The Cosmological Moduli Problem (revisited)

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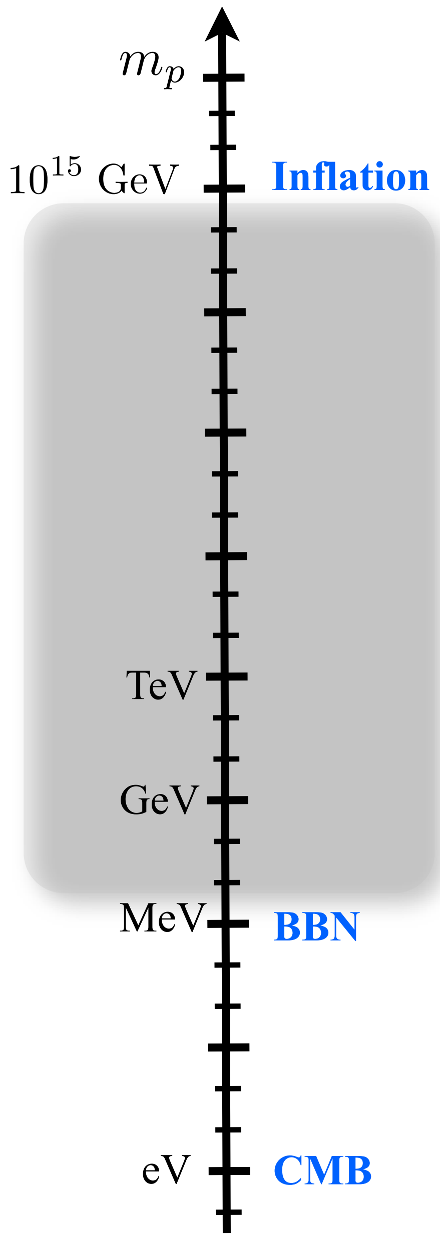
Reevaluating the Cosmological Origin of Dark Matter.
e-Print: arXiv:0912.3003

Acknowledgements:
Bobby Acharya, Konstantin Bobkov, Dan Feldman, Phill Grajek, Gordy Kane, Piyush Kumar, Aaron Pierce, Dan Phalen, Jing Shao

Conclusions



Non-thermal cosmology provides a viable alternative to the well motivated thermal scenario.

Unlike the thermal case, a non-thermal history would imply a direct connection to fundamental theory and an observational window on the properties of the early universe.

Working directly with fundamental theories non-thermal models can lead to predictions which are falsifiable in current and near term experiments.

Non-thermal Cosmologies

The idea of a non-thermal history is not new.

Many <u>phenomenological</u> based "toy models" exist in the literature.

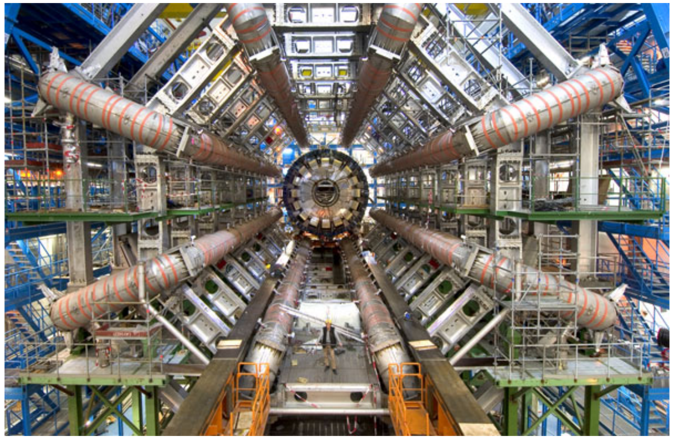
- Anomaly Mediated SUSY breaking
- Affleck-Dine condensates / Baryogenesis
- Wimpzillas
- Q-balls
- Many more....

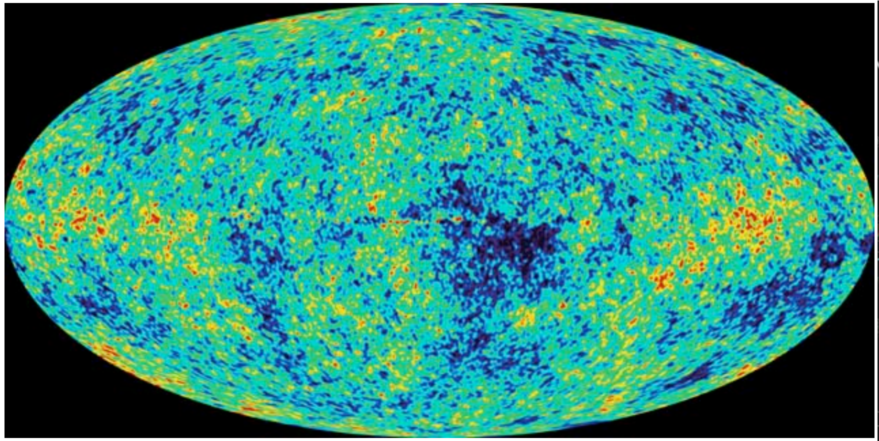
Can these ideas be realized within fundamental theory?

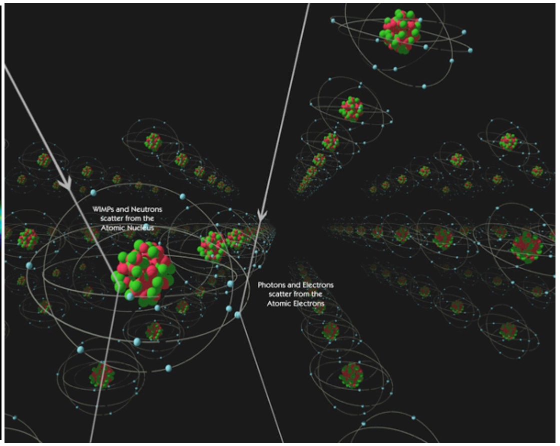
Non-thermal Cosmologies

Establishing the likelihood of a non-thermal cosmology is important for a number of reasons:

- It may alter the origin and expected properties of dark matter
- It may result in new benchmarks for discovery at LHC
- It may provide a window of opportunity for probing the early universe and fundamental theory (much like inflation)







