

Title: Probing fundamental physics with gravitational waves

Speakers: Cecilia Chirenti

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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.



PI

Probing fundamental physics with gravitational waves



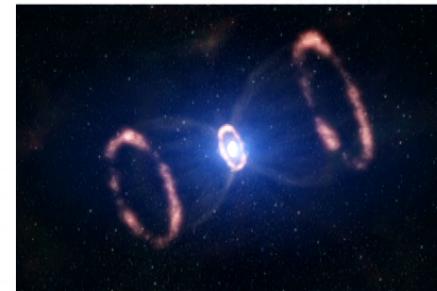
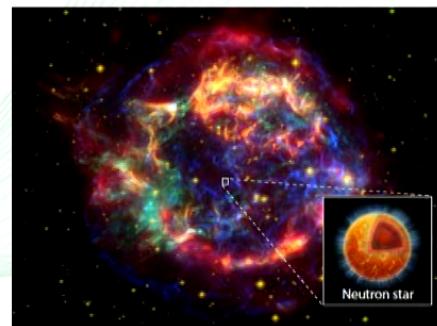
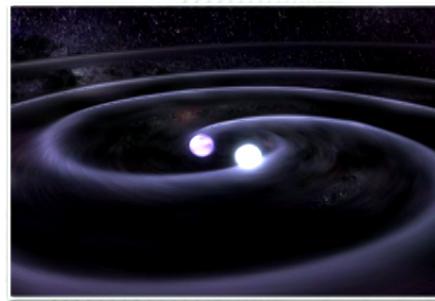
Cecilia Chirenti
UFABC - Santo André - Brazil



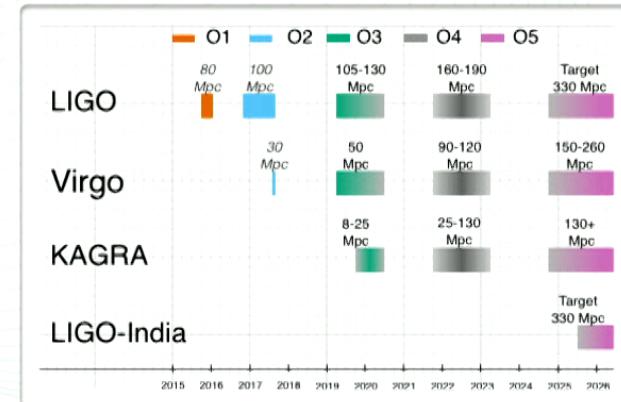
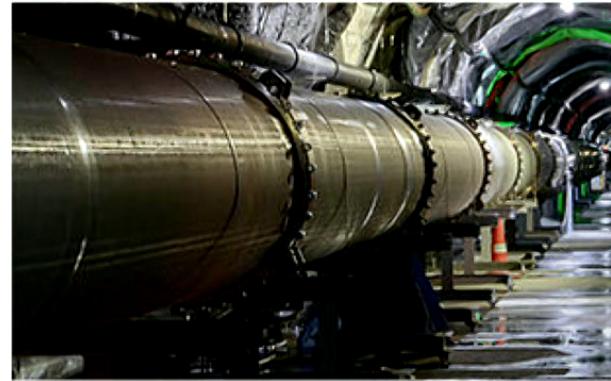
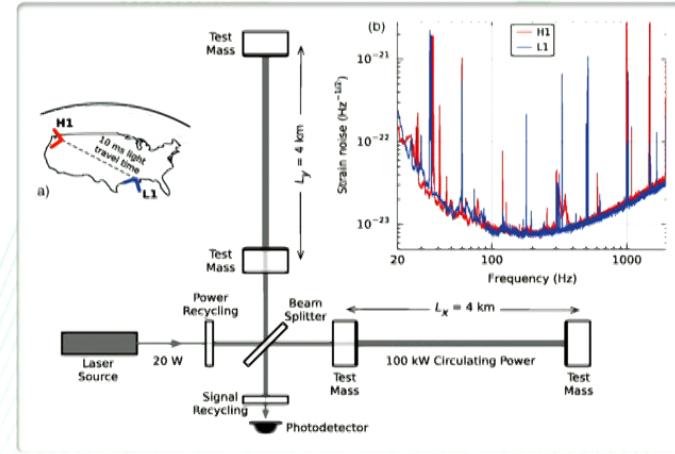
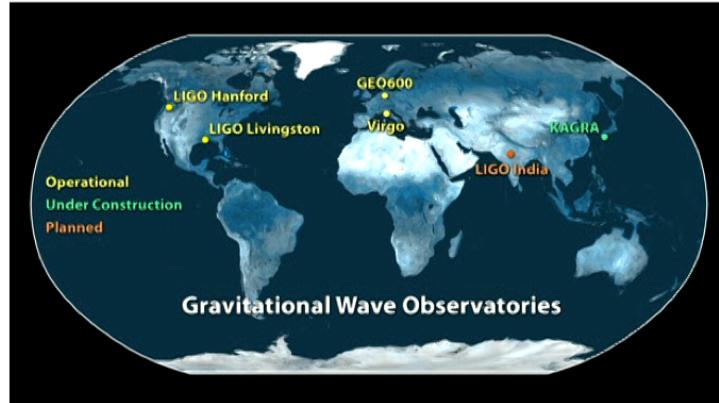
Emmy Noether Workshop, Perimeter Institute, November 18 2019

