The search for cosmological phase transitions through their gravitational wave signals

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CQUeST, 16 XI 2022

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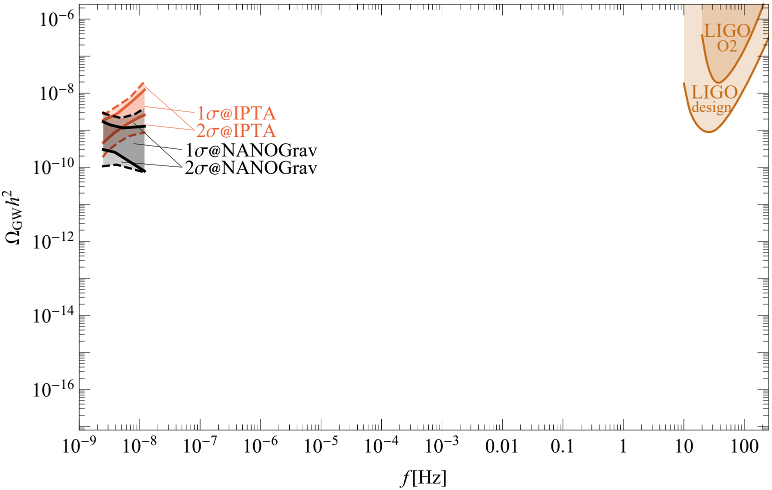
Plan

- Experimental prospects
- Astrophysical sources and their Stochastic GW foreground
- First-order phase transitions
- Bubble wall velocity
- GW spectra from strong transitions
- Conclusions



LIGO
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LIGO
design
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2σ@IPTA
1σ@NANOGrav
2σ@NANOGrav
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10^{-14}
10^{-16}
$\Omega_{\rm GW} h^2$
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10^{-8}
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1
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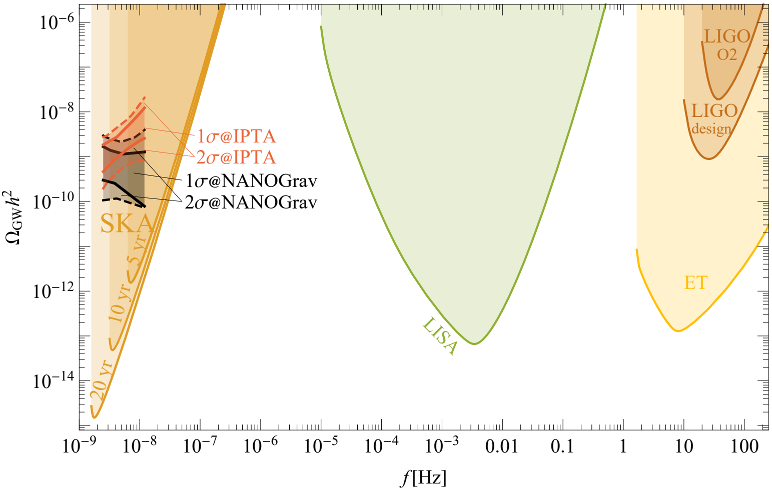
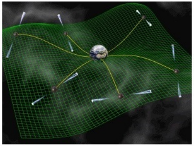
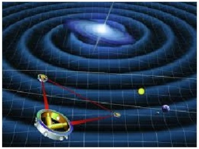
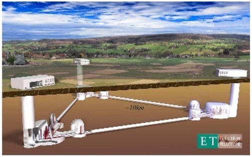




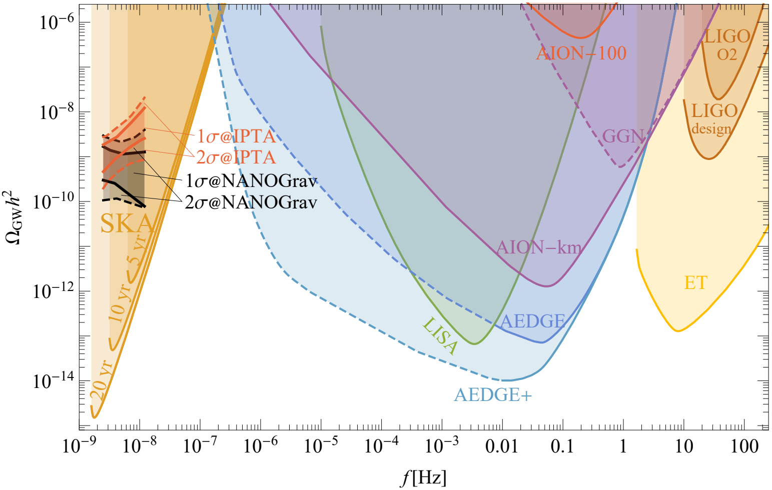
Pulsar Timing
[David Champion/NASA/JPL]

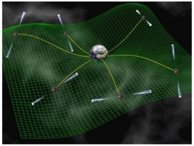


LISA
wiki/Laser_Interferometer_Space_Antenna



Einstein Telescope
www.et-gw.eu





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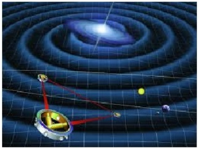

