Scalars and Cosmos

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Composite Dynamics:
From Lattice to the LHC Run II
4.-15.4.2016 MITP


(elementary) scalars ahead…

Outline

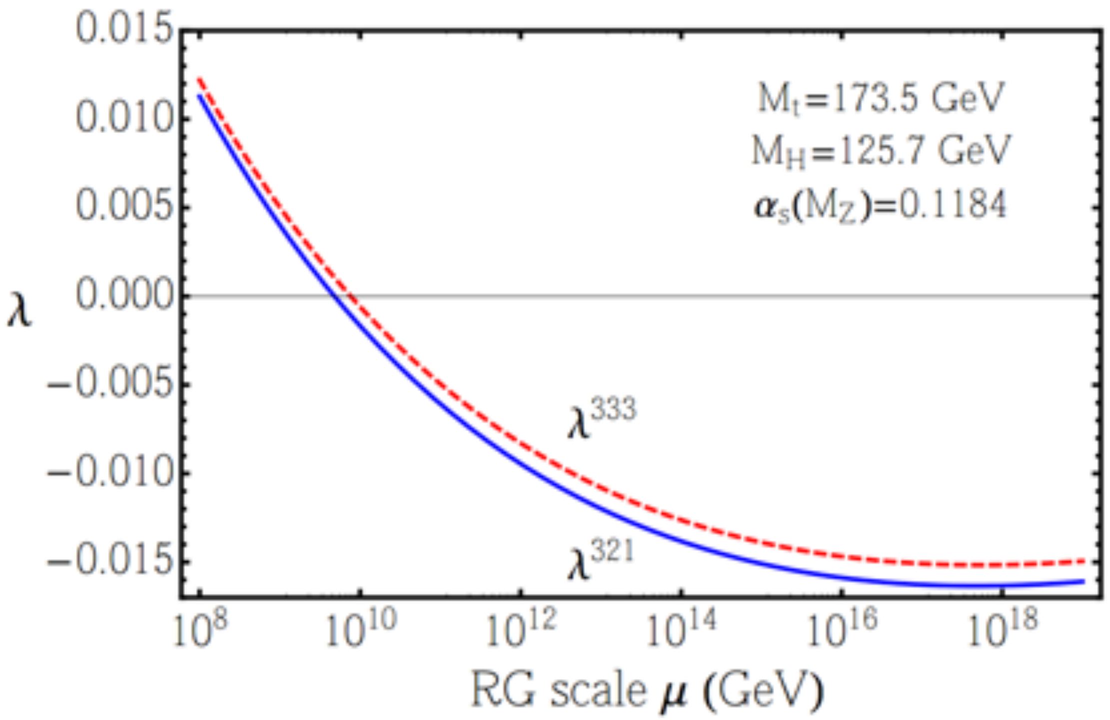
- Vacuum stability
- Baryogenesis
- Dark matter

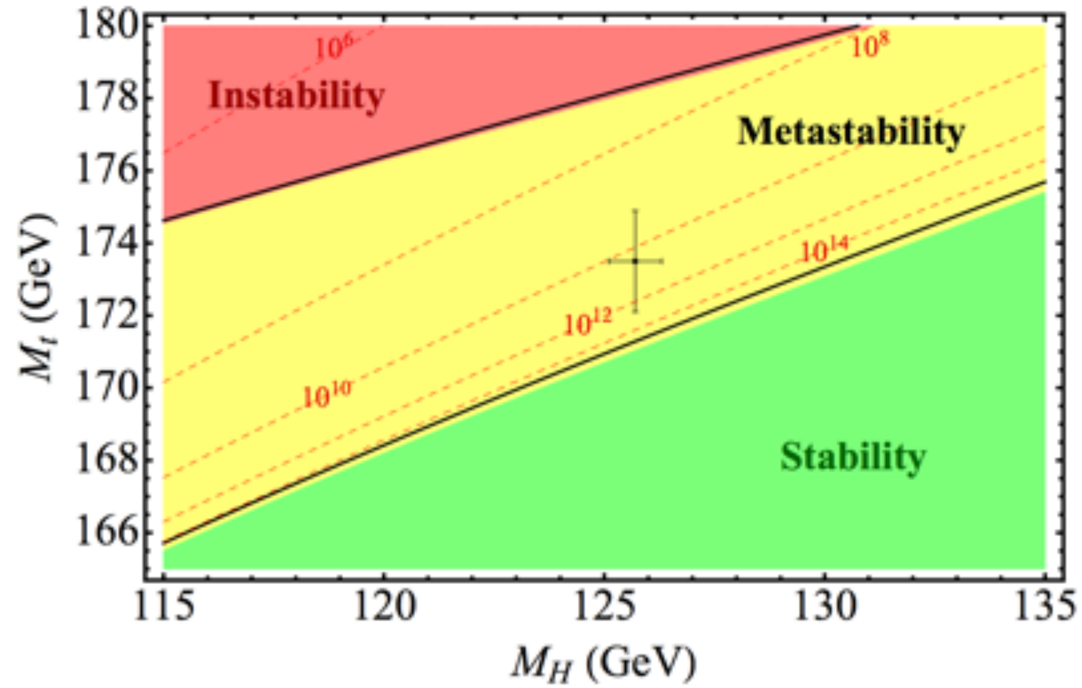
Collaborators:
K. Enqvist, M. Heikinheimo, K. Kainulainen,
S. Nurmi, T. Tenkanen, V. Vaskonen

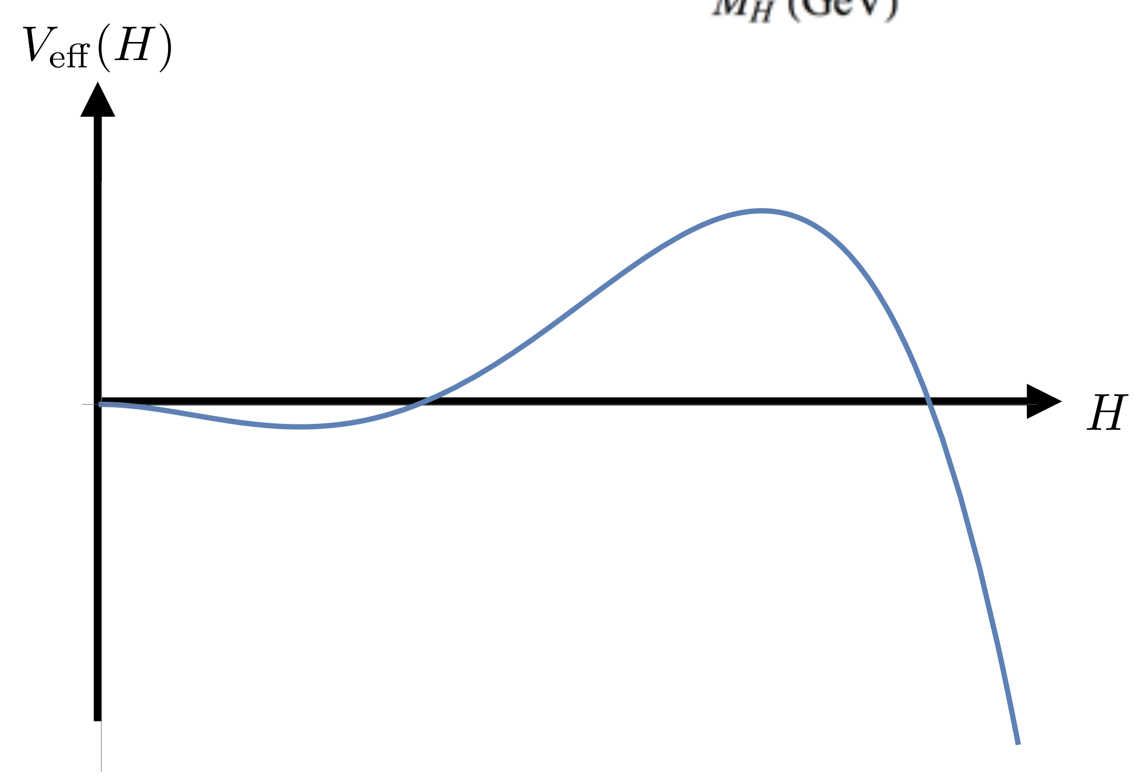
ArXiv: 1407.0688, 1506.04048, 1507.04931, 1601.07733
and in progress.

Vacuum stability

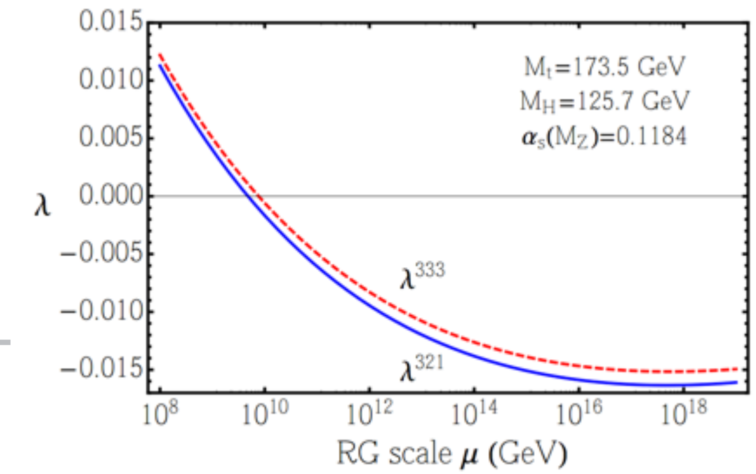
O. Antipin *et al.*, ArXiv:1306.3234,
G. Degrassi *et al.*, ArXiv:1205.6497.







Not a very big issue…



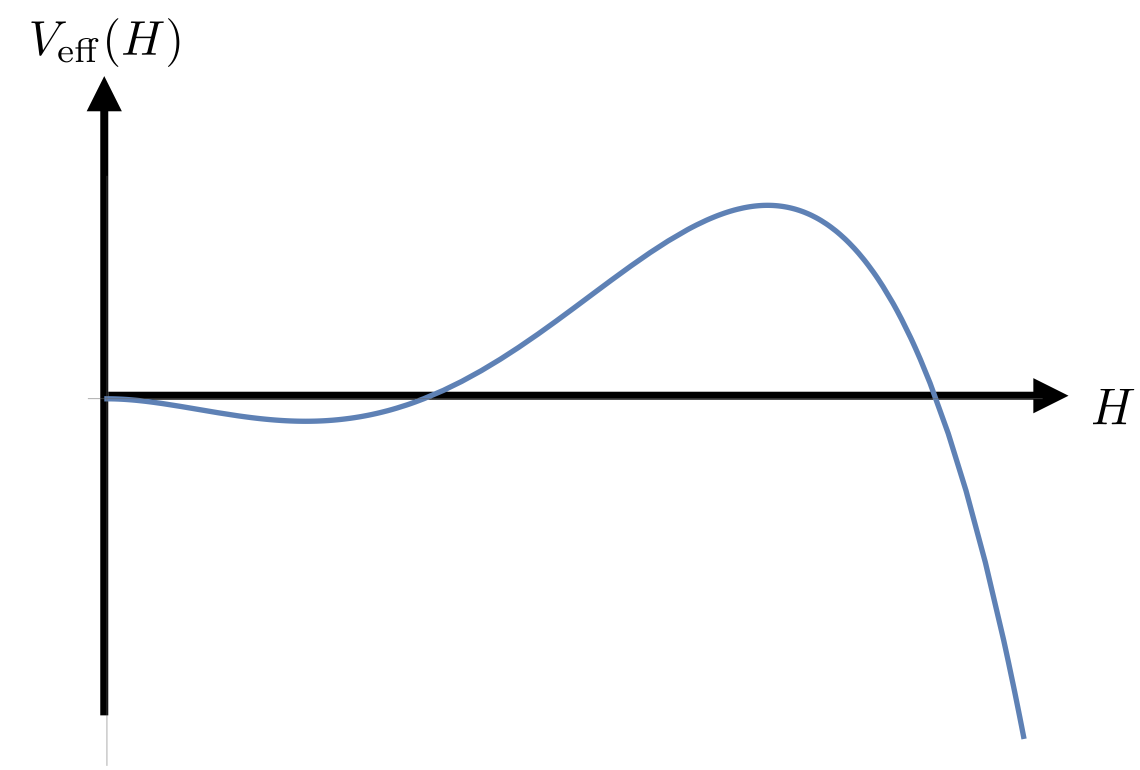
- Single extra scalar **lifts** $\lambda > 0$.

