Exploring fundamental physics with gravitational waves

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THE UNIVERSITY OF SYDNEY

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Outline

- Gravitational waves as a testing ground for new physics

- GW from binary systems:

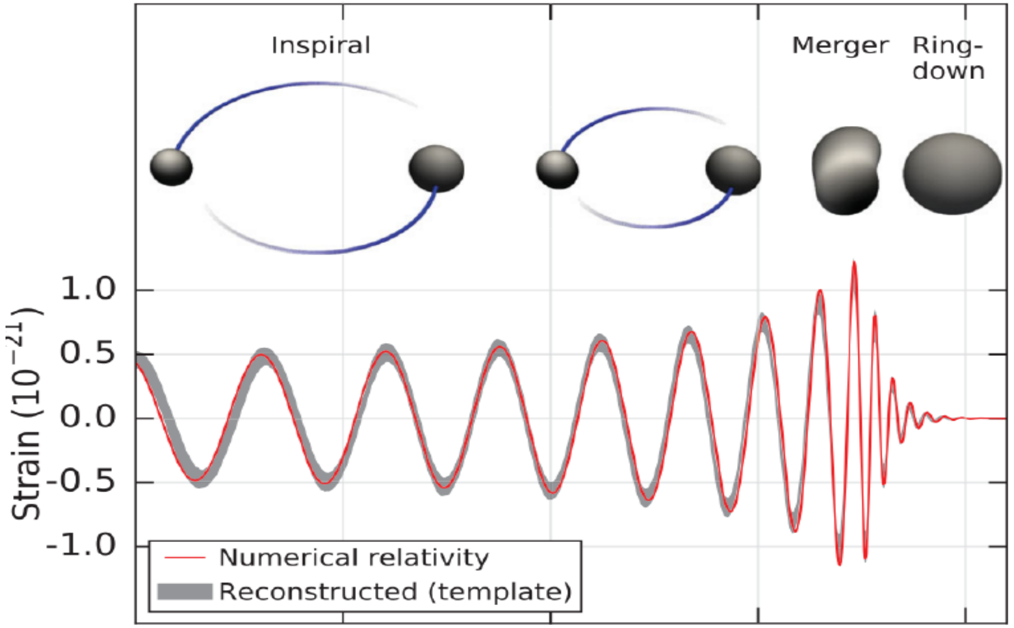
  - Inspiral phase: test of modified gravity; quantum space-time

  - Merger/ringdown phase: test of quantum horizons; exotic compact objects; dark energy; superradiance and light dark matter

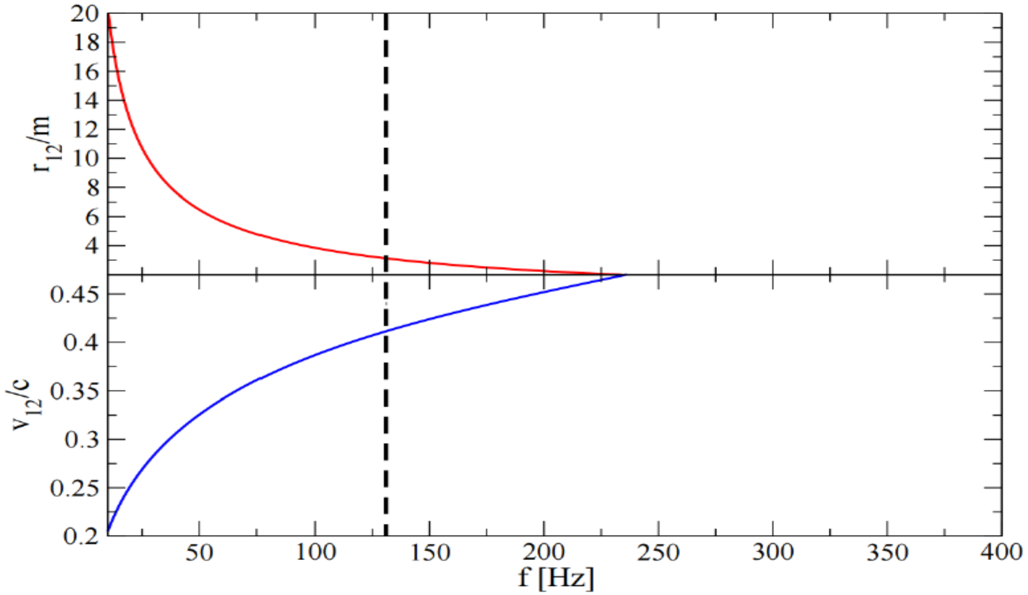
- GW and Higgs physics

GW150914,...

The LIGO detectors observed a binary black hole merger, with masses of $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$. Observed frequencies ranging from 35 to 250 Hz and speeds of up to $\sim 0.5c$.



[Phys. Rev. Lett. 116 (2016) 061102]



[arXiv:1603.08955]

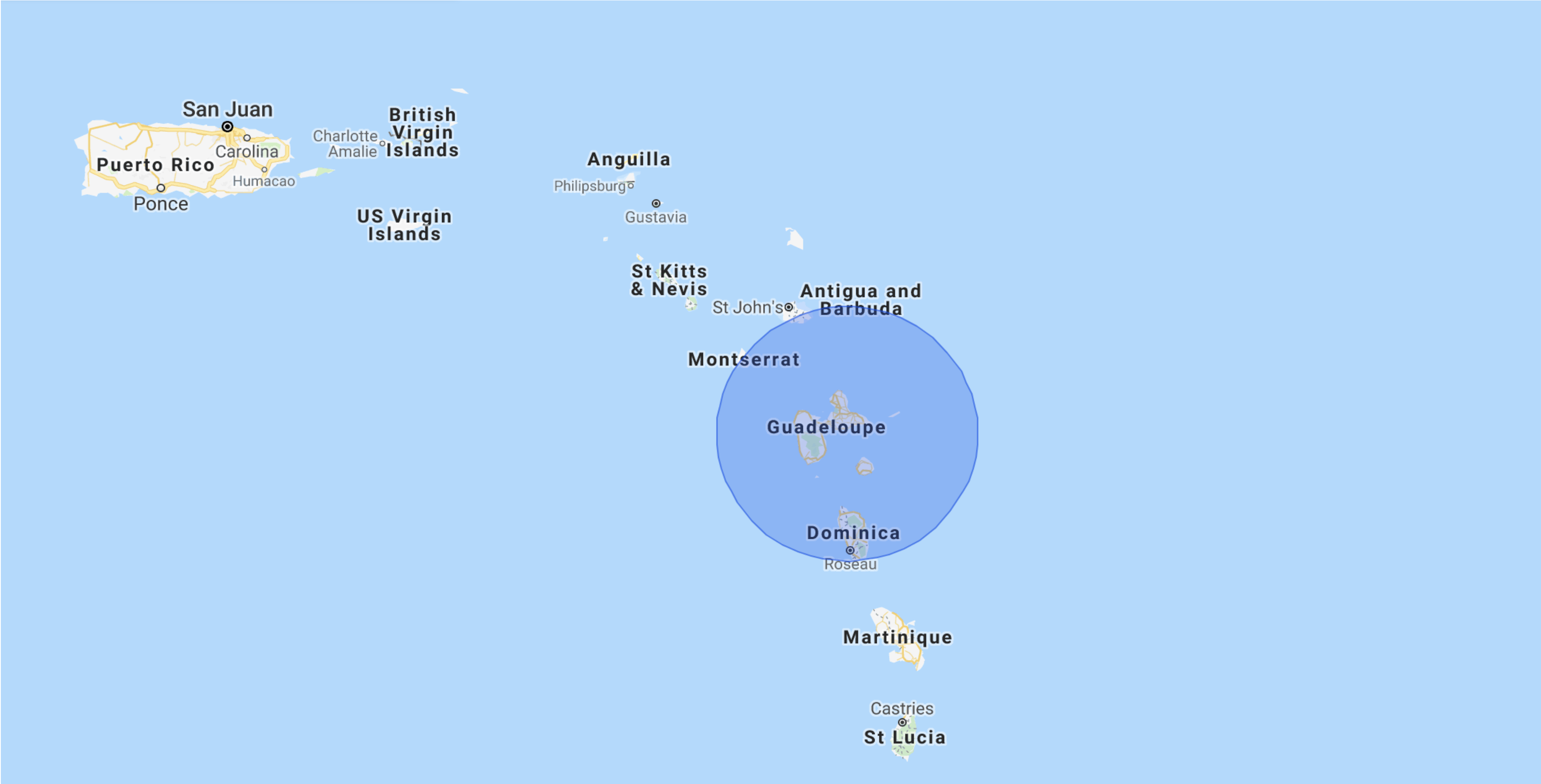
~410 Mpc away, emitted energy ~ 3 M_{sun} in 0.2s

GW150914,...

$$R_H = 2G(36M_{\odot}) \approx 106 \text{ km}$$

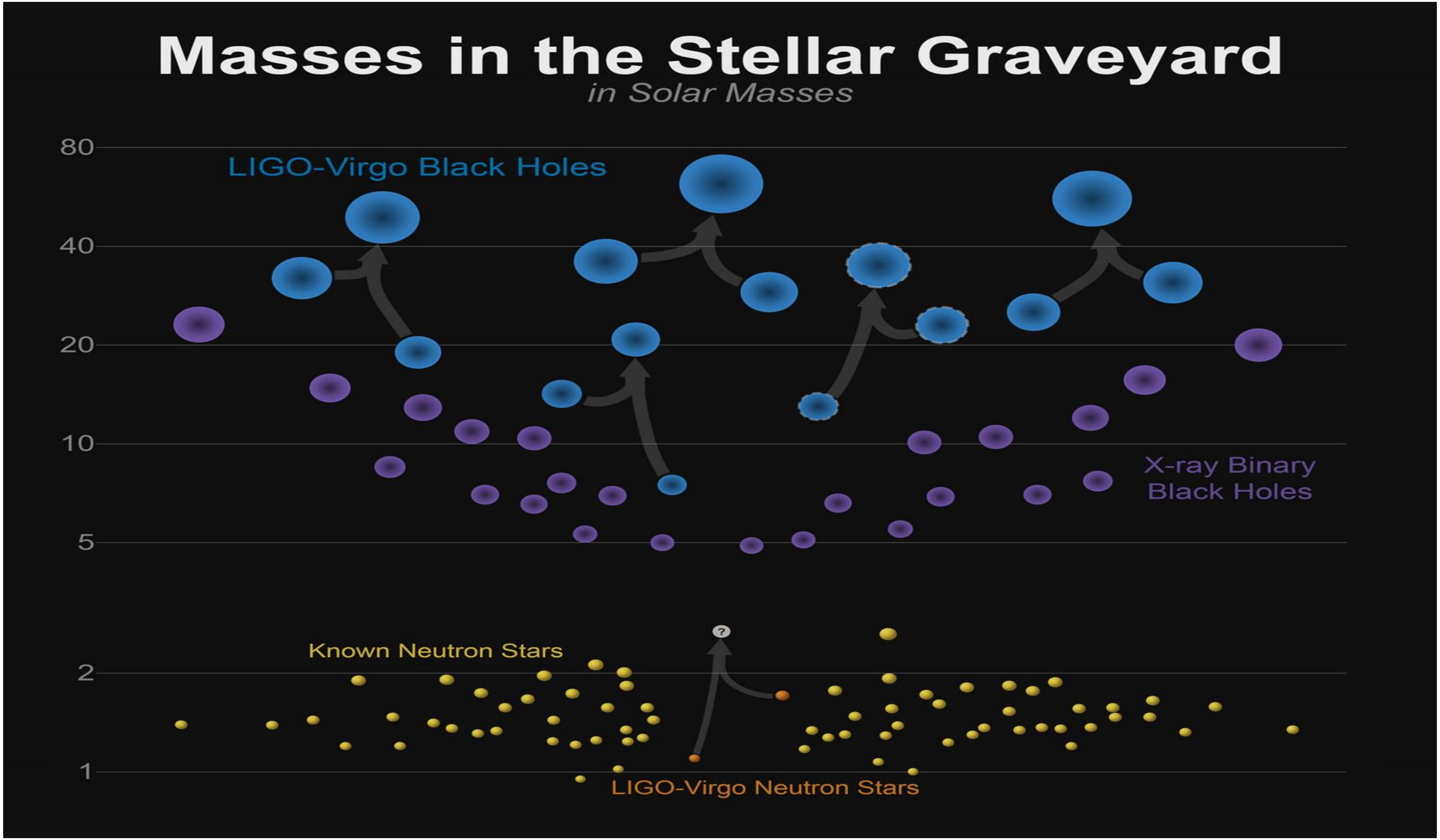
$$P = 3M_{\odot}/0.1s \approx 10^{22} L_{\odot}$$

(# of stars in the Universe ~10^{24})



