Modifying Dark Matter Freeze Out at the Electroweak Phase Transition

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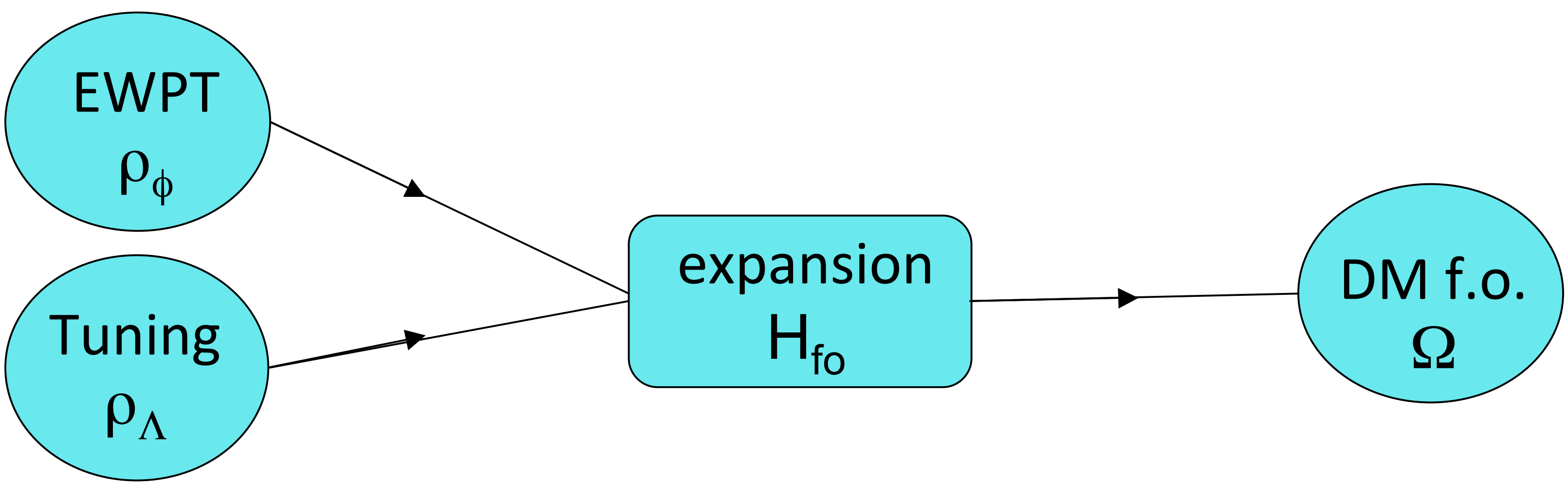
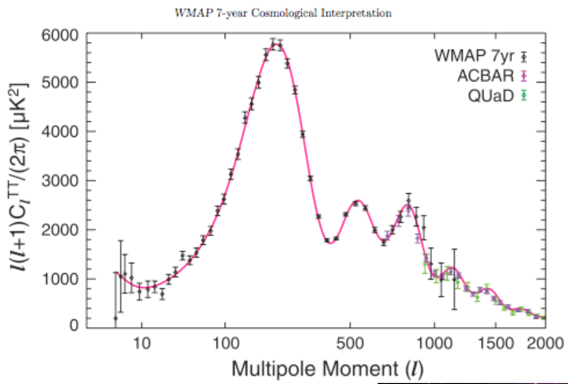
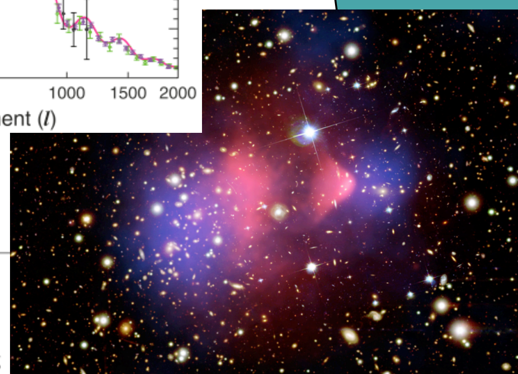


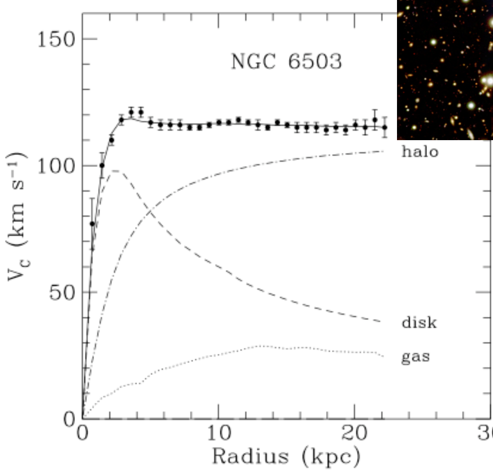
Cosmology & Astronomy

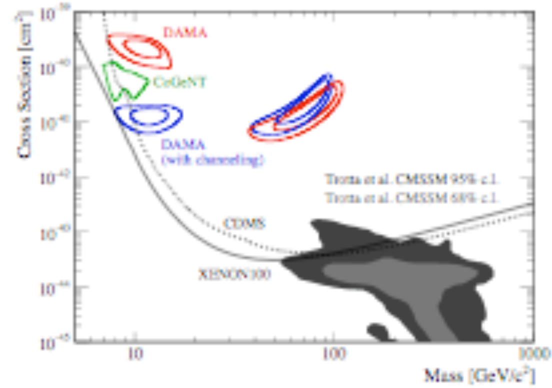
Will they match?

