Phenomenological Connections Between Particle Physics and Dark Energy

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Order of Presentation

- Connecting colliders and cosmology through cosmological constant (CC)
- Using thermal DM conjecture as probe of cosmology: in particular DE both in the forms of CC and quintessence.

Relevance of Particle Physics for Dark Energy

CC (problem) is predicted by particle physics (SM)

- Relevant UV-IR connecting dynamics? Change quantum mechanics?
  - No solid example
- Landscape conjecture: many possibilities for vacuum = tuning through historical reasons
  - Possible (to almost all fine tuning problems) but disappointing
  - Hard to test convincingly

Phase transitions are predicted by particle physics

- QCD phase transition
- Electroweak phase transition

What New Experimental Developments Are "Soon" Expected in Terrestrial Particle Physics?

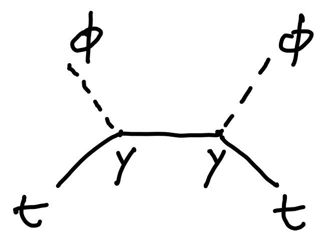
- Measure properties of Higgs sector
  - WW scattering unitary limit of around 2 TeV
  - Electroweak precision fits
- Measure dark matter's non-grav interactions
  - Numerology of thermal relic computation
  - Anomalies in astro/cosmo measurements

Possible connections to dark energy?
Higgs sector → light on electroweak phase transition
Dark matter sector → use thermal relic idea as a probe of cosmology, just as for the situation of BBN

Higgs sector and electroweak phase transition

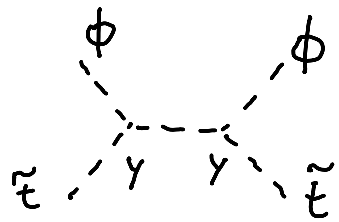
Textbook story: Interaction of the classical Higgs field with the thermal plasma leads to effective interactions that correct the Higgs effective potential.

e.g.



$$\Delta V \sim \underbrace{y^2}_{\text{positive mass contribution}} T^2 \phi^2 + \cdots$$

Bosonic interactions can introduce non-analytic terms.



$$\Delta V \supset \underbrace{y^{3/2}}_{\text{non-analytic in coupling}} \phi^3 T$$

Difference comes from infrared non-analytic behavior as in BE condensations.

These corrections lead to changes in DE contribution.

Accounting for all the fields in any given model is messy but standard.

$$V = V_{T=0} + V_1 + V_{\text{daisy}}$$

$$V_1(\phi_{cli};T) = \sum_b g_b f_B\left(\tilde{m}_b^2(\phi_c l);T\right) + \sum_f g_f f_F\left(\tilde{m}_f^2(\phi_c l);T\right)$$

$$f_B(m^2,T) = -\frac{\pi^2}{90}T^4 + \frac{1}{24}m^2T^2 - \frac{1}{12\pi}\left(m^2\right)^{3/2}T - \frac{(m^2)^2}{64\pi^2}\ln\left(\frac{Q^2}{\tilde{a}_B T^2}\right) \qquad m/T < 2.2$$

$$f_B(m^2,T) = \frac{(m^2)^2}{64\pi^2}\left[\ln\left(\frac{m^2}{Q^2}\right) - \frac{3}{2}\right] - \left(\frac{m}{2\pi T}\right)^{3/2} T^4 e^{-m/T}\left(1 + \frac{15}{8}T/m + \cdots\right) \qquad m/T > 2.2$$

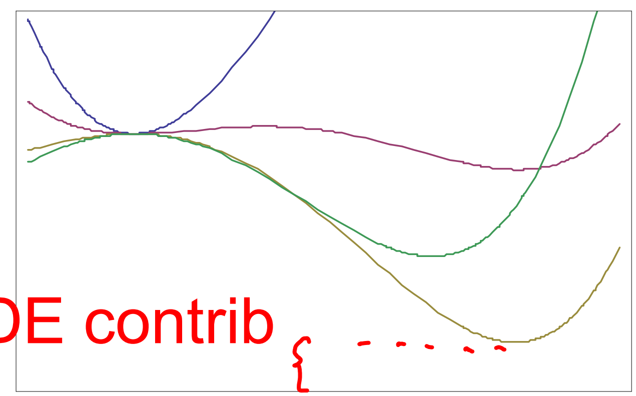
$$f_F(m^2,T) = -\frac{7\pi^2}{720}T^4 + \frac{1}{48}m^2T^2 + \frac{(m^2)^2}{64\pi^2}\ln\left(\frac{Q^2}{\tilde{a}_F T^2}\right) \qquad m/T < 1.9$$

$$f_F(m^2,T) = -\frac{(m^2)^2}{64\pi^2}\left[\ln\left(\frac{m^2}{Q^2}\right) - \frac{3}{2}\right] - \left(\frac{m}{2\pi T}\right)^{3/2} T^4 e^{-m/T}\left(1 + \frac{15}{8}T/m + \cdots\right) \qquad m/T > 1.9$$

$$V_{daisy} = -\frac{T}{12\pi}\sum g_b\left(\bar{m}_b^2(\phi_{cl};T) - \tilde{m}_b^2(\phi_{cl})\right)$$

mass matrix and daisy resummation issues make parametric and constraints sometimes tricky.

