# Progress in Electroweak Baryogenesis

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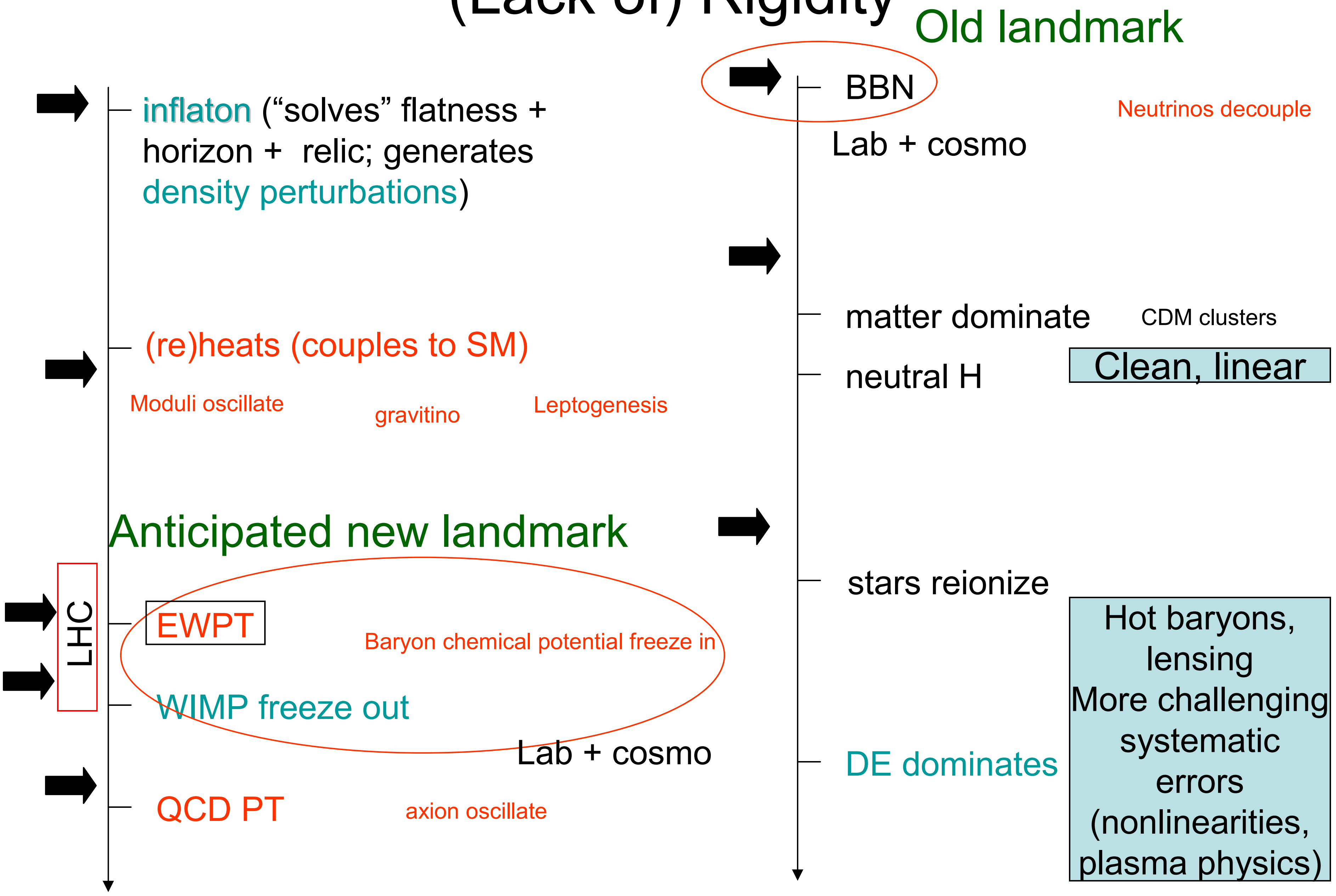
# Electroweak Baryogenesis References

- Incomplete list of ewbgenesis people:

  Ambjorn, Arnold, Ashoorion, Baek, Blum, Bochkarev, Bodeker, Brhlik, Carena, Chang, Cirigliano, Cline, Cohen, Davies, Davoudiasl, de Carlos, Dine, Dolan, Elmfors, Enqvist, Espinosa, Farrar, Froggatt, Gavela, Garbrecht, Giudice, Good, Grasso, Grinstein, Grojean, Hernandez, Huet, Huber, Jakiw, Jansen, Joyce, Kane, Kainulainen, Kajantie, Kaplan, Keung, Khlebnikov, Klinkhamer, Ko, Kolb, Konstandin, **Kuzmin**, Laine, Langacker, Lee, Linde, Liu, Losada, Menon, Moore, Moorhouse, Moreno, Morrissey, Multamaki, Murayama, Nelson,Nir, No, Olive, Orloff, Oaknin, Pietroni, Quimbay, Quiros, Pene, Pierce, Pilaftsis, Prokopec, Profumo, Rajagopal, Ramsey-Musolf, Ringwald, Riotto, **Rubakov**, Rummukainen, Sather, Schmidt, Seco, Senaha, Servant, **Shaposhnikov**, Shaughnessy, Singleton, Thomas, Tkachev, Trodden, Trott, Tsypin, Tulin, Turok, Vilja, Vischer, Wagner, Westphal, Weinstock, Wells, Worah, Yaffe...

- Some overview references
  - hep-ph/0609145
  - hep-ph/0312378
  - hep-ph/0303065
  - hep-ph/0208043
  - hep-ph/0006119
  - hep-ph/9901362
  - hep-ph/9901312
  - hep-ph/9802240

# (Lack of) Rigidity



inflaton ("solves" flatness + horizon + relic; generates density perturbations)

(re)heats (couples to SM)

Moduli oscillate

gravitino

Leptogenesis

Anticipated new landmark

LHC

EWPT

Baryon chemical potential freeze in

WIMP freeze out

Lab + cosmo

QCD PT

axion oscillate

Old landmark

BBN

Neutrinos decouple

Lab + cosmo

matter dominate

CDM clusters

neutral H

Clean, linear

stars reionize

Hot baryons, lensing
More challenging systematic errors (nonlinearities, plasma physics)

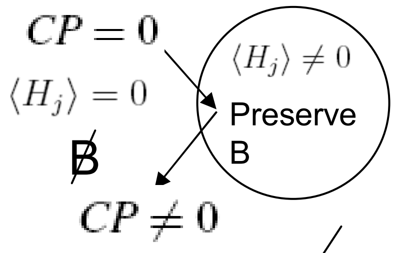
DE dominates

# Implications of EWPT?

- Electroweak Baryogenesis: Bubble plasma dynamics
  - Good: Overconstraint possible
  - Bad: 1 number, mild tuning of parameters
- Leptogenesis: B-L to B conversion
  - Good: Connection to a lot of “natural” UV physics
  - Bad: Overconstraint unlikely
- Gravity Waves: Bubble stirs up fluid
  - Good: Overconstraint possible
  - Bad: Measurability is uncertain
- DM: Freeze out physics can be affected
  - Good: Overconstraint possible
  - Bad: narrow parametric window
- CC: IR contribution
  - Good: Overconstraint possible
  - Bad: narrow parametric window, and dependence on multiple discoveries
- Clustering: too small scale and effects easily washed out

# Electroweak Bgenesis

[Kuzmin, Rubakov, Shaposhnikov 85]