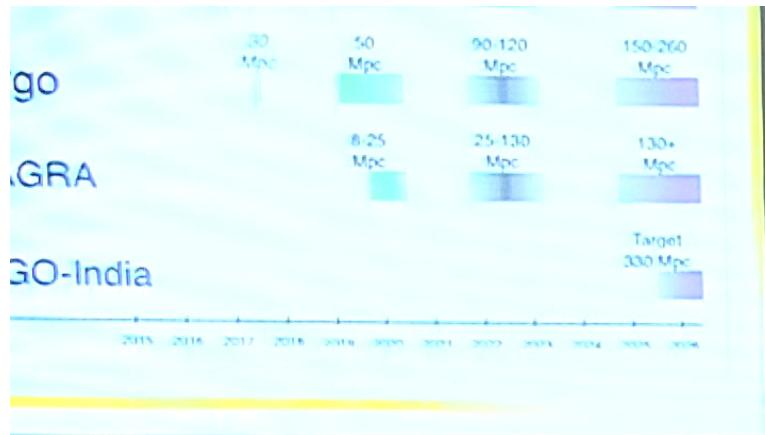
SIMONS
FOUNDATION

Possible gravitational wave sources...



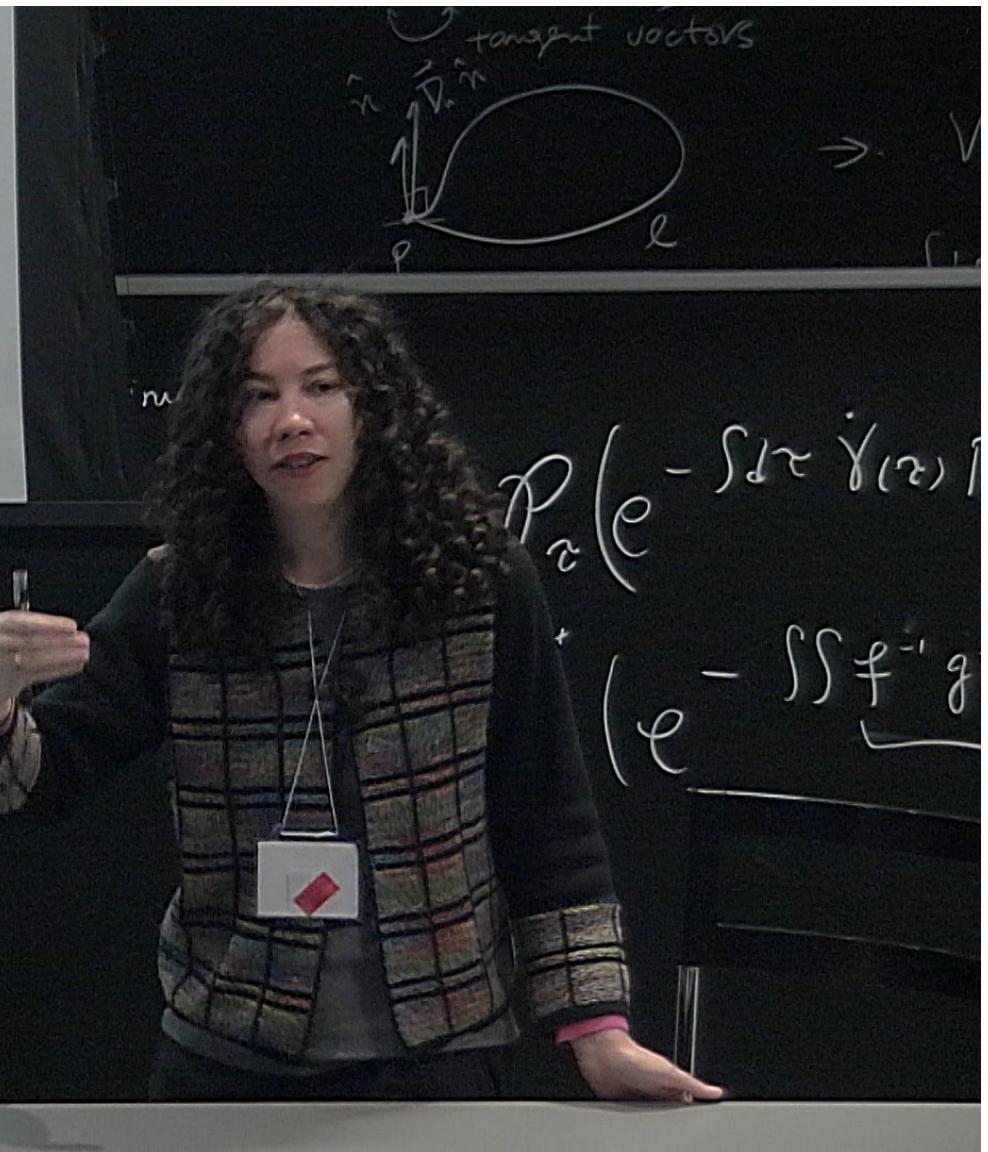
... and gravitational wave detectors



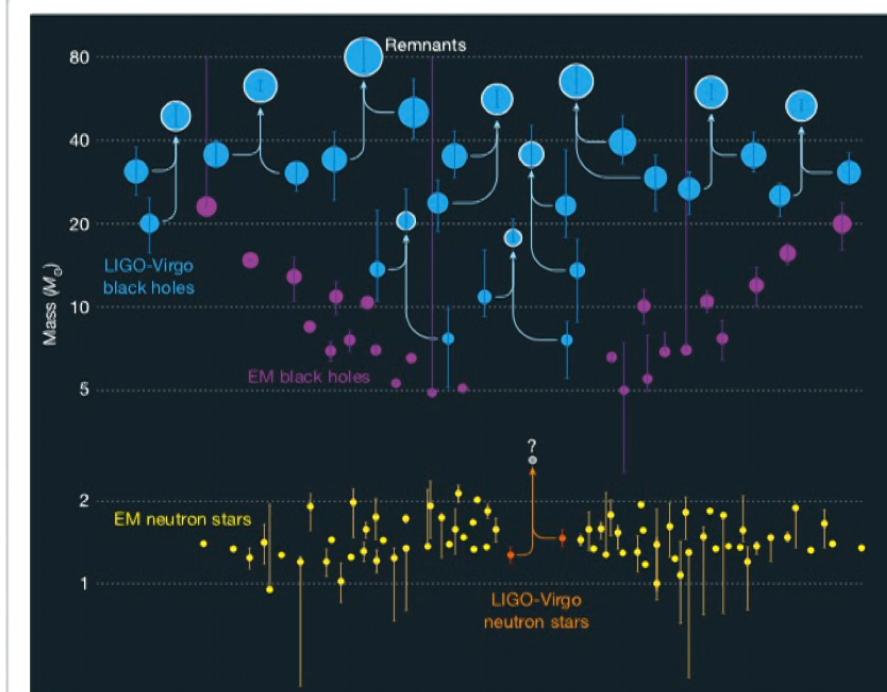


$m = 1\text{-dim.}$

\sim a totally geodesic surface



Gravitational waves from compact binary coalescences

