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Test of gravity with gravitational wave observations

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Aug. 8-10, 2018
MOGRA 2018 @ Nagoya U.

1. Introduction

2. GW propagation speed

3. GW amplitude damping

4. Generalized framework for testing GW propagation

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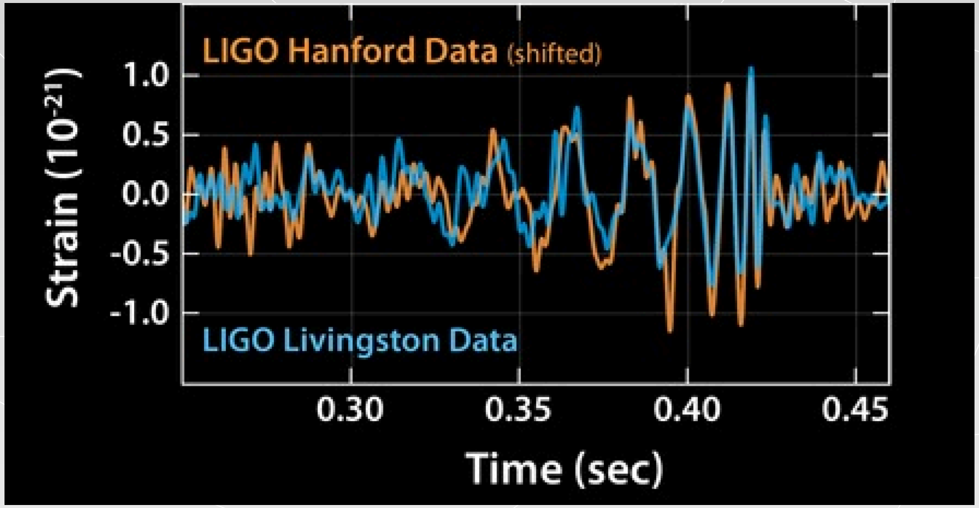
Gravitational Waves

- 5 GWs from BBH and 1 GW from BNS have been detected.



LIGO Scientific Collaboration 2016 – 2017

- merger rate BBH: $12 - 213\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

  BNS: $330 - 4740\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

- aLIGO & aVIRGO are expected to detect more events

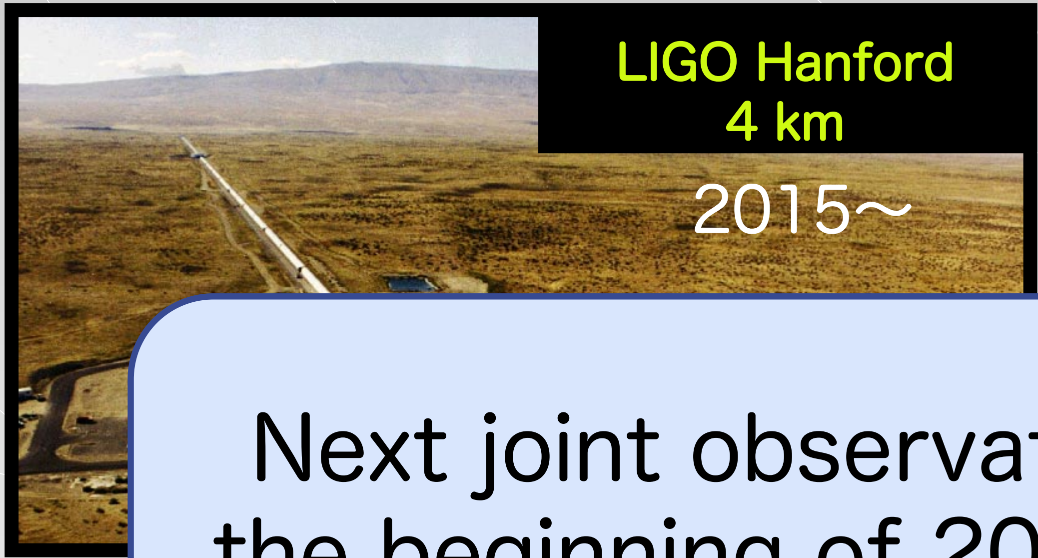
  $\sim 100 - 1000$ BBH up to $z \sim 1$

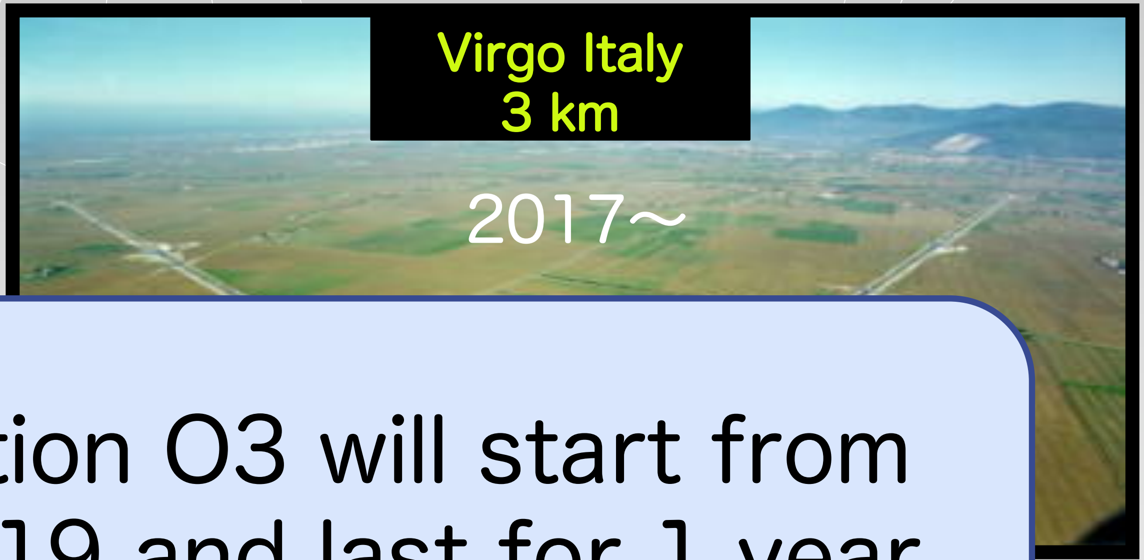
  $\sim 20 - 400$ BNS up to $z \sim 0.1$

This opens a new window to see the Universe.

