Electroweak Baryogenesis and Dark Matter with an Inert Doublet

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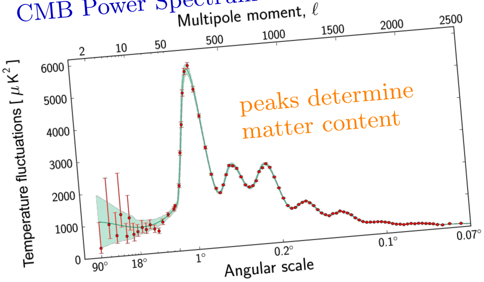
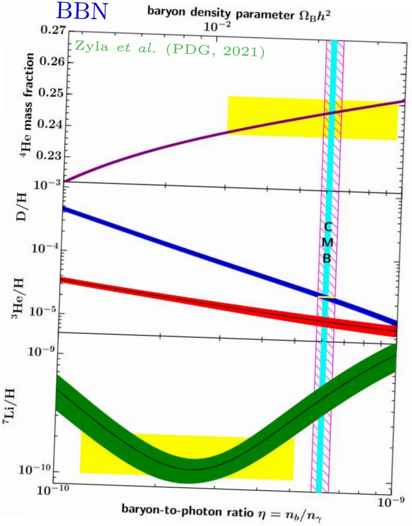
in collaboration with Florian Goertz and María Dias

Motivation

CMB Power Spectrum



BBN



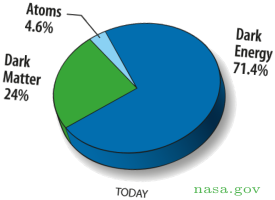
What is the new form of matter?

Why is there matter at all?

Standard Model cannot explain DM or baryon asymmetry
$\rightarrow$ new physics

Background – Dark Matter

- 'ordinary' matter only a small fraction of entire energy content
- WIMP (*weakly interacting massive particle*) as a possible candidate among others

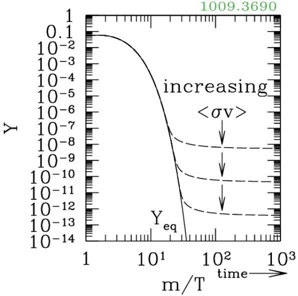


- number density n and entropy density s give rise to comoving DM abundance

$$Y\left(\frac{m}{T}\right) \overset{\text{def}}{=} n/s$$

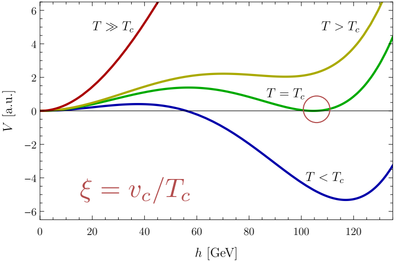
- relic abundance after freeze-out:

$$\Omega h^2 = 0.1200(12)$$



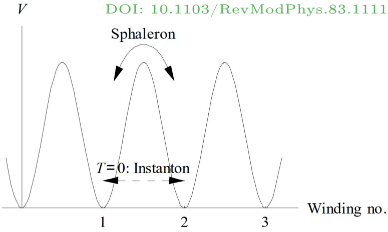
Background – Electroweak Baryogenesis

- Sakharov conditions:
  1. violation of baryon number conservation
  2. C and CP violation
  3. departure from thermal equilibrium → scalar potential



- B violation induced by the Adler-Bell-Jackiw anomaly
  - $SU(2)$ vacuum structure comprises degenerate vacua
  - $\Delta(B+L) \neq 0$ whereas $B-L$ preserved
  - sphalerons strongly suppressed in broken phase

DOI: 10.1103/RevModPhys.83.1111



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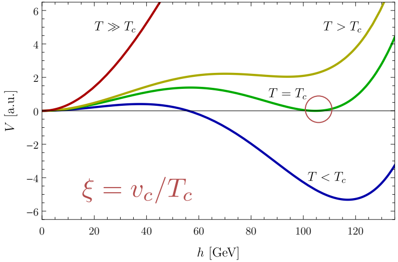
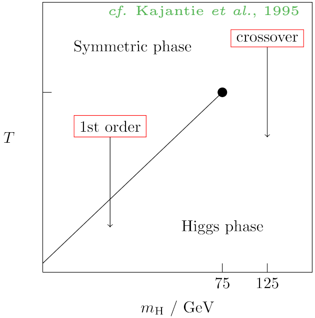


- related problems of the SM
  - lack of sufficient CP violation
  - SM Higgs boson too heavy

SM cannot be the final answer!



