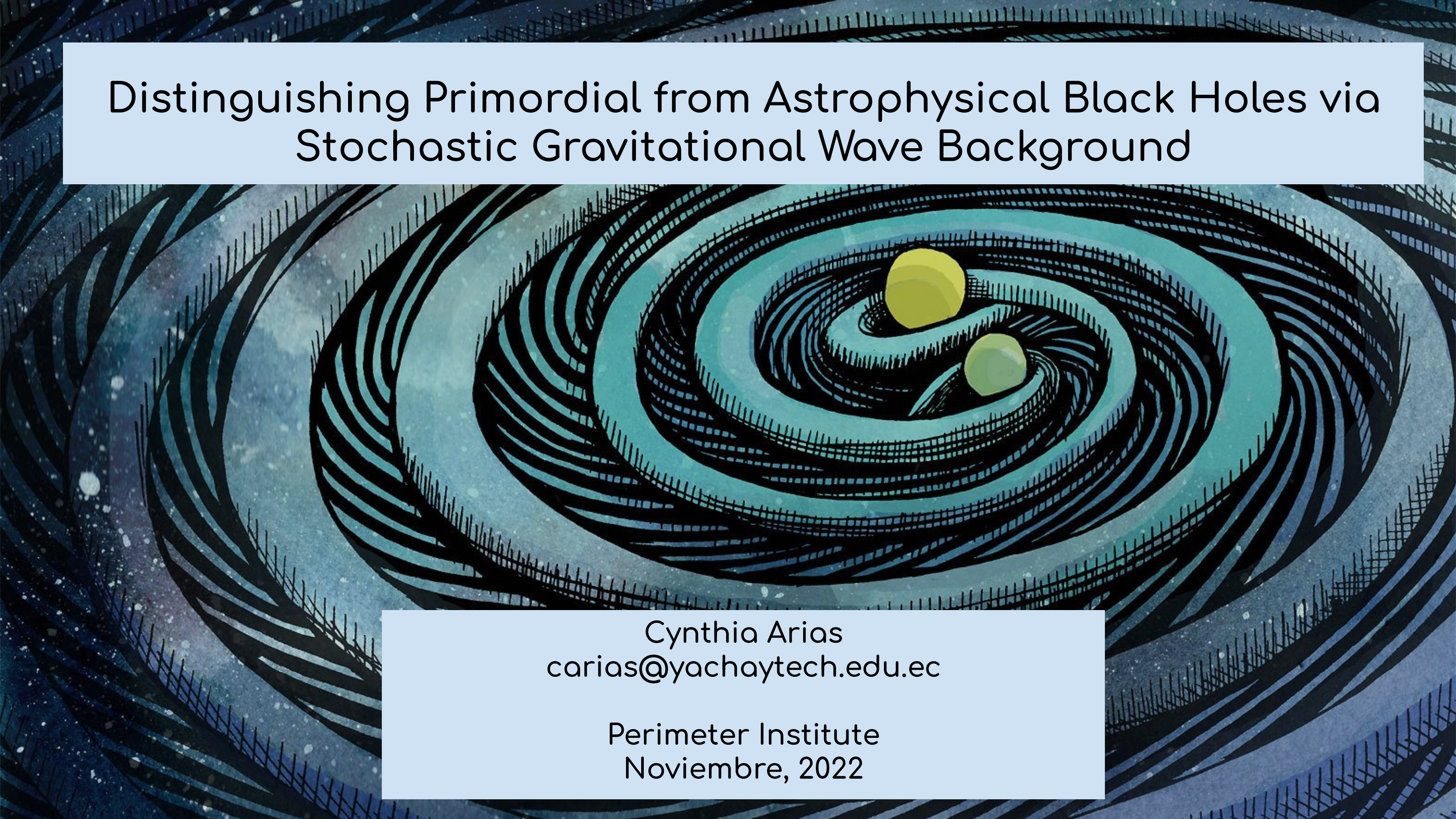
Distinguishing Primordial from Astrophysical Black Holes via Stochastic Gravitational Wave Background



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Keywords

Agujeros negros

- Primordiales
- Astrofísicos

Ondas gravitacionales

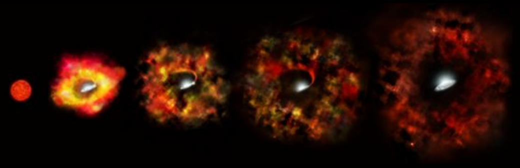
Fondo estocástico de ondas gravitacionales

AGUJEROS NEGROS

Canales de formación de agujeros negros

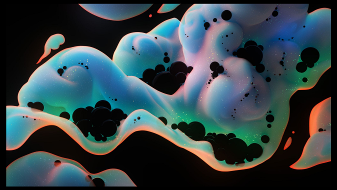
Astrofísicos

Se forman luego de la muerte de una estrella



Primordiales

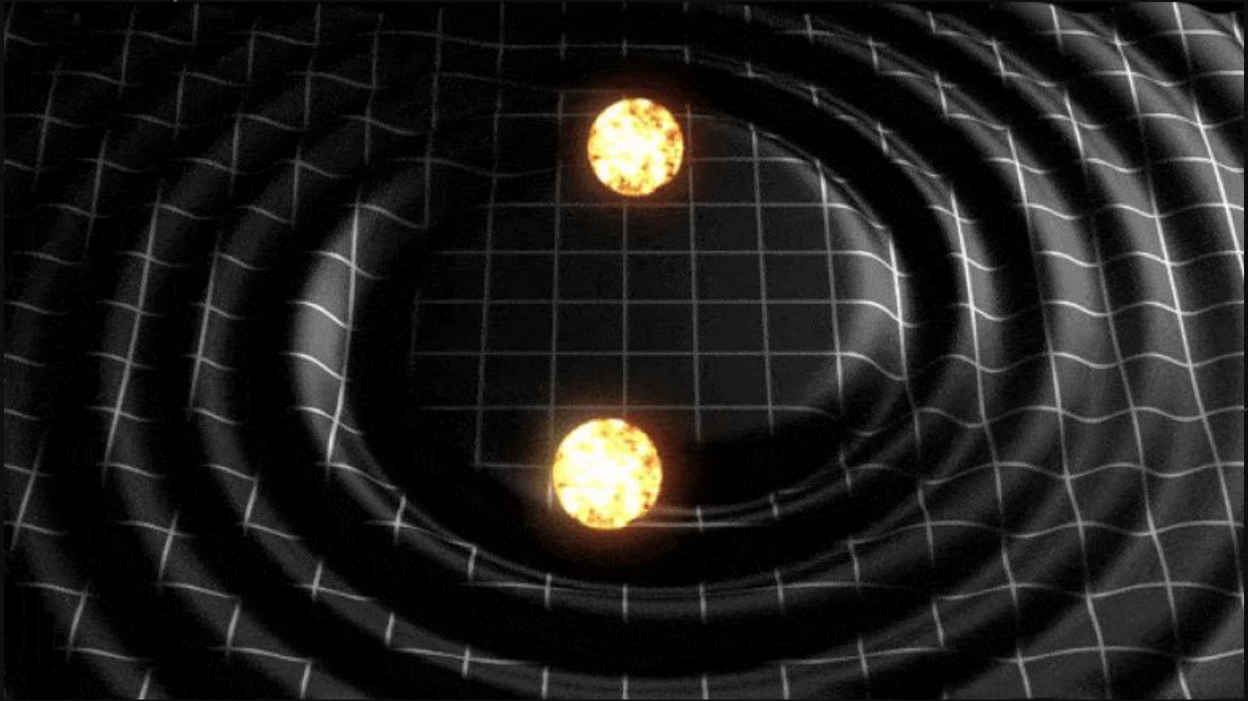
Formados a partir del colapso gravitacional de regiones muy densas durante el Universo temprano



Candidatos de materia oscura!

