Collaborative Research Center TRR 257
Particle Physics Phenomenology after the Higgs Discovery

Karlsruhe Institute of Technology

Electroweak Phase Transitions and Gravitational Radiation in 'CP in the Dark' with **BSMPT***

* talk based on [Eur.Phys.J.C 83 (2023), 5, 439] and [23xx.xxxx]

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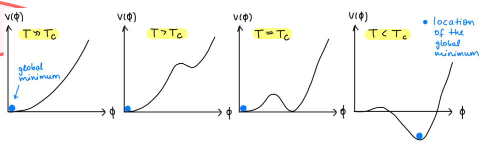
Higgs Hunting, Orsay-Paris 2023

WHY (SFO-)EWPTS IN DARK SECTORS WITH CPV?

Collider (LHC) + Direct Detection (XENON, LZ)

sensitive



Baryon Asymmetry

$$\eta \equiv \frac{\eta_B - \eta_{\bar{B}}}{\eta_\gamma} \simeq 6.1 \times 10^{-10}$$

[Planck, 2018]

requires

Strong first-order electroweak phase transition (**SFOEWPT**) (for electroweak baryogenesis (EWBG) [Sakharov, 1967], [Morrissey, Ramsey-Musolf, 2012])

not possible

Standard Model of Particle Physics (**SM**)

requires

Physics Beyond the SM (**BSM**) + additional ~~CP~~

can source

Gravitational Waves (**GW**s)

sensitive

Pulsar Timing Arrays, Space-bound Interferometers (LISA)

Dark Matter (**DM**)

'CP in the Dark'
[Azevedo et al., 2018]

The Model ‘CP in the Dark’ [Azevedo, Ferreira, Mühlleitner, Patel, Santos, Wittbrodt, 2018]

- N2HDM-like extended scalar sector, *one* discrete $\mathbb{Z}_2$ symmetry

$$\Phi_1 \to +\Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to -\Phi_S$$

- $SU(2)_L \times U(1)_Y$ and $\mathbb{Z}_2$-invariant tree-level potential:

$$\begin{aligned} V^{(0)} = {} & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 + \frac{m_S^2}{2}\Phi_S^2 + \left(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.\right) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 \\ & + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + h.c.\right] + \frac{\lambda_6}{4}\Phi_S^4 + \frac{\lambda_7}{2}|\Phi_1|^2\Phi_S^2 + \frac{\lambda_8}{2}|\Phi_2|^2\Phi_S^2 \end{aligned}$$

- general vacuum structure at $T \neq 0$:

↙ charge-breaking VEV, $\omega_{\text{CB}} = 0$

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \boldsymbol{\omega_1} + i\Psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \rho_2 + \omega_{\text{CB}} + i\eta_2 \\ \zeta_2 + \boldsymbol{\omega_2} + i(\Psi_2 + \omega_{\text{CP}}) \end{pmatrix}, \quad \Phi_S = \zeta_S + \omega_S$$

↖ CP-violating VEV

THE MODEL 'CP IN THE DARK'

- general vacuum structure at $T = 0$:

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\Psi_1 \end{pmatrix}, \; \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + i\eta_2 \\ \zeta_2 + i\Psi_2 \end{pmatrix}, \; \Phi_S = \zeta_S$$

$$\langle \Phi_1 \rangle|_{T=0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \; \langle \Phi_2 \rangle|_{T=0} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \; \langle \Phi_S \rangle|_{T=0} = 0$$

$\rightarrow$ $\boldsymbol{\omega_1}\big|_{T=0\,\text{GeV}} = v_1 \equiv v = 246.22\,\text{GeV}$, SM-Yukawa sector and tree-level FCNCs prohibited

$\rightarrow$ $\mathbb{Z}_2$ symmetry *unbroken* $\Rightarrow$ conserved quantum number: *dark charge*

- Φ_1 (*SM-like particles* with $+1$): $G^{\pm}, G^0, h$
- Φ_2, Φ_S (*dark particles* with -1) : $H^{\pm}, h_1, h_2, h_3$ ($m_{h_1} < m_{h_2} < m_{h_3}$)

