Possible Connections in Colliders, Dark Matter, and Dark Energy

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Daniel Chung
(U. Wisconsin – Madison)
Collaborators: L. Everett, K. Kong, K. Matchev

Quiz

- Which of the following would you bet for the assertion of radiation dominance of the universe for 100 MeV < T < 100 GeV?

a) < $10 b) $100 c) $1000 d) more

A General Program

LHC and future HE experiments may motivate changes in “popular” cosmologies for T>1 MeV.

Program: identify correlated signatures for each anticipated change

e.g. (relavant for this talk)

- The discovery of DM is arguably the most likely connection between colliders and cosmology.
- By measuring properties of DM through colliders and cosmology, investigate freezeout dynamics.
- “Minimality” in model building makes the conjecture of quintessence modifying standard freezeout dynamics “natural”
- Identify correlated signatures

Cosmology Dependence of Thermal Freeze-out

- CMB temperature + plausible/measurable particle physics + hot enough early universe (T>100 GeV) ⇒ Ω_M

cosmology

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

Weak cosmo

Particle physics
(electroweak scale)

$\frac{T_F}{m_\chi}$ ~1/20 with log dependence on $H_F, \langle \sigma_A v \rangle, m_\chi$

Cosmology Dependence of Thermal Freeze-out

- CMB temperature + plausible/measurable particle physics + hot enough early universe (T>100 GeV) $\Rightarrow \Omega_M$

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e.g. In standard cosmology, mass cancels

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

Scenario

- Focus: Thermal equilibrium init conds, but cosmology is nonstandard.
- 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

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

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)

What can change H in standard gravity during freeze out?

- Exotic component in the stress tensor
  - Extra gas of radiation or matter $a^{-4,-3}$
  - Extra coherent scalar field energy: potential a^{0}

    kinetic a^{-6}
- Scalar field KE domination: kination domination

[Salati 02, Kamionkowski & Turner 90, Barrow 82]

  - Minimal: light scalar field can exist because of DE
  - Avoid any hint of conflict with standard BBN
  - Gives us a way to **probe DE sector through colliders** since colliders can probe DM whose freezeout properties are influenced by DE.

A Large Class of Models

Kination domination scenario:

DE sector $$L_{DE} = \sum_i \frac{1}{2} \dot{\phi}_i^2 - V(\{\phi_j\})$$

$$\rho_{\phi DE} \sim \sum_i \frac{1}{2} \dot{\phi}_i^2$$ during DM freeze-out

$$H^2 = \frac{1}{3 M_p^2} \left(\rho_{\phi DE} + \rho_R \right) \quad > \quad H_{usual}^2 = \frac{1}{3 M_p^2} \left(\rho_R \right)$$

DM phenomenology characterized by 1 parameter:

$$\eta_\phi \equiv \left(\frac{\rho_\phi}{\rho_\gamma} \right)_{BBN} \quad \leq 1$$ BBN

Boosting

Recall:

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

Dark matter abundance is boosted:

$$\frac{\Omega^{(K)}}{\Omega^{(U)}} \sim 10^3 \sqrt{\eta_\phi} \left(\frac{m_\chi}{100\,GeV} \right) \qquad for \quad > 1$$

$$\frac{\Delta\,\Omega^{(K)}}{\Omega^{(U)}} \sim 10^6 \eta_\phi \left(\frac{m_\chi}{100\,GeV} \right)^2 \qquad for \quad \ll 1$$

