Black Hole Physics

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LIGO’s historic detection

followed by 3 ½ similar BH-BH detections
and one NS-NS

Opportunities for learning about astrophysics, and fundamental cosmology through astrophysics

For instance:

New standard candles for cosmological distances

Are these black holes (part of) dark matter?

Main claim

Black holes and gravitational waves exist,
and are well described by

$$R_{\mu\nu} = 0$$

Black holes and gravitational waves exist, and are well described by

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Or else, they are supplanted by excellent impostors

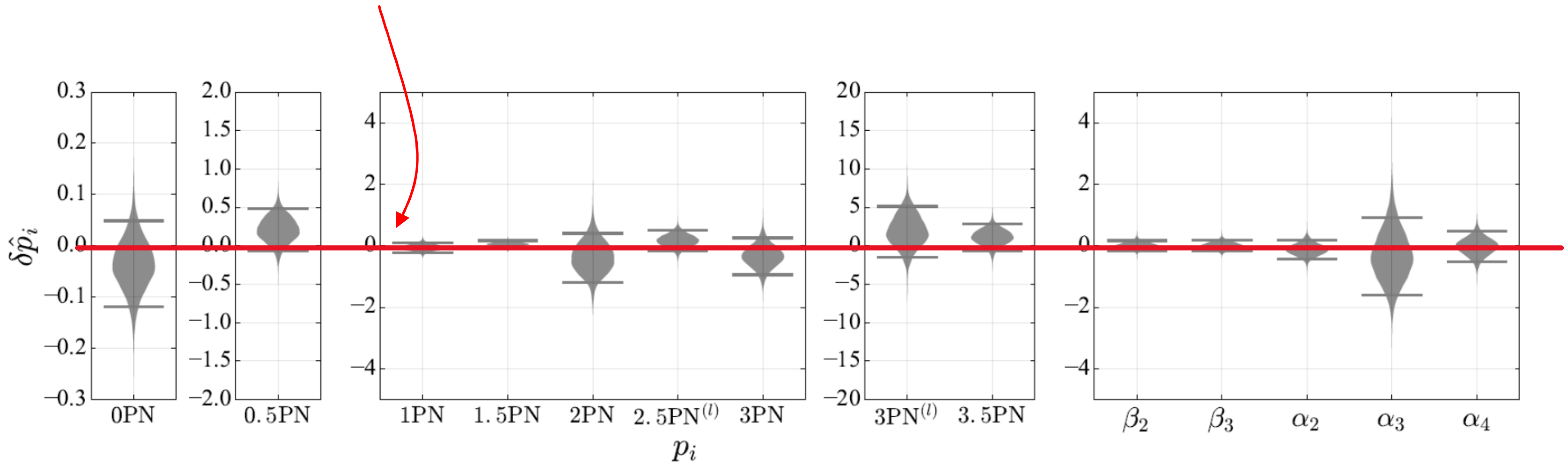
$R_{\mu\nu} = 0$ in weak field regime

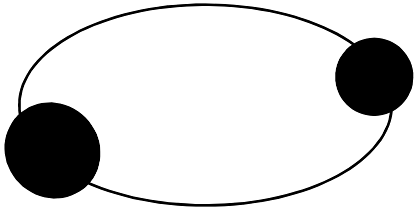
Inspiral phase

Wave propagation

Inspiral: post-Newtonian parameters

General Relativity





From GW170817 and GRB170817A

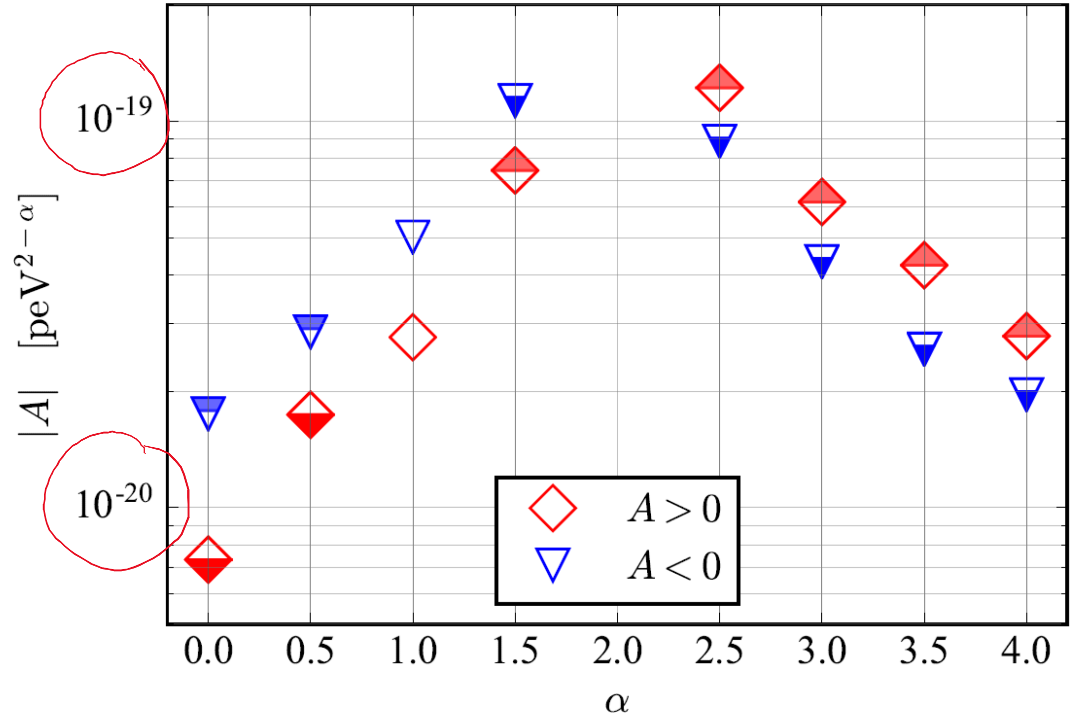
Fractional difference in propagation speed of gravitational and electromagnetic waves

