Search for new physics through primordial gravitational wave signals

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Warsaw, 12 I 2023

POLSKIE POWROTY
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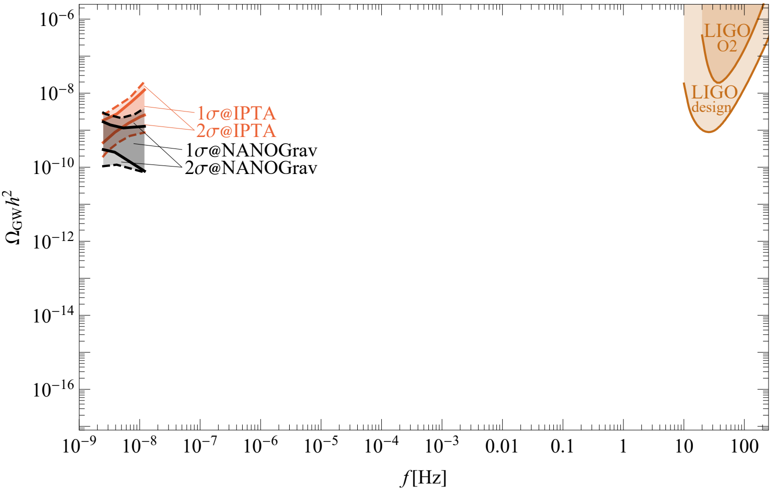
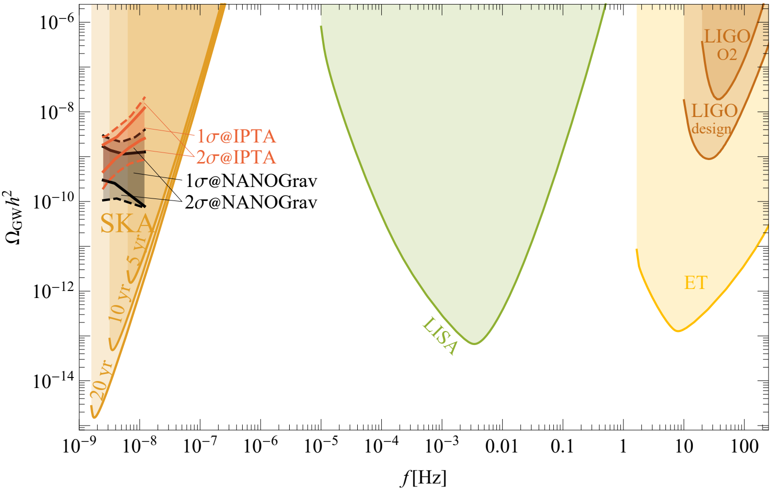
National Science Centre
Poland

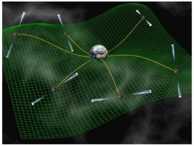
Plan

- Experimental prospects
- First-order phase transitions
  - Bubble wall velocity
  - Energy Budget of the transition
  - GW spectra from strong transitions
- GW background from Cosmic Strings and NANOGrav data
  - Cosmic Archaeology
- Conclusions

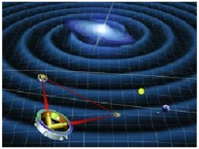


LIGO
O2
LIGO
design
1σ@IPTA
2σ@IPTA
1σ@NANOGrav
2σ@NANOGrav
$\Omega_{\rm GW}h^2$
f[Hz]
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
0.01
0.1
1
10
100

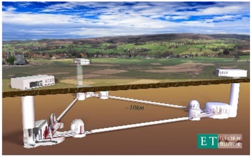




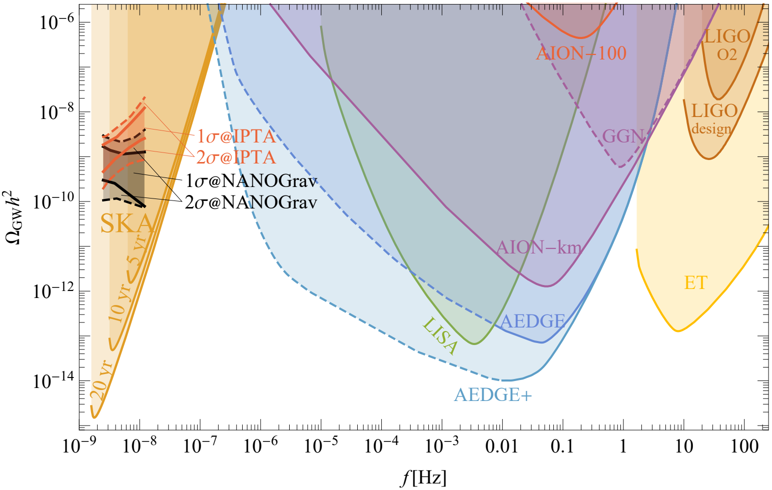
Pulsar Timing
[David Champion/NASA/JPL]

