Dark energy after gravitational wave observations

Filippo Vernizzi
IPhT - CEA, CNRS, Paris-Saclay

with Paolo Creminelli 1710.05877,
+ Matthew Lewandowski and Giovanni Tambalo, 1809.03484
+ Vicharit Yingcharoenrat, 1906.07015, 1910.14035

22 June 2020
Online “Newton 1665” seminars

Motivations

- General relativity is very well tested on Solar System scales
- Its validity is extrapolated on larger scales

Post-Newtonian parametrization

Table 4: Current limits on the PPN parameters.

Parameter	Effect	Limit	Remarks
$\gamma - 1$	time delay	2.3×10^{-5}	Cassini tracking
	light deflection	2×10^{-4}	VLBI
$\beta - 1$	perihelion shift	8×10^{-5}	$J_{2\odot} = (2.2 \pm 0.1) \times 10^{-7}$
	Nordtvedt effect	2.3×10^{-4}	$\eta_N = 4\beta - \gamma - 3$ assumed
ξ	spin precession	4×10^{-9}	millisecond pulsars
α_1	orbital polarization	10^{-4}	Lunar laser ranging
		4×10^{-5}	PSR J1738+0333
α_2	spin precession	2×10^{-9}	millisecond pulsars
α_3	pulsar acceleration	4×10^{-20}	pulsar $\dot{P}$ statistics
ζ_1	—	2×10^{-2}	combined PPN bounds
ζ_2	binary acceleration	4×10^{-5}	$\ddot{P}_p$ for PSR 1913+16
ζ_3	Newton's 3rd law	10^{-8}	lunar acceleration
ζ_4	—	—	not independent [see Eq. (73)]

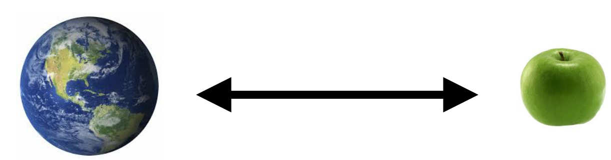
Motivations

- On large scales, constraints are weaker
- No measured deviations from ΛCDM (caveat H0 tension), but dark sector not well understood

DES '18

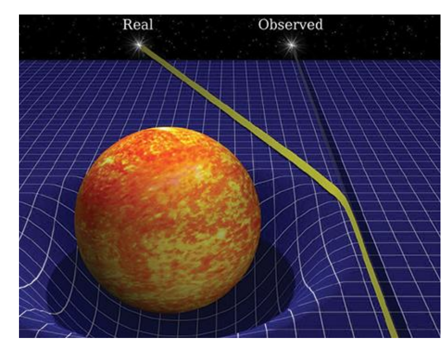
$$|\mu - 1| < 8 \times 10^{-2}$$

$$|\Sigma - 1| < 4 \times 10^{-1}$$



fifth force

$$dt^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)d\vec{x}^2$$



anomalous light bending

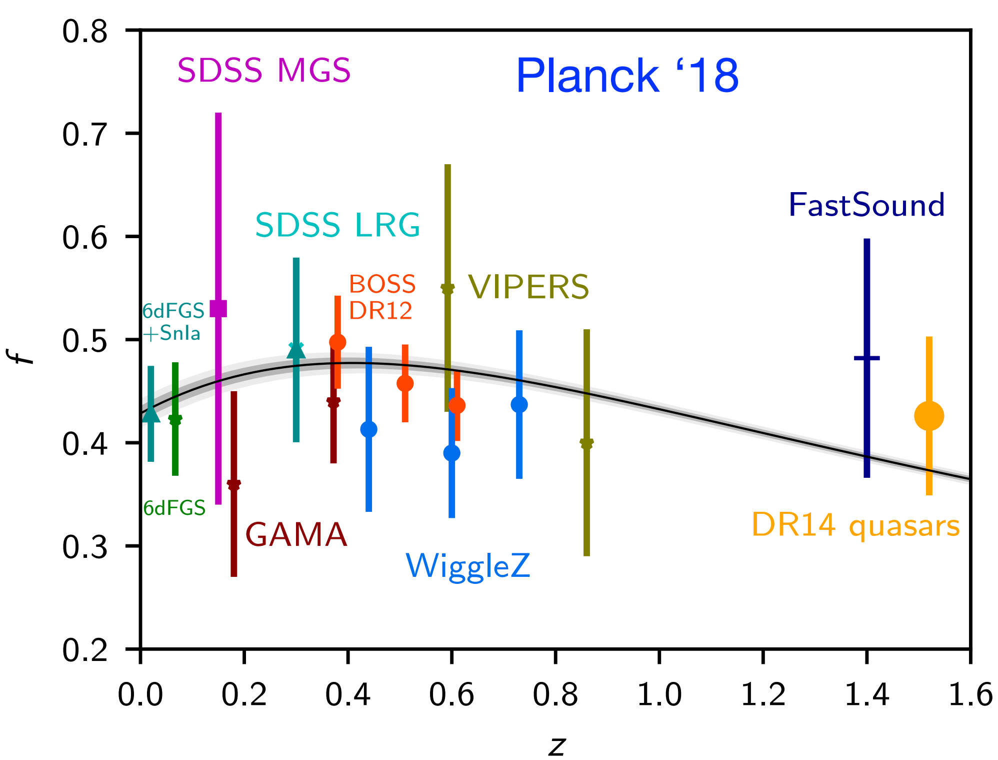
$$\nabla^2\Phi = 4\pi G\,\mu\,\delta\rho_{\rm m}$$

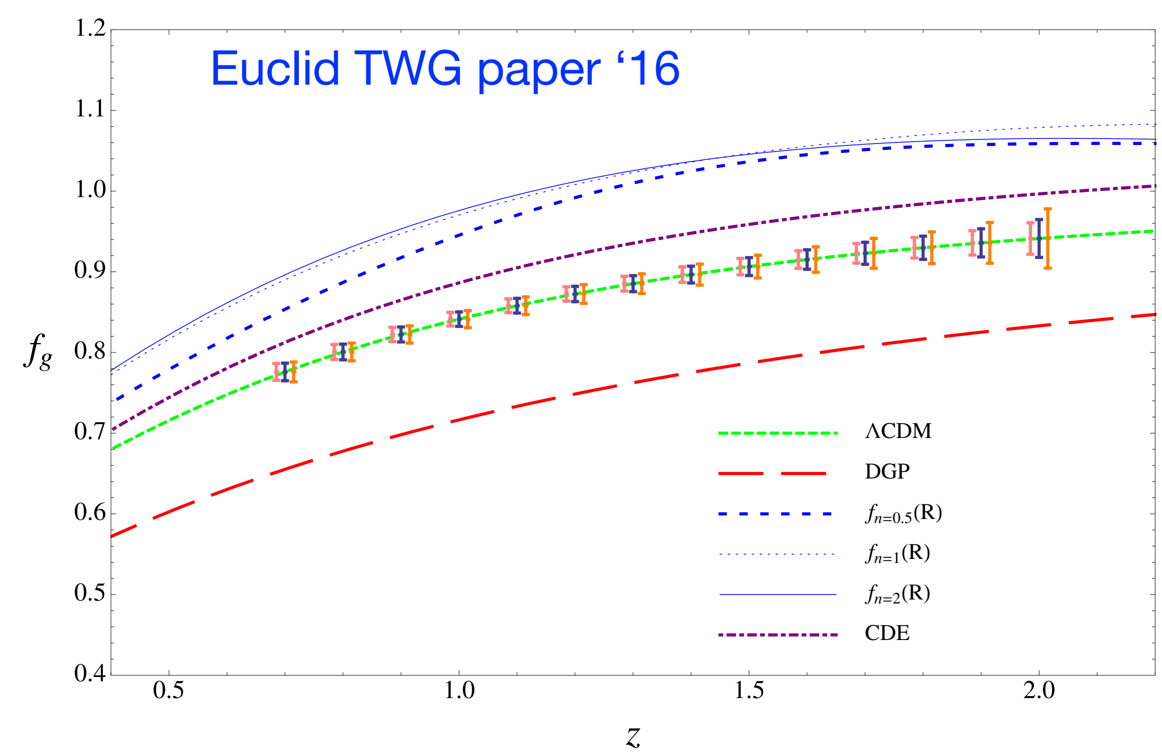
$$\nabla^2(\Phi+\Psi) = 8\pi G\,\Sigma\,\delta\rho_{\rm m}$$

Motivations

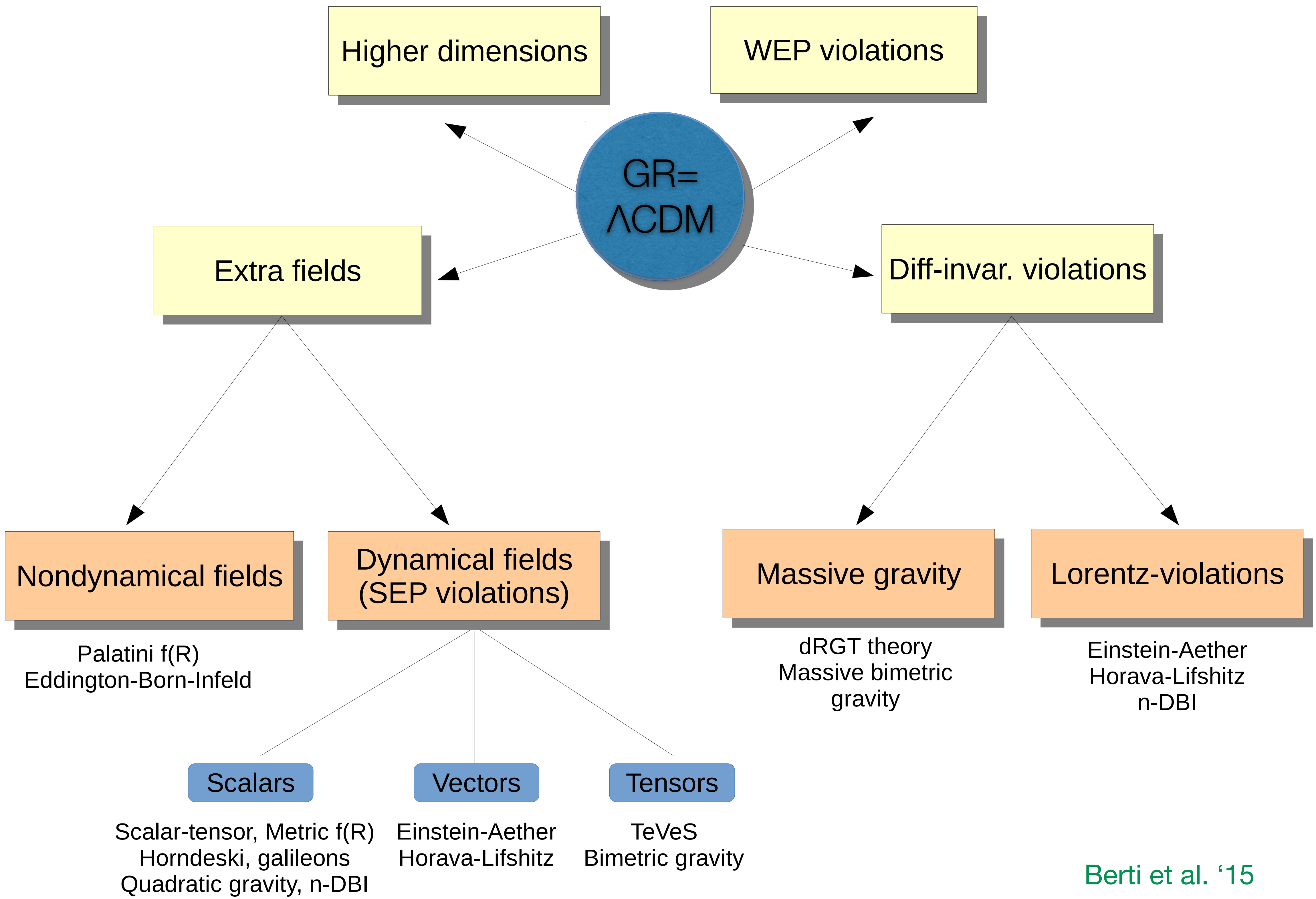
- On large scales, constraints are weaker
- No measured deviations from ΛCDM (caveat H0 tension), but dark sector not well understood

- Is ΛCDM the ultimate model or the simplest approximation given the current precision of data?
- Is there new physics on very large scales?

