Title: Phenomenological Connections between Particle Physics and Dark Energy

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Abstract: I explore possible connections between the Higgs sector and dark energy

Phenomenological Connections Between Particle Physics and Dark Energy

Daniel Chung
(University of Wisconsin – Madison)

Order of Presentation

- Connecting colliders and cosmology through cosmological constant (CC).
- Using thermal DM conjecture as probe of cosmology (similar to BBN): in particular CC.
- Using gravity waves as a probe.

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

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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 and symmetry restoration.

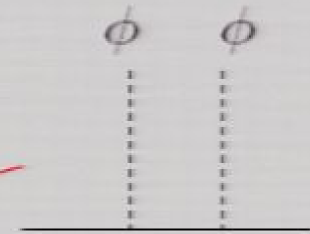
$$e^{-\frac{\Omega}{T}V(\phi)} \sim \int D\bar{\psi} D\psi \exp\left(-S_E[\bar{\psi}, \psi, \phi]\right)$$

1-loop thermal
= ideal gas

$$\rho_f \sim \omega n \sim \frac{\omega^4}{e^{\omega/T}+1} \sim \omega^4$$

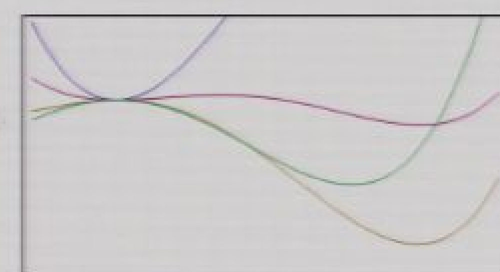
$$\omega \sim \sqrt{T^2 + y^2\phi^2}$$

$$\sim T\left[1 + \frac{1}{2}\frac{y^2\phi^2}{T^2}\right]$$



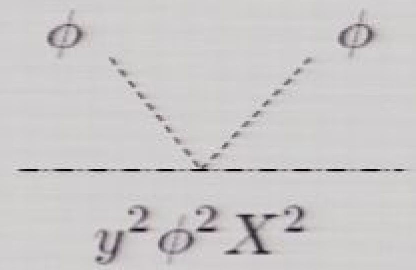
$$\rho_f \sim T^4\left[1 + 2\frac{y^2\phi^2}{T^2}\right]$$

$$\sim T^4 + 2y^2\phi^2T^2$$



Bosons can give non-analytic contributions.

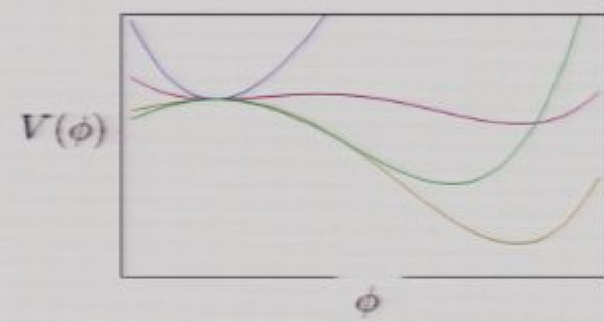
$$\rho_b \sim \omega n \sim \frac{\omega^4}{e^{\omega/T}-1} \sim T\omega_0^3 + \omega^4$$



$$\omega_0 = \sqrt{0 + y^2\phi^2}$$

$$\rho_b \sim T\left(y^2\phi^2\right)^{3/2} + T^4 + 2y^2\phi^2T^2$$

Can be important for 1st order PT.



$$V_{\text{dof}}(T,\phi) = \frac{T}{2\pi^2}\int_0^\infty dq q^2 \ln\left[1 \pm \exp\left(-\frac{\sqrt{q^2+m^2(\phi)}}{T}\right)\right]$$

Accounting for all the fields:

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

$$V_T(\phi) = V_{T=0} + V_1 + V_{\rm daisy}$$

$c_1(T)$ discrete

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

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

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

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

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

These corrections lead to changes in DE contribution.

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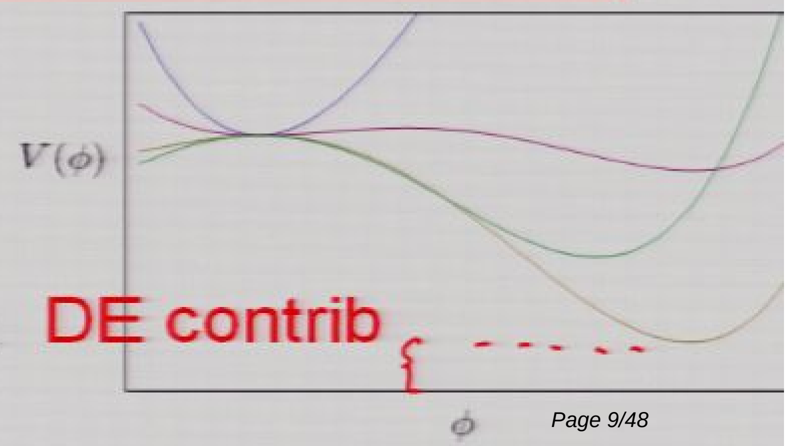
zero T renormalization issues make
parametric constraints difficult and ugly.



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$y^2\phi^2 X^2$

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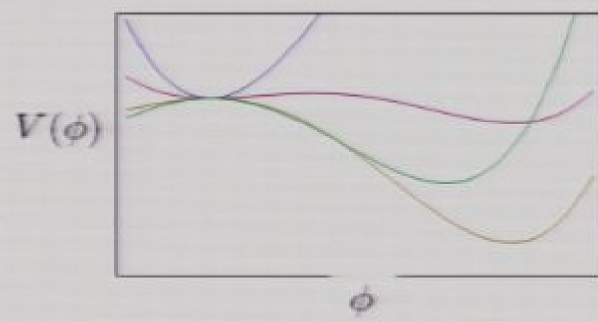

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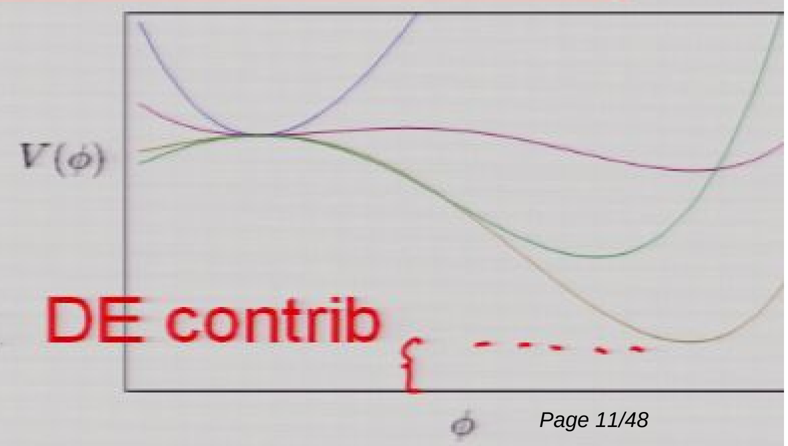


Assumptions/properties

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 ideas.

