# Primordial gravitational waves from melting domain walls

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Rubakov'70

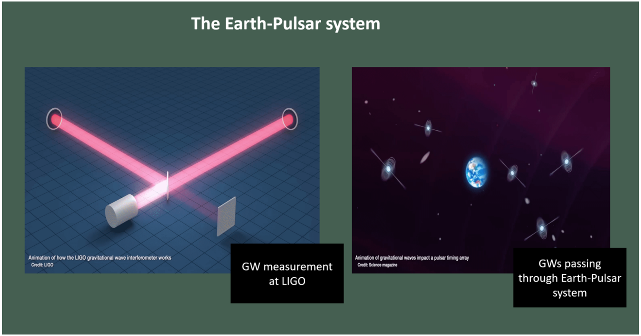
Based on 2406.17053, 2410.21971, 2307.04582

with E. Babichev, I. Dankovsky, D. Gorbunov, R. Samanta, A. Vikman

# Strong evidence of stochastic GW background has been reported: NANOGrav, EPTA+InPTA, CnPTA, PPTA

$$\Omega_{gw}(f) \simeq 5.8 \cdot 10^{-8} \cdot \left(\frac{f}{30\ \text{nHz}}\right)^{n} \qquad n = 1.8 \pm 0.6$$

$$\Omega_{gw}(f) \equiv \frac{d\rho_{gw}}{\rho_{tot}\, d\ln f}$$




GW detection with PTAs: Sazhin'78, Detweiler'79, Hellings and Downs'83

Supermassive black hole binaries (SMBHB) mergers are often quoted as the most common source of the background found, but...

- GW driven SMBHBs predict $n = 2/3$ (or $\gamma = 5 - n = 13/3$) versus the NANOGrav $n = 1.8 \pm 0.6$, excluded at more than $2\sigma$ CL
- final pc problem
- SMBHs are difficult to produce, $M \sim 10^{10}\ M_{\text{sun}}$

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NANOGrav: Afzal et al'23

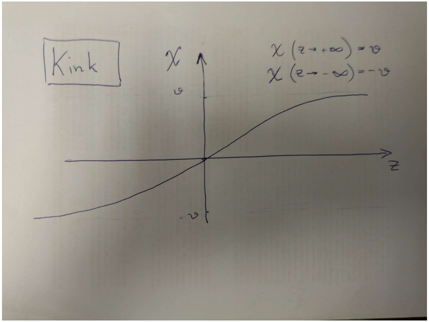
"*...we investigate potential cosmological interpretations of this signal, specifically cosmic inflation, scalar-induced GWs, first-order phase transitions, cosmic strings, and domain walls. We find that, with the exception of stable cosmic strings of field theory origin, all these models can reproduce the observed signal.*"

NB Cosmological =primordial=(in this context) operating at radiation domination or earlier epoch

Domain walls arise in models with spontaneous breaking of discrete symmetries, e.g., $Z_2$ Zel'dovich, Kobzarev, and Okun'74

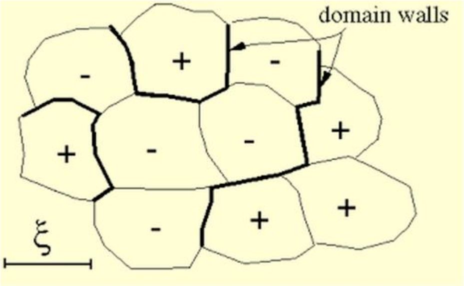
$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda \cdot (\chi^2 - v^2)^2}{4}$$

Static localized 1+1 solution Kink $\chi(z) = v \cdot \tanh\left(\sqrt{\frac{\lambda}{2}} \cdot v \cdot z\right)$



## Domain walls are embeddings of kinks into $1+3$

Domain walls separate regions, where $\chi = \pm v$




Domain wall tension: $\sigma_{wall} = \int_{-\infty}^{+\infty} dz' T_{00}(z') = \frac{2\sqrt{2\lambda}v^3}{3}$