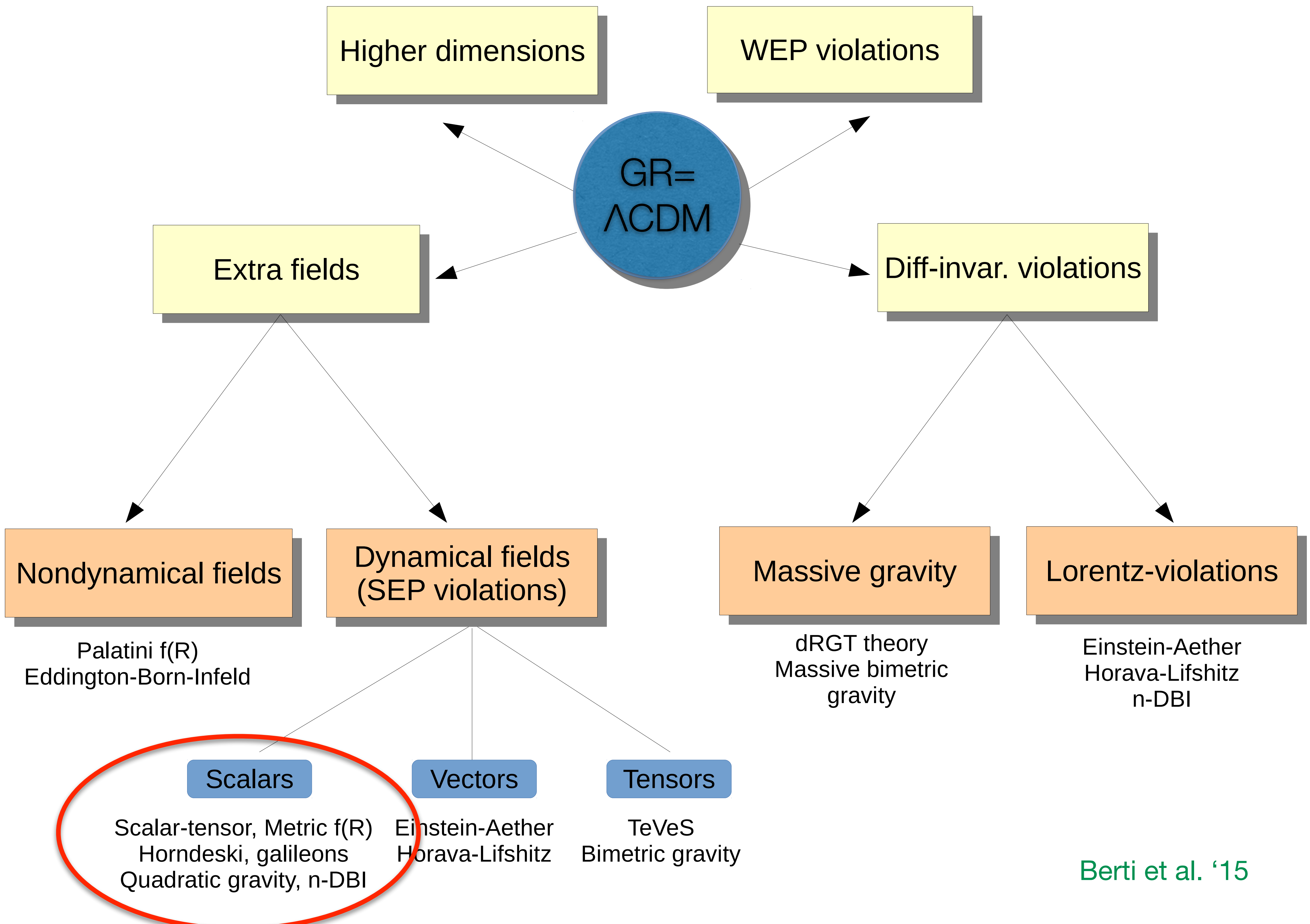




Cosmological precision tests of ΛCDM

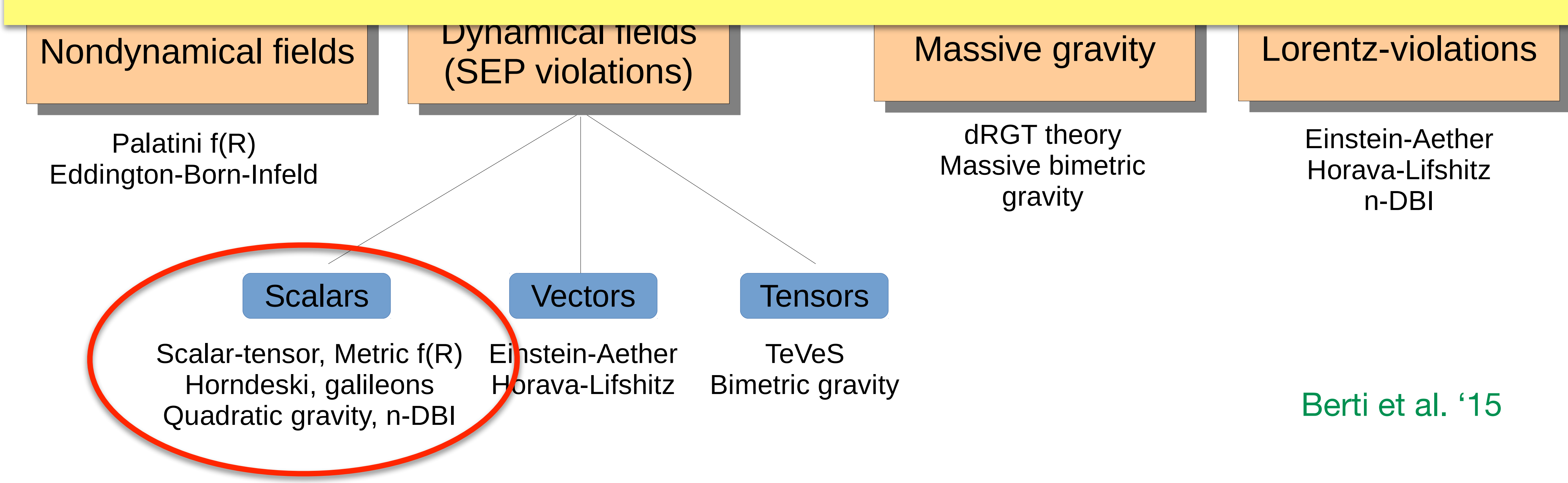


Berti et al. ‘15


Higher dimensions
WEP violations
GR=
ΛCDM
Extra fields
Diff-invar. violations
Nondynamical fields
Dynamical fields
(SEP violations)
Massive gravity
Lorentz-violations
Palatini f(R)
Eddington-Born-Infeld
dRGT theory
Massive bimetric
gravity
Einstein-Aether
Horava-Lifshitz
n-DBI
Scalars
Vectors
Tensors
Scalar-tensor, Metric f(R)
Horndeski, galileons
Quadratic gravity, n-DBI
Einstein-Aether
Horava-Lifshitz
TeVeS
Bimetric gravity
Berti et al. '15

GW observations

- severely constrain cosmological modifications of gravity
- dramatically reduce the parameter space of scalar-tensor gravity (self-accelerating and screening) and the discovery-potential of new physics in LSS surveys



Berti et al. '15

Generalized scalar-tensor theories

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$- 2G_{4,X}(\phi, X)\Big[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\Big]$$

$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\Big[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\Big]$$

$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

Generalized scalar-tensor theories

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$

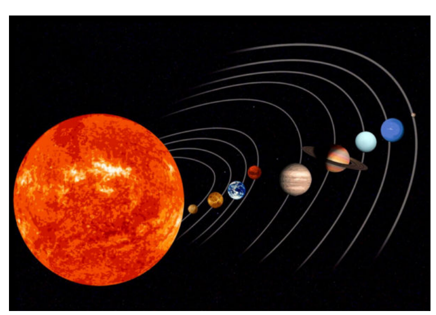
$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$

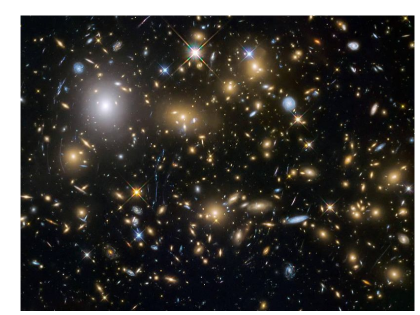
$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

Self-acceleration and screening: large classical scalar field nonlinearities

$$\Lambda_3 \equiv (H_0^2 M_{\rm Pl})^{1/3} \sim (1000\,{\rm km})^{-1}$$



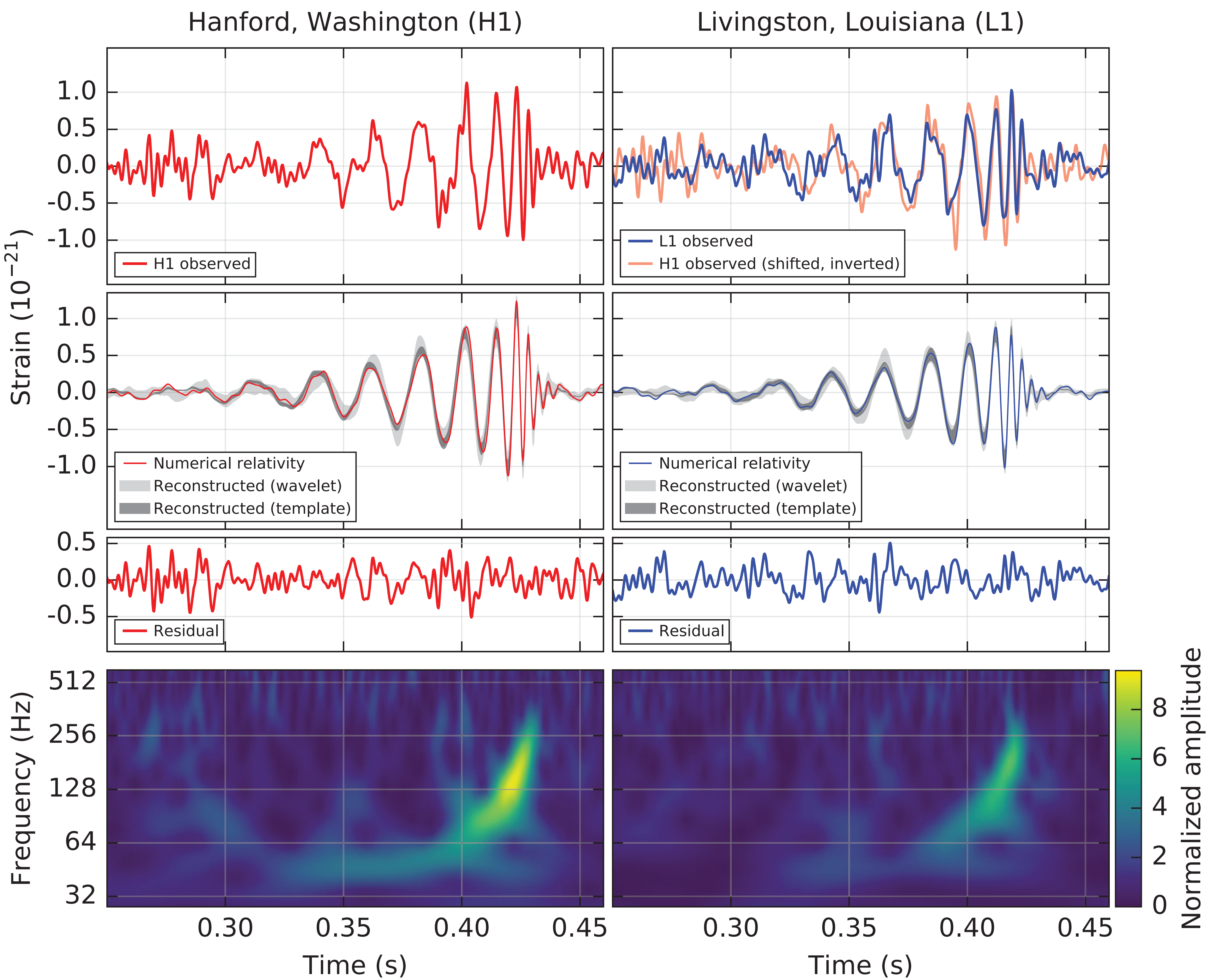


almost GR $\ll \mathcal{O}(10^{-2})$ ← → scalar-tensor $\mathcal{O}(1)$

1 $\quad \Lambda_3^{-1} \quad 10^4 \quad 10^8 \quad r_{\rm SS} \quad 10^{12} \quad 10^{16} \quad 10^{20} \quad H_0^{-1} \quad 10^{24}$ km

