Cosmological test of gravity with gravitational waves

Atsushi Nishizawa
KMI ⇒ RESCEU, U. of Tokyo

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1. Cosmological observation and gravity

2. Test of gravity with GW

3. Measurement of GW speed

4. Generalized framework for testing gravity with GWs

5. Summary

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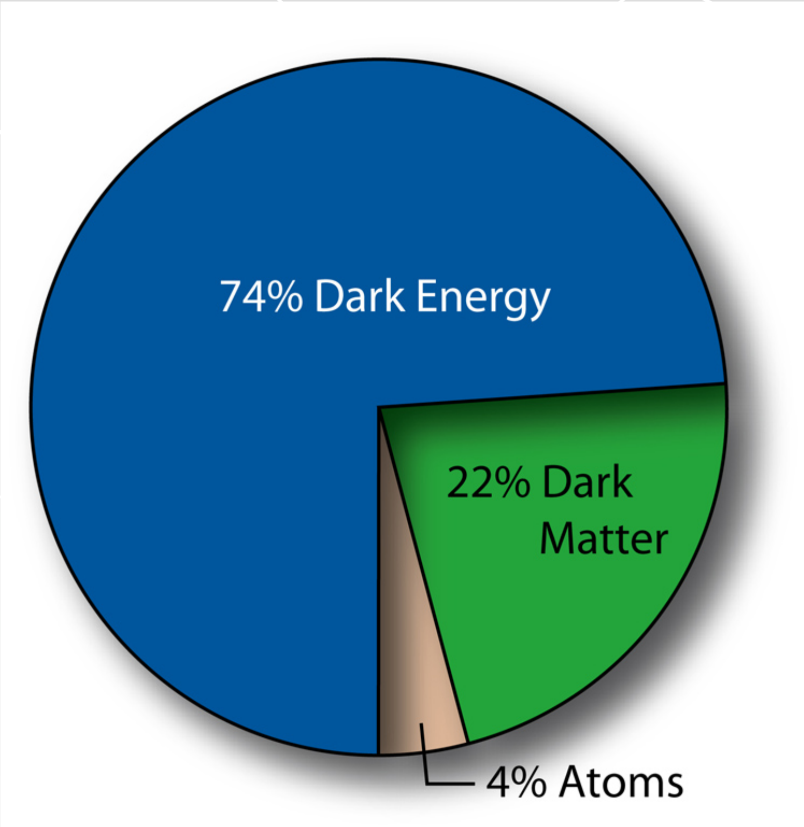
Cosmic acceleration

The current Universe is accelerating, but the physical mechanism is still unknown.



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- cosmological constant
- Introducing a new energy component in the Universe (e.g. scalar field)
- Modifying general relativity at cosmological scales

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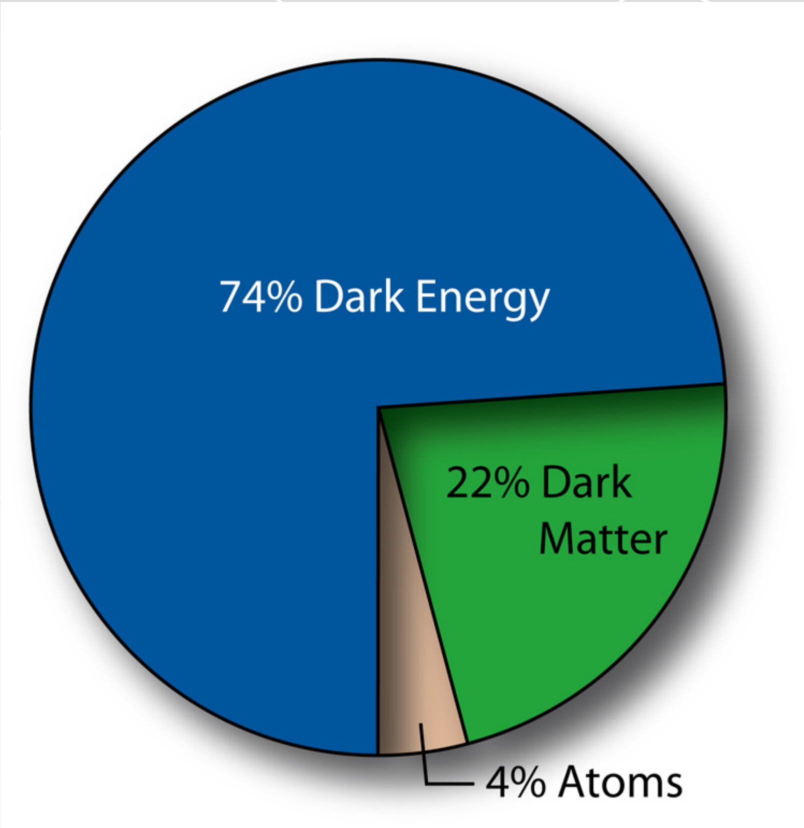

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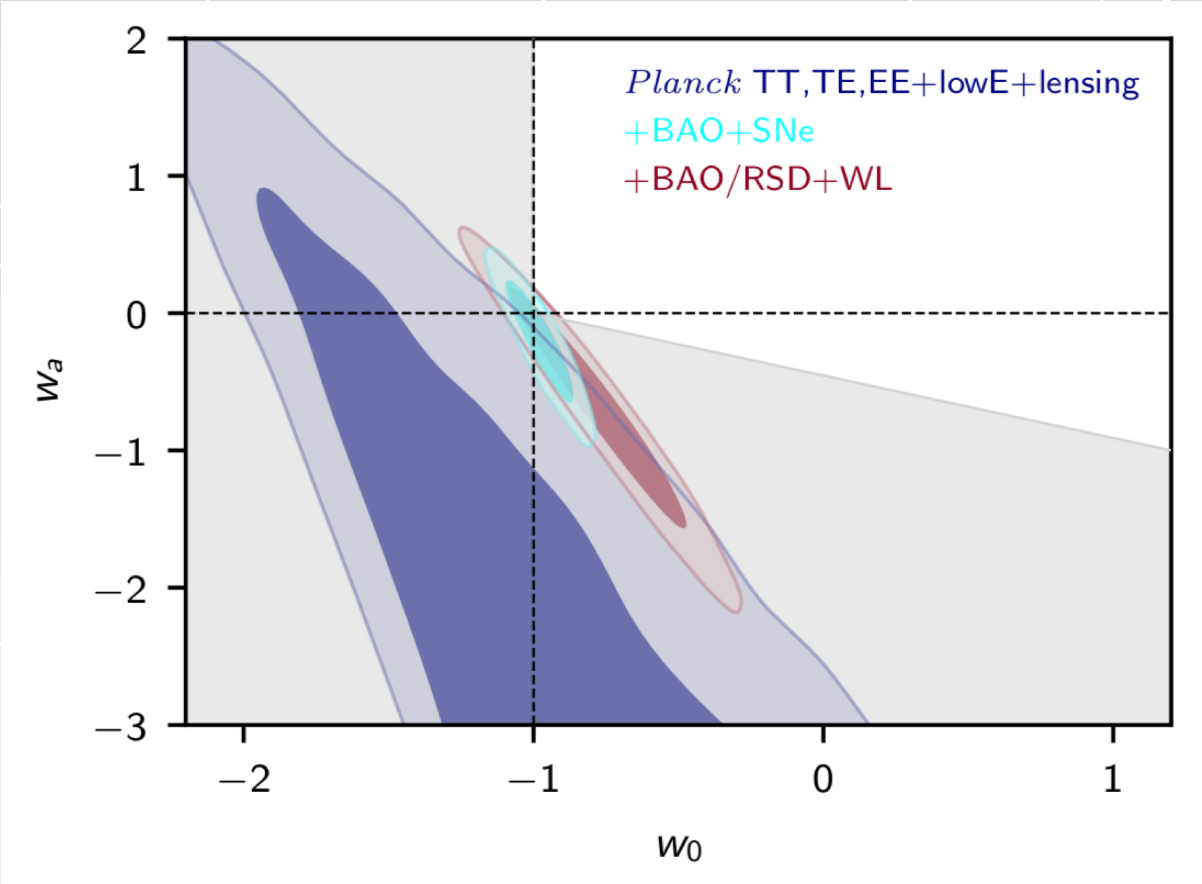
Observation of cosmic expansion

