Testing LCDM model and dark energy with LISA

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with Noemi Frusciante

and Marc Besancon, Enis Belgacem, Gianluca Calcagni, Marco Crisostomi, Saurya Das, Stephanie Escoffier, **José Maria Ezquiaga**, Stefano Foffa, Pierre Fleury, Lucas Lombriser, Michele Maggiore, Michele Mancarella, Alvise Raccanelli, Ippocratis D. Saltas, Bangalore S. Sathyaprakash, N. Tamanini, Elias Vagenas, …

26 May 2022
Fundamental Physics with LISA - 'Cosmological Frontiers in Fundamental Physics'

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My talk

José's talk

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  C. Large-scale structure
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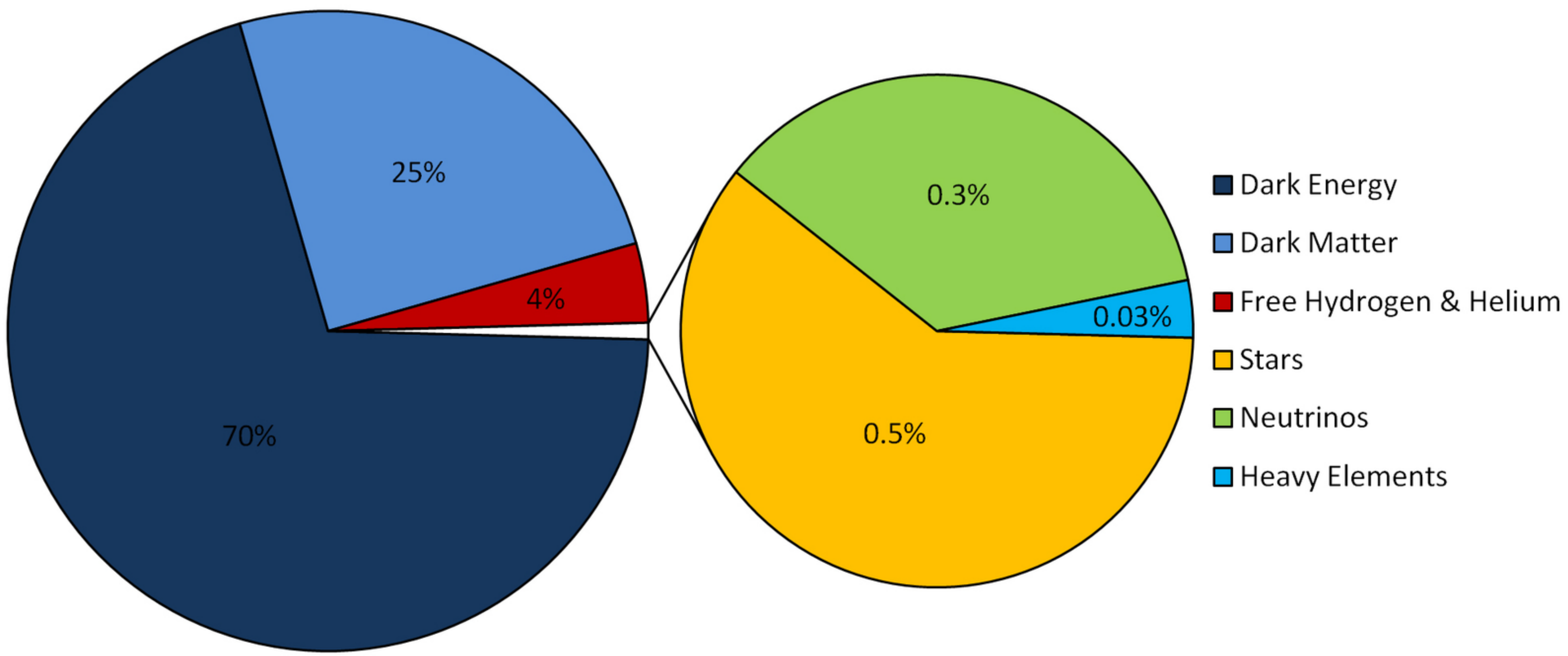
My talk

Archiman's focus talk

José's talk

ΛCDM model

Current Standard Model of cosmology is supported by many independent datasets (big bang nucleosynthesis, cosmic microwave background anisotropies, baryon acoustic oscillations, weak lensing, galaxy clustering, supernovae Type Ia, etc.)



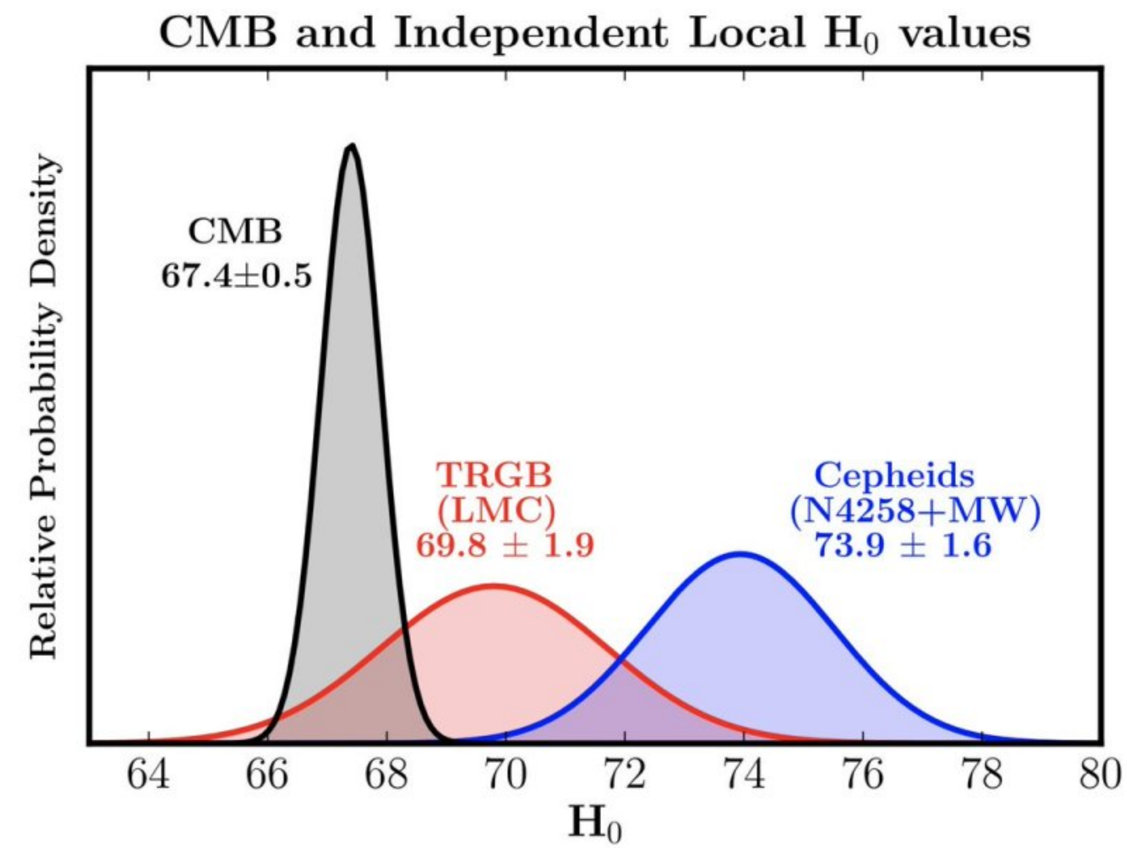
95% is unknown stuff: Dark Matter and Dark Energy

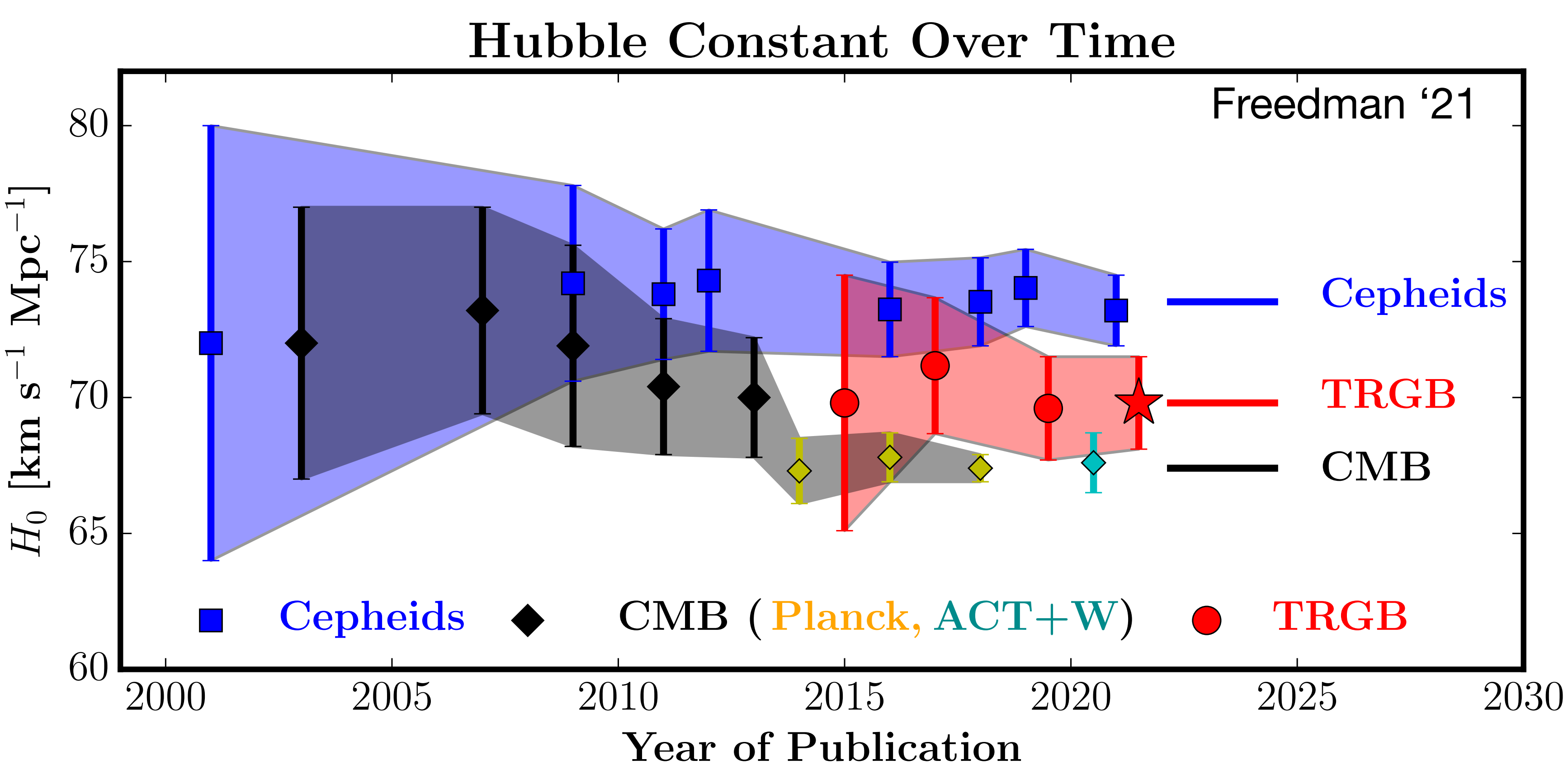
Equation of state: $w_{\rm X} \equiv p_{\rm X}/\rho_{\rm X}$

$$w_{\rm DM} \simeq c_s \simeq 0 \qquad\qquad w_{\rm DE} \simeq -1$$

H_0 tension

Most significant tension (~4σ) is $\boldsymbol{H_0}$ measured by **early-time** universe observations (CMB, BAO, LSS) vs **late-time** ones (distance-ladder, lensing time delay). Hint of breakdown of ΛCDM?