GW150914: Gravitational Waves

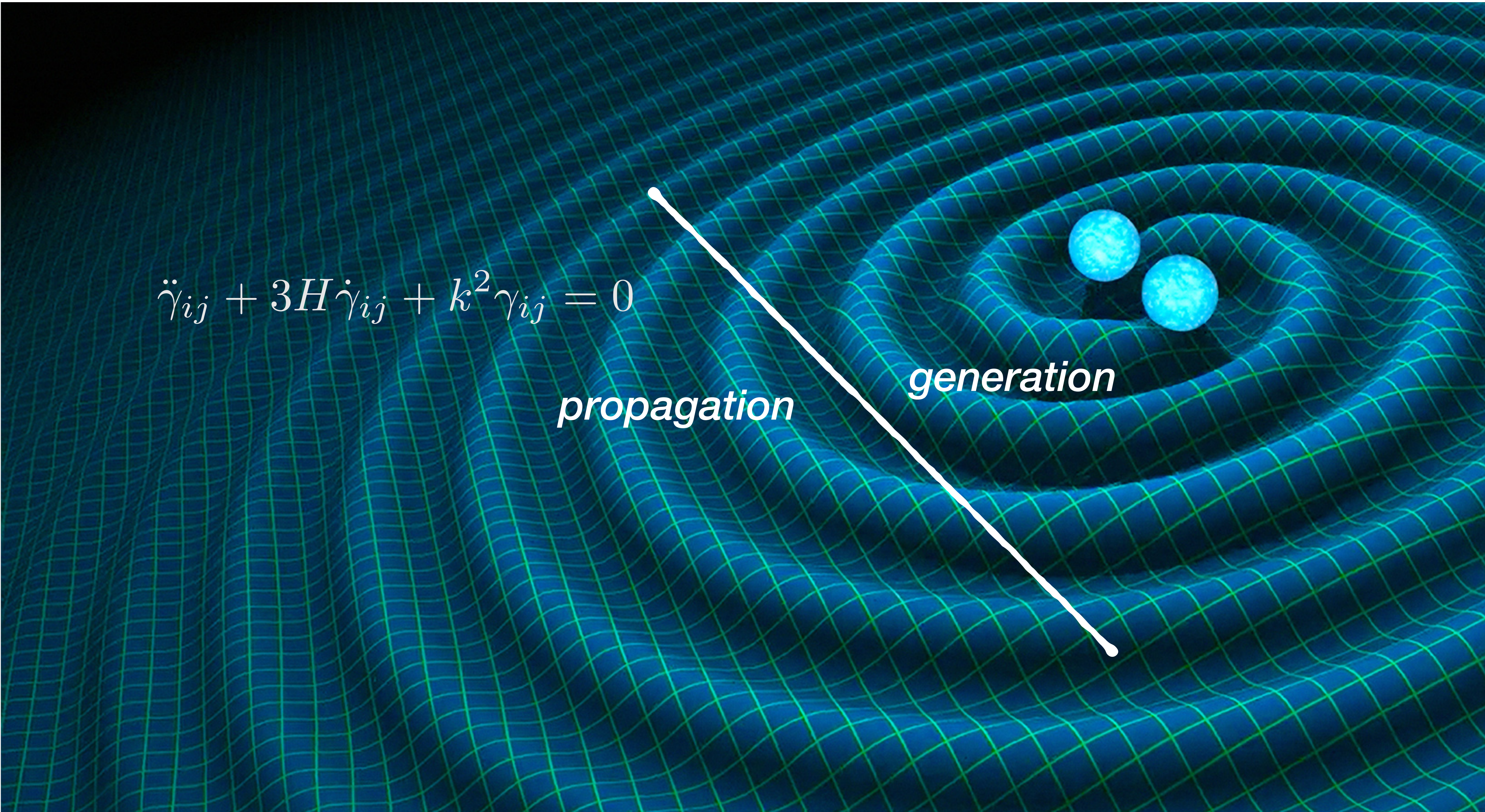
Abbott et al. '16
first detection: 09/14, 2015



Gravitational wave equation

Gravitational wave equation:

$$ds^2 = -dt^2 + a^2(t)\,[\delta_{ij} + \gamma_{ij}]\,d\vec{x}^i d\vec{x}^j \ , \qquad \gamma_{ii} = 0 = \partial_i \gamma_{ij} \ , \qquad H = \dot{a}/a$$

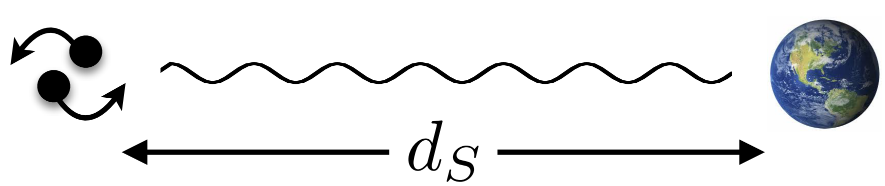


Modified gravitational wave propagation

Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed. Effects accumulate on long time-scale.

$$\ddot{\gamma}_{ij} + [(3+\alpha_{\rm M})H + \Gamma(k)]\,\dot{\gamma}_{ij} + \left[c_T^2 k^2 + f(k)\right]\gamma_{ij} = 0$$

$$\frac{\Gamma(k)}{\omega} \lesssim \frac{1}{d_S \omega} \qquad \frac{f(k)}{\omega^2} \lesssim \frac{1}{d_S \omega} \sim 10^{-18} \times \frac{2\pi \times 100\,\mathrm{Hz}}{\omega}\,\frac{40\,\mathrm{Mpc}}{d_S}$$



See e.g. Yunes, Yagi, Pretorius '16; Abbott et al. '17

Modified gravitational wave propagation

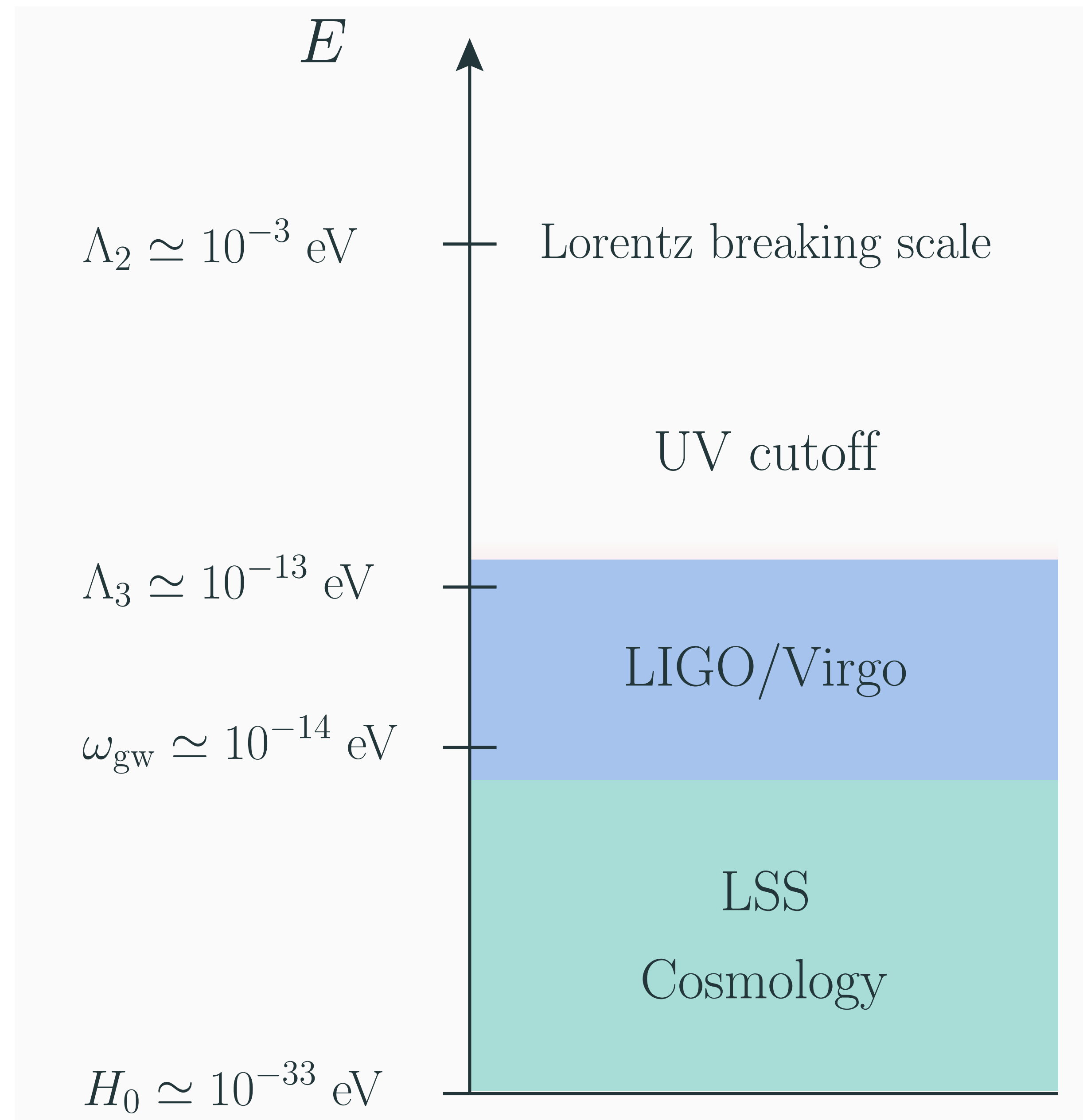
Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed. Effects accumulate on long time-scale.

$$\ddot{\gamma}_{ij} + \left[(3+\alpha_{\rm M})H + \Gamma(k)\right]\dot{\gamma}_{ij} + \left[c_T^2 k^2 + f(k)\right]\gamma_{ij} = 0$$

Modifications in the wave equation are related to modifications of gravity in the LSS:

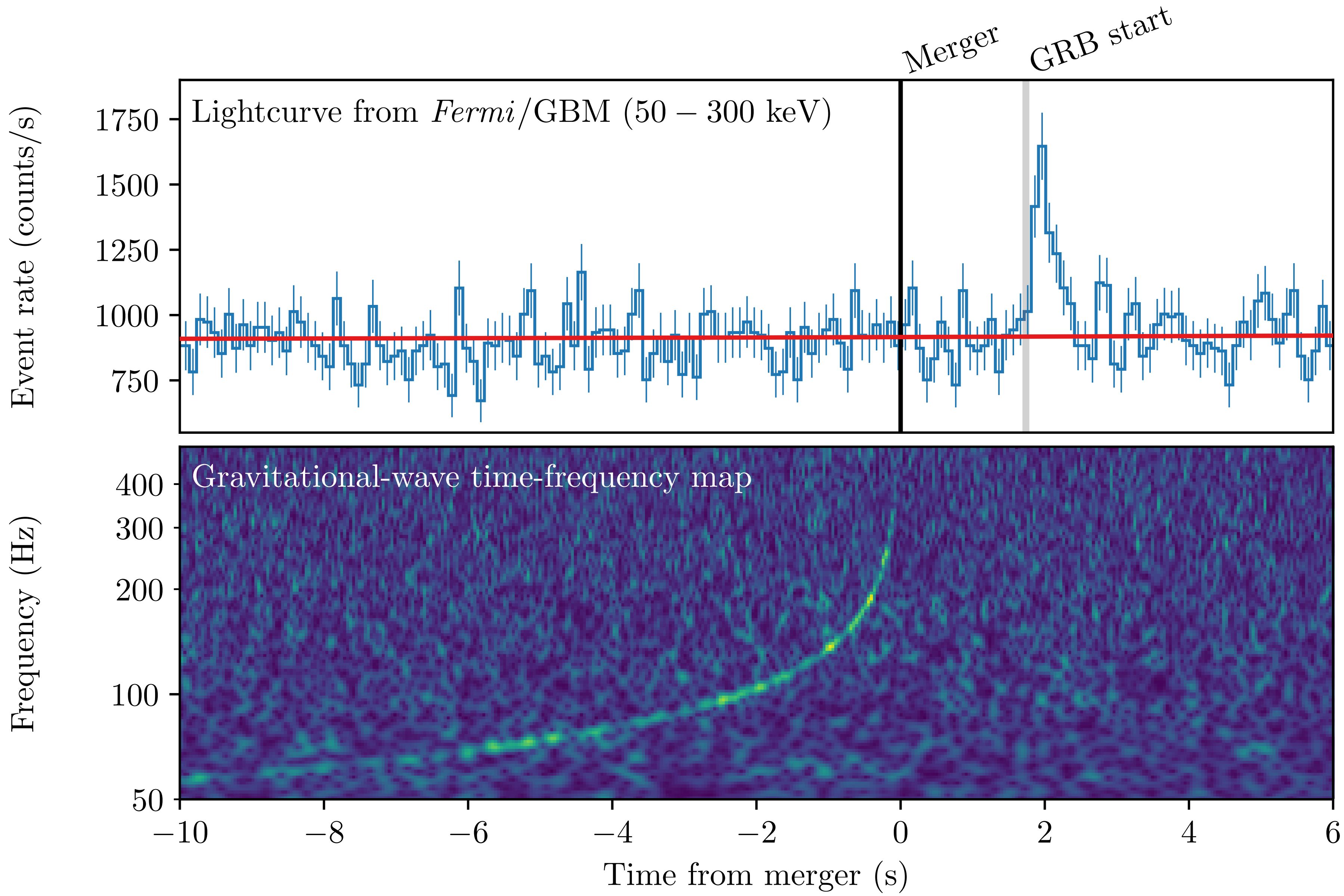
$$\mu = \mu(\dots)\,, \qquad \Sigma = \Sigma(\dots)$$