Planck Collaboration 2018



dark-energy equation of state

$$p = w\rho$$

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

$$w = -1$$

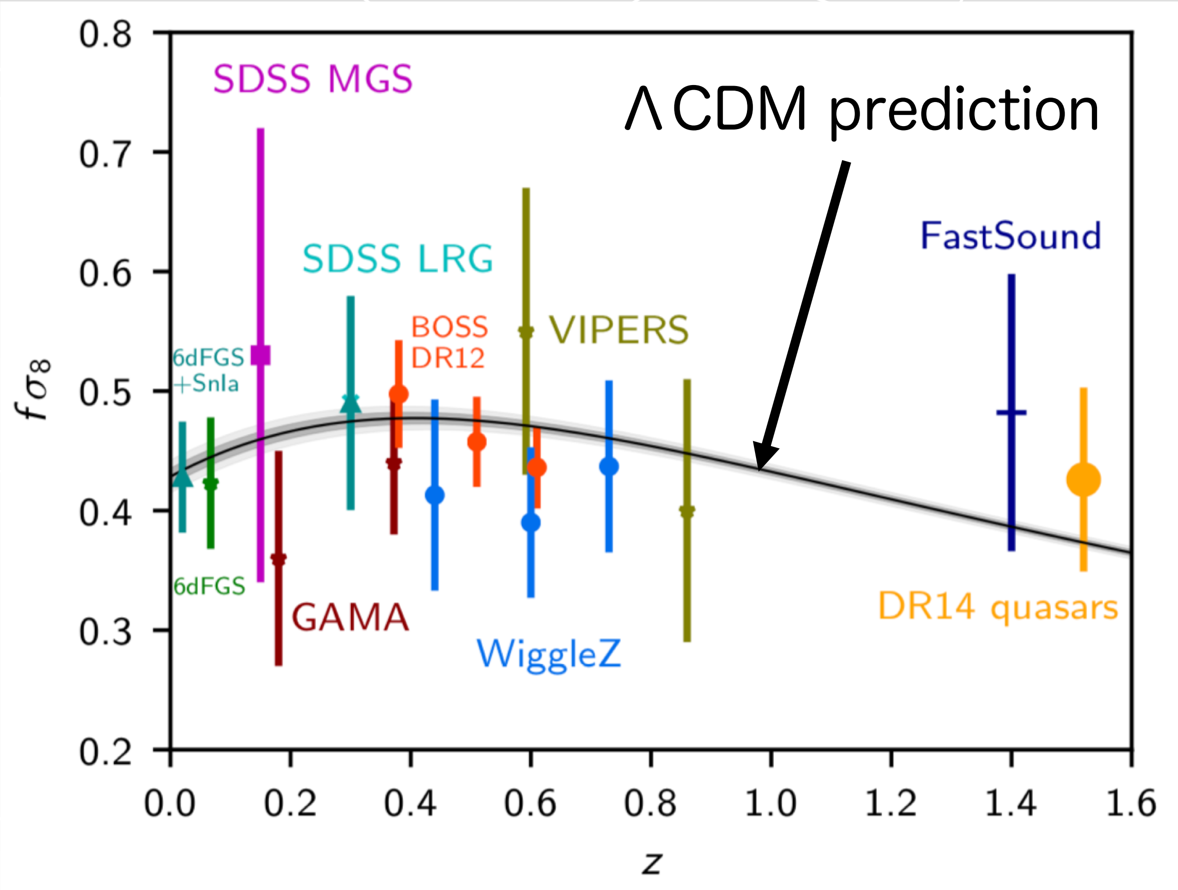
for cosmological constant

The cosmic expansion needs to be close (~10%)
to the ΛCDM model.

Observation of large scale structure

Not only background expasion but matter inhomogeneities in the Universe should match the observational data.

Planck Collaboration 2018

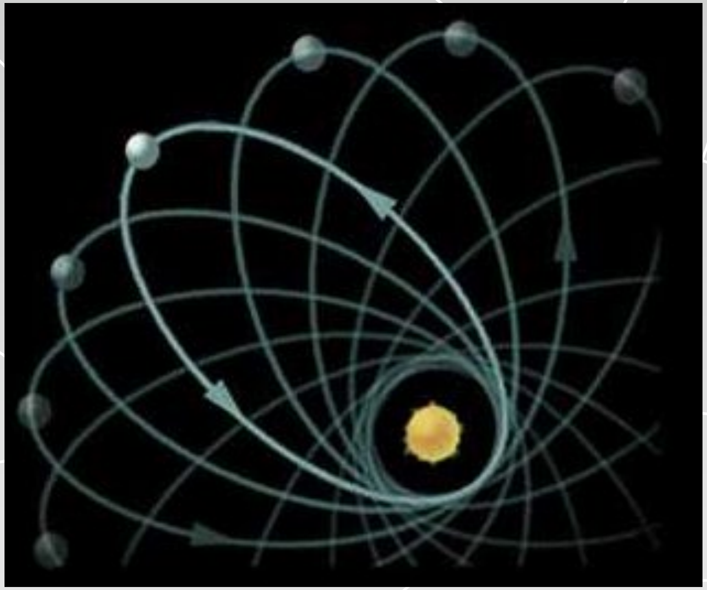


Current observational data from galaxy surveys limit the strength of matter clustering in the Universe.

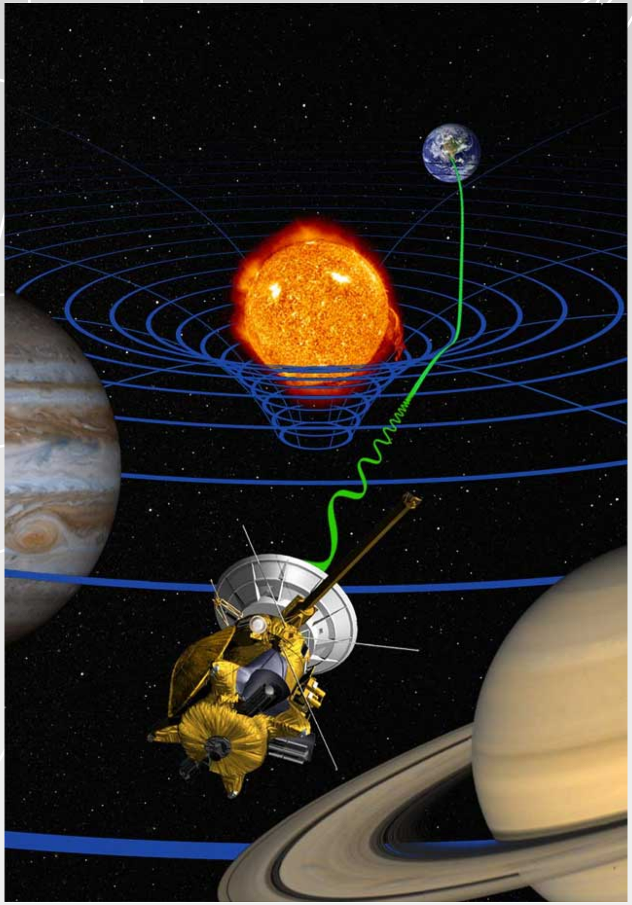
The growth rate needs to be close (~20-30%) to the ΛCDM model.

