Kent Yagi, JGRG 22(2012)111307

"Black hole solution and binary gravitational waves in dynamical Chern-Simons gravity"

RESCEU SYMPOSIUM ON

GENERAL RELATIVITY AND GRAVITATION

JGRG 22

November 12-16 2012

Koshiba Hall, The University of Tokyo, Hongo, Tokyo, Japan

Black Hole Solution and Binary Gravitational Waves in Dynamical Chern-Simons Gravity

JGRG22 @ University of Tokyo

November 13th 2012

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Collaborators:

Nicolas Yunes (Montana State Univ.)

Takahiro Tanaka (YITP)

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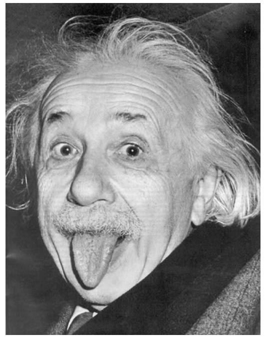
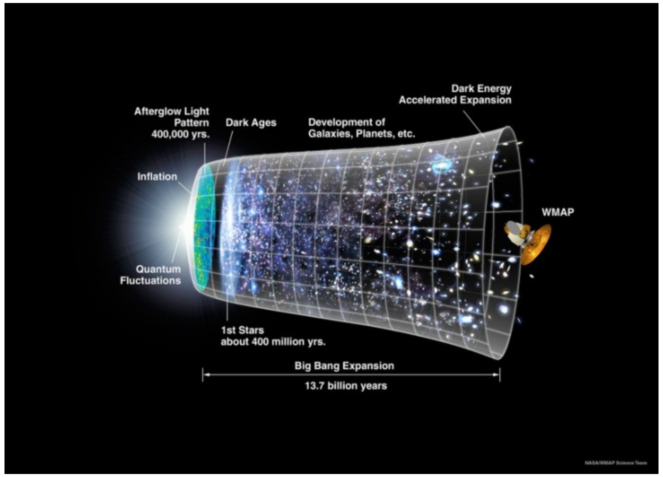
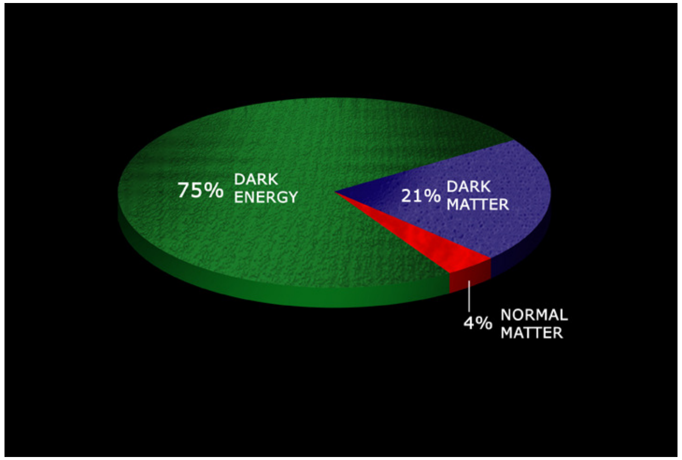
Probing alternative theories of gravity using compact binaries



Why modifications of gravity?

(I) Problems within GR can be naturally solved.





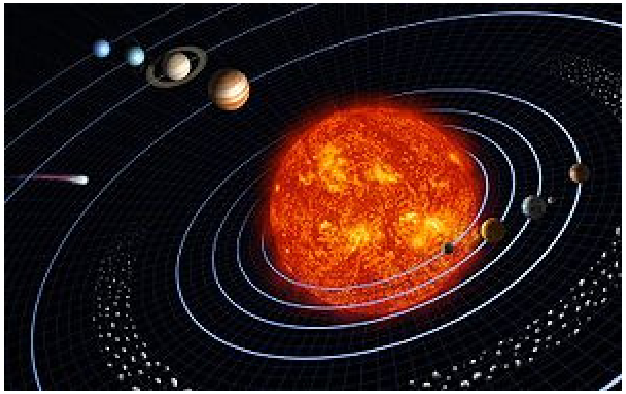
(II) Classical gravitational theory as a low-energy effective theory of a more fundamental theory

e.g. superstring theory ⇒ **Chern-Simons, Gauss-Bonnet, Scalar-tensor theories**

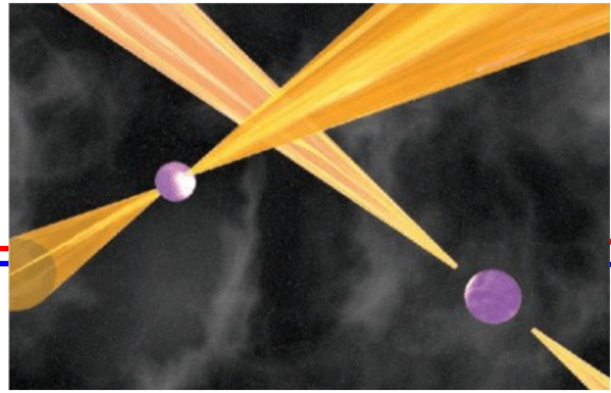
Testing GR

(I) Weak field, non-dynamical regime:

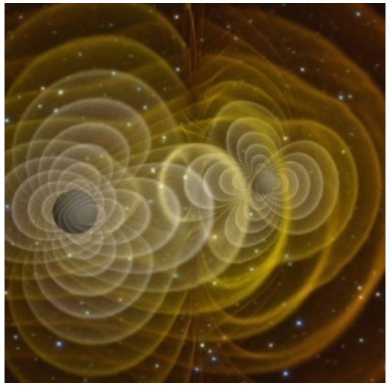
Solar System



Binary Pulsar



(II) Strong field, dynamical regime:



Gravitational Waves

Dynamical Chern-Simons Gravity

-Standard Model

-Superstring Theory

-Loop Quantum Gravity

-Inflation

Dynamical Chern-Simons Gravity

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- -Superstring Theory
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- **Action:**

$$S \equiv \int d^4x \sqrt{-g} \Big\{ \kappa_g R + \frac{\alpha}{4} \vartheta R_{\nu\mu\rho\sigma} {}^{*}R^{\mu\nu\rho\sigma} - \frac{\beta}{2} [\nabla_\mu \vartheta \nabla^\mu \vartheta + 2V(\vartheta)] + \mathcal{L}_{\rm mat} \Big\} .$$

