Search for new physics through primordial gravitational waves

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Copernicus Webinar, 21 VI 2022

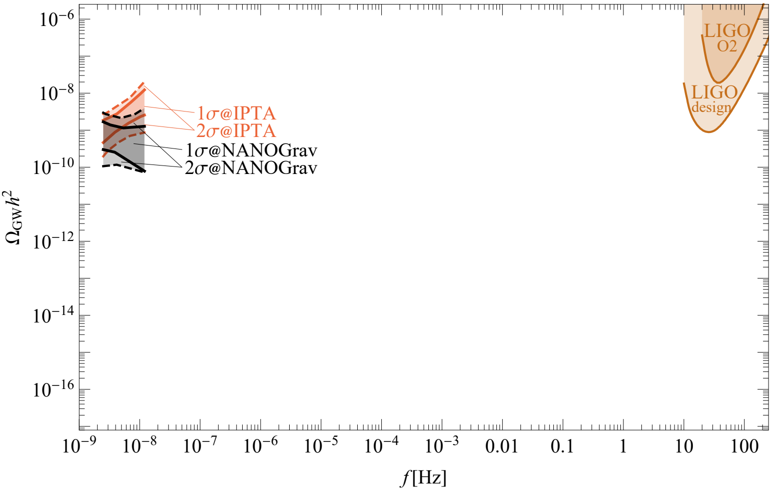
POLSKIE POWROTY
POLISH RETURNS

UNIVERSITY OF WARSAW

National Science Centre Poland

Plan

- Experimental prospects
- Astrophysical sources and their Stochastic GW foreground
- First-order phase transitions and their GW spectra
- GW background from Cosmic Strings and NANOGrav data
- Cosmic Archaeology
- Conclusions



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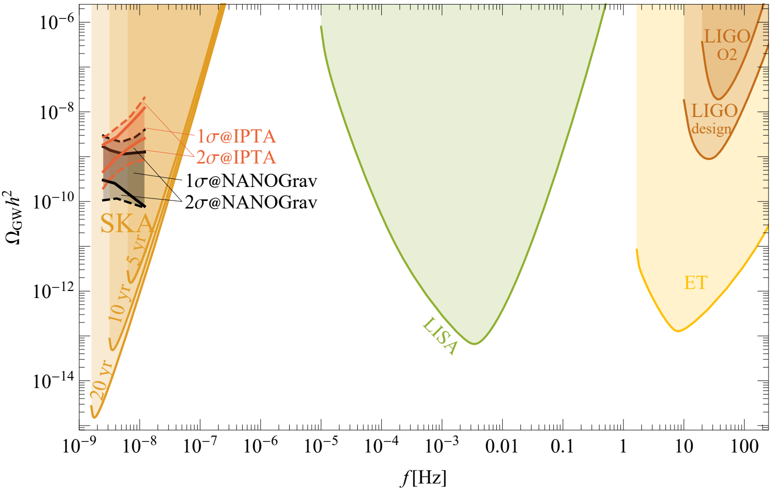
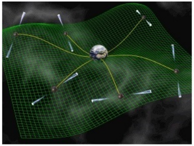
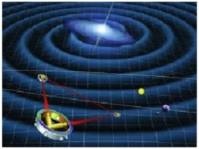
10
100
f[Hz]

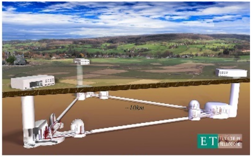




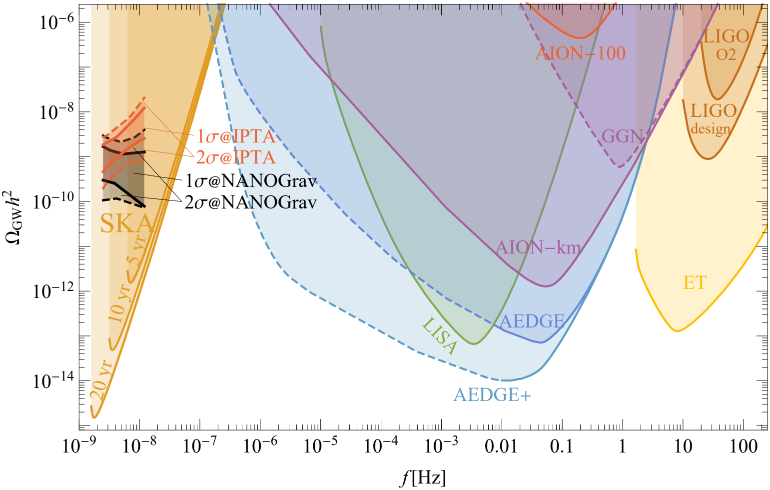
Pulsar Timing
[David Champion/NASA/JPL]

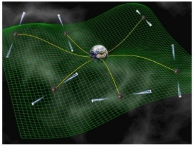


LISA
wiki/Laser_Interferometer_Space_Antenna



Einstein Telescope
www.et-gw.eu





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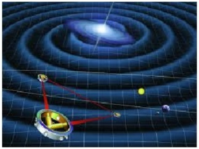

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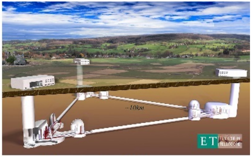
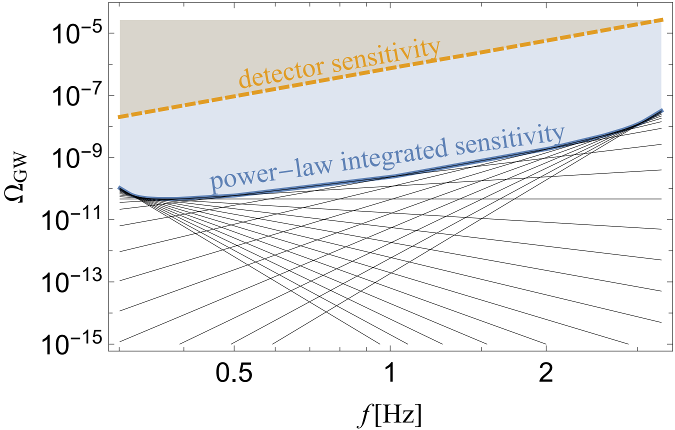