$CP = 0$

$\langle H_j \rangle = 0$

$\cancel{B}$

$CP \neq 0$

$\langle H_j \rangle \neq 0$

Preserve B

1st order PT

1) Bubble nucleate

2) CP violating scattering in bubble → source of CP asymmetry

3) CP charge diffuse out in front of bubble generating B through sphalerons

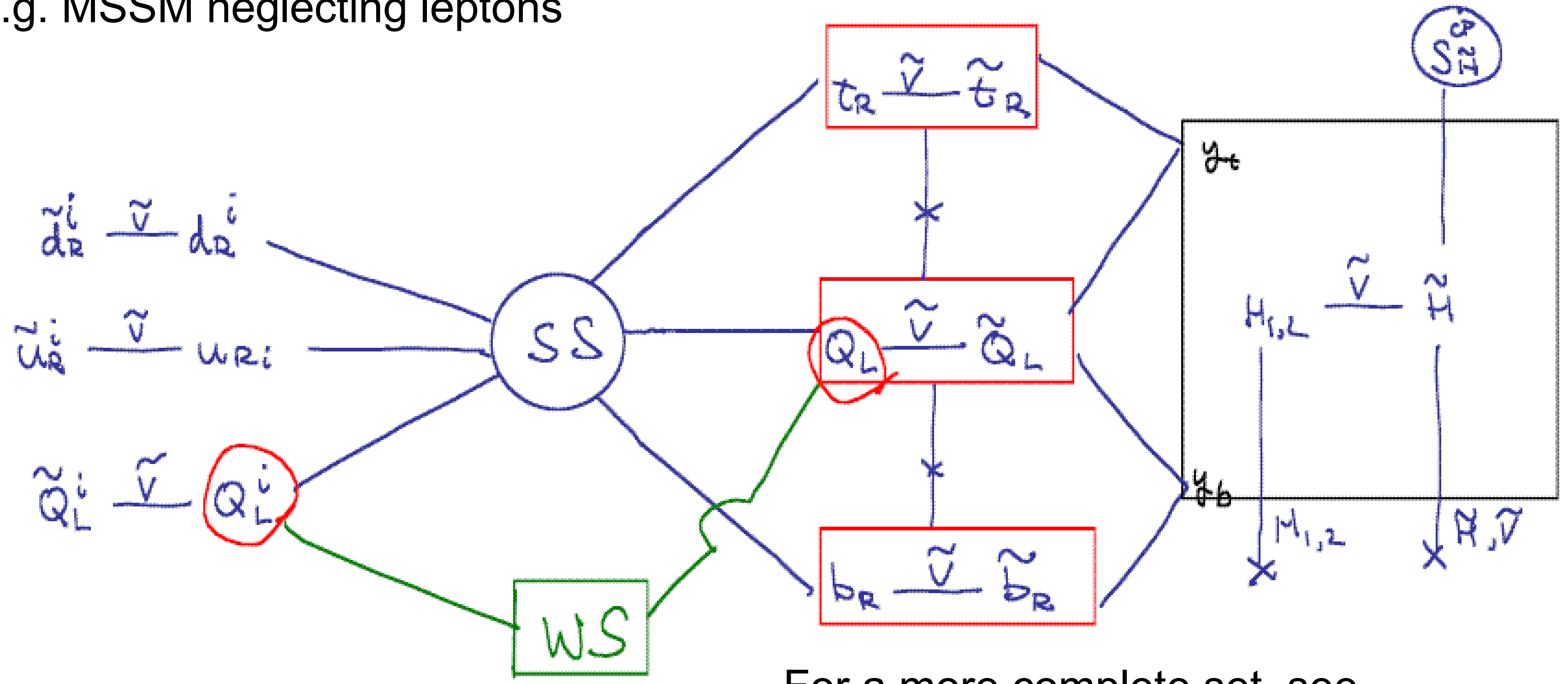
4) True vacuum phase captures the B-asymmetry created

$\cancel{CP}$

$\langle \sigma v \rangle$

1st order EWSB

e.g. MSSM neglecting leptons

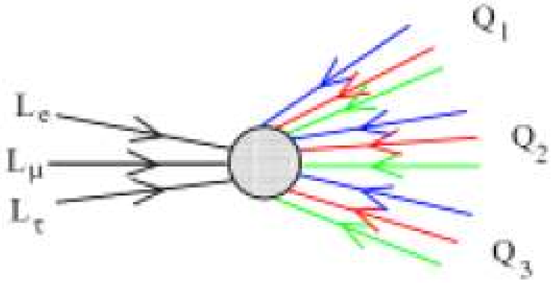


For a more complete set, see
[DC, Garbrecht, Ramsey-Musolf, Tulin 09]

# Ingredient 1

- Universe reheats to a high enough temperature such that B-violating sphalerons are unsuppressed:

[Kuzmin, Rubakov, Shaposhnikov 85; Arnold, McLerran 87;
Bodeker, Moore, Rummukainen 00]



$$\Gamma_{\mathrm{WS}\ v=0} \sim \underset{\substack{\uparrow \\ O(10)\alpha_W^5}}{10^{-5}} T$$

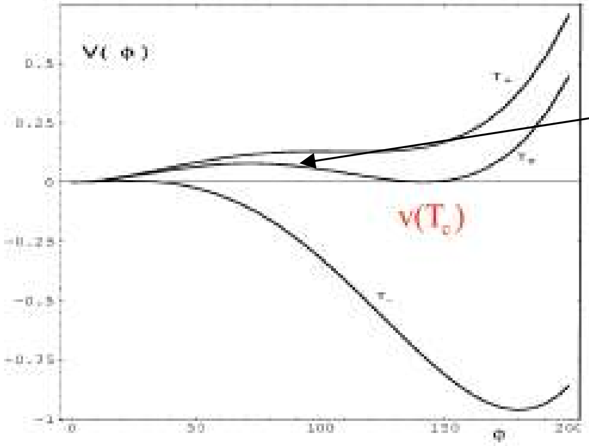
Plausible since low scale inflationary models are more fine tuned.

Note the smallness of baryon number comes partly from $10^{-5}$

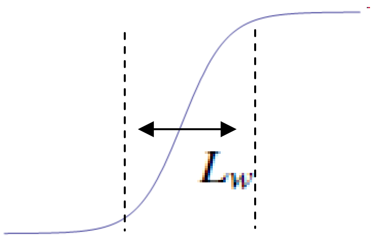
# Ingredient 2

- Bubble nucleation from EWSB sector or concurrently from another sector as long as bubble percolation completes nearly simultaneously:

e.g. [Moreno, Quiros, Seco 98; John, Schmidt 00; Moore 00; Csikor, Fodor, Hegedus, Jakovac, Katz, Piroth 00]



Barrier determines $L_w$



[Dine, Leigh, Huet, Linde, Linde 92]

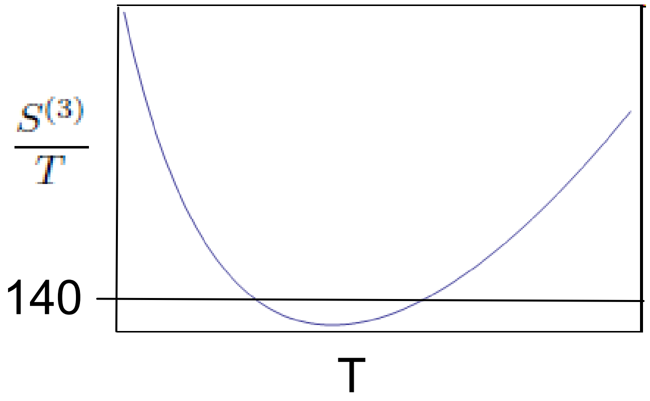
$$\frac{S^{(3)}}{T} \approx 13.7 \frac{\mathcal{E}}{T} \left(\frac{\alpha}{\lambda}\right)^{3/2} f(\alpha)$$

$$f(\alpha) \equiv 1 + \frac{\alpha}{4}\left(1 + \frac{2.4}{1-\alpha} + \frac{0.26}{(1-\alpha)^2}\right)$$

$$\alpha(T) = \alpha_0(1 - T^2/T_0^2)$$

$$T_0 = \sqrt{\frac{-M^2}{2c}} \qquad \alpha_0 \equiv \lambda M^2/2\mathcal{E}^2$$

Bubble action not monotonic.



