Dark energy after gravitational wave observations

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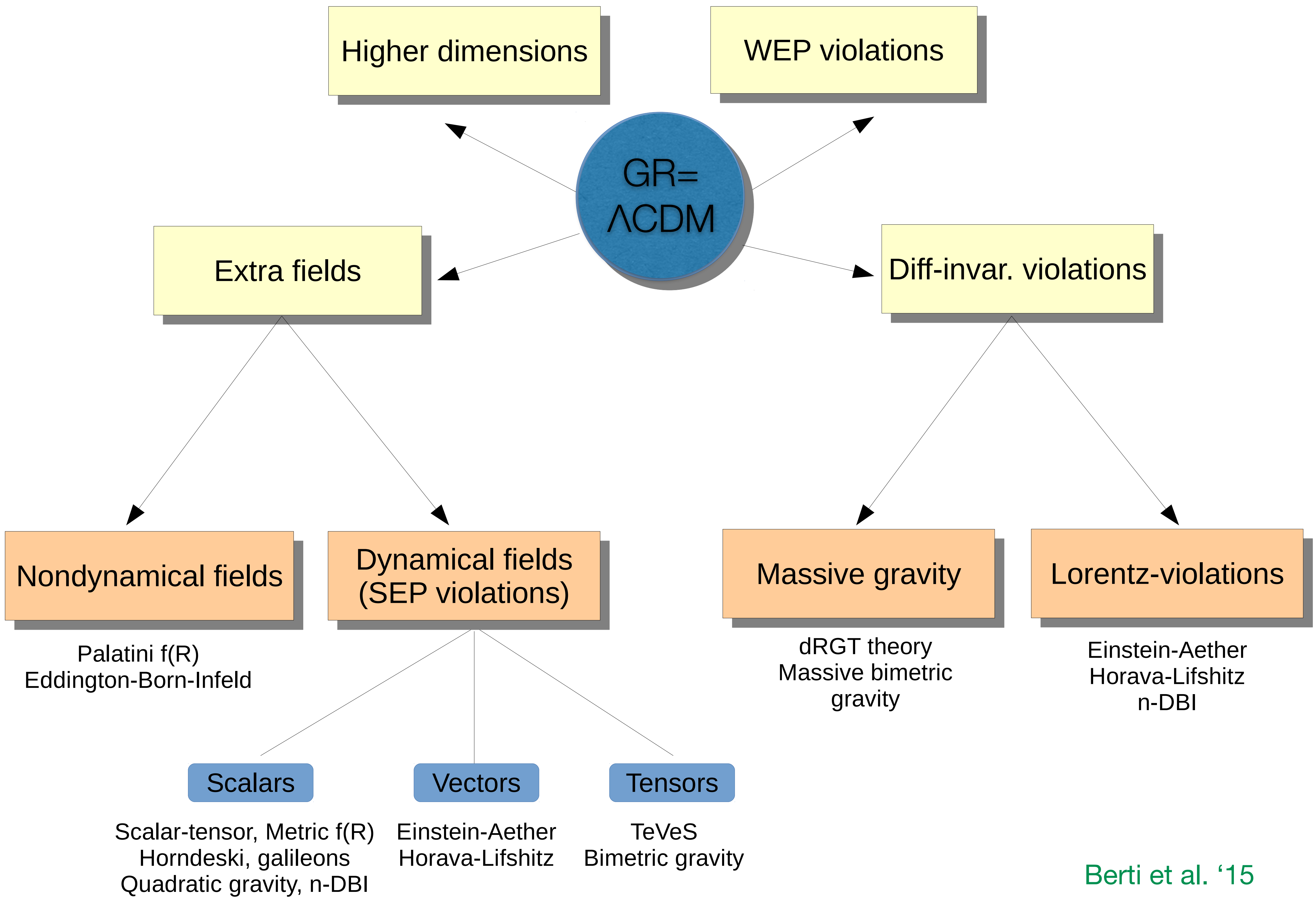
with Paolo Creminelli 1710.05877,
+ Matthew Lewandowski and Giovanni Tambalo, 1809.03484
+ Vicharit Yingcharoenrat, 1906.07015, 1910.14035

4 January 2020, Meudon

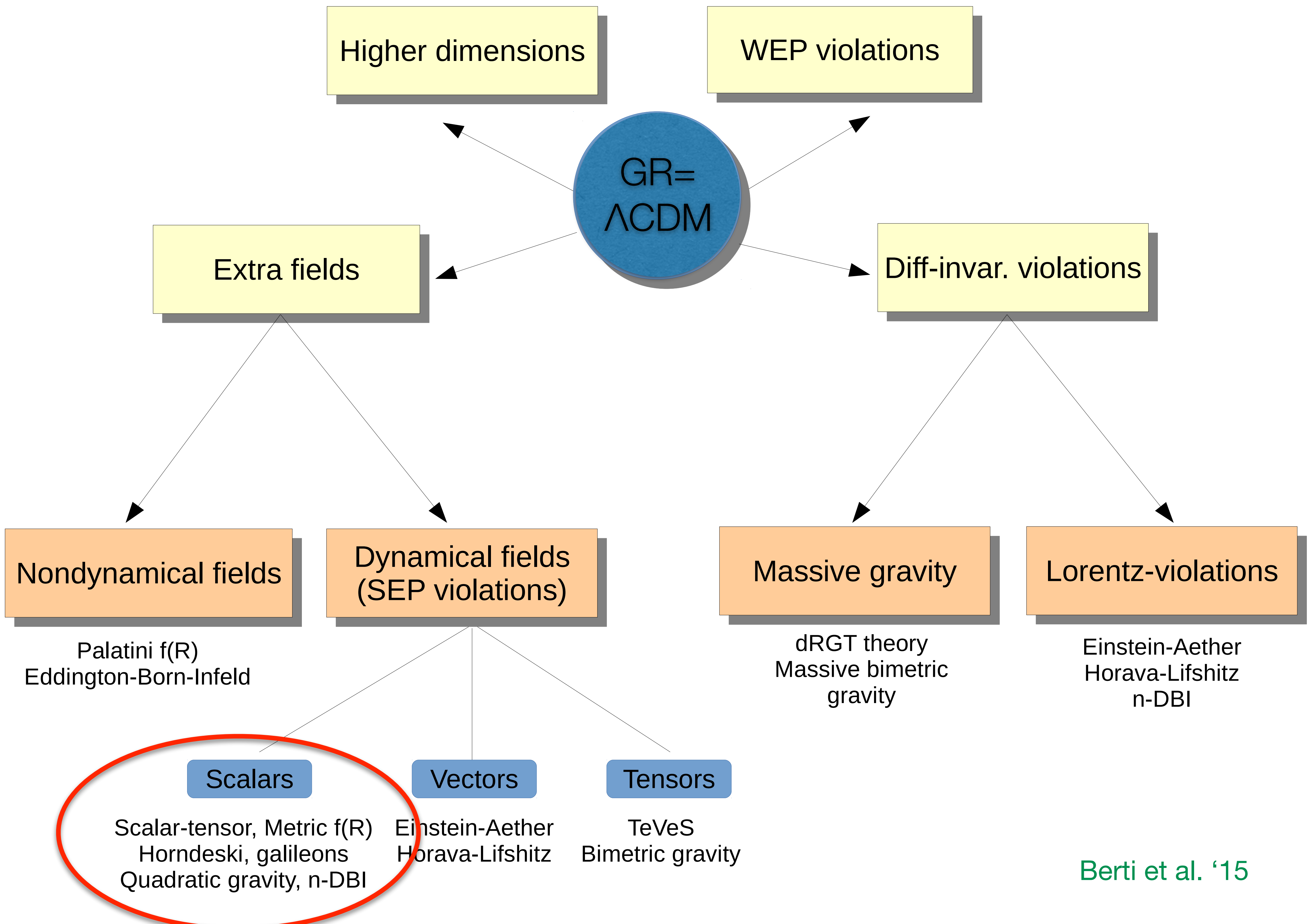
Rencontres des groupes de travails “Formes d’ondes” et “Tests de la relativité générale et théories alternatives”, GdR Ondes Gravitationnelles

Dark energy and modified gravity



Berti et al. ‘15

Dark energy and modified gravity



Berti et al. '15

Generalized scalar-tensor theories

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

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

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Generalized scalar-tensor theories