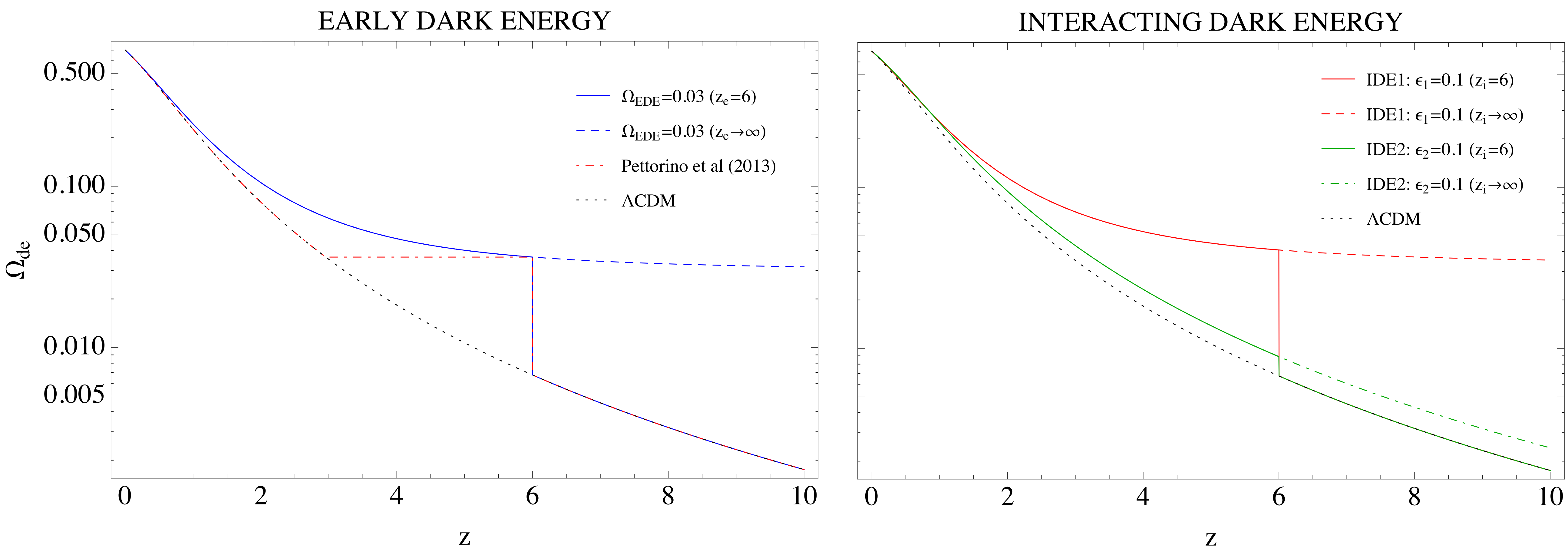
LISA will bring new independent way of measuring H_0.

See Archisman's talk

[See also Tamanini et al. '16]

Early and interacting dark energy

[Caprini & Tamanini '16]



E.g. axion:

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \phi)^2 - \Lambda^4 \left(1 - \cos\left(\phi/f\right)\right)^n - V_\Lambda$$

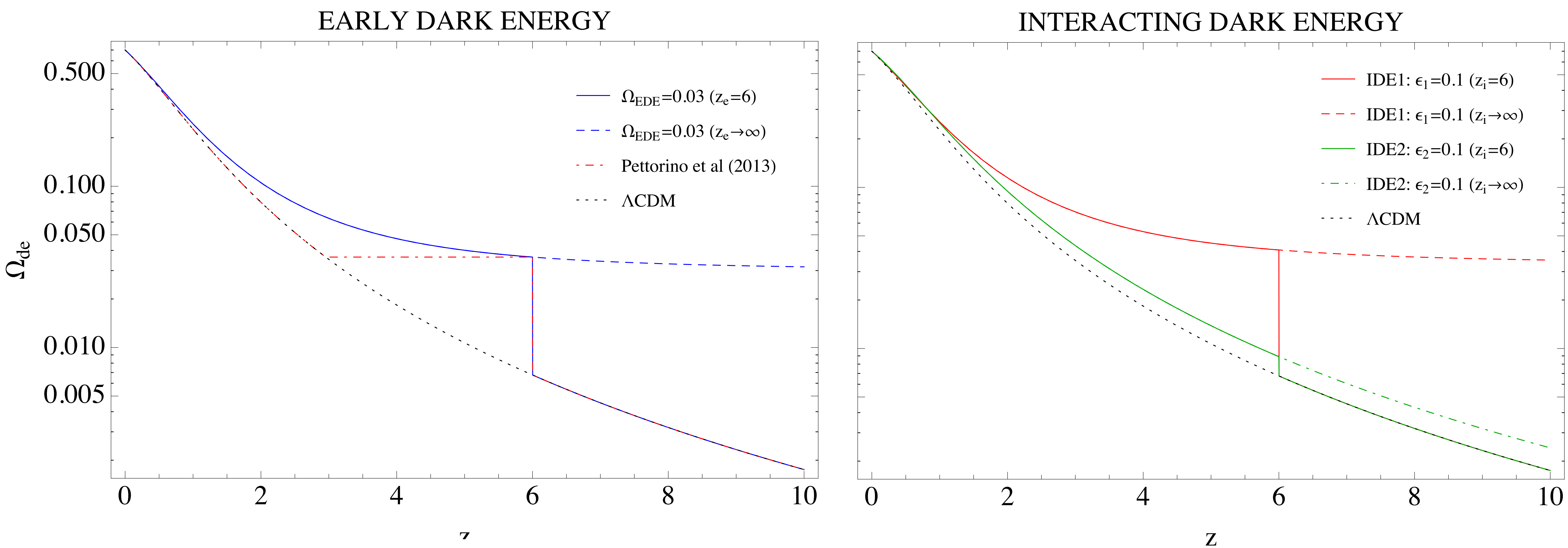
$$\dot\rho_{dm} + 3H\rho_{dm} = Q\,,$$
$$\dot\rho_{de} + 3H(1+w_0)\rho_{de} = -Q\,,$$

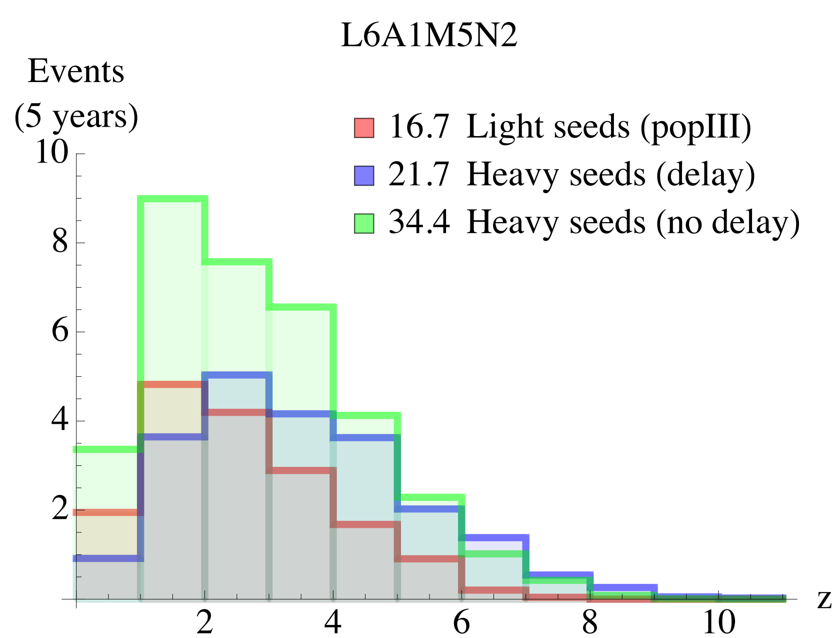
$$Q = \epsilon_1 H \rho_{dm} \quad \text{(IDE1)}$$

$$Q = \epsilon_2 H \rho_{de} \quad \text{(IDE2)}$$

Early and interacting dark energy

[Caprini & Tamanini '16]





Detailed constraints depend on MBHB populations

LISA very **sensitive** to changes in the **expansion history**.
Tested with **distance-redshift relation** at **high redshift** (z < 8)

Non-local model

Modifications of gravity in the IR from quantum effects. While fundamental action is local, quantum effective action can be **non-local**.

Consistent and **phenomenologically** well-behaved theory: [Belgacem et al. '18, '20]

Transverse part

RT model: $$G_{\mu\nu} - \frac{1}{3}\, m^2 \left(g_{\mu\nu}\Box^{-1}R\right)^{\mathrm{T}} = 8\pi G\, T_{\mu\nu}$$ [Maggiore '13]

