

Issues with Electroweak Baryogenesis

Kimmo Kainulainen,

The Big Bang and the little bangs - Nonequilibrium phenomena in cosmology and heavy-ion collisions **and scalar dark matter** CERN/18.8.2016

with:

Tommi Alanne, Jim Cline, Pat Scott, Mike Trott, Kimmo Tuominen, Ville Vaskonen, Christoph Weniger, … -SM almost UV-complete: follow simplicity -DM and BG as guiding principles -Singlet models, portals

EWBG:

 -Transition strength -CP-violation

2HD+S model

Paradigm I: UV-comple(x)(te) models

HIERARCHY PROBLEM UNIFICATION

BARYOGENESIS DARK MATTER

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MSSM: HP/U/DM/EWBG

Leszek Roszkowski (Nordita, June 2015):

[SUSY cannot be disproved, only abandoned]

Paradigm I: UV-comple(x)(te) models

HIERARCHY PROBLEM UNIFICATION

BARYOGENESIS DARK MATTER

MinimalWalkingTechniColor: HP/DM/U/EWBG?

K.K, K.Tuominen J.Virkajarvi,

- Phys.Rev. D82 (2010) 043511
- JCAP 1002 (2010) 029
- JCAP 1002 (2010) 029
- JCAP 1310 (2013) 036
- JCAP 1507 (2015) 034
- in progress (BG-part)

MSSM: HP/U/DM/EWBG

Leszek Roszkowski (Nordita, June 2015):

[SUSY cannot be disproved, only abandoned]

Me stress that both the stress terms are needed to match the size of DM and Raryon acummatry dependence of around the weak scale, caused by the 32*y*⁴ **But remain the questions of DM and Baryon asymmetry**

Asymptotic safety: if OK, no need for unification Gravitational Correction to Running of Gauge Couplings Sean P. Robinson* and Frank Wilczek† *Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,* two-dimensional spacetime may indeed be considered as an asymptotically \mathcal{L} Asvm Continued of the previous result to four dimensions has the previous result to four the previous results of the at *G*⇤ ^N = ✏*/b* + *O*(✏²). The precise values of *b* depends of the number of ouc salety: <u>IT OK, ho need for unific</u> \mathbf{A} is get a non-Gaussian fixed point in \mathbf{B} dimensions, <u>in the indiced for unitie</u>

two-dimensional spacetime may indeed be considered as an asymptotically defined as an asymptotically σ

DOI: 10.1103/PhysRevLett.96.231601 PACS numbers: 12.10.Kt, 04.60.!m, 11.10.Hi sions is an AS theory [13–18]. Furthermore, there is research done about AS \mathcal{C} (ind \mathcal{C} ultowoo): \log (internal renormalisation). **Running couplings** (incl. yukawas): **Running couplings**

$$
\mu \frac{\partial g_i}{\partial \mu} = \beta_{\rm SM}(g_i) + \beta_{\rm grav}(g_i)
$$
\n^{1.4}

be not so easy. Hard with functional renormalisation group \mathcal{H} and \mathcal{H} and \mathcal{H}

relativity at the coupling and coupling at the coupling α a vanishe gravity c rraction is **naramatrically Where** gravity correction is **parametrically:** $\begin{bmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \end{bmatrix}$ **Where** gravity correction is **parametrically**:

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

Portal models

Simple **Portal to** (complicated?) **DM sector**

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

KK, K.Tuominen and V.Vaskonen Phys.Rev. D93 (2016) 7 ,015016 T.Alanne, KK, K.Tuominen, V.Vaskonen arXiv:1607.03303, JCAP, to appear

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

 $\mathcal{N} = \{C_{\mathbf{M} = 0} \mid \mathcal{N}_{\mathbf{M} = 0}\}$ and 100 times, corresponding to $\mathcal{N}_{\mathbf{M} = 0}$. Note that for cases where the subdominant component of dark matter, we have rescaled the direct direct direct d (P. Ko's talk)

Motivation: Baryogenesis

Harder! EWBG context: * strength of the transition * CP-violation (enough B) Leptogenesis ARS nuMSM ?

To keep BA

aposhnikov, **nativ** $e^{(\mu \nu)}$ 100 $e^{(\mu \nu)}$ Ω^{Q} in U^{V} \mathbb{P}^{∞} in a CP violation was \mathbb{P}^{∞} \mathbb{R}^n installation as \mathbb{R}^n a 3D-

Se ainen and M.E. Shaposhnikov,

Si 189; PRL77, 2887 (1996)...

Equilibrium / Nonperturbative / Quantum

Equilibrium / Nonperturbrium / Quantum

Equilibrium / Nonperturbrium / Pen and M.E.Shaposhnikov,
189; PRL77, 2887 (1996)....
189; PRL77, 2887 (1996)....
189; PRL77, 2887 (1996)....
1996; MOStly Out-of-equilibrium / quantum •Dim. reduction to a 3D- Higgs-gauge theory simulated in Lattice K.Kajantie, M.Laine, K.R<mark>ummukainen and M.E.Shaposhnikov,</mark> NPB458 (1996) 90; NPB466 (1996) 189; PRL77, 2887 (1996).... **2-loop** *V***eff in LG ~OK** M.Laine, G.Nardini and K.Rummukainen, JCAP 1301 (2013) 011... •*V*eff in Landau *gauge* M.Garny and T.Konstandin, JHEP1207 (2012) 189, H.H.Patel, M.J.Ramsey-Musolf, C.Wainwright, S.Profumo JHEP 07 (2011) 029; PRD84 (2011) 023521; PRD86 (2012) 083537. $-\frac{1}{20}$ 20 40 60 80 100 120 −4 −2 0 2 4 6 8 10^{x} 10⁴ ϕ_n T_n *>* 1 (Small) sphaleron rate in the broken phase Kuzmin, Rubakov & Shapsohnkinov, Arnold & McLerran, Moore, Rummukainen…;

> **violation by sphalerons**

 $\langle H \rangle$ = 0 $/ \langle H \rangle$

 $\langle H \rangle = 0$ $\left\langle \langle H \rangle = \mathbf{v} \right\rangle$ **L**

R L

baryon # baryonconserved

 baryonR **conserved**R

CP B B H $\Gamma_{\Delta B}$ $m_f = 0$ $m_f = y\phi_h$ Interaction rate, ϕ z $(n-\overline{n})$ source asymmetry L v_w Broken phase Symmetric phase

To make BA

Sphaleron rate in the unbroken phase Ambjorn etal,... Moore; Rummukainen etal,..

