Title: Probing (beyond) general relativity with compact binaries and gravitational waves

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Abstract: General relativity enjoys phenomenal success in agreeing with experiments and observations, but it must break down at some point. Astrophysics can give guidance for what type of theory may correct general relativity, if we know which phenomenology to look for. I will discuss the possible corrections to the structure of compact objects, the binary problem, and observations with pulsar timing and gravitational wave detection. These corrections are computed in specific effective theories, such as Einstein-dilaton-Gauss-Bonnet (EdGB) and dynamical Chern-Simons (dCS) gravity, and we may further generalize the common aspects of these theories to build a parametrized framework which captures a large number of effective field theories.

Probing (beyond) general relativity with compact binaries and gravitational waves

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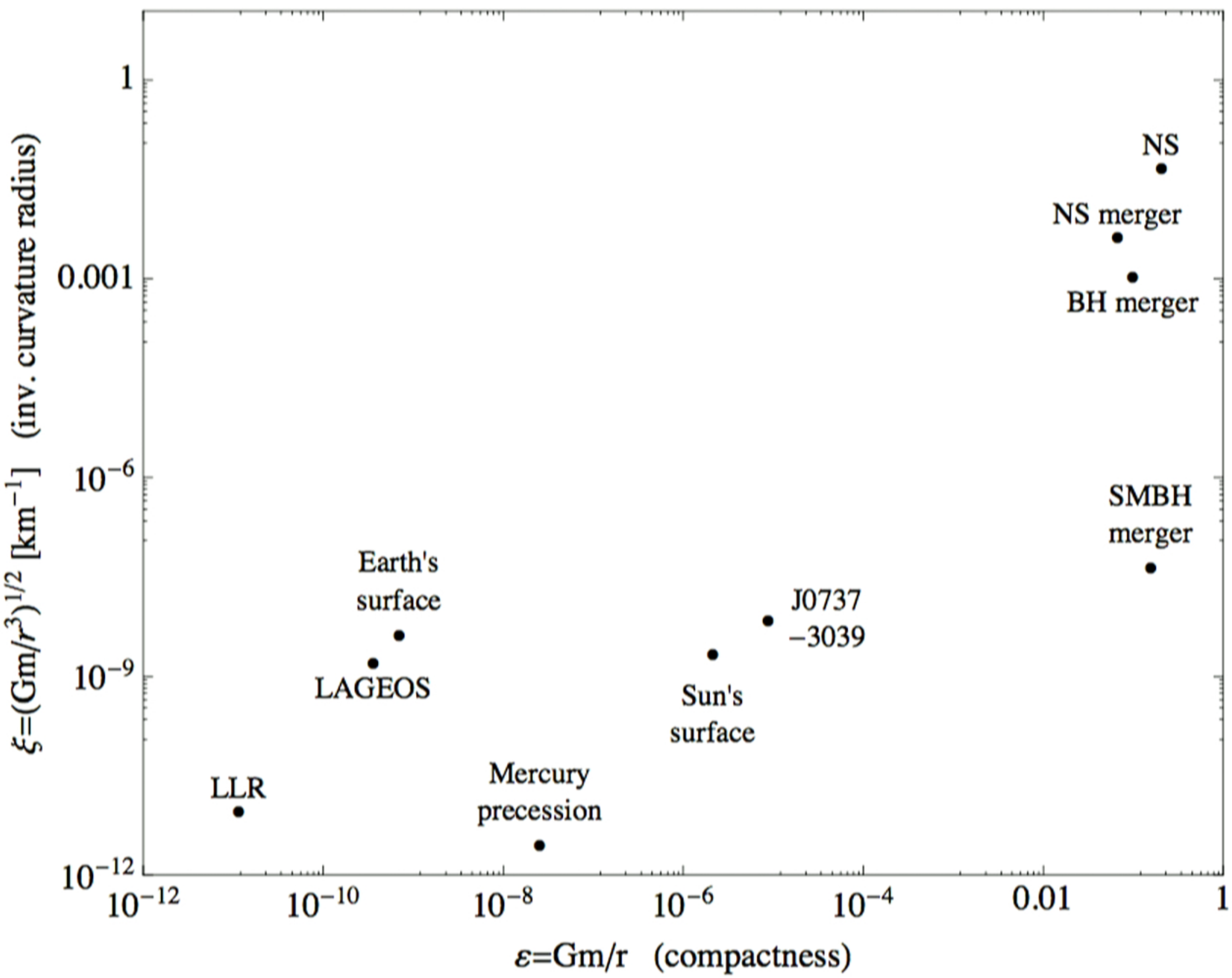
2 Oct. 2014 @ Perimeter

Motivation

1. GR successful but incomplete
   - GR+QM=new physics (e.g. BH thermo)
   - Planck scale phenomena? Other scales?
   - Expect GR is low-energy EFT
2. Ask nature
   - So far, only weak-field tests
   - Lots of theories $\approx$ GR
   - Need to explore strong-field
     - • Strong curvature • non-linear • dynamical



$\xi=(Gm/r^3)^{1/2}$ [km^{-1}] (inv. curvature radius)
1
0.001
10^{-6}
10^{-9}
10^{-12}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
0.01
1
ε=Gm/r (compactness)
NS
NS merger
BH merger
SMBH merger
Earth's surface
LAGEOS
J0737 −3039
Sun's surface
LLR
Mercury precession

The strong field

- "Potential" (Gm/r): Highly compact
- Curvature (Gm/r^3): Short length $\Longrightarrow$ low mass
- Dynamics $(\partial_t \sim \partial_x)$: High velocity

- Known pulsar binaries $v \sim 10^{-4}$
- Compact binary merger $v \sim 0.1$

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What phenomena come from UV completions?

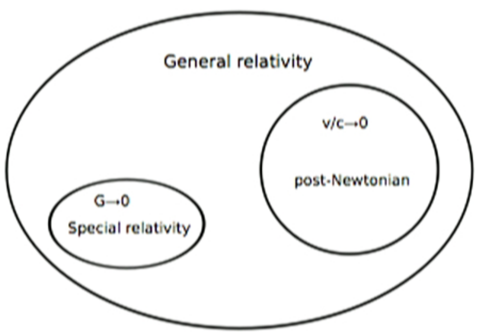
Theories

Fundamental approach:

- String theory • Loop quantum gravity
- TeVeS • Einstein-Æther • Hǒrava
- Massive gravity • dRGT • bi-metric
- ...

Pedestrian approach: effective field theory

- Learned from cond-mat, then nuclear and hep-th
- Theory with separation of scales
- "Integrate out," effective theory for long (or short) wavelengths
- Works backwards!



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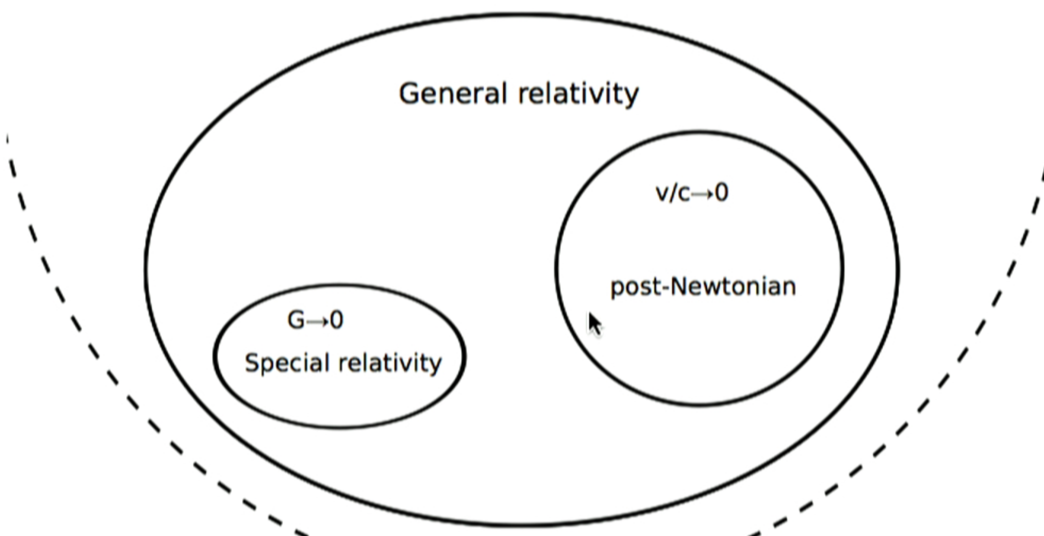


EFT works

Works for describing superconductivity, predicting W, higgs, etc.

Try to build EFT for gravity

- Metric, general covariance, Lorentz invariance
- Lowest order dynamical theory is Λ+GR!

Beyond GR: add new ℓ—want to constrain this

EFT approach

Systematize procedure for exploring low-E model space. Choose:

- Field content
  - Additional degrees of freedom (scalar, vector, etc.)
  - Many theories have a new scalar
    - Inflaton, $f(R)$, ST dilaton, quintessence, extra dims, massive gravity?
- Symmetries of theory (e.g. shift symmetry)
- Cutoff scale (related to ℓ)
- Operator/derivative order truncation
- Write down all terms and calculate

Plethora of theories

- Operators: $\Lambda,\ R,\ R_{ab}R^{ab},\dots$
- Λ+GR: $S_{\rm GR} = \int \Lambda + \frac{1}{2}m_{\rm pl}^2 R$
- Scalar kinetic term: $S_k = \int -\frac{1}{2}(\partial\theta)^2$
- Scalar-tensor: $\int c_1\ \theta R$
- EDGB: $\int c_2\ \theta(R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd})$
- dCS: $\int c_3\ \theta\ {}^*R_{abcd}R^{abcd}$

1. Specific theories

Past few years

Program to study *specific* EFTs: EDGB and dCS

- EDGB: $\mathcal{L} \sim m_{\rm pl} \ell^2 \theta (R^2 - 4 R_{ab} R^{ab} + R_{abcd} R^{abcd})$
- dCS: $\mathcal{L} \sim m_{\rm pl} \ell^2 \theta \; {}^*R_{abcd} R^{abcd}$

Studies:

