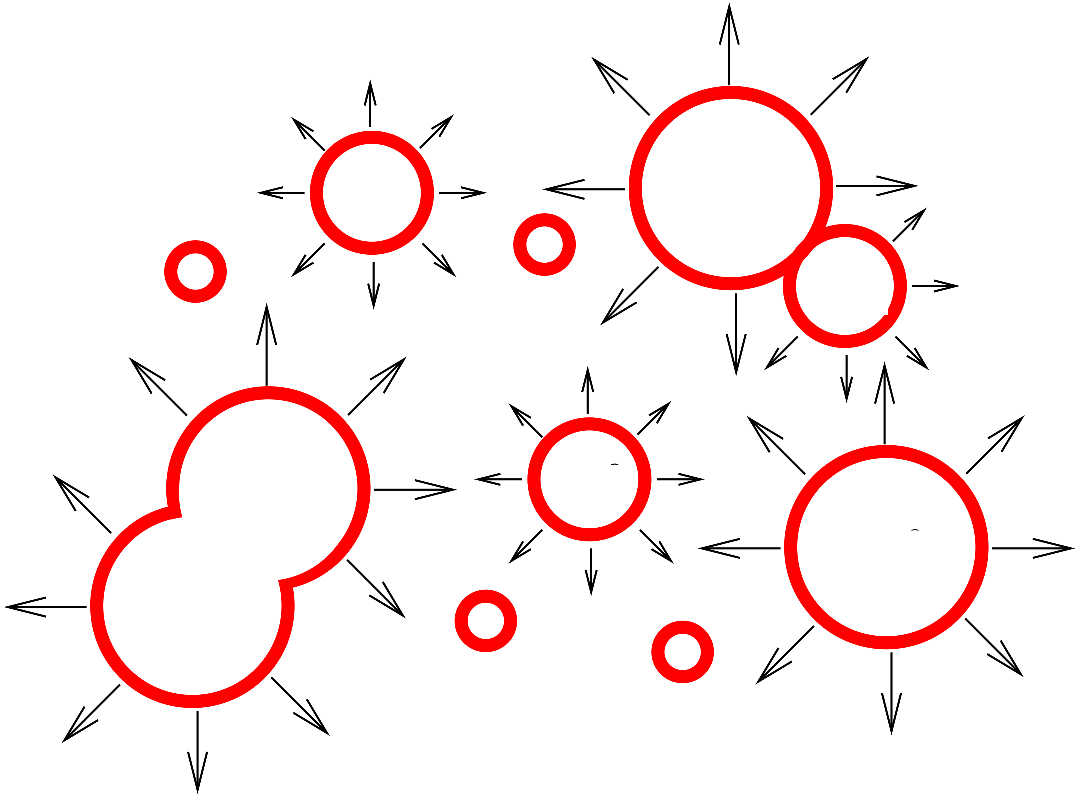
High-speed electroweak baryogenesis



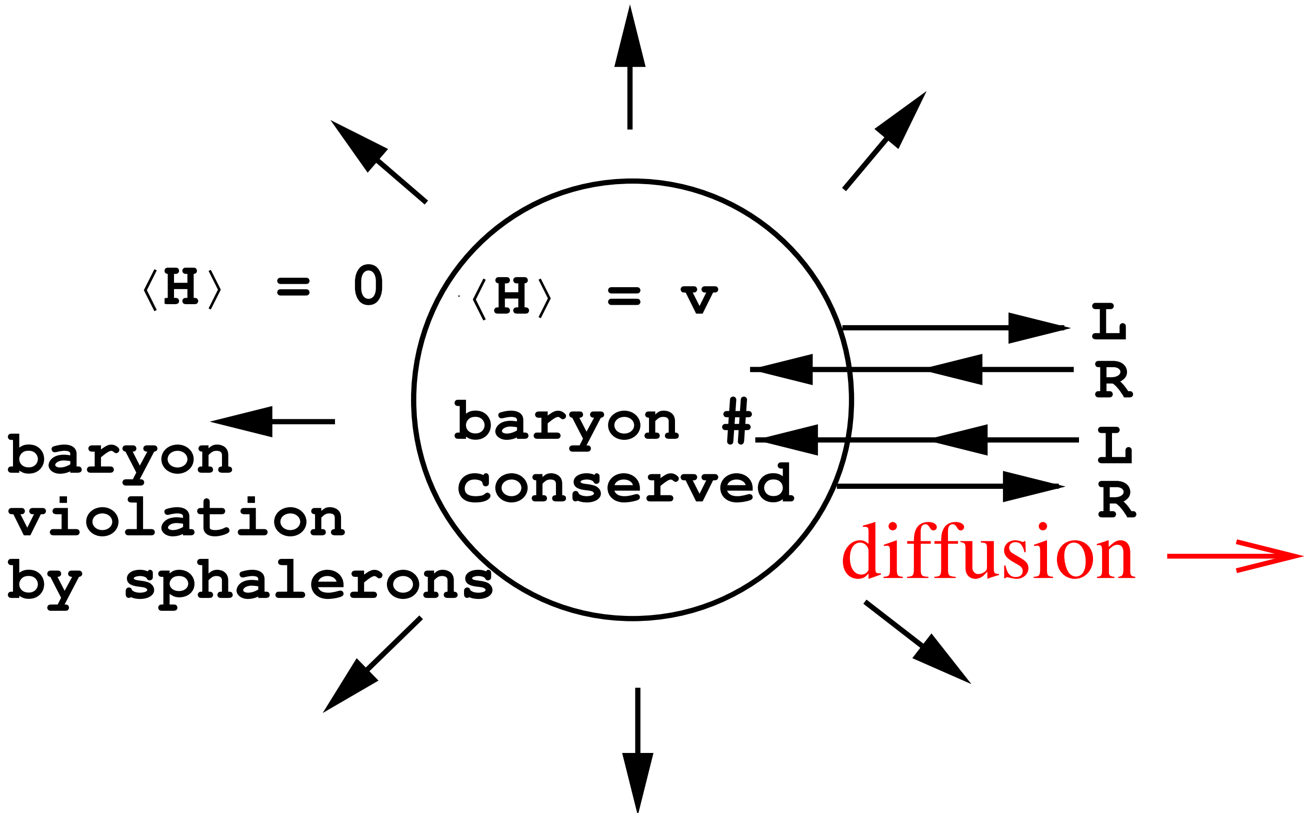
Jim Cline, McGill University

based on JC, K. Kainulainen 2001.00568

webinar, Stefan Institute, Ljubljana, 26 May, 2020

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.

Recently high wall velocities v_w became more interesting because of gravity waves. Can EWBG work at high v_w?

Lore

It was believed that EWBG gets quenched if $v_w \to 1/\sqrt{3}$, the speed of sound.

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Nonlocal electroweak baryogenesis. II. The classical regime

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The fluid equations (26) are calculated to leading order in v_w. A fuller analysis incorporating all orders in v_w can be performed and shows that the velocity at which the leading-order analysis breaks down is the speed of sound $v_w \sim v_s = 1/\sqrt{3}$ in the plasma. If the wall moves faster than this, there is no solution in front of the wall, and perturbations cannot propagate into this region. We are interested in the case when perturbations can propagate in front of the wall where the anomalous electroweak processes are unsuppressed. Thus, we assume

$$v_w < v_s = \frac{1}{\sqrt{3}}\,. \qquad (31)$$

Lore

It was believed that EWBG gets quenched if $v_w \to 1/\sqrt{3}$, the speed of sound.

