# Electroweak Baryogenesis and Dark Matter with an Inert Doublet

Sven Fabian

Max-Planck-Institut für Kernphysik

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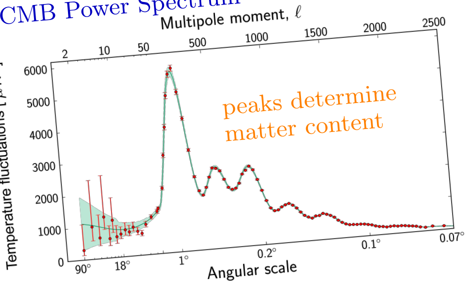
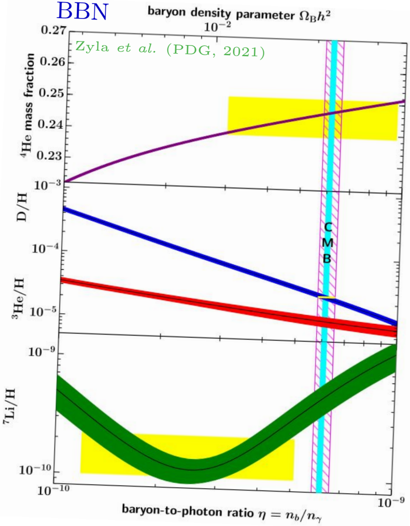
in collaboration with Florian Goertz and María Dias

# Motivation

CMB Power Spectrum




BBN




**What is the nature of dark matter?**

**What has caused the great excess of matter over antimatter?**

**Standard Model cannot explain DM or baryon asymmetry**

# Background – Dark Matter

- bullet cluster: small interaction cross section between DM and 'ordinary' matter
- many possible DM candidates:

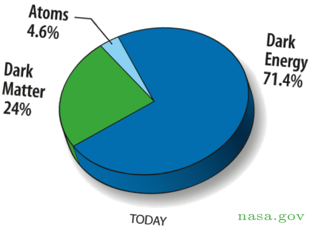
  → focus on WIMPs

Bullet Cluster

chandra.harvard.edu

- 'ordinary' matter only a small fraction of entire energy content
- relic abundance after freeze-out:

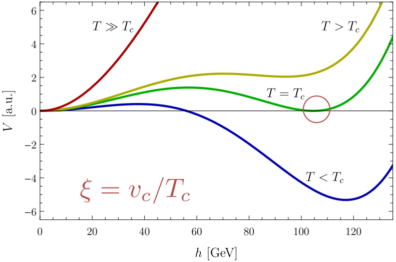
$$\Omega_{\mathrm{DM}} h^2 = 0.1200(12)$$




nasa.gov

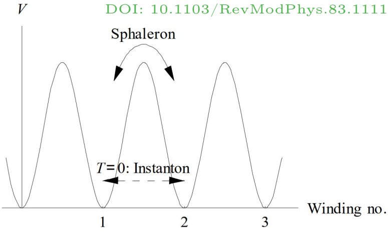
# Background – Electroweak Baryogenesis

- Sakharov conditions:
  (1) violation of baryon number conservation
  (2) $C$ and $CP$ violation
  (3) departure from thermal equilibrium $\rightarrow$ 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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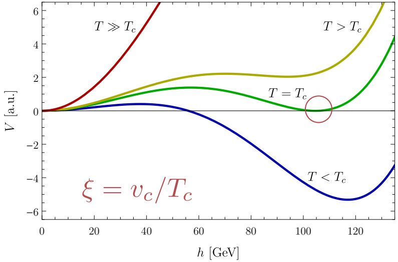
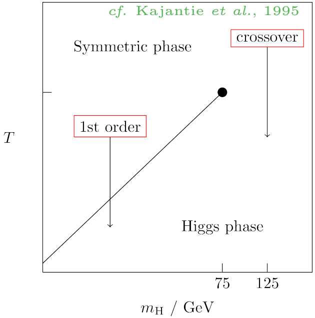