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

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

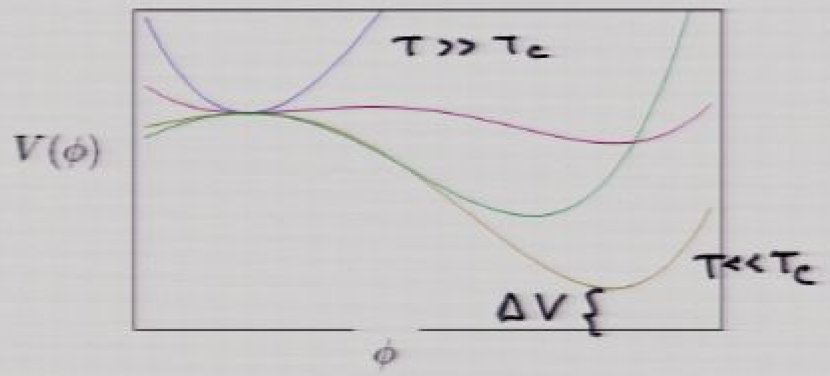
2) Vacuum energy can be read off only if the vev is sitting at the local minima and the movement of the vev can be energetically neglected.

$$= K + U(\phi_j) \mp T \lim_{\lambda\to 1} \frac{d}{d\lambda} \sum_i \lambda^{-3} \int \frac{d^3\tilde{p}}{(2\pi)^3} \left\{ \ln\left(1 \pm e^{-\frac{1}{T}(\tilde{\omega}_i(\phi_j)-\mu_i)}\right) + \ln\left(1 \pm e^{-\frac{1}{T}(\tilde{\omega}_i(\phi_j)+\mu_i)}\right.\right.$$

$$\omega_i = \sqrt{p^2 + m_i^2(\phi_j)}\ ,\ \tilde{\omega}_i \equiv \sqrt{\tilde{p} + \lambda^2 m_i^2(\phi_j)},\ \tilde{p} \equiv \lambda p$$

$$\rho = -P + Ts + \sum_i \mu_i n_i \qquad -V_T(\phi) + \ldots$$

$$P = K - U(\phi_j) \pm T \sum_i \int \frac{d^3p}{(2\pi)^3} \left\{ \ln\left(1 \pm e^{-\frac{1}{T}(\omega_i(\phi_j)-\mu_i)}\right) + \ln\left(1 \pm e^{-\frac{1}{T}(\omega_i(\phi_j)+\mu_i)}\right)\right\}$$



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!

Shift in H Compared to What?

$$= K + U(\phi_j) \mp T \lim_{\lambda \to 1} \frac{d}{d\lambda} \sum_i \lambda^{-3} \int \frac{d^3\tilde{p}}{(2\pi)^3} \left\{ \ln\left(1 \pm e^{-\frac{1}{T}(\tilde{\omega}_i(\phi_j)-\mu_i)}\right) + \ln\left(1 \pm e^{-\frac{1}{T}(\tilde{\omega}_i(\phi_j)+\mu_i)}\right)\right.$$

negligible

$\phi_j(T) \neq \phi_j(T=0)$

At 1-loop level, this correction is automatically taken care of by using ordinary Boltzmann equations with the right thermal/field dependent masses.

$$\frac{\Delta H}{H} = \frac{\Delta \rho}{2\rho_{\text{without U}}} = \frac{\rho_{\text{with U}} - \rho_{\text{without U}}}{2\rho_{\text{without U}}}$$

If there exists a relaxation mechanism for the cosmological constant which makes U contribution vanish or “different”, measurement of $\frac{\Delta H}{H}$ will constrain such mechanisms.

Key hope: Colliders will allow us to measure the Higgs sector sufficiently accurately and cosmological probes will improve.

Magnitude: How much does H shift typically?

$$V_T(\phi) = \left(\frac{-\mu^2 + cT^2}{2}\right)\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{\mu^4}{4\lambda}$$

neglect cubic

$$U(\phi_m(T)) = \frac{c^2 T^4}{4\lambda}$$

$$\rho_{\text{no field}} = \frac{\pi^2}{30} g_*(T) T^4 + \mathcal{O}\left(\left[\frac{m}{T}\right]^2\right)$$

$$\frac{\Delta H}{H} = \frac{15}{4\pi^2}\frac{c^2}{\lambda}\frac{1}{g_*}$$

Large!!

$$c(T) \approx \frac{1}{24}\sum_b g_b\left(\frac{1}{2}\partial_\phi^2 m_b^2(0)\right)\Theta\left(T - \frac{m_b}{2}\right) + \frac{1}{48}\sum_f g_f\left(\frac{1}{2}\partial_\phi^2 m_f^2(0)\right)\Theta\left(T - \frac{m_f}{2}\right) \text{ if Taylor expandab}$$

SM:

Simplify to gain intuition.

