Is electroweak baryogenesis dead?

with K. Kainulainen and D. Tucker-Smith

Jim Cline, McGill U.

Higgs cosmology meeting, 28 March, 2017

IS HINCHLIFFE'S RULE TRUE?*

Boris Peon

Abstract

Hinchliffe has asserted that whenever the title of a paper is a question with a yes/no answer, the answer is always no. This paper demonstrates that Hinchliffe's assertion is false, but only if it is true.

*Accepted for publication in *Annals of Gnosis*.

See also G. Servant's talk . . .

The SM BEH?

MORIOND 2017 EW Session March 19-25

Sunday March 19th

Morning Session : The SM BEH

Susumu Oda	Couplings and mass with 13 TeV data and expectations.
Giovanni Petrucciani	Evidence for ttH production with 13 TeV data?
Goetz Gaycken	2nd and 3rd generation couplings with 13 TeV data
Ulrich Haisch	Yukawas and trilinear H terms from loops
Luca Cadamuro	Search and prospects for HH production
Verena Martinez Outschoorn	Search for non standard Higgs states
Mark Andrew Owen	Top quark properties measurements at LHC (Mass, EW couplings)

Afternoon Session : SM measurements

Didar Dobur	Top quark production and decays at LHC
Pavol Bartos	Top Physics at Tevatron
Liang Han	EW masses (Tevatron)
Aram Apyan	EW precision measurements with Z and W (LHC)
Senka Duric	Studies of Diboson production at LHC
Gavin Salam	How bright is the proton?
Aldo Antognini	The proton radius from CREMA

Englert & Brout

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
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(Received 26 June 1964)

It is of interest to inquire whether gauge vector mesons acquire mass through interaction[1]; by a gauge vector meson we mean a Yang-Mills field[2] associated with the extension of a Lie group from global to local symmetry. The importance of this problem resides in the possibility that strong-interaction physics originates from massive gauge fields related to a system of conserved currents.[3] In this note, we shall show that in certain cases vector mesons do indeed acquire mass when the vacuum is degenerate with respect to a compact Lie group.

Theories with degenerate vacuum (broken those vector mesons which are coupled to currents that "rotate" the original vacuum are the ones which acquire mass [see Eq. (6)].

We shall then examine a particular model based on chirality invariance which may have a more fundamental significance. Here we begin with a chirality-invariant Lagrangian and introduce both vector and pseudovector gauge fields, thereby guaranteeing invariance under both local phase and local γ_5-phase transformations. In this model the gauge fields themselves may break the γ_5 invariance leading to a mass for the original Fermi field. We shall show in this case that the pseudovector field acquires mass.

No mention of the dynamics of the scalar whose VEV breaks the symmetry . . .

Higgs

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one quanta of some of the gauge fields acquire mass; the longitudinal degrees of freedom of these par-

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^{\,2} V''(\varphi_0^{\,2})\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^{\,2})\}^{1/2}$; Eqs. (2a) and (2c)

Equation of motion and mass of the Higgs field are front and center

Outline

- Has electroweak baryogenesis been ruled out?
- How adding a singlet scalar to Higgs sector helps
- Working model with dark matter producing the baryon asymmetry
- LHC constraints from MSSM $\tilde{\tau}$ searches

Why Electroweak Baryogenesis?

Why is there more baryonic matter than antimatter in the universe?

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \cong 6 \times 10^{-10}$$

from CBM and BBN. Standard model cannot explain it.

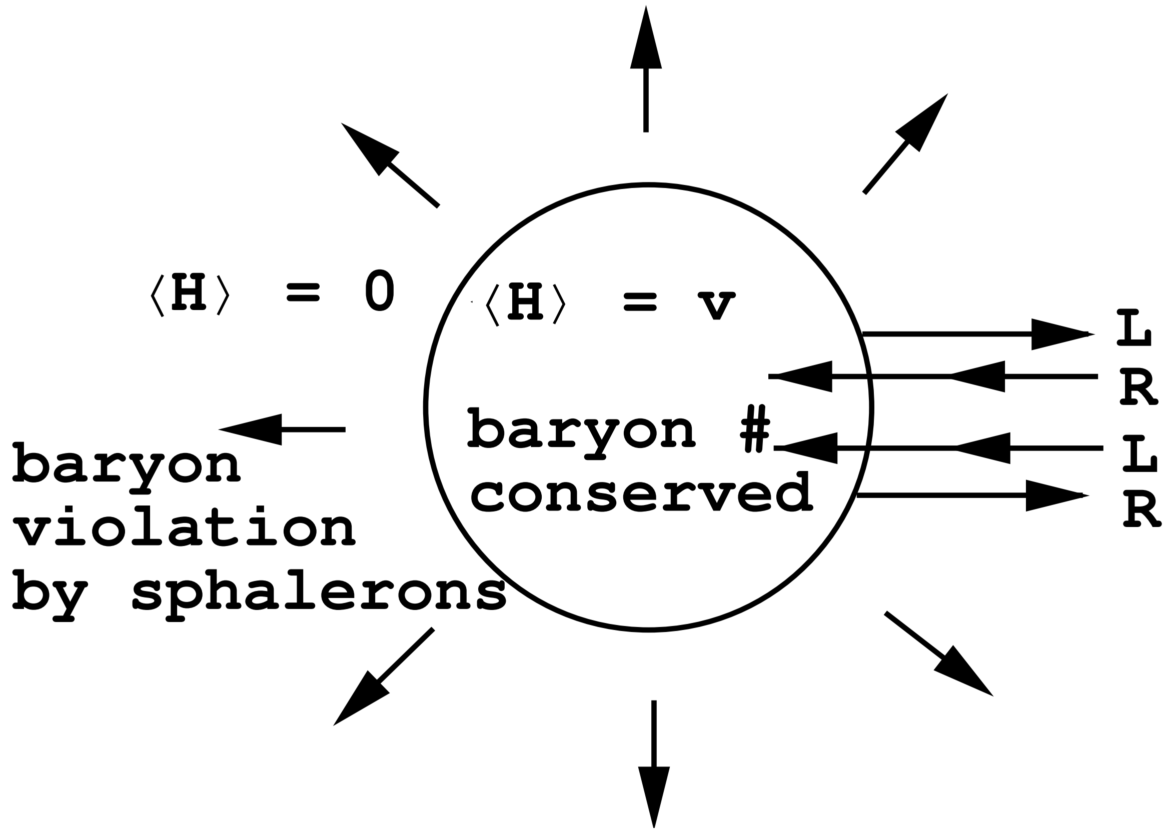
Leptogenesis is an elegant solution, but might never be testable.

Electroweak baryogenesis relies on minimal new physics near the weak scale; it is the most testable framework.

Is there still room for it to work after LHC Run 1?

Electroweak Baryogenesis

EWBG relies on a strongly 1st order electroweak phase transition, and CP violating interactions of fermions at the bubble walls,



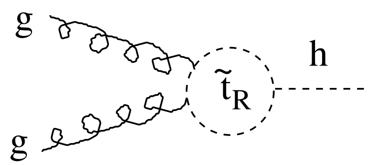
Needs new physics at the electroweak scale to get both ingredients.

It is practially ruled out in MSSM and two Higgs doublet models.

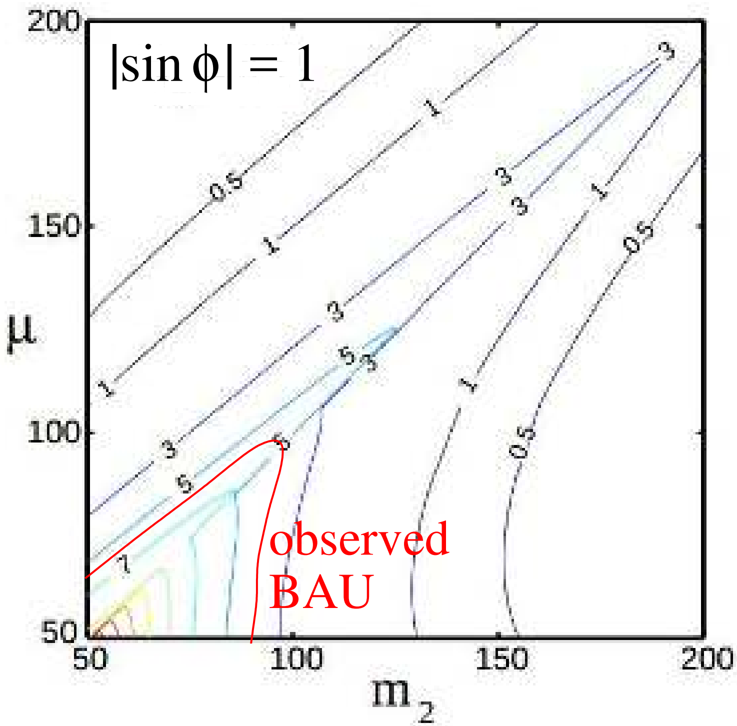
EWBG in the MSSM

Strong EWPT (with $m_h = 125\,\mathrm{GeV}$) needs light right-handed stop, $m_{\tilde{t}_R} \lesssim m_h$ and heavy left-handed stop, $m_{\tilde{t}_L} \gtrsim 100\,\mathrm{TeV}$