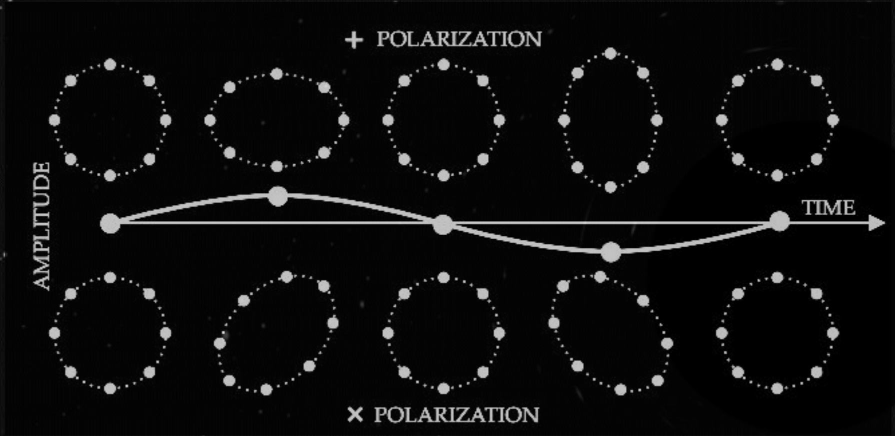
ONDAS GRAVITACIONALES

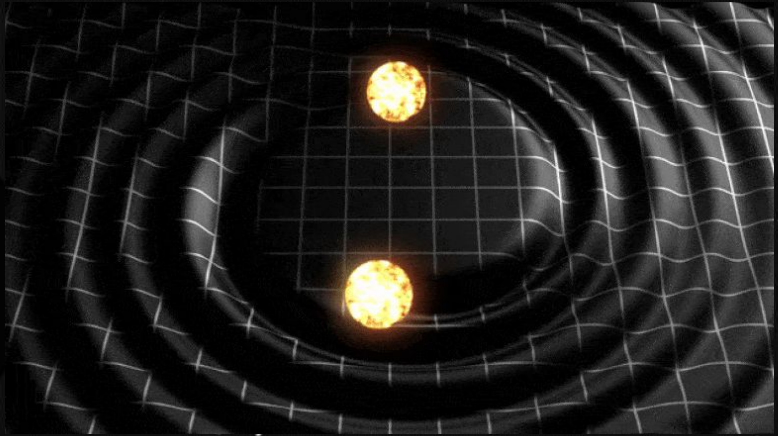
“Perturbaciones del espacio tiempo”



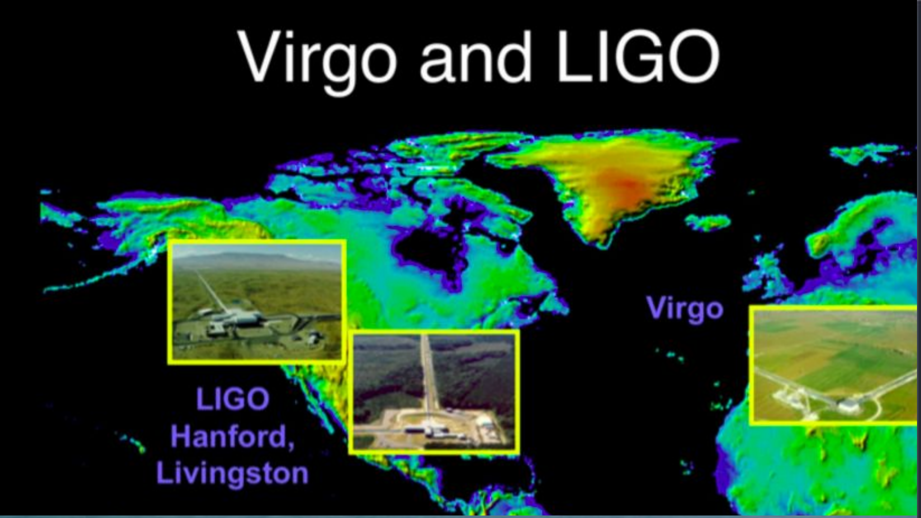
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1$$

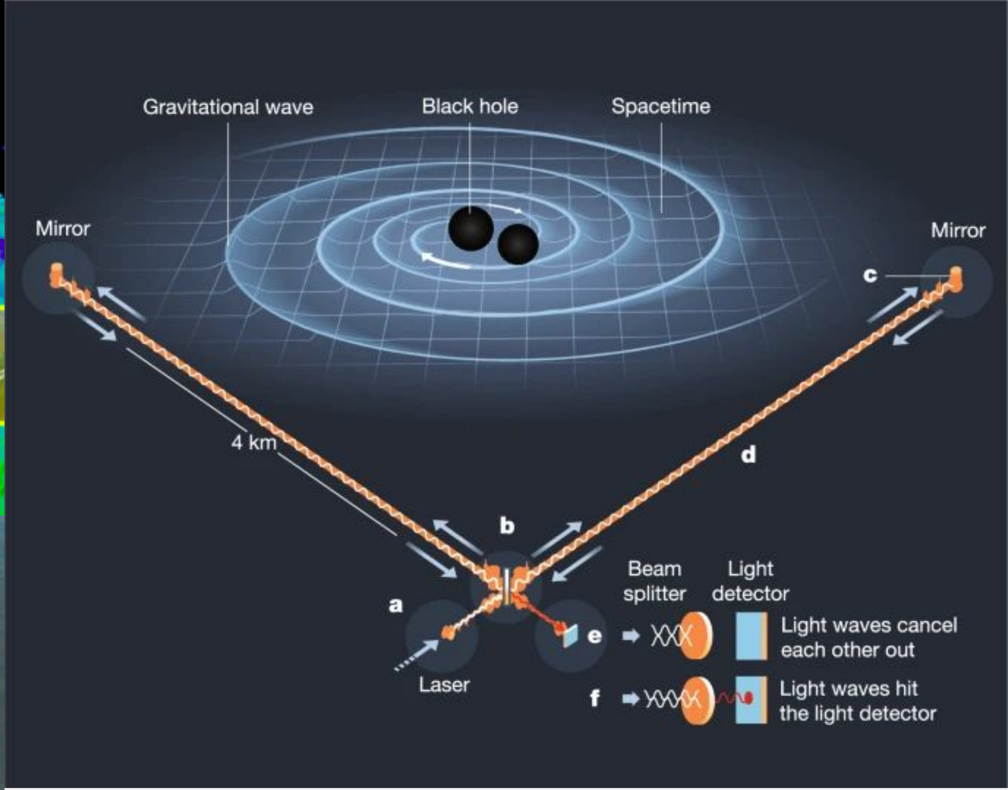
"Ripples of the space time"