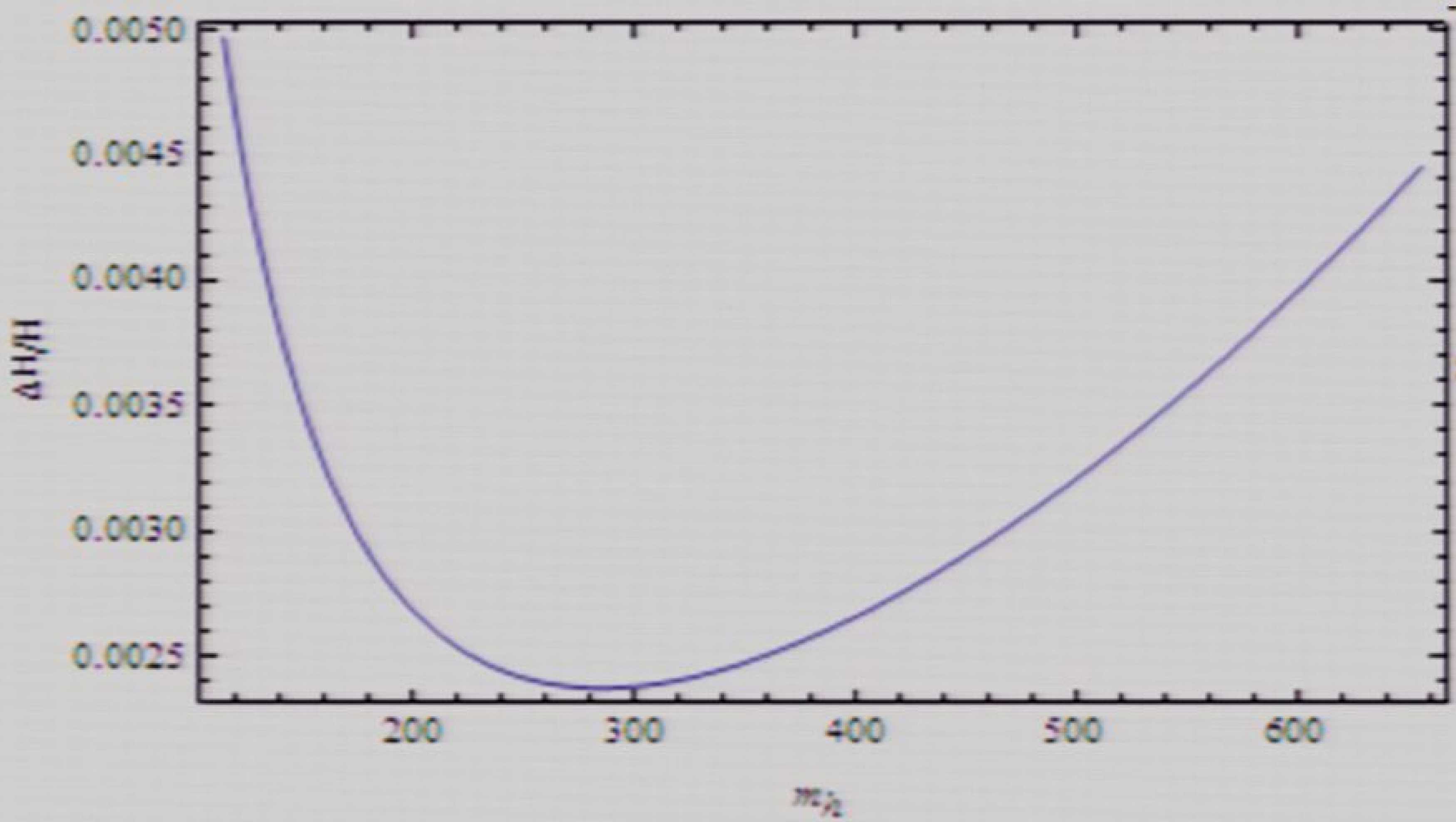
$$g_* = 106.75$$

$$\lambda = \frac{m_h^2\,\text{tree}}{2\,(246 \text{ GeV})^2}$$

$$c(T \sim 100 \text{ GeV}) \approx \frac{1}{4}\left\{\frac{3}{4}g^2 + \frac{g'^2}{4} + y_t^2 + \frac{m_h^2\,\text{tree}(0)}{(246 \text{ GeV})^2}\right\}$$

Maximum when the Higgs mass is small or large.

SM



n.b. Error increases on both ends.

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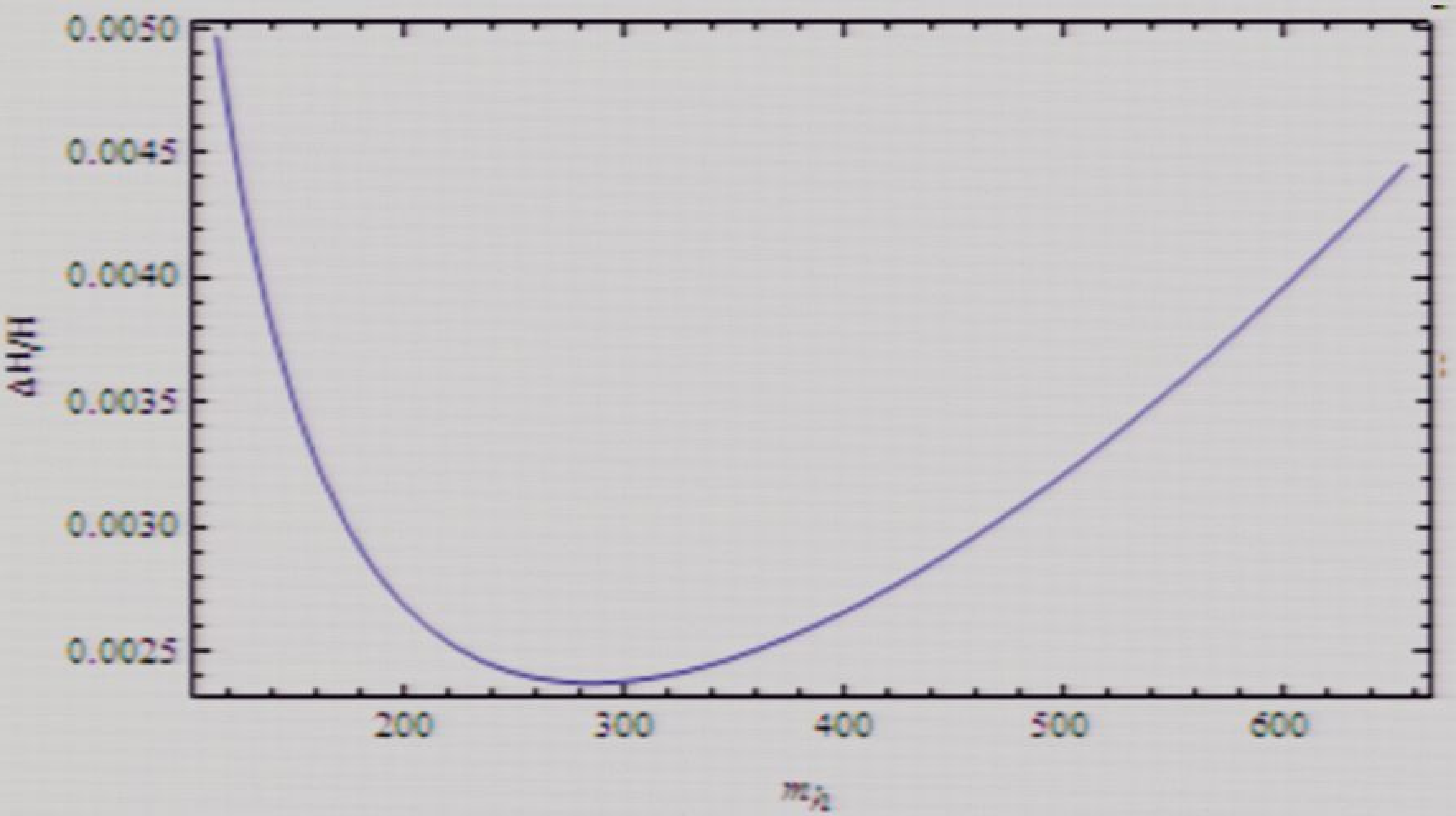