$c = G = 1$

$\kappa_g \equiv (16\pi)^{-1}$

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- Field Eqs.:

$$G_{\mu\nu}[g_{\mu\nu}] + \frac{\alpha}{\kappa_g}C_{\mu\nu}[\vartheta, g_{\mu\nu}] = \frac{1}{2\kappa_g}\left(T^{\rm mat}_{\mu\nu} + T^{\vartheta}_{\mu\nu}[\vartheta, g_{\mu\nu}]\right)$$

$$\Box\vartheta = -\frac{\alpha}{4\beta}{}^*RR + V'(\vartheta)$$

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- **Characteristic Length Scale:**

$$\xi^{1/4} \qquad \left(\xi \equiv \frac{\alpha^2}{\beta\kappa_g}\right)$$

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- **Characteristic Length Scale:**

$$\xi^{1/4} \qquad \left(\xi \equiv \frac{\alpha^2}{\beta\kappa_g}\right)$$

- **Small coupling approximation**

Dimensionless coupling constant: $\zeta \equiv \dfrac{\xi}{M^4} \ll 1$

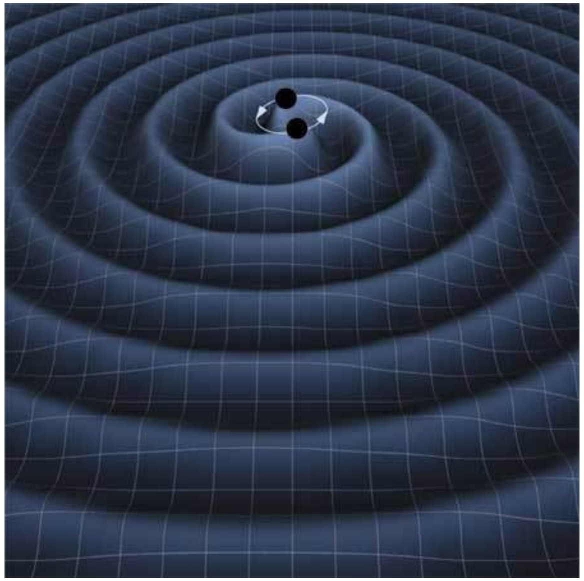
For simplicity, we set $V(\vartheta) = 0$

Corrections to GWs from BH Binaries

(I) Dissipative

Scalar & Gravitational Radiation

→ Modifies the orbital evolution

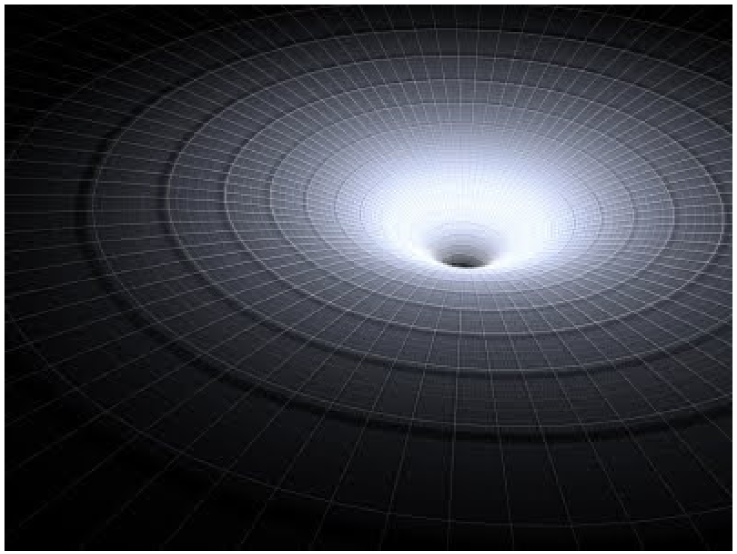


(II) Conservative

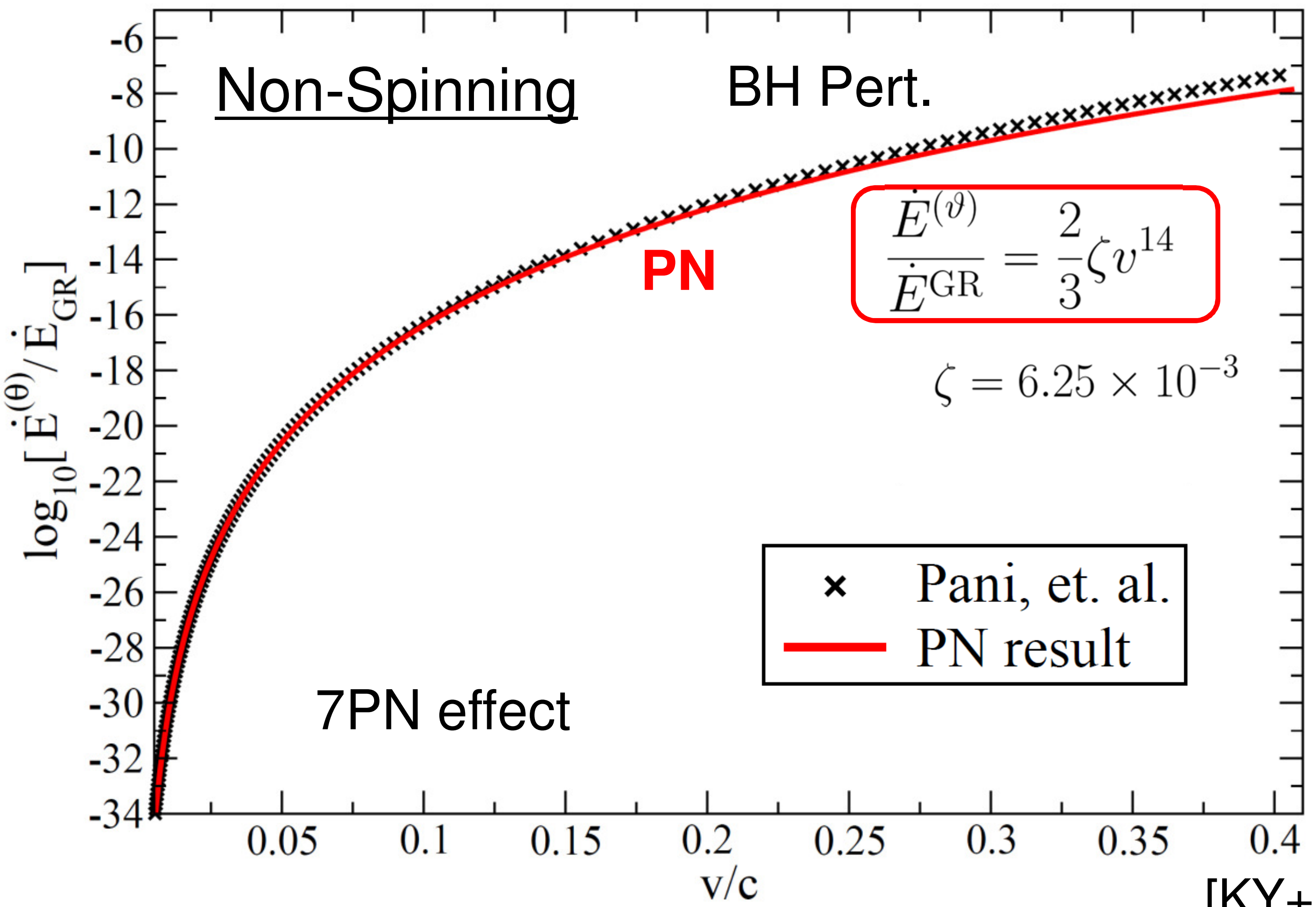
Modified BH Solution

→ Modifies the binding energy

→ Modifies the binary orbit



Dissipative Corrections in DCS Gravity



[KY+ (2012)]

For the spinning case, the correction is 2PN!

