Cosmological Implications of Electroweak Scale Phase Transition

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[focus: works with Andrew Long, Peng Zhou, Sean Tulin, Liantao Wang]

New Microphysics

- LHC may discover new physics at the electroweak scale: the origin of electroweak symmetry breaking.

- Higgs is a possible scalar involved, but many additional scalars may be involved.

→ motivates the existence of electroweak scale PT:
a powerful source of "nonthermality"

- Question: Implications for cosmology? Old question, but less explored territory remain.

Implications?

- 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
- Source of density inhomogeneity perturbations on small scale
  - Good: Overconstraint possible in principle
  - Bad: Any signal is likely to be completely erased due to phase space mixing

Electroweak Scale Baryogenesis

Electroweak Baryogenesis References

- Incomplete list of ewbgenesis people:

  Anderson, Ambjorn, Arnold, Ashoorion, Baek, 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, Hall, Hernandez, Huet, Huber, Jakiw, Jansen, Joyce, Kane, Kainulainen, Kajantie, Kaplan, Keung, Khlebnikov, Klinkhamer, Ko, Kolb, Konstandin, Kuzmin, Laine, Langacker, Lee, Leigh, Linde, Liu, Losada, Menon, Moore, Moorhouse, Moreno, Morrissey, Multamaki, Murayama, Nelson, Olive, Orloff, Oaknin, Pietroni, Quimbay, Quiros, Pene, Pierce, Pilaftsis, Prokopec, Profumo, Rajagopal, Ramsey-Musolf, Ringwald, Riotto, Rubakov, Rummukainen, Sather, Schmidt, Seco, 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

Some Open Questions about EW bgenesis

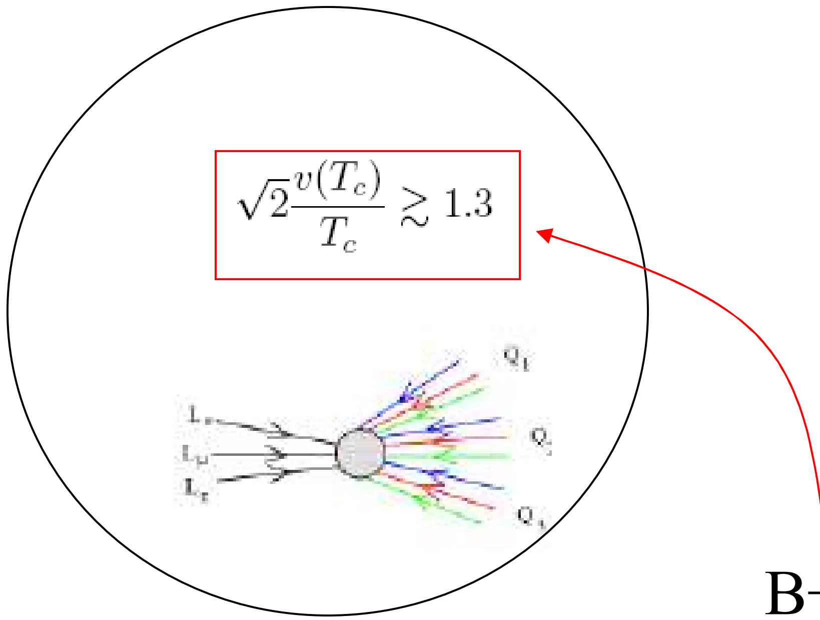
1) What are all correlated signatures of EW bgenesis?
   - Gravity waves
   - DM freeze out anomalies
   - Defect formation/evolution

2) Are there any special symmetries associated with SFOPT associated with EW bgenesis?

3) How should one compute properties of EWPT if it proceeds through a strongly coupled sector?

4) What is the error bar associated w/ current computational technology?

1) Bubble nucleate
2) CP violating scattering in bubble → source of CP asymmetry
3) Diffuse out in front of bubble
4) Bubble wall sweeps over preserving B-asymmetry
5) Percolation completes



$$\sqrt{2}\frac{v(T_c)}{T_c} \gtrsim 1.3$$

$$\langle H_j \rangle = 0$$

B+L viol. "inactive"

Need a sufficiently strong order 1st order PT.

Question: In multiple singlet extension of SM, find novel strongly 1st order PT points and analytic techniques to identify them.
Use $\mu\nu\mathrm{SSM}$ as a testbed for the analysis.

1^{st} order PT and Cosets

1^{st} order PT can typically be identified with a dynamically generated enhanced symmetry parametric point where the symmetry group is represented by the vacua: i.e. coset space

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:

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

When $\phi = \langle\phi\rangle + \delta\phi$ with $\langle\phi\rangle = \frac{2E}{\lambda}$, $\mathbb{Z}_2 \to 1$

Vacua {0, $\frac{2E}{\lambda}$ } represent the coset space $\mathbb{Z}_2/1$: i.e. under $\phi \to -\phi + \frac{2E}{\lambda}$

$$0 \leftrightarrow \frac{2E}{\lambda}$$

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

$T_c \to$ 0 when $E = \frac{\lambda}{2}\phi(0)$

Ideal parametric point!

By definition must contain a significant mixing with Higgs.
Hence $\phi(0)$ is constrained to be around 174 GeV
Can adjust M to keep this fixed while varying

Hence, one way to ensure a strong 1st order PT is to build in discrete symmetries or tune parameters to obtain approximate discrete symmetries.

A more general analysis in progress (w/ Long).

We illustrate a version of this idea in $\mu\nu\mathrm{SSM}$ where $\mathbb{Z}_3$ is utilized. [w/ Long 1004.0942]

An Example

$\mu\nu\mathrm{SSM}$ Use the N field of NMSSM as a right handed neutrino

[Lopez-Fogliani, Munoz 05]

$\mathbb{Z}_3$ → $Y_\nu^i \hat{L}_i \cdot \hat{H}_2 \hat{\nu}_i^c - \lambda \hat{H}_1 \cdot \hat{H}_2 \hat{\nu}_i^c + \frac{1}{3}\kappa \left(\hat{\nu}_i^c\right)^3$ in W

Multiple singlets

"mu" term
electroweak scale

→ low scale see-saw

→ standard thermal leptogenesis scenario is not an option.