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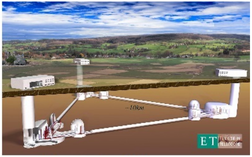

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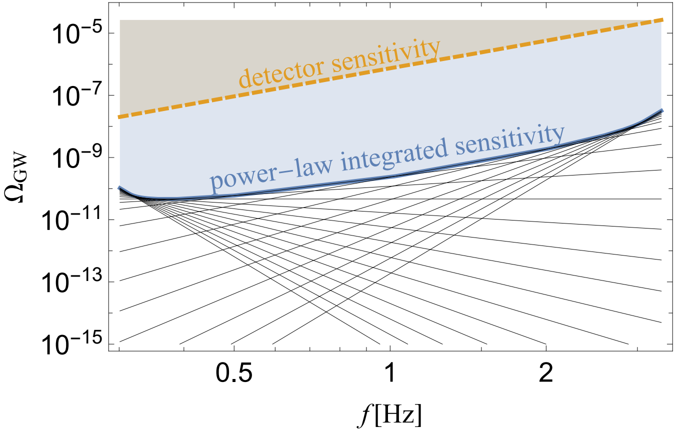
www.et-gw.eu

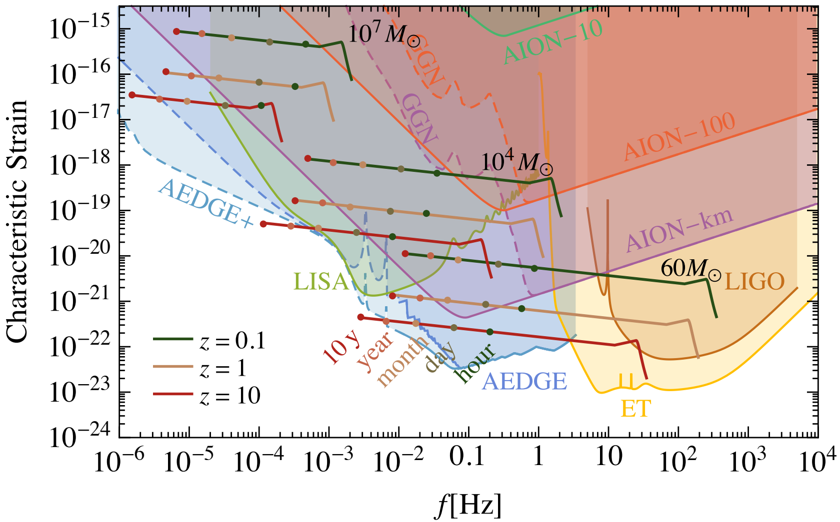
Power-law integrated sensitivity

$$\Omega_{\rm GW}^{\rm noise} = \frac{2\pi}{3}\frac{f^3 S_h^2}{H_0^2}, \qquad {\rm SNR} = \sqrt{\mathcal{T}\int df \left(\frac{\Omega_{\rm GW}^{\rm signal}}{\Omega_{\rm GW}^{\rm noise}}\right)^2}, \qquad \Omega_{\rm GW}^{\rm signal} = \Omega\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$$

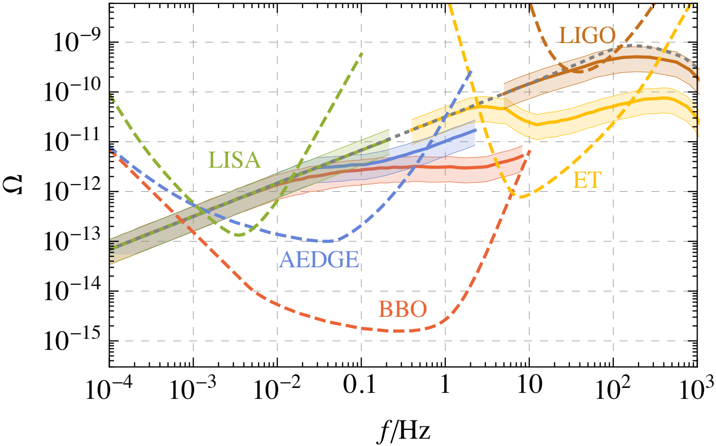


Thrane, Romano '13

Sensitivity to binary mergers



Foreground from LIGO-Virgo binaries



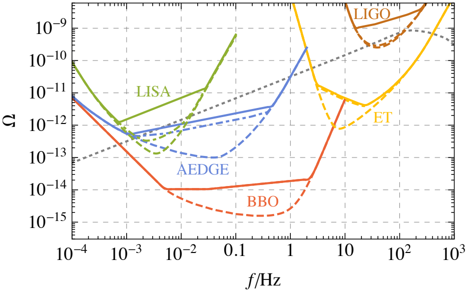
- Dashed gray line: total foreground from LIGO-Virgo binaries
- Thick lines: foreground without individually observable binaries

ML, Ville Vaskonen arXiv:2111.05847

Improved sensitivities from Fisher analysis

- assuming power-law signal as in PI sensitivity

$$\Omega_{\rm GW}(f) = \Omega\left(\frac{f}{f_{\rm ref}}\right)^{\alpha} + A\langle\Omega_{\rm BBH}(f)\rangle + \Omega_{\rm BWD}(f) + \Omega_{\rm instr}(f)$$



