Constrain alternative theories of gravity by gravitational wave observations

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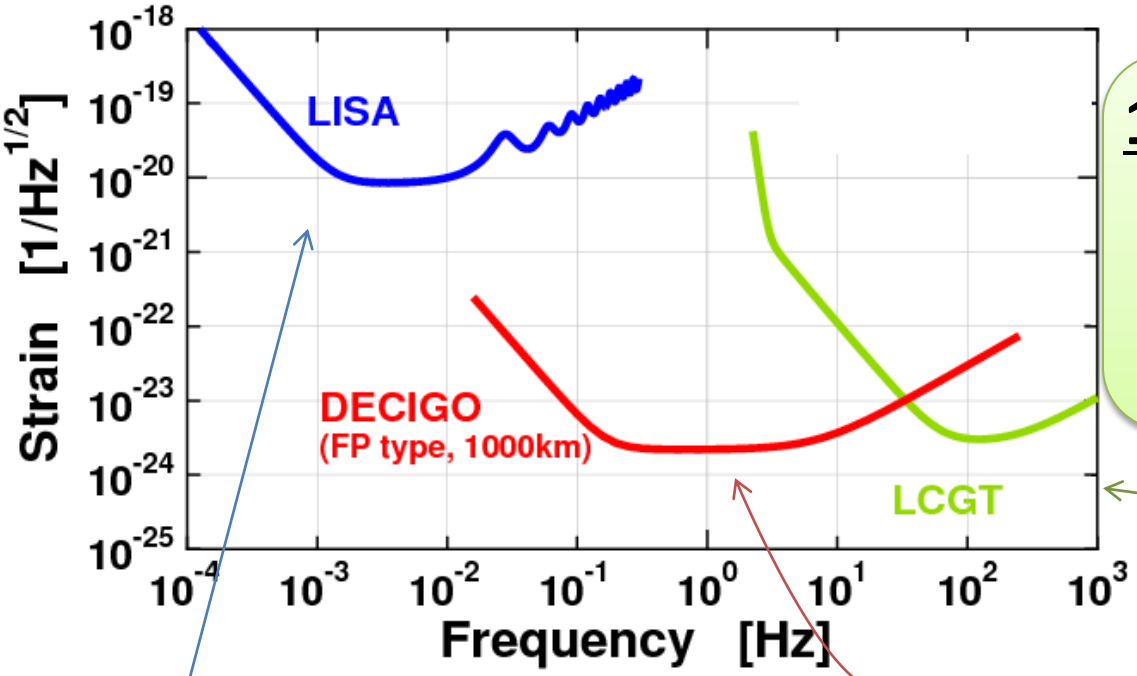
Gravitational wave observations



100Hz band : LIGO, LCGT, …

NS/BH merger

GRB central engine

Primordial black hole

1Hz band : DECIGO, BBO

GW from inflation

IMBH binary, EMRI

Cosmological binary

mHz band : LISA

super-massive BH binary

Extreme mass-ratio inspiral (EMRI)