Tree level relevant scalar potential.

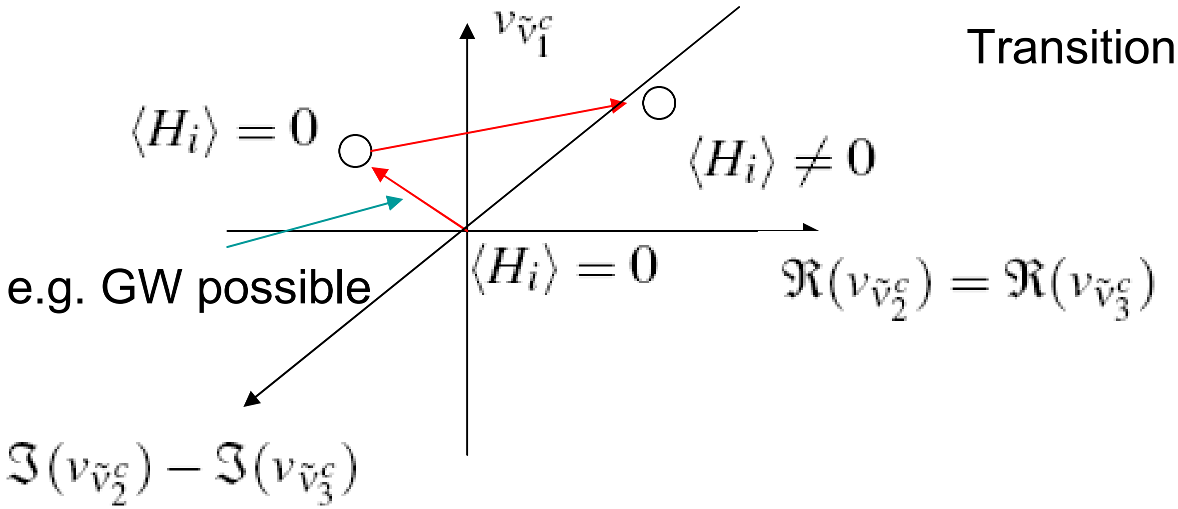
$$V_0 = m_{H_1}^2 \left|H_1^0\right|^2 + m_{H_2}^2 \left|H_2^0\right|^2 + m_{\tilde{\nu}^c}^2 \sum_i \left|\tilde{\nu}_i^c\right|^2 + \frac{g_1^2 + g_2^2}{8}\left(\left|H_1^0\right|^2 - \left|H_2^0\right|^2\right)^2$$

$$+ \sum_i \left[-a_\lambda H_1^0 H_2^0 \tilde{\nu}_i^c + \frac{1}{3} a_\kappa \left(\tilde{\nu}_i^c\right)^3 - \kappa\lambda \left(H_1^0 H_2^0\right)^\star \left(\tilde{\nu}_i^c\right)^2 + \mathrm{h.c.}\right]$$

$$+ 3\lambda^2 \left|H_1^0\right|^2 \left|H_2^0\right|^2 + \left|H_2^0\right|^2 \sum_i \left(Y_\nu^i\right)^2 \left|\tilde{\nu}_i^c\right|^2 + \lambda^2 \left(\left|H_1^0\right|^2 + \left|H_2^0\right|^2\right) \left|\sum_i \tilde{\nu}_i^c\right|^2 + \kappa^2 \sum_i \left|\tilde{\nu}_i^c\right|^4$$

Example of a Transition Different from NMSSM

[1004.0942 w/ Andrew Long]



Transitions which shut off B-violation.

How can one find this parametric point approximately analytically?

1) With $\langle H_i \rangle = 0$ look in a parametric region where there is a discrete symmetry G

→ Whenever singlets obtain VEVs (trivially achieved by soft masses), the coset space will form a rep. of G

2) Radiative corrections and $\langle H_i \rangle \neq 0$ lift degeneracy: look for a deeper min.

3) Look along the deeper min direction and tune $\frac{E_{\text{eff}}}{\lambda_{\text{eff}} \phi(0)} \approx \frac{1}{2}$ where

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

(more below)

With $\langle H_i \rangle = 0$ and setting the soft term $\tilde{\nu}_1^c \tilde{\nu}_2^c \tilde{\nu}_3^c$ to zero (stable at 1-loop),

$\mathbb{Z}_3 \longrightarrow \mathbb{Z}_3 \otimes \mathbb{Z}_3 \otimes \mathbb{Z}_3$ for tree level scalar potential (i.e. approx.)

$$\tilde{\nu}_j^c \longrightarrow e^{i n_j 2\pi/3} \tilde{\nu}_j^c$$

$m^2_{\tilde{\nu}^c} < 0$ breaks the approximate symmetry down to 1 → $\mathbb{Z}_3 \otimes \mathbb{Z}_3 \otimes \mathbb{Z}_3 / 1$

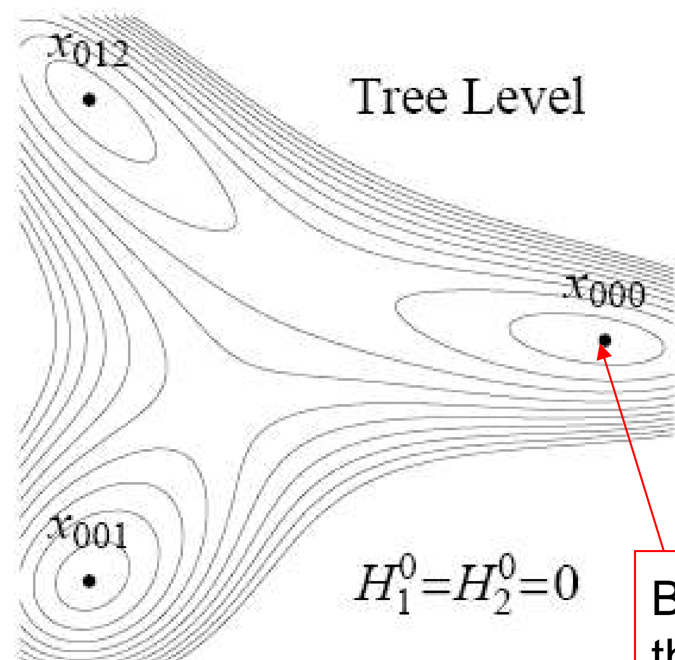
Make heavier than Higgs.