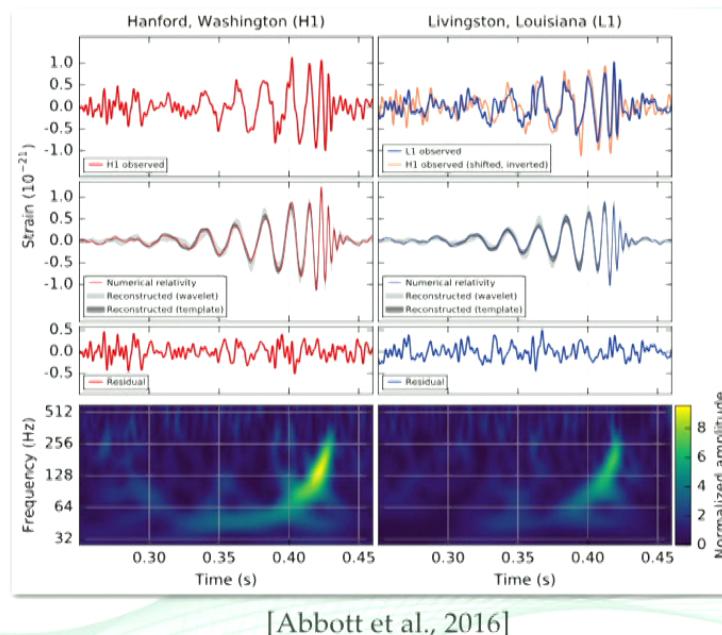


[LIGO-Virgo, Frank Elavsky, Northwestern]

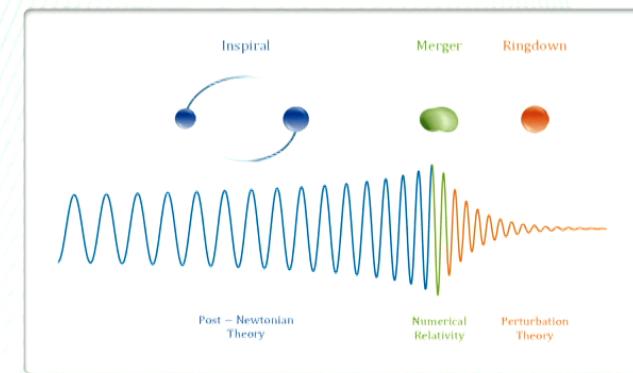


Inspiral-Merger-Ringdown

First Detection GW150914



3 stages:



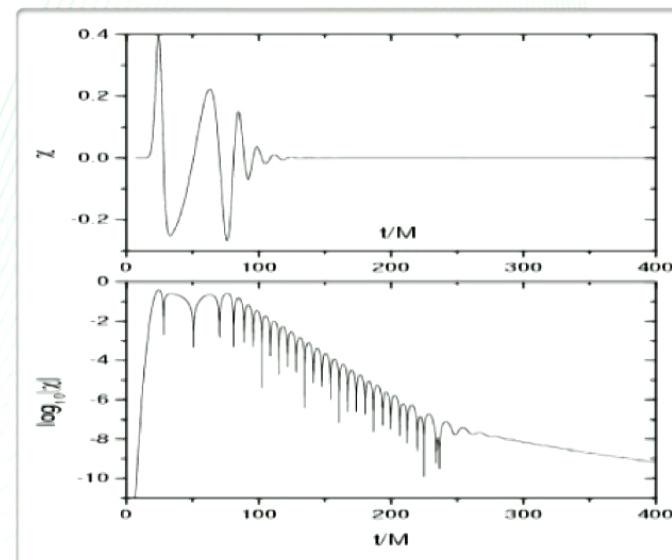
[Antelis et al. 2016]

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

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]



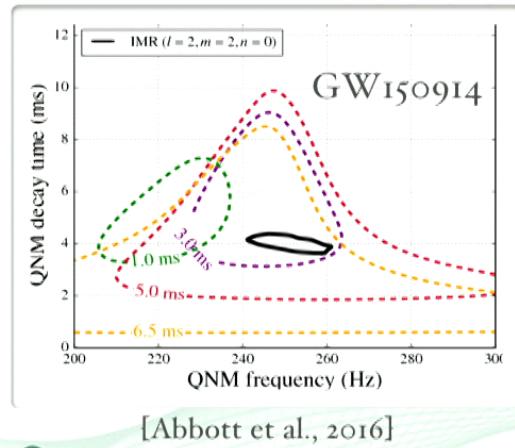
[Kokkotas and Schmidt, 1999]

Testing the no-hair theorem

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

Quasinormal mode frequencies depend **only** on M and α
(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)



