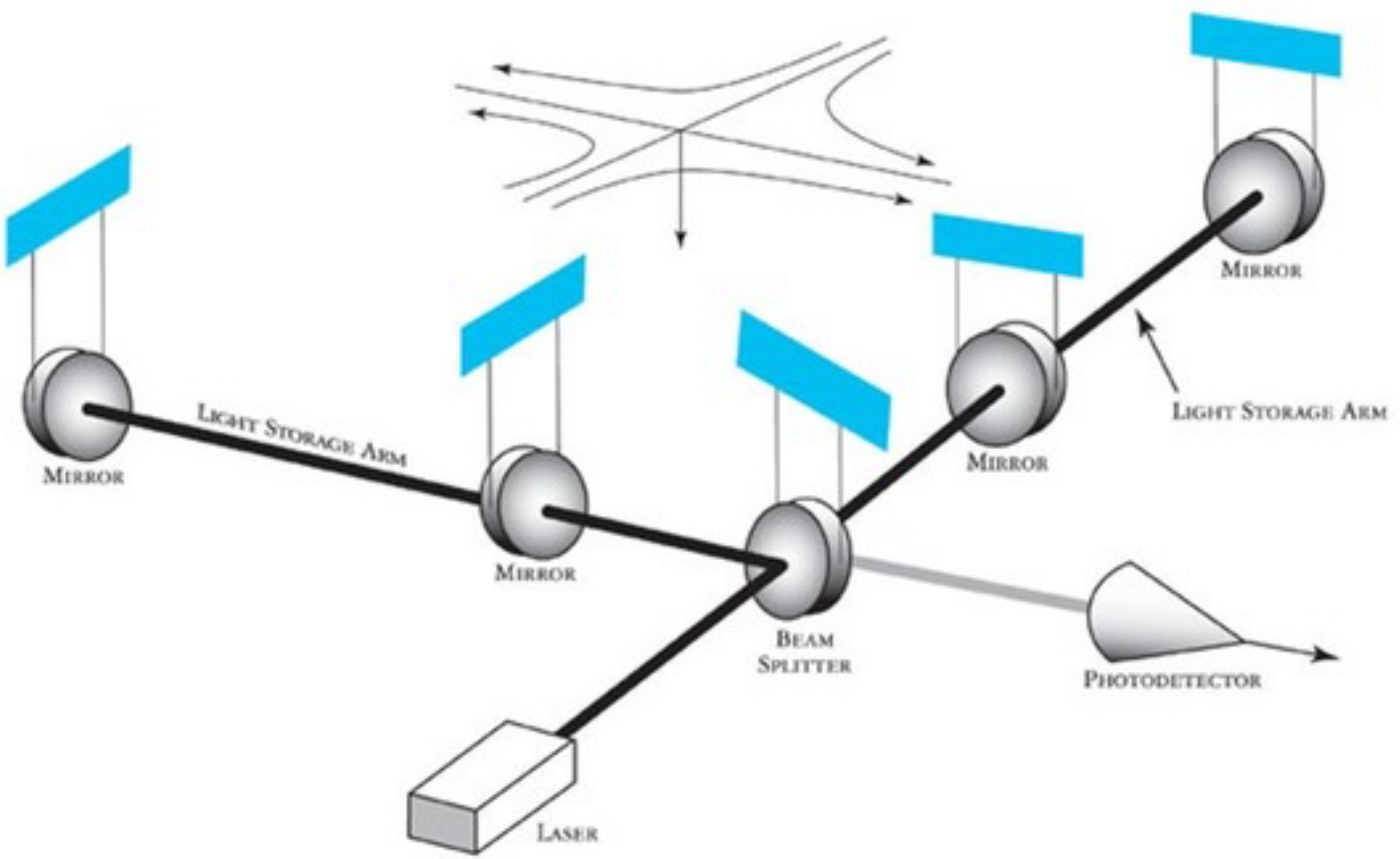
- What are the limiting noise sources?

- Seismic noise, requires passive and active isolation

- Quantum nature of light: shot noise and radiation pressure

Signal in Interferometers

- A gravitational wave arriving at the interferometer will change the relative time travel in the two arms, changing the interference pattern



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- A gravitational wave arriving at the interferometer will change the relative time travel in the two arms, changing the interference pattern
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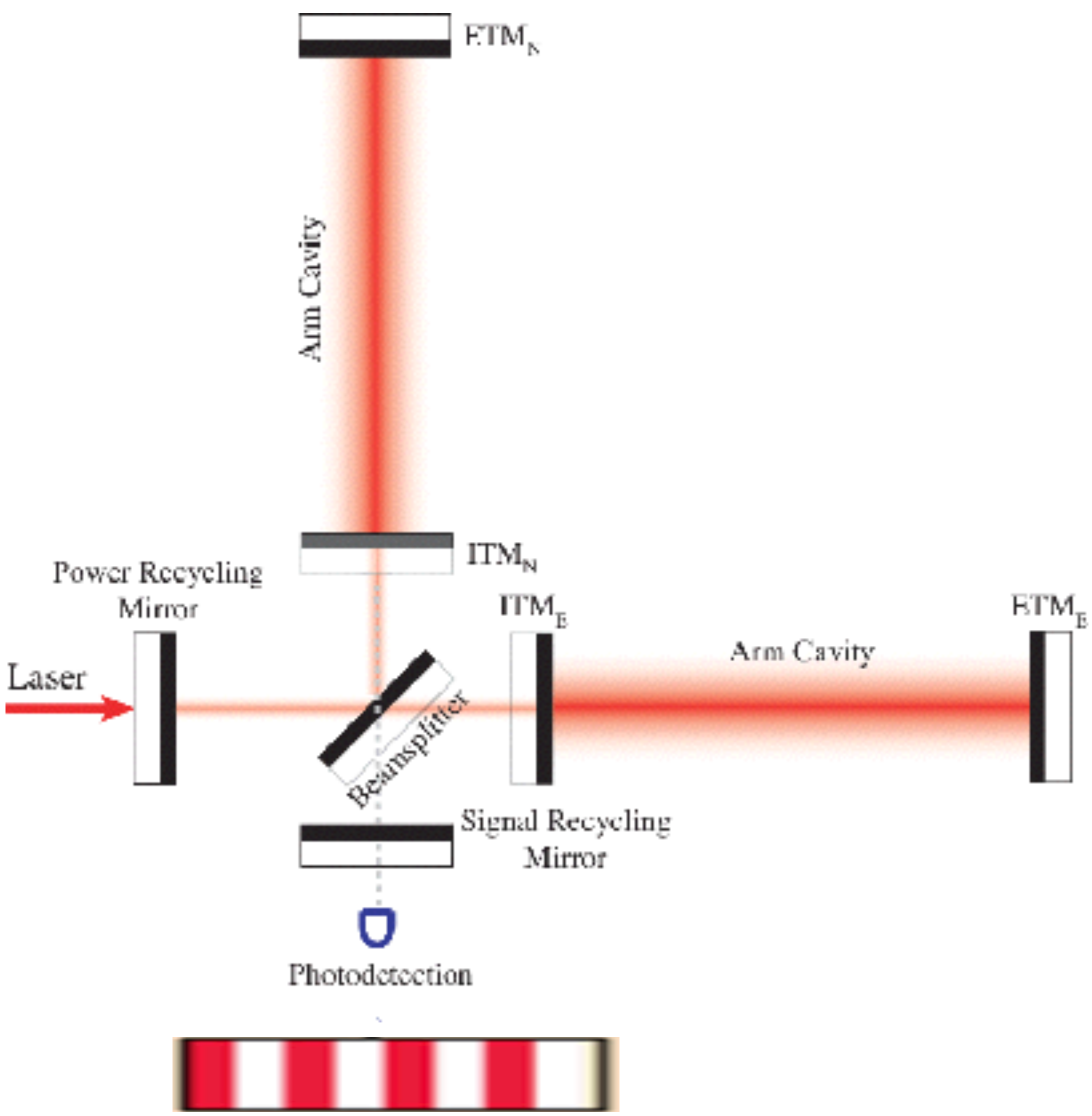

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$$P_{out} = P_{in} \cos^2(k_x L_x - k_y L_y)$$

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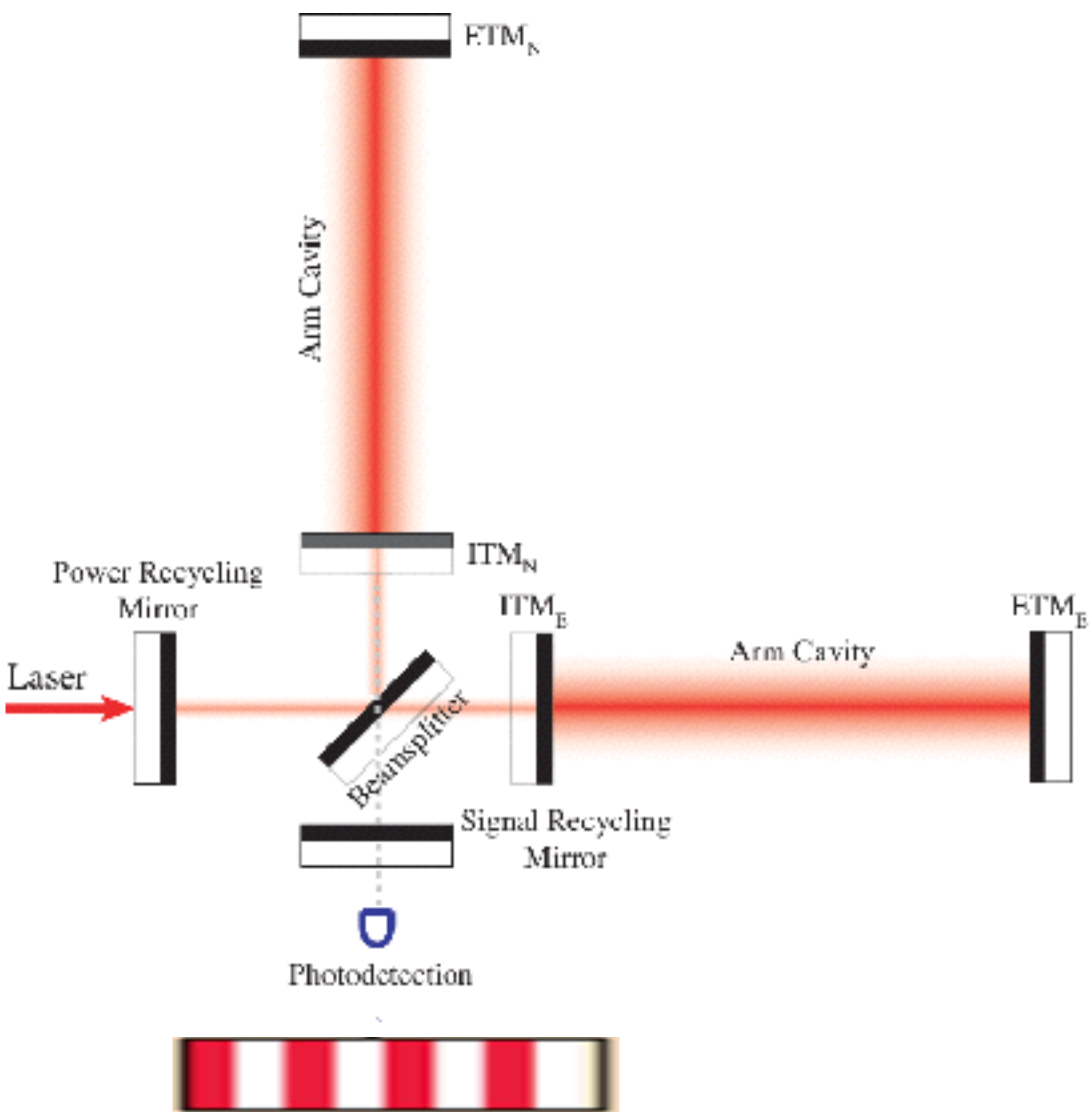

- The power at the output is

$$P_{out} = P_{in} \cos^2(k_x L_x - k_y L_y)$$

- Adding multiple `bounces' increases the effective length of the arms, giving a phase difference at the output of

$$\Delta\phi = h \frac{2NL}{c} \frac{2\pi c}{\lambda}$$

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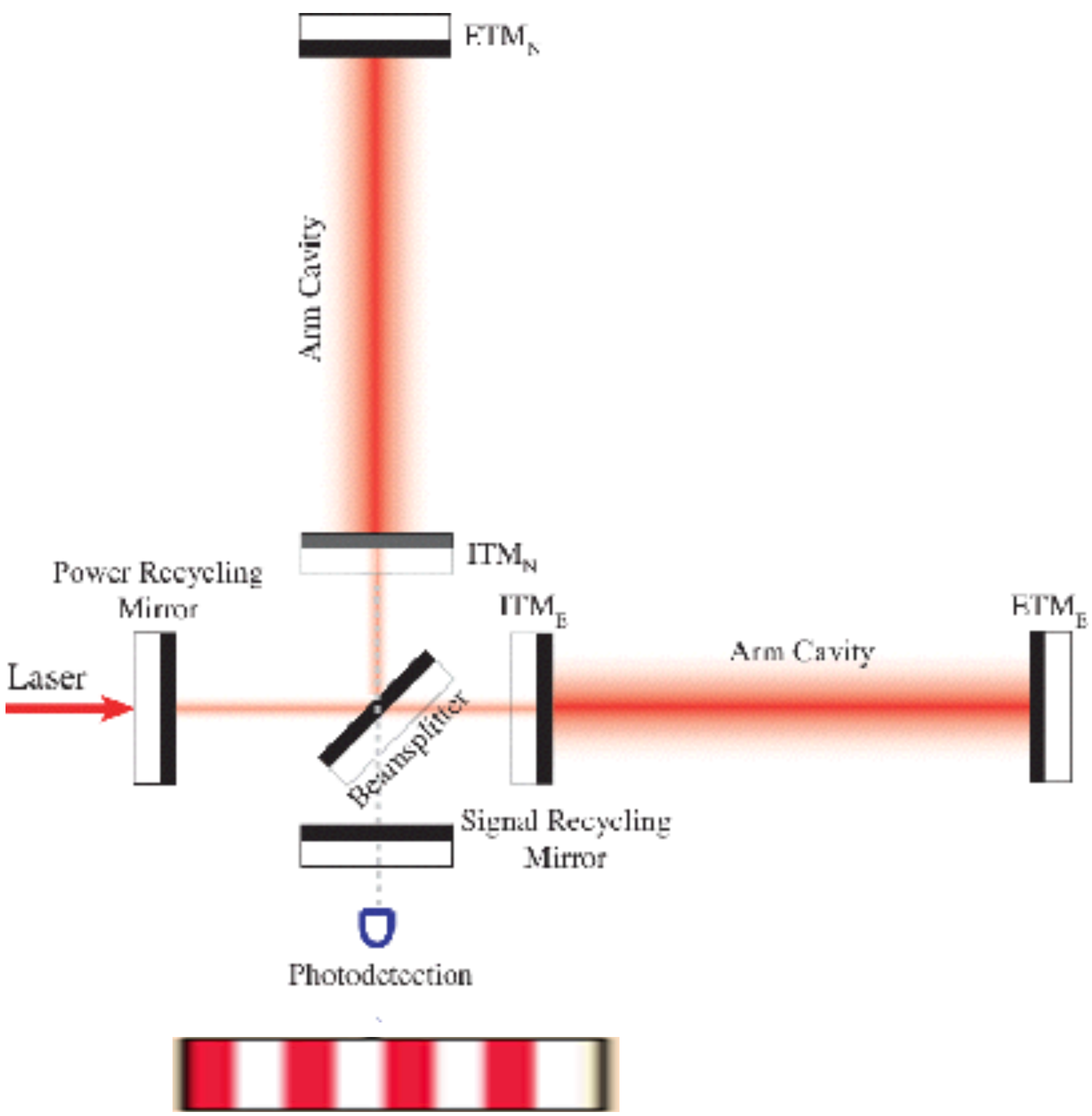

