Gravitational waves from bubble collisions in first order phase transitions

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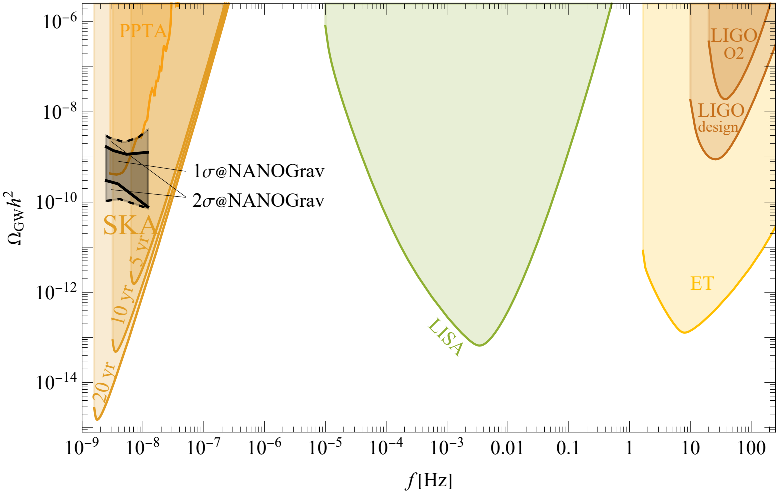
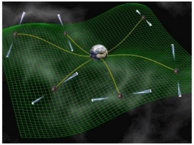
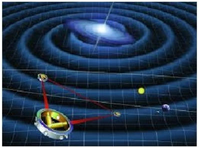
Based on:
J. Ellis, ML, J. M. No arXiv:1809.08242, 2003.07360
J. Ellis, ML, J. M. No, V. Vaskonen arXiv:1903.09642

ML, V. Vaskonen arXiv: 1912.00997, 2007.04967, 2012.07826

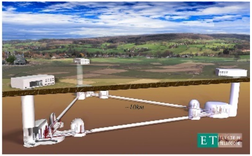




Pulsar Timing
[David Champion/NASA/JPL]



LISA
wiki/Laser_Interferometer_Space_Antenna



Einstein Telescope
www.et-gw.eu

Gravitational waves from a PT

- Strength of the transition

$$\alpha \approx \left.\frac{\Delta V}{\rho_R}\right|_{T=T_*}, \quad \Delta V = V_f - V_t$$

- Average size of bubbles upon collision (Characteristic scale)

$$HR_* = (8\pi)^{\frac{1}{3}} \left(\frac{\beta}{H}\right)^{-1}$$

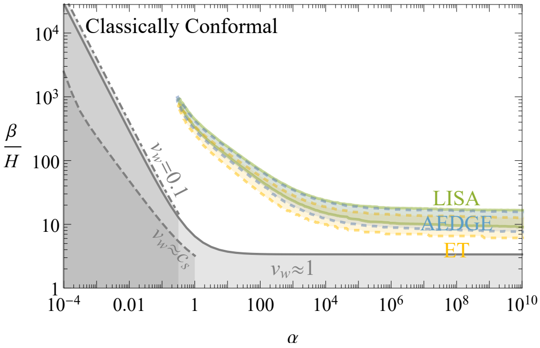
- Main mechanisms of GW production:
  - collisions of bubble walls: $\Omega_{\mathrm{col}} \propto \left(\kappa_{\mathrm{col}} \frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2$
  - sound waves: $\Omega_{\mathrm{sw}} \propto \left(\kappa_{\mathrm{sw}} \frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2$
  - turbulence $\Omega_{\mathrm{turb}} \propto \quad ?$
  -
- Bubble collisions are only relevant in very strong transitions

$$\kappa_{\mathrm{col}} \approx \mathcal{O}(1) \quad \text{only if} \quad alpha \ggg 1 \tag{1}$$

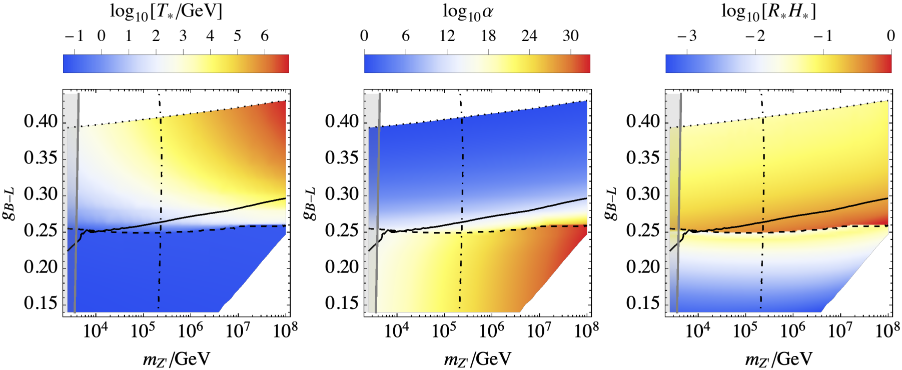
Classically scale-invariant CW-like potential

