Title: Probing fundamental physics with gravitational waves

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Collection: Emmy Noether Workshop: The Structure of Quantum Space Time

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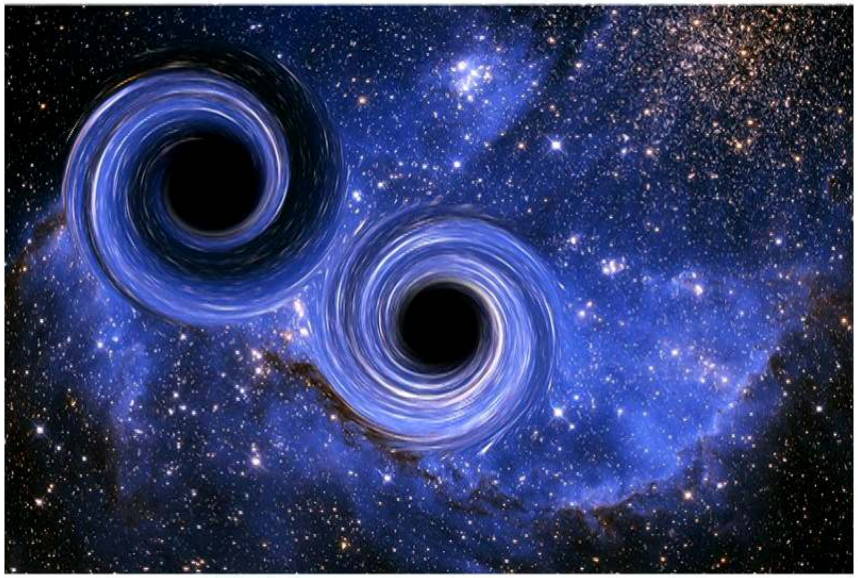
Abstract: According to general relativity, the coalescence of a compact binary system creates a gravitational wave signal generically described by an inspiral-merger-ringdown waveform. The recent observations of gravitational waves by LIGO allow us to test our theory of gravity in the strong field regime. In binary black hole detections, the ringdown portion of the wave can provide tests of the no-hair theorem, the most stringent proof of the existence of astrophysical black holes and even possible hints of quantum gravity. I will present the current status of these observations and discuss future prospects.

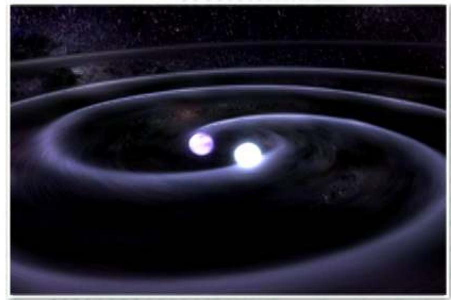
Probing fundamental physics with gravitational waves

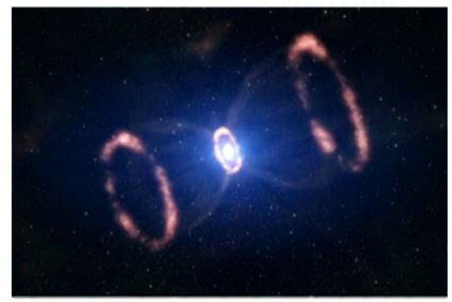


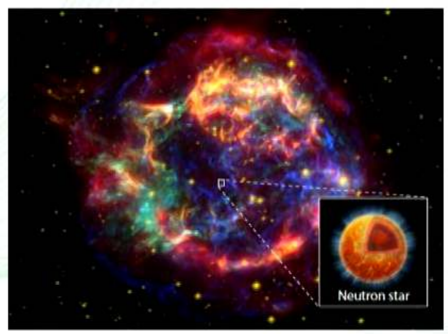
Cecilia Chirenti
UFABC - Santo André - Brazil

