Test of Gravity with Gravitational Wave Propagation

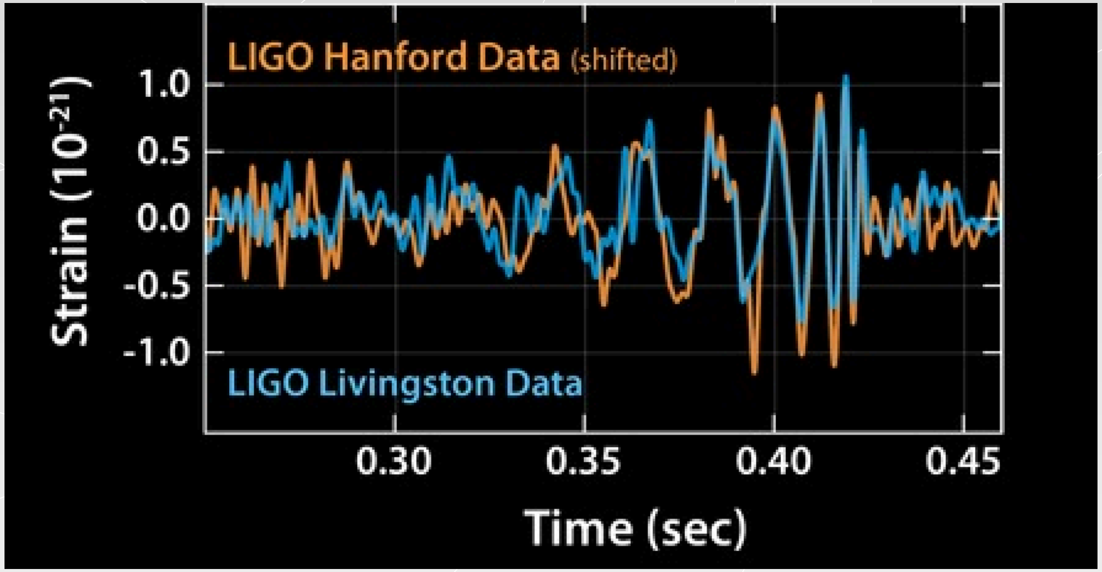
Atsushi Nishizawa
(KMI, Nagoya Univ.)

Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe

Mar 8-10, 2017 @ KEK
新学術領域 “Why does the Universe accelerate?- Exhaustive study and challenge for the future”

Gravitational Waves

- GWs have been detected! (GW150914, GW151226)
  [LIGO Scientific Collaboration 2016]



- BBH merger rate $9 - 240\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- aLIGO is expected to detect more events $\sim 100\,\mathrm{yr}^{-1}$

This opens new windows to astronomy, cosmology, and gravity.