Einstein Telescope
www.et-gw.eu

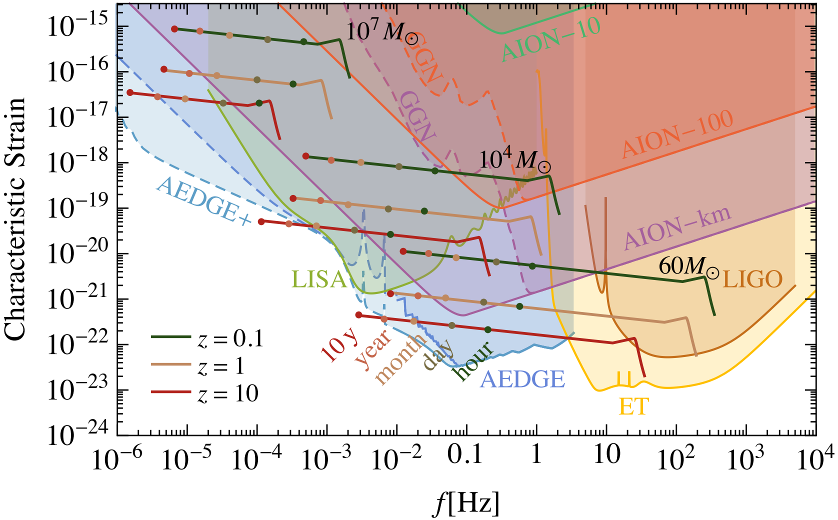
Power-law integrated sensitivity

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

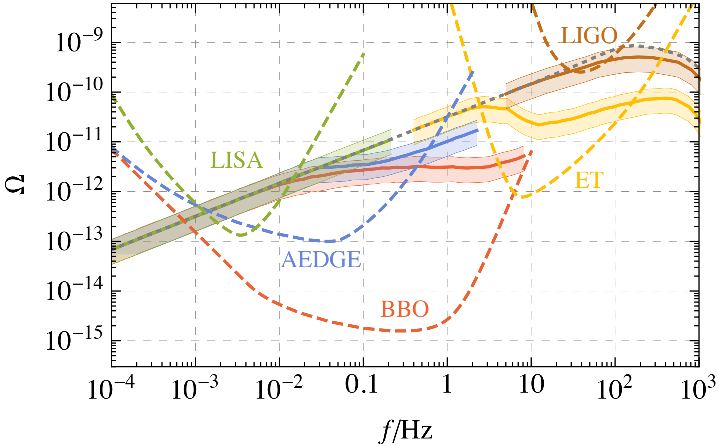


Thrane, Romano '13

Sensitivity to binary mergers



Foreground from LIGO-Virgo binaries



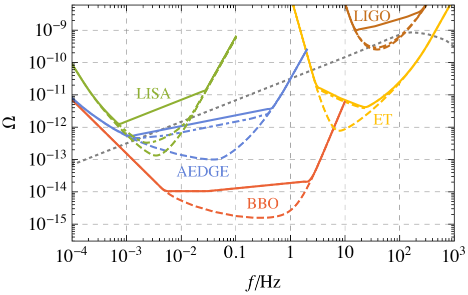
- Dashed gray line: total foreground from LIGO-Virgo binaries
- Thick lines: foreground without individually observable binaries

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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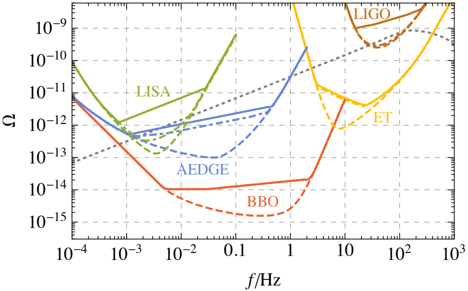
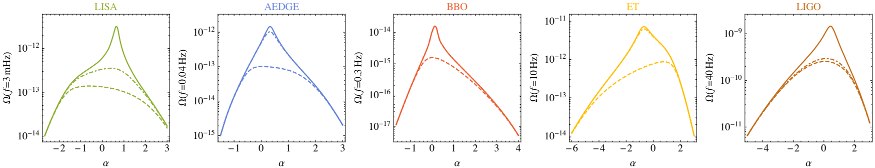
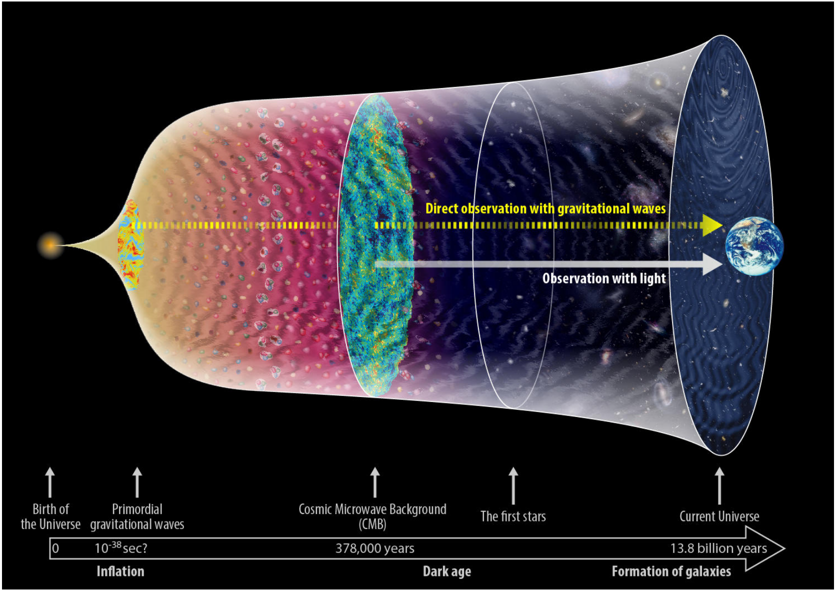




Early Universe Sources

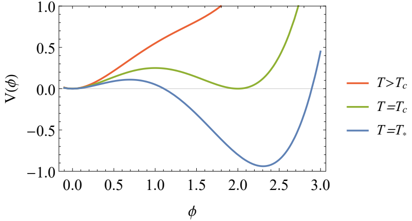


plot credit:https://gwpo.nao.ac.jp/en/gallery

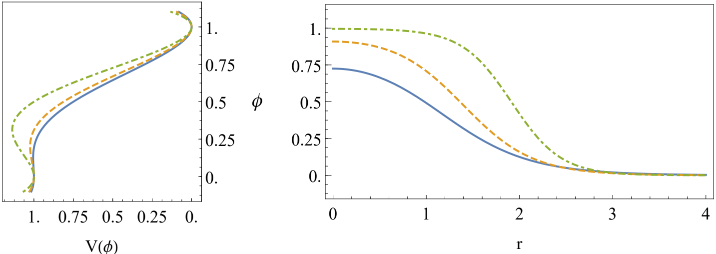
First Order Phase Transition

- Simple high temperature expansion

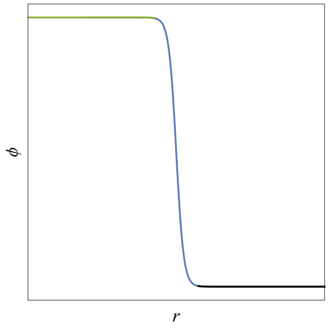
$$V(\phi, T) = \frac{g_{m^2}}{24}\left(T^2 - T_0^2\right)\phi^2 - \frac{g_m}{12\pi}T\phi^3 + \lambda\phi^4\,, \quad T_0^2 > 0$$



