First, thanks for the organizers for iniviting me here

and **thanks to Keith**

...for hiring me here in 1992 for my 2nd post doc and the first one "truly away from home".

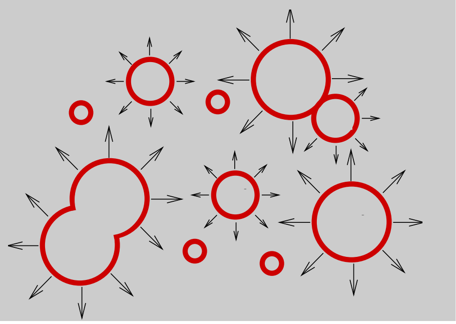
It was with Keith that I first started working on Baryogenesis (protecting primordial BAU), that eventually led me to work on **EWBG**

This was (is) a great place with great people, **Keith** obviously**,** but also **Arkadi, Larry, Mischa S and Mischa V,...** and a bunch of great post docs including **Jim Cline** (who sends his regards!).

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Baryogenesis from Dark Sector

Kimmo Kainulainen,
Olivefest 2017 / 17.5.2017



with:
Tommi Alanne, **Jim Cline**, Pat Scott,
Mike Trott, Kimmo Tuominen,
Ville Vaskonen, Christoph Weniger,
Dave Tucker-Simith, Sami Nurmi,
Tommi Tenkanen …

SM almost UV-complete:
- simplicity as a guiding principle, solve issues with **DM** and **BAU**

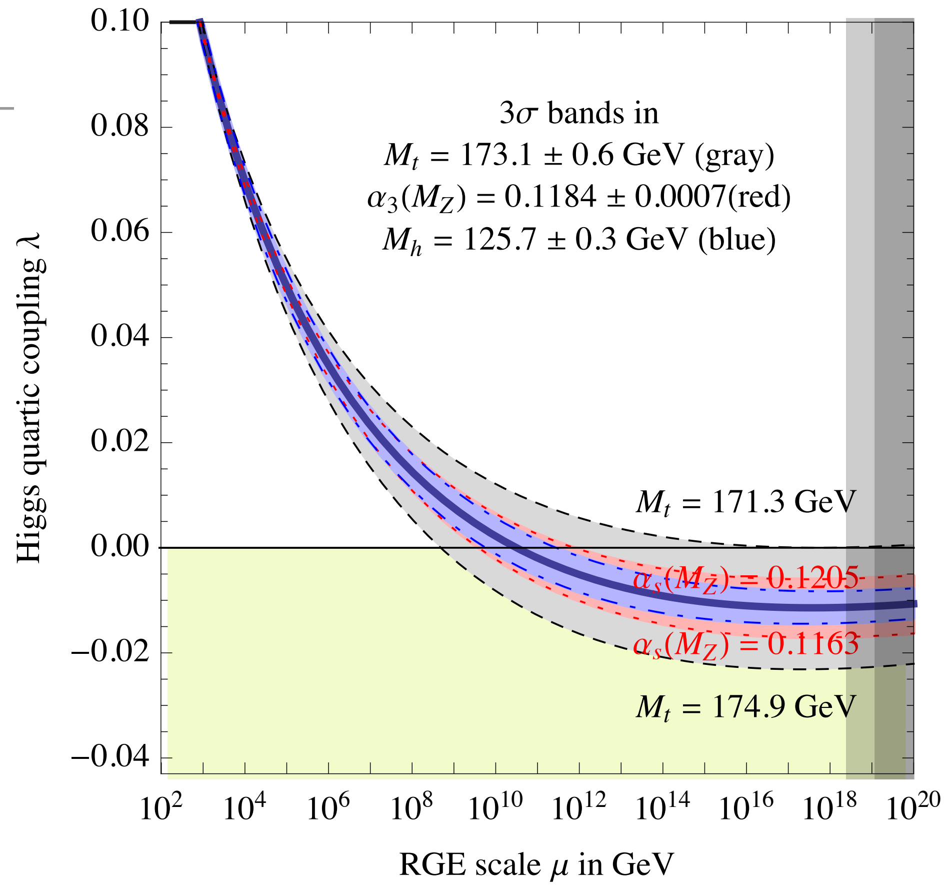
EWBG: Obvious models are ~dead:
~~**MSM, MSSM, 2HDM…**~~
- Transition strength (TS)?
- CP-violation ?

EWBG goes Dark Side
- Higgs portal/singlet models (DM,TS)
- CP-portal

UV-completion

May we have just (almost) SM all the way to the Planck scale?

Espinosa, Giudice, Riotto, JCAP 0805 (2008) 002
Degrassi etal, JHEP 1208 (2012) 098



Possible running to negative coupling can be cured for example by a *singlet S*

$$\frac{1}{2}\lambda_{hs}|H|^2S^2 \Rightarrow \beta(\lambda) \to \beta(\lambda)_{\rm SM} + \frac{1}{2}\lambda_{hs}^2 \quad (\lambda_{hs} \approx 0.7)$$

~~FT. UNIFICATION~~ → **Asymptotic safety** ✓
problem of gauge Landau poles — with gravity corrections, or…

Robinson and Wilczeck, PRL 96, 231601 (2006)
Wetterich and Shaposhnikov, Phys.Lett. B683 (2010)

~~HIERARCHY PROBLEM~~ → **No intermediate scales** ✓ (technically)
behaviour of relevant operators

Remain the problems of **BARYON ASYMMETRY** **DARK MATTER**

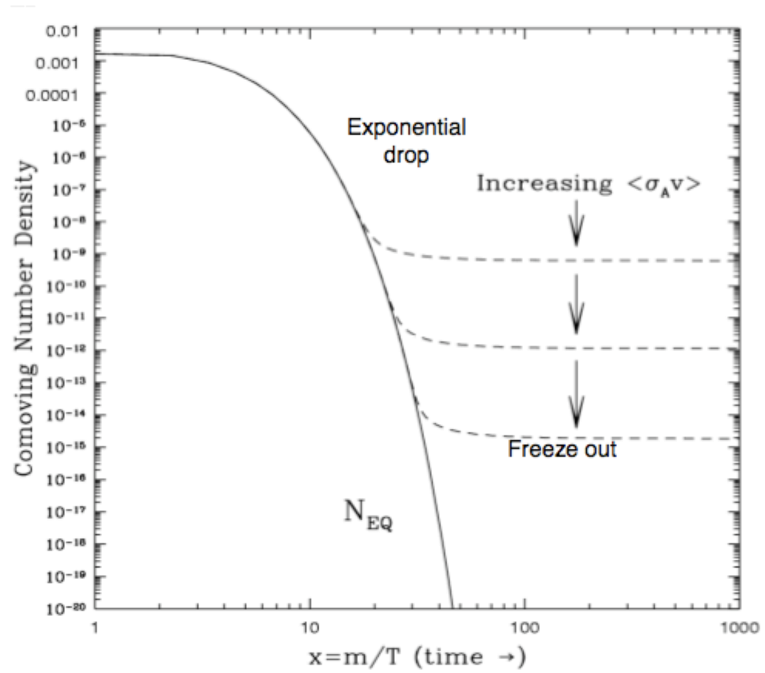
If **minimality** is the guiding principle, these **should** rather **be solved at low E**

Dark Matter (Thermal) **WIMP** (Freeze-out)

- Cold
- Non-baryonic
- Neutral, or weakly interacting
- **Stable (by some discrete symmetry)**

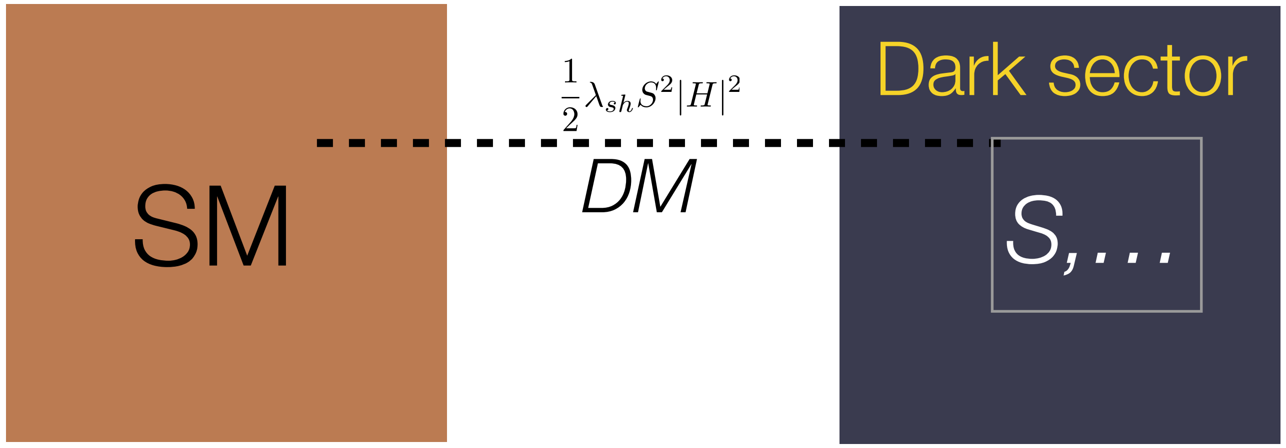
DM DM —> SM SM
DM $\not\to$ SM +…

$$\Omega_{DM} \sim \frac{1}{\langle v\sigma \rangle}$$



Popular context:

Simple **Portals to** (perhaps complex) **Dark sector**



J.M.Cline, KK,
JHEP 1111 (2011) 089
JCAP 1301 (2013) 012
Phys.Rev. D87 (2013)7,071701

J.M.Cline, KK, P.Scott, C.Weniger
PRD88 (2013) 055025

J.M.Cline, KK. D.Tucker-Smith,
in progress.

KK, K.Tuominen and V.Vaskonen
Phys.Rev. D93 (2016) 7 ,015016

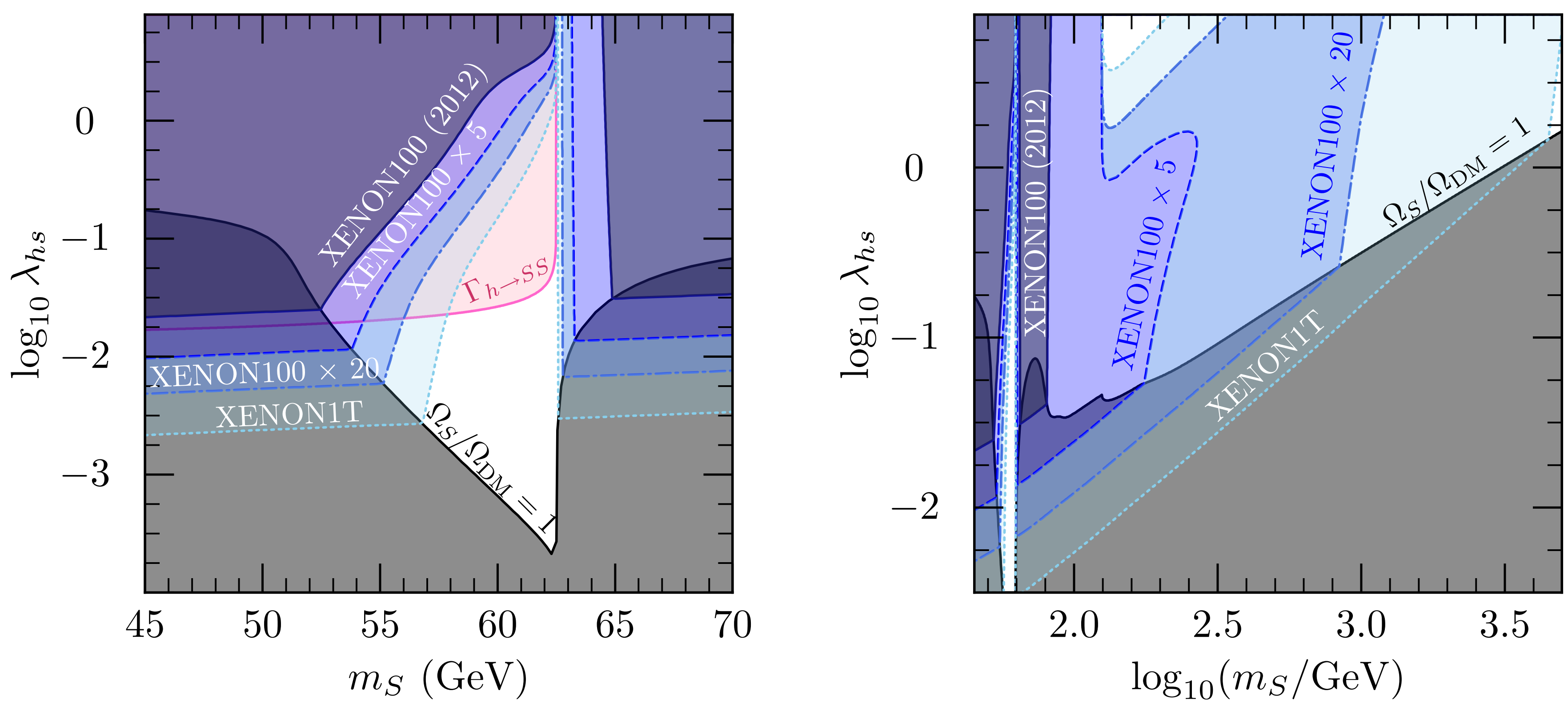
T.Alanne, KK, K.Tuominen, V.Vaskonen
JCAP 1608 (1016) no08, 057,

KK, S.Nurmi, T.Tenkanen,
K.Tuominen and V.Vaskonen
JCAP 1606 (2016) no.06, 022

Solution: DM (Given Z_2-symmetry) DM can be singlet scalar

The (simplest possible) **model:**

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



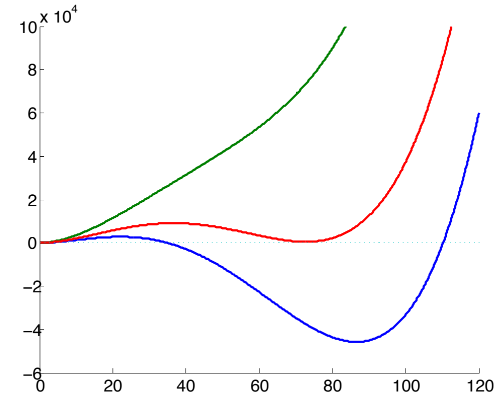
Xenon bounds account for the fact that $f_{\rm rel} \leq 1$.

J.M.Cline, KK, P.Scott, C.Weniger PRD88 (2013) 055025

$$\Omega \sim \frac{1}{\langle v_{\rm Mol}\sigma\rangle} \sim \frac{1}{\lambda_{\rm hs}^2}$$

MANY (more complicated) alternatives also work

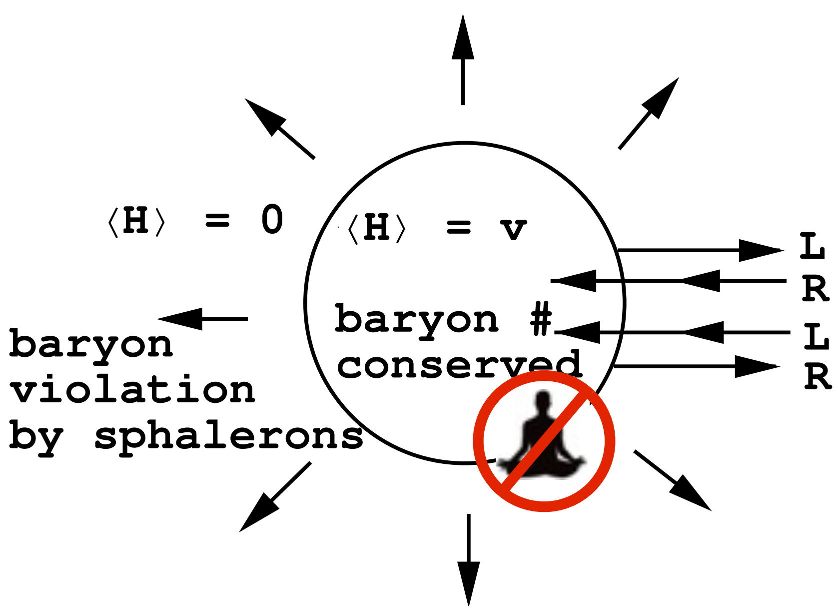
EWBG



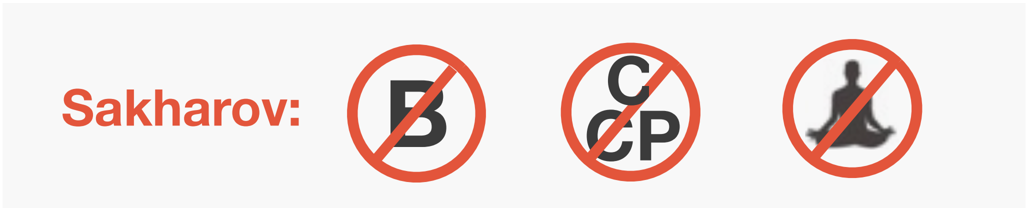
* Out-of-eq => BSM

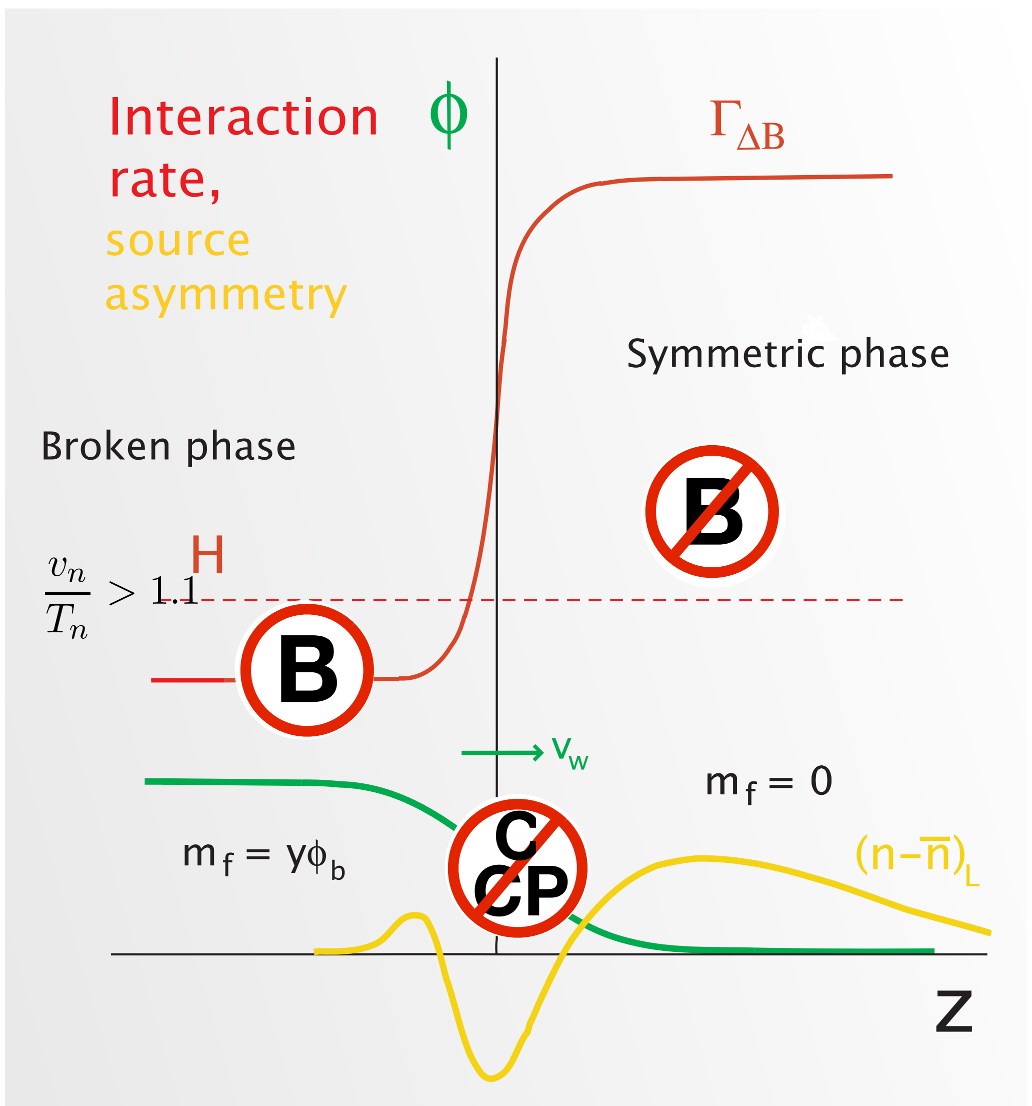
$$H \sim 10^{-14} T_{100}^2 \mathrm{GeV}$$
$$\Gamma \sim 10^{-5} T_{100} \mathrm{GeV}$$