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Lesson

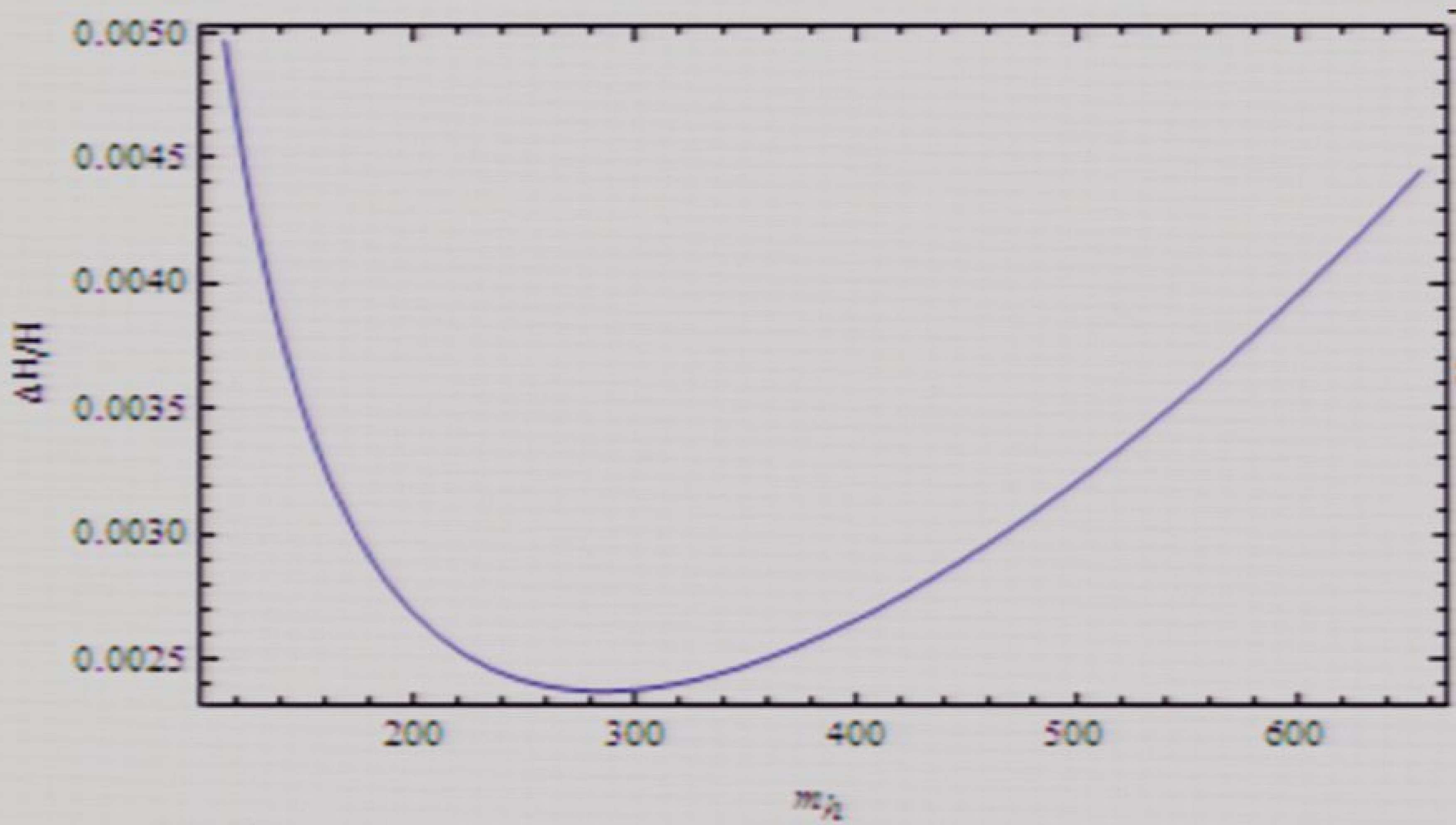
In SM and extensions with a similar structure, desired deviation is small, as it must fight the degree of freedom suppression.

i.e. Energy = partitioned among g_*

Higgs effects few species counted in g_* $\longrightarrow$ pressure

Force driving vev to true min is balanced by this pressure.