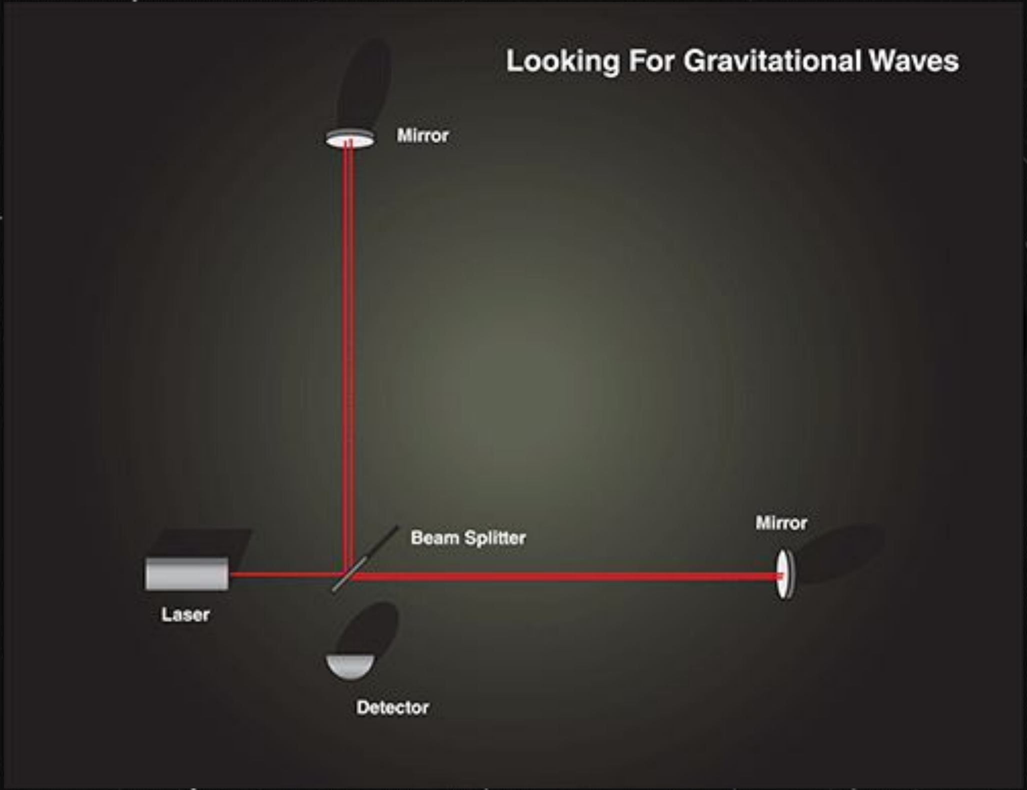
$$\begin{aligned}
\tilde{h}_{+}(f) &= \left(\frac{5}{24\pi^{4/3}}\right)^{1/2} e^{i\Psi_{+}(f)} \frac{c}{r} \left(\frac{GM_c}{c^3}\right)^{5/6} \frac{1}{f^{7/6}} \frac{1+\cos^2\iota}{2}, \\
\tilde{h}_{\times}(f) &= \left(\frac{5}{24\pi^{4/3}}\right)^{1/2} e^{i\Psi_{\times}(f)} \frac{c}{r} \left(\frac{GM_c}{c^3}\right)^{5/6} \frac{1}{f^{7/6}} \cos\iota.
\end{aligned}$$





En 2015, se detectaron ondas gravitacionales por primera vez usando un instrumento muy sensible llamado LIGO. Estas primeras ondas gravitacionales ocurrieron cuando dos agujeros negros chocaron entre sí. La colisión ocurrió hace 1.300 millones de años. ¡Pero las ondas no llegaron a la Tierra sino hasta 2015!

¿Cómo detecta un interferómetro una onda gravitacional?

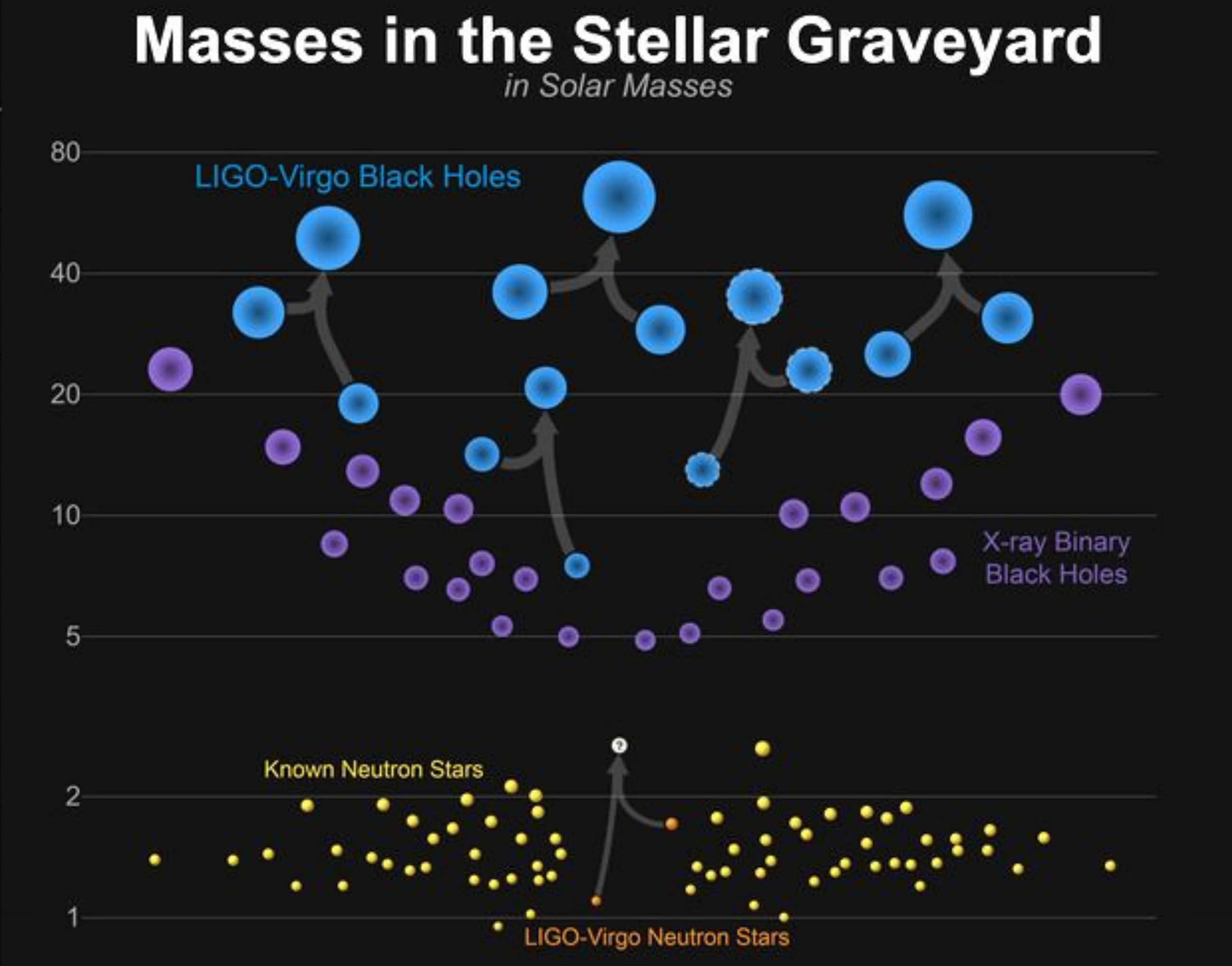


LIGO puede detectar la compresión y estiramiento del espacio tiempo.

