Searching for Gravitational Waves from Domain Walls in the Early Universe

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[1] In collaboration with R.Z. Ferreira, F. Rompineve, O. Pujolas.
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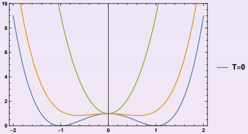
Discrete symmetry breaking

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



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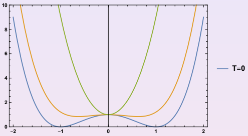

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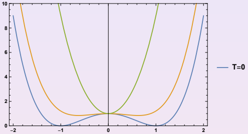

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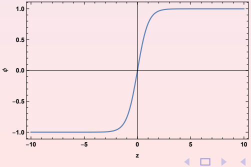
- Domain walls are produced at T_{PT}
- $\phi(z) = v \tanh(\sqrt{\lambda/2}vz)$



Domain Walls

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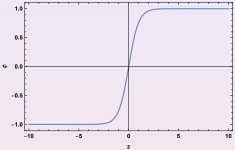


- Thickness $\delta = (\sqrt{\lambda} v)^{-1}$
- Wall with energy per unit area (tension)

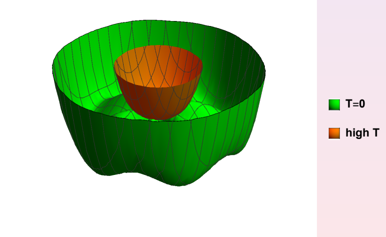
$$\sigma = 2 \int dz V(z) = \lambda v^3$$

Domain Walls

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

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

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



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- In expanding Universe with $H = \frac{\dot{a}}{a}$
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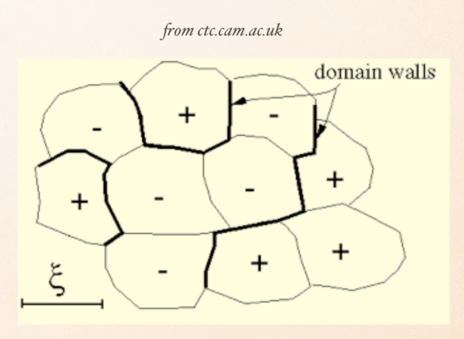

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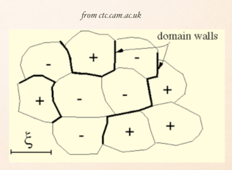

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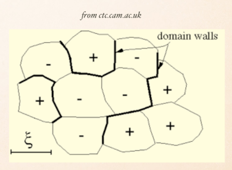

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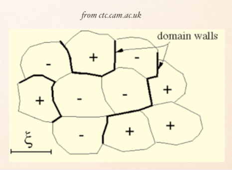

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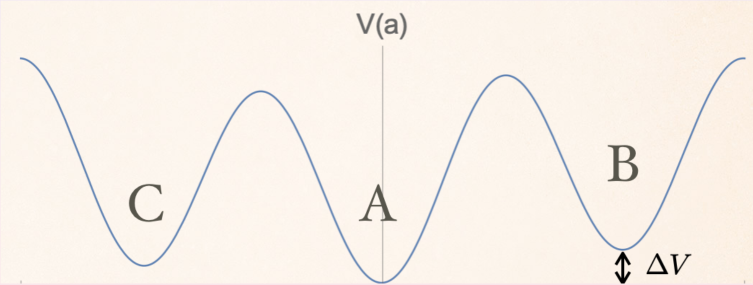
- Reach "Scaling regime", $\mathcal{O}(1)$ walls per Hubble patch
- By dimensional analysis $\rho_{DW}|_{\text{scaling}} \approx \sigma H$
- For σ large enough they quickly dominate over radiation background, $\rho_{RAD} = 3H^2 M_{Pl}^2$
- $\Longrightarrow$ Domain wall problem!