GW, Cosmology, Test of Gravity

GW propagation

GW, Cosmology, Test of Gravity

GW propagation

cosmic expansion,
gravitational lensing

cosmology

GW, Cosmology, Test of Gravity

GW propagation

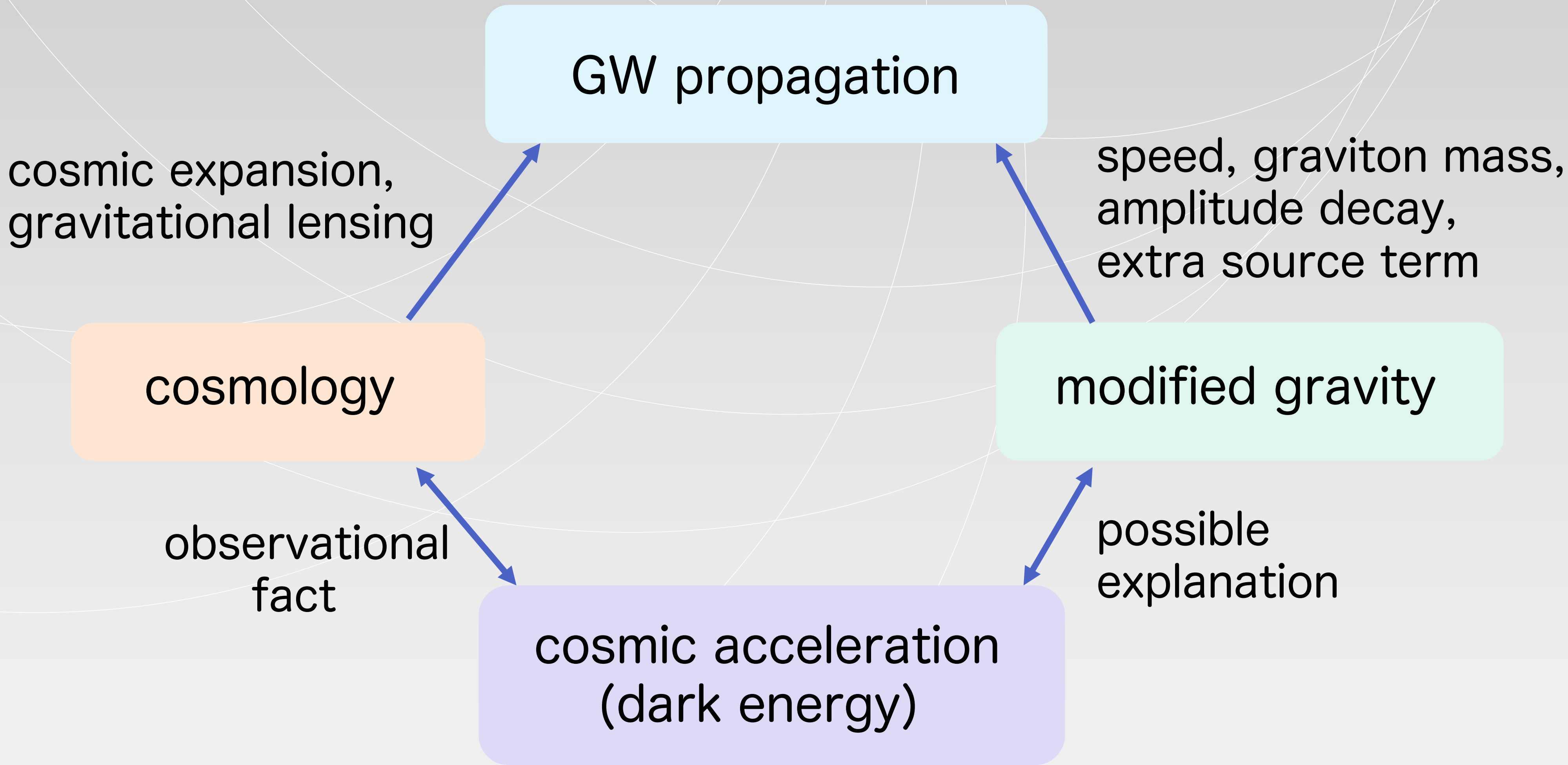
cosmic expansion,
gravitational lensing

speed, graviton mass,
amplitude decay,
extra source term

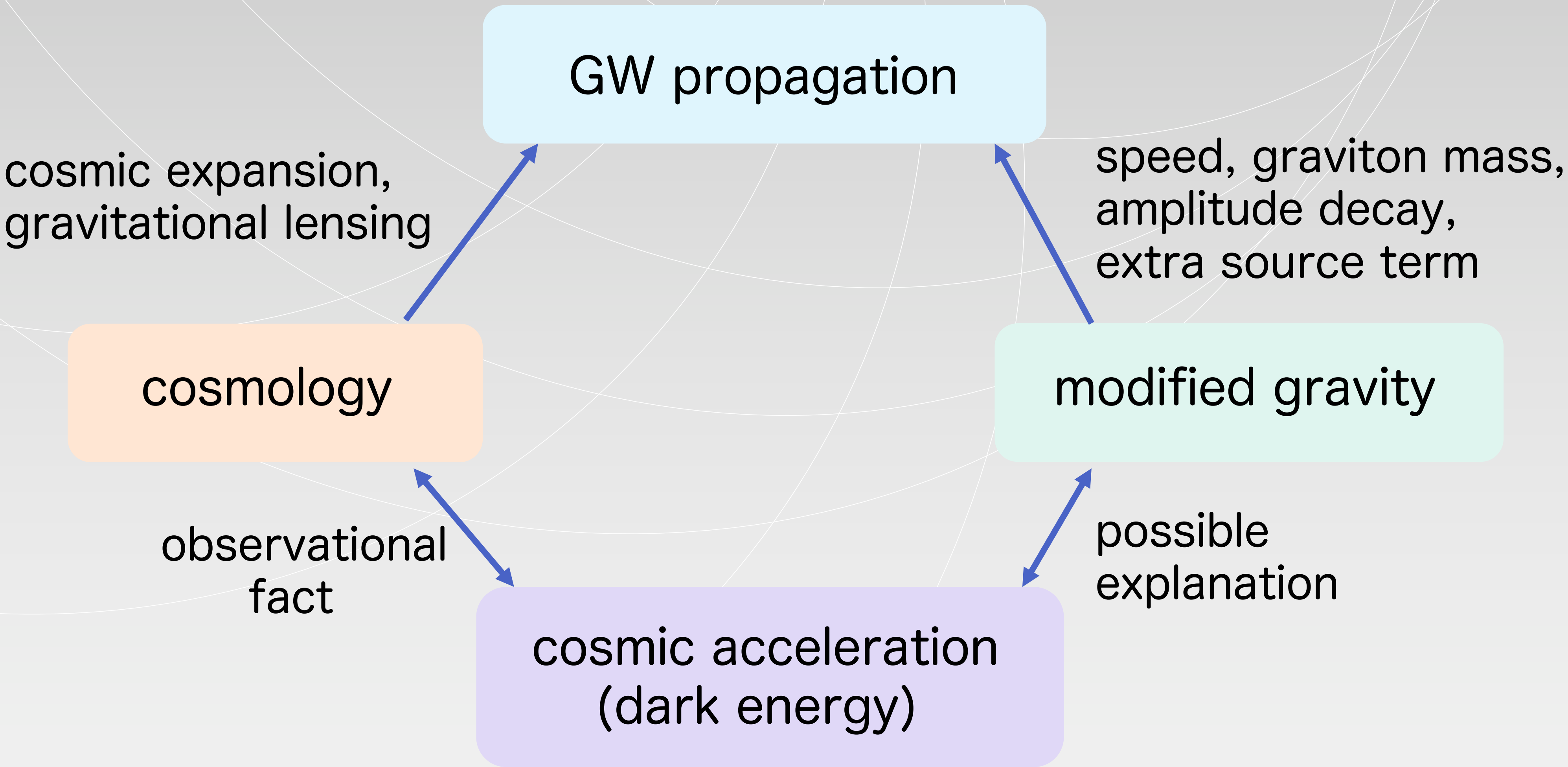
cosmology

modified gravity

GW, Cosmology, Test of Gravity



GW, Cosmology, Test of Gravity



Modification on GWs would be tiny, but are accumulated during propagation from a distant source. Any unified framework to test?

GW propagation eq.

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

[Saltas et al. 2014]

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

$\nu, c_{\mathrm{T}}, \mu, \Gamma$ are arbitrary functions of time.

GW propagation eq.

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

[Saltas et al. 2014]

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

C_T : GW propagation speed

- violation of Lorentz sym.
- violation of equivalence principle
- modified dispersion relation

GW propagation eq.

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

[Saltas et al. 2014]

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

μ : graviton mass

- massive gravity
- compactified extra dim.

GW propagation eq.

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

[Saltas et al. 2014]

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

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

- change of gravity strength
- effective friction of spacetime
  (escape to extra dim, quantized spacetime)

GW propagation eq.