Now, we need to compute the conservative one.

Contents

(I) Non-Spinning

Spherical Symmetry

- $^*RR = 0$
- No CS correction
- Schwarzschild BH

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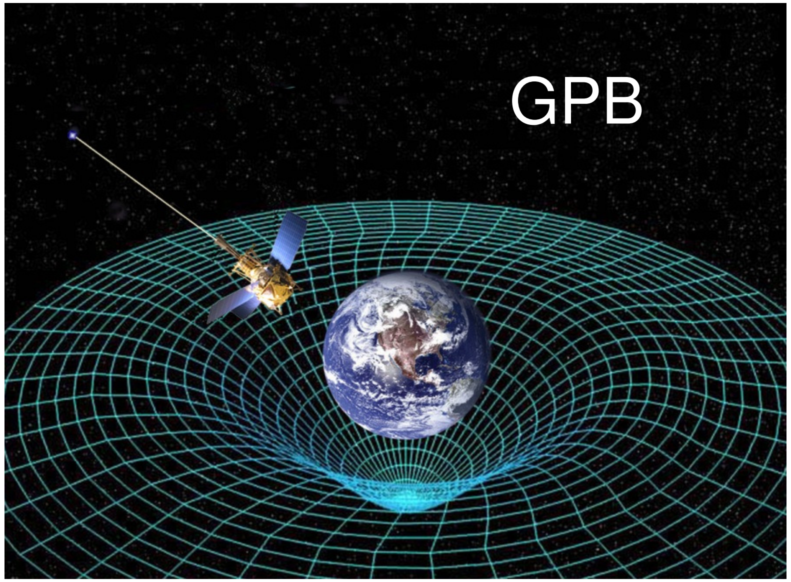

(II) Spinning

-Exact Solution unknown.

-Linear order in spin [Yunes & Pretorius (2009), Konno et al. (2009)]

$$ds^2 = ds_{\rm K}^2 + \underline{\frac{5}{4}\frac{\alpha^2}{\beta\kappa}\frac{a}{r^4}\left(1+\frac{12}{7}\frac{M}{r}+\frac{27}{10}\frac{M^2}{r^2}\right)\sin^2\theta dt d\phi},$$

→ **frame-dragging effect**

Gravity Probe B → $\xi^{1/4} < \mathcal{O}(10^8)$ km

[Ali-Haimoud & Chen (2011)]

BH Solution at Quadratic Order in Spin

Metric Perturbation: $$g_{\mu\nu} = \underbrace{\boxed{g^{(0)}_{\mu\nu}}}_{\text{GR}} + \underbrace{\boxed{\alpha'^2 g^{(2)}_{\mu\nu}}}_{\text{CS}} + \mathcal{O}(\alpha'^4)$$

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Expansion in spin:

$$\boxed{g^{(0)}_{\mu\nu}} = g^{(0,0)}_{\mu\nu} + \chi' g^{(1,0)}_{\mu\nu} + \chi'^2 g^{(2,0)}_{\mu\nu} + \mathcal{O}(\chi'^3)$$

$$g^{(m,n)}_{\mu\nu} \propto \chi^m \alpha^n$$

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Yunes & Pretorius, Konno et al.

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$$\boxed{\alpha'^2 g_{\mu\nu}^{(2)}} = \cancel{\alpha'^2 g_{\mu\nu}^{(0,2)}} + \alpha'^2 \chi' \underbrace{\boxed{g_{\mu\nu}^{(1,2)}}}_{\text{Yunes \& Pretorius, Konno et al.}} + \alpha'^2 \chi'^2 \underbrace{\boxed{g_{\mu\nu}^{(2,2)}}}_{\text{New!!}}$$
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New!!

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Field Eqs.: $$G^{(2,2)}_{\mu\nu}\left[g^{(0,0)}_{\mu\nu}, g^{(2,2)}_{\mu\nu}\right] = S^{(2,2)}_{\mu\nu}\left[g^{(0,0)}_{\mu\nu}, g^{(1,0)}_{\mu\nu}, g^{(1,2)}_{\mu\nu}, \vartheta^{(1,1)}\right]$$

at order (2,2)

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Spherical harmonic decomposition

➡ (r,θ) decouples

The New Metric

[KY+ (2012)]

$$g_{tt}^{\rm CS} = \zeta\chi^2 \frac{M^3}{r^3}\left[\frac{201}{1792}\left(1+\frac{M}{r}+\frac{4474}{4221}\frac{M^2}{r^2}-\frac{2060}{469}\frac{M^3}{r^3}+\frac{1500}{469}\frac{M^4}{r^4}-\frac{2140}{201}\frac{M^5}{r^5}+\frac{9256}{201}\frac{M^6}{r^6}-\frac{5376}{67}\frac{M^7}{r^7}\right)(3\cos^2\theta-1)\right.$$
$$\left.-\frac{5}{384}\frac{M^2}{r^2}\left(1+100\frac{M}{r}+194\frac{M^2}{r^2}+\frac{2220}{7}\frac{M^3}{r^3}-\frac{1512}{5}\frac{M^4}{r^4}\right)\right]+\mathcal{O}(\alpha'^2\chi'^4)\,, \tag{41}$$

$$g_{rr}^{\rm CS} = \zeta\chi^2 \frac{M^3}{r^3 f(r)^2}\left[\frac{201}{1792}f(r)\left(1+\frac{1459}{603}\frac{M}{r}+\frac{20000}{4221}\frac{M^2}{r^2}+\frac{51580}{1407}\frac{M^3}{r^3}-\frac{7580}{201}\frac{M^4}{r^4}\right.\right.$$
$$\left.-\frac{22492}{201}\frac{M^5}{r^5}-\frac{40320}{67}\frac{M^6}{r^6}\right)(3\cos^2\theta-1) \tag{42}$$
$$\left.-\frac{25}{384}\frac{M}{r}\left(1+3\frac{M}{r}+\frac{322}{5}\frac{M^2}{r^2}+\frac{198}{5}\frac{M^3}{r^3}+\frac{6276}{175}\frac{M^4}{r^4}-\frac{17496}{25}\frac{M^5}{r^5}\right)\right]+\mathcal{O}(\alpha'^2\chi'^4)\,,$$