Non-local mass term for the conformal mode of the metric

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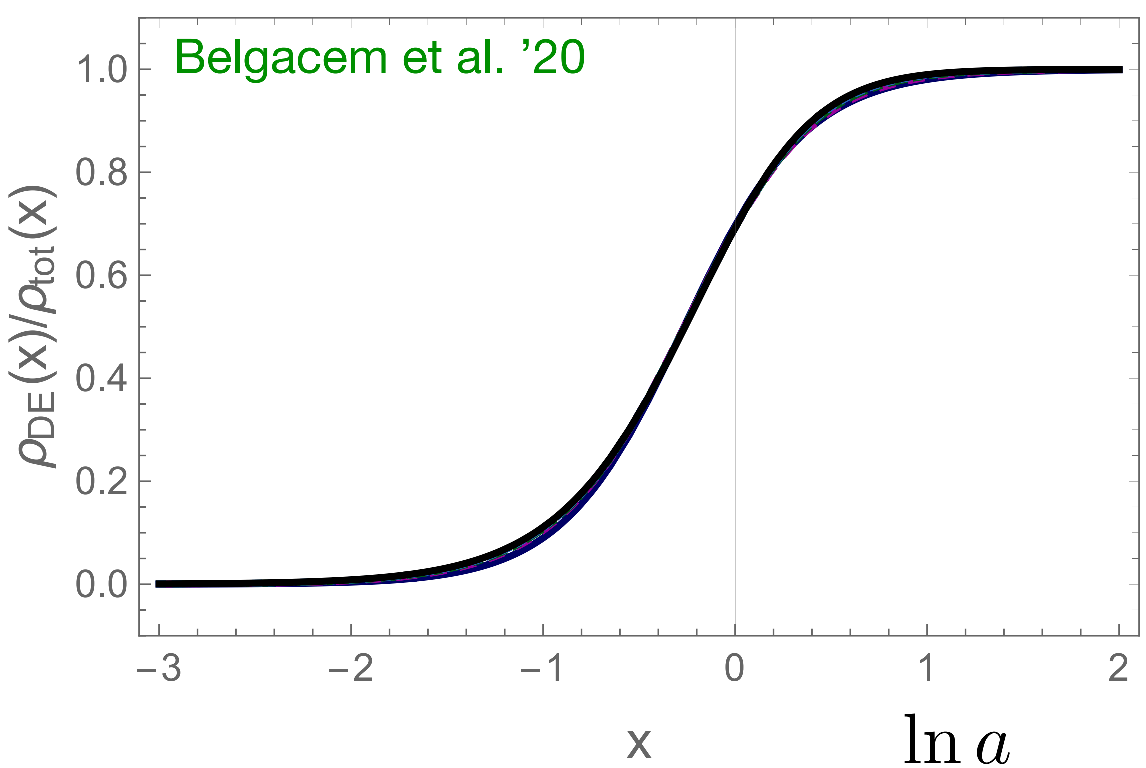
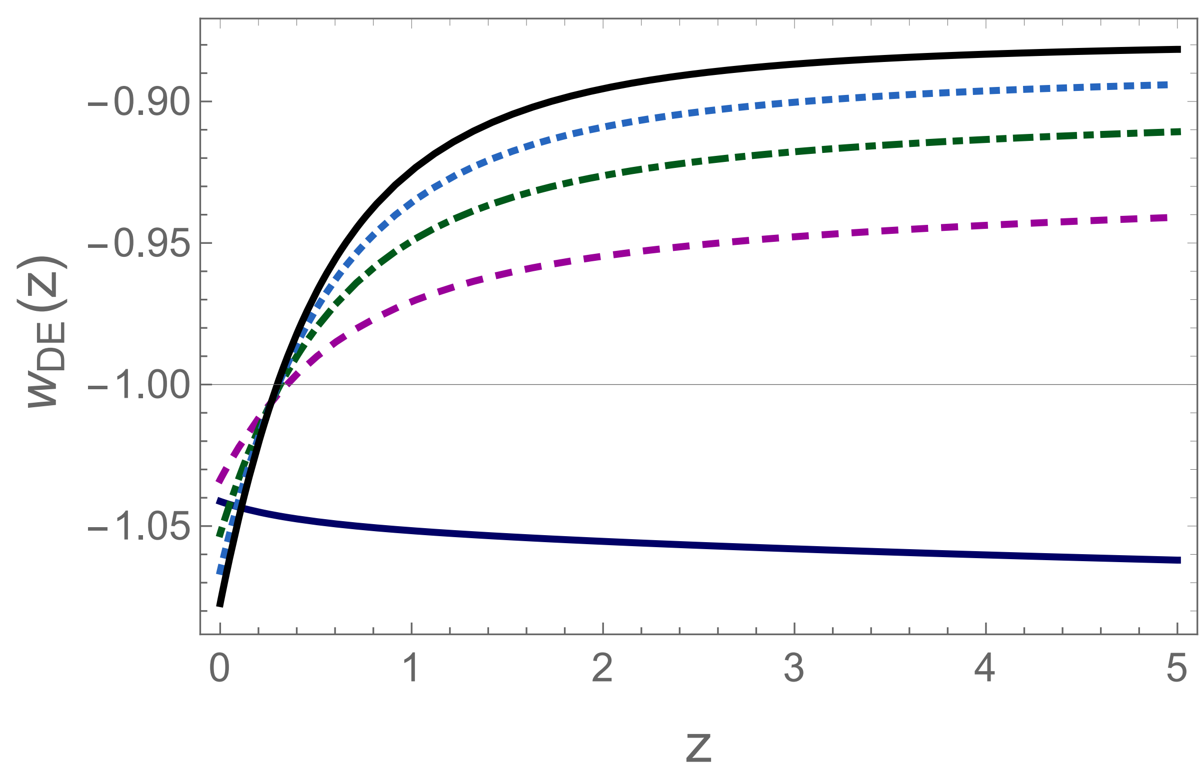
Non-local mass term for the conformal mode of the metric

Single mass scale: as many parameters as LCDM

Non-local term acts as a **dark energy** component





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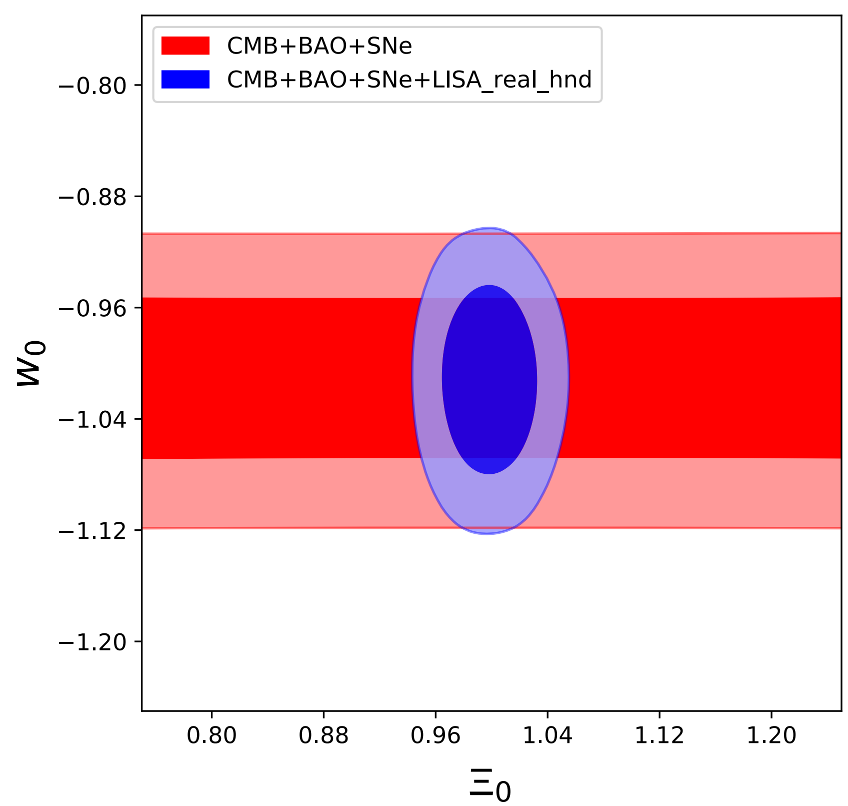
[Maggiore '13]

Non-local mass term for the conformal mode of the metric

Model passes Solar System constraints and fits cosmological probes (CMB, SNa, BAO, LSS) as well as ΛCDM [Kahagias & Maggiore '14, Begacem et al. '18, '19; Dirian et al. '14, 16; …]



LISA can probe **background expansion**

Propagation of GW affected: LISA crucial test (**see José's talk**)

Generalized scalar-tensor theories

Horndeski (second-order) and beyond:

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

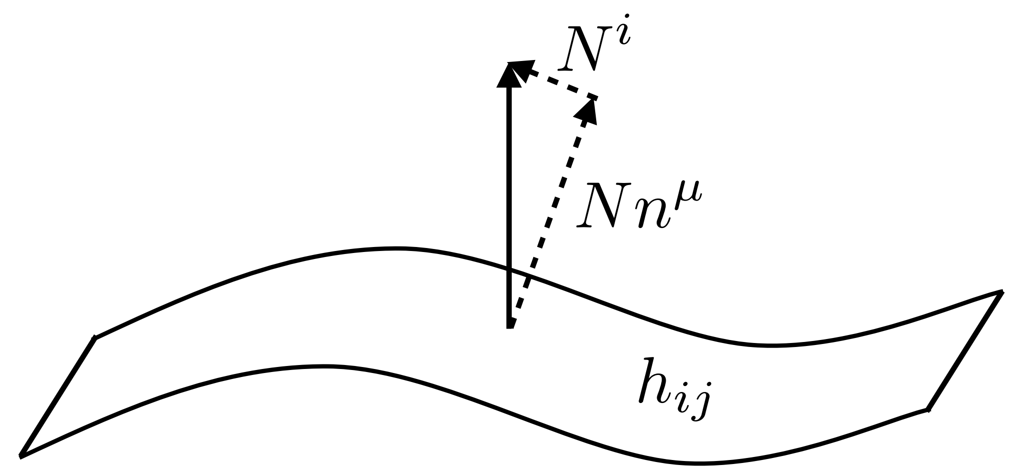
[Horndeski ’73; Deffayet et al ’11;
Gleyzes, et al. ’14, see also Zumalacarregui, Garcia-Bellido ’13]

Higher derivative ⇒ self-acceleration

More general theories, DHOST: [Langlois, Noui ’15, Crisostomi et al. ’16]

EFT of Dark Energy

Special time foliation (time-dependent background field). Action made of 4d covariant terms but also all 3d spatially diff-invariant terms:



$$S = \int d^4x\sqrt{-g}\,\mathcal{L}(R_{\mu\nu\alpha\beta}, g^{00}, K_{\mu\nu}, \nabla_\nu, t)$$

Expanding around a homogeneous FLRW background

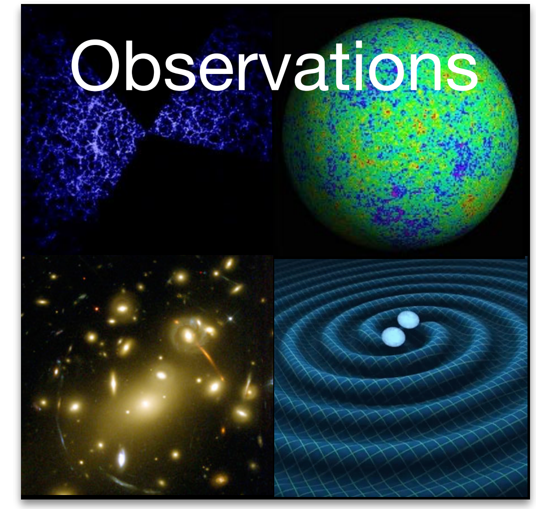
$$S = \int d^4x\sqrt{-g}\left[f(t)R - \Lambda(t) - c(t)g^{00} + \frac{m_2^4(t)}{2}(\delta g^{00})^2 - \frac{m_3^3(t)}{2}\delta K\delta g^{00} + \dots\right]$$

