Electroweak baryogenesis from a dark sector

with K. Kainulainen and D. Tucker-Smith

Jim Cline, McGill U.

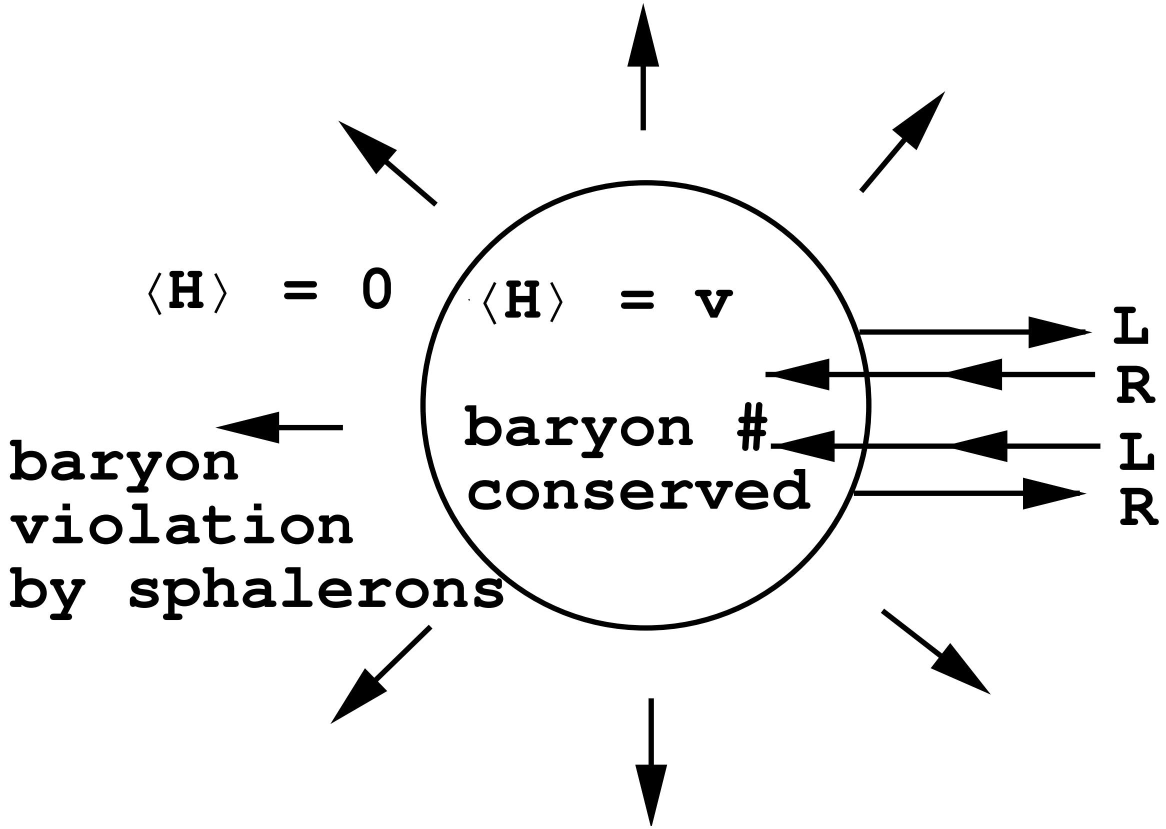
Moriond Electroweak, 24 Mar., 2017

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

Electroweak Baryogenesis

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



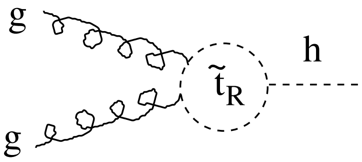
Needs new physics at the electroweak scale to get both ingredients.

A highly testable model of baryogenesis. Has it been tested out of existence?

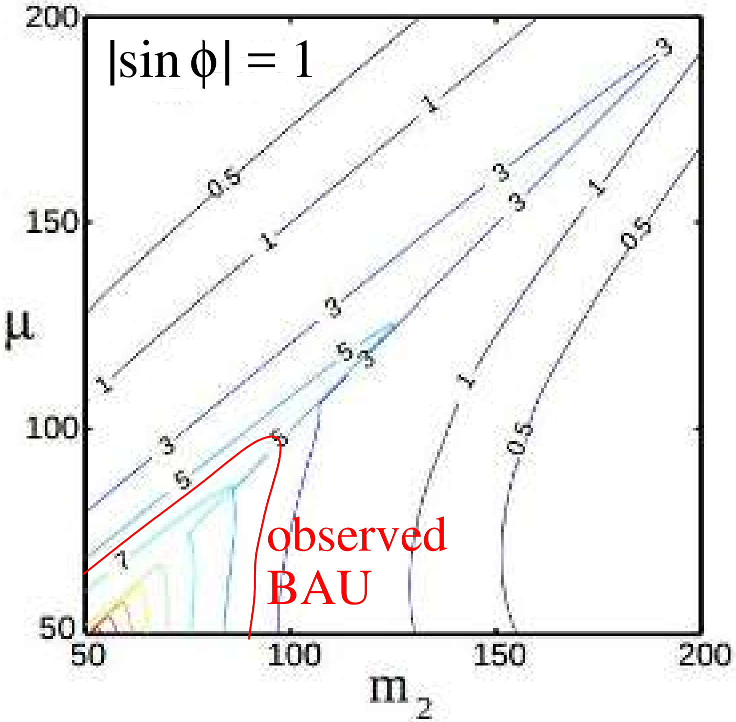
EWBG in the MSSM

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:



