Exotic Compact Objects with Soft Hair

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Black Holes and Neutron Stars in Modified Gravity - Meudon

18 November 2019

erc funded by the European Research Council
ADG GravBHs-692951

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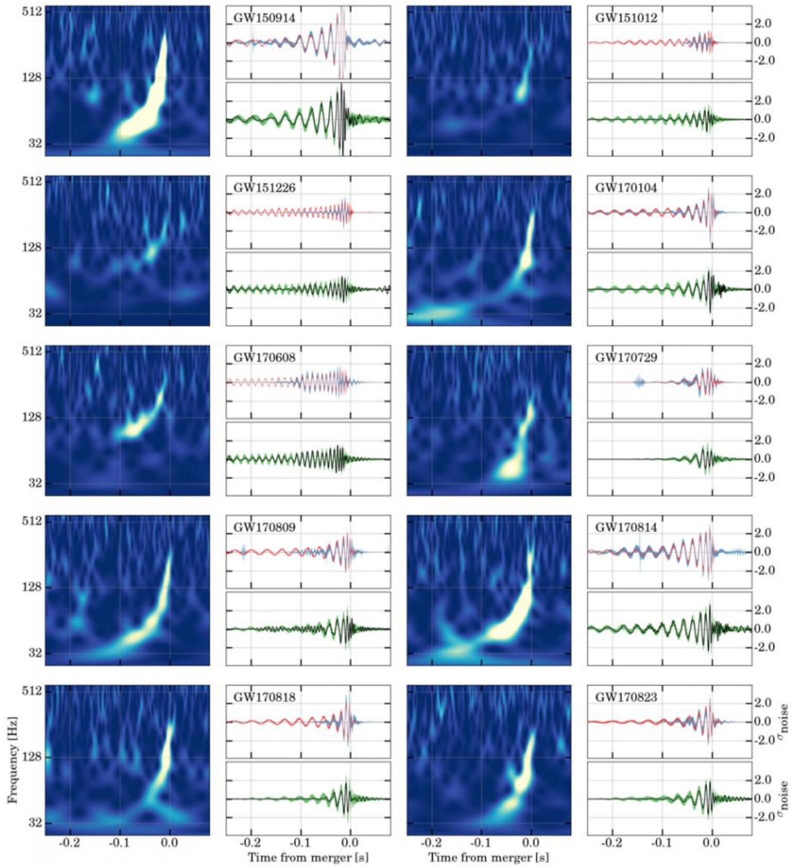
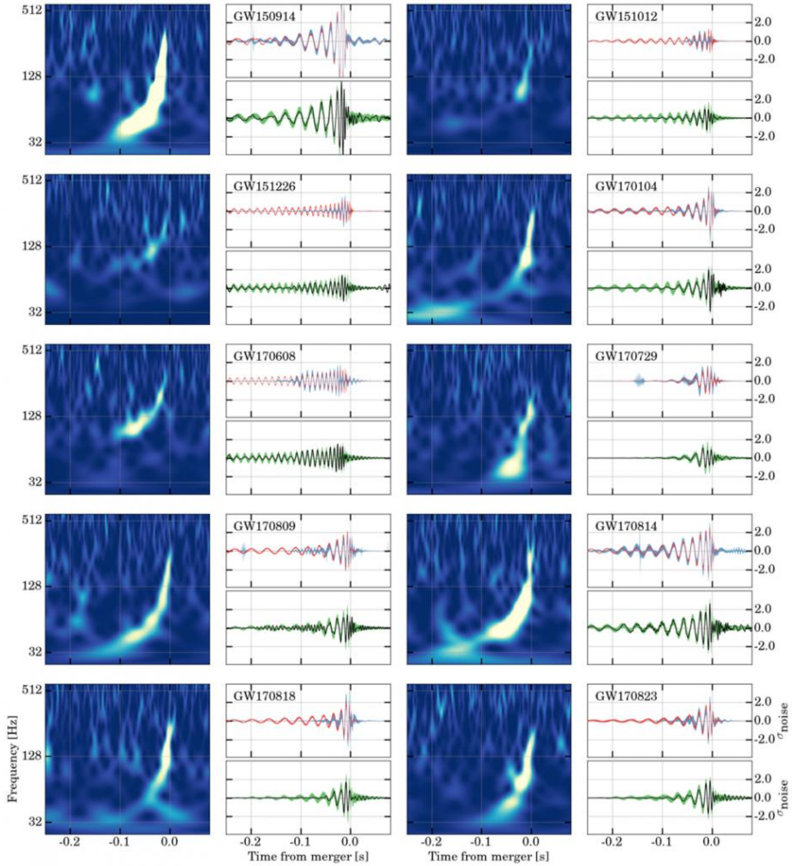
Phys.Rev. D99 (2019) 10, 104050
arXiv:1812.07615