- GW energy (PRD 83, 064038)
- BH structure (PRD 79, 084043; PRD 83, 104002; PRD 90, 044061)
- (Quasicircular BH) Binary inspirals (PRD 85, 064022)
- GWs from “” (PRL 109, 251105)
- NS structure, (eccentric) binary inspirals, GWs (PRD 87, 084058)

Modified field equations

$$S = S_{\rm GR} + \int -\frac{1}{2}(\partial\theta)^2 + c_3\, m_{\rm pl}\ell^2\, \theta\, {}^*R_{abcd}R^{abcd}$$

- Scalar sourced by curvature:

$$\Box\theta = c_3 m_{\rm pl}\ell^{2*}R_{abcd}R^{abcd}$$

- Correction to Einstein field equations

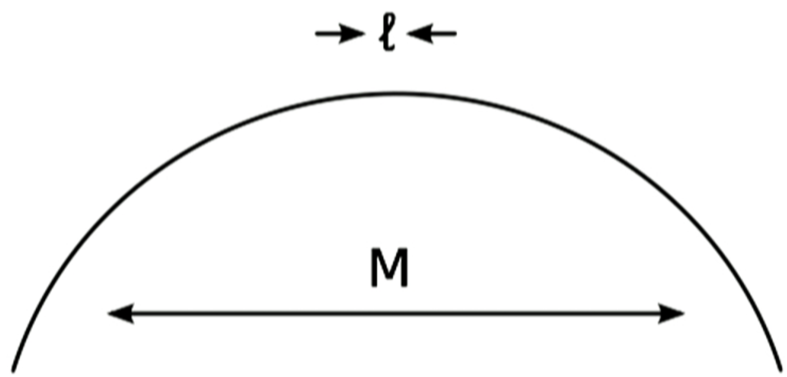
$$G_{ab} + \underbrace{C_{ab}}_{\propto\ell^2} = 8\pi G(T^{(\rm m)}_{ab} + T^{(\theta)}_{ab})$$

- May not make sense as exact theory, use decoupling limit

How to calculate

Rely on separation of scales:

$$\ell \ll L$$

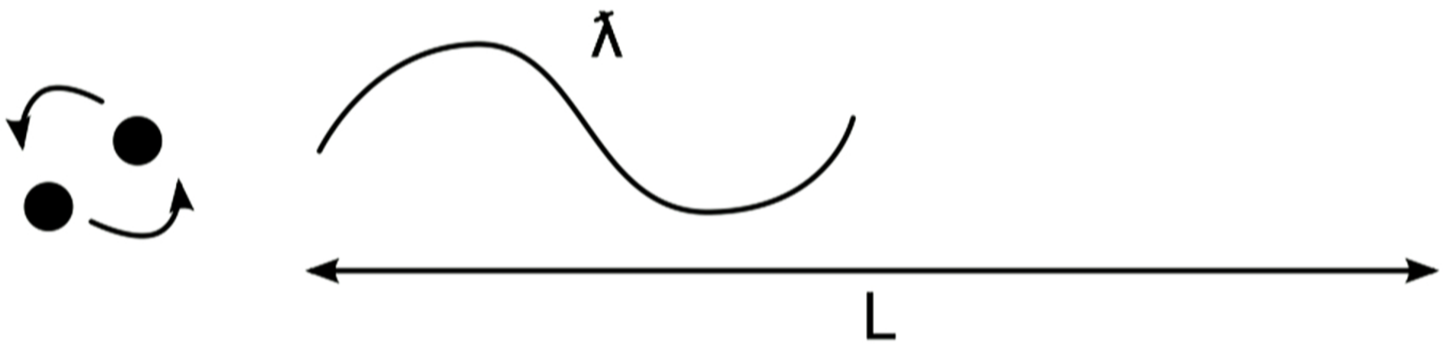


Do 1^{st}, 2^{nd} order perturbation theory in ℓ/L. Calculate everything

How to calculate

Rely on separation of scales:

$$\ell \ll L$$



Do 1^{st}, 2^{nd} order perturbation theory in ℓ/L. Calculate everything

Summary of phenomena

Isolated bodies

- Scalar hair
- Shift in $\omega(r)$, ISCO, EH
- M–R relation

Binaries

- Scalar interaction changes orbit
- Pericenter precession
- Scalar radiation
- Orbital decay

Gravitational waves

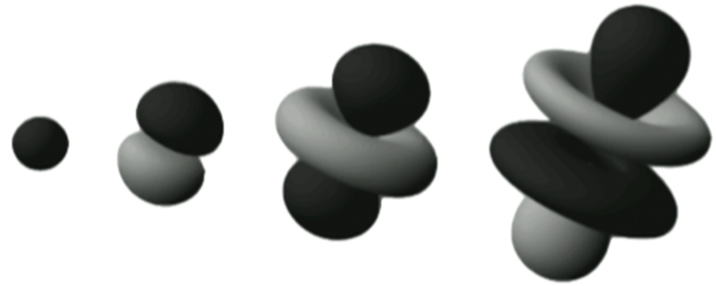
- Modified propagation
- New modes available
- Energy content
- Correction to waveforms

Scalar hair

- Scalar sourced by gravity, e.g.

$$\Box\theta \propto \ell^2 {}^*R_{abcd}R^{abcd}$$

- Compact objects acquire long-ranged scalar multipolar "hair"



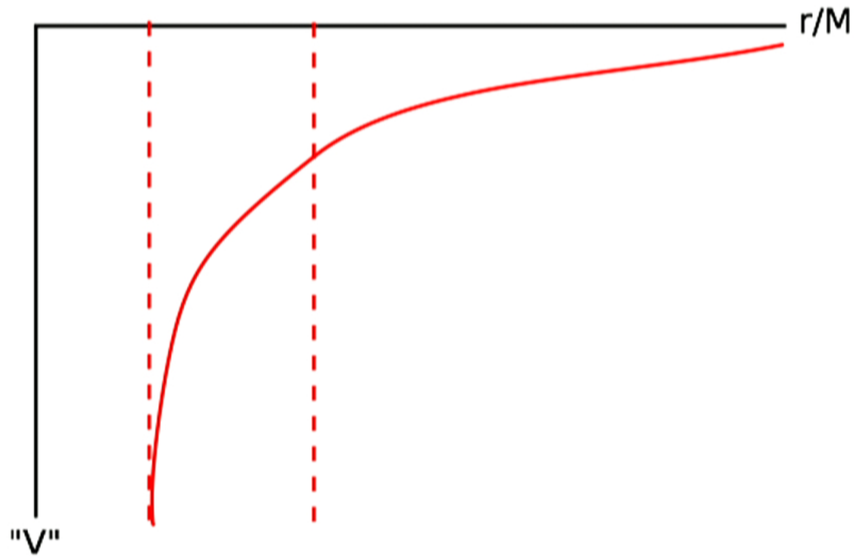
- Requires strong-field matching calculation

Examples

- dCS: $\theta_{\rm BH} \sim \mu^i \hat{n}_i / r^2$ (dipole $\propto \ell^2 S^i / M^2$; NS also dipole $\propto \ell^2 \hat{S}^i$) [Yunes and Pretorius, PRD (2009)]
- EDGB: $\theta_{\rm BH} \sim q/r$ (monopole $\propto \ell^2/M$; NS maybe quadrupole?) [Stein and Yunes, PRD (2011)]

$\omega(r)$, ISCO, EH

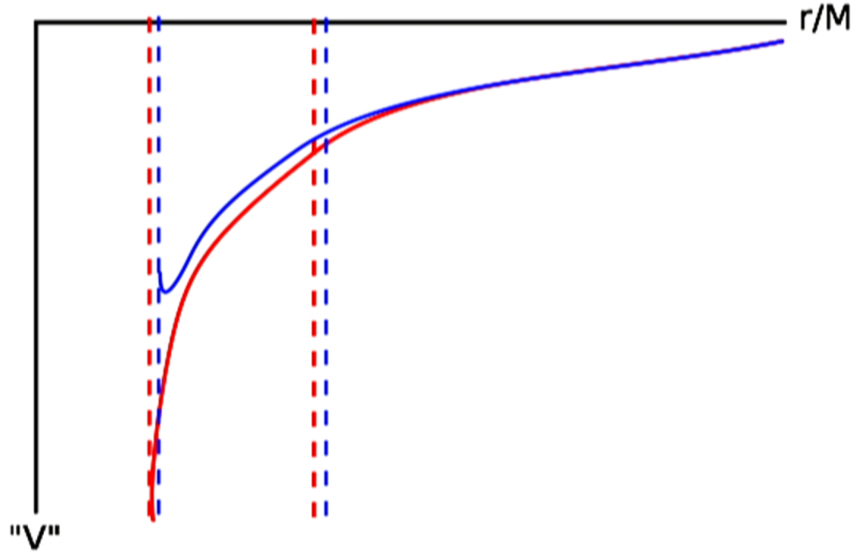
$$\omega^2(r) \sim \frac{M}{r^3}$$



[Yunes and Stein, PRD (2011)]