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

Black hole spectroscopy

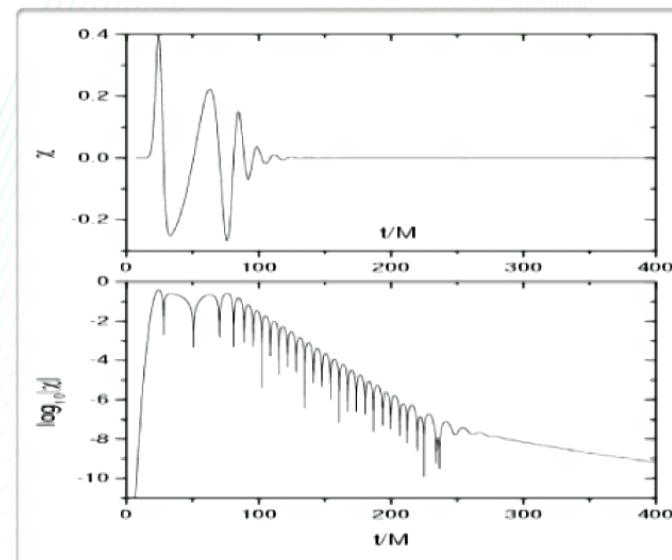
[Dreyer et al., 2004; Berti et al., 2006]



Quasinormal modes

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[Teukolsky, 1973]



[Kokkotas and Schmidt, 1999]

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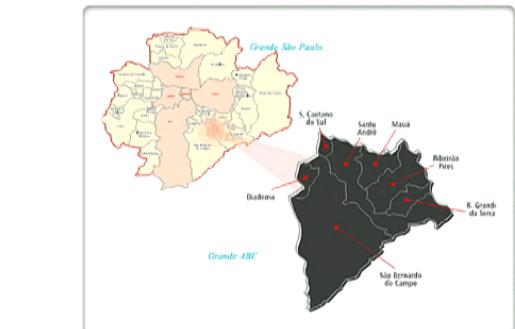
Victor Guedes



Alexssandra
Alves de Souza

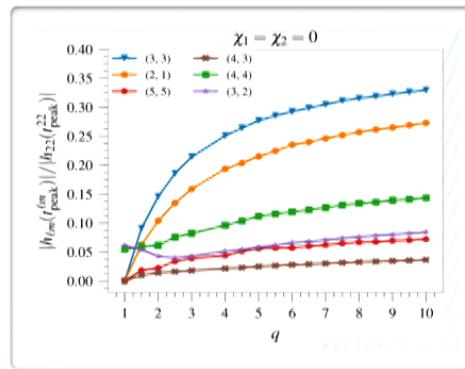


Diego Hideki

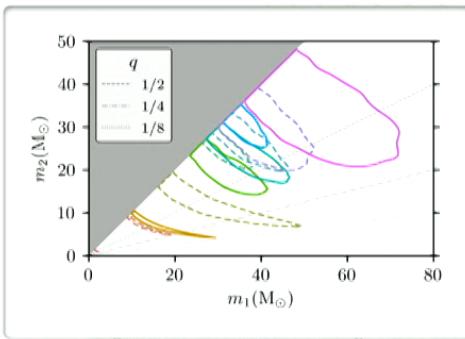


Where should we look?

Looking for
higher harmonics

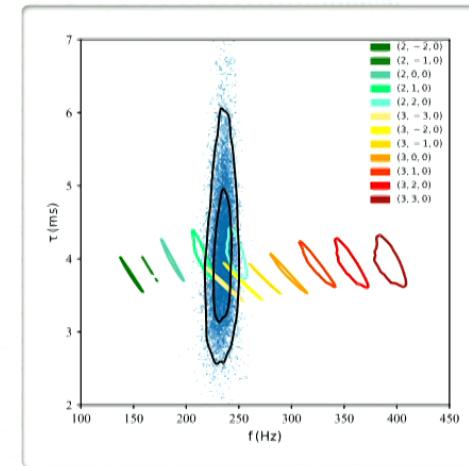


[Cotesta et al., 2018]



[Abbott et al., 2019]

higher harmonics are more relevant for **unequal** mass binaries



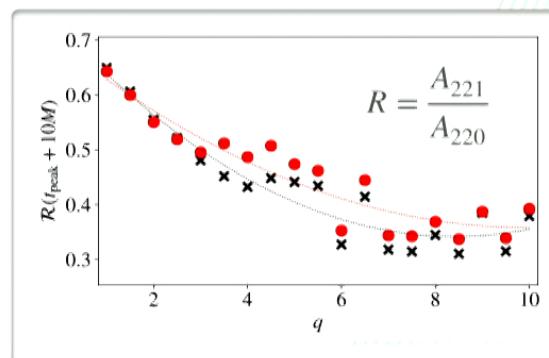
[Carullo et al., 2019]

but all detections so far
are compatible with
equal masses

and the frequencies of
different modes overlap
within the uncertainty

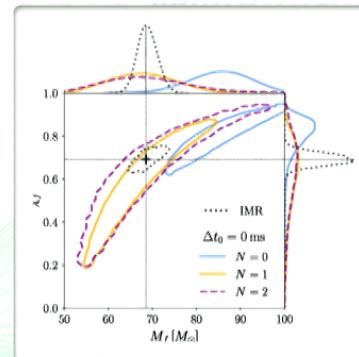
Where should we look?