- The wavelength of the LIGO laser is 1064 nm and the arms are 4km
- N ~100

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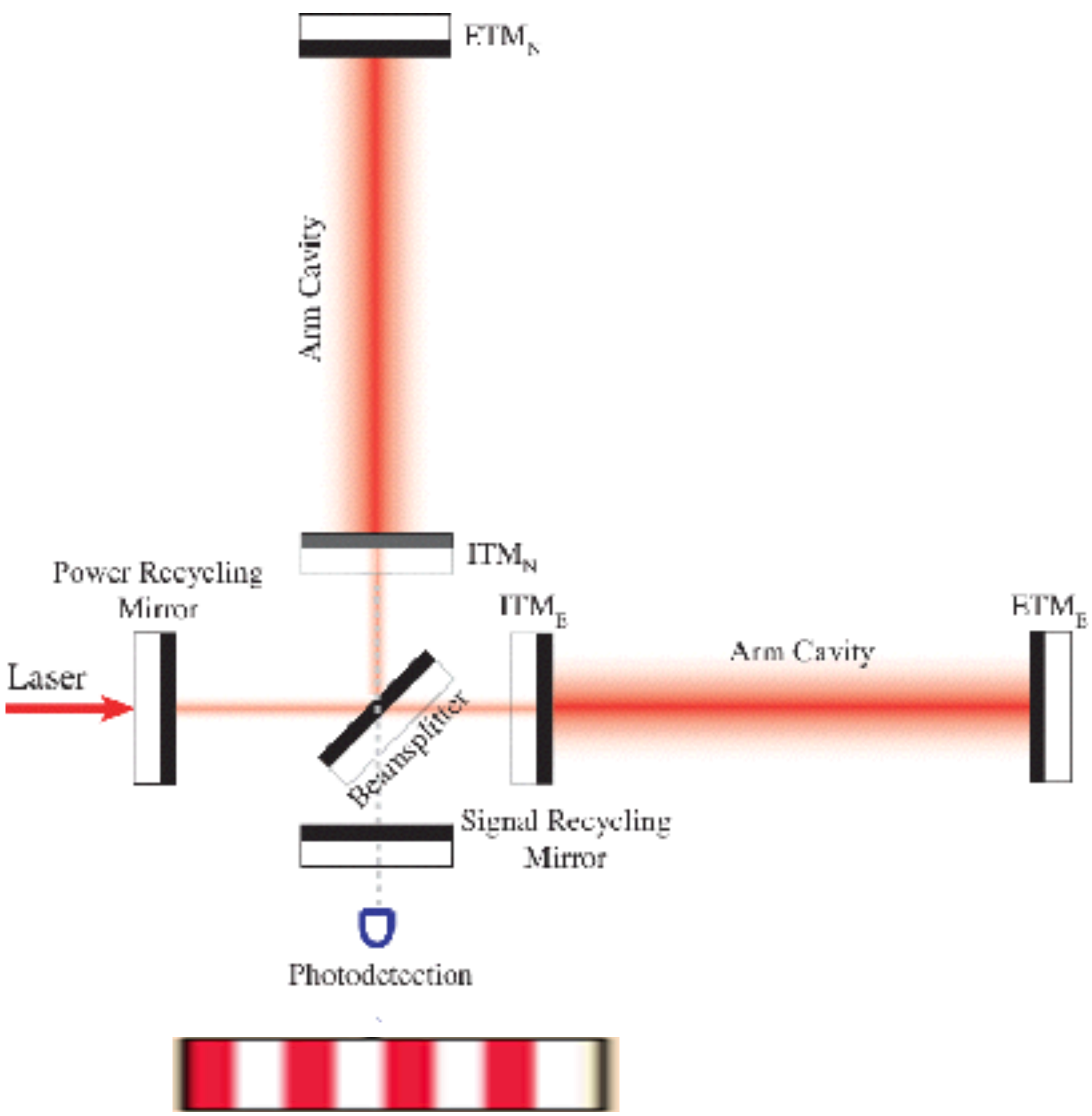

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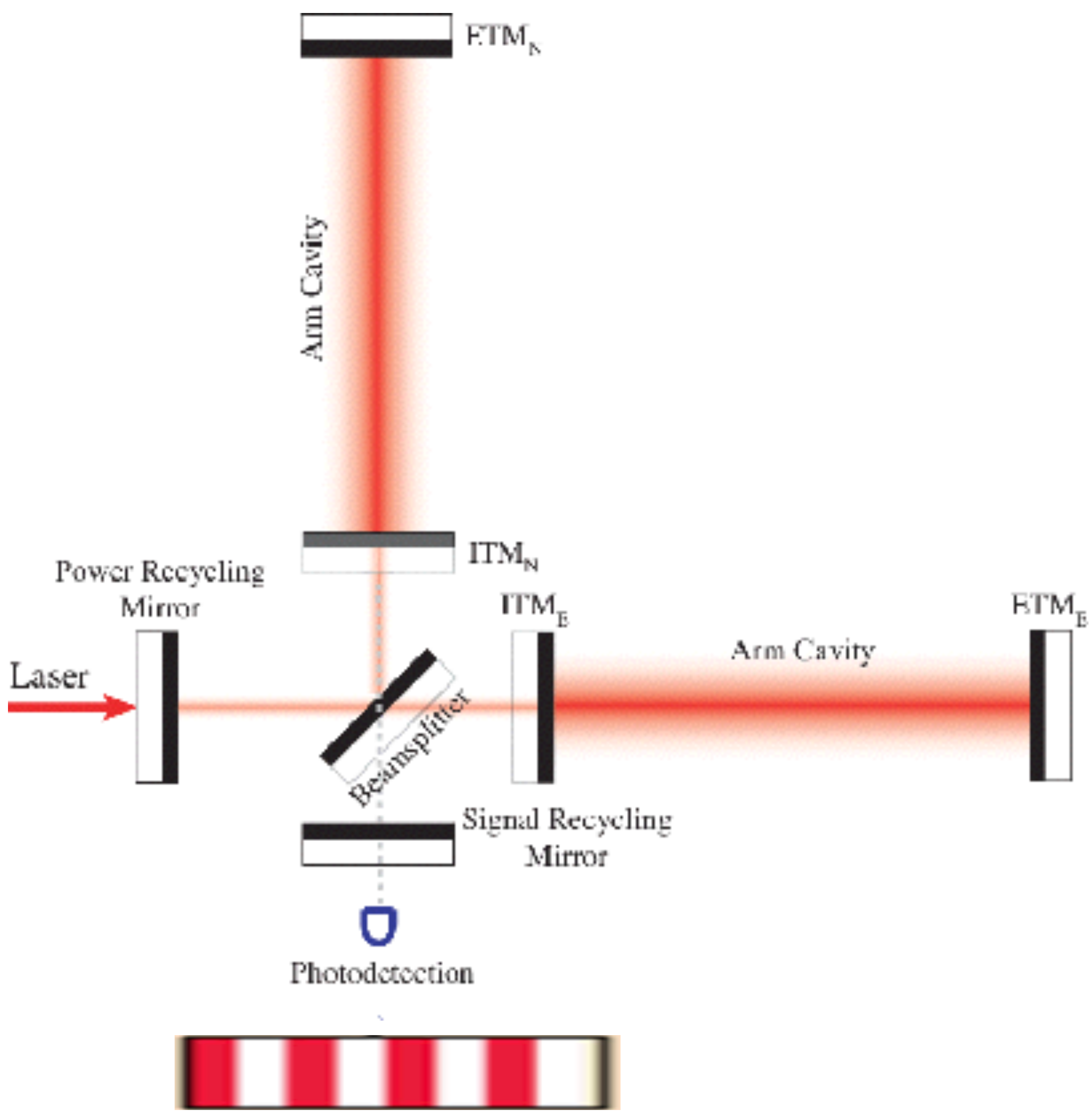
$$\Delta\phi = h\frac{2NL}{c}\frac{2\pi c}{\lambda}$$

- A change in phase of order 1 (light to dark) then corresponds to seeing strains of 10^-12
- To see a difference in power at the level of distinguishing phases of 1 part in 10^10, need 10^20 photons (within measurement time)!

Shot Noise:

- Changes in the number of photons hitting the detector can looks like the power is changing, i.e. the phase difference is changing.



- If on average the power is a kW, we have10^20 photons in 0.01 sec to measure 100 Hz frueqnecies
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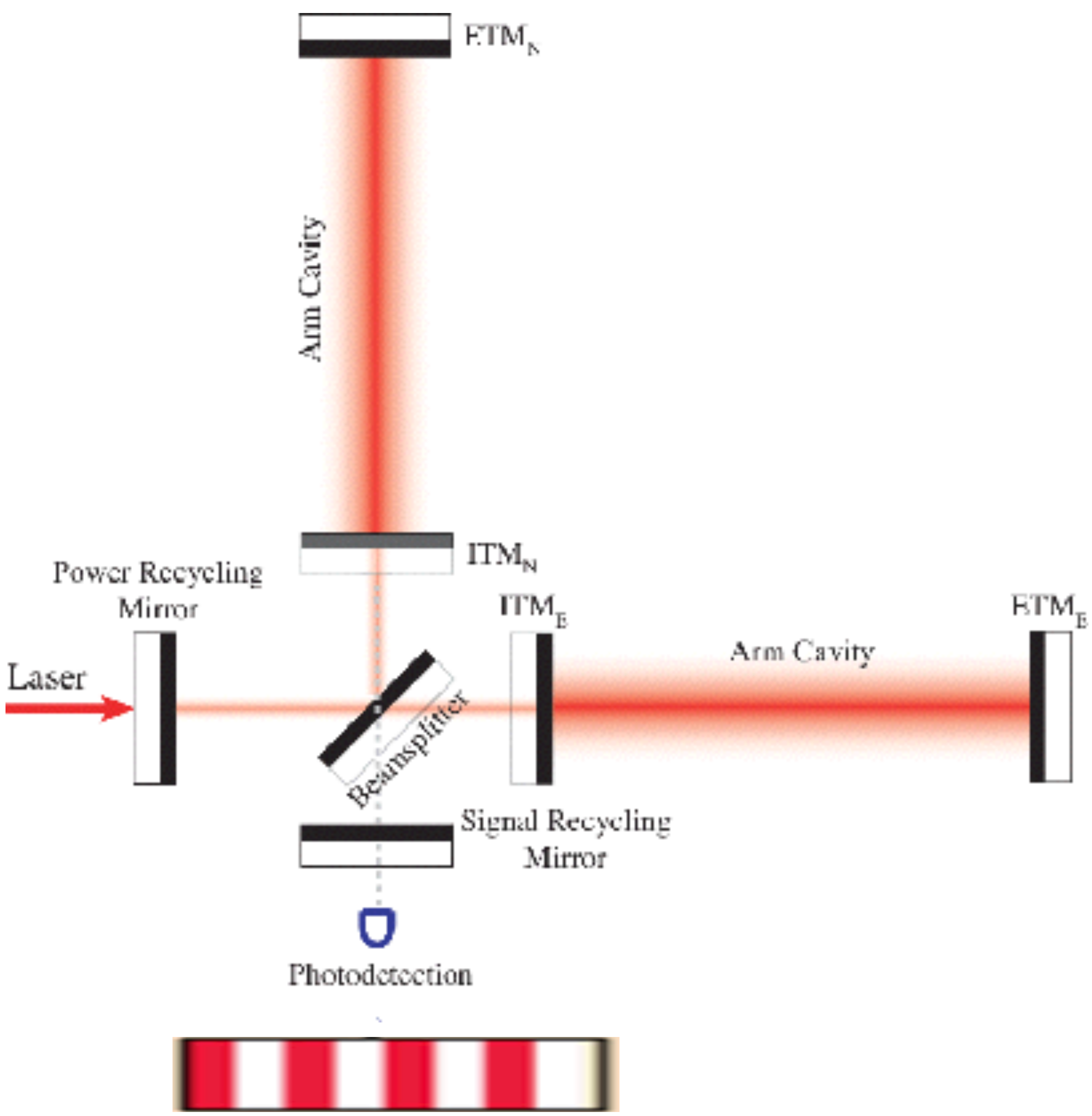
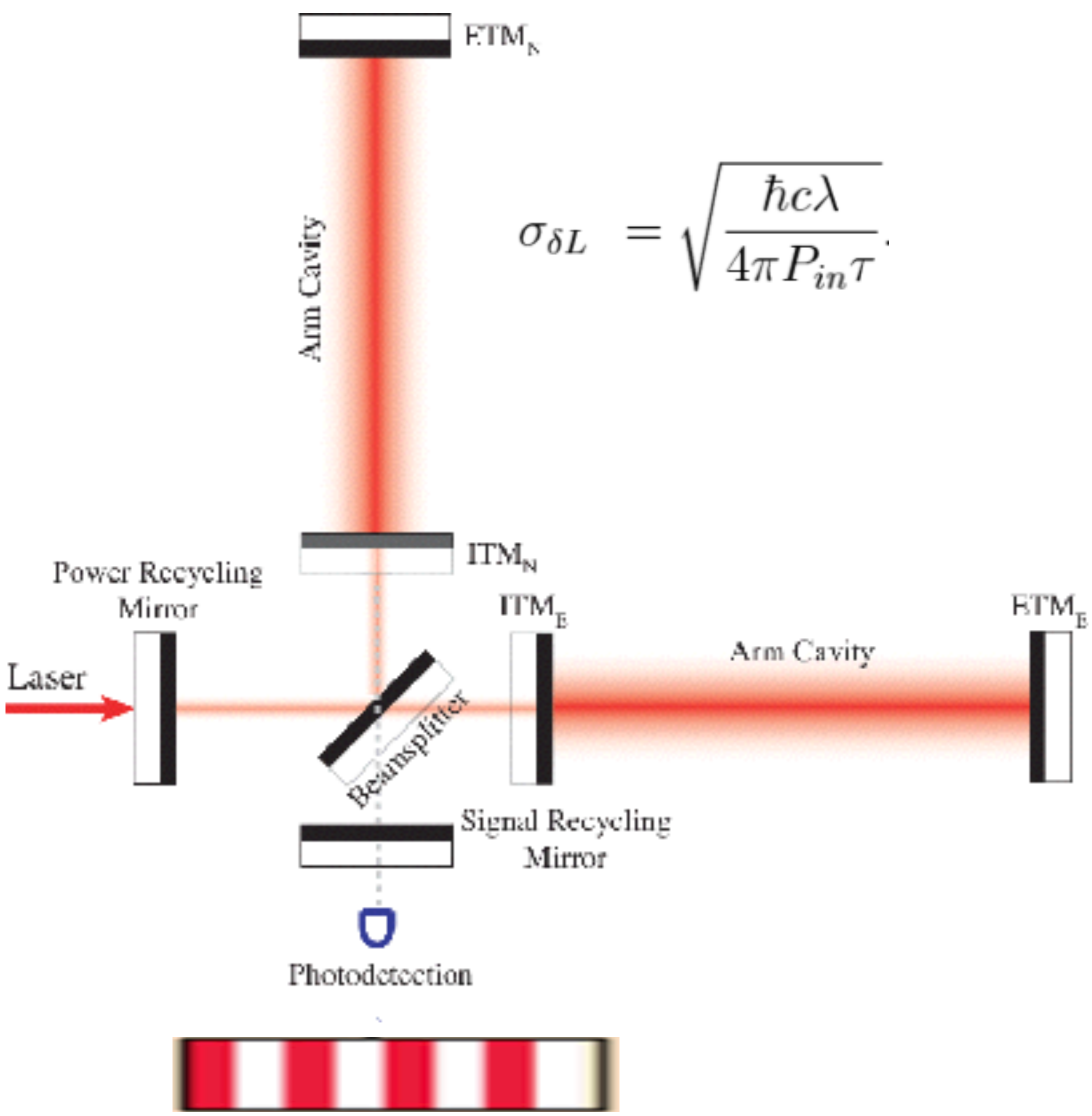


- If on average the power is a kW, we have10^20 photons in 0.01 sec to measure 100 Hz frueqnecies
- Then the flucuations in photon number are poissonian, i.e. dN ~10^10 photons
- These looks like changes in arm length of

$$\sigma_{\delta L} = \frac{\sigma_N}{N} / \frac{1}{P_{out}} \frac{dP_{out}}{dL} = \sqrt{\frac{\hbar c \lambda}{4\pi P_{in} \tau}}.$$

Turn up the power?