(Details depend on the BSM scenario.)

- Non-minimal coupling to gravity $\xi R|H|^2$ **stabilises.**
- Nonzero ξ is generated by **curved background.** **M. Herranen *et al.* 1407.3141**

Moreover:
Large inflationary scale
makes tunneling irrelevant.

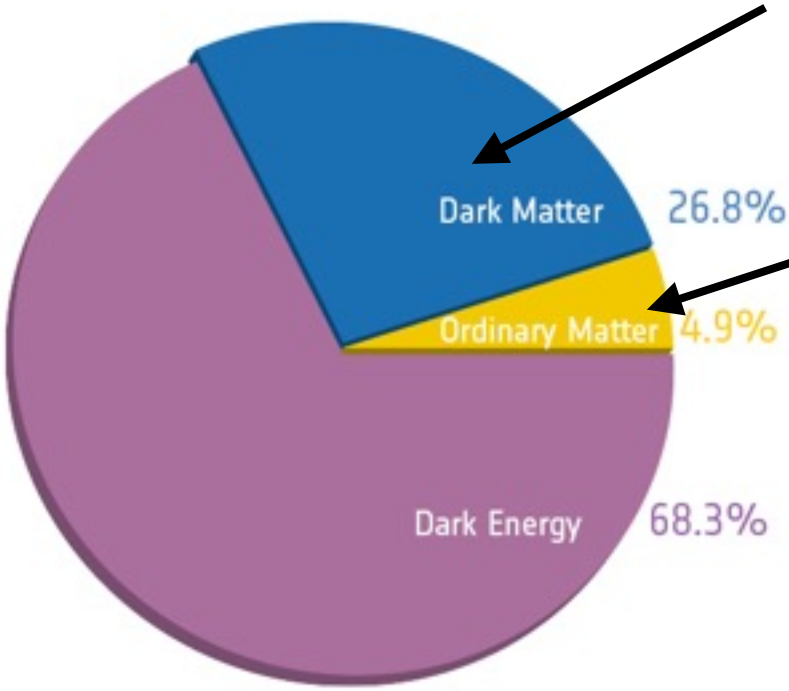
– the field rolls to false vacuum.



The cosmic pie:

P.Ade et al, ArXiv:1502.01589
(Planck 2015 Cosmological Parameters)

$\Omega_{\rm DM} h^2 = 0.1198 \pm 0.0015$ **Dark matter:** later…



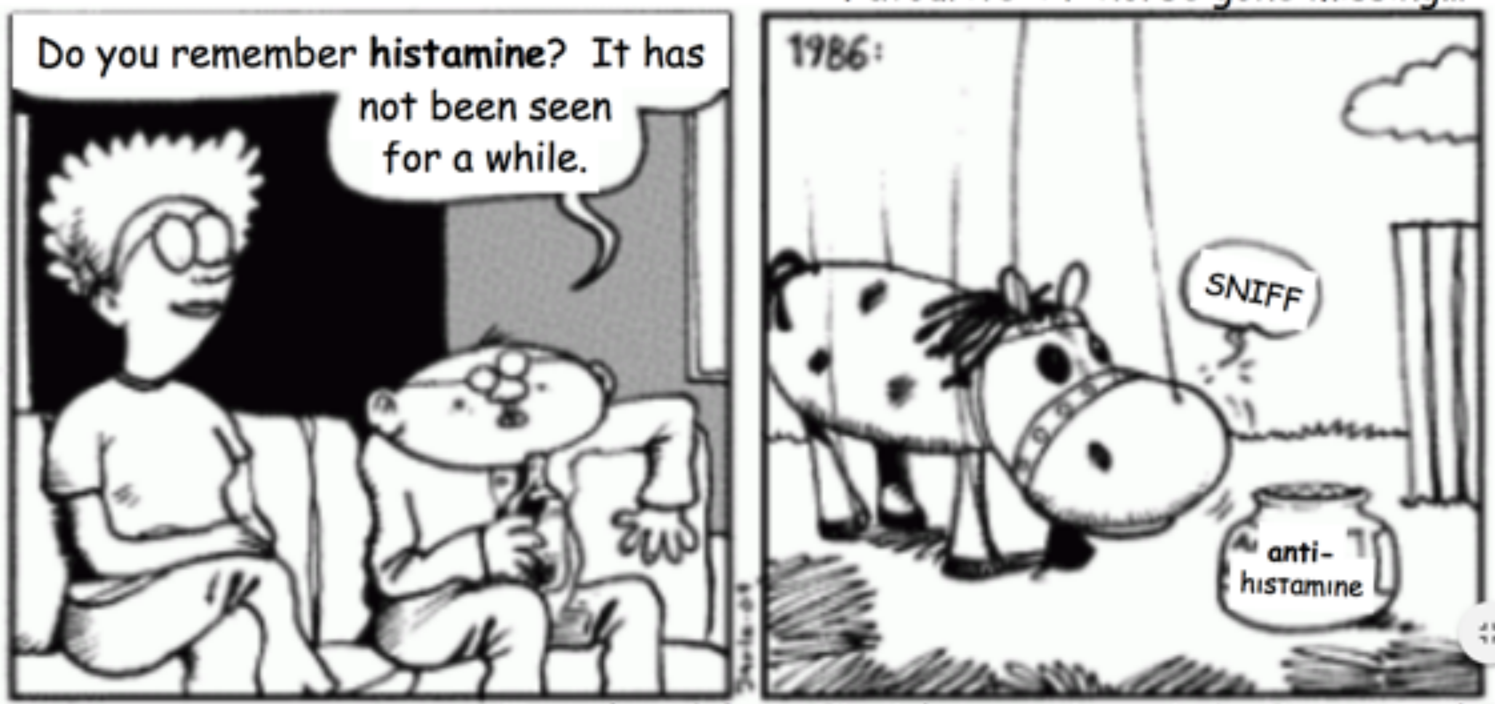
…start with visible matter:

$$\Omega_b h^2 = 0.02225 \pm 0.00016$$

Symmetric universe
→ radiation.
But we observe matter:

$$\eta_B = \frac{n_B}{n_\gamma} \simeq 8.7 \cdot 10^{-11}$$

Favourite TV-horse gone missing...



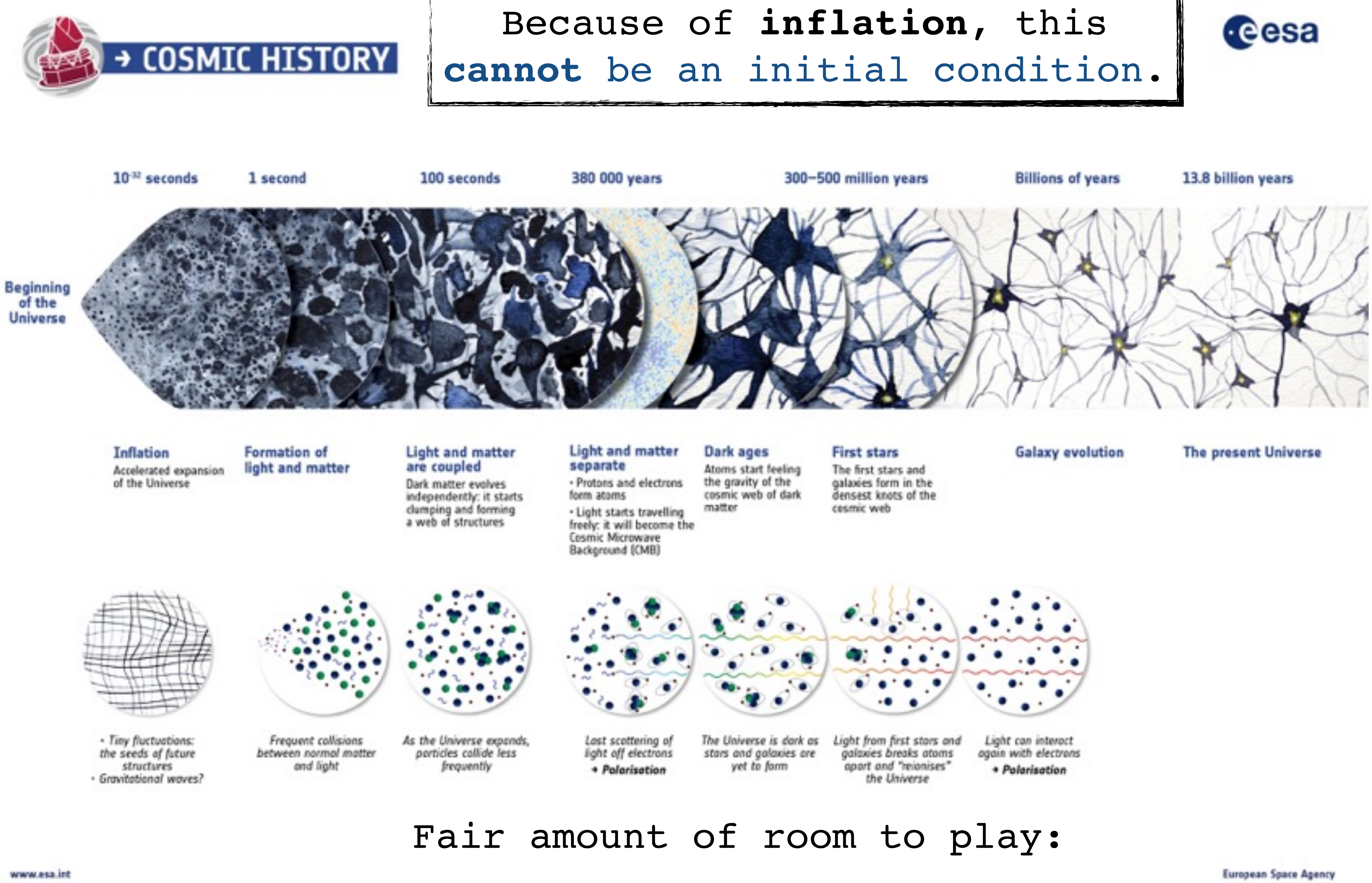
Translated from Finnish, a comic strip by Pertti Jarl

P.Ade et al, ArXiv:1502.01589
(Planck 2015 Cosmological Parameters)

Baryon asymmetry

$$\Omega_b h^2 = 0.02225 \pm 0.00016$$

Because of **inflation**, this **cannot** be an initial condition.