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

[Saltas et al. 2014]

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

Γ : source for GW

- energy injection from extra dim.
- nonminimal coupling to other fields

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

For $h = Ae^{iB}$ & $\Gamma = 0$ [AN in preparation]

(A should be a slowly varying function with cosmo timescale.)

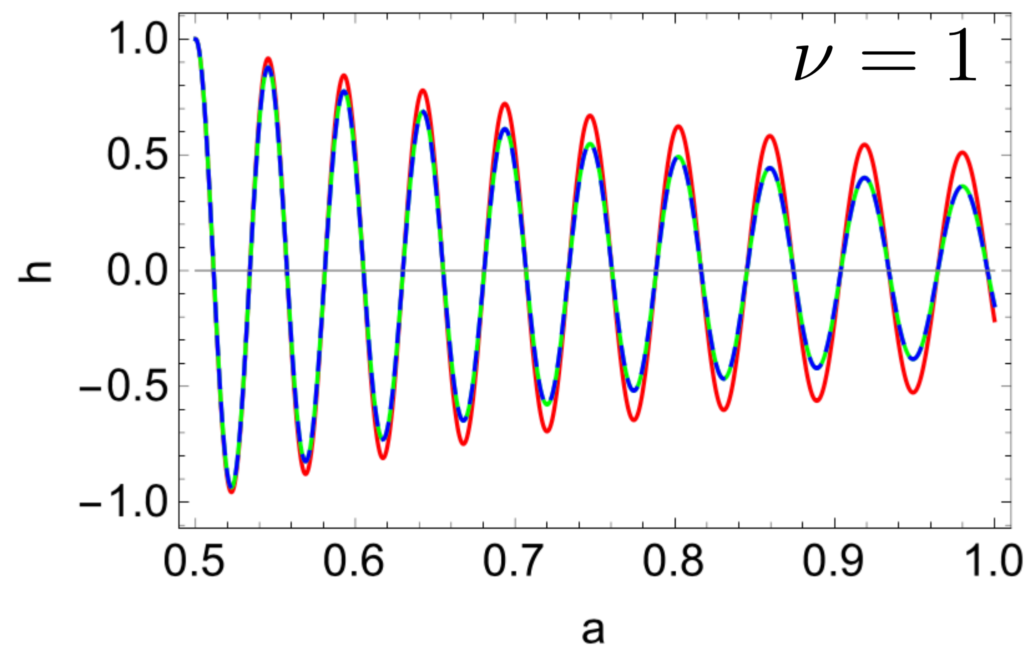
Defining $c_T \equiv 1 - \delta_g$ and dropping δ_g & μ in amplitude

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

$$\mathcal{D} \equiv \frac{1}{2}\int^{\tau} \nu \mathcal{H} d\tau'$$ damping factor

$$\Delta T \equiv \int^{\tau} \left(\delta_g - \frac{a^2\mu^2}{2k^2} \right) d\tau'$$ extra time delay