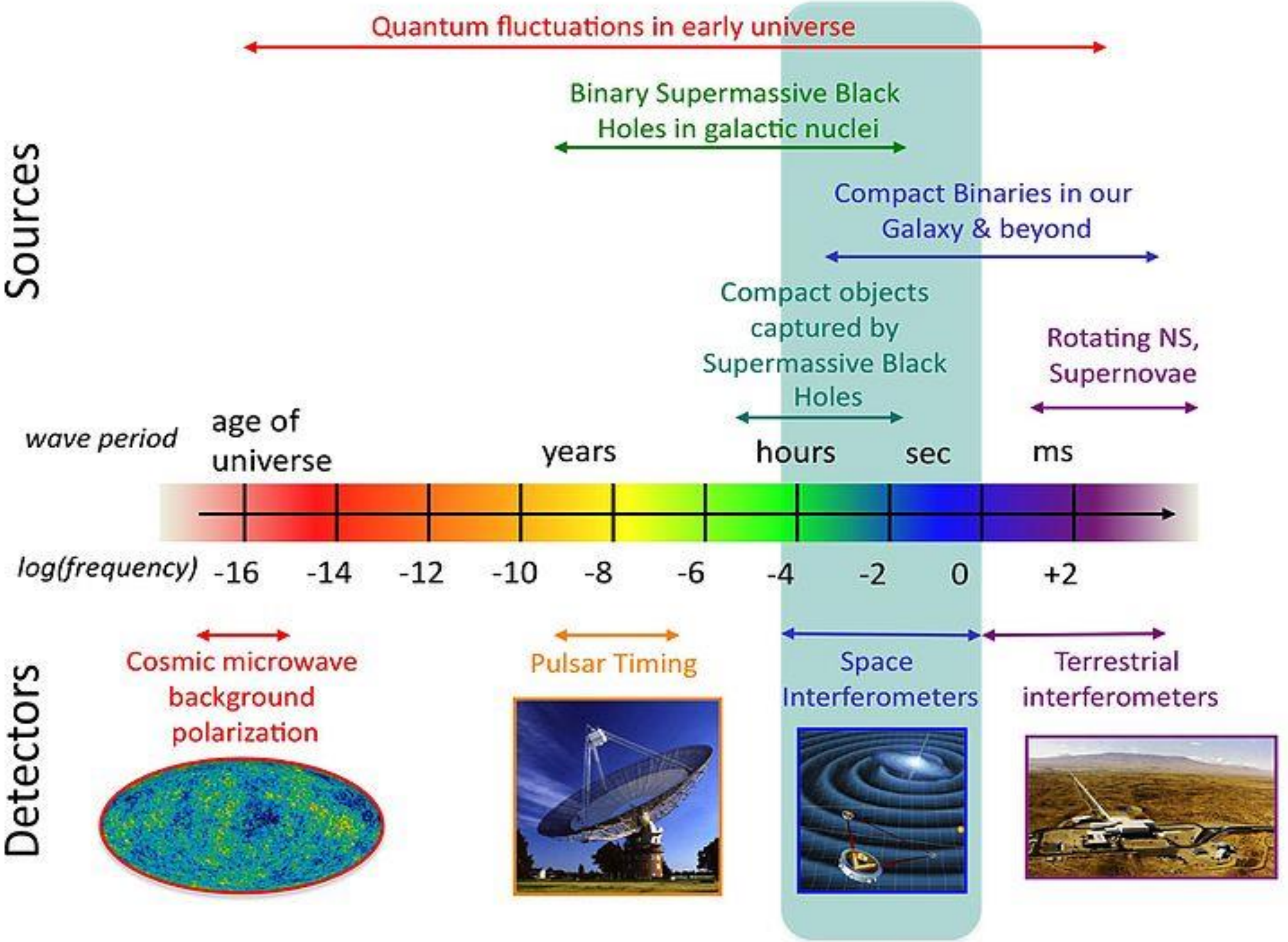
GW150914,…

GW detected in LIGO detectors via a subtle (~10^{-18} m) change in distance between their mirrors.

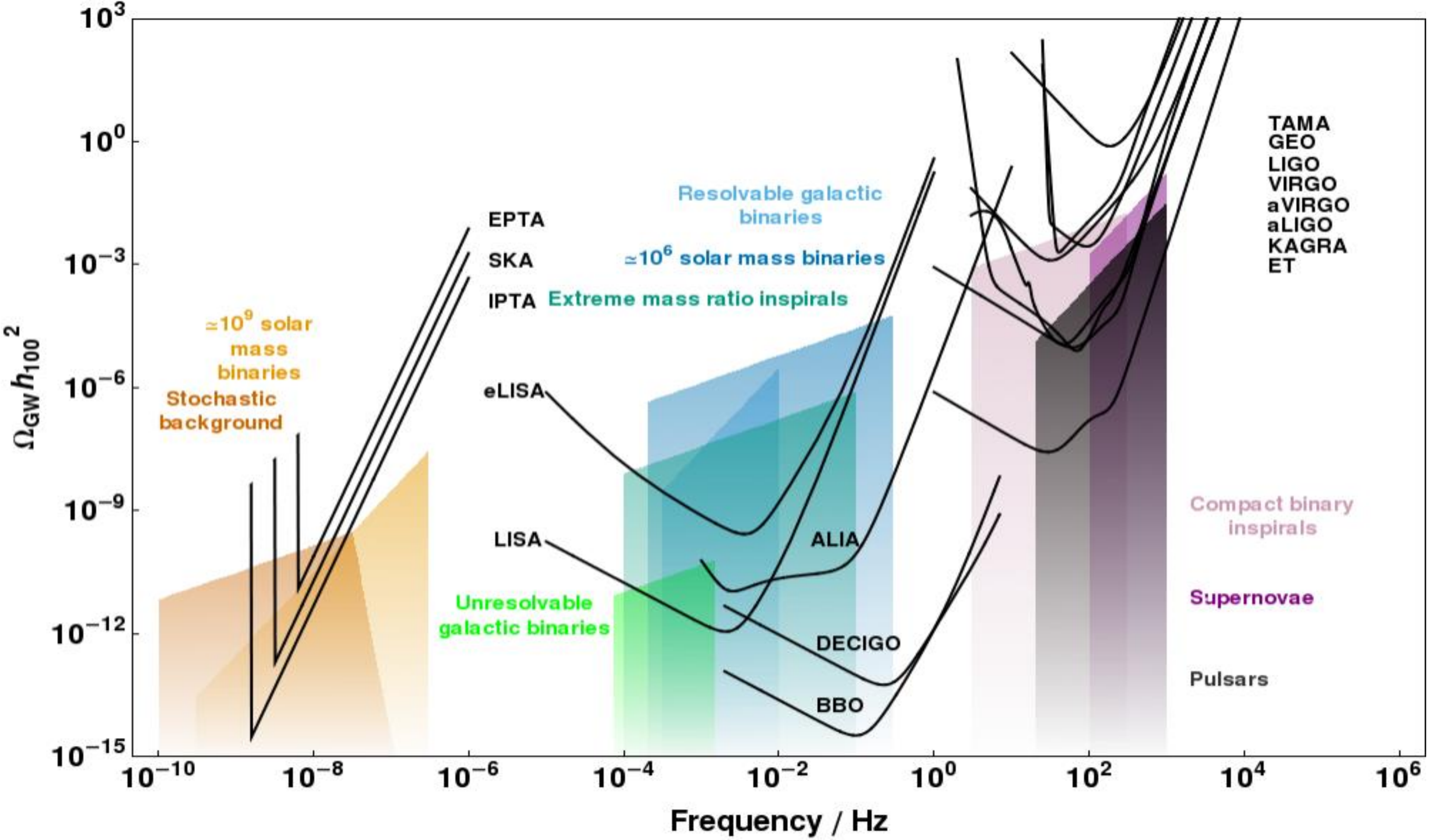


Credit: LIGO/VIRGO Collaboration

The Gravitational Wave Spectrum

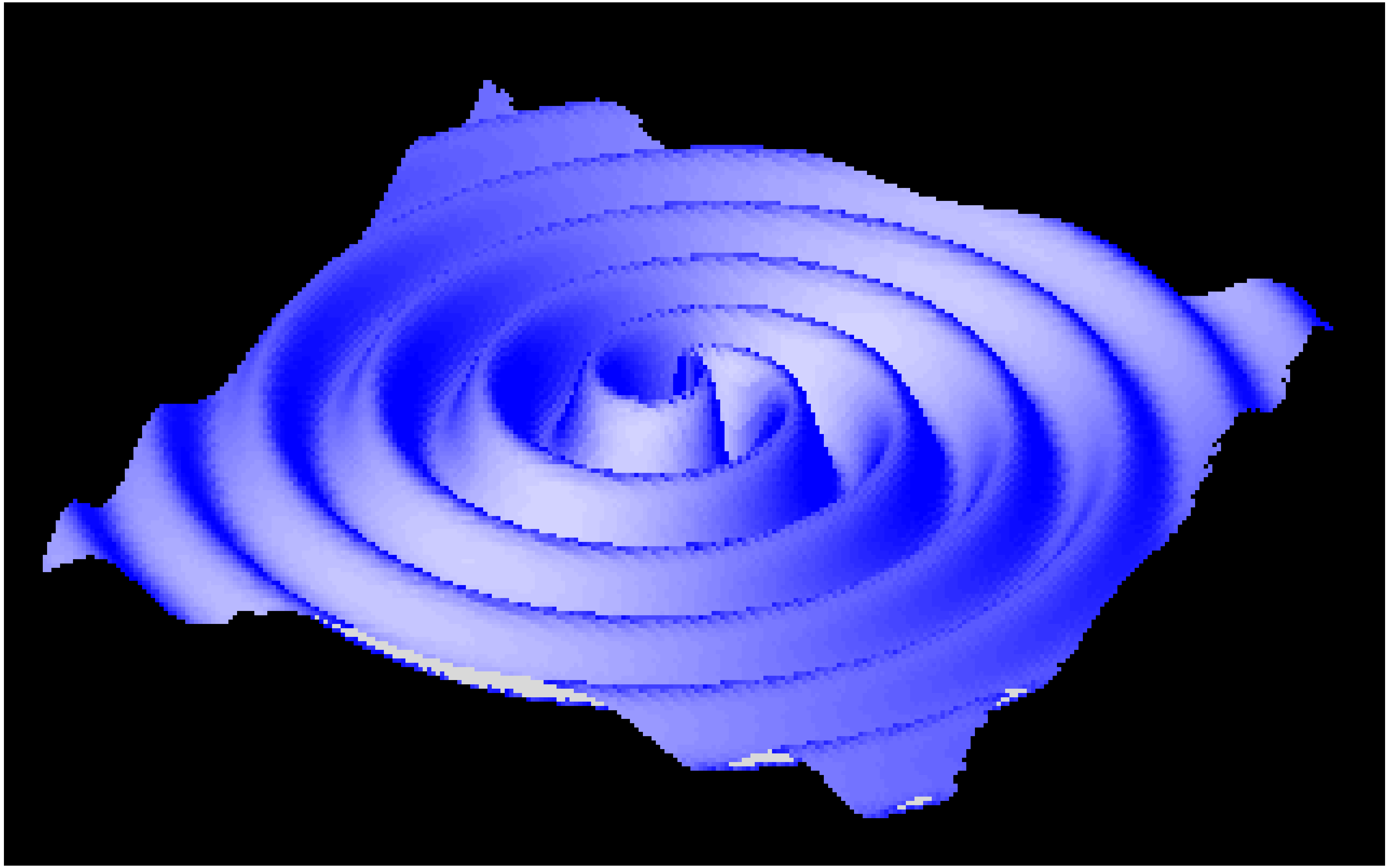


Credit: NASA Goddard Space Flight Center



C.J. Moore *et al.* Class.Quant.Grav. 32 (2015), 015014

Gravitational wave basics



GW basics: Radiation from compact objects

Gravitational waves

- Monopole - *M*

$$g \sim M/r^3,\ \dot{M}/r^2$$

(Gauge invariance = Birkhoff's theorem)

- Dipole - $P = \sum_i M_i s_i$

$$g \sim P/r^4,\ \dot{P}/r^3,\ \ddot{P}/r^2$$

(Newton's 3rd law)