$$\nabla^2\Phi = 4\pi G\,\mu\,\delta\rho_{\rm m}$$
$$\nabla^2(\Phi+\Psi) = 4\pi G\,\Sigma\,\delta\rho_{\rm m}$$



GW170817: neutron star merger

Multi-messenger observation



$$-3 \times 10^{-15} \leq \frac{c_T - c}{c} \leq 7 \times 10^{-16}$$

c_T=1 implications

$$\mathcal{L} = G_4(\phi,X)R + G_2(\phi,X) + G_3(\phi,X)\Box\phi \qquad \Box\phi \equiv \phi^{;\mu}_{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$- 2G_{4,X}(\phi,X)\Big[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\Big]$$

$$+ G_5(\phi,X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi,X)\Big[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\Big]$$

$$- F_4(\phi,X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi,X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

c_T=1 implications

$\dot{\gamma}_{ij}^2 - (\partial_k \gamma_{ij})^2$

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$

$\dot{\gamma}_{ij}^2$

$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$

$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

$$c_T^2 - 1 \propto -2G_{4,X} - G_{5,\phi} - (H\dot{\phi} - \ddot{\phi})G_{5,X} + XF_4 - 3HX\dot{\phi}F_5$$

c_T=1 implications

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$

$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$

$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

$$c_T^2 - 1 \propto -2G_{4,X} - G_{5,\phi} - (H\dot{\phi} - \ddot{\phi})G_{5,X} + XF_4 - 3HX\dot{\phi}F_5$$

Most general theory compatible with c_T=1: $G_5 = F_5 = 0 \;, \qquad XF_4 = 2G_{4,X}$

Creminelli, FV ’17; Sakstein, Jain ’17 ; Ezquiaga, Zumalacarregui ’17 ; Baker+ ’17

$$\delta c_T \sim (\Lambda_3/\Lambda_2)^4 \sim 10^{-40} \quad \ll 10^{-15}$$

c_T=1 tuning is stable

Can we rule out more?

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi$$
$$- 2G_{4,X}(\phi, X)\Big[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\Big]$$
$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$\Box\phi \equiv \phi_{;\mu}^{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$XF_4 = 2G_{4,X}$$

Can we rule out more?

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi$$
$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$
$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$\Box\phi \equiv \phi^{;\mu}_{;\mu} \qquad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$XF_4 = 2G_{4,X}$$

- ***Beyond Horndeski:*** $\alpha_H \equiv -\frac{X^2 F_4}{G_4}$
- ***Braiding:*** $\alpha_B = \frac{\dot{\phi} X G_{3,X}}{H G_4}$

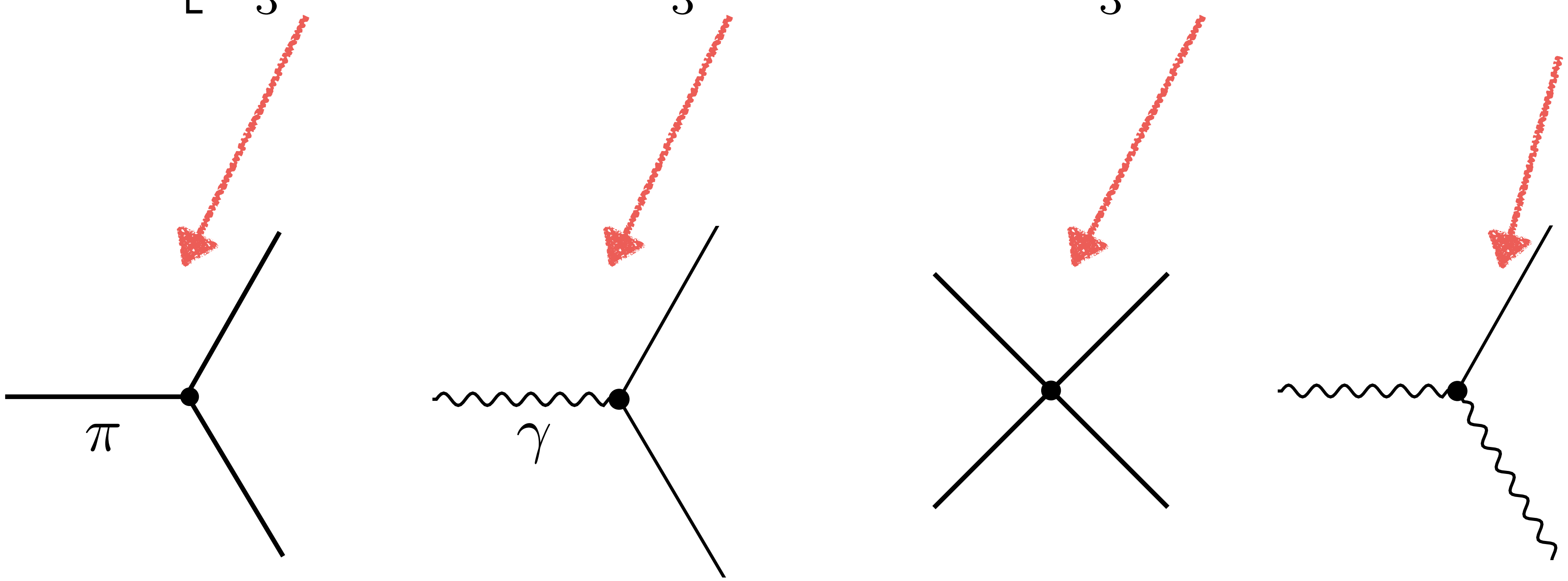
Forecasted constraints from the large-scale structure

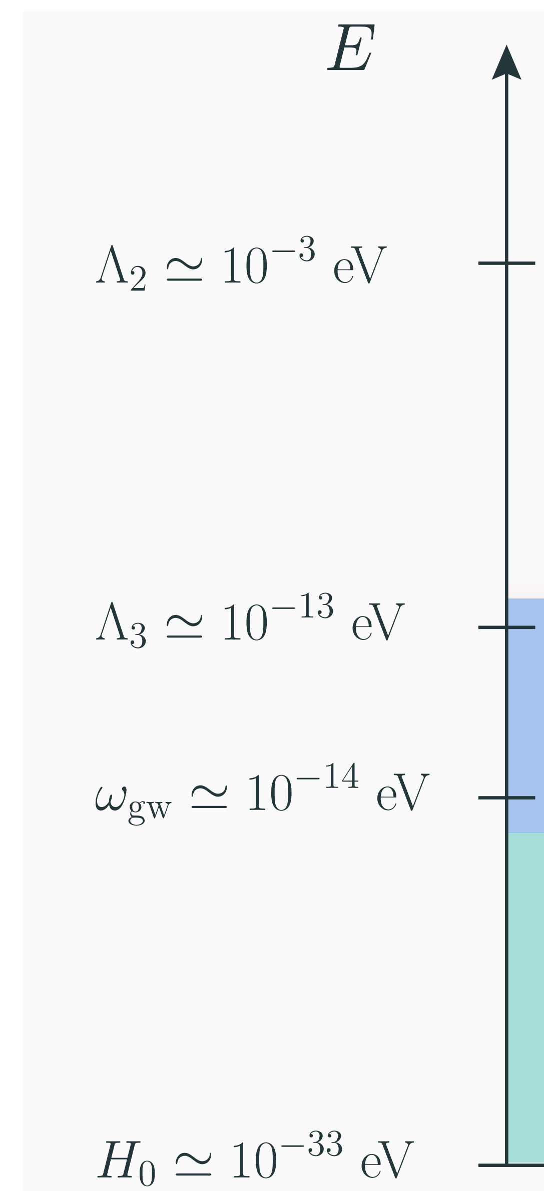
$$|\alpha_H| \lesssim 10^{-2} \qquad |\alpha_B| \lesssim 10^{-2}$$

Expanded action for α_H

$$\mathcal{L} = \frac{1}{2}\left(\dot{\pi}^2 - c_s^2(\partial_k \pi)^2\right) + \frac{1}{4}\left((\dot{\gamma}_{ij})^2 - (\partial_k \gamma_{ij})^2\right) \qquad \pi \equiv \delta\phi/\dot{\phi}_0$$

$$+\alpha_H \left[\frac{1}{\Lambda_3^3}\partial^2\pi(\partial\pi)^2 + \frac{1}{\Lambda_3^3}\ddot{\gamma}_{ij}\partial_i\pi\partial_j\pi + \frac{1}{\Lambda_3^6}(\Box\pi)^2(\partial\pi)^2 + \frac{1}{\Lambda_2^2}\dot{\pi}\dot{\gamma}_{ij}^2\right]$$



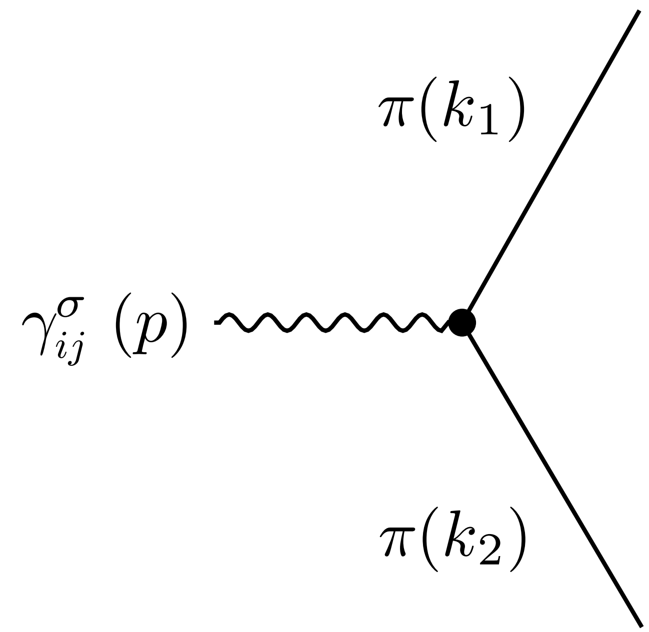


Graviton decay into dark energy

Creminelli, Lewandowski, Tambalo, FV '18

$$\mathcal{L}_{\gamma\pi\pi} = \frac{\alpha_H}{\Lambda_3^3}\ddot{\gamma}_{ij}^c \partial_i \pi_c \partial_j \pi_c$$

$$\Lambda_3 \equiv (M_{\rm Pl} H_0^2)^{1/3}$$

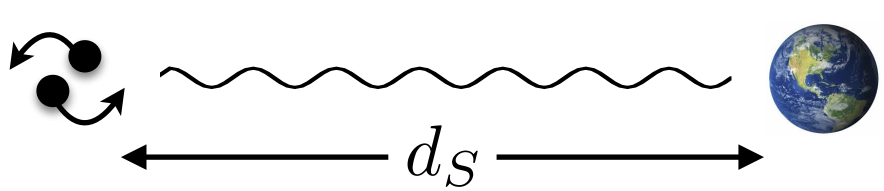


Beyond Horndeski interactions imply GW decay into scalar fluctuations π.
Analogous to light absorption into a material

