Instituto de Física Teórica UAM-CSIC

UNIVERSIDAD AUTONOMA DE MADRID

Extended Higgs Sectors & Baryogenesis

Based on S. J. Huber, K. Mimasu, JMN, PRD 107 (2023) 075042 ***(2208.10512)***

+ J. M. Cano, S. Gori, K. Mimasu, JMN *(23xx.xxxxx)*

Jose Miguel No

IFT-UAM/CSIC, Madrid

EXCELENCIA SEVERO OCHOA

Origin of Matter-Antimatter Asymmetry

(Baryogenesis)

Sakharov Conditions

(for dynamical generation of baryon asymmetry)

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

Origin of Matter-Antimatter Asymmetry

In the SM?

<u>Sakharov Conditions</u> (*for dynamical generation of baryon asymmetry*)

- B Violation ✔ (Sphalerons) (non-perturbative, high-temperature)
- C/CP Violation ✘ not enough
  *Gavela, Hernandez, Orloff, Pene, Quimbay, Nucl. Phys. B **430** (1994) 382*
- Departure from Thermal Equilibrium ✘ not enough
  *Kajantie, Laine, Rummukainen, Shaposhnikov, Phys. Rev. Lett. **77** (1996) 2887*

Origin of Matter-Antimatter Asymmetry

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

- B Violation ✔ (Sphalerons) (non-perturbative, high-temperature)

In the SM?

- C/CP Violation ✘ not enough*

*SM CP Violation insufficient by ~ 10 orders of magnitude

via 3-family fermion mixing (CKM matrix)

Origin of Matter-Antimatter Asymmetry

In the SM?

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*The EW Phase Transition in SM is smooth, no out-of-equilibrium (crossover)

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Higgs Evolution in Early Universe ➔

Finite-Temperature Effective Potential

$$V_{\rm eff}(h,T) = V_0(h) + V_0^{\rm loop}(h) + V_T(h,T)$$

Tree-level potential | Loop corrections | Thermal corrections

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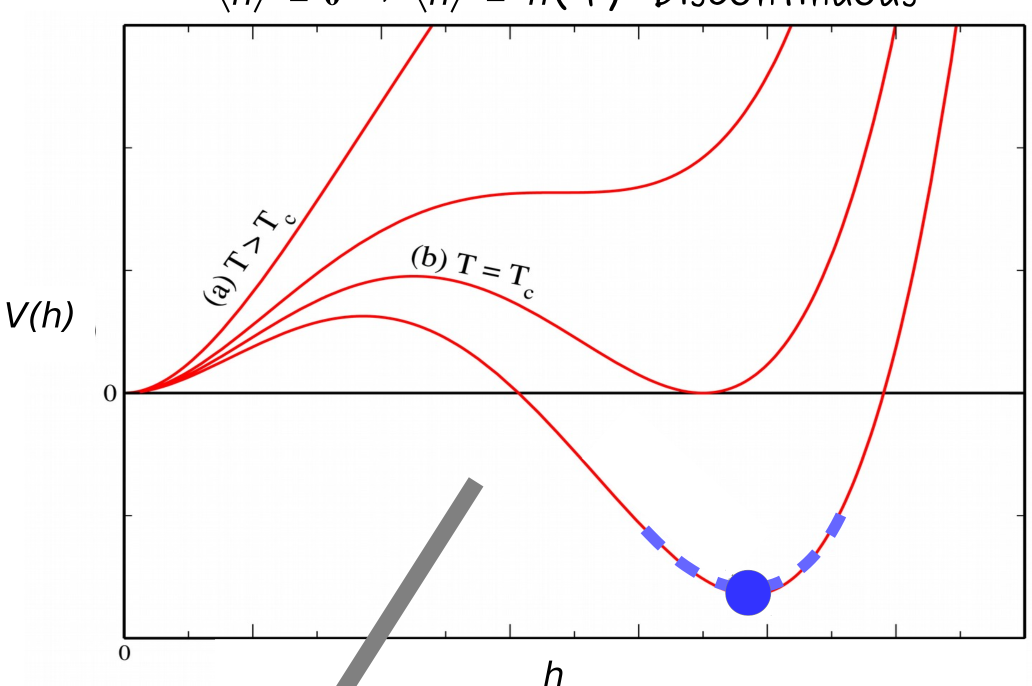
(Perturbative) **Nature of EW Phase Transition**

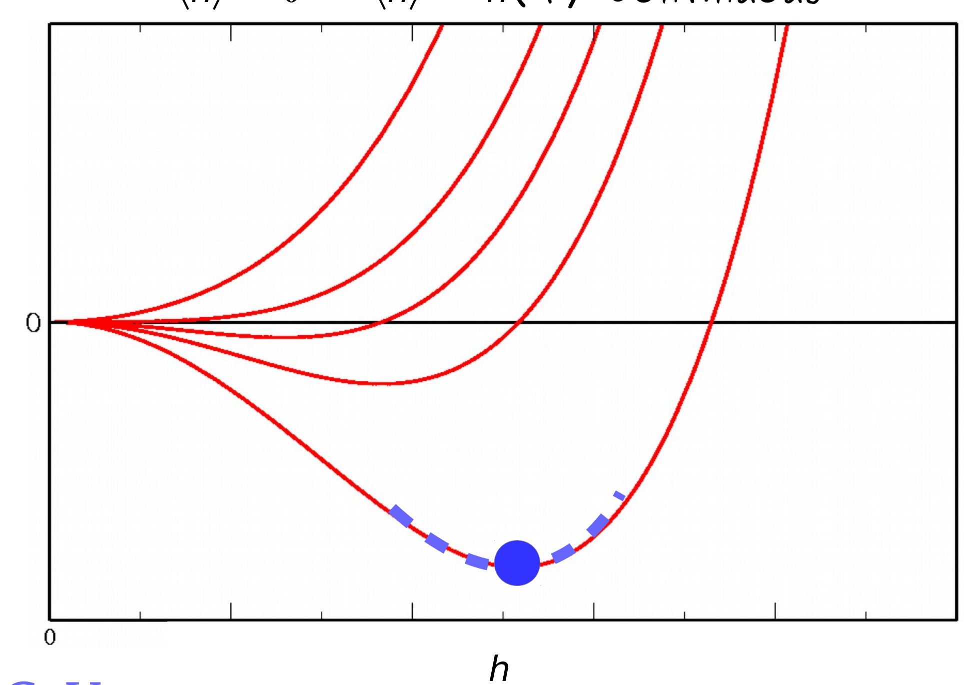
1st Order:

$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Discontinuous



2nd Order:

$\langle h \rangle = 0 \rightarrow \langle h \rangle = h(T)$ Continuous



v = 246 GeV
m_h = 125 GeV

Out-of-equilibrium

(*The EW Phase Transition in SM is smooth, no out-of-equilibrium)

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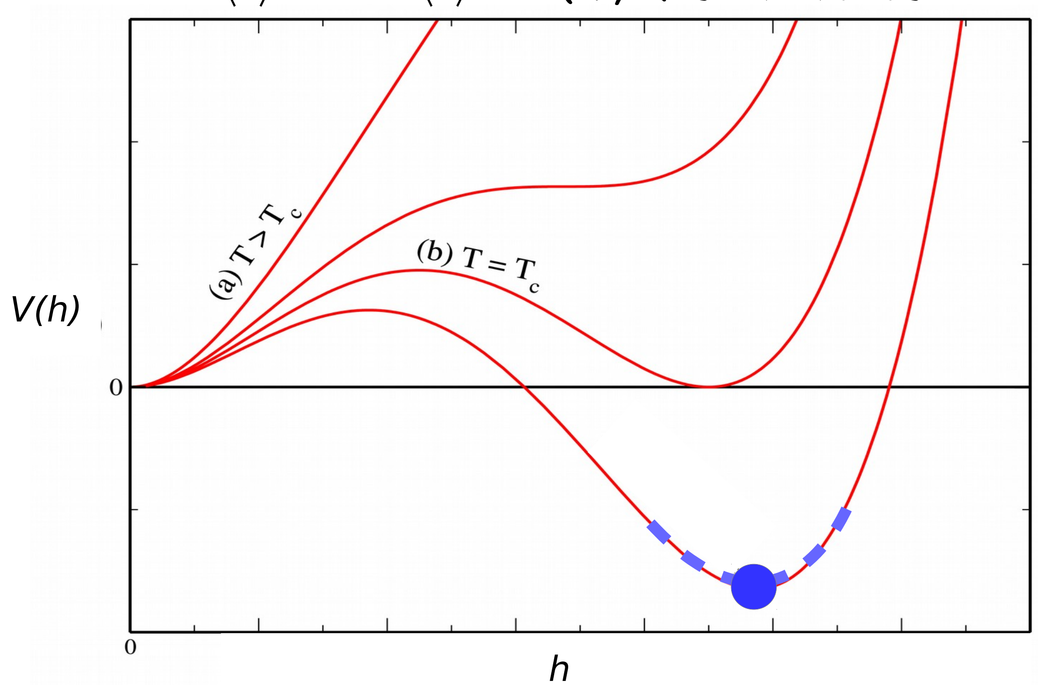