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

To make BA

EWBG

SM, Transition strength / Sphaleron rate strength / Sphalerc of this magnitude was also observed in ref. [25]. $p \cdot \mathbf{a}$ in the early Universe, T were done with Higgs mass \sim 50 μ GeV, which is far from \sim Snhalaron rata cluded their result is a factor of ≈ 150 below our rate, 1 Traneitian etrang work, they can be seen \mathbf{v} the almost horizontal line. theory reproduces T^c perfectly, and v² is slightly larger

Transition strength, extensions / LSS

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

Need new light (*m*i *< T*) bosonic fields strongly coupled to **Higgs**

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

=> **L**ight **S**top **S**cenario in the MSSM and NMSSM [Carena, Quiros, Wagner (1996),...] => LIONI SI **A** butions to the self-energies are UV finite. Once the sum over the Matsubara

However, also higgs mass mostly from

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

Tension: light t_R => very heavy t_L

FIG. 3. Shape of the Higgs potential at the critical tem $p = p$ erent choices of parameters of par Early times early-**mid-90'**s:

 $V_{\text{1-loop}}$: Espinosa,Quiros,Zwirner, Carena, Wagner,... son mass λ , λ , λ , we have fixed panel). While varying λ , we have fixed particles λ 1-loop DR: Laine,Cline,KK,Losada,...

J.R.Espinosa -96: 75% 2-loop enhancement on *v/T* NPB475 (1996) 273.

Transition strength, MSSM-LSS Transition strength. lightest stop to the Higgs is suppressed, turning the electroweak phase transition too

RGE-improved potential: models (*metastable* against color breaking)

M.Carena, G.ardini, M.Quiros & C.Wagner, NPB812 (2009)

LHC: $\frac{1}{\sqrt{1-\frac{1$ with the longitudinal modes of the gluon. In our work we considered that, due to the gluon. In our work we considered that, due to the gluon. In our work we considered that, due to the gluon. In our work we can consider t

Tension with light stop-enhanced gg-fusion Higgs production ... needs to be balanced by an invisible DW to light neutralinos (<60GeV) …

M.Carena, G.Nardini, M.Quiros & C.Wagner, NPB812 (2013)

Rummukainen, Nardini and Laine ... F_{eff} is a perturbative and lattice results for the phase transition of t **Lattice** is a bit more generous:

$$
\left(\frac{v}{T_c}\right)_{\text{latt}} = 1.117(5) \qquad \left(\frac{v}{T_c}\right)_{\text{Landau}} = 0.9
$$

 $\frac{3}{2}$ DW **But** $m_{\text{stop}} > 210$ **-540 GeV (depending on neutral higgsino mass)** W_{max} view of ω about generic features of the dynamics of the theory, probably appli- $\sum_{i=1}^{\infty}$ cobuntinue call, injointeed here $\sum_{i=1}^{\infty}$

to m^h ≃ 126 GeV, we proceed to comparing the lattice results with those of 2-loop pertur-

Strong transition from a singlet Anderson, Hall, PRD45, 2685 (1992)

Profumo, Ramsey-Musolf, Shaughnessy, JHEP 0708 (2007) 010

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

subdominant DM. 3 **Variants of the scheme:**

Small finance, Ovanesyan, Ramsey-Musolf,
free only 112 has a company of the PRD93 (2016) 015013, etc… Inoue, Ovanesyan, Ramsey-Musolf,

while still interacting the MSSM ~color breaking strongly enough with nuclei to be potentially detectable. If \sim 1, \sim 1, *M* idea actually present in the \blacksquare DM component in the substitution to the total DM density, present in the total DM density, \blacksquare then the relic density of *S* is suppressed relative to the observed value by *f*rel, and larger

diana, mananananany, propinsition, because the following. The following in the followi **Laine, Rummukainen,** which controls the coupling α Cip_1 noon Cip_2 values Cip_3

Strong transition and S-DM? (Not in simplest case)

ما (ه

However, **needs for a large v/T (large λ***hs***) and a large Ω are in contrast:**

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

Large v/T implies a **subdominant DM**

. The small slive for small slives for small slives \mathbb{R}^n , \mathbb{R}^n ,

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

Obviously, with two singlets,

with suitable λ _{hs}'s and masses,

both strong transition and DM

are bound to work!

Extend DS eg. with a DM-fermion

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

Electroweak baryogenesis: \blacksquare \blacks $h = \frac{1}{2}$ \blacksquare chirality flipping rate comparable to the sphale it also to be it also to be it also to be it also to be i out of equilibrium, with the SM spectrum, which with the SM spectrum, which we are spectrum, which would apply if all squarks \mathbf{r} paryogenesis: were also and hence \sim which are light enough to be present at T $=$ 100 G $=$ 100 G $=$ 100 G $=$ 100 G $=$ 100 G

Ξ

⇥⇤¹

Need to compute: compute:

$$
\xi_{q_L}(z) \sim n_L(x) - \bar{n}_L(x)
$$

asymmetry

it is easy to integrate the equation to obtain the baryon to obtain the baryon the baryon state of \mathcal{L} to get

$$
n_B = \frac{3 \Gamma_{\rm sph}}{2 v_w} \int_0^\infty dz \, \xi_{q_L}(z) e^{-k_B z}
$$

$$
k_B \equiv \frac{3A}{2v_w} \frac{\Gamma_{\rm sph}}{T^3}
$$

•Semiclassical, WKB-regime \bullet Quantum m rer 1e $\overline{}$ ·Quantum reflection

> Nee \mathbf{A} treatment dy KE's for ful UI IUII Needs **QKE's** for full

WKB-regime: Semiclassical baryogenesis = vg(xvg)^p^c ⇥ (^x)^p^c (^p^c vg)^x . (2.15) force (5.3) agree with the full Schwinger–Keldysh result [23]. second order the conduction of the conduction of \mathbf{C}

relations and their corresponding canonical equations of motion. This is a reasonable

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

Integration with weights **1** and **p/E**

s

2

$$
v_g = \frac{p_0}{\omega} \left(1 + s_{\text{CP}} \frac{s|m|^2 \theta'}{2p_0^2 \omega} \right)
$$
\n
$$
F = -\frac{|m||m|'}{\omega} + s_{\text{CP}} \frac{s(|m|^2 \theta')'}{2\omega^2}.
$$
\nForce

the chemical and kinetic equilibrium with the fluid-type truncation in the rest frame of the

so that the perturbations to second order for particles differ from those for antiparticles.