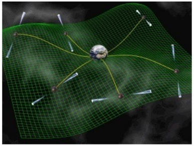


LISA
wiki/Laser_Interferometer_Space_Antenna



Einstein Telescope
www.et-gw.eu





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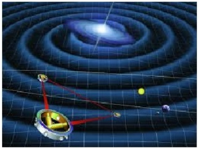

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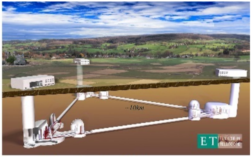

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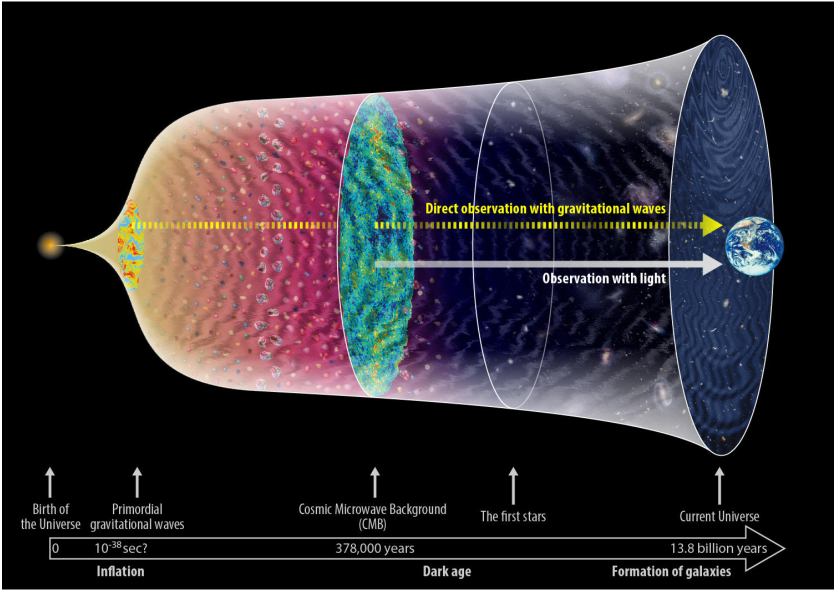
Early Universe Sources