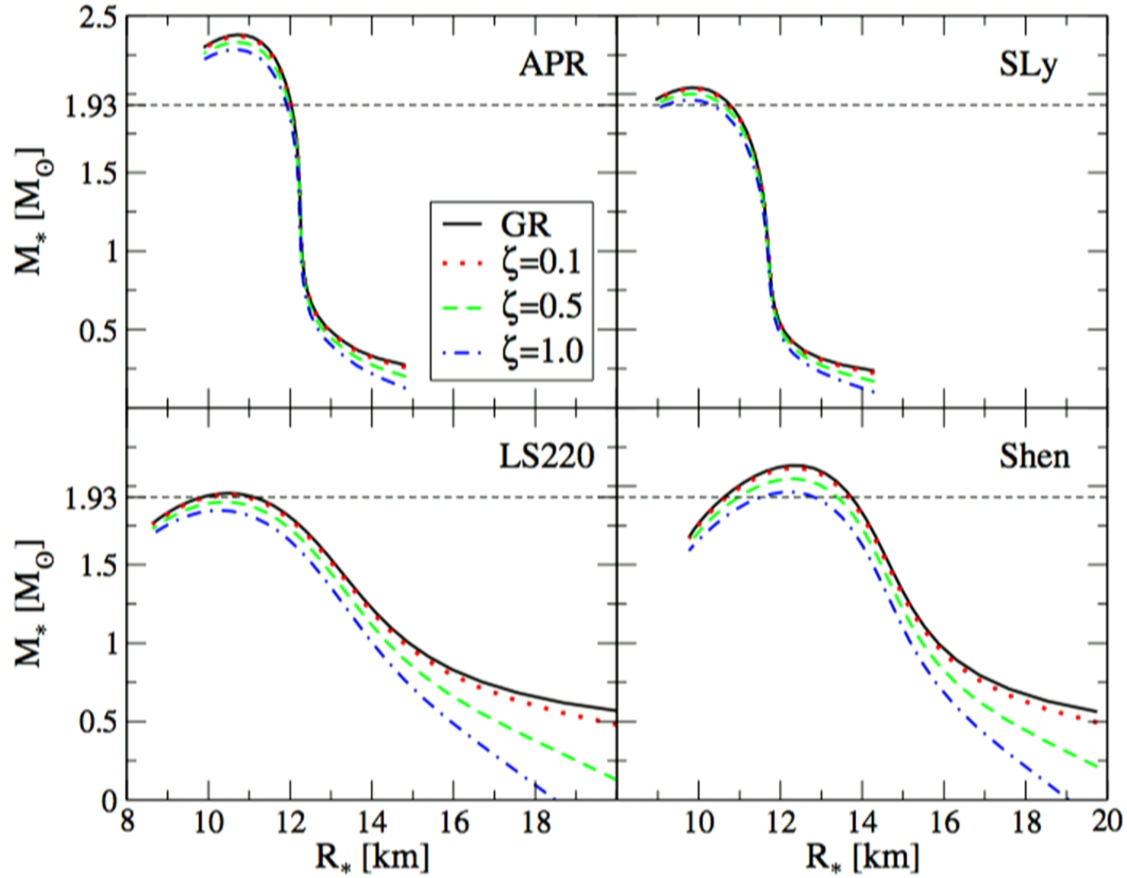
$\omega(r)$, ISCO, EH

$$\omega^2(r) \sim \frac{M}{r^3}\left[1 - \frac{1}{2}\left(\frac{\ell}{GM}\right)^4\left(\frac{M}{r}\right)^2\right]$$



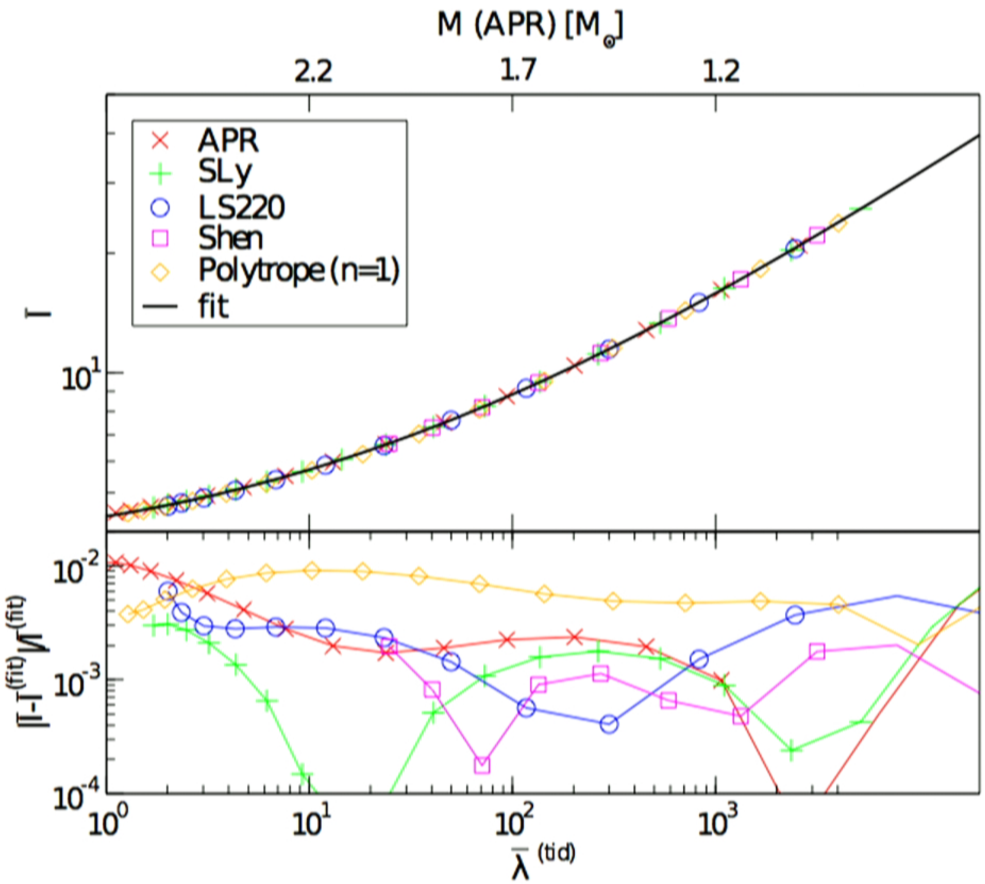
[Yunes and Stein, PRD (2011)]

M–R relation



[Yagi, Stein, Yunes, and Tanaka, PRD (2013)]

I-Love-Q relation



[Yagi and Yunes (2013); Stein, Yagi, Yunes (2014); Yagi, Stein+(2014)]

Conservative binary effects

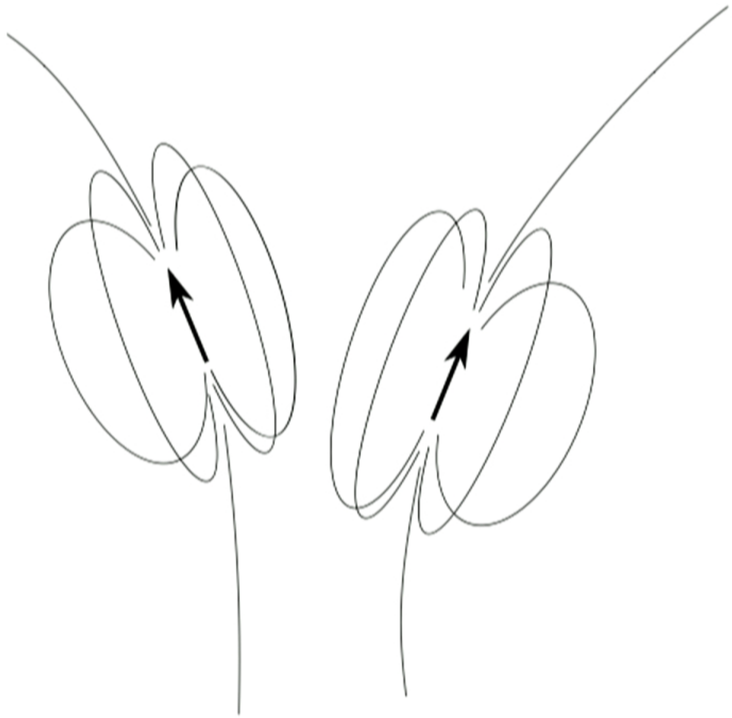
- Post-Newtonian theory
- δQ causes additional force
- Scalar hair causes scalar-scalar interaction, extra force
- Pericenter precession

[Yagi, Stein Yunes, and Tanaka, PRD (2013)]

Scalar interaction

Integrate out scalar field:

$$L_{\text{int}} = L[\vartheta[x_1, x_2]] \propto 4\pi \frac{1}{r_{12}^3} \left[3(\mu_1 \cdot n_{12})(\mu_2 \cdot n_{12}) - (\mu_1 \cdot \mu_2)\right]$$



Pericenter precession

$$\langle \dot{\omega} \rangle = \langle \dot{\omega} \rangle^{\mathrm{GR}} \left[1 + (\ell/Gm)^4 f(m, \chi, e, \mathrm{EOS}) v^2 + \ldots \right]$$

- Currently measured at 10^{-6} level
- Correction enters as v^2, with typical $|v| \sim 10^{-4} \Rightarrow 10^{-8}$ level
- Numerically calculated $\langle \delta\dot{\omega} \rangle$ / $\langle \dot{\omega} \rangle_{\mathrm{GR}}$ for J0737-3039, $\sim (\ell/Gm)^4 (10^{-9}\text{–}10^{-8})$ (APR, SLy, LS, Shen)
- Need more extreme system, better measurements

[Yagi, Stein, Yunes, and Tanaka (2013)]

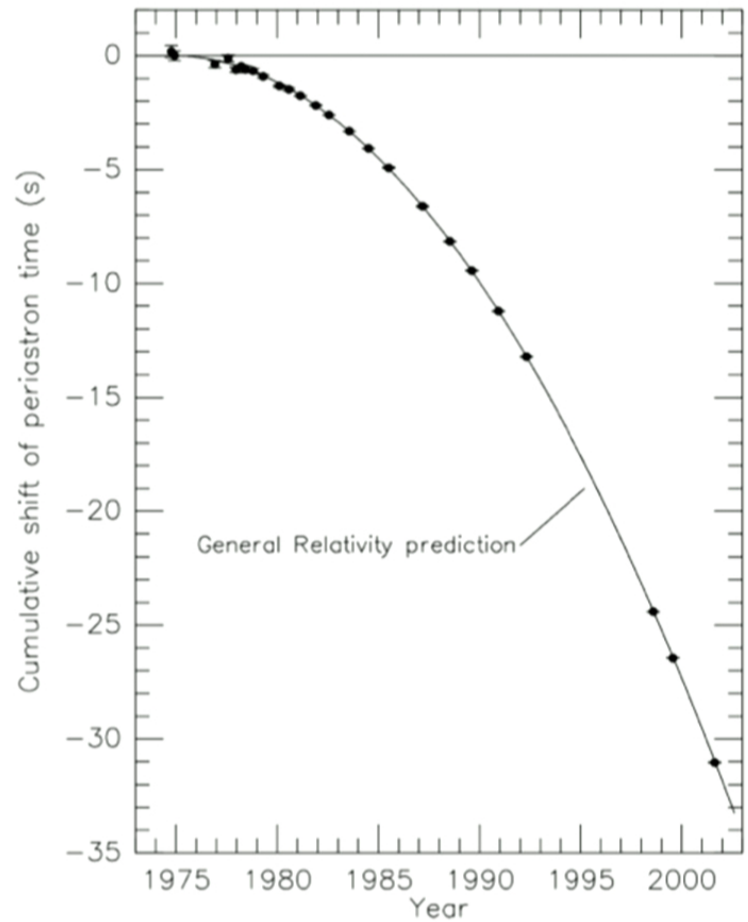
Scalar radiation reaction

- Flux balance, $\dot{E}_{\rm bind} = -\dot{E}^{(\theta)}$

$$\dot{E}^{(\varphi)} = \lim_{r\to\infty} \int_{S^2_r} \left\langle T^{(\varphi)}_{ti} n^i \right\rangle_{\rm orb} r^2 d\Omega \,,$$

