Instituto de Física Teórica
UAM-CSIC

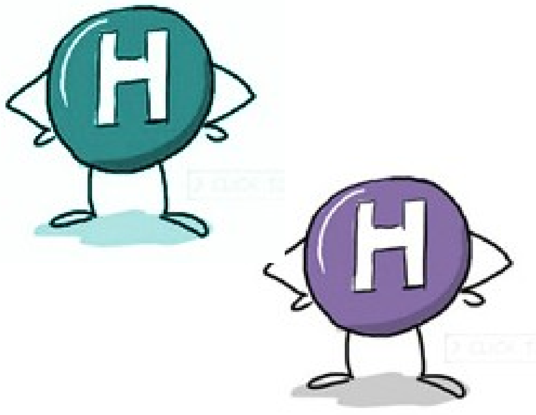
UNIVERSIDAD AUTONOMA DE MADRID

Transient CP Violation
(in the early Universe)
& Baryogenesis

CATCH 2022+2
DIAS, Dublin

Jose Miguel No
IFT-UAM/CSIC, Madrid

EXCELENCIA SEVERO OCHOA



SM symmetries in early Universe?

Symmetry (discrete, continuous, gauge?) of SM not present in early Universe...*

"Transient symmetry breaking"

*Related ideas: (surely incomplete!)

*Patel, Ramsey-Musolf, Wise, Phys. Rev. D**88** (2013) 015003*
*Servant, Phys. Rev. Lett. **113** (2014) 171803*
*Inoue, Ovanesyan, Ramsey-Musolf, Phys. Rev. D**93** (2016) 015013*
*Ipek, Tait, Phys. Rev. Lett. **122** (2019) 112001*
Aoki, Biermann, Borschensky, Ivanov, Muhlleitner, JHEP 02 (2024) 232

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Ipek, Tait, Phys. Rev. Lett. 122 (2019) 112001 → **Seyda Ipek's talk tomorrow!**
Aoki, Biermann, Borschensky, Ivanov, Muhlleitner, JHEP 02 (2024) 232

SM symmetries in early Universe?

Symmetry (discrete, continuous, gauge?) of SM not present in early Universe…

"Transient symmetry breaking"

… to solve open problem(s) of SM

I here focus on CP symmetry breaking

Why CP? → Origin of Matter-Antimatter Asymmetry

Sakharov Conditions (*for dynamical generation of baryon asymmetry*)

- B Violation
- **C/CP Violation**
- Departure from Thermal Equilibrium

Why CP? → Origin of Matter-Antimatter Asymmetry

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- B Violation
- **C/CP Violation**
- Departure from Thermal Equilibrium

SM CP Violation insufficient by ~ **10** orders of magnitude

*Gavela, Hernandez, Orloff, Pene, Quimbay, Nucl. Phys. B **430** (1994) 382*

$$\not{C}P \sim \frac{\prod_{i\neq j}^{u,c,t} |m_i^2 - m_j^2| \times \prod_{i\neq j}^{d,s,b} |m_i^2 - m_j^2|}{T^{12}} \times J \;\sim 10^{-20}$$

Jarlskog Invariant
(3-family fermion mixing)

… but BSM CP Violation (very) strongly constrained by EDMs

$$\frac{|d_e|}{e} < 1.1 \times 10^{-29}\ \mathrm{cm}$$

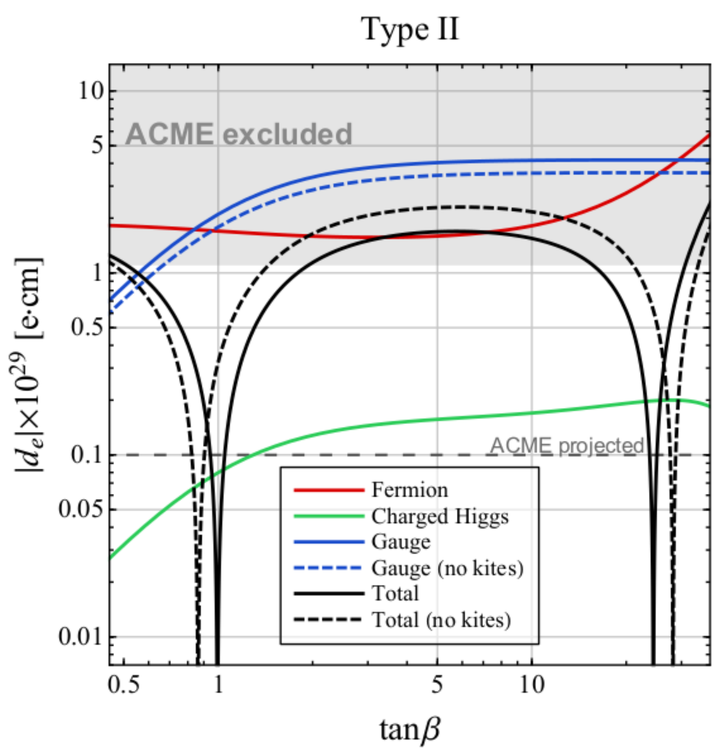
*Andreev et al (ACME Collaboration), Nature **562** (2018) 7727*

e.g. 2HDM CPV

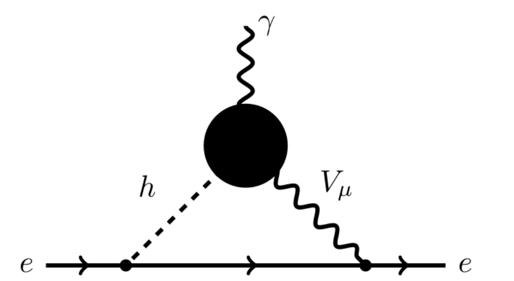
$$V_{\text{2HDM}} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - [\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \frac{1}{2}\left[\lambda_5 (H_1^\dagger H_2)^2 + \text{h.c.}\right]$$

Phase of $\lambda_5^* (\mu_{12}^2)^2$ is physical

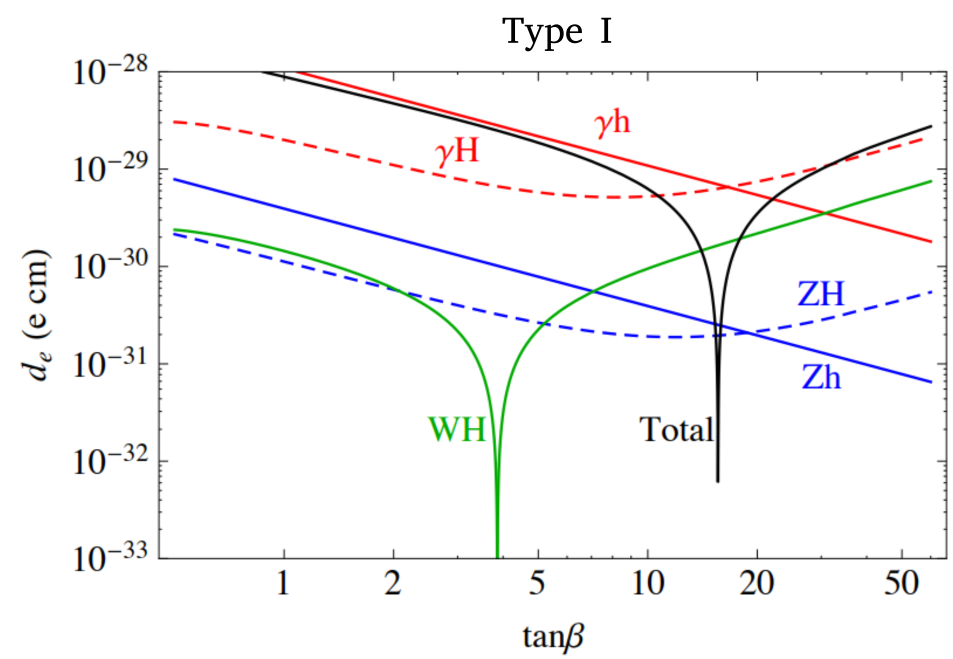
Electric Dipole Moments:



Altmannshofer, Gori, Hamer, Patel, PRD **102** (2020) 115042



Two-loop "Barr-Zee" electron EDM contribution



Inoue, Ramsey-Musolf, Zhang, PRD **89** (2014) 115023

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$$V_{2\mathrm{HDM}} = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left[\mu_{12}^2 H_1^\dagger H_2 + \mathrm{h.c.}\right] + \frac{\lambda_1}{2}|H_1|^4 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \mathrm{h.c.}\right]$$