 W follow the computation and notation presented in ref. \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n , \mathbb{R}^n

$$
(v_{gz}\partial_z + F_z\partial_{p_z})f_i = \mathbf{C}_i[f]
$$

the chemical and kinetic equilibrium with the fluid-type truncation in the rest frame of the **Fluid ansaz** where \mathbb{R} = 1/T and γw = 1/T and γw 15a∠
|

gime: Semiclassical baryogenesis
\n
$$
\begin{array}{ll}\n\lim_{(x) \mid, k_{0} \mid} & \lim_{(y_{g} \mid p) \neq} & \lim_{(y_{g}, y_{g} \mid + F \cdot \partial_{p}) \int_{i} = C[f_{i}, f_{j}, \ldots]. & \text{Higgs} \text{ (a) } \text{ (b) } \text{ (c) } \text{ (d) } \text{ (e)} \text{ (e)} \text{ (f)} \text{ (f)} \text{ (g)} \text{ (h)} \text{ (h)} \text{ (i) } \text{ (i) } \text{ (j) } \text{ (k) } \text{ (k) } \text{ (l) } \text{ (l)
$$

The latter do not contribute to the particle density, i.e. α and β $=$ 0. To finally distribute to first order in

 $1\leq i\leq n$ i,2o + $2\leq i\leq n$ i,2e, $2\leq i\leq n$ i,2o + δ i,2o + δ

so that the perturbations to second order for particles differ from those for antiparticles.

without any explicit time dependence, as we are looking for a stationary solution. The stationary solution is s

In the semiclassical approximation the evolution of the particle distribution of the particle distributions fi is α

Cⁱ are the collision terms describing the change of the phase-space density by particle

described by a set of classical Boltzmann equations. We assume a planar wall moving with

interactions that drive the system back to equilibrium. We introduce perturbations around

 $\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left[\mathbb{P}_{\mathbb{P}_{\mathbb{P}}}\left$

w, and plus (minus) referred to fermions (bosons). Here α

Integration with weights 1 and p/E

 $\frac{1}{\sqrt{2}}$ have Countries for $1\leq i\leq n$ i,2o + $2\leq i\leq n$ i,2e, $2\leq i\leq n$ i,2e, $2\leq i\leq n$ In order to compute the asymmetry in the left-handed quark density, we expand the left-handed quark density, we expand the left-handed density, we expand the left-handed density, we expand the left-handed density, we expa **µ** and

 \mathbf{WKB} J.M. Cline, M. Joyce and K. Kainulainen. PLB417 (1998) 79; JHEP 0007 (2000) 018
 \mathbf{WKB} J.M. Cline and K. Kainulainen, PRL85 (2000) 5519. m. Joyce, T. Prokopec und N. Turok, PRD33, 2938 (1990), PRL73, 1093 (1993), PRD33, 293 $\frac{1}{2000}$ M. Joyce, T. Prokopec and N. Turok, PRD53, 2958 (1996); PRL75, 1695 (1995); PRD53, 2930 (1996). JHEP07(2000)018 $R = \text{Time}, \text{cm}, \text{SUS}$ e and s
s WKB J.M. Cline, M. Joyce and K. Kainulainen. PLB41 J.M. Cline, M. Joyce and K. Kainulainen. PLB417 (1998) 79; JHEP 0007 (2000) 018 J.M. Cline and K. Kainulainen, PRL85 (2000) 5519. flavors and the leptons can be neglected thanks to the leptons coupling thanks to the leptons of the leptons of ~ 1000 couplings. In additional Vulgory coupling to the leptons of ~ 1000 couplings. In additional vulgo Γα Κ. Κατημιατήen. Ρίβ417 (1998) 79; ΙΗΕΡ 0007 (2000) 018
Ilainen, PRL85 (2000) 5519. $p(1996)$: PRI 75, 1695 (1995): PRD53, 2930 (1996).

 $\mathbf{C}\mathbf{TP}$ K. Kainulainen, I. Prokopec, M.G. Schmidt and S. Weinstock, JHEP 0106, 031 (2001); PRI
 $\mathbf{CP}\mathbf{P}$ T. Prokopec, M.G. Schmidt and S.Weinstock, Annals Phys. 314, 208 (2004), Annals Phys. ical momentum for left- and right- and right-handed particles. From the imper- $\bigcap \mathbf D$ K. Kainulainen, T. Prokopec, M.G. Schmidt and ${\rm CTP}$ K. Kainulainen, T. Prokopec, M.G. Schmidt and S. Weinstock, JHEP 0106, 031 (2001); PRD66 (2002) 043502.
 ${\rm CTP}$ T. Prokopec, M.G. Schmidt and S.Weinstock, Annals Phys. 314, 208 (2004), Annals Phys. 314, 267 (2004) T. Prokopec, M.G. Schmidt and S.Weinstock, Annals Phys. 314, 208 (2004), Annals Phys. 314, 267 (2004) $\frac{1}{2}$, $\frac{1$ present in the broad present in the broad present.
Phys. 314, 208 (2004), Annals Phys. 314, 267 (2004). A ₁₁₁ B ₁₁ B ₃, 314 , we fock, JHEP 0106, 031 (2001); PRD66 (2002) 043502. m Priys. 514, 208 (2004), annuts Priys. 514, 207 (2004)

BAU generation, MSSM MSSM is a controversial topic. One difference to the other models discussed J deneration MSSM s source of CP via the charginos and neutralinos and neutralinos and neutralinos. For s

example the chargino mass can be written

Chargino transport

Chargino transport	$\mathcal{M}_{\chi_{\pm}} = \begin{pmatrix} M_2 & gh_2 \\ gh_1 & \mu \end{pmatrix}$
--------------------	---

J.M.Cline, M.Joyce and KK, JHEP 0007 (2000) 018.

Similar results were found by

T.Konstandin, T.Prokopec, M.G.Schmidt, and M.Seco, NPB738 (2006) 1.

which also used SC/CTP approach and included flavour mixing effects

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However, there are differences (in the evaluation of the source) in the literature: as y larger than our control and control of the control o

T.Konstandin, arXiv:1302.6713 [hep-ph]

Stop transport:

J.Kozaczuk, S.Profumo, M.Ramsey-Musolf and CL. Wainwrigh, PRD86 (2012) 096001

Neutralino transport: Y.Li, S.Profumo, and M.Ramsey-Musolf, PLB673 (2009) 95–100.

Does it work? (Not likely)

Singlet model and BAU \bullet singlet Higgs was nothinglet \bullet required to be a DM candidate. For example, nothing prevents \bullet us from choosing the phase of \sim two-loop Barr-Zee contributions to the electric dipole moments of the electric dipole moments of the electric d
The electric dipole moments of the electric dipole moments of the electric dipole moments of the electron and

But this requires *h*-*s* mixing, which does not occur in our model. Ours is similar to models

in which CP is broken spontaneously at high temperature in this respective in this respective in this respectiv

DM stability =>Z₂ symmetry: $\langle S \rangle_{T=0} = 0$

Source of CP violation Dim-6 operation that the source of CP violation that biases sphalers are solved that the source of \Box (If not DM could take Dim-5 as well) Espinosa, etal $\eta_B/\eta_B/\eta_B$

on its mass from collider searches, nor from precision electroweak observables.