=> need a **bubble**



$$\frac{1}{t_w} \sim \frac{v_w}{L_w} \sim 10^{-5} T_{100}$$

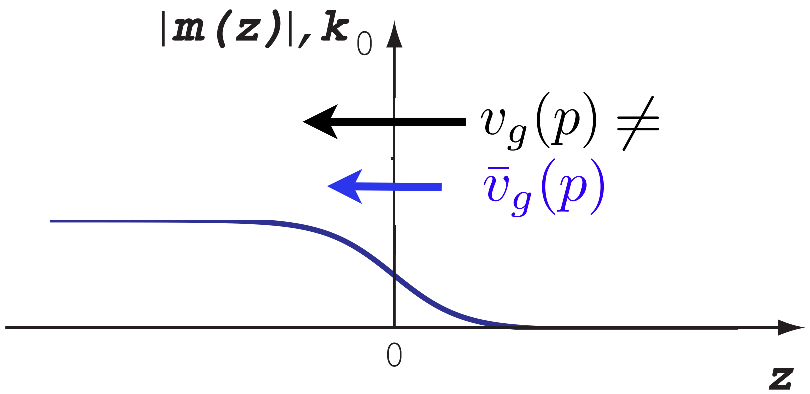




May be killed by lack of

* Strong transition
* CP-violation

Creating baryons / CP-violation / Semiclassical limit

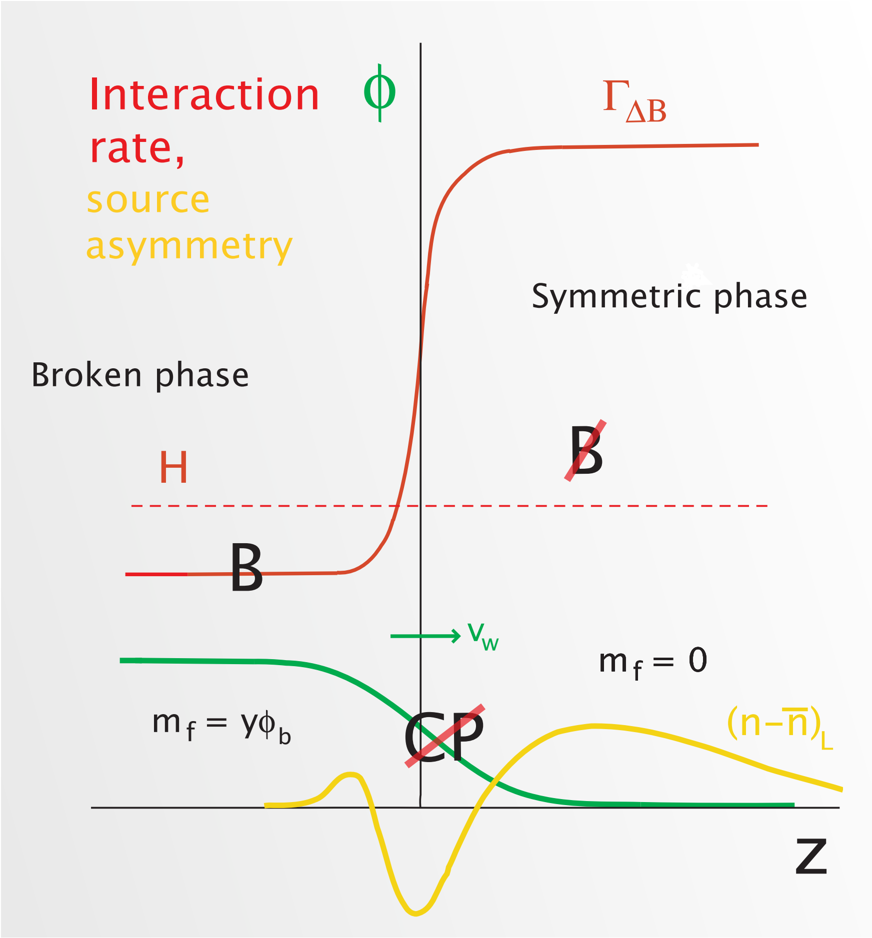


$$(\partial_t + \mathbf{v}_g \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) f_i = C[f_i, f_j, \ldots] \,.$$

$$v_g = \frac{p_0}{\omega}\left(1 + s_{\rm CP}\frac{s|m|^2\theta'}{2p_0^2\omega}\right) \qquad m = |m(z)|e^{i\theta(z)}$$

$$F = -\frac{|m||m|'}{\omega} + s_{\rm CP}\frac{s(|m|^2\theta')'}{2\omega^2} \,.$$

CP -force



NEEDS LARGE, CHANGING CP-VIOLATING PHASES AT THE TRANSITION REGION

WKB J.M. Cline, M. Joyce and K. Kainulainen. PLB417 (1998) 79; JHEP 0007 (2000) 018
J.M. Cline and K. Kainulainen, PRL85 (2000) 5519.
M. Joyce, T. Prokopec and N. Turok, PRD53, 2958 (1996); PRL75, 1695 (1995); PRD53, 2930 (1996).

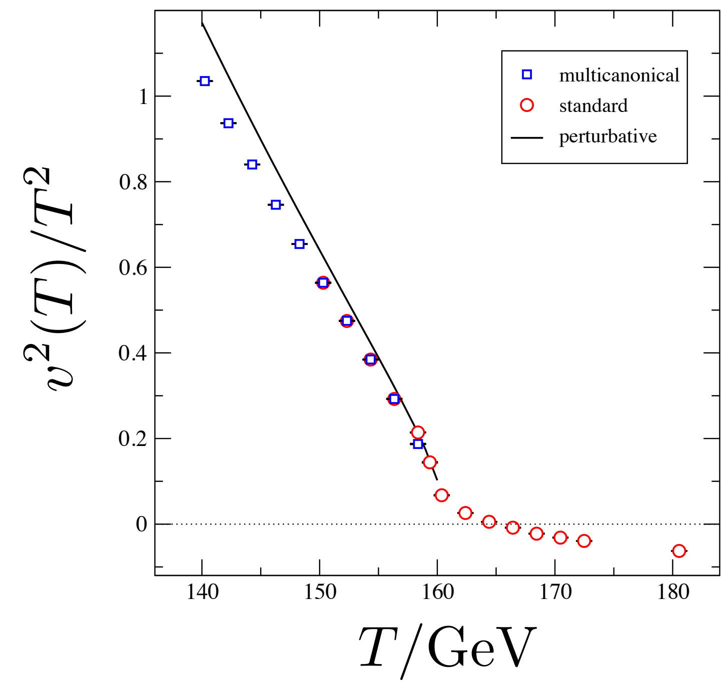
CTP K. Kainulainen, T. Prokopec, M.G. Schmidt and S. Weinstock, JHEP 0106, 031 (2001); PRD66 (2002) 043502.
T. Prokopec, M.G. Schmidt and S.Weinstock, Annals Phys. 314, 208 (2004), Annals Phys. 314, 267 (2004)

MSM Transition strength ✗ / B-violation rate ✓

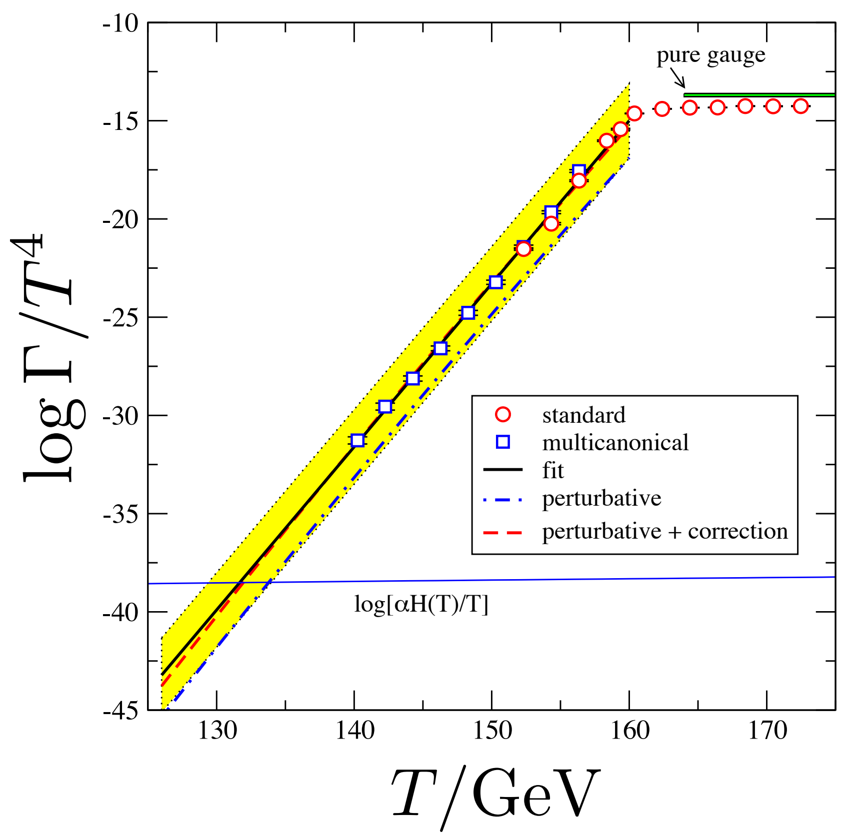
PT in SM, is a **cross-over** at

T = 159.6 ± 0.1 ± 1.5 GeV

M.d'Onofrio, K.Rummukainen, A.Tranberg, Phys.Rev.Lett. 113 (2014) no.14, 141602



no bubble



Sphaleron rate in SM

$$\Gamma_{\mathrm{Symm.}}/T^4 = (8.0 \pm 1.3) \times 10^{-7} \approx (18 \pm 3)\alpha_W^5$$

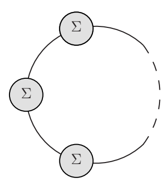
$$\log \frac{\Gamma_{\mathrm{Broken}}}{T^4} = (0.83 \pm 0.01)\frac{T}{\mathrm{GeV}} - (147.7 \pm 1.9)$$

Sphalerons in equilibrium until $T \approx 132$ GeV $< T_{PT}$ => **washout** !

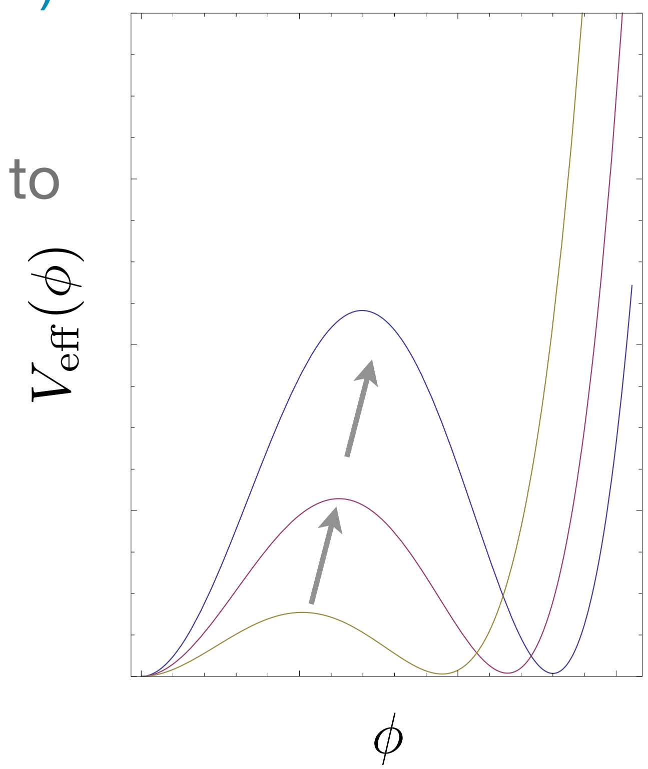
MSSM LSS - transition strength

Traditionally: **increase the strength by** (effective cubic) **loop corrections**

Need new light ($m_i < T$) bosonic fields strongly coupled to Higgs



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



=> **Light Stop Scenario** in **the MSSM** and NMSSM

[Carena, Quiros, Wagner (1996), … Espinosa, Quiros, Zwirner, Laine,Cline,KK,Losada,...]

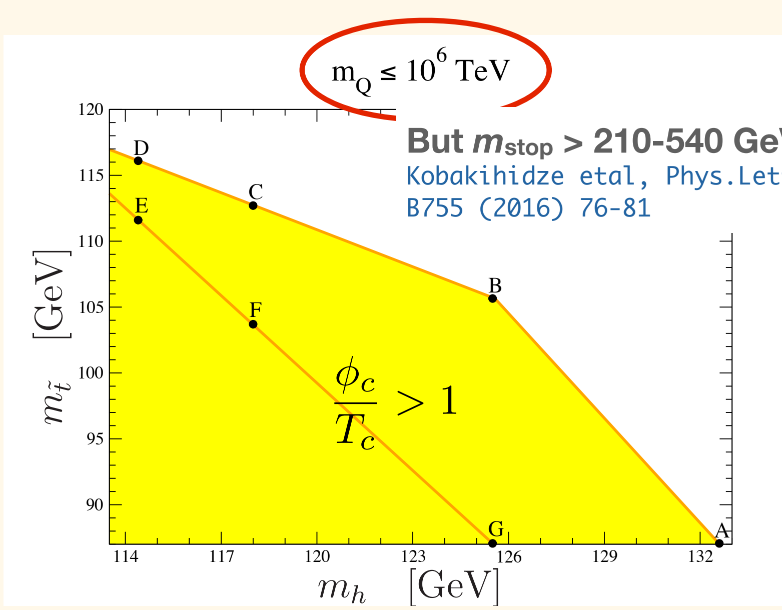
However, higgs mass mostly from squarks:

$$m_h^2 \sim y_t^2 \log \frac{m_{\tilde{t}_R}^2 m_{\tilde{t}_L}^2}{m_t^4}$$

Tension: light t_R => **very heavy t_L**

.. and this just has gotten too tight …

Carena, etal. 2009, 2013



But m_{stop} > 210-540 GeV
Kobakihidze etal, Phys.Lett. B755 (2016) 76-81

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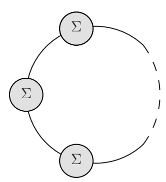

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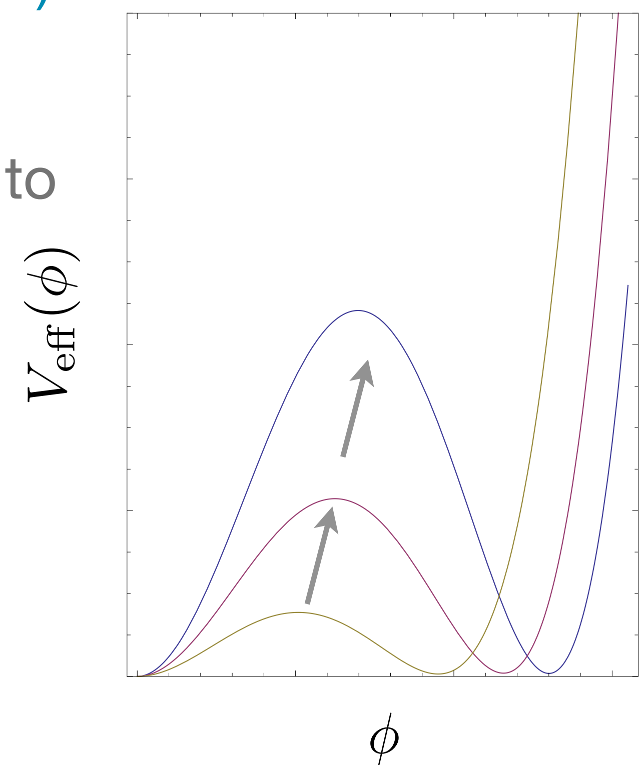

Leszek Roszkowski (Nordita, June 2015):

“SUSY cannot be disproved, only abandoned”

(the actual content misunderstood here in purpose)

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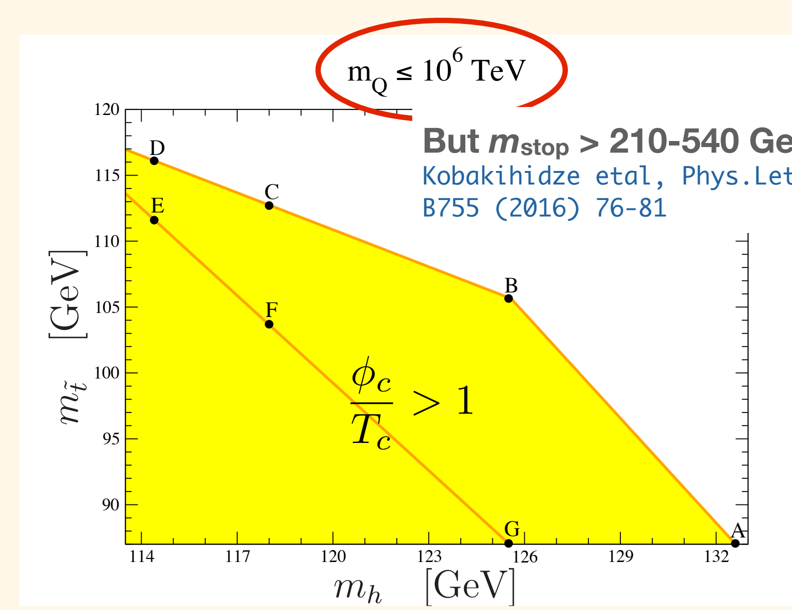

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2HD models (no DM ✗)

many new CP-violating pms.