- related problems of the SM
  - lack of sufficient $CP$ violation
  - SM Higgs boson too heavy

**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:
$H_1 \to H_1$
$H_2 \to -H_2$

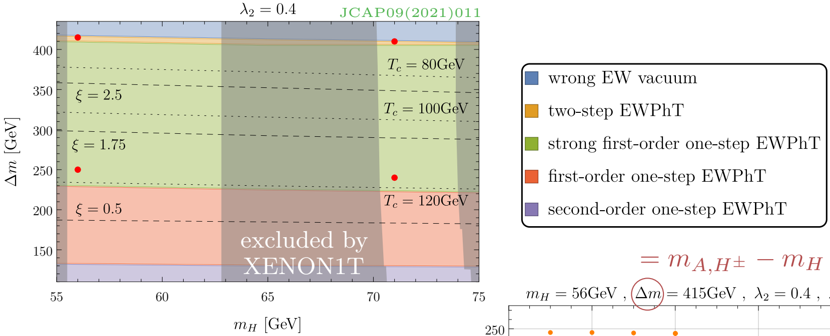
$$V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4$$
$$+ \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 \left| H_1^\dagger H_2 \right|^2 + \frac{\lambda_5}{2} \left[ \left( H_1^\dagger H_2 \right)^2 + \text{h.c.} \right]$$

Higgs-portal coupling

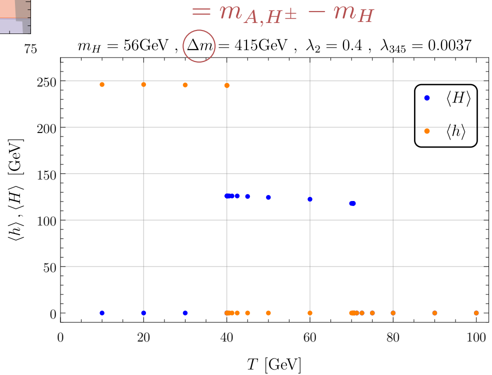
- free parameters: $\{\lambda_2, \lambda_{345}, m_H, m_{H^\pm}, m_A\}$

$= \lambda_3 + \lambda_4 + \lambda_5$

# EWPhT in low-mass regime




**strong 1st-order EWPhT via one or two steps**



# $CP$ violation with inert doublet

cf. Dine *et al.* (1991)

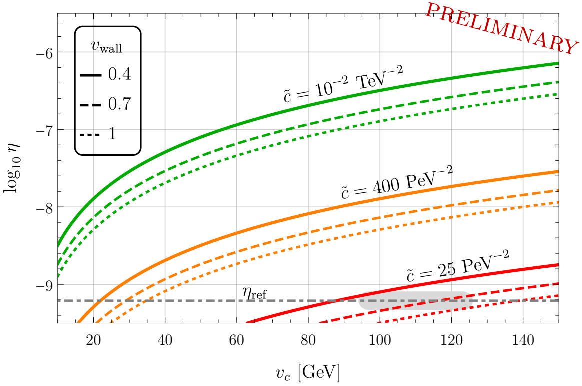
(DOI: 10.1016/0370-2693(91)91905-B)

- dimension-6 operator:

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

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

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



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**asymmetry parameter**

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

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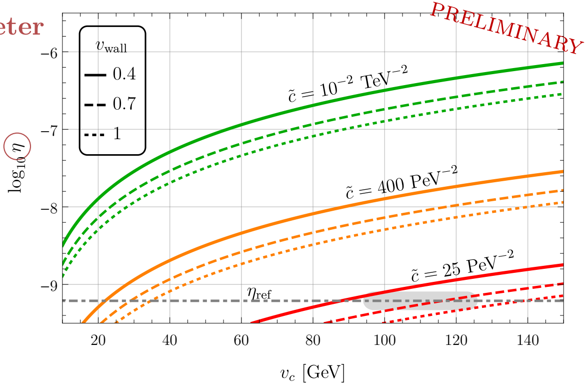