Such a light stop increases hgg fusion production; essentially ruled out



Getting large enough baryon asymmetry requires too much CP violation and too light charginos/neutralinos:



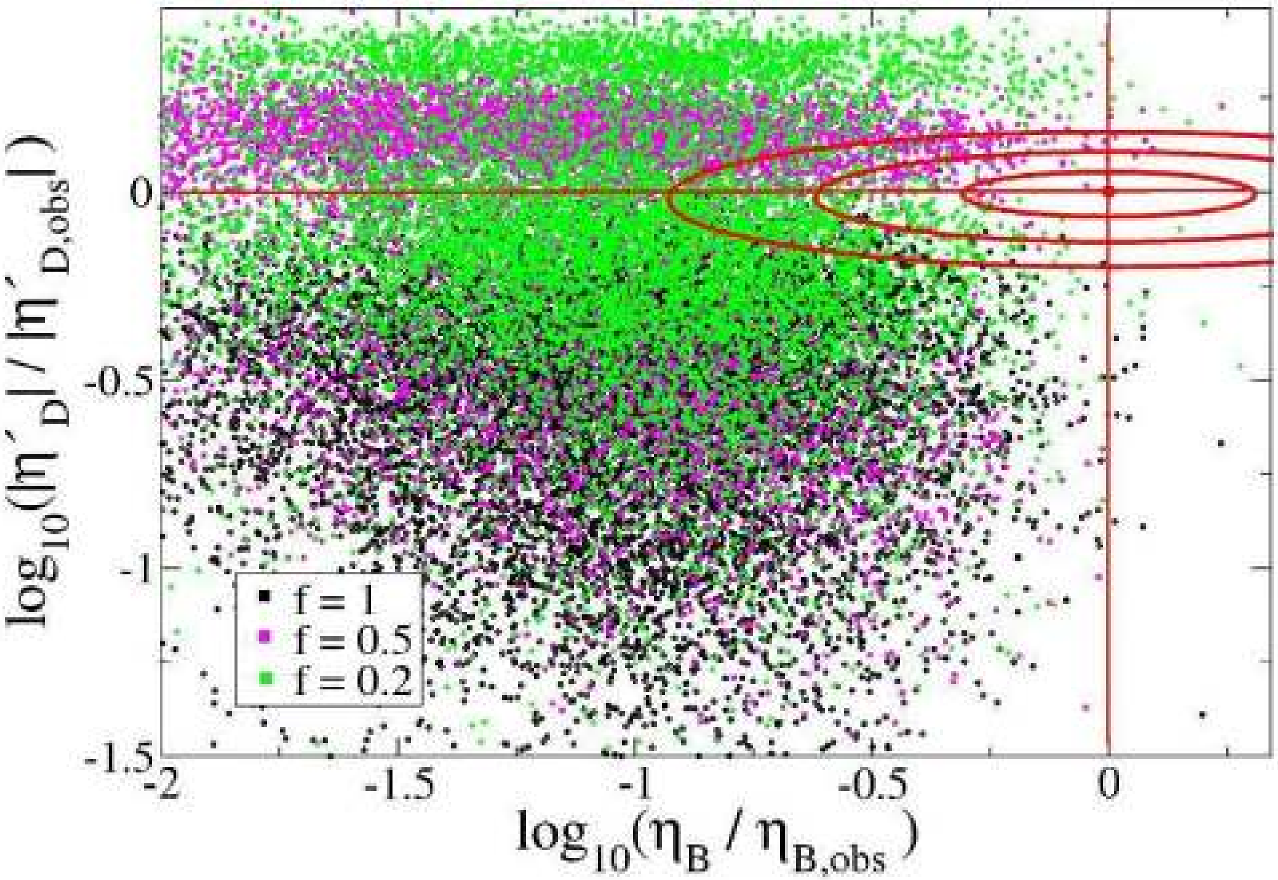
Cline & Kainulainen, PRL 85 (2000) 5519 (hep−ph/000272)

maximal CP phase ruled out by neutron EDM, need even lighter sparticles

EWBG in two Higgs doublet models

MSSM is a two Higgs doublet model. More general 2HDMs have the needed ingredients for EWBG. But the parameter space that works is extremely small.

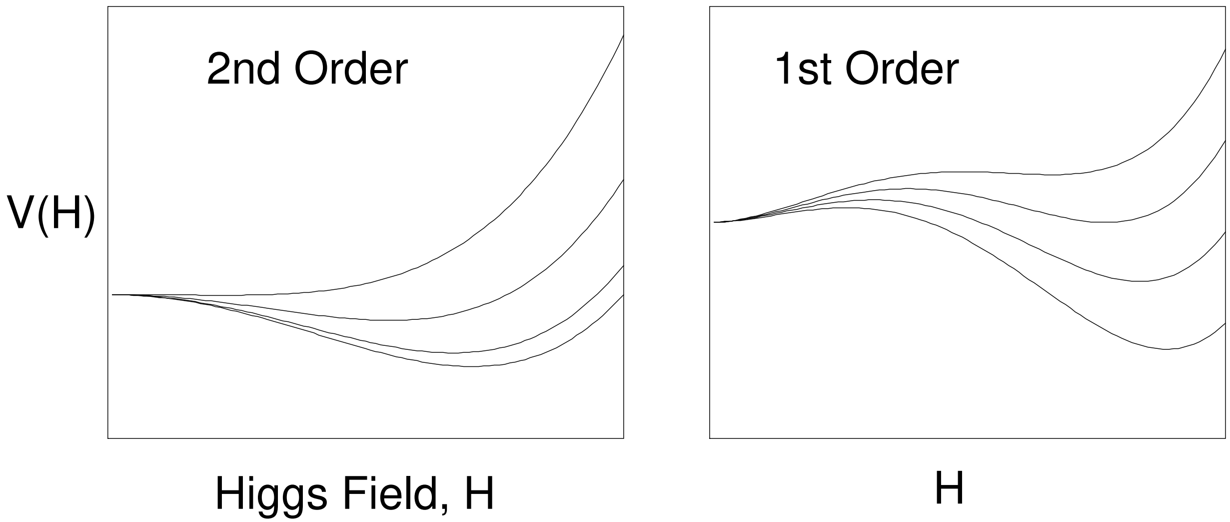
Results from MCMC scan of 10,000 models (JC, Kainulainen, Trott, 1107.3559). Only a handful give big enough asymmetry.



Demanding no Landau pole below 1 TeV is a crucial constraint!

Difficult to get strong phase transition

First order phase transition requires potential barrier,



Traditionally, the barrier came from finite-temperature cubic correction to potential,

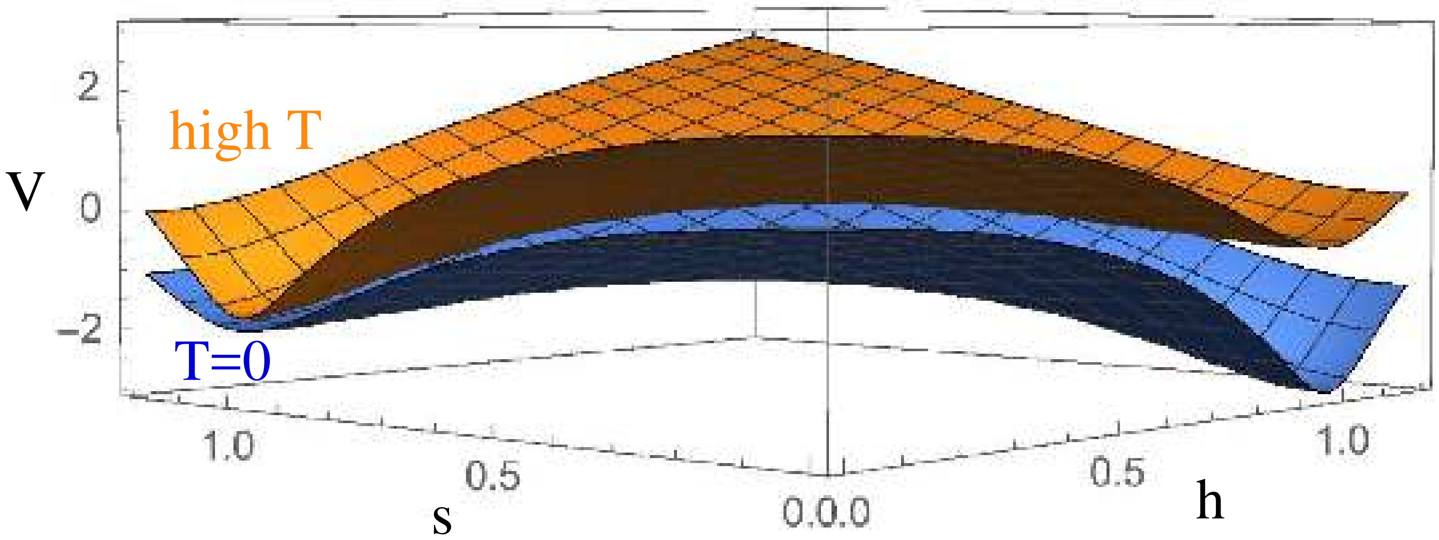
$$\Delta V = -\frac{T}{12\pi}\sum_i (m_i^2(h))^{3/2} = -\frac{T}{12\pi}\sum_i (m_{i,0}^2 + g_i^2 h^2 + c_i T^2)^{3/2}$$

It is typically not very cubic, and not big enough. Tends to give only a 2nd order or weak 1st order phase transition, $v/T < 1$.