Full GL(2,C)-reparametrization invariant potential

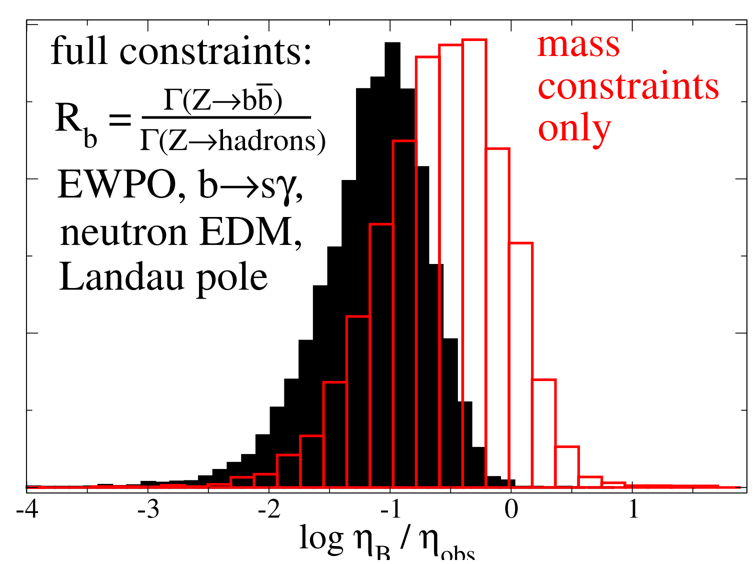
J.Cline, KK, M.Trott, JHEP 1111 (2011) 089

$$
\begin{aligned}
V = {} & \frac{\lambda}{4}\left(H^{\dagger\, i} H_i - \frac{v^2}{2}\right)^2 + m_1^2\,(S^{\dagger i}\, S_i) + (m_2^2\, H^{\dagger\, i} S_i + \text{h.c.}) \\
& + \lambda_1\,(H^{\dagger\, i} H_i)\,(S^{\dagger\, j} S_j), + \lambda_2\,(H^{\dagger i}\, H_j)\,(S^{\dagger j}\, S_i) + \left[\lambda_3 H^{\dagger i}\, H^{\dagger j}\, S_i\, S_j + \text{h.c.}\right], \\
& + \left[\lambda_4 H^{\dagger i}\, S^{\dagger j}\, S_i\, S_j + \lambda_5 S^{\dagger i}\, H^{\dagger j}\, H_i\, H_j + \text{h.c.}\right] + \lambda_6 (S^{\dagger i} S_i)^2, \\
& + y_t \bar{t}_L (H^{0*} \delta_{ti} + (\eta_U \delta_{ti} + \eta'_U V^*_{tb} V_{bi})) S^{0*}) q^i_R
\end{aligned}
$$

MFV to avoid **FCNC** (Yukawa sector)

G.C.Branco, W.Grimus & L.Lavoura, PLB380 (1996) 119

Strong EWPT and large BAU points were rare then: **<1/10⁴**.



Strongest bounds always from EDM's, so ACME killed these models

ACME Collaboration, Science 343 (2014) 269–272

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$$+\lambda_1 (H^{\dagger i} H_i)(S^{\dagger j} S_j), +\lambda_2 (H^{\dagger i} H_j)(S^{\dagger j} S_i) + \left[\lambda_3 H^{\dagger i} H^{\dagger j} S_i S_j + \text{h.c.}\right],$$
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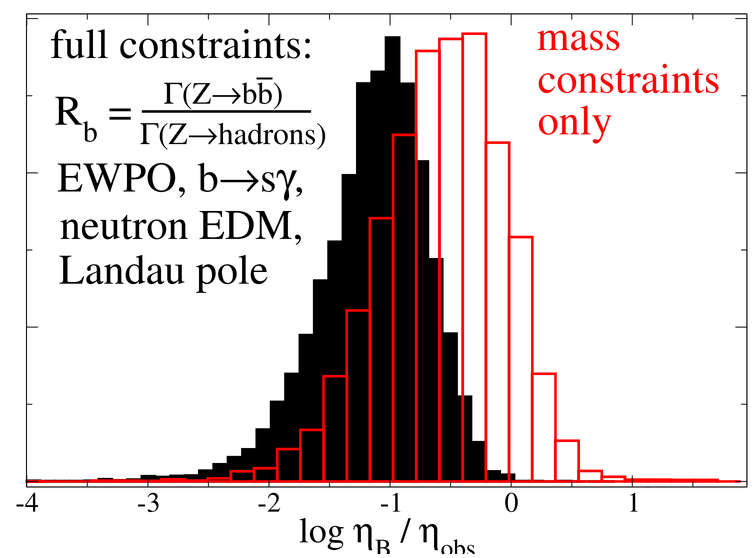

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ACME Collaboration, Science 343 (2014) 269–272

Strong transition and strong CP-violation

Generic issue:

Strong transition > large $|\lambda_i$'s$|$

Large B > large phases

-> large EDM's

Need something to alleviate burden on 2HDM λ_i's

Singlet model Strong transition

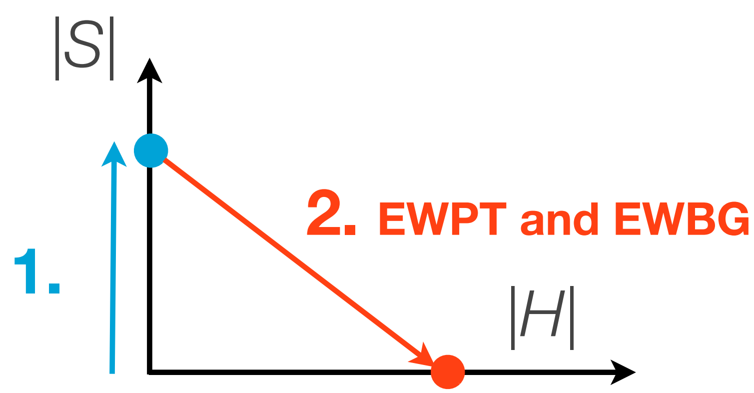
Anderson, Hall, PRD45, 2685 (1992)
Profumo, Ramsey-Musolf, Shaughnessy, JHEP 0708 (2007) 010

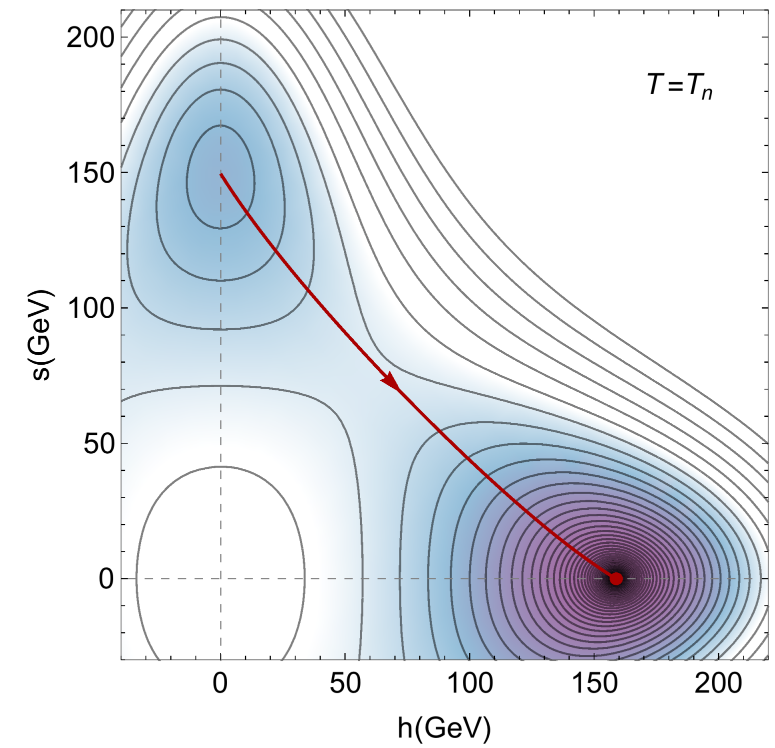
Use tree level barrier:

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

only the leading high-T

$$V = \frac{1}{2}\lambda_{hs} h^2 s^2 - (\mu_s^2 - c_s T^2) s^2 - (\mu_h^2 - c_h T^2) h^2 + \ldots$$





Arrange c_s, c_h, μ_s and μ_h so that transition goes in *two steps*
→ large barrier at T_c → strong transition. This WORKS

- large barrier requires largish λ_{hs}
- 2-step mechanism needs small m_s

Variants of the scheme:
Inoue, Ovanesyan, Ramsey-Musolf, PRD93 (2016) 015013, etc…

Idea actually present in the MSSM ~color breaking
Laine, Rummukainen, Cline, Moore, Quiros …,

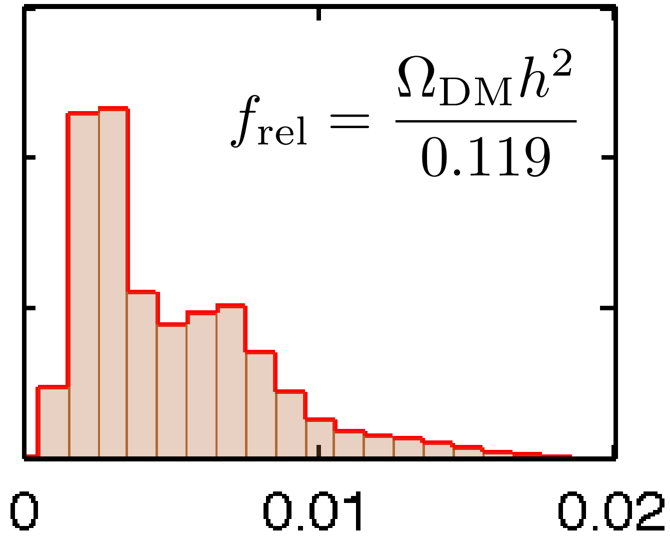
Singlet model Strong transition *and* S-DM?

However, large λ_{hs} gives small Ω:

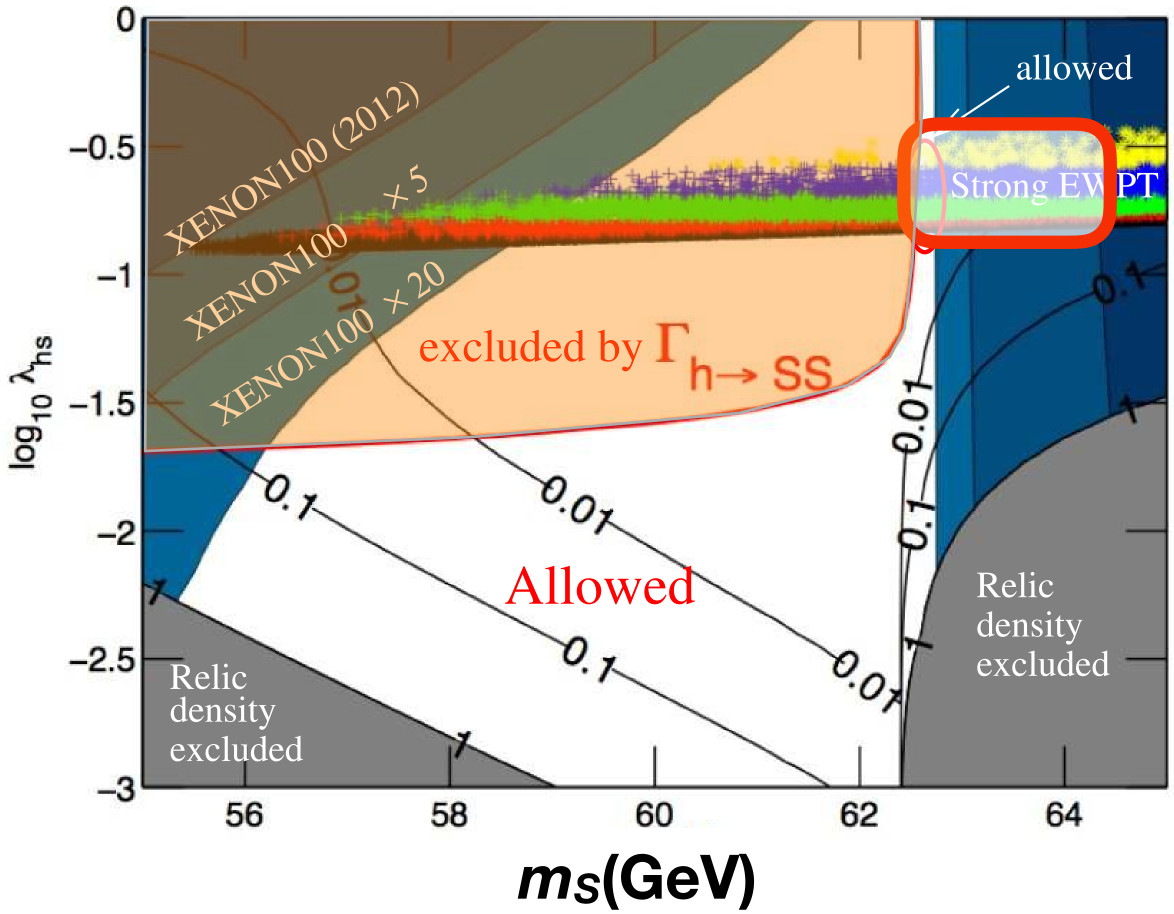
$$\Omega \sim \frac{1}{\langle v_{\rm Mol}\sigma\rangle} \sim \frac{1}{\lambda^2_{\rm hs}}$$

Strong transition implies a **subdominant DM**

BAU acceptable *v/T >1* models



J.M. Cline, KK, JCAP 1301 (2013) 012



J.M.Cline, KK, P.Scott and C.Weniger, PRD88 (2013) 055025

Further extensions with more singlets, or new fermions, or ...

KK, K.Tuominen and V.Vaskonen, PRD93(2016) 7,015016

Singlet model **Strong transition *and* BAU?**

BAU from top transport

DM stability =>Z_2 symmetry: $\langle S \rangle_{T=0} = 0$

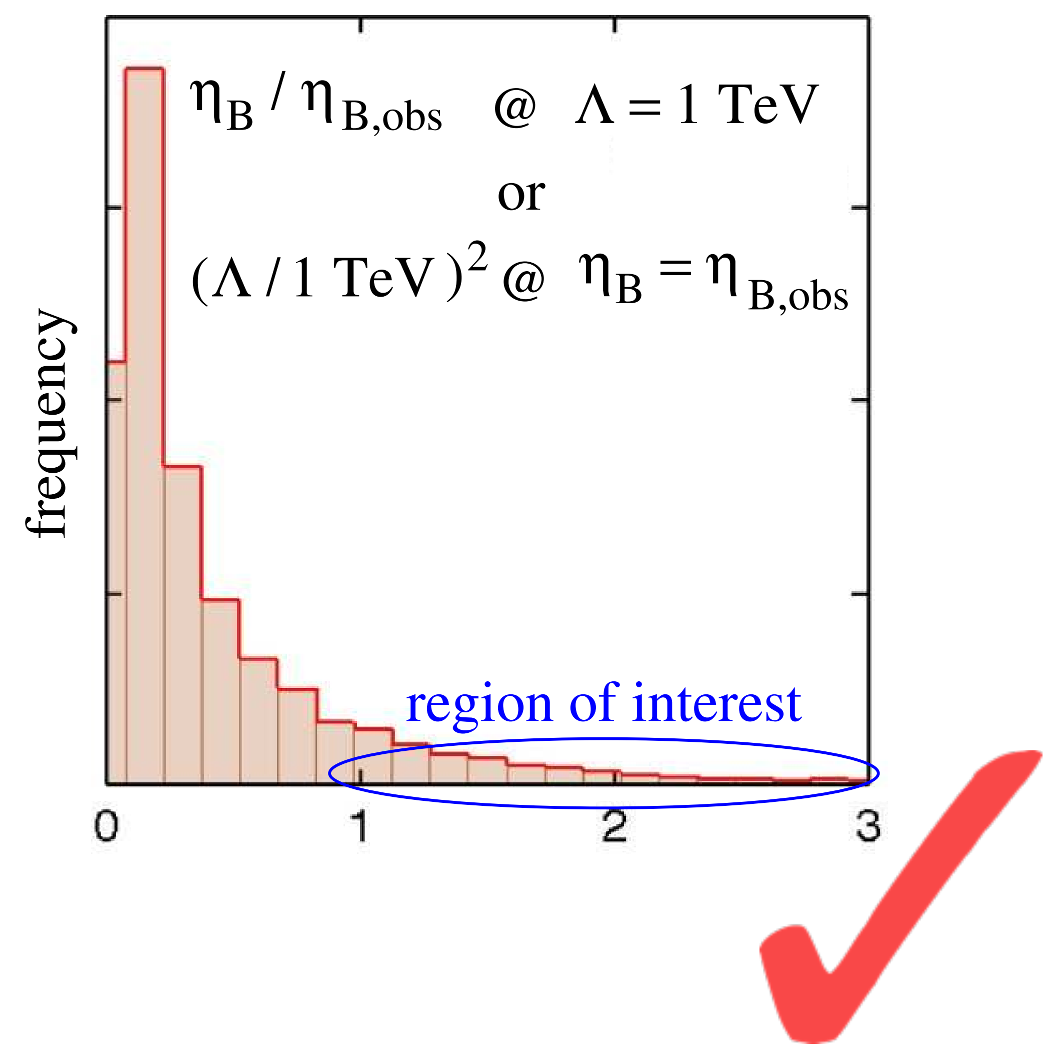
CP violation, NEW PHYSICS: Dim-6 operator

(If not DM could take Dim-5 as well) Espinosa, etal

$$y_t \bar{Q}_L H \left(1 + \frac{\eta}{\Lambda^2} S^2\right) t_R + \text{h.c.} \quad (\eta \equiv i)$$

$$m_t(z) = \frac{y_t}{\sqrt{2}} h(z) \left(1 + i \frac{S^2(z)}{\Lambda^2}\right)$$

J.M. Cline, KK, JCAP 1301 (2013) 012



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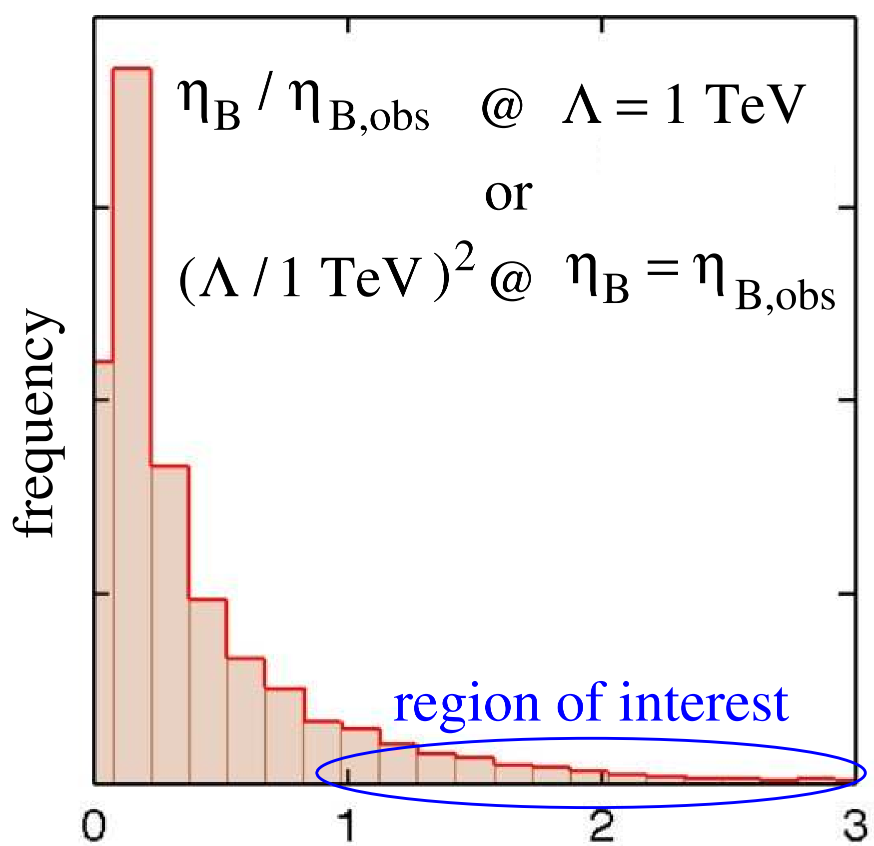


