UV-completion & Gravitational Waves: Peccei-Quinn Phase Transition

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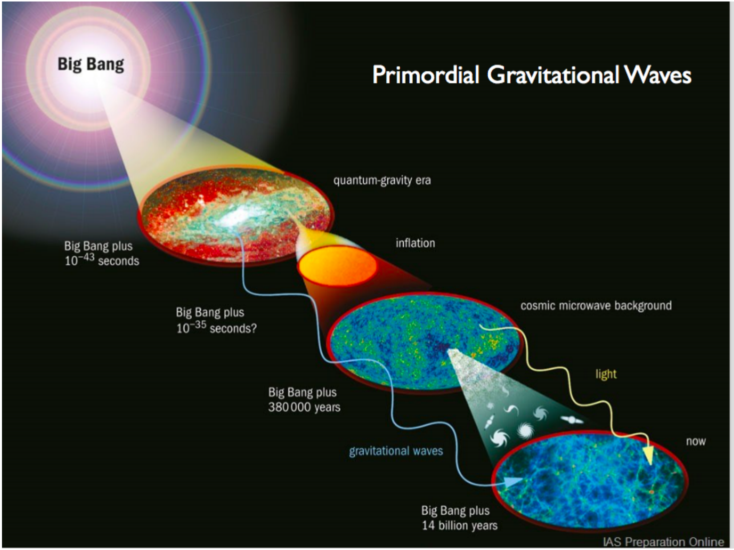
Outline of talk:

- UV completion in particle physics: Total Asymptotic Freedom Principle.
- Sources of Gravitational Waves of Cosmic Origin.
- Stochastic Gravitational Waves from Phase Transitions
  - Peccei-Quinn Phase Transition & Gravitational Waves.
  - Predictions in UV-complete Axion model.
  - Predictions in Conformal Symmetry Breaking.
- Recent NanoGrav GW detection.
- Conclusion

History of the Universe



Gravitational Waves

- Gravitational Waves (GW) first detected in 2016.
- New Window into the Early Universe.
- New Probes of Particle Phenomenology beyond TeV.
- Robust predictions of GW signatures from UV-completion conditions.
- Sources of GW from cosmic origin & corresponding spectrum:
  - Inflation: Primordial GW.
  - Inflation: Secondary GW.
  - Strong First-order Phase Transition.
  - Re-heating.
  - Graviton bremsstrahlung.
  - Topological Defects.
  - Oscillon.
  - Primordial BH-induced GW.
- Strong CP Problem dictates U(1) symmetry breaking. Peccei-Quinn Phase Transition.

GW - - preliminary

perturbations of the background metric: $ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu}(\mathbf{x},\tau))dx^\mu dx^\nu$

scale factor: cosmological expansion — background metric — GW

governed by linearized Einstein equation $(\tilde{h}_{ij} = a h_{ij},\ \mathrm{TT}$ - gauge$)$

$$\tilde{h}''_{ij}(\boldsymbol{k},\tau) + \underbrace{\left(k^2 - \frac{a''}{a}\right)}_{\sim a^2H^2}\tilde{h}_{ij}(\boldsymbol{k},\tau) = \underbrace{16\pi G\, a\, \Pi_{ij}(\boldsymbol{k},\tau)}_{\text{source term from } \delta T_{\mu\nu}}$$

source: anisotropic stress-energy tensor

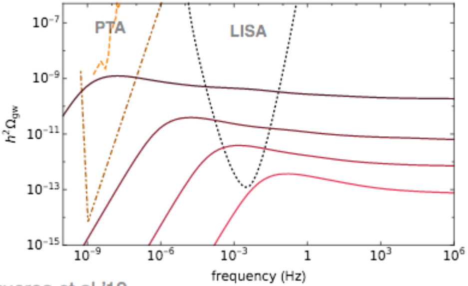
$k \gg aH:\ h_{ij} \sim \cos(\omega\tau)/a\,,\quad k \ll aH:\ h_{ij} \sim \mathrm{const.}$

a useful plane wave expansion: $$h_{ij}(\boldsymbol{x},\tau) = \sum_{P=+,\times}\int_{-\infty}^{+\infty}\frac{dk}{2\pi}\int d^2\hat{\boldsymbol{k}}\; h_P(\boldsymbol{k})\; \underbrace{T_k(\tau)}_{\sim a(\tau_i)/a(\tau)}\; e^P_{ij}(\hat{k})\, e^{-ik(\tau - \hat{\boldsymbol{k}}\boldsymbol{x})}$$