$$-3 \times 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq 7 \times 10^{-16}$$

Modified dispersion relation (gravity's rainbow)

$$\frac{v_g}{c} = 1 - (\alpha - 1) A E^{\alpha - 2}/2$$

A: Energy scale



Spin-2 tensor waves

Scalar radiation component: best bounds still from binary pulsar

Three-detector observations allow to test polarization: purely tensor preferred over purely vector or purely scalar

$R_{\mu\nu} = 0$ in **strong** field regime

Is it a black hole?

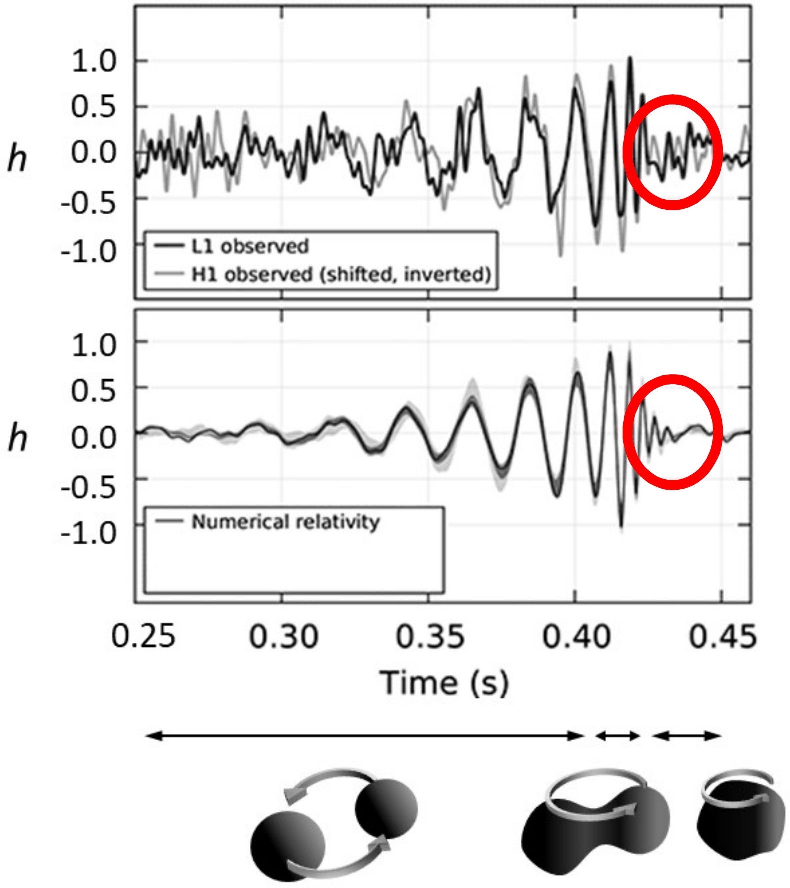
No conventional object (eg, neutron star) can contain so much mass inside so small a space

Total (chirp) mass determined by evolution of frequency vs time

Minimum size determined by maximum frequency

More detailed evidence of black hole nature

Ringdown relaxation waveform is dominated by quasinormal oscillations



These oscillations are specific properties of
the final object

So far not very precisely observed

but consistent with final Kerr black hole

rapid drop of signal → quick hair loss

But does this tell us that the object is really a black hole?

That it has a horizon?

Do we have any reason to suspect

anything different than what GR predicts

(objects with regular horizons)?