Tree-level barrier with a singlet scalar

A more robust way is to couple a scalar singlet s to SM Higgs h.

Choi & Volkas, hep-ph/9308234; Espinosa, Konstandin, Riva, 1107.5441



At $T = 0$, EWSB vacuum is deepest, but at higher T, the $h = 0$, $s \neq 0$ vacuum has lower energy.

The transition is controlled by the leading $T^2\phi_i^2$ corrections in the finite-T potential.

Phase transition can easily be very strong.

Singlet can help with CP violation

JC, K. Kainulainen (1210.4196) introduce dimension-6 coupling* to top quark, $i(s/\Lambda)^2\bar{Q}_L H t_R$, to give complex mass in the bubble wall,

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

This gives the CP-violating interactions of t in the wall, producing CP asymmetry between t_L and t_R.

MCMC no longer needed to find good models, a random scan suffices.

But need $\Lambda \sim \mathrm{TeV}$ to get large enough BAU. What is the new physics at this scale?

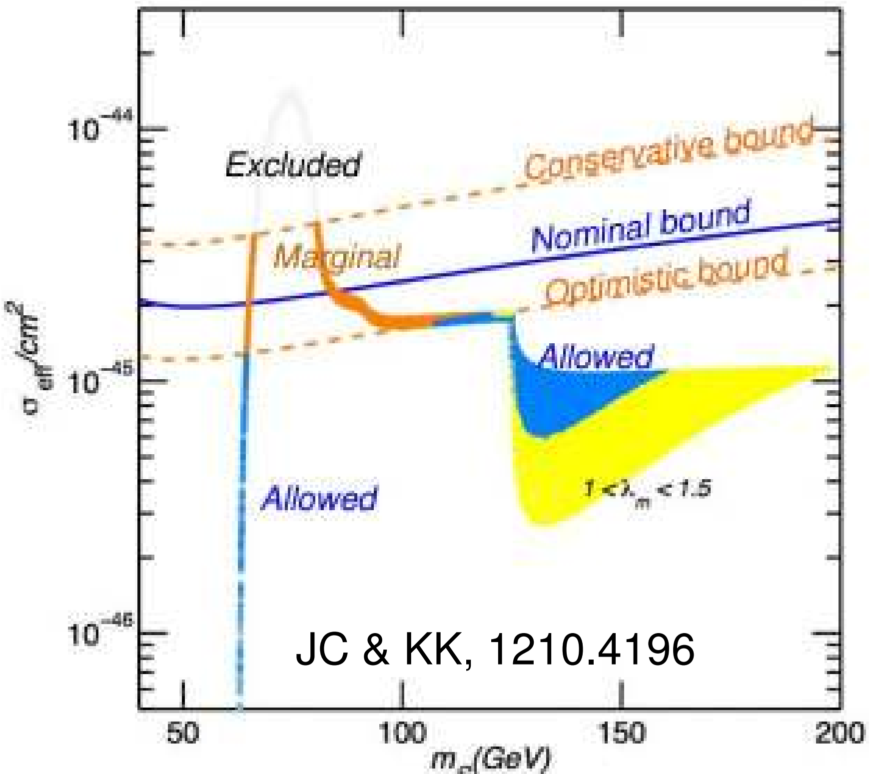
*Dimension-5 also works, but with dim-6, S can be stable dark matter candidate.

Singlet can be dark matter candidate

$\lambda_m h^2 s^2$ coupling provides tree-level barrier, and Higgs portal interaction.

λ_m determines both relic density and cross section σ for s scattering on nucleons.

For strong EWPT, $\lambda_m \gtrsim 0.25$, singlet can only constitute fraction $f_{\rm rel} \lesssim 0.01$ of the total DM density, but still detectable



Define $\sigma_{\rm eff} = f_{\rm rel}\,\sigma$

Blue: allowed by XENON100 (and mostly LUX) with $\lambda_m < 1$

Orange: marginally excluded, depending on astrophysical uncertainty in local DM density.

Yellow: allowed, with $1 < \lambda_m < 1.5$

Can we do better?

EWBG with singlet to facilitate EWPT is less constrained, but needs additional new physics below the TeV scale.

Can we find reasonable UV-complete (renormalizable) models that satisfy all criteria?

Need to couple singlet to new fermions, with CP-violating couplings.

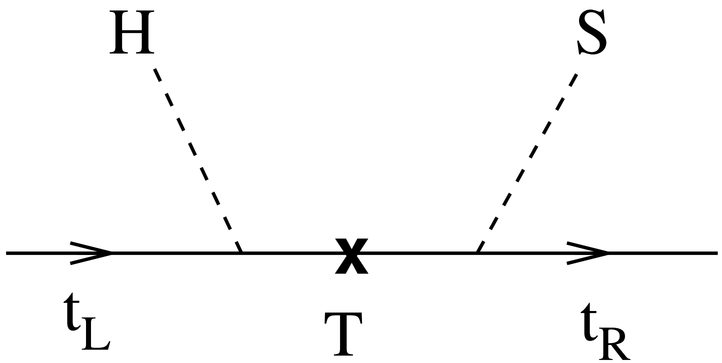
CP asymmetry in new fermions must be communicated to sphalerons.

Heavy top partners

A simple UV completion is a vector-like top partner $T_{R,L}$ coupling to singlet,

$$\eta\,\bar{t}_R S T_L + M\bar{T}_L T_R + y'\bar{T}_R H t_L$$

Integrate out heavy state:



Generates desired coupling

$$\frac{\eta y'}{M}\,\bar{t}_R S H t_L$$

which can be CP-violating and large enough.

ATLAS limit $M \gtrsim 900\,\mathrm{GeV}$ might be weakened by $T \to St$ decays.

Here we consider a different model . . .

A working model with dark matter

Introduce Majorana fermion χ,

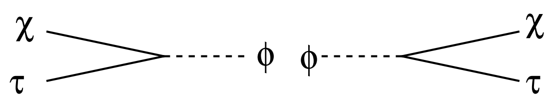
$$\frac{1}{2}\,\bar\chi\,[m_\chi + S(\eta\,P_L + \eta^* P_R)]\,\chi$$

with $\mathrm{Im}(m_\chi\,\eta) \neq 0$. Creates CP asymmetry between χ helicities at bubble wall. Bonus: χ is a dark matter candidate

To transfer CP asymmetry to SM leptons, need an inert Higgs doublet ϕ and coupling ("CP portal interaction")

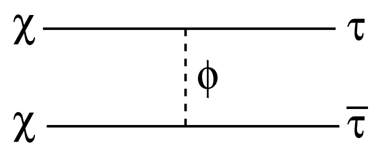
$$y\,\bar\chi\phi L_\tau$$

Asymmetry is transferred by (inverse) decays,



$$\chi\bar L_\tau \to \phi, \qquad \phi \to \bar L_\tau \chi,$$

New coupling also controls the DM relic density,



Note Z_2 symmetry $\phi \to -\phi$, $\chi \to -\chi$.

DM must be χ rather than ϕ because of direct detection constraints.

Scalar potential

For simplicity we impose $S \to -S$ symmetry on the potential,

$$V = \tfrac{1}{4}\lambda_h (h^2 - v^2)^2 + \tfrac{1}{4}\lambda_s (S^2 - w^2)^2 + \tfrac{1}{2}\lambda_m h^2 S^2$$

and take (CP-conserving) pseudoscalar coupling to χ,

$$\tfrac{1}{2}\bar{\chi}(m_\chi + i\,\eta\,\gamma_5\,S)\chi$$

giving no S or S^3 terms from fermion loop. (Must break $S \to -S$ slightly to avoid domain walls.)

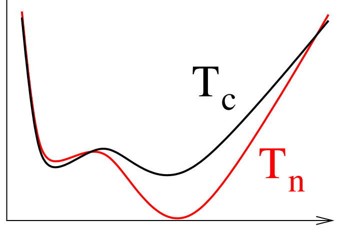
CP violation is spontaneous, due to $\langle S \rangle$, disappears at $T = 0$:
No constraints from EDMs

At finite temperature, we just need leading $O(T^2)$ correction. V can be written as

$$V = \frac{\lambda_h}{4}\left(h^2 - v_c^2 + \frac{v_c^2}{w_c^2}S^2\right)^2 + \frac{\kappa}{4}S^2 h^2 + \tfrac{1}{2}(T^2 - T_c^2)(c_h h^2 + c_s S^2)$$

where $T_c = [(\lambda_h/c_h)(v^2 - v_c^2)]^{1/2}$ = critical temperature,
v_c, w_c = critical VEVs.