- Insert scalar stress-energy tensor, scalar field solution
  - dCS: scalar dipoles, quadrupole radiation
  - EDGB: dipole radiation for BHs, higher for NSs

Gravitational waves



Modifications to gravitational waves

- GW propagation equation modified

$$\Box h + 2\mathrm{Riem} h + \delta C[h] = \mathrm{matter} + \delta T^{(\theta)}$$

- Extra modes
- Energy they carry (2^{nd} order)

$$\lim_{r\to\infty} T^{\mathrm{eff}}_{ab} \sim \langle \partial_a h^{cd} \partial_b h_{cd} \rangle$$

- Motion of binary differs $\implies$ different waveform

Gravitational wave energy

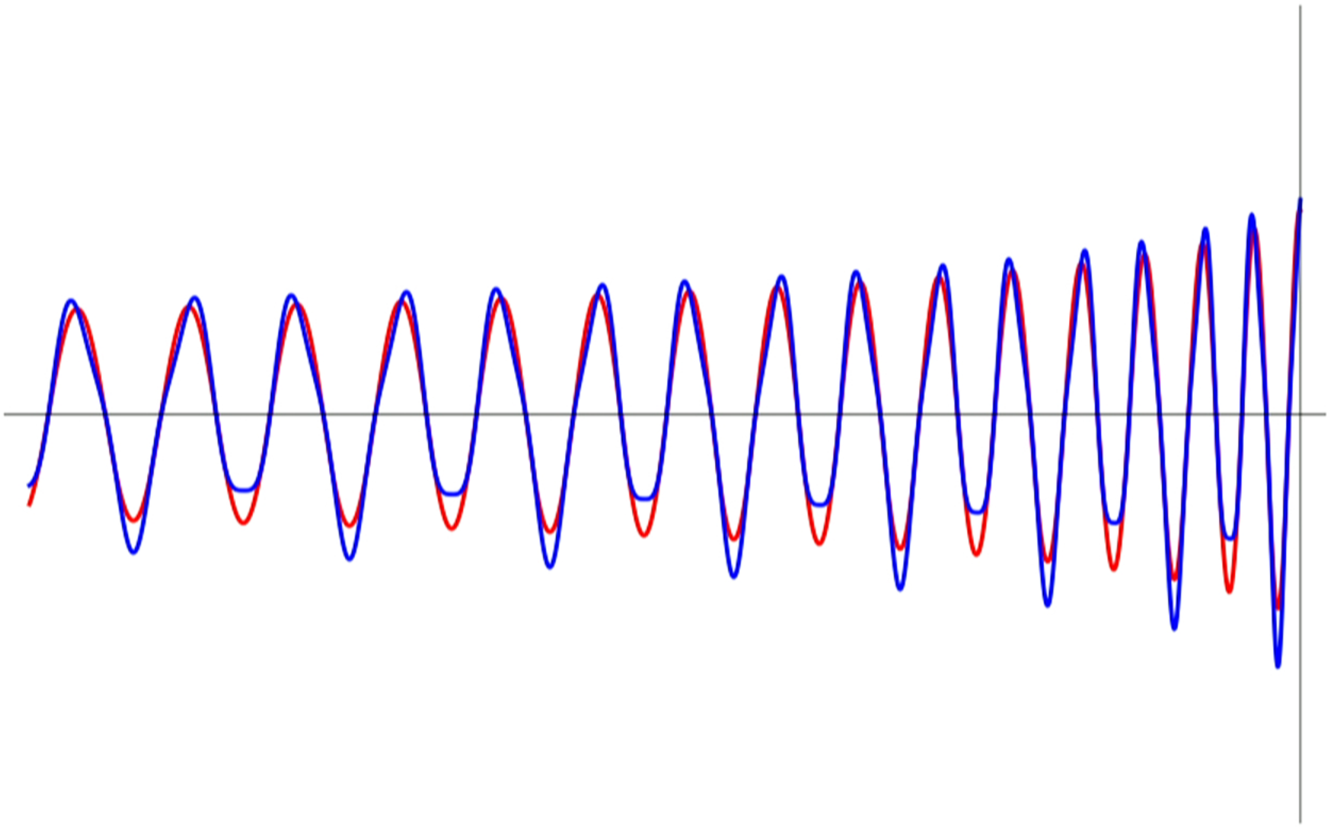
Approaching $r \to \infty$,

- Modes reduce to GR modes
- Linearized EOM approaches GR
- Energy functional approaches GR

$$\lim_{r\to\infty} T^{\text{eff}}_{ab}[h] \to T^{\text{eff,GR}}_{ab}[h]$$

[Stein and Yunes, PRD (2011)]

Gravitational waveform



$$\Psi_{\rm ppE}(f) = \Psi_{\rm GR}(f) + \beta_{\rm ppE}(\pi G\mathcal{M}f)^{b_{\rm ppE}}$$

Gravitational waveform effects

Four effects imprint on gravitational waves:

1. δE_{bind} from scalar pole-pole interaction

$$\delta E_{\text{bind}} \sim \mu_1 \cdot \mu_2 \, r^{-3} \qquad \text{(dCS)}$$

2. Metric deformation changes binding energy
3. $\dot{E}^{(\theta)}$
4. h has additional source terms

Computing GW phase

- Compute modified Kepler law $r(\omega)$ from conservative effects
- Compute modified binding energy $E(r) \to E(\omega)$
- Compute modified $\dot{E}(r) \to \dot{E}(\omega)$
- Integrate up phase

$$\frac{d^2\Psi}{d\omega^2} = 2\frac{dE}{d\omega}\frac{dt}{dE}$$

- Find ppE parameters

$$\Psi_{\rm ppE}(f) = \Psi_{\rm GR}(f) + \beta_{\rm ppE}(\pi G\mathcal{M}f)^{b_{\rm ppE}}$$

- dCS: $b_{\rm ppE} = -1/3$, $\beta_{\rm ppE} \propto [\ell/(Gm)]^4\eta^{-14/5}f(m_i, S_i, {\rm EOS})$
- EDGB BHs: $b_{\rm ppE} = -7/3$, $\beta_{\rm ppE} \sim [\ell/(Gm)]^4\eta^{-18/5}(\delta m/m)^2$

Scalar hair

Implications:

- "No-hair theorems" violated
- Effacement principle lost
- Scalar multipole-multipole interaction in binary

$$\langle\dot{\omega}\rangle_{\rm dCS} = \langle\dot{\omega}\rangle^{\rm GR}\left[1 + (\ell/Gm)^4 f(m,\chi,e,{\rm EOS}) v^2 + \ldots\right]$$

- Scalar radiation from binary

$$\Psi_{\rm dCS}(f) = \Psi_{\rm GR}(f) + (\ell/Gm)^4 f(m,\chi,e,{\rm EOS})(\pi G\mathcal{M}f)^{-1/3} + \ldots$$

Parametrize the action

- Operator+derivative expansion of interaction
- First term:

$$\mathcal{L}_{\rm int} \sim (m_{\rm pl}\ell)\, \ell^{\wp}\; \theta\; T[g, \epsilon^{0,1}, \nabla^d, R^r]$$

- $\wp = d + 2r - 3$ for correct dimension

Theory	$\lvert\epsilon\rvert$	d	r	$\wp$
"Scalar-Tensor"	0	0	1	-1
EDGB	0	0	2	1
dCS	1	0	2	1

[Stein and Yagi (2014)]

Scalar hair

- Parametrize hair
- Lowest non-vanishing moment $\ell_{\rm NS}$ or $\ell_{\rm BH}$ dominates
- $|S| = s$, $S = i_1 i_2 \dots i_s$ with $s = \ell_{\rm NS,BH}$

$$\theta_*^{\rm FZ} = \mu_*^S \partial_S \frac{1}{r_*}$$

- Matching calculation for μ_*^S
- Far away ($\sim$ Minkowski) represent with effective source

$$\tau_{\rm eff} = (-)^s \mu_*^S \partial_S \delta^{(3)}(\mathbf{x} - \mathbf{x}_*)$$

Theory	$\lvert\epsilon\rvert$	d	r	$\wp$	$\ell_{\rm BH}$	$\ell_{\rm NS}$
"Scalar-Tensor"	0	0	1	-1	—	0
EDGB	0	0	2	1	0	2
dCS	1	0	2	1	1	1

Multipole scaling

- Scaling arguments for μ^Q

$$\mu^Q \sim \int \tau x^Q d^3x \sim (m_{\rm pl}\ell)\ell^{\wp} \int T[g, \epsilon^{0,1}, \nabla^d, R^r] x^Q d^3x$$

- $\nabla \sim R_*^{-1}$, $R \sim G\rho$
- $|Q|$ has same parity as $|\epsilon|$

$$\mu^Q \sim (m_{\rm pl}\ell)\left(\frac{\ell}{R_*}\right)^{\wp} C_*^r R_*^q \times (\text{dim.less func.}) \qquad |\epsilon| = 0$$

$$\mu^Q \sim S(m_{\rm pl}\ell)\left(\frac{\ell}{R_*}\right)^{\wp} C_*^{r-1} R_*^{q-2} \times (\text{func.}) \qquad |\epsilon| = 1$$

