Cosmological Implications of Electroweak Phase Transition

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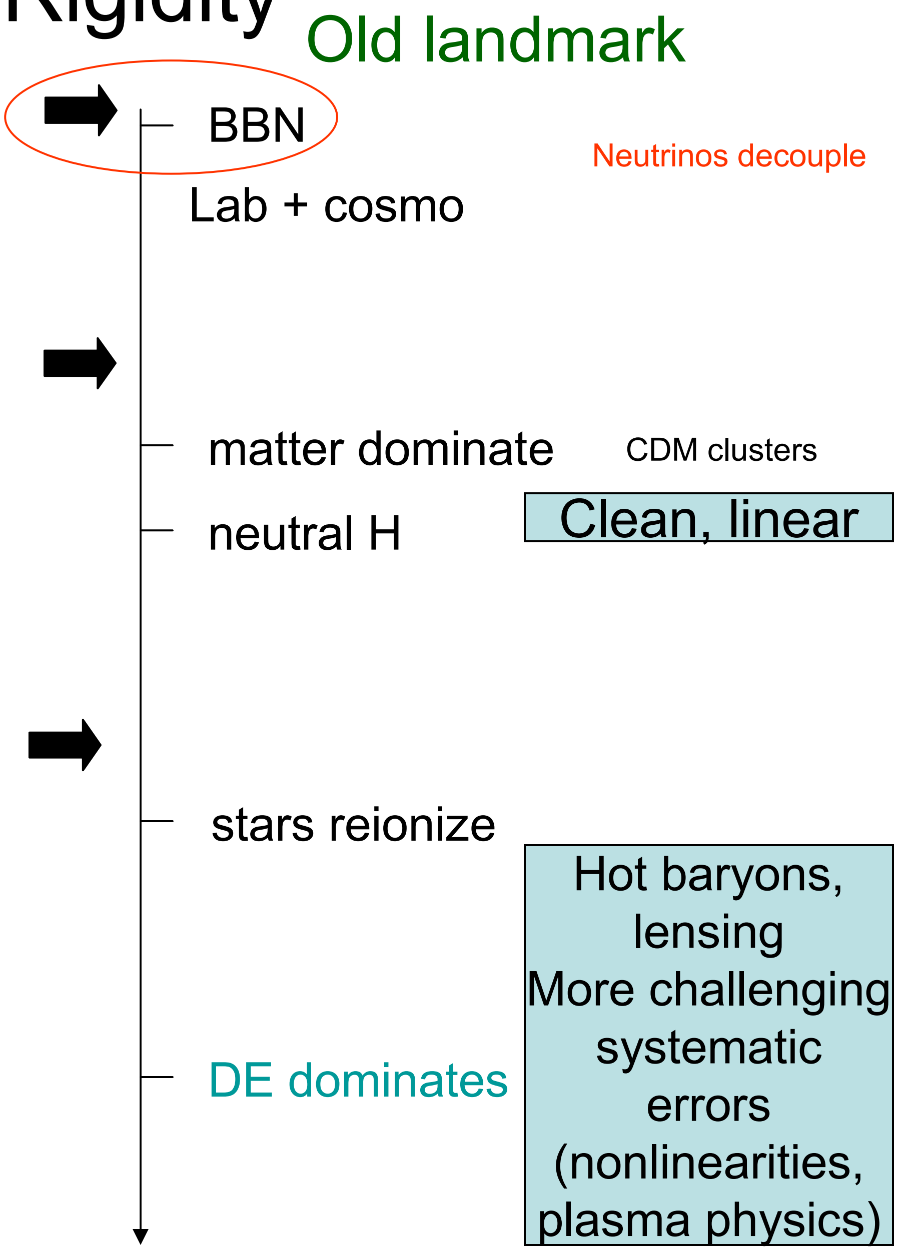
[focus: works with Andrew Long (1004.0942)
& Peng Zhou (1003.2462)]

