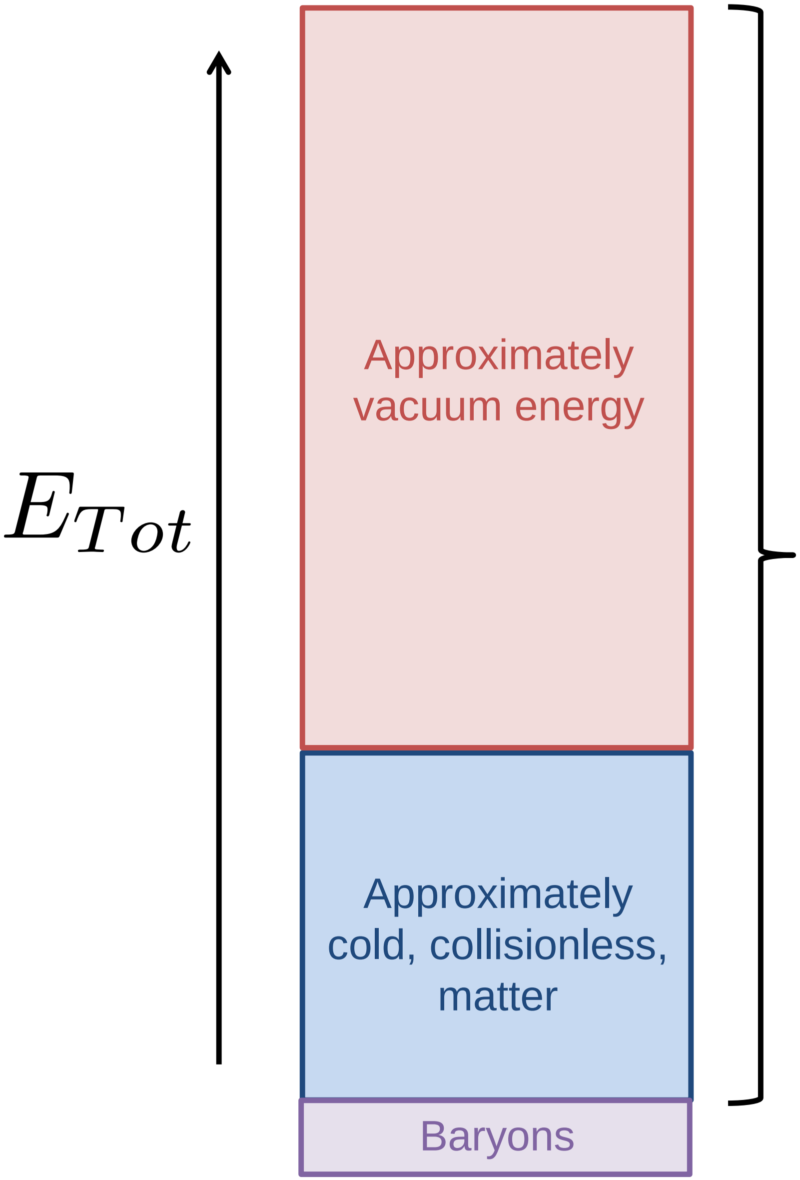
Hunting for Dark Particles with Gravitational Waves

3rd NPKI Workshop
Korea University
June 14th 2016

Matthew McCullough

with Gian Giudice and Alfredo Urbano

Our Universe

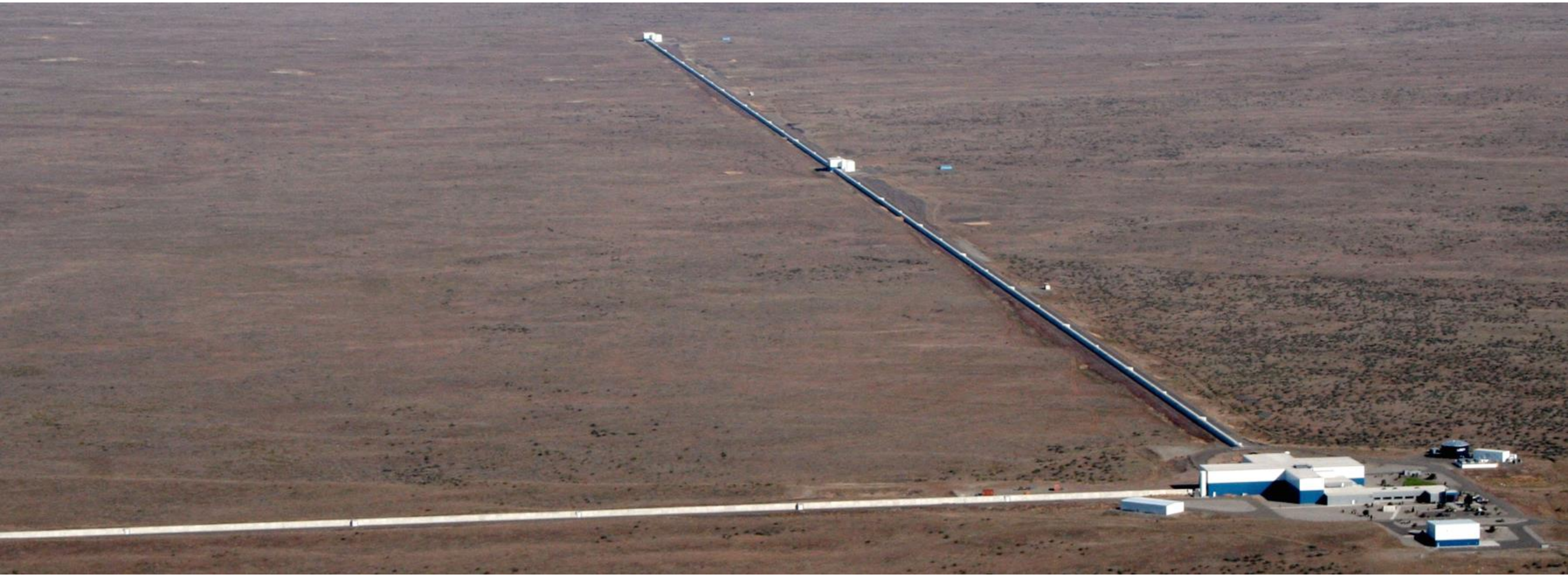


All the evidence for these components is purely gravitational!

- Effects on CMB
- Expansion / SN redshift
- Large scale structure
- Rotation curves
- Velocity dispersions
- Gravitational lensing…