Domain Walls Annihilation

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



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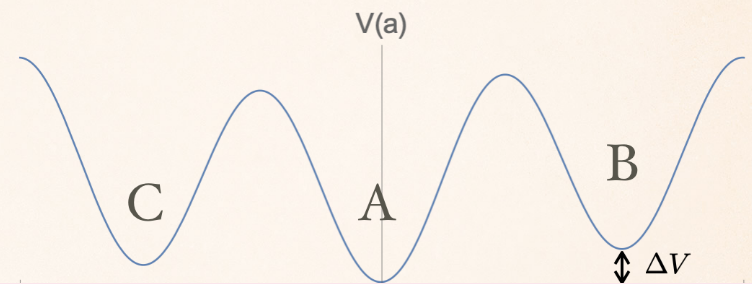

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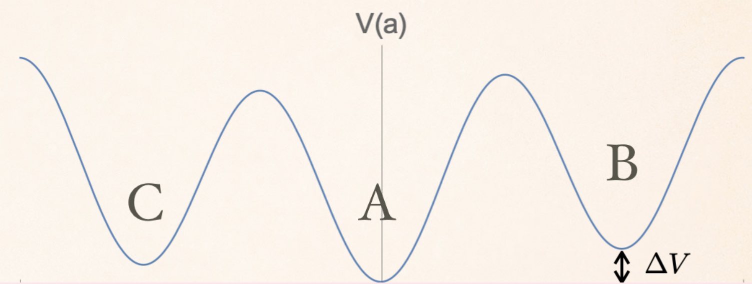

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- Alternative: ... maybe symmetry restoration at low-T? "Inverse Phase Transition"

GW in a nutshell

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

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

where $\eta_{ab} = \mathrm{diag}\{-1, 1, 1, 1\}$ and

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- GW are generated by any large inhomogeneous stress energy tensor T_{ab} (Traceless and Transverse)

$$\Box h_{ab} = 2\frac{T_{ab}^{TT}}{M_{Pl}^2}$$

- $\rho_{GW} = \frac{M_{Pl}^2}{4}\dot{h}_{ij}\dot{h}^{ij}$

Domain wall radiate GW

- Simple estimate,

$$\rho_{GW} = \frac{M_{Pl}^2}{4}\dot{h}_{ij}\dot{h}^{ij}\,, \implies \rho_{GW} \approx \frac{\sigma^2}{M_{Pl}^2}$$

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- More precisely, simulations give
  $\Omega_{\rm GW} h^2 \simeq 0.05\ (\Omega^0_\gamma h^2)\ \tilde{\epsilon} \left(\frac{\rho_{\rm DW}}{\rho_{\rm RAD}}\right)^2_{T=T_{\rm ann}\equiv T_*}\,,$
- $\tilde{\epsilon} = 0.1 - 1$ is an efficiency parameter

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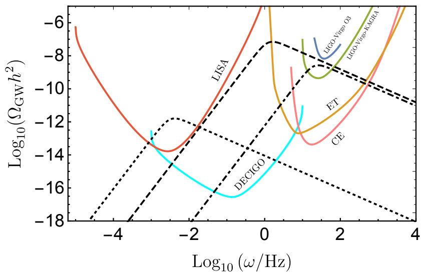
- Two free parameters σ (or α_*) and T_*

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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where

$$\Delta h_{ij} \equiv h_{ij}(t_{\mathrm{P}},\hat{\Omega}) - h_{ij}(t,\hat{\Omega}),$$

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)
- Integrate over all possible $\hat{\Omega}$:

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$\xi \equiv \arccos(\hat{p}_1 \cdot \hat{p}_2)$, and $F^A(\hat{\Omega}) \equiv e_{ij}^A(\hat{\Omega})\frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}}$.