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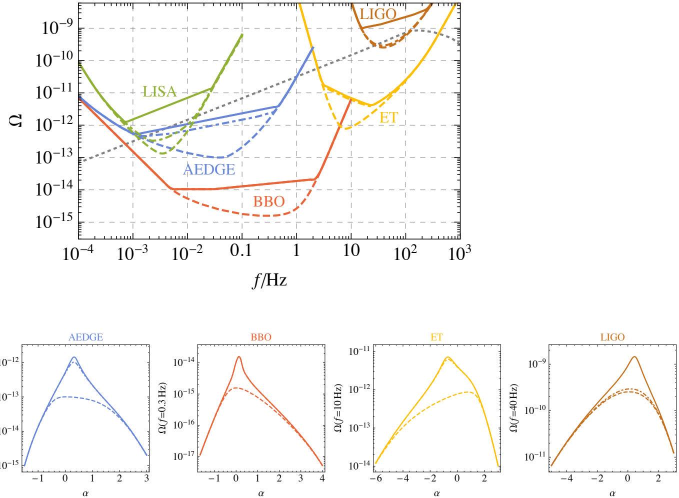
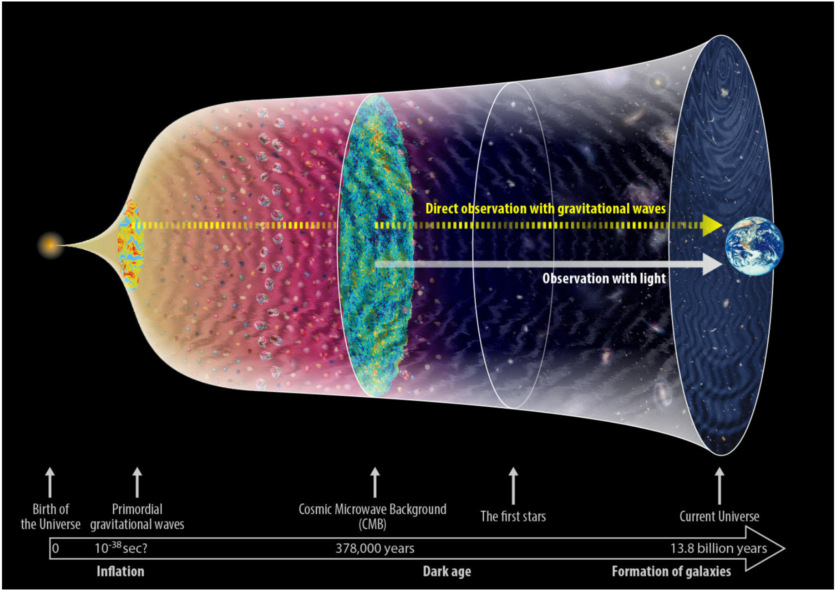


Early Universe Sources

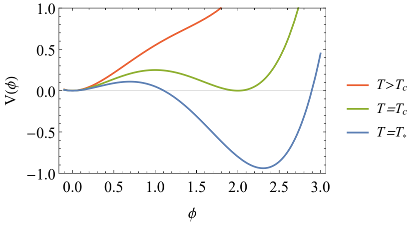


plot credit:https://gwpo.nao.ac.jp/en/gallery

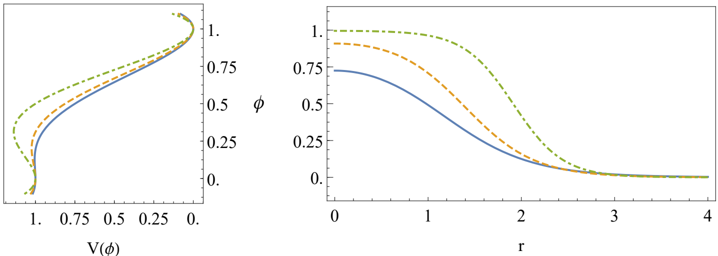
First Order Phase Transition

- Simple high temperature expansion

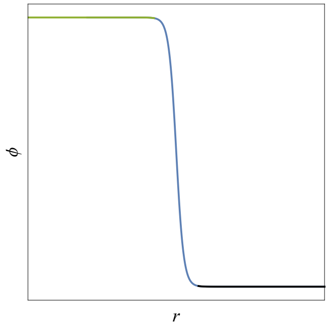
$$V(\phi, T) = \frac{g_{m^2}}{24}\left(T^2 - T_0^2\right)\phi^2 - \frac{g_m}{12\pi}T\phi^3 + \lambda\phi^4\,, \quad T_0^2 > 0$$



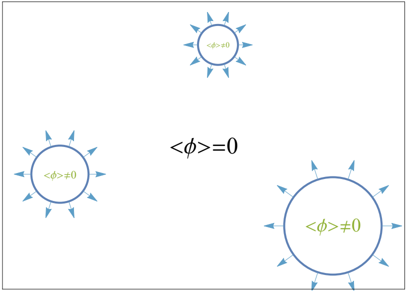
- Eventually the barrier becomes small enough that bubbles can nucleate



