Dark energy after GW170817

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with P. Creminelli 1710.05877, + M. Lewandowski and G.Tambalo, 1809.03484
+ V. Yingcharoenrat, in progress

26 Marzo 2019
Dipartimento di Fisica, Università di Genova

The Universe accelerates

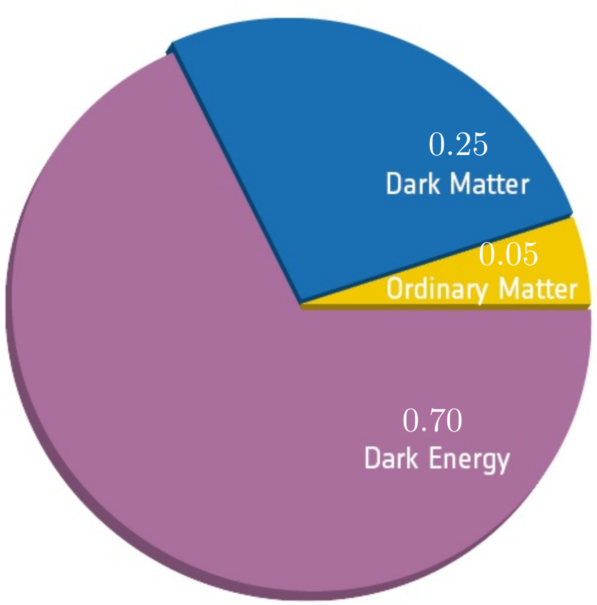
FRW metric: $ds^2 = -dt^2 + a^2(t)d\vec{x}^2$

Einstein's equation: $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}^{(\mathrm{matter})}$

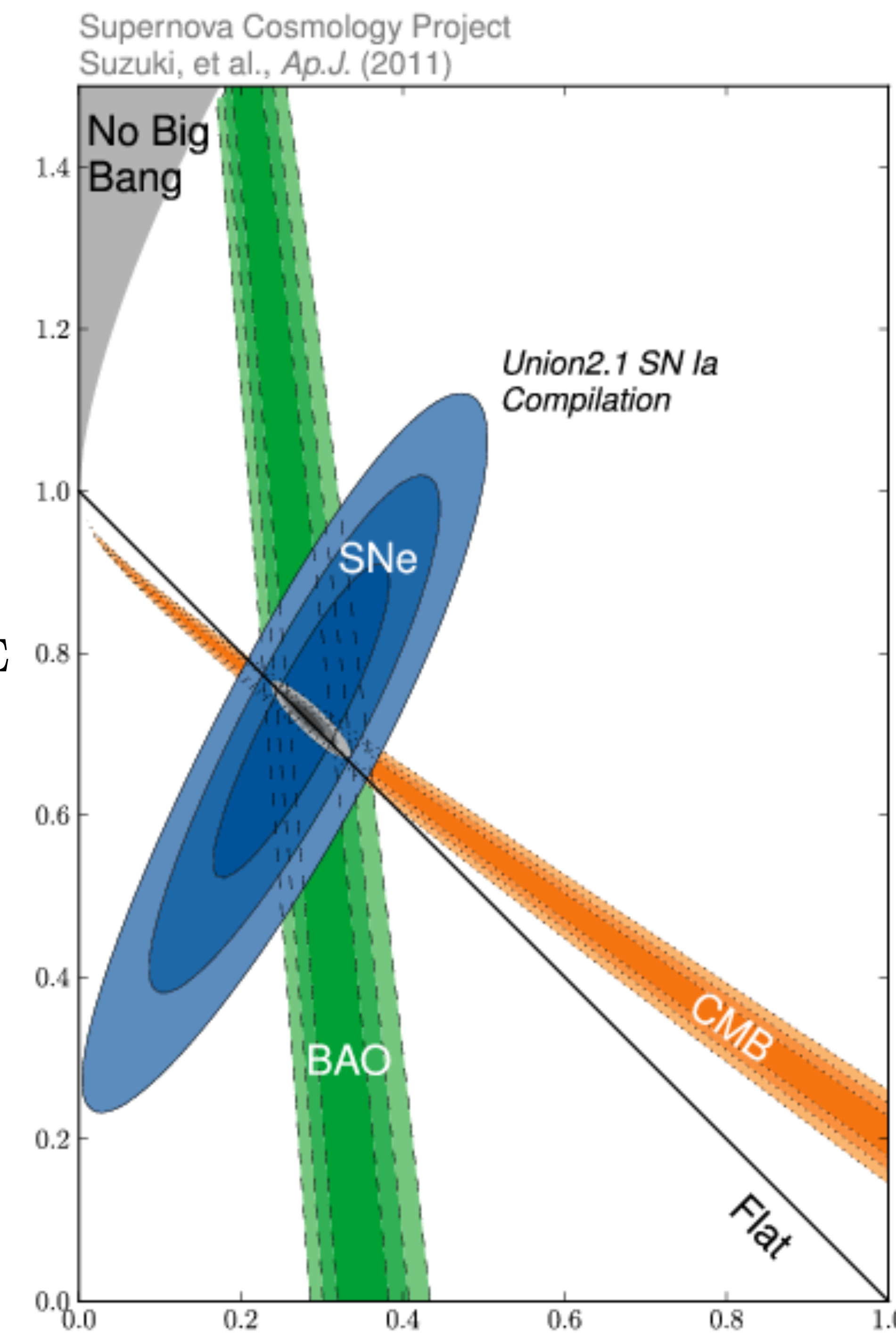
Accelerated expansion:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) > 0$$

Dark energy: new form of matter with negative pressure



Ω_{DE}



Ω_{SM}

Cosmological Constant: ΛCDM

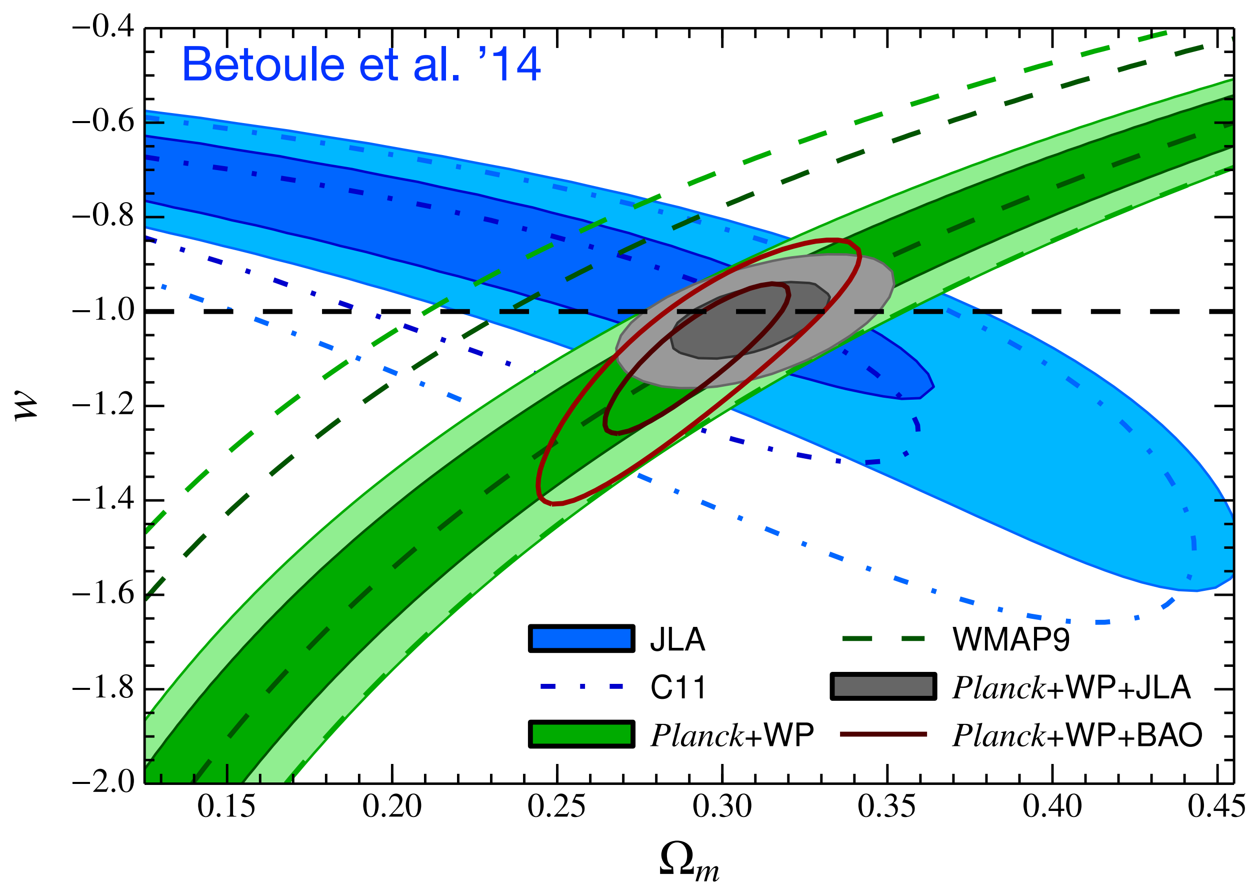
Equation of state very close to -1

$$w \equiv p/\rho$$

$$\rho \propto a^{-3(1+w)}$$

Cosmological constant: vacuum energy, simplest explanation, consistent with all data

$$T^{(\mathrm{C.C.})}_{\mu\nu} = -\Lambda g_{\mu\nu}$$



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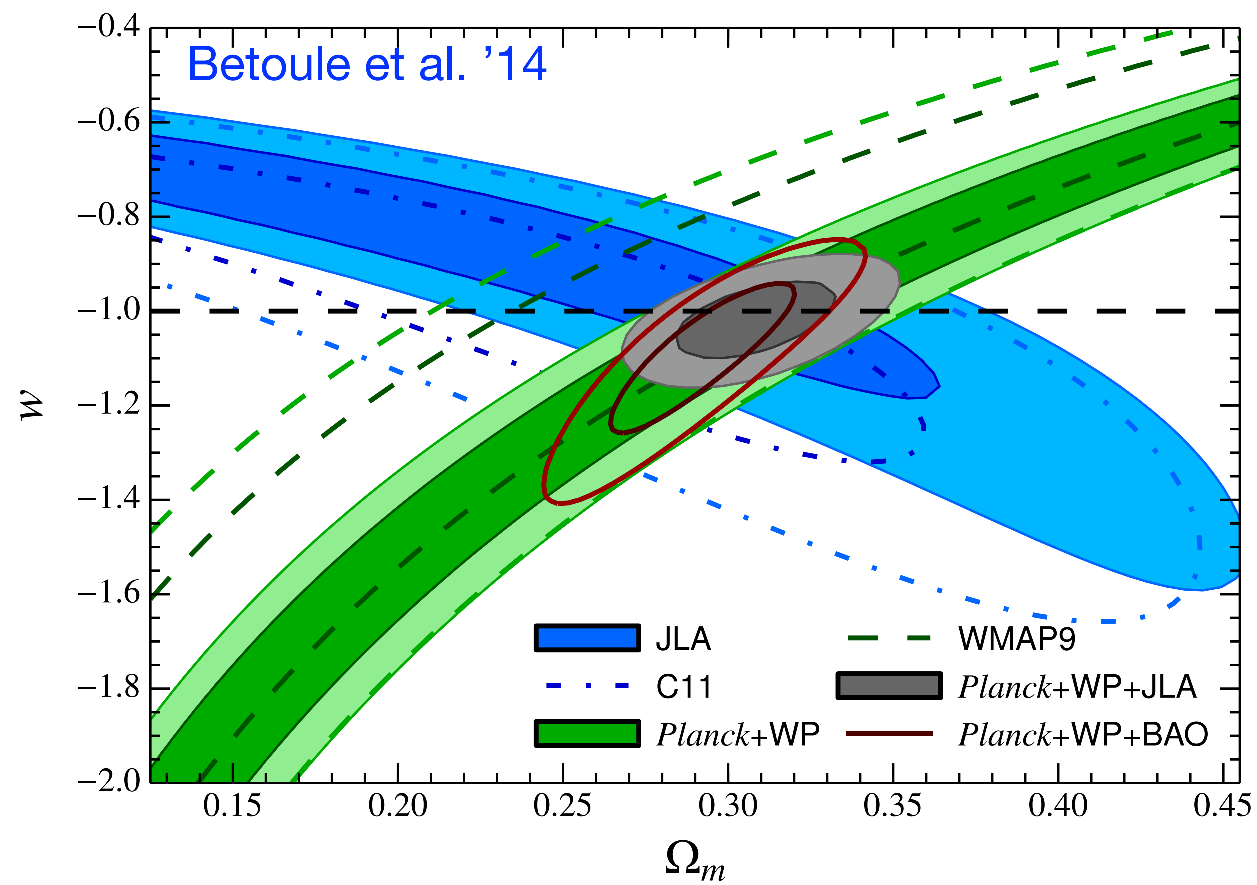

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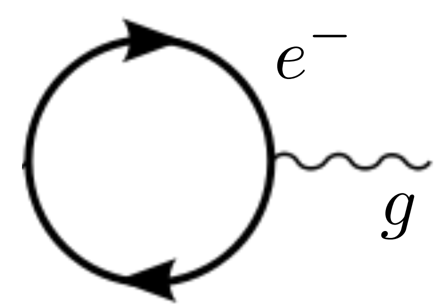
$$T^{(\mathrm{C.C.})}_{\mu\nu} = -\Lambda g_{\mu\nu}$$

But $\Lambda = \rho_{\mathrm{de}} \simeq (10^{-3}\mathrm{eV})^4$ unnaturally small

Very UV sensitive. Cancelation with vacuum energy of each particle at any loop-order in perturbation theory

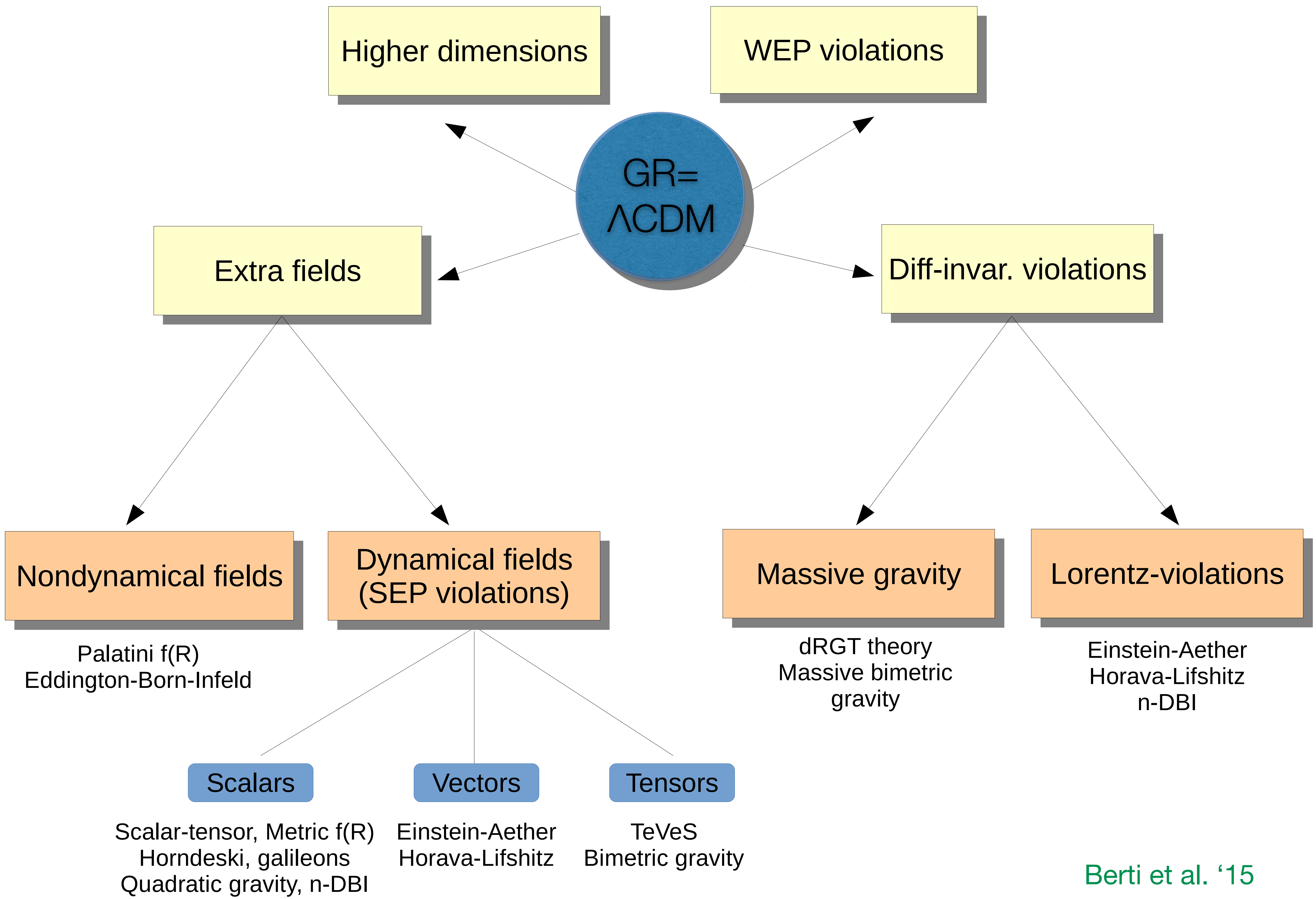
e.g. Burgess 13; Padilla 15

$$\Lambda_{\mathrm{obs}} = \Lambda_{\mathrm{bare}} + \sum_i c_i m_i^4$$



Cosmological constant problem

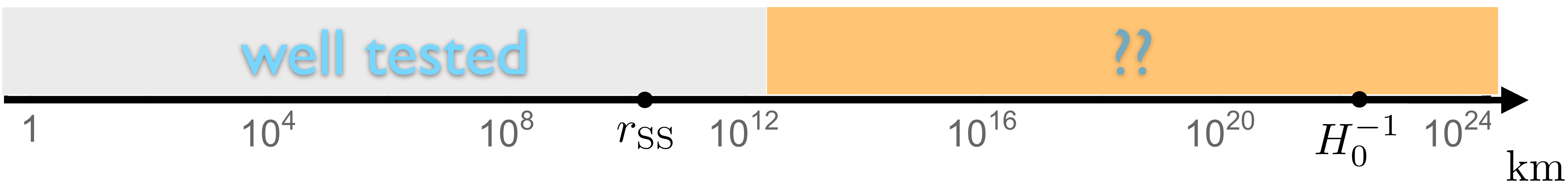
Dark energy and modified gravity

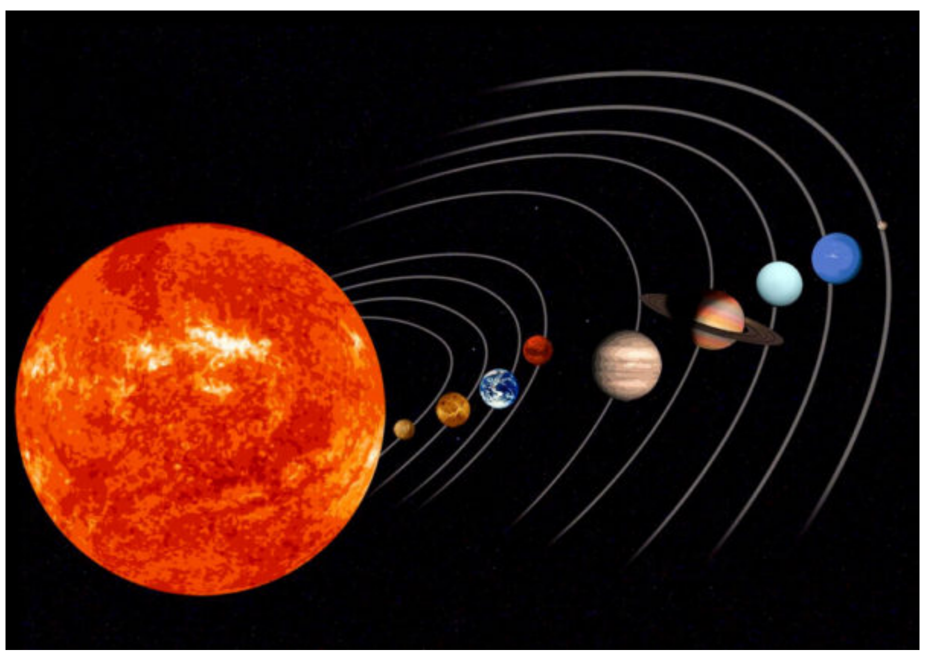


Berti et al. ‘15

Motivations

General relativity extrapolated over large ranges of scales and masses. Cosmology is a window for testing it on very large distances. Distinguish among models and discover new physics. Cosmological precision tests of ΛCDM (precision tests of the Standard Model at the LHC)