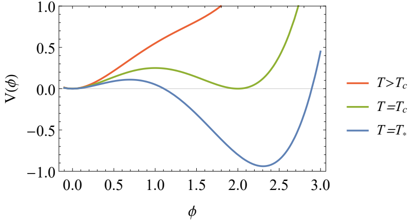


plot credit:https://gwpo.nao.ac.jp/en/gallery

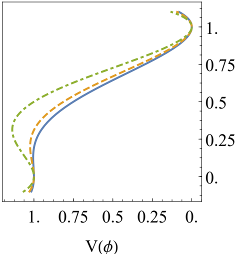
First Order Phase Transition

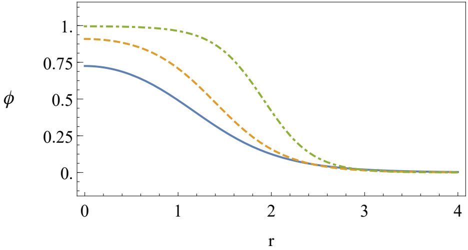
- Simple high temperature expansion

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

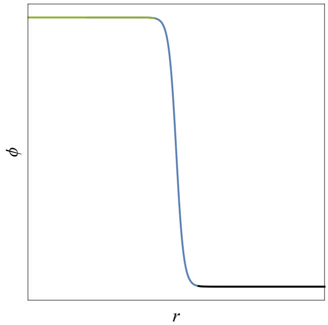


- Eventually the barrier becomes small enough that bubbles can nucleate

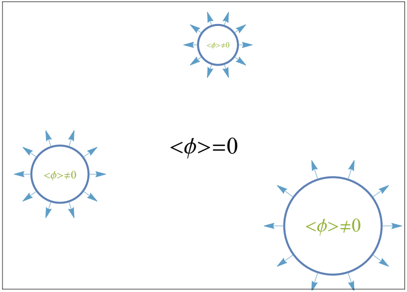




First Order Phase Transition



$\Longrightarrow$



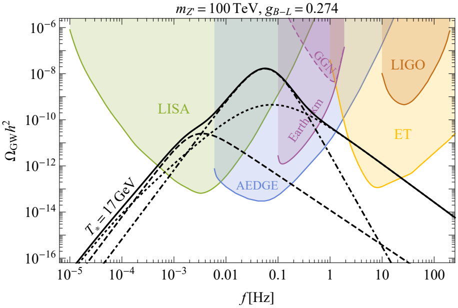
- Strength of the transition

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

- 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



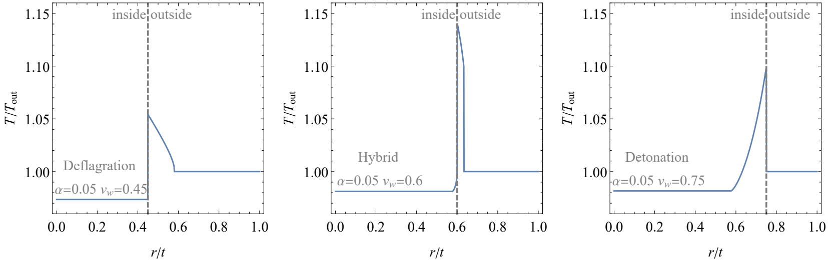
- Gravitational wave signals are produced by three main mechanisms:
  - collisions of bubble walls $\Omega_{\rm col} \propto \left(\kappa_{\rm col} \frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2$

    Kamionkowski '93, Huber '08, Hindmarsh '18 '20 **Lewicki** '19 '20 '22,
  - sound waves $\Omega_{\rm sw} \propto \left(\kappa_{\rm sw} \frac{\alpha}{\alpha+1}\right)^2 (HR_*)(H\tau_{sw})$

    Hindmarsh '13 '15 '17 '19 '21, **Ellis** '18 '19 '20, Jinno '20
  - turbulence $\Omega_{\rm turb} \propto\ ?$

    Caprini '06 '09 '20, Brandenburg '10 '12 '17, Roper-Pol '17 '19 '21, Ellis '19 '20

Wall Velocity



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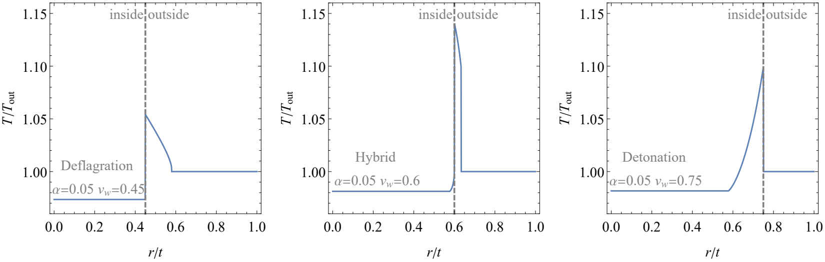
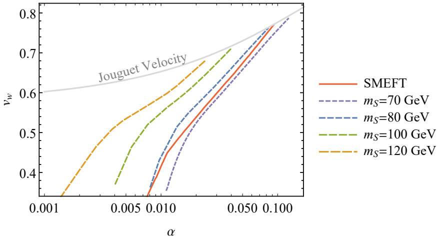


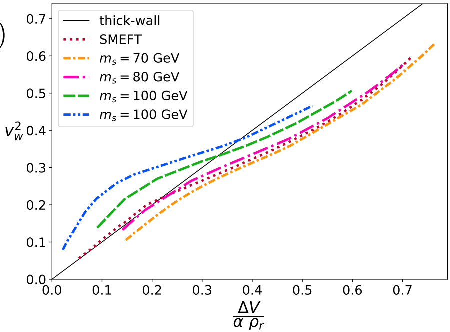
- No solutions found beyond $v_J = \frac{1}{\sqrt{3}} \frac{1+\sqrt{3\alpha^2+2\alpha}}{1+\alpha}$.