- Quadrupole - $I = \sum_i M_i s_i \otimes s_j$

$$g \sim I/r^5,\ \dot{I}/r^4,\ \ddot{I}/r^3,\ \dddot{I}/r^2,\ \ddddot{I}/r$$

Electromagnetic waves

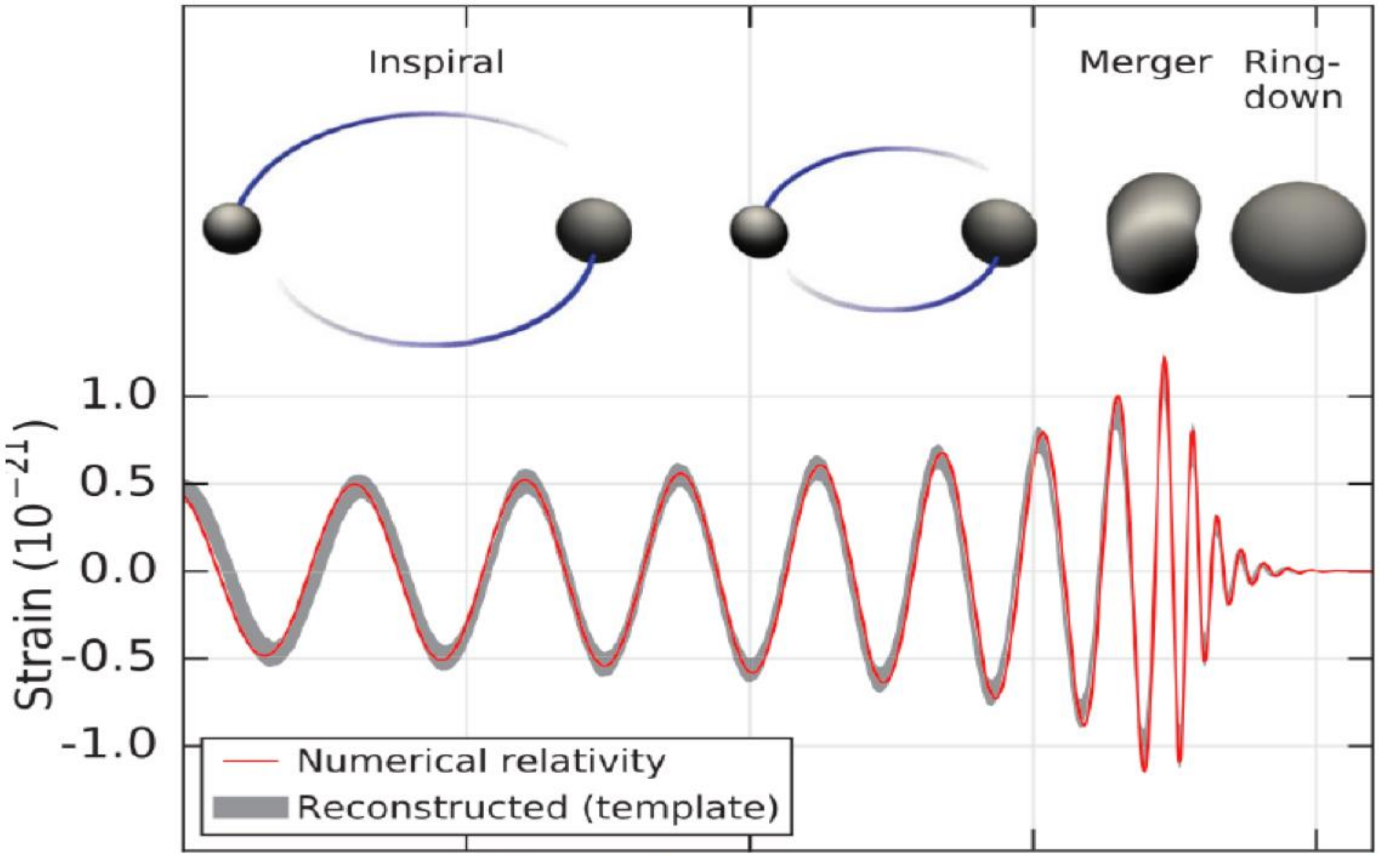
- Monopole - Q

$$E \sim Q/r^2,\ \dot{Q}/r$$

(Gauge invariance)

- Dipole - $P = \sum_i Q_i s_i$

$$E \sim P/r^3,\ \dot{P}/r^2,\ \ddot{P}/r$$

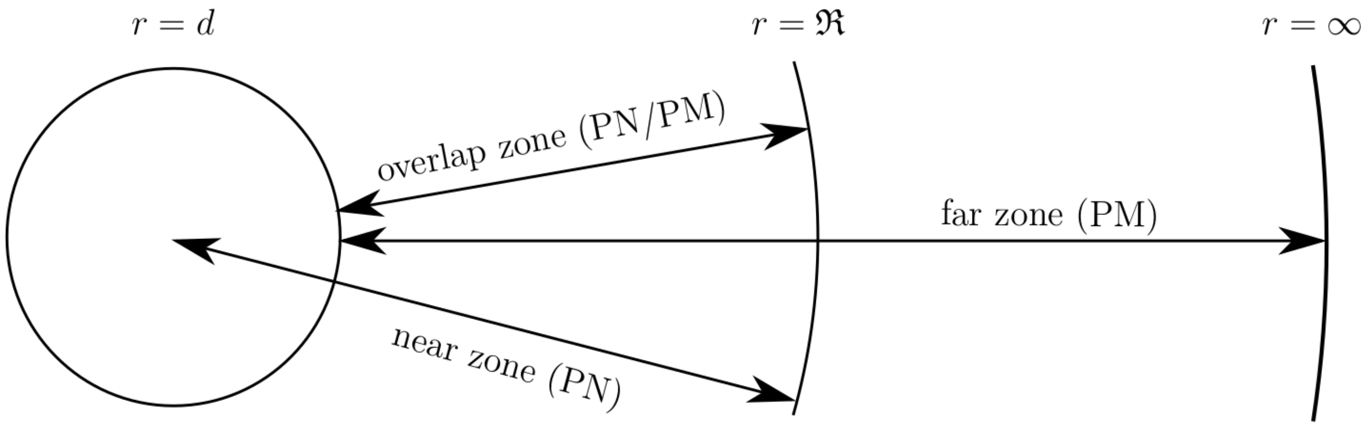


[Phys. Rev. Lett. 116 (2016) 061102]

- Insriral – analytical (3.5PN)
- Merger – numerical calculation (mainly GR)
- Ringdown – analytical (quasi-normal modes)

Inspiral phase – perturbative calculations

L. Blanchet, arXiv:1310.1528



PN expansion – $(v/c)^{2n}$

$$h^{\alpha\beta} = \sum_{n=2}^{\infty} \frac{1}{c^n} h_n^{\alpha\beta}$$

$$\tau^{\alpha\beta} = \sum_{n=-2}^{\infty} \frac{1}{c^n} \tau_n^{\alpha\beta}$$

$$\nabla^2 h_n^{\alpha\beta} = 16\pi G\, \tau_{n-4}^{\alpha\beta} + \partial_t^2 h_{n-2}^{\alpha\beta}$$

PM expansion – G^n

$$h^{\alpha\beta} = \sum_{n=1}^{\infty} G^n h_n^{\alpha\beta}$$

$$\Box h^{\alpha\beta} = \Lambda^{\alpha\beta}$$

$$\Box h_n^{\alpha\beta} = \Lambda_n^{\alpha\beta}[h_1, \cdots, h_{n-1}]$$

Inspiral phase – perturbative calculations

- BHs are considered as point masses:

$$T^{\mu\nu}(\mathbf{x},t) = \frac{m_1}{\sqrt{g g_{\rho\sigma}\frac{v_1^\rho v_1^\sigma}{c^2}}} v_1^\mu(t) v_1^\nu(t)\ \delta^3(\mathbf{x}-\mathbf{y}_1(t)) + 1 \leftrightarrow 2$$

(Requires regularization)

- Parameterization

$$M = m_1 + m_2$$

$$\mu = \frac{m_1 m_2}{M}$$

$$\nu = \frac{\mu}{M} = \frac{m_1 m_2}{M^2}$$

Inspiral phase – perturbative calculations

- EoM and Energy

$$\nabla_\nu T^{\mu\nu} = 0$$

$$\mathbf{a}_1 = -\frac{Gm_2}{r_{12}^2}\mathbf{n}_{12} + \mathcal{O}(2)$$

$$E = \frac{m_1 v_1^2}{2} - \frac{Gm_1 m_2}{2r_{12}} + \mathcal{O}(2) + 1 \leftrightarrow 2$$

- Radiated flux

$$\mathcal{F} = \frac{G}{c^5}\left(\frac{1}{5}I_{ij}^{(3)}I_{ij}^{(3)} + \mathcal{O}(2)\right) = \frac{G}{c^5}\left(\frac{32G^3M^5\nu^2}{5r^5} + \mathcal{O}(2)\right)$$

- Balance eq.

$$\frac{dE}{dt} = -\mathcal{F} \quad \Rightarrow \quad \phi = \int \Omega(t)dt$$

Constraints from GW150914

N. Yunes, K.Yagi, F. Pretorius, PRD 94 (2016) 084002

Theoretical Mechanism	GR Pillar	PN	$\lvert\beta\rvert$ GW150914	$\lvert\beta\rvert$ GW151226	Repr. Parameters	Example Theory Constraints GW150914	Example Theory Constraints GW151226	Current Bounds
Scalar Field Activation	SEP	-1	$\mathbf{1.6 \times 10^{-4}}$	$\mathbf{4.4 \times 10^{-5}}$	$\sqrt{\lvert\alpha_{\rm EdGB}\rvert}$ [km] $\lvert\dot{\phi}\rvert$ [1/sec]	— —	— —	10^7 [56], 2 [57–59] 10^{-6} [60]
Scalar Field Activation	SEP, PI	$+2$	$\mathbf{1.3 \times 10^{1}}$	$\mathbf{4.1}$	$\sqrt{\lvert\alpha_{\rm dCS}\rvert}$ [km]	—	—	10^8 [61, 62]
Vector Field Activation	SEP, LI	0	$\mathbf{7.2 \times 10^{-3}}$	$\mathbf{3.4 \times 10^{-3}}$	(c_+, c_-) $(\beta_{\rm KG}, \lambda_{\rm KG})$	$\mathbf{(0.9, 2.1)}$ $\mathbf{(0.42, -)}$	$\mathbf{(0.8, 1.1)}$ $\mathbf{(0.40, -)}$	$(0.03, 0.003)$ [63, 64] $(0.005, 0.1)$ [63, 64]
Extra Dimensions	4D	-4	$\mathbf{9.1 \times 10^{-9}}$	$\mathbf{9.1 \times 10^{-11}}$	ℓ [μm]	$\mathbf{5.4 \times 10^{10}}$	$\mathbf{2.0 \times 10^{9}}$	10–10^3 [65–69]
Time-Varying G	SEP	-4	$\mathbf{9.1 \times 10^{-9}}$	$\mathbf{9.1 \times 10^{-11}}$	$\lvert\dot{G}\rvert$ [10^{-12}/yr]	$\mathbf{5.4 \times 10^{18}}$	$\mathbf{1.7 \times 10^{17}}$	0.1–1 [70–74]
Massive graviton	$m_g = 0$	$+1$	$\mathbf{1.3 \times 10^{-1}}$	$\mathbf{8.9 \times 10^{-2}}$	m_g [eV]	$\mathbf{10^{-22}}$ [19]	$\mathbf{10^{-22}}$ [5]	10^{-29}–10^{-18} [75–79]
Mod. Disp. Rel. (*Multifractional*)	LI	$+4.75$	$\mathbf{1.1 \times 10^{2}}$	$\mathbf{2.6 \times 10^{2}}$	E_*^{-1} [eV^{-1}] (time) E_*^{-1} [eV^{-1}] (space)	$\mathbf{5.8 \times 10^{-27}}$ $\mathbf{1.0 \times 10^{-26}}$	$\mathbf{3.3 \times 10^{-26}}$ $\mathbf{5.7 \times 10^{-26}}$	— 3.9×10^{-53} [80]
Mod. Disp. Rel. (*Modified Special Rel.*)	LI	$+5.5$	$\mathbf{1.4 \times 10^{2}}$	$\mathbf{4.3 \times 10^{2}}$	$\eta_{\rm dsrt}/L_{\rm Pl} > 0$ $\eta_{\rm dsrt}/L_{\rm Pl} < 0$	$\mathbf{1.3 \times 10^{22}}$	$\mathbf{3.8 \times 10^{22}}$	— 2.1×10^{-7} [80]
Mod. Disp. Rel. (*Extra Dim.*)	4D	$+7$	$\mathbf{5.3 \times 10^{2}}$	$\mathbf{2.4 \times 10^{3}}$	$\alpha_{\rm edt}/L_{\rm Pl}^2 > 0$ $\alpha_{\rm edt}/L_{\rm Pl}^2 < 0$	$\mathbf{5.5 \times 10^{62}}$	$\mathbf{2.5 \times 10^{63}}$	2.7×10^{2} [80] —
Mod. Disp. Rel. (*Standard Model Ext.*)	LI	$+4$	—	—	$\mathring{k}^{(4)}_{(I)} > 0$ $\mathring{k}^{(4)}_{(I)} < 0$	— $\mathbf{0.64}$	— $\mathbf{19}$	6.1×10^{-17} [80, 81] —
		$+5.5$	$\mathbf{1.4 \times 10^{2}}$	$\mathbf{4.3 \times 10^{2}}$	$\mathring{k}^{(5)}_{(V)} > 0$ [cm] $\mathring{k}^{(5)}_{(V)} < 0$ [cm]	$\mathbf{1.7 \times 10^{-12}}$ [82]	$\mathbf{3.1 \times 10^{-11}}$	1.7×10^{-40} [80, 81] —
		$+7$	$\mathbf{5.3 \times 10^{2}}$	$\mathbf{2.4 \times 10^{3}}$	$\mathring{k}^{(6)}_{(I)} > 0$ [cm^2] $\mathring{k}^{(6)}_{(I)} < 0$ [cm^2]	$\mathbf{7.2 \times 10^{-4}}$	$\mathbf{3.3 \times 10^{-3}}$	3.5×10^{-64} [80, 81] —
Mod. Disp. Rel. (*Hořava-Lifshitz*)	LI	$+7$	$\mathbf{5.3 \times 10^{2}}$	$\mathbf{2.4 \times 10^{3}}$	$\kappa_{\rm hl}^4 \mu_{\rm hl}^2$ [1/eV^2]	$\mathbf{1.5 \times 10^{6}}$	$\mathbf{6.9 \times 10^{6}}$	—
Mod. Disp. Rel. (*Lorentz Violation*)	LI	$+4$	—	—	c_+	$\mathbf{0.7}$ [83]	$\mathbf{0.998}$	0.03 [63, 64]

Most of the competitive bounds so far come from the propagation of gravitational waves. Lack of theoretical understanding of the coalescence regime in almost all relevant modified gravity theories severely limits the true potential of current gravitational wave observations to explore such theories. More theoretical work must be done.