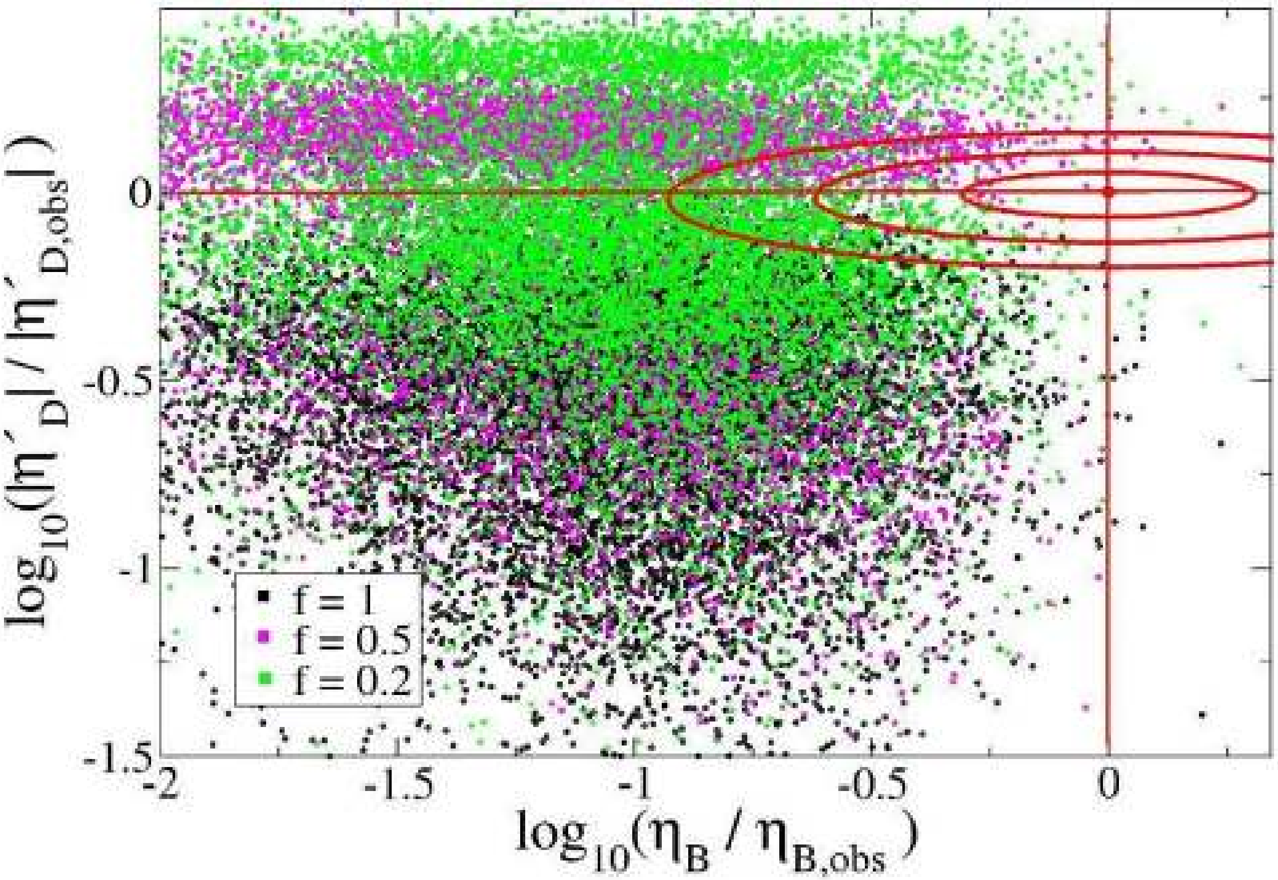
Cline & Kainulainen, PRL 85 (2000) 5519 (hep−ph/000272)

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

EWBG in two Higgs doublet models

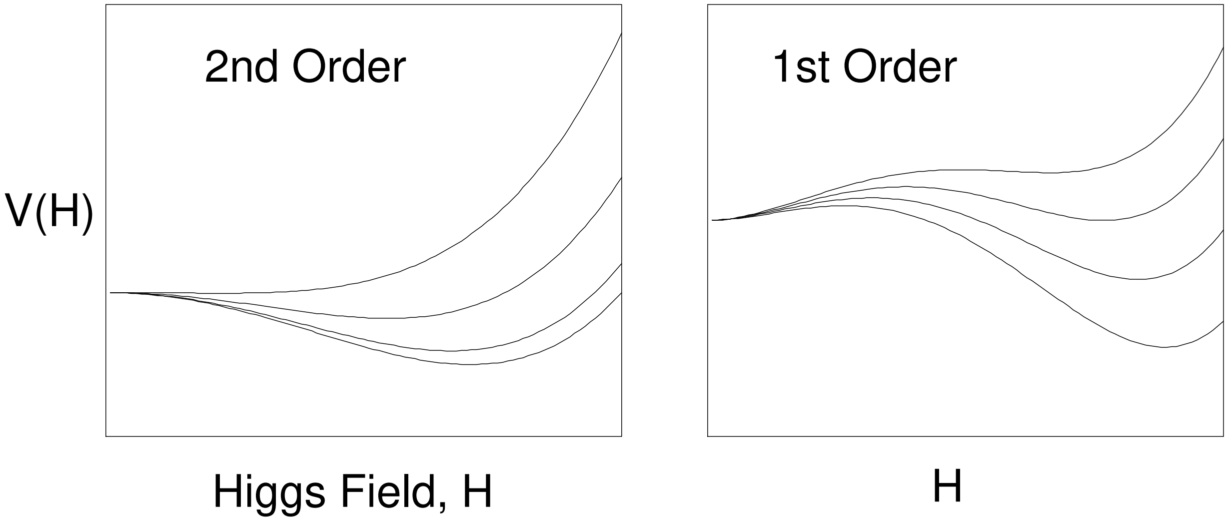
MSSM is a two Higgs doublet model. More general 2HDMs have the needed ingredients for EWBG. But the parameter space that works is extremely small.