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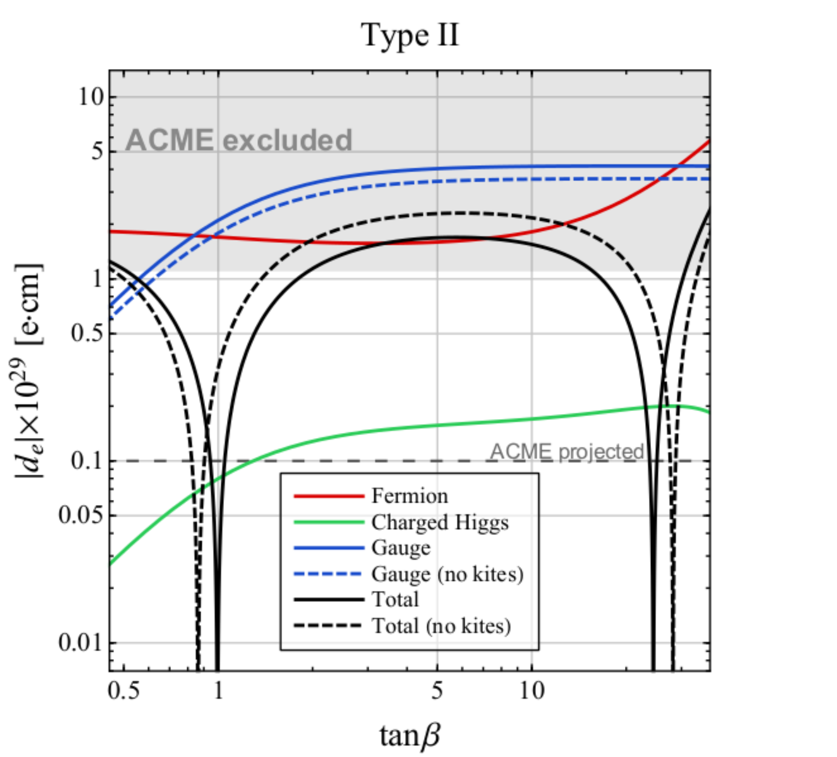

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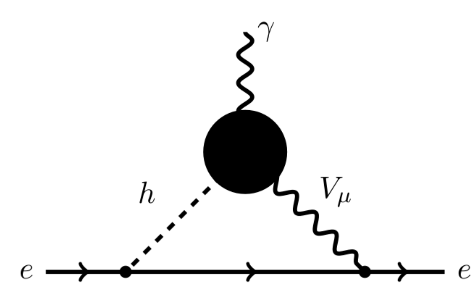

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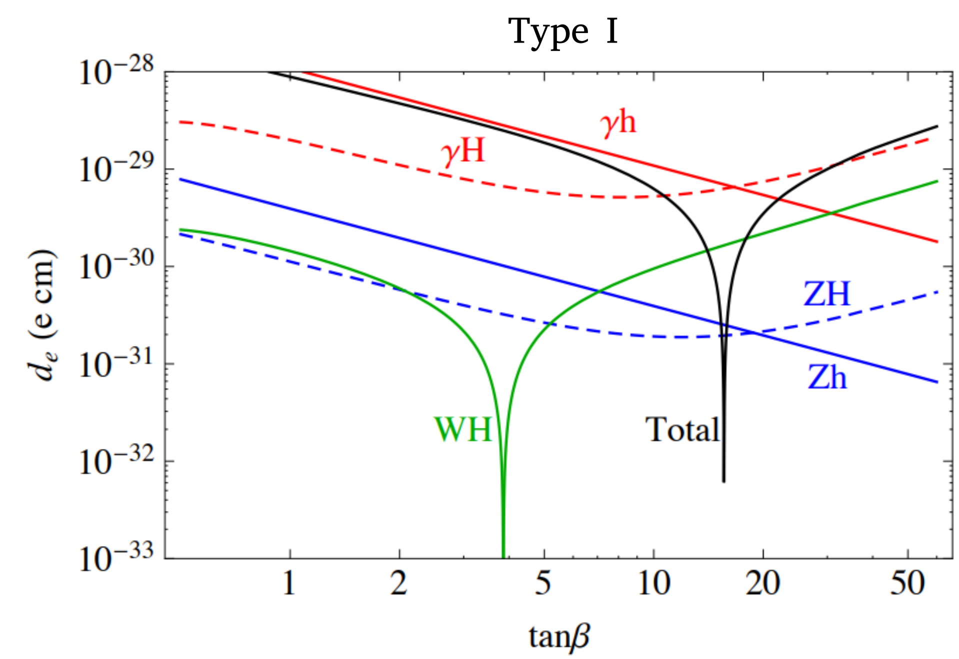
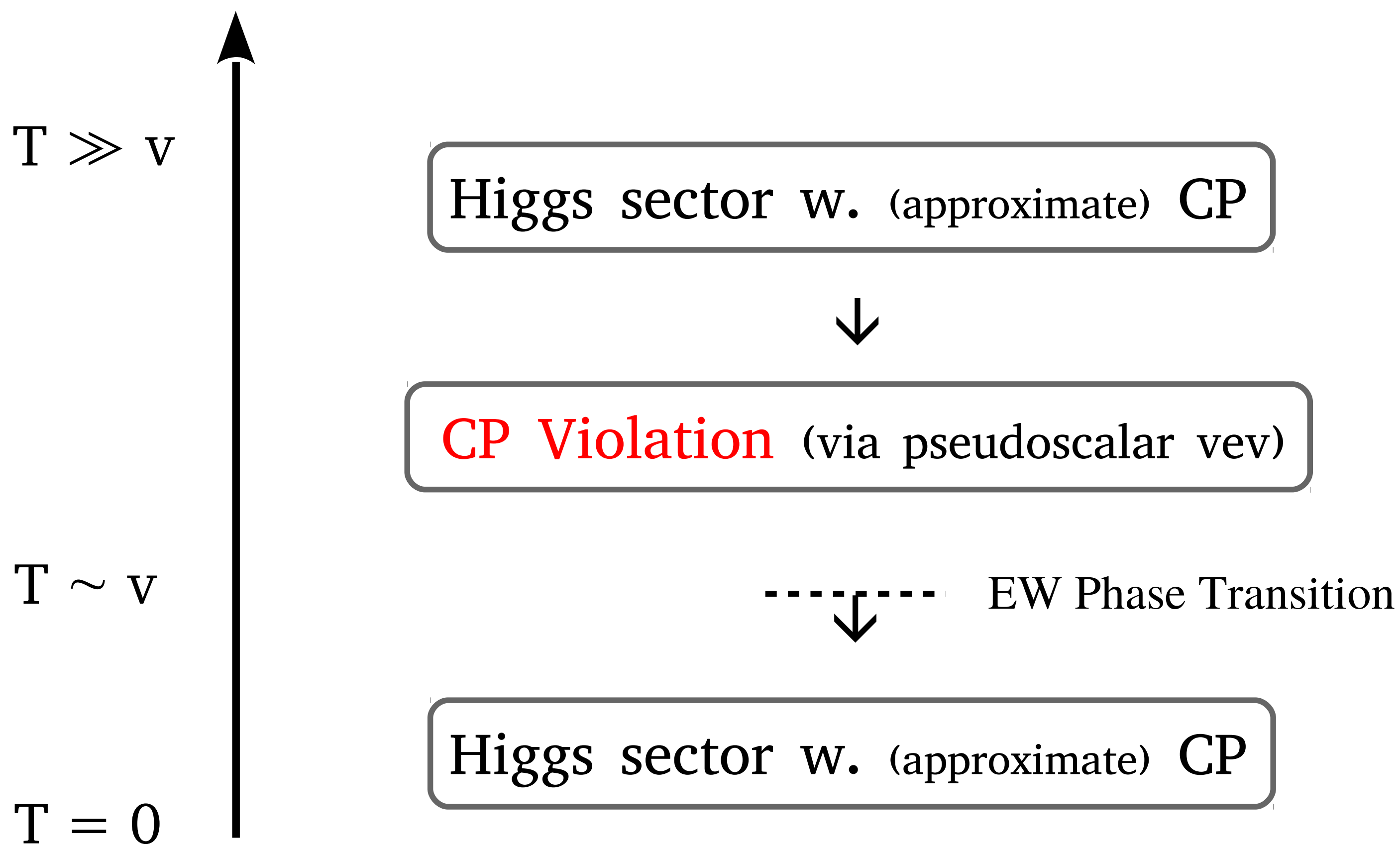


Inoue, Ramsey-Musolf, Zhang, PRD **89** (2014) 115023

Biggest challenge for successful EW Baryogenesis?

Transient (early Universe) CPV can circunvent EDM Constraints!

Non-Minimal Higgs sector inducing CP Violation in early Universe



Explicit realization I: 2HDM + a

Huber, Mimasu, JMN, PRD 107 (2023) 07542

(Two Higgs doublets + singlet pseudoscalar) $V = V_{\rm 2HDM} + V_a$

$$V_a = \frac{\mu_a^2}{2}\, a^2 + \frac{\lambda_a}{4} a^4 + \left(i\,\kappa\, a\, H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1}\, a^2\, |H_1|^2 + \lambda_{aH_2}\, a^2\, |H_2|^2$$

$$\begin{aligned} V_{\rm 2HDM} &= \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 - \left[\mu_{12}^2\, H_1^\dagger H_2 + \text{h.c.}\right] \\ &+ \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2 \\ &+ \lambda_4\left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right] \end{aligned}$$

[LHC DM WG benchmark model] (Pseudoscalar portal to DM)

Abe et al, Phys. Dark. Univ. 27 (2020), 100351

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Simplifying parameter assumptions

$$m_{H_0}^2 = m_{A_0}^2 = m_{H^\pm}^2 = M^2 \equiv \mu_{12}^2/(s_\beta c_\beta)$$

$$c_{\beta-\alpha} = 0$$

… & forget about DM!