**not EPR but RPE*


GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
Frequency [Hz]
Time from merger [s]
σ_{noise}

O1-O2

BH-BH



O1-O2

Are they really black holes?
Or very good impostors?

Impostors (aka mimickers) must be extremely compact

Exist over a wide mass range?
Stellar only?
All stellar range, or only low?
Supermassive too?

Black holes are scale-free
Very difficult to have scale-free material objects

Impostors may replace BHs entirely, or be a preferred alternative in certain phenomena/mass ranges

Horizonless impostors may play a role in BH info problem

(eg fuzzballs)

Impostors require drastically new physics

Exotic Compact Objects
ECOs

They may be unlikely, but

- foil to test BH paradigm
- discovery would be a bombshell

ECOs vs BHs

BHs

Extreme simplicity

Uniqueness

Their physics is determined by just two numbers

M, J

Kerr multipoles

Geroch, Hansen

mass: $\mathcal{M}_\ell$ current: $\mathcal{S}_\ell$

$$\mathcal{M}_0 = M \qquad \mathcal{S}_1 = J$$

$$\mathcal{M}_\ell^{BH} + i\mathcal{S}_\ell^{BH} = M^{\ell+1}\left(i\frac{J}{M^2}\right)^\ell$$

dimensionless

$$\bar{\mathcal{M}}_\ell^{BH} + i\bar{\mathcal{S}}_\ell^{BH} = \left(i\frac{J}{M^2}\right)^\ell$$

eg

$$\bar{\mathcal{M}}_2^{BH} = -\left(\frac{J}{M^2}\right)^2$$: mass quadrupole

$$\bar{\mathcal{S}}_3^{BH} = -\left(\frac{J}{M^2}\right)^3$$: current octupole

$$\mathcal{M}_\ell^{BH} + i\mathcal{S}_\ell^{BH} = M^{\ell+1}\left(i\frac{J}{M^2}\right)^\ell$$

Any independent measure of **three** multipoles is a null test of Kerr

eg M, J and quadrupole $\mathcal{M}_2$

Quasinormal ringdown

Two qnm's

Tidal deformation

Zero for Schwarzschild/slow Kerr

Non-tidal multipoles?

ECOs

Huge model dependence

Stationary compact objects:

multipoles depend on specific physics model

Can we find a general parametrization?

What kind of physics

—eg new scales of physics—

is involved if a non-Kerr multipole is measured?

ECOs in **Unmodifed gravity**

A general, ECO-model-independent analysis

Agnostic about what goes on below the ECO surface

Assume vacuum GR rules the exterior of the ECO

Unmodified gravity

Exotism is *all in the matter*, none in the gravity

Vacuum GR rules exterior

$\Rightarrow$ matter-model-independent characterization of deviations from Kerr

Different ECO models ⇒ different boundary conditions at the surface of the ECO

Different boundary conds ⇔ multipoles

$$\mathcal{M}_\ell^{\rm ECO} = \mathcal{M}_\ell^{\rm BH} + \delta\mathcal{M}_\ell \,,$$
$$\mathcal{S}_\ell^{\rm ECO} = \mathcal{S}_\ell^{\rm BH} + \delta\mathcal{S}_\ell \,,$$

Soft ECOs

Curvature at the surface is comparable to curvature of black hole

Smooth limit to black hole

No scale of new physics is distinguishable from exterior

Hard ECOs

Curvature at the surface is much larger than curvature of black hole

Singular limit to black hole

Imply new scale of physics

High-energy effects drastically modify near-surface geometry

Note:

Softness of ECO refers to soft scales noticeable from the exterior

Interior physics may still require very high energy physics (eg large pressures) in order to support object near the BH limit

This talk

Soft ECOs

Perturbative analysis of Schwarzschild solution

(slow rotation)

Stationary, axisymmetric

No equatorial symmetry assumed

Perturbations of Schwarzschild in vacuum GR $R_{\mu\nu} = 0$

Multipolar decomposition

Boundary conditions

Asymp flatness

+

ECO surface: ECOphysics

ECOphysics

Boundary conds specified for each $\ell \geq 2$ by

$\mathcal{M}_\ell$ and $\mathcal{S}_\ell$

General & physical parametrization of soft hair
(after hair conditioning)

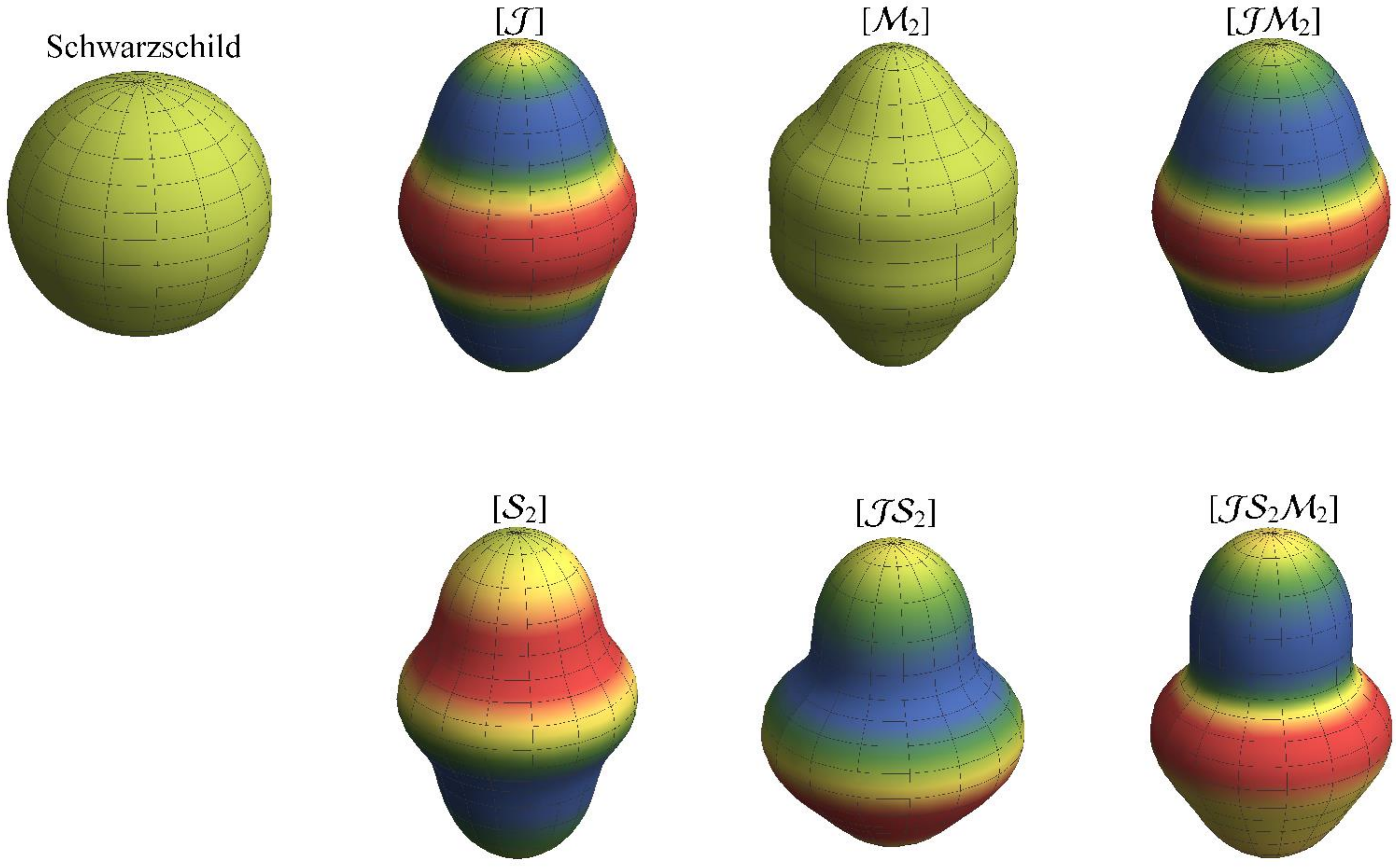
Multipoles couple at higher perturbation orders

