Improvements in N_{eff} & isocurvature modes from CMB-S4 inform future GW observations.

Evangelos Sfakianakis

U.T. Austin & Harvard U.

CMB-S4 meeting

Based on

- previous work with Y. Cui & P. Saha
- ongoing work with R. Everett, G. Montefalcone & K. Freese

A model-builder's view on CMB-S4

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Challenges in early universe cosmology

What we ponder:

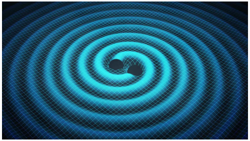
- Transition to the **hot Big Bang** (reheating)
- **String Theory**
  - Axions & Moduli Fields
  - Inflation in String Theory & Swampland
- The **Standard Model** and beyond
  - Neutrinos
  - The Higgs & SM running

What we (hope to) see:

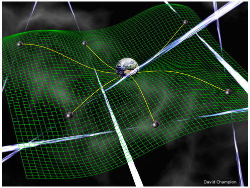
- **CMB**: CMB-S4 & others looking for B-modes, $N_{\rm eff}$, ...
- **Relics** from the early universe
  - baryon number
  - Primordial Black Holes
  - Intergalactic magnetic fields
- Stochastic **GWs**: NANOGrav, LISA, CE, ...

Gravitation waves: a different window to new physics

- LIGO-Virgo discovery of GWs from BH mergers (2016)
  $\Rightarrow$ GW astronomy is born



- Pulsar Timing Arrays find compelling evidence for stochastic GWs (2023)
  $\Rightarrow$ Is it astrophysics (e.g. BHs) or hints of new particle physics / cosmology?



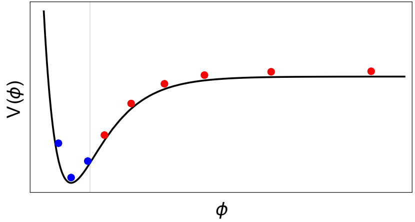
Necessary to evaluate the potential of **GWs** for discovering (hints of) **new physics** (e.g. DM)

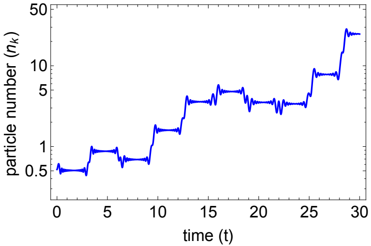
$\Downarrow$

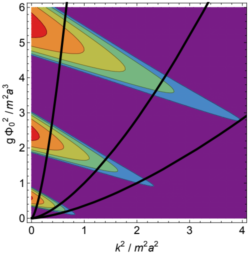
Correlated observables

Fate of rolling scalars

$$\ddot{\delta\chi}_k + 3H\dot{\delta\chi}_k + \left(\frac{k^2}{a^2} + F(\phi)\right)\delta\chi_k = 0$$



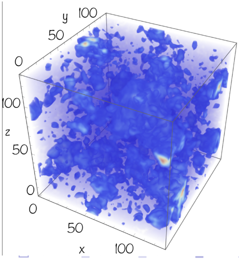




Parametric resonance

$\Downarrow$

inhomogeneous $\mathbf{T}_{\mu\nu}$



Motivation

Questions:

- Are there **simple models** that produce observable GW's?
- What else do they predict?

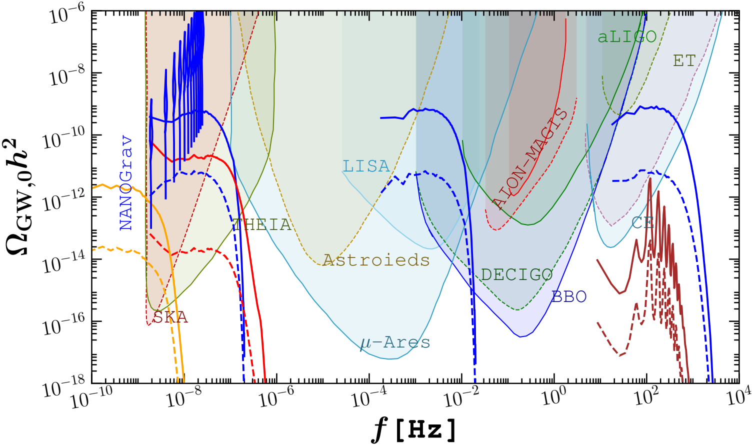
Theoretical motivation:

- A **plethora of scalar fields** expected (e.g. axions, moduli)
- Some of them **light** w.r.t. the inflaton
- Inflationary dynamics can (will) **displace them from their minimum** $\sqrt{\langle\phi^2\rangle} \sim H_{\rm infl}/\lambda^{1/4}, H_{\rm infl}^2/m_\phi$
- While **frozen at early times**, they roll when $H \lesssim m_{\rm eff}$