- Increasing length of the interferometer increases signal but not noise. decreasing wavelength can help
- Clearly increasing power gets rid of this issue



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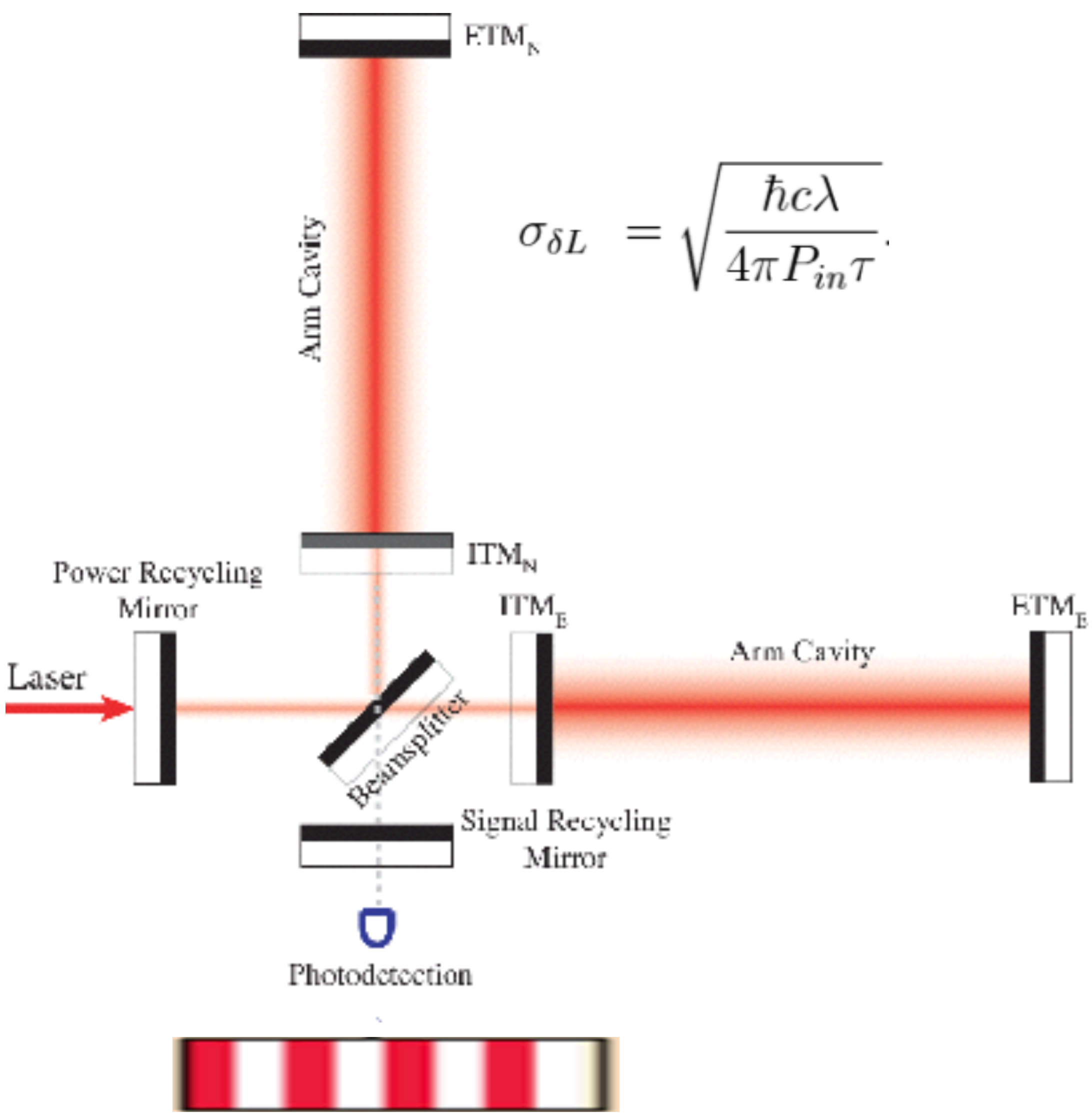

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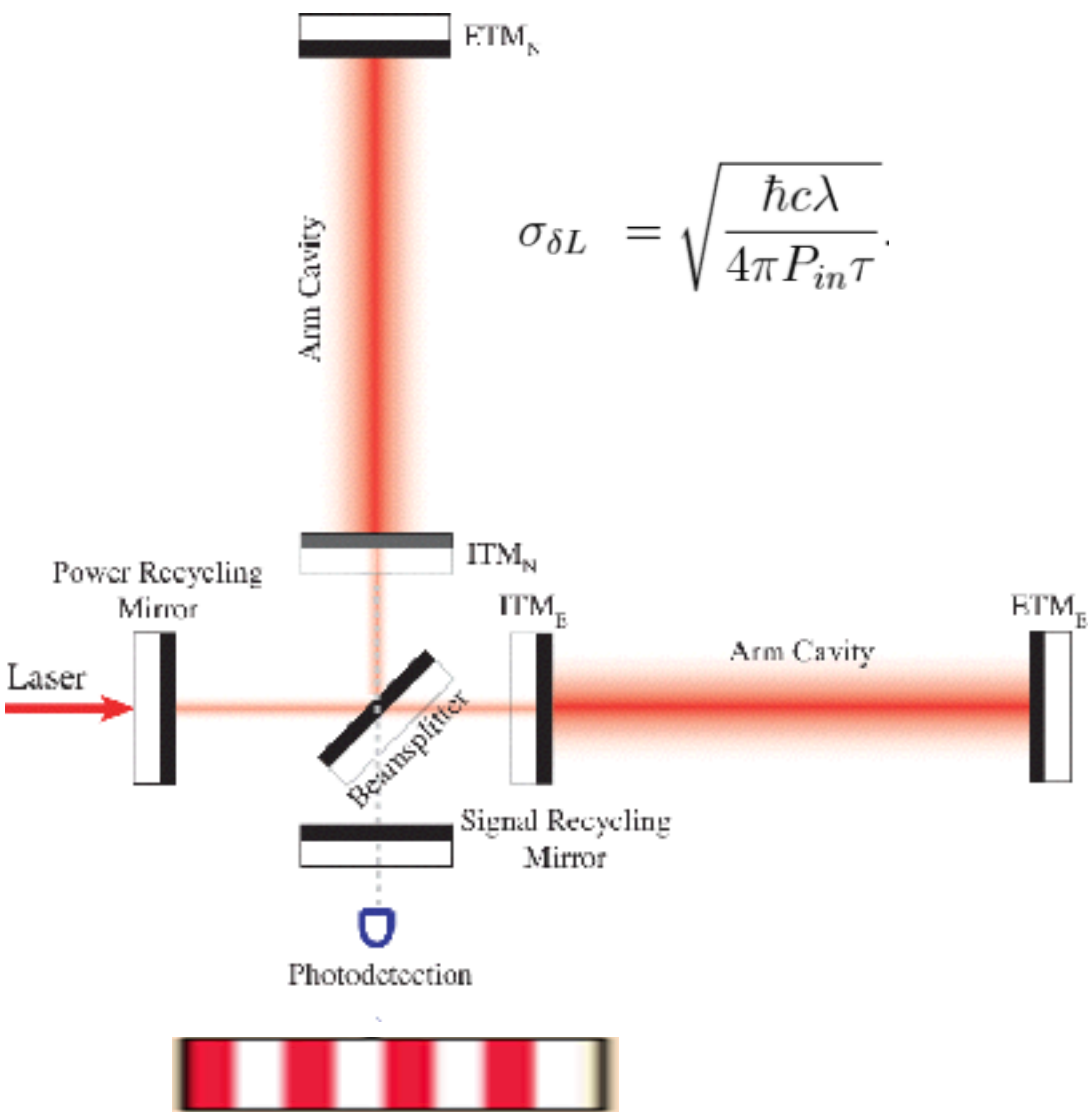

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- **However**, increasing power increases the force on the mirror
- For a perfect mirror, the radiation pressure force is equal to the power
- Fluctuations in the power give fluctuations in the force, and thus fluctuations in the mirror position

$$x(f) = \frac{1}{m(2\pi f)^2} F(f) = \frac{1}{m f^2} \sqrt{\frac{\hbar P_{in}}{8\pi^3 c \lambda}}$$

Noise in Interferometers

- As power is increased, tradeoff between shot noise and radiation pressure noise in interferometers
- Attempting to measure system more precisely (more photons) eventually causes a backreaction and disturbs the system you're trying to measure
- `Standard quantum limit'

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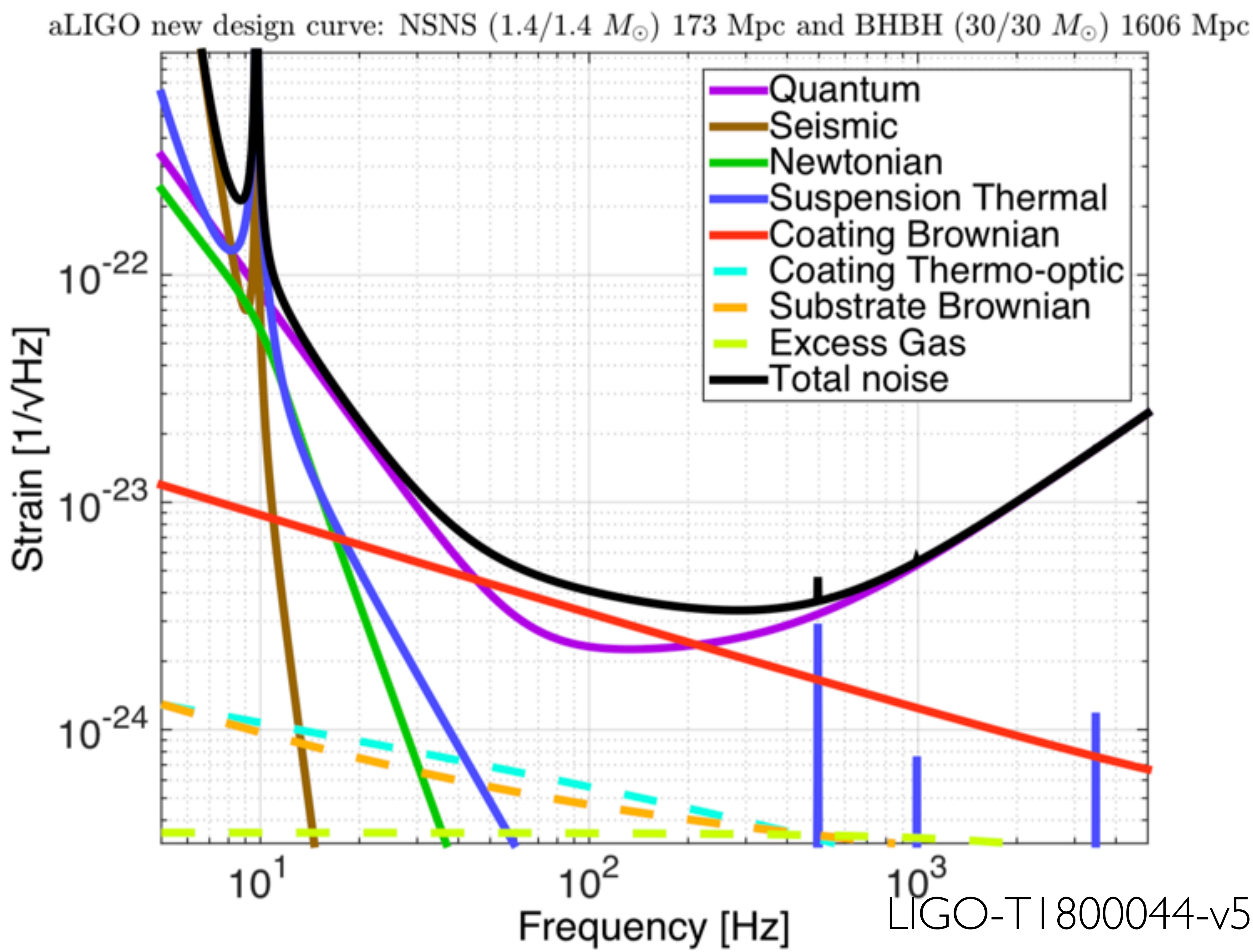
From original LIGO proposal (`89):

The radiation-pressure fluctuations are $\propto \sqrt{P}$, while the sensing shot noise is $\propto \sqrt{1/P}$. Consequently, there is an optimum circulating optical power in the interferometer that minimizes the total noise. When the interferometer operates at this power, the noise is at the standard quantum limit given by

$$h(f)_{\rm opt} = \sqrt{4/\pi}\left(\frac{2\pi\hbar}{\eta^{1/2}m}\right)^{1/2}\frac{1}{2\pi f L} \qquad \text{(III.3)}$$

where $2\pi\hbar$ is Planck's constant, η the quantum efficiency of the photodetector, and m is the mass of the test mass. Figure III–2 shows the standard quantum limit for the representative system. The quantum limit is not a concern for the initial interferometers; however, it may be a fundamental limit to sensitivity and, like all other sources of random force, argues for a large detector length L.

Gravitational Wave Signals



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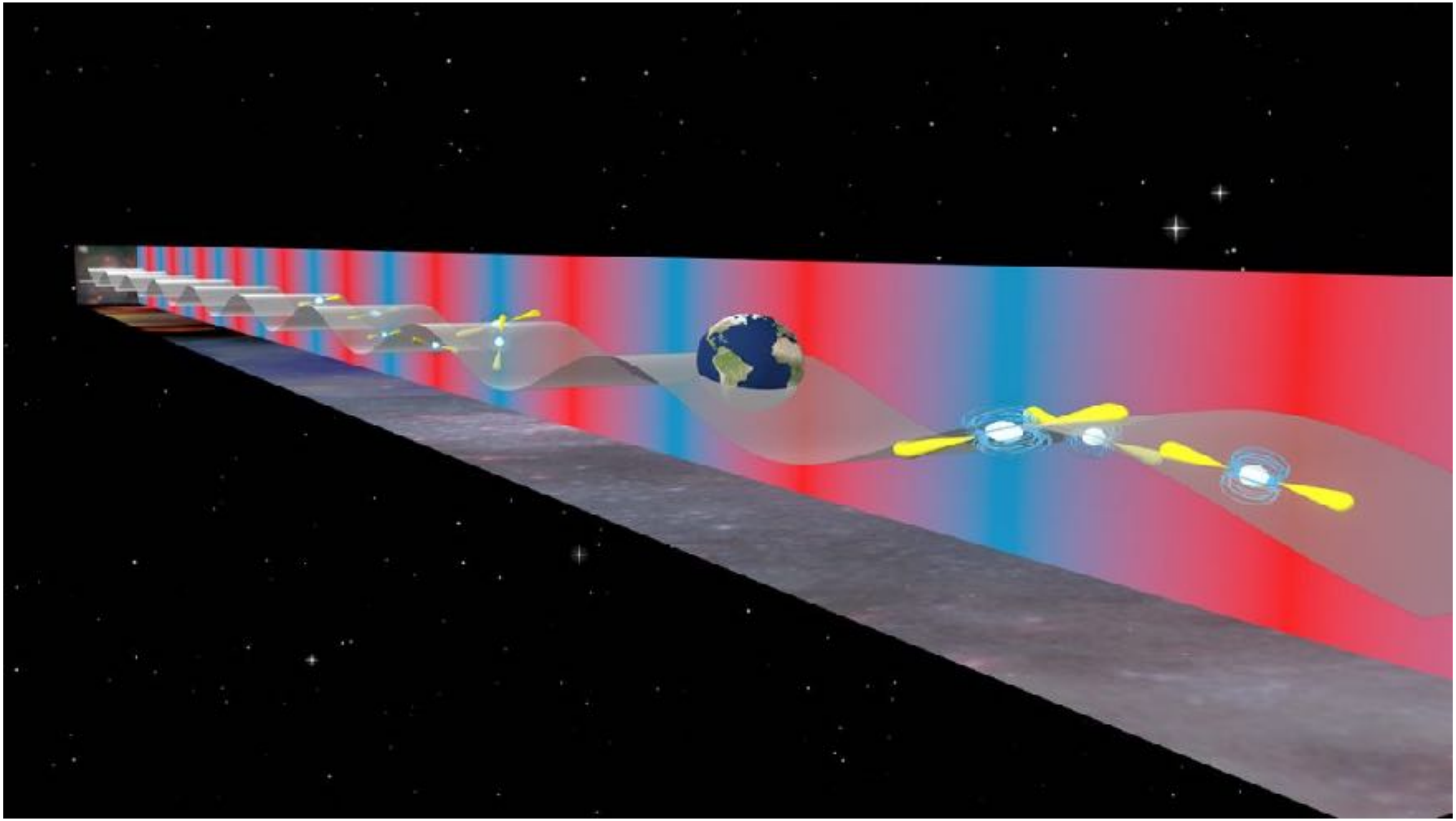
Pulsar Timing Arrays

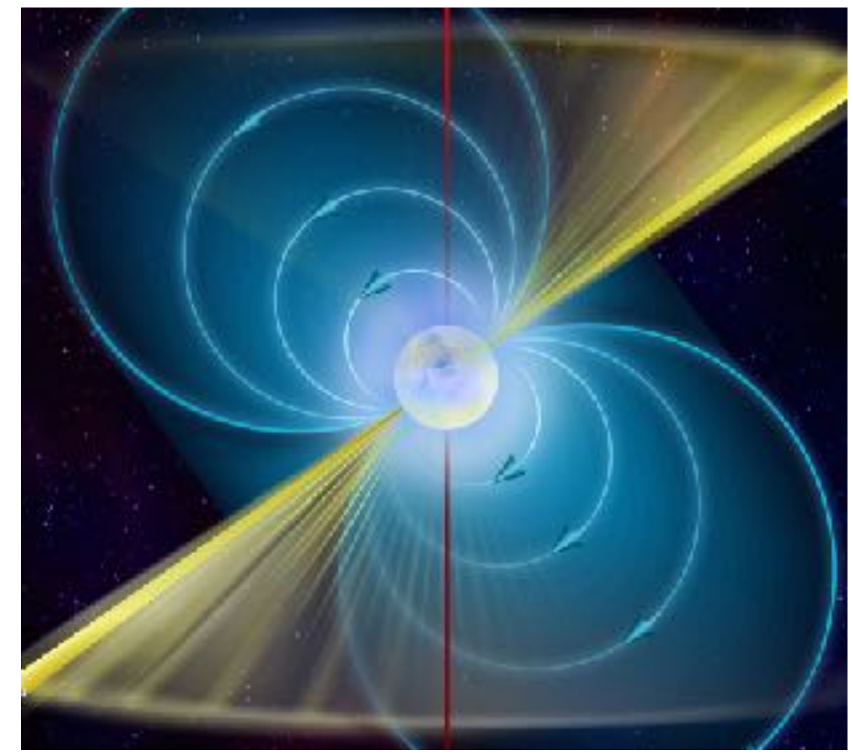


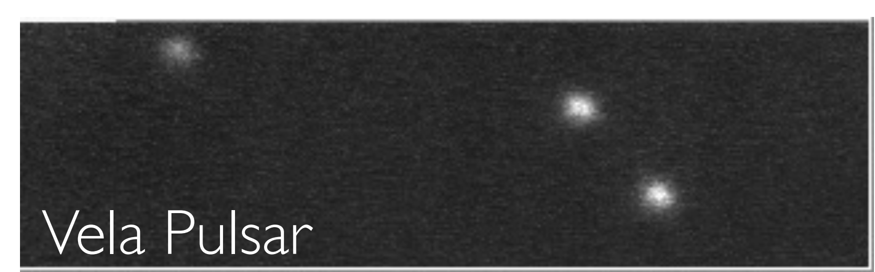
Credit: B. Saxton (NRAO/AUI/NSF)

Pulsar Timing Arrays

- Pulsars: highly magnetized rapidly rotating neutron stars with a coherent source of radio waves. Millisecond pulsars are the special class of pulsars with a stable rotational period of ~ 1-10 ms and stable pulse frequency.