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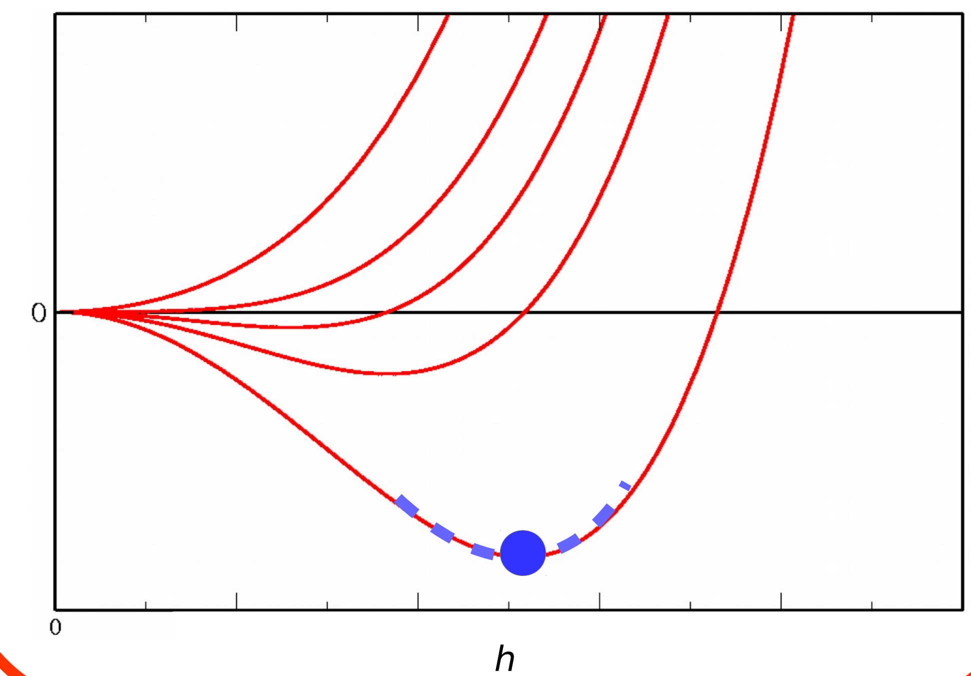

In the SM...

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Higgs Evolution in Early Universe → Finite-Temperature Effective Potential

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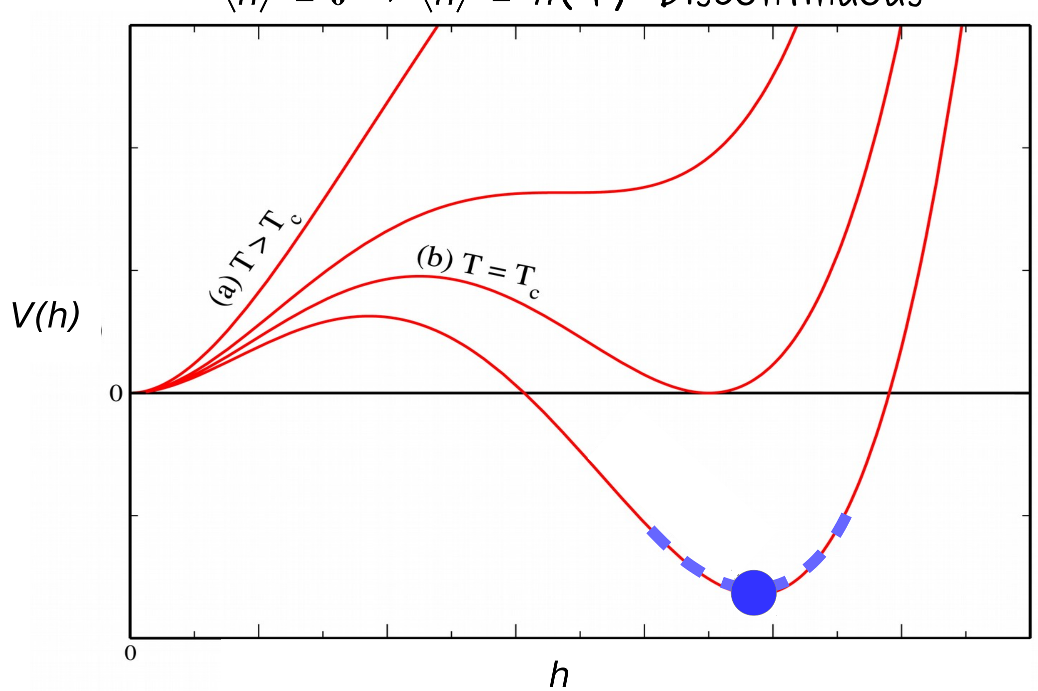
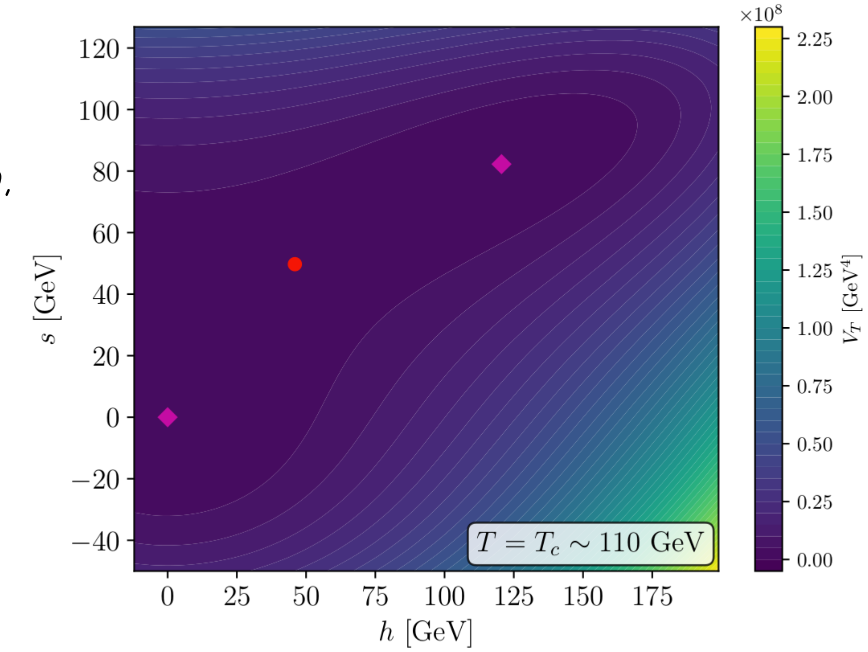


BSM can induce 1st Order Phase Transition

Non-Minimal Higgs sectors can yield 1st order EW phase transition

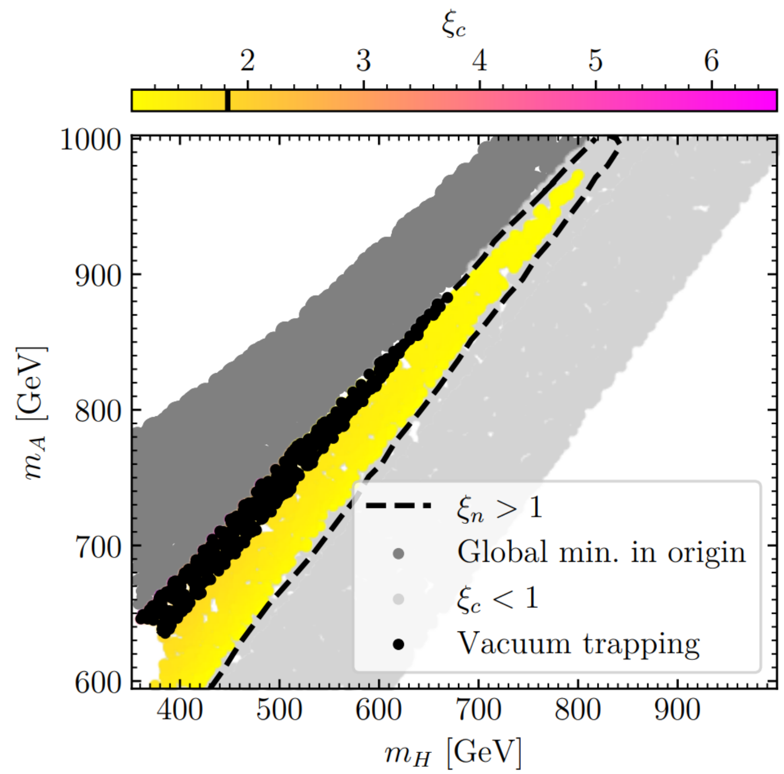
(multi-scalar dynamics in early Universe)

e.g. **Higgs + singlet** (Espinosa, Quiros 93, Choi, Volkas 93, Profumo, Ramsey-Musolf, Shaughnessy 07, Noble, Perelstein 07, Espinosa, Konstandin, No, Quiros 08, Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy 09, Ashoorioon, Konstandin 09, Espinosa, Konstandin, Riva 11, Barger, Chung, Long, Wang 12, Fairbairn, Hogan 13, Katz, Perelstein 14, Profumo, Ramsey-Musolf, Wainwright, Winslow 14... + many more recently!)



Fernández-Martínez, López-Pavón, JMN, Ota, Rosauro-Alcaraz, 2210.16279

e.g. **2HDM** (Turok, Zadrozny 92, Cline, Lemieux 97, Froome, Huber, Seniuch 06, Cline, Kainulainen, Trott 11, Dorsch, Huber, No 13, Dorsch, Huber, Mimasu, No 14, Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka 16, Dorsch, Huber, Mimasu, No 17, Bernon, Bian, Jiang 17... + many more recently!)