Test in the Solar system

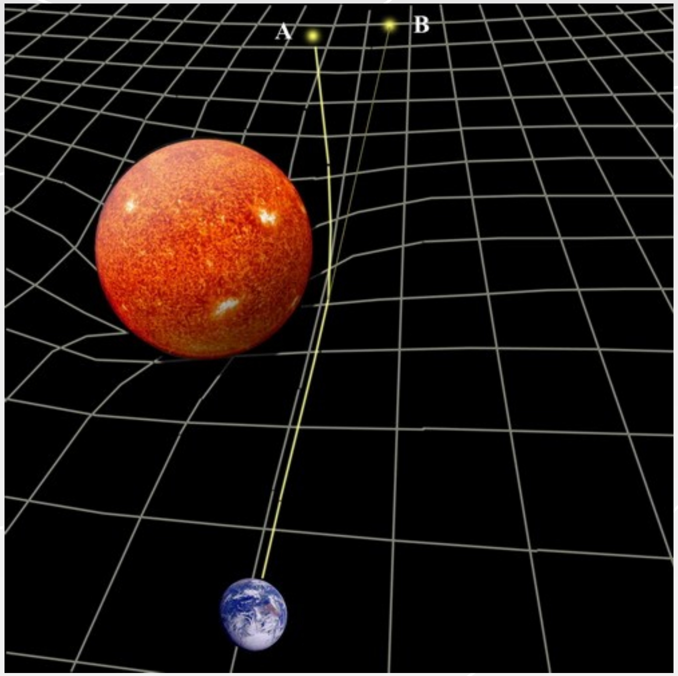
Perihelion shift of the Mercury



Shapiro time delay

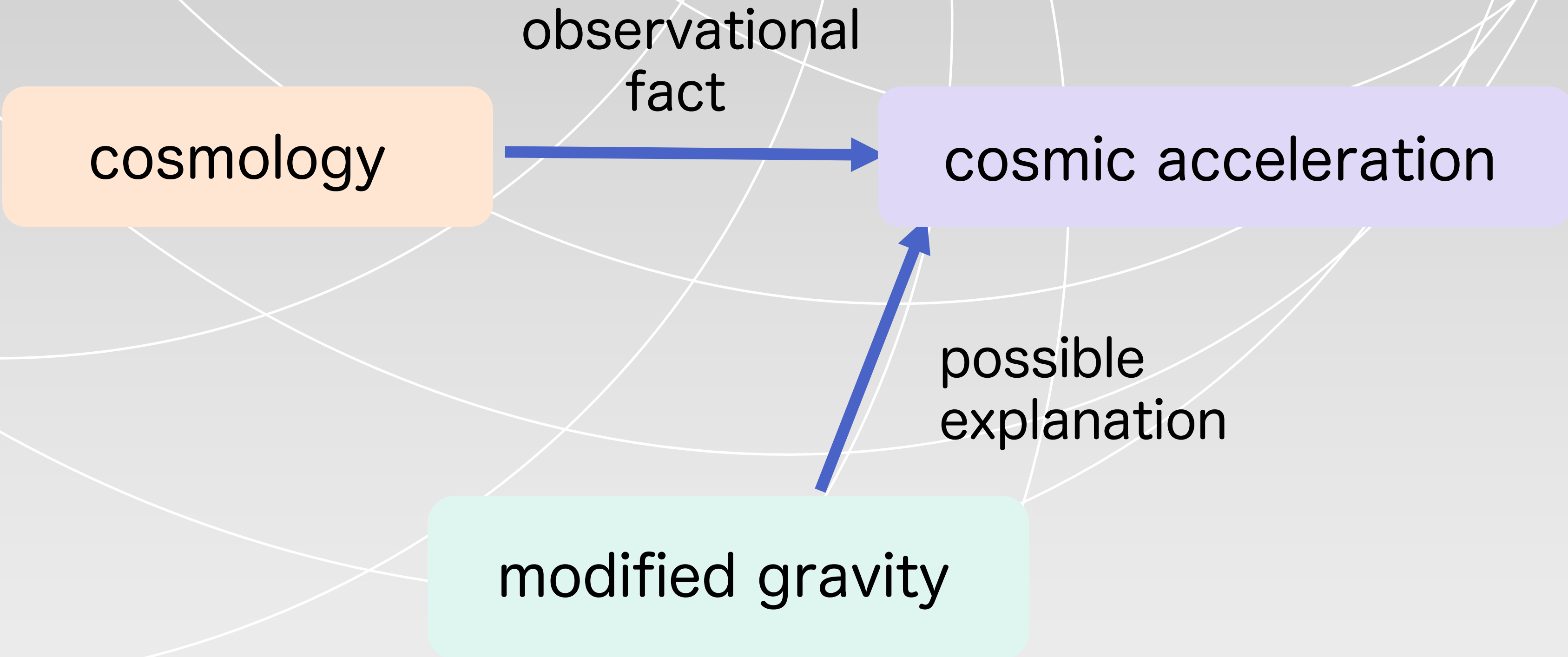


light bending

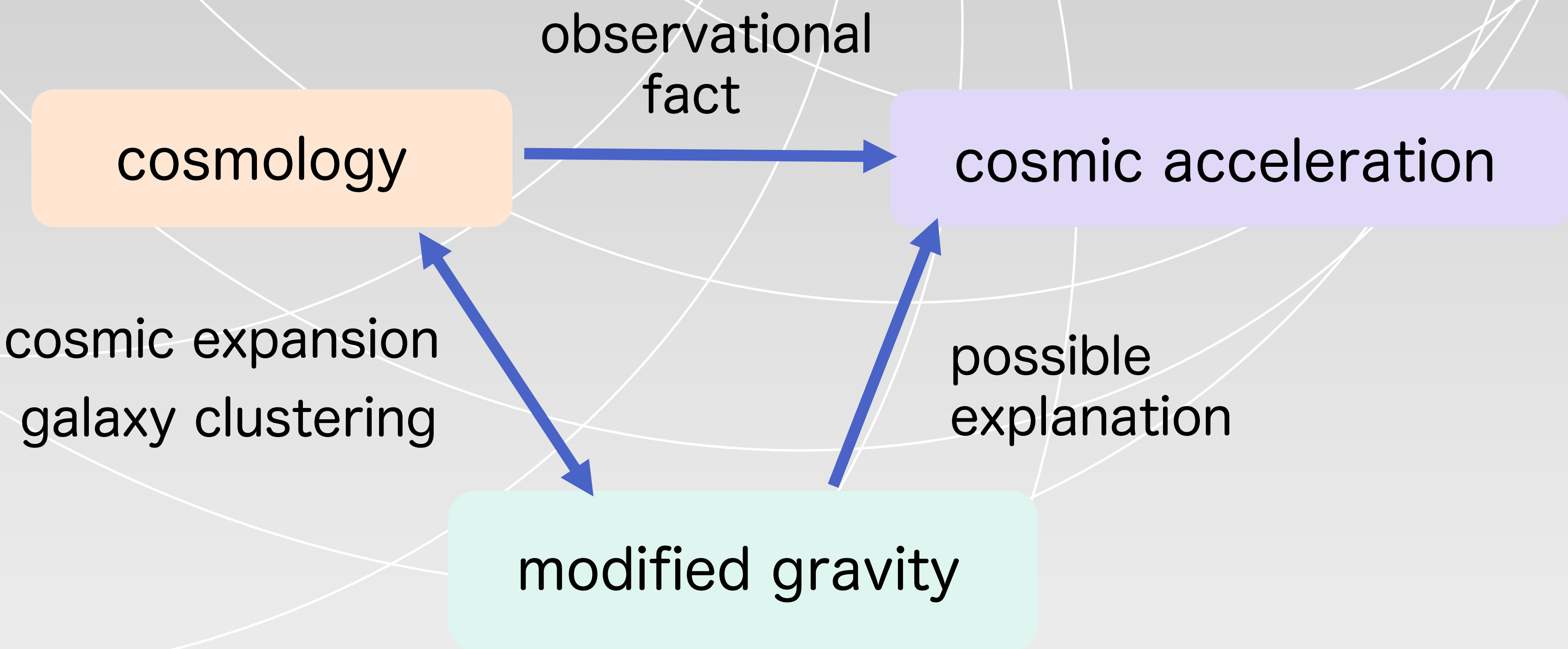


Currently general relativity passes tests in the Solar system at the precision of 0.001%.