GW detector network

GW detector network

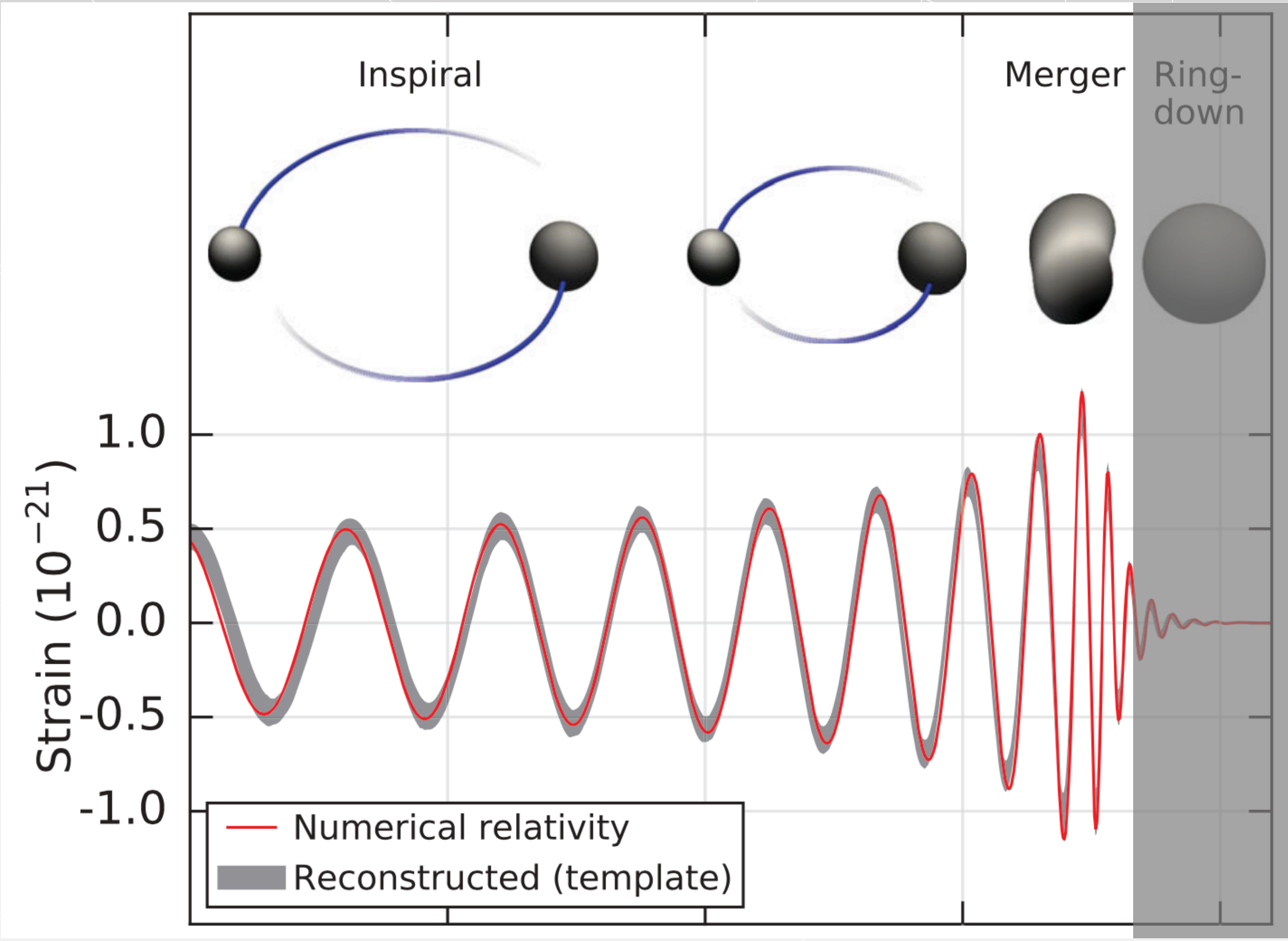




Next joint observation O3 will start from the beginning of 2019 and last for 1 year.
KAGRA will join at later time.

GW waveform

BH-BH, NS-BH, NS-NS binary



depends on neutron star or black hole

In case of neutron stars, mass ejection occurs.
(waveform is not so clean)

LIGO Scientific Collaboration, PRL 2016 (GW150914)

GW in modified gravity

So far, various modified gravity theories have been suggested.
(scalar-tensor theory, f(R) gravity, massive gravity etc.)

Those theories could alter tensor perturbations and predict the properties of GWs different from GR:

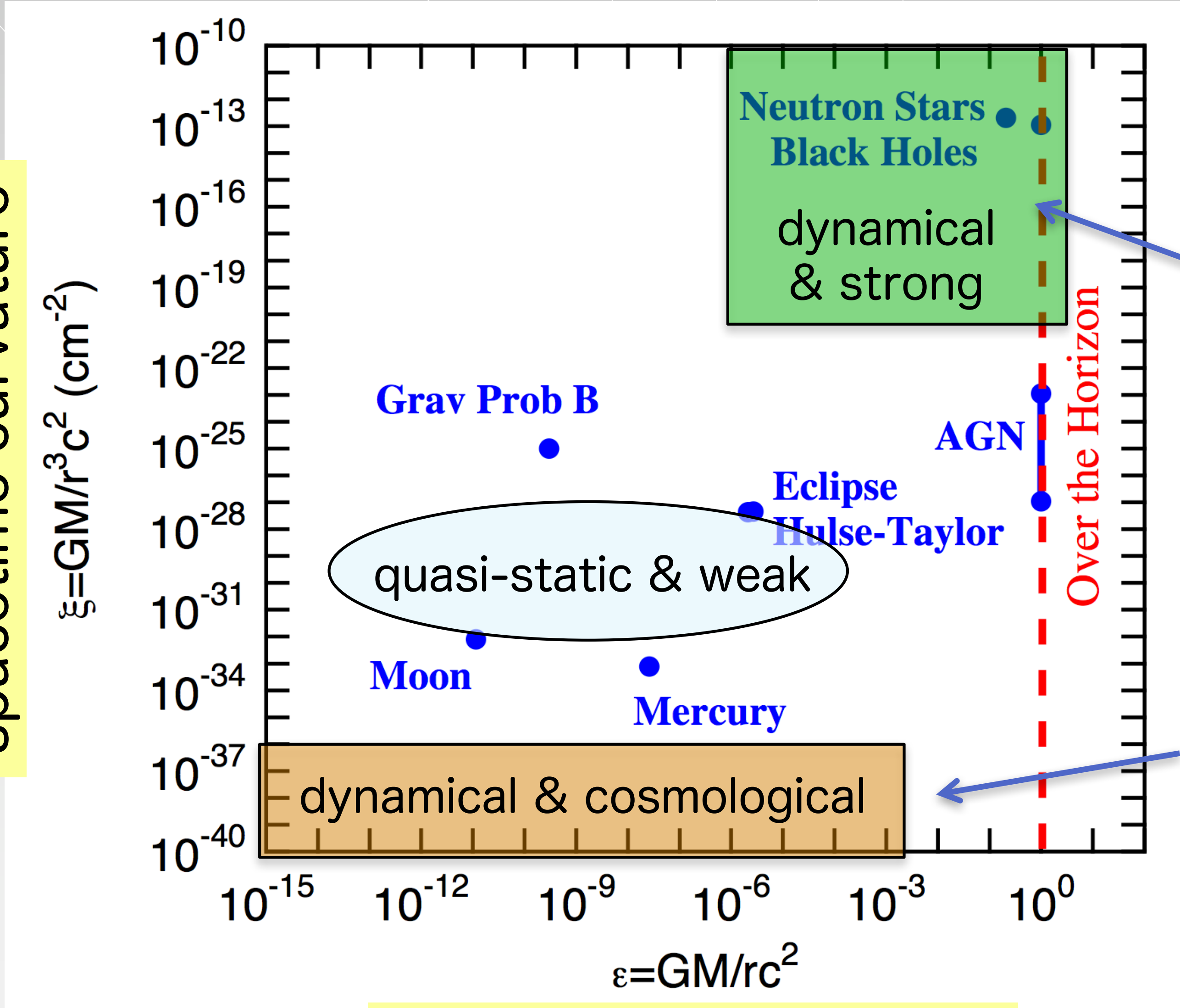
- different phase evolution of GWs
- additional GW polarizations (scalar & vector pols.)
- different propagation of GW
- massive gravitons

GW observation can be utilized for
- direct test of general relativity
- probe for the extended theories beyond GR

Gravity test with GW

small scale

spacetime curvature



Psaltis 2008 (modified)

GW generation

GW propagation

large scale

gravitational potential

weak → strong

Advantages for GW propagation

1. GW propagation can test gravity in dynamical regime
   at cosmological distance.

2. Even if modification on gravity is a tiny effect, propagation
   can accumulate the effect because of long distance.

3. Propagation equation is covariant, i.e. independent of
   GW sources and background spacetimes
   (NS, BH, supernova, pulsar, stochastic background etc.)

4. Parametrization is directly related to observables and physics
   behind them and is easy to combine with other observations
   (cosmology, binary pulsar, Solar system)

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Constraints on GW speed before GW170817

From the observations of ultra-high energy cosmic rays (UHECR)

Moore & Nelson 2001

If a graviton propagates with subluminal speed, it looses energy due to gravitational Cherenkov radiation.

$$\delta_g \equiv 1 - \frac{v_g}{c} < 2 \times 10^{-15}$$

applied only to subluminal case

at $\sim 10^{33}\,\mathrm{Hz}$

From arrival time difference between LIGOs

Cornish et al. 2017

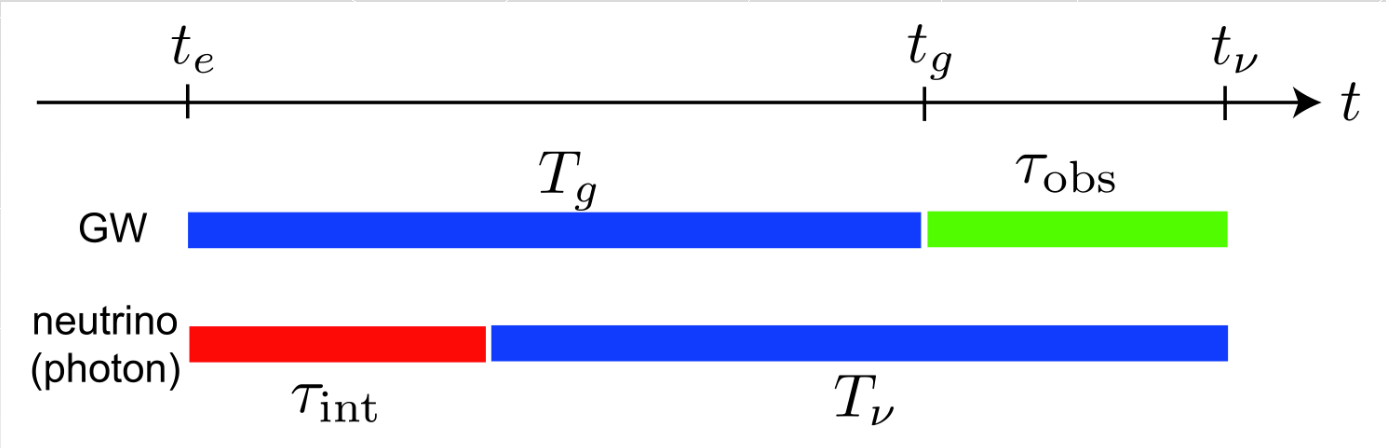
GW150914	$6.9 \pm 0.30\,\mathrm{ms}$
GW151226	$1.1 \pm 0.18\,\mathrm{ms}$
GW170104	$3.0 \pm 0.30\,\mathrm{ms}$

⇒ $-0.42 < \delta_g < 0.45$

Measuring GW speed

Nishizawa & Nakamura 2014

arrival time difference between GW and short GRB



$$|\delta_g| < \frac{c\,\Delta\tau_{\rm int}}{D} \qquad \delta_g \equiv \frac{c - v_g}{c}$$

$\Delta\tau_{\rm int}$: uncertainty of intrinsic time delay

$\Delta\tau_{\rm int} = 10\,{\rm sec}$, $D = 200\,{\rm Mpc}$ ⇨ $|\delta_g| < 5 \times 10^{-16}$