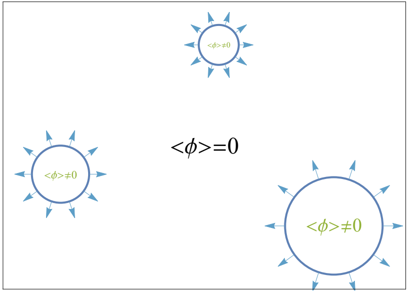
- Eventually the barrier becomes small enough that bubbles can nucleate



First Order Phase Transition



$\Longrightarrow$



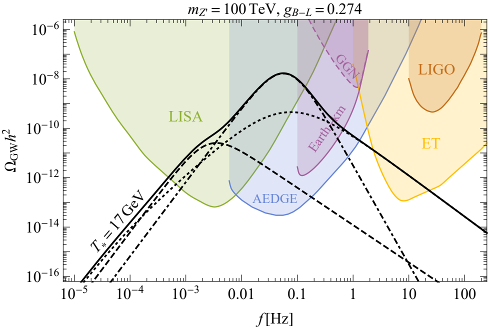
- Strength of the transition

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

- Characteristic scale

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

Gravitational waves from a PT



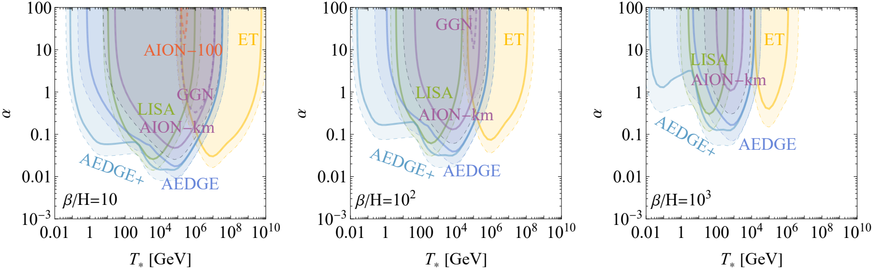
- Signals are produced by three main mechanisms:
  - collisions of bubble walls $\Omega_{\rm col} \propto \left(\kappa_{\rm col}\frac{\alpha}{\alpha+1}\right)^2 (HR_*)^2$
    Kamionkowski '93, Huber '08, Hindmarsh '18 '20 Lewicki '19 '20,
  - sound waves $\Omega_{\rm sw} \propto \left(\kappa_{\rm sw}\frac{\alpha}{\alpha+1}\right)^2 (HR_*)\,(H\tau_{sw})$
    Hindmarsh '13 '15 '17 '19 '21, Ellis '18 '19 '20, Jinno '20
  - turbulence $\Omega_{\rm turb} \propto \left(\kappa_{\rm sw}\frac{\alpha}{\alpha+1}\right)^2 (HR_*)\,(1 - H\tau_{sw})$
    Caprini '06 '09 '20, Brandenburg '10 '12 '17, Roper-Pol '17 '19 '21, Ellis '19 '20

Reach of upcoming experiments

- Position of the peak

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

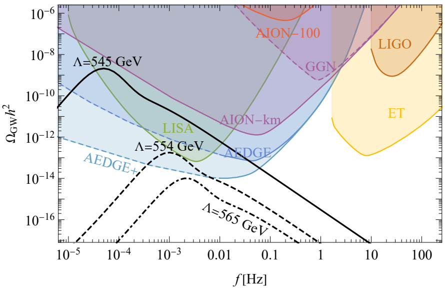
- Detectibility assuming plasma related sources

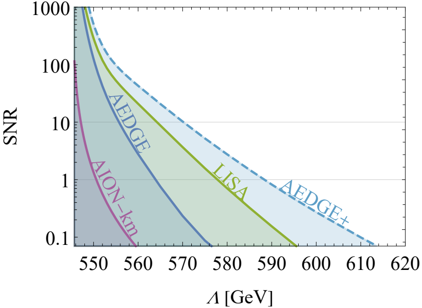


Plasma related GW sources

- Standard Model supplemented with a non-renormalisable operator

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

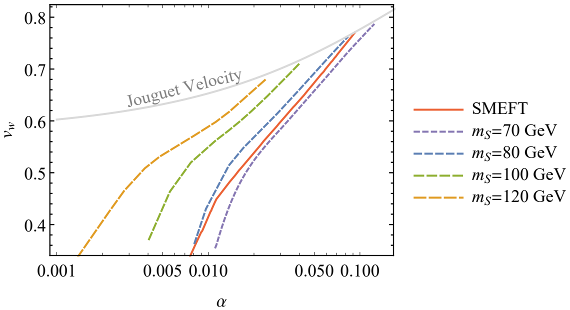




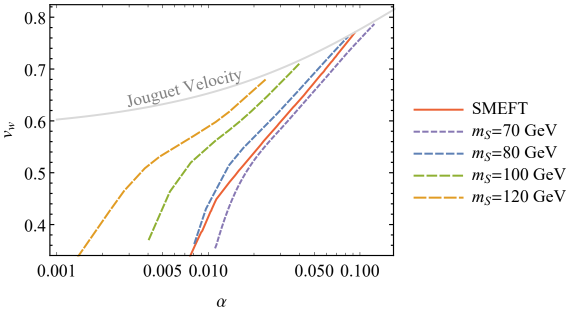
- Connection with baryogenesis

  ML, Marco Merchand, Mateusz Zych arXiv:: 2111.02393

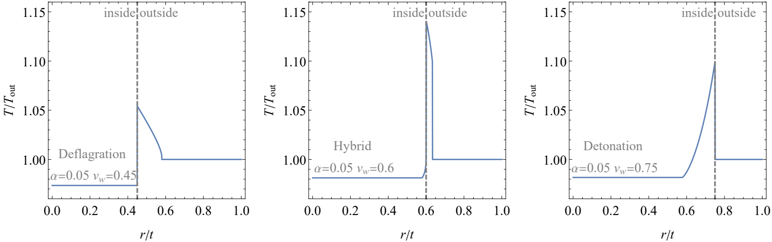
Wall Velocity



Wall Velocity



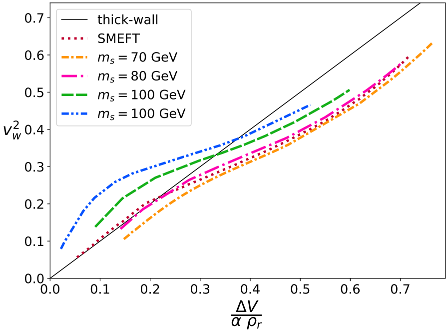
- No solutions found beyond $v_J = \frac{1}{\sqrt{3}} \frac{1+\sqrt{3\alpha^2+2\alpha}}{1+\alpha}$.