Biekotter, Heinemeyer, JMN, Olea, Weiglein, JCAP 03 (2023), 031

What about CPV? (*SM CP Violation insufficient)

Non-Minimal Higgs sectors can yield BSM CP Violation 
(complex parameters)

e.g. Two-Higgs-Doublet-Model

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

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

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(complex parameters)

BSM CP Violation (very) strongly constrained by electric dipole moments!
(EDM experimental searches)

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

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

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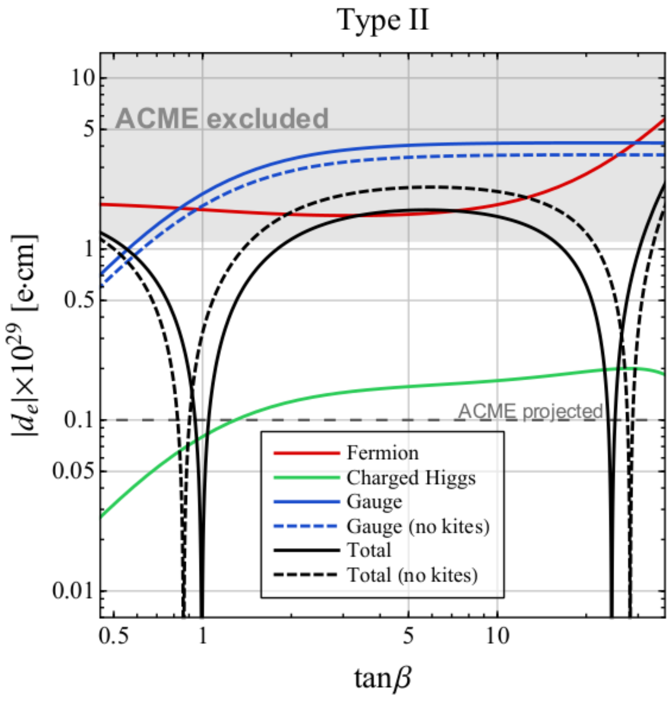
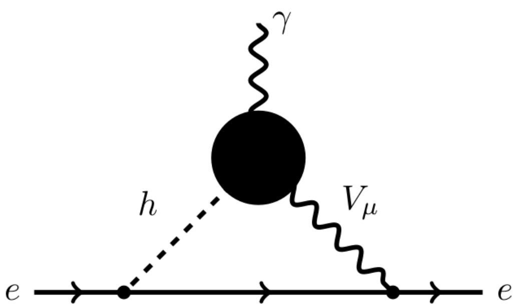


*Altmannshofer, Gori, Hamer, Patel, Phys. Rev. D **102** (2020) 115042*



Two-loop "Barr-Zee" electron EDM contribution

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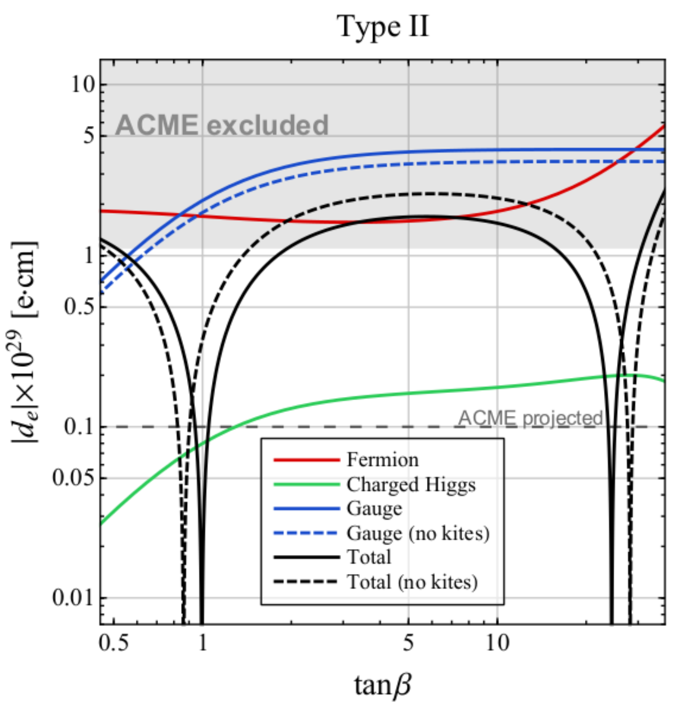

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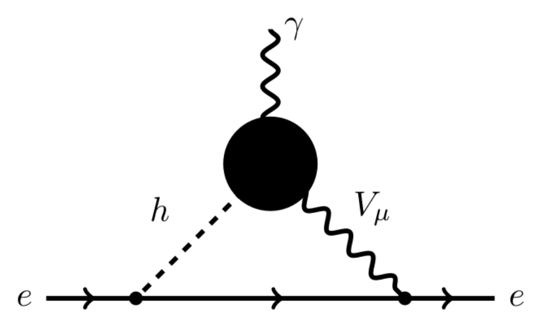

Two-loop "Barr-Zee" electron EDM contribution

CPV: biggest challenge for successful EW Baryogenesis

Can Higgs sector help circunvent EDM Constraints?

Non-Minimal Higgs sector inducing
CP Violation in early Universe?

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Non-Minimal Higgs sector inducing CP Violation in early Universe?

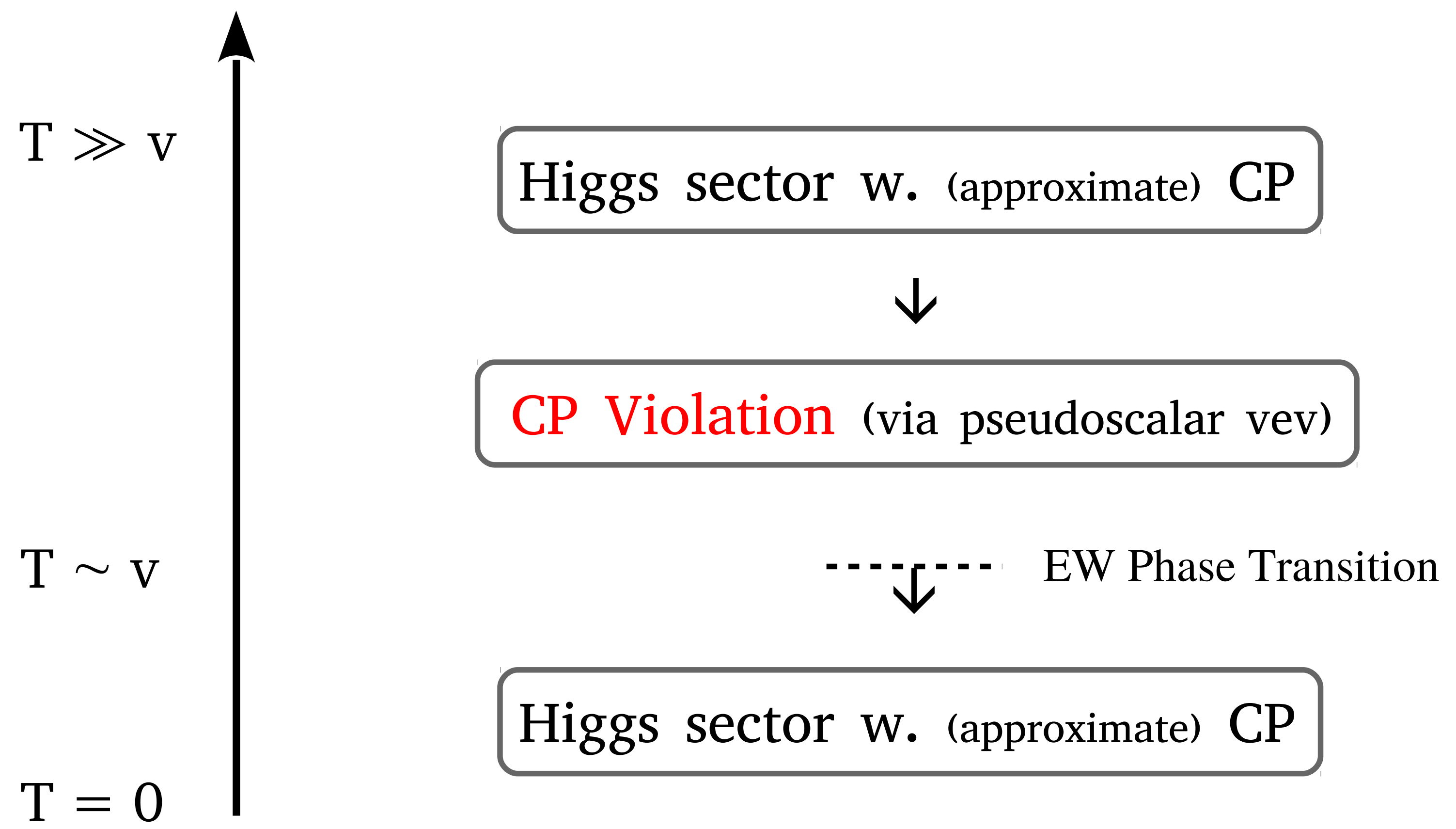
THE talk

[courtesy of Wikipedia]

Finally!

Can Higgs sector help circunvent EDM Constraints?

Non-Minimal Higgs sector inducing
CP Violation in early Universe?



Explicit realization: 2HDM + a

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

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

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

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

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

Higgs boson coupling to light pseudoscalar: $\lambda_\beta \equiv (\lambda_{aH_1} + \lambda_{aH_2}\, t_\beta^2)/(1 + t_\beta^2)$

Simplifying parameter assumptions

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

$c_{\beta-\alpha} = 0$ (2HDM alignment limit)

2HDM + a CP Violation

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

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

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

If non-zero vev, CP Violation!