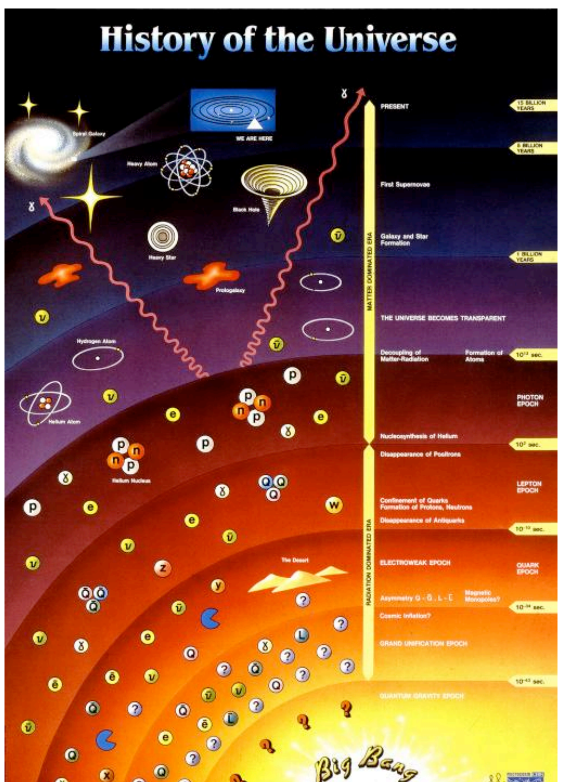
Cosmic History

TeV

GeV

MeV

eV



Cosmic History

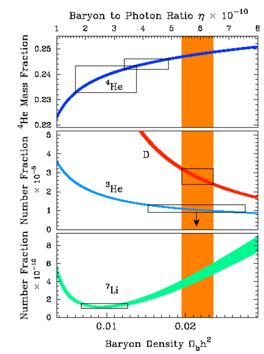
TeV

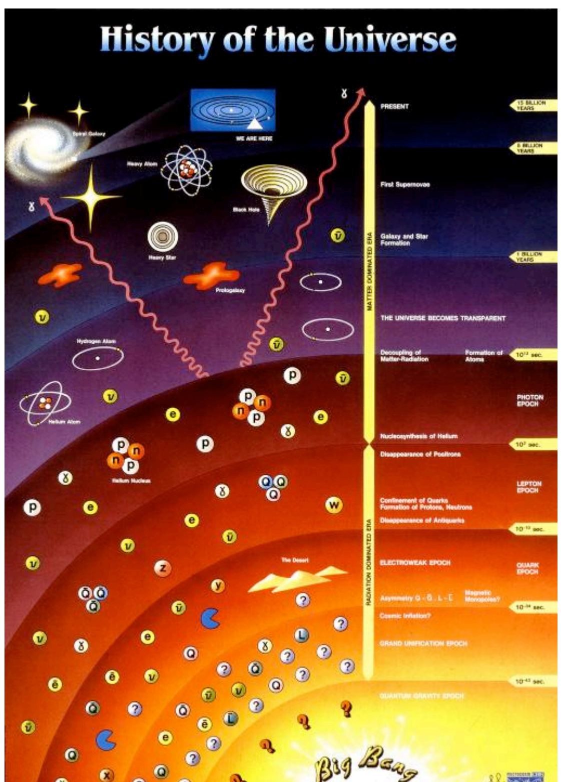
GeV

MeV

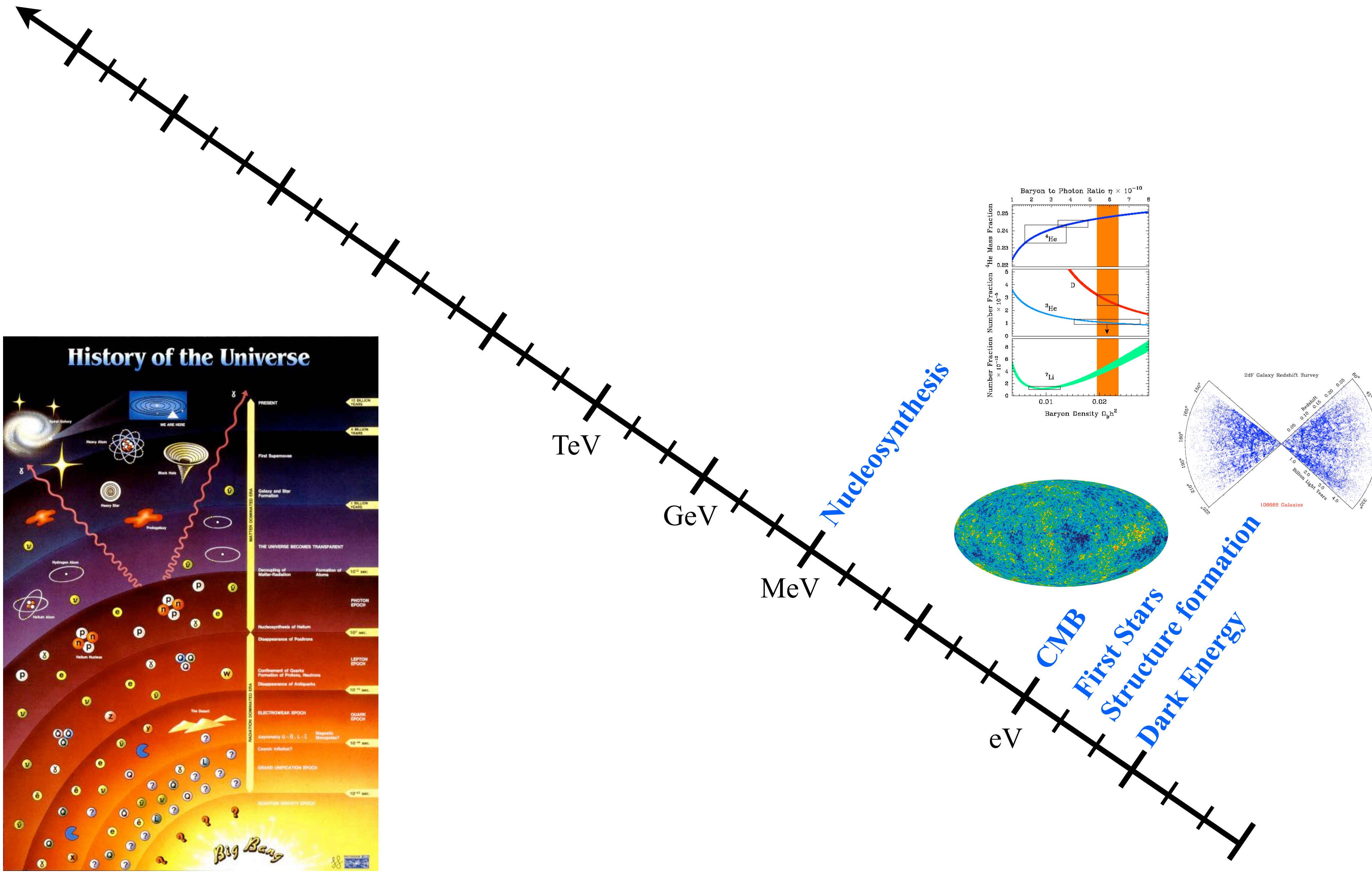
eV

Nucleosynthesis

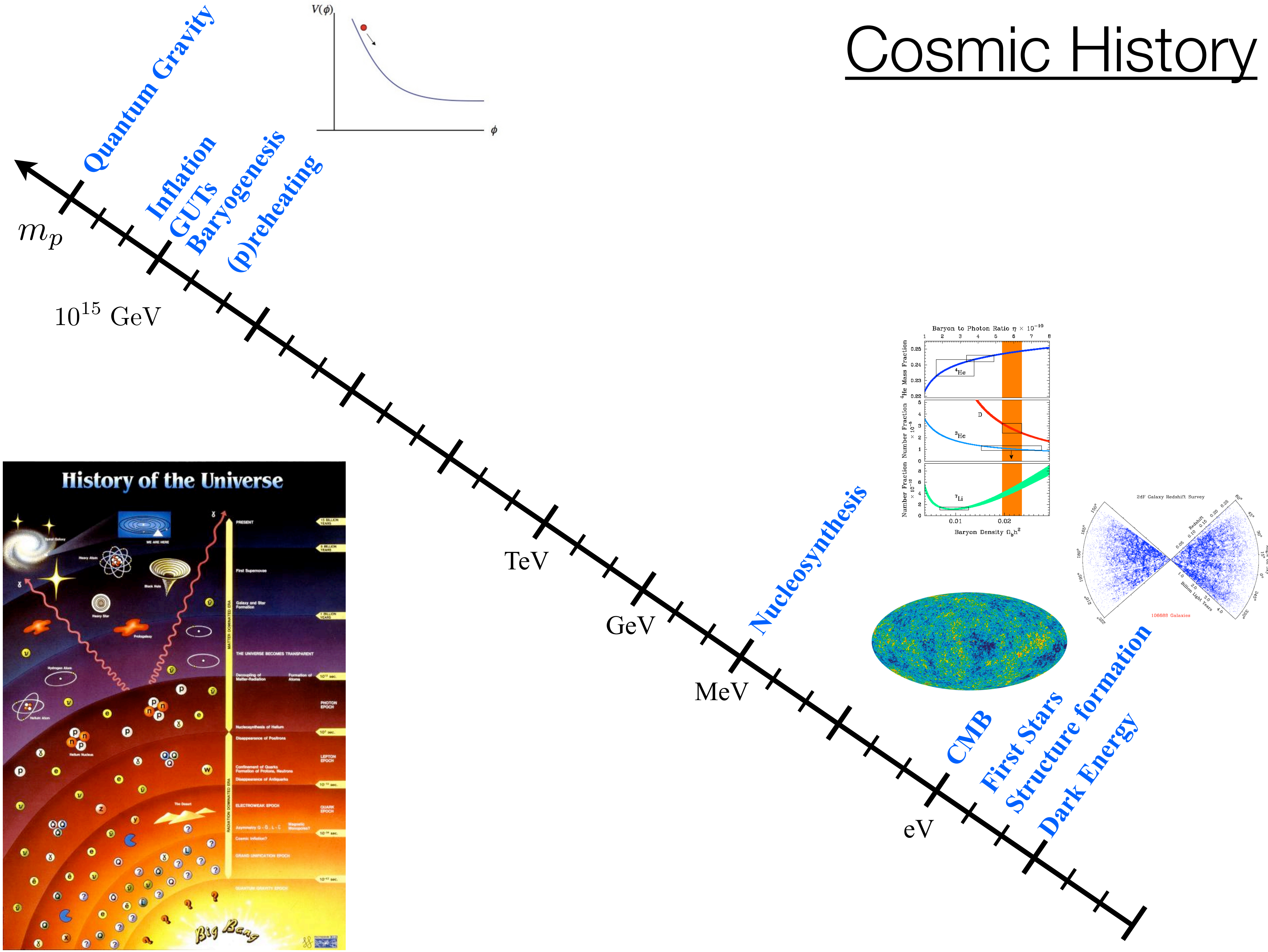




Cosmic History



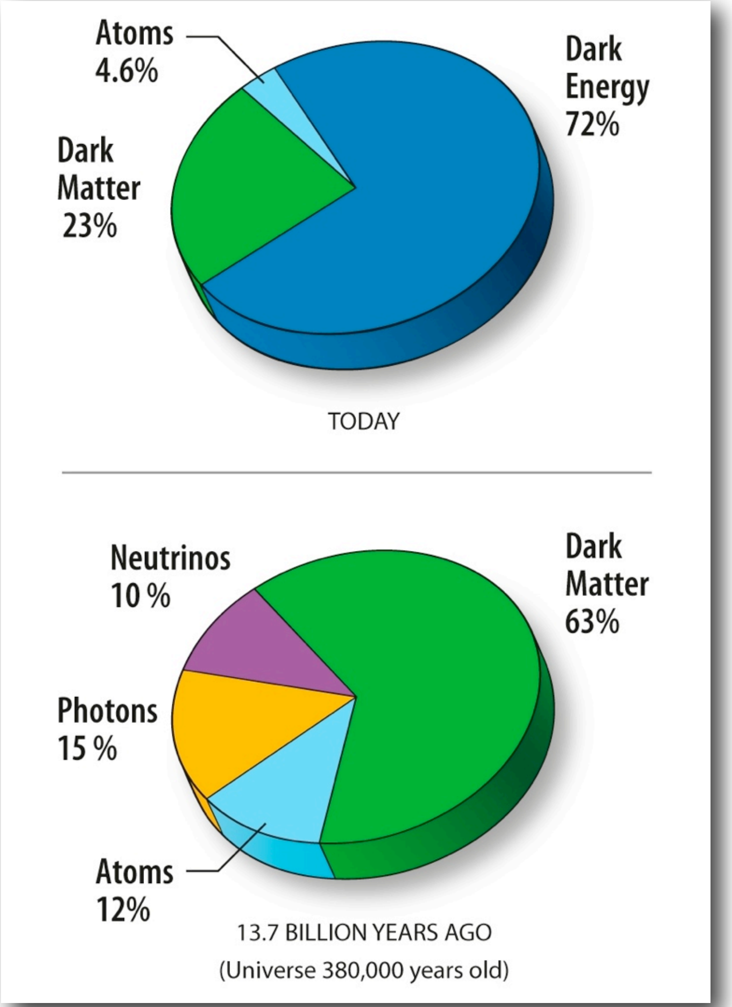
Cosmic History



Precision Cosmology

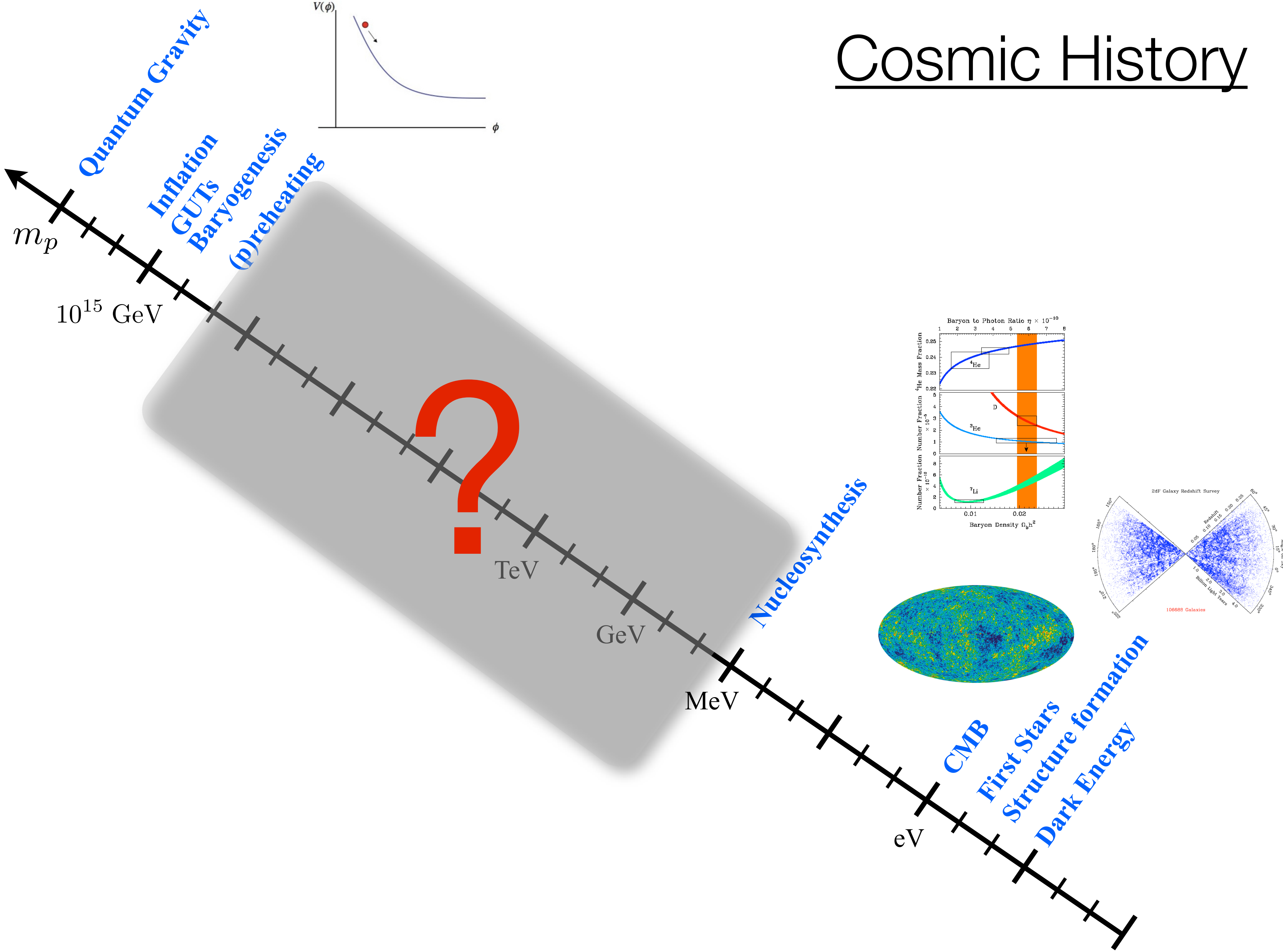
Cosmic Energy Budget Today

- Dark Energy 72%
- Dark Matter 23%
- Baryons 5%
- Early universe remarkably homogeneous
- Very small density contrast (1:100,000) at time of decoupling of CMB