Nucleation temperature, T_n



For not too strong phase transitions, bubbles nucleate near the critical temperature. For stronger PTs, T_n can be significantly $< T_c$.

Criterion to avoid sphaleron washout inside bubbles is

$$\frac{v_n}{T_n} > 1.1, \quad \text{not} \quad \frac{v_c}{T_c} > 1.1$$

Must compute bubble action S_3

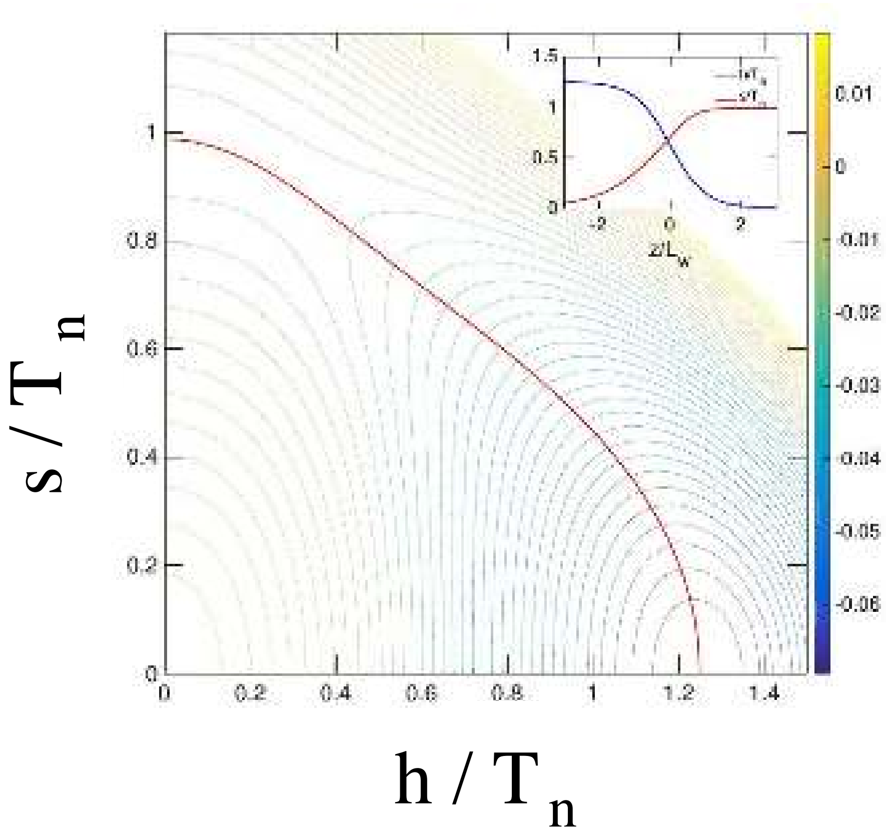
$$S_3 = 4\pi \int_0^\infty dr\, r^2 \left(\tfrac{1}{2}(h'^2 + s'^2) + V(h,s) - V(0,s_T)\right)$$

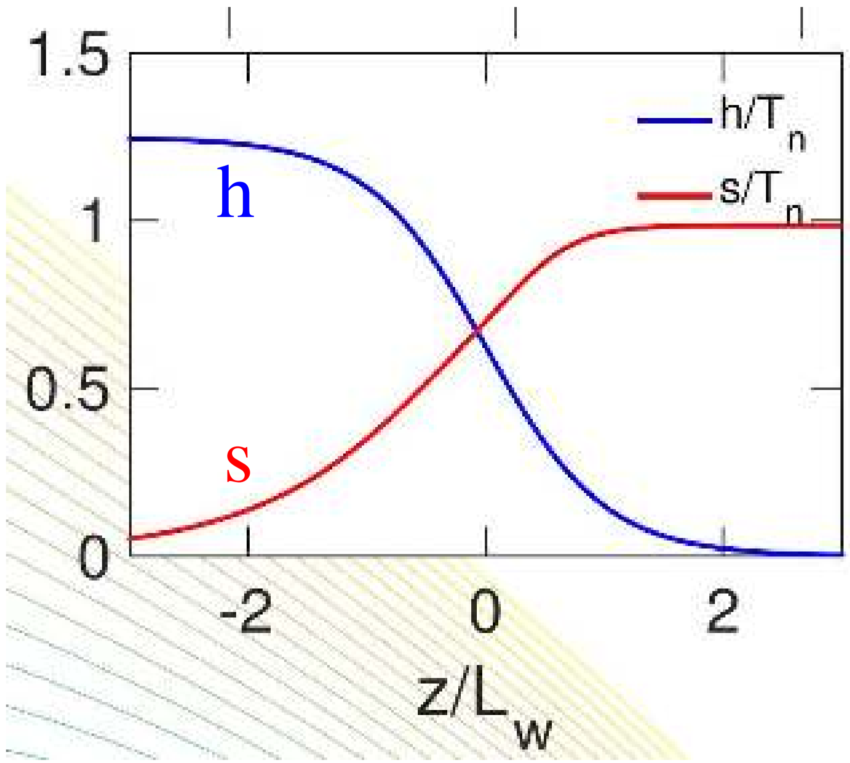
and solve

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

for T_n. Finding bubble wall solution at $T < T_c$ is numerically tricky.

Shape of the bubble wall





Small wall width $L_w \implies$ larger baryon asymmetry, but we need $L_w > \text{few}/T$ to justify semiclassical approximation for diffusion eqs.

We find $$L_w \sim \frac{1}{\sqrt{\lambda_h} v_c} \sim \frac{8}{T_n}$$ for our working models.

The baryon asymmetry

We need chemical potentials for χ helicity, ϕ and τ near the bubble wall: μ_χ, μ_ϕ, μ_τ

Baryon production via sphalerons depends only on μ_τ,

$$\eta_B = \frac{405\,\Gamma_{\rm sph}}{4\pi^2\, v_w\, g_* T} \int_{-\infty}^{\infty} dz\, \mu_\tau\, f_{\rm sph}(z)\, e^{-45\,\Gamma_{\rm sph}\, z/(4v_w)}$$

with $\Gamma_{\rm sph}\, f_{\rm sph}(z) =$ local sphaleron rate in wall.

μ_τ comes from network of diffusion equations together with μ_χ, μ_ϕ, and velocity potentials u_i,

$$\begin{pmatrix} v_w K_{1,\chi} & 1 \\ -K_{4,\chi} & v_w K_5 \end{pmatrix} \begin{pmatrix} \mu'_\chi \\ u'_\chi \end{pmatrix} = \begin{pmatrix} -v_w K_{2,\chi}\, M_\chi^{2\prime} \mu_\chi + 2\Gamma_{\rm hf}\, \mu_\chi + \Gamma_d\, (\mu_\chi + c\mu_\tau - c\mu_\phi) \\ -v_w K_{6,\chi}\, M_\chi^{2\prime} u_\chi - \Gamma_{{\rm el},\chi}\, u_\chi + S_\chi \end{pmatrix}$$

$$\begin{pmatrix} v_w K_{1,\phi} & 1 \\ -K_{4,\phi} & v_w K_5 \end{pmatrix} \begin{pmatrix} \mu'_\phi \\ u'_\phi \end{pmatrix} = \begin{pmatrix} \Gamma_d\, (\mu_\phi - \mu_\tau - c\mu_\chi) + 2\Gamma_{\times,\phi}(\mu_\phi - \mu_\tau) \\ -\Gamma_{{\rm el},\phi}\, u_\phi \end{pmatrix}$$

$$\begin{pmatrix} v_w K_{1,0} & 1 \\ -K_{4,0} & v_w K_5 \end{pmatrix} \begin{pmatrix} \mu'_\tau \\ u'_\tau \end{pmatrix} = \begin{pmatrix} \Gamma_d(\mu_\tau + c\mu_\chi - \mu_\phi) + 2\Gamma_{\times,\tau}(\mu_\tau - \mu_\phi) \\ -\Gamma_{{\rm el},\tau}\, u_\tau \end{pmatrix}$$

$\Gamma_d =$ decay rate for $\phi \to \chi\tau$

$\Gamma_{\rm hf} =$ rate of χ helicity flips

$\Gamma_{{\rm el},i} =$ elastic scattering rate for particle i

$\Gamma_{\times,i}$ = rate of $\phi\bar\tau \to \phi^*\tau$ due to χ mass insertions

$K_i =$ thermal kinematic coefficients

$S_\chi =$ source term from semiclassical force $\sim v_w(m_\chi^2\theta')'$

Diffusion equations

Formalism developed by JC, Joyce, Kainulainen hep-ph/0006119, refined by Fromme, Huber hep-ph/0604159