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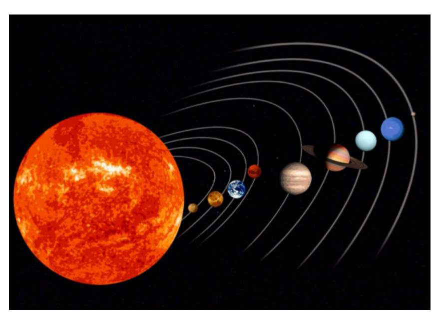
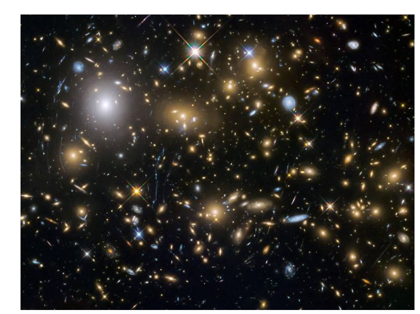
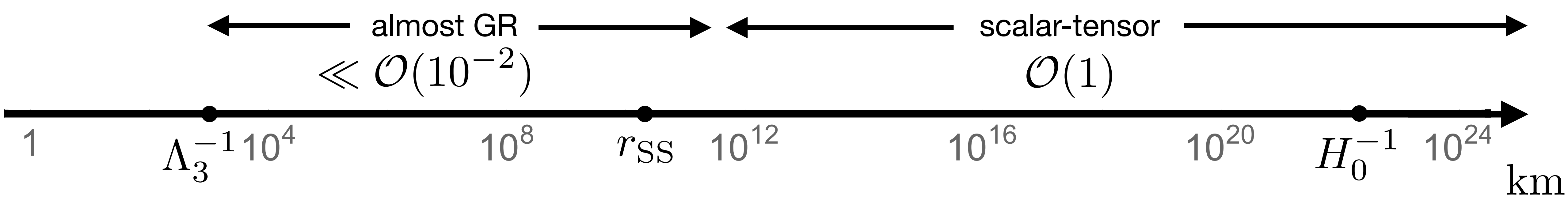
\end{aligned}
$$

Self-acceleration and screening: large classical scalar field nonlinearities

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







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Cubic Galileon, kinetic braiding, DGP…

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

Quintessence, k-essence, Brans-Dicke, f(R),…

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

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- ***Braiding:*** scalar mixes with gravity $\mathcal{L} \supset \dot{\Psi}\dot{\pi}\ ,\ \partial\Psi\partial\pi$ Deffayet et al. 2010
    - Different than usual Brans-Dicke or f(R), e.g., $\Phi = \Psi$

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Galileons, Horndeski
Horndeski 73
Deffayet et al. 11

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  - Different than usual Brans-Dicke or f(R), e.g., $\Phi = \Psi$
- ***Horndeski:*** most generic theory with 2nd order EOM

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Beyond Horndeski

Gleyzes, Langlois, Piazza, FV ’14
(See also Zumalacarregui, Garcia-Bellido ’13)

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  - Different than usual Brans-Dicke or f(R), e.g., $\Phi = \Psi$

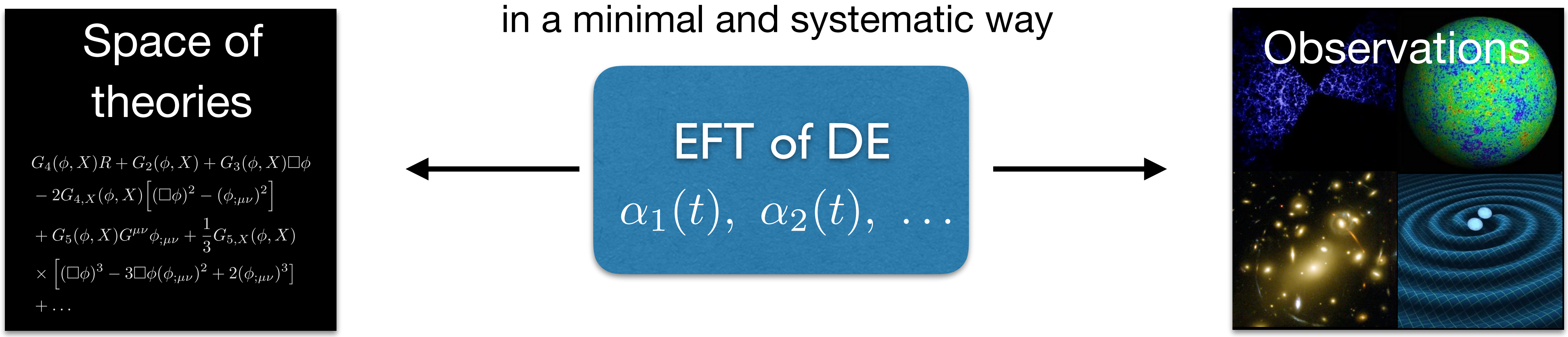
- ***Horndeski:*** most generic theory with 2[nd] order EOM

- ***Beyond Horndeski:*** more than 2 derivatives in EOM but degenerate with no ghosts
  - Vainshtein screening violated inside matter
    Kobayashi, Watanabe, Yamaguchi et al. 2018

$$\frac{d\Phi}{dr} = G\left[\frac{M(r)}{r^2} - \epsilon\frac{d^2M(r)}{dr^2}\right]$$