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



Difficult to get strong phase transition

First order phase transition requires potential barrier,



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

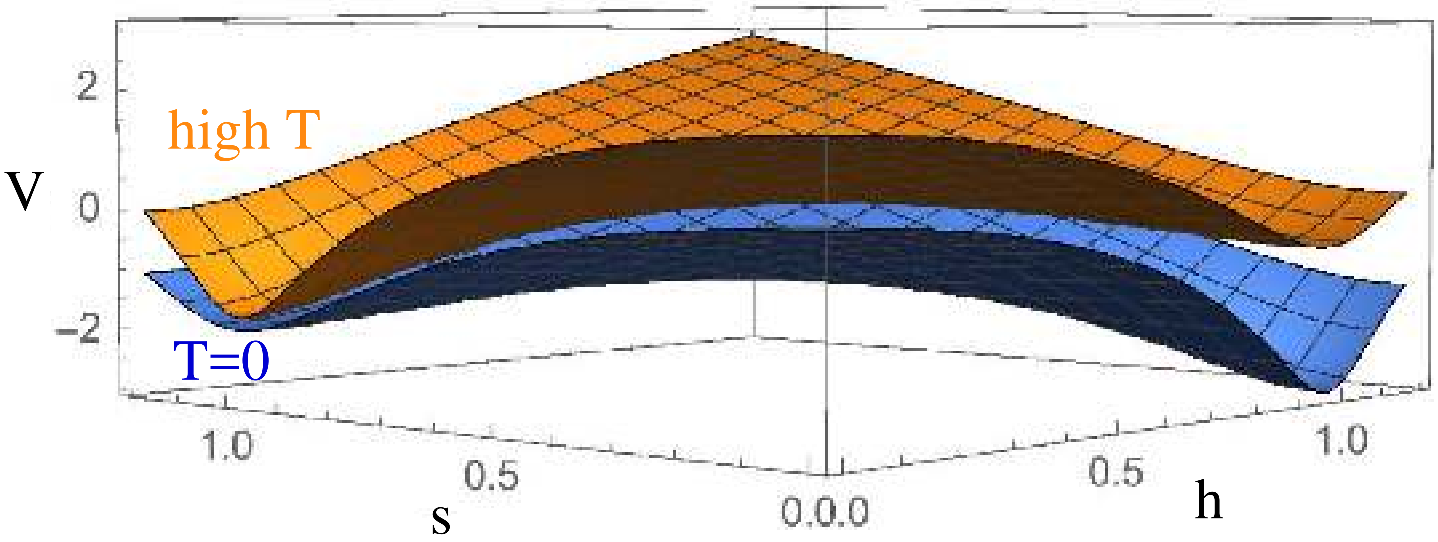
$$\Delta V = -\frac{T}{12\pi}\sum_i (m_i^2(h))^{3/2} = -\frac{T}{12\pi}\sum_i (m_{i,0}^2 + g_i^2 h^2 + c_i T^2)^{3/2}$$

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 use a scalar singlet s.

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 is 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?

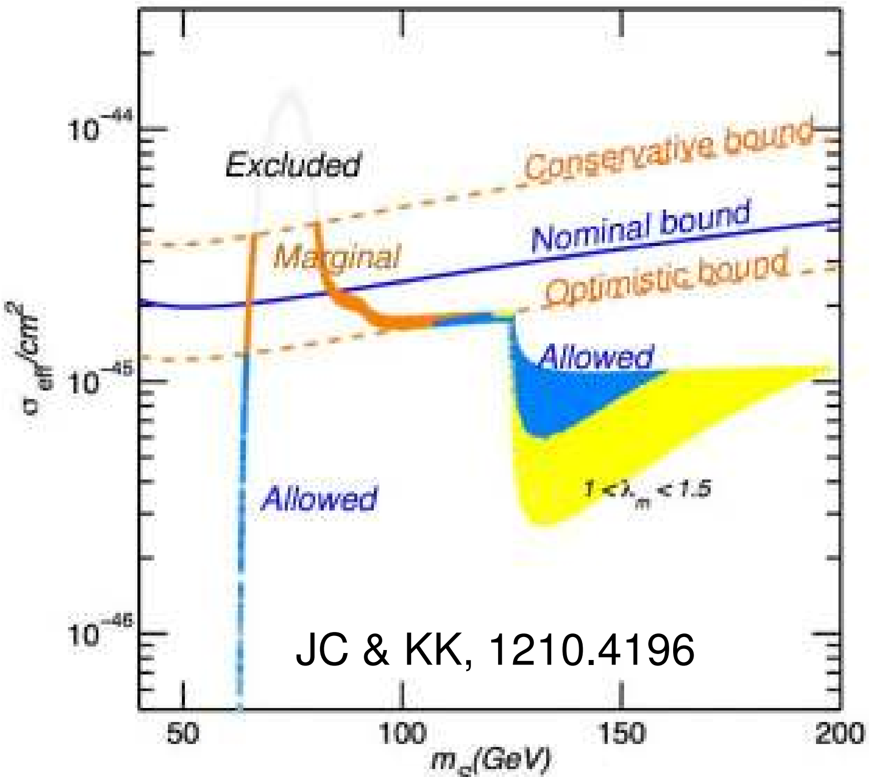
*Dimension-5 also works, but with dim-6, S can be stable dark matter candidate.

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



JC & KK, 1210.4196

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.

A working model

Introduce Majorana fermion χ,

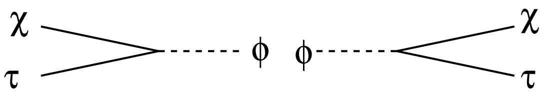
$$\frac{1}{2}\,\bar{\chi}\,[m_\chi + S(\eta\, P_L + \eta^* P_R)]\,\chi$$

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")