First Order Phase Transition



$\Longrightarrow$



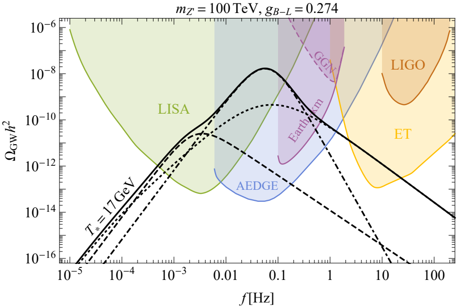
- Strength of the transition

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

- Average size of bubbles upon collision (Characteristic scale)

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

Gravitational waves from a PT



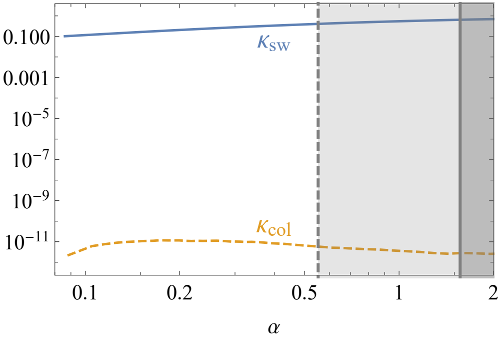
- Main mechanisms of GW production:
  - collisions of bubble walls: $\Omega_{\rm col} \propto \left(\kappa_{\rm col}\frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2$
  - sound waves: $\Omega_{\rm sw} \propto \left(\kappa_{\rm sw}\frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2$
  - turbulence $\Omega_{\rm turb} \propto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

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

Plasma related GW sources

- Standard Model supplemented with a non-renormalisable operator

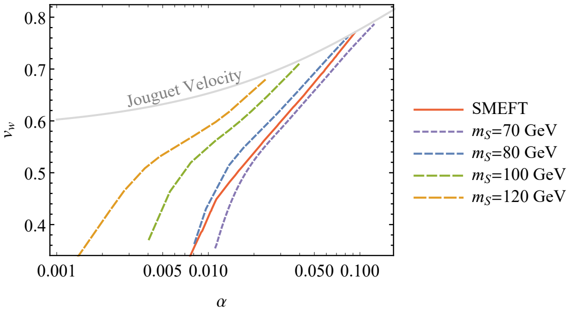
$$V(H) = -m^2|H|^2 + \lambda|H|^4 + \frac{1}{\Lambda^2}|H|^6$$



- Standard Model with an additional singlet scalar

$$V(H,s) = -\mu_h^2|H|^2 + \lambda|H|^4 + \frac{\lambda_{hs}}{2}S^2|H|^2 + \left(m_s{}^2 - \frac{\lambda_{hs}v^2}{2}\right)\frac{s^2}{2} + \frac{\lambda_s}{4}S^4$$

Wall Velocity



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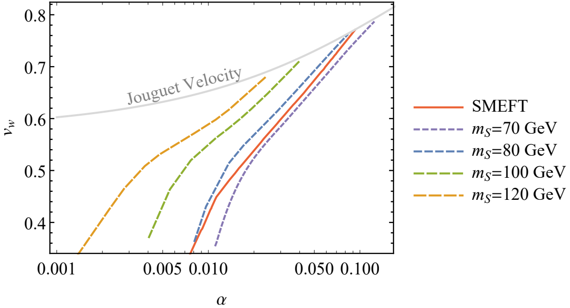
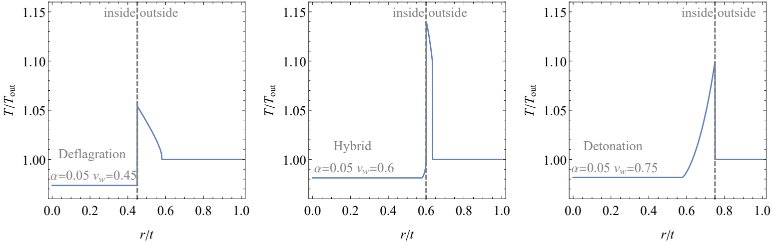


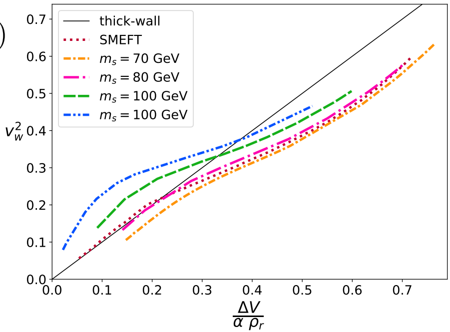
- No solutions found beyond $v_J = \frac{1}{\sqrt{3}} \frac{1+\sqrt{3\alpha^2+2\alpha}}{1+\alpha}$.