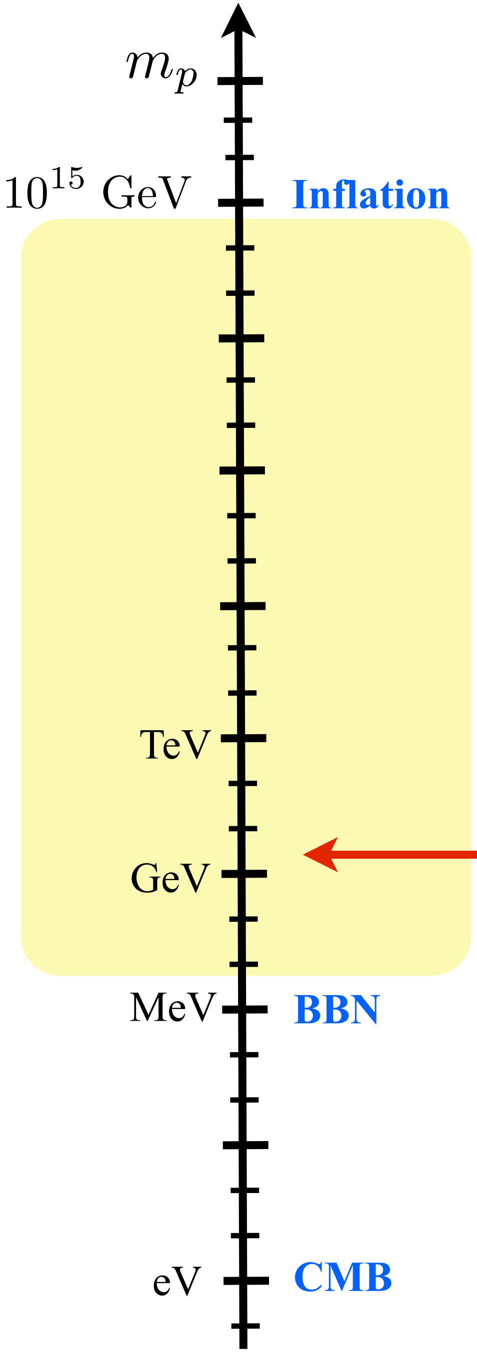


All suggest physics beyond the standard model.

Cosmic History



Thermal Microscopic History

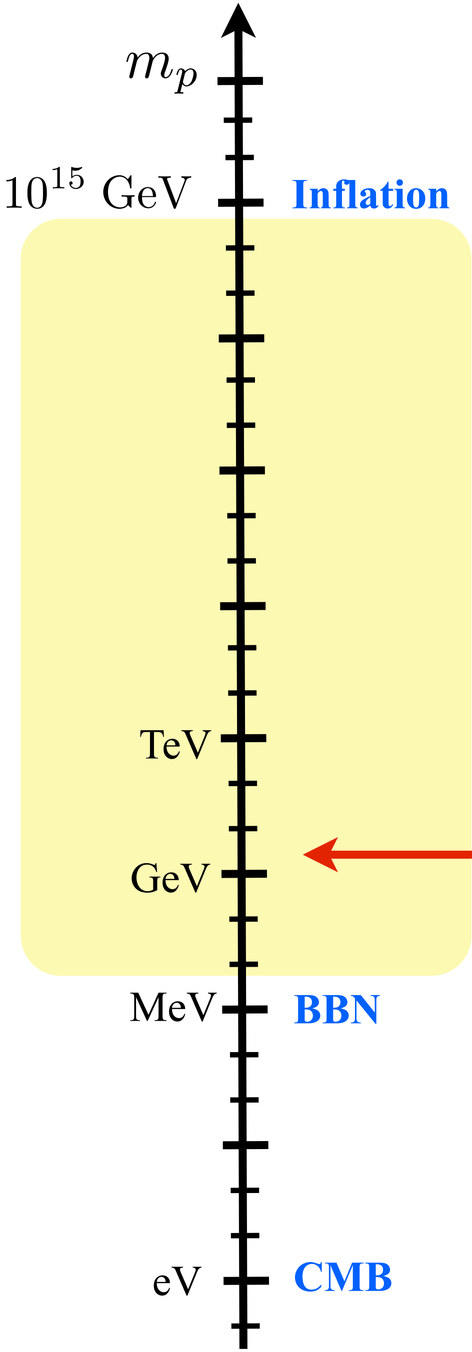


Dark Matter Abundance from Thermal Production

$$\Omega_{dm} \equiv \frac{\rho_{dm}}{\rho_c} = 0.23 \times \left(\frac{10^{-26}\mathrm{cm}^3 \cdot s^{-1}}{\langle \sigma v \rangle} \right)$$

Dark Matter WIMPs?

Thermal Microscopic History



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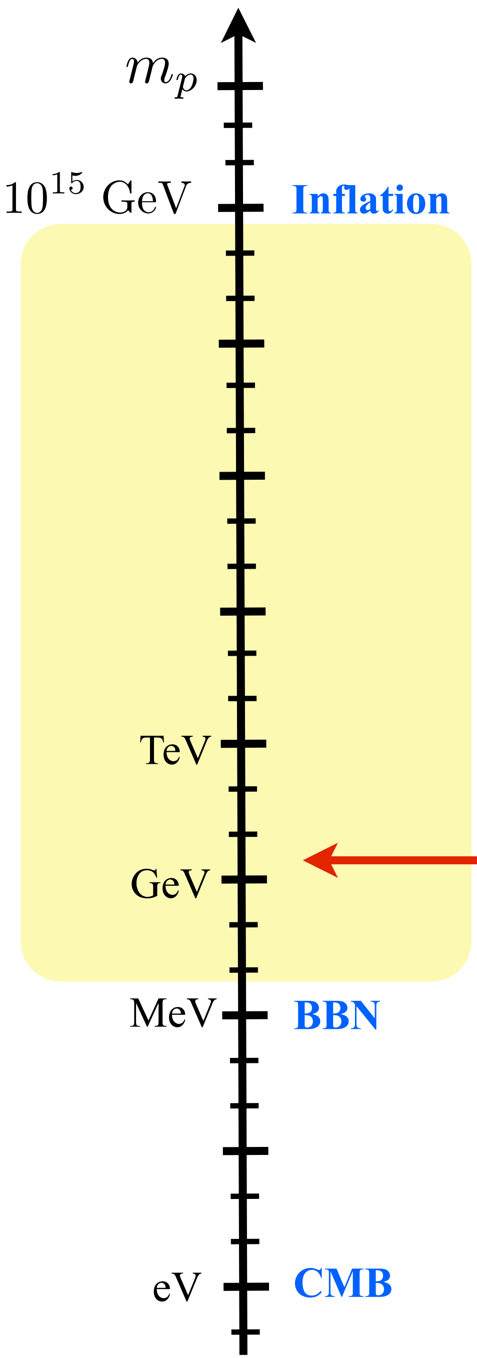
Cosmological Measurement

Weak Scale Physics

Dark Matter WIMPs?

Are things so simple?