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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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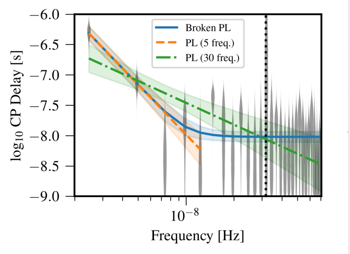

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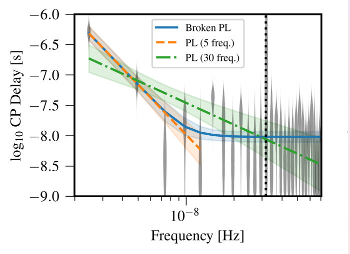
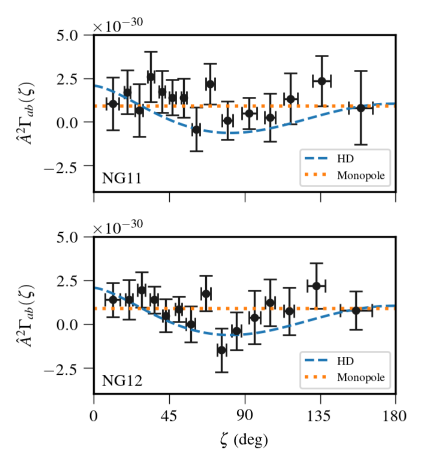


- Pulsar-intrinsic noise at high frequencies
- NANOGrav Collaboration simple solution: consider only 5 lowest frequencies.

NANOGRAV 12.5 year

- No evidence yet for HD angular correlation from GW



NANOGRAV 12.5 year

- Power-law fit, exponent γ_{CP}

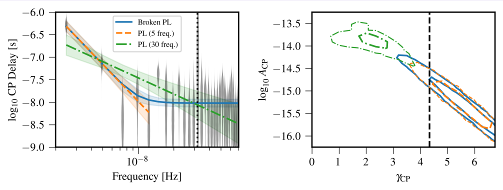


Figure: Arzoumanian et al. Ap.J. Lett. (2020)

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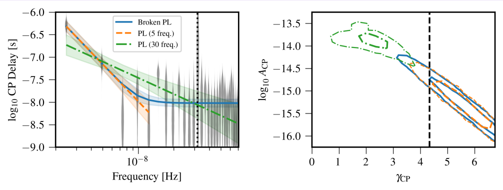

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$$h(f) = A_{GWB}\left(\frac{f}{f_{yr}}\right)^{-\frac{2}{3}} =$$

NANOGRAV 12.5 year

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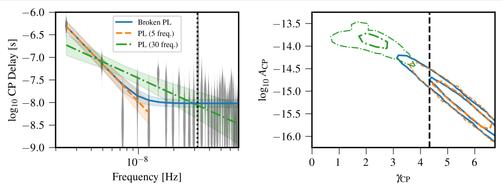

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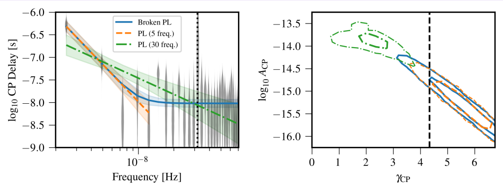

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- Alternative: GWB from Early Universe

NANOGRAV 12.5 year

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

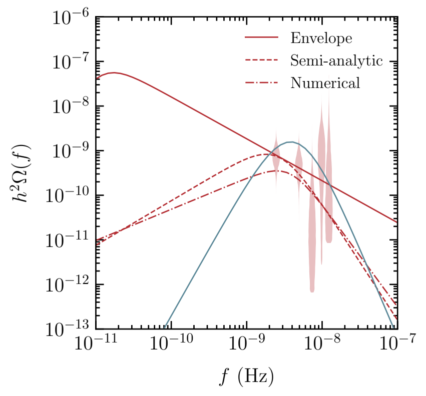

Figure: Arzoumanian et al. Phys.Rev.Lett. 127 (2021)