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

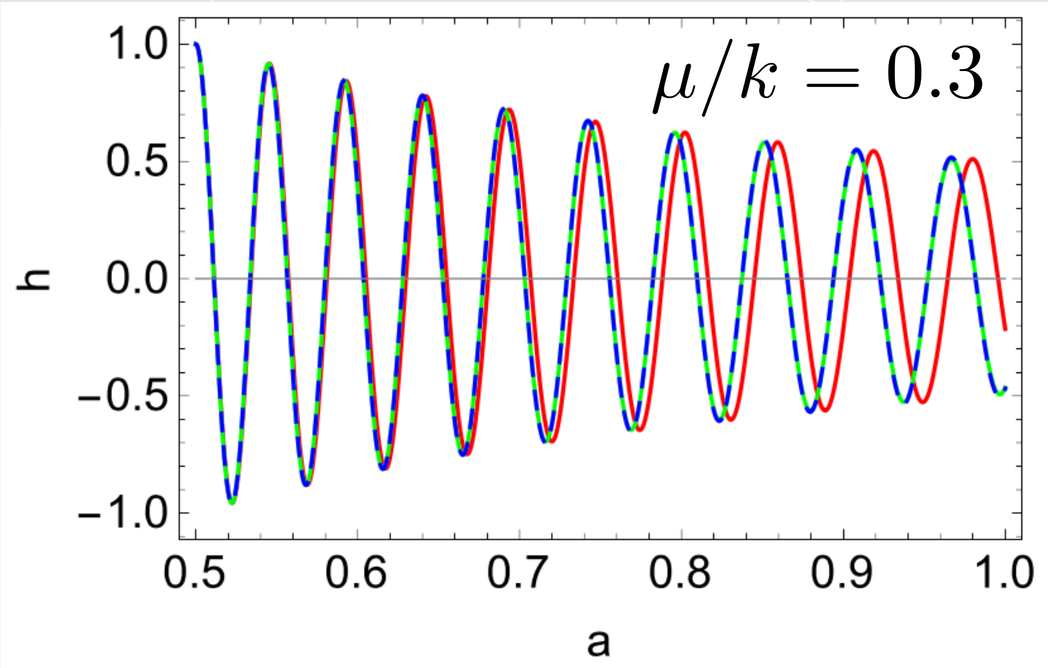


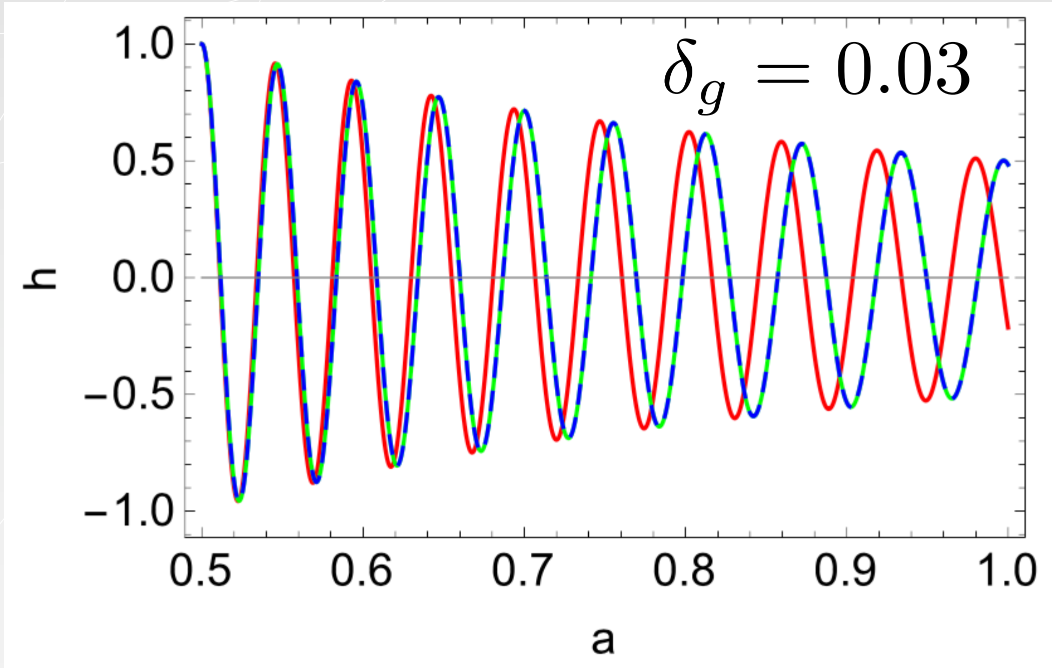
GW emitted at z=1 (a=0.5)