Possible to switch-on & switch-off $\langle a \rangle$ in early Universe

"Transient CPV"

2HDM + a CP Violation

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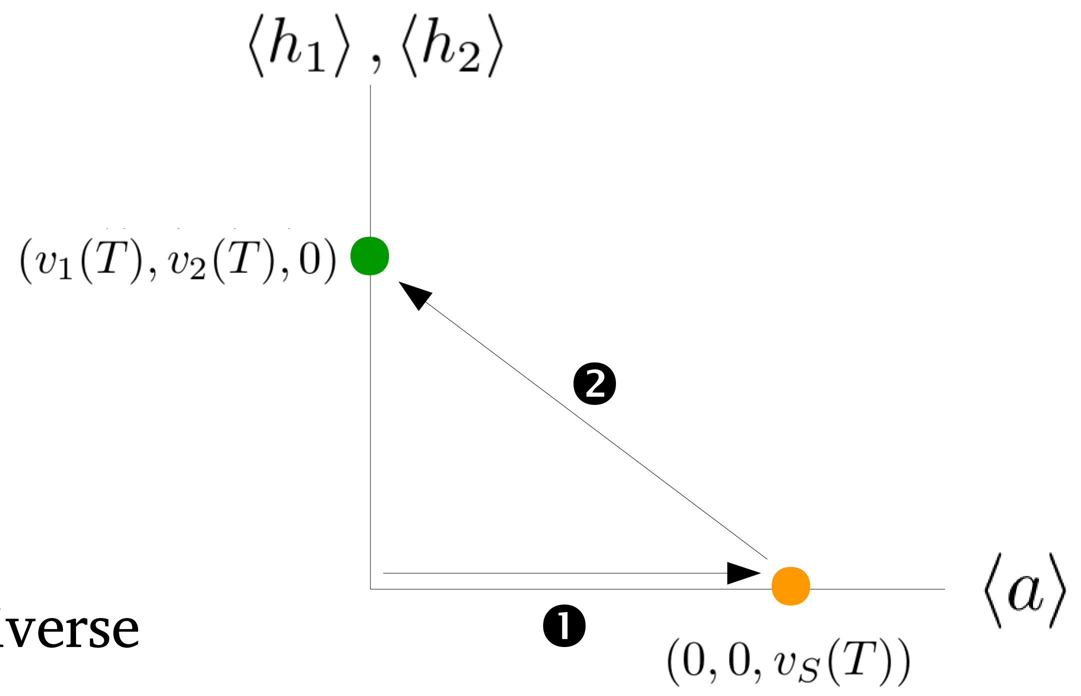

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Transient CPV:

Transient CPV: Requirements (I)

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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)

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

T > 0 (2HDM + a thermal history)

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

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

▷ EW breaking @ T_h

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

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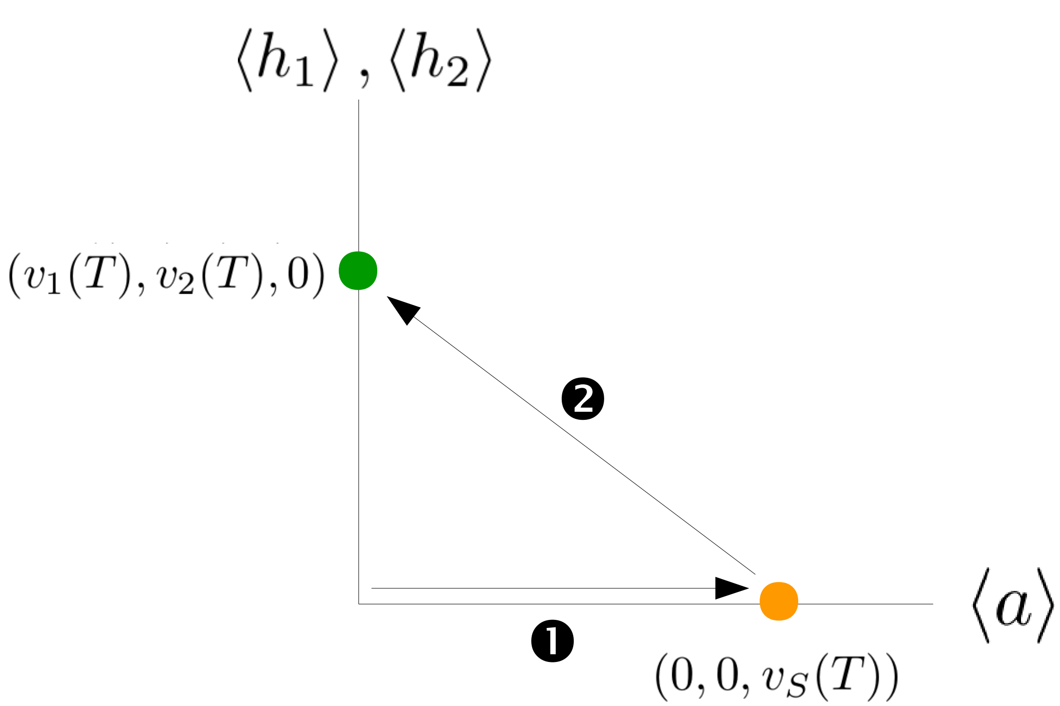
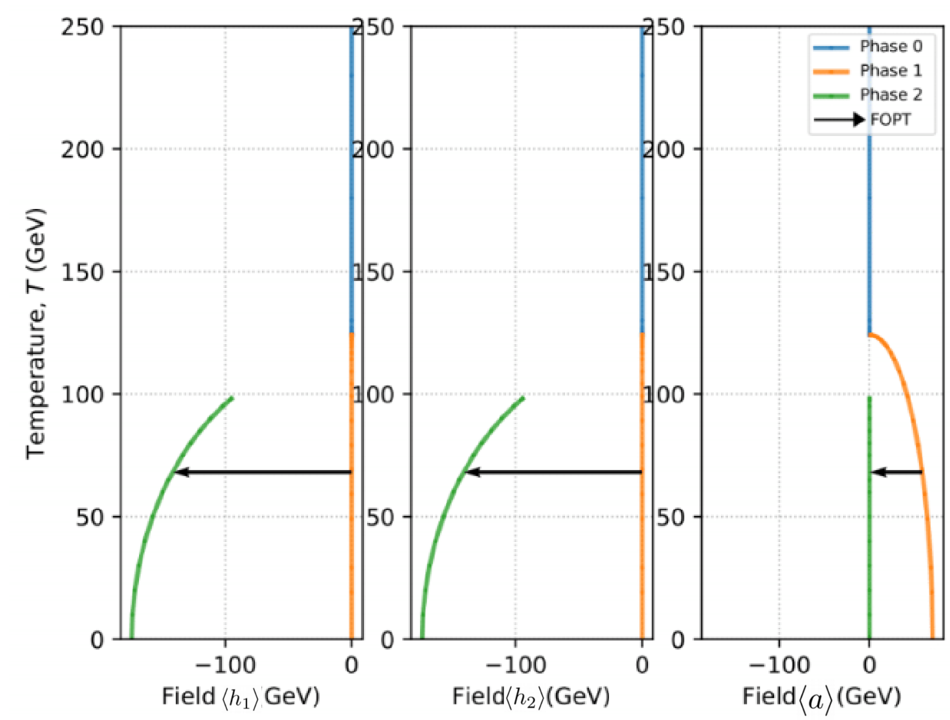
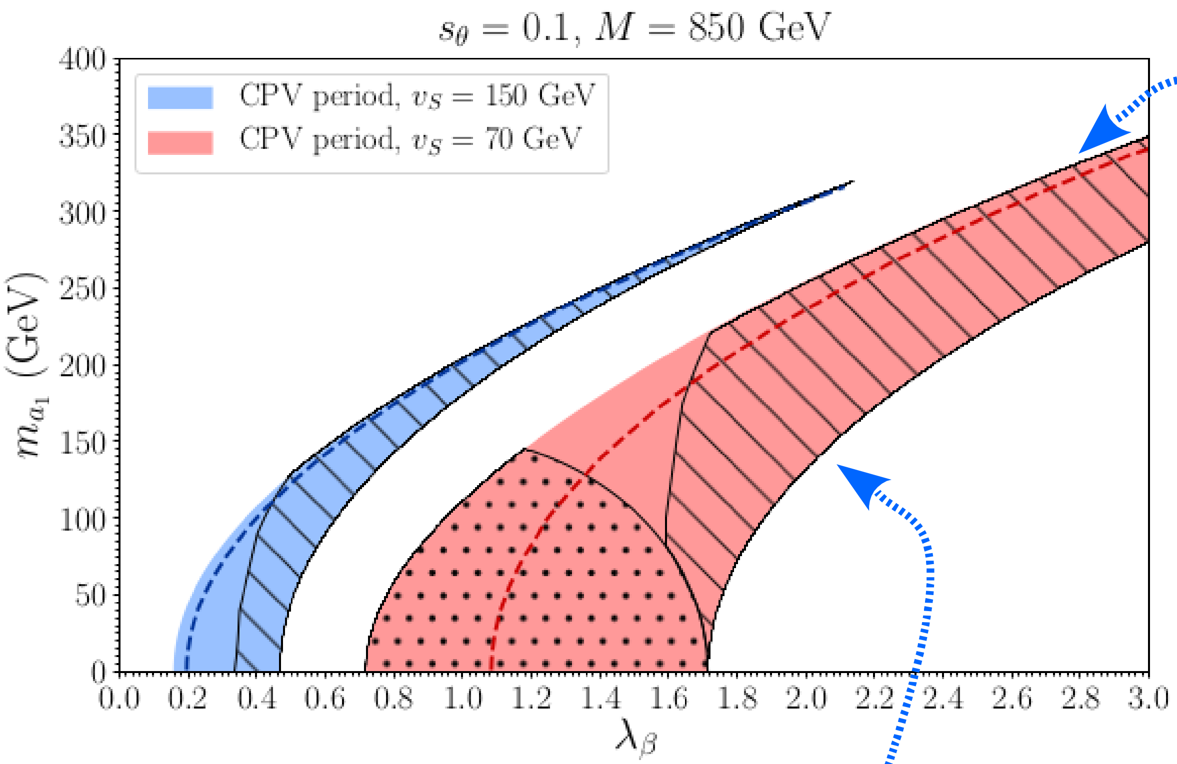
- $T_S > T_h$