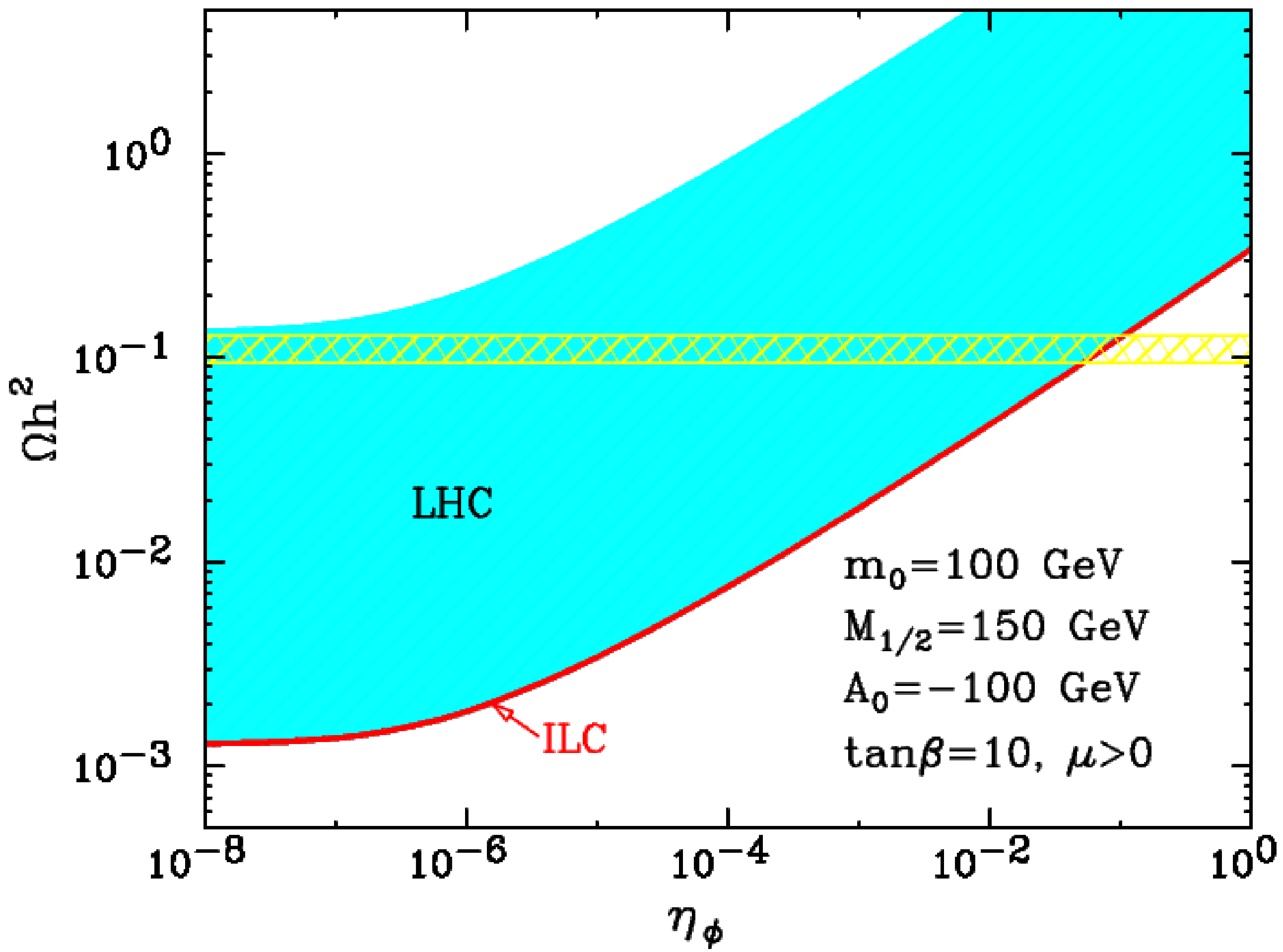
Prediction:

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

CONNECTING LHC, ILC, AND QUINTESSENCE

(w/ Everett, Kong, Matchev)

- ILC can measure quintessence!



This 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

$$2m_\chi - m_h$$

Other regions are not as dramatic, but qualitatively similar.

A Surprising Signature

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 $\Rightarrow$ V dependent lower bound on ρ_γ

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

   V $\Rightarrow$ 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 $\eta_\phi > 10^{-8}$

Inflation

quasi-dS

cold universe with most of the energy in the universe in vacuum

Thus, need to (re)heat.

If there exists fields with m < H, minimum reheat temperature exists:

$$T > \frac{H}{2\pi}$$

DS horizon temperature

V dependent lower bound on ρ_γ

Can compute explicitly given various models: e.g.

