Dark energy after gravitational wave observations

Filippo Vernizzi
IPhT - CEA, CNRS, Paris-Saclay

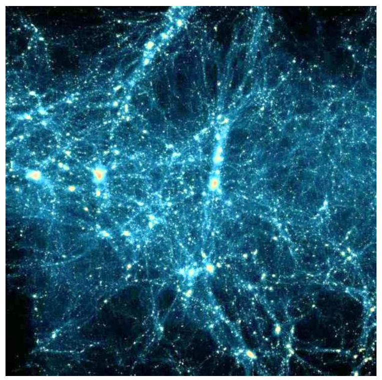
with P. Creminelli 1710.05877,
+ M. Lewandowski and G. Tambalo, 1809.03484
+ V. Yingcharoenrat, 1906.07015, 1910.14035

4 January 2021
Cosmology 2021: the Rise of Field Theory

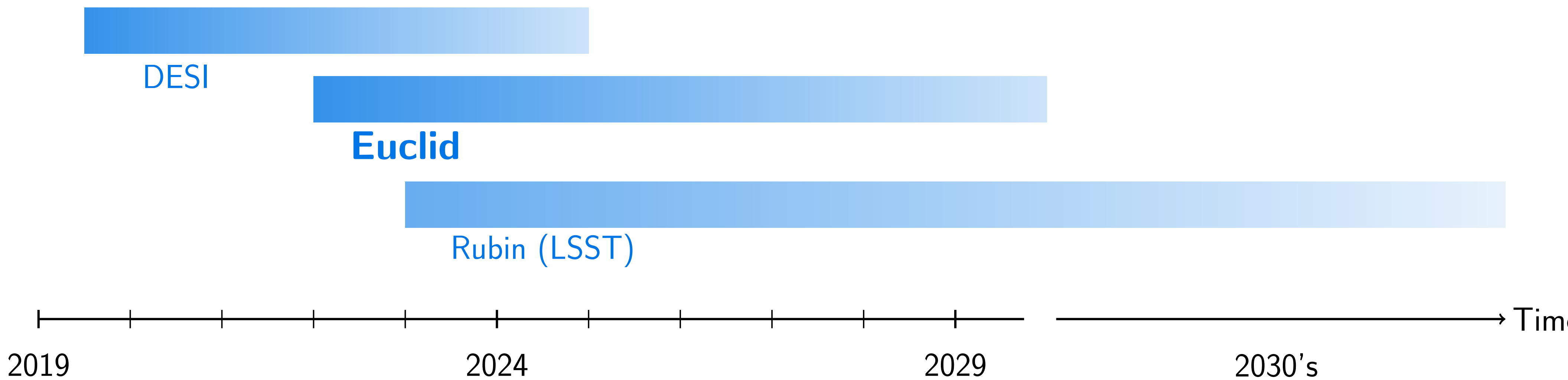
Present and future

Future is observationally bright: expected large amount of data from LSS

Test GR (& ΛCDM) on large scales, constrain deviations from GR (dark energy, modified gravity)



Credit Zumalacarregui 20



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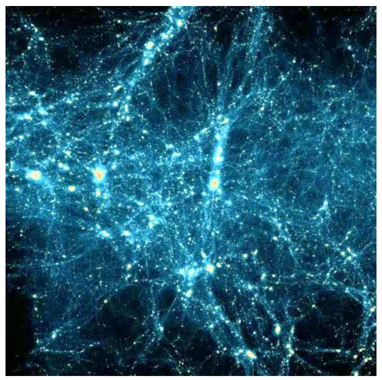

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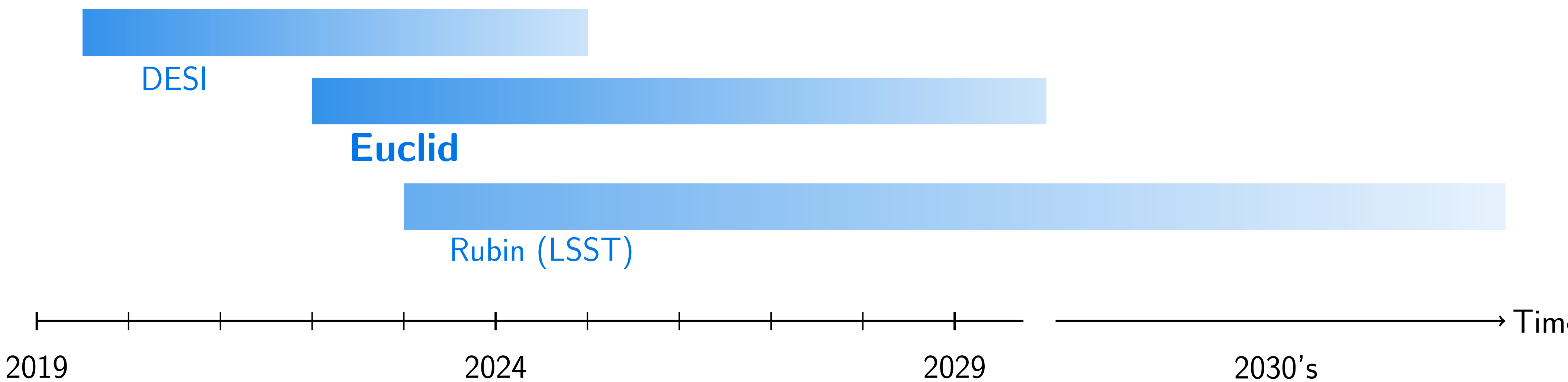
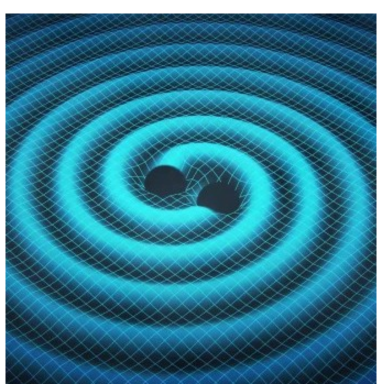


Gravitational Waves: new probe of gravity. Emission and propagation.



Present and future

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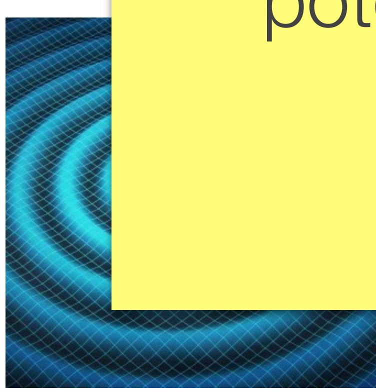
Credit

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

me

Gr



Generalized scalar-tensor theories

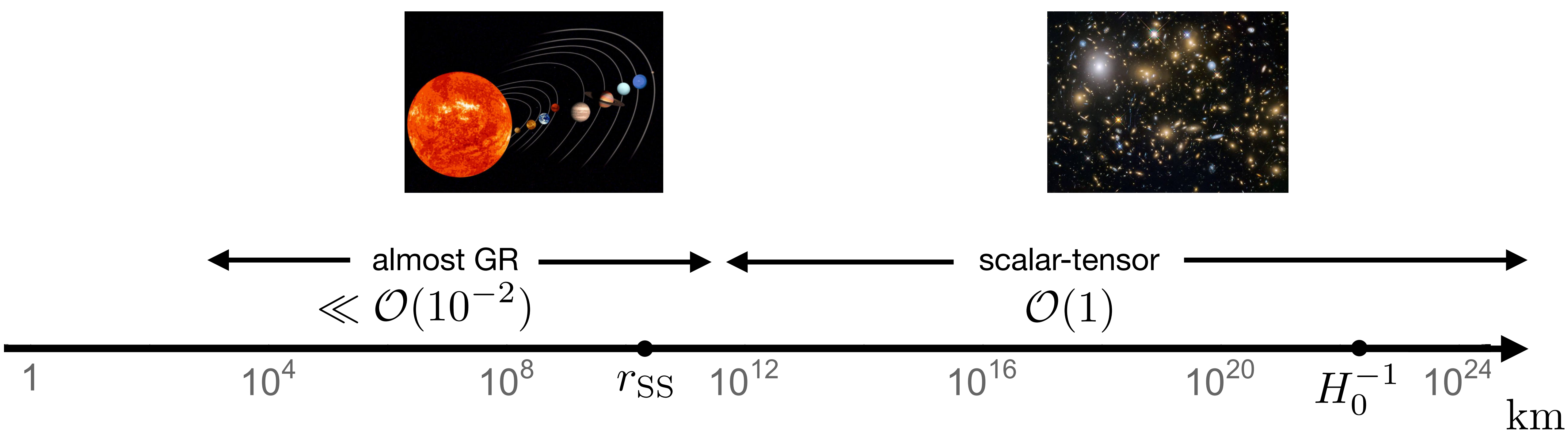
Dark energy: single scalar

$$\mathcal{L}(\phi, \nabla_\mu \phi)$$

Most general approach (single scalar): stable theories with higher derivatives

$$\mathcal{L}(\phi, \nabla_\mu \phi, \nabla_\mu \nabla_\nu \phi, \ldots)$$

Self-acceleration and screening: large classical scalar field nonlinearities



Generalized scalar-tensor theories

Horndeski (second-order) and beyond:

Horndeski 73, Deffayet et al. '11

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

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

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

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

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Gleyzes, et al. '14

(see also Zumalacarregui, Garcia-Bellido '13,
Langlois, Noui '15 and Crisostomi et al. '16 for more general theories)

Behind Horndeski

Low energy: $$\mathcal{L} = \sum_{n=0}^{\infty} \sum_{m=0}^{3} c_{n,m}(\phi) X \left(\frac{X}{\Lambda_2^4} \right)^n \left(\frac{\partial^2 \phi}{\Lambda_3^3} \right)^m$$

2 mass scales: $\Lambda_2 \equiv (H_0 M_{\rm Pl})^{1/2} \sim 10^{-3} {\rm eV}$ ~ symmetry breaking scale

$\Lambda_3 \equiv (H_0^2 M_{\rm Pl})^{1/3} \sim 10^{-13} {\rm eV}$ ~ EFT cut-off

For $\Lambda_2 \to \infty \, , \quad \Lambda_3 = {\rm const} \, , \quad c_{n,m} = {\rm const}$: Galileons: $\phi \to \phi + c + b_\mu x^\mu$

Higher-order operators generated but suppressed by ∂ / Λ_3 and/or $(\Lambda_3/\Lambda_2)^4$ (non-renormalization th.)

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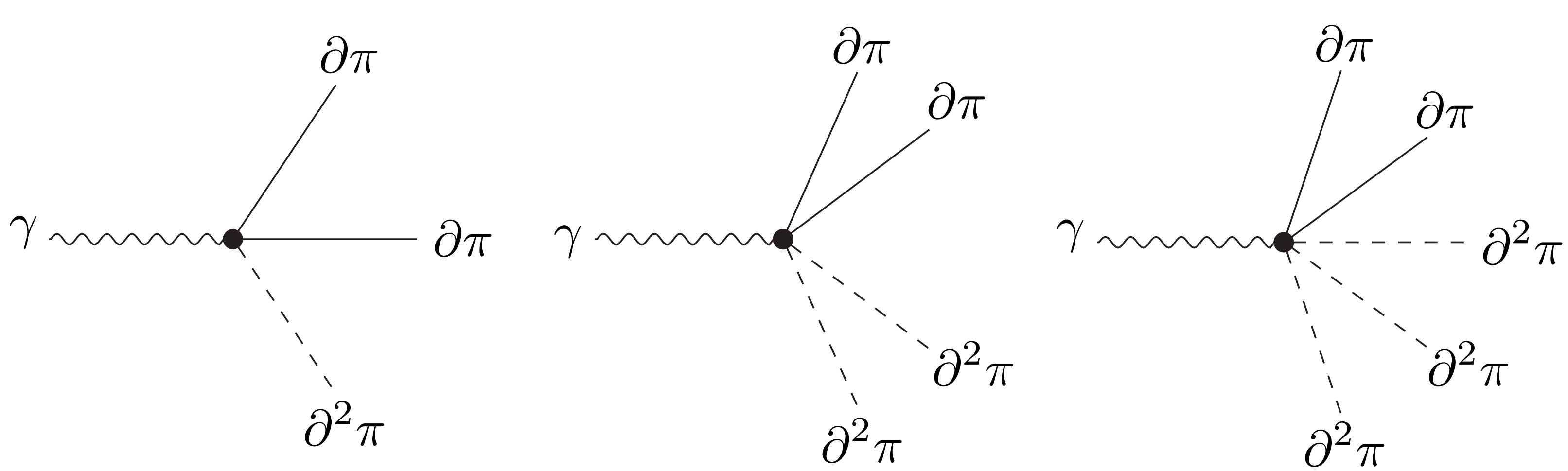
Galileon invariance broken by gravity. Horndeski coupling keeps approximate Galileon invariance

Pirtskhalava, Santoni, Trincherini, FV '15



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Higher-order operators generated but suppressed by ∂ / Λ_3 and/or $(\Lambda_3/\Lambda_2)^4$ (non-renormalization th.)