# Ingredient 3

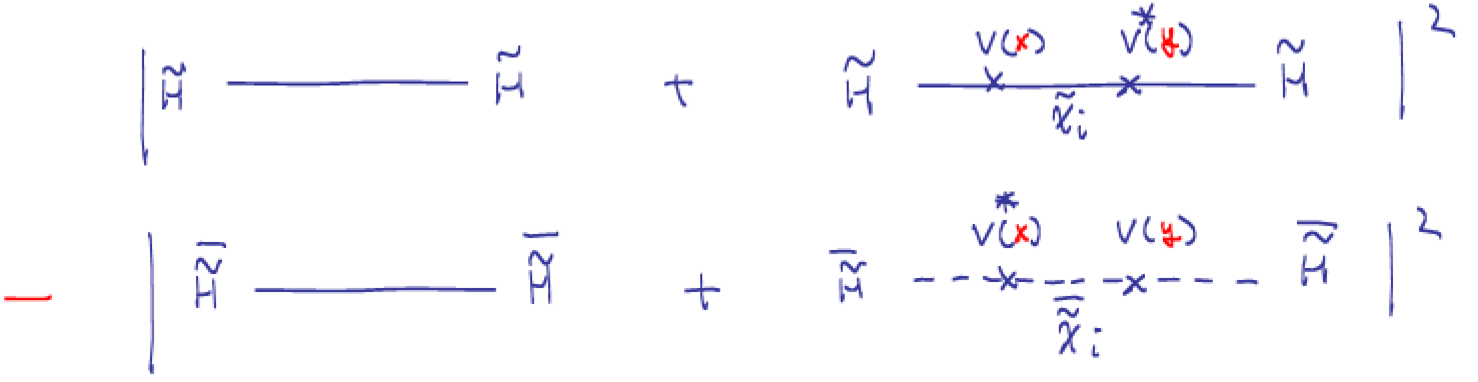
- Unsuppressed bubble (i.e. $\phi = v(t, \vec{x})$ ) coupling to CP violating physics.

e.g. one popularly considered source in MSSM

Physics: local mass eigenstates do not remain mass eigenstates over $L_w$

VEV insertion approx [Riotto 96; Carena, Quiros, Riotto, Vilja, Wagner 97]

$$V(x) \equiv v_2(x) - \frac{\mu}{|\mu|} v_1(x)$$

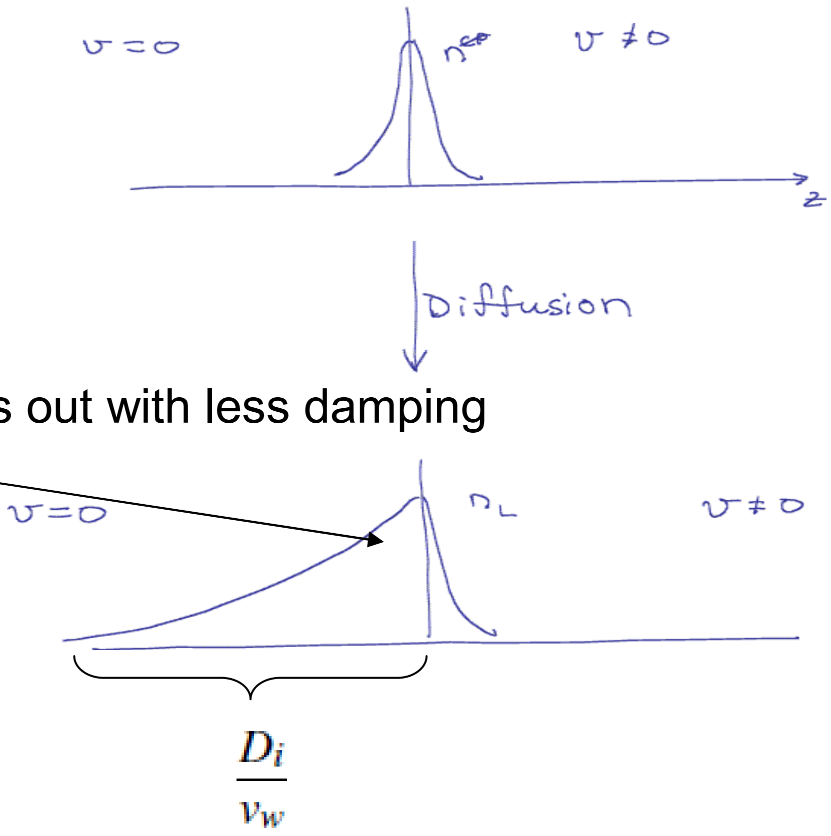


$$\propto \boxed{\alpha_i} \, \mathrm{Im}(\mu M_i) \underbrace{\left[v_1(y) v_2(x) - v_1(x) v_2(y)\right]}_{v_w \beta'(z) v^2(x)}$$

CP asymmetry carriers must be thermally populated.

# Ingredient 4

- Efficient diffusion is useful [Cohen et al 94; Joyce, Prokopec, Turok 94]



More charge gets out with less damping

$$D_i \sim \frac{1}{\Gamma_i}\frac{\langle \frac{p_z^2}{E^2}\frac{\partial f_0}{\partial E}\rangle}{\langle \frac{\partial f_0}{\partial E}\rangle} \longrightarrow$$

Weakly interacting CP asymmetry carrier.
(Higgs compared to quarks)

# Ingredients 5 & 6

- Efficient transfer of CP asymmetry to the B-violating sector
e.g. MSSM and similar scenarios: top Yukawa

also $y_b$ for $\tan\beta \gtrsim 5$

even $y_\tau$ for $\tan\beta \gtrsim 15$

[DC, Garbrecht, Ramsey-Musolf, Tulin, 08,09]

- Strong enough phase transition to prevent wash-out

Fixed by
T=0 VEV

$$\Gamma = A(T)\exp\left[-E^{sph}(T)/T\right] \longrightarrow \frac{v(T_c)}{T_c} \gtrsim 1$$

What class of
models have
$T_c \to 0$ ?

Requires O(0.1) parametric tuning/hierarchy

Mass about origin.

$$T_c \sim \frac{M_{\text{scalar}}}{O(y/5)} \longrightarrow \boxed{M_{\text{scalar}} \ll v}$$

NOT the scalar mass at T=0

Can utilize approximate discrete symmetry to guide parametric tuning.

[DC, Long 10] Pragmatic also for big field space dimension (e.g.8).

# Enhanced Symmetry

e.g. 1D

$$V(\phi,T) \approx \left[\frac{M^2}{2} + c_1 T^2\right]\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4$$

At T= $T_c$

$$V(\phi,T_c) = \frac{\phi^2}{4\lambda}(\lambda\phi - 2E)^2$$

At this temperature there is an enhanced $\mathbb{Z}_2$ symmetry:

$$\phi \longrightarrow -\phi + \frac{2E}{\lambda}$$

Choose a parameter to build in this enhanced symmetry at T=0.

