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Detecting new forces in the gravitational wave background

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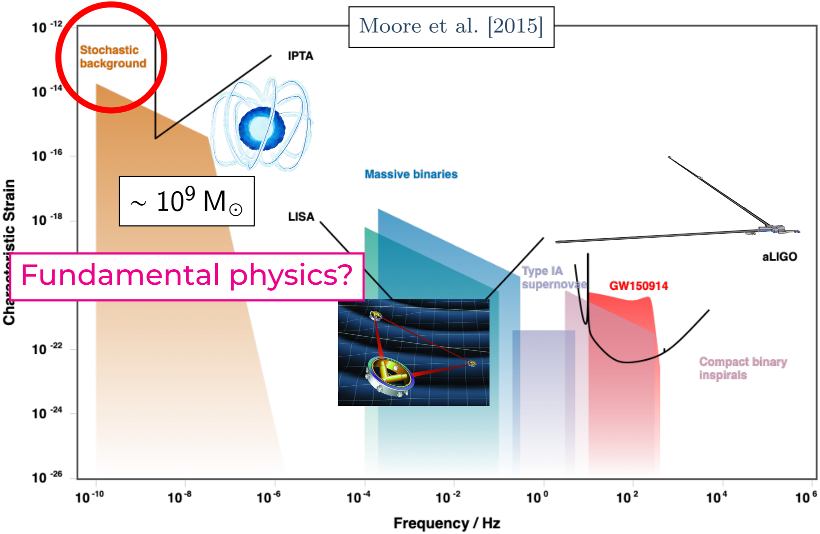
The era of gravitational waves



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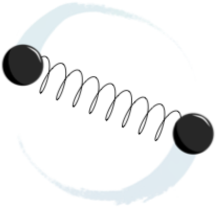
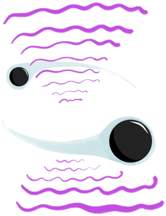
This talk in one slide





1. SMBH GW background is a guaranteed discovery

2. Long range forces can *detectably* modify spectrum

3. SMBH GWs potentially probe many BSM scenarios

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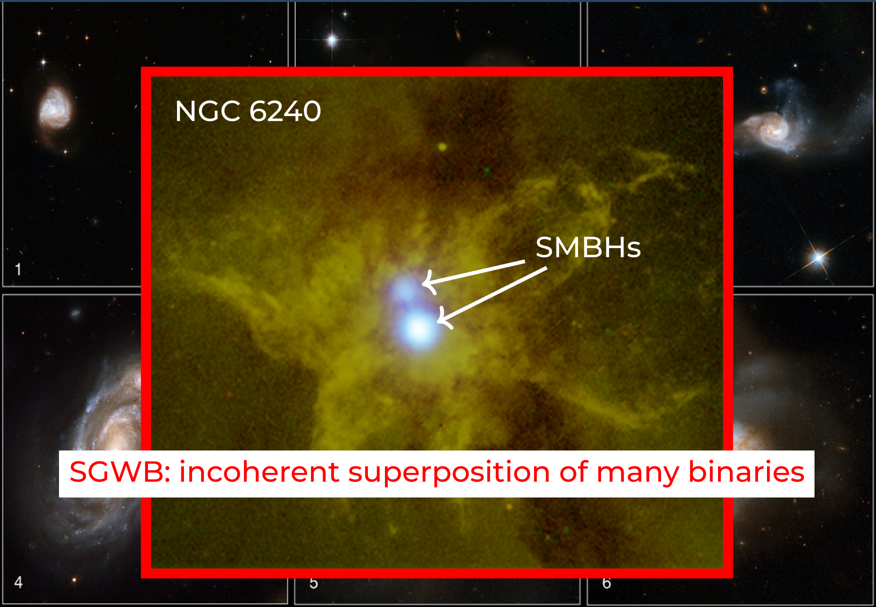
The stochastic GW background