Same holds for beyond Horndeski theories

Santoni, Trincherini, Trombetta ‘18

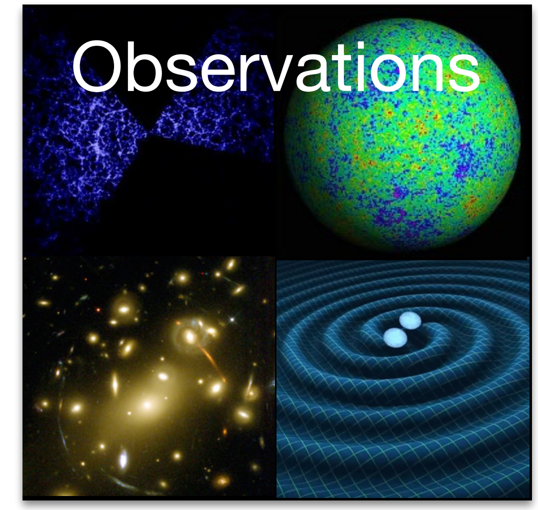
EFT of Dark Energy

Covariant theories

$$G_4(\phi,X)R + G_2(\phi,X) + G_3(\phi,X)\Box\phi - 2G_{4,X}(\phi,X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right] + G_5(\phi,X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi,X) \times \left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right] + \dots$$

← **EFT of DE** →

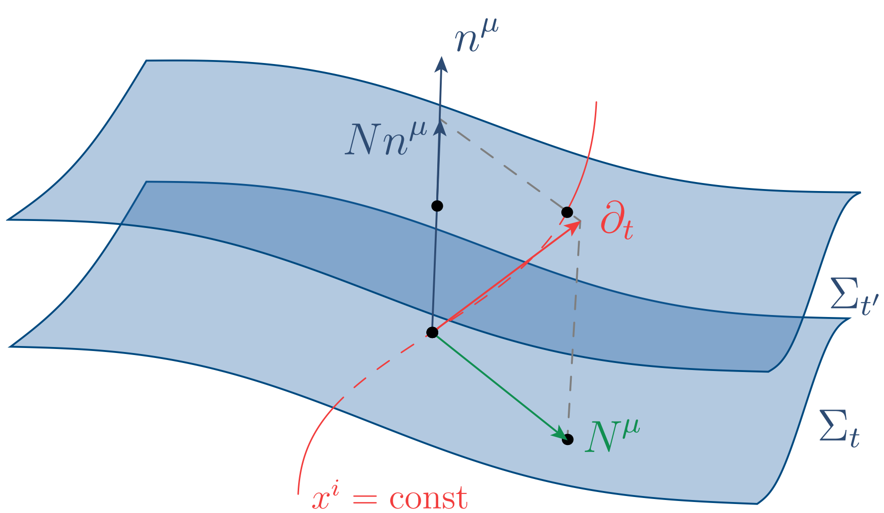
$$S = \int d^4x \sqrt{h}\frac{M^2}{2}\Big\{\left[1 + (1-\alpha_V)\delta N\right](\delta K^j_i \delta K^i_j - \delta K^2) + (1+\alpha_T^2)\,{}^{(3)}R + H^2\alpha_K\delta N^2 + 4H\alpha_B\delta K\delta N + (1+\alpha_H)\,{}^{(3)}R\delta N\Big\}$$



Action contains all possible operators invariant under spatial diffs, ordered by number of perts and derivatives

$$ds^2 = -N^2dt^2 + h_{ij}(N^idt + dx^i)(N^jdt + dx^j)$$

Cheung et al. ’07, Gubitosi et al. ’13, Gleyzes et al. ’13, Bellini and Sawicki ’14, …



Bridge models and observations in a minimal and systematic way

EFT of Dark Energy

Covariant theories

$$G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi$$
$$- 2G_{4,X}(\phi, X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right]$$
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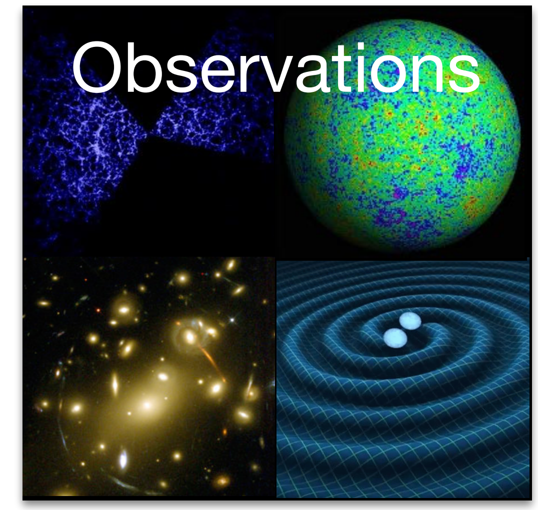
$$\times\left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right]$$
$$+ \dots$$

EFT of DE

$$S = \int d^4x\sqrt{h}\frac{M^2}{2}\Big\{\big[1 + (1-\alpha_V)\delta N\big](\delta K^j_i\delta K^i_j - \delta K^2) + (1+\alpha_T^2)^{(3)}R + H^2\alpha_K\delta N^2 + 4H\alpha_B\delta K\delta N + (1+\alpha_H)^{(3)}R\delta N\Big\}$$



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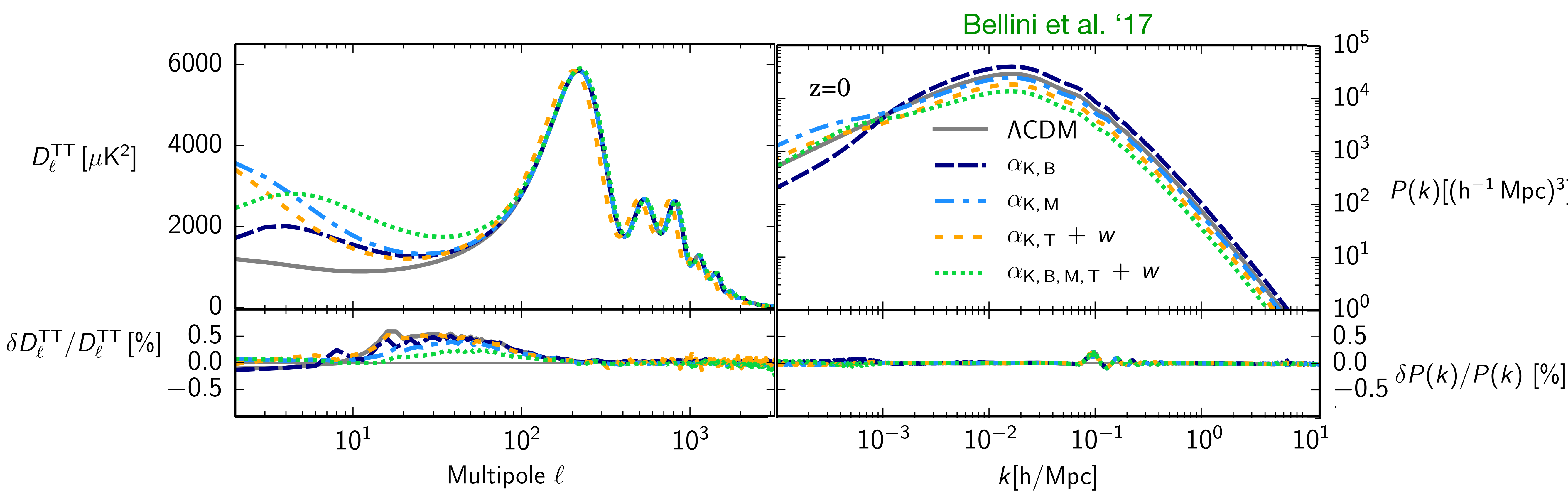

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EFT of DE

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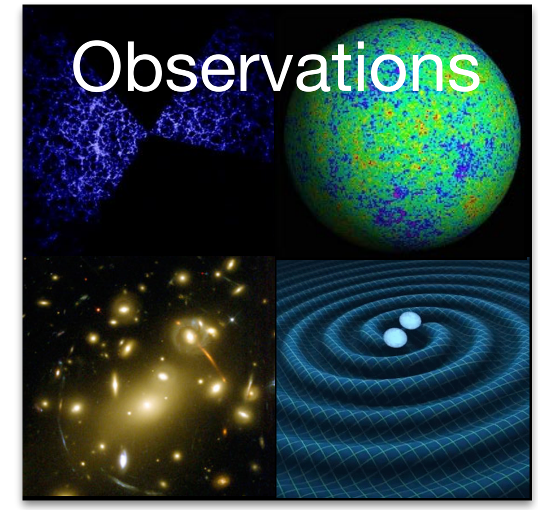


Action contains all possible operators invariant under spatial diffs, ordered by number of perts and derivatives

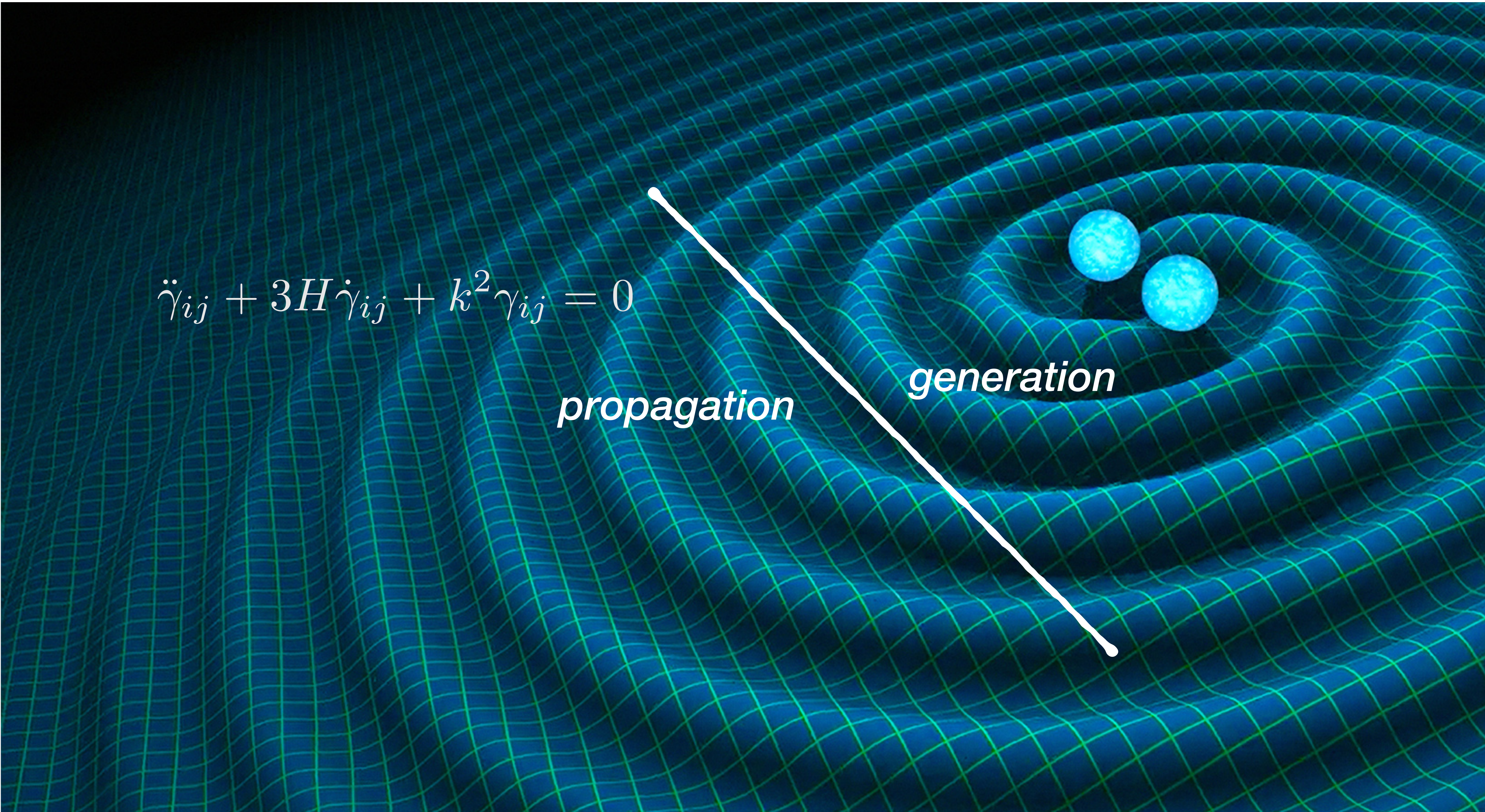
Future LSS observations:

$$|\alpha_i| \simeq \text{few} \times 0.01$$

Gravitational wave equation

Gravitational wave equation:

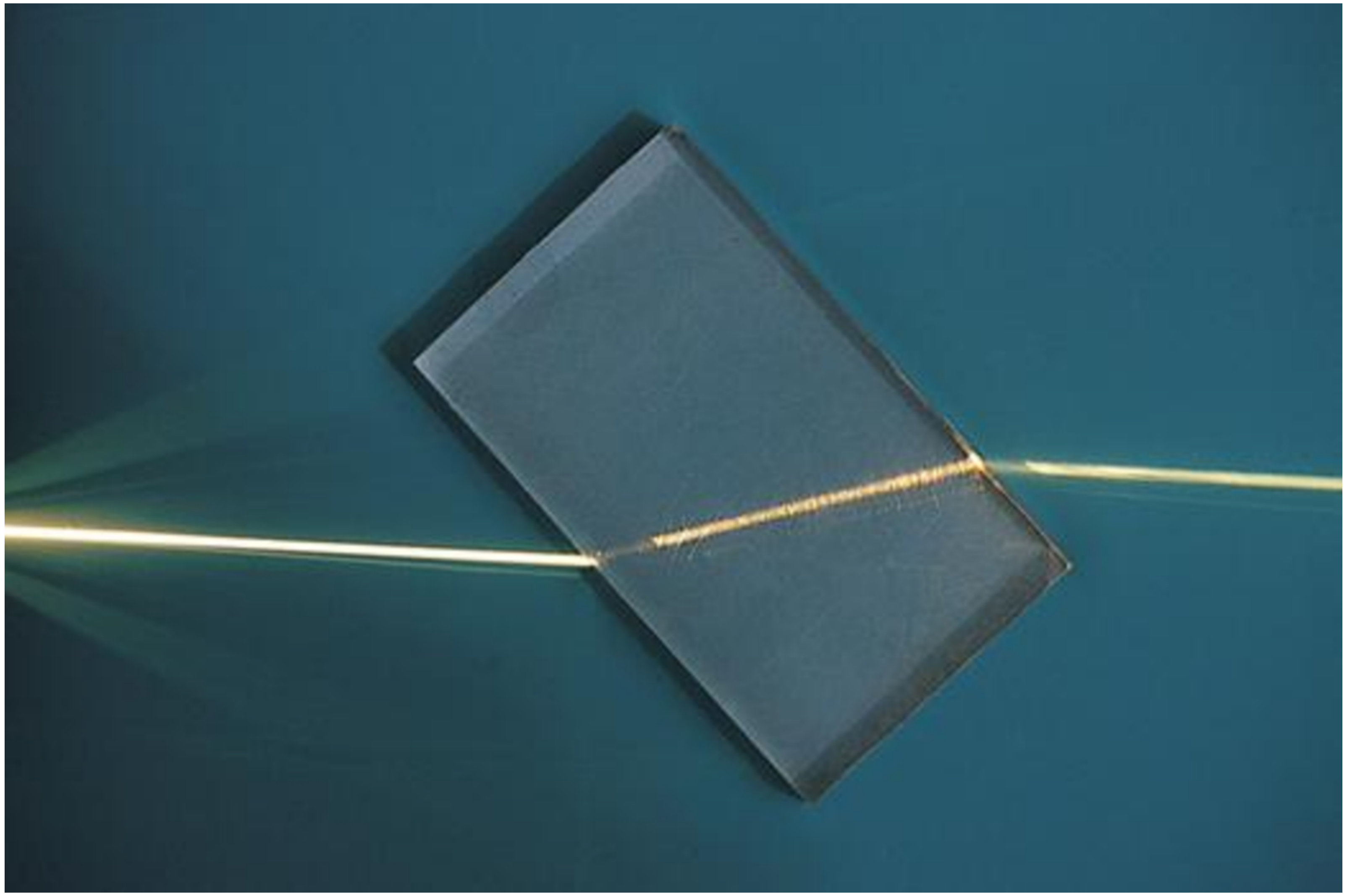
$$ds^2 = -dt^2 + a^2(t)\left[\delta_{ij} + \gamma_{ij}\right] d\vec{x}^i d\vec{x}^j \ , \qquad \gamma_{ii} = 0 = \partial_i \gamma_{ij} \ , \qquad H = \dot{a}/a$$



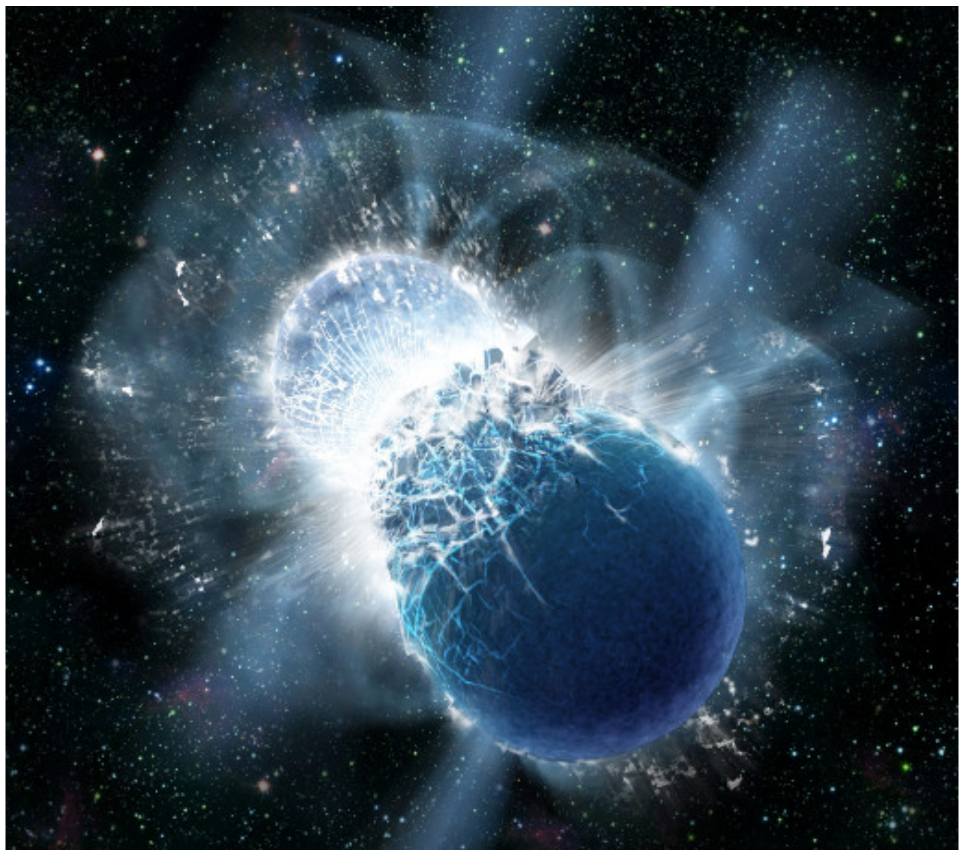
Modified speed of propagation

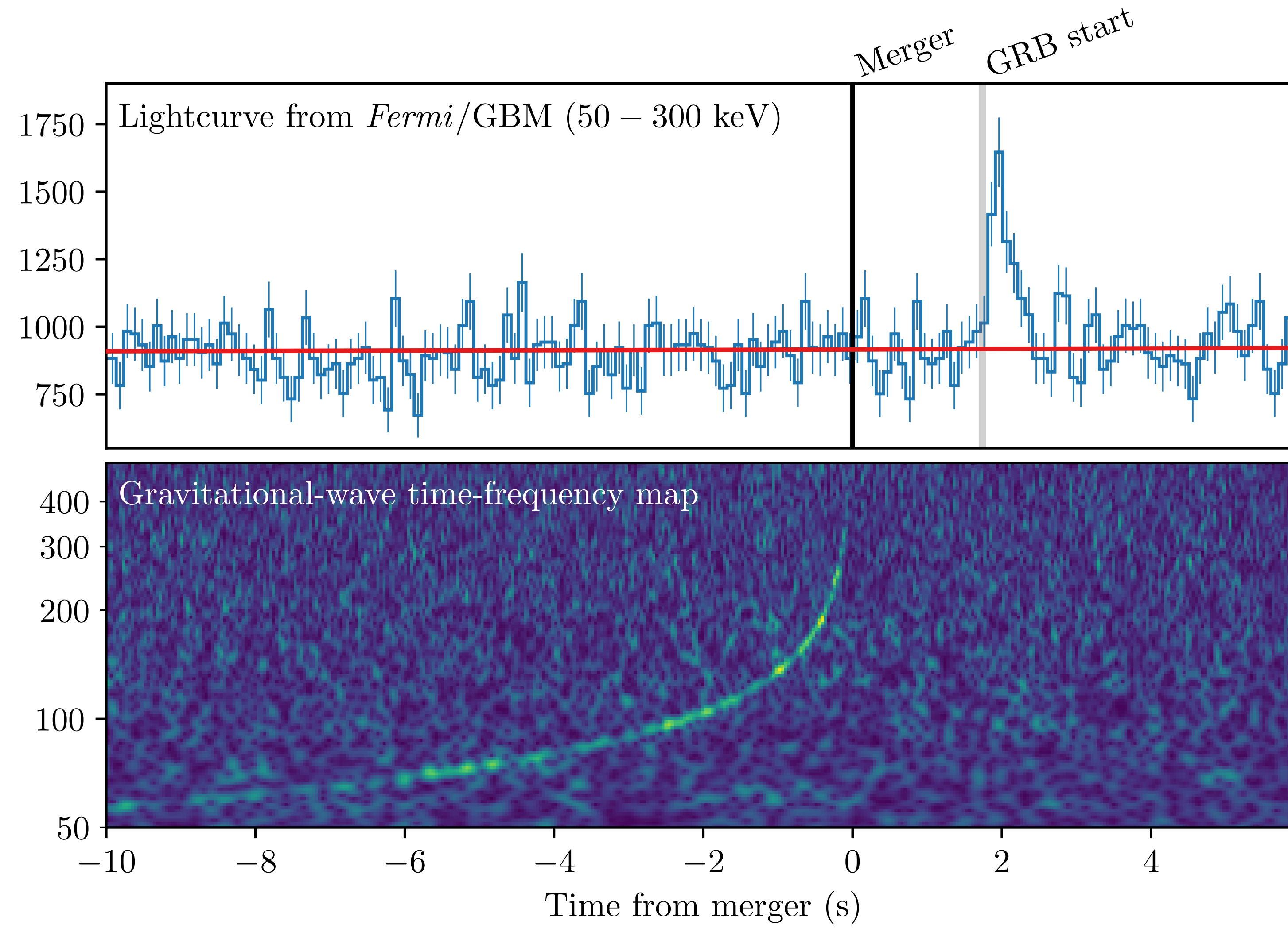
Spontaneously broken Lorentz invariance: refraction

$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + c_T^2 k^2 \gamma_{ij} = 0$$