$\delta_{wall} \sim \sqrt{\frac{2}{\lambda}}\frac{1}{v} \sim \frac{1}{m_\chi}$

http://www.ctc.cam.ac.uk/

Standard DWs

$$\boxed{v = \text{const}}$$

Melting DWs

$$\boxed{v(t) \propto T(t) \propto \frac{1}{a(t)}}$$

Standard domain walls are too energetic
and threat well-established cosmological evolution.

$$\rho_{wall} \sim \sigma_{wall} H \sim \sigma_{wall} \cdot \frac{T^2}{M_{Pl}} \quad \text{vs} \quad \rho_{rad} \sim T^4$$

$$\frac{\rho_{wall}}{\rho_{rad}} \propto \frac{1}{T^2(t)} \propto a^2(t) \Longrightarrow$$

# Melting domain walls

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda(\chi^2 - v^2(T))^2}{4} \qquad v \propto T \propto \frac{1}{a}$$

$$\sigma_{wall} = \frac{2\sqrt{2\lambda}v^3}{3} \propto T^3$$

$$\rho_{wall} \simeq \sigma_{wall} H \propto T^5 \qquad \frac{\rho_{wall}}{\rho_{rad}} \propto T(t) \propto \frac{1}{a(t)}$$

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Energy density of domain walls redshifts faster than radiation $\Longrightarrow$ no domain wall problem

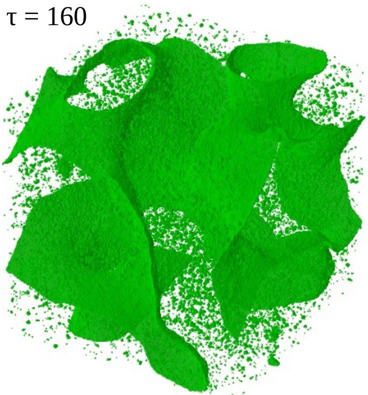
Vilenkin'81

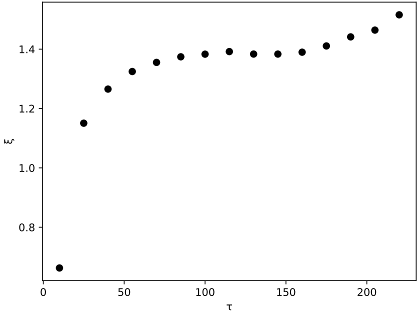
## CosmoLattice: Figueroa Florio, Torrenti, Valkenburg'20'21

Domain walls enter the scaling regime, where their evolution is described by the only length scale — $H^{-1}$.

$$\xi = \frac{St}{a(t)V} \approx \text{const}$$

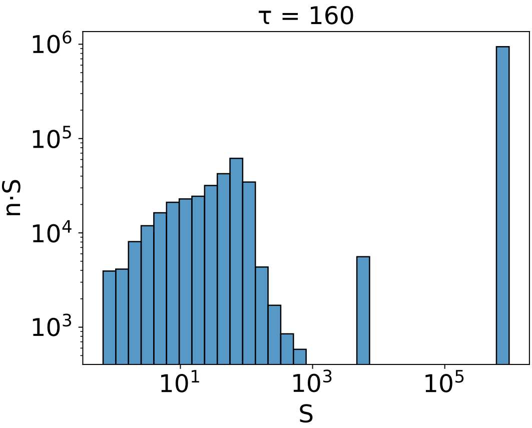
$$\delta_{wall} \sim 0.05 H^{-1}_{scaling}$$



$$r = \frac{S(\text{closed walls})}{S(\text{long wall})} \simeq 0.3 \Longrightarrow$$

It sounds plausible that melting domain walls enter scaling by formation of collapsing closed walls



# Domain walls emit gravitational waves

- By construction, domain walls are spatially inhomogeneous.

$$\left( \frac{\partial^2}{\partial \tau^2} + \frac{2a'}{a} \frac{\partial}{\partial \tau} - \frac{\partial^2}{\partial \mathrm{x}^2} \right) h_{ij}^{TT} = 16\pi G_N T_{ij}^{TT}$$

