Hunting for dark particles with Gravitational Waves

Alfredo Urbano
CERN

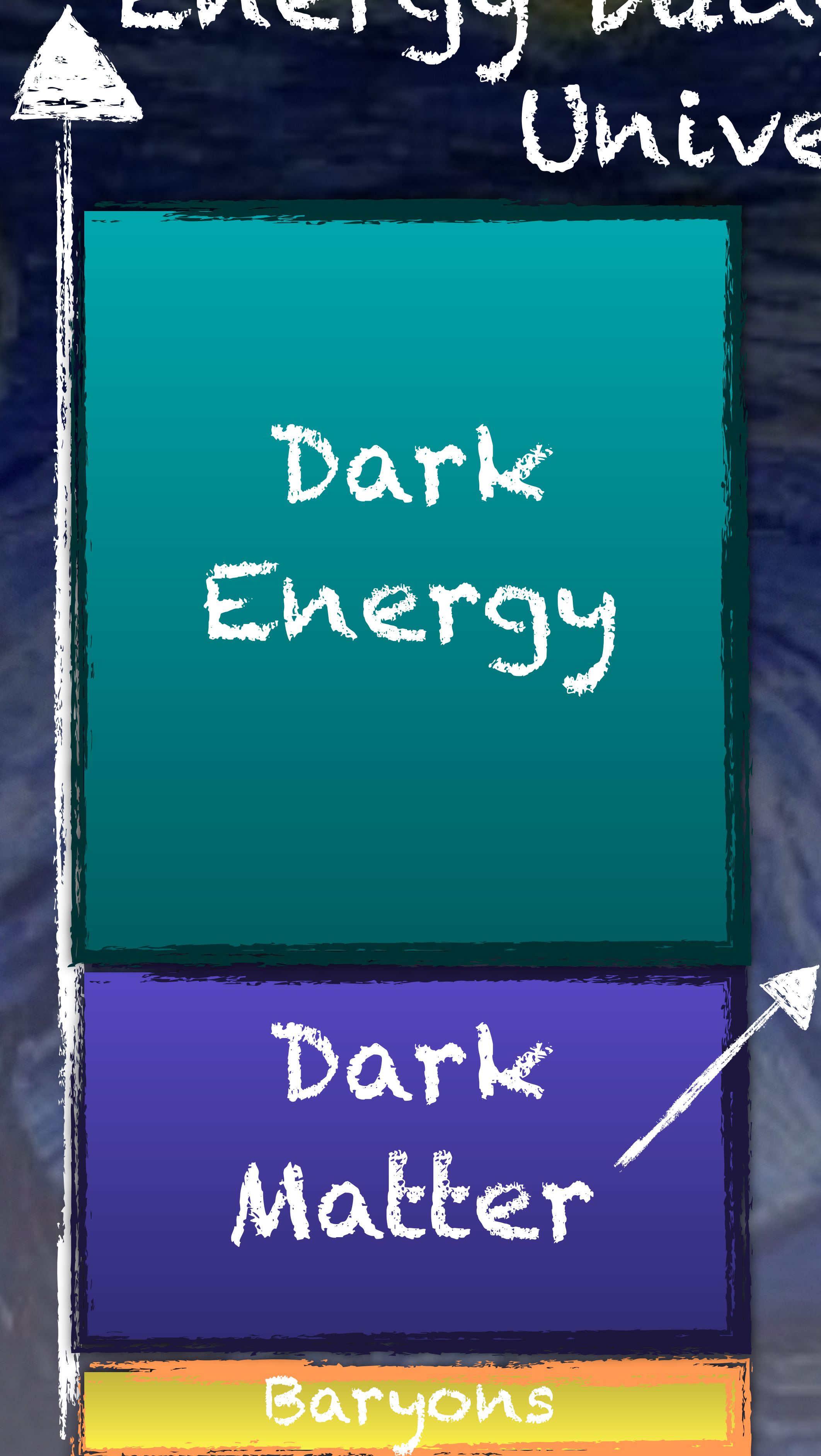
JCAP 1610(2016)10,001
[arXiv:1605.01209]
with Gian Giudice
and Matthew McCullough

GW & Cosmology workshop
DESY - Hamburg, 17 October 2016

Introduction

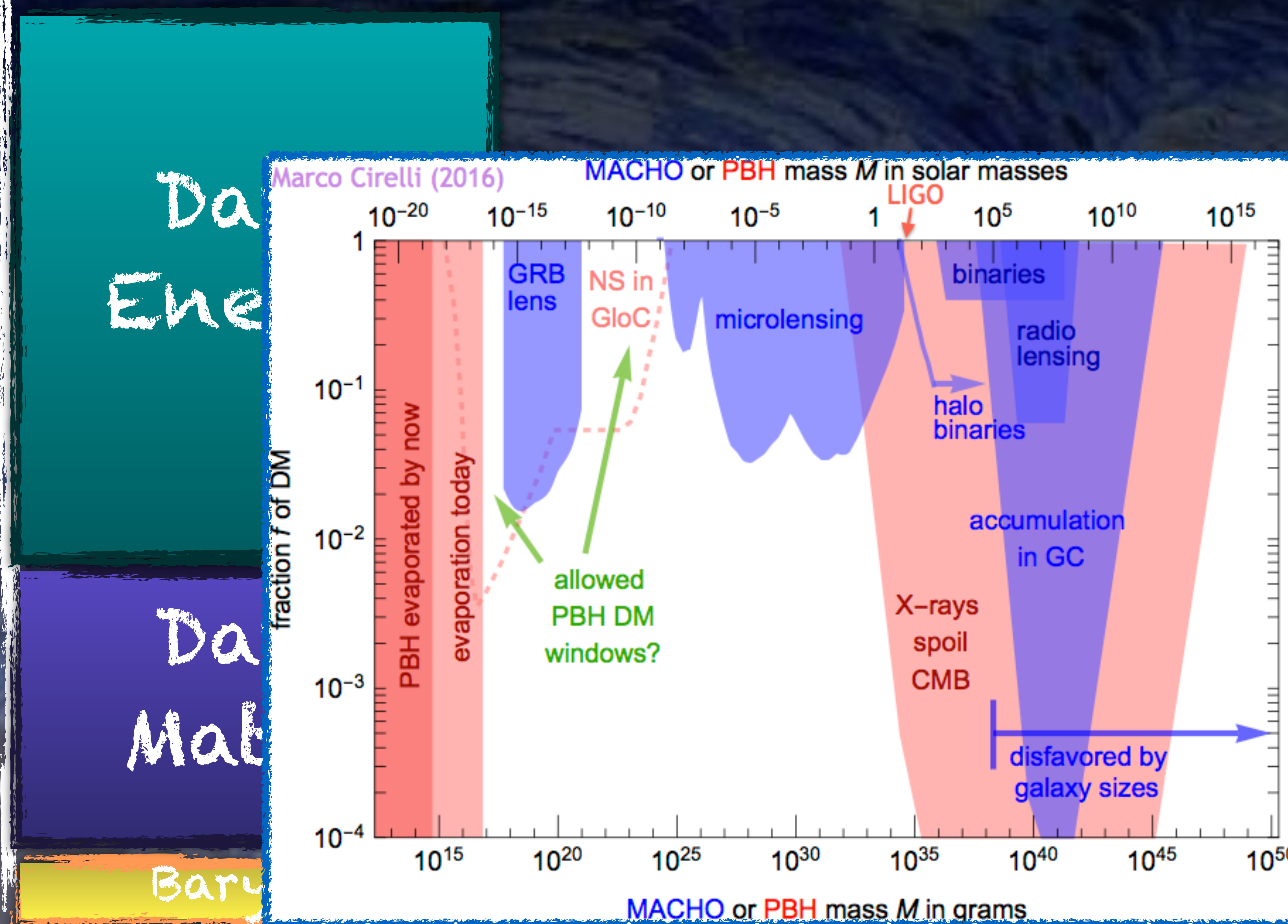
Energy budget of the Universe

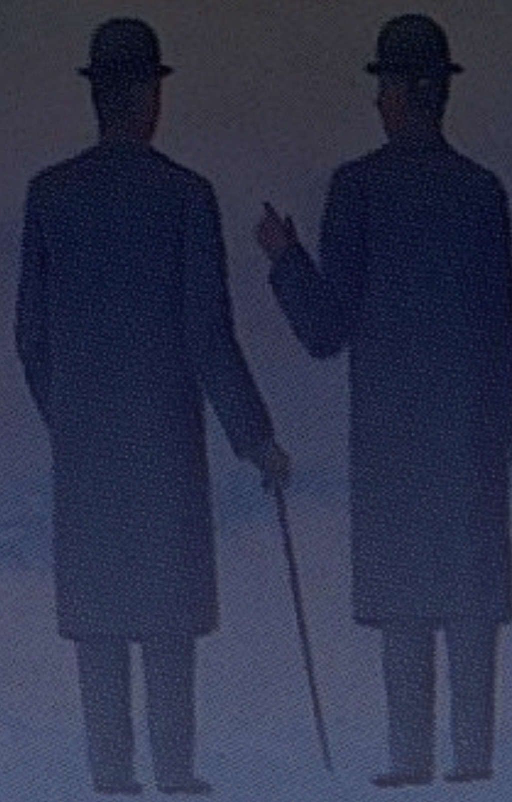
Energy budget of the Universe



Cold, collisionless matter.
Evidences from:
Rotation curves,
Galaxy clusters,
Gravitational lensing
CMB,
Structure formation,
...