Fair amount of room to play:

$$100\,\mathrm{GeV} < T_{\mathrm{BAU}} < 10^{16}\,\mathrm{GeV}$$

Baryon asymmetry/ mechanisms

Sakharov:

Electroweak BG

SM, MSSM, NMSSM, 2HDM, …

Leptogenesis

- resonant,
- non-resonant

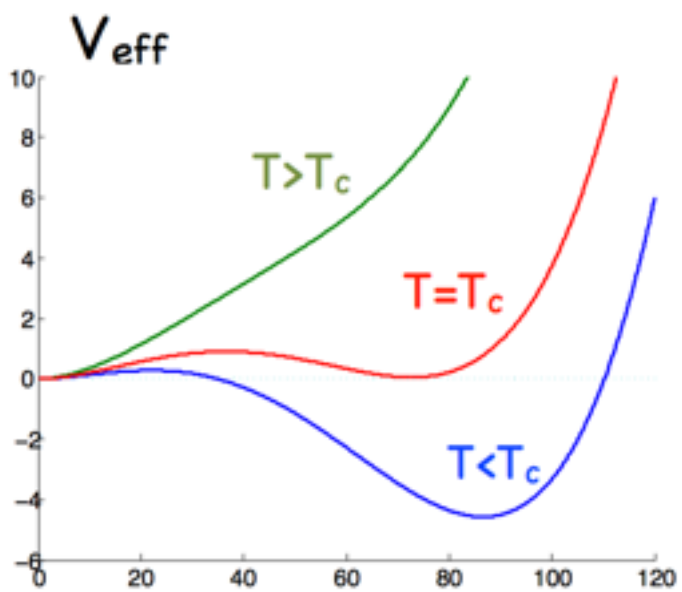
Many others:

Affleck-Dine mechanism,
GUTs,
Neutrino oscillation,
Irrelevant operators,
Inflation, …

Electroweak BG works at lowest possible temperature: $T_{\mathrm{EWBG}} \simeq 100\,\mathrm{GeV}$

Testability appeal.

Baryon asymmetry/ EWBG nutshell



1st order phase transition @ $T_{\rm EW} \simeq 100\,{\rm GeV}$

Bubbles of **true vacuum,** $\langle H \rangle \neq 0$ **,** form.

Start to **expand into the false symmetric vacuum.**

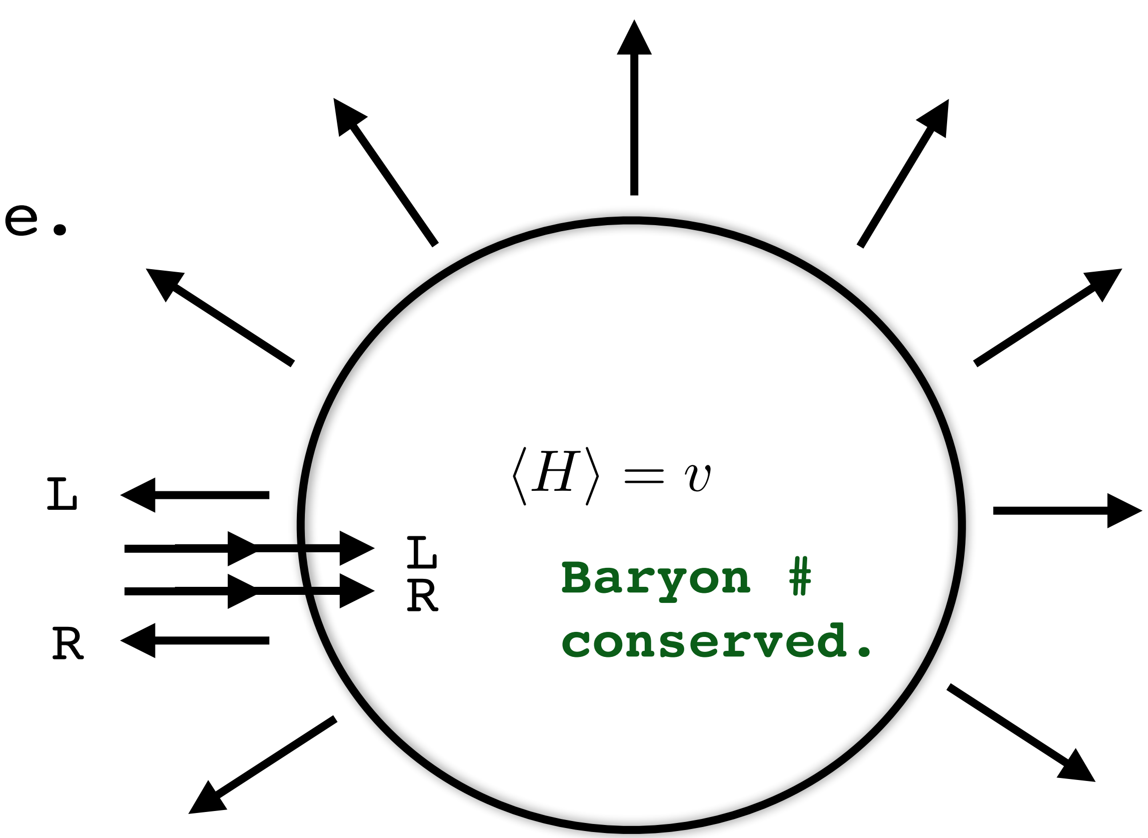
Particles interact with the bubble wall
in **CP-violating way.**

Baryon **asymmetry forms** inside the bubble.

Requires: $\dfrac{v(T_c)}{T_c} > 1$

$\langle H \rangle = 0$

Baryon # violation by sphalerons.

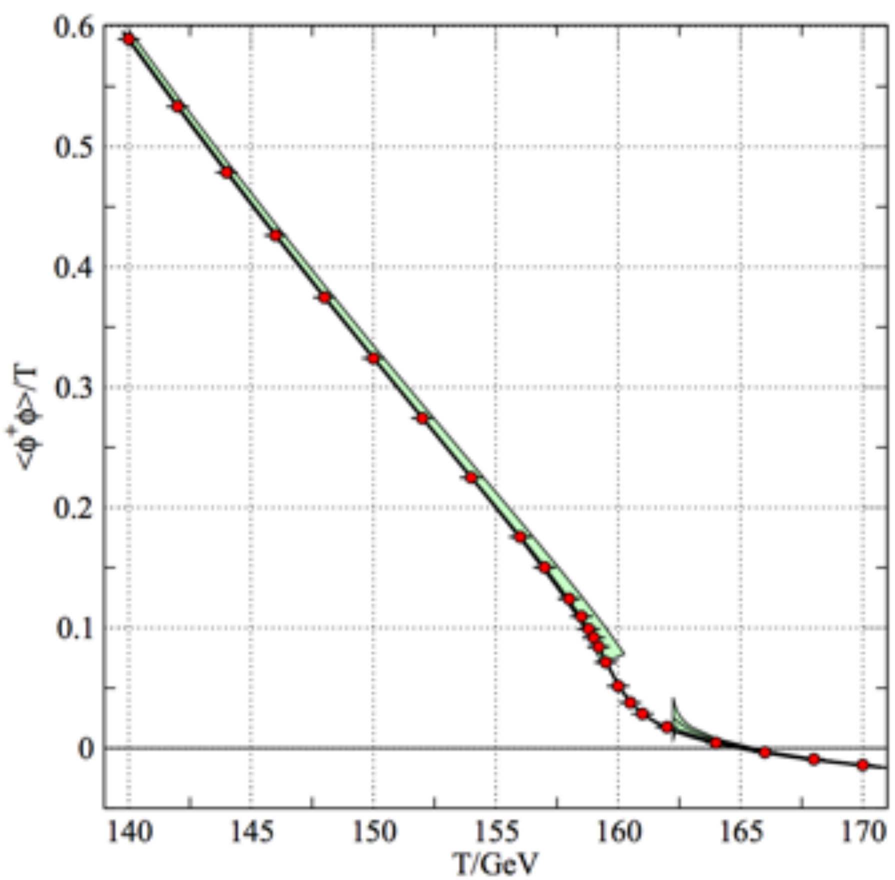


EWBG in SM — Dead

Known since 1996:
Kajantie, Laine, Rummukainen, Shaposhnikov, PRL 77 (1996).

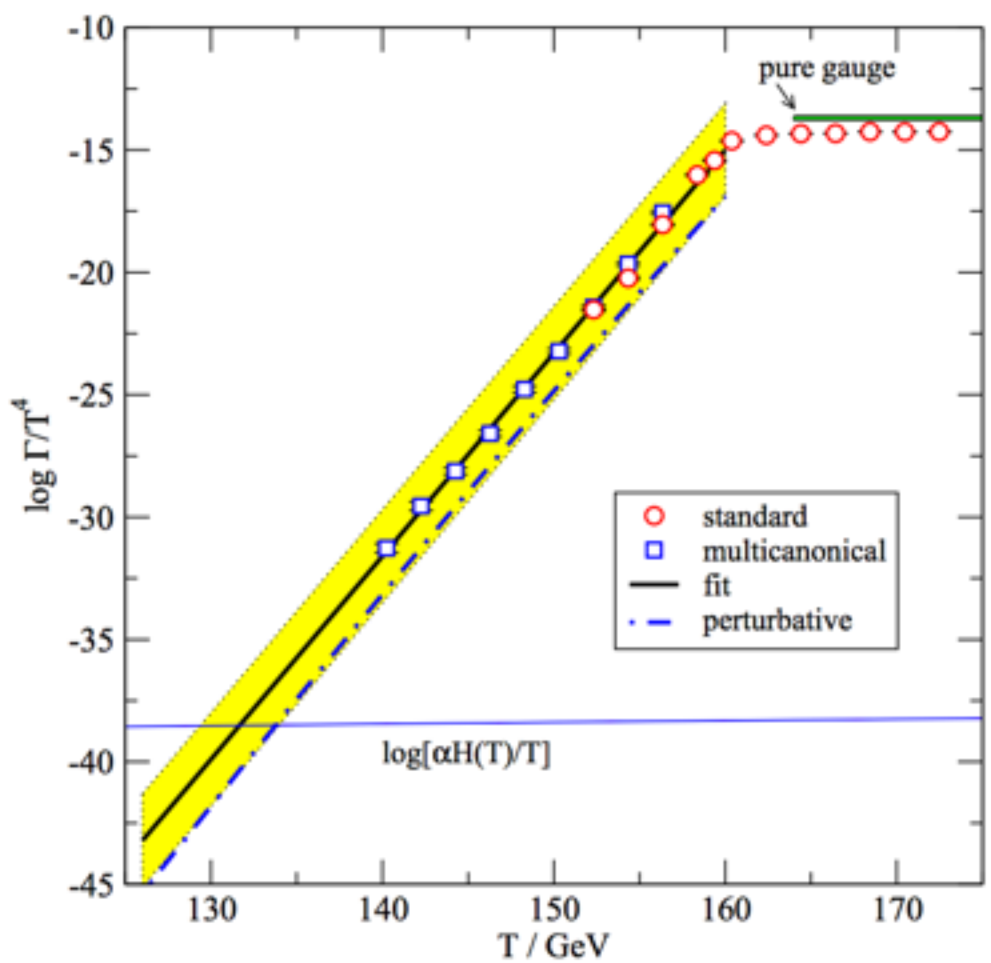
PT in **SM** is a cross over, $T_c \simeq 160\,\mathrm{GeV}$

M. D'Onofrio, K. Rummukainen, ArXiv:1508.07161.



Sphaleron processes
drop out of equilibrium: $T_* \simeq 130\,\mathrm{GeV}$

M. D'Onofrio, K. Rummukainen, A. Tranberg
ArXiv:1404.3565



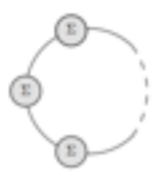
We exist, BSM physics exists.