Inert Doublet Model

further reading: hep-ph/0612275, 1204.4722, 1504.05949, 1508.01671, 1612.00511, ...

- extended scalar sector of the SM:

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi^+ \\ h + i\phi \end{pmatrix} \quad , \quad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ H + iA \end{pmatrix}$$

- DM particle H stable for $\mathbb{Z}_2$ symmetry

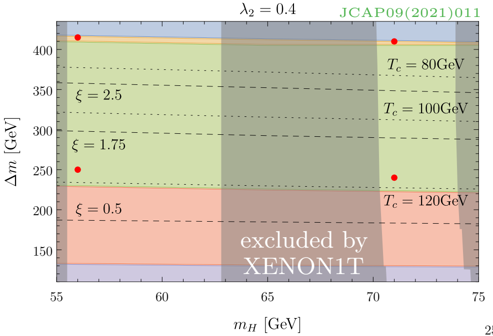
$\mathbb{Z}_2$ symmetry:
$H_1 \to H_1$
$H_2 \to -H_2$

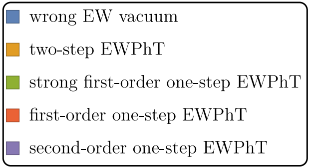
$$\begin{aligned} V_{\text{tree}} =& \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 \\ &+ \boxed{\lambda_3} |H_1|^2 |H_2|^2 + \boxed{\lambda_4} \left| H_1^\dagger H_2 \right|^2 + \frac{\boxed{\lambda_5}}{2} \left[\left(H_1^\dagger H_2 \right)^2 + \text{h.c.} \right] \end{aligned}$$

- free parameters: $\{\lambda_2, \boxed{\lambda_{345}}, m_H, m_{H^\pm}, m_A\}$

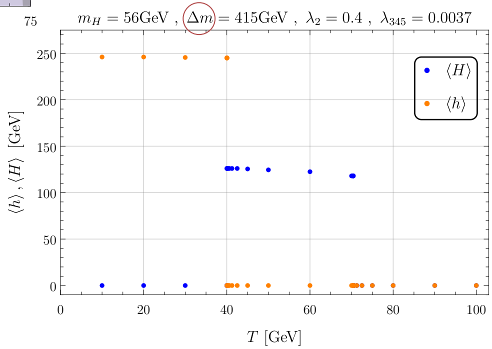
$$= \lambda_3 + \lambda_4 + \lambda_5$$

EWPhT in low-mass regime





$= m_{A,H^\pm} - m_H$



strong 1st-order EWPhT via one or two steps

CP violation with inert doublet

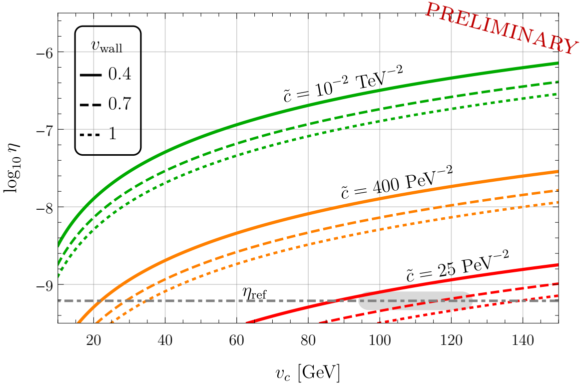
see Dine *et al.* (1991)
(DOI: 10.1016/0370-2693(91)91905-B)

- dimension-6 operator:

$$\mathcal{L}_{\not{C}\not{P}} = \underbrace{\tilde{c}}_{=\tilde{\lambda}/\Lambda^2} |H_2|^2 W^a_{\mu\nu} \widetilde{W}^{a,\mu\nu} = \tilde{c}\, j^\mu_B\, \partial_\mu |H_2|^2$$

$\rightarrow$ baryon asymmetry $j^0_B \sim \tilde{c}\, v_c^2\, T_c^3 / v_{\text{wall}}$

- unbroken phase: minimum of free energy at $j^0_B = 0$
- PhT leads to shift of minimum
- sphalerons drive j^0_B to new minimum