Cosmology, modified gravity, GW



Cosmology, modified gravity, GW



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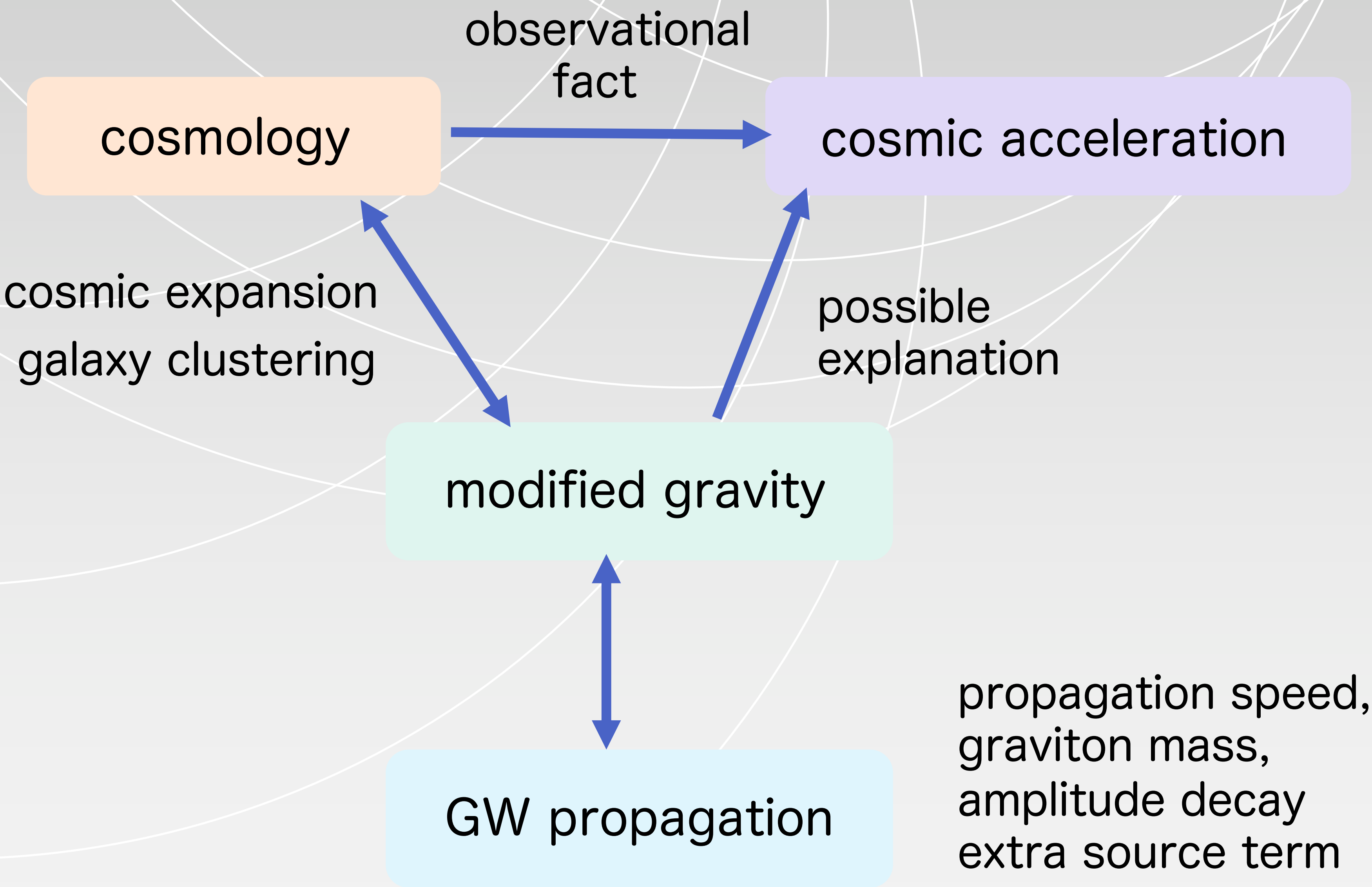

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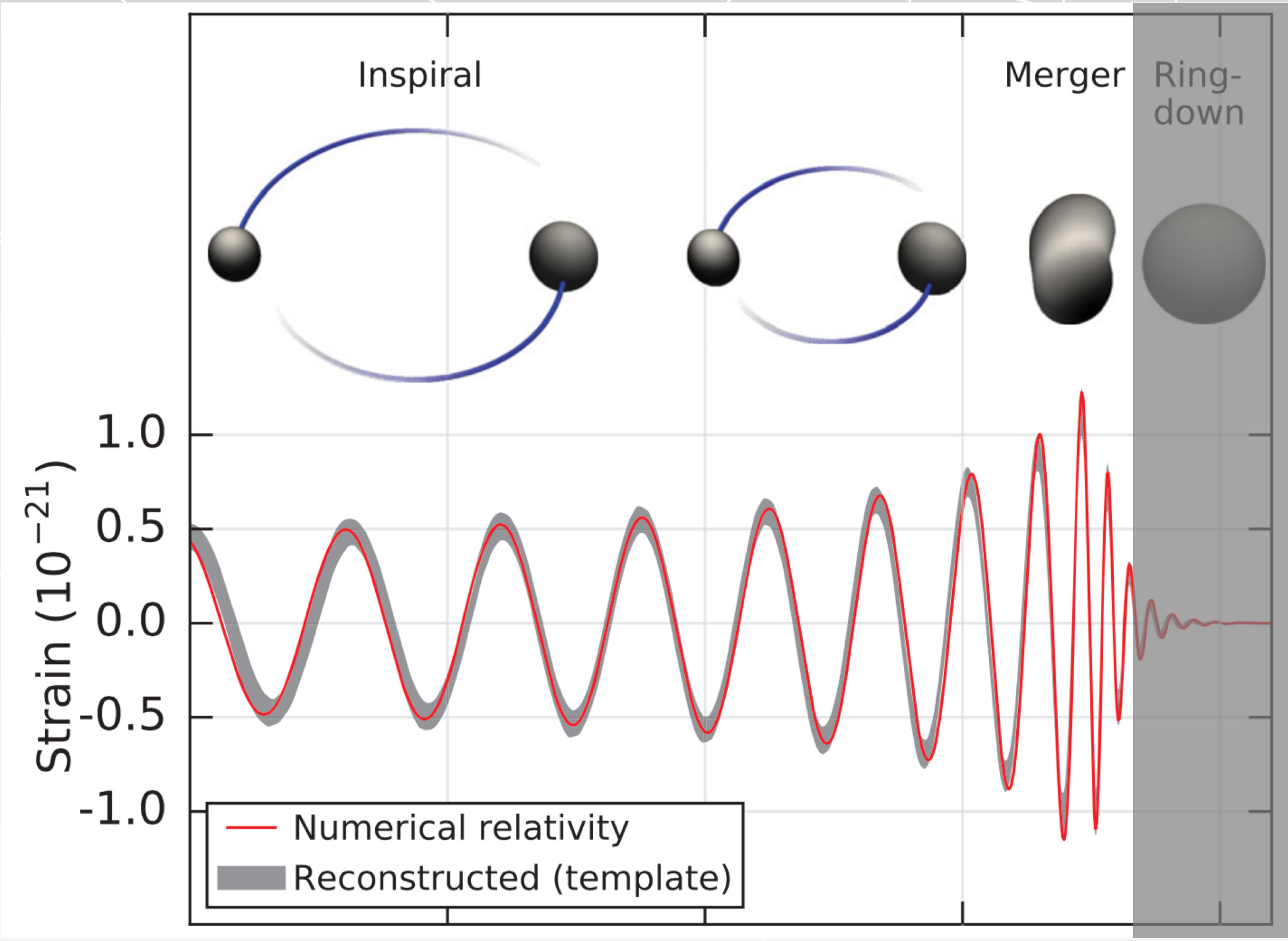
GW waveform

compact binaries (BBH, BNS, NS-BH)



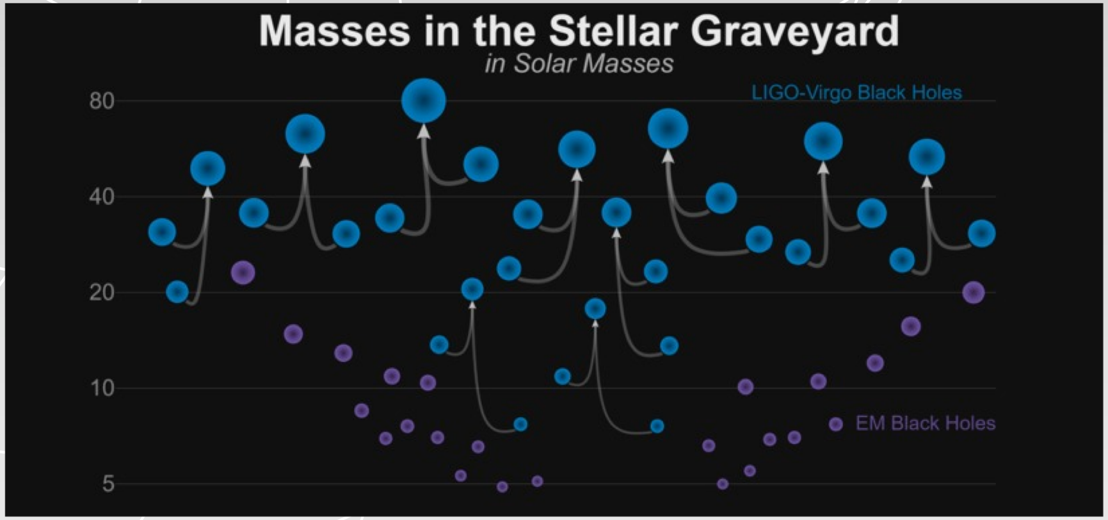
depending on
NS or BH

LIGO Scientific
Collaboration,
PRL 2016 (GW150914)

Current status of GW observation

- 10 BBH and 1 BNS have been detected so far.