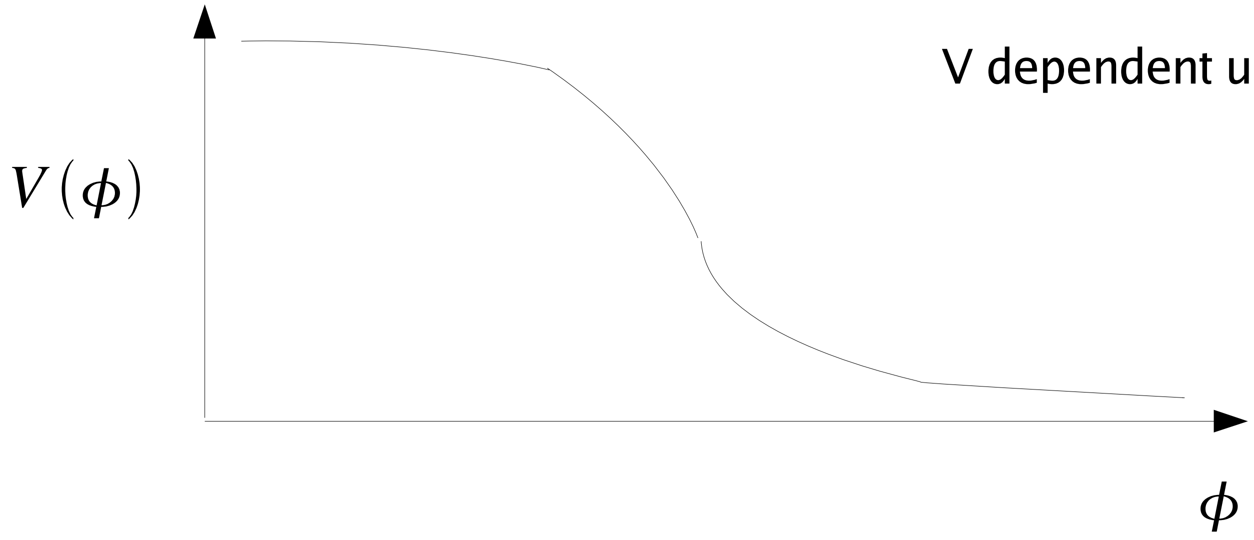
$$\begin{aligned}\beta_k \;\approx\; & \frac{1}{4}\int_{k^2}^{x_1}\frac{dx}{x}\exp\left[-i2\sqrt{3}\sqrt{\frac{1}{6}+\xi}\left(\frac{2\sqrt{x}\sqrt{k^2-x}}{x-k^2}-2\arctan\left[\frac{\sqrt{k^2-x^2}\sqrt{x}}{x-k^2}\right]+C_1(k^2)\right)\right]\\ & +\frac{1}{4}\int_{x_2}^{k^2}\frac{dx}{x}\exp\left[-i\sqrt{\frac{3}{2}}\sqrt{\frac{1}{6}+\xi}\left(\frac{-2\sqrt{x}}{\sqrt{x-k^2}}+2\ln\left[\sqrt{x-k^2}+\sqrt{x}\right]+C_2(k^2)\right)\right],\end{aligned}$$

Origin of Kinetic Energy?

Most of the energy at the end of inflation is in the inflaton.

The maximum kination energy is thus the energy at the end of inflation.

Example:



V dependent upper bound on ρ_ϕ

Bound on Inflationary Energy Density

Tensor perturbations:

$$\delta g_{\mu\nu}^{(T)} = \begin{pmatrix} 0 & 0 \\ 0 & h_{ij} \end{pmatrix}$$

$$P_T(k) \equiv \frac{k^3}{\pi^2}\left(|h_{+k}|^2 + |h_{\times k}|^2\right)$$

$$P_T = 8\frac{H^2}{(2\pi)^2 M_P^4} \propto \frac{V}{M_P^4} \qquad r \equiv \frac{P_T}{P_R}$$

CMB polarization generated by Thomson scattering in the background of gravity waves.
Generates B-mode polarization.

Optimistically: Can only measure $r \geq 10^{-4}$

Therefore, measurement of B-mode leads to V> $V_{min} \sim 10^{15} GeV$

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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 $\eta_\phi \equiv \left(\frac{\rho_\phi}{\rho_\gamma}\right)_{BBN}$