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Electroweak baryogenesis in supersymmetric models

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tion. Should the wall velocity approach or be larger than the speed of sound, diffusion is not a good approximation to transport and our computations are invalid. An improved cal-

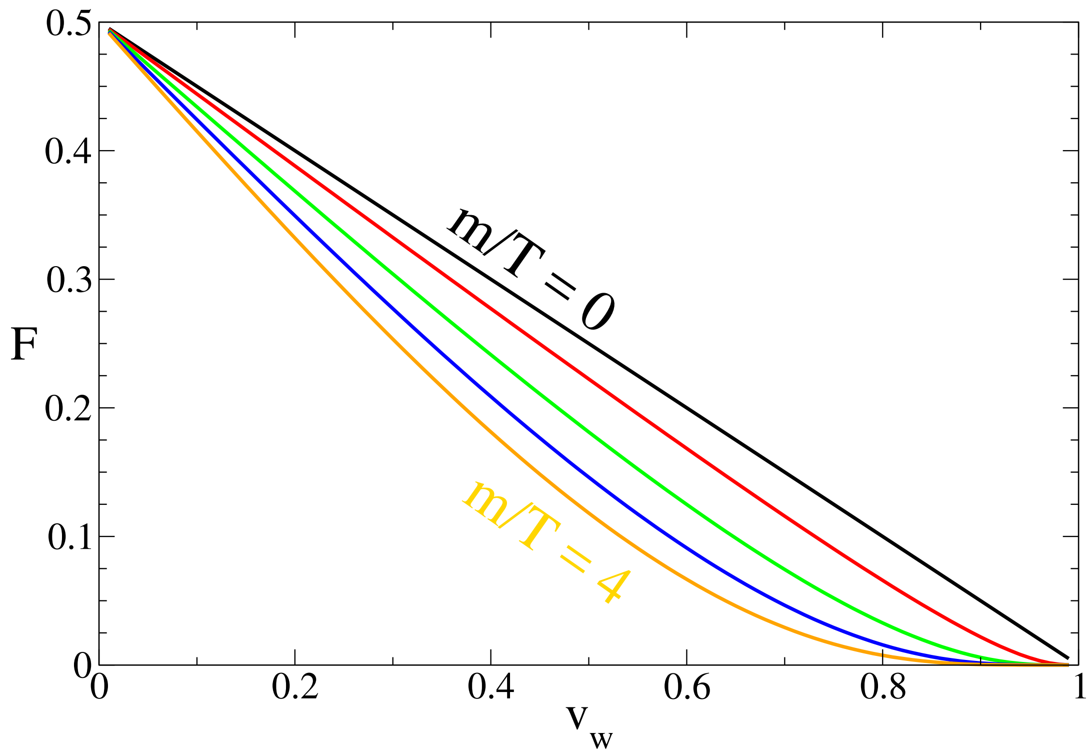
People thought that particles in front of a supersonic wall don't have time to diffuse away from the wall.

But is it true? Sound propagation and diffusion are entirely different phenomena!

Simple exercise

Compute the fraction F of particles in a thermal gas that have $v_z = p_z/E > v$ (can stay ahead of the wall) as a function of v.

$$F = \frac{\frac{1}{2}\int_{\gamma_w v_w m}^{\infty} dp\, p^2 (1 - v_w E/p)/(e^{\beta E}+1)}{\int_0^{\infty} dp\, p^2/(e^{\beta E}+1)}$$



Nothing special happens at $v = 1/\sqrt{3}$! Diffusion only needs random particle motions.

Our result

A consistent derivation of fluid equations leads to physically sensible result: diffusion can occur up to $v_w \lesssim 1$.

If your fluid equations predict something else, there is a problem.

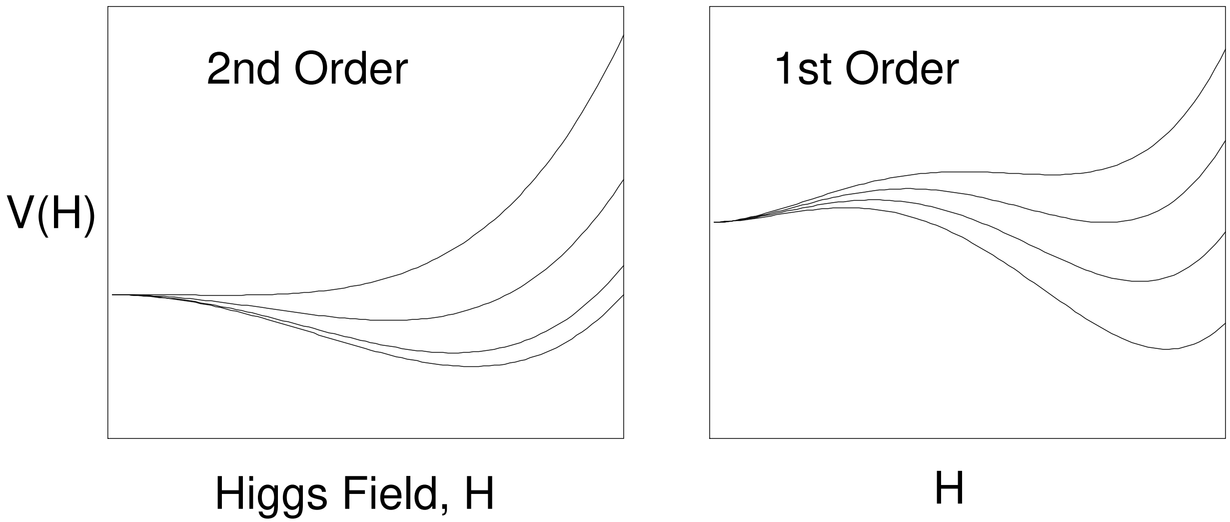
Hence EWBG can in principle work for $v_w > 1/\sqrt{3}$

Same phase transition might produce both EWBG and gravity waves observable by LISA

But first some more general background on EWBG . . .

How to get a 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, $v/T < 1$.

Previous attempts

In the past, much attention was given to EWBG in the MSSM with light stops, and two Higgs doublet models (2HDMs).
These are largely defunct.