Wall Velocity analytic approximation

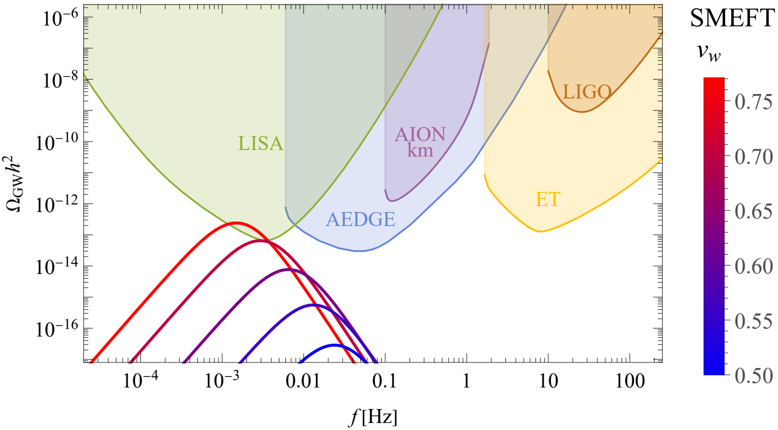
$$v_w = \begin{cases} \sqrt{\frac{\Delta V}{\alpha \rho_R}} & \text{for} \quad \sqrt{\frac{\Delta V}{\alpha \rho_R}} < v_J(\alpha) \\ 1 & \text{for} \quad \sqrt{\frac{\Delta V}{\alpha \rho_R}} \geq v_J(\alpha) \end{cases}$$

- Here: $\alpha = \frac{1}{\rho_R}\left(\Delta V - \frac{T}{4}\frac{\partial \Delta V}{\partial T}\right)$
- Formula does not require solving transport equations
- Only the form of the potential is important



ML, Marco Merchand, Mateusz Zych arXiv: 2111.02393

Gravitational wave signals



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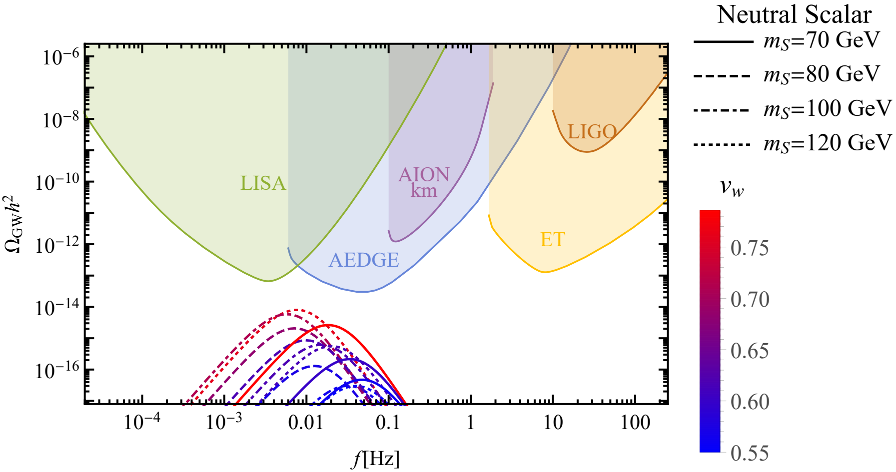

ML, Marco Merchand, Mateusz Zych arXiv: 2111.02393

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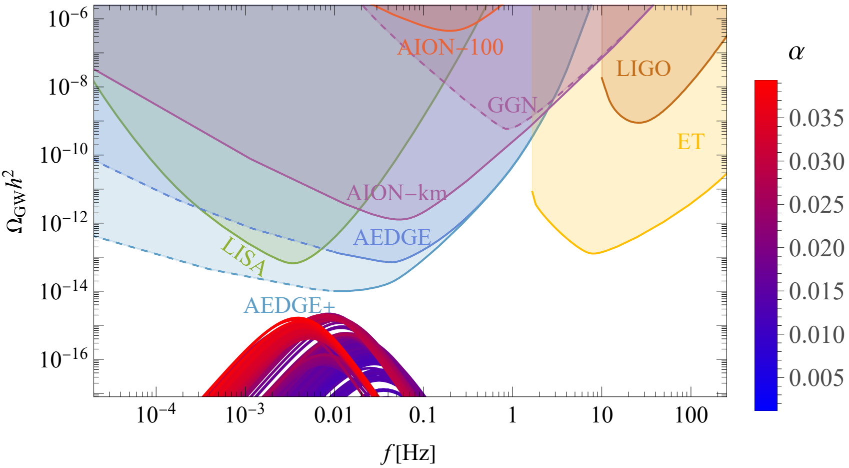


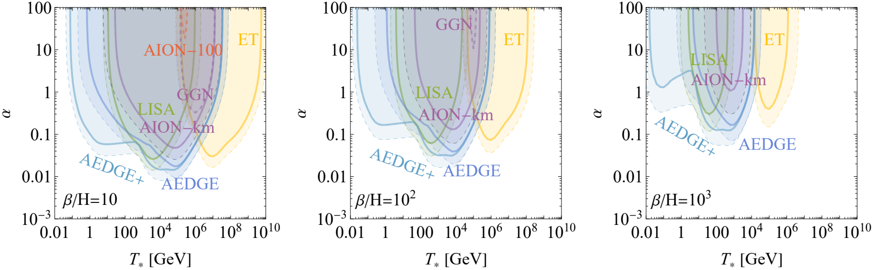
John Ellis, ML, Marco Merchand, José Miguel No, Mateusz Zych arXiv: 2210.16305

Reach of upcoming experiments

- Position of the peak

$$\Omega_{\rm peak} \propto \left(\frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2 \,, \qquad f_{\rm peak} \propto T_* \,(HR_*)^{-1}$$

- Detectibility assuming plasma related sources



Can the walls run away?