Constraining quantum spacetime

AK, C. Lagger, A. Manning, PRD 94 (2016), 064033

- The idea of quantum spacetime traces back to Heisenberg and Pauli – regularization of divergences in QFT – H. Snyder Phys. Rev. 71 (1947) 38-41

- Revival within the string theory – F. Ardalan, H. Arfaei, M.M. Sheikh-Jabbari, JHEP 9902 (1999) 016; N. Seiberg and E. Witten, JHEP 9909 (1999) 032.

$$[\hat{x}^{\mu}, \hat{x}^{\nu}] = i\ell^2\theta^{\mu\nu}$$

- Particle physics constraints: $\ell \sim 1/TeV$

NC correction to GW waveform

- Corrections to EM tensor

$$T^{\mu\nu}(\mathbf{x},t) = m_1\gamma_1 v_1^\mu v_1^\nu \delta^3(\mathbf{x}-\mathbf{y}_1(t)) + \frac{m_1^3 G^2 \Lambda^2}{8c^4} v_1^\mu v_1^\nu \theta^k \theta^l \partial_k \partial_l \, \delta^3(\mathbf{x}-\mathbf{y}_1(t)) + 1 \leftrightarrow 2$$

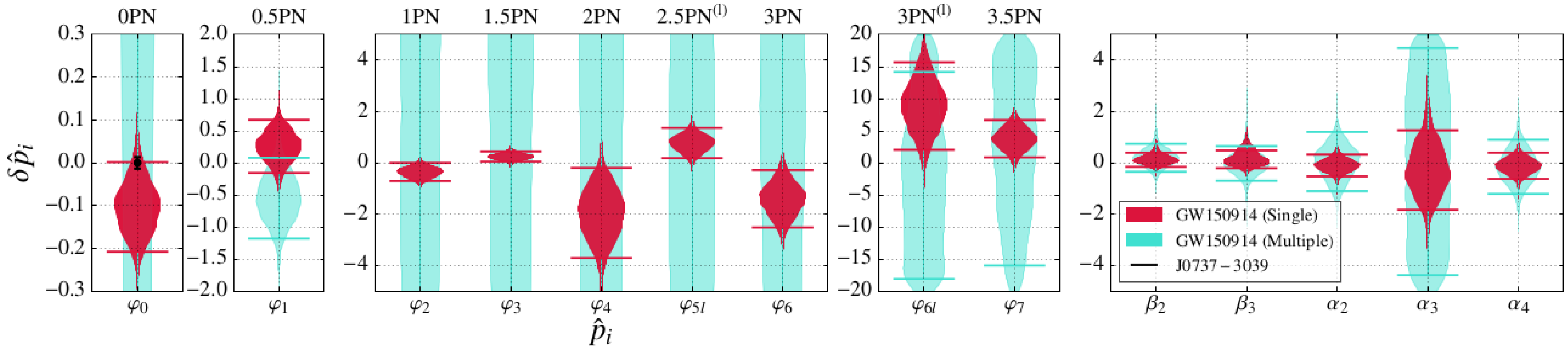
$$\Lambda\theta^i = \frac{\ell^2 \theta^{0i}}{l_P t_P}.$$

- Correction to GR model-dependent, $\mathcal{O}(\ell^4)$ - ignore

- After lengthy calculations we find NC correction to the phase at 2PN

$$\varphi_4 = \frac{15293365}{508032} + \frac{27145}{504}\nu + \frac{3085}{72}\nu^2 + \frac{5}{4}(1-2\nu)\Lambda^2$$

waveform regime	parameter	f-dependence	median single	median multiple	GR quantile single	GR quantile multiple	$\log_{10} B^{\rm GR}_{\rm model}$ single	$\log_{10} B^{\rm GR}_{\rm model}$ multiple
early-inspiral regime	$\delta\hat{\varphi}_0$	$f^{-5/3}$	$-0.1^{+0.1}_{-0.1}$	$1.3^{+3.0}_{-3.2}$	0.94	0.30	1.9 ± 0.2	3.7 ± 0.6
	$\delta\hat{\varphi}_1$	$f^{-4/3}$	$0.3^{+0.4}_{-0.4}$	$-0.5^{+0.6}_{-0.6}$	0.16	0.93	1.6 ± 0.2	
	$\delta\hat{\varphi}_2$	f^{-1}	$-0.4^{+0.3}_{-0.4}$	$-1.6^{+18.8}_{-16.6}$	0.96	0.56	1.2 ± 0.2	
	$\delta\hat{\varphi}_3$	$f^{-2/3}$	$0.2^{+0.2}_{-0.2}$	$2.0^{+13.4}_{-13.9}$	0.02	0.42	1.2 ± 0.2	
	$\delta\hat{\varphi}_4$	$f^{-1/3}$	$-1.9^{+1.6}_{-1.7}$	$-1.9^{+19.3}_{-16.4}$	0.98	0.56	0.3 ± 0.2	
	$\delta\hat{\varphi}_{5l}$	$\log(f)$	$0.8^{+0.5}_{-0.6}$	$-1.4^{+18.6}_{-16.9}$	0.01	0.55	0.7 ± 0.4	
	$\delta\hat{\varphi}_6$	$f^{1/3}$	$-1.4^{+1.1}_{-1.1}$	$1.2^{+16.8}_{-18.9}$	0.99	0.47	0.4 ± 0.2	
	$\delta\hat{\varphi}_{6l}$	$f^{1/3}\log(f)$	$8.9^{+6.8}_{-6.8}$	$-1.9^{+19.1}_{-16.1}$	0.02	0.57	-0.3 ± 0.2	
	$\delta\hat{\varphi}_7$	$f^{2/3}$	$3.8^{+2.9}_{-2.9}$	$3.2^{+15.1}_{-19.2}$	0.02	0.41	-0.0 ± 0.2	
intermediate regime	$\delta\hat{\beta}_2$	$\log f$	$0.1^{+0.4}_{-0.3}$	$0.2^{+0.6}_{-0.5}$	0.24	0.28	1.4 ± 0.2	2.3 ± 0.2
	$\delta\hat{\beta}_3$	f^{-3}	$0.1^{+0.6}_{-0.3}$	$-0.0^{+0.8}_{-0.7}$	0.31	0.56	1.2 ± 0.4	
merger-ringdown regime	$\delta\hat{\alpha}_2$	f^{-1}	$-0.1^{+0.4}_{-0.4}$	$0.0^{+1.0}_{-1.2}$	0.68	0.50	1.2 ± 0.2	2.1 ± 0.4
	$\delta\hat{\alpha}_3$	$f^{3/4}$	$-0.3^{+1.9}_{-1.5}$	$0.0^{+4.4}_{-4.4}$	0.60	0.51	0.7 ± 0.2	
	$\delta\hat{\alpha}_4$	$\tan^{-1}(af+b)$	$-0.1^{+0.5}_{-0.5}$	$-0.1^{+1.1}_{-1.0}$	0.68	0.62	1.1 ± 0.2	



Constraint on NC parameter from GW150914

$$\delta\varphi_4^{NC} = \frac{\varphi_4^{NC}}{\varphi_4^{GR}} = \frac{1270080\,(1-2\nu)}{4353552\,\nu^2 + 5472432\,\nu + 3058673}\Lambda^2$$

$$|\delta\varphi_4^{NC}| \lesssim 20 \Rightarrow \sqrt{\Lambda} \lesssim 3.5$$

- Plnack-scale noncommutativity, 15 orders of magnitude stronger bound compared to previous constraints derived from particle physics processes.

Merger/ringdown phase

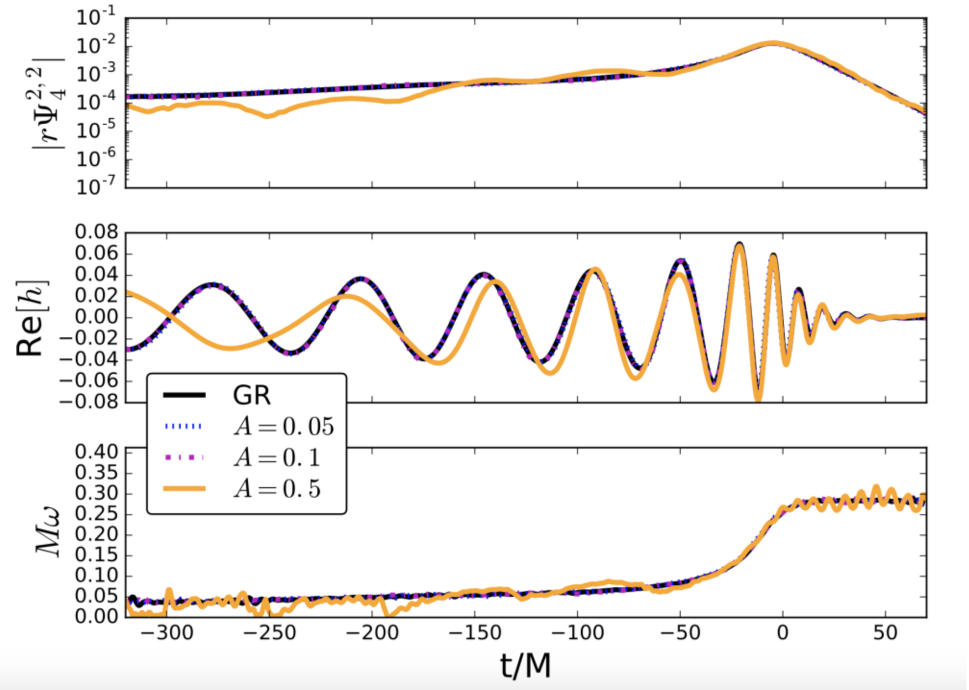
- Merger phase:
  - Access to the strong gravity regime
  - Numerical studies beyond GR are currently scarce

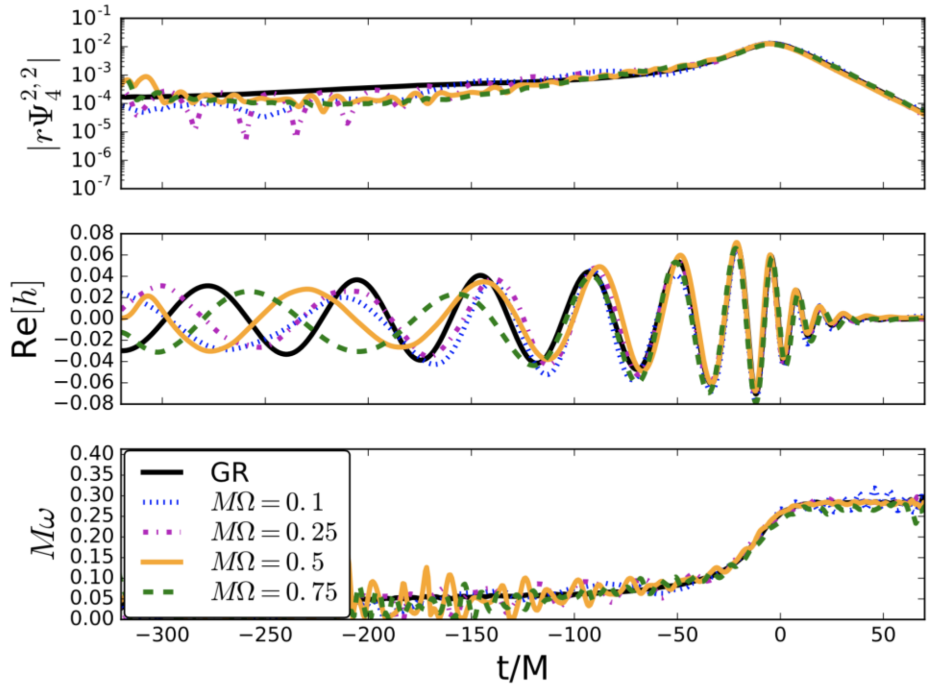
- Ringdown phase
  - Linear perturbation of black hole; quasi-normal modes (QNM)

- Test of physics beyond classical black holes potentially related with quantum corrections to classical horizons and proposed resolutions of information loss paradox (fuzzball, firewalls, non-violent non-locality); Exotic compact objects (gravastar, dark matter stars, NS stars with modified QCD equation of state, etc.)

Non-violent non-locality – merger phase test

- Black hole interior transmits information via large near horizon fluctuations, which must be soft to comply with local QFT [S. Giddings, PRD 88 (2013) 064023].
- Incorporate such metric fluctuations into numerical calculation of waveform [S.L. Liebling, M. Lippert, M. Kavsic, JHEP 1803 (2018) 176].