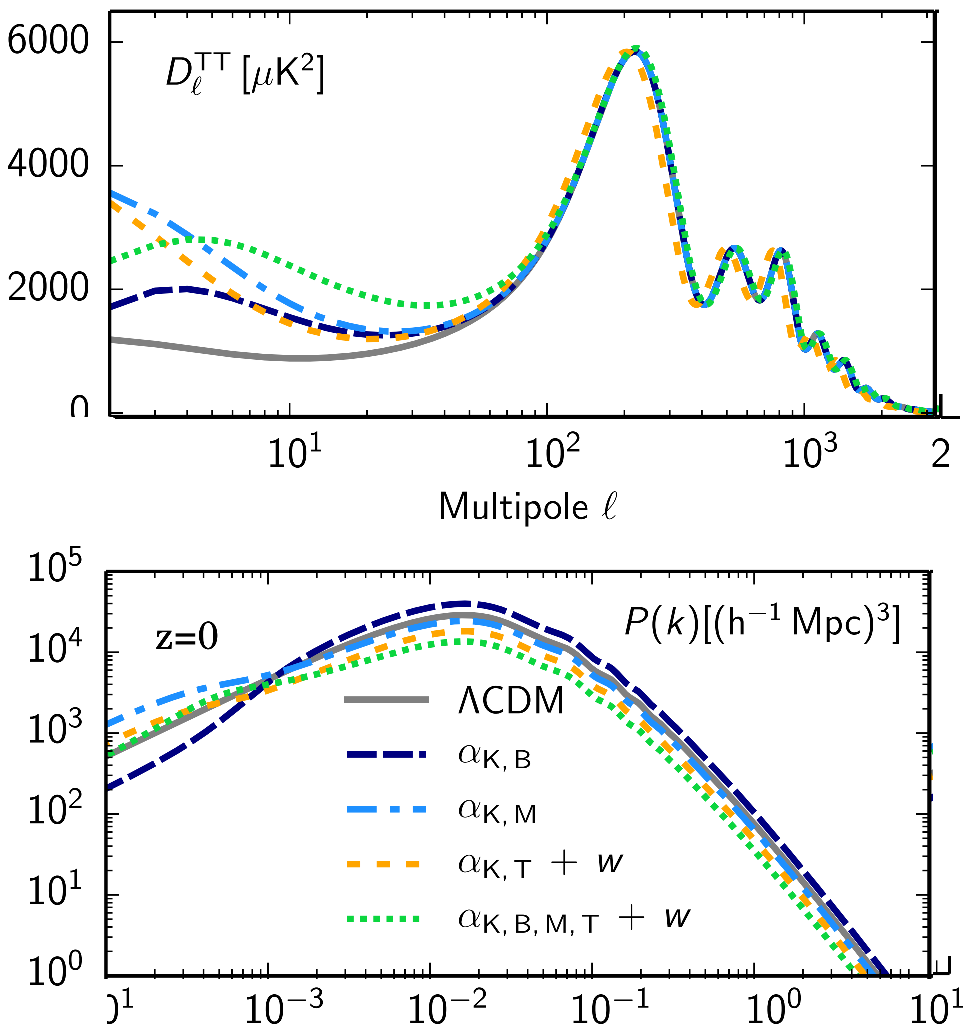
EFT of Dark Energy

Covariant theories

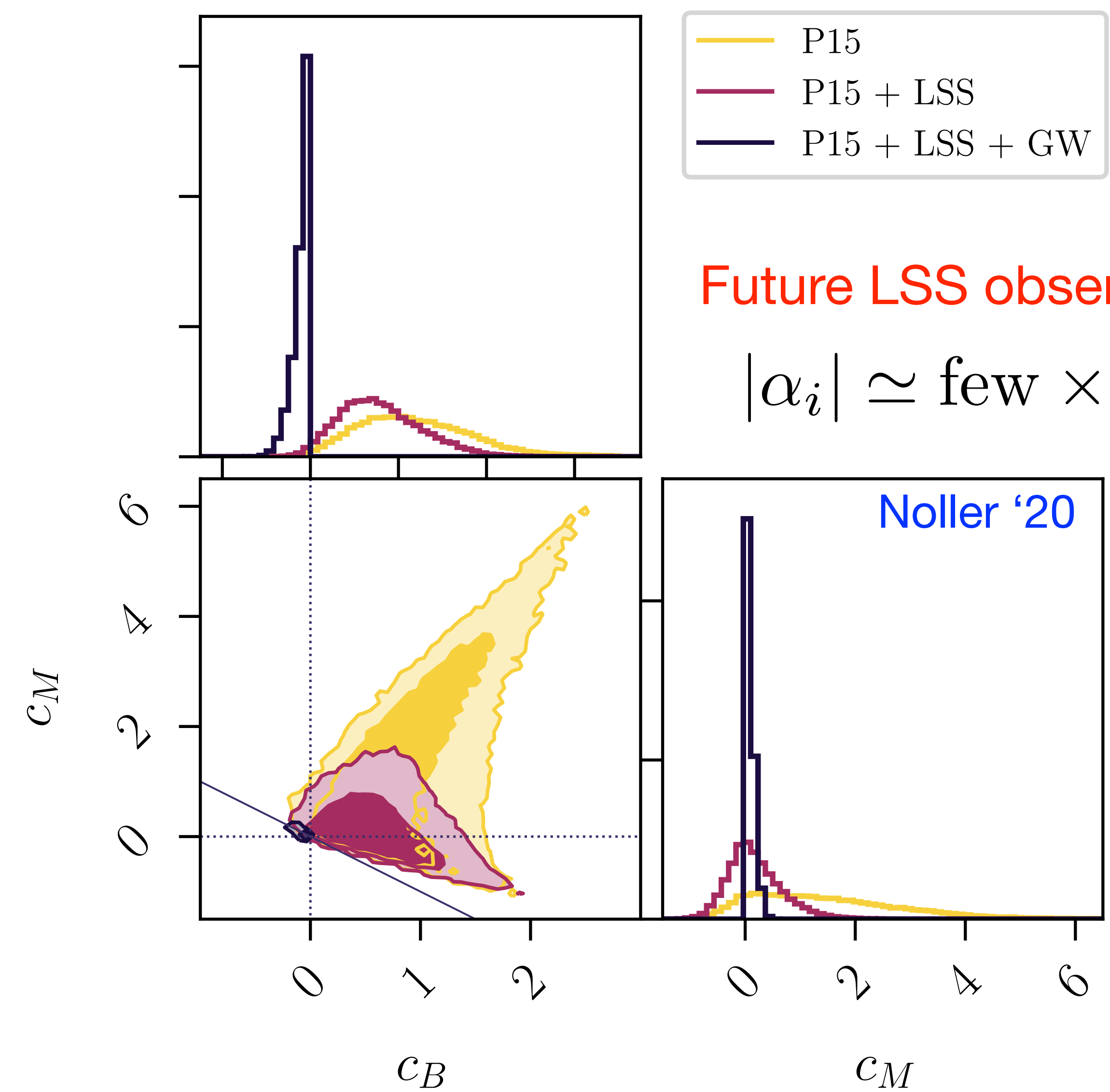
$$G_4(\phi,X)R + G_2(\phi,X) + G_3(\phi,X)\Box\phi - 2G_{4,X}(\phi,X)\left[(\Box\phi)^2 - (\phi_{;\mu\nu})^2\right] + G_5(\phi,X)G^{\mu\nu}\phi_{;\mu\nu} + \frac{1}{3}G_{5,X}(\phi,X) \times \left[(\Box\phi)^3 - 3\Box\phi(\phi_{;\mu\nu})^2 + 2(\phi_{;\mu\nu})^3\right] + \ldots$$

⟵ **EFT of DE** $\alpha_B,\ \alpha_M,\ \alpha_H, \ldots$ ⟶





Bellini et al. '17



Future LSS observations:

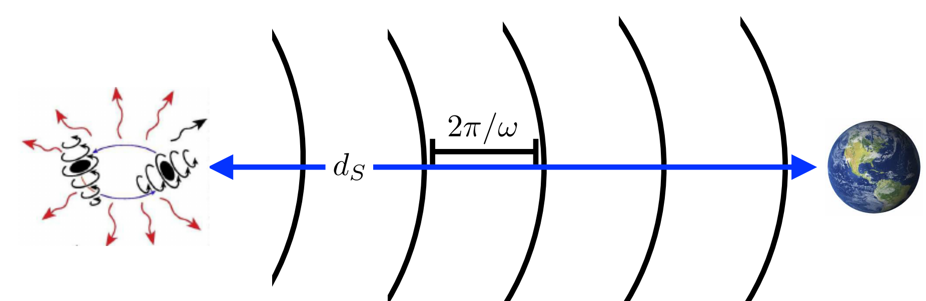
$$|\alpha_i| \simeq \text{few} \times 0.01$$

EFT of Dark Energy

How to use GW physics/astronomy to constraints dark energy?

1) Extrapolation to strong field regime

2) Propagation of GW



Cosmology and strong-field connection

If the same EFT describes both dark energy and strong-field regime, one can constrain dark energy with black hole perturbations

EFT of Black Hole perturbations with time-like scalar profile: [Mukohyama and Yingcharoenrat '22; see also Franciolini et al. '18]

Action expanded around a spatially inhomogeneous solution (e.g. spherically symmetric one):

$$S = \int d^4x \sqrt{-g}\, \mathcal{L}(R_{\mu\nu\alpha\beta}, g^{00}, K_{\mu\nu}, \nabla_\nu, t)$$

Connection with well-known stealth solutions

[Babichev, Charmousis, Kobayashi, Tanahashi, Ben Achour, Lehébel, Liu, Motohashi, Crisostomi, Gregory, Stergioulas, Minamitsouji, etc.]

Constrains on **dark energy** can come from the **strong field regime** (QNMs, EMRIs, tidal Love numbers, etc.) with LISA

EFT of Dark Energy

How to use GW physics/astronomy to constraints dark energy?

1) Extrapolation to strong field regime

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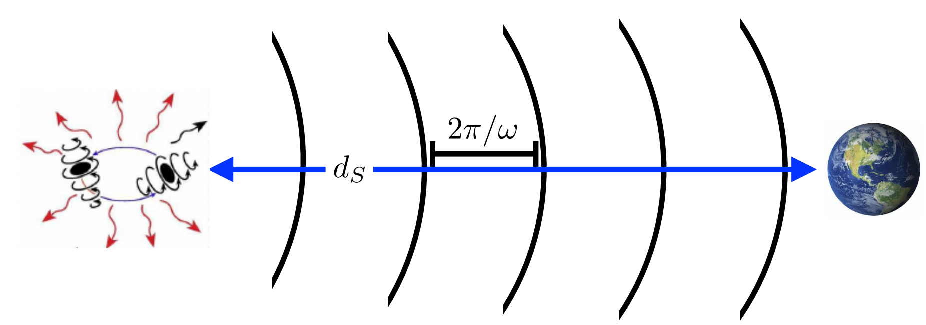

Frequency dependence

LIGO/Virgo constraints on speed of propagation $\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + c_T^2 k^2 \gamma_{ij} = 0$

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

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

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

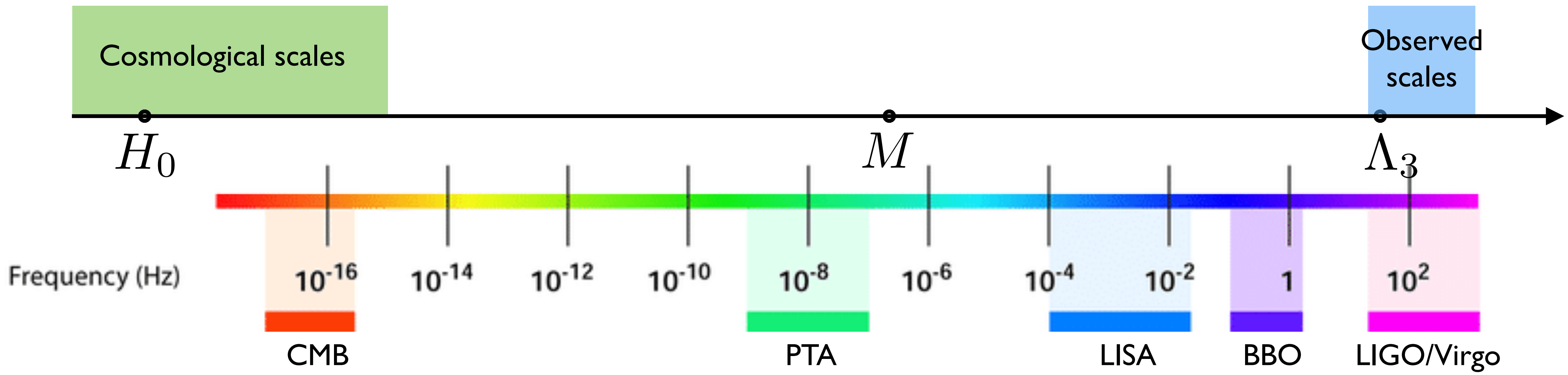
$$G_5 = F_5 = 0 \ , \qquad XF_4 = 2G_{4,X}$$