Thermal Microscopic History



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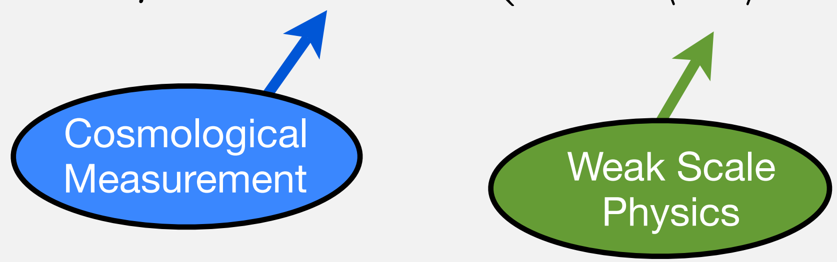
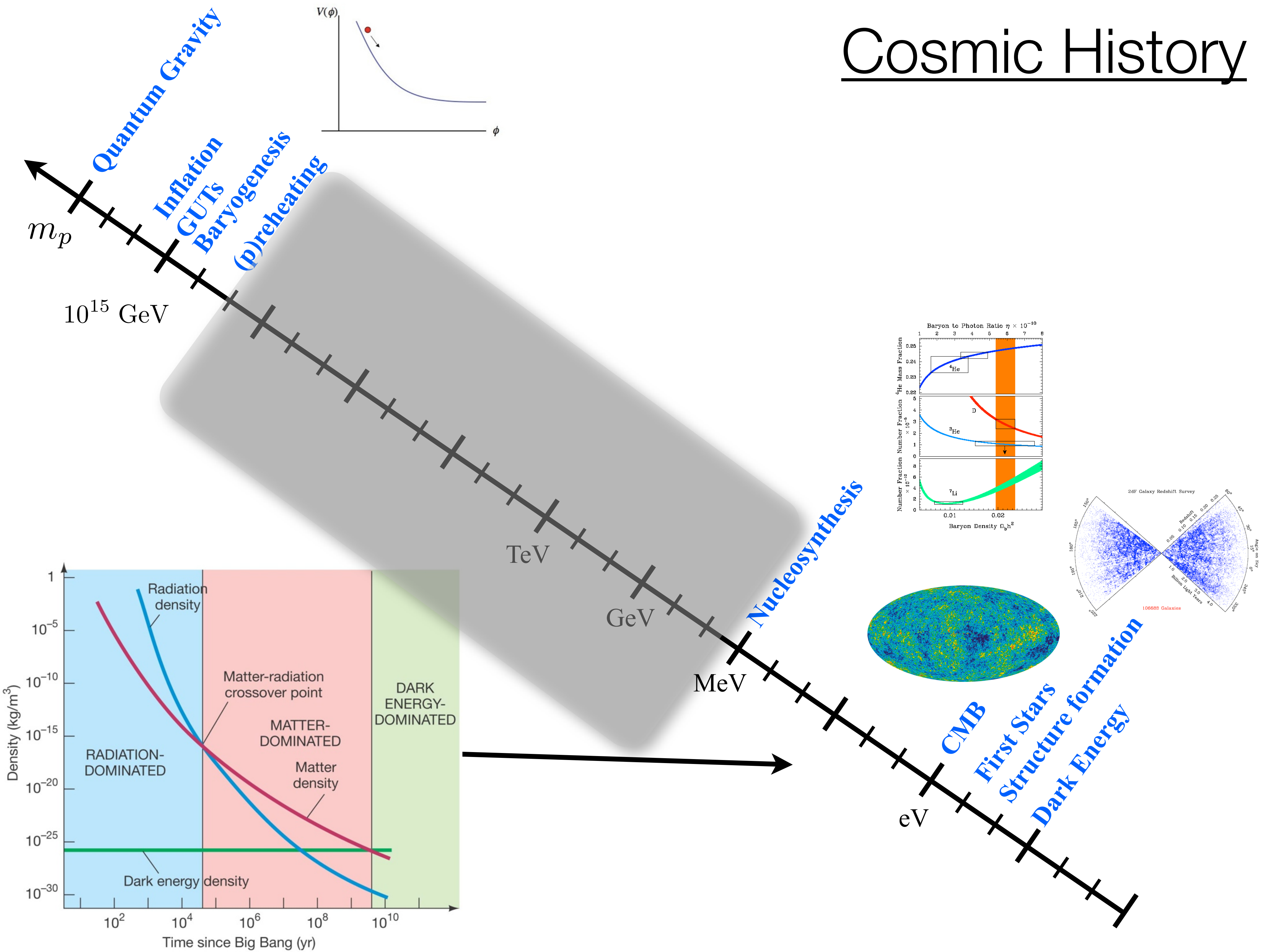


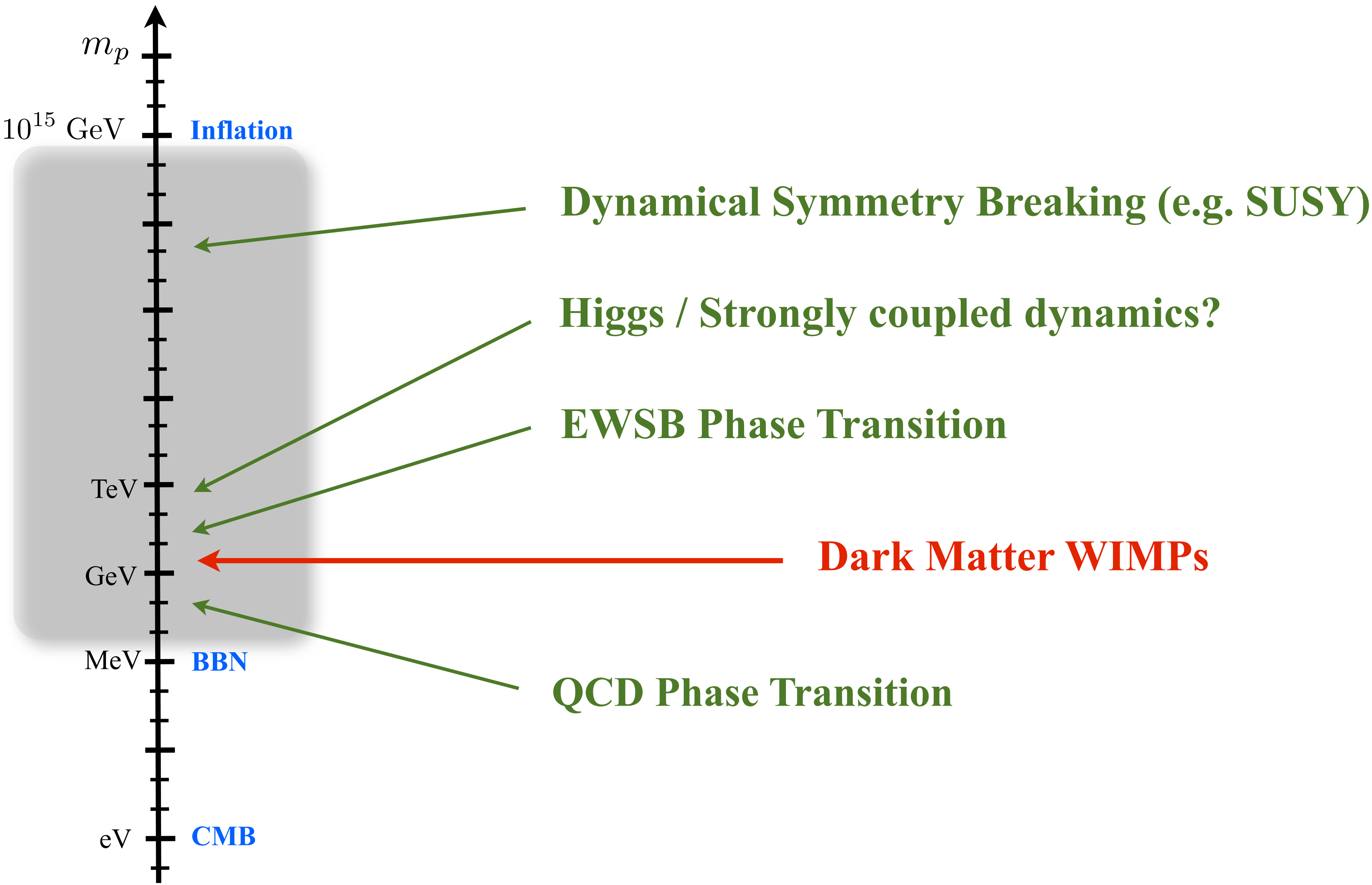
Dark Matter WIMPs?

*Assumed thermal equilibrium was reached
*Assumed radiation dominated universe at freeze-out
*Assumed no entropy production after freeze-out
*Assumed no other sources of cdm (e.g. late decays)

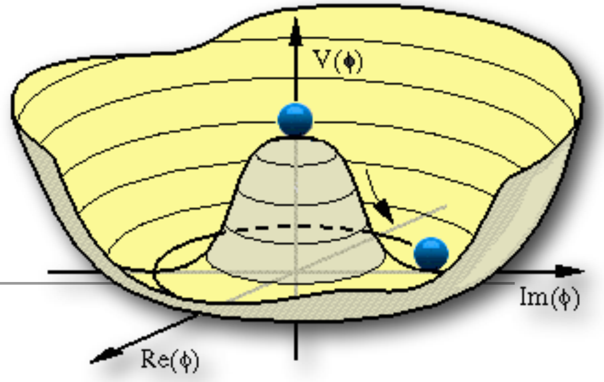
Cosmic History



Microscopic History



Light Scalars in the Early Universe



Light scalars are a generic prediction of physics beyond the standard model

- Some have a geometric interpretation (e.g. extra dimensions), others are scalar partners of standard model fermions (SUSY)
- Low energy parameters become dynamical fields in early universe

$$\langle h \rangle \to h(t, \vec{x}) \qquad m, g \to m(h), g(h)$$

- Many of these fields pass through cosmological phases where they have little or no potential: "Approximate Moduli"

Approximate Moduli

Moduli Potential

$$V_\varphi(T, H, \varphi) = 0$$

Approximate Moduli

Moduli Potential

$$V_{\varphi}(T, H, \varphi) = 0 + V_{soft}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T, H, \varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA} + V_{np}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA} + V_{np} + V_{thermal}$$

Approximate Moduli

Moduli Potential

$$V_\varphi(T,H,\varphi) = 0 + V_{soft} + \frac{1}{M^{2n}}\varphi^{4+2n} + V_{SUGRA} + V_{np} + V_{thermal}$$

Example:

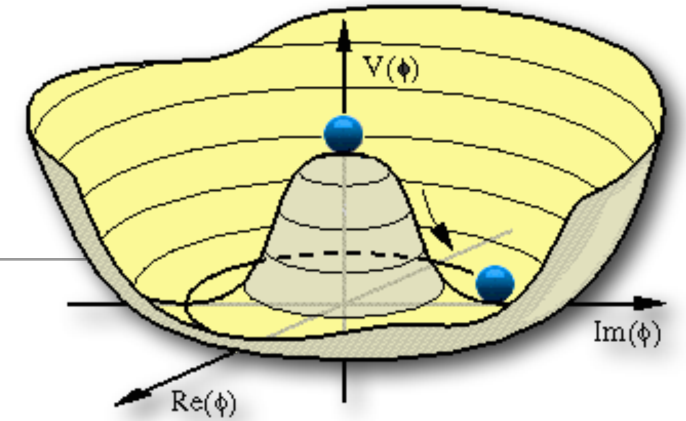
$$V(T,H,\varphi) = 0 + m_{soft}^2\varphi^2 - H^2\varphi^2 + \frac{1}{M^{2n}}\varphi^{4+2n}$$

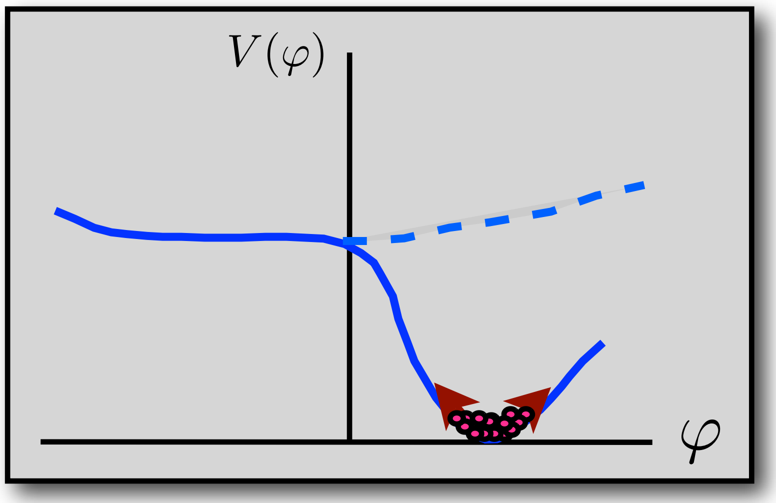
$$\langle\varphi\rangle \sim M\left(\frac{H}{M}\right)^{\frac{1}{n+1}} \qquad H \gg m_{3/2} \sim \text{TeV}$$

$$\langle\varphi\rangle \approx 0 \qquad H \ll M$$

$\Delta\Phi \rightarrow \Delta E$ ⟶ Scalar Condensate

Scalar Condensates





Coherent Oscillations

$$V(\Phi) \sim \Phi^{\gamma}, \quad p = \left(\frac{2\gamma}{2+\gamma} - 1\right)\rho.$$

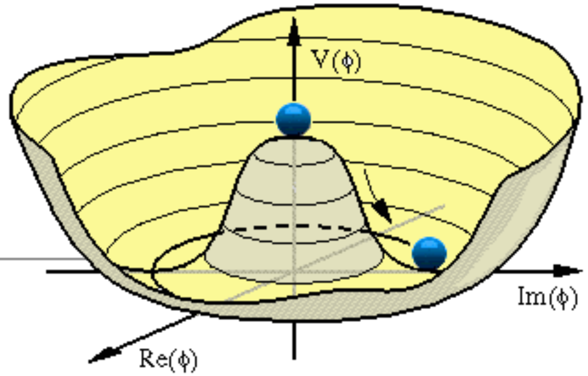
$\gamma = 0$	$p = -\rho,$	Λ
$\gamma = 1$	$p = -\frac{1}{3}\rho,$	tadpole
$\gamma = 2$	$p = 0,$	matter
$\gamma = 4$	$p = \frac{1}{3}\rho,$	radiation
$\gamma = \pm\infty$	$p = \rho,$	stiff fluid

Scalar Condensate forms

$$\Delta\Phi \rightarrow \Delta E$$

Cosmological Moduli Problem

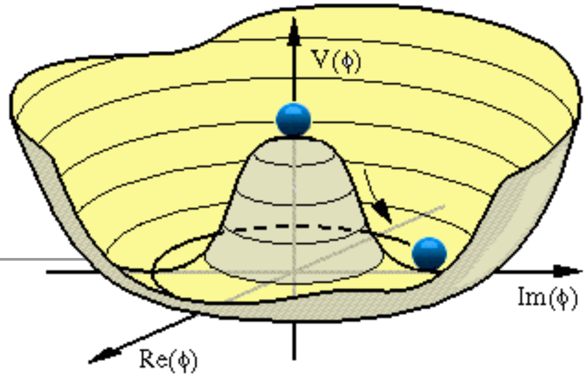
Coughlan, Fischler, Kolb, Raby, and Ross -- Phys. Lett. B131, 1983



Decay Gravitationally

$$\Gamma_\varphi \sim \frac{m_\varphi^3}{m_p^2}$$

Cosmological Moduli Problem



Coughlan, Fischler, Kolb, Raby, and Ross -- Phys. Lett. B131, 1983

Decay Gravitationally

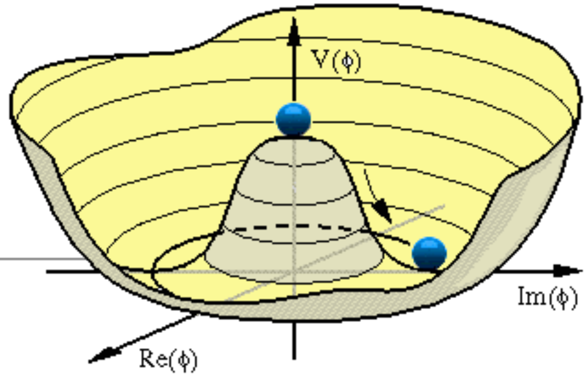
$$\Gamma_\varphi \sim \frac{m_\varphi^3}{m_p^2}$$

Two possibilities:

Stable

$$m_\varphi < TeV \longrightarrow \rho_{mod} < \rho_c \longrightarrow \boxed{m_\varphi < 10^{-26}\ eV}$$

Cosmological Moduli Problem



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Decay Gravitationally

$$\Gamma_\varphi \sim \frac{m_\varphi^3}{m_p^2}$$

Two possibilities:

Stable

$$m_\varphi < TeV \longrightarrow \rho_{mod} < \rho_c \longrightarrow m_\varphi < 10^{-26}\ eV$$

Decay

$$m_\varphi > TeV \qquad T_r > 1\ MeV\ (BBN) \longrightarrow m_\varphi > 10\ TeV$$

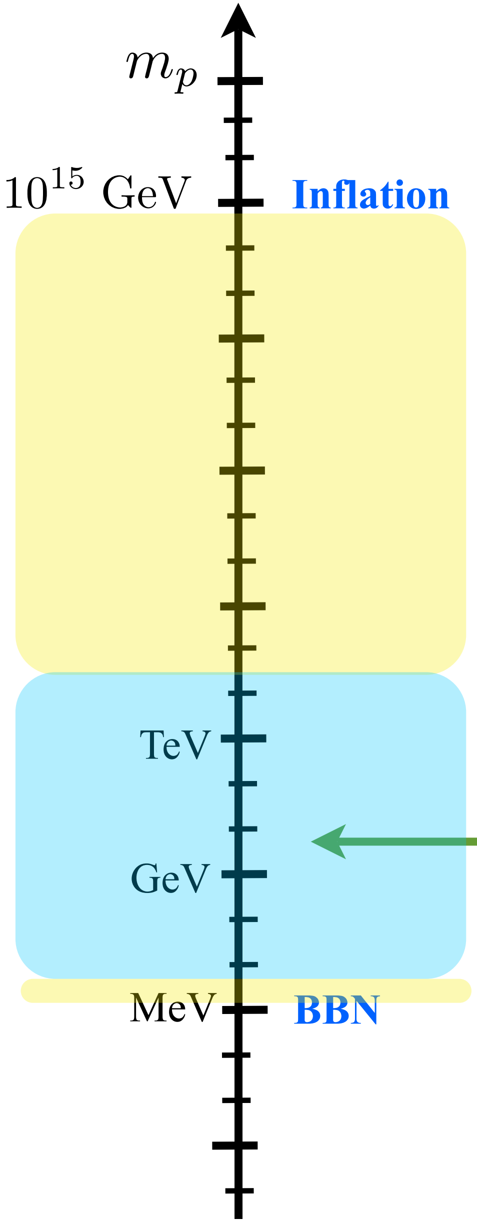
Concern: Decay to secondaries (model dependent) --> e.g. gravitino problem

Thermal relics and the Cosmological Moduli Problem

$$\Omega_{cdm} \sim \frac{m_x}{T}\left(\frac{H}{T^2\langle\sigma v\rangle}\right)_{T=T_f}$$

- Alter cosmic expansion
  (Salati - astro-ph/0207396, Chung, Everett, and Matchev - arXiv:0704.3285)
- Alter cross-section after freeze-out
  - Phase transition (changing coupling) after freeze-out
    (Cohen, Morrissey, and Pierce - arXiv:0808.3994)
- Non-thermal Production (e.g. Decay of Light Scalar)

Example: Non-thermal Production of Dark Matter



Initial Radiation Phase

Moduli Domination begins $H \sim m_\varphi$

Standard Thermal WIMP freeze-out

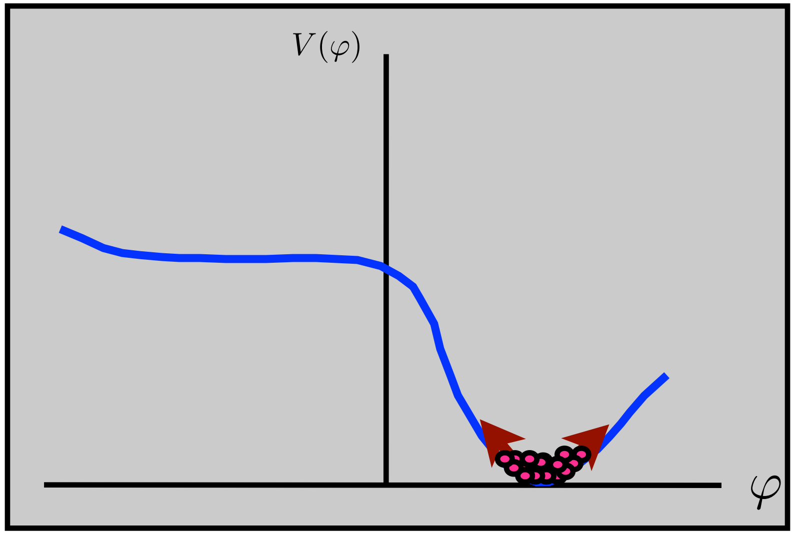
Moduli Decay and Reheat $H \sim \Gamma_\varphi$

- Dark matter from direct decay
- Entropy produced (dilute relic densities)
- Radiation dominated universe
- Baryons?