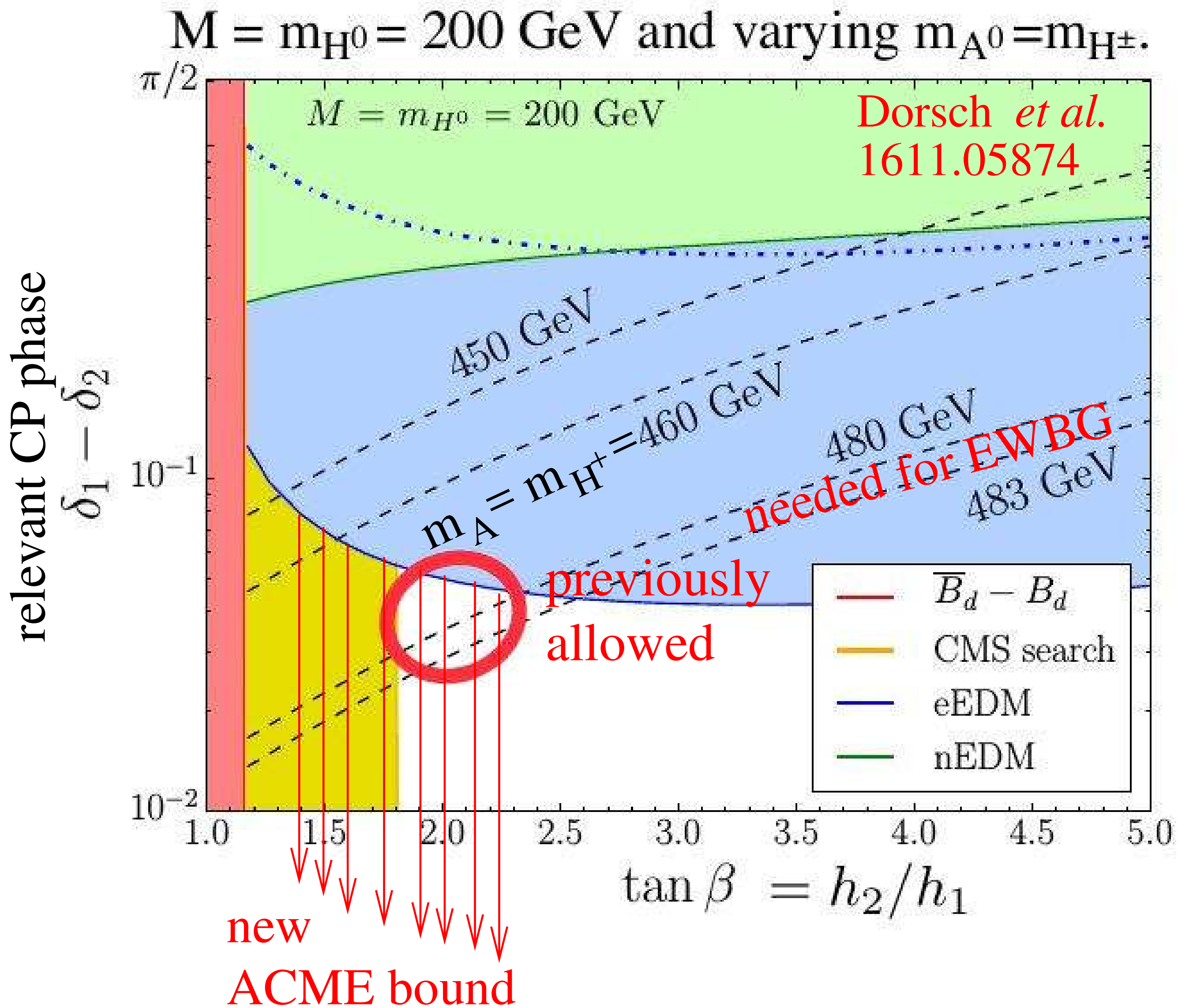
artwork credit: K. Kainulainen

No light stops observed, and EDM constraints on needed CP violation are severe.

Recent studies of 2HDM viability (Dorsch, Huber, Konstandin, No, arXiv:1611.05874) are trumped by improved EDM constraints.

Demise of 2HDM EWBG

ACME (Nature 562 (2018) 355) killed 2HDM EWBG:

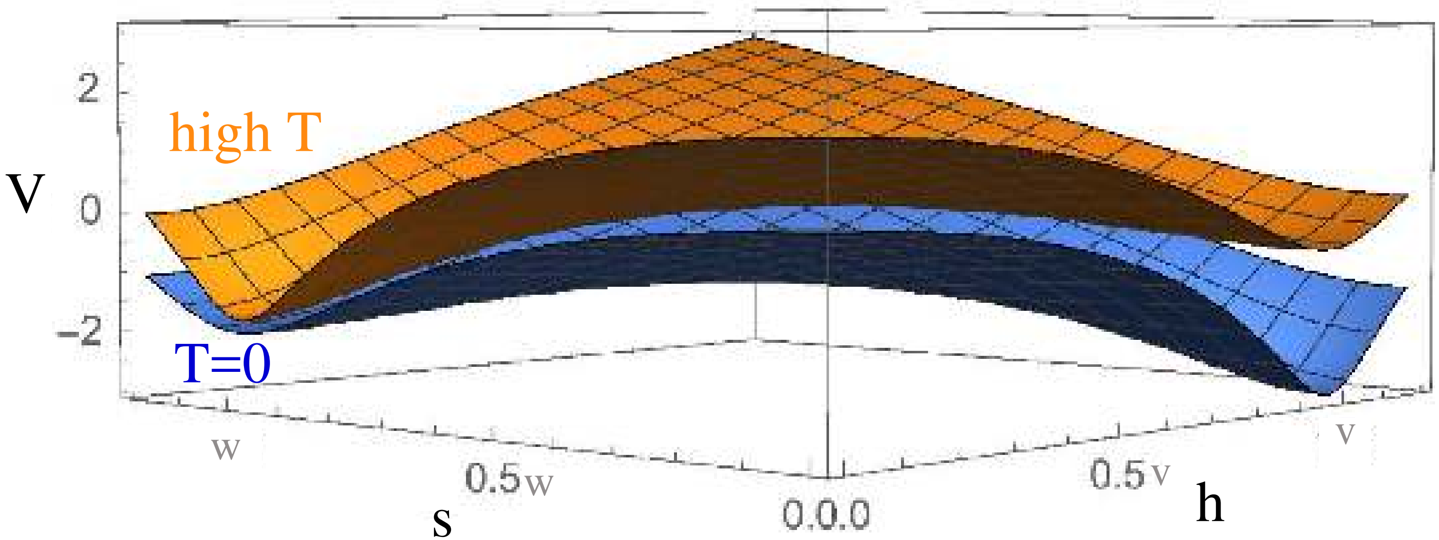


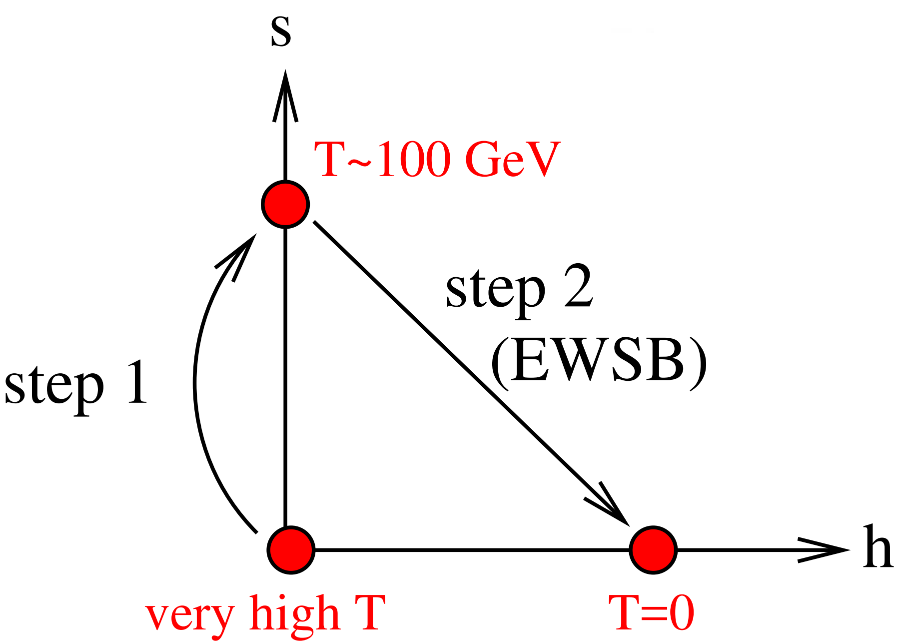
Desired region is completely excluded!