The horizon and the interior are problematic in quantum gravity

Information seems to be irreversibly lost inside the black hole – not even Hawking radiation can encode it

But Quantum Mechanical unitary evolution is reversible

Maybe there is no black hole interior

(i) The interior may *not exist independently* of the exterior

but GR still a good effective description of infalling experience

(ii) The interior, and the horizon, may *not exist at all*

infalling experience completely unlike GR

(i) is a conservative possibility
— very hard to test

(ii) is drastic (and more testable)

QM would force strong breakdown of GR
before reaching the horizon
in a region of arbitrarily small curvature

This is a desperate measure

Normally, quantum effects should be negligible at horizon scale

0.000 000 000 000 000 000 000 000 000 000 000 000 0**1**

should be balanced against

1

How could QM effects possibly prevent the formation of a horizon?

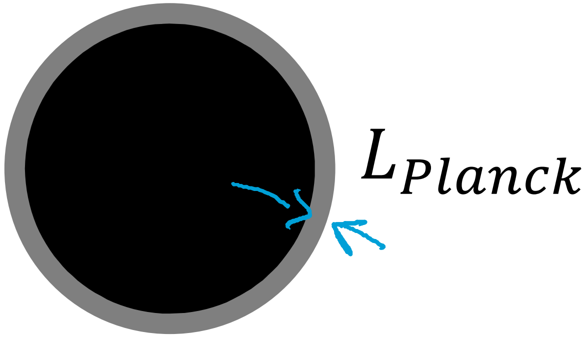
Not at all clear

Maybe collapsing matter tunnels to an enormously entropic quantum fuzzball

Mathur

Won’t worry about this here...

If the black hole is replaced by something else at a distance $\sim L_{Planck}$ above the horizon, is there any way to reveal it?



If this is Quantum gravity, can we test

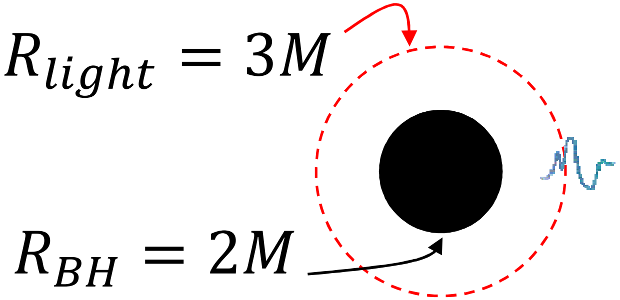
it using Classical gravitational waves?

Simplest model for info-preservation:
for quanta of Hawking wavelength $\sim GM$ the
horizon is not smooth and absorptive

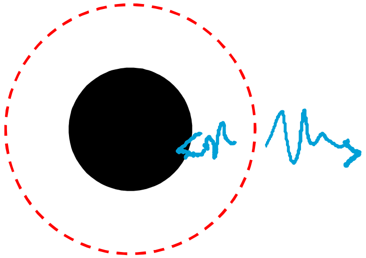
But $\sim GM$ is also the wavelength of classical
quasinormal oscillations of the black hole

Gravitational waves may reveal whether there is a perfectly absorptive horizon or not

Quasinormal mode wavefunctions are not peaked at the horizon but around the “light ring”



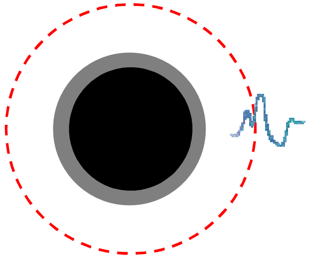
Oscillations there partly disperse towards infinity, partly towards the horizon



Use this to test (with LIGO) if gravitational waves of length $\sim GM$ perceive the horizon as a smooth place