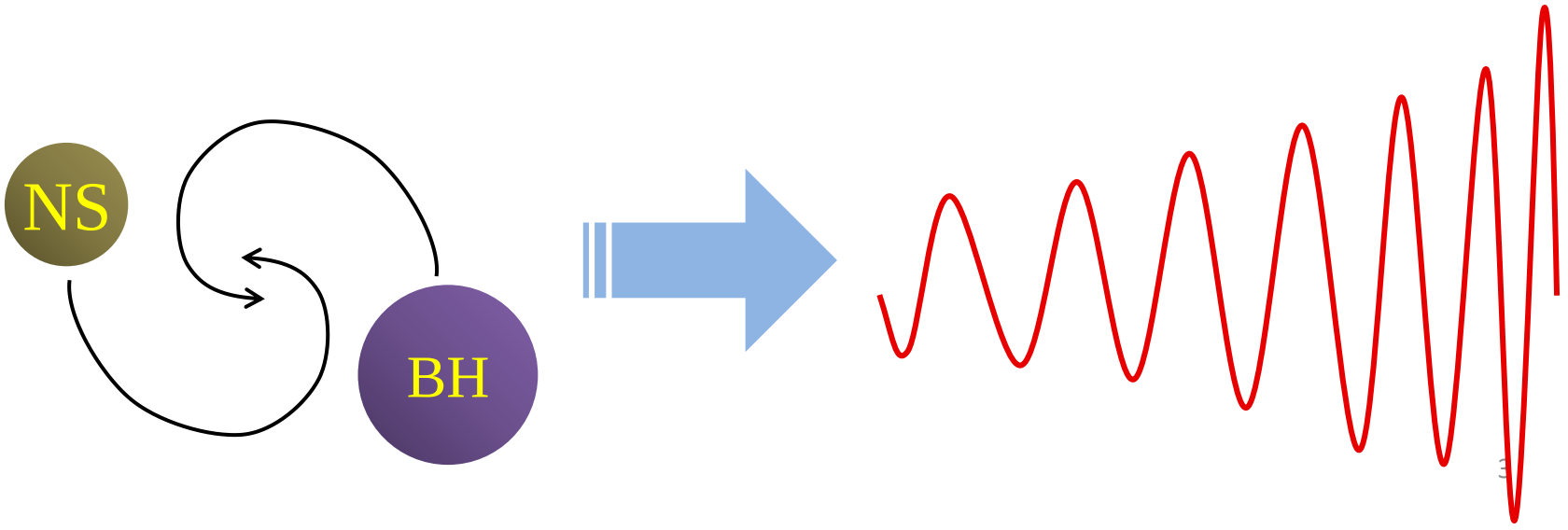
Galactic binary

Gravitational wave observations

- Binary and Gravitational wave
  - Quadrupole formula for gravitational wave emission

$$\text{(GW power)} = \frac{1}{5}\left\langle \dddot{Q}_{ij}\dddot{Q}_{ij} \right\rangle$$

$$Q_{ij} = \int d^3x\ \rho\left(x^i x^j - \frac{1}{3}r^2\delta^{ij}\right)$$: mass quadrupole moment



Gravitational wave observations

- Binary parameters : $\boldsymbol{\theta} \in (M, J, \ldots)$
- GW wave form : $h = h(f, \boldsymbol{\theta})$
- signal : $s = h(f, \boldsymbol{\theta}) + n(f)$

- Parameters $\boldsymbol{\theta}$ can be read out from signal s by taking correlation with theoretical wave form h.
  - (signal-to-noise ratio) $\approx \int h \cdot s \, df$
  - Estimated $\boldsymbol{\theta}$ = $\boldsymbol{\theta}$ that maximizes SNR
  - Estimation error = degeneracy of h around $\boldsymbol{\theta}$

$$\approx \int (\partial h / \partial \boldsymbol{\theta})^2 \, df$$

Probe modified gravity by GW

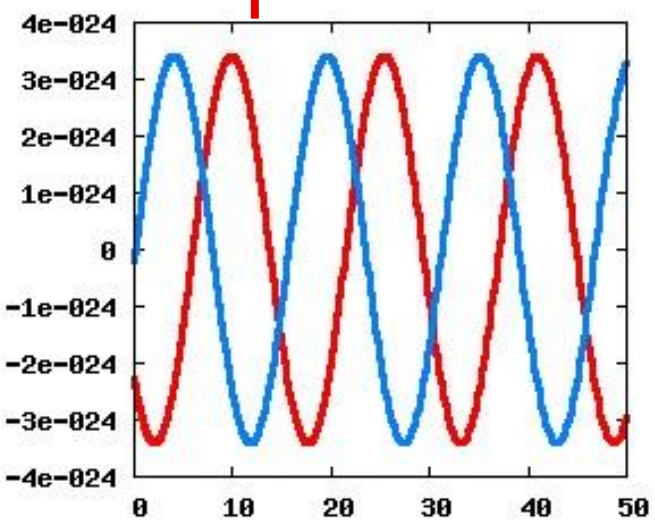
- When the **Einstein gravity is modified**, both of
  - **binary motion**
  - **quadrupole formula**

  are modified.