Tree-level barrier with a singlet scalar

A more robust scenario introduces 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

Can introduce dimension-5 coupling to top quark, $i(s/\Lambda)\bar{Q}_L H t_R$, to give complex mass in the bubble wall,

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

Can be derived from model with heavy vector-like top partner coupling to s.

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

The new CP violation is spontaneous, due to $\langle s \rangle \neq 0$ during EWPT, and disappears at $T \lesssim m_W$.

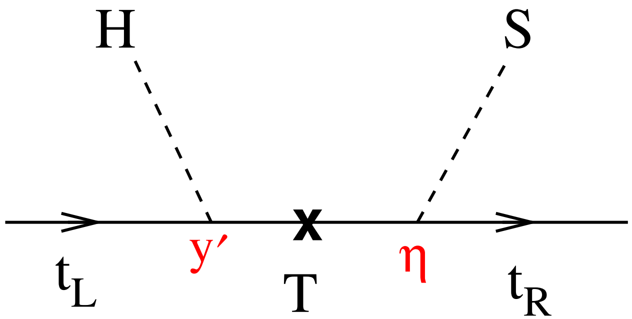
One escapes stringent constraints on new CP-violation from EDM searches.

Heavy top partners

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

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

Integrate out heavy state:



Generates desired coupling

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

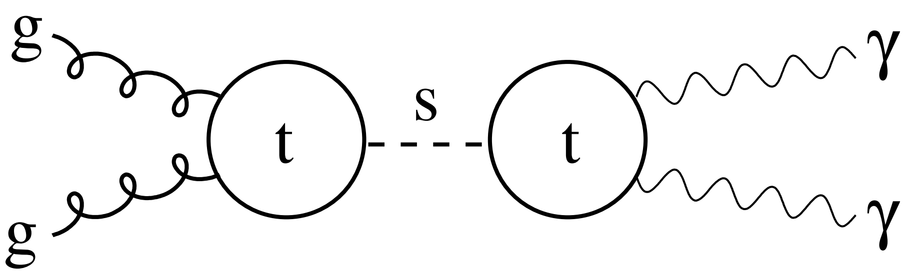
which can be imaginary (CP violation) and large enough.

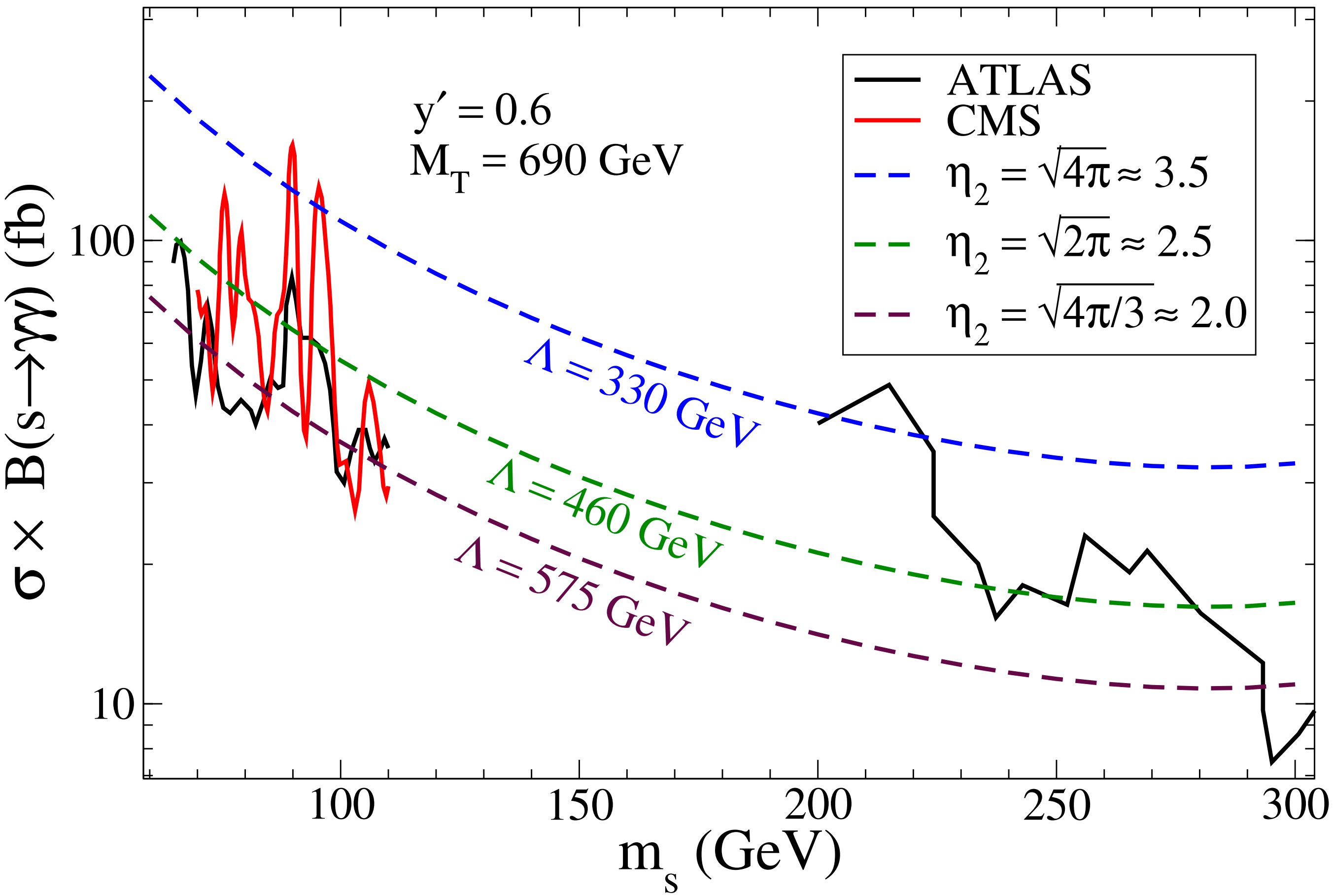
LHC limits are weakened, $M_T \gtrsim 700\,\mathrm{GeV}$, due to dominant $T \to St$ deca