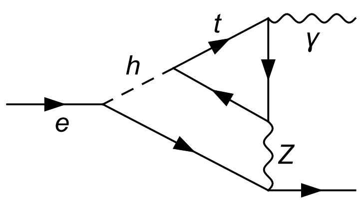
However, there goes the UV-completion

$$\mathcal{L}_{\rm scalar} = Z^{ij}(D^\mu H_i)^\dagger D_\mu H_j + \frac{1}{2}(\partial_\mu S)^2 - V(H_1,H_2)_{\rm 2HDM}$$
$$-\Big[\ \tfrac{1}{4}\lambda_S S^4 + \tfrac{1}{2}\lambda_{S1} S^2|H_1|^2 + \tfrac{1}{2}\lambda_{S2}S^2|H_2|^2 + \Big(\tfrac{1}{2}\lambda_{S12}S^2 H_2^\dagger H_1 + \text{ h.c.}\Big)\ \Big]$$

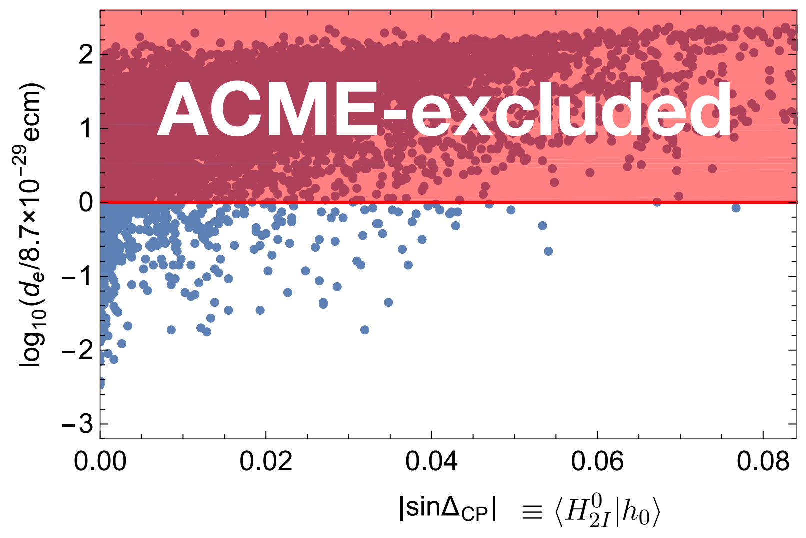
2HD+S model ~~CP~~ from 2HDM - strength from S / constraints

MCMC scan of parameter space with:

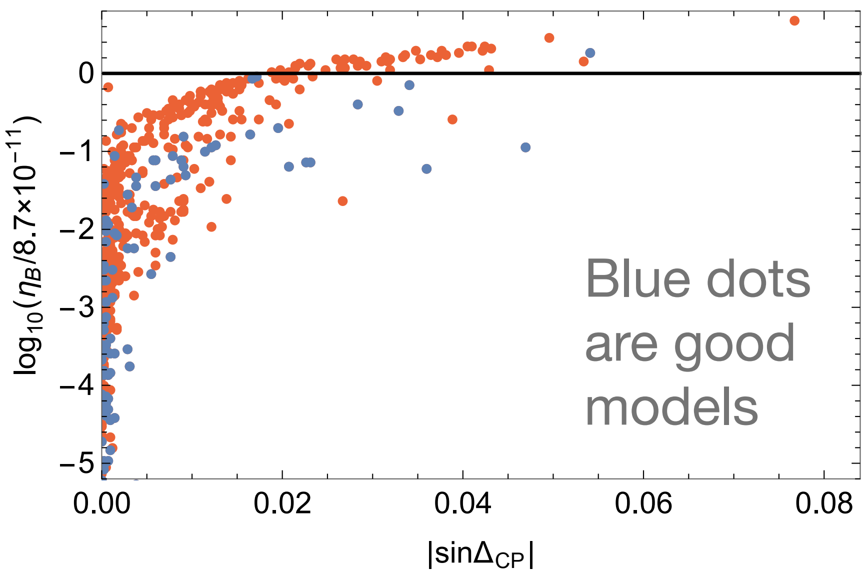
- Accelerator constraints
- EWP-data
- EDM's (electron, ACME)
- Perturbativity up to 1.5 TeV
- LUX-limits on DM (singlet *s*)
- Strong transition (=>*s* is subleading DM)



ACME Collaboration, Science 343 (2014) 269–272



If all above ok, compute BAU



T.Alanne, KK, K.Tuominene and V.Vaskonen JCAP 1608 (2016) no.08, 057

$$\mathcal{L}_{\rm scalar} = Z^{ij}(D^\mu H_i)^\dagger D_\mu H_j + \frac{1}{2}(\partial_\mu S)^2 - V(H_1,H_2)_{\rm 2HDM}$$
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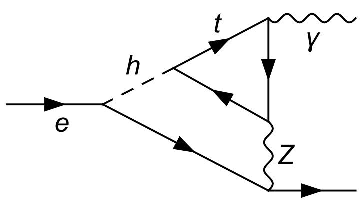
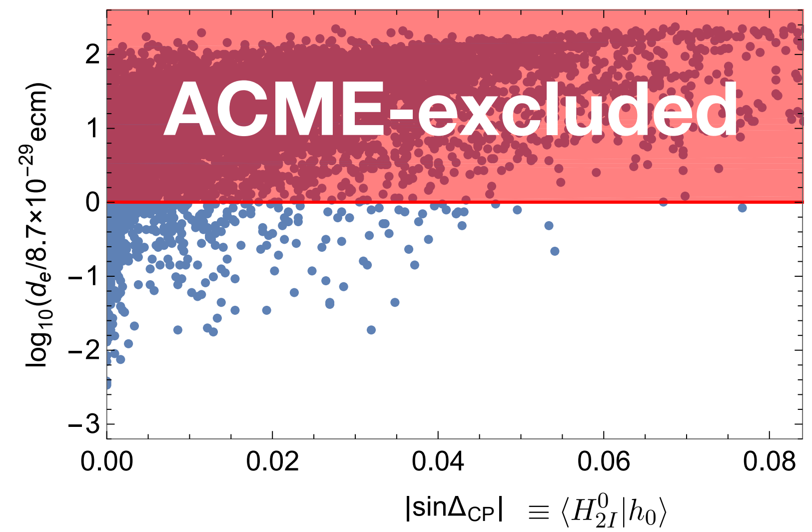
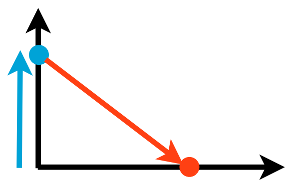
- **Strong transition (=>*s* is subleading DM)**

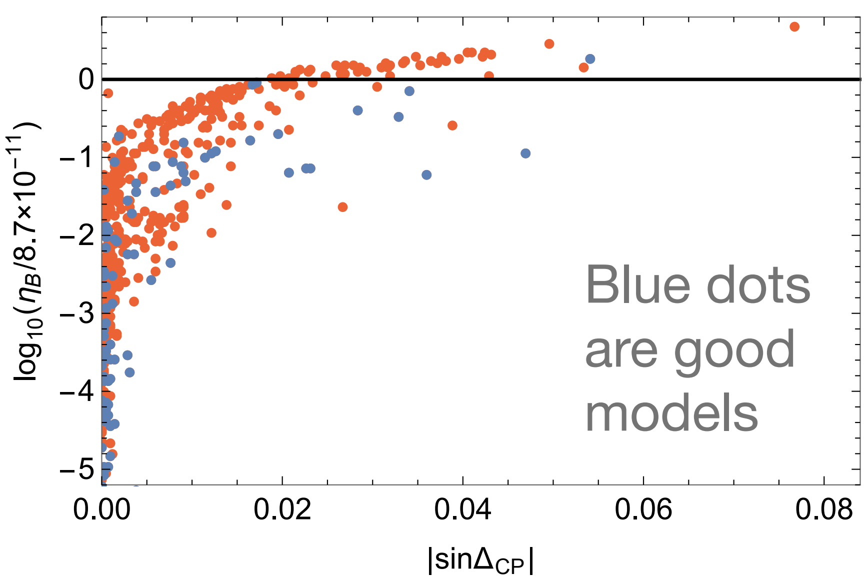


ACME Collaboration,
Science 343 (2014)
269–272





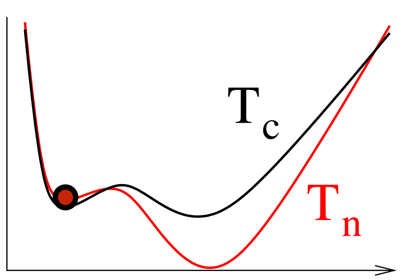
If all above ok, compute BAU



T.Alanne, KK, K.Tuominene and V.Vaskonen
JCAP 1608 (2016) no.08, 057

The bubble nucleation rate

$$\Gamma \sim T^4\left(\frac{S_3(T)}{2\pi T}\right)^{3/2}\exp\left(-\frac{S_3(T)}{T}\right)$$



is slow if $T_n \ll T_c$ (lot of supercooling) =>

Danger of being trapped => No EW-breaking

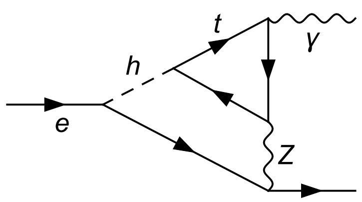
Indeed: Models in red: **no T_n**

$$\mathcal{L}_{\rm scalar} = Z^{ij}(D^\mu H_i)^\dagger D_\mu H_j + \frac{1}{2}(\partial_\mu S)^2 - V(H_1,H_2)_{\rm 2HDM}$$
$$-\Big[\ \tfrac{1}{4}\lambda_S S^4 + \tfrac{1}{2}\lambda_{S1} S^2|H_1|^2 + \tfrac{1}{2}\lambda_{S2}S^2|H_2|^2 + \Big(\tfrac{1}{2}\lambda_{S12}S^2 H_2^\dagger H_1 + \text{ h.c.}\Big)\ \Big]$$

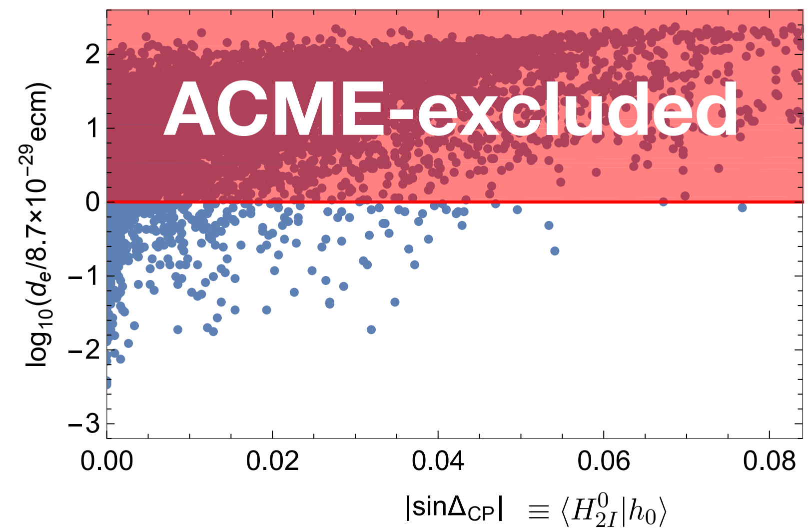
2HD+S model ~~CP~~ from 2HDM - strength from S / constraints

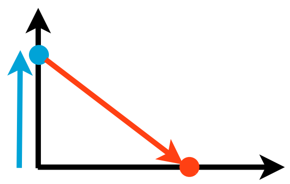
MCMC scan of parameter space with:

- **Accelerator constraints**
- **EWP-data**
- **EDM's (electron, ACME)**
- **Perturbativity up to 1.5 TeV**
- **LUX-limits on DM (singlet *s*)**
- **Strong transition (=>*s* is subleading DM)**

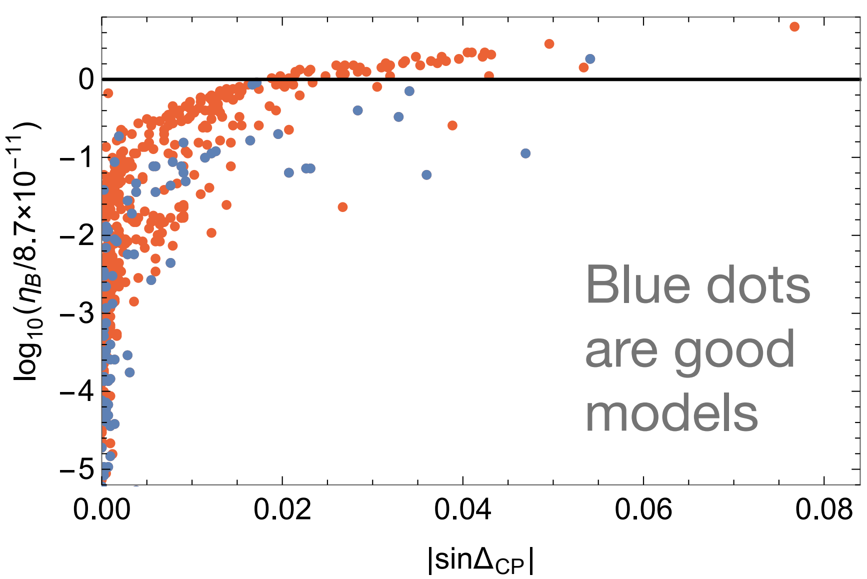


ACME Collaboration, Science 343 (2014) 269–272





If all above ok, compute BAU



T.Alanne, KK, K.Tuominene and V.Vaskonen JCAP 1608 (2016) no.08, 057

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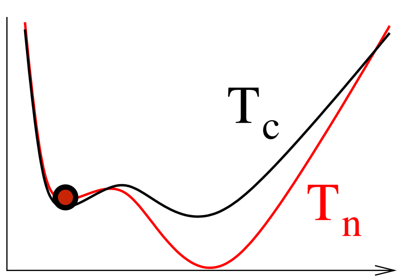
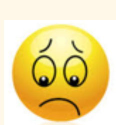


is slow if $T_n << T_c$ (lot of supercooling) =>

Danger of being trapped => No EW-breaking

+ low energy Landau poles < 10-100 TeV



- No UV-completion => *solving B => need for BSM*
- ***Problem is with the CP-violation and DM***

Dark sector EWBG

Generic issue: **Difficulty of obtaining large CP-violation consistent with observations (and UV-completeness idea)**

Idea: **Move CP-violation to dark sector**

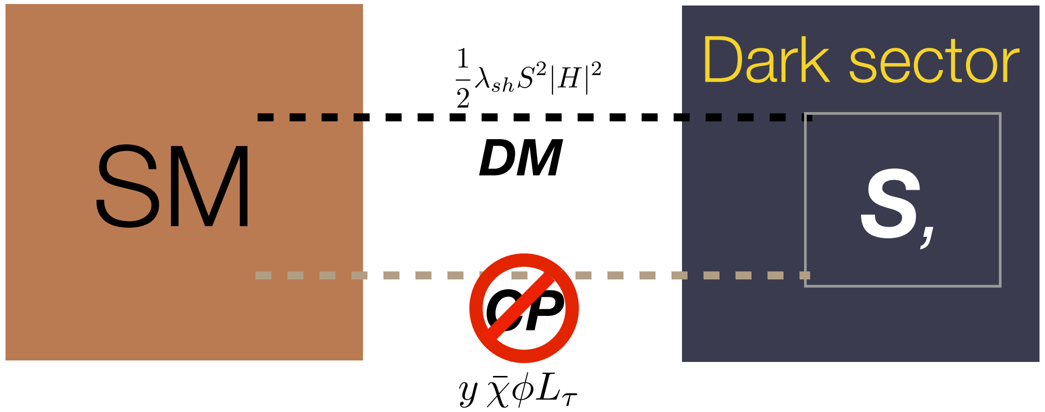
Gain: Get rid of most constraints, EDM's in particular

Problem: How to transfer the asymmetry to the visible sector / sphalerons?

Solution: a **CP-portal**

"Electroweak baryogenesis from a dark sector"

James M. Cline, KK and David Tucker-Smith
CERN-TH-2017-050, arXiv:1702.08909 [hep-ph]
accepted for publication in PRD



Dark sector EWBG main features (IDM + S + χ)

1. CP-asymmetry source involving a **sterile neutrino** χ

singlet scalar

$$\mathcal{L} \ni \tfrac{1}{2}\,\bar\chi\,[m_\chi + S(\eta\, P_L + \eta^* P_R)]\,\chi$$

spontaneous CP-violation => χ-helicity asymmetry

2. CP-portal: involving an **inert doublet** Φ

$$\mathcal{L} \ni y\,\bar\chi\phi L_\tau$$

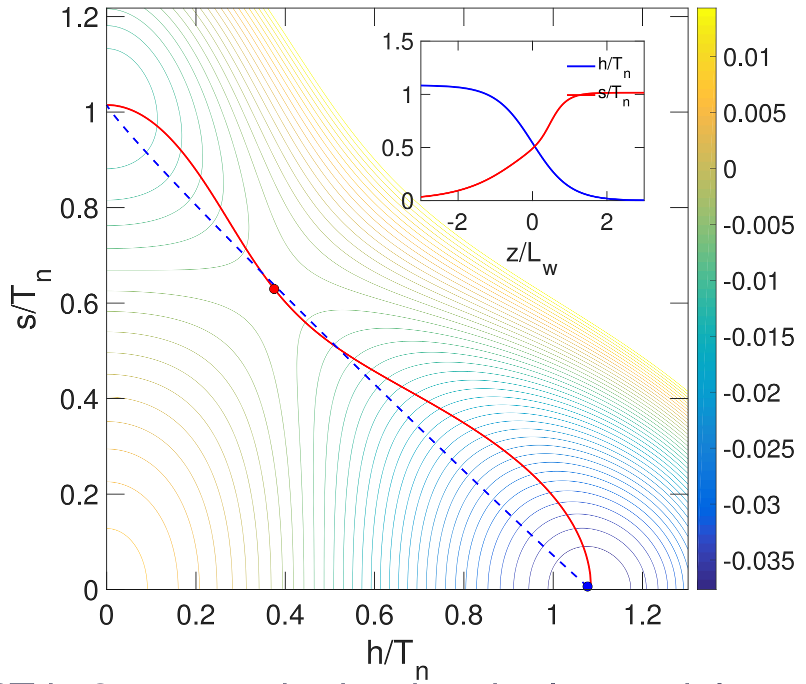
Asymmetry transported to **τ's** mainly via decays
$\chi\bar L_\tau \to \phi, \qquad \phi \to \bar L_\tau \chi$

3. τ's bias sphalerons to produce baryon asymmetry

This can be made to work with reasonable parameters:

$$m_\chi \sim 50\,\mathrm{GeV}, \quad m_\phi \sim 150\,\mathrm{GeV}, \quad y \cong 0.65 \qquad \eta \cong 0.1$$

4. Bonus: χ is a natural **DM** candidate



PT is 2-step as in the the singlet model
Blue line: tunneling path at T_n
Red line: path over the expanding bubble wall.