Emmy Noether Workshop, Perimeter Institute, November 18 2019

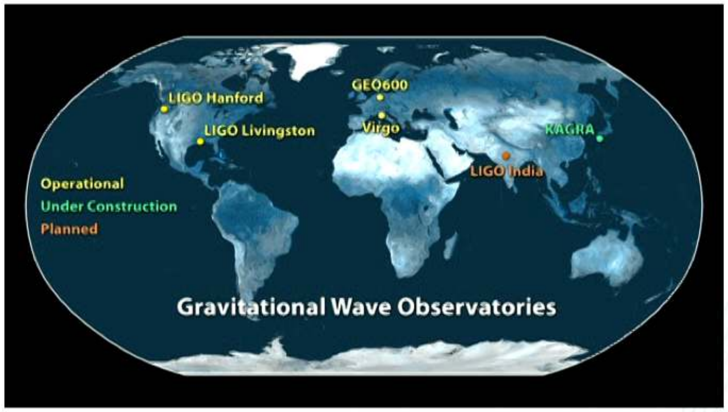
Possible gravitational wave sources…

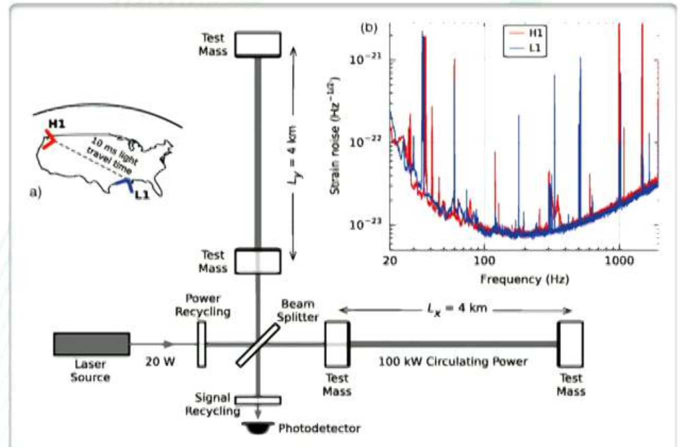


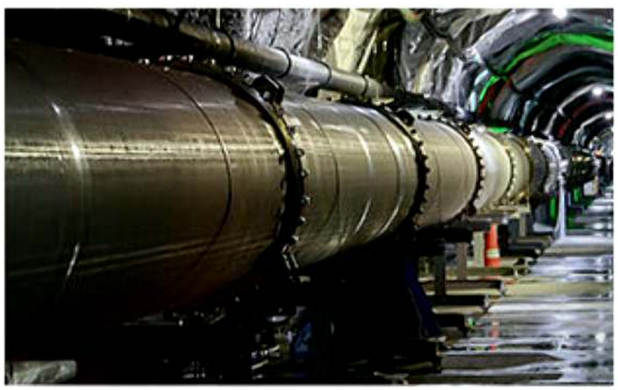




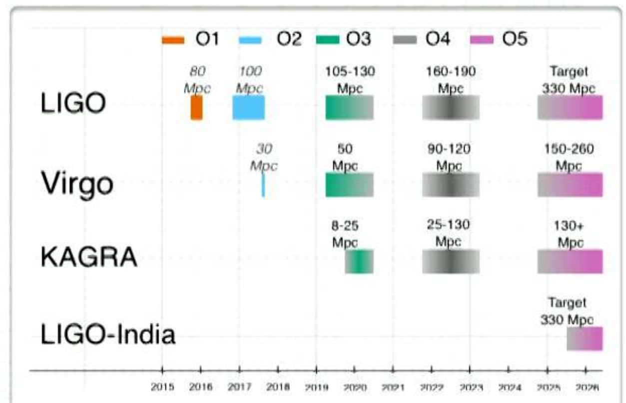
… and gravitational wave detectors







KAGRA



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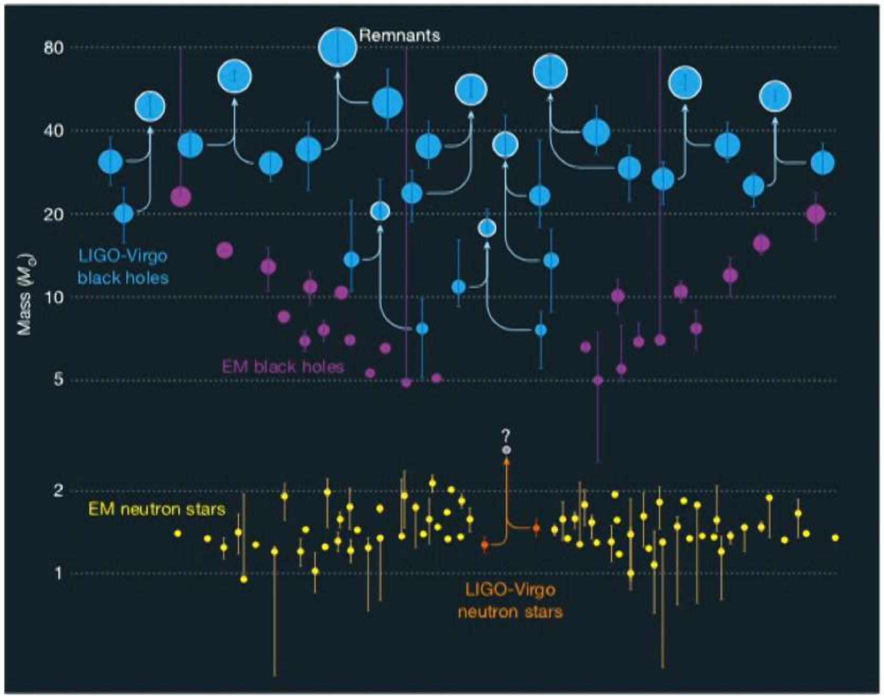
50 Mpc
90-120 Mpc
150-260 Mpc
8-25 Mpc
25-130 Mpc
130+ Mpc
Target 330 Mpc
GO-India
tangent vectors
totally geodesic surface
CAUTION