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

Frequency dependence

LIGO/Virgo constraints on speed of propagation $\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + c_T^2 k^2 \gamma_{ij} = 0$

EFT of cosmological scales may not apply to LIGO-Virgo scales [de Rham, Melville '18]



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

Tensor speed may go back to luminal on short scales

Analogous to light propagation in dielectric: $n(\omega) = 1 + \frac{2\pi N e^2}{m_e} \frac{f}{\omega_0^2 - \omega^2 - i\gamma\omega}$

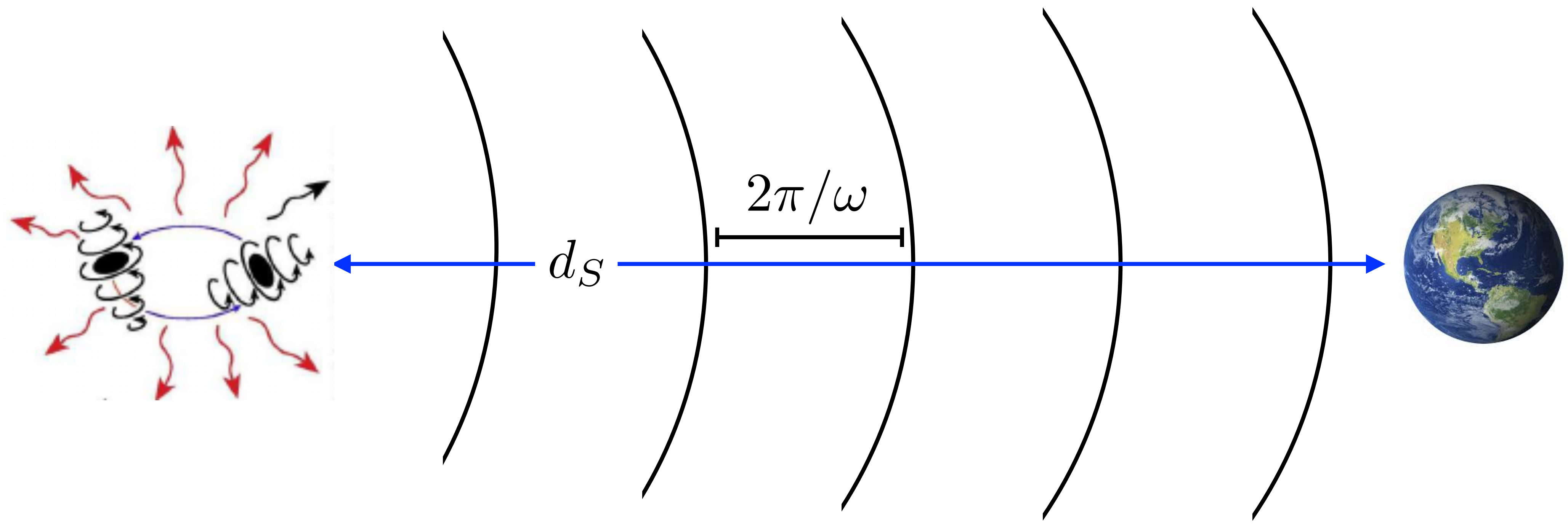
Naive scaling: $\omega^2 = k^2 \left(1 + \mathcal{O}(M^2/k^2)\right)$ $M \lesssim 10^{-8}\Lambda_3 \sim (10^{11}\ \mathrm{km})^{-1}$

There can be **surprises** in the LISA band! [Baker et al. '22]

Propagation of GW

Dark energy and modified gravity spontaneously breaks Lorentz invariance: refraction, absorption, dispersion,…

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



$$\frac{\Gamma(k)}{\omega} \lesssim \frac{1}{d_S\omega}$$

$$\frac{f(k)}{\omega^2} \lesssim \frac{1}{d_S\omega} \sim 10^{-16} \times \frac{2\pi \times 0.1\mathrm{Hz}}{\omega}\,\frac{400\mathrm{Mpc}}{d_S}$$

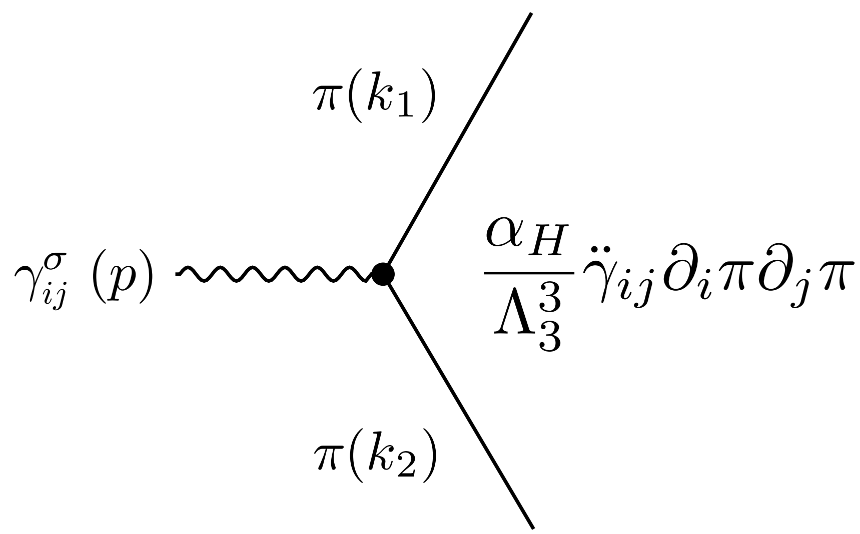
[Yunes, Yagi, Pretorius ’16; Abbott et al. ’17]

Graviton decay into dark energy

Creminelli, Lewandowski, Tambalo, FV ‘18

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

For LIGO/Virgo, interesting decay is perturbative:



$$\pi \equiv \delta\phi/\dot{\phi}_0$$

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

$$\alpha_H \equiv -\frac{X^2 F_4}{G_4}$$

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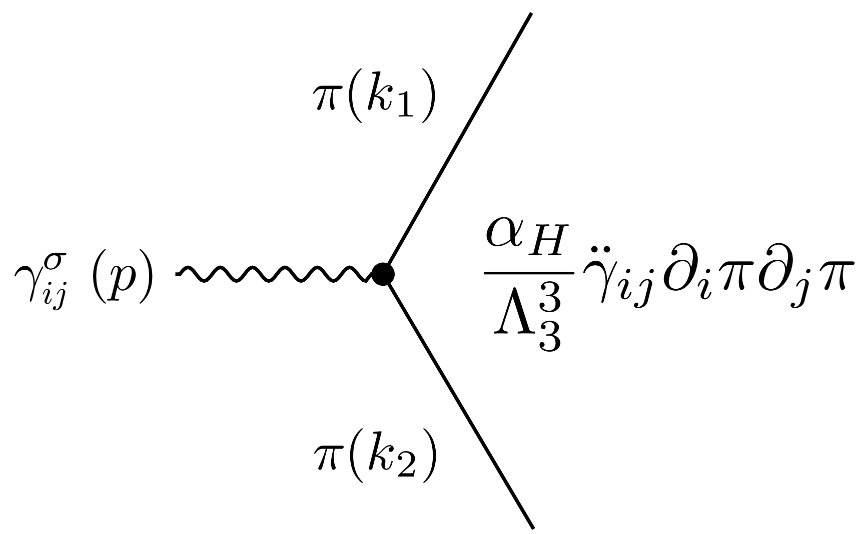

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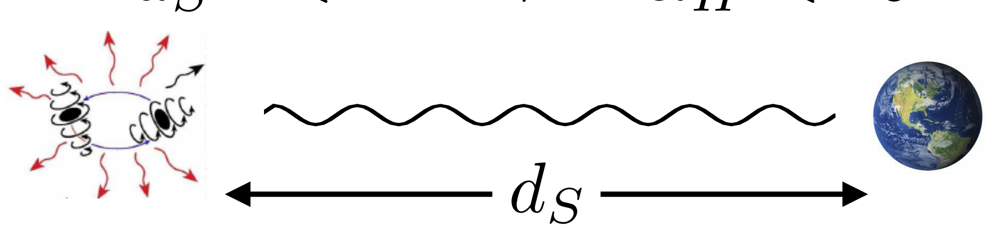
GW decay into scalar fluctuations π. Analogous to light absorption into a material.

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)

Resonant decay

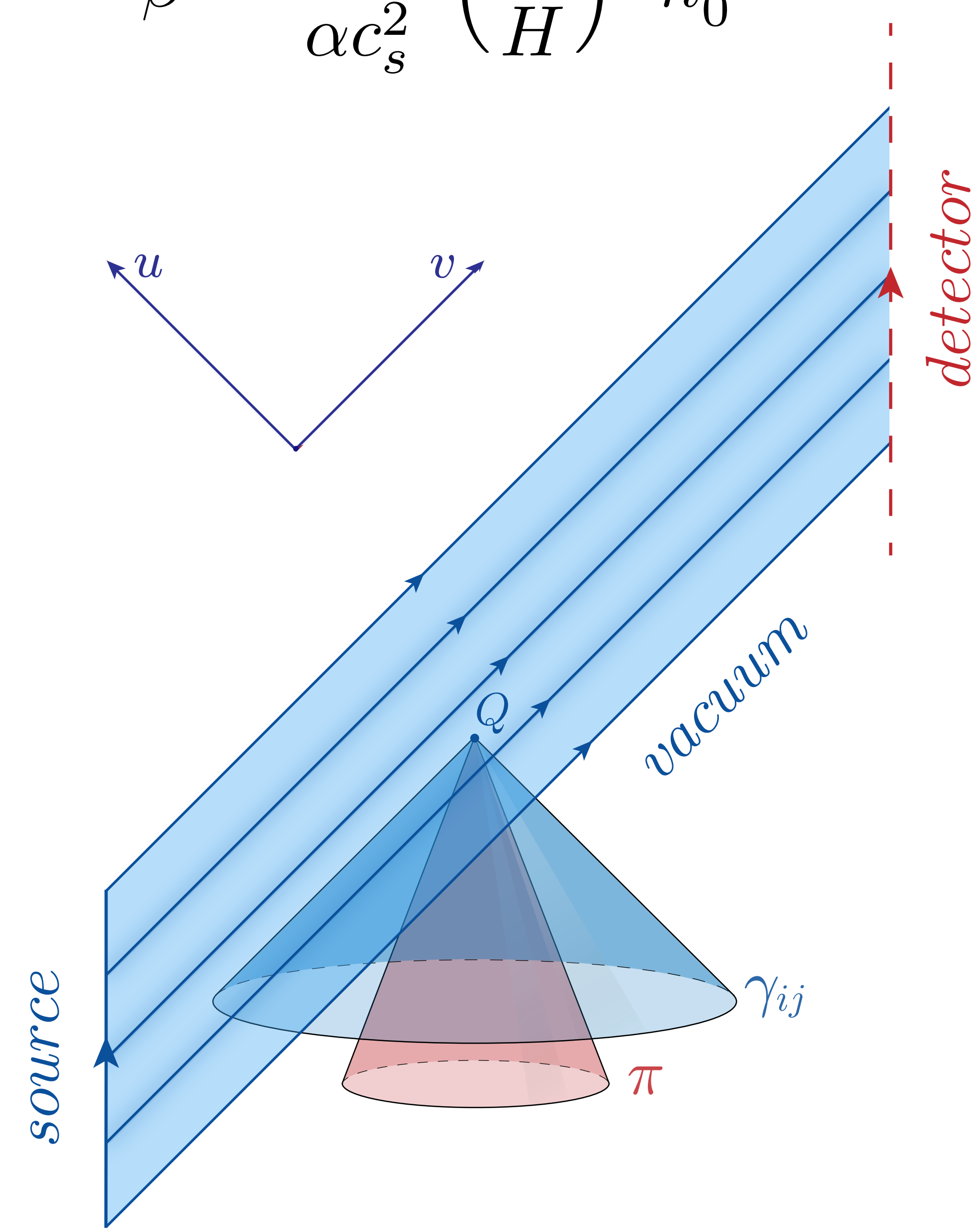
Creminelli, Tambalo, FV, Yingcharoenrat, ‘19