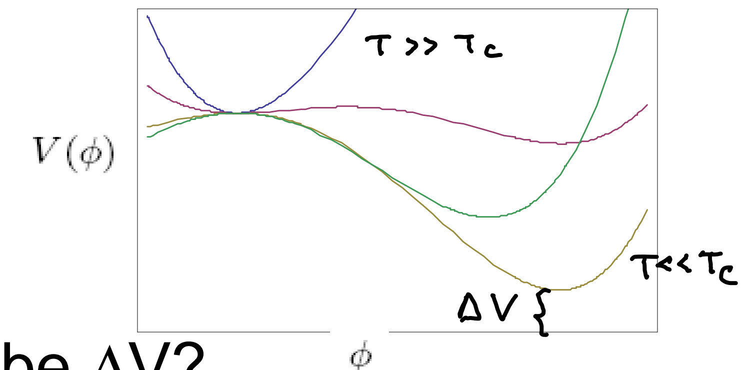
$V(\phi)$



ϕ

Assumptions/properties

1) 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 “solutions.”
2) Vacuum energy can be read off only if the vev is sitting at the local minima and the movement of the vev can be energetically neglected.



How can we probe ΔV?
Anything that can probe H can probe ΔV.
(dark matter, gravity wave, BBN, usual DE probes, etc.)
[ongoing work with Wang, Long, and Tulin]
This then gives an empirical probe of the CC tuning!

Magnitude: How much does H shift typically?

$$V_T(\phi) = (\frac{-1}{2}\mu^2 + c_1(T)T^2)\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4$$

If $E/\lambda \lesssim \sqrt{c_1 T^2 - \frac{1}{2}\mu^2}$

$$\boxed{\frac{\Delta H}{H} \sim \frac{c_1(T)\mu^2}{\lambda g_* T^2}}$$

In SM and extensions with a similar structure, this is small, as it must fight the degree of freedom suppression.

$$\frac{\Delta H}{H} \sim \frac{1}{g_*(100\text{ GeV})} \sim 10^{-2}$$

Reasons:

1) $c_1(T)$ function decreases when T drops below mass thresholds and the mass distribution function is sufficiently unhelpful.

e.g. Yukawa contribution to $c_1(T)$ goes as y^2 and the attendant fermion masses also go as y^2

2) The broken phase has $\langle\phi\rangle \sim T$ during the phase transition.

Examples

$$V_T(\phi) = (\frac{-1}{2}\mu^2 + c_1(T)T^2)\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4 \qquad \frac{\Delta H}{H} \sim \frac{c_1(T)\mu^2}{\lambda g_* T^2}$$

- SM only with T near the phase transition

$$c_1(T) \approx \frac{2m_W^2 + m_Z^2 + 2m_t^2}{8v^2} \approx 0.168 \qquad \frac{\Delta H}{H_U} \lesssim 0.02 \left(\frac{g_*(T)}{100}\right)^{-1} \left(\frac{T}{90\ \text{GeV}}\right)^{-2}$$

- Near 5 GeV: assume b Yukawa coupling is dominant correction to minimal Higgs

$$c_1(T) \approx \frac{m_b^2}{4v^2} \sim 8 \times 10^{-5} \qquad \frac{\Delta H}{H_U} \lesssim 0.01 \left(\frac{g_*(T)}{60}\right)^{-1} \left(\frac{T}{5\text{GeV}}\right)^{-2}$$

Consistently with generic arguments, we have $\mathcal{O}(10^{-2})$

Unfortunately, we will probably need to wait 40 yrs for this kind of precision. However, these are minimal models. We may get lucky to discover Higgs sector with larger effects (model survey is in progress).

DM as new probes of cosmology

- As discussed in the intro, DM property is something new expected to be measured at the LHC. Hence, it is appropriate to explore what we can learn about cosmology from this.
- With thermal relics, we can probe H at the time of freeze out.

cosmology

$$\Omega_M h^2 \propto \left(\frac{T_0}{m_X x_F}\right)^3 \left(\frac{m_X H_F}{\langle \sigma_A v \rangle}\right)$$

Weak cosmo

Particle physics
(electroweak scale)

e.g. In standard cosmology, mass cancels

$$\Omega_M h^2 \propto \left(\frac{T_0}{m_X x_F}\right)^3 \left(\frac{m_X (x_F m_X)^2 / M_p}{\langle \sigma_A v \rangle}\right)$$

$x_F \equiv \dfrac{T_F}{m_X}$ ~1/20 with log dependence on $H_F, \langle \sigma_A v \rangle, m_X$

Possible Future Evidence?