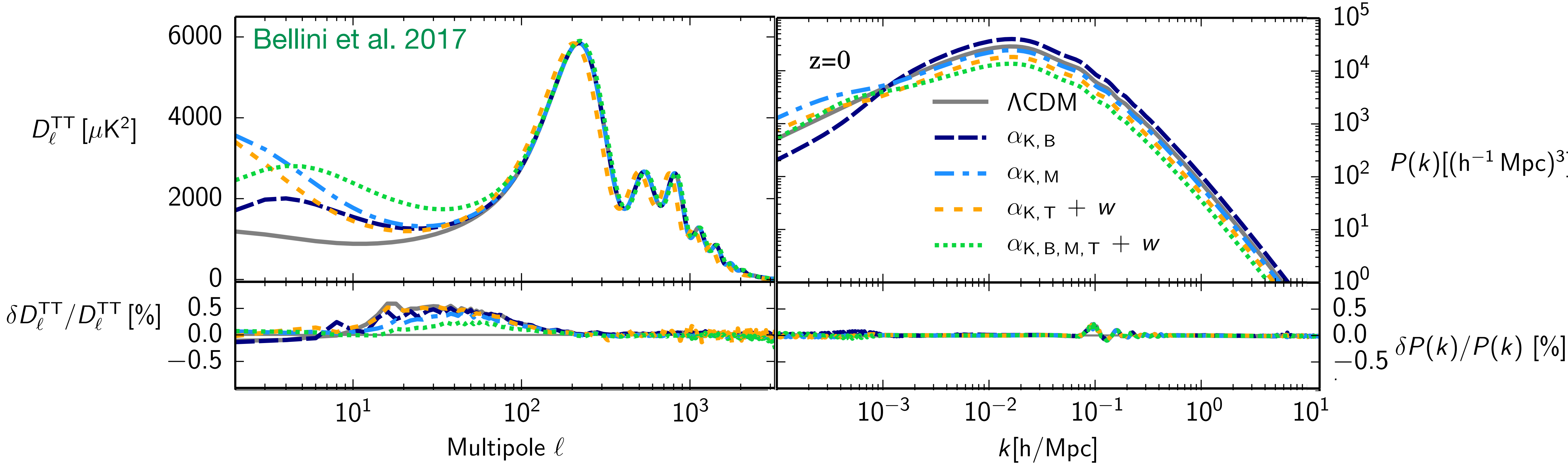
EFT of Dark Energy

Bridge models and observations
in a minimal and systematic way



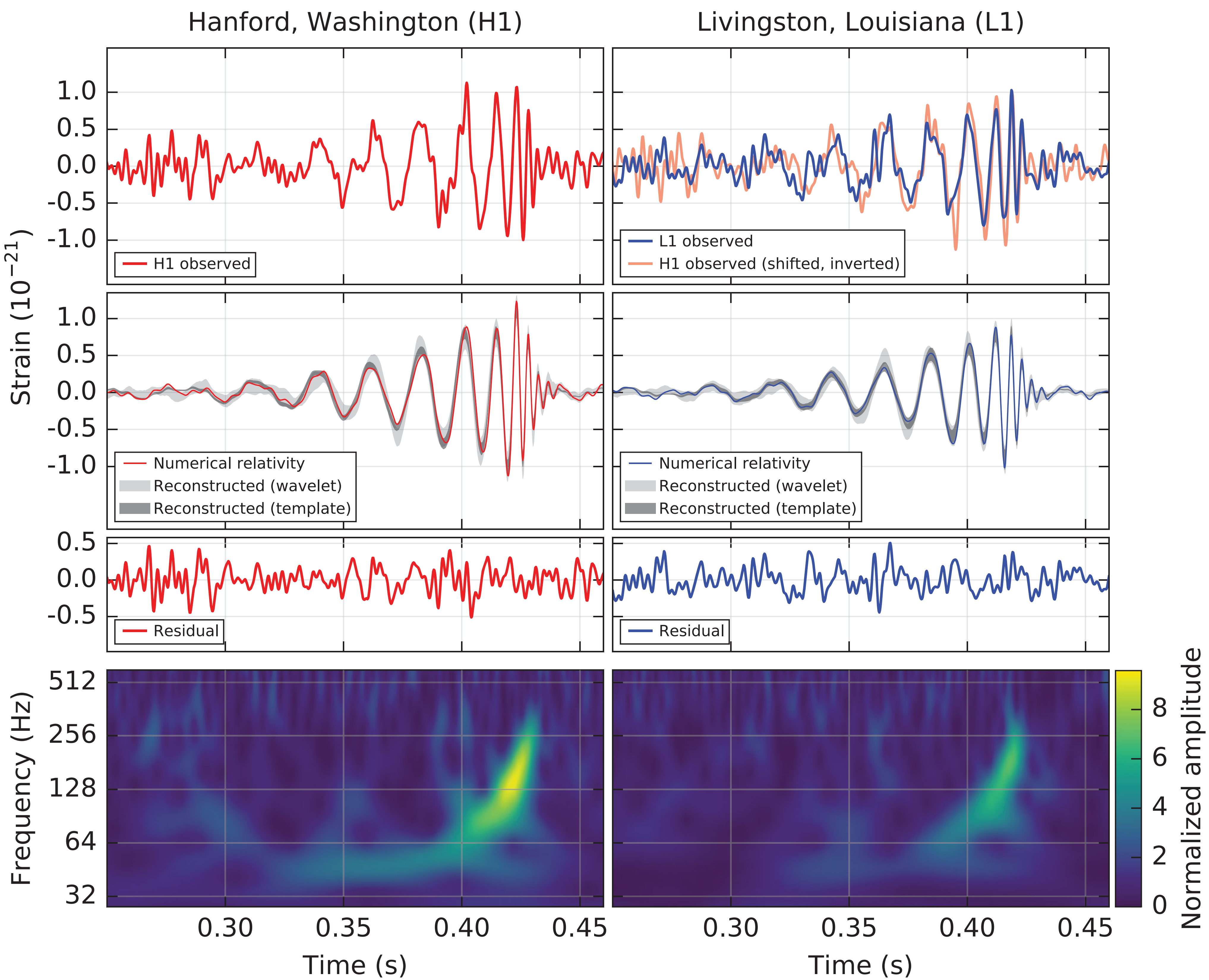
$$\mu = \mu\big(k; \alpha_1(t), \alpha_2(t), \ldots\big)$$
$$\Sigma = \Sigma\big(k; \alpha_1(t), \alpha_2(t), \ldots\big)$$

$$\nabla^2\Phi = 4\pi G\,\mu\,\delta\rho_{\rm m}$$
$$\nabla^2(\Phi + \Psi) = 8\pi G\,\Sigma\,\delta\rho_{\rm m}$$



GW150914: Gravitational Waves

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



Modified gravitational wave propagation

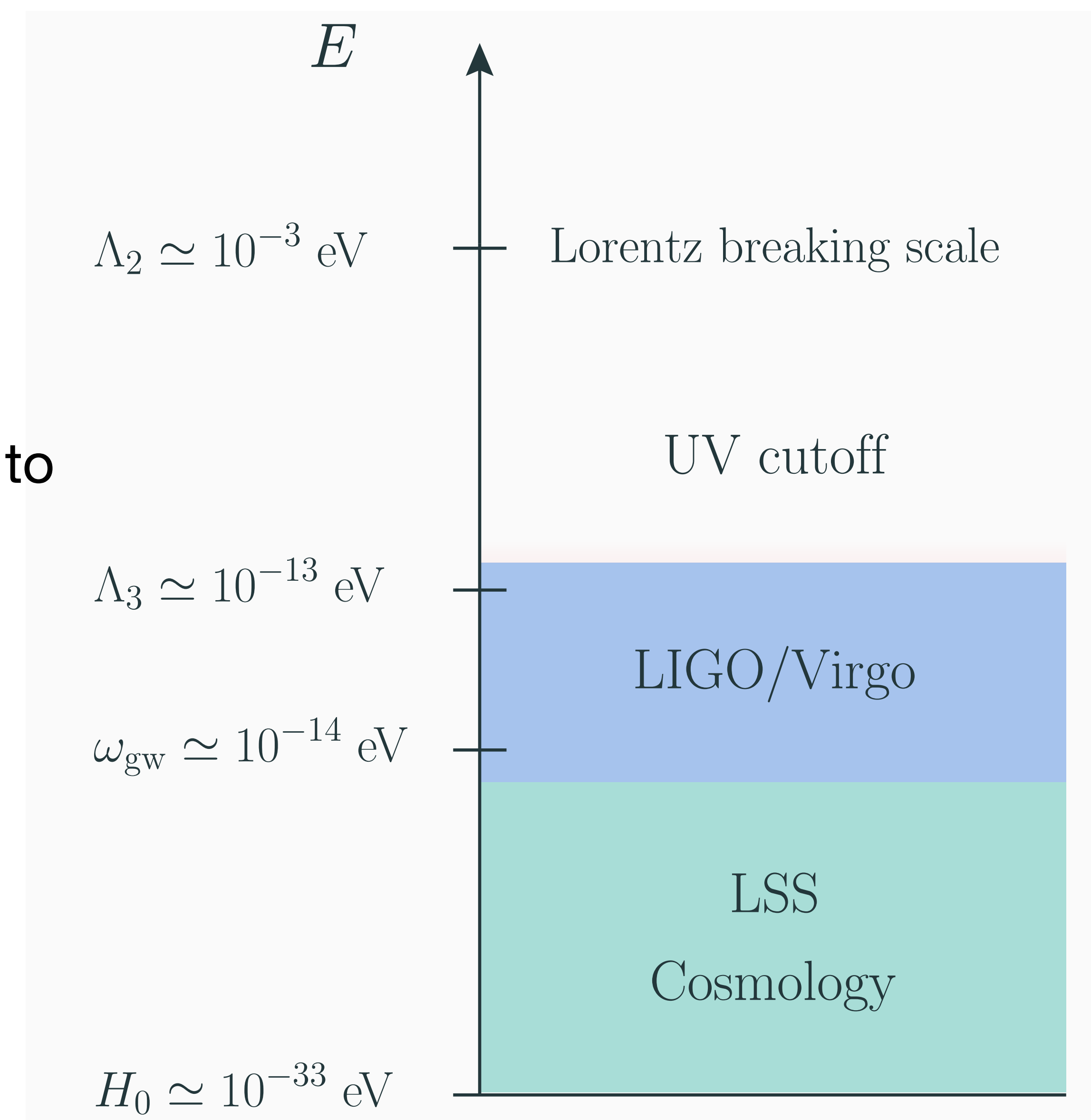
Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed. Effects accumulate on long time-scale.