Example: Non-thermal Dark Matter from Light Scalars

Moroi and Randall -- hep-ph/9906527

Dark Matter from Scalar Decay:



- Moduli generically displaced in early universe
- Energy stored in scalar condensate

$$\Delta\Phi \rightarrow \Delta E$$

- Typically decays through gravitational coupling

$$T_r \simeq \left(\frac{m_\phi}{10 \text{ TeV}}\right)^{3/2} \text{ MeV}$$

- Large entropy production dilutes existing dark matter of thermal origin

$$\Omega_{cdm} \rightarrow \Omega_{cdm} \left(\frac{T_r}{T_f}\right)^3$$

Thermal abundance diluted

Example: Dark Matter from Scalar Decay

Review: G. Kane, S.W. arXiv:0807.2244

Dark Matter will be replenished

Given $T_r < T_f$ then dark matter populated non-thermally

$$\Omega_{cdm} \sim \frac{m_x}{T}\left(\frac{H}{T^2\langle\sigma v\rangle}\right)\Bigg|_{\sout{T=T_f}\ T=T_r}$$

$$\Omega_{cdm}^{NT} = 0.23 \times \left(\frac{10^{-26}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}\right)\left(\frac{T_f}{T_r}\right)$$

T_f ← Freeze-out temp

T_r ← Reheat temp

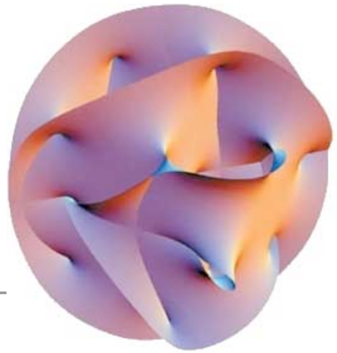
Allowed values still imply weak-scale physics
"WIMP Miracle" survives

Are other cosmic histories possible?

Yes. ✓

Is a non-thermal history an exotic or
a robust possibility?

Guidance from Fundamental Theory



What is needed from a top-down approach:

- 4D Effective theory
- Spontaneously broken SUSY
- Explanation for how $M_{EWSB} \ll M_p$
- Small and Positive Vacuum Energy

In String theory, all these problems are related and are essentially a problem of stabilizing scalars.

What were the key ingredients?

1. "Light" Scalar

$$m_\phi \approx 10\ \mathrm{TeV}$$

2. Gravitationally coupled

$$\Gamma_\phi \sim \frac{m_\phi^3}{M_p^2}$$

3. Stable dark matter particle

$$m_x \approx 100\ \mathrm{GeV}$$

What were the key ingredients?

1

"Light" Scalar

$$m_\phi \approx 10 \text{ TeV}$$

Light enough for decay after freeze-out,
Heavy enough to evade BBN bounds

3

Stable dark matter particle

$$m_x \approx 100 \text{ GeV}$$

The Cosmological Moduli Problem

Coughlan, Fischler, Kolb, Raby, and Ross -- Phys. Lett. B131, 1983
Banks, Kaplan, and Nelson -- Phys. Rev. D49, 1994

“ Model Independent properties and cosmological implications of the dilaton and moduli sectors of 4-d strings ”
Carlos, Casas, and Quevedo -- Phys. Lett. B318, 1993

$$V = e^{\frac{K}{m_p^2}} |DW|^2 - 3m_{3/2}^2 m_p^2$$

Shift symmetry

$$\Phi = \phi + ia \longrightarrow W \neq W(\Phi)$$

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$$V = e^{\frac{K}{m_p^2}} |DW|^2 - 3 m_{3/2}^2 m_p^2$$

Shift symmetry

$$\Phi = \phi + ia \longrightarrow W \neq W(\Phi)$$

Zero vacuum energy, stabilize scalar, break SUSY (spontaneously)

$$\Delta V(\Phi) = m_{3/2}^2 m_p^2 \, f\left(\frac{\Phi}{m_p}\right)$$

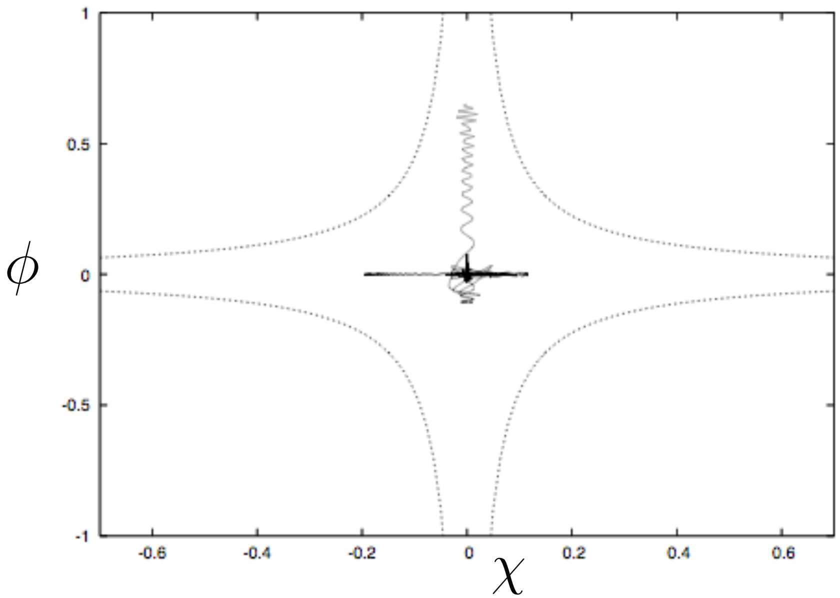
$$m_\phi \sim m_{3/2} \sim \text{ TeV}$$

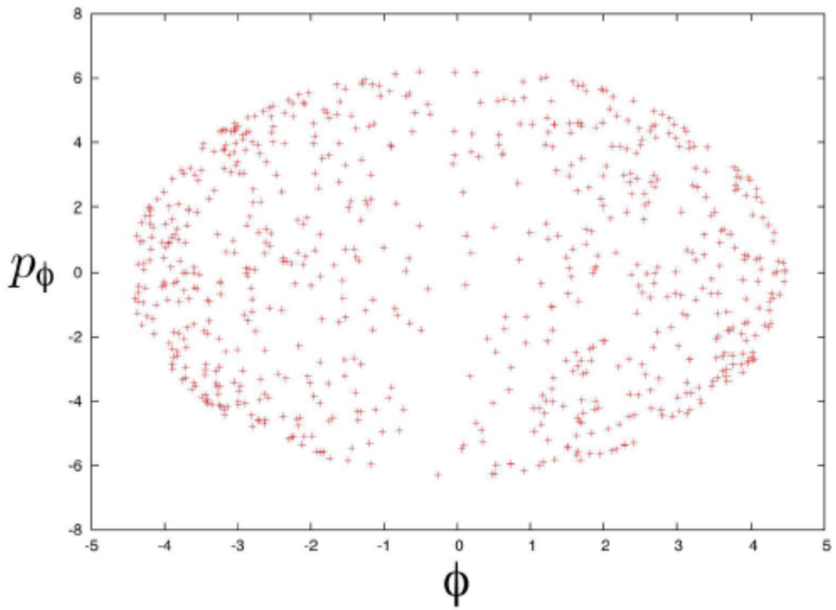
Mismatch with UV minimum

Stabilizing the String Vacuum

- Kofman, et. al. hep-th/0403001
- S.W. hep-th/0404177
- Cremonini & S.W. hep-th/0601082
- Greene, Judes, Levin, Weltman, & S.W. hep-th/0702220

If scalars stabilized near points of enhanced symmetry this can prevent the formation of condensates (Dine)

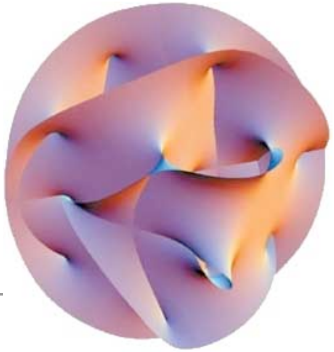




Study dynamics:

- Scalars typically sample all of field space in finite time
- These points are dynamical attractors (new d.o.f.)

Stabilizing Scalars in String Theory



Include addition degrees of freedom: Gauge Fields / Branes

Most scalars will receive string scale masses and "stringy physics" will decouple from the low energy theory

$$m_z \approx M_s \approx 10^{17}\ \mathrm{GeV}$$

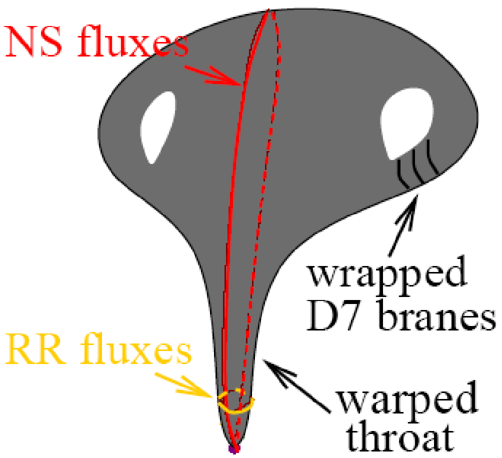
However, at least one light scalar typically remains

$$W(\phi) = W_0 + Ae^{-a\phi}$$

Nonperturbative stabilization at dS vacuum (w/ hierarchy respected)

$$m_\phi \approx m_{3/2} \approx \mathrm{TeV}$$

Recipe for string vacuum (IIB)



Step One:

Flux provides stabilizing potential for many of the scalars in the theory (e.g. dilaton and structure moduli)

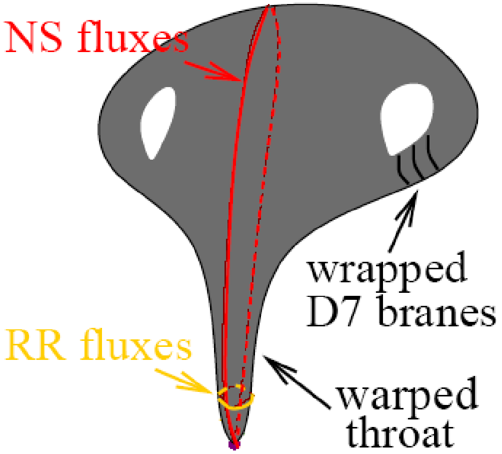
String scale masses

$$m_z \approx M_s \approx 10^{17}\ \mathrm{GeV}$$

At low scales most string scale physics decouples

$$W = W_0$$

Recipe for string vacuum (IIB)