$$g_{\theta\theta}^{\rm CS} = \frac{201}{1792}\zeta\chi^2 M^2\frac{M}{r}\left(1+\frac{1420}{603}\frac{M}{r}+\frac{18908}{4221}\frac{M^2}{r^2}+\frac{1480}{603}\frac{M^3}{r^3}+\frac{22460}{1407}\frac{M^4}{r^4}+\frac{3848}{201}\frac{M^5}{r^5}+\frac{5376}{67}\frac{M^6}{r^6}\right)(3\cos^2\theta-1)$$
$$+\mathcal{O}(\alpha'^2\chi'^4)\,, \tag{43}$$

$$g_{\phi\phi}^{\rm CS} = \sin^2\theta\, g_{\theta\theta}^{\rm CS}+\mathcal{O}(\alpha'^2\chi'^4) \tag{44}$$

Contents

GWs from BH Binaries in CS Gravity

parameterized post-Einsteinian waveform: Yunes & Pretorius (2009)

$$\tilde{h}(f) = \tilde{h}_{\rm GR}(f)\left[1 + \boxed{\alpha_{\rm ppE}}\, u^{\boxed{a_{\rm ppE}}}\right] \exp\left(i \boxed{\beta_{\rm ppE}}\, u^{\boxed{b_{\rm ppE}}}\right)$$

$$u \equiv \pi \mathcal{M} f \propto v^3$$

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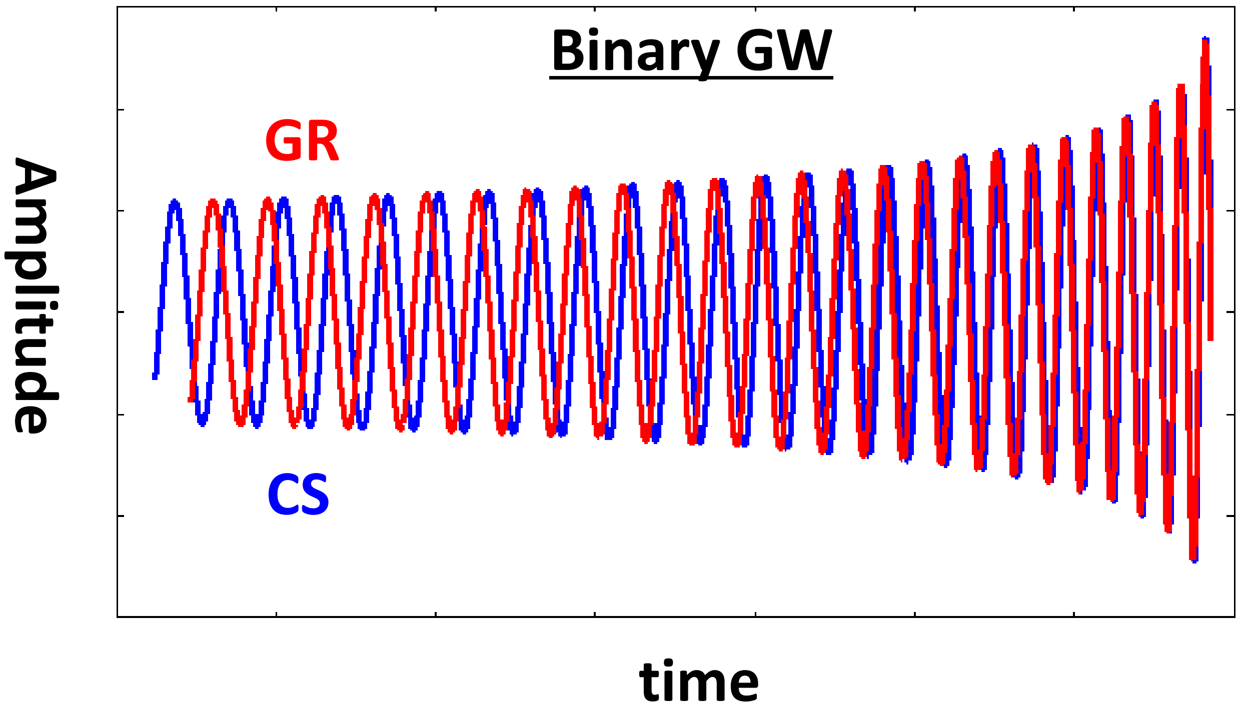
$$u \equiv \pi \mathcal{M} f \propto v^3$$

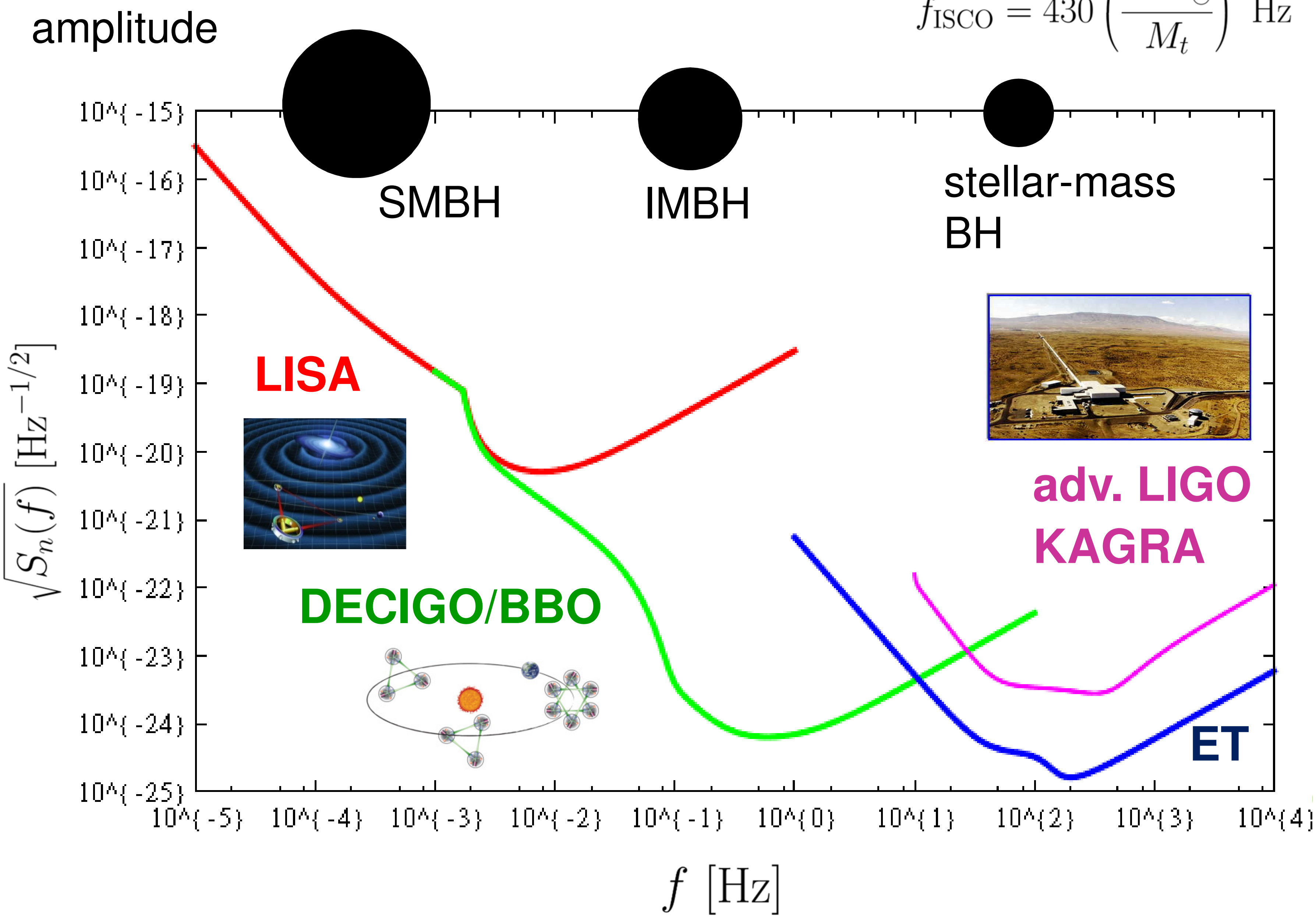
CS Gravity: $\boxed{\alpha_{\rm ppE}} = 0$ $\quad \boxed{\beta_{\rm ppE}} = C(m_{1,2}, \hat{S}^i_{1,2})\zeta\chi^2$ $\quad \boxed{b_{\rm ppE}} = -\frac{1}{3}$