ML, Marco Merchand, Mateusz Zych, JHEP **02** (2022) 017, arXiv: 2111.02393

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, JHEP **02** (2022) 017, arXiv: 2111.02393

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

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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$$p_0 = \Delta V$$

- 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

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

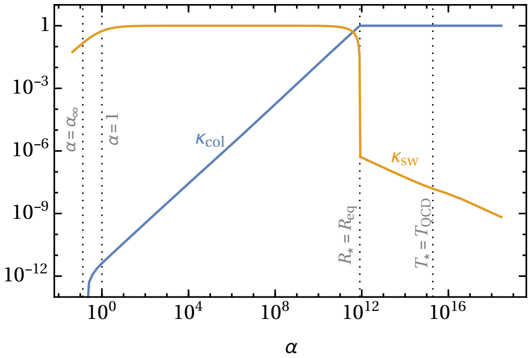
- Next-To-Leading order plasma contribution with resummation
  Hoche '20

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

- Terminal velocity corresponds to $\gamma_{\rm eq}$
- Without friction we would find γ_*

$$\kappa_{\rm col} = \frac{E_{\rm wall}}{E_V} = \begin{cases} \left[1 - \frac{1}{3}\left(\frac{\gamma_*}{\gamma_{\rm eq}}\right)^2\right]\left[1 - \frac{P_{1\to 1}}{\Delta V}\right], & \gamma_* < \gamma_{\rm eq}\,, \\ \frac{2}{3}\frac{\gamma_{\rm eq}}{\gamma_*}\left[1 - \frac{P_{1\to 1}}{\Delta V}\right], & \gamma_* > \gamma_{\rm eq}\,, \end{cases}$$

$$\kappa_{\rm sw} = \frac{\alpha_{\rm eff}}{\alpha}\frac{\alpha_{\rm eff}}{0.73 + 0.083\sqrt{\alpha_{\rm eff}} + \alpha_{\rm eff}}\,, \quad \text{with} \quad \alpha_{\rm eff} = \alpha(1 - \kappa_{\rm col})\,.$$

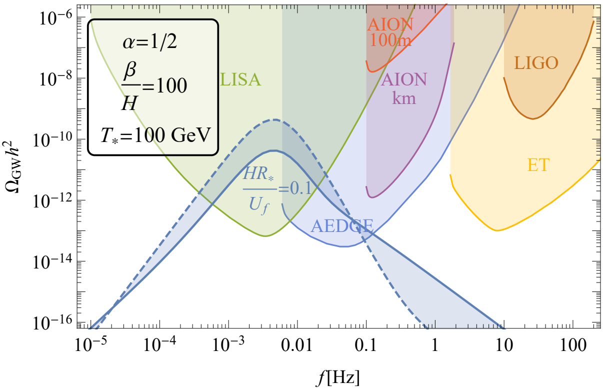


John Ellis, ML, José Miguel No, Ville Vaskonen, JCAP **06** (2019), 024, arXiv:1903.09642

Plasma related GW sources

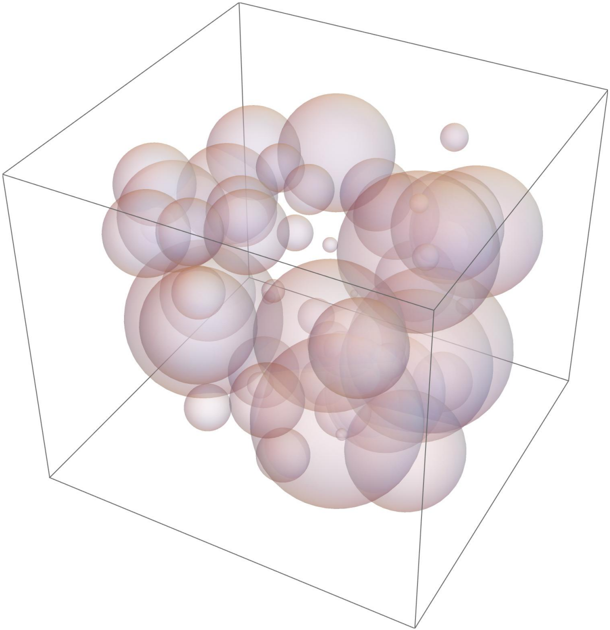
- Sound wave spectrum reduction and earlier onset of turbulence

$$\Omega_{\rm sw} \propto H\tau_{\rm sw} = \frac{HR_*}{U_f}, \quad \Omega_{\rm turb} \propto 1 - H\tau_{\rm sw} = 1 - \frac{HR_*}{U_f}$$