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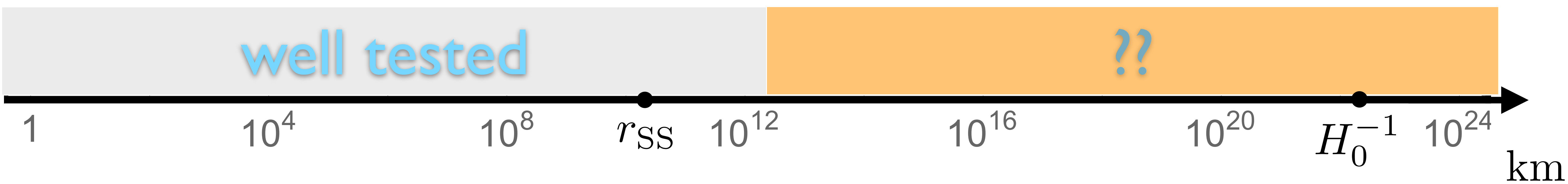
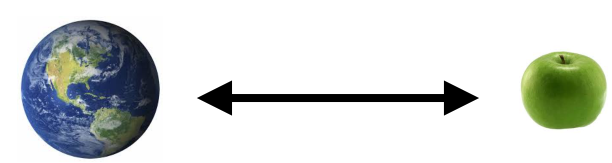


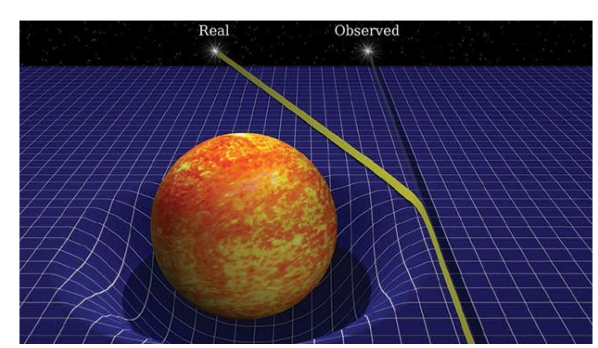
$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Psi)d\vec{x}^2$$

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

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



fifth force



anomalous light bending

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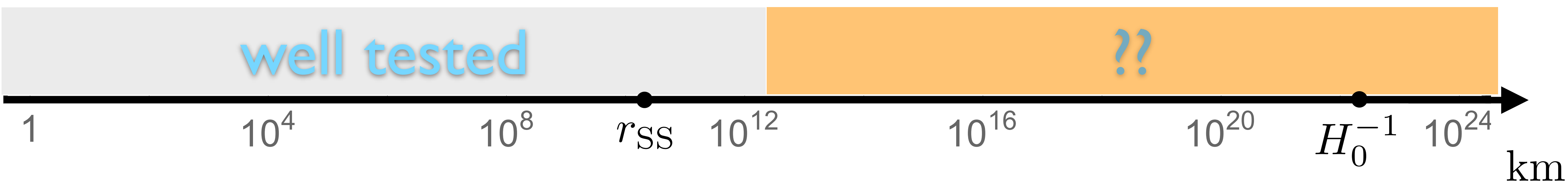

Will '14 $|\mu - 1| < 10^{-3} \div 10^{-6}$

$|\Sigma - 1| < 10^{-5}$

Solar System scales

DES '18 $|\mu - 1| < 8 \times 10^{-2}$

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

Cosmological scales

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

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

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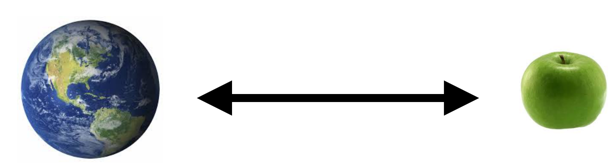

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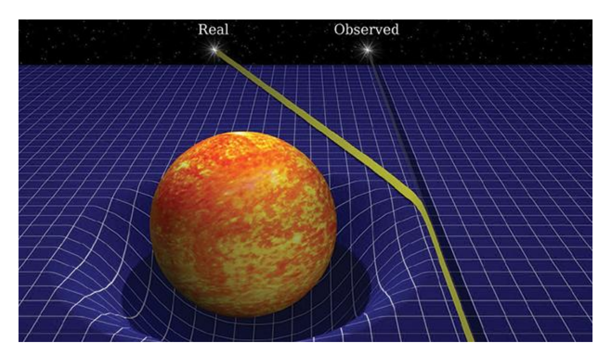

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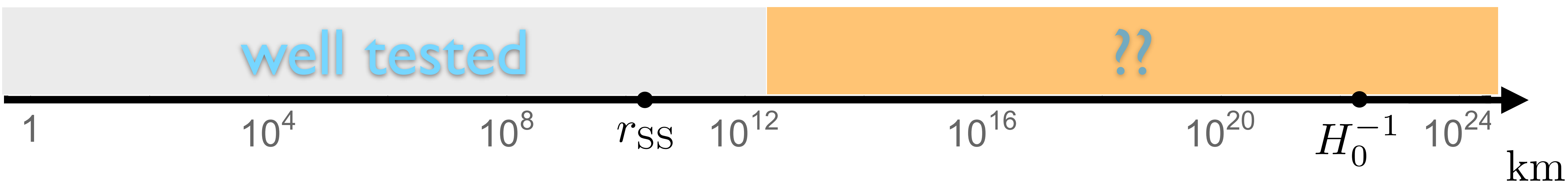
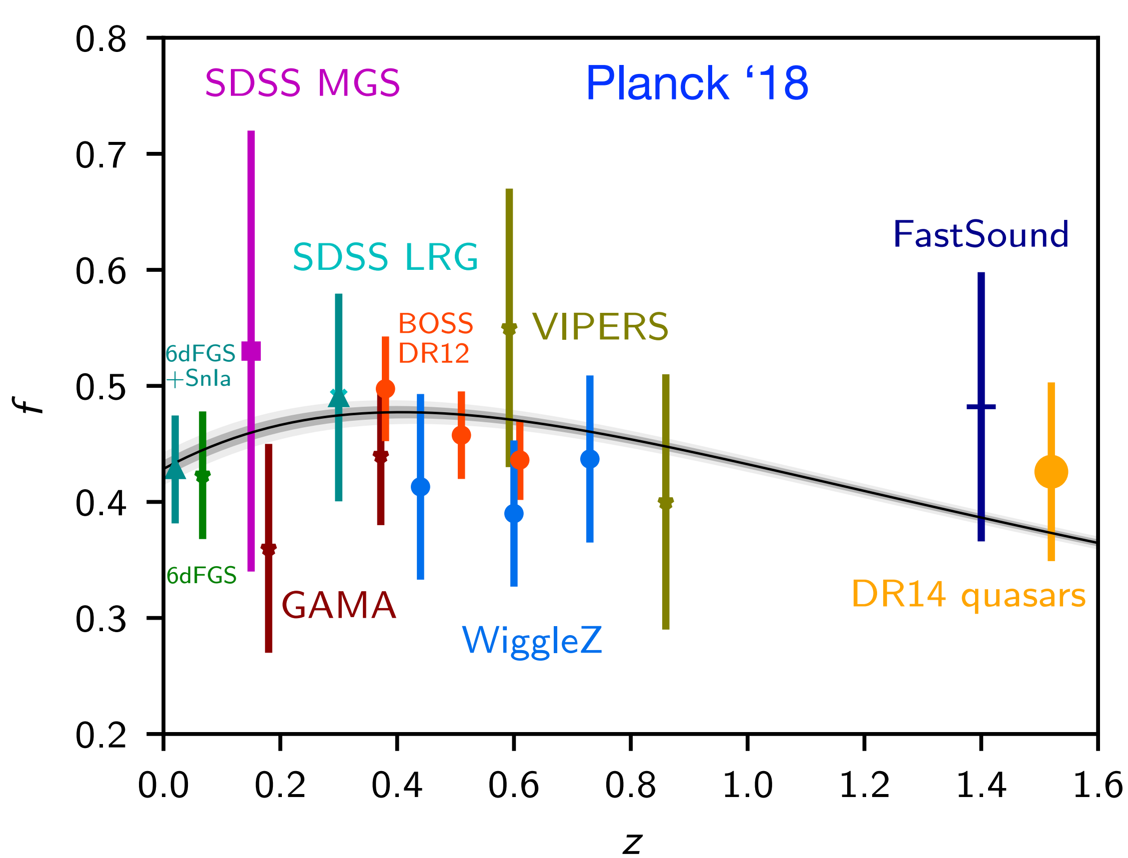
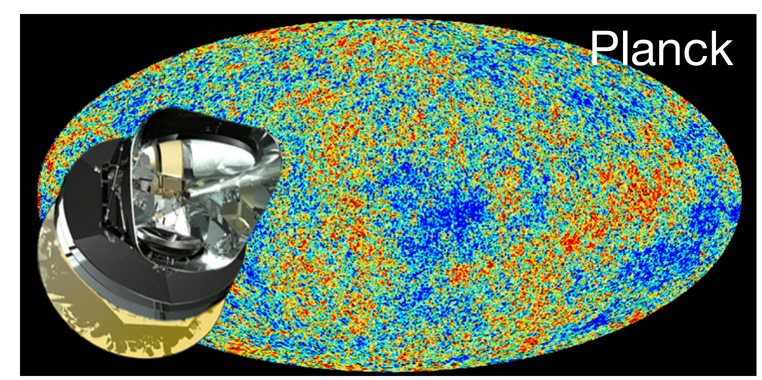
Precision tests

General relativity extrapolated over large ranges of scales and masses. Cosmology is a window for testing it on very large distances. Distinguish among models and discover new physics. Cosmological precision tests of ΛCDM (precision tests of the Standard Model at the LHC)







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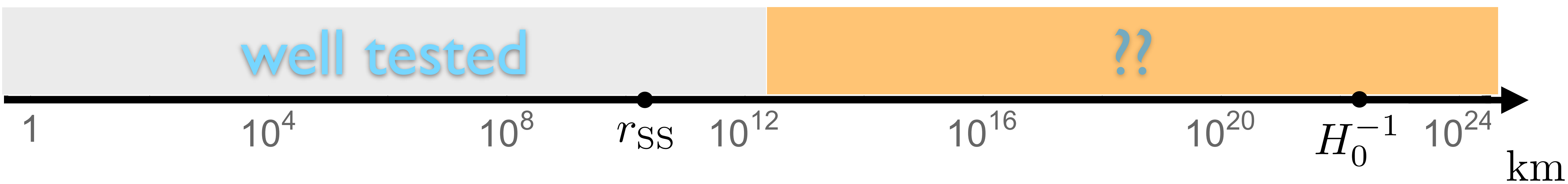