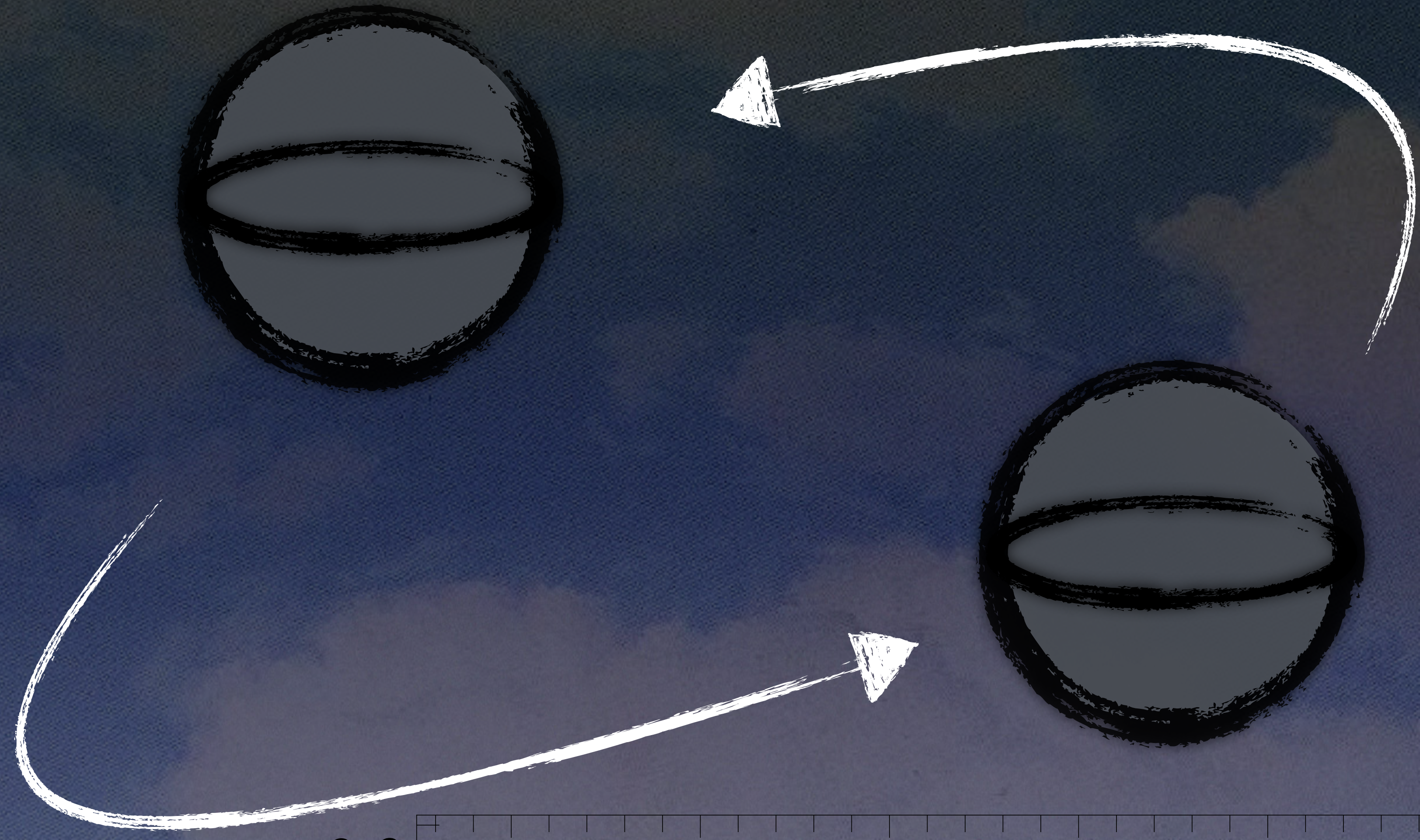
Energy budget of the Universe

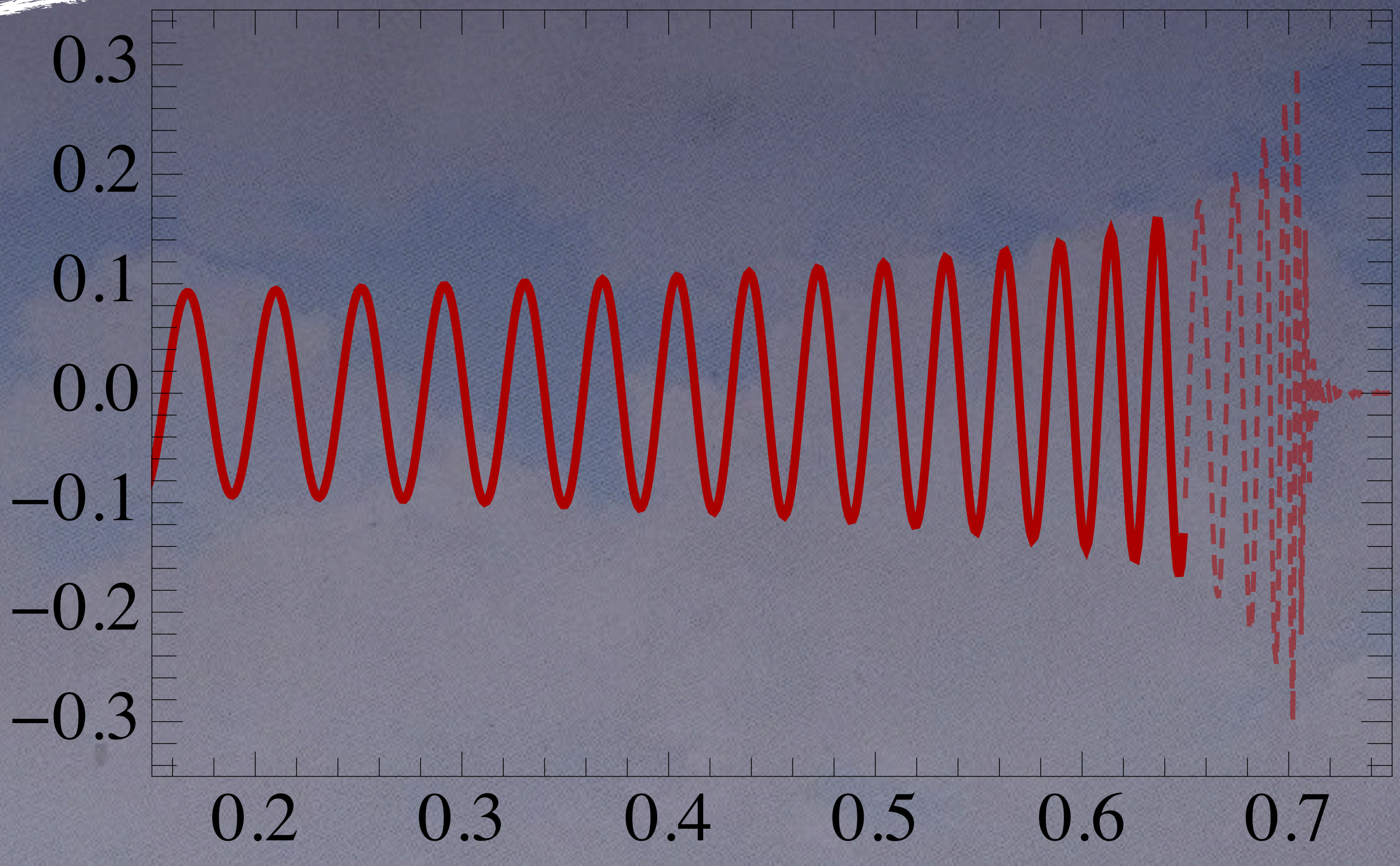


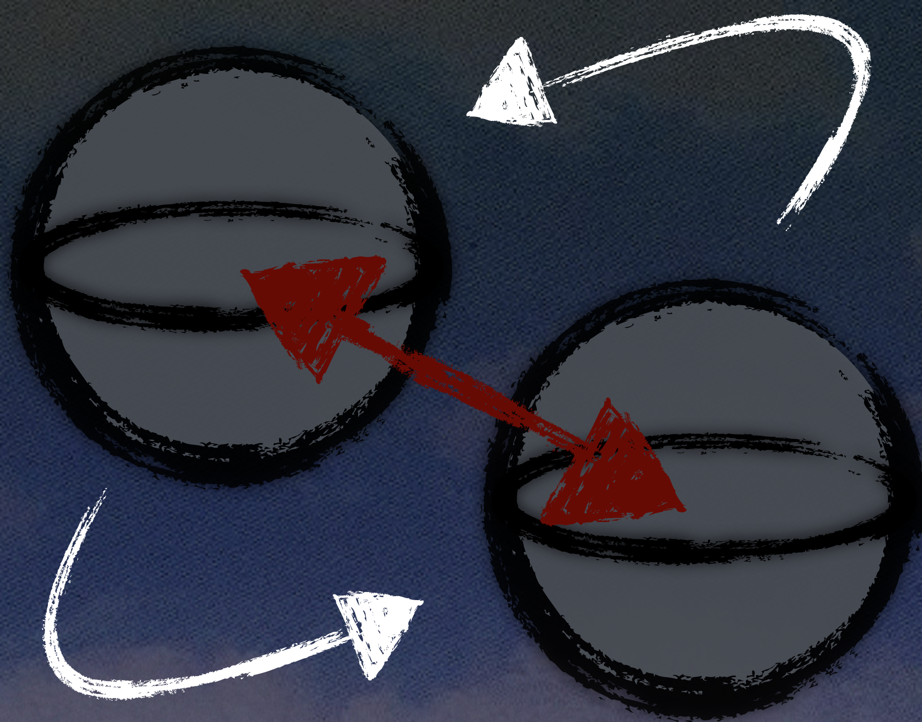


What did LIGO detect ?