SM



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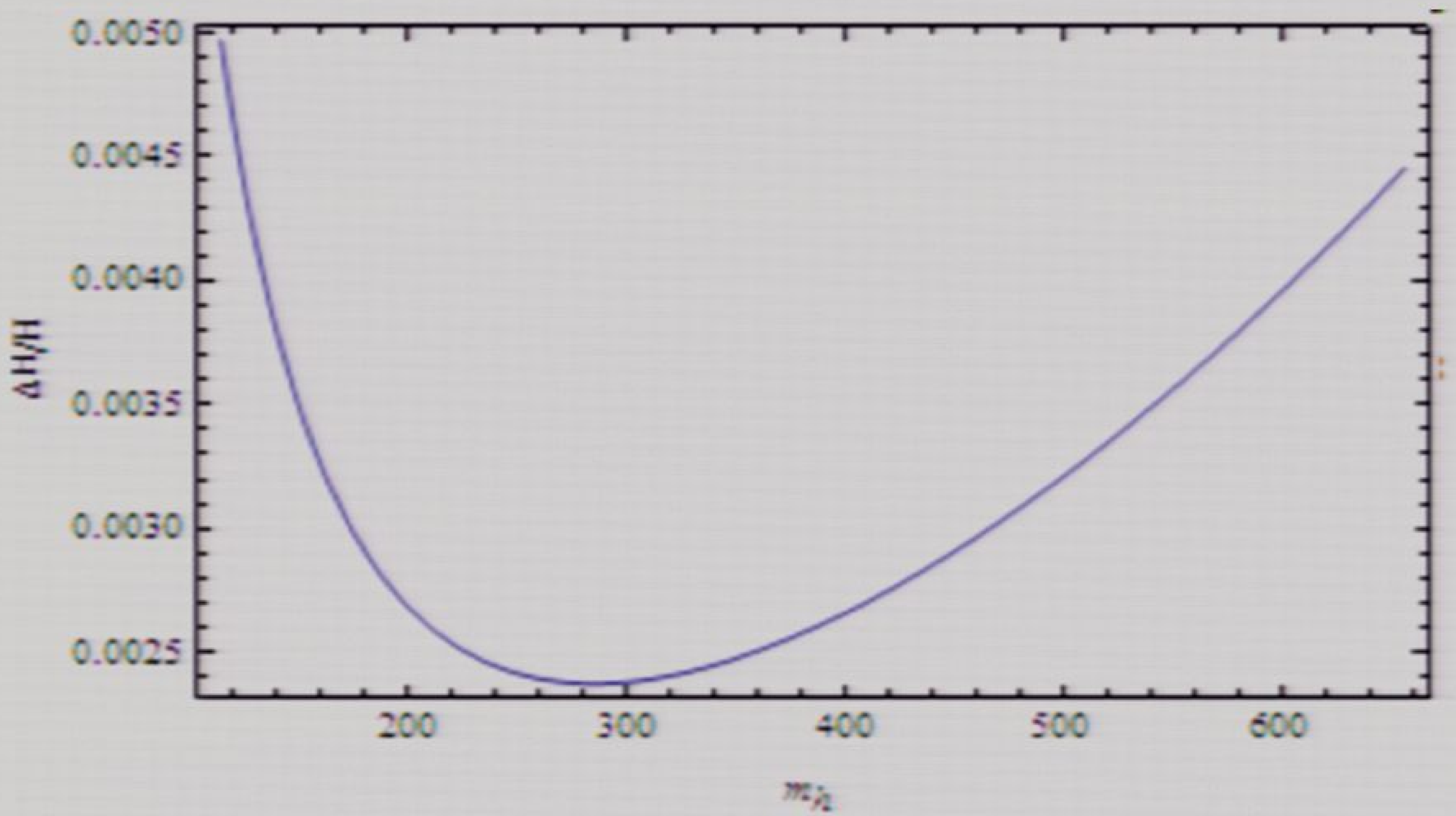

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Force driving vev to true min is balanced by this pressure.

Lower Temperature?

$$\frac{\Delta H}{H} = \frac{15}{4\pi^2}\frac{c^2}{\lambda}\frac{1}{g_*}$$

e.g.

$$g_*(T = 10\text{ MeV}) = 10.75$$

Unfortunately, this does not work SM.

$$c(T) \approx \frac{1}{24}\sum_b g_b\left(\frac{1}{2}\partial_\phi^2 m_b^2(0)\right)\Theta\left(T-\frac{m_b}{2}\right)+\frac{1}{48}\sum_f g_f\left(\frac{1}{2}\partial_\phi^2 m_f^2(0)\right)\Theta\left(T-\frac{m_f}{2}\right) \text{ if Taylor expandable}$$

$$\partial_\phi^2 m_X^2 \sim \frac{m_X^2}{(246\text{ GeV})^2} \lesssim \frac{T^2}{(246\text{ GeV})^2}$$

Beyond SM?

- From generic arguments given before, natural models are unlikely to give orders of magnitude enhancement. (Explicitly checked form MSSM and nMSSM.)
- Fine tuned multiple scalar models should exist (something like hybrid inflation).

Extreme: If entering into inflation is desired,

$$\left|\frac{M_p V'(\phi)}{V(\phi)}\right| \ll \left|\frac{\phi_f}{M_p}\right|$$

Model survey is in progress.

Probes

- Even if we could obtain a significantly larger $\frac{\Delta H}{H}$, how would we probe them if the effects are near T=100 GeV?
    - DM
    - Gravity waves
    - Baryogenesis

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

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

$x_F \equiv \frac{T_F}{m_X}$ ~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

) Entropy release (e.g. Thermal infl, late decay)

) Scalar-tensor gravity

) 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/030215

c) More severe modifications to grav

d) More DM candidates (perhaps too weakly interacting for collider measure

Stay tuned for Lisa Everett's talk focusing on the particle physics signature aspect of the dark matter method.

CC shift near 100 GeV?

Tuned CC conjecture

DM

fix discrepency

Requires heavy dark matter since

$$m_X \approx 1\text{TeV}\left(\frac{T_F}{50\text{ GeV}}\right)$$

GW

EW Bgenesis

Other conjectures are better overconstrained

Kination conjecture
(see Lisa Everett's talk for detail of scenario)

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.

EW Bgenesis
out of equilib
[0704.3285]
details needs work

Bubbles during EWPT

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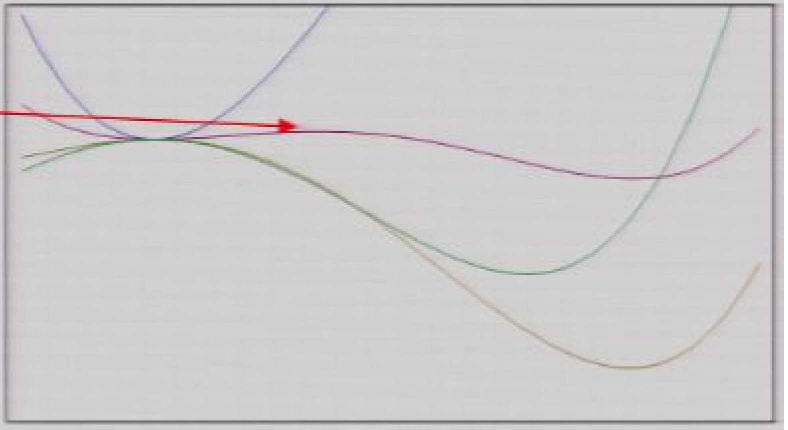
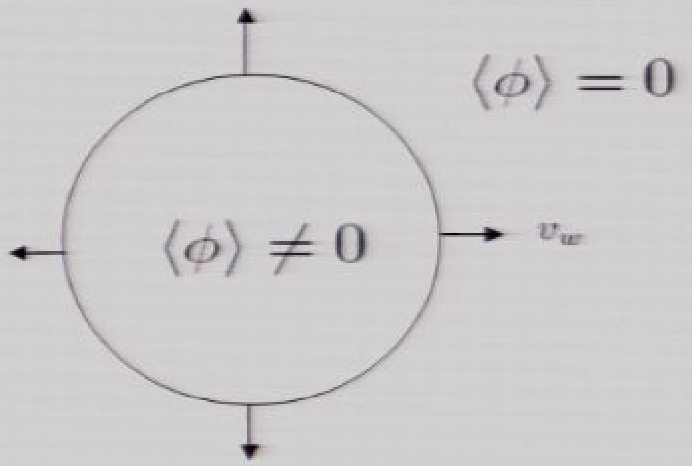