- The stability (although not very well understood) of these millisecond pulsars can be used to make a galaxy-wide network of precise clocks, by measuring the arrival time of the pulses





Cambridge University Lucky Imaging Group

Pulsar Timing Arrays

- Parkes Pulsar Timing Array (PPTA) observing 25 pulsars
- North American Nanohertz Observatory for Gravitational Waves (NANOGrav) observating 45 pulsars
- European Pulsar Timing Array (EPTA) observing 42 pulsars

- International Pulsar Timing Array (IPTA) collaboration of all three: new data release consists of 65 pulsars in 2019

Pulsar Timing Arrays

- Astronomers know of a few thousand neutron stars, a subset of those pulsars, with varying levels of stability
- Pulsar J1909-3744 has been observed Parkes Radio Telescope for 11 years.

- During this time all 115,836,854,515 rotations can be fit
- The rotational period of this star is known to 15 decimal places
- One of the most accurate clocks in the universe!

Pulsar Timing Arrays

- Pulsar timing arrays can detect low frequency gravitational waves (10−9 – 10−7 Hz), limited by observation time. Earth- pulsar systems act as a huge arm length.

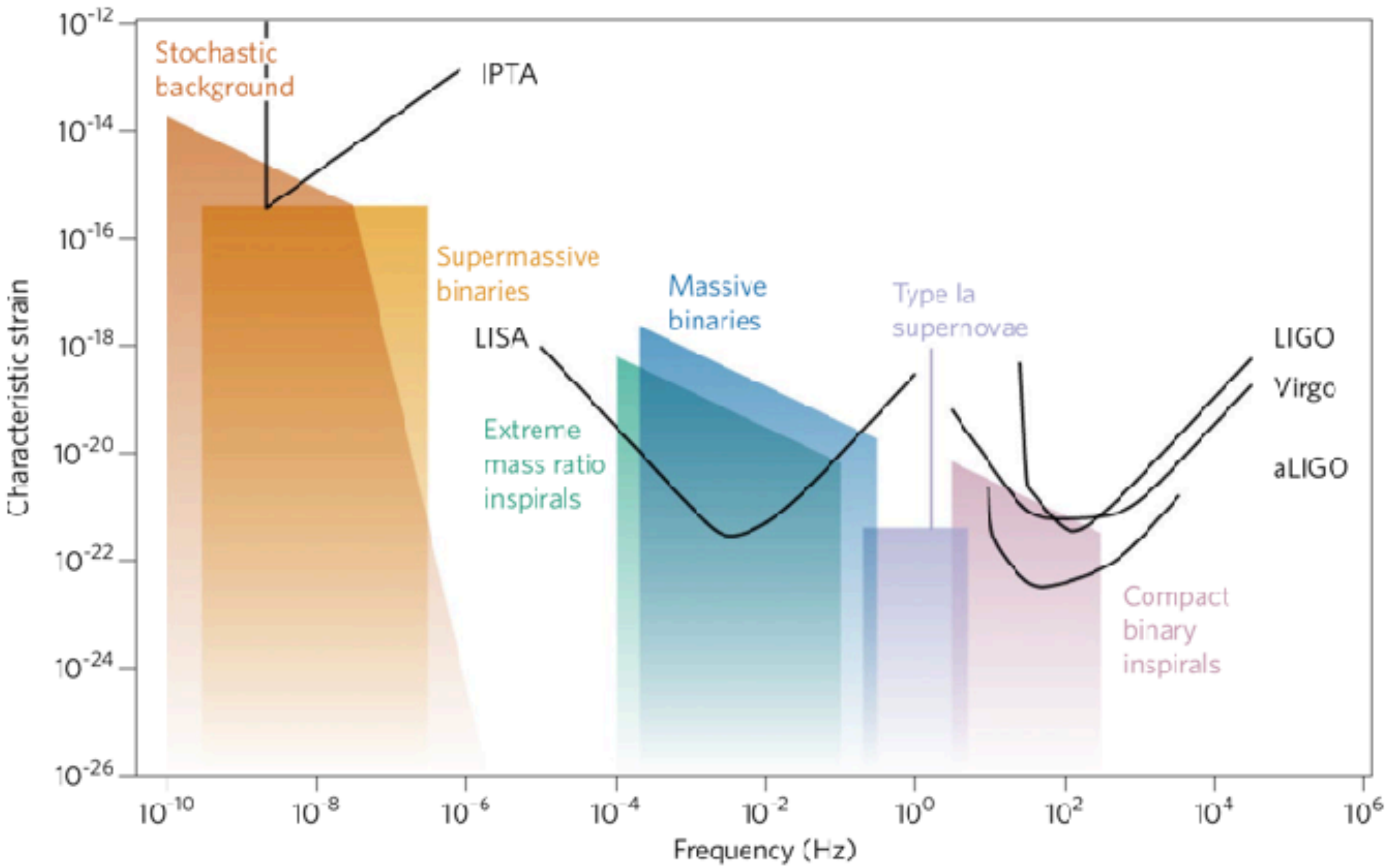
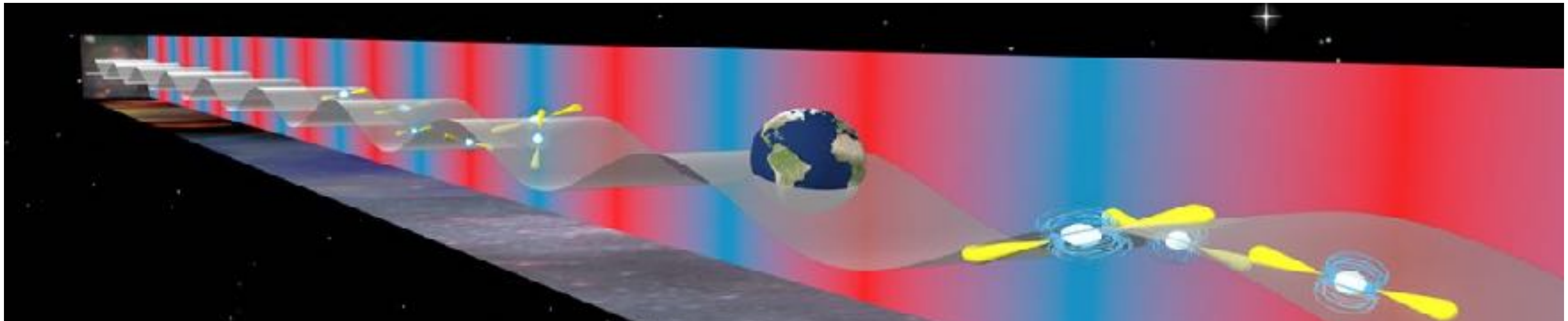


Fig. 1 | The sensitivity space of gravitational wave experiments (marked in black) to different sources of gravitational waves (coloured blocks). Credit: Reproduced from ref. [12], IOP.

Pulsar Timing Arrays

When a gravitational wave passes between the Earth and pulsar system, the time of arrival of the pulsar signal from the pulsars changes.



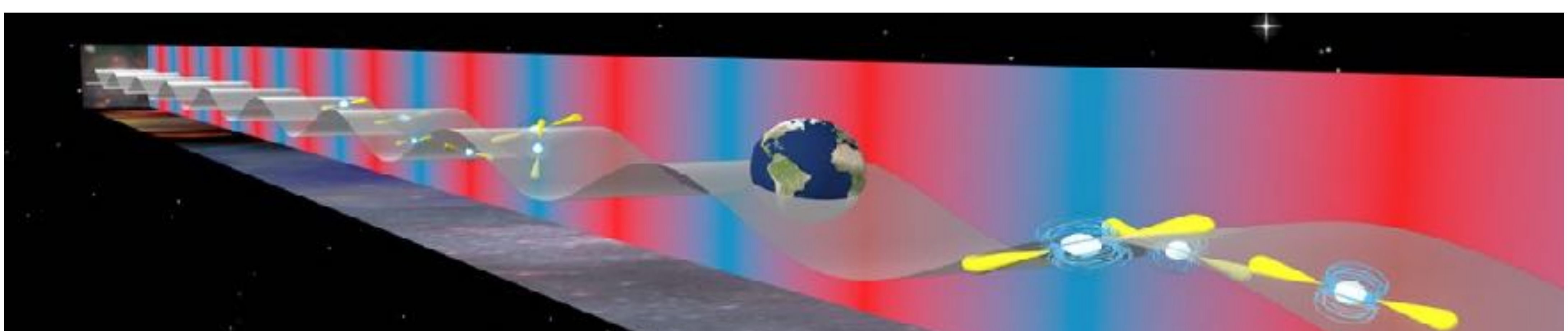
Pulsar Timing Arrays

When a gravitational wave passes between the Earth and pulsar system, the time of arrival of the pulsar signal from the pulsars changes.

This induced frequency change due to the gravitational wave is given by

$$\delta\nu/\nu = -f(\theta_e, \theta_p, \theta_{gw})^{ij}\left(h_{ij}(t_e, x_e^i) - h_{ij}(t_p, x_p^i)\right)$$

f^{ij} depends on the angle between the earth, pulsar and the source of gravitational wave. h_{ij} is the dimensionless amplitude of gravitational wave at the earth (at position $\vec{x_e}$ and time t_e) and at the pulsar (at position $\vec{x_p}$ and time $t_p = t_e - D/c$, D being the distance between the earth and the pulsar)

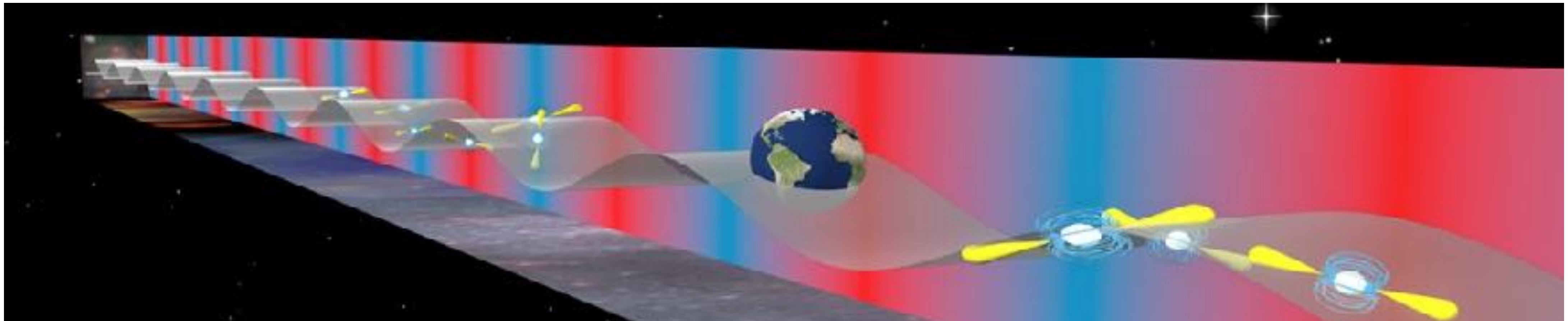


Pulsar Timing Arrays

This variation in pulse frequency due to gravitational wave appears as an anomalous residual in pulse arrival time, and is given by:

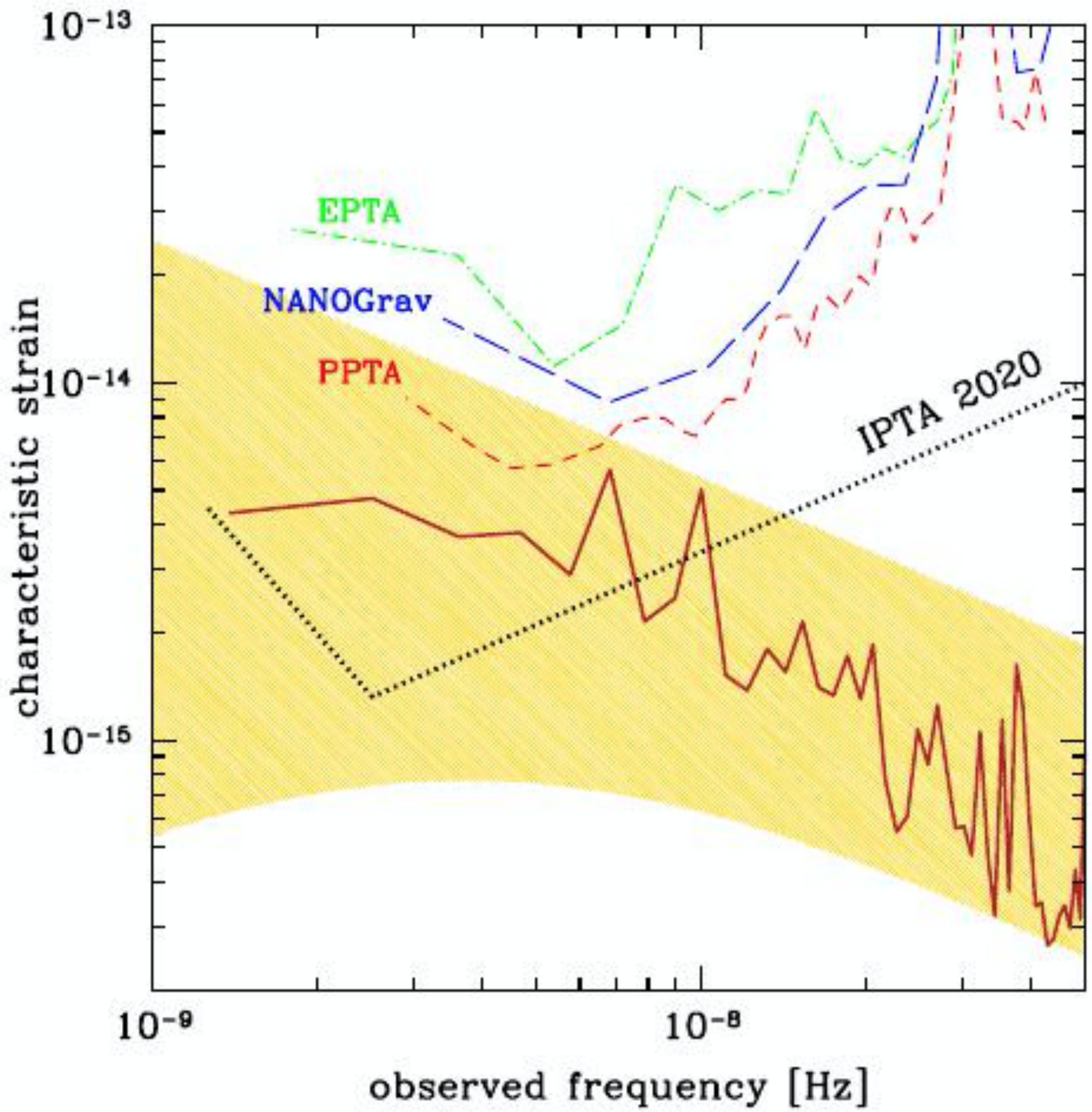
$$R(t) = -\int_0^t \frac{\delta\nu}{\nu} dt$$

Look for the correlation in arrival times of pulses emitted by different pulsars. This correlation is contributed by the gravitational wave strain $h_{ij}(\vec{x_e}, t_e)$ at the earth and not by $h_{ij}(\vec{x_p}, t_p)$ at the pulsar.