GW170817/GRB170817A

LSC + Fermi + INTEGRAL, ApJL 848, L13

measured values $\tau_{\rm obs} = 1.7\,\mathrm{sec}\,,\quad D_{\rm min} = 26\,\mathrm{Mpc}$

$$\delta_g \equiv \frac{c - v_g}{c}$$

- superluminal

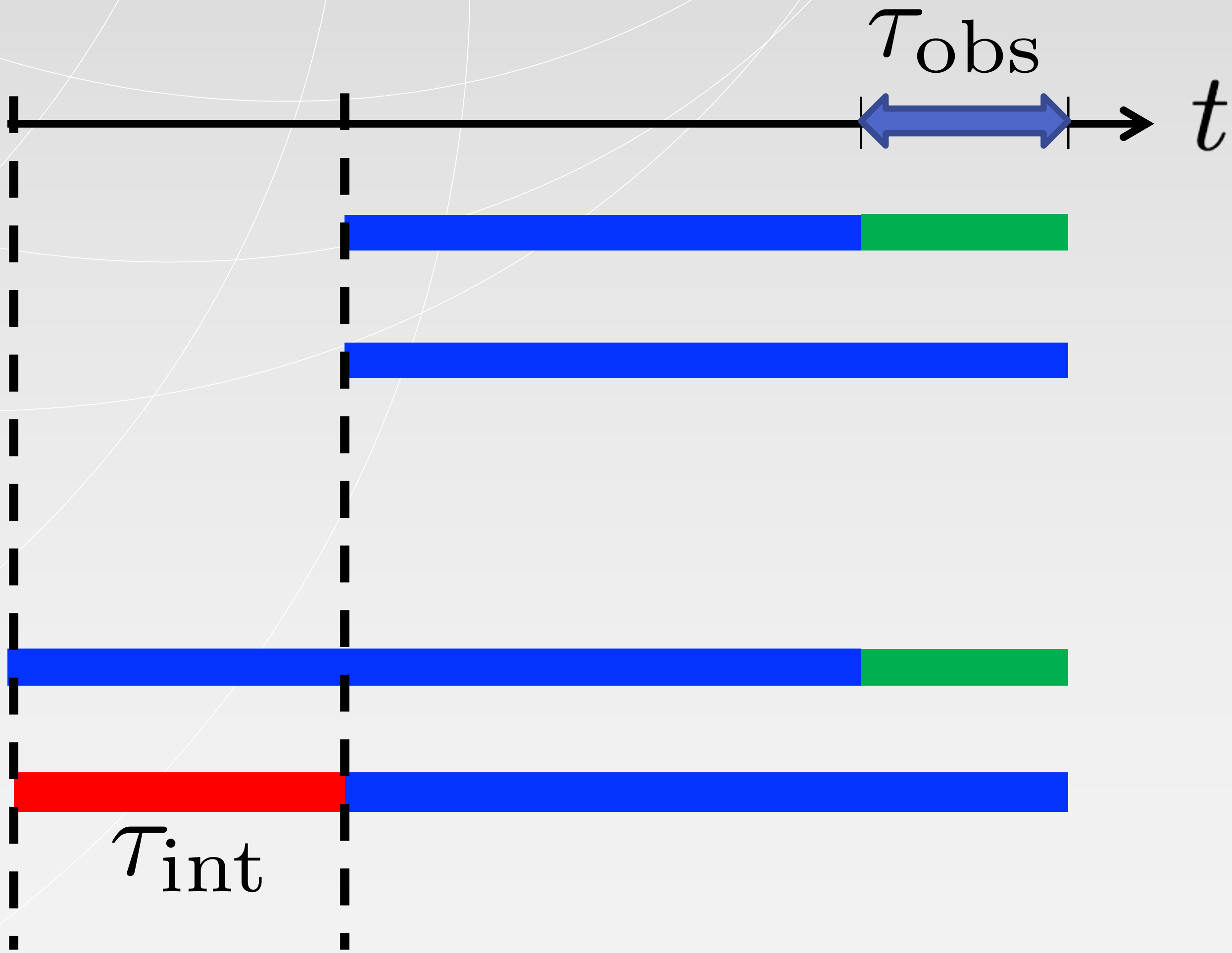
$\tau_{\rm int} > 0$

$-7 \times 10^{-16} < \delta_g \leq 0$

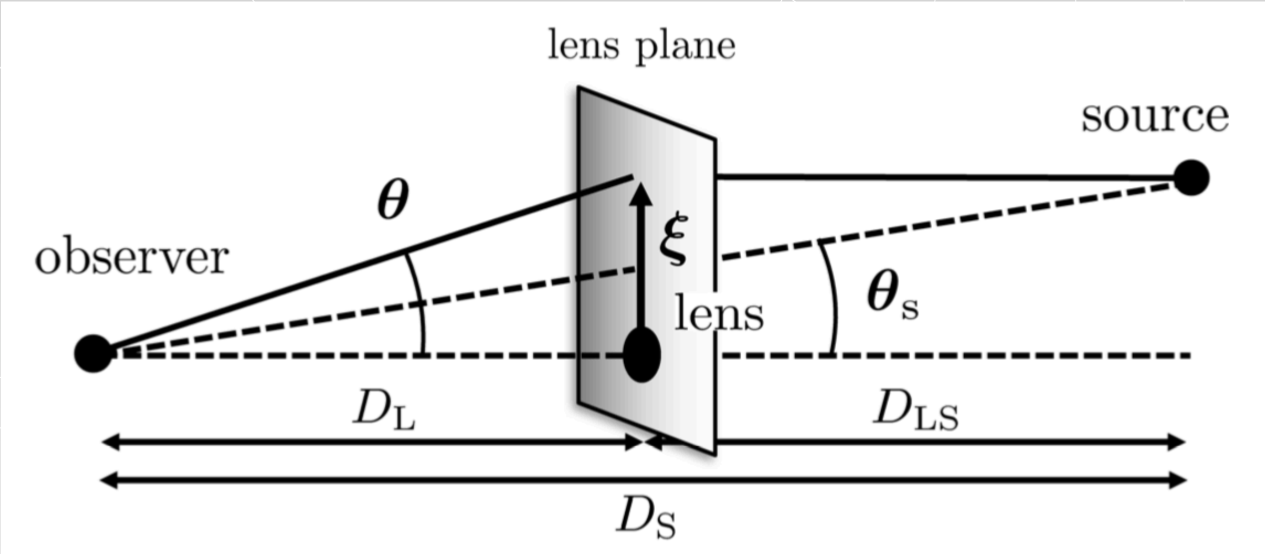
- subluminal

$\tau_{\rm int} < 10\,\mathrm{sec}$

$0 \leq \delta_g < 3 \times 10^{-15}$



Wave effect of lensing



R. Takahashi 2017

The geometrical optics breaks down for GW lensed by

mass of $\lesssim 10^5\, M_\odot \left(\frac{1\,\mathrm{Hz}}{f}\right)$

GW with frequency f can arrive earliar than EM wave by

time lag of $0.1\,\mathrm{sec}\left(\frac{1\,\mathrm{Hz}}{f}\right)$ ⇒ relevant to space-baced detectors (LISA, DECIGO)