$$f = \sqrt{\frac{M_{\rm tot}}{\pi^2 l^3}}\ .$$

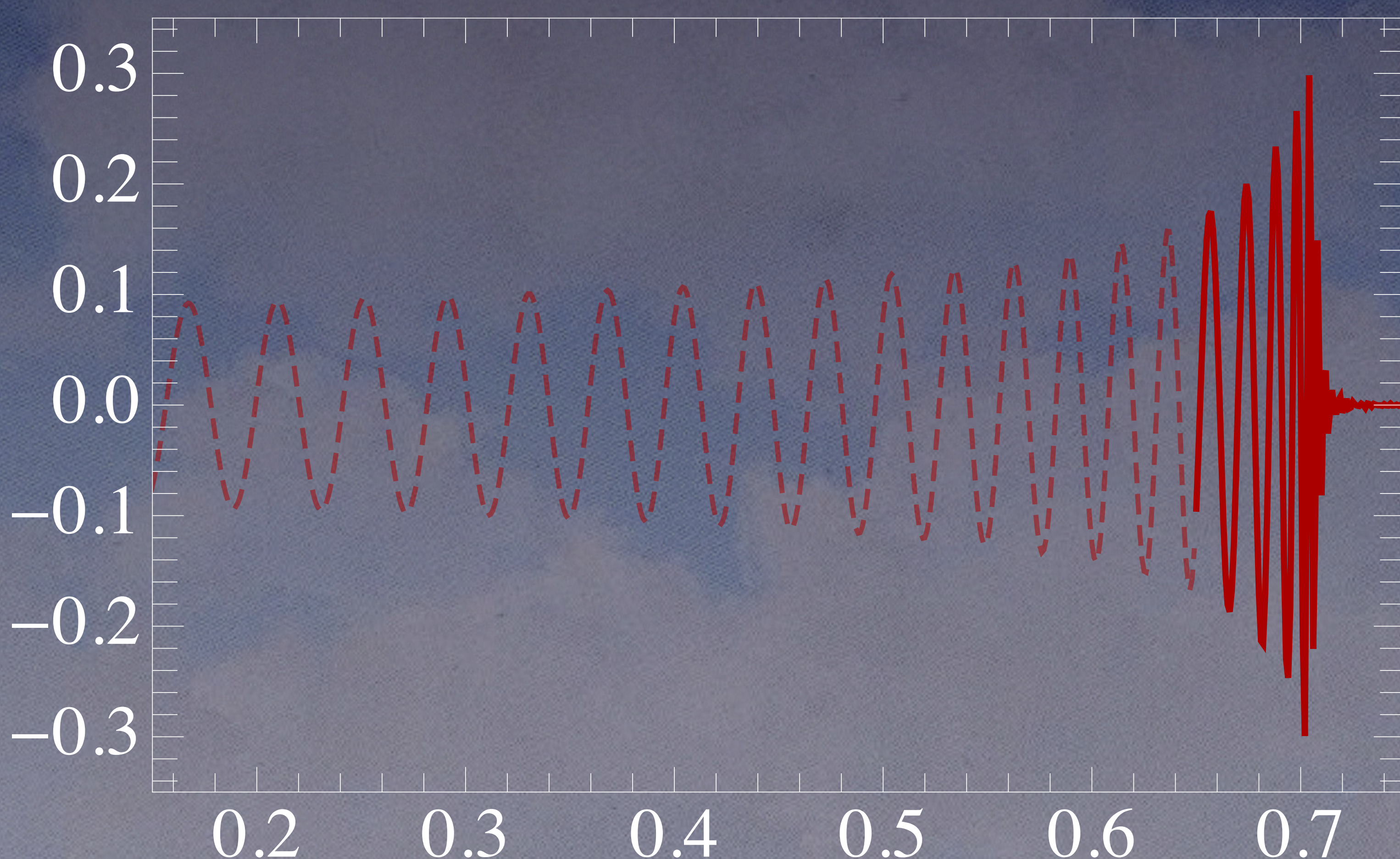


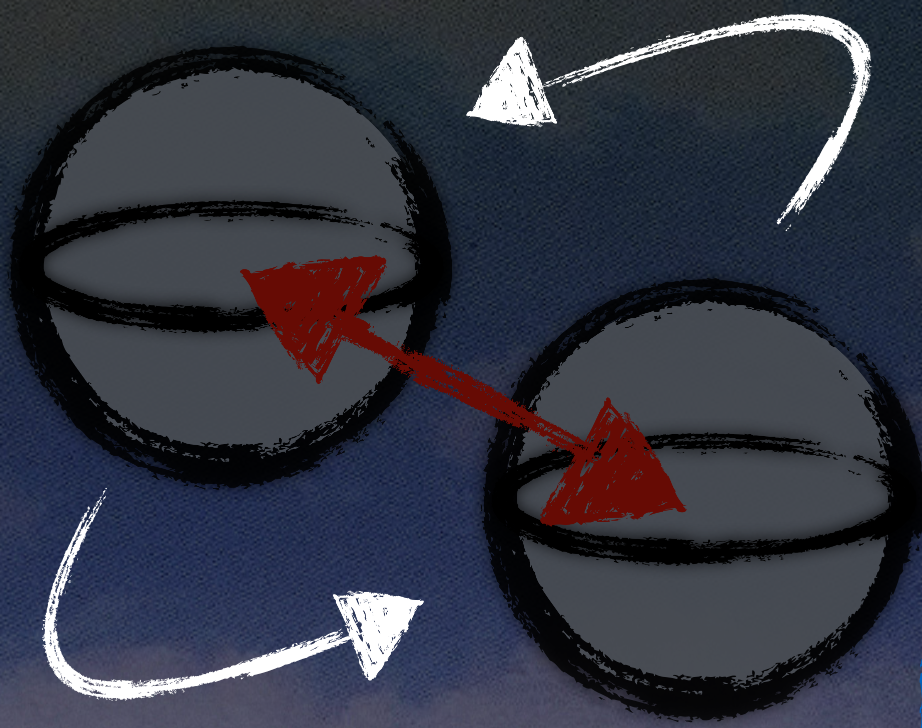




$$f = \sqrt{\frac{M_{\rm tot}}{\pi^2 l^3}} \; .$$

$$R_{BH}^{\rm ISCO} \equiv 6 M_{\rm tot} \; .$$

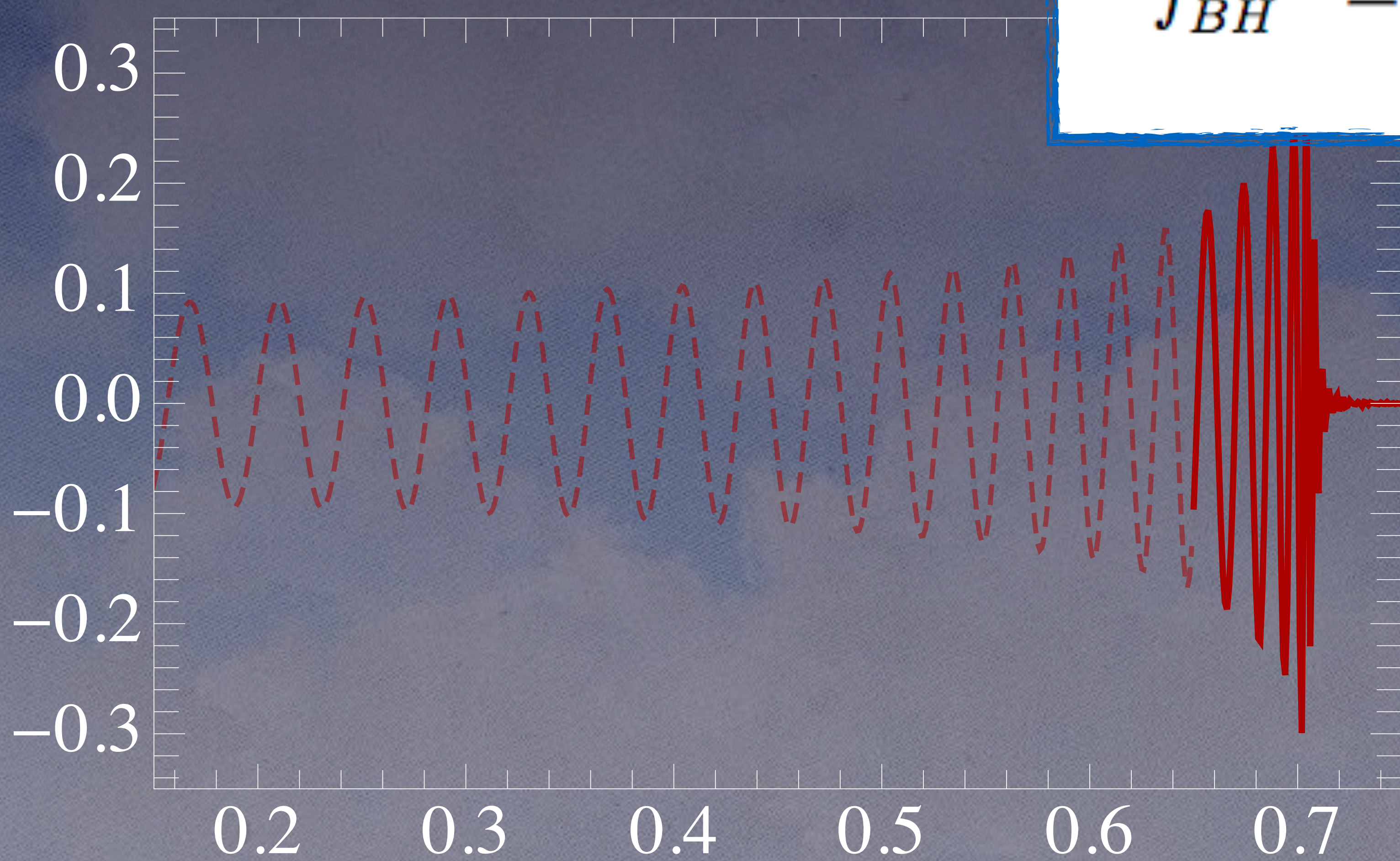


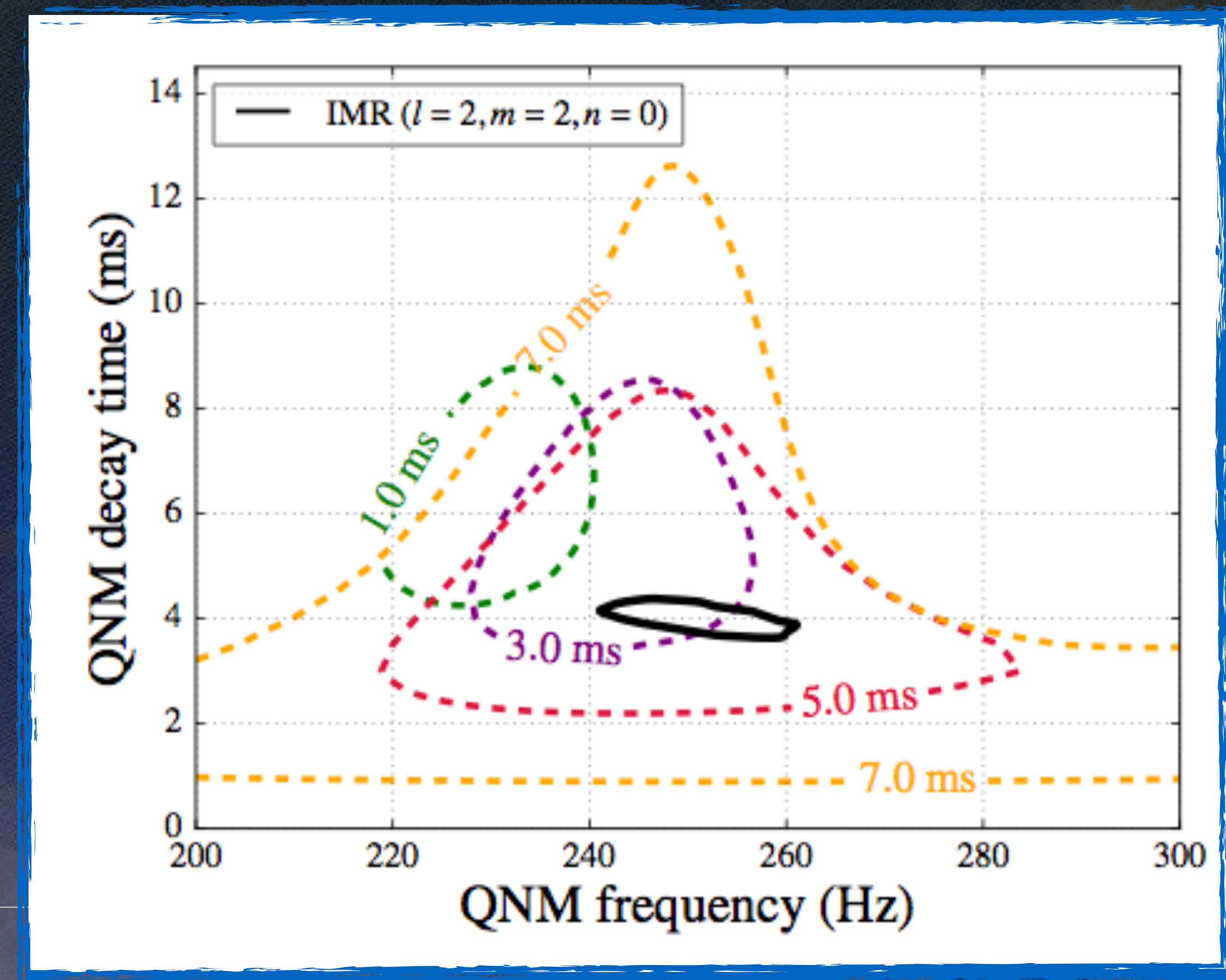


$$f = \sqrt{\frac{M_{\rm tot}}{\pi^2 l^3}}\ .$$

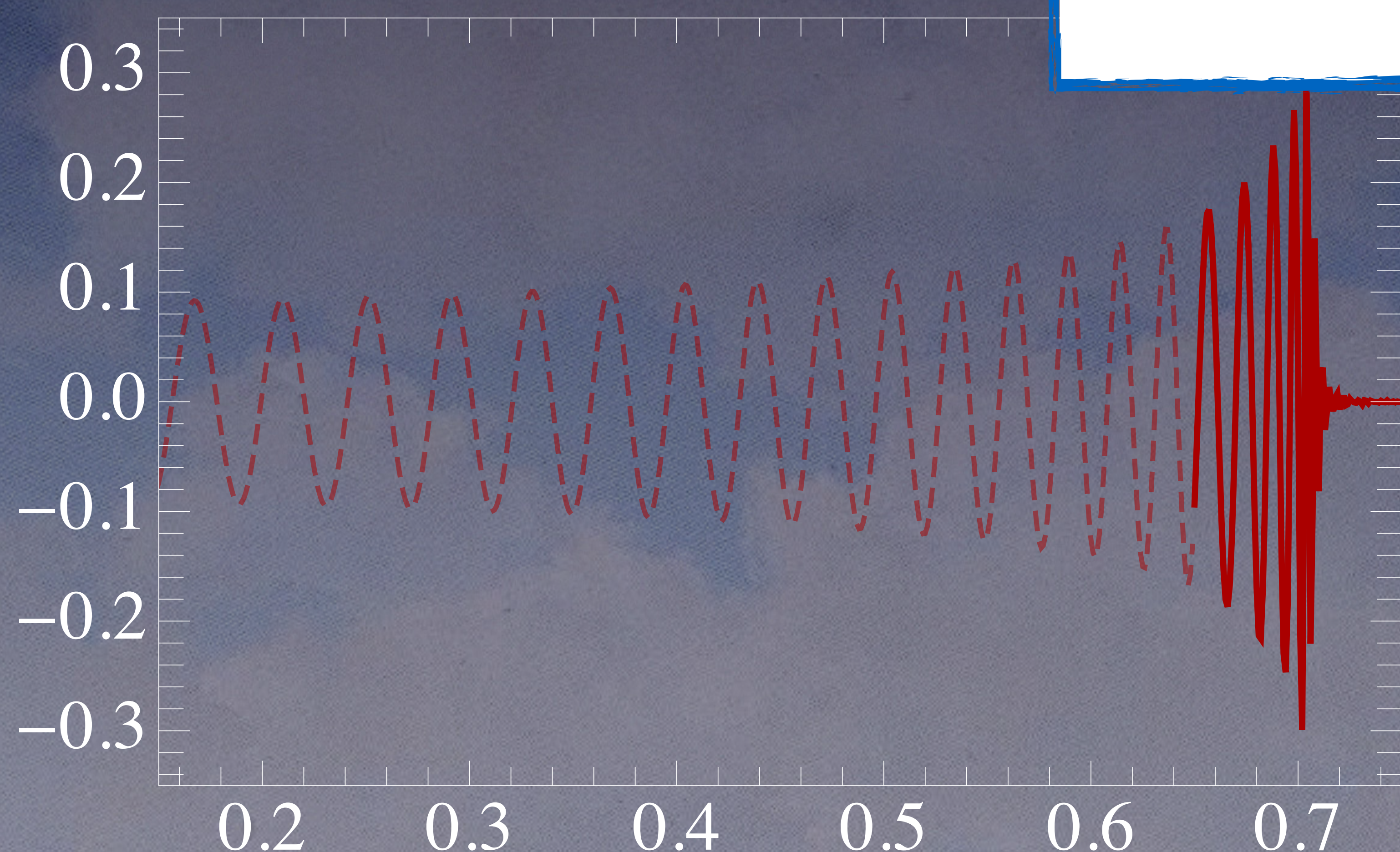
$$R^{\rm ISCO}_{BH} \equiv 6 M_{\rm tot}\ .$$

$$f^{\rm ISCO}_{BH} = \frac{1}{6^{3/2}\pi M_{\rm tot}} \qquad (\text{for BH})\,.$$





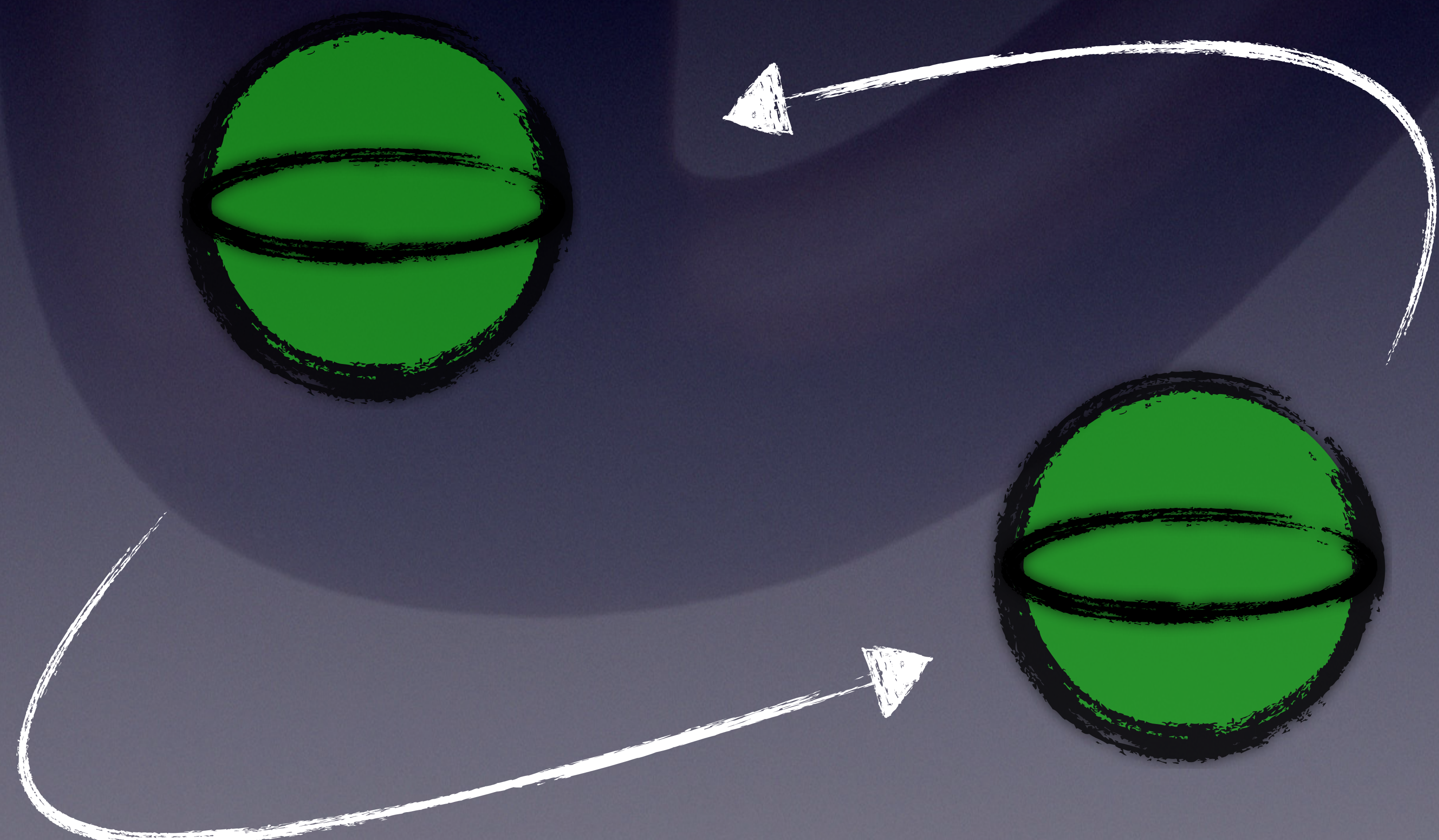
14
12
10
8
6
4
2
0
200
220
240
260
280
300
QNM decay time (ms)
QNM frequency (Hz)
IMR ($l = 2, m = 2, n = 0$)
7.0 ms
1.0 ms
3.0 ms
5.0 ms
7.0 ms



0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
0.2
0.3
0.4
0.5
0.6
0.7

What can LIGO detect ?

What can LIGO detect ?



The GW signal emitted in the merger of compact objects with mass in the range of 10's solar masses and compactness comparable to a black hole

Which objects fit this bill ?

Which objects fit this bill ?

Neutron Stars

Need no introduction.

Theoretical upper bound on mass:

$$M_{NS} \lesssim 4.3 M_\odot$$

Less compact than a BH:

$$0.13 \lesssim M/R \lesssim 0.23$$

Black Holes

Need no introduction.

Formation scenarios suggest:

$$M_{BH} \gtrsim \mathcal{O}(\sim 5) M_\odot$$

Compactness maximal:

$$M/R = 0.5$$

Which objects fit this bill ?

Boson Stars

If a light scalar field has weak self interactions, can condense.

Supported from collapse by uncertainty principle: cannot be localized below inverse mass. Total mass:

$$M_{BS} \approx \left(\frac{10^{-10}\ \mathrm{eV}}{m_B}\right) M_\odot$$

Compactness:

$$M/R < 0.08$$

Interacting Boson Stars

Self-interaction can increase repulsion:

$$V \approx M_B^2 |\phi|^2 + \frac{\lambda}{2}|\phi|^4$$

Total mass:

$$M_{BS} \approx \sqrt{\lambda}\left(\frac{100\ \mathrm{MeV}}{m_B}\right)^2 10 M_\odot$$

Compactness:

$$M/R < 0.16$$

Which objects fit this bill ?

Fermion Stars

Supported from collapse by fermion degeneracy pressure. Chandrasekhar mass

$$M \lesssim \frac{M_P^3}{m_F^2}$$

Thus:

$$M \lesssim \left(\frac{250 \text{ MeV}}{m_F}\right)^2 10 M_\odot$$

Compactness

$$M/R < 0.16$$

Dark Matter Stars

Perhaps the light bosons could be axion-like DM.   Formation of compact objects unclear, but may occur due to primordial density spikes

Or the

$$M \approx 100\text{'s MeV}$$

scalars or fermions could be WIMP-like dark matter. Formation through cooling with light force carrier, perhaps suggested by anomalies?

BHs vs ECOs

$$f = \sqrt{\frac{M_{\rm tot}}{\pi^2 l^3}} \, .$$

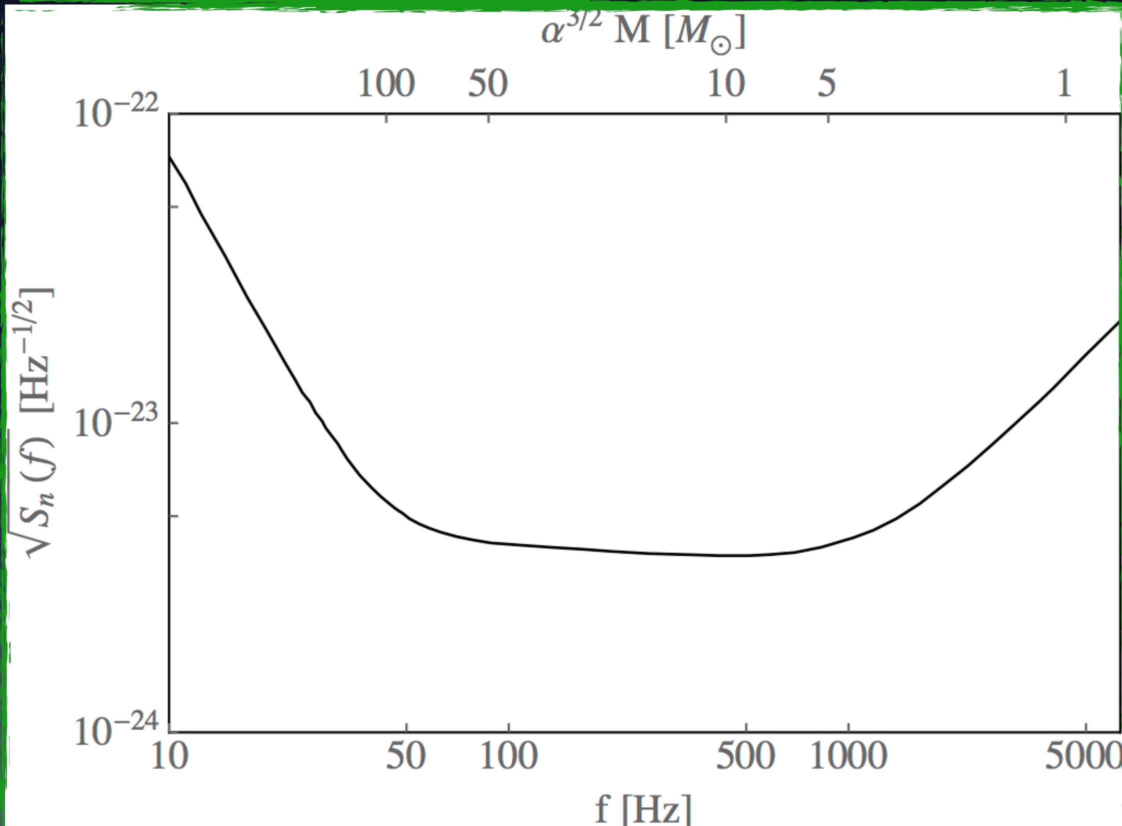
$$R_{BH}^{\rm ISCO} \equiv 6M_{\rm tot} \, .$$