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- Most energetic GWs are emitted at the earliest possible times, i.e., when DWs only enter the scaling regime

$$\rho_{gw} = \frac{1}{32\pi G_N a^2} \cdot \langle \frac{\partial h_{ij}^{TT}}{\partial\tau} \frac{\partial h_{ij}^{TT}}{\partial\tau} \rangle$$

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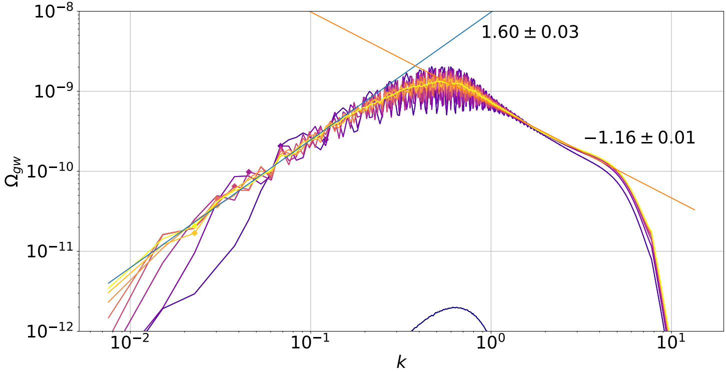
- Emission occurs at a characteristic frequency $\sim H_{scaling}^{-1}$

  100 MeV $\lesssim T \lesssim 10^{10}$ GeV $\Longrightarrow$

  frequency is in a wide range covering PTAs and Einstein Telescope

$\rho_{wall} \propto T^5 \propto \frac{1}{a^5}$ +scaling+statistical homegeneity+isotropy

$$\Longrightarrow \Omega_{gw} \propto k^2 \qquad \frac{2\pi}{\tau_f} \ll k \ll k_{peak}$$



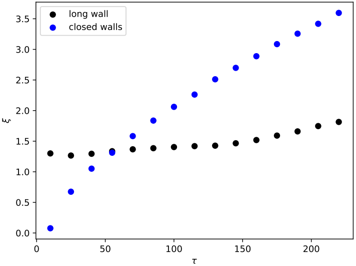

Very good agreement with the NANOGrav 15 yr $n = 1.8 \pm 0.6$

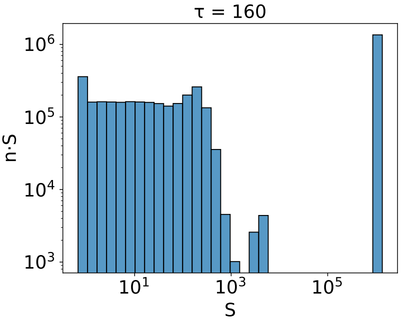
No violation of causality: causal tail $n = 3$ is shfited towards very small frequencies

Scaling is violated for large initial scalar fluctuations $\delta\chi_i \gtrsim 0.1 v_i$

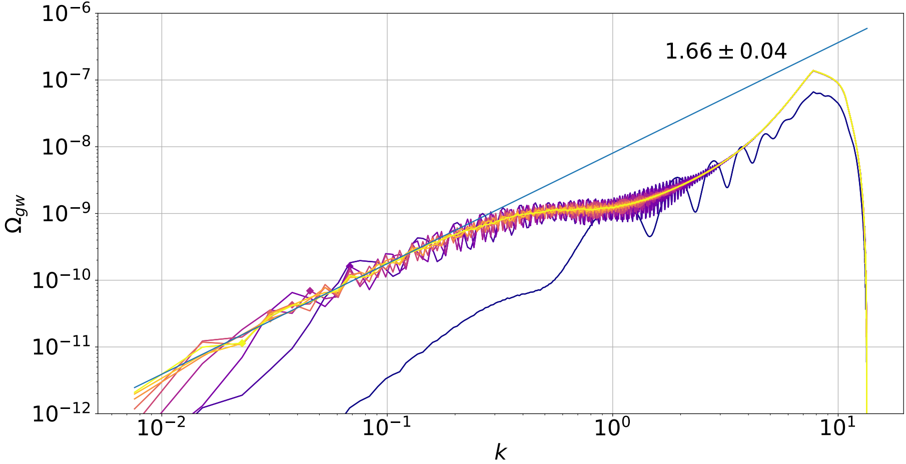
This violation is mainly due to abundant production of closed walls