- reproduces strong-field solutions from dCS, EDGB

Generic pole-pole interaction

- Two bodies of lowest non-vanishing multipoles s, t

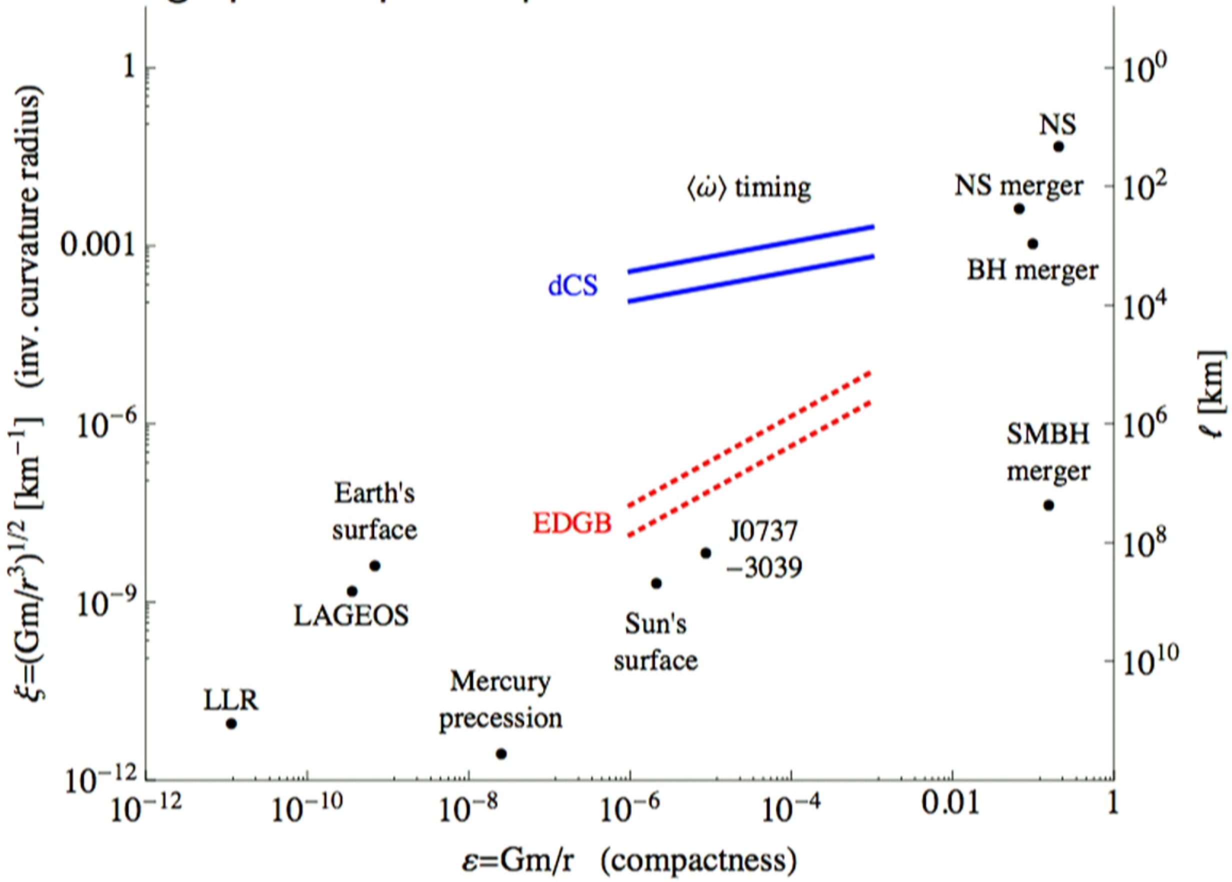
$$L_\times[\mathbf{x}_1, \mathbf{x}_2] = (-)^{t+1} 4\pi (2s + 2t - 1)!! \frac{\mu_1^S \mu_2^T n_{12}^{<ST>}}{r_{12}^{1+s+t}}$$

- Scaling estimate of pericenter precession

$$\frac{\langle \dot\omega \rangle}{\langle \dot\omega \rangle_{\mathrm{GR}}} \sim (-)^t (2s + 2t + 1)!! \frac{\ell^2}{(Gm)(G\mu)} \left(\frac{\ell^2}{R_1 R_2}\right)^{\wp} (C_1 C_2)^r \times \\ \times \left(\frac{R_1}{Gm}\right)^s \left(\frac{R_2}{Gm}\right)^t f_2(e) v^{2(s+t-1)}$$

Estimated pulsar constraints

Measure enough post-Keplerian parameters



Scalar radiation

- Scalar field is radiative, $\theta = \sum_{q=0}^{\infty} \frac{(-)^q}{q!} \left(\frac{1}{r} \mu_{\mathrm{bin}}^{Q} \right)_{,Q}$
- Source term is superposition of two effective source terms

$$\mu_{\mathrm{bin}}^{Q} = \begin{cases} \frac{q!}{h!} \mu_1^{(k_1 \cdots k_h} x_1^{k_{h+1} \cdots k_q)} + (1 \leftrightarrow 2) & q \geq h \\ 0 & \text{otherwise} \end{cases}$$

- q^{th} binary source moment contains $\min(0, q - \ell_A)$ powers of x_A^k
- Lowest binary moment probably $1 + \min(\ell_1, \ell_2)$ but might be higher

Theory	$\lvert\epsilon\rvert$	d	r	$\wp$	ℓ_{BH}	ℓ_{NS}	$\ell_{\mathrm{rad}}^{\mathrm{HH}}$	$\ell_{\mathrm{rad}}^{\mathrm{HS}}$	$\ell_{\mathrm{rad}}^{\mathrm{SS}}$
"Scalar-Tensor"	0	0	1	-1	—	0	—	1	1
EDGB	0	0	2	1	0	2	1	1	3
dCS	1	0	2	1	1	1	2	2	2

Scalar radiation scaling estimate

Scaling of scalar energy flux controlled by difference $s - \wp$

$$\frac{\dot{E}^{(\theta)}}{\dot{E}^{\mathrm{GW}}} \sim \frac{v^{6s-2}}{(2w+1)(s!)^2} \frac{\ell^2}{(G\mu)^2} \left(\frac{\ell}{Gm}\right)^{2\wp} \frac{\delta m^2}{\mu^2} \qquad (s - \wp = -1)$$

$$\frac{\dot{E}^{(\theta)}}{\dot{E}^{\mathrm{GW}}} \sim \frac{v^{6s-2}}{(2w+1)(s!)^2} \frac{\ell^2}{(G\mu)^2} \left(\frac{\ell}{Gm}\right)^{2\wp} \frac{\delta m^2}{m^2} \qquad (s - \wp = 0)$$

$$\frac{\dot{E}^{(\theta)}}{\dot{E}^{\mathrm{GW}}} \sim \frac{v^{6s-2}}{(2w+1)(s!)^2} \frac{\ell^2}{(Gm)^2} \left(\frac{\ell}{Gm}\right)^{2\wp} \qquad (s - \wp = +1)$$

$$\frac{\dot{E}^{(\theta)}}{\dot{E}^{\mathrm{GW}}} \sim \frac{v^{6s-2}}{(2w+1)(s!)^2} \frac{\ell^2}{(Gm)^2} \left(\frac{\ell}{Gm}\right)^{2\wp} \frac{\delta m^2}{m^2} \qquad (s - \wp = +2)$$

ppE parameters

$$b^{(1)}_{\rm ppE} = (4s-5)/3$$
$$b^{(3)}_{\rm ppE} = (6s-7)/3$$

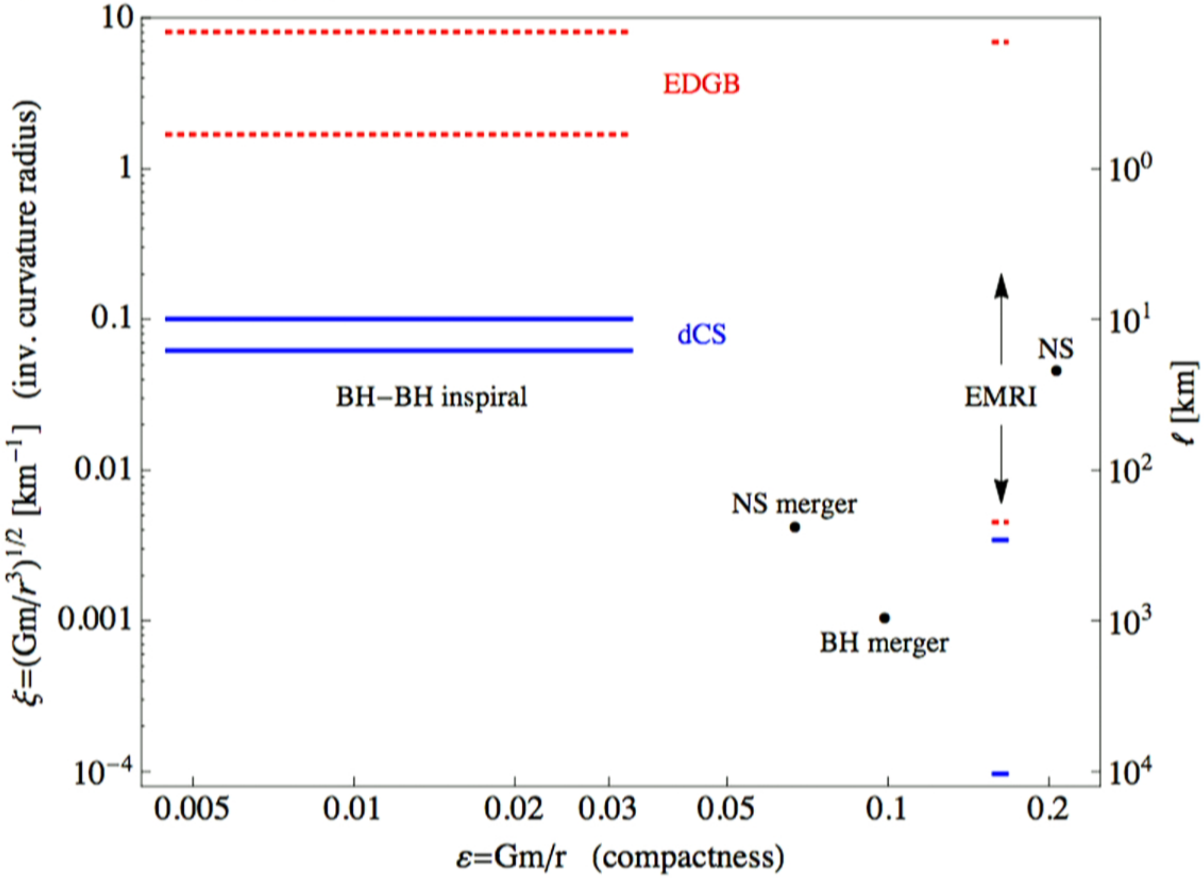
$$\beta^{(1)}_{\rm ppE} \sim \frac{\ell^2}{\eta^{1+4s/5}(Gm)^2}\left(\frac{\ell^2}{R_1R_2}\right)^{\wp}\left(\frac{R_1R_2}{(Gm)^2}\right)^{s}(C_1C_2)^r$$

$$\beta^{(3)}_{\rm ppE} \sim \frac{1}{\eta^{(12+6\wp)/5}}\left(\frac{\ell}{Gm}\right)^{2+2\wp}\left(\frac{\delta m}{m}\right)^2 \qquad (s-\wp=-1)$$
$$\beta^{(3)}_{\rm ppE} \sim \frac{1}{\eta^{(8+6\wp)/5}}\left(\frac{\ell}{Gm}\right)^{2+2\wp}\left(\frac{\delta m}{m}\right)^2 \qquad (s-\wp=0)$$