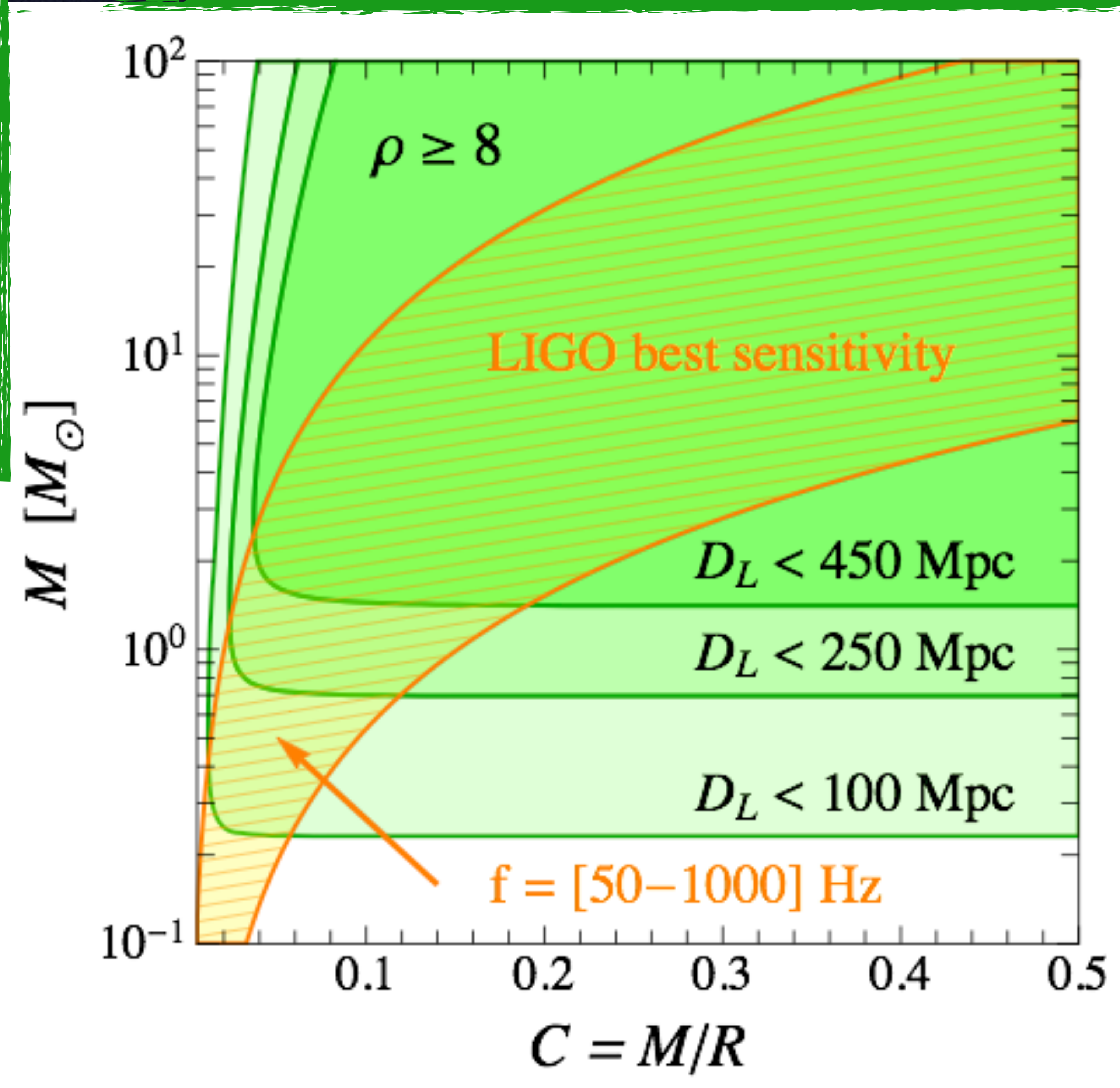
$$f_{BH}^{\rm ISCO} = \frac{1}{6^{3/2}\pi M_{\rm tot}} \qquad \text{(for BH)} \, .$$

$$R_{ECO}^{\rm ISCO} \equiv 3M_{\rm tot}/C$$

$$f_{ECO}^{\rm ISCO} = \frac{C^{3/2}}{3^{3/2}\pi M_{\rm tot}} \qquad \text{(for ECO)} \, .$$

BHs vs ECOs





Macroscopic properties

BHs vs ECOs

VOLUME 57, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

Boson Stars: Gravitational Equilibria of Self-Interacting Scalar Fields

Monica Colpi,[a] Stuart L. Shapiro, and Ira Wasserman
Center for Radiophysics and Space Research, Cornell University, Ithaca, New York 14853
(Received 13 August 1986)

Spherically symmetric gravitational equilibria of self-interacting scalar fields ϕ with interaction potential $V(\phi)=\frac{1}{4}\lambda|\phi|^4$ are determined. Surprisingly, the resulting configuration may differ markedly from the noninteracting case even when $\lambda \ll 1$. Contrary to generally accepted astrophysical folklore, it is found that the maximum masses of such boson stars may be comparable to the Chandrasekhar mass for fermions of mass $m_{\text{fermion}} \sim \lambda^{-1/4} m_{\text{boson}}$.

PACS numbers: 04.20.Jb, 11.10.−z, 95.30.Sf

Micriscopic properties

BHs vs ECOs

VOLUME 57, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

Boson Stars: Gravitational Equilibria of Self-Interacting Scalar Fields

Monica Colpi,
Center for Radiophysics and S

Spherically symmetric gravitation
tial $V(\phi)=\frac{1}{4}\lambda|\phi|^4$ are determined.
the noninteracting case even when
found that the maximum masses of
fermions of mass $m_{fermion}\sim\lambda^{-1/4}m_{bo}$

PACS numbers: 04.20.Jb, 11.10.−z, 95.

$$\frac{A'}{A^2x}+\frac{1}{x^2}\left(1-\frac{1}{A}\right)=\left(\frac{\Omega^2}{B}+1\right)\sigma^2+\frac{\Lambda}{2}\sigma^4+\frac{(\sigma')^2}{A}, \quad (9a)$$

$$\frac{B'}{ABx}-\frac{1}{x^2}\left(1-\frac{1}{A}\right)=\left(\frac{\Omega^2}{B}-1\right)\sigma^2-\frac{\Lambda}{2}\sigma^4+\frac{(\sigma')^2}{A}, \quad (9b)$$

$$\sigma''+\left(\frac{2}{x}+\frac{B'}{2B}-\frac{A'}{2A}\right)\sigma'+A\left[\left(\frac{\Omega^2}{B}-1\right)\sigma-\Lambda\sigma^3\right]=0, \quad (9c)$$

where $x=mr$, primes denote d/dx, $\sigma=(4\pi G)^{1/2}\Phi=(4\pi)^{1/2}\Phi/M_{Planck}$, $\Omega=\omega/m$, and Λ is given by Eq. (2). If we write

$$A(x)=[1-2\mathcal{M}(x)/x]^{-1} \quad (10)$$

we may rewrite Eq. (9a) as

$$\mathcal{M}'(x)=x^2\left[\frac{1}{2}\left(\frac{\Omega^2}{B}+1\right)\sigma^2=\frac{\Lambda}{4}\sigma^4+\frac{(\sigma')^2}{2A}\right]. \quad (9a')$$

Micriscopic properties

BHs vs ECOs

Too big to fail: $$\frac{\sigma}{m_{DM}} \lesssim 0.1 \to 10\ \mathrm{cm}^2/\mathrm{g}$$

Core-cusp problem: $$\frac{\sigma}{m_{DM}} \lesssim 0.1 \to 1\ \mathrm{cm}^2/\mathrm{g}$$

Interacting Boson Stars

To resolve these puzzles require parameters in the range

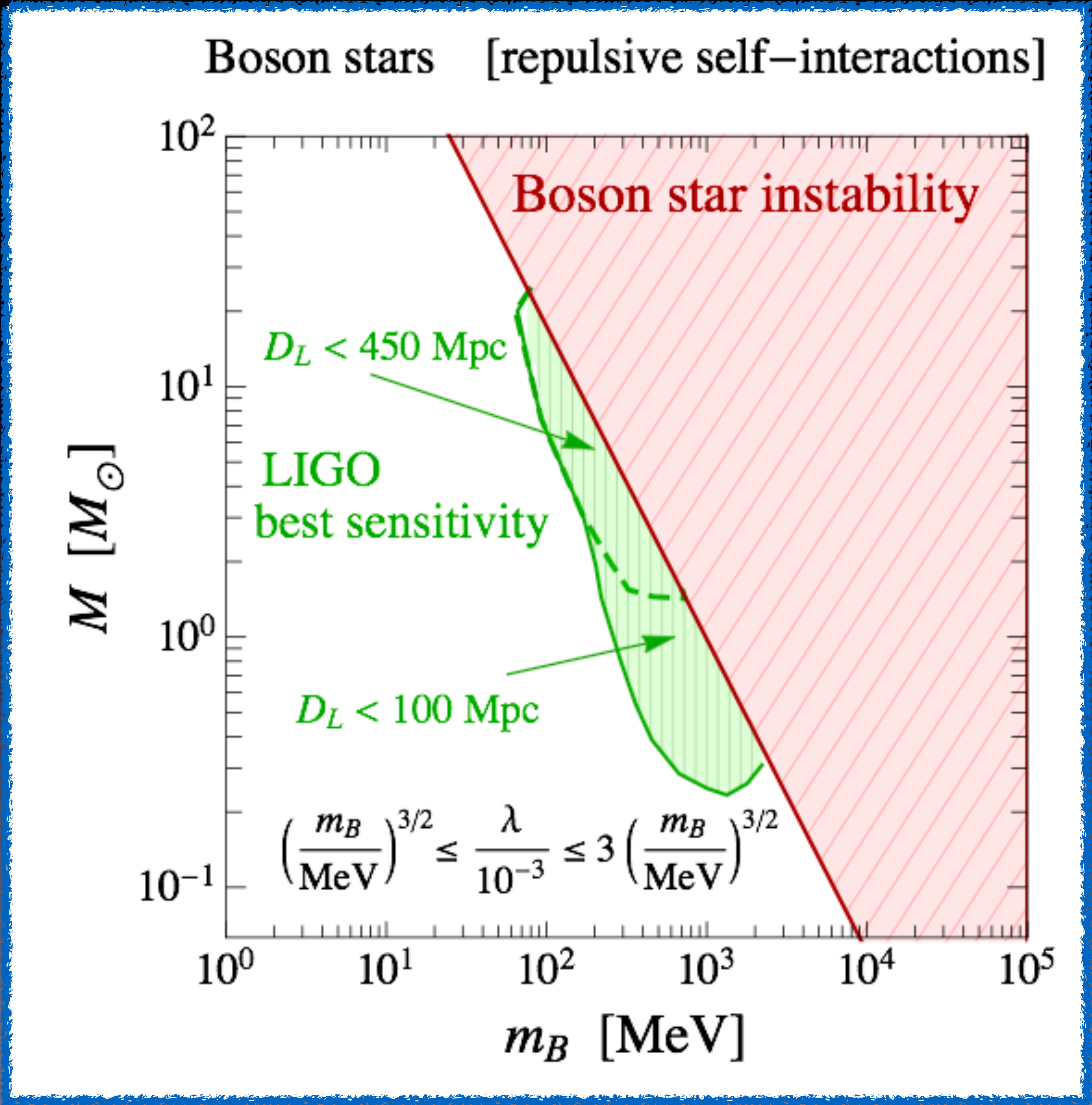
$$\left(\frac{m_B}{\mathrm{MeV}}\right)^{3/2} \lesssim \frac{\lambda}{10^{-3}} \lesssim 3 \times \left(\frac{m_B}{\mathrm{MeV}}\right)^{3/2}.$$

Fermion Stars

For a coupling $\alpha = 0.01$

Require mediator masses:

$$0.01 \lesssim m_\phi[\mathrm{GeV}] \lesssim 0.1$$

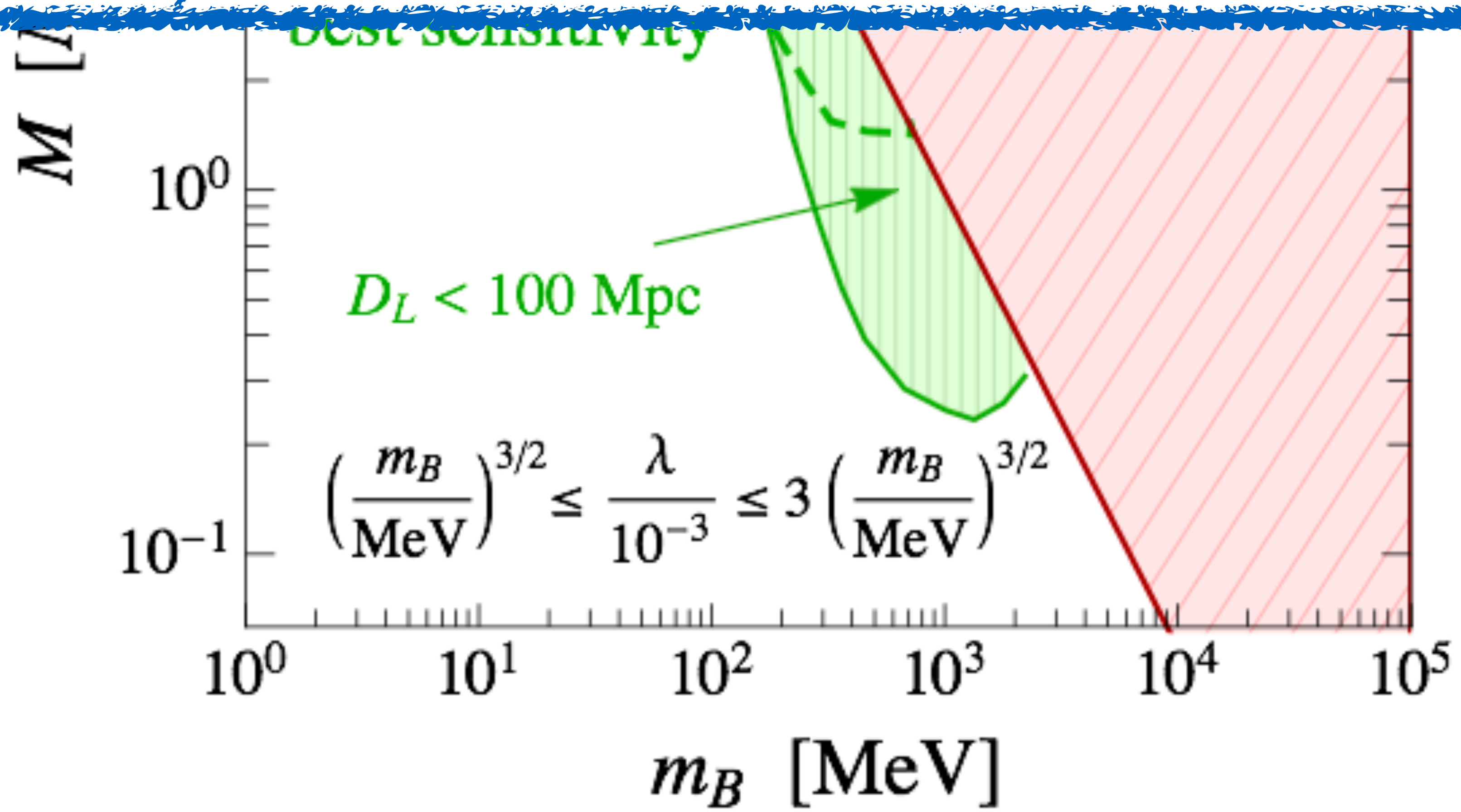

Boson stars [repulsive self−interactions]
Boson star instability
$D_L < 450$ Mpc
LIGO
best sensitivity
$D_L < 100$ Mpc
$\left(\frac{m_B}{\text{MeV}}\right)^{3/2} \leq \frac{\lambda}{10^{-3}} \leq 3\left(\frac{m_B}{\text{MeV}}\right)^{3/2}$
M [$M_\odot$]
m_B [MeV]
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

Boson stars [repulsive self–interactions]

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - V(\phi)$$

$$V(\phi) = \Lambda^4\left[1-\cos\left(\frac{\phi}{f}\right)\right] = \Lambda^4\left(\frac{\phi^2}{2f^2} - \frac{\phi^4}{24f^4} + \dots\right)$$