2PN correction



GW DETECTORS

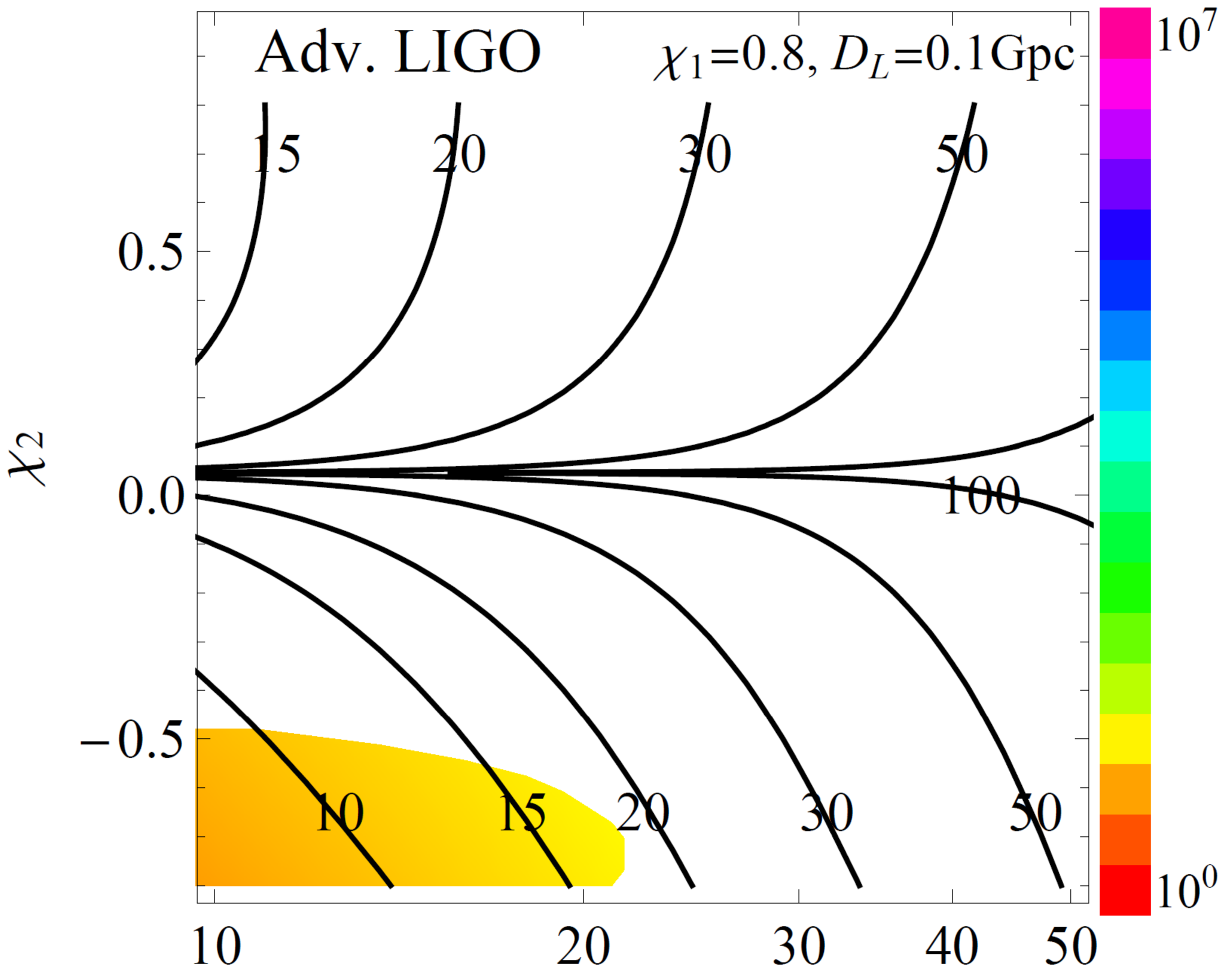
$$f_{\rm ISCO} = 430 \left(\frac{10 M_\odot}{M_t} \right) \ \mathrm{Hz}$$



Results: Adv. LIGO, KAGRA

$m_1/m_2 = 2$

Constraints on $\xi^{1/4}(\mathrm{km})$



total mass $m/M_\odot$ [KY+ (2012)]