$$\frac{\langle\phi(T_c)\rangle}{T_c} \longrightarrow \infty$$

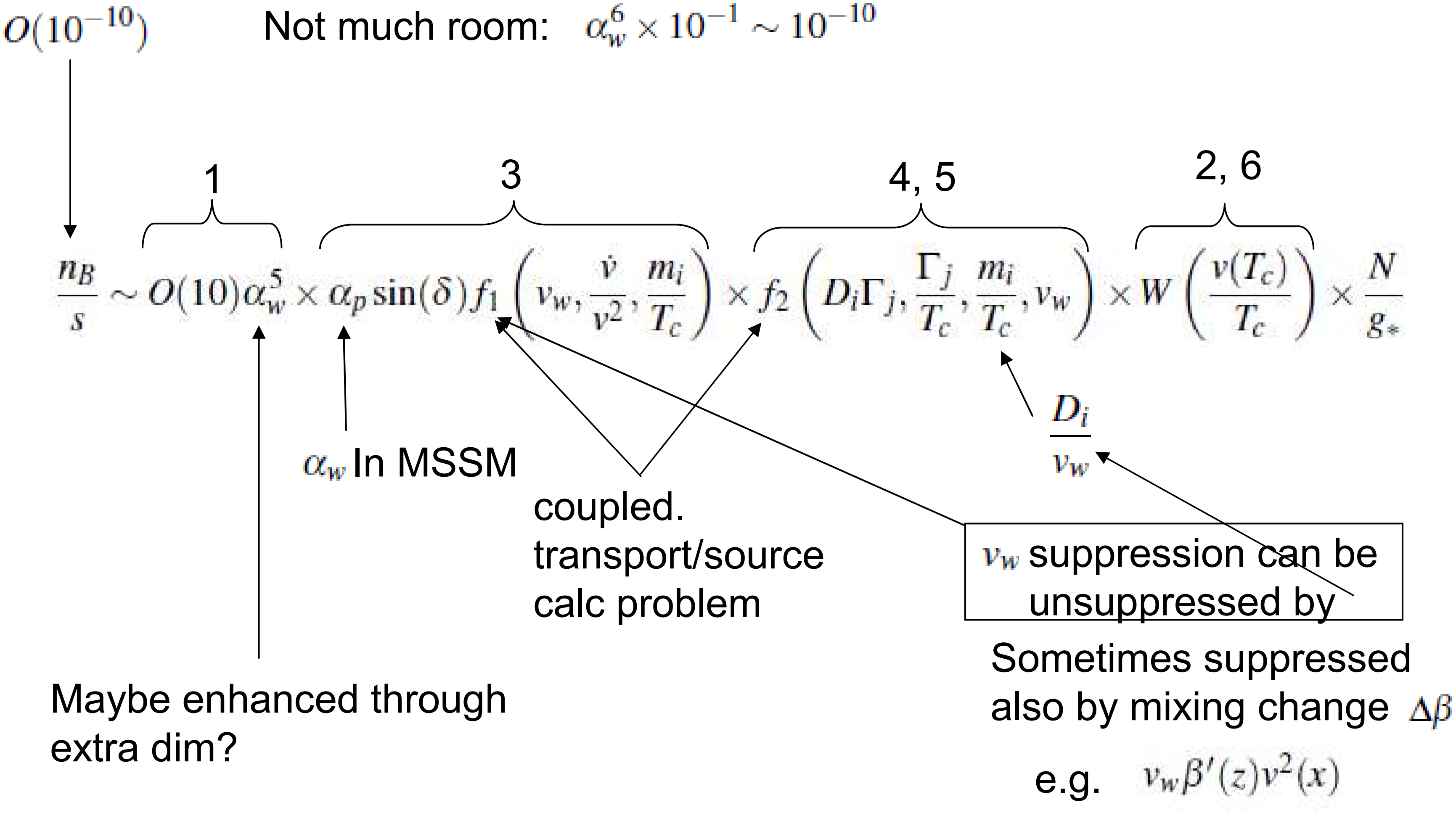
$T_c \to$ 0 when $E = \sqrt{\frac{\lambda}{2}}M$

Ideal parametric point!

Note even in the non-renormalizable operator scenario, there is a symmetry.

BSM ingredients (blue = not  generic without singlets; red = tuned):

1) High T; 2) bubbles nucleate; 3) bubble coupling to CPV; 4) efficient diffusion;
5) CP charge → quarks + leptons;
6) B-violating sphaleron suppression in broken phase



$O(10^{-10})$ Not much room: $\alpha_w^6 \times 10^{-1} \sim 10^{-10}$

$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

$\alpha_w$ In MSSM

coupled.
transport/source
calc problem

$\frac{D_i}{v_w}$

$v_w$ suppression can be
unsuppressed by

Sometimes suppressed
also by mixing change $\Delta\beta$

e.g. $v_w\beta'(z)v^2(x)$

Maybe enhanced through
extra dim?

BSM ingredients (blue = not generic without singlets; red = tuned):

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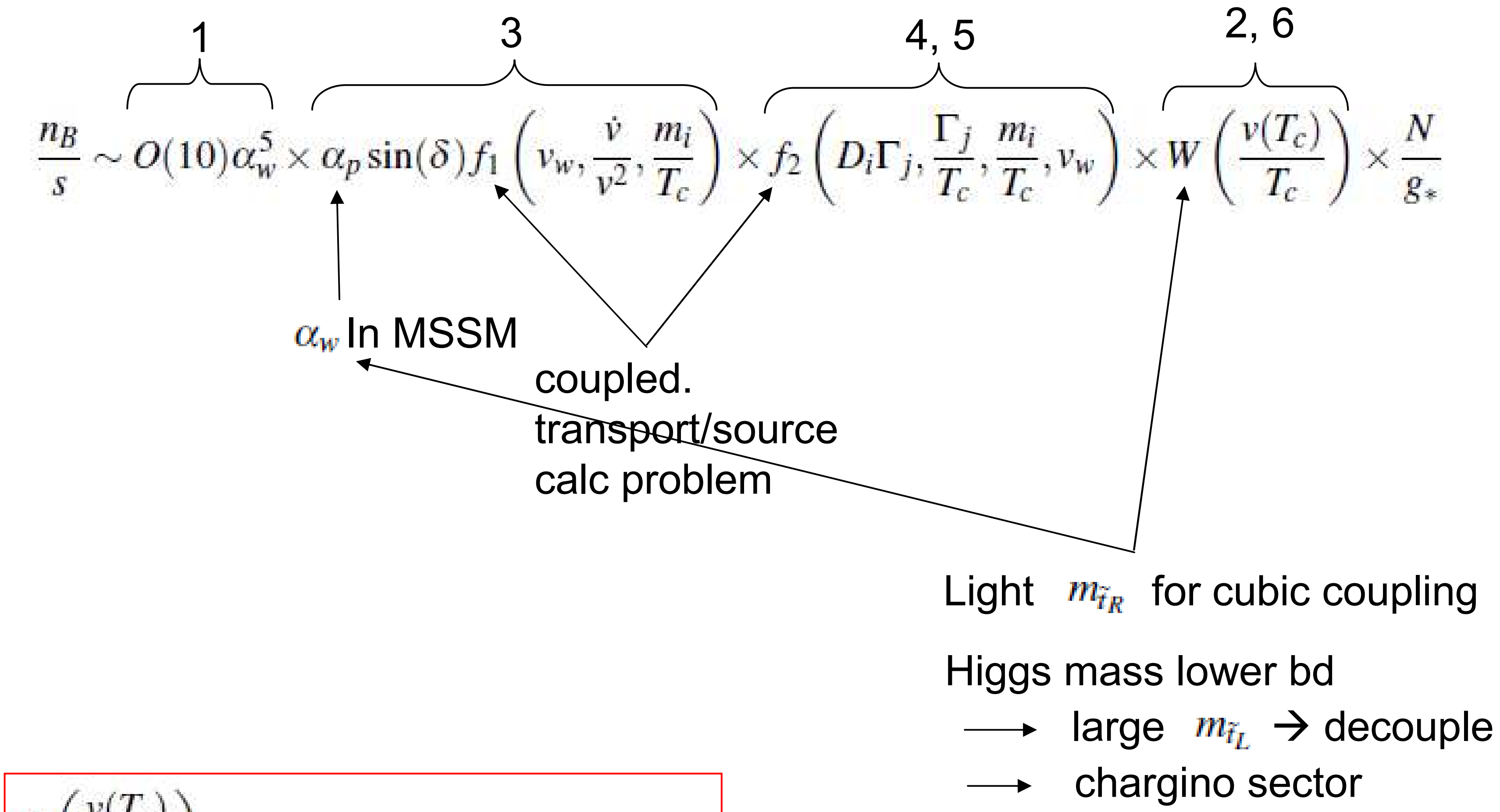
6) B-violating sphaleron suppression in broken phase



$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

$\alpha_w$ In MSSM

coupled.
transport/source
calc problem

Light $m_{\tilde{t}_R}$ for cubic coupling

Higgs mass lower bd

→ large $m_{\tilde{t}_L}$ → decouple

→ chargino sector

$W\left(\frac{v(T_c)}{T_c}\right)$ corners parameter spaces.