Results

$$V_A = \frac{m_\phi^2}{2}\phi^2 + \frac{g}{2}\phi^2\chi^2 \qquad V_B = \frac{m_\phi^2}{2}\phi^2 + \frac{\sigma}{2}\phi\chi^2$$

$$V_D = \frac{\lambda_\phi}{4}\phi^4 + \frac{g}{2}\phi^2\chi^2 \qquad V_C = \frac{\lambda_\phi}{4}\phi^4$$



Cui & **EIS**, arXiv:2310.13060 [hep-ph]

Results

Model	m_ϕ (eV)	g	σ (eV)	λ_χ	$\nu_{\rm GW}$(Hz)	$\Omega_{\rm GW}$
A	10^{-13}	10^{-75}	-	-	10^{-9}	10^{-10}
A*	10^8	10^{-36}	-	-	100	10^{-9}
B	10^{-13}	-	10^{-52}	10^{-75}	10^{-9}	10^{-9}
B*	10^{-2}	-	10^{-30}	10^{-53}	10^{-3}	10^{-9}
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	λ_ϕ	g	σ (eV)	λ_χ	$\nu_{\rm GW}$(Hz)	$\Omega_{\rm GW}$
C	10^{-35}	-	-	-	100	$10^{-11.5}$
D	10^{-79}	10^{-79}	-	-	10^{-9}	10^{-12}

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Wide range of GW frequency $\Rightarrow$ Wide range of **new physics** scale

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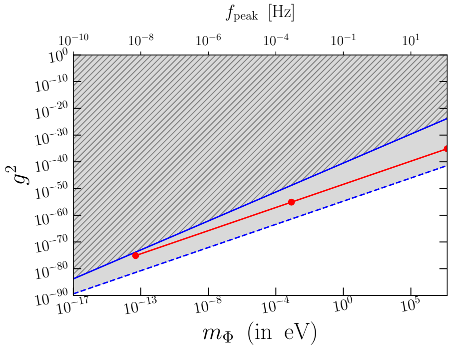
e.g. Dark Matter candidate & potential source of PTA signal

Complementary phenomenology: Dark Matter

After parametric resonance shuts off (at $T_{\rm end}$) for massive and stable ϕ field, residual ϕ condensate can act as dark matter.

$$\Omega_{\phi,0} \equiv \frac{\rho_{\phi,0}}{\rho_{\rm tot,0}} = \frac{\frac{1}{2} m_\phi^2 \phi_{\rm end}^2}{3 M_{\rm Pl}^2 H_0^2} \frac{g_{*,0}}{g_{*,\rm end}} \left(\frac{T_0}{T_{\rm end}} \right)^3$$

Benchmark: $m_\phi \sim 10^{-13}\,\mathrm{eV}$
$\nu_{GW} \sim \mathrm{nHz}\,, \quad \Omega_{GW} \sim 10^{-9}$



- Potential DM candidate & source of PTA signal
- Wave-like DM has distinct signatures

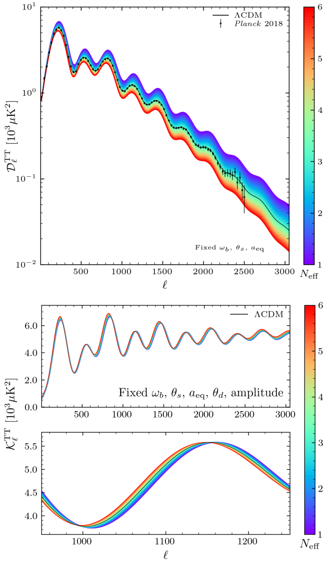
Complementary phenomenology: Dark Radiation

Extra relativistic degrees of freedom are constrained by the CMB, currently at $|\Delta N_{\rm eff}| \lesssim 0.29$.

We have two extra sources of $\Delta N_{\rm eff}$: GW's and massless fields.

- GWs: $\frac{\Omega_{\rm GW,0} h^2}{\Omega_{\gamma,0} h^2} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \Delta N_{\rm eff} \Rightarrow \Delta N_{\rm eff} \simeq 10^4 \Omega_{\rm GW,0}$
  Negligible contribution for $\Omega_{\rm GW,0} \lesssim 10^{-9} \Rightarrow \Delta N_{\rm eff} \ll 0.01$
- $\Delta N_{\rm eff} = \frac{4}{7}\alpha\xi\hat{g}_* \left(\frac{g_*}{\hat{g}_*}\right)^{4/3} \left(\frac{\hat{g}_{*,\rm osc}}{g_{*,\rm osc}}\right)^{1/3}$
  - Estimate: $\alpha \sim 10\% \Rightarrow \Delta N_{\rm eff} \sim 0.1$ and $\alpha \sim 1\% \Rightarrow \Delta N_{\rm eff} \sim 0.01$
  - example for Model B with $m_\phi \sim 10^{-13}$eV and nHz GWs, $\alpha = 1\%$ leads to $\Delta N_{\rm eff} = 0.016$

Safe for now, detectable with CMB-S4



Free-Streaming Neutrinos and Their Phase Shift in Current and Future CMB Power Spectra