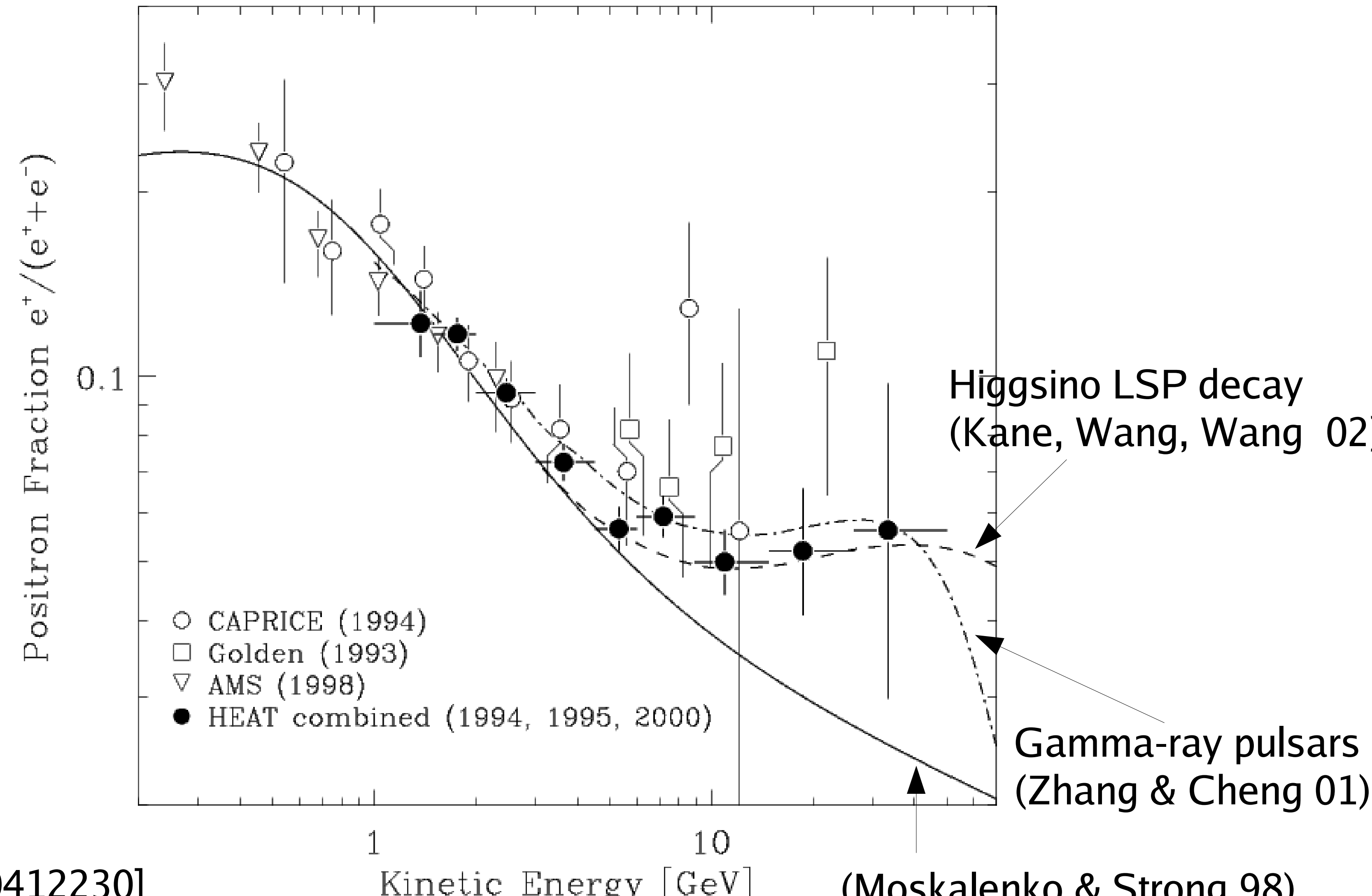
$$\eta_\phi \leq 10^{-13}\left(\frac{\theta}{10}\right)^2\left(\frac{r_{min}}{10^{-4}}\right)^{-2}\left(\frac{g_*(T_e)}{100}\right)^{-2} \ll 10^{-8}$$

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

Signatures

- There will be a discrepancy between cosmology and colliders.
- Can be ruled out almost model independently if primordial CMB B-modes are observed.
- Shift in the peak of the electroweak phase transition gravity wave spectrum possibly measured by LISA and LIGO.
- Higgs bound for electroweak baryogenesis can be shifted.
- Positron excess explanation through DM annihilation improved through this scenario.
- Leptogenesis will need to be resonant because of low T_{RH}
- Residual annihilation effects of DM will be affected.
- Possible measurement of $w > -1$ [See also Profumo and Ullio 03]

Positron Excess



[astro-ph/0412230]

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.

Conclusion

- There is exciting prospects for probing cosmology with colliders through DM physics. e.g. Measurements may yield $\Omega_{\chi\, coll\ \ usual} < \Omega_{\chi\, astro}$
- Such discrepancies can be enhanced by a period of kination domination.
- Minimality makes it natural to use quintessence (especially if w > -1 is confirmed): DE ⇔ colliders
- Large class of models can be ruled out by future CMB experiments
- Correlated signatures can support the scenario.

Connecting DE and DM To Do List

- Comparative studies with other mechanisms for mismatching collider and cosmology.
- Compute detailed gravity wave spectrum arising from electroweak phase transition within this context.
- Compute Higgs mass bound shift associated with quint. effects.
- Study resonant leptogenesis possibilities.
- Residual annihilation BBN effects.
- Effects on cosmic string network evolution and signatures.