LIGO tiene dos "brazos" que miden 4 kilómetros de largo.

Una onda gravitacional cambia ligeramente la longitud de los brazos.

LIGO utiliza láseres, espejos e instrumentos extremadamente sensibles para detectar estos pequeños cambios.


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars
?

Horizonte de detección de ondas gravitacionales

$$h_{+,\times} \propto \frac{1}{d_l}$$

Fondo estocástico de Ondas Gravitacionales (SGWB)

¿Cómo caracterizar el SGWB?

A través del espectro de energía de ondas gravitacionales

$$\Omega_{gw}(f) = \frac{1}{\rho_c c^2} \int_0^{\infty} \boxed{N(z)} \frac{1}{1+z} \left(f_r \boxed{\frac{dE_{gw}}{df_r}} \right) \Bigg|_{f_r = f(1+z)} \boxed{dz}$$

Número de eventos por unidad de volumen ocurriendo entre z and z+dz

Energía emitida en ondas gravitacionales por cada evento entre fr and fr + dfr

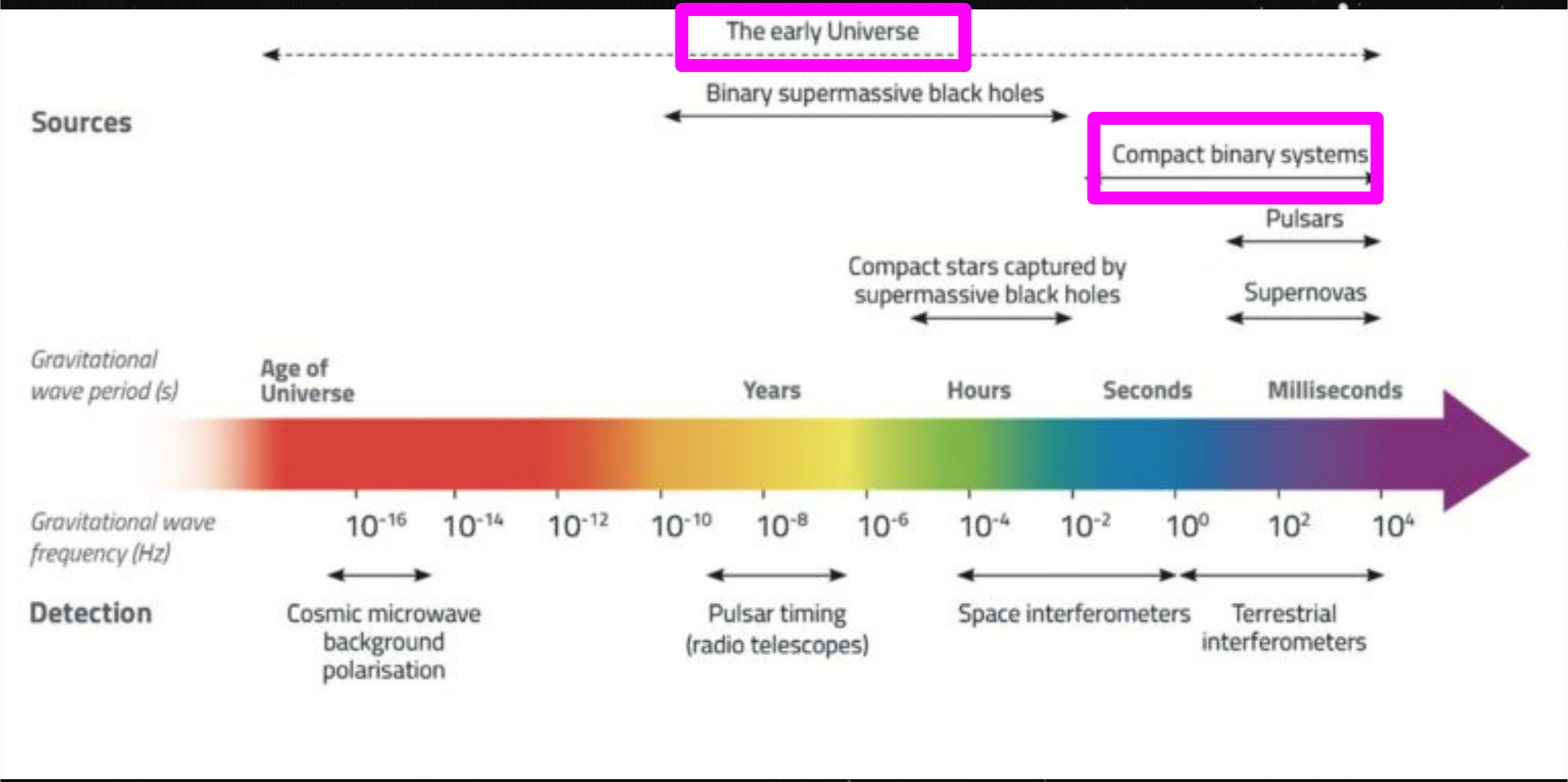
¿Qué eventos contribuyen al fondo estocástico?