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asymmetry parameter

$\eta = \frac{n_B - \bar{n}_B}{n_\gamma}$

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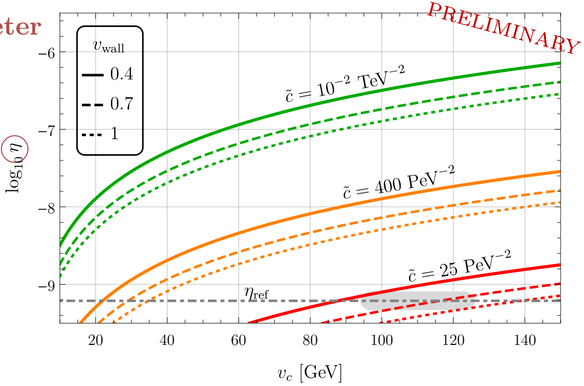

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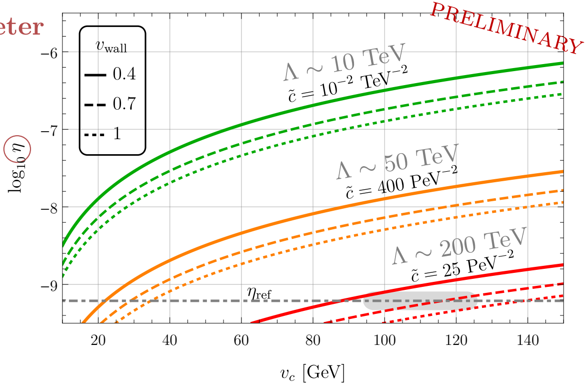
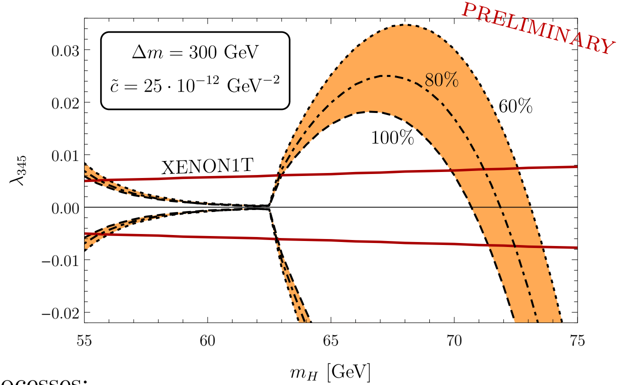
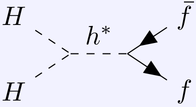


DM results for low-mass regime



dominant processes:

$m_H < m_h/2$:



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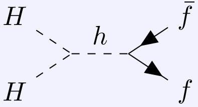

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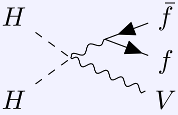

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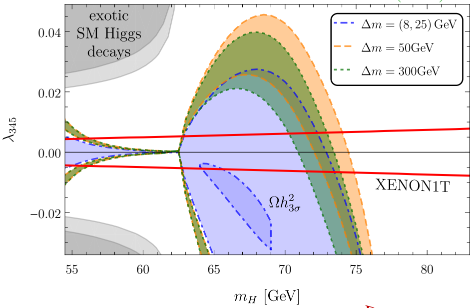
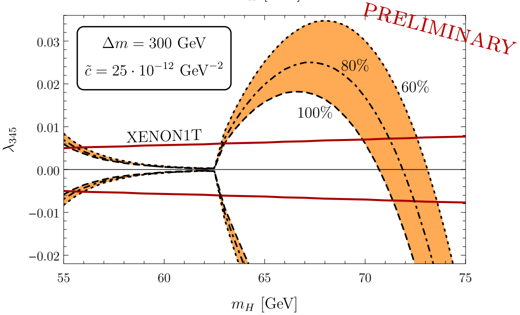
JCAP09(2021)011



- new operator has minor impact on DM abundance

→ results from previous studies (most likely) apply to this extension of the IDM

Viable parameter space in low-mass regime!