BSM ingredients (blue = not generic without singlets; red = tuned):

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coupled.
transport/source
calc problem

Enlarge param space with singlets [ Anderson and Hall 92; Pietroni 93; many others since then]

Nonrenormalizable ops [e.g. Zhang 93; Grojean, Servant, Wells 04; …; Blum, Nir 08]

BSM ingredients (blue = not generic without singlets; red = tuned):

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coupled.
transport/source
calc problem

Where the phase occurs allows weaker EDM
bounds either through coupling suppression
or sector sequestering and/or spontaneous CP violation.

[e.g. recently in sMSSM (4 SM singlets + 2 doublets) Kang, Langacker, Li, Liu 09]

BSM ingredients (blue = not generic without singlets; red = tuned):

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$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\,5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\,6} \times \frac{N}{g_*}$$

Picture that emerges:
1) The scalar sector will be non-minimal in either d.o.f. and/or physics.

2) Either by discrete symmetry or accidental cancellation (0.1 tuning)

$$\frac{v(T_c)}{T_c} \gtrsim 1$$

3) CP violation sector is either secluded or we will see EDMs if we continue to push experimental sensitivity.

$$\alpha_w^6 \times 10^{-1} \sim 10^{-10}$$

$$\overset{O(10^{-10})}{\downarrow}$$

$$\frac{n_B}{s} \sim \overbrace{O(10)\alpha_w^5}^{1} \times \overbrace{\alpha_p \sin(\delta) f_1\left(v_w, \frac{\dot{v}}{v^2}, \frac{m_i}{T_c}\right)}^{3} \times \overbrace{f_2\left(D_i\Gamma_j, \frac{\Gamma_j}{T_c}, \frac{m_i}{T_c}, v_w\right)}^{4,\ 5} \times \overbrace{W\left(\frac{v(T_c)}{T_c}\right)}^{2,\ 6} \times \frac{N}{g_*}$$

coupled.
transport/source
calc problem

A popularly discussed
source of technical
challenges

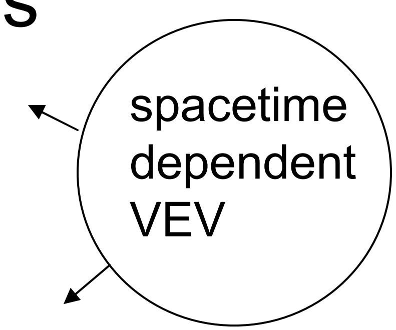
[Riotto 96; Carena, Quiros, Riotto, Vilja, Wagner 97; Carena, Moreno, Quiros, Seco, Wagner 00; Prokopec, Schmidt, Weinstock 01, 03; Kainulainen, Prokopec, Schmidt, Weinstock 01; Konstandin, Prokopec, Schmidt 04; Huber, Konstandin, Prokopec, Schmidt 06; …]

# Theoretical Uncertainties

Transport challenges:

1) spatially inhomogeneous
2) out of equilibrium
3) messy thermal kinematics
4) many order 1 effects
5) BSM can have large number of dof

$\langle j^{\mu}(x)\rangle$



Approximations involve expansions that can be subtle:

$$\partial_\mu \langle j^{\mu}(x)\rangle = \int d^4 z\, \underbrace{\left[\Pi^{>}(x,z)\Delta^{<}(z,x) - \Delta^{>}(x,z)\Pi^{<}(z,x) + \Delta^{<}(x,z)\Pi^{>}(z,x) - \Pi^{<}(x,z)\Delta^{>}(z,x)\right]}_{\text{Collisions and mixing}}$$

Ideally, want to begin with above

$$v_w \partial_z n_{\tilde{H}} - D_{\tilde{H}} \partial_z^2 n_{\tilde{H}} = -\Gamma_Y \left(\frac{n_{\tilde{H}}}{k_{\tilde{H}}} - \frac{n_t}{k_t} + \frac{n_{\tilde{q}}}{k_{\tilde{q}}}\right) + S_{\tilde{H}}^{CPV} + \ldots$$

# Theoretical Uncertainties

Transport challenges:

1) spatially inhomogeneous
2) out of equilibrium
3) messy thermal kinematics
4) many order 1 effects
5) BSM can have large number of dof

$\langle j^\mu(x)\rangle$

spacetime dependent VEV

Approximations involve expansions that can be subtle:

$$\partial_\mu \langle j^\mu(x)\rangle = \int d^4z\, \underbrace{\left[\Pi^>(x,z)\Delta^<(z,x) - \Delta^>(x,z)\Pi^<(z,x) + \Delta^<(x,z)\Pi^>(z,x) - \Pi^<(x,z)\Delta^>(z,x)\right]}_{\text{Collisions and mixing}}$$

Ideally, want to begin with above

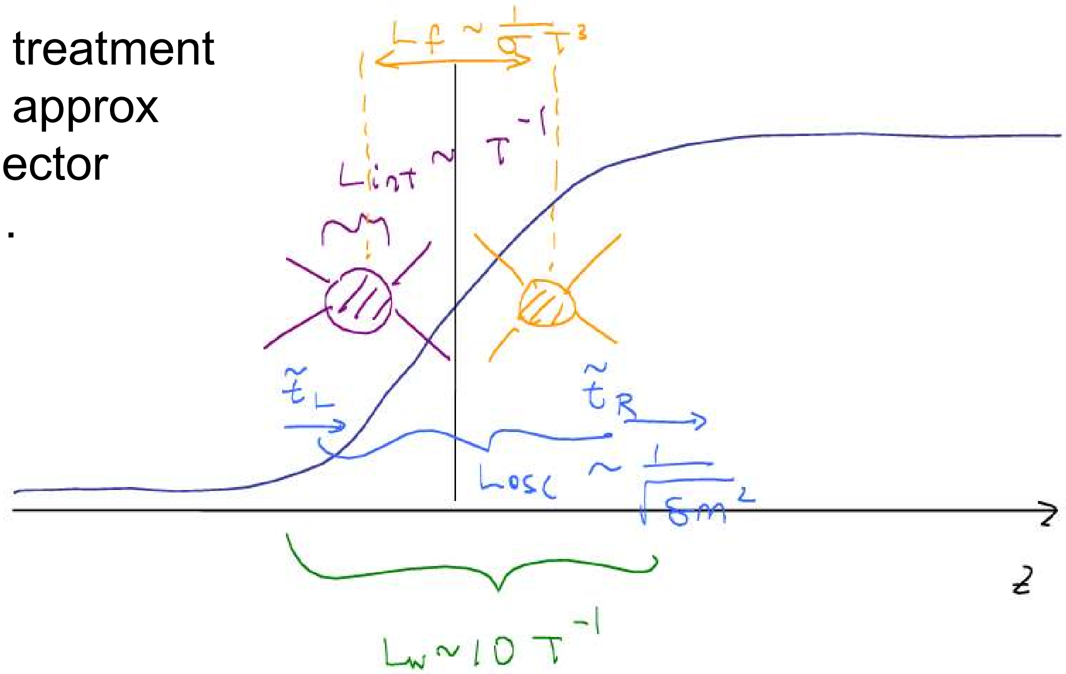
approximations sometimes very uncertain

$$v_w\partial_z n_{\tilde H} - D_{\tilde H}\partial_z^2 n_{\tilde H} = -\Gamma_Y\left(\frac{n_{\tilde H}}{k_{\tilde H}} - \frac{n_t}{k_t} + \frac{n_{\tilde q}}{k_{\tilde q}}\right) + S_{\tilde H}^{CPV} + \ldots$$

e.g. Resonant regime in MSSM

[Cirigliano, Lee , Tulin 11] improves upon an aspect of the work by [Konstandin, Prokopec, Schmidt, Seco 05]