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Singlet-doublet pseudoscalar mixing: $a \;\; A_0 \longrightarrow a_{1,2}$

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- Besides $\lambda_5^* (\mu_{12}^2)^2$, **more CPV phases**: e.g. $\kappa^* \mu_{12}^2$

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- Besides $\lambda_5^* (\mu_{12}^2)^2$, more CPV phases: e.g. $\kappa^* \mu_{12}^2$

- For λ_5 , μ_{12}^2, $\kappa \in \mathbb{R}$, CP Conservation!
  (if $\langle a \rangle = 0$)

Explicit realization I: 2HDM + a

Huber, Mimasu, JMN, PRD 107 (2023) 07542

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- Besides $\lambda_5^*(\mu_{12}^2)^2$, more CPV phases: e.g. $\kappa^*\mu_{12}^2$
- For λ_5 , μ_{12}^2, $\kappa \in \mathbb{R}$, CP Conservation!

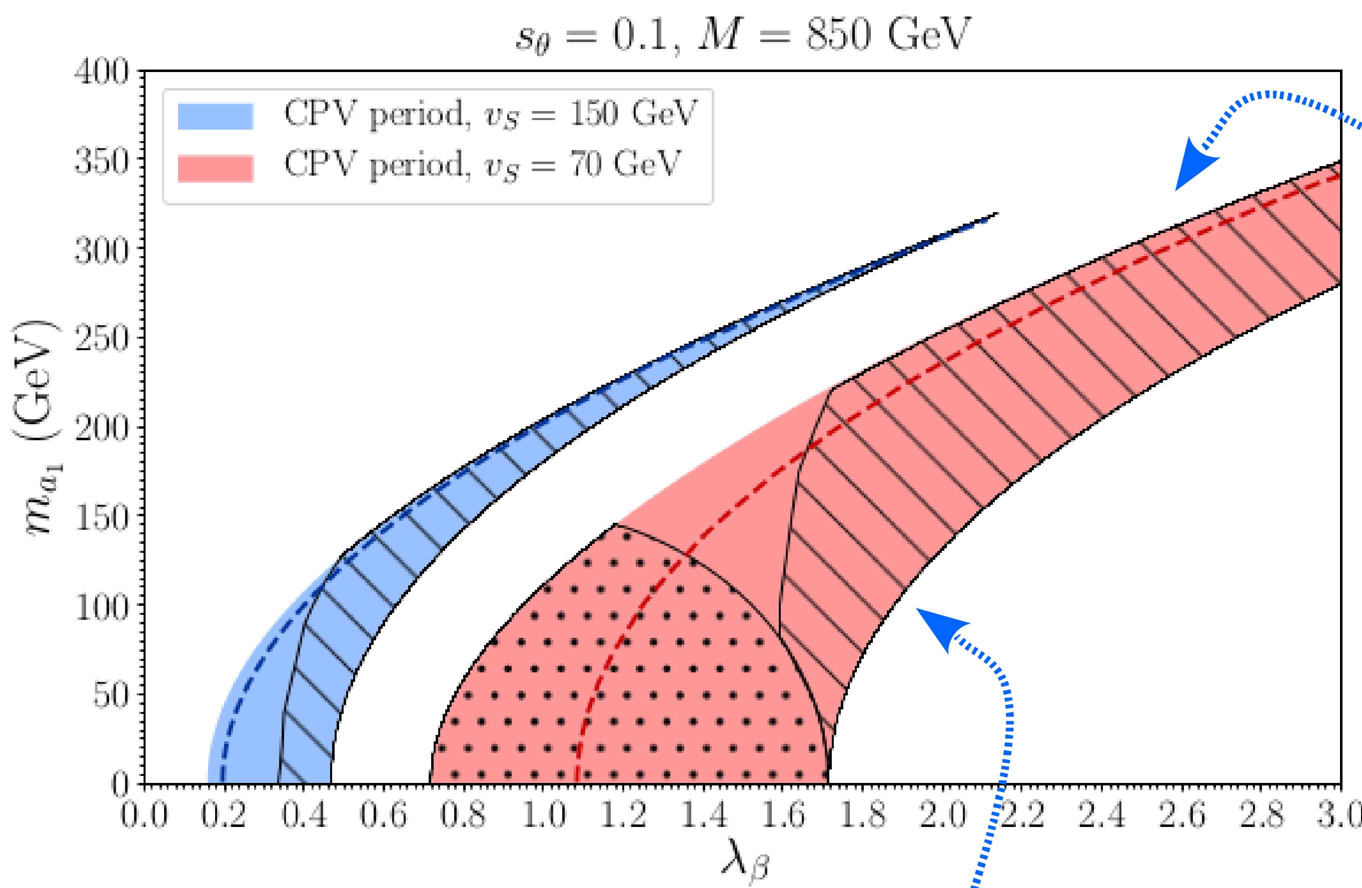
(if $\langle a\rangle = 0$)

If non-zero vev, CP Violation!

Varying $\langle a\rangle$ in early Universe

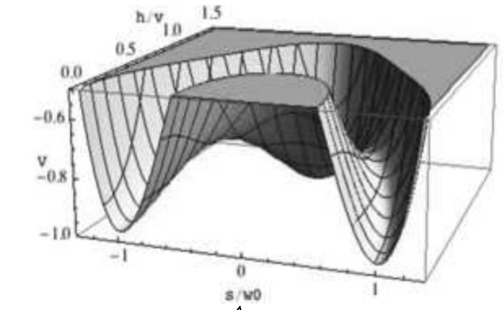
"Transient CPV"