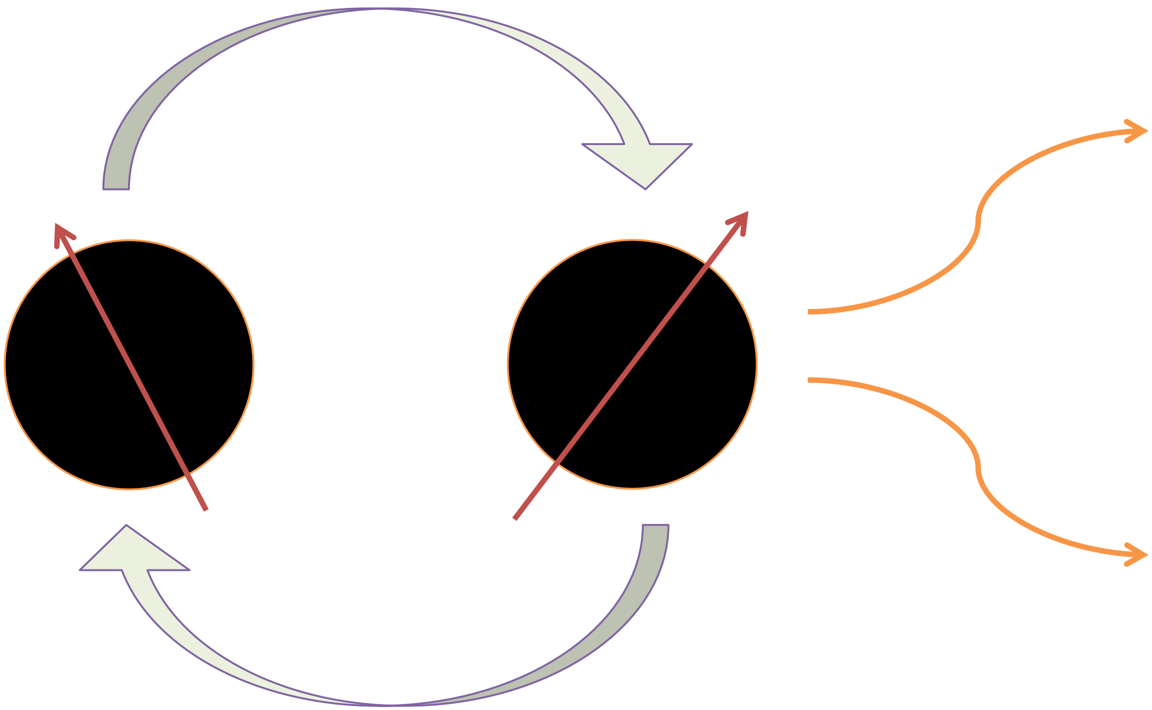
Each new gravitational probe leads to precious new information on the possible particle nature and make up of these different components.

These are some of the biggest questions we face.

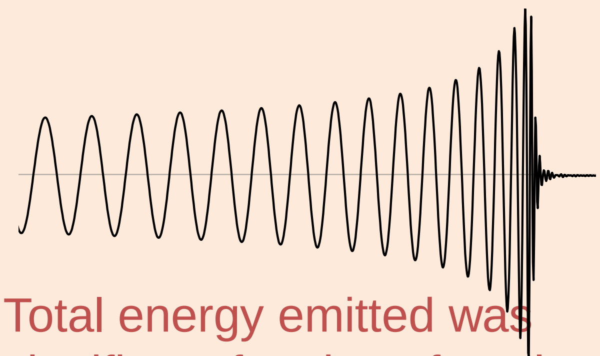


Answering them will require big experiments.

What did LIGO detect?



The gravitational wave signal emitted in the merger of a binary black hole system:



Total energy emitted was significant fraction of total mass. Why? Crudely:

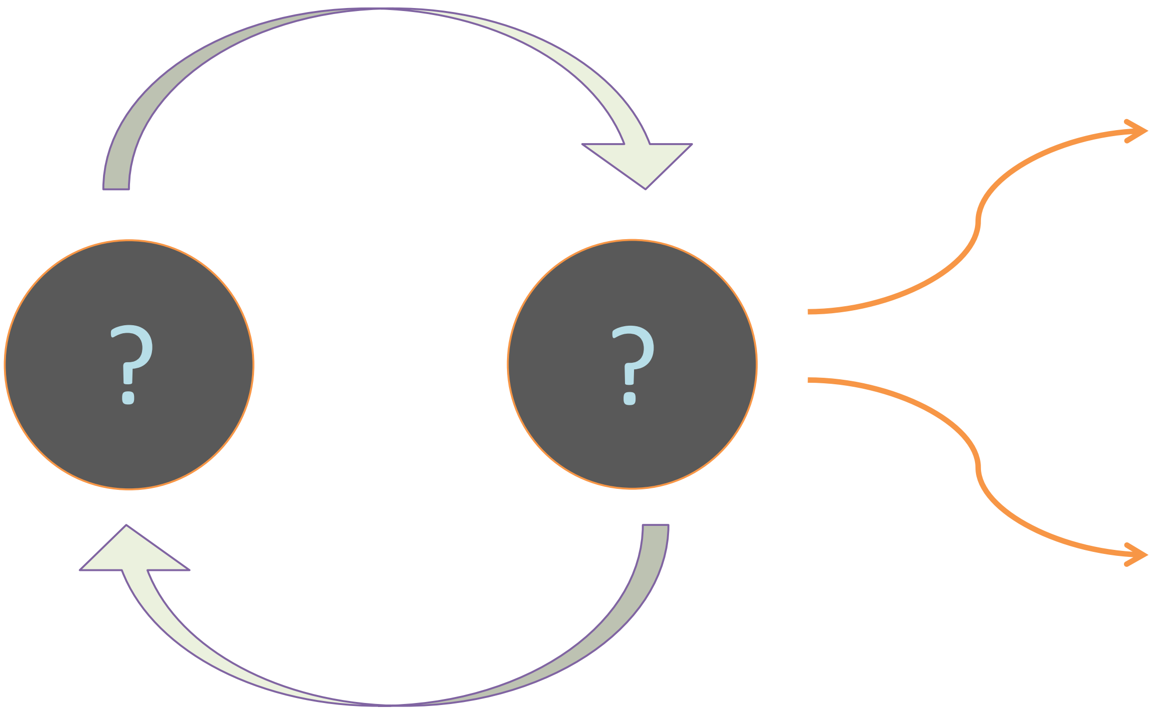
$$R \sim 3R_{BH} \sim 6M_{BH}$$

So expect:

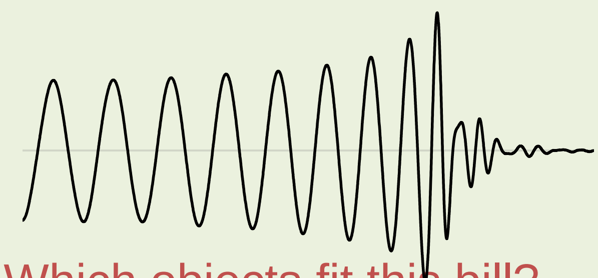
$$\Delta U \sim \mathcal{O}\left(\frac{M^2}{R}\right) \sim \mathcal{O}\left(\frac{M}{6}\right)$$

Significant fraction of mass energy carried off.

What <u>can</u> LIGO detect?



The gravitational wave signal emitted in the merger of compact objects with mass in the range of 10’s solar masses, and compactness comparable to a BH.



Which objects fit this bill?

SM Compact Objects

Black Holes

Need no introduction.

Formation scenarios suggest:

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

Compactness maximal:

$$M/R = 0.5$$

Neutron Stars

Need no introduction.

Theoretical upper bound on mass:

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

Less compact than a BH:

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

BSM Compact Objects

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:

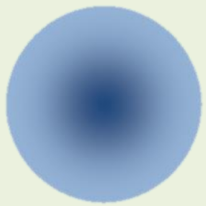
$$M_{BS} \approx \sqrt{\lambda} \left(\frac{100\ \mathrm{MeV}}{m_B} \right)^2 10 M_\odot$$

Compactness:

$$M/R < 0.16$$

BSM Compact Objects

Fermion Stars



Supported from collapse by fermion degeneracy pressure. Chandrasekhar mass

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

Thus:

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

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

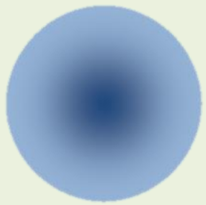
Or the

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

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

BSM Compact Objects

Fermion Stars



Supported from collapse by fermion degeneracy pressure. Chandrasekhar mass

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

Thus:

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

Compactness

$$M/R < 0.16$$

Dark Matter Stars

Pe aps the light bosons could be a DM. Formation of clear, but may sity

Or

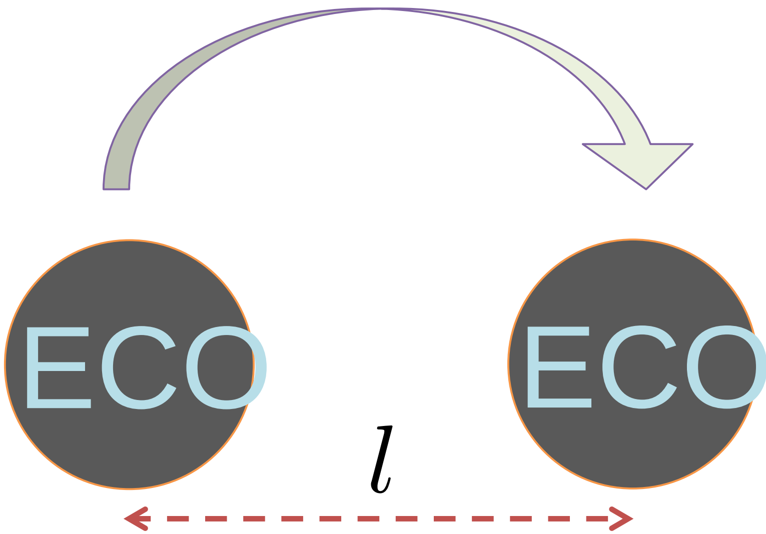
$M \approx 1$

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

Will return to this possibility later

What <u>can</u> LIGO detect?

Well-motivated BSM scenarios furnish exotic compact objects (hereafter ECOs) with mass and compactness in the right ballpark!



ISCO orbit at

$$l^{ISCO} = 3M_{Tot}/C$$

GW Primer

GW frequency is twice rotational period, thus

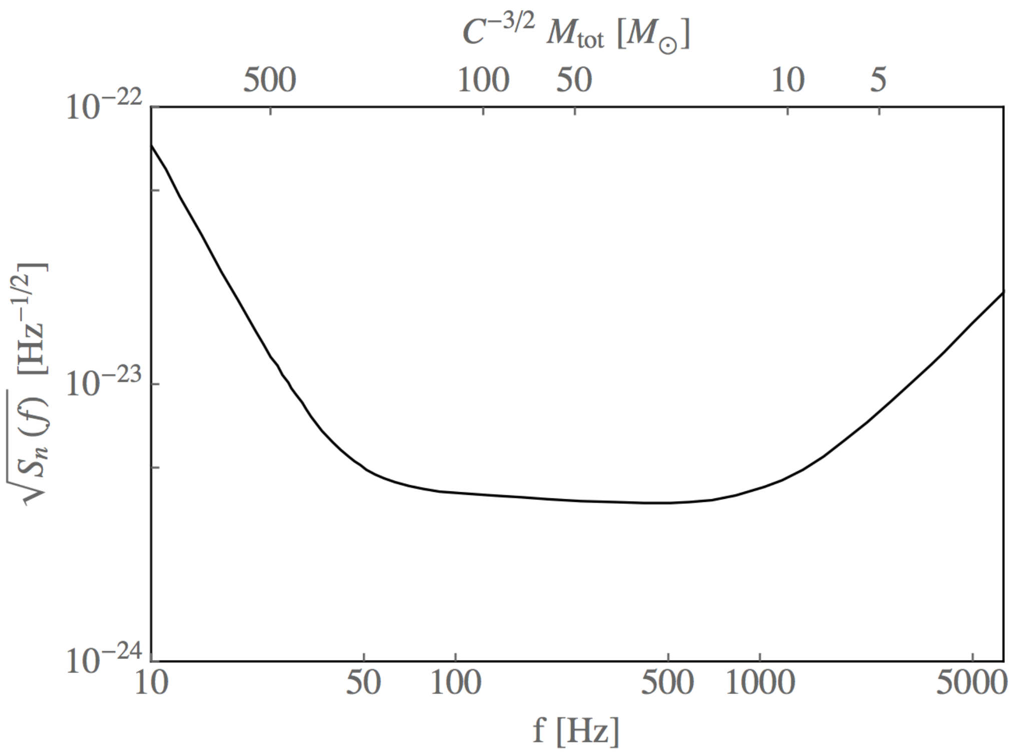
$$f_{GW} = \sqrt{\frac{M_{Tot}}{\pi^2 l^3}}$$

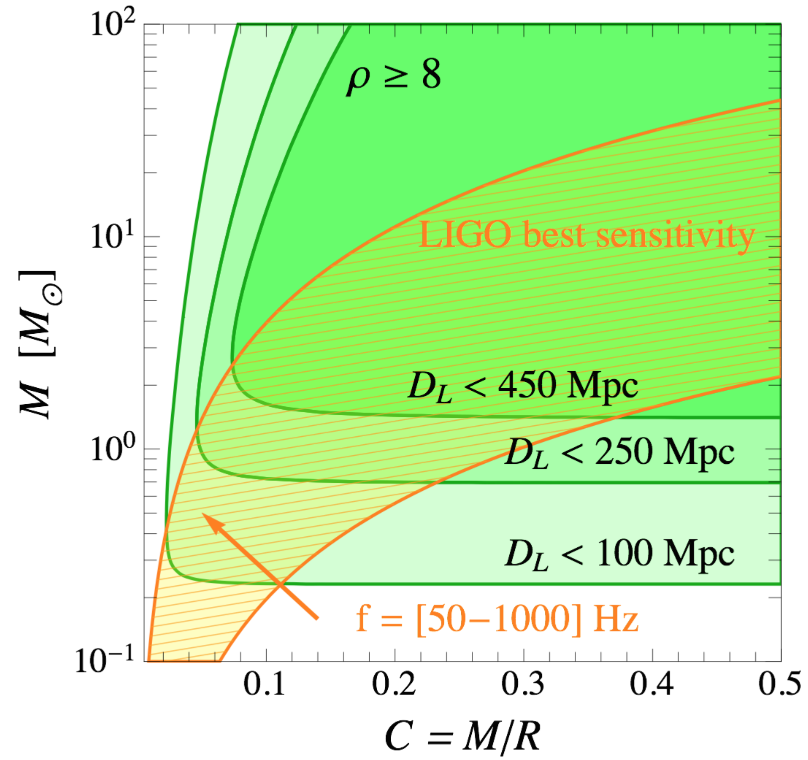
Merger onset begins when orbit smaller than “Innermost Stable Circular Orbit”

$$f_{ECO}^{ISCO} \approx \frac{C^{3/2}}{3^{3/2}\pi M_{Tot}}$$

What can LIGO detect?

Can determine the detectable ECO properties by considering the LIGO frequency range:

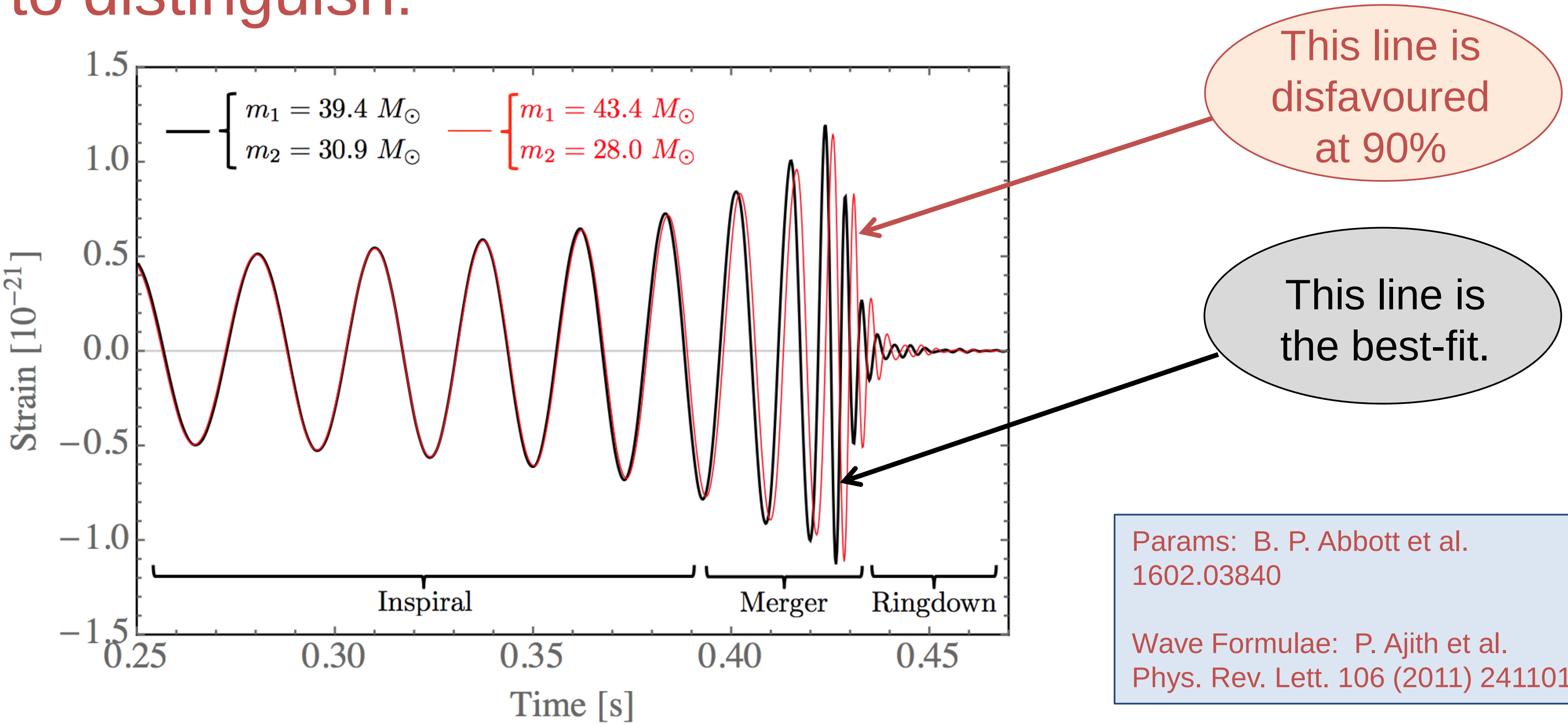




This demonstrates LIGO has sensitivity to ECOs. However, could you tell they aren't NS or BHs?

Distinguishing BH from BH

LIGO has already demonstrated extraordinary ability to distinguish:



Params: B. P. Abbott et al. 1602.03840

Wave Formulae: P. Ajith et al. Phys. Rev. Lett. 106 (2011) 241101

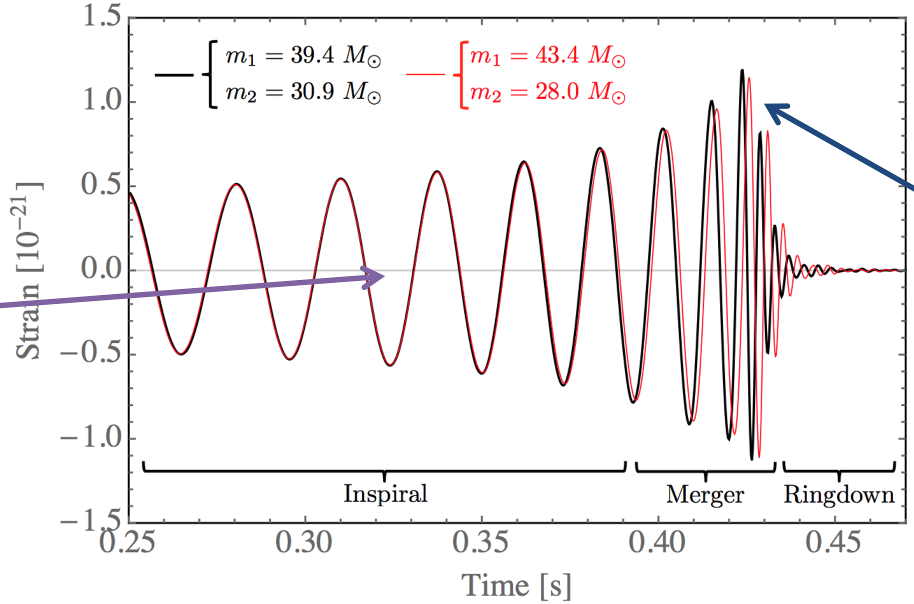
When an event is observed with large enough amplitude, discriminating power substantial!

Distinguishing ECO from BH

Can BHs mimic ECOs?

This part of the waveform, especially rate of change of frequency, determined by "Chirp Mass"

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



The frequency at this part of the waveform is the ISCO frequency.

$$f_{BH}^{ISCO} = \frac{1}{6^{3/2}\pi(M_1 + M_2)}$$

Could we reproduce both for ECOs with BHs?

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

Where the "symmetric mass ratio" is

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

Distinguishing ECO from BH

Thus, by choosing appropriate mass ratio, can have the <u>same Chirp Mass</u> and <u>same ISCO frequency</u> with BHs as with ECOs!

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

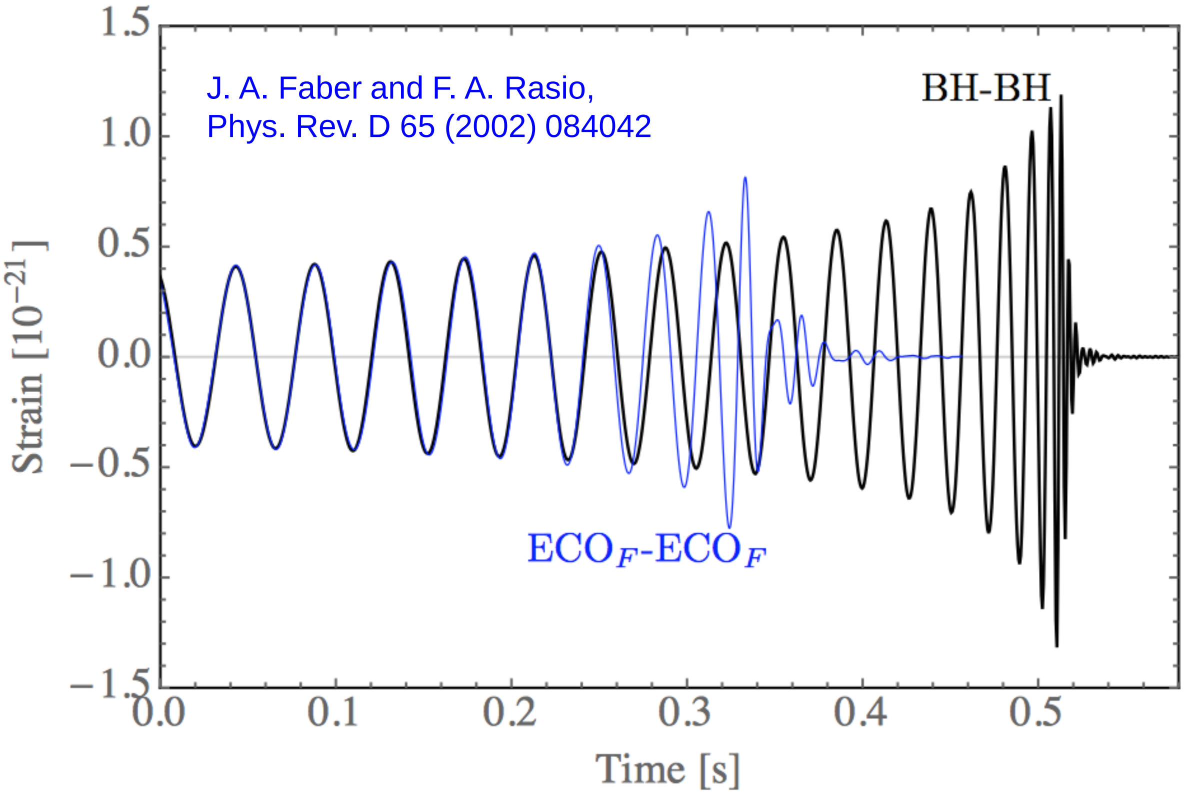
Practically speaking, for the compactness of the ECOs considered here, both reproduced for a BH symmetric mass ratio of:

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

Does this mean we cannot distinguish?