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)
- 53 pulsars

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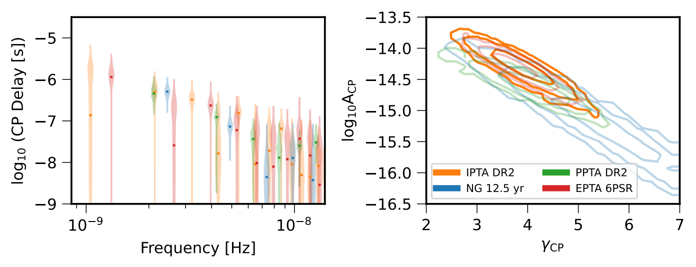

- Similar results (slightly smaller γ_{CP})

GW Search from Domain Walls in NANOGRAV and IPTA

- Search for GW from Domain Walls [3]:

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

  where $\tilde{\epsilon} \simeq 0.1 - 1$ (efficiency parameter)
- $S(x)$ models the shape:

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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

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

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

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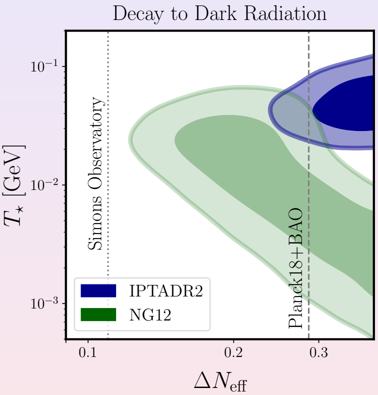
- Current limits $\Delta N_{\mathrm{eff}} \lesssim 0.3$ (*Planck 2018 + BAO*)

Results (CASE I): Decay into Dark Radiation



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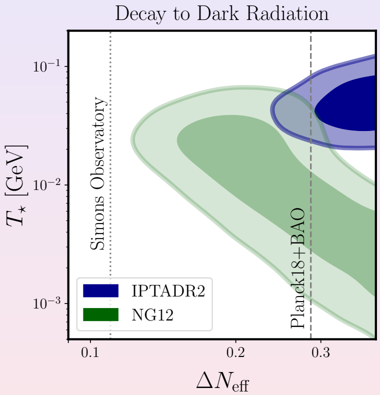
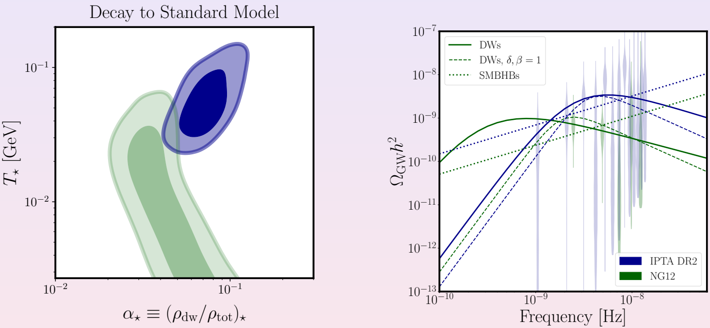


- Currently constrained (Planck+BBN)
- Future Forecast: visible by CMB experiments

Results (CASE II): Decay into Standard Model



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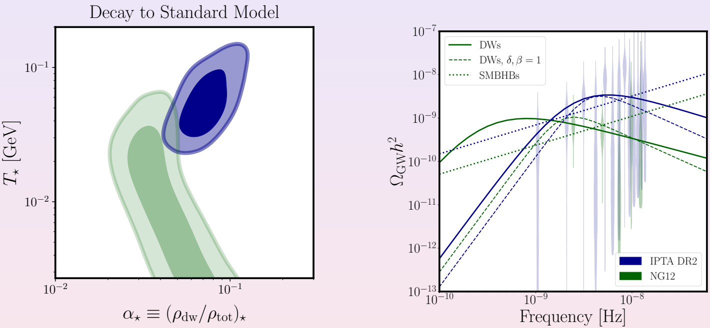