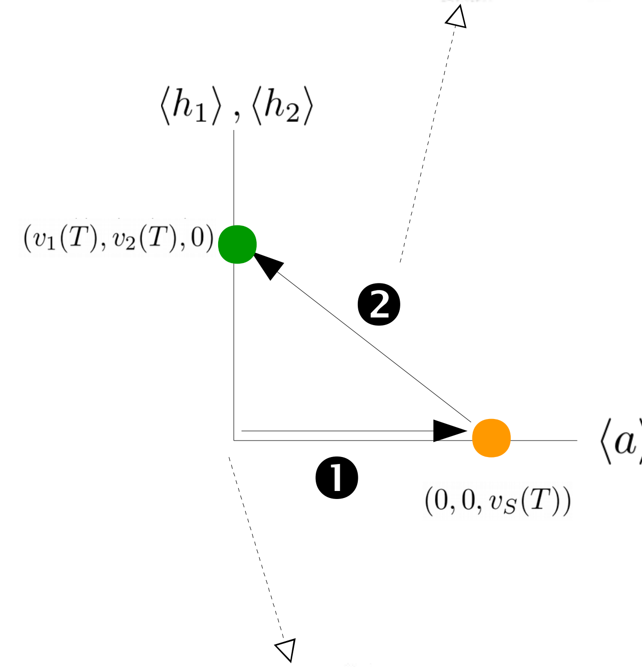
Transient CPV

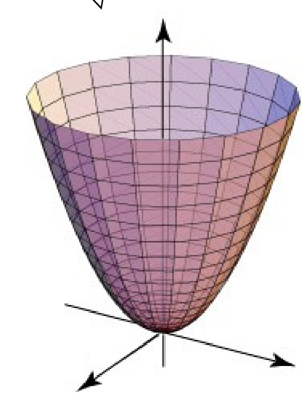


$T_S > T_h$

EW vacuum
deepest @ T = 0



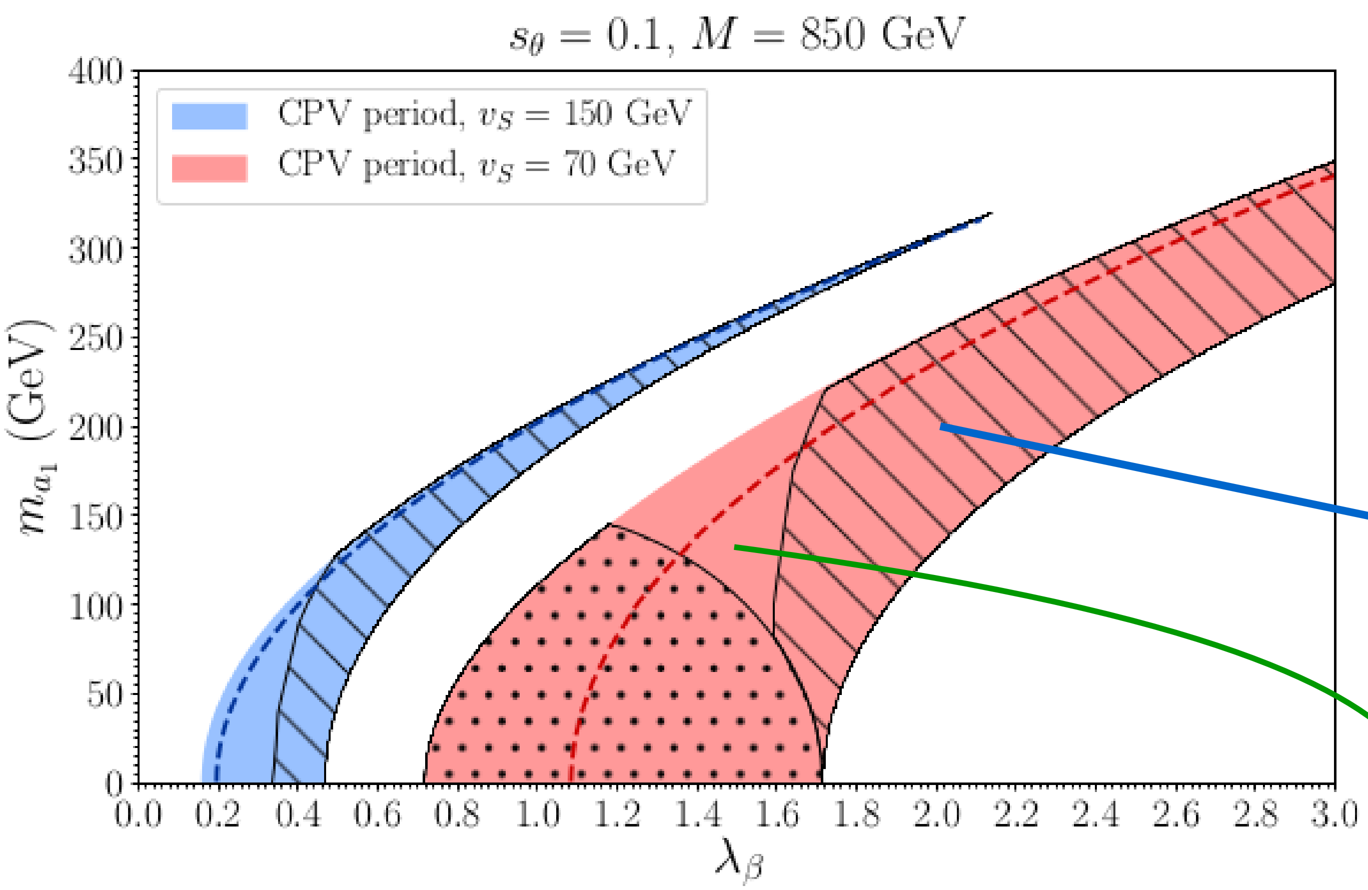


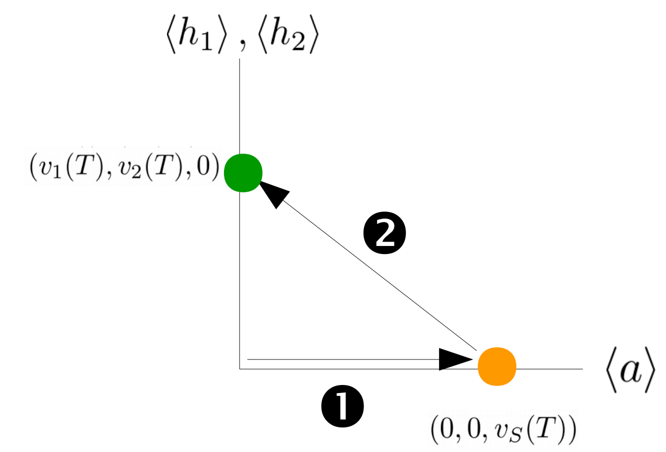


@ very high-T

$\lambda_\beta \equiv (\lambda_{aH_1} + \lambda_{aH_2}\, t_\beta^2)/(1 + t_\beta^2)$

Transient CPV





Universe trapped at $T = 0$ in CPV vacuum (unphysical!)

see e.g.

Baum, Carena, Shah, Wagner, Wang, JHEP **03** (2021) 055

Biekotter, Heinemeyer, Olea, JMN, Weiglein, JCAP **06** (2021) 018

Successful transient CPV needs light singlet-like pseudoscalar

$\lambda_\beta \equiv (\lambda_{aH_1} + \lambda_{aH_2}\, t_\beta^2)/(1 + t_\beta^2)$

Baryogenesis

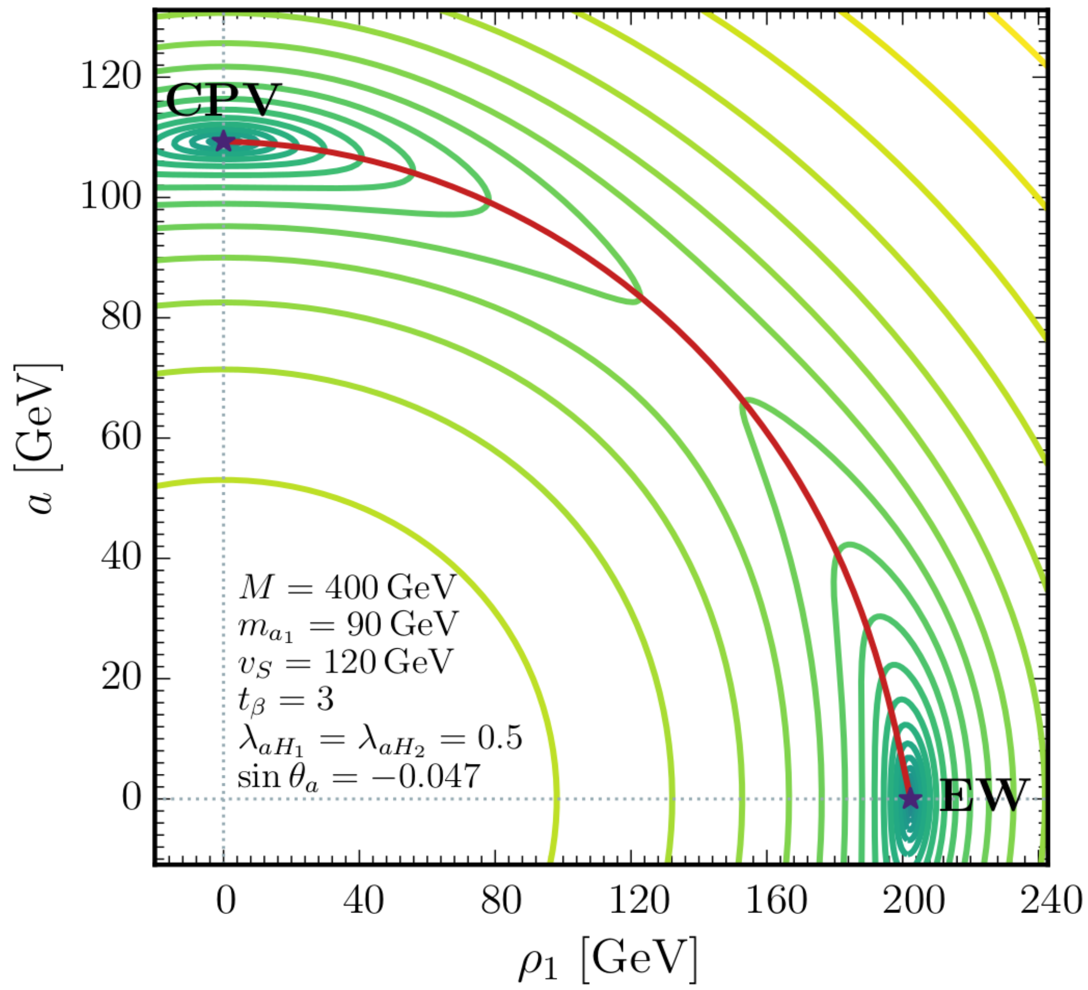
$$\delta_t = \delta_S/(1+t_\beta^2)$$

$$\frac{\eta}{10^{-11}} \sim 6\times 10^2\, \frac{\sin(\delta_t)\,\xi_c^2}{L_W T_c}$$