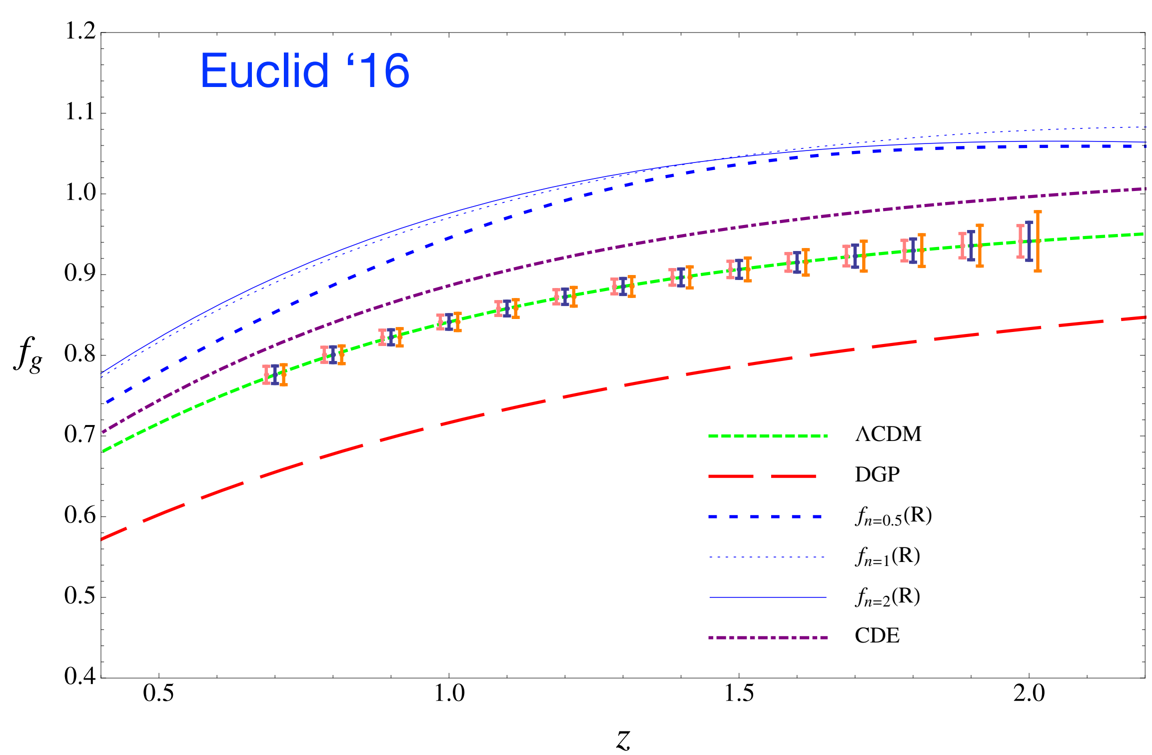

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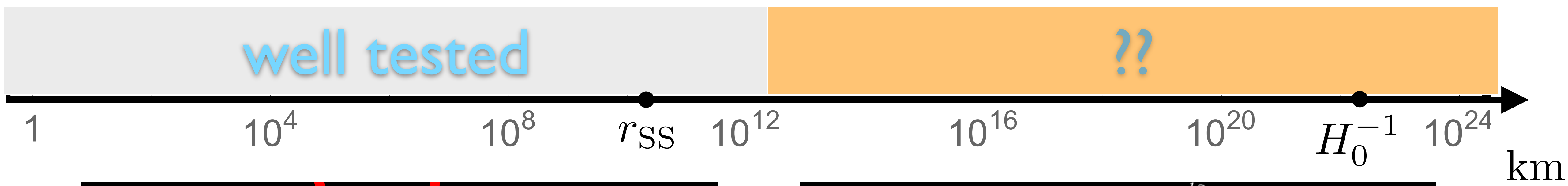
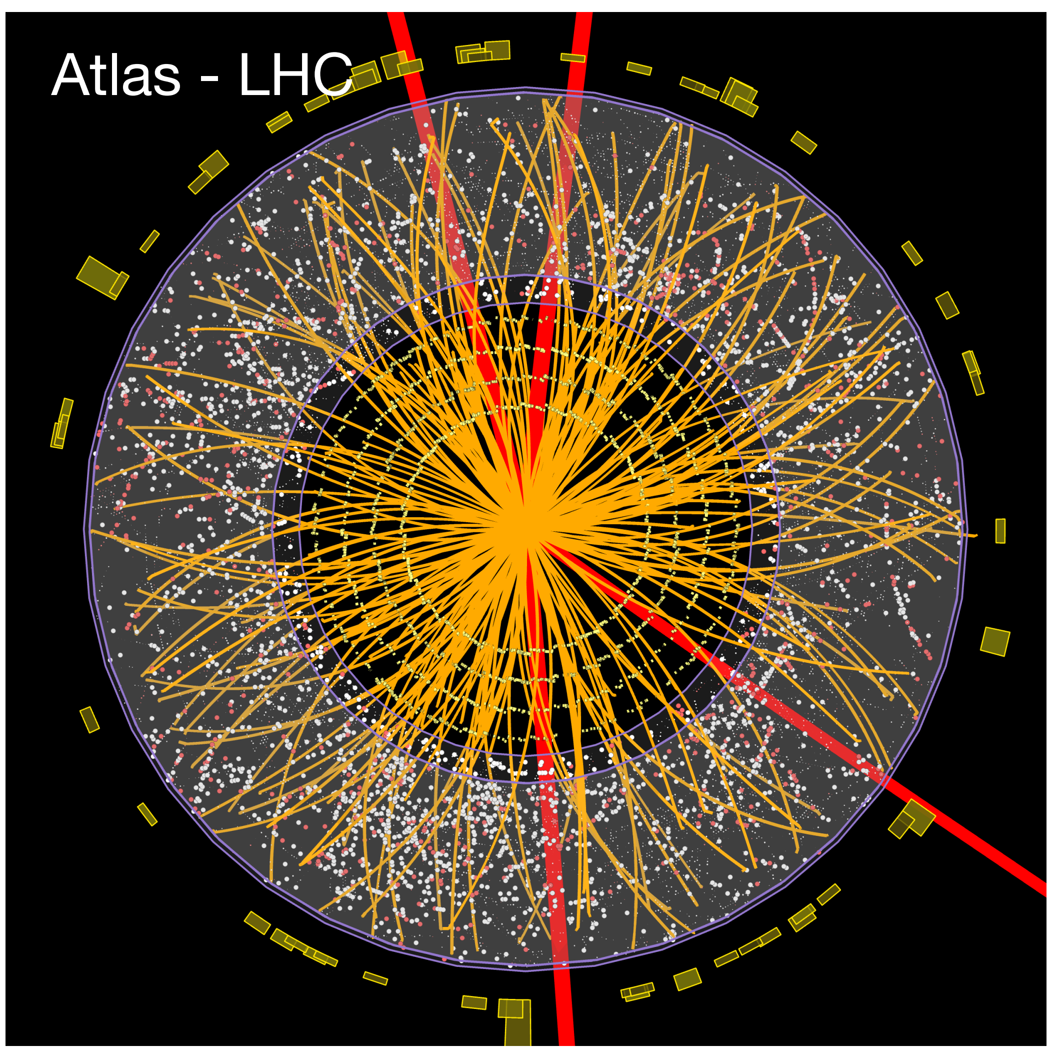
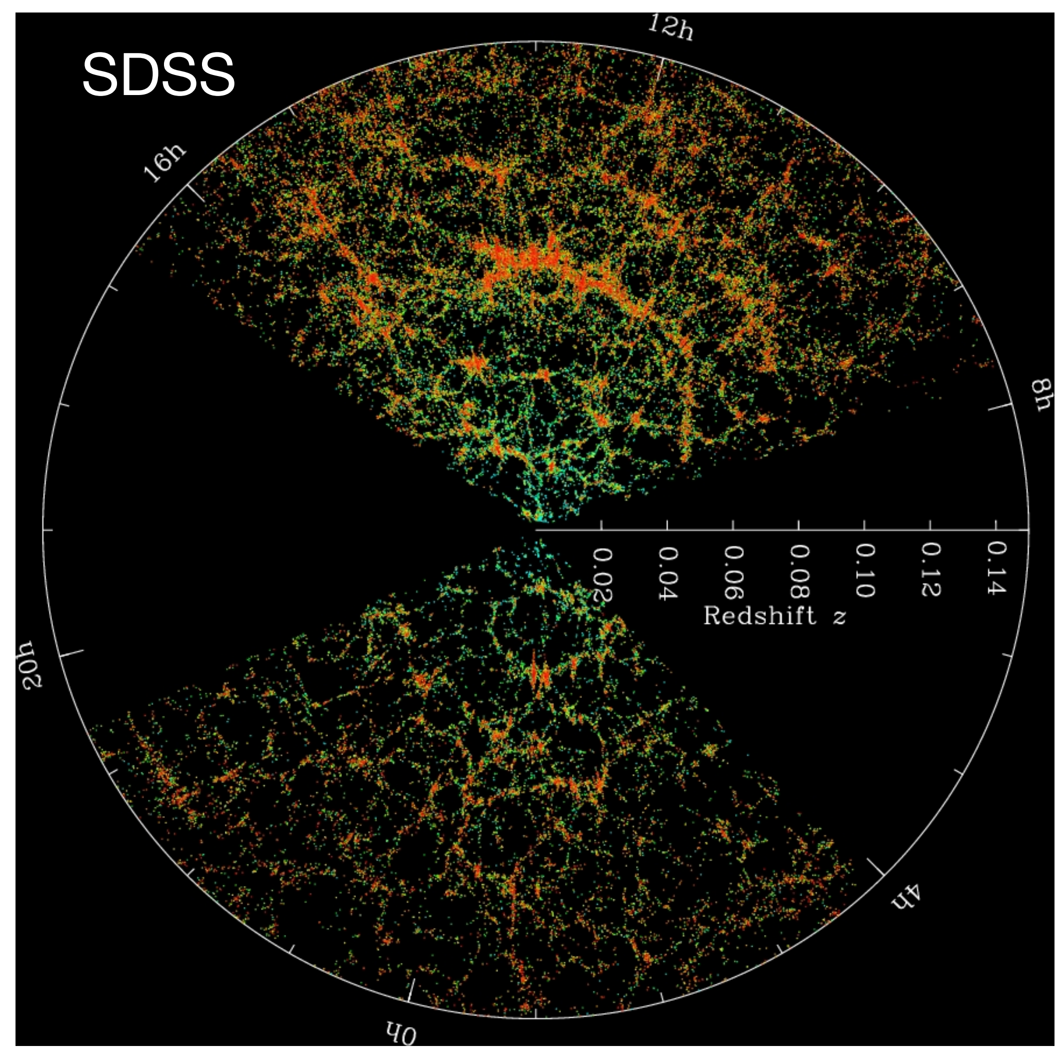
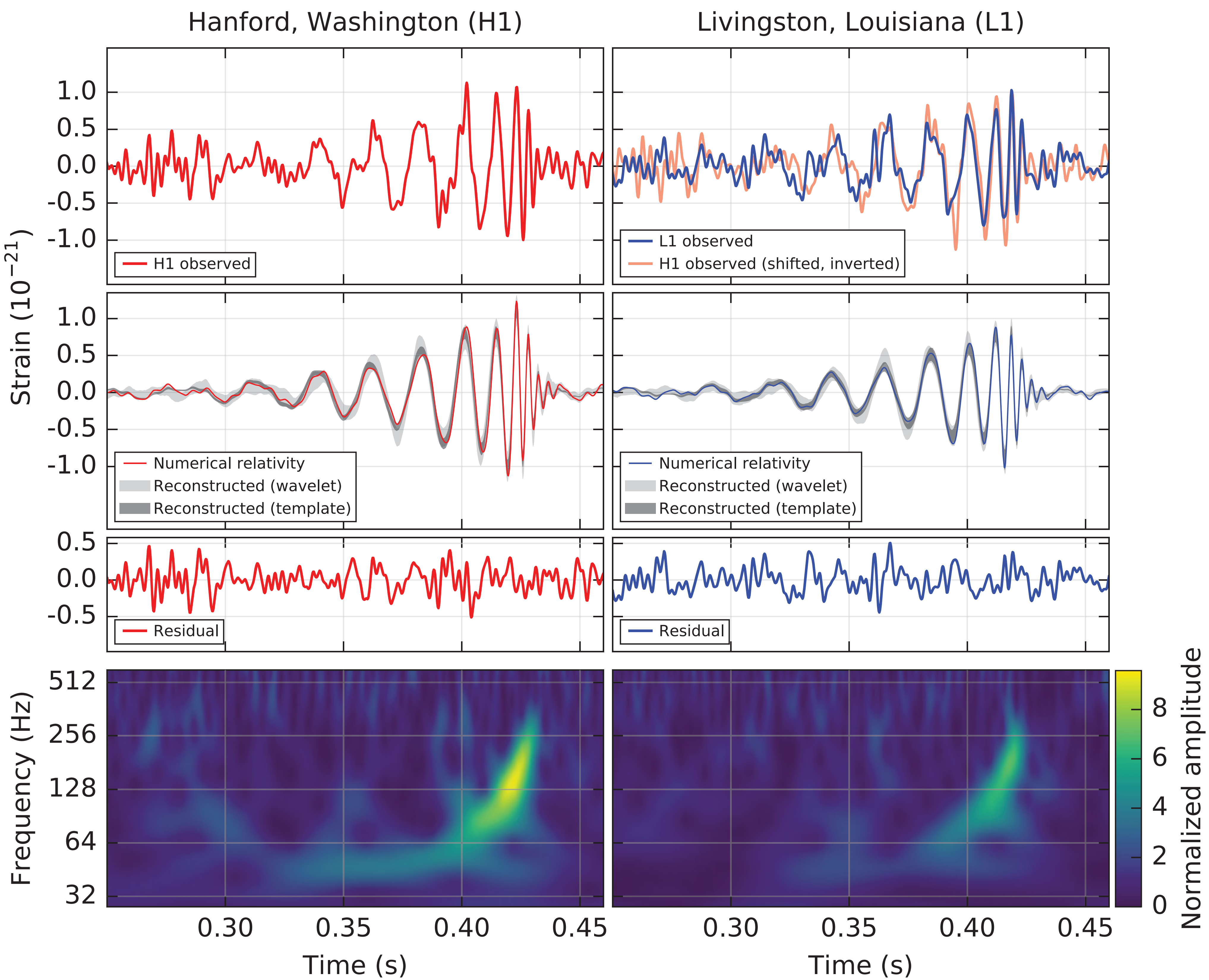






GW140915: Gravitational Waves

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



Wave equation

Gravitational wave equation:

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

$$\ddot{\gamma}^{\lambda}_{ij} + 3H\dot{\gamma}^{\lambda}_{ij} + k^2 \gamma^{\lambda}_{ij} = 16\pi G\, S^{\lambda}_{ij}\ , \qquad \lambda = +, \times$$

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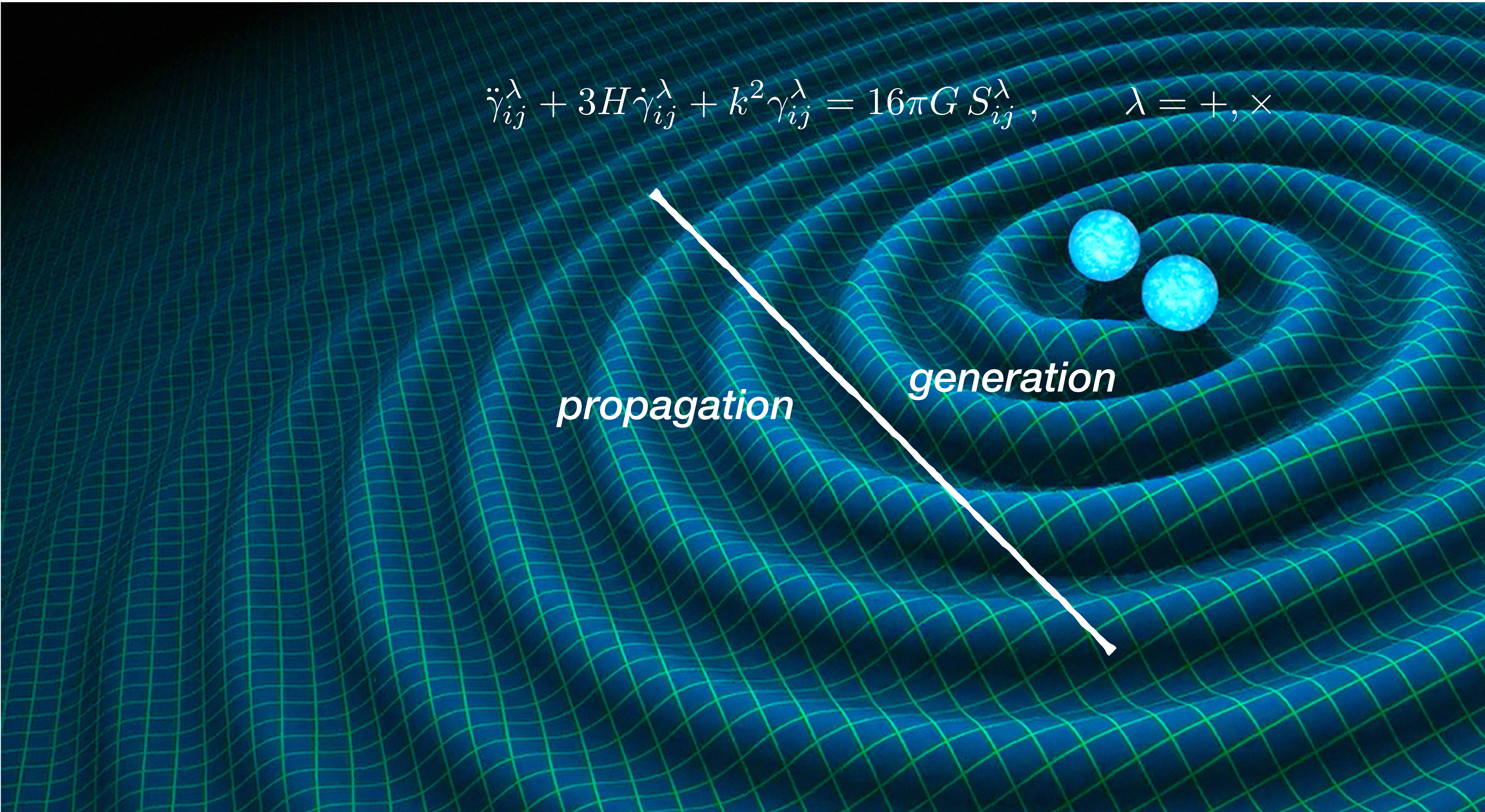

Modified wave equation

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damping dispersion source polarizations

$$\ddot{\gamma}_{ij}^{\lambda} + H\left[3 + \ldots\right]\dot{\gamma}_{ij}^{\lambda} + \left[c_T^2 k^2 + \ldots\right]\gamma_{ij}^{\lambda} = 16\pi G\, S_{ij}^{\lambda} \ , \qquad \lambda = +, \times$$

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

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

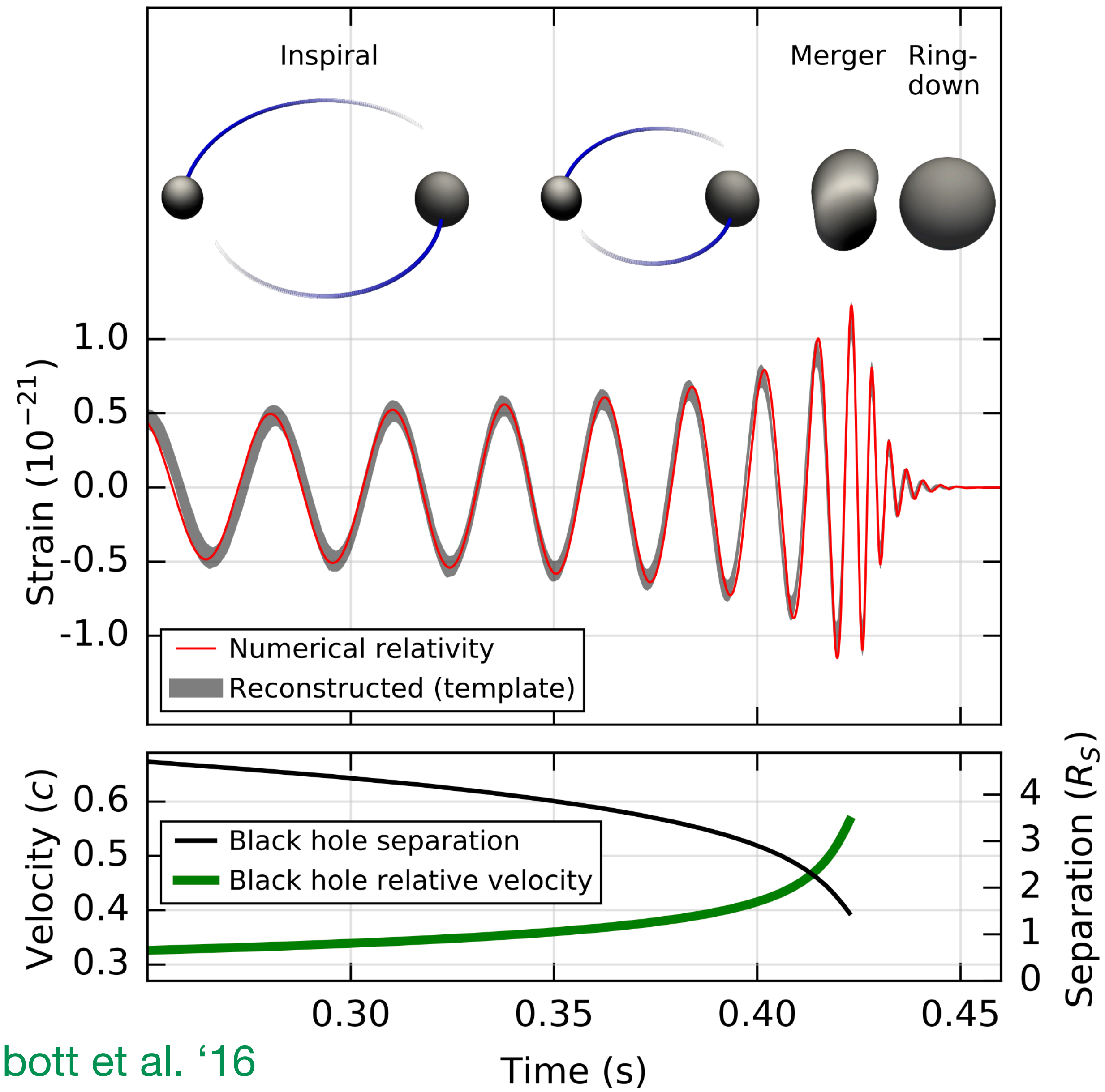
$$\nabla^2 \Phi = 4\pi G\, \mu\, \delta\rho_{\rm m}$$

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

Source

Modifications of the motion of inspiral objects and thus of the production mechanism. Affects GW phase (and amplitude)

$$\ddot{\gamma}_{ij}^{\lambda} + 3H\dot{\gamma}_{ij}^{\lambda} + k^2\gamma_{ij}^{\lambda} = 16\pi G\, S_{ij}^{\lambda} \,, \qquad \lambda = +, \times$$