Distinguishing ECO from BH

a) Are waveforms the same?



Can estimate fermion ECO waveform directly from NS-NS waveform. Both are degenerate fermion stars, with similar EOS and compactness.

Thus, for larger mass ECOs just rescale time and amplitude axes accordingly. (See e.g. http://astrogravs.gsfc.nasa.gov)

Equal mass ECOs clearly distinguishable from equal mass BHs

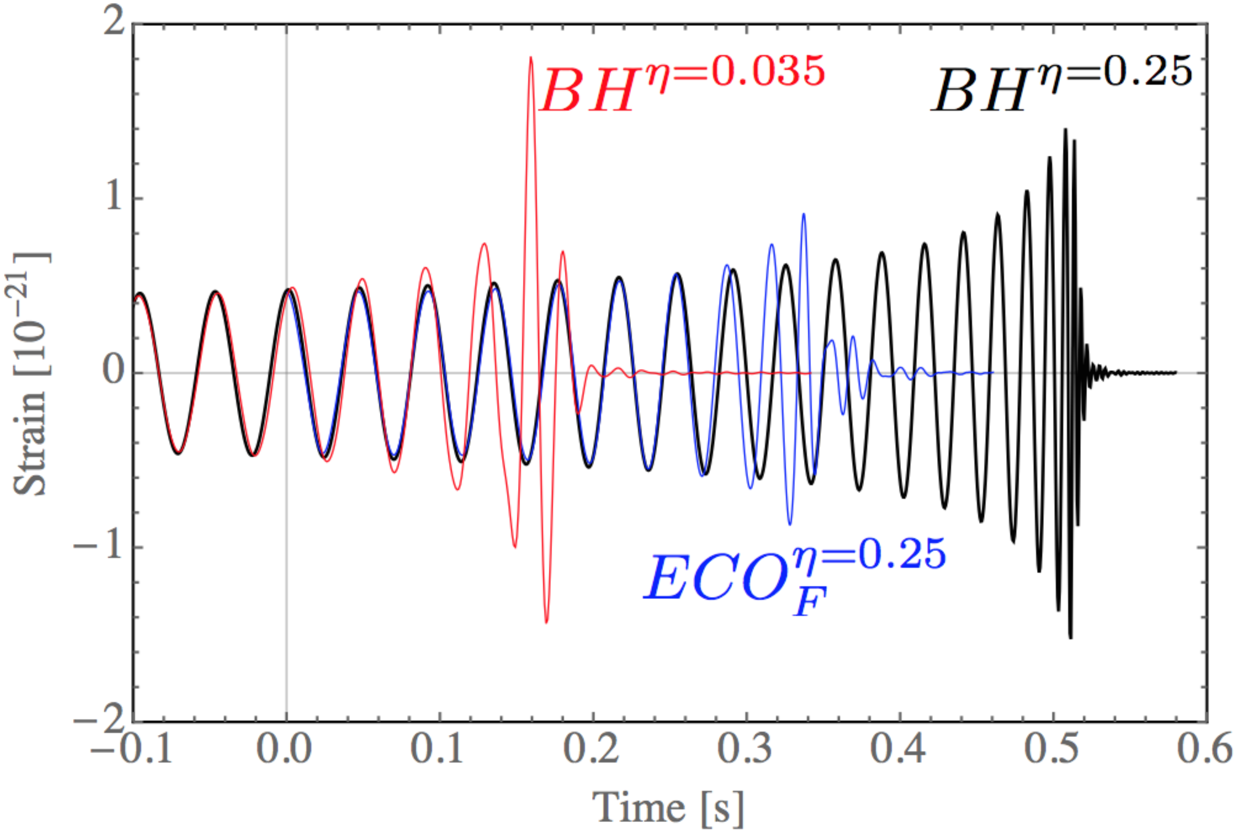
Distinguishing ECO from BH

a) Are waveforms the same?

When BH mass ratio tuned to give same chirp and ISCO?

Clearly merger and especially ringdown different. In amplitude and form.

Relation to chirp also different.

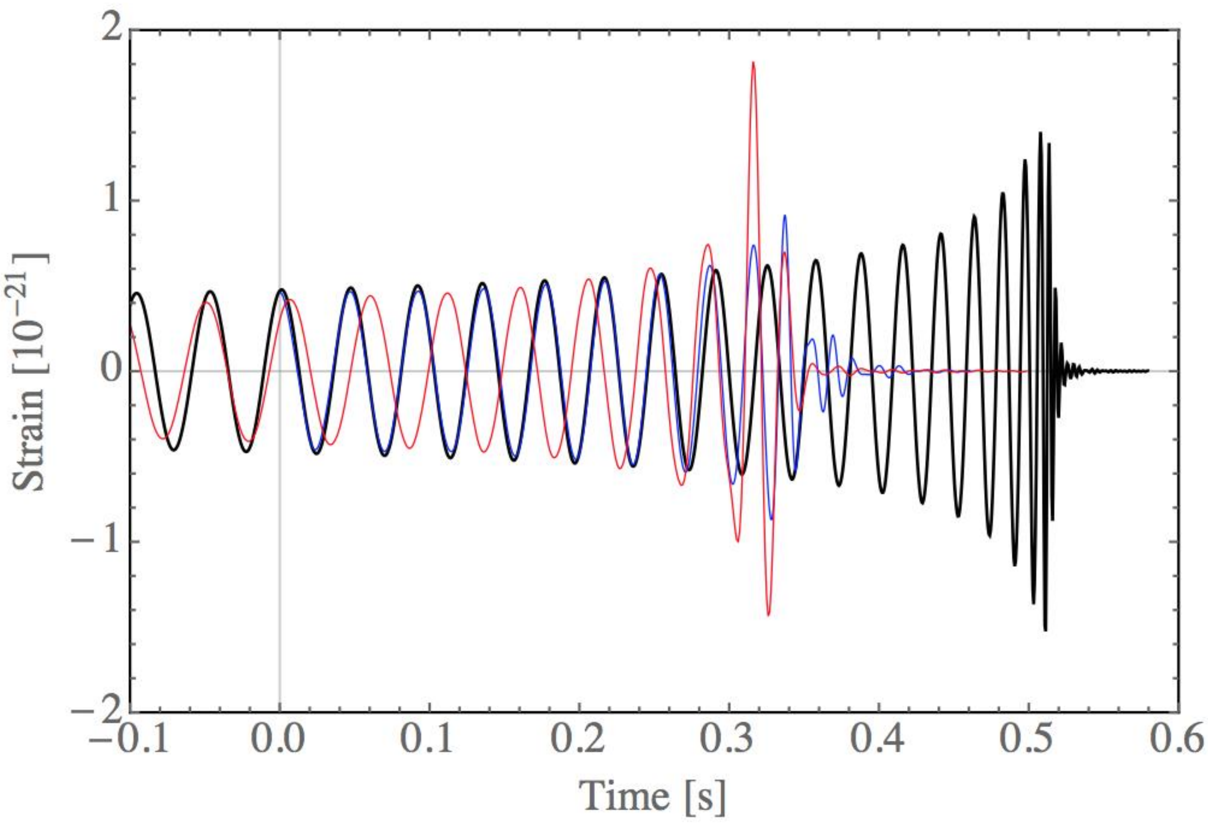


Equal mass ECOs distinguishable from unequal mass BHs.