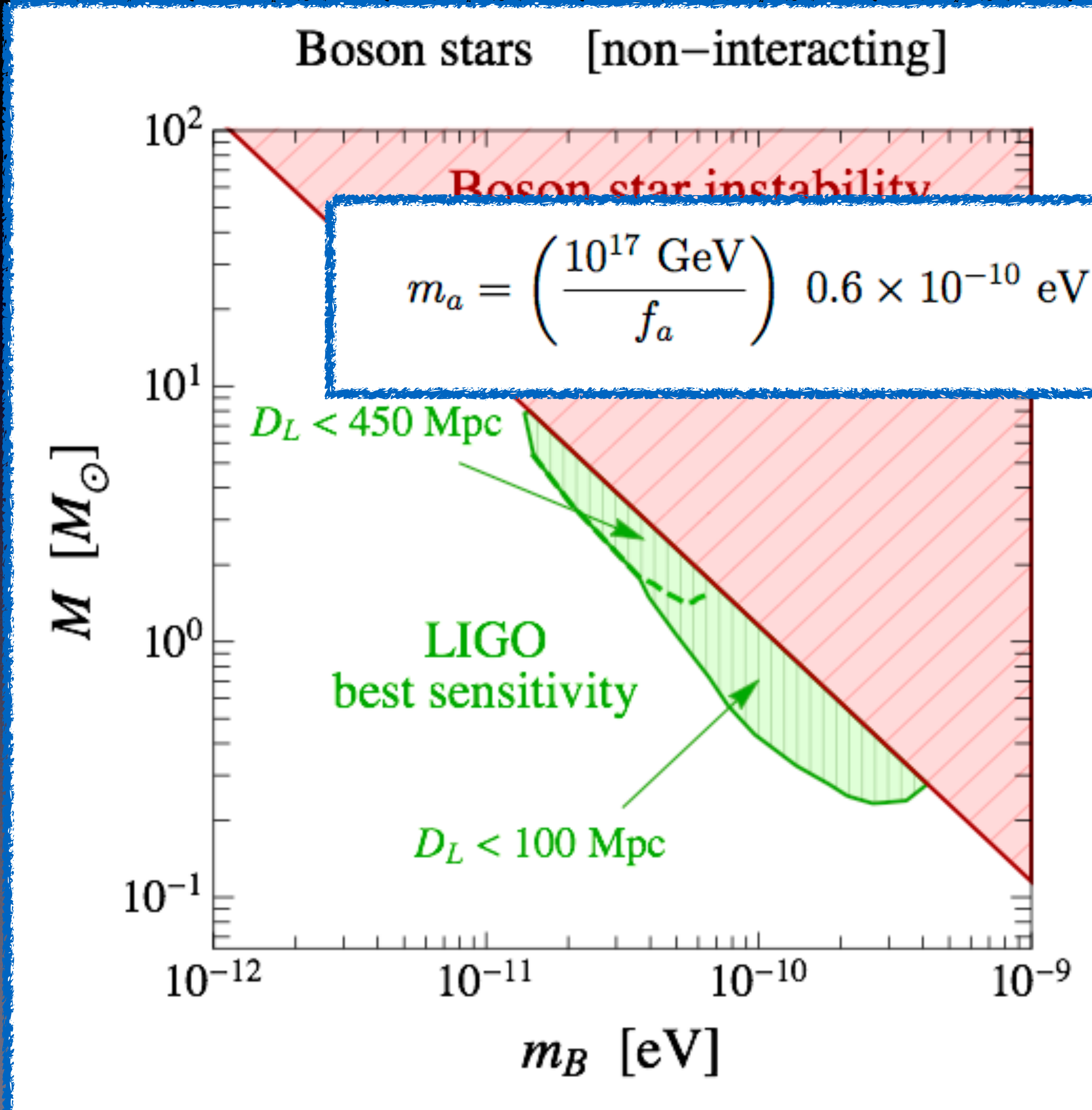
JiJi Fan, 1603.06580



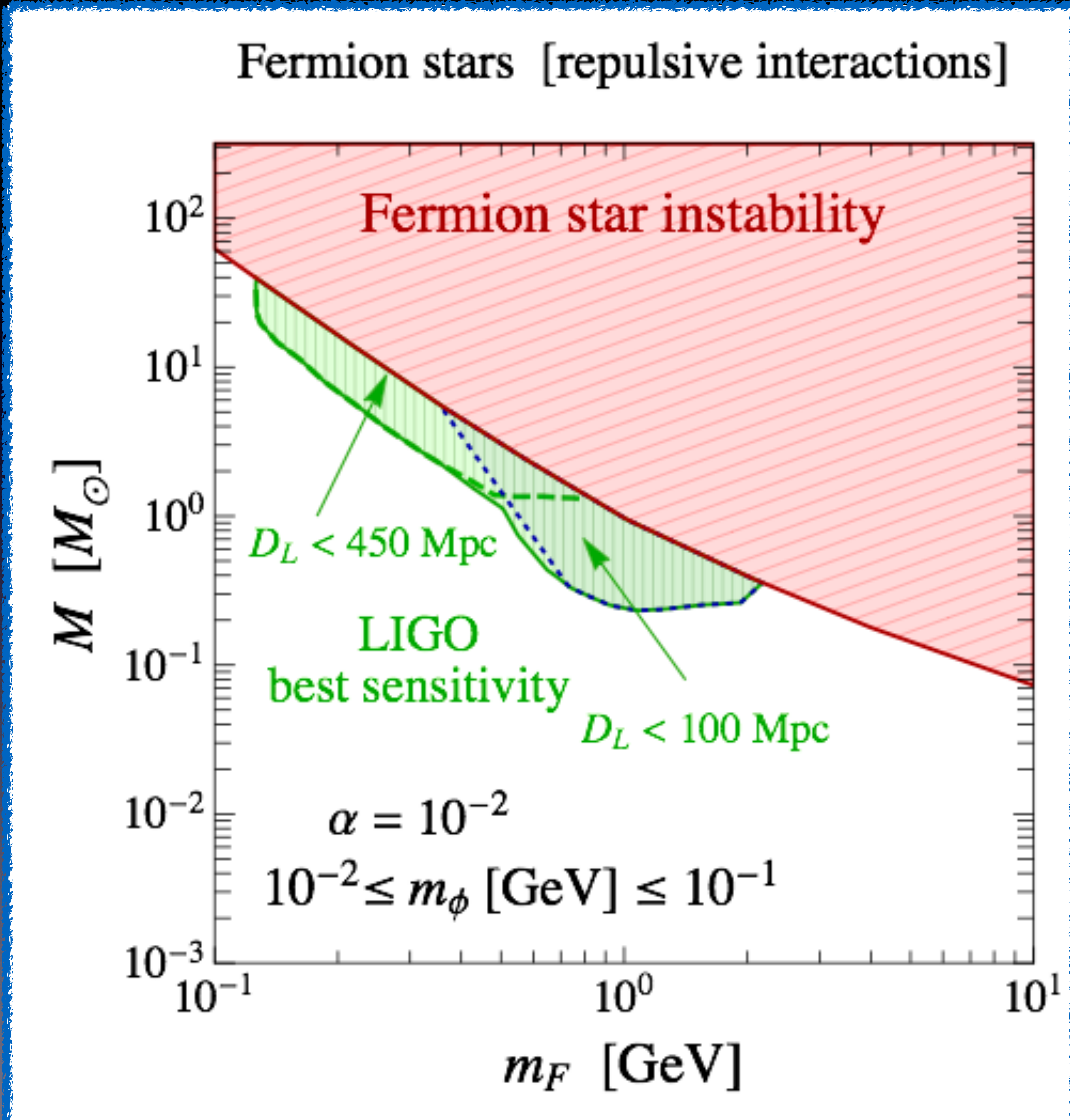
Formation of "axion stars" studied by Kolb and Tkachev

Phys.Rev.Lett.71.3051

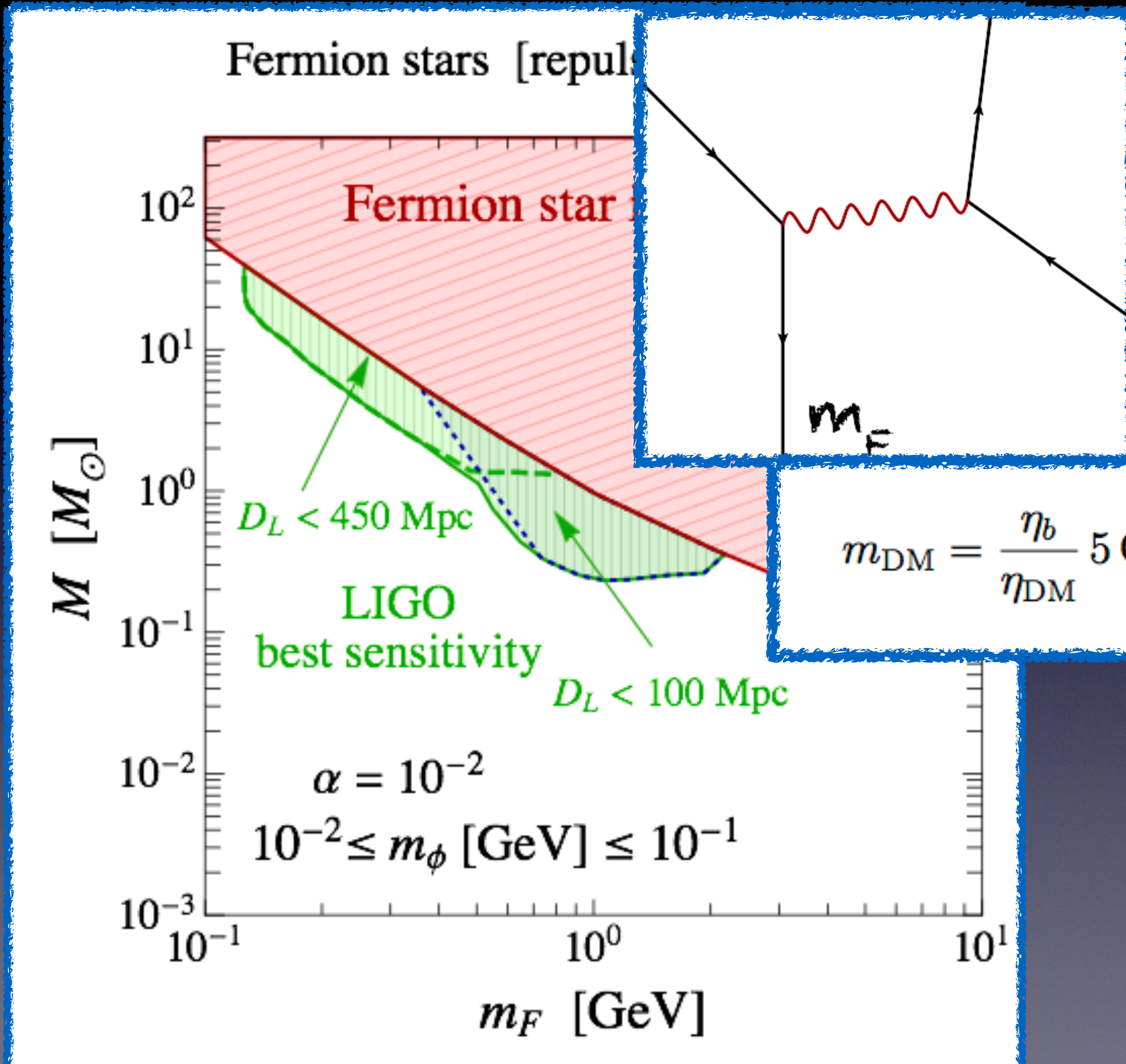
Phys.Rev.D49.5040



$$m_a = \left(\frac{10^{17}\ \mathrm{GeV}}{f_a}\right)\ 0.6 \times 10^{-10}\ \mathrm{eV}$$



Fermion stars [repulsive interactions]
Fermion star instability
$D_L < 450$ Mpc
$D_L < 100$ Mpc
LIGO
best sensitivity
$\alpha = 10^{-2}$
$10^{-2} \leq m_\phi$ [GeV] $\leq 10^{-1}$
M [$M_\odot$]
m_F [GeV]
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-1}
10^0
10^1