Strongest constraints are from resonant s production + EWPD…

Constraint from s production

Strongest constraint is from $gg \to s \to \gamma\gamma$





Constrains largest allowed value of η, hence of

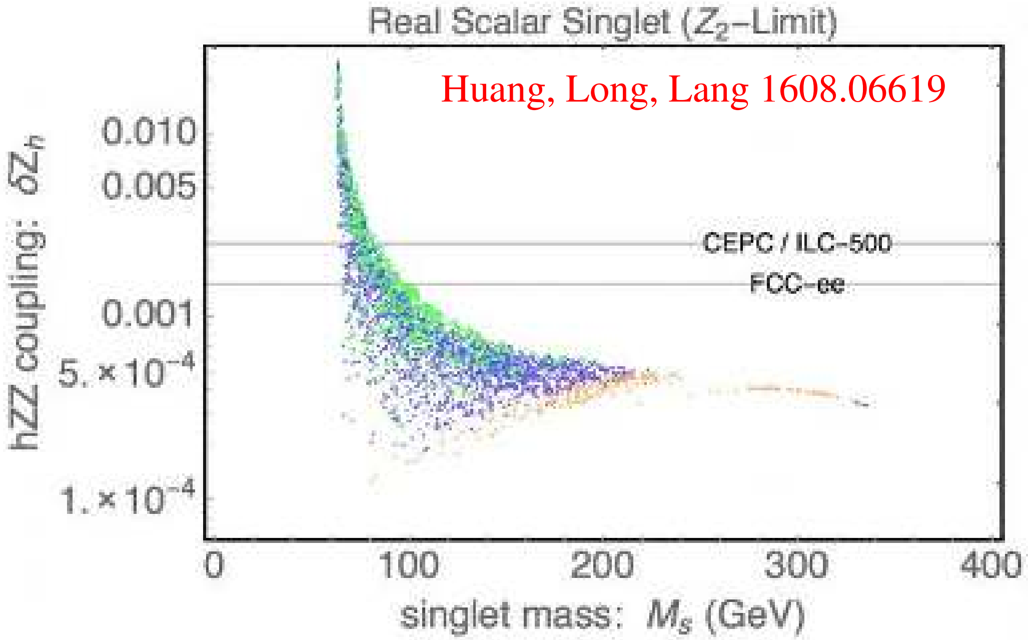
$$\frac{1}{\Lambda} = \frac{y'\eta}{y_t M_T}$$

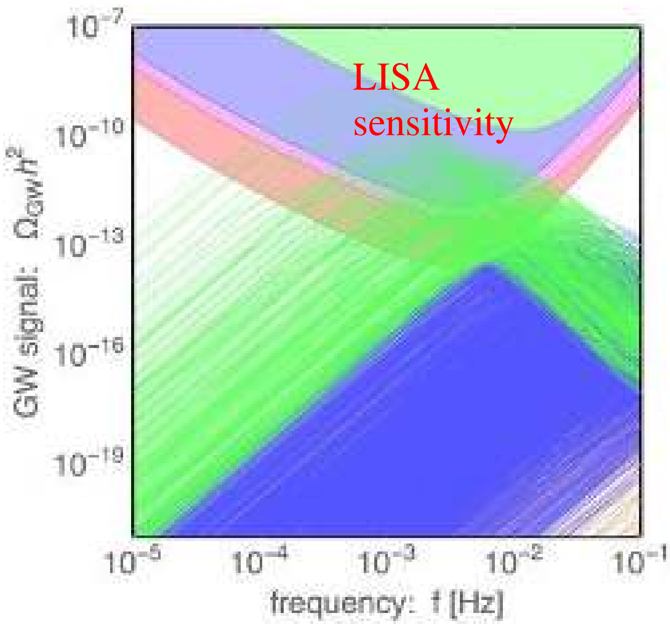
EWPD oblique parameter T constrains y' through t_L-T_L mixing

EWPT & observable gravity waves

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

Mixing of s and h could modify hZZ coupling in a correlated way.





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

But you need more than a strong EWPT for EWBG; you need to make large enough baryon asymmetry too!

Computing baryon asymmetry (BAU)

Complex top-quark mass $|m(z)|e^{i\theta(z)}$ in bubble wall produces a CP-violating force acting oppositely on particles/antiparticles:

$$\vec{F} = F\hat{z} \cong -\frac{(m^2)'}{2E} \pm \frac{(m^2\theta')'}{2E^2} + O(\theta^2) \quad [\,' = d/dz]$$

Distorts the phase space distribution of top quarks (and h, b_L that couple to t through collision term $\mathcal{C}$) via Boltzmann equation

$$\left(\frac{d}{dt} + \vec{v}\cdot\vec{\nabla} + \frac{\vec{F}}{m}\cdot\vec{\nabla}_p\right) f = \mathcal{C}[f]$$

Split f into two pieces (JC, Joyce, Kainulainen hep-ph/0006119)

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

deviation from chemical equilibrium encoded in μ_i

deviation from kinetic equilibrium

with form of δf_i unspecified. Linearize in perturbations μ_i, δf_i. Define "velocity potential" $u_i = \int d^3p\,(p_z/E)\delta f_i$.

Fluid equations $\rightarrow$ BAU

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

In wall rest frame, linearized Boltzmann eq. (neglecting m' contributions) is

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

wall velocity; Semiclassical force, $\dot{p} = -\frac{|m||m|'}{E} + s_{CP}\frac{s(|m|^2\theta')'}{2E^2}$; collision term; CP violating source term

Take first two moments to derive fluid equations,

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

Demand that $\int d^3p\,\delta f_i \equiv 0$ (u_i is “orthogonal” to μ_i)

Solve coupled eqs. for μ_{t_L}, μ_{t_R}, μ_h, μ_{b_L}; these feed into sphaleron rate equation,

$$\dot{n}_B = -\frac{3}{2}\frac{\Gamma_{\rm sph}}{T}\sum_{i=1}^{3}\left(3\mu^i_{u_L} + 3\mu^i_{d_L}\right)$$

Baryon asymmetry is integral of this.

The devil is in the details!

We do not make an explicit ansatz for the form of δf.

From JC, Joyce, Kainulainen, hep-ph/0006119:

> The $\delta f(x, p)$ term will play the role of an auxiliary field in the following derivation. It cannot be neglected, for the Boltzmann equations with a force term can only be self-consistently solved if there is a perturbation which is anisotropic in momentum space.[4] The shape of $\delta f_i(p, x)$ cannot be consistently restricted beyond (79), since this would require some hierarchy between the elastic interaction rates that would allow certain perturbations to be damped more slowly than others.

But we have to evaluate integrals like

$$\int d^3p \left(\frac{p_z}{E}\right)^2 \delta f \stackrel{?}{=} u \int d^3p \left(\frac{p_z}{E}\right) f_{0,v_w} \Big/ \int d^3p \, f_{0,v_w}$$

with $f_{0,v} = (e^{\gamma_w \beta(E+v_w p_z)} + 1)^{-1}$ in wall rest frame. We assume it *factorizes* as above.

This is necessary for getting the expected v_w-dependence. Adopting an explicit ansatz always leads to the wrong behavior.