Multi-messenger observation



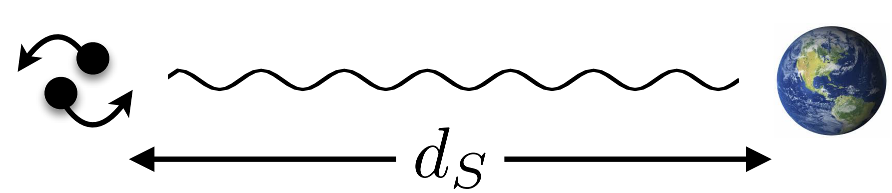


$$-3 \times 10^{-15} \leq \frac{c_T - c}{c} \leq 7 \times 10^{-16}$$

Virgo, Fermi-GBM, INTEGRAL, LIGO '17

Effect accumulates over long time

$$\frac{\Delta c}{c} \sim \frac{\Delta t}{d_S}$$



c_T=1 implications

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c_T=1 implications

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

$$\mathcal{L} = G_4(\phi, X)R + G_2(\phi, X) + G_3(\phi, X)\Box\phi \qquad \Box\phi \equiv \phi^{;\mu}_{;\mu} \quad X \equiv g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$
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$$\dot{\gamma}_{ij}^2$$

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

c_T=1 implications

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

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

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

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

After c_T=1

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

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

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

Caveat

de Rham, Melville '18

EFT of cosmological scales may not apply to LIGO-Virgo scales

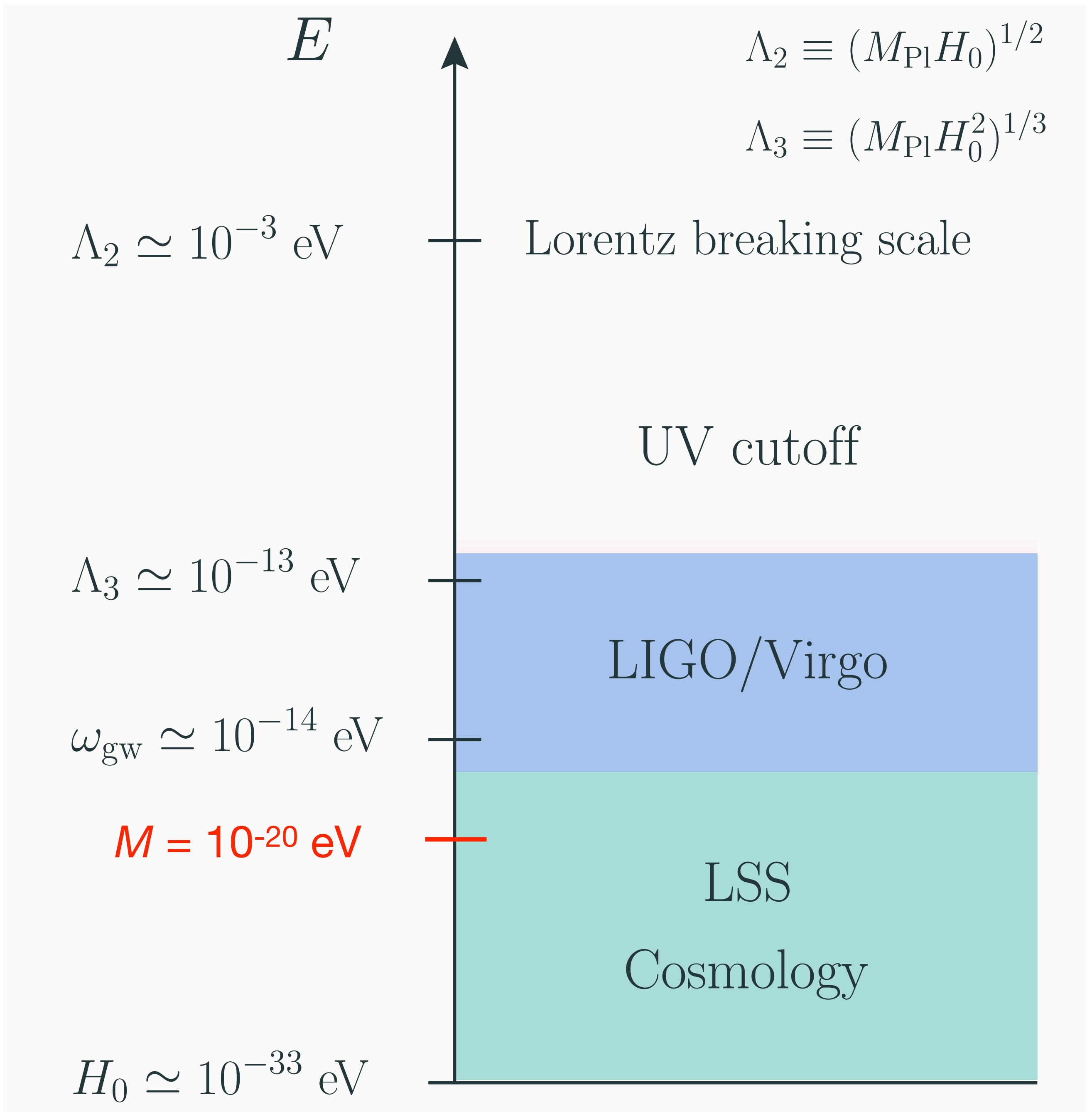
Theory may break down (new states) at a scale parametrically lower than cutoff Λ_3

Speed of gravity may go to 1 at "short" scales

$$\omega^2 = c_T^2 k^2 + \frac{k^4}{M^2} + \dots$$
$$= k^2 \left(1 + \mathcal{O}(M^2/k^2)\right) \qquad M \ll \Lambda_3$$

Naively: $M \lesssim 10^{-8}\Lambda_3 \sim (10^{11} \text{ km})^{-1}$

- How to reconcile with local tests of gravity?
- Can we say something general about UV completion? Analogous to frequency dependent refraction index: Kramers-Kronig?



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

Can we rule out more?

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

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

- ***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

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

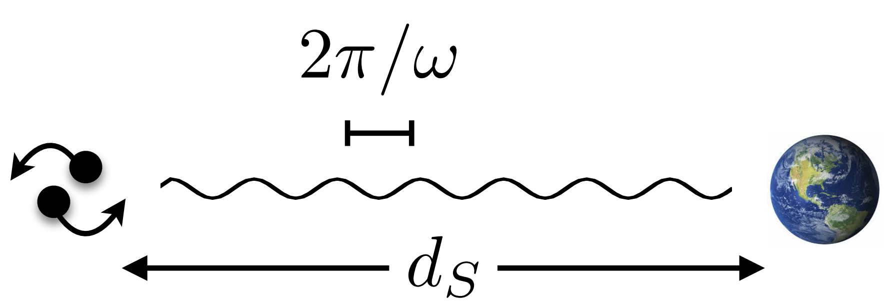
Modified gravitational wave propagation

Spontaneously broken Lorentz invariance: absorption and dispersion. Effects depend on frequency.

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

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

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

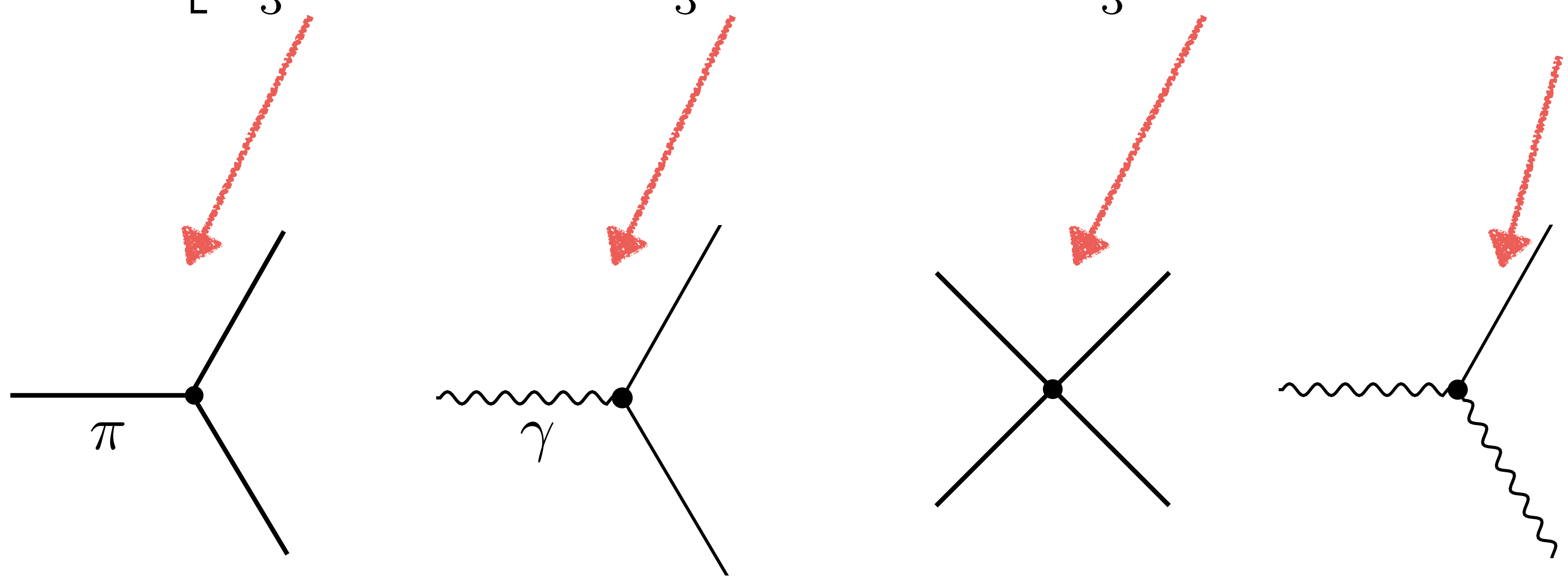


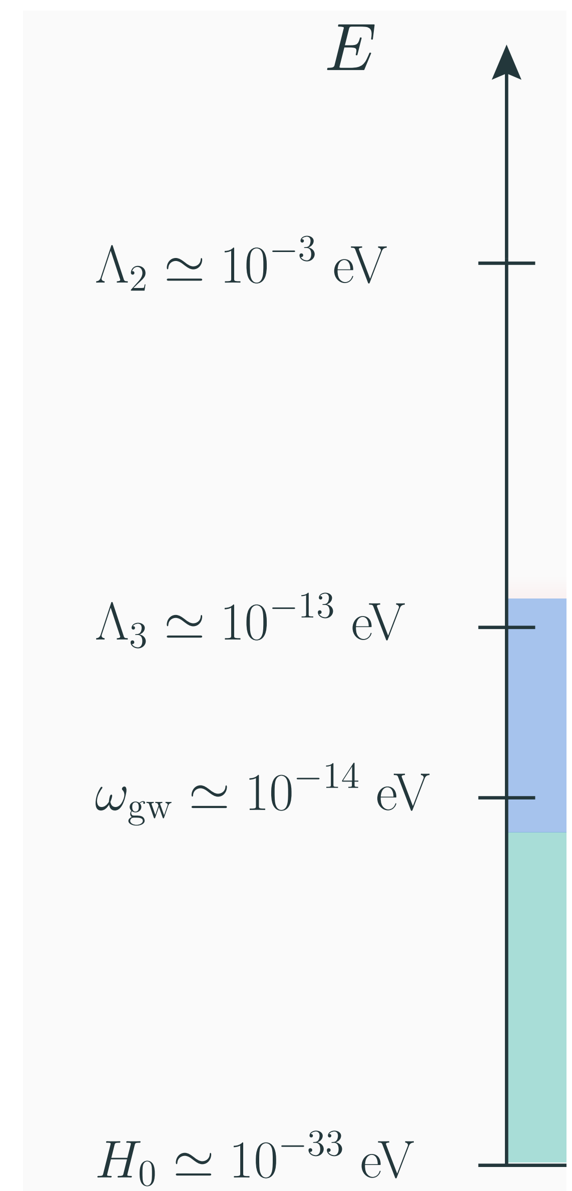
(See also Nishizawa '17; Ezquiaga & Zumalacarregui '18, '20; Dalang, Fleury, Lombriser '20)

Expanded action for α_H

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

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



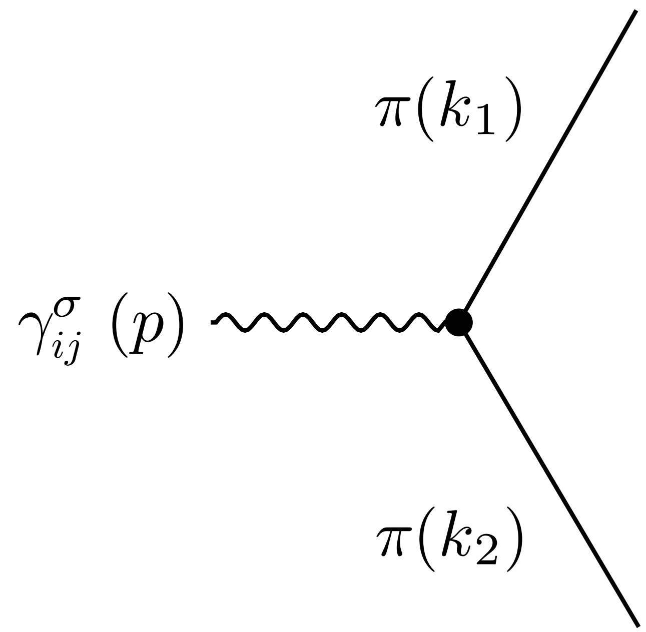


Graviton decay into dark energy

Creminelli, Lewandowski, Tambalo, FV '18

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

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



$$\sim \alpha_H \frac{p^2}{\Lambda_3^3} \epsilon_{ij}^{*\lambda}(\mathbf{p}) k_1^i k_2^j$$

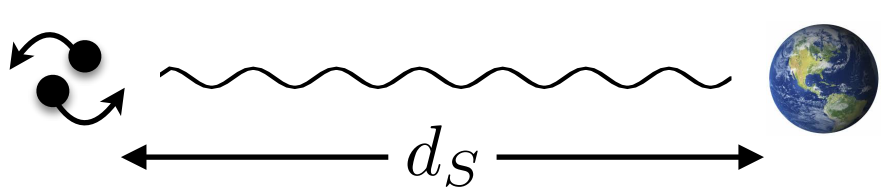
GW decay into scalar fluctuations π. Analogous to light absorption into a material.