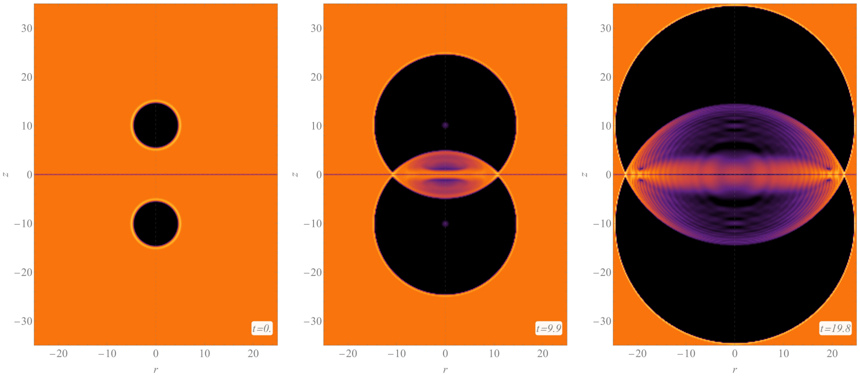


John Ellis, ML, José Miguel No arXiv:1809.08242
John Ellis, ML, José Miguel No, Ville Vaskonen arXiv:1903.09642

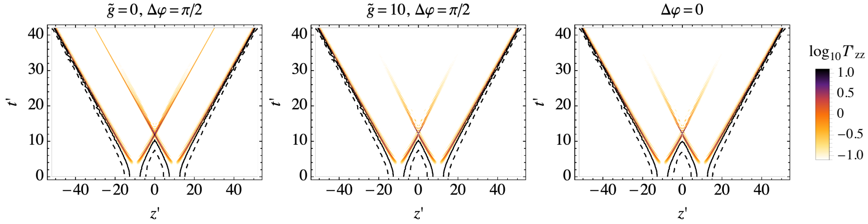
Computation of the GW spectrum

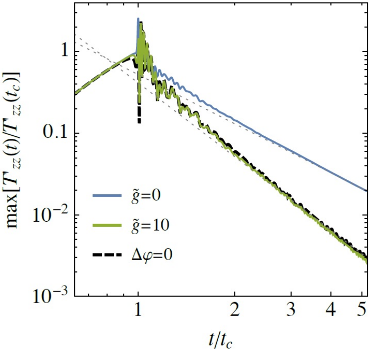


Bubble Collisions



Abelian Higgs Model: Energy Scaling





- scaled gauge coupling:

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

- Global Symmetry breaking:

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

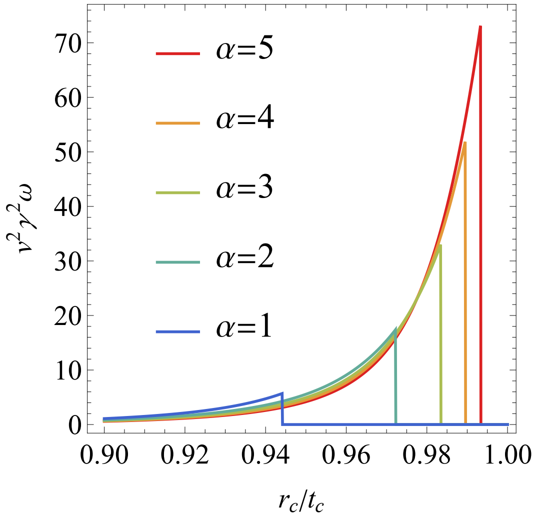
- Gauge Symmetry breaking:

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

ML, Ville Vaskonen, Eur. Phys. J. C **80** (2020) no.11, 1003, arXiv: 2007.04967

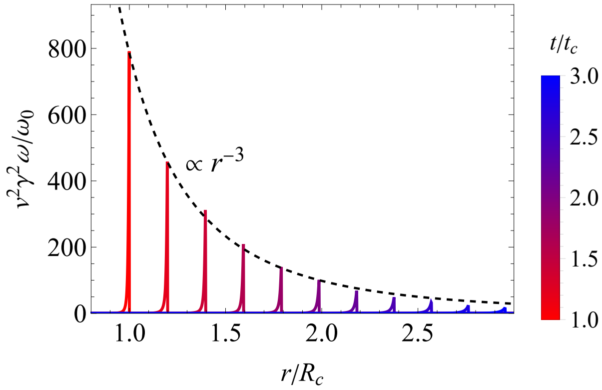
Fluid Shells

- Plasma profiles for $v_w \gtrsim v_J$



Fluid Shell Evolution

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



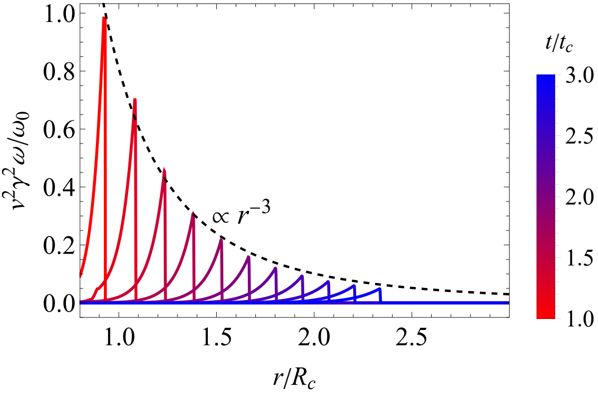
- Fluid shells with $\alpha \gg 1$:

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

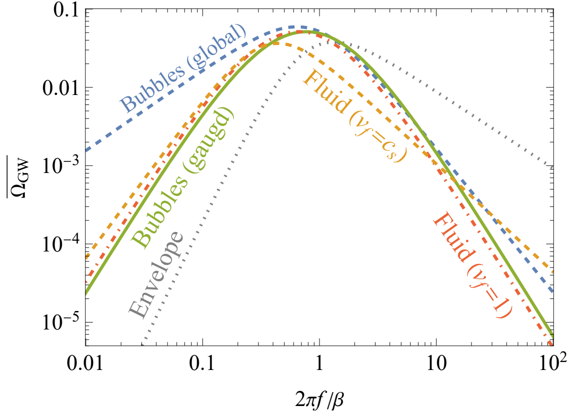
ML, Ville Vaskonen arXiv:2208.11697

Fluid Shell Evolution

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



ML, Ville Vaskonen arXiv:2208.11697



- Resulting spectrum:

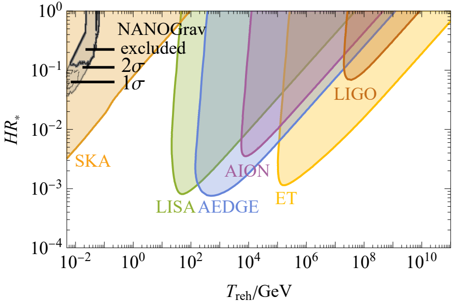
$$\overline{\Omega_{GW}} = \frac{A\,(a+b)^c}{\left[b\left(\frac{f}{f_p}\right)^{-\frac{a}{c}} + a\left(\frac{f}{f_p}\right)^{\frac{b}{c}}\right]^c}$$

	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

ML, Ville Vaskonen, Eur. Phys. J. C **80** (2020) no.11, 1003, arXiv: 2007.04967

Conclusions



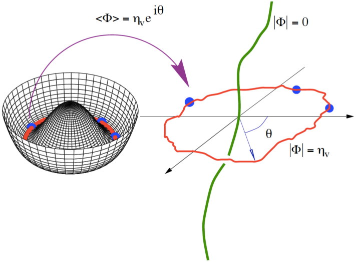
- GW signals strong enough to be observed can only be produced in transitions with very relativistic wall velocities $v_w \approx 1$.
- Sound wave period generically last less than a Hubble time.
  - → This leads to a much weaker sound wave sourced GW signal and potentially a significant increase in the signal sourced by turbulence.
- 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.

Cosmic Strings

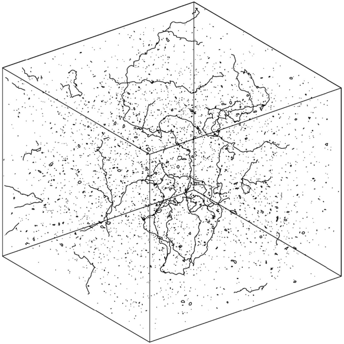
- Charged complex scalar field

$$V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$$

- Horizon size at early time (high temperature) $d_H \propto M_p/T^2$



Christophe Ringeval (Adv.Astron. 2010)