(Lack of) Rigidity



(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

DE dominates

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

Perturbative Scalar EWSB as Universe Cools

UV sensitivity of scalar field + symmetry commuting with KMS

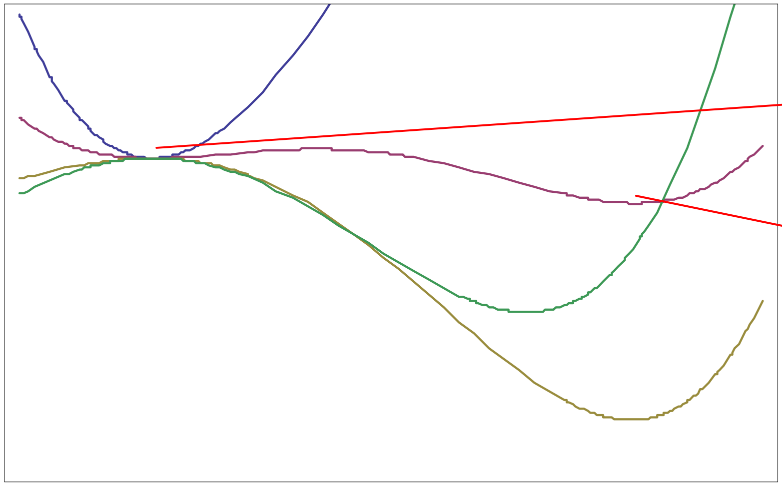
$$\longrightarrow \quad c_{1i}\Lambda^2\phi_i + c_{2i}\Lambda^2\phi_i^2$$

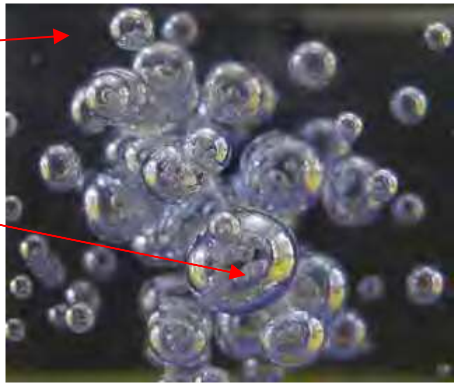
$$\longrightarrow \quad c'_{1i}T^2\phi_i + c'_{2i}T^2\phi_i^2$$

$SU(2)_L \otimes U(1)_Y$ if Higgs

EW symmetry restoration at high temperature. Broken at low temperature.

[Kirzhnits, Linde 72]





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

new analysis w/
Long, Tulin, and Wang
In progress

- Clustering: too small scale and effects easily washed out

Electroweak Baryogenesis in $\mu\nu$SSM

$\mu\nu$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

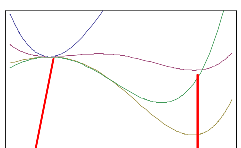
Multiple singlets

"mu" term
electroweak scale

→ low scale see-saw

→ standard thermal leptogenesis scenario is not an option.

Question: Is electroweak baryogenesis possible? [Kuzmin, Rubakov, Shaposhnikov 85]



$\langle H_j \rangle = 0$

$\langle H_j \rangle \neq 0$
Preserve B

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

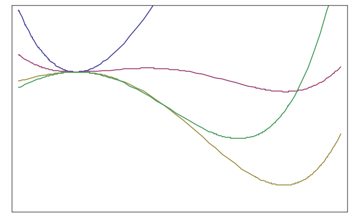
Partial answer: There are parameter regions giving strongly 1st order PT.

Not too large, not too small

$$V_T(\phi) \approx (\frac{1}{2}M^2 + c_1 T^2)\phi^2 - E_{\rm eff}\phi^3 + F_{\rm na}(\phi, T) + \frac{\lambda_{\rm eff}}{4}\phi^4$$

$$0 \le \frac{E_{\rm eff}}{\lambda_{\rm eff}\phi(0)} \le \frac{1}{2}$$

174 GeV



Like NMSSM

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

W + D-terms → Higgs mass dependence

$Y_\nu \approx 6 \times 10^{-7} \left(\frac{\sin[\beta]}{\sin[\arctan 2.6]} \right)^{-1}$ is unimportant for this.

½ marks the point when $\frac{v(T_c)}{T_c} \longrightarrow \infty$, $T_c \rightarrow 0$

However, phase transition parametric search can be different than NMSSM because of rotation in singlet vector space during PT.

Example of a Transition Different from NMSSM

At high T

$H_i = 0$ + all nonsinglet scalars vanish. e.g. $-a_\lambda H_1 \cdot H_2 \tilde{\nu}_i^c$

Freeze these scalars and consider tree level: $\mathbb{Z}_3$ → $\mathbb{Z}_3 \otimes \mathbb{Z}_3 \otimes \mathbb{Z}_3$

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

When T is lowered, degenerate minima forms

→ coset rep of $\mathbb{Z}_3 \otimes \mathbb{Z}_3 \otimes \mathbb{Z}_3$

Since an artifact of freezing by hand and omitting field fluctuations,
loop corrections break the degeneracy.