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

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

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

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



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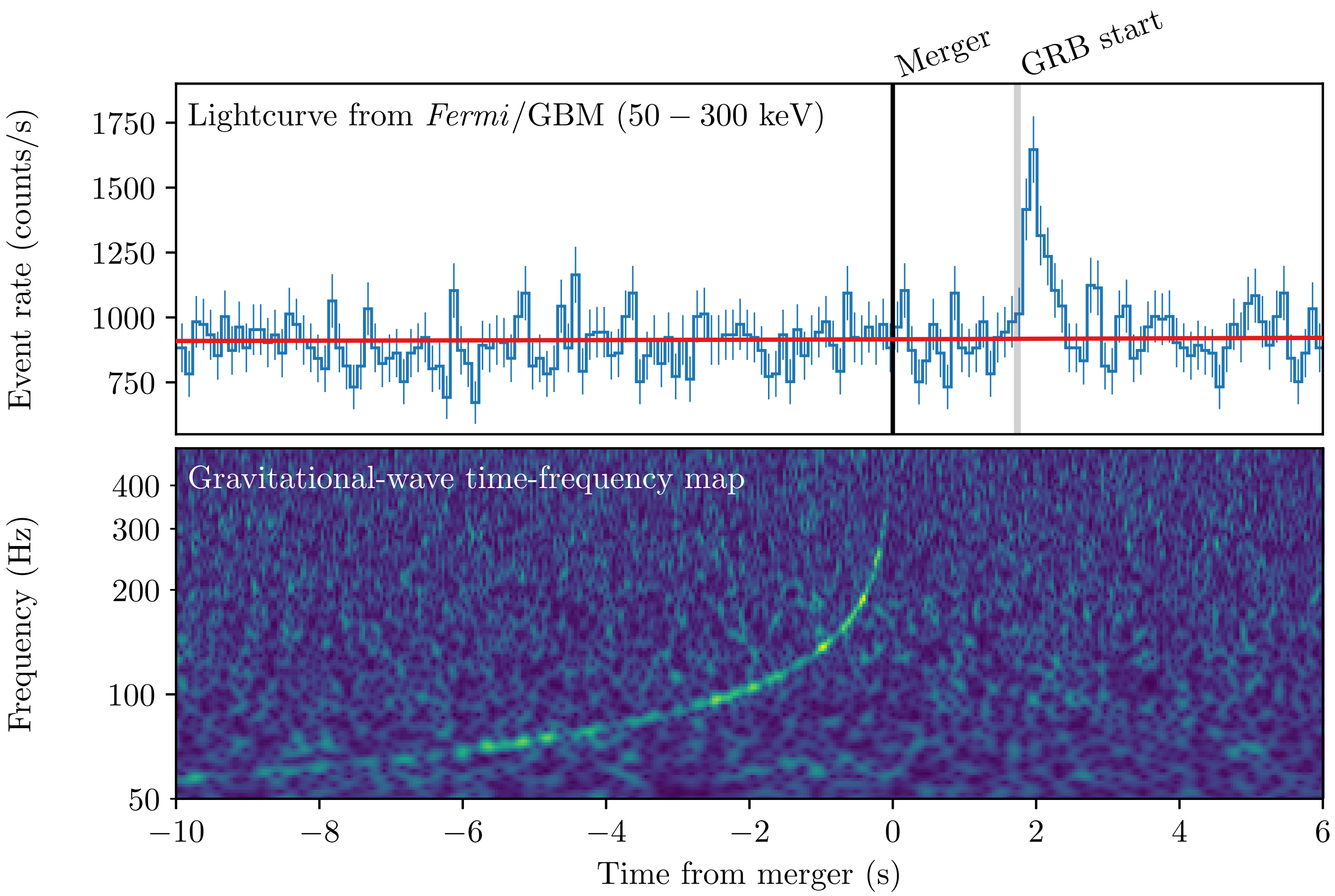

$$-3 \times 10^{-15} \leq \frac{c_T - c}{c} \leq 7 \times 10^{-16}$$

c_T=1 implications

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c_T=1 implications

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

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$$G_5 = F_5 = 0\ , \qquad XF_4 = 2G_{4,X}$$

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
(approx. Galileon symmetry)

Can we rule out more?

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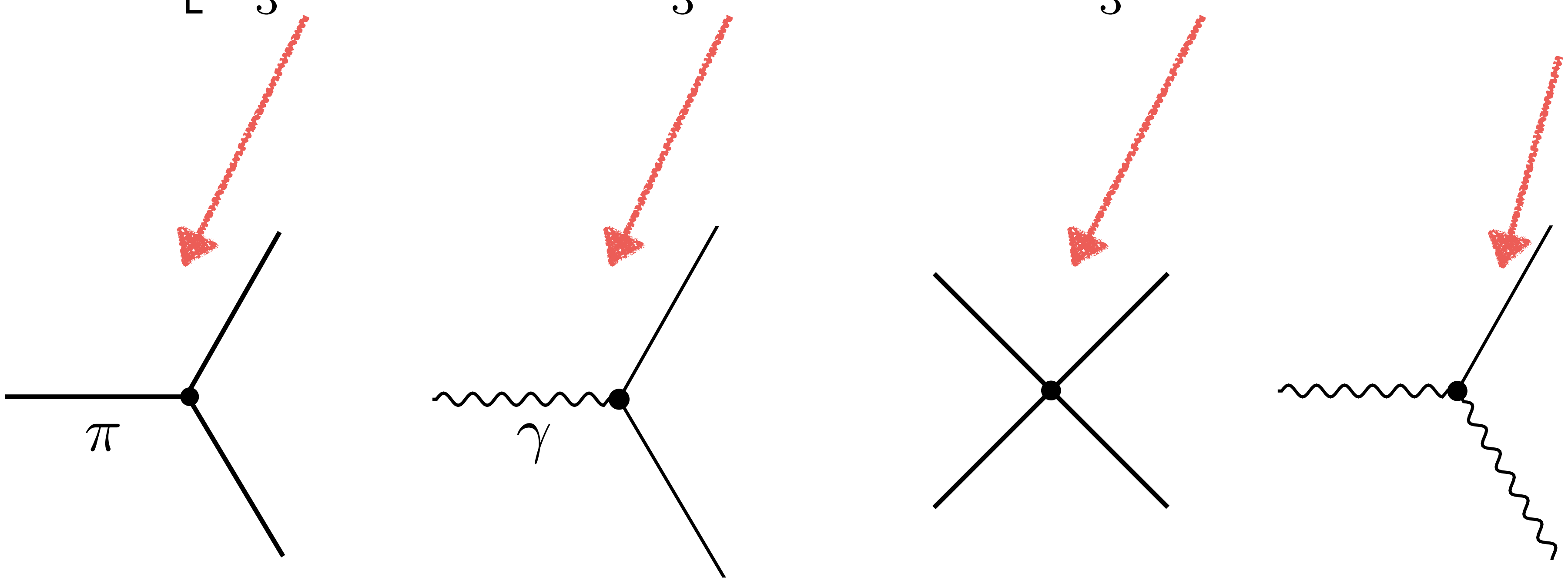
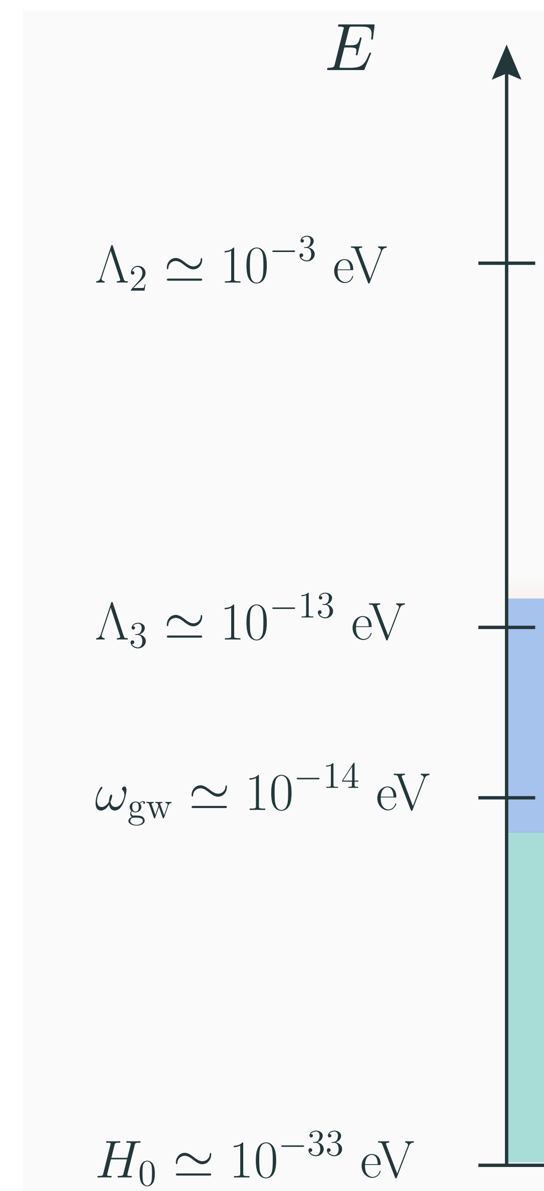
- ***Beyond Horndeski:*** $\alpha_H \equiv -\dfrac{X^2 F_4}{G_4}$

Expanded action for α_H

$$\mathcal{L} = \frac{1}{2}\left(\dot\pi^2 - c_s^2(\partial_k\pi)^2\right) + \frac{1}{4}\left((\dot\gamma_{ij})^2 - (\partial_k\gamma_{ij})^2\right) \qquad \pi \equiv \delta\phi/\dot\phi_0$$