$$\Gamma(t) = A(t)e^{-S(t)}$$

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

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



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a) Extra contribution to H

b) Scalar-tensor grav. (hep-ph/03021

c) More severe modifications to grav

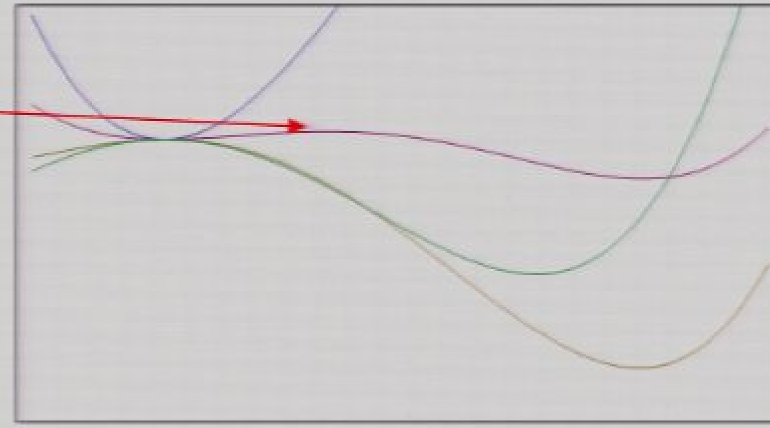
d) More DM candidates (perhaps too

weakly interacting for collider measur

Stay tuned for Lisa Everett's talk focusing on the particle physics signature aspect of the dark matter method.

Bubbles during EWPT

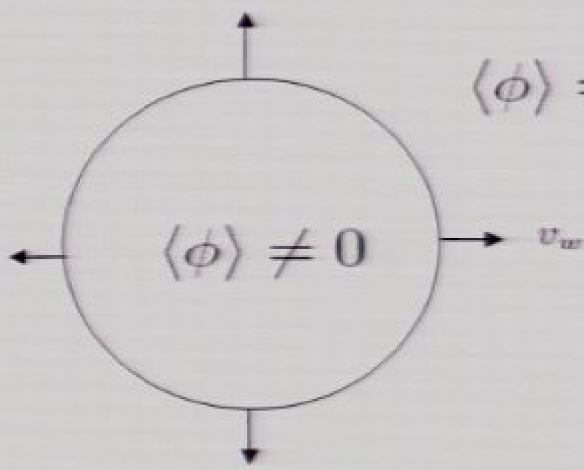
$$V_T(\phi) = (\frac{-1}{2}\mu^2 + c_1(T)T^2)\phi^2 - E\phi^3 + \frac{\lambda}{4}\phi^4$$



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

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

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



CC shift near 100 GeV?

Tuned CC conjecture

DM

fix discrepency

Requires heavy dark matter since

$$m_X \approx 1\text{TeV}\left(\frac{T_F}{50\ \text{GeV}}\right)$$

GW

EW Bgenesis

Bubbles during EWPT

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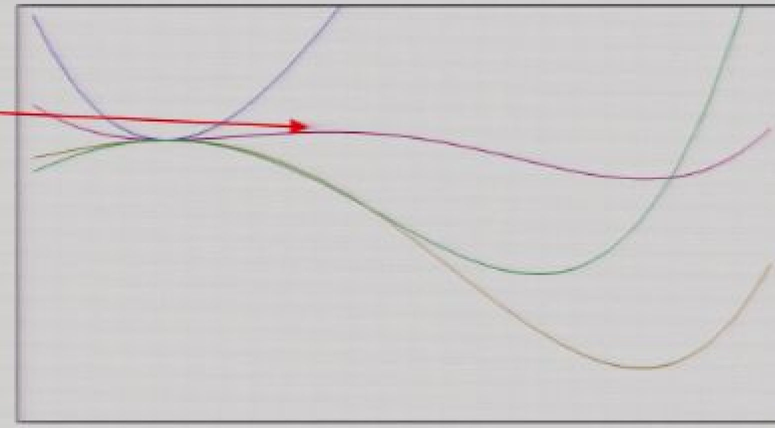

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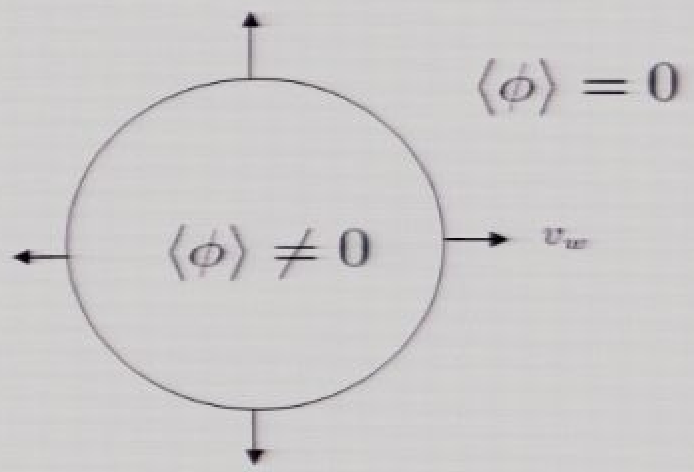


Many examples possible in beyond SM

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

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

[hep-ph/0508297, 0810.1507]

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

Effectively 5 D param space.