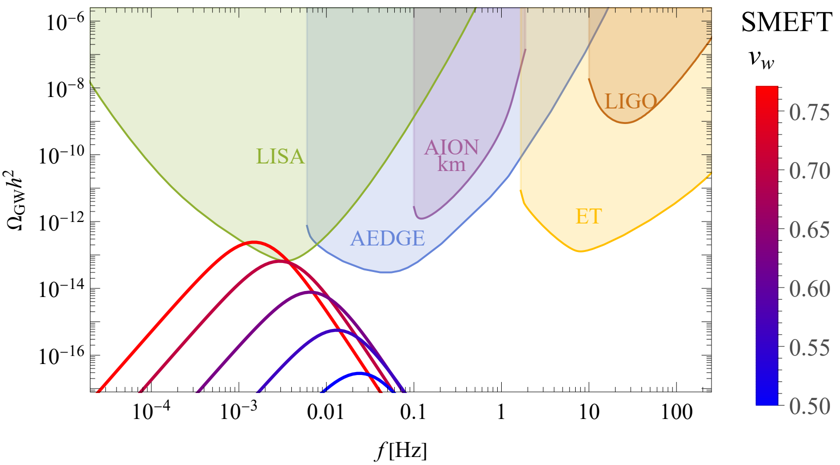
bubble wall analytic results

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

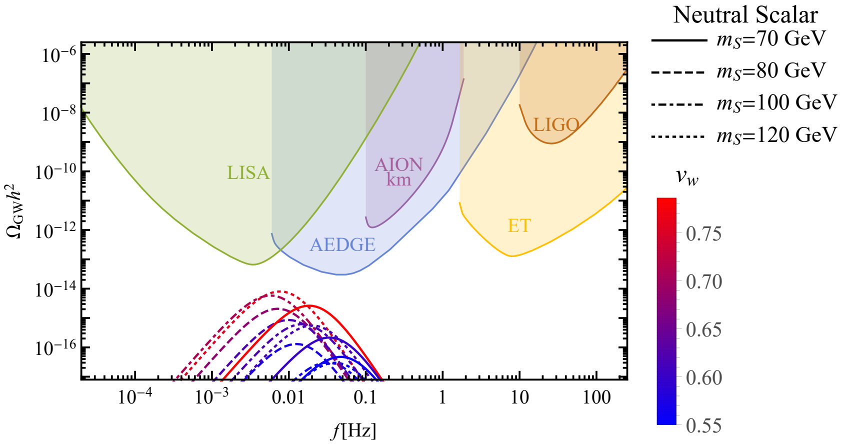
- Simple arguments of thermal equilibrium imply the relation $v_w^2 \sim \Delta p / \Delta \rho$:
- Formula does not require solving transport equations
- Only the form of the potential is important



Gravitational wave signals



Gravitational wave signals

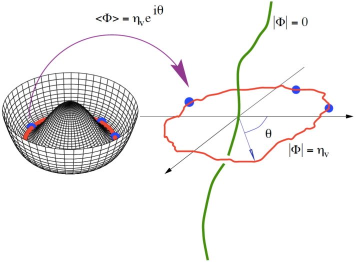


Cosmic Strings

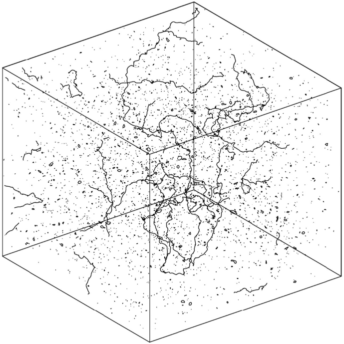
- Charged complex scalar field

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

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



Christophe Ringeval (Adv.Astron. 2010)



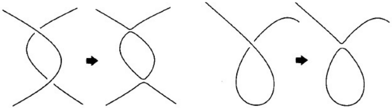
Vilenkin and Shellard '94

Cosmic String network evolution

- Static string network would red-shift as

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

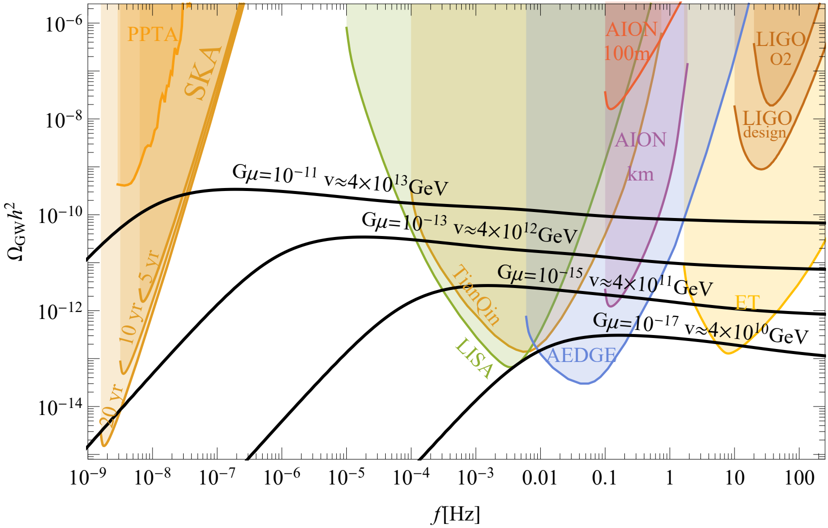
- strings intercommute on collision



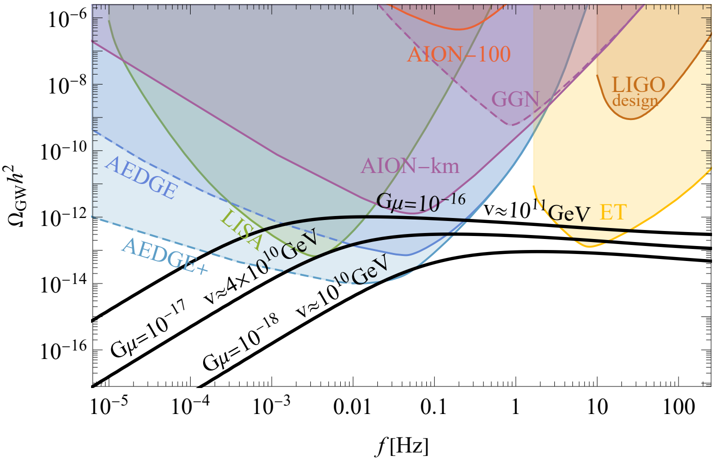
- overall energy density of the network scales with total energy density