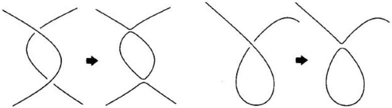
Vilenkin and Shellard '94

Cosmic String network evolution

- Static string network would red-shift as

$$\rho_\infty \propto a^{-2}$$

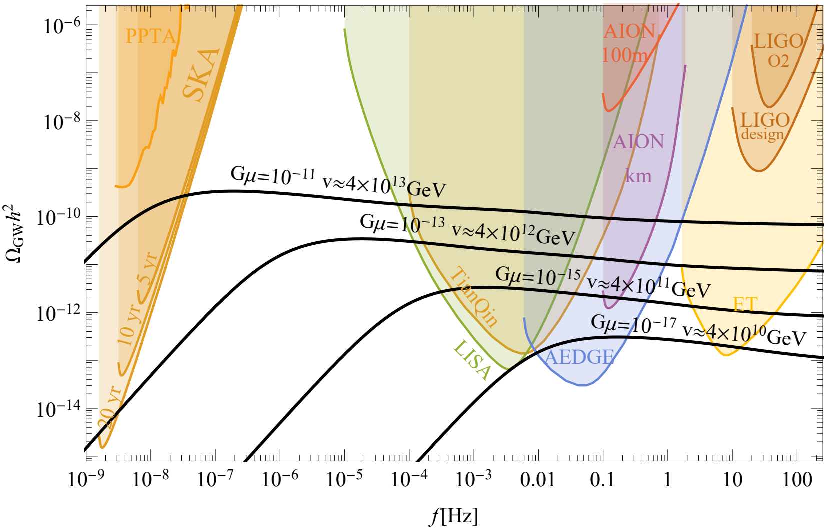
- strings intercommute on collision



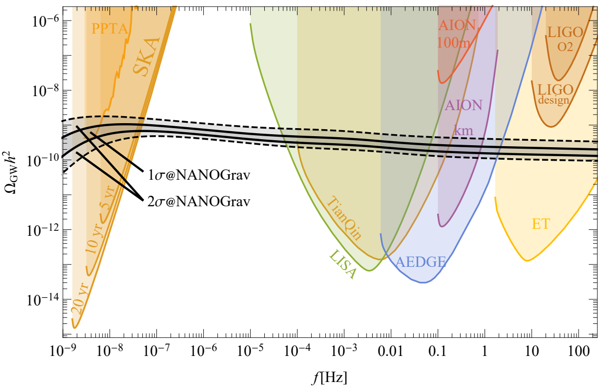
- overall energy density of the network scales with total energy density

$$\frac{\rho_\infty}{\rho_{\rm tot}} \propto G\mu \propto \frac{v^2}{M_p^2}$$

Stochastic GW background from Cosmic Strings



Cosmic String fit to NANOGrav data



- results within the 68% CL

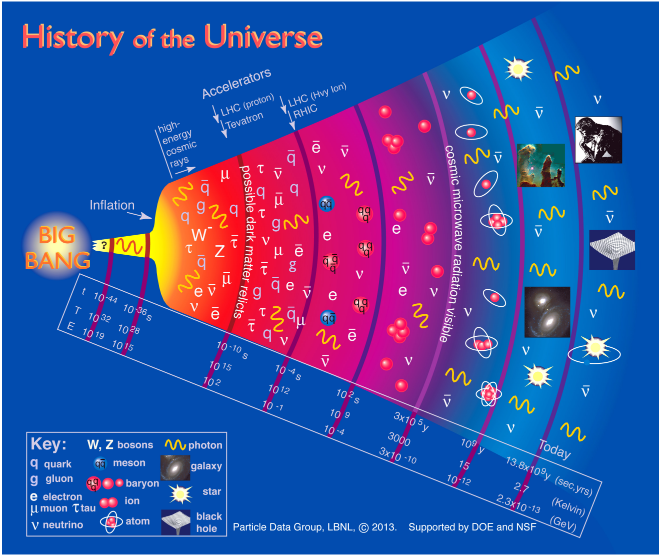
$$G\mu \in (4 \times 10^{-11}, 10^{-10})$$