Abbott et al. '16

$$v^2 = \frac{G_N m}{r}$$

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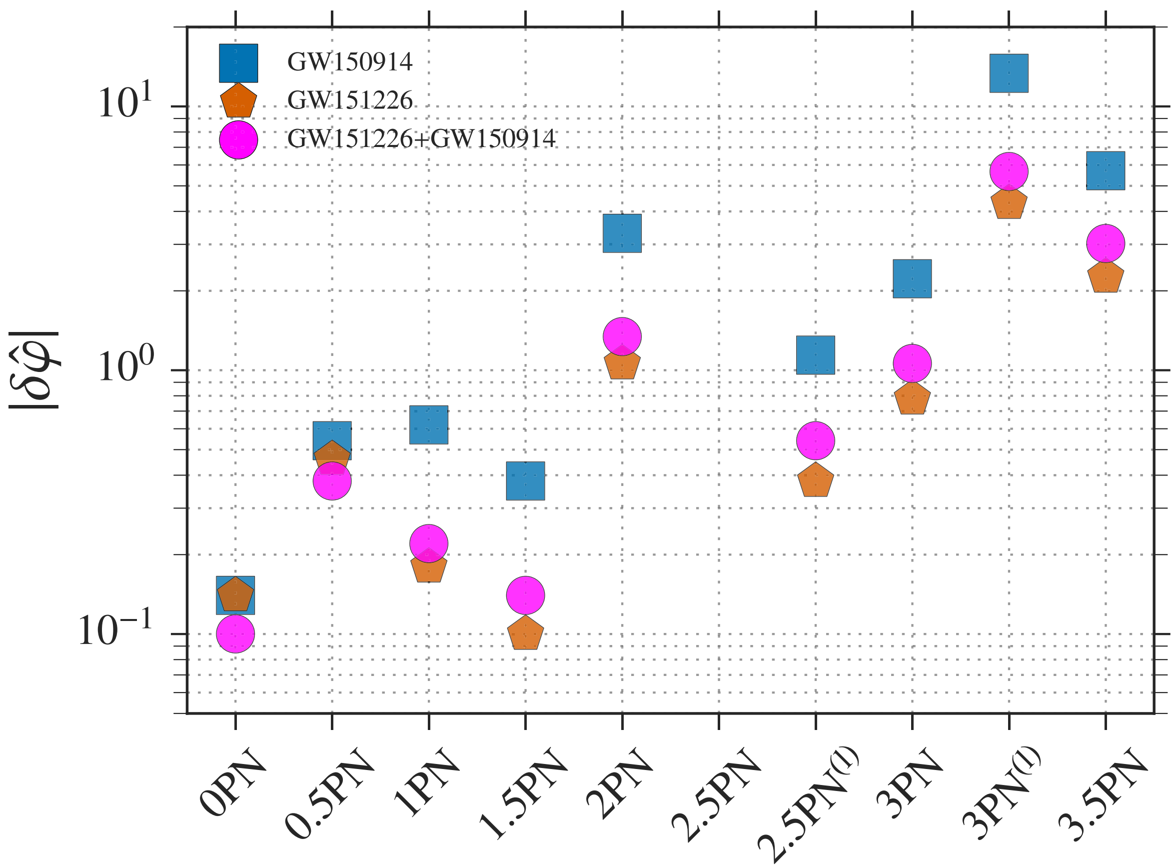
$$\ddot{\gamma}_{ij}^{\lambda} + 3H\dot{\gamma}_{ij}^{\lambda} + k^2\gamma_{ij}^{\lambda} = 16\pi G\, S_{ij}^{\lambda}\ , \qquad \lambda = +, \times$$

Consistency check of general relativity:

$$\varphi = \varphi_0 - \frac{1}{32}\left(\frac{GM_c\omega}{c^3}\right)^{-5/3}\left[1 + 1\mathrm{PN} + 1.5\mathrm{PN} + \ldots + 3.5\mathrm{PN} + \mathcal{O}\left(\frac{1}{c^8}\right)\right]$$



90% CL upper bound on relative deviations on PN parameters

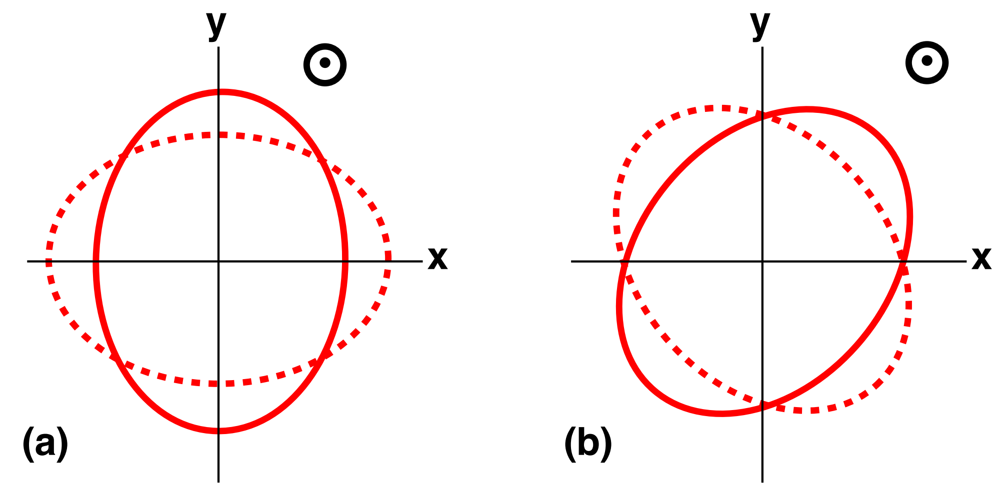
Abbott et al. ‘16

Polarizations

Different polarizations can be generated or propagate differently: parity violations (ex. Cherns-Simons gravity)

Jackiw & Pi ‘03

$$\ddot{\gamma}_{ij}^{\lambda} + 3H\dot{\gamma}_{ij}^{\lambda} + \left[k^2 + f^{\lambda}(k)\right]\gamma_{ij}^{\lambda} = 16\pi G\, S_{ij}^{\lambda}\ , \qquad \lambda = +, \times$$



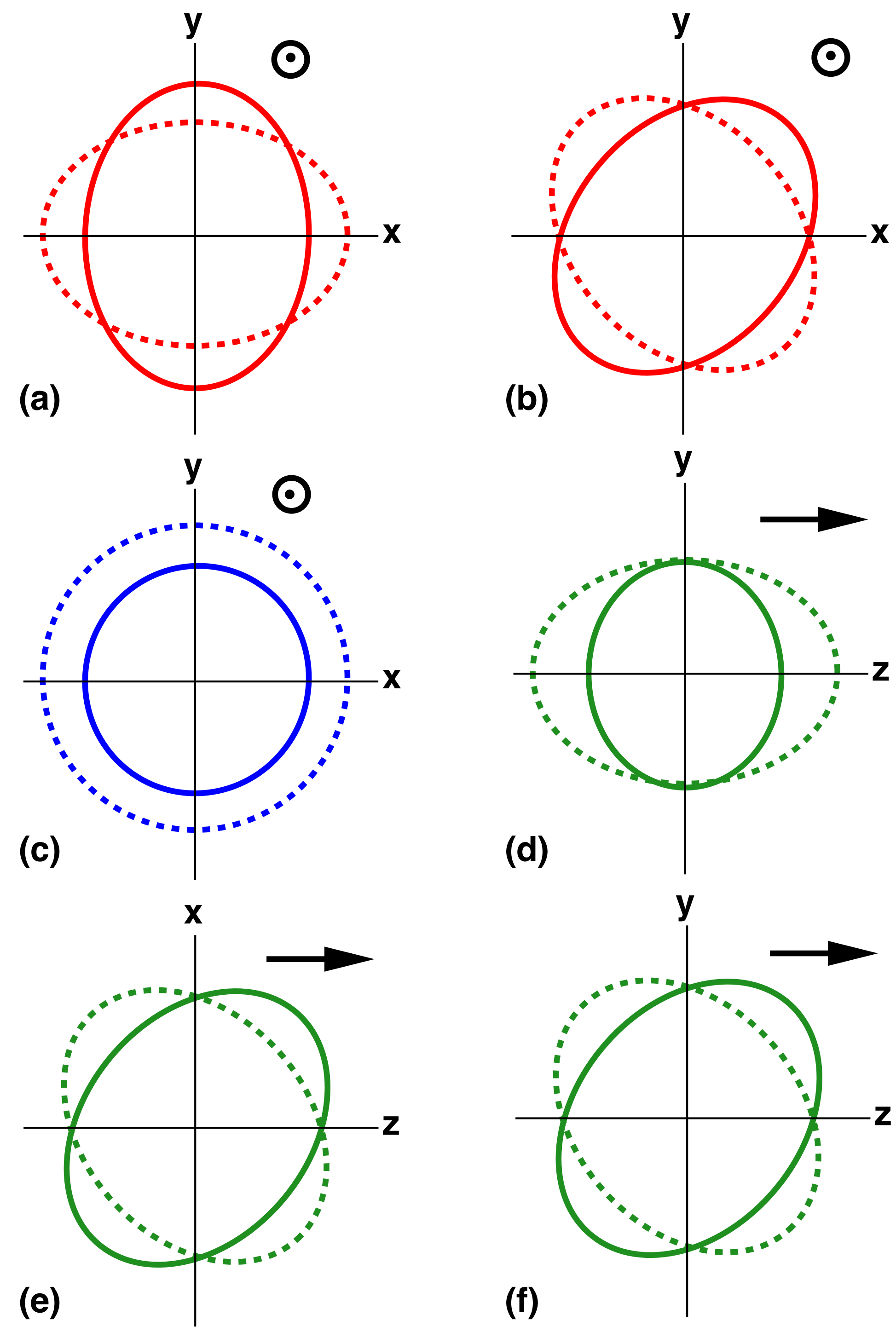
$$\gamma_{ij} = \begin{pmatrix} A_+ & A_\times & 0 \\ A_\times & -A_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Polarizations

Modified gravity can involve different degrees of freedom: scalar, vectors, extra tensors

Will '14

$$\gamma_{ij} = \begin{pmatrix} A_S + A_+ & A_\times & A_{\rm V1} \\ A_\times & A_S - A_+ & A_{\rm V2} \\ A_{\rm V1} & A_{\rm V2} & A_{\rm L} \end{pmatrix}$$



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Will '14

Standard GR: 2 transverse modes (spin-2)

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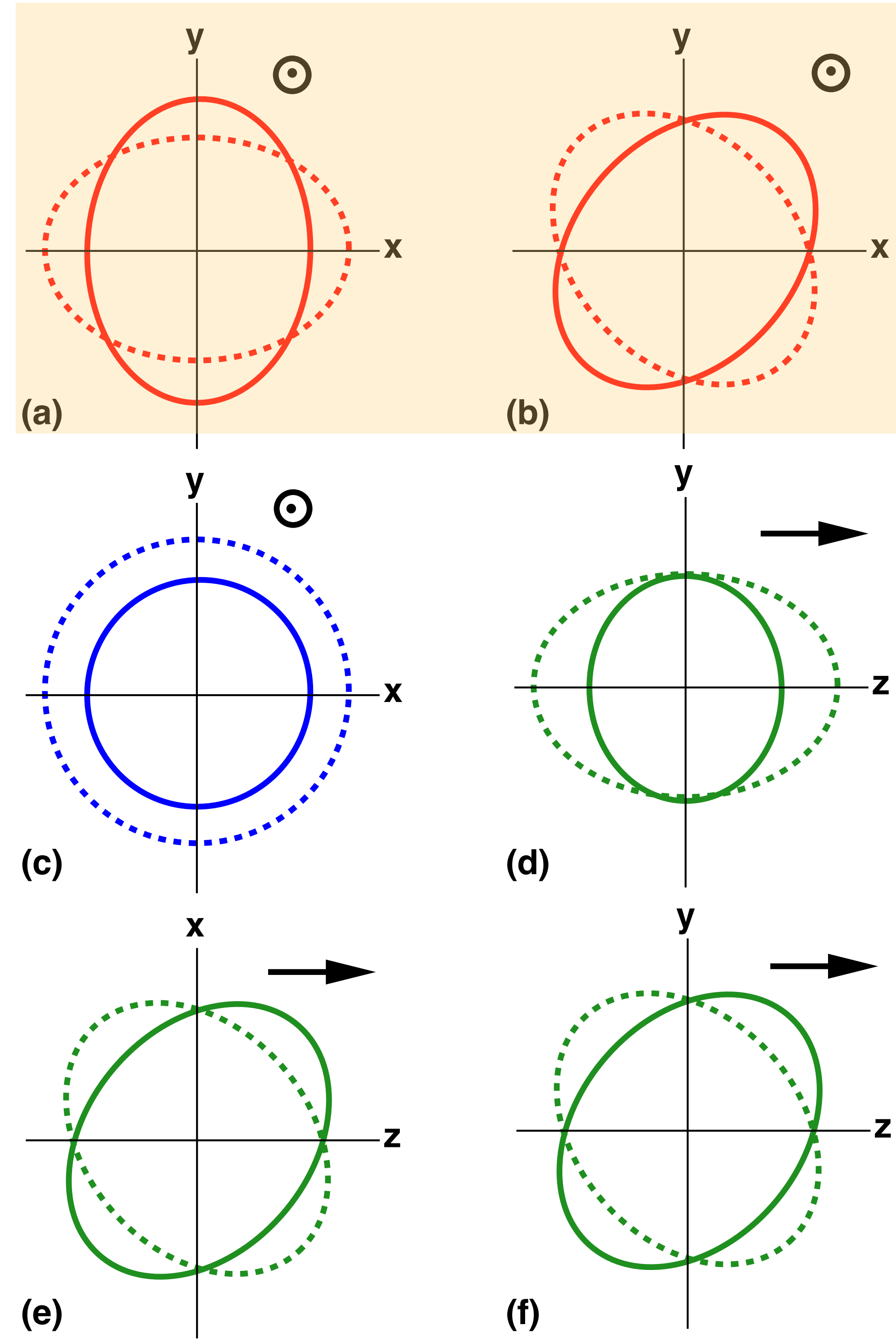


Polarizations

Modified gravity can involve different degrees of freedom: scalar, vectors, extra tensors

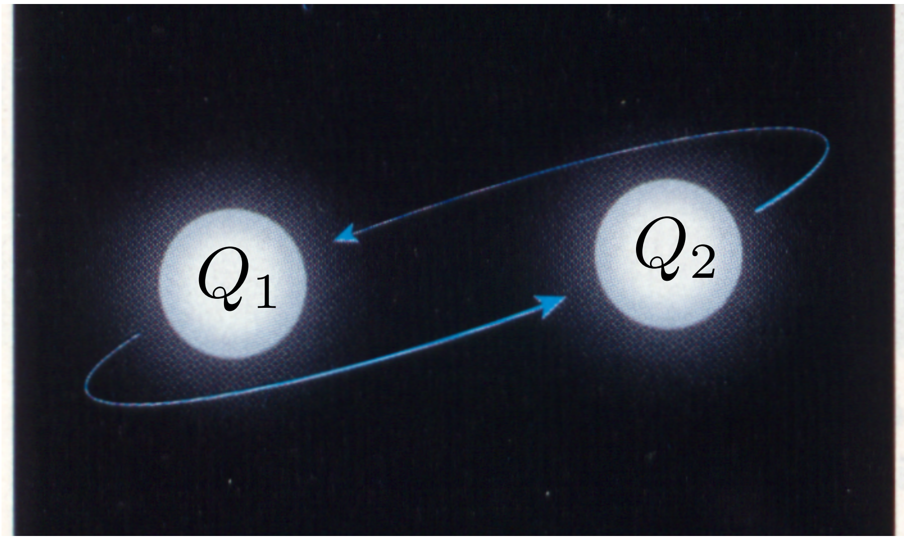
Will '14

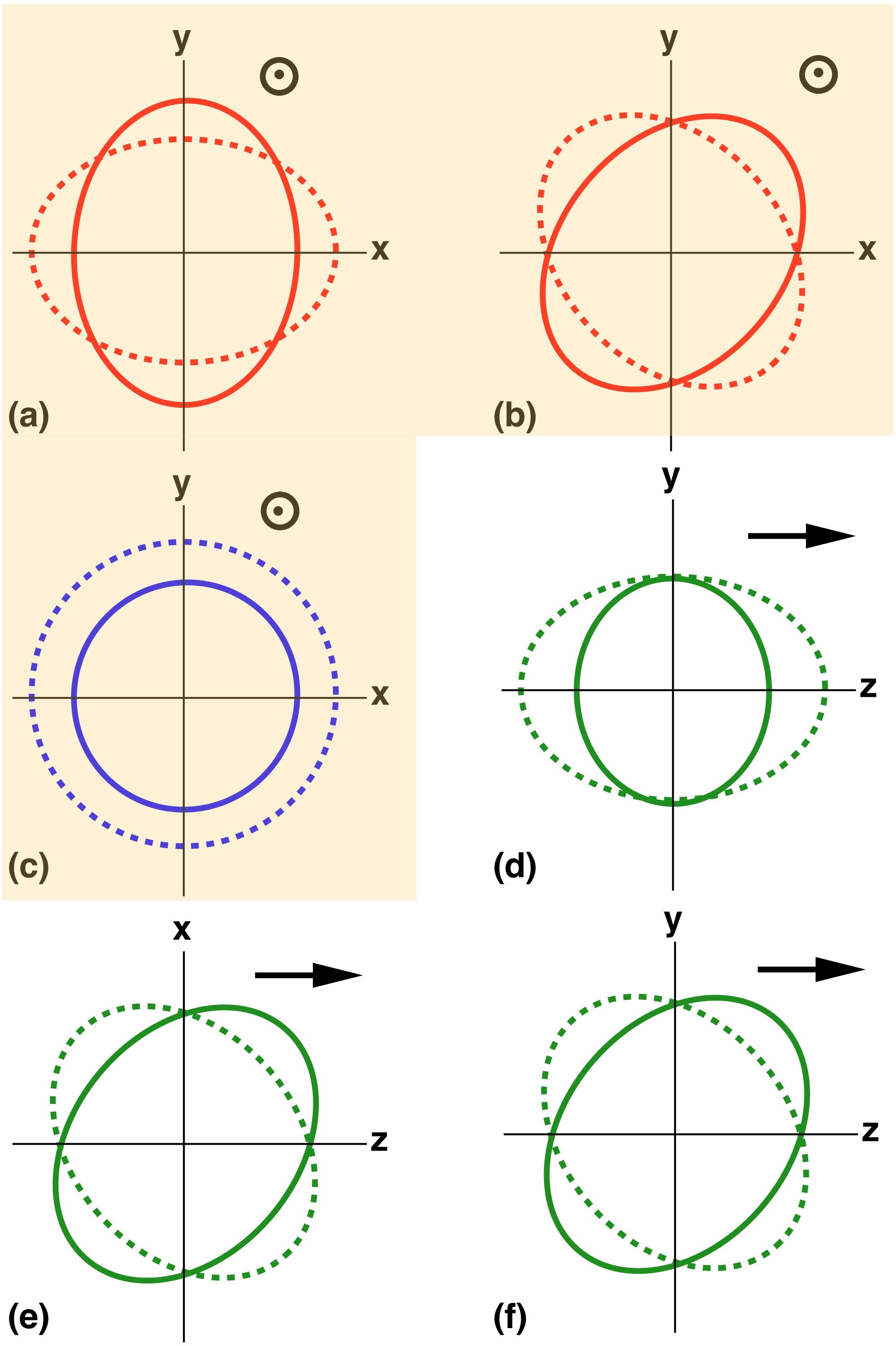
Scalar-Tensor: 2 transverse modes (spin 2) + 1 transverse mode (spin 0)

$$\gamma_{ij} = \begin{pmatrix} A_S + A_+ & A_\times & 0 \\ A_\times & A_S - A_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$P_\phi \propto (Q_1 - Q_2)^2 \omega^{8/3}$$