Horndeski theory

$$S = \int dx^4 \sqrt{-g} \left[\sum_{i=2}^{5} \mathcal{L}_{\rm i} + \mathcal{L}_{\rm m} \right]$$

Horndeski 1974
Deffayet, Gao, Steer, and Zahariade 2011
Kobayashi, Yamaguchi, Yokoyama 2011

$$\mathcal{L}_2 = K(\phi, X) \,,$$

$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi \,,$$

$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right] \,,$$

$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}(\nabla^\mu\nabla^\nu\phi) - \frac{1}{6}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)(\nabla^\alpha\nabla_\beta\phi)(\nabla^\beta\nabla_\mu\phi)\right]$$

- Most general scalar-tensor theory containing up to 2nd order spacetime derivatives.
- A single scalar field, but with arbitrary functions of ϕ and $X = -\nabla_\mu\phi\nabla^\mu\phi/2$ $\longrightarrow$ $G_2(K), G_3, G_4, G_5$

Constraint on gravity theories

GW propagation speed

$$c_{\mathrm{T}}^2 - 1 = \frac{X\{2G_{4,X} - 2G_{5,\phi} - (\ddot{\phi} - \dot{\phi}H)G_{5,X}\}}{G_4 - 2XG_{4,X} + XG_{5,\phi} - \dot{\phi}HXG_{5,X}}$$

⇩

Without fine-tuning for the cancellation,

$$G_{4,X} = 0,\ G_5 = 0.$$

Baker et al. 2017
Creminelli & Vernizzi 2017
Ezquiaga & Zumalacarregui 2017
Sakstein & Jain 2017
Arai & Nishizawa 2018

Horndeski theory after GW170817

$$\mathcal{L}_{\rm Horn} = K(\phi, X) - G_3(\phi, X)\Box\phi + G_4(\phi)R$$

Now, without fine-tuning, specific modified gravity theories for cosmic acceleration are

still allowed

quintessence
f(R) gravity
nonlinear kinetic theory

ruled out

cubic galileons
covariant galileons
Fab four

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Standard siren

GW from a compact binary can be a cosmological tool to measure distance to a source. Schutz 1986, Holz & Hughes 2005

GW phase

from $L_{\rm gw} = -\dfrac{dE_{\rm orbit}}{dt}$

$$\dot{f}(t) \propto \{(1+z)M_c\}^{5/3} f^{11/3}$$

GW amplitude

$$h(t) \propto \frac{\{(1+z)M_c\}^{5/3} f^{2/3}}{D_L}$$

From observational data,

$$h, f, \dot{f} \cdots$$

⬇

$$M_z \equiv (1+z)M_c$$

⬇

luminosity distance

$$D_L$$

Hubble constant from GW170817

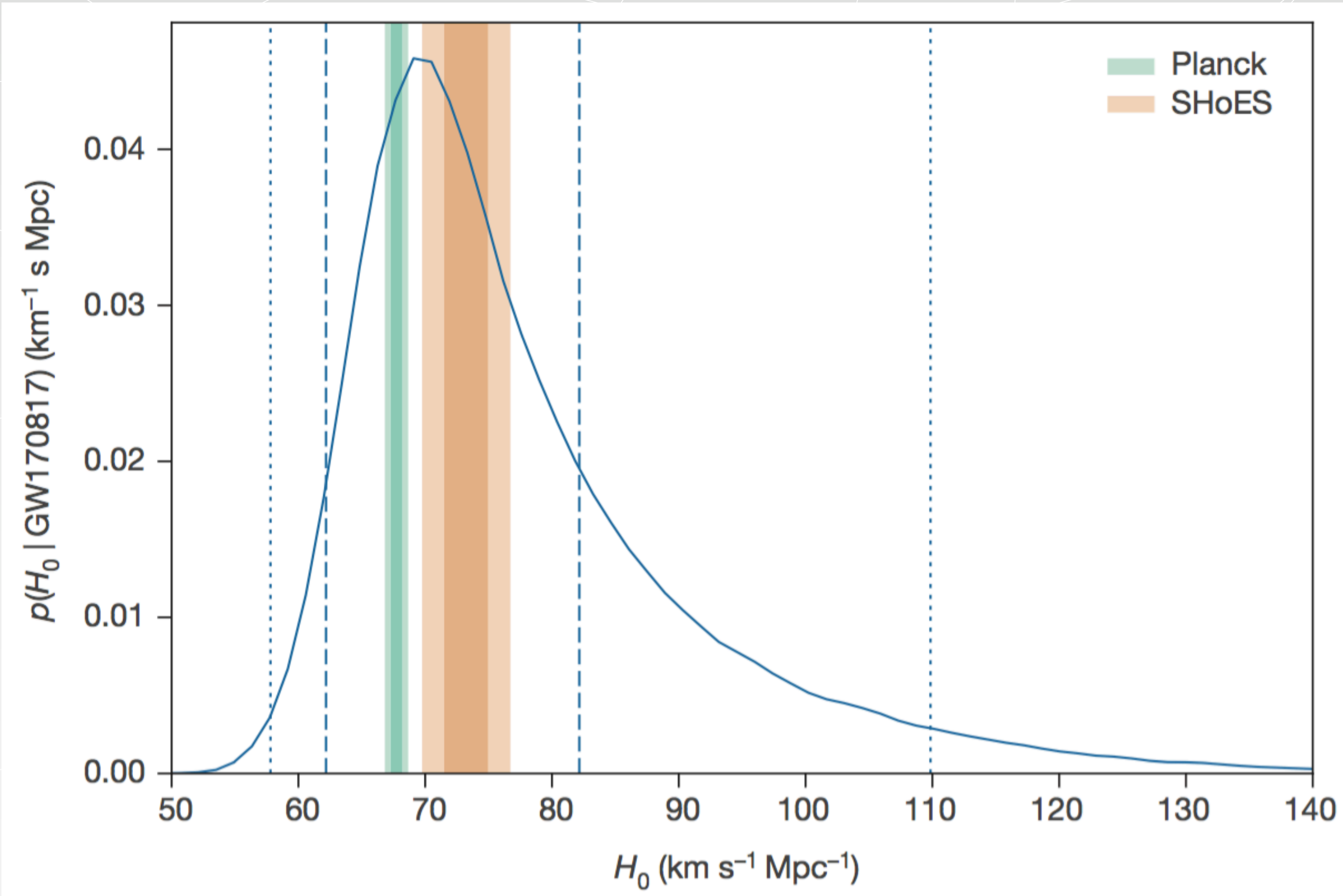
LSC + optical telescopes, Nature 551, 85