Distinguishing ECO from BH

a) Are waveforms the same?

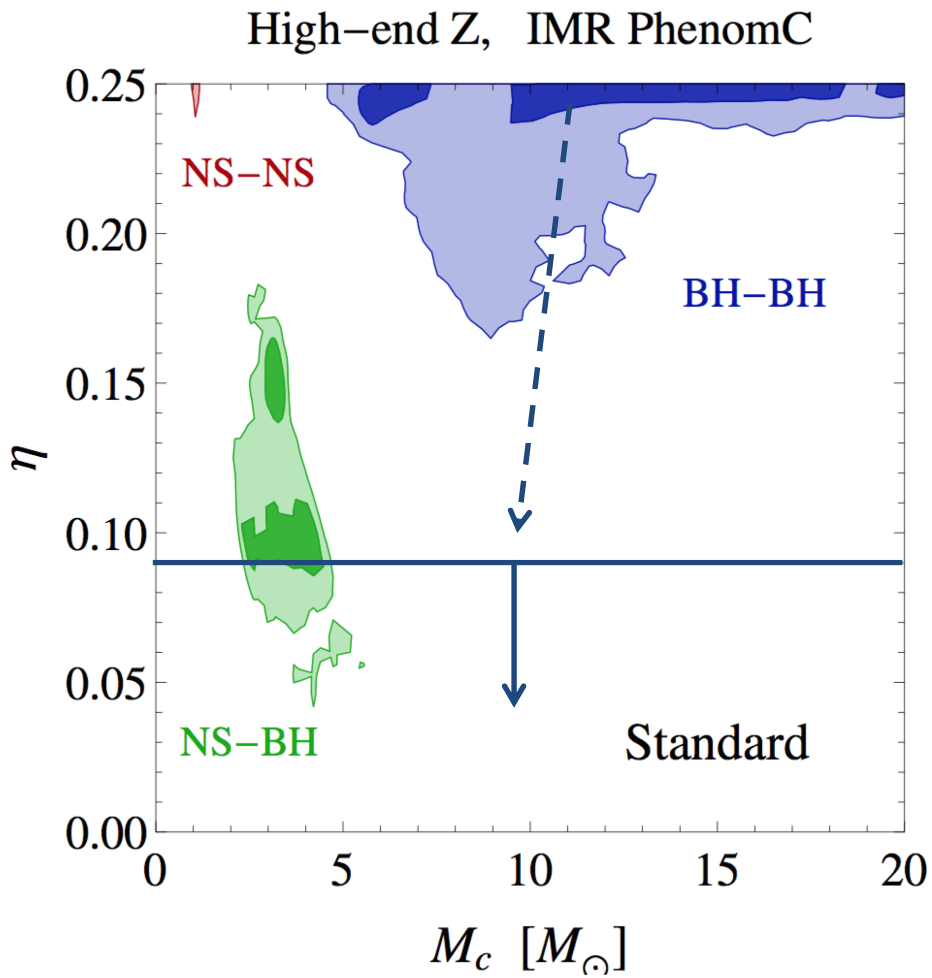
Overlaying BH merger onto ECO merger can see that ISCO can be matched well, but other aspects of waveform distinguishable.



Equal mass ECOs distinguishable from unequal mass BHs.

Distinguishing ECO from BH

b) Is this mass ratio likely?



BH binary merger models suggest it is very unlikely to have a BH-BH system with the mass range which could mimic an ECO.

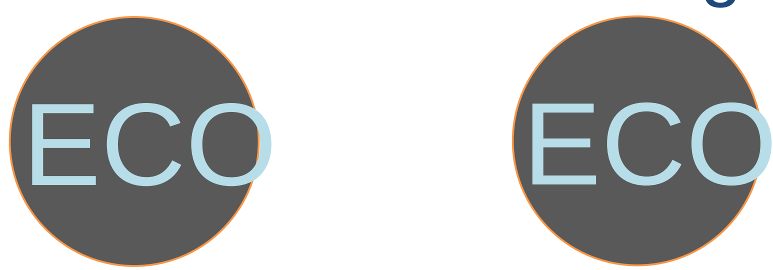
$$\eta_{BH} \leq 0.09 \times \left(\frac{C}{0.2}\right)^{5/2}$$

Distinguishing ECO from BH

Mini-Summary:

Only known COs of mass $M \gtrsim 5 M_\odot$ are BHs:

BSM ECOs could lie in this mass range $M \gtrsim 5 M_\odot$



Their gravitational wave signature could be distinguished from BHs!

DM Targets

How does the LIGO reach compare to BSM models?

$$\left(\frac{C}{0.2}\right)^{3/2} 1.1 M_\odot \lesssim M_{Tot} \lesssim \left(\frac{C}{0.5}\right)^{3/2} 88 M_\odot$$

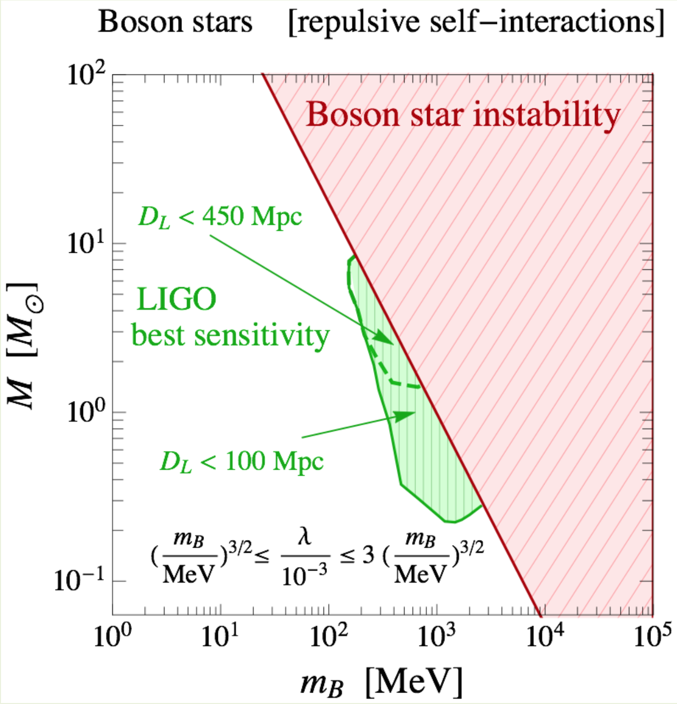
Lets consider DM candidates with self interactions motivated by the CDM puzzles:

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

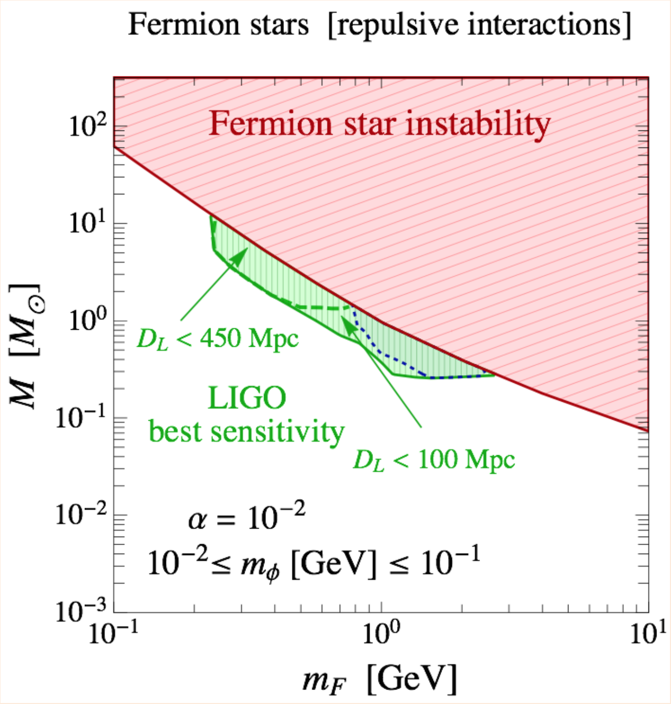
Core-cusp problem: $$\frac{\sigma}{m_{DM}} \gtrsim 0.1 \to 1\ \mathrm{cm}^2/\mathrm{g}$$

What can LIGO detect?