Fromme, Huber, JHEP 03 (2007), 049

$$\xi_c = v_c/T_c$$

Transition strength



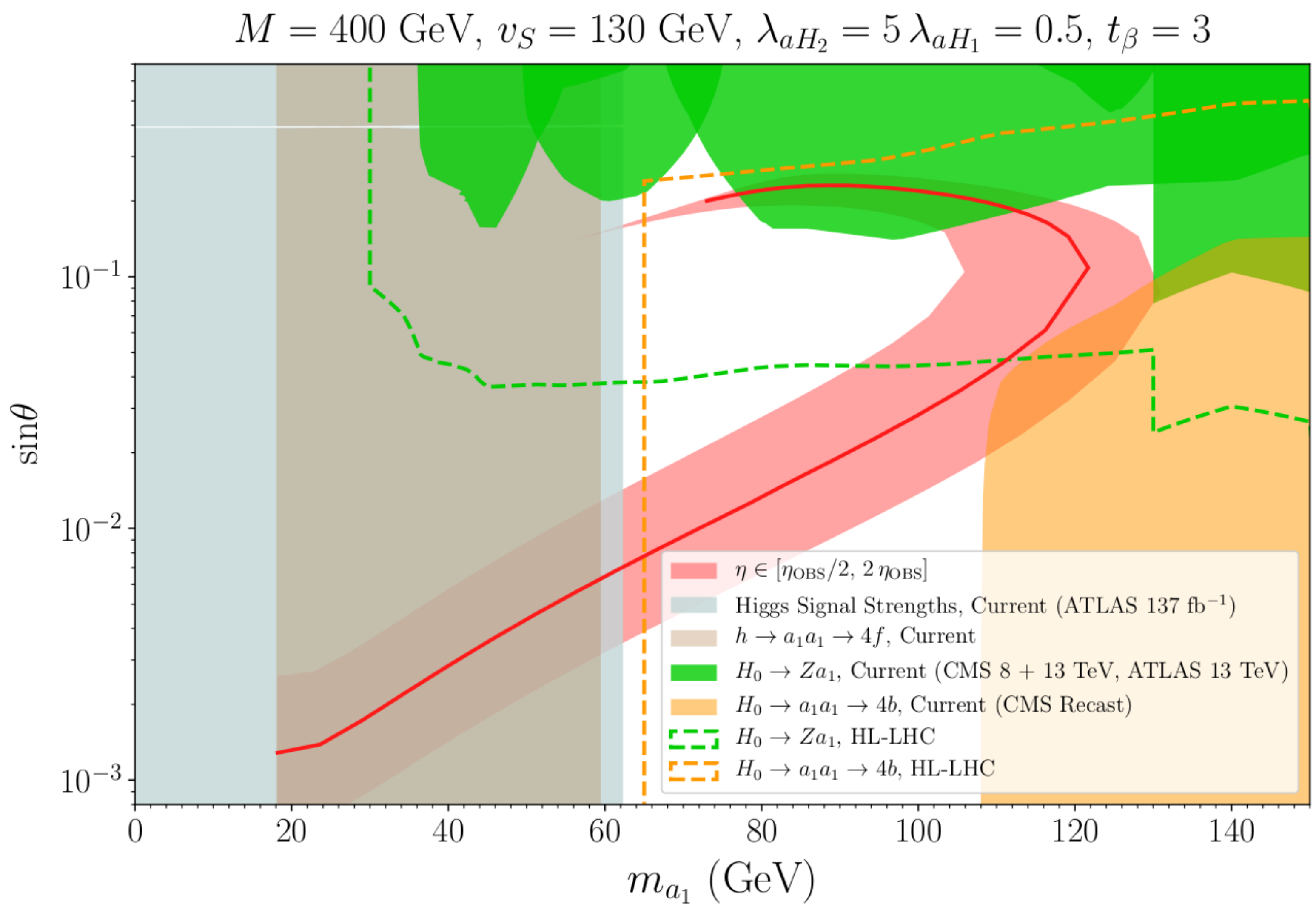
Baryon Asymmetry can be related to 2HDM Baryogenesis studies

Phase difference between **"CPV"** and **EW** minima

$$\delta_S = \mathrm{Arg}[\mu_{12}^2(T)^*\mu_{12}^2]$$

$$\mu_{12}^2(T) = \mu_{12}^2 - i\,\kappa\, v_S(T)$$

Baryogenesis

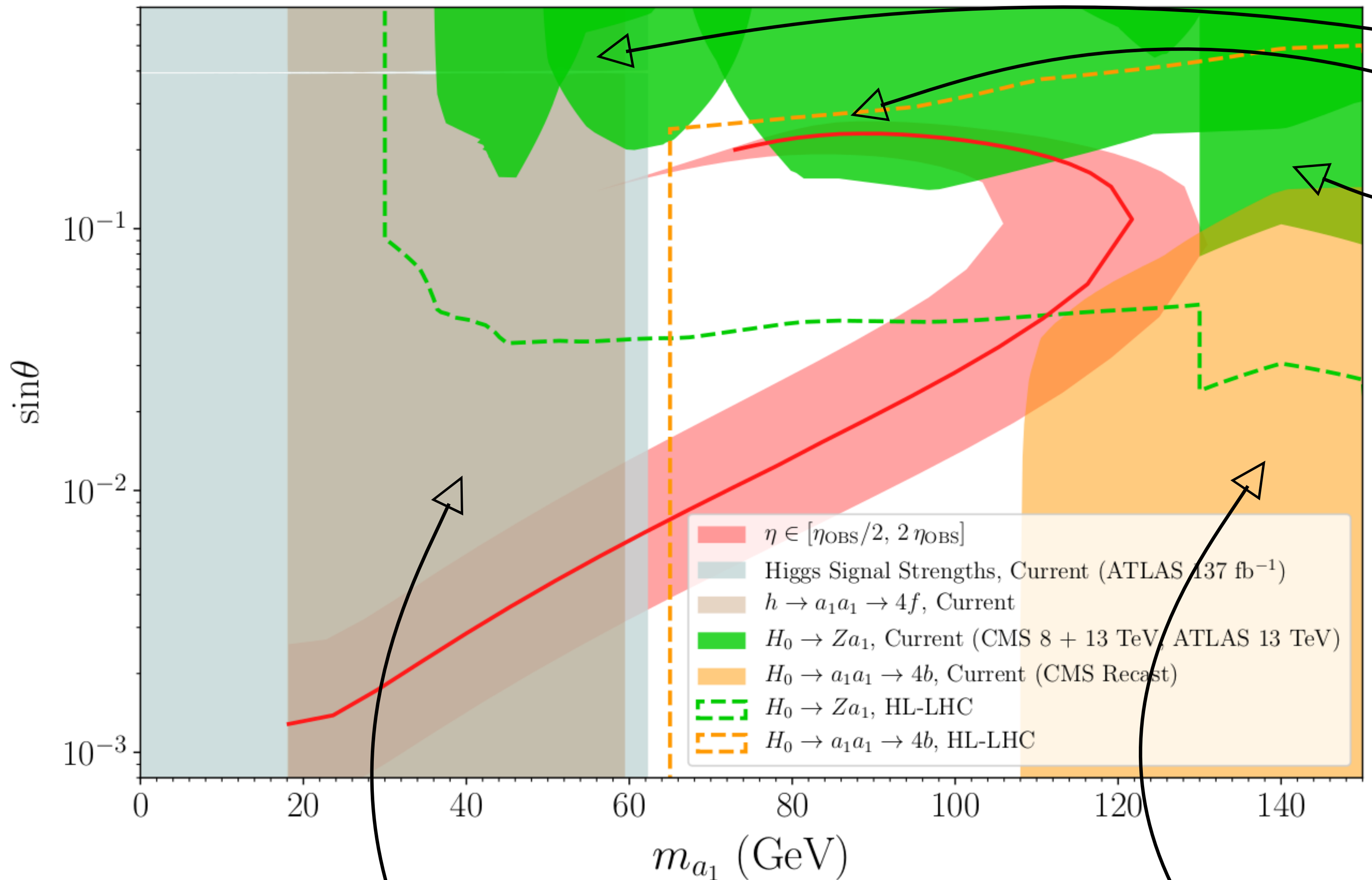


$\eta \in [\eta_{\rm OBS}/2,\, 2\,\eta_{\rm OBS}]$

$\eta_{\rm OBS} = 8.7 \times 10^{-11}$

#HowTo Search? LHC

$M = 400$ GeV, $v_S = 130$ GeV, $\lambda_{aH_2} = 5\,\lambda_{aH_1} = 0.5$, $t_\beta = 3$



$$H_0 \to Za_1 \to \ell\ell\bar{b}b$$

CMS, Phys. Lett. B 759 (2016), 369 (8 TeV)

CMS-PAS-HIG-18-012 (13 TeV)

ATLAS, Phys. Lett. B 783 (2018), 392 (13 TeV)

ATLAS more sensitive (more lumi), yet no quoted limit below 130 GeV

$$\Gamma\left(H_0 \to Za_1\right) \propto s_\theta^2$$

RULED OUT
(LHC Higgs signal strengths)

$$H_0 \to a_1 a_1 \to b\bar{b}b\bar{b}$$

CMS, JHEP 08 (2018), 152 (13 TeV)

Limits are recast of H $\to hh$ CMS search

Barducci, Mimasu, JMN, Vernieri, Zurita, JHEP 02 (2020), 002

$$\Gamma\left(H_0 \to a_1 a_1\right) \propto (\lambda_{aH_1} - \lambda_{aH_2})^2\, c_\theta^4$$

Explicit realization II: 2HDM + S (with "dark" Z_2 symmetry)

Biekotter, Cano, Gori, Mimasu, JMN, 24xx.xxxxx

Explicit CPV, secluded in dark sector

$$
\begin{aligned}
V(H_1, H_2, S) = {} & \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 - \left[\boxed{\mu_{12}^2} H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4 \\
& + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right] \\
& + \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \lambda_{S_1} S^2 |H_1|^2 + \lambda_{S_2} S^2 |H_2|^2 + \frac{1}{2}\left[\boxed{\lambda_{S_3}} S^2 H_1^\dagger H_2 + \text{h.c.}\right]
\end{aligned}
$$