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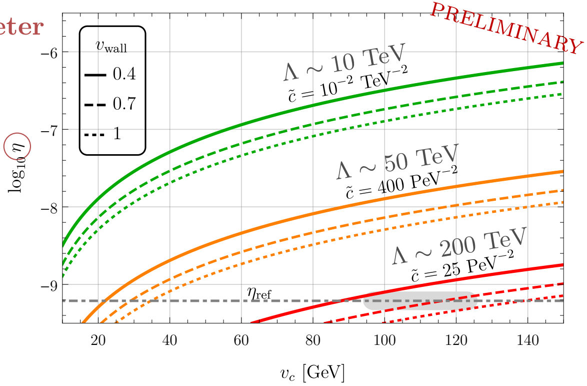
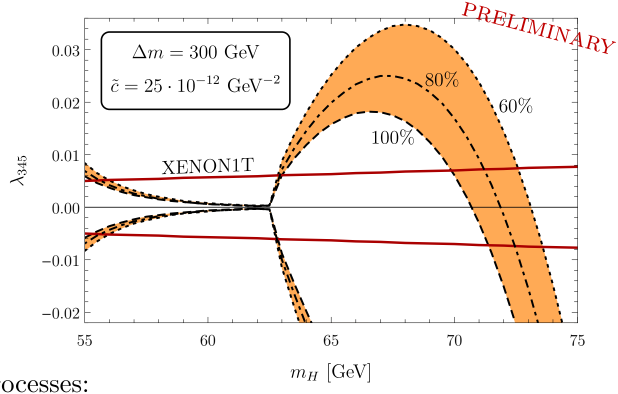
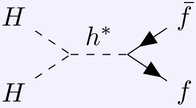


# DM results for low-mass regime




dominant processes:

$m_H < m_h/2$:

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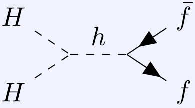


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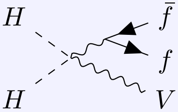


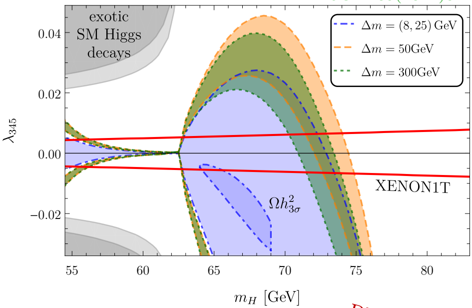
# DM results for low-mass regime

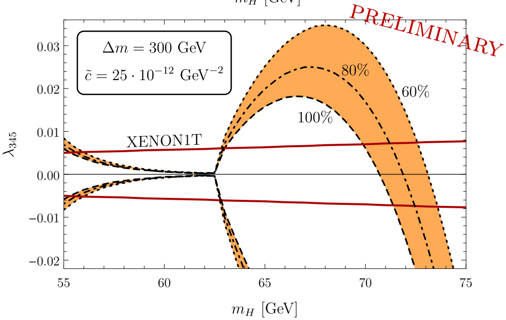
- new operator has minor impact on DM abundance