Decay allowed for $c_s < 1$ (c_s = sound speed of π fluctuations; assume c_T=1)

$$\Gamma \simeq \left(\frac{\alpha_H}{\Lambda_3^3}\right)^2 \frac{\omega_{\rm gw}^7 (1-c_s^2)^2}{c_s^7}$$ decay rate

$$d_S \Gamma < 1 \quad \Rightarrow \quad \alpha_H < 10^{-10}$$



irrelevant for LSS observations $\alpha_H \lesssim 10^{-2}$

(unless c_s=1 with great precision)

Coherent decay

Creminelli, Tambalo, FV, Yingcharoenrat, '19

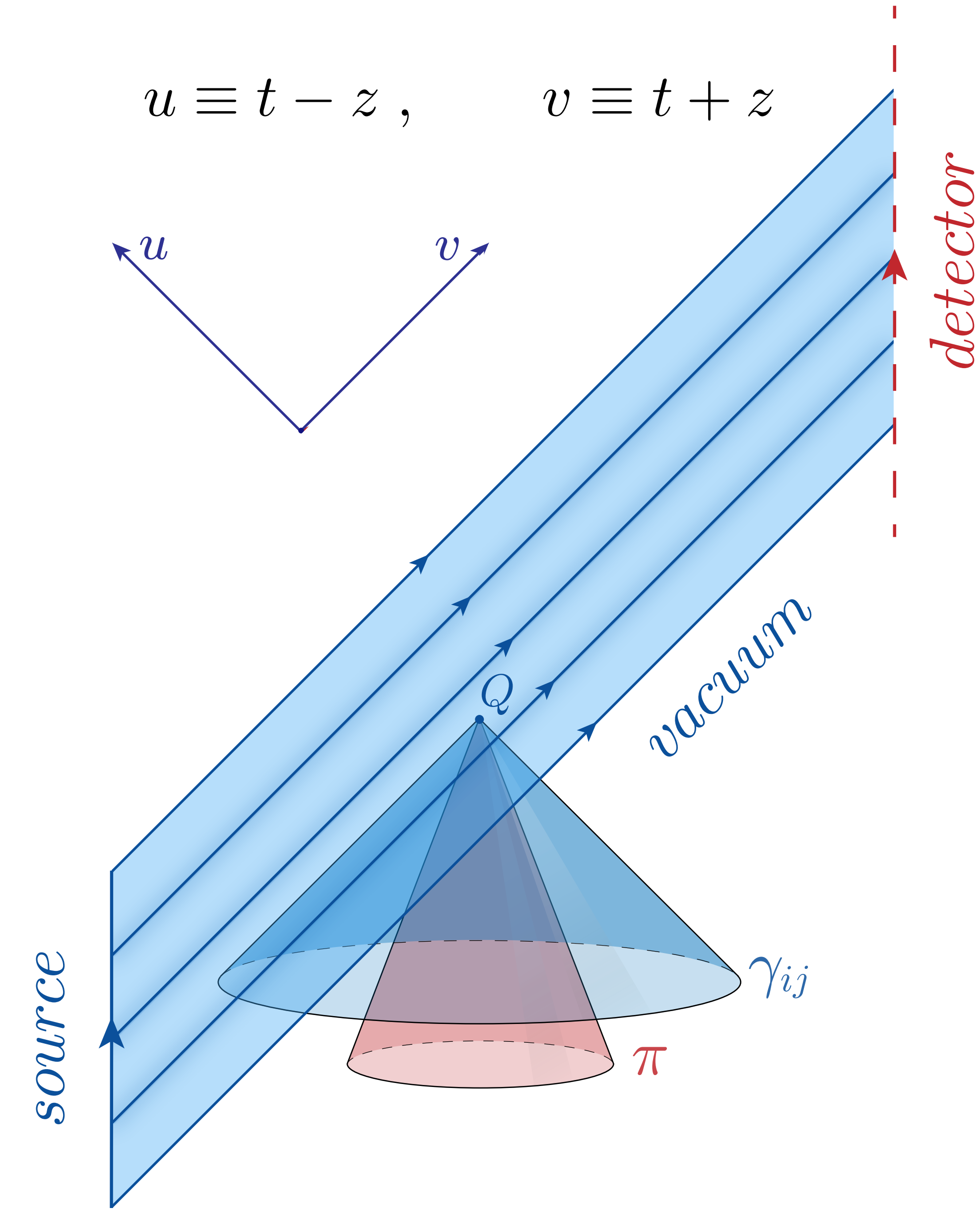
Decay enhanced by the large occupation number of the GWs ~ preheating

Classical wave: $\gamma_{ij} = M_{\rm Pl} h_0^+ \cos(\omega u)\epsilon_{ij}^+ \,, \qquad \beta = \frac{|\alpha_H|}{\alpha c_s^2}\left(\frac{\omega}{H}\right)^2 h_0^+$

Oscillator with changing frequency:

$$\ddot{\pi} - c_s^2\left[\nabla^2 + \beta\cos(\omega u)\epsilon_{ij}^+\partial_i\partial_j\right]\pi = 0$$

$u \equiv t - z \,, \qquad v \equiv t + z$



Coherent decay

Creminelli, Tambalo, FV, Yingcharoenrat, ‘19

Decay enhanced by the large occupation number of the GWs ~ preheating

Classical wave: $$\gamma_{ij} = M_{\rm Pl} h_0^+ \cos(\omega u)\epsilon_{ij}^+ \,, \qquad \beta = \frac{|\alpha_H|}{\alpha c_s^2}\left(\frac{\omega}{H}\right)^2 h_0^+$$

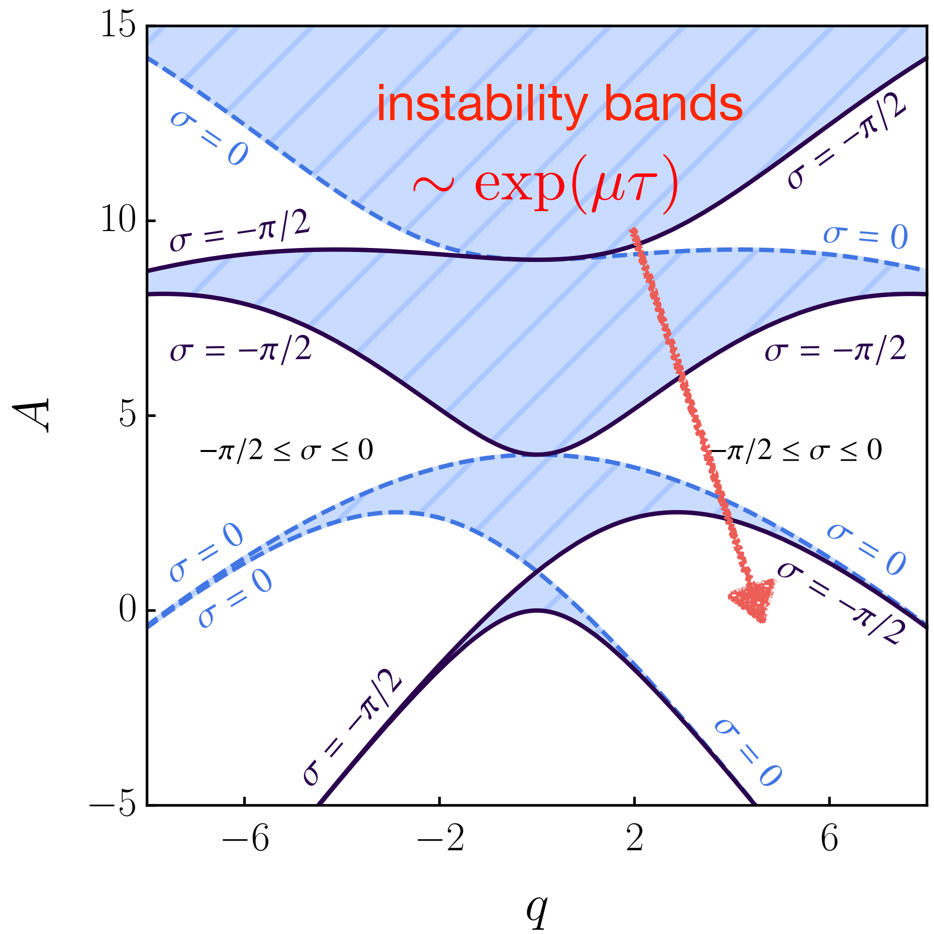
Oscillator with changing frequency:

$$\ddot{\pi} - c_s^2\left[\nabla^2 + \beta\cos(\omega u)\epsilon_{ij}^+\partial_i\partial_j\right]\pi = 0$$

Each Fourier mode satisfies a Mathieu equation
⇒ parametric resonance.

$$\frac{d^2\pi_{\vec{k}}}{d\tau^2} + (A_{\vec{k}} - 2q_{\vec{k}}\cos(2\tau))\pi_{\vec{k}} = 0$$

Resonant modes grow exponentially: $\pi_{\vec{k}} \sim e^{\mu_{\vec{k}}\tau}$

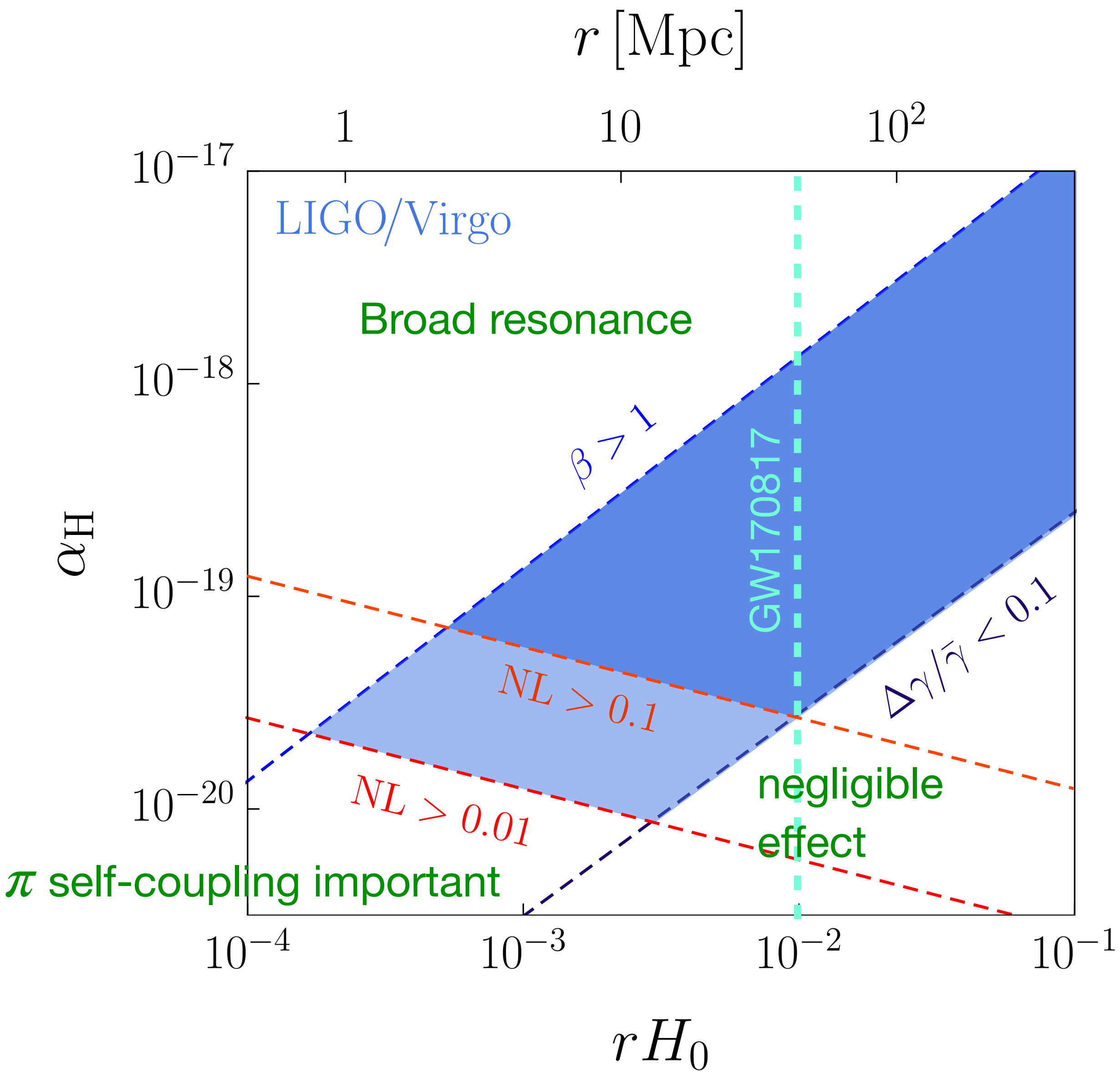


Narrow resonance $\beta \ll 1$: $\mu \sim \beta/4 \quad \Rightarrow \quad \rho_\pi \propto e^{\beta\omega u/4} \quad \Rightarrow \quad \Delta\gamma_{ij} \propto v\gamma_0 e^{\beta\omega u/4}\epsilon_{ij}^+$