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

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

of the *Z*² symmetry *S* ⇤ *S* needed to prevent decay of *S*, as befits a dark matter candidate. **We are also constructed of the method of the enable potential in section of the enable potential in section 2, constraints and construction of the enable potential in section 2, constraints and constraints and constraints** 2 singlets + CP-source: DM & BAU

We follow ref. [48] in approximation ref. [48] in approximation ref. [48] in approximation ref. [48] in the form

matter candidate in section 4 along with some results from a random scan over model pa-

rameters. The absence of other constraints on the model is explained in section 5. The

computation and resulting distributions of value for the baryon asymmetry are described in

Dimension-6 operator (S/Λ)² t

Baryon asymmetry with singlet DM

coefficient gives new source of CP violation for CP violation for CP violation for CP violation for CP violation for

computation and resulting distributions of value for the baryon asymmetry are described in

Pure 2HD models (at least renormalizable...) We decompose the second scalar doublet as S = (S+, S0), where S = (S+, S0), where S

Pure 2HD models (at least renormalizable...) We decompose the second scalar doublet as S = (S+, S0), where S = (S+, S0), where S

OHDIS model completions ETTP TV MURTING THE PRESENCE OF A SIDINGLET DOME <u>2 The model</u> **Where** It and Zij vij de Most general potential is given by the m \mathcal{L} is the semi-direct product of special linear transformations \mathcal{L} \blacksquare 2HD+5 MOdel: <mark>OP</mark> from 2HDM - strength from transformation to bring the kinetic term into the canonical form, Z*ij* ! diag(1*,* 1), i.e. **2HD+S model: CP from 2HDM - strength from S 1/7**

¹*|H*1*|*

Scalar sector: with the same matrix structure (since *S* is a singlet under SM gauge interactions its couplings the scalar goots Z*ij* (*DµHi*)

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

² *^m*²

² ⁺ *[|]DµH*2*[|]*

²*|H*2*|*

2 *.*

2

⇣ *m*²

12*H†*

model because it will disentent the source of a strongly first-order transition from that order transition from

²*H*¹ + h.c.⌘

¹

2*m*²

*SS*²

Fermions: Universal ($C_i^a \equiv C_i$) **Yukawa alignment** \Rightarrow **No FCNC's** *ⁱ* ⁶⁼ *^C^b ⁱ* . However, for simplicity, we choose to work in the Fermions: Universal ($C_i^a \equiv C_i$) Yukawa alignment $\;\;$ > N Both doublets *Hⁱ* are assumed to be gauged under SU(2)^L ⇥ U(1)*^Y* , while the scalar *S* Fermions: Universal ($C_i^a\equiv C_i$) Yukawa alignment $\,$ => No FCNC's

We start from the most general two-Higgs-doublet and inertial two-Higgs-doublet and inertial two-Higgs-doublet extension of the SM with \sim

$$
\mathcal{L}_{\text{Yukawa}} = y_u C_u^i \bar{Q}_L \tilde{H}_i u_R + y_d C_d^i \bar{Q}_L H_i d_R + y_\ell C_\ell^i L_L H_i e_R + \text{h.c}
$$
 consistent GL(2,C)-inv

^V (*H*1*, H*2*, S*) = *^m*²

$$
V_{\text{ukawa}} = y_u C_u^i \bar{Q}_L \tilde{H}_i u_R + y_d C_d^i \bar{Q}_L H_i d_R + y_\ell C_\ell^i L_L H_i e_R + \text{h.c}
$$
\n
$$
\text{Consistent with}
$$
\n
$$
C_1^i \to 0
$$
\n
$$
C_2^i \to 1
$$

OHDIS model completions ETTP TV MURTING THE PRESENCE OF A SIDINGLET DOME <u>2 The model</u> **Where** It and Zij vij de Most general potential is given by the m \mathcal{L} is the semi-direct product of special linear transformations \mathcal{L} \blacksquare 2HD+5 MOdel: <mark>OP</mark> from 2HDM - strength from transformation to bring the kinetic term into the canonical form, Z*ij* ! diag(1*,* 1), i.e. + 1*|H*1*|* ⁴ ⁺ 2*|H*2*[|]* ⁴ ⁺ 3*|H*1*[|]* ²*|H*2*[|]* ² + 4(*H†* 1*H*2)(*H†* ²*H*1) **SHERRY HOW AND HOT AND HIS SUCH STATE** ²*H*1) ² ⁺ 6*|H*1*[|]* ²*H*1) + 7*|H*2*|* S at the SM fields through its renormalizable S energies the strong technical in terms of an election of an election of an election of an election and the str $\overline{}$ 2.1 Reparametrization invariance and tree-level vacuum stability *Sµ* ⌘ (*S*¹ + *S*2*,* 2*S*12*R,* 2*S*12*^I , S*¹ *S*2) (2.8) **DOCLE CP** fro 0 ¹ + ² + ³ 6*^R* + 7*^R* 6*^I* + 7*^I* ¹ ² **2HD+S model: CP from 2HDM - strength from S 1/7**

¹*|H*1*|*

Scalar sector: with the same matrix structure (since *S* is a singlet under SM gauge interactions its couplings S *Calar sector:* Z*ij* (*DµHi*) The original Lagrangian with the most general potential, kinetic term, and the universal potential, kinetic te aligned Yukawa sector: $\overline{}$ real parameters (not counting the parameters entering the parameter

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

² *^m*²

6*^R* + 7*^R* ⁴ + 25*^R* 25*^I* 6*^R* 7*^R*

² ⁺ *[|]DµH*2*[|]*

²*|H*2*|*

2 *.*

2

⇣ *m*²

12*H†*

model because it will disentent the source of a strongly first-order transition from that order transition from

²*H*¹ + h.c.⌘

Fermions: Universal ($C_i^a \equiv C_i$) **Yukawa alignment** \Rightarrow **No FCNC's** *ⁱ* ⁶⁼ *^C^b ⁱ* . However, for simplicity, we choose to work in the Fermions: Universal ($C_i^a \equiv C_i$) Yukawa alignment $\;\;$ > N Both doublets *Hⁱ* are assumed to be gauged under SU(2)^L ⇥ U(1)*^Y* , while the scalar *S* Fermions: Universal ($C_i^a \equiv C_i$) Yukawa alignment \Rightarrow No FCNC's *P* (and a simultaneous rescaling of *S*), where *P* is an element of the general linear group where \mathbf{r} is an arbitrary Hermitian 2 \mathbf{r} matrix and the most general potential is given by \mathbf{r} *^V* (*H*1*, H*2*, S*) = *^m*² ¹*|H*1*|* ² *^m*² $\mathsf{Formula}$ **Furnions.** Oniversal $\mathcal{C}_i = \mathcal{C}_i$ fundwa anginhem $=$ two from stable First consider the direction *S* = 0 in the potential (2.7). Here the term *rµµ*⌫*r*⌫ must \mathbf{Id} ($C^u_i\equiv C_i$) Yukawa alignment $\;$ => <code>No FCNC's</code>

We start from the most general two-Higgs-doublet and inertial two-Higgs-doublet and inertial two-Higgs-doublet extension of the SM with \sim