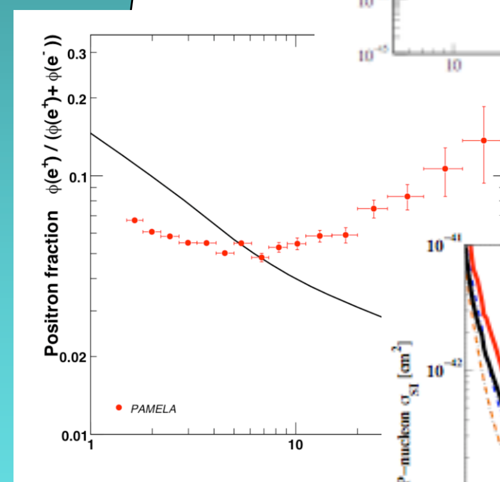
Collider & (In)Direct Search

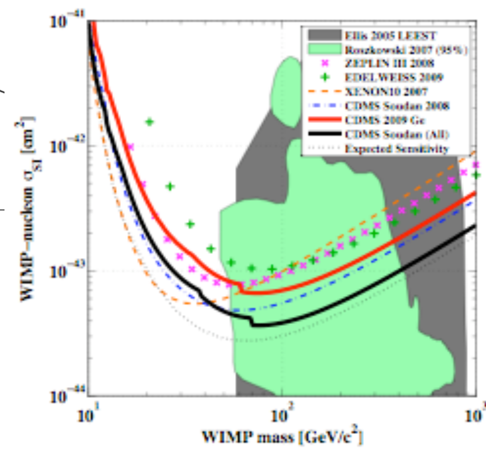








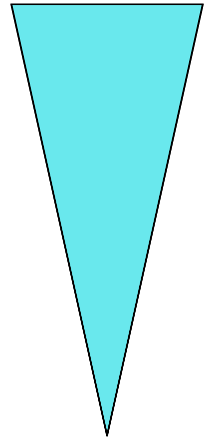




$$\Omega_{DM}^{\rm cosmo} \approx 0.22 \pm 0.02$$

$$\Omega_{DM}^{\rm infer} \approx \frac{x_f T_0^3}{30\, m_{DM}^2 \langle \sigma v \rangle \rho_{cr}} H_{fo}$$

Suppose they don't match!



$$\Omega_{DM}^{\text{cosmo}} \neq \Omega_{DM}^{\text{infer}}$$

What went wrong? -- We should not *assume* radiation dominates at freeze out

$$\Omega_{DM}^{\text{infer}} \approx \frac{x_f T_0^3}{30\, m_{DM}^2 \, \langle \sigma v \rangle \, \rho_{cr}} H_{fo} \qquad H_{fo}^2 = \frac{8\pi G}{3} \rho_r$$

[Kolb & Wolfram, 1980] - Tune CC against SM Higgs vacuum energy

[Barrow, 1982] - Anisotropic expansion boosts relic abundance

[McDonald, 1990] - Decaying massive particles dominate ρ at freeze out

[Kamionkowski & Turner, 1990] - "Thermal Relics: Do we know their abundance?"

[Joyce, 1997] - Kination dominated scalar field modifies H at EWPT

[Salati, 2003] - Quintessence modifies H at freeze out

[Profumo & Ullio, 2003] - Kination dom. quintessence modifies χ_0 abundance

[Megevand & Sanchez, 2008] - Entropy production at first order PT & dilutes relic