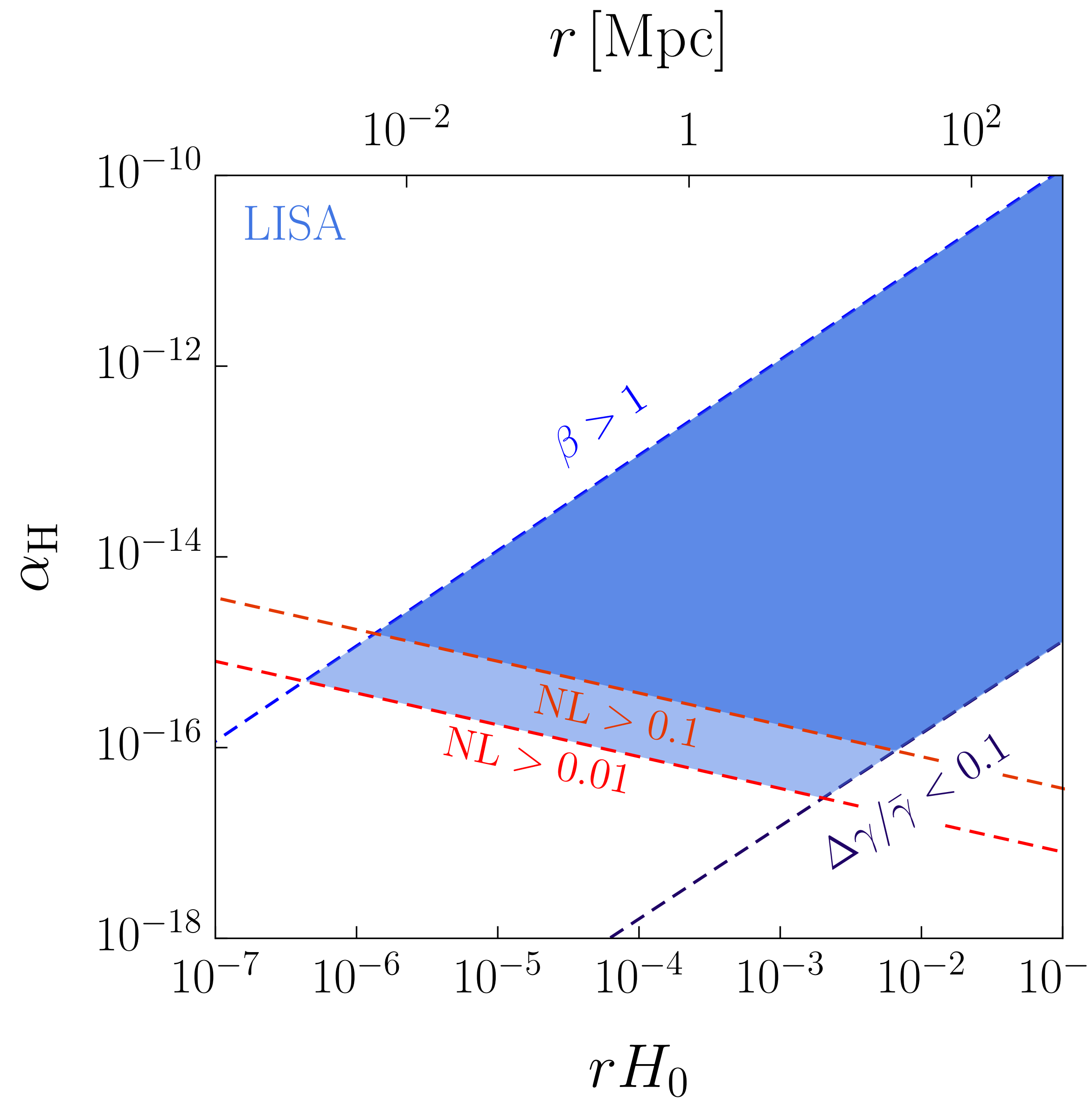
Same direction and polarization. Same frequency + higher harmonics (precursors)

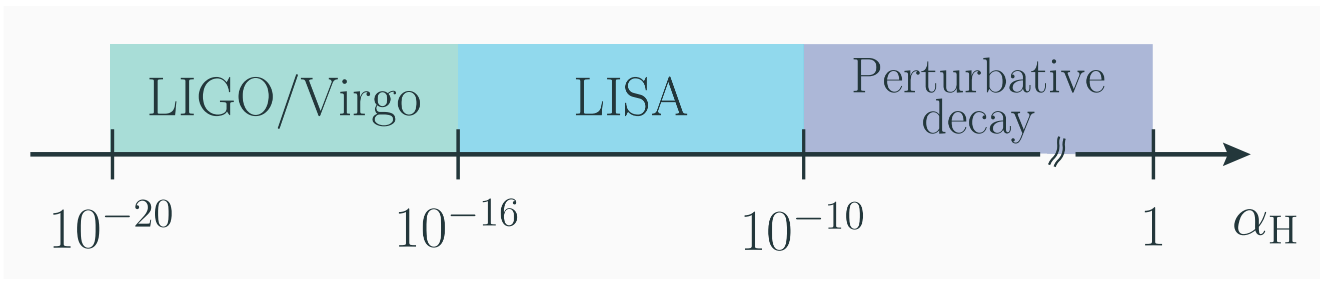
GW modification

$$f = 30\,\mathrm{Hz}\,, \quad M_c = 1.2 M_\odot$$



$$f = 10^{-2}\,\mathrm{Hz}\,, \quad M_c = 30 M_\odot$$

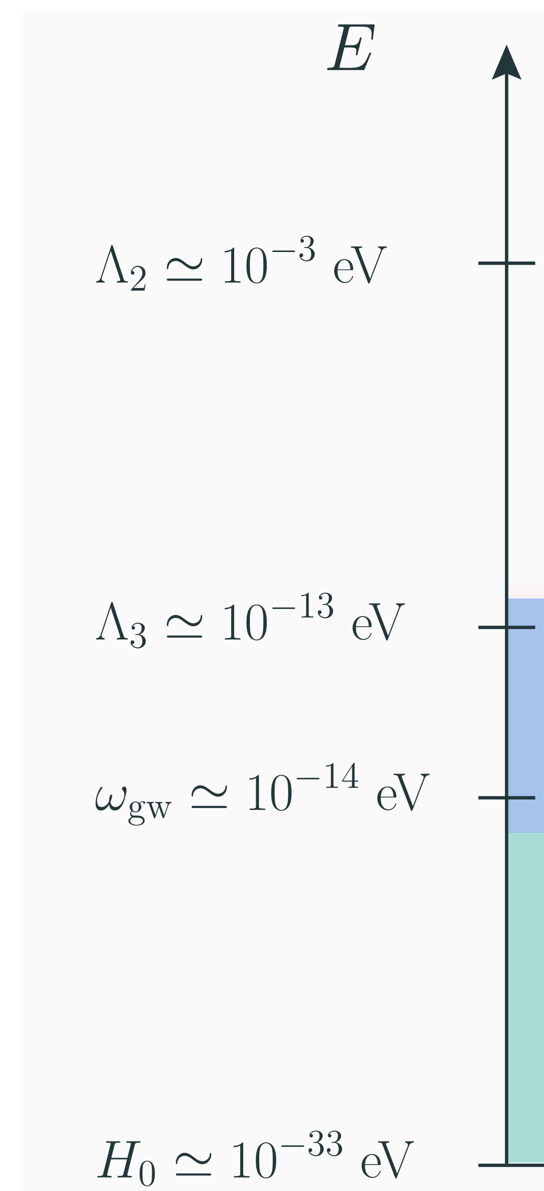




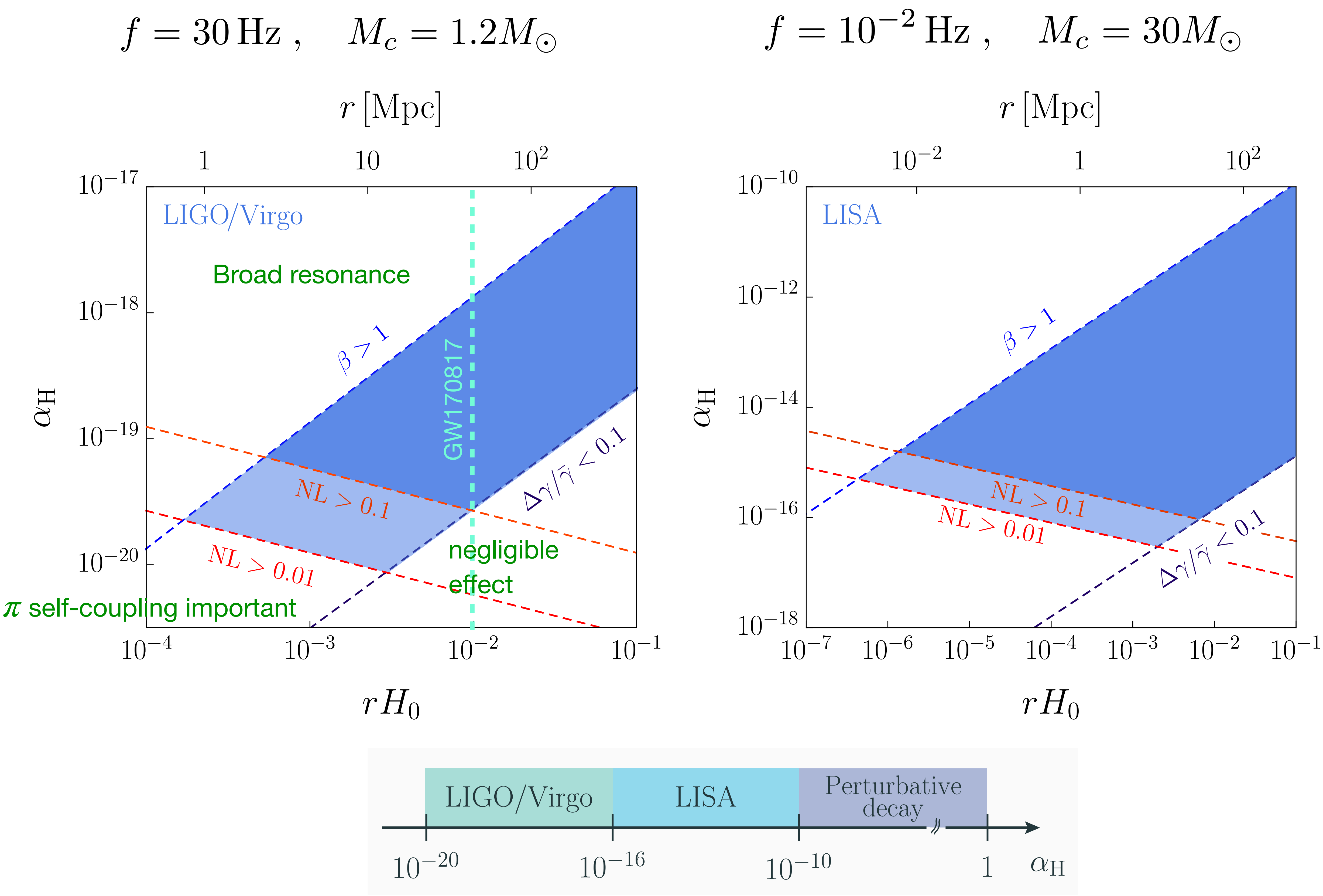
Expanded action for α_H

$$\mathcal{L} = \frac{1}{2}\left(\dot{\pi}^2 - c_s^2(\partial_k \pi)^2\right) + \frac{1}{4}\left((\dot{\gamma}_{ij})^2 - (\partial_k \gamma_{ij})^2\right) \qquad \alpha_H \equiv -\frac{X^2 F_4}{G_4}$$

$$+\alpha_H\left[\frac{1}{\Lambda_3^3}\partial^2\pi(\partial\pi)^2 + \frac{1}{\Lambda_3^3}\ddot{\gamma}_{ij}\partial_i\pi\partial_j\pi + \frac{1}{\Lambda_3^6}(\Box\pi)^2(\partial\pi)^2 + \frac{1}{\Lambda_2^2}\dot{\pi}\dot{\gamma}_{ij}^2\right]$$