Pulsar Timing Arrays

- PTAs could detect the stochastic signals from supermassive black holes in the early stage of inspirals, as well as other low-frequency signals
- Also measure properties of solar system



PTA searches for scalar dark matter

- As we know (and you learned from Francesco), we know there is dark matter in the galaxy.
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On the exercises yesterday you looked at a nonrelativistic scalar field

$$\phi(\mathbf{x}, t) = \phi_0(\mathbf{x}) \cos(m t + k\mathbf{x} + \beta)$$

The energy-momentum tensor of a free scalar field is given by

$$T_{\mu\nu} = \partial_\mu \phi \, \partial_\nu \phi - \frac{1}{2} g_{\mu\nu} \left((\partial \phi)^2 - m^2 \phi^2 \right) \ .$$

PTA searches for scalar dark matter

- Blackboard

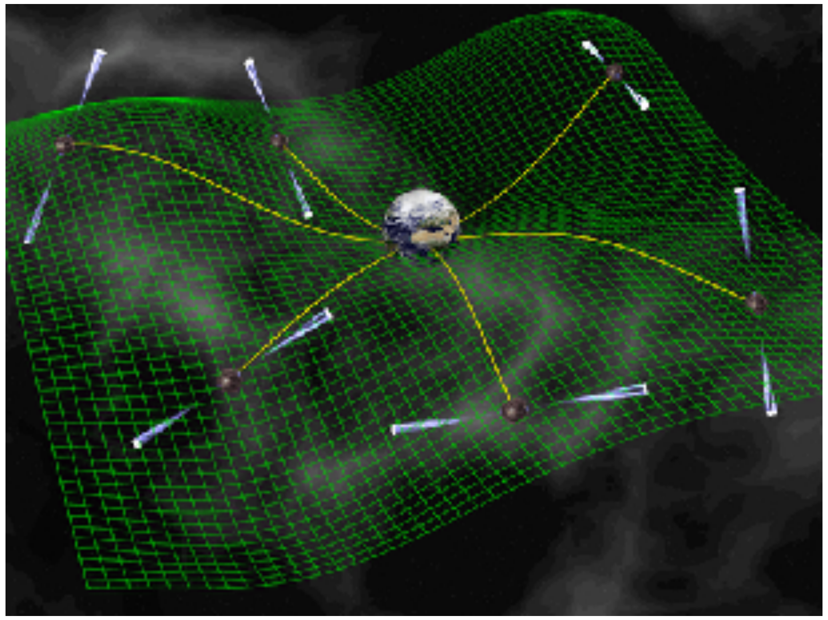
PTA searches for scalar dark matter

The amplitude Ψ_c, which can be effectively probed in pulsar timing experiments, depends on the local density of dark matter $\rho_{\rm SF}$,

$$\Psi_c = \frac{G\rho_{\rm SF}}{\pi f^2} \approx 6.1 \times 10^{-18} \left(\frac{m}{10^{-22}\ {\rm eV}}\right)^{-2} \left(\frac{\rho_{\rm SF}}{\rho_0}\right), \quad (7)$$

where $\rho_0 = 0.4\ {\rm GeV\,cm^{-3}}$ is the measured local dark matter density [56–58]. The root-mean-square (rms) amplitude of induced pulsar-timing residuals is

$$\delta t \approx 0.02\ {\rm ns} \left(\frac{m}{10^{-22}\ {\rm eV}}\right)^{-3} \left(\frac{\rho_{\rm SF}}{0.4\ {\rm GeV\,cm^{-3}}}\right). \quad (8)$$



PTA searches for scalar dark matter

Parkes Pulsar Timing Array constraints on ultralight scalar-field dark matter

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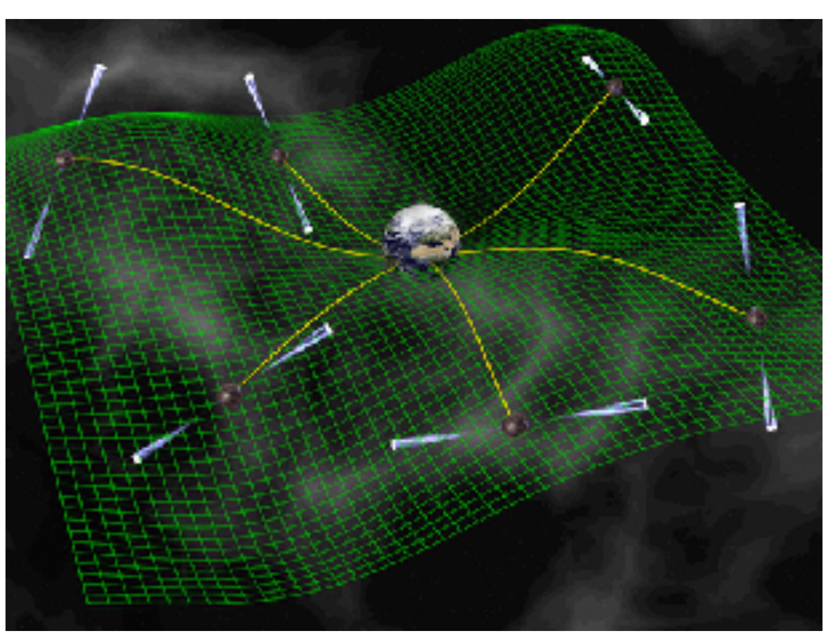

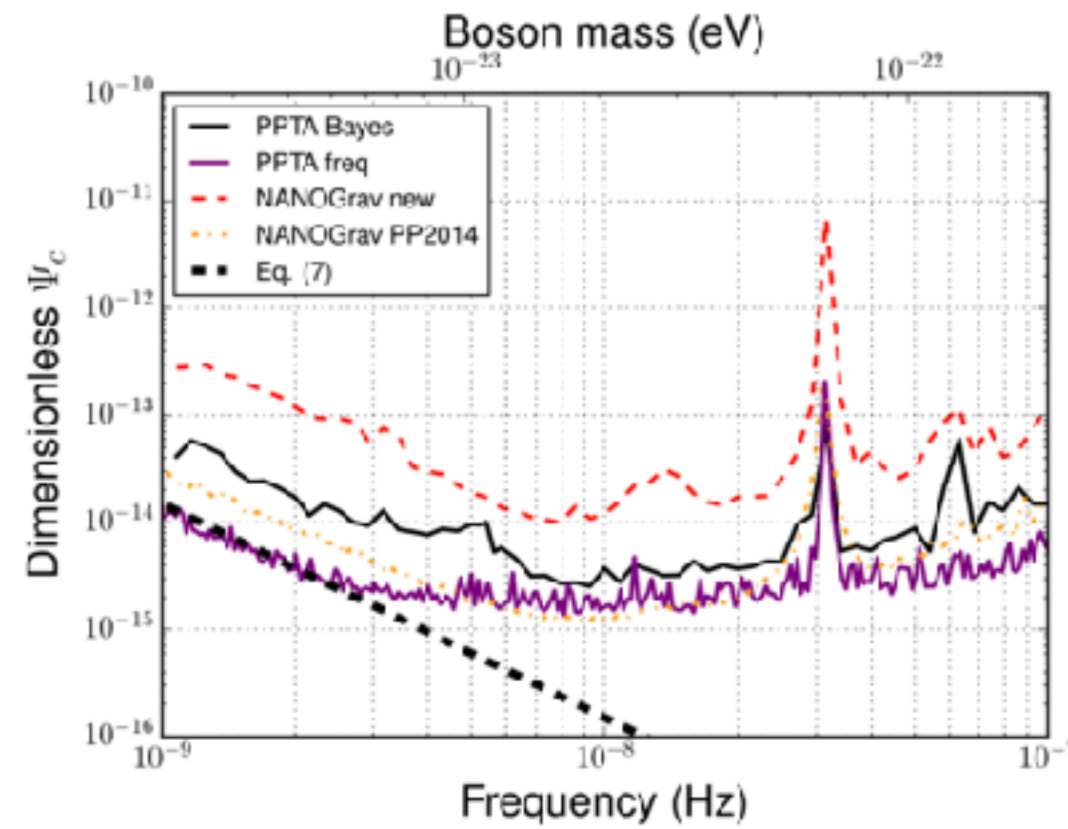

FIG. 3. Upper limits on the signal amplitude Ψ_c, generated by the scalar field dark matter in the Galaxy, as a function of frequency (boson mass). The purple solid line shows results from Frequentist analysis of the full data set of 24 pulsars, while the black solid line demonstrates the upper limits derived within a Bayesian framework (only the five best pulsars were used). These are compared with previous studies using the NANOGrav 5-yr data set: dash-dotted orange — upper limits set in [35], dashed red — upper limits recalculated in this work. The thick black dashed line shows the model amplitude Ψ_c, assuming $\rho_{\rm SF} = 0.4\ \mathrm{GeV\,cm^{-3}}$, given by Eq. (7).

PHYSICAL REVIEW D **98,** 102002 (2018)

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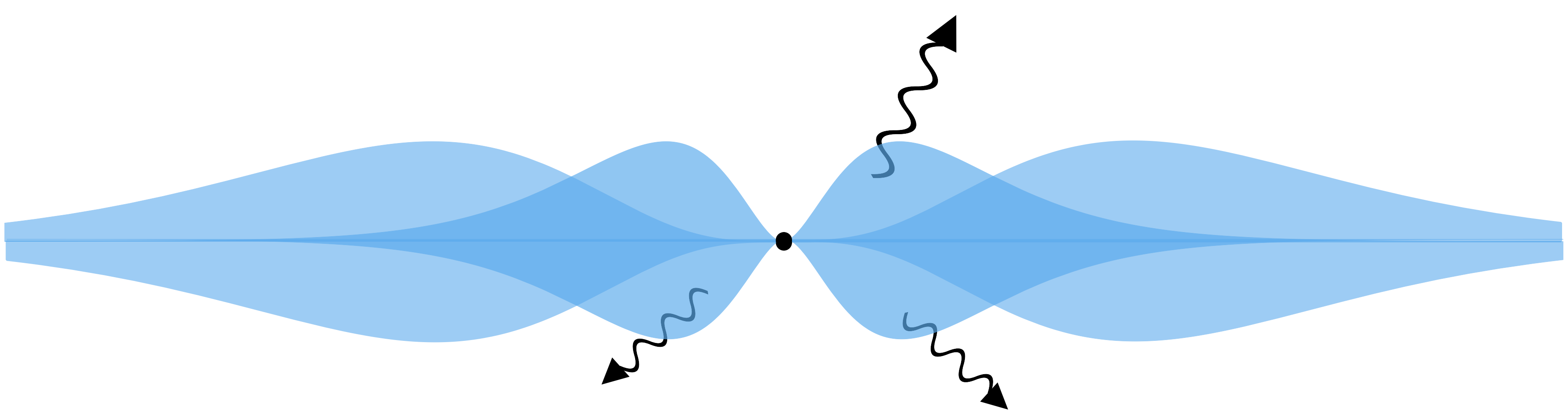
Superradiance and Black Holes

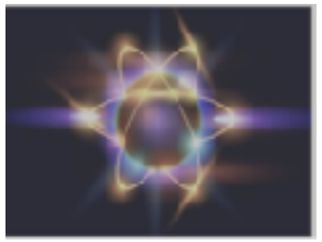
or

How to Extract Energy from Black Holes
and
Discover New Particles

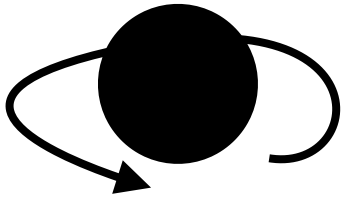


Outline

- Superradiance and rotating BHs
- Gravitational Atoms



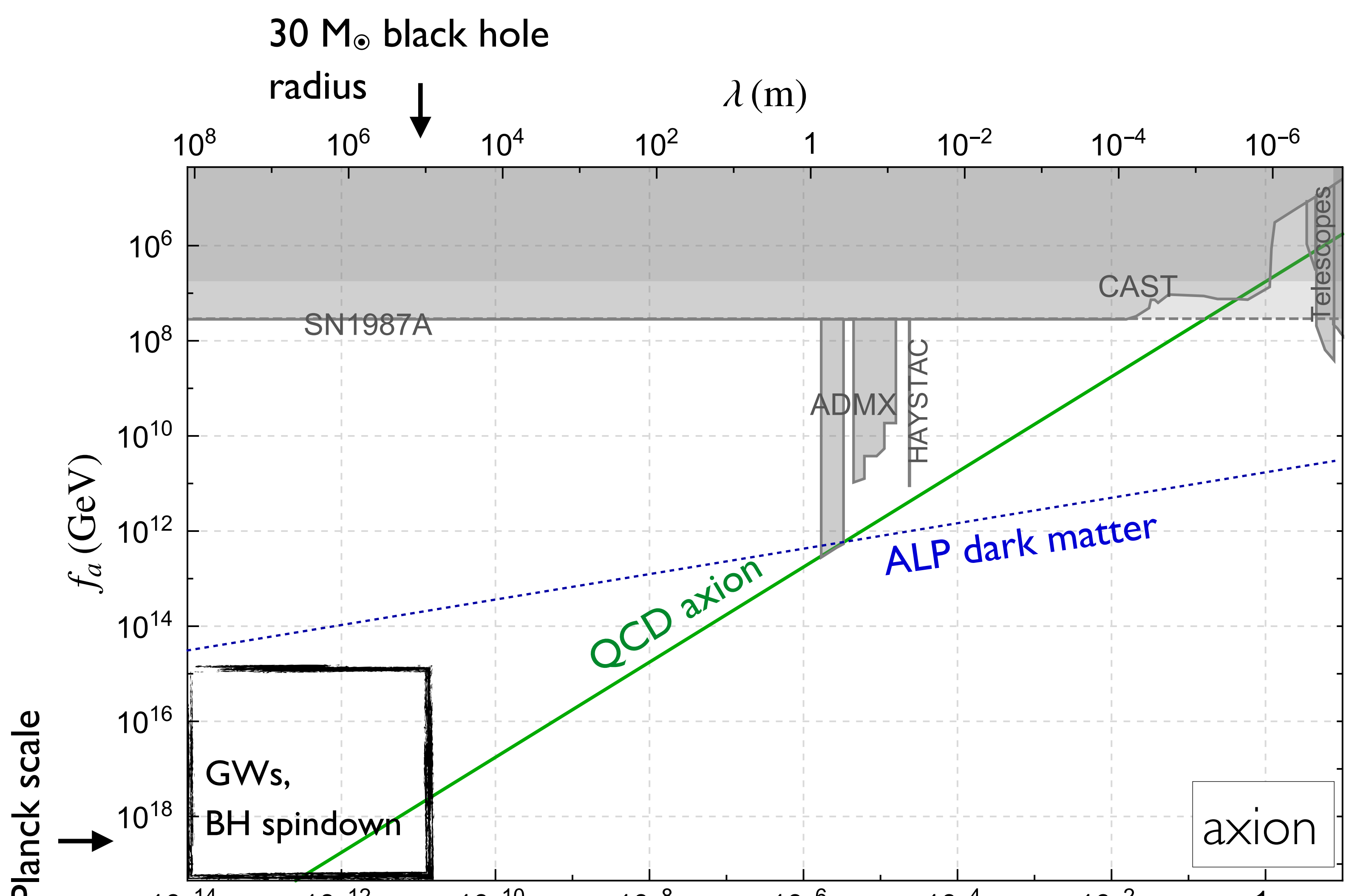
- Signs of New Particles
  - Black Hole Spindown



  - GW signals

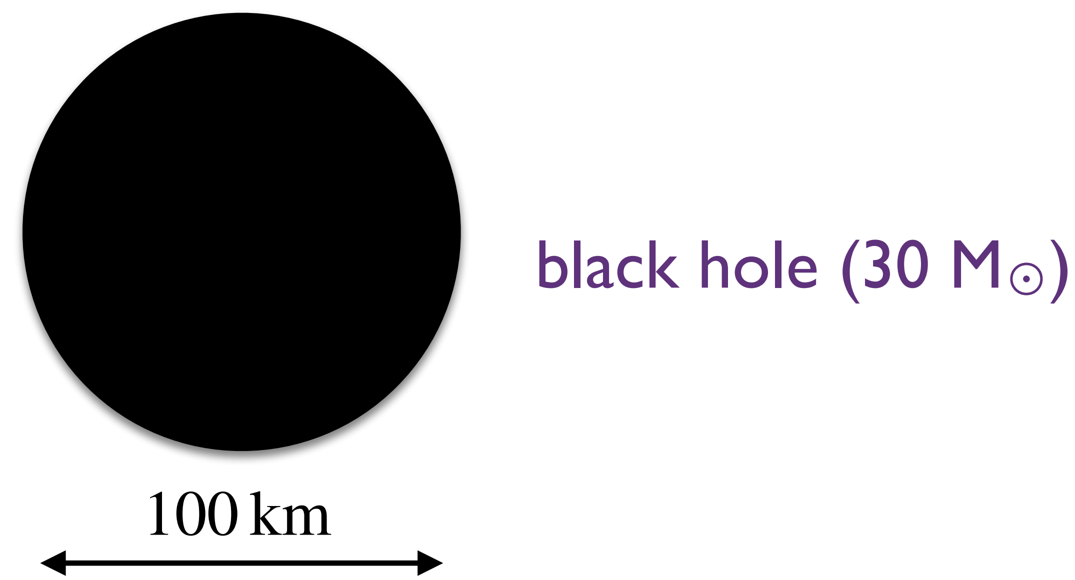
Motivation

- Ultralight scalar particles often found in theories beyond the Standard Model
- E.g. the QCD axion solves the `strong-CP' problem
- As already discussed, ultralight scalars can make up the DM

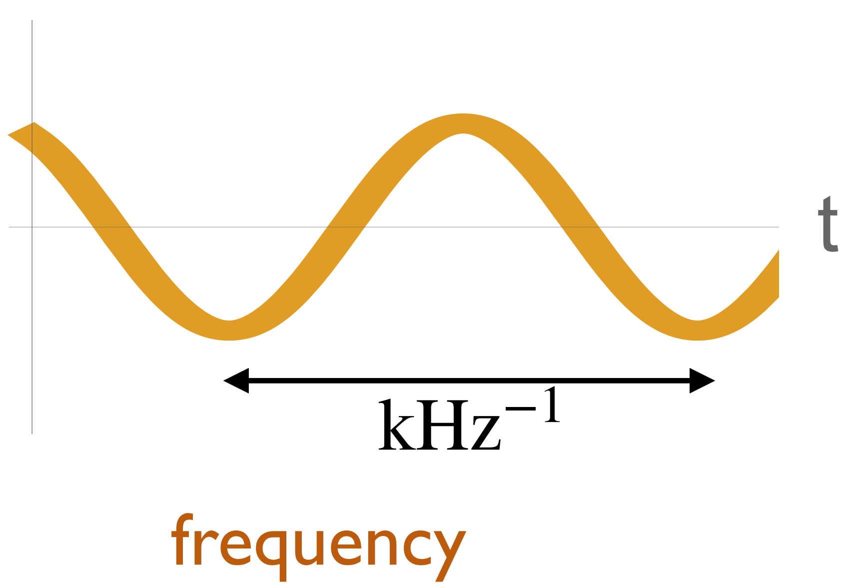


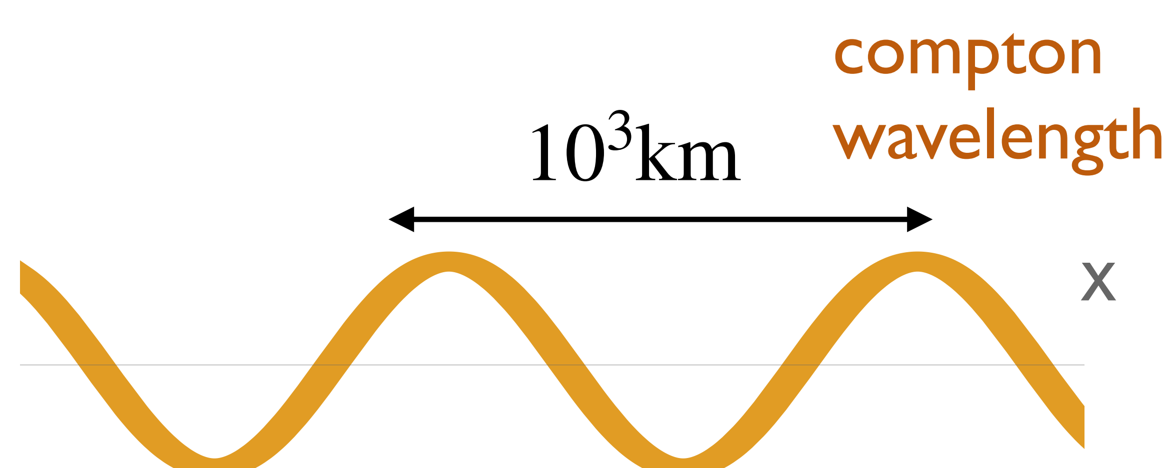
Astrophysical Black Holes and Ultralight Particles