- Suppose: collider measurement

cosmological data

indirect detection

direct detection

astrophysics

$$\Omega_{\chi\,coll\ \ usual} > \Omega_{\chi\,astro}$$

Dilution mechanisms

a) Entropy release (e.g. Thermal infl, late decay)
b) Scalar-tensor gravity
c) More severe modifications of gravity

$$\Omega_M h^2 \propto \left(\frac{T_0}{m_\chi x_F}\right)^3 \left(\frac{m_\chi H_F}{\langle \sigma_A v \rangle}\right)$$

$$\Omega_{\chi\,coll\ \ usual} < \Omega_{\chi\,astro}$$

Enhancement mechanisms

a) Extra contribution to H
b) Scalar-tensor grav. (hep-ph/0302159)
c) More severe modifications to grav
d) More DM candidates (perhaps too weakly interacting for collider measure)

Extra contribution sources for this talk: DE sector

Probing DE sector

$$\frac{\Delta\Omega_{DM}}{\Omega_{DM}} \sim \frac{\Delta H_F}{H_F}$$

- The cosmological constant from the phase transition potential (examples already given)
- What about quintessence?

A defining property of quintessence:

Dynamical d.o.f. → time dependence

Close to z=0, not much different from CC.

Hence, go to the opposite limit: when z >> 3, kination domination is a generic possibility.

A Quintessence Kination Phase

- The key feature that distinguishes quintessence from cosmological constant is $\frac{1}{2}(\partial\phi)^2$
- This is not just about nearly massless particles if homogeneous: "kination phase"

$$\dot{\phi} \propto \frac{1}{a^3} \qquad \rho \propto \dot{\phi}^2 \propto \frac{1}{a^6} \qquad \rho_{rad} \propto \frac{1}{a^4}$$

- A measurement of this object is more about homogeneity and masslessness than minimality of kinetic terms. $\mathcal{L} = \frac{(\partial\phi)^4}{4\Lambda^4} + \frac{(\partial\phi)^2}{2}$

$$\dot{\phi} = \frac{c}{a^3} + \frac{\dot{\phi}^3}{\Lambda^4} = \frac{c}{a^3} + \frac{c^3}{a^9\Lambda^4} + \frac{3c^2}{a^6}\frac{\dot{\phi}^3}{\Lambda^8} + \frac{3c}{a^3}\frac{\dot{\phi}^6}{\Lambda^{12}} + \frac{\dot{\phi}^9}{\Lambda^{12}}$$

A stable phase

parametric dependence (minimally 1 param model):

$$\frac{\rho_\phi}{\rho_\gamma} \sim \frac{\rho_\phi}{\rho_\gamma}\Big|_{BBN} \left(\frac{a_{BBN}}{a}\right)^2$$

$$\eta_\phi \equiv \frac{\rho_\phi}{\rho_\gamma}\Big|_{BBN}$$

Dark matter abundance is boosted:

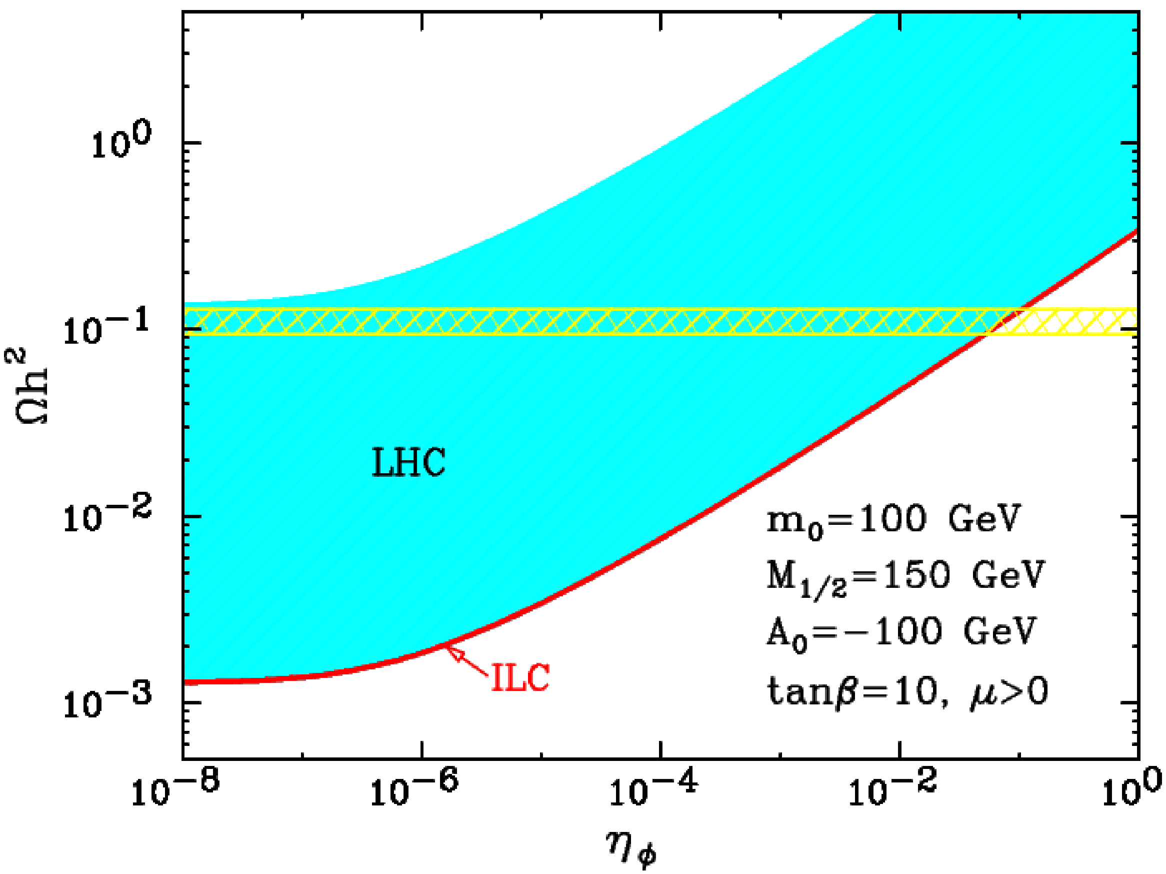
$$\boxed{\begin{array}{ll} \dfrac{\Omega^{(K)}}{\Omega^{(U)}} \sim 10^3 \sqrt{\eta_\phi} \left(\dfrac{m_\chi}{100\,GeV}\right) & for \quad > 1 \\[2ex] \dfrac{\Delta\,\Omega^{(K)}}{\Omega^{(U)}} \sim 10^6\, \eta_\phi \left(\dfrac{m_\chi}{100\,GeV}\right)^2 & for \quad \ll 1 \end{array}}$$