Spins are known *a priori*

Colored Region:

$$\Delta\zeta < 1$$

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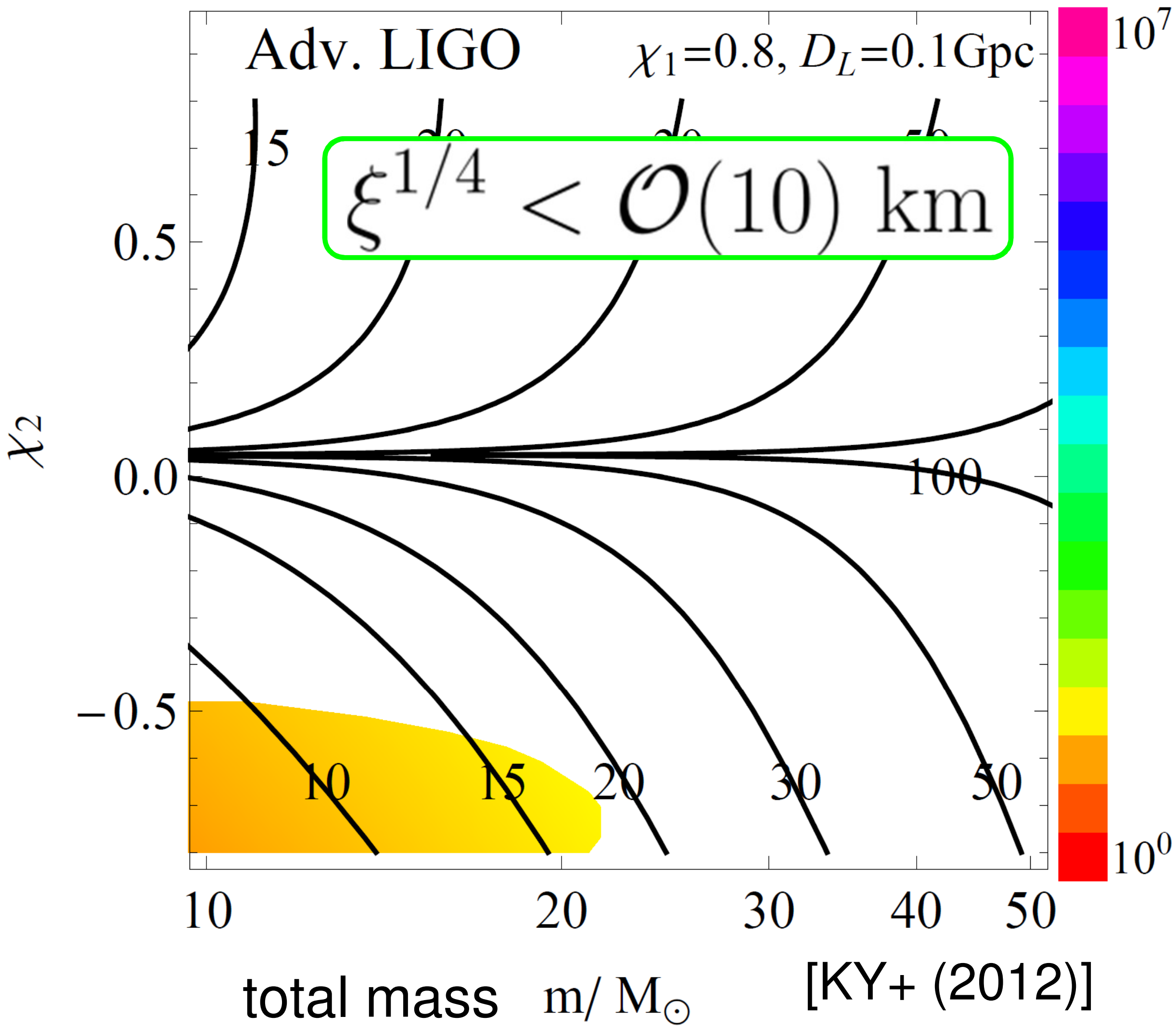

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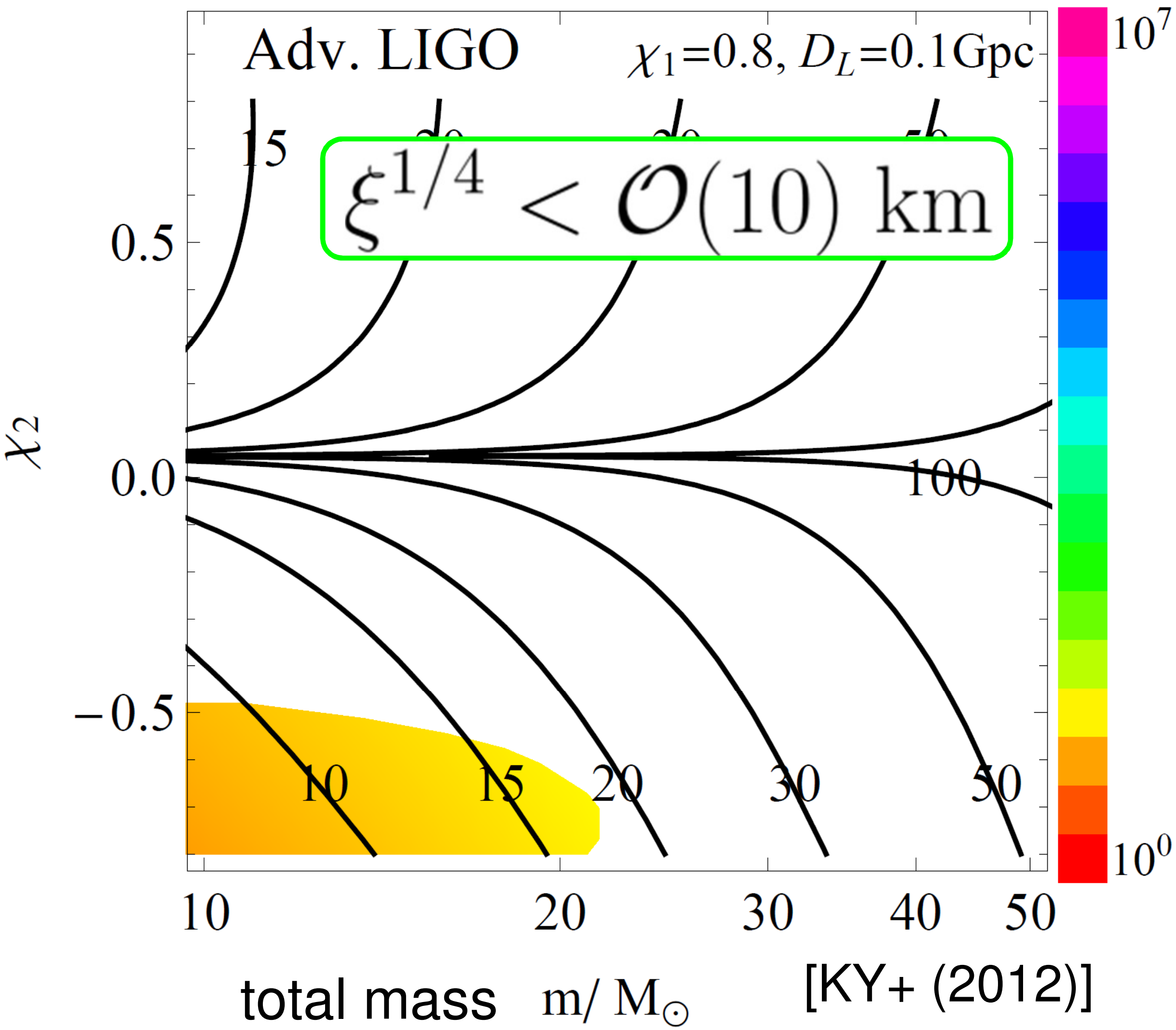

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The bound roughly corresponds to the BH horizon size.

