Searching for Gravitational Waves from Domain Walls in the Early Universe

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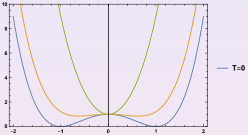
Outline

Discrete symmetry breaking

- Simple example: scalar field with Z_2 symmetry
  $V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$



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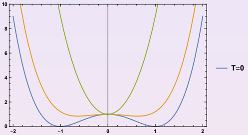

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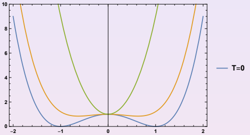
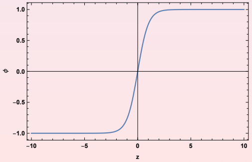


- Symmetry broken below some Temperature T_{PT}
- ϕ takes different (uncorrelated) values ($\pm v$) in different Hubble patches
- Domain walls, produced at T_{PT}, $\phi(z) = v\tanh(\sqrt{\frac{\lambda}{2}}vz)$



Domain Walls

GW from Domain Walls

Domain Walls

Gravitational Waves from DWs

Pulsar Timing Arrays (PTA)

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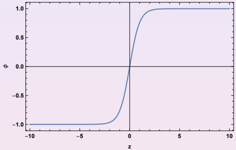


- Thickness $\delta = (\sqrt{\lambda} v)^{-1}$
- Wall with energy per unit area (tension)

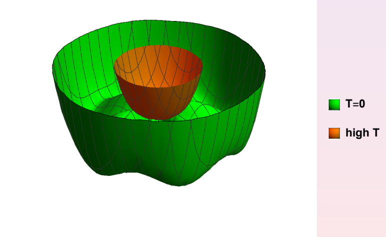
$$\sigma = 2 \int dz V(z) = \lambda v^3$$

Domain Walls

- Another example: Complex field with $U(1)$ symmetry at high T, broken to Z_N at $T = 0$

$$V(\Phi) = \lambda(|\Phi|^2 - v^2)^2 + V_0 \cos\left(N\frac{a}{v}\right)$$

$$\Phi = |\Phi| e^{i\frac{a}{v}}$$



- Symmetry broken below some T_{PT}
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Domain Walls Cosmology

- In expanding Universe with $H = \frac{\dot{a}}{a}$
- At T_{PT} (uncorrelated) values in different Hubble patches ($\mathcal{O}(H^{-1})$)

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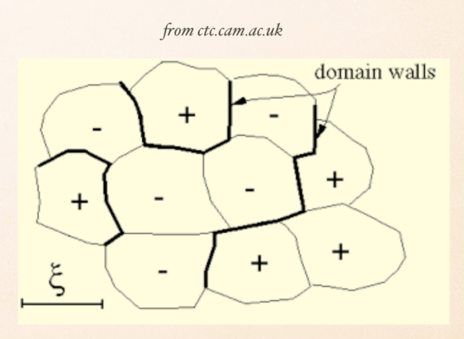

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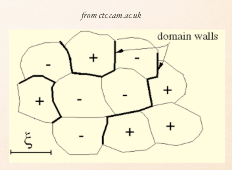

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- Reach "Scaling regime", $\mathcal{O}(1)$ walls per Hubble patch

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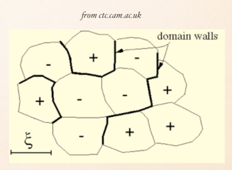

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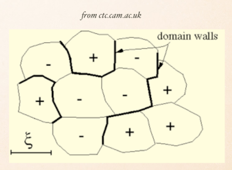

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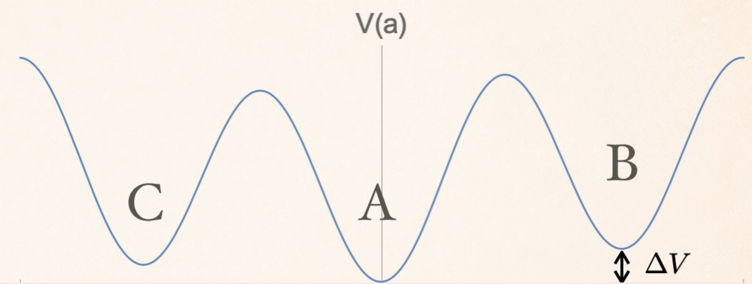
- For σ large enough they quickly dominate over radiation background, $\rho_{RAD} = 3H^2 M_{Pl}^2$
- $\Longrightarrow$ Domain wall problem!
(unless tension is small, $\sigma^{1/3} \lesssim 100$ MeV)