Prediction:

$\eta_\phi > 10^{-8}$ for larger than 1% variation

[with Everett, Kong, Matchev, 07]

In this sense, ILC can measure quintessence!



$$\eta_\phi \equiv \rho_\phi/\rho_\gamma|_{T=1\,\mathrm{MeV}}$$

This propaganda example: LHC/LC's SPS1a (or Peskin et al's LCC1 study point) except with fermion mass shifted lower

Reason for ILC's Improvement: Higgs resonance

Other regions are not as dramatic, but qualitatively similar.

Cosmological Signature

[with Everett and Matchev 07]

- Surprise: Can be ruled out almost model independently if primordial CMB B-modes are observed.
- Assumptions:

  1) There is only one period of inflation.

  2) RH related fields lighter than H exist at the end of inflation.

Reasoning leading to the bound:

1) The minimum radiation temperature at the end of inflation is the dS horizon temperature.

2) Horizon temperature depends on the energy density during inflation: V

V dependent lower bound on ρ_γ

3) The maximum kination energy density is also determined by V

V dependent upper bound on ρ_ϕ

4) Within the foreseeable future, measurement of primordial gravity wave induced B mode requires $V > V_{min}$

5) Hence, measurement of primordial B-mode gives an upper bound on $\eta_\phi \equiv \left(\frac{\rho_\phi}{\rho_\gamma}\right)_{BBN}$

$$\eta_\phi \ll 10^{-8}$$

6) 1% enhancement of Ω_M from the usual scenario requires $\eta_\phi > 10^{-8}$

Beyond Falsification

Kination conjecture

DE

$w'(a) \neq 0$

[astro-ph/0207396, hep-ph/0309220, 0704.3285]

DM

fix discrepency [astro-ph/0207396, hep-ph/0309220, 0706.2375]

Inflation

no B-mode [0704.3285]

GW

peak shift [0704.3285] details of spectrum [w/ Zhou in progress]

Pamela/ HEAT excess

i) boost factor [0704.3285]

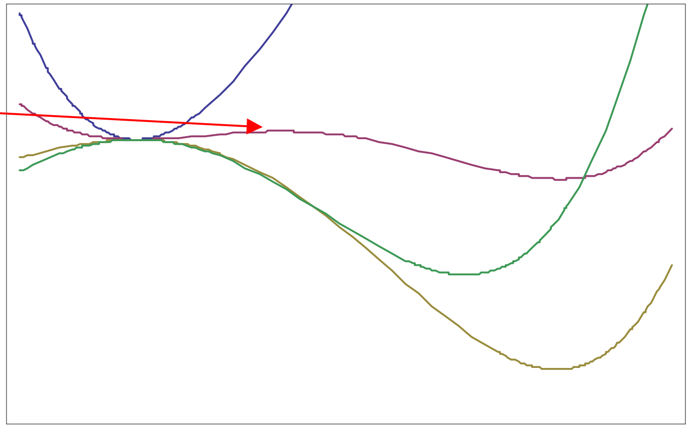
ii) model dep. [w/ Everett, Wang In progress]