$$\rho_1 = \rho_2 = \rho_3 \approx v_{\tilde{\nu}^c}$$

$$\frac{1}{4\kappa^2}\left(-a_\kappa + \sqrt{a_\kappa^2 - 8 m^2_{\tilde{\nu}^c}\kappa^2}\right) \approx v_{\tilde{\nu}^c}$$

$$\tilde{\nu}_i^c = \rho_i e^{i n_i \frac{2\pi}{3}} \qquad n_i \in \{0, 1, 2\}$$

Coset space spanned by $\vec{x}_{n_1 n_2 n_3}$

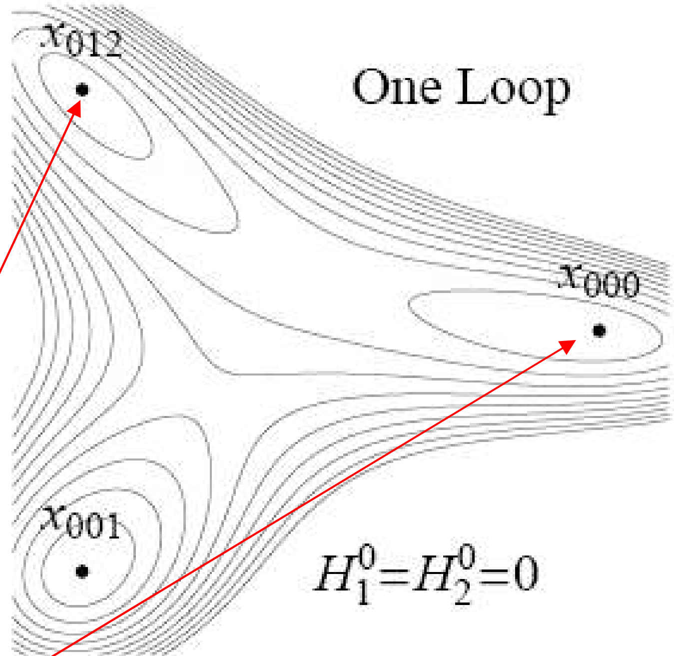


Belongs to the coset space of $\mathbb{Z}_3/1$ also.

Radiative corrections break the scalar tree level symmetry.

e.g. $\quad -a_\lambda H_1^0 H_2^0 \tilde{\nu}_i^c \qquad W \ni \lambda \hat{H}_1 \cdot \hat{H}_2 \hat{\nu}_i^c$

$$V_1^0(\vec{x}_{012}) < V_1^0(\vec{x}_{001}) < V_1^0(\vec{x}_{000})$$



$$\sigma = 2\left(\frac{a_\lambda}{m_{\rm ch}\lambda} + \frac{\kappa}{3\lambda}\right)$$

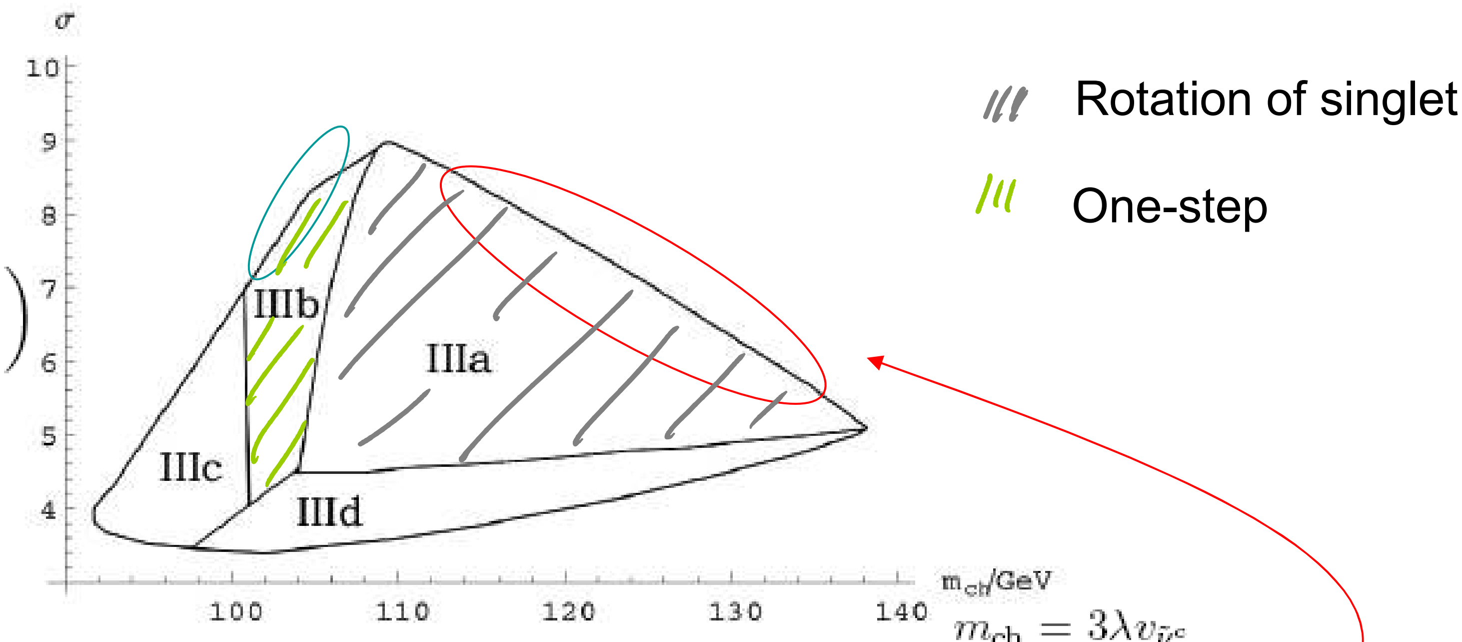
$$64\pi^2 \Delta V_1^a \approx 6 m_{\rm ch}^4 \log \frac{m_{\rm ch}^2}{e^{3/2}\mu^2} - 2 m_{\rm ch}^4 \left(\sigma^2 + 4\sigma \csc 2\beta - 4\right) + 24\lambda^2 v^2 m_{\rm ch}^2$$