at low redshift ,

from GW observation

$$d_{\mathrm{L}} \approx \frac{z}{H_0}$$

from EM observation of the host galaxy



Amplitude damping in MG

F(R) gravity   Hwang &Noh 1996

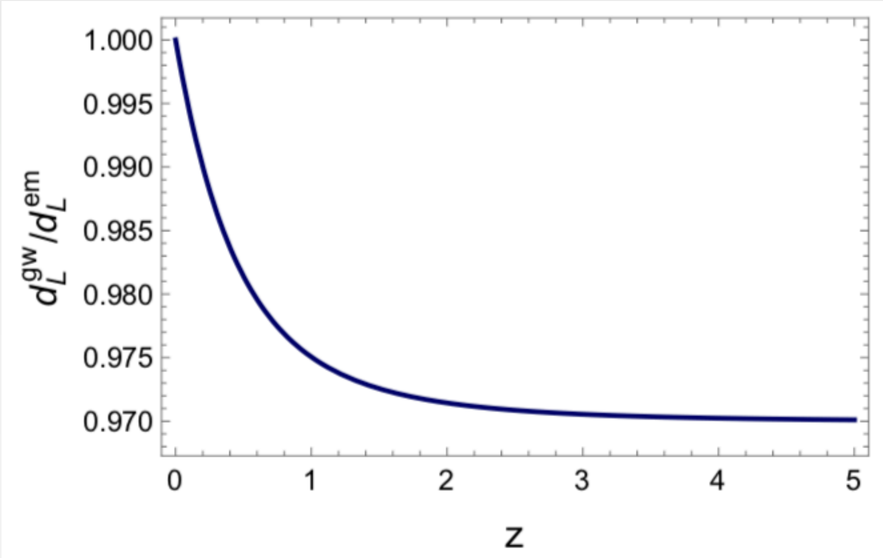
$$h''_{ij} + \left(2\mathcal{H} + \frac{\dot{F}}{F}\right) h'_{ij} + c^2 k^2 h_{ij} = 0 \qquad F \equiv \frac{df(R)}{dR}$$

If $\dot{F}/F = \mathrm{const.}\ ,\qquad d_L^{(\mathrm{eff})}(z) = (1+z)^{\dot{F}/2F} d_L(z)$

nonlocal RR gravity   Belgacem et al. 2018

$$\mathcal{L} \supset m^2 R \Box^{-2} R$$

$$h''_{ij} + \{2 - \delta(\tau)\}\, \mathcal{H} h'_{ij} + c^2 k^2 h_{ij} = 0$$



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Generalized propagation of GW

Saltas et al. 2014

GW propagation eq. in the effective field theory at the linear level

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + (c_T^2 k^2 + a^2\mu^2)h_{ij} = a^2\Gamma\gamma_{ij}$$

C_T : GW propagation speed

μ : graviton mass

$\nu = \mathcal{H}^{-1}\frac{d\ln M_*^2}{dt}$: effective Planck mass run rate (variation of G)

Γ : source for GW

Classification of gravity theories

gravity theory	ν	$c_T^2 - 1$	μ	Γ
general relativity	0	0	0	0
Horndeski theory	α_M	α_T	0	0
f(R) gravity	$F'/\mathcal{H}F$	0	0	0
Einstein-aether theory	0	$c_\sigma/(1+c_\sigma)$	0	0
bimetric massive gravity theory	0	0	$m^2 f_1$	$m^2 f_1$
quantum gravity phenom.	0	$(n_{\rm QG}-1)\mathbb{A}E^{n_{\rm QG}-2}$	when $n_{\rm QG}=0$	0

$$E^2 = p^2 \left[1 + \xi \left(\frac{E}{E_{\rm QG}} \right)^{n_{\rm QG}-2} \right]$$

doubly special relativity
extra dimensional theories
Horava-Lifshitz theory
gravitational SME
⋮