Models of strong PT

Prospects for composite theories too!

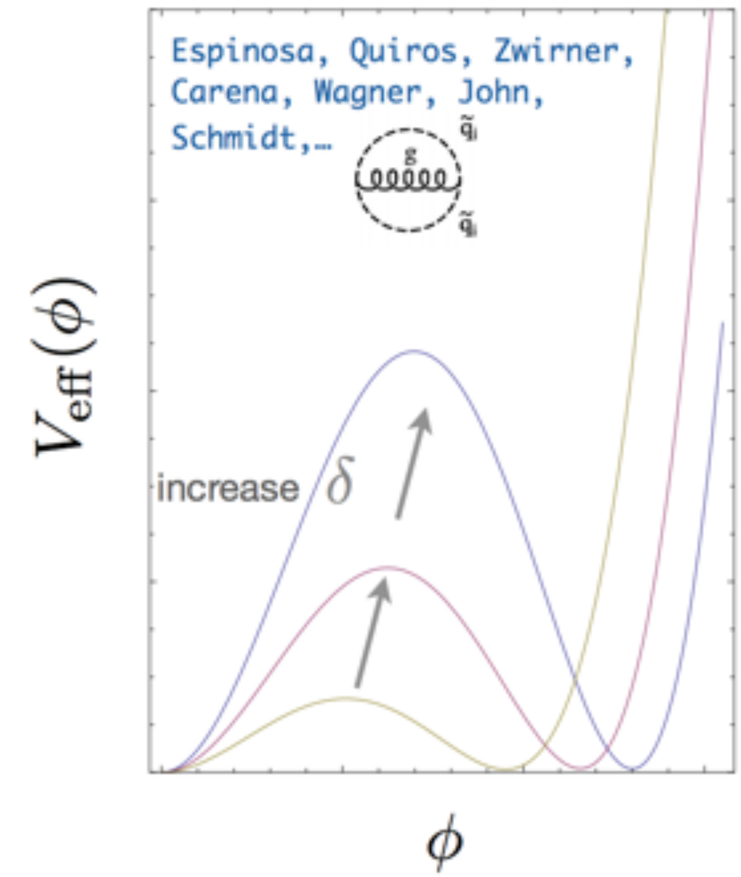
Most efforts **usually** to increase the **cubic term** by loop corrections.

New **light bosonic fields**, strongly coupled with the Higgs.



$$\delta V_{\rm eff} = -\sum_i \frac{T m_i^3(\phi, T)}{12\pi} + \dots$$

e.g. **Light Stop Scenario** in **MSSM**.



Same phases which generate BAU also contribute to eEDM:

2013 ACME-bound on eEDM: $d_e < 8.7 \cdot 10^{-29}\, e\mathrm{cm}$

ACME collaboration, Science 343 (2014) 6168, 269-272

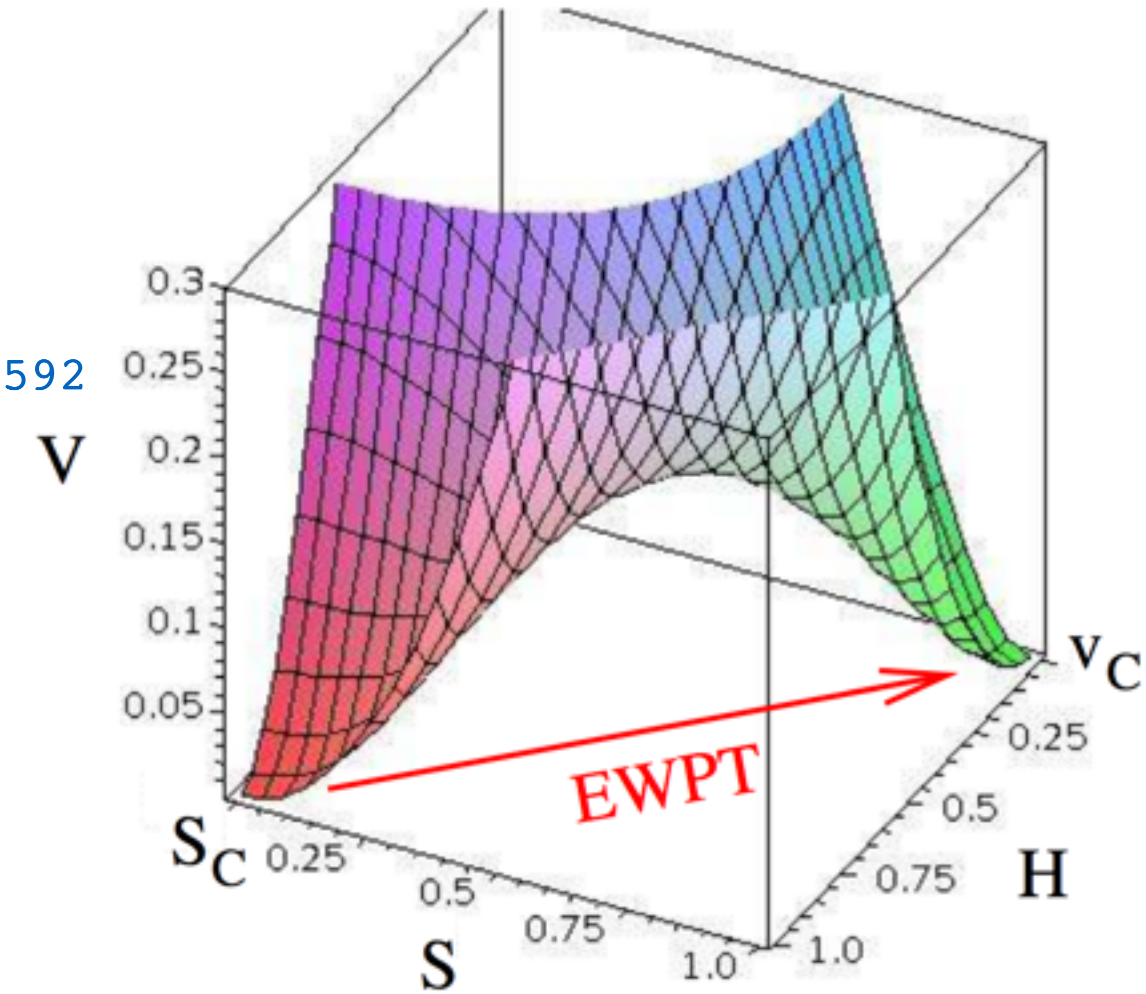
SM+singlet scalar: strong PT @ tree level

$$V = V_{\rm SM} + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{\rm sh} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4 \qquad \mu_S^2 < 0$$

If $\lambda_{\rm sh}$ is large enough,
a potential barrier between
the two vacua exists.

Strong phase transition already at tree level.

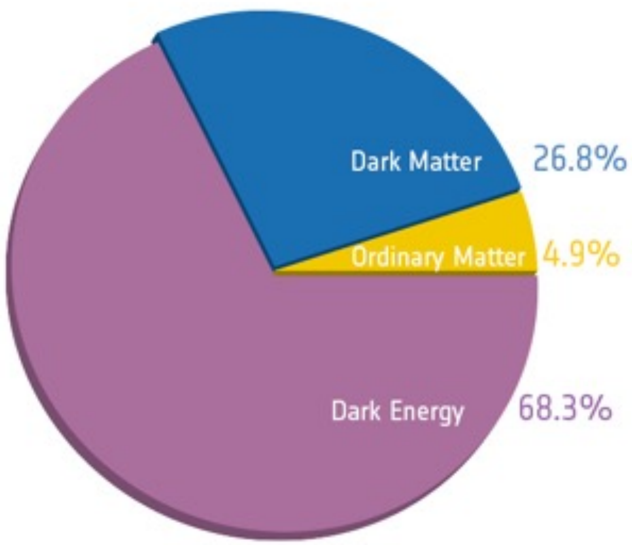
J.R. Espinosa, T. Konstandin, F. Riva, NPB854 (2012) 592



Tension, if also dark matter…

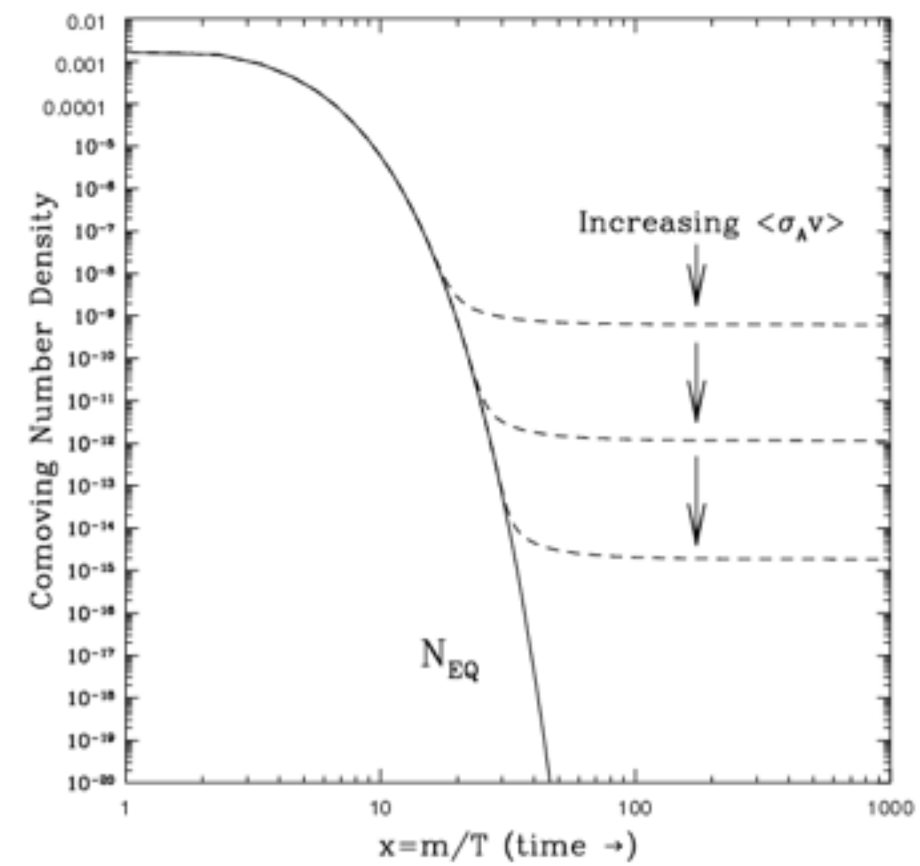
$$\Omega_S h^2 \sim \frac{1}{\langle \sigma v \rangle} \sim \frac{1}{\lambda_{\rm sh}^2}$$