[Wainwright & Profumo, 2009] - Entropy production saves SUSY models

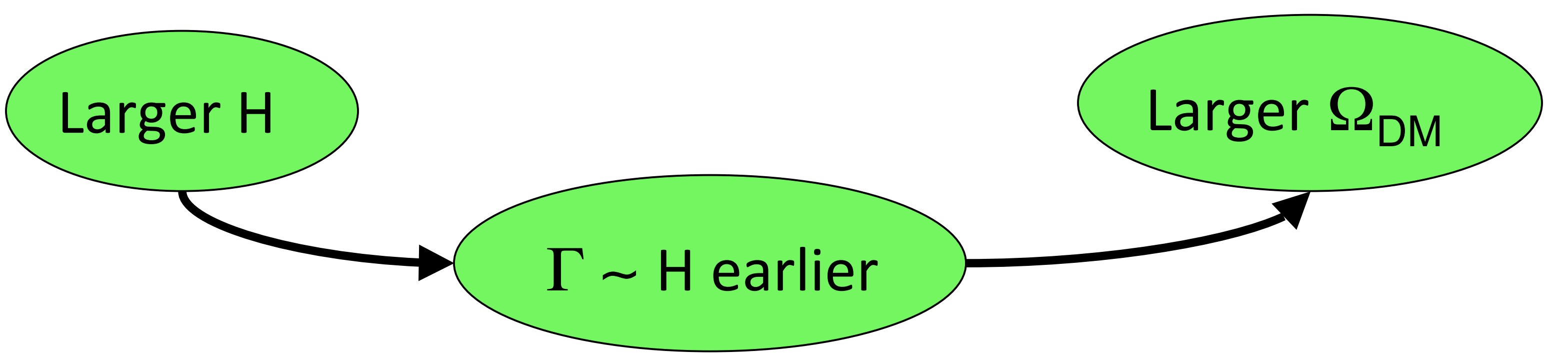
Suppose they don't match!

$$\Omega_{DM}^{\text{cosmo}} \neq \Omega_{DM}^{\text{infer}}$$

What went wrong? -- We should not *assume* radiation dominates at freeze out

$$\Omega_{DM}^{\text{infer}} \approx \frac{x_f T_0^3}{30\, m_{DM}^2 \langle \sigma v \rangle \rho_{cr}} H_{fo} \left(1 + \frac{\Delta H}{H} \right) \qquad H_{fo}^2 = \frac{8\pi G}{3} (\rho_r + \rho_\phi + \rho_\Lambda)$$

Additional contribution to ρ from scalar & tuned cosmological constant



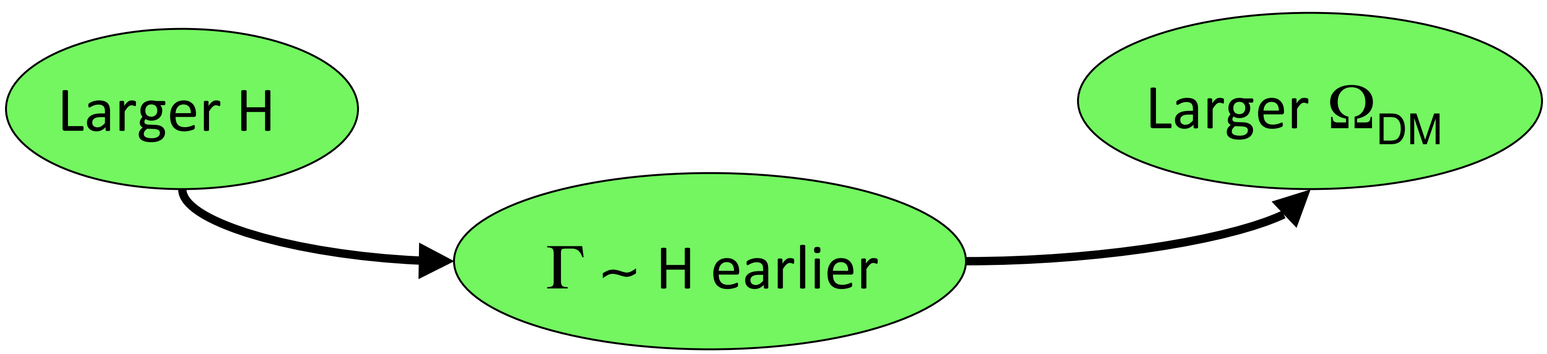
Suppose they don't match!

Mismatch $\Omega_{DM}^{\text{cosmo}} \neq \Omega_{DM}^{\text{infer}}$ signals new physics in Higgs sector & CC tuning

What went wrong? -- We should not *assume* radiation dominates at freeze out

$$\Omega_{DM}^{\text{infer}} \approx \frac{x_f T_0^3}{30\, m_{DM}^2 \langle \sigma v \rangle \rho_{cr}} H_{fo} \left(1 + \frac{\Delta H}{H} \right) \qquad H_{fo}^2 = \frac{8\pi G}{3} (\rho_r + \rho_\phi + \rho_\Lambda)$$

Additional contribution to ρ from scalar & tuned cosmological constant



Cosmological History

Standard Cosmology

EWPT

freeze out during ρ_r domination

BBN (ρ_r dom.)