EW Bgenesis

out of equilib [0704.3285] details needs work

Bubbles during EWPT

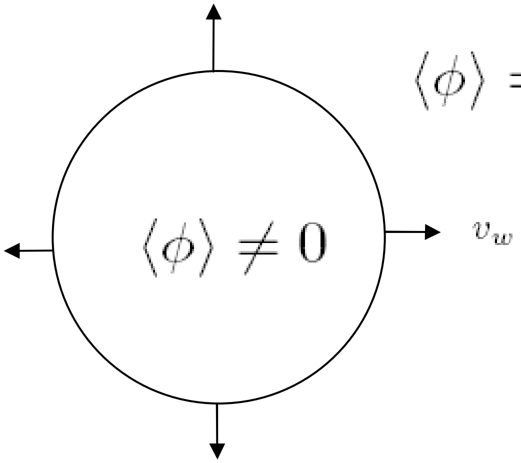
$$V_T(\phi) = (\frac{-1}{2}\mu^2 + c_1(T)T^2)\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4$$



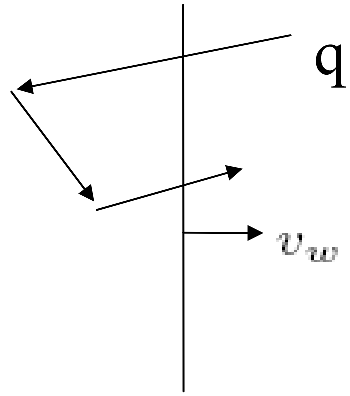
$$\Gamma(t) = A(t)e^{-S(t)}$$

$$S_3 = \int 4\pi r^2 dr \left[\frac{1}{2}\left(\frac{d\phi_b}{dr}\right)^2 + V(\phi_b, T)\right]$$

$$\frac{d^2\phi_b}{dr^2} + \frac{2}{r}\frac{d\phi_b}{dr} - \frac{\partial V}{\partial \phi_b} = 0, \quad \text{with} \quad \left.\frac{d\phi_b}{dr}\right|_{r=0} = 0 \quad \text{and} \quad \phi_b|_{r=\infty} = 0$$



Need for B-genesis:



$\langle\phi\rangle \neq 0$

$\langle\phi\rangle = 0$

sphalerons active

$\Delta(n_b^L - n_{\bar{b}}^L)$

sphalerons inactive

$$n_b - n_{\bar{b}} = n_b^L + n_b^R - n_{\bar{b}}^L - n_{\bar{b}}^R \neq 0$$

e.g. 1 generation $u_R \to u_R$

$\bar{u}_L \to d_L d_L \nu_e \qquad B=1$

$\hookrightarrow \overline{u}_L \overline{d}_L \overline{\nu}_e \qquad B=0$

To forbid, need small $\Gamma \propto \exp[-\frac{E_{sph}(T_c)}{T_c}]$

$$\frac{E_{sph}(T_c)}{T_c} \geq 37 - 45$$

Typical model param const: $\frac{c_1(T)E}{\lambda^{3/2} 246\ \mathrm{GeV}} \gtrsim 1$ Good for bubbles.

$$V_T(\phi) = (\frac{-1}{2}\mu^2 + c_1(T)T^2)\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4$$

Many examples possible in beyond SM

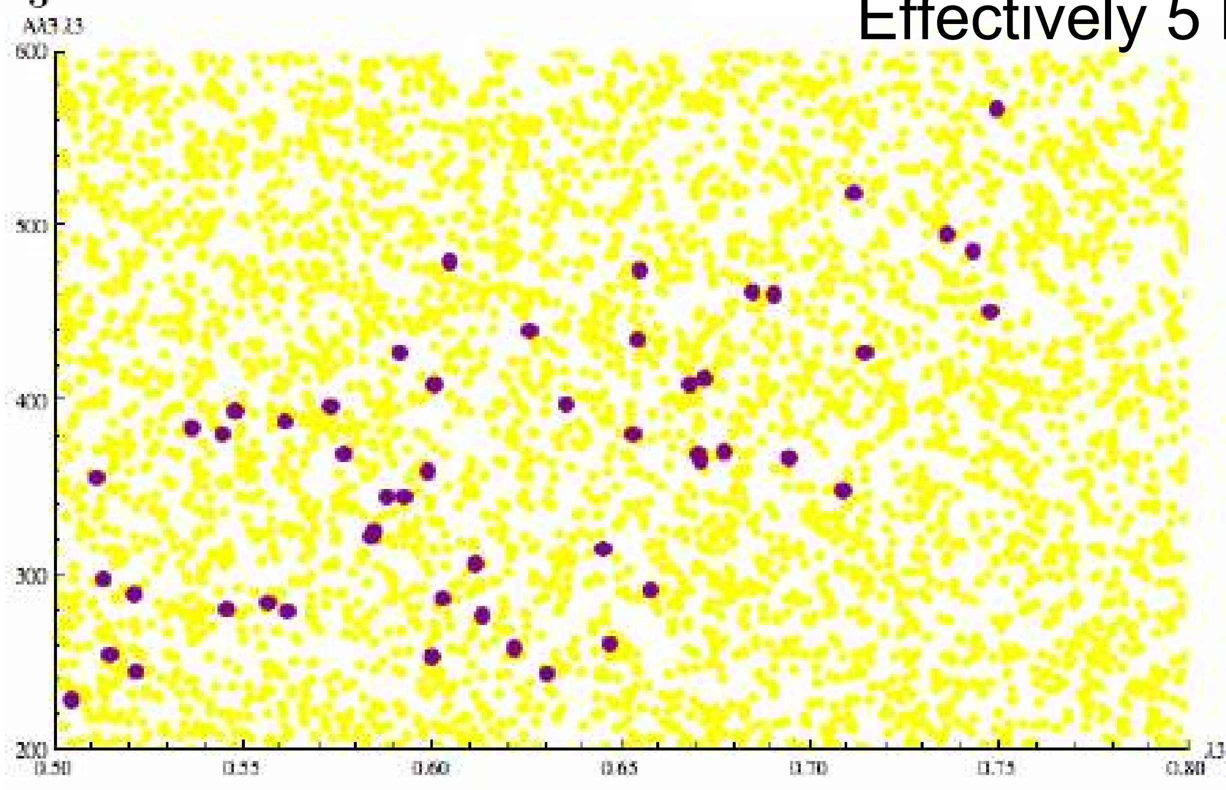
e.g. Consider usual Z_3 based NMSSM with the addition of economical assumption of singlet playing RH neutrino.