[related hep-ph/9207227]

$$\frac{v(T_c)}{T_c} = \frac{2\sqrt{2c_1}E}{\lambda^{3/2}v(0)\sqrt{\left(1-\frac{E}{\lambda v(0)}\right)\left(1-\frac{2E}{\lambda v(0)}\right)}}$$

$$\left\{0 \le \frac{E}{\lambda v(0)} \le \frac{1}{2}, 0 \le \sqrt{\frac{c_1}{\lambda}} \le \infty\right\}$$

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

[w/ A. Long in progress]

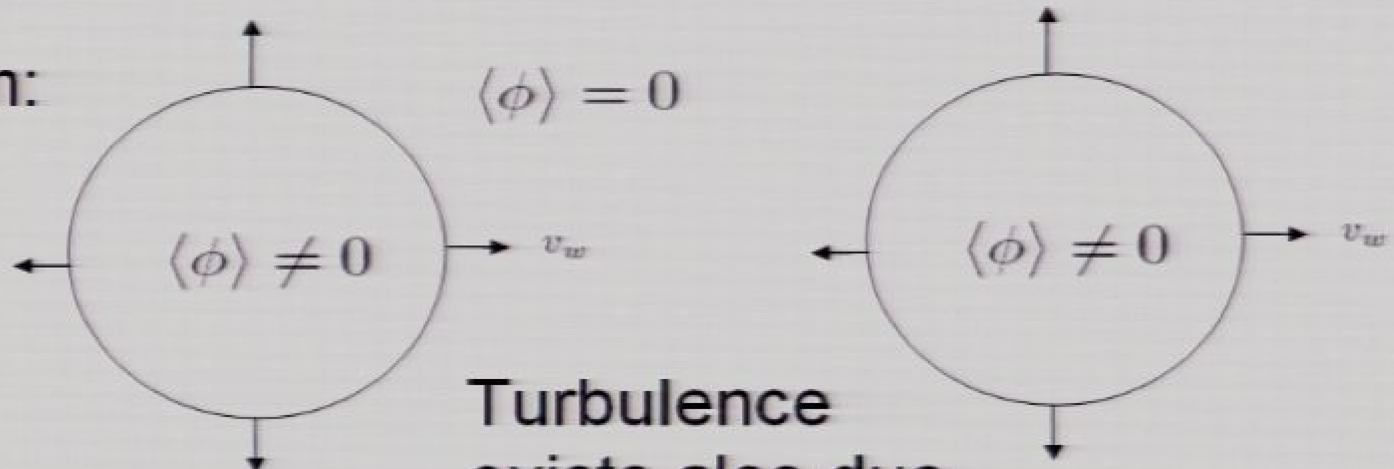
$$\lambda \approx \frac{4v_{\nu^c}^4}{\left(v^2+v_\nu^2+v_{\nu^c}^2\right)^2}\left[\kappa_3^2 + \frac{v^2}{v_{\nu^c}^2}\left(\lambda_3^2 - \kappa_3\lambda_3\sin 2\beta\right) + \right.$$
$$\left. + \frac{v^4}{16v_{\nu^c}^4}\left\{(g_1^2+g_2^2)(1+\cos 4\beta) + 4(\lambda_1^2+\lambda_2^2+\lambda_3^2)\sin^2 2\beta\right\}\right]$$

$$E \approx \frac{v_{\nu^c}^3}{3\left(v^2+v_\nu^2+v_{\nu^c}^2\right)^{3/2}}\left(3\frac{v^2}{v_{\nu^c}^2}\tilde{A}_{\lambda_3}\sin 2\beta - 2\tilde{A}_{\kappa_3}\right)$$

$$c_1 = \frac{1}{2v}\left[\frac{2v_{\nu^c}^2}{3}\kappa_3^2 + \frac{v^2}{2}\left(\lambda_1^2+\lambda_2^2\right) + \frac{2v^2+3v_{\nu^c}^2}{4}\lambda_3^2 + \frac{3g_1^2+8g_2^2}{12}v^2 + \frac{3m_t^2}{2} + f\left(\beta, v_\nu, v_{\nu^c}, Y_i\right)\right]$$

Bubble collisions may even generate observable gravity waves.

Detonation:



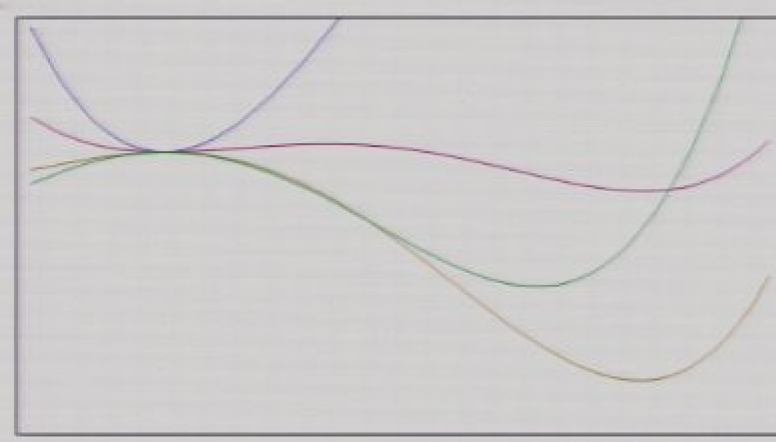
Turbulence exists also due to stirring.

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

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

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

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



End game is important.

Gravity Wave at EWPT

Following arguments of 0711.2593 and astro-ph/9310044:

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

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

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

- $\left[\rho_B\gamma^2 v_w^2\right]^2$: disconnected diagram energy scaling
- $\cos\left[k(t_1'-t_2')\right]$: propagation
- $\left[k^3 P(k,t_1',t_2')\right]$: Spatial dependence of correlator: bubble wall spatial distribution /deformations

uncertain (between disconnected diagram energy scaling and spatial dependence of correlator)

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

Conclusions

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

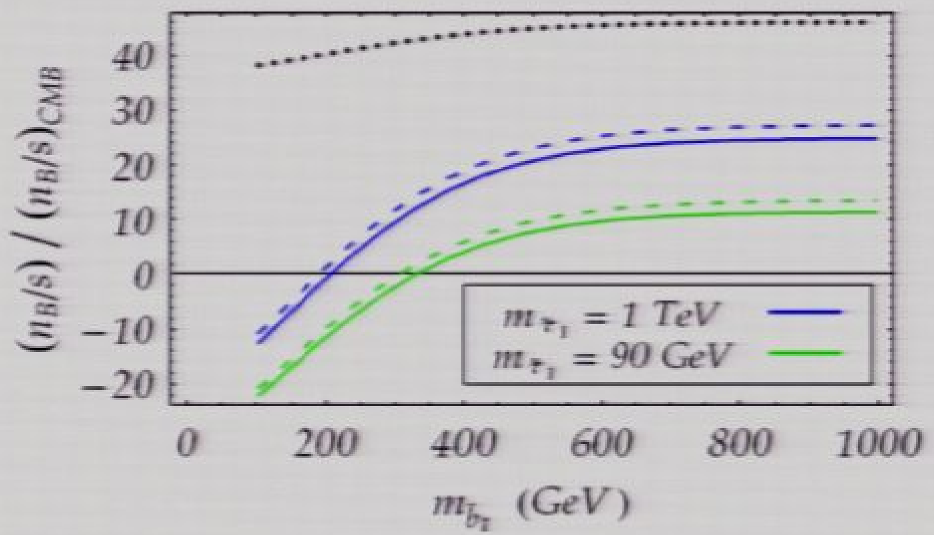
$$\frac{\Delta H}{H} = \frac{15}{4\pi^2}\frac{c^2}{\lambda}\frac{1}{g_*}$$

- DM candidate detection at collider presents an interesting new probe of early universe cosmology.
- Gravity wave peak shift and amplitude are sensitive to Hubble expansion rate during EWPT.