^V (*H*1*, H*2*, S*) = *^m*²

$$
\mathcal{L}_{\text{Yukawa}} = y_u C_u^i \bar{Q}_L \tilde{H}_i u_R + y_d C_d^i \bar{Q}_L H_i d_R + y_\ell C_\ell^i L_L H_i e_R + \text{h.c}
$$

Consistent
GL(2,C)-inv

$$
\mathcal{L}_{\text{Yukawa}} = y_u C_u^i \bar{Q}_L \tilde{H}_i u_R + y_d C_d^i \bar{Q}_L H_i d_R + y_\ell C_\ell^i L_L H_i e_R + \text{h.c}
$$
\n
$$
\text{Consistent with}
$$
\n
$$
C_1^i \rightarrow 0
$$
\n
$$
C_2^i \rightarrow 1
$$

¹

2*m*²

*SS*²

Use GL(2,C)-invariance to construct all bounded poterary ⌘ (*H*1*, H*2) are doublet-index dependent complex numbers. In general the alignment may be di↵erent Use GL(2,C)-invariance to construct all <u>bounded potentials</u> **Use GL(2, C)-invariance to construct all bounded potentials** ⁴*SS*⁴ ⁺ ¹ model potential *V* (*H*1*, H*2*, S*). Our next task is to find out which sets of these parameters Both doublets *Hⁱ* are assumed to be gauged under SU(2)^L ⇥ U(1)*^Y* , while the scalar *S* correspond to physically viable models with a stable potential. The stable potential of the stable potential. GL(2,C)-invariance to construct all **bounded potentials** ten real degrees of freedom in the most general 2HDM potential. Second, if we set *r^µ* = 0 ance to construct all <u>boun</u>

 $7^{ij}(D^{\mu}H.)^{\dagger}D \quad H.$ and a rotation and a redefinition and $D \quad H.$ $2\left(\frac{\nu}{\mu}\right) \frac{D_{\mu}}{\mu}$, $\frac{D_{\mu}}{\mu}$, $\frac{D_{\mu}}{\mu}$, $\frac{D_{\mu}}{\mu}$, $\frac{D_{\mu}}{\mu}$ Ω is the semi-direct product of semi-direct product of special linear transformations Ω $\theta \mapsto |\mathcal{D}_{\mu}H_1|^2 + |\mathcal{D}_{\mu}H_2|^2$ special case of *universal Yukawa alignment*, where C _{*a*} $I^{ij}(D^{\mu}H_i)^{\dagger}D_{\mu}H_j \rightarrow |D_{\mu}H_1|^2 + |D_{\mu}H_2|^2$ corresponds to setting *C*¹ = 0 and *C*² = 11, so that: transformation to bring the kinetic term into the canonical form, Z*ij* ! diag(1*,* 1), i.e. $Z^{ij}(D^{\mu}H_i)^{\dagger}D_{\mu}H_j \longrightarrow |D_{\mu}H_1|^2 + |D_{\mu}H_2|^2$ $D_u H_2|^2$ suciently strong CP violation. The bilinear four-vector r*a* μ is positive definites to μ is, μ ^{*n*} vectors span the future light definite μ is, μ ⁿ vectors span the future light definite μ is, μ vectors span the future light defin $Z^{ij}(D^{\mu}H_i)^{\dagger}D_{\mu}H_j \rightarrow |D_{\mu}H_1|^2 + |D_{\mu}H_2|^2$ $i \overline{i}$ $H_i)^\dagger D_\mu H_j \quad \rightarrow \quad |D_\mu H_1|^2 + |D_\mu H_2|^2$ $(D_{\mu}H_{i} \rightarrow |D_{\mu}H_{1}|^{2} + |D_{\mu}H_{2}|^{2}$ **dilatations** 6*^R* + 7*^R* ⁴ + 25*^R* 25*^I* 6*^R* 7*^R* $I^{ij}(D^{\mu}H)^\dagger D_{\nu}H \longrightarrow [D_{\nu}H_1]^2+I^2$ $1 - \mu - 1$ $1 - \mu - 1$ $(H_2)^2$ μ *H*_j \rightarrow $|\mathcal{D}_{\mu}$ *H*₁] \rightarrow $|\mathcal{D}_{\mu}$ *H*₂]

for this scheme on the large top-quark coupling on the large top-quark coupling. The only exception is more top-Remaining SL(2,C)-invariant, bounded potential: one can rewriting $\frac{1}{2}$ in a very compact for a very compact for $\frac{1}{2}$ Remaining SL(2,C)-invariant, bounded potential: tively. The reparametrization invariance is manifest in Eq. (2.7), because *V* depends only **µ** on Lorentz-invariant products of vectors and tensors. This form is particularly suitable for a

$$
V = -\frac{1}{2}m_S^2S^2 - \frac{1}{2}M_\mu^2r^\mu + \frac{1}{4}r^\mu\lambda_{\mu\nu}r^\nu + \frac{1}{4}\lambda_{S\mu}r^\mu S^2 + \frac{1}{4}\lambda_S S^4
$$

$$
\Phi \equiv (H_1, H_2)^T
$$

 $*h*$ $*u*$ $*h*$ $*u*$ w here

where $SO(1,3)^+$ -transformation of LC⁺ where *Sµr^µ <* 0. Having found an acceptable set, we generate a random Lorentz *^V*quartic ⁼ ¹

$$
\lambda_{\mu\nu} \equiv \Lambda_{\mu}{}^{\alpha} \lambda_{\alpha\beta}^{D} \Lambda^{\beta}{}_{\nu} \quad \text{and} \quad \lambda_{S}^{\mu} \equiv \Lambda^{\mu}{}_{\nu} (\lambda_{S}^{D})^{\nu}
$$
\n
$$
\lambda_{\alpha\beta}^{\mu} = \text{diag}(\lambda_{00}^{D}, -\lambda_{11}^{D}, -\lambda_{22}^{D}, -\lambda_{33}^{D}), \quad \text{with} \quad \lambda_{00}^{D} > 0 \quad \text{and} \quad \lambda_{00}^{D} > \lambda_{ii}^{D}
$$
\n
$$
\lambda_{\mu\nu} \equiv \begin{pmatrix} \lambda_{1} + \lambda_{2} + \lambda_{3} & \lambda_{6R} + \lambda_{7R} & -\lambda_{6I} + \lambda_{7I} & \lambda_{1R} \\ \lambda_{6R} + \lambda_{7R} & \lambda_{4} + 2\lambda_{5R} & -2\lambda_{5I} & \lambda_{6R} \\ -\lambda_{6I} + \lambda_{7I} & -2\lambda_{5I} & \lambda_{4} - 2\lambda_{5R} & -\lambda_{6I} \\ \lambda_{1} - \lambda_{2} & \lambda_{6R} - \lambda_{7R} & -\lambda_{6I} - \lambda_{7I} & \lambda_{1} + 2\lambda_{6I} & \lambda_{1} + 2\lambda_{6I} \\ \lambda_{1} - \lambda_{2} & \lambda_{6R} - \lambda_{7R} & -\lambda_{6I} - \lambda_{7I} & \lambda_{1} + 2\lambda_{6I} & \lambda_{1}
$$