Gravitational waves from compact binary coalescences



[LIGO-Virgo, Frank Elavsky, Northwestern]

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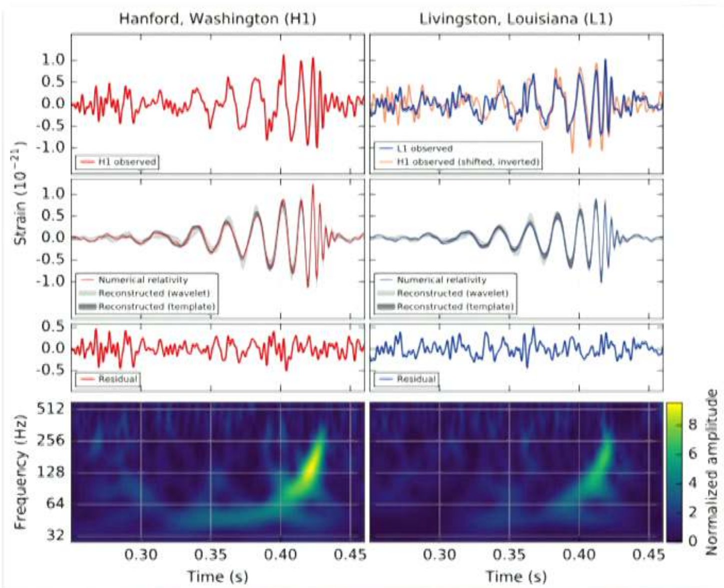
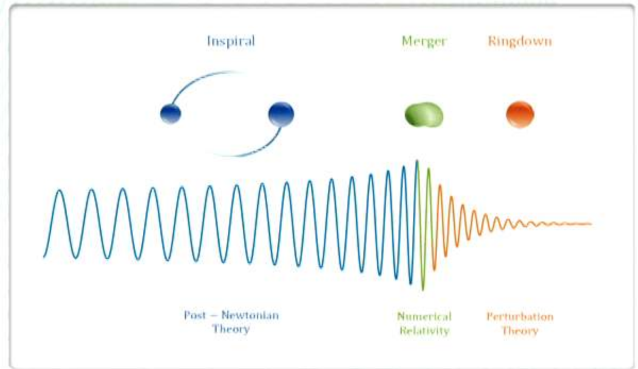
Inspiral-Merger-Ringdown

First Detection GW150914



[Abbott et al., 2016]

3 stages:



[Antelis et al. 2016]

The ringdown can be well approximated by the *quasinormal modes* of the system

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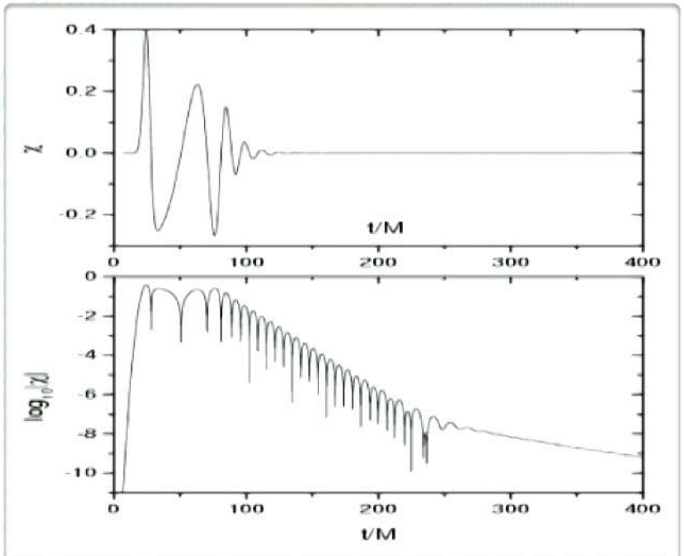
Quasinormal modes