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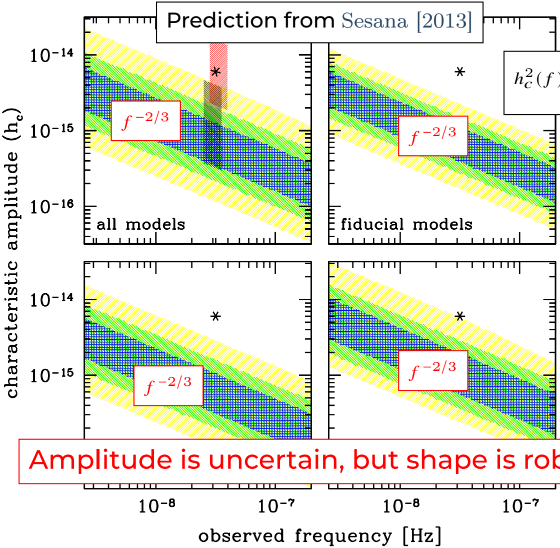
Stochastic background spectrum



$$h_c^2(f) \propto \frac{1}{f} \sum_{\text{sources}} \frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f}$$

$$h_c \propto f^{-2/3}$$

Amplitude is uncertain, but shape is robust

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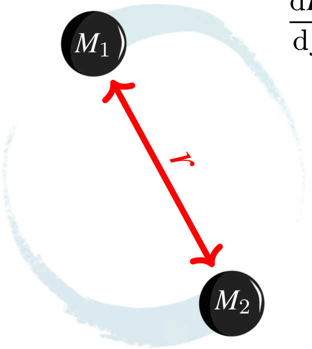
Why is the index $-2/3$?

Gravitational waves drive the evolution of the binary



$2 f_{\rm orbit}$

$$\frac{dE_{\rm GW}}{df_{\rm GW}} = -\pi^2 \mu r^2 f_{\rm GW} \left(\frac{2 f_{\rm GW}}{r} \frac{dr}{df_{\rm GW}} + 1 \right)$$

$$f_{\rm orbit}(r) = \left(\frac{G(M_1 + M_2)}{4\pi^2 r^3} \right)^{1/2}$$

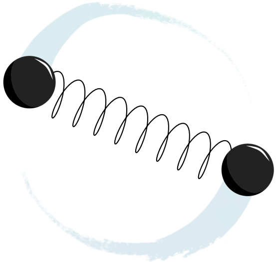
(Kepler's third law)

$$\frac{dE_{\rm GW}}{df_{\rm GW}} \propto f^{-1/3} \implies \frac{dh_c}{df_{\rm GW}} \propto f^{-2/3}$$

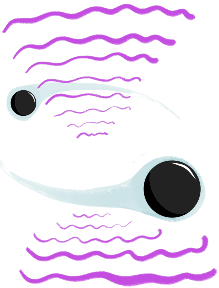
[Phinney, 2001]

New physics can break this prediction

❶ $f \leftrightarrow r$ relation
Kepler's law



❷ All energy loss is
gravitational



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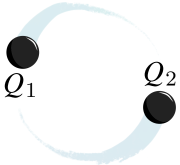
Benchmark model

Additional dynamics spoil the $-2/3$

Toy model: charge BHs* under a new long-range force

*or their surroundings

1. New force changes Kepler's law
2. New radiation takes energy

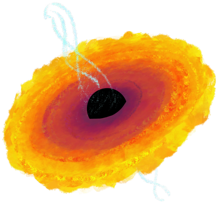


Charge parameters

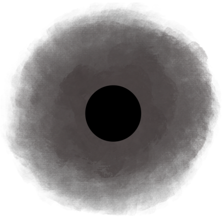
$$\underbrace{\alpha = \frac{Q_1 Q_2}{G M_1 M_2}}_{\text{Force}}$$

$$\underbrace{\gamma^2 = \frac{1}{G}\left(\frac{Q_1}{M_1} - \frac{Q_2}{M_2}\right)^2}_{\text{Radiation}}$$

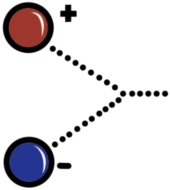
Whence charge?