Modified Cosmology

supercooling
$\rho_\phi + \rho_\Lambda \sim \rho_r$

freeze out while H boosted

phase transition completes

H at EWPT & Tuning CC

The Calculation:

1) Calculate thermal effective potential $V_T(\phi)$--free energy density of a gas at temperature T coupled to condensate ϕ
2) Tune CC against scalar vacuum energy at zero temperature

$$\rho_\Lambda + V_0\left(\langle\phi\rangle_{T=0}\right) \approx meV^4 \approx 0$$

3) Calculate $\Delta H/H$ as a function of temperature

$$\frac{\Delta H}{H} \approx \frac{1}{2}\frac{\rho_\phi(T)+\rho_\Lambda}{\rho_r(T)} \approx \frac{15}{\pi^2}\frac{1}{g_\star(T)}\frac{V_0\left(\langle\phi\rangle_T\right)+\rho_\Lambda}{T^4}$$

4) (Embed scalar sector into a model of DM with freeze out occuring before or during EWPT when $\Delta H/H$ is maximal)

Second Order PT & SM

Standard Model phase transition

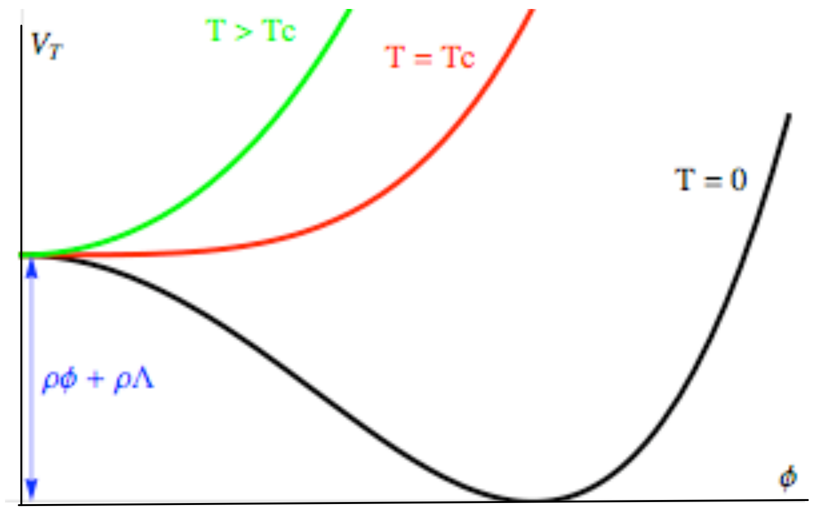
$$V_T(\phi) = \frac{1}{2}\left(c_1 T^2 - \lambda v^2\right)\phi^2 + \frac{\lambda}{4}\phi^4$$

$$\rho_\Lambda = \lambda v^4/4$$ ← tuning CC

$$T_c^2 \approx \lambda v^2/c_1$$

$c_1 \sim h_t^2 + g^2$

$$\frac{\Delta H}{H} \approx \frac{15}{\pi^2}\frac{1}{g_\star}\frac{c_1^2}{4\lambda} \approx 0.002$$



Why is ΔH/H so small?

- Same parameters control vacuum energy & temperature: $V(T)/T^4 \sim O(1)$
- Hard to beat $g_* \sim 100$ suppression

solution = supercooling

First Order PT & xSM

- The Hubble parameter receives a larger correction when the universe is suspended in a metastable phase
- Then, $\Delta H/H \sim V/T^4$ grows at T drops
- Real singlet extension admits a 1PT

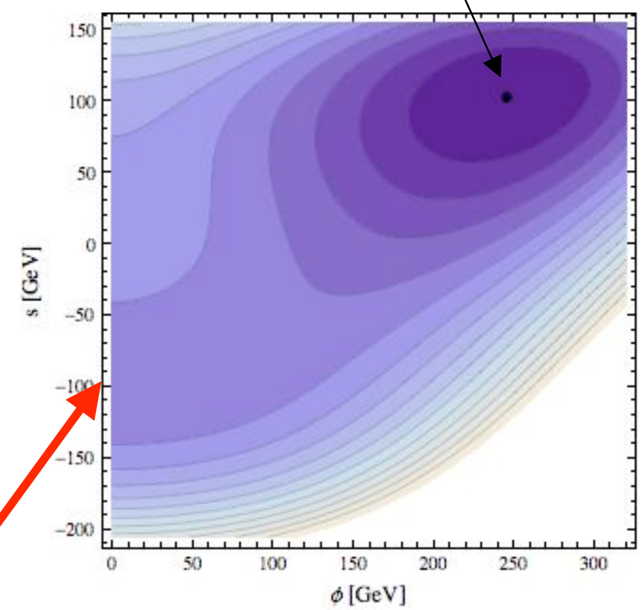
tuning CC

[Ramsey-Musolf, et. al., 2007]

$$V(\phi, s) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4 + \frac{a_1}{2}s\phi^2 + \frac{a_2}{2}s^2\phi^2 + b_1 s + \frac{b_2}{2}s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$