[courtesy of Jose Manuel Cano]

Transient CPV: I + II



$T_S > T_h$

$$m^2_{a_1,\max} = \frac{1}{c_\theta^2 - s_\theta^2}\left[c_\theta^2\, v^2\, \lambda_\beta (1 - F) - s_\theta^2\, M^2\right]$$

$$F = \frac{(4\,\lambda_{aH_1} + 4\,\lambda_{aH_2} + 3\,\lambda_a)\, m_h^2}{2\,(5m_h^2 + \lambda_\beta v^2 + 6m_W^2 + 3m_Z^2 + 6m_t^2)}$$

EW vacuum deepest @ T = 0

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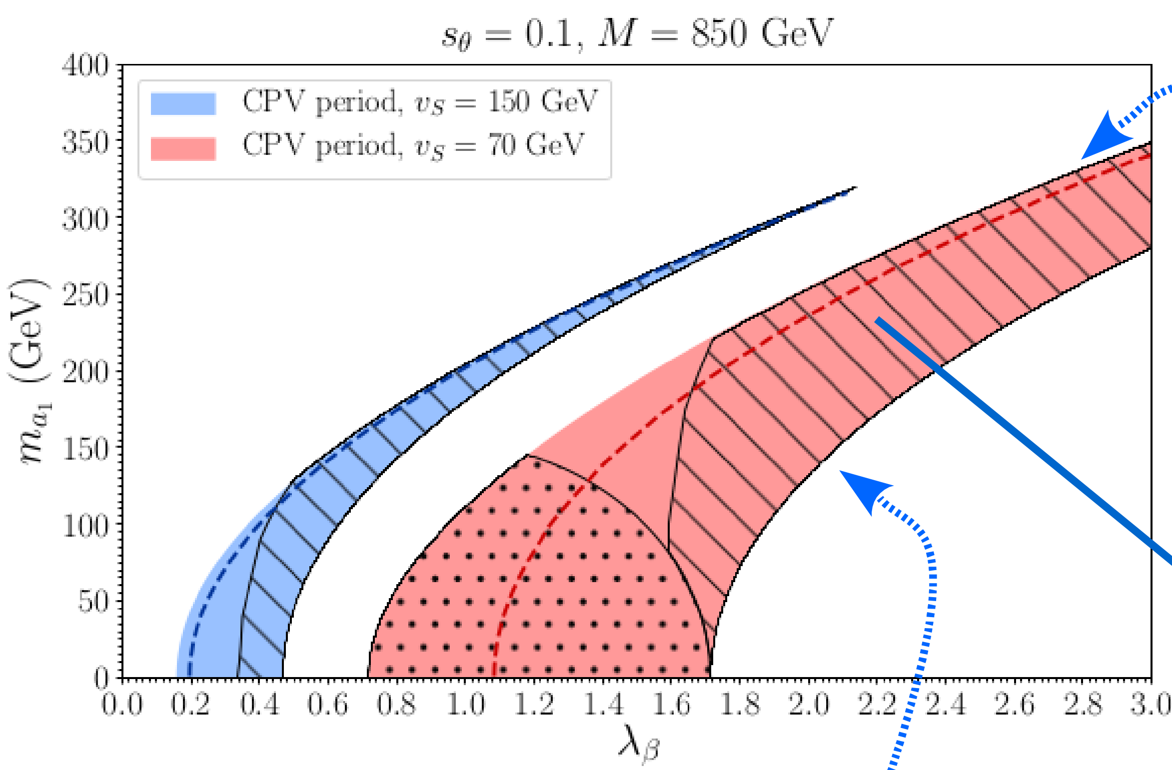

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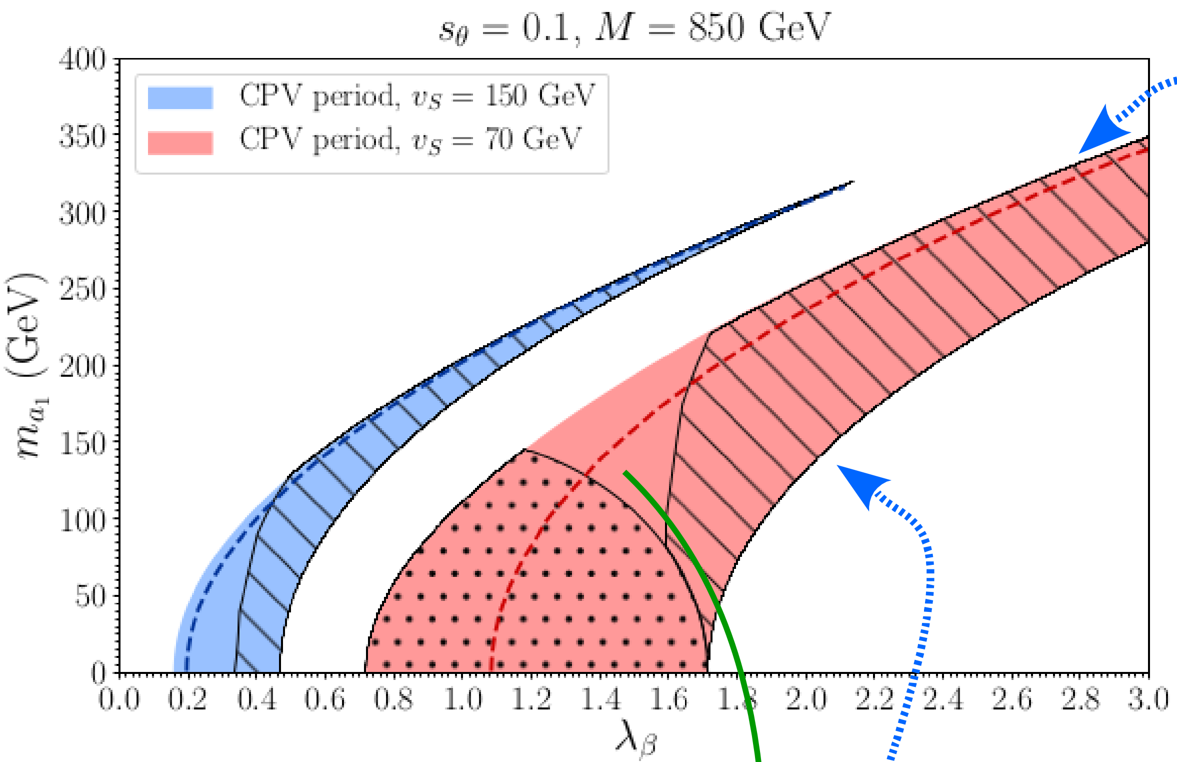
Universe trapped at $T = 0$ in CPV vacuum (unphysical!)