transfer function , expansion coefficients , polarization tensor $P = +, \times$

GW - - Cosmic String

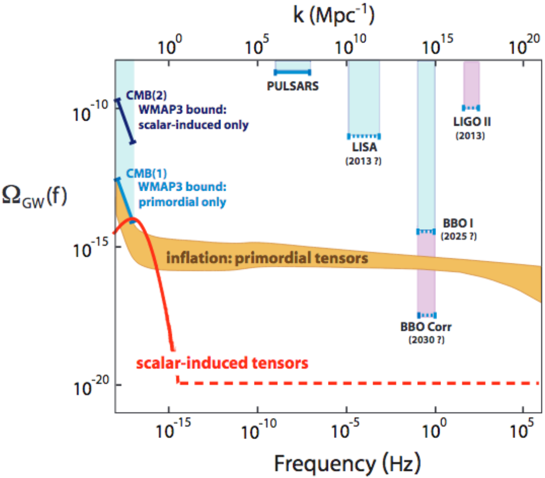
Topological defects like cosmic strings give rise to scale invariant GW spectrum.



Figueroa et al '19

GW - - Scalar Induced Secondary GW

Secondary Tensor Spectrum induced by first-order scalar perturbation via mixing.
Can be tuned to generate high amplitude in high frequency regions.



Baumann (2007)

GW - - PBH-induced GW

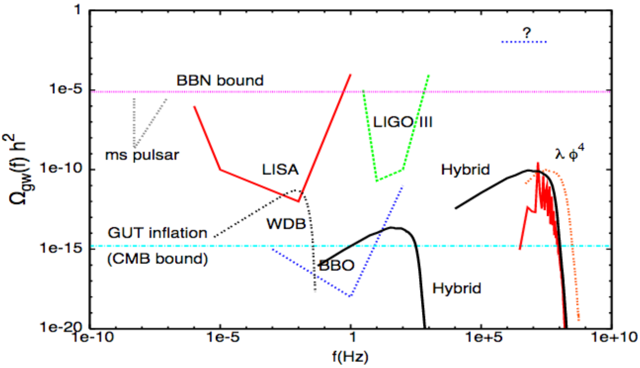
PBH-induced GW.

$$\frac{\Omega_{\rm GW}(k)}{\Omega_r} = \frac{c_g}{72}\int_{-\frac{1}{\sqrt{3}}}^{\frac{1}{\sqrt{3}}} \mathrm{d}d \int_{\frac{1}{\sqrt{3}}}^{\infty} \mathrm{d}s \left[\frac{(s^2-\frac{1}{3})(d^2-\frac{1}{3})}{s^2+d^2}\right]^2 \times P_\zeta(kx)P_\zeta(ky)\left(I_c^2+I_s^2\right) , \quad (13)$$

Baumann (2007)

GW - - (P)-reheating

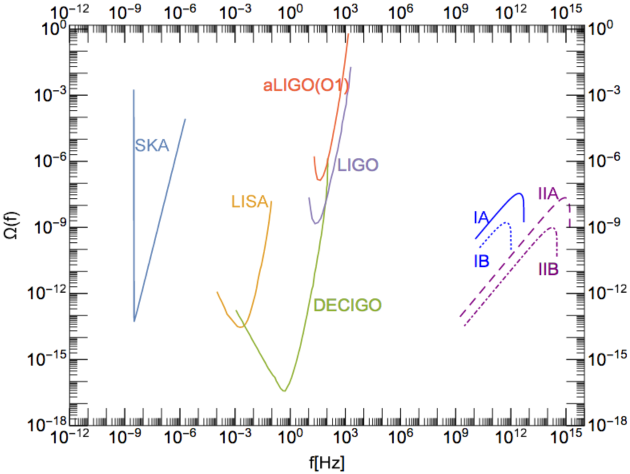
Production during inflaton oscillating in FRW background.