Step One:

$$W = W_0$$

Want: $m_{3/2} \approx \mathrm{TeV}$

$$m_{3/2} = \frac{|W_0|}{M_p^2 V_6}$$

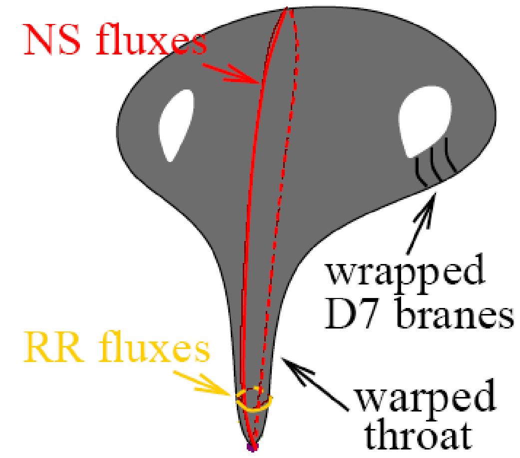
$W_0 \ll 1$ (KKLT)

or

"Large Volume"

$V_6 \gg 1$ $V_6 \approx 10^{14}$

Recipe for string vacuum (IIB)



Step Two:

Some scalars naturally remain light

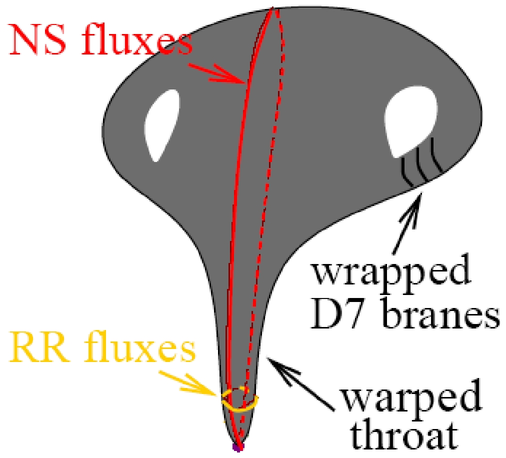
(Axionic shift symmetry / No scale structure)

Stabilize by non-perturbative dynamics

$$W = W_0 + Ae^{-aX}$$

SUSY restored, Anti-deSitter Minimum

$$V \ll 0$$



Recipe for string vacuum (IIB)

Final Step:

Uplift (anti-brane / charged matter / string corrections) minimum to dS, SUSY broken

Result:

If W_0 appropriately tuned (exponential and discrete) to preserve hierarchy:

$$m_\phi \simeq \log\left(\frac{m_p}{m_{3/2}}\right) m_{3/2}$$

Other models with possible non-thermal contribution:

- Large Volume Compactifications
  e.g. Conlon and Quevedo -- arXiv:0705.3460
- F-theory
  Heckman, Tavanfar, and Vafa-- arXiv:0812.3155
- M-theory on G2 manifolds
  Acharya, et. al. -- arXiv:0804.0863

$$W = \cancel{W_0} + c_1 f(\phi) e^{-aX} + c_2 e^{-bX}$$

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Remarks

- Many open questions:
  Embedding visible sector, uplifting, path to 4d, SUSY breaking
- Gaugino (dark matter) has three robust patterns
  "The Gaugino Code", Choi and Nilles -- arXiv:hep-ph/0702146
- Light scalar may be robust prediction
  "A Non-thermal WIMP Miracle", Acharya, et. al. -- 0908.2430

A Non-thermal WIMP Miracle

B. Acharya, G. Kane, P. Kumar, S.W. -- Phys. Rev. D80 arXiv:0908.2430

If scalars stabilized without reintroducing electroweak hierarchy and accounting for small and positive vacuum energy this typically implies:

$$m_\phi \approx m_{3/2} \approx \mathrm{TeV}$$

A new "WIMP" miracle

- **Scalar decays into Dark Matter and radiation** $\phi \rightarrow X$

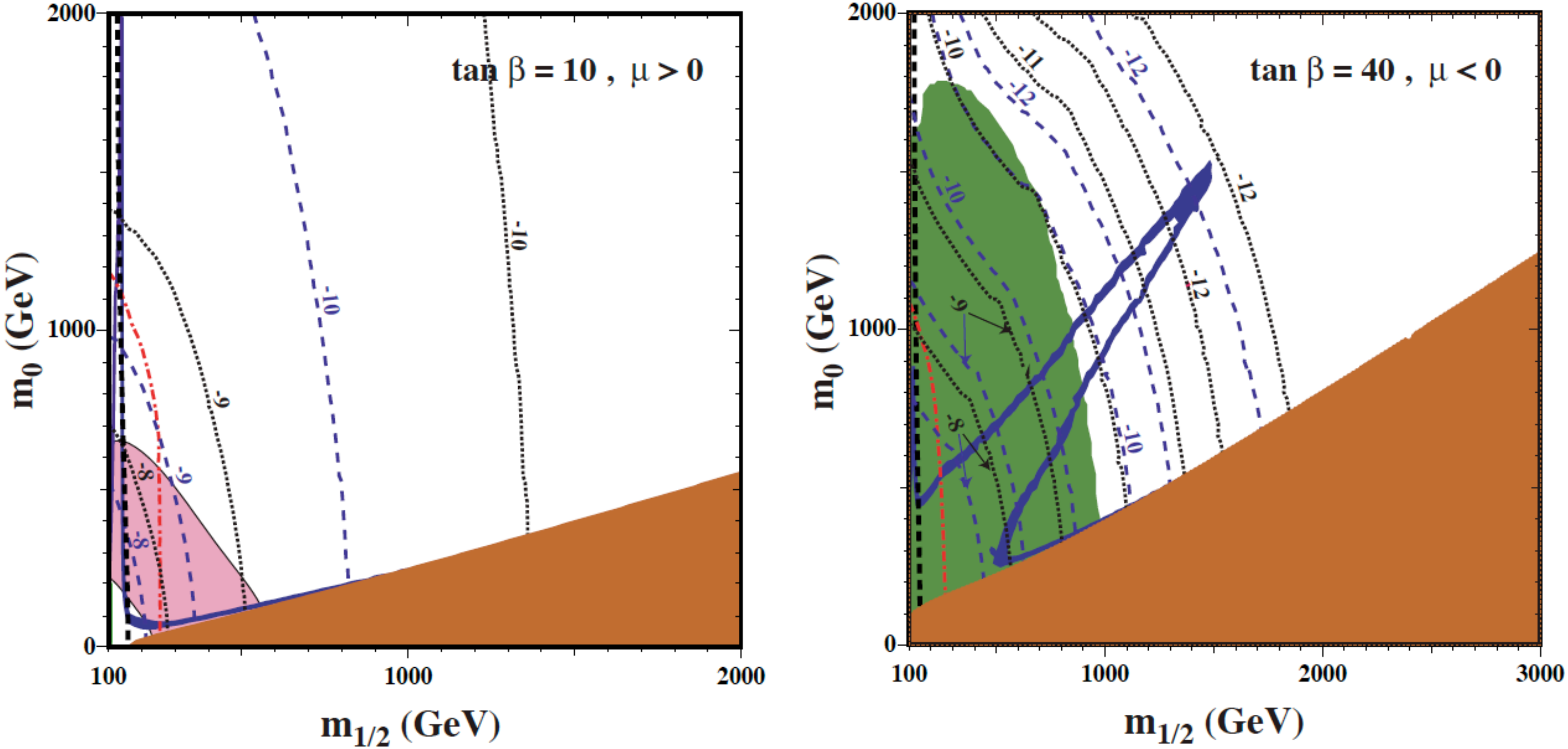
- **Initial abundances diluted** $\Omega_{cdm} \rightarrow \Omega_{cdm} \left(\frac{T_r}{T_f}\right)^3$

- **Dark Matter produced in accordance with cosmological constraint with higher cross-section**

$$\Omega_{\mathrm{cdm}} \sim \frac{m_x}{T} \left(\frac{H}{T^2 \langle \sigma v \rangle} \right) \Bigg|_{T=T_r}$$

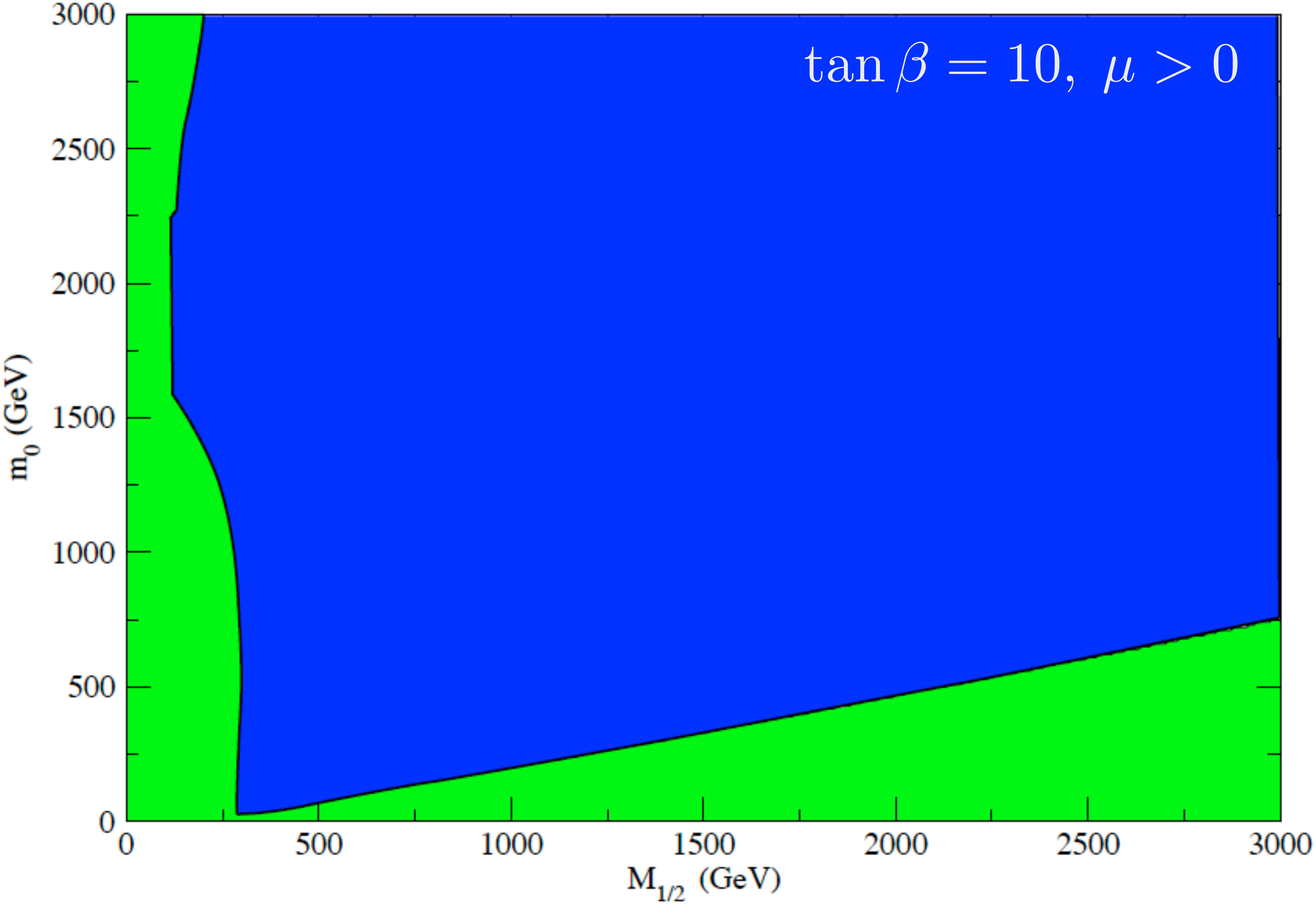
Some Phenomenological Implications of a Non-thermal history