$\Rightarrow$ **DM**: *stable* particle dark matter candidate h_1

$\Rightarrow$ **explicit CPV**: introduced through $\text{Im}\,(A) \neq 0$

$\rightarrow$ CPV after SSB, but vacuum is CP-symmetric $\Rightarrow$ CPV is ***explicit***

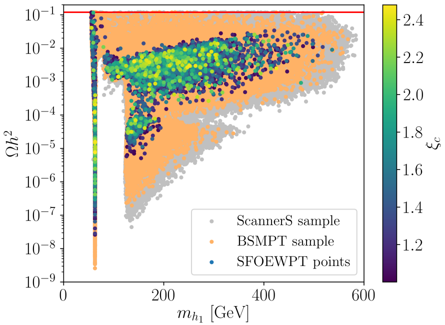
$\rightarrow$ solely in the dark sector - h_1, h_2, h_3: states with mixed CP quantum number

$\Rightarrow$ *not* constrained by EDM constraints

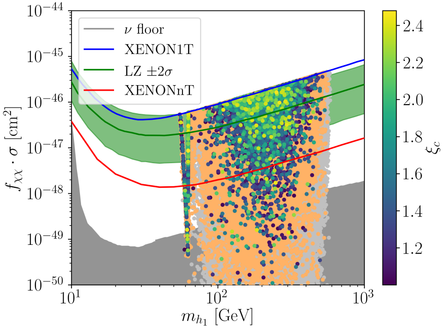
$\Rightarrow$ **'CP in the Dark'** - CPV + DM + SFOEWPT (?) (+ GW (??))

Strong first-order EWPTs with BSMPTv2

$\Omega_{\text{obs}} h^2 = 0.1200 \pm 0.0012$
[Aghanim et al., 2018]



[Billard et al., 2013; Aprile et al., 2018; Aprile et al., 2020; Aalbers et al., 2022]



Viable SFOEWPT parameter points

$\Rightarrow$ allowed by Higgs sector collider constraints

$\Rightarrow$ compatible with *relic density* ($< \Omega h^2$)

$\Rightarrow$ above neutrino floor

$\Rightarrow$ testable at future *direct detection* experiments

$$f_{\chi\chi} \cdot \sigma_{\text{SI, DM-nucl.}} \equiv \frac{\Omega_{\text{prod}} h^2}{\Omega_{\text{obs}} h^2} \cdot \sigma_{\text{SI, DM-nucl.}}$$

viable parameter points:

- pass constraints imposed by: **ScannerS** [Coimbra et al., 2013; Mühlleitner et al., 2020], **BSMPTv2** [Basler et al., 2018/20]
- $\text{BR}(h \to \text{inv.}) < 0.11$ [Aaboud et al., 2019]
- $\mu_{h\to\gamma\gamma} = 1.12 \pm 0.09$ [Sirunyan et al., 2021]
- LUX-ZEPLIN exclusion limit [Aalbers et al., 2022]

Gravitational Waves with BSMPTv3

- vacuum decay rate of FOEWPT determined by **bounce solution***
- bubble expansion *races* against expanding universe and interactions with plasma
- timescales: critical T_c, nucleation T_n and percolation temperature T_*
- GWs sourced by breaking of spherical symmetry: sound waves [Giblin, Mertens '13/14; Hindmarsh et al., '14/15] **dominant** if enough friction with plasma (terminal wall velocity) and no early onset of turbulence ($\alpha < 1$)
- frequency f^{peak} and amplitude $h^2\Omega_{\text{GW}}^{\text{peak}}$ determined by
  - released latent heat α
  - inverse time scale of the phase transition $\frac{\beta}{H}$
  - bubble wall velocity v_b
- *: Available codes to calculate the bounce solution:
  - `CosmoTransitions` [Wainwright, 2011]
  - `AnyBubble` [Masoumi, 2017]
  - `BubbleProfiler` [Athron et al., 2019]
  - `SimpleBounce` [Sato, 2019]
  - `FindBounce` [Guada et al., 2018/20]
  - `OptiBounce` [Bardsley, 2021]

GRAVITATIONAL WAVES WITH BSMPTv3

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$\Rightarrow$ [coming 2023] **BSMPTv3**!