Transient CPV: I + II



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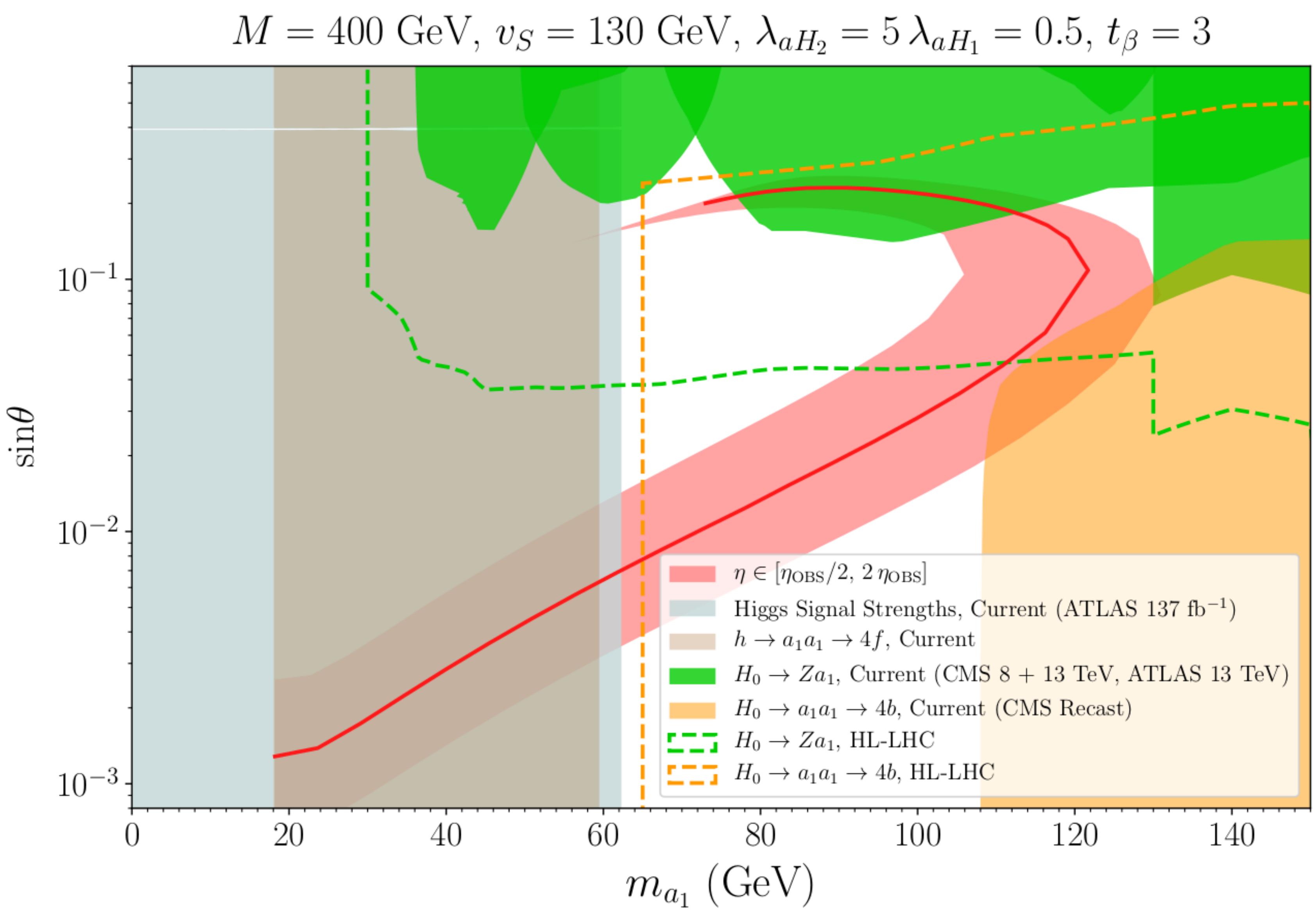
EW vacuum deepest @ T = 0

Successful transient CPV needs light singlet-like pseudoscalar

2HDM + a: **Baryogenesis** vs LHC



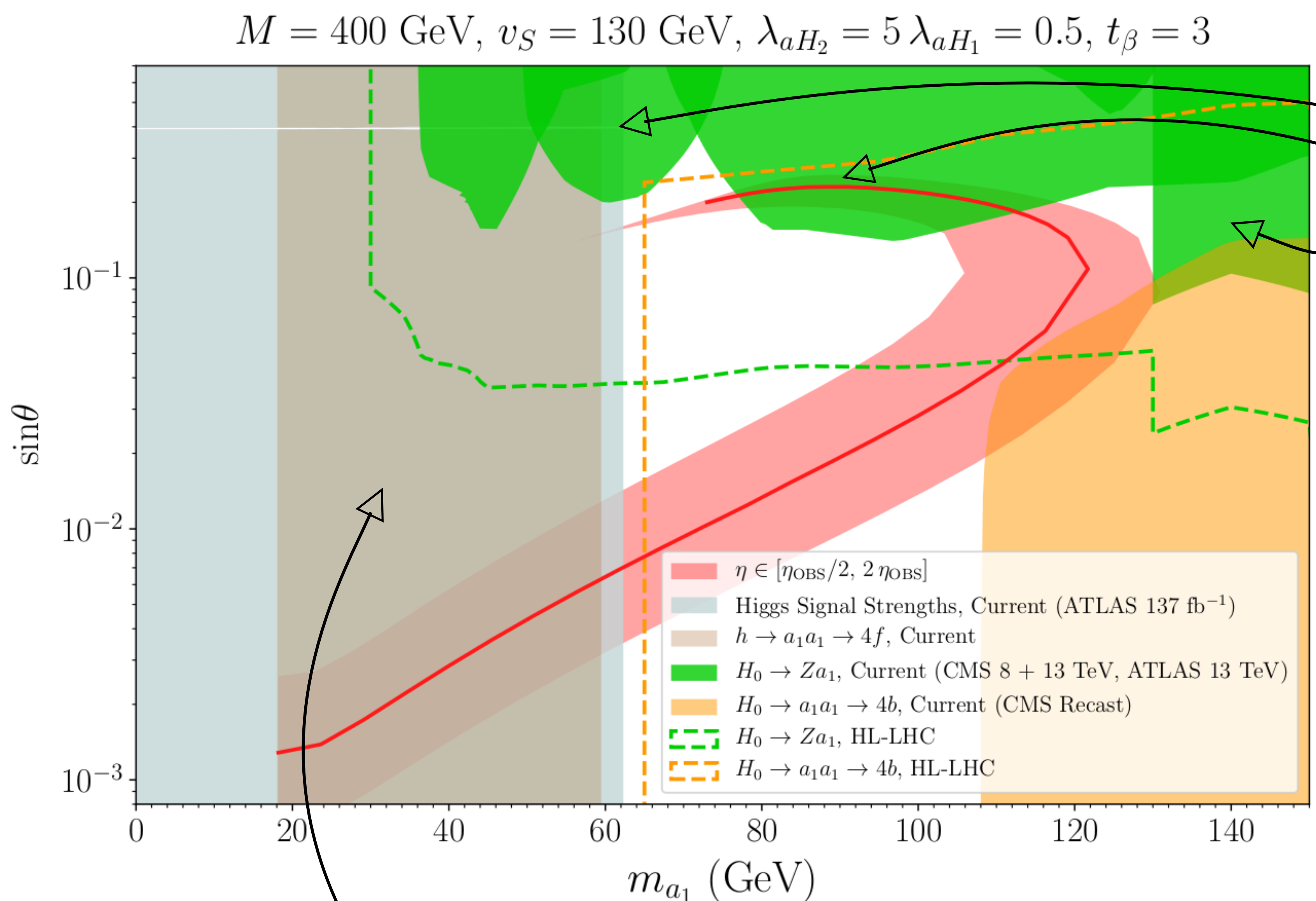
$$\eta \in [\eta_{\rm OBS}/2,\, 2\,\eta_{\rm OBS}]$$

$$\frac{\eta}{10^{-11}} \sim 6 \times 10^2\, \frac{\sin(\delta_{\rm t})\, \xi_{\rm c}^2}{L_W T_c}$$

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

Fromme, Huber, JHEP 03 (2007), 049

2HDM + a: Baryogenesis vs LHC



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

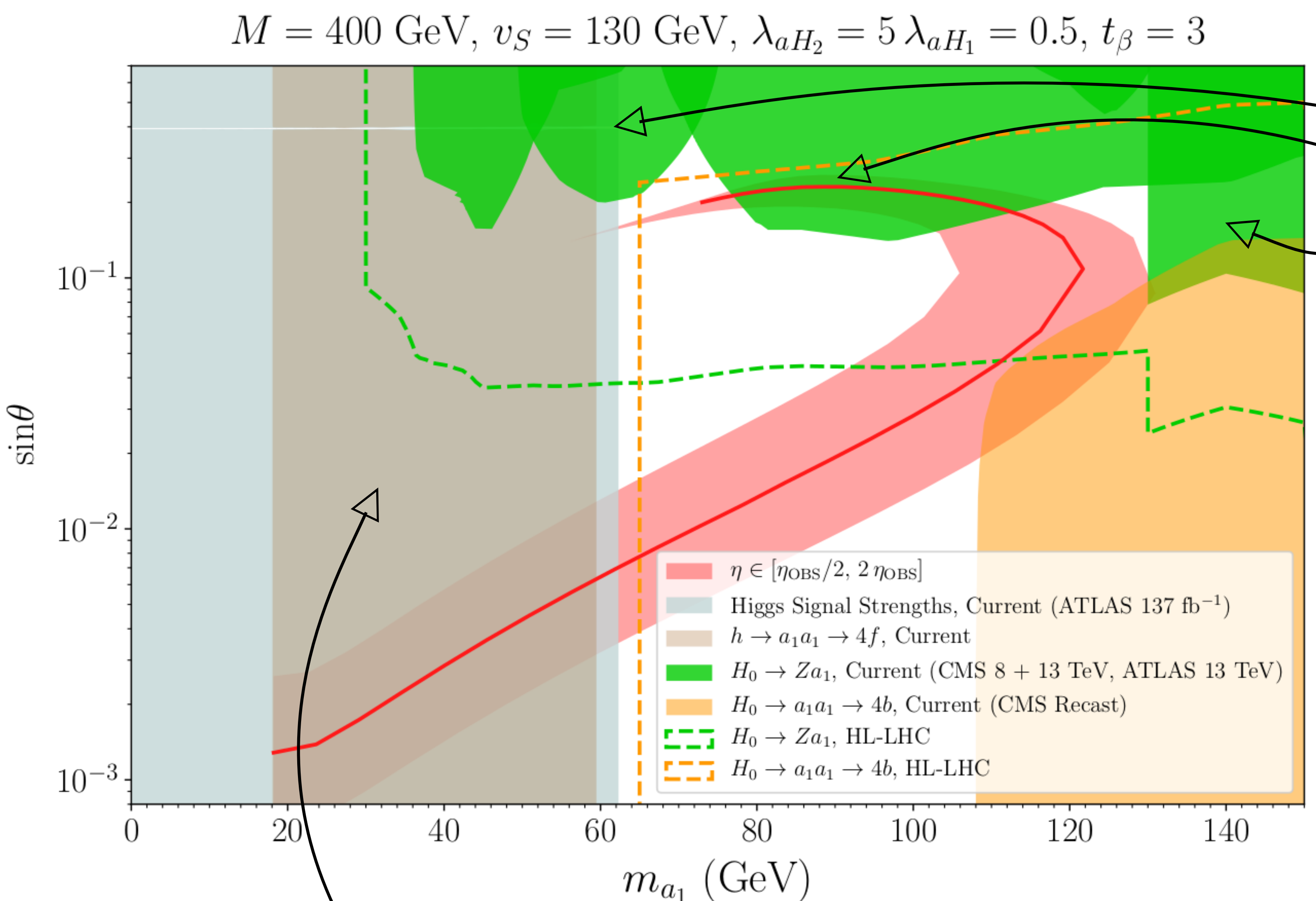
CMS, Phys. Lett. B 759 (2016), 369 (8 TeV)