$\ldots$

Estimated GW bounds

Roughly bound $|\beta| \lesssim 1/SNR$



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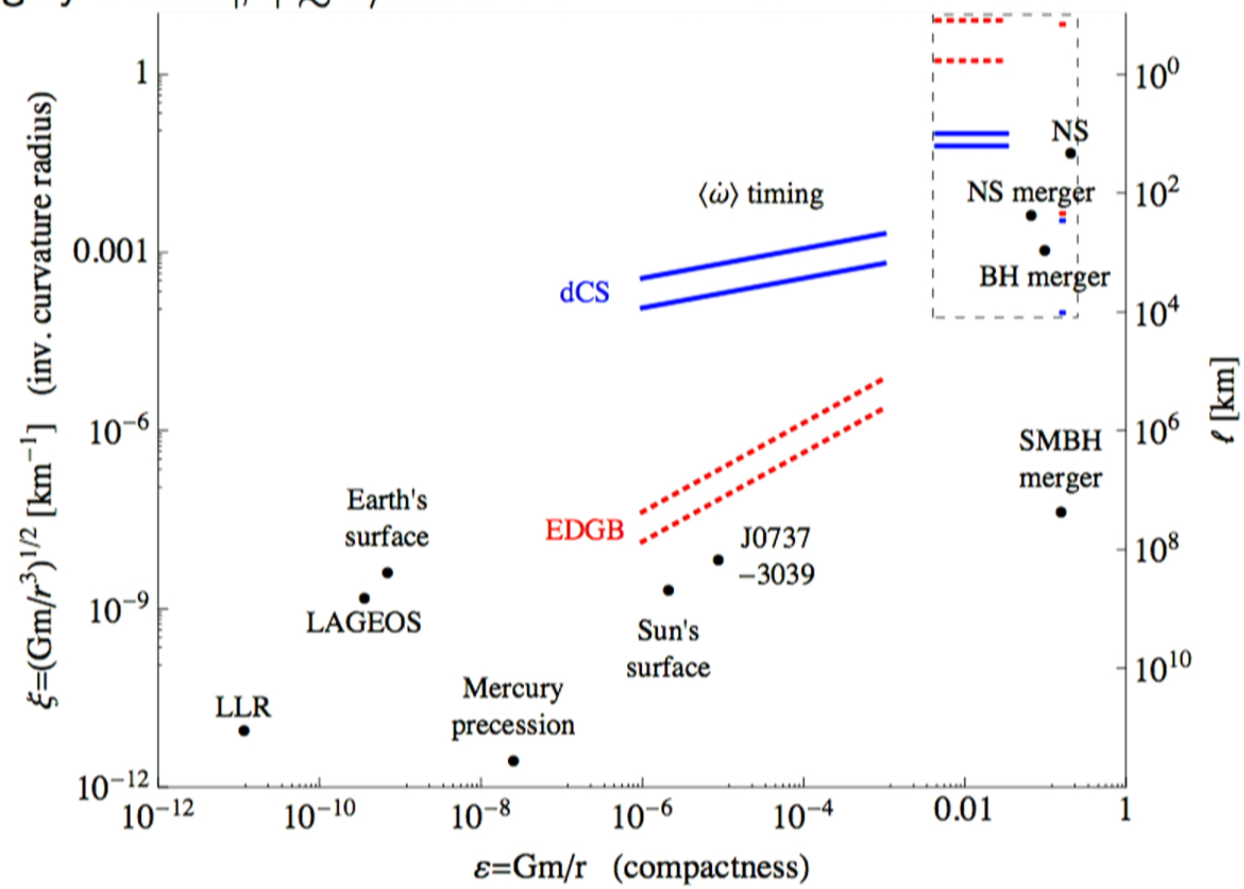


3. Validity

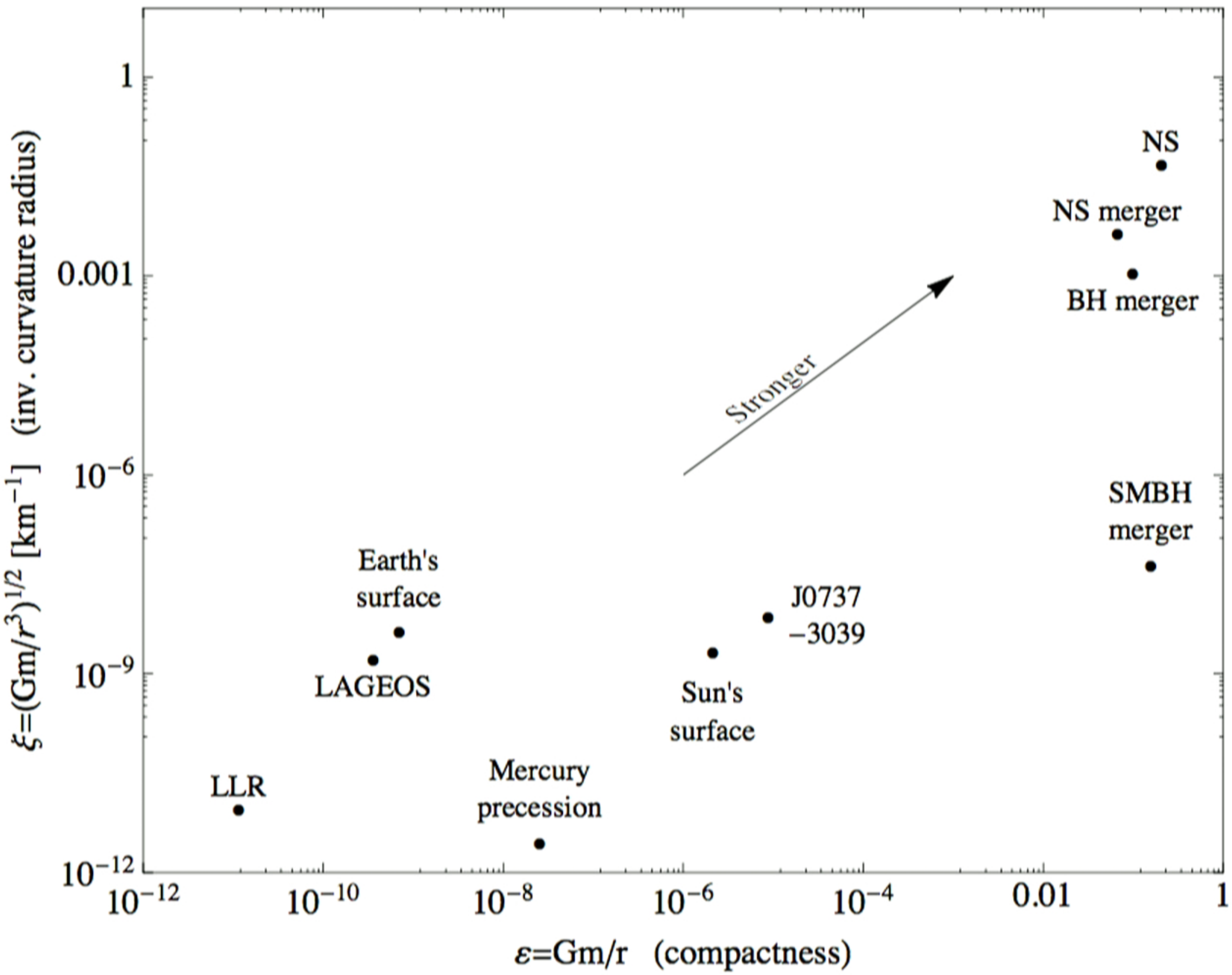
Decoupling limit

- Most EFTs don't make sense as exact theories (see e.g. Delsate+Hilditch+Witek)
- (Almost) All corrections introduce new ℓ
- Can't be too long
- Expand fields, EOMs in powers of $\ell/\mathcal{R}_{\mathrm{BG}}$, perturbation scheme

Question: What is regime of validity of decoupling limit?

Where is dCS correction largest?

- dCS is higher-curvature and parity-odd



ξ=(Gm/r³)^1/2 [km⁻¹] (inv. curvature radius)
ε=Gm/r (compactness)
1
0.001
10⁻⁶
10⁻⁹
10⁻¹²
10⁻¹²
10⁻¹⁰
10⁻⁸
10⁻⁶
10⁻⁴
0.01
1
NS
NS merger
BH merger
Stronger
SMBH merger
Earth's surface
LAGEOS
J0737 −3039
Sun's surface
LLR
Mercury precession

Black holes in dCS

- $a = 0$ (Schwarzschild) is exact solution with $\vartheta = 0$
- Analytically known solutions in decoupling limit
  - $a \ll M$ limit up to $\mathcal{O}(a^2)$, valid $\forall r$ (see Yunes+Pretorius, Yagi+Yunes+Tanaka)
  - $r \gg M$ limit for $l = 1$, valid $\forall a$ (see Yagi+Yunes+Tanaka)
- [Stein (2014)]: Constructed numerical solutions $\forall r, \forall a$

When does decoupling scheme break down?