Dark matter: $\Omega_{\rm DM} h^2 = 0.1198 \pm 0.0015$



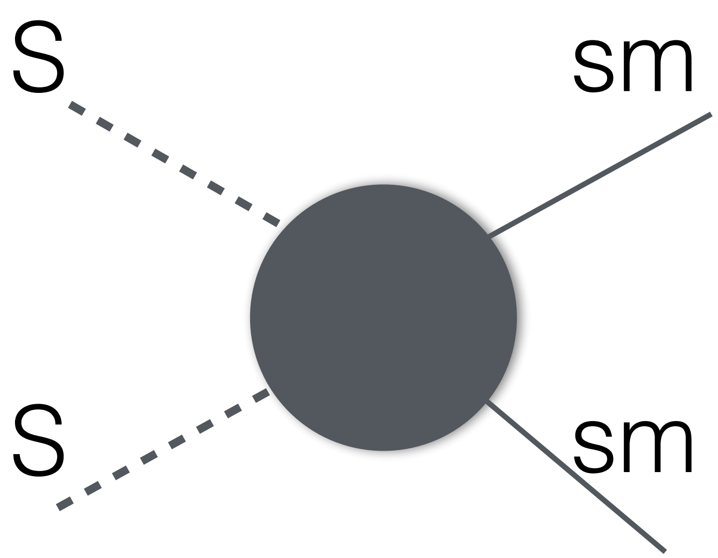
The WIMP paradigm:

Thermal relic,
Weakly interacting,
Massive



Prediction: should see systems like the bullet cluster

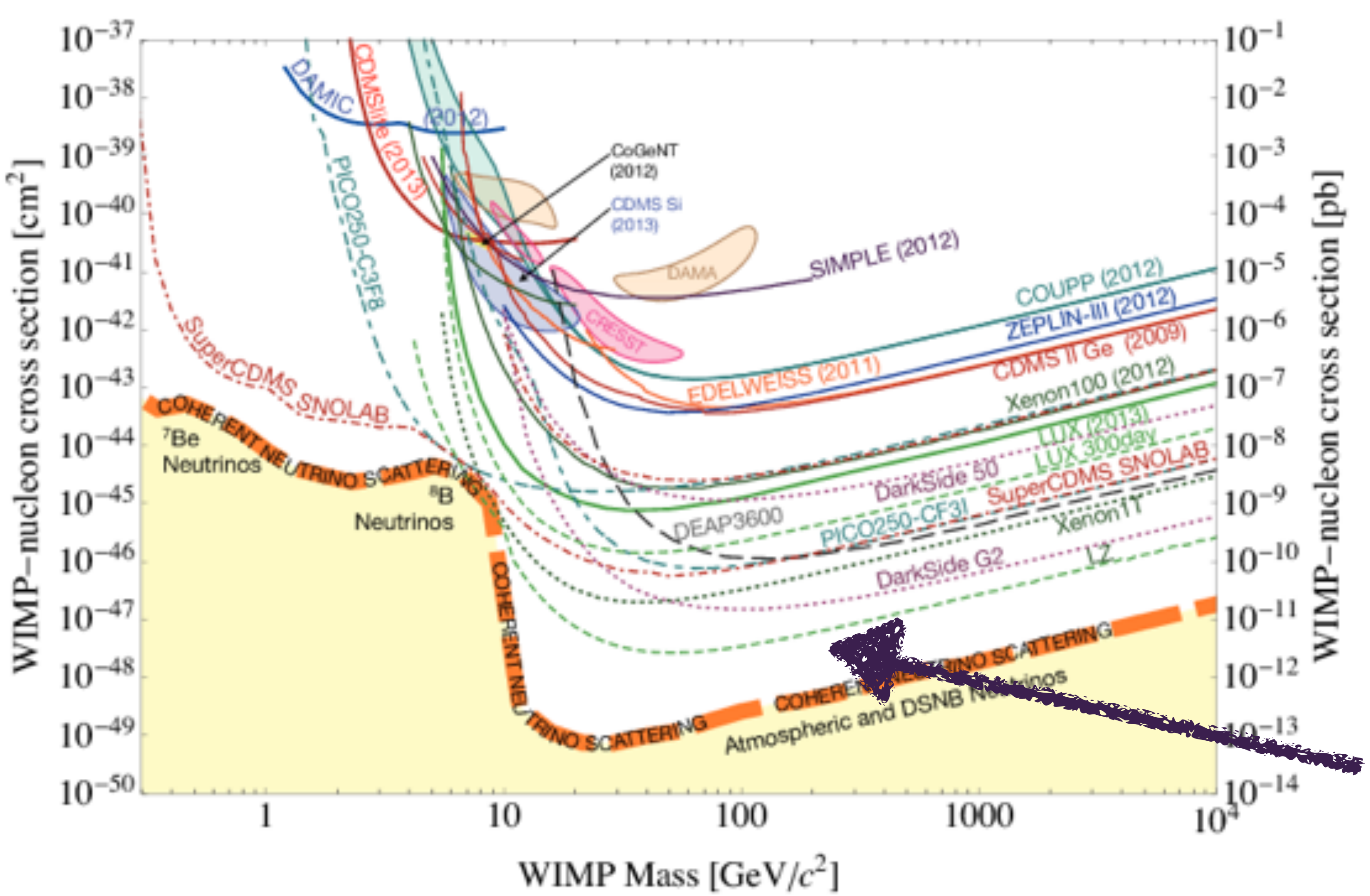
Thermal relic & direct detection



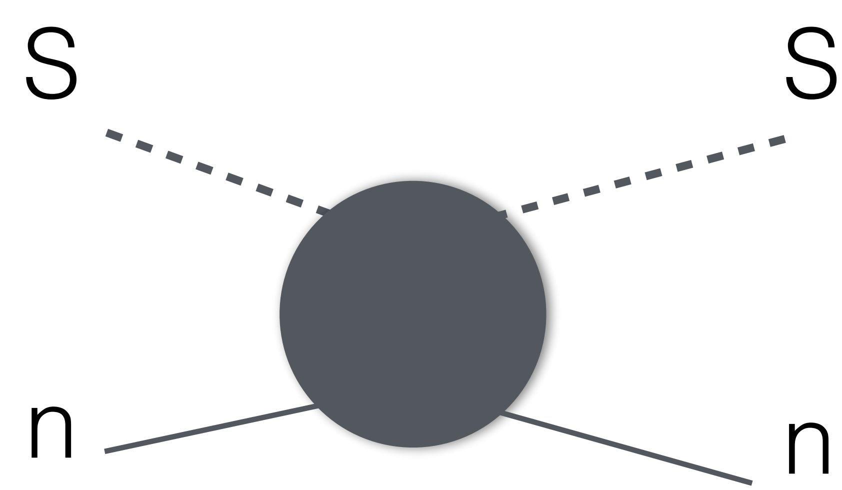
1. Abundance from ZOPLW-equ.

Y. Zel'dovich, L. Okun, S. Pikelner
Sov. Phys. Uspekhi. 8 (1966) 702-709.

B.W. Lee and S. Weinberg
PRL 39 (1977) 165-168.



2. Constraints from direct searches



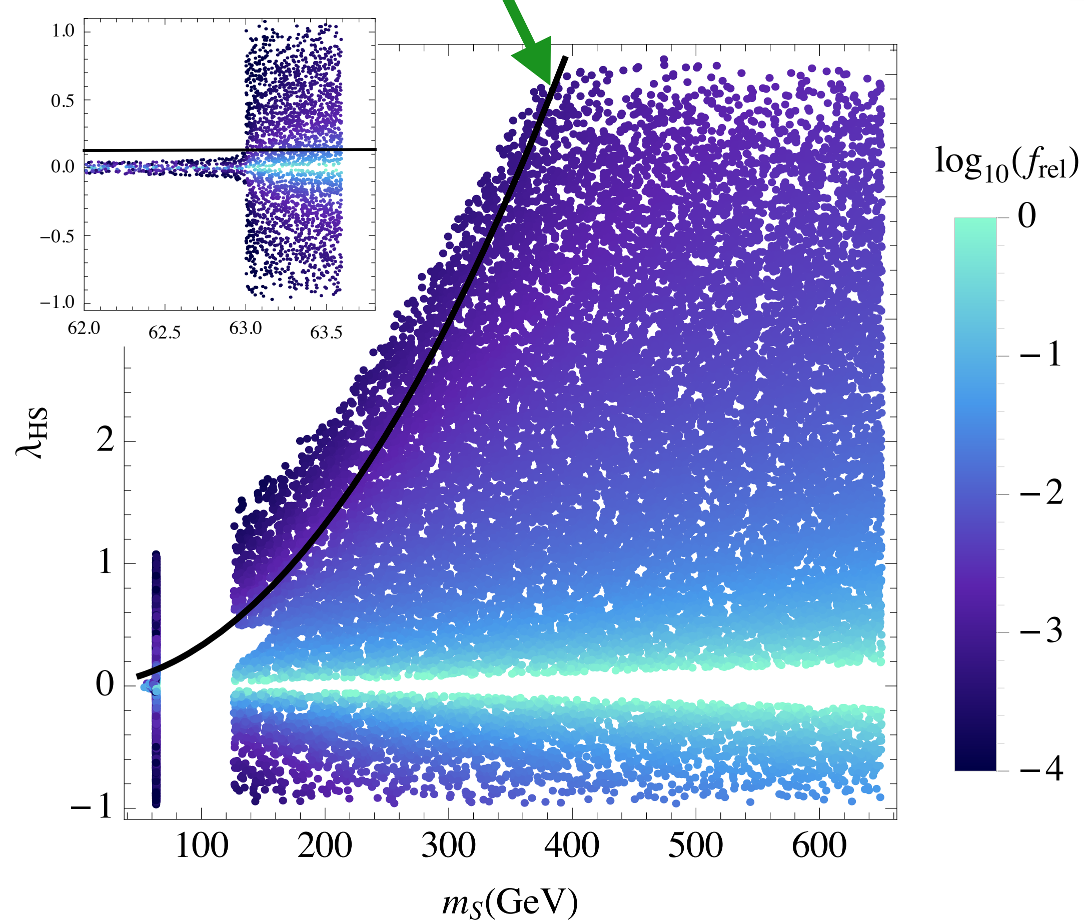
Note implicit assumptions in this plot!