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

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

RULED OUT
(LHC Higgs signal strengths)

2HDM + a: Baryogenesis vs **LHC**



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

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

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A → Z H / H → Z A searches were originally targeting baryogenesis in 2HDM!

*Dorsch, Huber, Mimasu, JMN, PRL **113** (2014) 211802*

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

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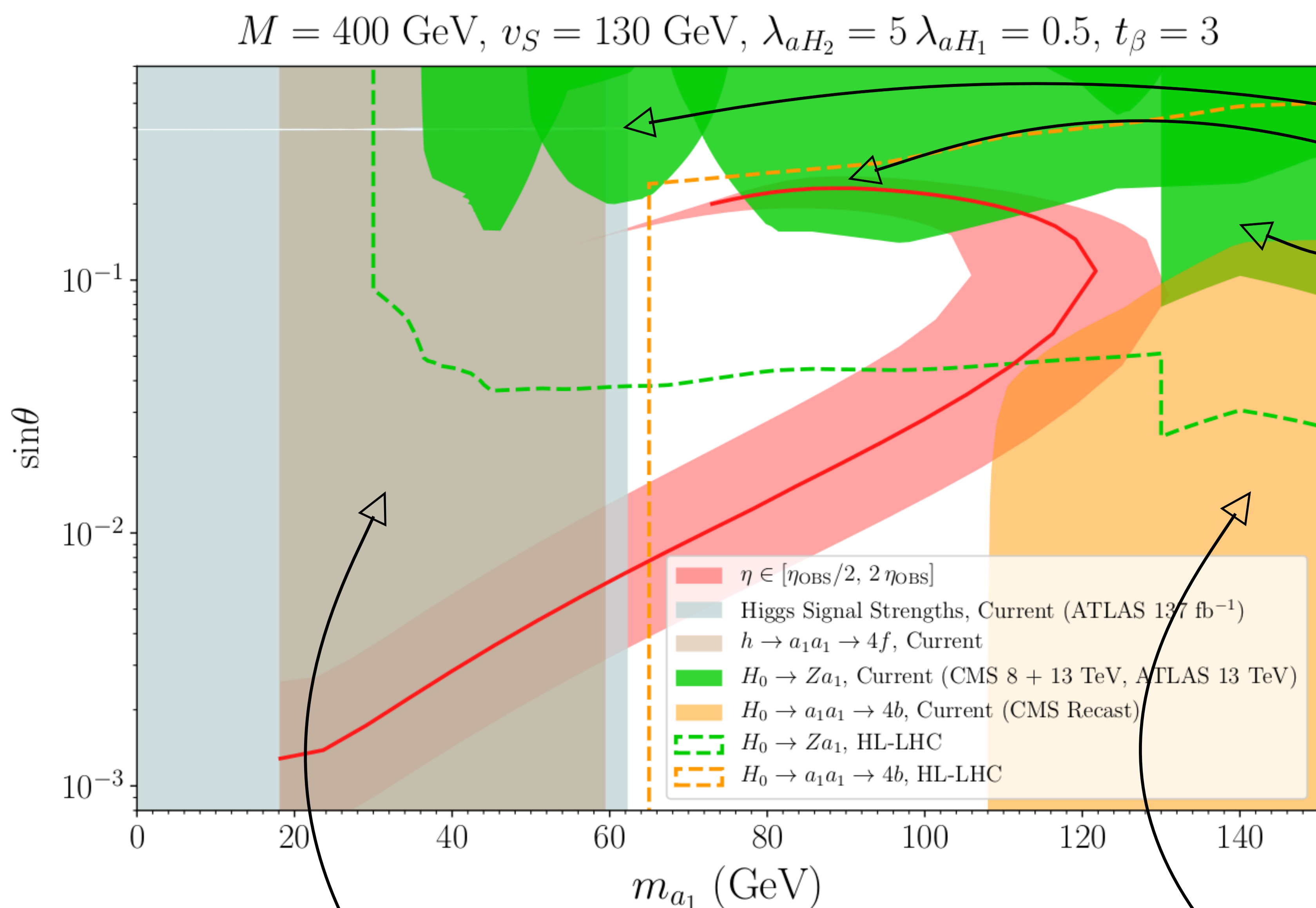

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CMS, JHEP 08 (2018), 152 (13 TeV)

Limits are recast of H → *hh* CMS search

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

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

Summary

▷ Early Universe "Transient" CPV: Baryogenesis & No EDM constraints

▷ "Transient" CPV requires light (~100 GeV) pseudoscalar* & coupled to 125 GeV Higgs boson (& rest of Higgs sector)...

Within LHC reach!

Cascade scalar decays @LHC

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

* [In this realization! Other realizations lead to other light states: **Cano, Gori, Mimasu, JMN, 23XX.XXXXX**]

STAY TUNED

Summary

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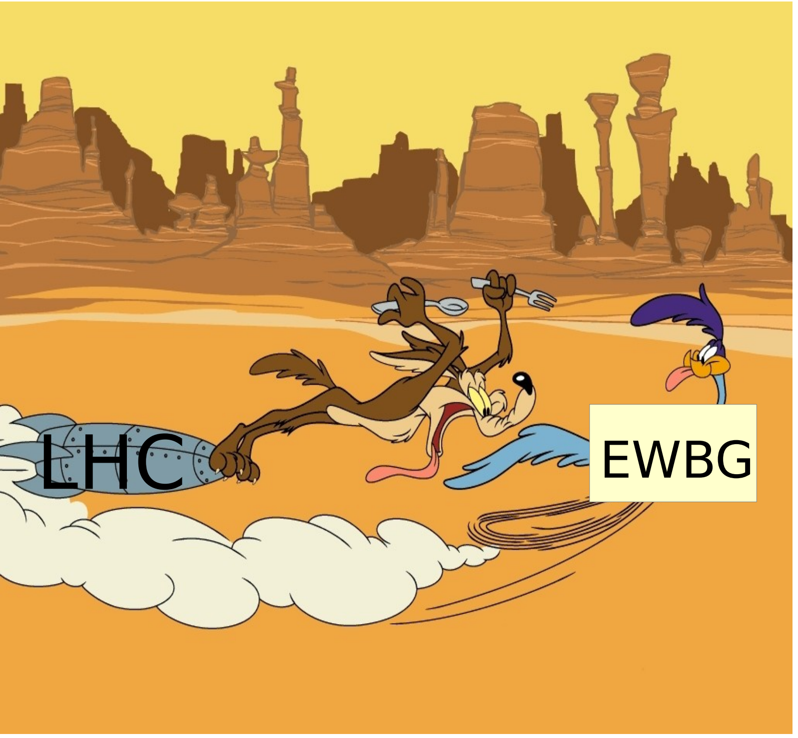

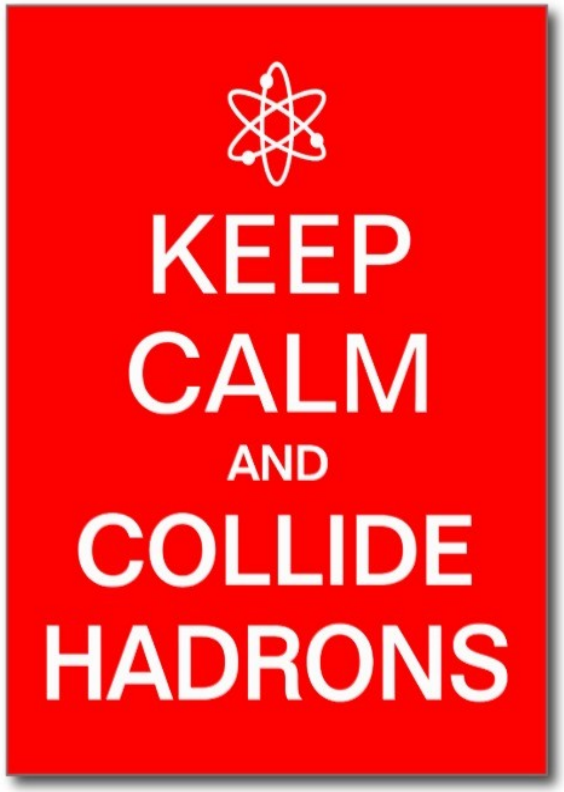

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$$H_0 \to Z a_1 \to \ell\ell\bar{b}b$$
...