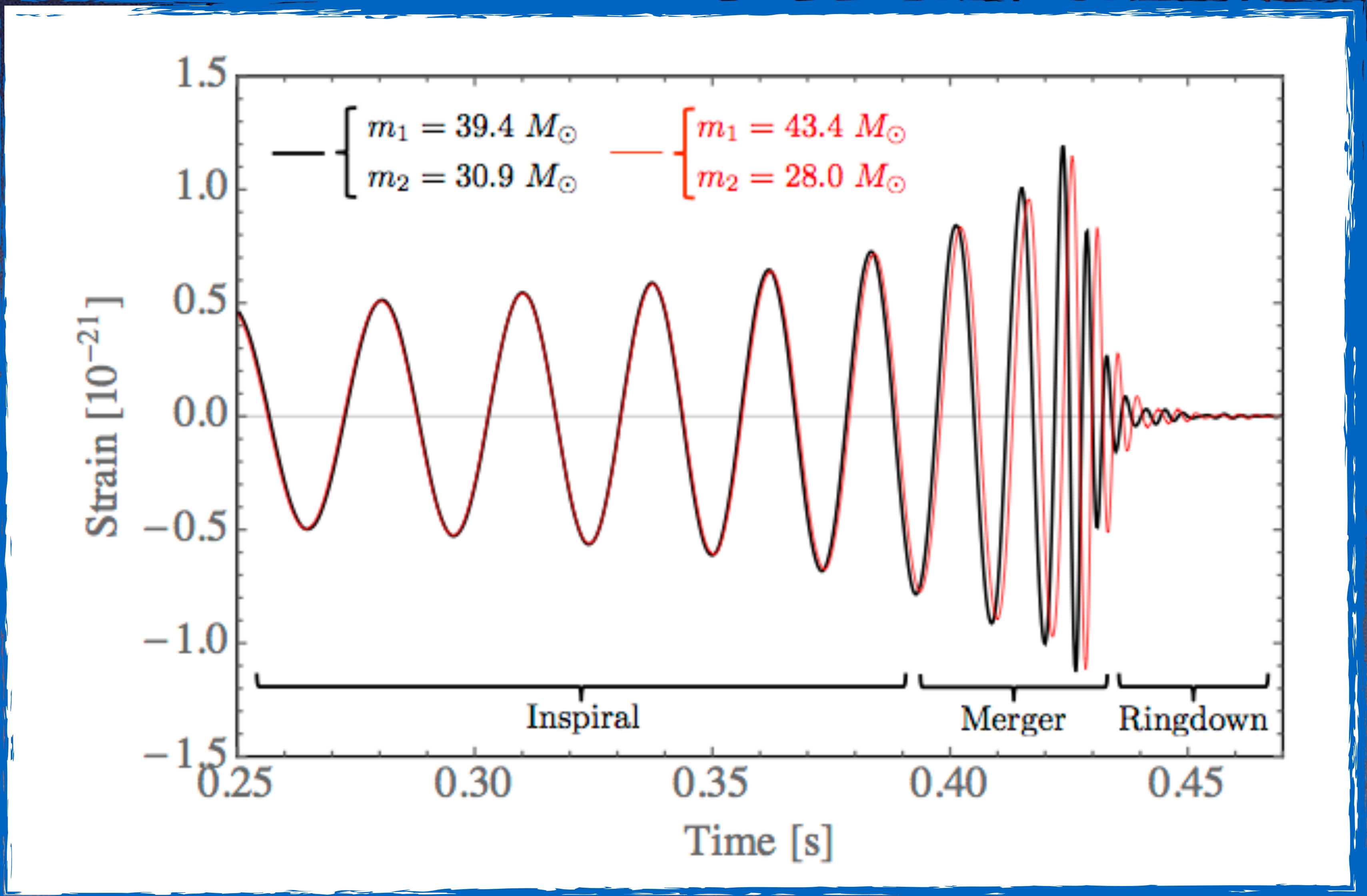


$$m_{\rm DM} = \frac{\eta_b}{\eta_{\rm DM}}\, 5\,{\rm GeV}$$

Distinguishing ECOs from BHs

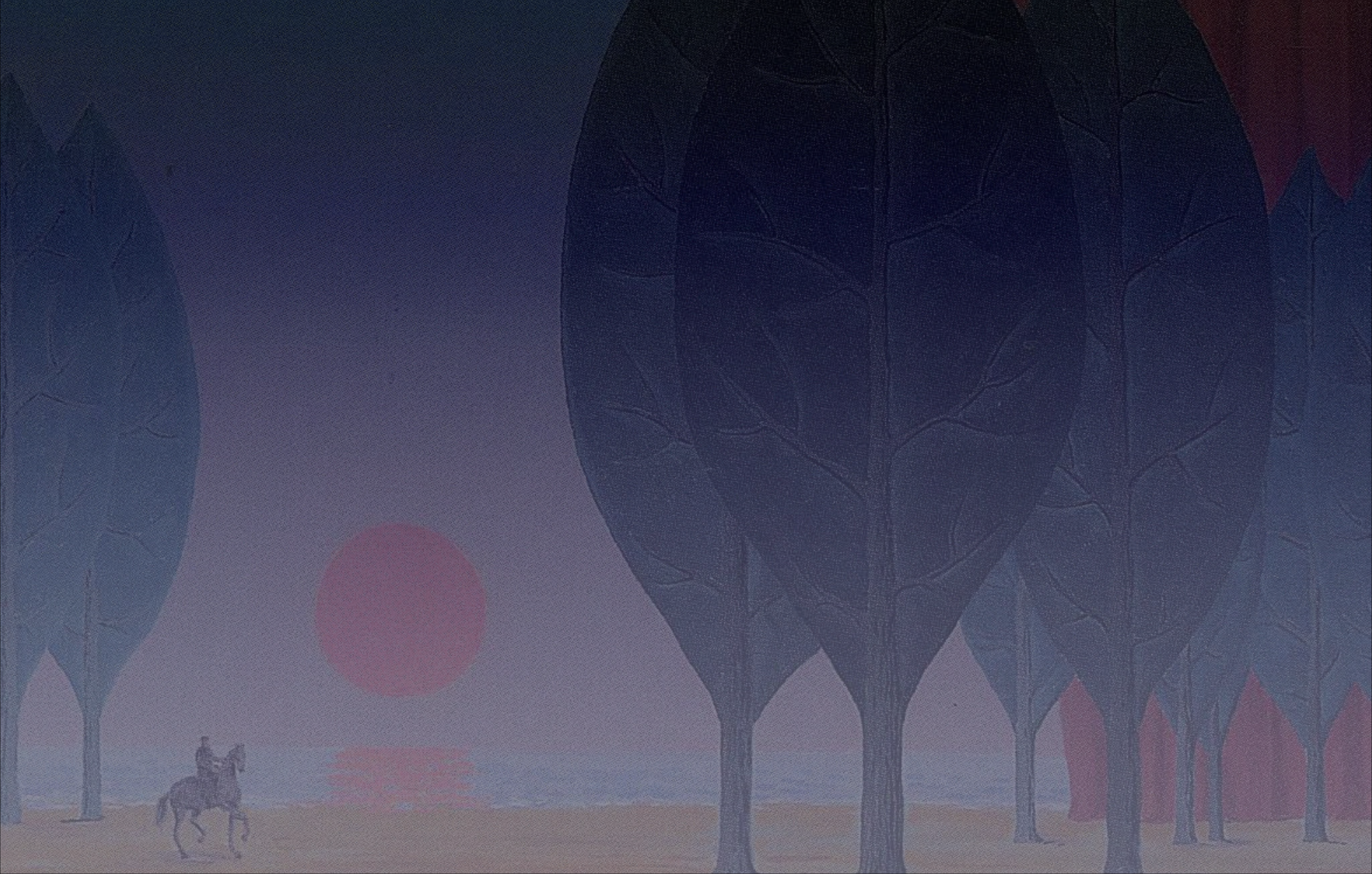
LIGO has sensitivity to detect motivated ECOs. However, could you tell they are not NS or BHs ?

Distinguishing ECOs from BHs

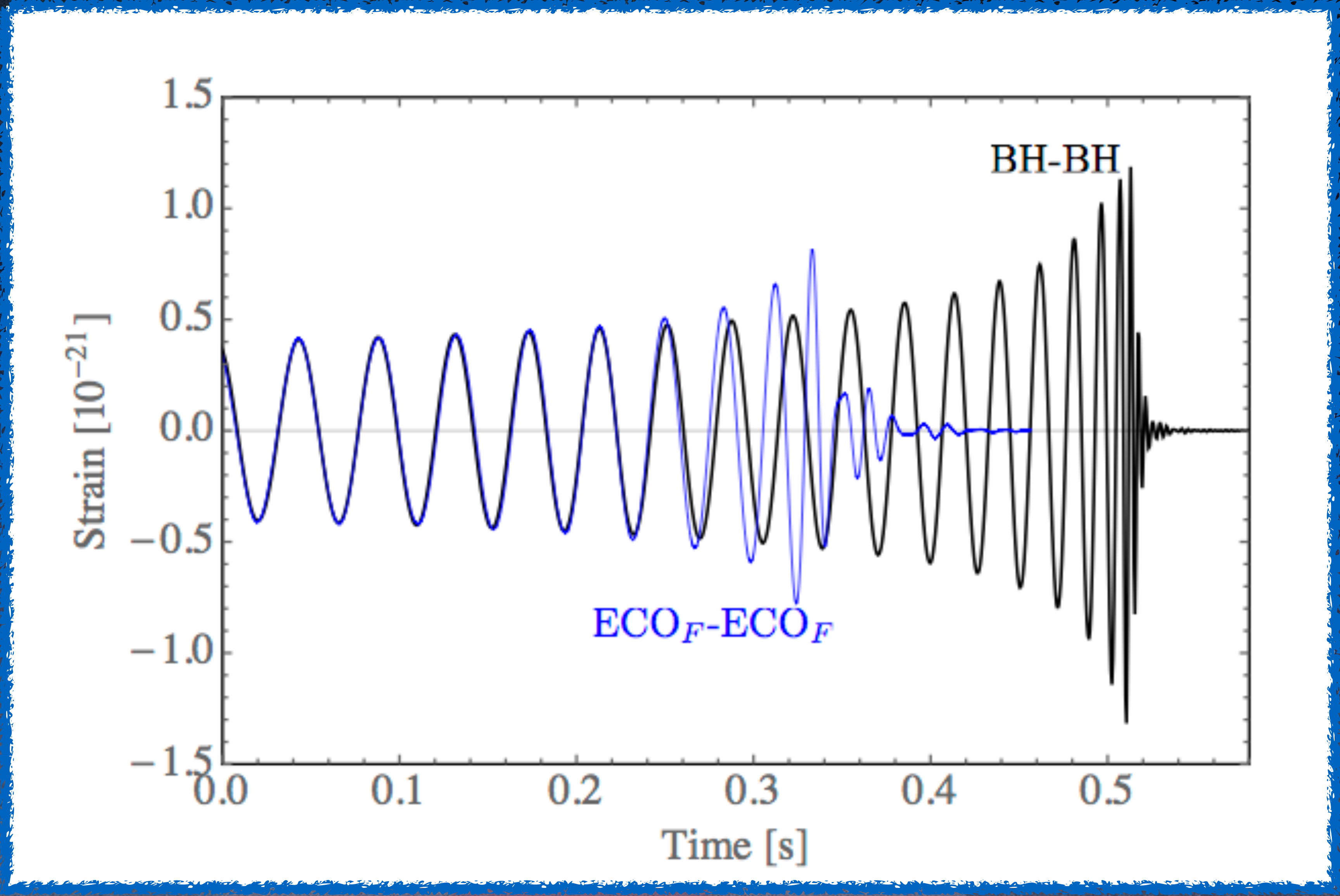


Waveforms from P. Ajith et al.
Phys. Rev. Lett. 106 (2011) 241101

Are the waveforms the same ?



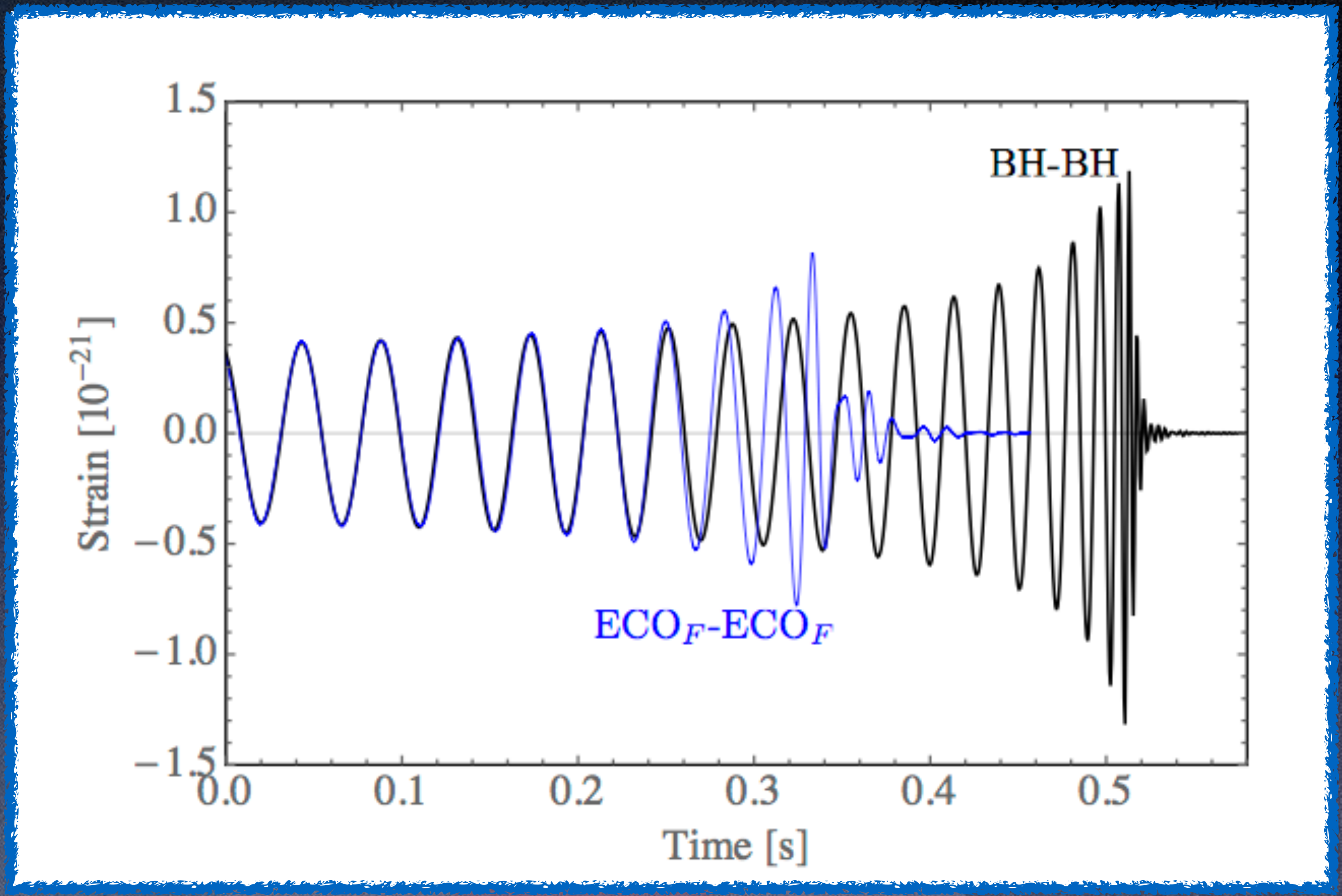
Are the waveforms the same ?



We estimated the waveform considering the NS-NS merger. NS and ECOs are degenerate fermion stars, with similar compactness and EOS.

Waveforms from J. A. Faber and F. A. Rasio, Phys. Rev. D 65 (2002) 084042

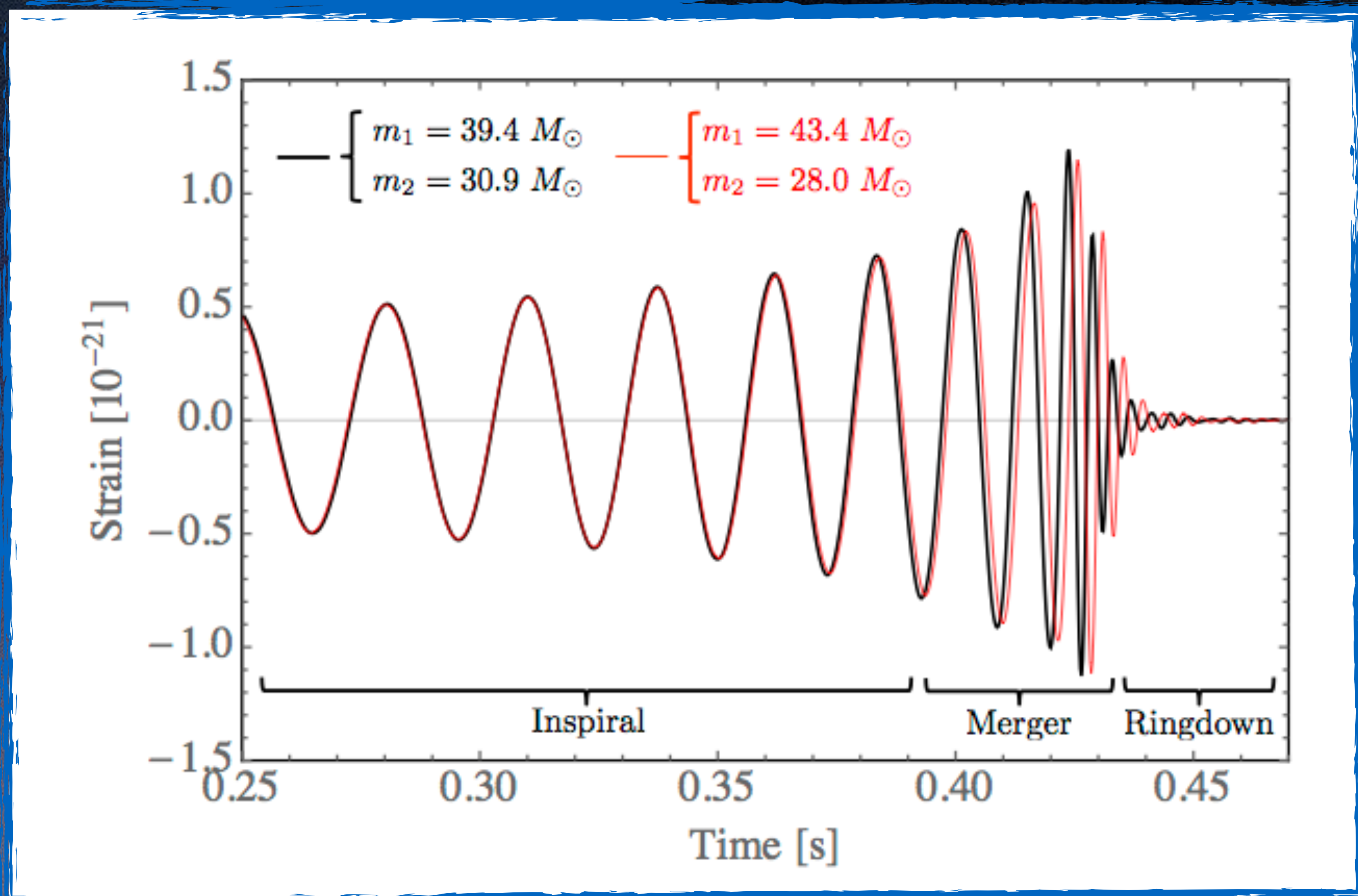
Are the waveforms the same ?