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

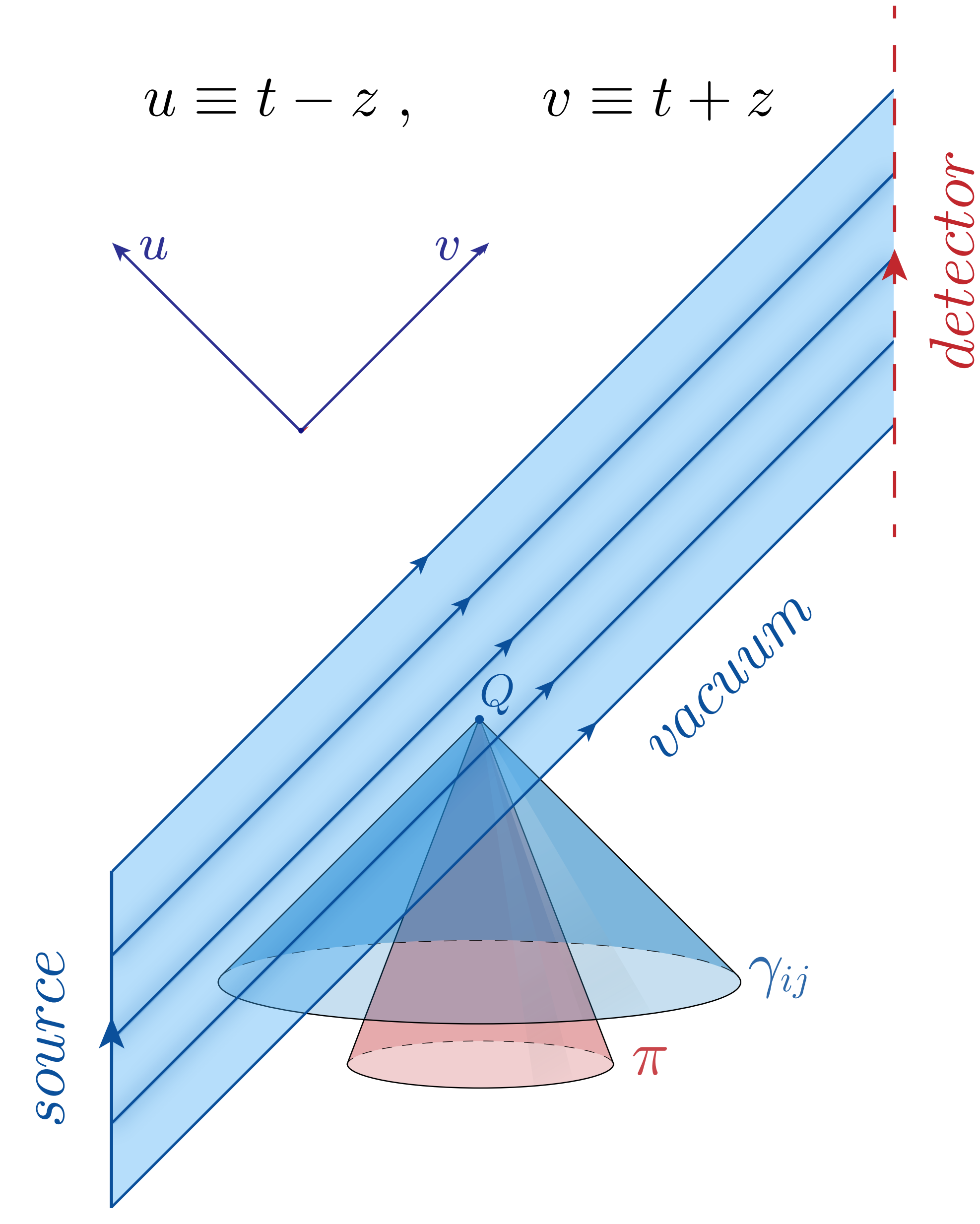
Decay enhanced by the large occupation number of the GWs ~ preheating

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:

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

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



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Oscillator with changing frequency:

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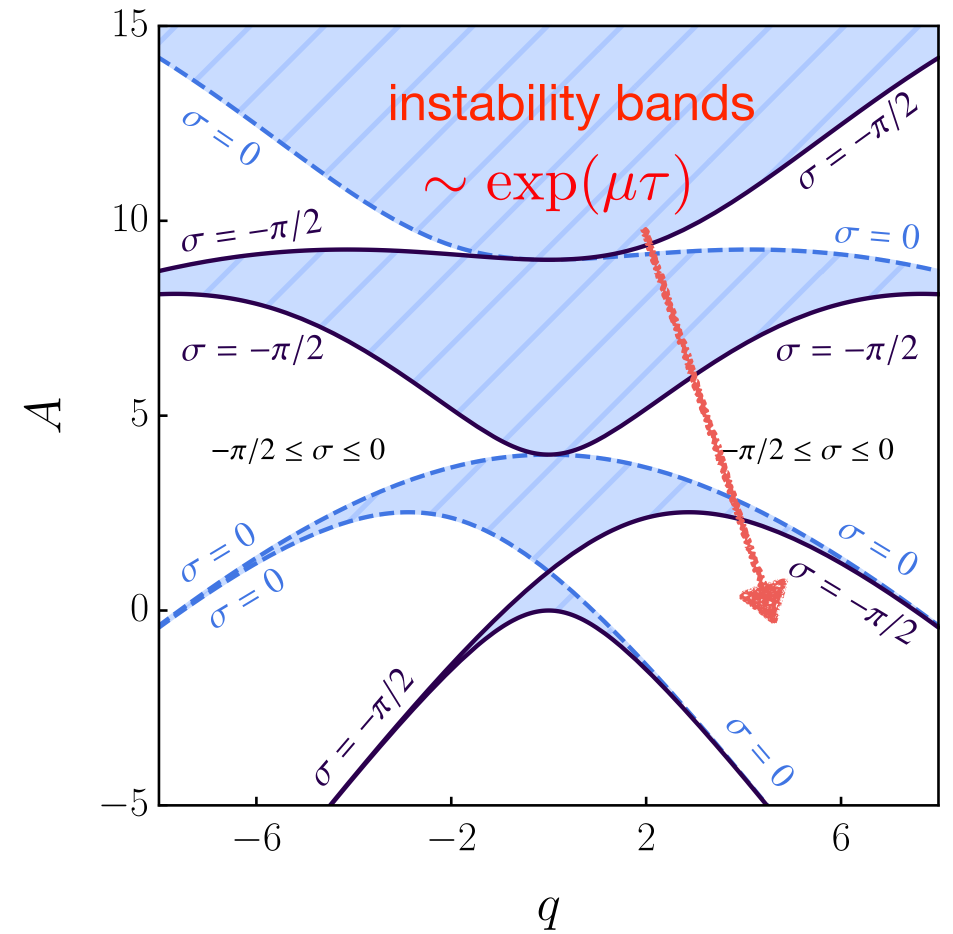
Each Fourier mode satisfies a Mathieu equation
⇒ parametric resonance.

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

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

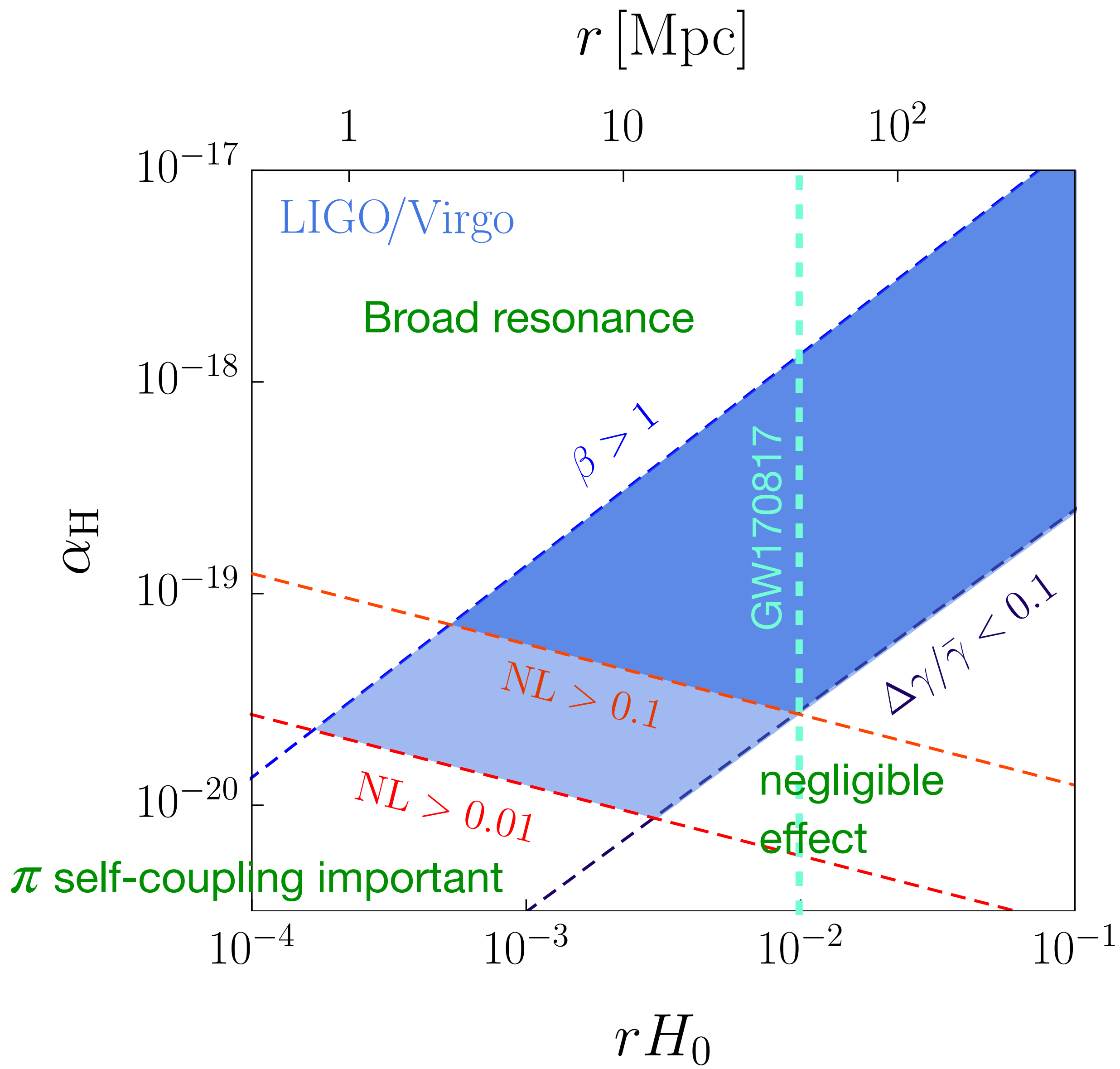


Narrow resonance $\beta \ll 1$: $\mu \sim \beta/4 \quad \Rightarrow \quad \rho_\pi \propto e^{\beta\omega u/4} \quad \Rightarrow \quad \Delta\gamma_{ij} \propto v\gamma_0 e^{\beta\omega u/4}\epsilon^+_{ij}$