- Consider metric determinant perturbation:

$$\sqrt{-g} = \sqrt{-g_{\rm GR}}\left(1 + \varepsilon^2 \tfrac{1}{2} h^{\rm def} + \mathcal{O}(\varepsilon^3)\right)$$

- If $h^{\rm def} \sim \mathcal{O}(1)$, should keep higher $\mathcal{O}(\varepsilon)$
- Criterion for validity of PT:

$$|h^{\rm def}| \lesssim 1 \qquad \text{everywhere}$$

- Program: Solve for $\vartheta^{(1)}, h^{\rm def}$ as functions of r, θ for all a

Approach to solving

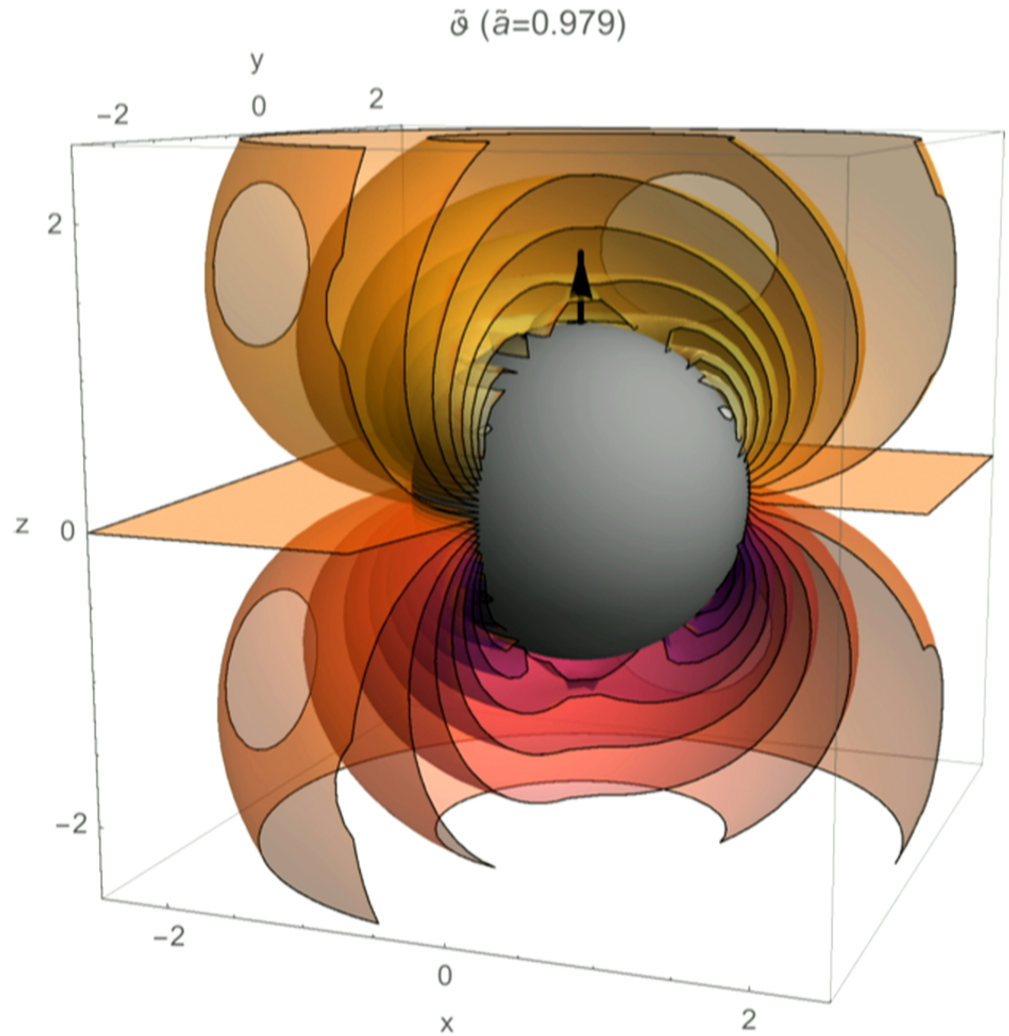
- In Lorenz gauge, can get $Tr(h)$ with just a scalar equation:

$$\frac{1}{2}m_{\rm pl}^2\Box h^{\rm def} = -(\nabla^a\vartheta^{(1)})(\nabla_a\vartheta^{(1)})$$

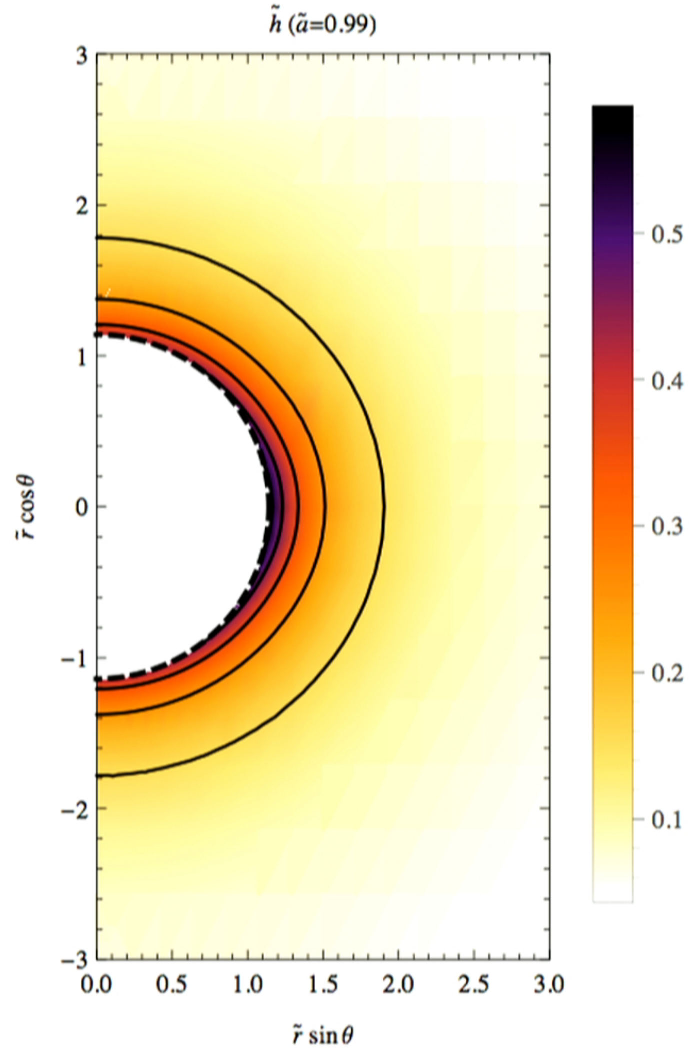
- Symmetry reduced, $\vartheta = \vartheta(r,\theta)$. $\Box \to \Delta$. Elliptic.
- Numerical separation of variables. Each j mode is an ODE.
- Compactify r
- Pseudospectral collocation method
- Directly solve discrete ODE operator ("numerical Green's function")

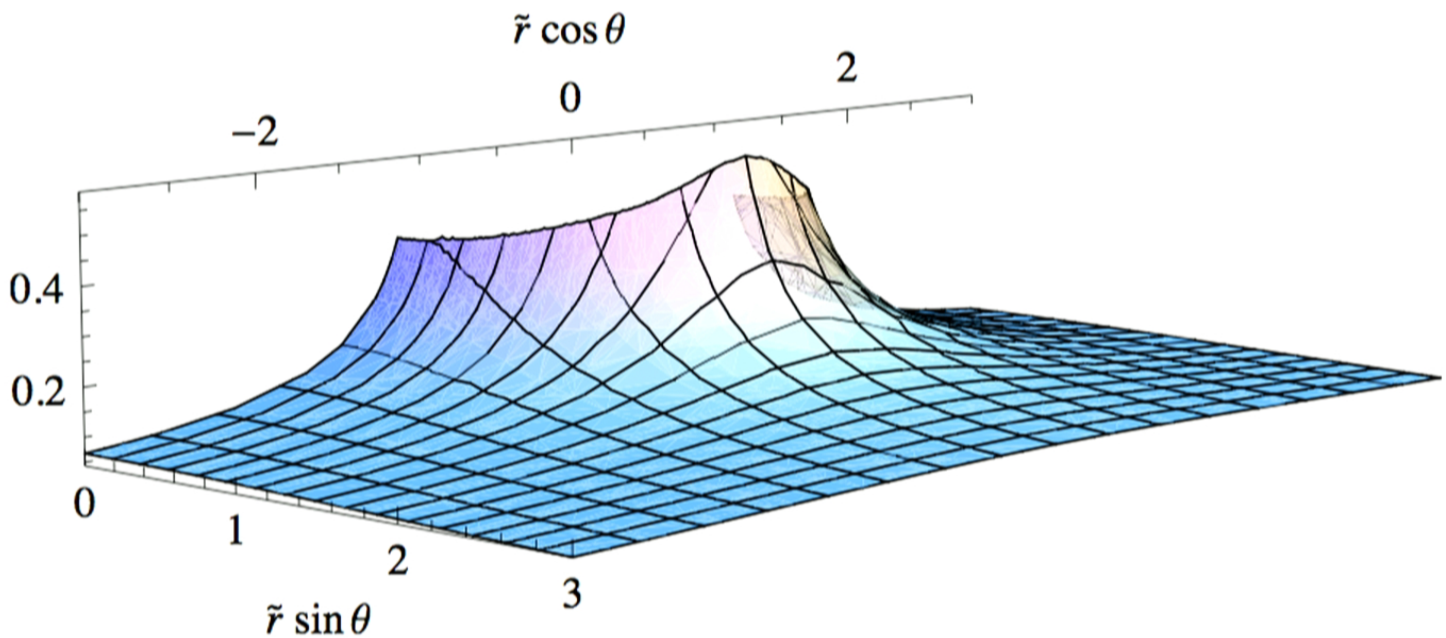
Numerical approach

- For each a, find $\vartheta(r, \theta; a)$, compute $(\partial\vartheta)^2$, find $h^{\rm def}(r, \theta; a)$
- Evaluate $\max |h^{\rm def}|$ and find regime of validity