SM+singlet scalar with Z2 symmetry: strong PT @ tree level and dark matter

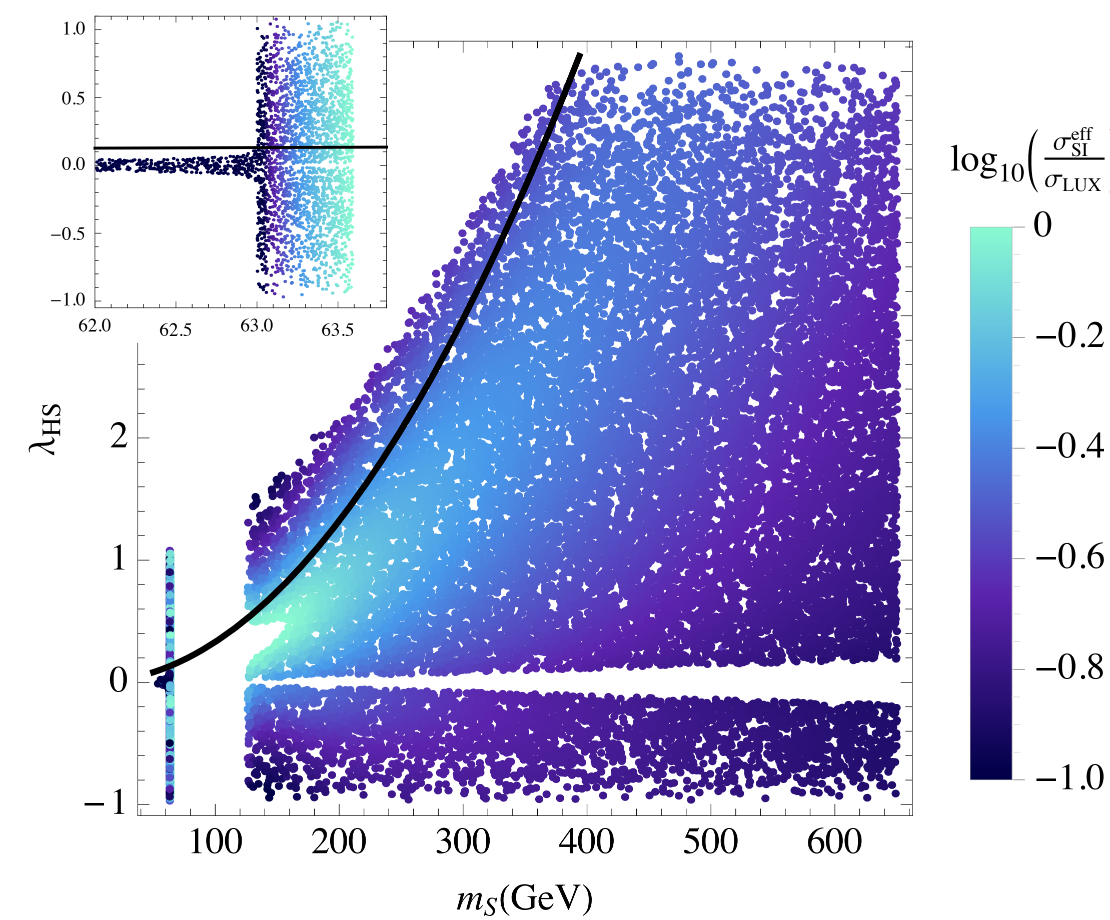
T. Alanne, KT, V.Vaskonen, 1407.0688.   + BG: K.Kainulainen, J. Cline, 1210.4196

$$V = V_{\rm SM} + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{\rm sh} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4$$

above the line $\mu_S^2 < 0$



$$f_{\rm rel} \equiv \frac{\Omega_S h^2}{0.12}$$



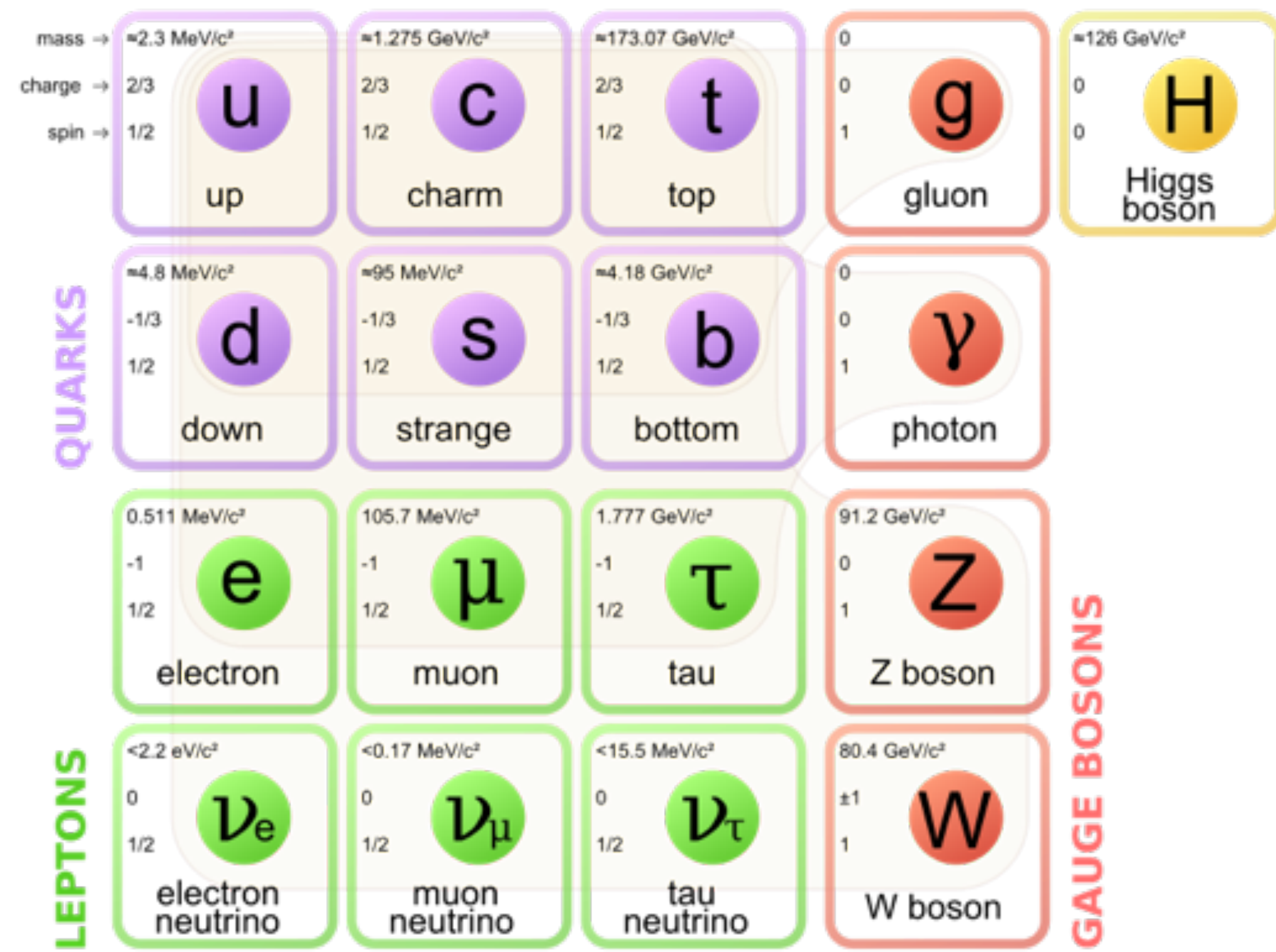
If strong PT required,
only subdominant DM possible.

If only subdominant DM from scalar,
more complex dark sector needed.

$$\sigma_{\rm SI} = \frac{1}{4\pi}\frac{\lambda_{HS}^2 \mu_N^2 f_N^2 m_N^2}{m_h^4 m_S^2}$$

$\Omega_b h^2 = 0.02225 \pm 0.00016$ is **not** simple.

Why $\Omega_{\rm DM} h^2 = 0.1198 \pm 0.0015$ should be?



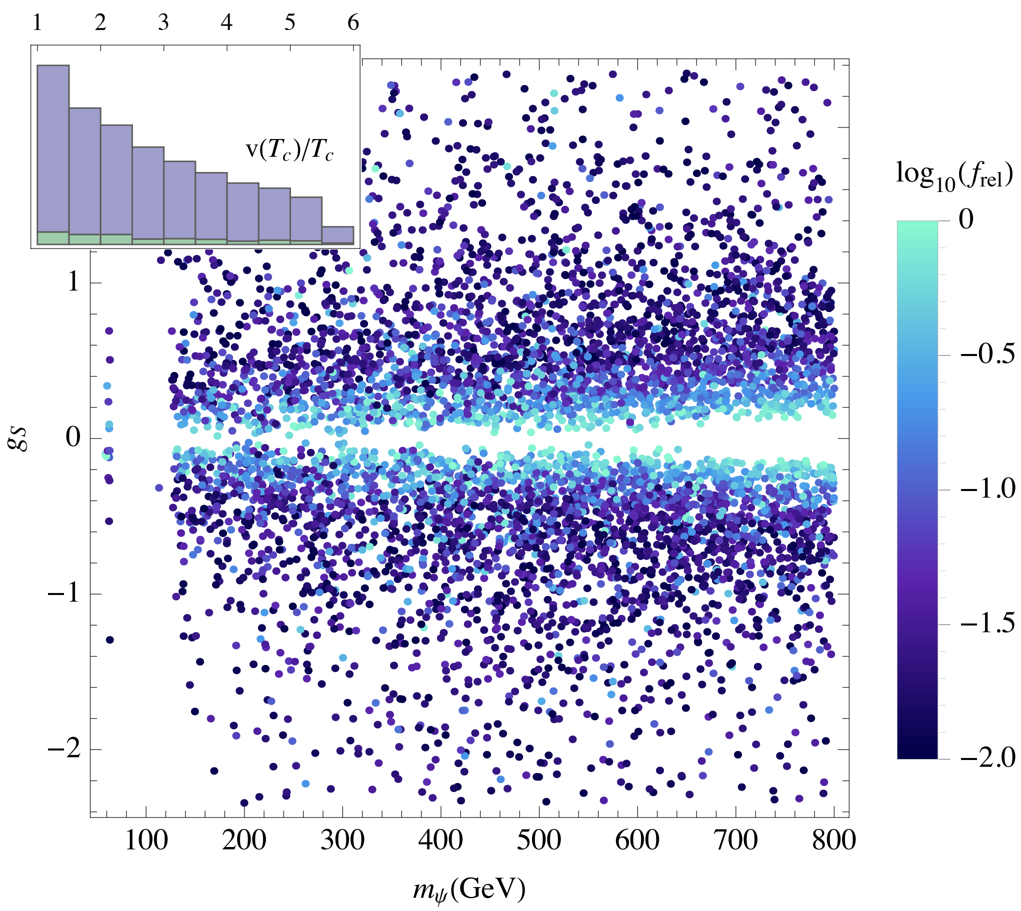
This to explain 4% of the universe…

Why not also some similar patterns to explain the rest?

- **Vector, scalar, fermion** dofs.
- **Compositeness.**

Example 1: SM+singlet scalar and fermion.