Dark sector EWBG fluid equations sample solutions

Fluid equations are generically of the form:

$$A_\chi \begin{pmatrix} \mu'_\chi \\ u'_\chi \end{pmatrix} = C_\chi - v_w m_\chi^{2\,\prime} \begin{pmatrix} K_{2,\chi}\mu_\chi \\ K_{6,\chi} u_\chi \end{pmatrix} + \begin{pmatrix} 0 \\ S^h_\chi \end{pmatrix}$$

$$A_i \begin{pmatrix} \mu'_i \\ u'_i \end{pmatrix} = C_i, \quad \text{for} \quad i = \phi, \tau$$

where

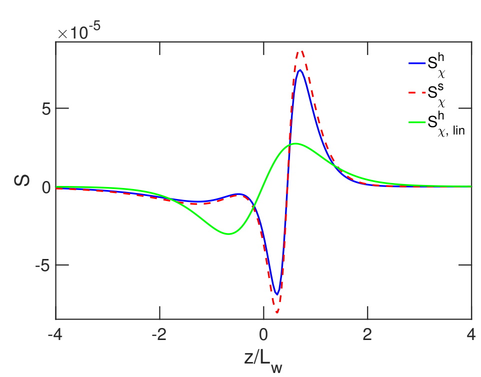
$$A_i \equiv \begin{pmatrix} v_w K_{1,i} & 1 \\ -K_{4,i} & v_w K_{5,i} \end{pmatrix}, \quad C_i \equiv \begin{pmatrix} C_i^\mu \\ -\tilde{\Gamma}_{\rm el,i}\, u_i \end{pmatrix},$$

and (model specific) collision terms are

$$\begin{aligned} C^\mu_\chi &= 2\tilde{\Gamma}_{\rm hf}\,\mu_\chi + 2\tilde{\Gamma}_d\,(\mu_\chi + c\mu_\tau - c\mu_\phi) \\ C^\mu_\phi &= \tilde{\Gamma}_d\,(\mu_\phi - \mu_\tau - c\mu_\chi) + 2\tilde{\Gamma}_{\times,\phi}(\mu_\phi - \mu_\tau) \\ C^\mu_\tau &= \tilde{\Gamma}_d(\mu_\tau + c\mu_\chi - \mu_\phi) + 2\tilde{\Gamma}_{\times,\tau}(\mu_\tau - \mu_\phi) \end{aligned}$$

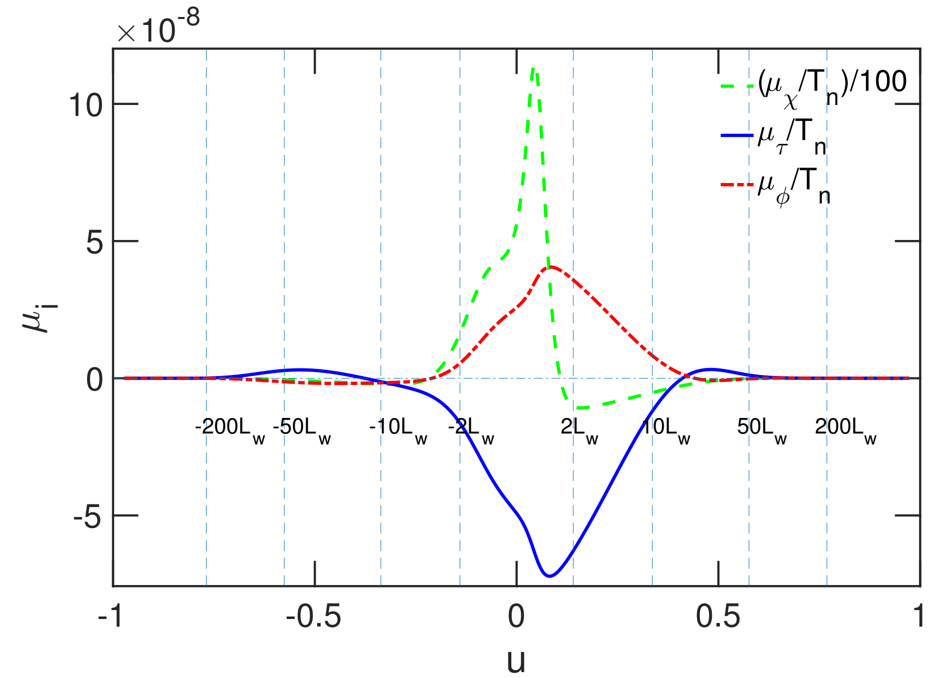
and the **source**

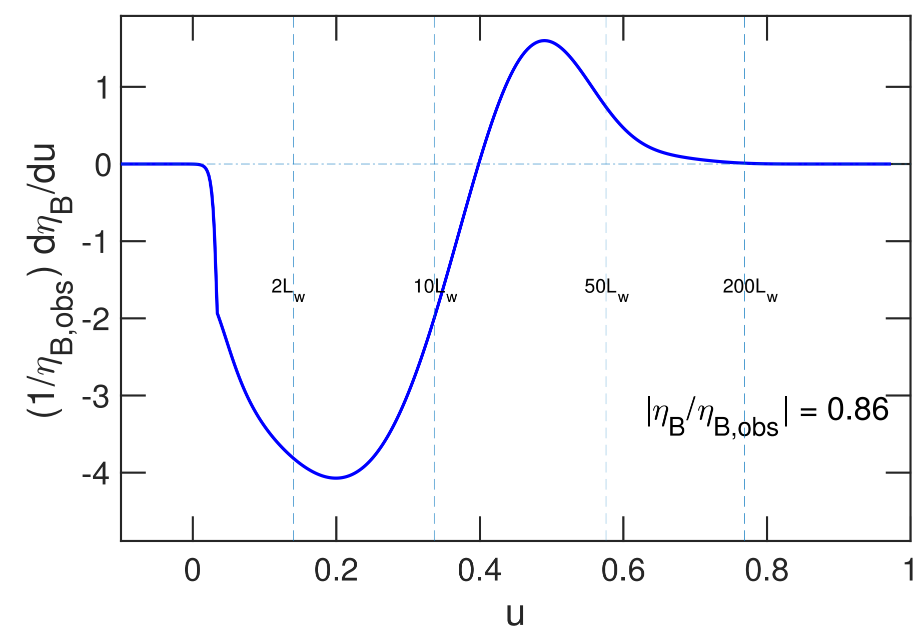
$$S^h_\chi = v_w \left(-K^h_8\,(m_\chi^2 \theta')' + K^h_9\,\theta' m_\chi^2 m_\chi^{2\,\prime} \right)$$



with kinematic functions:

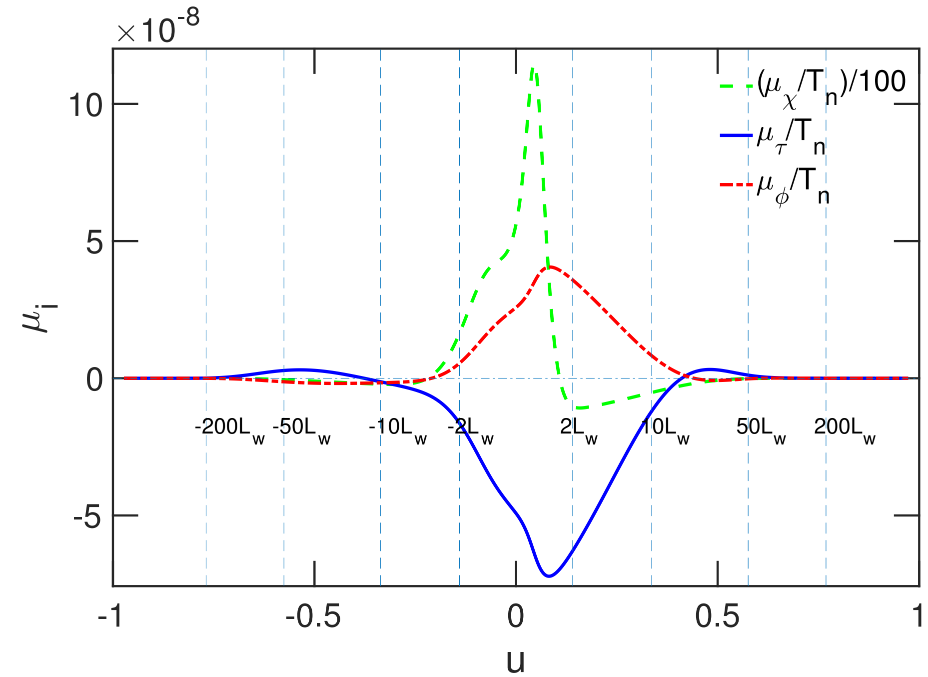
$$K_8^h(x) = \left\langle \frac{k_z^2 f_0'}{2\omega_0 \omega_{0\parallel}^2 |\mathbf{k}|} \right\rangle \quad K_9^h(x) = \left\langle \frac{k_z^2}{4\omega_0^2 \omega_{0\parallel}^2 |\mathbf{k}|} \left(\frac{f_0'}{\omega_0} - f_0'' \right) \right\rangle$$





$$\eta_B = \frac{405\,\Gamma_{\rm sph}}{4\pi^2\, v_w\, g_* T} \int_{-\infty}^{\infty} dz\, \mu_\tau\, f_{\rm sph}\, e^{-\nu z}$$

Dark sector EWBG fluid equations sample solutions



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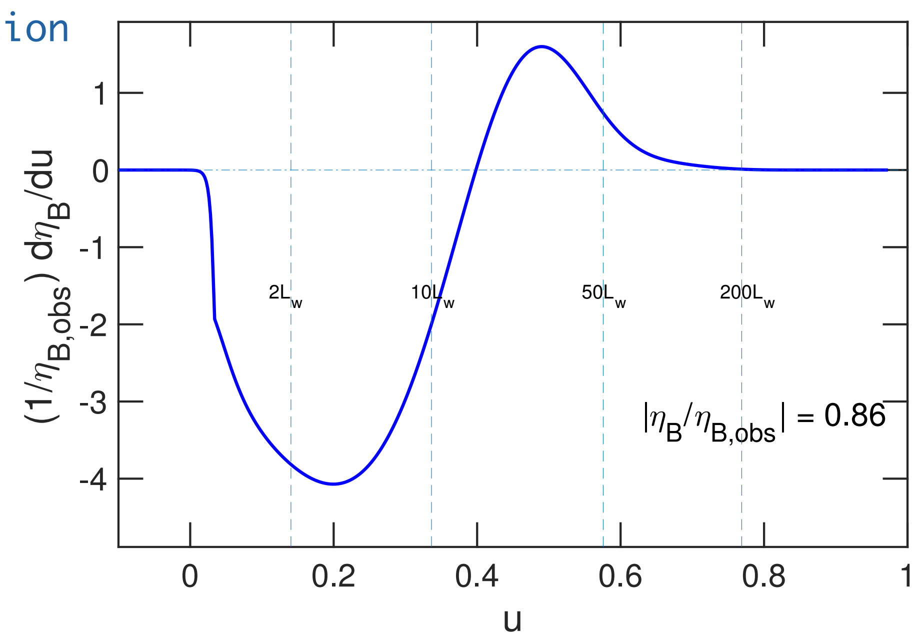
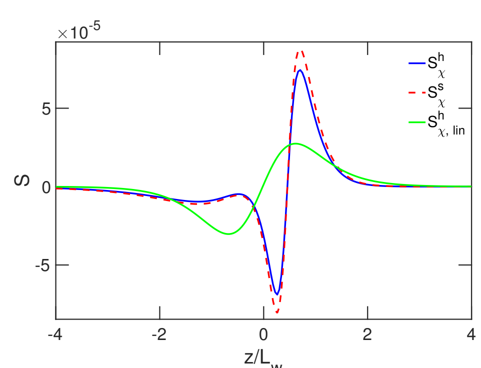
CP-potal interaction From, JM. Cline, KK and K.Olive, PRD49 (1994) 6394-6409

$$C_\chi^\mu = 2\tilde{\Gamma}_{\mathrm{hf}}\,\mu_\chi + 2\tilde{\Gamma}_d\,(\mu_\chi + c\mu_\tau - c\mu_\phi)$$
$$C_\phi^\mu = \tilde{\Gamma}_d\,(\mu_\phi - \mu_\tau - c\mu_\chi) + 2\tilde{\Gamma}_{\times,\phi}(\mu_\phi - \mu_\tau)$$
$$C_\tau^\mu = \tilde{\Gamma}_d(\mu_\tau + c\mu_\chi - \mu_\phi) + 2\tilde{\Gamma}_{\times,\tau}(\mu_\tau - \mu_\phi)$$



and the **source**

$$S^h_\chi = v_w \left(-K_8^h\,(m_\chi^2\theta')' + K_9^h\,\theta' m_\chi^2 m_\chi^{2\,\prime}\right)$$



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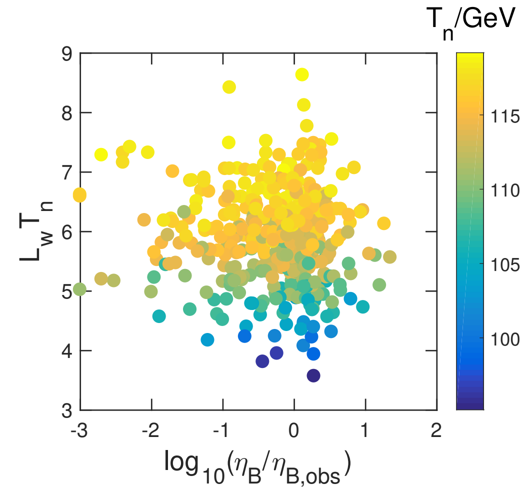
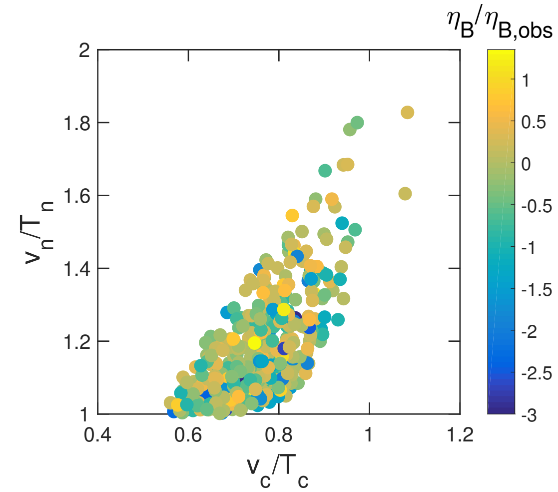
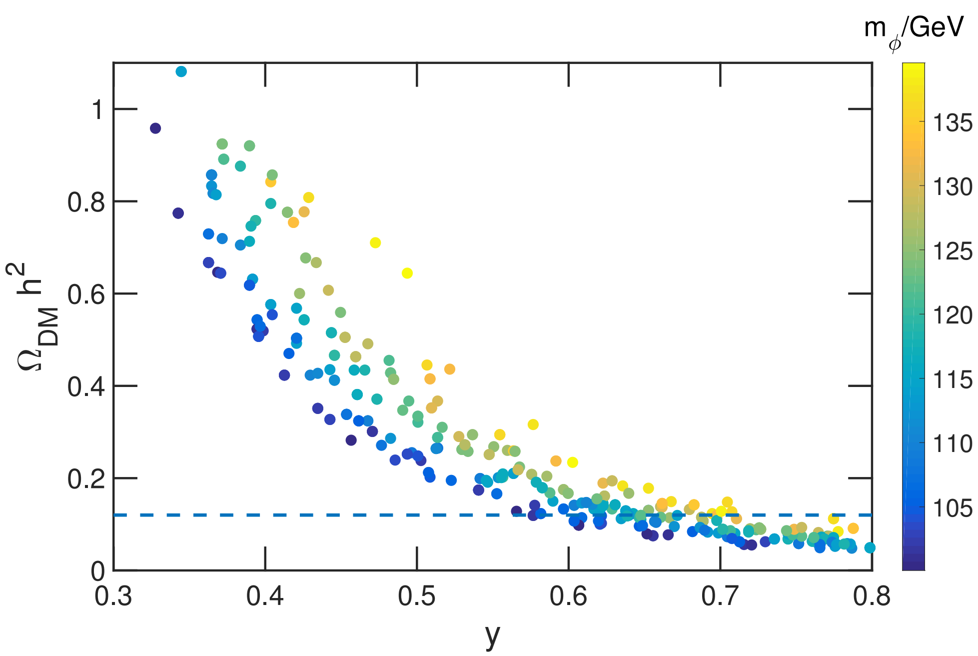
Dark sector EWBG succesfull EWBG *and* DM

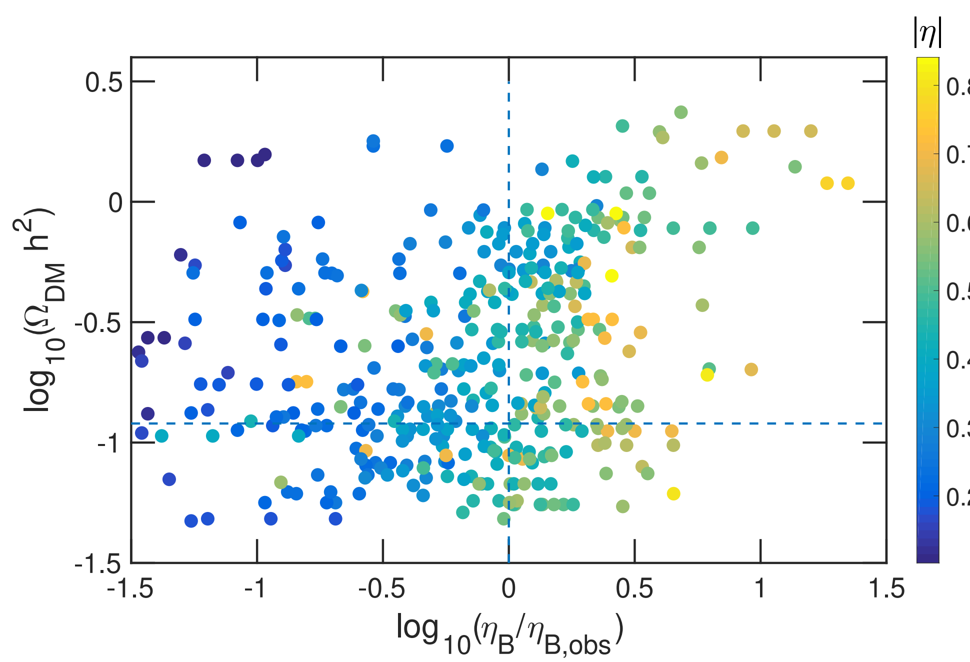
Parameter scan:
Region of parameters that gives the BAU and DM of the right magnitude:

$$y \in [0.5, 0.9],\ \eta \in [0.025, 0.25],\ \lambda_m \in [0.5, 0.8]$$
$$m_\chi \in [40, 60],\quad m_\phi \in [100, 140],$$









Couplings reasonably small, so should easily be made UV-complete (not tested yet)

Dark sector EWBG main (collider) constraint

Main collider signature of the singlet χ and inert doublet ϕ model is the Drell-Yan production of $\phi^+\phi^-$ followed by $\phi_\pm \to \tau^\pm\chi$, exactly as $pp \to \tilde{\tau}\tilde{\tau}^*$, $\tilde{\tau} \to \tau\chi^0_1$ in the MSSM.