→ Intermediate T singlet minimum energy is sensitive to radiative corrections!

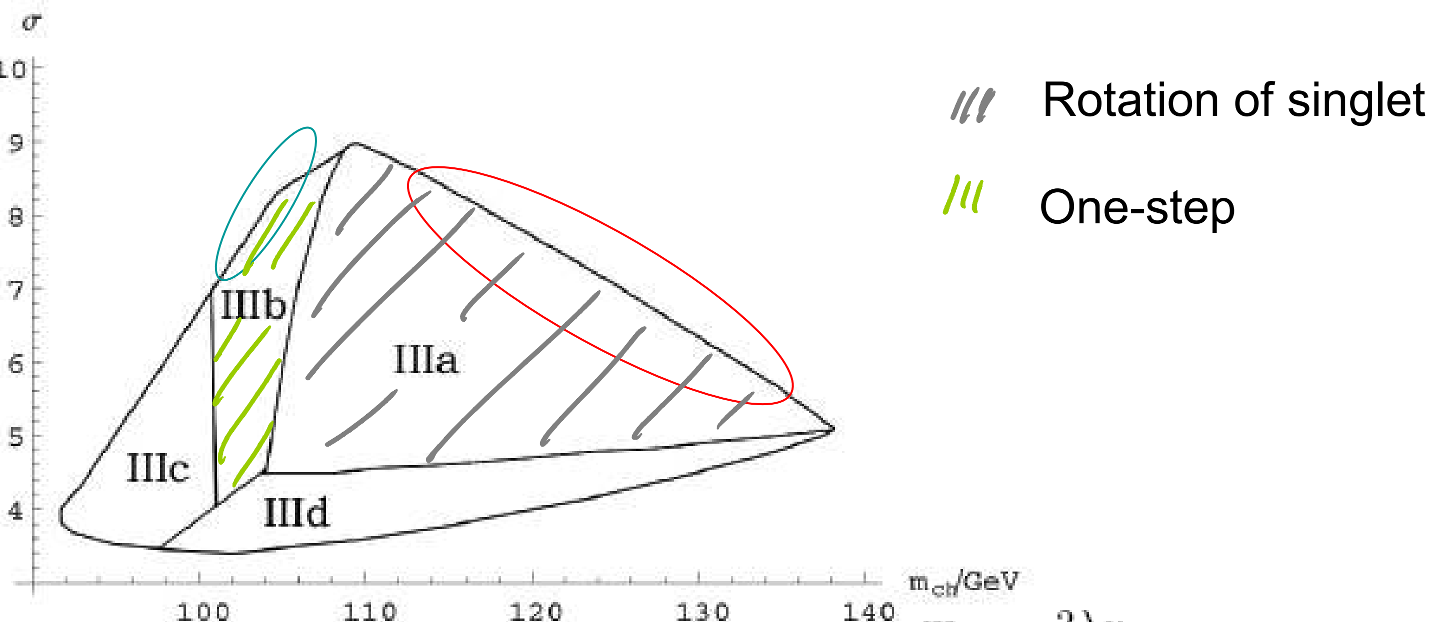
From one of these minima, EWPT occurs.

Tuning to achieve $\frac{E_{\rm eff}}{\lambda_{\rm eff}\phi(0)} \approx \frac{1}{2}$ → Sensitive to radiative corrections.

$a_\lambda H_1 \cdot H_2 \tilde{\nu}_i^c$ and $-m_{\tilde{\nu}^c}^2 |\tilde{\nu}_i^c|^2$ become important

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

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



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

[1004.0942 w/ Andrew Long]

Interesting: tuning has a group theoretic origin.

Gravity Wave at EWPT

[Steinhardt, Witten, Kosowsky, Turner, Watkins, Kamionkowski, Apreda, Maggiore, Nicolis, Riotto, Caprini, Durrer, Servant, Grojean, Huber, Konstandin, Ashoorion,…]

Following arguments of 0711.2593 and astro-ph/9310044:

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

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

bubble wall spatial distribution/deformations

Observe:

assumption

$[M]^0$ → $F_{k\Delta t}((t_1' - t_*)/\Delta t, (t_2' - t_*)/\Delta t) \equiv k^3 P(k, t_1', t_2')$

assumption of leading conformal symmetry breaking scale.