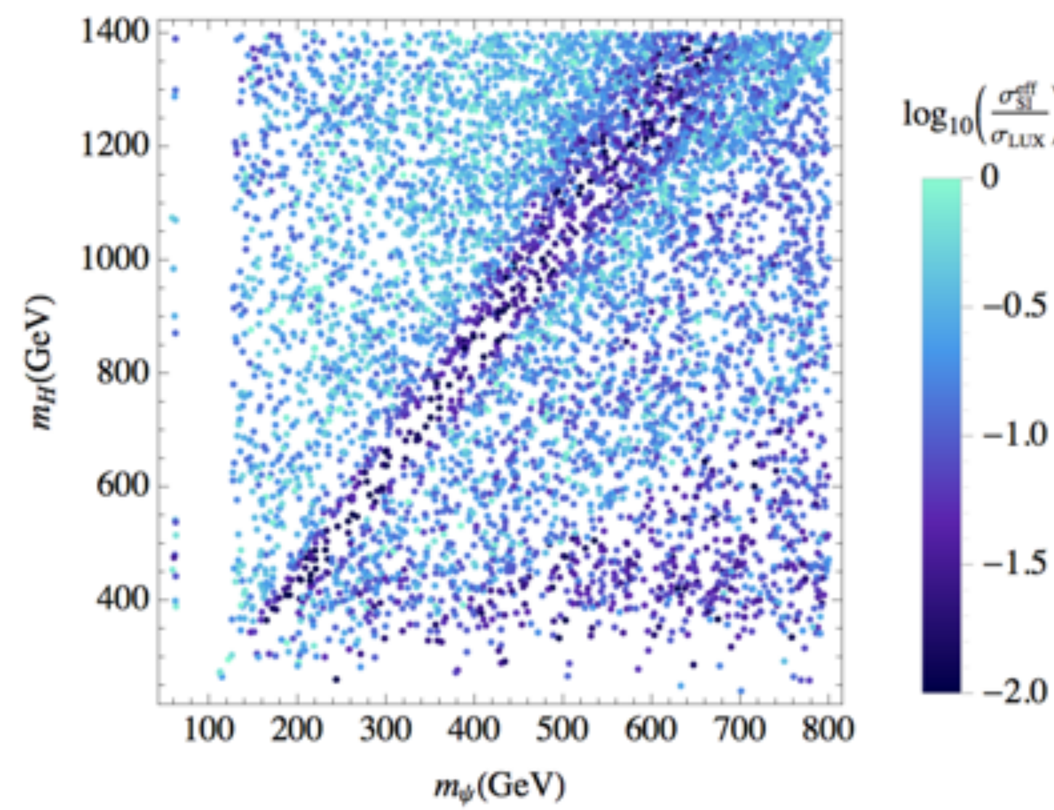
$$\mathcal{L}_{\rm DM} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + g_S S\bar{\psi}\psi.$$



✓ **Strong** 1st oder PT.

✓ **Dark matter** abundance

✓ **Compatible** with direct searches



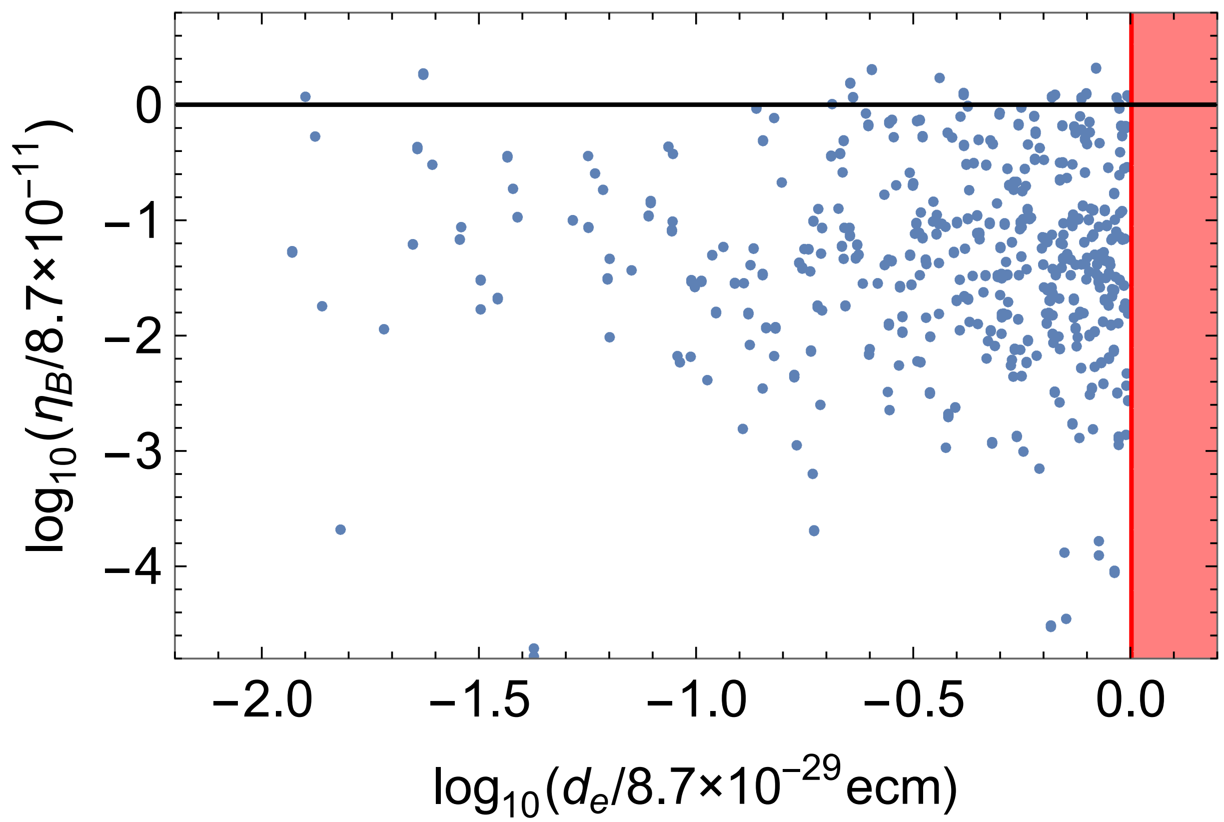
Example 2: S-2HDM

Motivated by
- MSSM
- Bosonic TC

Many new CP-violating phases.

$$V(H_1,H_2,S) = -m_1^2|H_1|^2 - m_2^2|H_2|^2 - \left(m_{12}^2 H_2^\dagger H_1 + h.c.\right) - \tfrac{1}{2}m_S^2 S^2$$
$$+ \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \left(\lambda_5(H_2^\dagger H_1)^2 + \lambda_6|H_1|^2(H_2^\dagger H_1) + \lambda_7|H_2|^2(H_2^\dagger H_1) + h.c.\right)$$
$$+ \tfrac{1}{4}\lambda_S S^4 + \tfrac{1}{2}\lambda_{S1}S^2|H_1|^2 + \tfrac{1}{2}\lambda_{S2}S^2|H_2|^2 + \left(\tfrac{1}{2}\lambda_{S12}S^2 H_2^\dagger H_1 + h.c.\right)$$

V. Vaskonen et al. in progress..



- ✓ **Strong** 1st oder PT.
- ✓ **Baryon asymmetry** generated.
- ✓ **OK** with **ACME** bound on eEDM.

Subdominant scalar WIMP DM
(similar as in SSM)

Hidden sectors

- Elementary or composite
- Very weakly coupled with SM
- Motivated by Dark Matter
- Gravitational waves,
- …

T. Hur, P. Ko, 1103.2571,
R. Lewis, C. Pica and F. Sannino, 1109.3513,
T. Appelquist et al. 1503.04203,
P. Schwaller, 1504.07263

(Strong) self-interactions

Self-interacting dark matter

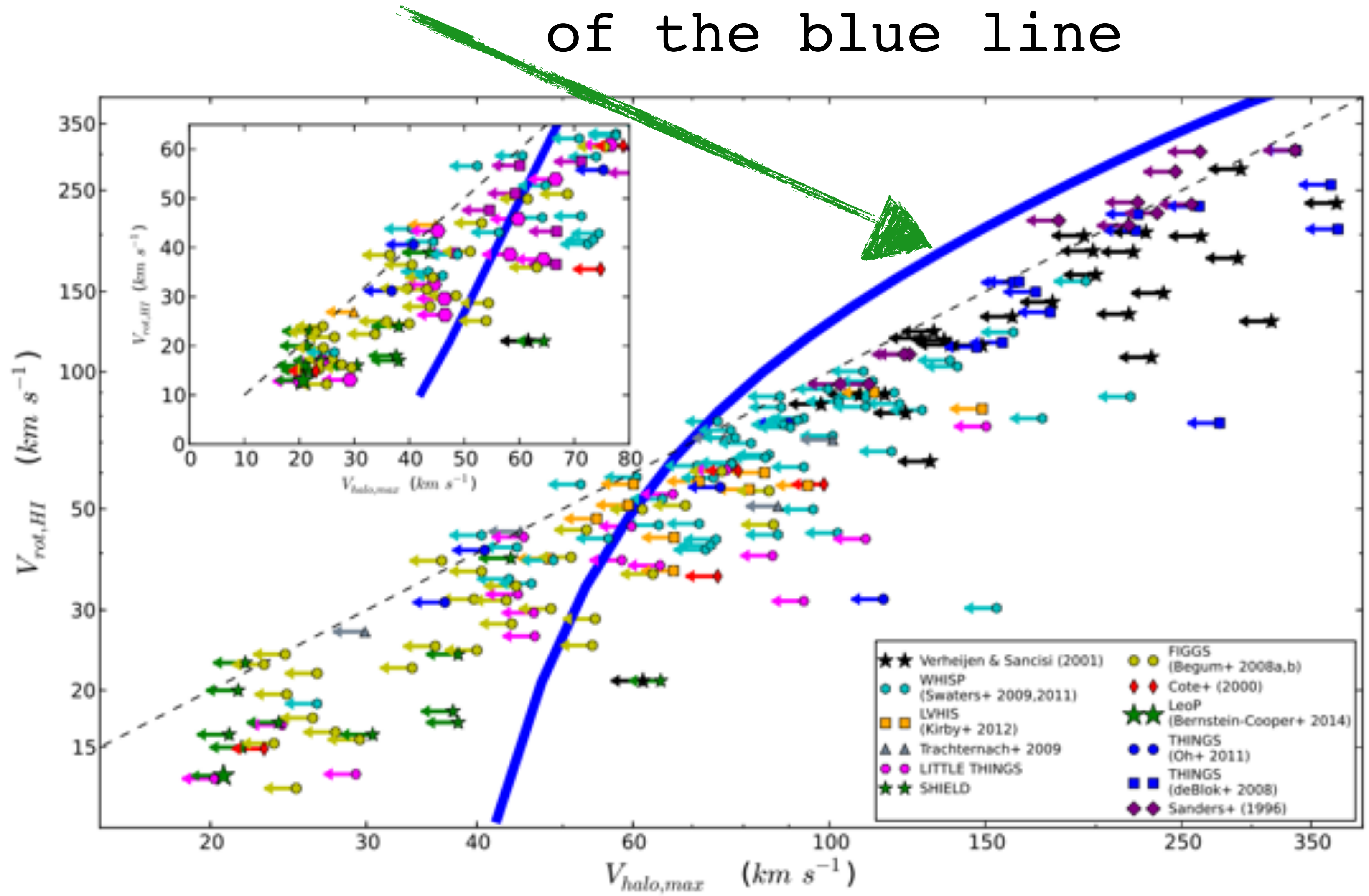
Problems* in ΛCDM
small scale structure:

- Missing satellites
- Core-cusp problem

Solved if DM has
self-interactions:

$$\frac{\sigma}{m} \sim (0.1 \ldots 10) \frac{\text{cm}^2}{g}$$

ΛCDM prediction to the right
of the blue line



E. Papastergis *et al.* 1407.4665

*I assume that these are **not** numerical glitches, but
real physical issues that can be resolved by self-interacting DM.