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



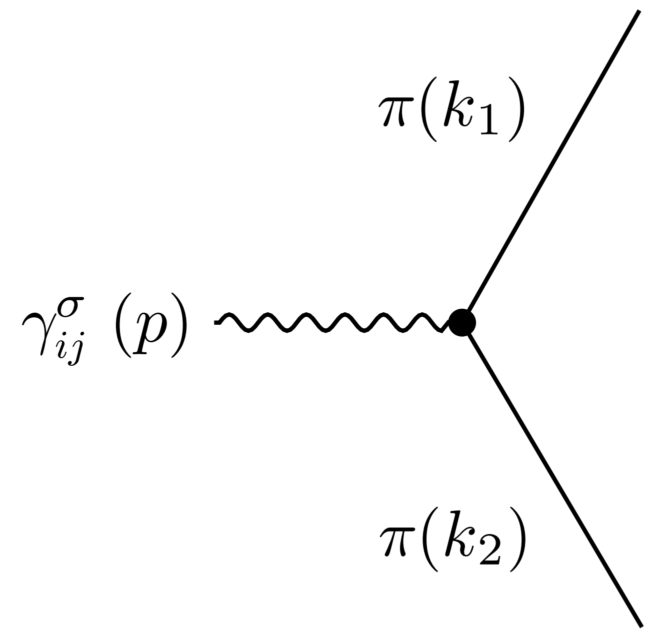


Graviton decay into dark energy

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

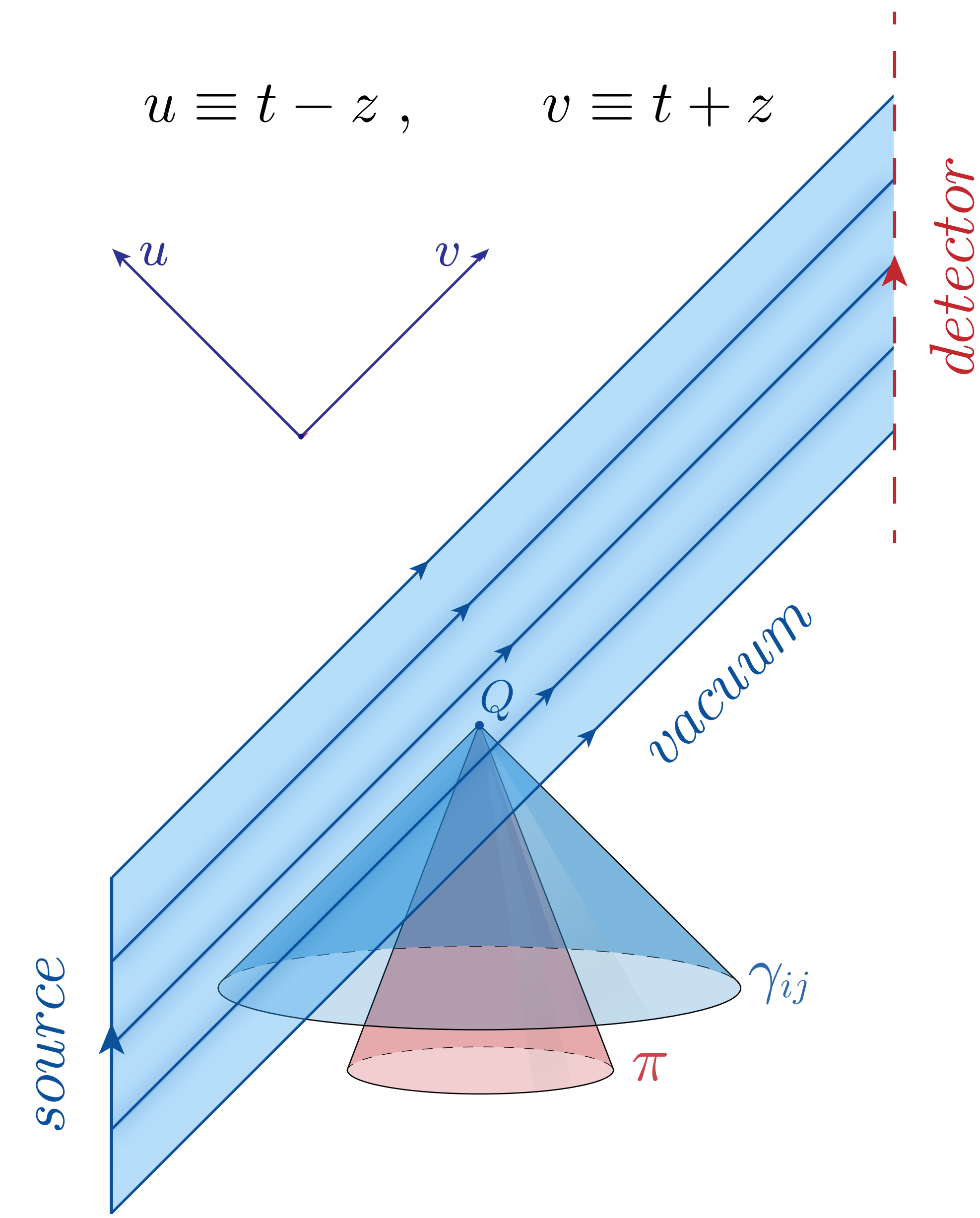
Creminelli, Tambalo, FV, Yingcharoenrat, '19

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:

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



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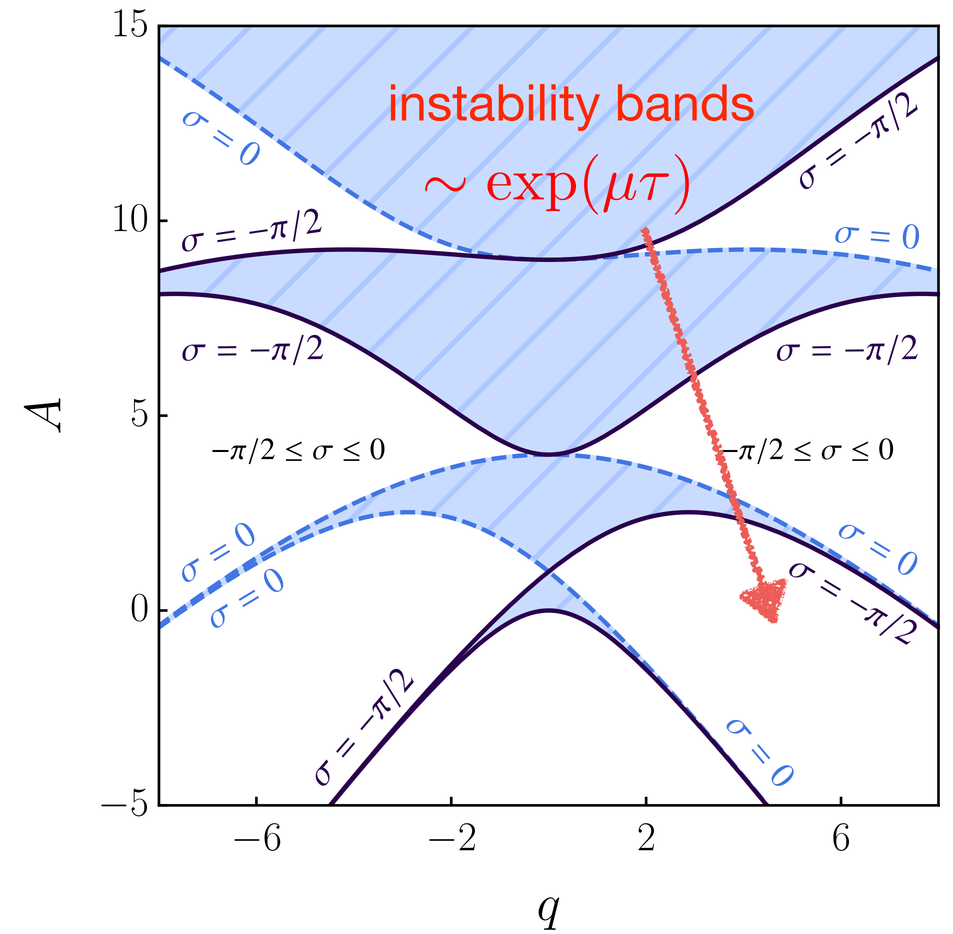
Each Fourier mode satisfies a Mathieu equation
⇒ parametric resonance.