→ **Gravitational wave will be modified**,
and **may be detectable.**

years before merger

binary merger



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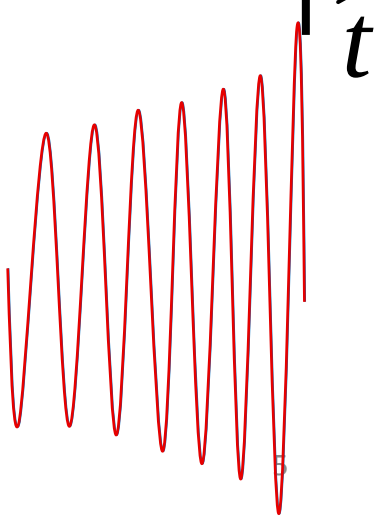
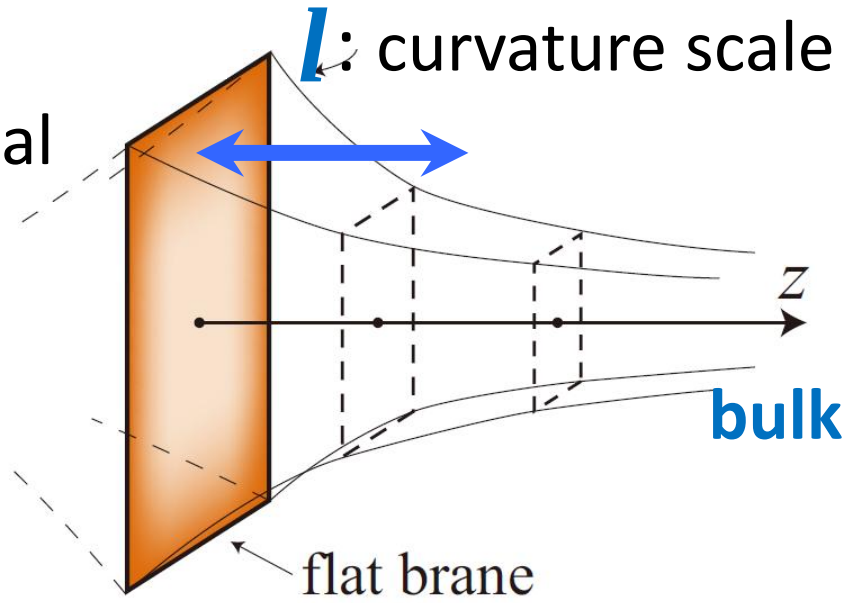
red: GR

blue: modified gravity



Braneworld model

- ✓ 4D **brane** in higher-dimensional spacetime (**bulk**)
- ✓ **Only gravity can propagate in the bulk**



- Randall-Sundrum II (RS-II) model
  - **5D AdS bulk** / **flat 4D spacetime on the brane**
  - **Weak gravitation on the brane mimics 4D gravity**

$$V(r) = \frac{Gm_1m_2}{r}\left(1 + \frac{2l^2}{3r^2}\right)$$

5D correction

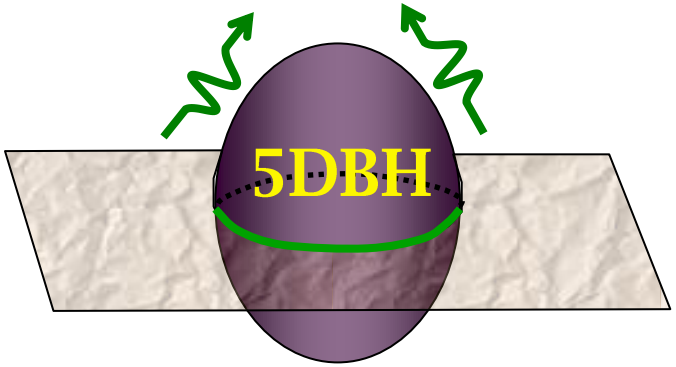
- **5D BH** in RS-II model ≈ Rapidly evaporating 4D BH

[Tanaka, 2002; Emparan et al., 2002]

5D picture :

5D BH

deforming due to some instability



4D picture :

4D BH

losing its mass via

Hawking radiation

where **radiation is amplified** by

$$l^2/G_4 = 10^{73} \text{ x } (l / 1\text{mm})^2$$

(l: codimension scale)

Constrain l by DECIGO/BBO

[Yagi, NT & Tanaka, in prep.]

- Strong Hawking radiation from BH modulates GW.
- Larger l → stronger rad. → larger GW modulation

- If we observe GW that is consistent with pure GR, we can constrain l up to estimation error $\int (\partial h / \partial \theta)^2 \, df$.

BBO (4 clusters), $(1.4+10)M_{\odot}$,
statistical anlysis of 10^4 binaries

Obs. time	Upper bound on l
1yr	9.62 (μ m)
3yr	3.73 (μ m)
5yr	2.62 (μ m)

10 time better than table-top experiments!
($l \leq 50\mu m$)

Summary

- GW observation may be useful to constrain alternative theories of gravity.

- In the RS-II braneworld model, we may observe the extradimension scale l via observations of astrophysical black holes.
  - Observation of the effect of strong radiation from BH encoded in GW modulation

- GW observation by DECIGO/BBO

  → can make the upperbound ***10 times stronger***.