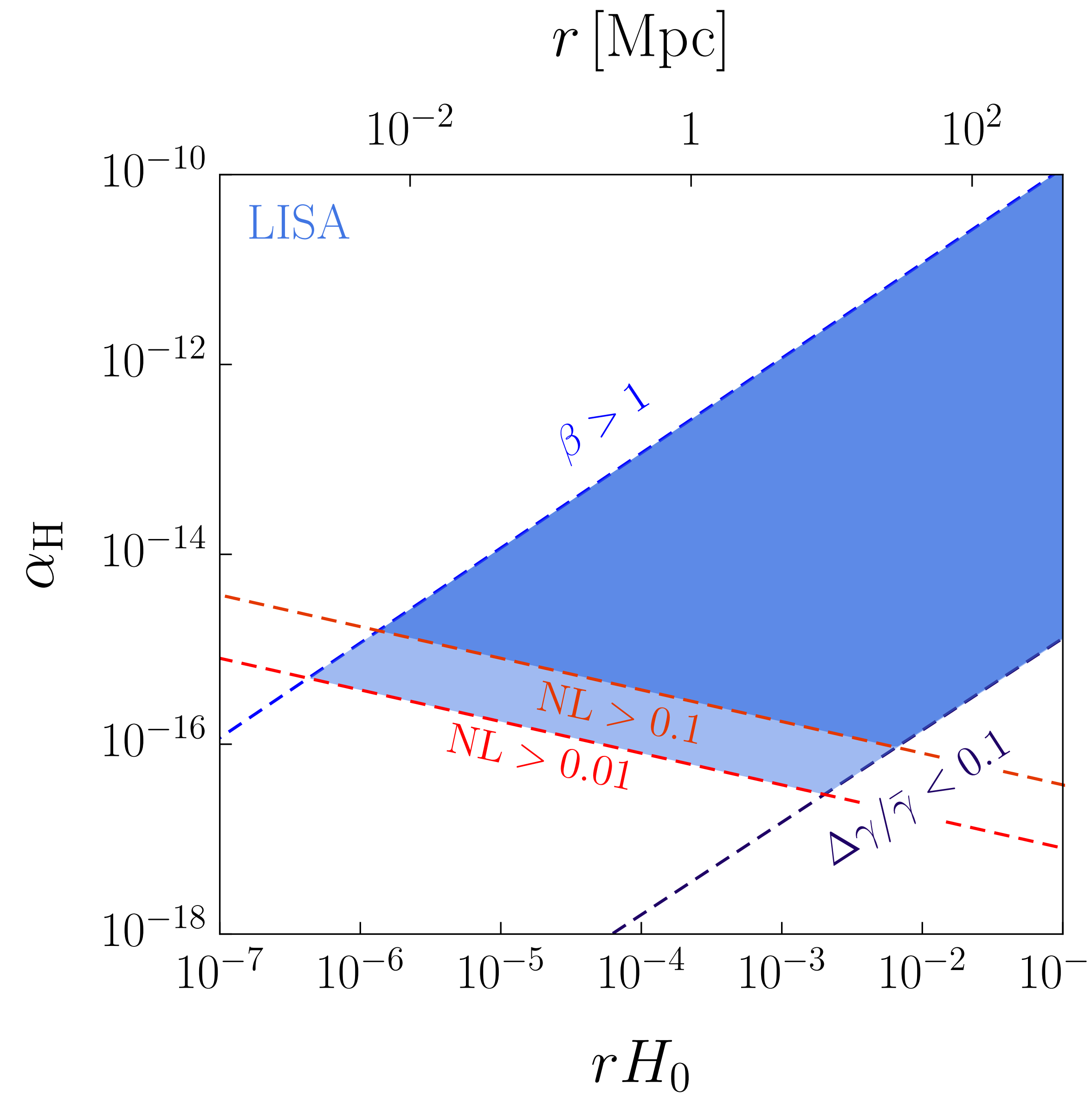
Same direction and polarization. Same frequency + higher harmonics (precursors)

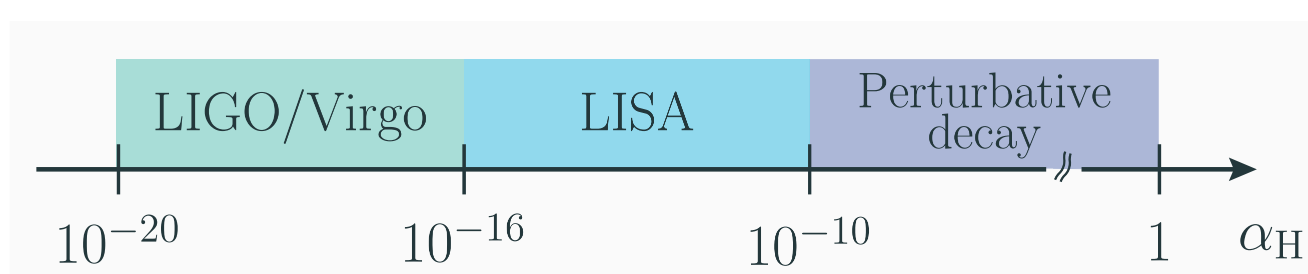
GW modification

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



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

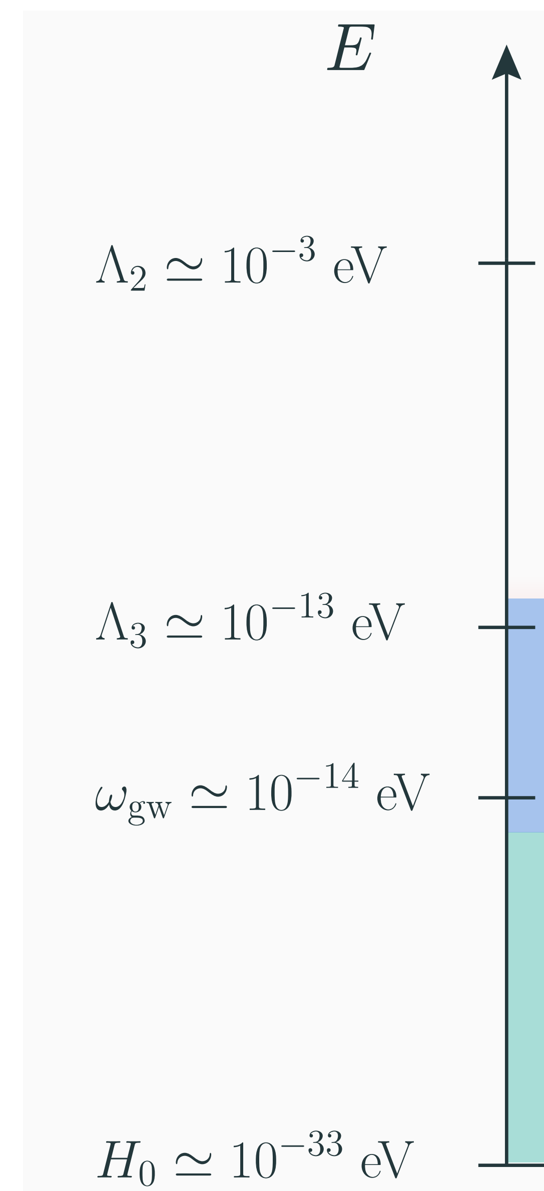




Expanded action for α_H

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

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



GW modification

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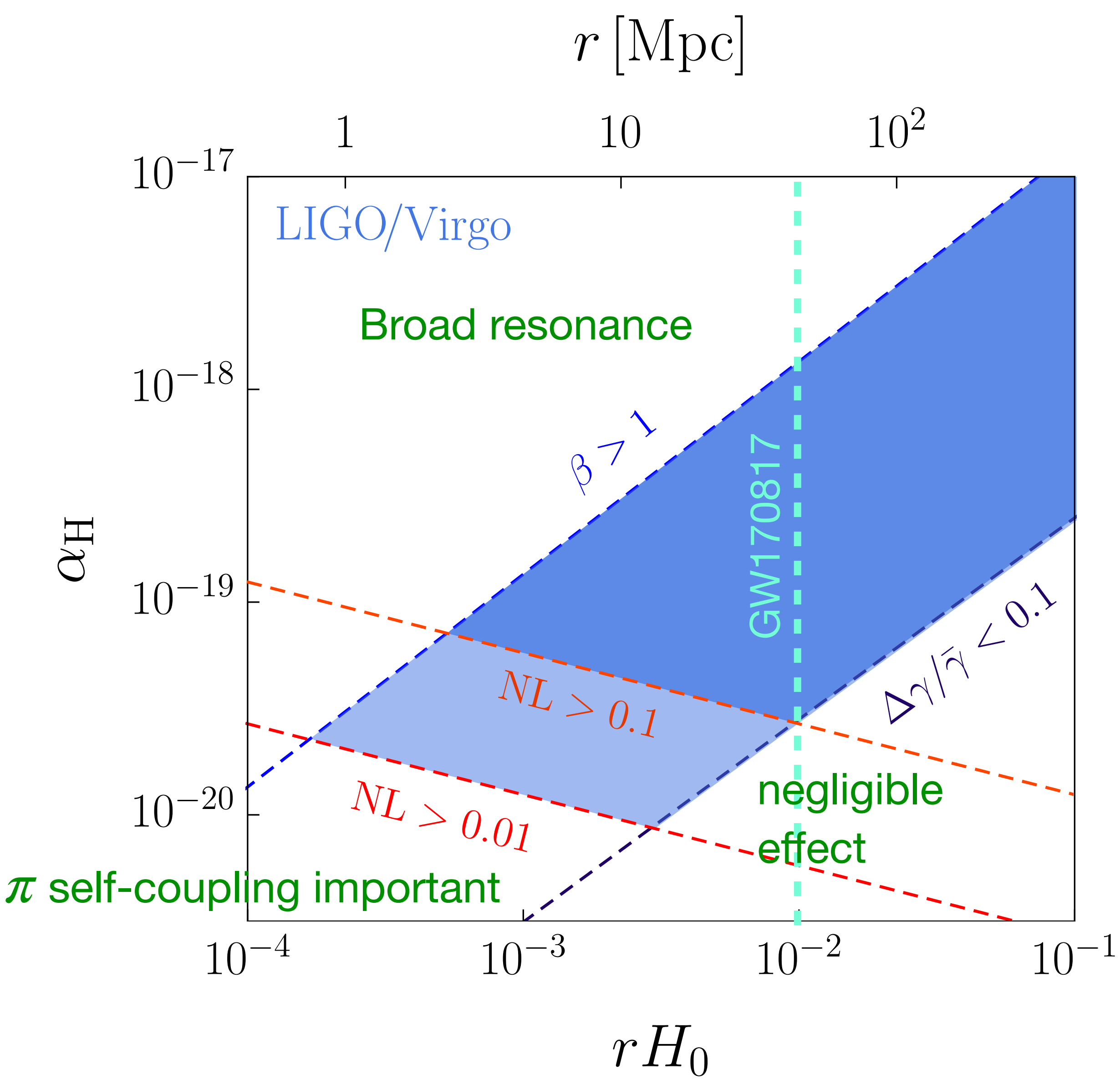