At lower temperature, the EWSB PT will be made to a $\mathbb{Z}_3/1$ point y_{000} which is related to x_{000} except with $H_i^0 \neq 0$ approximately fixed by T=0 EWSB.

$$\Delta V_0^b = V_0(\vec{x}_{000}) - V_0(\vec{y}_{000}) = \frac{1}{8}\left[\left(g_1^2 + g_2^2\right)\cos^2 2\beta + 6\lambda^2 \sin^2 2\beta\right] v^4$$

$$a_\lambda H_1 \cdot H_2 \tilde{\nu}_i^c \in \mathcal{L}_s \qquad -\lambda H_1 \cdot H_2 \nu_i^c + \frac{1}{3}\kappa (\nu_i^c)^3 \in W$$

$$\sigma = 2\left(\frac{a_\lambda}{m_{\rm ch}\lambda} + \frac{\kappa}{3\lambda}\right)$$



$$m_{\rm ch} = 3\lambda v_{\tilde{\nu}^c}$$

$$m^2_{\tilde{\nu}^c}$$

[1004.0942 w/ Andrew Long]

boundary occurs when $\frac{E_{\rm eff}}{\lambda_{\rm eff}\phi(0)} \approx \frac{1}{2}$

Discrete symmetry helps us to tune to idealize strong first order PT.

Domain Walls

[following the arguments of Abel, Sarkar, White 95]

Pressure difference induced by small symmetry breaking operator can easily melt away domain walls.

Suppose one imposes domain wall melts away T>10 MeV

Energy dens difference: $\epsilon > \frac{\sigma}{R(t)}$

$$R \sim t \sim 1/H \qquad \sigma \sim v^3$$

$$\epsilon \sim c_u \frac{v^{4+u}}{\Lambda^u}$$

$$\Lambda = 100 \text{ TeV}$$

$$\boxed{c_u > 10^{-24} 500^u}$$

Gravity Waves from EW scale PT

Selected Questions about GWs from EW Scale PTs

1) Cross correlations of GWs w/ other aspects of cosmo.

2) Which BSM leads to measurable GWs?
   Any symmetries?

3) Stochastic GW sources that mask EW scale PT GWs?

4) Fluid velocity computation during EW scale PT.

5) MHD turbulence contribution peaks near PT or later?

6) What is the error bar associated w/ current
   computational technology?

Cross Correlate Dark Sector and GW

BBN + relative isotope measurements probe H(1 MeV)

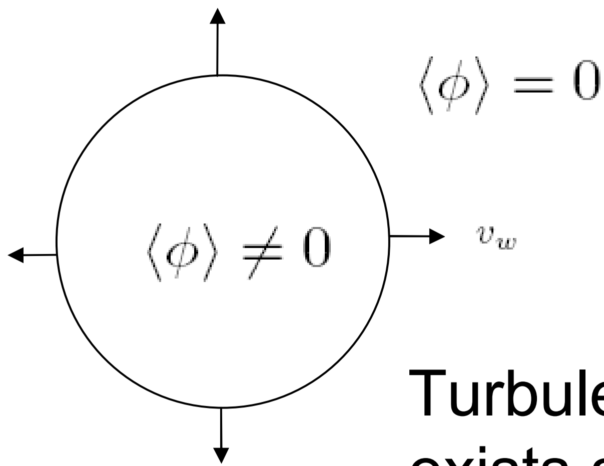
dark sector constrained (sterile neutrinos, dark energy,…)

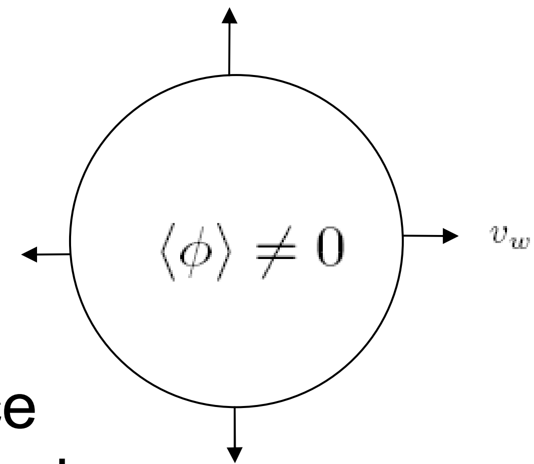
Similarly, use gravity waves to constrain H(100 GeV)

[1003.2462 w/ Peng Zhou]

Gravity Waves from EWPT

Collision:





Turbulence exists also due to stirring.