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

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.

Also lepton driven EW bgenesis is possible. Diffusion of left and right handed lepton currents are very different. [with Garbrecht, Ramsey-Musolf, Tulin to be submitted, 09]

Spectrum shift?

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

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.

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

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

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

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

Estimates

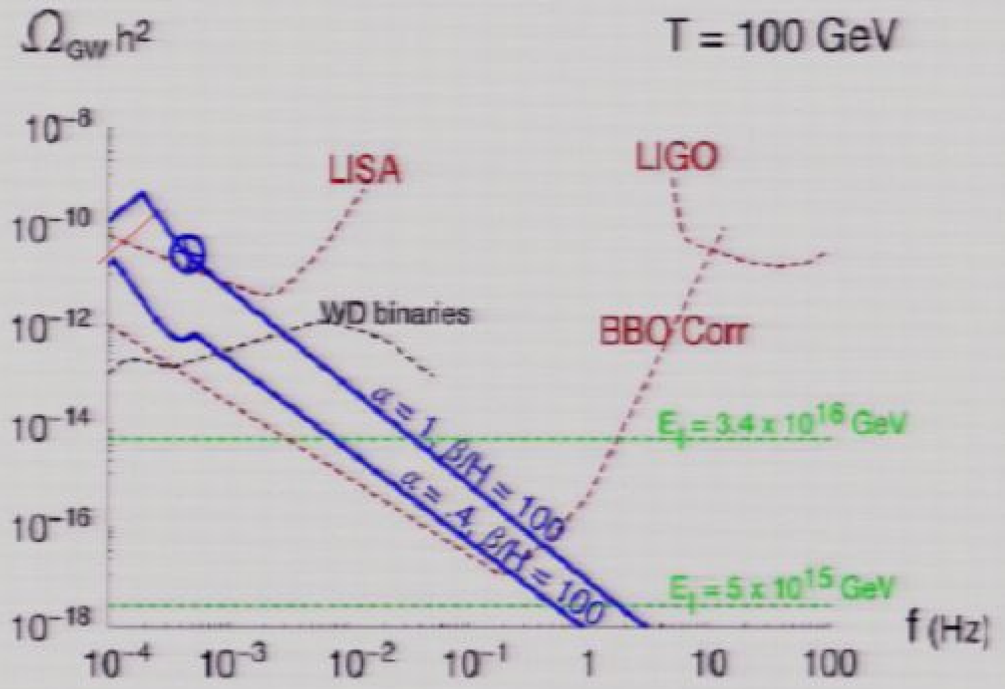
[prelim: with Zhou]

The amplitude also scales:

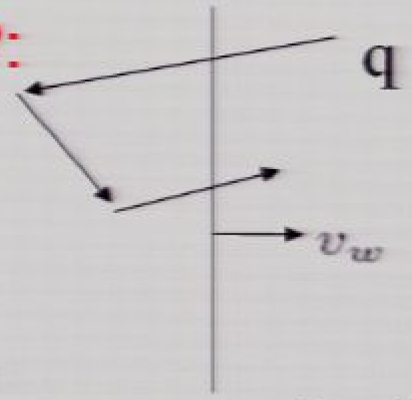
$$\frac{d\rho_{GW}}{d\ln k} \sim \frac{1}{M_p^2}\left(\frac{a_*}{a}\right)^4 \left[\rho_B^{rest}\gamma^2 v_w^2\right]^2 (\Delta t)^2 \int dq_1' dq_2' \cos\left[k\Delta t(q_1' - q_2')\right] F_{k\Delta t}(q_1', q_2'$$

$$\frac{d\rho_{GW}(k)}{d\ln k} \rightarrow \frac{1}{\xi^2}\frac{d\rho_{GW}(k/\xi)}{d\ln k} \qquad \xi \equiv \frac{H^{(Q)}}{H^{(U)}}$$

Drawn on top of fig from hep-ph/0607107



B-genesis sensitivity?:



$\langle \phi \rangle \neq 0$

sphalerons inactive

$\langle \phi \rangle = 0$

sphalerons active

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

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

e.g. 1 generation: $u_R \rightarrow u_R$

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

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

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

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

↑

This number has a mild dependence on H.

(see e.g. hep-ph/0112209)
Scenarios beyond this exist and requires study.

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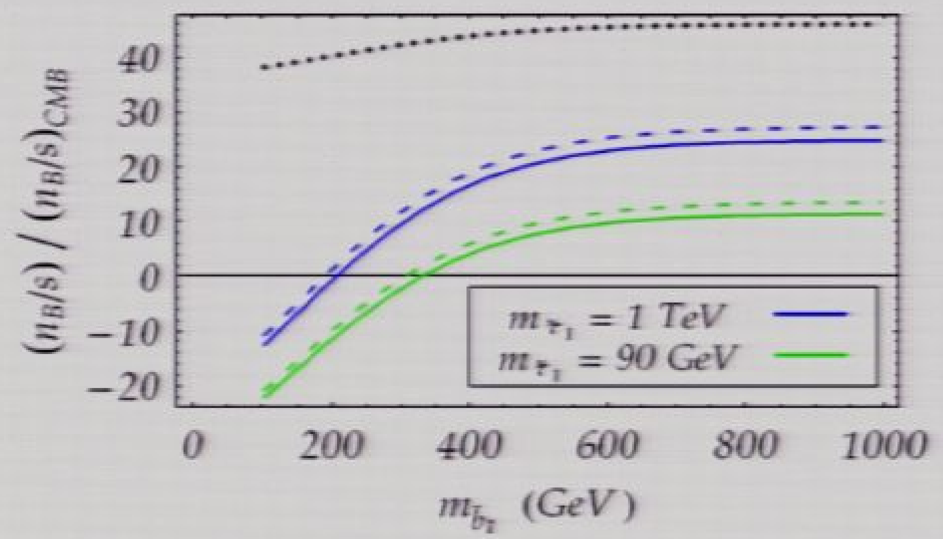
[with Garbrecht, Ramsey-Musolf, Tulin 08]



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No Signal

VGA-1