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

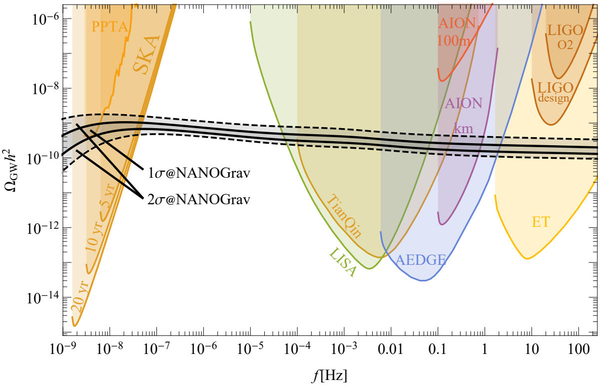
Stochastic GW background from Cosmic Strings



Stochastic GW background from Cosmic Strings



Cosmic String fit to NANOGrav data



- results within the 68% CL

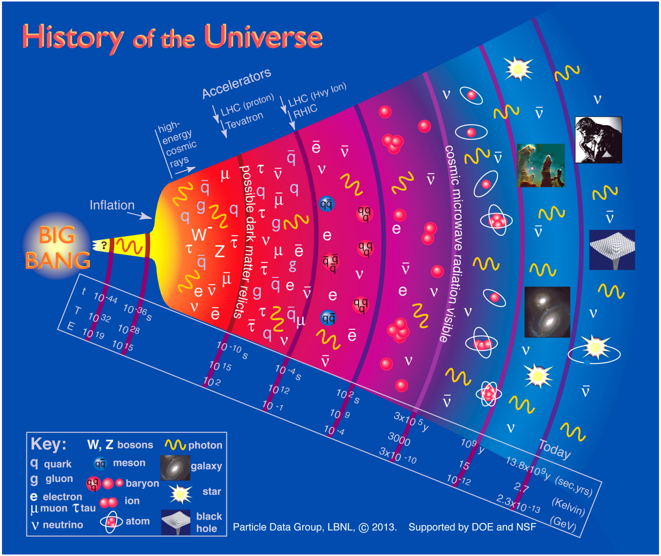
$$G\mu \in (4 \times 10^{-11}, 10^{-10})$$

- results within the 95% CL

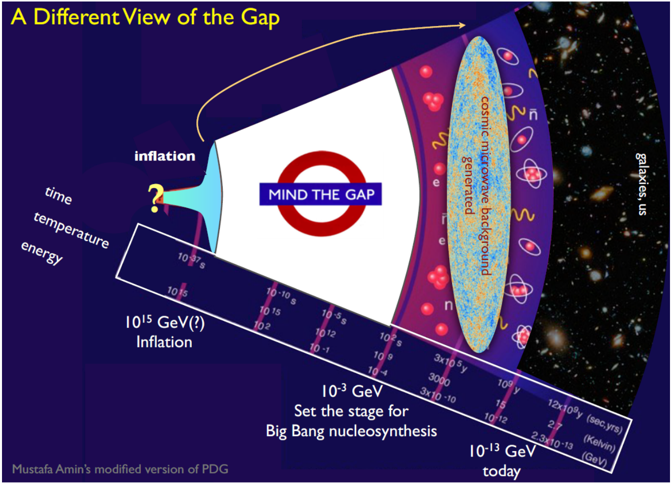
$$G\mu \in (2 \times 10^{-11}, 3 \times 10^{-10})$$

John Ellis, ML arXiv: 2009.06555

Cosmic Archaeology



Cosmic Archaeology

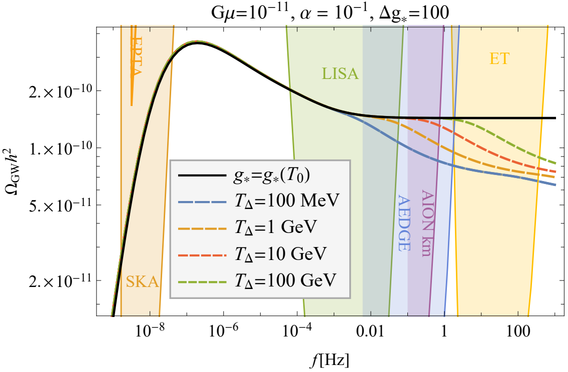


Cosmic Strings GW signal and expansion history

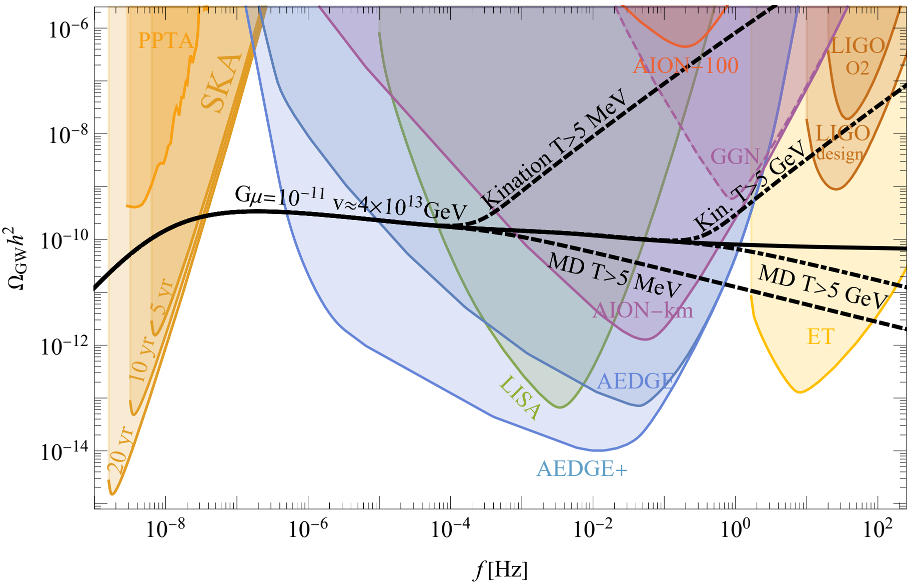
- We add Δg_* new degrees of freedom at T_Δ