GW modification



Theory after no decay

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi^{;\mu}_{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

$$-2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$

$$-F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'} \qquad XF_4 = 2G_{4,X}$$

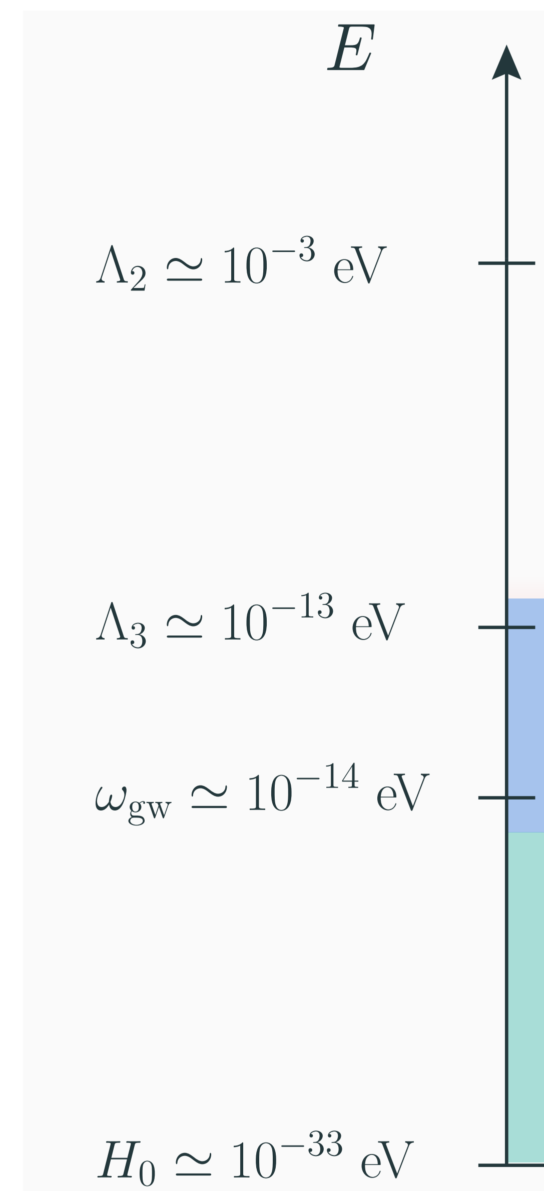
- ~~*Beyond Horndeski:*~~ $\alpha_H = \frac{X^2 F_4}{G_4}$
- ***Braiding:*** $\alpha_B = \frac{\dot{\phi} X G_{3,X}}{H G_4}$

Expanded action for α_B

$$\mathcal{L} = \frac{1}{2}\left(\dot{\pi}^2 - c_s^2(\partial_k \pi)^2\right) + \frac{1}{4}\left((\dot{\gamma}_{ij})^2 - (\partial_k \gamma_{ij})^2\right)$$
$$+\alpha_B \left[\frac{1}{\Lambda_3^3}\partial^2\pi(\partial\pi)^2 + \frac{1}{\Lambda_2^2}\dot{\gamma}_{ij}\partial_i\pi\partial_j\pi + \frac{1}{M_{\rm Pl}}\pi\dot{\gamma}_{ij}^2\right]$$

$$\alpha_B = \frac{\dot{\phi} X G_{3,X}}{H G_4}$$

$$\Lambda_2 \equiv (H_0 M_{\rm Pl})^{1/2}$$



Same calculation but with $\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+$

Exponential growth quenched by large self-couplings of π.

Kills the effect? Simulations ~ preheating

No clear constraints on α_B ...

Expanded action for α_B

$$\mathcal{L} = \frac{1}{2}\left(\dot\pi^2 - c_s^2(\partial_k\pi)^2\right) + \frac{1}{4}\left((\dot\gamma_{ij})^2 - (\partial_k\gamma_{ij})^2\right)$$
$$+\alpha_B\left[\frac{1}{\Lambda_3^3}\partial^2\pi(\partial\pi)^2 + \frac{1}{\Lambda_2^2}\dot\gamma_{ij}\partial_i\pi\partial_j\pi + \frac{1}{M_{\rm Pl}}\pi\dot\gamma_{ij}^2\right]$$

$$\alpha_B = \frac{\dot\phi X G_{3,X}}{H G_4}$$

The regime $\beta > 1$ seems problematic:

$$\ddot\pi + c_s^2\left[k^2 + \beta\cos(\omega u)\epsilon^+_{ij}k^i k^j\right]\pi = 0$$

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+$$

gradient instability < 0

Expanded action for α_B

$$\mathcal{L} = \frac{1}{2}\left(\dot{\pi}^2 - c_s^2(\partial_k\pi)^2\right) + \frac{1}{4}\left((\dot{\gamma}_{ij})^2 - (\partial_k\gamma_{ij})^2\right)$$

$$+\alpha_B\left[\frac{1}{\Lambda_3^3}\partial^2\pi(\partial\pi)^2 + \frac{1}{\Lambda_2^2}\dot{\gamma}_{ij}\partial_i\pi\partial_j\pi + \frac{1}{M_{\rm Pl}}\pi\dot{\gamma}_{ij}^2\right]$$

$$\alpha_B = \frac{\dot{\phi}XG_{3,X}}{HG_4}$$

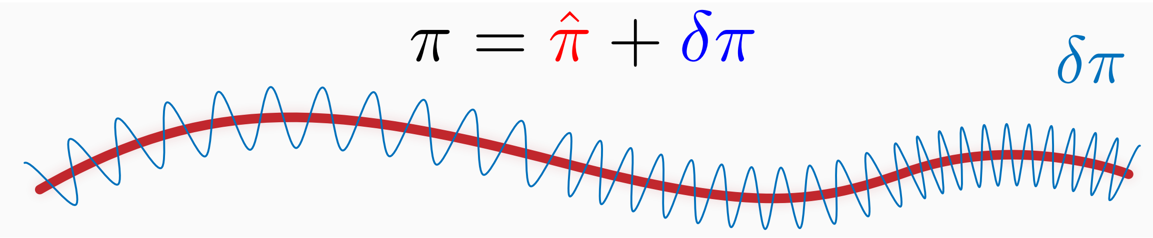
The regime $\beta > 1$ seems problematic:

$$\ddot{\pi} + c_s^2\left[k^2 + \beta\cos(\omega u)\epsilon_{ij}^{+}k^ik^j\right]\pi = 0$$

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+$$

We must check whether this is true even when we include nonlinearities

$$Z_{\mu\nu}[\hat{\pi}(x)]\partial^\mu\partial^\nu\delta\pi = 0$$



- Gradient instabilities: imaginary solution of $Z_{\mu\nu}k^\mu k^\nu = 0$ for k^μ
- Ghost instabilities: $Z_{00} < 0$

Expanded action for α_B

$$\mathcal{L} = \frac{1}{2}\left(\dot{\pi}^2 - c_s^2(\partial_k\pi)^2\right) + \frac{1}{4}\left((\dot{\gamma}_{ij})^2 - (\partial_k\gamma_{ij})^2\right)$$

$$+\alpha_B\left[\frac{1}{\Lambda_3^3}\partial^2\pi(\partial\pi)^2 + \frac{1}{\Lambda_2^2}\dot{\gamma}_{ij}\partial_i\pi\partial_j\pi + \frac{1}{M_{\rm Pl}}\pi\dot{\gamma}_{ij}^2\right]$$

$$\alpha_B = \frac{\dot{\phi}XG_{3,X}}{HG_4}$$

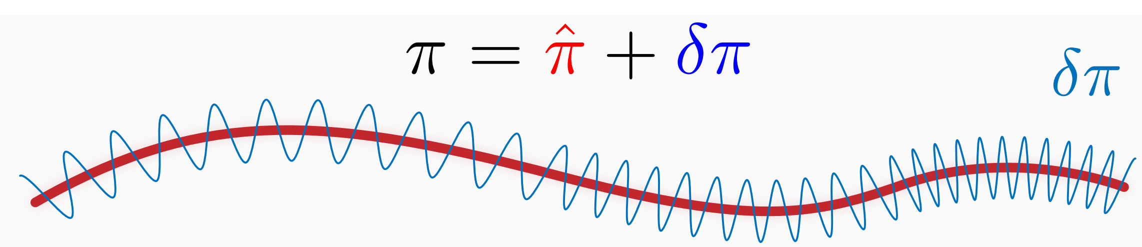
The regime $\beta > 1$ seems problematic:

$$\ddot{\pi} + c_s^2\left[k^2 + \beta\cos(\omega u)\epsilon^+_{ij}k^ik^j\right]\pi = 0$$

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+$$

We must check whether this is true even when we include nonlinearities

$$Z_{\mu\nu}[\hat{\pi}(x)]\partial^\mu\partial^\nu\delta\pi = 0$$



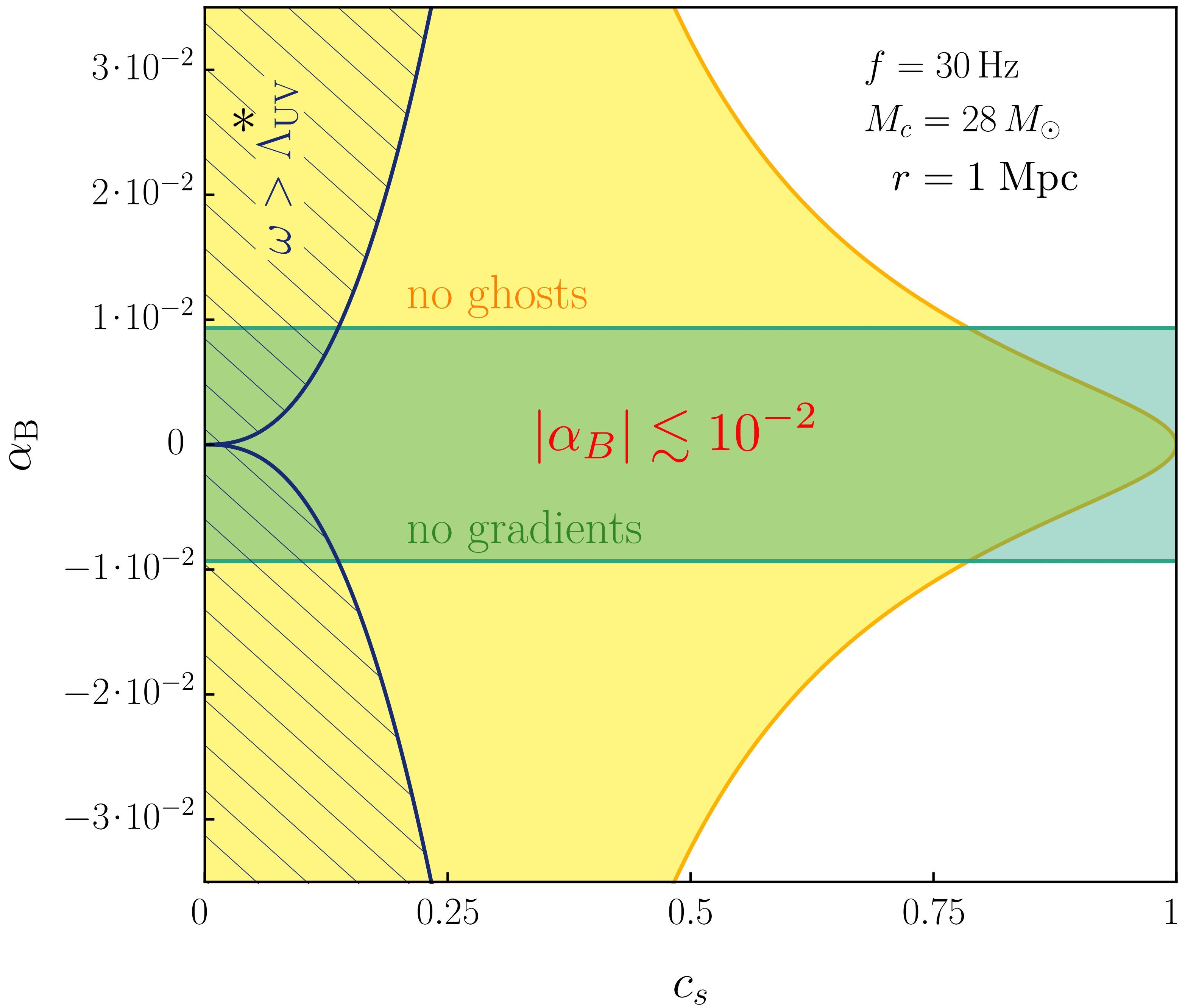
- Gradient instabilities: imaginary solution of $Z_{\mu\nu}k^\mu k^\nu = 0$ for k^μ $\quad \beta > 1$
- Ghost instabilities: $Z_{00} < 0$ $\quad \beta^2 > (1 - c_s^2)c_s^{-4}$

Constraints for stellar-mass BHs

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2} \frac{\omega}{H} h_0^+$$

$$h_0^+ \sim \frac{1}{\sqrt{2}} \cdot \frac{4}{r} (G M_c)^{5/3} (\pi f)^{2/3}$$

- $\beta > 1$: gradient inst.
- $\beta^2 > (1 - c_s^2) c_s^{-4}$: ghost inst.