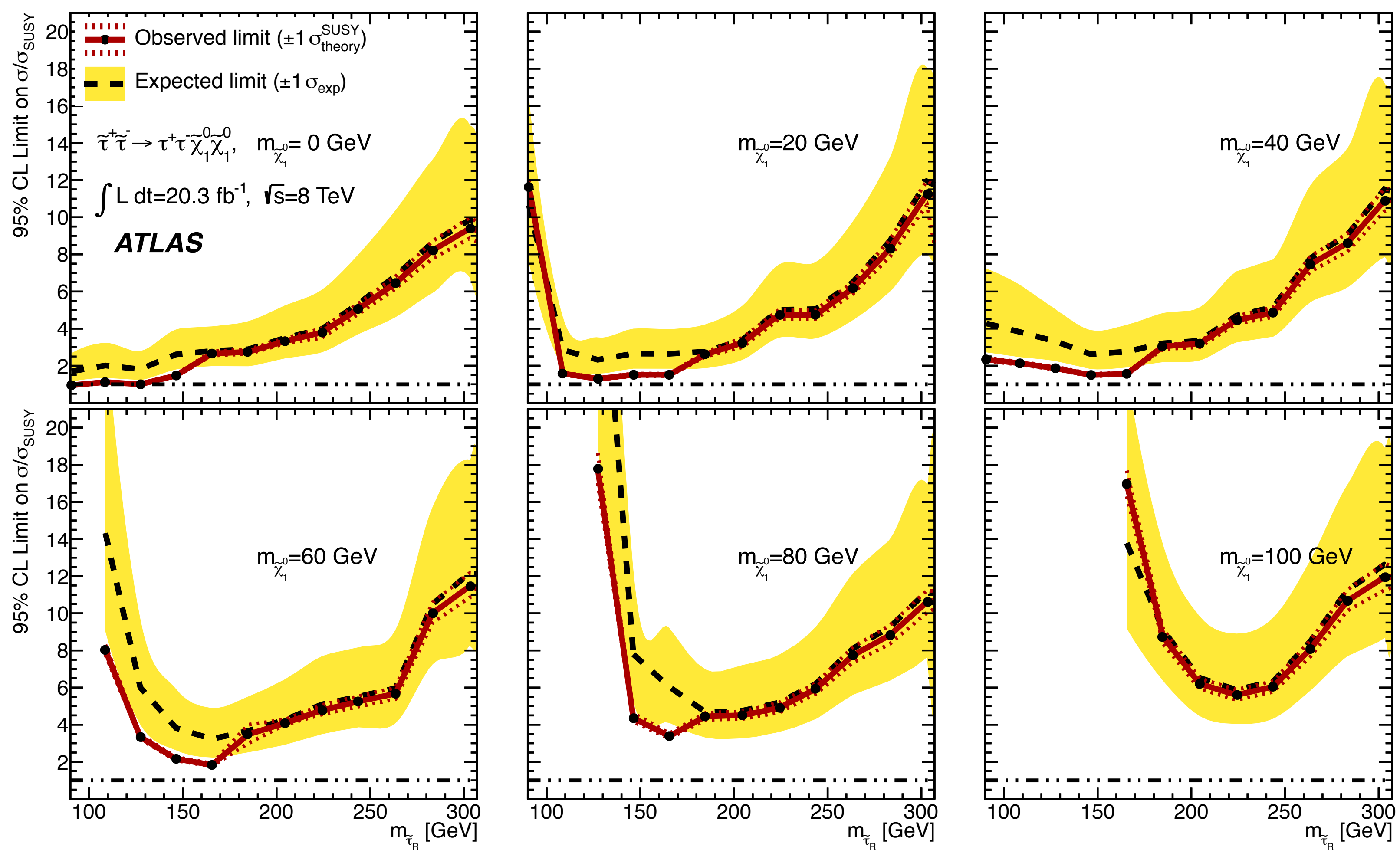
ATLAS: 1407.0350

JHEP 1410 (2014) 096

$m_\chi \lesssim 20\,\mathrm{GeV}$

$m_\phi < 130\,\mathrm{GeV}$

~Excluded



Run 2 should probe the model in interesting parameter range $m_\chi \cong 40\,\mathrm{GeV}$ and $m_\phi < 170\,\mathrm{GeV}$

Conclusions

DM and BAU require BSM physics

- "Complete" solutions appear to be in decline (no SUSY found)

Simplicity: an interesting paradigm to follow

- Unification and Hieararchy Problem maybe not relevant

Some aspects are easily realized with help of singlets

- DM
- Strong EWPT

EWBG challenged by need for new, unconstrained CP-violation

Dark sector EWBG with a CP-portal, can fulfill all expectations: DM, BAU and (likely) UV-completeness

Will be probed by LHC run II

Thank you for your patience

and **thanks again to**
Keith

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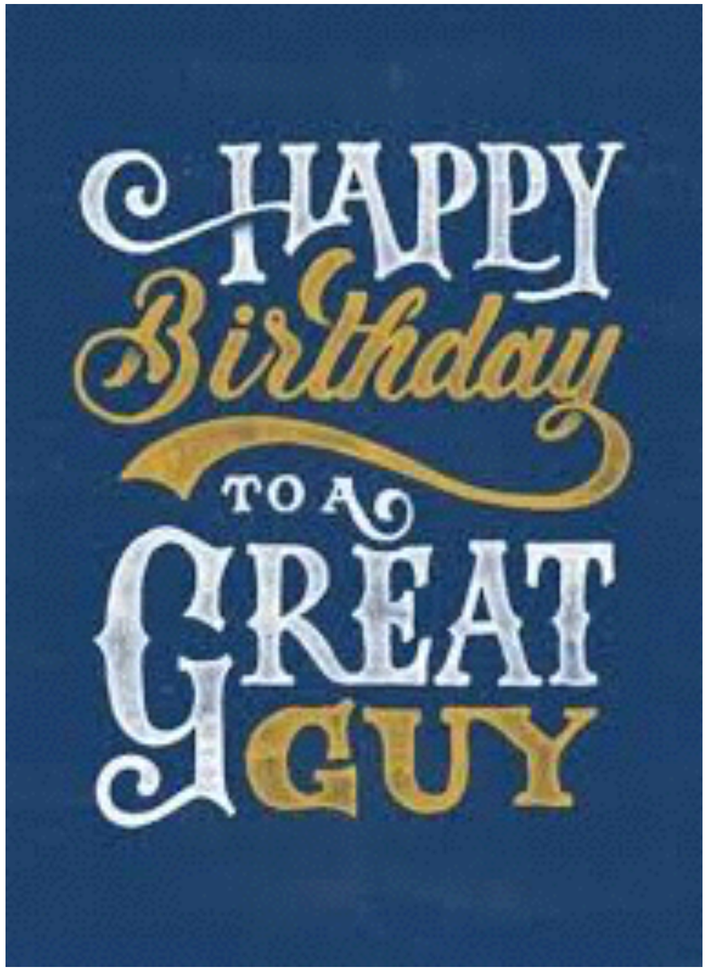
and **thanks again to**
Keith



Extra slides. Please remove these from the web-version …

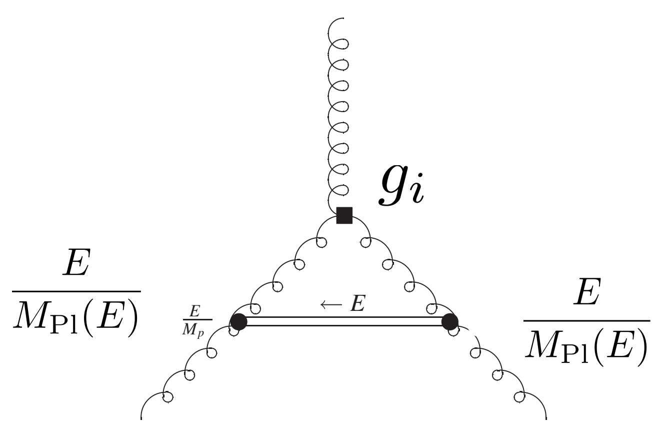
Asymptotic safety by Gravity, maybe
no need for FT unification

Running couplings (incl. yukawas):

$$\mu \frac{\partial g_i}{\partial \mu} = \beta_{\rm SM}(g_i) + \beta_{\rm grav}(g_i)$$

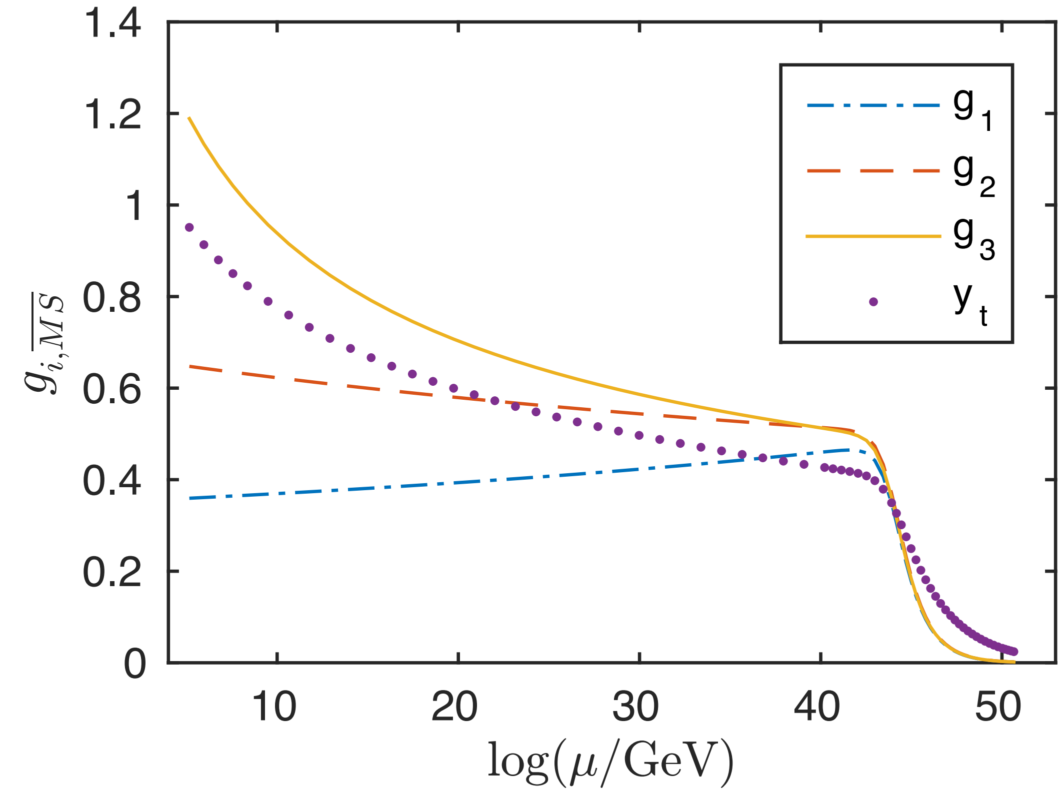
Where gravity correction is **parametrically**:

$$\beta(g_i)_{\rm grav} = \frac{a_i \mu^2}{M_{\rm Pl}^2 + \xi \mu^2} g_i$$



S.P. Robinson and F.Wilczek, PRL96 (2006) 231601

Laura Laulumaa,
MSc Thesis, JyU 2015



$$a_g \approx -1$$
$$a_{y_t} \approx -0.5$$
$$\xi \approx 0.024$$

Wetterich and Shaposhnikov,
Phys.Lett. B683 (2010) …

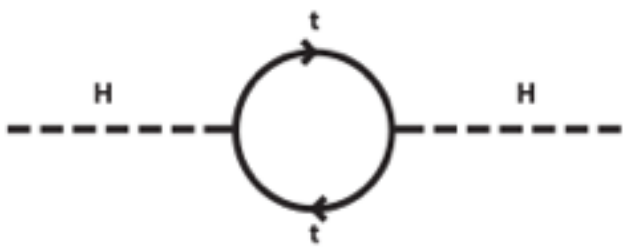
Gravity may remain non-renormalizable for all E

Hierarchy problem

Excessive running of Higgs mass:

Naive **renormalization with a cutoff:**

$$\Delta m_H^2 = -\frac{3y_f^2}{8\pi^2}\Lambda_{UV}^2$$



Same also from **Wilsonian RGE-flow** argument

$\lambda\phi^4, F_{\mu\nu}F^{\mu\nu}, \bar{\psi}\phi\psi$ ~constant
$g\phi^5, (F^{\mu\nu}_{\mu\nu})^2, \bar{\psi}\phi^2\psi$ die
} => hence FT:s are so simple!

$m^2\phi^2, g\phi^3$ *grow* => problem

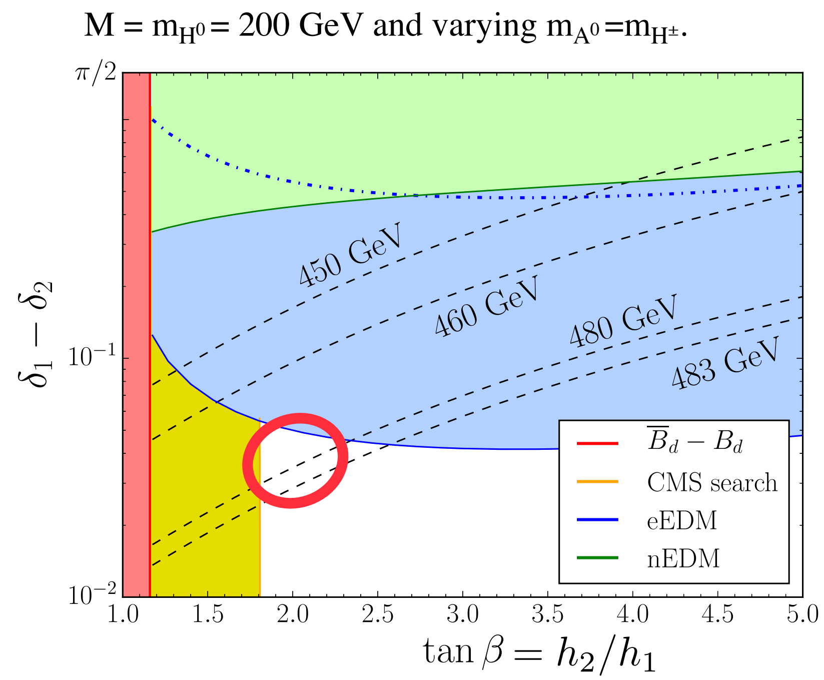
<u>However</u>, **both** arguments **introduce an arbitrary scale**, *breaking conformal invariance*. Eg. in dimensional regularization, instead:

$$\Delta m_H^2 \sim -\frac{3y_f^2}{8\pi^2}\frac{m_f^2}{\epsilon}$$

1) same as for fermions
2) vanishes if no new mass scales

2HDM bounces back (not likely)

Recent paper claim 2HDM (with Z_2 symmetry) is still OK (and may also give lots of GW's)



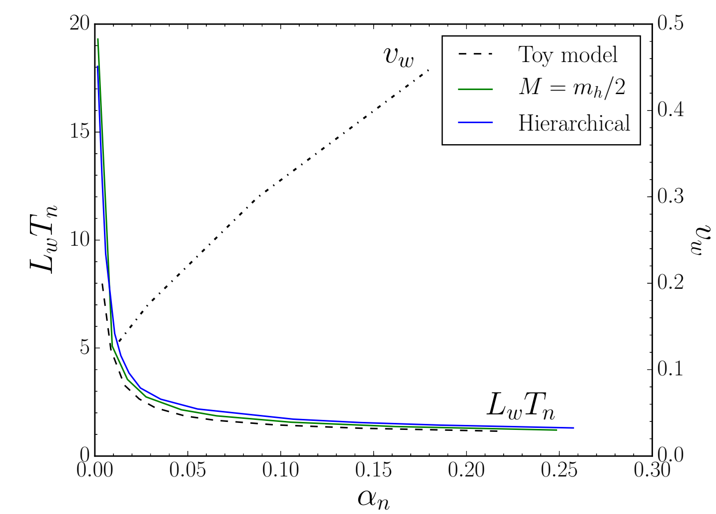
Dorsh, Huber, Konstandin and No,
arXiv:1611.05874

But model requires

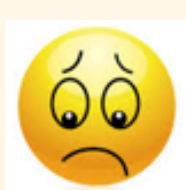
very small $L_w T$<2,

very large $v_n/T_n \approx$ 3-5

very large couplings



=> Neither the semiclassical BEq's, nor perturbative effective action reliable.