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

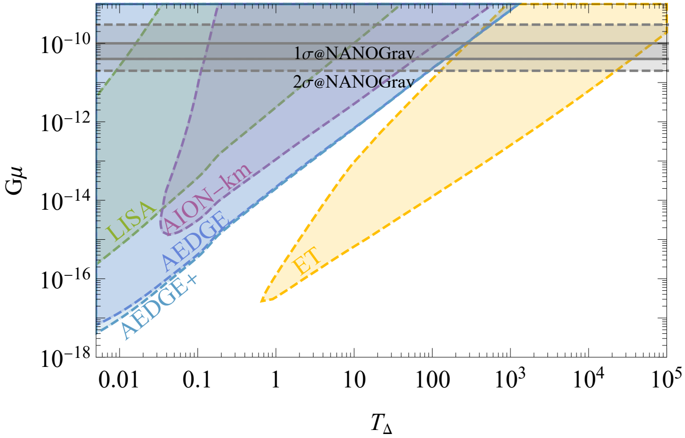
- An example with $\Delta g_* = 100$



Cosmic Strings GW signal and expansion history



Detection capabilities



- frequency of the modification

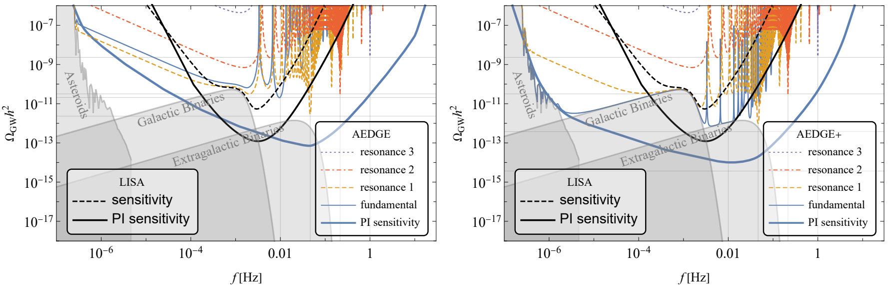
$$f_\Delta = (8.67 \times 10^{-9}\,\mathrm{Hz})\,\frac{T_\Delta/\mathrm{GeV}}{\sqrt{\alpha\, G\mu}}\left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}}\left(\frac{g_S(T_0)}{g_S(T_\Delta)}\right)^{-\frac{7}{6}}$$

Thank you for your attention!

Conclusions:

- Gravitational wave foreground from astrophysical objects will have a significant impact on searches for primordial signals.
- The next generation of experiments will allow us to probe phase transitions in a wide range of temperatures provided only they are strong enough.
- Cosmic strings are a viable explanation for recent observations of pulsar timing experiments. If this posibility is realised probing the evolution of the Universe via GW signals from cosmic strings would allow to masure the expansion rate up to temperatures 10^7 larger than the currently available data.

AEDGE noise sources



- Thin lines: instantaneous sensitivity of operation modes
- Thick lines: Power-Law integrated sensitivities

- 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

$$p_0 = \Delta V$$

- Energy of the bubble

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

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  Coleman '73

$$p_0 = \Delta V$$

- Leading order plasma contribution
  Bodeker '09 Caprini '09

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

- Energy of the bubble

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

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

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

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

- 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 γ factor and the value in absence of friction

$$\gamma_{\rm eq} = \sqrt{\frac{\Delta V - P_{1\to 1}}{P_{1\to N}}} \simeq \sqrt{\frac{\Delta V - 0.04\Delta m^2 T^2}{0.005 g^2 T^4}}\,, \qquad \gamma_* \equiv \frac{2}{3}\,\frac{R_*}{R_0}\,,$$

- terminal velocity γ factor and the value in absence of friction

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- Amount of energy stored in the wall

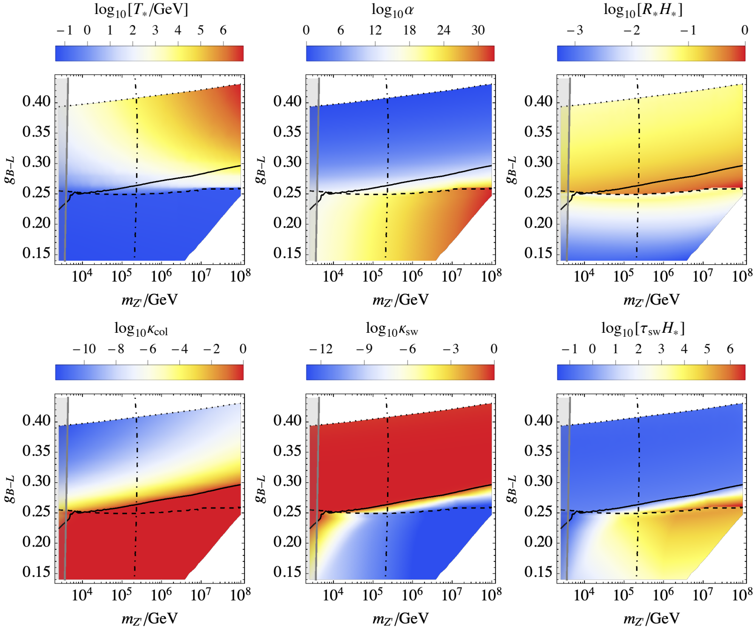
$$E_{\rm wall} = \frac{4\pi R^2}{3}\int_0^R dR' \left[\Delta V - P_{1\to 1} - \gamma^2(R') P_{1\to N}\,,\right.$$

- Finally the efficiency factors read

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

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

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



Purely thermal transition: no $T = 0$ potential barrier

- Simple polynomial potential

$$V(\phi) = m^2\phi^2 - a\,\phi^3 + \lambda\phi^4$$

- Has a semi-analytical solution

$$\frac{S_3}{T} = \frac{a}{T\lambda^{3/2}}\frac{8\pi\sqrt{\delta}\left(\beta_1\delta + \beta_2\delta^2 + \beta_3\delta^3\right)}{81(2-\delta)^2}, \quad \text{where} \quad \delta \equiv \frac{8\lambda m^2}{a^2}$$

Adams '93

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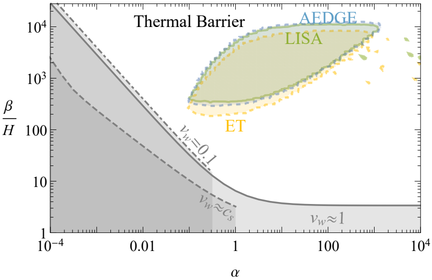
Adams '93