$$W = \epsilon_{ab}\left(Y_u^{ij}\hat{H}_2^b\hat{Q}_i^a\hat{u}_j^c + Y_d^{ij}\hat{H}_1^a\hat{Q}_i^b\hat{d}_j^c + Y_e^{ij}\hat{H}_1^a\hat{L}_i^b\hat{e}_j^c + Y_\nu^{ij}\hat{H}_2^b\hat{L}_i^a\hat{\nu}_j^c\right) - \epsilon_{ab}\lambda^i\hat{\nu}_i^c\hat{H}_1^a\hat{H}_2^b + \frac{1}{3}\kappa^{ijk}\hat{\nu}_i^c\hat{\nu}_j^c\hat{\nu}_k^c$$

$$V_{soft} \ni \frac{1}{3}A_{\kappa_3}\kappa_3\left(\tilde{\nu_\tau}^c\right)^3 - A_{\lambda_3}\lambda_3\epsilon_{ab}H_1^aH_2^b\tilde{\nu_\tau}^c$$

[hep-ph/0508297, 0810.1507]

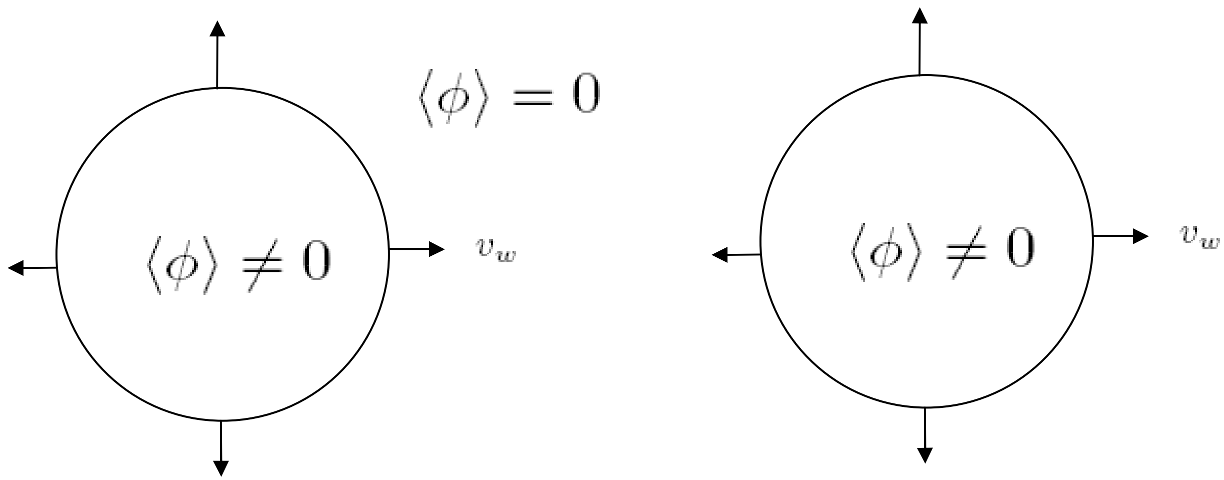
Effectively 5 D param space.



$$\frac{c_1(T)E}{\lambda^{3/2}246\ \mathrm{GeV}} \gtrsim 1$$

[w/ A. Long in progress]

Bubble collisions may even generate observable gravity waves.