Domain Walls Annihilation

- Possible way out:
- Make them unstable, assuming a "bias" ΔV



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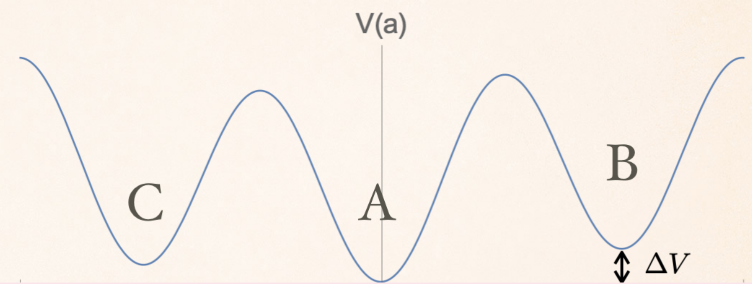

- Annihilation happens when ΔV becomes $\simeq \rho_{DW}$

GW in a nutshell

- The physical metric for a GW (traveling along the z-axis)

$$g_{ab} = \eta_{ab} + h_{ab} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 + h_+ & h_\times & 0 \\ 0 & h_\times & 1 - h_+ & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

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- Today: $\Omega^0_{GW} \approx \Omega^0_\gamma \alpha_*^2 \approx 10^{-5}\alpha_*^2$
- More precisely, simulations give $\Omega_{GW} h^2 \simeq 0.05\ (\Omega^0_\gamma h^2)\ \tilde{\epsilon}\ \left(\frac{\rho_{DW}}{\rho_{RAD}}\right)^2\Big|_{\rm ANN}$, ($\tilde{\epsilon} = 0.1 - 1$ is an efficiency parameter)

Relic GW from Domain walls

- $$\boxed{\Omega_{\rm GW} h^2 \simeq 0.05\,(\Omega_\gamma^0 h^2)\,\tilde{\epsilon}\left(\frac{\rho_{\rm dw}}{\rho_{\rm rad}}\right)^2_{T=T_*}},$$

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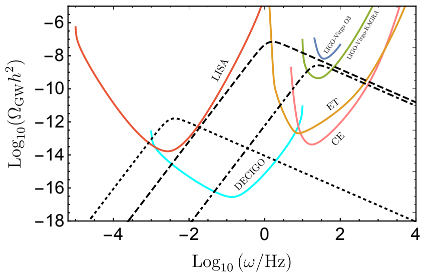
- Two free parameters σ (or α_*) and T_*

GW spectra

- GW spectrum $\rho_{\rm GW} \equiv \int \frac{d\rho_{\rm GW}}{d\log k}\frac{dk}{k}$:

$$\frac{d\rho_{GW}}{d\log k} = \begin{cases} f^3 \text{ for } f < f^0_{\rm peak}, \text{ (causality)} \\ f^{-1} \text{ for } f > f^0_{\rm peak} \text{ , (until cutoff given by DW width).} \end{cases}$$

(e.g. simulations, Hiramatsu, Kawasaki, Saikawa, 2014)



Pulsar Timing redshift

- Consider a pulsar emitting in the $\hat{p}$ direction with frequency ν_0
- And a GW traveling in the direction $\hat{\Omega}$

[2] see e.g. Anholm et al. PRD (2009)

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$$z(t,\hat{\Omega}) \equiv \frac{\nu_0 - \nu(t)}{\nu_0} = \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}\left(h_{ij}(t_{\mathrm{P}},\hat{\Omega}) - h_{ij}(t,\hat{\Omega})\right)$$

difference at the pulsar (t_{P}) and at the center of the solar system (t).