GR solution

MG numerical solution

MG WKB solution

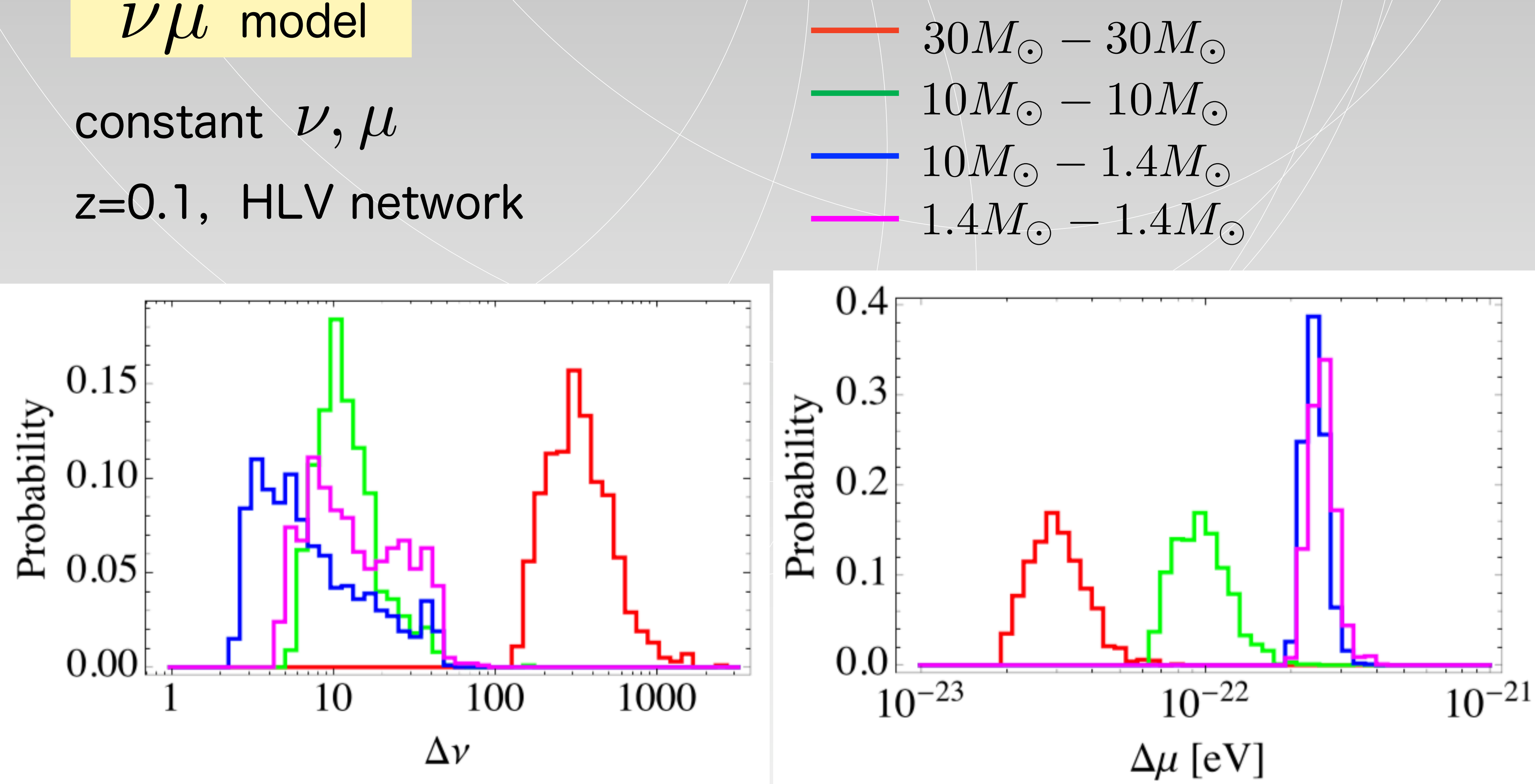




$\nu\mu$ model

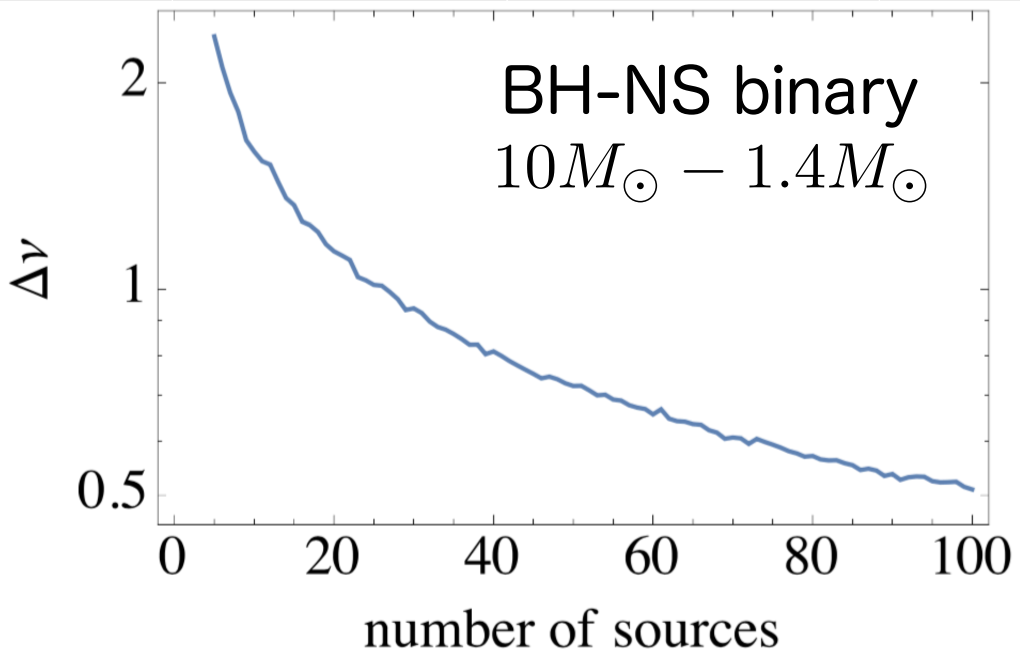
constant ν, μ