→ results from our previous studies apply to this extension of the IDM

**Viable parameter space in low-mass regime!**

JCAP09(2021)011

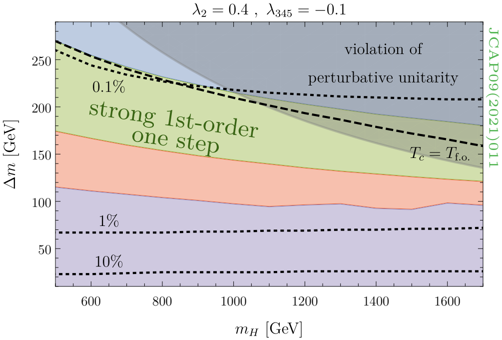


# DM and EWPhT in high-mass regime

- large $\Delta m$ required for strong EWPhT

  BUT small $\Delta m$ necessary for a significant DM abundance



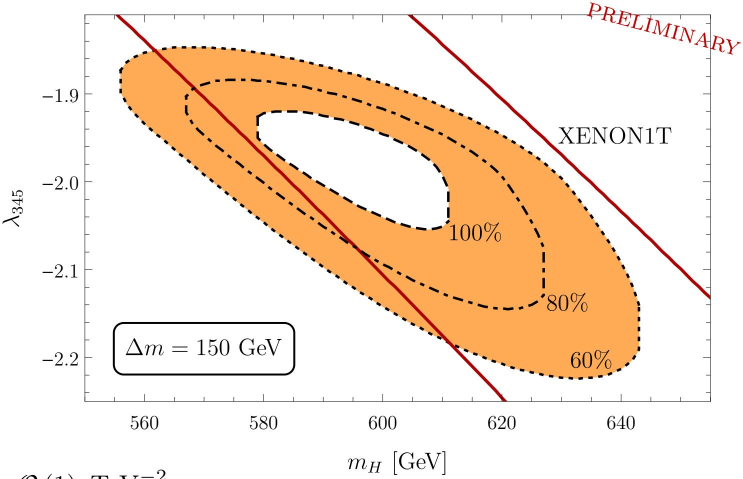

- no 2-step EWPhT in high-mass regime

→ 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




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

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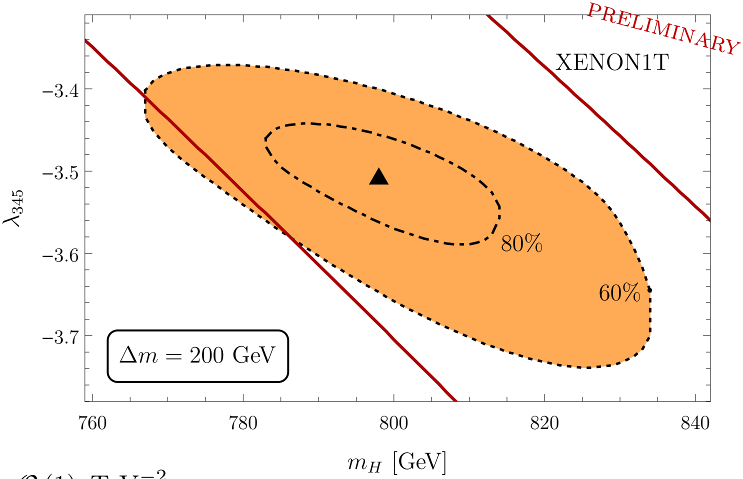


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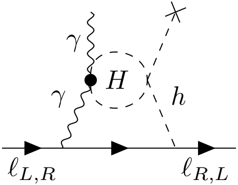
# Conclusions & Outlook

- Goal: eliminate shortcomings of vanilla IDM w.r.t. $CP$ violation

  $\rightarrow$ low-mass regime: baryogenesis & DM via

  $$\mathcal{L}_{\not{C}\not{P}} = \frac{\tilde{\lambda}}{\Lambda^2} |H_2|^2 W^a_{\mu\nu} \widetilde{W}^{a,\mu\nu} \text{ with } \Lambda \sim 20 \text{ TeV for } \tilde{\lambda} \sim \mathcal{O}\left(10^{-2}\right)$$

  $\rightarrow$ high-mass regime: DM & strong 1st-order EWPhT
- strong 1st-order EWPhT testable gravitational wave signatures?
- EDM experiments for probing the operator



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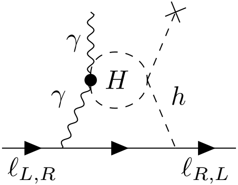
**Thanks for your attention**

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

- bullet cluster

  https://chandra.harvard.edu/photo/2006/1e0657/more.html

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