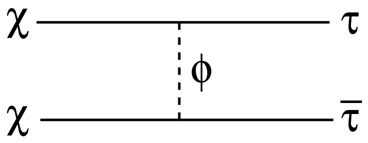
$$y\,\bar{\chi}\phi L_\tau$$

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

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

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

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

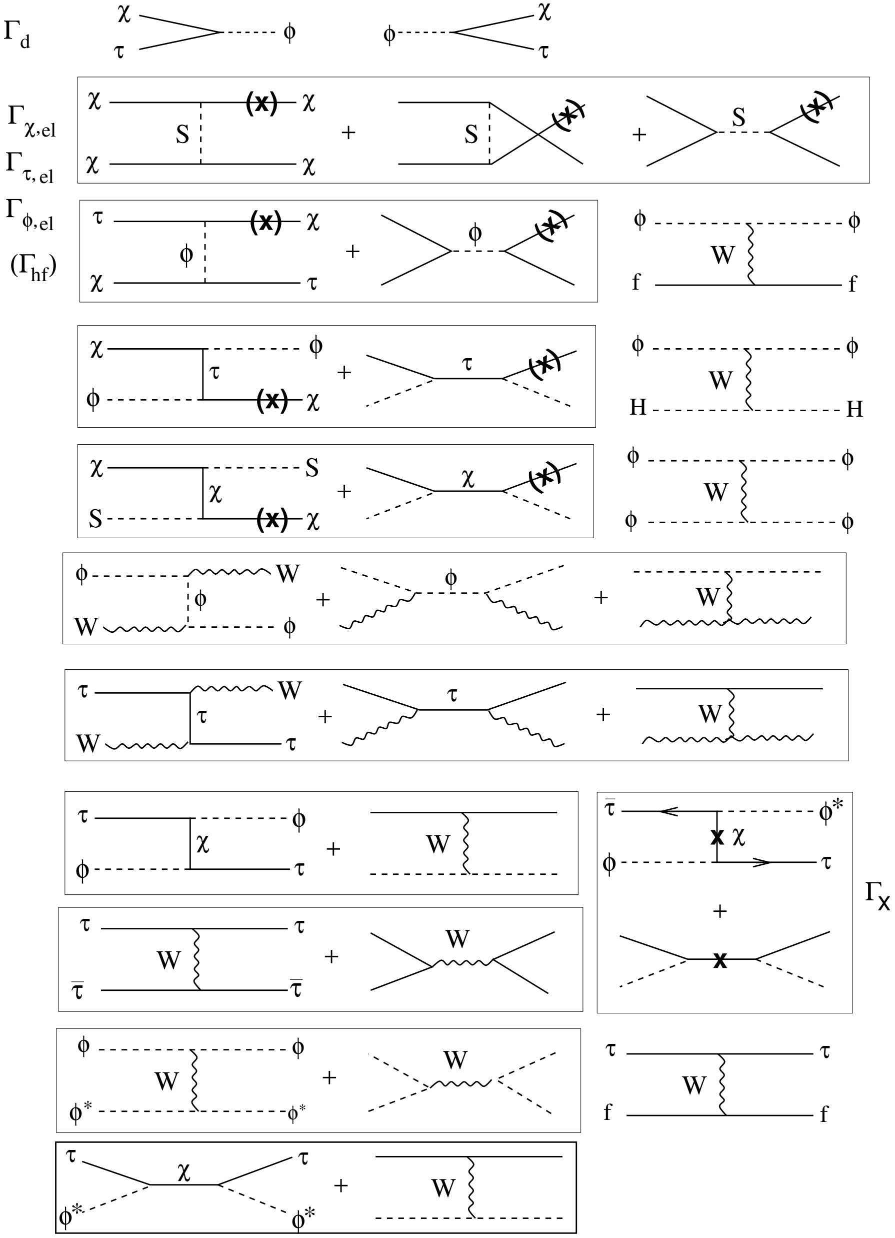
$\Gamma_{\times,i}$ = rate of $\phi\bar\tau \to \phi^*\tau$ due to χ mass insertions