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- Common assumption: Neglect the pulsar (t_{P}) term

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Pulsar Timing Arrays

- Fourier transform and consider $\langle z_1^*(f, \hat{\Omega}) z_2(f', \hat{\Omega}) \rangle$ from two Pulsars (1 and 2)
- Stochastic background: integrate over all possible $\hat{\Omega}$:

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- Common spectrum $|f|^{-3}\Omega_{\rm GW}(|f|)$
- Angular "Hellings-Downs" (HD) correlation Γ_{12} between two pulsars, 1 and 2

NANOGRAV 12.5 year

- *North American Nanohertz Observatory for Gravitational Waves*
- 45 analyzed pulsars (Arzoumanian et al. Ap.J. Lett. (2020)) with at least 3 years data
- Strong evidence for common-spectrum stochastic process

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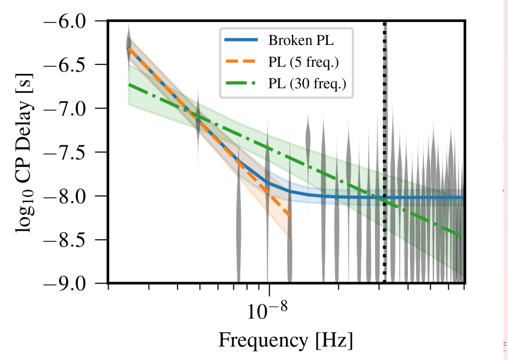

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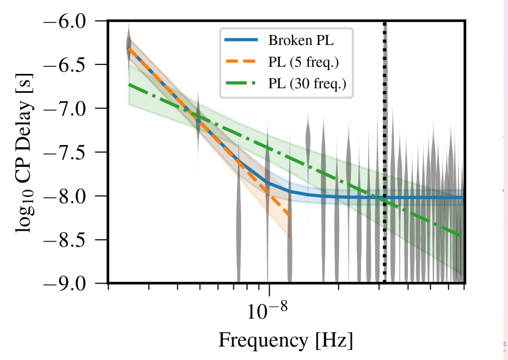
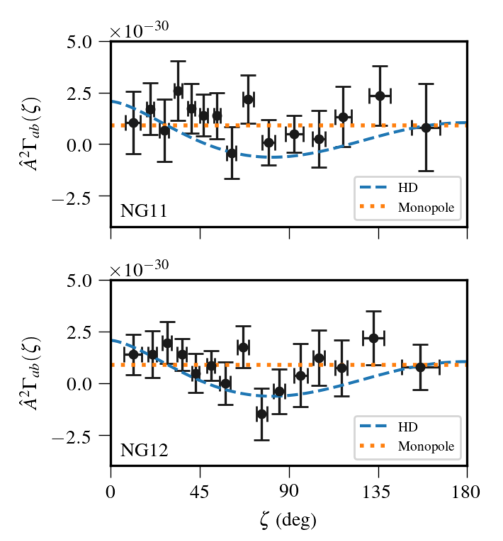


NANOGRAV 12.5 year

- No evidence yet for HD angular correlation from GW



NANOGRAV 12.5 year

- Power-law fit, exponent γ_{CP}

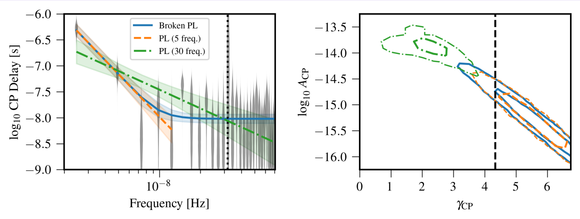


Figure: Arzoumanian et al. Ap.J. Lett. (2020)

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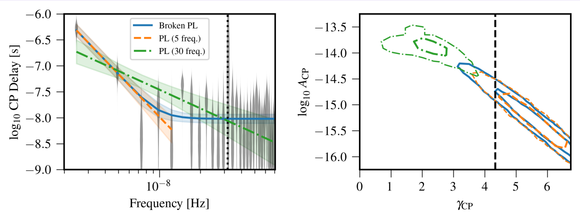

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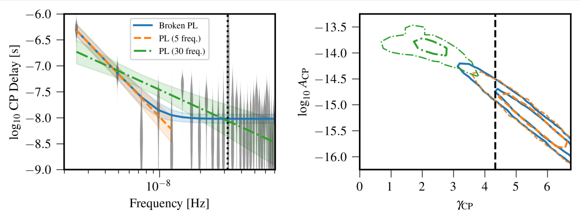

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$$h(f) = A\left(\frac{f}{f_{yr}}\right)^{-\frac{2}{3}} = A\left(\frac{f}{f_{yr}}\right)^{\frac{3-\gamma_{CP}}{2}} \implies \gamma_{CP} = 4.33$$