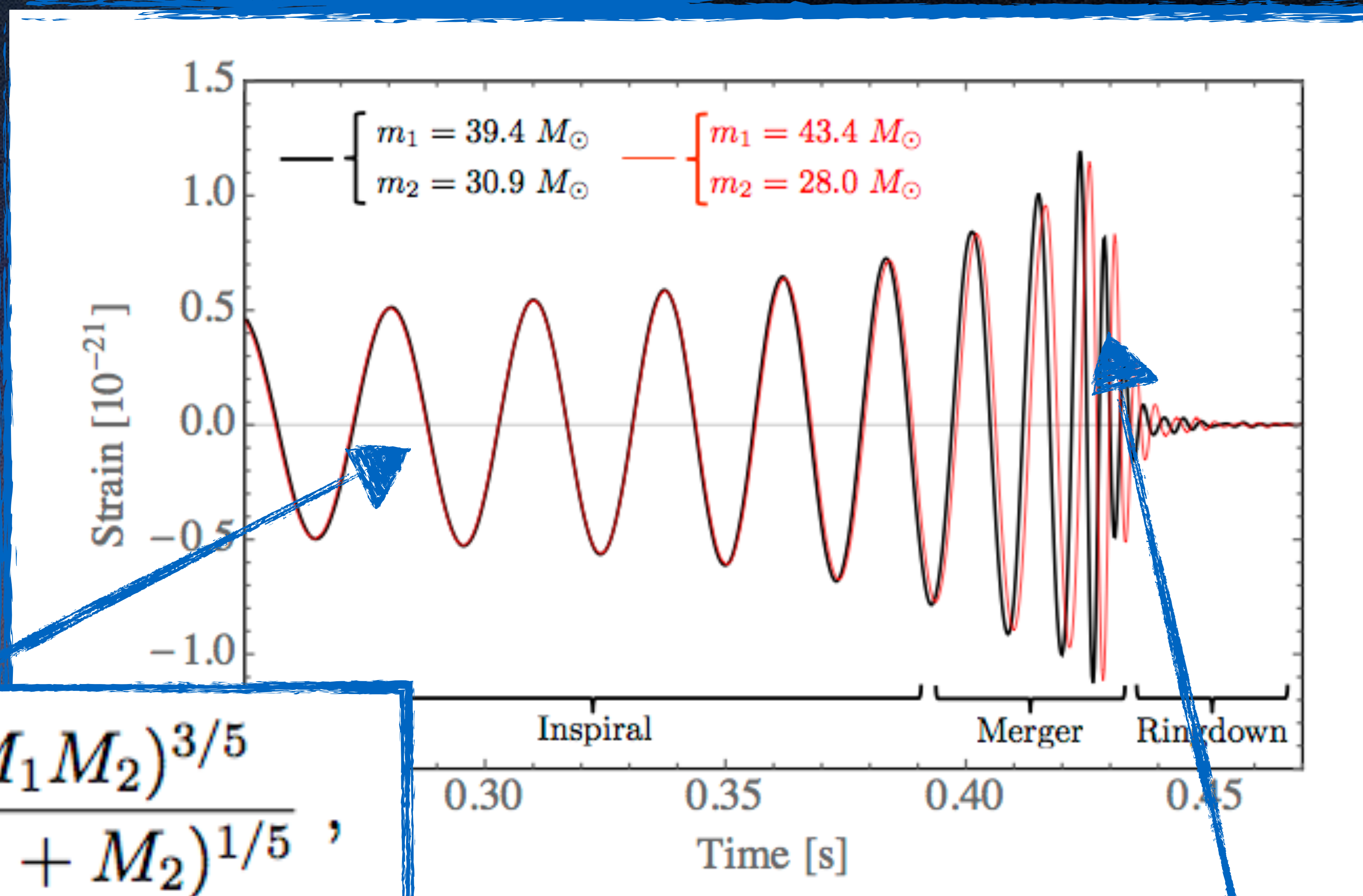
Equal-mass ECOs clearly distinguishable from equal-mass BH-BH merger

Can BHs mimic ECOs ?

Can BHs mimic ECOs ?



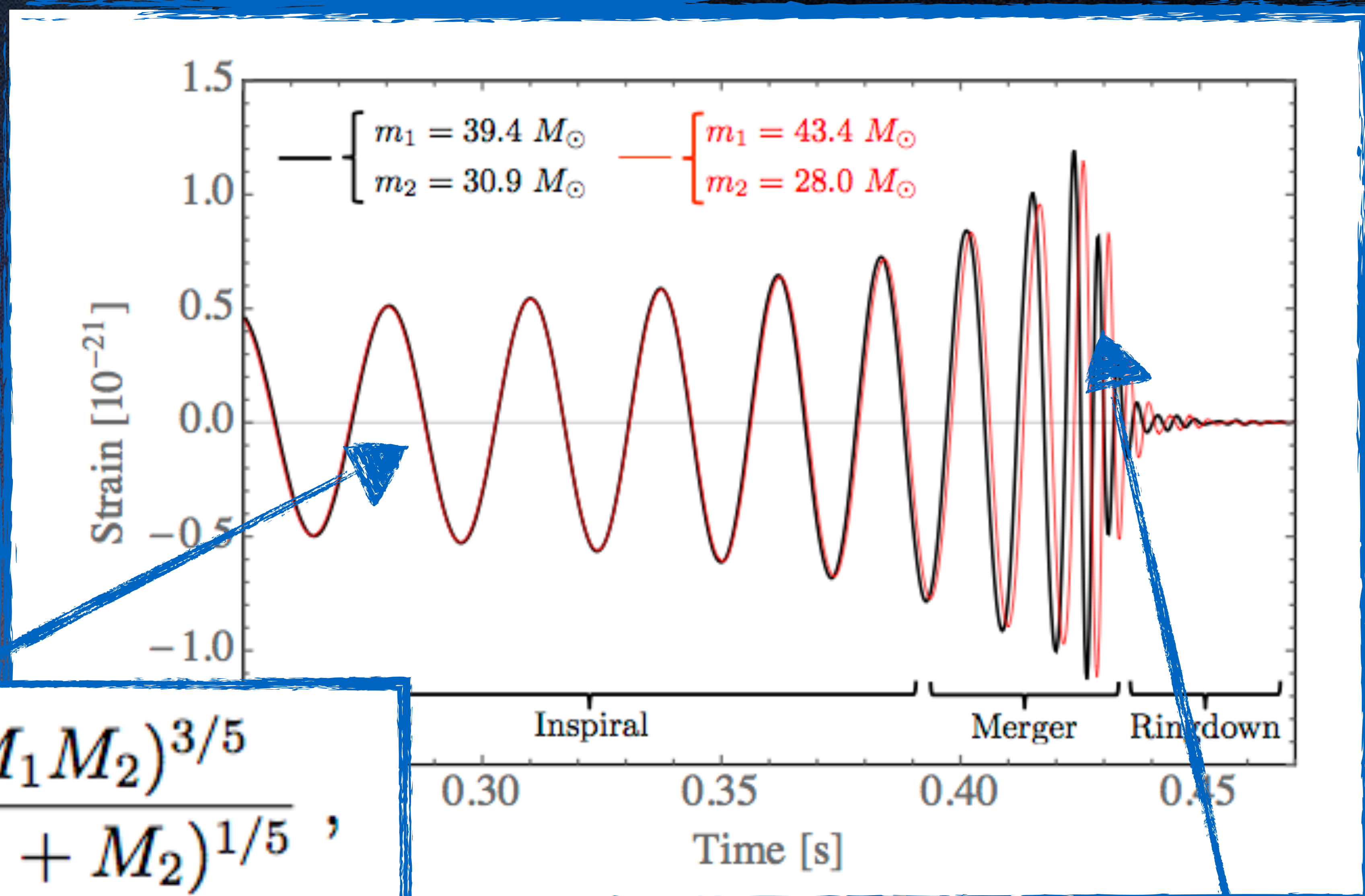
Can BHs mimic ECOs ?



$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}},$$

ISCO frequency

Can BHs mimic ECOs ?



$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} ,$$

ISCO frequency

Can BHs mimic ECOs ?

$$f_{BH}^{\rm ISCO} = \frac{1}{6^{3/2}\pi M_{\rm tot}} \qquad \text{(for BH)}\,.$$

$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}\,,$$

$$f_{ECO}^{\rm ISCO} = \frac{C^{3/2}}{3^{3/2}\pi M_{\rm tot}} \qquad \text{(for ECO)}\,.$$

ISCO frequency

Can BHs mimic ECOs ?

$$M_c = M_{\rm tot}\eta^{3/5}$$

$$\eta = \frac{M_1 M_2}{(M_1+M_2)^2} .$$

$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}} ,$$

$$f_{BH}^{\rm ISCO} = \frac{(1+\Delta_{BH})\eta_{BH}^{3/5}}{6^{3/2}\pi M_c} ,$$

$$f_{ECO}^{\rm ISCO} = \frac{(1+\Delta_{ECO})\eta_{ECO}^{3/5} C^{3/2}}{3^{3/2}\pi M_c} .$$

ISCO frequency

Can BHs mimic ECOs ?

By choosing appropriate mass ratio, we can have the same Chirp Mass and the same ISCO frequency comparing ECOs and BHs

$$M_c = M_{\text{tot}} \eta^{3/5}$$

$$\eta = \frac{M_1 M_2}{(M_1 + M_2)^2} \, .$$

$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} \, ,$$

$$f_{BH}^{\text{ISCO}} = \frac{(1 + \Delta_{BH}) \eta_{BH}^{3/5}}{6^{3/2} \pi M_c} \, ,$$

$$f_{ECO}^{\text{ISCO}} = \frac{(1 + \Delta_{ECO}) \eta_{ECO}^{3/5} C^{3/2}}{3^{3/2} \pi M_c} \, .$$

ISCO frequency

Can BHs mimic ECOs ?

By choosing appropriate mass ratio, we can have the same Chirp Mass and the same ISCO frequency comparing ECOs and BHs

$$M_c = M_{\rm tot}\eta^{3/5}$$

$$\eta = \frac{M_1 M_2}{(M_1 + M_2)^2} \, .$$

$$M_c = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} \, ,$$

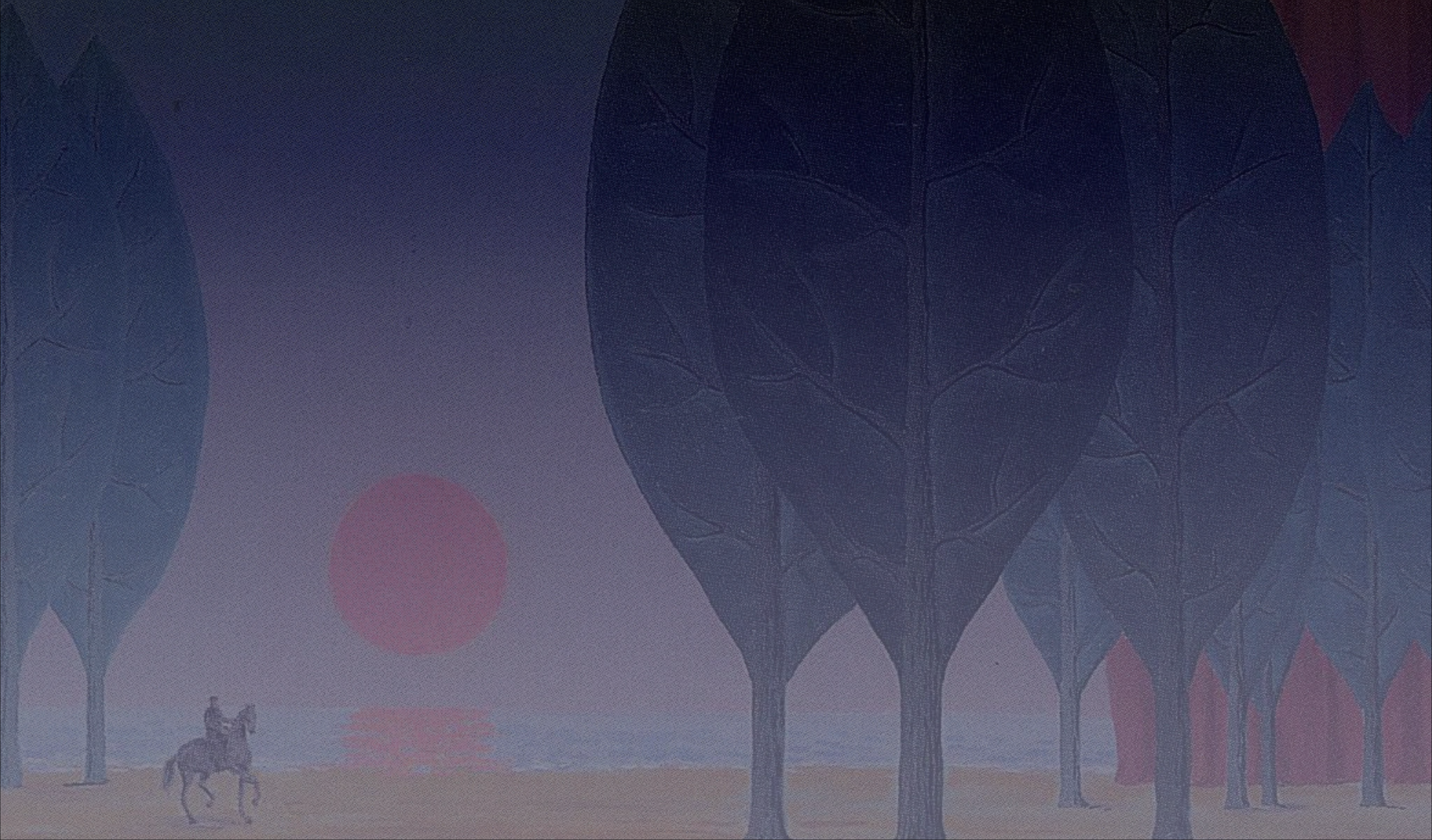
$$f_{BH}^{\rm ISCO} = \frac{(1+\Delta_{BH})\eta_{BH}^{3/5}}{6^{3/2}\pi M_c} \, ,$$

$$f_{ECO}^{\rm ISCO} = \frac{(1+\Delta_{ECO})\eta_{ECO}^{3/5} C^{3/2}}{3^{3/2}\pi M_c} \, .$$