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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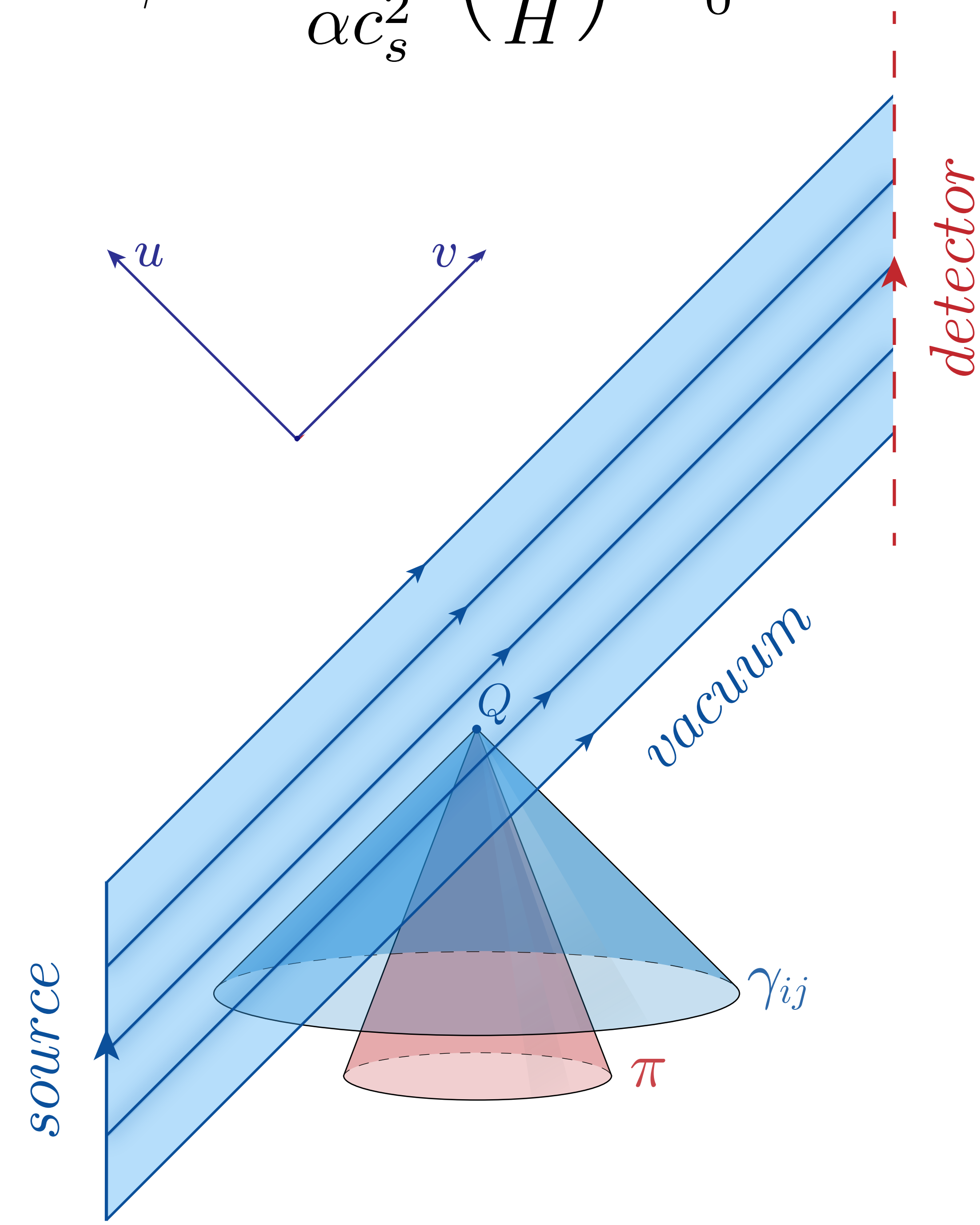

Fourier modes satisfy Mathieu equation

⇒ 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

Narrow resonance: $\beta \ll 1 \;\Rightarrow\; \rho_\pi \propto e^{\beta\omega u/4}$

$$\Delta\gamma_{ij} \propto v\gamma_0 e^{\beta\omega u/4}\epsilon_{ij}^+$$

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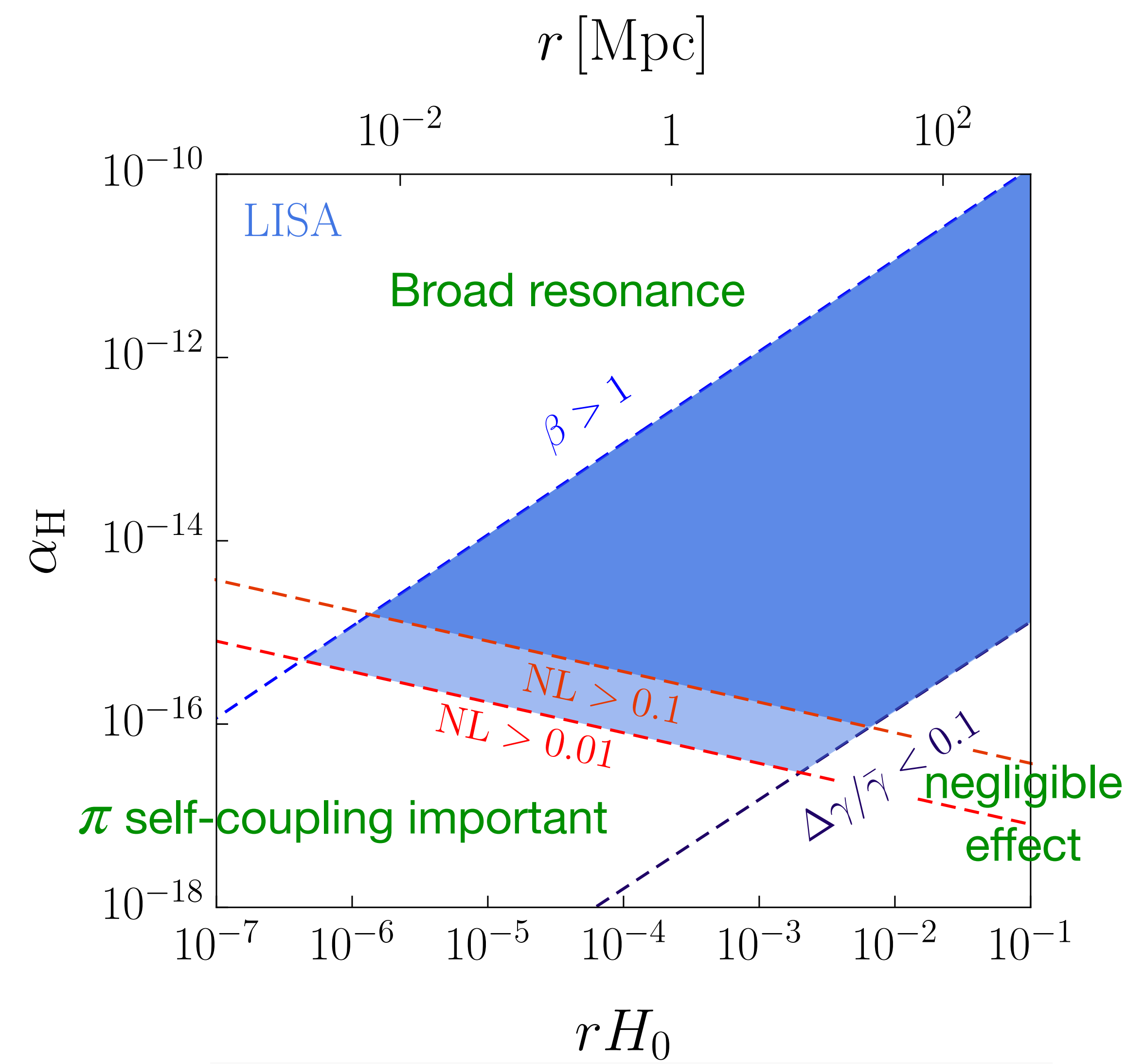
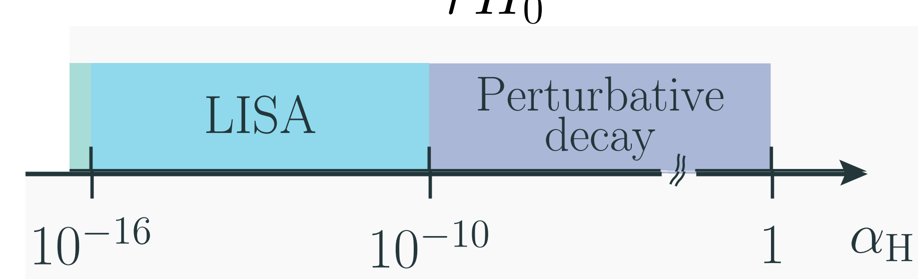
More detailed predictions need numerical work





Screening the fifth force

Self-acceleration ⇒ non-minimally coupled (almost) massless field ⇒ fifth force and anomalous light bending on all scales.

$$\mathcal{L} = -\frac{1}{2} Z^{\mu\nu}\left(\phi, \partial\phi, \partial^2\phi, \ldots\right) \partial_\mu\phi\partial_\nu\phi - V(\phi) + \frac{\alpha(\phi)}{M_{\rm Pl}} T$$

Fifth force $$\delta\phi = -\frac{2\alpha M_{\rm Pl}}{Z} \, \frac{GM}{r} \, e^{-\frac{m_\phi}{\sqrt{Z}}}$$

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Fifth force $$\delta\phi = -\frac{2\alpha M_{\rm Pl}}{Z} \frac{GM}{r} e^{-\frac{m_\phi}{\sqrt{Z}}}$$

How to modify gravity on large scales and simultaneously pass Solar System tests?