Thank you!


KEEP
CALM
AND
BACKUP
YOUR
WORK

2HDM + a

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

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

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

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

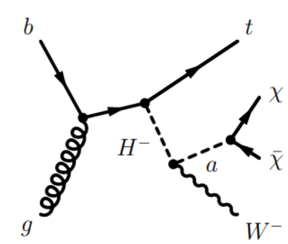
Pseudoscalar portal to DM

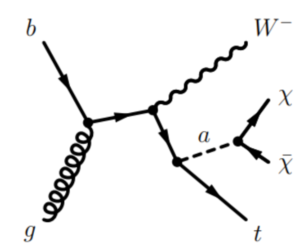
Ipek, McKeen, Nelson, PRD 90 (2014), 055021
JMN, PRD 93 (2016), 031701
Goncalves, Machado, JMN, PRD 95 (2017), 055027
Bauer, Haisch, Kahlhoefer, JHEP 05 (2017), 138
Robens, Symmetry 12 (2021) 12, 2341

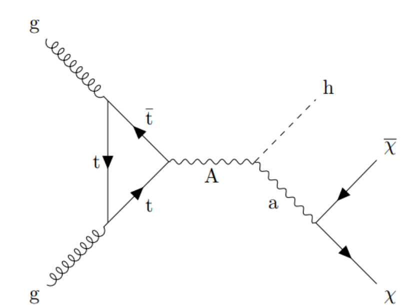
[LHC DM WG Benchmark]

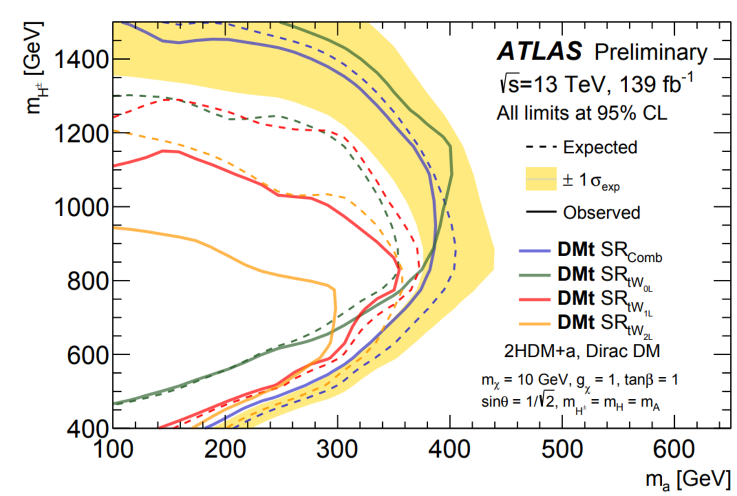
Abe et al, Phys. Dark. Univ. 27 (2020), 100351

e.g.

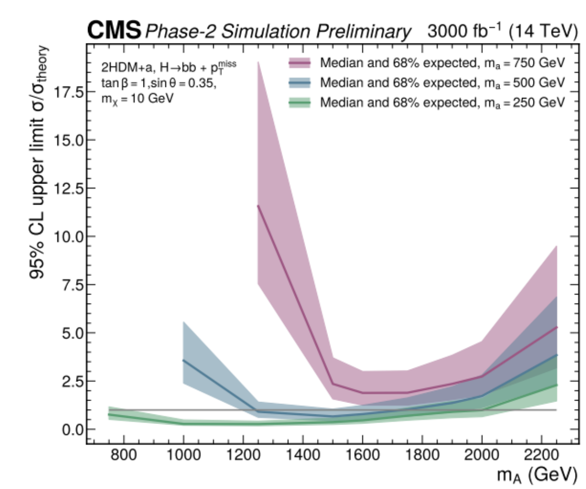








ATLAS-CONF-22-012



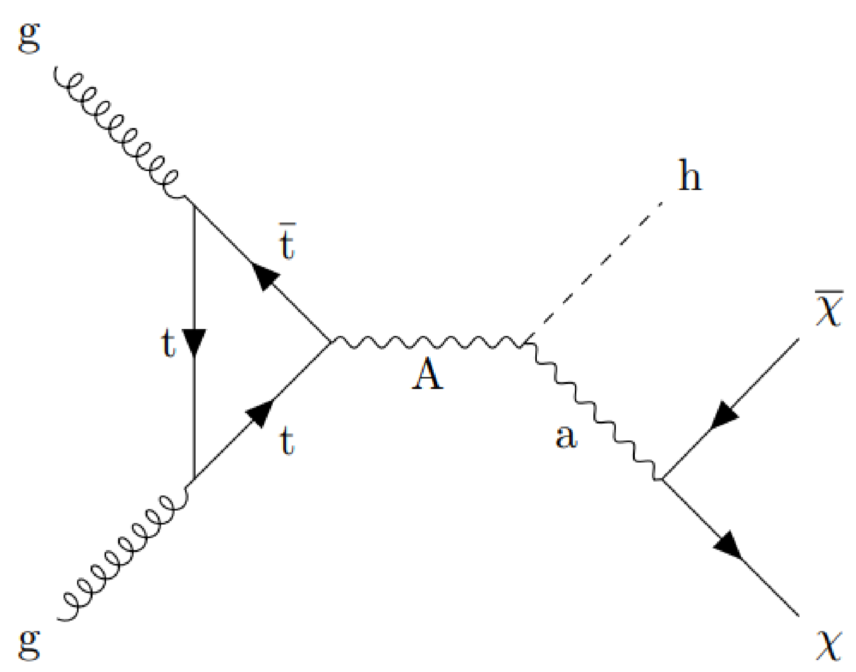
CMS-PAS-FTR-22-005

2HDM + a: **Dark Matter?**

$\ldots \quad + m_\chi \, \bar{\chi}\chi + y_\chi \, a\bar{\chi}\gamma_5\chi$

Very different LHC signatures!

Invisible decays of singlet-like pseudoscalar



2HDM + a: **Dark Matter?**

$$\ldots \quad + m_\chi \, \bar{\chi}\chi + y_\chi \, a\bar{\chi}\gamma_5\chi$$

Recall:

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

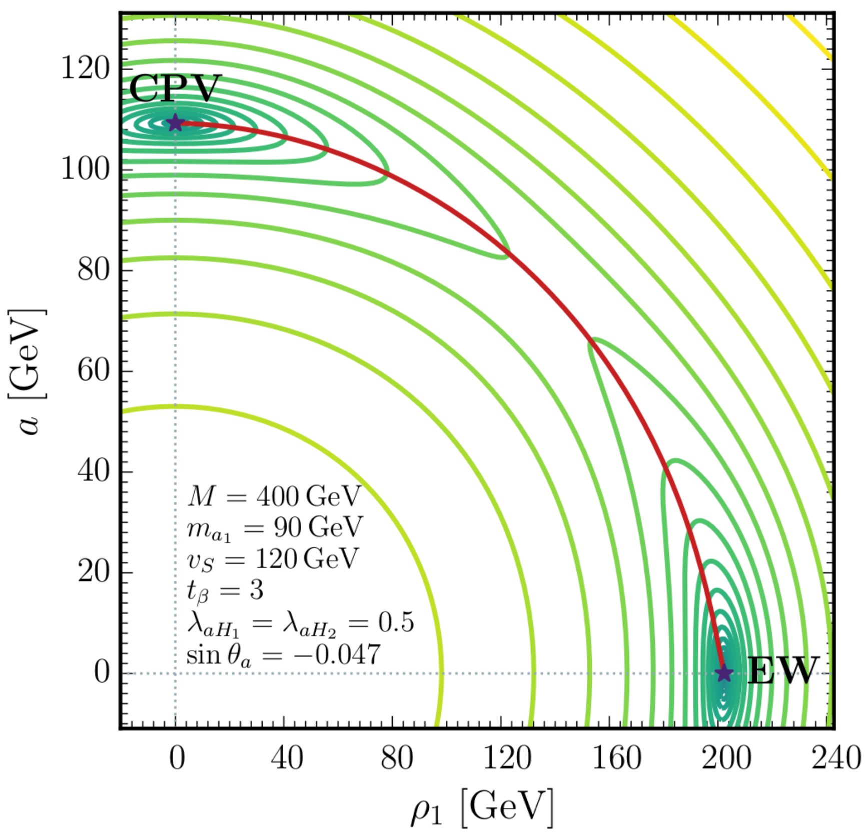
DM coupling yields

$$4\,\lambda_{aH_1} + 4\,\lambda_{aH_2} + 3\,\lambda_a \to 4\,\lambda_{aH_1} + 4\,\lambda_{aH_2} + 3\,\lambda_a + 2\,y_\chi^2$$

Decrease in Singlet Temperature!

$T_S > T_h$ **?**

2HDM + a : Baryogenesis



$T = T_c$

$(0, 0, v_S(T))$, $(v_1(T), v_2(T), 0)$
degenerate in energy

$$\xi_c = v_c/T_c$$

Transition strength

CP Violation & Baryogenesis

$\mu_{12}^2(T) = \mu_{12}^2 - i\,\kappa\, v_S(T)$ (complex parameter in scalar potential)

Phase diff. between CPV and EW minima $\longrightarrow$ $\delta_S = \mathrm{Arg}[\mu_{12}^2(T)^* \mu_{12}^2]$

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

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

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

Fromme, Huber, JHEP 03 (2007), 049