Interacting Boson Stars



Fermion Stars

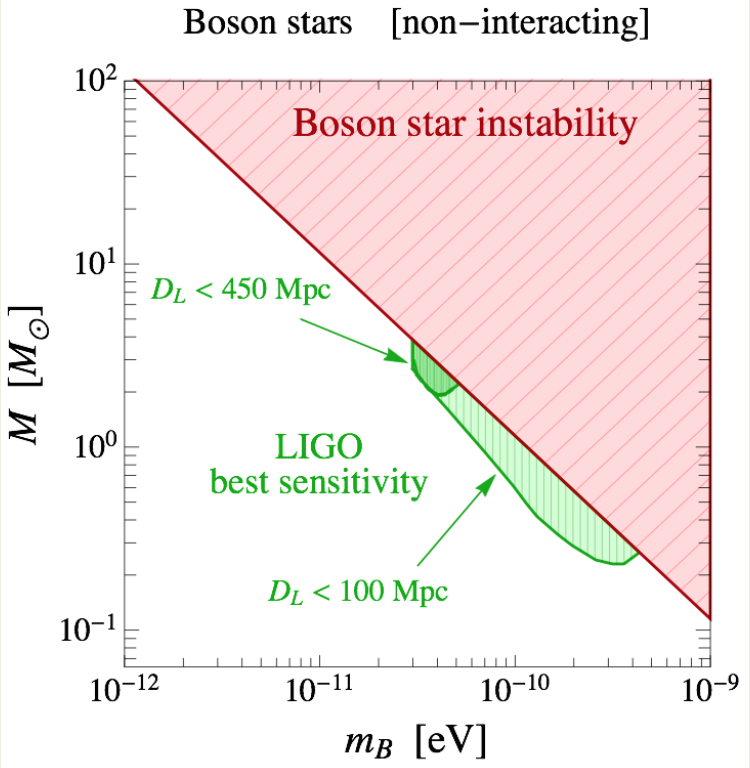


Health warning: It has been established that stable solutions exist for these scenarios, but formation is still an open question.

What can LIGO detect?

Non-Interacting Boson Stars

Clearly no connection to self-interacting DM puzzles. However, motivation could come from ALPs, such as the QCD axion.



Expected mass range:

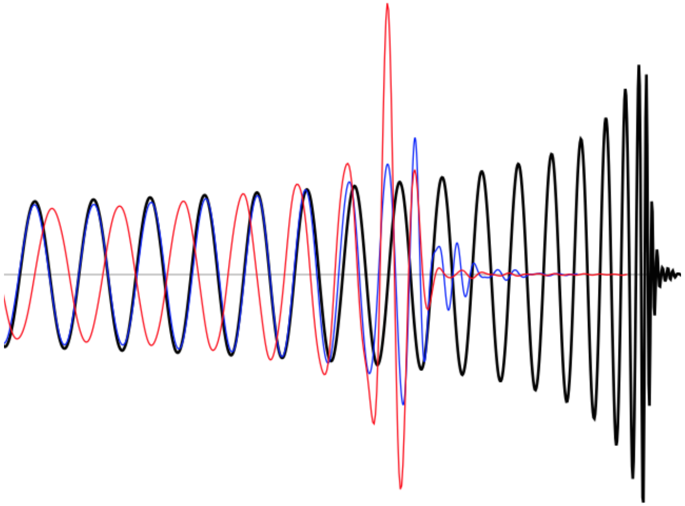
$$m_a = \left(\frac{10^{17}\ \mathrm{GeV}}{f_a}\right) 0.6 \times 10^{-10}\ \mathrm{eV}$$

Health warning: It has been established that stable solutions exist for these scenarios, but formation is still an open question.

Summary

The detection of GWs from a binary merger has opened a new window into the dark sector!

Dark sector compact objects (ECOs) are plausible, and in well-motivated parameter ranges, mergers are detectable.



If the ECO masses exceed a few solar masses, and the waveform is sufficiently exotic, it could be discriminated from a BH-BH merger.

Waveform not Distinguished?

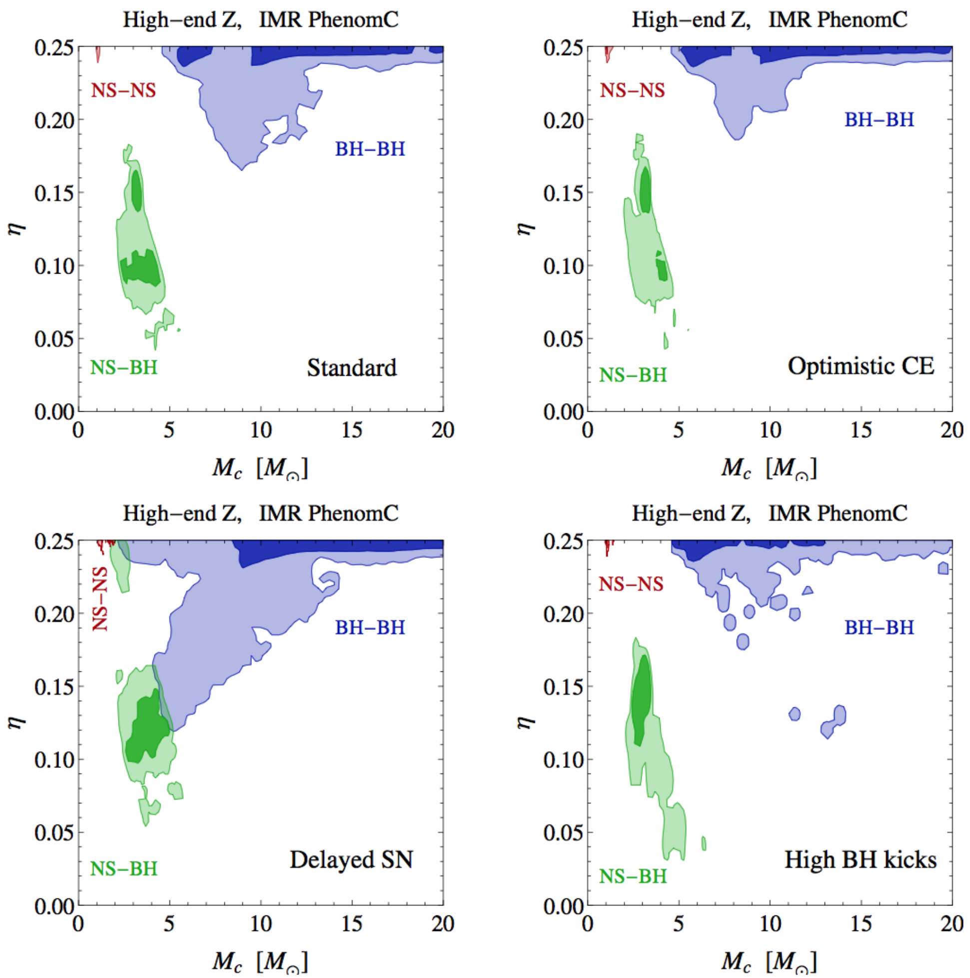
Although there are still very significant uncertainties, studies of population of binaries have been performed:

In terms of the binary mass parameters, there are different models which give similar expectations.