Figuera (2007)

GW - - Graviton Bremmstrahlung

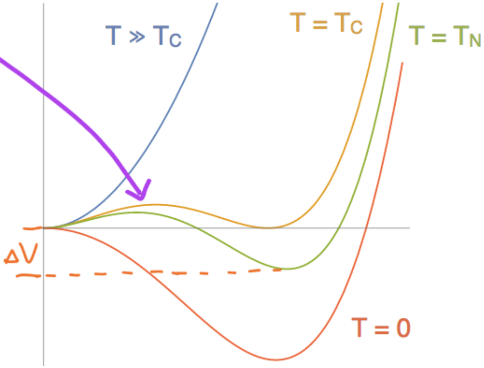
Inflaton radiating away gravitons forming Stochastic GW background.



Nakayama (2018)

Phase Transition

- QFT at finite temperature → symmetry restoration
- For first order PT
  - Need barrier here
- PT occurs at T_N
- Potential energy ΔV
  ↓
  GWs
- Not in SM! Possible in BSM scenarios

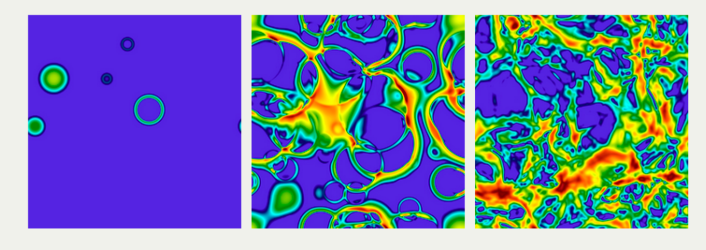


Schwaller (Amsterdam (2019))

Phase Transition

Phase Transitions:

- Bubbles nucleate and grow.
- Expand in plasma.
- Bubbles and fronts collide - - violent process.
- Sound Waves left behind in thermal plasma.
- Turbulence, damping.



Phase Transition GW - Parameter Dependence

- Total GW energy budget from 3 sources

$$h^2\Omega_{\text{GW}} = h^2\Omega_\phi + h^2\Omega_{\text{SW}} + h^2\Omega_{\text{MHD}}$$

Depends on two important parameters:

- Vacuum energy density: $\alpha = \frac{\rho_{\text{vac}}}{\rho^*_{\text{rad}}}$ with $\rho^*_{\text{rad}} = g_* \pi^2 \frac{T_*^4}{30}$
- (Inverse) Bubble nucleation rate: $\beta / H_* = T \sqrt{\frac{d^2 S_E(T)}{dT^2}}\Big|_{T=T_*}$

- $$h^2\Omega_\phi \propto \left(\frac{\beta}{H_*}\right)^{-2}, \quad h^2\Omega_{\text{SW}} \propto \left(\frac{\beta}{H_*}\right)^{-1}, \quad h^2\Omega_{\text{MHD}} \propto \left(\frac{\beta}{H_*}\right)^{-1}$$

- The bubble nucleation rate per unit volume at a finite temperature is given by

$$\Gamma(T) = \Gamma_0 e^{-S(T)} \simeq \Gamma_0 e^{-S_E^3(T)/T},$$

- Other important parameter: bubble wall speed v_w, efficiency factors.

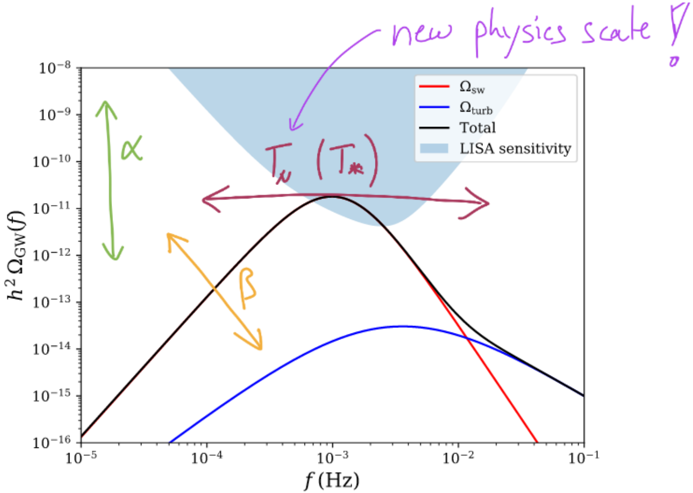
Bounce Action:

$$\partial^2 \phi + V'_{\text{eff}}(\phi, T) + \sum_i \frac{dm_i^2}{d\phi} \int \frac{\mathrm{d}^3 k}{(2\pi)^3\, 2E_i} \delta f_i(\mathbf{k}, \mathbf{x}) = 0$$