NANOGRAV 12.5 year

- Power-law fit, exponent γ_{CP}

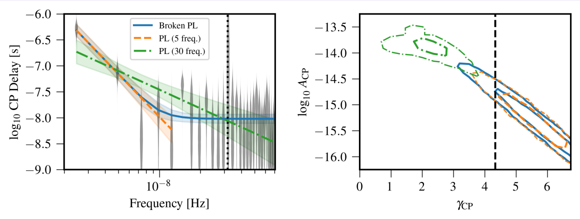

Figure: Arzoumanian et al. Ap.J. Lett. (2020)

- Most “conservative" interpretation: GW from SuperMassive Black Hole Binaries (SMBHB)

$$h(f) = A\left(\frac{f}{f_{yr}}\right)^{-\frac{2}{3}} = A\left(\frac{f}{f_{yr}}\right)^{\frac{3-\gamma_{CP}}{2}} \implies \gamma_{CP} = 4.33$$

- Alternative: GWB from Early Universe

IPTA DR2 Dataset

- International Collaboration (North America, Europe, Australia) (J. Antoniadis et al. MNRAS (2022))
- Combination of European Pulsar Timing Array (EPTA), NANOGrav, and the Parkes Pulsar Timing array (PPTA)
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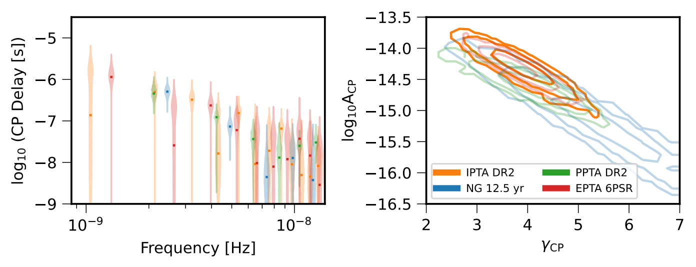

- Similar results (slightly smaller $\gamma_{\rm CP}$)

GW Search from Domain Walls in NANOGRAV and IPTA

- Search for GW from Domain Walls [3]:

$$\Omega_{\rm GW,DW}(f)h^2 \simeq 10^{-10}\,\tilde{\epsilon}\left(\frac{10.75}{g_*(T_\star)}\right)^{\frac{1}{3}}\left(\frac{\alpha_\star}{0.01}\right)^2 S\left(\frac{f}{f_p^0}\right),$$

- $S(x)$ models the shape:

[3] R. Z. Ferreira, A.N., O. Pujolas, F. Rompineve, e-Print: 2204.04228

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- $S(x)$ models the shape:

$$S(x) = \frac{(\gamma+\beta)^\delta}{(\beta x^{-\frac{\gamma}{\delta}} + \gamma x^{\frac{\beta}{\delta}})^\delta},$$

$$\begin{cases} \text{At low frequency } S \propto f^3 \\ \text{At high } f\text{, simulations suggest } \delta \approx \beta \approx 1 \implies S \propto f^{-1} \end{cases}$$

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Decay of the network

GW from Domain Walls

Domain Walls

Gravitational Waves from DWs

Pulsar Timing Arrays (PTA)

- Assume DW decay into ϕ quanta and subsequently:
- Two scenarios

$$\begin{cases} \phi \text{ Decay to Dark Radiation } \text{problem if too much} \\ \phi \text{ Decay to Standard Model } \text{Before BBN } T_* \gtrsim 3MeV \end{cases}$$

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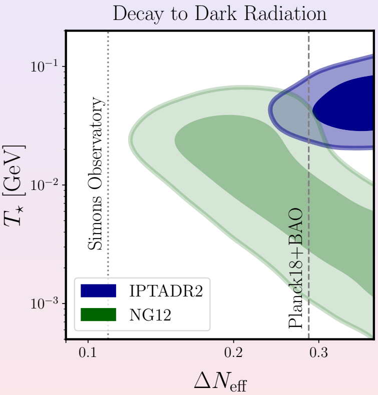
$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}}{\rho_\nu} \approx \frac{\rho_{\rm DW}}{\rho_\nu} = 13.6 g_*|_{T_*}^{-1/3} \alpha_*$$

,

- Current limited by CMB: $\Delta N_{\rm eff} \lesssim 0.3$ (*Planck 2018 + BAO*)