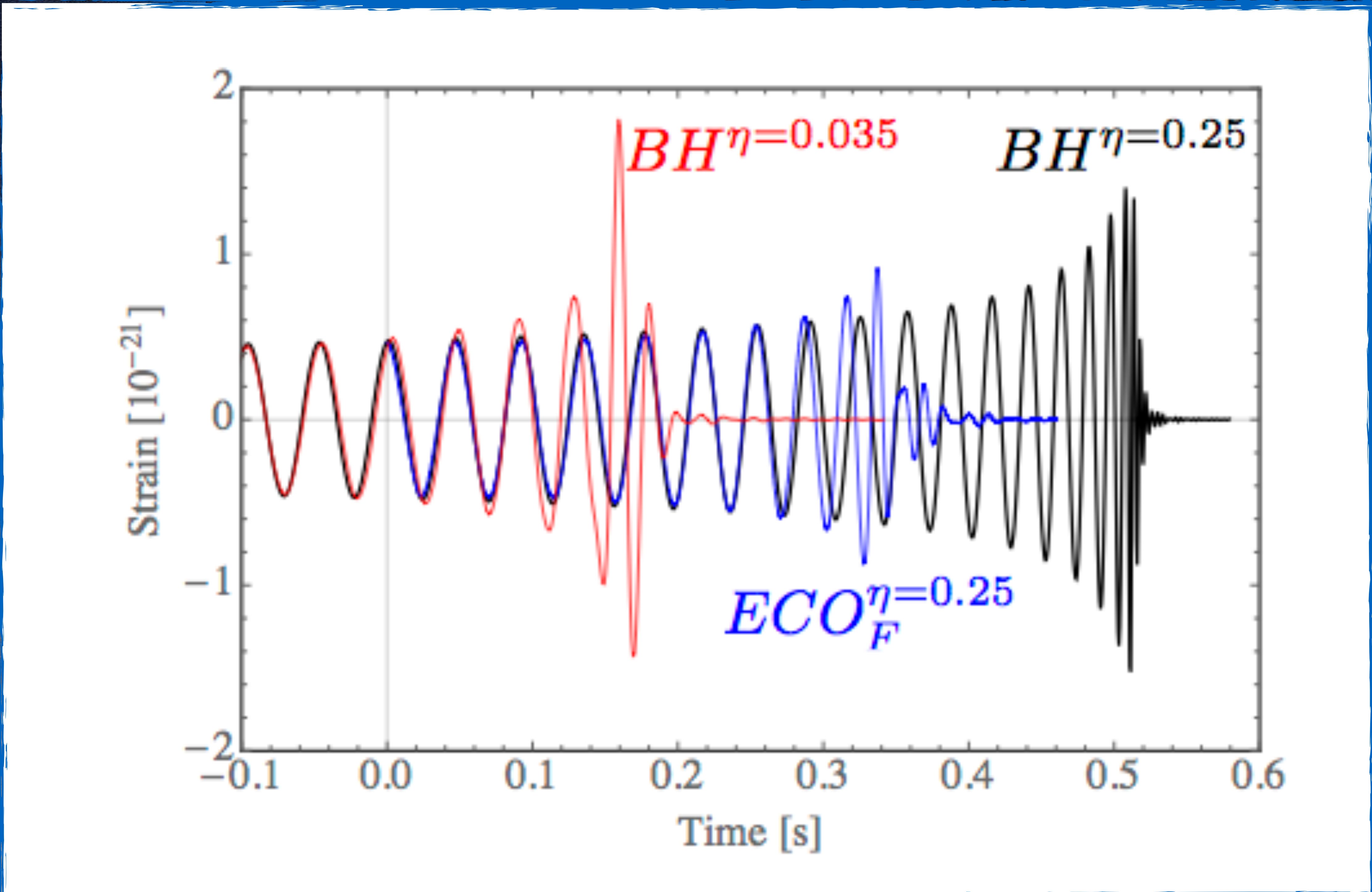
frequency

$$\eta_{BH} = \eta_{ECO} \left(\frac{1+\Delta_{ECO}}{1+\Delta_{BH}} \right)^{5/3} (2C)^{5/2}$$

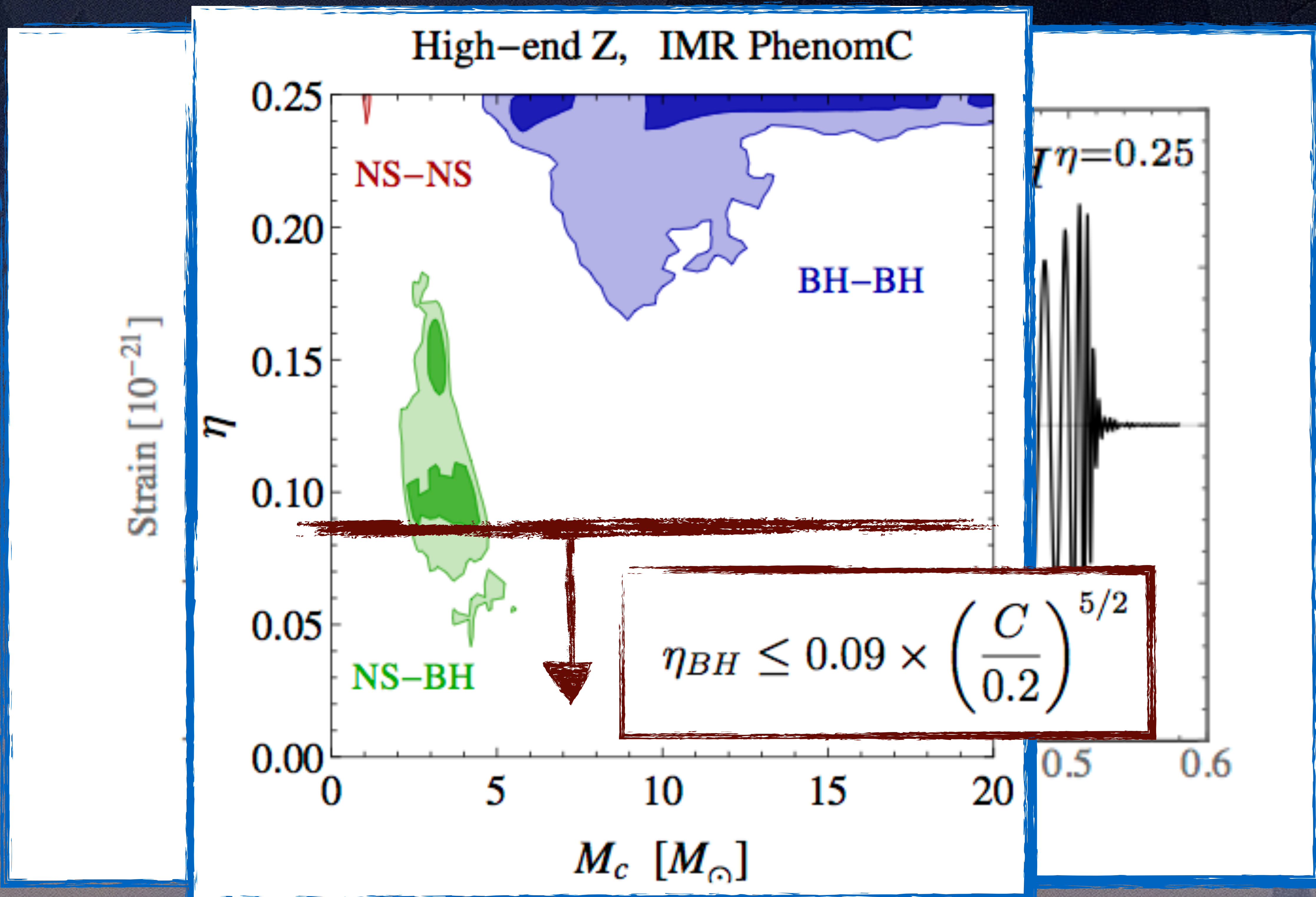
Does it mean we cannot distinguish them ?



Does it mean we cannot distinguish them ?

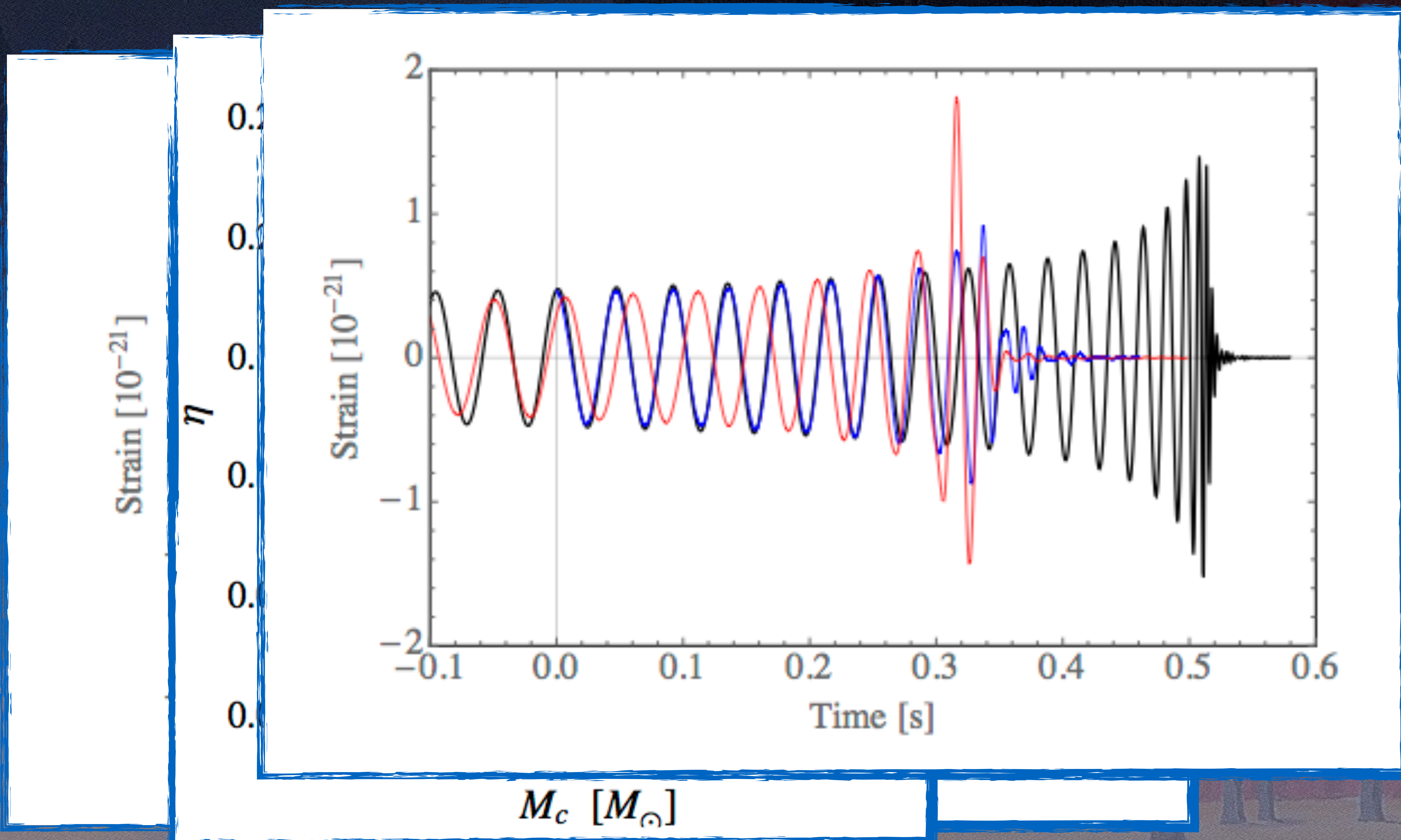


Does it mean we cannot distinguish them ?



$$\eta_{BH} \le 0.09 \times \left(\frac{C}{0.2}\right)^{5/2}$$

Does it mean we cannot distinguish them ?



Summary

The only known CO with
M > 5 solar masses are BHs.

ECOs could lie in this mass range.

ECOs are plausible, and in well-motivated parameter ranges, mergers are detectable.

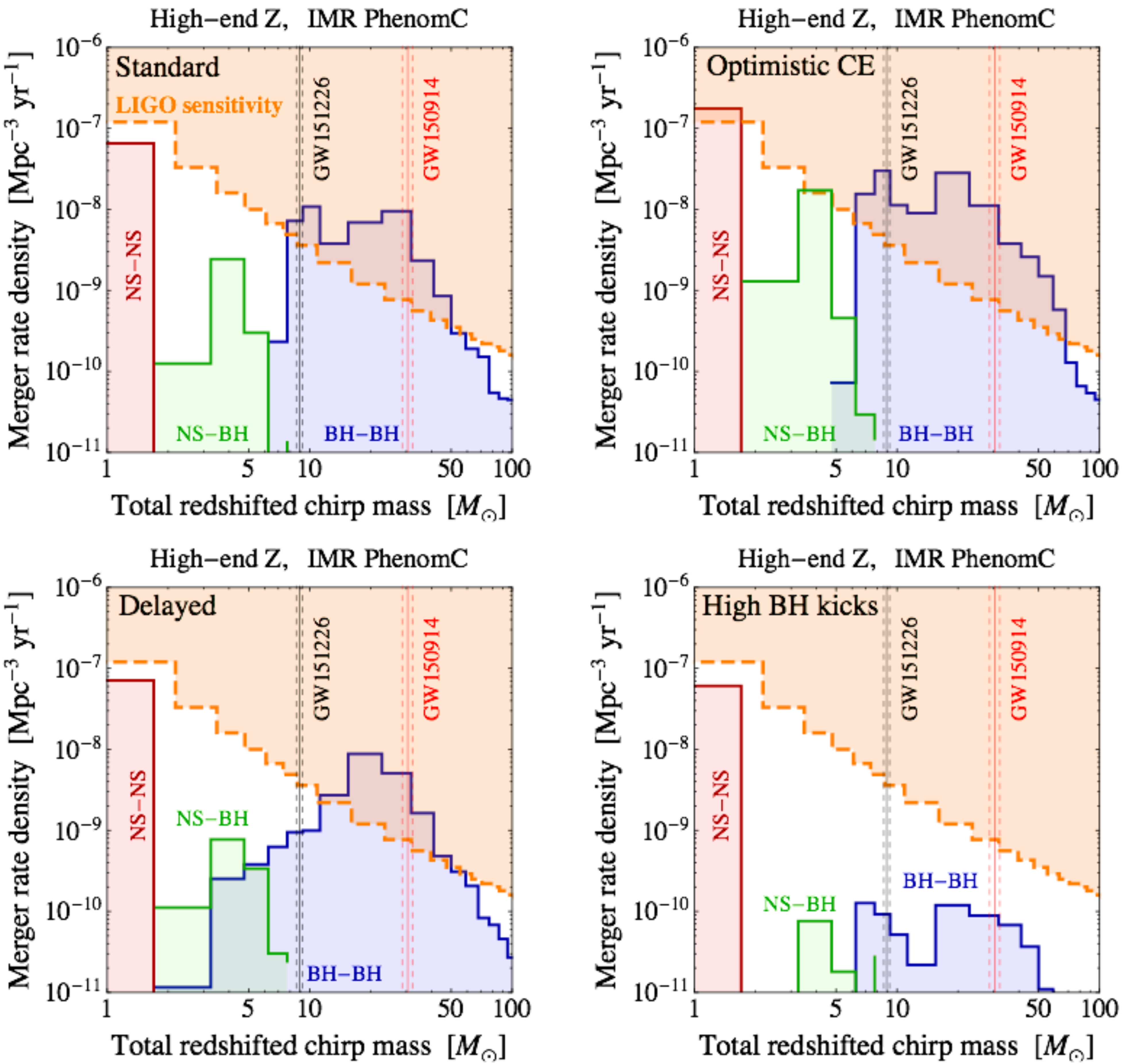
Their gravitational wave signature could be distinguished from BHs, thus ECO in this mass range means new physics!

What if the waveform cannot be distinguished ?

What if the waveform cannot be distinguished ?

Although there are still very significant uncertainties, studies of population of binaries have been performed.

[See the "Synthetic Universe" project http://www.syntheticuniverse.org/ and references therein]


High−end Z, IMR PhenomC
Standard
LIGO sensitivity
Optimistic CE
Delayed
High BH kicks
GW151226
GW150914
NS−NS
NS−BH
BH−BH
Merger rate density [Mpc^{-3} yr^{-1}]
Total redshifted chirp mass [$M_\odot$]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1
5
10
50
100

Outlook

Outlook

1) Formation

Cosmology

2) Distribution

Dark matter

Bird et al., Phys.Rev.Lett.116.201301

3) Waveform

Numerical relativity