Remaining SL(2,C)-invariant, bounded potential:

\n
$$
V = -\frac{1}{2}m_S^2 S^2 - \frac{1}{2}M_\mu^2 r^\mu + \frac{1}{4}r^\mu \lambda_{\mu\nu} r^\nu + \frac{1}{4}\lambda_{\mu\nu} r^\mu S^2 + \frac{1}{4}\lambda_S S^4 \qquad \Phi \equiv (H_1, H_2)^T
$$
\nwhere $\sigma^\mu = (1, \sigma_i)$

formation
\n
$$
M_{\mu}^{2} \equiv (m_{1}^{2} + m_{2}^{2}, 2m_{12R}^{2}, -2m_{12I}^{2}, m_{1}^{2} - m_{2}^{2}),
$$
\n
$$
\lambda_{S\mu} \equiv (\lambda_{S1} + \lambda_{S2}, 2\lambda_{S12R}, -2\lambda_{S12I}, \lambda_{S1} - \lambda_{S2})
$$
\n
$$
\lambda_{S\mu}^{H} \equiv (\lambda_{S1} + \lambda_{S2}, 2\lambda_{S12R}, -2\lambda_{S12I}, \lambda_{S1} - \lambda_{S2})
$$
\n
$$
\lambda_{S\mu}^{H} \equiv (\lambda_{S1} + \lambda_{S2}, 2\lambda_{S12R}, -2\lambda_{S12I}, \lambda_{S1} - \lambda_{S2})
$$
\n
$$
\lambda_{B\mu}^{2} \equiv \begin{pmatrix} \lambda_{1} + \lambda_{2} + \lambda_{3} & \lambda_{6R} + \lambda_{7R} & -\lambda_{6I} + \lambda_{7I} & \lambda_{1} - \lambda_{2} \\ \lambda_{6R} + \lambda_{7R} & \lambda_{4} + 2\lambda_{5R} & -2\lambda_{5I} & \lambda_{6R} - \lambda_{7R} \\ -\lambda_{6I} + \lambda_{7I} & -2\lambda_{5I} & \lambda_{4} - 2\lambda_{5R} & -\lambda_{6I} - \lambda_{7I} \\ \lambda_{1} - \lambda_{2} & \lambda_{6R} - \lambda_{7R} & -\lambda_{6I} - \lambda_{7I} & \lambda_{1} + \lambda_{2} - \lambda_{3} \end{pmatrix}
$$
\n
$$
M_{\mu\nu} \equiv \begin{pmatrix} \lambda_{1} + \lambda_{2} + \lambda_{3} & \lambda_{6R} + \lambda_{7R} & -\lambda_{6I} + \lambda_{7I} & \lambda_{1} - \lambda_{2} \\ \lambda_{6R} + \lambda_{7R} & \lambda_{4} + 2\lambda_{5R} & -2\lambda_{5I} & \lambda_{6R} - \lambda_{7R} \\ \lambda_{1} - \lambda_{2} & \lambda_{6R} - \lambda_{7R} & -\lambda_{6I} - \lambda_{7I} & \lambda_{1} + \lambda_{2} - \lambda_{3} \end{pmatrix}
$$

2HD+S model: CP from 2HDM - strength from S 2/7 **ZNU+5 INOUCL CP** from 2HDM - strength from S arising from the two Higgs doublets: the two neutral scalar states *h*⁰ and *H*0, two charged

$C_{\rm P}$ top-transport a model where $3/7$ realized. Here we will have been to the singlet scalar temperature will be the condition of the condition of the
In the singlet scalar temperature in the condition of the condition (3.10) of the condition of the condition holds. The covariant derivatives involve the classical *Z^µ* field: *D^µ* = @*^µ ig/*(2 cos ✓W)*Zµ*. **EIIDTO IIIUUGI. EWBU SOUICE:** C model rupe. 2HD+S model: EWBG source: top-transport 3/7 <u>XIX Services of the services of the services of product</u>

holds. The covariant derivatives involve the classical *Z^µ* field: *D^µ* = @*^µ ig/*(2 cos ✓W)*Zµ*. We write the neutral components of the doublets as *hjei*'*^j* and observe that the e↵ective

² +

2

(@*zS*)

² +

(@*z*')

2 *h*2

¹ + *h*²

extension of the SM. T

² + *V* (*h*1*, h*2*, S,* '*, Tc*)

. (3.15)

(@*z*')

² + *V* (*h*1*, h*2*, S,* '*, Tc*)

 M **inimize the Action** (in $7-0$ -aquae) at $T-T$, $-\times$ H, H₂ S and α , α **Minimize the Action** (in $Z=0$ -gauge) at $I=I_c$ The invariance of the potential under the change of the total phase '¹ + '² implies a **Minimize the Action** (in Z=0-gauge) at $T=T_c \Rightarrow H_1,H_2$, S and φ $\qquad \qquad$ \qquad \qquad

(@*zhi*)

² +

2

(@*zS*)

$$
S_1 = \int dz \left(\sum_i \frac{1}{2} (\partial_z h_i)^2 + \frac{1}{2} (\partial_z S)^2 + \frac{1}{2} \frac{h_1^2 h_2^2}{h_1^2 + h_2^2} (\partial_z \varphi)^2 + V(h_1, h_2, S, \varphi, T_c) \right)
$$

relative phase between H_1 and H_2 $\hspace{1cm}$ $\hspace{1cm}$ conservative phase between H_1 and H_2

$$
\partial_z \varphi_2 = -\frac{h_1^2}{h_1^2 + h_2^2} \partial_z \varphi \qquad \Longrightarrow \qquad m_t(z) = \frac{y_t}{\sqrt{2}} h_2(z) e^{i\varphi_2(z)} \qquad \qquad \underbrace{\stackrel{\circ}{\circ}}_{50}
$$

CP-violating SC-source $(x_t = m_t/T)$: the modulus *h*2(*z*): *^mt*(*z*) = *^y^t h*2(*z*)*ei*'2(*z*) $\text{Ind } \text{SC-source } (x_t = m_t / T):$ p2 \mathbf{I} factor on the top phase, since $\mathbf{I}(\mathbf{A} \mid \mathbf{I})$ is derived by phase, given by $\mathbf{I}(\mathbf{I} \mid \mathbf{I})$ **CP-violating SC-source** $(x_t = m_t/T)$:

potential can depend only only only on the relative phase ' α ' 1 $\$ the gauge *Z^µ* = 0, whereby we need to account for four fields: *h*1*, h*2*, S* and ', while solving

d*z*

² +

*S*¹ =

(@*zhi*)