$$h_{+,\times} \propto \frac{1}{d_l}$$

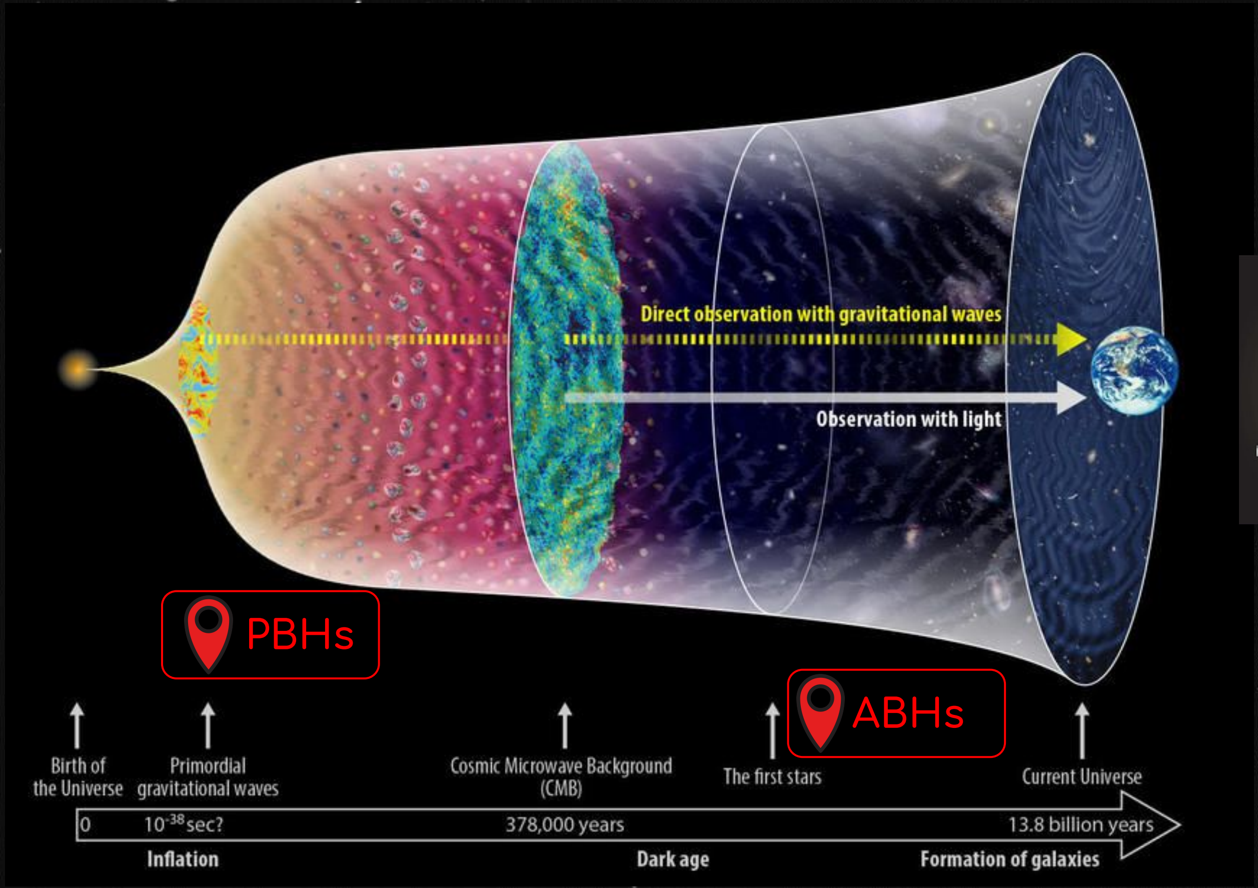
Señal débil

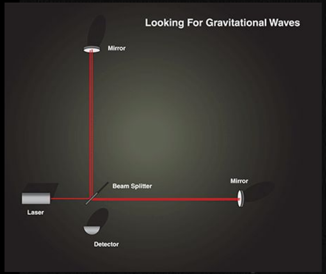
Redshift alto

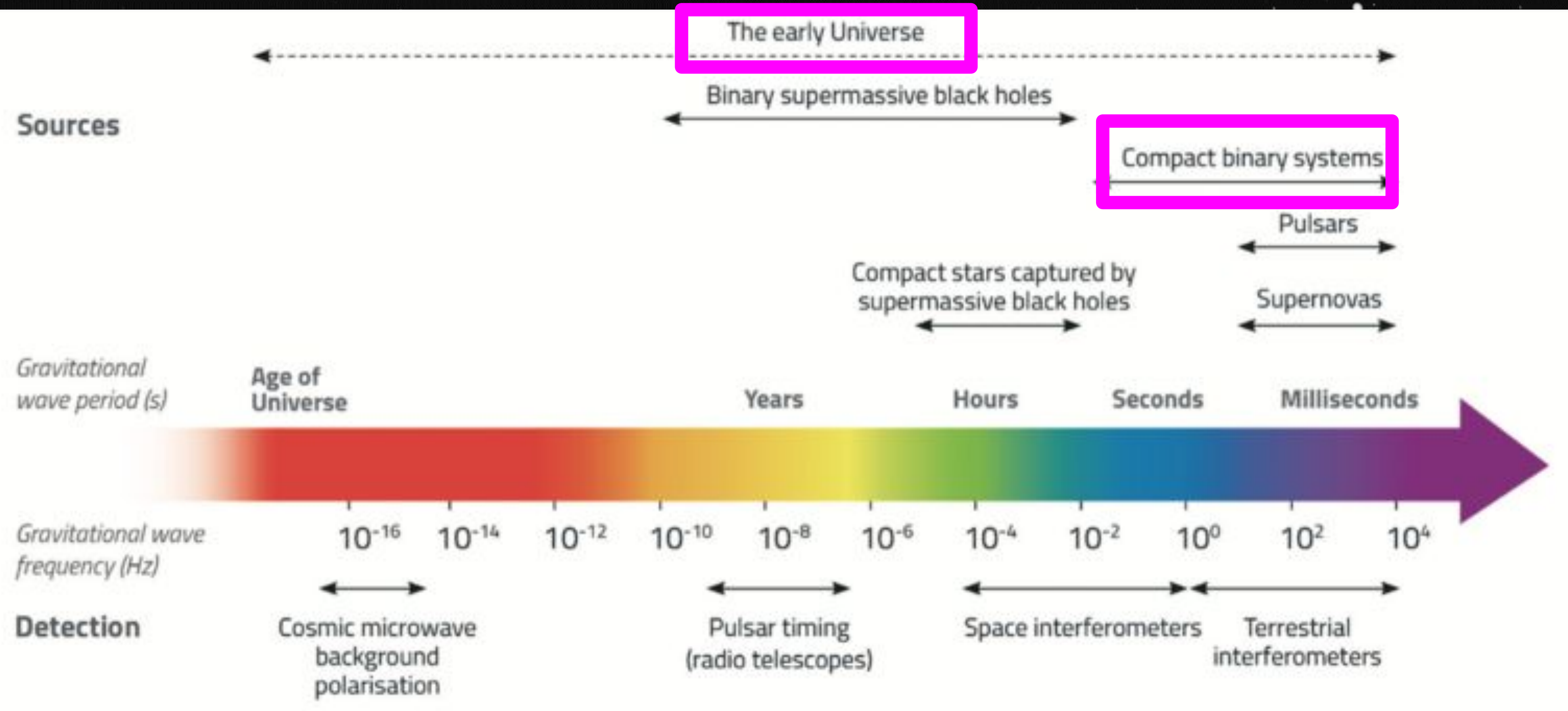
Objetos sin resolver


The early Universe
Binary supermassive black holes
Sources
Compact binary systems
Pulsars
Compact stars captured by supermassive black holes
Supernovas
Gravitational wave period (s)
Age of Universe
Years
Hours
Seconds
Milliseconds
Gravitational wave frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Detection
Cosmic microwave background polarisation
Pulsar timing (radio telescopes)
Space interferometers
Terrestrial interferometers

¿Cómo distinguir entre PBHs y ABHs?