- Characteristic modes of oscillation [Vishveshwara, 1970]
- Independent from the initial perturbation: "fingerprint" from the source
- Infinite countable set of modes, but do not form a complete set
- Linear perturbation stability analysis
- Solution of the Teukolsky eq. with appropriate boundary conditions:
    - outgoing at infinity
    - ingoing at the horizon

[Teukolsky, 1973]



[Kokkotas and Schmidt, 1999]

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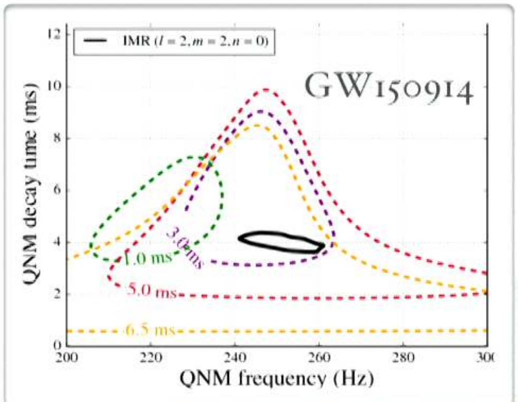
Testing the no-hair theorem

$$\psi_{\ell m} = \sum_n A_{\ell mn} e^{i[\omega_{\ell mn}(t-t_i)+\phi_{\ell mn}]}$$

$$\omega_{\ell mn} \equiv \omega^r_{\ell mn} + i\omega^i_{\ell mn}$$

Quasinormal mode frequencies depend only on M and a (and on the theory of gravity)

from GW150914 it was possible to determine the frequency and damping time of the fundamental mode in the ringdown (post-merger)



[Abbott et al., 2016]

Can we detect more than one mode?
Can we combine information from different detections?

Black hole spectroscopy

[Dreyer et al., 2004; Berti et al., 2006]

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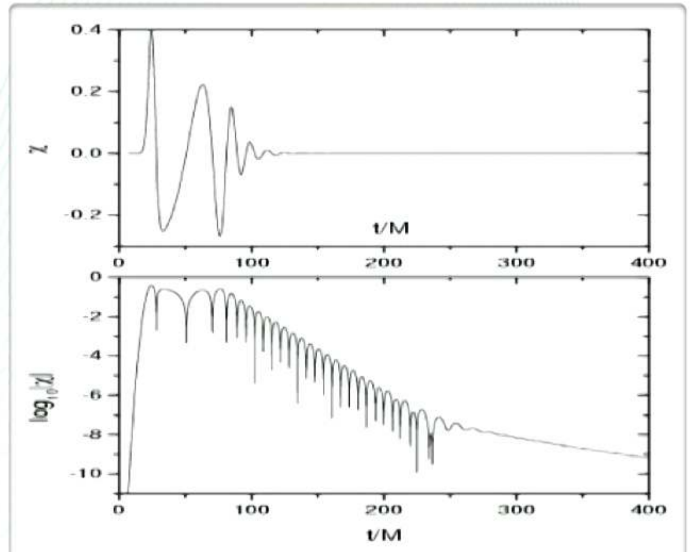
[Teukolsky, 1973]



[Kokkotas and Schmidt, 1999]

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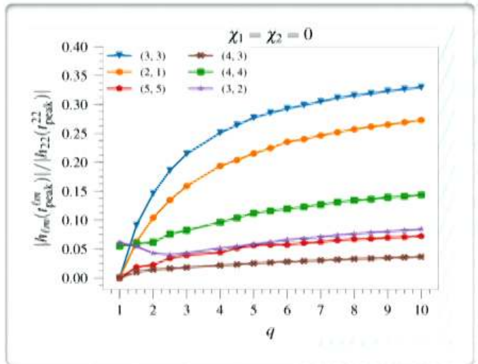
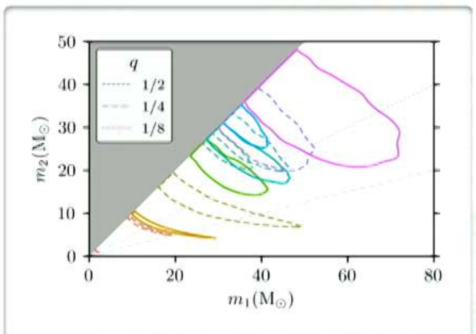
Where should we look?