FEATURES OF BSMPTv3:

→ optimized **minimum tracing** over any temperature interval

→ numerical derivation of the **bounce solution** for any number of field dimensions

→ calculation of T_c, T_n, T_*

→ derivation of α, β/H, f_{peak}, $h^2\Omega_{\text{peak}}$ and SNR at LISA

→ embedded into the framework of **BSMPTv2** [Basler et al., 2018/20]:

- singlet-/doublet-extensions of SM implemented
- interface to implement own model
- designed to use input from **ScannerS** [Coimbra et al., '13; Mühlleitner et al., '20]

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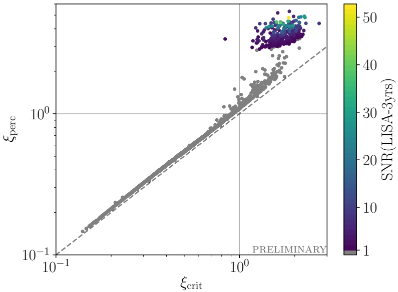
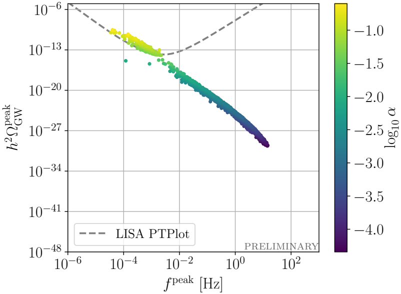
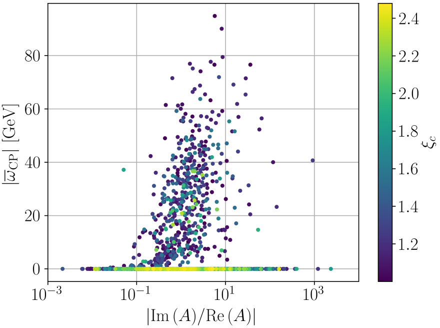
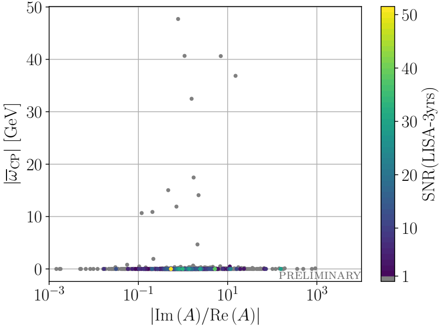
⇒ [coming 2023] **BSMPTv3**! First results:





Spontaneous CP violation





- possiblity of strong first-order EWPT and **spontaneous** CP violation $|\overline{\omega}_{\rm CP}| \equiv |\omega_{\rm CP}(T = T_c)| > 0$
- SNR(LISA-3yrs) > 1 for maximal $|\overline{\omega}_{\rm CP}| = \mathcal{O}(10^{-1})$

$\rightarrow$ spon. CPV $\Rightarrow$ spon. $\mathbb{Z}_2-$violation $\rightarrow$ dark charge no longer conserved $\rightarrow$ dark sector mixes with SM-like particles $\Rightarrow$ additional non-standard CPV transferred to the SM-like couplings to fermions at finite temperature

$\rightarrow$ exciting model candidate for **Electroweak Baryogenesis**!

- spon. $\mathbb{Z}_2-$violation leads to plasma friction also with (former) dark directions

$\rightarrow$ spon. CPV *escapes* the run-away case?

Conclusion & Outlook

- 'CP in the Dark': SM + doublet + real singlet + one discrete $\mathbb{Z}_2$-symmetry
  - $\rightarrow$ additional explicit dark-sector CP violation
  - $\rightarrow$ DM candidate
- viable SFOEWPT parameter points within reach of future direct detection experiments
- allows for acoustic GWs with SNR(LISA-3yrs) > 1 in agreement with experimental constraints
- possibility of spontaneous CP violation at finite temperature + SFOEWPT + GW!
- … *stay tuned* for the release of `BSMPTv3`!

Thanks for Your attention!