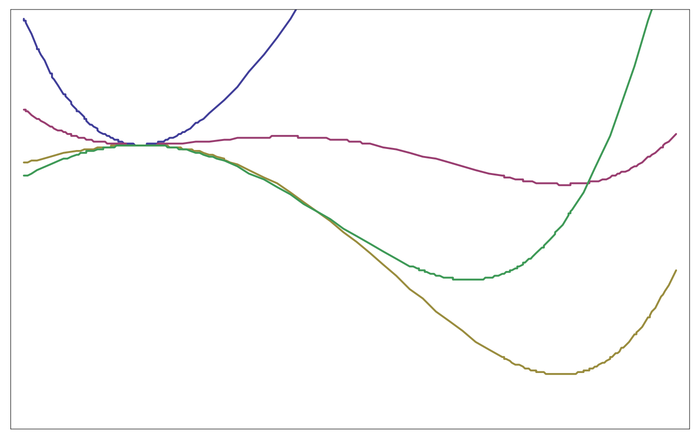
[recent review: Durrer 10]

$$\Gamma(t) = A(t)e^{-S(t)}$$

$$\Gamma \sim A \exp\left[-S(t_i) - \boxed{\frac{dS}{dt}|_{t_i}}(t - t_i)\right]$$

$$\frac{dS}{dt} = -H\frac{dS}{d\ln T}$$

$$\Delta t = t_f - t_i \propto \frac{1}{|\frac{dS}{dt}|} = \boxed{\frac{1}{H}\frac{1}{\frac{dS}{d\ln T}}}$$



End game is important.

Gravity Wave at EWPT

Following arguments of 0711.2593 and astro-ph/9310044:

$$\rho_{GW} \sim \frac{1}{M_p^2}\left(\frac{a_{PT}}{a}\right)^4 \langle \frac{d}{dt}\left(\frac{1}{\Box}T_{ij}\right)\frac{d}{dt}\left(\frac{1}{\Box}T_{ij}\right)\rangle|_{PT}$$

$$\left\langle \tilde{T}_{ij}(t_1',\vec{k}_1)\tilde{T}^*_{ij}(t_2',\vec{k}_2)\right\rangle = (2\pi)^3\delta^{(3)}(\vec{k}_1-\vec{k}_2)P(k_1,t_1',t_2')\left[\rho_f^{\mathrm{rest}}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2$$

$$\frac{d\rho_{GW}}{d\ln k} = \frac{1}{(2\pi)^2}\frac{1}{M_p^2}\left(\frac{a_*}{a}\right)^4\left[\rho_f^{\mathrm{rest}}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2\int dt_1' dt_2' \cos\left[k(t_1'-t_2')\right]\left[k^3 P(k,t_1',t_2')\right]$$

dimless

Stress tensor amplitude

propagation

Spatial dependence of correlator: bubble wall spatial distribution /deformations

Uncertain

Dimensionful parameters:

BC scales: $t_*^{-1},\ T$

Short distance scales: $m_h(0)$

Nonequilibrium scales: $(\Delta t)^{-1},\ H$

100 GeV

10^{-12} GeV

10^{-14} GeV

Decoupling and Mass Scale Left

Intuition for dimensional analysis:

Dimensionful parameters:

coordinate origin

BC scales: t_*^{-1}, T

Short distance scales: $m_h(0)$

Nonequilibrium scales: $(\Delta t)^{-1}$, H

100 GeV

Integrate out

Λ

10^{-12} GeV

10^{-14} GeV

$= \text{dimless number} \times H$

Effects of H through these ops are suppressed by $(H/\Lambda)^n$

Scales of interest for measurement.

More accurately, it is a classical analog + (reasonable and mild) assumptions:

1) $\frac{k}{a_*} \in [10^{-13}, 10^{-7}] \left(\frac{g_*(t_0)}{3.9}\right)^{-1/3} \left(\frac{g_*(t_*)}{10^2}\right)^{1/3} \left(\frac{T_*}{10^2 \text{ GeV}}\right) \text{GeV}$ estimated LISA & BBO sens.

2) $\langle T_{ij}(t_1', \vec{x}) T_{ij}(t_2', \vec{y})\rangle = \left[\rho_B^{\text{rest}} \gamma_{v_f}^2 v_f^2\right]^2 a_*^2 \int \frac{d^3 k_1}{(2\pi)^3} e^{i\vec{k}_1 \cdot (\vec{x} - \vec{y})} P(k_1, t_1', t_2')$ ← approx order of magnitude

3) Dominant support of $\langle T_{ij}(t_1', \vec{x}_1) T_{ij}(t_2', \vec{x}_2)\rangle$ in the interval $t \in [t_*, t_* + \Delta t]$

GW as a Probe of Early Universe H

$= \text{dimless number} \times H^{-1}$

Observe:

$[M]^0 \rightarrow$

$$F_{k\Delta t}((t_1' - t_*)/\Delta t, (t_2' - t_*)/\Delta t) \equiv k^3 P(k, t_1', t_2')$$

assumption of leading conformal symmetry breaking scale.

$$\frac{d\rho_{GW}}{d\ln k} = \frac{1}{(2\pi)^2}\frac{1}{M_p^2}\left(\frac{a_*}{a}\right)^4 \left[\rho_f^{\text{rest}}\gamma_{v_f}^2 v_f^2\right]^2 a_*^2 \int dt_1' dt_2' \cos\left[k(t_1' - t_2')\right]\left[k^3 P(k, t_1', t_2')\right]$$

Since $\Delta t \propto \frac{1}{H(T_*)}$, $H(T_*)$ sensitivity can be read off.

$$\left(H^{(U)}\right)^2 = \frac{\rho_R}{3M_p^2} \qquad H^2 = \frac{\rho_R + \rho_{\text{hidden}}}{3M_p^2} \qquad \xi \equiv \frac{H(T_*)}{H^{(U)}(T_*)}$$

$$\frac{d\rho_{GW}(k)}{d\ln k} \rightarrow \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k}$$

[1003.2462 w/ Peng Zhou]

Observational Predictions are More Complicated

What is measured:

$$\frac{\rho_G}{\rho_R}$$

Can still suffer from non-standard cosmological dependence.
e.g. late time entropy dilution. [e.g. Lyth, Stewart 92, 95; Fox, Pierce, Thomas 04; Kumar 08; Acharya, Kane, Kuflik 10]

Good and bad.