- Useful for high temperature expansion

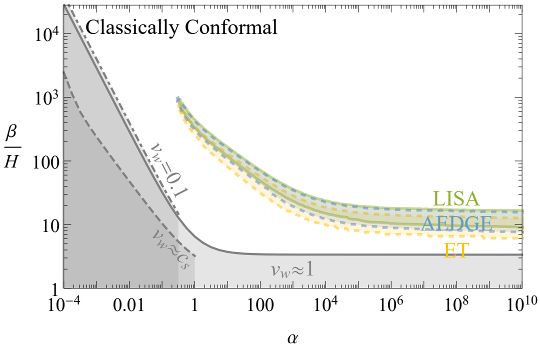
$$V(\phi, T) = \frac{g_{m^2}}{24}\left(T^2 - T_0^2\right)\phi^2 - \frac{g_m}{12\pi}T\phi^3 + \lambda\phi^4\,, \quad T_0^2 > 0$$



Classically scale-invariant CW-like potential

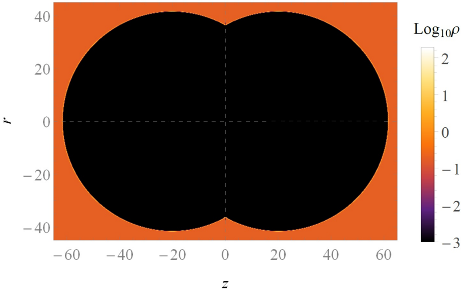
- Generic classically scale-invariant potential

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



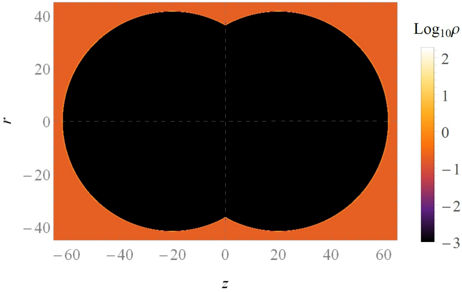
Bubble Collisions

- Envelope

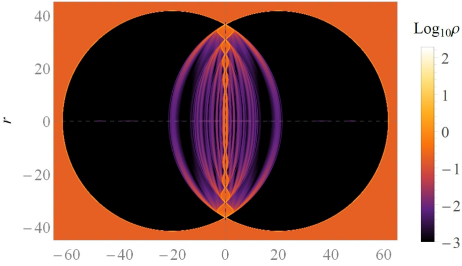


Bubble Collisions

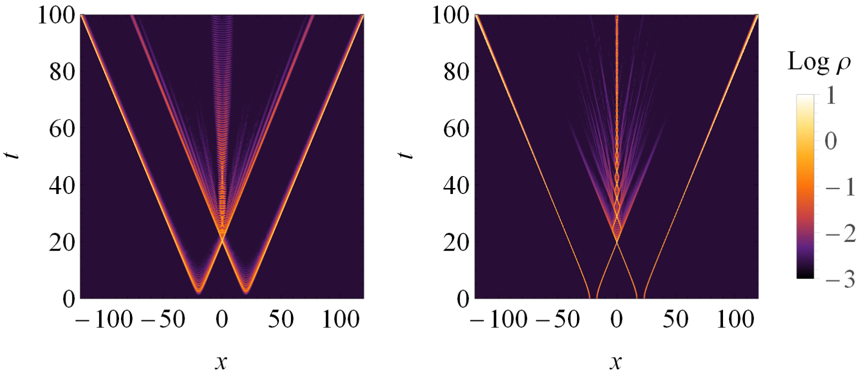
- Envelope



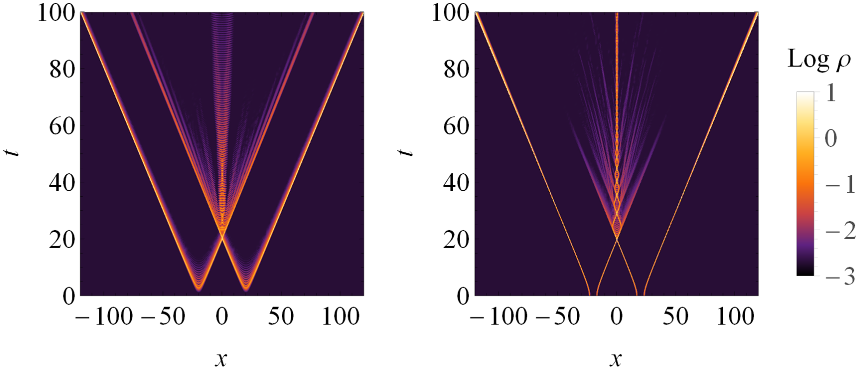
- Simulation



Vacuum Trapping



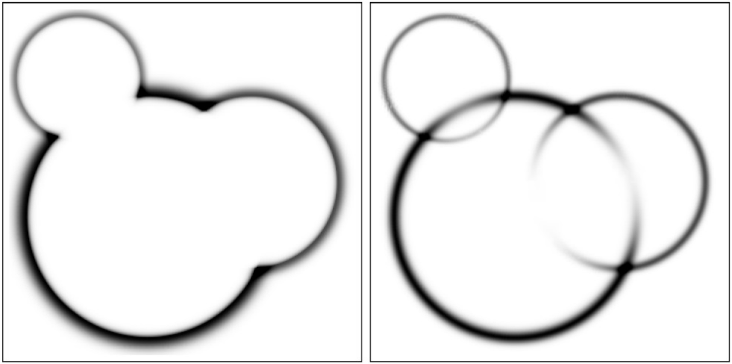
Vacuum Trapping



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

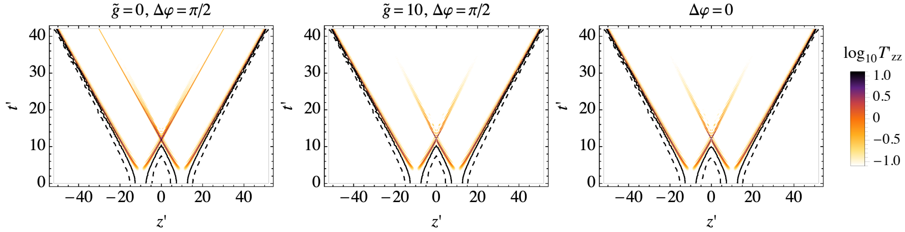
Computation of the GW spectrum

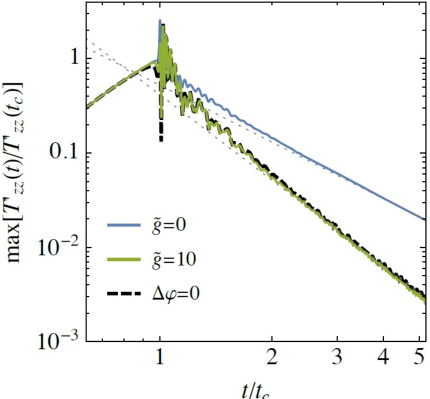
- Bulk Flow model: $E \propto R^{-2}$
  R. Jinno and M. Takimoto 1707.03111, T. Konstandin 1712.06869