*S*¹ =

d*z*

. (3.15)

@*z*'² ⁼ *^h*² *h*2 ¹ + *h*² 2 The complex, spatially-varying top mass can now be constructed from the phase '2(*x*) and various thermal averages \mathbf{A} . (5.8) and (5.8) and (5.8) and (5.8) are defined similar to ref. [14]. $\blacktriangle \blacksquare$ include the Baryon asymmetry

2HD+S model: Baryon asymmetry\n
$$
4/7
$$
\nSolve the diffusion equations:\n
$$
\mu_{B_L} = \mu_{q_1,2} + \mu_{q_2,2} + \frac{1}{2}(\mu_{t,2} + \mu_{b,2})
$$
\n
$$
= \frac{1}{2}(1 + 4K_{1,t})\mu_{t,2} + \frac{1}{2}(1 + 4K_{1,b})\mu_{b,2} - 2K_{1,t}\mu_{t',2}
$$
\n
$$
\eta_B = \frac{405}{4\pi^2\xi_w g_*T_c} \int_0^\infty dz \Gamma_{\rm sph}(z)\mu_{B_L}(z)e^{-45\Gamma_{\rm sph}(z)z/4\xi_w}
$$

arvive even with large η Large η_B correlates with small d_e Models survive even with large η_B

the modulus *h*2(*z*):

2HD+S model: Nucleation rate $\left| \begin{array}{c} \text{the tree-level barrier does not} \\ \text{dissensar with decreasing } T \end{array} \right|$ 5/7 \sim so far we have that the bubble nucleation takes place at a temperature nucleation takes place at a temperature \sim not too di↵erent from the critical temperature. This is typically the case in models where the $f(x)$ is e $f(x)$ is easily produced by corrections to potential from infrared modes, the potential from $f(x)$ \Box $\blacktriangle \blacksquare$ not too diেerent from the critical temperature. This is typically the case in models where the case in \vert Da $\boldsymbol{\sigma}$ $\boldsymbol{\Pi}$ $\boldsymbol{\Gamma}$ $\boldsymbol{\Gamma}$ $\boldsymbol{\sigma}$ and $\boldsymbol{\sigma}$ and $\boldsymbol{\sigma}$ infrared modes, we have $\boldsymbol{\Gamma}$ infrared modes, $\boldsymbol{\Gamma}$ infrared modes, $\boldsymbol{\Gamma}$ in $\boldsymbol{\sigma}$ \blacksquare if the ratio superconduction is and superconduction is a small latent heat release. Here the situation is a single set of \blacksquare

term. Thus a stronger supercooling and more latent heat release may be expected, or even in the expected, or e
Thus and more latent heat release may be expected, or even in the expected, or even in the expected, or even i

not too di∟erent from the critical temperature. This is typical temperature. This is typically the case in model
This is typically the case in models where the case in models where the case in models where the case is the

a possibility of a formation of a formation of a metastable vacuum where the electroweak breaking never the ele

first-order phase transition is e \blacksquare **Danger: unlike the cubic term** in \blacksquare term. Thus a stronger supercooling and more latent heat release may be expected, or even in the expected, or e So far we have implicitly assumed that the bubble nucleation takes place at a temperature at a temperature at a dierent, because the barrier because the barrier between the degenerate minima is essentially due to a tree-le the tree-level barrier does not **5/7** disappear with decreasing **T**_c. **below the line** α **disappear with decreasing T.**

by = 0*.*7. See text for details. We used ↵max = 0*.*3, corresponding to ⇠*^w* ⇡ 0*.*1.

<u>e pubble</u> takes place.

$$
\Gamma \sim T^4 \left(\frac{S_3(T)}{2\pi T}\right)^{3/2} \exp\left(-\frac{S_3(T)}{T}\right) \qquad \begin{array}{c}\n\frac{1}{8} & -2 \\
\frac{1}{8} & -3 \\
\frac{1}{8} & -4\n\end{array} \qquad \begin{array}{c}\n\frac{1}{8} & -2 \\
\frac{1}{8} & -3 \\
\frac{1}{8} & -4\n\end{array}
$$

3 ⇠ *^T*⁴ 2⇡*T* **In thin wall limit:**

electroweak-broken minima and $\frac{16\pi}{\sigma^3}$ \overline{Q} $\sigma =$ $d\phi$ $S_3(T) = \frac{16\pi}{2} \frac{\sigma^3}{\Delta V(T)^2}$ $\sigma = \int d\phi \sqrt{\frac{2\pi}{T}}$ $2V$ 3 σ^3 $\overline{\Delta V(T)^2}$ $\qquad \sigma = \int d\phi \sqrt{2V}$ \overline{a} 2*V ,* (3.24) \int_{Ω} \int_{Ω} $\sqrt{2}$ \int_{Ω} $=$ $\int a\varphi \sqrt{2V}$ below the line ↵*/*↵max = 1 are allowed. For yellow points the nucleation temperatures were rescaled

independent from the path $\bm{u} = \bm{\Pi}(\bm{I}c)^T$. Nucleation temperature $(\Gamma = H(T_c)^4)$: least one bubble per horizon volume is of order one. This condition can be written as **Nucleation temperature** $(\Gamma = H(T_c)^4)$ **:**

$$
\frac{S_3(T_n)}{T_n} = -\log\left(\frac{3}{4\pi} \left(\frac{H(T_n)}{T_n}\right)^4 \left(\frac{2\pi T_n}{S_3(T_n)}\right)^{3/2}\right)
$$

least one bubble per horizon volume is of order one. This condition can be written as **Problem:**

- rioge – 15 – 4⇡ *Tn S*3(*Tn*) – 15 – - For most models, shown in red, **no** *Tn*
- Remaining ones are, or are in danger of being detonations and the scotting of the scope of the scope of the scope