Don’t be Fooled

[Kamionkowski, Kosowsky, Turner 94]

Numerical simulation:

$$\Omega_{GW} h^2 \approx 1.1 \times 10^{-6} \kappa^2 \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\alpha}{1+\alpha}\right)^2 \left(\frac{v_w^3}{0.24 + v_w^3}\right) \left(\frac{100}{g_*}\right)^{1/3}$$

$$f_{max} \approx 5.2 \times 10^{-8} \text{Hz} \left(\frac{\beta}{H_*}\right) \left(\frac{T_*}{1 \text{ GeV}}\right) \left(\frac{g_*}{100}\right)^{1/6}$$

$$\xi \equiv \frac{H(T_*)}{H^{(U)}(T_*)}$$

$$\frac{d\rho_{GW}(k)}{d \ln k} \longrightarrow \frac{1}{\xi^2} \frac{d\rho_{GW}(k/\xi)}{d \ln k}$$

[1003.2462 w/ Peng Zhou]

Naïvely contradiction. However consistent since H_* has origins here to denote temperature and **not** the expansion rate.

Application: Kination Phase of Quintessence

Quintessence's main difference from CC = kinetic energy

$$\rho_Q = \frac{1}{2}\dot{Q}^2 + V(Q)$$

$\frac{1}{2}\dot{Q}^2 \rightarrow \left(\frac{a_*}{a}\right)^6$ ← Energy disappears relative to rad by BBN.

$V(Q) \rightarrow\ \ll \rho_Q$

$$\xi = \sqrt{1 + \left(\frac{a_{\mathrm{bbn}}}{a}\right)^2 \eta}$$

$$\eta \equiv \left(\frac{\rho_Q}{\rho_R}\right)_{\mathrm{BBN}}$$ ← 1-parameter model

$$\frac{d\rho_{GW}(k)}{d\ln k} \to \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k}$$

Example

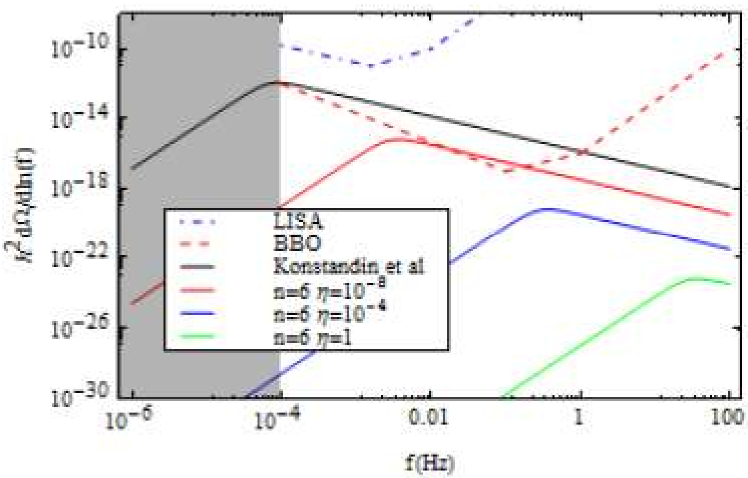
Optimistic example in nMSSM,

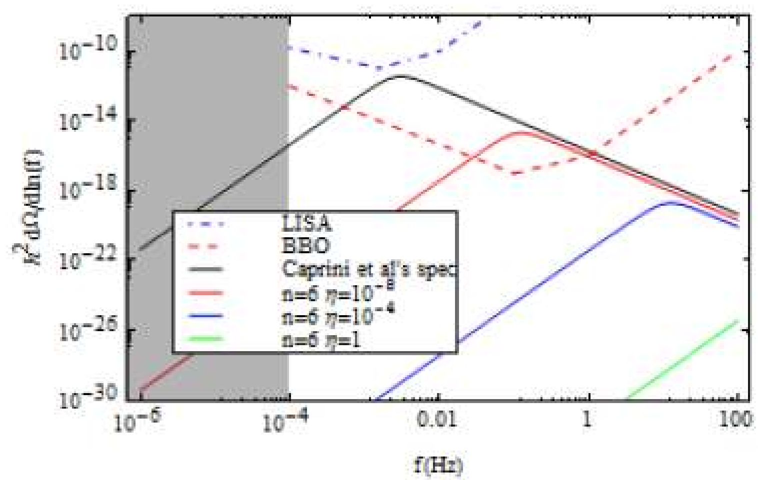
$$W_{nMSSM} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 - \frac{m_{12}^2}{\lambda} \hat{S} + W_{MSSM}$$ [0709.2091]

Apply to 2 analytic estimates:
Huber, Konstandin 08;
Caprini, Durrer, Servant 07

$$\frac{V(\vec{\phi}_i) - V(\vec{\phi}_f)}{\rho_{\rm rad}} = 0.2 \qquad v_b = 0.82 \qquad T_* = 70 \text{ GeV}$$

$$\beta / H_* = 30$$



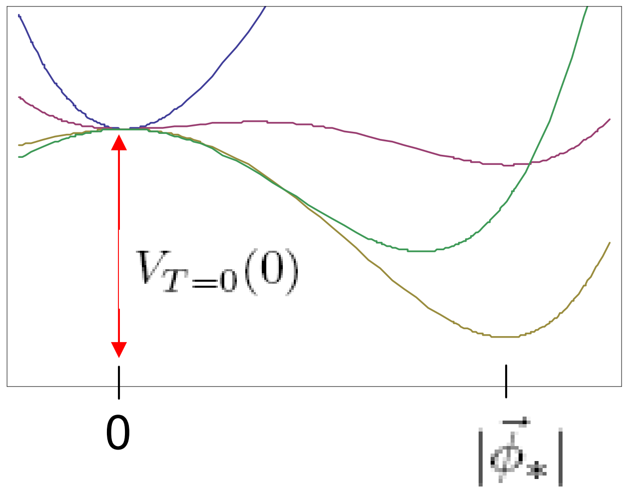


[1003.2462 w/ Peng Zhou]

Good: can rule out kination
Bad: may be negative signal

CC ⟷ colliders through DM

CC Energy Contribution



[Linde 74;
Ellis, Gaillard, Nanopoulos 76]

Assumptions

A crucial assumption made in these drawings: V at T=0 has been tuned to zero by a cosmological constant. This is consistent with a large class of landscape ideas.

$$\{\partial_i V_{T=0}(\vec{\phi}_*) = 0\}$$

$$V_{T=0}(\vec{\phi}_*) = V_{\text{classiical}}(\vec{\phi}_*) + V_{\text{quantum}}(\vec{\phi}_*) + V_\Lambda = 0$$

$$H \propto \sqrt{\rho_{\text{particles}} + V_{T=0}(0)}$$

calculable prediction

Selected Questions About Tuned CC

1) What are observational consequences of this conjecture?