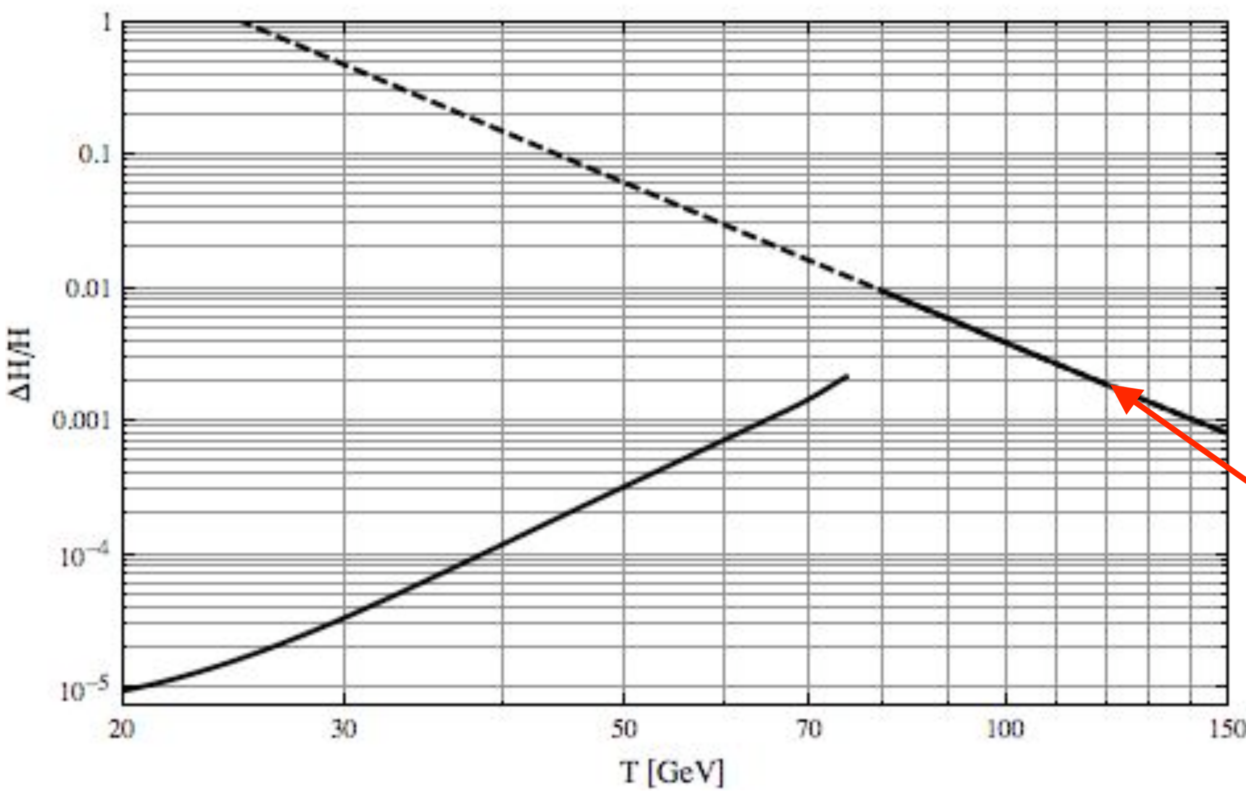
gauge singlet

$$\rho_\Lambda = -V(v, v_s)$$

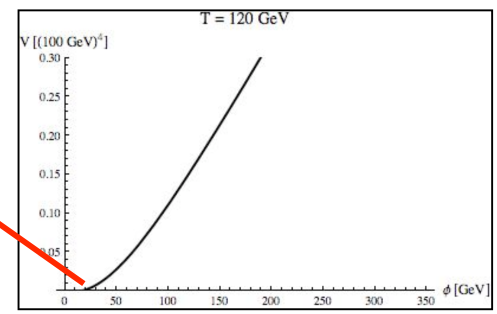


at $T \sim T_c$, metastable minimum here

$$\frac{\Delta\Omega}{\Omega} \sim \frac{\Delta H}{H} \approx \frac{15}{\pi^2}\frac{1}{g_*(T)}\frac{V_0\left(\langle\phi\rangle_T\right)+\rho_\Lambda}{T^4}$$