- Black holes in our universe provide nature's laboratories to search for light particles
- Set a typical length scale, and are a huge source of energy
- Sensitive to QCD axions with GUT- to Planck-scale decay constants f_a



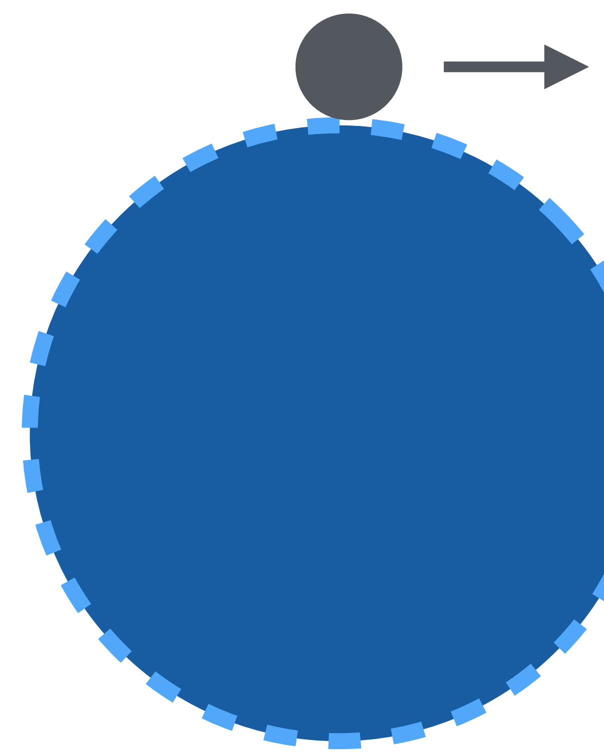
for a 10^{-12} eV particle:





Superradiance: gaining from dissipation part I

- A an object scattering off a **rotating** cylinder can increase in angular momentum and energy.
- Effect depends on **dissipation**, necessary to change the velocity



Ball scattering off cylinder with lossy surface slows down

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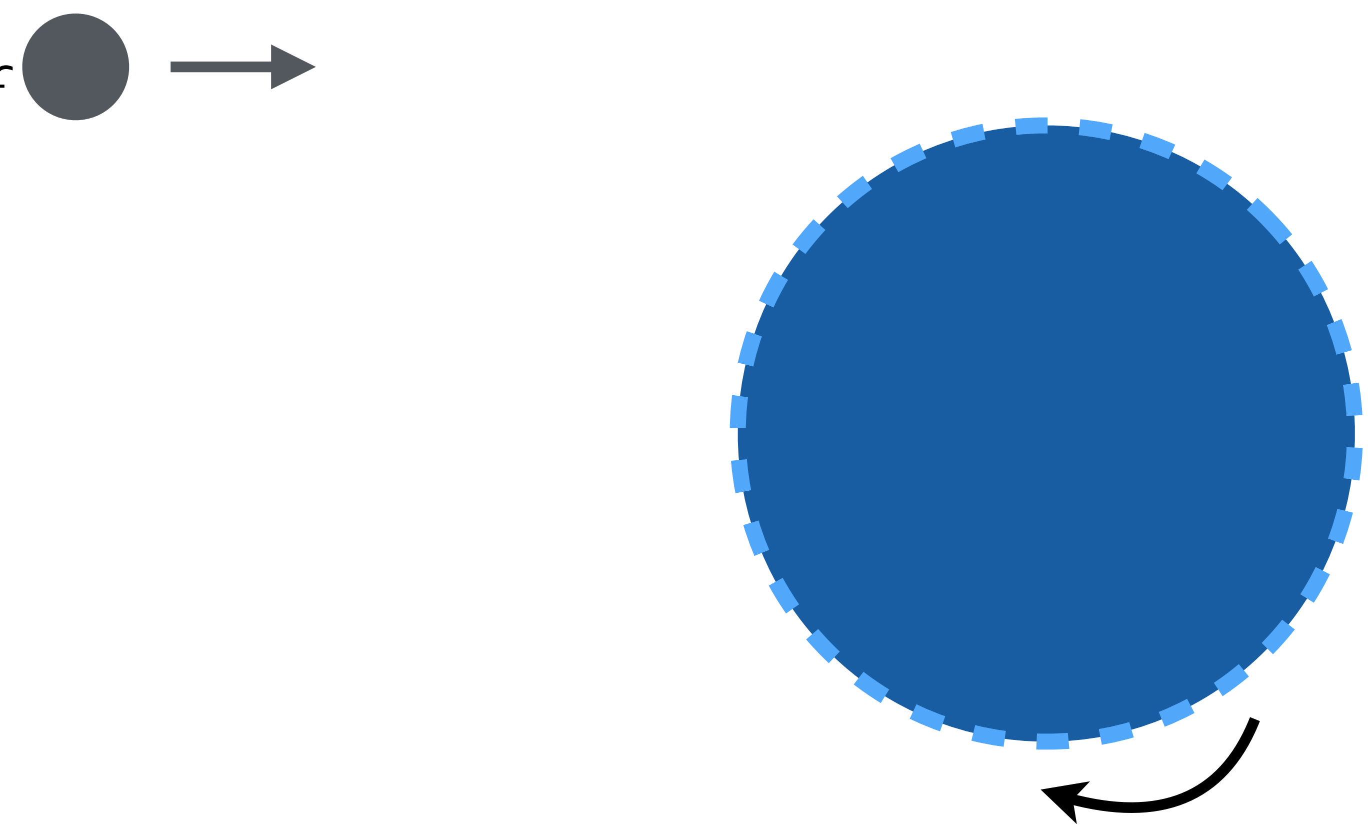
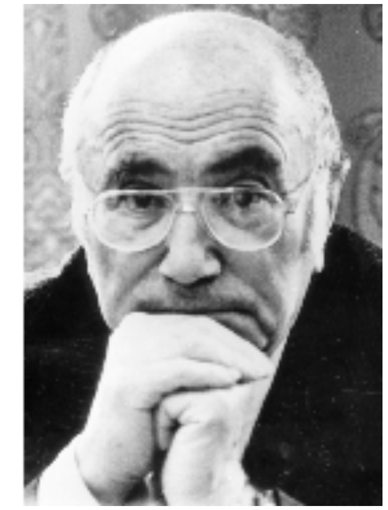
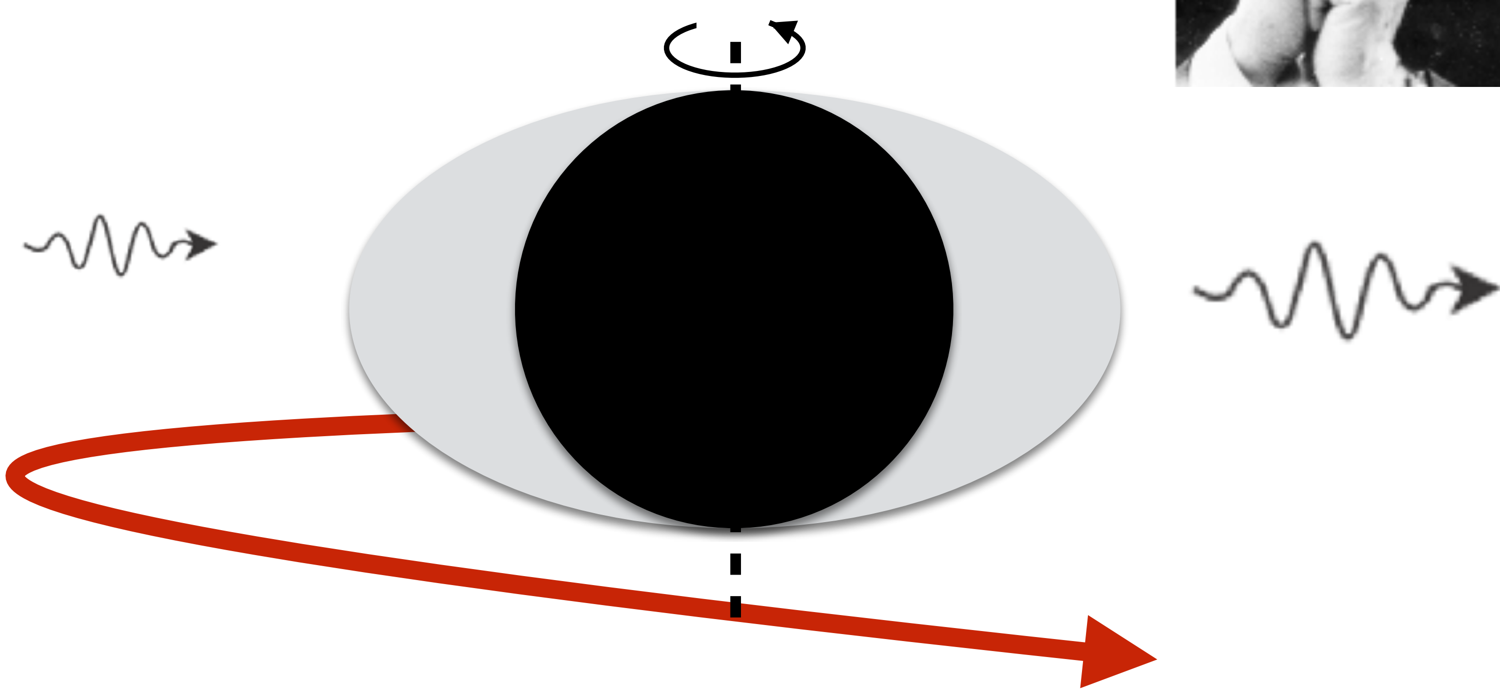


Ball scattering off rapidly rotating cylinder with **lossy** surface speeds up!

Superradiance: gaining from dissipation part I



- A wave scattering off a rotating object can increase in amplitude by extracting angular momentum and energy.
- Growth proportional to probability of absorption when rotating object is at rest: **dissipation** necessary to increase wave amplitude



Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

Zel'dovich; Starobinskii; Misner

Superradiance

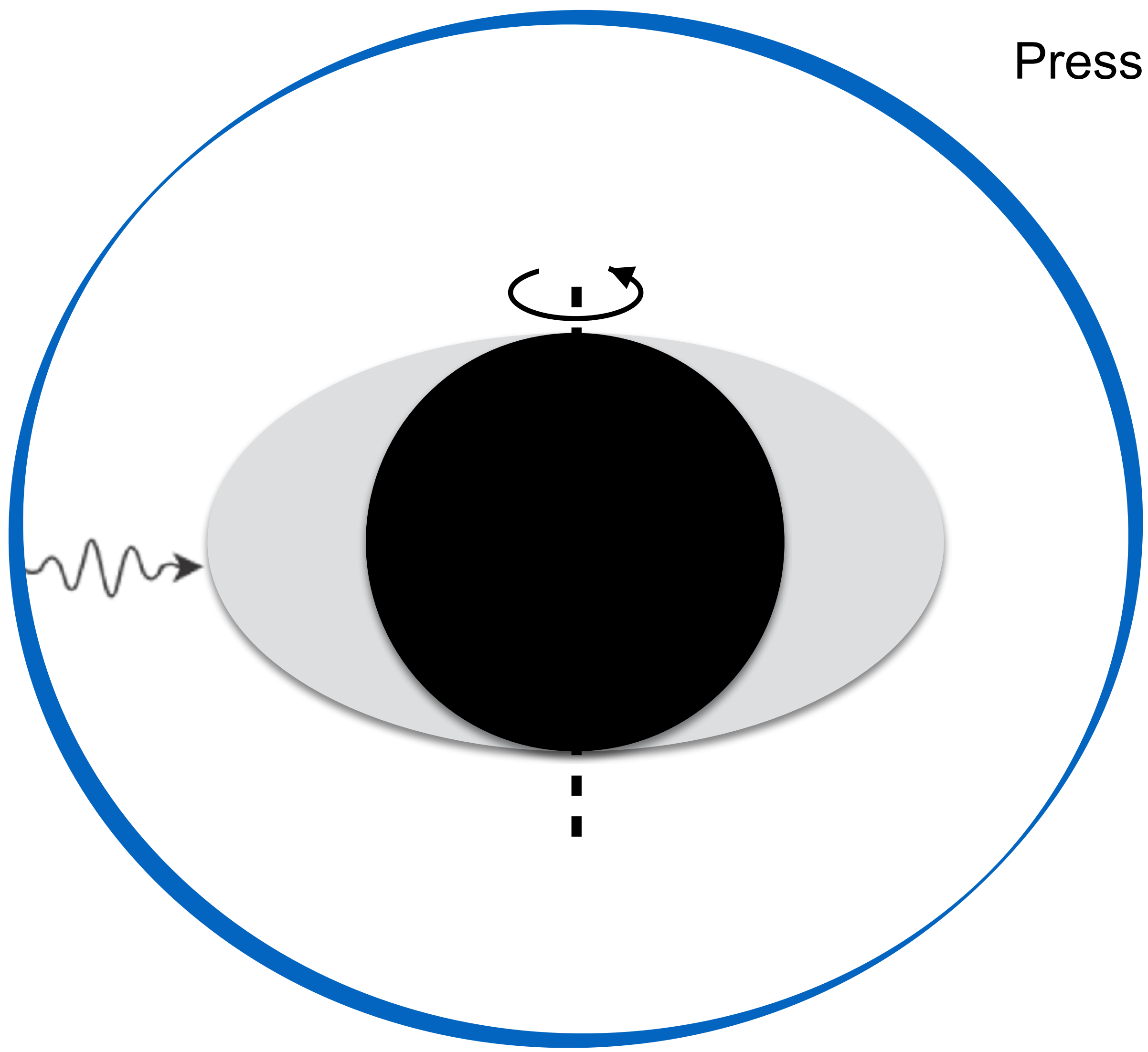
Gravitational wave amplified when scattering from a rapidly rotating black hole

Numerical GR simulation by Will East

Superradiance

Particles/waves trapped in orbit around the BH repeat this process continuously

Press & Teulkosky



"Black hole bomb" exponential instability when surround BH by a mirror

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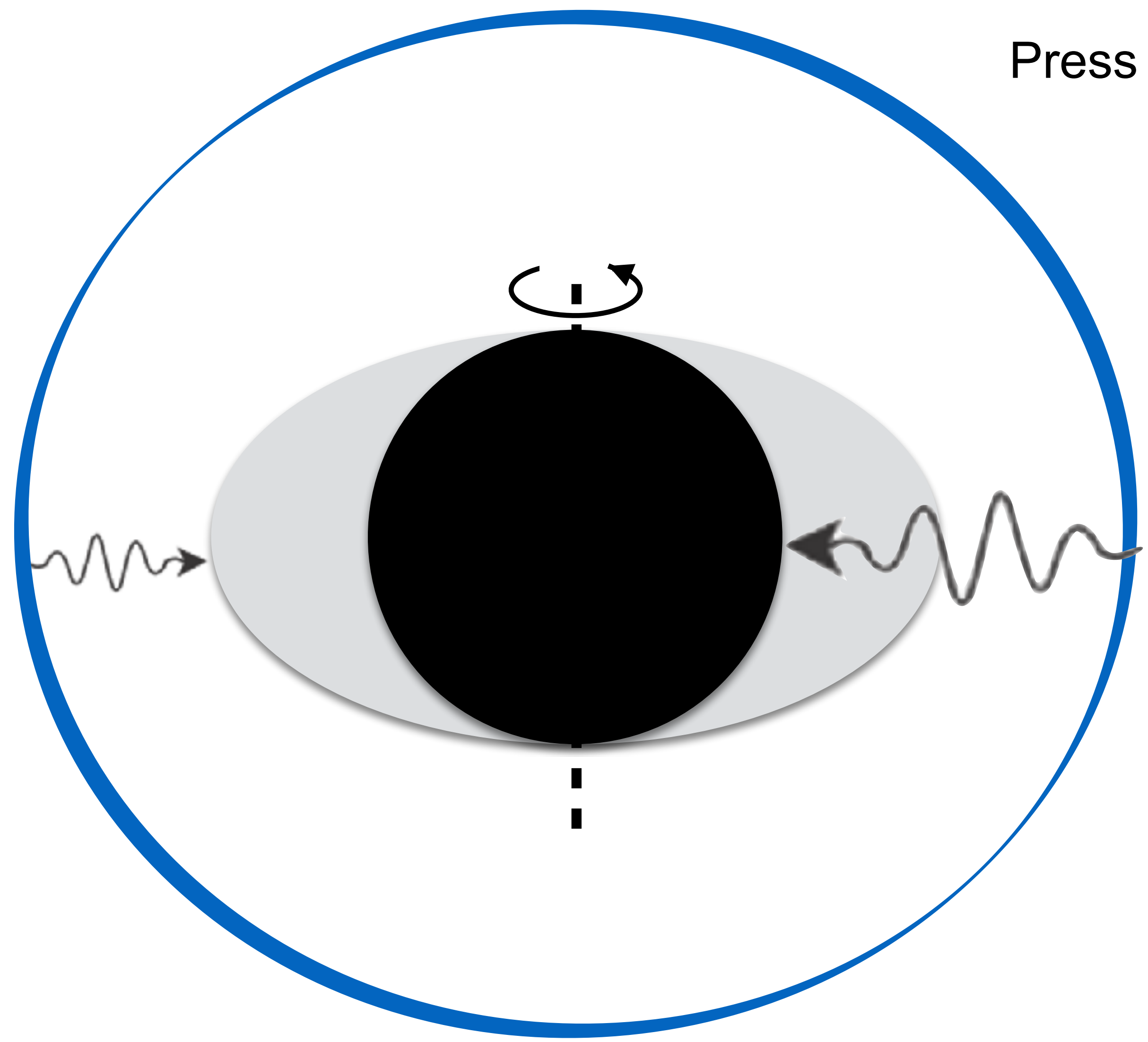