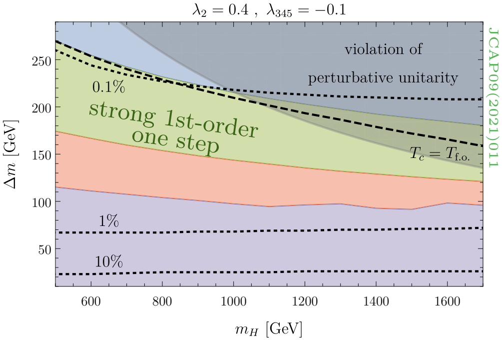
DM and EWPhT in high-mass regime

- large Δm required for strong EWPhT

  BUT small Δm necessary for a significant DM abundance

- no 2-step EWPhT in high-mass regime

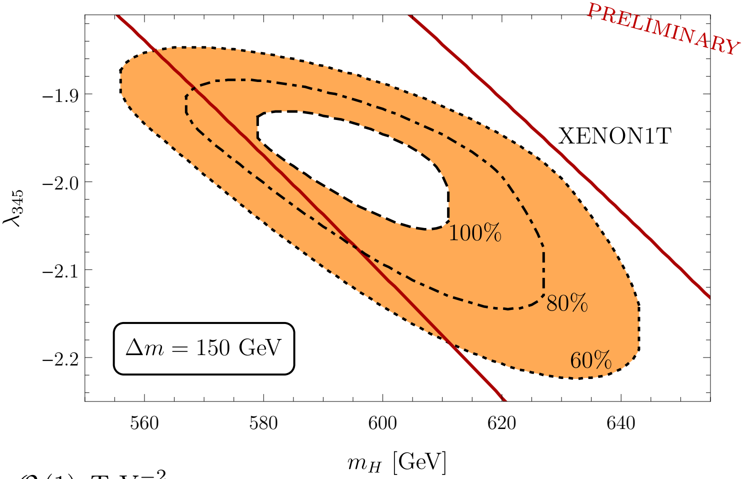
→ new source of CP violation required!



- alleviate this problem by introducing further operators:

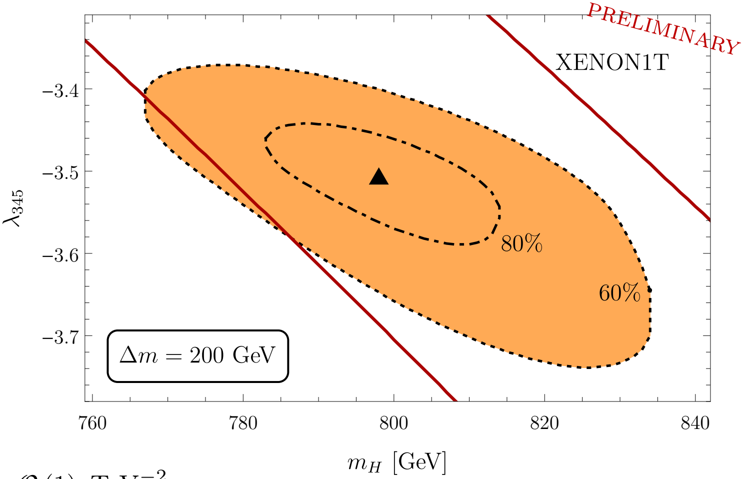
$$\mathcal{L}^{(6)} \supset c_1 \left|H_1\right|^2 \left|D_\mu H_2\right|^2 + c_2 \left|H_2\right|^2 \left|D_\mu H_1\right|^2$$
$$+ \left[c_3 H_1^\dagger H_2 \left(D_\mu H_1\right)^\dagger D^\mu H_2 + c_4 H_1^\dagger H_2 \left(D_\mu H_2\right)^\dagger D^\mu H_1 + \text{h.c.}\right]$$

DM results for high-mass regime



$c_i \sim \mathcal{O}(1)\ \text{TeV}^{-2}$

DM results for high-mass regime



$c_i \sim \mathcal{O}(1)$ TeV^{-2}

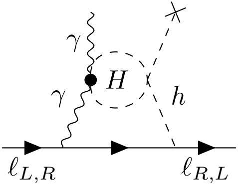
Conclusions & Outlook

- vanilla IDM fails in accounting for observed baryon asymmetry

  $\rightarrow$ invoke additional CP violation in low-mass regime by adding

$$\mathcal{L}_{\not{C}\not{P}} = \frac{\tilde{\lambda}}{\Lambda^2} \left|H_2\right|^2 W^a_{\mu\nu} \widetilde{W}^{a,\mu\nu}$$

  with new-physics scale $\Lambda \sim 200$ TeV for $\tilde{\lambda} \sim \mathcal{O}(1)$
- extended IDM can account for both DM and baryon asymmetry
- strong 1st-order EWPhT testable gravitational wave signatures?
- EDM experiments for probing the operator



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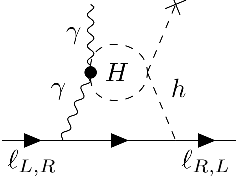
Thanks for your attention

Feel free to contact me for discussions:

fabian@mpi-hd.mpg.de



Sources for images

Sec. *Motivation*:

- CMB

  https://sci.esa.int/s/wRVmdjw

Sec. *Background – Dark Matter*:

- energy budget

  https://map.gsfc.nasa.gov/universe/uni_matter.html

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