Looking for higher harmonics



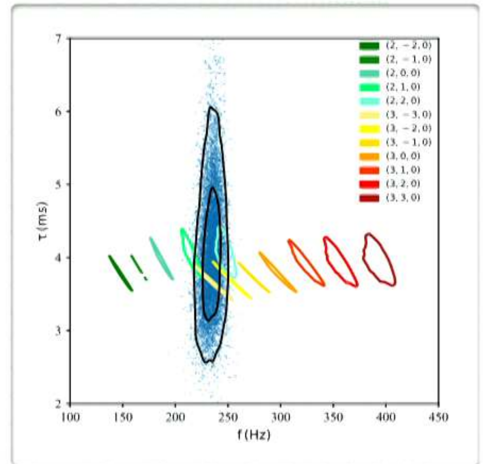
[Cotesta et al., 2018]

higher harmonics are more relevant for unequal mass binaries



[Abbott et al., 2019]

but all detections so far are compatible with equal masses



[Carullo et al., 2019]

and the frequencies of different modes overlap within the uncertainty

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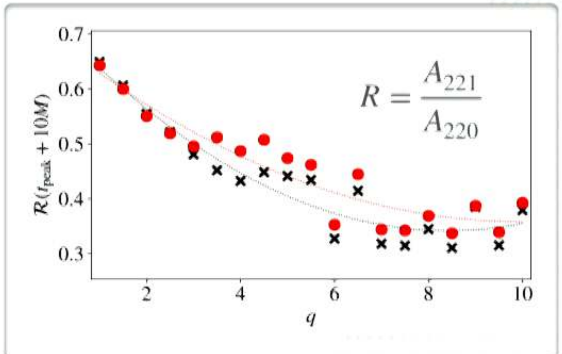
Where should we look?

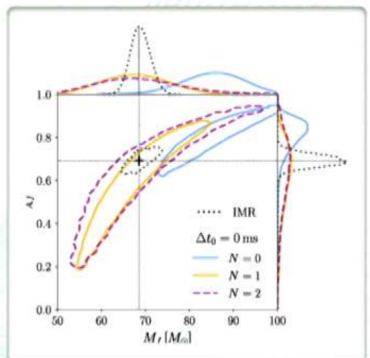
Looking for overtones



[Ota and Chirenti, 2019]

overtones are more relevant for equal mass binaries

preliminary results show evidence for the overtone in GW150914



[Isi et al., 2019]

But a more confident identification may need a detection with SNR ~ 30

[Bagwhat et al., 2019]

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Black holes alternatives

If we aren't detecting black holes, but something that looks very similar instead...

- Non-singular black holes, black hole mimickers, exotic compact objects, etc
- What are the (possible) problems with the standard black hole model? Quantum gravity considerations?
- Why bother? Haven't we already seen evidence that black holes exist?

[EHT]

- Another motivation: is it possible to give irrefutable proof of the existence of the event horizon? [Abramowicz et al., 2002]

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Some of our candidates...

(How should we choose a candidate?)

- gravastars
- boson stars
- wormholes
- superspinars
- etc...

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Formation of a gravastar

- Gravitational collapse of a massive star
- Phase transition as stellar radius approaches its Schwarzschild radius...
- ... leading to the formation of a de Sitter core!
- Baryonic mass of the star becomes a shell of stiff matter surrounding the core

(Speculation!)

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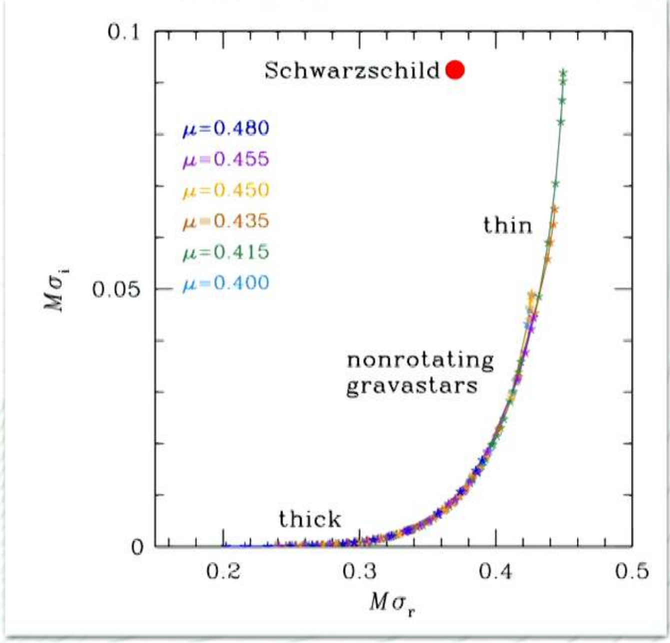
Quasinormal mode signature of a gravastar