Particle production



Accretion



Separation

Toy model assumption:

charge is pointlike relative to binary separation

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Modified single-source spectrum

New force and radiation modify the spectrum

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f_{\mathrm{GW}}} = -\pi^2 \mu r^2 f_{\mathrm{GW}} \left(\frac{2 f_{\mathrm{GW}}}{r} \frac{\mathrm{d}r}{\mathrm{d}f_{\mathrm{GW}}} + 1 \right) \underbrace{\frac{P_{\mathrm{GW}}}{P_{\mathrm{GW}} + P_{\mathrm{new}}}}_{\text{radiation}}$$

$m =$ mediator mass

$\omega = 2\pi f_{\mathrm{orbit}}$

$$F = \frac{G M_1 M_2}{r^2} \left(1 - \underbrace{\alpha e^{-mr} (1 + mr)}_{\text{new force}} \right)$$

$$P_{\mathrm{new}} = \frac{1}{3} G \gamma^2 \mu^2 r^2 \omega^4 \, \mathrm{Re} \left[\sqrt{1 - \frac{m^2}{\omega^2}} \right] \begin{cases} \left(1 - \frac{m^2}{2\omega^2} \right) & \text{(scalar)} \\ 2 \left(1 + \frac{m^2}{2\omega^2} \right) & \text{(vector)} \end{cases}$$

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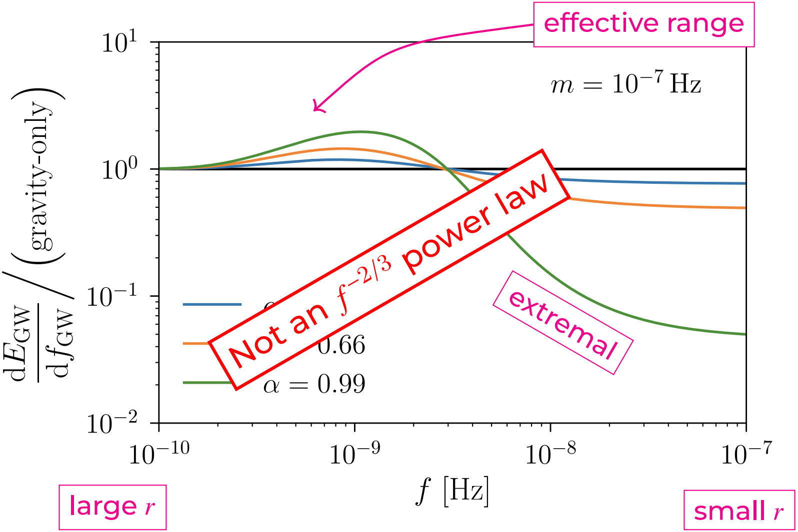
Modifying the force law ($\alpha \neq 0$)



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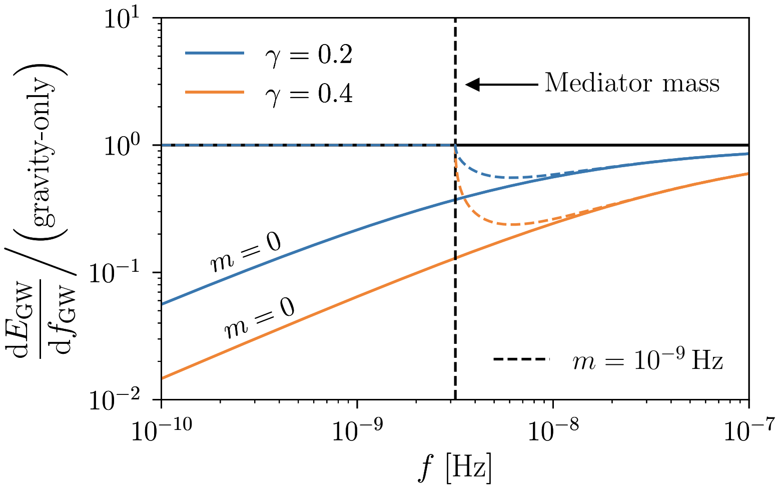
New dipole radiation ($\gamma \neq 0$)