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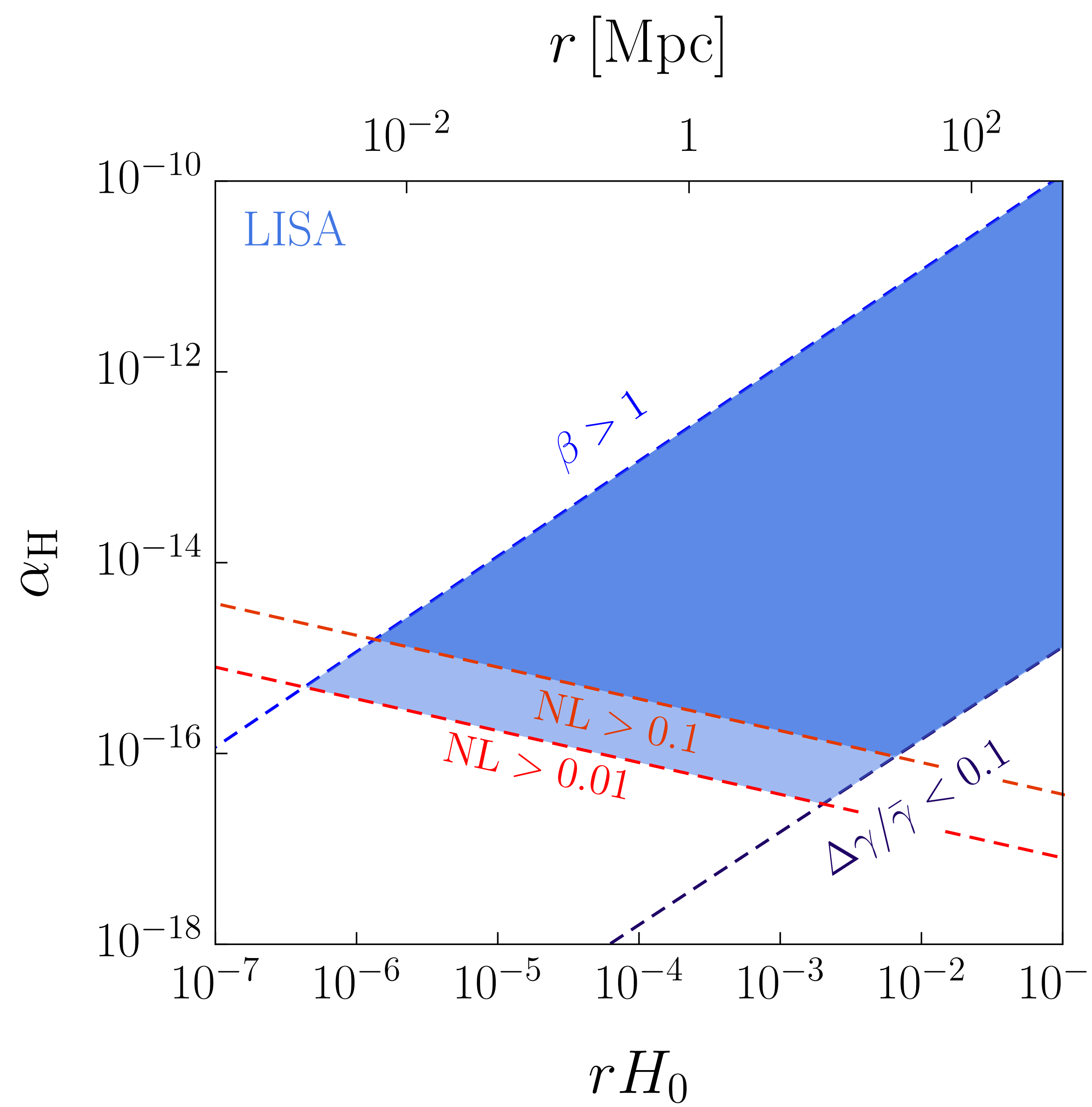
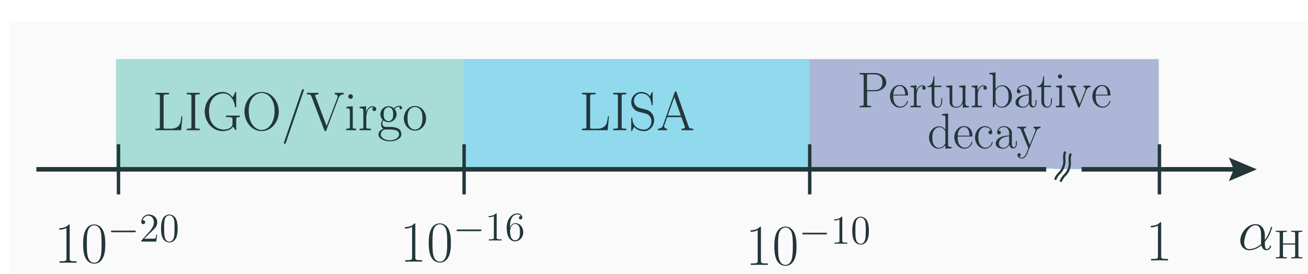




Theory after no decay

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

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

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

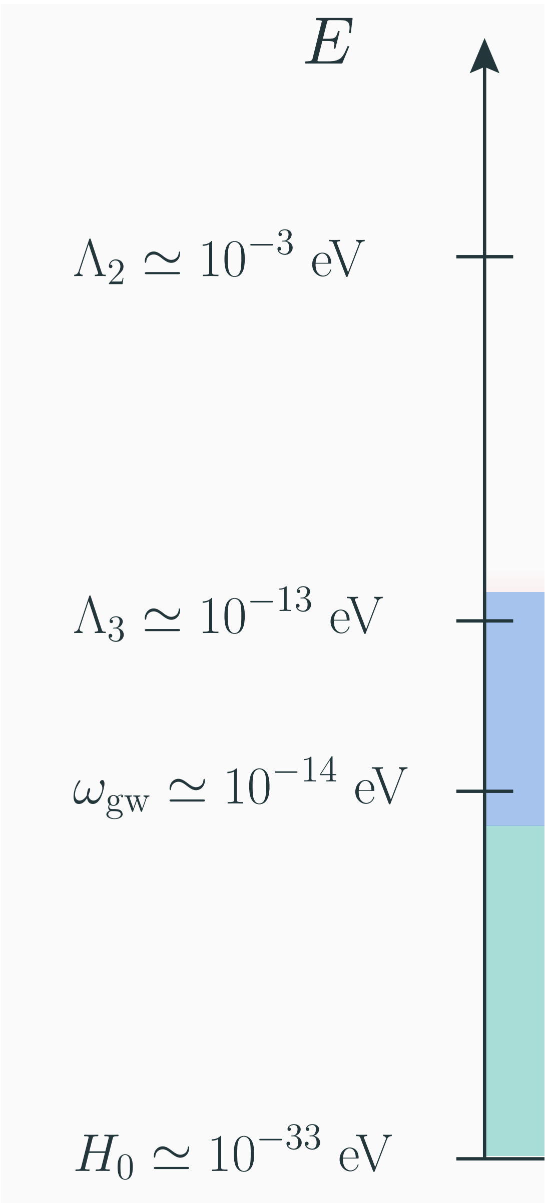
- *Beyond Horndeski:* $\alpha_H = \dfrac{X^2 F_4}{G_4}$
- *Braiding:* $\alpha_B = \dfrac{\dot{\phi} X G_{3,X}}{H G_4}$

Expanded action for α_B

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

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

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



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

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

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

The regime $\beta > 1$ seems problematic:

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

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

gradient instability < 0

Expanded action for α_B

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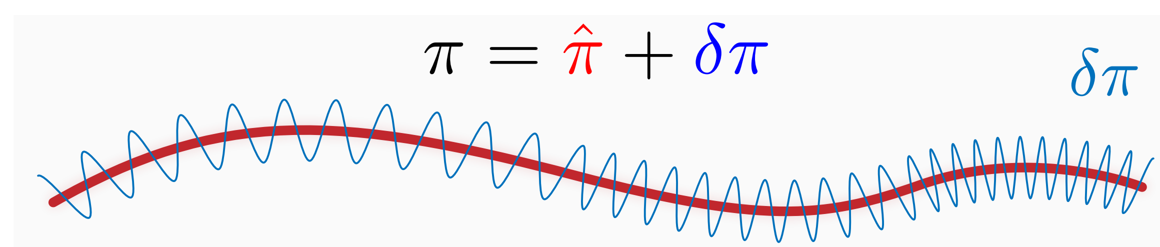
$$\beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^+$$

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

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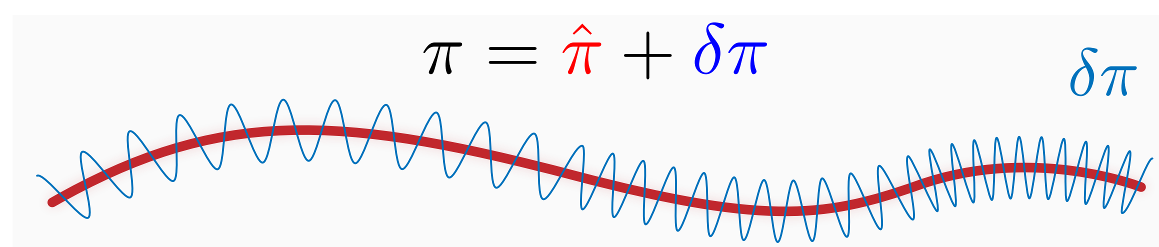


- Gradient instabilities: imaginary solution of $Z_{\mu\nu}k^\mu k^\nu = 0$ for k^μ $\quad \beta > 1$
- Ghost instabilities: $Z_{00} < 0$ $\quad \beta^2 > (1 - c_s^2)c_s^{-4}$

Triggering the instability

instability parameter

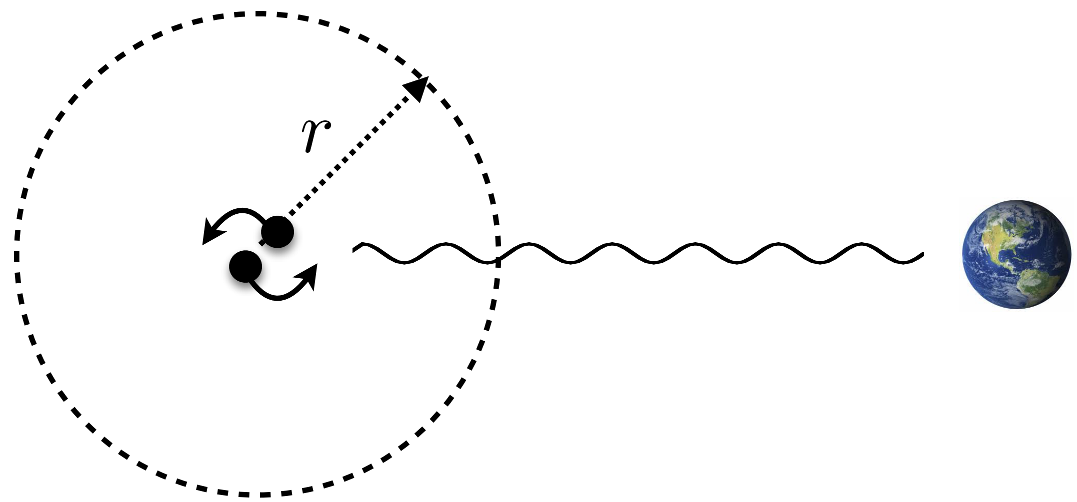
$$\beta = \frac{|\alpha_B|}{\alpha c_s^2} \frac{\omega}{H} h_0^+$$

GW amplitude

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

condition on frequency

$$f < f_{\rm ISCO} \simeq \frac{0.034}{\pi G M_c}$$



- r = 1 Mpc (stellar mass BHBs/LIGO frequencies): instability triggered around dense regions
- r = 10 Mpc (heavier BHBs/lower frequencies): instability triggered everywhere

(scales larger than typical screened region)