Critical wall speed

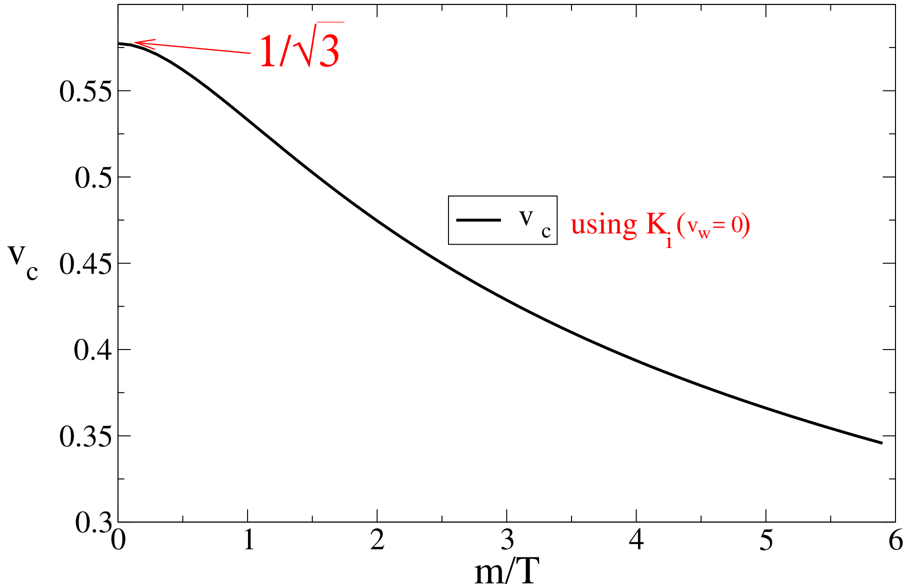
Define $w = (\mu, u)$; fluid equations take matrix form

$$\underbrace{Aw' - (m^2)'Bw}_{\text{Liouville terms}} = \underbrace{S}_{\text{source term}} + \underbrace{Cw}_{\text{collision terms}}$$

with

$$A = \begin{pmatrix} v_w K_1 & 1 \\ -K_4 & -v_w \end{pmatrix}, \qquad K_i = K_i(v_w, m/T)$$

Diffusion breaks down if $\det A \to 0$; this defines critical wall speed v_c:



Common approximation: evaluate K_i at $v_w = 0$. At $m/T = 0$, $K_1 \to 1$, $K_4 \to 1/3$, $v_c = 1/\sqrt{3}$.

This may have reinforced the "lore"

But if we keep the full v_w-dependence of K_i, we get the right answer, $v_c = 1$!

Explicit ansatz problem

The first papers did choose explicit form for δf

(Joyce, Prokopec, Turok hep-ph/9410282; Moore, Prokopec hep-ph/9506475):

$$f(\vec{p},\vec{x},t) = \frac{1}{e^{\beta(\gamma(E-\vec{v}\cdot\vec{p}))-\mu} \pm 1}$$

with three perturbations: $w = (\mu, \delta T/T, v)$, In the $m/T \to 0$ limit, the A matrix is

$$A \equiv \begin{pmatrix} v_w c_2 & v_w c_3 & \frac{1}{3}c_3 \\ v_w c_3 & v_w c_4 & \frac{1}{3}c_4 \\ \frac{1}{3}c_3 & \frac{1}{3}c_4 & \frac{1}{3}v_w c_4 \end{pmatrix}; \quad c_2 = \tfrac{1}{6},\ c_3 = \frac{9\zeta(3)}{4\pi^2},\ c_4 = \frac{7\pi^2}{60}$$

Singular at $v_w = {}^1\!/\!\sqrt{3}$! Origin of the "lore."

This is still the standard practice for computing CP-even perturbations, needed to find properties of the bubble wall (friction, wall speed and shape).

Full fluid equation network

We correct the results of Fromme, Huber hep-ph/0604159; most coefficient functions K_i are revised, some new ones added

$$\begin{aligned}
&3v_w K_{1,t}\mu'_{t,2} + 3v_w K_{2,t}(m_t^2)'\mu_{t,2} + 3u'_{t,2} \\
&-3\Gamma_y(\mu_{t,2}+\mu_{t^c,2}+\mu_{h,2}) - 6\Gamma_m(\mu_{t,2}+\mu_{t^c,2}) - 3\Gamma_W(\mu_{t,2}-\mu_{b,2}) \\
&-3\Gamma_{ss}[(1+9K_{1,t})\mu_{t,2}+(1+9K_{1,b})\mu_{b,2}+(1-9K_{1,t})\mu_{t^c,2}] = S'
\end{aligned}$$

$$X - 3K_{4,t}\mu'_{t,2} + 3v_w\tilde{K}_{5,t}u'_{t,2} + 3v_w\tilde{K}_{6,t}(m_t^2)'u_{t,2} + 3\Gamma_t^{tot}u_{t,2} = S_t$$

$$\begin{aligned}
&3v_w K_{1,b}\mu'_{b,2} + 3u'_{b,2} \\
&-3\Gamma_y(\mu_{b,2}+\mu_{t^c,2}+\mu_{h,2}) - 3\Gamma_W(\mu_{b,2}-\mu_{t,2}) \\
&-3\Gamma_{ss}[(1+9K_{1,t})\mu_{t,2}+(1+9K_{1,b})\mu_{b,2}+(1-9K_{1,t})\mu_{t^c,2}] = 0
\end{aligned}$$

$$-3K_{4,b}\mu'_{b,2} + 3v_w\tilde{K}_{5,b}u'_{b,2} + 3\Gamma_b^{tot}u_{b,2} = 0$$

$$\begin{aligned}
&3v_w K_{1,t}\mu'_{t^c,2} + 3v_w K_{2,t}(m_t^2)'\mu_{t^c,2} + 3u'_{t^c,2} \\
&-3\Gamma_y(\mu_{t,2}+\mu_{b,2}+2\mu_{t^c,2}+2\mu_{h,2}) - 6\Gamma_m(\mu_{t,2}+\mu_{t^c,2}) \\
&-3\Gamma_{ss}[(1+9K_{1,t})\mu_{t,2}+(1+9K_{1,b})\mu_{b,2}+(1-9K_{1,t})\mu_{t^c,2}] = S'
\end{aligned}$$

$$X - 3K_{4,t}\mu'_{t^c,2} + 3v_w\tilde{K}_{5,t}u'_{t^c,2} + 3v_w\tilde{K}_{6,t}(m_t^2)'u_{t^c,2} + 3\Gamma_t^{tot}u_{t^c,2} = S_t$$

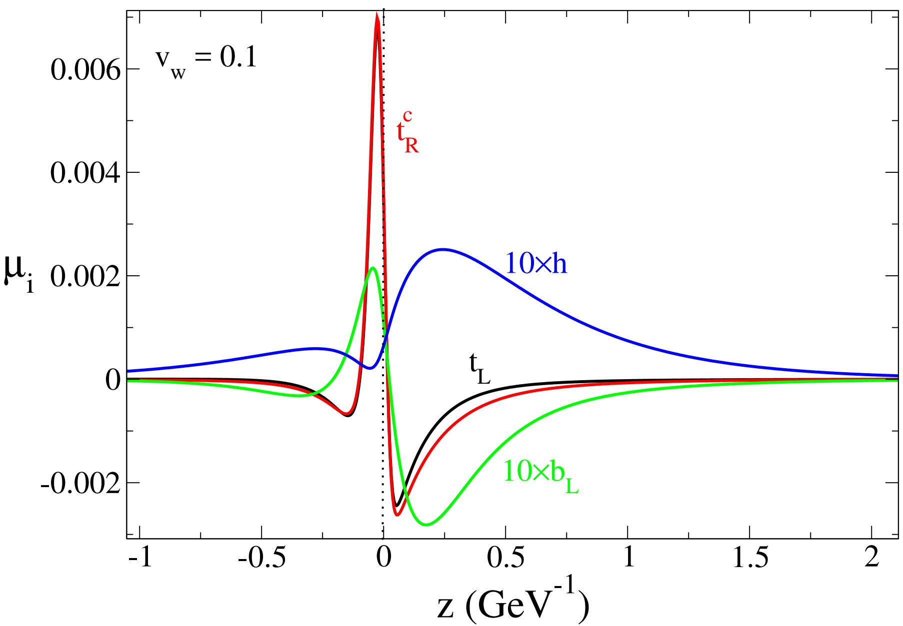
$$\begin{aligned}
&4v_w K_{1,h}\mu'_{h,2} + 4u'_{h,2} \\
&-3\Gamma_y(\mu_{t,2}+\mu_{b,2}+2\mu_{t^c,2}+2\mu_{h,2}) - 4\Gamma_h\mu_{h,2} = 0
\end{aligned}$$