Cosmic colliders

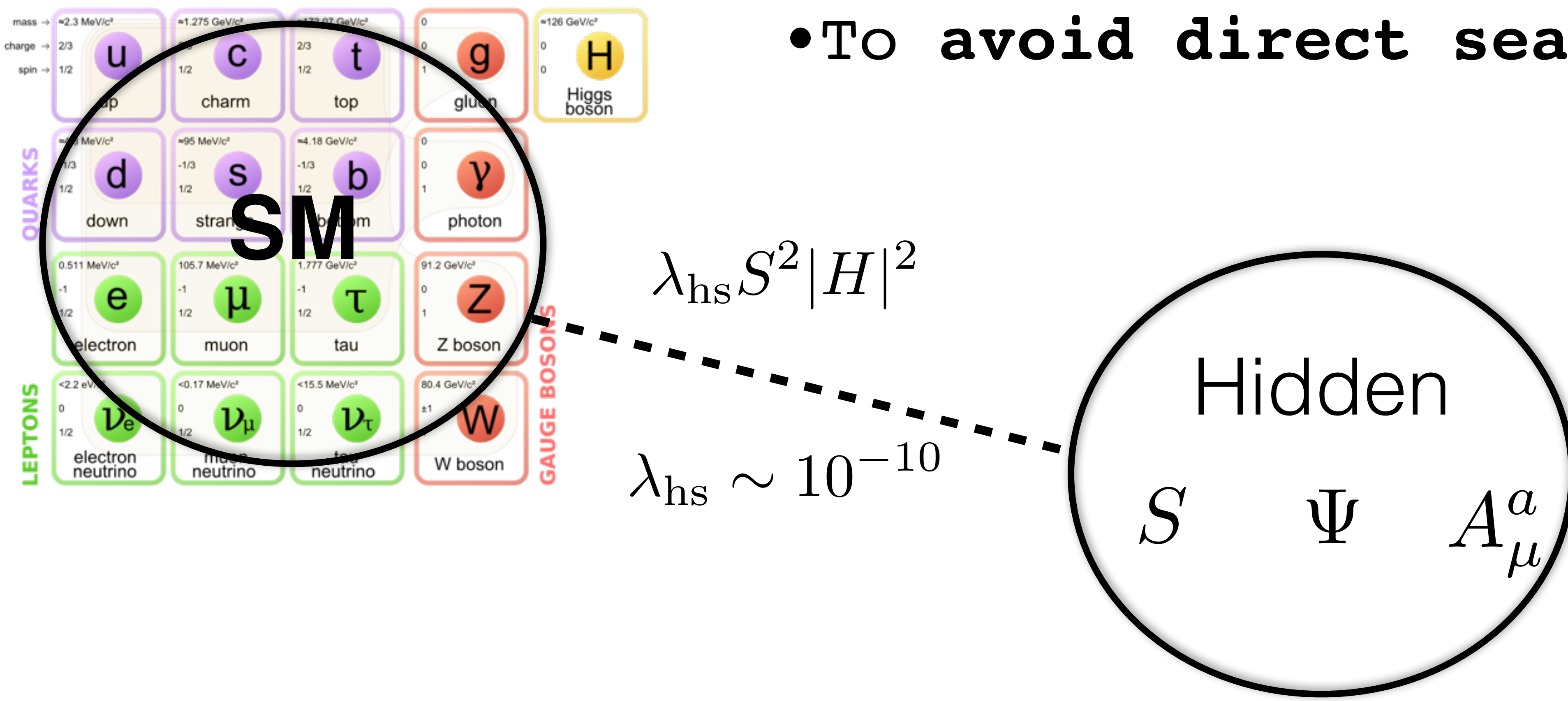
Bullet cluster:

$$\frac{\sigma}{m} \leq 1\,\frac{\mathrm{cm}^2}{\mathrm{g}}$$

Abell 520 (and 3827):

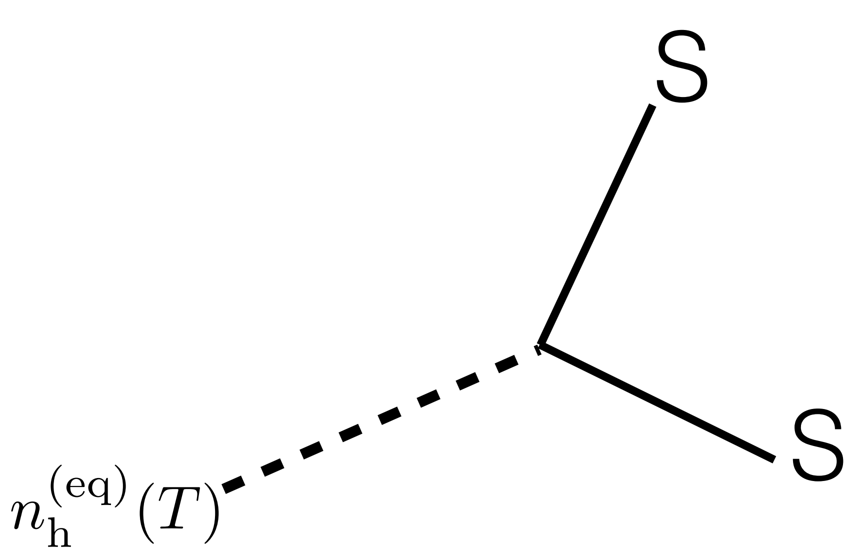
$$\frac{\sigma}{m} \sim 1\,\frac{\mathrm{cm}^2}{\mathrm{g}}$$

(Almost) decoupled singlet sectors



- To **avoid direct search** limits

- **Abundance** can be produced via **freeze-in.**



$$\lambda_{\rm hs} \simeq 10^{-11} \left(\frac{\Omega_{\rm DM} h^2}{0.12}\right)^{1/2} \left(\frac{\rm GeV}{m_s}\right)^{1/2}$$

- S **self-interactions** can be **large.**

Fluctuations

P.Ade et al, ArXiv:1502.02114
(Planck 2015 Constraints on Inflation)

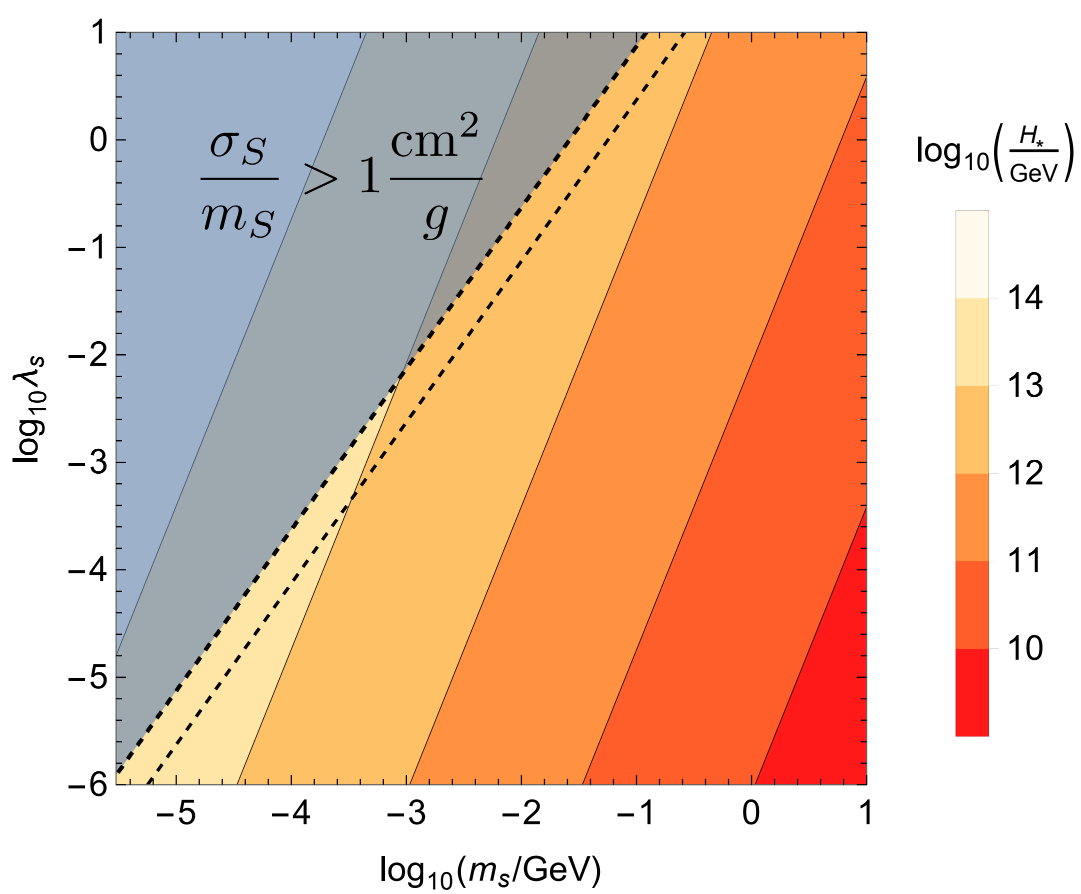
K. Kainulainen, S. Nurmi, T. Tenkanen, KT, V. Vaskonen, 1601.07733

$$V = V_{\rm SM} + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{\rm sh} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4$$

$$\mu_S^2 > 0$$
$$\lambda_{\rm sh} \sim 10^{-10}$$

At the end of the inflationary epoch, the scalar fields are displaced from origin:

$$h_* \simeq 0.36 \frac{H_*}{\lambda_{\rm h}^{1/4}}, \qquad s_* \simeq 0.36 \frac{H_*}{\lambda_s^{1/4}}$$



The coherent higgs field dissipates rapidly into the SM thermal bath.

- S remains out of equilibrium.
- contributes to dark matter
- primordial isocurvature fluctuations

Constraint from Planck data:

$$\frac{m_{\rm DM}}{\rm GeV} \leq 6\lambda_s^{3/8}\left(\frac{H_*}{10^{11}\rm GeV}\right)^{-3/2}$$

Lower bound on self coupling.

Favours strong coupling.
Thermalisation within the singlet sector?

“Conclusions”

- BSM building provides new opportunities for EWBG.

- Elementary or composite hidden sector dark matter.

- Constraints from inflation, new paradigms for EU thermo.