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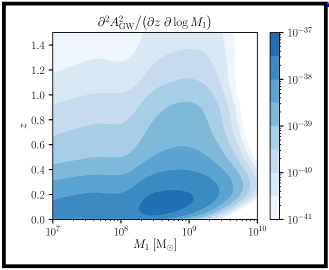
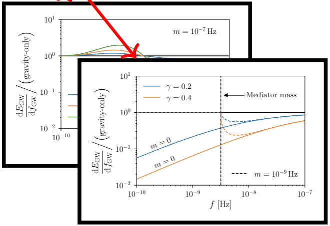
From single sources to h_c

$$h_c^2(f) = \int \mathrm{d}z\,\mathrm{d}M_1\,\mathrm{d}M_2\, \frac{\mathrm{d}n_{\mathrm{G}}}{\mathrm{d}z\,\mathrm{d}M_1\,\mathrm{d}M_2} \frac{f_{\mathrm{s}}}{1+z} \frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}f_{\mathrm{s}}} \frac{3H_0^2}{2\pi^2\rho_c^2}$$



Source distribution



Single-source spectrum

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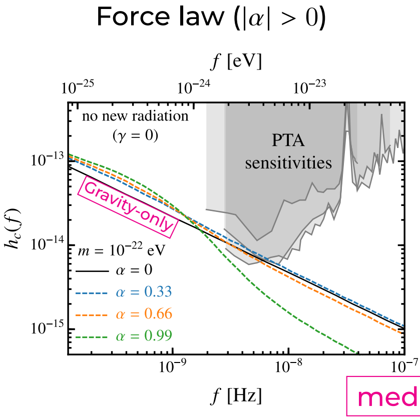
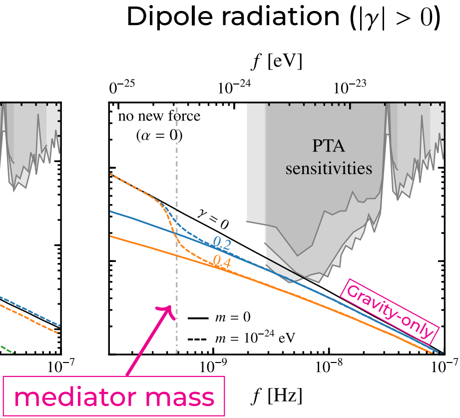
Observables





1. Single-source features are intact
2. Both modified slope and novel features observable
3. Sensitivity curves: this is happening **NOW**

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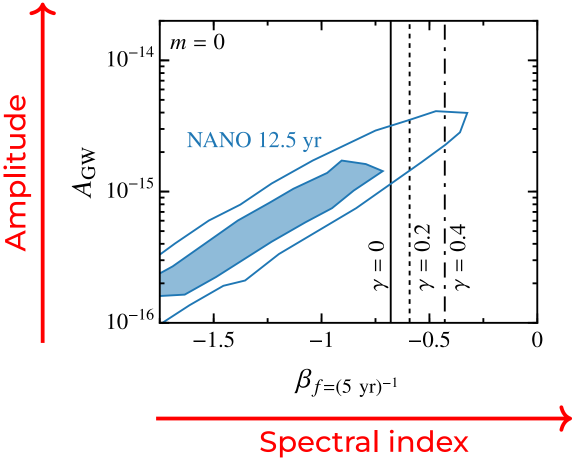
Interpret the **NANOGrav 12.5-yr result** in this framework

[Arzoumanian et al., 2020]



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Beyond the benchmark

Probe **any** new physics that affects binary dynamics

1. Charged clouds
2. Dark matter spikes
3. Superradiance

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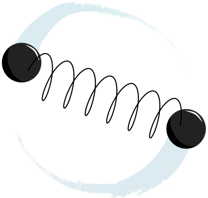
Conclusions

Supermassive black holes are our new laboratories

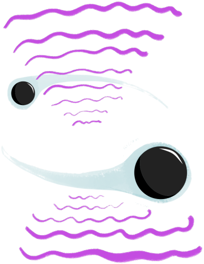
SGWB discovery

is imminent



Long-range forces

are detectable



SMBHs can probe

many NP scenarios

Data is on the way!

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