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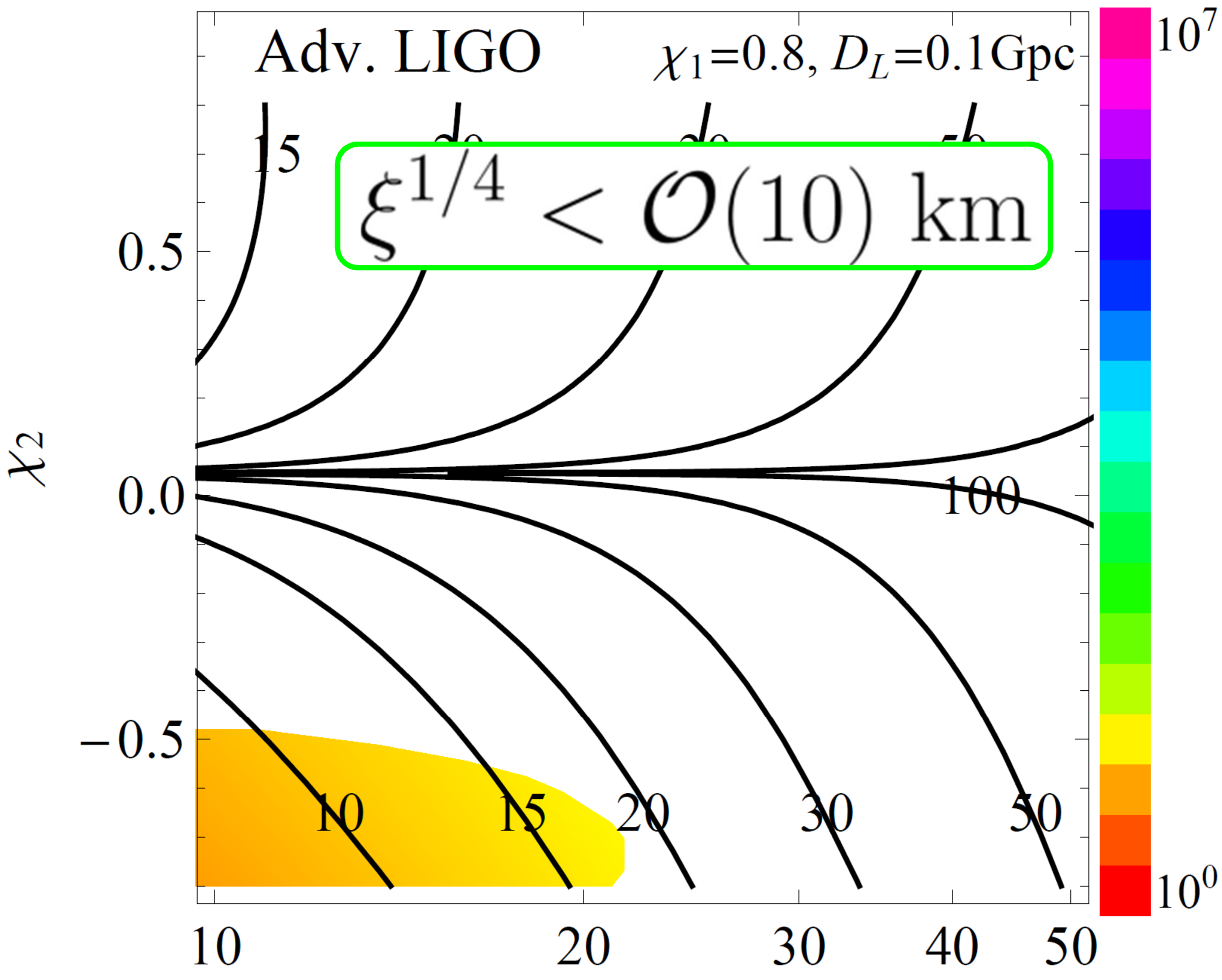

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Solar system:

$$\xi^{1/4} < \mathcal{O}(10^8)\ \mathrm{km}$$

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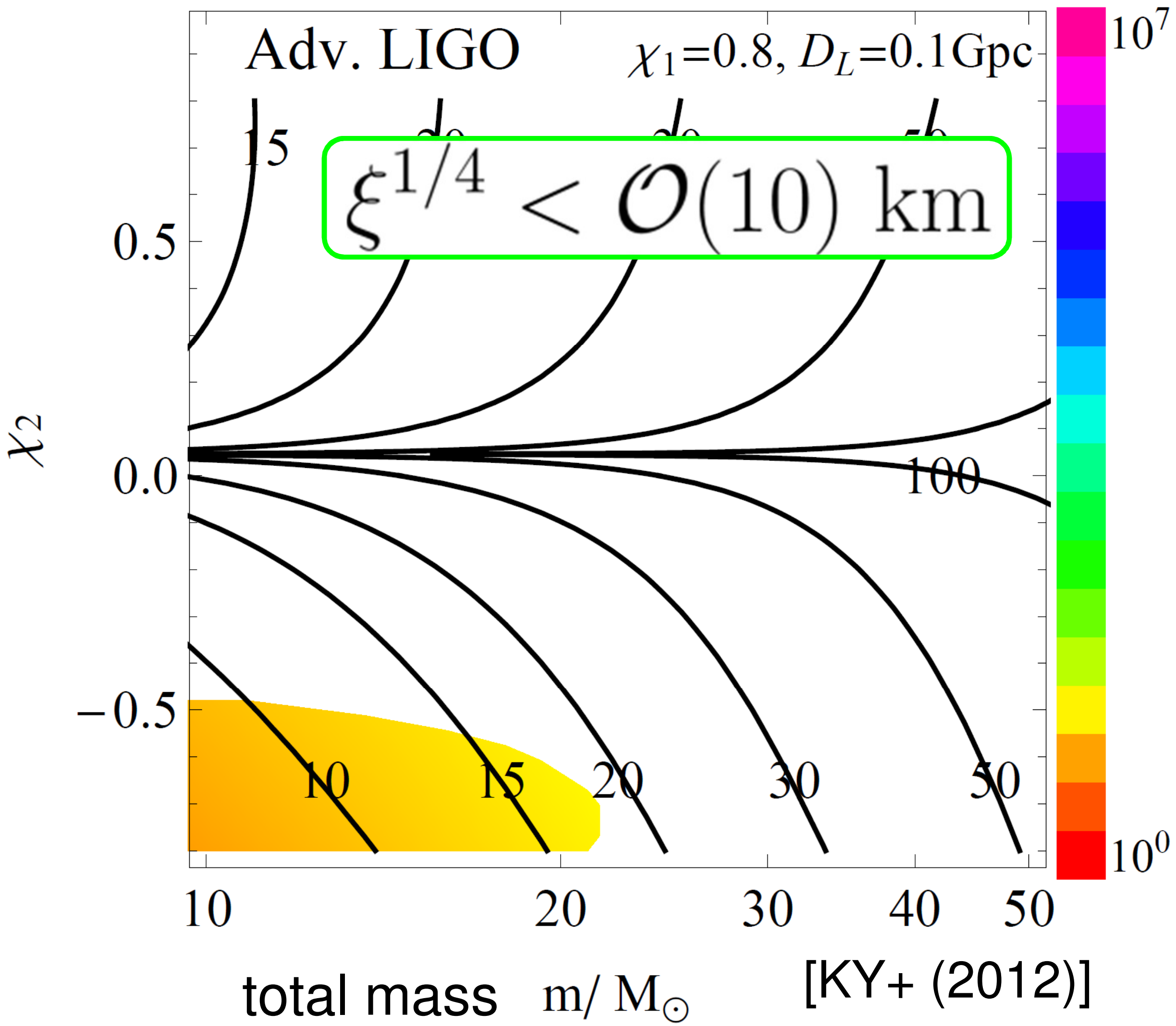