Numerical treatment
with fewer approx
in a stop sector
toy model..



$$\varepsilon_{\text{coll}} \equiv \frac{L_{\text{int}}}{L_f}$$

$$\varepsilon_{\text{wall}} \equiv \frac{L_{\text{int}}}{L_w}$$

$$(u \cdot \partial_x + \mathbf{F} \cdot \nabla_{\mathbf{k}})\, f_m(\mathbf{k}, x) \;=\; -\,[i\,\omega_{\mathbf{k}} + u \cdot \Sigma,\; f_m(\mathbf{k}, x)] + \mathscr{C}_m[f_m, \bar{f}_m](\mathbf{k}, x)$$

$$\left[\Sigma, f\right] = \begin{pmatrix} \Sigma_{12} f_{21} - \Sigma_{21} f_{12} & -\Sigma_{12}\left(f_{11} - f_{22}\right) + \left(\Sigma_{11} - \Sigma_{22}\right) f_{12} \\ \Sigma_{21}\left(f_{11} - f_{22}\right) - \left(\Sigma_{11} - \Sigma_{22}\right) f_{21} & \Sigma_{21} f_{12} - \Sigma_{12} f_{21} \end{pmatrix}$$

$$\left[\Sigma, f\right]_{\text{Ref. [9]}} = \begin{pmatrix} 0 & -\Sigma_{12}\left(n_B(\omega_1) - n_B(\omega_2)\right) \\ \Sigma_{21}\left(n_B(\omega_1) - n_B(\omega_2)\right) & 0 \end{pmatrix} + \mathcal{O}(\epsilon_{\text{wall}}^2)$$

$\dfrac{\varepsilon_{\text{wall}}^2}{\varepsilon_{\text{coll}} v_w}$ unsuppresion due to integration

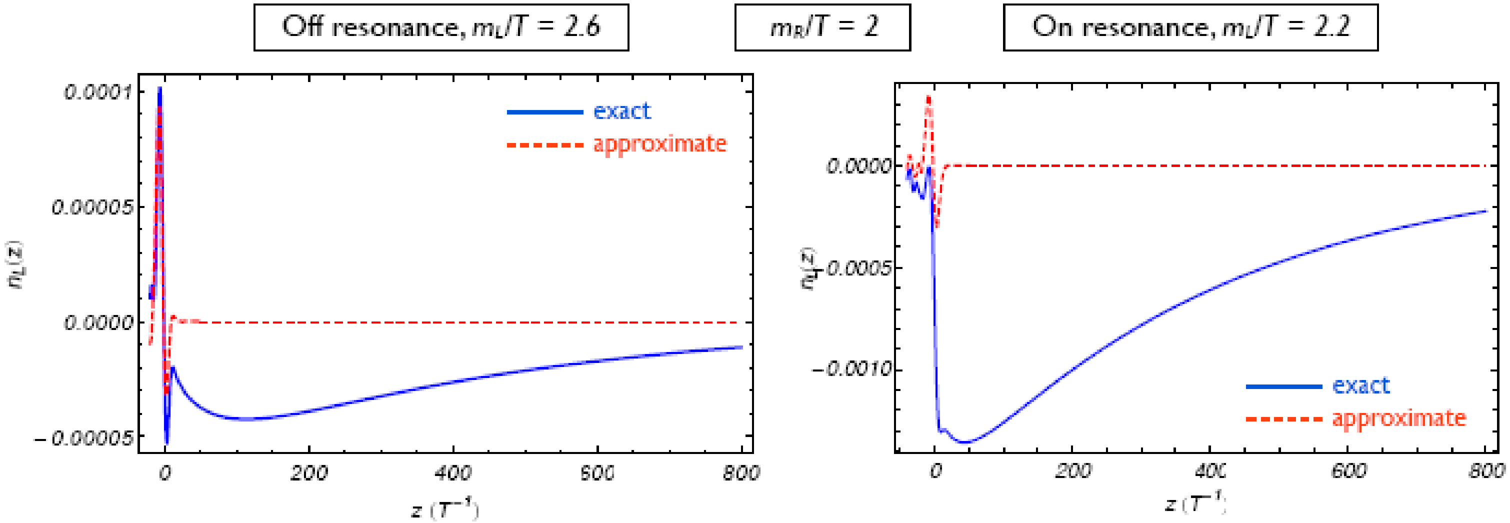


FIG. 7: *Charge density profiles* $n_L(z)$ *from the solution of the full equations (solid line) and the approximate decoupled equations (dashed line) that mimic the procedure of Ref. [9]. The left panel correspond to the off-resonance regime* $m_L/T = 2.6, m_R/T = 2$, *while the right panel corresponds to the resonant regime* $m_L/T = 2.2, m_R/T = 2$.

[Carena, Nardini, Quiros, Wagner 08]

MSSM still viable
based on more
approximate treatment.

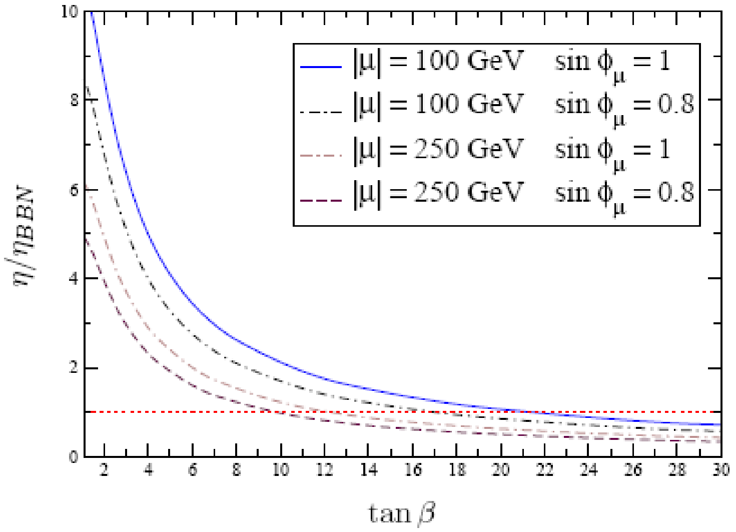


Figure 1: $\eta/\eta_{BBN}$ as function of $\tan\beta$ for several values of $\mu$ and imposing $\phi(T_H^n)/T_H^n \simeq 1$, $M_1 = M_2 = 200$ GeV, $L_w \simeq 1.7$ and $v_w \simeq 0.1$.