Extra EDM suppression (3-loop) 

A CP-violating Higgs portal: Assisting baryogenesis from the dark

T. Biekötter,[a] J. M. Cano,[b,c] S. Gori,[d] K. Mimasu,[e] J. M. No[b,c]

[a] Institute for Theoretical Physics, Karlsruhe Institute of Technology, Wolfgang-Gaede-Str. 1, 76131 Karlsruhe, Germany
[b] Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco, E-28049, Madrid, Spain
[c] Instituto de Física Teórica IFT-UAM/CSIC, Cantoblanco, E-28049, Madrid, Spain
[d] UCSD
[e] KCL

E-mail: thomas.biekoetter@kit.edu, josem.cano@uam.es, sgori@ucsc.edu, ken.mimasu@kcl.ac.uk, josemiguel.no@uam.es

Abstract: Electric dipole moments yield very strong constraints on the existence of beyond the SM sources of CP violation that could catalyze baryogenesis. We explore the possibility that CP violation needed for baryogenesis is active in the early Universe but is suppressed now. We consider that CP violation is caused by the interactions between a dark sector and the Higgs sector of the SM, and the multi-scalar dynamics in the early Universe yields

Explicit realization II: 2HDM + S (with "dark" Z_2 symmetry)

Biekotter, Cano, Gori, Mimasu, JMN, 24xx.xxxxx

Explicit CPV, secluded in dark sector

$$V(H_1,H_2,S) = \mu_1^2\,|H_1|^2 + \mu_2^2\,|H_2|^2 - \left[\mu_{12}^2 H_1^\dagger H_2 + \text{h.c.}\right] + \frac{\lambda_1}{2}\,|H_1|^4 + \frac{\lambda_2}{2}\,|H_2|^4$$
$$+ \lambda_3\,|H_1|^2\,|H_2|^2 + \lambda_4\,\left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5\left(H_1^\dagger H_2\right)^2 + \text{h.c.}\right]$$
$$+ \frac{\mu_S^2}{2}\,S^2 + \frac{\lambda_S}{4}S^4 + \lambda_{S_1}S^2\,|H_1|^2 + \lambda_{S_2}S^2\,|H_2|^2 + \frac{1}{2}\left[\lambda_{S_3}S^2 H_1^\dagger H_2 + \text{h.c.}\right]$$

Extra EDM suppression (3-loop)

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Assisting baryogenesis from the dark

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E-mail: thomas.biekoetter@kit.edu, josem.cano@uam.es, sgori@ucsc.edu, ken.mimasu@kcl.ac.uk, josemiguel.no@uam.es

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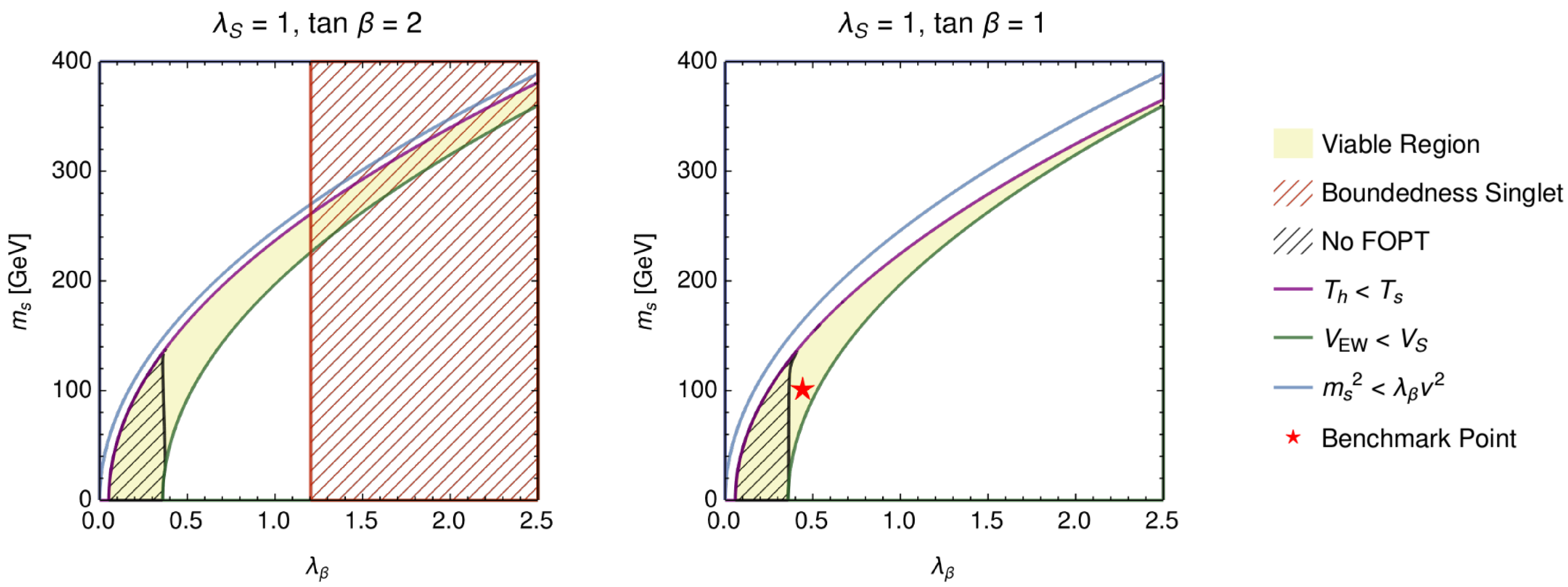
Transient CPV provides CPV link to visible sector

Explicit realization II: 2HDM + S (with "dark" Z_2 symmetry)

Biekotter, Cano, Gori, Mimasu, JMN, 24xx.xxxxx

Parameter regions of transient CPV *similar to Realization I ...*



(Again) successful transient CPV needs light singlet

Explicit realization II: 2HDM + S (with "dark" Z_2 symmetry)

Biekotter, Cano, Gori, Mimasu, JMN, 24xx.xxxxx

For $m_{A_0}, m_{H_0} > 2\,m_S$ phenomenology as 2HDM with **extra invisible decays** of both BSM neutral scalars!

Explicit realization II: 2HDM + S (with "dark" Z_2 symmetry)