- IPTA prefers a peak
- NANOGrav ok with a power-law

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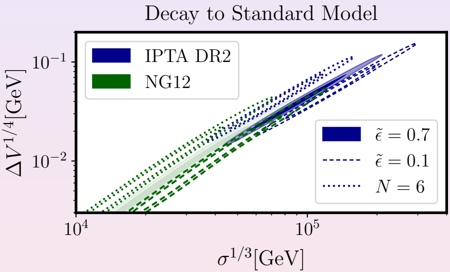
- Decay Temperature T_* and fraction α_* could be traded for bias (ΔV) and tension (σ),



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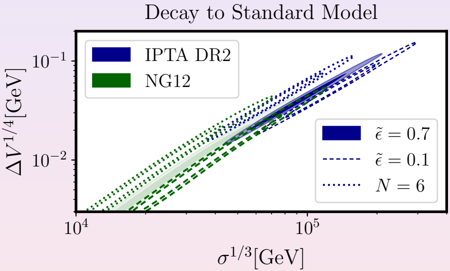
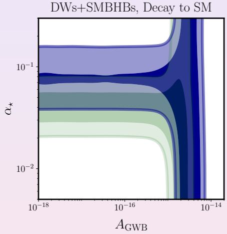


- In a $\mathbb{Z}_2$ model with $V(\phi) = \lambda(\phi^2 - v^2)^2$, $\implies$ $v \approx (10 - 100\,TeV)/\lambda^{1/3}$
- Bias points to a scale of $\Delta V^{\frac{1}{4}} = 10 - 100$ MeV, close to QCD scale

Results: Combine with SMBHM

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



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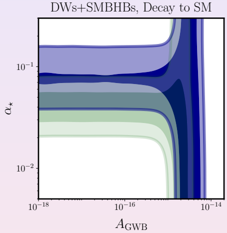

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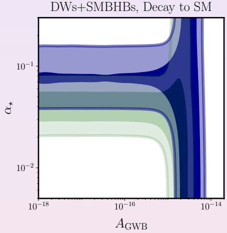

- We also compared models via Bayes factors $\log_{10} B_{i,j}$
- For NG12, we find: $\log_{10} B_{\text{SMBHBs, DW}} \simeq 0.16$, $\log_{10} B_{\text{DW, DW+SMBHBs}} \simeq 0.07$.
- For IPTADR2, we find: $\log_{10} B_{\text{DW, SMBHBs}} \simeq 0.48$, $\log_{10} B_{\text{DW, DW+SMBHBs}} \simeq 0.38$.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

Axion realization

- I discuss now realizations of Decaying DW with Axions
- Many axion models have a Z_N symmetry at low T.

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- Introduce first the "Standard QCD Axion"

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- f *(Axion "decay constant")* $\Leftrightarrow m_a$

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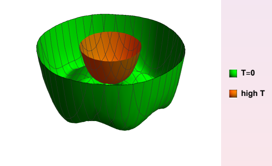

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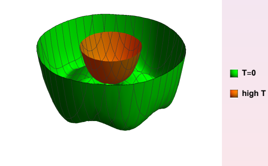

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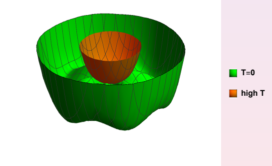

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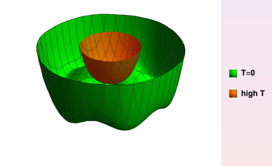

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- Generically $\delta_0 \neq 0 \Longrightarrow$ Minimum is NOT at $\theta = \frac{a}{f} = 0$ $\Longrightarrow$ Strong CP problem NOT solved

Solution: "Heavy" axion?

- Suppose one engineers a high energy contribution aligned with QCD at high scale Λ_H:

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- Small, potentially observable, CP violation:

$$\Delta\theta \simeq \left(\frac{\mu_b^4}{\Lambda^4_{\mathrm{H}}} \right) \sin \delta_0 \ll 1$$

- nEDM measurements require $\Delta\theta \lesssim 10^{-10}$

Solution to “Axion Quality Problem”: Heavy QCD axion?