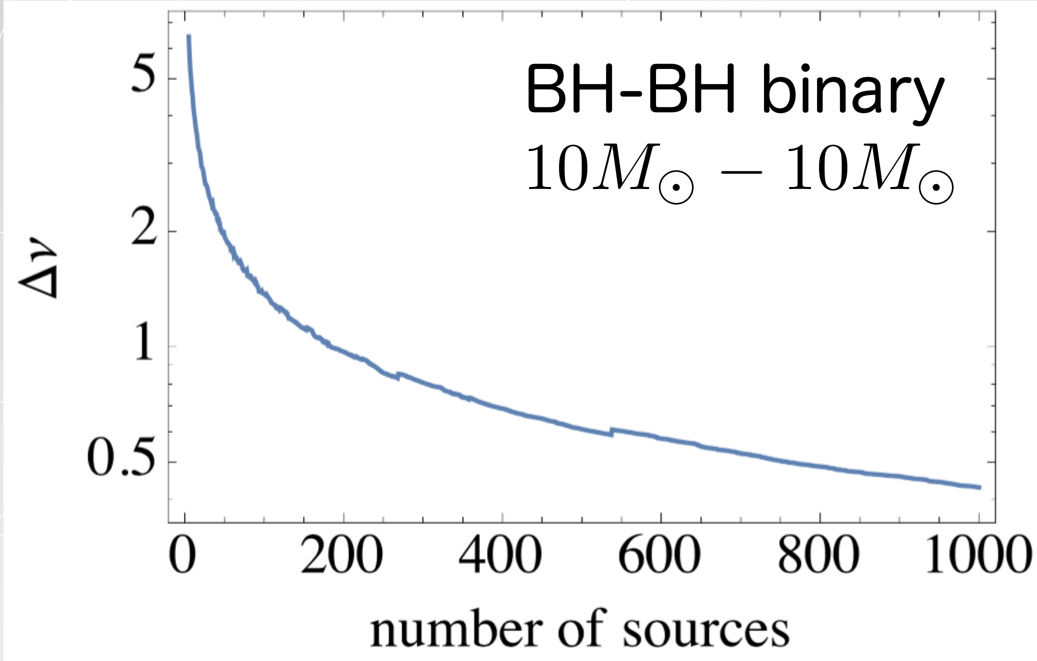
z=0.1, HLV network



Amp damping is not well constrained from a single source.
Graviton mass is better constrained from a heavier source.