[Konstandin, Prokopec, Schmidt, Seco 05]

MSSM unlikely to be viable

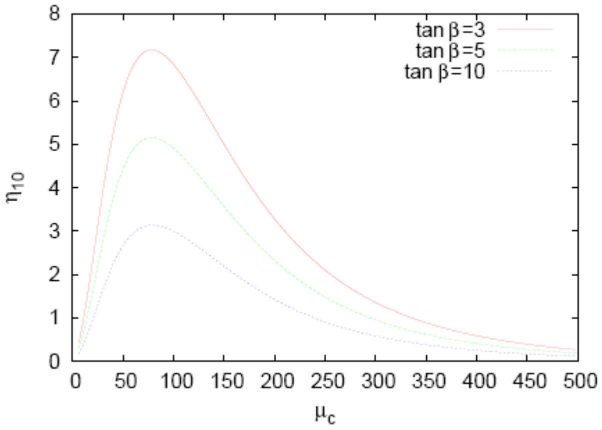
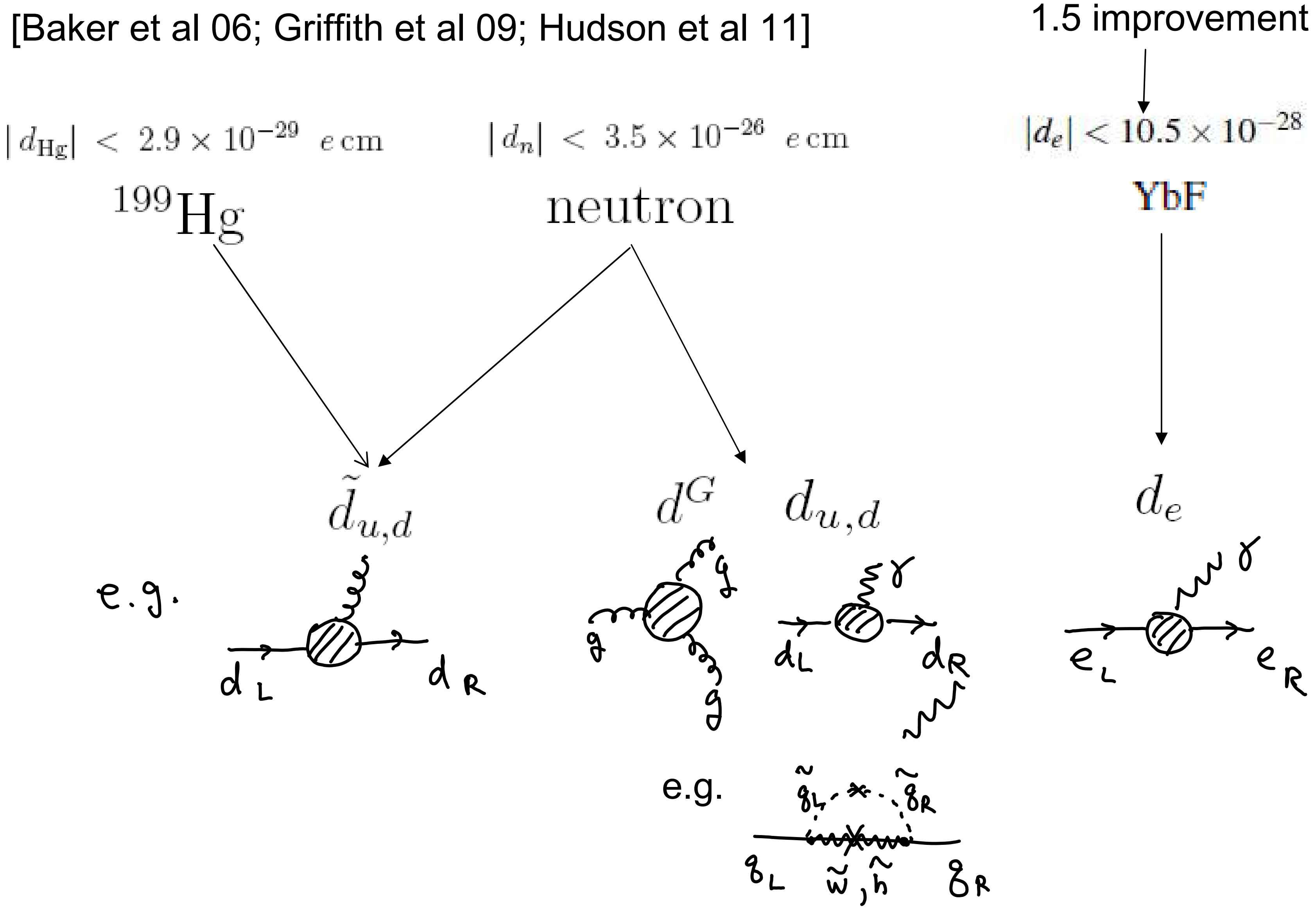


FIG. 6: This plot shows $\eta_{10} = 10^{10}\eta$ as a function of $\mu_c$, $M_2 = \mu_c - 20$ GeV, $m_A = 150$ GeV and for several values of $\tan\beta$.

Although all agree that the window is small,
Its viability is still unclear.

# EDM Constraints

[Baker et al 06; Griffith et al 09; Hudson et al 11]



1.5 improvement

$|d_{\mathrm{Hg}}| < 2.9 \times 10^{-29}\ e\,\mathrm{cm}$

$|d_n| < 3.5 \times 10^{-26}\ e\,\mathrm{cm}$

$|d_e| < 10.5 \times 10^{-28}$

$^{199}\mathrm{Hg}$

neutron

YbF

$\tilde{d}_{u,d}$

$d^G$

$d_{u,d}$

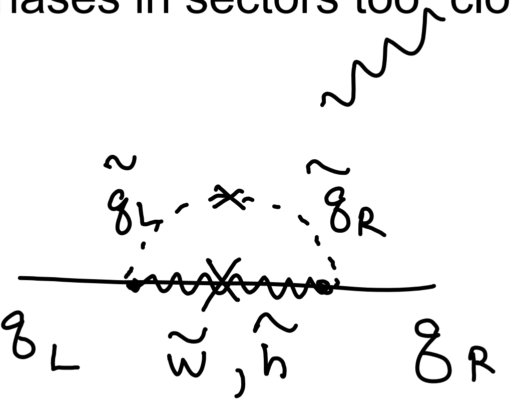
$d_e$

e.g.

e.g.

# One Loop MSSM

BSM such as MSSM has phases in sectors too “close” to the light particles.



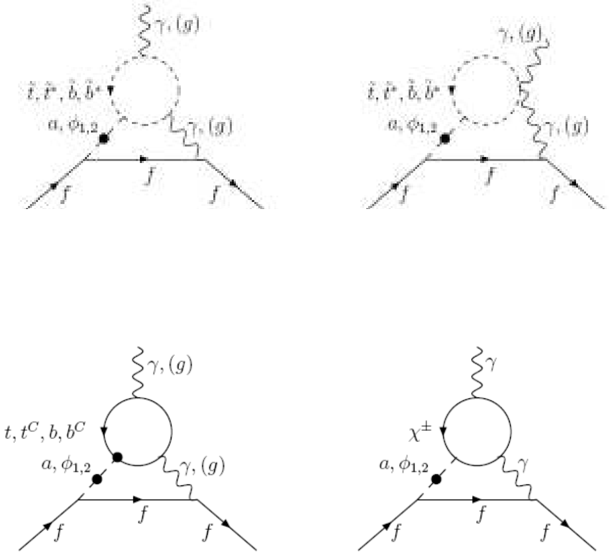
$$\left(\frac{d_{u,d}}{e}\right) \sim (10^{-25}\ \mathrm{cm}) \; \frac{\Im m(M_2 \mu)}{M_{\tilde{u},\tilde{d}}} \left(\frac{1\ \mathrm{TeV}}{M_{\tilde{u},\tilde{d}}}\right)^2 \left(\frac{m_{u,d}}{10\ \mathrm{MeV}}\right)$$

[Ellis, Ferrara, Nanopoulos 82; Buchmueller and Wyler 83; Polchinski and Wise 83]

Can make small by taking first two generation sfermion masses large.