non-rotating

Parameters: M, r_1, r_2
r_1 : radius of the core
r_2 : surface radius

or M, δ, μ
$\delta = r_2 - r_1$: thickness
$\mu = M/r_2$: compactness



[Chirenti and Rezzolla, 2016]

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Quasinormal mode signature of a gravastar

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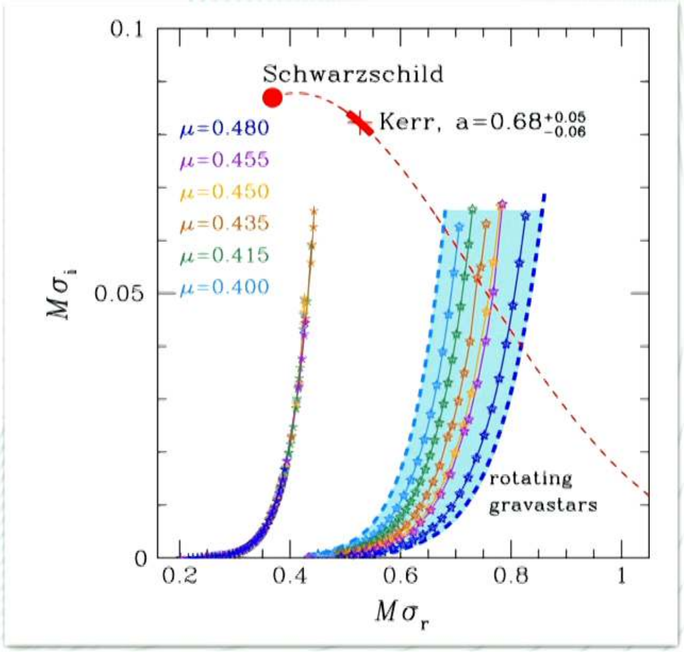
adding **rotation**



[Chirenti and Rezzolla, 2016]

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Extending analytical solutions

1916: Schwarzschild interior solution describes a uniform density star

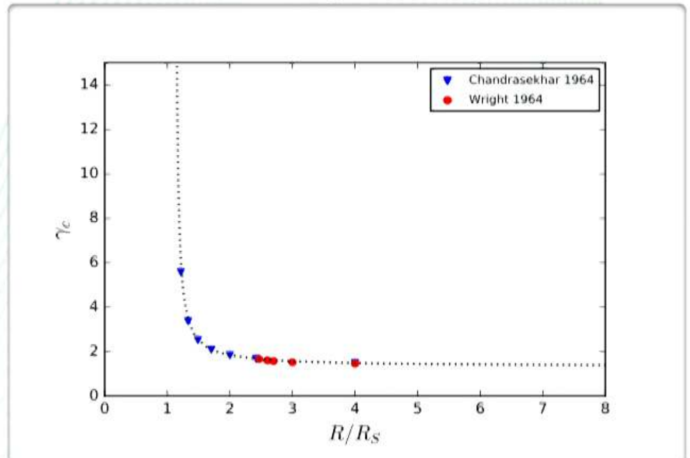
$$p_c = \epsilon \left(\frac{1 - y_1}{3y_1 - 1} \right) \quad \text{with} \quad y_1^2 = 1 - \frac{R_S}{R}$$

positive pressure requirement limits maximum allowed compactness

$$3y_1 > 1 \Rightarrow R/R_S > 9/8$$

[Buchdahl, 1959]

Buchdahl limit:
$R/R_S = 9/8 = 1.125$



[Posada and Chirenti, 2019]

Radial stability requires critical adiabatic index γ_c finite and results in the same limit!