Gabriele Montefalcone,★ Benjamin Wallisch,♠,♦,★ and Katherine Freese★,♠,♦

arXiv: 2501.13788[astro-ph.CO]

$$N_{ef} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma}$$

Model	$10^5\,\omega_b$	$10^4\,\omega_c$	$10^7\,\theta_s$	$10^3\,n_s$	N_{eff}	$N_{eff}^{\delta\phi}$	Y_p
ΛCDM	2.7	6.5	5.5	1.8	–	–	–
ΛCDM + N_{eff}	4.0	7.5	6.7	2.9	0.030	–	–
ΛCDM + $N_{eff}^{\delta\phi}$	2.7	6.5	16	1.8		0.078	–
ΛCDM + N_{eff} + $N_{eff}^{\delta\phi}$	4.1	7.5	16	2.9	0.031	0.080	–
ΛCDM + Y_p	4.1	6.6	5.8	2.8	–	–	0.0021
ΛCDM + N_{eff} + Y_p	4.1	13	14	2.9	0.076	–	0.0044
ΛCDM + $N_{eff}^{\delta\phi}$ + Y_p	4.1	6.6	16	2.8	–	0.079	0.0022
ΛCDM + N_{eff} + $N_{eff}^{\delta\phi}$ + Y_p	4.1	32	16	3.1	0.20	0.080	0.011

(b) CMB-S4

$\Delta N_{eff} = \mathcal{O}(0.01)$ is essential for these models.

Affleck-Dine Baryogenesis

Problem: $\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6 \times 10^{-10}$

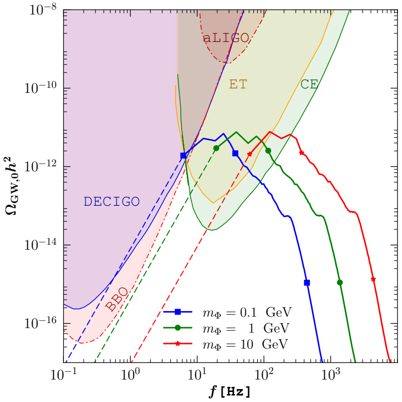
Answer by Affleck & Dine (1985):
A **complex scalar field** carrying baryon number

$$V(\Phi) = \lambda_\Phi |\Phi|^4 + m_\Phi^2 |\Phi|^2 - A(\Phi^n + \Phi_*^n)$$

Do GWs offer a detection channel?

Between the SM hammer and the GW anvil

- For Φ to decay to baryons (before BBN), it is subject to kinematic conditions: $m_\Phi \gtrsim 2$ GeV, $m_\chi \gtrsim 1$ GeV
- For Φ asymmetry to be transferred to SM leptons via N before the EWPT $m_\Phi > 2m_N \gtrsim \mathcal{O}(0.1)$ GeV
- $\nu_{GW} \sim 30\sqrt{m_\Phi/\mathrm{GeV}}$ Hz, detectability $\nu_{GW} \lesssim 100$ Hz $\Rightarrow m_\Phi \lesssim 10$ GeV



A narrow range of masses & GW frequencies, right at the heart of CE & ET $\Rightarrow$ **Testable prediction**

The angular direction has fluctuations

$$\langle \delta\theta^2 \rangle \sim \frac{1}{4\pi^2} \frac{H_I^2}{M_{\rm Pl}^2}$$

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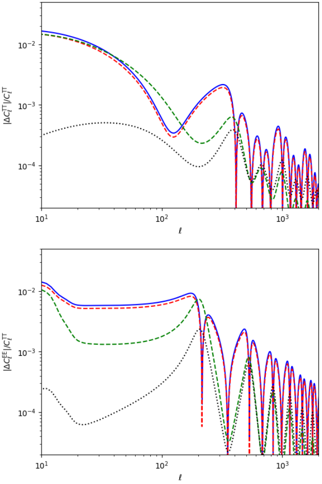
Baryon Isocurvature

The ratio between isocurvature and adiabatic power is

$\alpha_{II} \sim n^2 r \sim 3n^2 \times 10^{-3}$. (Starobinsky)

From Planck: $\alpha_{II} < 3.9 \times 10^{-2}$ with tighter limits from ACT.



Room for constraints - discovery using CMB-S4 (to appear)

Summary

- Simple spectator scalar fields $\Rightarrow$ observable GWs
- Model-dependent: viable DM model –possible PTA connection

Constrainable $N_{\rm eff}$ with CMB-S4: Correlated signal

- Make Φ complex $\Rightarrow$ AD baryogenesis
- **GWs** with frequency $\mathcal{O}(10 - 100)$ Hz $\Rightarrow$ **target for CE, ET**
- **New physics scale** $\mathcal{O}(0.1 - 10)$ **GeV** $\Rightarrow$ **lab searches**

isocurvature constraints AD-type models

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CMB-S4 needed to make sense of stochastic GW signals