- Energy of the bubble

$$\mathcal{E} = 4\pi R^2 \sigma \gamma - \frac{4\pi}{3} R^3 p\,, \qquad \gamma = \frac{1}{\sqrt{1-\dot{R}^2}}$$

- Vacuum pressure on the wall
  Coleman '73

$$p_0 = \Delta V$$

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- Leading order plasma contribution
  Bodeker '09 Caprini '09

$$p_1 = \Delta V - \Delta P_{\rm LO} \approx \Delta V - \frac{\Delta m^2 T^2}{24} \,,$$

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$$p_1 = \Delta V - \Delta P_{\rm LO} \approx \Delta V - \frac{\Delta m^2 T^2}{24} \,,$$

- Next-To-Leading order plasma contribution
  Bodeker '17 Gouttenoire '21

$$p = \Delta V - \Delta P_{\rm LO} - \gamma \Delta P_{\rm NLO} \approx \Delta V - \frac{\Delta m^2 T^2}{24} - \gamma\, g^2 \Delta m_V T^3 \,.$$

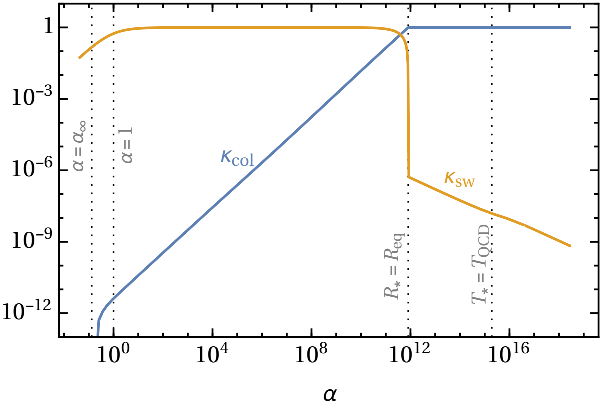
- Next-To-Leading order plasma contribution with resummation
  Hoche '20

$$P = \Delta V - P_{1\to1} - \gamma^2 P_{1\to N} \approx \Delta V - 0.04 \Delta m^2 T^2 - 0.005 g^2 \gamma^2 T^4 \,.$$

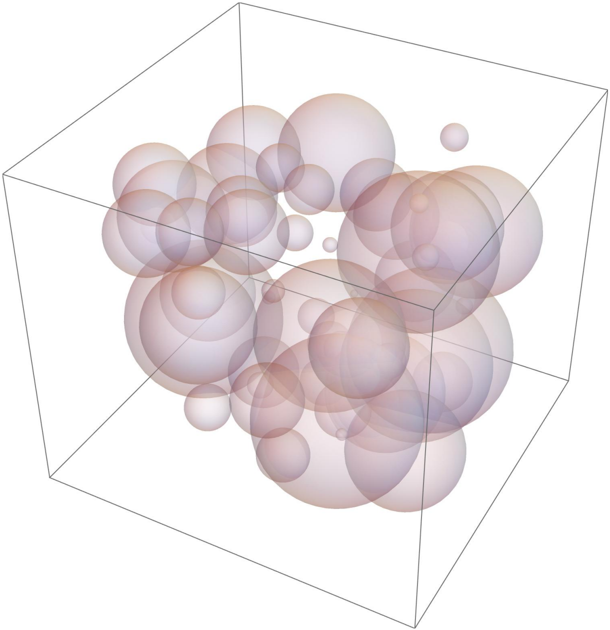
Classically scale-invariant $U(1)_{B-L}$

- Generic classically scale-invariant potential

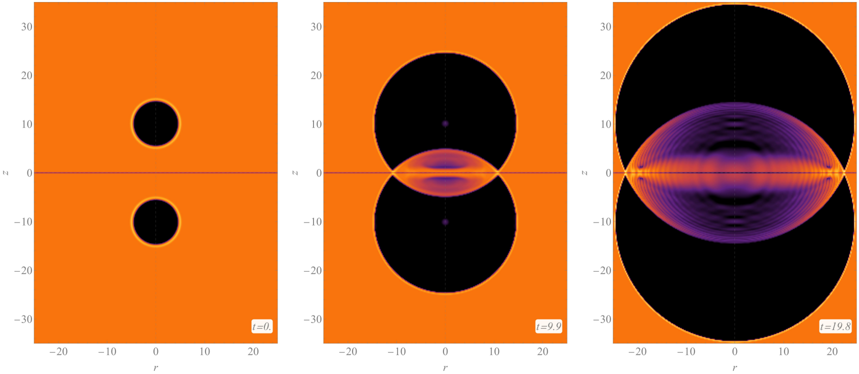
$$V(\phi, T) = g^2 T^2 \phi^2 + \frac{3g^4}{4\pi^2}\phi^4 \left(\log\left(\frac{\phi^2}{v^2}\right) - \frac{1}{2} - \frac{g^2 T^2}{2v^2}\right)$$