Simplest are sourced by lowest multipoles

Spin-induced

Mass-quadrupole-induced

We've generated a variety of them



color: $g_{t\varphi}$

Hair conditioner for ECOs

Softness of black hole limit

How large can soft hair be?

Depends on compactness and multipole type

Compactness

$$\delta = \frac{r_0}{2M} - 1$$

r_0= circumferential radius (axial symmetry)

Bounds on multipoles from soft curvature

Induce a mass quadrupole $\bar{\mathcal{M}}_2$ from spin

Kretschmann $$\mathcal{K} \sim \frac{1}{M^4}\left(\bar{\mathcal{M}}_2 - \bar{\mathcal{M}}_2^{BH}\right)\log\delta$$

Hair conditioning

$$\Rightarrow \bar{\mathcal{M}}_2 - \bar{\mathcal{M}}_2^{BH} \sim \frac{1}{\log\delta}$$

Bounds on multipoles from soft curvature

Non-spin-induced $\bar{S}_2$

$$\mathcal{K} \sim \frac{1}{M^4}\left(\frac{\bar{S}_2}{\delta}\right)^2$$

Hair conditioning

$$\Rightarrow \; \bar{S}_2 \sim \delta$$

Requiring regular BH limit (soft hair) implies

Non-spin-induced moments
are $\propto \delta$

Spin-induced moments
are larger $\propto \frac{1}{\log \delta}$

“Soft-hair theorem” for ECOs

The closer a soft ECO is to a black hole,
the less hairy it must be,
with

$$\delta\mathcal{M}_\ell \to a_\ell \frac{\chi^\ell}{\log\delta}\mathcal{M}^{\ell+1}\,, \quad \delta\mathcal{S}_\ell \to c_\ell \frac{\chi^\ell}{\log\delta}\mathcal{M}^{\ell+1}$$

spin-induced

$$\delta\mathcal{M}_\ell \to b_\ell \mathcal{M}^{\ell+1}\delta\,, \quad \delta\mathcal{S}_\ell \to d_\ell \mathcal{M}^{\ell+1}\delta$$

non-spin-induced

Constraining soft ECOs with observations?

(preliminary)

Spin-induced moments can be larger for given compactness

$\Rightarrow$ easier to constrain

EMRIs in LISA can constrain

$$\frac{\delta \mathcal{M}_2}{M^3} < 10^{-4}$$

for central supermassive object

Applied to soft ECOs:

$$\frac{\delta\mathcal{M}_2}{\mathcal{M}^3} \sim \begin{cases} |\log\delta|^{-1} \sim 10^{-2}\left|\log\left(\frac{10^6 M_\odot}{\ell_P}\right)\right|^{-1} \\ \delta^{-1} \sim 10^{-4}\left(\frac{L}{10^6 M_\odot}\right) \end{cases}$$

$\Rightarrow$ spin-induced multipolar deviations from Kerr can be constrained for objects with Planck-scale non-compactness

Caveats

Vacuum GR exterior

but valid if fall-off is fast

Caveats

Perturbatively small multipoles

Not always valid: eg spin of boson star is quantized

Compactness not connected to BH limit

Caveats

Stability?

Depends on internal composition of object

(or boundary conditions for time-dependent perturbations)

Must be assessed case-by-case

Hard ECOs?

Stationary axisymmetric sector of vacuum GR is integrable

Exact solutions can be systematically constructed

Hard ECOs?

Hard ECOs can be readily studied with low multipoles

No smooth limit to BH

Hard ECOs?

May characterize hard scale vs compactness

Hard-hair theorem?

Thank you