dipole





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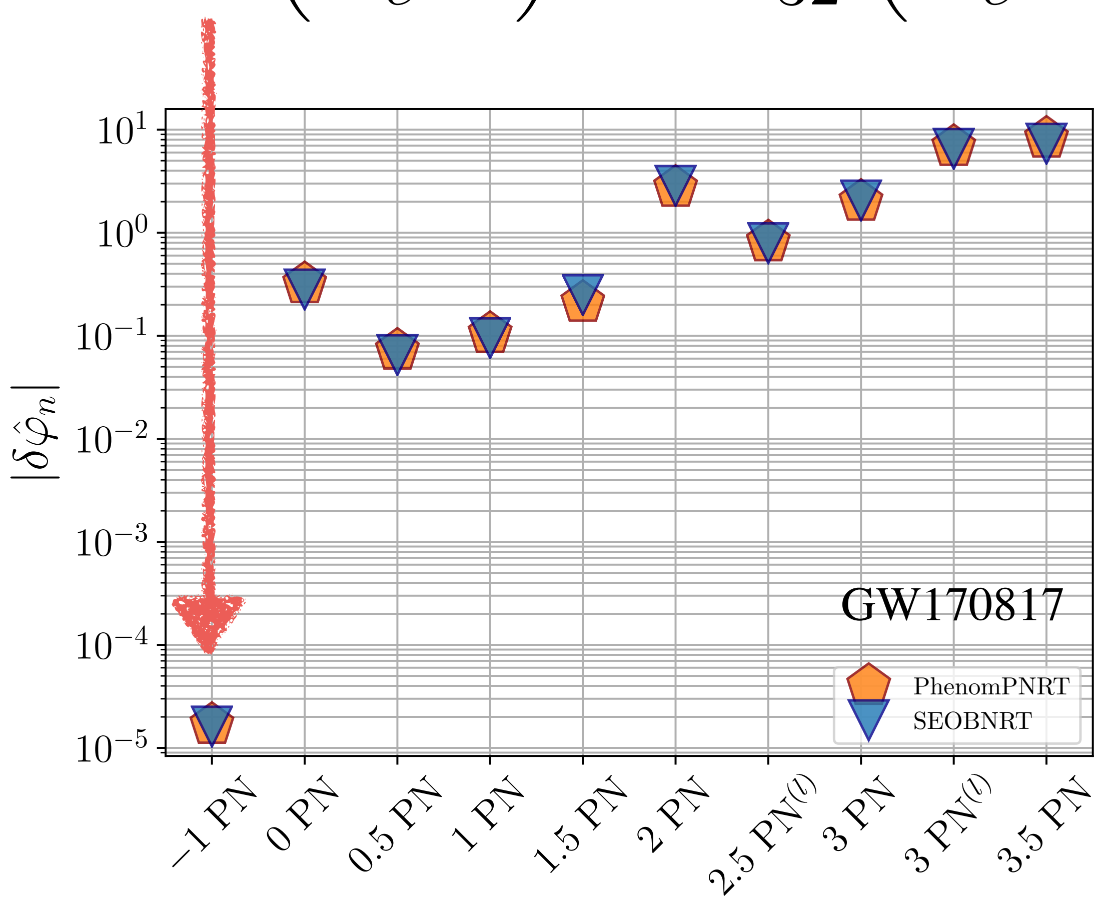


90% CL upper bound on relative deviations on PN parameters

Abbott et al. '18

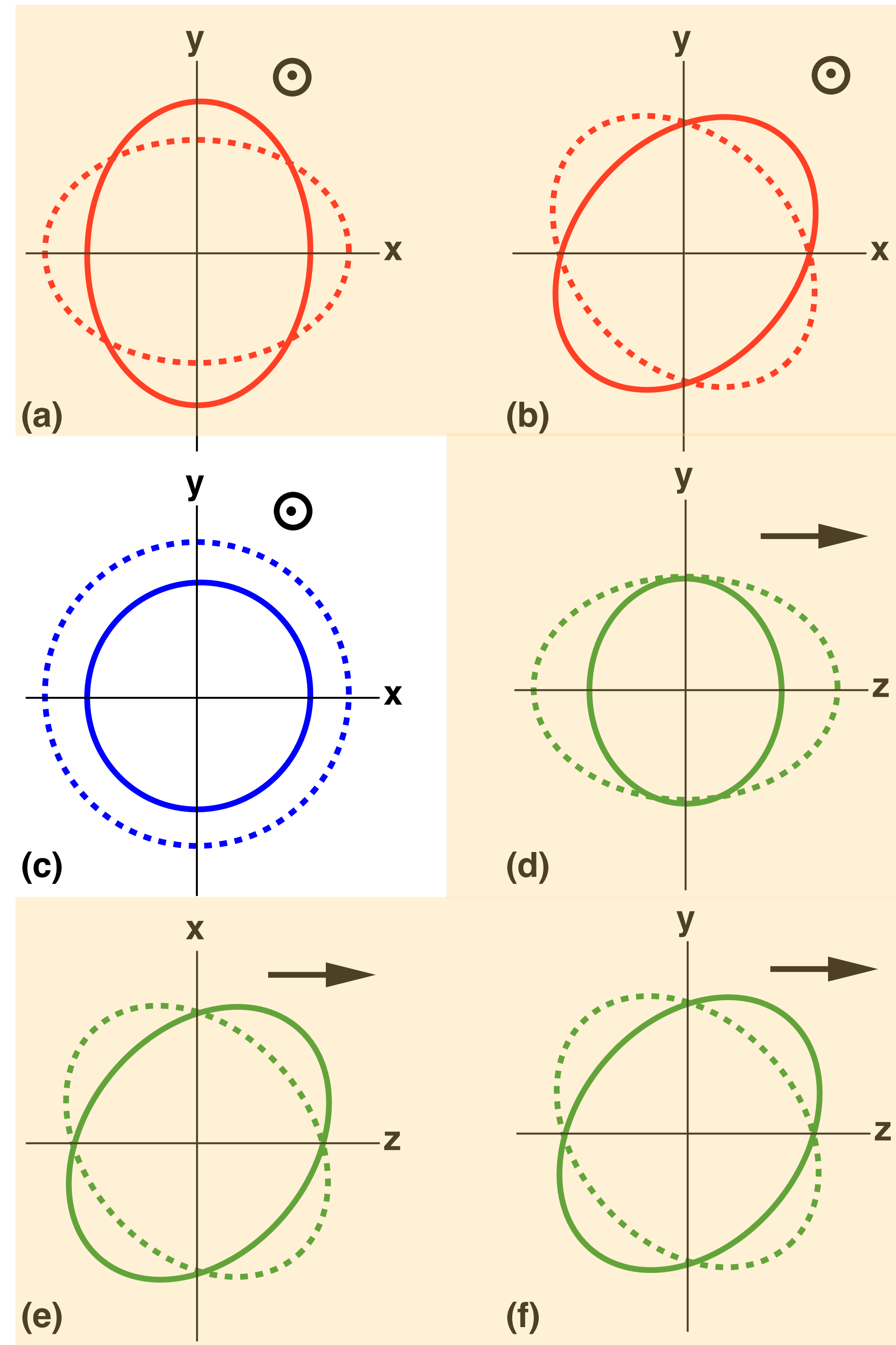
Polarizations

Modified gravity can involve different degrees of freedom: scalar, vectors, extra tensors

Will '14

Massive graviton: 2 transverse modes (spin-2) + 2 longitudinal modes (spin 1) + 1 longitudinal mode (spin 0)

$$\gamma_{ij} = \begin{pmatrix} A_+ & A_\times & A_{\rm V1} \\ A_\times & -A_+ & A_{\rm V2} \\ A_{\rm V1} & A_{\rm V2} & A_{\rm L} \end{pmatrix}$$



Polarizations

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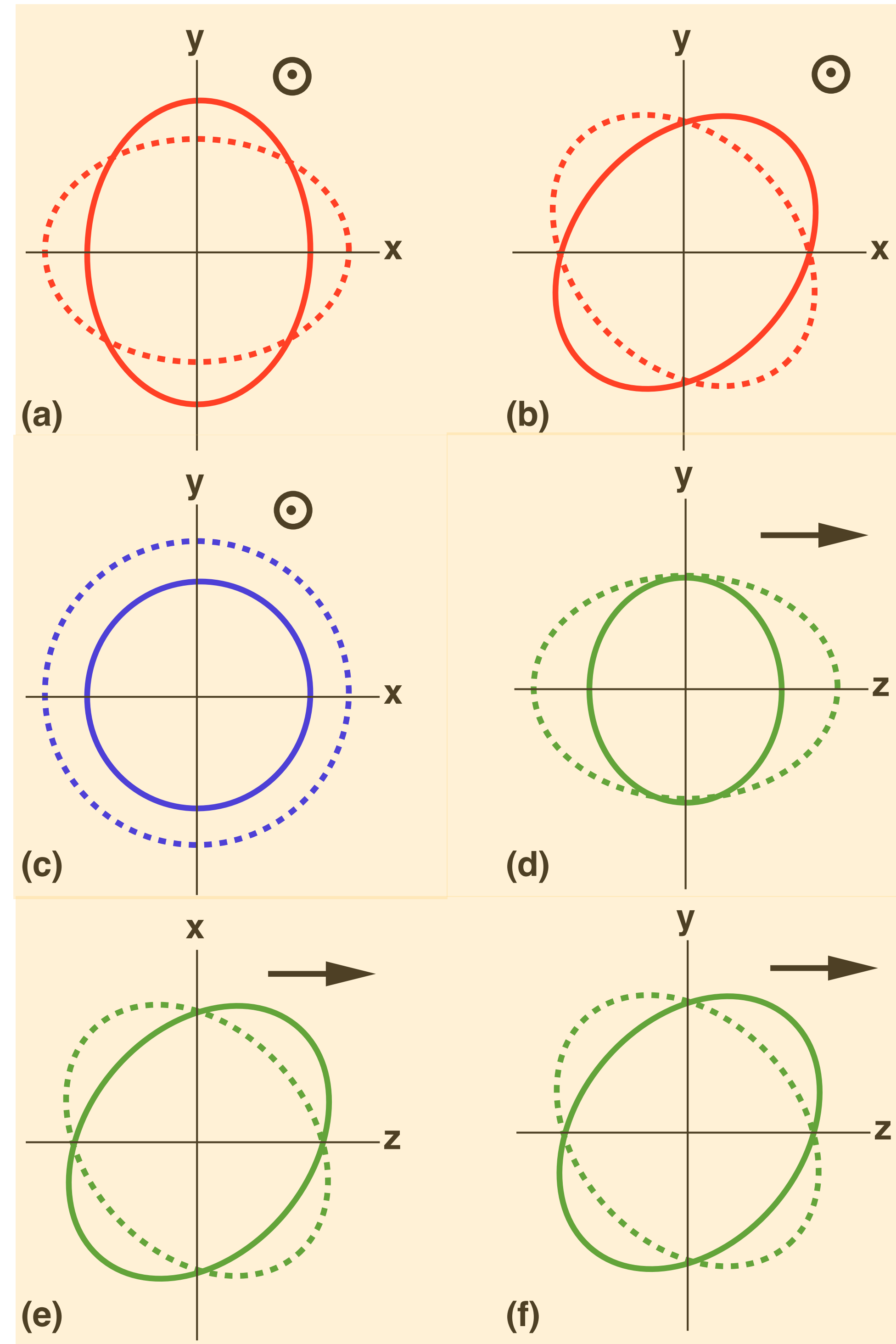
Will '14

Scalar-Vector-Tensor: 2 transverse modes (spin-2) + 1 transverse mode (spin 0) + 2 longitudinal modes (spin 1) + 1 longitudinal mode (spin 0)

$$\gamma_{ij} = \begin{pmatrix} A_S + A_+ & A_\times & A_{V1} \\ A_\times & A_S - A_+ & A_{V2} \\ A_{V1} & A_{V2} & A_L \end{pmatrix}$$



Polarizations

Modified gravity can involve different degrees of freedom: scalar, vectors, extra tensors

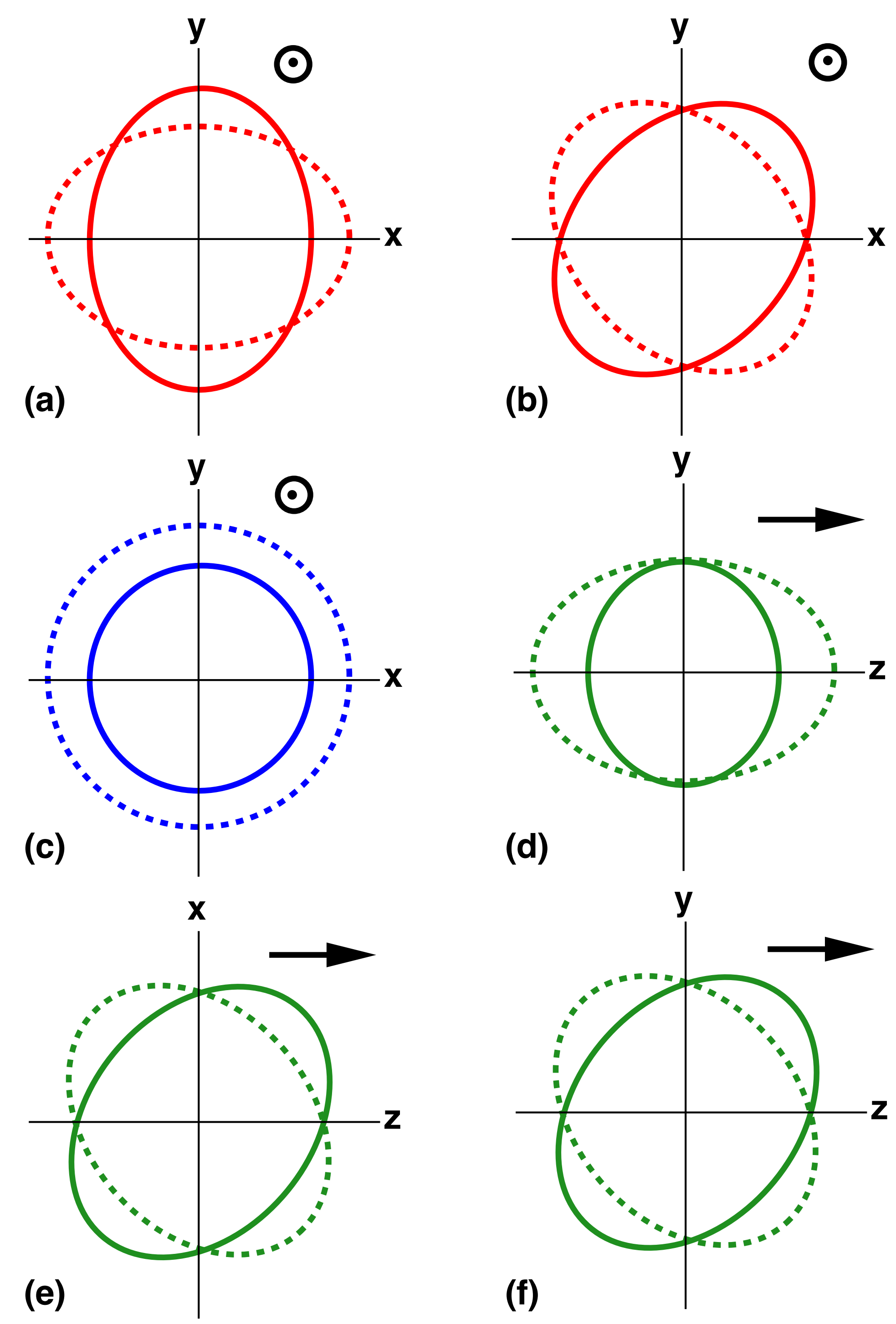
Will '14

6 polarizations + 2 directions = 8 unknowns

Assuming only transverse polarizations and known positions = 3 detectors enough

- Signal consistent with the two standard longitudinal tensor modes
- No evidence for extra polarizations (in the unmixed case)

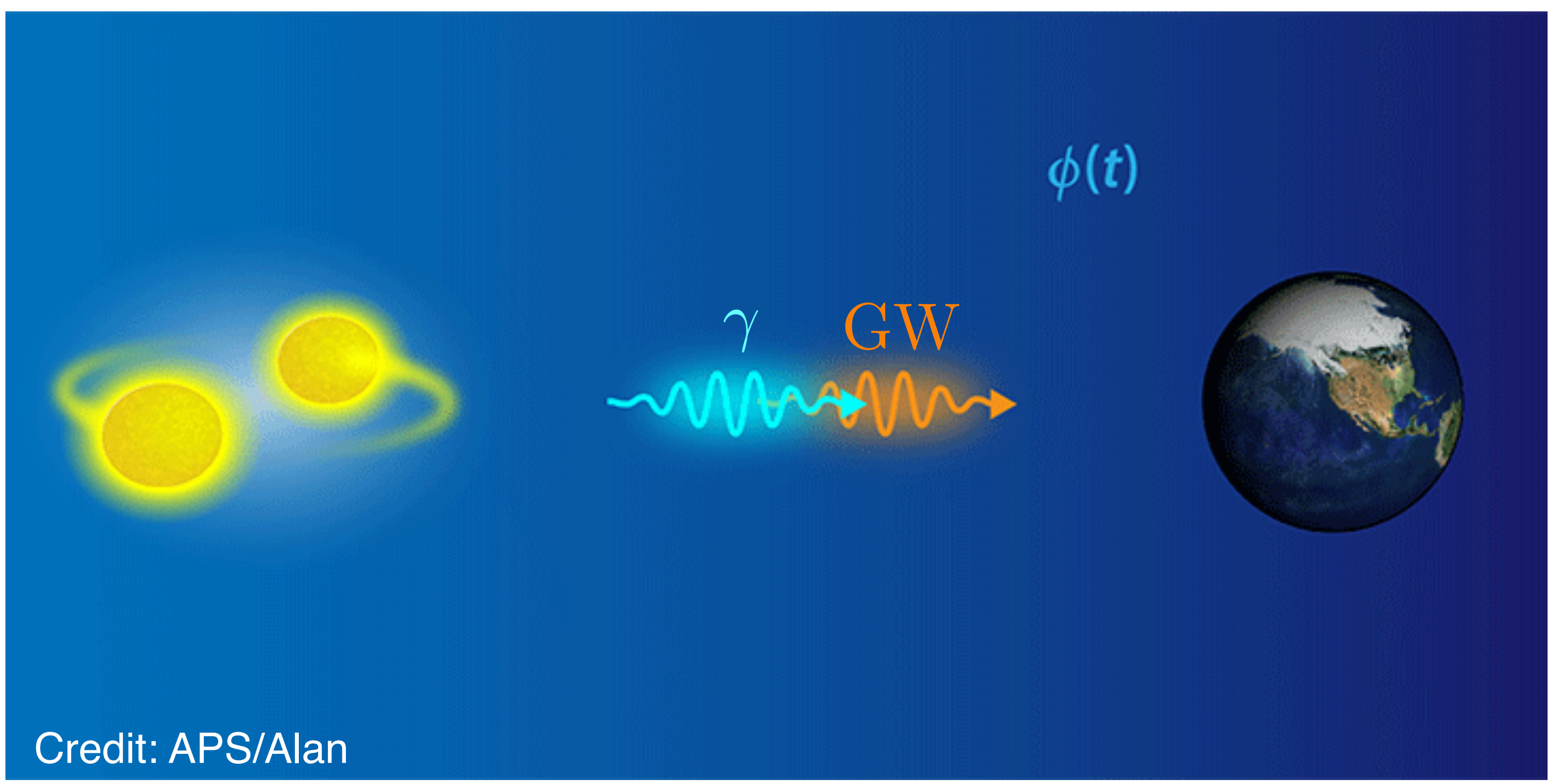
Abbott et al. '16, '18



Gravitational Waves propagation

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

$$\ddot{\gamma}_{ij}^{\lambda} + H\left[3 + \ldots\right]\dot{\gamma}_{ij}^{\lambda} + \left[c_T^2 k^2 + \ldots\right]\gamma_{ij}^{\lambda} = 0$$