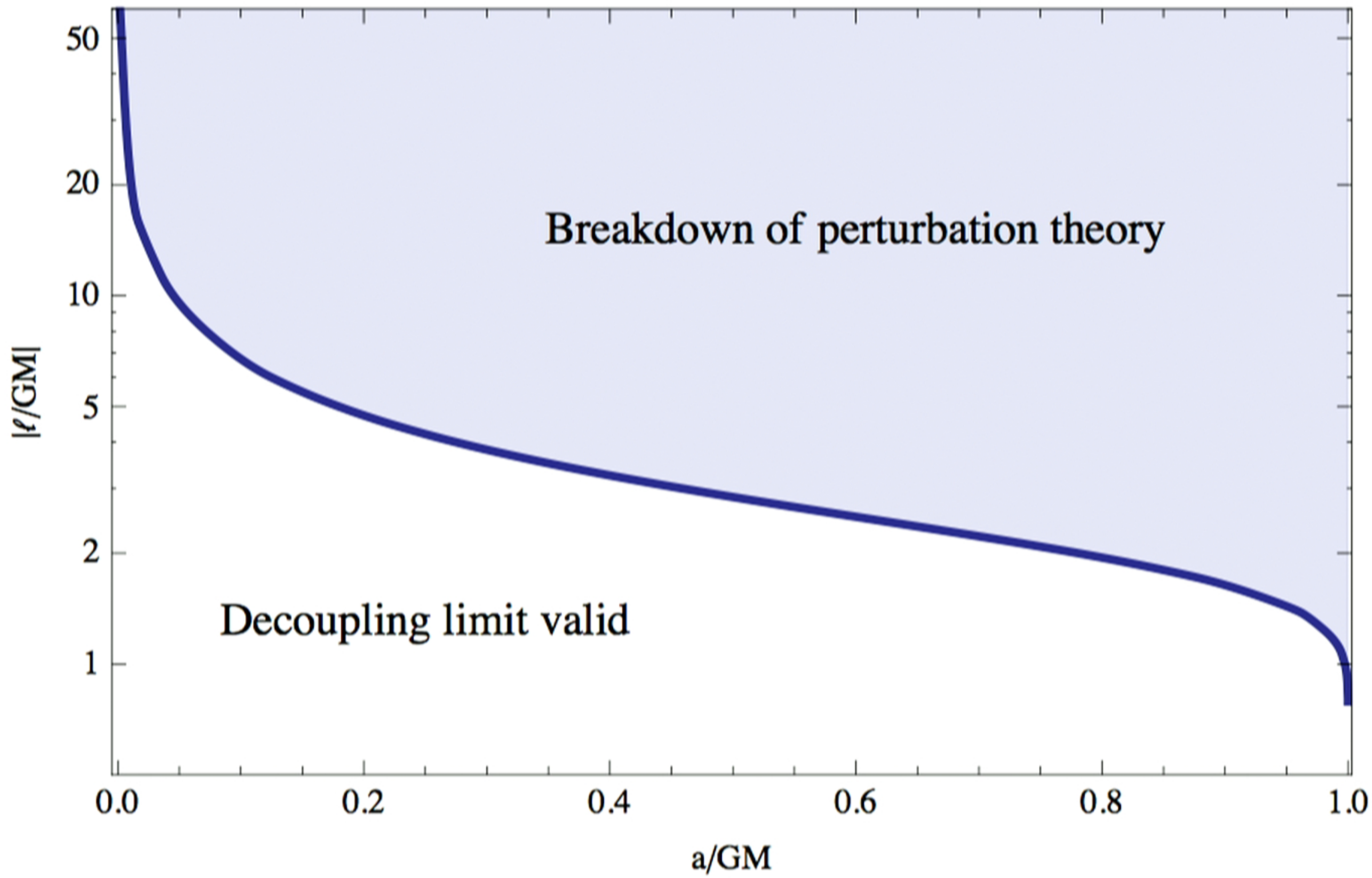


$\tilde{\vartheta}$ ($\tilde{a}$=0.979)
y
−2
0
2
2
z
0
−2
−2
0
x
2


$\tilde{h}$ ($\tilde{a}$=0.99)
$\tilde{r}\cos\theta$
$\tilde{r}\sin\theta$
3
2
1
0
−1
−2
−3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.5
0.4
0.3
0.2
0.1

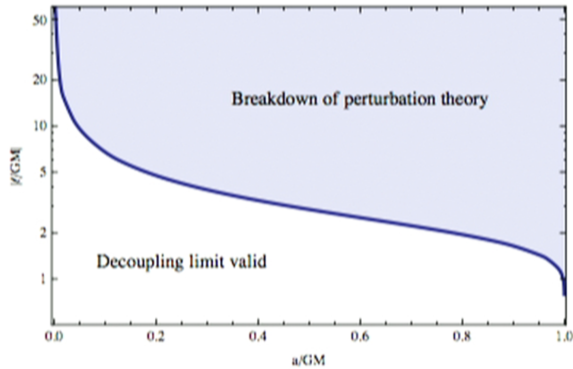

$\tilde{r}\cos\theta$
−2
0
2
0.4
0.2
0
1
2
3
$\tilde{r}\sin\theta$

Regime of validity



Forecasting bounds

- Observation of BH indistinguishable from GR predictions
- Size of ℓ correction below breakdown (caveat: cancellation)
- GRO J1655–40: $M = 6.30 \pm 0.27 M_{\odot}$, $\tilde{a} \approx 0.65$–0.75



$$\implies \ell \lesssim 22\text{km}$$

- Better by 10^7 than Solar System bounds

Multipole scaling

- Scaling arguments for μ^Q

$$\mu^Q \sim \int \tau x^Q d^3x \sim (m_{\rm pl}\ell)\ell^{\wp} \int T[g, \epsilon^{0,1}, \nabla^d, R^r] x^Q d^3x$$

- $\nabla \sim R_*^{-1}$, $R \sim G\rho$
- $|Q|$ has same parity as $|\epsilon|$

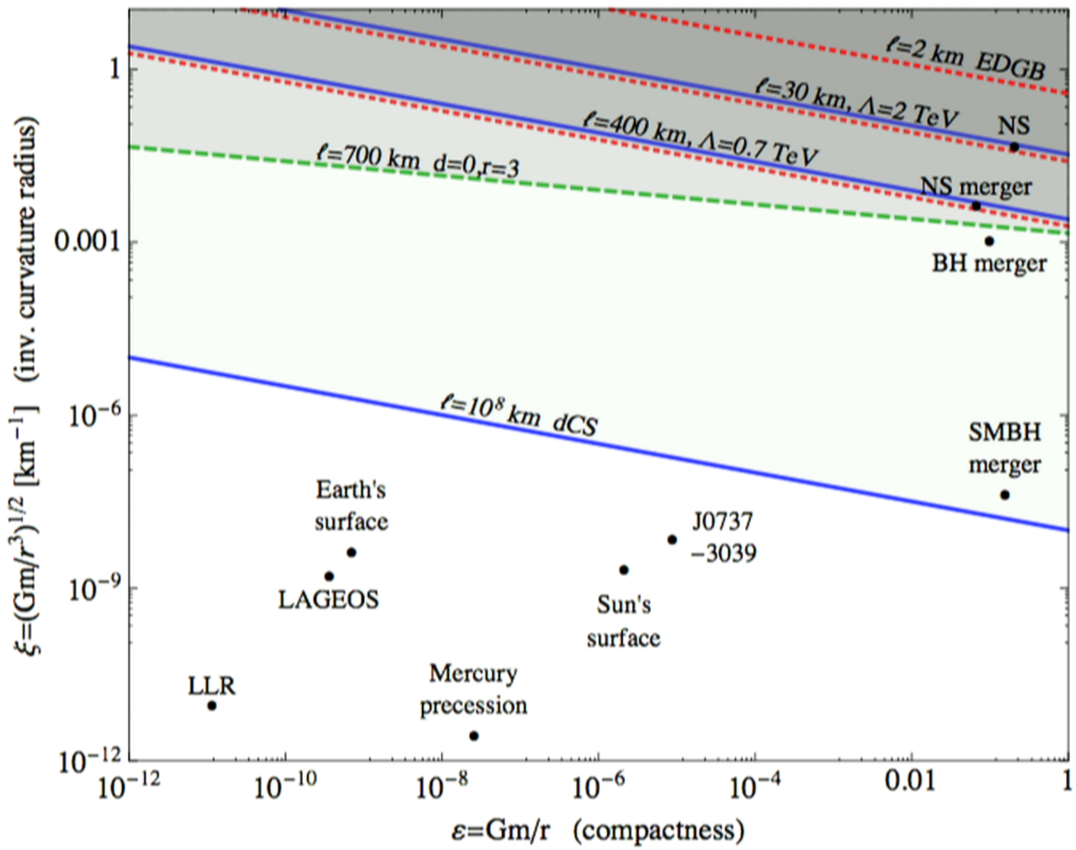
$$\mu^Q \sim (m_{\rm pl}\ell)\left(\frac{\ell}{R_*}\right)^{\wp} C_*^r R_*^q \times (\text{dim.less func.}) \qquad |\epsilon| = 0$$

$$\mu^Q \sim S(m_{\rm pl}\ell)\left(\frac{\ell}{R_*}\right)^{\wp} C_*^{r-1} R_*^{q-2} \times (\text{func.}) \qquad |\epsilon| = 1$$

- reproduces strong-field solutions from dCS, EDGB

Regime of validity

Compare $\frac{1}{2}m_{\rm pl}^2 R$ to $(m_{\rm pl}\ell)\ell^{\wp}\theta T[\epsilon^{0,1}, g, \nabla^d, R^r]$



Validity

- Breakdown of EFT vs. decoupling limit
- Is EFT valid at all?
  - Suggestions from AdS/CFT: turbulent gravity
  - Turbulent cascade $\Longrightarrow$ no separation of scales

Summary

- Expect GR incomplete, consider EFTs
- Phenomena to compute for any UV completion
  - Isolated bodies: scalar hair, M–R relation
  - Compact binaries: pericenter precession, orbital decay
  - Gravitational waves: polarizations, energy, ppE phase
- Parameterized over many theories
  - $(|\epsilon|, d, r, \wp, \ell_{\rm BH}, \ell_{\rm NS}, \ell^{\rm HH}_{\rm rad}, \ell^{\rm HS}_{\rm rad}, \ell^{\rm SS}_{\rm rad})$
- Caveats
  - Weak-coupling breaks down
  - Is EFT valid?

In the works: pulsar timing in parameterized theories, connect to ppE