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10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}
Detection
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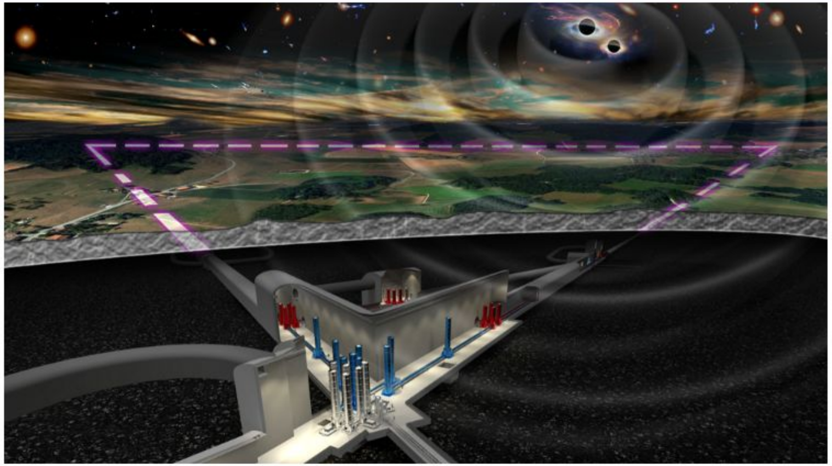
EINSTEIN TELESCOPE



The Einstein Telescope will make it possible, for the first time, to explore the Universe through gravitational waves along its cosmic history up to the cosmological dark ages, shedding light on open questions of fundamental physics and cosmology. It will probe the physics near black-hole horizons (from tests of general relativity to quantum gravity), help understanding the nature of dark matter (such as primordial BHs, axion clouds, dark matter accreting on compact objects), and the nature of dark energy and possible modifications of general relativity at cosmological scales. Exploiting the ET

¿Cómo distinguir entre PBHs y ABHs?

1. Distribución de masas

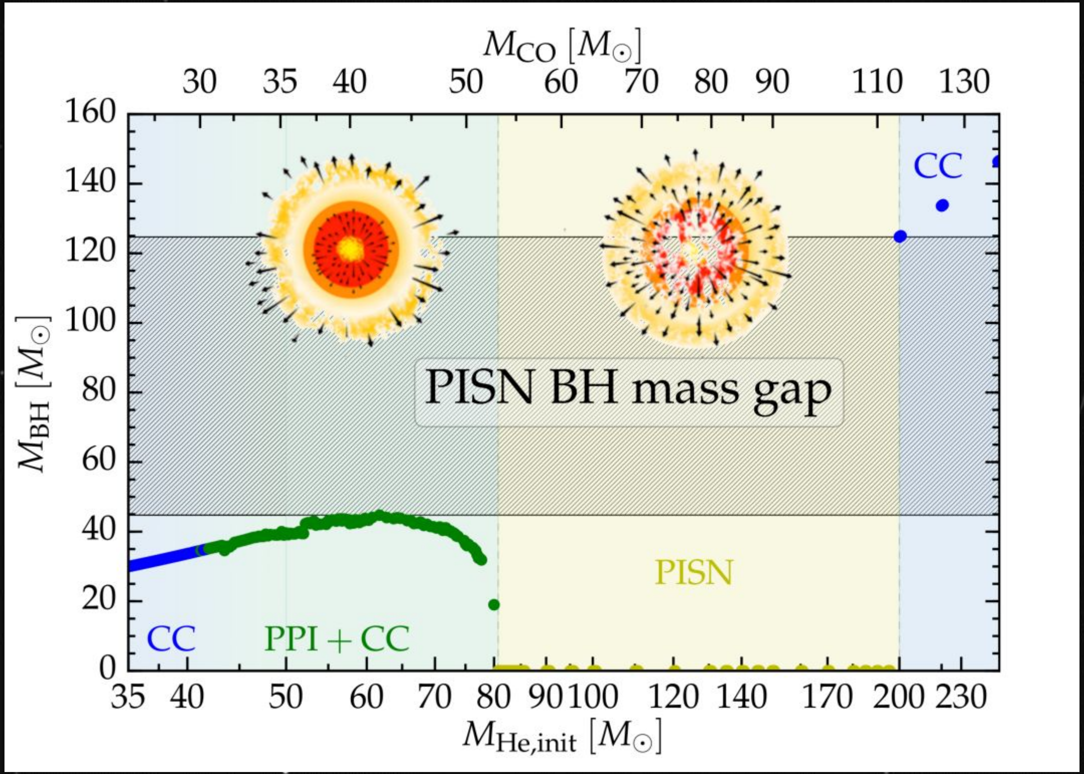
2. Distribución de spin

¿Cómo distinguir entre PBHs y ABHs?

★ Usando distribución de masa

- Necesitamos saber la probabilidad de que un agujero negro exista en un determinado rango de masas.
- Diferentes tipos de agujeros negros tendrán una distribución de masas distinta.

Distribución de masas



Modelos de supernovas sugieren que no hay agujeros negros aldedor de ~50 – 150 $M_\odot$

Si llegamos a encontrar una población considerable de agujeros negros en ese "GAP", podrían ser de origen primordial.

Cálculo del espectro para sistemas binarios de agujeros negros

$$\Omega_{gw}(f) = \frac{1}{\rho_c c^2} \int_{zmin}^{zmax} dz \int d\theta \, p(\theta) \, \frac{N(z)}{1+z} \left(f_r \frac{dE_{gw}(\theta)}{df_r} \right) \Bigg|_{f_r = f(1+z)}$$

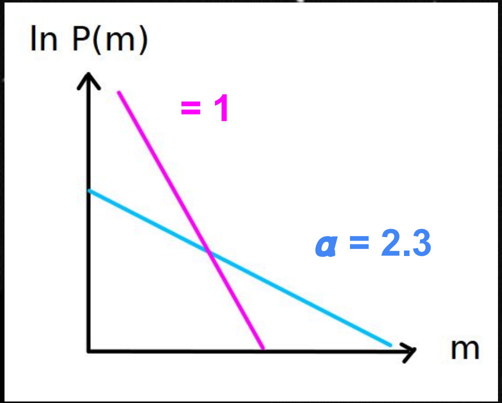
$$N(z) = R_m \frac{1}{(1+z) H_0 E(z)}$$

$$\frac{dE_{gw}}{df_r} = \frac{2\pi^2 c^3}{G} d_M^2 f^2 \langle |\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2 \rangle_{\Omega_s}$$

Modelo para distinguir PBHs de ABHs

$$P(m) = \frac{1}{m^{\alpha}}$$

ABHs: Power law



Since stars have a power-law mass distribution, we might also expect a power-law mass distribution for black holes.