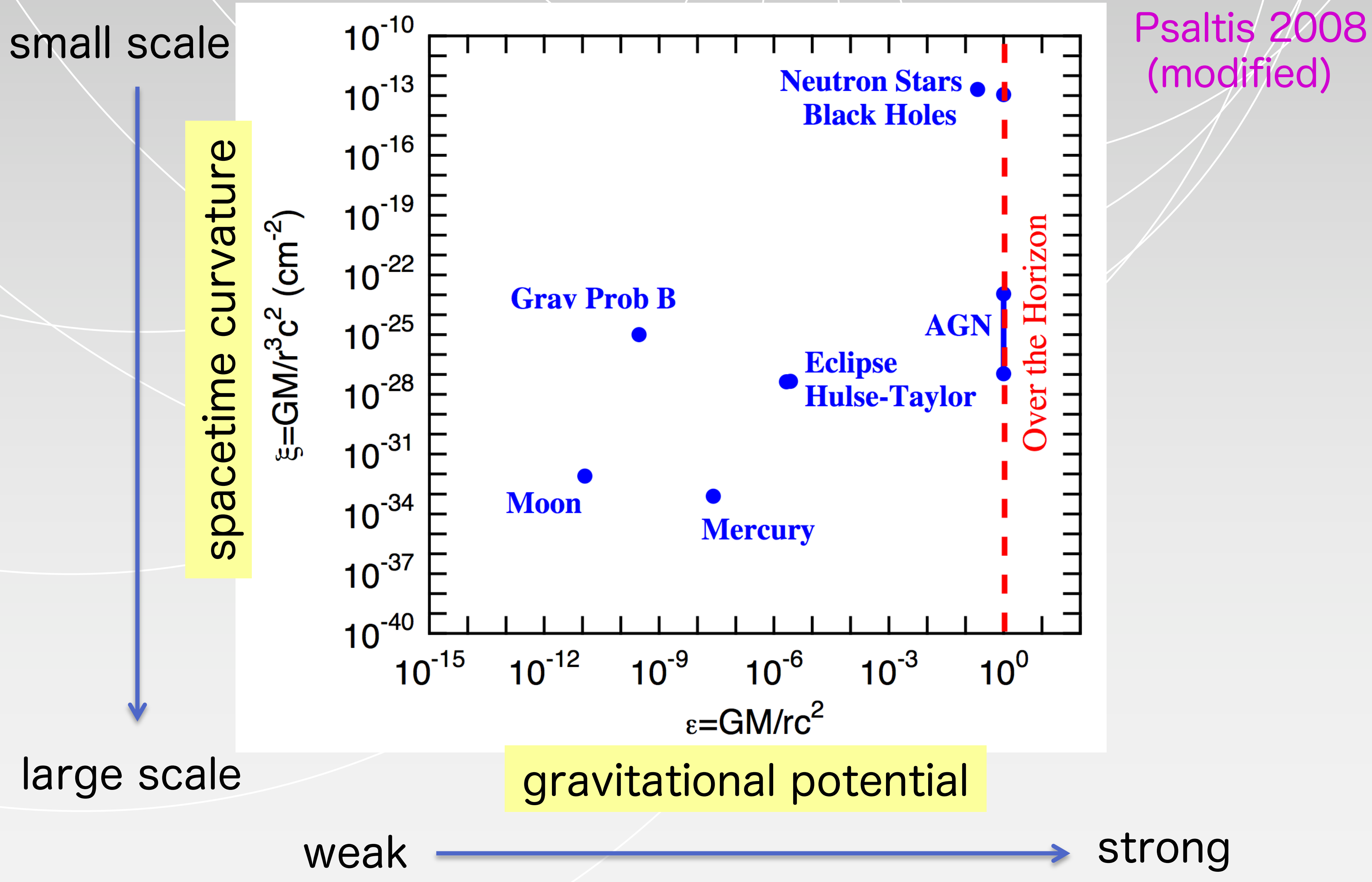
  LIGO Scientific Collaboration 2016 – 2018



- aLIGO and aVIRGO will start O3 observation from Apr. 2019. KAGRA will join the observation from late 2019.

- They will reach their design sensitivities in 3-5 yrs and detect $\sim 100-1000$ BBH and $\sim 20-400$ BNS.