WKB solution

Nishizawa 2018

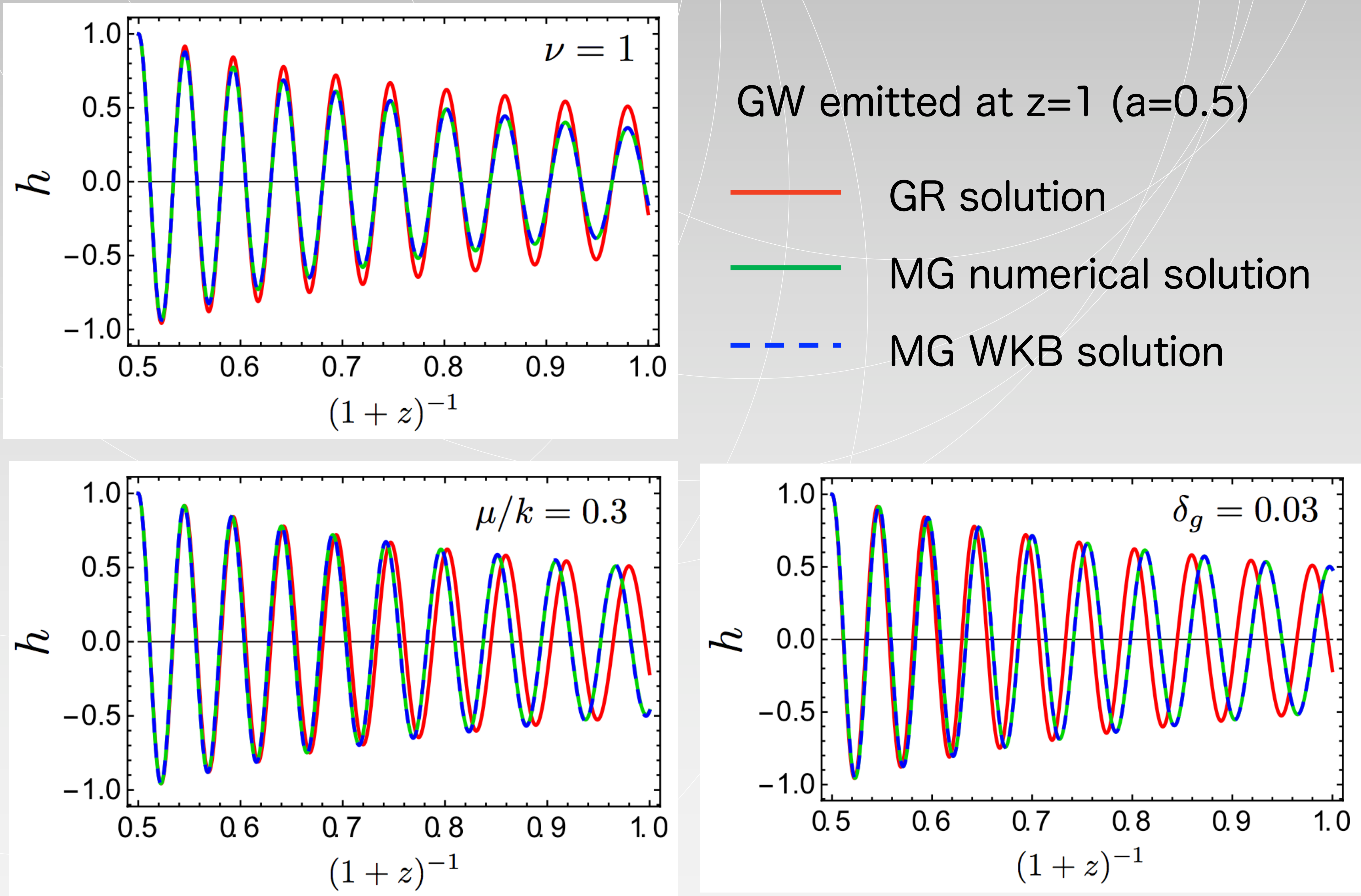
For $\Gamma = 0$, the eq. can be solved analytically, if the amplitude is a slowly varying function with cosmo timescale.

$$h = \mathcal{C}_{\rm MG} h_{\rm GR} \qquad \mathcal{C}_{\rm MG} = e^{-\mathcal{D}} e^{-ik\Delta T}$$

damping factor $\mathcal{D} = \frac{1}{2}\int_0^z \frac{\nu}{1+z'} dz'$ $\qquad c_T \equiv 1 - \delta_g$

extra time delay $\Delta T = \int_0^z \frac{1}{\mathcal{H}} \left(\frac{\delta_g}{1+z'} - \frac{\mu^2}{2k^2(1+z')^3} \right) dz'$

Even when $\Gamma \neq 0$, an analytical solution is also obtained.


GW emitted at z=1 (a=0.5)
GR solution
MG numerical solution
MG WKB solution
ν = 1
μ/k = 0.3
δ_g = 0.03
h
(1 + z)^{-1}
1.0
0.5
0.0
−0.5
−1.0
0.5
0.6
0.7
0.8
0.9
1.0

Constraining the time evolution

- Expansion up to linear order in time

Arai & Nishizawa 2018

$$\nu = \nu_0 - \nu_1 H_0 t_{\rm LB}$$
$$\delta_g = \delta_{g0} - \delta_{g1} H_0 t_{\rm LB}$$

$t_{\rm LB}(t)$: lookback time in the standard ΛCDM universe

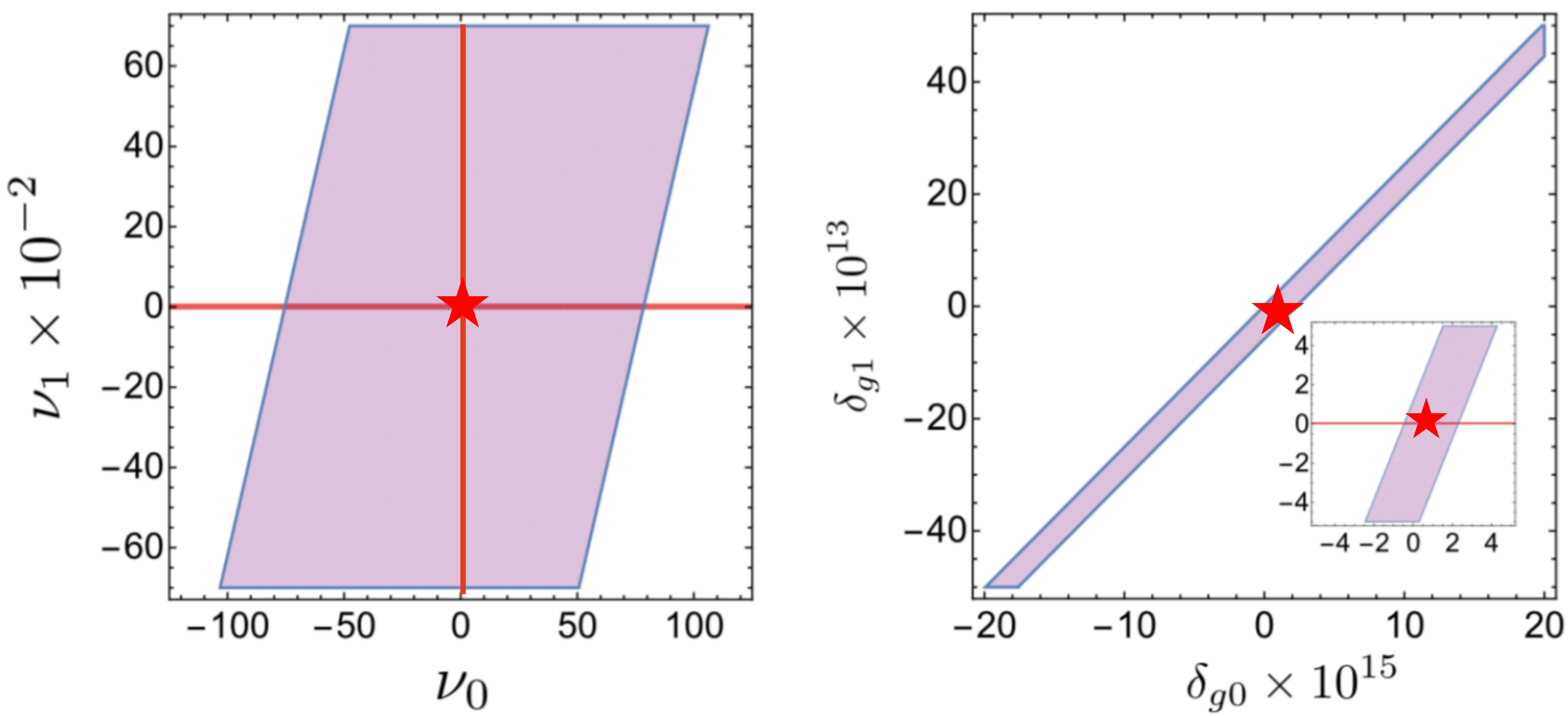
- Observables are expressed in terms of new parameters