2HD+S model: Nucleation rate $\left| \begin{array}{c} \text{the tree-level barrier does not} \\ \text{dissensar with decreasing } T \end{array} \right|$ 5/7 \sim so far we have that the bubble nucleation takes place at a temperature nucleation takes place at a temperature \sim not too di↵erent from the critical temperature. This is typically the case in models where the $f(x)$ is e $f(x)$ is the sequential from infrared modes, the potential from infrared modes, the potential from $f(x)$ \Box $\blacktriangle \blacksquare$ not too diেerent from the critical temperature. This is typically the case in models where the case in \vert Da $\boldsymbol{\sigma}$ $\boldsymbol{\Pi}$ $\boldsymbol{\Gamma}$ $\boldsymbol{\Gamma}$ $\boldsymbol{\sigma}$ and $\boldsymbol{\sigma}$ and $\boldsymbol{\sigma}$ infrared modes, we have $\boldsymbol{\Gamma}$ infrared modes, $\boldsymbol{\Gamma}$ infrared modes, $\boldsymbol{\Gamma}$ in $\boldsymbol{\sigma}$ \blacksquare if the ratio superconduction is and superconduction is a small latent heat release. Here the situation is a single set of \blacksquare

term. Thus a stronger supercooling and more latent heat release may be expected, or even in the expected, or e
Thus and more latent heat release may be expected, or even in the expected, or even in the expected, or even i

first-order phase transition is e \blacksquare **Danger: unlike the cubic term** in \blacksquare term. Thus a stronger supercooling and more latent heat release may be expected, or even in the expected, or e So far we have implicitly assumed that the bubble nucleation takes place at a temperature at a temperature at a dierent, because the barrier because the barrier between the degenerate minima is essentially due to a tree-le the tree-level barrier does not **5/7** disappear with decreasing **T**_c. **below the line** α **disappear with decreasing T.**

by = 0*.*7. See text for details. We used ↵max = 0*.*3, corresponding to ⇠*^w* ⇡ 0*.*1.

a possibility of a formation of a metastable vacuum where the electroweak breaking never the thin-wall limit i <u>e pubble</u> which leads to release to rather mild supercooling and small latent here the situation is a release. Here the situation is a release of the situation is a release of the situation is a release. Here the situation is a rele The <u>bubble nucleation</u> rate is:

The <u>bubble nucleation</u> rate is: takes place.

$$
\Gamma \sim T^{4} \left(\frac{S_{3}(T)}{2\pi T}\right)^{3/2} \exp\left(-\frac{S_{3}(T)}{T}\right) \qquad \begin{array}{c}\n\frac{1}{5} - 2 \\
\frac{1}{5} - 3 \\
\frac{1}{5} - 4 \\
\frac{1}{5} - 5\n\end{array} \qquad \begin{array}{c}\n\frac{1}{5} - 2 \\
\frac{1}{5} - 3 \\
\frac{1}{5} - 4 \\
\frac{1}{5} - 5\n\end{array}
$$

 T_n/T

 $\sum_{i=1}^{\infty}$ -1 $\sum_{i=1}^{\infty}$ -1

 $\widehat{\tau}$ -1. The nucleation problem in the thin-wall limit $\widehat{\tau}$ -1.

Figure 17 Thin wall limit: 0.4 0.5 0.6 0.7 0.8 0.9 0.4 3 ⇠ *^T*⁴ 2⇡*T* **In thin wall limit:** T_n/T_c

$$
S_3(T) = \frac{16\pi}{3} \frac{\sigma^3}{\Delta V(T)^2} \qquad \sigma = \int d\phi \sqrt{2V}
$$

independent from the path $\bm{u} = \bm{\Pi}(\bm{I}c)^T$. **Nucleation temperature** $(\Gamma = H(T_c)^4)$: least one bubble per horizon volume is of order one. This condition can be written as **Nucleation temperature** $(\Gamma = H(T_c)^4)$ **:**

$$
\frac{S_3(T_n)}{T_n} = -\log\left(\frac{3}{4\pi} \left(\frac{H(T_n)}{T_n}\right)^4 \left(\frac{2\pi T_n}{S_3(T_n)}\right)^{3/2}\right)
$$

least one bubble per horizon volume is of order one. This condition can be written as **Problem:**

- rioge – 15 – 4⇡ *Tn S*3(*Tn*) – 15 – - For most models, shown in red, **no** *Tn*
- Remaining ones are, or are in danger of being detonations and the scotting of the scope of the scope of the scope

V (*D.4 D.5 0.6* , $\frac{1}{2}$

✓*S*3(*T*)

not too di∟erent from the critical temperature. This is typical temperature. This is typically the case in model
This is typically the case in models where the case in models where the case in models where the case is the

a possibility of a formation of a formation of a metastable vacuum where the electroweak breaking never the ele

◆3*/*²

-1

0

*S*3(*T*) *T*

 $\times 10^{-11}$)

B/8.7

log10(η

3

-5

-4

-3

-2

exp ✓

◆

, (3.22)

Product of the second of

*S*3(*T*)

, (3.22)

0.4 0.5 0.6 0.7 0.8 0.9

 T_n/T_c

$$
5/7
$$

⇢(*Tn*) *<* 3 **EXTREM INDEPTE THE READIMER CONCLUST CONCLUSTED ENGINEERING** ENGINEERING STATION ENGINEERING CONDITION ENGINEERIN the right panel of Γ fig. 6 (blue dots) for the set of models shown in the left panel. As expected, as expected, **2HD+S model: fate of false vacuum, ameliorations 6/7**

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Solve exactly in SM + Singlet model $\qquad \qquad \vdots$ calculation. Gray lines connect pairs corresponding to the same physical parameters. The dotted line **Solve exactly in SM + Singlet model**

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S_3(T) = 4\pi \int r^2 dr \left(\frac{1}{2} \left(\frac{dh}{dr}\right)^2 + \frac{1}{2} \left(\frac{dS}{dr}\right)^2 + V_{SSM}(h, S, T)\right)
$$

for the models with the lowest nucleation temperatures, deflagrations are not possible. This

temperature in the thin-wall approximation and the yellow dots the same quantity found Find: T_n systematically larger than in tw-case:

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T_n = T_c + \kappa (T_c - T_n^{\text{tw}}) \qquad \kappa \approx 0.7
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Find: situation less severe. $\frac{2}{9}$ -1.5 $\begin{bmatrix} \text{SO}, \dots \text{maybe.} \end{bmatrix}$

2HDM+S, summary 7/7

Generic issue: 2-step transition tends to be "too strong": *bubble nucleation* **delayed:** *Tn << Tc.* also: Profumo etal, Phys.Rev. D91 (2015) no.3, 035018

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 -5

Because of generic low energy Landau poles^{*} 2HD-models no better than singlet model with Dim N>4 operators**.

- **No UV-completion => solving BAU recreates need for BSM**
- **Problem is with the CP-violation**

***** Out of 10000 models in our final scan, ten

 $\overline{\mathsf{M}}$ *r*2 ea
ido survived to 10 TeV and none to 100 TeV.

the NMSSM Demidov, Gorbunov, Kiripichnikov, arXiv:1608.01985v1 + *V*˜ (*h, s, T*) ******Unless embedded in an UV-complete setup, such as

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Conclusions

"Simple and yet complete" an interesting paradigm to follow

Unification and Hieararchy Problem not necessarily relevant

Some aspects are easily realized with help of singlets

DM Strong EWPT

EWBG challenging due to need for new CP-violation

EWBG is *maybe* **in 2HD+S model, but not UV-complete (NMSSM?)**

Maybe some alternatives fit better into completenes scheme:

Leptogenesis (but beware of hierarchy problem) Akhmedov-Rubakov-Smirnov mechanism nuMSM