α tells us how steptly the probability decreases with increasing mass

Mass distribution

PBHs: Log normal distribution

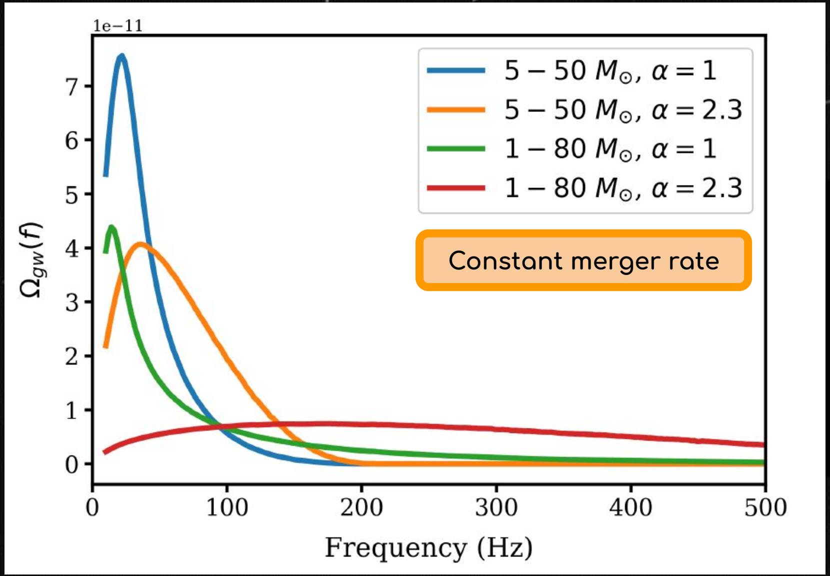
$$P_{PBH}(m) = \frac{1}{\sqrt{2\pi}\sigma m} \exp\left(\frac{-\log^2(m/M_c)}{2\sigma^2}\right)$$

Motivated by studies about small-scale density fluctuations (Dolgov & Silk 1993: Carr et al. 2017.

Mc = 100 msun as characteristic BH formation mass
Standard deviation σ = 5 msun

Resultados preliminares

SGWB from ABHs (low mass)



<u>5 - 50 msun</u>

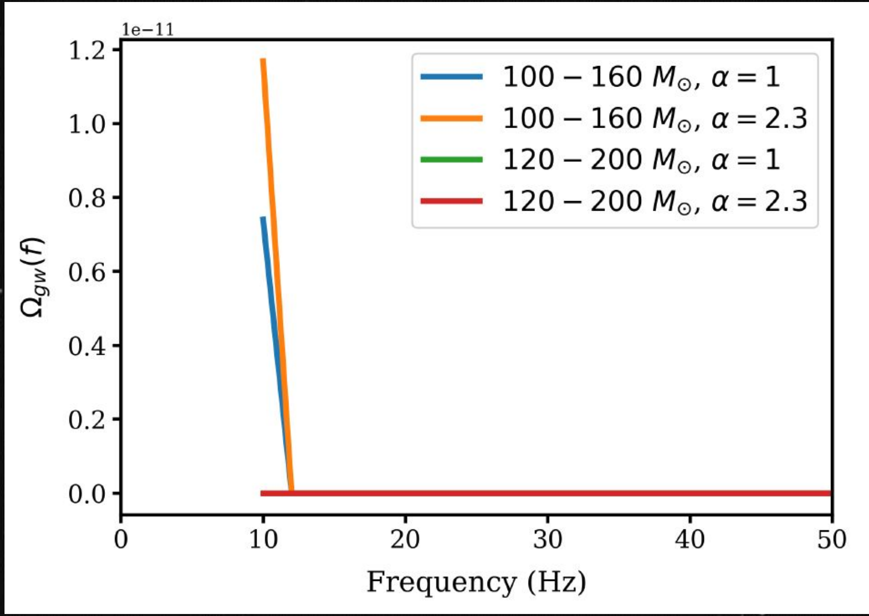
★ SGWB (**α** = 1) > SGWB (**α** = 2.3)

<u>1- 80 msun</u>

★ SGWB (**α** = 1) > SGWB (**α** = 2.3)

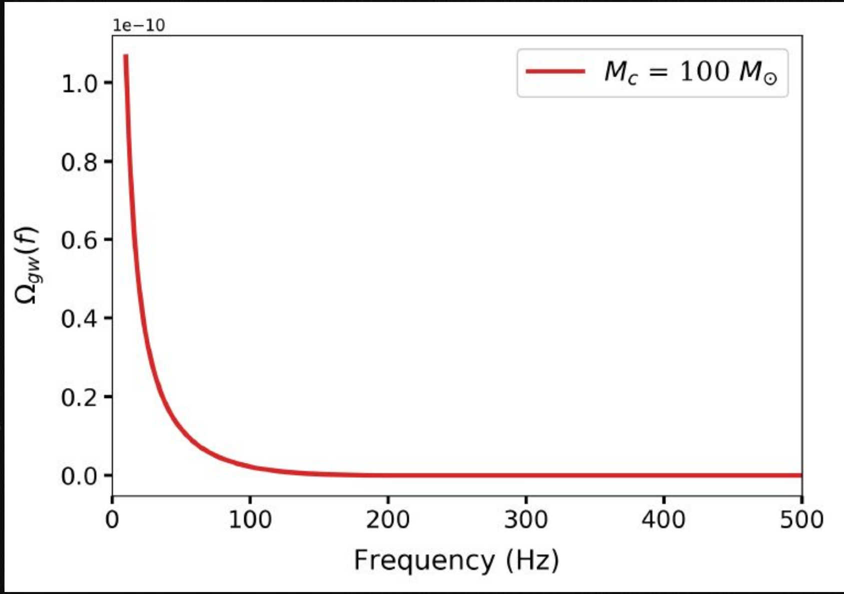
*Because **α** = 1 consider heavier masses*

SGWB from ABHs (high mass)



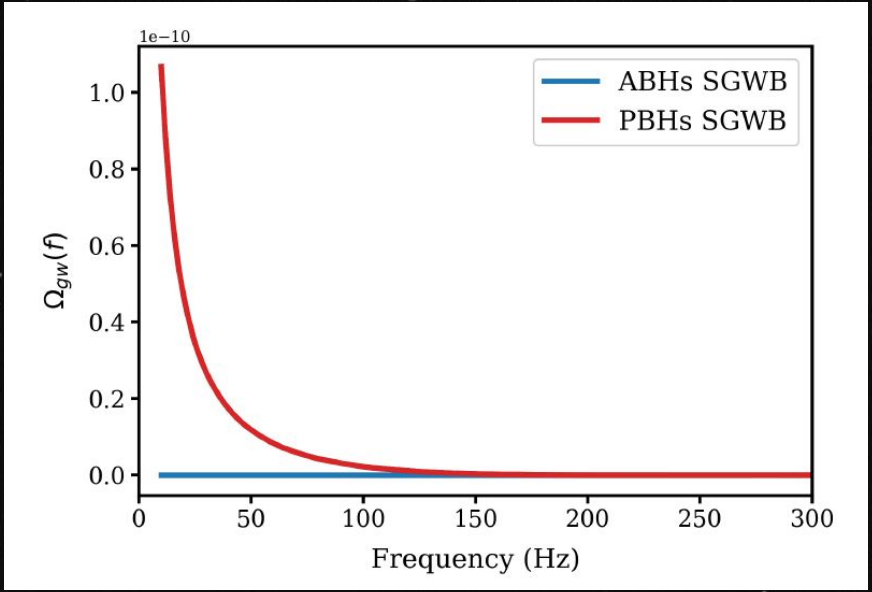
Constant merger rate

SGWB from PBHs (high mass)



Constant merger rate

Comparison between SGWB of different origin (high mass)



Constant merger rate

Conclusions and future work

A python code to:

★ Calculate GWs power spectrum BBHs

★ Distinguish between PBHs and ABHs through:
Mass distribution and merger rate evolution

Next

- Implement the merger rate for each type of BH and study their SGWB power spectrum!