- Possible high energy aligned contributions:
  - Additional gauge group at scale Λ_H unified with QCD at high energy:

    V. A. Rubakov, Grand unification and heavy axion, JETP Lett. 65 (1997) 621Ð624.
    T. Gherghetta, N. Nagata, and M. Shifman, A Visible QCD Axion from an Enlarged Color Group, Phys. Rev. D 93 (2016), no. 11 115010.
    T. Gherghetta and M. D. Nguyen, A Composite Higgs with a Heavy Composite Axion, JHEP 12 (2020) 094.
  - QCD strong again at high energies Λ_H:

    B. Holdom and M. E. Peskin, Raising the Axion Mass, Nucl. Phys. B 208 (1982) 397Ð412,
    B. Holdom, Strong QCD at High-energies and a Heavy Axion, Phys. Lett. B 154 (1985) 316.
    T. Gherghetta, V. V. Khoze, A. Pomarol, and Y. Shirman, The Axion Mass from 5D Small Instantons, JHEP 03 (2020) 063.

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- Observability at colliders:

  S. Dimopoulos, A. Hook, J. Huang, and G. Marques-Tavares, A collider observable QCD axion, JHEP 11 (2016) 052,
  A. Hook, S. Kumar, Z. Liu, and R. Sundrum, High Quality QCD Axion and the LHC, Phys. Rev. Lett. 124 (2020), no. 22 221801,
  M. Bauer, M. Heiles, M. Neubert, and A. Thamm, Axion-Like Particles at Future Colliders, Eur. Phys. J. C 79 (2019), no. 1 74,
  S. Chakraborty, M. Kraus, V. Loladze, T. Okui, and K. Tobioka, Heavy QCD Axion in $b \to s$ transition: Enhanced Limits and Projections, arXiv:2102.04474.

Cosmology of “Heavy" axion

- Summary:

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

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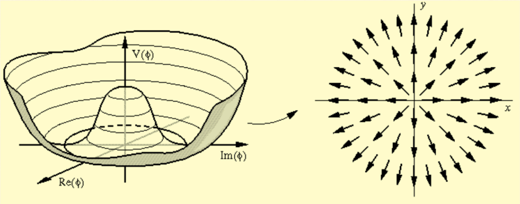
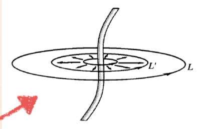
- a takes random values in different Hubble patches
- Cosmic strings formation (where a goes from 0 to 2π)
- Strings radiate axion quanta, reach scaling regime $\rho_S \approx f^2 H^2$

Cosmology of “Heavy" axion



From Vilenkin, Cosmic Strings and other topological defects



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

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

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

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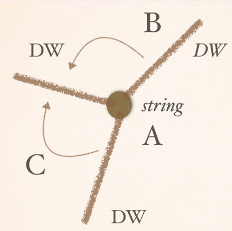

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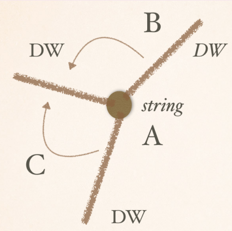
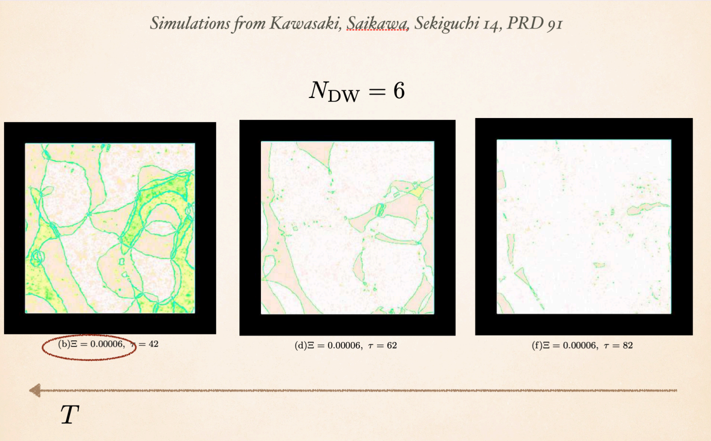