- results within the 95% CL

$$G\mu \in (2 \times 10^{-11}, 3 \times 10^{-10})$$

John Ellis, ML, Phys. Rev. Lett. **126** (2021) no.4, 041304, arXiv: 2009.06555

Cosmic Archaeology



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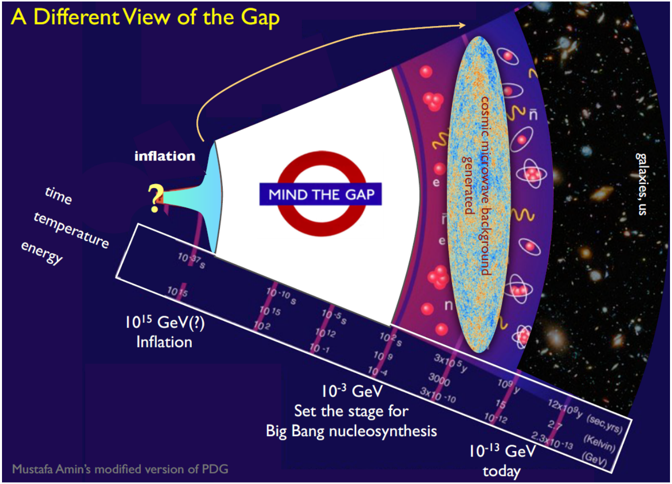
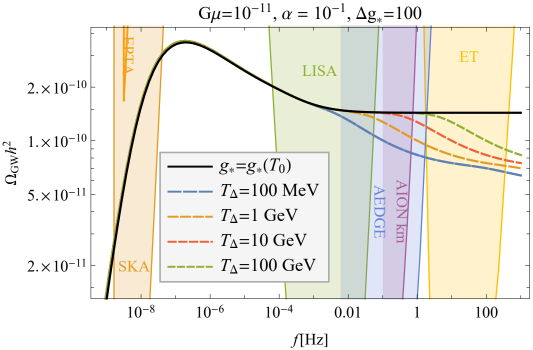


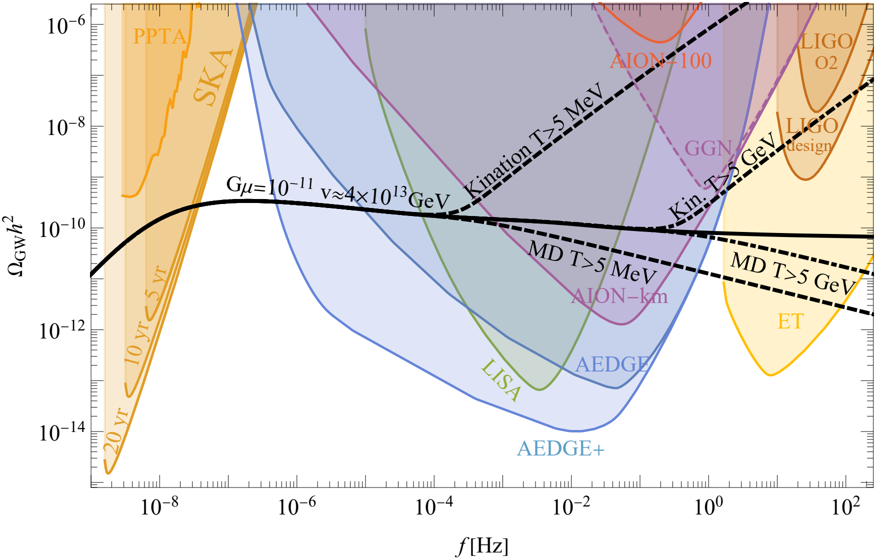
- We add Δg_* new degrees of freedom at T_Δ

$$g_*(T) = \begin{cases} g_*(T_0) & \text{for} \quad T < T_\Delta \\ g_*(T_0) + \Delta g_* & \text{for} \quad T > T_\Delta \end{cases}$$

- An example with $\Delta g_* = 100$



Y. Cui, ML, D. E. Morrissey, J. D. Wells,
Phys. Rev. D **97** (2018) no.12, 123505, arXiv:1711.03104
JHEP **01** (2019), 081, arXiv:1808.08968
Phys. Rev. Lett. **125** (2020) no.21, 211302, arXiv:1912.08832



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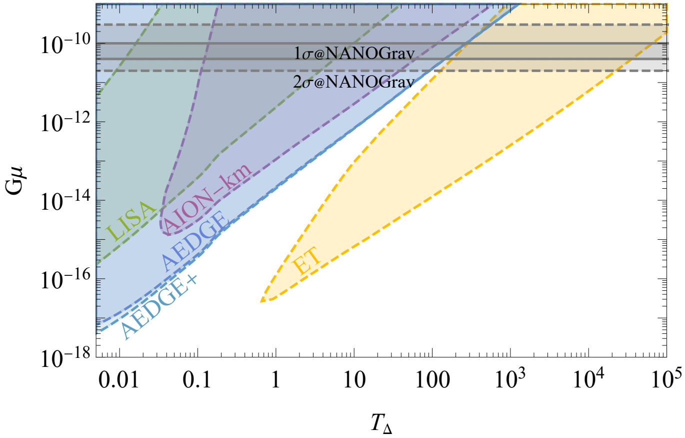
Conclusions



1. Cosmic strings provide a very good fit to the NANOGrav data.
2. If confirmed they would provide a powerful tool for probing the cosmological evolution to time well before the currently available BBN data.