- $V'_{\text{eff}}(\phi)$: gradient of finite-T effective potential
- $\delta f_i(\mathbf{k}, \mathbf{x})$: deviation from equilibrium phase space density of ith species
- m_i: effective mass of ith species

Ref.:https://saoghal.net/slides/brda//6

Phase Transition GW - Parameter Dependence



Schwaller (Amsterdam, 2019)

Axion

Strong CP Problem:

$$\frac{\theta}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \qquad \theta + \mathrm{Arg}[\mathrm{Det}(y_u y_d)] < 10^{-10}$$

Axion solution:

$$\theta \to \frac{a(x)}{f} \qquad \mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G\tilde{G}$$

[Peccei-Quinn '77
Weinberg-Wilczek '78]

- PQWW axion:
  Axion identified with the phase of the Higgs in a 2HDM
  ($f_a \sim V_{EW}$ was quickly ruled out long ago) [Peccei, Quinn (1977), Weinberg (1978), Wilczek (1978)]

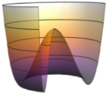
The need to require $f_a \gg V_{EW}$: "invisible axion"

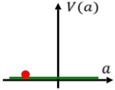
- DSFZ Axion: SM quarks and Higgs charged under PQ.
  Requires 2HDM + 1 scalar singlet. SM leptons can also be charged.
  [Dine, Fischler, Srednicki (1981), Zhitnitsky (1980)]

- KSVZ axion (or QCD axion, or hadronic axion):
  All SM fields are neutral under PQ. QCD anomaly is induced by new quarks, vectorlike under the SM, chiral under PQ.
  [Kim (1979), Shifman, Vainshtein, Sakharov (1980)]

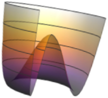
Axion as DM

- As long as $\Lambda_{QCD} < T < f_a$:
  $U(1)_{PQ}$ broken only spontaneously,
  $m_a = 0$, $\langle a_0 \rangle = \theta_0 f_a \sim f_a$

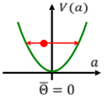




- As soon as $T \sim \Lambda_{QCD}$:
  $U(1)_{PQ}$ explicit breaking (instanton effects)
  $m_a(T)$ turns on. When $m_a(T) > H \sim 10^{-9}$ eV,
  $\langle a_0 \rangle \longrightarrow 0$ and starts oscillating undamped



$$\ddot{a} + \cancel{3H\dot{a}} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) = 0$$



- Energy stored in oscillations behaves as CDM

Axion Pheno

- Axion or ALP couplings to SM particles are always suppressed by inverse powers of $U(1)_{PQ}$ symmetry breaking scale f_a.
- Phenomenological scalar with complex singlet scalar Φ:

$$\Phi(x) = \frac{1}{\sqrt{2}}(f_a + \phi(x))e^{ia(x)/f_a} \tag{1}$$

- Spontaneous breaking of U(1) may lead to strong first-order phase transition at the f_a scale & generate GW signals to be detected at the current and future detectors.

Phase Transition GW - Finite Temperature

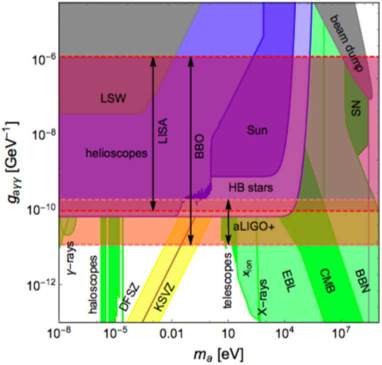
$$\mathcal{V}(\phi,T) = \mathcal{V}_0(\phi) + \mathcal{V}_{\rm CW}(\phi) + \mathcal{V}_T(\phi,T)\,,$$

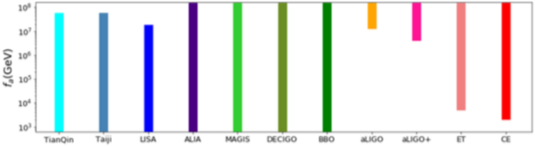
- Tree-level: $$\mathcal{V}_0 = -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a\left(|\Phi|^2 - \frac{1}{2}f_a^2\right)^2 . \\ = \frac{\lambda_a}{4}\left(\phi^2 - f_a^2\right)^2 + \left[\frac{\kappa}{2}\phi^2 - \mu^2\right]\left(\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right) \\ + \lambda\left[\frac{1}{2}h^2 + \frac{1}{2}G_0^2 + G_+G_-\right]^2 .$$
- One-loop: $$\mathcal{V}_{\rm CW}(\phi) = \sum_i (-1)^F n_i \frac{m_i^4(\phi)}{64\pi^2}\left[\log\frac{m_i^2(\phi)}{\Lambda^2} - C_i\right] .$$
- Finite-temperature: $$\mathcal{V}_T(\phi,T) = \sum_i (-1)^F n_i \frac{T^4}{2\pi^2} J_{B/F}\left(\frac{m_i^2(\phi)}{T^2}\right) ,$$
- Temperature-dependent mass terms:

$$\Pi_h(T) = \Pi_{G_{0,\pm}}(T) = \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda + 4\kappa\right)T^2 ,$$
$$\Pi_\phi(T) = \frac{1}{3}(\kappa + 2\lambda_a)T^2 .$$

[Dolan, Jackiw (PRD '74); Arnold, Espinosa (PRD '93); Curtin, Meade, Ramani (EPJC '18)]

Phase Transition GW - Parameter Dependence





Dev et. al. (2019)

KSVZ Axion

– KSVZ axion:

$$U(1)_{\rm PQ}: \qquad X \to e^{i\alpha} X$$

$$\lambda_X (|X|^2 - f^2/2)^2 + (yXQQ^c + h.c.)$$

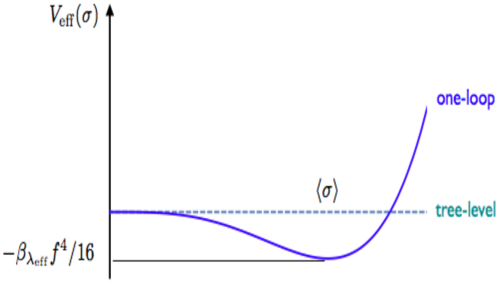
- No massless bosons coupling to X while Peccei-Quinn symmetry is restored.
- Fermion contribution to V_{eff} contributes is negatively.
- Finite temperature corrected potential is of the form $m(T)^{|}X|^2 + \lambda(T)|X|^4$.
- PQ phase transition is of second-order in the minimal case.
- In order of make strong first-order phase transition (PT), and thus enhanced GW, we go to supercooling regime. This requires PT to last long enough.
- This means $\frac{S_3}{T} \sim$ constant $\to$ scale invariant.
- Break PQ symmetry radiatively.
- Or, break non-minimally like strong coupling regime, non-perturbative, extra-dimension etc. (See Delle Rosse (2019) & Von Harling (2019).)

Conformal Symmetry Breaking

Due to conformal symmetry-breaking, the flat direction is lifted at 1-loop when

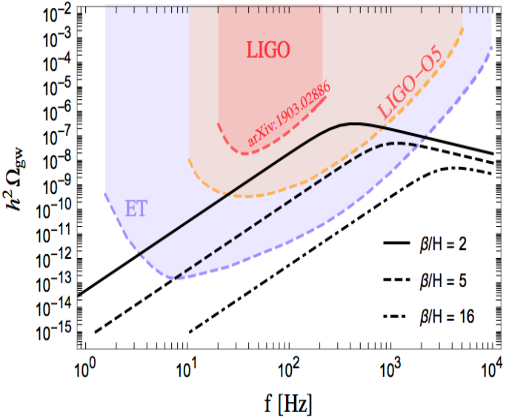
$$V_{eff} = \frac{\beta_\lambda}{4}\sigma^4(log(\frac{\sigma}{f_a} - \frac{1}{4})),$$

where $< \sigma >= f_a$.



Conformal Symmetry Breaking

Strong super-cooling enhances GW signals:



delle Rosse et. al. (2019), von Harling et. al. (2019)

TAF Principle

- Total Asymptotic Freedom (TAF) as a direction for UV completion of particle physics.
- All couplings flow to zero in the UV.
- No Landau poles in theory.
- For $U(1)_{PQ}$, simpliest possibility to replace by $SU(2)_a$.
- Generic conditions for TAF already studied in several place [Giudice (2014), Holdom (2015), Pelaggi (2015)].
- Gravitational Corrections not included.

Low energy spectrum of the theory contains extra dark photon on top of the SM.
All masses of extra quarks and scalars are expressed in terms of the free parameter f_a.