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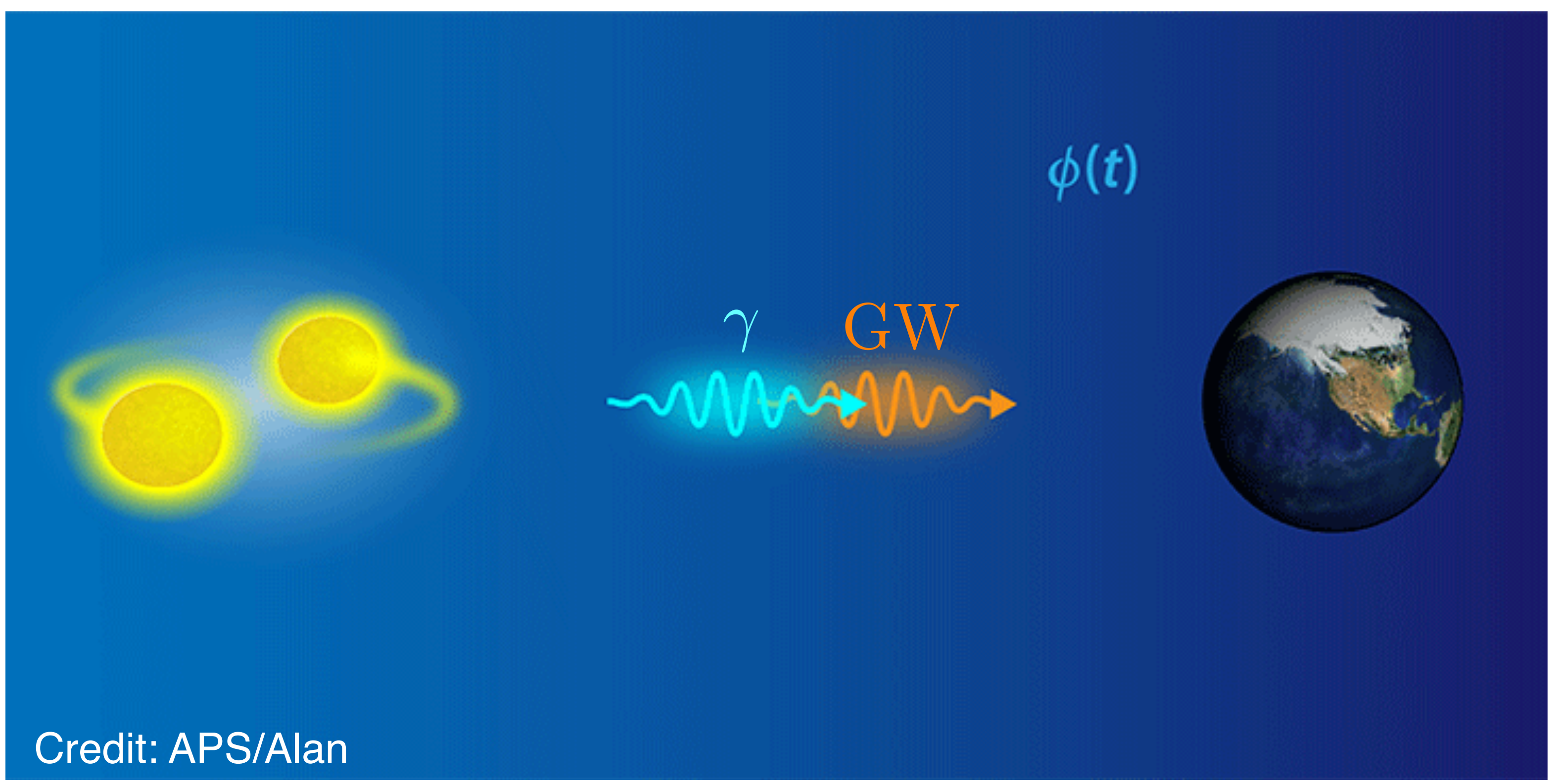

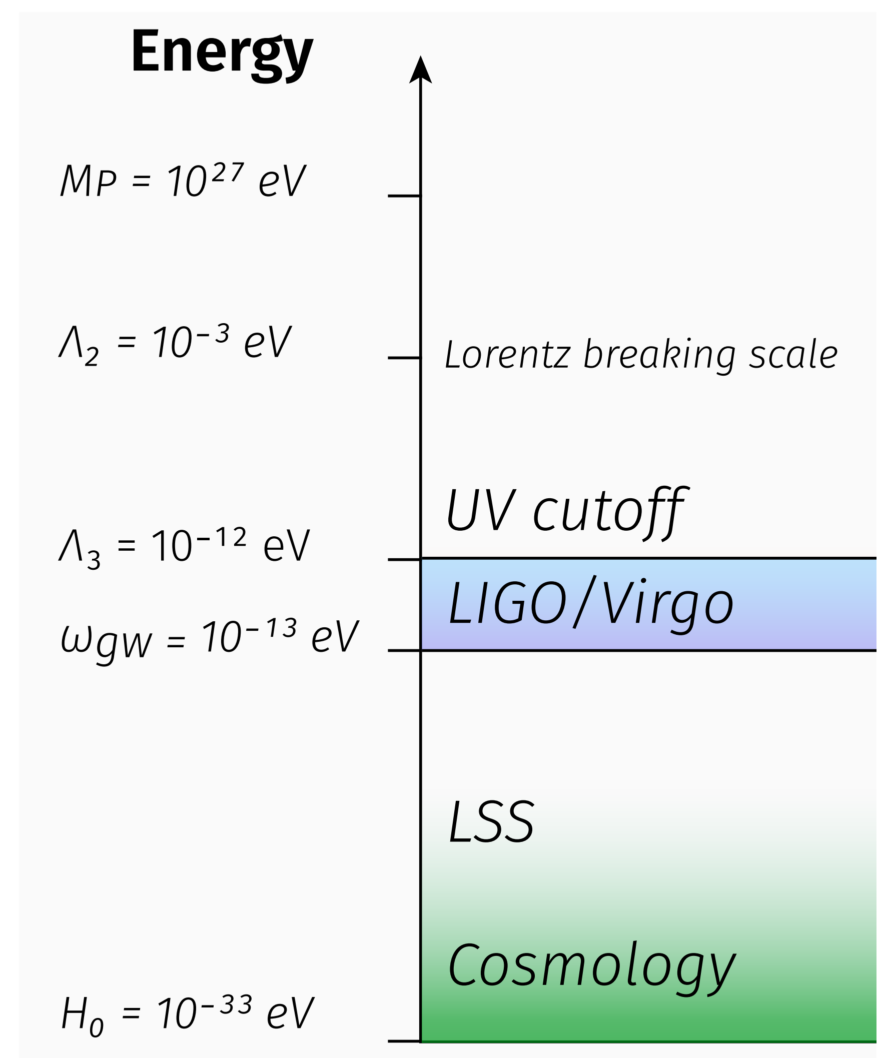

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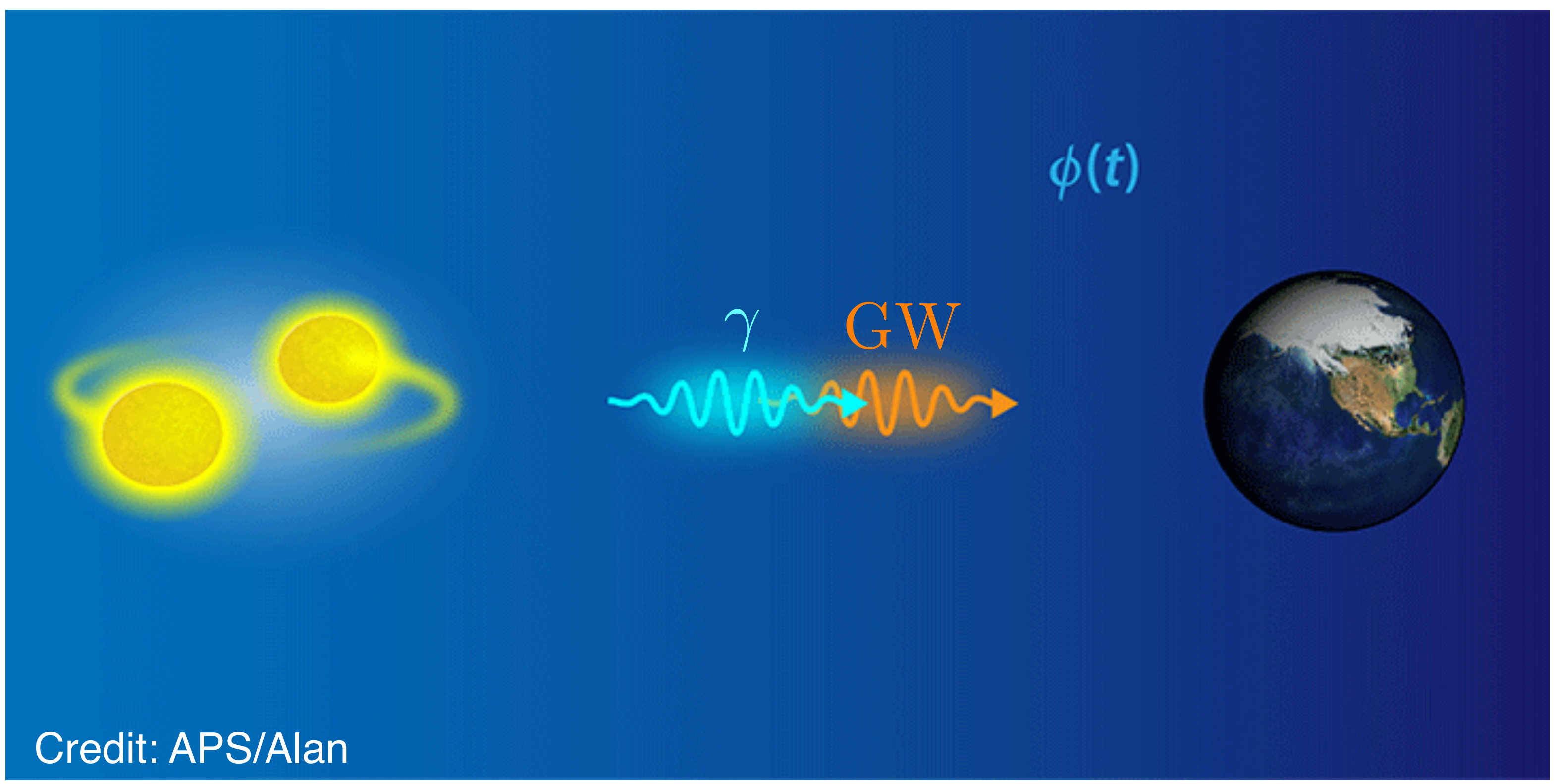

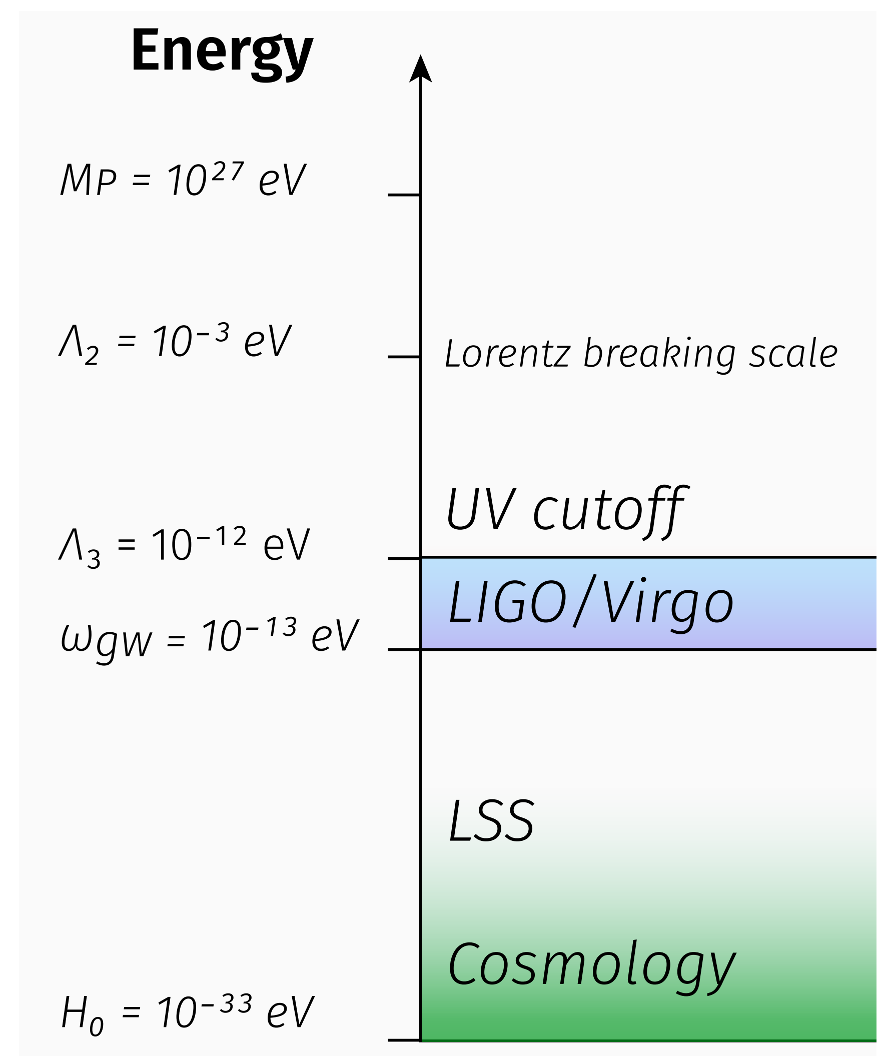

Similar to GW damping by neutrinos after or damping and modification of the propagation speed by CDM

Weinberg ’03; Flauger & Weinberg ‘18

GW propagation

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

Frequency independent effects:

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

damping (α_M)

speed of propagation (c_T^2)

$$\mu = \mu(\alpha_M, c_T^2, \ldots) \;, \qquad \Sigma = \Sigma(\alpha_M, c_T^2, \ldots)$$

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

damping — speed of propagation

$d_L^{\rm gw} \neq d_L^{\rm em}$ different luminosity distances

Deffayet, Menou '07;
Calabrese, Battaglia, Spergel, '16;
Amendola et al. '17, Belgacem et al. '17,
etc…

- Time variation of G
- Extra-dimensional leakage
- Nonlocal models
- …

LISA: $\sigma_{\alpha_M} \approx 0.03 - 0.1$

Amendola, Sawicki, Kunz, Saltas '18

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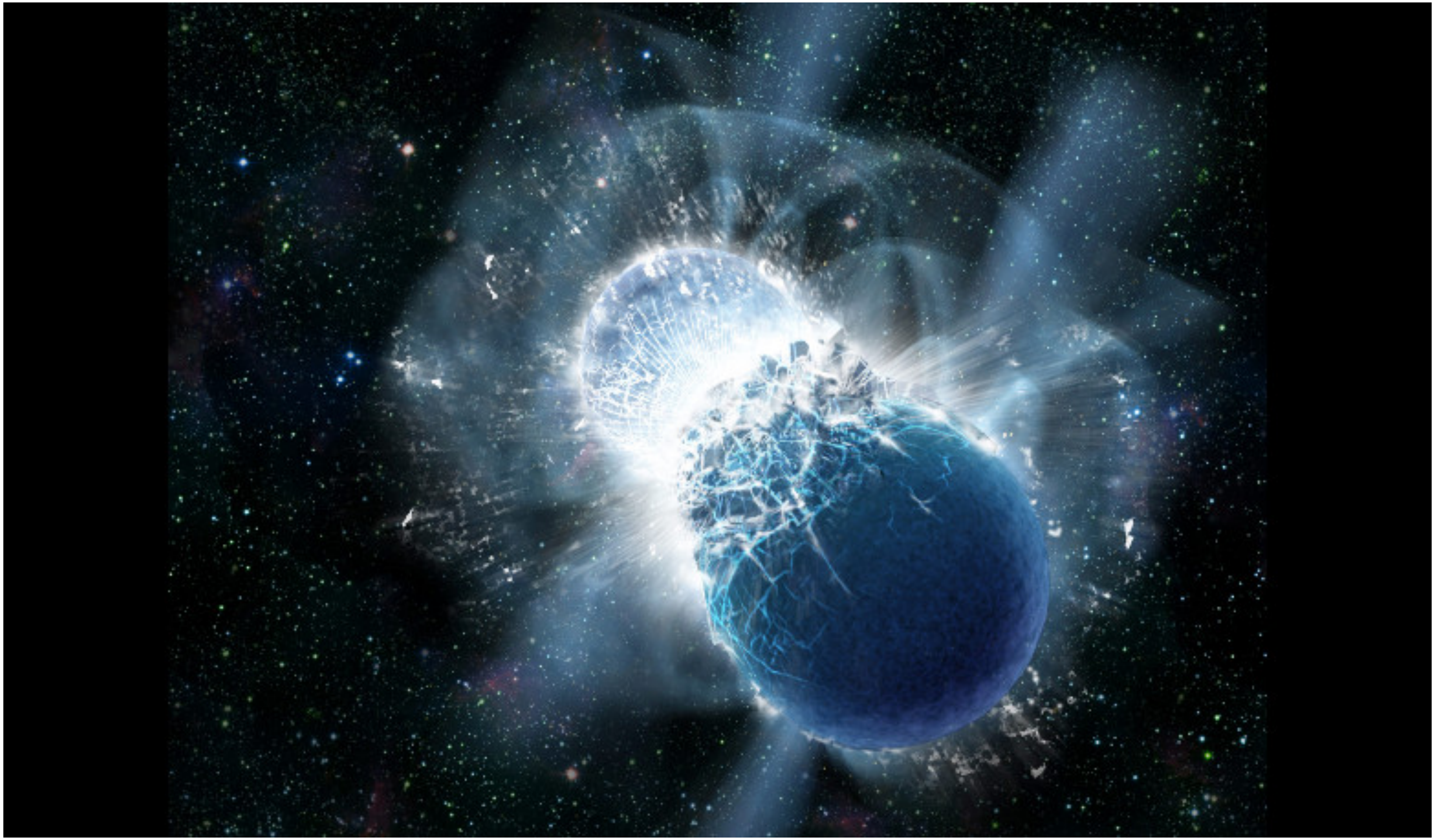
$$\ddot{\gamma}_{ij} + H(3 + \alpha_M)\dot{\gamma}_{ij} + c_T^2 k^2 \gamma_{ij} = 0$$