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

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

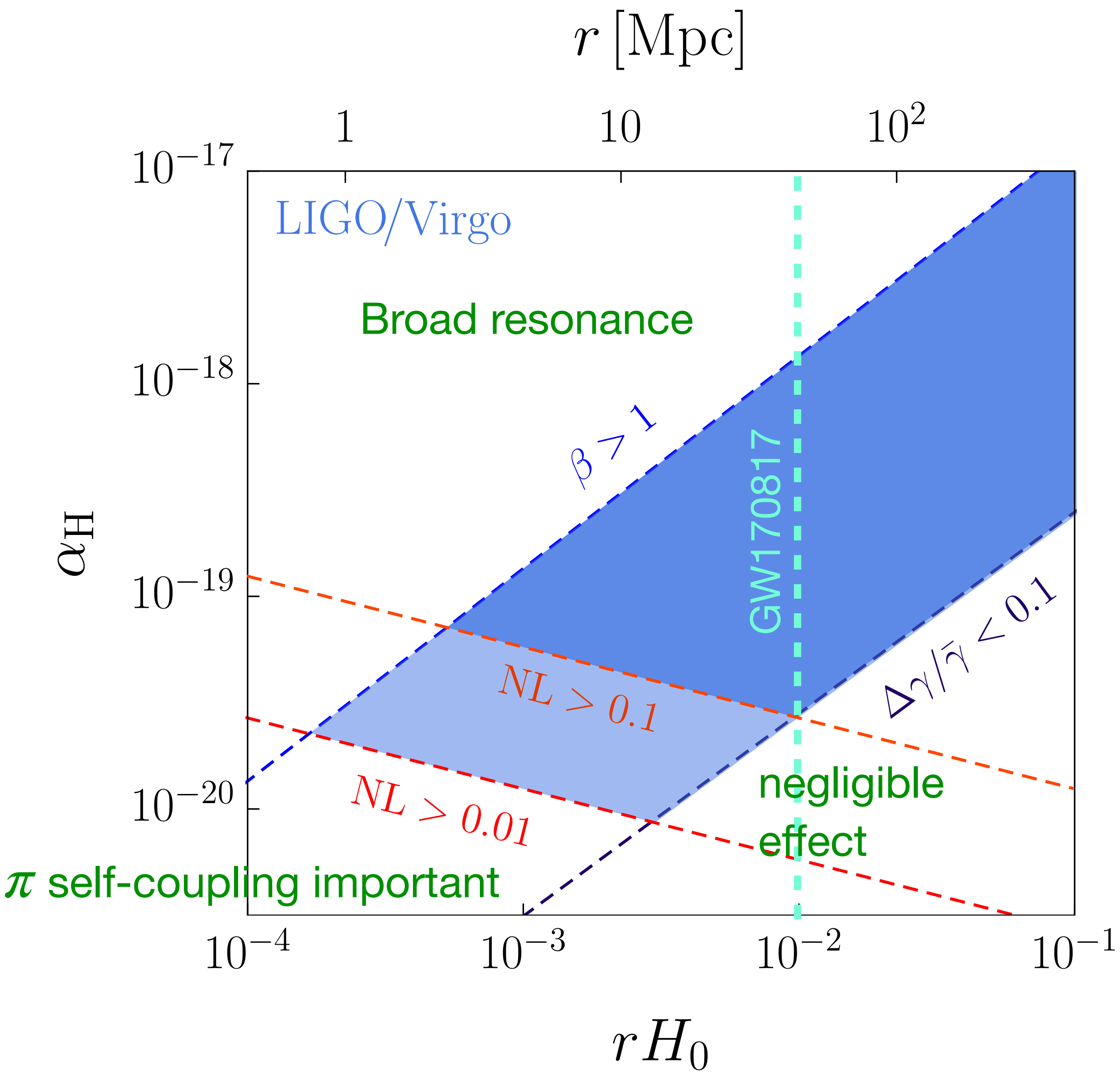


Narrow resonance $\beta \ll 1$: $\mu \sim \beta/4 \quad \Rightarrow \quad \rho_\pi \propto e^{\beta\omega u/4} \quad \Rightarrow \quad \Delta\gamma_{ij} \propto v\gamma_0 e^{\beta\omega u/4}\epsilon_{ij}^+$

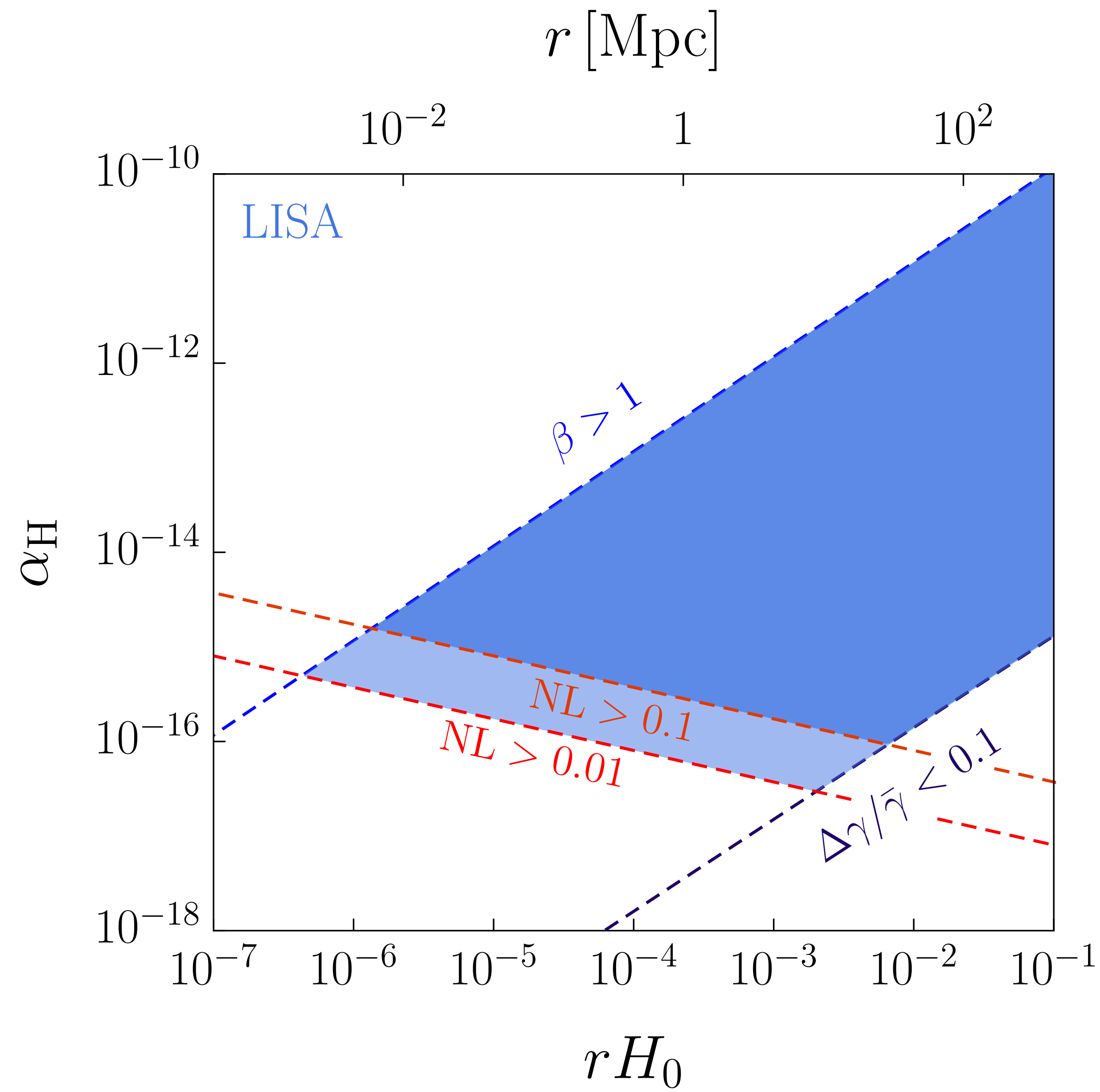
Same direction and polarization. Same frequency + higher harmonics (precursors)