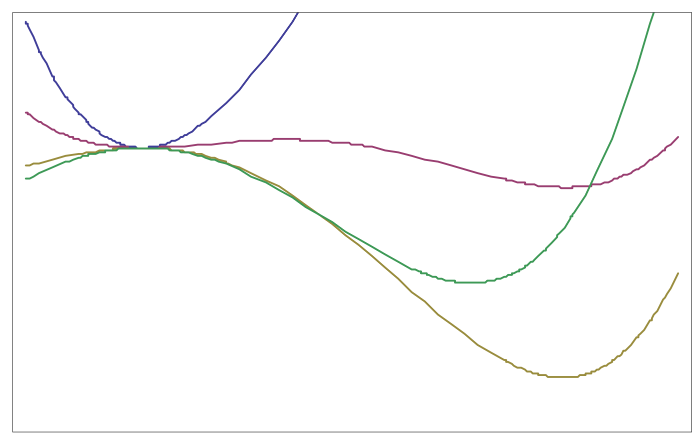


$$\Gamma(t) = A(t)e^{-S(t)}$$

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

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

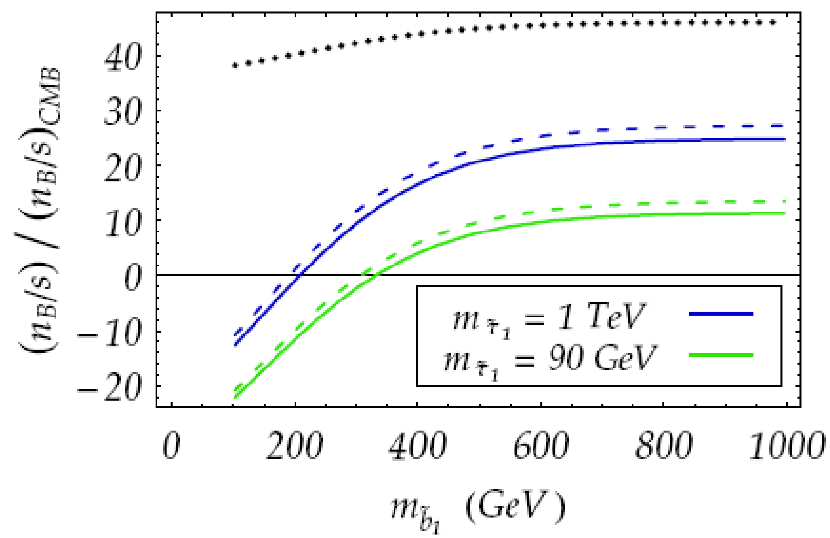
$$\Delta t = t_f - t_i \propto \frac{1}{|\frac{dS}{dt}|} = \boxed{\frac{1}{H}\frac{1}{\frac{dS}{d\ln T}}}$$



End game is important.

Aside: interesting new developments in EW baryogenesis

[with Garbrecht, Ramsey-Musolf, Tulin 08]



People wrongly neglected the bottom Yukawa: may even get the wrong sign.

Gravity Wave at EWPT

Following arguments of 0711.2593 and astro-ph/9310044:

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

$$\langle \tilde{T}_{ij}(t_1',\vec{k}_1)\tilde{T}_{ij}(t_2',\vec{k}_2)\rangle \sim \delta^{(3)}(\vec{k}_1-\vec{k}_2)P_{k_1}(t_1',t_2')\left[\rho_B\gamma^2 v_w^2\right]^2$$

$$\frac{d\rho_{GW}}{d\ln k}|_0 \sim \frac{1}{M_p^2}\left(\frac{a_{PT}}{a}\right)^4\left[\rho_B\gamma^2 v_w^2\right]^2\int dt_1' dt_2' \cos\left[k(t_1'-t_2')\right]\left[k^3 P(k,t_1',t_2')\right]$$

disconnected diagram energy scaling

propagation

Spatial dependence of correlator: bubble wall spatial distribution /deformations

uncertain

See 0901.1661 and
Caprini and Durrer 06 for a discussion of uncertainties.

Spectrum shift?

$$\frac{d\rho_{GW}}{d\ln k}|_0 \sim \frac{1}{M_p^2}\left(\frac{a_{PT}}{a}\right)^4 \left[\rho_B \gamma^2 v_w^2\right]^2 \int dt_1' dt_2' \cos\left[k(t_1'-t_2')\right]\left[k^3 P(k,t_1',t_2')\right]$$

What is the characteristic size governing P?
Characteristic size of the colliding region. There are two obvious length scales: duration of the phase transition and the size of the typical bubble.

$$\frac{1}{R} \sim \frac{1}{v_w \Delta t} \propto H \qquad\qquad \frac{1}{\Delta t} \propto H$$

$$\boxed{k^3 P(kR^{(U)}, k\Delta t^{(U)}) \to k^3 P\left(kR^{(U)}\frac{H^{(U)}}{H^{(Q)}}, k\Delta t^{(U)}\frac{H^{(U)}}{H^{(Q)}}\right)}$$

$$\boxed{k_P \to k_P \frac{H^{(Q)}}{H^{(U)}}}$$

Caveat: other dynamical length scales may exist + bubble interactions have been implicitly neglected.