Looking for
overtones



[Ota and Chirenti, 2019]

preliminary results
show evidence for the
overtone in GW150914



[Isi et al., 2019]

overtones are more
relevant for **equal** mass
binaries

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

[Bagwhat et al., 2019]

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



[EHT]

Some of our candidates...

(How should we choose a candidate?)

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



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

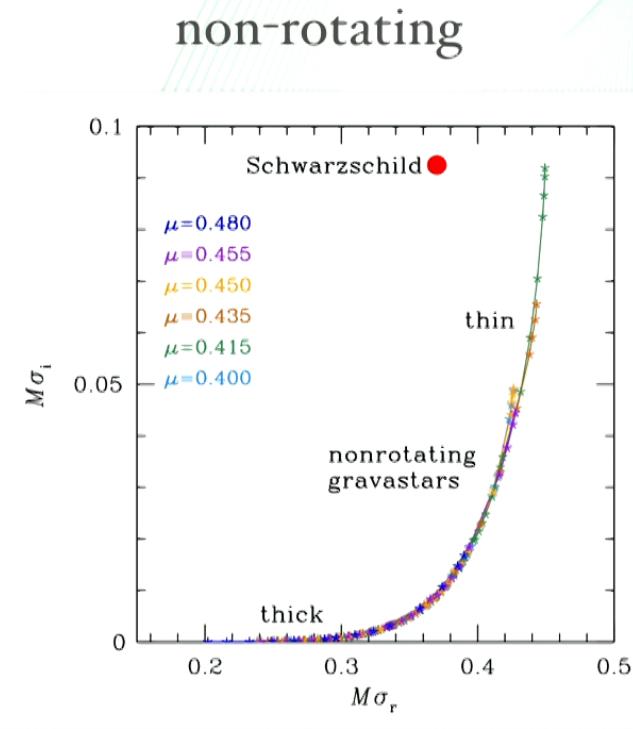
(Speculation!)



Quasinormal mode signature of a gravastar

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



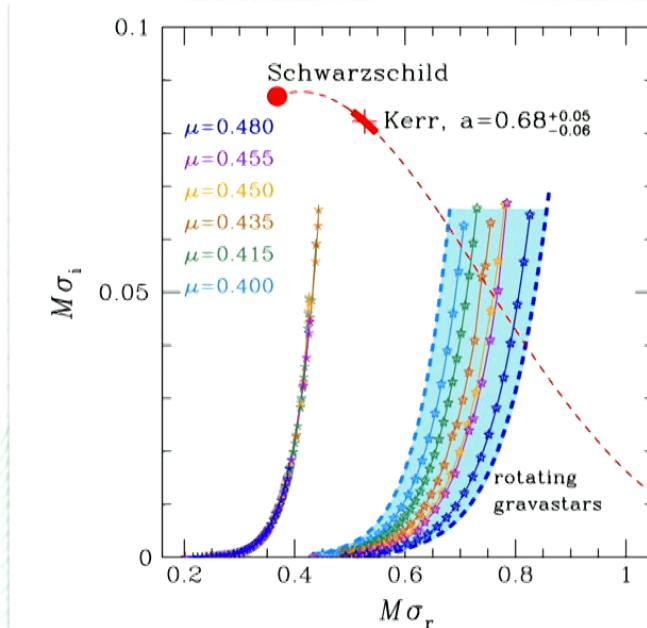
[Chirenti and Rezzolla, 2016]

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adding rotation



[Chirenti and Rezzolla, 2016]