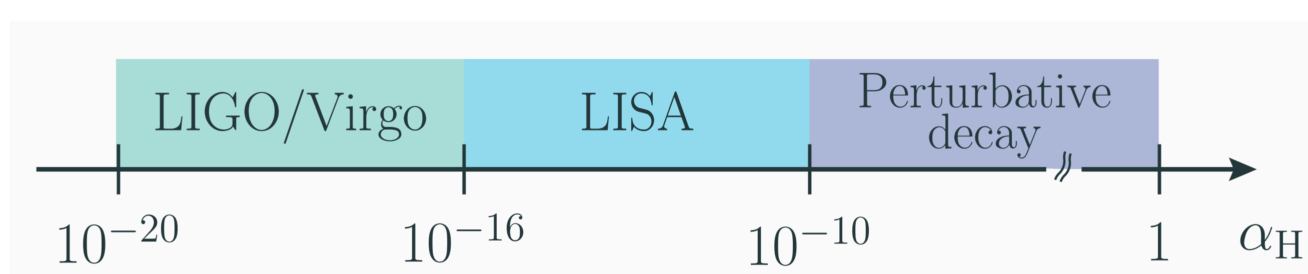
GW modification

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



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

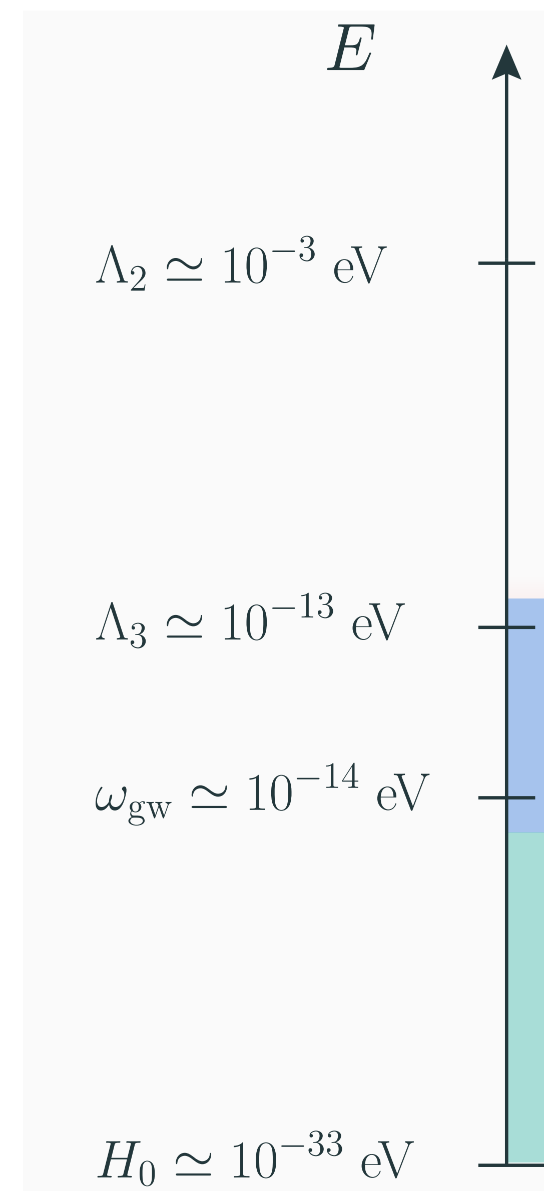




Expanded action for α_H

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

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



Theory after no decay

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- *Beyond Horndeski:* $\alpha_H \equiv -\frac{X^2 F_4}{G_4}$

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- ***Braiding:*** $\alpha_B = \dfrac{\dot{\phi}XG_{3,X}}{HG_4}$

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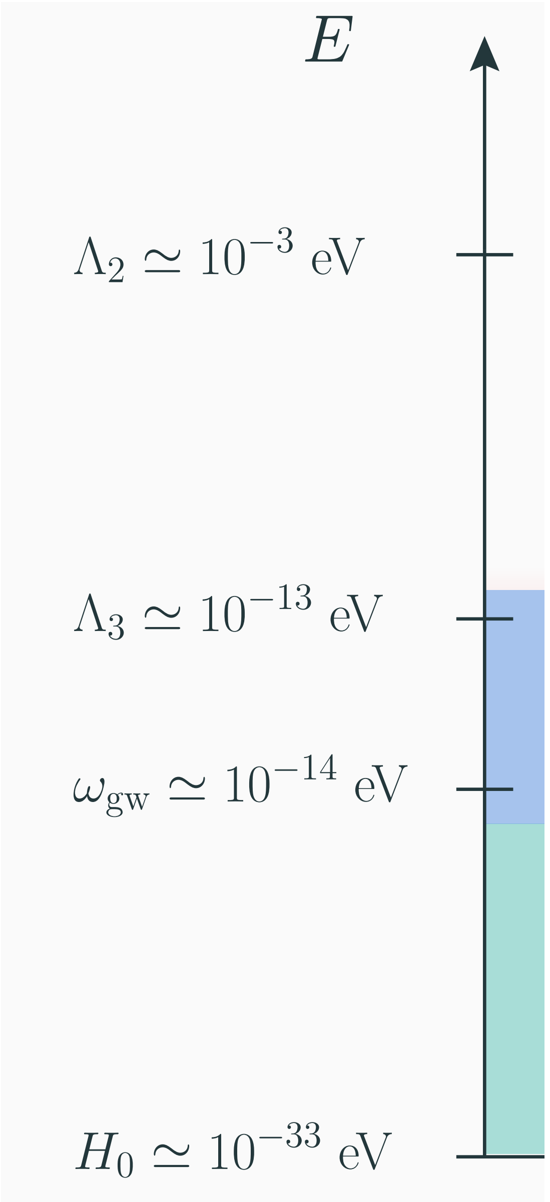
$$\alpha_B = \frac{\dot{\phi} X G_{3,X}}{H G_4}$$

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

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



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

Creminelli, Tambalo, FV, Yingcharoenrat, '19

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

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

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

The regime $\beta > 1$ seems problematic:

gradient instability < 0

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

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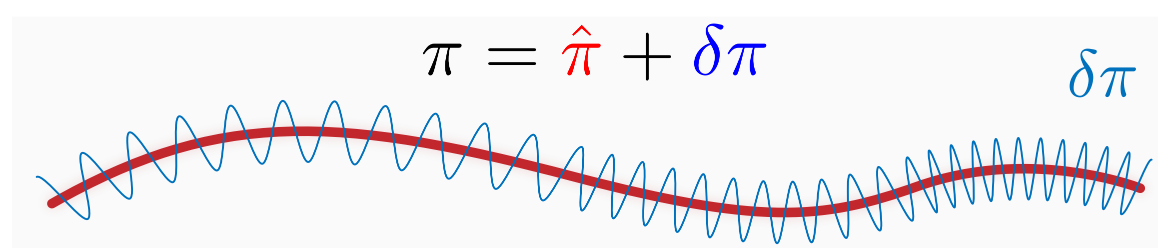
Better analysis: We include nonlinearities of π

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



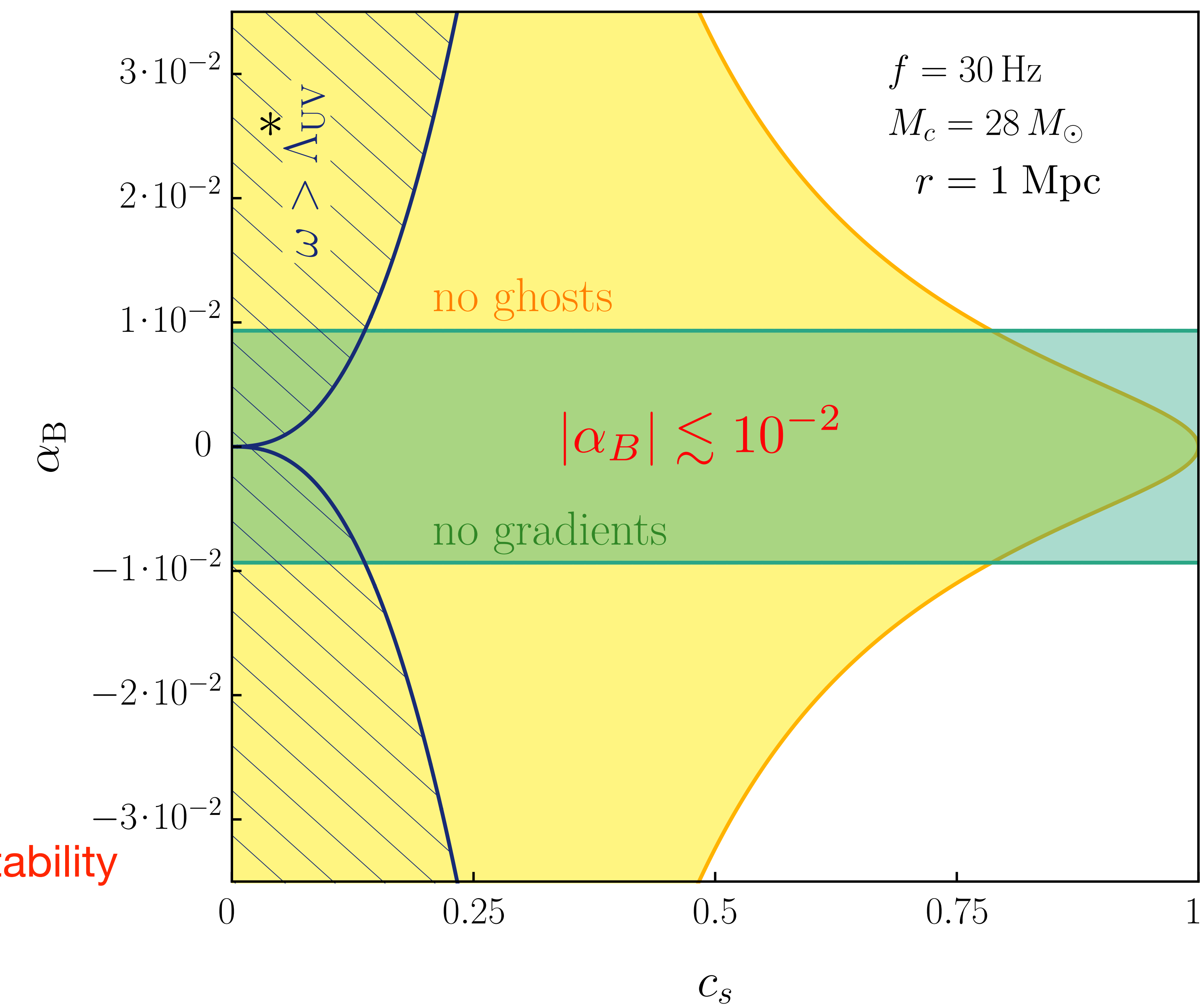
- $\beta > 1$: gradient instability
- $\beta^2 > (1 - c_s^2)c_s^{-4}$: ghost instability