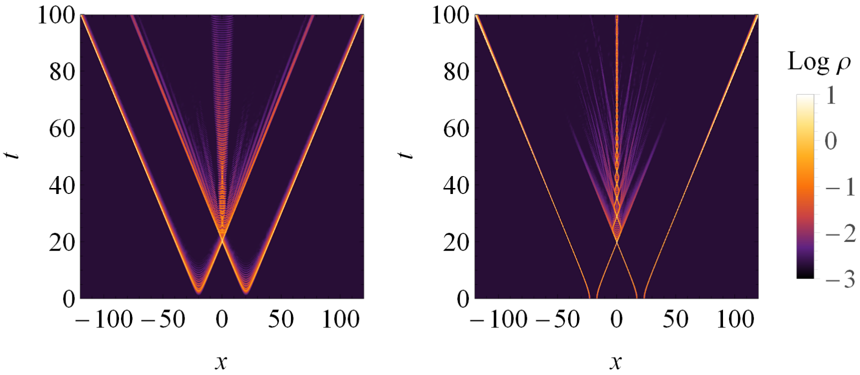
Computation of the GW spectrum



Bubble Collisions



Vacuum Trapping



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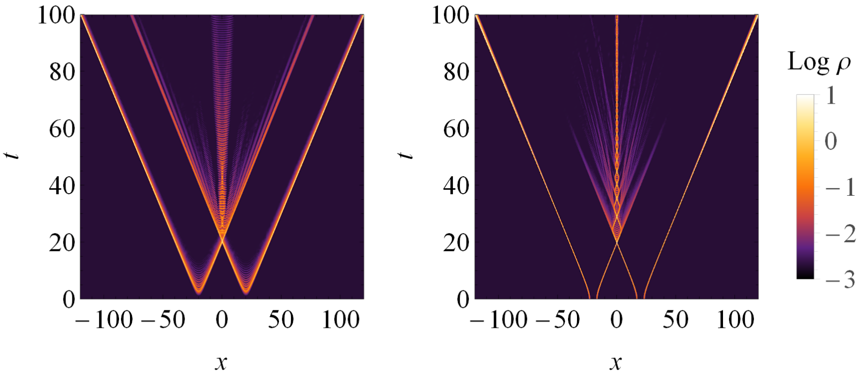
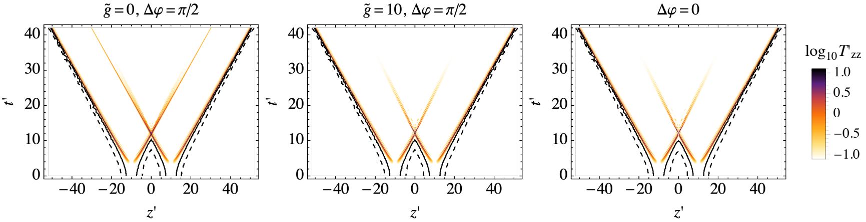
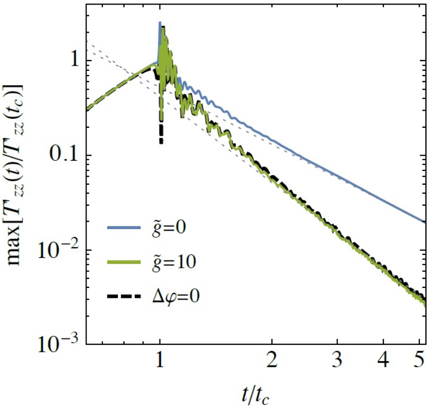


- scale-invariant vs. polynomial
- can also be verified analytically:
  R. Jinno, T. Konstandin and M. Takimoto: 1906.02588

Abelian Higgs Model: Energy Scaling





- scaled gauge coupling:

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

- Global Symmetry breaking:

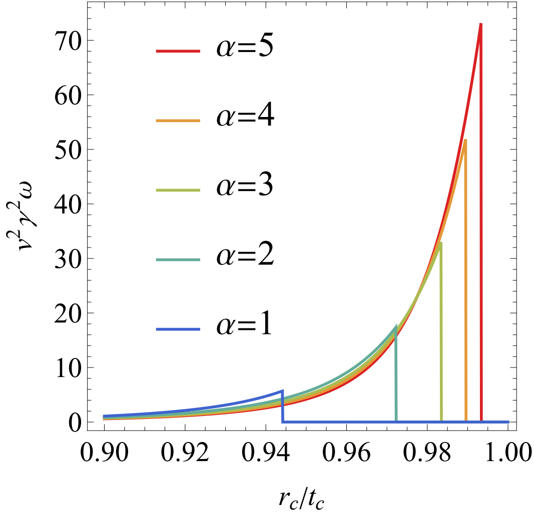
$$T_{zz} \propto R^{-2}$$

- Gauge Symmetry breaking and Fluid Shells:

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

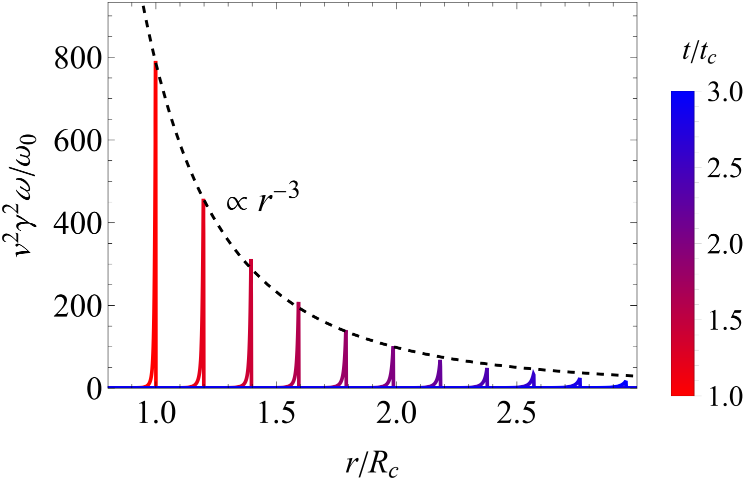
Fluid Shells

- Plasma profiles for $v_w \gtrsim v_J$



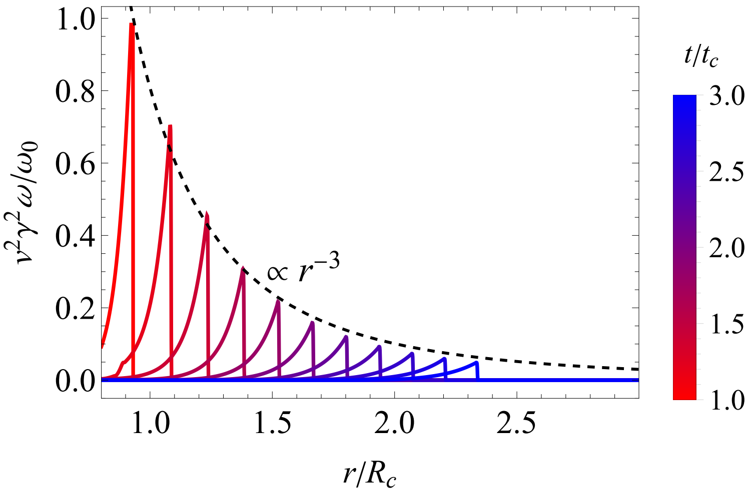
Fluid Shell Evolution

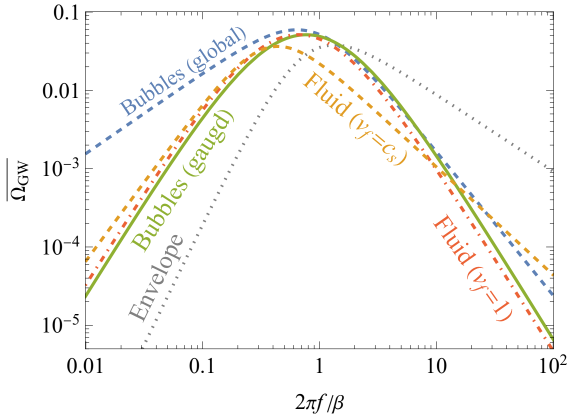
- Plasma profile evolution with $\alpha = 20$ and $\gamma_w = 50$



Fluid Shell Evolution

- Plasma profile evolution with $\alpha = 0.5$ and $\gamma_w = 3$





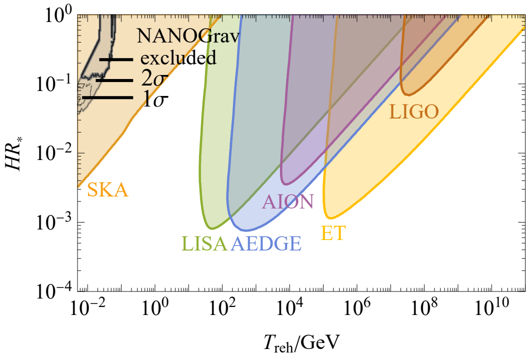
- Resulting spectrum:

$$\overline{\Omega_{GW}} = \frac{A\,(a+b)^c}{\left[b\left(\frac{f}{f_p}\right)^{-\frac{a}{c}} + a\left(\frac{f}{f_p}\right)^{\frac{b}{c}}\right]^c}$$

	Bubbles		Fluid	
	Global($T \propto R^{-2}$)	Gauged ($T \propto R^{-3}$)	$v_{\rm fluid} = 1$	$v_{\rm fluid} = c_s$
$100\,A$	5.93 ± 0.05	5.13 ± 0.05	5.14 ± 0.04	3.64 ± 0.02
a	1.03 ± 0.04	2.41 ± 0.10	2.36 ± 0.09	2.02 ± 0.08
b	1.84 ± 0.17	2.42 ± 0.11	2.36 ± 0.09	1.38 ± 0.06
c	1.91 ± 0.29	1.45 ± 0.34	3.69 ± 0.48	1.48 ± 0.32
$2\pi f_p/\beta$	1.33 ± 0.19	0.64 ± 0.09	0.66 ± 0.04	0.44 ± 0.04

ML, Ville Vaskonen arXiv:2208.11697

Conclusions



- GW signals strong enough to be observed can only be produced in transitions with very relativistic wall velocities $v_w \approx 1$.
- Observable bubble collision signal is produced in very strong transitions $\alpha > 10^{10}$, however, also fluid shells in a very strong transition $\alpha \gg 1$ would produce the same spectrum.