Gravitational echoes – ringdown phase test of ECOs

- Space-time of a compact spherical object of mass *M* and size :

$$r_0 = r_{bh}(1+\epsilon),\ \ r_{bh} = 2GM$$

$$ds^2 = -F(r)dt^2 + B(r)dr^2 + r^2 d\Omega^2$$

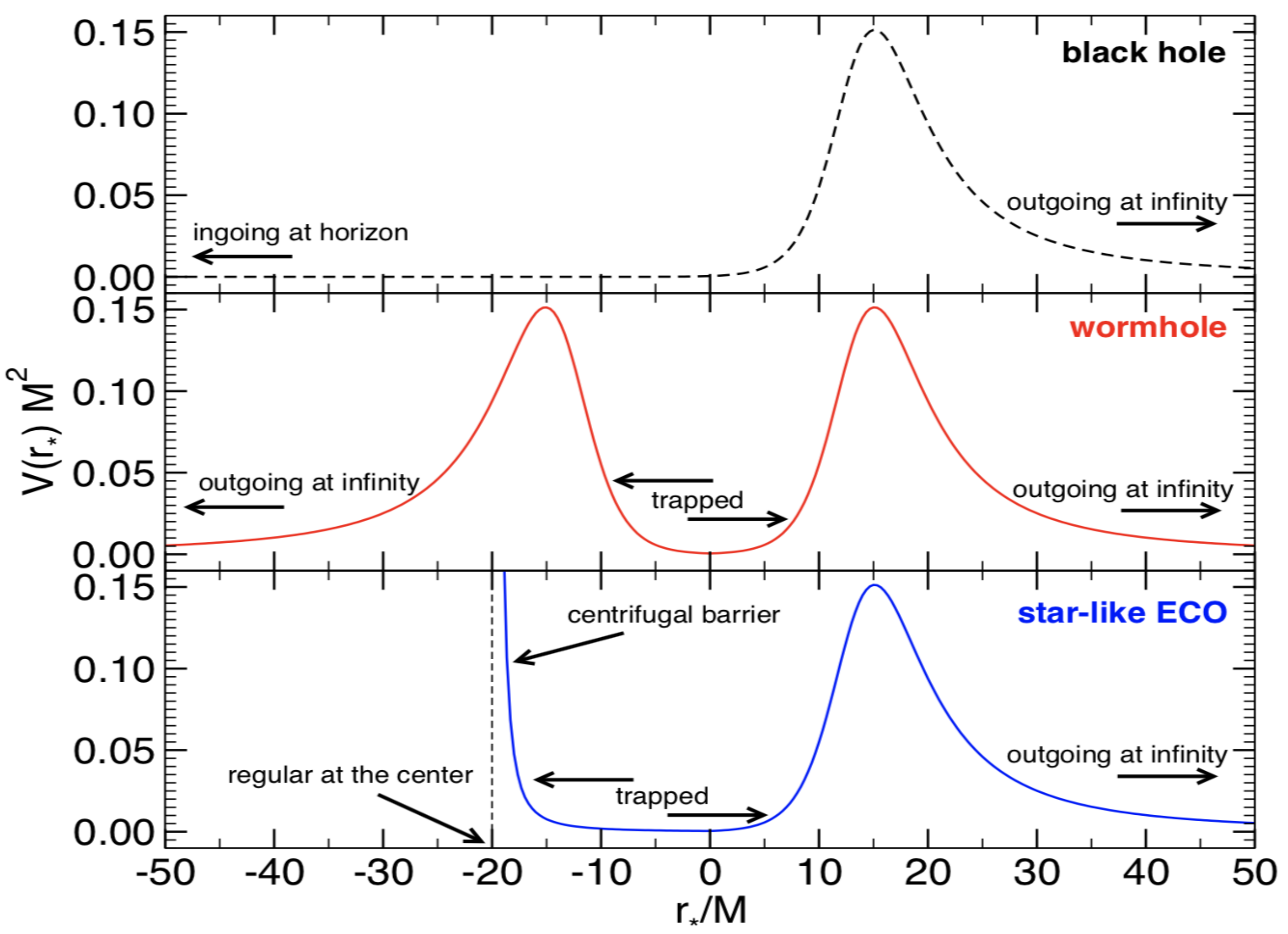
For r > r_0, $F(r) = 1/B(r) = 1 - 2GM/r$ (Birkhoff's theorem)

- Linear equation for perturbations (describes the ringdown phase):

$$\left[\frac{d^2}{dr_*^2} + \omega^2 - V_l(r)\right]\Psi_{lm\omega}(r) = 0, \quad dr_* = \sqrt{F/B}dr$$

$$V_l(r) = F\left(\frac{l(l+1)}{r^2} + \frac{B'}{2r} + \frac{BF'}{2rF}\right)$$

Gravitational echoes – ringdown phase test of ECOs



Gravitational echoes – ringdown phase test of ECOs

Zoo of ECOs

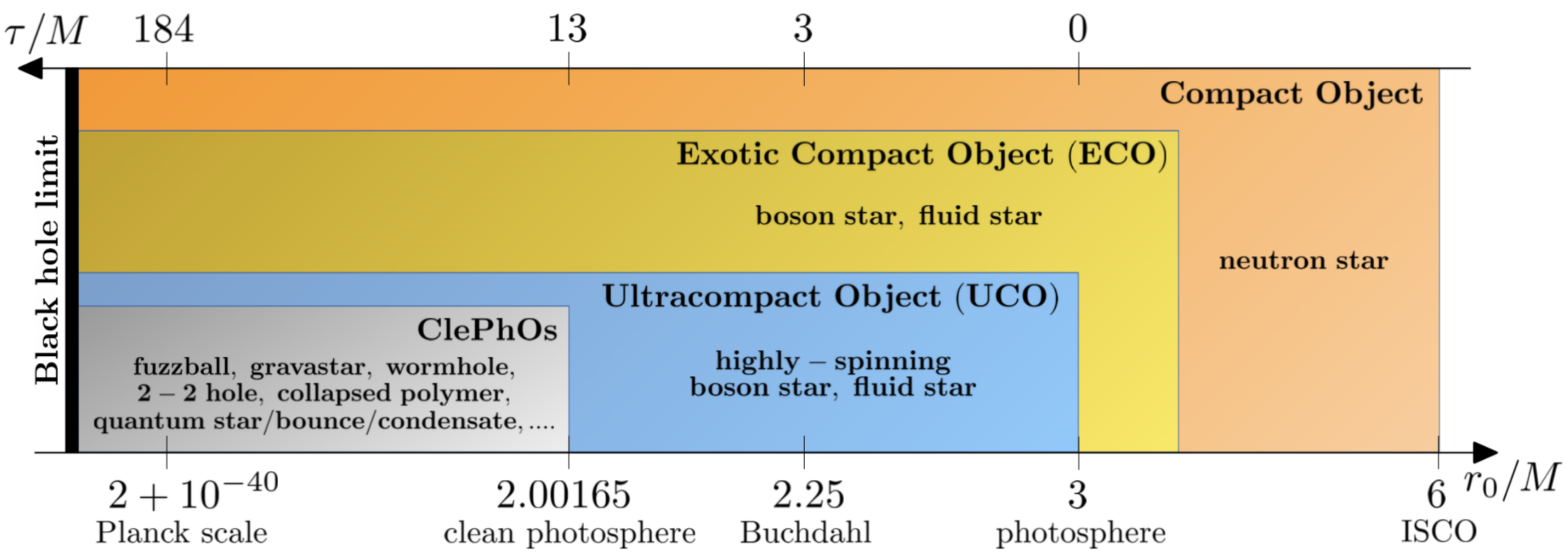
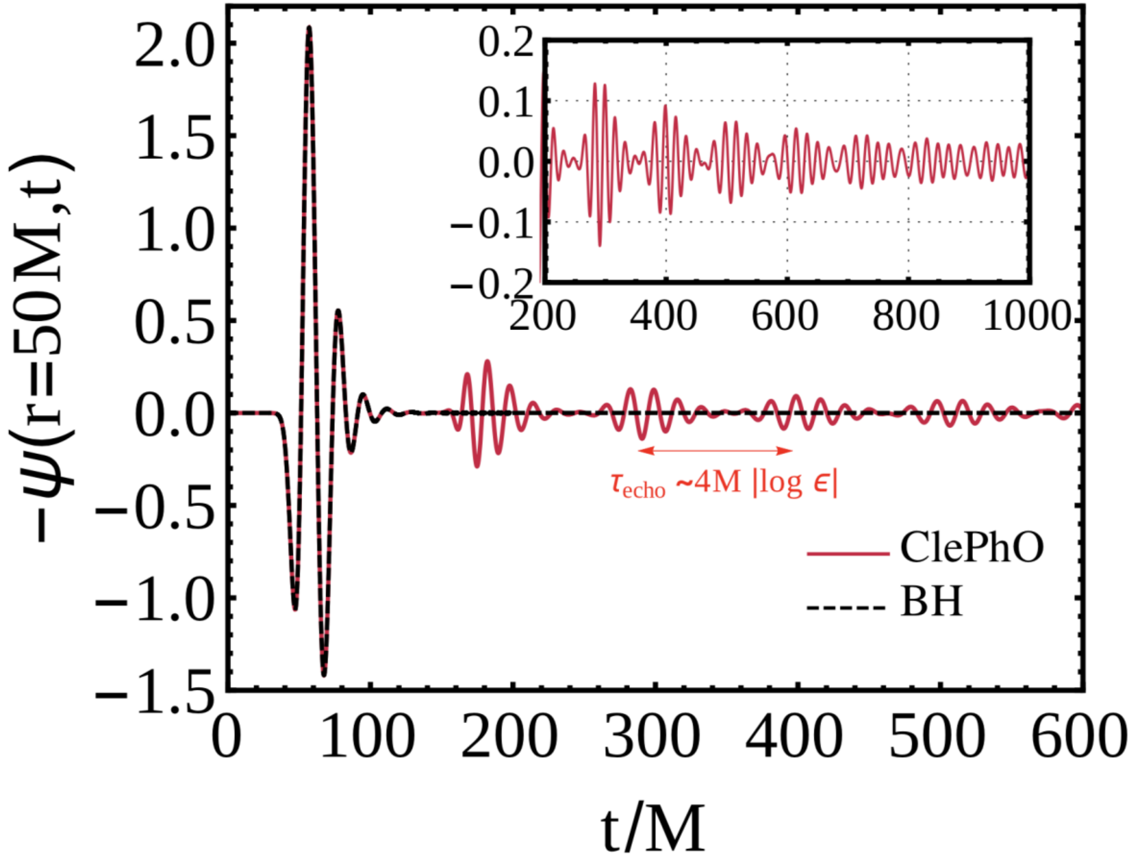


Figure 2: Schematic classification of compact objects according to their compactness (in a logarithmic scale). Objects in the same category have similar dynamical properties on a timescale τ.

Taken from V. Cardoso, P. Pani, arXiv: 1707.03021

Gravitational echoes – ringdown phase test of ECOs

- Perturbation dominates by quasi-normal modes – measurement of ringdown frequency and amplitude may discriminate between some ECOs
- For trapped modes of ECOs (not for classical black holes) there are also subdominant emissions with periodicity $\tau_{echo} \sim 4M|\log \epsilon|$ - gravi-echoes

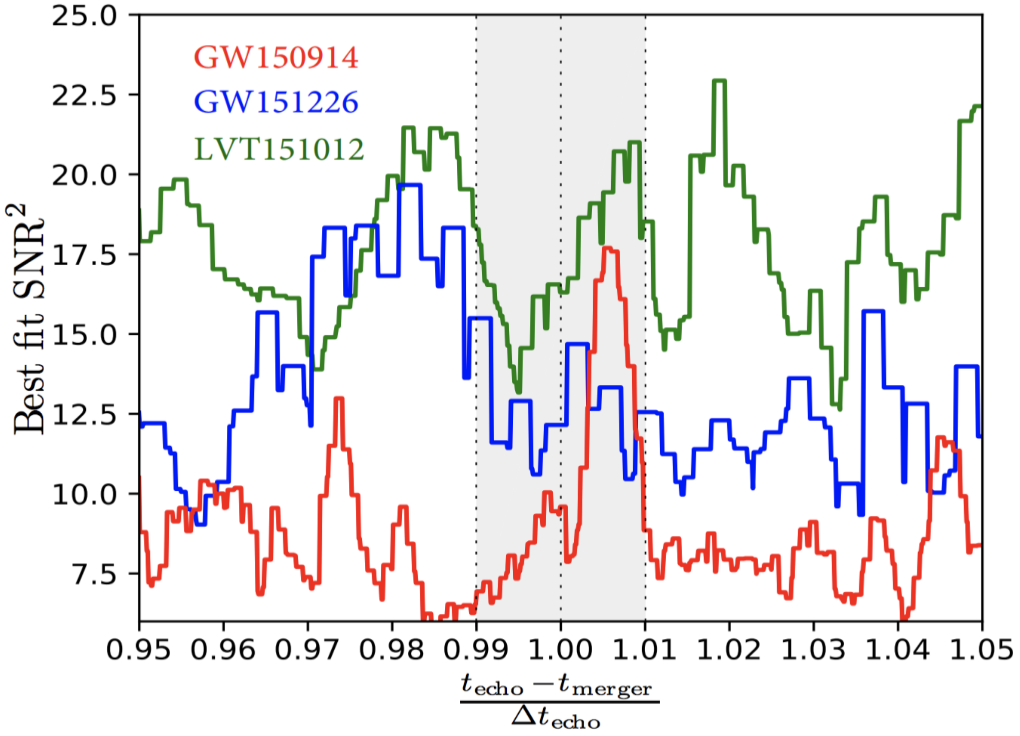


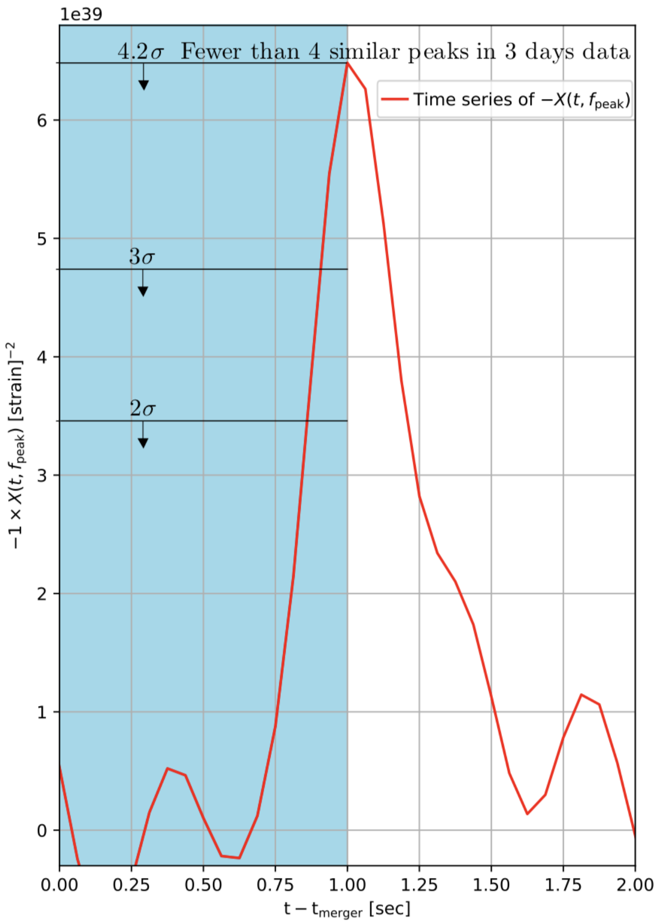
Taken from V. Cardoso, P. Pani, arXiv: 1707.03021