$$\mathcal{D} \approx \frac{1}{2}\left\{\nu_0 \ln(1+z) - \frac{\nu_1}{2}(H_0 t_{\rm LB})^2\right\}$$
$$\Delta T \approx \frac{1}{H_0}\left\{\delta_{g0} H_0 t_{\rm LB} - \frac{\delta_{g1}}{2}(H_0 t_{\rm LB})^2\right\}$$

- GW170817 was the first opportunity to measure them.

Observational limit on model parameters

Arai & Nishizawa 2018



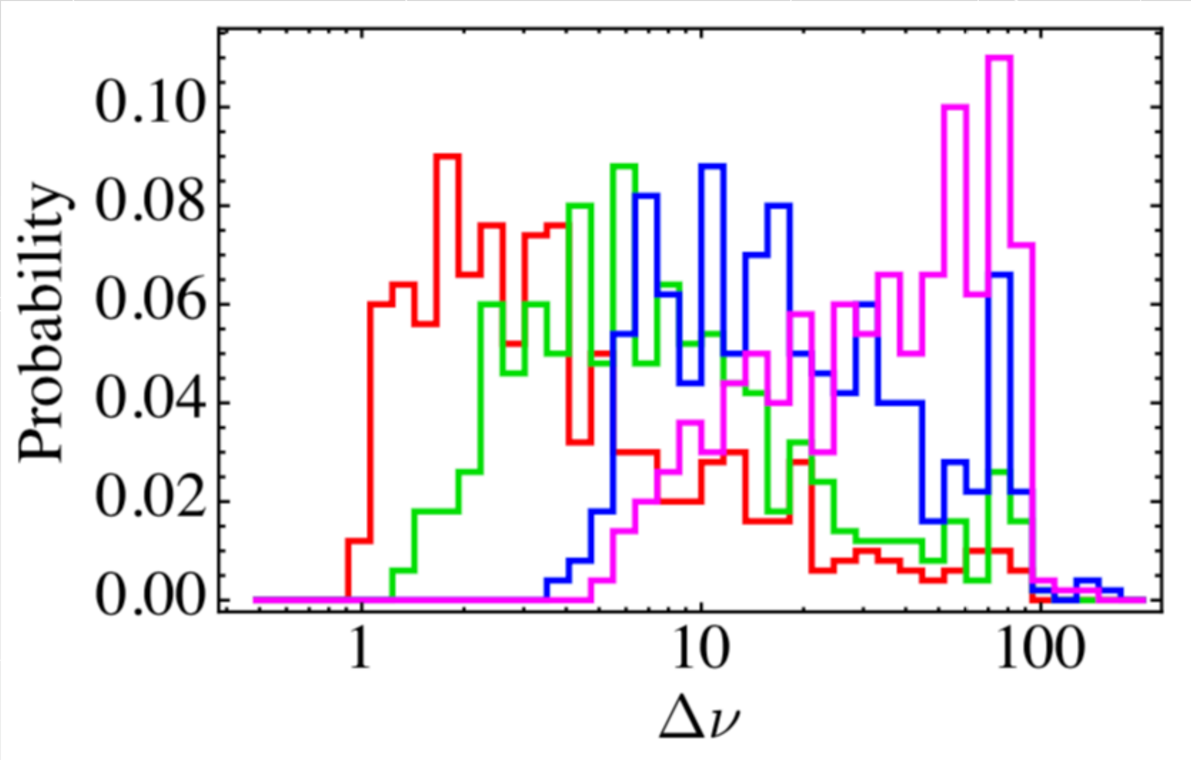
$$-75.3 \leq \nu_0 \leq 78.4$$

$$-4.7 \times 10^{-16} \leq \delta_{g0} \leq 2.2 \times 10^{-15}$$

Future forecast

Nishizawa 2018

HLV network, redshift prior $\Delta z = 10^{-3}$



constant ν, μ

$30M_\odot - 30M_\odot$

$10M_\odot - 10M_\odot$

$10M_\odot - 1.4M_\odot$

$1.4\,M_\odot - 1.4\,M_\odot$

$m_1(M_\odot)$	$m_2(M_\odot)$	$\Delta\nu$ (median)	$\Delta\nu$ (top 10%)	$\Delta\mu$(eV) (median)	$\Delta\mu$(eV) (top 10%)
30	30	3.21	1.33	5.85×10^{-23}	4.74×10^{-23}
10	10	6.37	2.46	2.03×10^{-22}	1.82×10^{-22}
10	1.4	16.1	6.54	4.89×10^{-22}	3.87×10^{-22}
1.4	1.4	35.9	9.92	4.09×10^{-22}	3.71×10^{-22}

Summary

- GW propagation can be a powerful probe for testing gravity in dynamical regime and at cosmological distance.
- GW propagation speed has been measured so tightly from GW170817.
- With the GW speed constraint, viable cosmological models in Horndeski theory are those with simpler Lagrangians, G_2 and G_4.
- Constraint on GW amplitude damping is still too weak to discuss the implication for the test of gravity, but would be important in the future.