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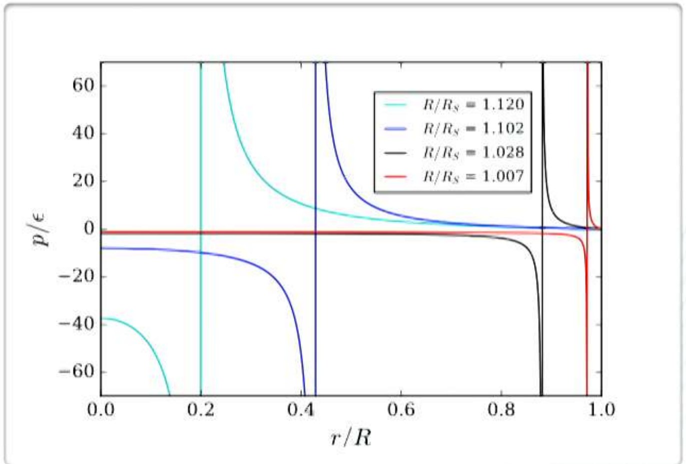
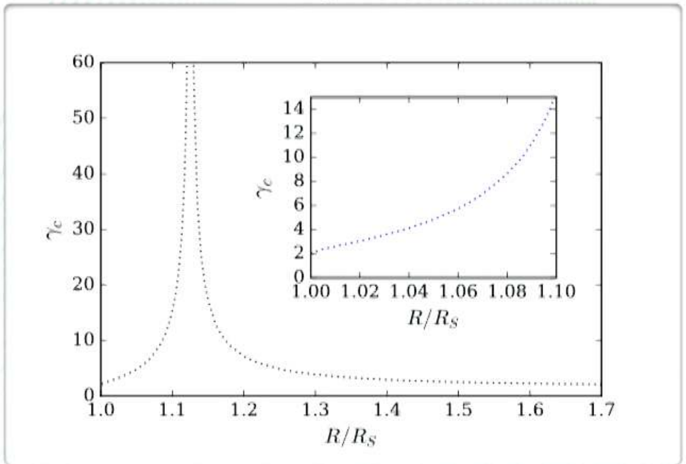
Extending analytical solutions

What if $R/R_S < 9/8$?



Buchdahl limit:
$R/R_S = 9/8 = 1.125$



[Posada and Chirenti, 2019]

More compact solutions exist, but with negative pressure interior: looks like a gravastar?
Stability is regained beyond the Buchdahl limit!

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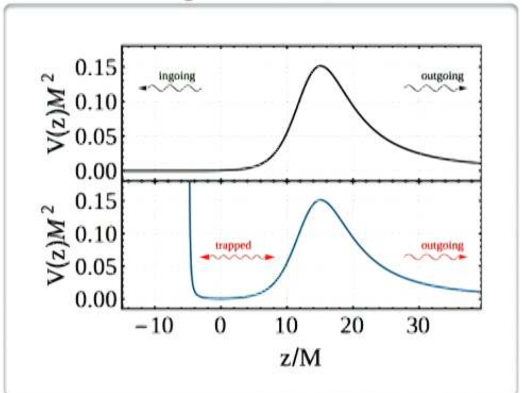
Modified ringdown tests

model-independent formulation

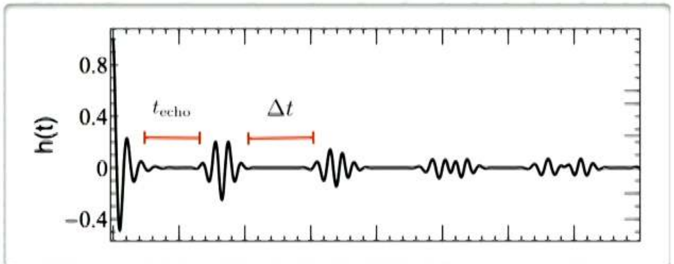


[Cardoso et al. 2016]

If the surface of the object is infinitesimally close (order l_{Pl}) to the black hole event horizon, how could we tell the difference?

Ringdown = black hole QNMs (early)
+ trapped modes leaking out or
"echoes" (later)

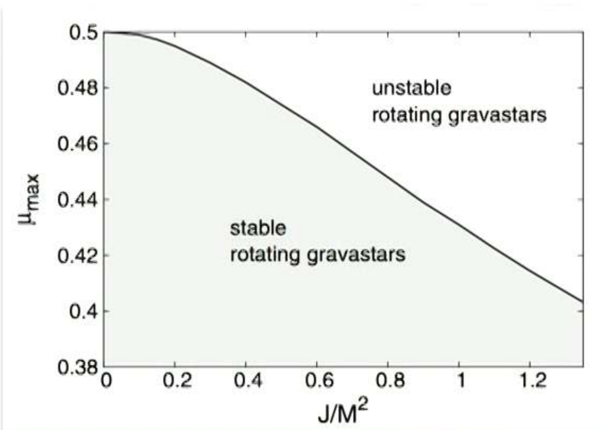
Observational controversy:
Abedi, Dykaar & Afshordi, 2017
Westerweck et al. 2018
Conklin, Holdom & Ren , 2018