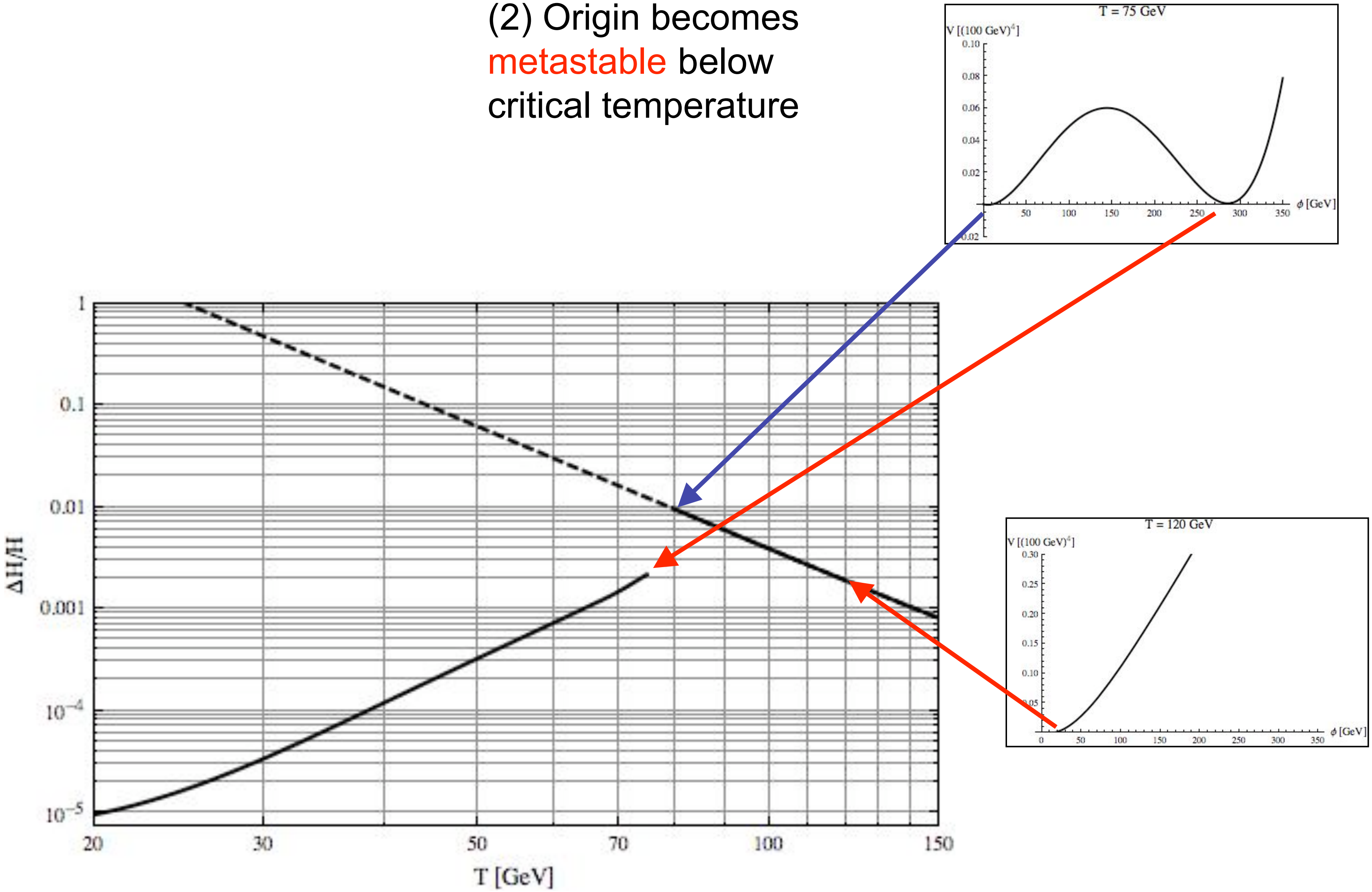


(1) Symmetry restored at high temperature



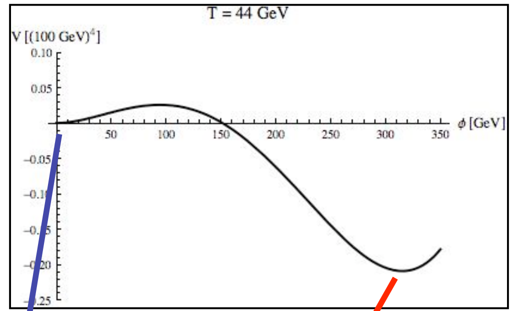
$$\frac{\Delta\Omega}{\Omega} \sim \frac{\Delta H}{H} \approx \frac{15}{\pi^2}\frac{1}{g_*(T)}\frac{V_0(\langle\phi\rangle_T)+\rho_\Lambda}{T^4}$$

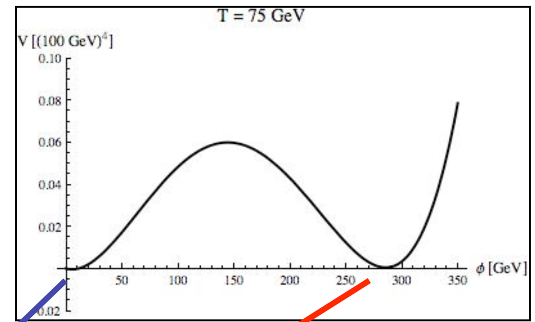
(2) Origin becomes metastable below critical temperature