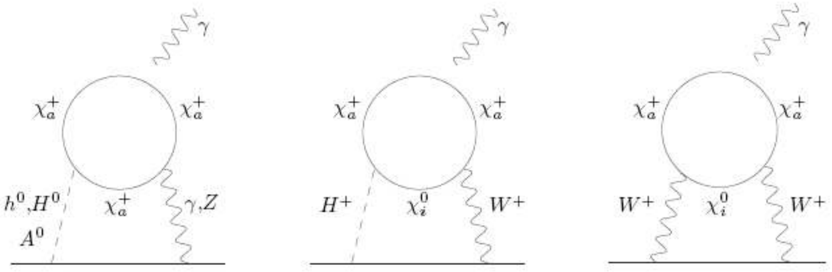
# 2-loops & MSSM Bino

[Barr, Zee (90); Chang, Keung, Pilaftsis (99); Pilaftsis (02)]



$$d_e \propto \tan\beta, \arg(\mu M_2), \frac{1}{M_a}$$

[Li, Profumo, Ramsey-Musolf 08] considered the subdominant neutralino contributions.



$d_1/d_2 \sim 0.02$

B-genesis source term is suppressed less, making the tradeoff a good deal.

# NMSSM EDM 2-Loop Analysis

[Cheung, Hou, Lee, Senaha 11]

$$W_{\rm NMSSM} \; = \; \widehat{U}^C {\bf h}_u \widehat{Q} \widehat{H_u} \; + \; \widehat{D}^C {\bf h}_d \widehat{H}_d \widehat{Q} \; + \; \widehat{E}^C {\bf h}_e \widehat{H}_d \widehat{L} \; + \; \lambda \widehat{S} \widehat{H}_u \widehat{H}_d \; + \; \frac{\kappa}{3} \, \widehat{S}^3$$

$(\phi'_\lambda - \phi'_\kappa)$

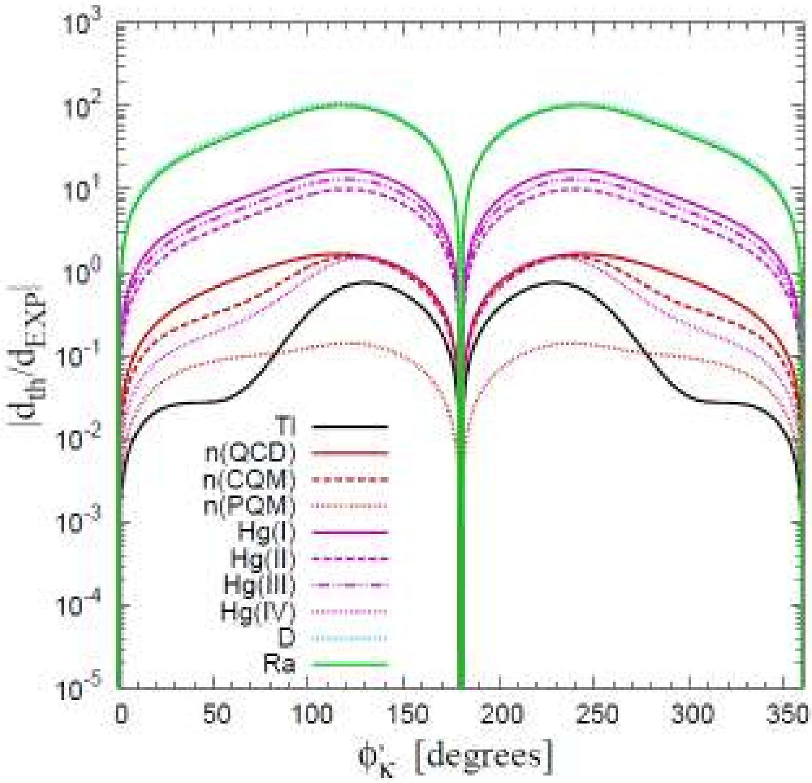


Figure 5: The observable EDMs taking $|\lambda| = 0.81$, $|\kappa| = 0.08$, $|A_\lambda| = 575$ GeV, and $A_\kappa| = 110$ GeV. The other parameters are fixed as in Eq. (51)

# PT Phenomenon can be correlated

- Electroweak Baryogenesis
- Gravity Waves: Bubble stirs up fluid
- DM: Freeze out physics can be affected
- CC: IR contribution

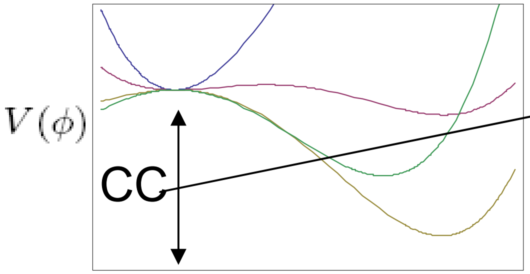
e.g. DM can be used to probe phase transitions [DC, Long, Wang 11]

$$\delta n_X(t_0) = c_1\,\epsilon_1 + c_2\,\epsilon_2 + c_{31}\,\epsilon_{31} + c_{32}\,\epsilon_{32} + c_4\,\epsilon_4$$

change in observed DM density

CC → Increases H

Converts into entropy

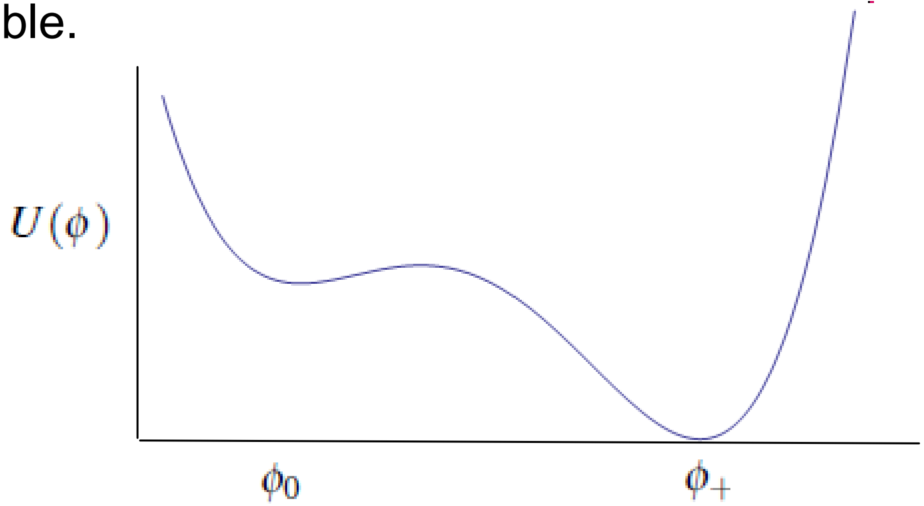


Has to fight $\frac{1}{g_*} \lesssim O(10^{-2})$

Same degree of model tuning → O(1) effect

For this program to work: reconstruct EWSB PT from collider measurements.

A remarkable feat if possible.



$$\langle \phi_0, \vec{p} | \phi_+, \vec{k} \rangle \propto \lim_{\Omega \to \infty} \exp(-\Omega^n c) = 0$$

Because Legendre transformation breaks down, no linear source induced shift $\phi_+ \to \phi_0$ is possible. Dim 0, 1, 2 UV-IR mixing → ambiguity in tachyonic region

Hence, remarkable if few particle collisions ⟶ non-perturbative condensation information

Question: What are the implicit assumptions that are used in the literature and what alternative assumptions might exist? [work in progress]

# Conclusions

1) Electroweak Bgenesis predictions:
   - a) The scalar sector will be non-minimal either in d.o.f. and/or physics.
   - b) There is likely to be a discrete symmetry or an accidental cancellation in the scalar sector.
   - c) CP violation sector is either secluded or we will see EDMs if we continue to push experimental sensitivity. If secluded, richer spectrum is likely explaining why we do not see EDMs.

2) CPV source/diffusion computation technology is converging, although still incomplete.

3) Reconstructibility of the EWPT without non-perturbative data is not obvious. Correlated probes such as DM and gravity waves might provide complementary data.