- We follow a similar approach using scaling from lattice simulations

Abelian Higgs Model: Energy Scaling





- scaled gauge coupling:

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

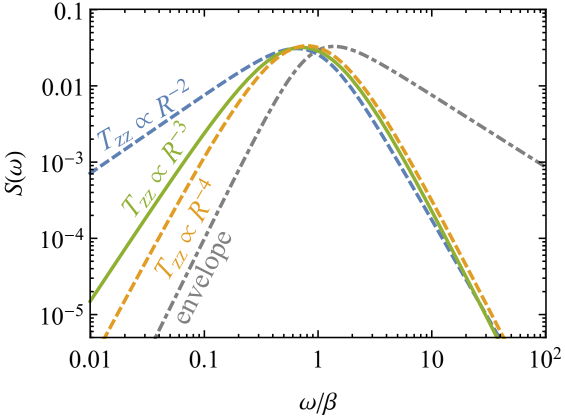
- Global Symmetry breaking:

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

- Gauge Symmetry breaking:

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

Bubble Collision Spectrum



- Global Symmetry breaking:

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

- Gauge Symmetry breaking:

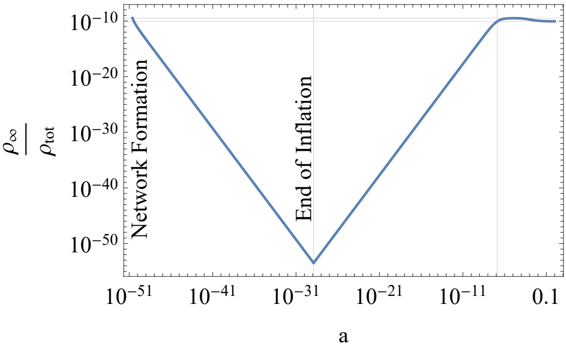
$$T_{zz} \propto R^{-3}$$

- 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
$T_{zz} \propto R^{-2}$	3.1 ± 0.1	0.64 ± 0.01	1.00 ± 0.01	2.61 ± 0.06	1.5 ± 0.1
$T_{zz} \propto R^{-3}$	3.2 ± 0.1	0.71 ± 0.01	2.25 ± 0.02	2.94 ± 0.02	3.5 ± 0.1
$T_{zz} \propto R^{-4}$	3.3 ± 0.1	0.80 ± 0.01	2.78 ± 0.02	2.91 ± 0.02	3.9 ± 0.1
env.	3.3 ± 0.1	1.38 ± 0.03	3.01 ± 0.01	0.94 ± 0.03	1.5 ± 0.1

Strings diluted by inflation



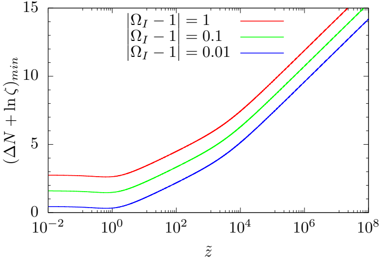
- When loop production is inefficient energy density network scales as

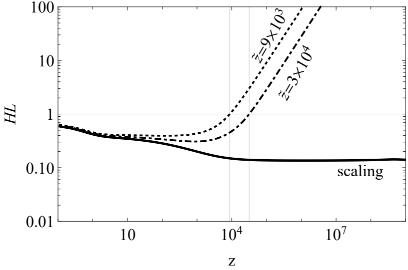
$$\rho_\infty \propto a^{-2}$$

- How many efolds of dilution ?

$$\Delta N \;\geq\; 2.7 + \frac{1}{2}\ln(|\Omega_I - 1|) + \frac{1}{2}\ln\left[\Omega_\Lambda(1+\tilde{z})^{-2} + \Omega_m(1+\tilde{z}) + \Omega_r(1+\tilde{z})^2\right]$$

Strings diluted by inflation





- Initial overdensity has a similar effect

$$L_f = \frac{1}{\zeta H_I} \to \rho_\infty \propto \zeta^2$$

- How many efolds of dilution or initial overdensity ?

$$\Delta N + \ln\zeta \;\geq\; 2.7 + \frac{1}{2}\ln(|\Omega_I - 1|) + \frac{1}{2}\ln\left[\Omega_\Lambda(1+\tilde{z})^{-2} + \Omega_m(1+\tilde{z}) + \Omega_r(1+\tilde{z})^2\right]$$

Strings diluted by inflation

- Stochastic background as sum of bursts

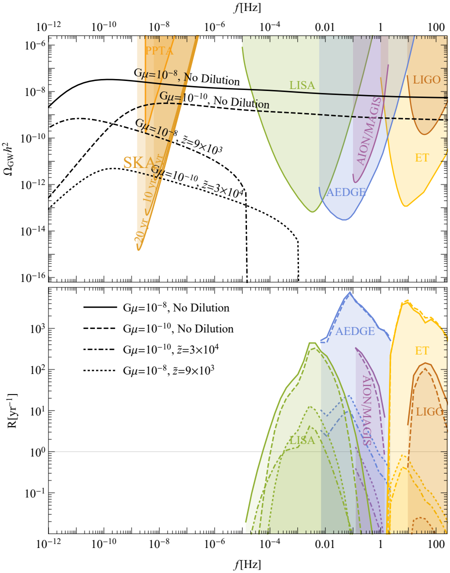
$$\Omega_{\rm GW}(f) = \frac{4\pi^2 f^3}{3H_0^2} \int_{z_*}^{\infty} dz \int_{h_{\rm min}}^{h_{\rm max}} dh\, h^2\, \frac{d^2R}{dz\, dh}(h,z,f)$$

- With individually observable bursts excluded

$$f = \int_0^{z_*} dz \int_{h_{\rm min}}^{h_{\rm max}} dh\, \frac{d^2R}{dz\, dh}(h,z,f)\,.$$

- Rate of individually observable bursts

$$R_{\rm exp}(f) = \int_0^{z_*} dz \int_{\max(h_{\rm min},h_{\rm exp})}^{h_{\rm max}} dh\, \frac{d^2R}{dz\, dh}(h,z,f)$$



Strings diluted by inflation parameter space