$K_i =$ thermal kinematic coefficients

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

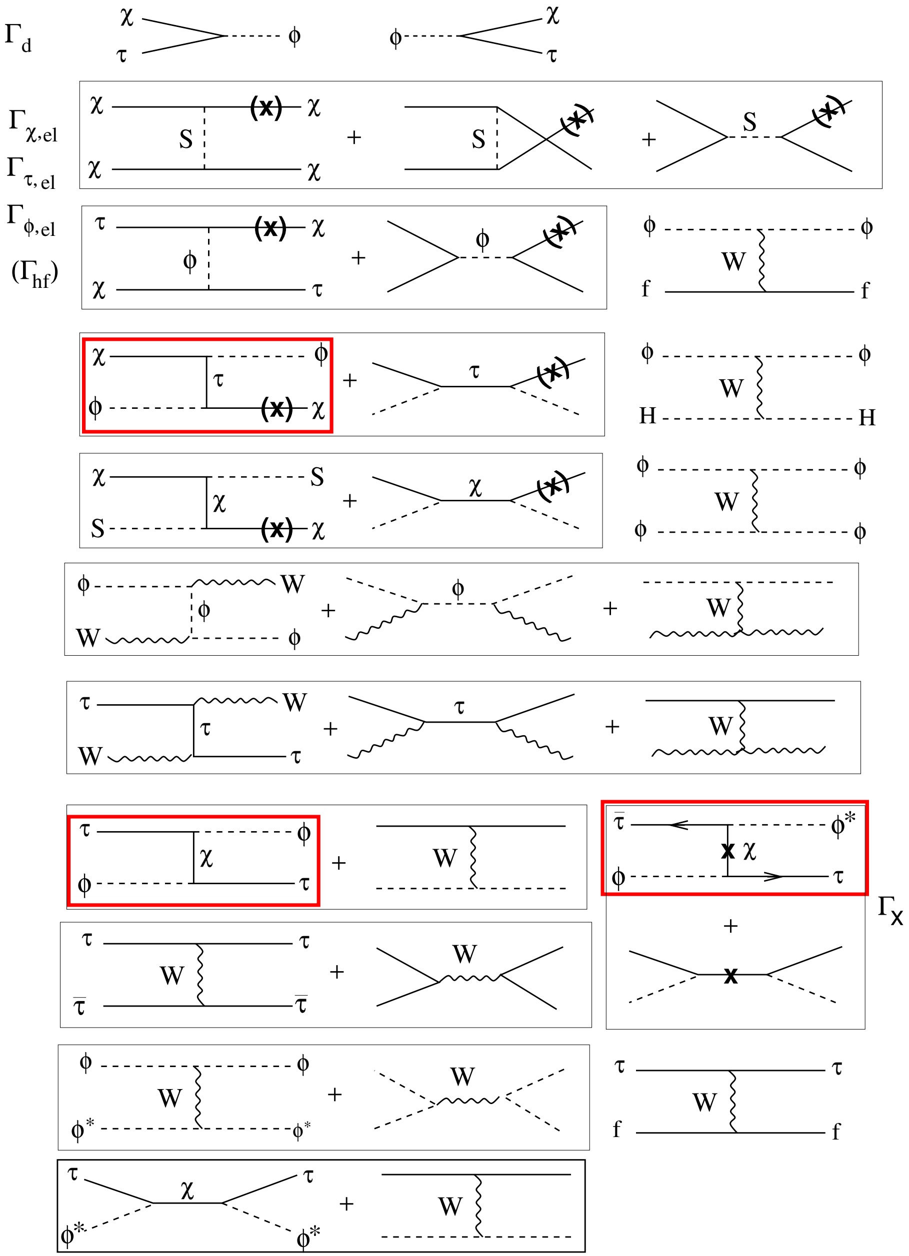
Decay and scattering rates

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

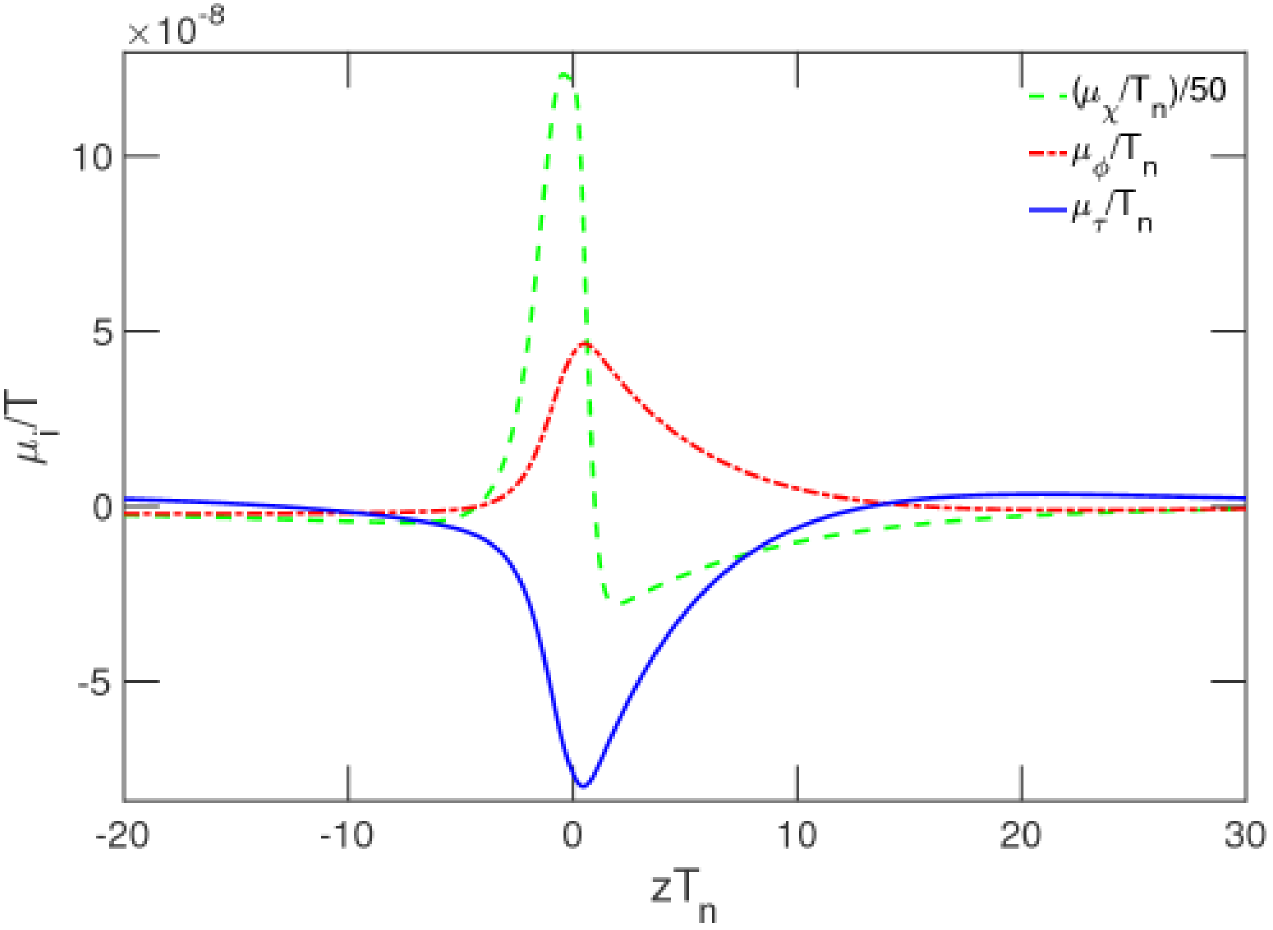
(Due to ϕ decay followed by inverse decay)

Thermal width of t−channel particle renders cross section finite

Solution of diffusion equations

Example: (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	$\frac{\eta_B}{\eta_{B,\rm obs}}$	$\Omega_{\rm dm}h^2$
0.45	0.66	0.51	56	124	102	85	111	82	140	129	112	0.9	0.12



Dark matter relic density

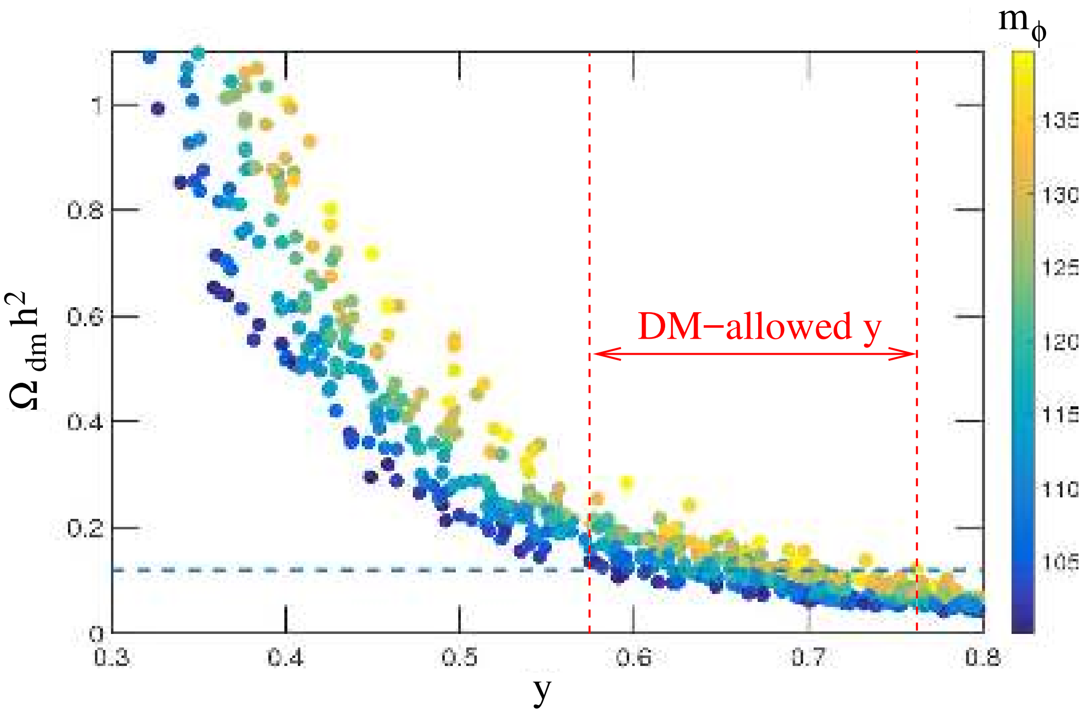
We get thermal relic abundance from annihilations