Results (CASE I): Decay into Dark Radiation



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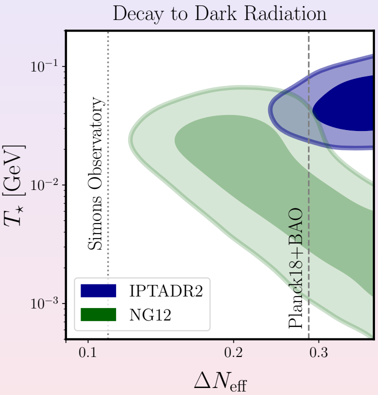
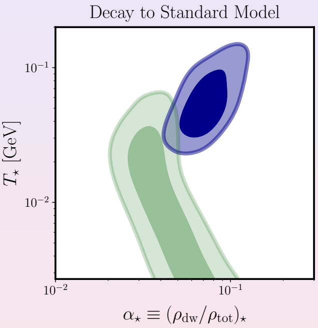
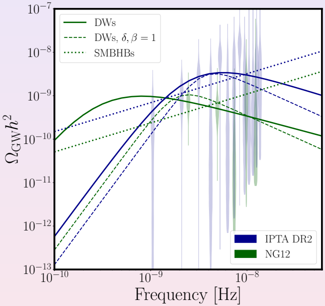


- Currently constrained (Planck+BBN)
- Future Forecast: visible by CMB experiments

Results (CASE II): Decay into Standard Model





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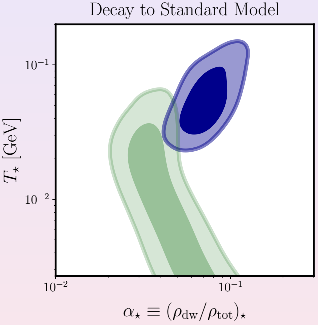
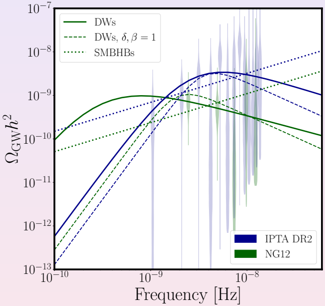
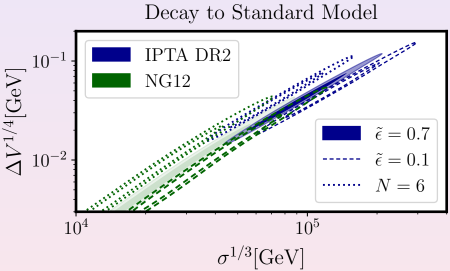




- IPTA prefers a peak
- NANOGrav ok with a power-law

Results: Decay into Standard Model

- Decay Temperature T_* and fraction α_* could be traded for bias (ΔV) and tension (σ),



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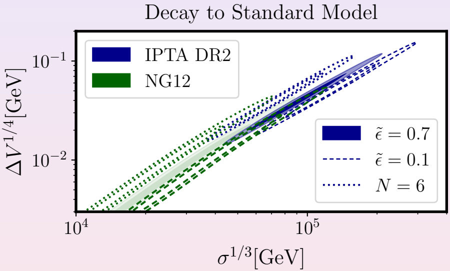
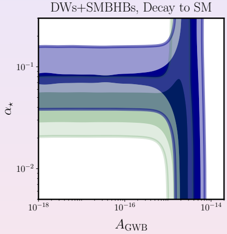


- In a $\mathbb{Z}_2$ model with $V(\phi) = \lambda(\phi^2 - v^2)^2$, $\implies$ $v \approx (10 - 100\, TeV)/\lambda^{1/3}$
- Bias scale: $\Delta V^{\frac{1}{4}} = 10 - 100$ MeV, close to QCD scale

Results: Combine with SMBHM

- We also combined with "standard" expected signal from Supermassive Black Holes Mergers (SMBHM)



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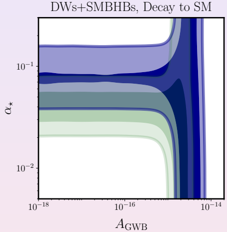

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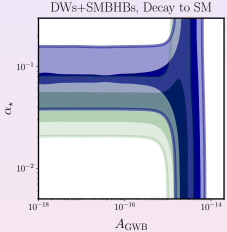

- We also compared models via Bayes factors $\log_{10} B_{i,j}$
- For NG12, we find: $\log_{10} B_{\text{SMBHBs, DW}} \simeq 0.16$, $\log_{10} B_{\text{DW, DW+SMBHBs}} \simeq 0.07$.
- For IPTADR2, we find: $\log_{10} B_{\text{DW, SMBHBs}} \simeq 0.48$, $\log_{10} B_{\text{DW, DW+SMBHBs}} \simeq 0.38$.
- $\Longrightarrow$ no substantial evidence for one model against any other one.