- Generic classically scale-invariant potential

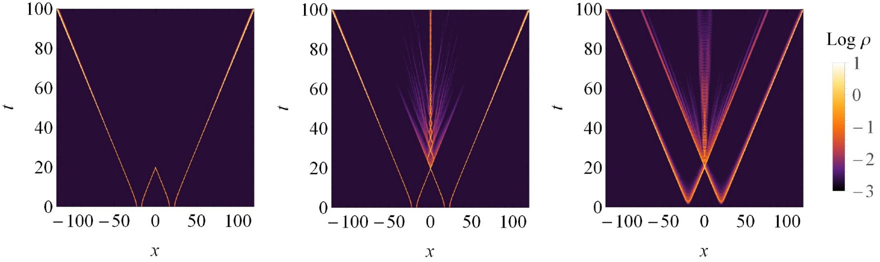
$$V(\phi, T) = g^2 T^2 \phi^2 + \frac{3g^4}{4\pi^2}\phi^4 \left(\log\left(\frac{\phi^2}{v^2}\right) - \frac{1}{2} - \frac{g^2 T^2}{2v^2}\right)$$



$U(1)_{B-L}$ Example

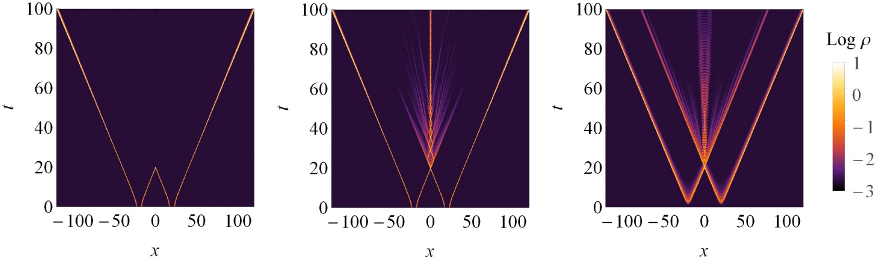


Energy propagation from lattice simulations



Envelope polynomial scale-invariant

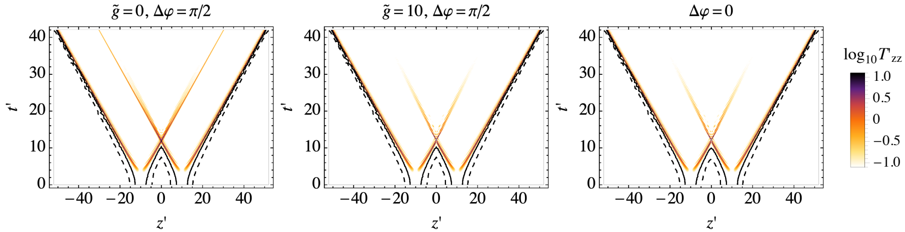
Energy propagation from lattice simulations

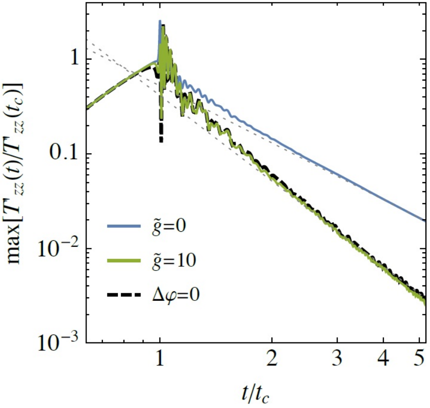


Envelope polynomial scale-invariant

- Vacuum Trapping can also be verified analytically:
  R. Jinno, T. Konstandin and M. Takimoto: 1906.02588

Abelian Higgs Model: Energy Scaling





- scaled gauge coupling:

$$\tilde{g} = \frac{gv^2}{\sqrt{\Delta V}}$$

- Global Symmetry breaking:

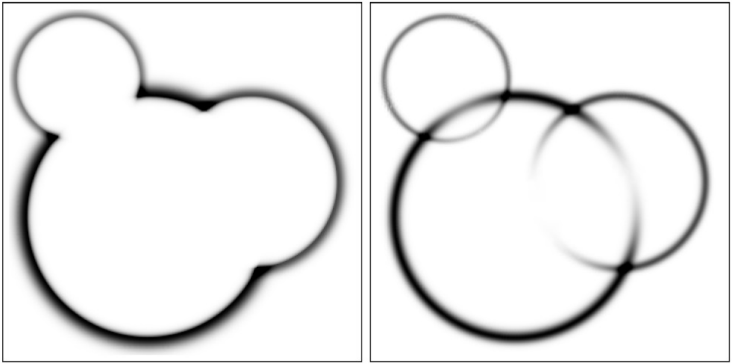
$$T_{zz} \propto R^{-2}$$

- Gauge Symmetry breaking:

$$T_{zz} \propto R^{-3}$$

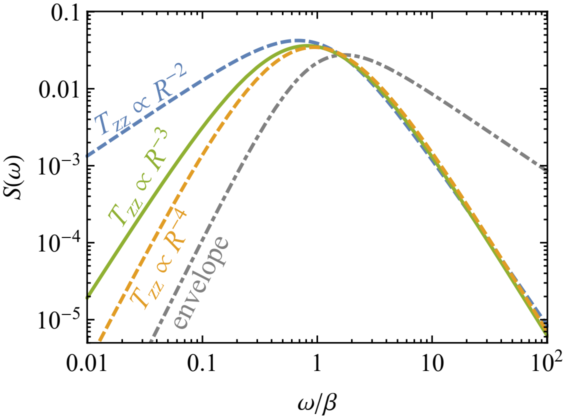
Computation of the GW spectrum

- 3D simulation with energy scaling as $E \propto R^{-n}$ after collision



plot from T. Konstandin 1712.06869 with $E \propto R^{-2}$

Bubble Collision Spectrum



- Global Symmetry breaking:

$$T_{zz} \propto R^{-2}$$

- Gauge Symmetry breaking:

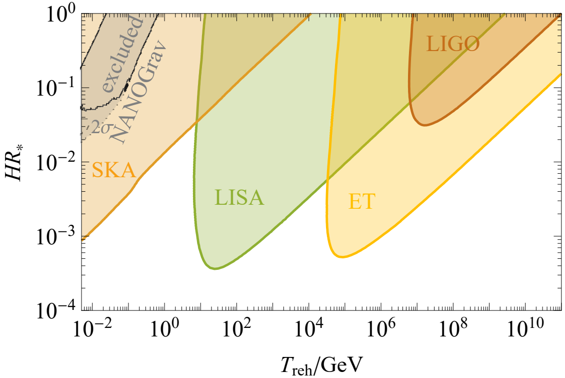
$$T_{zz} \propto R^{-3}$$

- Resulting spectrum:

$$S(\omega) = \frac{\bar{S}\,(a+b)^c}{\left[b\left(\frac{\omega}{\bar{\omega}}\right)^{-a/c} + a\left(\frac{\omega}{\bar{\omega}}\right)^{b/c}\right]^c}$$

	$100\bar{S}$	$\bar{\omega}/\beta$	a	b	c
$T_{zz} \propto R^{-2}$	4.23 ± 0.1	0.68 ± 0.01	1.00 ± 0.02	2.17 ± 0.05	2.02 ± 0.1
$T_{zz} \propto R^{-3}$	3.61 ± 0.1	0.82 ± 0.01	2.34 ± 0.03	2.41 ± 0.02	4.20 ± 0.2
$T_{zz} \propto R^{-4}$	3.46 ± 0.1	0.93 ± 0.01	2.87 ± 0.04	2.42 ± 0.02	4.63 ± 0.2
env.	2.75 ± 0.1	1.72 ± 0.04	2.98 ± 0.02	1.01 ± 0.02	2.18 ± 0.1

Conclusions



- LISA will have optimal reach for transition in the $T_{reh} \approx 10 - 100$ GeV range.
- Observable bubble collision signal occure in very strong transitions $\alpha > 10^{10}$.
  - $\rightarrow$ Bubble collision signal would indicate a scale invariant model.
- Shape of the spectrum encodes details of the particle physics model:
  - $\rightarrow$ $\Omega \propto f$ at low frequencies indicates global symmetry breaking.
  - $\rightarrow$ $\Omega \propto f^{2.3}$ at low frequencies indicates gauge symmetry breaking.