2) For which SM and BSM are the observational prospects most favorable?

Connection to DM

$$H \propto \sqrt{\rho_{\text{particles}} + V_{T=0}(\langle\phi(T)\rangle)}$$

→ $$n_X(t_0) = \left(\int_0^{\ln a_0/a_f} \frac{d \ln(a/a_f)}{H} \langle \sigma v \rangle \frac{a_0^3}{a^3} \right)^{-1}$$

$\delta n_X(t_0)$ effect $\sim \dfrac{V_{T=0}(\langle\phi(T)\rangle)}{\rho_{\text{particles}}}$

$$\sim \frac{1}{g_*(T_c)} < 10^{-2}$$

Since entropy maximized

Better for QCD PT, but different talk.

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

$$c_1 \equiv \frac{1}{2}\left(\delta + \frac{(1+3\delta)}{n-3}\left(1 - \frac{\Delta\rho_{\rm ex}}{\rho_{\rm ex}}\right)\right) - \frac{3}{2}\frac{1}{\ln A}$$

$$c_2 \equiv -\frac{1}{3}(1+2\delta)$$

$$c_{31} \equiv \frac{1}{6}(1-\delta)$$

$$c_{32} \equiv \frac{1}{6}\int_1^{a_0/a_f|_{\rm usual}} \frac{dx}{x^2} f(x)$$

$$c_4 \equiv 1-\delta$$

$$\epsilon_1 \equiv \frac{\rho_{\rm ex}}{\frac{\pi^2}{30} g_E(T_f)\, T_f^4} = \text{fractional energy of the exotic during freeze out}$$

$$\epsilon_2 \equiv \left(\frac{a_{PT}}{a_f}\right)^3 \frac{\Delta s}{\frac{2\pi^2}{45} g_S(T_f)\, T_f^3} = \text{fractional entropy increase during PT}$$

$$\epsilon_{31} \equiv \frac{\frac{7}{8}N_{PT}}{g_E(T_f)} = \text{fractional decoupling degrees of freedom during PT}$$

$$\epsilon_{32} \equiv \frac{\frac{7}{8}N}{g_E(T_f)} = \text{fractional decoupling degrees of freedom near freeze out}$$

$$\epsilon_4 \equiv -\frac{\Delta_\sigma}{\langle\sigma v\rangle^{(U)}}$$

[Similar issues discussed by Cohen, Morrissey, Pierce 08; Wainwright, Profumo 09]

2^{nd} order + Idealized WIMP

$$V_{eff}(h,T) \approx \frac{\lambda_{eff}}{4}\left(h^2 - v^2\right)^2 + c\,T^2 h^2 + h\text{-independent / subdominant / log terms}$$

$$c_{SM} = \frac{1}{24v^2}\left(6m_t^2 + 6m_b^2 + 6m_w^2 + 3m_z^2 + \frac{3}{2}m_h^2\right) \approx 0.18$$