Cosmology of "Heavy" axion, with $N_{DW} > 1$

Simulations from Kawasaki, Saikawa, Sekiguchi 14, PRD 91

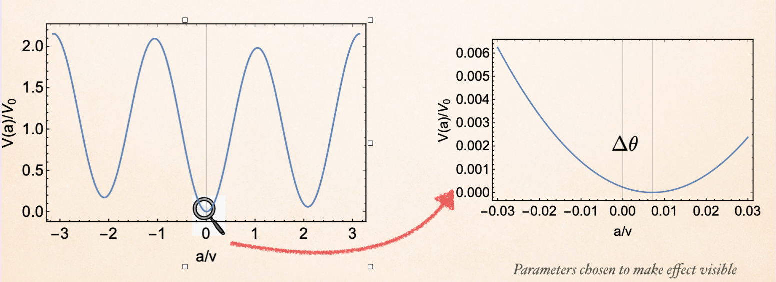
$N_{\rm DW} = 6$

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



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

Small CP violation at the minimum



Heavy Axion at NANOGrav - IPTA

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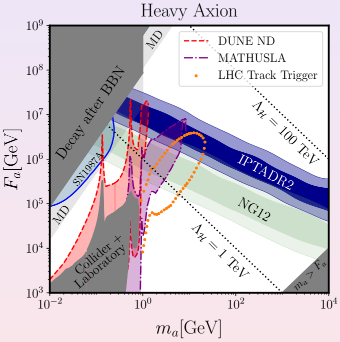

Figure: Marginalized over bias μ_b

(R. Z. Ferreira, A.N., O. Pujolas, F. Rompineve, arXiv: 2204.04228 (2022))

- Decay rate into gluons/photons $\Gamma \approx m_a^3/f^2$

Heavy Axion at LIGO/Virgo/KAGRA and LISA

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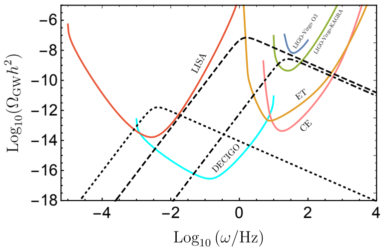

Figure: GW spectra ($N_b = 1, N_{\rm DW} = 6, \delta_0 = 0.3$).
Dashed: $\Lambda_{\rm H} = 10^{10}$ GeV, $f = 10^{11}$ GeV and $\Delta\theta \simeq 8 \cdot 10^{-13}$.
Dotted: $\Lambda_{\rm H} = 10^{7}$ GeV, $f = 2.5 \cdot 10^{10}$ GeV $\Delta\theta \simeq 8 \cdot 10^{-13}$.
Dot-dashed: $\Lambda_{\rm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

Heavy Axion : GW and nEDM experiments

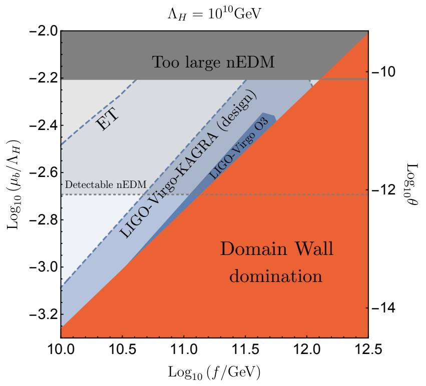

Figure: Here $\Lambda_H = 10^{10}$ GeV.

- GW from decaying DWs correlated to Neutron Electic Dipole (nEDM)

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- Heavy Axion models could also give a signal at LISA, LIGO/Virgo/KAGRA, correlated with nEDM)