Gravitational echoes – ringdown phase test of ECOs

Claimed evidence for gravitational echoes:

2.5σ, J. Abedi, H. Dykaar, N. Afshordi, PRD 96 (2017) 082004 & 4.2σ (GW170817), J. Abedi, N. Afshordi, arXiv:1803.10454



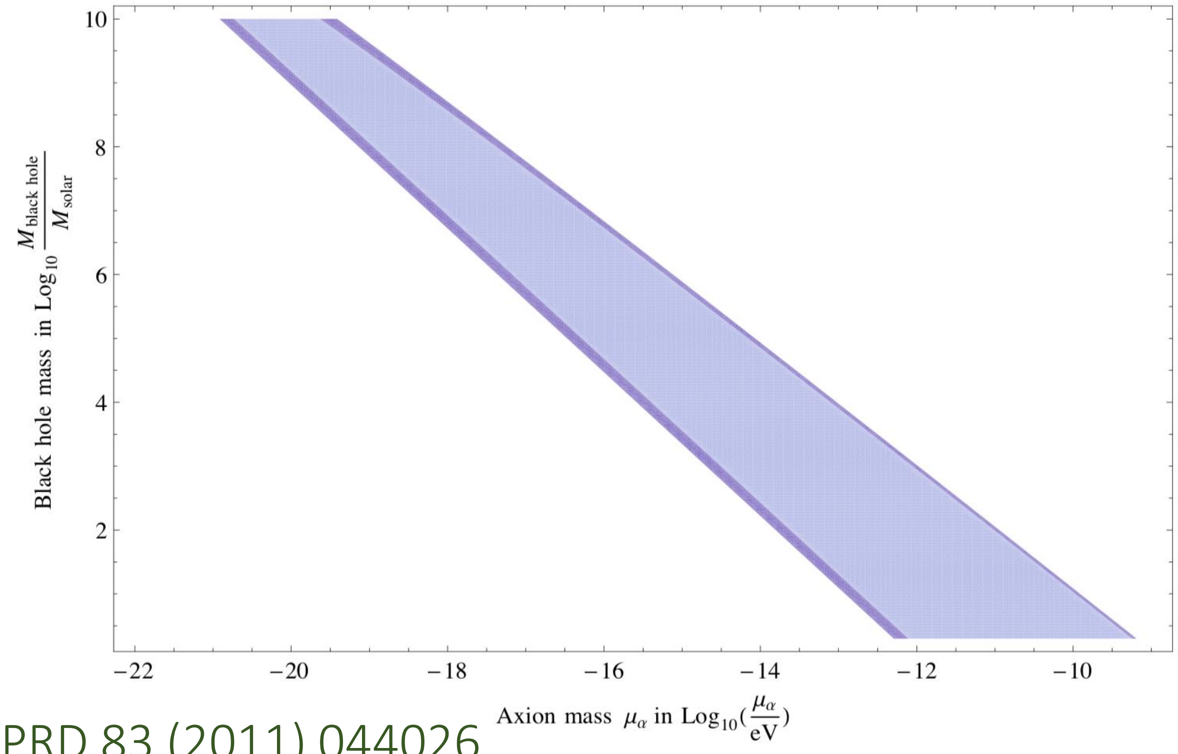


Criticism: G. Ashton et al., arXiv:1612.05625

J. Westerweck et al., PRD 97 (2018) 124037

BH superradiance – search for light dark matter

- A bosonic particle with mass $m_a \sim 1/r_{bh}$, in the vicinity of a rotating black hole populates energy levels in the supperadiance band by extracting energy from BH ergozone (the Penrose process), and forms a Bose-Einstein condensate. It radiates then gravitational waves once particle transitions ’atomic’ levels.



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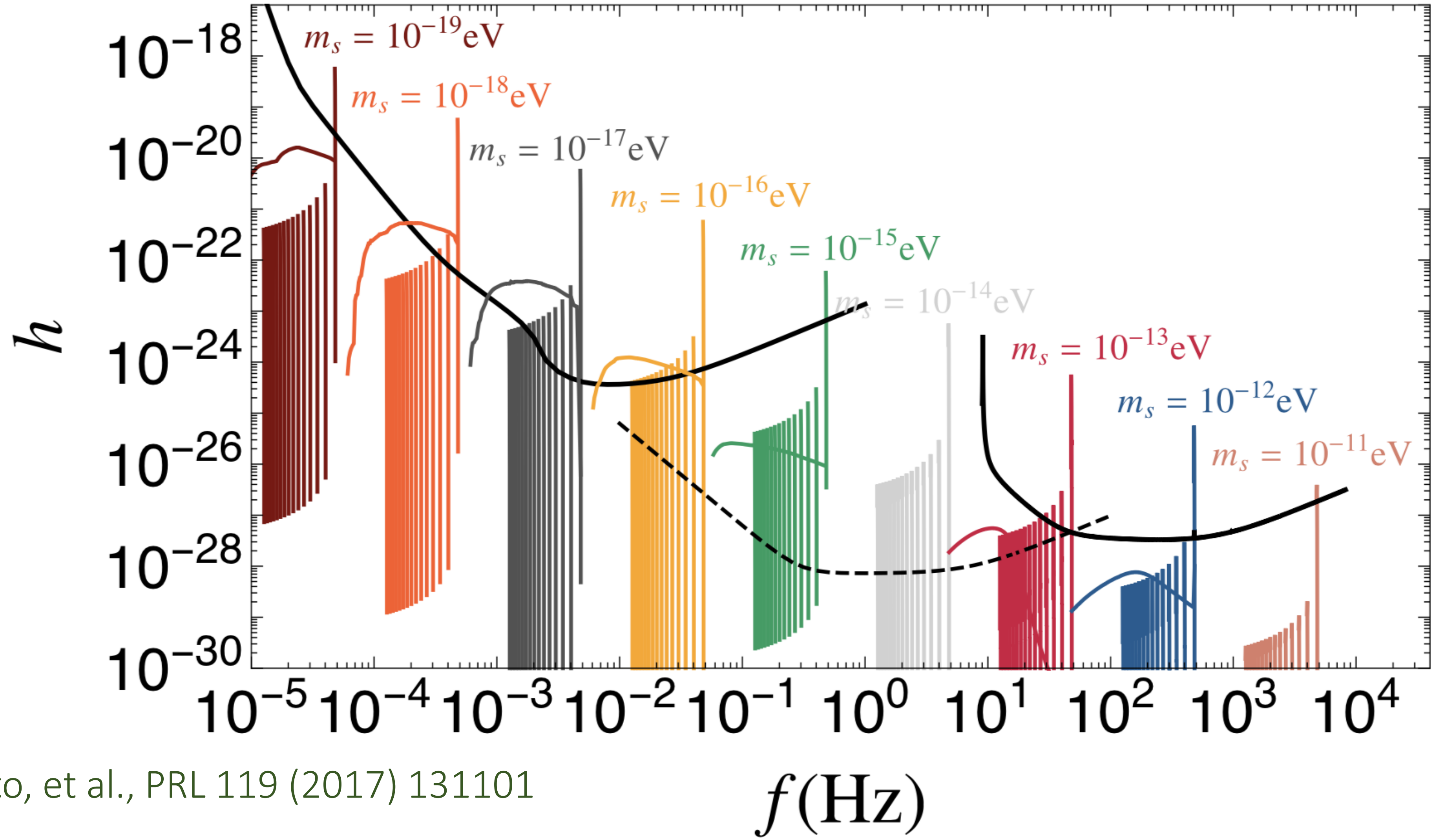
A.Arvanitaki and S.Dubovsky, PRD 83 (2011) 044026

BH superradiance – search for light dark matter



R. Britto, et al., PRL 119 (2017) 131101

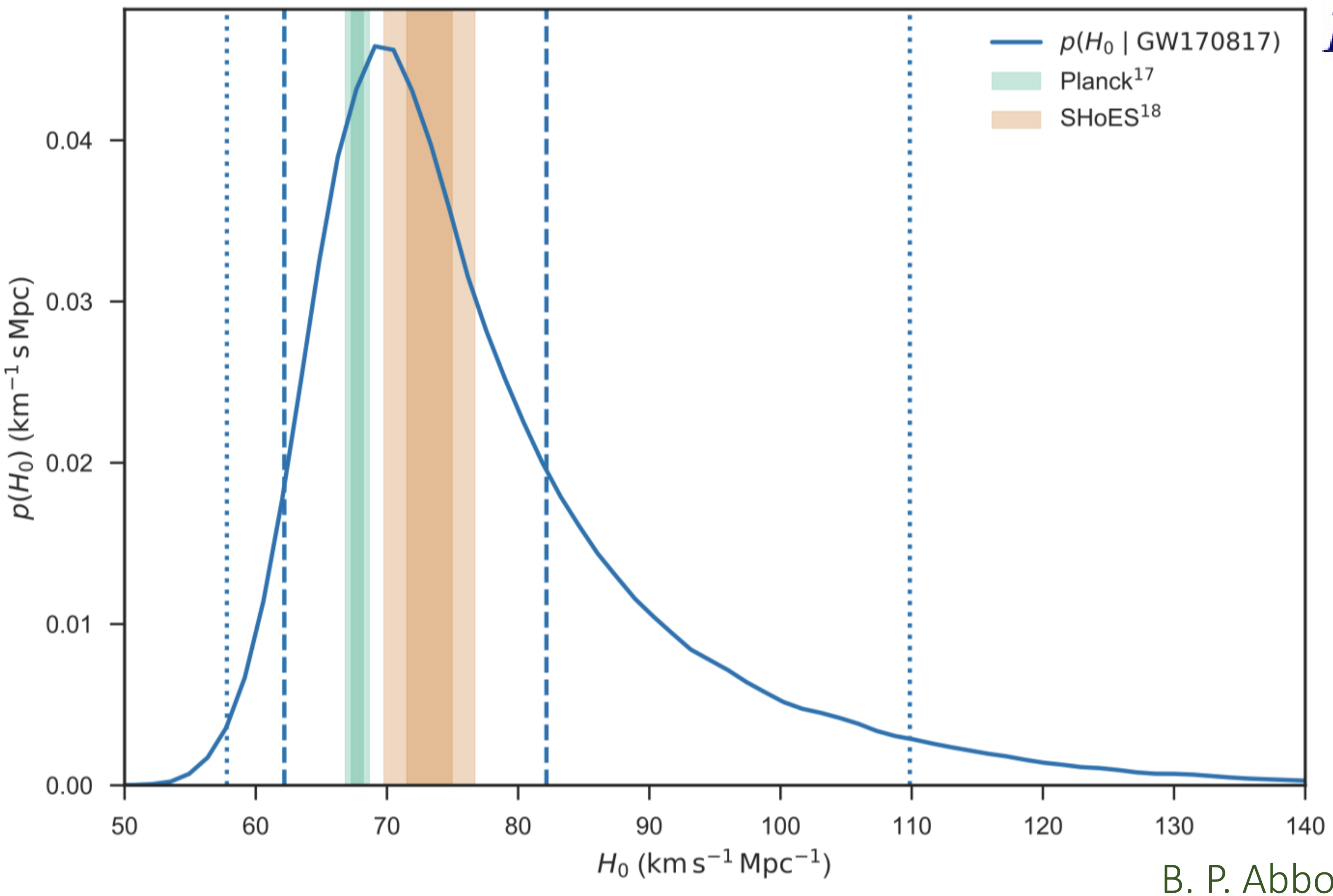
BH superradiance – search for light dark matter

- Light dark matter (axion, dilaton,…) mass range that cannot be accessed by other experiments

- Other couplings: $aF\tilde{F}, \quad aR\tilde{R}, \quad \chi R, \quad \chi F^2, \ldots$ lead to a variety of different signatures: electromagnetic follow up for BH merger, scalarisation, polarization of GW.