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Superradiance condition:

Angular velocity of wave slower than angular velocity of BH horizon,

$$\Omega_a < \Omega_{BH}$$

Superradiance

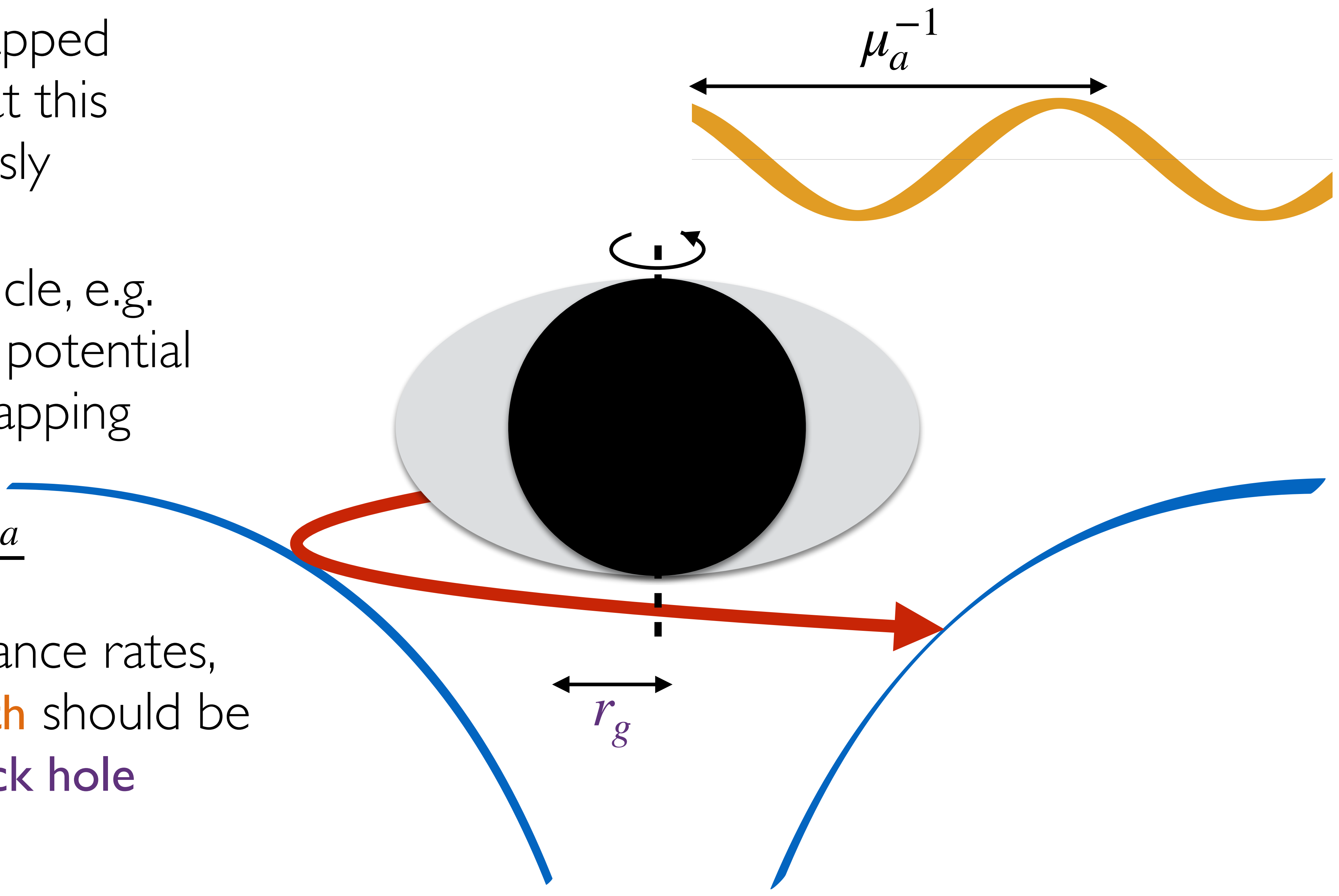
- Particles/waves trapped near the BH repeat this process continuously

- For a massive particle, e.g. axion, gravitational potential barrier provides trapping

$$V(r) = -\frac{G_{\mathrm{N}} M_{\mathrm{BH}} \mu_a}{r}$$

- For high superradiance rates, compton wavelength should be comparable to black hole radius:

$$r_g \lesssim \mu_a^{-1} \sim 3\,\mathrm{km}\,\frac{6\times10^{-11}\mathrm{eV}}{\mu_a}$$

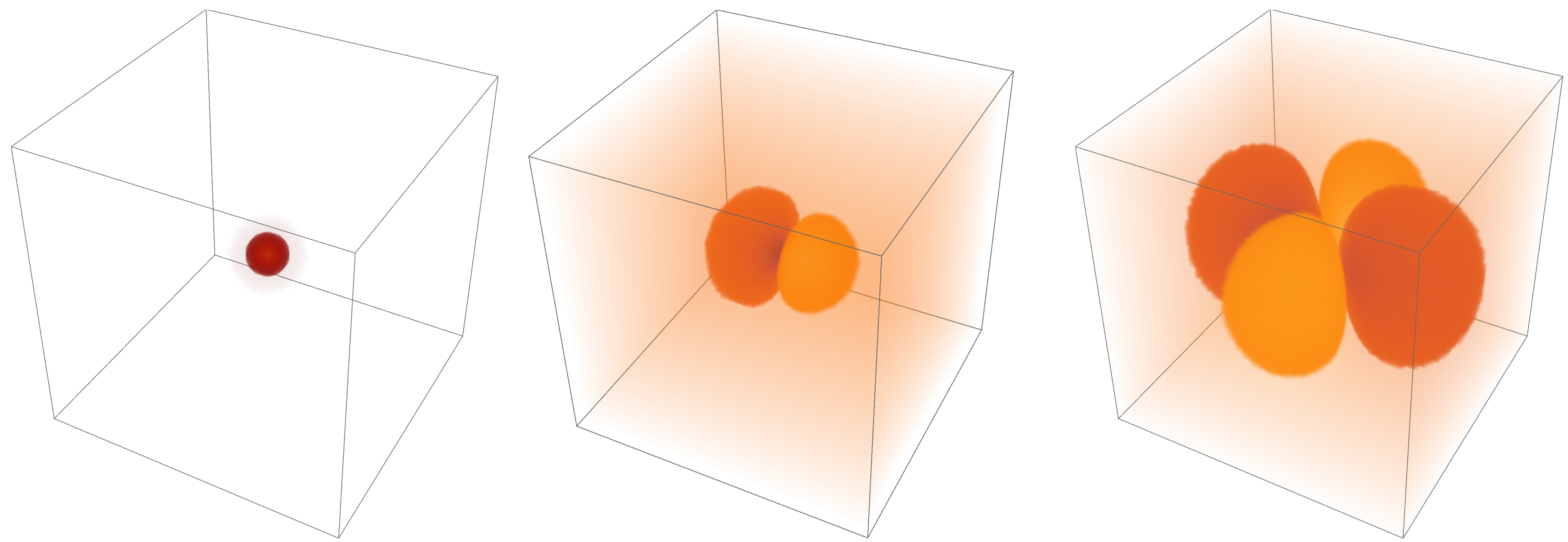


[Zouros & Eardley'79; Damour et al '76; Detweiler'80; Gaina et al '78]
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 2009; Arvanitaki, Dubovsky 2010]

Gravitational Atoms

Axion
Gravitational Atoms

$$V(r) = -\frac{G_{\rm N} M_{\rm BH} \mu_a}{r}$$



$n = 1, \ell = 0, m = 0$ $\quad$ $n = 2, \ell = 1, m = 1$ $\quad$ $n = 3, \ell = 2, m = 2$

Gravitational potential similar to hydrogen atom

`Fine structure constant`

$$\alpha \equiv G_{\rm N} M_{\rm BH} \mu_a \equiv r_g \mu_a$$

Radius

$$r_c \simeq \frac{n^2}{\alpha\, \mu_a} \sim 4 - 400 r_g$$

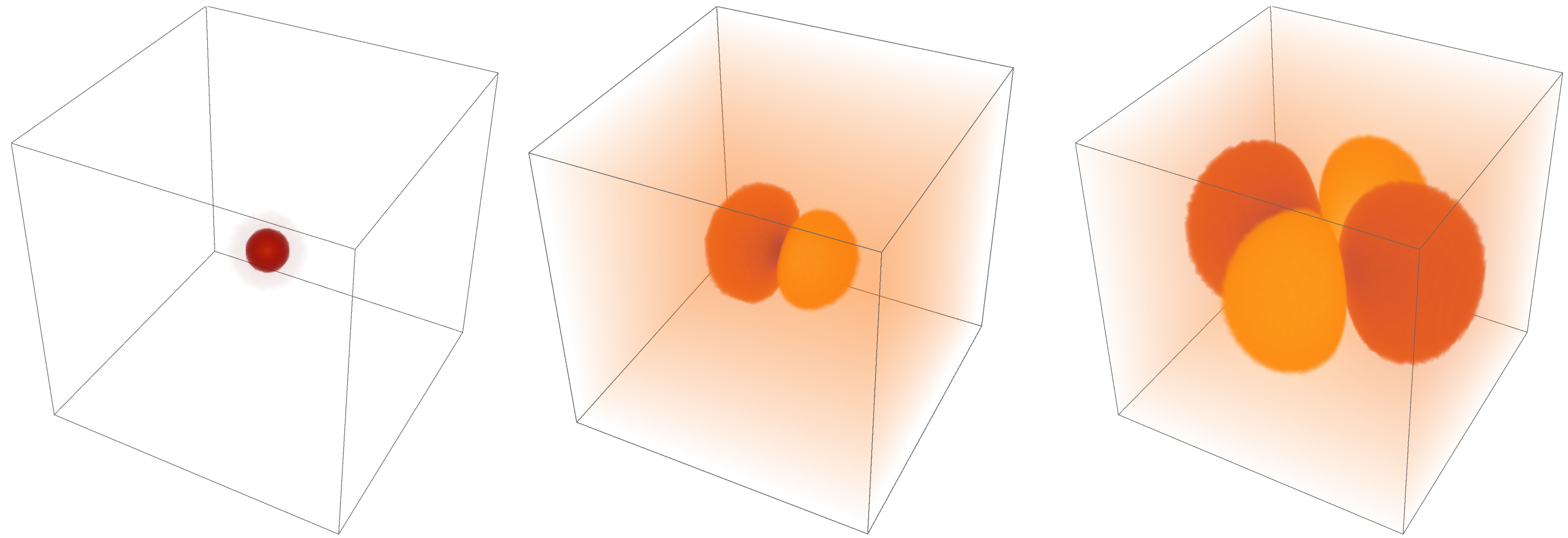
Occupation number

$$N \sim 10^{75} - 10^{80}$$

Gravitational Atoms

Axion Gravitational Atoms

$$V(r) = -\frac{G_N M_{BH} \mu_a}{r}$$



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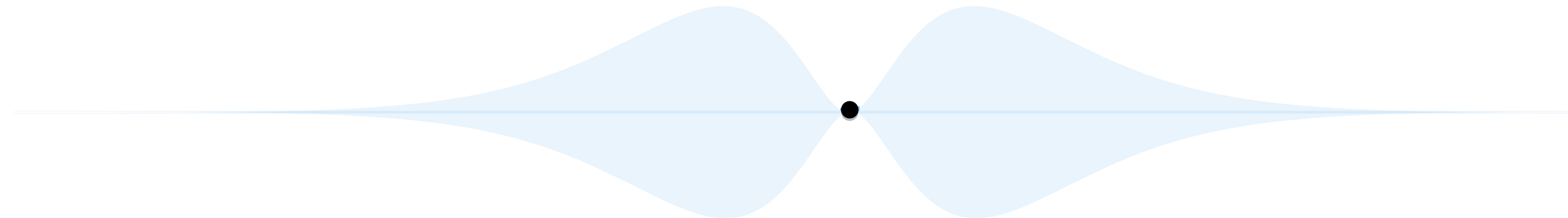
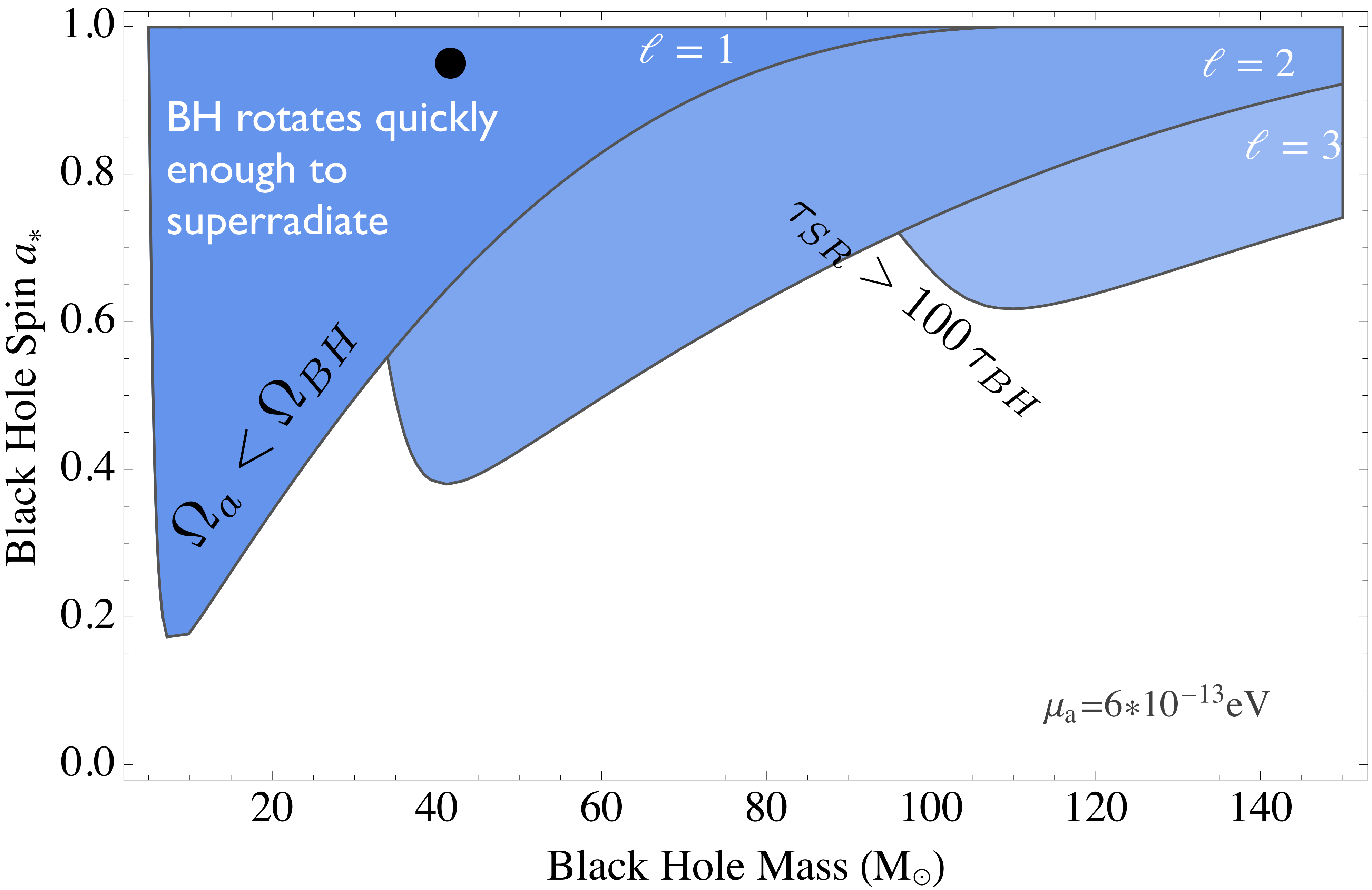
Boundary conditions at horizon give imaginary frequency: **exponential growth for rapidly rotating black holes**

$$E \simeq \mu \left(1 - \frac{\alpha^2}{2n^2}\right) + i\Gamma_{sr}$$

Superradiance: a stellar black hole history



A black hole is born with spin a* = 0.95, M = 40 M⊙.