Estimates

[prelim: with Zhou]

Good news:

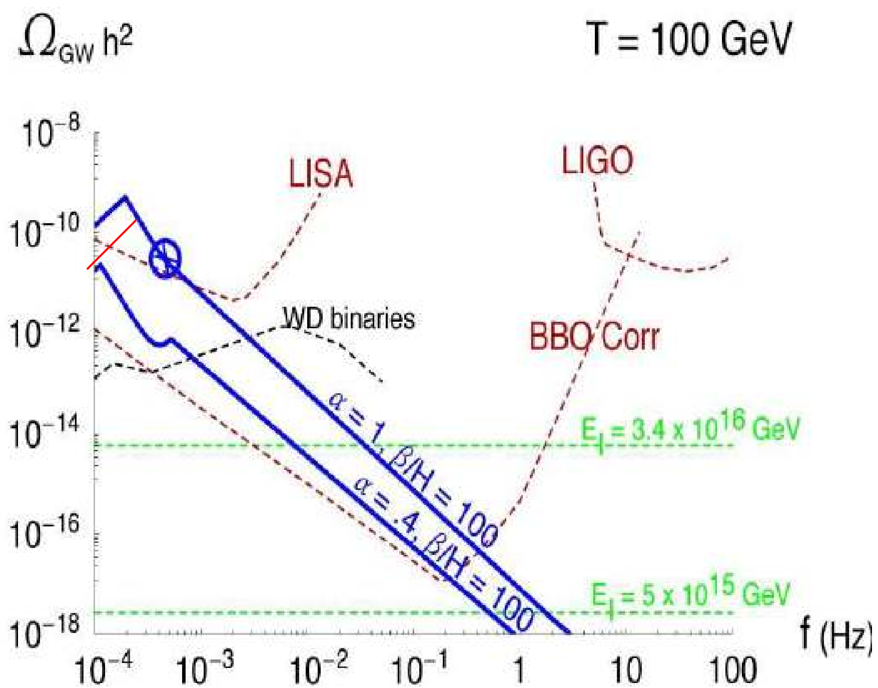
$$f_*^{(Q)} \approx 10^5 \eta_\phi \left(\frac{T_{PT}}{10^2\ \mathrm{GeV}} \right) f_*^{(U)}$$

Sensitive probe

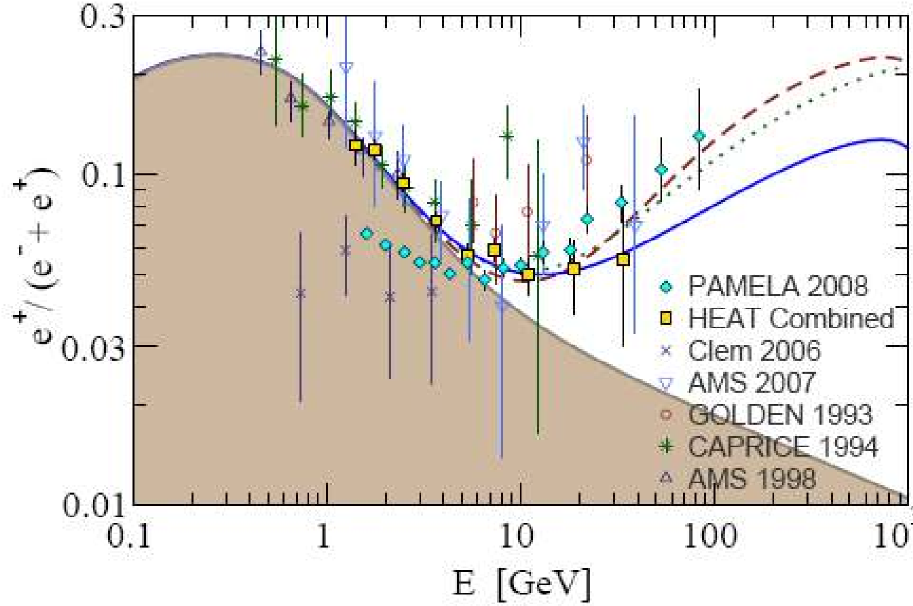
Bad news:

$$\left.\frac{d\rho_{GW}}{d\ln k}^{(Q)} \middle/ \frac{d\rho_{GW}}{d\ln k}^{(U)} \right|_{\text{rising}} \sim \left[10^5 \eta_\phi \left(\frac{T_{PT}}{10^2\ \mathrm{GeV}} \right) \right]^{-2}$$

hep-ph/0607107



Pamela?



[plot from 0810.2784]

Efficiency of annihilation to explain positron excess gives too low density in standard scenario.
[Baltz, Edsjo, Freese, Gondolo 01]

This can be evaded by the nonstandard cosmology scenario presented here.

Boost factors of 10-1000 easily achievable.

Problems with antiprotons, but enough uncertainty may exist. [0812.4555]

[model exploration in progess w/ Everett and Wang]

Conclusions

- Fine tuned CC conjecture may be testable by combining collider data and cosmology:

$$\frac{\Delta H}{H} \sim \frac{c_1(T)\mu^2}{\lambda g_* T^2}$$

- DM candidate detection at collider presents an interesting new probe of early universe cosmology: examples – CC and quint. kination
- Kination signatures:
  - » $w'(a) \neq 0$
  - » Discrepancy between colliders and cosmology
  - » No B-mode measurement
  - » GW peak spectral change
  - » Positron excess
  - » EW Baryogenesis