- Perhaps, these effects must be studied in complex

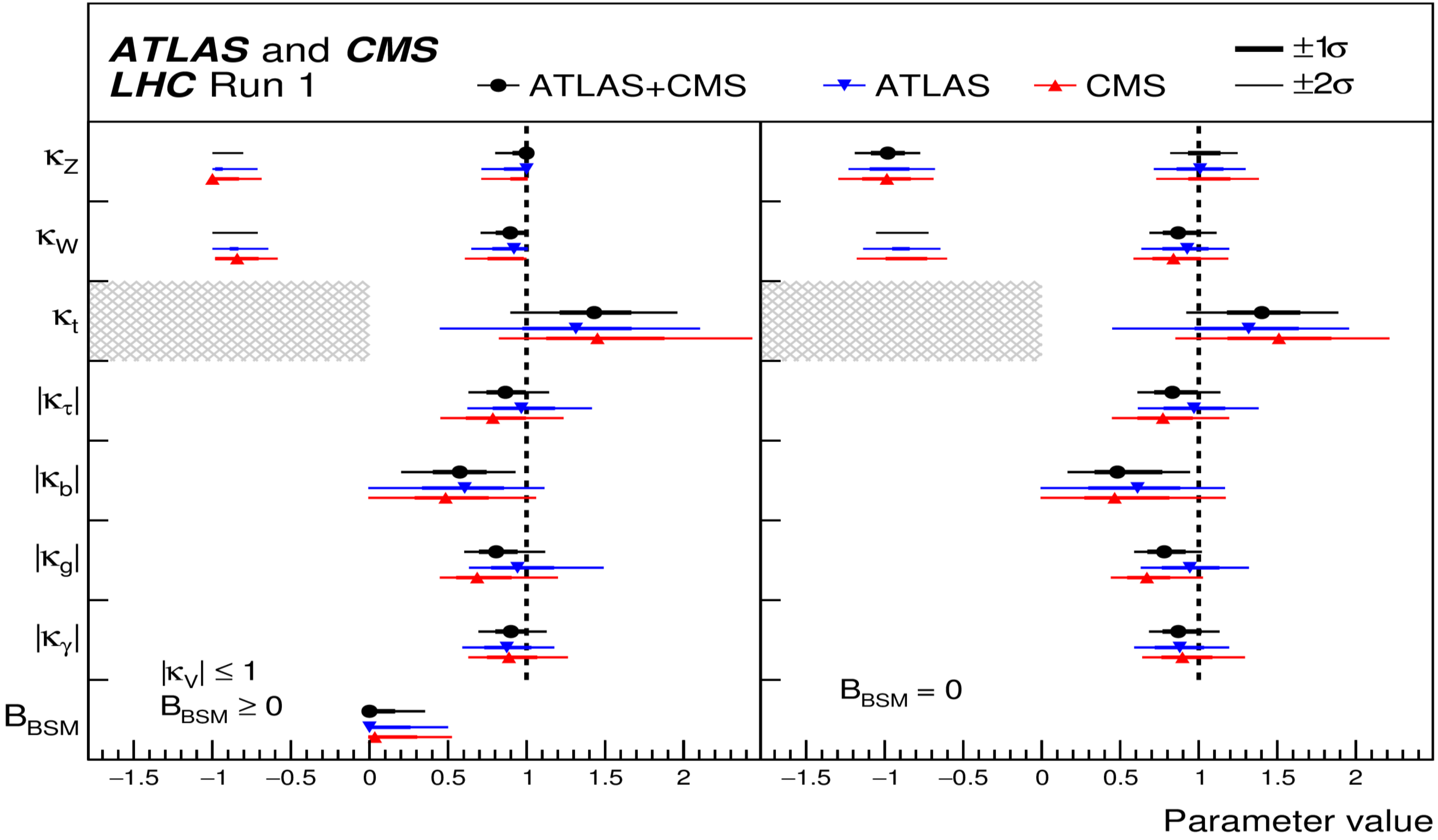
GW as standard sirens – measurement of H_0



$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\ s^{-1} Mpc^{-1}}$$

B. P. Abbott et al., Nature 551 (2017) 85

Higgs after LHC Run 1



Many important properties of the Higgs boson still need to be verified. In particular, precision measurements of the Higgs couplings are important to determine the nature of the electroweak symmetry and of the electroweak phase transition in the early universe.

Parameterizing new physics

- High-dimensional operators consistent with gauge invariance $SU(3)\times SU(2)\times U(1)$

$$\mathcal{O}_6 = \frac{c_6}{\Lambda^2}(H^\dagger H)^3 \Rightarrow \frac{\sigma}{3}h^3$$

- Non-linear realisation – $[SU(3)\times SU(2)\times U(1)]\,/\,[SU(3)\times U(1)_{\mathrm{EM}}]$

- Parameterize coset with: $\mathcal{X}(x) = e^{\frac{i}{2}\pi_i(x)T_i}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

- Higgs is residing in a singlet field: $\rho(x) = h(x) + v$

- The standard Higgs doublet: $H(x) = \frac{\rho(x)}{\sqrt{2}}\mathcal{X}(x)$

Non-linear realisation

- Many new couplings – constraints from electroweak precision data, flavour data, violation of perturbative unitarity…

- Simplified model – less constrained, relevant for the electroweaak phase transition –

$$V = \frac{\mu^2}{2}\rho^2 + \frac{\kappa}{3}\rho^3 + \frac{\lambda}{4}\rho^4$$

- Perturbative unitarity – $E \gtrsim few \cdot 10 \text{ TeV}$

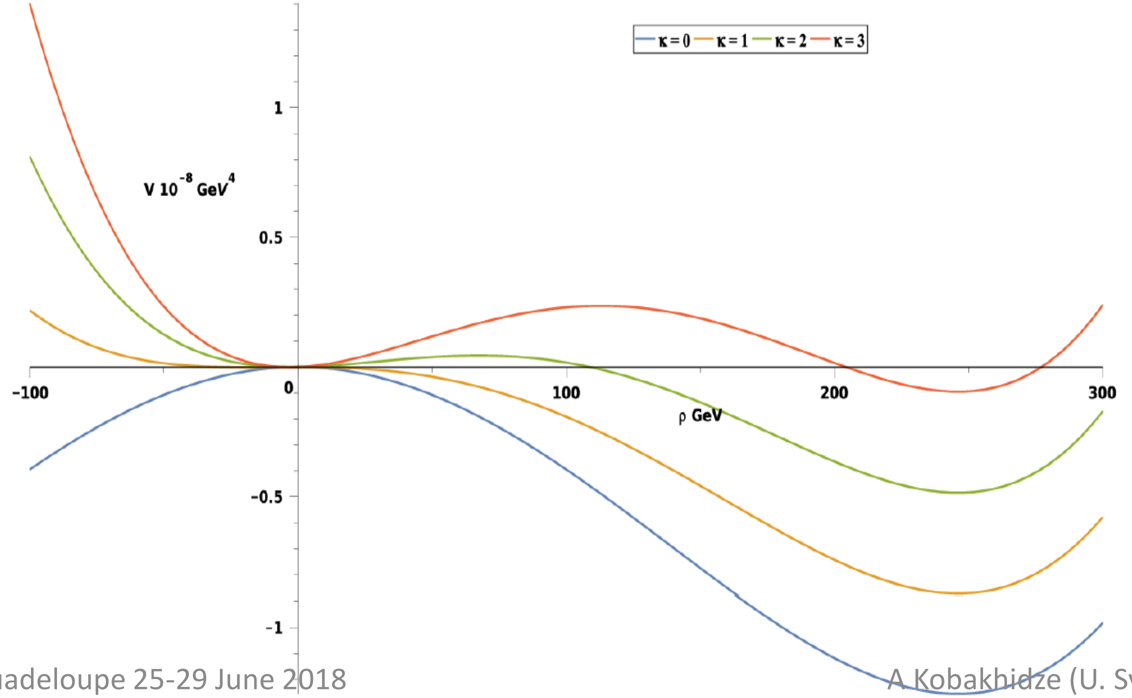
- No 1-loop corrections to S, T, U parameters

Supercooled electroweak phase transition

- Higgs potential:

$$V(\rho_c, T) = V_c + V_{CW} + V_T$$

- Classical potential at zero temperature :



$$V_c = -\frac{\mu^2}{2}\rho_c + \frac{\lambda}{4}\rho_c^4 + \frac{\kappa}{3}\rho_c^3$$

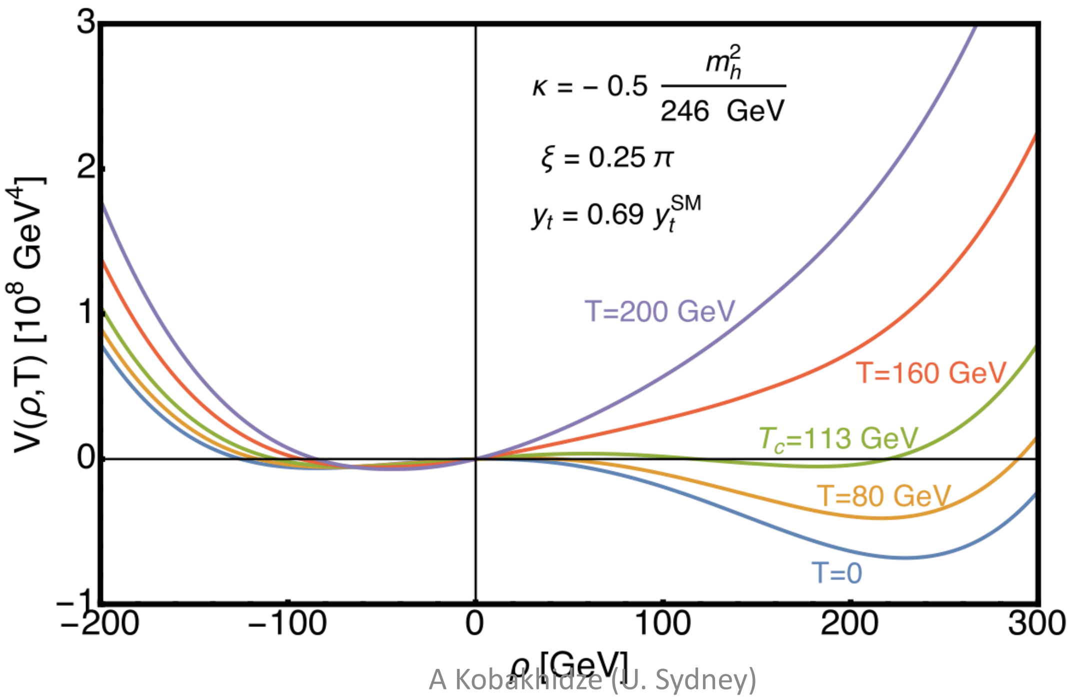
- $\mu^2 < 0$, min [0,v], $-3m_h^2 < v\kappa < -m_h^2$
- $\mu^2 > 0$, min [v',v], $-m_h^2 < v\kappa < 0$
- $\mu^2 = 0$, $v = -\kappa/\lambda$

Supercooled electroweak phase transition

- Finite temperature potential (high-T limit):

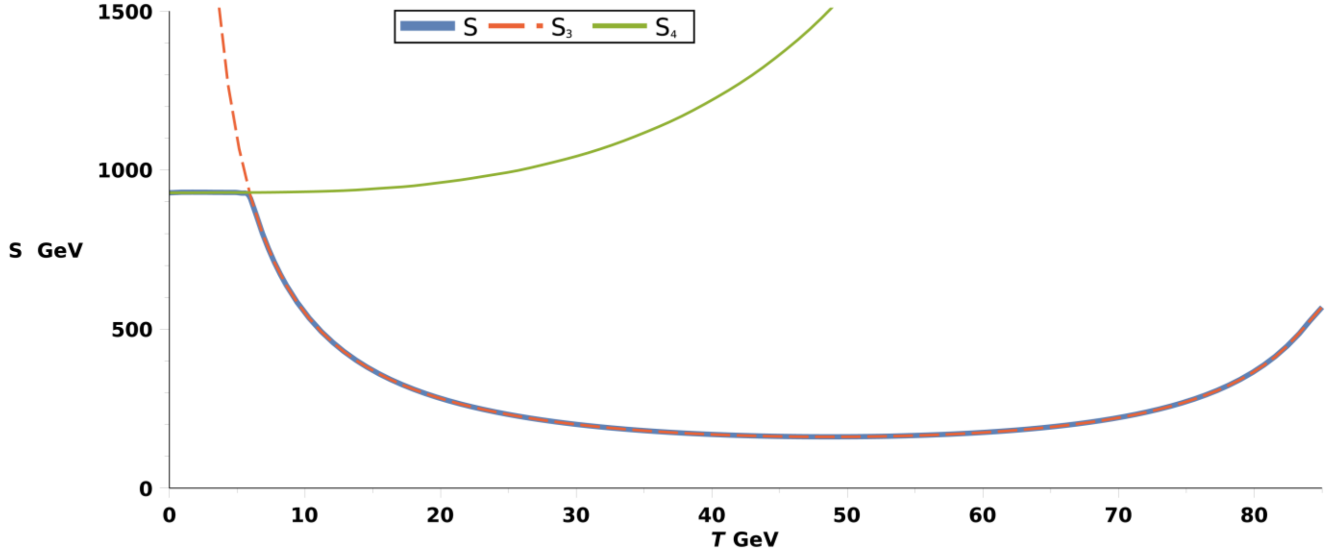
$$V(\phi_c, T) = \frac{\lambda}{4}\phi_c^4 + \frac{\kappa}{3}\phi_c^3 + \phi_c^2\left(-\frac{\mu^2}{2} + \frac{T^2}{32}(3g_2^2 + g_1^2 + 4\lambda + 4y_t^2)\right)$$

$$+ \frac{T^2}{12}(\kappa + 3\sqrt{2}y_t m_t' \cos\xi)\phi_c + \ldots$$



Supercooled electroweak phase transition

- Prolonged transition – full bounce solution – O(4) (quantum dominated) + O(3) (thermal dominated)