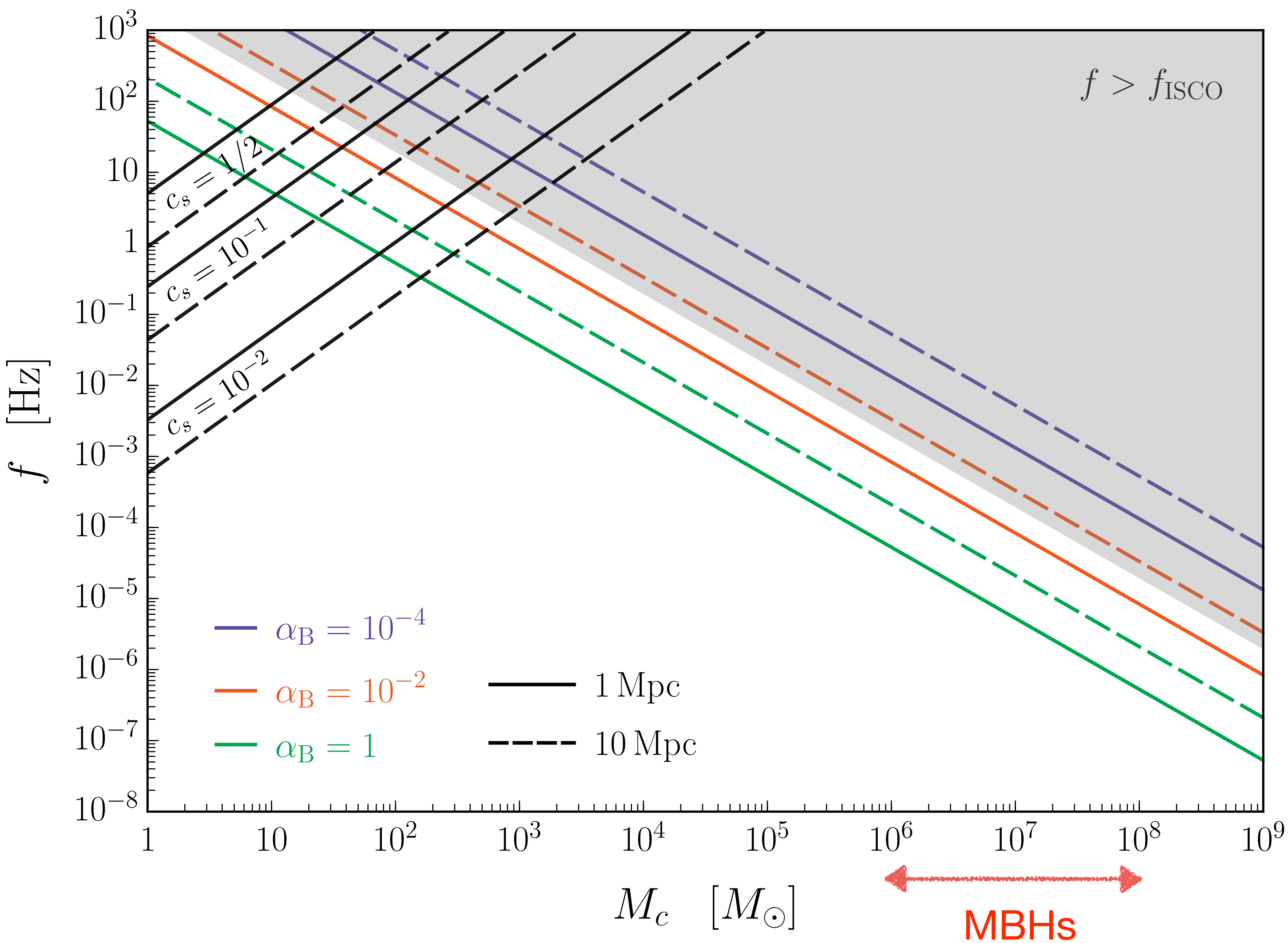


$* \quad \Lambda_{\rm UV} \sim \frac{\alpha^{1/2} c_s^{11/6}}{\alpha_B^{1/3}} \Lambda_3$

Gradient instability, $\beta > 1$, for α_B

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+$$

$$h_0^+ \sim \frac{1}{\sqrt{2}}\cdot\frac{4}{r}(GM_c)^{5/3}(\pi f)^{2/3}$$



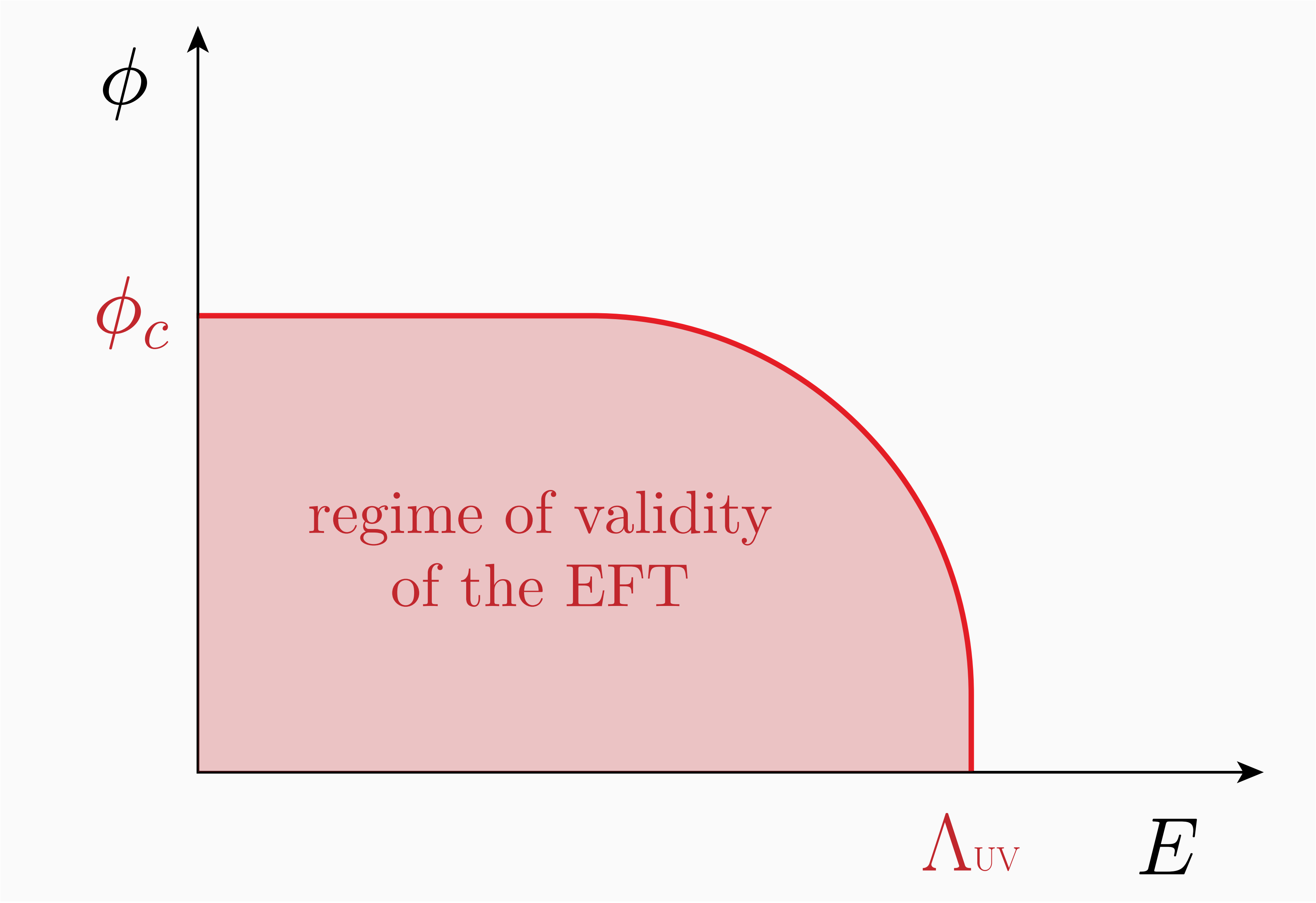
$|\alpha_B| \lesssim 10^{-2}$

Population of MBHs is enough to globally trigger the instability

Down to 10^{10} Km

Fate of instability

Is the instability real or artefact of EFT? Gradient and ghost instabilities can appear in the low energy EFT of stable UV complete theories



Fate of instability depends on the (unknown) UV completion of these theories

To trust the EFT: $|\alpha_B| \lesssim 10^{-2}$. Interestingly close to constraints from the large-scale structure

Summary and conclusion

Gravitational waves probe modified gravity as light probes material

In many cases very effectively, more than what large-scale structure can do

$$
\begin{aligned}
\mathcal{L} = & \, G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \\
& - 2G_{4,X}(\phi, X)\Big[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\Big] \\
& + G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\Big[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\Big] \\
& - F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'} \\
& - F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}
\end{aligned}
$$

Summary and conclusion

Gravitational waves probe modified gravity as light probes material

In many cases very effectively, more than what large-scale structure can do

- Speed of GW: $|c_T - 1| \lesssim 10^{-15}$

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

$$- 2G_{4,X}(\phi, X)\Big[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\Big]$$

$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\Big[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\Big]$$

$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

Summary and conclusion

Gravitational waves probe modified gravity as light probes material

In many cases very effectively, more than what large-scale structure can do

- Speed of GW: $|c_T - 1| \lesssim 10^{-15}$
- Resonant graviton decay $10^{-10} \lesssim |\alpha_H| \lesssim 10^{-20}$
- Perturbative decay and dispersion $|\alpha_H| \lesssim 10^{-10}$

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

$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$

$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$

$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$

$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$

Summary and conclusion

Gravitational waves probe modified gravity as light probes material

In many cases very effectively, more than what large-scale structure can do

- Speed of GW: $|c_T - 1| \lesssim 10^{-15}$
- Resonant graviton decay $10^{-10} \lesssim |\alpha_H| \lesssim 10^{-20}$
- Perturbative decay and dispersion $|\alpha_H| \lesssim 10^{-10}$
- Instabilities due to GW $|\alpha_B| \lesssim 10^{-2}$

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi$$
$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$
$$+ G_5(\phi, X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi, X)\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$
$$- F_4(\phi, X)\epsilon^{\mu\nu\rho}{}_{\sigma}\epsilon^{\mu'\nu'\rho'\sigma}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}$$
$$- F_5(\phi, X)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\mu'\nu'\rho'\sigma'}\phi_{;\mu}\phi_{;\mu'}\phi_{;\nu\nu'}\phi_{;\rho\rho'}\phi_{;\sigma\sigma'}$$