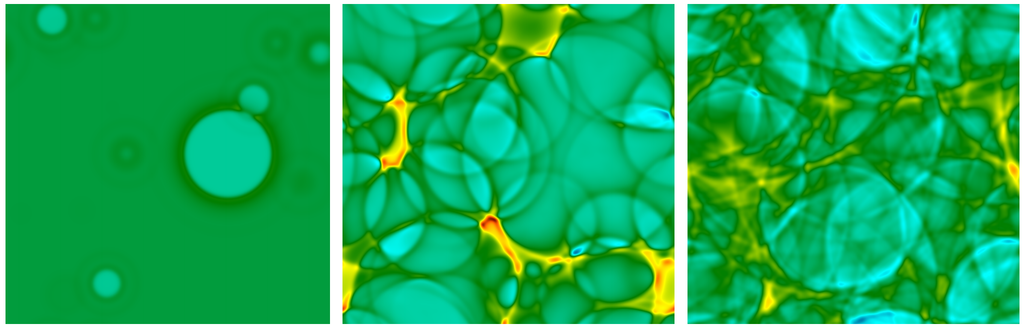


Very low scale Landau poles at ~TeV =>

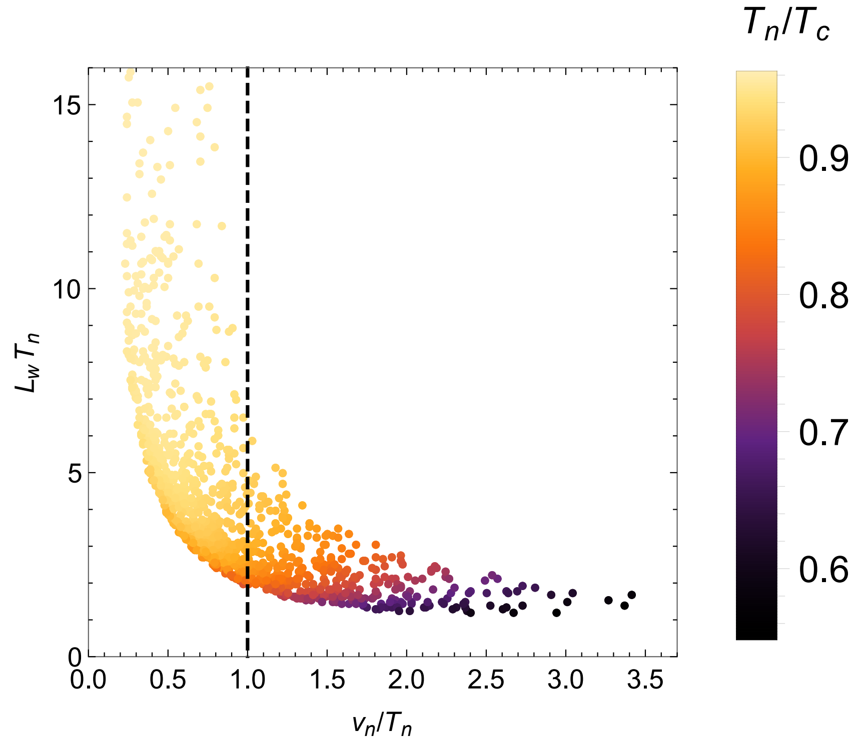
- No UV-completion
- ***Problem is with the CP-violation***

Singlet model: BAU *and* gravitational waves

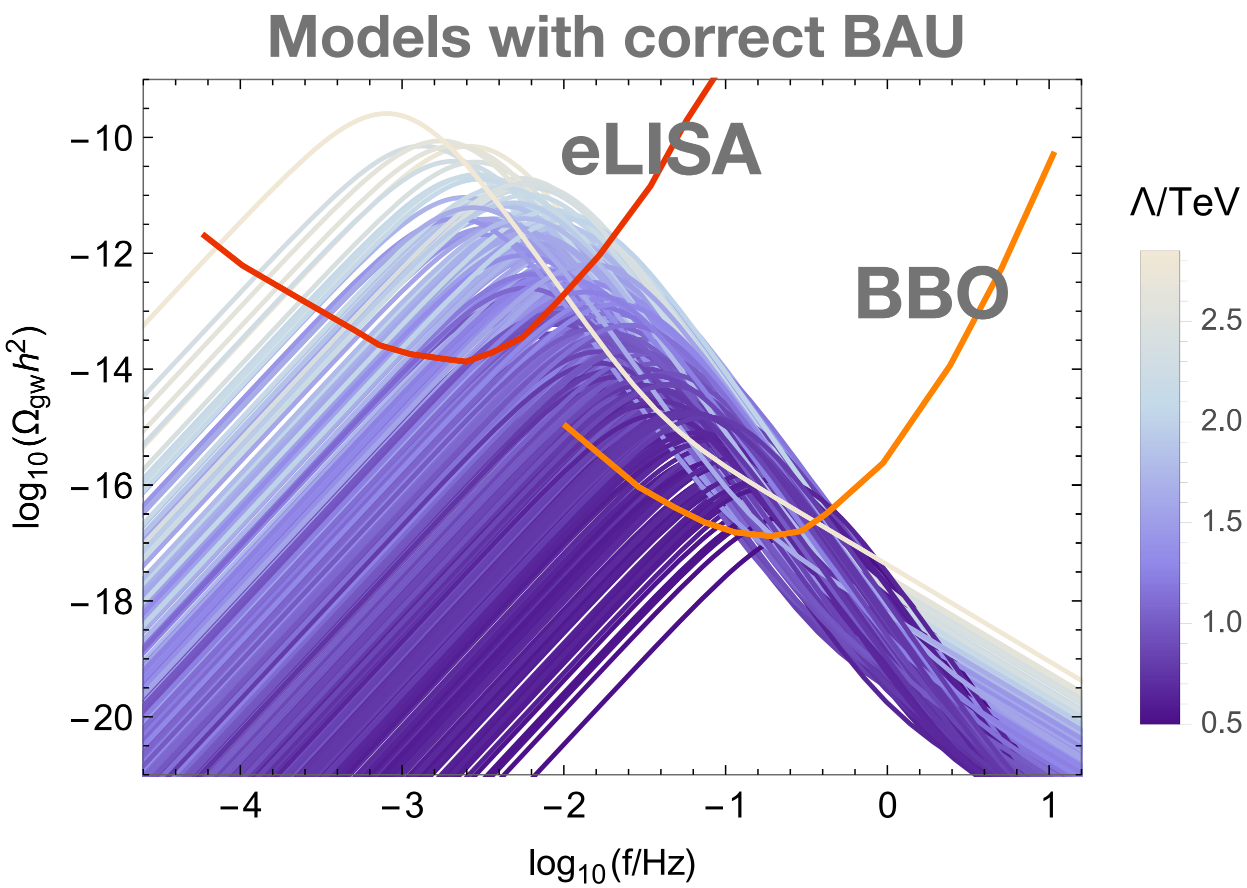
This singlet model can also give rise to an observable gravitational wave signature:



Kari Rummukainen, Physics Days 2016



Large GW-signal correlates with strong transition (large supercooling) and **a very thin wall** …



Ville Vaskonen, arXiv:1611.02073

Short history of the EWBG

B-violation in SM

't Hooft -76
Klinkhamer, Manton -84

1985 Kuzmin, Rubakov, **Shaposhnikov**, **fast B at high T in SM**

1987 Arnold, McLerran,..
Affleck-Langer, broken phase

$$\Gamma \sim Ae^{-E/T}$$

1990 Ambjørn, Krasniz, Shaposhnikov
first **Lattice** results (symm.ph)

$$\Gamma \sim \#\alpha^4 T$$

\- Rummukainen, Laine,
Moore, Bödeker,…
ChS-# diffusion in Lattice,
HTL, Langevin eqs,..

200n

$$\Gamma \sim \#\alpha^5 T$$

Rummukainen, Moore,…
updates
Ramsey-Musolf,
Garny Konstandin,
gauge dep.
Riotto,…
B-dependence,…

2014 Rummukainen, d'Onofrio,
Tranberg: definite results **SM-Lattice**

Transition strength

197n Weinberg,Jackiw,Kiritsis,Linde,Niemi,Semenoff,…
FTFT, $V_{eff}(\phi,T)$

1992 Carrington: **$V_{eff}(\phi,T)_{SM}$**

1993 - Arnold, O.Espinosa, Buchmuller
Fodor,… **EWPT industry using V_{eff}**

1993 -1995 **TOP**

Kajantie, Rummukainen,
Laine, Shaposhnikov:
DR+Lattice => **SMEWBG dead**

1995-1996 **LSS in MSSM,**
Carena, Quiros, Wagner, J.R.Espinosa,… **(V_{eff})**
Cline, KK, Rummukainen, Laine, Losada…
DR+Lattice

1996 ~ 2000

2000- **MSSM / phenomenology**
Carena, Quiros, Wagner, Nardini,..
Rummukainen, Laine, …
constraints on **LSS getting worse…**

2011 J.R.Espinosa, Gripaios, Konstandin, Riva:
strong 2-step trans. in SM+S

2012 **HIGGS**

2013- Renewed interest on
SM+S, portals, 2HDM's,…

Baryon creation, QKE's

1990 Cohen, Kaplan, Nelson
spontaneous BG, …

1993-4 Farrar, Shaposhnikov,
Gavela, Hernandez,Orloff,Pene,..
Quantum Reflection

1994 -2002 M.Joyce, T.Prokopec, N.Turok,
Cline, KK, MJ,TP, Schmidt,…
Semiclassical force BG
WKB / CTP $S_{CP}(z)$

1996 -200n Riotto, Carena, Quiros, Wagner,….
"vev-insertion method",
also from **CTP**
… Profumo,Ramsey-Musolf,Tulin,..

2003- **CTP** mostly used to
defelop **QKE's** for
(resonant)
Leptogenesis
Pilaftsis etal,
Buchmuller etal, Garny etal,
Garbrecht etal, Herranen, KK,..,

~2010- (Morrissey, Ramsey-Musolf,…
Prokopec, Konstandin,…
Flavour mixing …)

~2009- **cQPA** combines **SCBG**
and **QR**, using **CTP**
Herranen, KK, Rahkila

2017 **EWBG goes Dark Side**

Dark energy ...

It may require:

"Extended" gravity

or

"Alternative" gravity

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gravity = truth, facts

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gravity = truth, facts

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gravity = truth, facts

…or it is an illusion. Anyway, I will not consider it here…

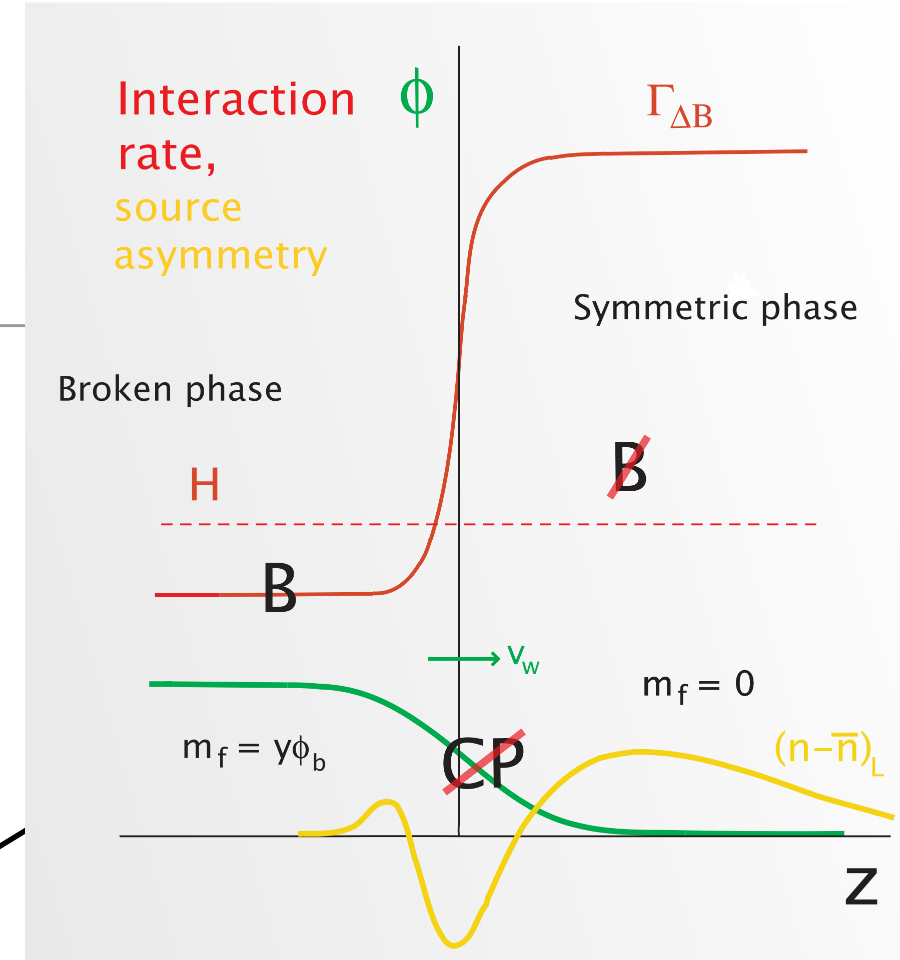
EWBG

$$H \sim 10^{-14} T_{100}^2 \text{GeV}$$
$$\Gamma \sim 10^{-5} T_{100} \text{GeV}$$

→ 

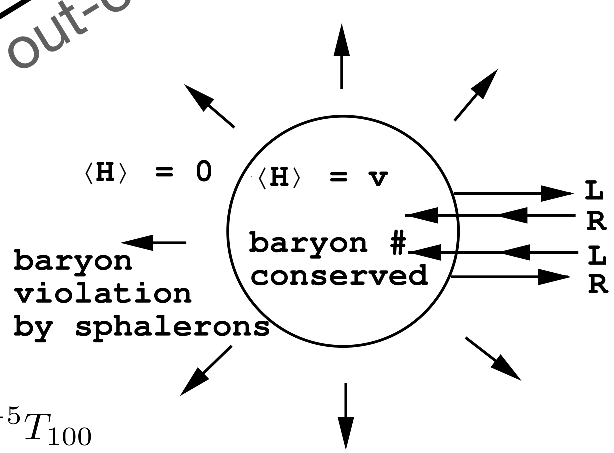
PT must be 1st order

To keep BA



Equilibrium / Nonperturbative / Gauge issues

Mostly out-of-equilibrium / quantum



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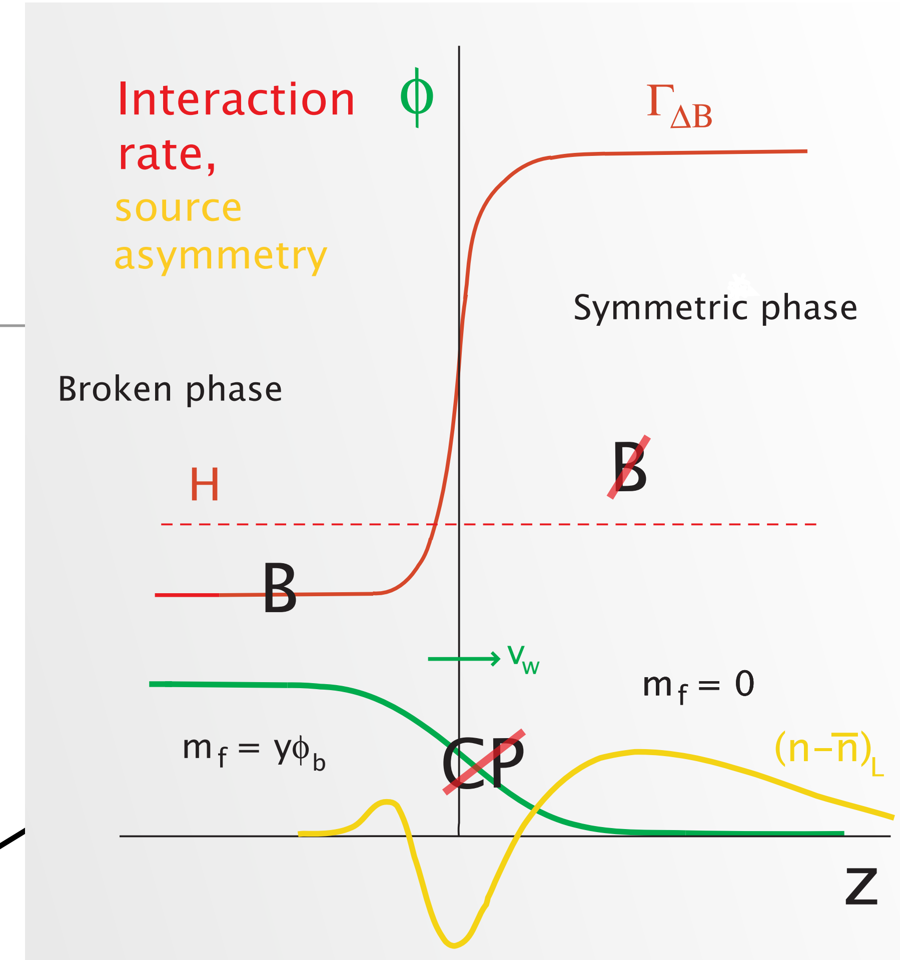

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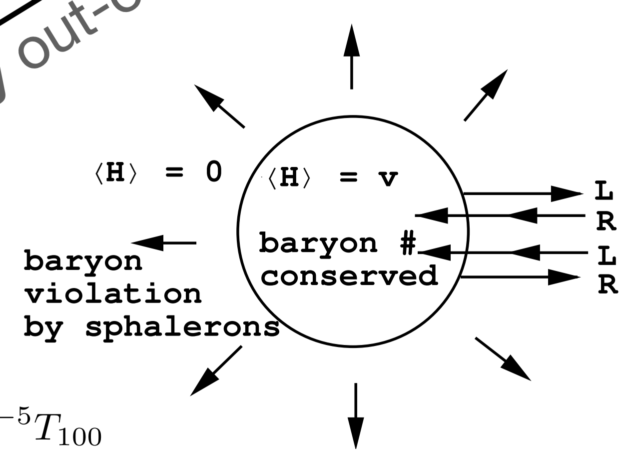

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Sphaleron rate in the unbroken phase (equilibrium)

Ambjorn etal,... Moore; Rummukainen etal,..

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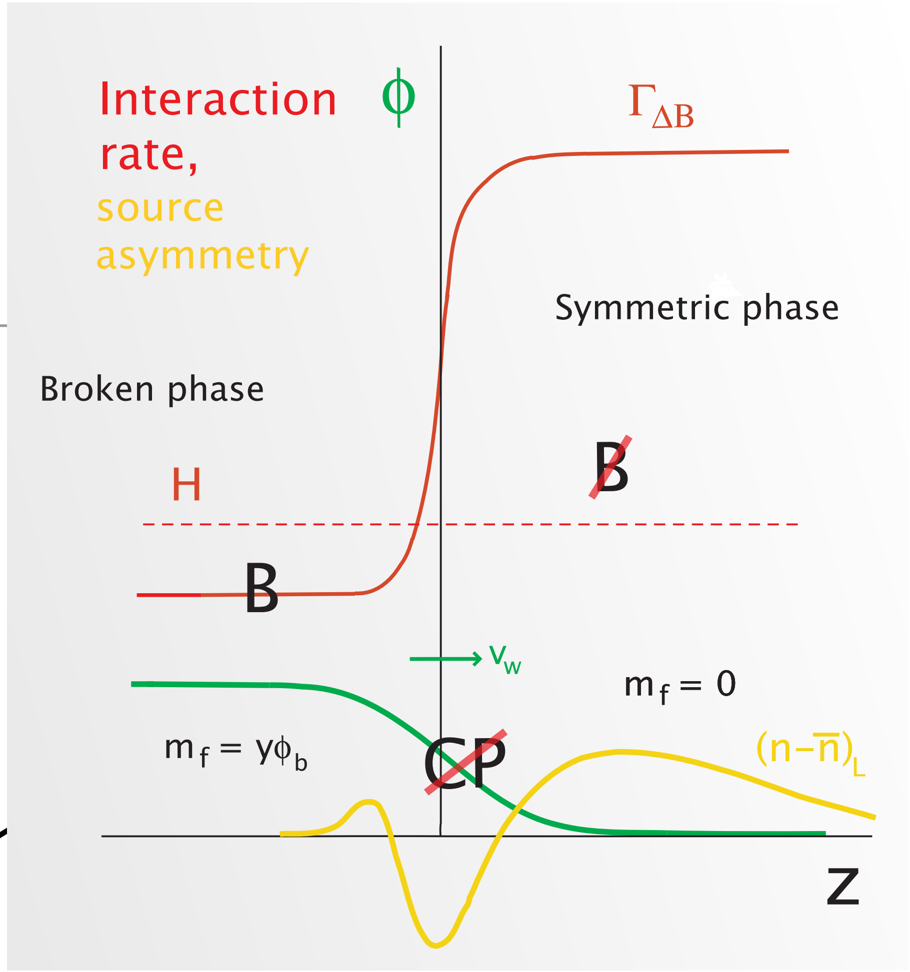

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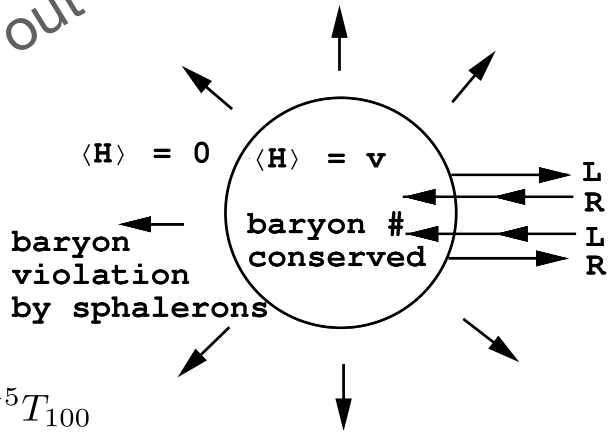