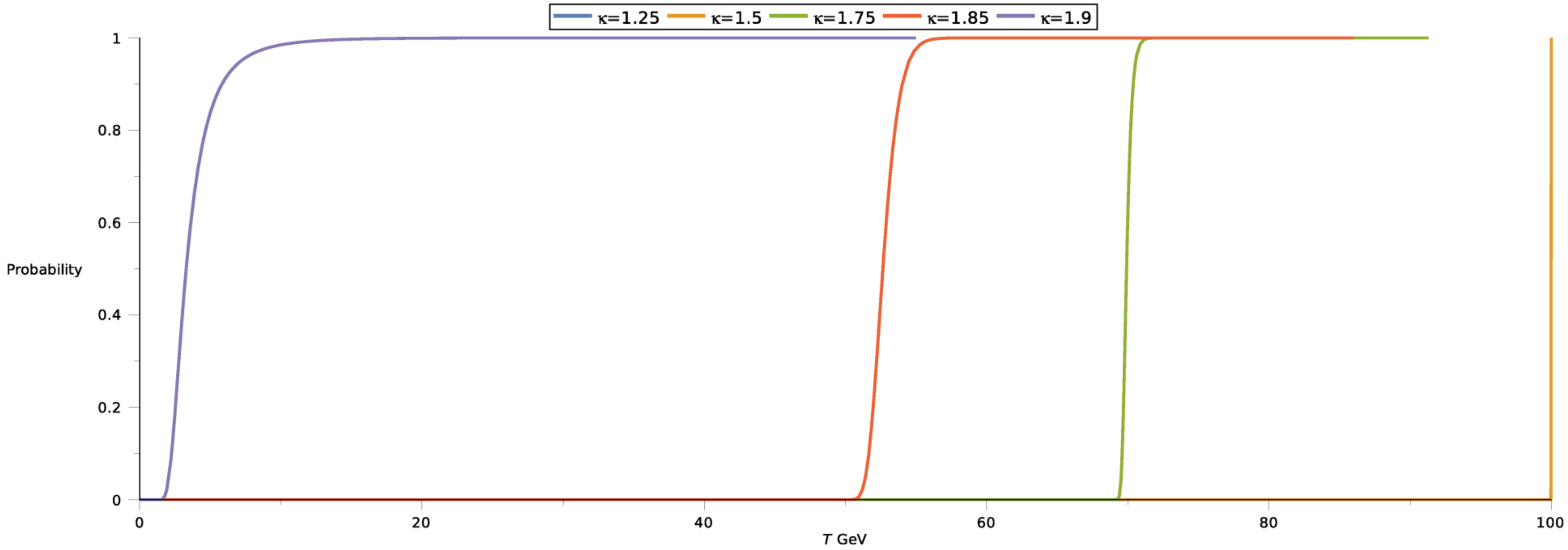
- Nucleated bubbles grow substantially after nucleation

$$H = 1/(2t),\ d = d_0 + c \cdot t \approx t$$

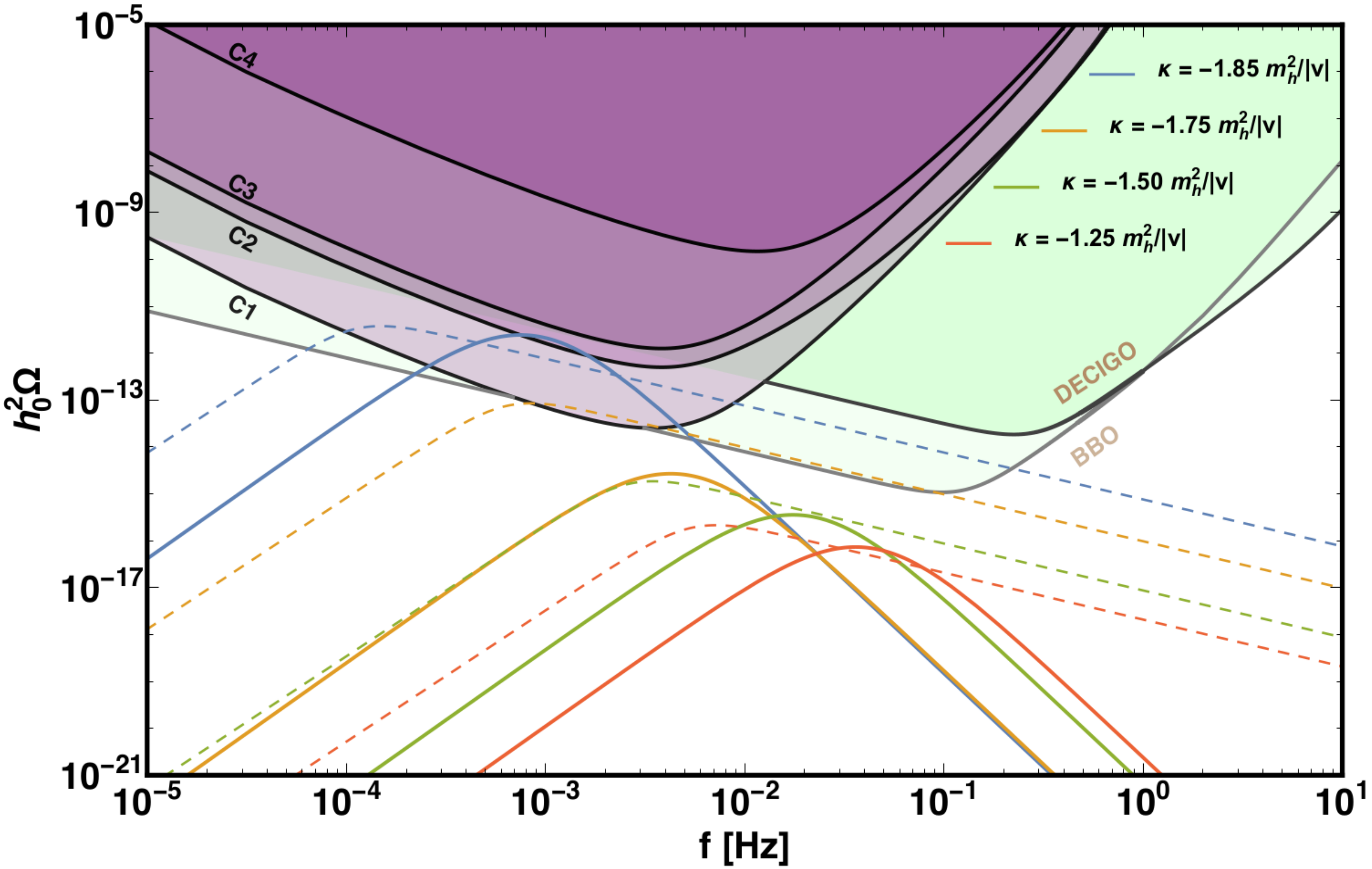
$$(Hd) \approx 1/2$$

Supercooled electroweak phase transition

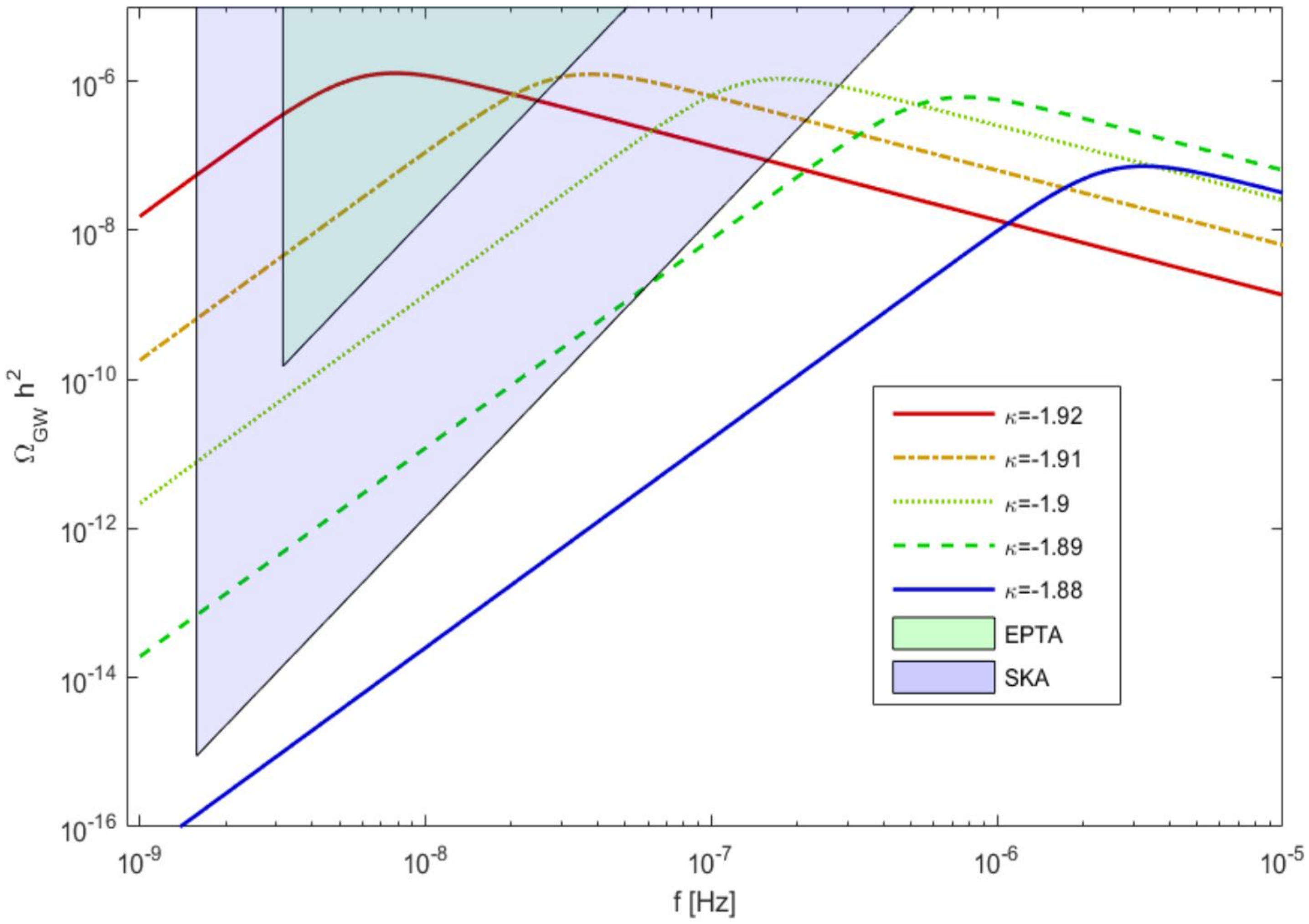
- Large latent heat (large potential barrier) and large bubbles result in enhanced amplitude of gravitational waves
- Low nucleation temperature (large bubbles) shifts pick frequency to lower values



GW from supercooled EWPT



GW from supercooled EWPT



GW vs trilinear Higgs coupling at HL-LHC

$$\lambda_{hhh} \approx 1.7\lambda_{hhh}^{\rm SM}$$

Table 1-22. *Signal significance for $pp \to HH \to bb\gamma\gamma$ and percentage uncertainty on the Higgs self-coupling at future hadron colliders, from [102].*

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot {\rm BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

arXiv:1308.6302

Other interesting GW scenarios from Higgs

- GW from Higgs vacuum instability => LISA or aLIGO sensitivity range (depending oh Higgs & top masses), primordial black holes dark matter [J.R. Espinosa, D. Racco, A. Riotto, arXiv: 1804.07732]

- GW from scale invariant Standard Model with a light dilaton, phase transition at T~130 MeV => SKA sensitivity range, $\sim M_{\odot}$ primordial black holes [S. Arunasalam, AK, C. Lagger, S. Liang, A. Zhou, PLB 776 (2018) 48]

- Supersymmetry breaking phase transition in hidden sector at ~ 10^{11} GeV
- …

Conclusion

- Gravitational waves emerge as a new tool for exploring fundamental physics
- Test of various modifications of GR, quantum nature of spacetime, quantum horizons and exotic compact objects (gravitational echos), superlight dark matter and independent measurement of H_0 (dark energy) – requires more theoretical work together with increase of experimental sensitivity
- Stochastic gravitational waves from cosmological phase transitions – may provide insight into Higgs self-interaction and electroweak phase transition in the early universe.