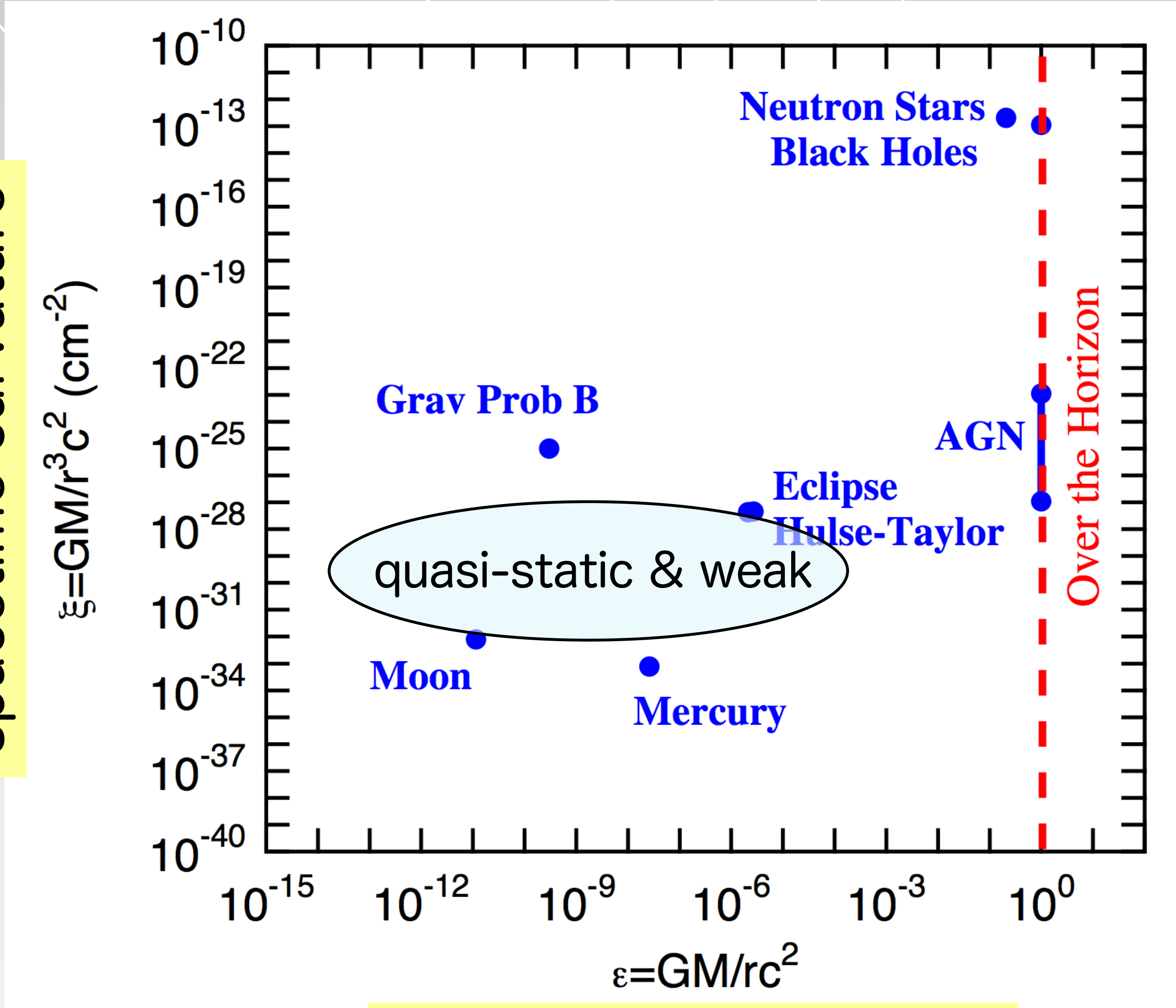
Gravity test with GW



Gravity test with GW

small scale

spacetime curvature



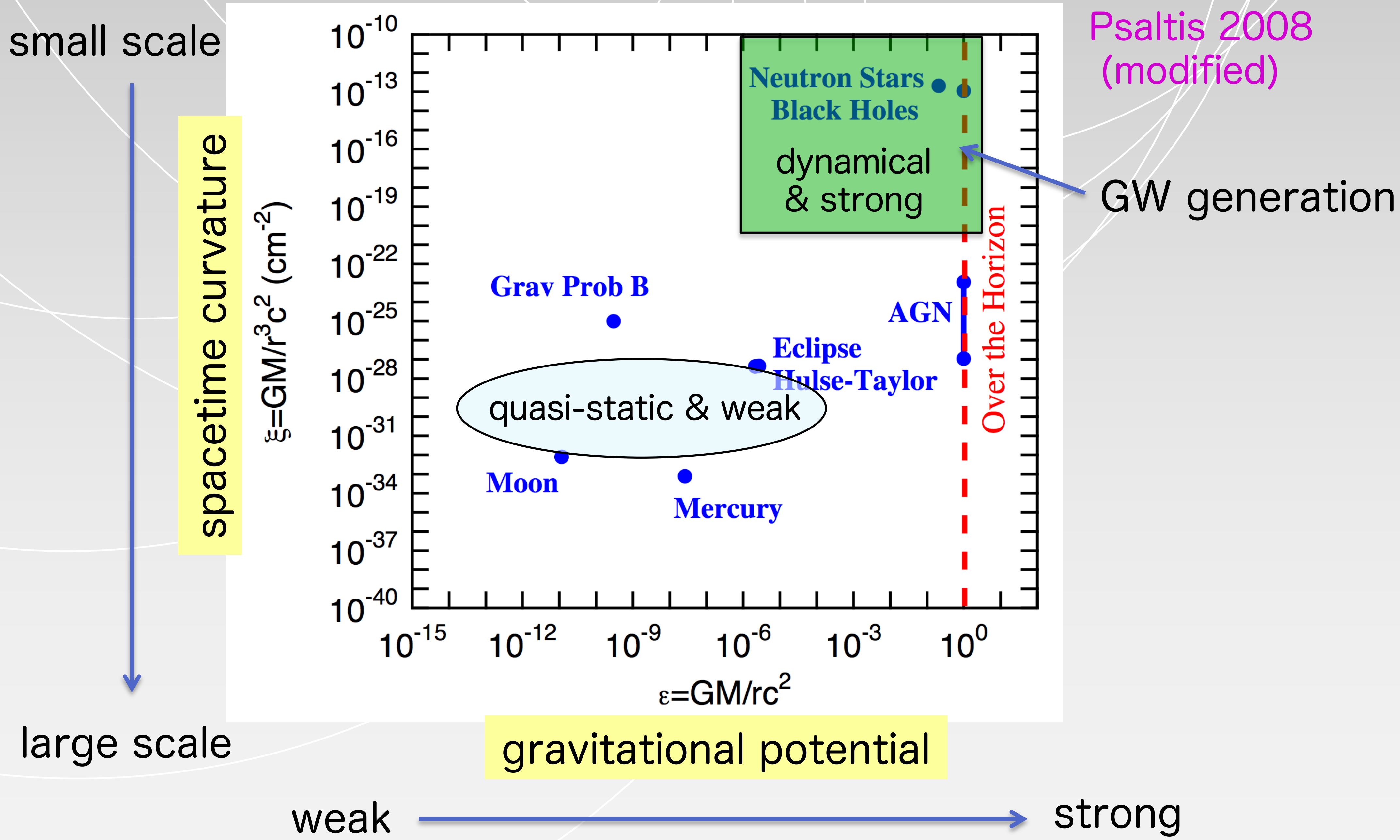
Psaltis 2008 (modified)

large scale

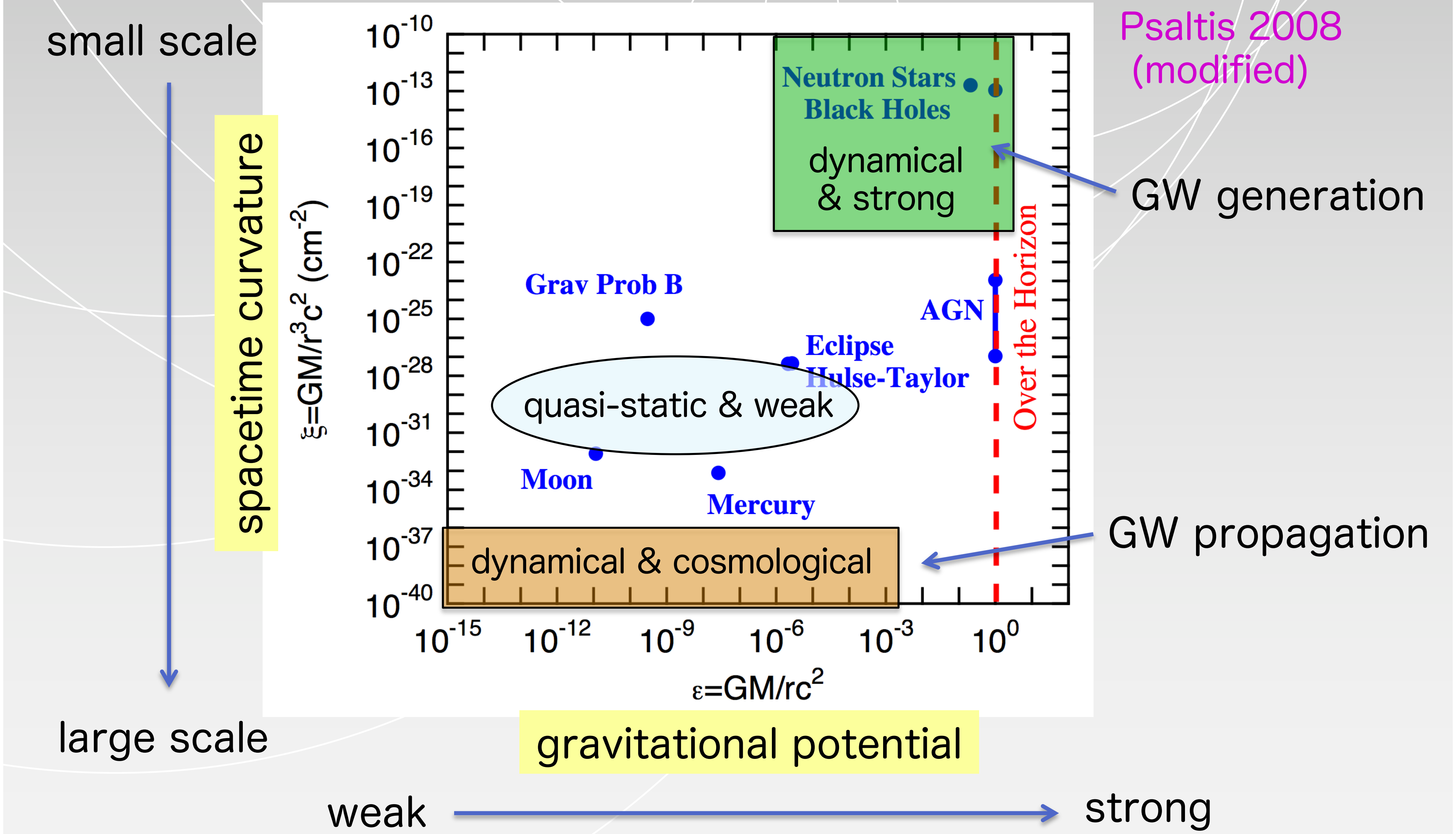
gravitational potential

weak → strong

Gravity test with GW



Gravity test with GW



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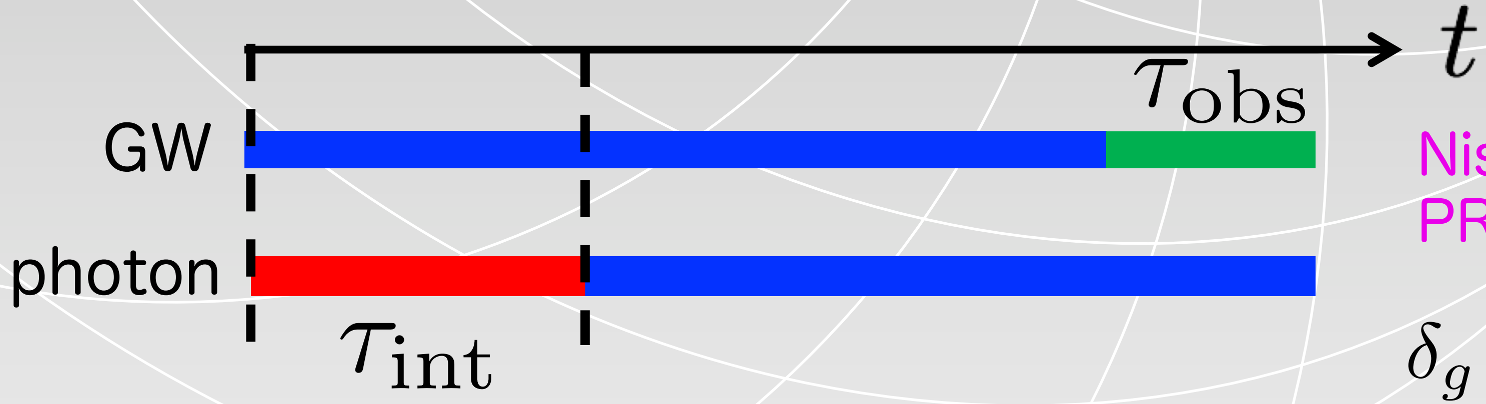
Measurement of GW speed