Phase Transition GW - Parameter Dependence

RGE of the parameters:

$$\frac{dg^2}{dt} = -bg^4, \qquad b \equiv \frac{11}{3}C_2(G) - \frac{4}{3}S_2(F) - \frac{1}{6}S_2(S),$$

$$b_s = \frac{29}{3} - \Delta, \quad \frac{dy^2}{dt} = y^2\left(\frac{9y^2}{2} - 8g_s^2 - \frac{9g_a^2}{2}\right)$$

and $b_a = \frac{14}{3}$, $t = \frac{ln(\mu^2/\mu_0^2)}{(4\pi)^2}$, where μ_0 is arbitrary energy scale.
Δ is the extra contributions from scalars and fermions in the theory.

$$g_s^2(t) = \frac{\tilde{g}_s^2}{t}, \quad g_a^2(t) = \frac{\tilde{g}_a^2}{t}, \quad y^2(t) = \frac{\tilde{y}^2}{t}, \quad \lambda_i(t) = \frac{\tilde{\lambda}_i}{t},$$

Phase Transition GW - Parameter Dependence

Axion potential:

$$V_A = -m^2 \mathrm{Tr}(A^\dagger A) + \lambda_1 \mathrm{Tr}^2(A^\dagger A) + \lambda_2 |\mathrm{Tr}(AA)|^2,$$

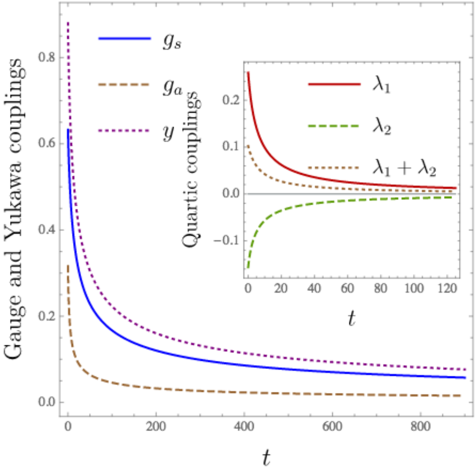
RGEs of λ_1 and λ_2 are $\frac{d\lambda_1}{dt} = \beta_1$, and $\frac{d\lambda_2}{dt} = \beta_2$, where

$$\beta_1(g, y, \lambda) = \frac{9}{2} g_a^4 + \lambda_1 \left(8\lambda_2 + 6y^2 - 12g_a^2\right) + 14\lambda_1^2 + 8\lambda_2^2 - 3y^4$$

$$\beta_2(g, y, \lambda) = \frac{3}{2} g_a^4 + \lambda_2 \left(12\lambda_1 + 6y^2 - 12g_a^2\right) + 6\lambda_2^2 + \frac{3}{2} y^4.$$

X and A are used inter-changeably for denoting the radial part of the axion field.

Phase Transition GW - Parameter Dependence



Phase Transition GW - Parameter Dependence

Some values for satisfying TAF principle.

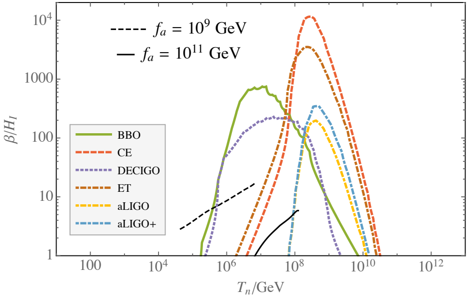
Δ	n_e	unstable vacuum	stable vacuum
28/3	1	(0.219, −3.25)	(1.70, −0.965)
//	2	(0.268, −3.27)	(1.73, −0.986)
//	3	(0.344, −3.30)	(1.77, −1.02)
//	4	(0.469, −3.34)	(1.84, −1.08)
//	5	(0.722, −3.42)	(1.97, −1.20)
//	6	(1.50, −3.49)	(2.34, −1.70)
26/3	1	(0.185, −1.06)	(0.593, −0.362)
//	2	(0.237, −1.07)	(0.619, −0.389)
//	3	(0.314, −1.08)	(0.656, −0.435)
//	4	(0.447, −1.08)	(0.712, −0.528)
8	1	(0.182, −0.601)	(0.365, −0.255)
//	2	(0.236, −0.599)	(0.387, −0.294)
//	3	(0.324, −0.570)	(0.411, −0.376)

Figure: Values of $(\tilde{\lambda_1}, \tilde{\lambda_2})$ satisfying TAF condition. n_e is the number of vector-like Dirac fermions in the adjoint of $SU(2)_a$.