With multiple sources,
(constant merger rate & fixed masses)





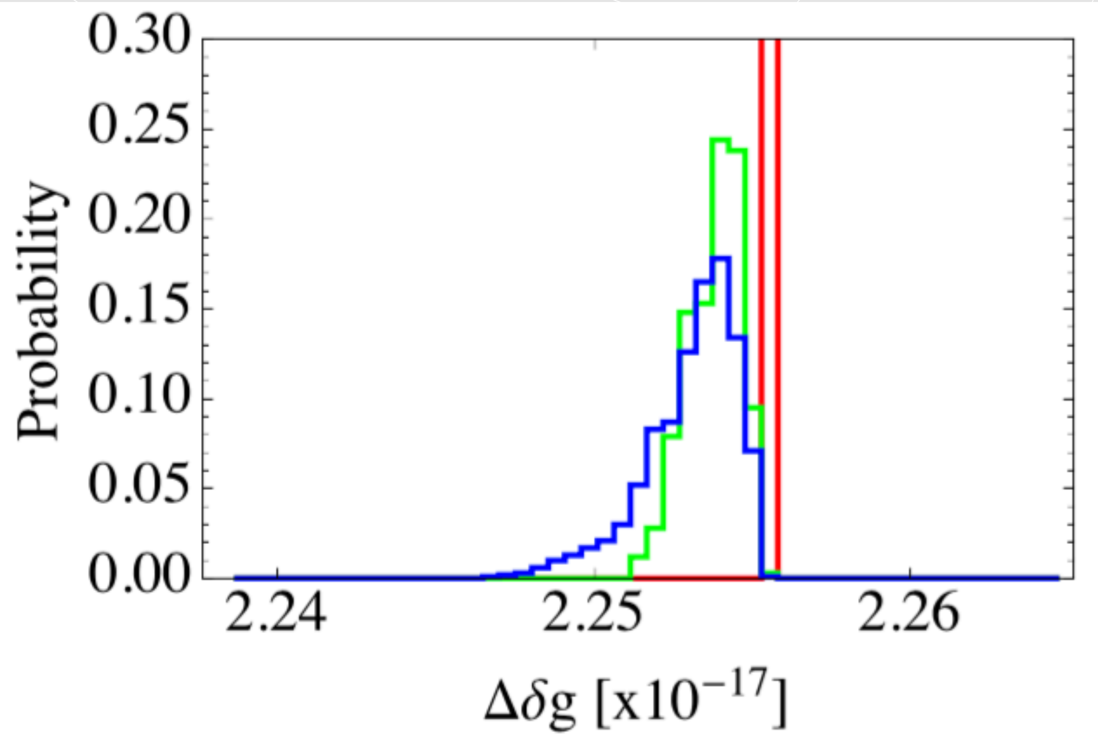
In the future observation with HLV network,
the error will reach $\Delta\nu \approx 0.5$

δ_g model

δ_g is completely degenerated with t_c.

➡ Need t_c prior from EM obs. $\Delta t_c = 1\,\mathrm{sec}$

➡ GW sources should be BH-NS or NS-NS binary



constant δ_g

z=0.1, HLV network

— $30M_\odot - 1.4M_\odot$

— $10M_\odot - 1.4M_\odot$

— $1.4M_\odot - 1.4M_\odot$

Summary

- GW propagation, test of gravity, and cosmology are intimately related each other.
- We have proposed a unified framework to test gravity with GW propagation, based on an effective field-theory approach.
- From the future obs of GWs, dynamical aspects of gravity will be constrained tightly. These GW constraints should be combined with other constraints from cosmology.