- method with arrival time difference between GW and short GRB



Nishizawa & Nakamura, PRD (2014)

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

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

- GW170817/GRB170817A

LSC + Fermi + INTEGRAL, ApJL (2017)

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

$$\Rightarrow\; -7 \times 10^{-16} < \delta_g < 3 \times 10^{-15}$$

Horndeski theory

$$S = \int dx^4 \sqrt{-g} \left(\sum_{i=2}^{5} \mathcal{L}_i + \mathcal{L}_{\mathrm{m}} \right)$$

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

$$\mathcal{L}_2 = G_2(\phi, X) \ ,$$
$$\mathcal{L}_3 = -G_3(\phi, X)\Box\phi \ ,$$
$$\mathcal{L}_4 = G_4(\phi, X)R + G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi)\right] \ ,$$
$$\mathcal{L}_5 = G_5(\phi, X)G_{\mu\nu}(\nabla^\mu\nabla^\nu\phi)$$
$$- \frac{1}{6}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3(\Box\phi)(\nabla_\mu\nabla_\nu\phi)(\nabla^\mu\nabla^\nu\phi) + 2(\nabla^\mu\nabla_\alpha\phi)(\nabla^\alpha\nabla_\beta\phi)(\nabla^\beta\nabla_\mu\phi)\right]$$

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

Constraint from GW170817

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., PRL (2017)
Creminelli & Vernizzi, PRL (2017)
Ezquiaga & Zumalacarregui, PRL (2017)
Sakstein & Jain, PRL (2017)

With a numerical approach, we also reached the same conclusion.

Arai & Nishizawa, PRD (2018)

Horndeski theory after GW170817

$$\mathcal{L} = G_2(\phi, X) - G_3(\phi, X)\Box\phi + G_4(\phi)R$$

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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Generalized propagation of GW

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

Saltas et al., PRL (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

μ : graviton mass

Γ : source for GW

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

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
⋮

Analytical solution

Nishizawa 2018

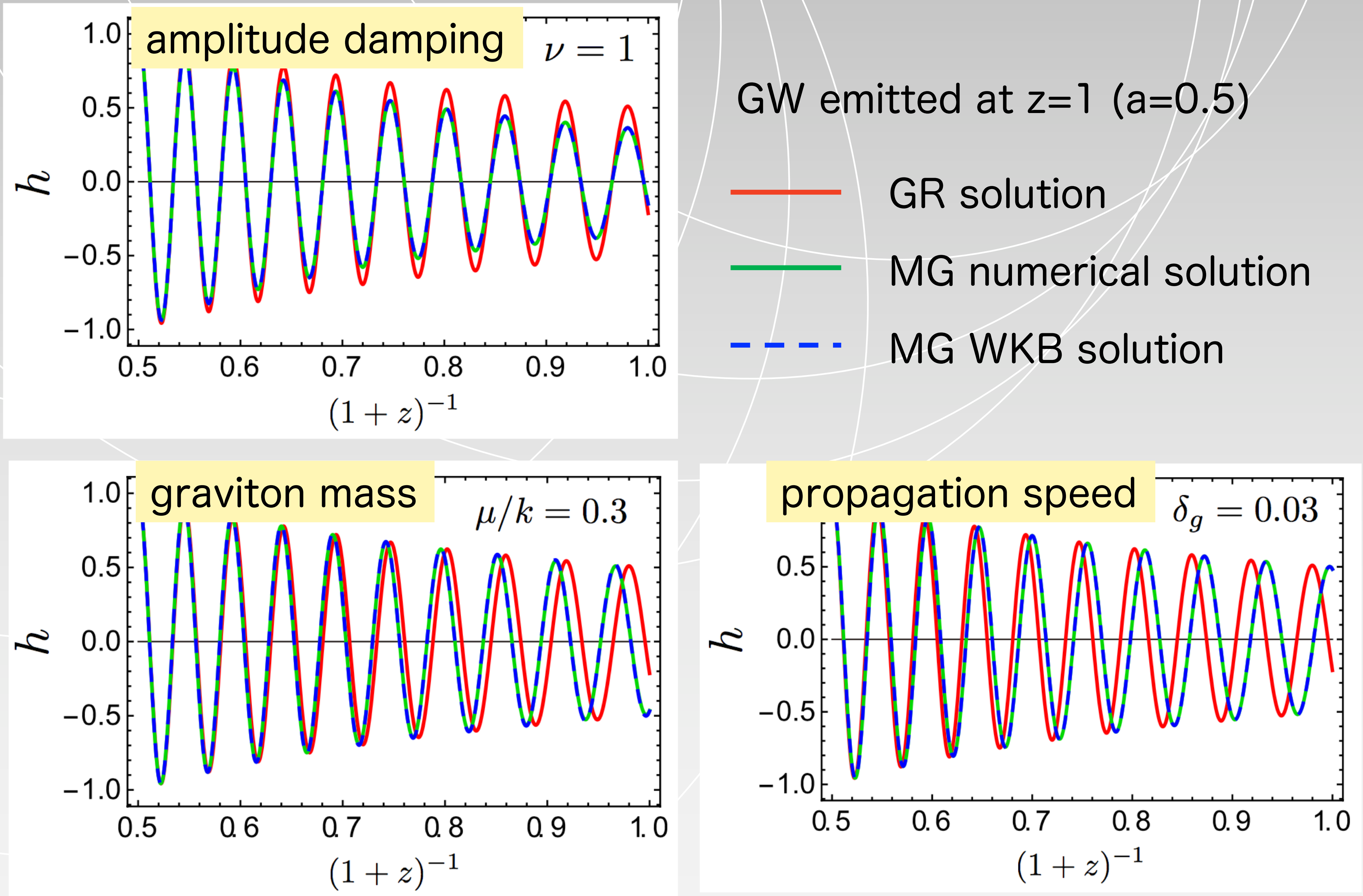
For $\Gamma = 0$, the eq. can be solved analytically, if the amplitude is a slowly varying function with cosmo timescale.

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

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.


amplitude damping
$\nu = 1$
GW emitted at z=1 (a=0.5)
GR solution
MG numerical solution
MG WKB solution
graviton mass
$\mu/k = 0.3$
propagation speed
$\delta_g = 0.03$
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

Summary of current constraints

- GW propagation

$$h''_{ij} + (2+\nu)\mathcal{H}h'_{ij} + (c_{\rm T}^2 k^2 + a^2\mu^2)h_{ij} = 0$$

- graviton mass $\mu \leq 7.7 \times 10^{-23}\,\mathrm{eV}$ LIGO Scientific Collaboration 2017

- From GW170817/GRB170817A, GW speed has been measured so precisely LSC + Fermi + INTEGRAL, ApJL (2017)

$$-3 \times 10^{-15} < \frac{c_{\rm T} - c}{c} < 7 \times 10^{-16}$$

- Constraint on amplitude damping rate

$$-75.3 \leq \nu \leq 78.4$$ Arai & Nishizawa, PRD (2018)

GW amplitude damping in Horndeski theory

Set $\alpha_{\mathrm{T}} = c_{\mathrm{T}}^2 - 1 = 0$,

Nishizawa, PRD (2018)

$$h = e^{-\mathcal{D}} h_{\mathrm{GR}}$$

$$\mathcal{D} = \frac{1}{2} \int_0^z \frac{\nu}{1+z'} dz'$$

$$\nu = \alpha_{\mathrm{M}} = H^{-1} \frac{d \log M_*^2}{dt}$$

$$e^{-\mathcal{D}} = \frac{M_*(z)}{M_*(0)} = \sqrt{\frac{G_{\mathrm{gw}}(0)}{G_{\mathrm{gw}}(z)}}$$

G_{gw} : gravitational constant for GWs

effective distance to a source $$d_{\mathrm{L,eff}}(z) = \sqrt{\frac{G_{\mathrm{gw}}(z)}{G_{\mathrm{gw}}(0)}}\, d_{\mathrm{L}}(z)$$

Source redshift is necessary to compare with true distance.