Split distribution function into two pieces,

$$f_i(p,x) = \frac{1}{e^{\beta[\gamma_w(\omega+v_w p_z)-\mu_i(x)]} \pm 1} + \delta f_i(p,x)$$

deviation from chemical equilibrium encoded in μ_i

deviation from kinetic equilibrium

with $\int d^3p\, \delta f_i \equiv 0$, $\int d^3p\, (p_z/\omega)\delta f_i \propto u_i$: "velocity potential"

To leading order in small quantities, Boltzmann eq. is

$$\frac{\partial f_i}{\partial \omega}\left(v_w F_{i,z} - \mu_i' \frac{p_z}{\omega}\right) + \frac{p_z}{\omega}\delta f_i' = C[f_i, f_j, \ldots]$$

wall velocity

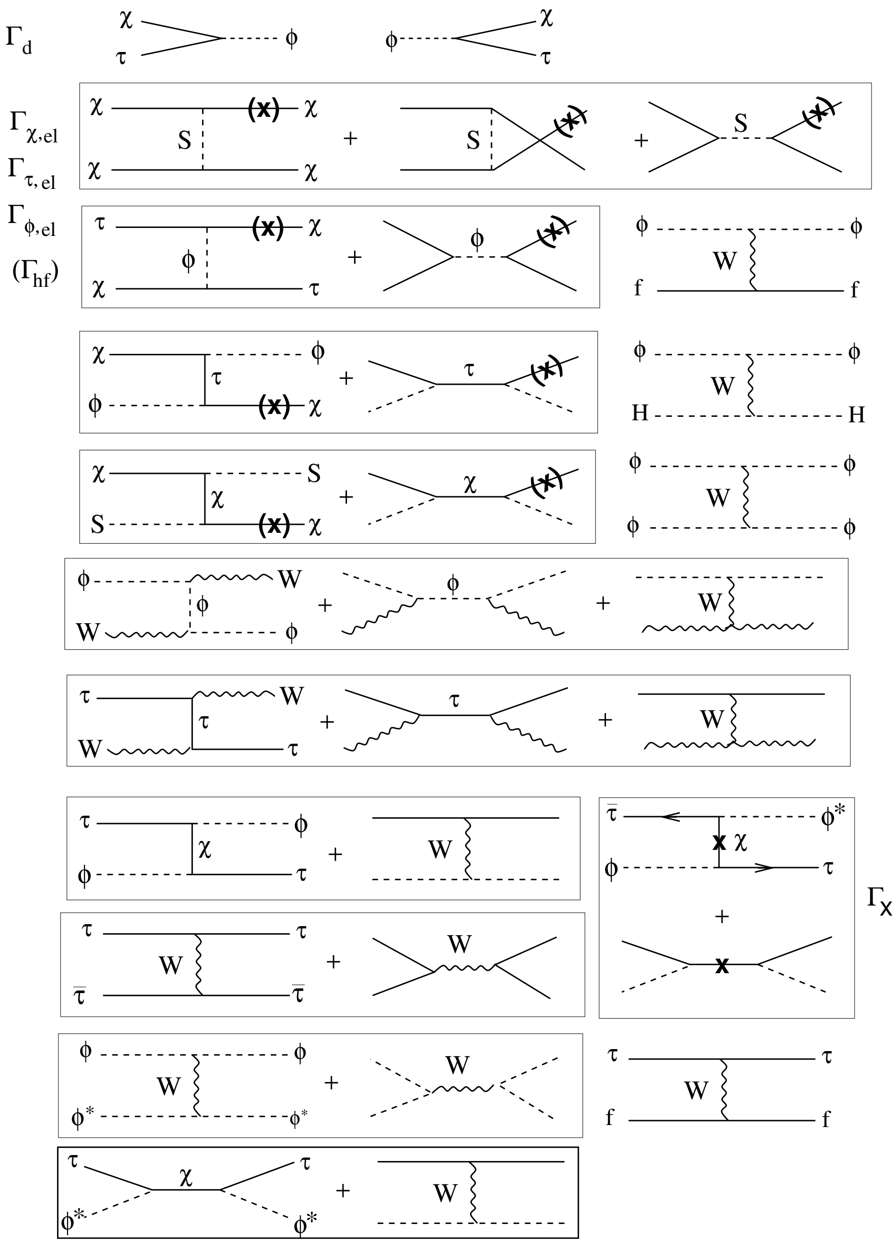
Semiclassical force, $\dot{p} = -\frac{|m||m|'}{\omega} + s_{CP}\frac{s(|m|^2\theta')'}{2\omega^2}$

Then take first two moments to derive diffusion equations,

$$\int d^3p\, (\text{B.E.}), \quad \int d^3p\, \frac{p_z}{\omega}(\text{B.E.})$$

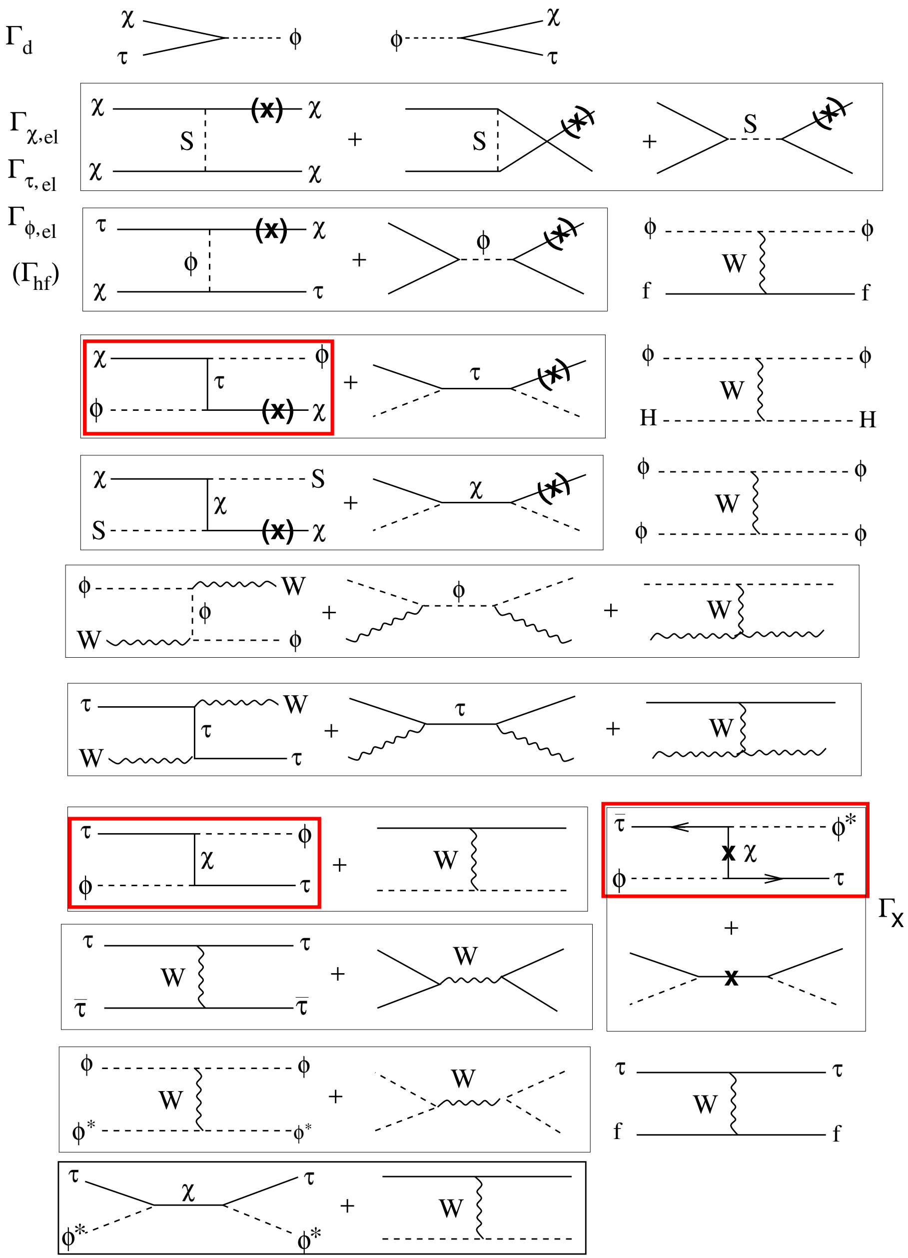
Decay and scattering rates

These processes govern the rates appearing in the diffusion equations.