Stellar-mass BHs (r = 1Mpc)

instability parameter

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

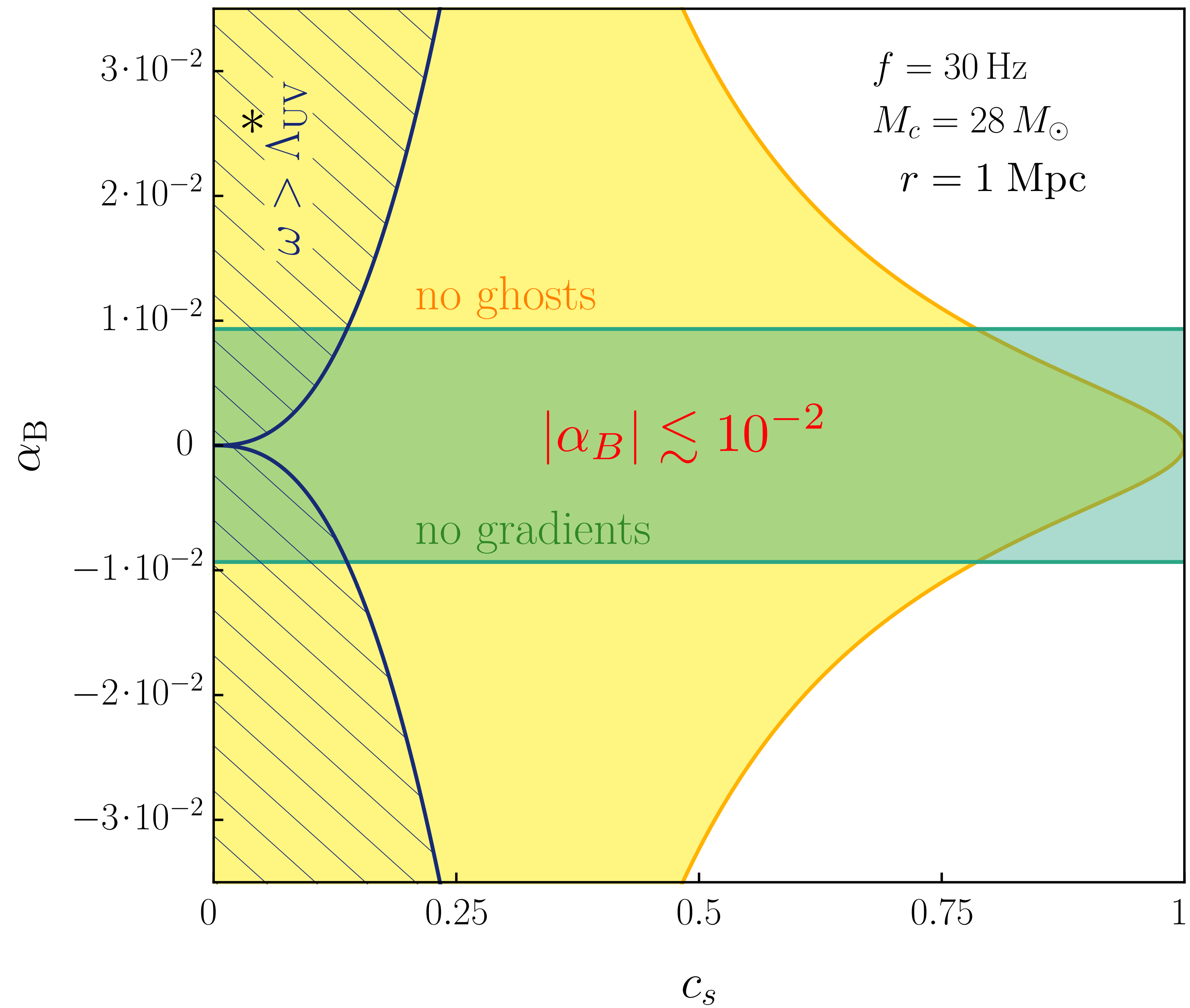
GW amplitude

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

condition on frequency

$$f < f_{\rm ISCO} \simeq \frac{0.034}{\pi G M_c}$$

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



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

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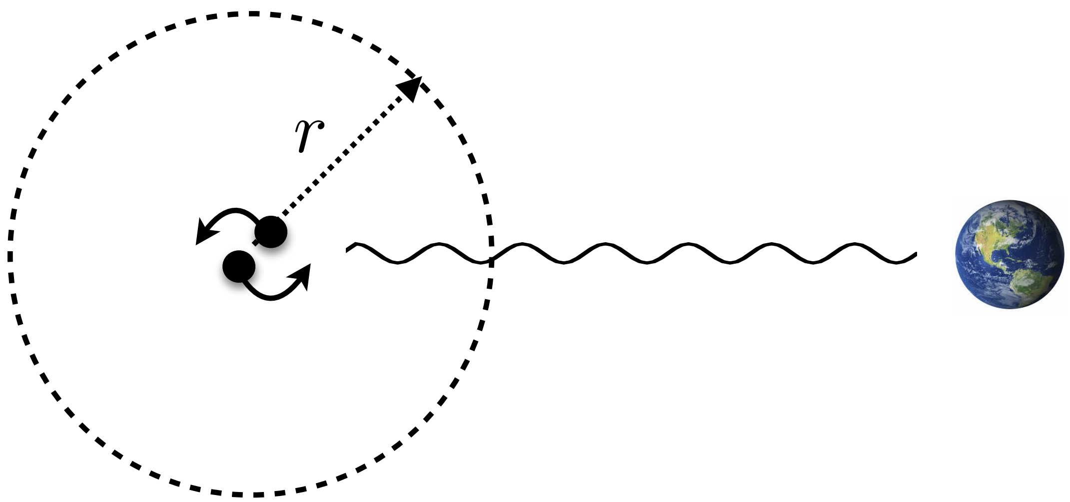

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- r = 10 Mpc (heavier BHBs/lower frequencies): instability triggered everywhere

(scales larger than typical screened region)

Gradient instability, β > 1, for α_B

instability parameter

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

GW amplitude

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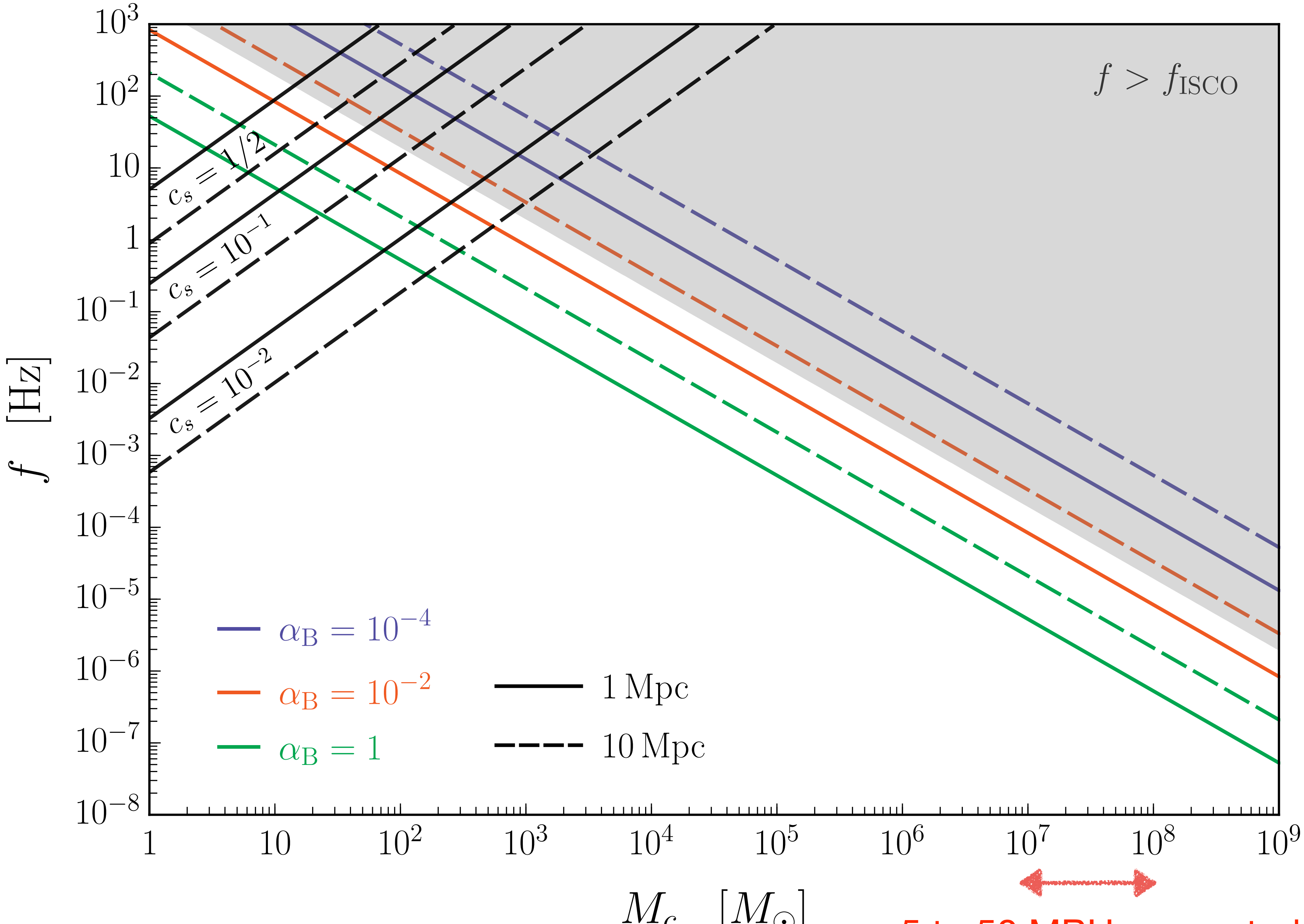


5 to 50 MBHs expected

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

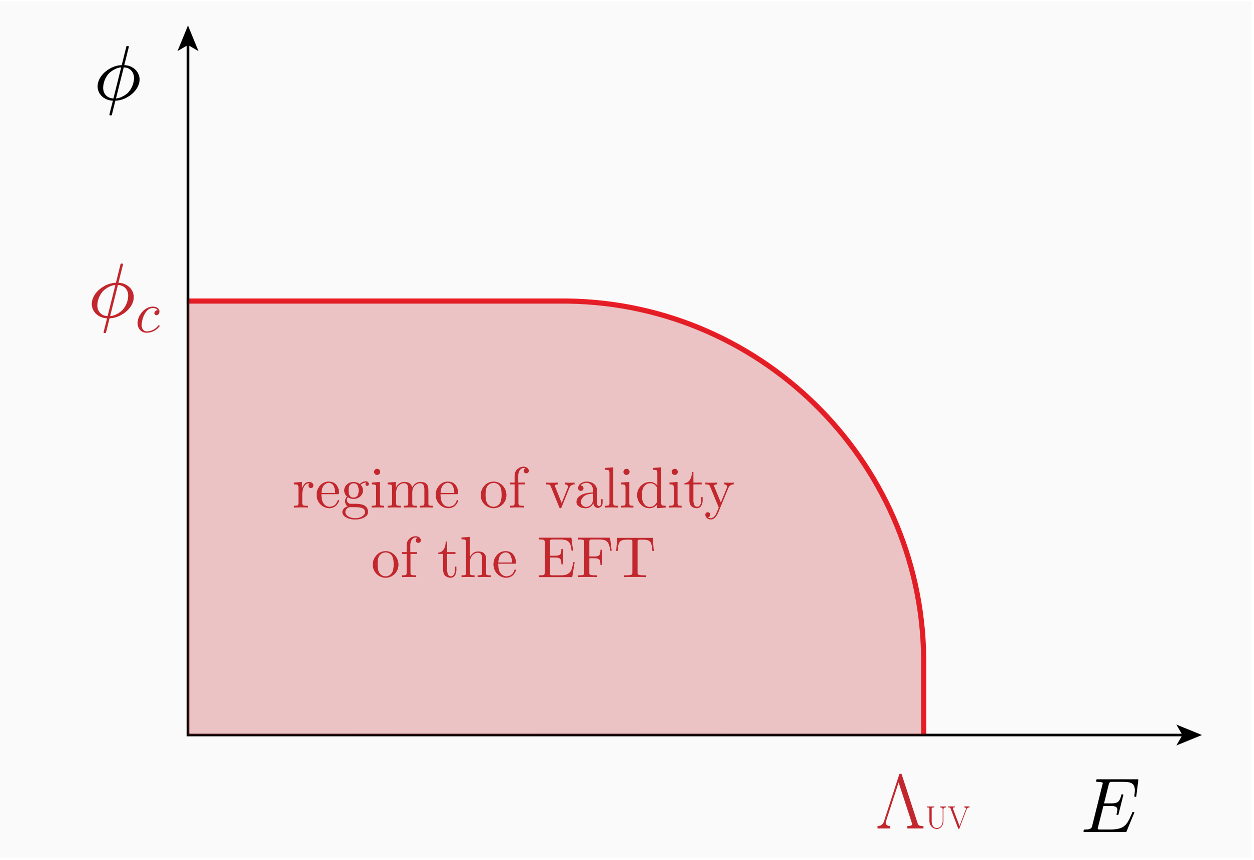
Population of MBHs is enough to globally trigger the instability

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

Validity of EFT modified by presence of sizeable background



Fate of instability depends on the (unknown) UV completion: no guarantee of physical effects

$$\rho_{\rm inst.} \sim \Lambda_{\rm UV}^4 \ll \rho_{\rm gw} \sim \Lambda_2^4$$

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

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