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

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,



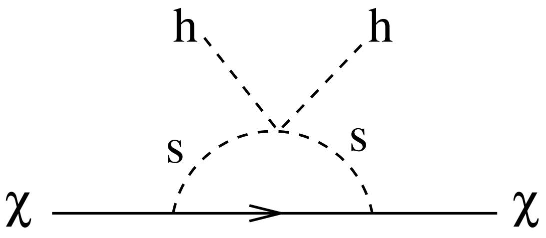
$m_\chi \sim 50\,\mathrm{GeV}$,

$m_\phi \sim 100\text{–}150\,\mathrm{GeV}$,

$y \cong 0.6 - 0.7$

Direct detection: signal is small

Higgs portal at one loop gives strongest interaction with nuclei:

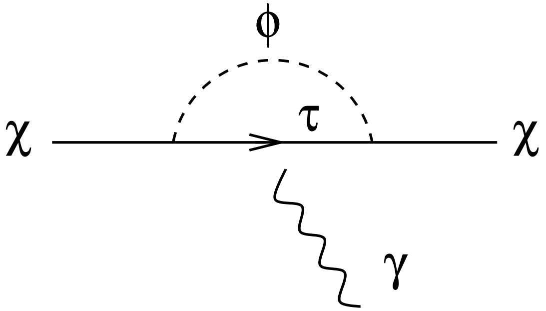


Cross section is

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

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,

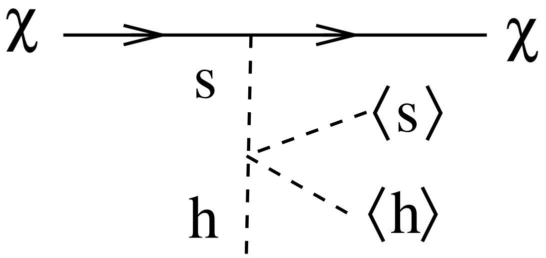


Cross section is velocity-suppressed,

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

even smaller

Small S VEV would give tree-level Higgs portal:



Cross section is suppressed by higgs-scalar mixing angle,

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

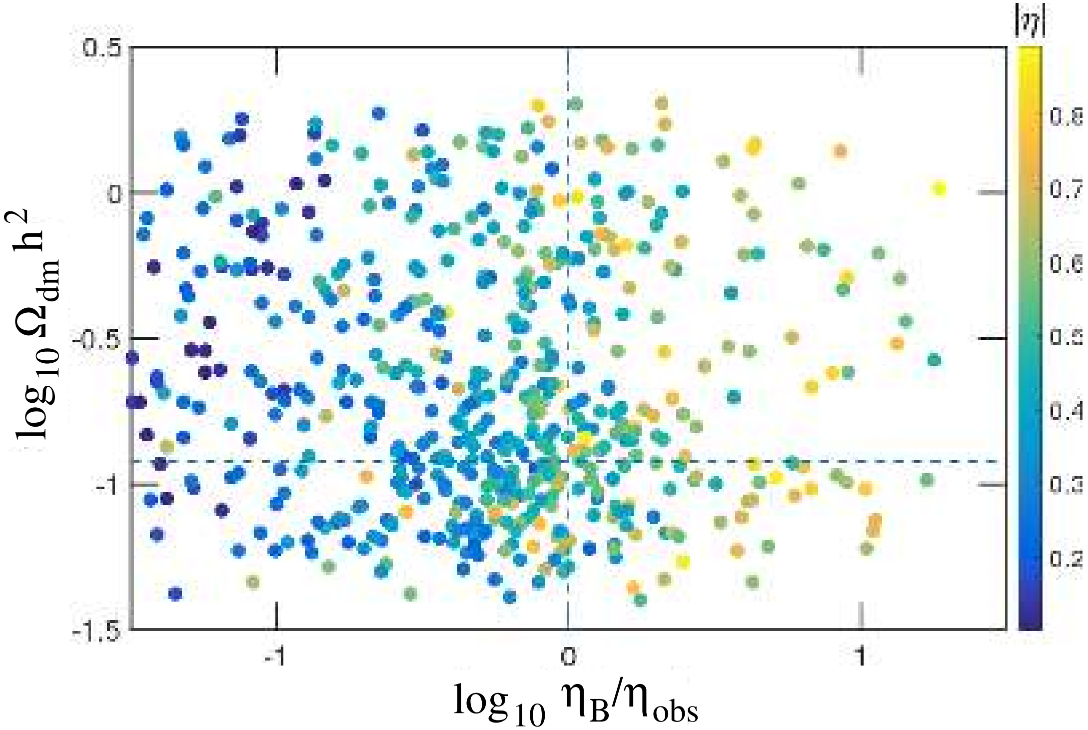
assuming scalar coupling $\eta S\bar\chi\chi$

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)