It is likely to be of non-physical origin $\Longrightarrow$ small scalar fluctuations of non-topological origin are misinterpreted as closed walls



Effect of scaling violation on GW spectrum: peak $\rightarrow$ inflection point, but remarkably the IR part of the spectrum is almost unaffected



$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{\lambda \cdot \chi^4}{4} + \frac{g^2 \chi^2 \phi^\dagger \phi}{2}$$

2104.13722

$\chi$ is cold

$\phi$ is in thermal equilibrium with plasma

$$0 < g^2 \ll 1$$

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$$\langle \phi^\dagger \phi \rangle_T = \frac{\mathcal{N} T^2}{12} \Longrightarrow V_{eff} = \frac{\lambda \cdot \chi^4}{4} - \frac{\mathcal{N} g^2 T^2 \chi^2}{24}$$

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$T \propto \frac{1}{a(t)} \implies Z_2$-symmetry breaking at early times

$$v^2 = \frac{\mathcal{N} g^2 T^2}{12\lambda}$$

# Fitting to NANOGrav

$$f_{peak} \simeq \frac{15\ \text{nHz}\sqrt{\mathcal{N}}}{g_*^{1/3}(T_{sc})} \cdot \left(\frac{g}{10^{-18}}\right)$$

$$\Omega_{gw,peak} h_0^2 \simeq \frac{5 \cdot 10^{-11} \mathcal{N}^4}{g_*^{7/3}(T_{sc}) \cdot \beta^2}$$

Vanilla region: $\beta \equiv \frac{\lambda}{g^4} \simeq 1$ $\quad$ $\mathcal{N} \gg 1$

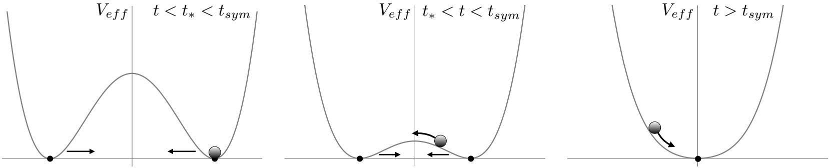
## The field $\chi$ should be extremely weakly coupled!

Not an unfamiliar situation in physics, cf. axions, but we deal with a different group of underlying symmetries.

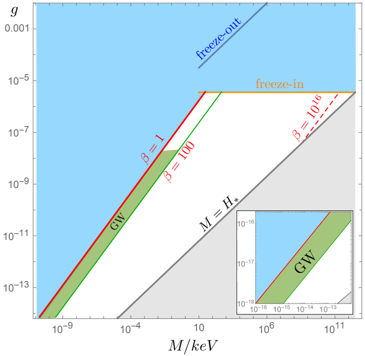
## A bit of dark matter

Slightly break conformal invariance $\Longrightarrow$ dark matter
2104.13722, 2112.12608,

$$\mathcal{L} = \frac{(\partial_\mu \chi)^2}{2} - \frac{M^2 \cdot \chi^2}{2} - \frac{\lambda \cdot \chi^4}{4} + \frac{g^2 \chi^2 \phi^\dagger \phi}{2} .$$



Abundance constraint: $M \simeq 3\times 10^{-13}\text{eV}\cdot\frac{\beta^{3/5}}{\sqrt{\mathcal{N}}}\cdot\left(\frac{g}{10^{-18}}\right)^{7/5}$




$M \simeq 10^{-12} - 10^{-13}$ eV $\Longrightarrow$ superradiance Zel'dovich

- Melting domain walls avoid the problem of overclosing the Universe+ the spectral index of GWs is in excellent agreement with PTA data.
- The field constituting melting domain walls is extremely weakly coupled in the PTA range. However, the model is not limited to PTA, also LISA, TianQin, Einstein Telescope...
- The same field can be also a dark matter candidate with possible implications for Kerr black holes.

Thanks for your attention!!!