Biekotter, Cano, Gori, Mimasu, JMN, 24xx.xxxxx

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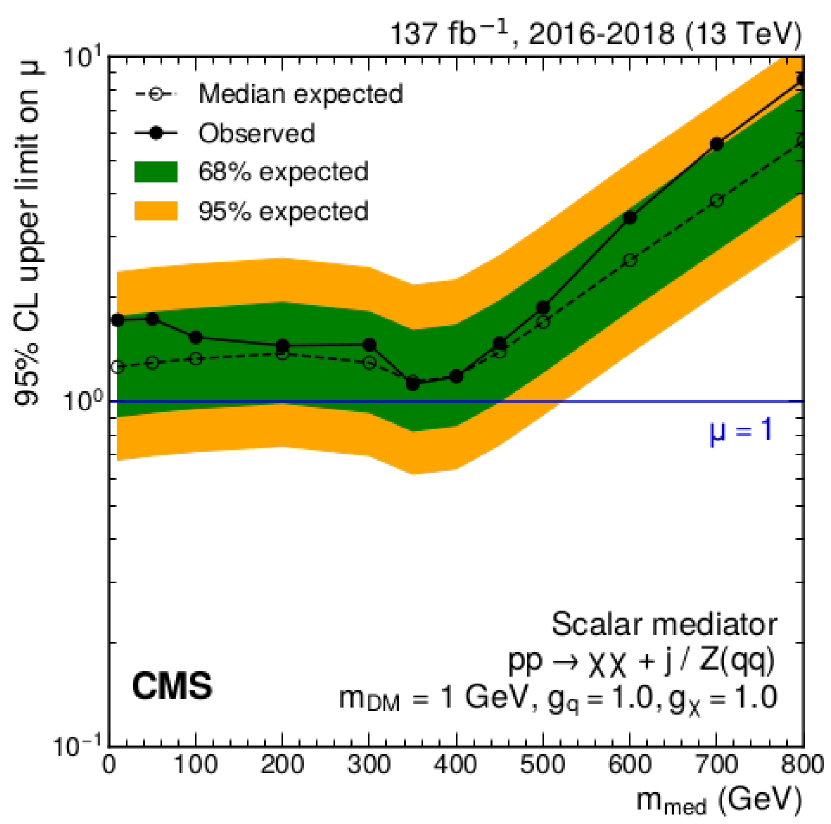
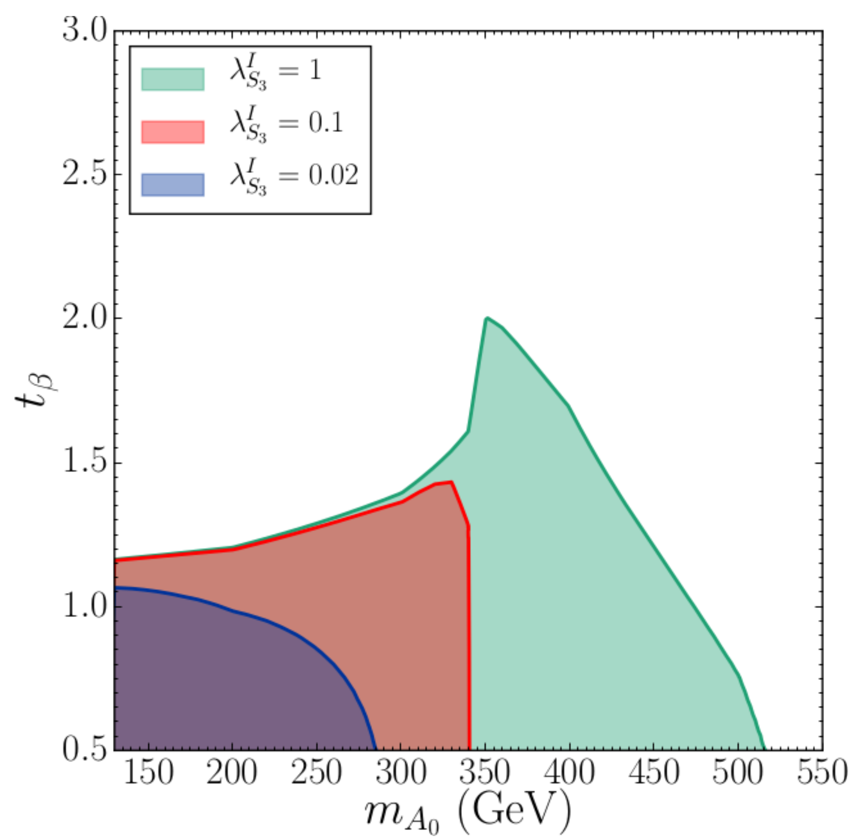
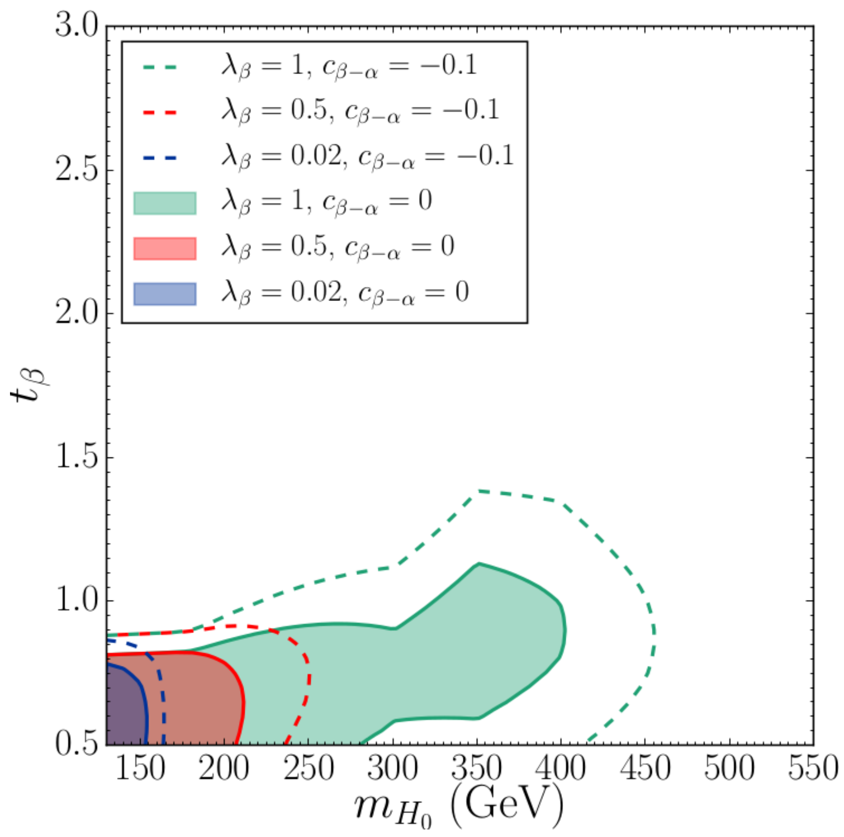
Bounds on invisible decays of BSM scalars constrained by LHC DM searches:
Reinterpretation of simplified DM models with scalar/pseudoscalar mediator

e. g. **Mono-Jet** **CMS-EXO-20-004**







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- Transient (early Universe) breaking of SM symmetries to solve SM problems?

- Transient **CPV** *circunvents EDM constraints*, allows for **EWBG**

… needs light d.o.f. (& coupled to Higgs)

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Cascade scalar decays @LHC

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▷ Realization II: Invisible decays of BSM neutral (2HDM) scalars

Biekotter, Cano, Gori, Mimasu, JMN, 24XX.XXXXX]

DM-like signatures
(Mono-X)

EW baryogenesis is alive and testable!

"Michael J. Ramsey-Musolf"

Thank you!

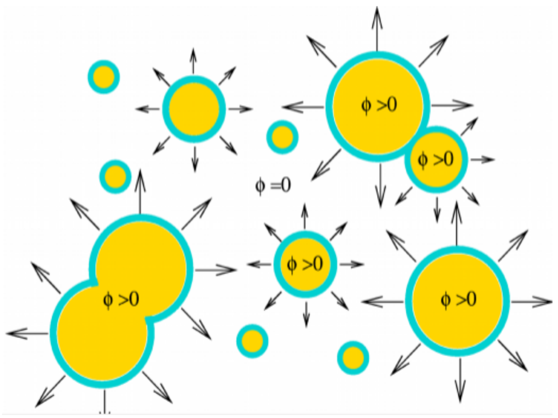

KEEP
CALM
AND
BACKUP
YOUR
WORK

Subtlety regarding CPV & EWBG

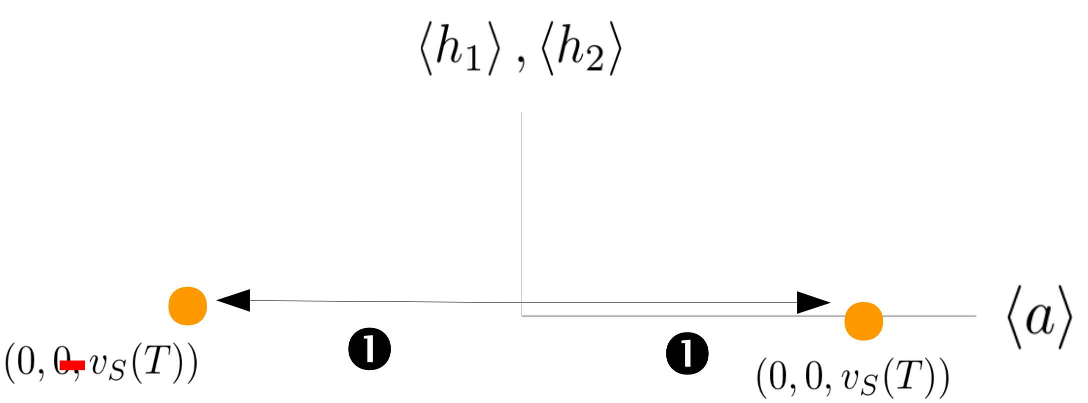
▷ "Local" vs "Global" EWBG:

Baryon density generated in vicinity of Higgs bubble walls

Average Baryon density per Hubble volume



What's the problem?



Equivalent vacua (same energy)

But CPV phases from vacua will have opposite signs!

"Global" Baryon density = 0

Subtlety regarding CPV & EWBG

▷ "Local" vs "Global" EWBG:

Baryon density generated in vicinity of Higgs bubble walls

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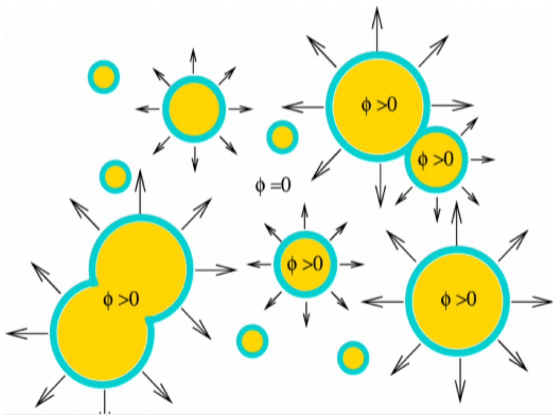