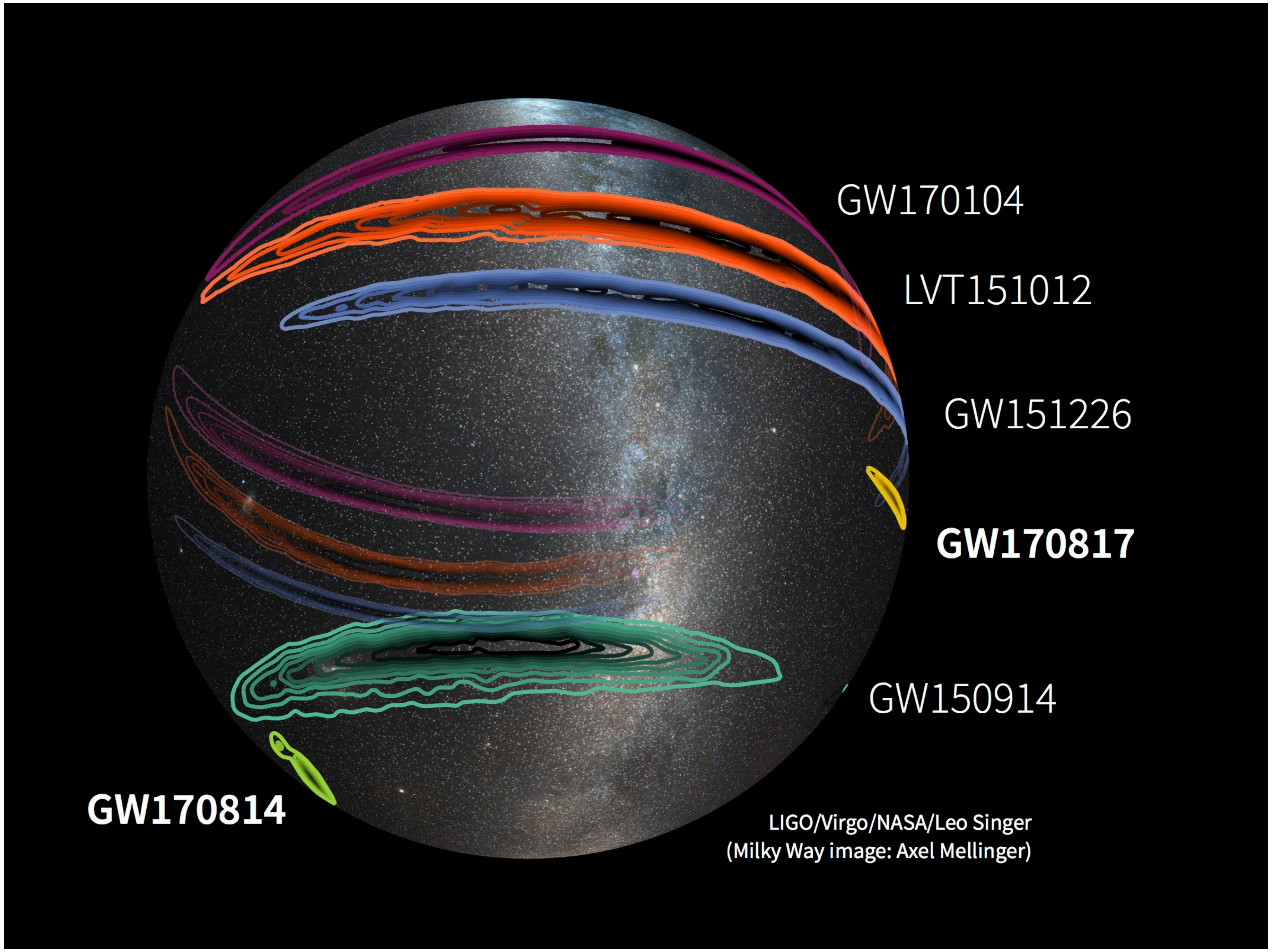
damping

speed of propagation

GW170817: neutron star merger

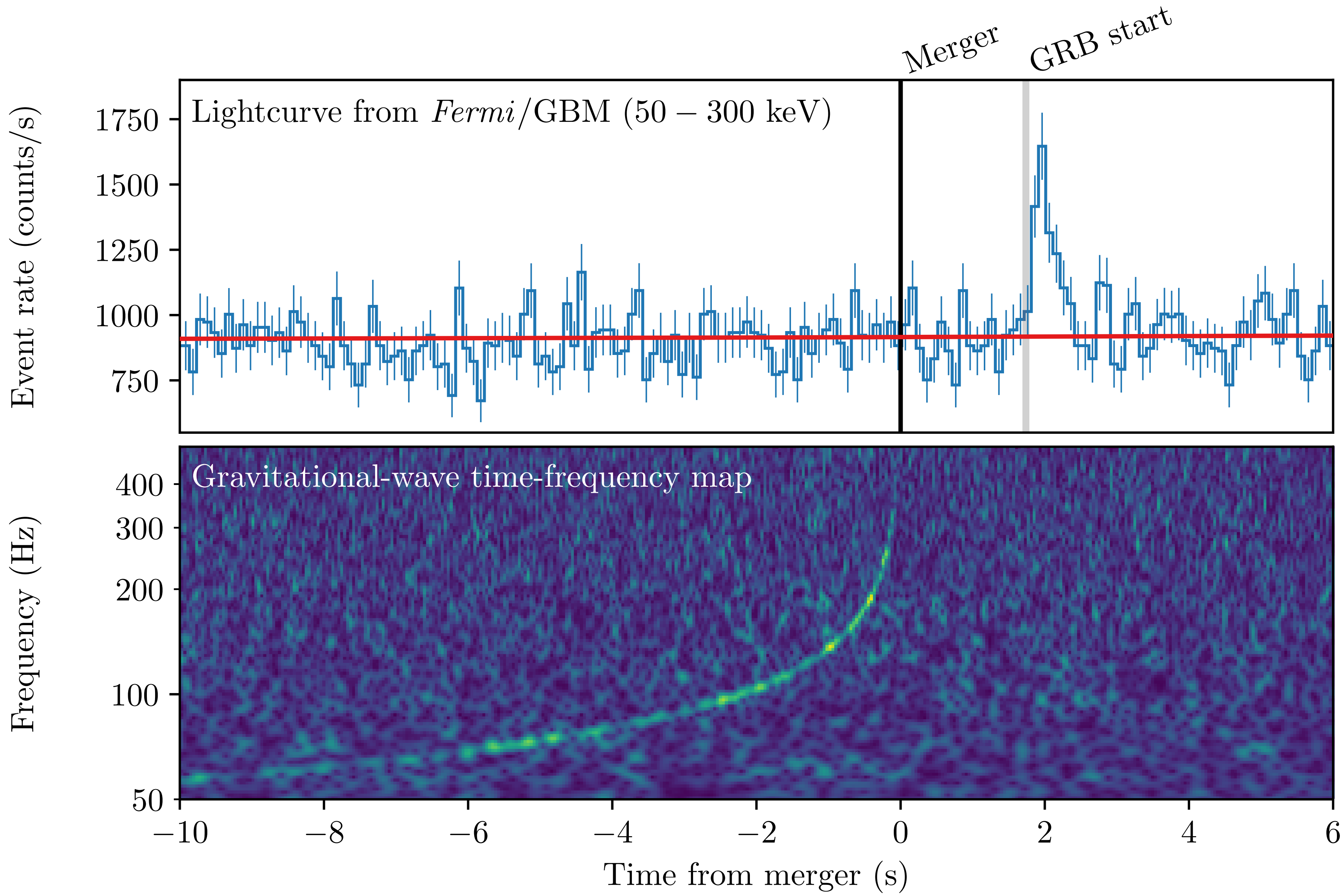


GW170817: neutron star merger



Efficient localization with three detectors

Multi-messenger observation



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

- Previous (inderect) limit only on GW slower than light.
- Low energy ($\lambda \lesssim 10^4\,\mathrm{km}$)
- Over cosmological distances

GW propagation

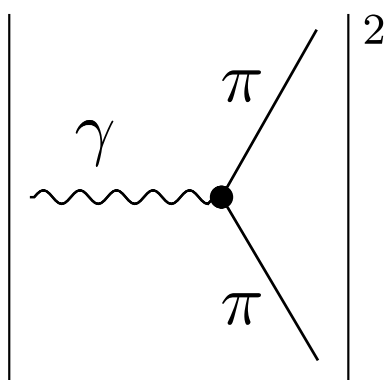
Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed. Effects accumulate on long time-scale.

Frequency dependent effects:

Creminelli, Lewandowski, Tambalo, FV ‘18

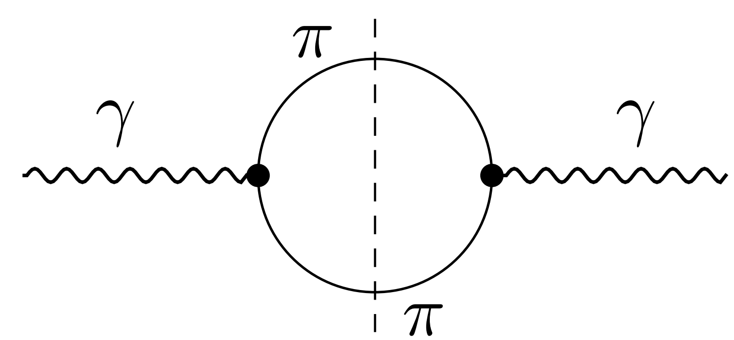
$$\ddot{\gamma}_{ij} + [(3+\alpha_{\rm M})H + \Gamma(k)]\,\dot{\gamma}_{ij} + \left[c_T^2 k^2 + f(k)\right]\gamma_{ij} = 0$$

decay



Similar to Cherenkov radiation

dispersion



Similar to a refractive material

Related by optical theorem: $\Gamma(k)\omega(k) = \mathrm{Im}\left[f(k)\right]$

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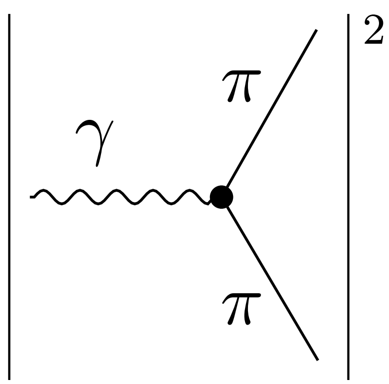

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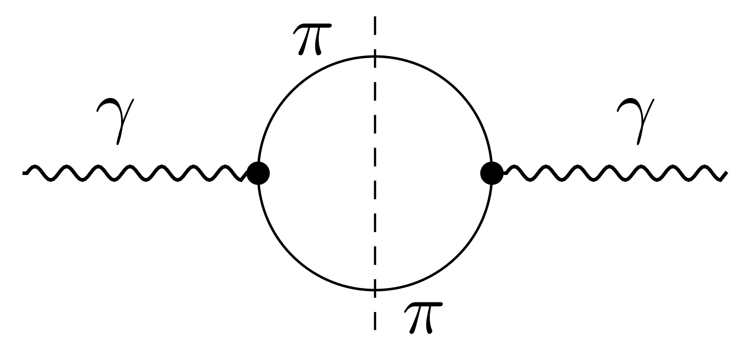

Similar to a refractive material

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

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

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

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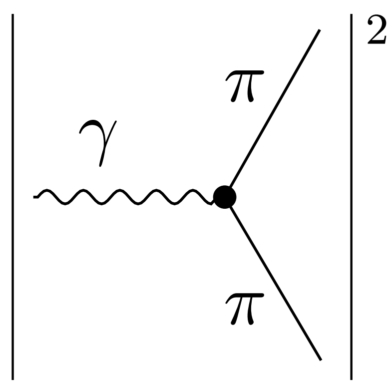

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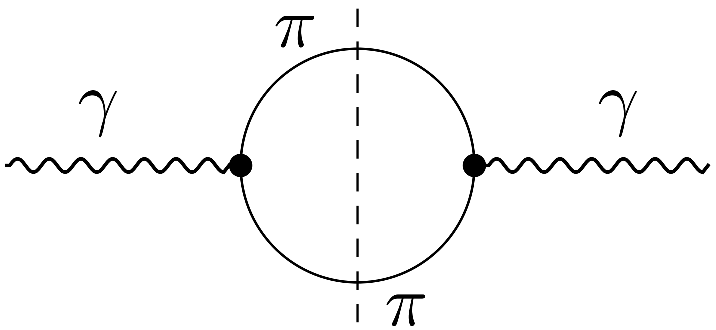
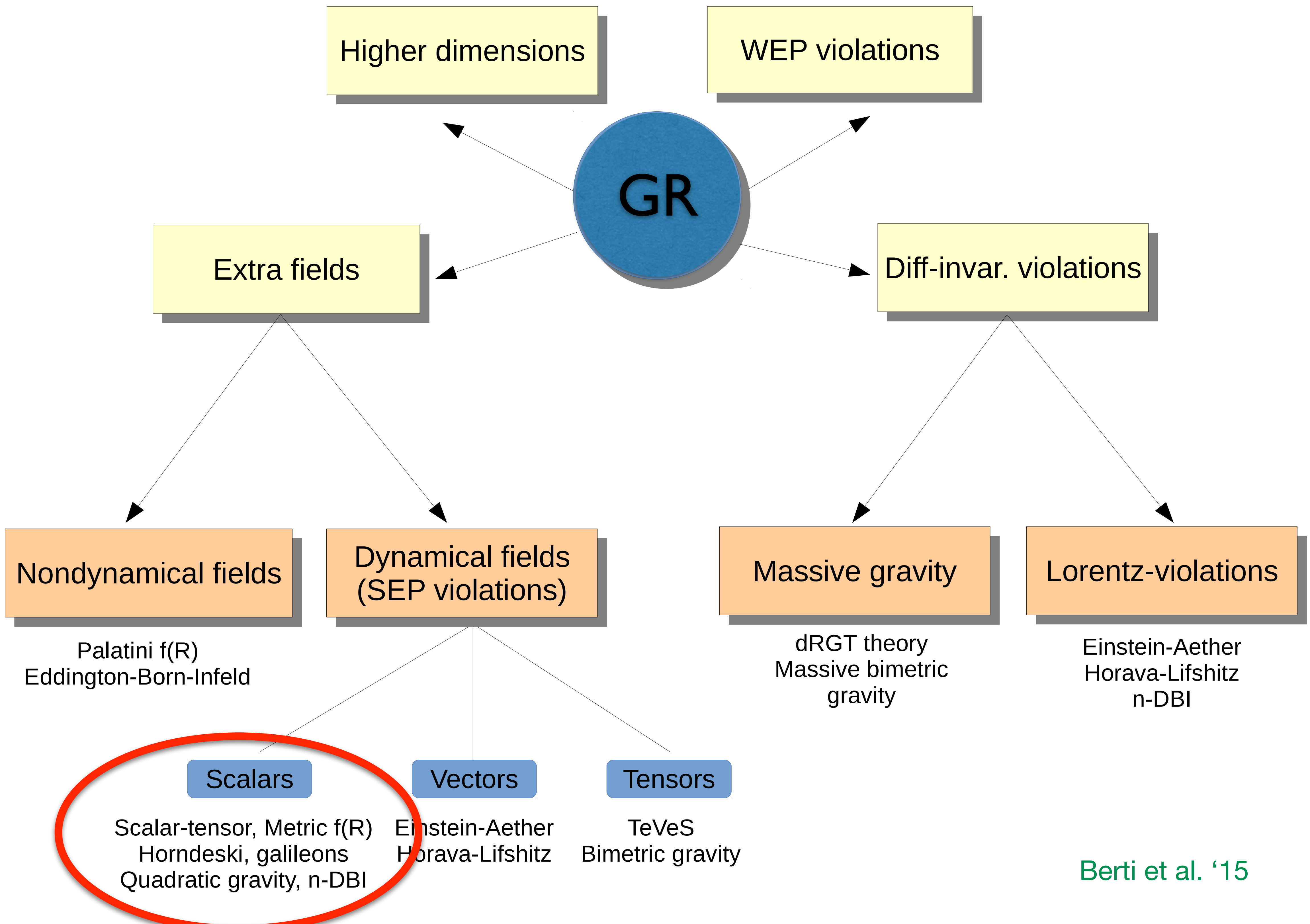


Similar to a refractive material

Simplest case: $f(k) \equiv m_\gamma^2\,, \qquad m_\gamma^2/\omega^2 < (d_S\omega)^{-1} \quad \Rightarrow \quad m_\gamma < 10^{-22}\ {\rm eV}$

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

Dark energy and modified gravity



Berti et al. ‘15

Scalar-tensor theories

Simplest models of modified gravity are base on single scalar field (universal coupling)

Ex: $$\mathcal{L} = R + V(\phi) - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$ quintessence

$$G_{\mu\nu} = 8\pi G \left(T^{(\mathrm{matter})}_{\mu\nu} + T^{(\phi)}_{\mu\nu} \right)$$

w ≠ -1

Scalar-tensor theories

Simplest models of modified gravity are base on single scalar field (universal coupling)

Ex: $$\mathcal{L} = R + G_2(\phi, X) \ , \quad X \equiv g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$ k-essence

$$G_{\mu\nu} = 8\pi G \left(T_{\mu\nu}^{(\mathrm{matter})} + T_{\mu\nu}^{(\phi)} \right)$$

$c_s^2 \neq 1$: clustering

Scalar-tensor theories

Simplest models of modified gravity are base on single scalar field (universal coupling)