Conclusions

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Conclusions

- Did NANOGrav/IPTA see GWs?
- Wait for Hellings-Downs angular correlations
- If yes, decaying DWs fit well the data
- Interesting scales: $\sigma^{1/3} \approx 10 - 100\,TeV$ and $\Delta V \approx 10 - 100\,MeV$ (close to QCD PT)

THE END

(EXTRA SLIDES)

NANOGRAV 12.5 year: Phase Transitions

- NANOGrav search for GWB from Primordial Phase Transitions (bubble collisions)

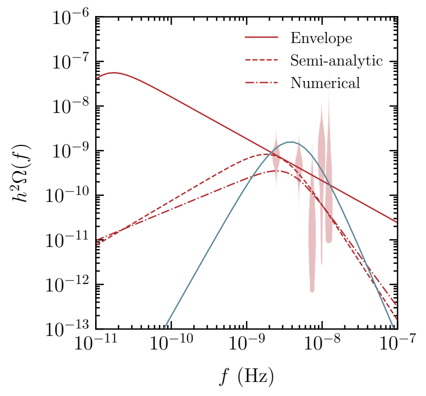

Figure: Arzoumanian et al. Phys.Rev.Lett. 127 (2021)

Cosmology of “Heavy" axion

- Heavy axion with a small bias:

$$V_{TOT}(a) = \left(\Lambda^4_{\rm QCD} + \Lambda^4_{\rm H} \right) \left(1 - \cos \frac{a}{f}\right) - \mu_b^4 \cos\left(\frac{a}{v} - \delta_0\right),$$

with $\Lambda_H \gg \mu_b$ (and Λ_{QCD} negligible)

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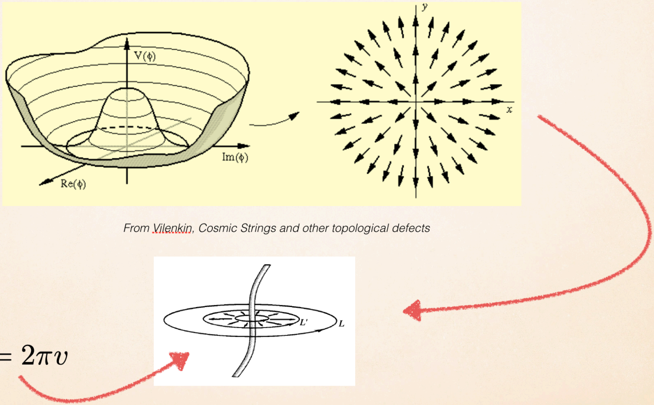
- Cosmic strings formation (where a goes from 0 to 2π)
- Strings radiate axion quanta, reach scaling regime $\rho_S \approx f^2 H^2$

Cosmology of “Heavy" axion



From Vilenkin, Cosmic Strings and other topological defects

$$\Delta a = 2\pi v$$

Cosmology of “Heavy” axion, with $N_{DW} > 1$

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  $\Longrightarrow m_a^2 \approx \frac{\Lambda_H^4}{f^2}$
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- Inhomogeneous field $\Longrightarrow$ domain walls (where $\frac{a}{f} \approx \pi$)
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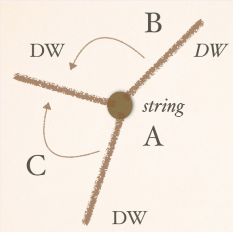

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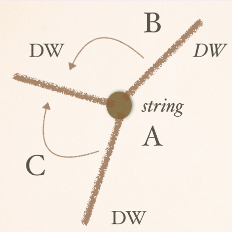

- Tension $\sigma = m_a f^2$
  (much larger than for “Standard" QCD Axion)