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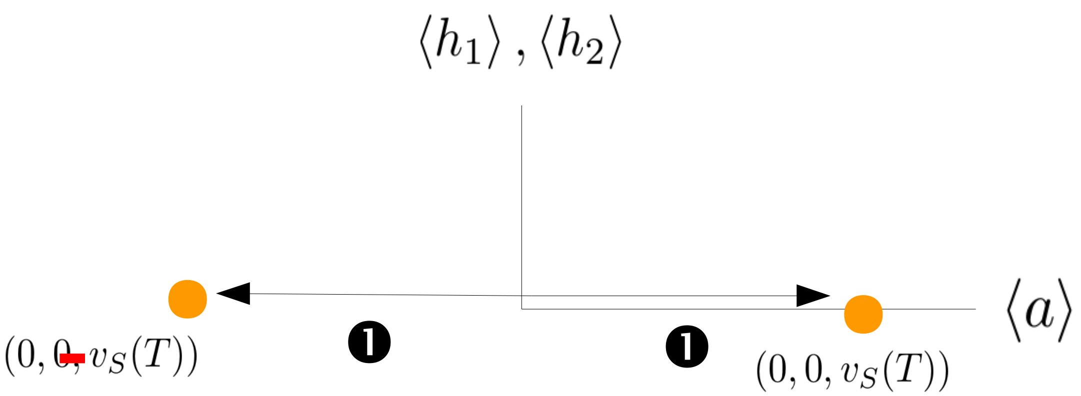


Biased vacua $(\mu_3/3)a^3$

$$\Delta V = \frac{\mu_3(\mu_3^2 + \lambda_a \mu_a^2)\sqrt{\mu_3^2 + 4\lambda_a \mu_a^2}}{6\lambda_a^3}$$

Need Explicit CPV

Albeit Tiny!

$$\Delta V / T^4 \gg 10^{-16}$$

McDonald, PLB 323 (1994), 339

Transient CPV: Requirements (I)

$$V_a = \frac{\mu_a^2}{2}\,a^2 + \frac{\lambda_a}{4}a^4 + \left(i\,\kappa\,a\,H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1}\,a^2\,|H_1|^2 + \lambda_{aH_2}\,a^2\,|H_2|^2$$

T = 0

- $\mu_a^2 < 0$ (needed for $\langle a \rangle \neq 0$ at T > 0)

- $\mu_a^2 + \left(\lambda_{aH_1}\,v_1^2 + \lambda_{aH_2}\,v_2^2\right) > 0$ (yields $\langle a \rangle = 0$ at T = 0)

$$v_{1,2} = \sqrt{2}\,\langle H_{1,2} \rangle$$

- EW vacuum deepest minimum at T = 0

Transient CPV: Requirements (II)

(2HDM + thermal history)

$$V_a = \frac{\mu_a^2}{2}\,a^2 + \frac{\lambda_a}{4}a^4 + \left(i\,\kappa\,a\,H_1^\dagger H_2 + \text{h.c.}\right) + \lambda_{aH_1}\,a^2\,|H_1|^2 + \lambda_{aH_2}\,a^2\,|H_2|^2$$

T > 0

We add thermal $\mathcal{O}(T^2)$ corrections to scalar potential:

$$V_T = \frac{T^2}{24}\sum_b n_b\,M_b^2 + \frac{T^2}{48}\sum_f n_f\,M_f^2$$

Background-field dependent massses

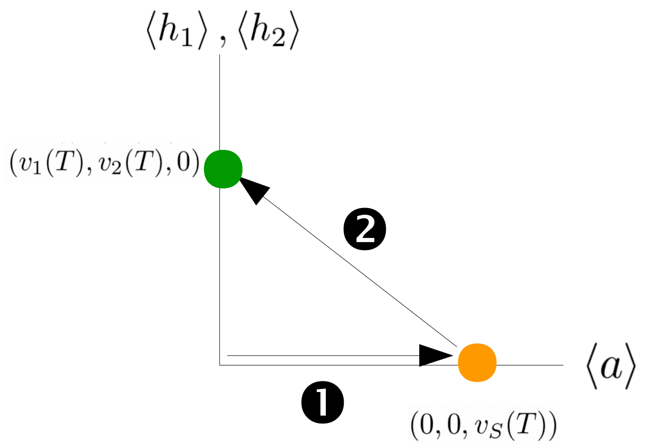
▷ CP breaking ($\langle a \rangle \neq 0$) @ T_S

$$T_S^2 \;=\; 12\,|\mu_a^2|\,/(4\,\lambda_{aH_1} + 4\,\lambda_{aH_2} + 3\,\lambda_a)$$

▷ EW breaking @ T_h

$$T_h^2 \;\simeq\; 6\,m_h^2\,v^2/\left(5m_h^2 + \lambda_\beta\,v^2 + 6m_W^2 + 3m_Z^2 + 6m_t^2\right)$$

$$T_S > T_h$$



(Two Higgs doublets + singlet pseudoscalar) $V = V_{2\mathrm{HDM}} + V_a$

$$V_a = \frac{\mu_a^2}{2}\, a^2 + \frac{\lambda_a}{4} a^4 + \left(i\,\kappa\, a\, H_1^\dagger H_2 + \mathrm{h.c.}\right) + \lambda_{aH_1}\, a^2\, |H_1|^2 + \lambda_{aH_2}\, a^2\, |H_2|^2$$

$$V_{2\mathrm{HDM}} = \mu_1^2\, |H_1|^2 + \mu_2^2\, |H_2|^2 - \left[\mu_{12}^2\, H_1^\dagger H_2 + \mathrm{h.c.}\right] + \frac{\lambda_1}{2}\, |H_1|^4 + \frac{\lambda_2}{2}\, |H_2|^4 + \lambda_3\, |H_1|^2\, |H_2|^2 + \lambda_4 \left|H_1^\dagger H_2\right|^2 + \frac{1}{2}\left[\lambda_5 \left(H_1^\dagger H_2\right)^2 + \mathrm{h.c.}\right]$$

$$\ldots\ + m_\chi\, \bar{\chi}\chi + g_\chi\ a\ \bar{\chi} i \gamma^5 \chi$$

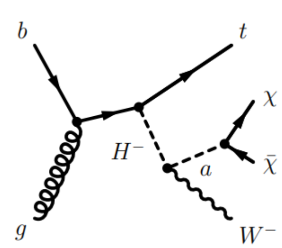
Pseudoscalar portal to DM

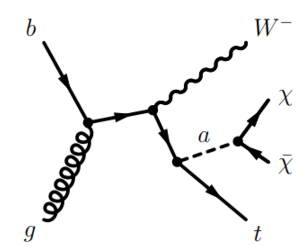
Ipek, McKeen, Nelson, PRD 90 (2014), 055021
JMN, PRD 93 (2016), 031701
Goncalves, Machado, JMN, PRD 95 (2017), 055027
Bauer, Haisch, Kahlhoefer, JHEP 05 (2017), 138
Robens, Symmetry 12 (2021) 12, 2341

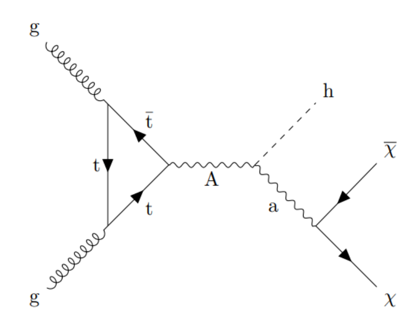
[LHC DM WG Benchmark]

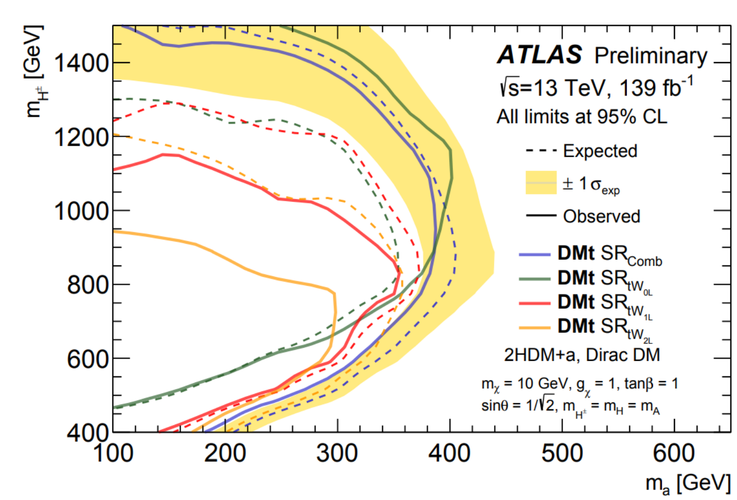
Abe et al, Phys. Dark. Univ. 27 (2020), 100351

e.g.

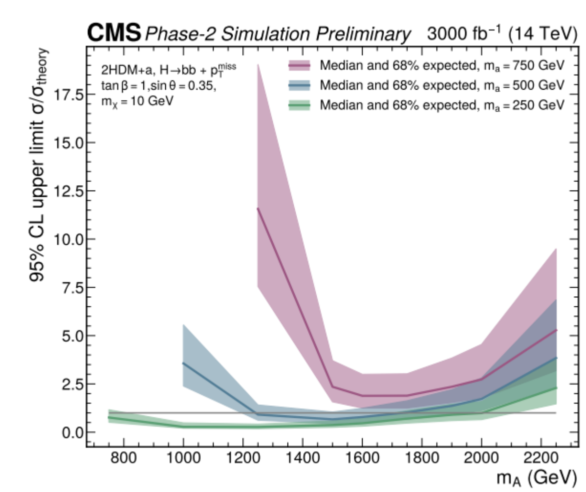








ATLAS-CONF-22-012



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