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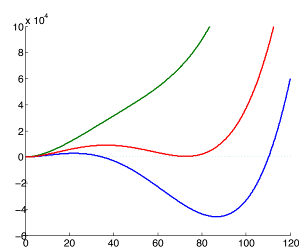

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2-loop V_{eff} in LG ~OK

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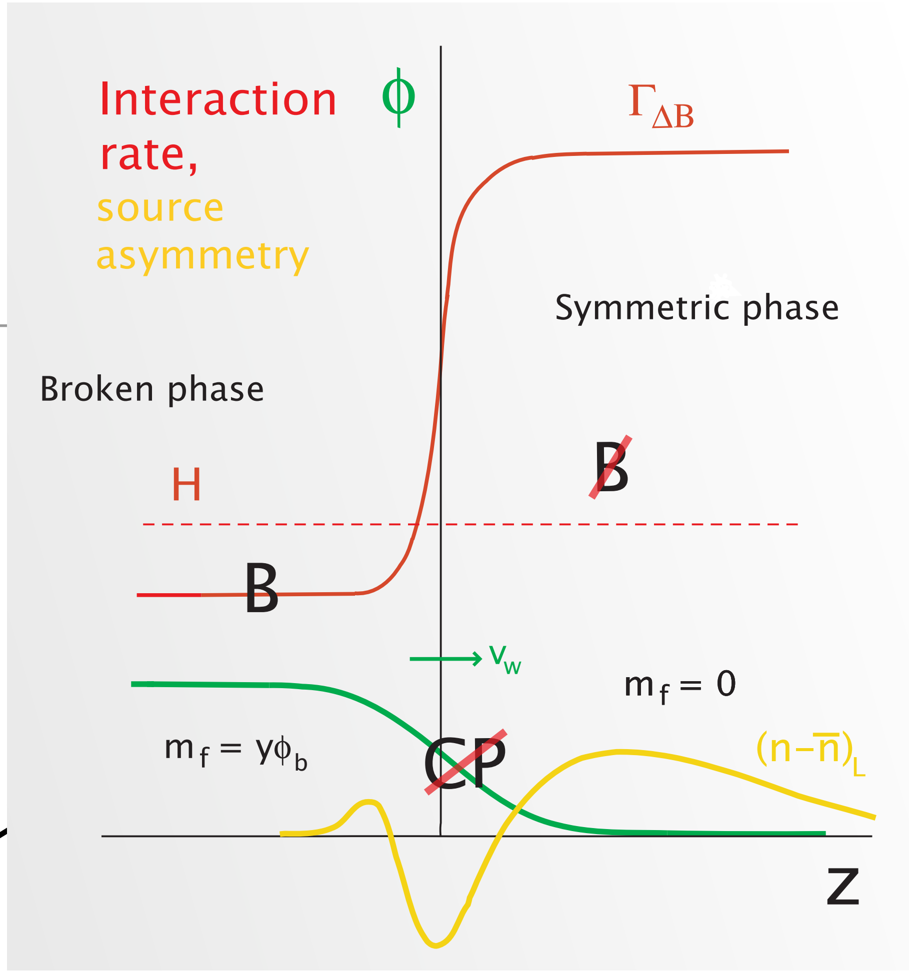

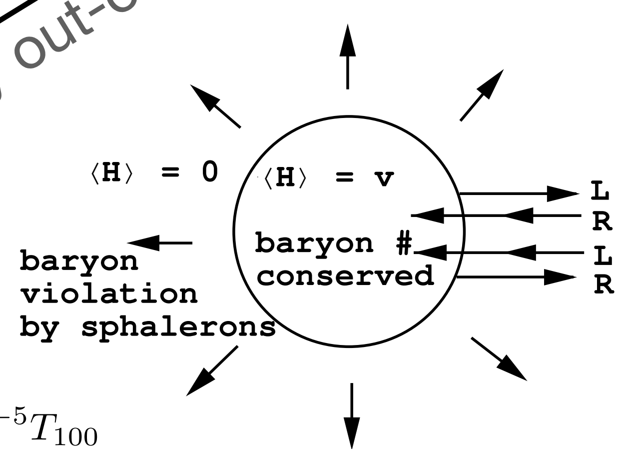

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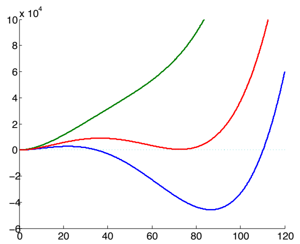

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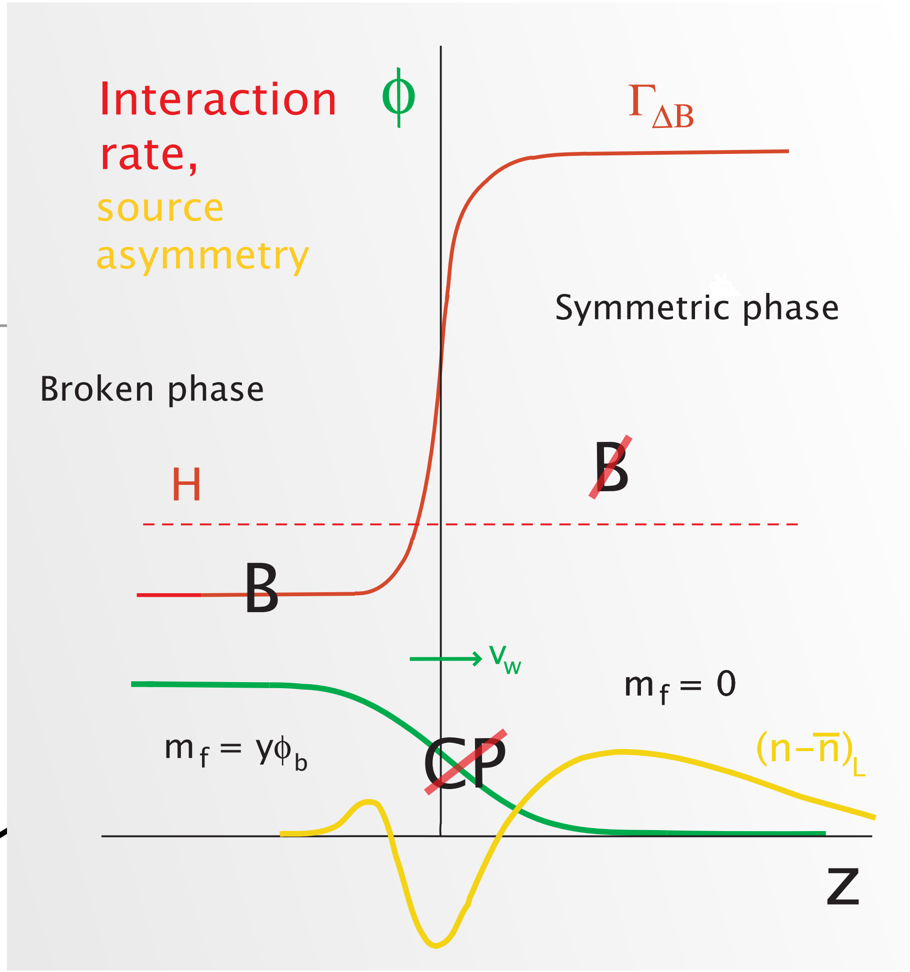
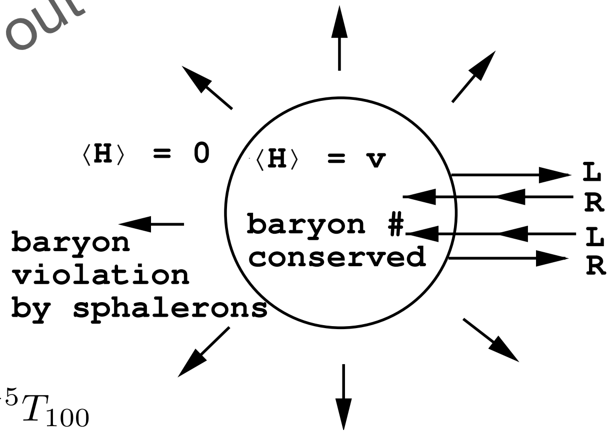


CP-violating **source** in **transport eqs**.

- Thin wall: *quantum*
- Thick wall SC: ✓?

SC force Joyce, Prokopec, Turok, Cline, KK, Schmidt, Weinstock, Konstandin, ...

vev-insertion expansion Riotto, Carena, Quiros, Wagner, ...



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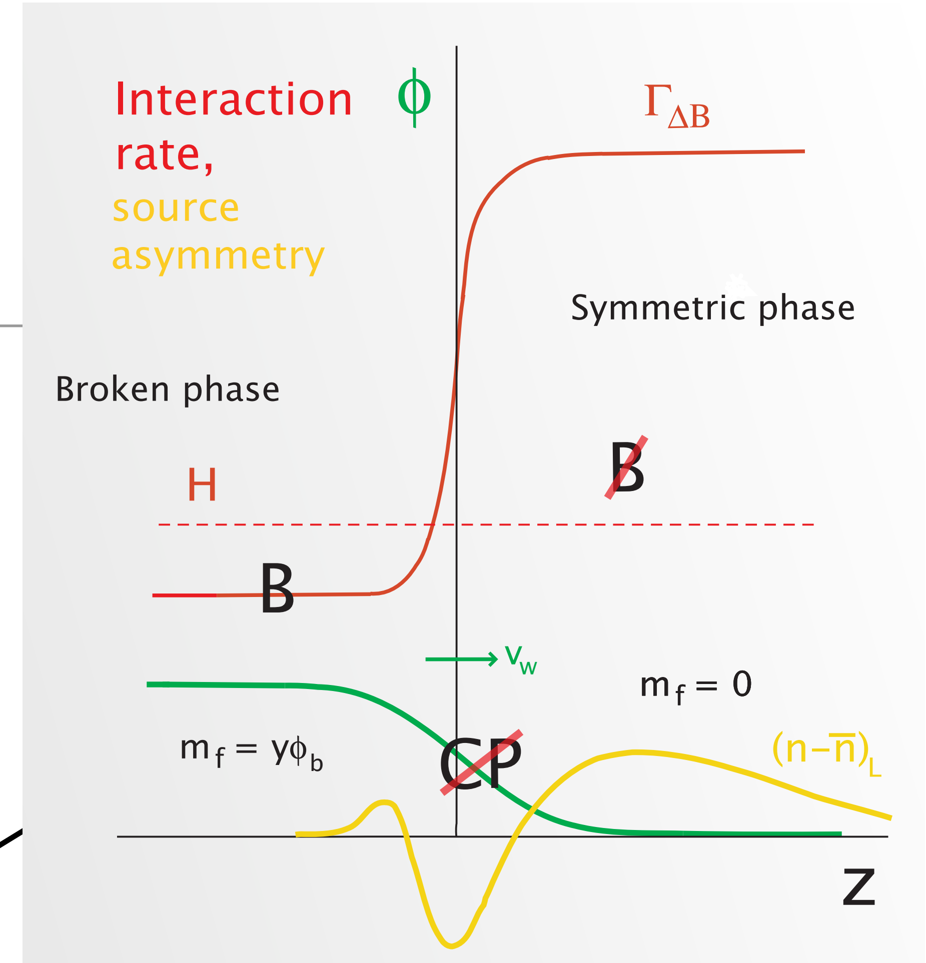

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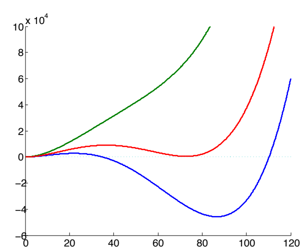

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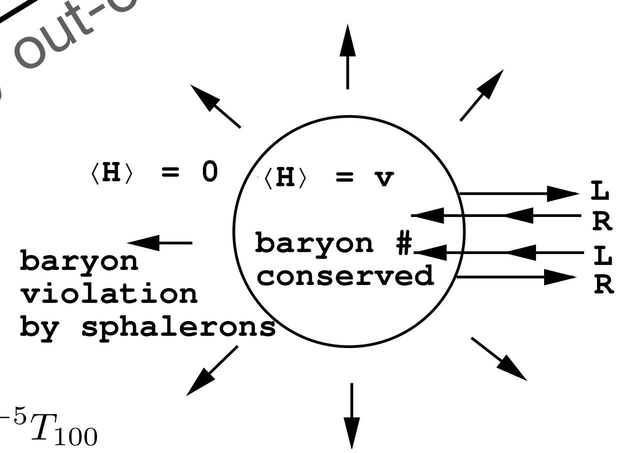
(CP-even) dynamics of the expanding wall ✓?

Parametrized by v_w and $\phi(z)$

Kajantie etal, Prokopec & Moore, John & Smith Espinosa, Konstandin, No & Servant (2010)....



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To make BA

B-violation I/EW chiral anomaly

B perturbatively conserved in SM => Proton stability!

Baryon + (and) lepton current

Chern-Simons current

$$\partial_\mu j^\mu_{\mathrm{B+L}} = N_{\mathrm{f}}\, \frac{g^2}{16\pi^2}\, {}^*F_{\mu\nu}F^{\mu\nu} \quad = \quad N_{\mathrm{f}}\, \partial_\mu j^\mu_{\mathrm{CS}}\left[A^a_\mu\right]$$

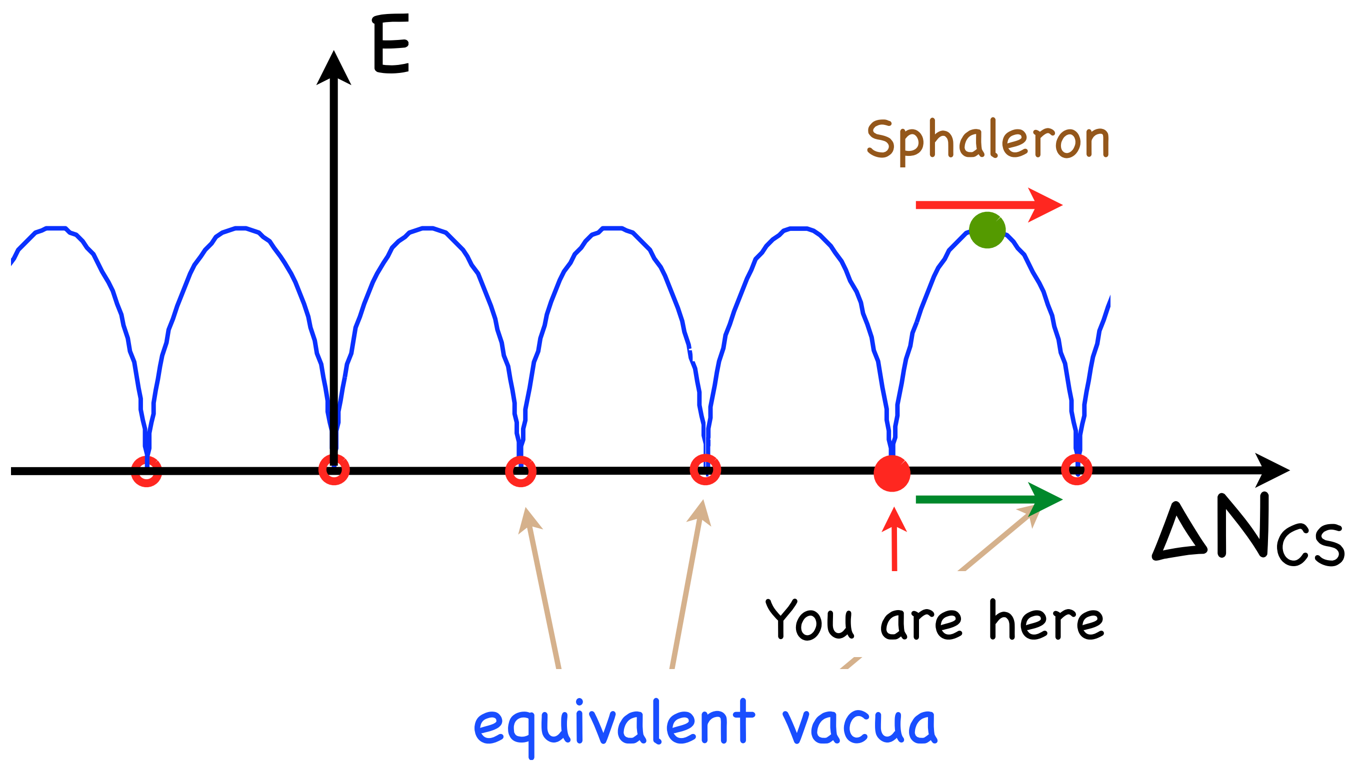
gauge fields

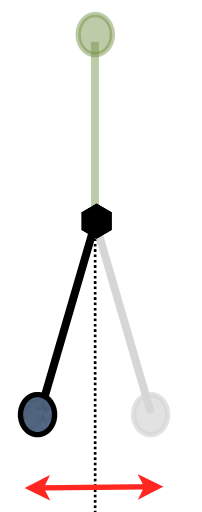
NOETHER:

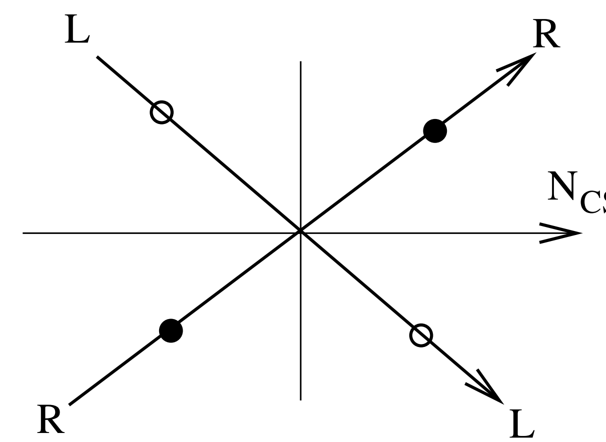
$$\Delta N_{\mathrm{B+L}} = N_f\, \Delta N_{\mathrm{CS}}$$

Nonperturbative fluctuations can lead to "large" gauge transformations that to change baryon and lepton numbers.

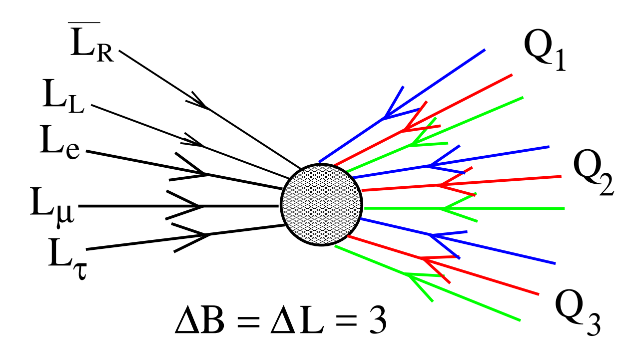
B-violation II/G-vacuum/CS#-diffusion/level crossing







Fermion zero modes kicked from vacuum



- SLOW at T=0 (tunnelling) `tHooft -76
- FAST at high T (thermal activation) Kuzmin, Rubakov and Shaposhnikov, -85

$$\Gamma \sim e^{-E_{\rm Sph}(T)/T}$$

$$\frac{E_{\rm Sph}(T)}{T} \approx 40\frac{\phi}{T}$$

B , if $\phi/T < 1.1$

$\not{B}$, if $\phi/T > 1.1$

NEEDS A BIG JUMP IN THE ORDER PARAMETER AT TRANSITION