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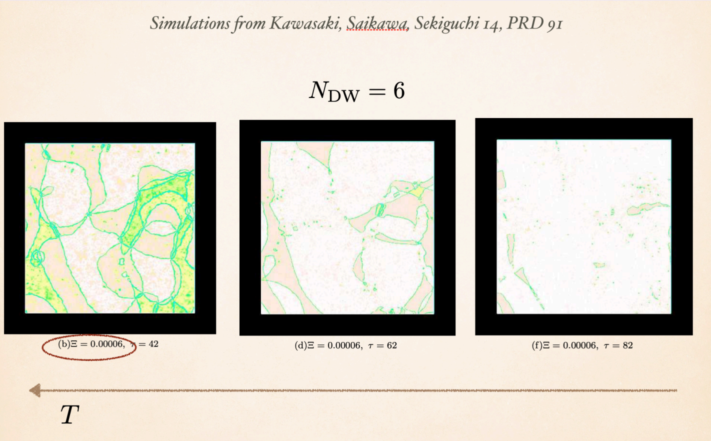

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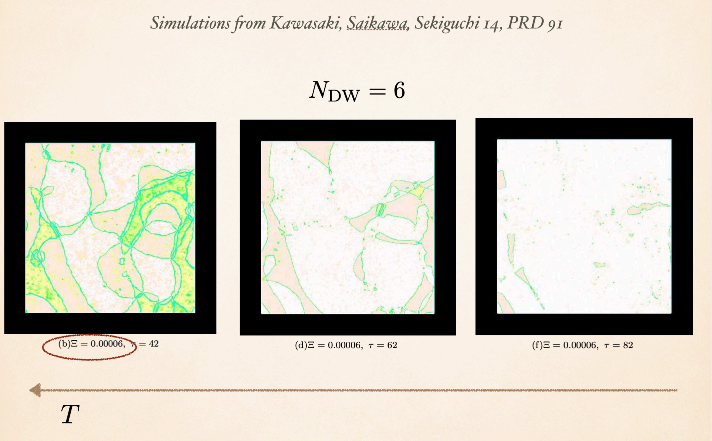


- Later μ_b breaks degeneracy among vacua
  $\Longrightarrow$ DW decay $\Longrightarrow$ a sits in true vacuum

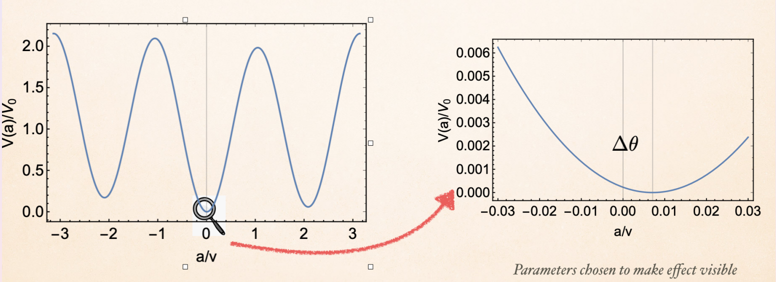
Small CP violation at the minimum

GW from Domain Walls

Domain Walls

Gravitational Waves from DWs

Pulsar Timing Arrays (PTA)



Heavy Axion at LIGO/Virgo/KAGRA and LISA

- Heavy axion with High scale $\Lambda_H \implies$ signals at Interferometers (R. Z. Ferreira, A.N., O. Pujolas, F. Rompineve, PRL 2022)

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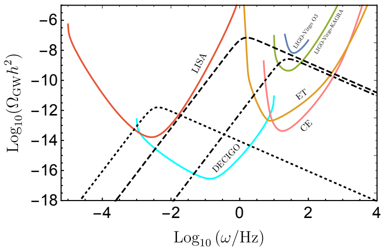

Figure: GW spectra ($N_b = 1, N_{\rm DW} = 6, \delta_0 = 0.3$).
Dashed: $\Lambda_{\rm H} = 10^{10}$ GeV, $f = 10^{11}$ GeV and $\Delta\theta \simeq 8 \cdot 10^{-13}$.
Dotted: $\Lambda_{\rm H} = 10^{7}$ GeV, $f = 2.5 \cdot 10^{10}$ GeV $\Delta\theta \simeq 8 \cdot 10^{-13}$.
Dot-dashed: $\Lambda_{\rm H} = 10^{11}$ GeV, $f = 1.6 \cdot 10^{11}$ GeV and $\Delta\theta \simeq 1.5 \cdot 10^{-11}$.