We will also find ghost instabilities $Z_{00} < 0$

See also Babichev '20

Constraints for stellar-mass BHs

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+ \qquad h_0^+ \sim \frac{1}{\sqrt{2}}\cdot\frac{4}{r}(GM_c)^{5/3}(\pi f)^{2/3}$$



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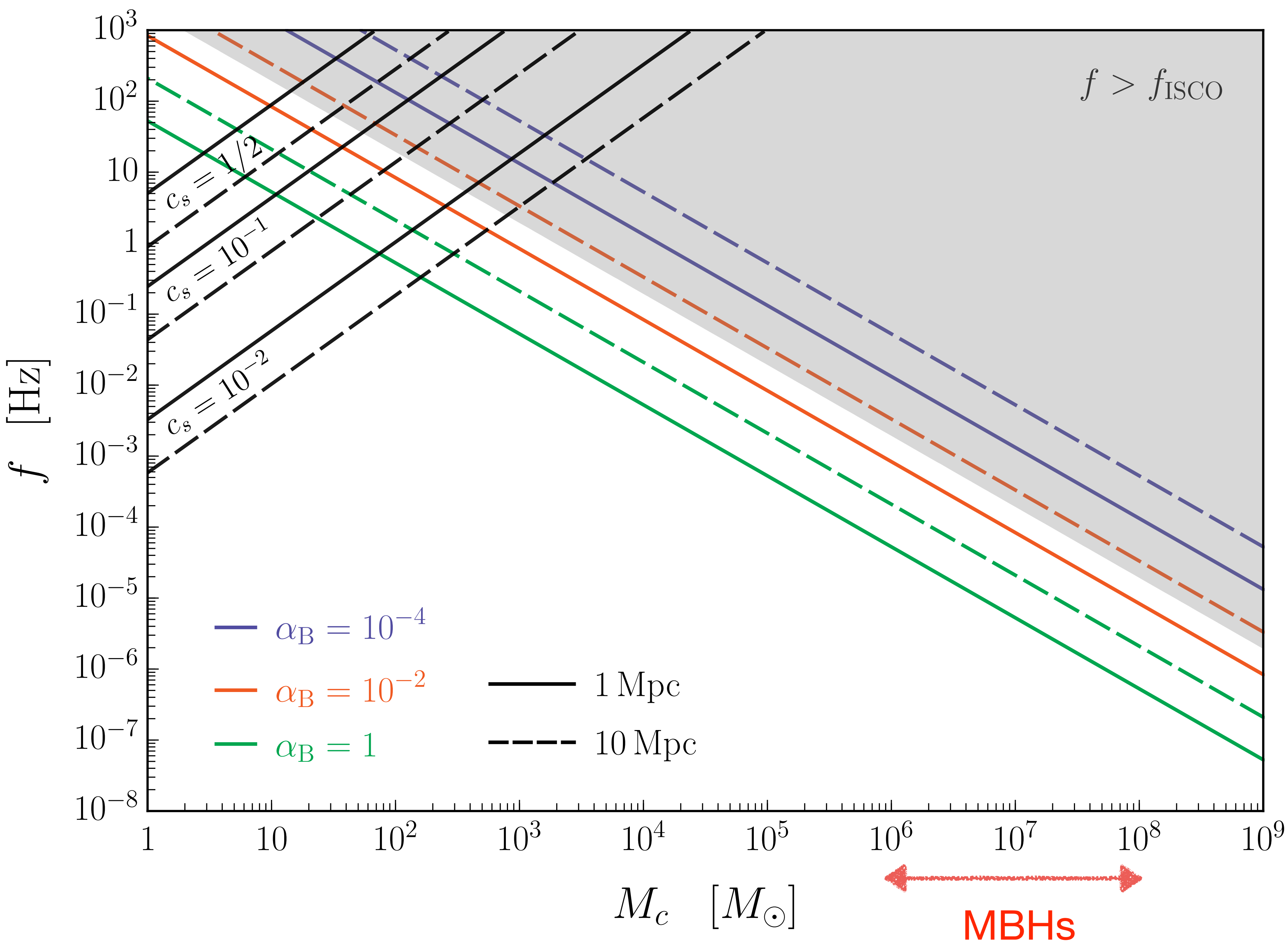
$*\quad \Lambda_{\mathrm{UV}} \sim \frac{\alpha^{1/2}c_s^{11/6}}{\alpha_B^{1/3}}\Lambda_3$

Gradient instability, β > 1, for α_B

$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+ \qquad h_0^+ \sim \frac{1}{\sqrt{2}}\cdot\frac{4}{r}(GM_c)^{5/3}(\pi f)^{2/3}$$



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

Population of MBHs is enough to globally trigger the instability

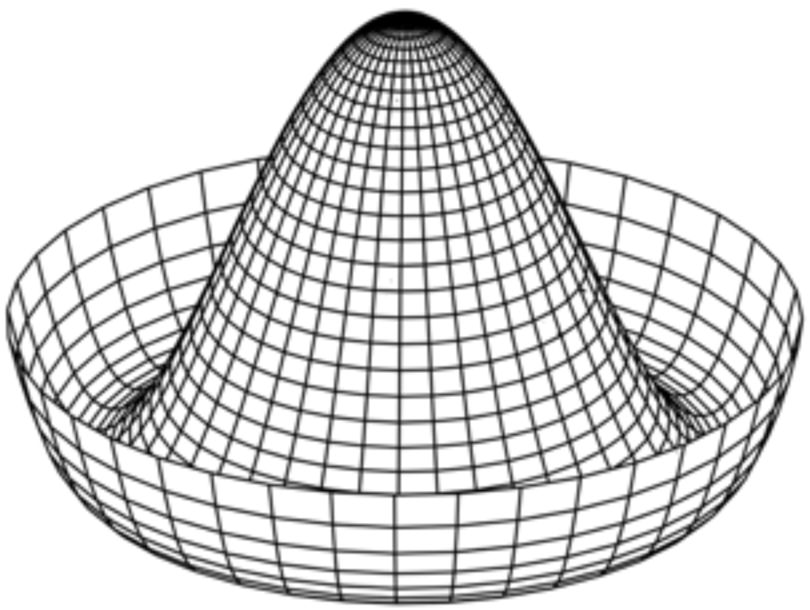
Down to 10^{10} Km

The fate of UV instability

Most unstable modes are at the UV cutoff. Instability depends on the UV completion

U(1) *ad hoc* example: complex scalar in the broken phase

See also Babichev, Ramazanov, Vikman '18



Integrating out radial direction ⇒ $\mathcal{L} \simeq -\frac{1}{4\lambda} X(\mu^2 - X)$

$$X = (\partial\phi)^2 \qquad \mu^2 = 4\lambda v^2$$

- Gradient instabilities for $\frac{\mu^2}{6} < \hat{X} < \frac{\mu^2}{2}$

  In UV theory, instability is saturated at μ: stable for k >> μ

- Ghost instabilities for $\hat{X} > \frac{\mu^2}{2}$

  EFT has no applicability: radial mode becomes massless

Time evolution of the system (Cauchy problem), and thus compatibility of the EFT with the data, depend on the UV completion

Theory after no decay and no instabilities

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

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

- ***Braiding:*** $\alpha_B = \dfrac{\dot{\phi} X G_{3,X}}{H G_4}$

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

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- Resonant graviton decay $10^{-10} \lesssim |\alpha_H| \lesssim 10^{-20}$
- Perturbative decay and dispersion $|\alpha_H| \lesssim 10^{-10}$
- Instabilities due to GW $|\alpha_B| \lesssim 10^{-2}$

$$\begin{aligned}
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\end{aligned}$$