[Maselli, Völkel & Kokkotas, 2017]

Adding rotation

Ergoregion instability limits the maximum compactness for fast spinning horizonless objects [Friedman, 1978; Vilenkin, 1978, Cardoso et al., 2008]



[Chirenti and Rezzolla, 2008]

But the stability can be "quenched" by adding absorption, or reflectivity $R < 1$

[Maggio et al., 2019]

What happens with the echoes?

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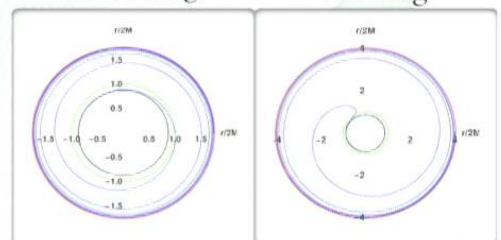
Adding rotation

We can use an infalling particle to excite the echoes
[Mark et al, 2017]

But when we add rotation, the waveform *depends on the orbit*

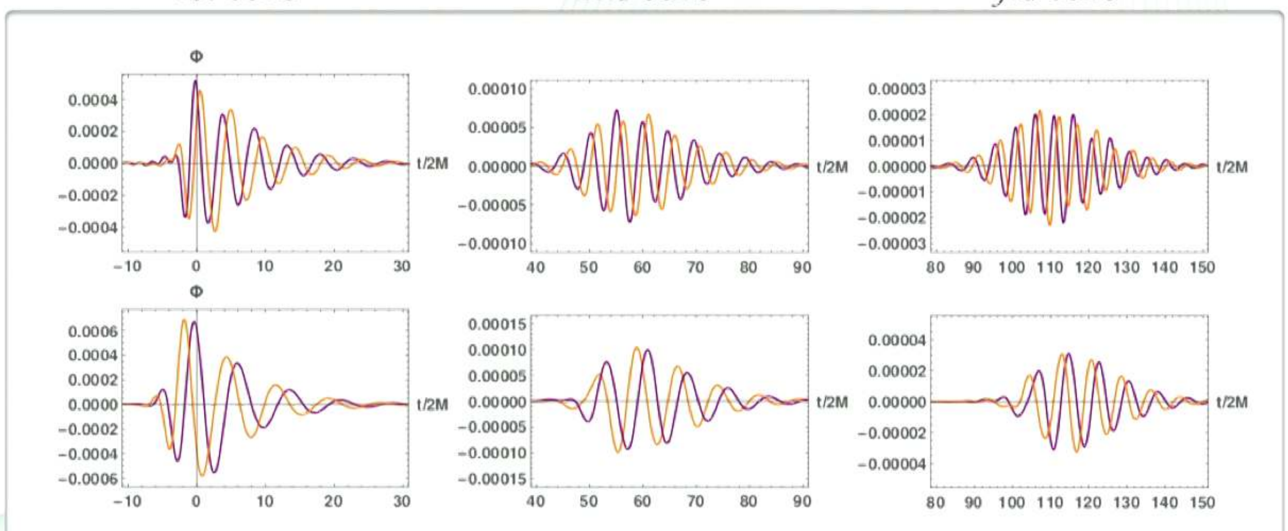
corotating / counter rotating



1st echo / 2nd echo / 3rd echo

corotating

counter rotating



[Micchi and Chirenti, to appear]

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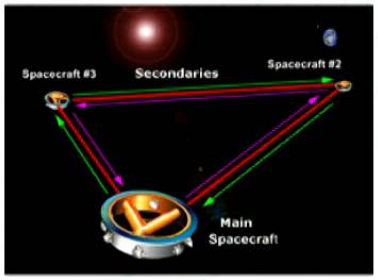
Final remarks

- There are exciting prospects for testing gravity and the existence of new types of astrophysical objects with gravitational wave detections

- However, caution is needed: finer tests require higher SNR for conclusive answers (and extraordinary claims require extraordinary evidence!)
- Will data stacking help for tests with current ground based detectors?
- 3G detectors will help (2030's);
  LISA will have even higher SNR (2034)!



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