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The bound roughly corresponds to the BH horizon size.

Solar system:

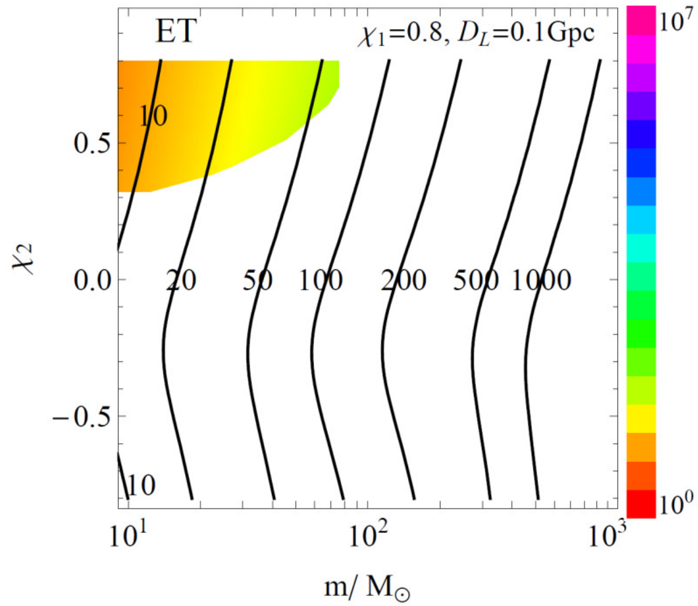
$$\xi^{1/4} < \mathcal{O}(10^8)\ \mathrm{km}$$

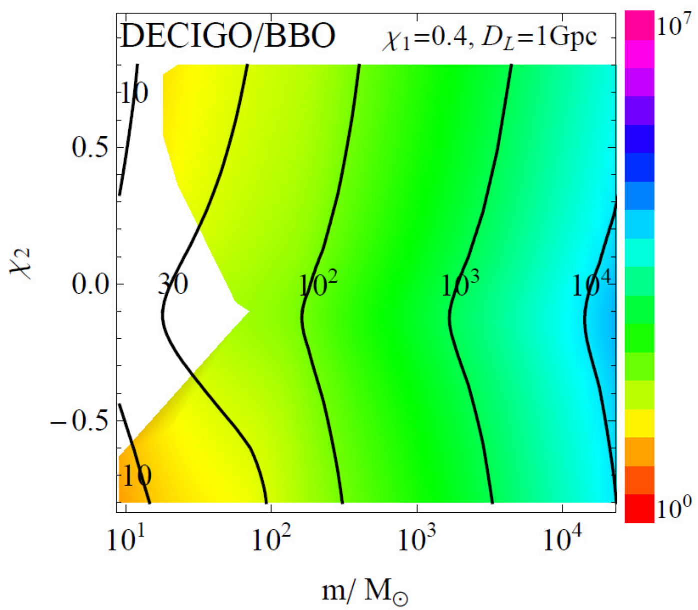
7 orders of magnitude stronger constraint than the solar system bound!!

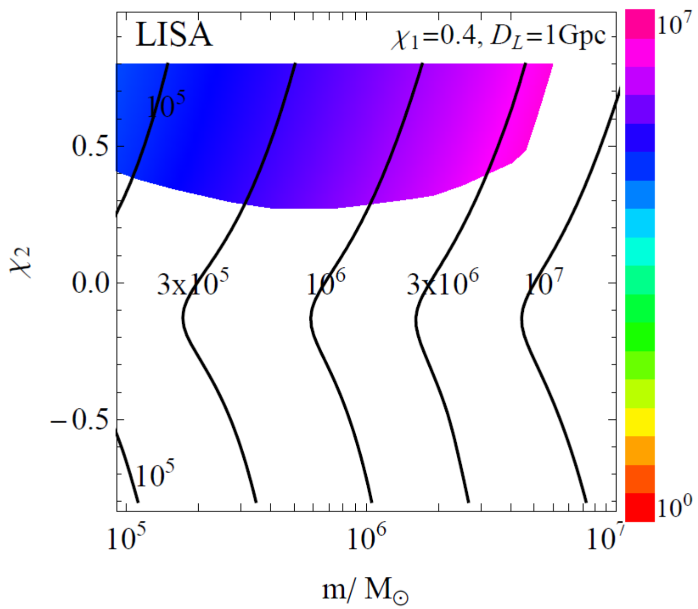
Results: Other Detectors

spin (anti-)aligned binaries

(Spins are included into parameters.)







Contents

-New BH Solution to quadratic order in spin

➡ 2PN Conservative Correction

-PN Scheme ➡ 2PN Dissipative Correction

➡ First self-consistent BH Binary gravitational waveforms

2nd generation ground-based interferometers

➡ 7 orders of magnitude stronger constraint than the solar system bound!!

Future Work

- Precessing BH binaries
- Bayesian analysis, more realistic detector noises
- Modeling NSs in dynamical CS gravity

➡ Current constraints from double binary pulsar obs.