- Provide insights for the next generation of GW detectors

THANKS FOR YOUR ATTENTION!

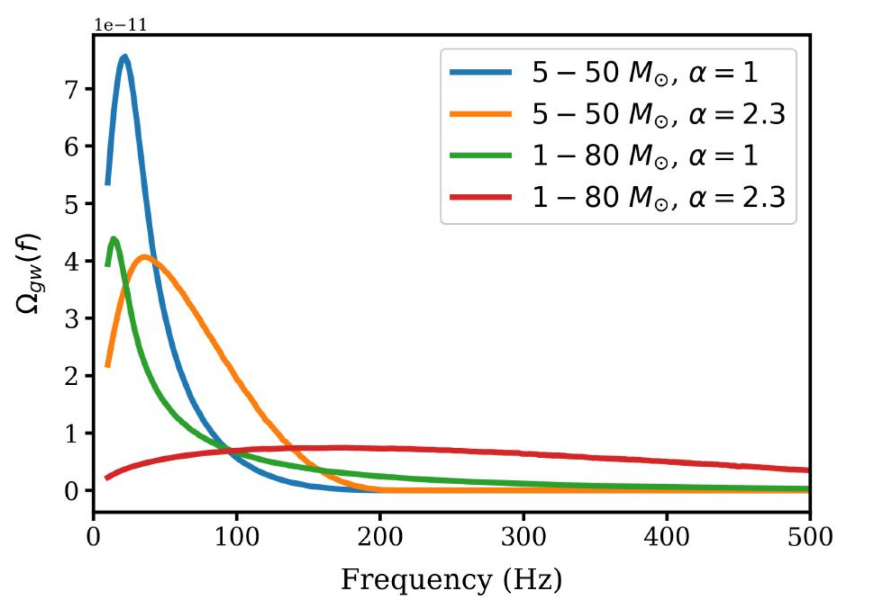
EXTRA SLIDES

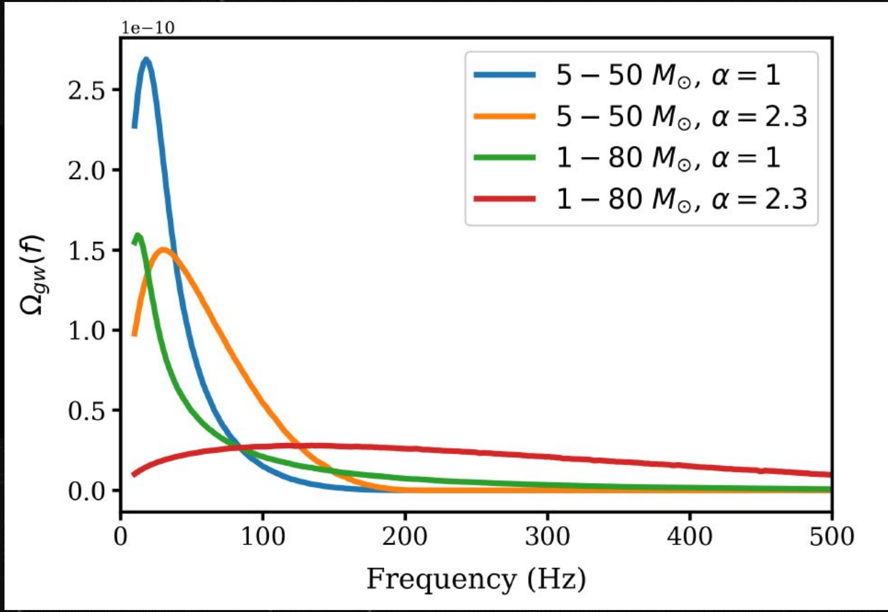
¿Cómo distinguir entre PBHs y ABHs?

2. Redshift evolution of the merger rate

Indicates the number of BBHs mergers per volume os space as function of redshift.

SGWB from ABHs (low mass)

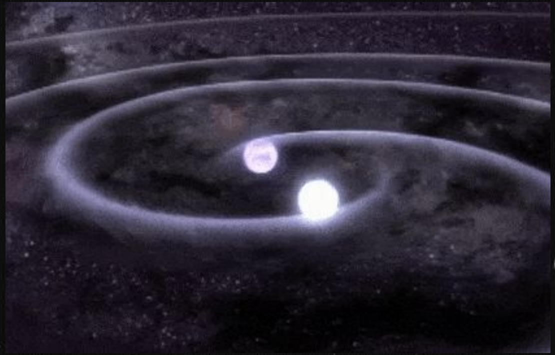




Constant merger rate

Variable merger rate

From the redshift evolution of the merger rate



Black holes at different redshift, have different merger rates.

ABHs and PBHs will exhibit different merger rates.

A naive approximation is considering constant rate in comoving volume

Our model to distinguish PBHs from ABHs

Merger rate

" Toy model "

Constant

A naive approximation is considering constant rate in comoving volume

$$R_m = 10\, Gpc^{-3} \cdot yr^{-1}$$

Redshift dependent

$$R_m(z) = R_0 \cdot (1+z)^2,$$

$$R_0 = 20\ Gpc^{-3} \cdot yr^{-1}$$

A power law model because merger rate always increases as function of redshift

Linearized Einstein Field Equations (LEFE)

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1.$$

$$\Box \bar{h}_{\mu\nu} = -16\pi G T_{\mu\nu}.$$

Solution: HOMOGENEOUS wave equation + particular solution

$$\Box \bar{h}_{\mu\nu} = 0.$$

LEFE in vacuum

$$\boxed{h_{0\mu} = 0, \quad h^i{}_i = 0, \quad \partial^j h_{ij} = 0.}$$

$$\boxed{\Box h_{ij} = 0.}$$

EFE in TT gauge

- ➔ In vacuum, GW's propagate at ***c.***
- ➔ **2** dof

Frequency Domain waveforms

$$
\begin{aligned}
\tilde{h}_+(f) &= \left(\frac{5}{24\pi^{4/3}}\right)^{1/2} e^{i\Psi_+(f)} \frac{c}{r} \left(\frac{GM_c}{c^3}\right)^{5/6} \frac{1}{f^{7/6}} \frac{1+\cos^2\iota}{2}, \\
\tilde{h}_\times(f) &= \left(\frac{5}{24\pi^{4/3}}\right)^{1/2} e^{i\Psi_\times(f)} \frac{c}{r} \left(\frac{GM_c}{c^3}\right)^{5/6} \frac{1}{f^{7/6}} \cos\iota.
\end{aligned}
$$

$$
\begin{aligned}
\Psi_+(f) &= 2\pi f(t_{\text{coal}} + r/c) - \Phi_0 - \frac{\pi}{4} + \frac{3}{4}\left(\frac{GM_c}{c^3} 8\pi f\right)^{-5/3}, \\
\Psi_\times(f) &= \Psi_+(f) + \frac{\pi}{2},
\end{aligned}
$$