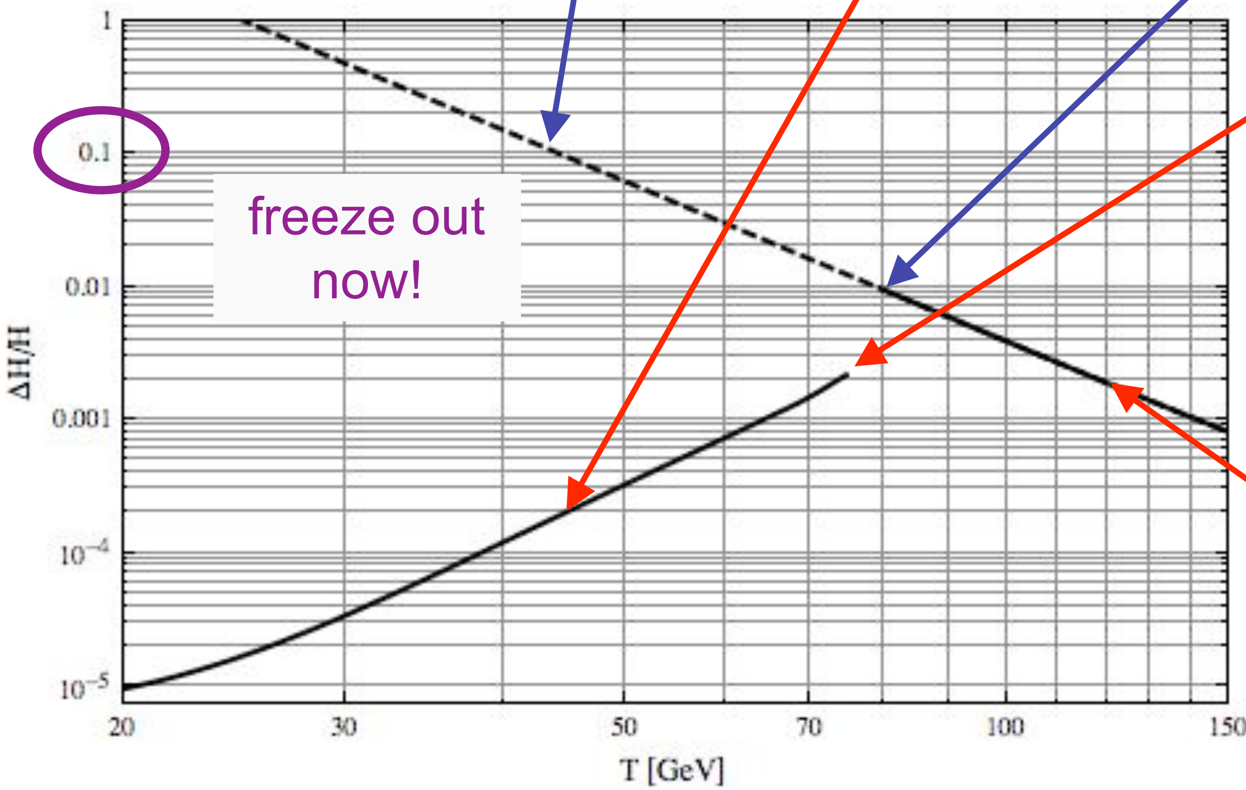


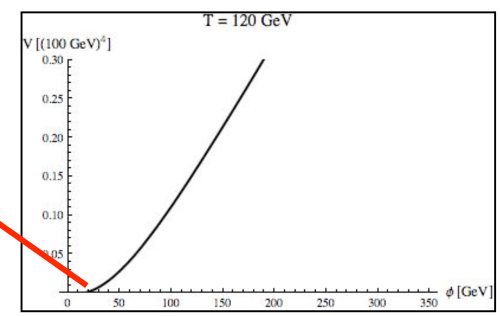
$$\frac{\Delta\Omega}{\Omega} \sim \frac{\Delta H}{H} \approx \frac{15}{\pi^2}\frac{1}{g_*(T)}\frac{V_0(\langle\phi\rangle_T) + \rho_\Lambda}{T^4}$$