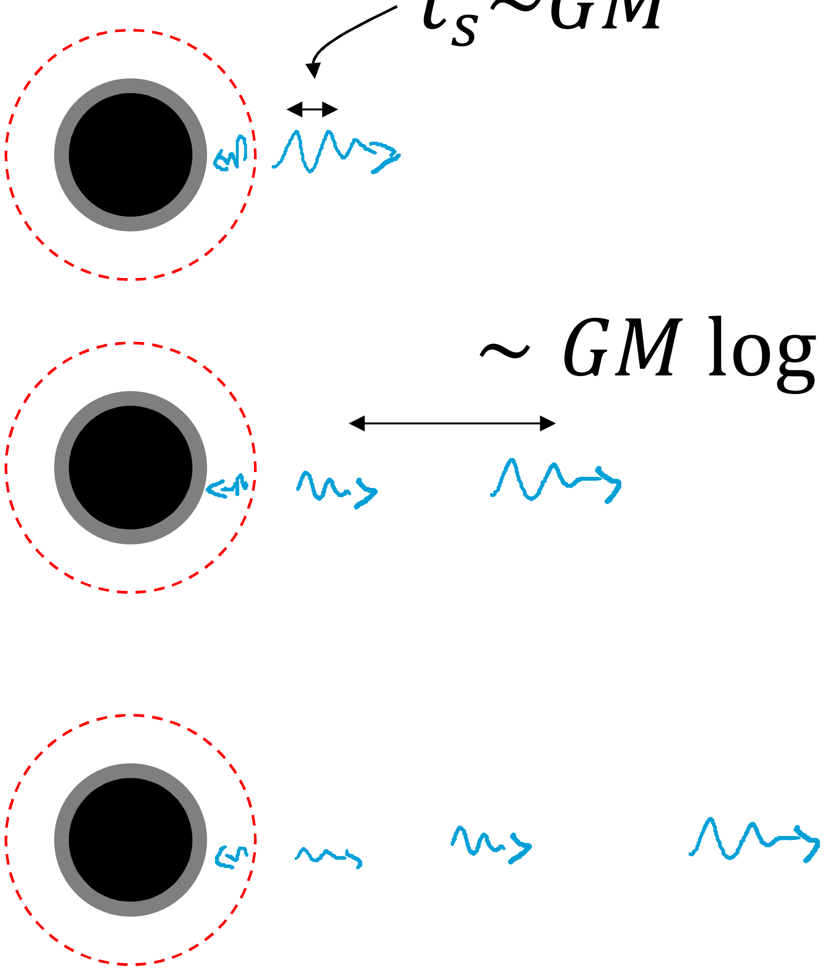
Assume a very good black hole impostor

instead of perfectly-absorbing horizon, it has a reflecting surface at a distance $\sim L_{Planck}$ above the horizon

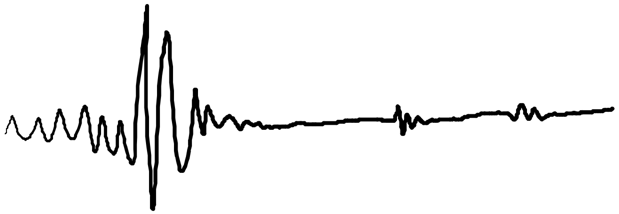


Echoes at ringdown

$t_s \sim GM$



$$\sim GM \log \frac{GM}{L_{Planck}} \sim 40\ GM$$



Presence of echoes would signal reflecting structure just above the horizon

Cardoso et al

Need very good signal-to-noise during ringdown

LIGO data not good enough yet – but will get there

Afshordi et al

Ashton et al

Some black hole impostors

Firewalls – drastic measure: declare that horizons cannot exist

Unclear what replaces the horizon

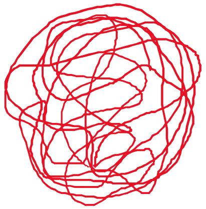
Fuzzballs – string-motivated fuzz

Worked out in varying detail in some unrealistic contexts (near-susy, near-extremal)

Hard to extract predictions for realistic black holes

Some fuzzball models seem to perfectly absorb infalling objects

quickly entangled in complicated ball of string



Firewalls —whatever they are— might act similarly

No good suggestion (so far) for uncovering these impostors

Boson stars, gravastars, traversable wormholes

Poor fundamental motivation

To varying degree: unknown how they form, what their full dynamics is, even if they're stable

Big issue: these models come with a scale

It's extremely hard that they be impostors of black holes ***of all sizes*** – from stellar mass to supermassive black holes

No need to be wedded to any specific proposal for a bh impostor

Just look for breakdowns of GR paradigm near the horizon

Parametrize boundary conditions at L_{Planck} above horizon, for dominant quasinormal modes

Work out echo signal *as function of parameters*

Check against data

Outlook is good!

Looking for echoes is easy and cheap

Data will be aplenty

No need to build any new expensive instrument

Super-horizon structure is a **crazy** idea

(an unlikely one, IMHO)

but **not** necessarily **silly** – as long as you're aware of how radical it is

and it is one testable idea, seriously proposed in quantum gravity

Seeking other new fundamental physics, using GWs in binary collisions

Plenty of ideas for testing a slew of “modified gravities” and ultra-light scalar fields

They can modify the GW signal at different stages of collision

Merger is hardest – need to do full numerics

Fundamental physics motivation for these ideas is poor

But –again— there'll be *observational* data to test them

No need to design any new instrument

Concluding remarks

The GR paradigm (including its black holes)
works *very well* for all GW events so far

There’s no compelling alternative

There are a few crazy ideas,

and many not-so-well-motivated proposals

(and several silly ideas)

For the theorist the quandary is between

the effort of developing and extracting predictions of *ill-motivated* and/or *highly unlikely* ideas

vs

the reward of a positive detection that (if clear) would be *revolutionary*

Data will be pouring out of LIGO *et al*!