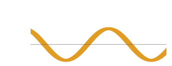


BH lightcrossing time

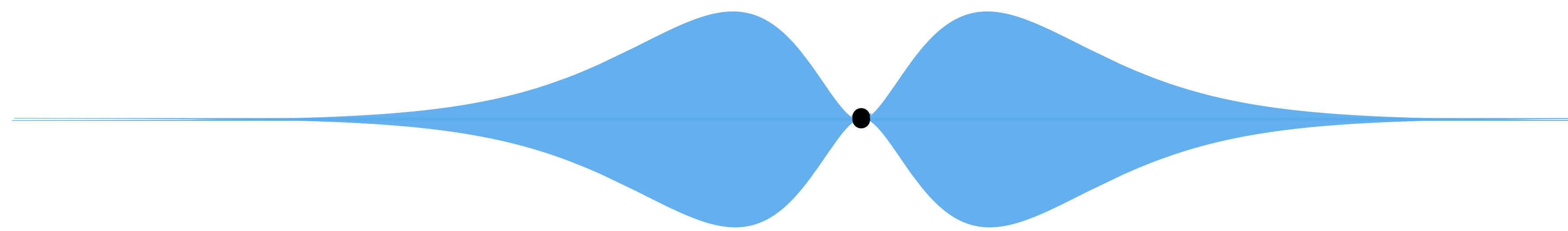
0.2 msec (60 km)

Particle wavelength

1 msec (300 km)

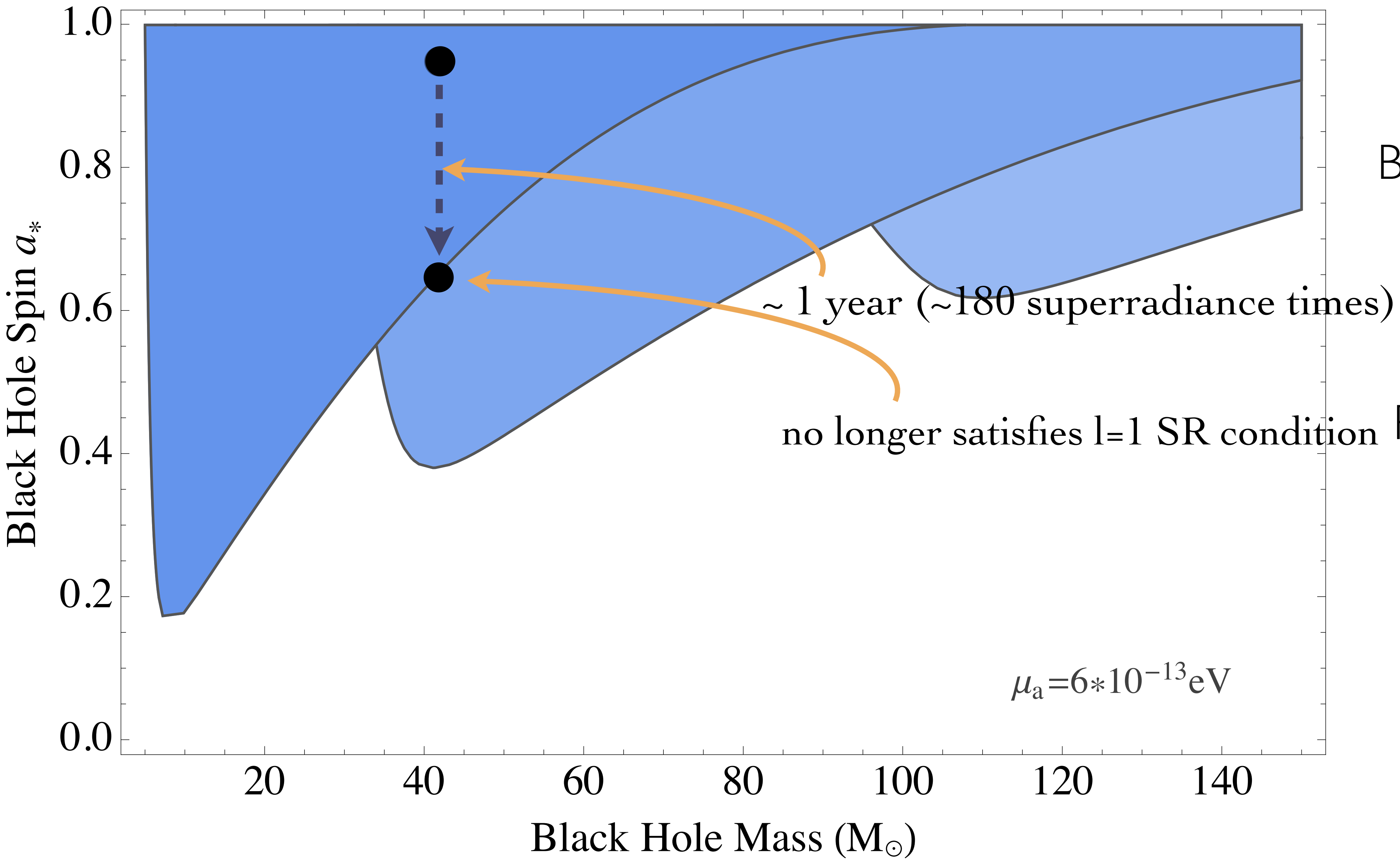


Superradiance: a stellar black hole history



BH spins down and fastest-growing level is formed

Once BH angular velocity matches that of the level, growth stops



Cloud radius

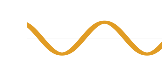
6 msec (2000 km)

BH lightcrossing time

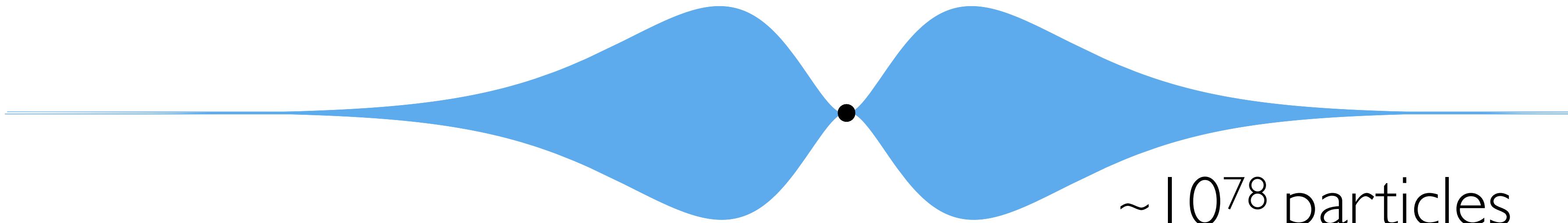
0.2 msec (60 km)

Particle wavelength

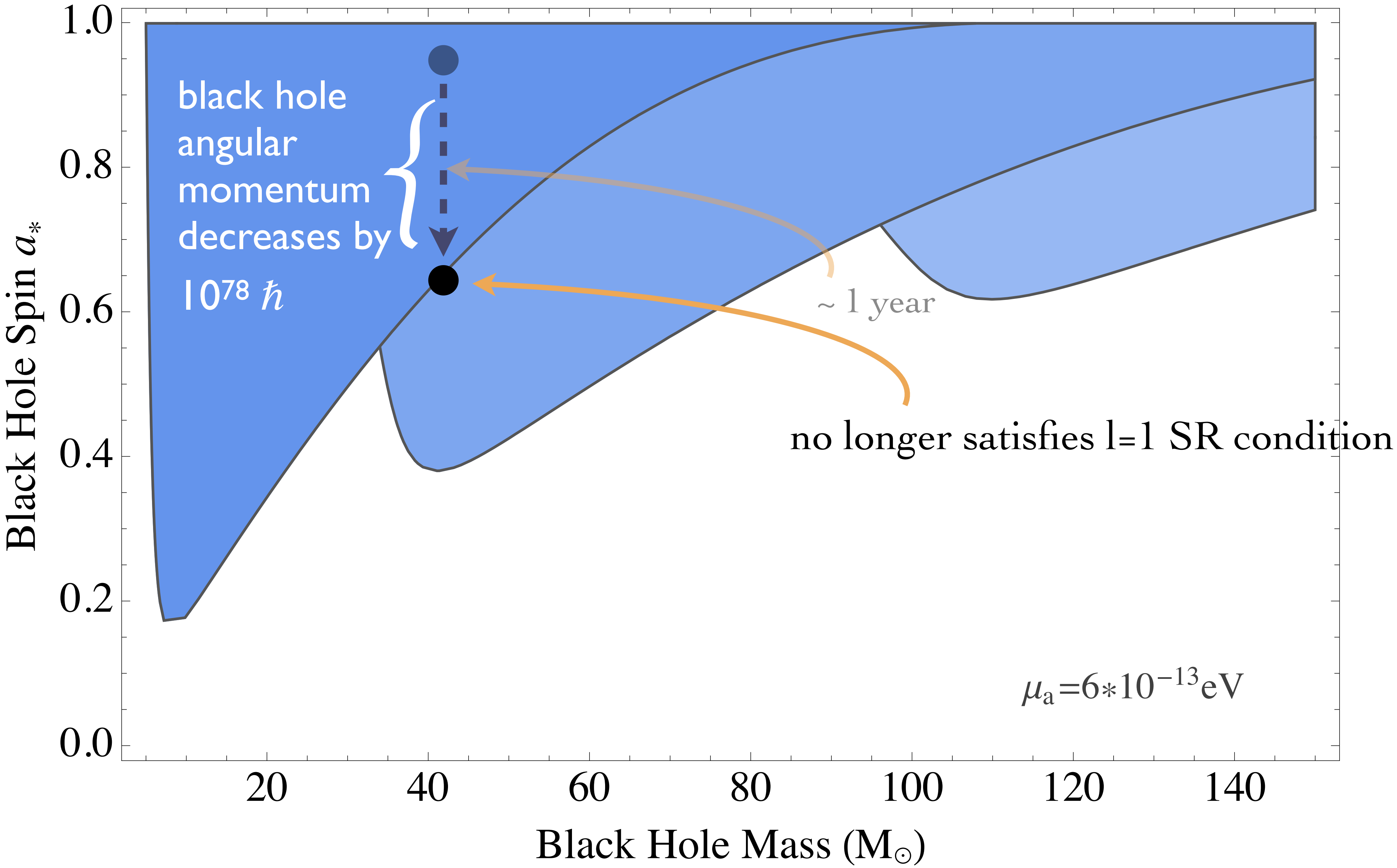
1 msec (300 km)



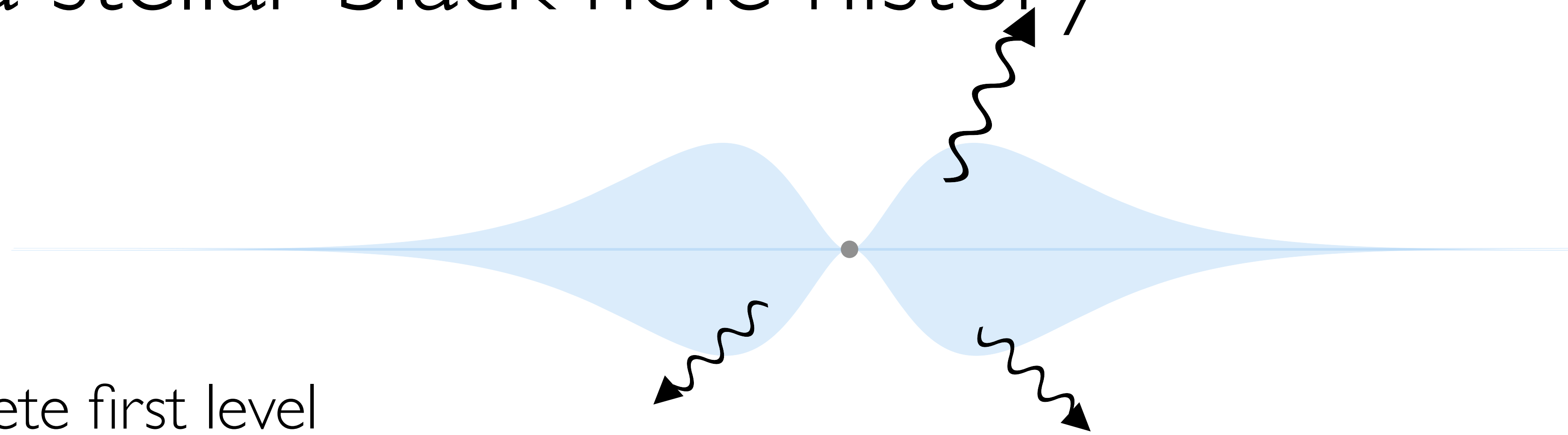
Superradiance: a stellar black hole history



Cloud can carry up to a few percent of the black hole mass: huge energy density

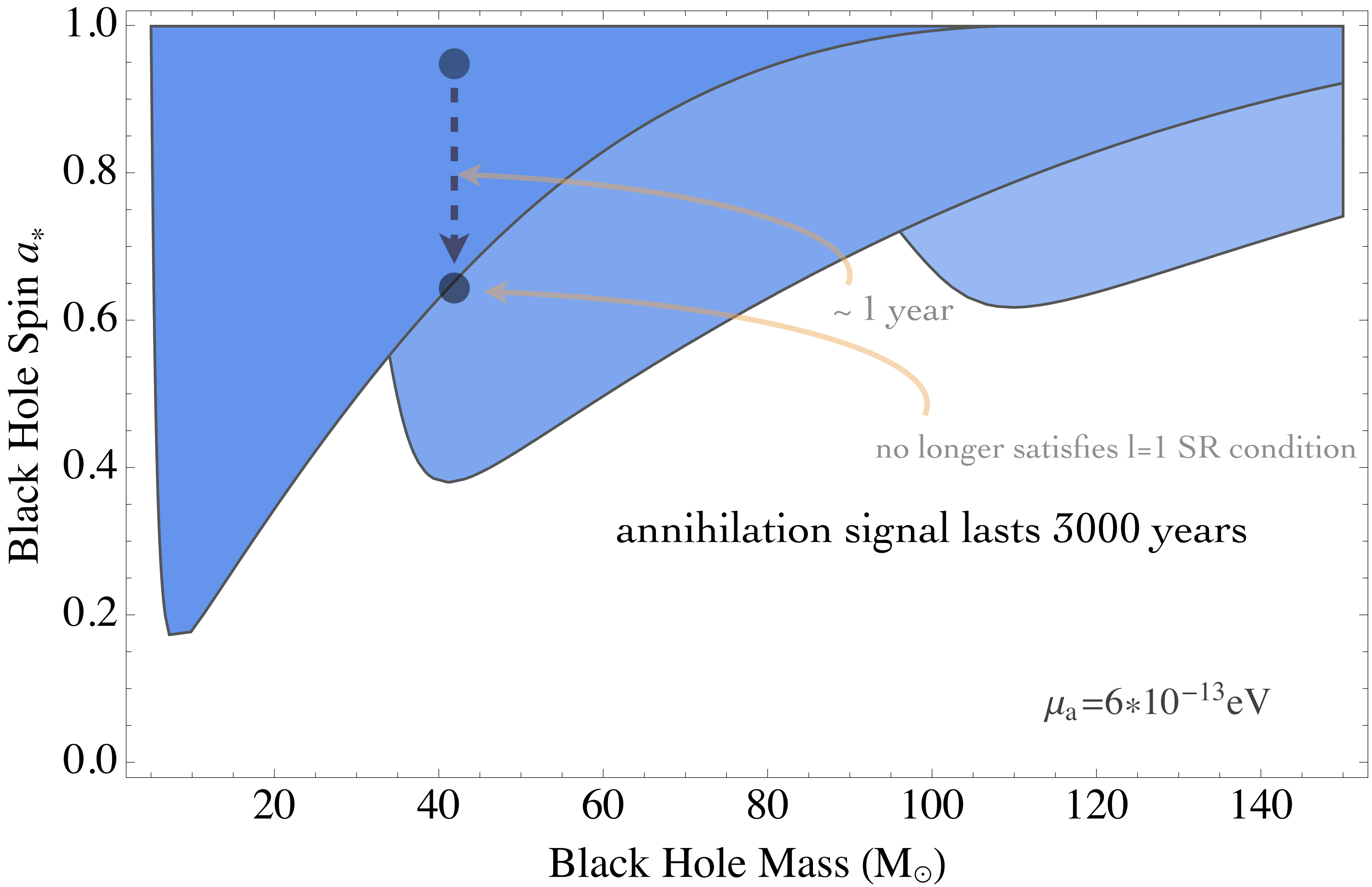


Superradiance: a stellar black hole history



Annihilations to GWs deplete first level

Gravitational waves can be observed in LIGO continuous wave searches



Signals fall into ongoing searches for gravitational waves from asymmetric rotating neutron stars

Up to thousands of observable signals above current LIGO upper limits — lack of observation disfavors a range of axion masses