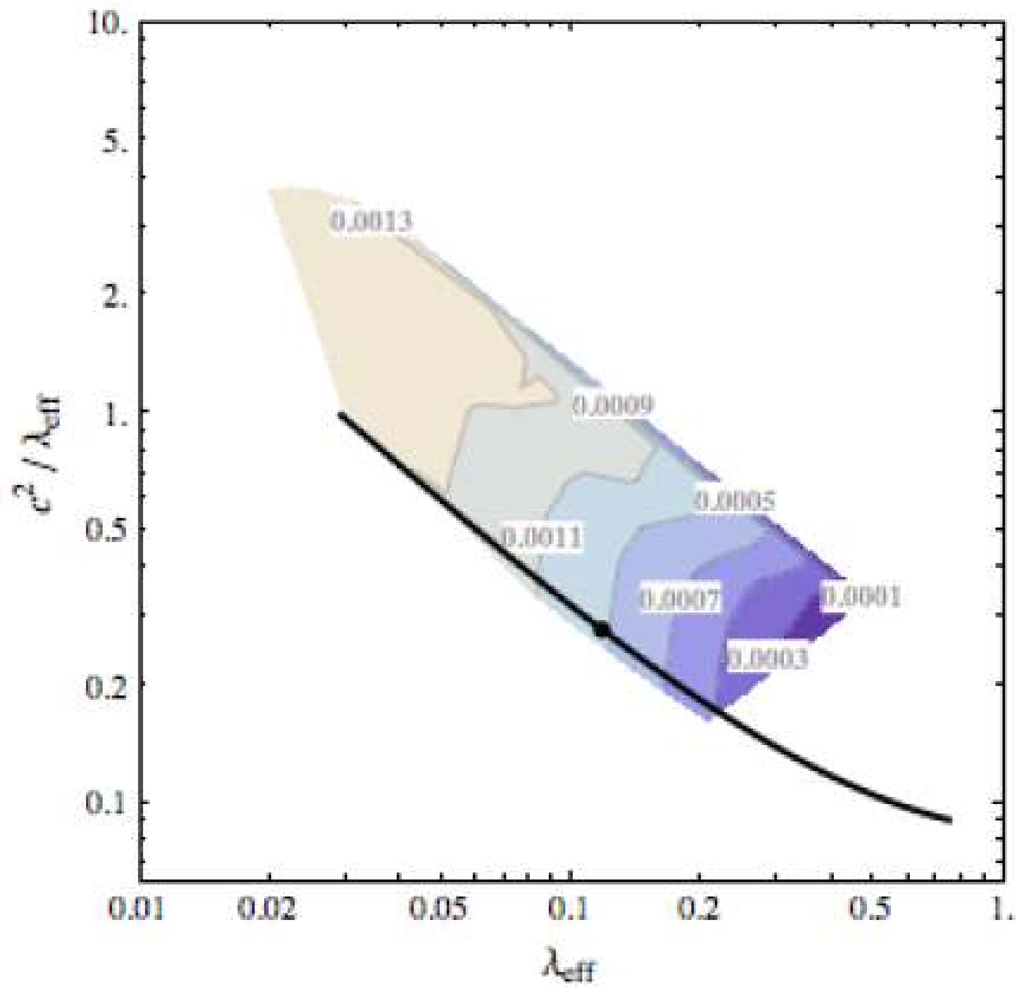
$$m_X = 4 \text{ TeV}$$

$$\delta n_X(t_0) \sim \frac{1}{10}\frac{1}{g_E}\frac{c^2}{\lambda_{eff}}$$

Singlet extension does not help much for 2^{nd} order.

$$\frac{a_2}{2}s^2\left(h^2 - v^2\right)$$

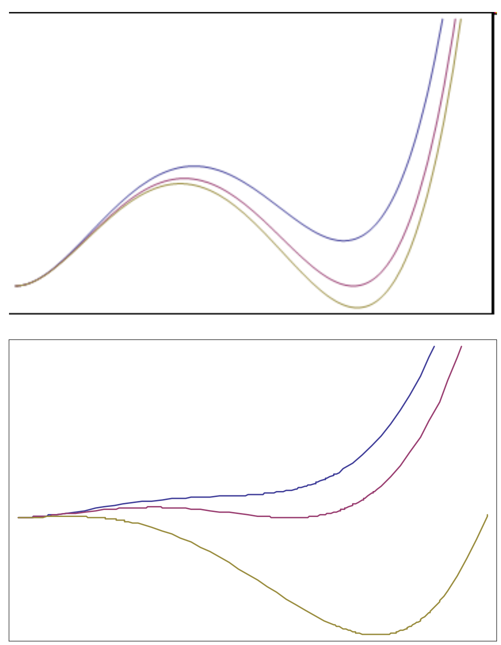
$$c = c_{SM} + \frac{a_2}{24}$$

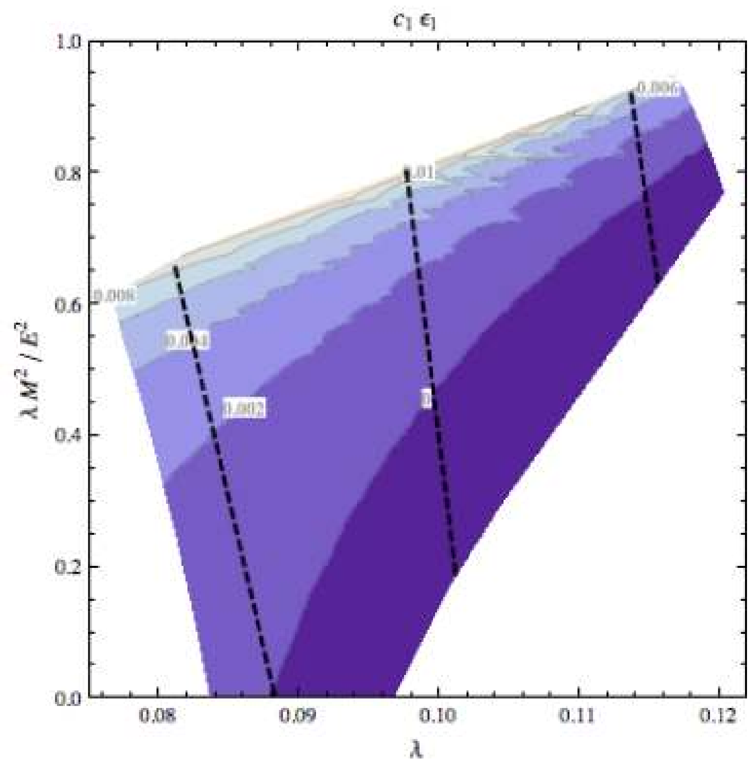


1st order PT + Idealized WIMP

$V_0(\{h, s\})$ 1st order PT does better

Want large supercooling.





[Nearly complete with Long, Tulin, and Wang.]

$$V_{eff}(\varphi, T) = \rho_{ex} + \frac{1}{2}M^2\varphi^2 - E\varphi^3 + \frac{\lambda}{4}\varphi^4 + c\,T^2\varphi^2$$

1) Take λ to be small
2) Tune $\eta = \lambda M^2/E^2$ to maximize $\delta_{SC} = T_c/T_{PT}^{-} - 1$
3) Let m_X s.t. $T_f \gtrsim T_{PT}^{-}$

$\frac{S^{(3)}}{T}$ ↑

↓ without tuning

$\frac{dS^{(3)}}{dT}$ ↑

However, desire

$\frac{S^{(3)}}{T}$ ↑ + $\frac{dS^{(3)}}{dT}$ ↓

Conclusions

- Many unexplored questions exist for

  EW scale 1st order PT ↔ cosmology

- SFOPT for bgenesis can be associated with enhanced discrete symmetric points in the parameter/moduli space. Illustrated with $\mu\nu\mathrm{SSM}$: relevant cosets involved were

  $\mathbb{Z}_3 \otimes \mathbb{Z}_3 \otimes \mathbb{Z}_3 / 1$ and $\mathbb{Z}_3 / 1$ [w/ Long 1004.0942]

- Insensitive to the uncertainties in the computational technology,

  $$\frac{d\rho_{GW}(k)}{d\ln k} \rightarrow \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k}$$ [1003.2462 w/ Peng Zhou]

- In very lucky circumstances involving 1st order Pts, one can hope to hunt for a few percent effect coming from CC testing the tuning of CC.