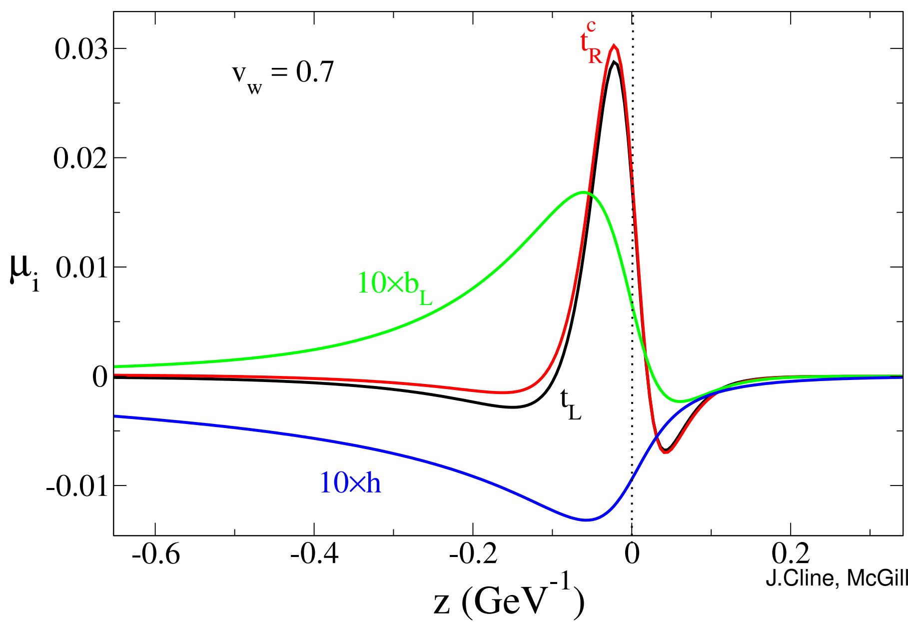
$$-4K_{4,h}\mu'_{h,2} + 4v_w\tilde{K}_{5,h}u'_{h,2} + 4\Gamma_h^{tot}u_{h,2} = 0.$$

X = new $O(v_w)$ m' correction

S′ = new $O(v_w^2)$ source term

$$S_t = -v_w K_8(m_t^2\theta_t')' + v_w K_9\theta_t' m_t^2 (m_t^2)'.$$





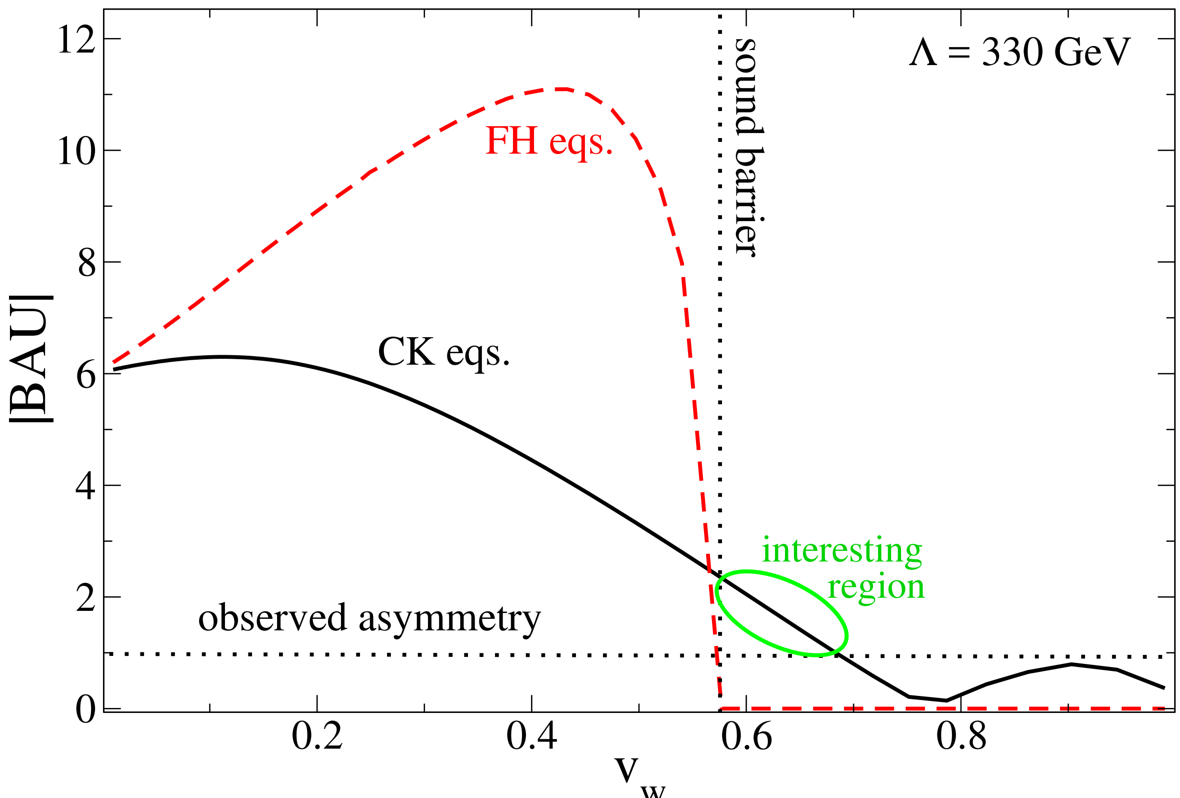
The baryon asymmetry

Integrating the sphaleron rate equation gives

$$\eta_B = \frac{405\,\Gamma_{\rm sph}}{4\pi^2 v_w \gamma_w g_* T} \int dz\, \mu_{B_{\rm L}} f_{\rm sph}\, e^{-45\Gamma_{\rm sph}|z|/4v_w\gamma_w}$$