Extending analytical solutions

1916: Schwarzschild interior solution
describes a uniform density star

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

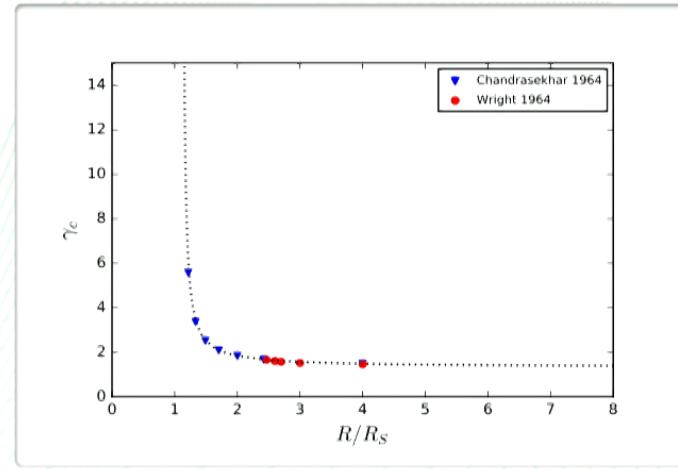
positive pressure requirement limits
maximum allowed compactness

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

[Buchdahl, 1959]

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

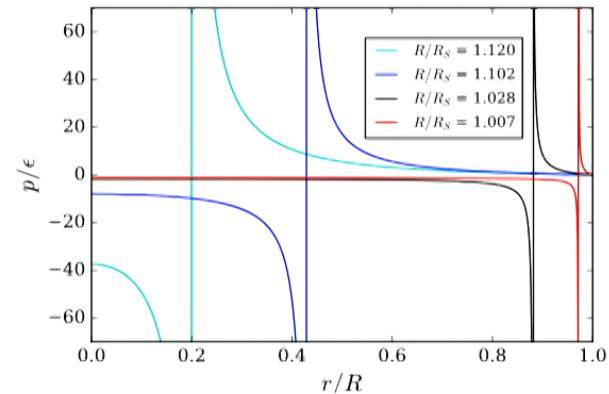
Buchdahl limit:
 $R/R_S = 9/8 = 1.125$



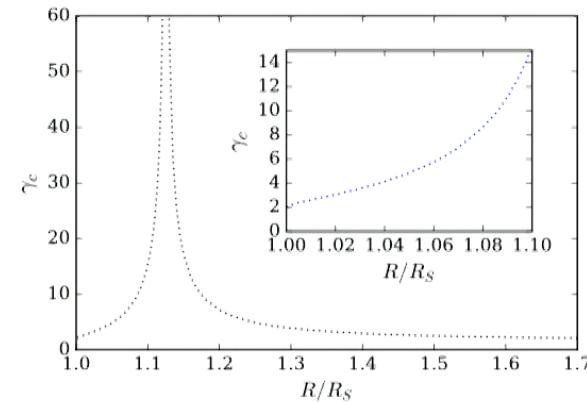
[Posada and Chirenti, 2019]

Extending analytical solutions

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



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



[Posada and Chirenti, 2019]

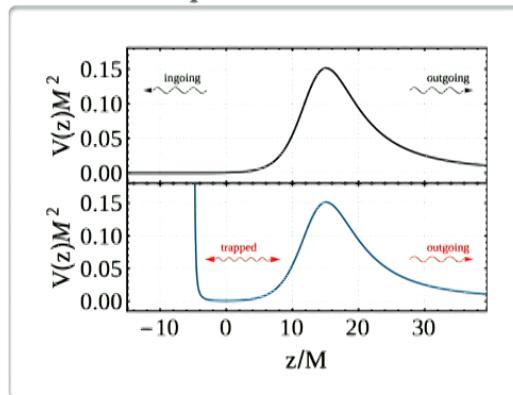
More compact solutions exist, but with negative pressure
interior: looks like a gravastar?

Stability is regained beyond the Buchdahl limit!

Modified ringdown tests

PI

model-independent formulation



[Cardoso et al. 2016]

Observational controversy:

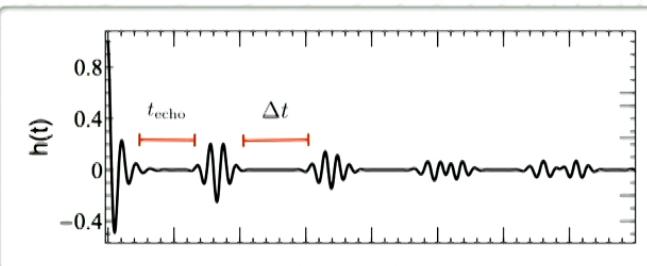
Abedi, Dykaar & Afshordi, 2017

Westerweck et al. 2018

Conklin, Holdom & Ren , 2018

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

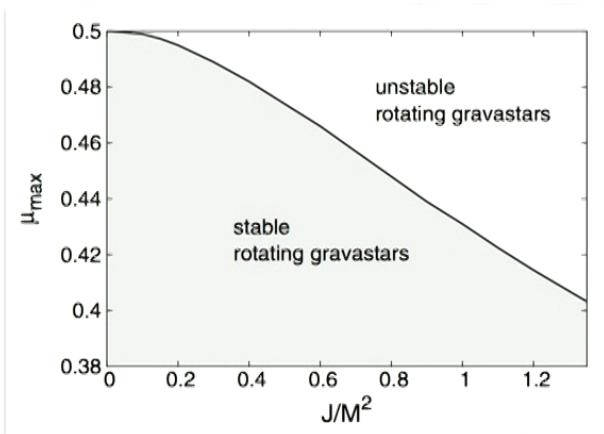
Ringdown = black hole QNMs (early)
+ trapped modes leaking out or
“echoes” (later)



[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]

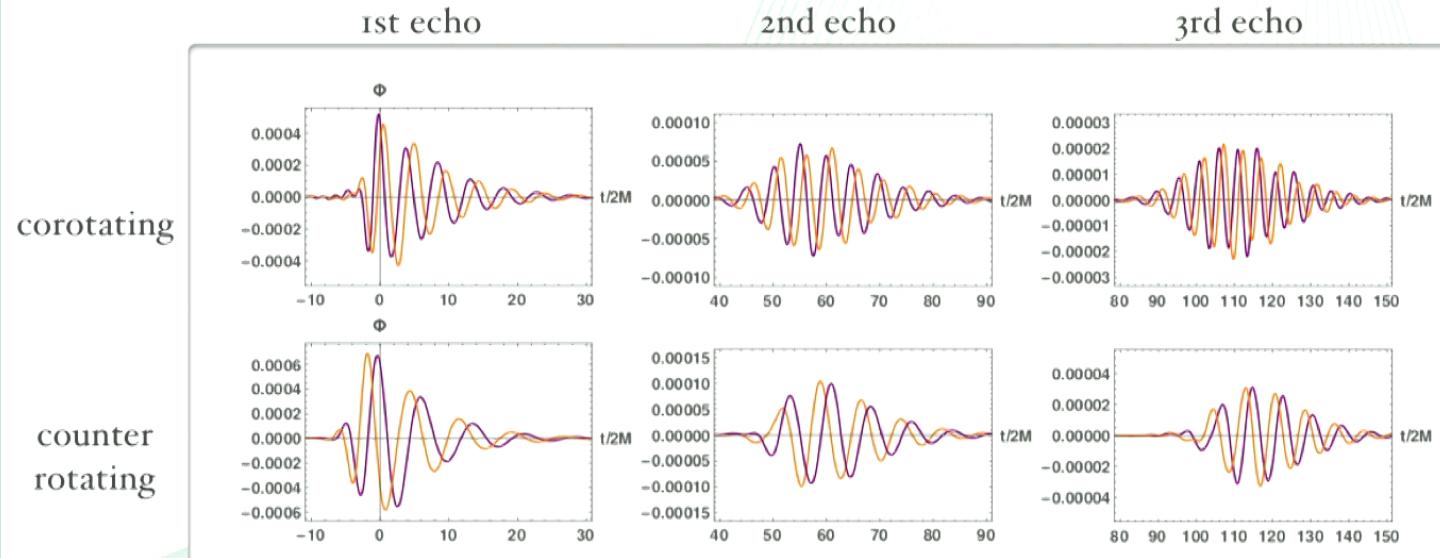
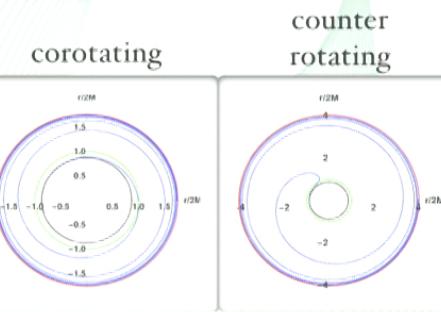
But the stability can be “quenched” by adding absorption, or reflectivity $R < 1$
[Maggio et al., 2019]

What happens with
the echoes?

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



[Micchi and Chirenti, to appear]

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)!