i.e. $\Lambda/\Delta t$ related quantities are suppressed in the relevant k range

$$\frac{d\rho_{GW}}{d\ln k} \sim \frac{(\Delta t)^2}{M_p^2}\left(\frac{a_*}{a}\right)^4\left[\rho_f^{\rm rest}\gamma_{v_f}^2 v_f^2\right]^2\int dq_1' dq_2' \cos\left[k\Delta t(q_1' - q_2')\right]F_{k\Delta t}(q_1', q_2')$$

propagation

Since $\Delta t \propto H_*^{-1}$, H_* sensitivity can be read off.

$$H^2 = \frac{\rho_R + \rho_{\rm hidden}}{3M_p^2}$$

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

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

[1003.2462 w/ Peng Zhou]

Because of the large k separation between peak k scales relevant for GW measurement

$$\Delta t \sim 10^{12}\ \mathrm{GeV}^{-1}$$

and short distance $(gT_*)^{-1} \sim 0.1\ \mathrm{GeV}^{-1}$ physics scales,

robust and insensitive to computational uncertainties.

Can still suffer from non-standard cosmological dependence.
e.g. late time entropy dilution.

Application: Quintessence BC with kinetic energy dominance

[Barrow, Kamionkowski, Turner, Salati, Rosati, Profumo, Ullio, Pallis, Everett, Matchev,…]

1-parameter class (many functional forms) can be overconstrained

DE
$w'(a) \neq 0$

DM
fix discrepency

LHC

Inflation
no B-mode

need
direct det.

GW
peak and
amplitude
shift

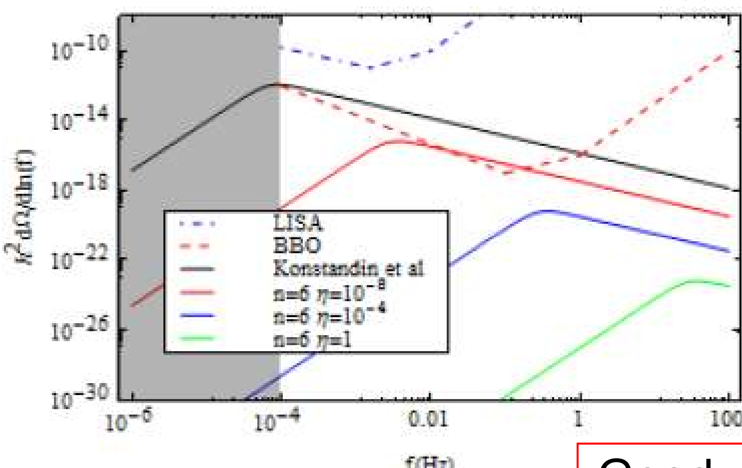
Pamela/
HEAT excess
boost factor

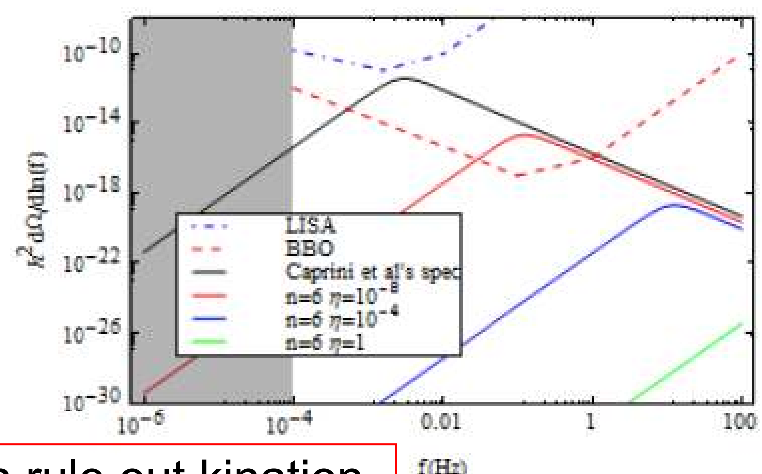
EW Bgenesis
out of equilib

LHC

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

Optimistic example, $\frac{V(\vec{\phi}_i) - V(\vec{\phi}_f)}{\rho_{\rm rad}} = 0.2$ $\quad v_b = 0.82$





[1003.2462 w/ Peng Zhou]

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

Summary

- Measuring the scalar sector sufficiently accurately → BBN of the new century
- $\mu\nu\mathrm{SSM}$ satisfies the 1st order PT requirement for electroweak baryogenesis.
    - Singlet vector rotation during PT is different from NMSSM.
    - T=0 radiative corrections are Important.
- Gravity waves from EW scale PT is a robust probe of the decoupled (from SM) energy contribution to that era.

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

Acknowledgments

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- 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