Salvio et. al. (2020)

Phase Transition GW - Parameter Dependence

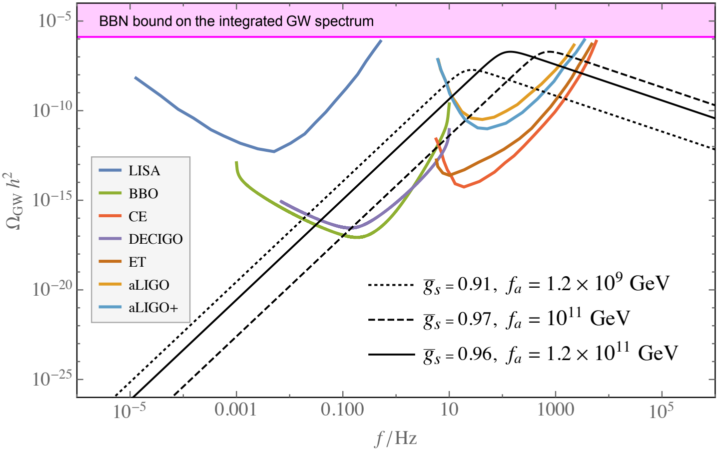
Predictions for some benchmark values.



Imposing conformal symmetry on the axion potential leaves us with only 2 free parameters, thereby very predictive. Ghoshal et. al. (2020)

Phase Transition GW - Parameter Dependence

Predictions on the GW spectrum



Ghoshal et. al. (2020)

Conclusion: PQ Phase Transition & Gravitational Waves

- GW detectors will be probing the pre-BBN era.
- UV completion of axion models is insensitive to laboratory or astrophysics searches but predictable in early universe dyanamics.
- GW from strong first-order Peccei-Quinn phase transitions will be testable in near future.
- Conformal symmetry breaking makes PQ phase transition very very strong.
- Supercooling induces high-amplitudes GW.
- TAF Principle predicts very characteristic & verifiable GW spectrum.
- Gravitational Wave era invitation to dare, propose and test UV completions of QFT and Gravity.

NanoGrav GW Detection

NanoGrav recently detected GW events. Many cosmic sources have been proposed. The GW spectrum nicely fits cosmic strings origin hypothesis.

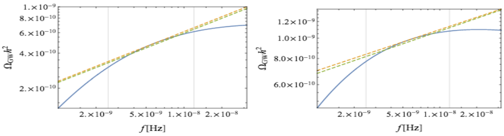
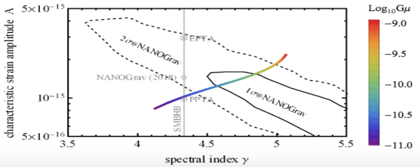


Figure 1. *Cosmic string spectra (solid blue curves) together with our fitted power laws for* $G\mu = 4 \times 10^{-11}$*, and* $G\mu = 10^{-10}$*. The green dashed lines show the results of numerically fitting the curves, while the orange lines result from the simple logarithmic derivative in Eq. (3.3). The thin grey lines indicate the frequency range of interest that was used in the NANOGrav linear fit.*



Ellis (2020)

Backup: (Percolation Criteria)

$$I_V(t) = \frac{4\pi}{3}\int_{t_c}^{t} dt'\,\Gamma(t')\,a_V(t')^3\,r_V(t,t')^3 = \frac{4\pi}{3}\left(\frac{v_w}{H_V}\right)^3\int_{t_c}^{t} dt'\,\Gamma(t')\,\left(1-e^{-H_V(t-t')}\right)^3$$
$$\xrightarrow[t\to\infty]{} \frac{4\pi}{3}\left(\frac{v_w}{H_V}\right)^3\Gamma\times t\,, \qquad (2.25)$$

The criterion (2.26) may also be compared to the one originally used in [43] for strongly supercooled phase transitions. Expanding $I(t)$ around some instant t_0, the percolation criterion from [43] reads

$$\epsilon \equiv \frac{3}{4\pi\,H(t_0)}\left.\frac{dI(t)}{dt}\right|_{t_0} > \frac{9\,n_c}{4\pi} \simeq 0.243\,, \qquad (2.27)$$

which is automatically fulfilled (a weaker condition) if (2.26) is satisfied at time t_0.

Ellis (2018)