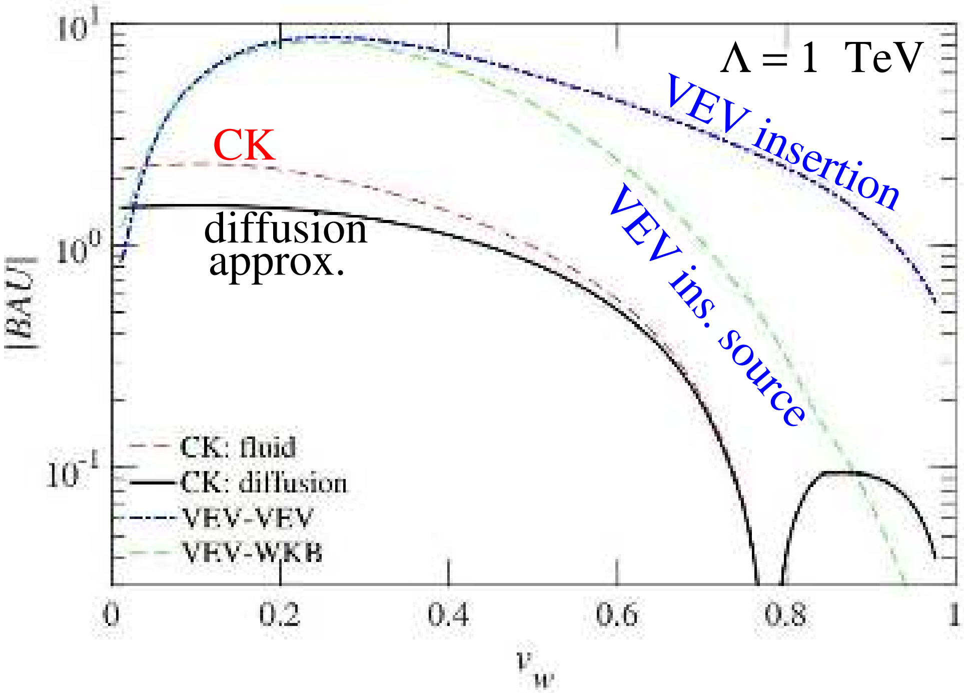
with strong sphalerons relating $\mu_{u,d,s,c}$ to $\mu_{t,b}$:

$$\mu_{B_L} = \tfrac{1}{2}(1+4D_0^t)\mu_{t_L} + \tfrac{1}{2}(1+4D_0^b)\mu_{b_L} + 2D_0^t\mu_{t_R}.$$



Dependence of BAU on v_w

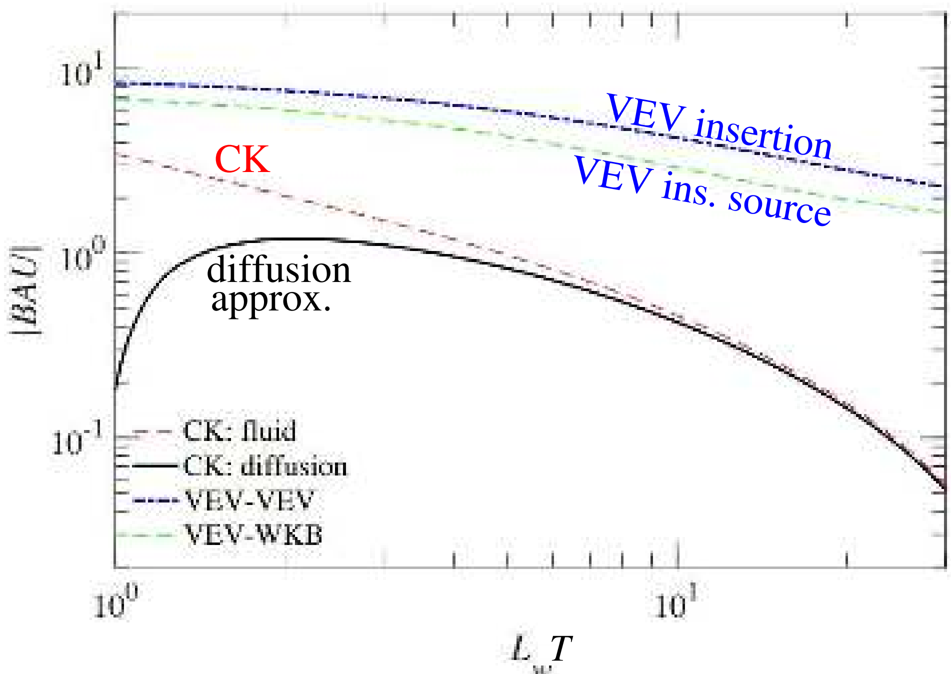
Other comparisons



Diffusion approximation: integrate out u to get second order equation for μ alone

VEV insertion formalism uses different source and diffusion equations.

VEV insertion source + our equations still overestimates BAU



Dependence on wall thickness (in units of $1/T$)

Conclusions

EWBG is a testable framework for baryogenesis. LHC continues to put pressure on allowed models, but possiblities still exist.

Strong 1st order transitions naturally favor high wall speeds, which also tend to produce observable gravity waves.

Improved transport equations make EWBG feasible for supersonic walls, although challenging to get large enough BAU

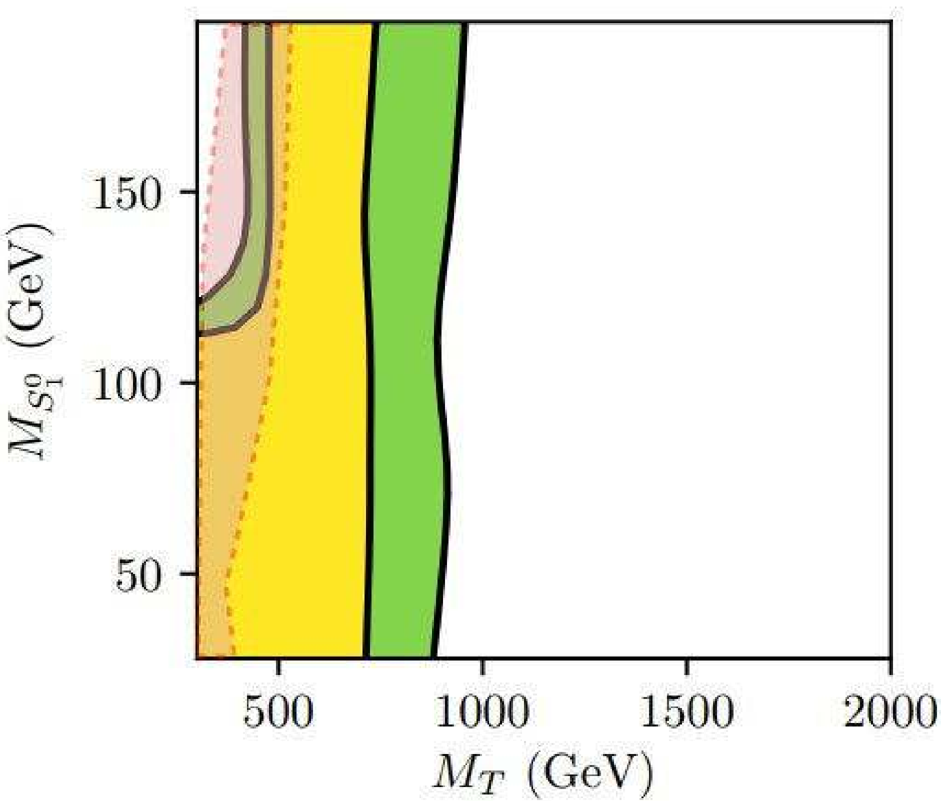
These improvements should be applied to the CP-even fluid perturbations, to see how they may effect the microscopically computed wall properties (especially v_w and L_w)

Collision terms should be reevaluated. Some date back to 1996!

Extra slides

LHC limit on top partner

ATLAS and CMS constraint vectorlike top-quark partner mass $> 1\,\mathrm{TeV}$ if $T \to Zt$ or $T \to ht$ dominates. In our model, $T \to st$ dominates, and $s \to gg$ is main singlet decay channel.



Recasting of previous limits by 2002.12220 gives $M_T \gtrsim 700\,\mathrm{GeV}$