These numerical results are available at “The Synthetic Universe”

http://www.syntheticuniverse.org

Including references therein.

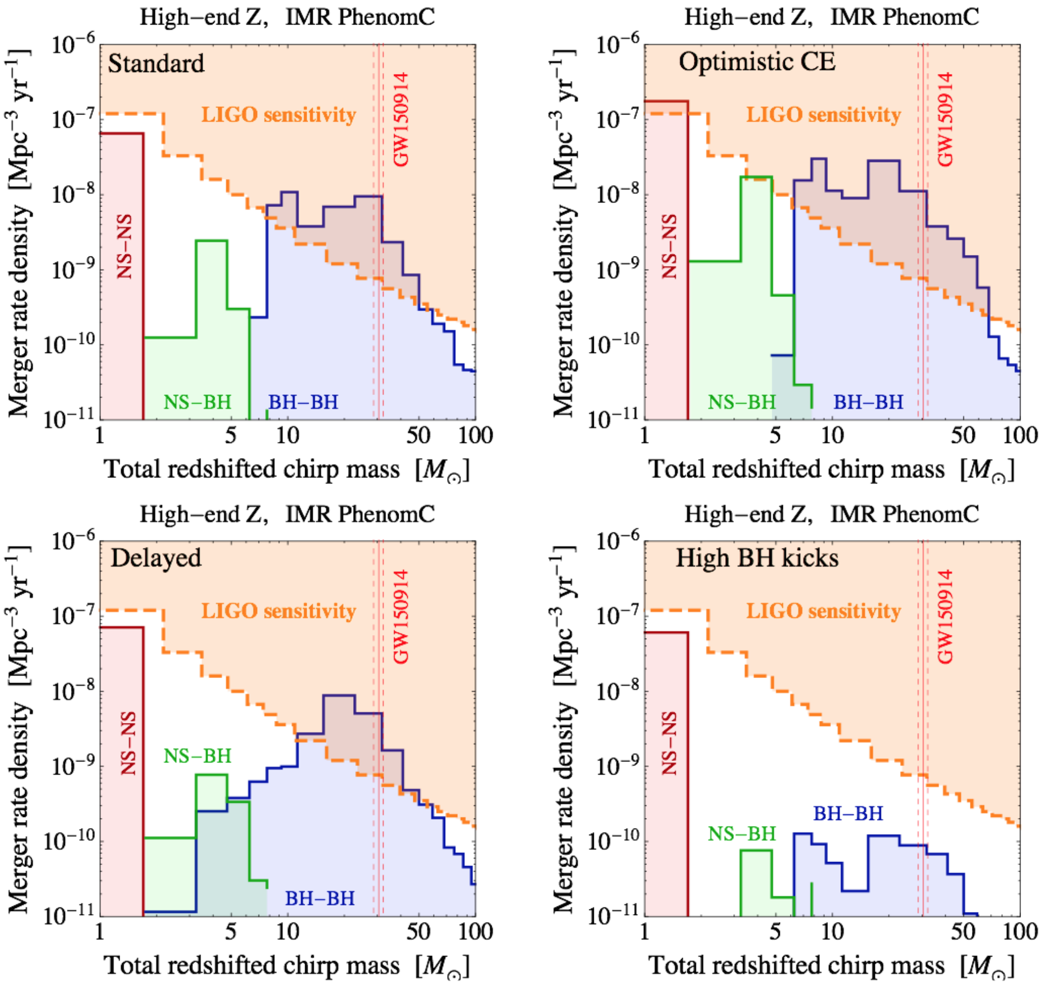


Waveform not Distinguished?

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

In terms of the observable quantity, which is the redshifted chirp mass, these distributions show a clear gap between NS-NS and BH-BH, although this is still up for debate.

There is no reason to expect new physics populations to have the same mass gap, so with better understanding of populations ECOs may show up as a new population in this distribution.



DM Targets

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

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

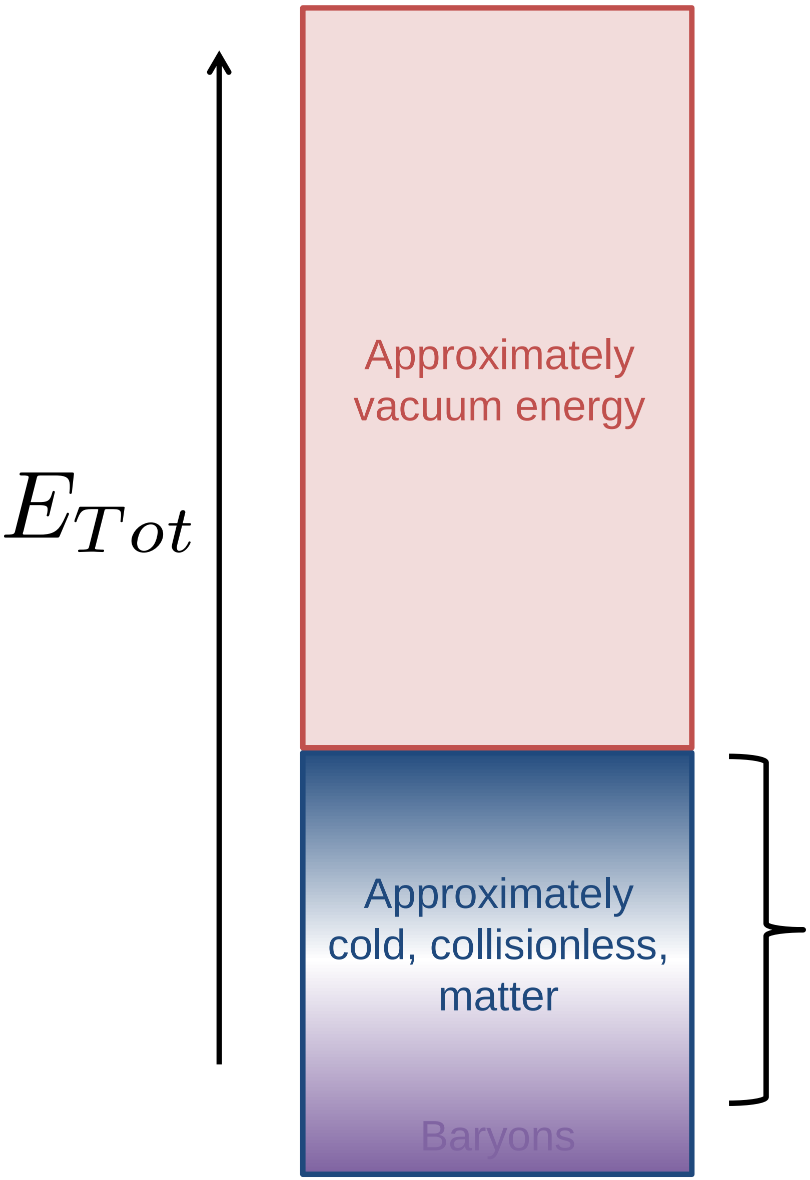
Fermion Stars

For a coupling $\alpha = 0.01$

Require mediator masses:

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

Our Universe



Maybe even a rich cocktail of stable states, of which our sector is simply one component?