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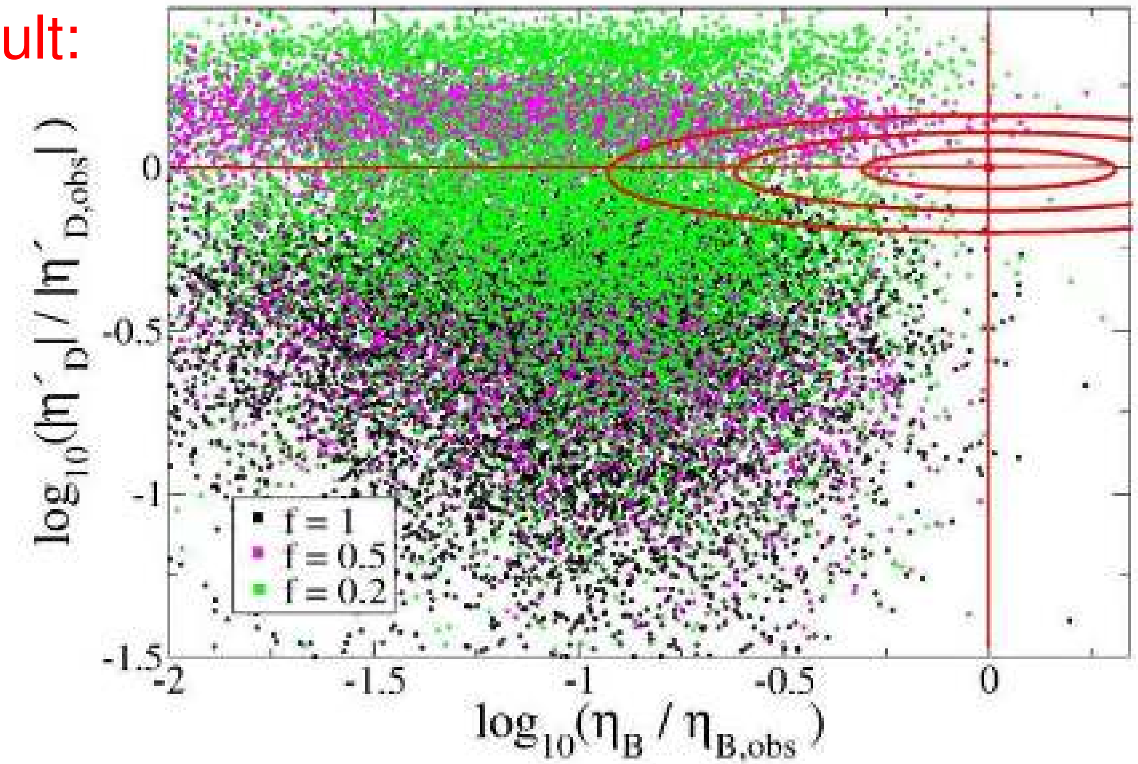
Recall 2HDM result:



Now we have good overlap

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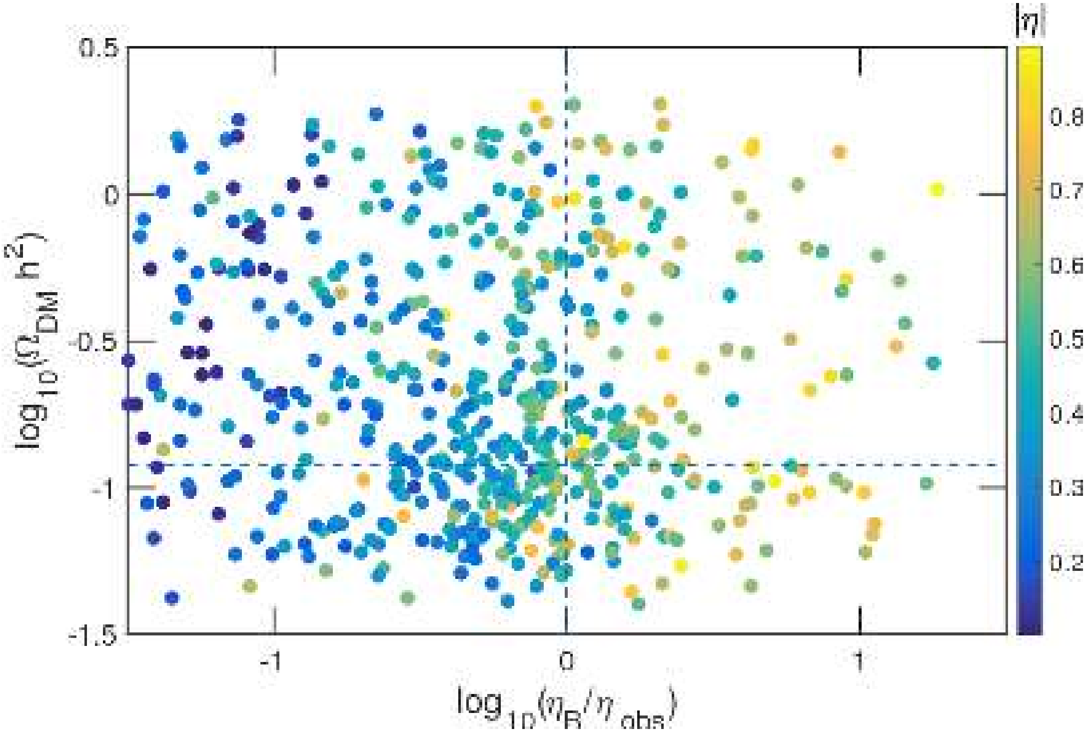
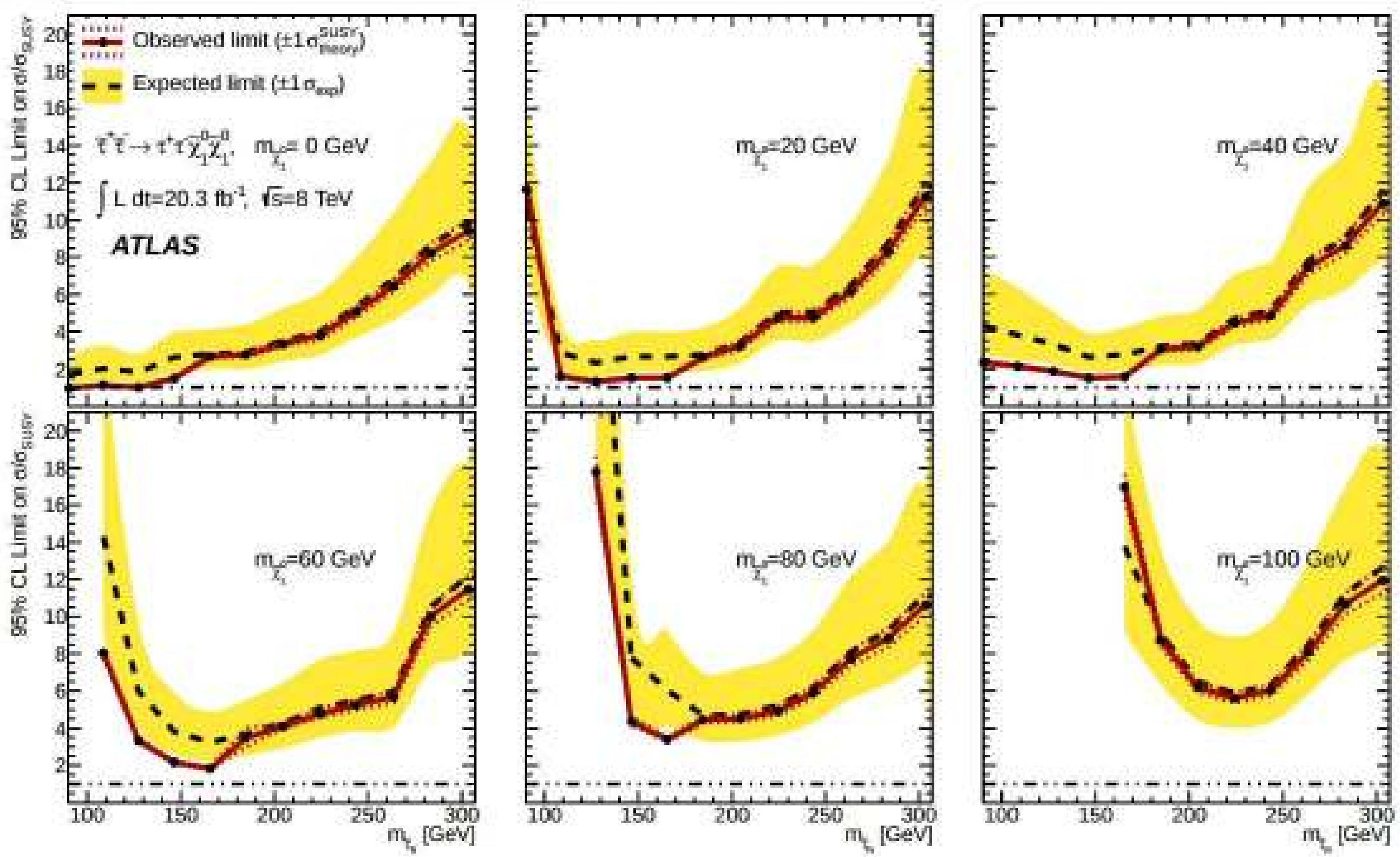