Equivalence principle in modified gravity

GWs $G_{\rm gw}$ $\mathcal{L}_{\rm gw} = \frac{1}{64\pi G_{\rm gw}} \left\{ \dot{h}_{ij}^2 - a^{-2} (\nabla h_{ij})^2 \right\}$

galaxy clustering $G_{\rm matter}$

$k^2 \Psi = -4\pi G_{\rm matter}(k, \tau) \delta\rho_{\rm m}$

gravitational lensing $G_{\rm light}$

$k^2 (\Psi + \Phi) = -8\pi G_{\rm light}(k, \tau) \delta\rho_{\rm m}$

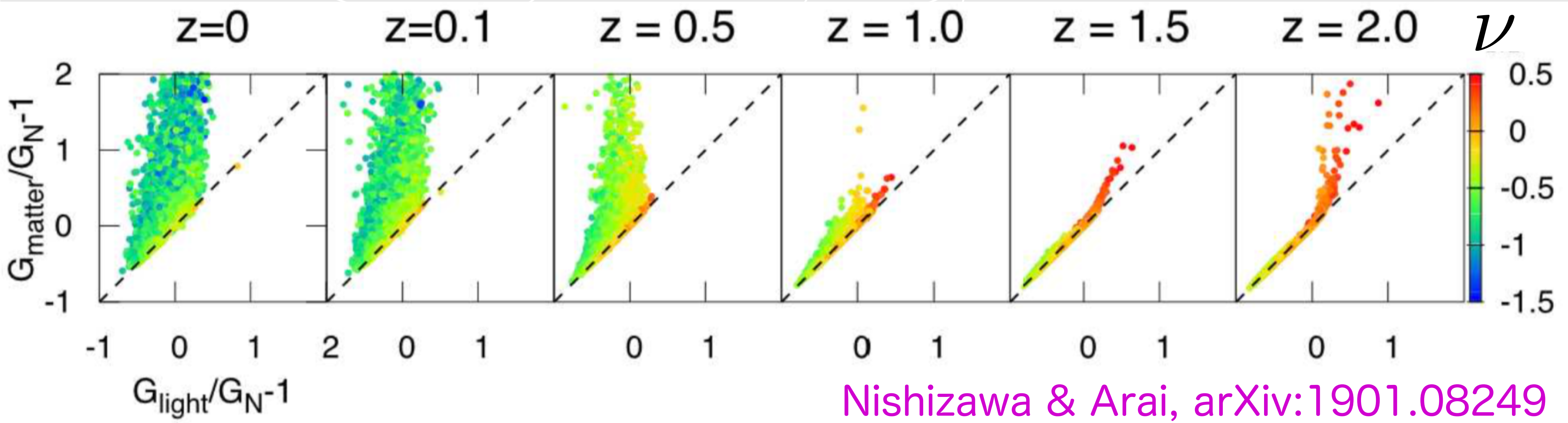
All are $G_{\rm N}$ in GR

Well constrained at small scale, but not at cosmological distance yet.

Distribution of gravitional couplings in Horndeski theory

$$\mathcal{L} = G_2(\phi, X) - G_3(\phi, X)\Box\phi + G_4(\phi)R$$

- Generate models with Monte-Carlo method numerically.
- Filter the models by the stability conditions of the theory and the condition to accelerate the Universe similarly to ΛCDM.



Nishizawa & Arai, arXiv:1901.08249

Sensitivity to amplitude damping

We generate Mock GW catalogs and estimate the measurement errors of model parameters with the Fisher information matrix.

current detector network (aLIGO, KAGRA, etc.)

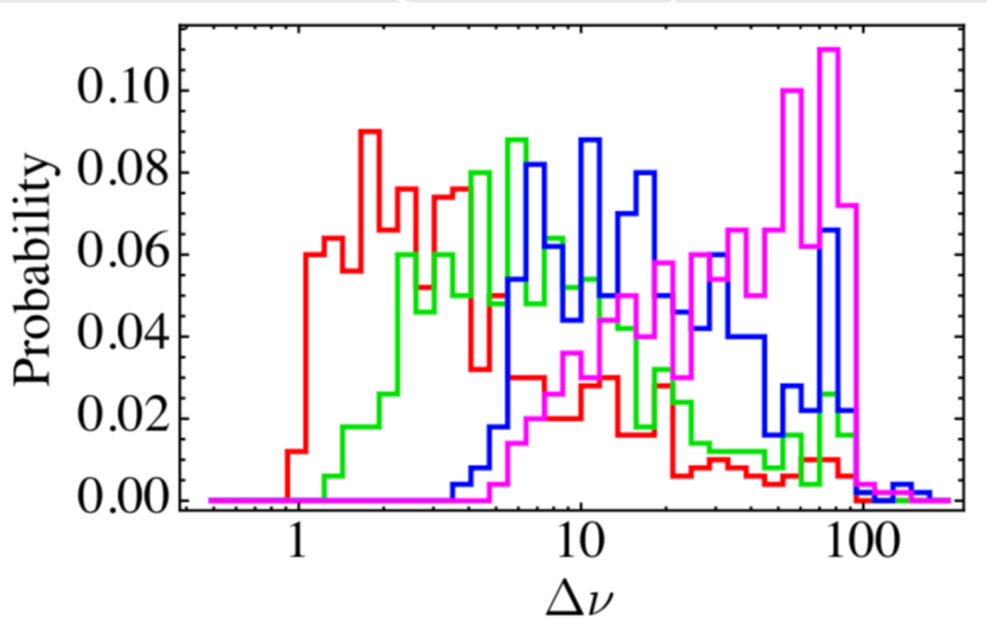
Nishizawa, PRD (2018)

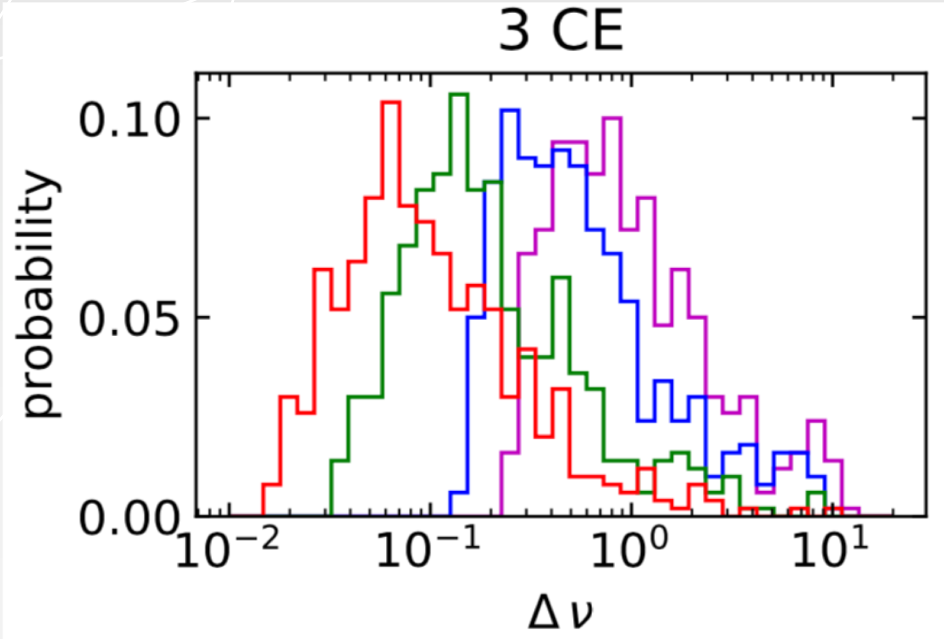
$$\Delta\nu \sim \mathcal{O}(1)$$

future detector network (ET-D, CE, etc.)

Nishizawa & Arai, arXiv:1901.08249

$$\Delta\nu \sim \mathcal{O}(0.01)$$





Summary

- Gravity at cosmological scales may cause the cosmic accelerating expasion of the Universe.

- The observation of GW propagation plays an important role to test gravity at cosmological distance.

- GW propagation speed has been measured tightly from GW170817 and constrained modified gravity theories.

- Gravitational constant for GW is proved by measuring the amplitude damping rate and enable us to test the equivalence principle at cosmological scales at precisions of

  $\Delta\nu \sim \mathcal{O}(1)$ with current detectors (aLIGO, KAGRA, etc.)

  $\Delta\nu \sim \mathcal{O}(0.01)$ with future detectors (ET-D, CE, etc.)