Symmetron: vanishing coupling in high-density region $\alpha = 0$ [Hinterbichler & Khoury '10]

Chameleon: large scalar mass in high density region $m_\phi \to \infty$ [Khoury & Weltman '04]

Vainshtein: enhanced kinetic term in high density region $\partial^2\phi/\Lambda_V^3 \gg 1$ [Vainshtein '72]

Kinetic screening: enhanced kinetic term in HD region $(\partial\phi)^2/\Lambda_*^4 \gg 1$ [Babichev & Deffayet '09]

Vainshtein screening

Cubic Galileon model:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - (\partial\phi)^2\left(1+\frac{\Box\phi}{\Lambda_V^3}\right) + \frac{1}{2}h_{\mu\nu}T^{\mu\nu} + \frac{\alpha}{2M_{\rm Pl}}\phi T\right]$$

Second-order EOM. Quadratic equation.

Assume spherical symmetry and quasi-static. Solution with point-particle source of mass *M*:

$$\delta\phi'(r) = -\frac{r\alpha}{2\pi r_V^3}\frac{M}{M_{\rm Pl}}\left(1\pm\sqrt{1+\left(\frac{r_V}{r}\right)^3}\right) \qquad r_V = \frac{1}{\Lambda_V}\left(\frac{\alpha M}{M_{\rm Pl}}\right)^{1/3}$$

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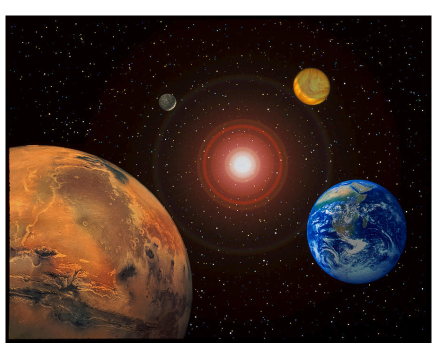
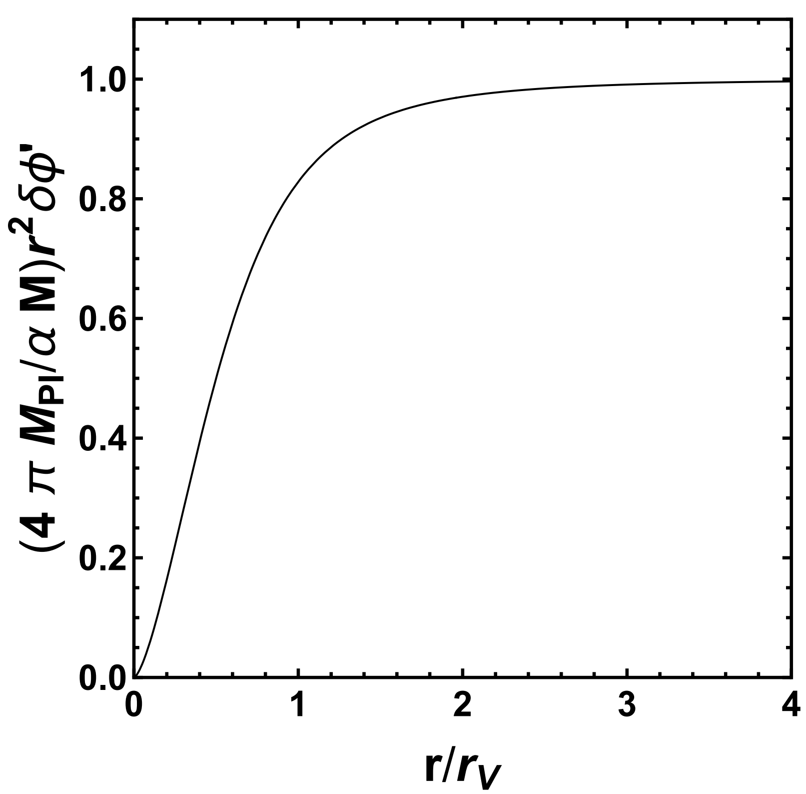
$r \ll r_V$



Fifth force suppressed

$$\delta\phi' \simeq \left(\frac{r}{r_V}\right)^{3/2}\frac{\alpha}{r^2}\frac{M}{M_{\rm Pl}}$$



$r \gg r_V$

Standard $1/r^2$ behaviour: fifth force!

$$\delta\phi' \simeq \frac{\alpha}{r^2}\frac{M}{M_{\rm Pl}}$$

Vainshtein screening

Cubic Galileon model:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - (\partial\phi)^2\left(1+\frac{\Box\phi}{\Lambda_V^3}\right) + \frac{1}{2}h_{\mu\nu}T^{\mu\nu} + \frac{\alpha}{2M_{\rm Pl}}\phi T\right]$$

Second-order EOM. Quadratic equation.
Assume spherical symmetry and quasi-static. Solution with point-particle source of mass *M*:

$$\delta\phi'(r) = -\frac{r\alpha}{2\pi r_V^3}\frac{M}{M_{\rm Pl}}\left(1\pm\sqrt{1+\left(\frac{r_V}{r}\right)^3}\right) \qquad r_V = \frac{1}{\Lambda_V}\left(\frac{\alpha M}{M_{\rm Pl}}\right)^{1/3}$$

How big is the Vainshtein radius?

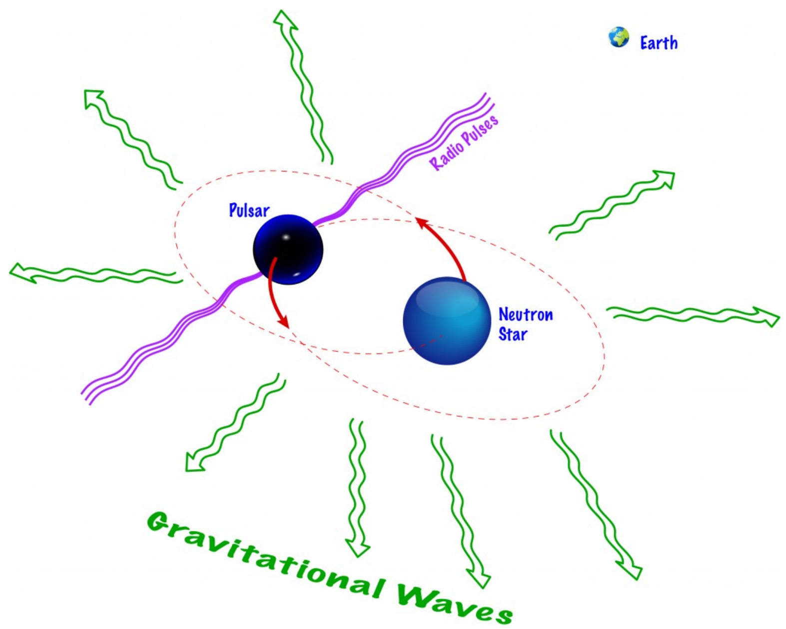
$$\Lambda_V \sim (H_0^2 M_{\rm Pl})^{1/3} \sim 10^{-13}\mathrm{eV} \sim (1000\,\mathrm{km})^{-1}$$

$$r_V \sim 100\left(\frac{M}{M_\odot}\right)^{1/3}\mathrm{pc}$$

- $r_V^{\rm Earth} \sim 0.1\,\mathrm{pc}$
- $r_V^{\odot} \sim 100\,\mathrm{pc}$
- $r_V^{\rm Milky\ Way} \sim 1\ \mathrm{Mpc}$

Vainshtein screening in binaries

Most studies assume static approx and spherical symmetry. Screening is less well understood in time-dependent systems. Binary pulsars predictions?



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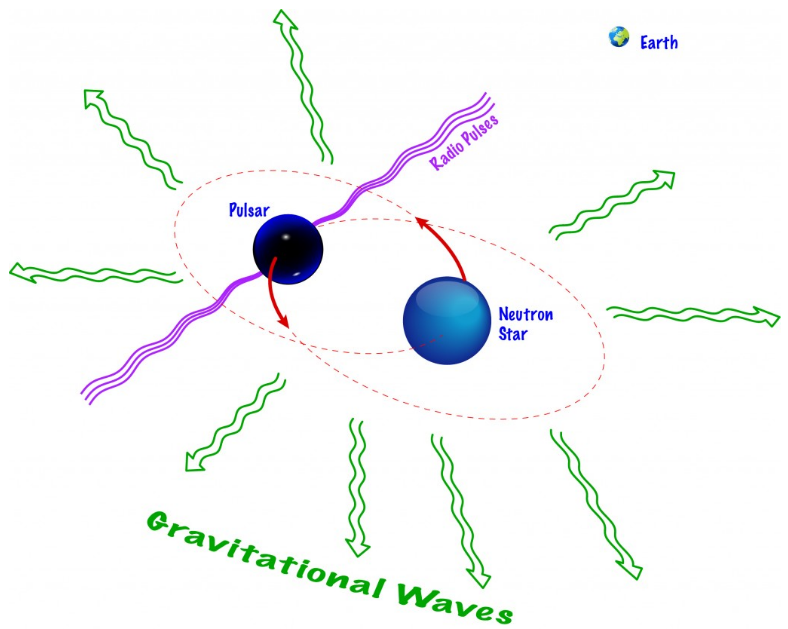

Analytic calculation: enhancement of monopole and quadrupole scalar radiation (dipole negligible) [de Rham, Tolley, Wesley '12; Chu & Trodden '13]

$$\frac{P^{(\phi)}_{\rm monopole}}{P^{(\rm GR)}_{\rm quadrupole}} \sim \left(\frac{r}{r_V}\right)^{3/2} v^{-3/2} \qquad \frac{P^{(\phi)}_{\rm quadrupole}}{P^{(\rm GR)}_{\rm quadrupole}} \sim \left(\frac{r}{r_V}\right)^{3/2} v^{-5/2}$$

Confirmed by full numerical two-body simulation [Dar et al. '19]

Small effects for binary pulsars. **What about LISA**?