Couplings are reasonably small, we succeed in being UV complete

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

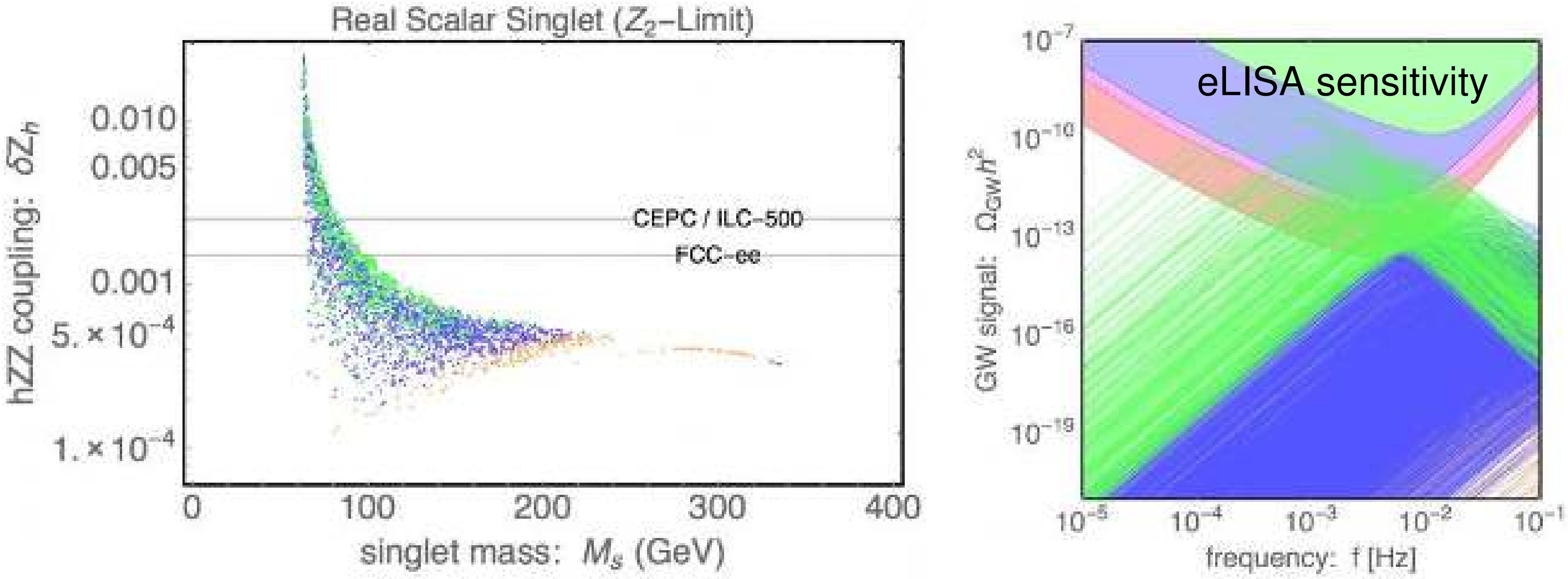
- Singlet Higgs field can significantly enhance allowed parameter space for electroweak baryogenesis
- First example of EWBG where CP asymmetry is generated by the dark matter.
- New “CP portal” mechanism to transport CP asymmetry into SM sector
- We find renormalizable example without fine tuning or too large couplings
- Potential for discovery in Run 2 of LHC (though not by direct DM detection)

Backup slides

EWPT & observable gravity waves

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

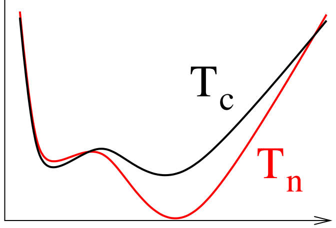
Huang, Long, Wang (1608.06619) find



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

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. But finding bubble wall solution at $T < T_c$ is numerically tricky.

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,

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