Decay and scattering rates

Scattering is dominated by IR divergent processes



Intermediate fermion can go on shell

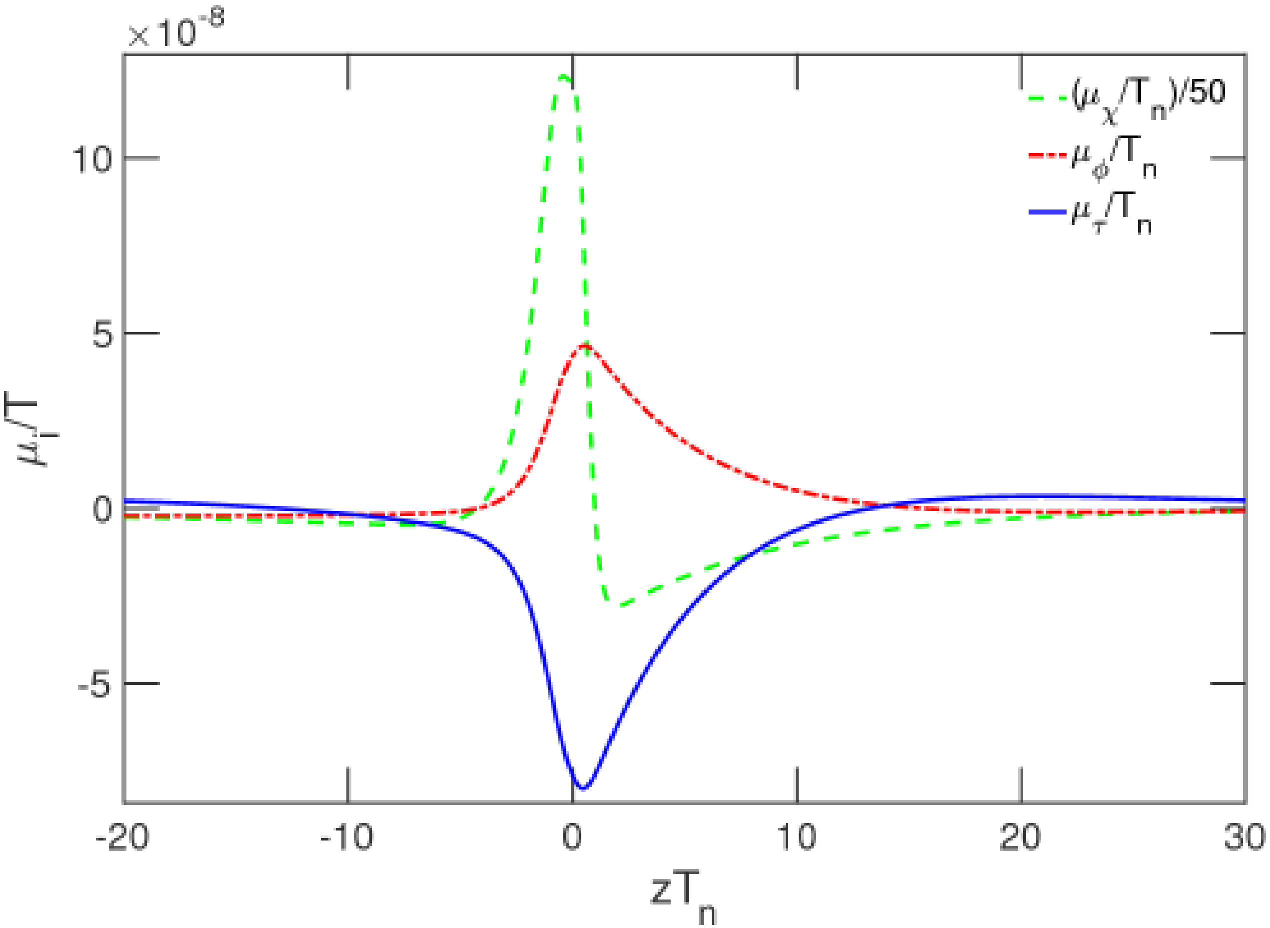
(Due to ϕ decay followed by inverse decay)

Thermal width of t−channel particle renders cross section finite

Solution of diffusion equations

Benchmark model: (subscript c = critical, n = nucleation)

λ_m	y	η	m_χ	m_ϕ	m_S	w_c	w_n	v_c	v_n	T_c	T_n	$\frac{\eta_B}{\eta_{B,\mathrm{obs}}}$	$\Omega_{\mathrm{dm}} h^2$
0.45	0.66	0.51	56	124	102	85	111	82	140	129	112	0.9	0.12



Dark matter relic density

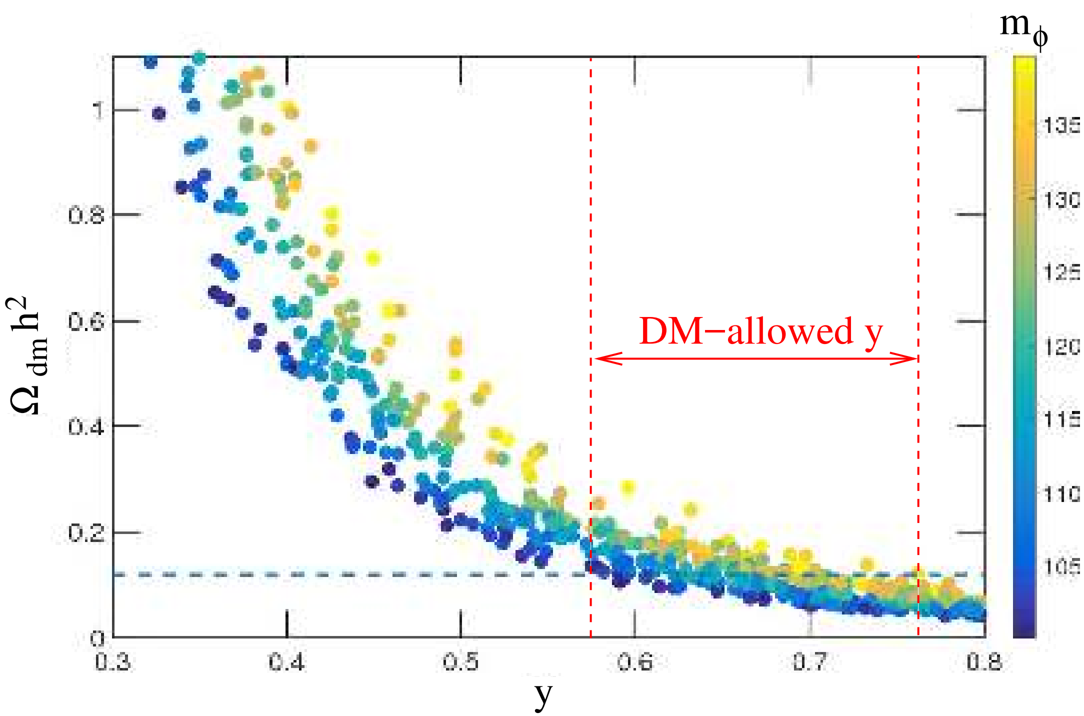
We get thermal relic abundance from annihilations

$$\chi\chi \to \tau\bar{\tau},\, \nu_\tau\bar{\nu}_\tau$$

Cross section is p-wave suppressed,

$$\langle \sigma v \rangle_{\tau\bar{\tau}} \;=\; \frac{y^4\, m_\chi (m_\chi^4 + m_\phi^4)\, T}{4\pi\, (m_\chi^2 + m_\phi^2)^4}$$

We get right relic density for reasonable values of parameters,



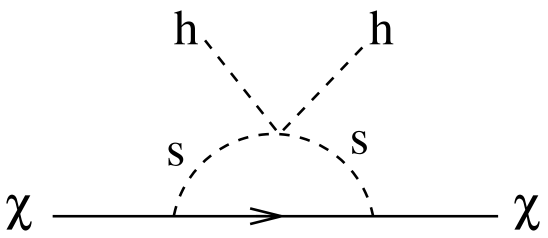
$m_\chi \sim 45\text{–}55\,\mathrm{GeV}$,

$m_\phi \sim 105\text{–}140\,\mathrm{GeV}$,

$y \cong 0.6 - 0.75$

Direct detection: signal is small

Higgs portal at one loop gives strongest interaction with nuclei:

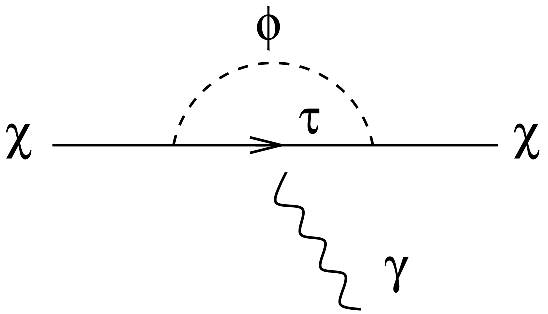


Cross section is

$$\sigma \cong \frac{0.3^2\, \eta^4\, \lambda_m^2\, m_\chi^2\, m_N^4}{16^2\, \pi^5\, m_\phi^4\, m_h^4} \cong 10^{-48}\ \mathrm{cm}^2$$

Well below LUX bound of $10^{-45}\ \mathrm{cm}^2$

Anapole moment $\bar\chi\gamma_5\gamma_\mu\chi\,\partial_\nu F^{\mu\nu}$ is also induced at one loop,