Ex: $$\mathcal{L} = f(\phi)R + G_2(\phi, X) \ , \quad X \equiv g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$ scalar-tensor gravity

$$G_{\mu\nu}^{(\mathrm{modified})} = 8\pi G \left(T_{\mu\nu}^{(\mathrm{matter})} + T_{\mu\nu}^{(\phi)} \right)$$

self-acceleration

Modified gravity

Simplest models of modified gravity are base on single scalar field (universal coupling)

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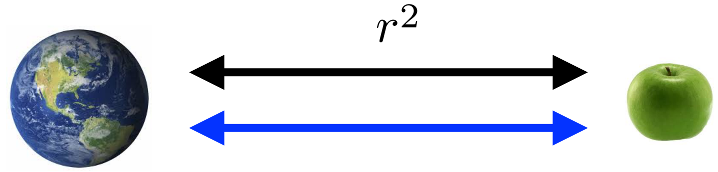
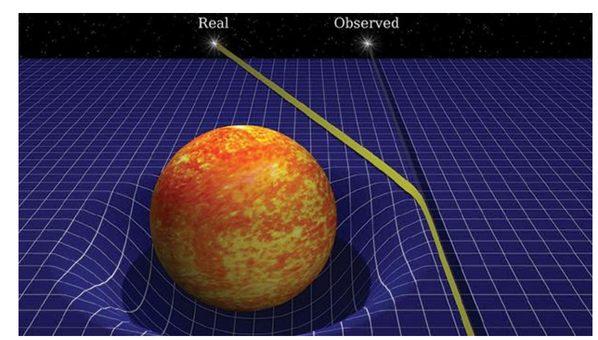
$$G_{\mu\nu}^{(\text{modified})} = 8\pi G \left(T_{\mu\nu}^{(\text{matter})} + T_{\mu\nu}^{(\phi)} \right)$$

$\frac{Gm_1m_2}{r^2}$



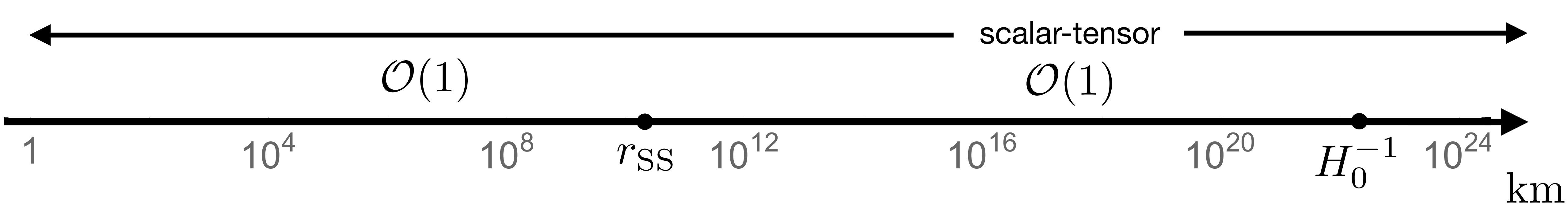
$\alpha^2\frac{Gm_1m_2}{r^2}$

fifth force



$\Psi \neq \Phi$

anomalous light bending



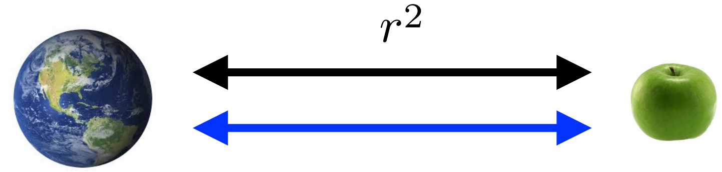
Screening

Simplest models of modified gravity are base on single scalar field (universal coupling)

Ex: $$\mathcal{L} = f(\phi)R + G_2(\phi, X) + \frac{\Box\phi}{\Lambda_3^3} G_3(\phi, X) \qquad \Box \equiv g^{\mu\nu}\nabla_\mu\nabla_\nu$$

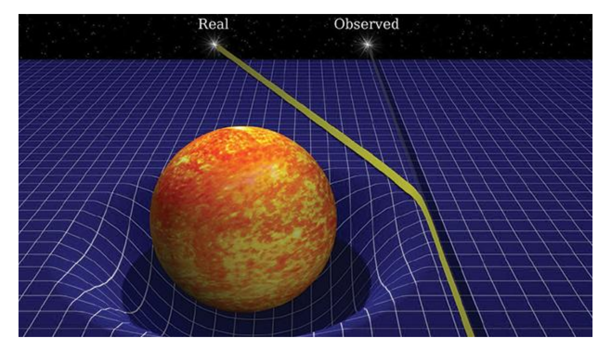
$\frac{\Box\phi}{\Lambda_3^3} \gg 1$ Vainshtein screening: large classical scalar field nonlinearities

$\frac{G m_1 m_2}{r^2}$



$\alpha^2 \frac{G m_1 m_2}{r^2}$

fifth force



$\Psi \neq \Phi$

anomalous light bending

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

scalar-tensor

$\mathcal{O}(1)$ $\mathcal{O}(1)$

1 Λ_3^{-1} 10^4 10^8 $r_{\rm SS}$ 10^{12} 10^{16} 10^{20} H_0^{-1} 10^{24}

km

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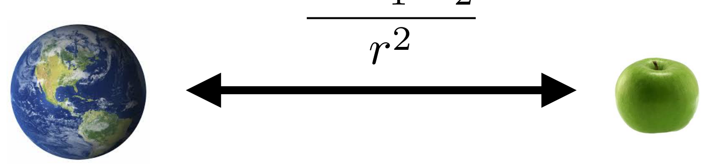

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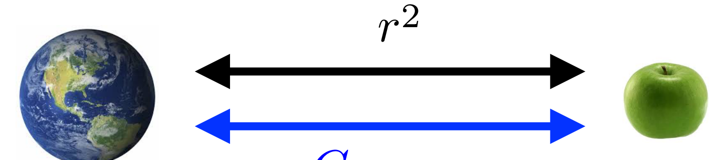

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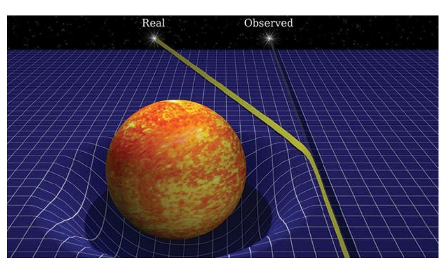
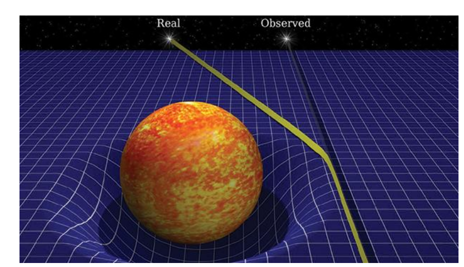


$\Psi = \Phi$



$\Psi \neq \Phi$

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

almost GR: $\ll \mathcal{O}(10^{-2})$

scalar-tensor: $\mathcal{O}(1)$

1 Λ_3^{-1} 10^4 10^8 $r_{\rm SS}$ 10^{12} 10^{16} 10^{20} H_0^{-1} 10^{24} km

$$\mathcal{L} = f(\phi)R + G_2(\phi, X) + \frac{\Box\phi}{\Lambda_3^3} G_3(\phi, X)$$

Is this the end of the story?

Generalized theories

Horndeski 73
Deffayet et al. 11

Most general Lorentz-invariant scalar-tensor theory with 2nd-order EOM.

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

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

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

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Degenerate theories: most general stable theory.

Langlois, Noui '15; Crisostomi, Koyama, Tasinato '16
Zumalacarregui, Garcia-Bellido '13

Beyond Horndeski theories:

Gleyzes, Langlois, Piazza, FV '14

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

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

$$XG_{5,X}F_4 = 3F_5\left[G_4 - 2XG_{4,X} - (X/2)G_{5,\phi}\right]$$

Setting c_T=1

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

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Scalar field play with gravity through higher derivatives:

$$\nabla_\mu\nabla_\nu\phi \supset \Gamma^\rho_{\mu\nu}\partial_\rho\phi \qquad \Rightarrow \qquad \Gamma^0_{ij}\,\dot\phi \supset \dot\gamma_{ij}\,\dot\phi$$

$$\mathcal{L}_\gamma \sim (\dot\gamma_{ij})^2 - c_T^2(\partial_k\gamma_{ij})^2$$

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

Expected from LSS: $|c_T^2 - 1| \lesssim \text{few} \times 0.01$

Setting c_T=1

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

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

What remains

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

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

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

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

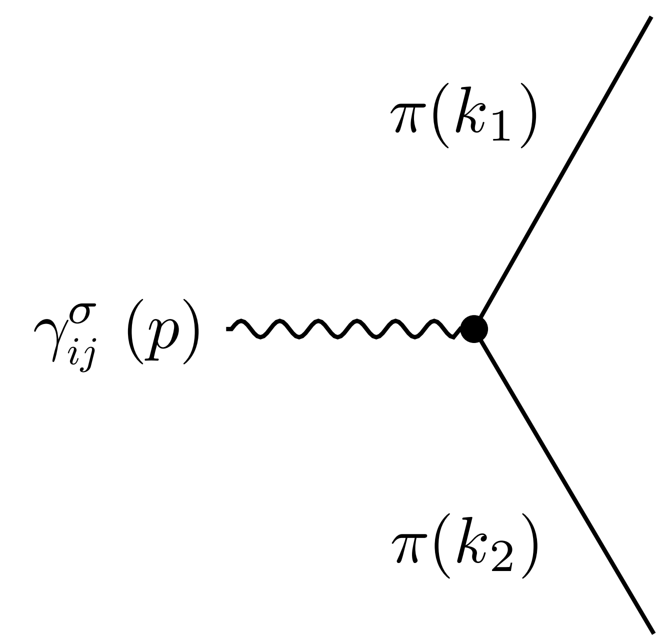
The decay of GW

Creminelli, Lewandowski, Tambalo, FV ‘18

Beyond Horndeski implies cubic interactions between GW and scalar fluctuations π

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

$$\Lambda_3 \equiv (M_{\rm Pl} H_0^2)^{1/3} \qquad \pi \equiv \delta\phi/\dot{\phi}_0$$



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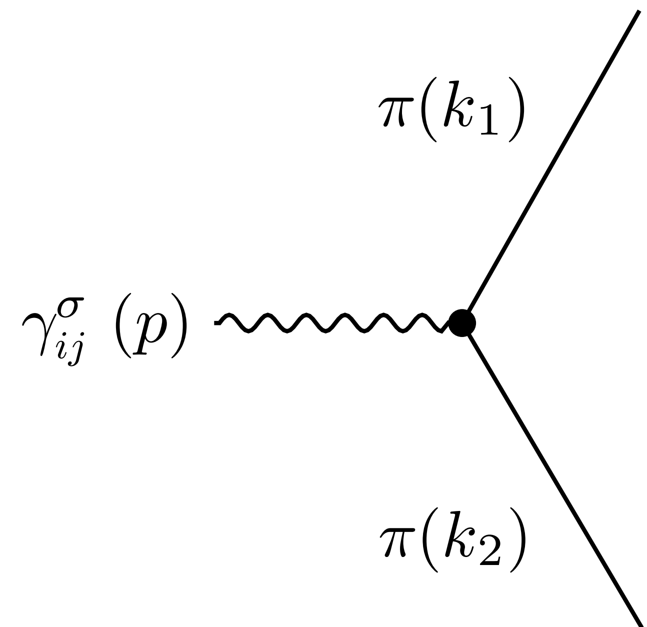


For $c_s < 1$ (c_s = sound speed of π fluctuations; assume c_T=1) GWs can decay into dark energy fluctuations πs. Analogous to Cherenkov radiation

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

decay rate

$$d_S \Gamma \ll 1 \qquad \Rightarrow \qquad \alpha_H \ll 10^{-10}$$

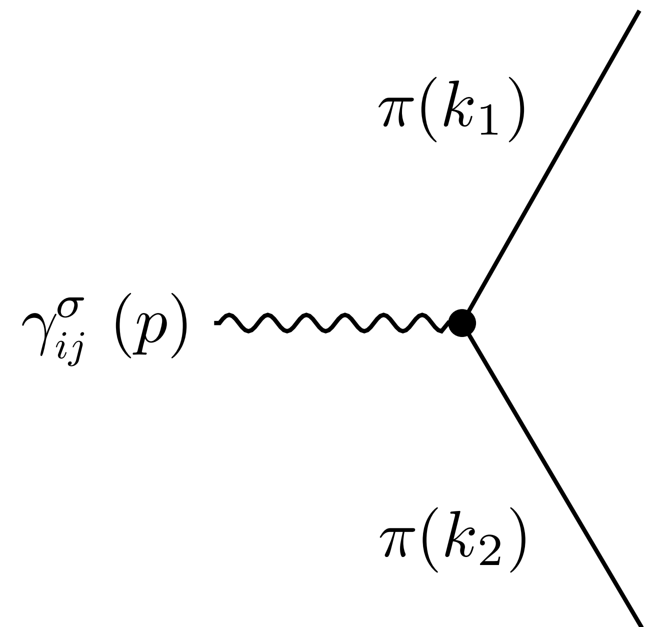
GW dispersion

Creminelli, Lewandowski, Tambalo, FV ‘18

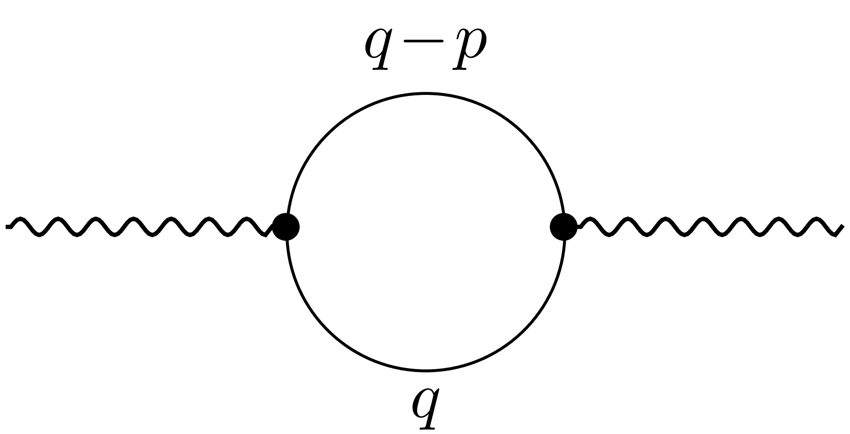
Spontaneous Lorentz-breaking implies modifications of the dispersion relation

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

$$\Lambda_3 \equiv (M_{\rm Pl} H_0^2)^{1/3} \qquad \pi \equiv \delta\phi/\dot{\phi}_0$$



Graviton self-energy, focussing on the calculable part:



$$\omega^2 = k^2 - \left(\frac{\alpha_H}{\Lambda_3^3}\right)^2 \frac{k^8(1-c_s^2)^2}{\pi c_s^7} \log\left(-(1-c_s^2)\frac{k^2}{\mu^2}\right)$$

Valid also for $c_s > 1$ (off-shell πs). Gives similar constraints on α_H.

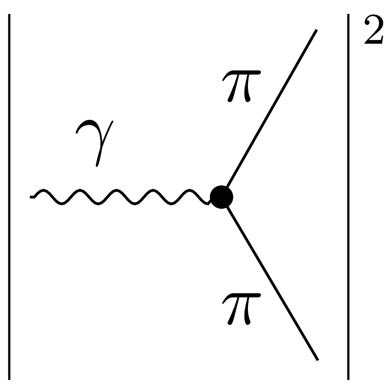
Optical theorem: $\Gamma(k)\omega(k) = \mathrm{Im}\left[f(k)\right]$

Gravitational Waves propagation

Modified gravity spontaneously breaks Lorentz Invariance. Acts like a medium, where gravitons are absorbed and dispersed.

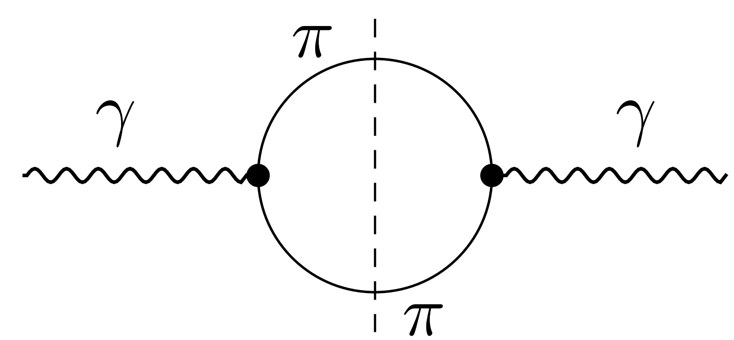
$$\ddot{\gamma}_{ij} + [(3+\alpha_{\rm M})H + \Gamma(k)]\,\dot{\gamma}_{ij} + \left[c_T^2 k^2 + f(k)\right]\gamma_{ij} = 0$$

decay



Similar to Cherenkov radiation

dispersion



Similar to a refractive material

$$\mu = \mu(\alpha_M, c_T^2 = 1, \alpha_H = 0, \ldots)\;, \qquad \Sigma = \Sigma(\alpha_M, c_T^2 = 1, \alpha_H = 0, \ldots)$$

What remains

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

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

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

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

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

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

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

What remains

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

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

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

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

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

$$XF_4 = 2G_{4,X} = 0$$

$$\alpha_H \equiv -\frac{X^2F_4}{G_4} = 0$$

What remains

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

Is this the end of the story?

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

Is this the end of the story? Yes.

GW decay rate and modification of the dispersion relation are suppressed

$$\mathcal{L}_{\gamma\pi\pi} \simeq \frac{1}{\Lambda_2^2}\dot{\gamma}_{ij}^c \partial_i \pi_c \partial_j \pi_c$$

$$\Lambda_2 \equiv (M_{\rm Pl} H_0)^{1/2} \sim 10^{10}\Lambda_3$$

The decay could be enhanced by the large occupation number ($\sim 10^{40}$) of the GW. Similar to preheating vs reheating.

$$\ddot{\pi} - c_s^2 \nabla^2 \pi + \frac{2\omega M_{\rm Pl}|h^+|}{\Lambda^2}\cos(\omega(t-z))(\partial_x^2 - \partial_y^2)\pi = 0$$

Analogous to a Mathieu equation ⇒ parametric resonance. Can we rule out G_3 as well?

Creminelli, Tambalo, FV, Yingcharoenrat, in progress…

Conclusion

- GWs can test gravity in the (strong) field regime (deviations in the dissipative and conservative dynamics, extra-polarizations, dipole, etc.)

- GWs also dramatically change the prospect for LSS: huge cut in available models

- Because c_T=1 and GW do not decay, many theories are ruled out: G_4, G_5, F_4, F_5 are absent