Instability due to GWs

Cubic Galileon model: $$\mathcal{L} = -\sqrt{-g}(\partial\phi)^2\left(1 + \frac{\Box\phi}{\Lambda_V^3}\right)$$

The regime $\beta > 1$ is problematic: $$\pi \equiv \delta\phi/\dot{\phi}_0$$

$$\ddot{\pi} + c_s^2\left[k^2 + \beta\cos(\omega u)\epsilon_{ij}^{+}k^i k^j\right]\pi = 0 \qquad \beta = \frac{|\alpha_B|}{\alpha c_s^2}\frac{\omega}{H}h_0^{+} \qquad \alpha_B = \frac{1}{\Lambda_V^3}\frac{\dot{\phi}_0^3}{H_0 M_{\rm Pl}^2}$$

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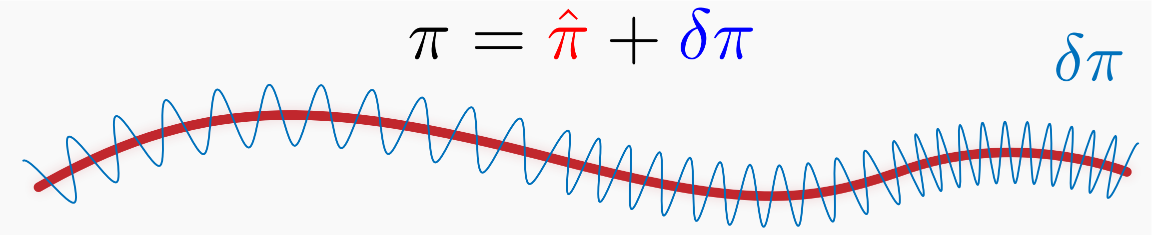
Small perturbations around a background generated by the GW:

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



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

To be contrasted with nonlinear stability of cubic Galileon — Nicolis, Rattazzi '04

Instability due to GWs

instability parameter

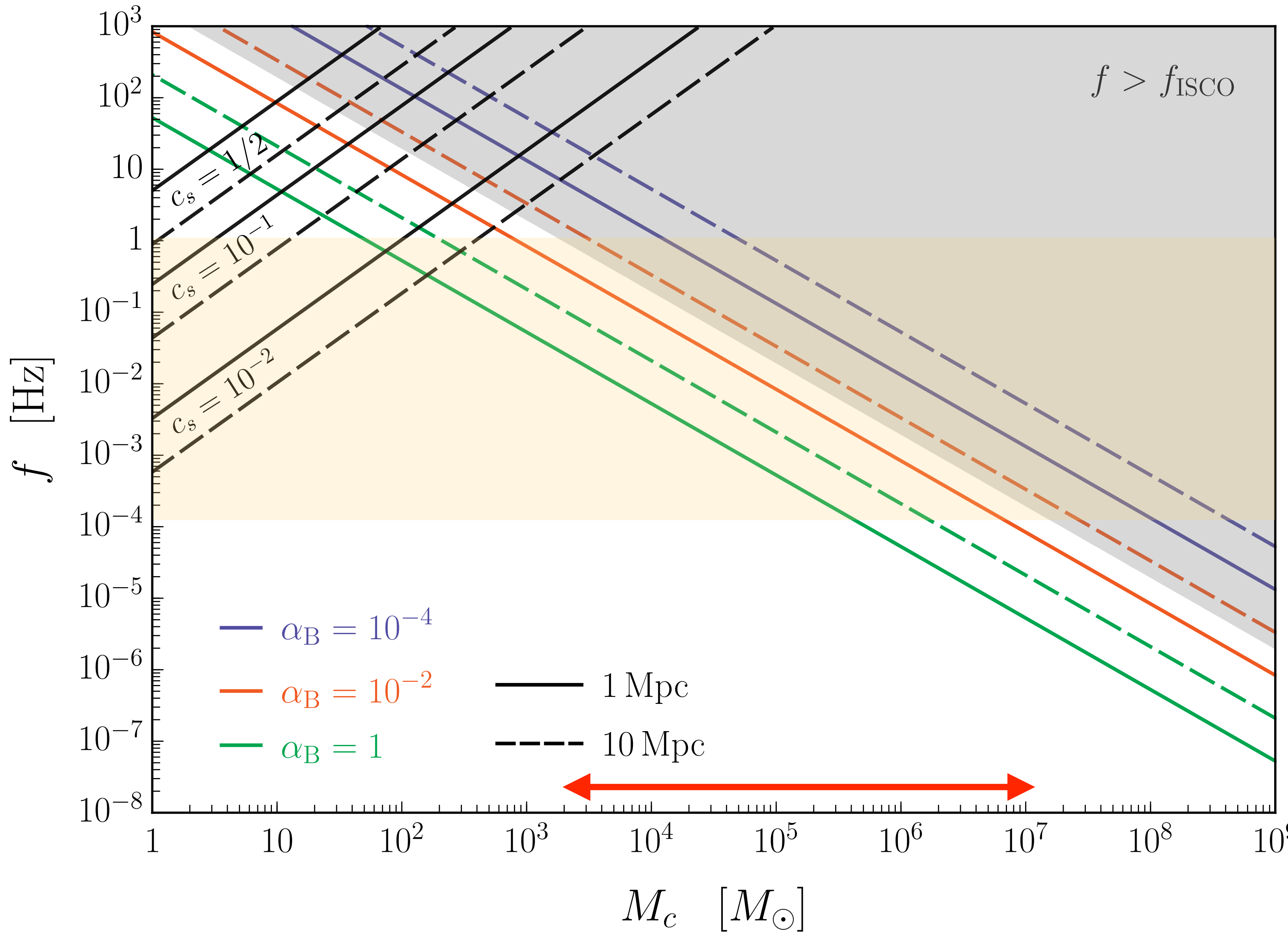
$$\beta = \frac{|\alpha_B|}{\alpha c_s^2} \frac{\omega}{H} h_0^+$$

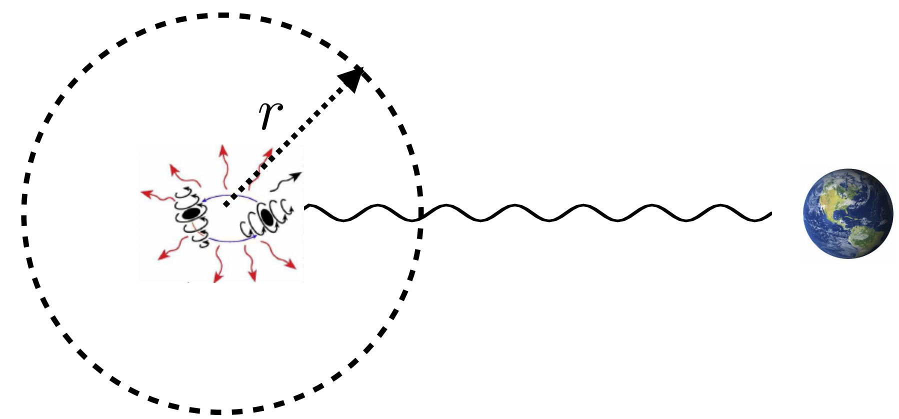
GW amplitude

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

condition on frequency

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





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

Events where instability is in the LISA band

Instability easily triggered by LISA events.

Are these instabilities present also in other theories?

Kinetic screening

K-essence model:

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R - (\partial\phi)^2\left(1 + \frac{(\partial\phi)^2}{\Lambda_*^4}\right) + \frac{1}{2}h_{\mu\nu}T^{\mu\nu} + \frac{\alpha}{2M_{\rm Pl}}\phi T\right]$$

Similar to Vainshtein screening

$$\delta\phi' \simeq \left(\frac{r}{r_*}\right)^{4/3}\frac{\alpha}{r^2}\frac{M}{M_{\rm Pl}} \qquad r \ll r_*$$

$$\delta\phi' \simeq \frac{\alpha}{r^2}\frac{M}{M_{\rm Pl}} \qquad r \gg r_*$$

$$r_* = \frac{1}{\Lambda_*}\left(\frac{\alpha M}{M_{\rm Pl}}\right)^{1/2}$$

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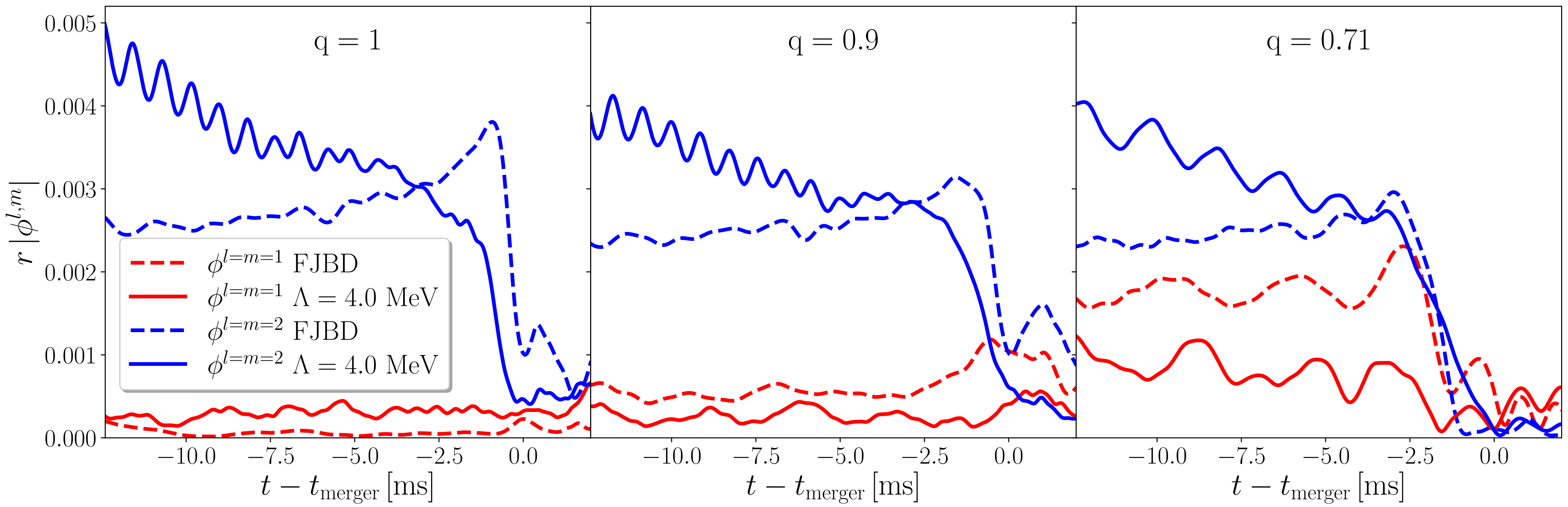
Relativistic simulation of NSs. Suppressed dipole but important quadrupolar emission



[Bezares et al. '21; ter Haar et al. '22]

mass ratio $q = M_2/M_1$

3Gs

In screened environments, the 3 “Newton constants” are typically independent

[Dalang and Lombriser, 2019; Lombriser and Taylor, 2016; Tsujikawa, 2019; Wolf and Lagos, 2020]

1) Graviton kinetic term normalization $G_{\rm gw}$ $$S = \frac{1}{16\pi G_{\rm gw}} \int d^4x \left(-\frac{1}{4} h^{\mu\nu} (\mathcal{E} h_{\mu\nu}) \right)$$

Constrained by GW propagation

2) Dynamical G (the one in the Poisson equation) $G_{\rm dyn}$

Constrained by Cavendish exp., Lunar Laser Ranging

3) Light G (intervening in light bending/time delay) $G_{\rm light}$

Constrained by time delay/light bending

Gravitational waves (emission and propagation) carry unique information about $G_{\rm gw}$ that cannot be extracted with other tests

How can we combine LISA and cosmological constraints?

Conclusions and burning questions

- **LISA sensitive to expansion history** at low and high redshift ($z < 10$). Help in solving H_0 tension and detecting extra components (early and interacting dark energy). **What else can we learn?**

- Can we **connect strong-field** regime (compact objects) constraints to **weak-field** (cosmology) ones? What **new constraints** can we put on dark energy/modified gravity with LISA?

- LIGO/Virgo have radically **constrained cosmological modification of gravity** via effects on propagation. But EFT at LIGO and LISA frequencies can be different. **What do we expect to learn with LISA?**

- **Scalar-field and GWs interplay** displaly new interesting effects (**decay, instability**) relevant for LISA. More detailed calculations needed.

- **Screening** ubiquitous in theories of modified gravity. Should affect all LISA observables. To what level? Improvement in our **theoretical understanding** needed.

- GWs propagate through **overdense** (possibly screened) regions. What is the **effect of screening** on the **GW propagation?**