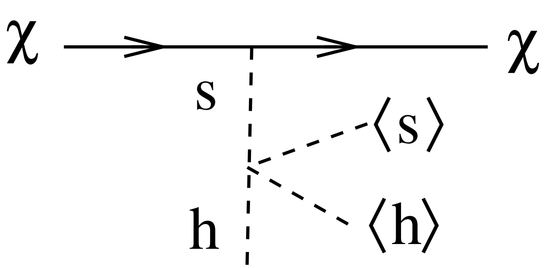


Cross section is velocity-suppressed,

$$\sigma_p \sim v^2 \frac{\alpha^2\, y^4\, m_p^2}{16\pi^3\, m_\phi^4} \cong 10^{-51}\ \mathrm{cm}^2$$

even smaller

Small S VEV would give tree-level Higgs portal:



Cross section is suppressed by higgs-scalar mixing angle,

$$\sigma \sim 10^{-46}\ \mathrm{cm}^2 \left(\frac{\theta_{hs}}{0.03}\right)^2$$

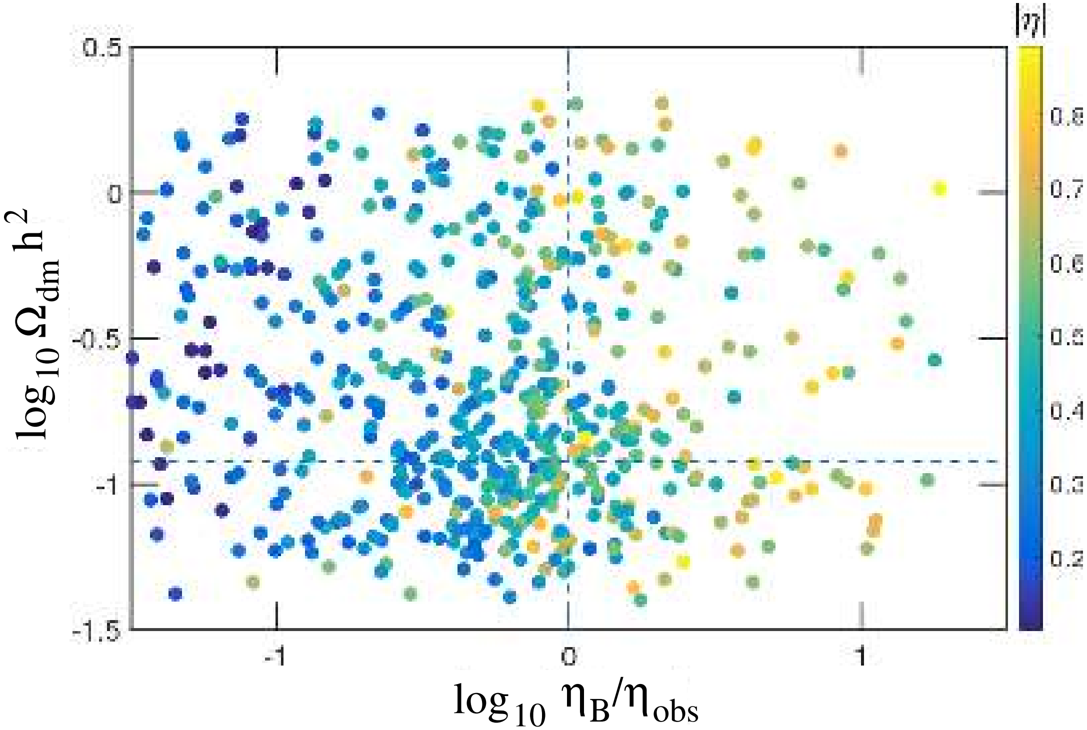
assuming scalar coupling $\eta S\bar\chi\chi$

Sample models

A region of parameter space that gives relic density and baryon asymmetry of right order of magnitude:

$$y \in [0.6, 0.8], \quad \eta \in [0.1, 0.9], \quad \lambda_m \in [0.3, 0.6]$$

$$m_\chi \in [40, 60], \quad m_\phi \in [100, 140], \quad \frac{v_0}{v_c} \in [1, 10], \quad \frac{v_c}{w_c} \in [0.01, 2]$$



(600 good models out of 380,000 tries in random scan)

Sample models

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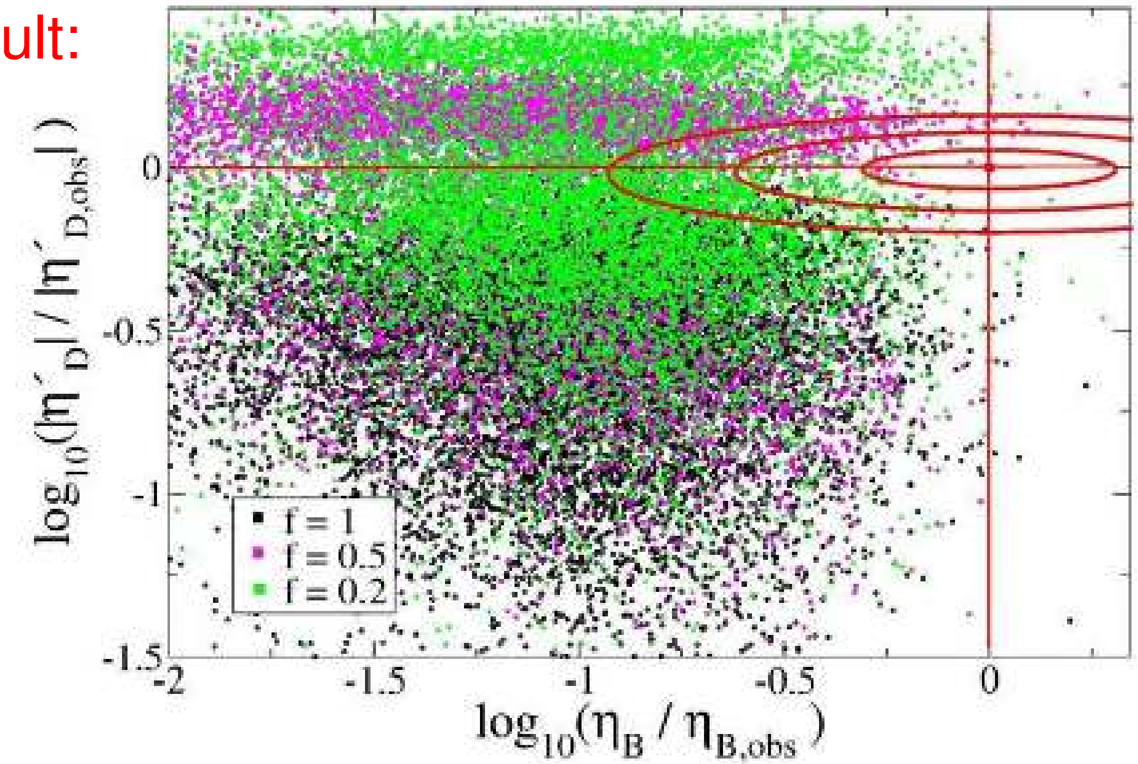
Recall 2HDM result:



Now we have good overlap

Sample models

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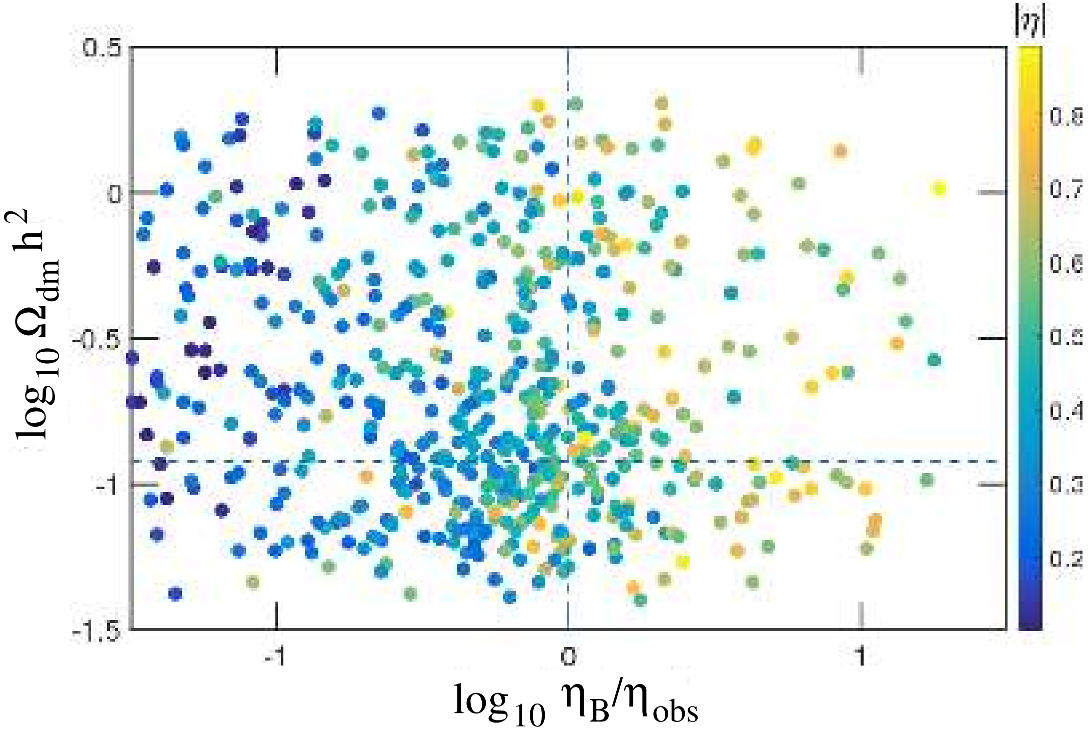
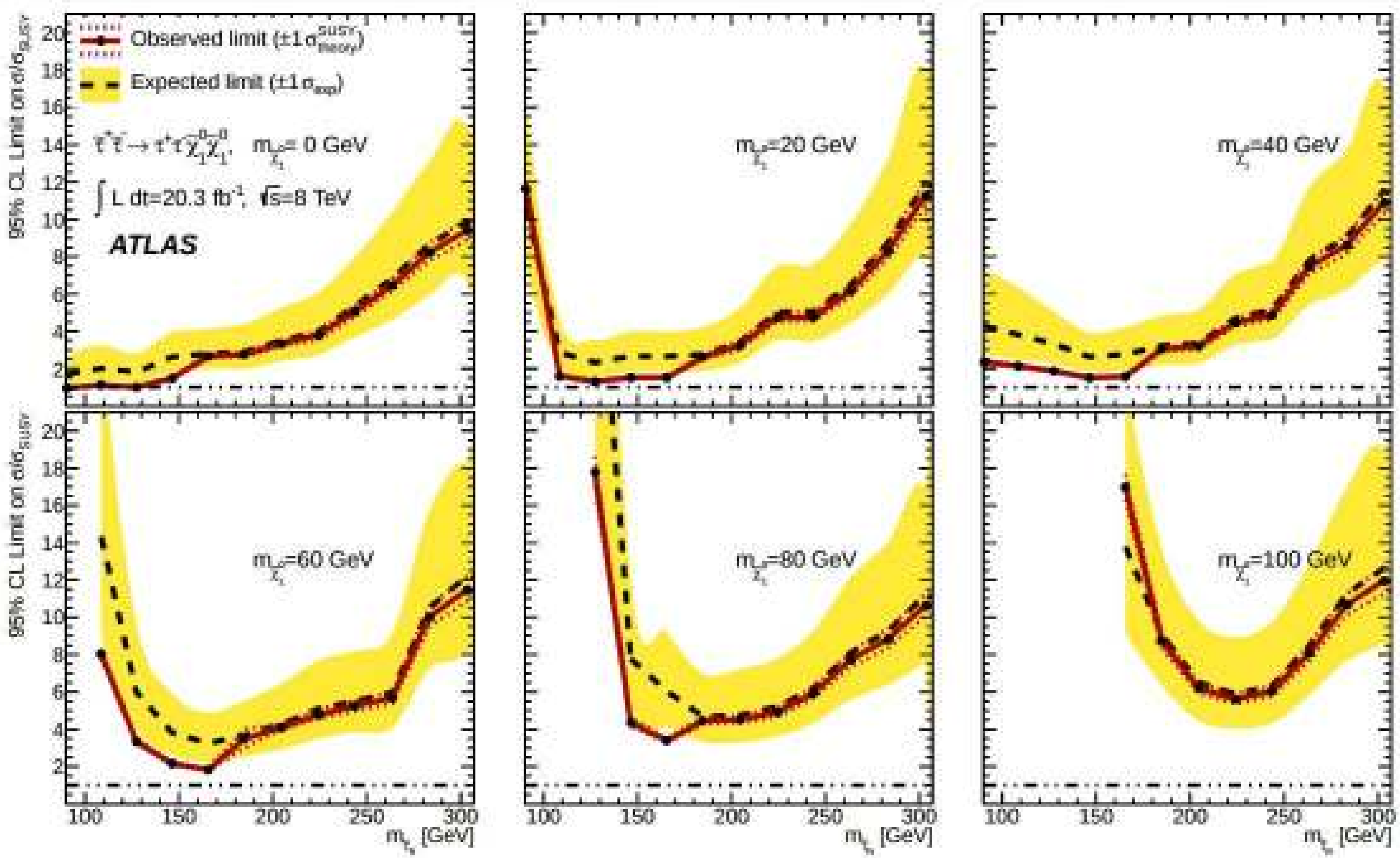


Couplings are reasonably small, we succeed in being UV complete

LHC constraints

Drell-Yan production of $\phi^+\phi^-$ followed by $\phi_\pm \to \tau^\pm\chi$ is main collider signature. This resembles $pp \to \tilde\tau\tilde\tau^*$, $\tilde\tau \to \tau\chi_1^0$ in the MSSM.

ATLAS (1407.0350) has constrained this in Run 1,



Limits are still weak, but could improve significantly in Run 2.
Analysis has not yet been redone!

Conclusions

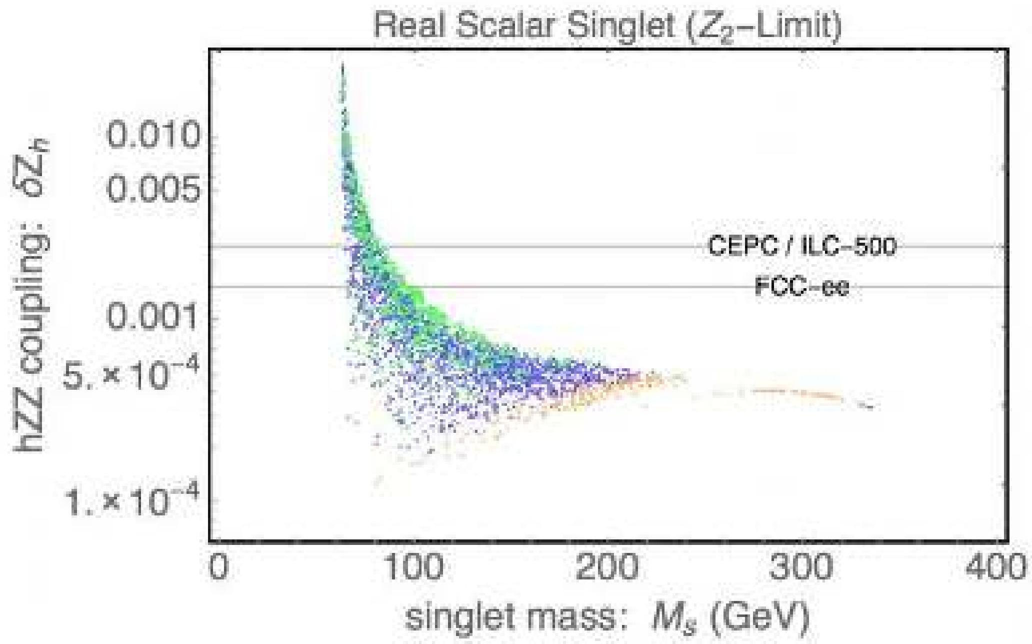
- Singlet Higgs field can significantly enhance allowed parameter space for electroweak baryogenesis
- First example of EWBG where CP asymmetry is generated by the dark matter.
- New “CP portal” mechanism to transport CP asymmetry into SM sector
- We find renormalizable example without fine tuning or too large couplings
- Potential for discovery in Run 2 of LHC
- Basic mechanism can be realized in other ways, *e.g.* using heavy top partner

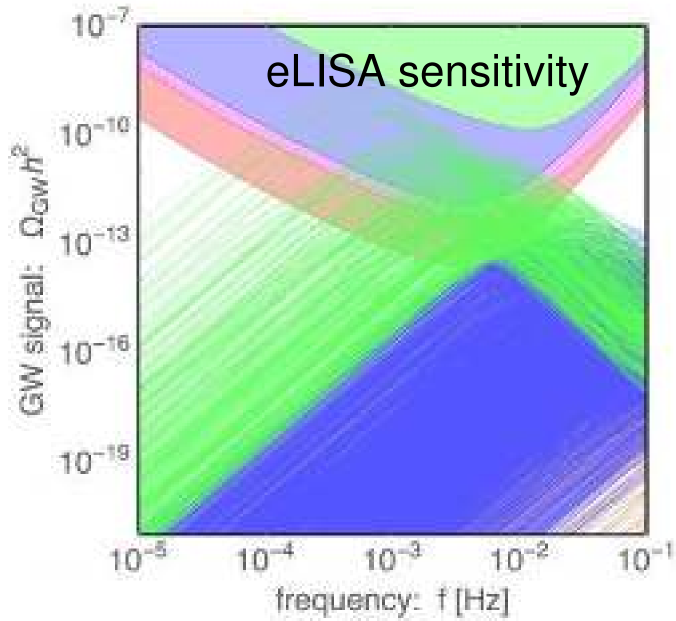
Backup slides

EWPT & observable gravity waves

A strongly first order transition can produce gravity waves, potentially observable by eLISA experiment.

Huang, Long, Wang (1608.06619) find





Orange: 1st order; blue: strongly 1st order (EWBG); green: very strongly 1st order (gravity waves)

Small perturbation to hZZ coupling may be observable at future colliders