(3) During supercooling, $\Delta H/H$ grows like $1/T^4$ in metastable phase



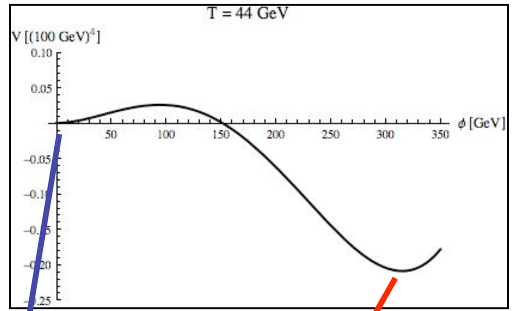


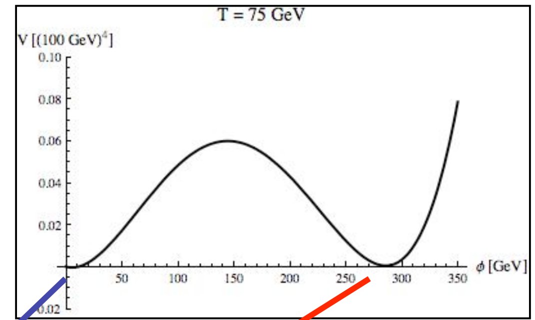


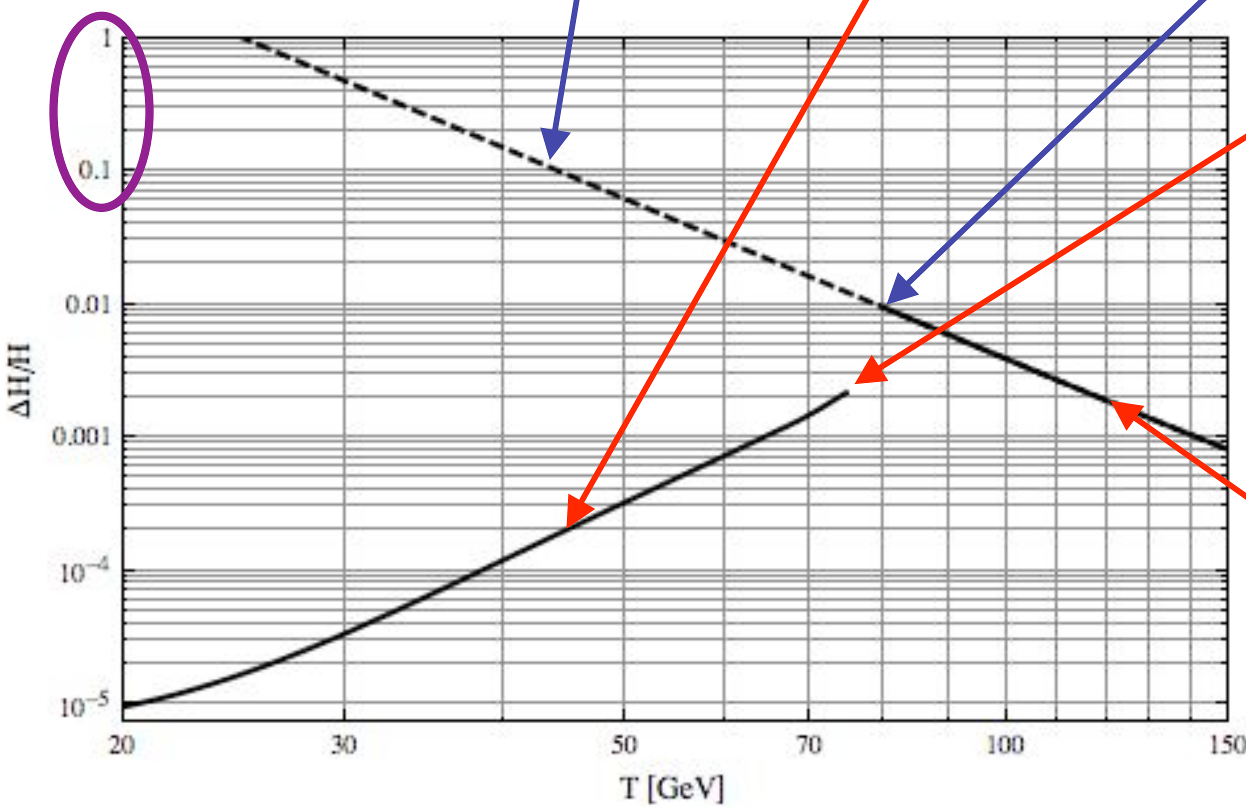


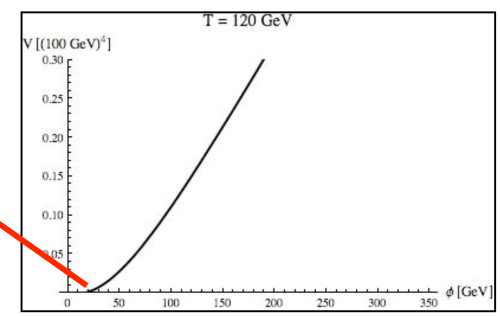
$$\frac{\Delta\Omega}{\Omega} \sim \frac{\Delta H}{H} \approx \frac{15}{\pi^2} \frac{1}{g_*(T)} \frac{V_0(\langle\phi\rangle_T) + \rho_\Lambda}{T^4}$$

(4) At a lower temperature the PT completes









Summary -- What to do if $\Omega_{DM}^{\rm cosmo} \neq \Omega_{DM}^{\rm infer}$

1) DM relic abundance can be enhanced by O(10%) if freeze out occurs during a first order electroweak phase transition
2) Favors:
   a) Extended scalar sector
   b) Low temperature phase transition & high temperature freeze out (10s GeV) ⟶ heavy dark matter favored by PAMELA
   c) Sufficient supercooling ⟶ strongly first order phase transitions allow for interesting physics such as baryogenesis and gravity waves
3) Mismatch between cosmological and collider-inferred relic abundance may provide evidence for a link between dark matter, the Higgs sector, and tuning of the cosmological constant