SUSY Model Constraints Enforcing WMAP (blue)



Ellis, et. al. 2005

SUSY Model Constraints Without Enforcing WMAP (blue)



Gelmini, Gondolo, Soldatenko, Yaguna hep-ph/0605016

PAMELA -- Indirect Evidence for WIMPs?

Expected Positron Flux

$$\Phi \sim \frac{\langle \sigma v \rangle}{m_X^2} \times \rho^2(r)$$

Microphysics Astrophysics

Important Considerations

- Astrophysical uncertainties: Halo profile, propagation, backgrounds
- Unknown astrophysical sources, e.g. Pulsars
- Proton contamination (10,000/1)

Taken alone probably not a compelling case for dark matter

Larger cross-section can address PAMELA excess

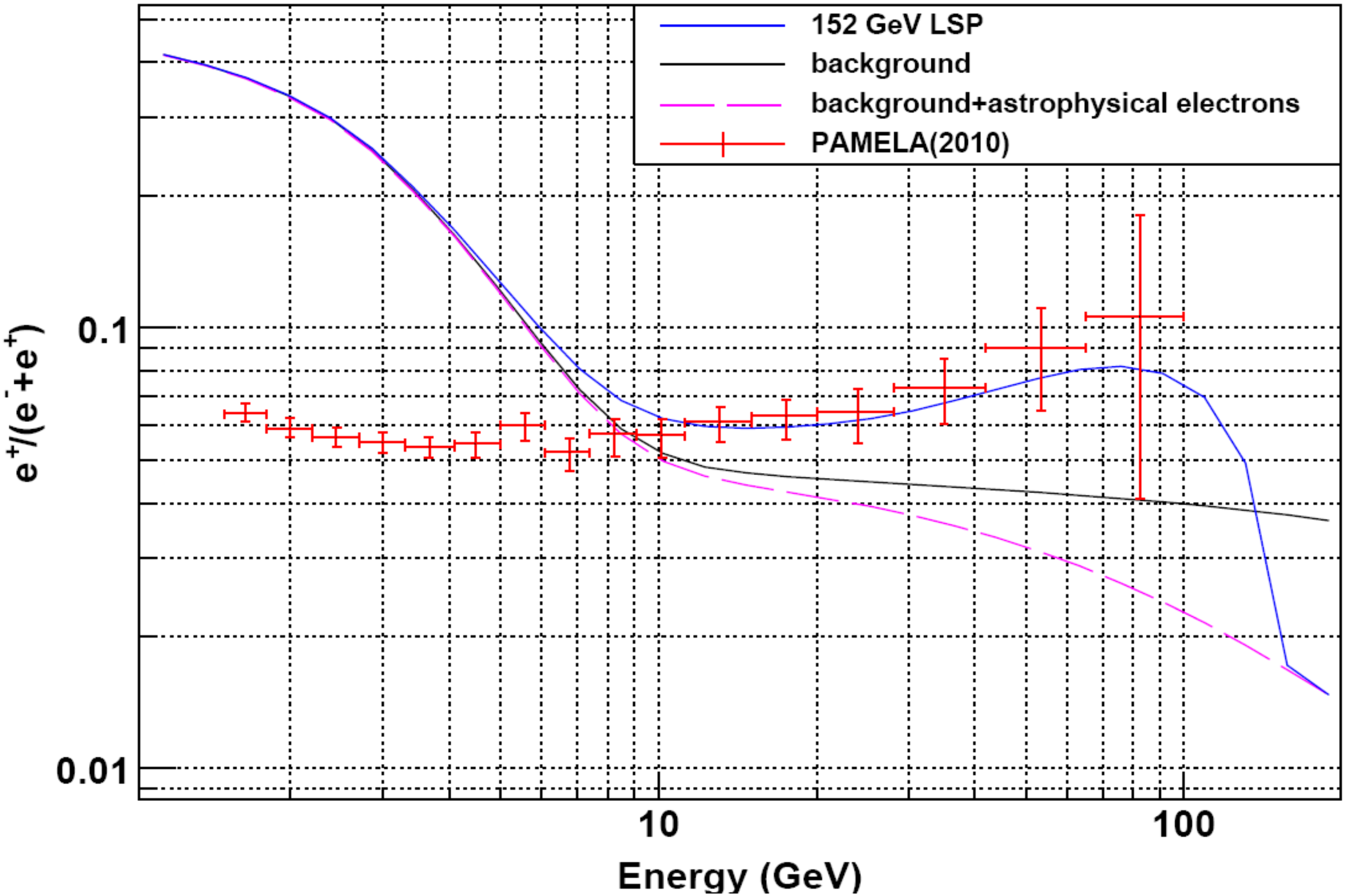


Figure by Ran Lu (grad student MCTP)

Pamela anti-protons

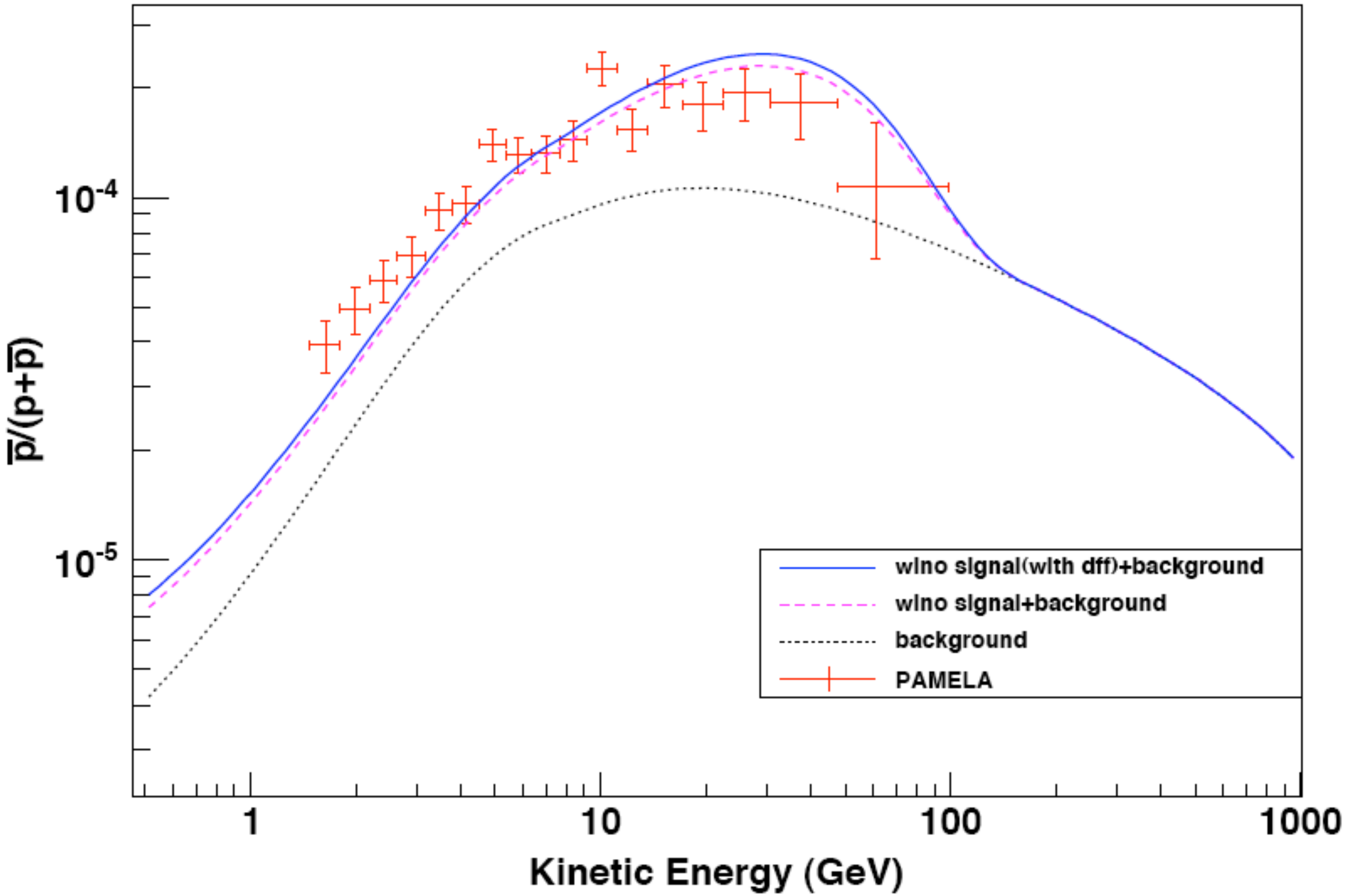


Figure by Ran Lu (grad student MCTP)

Fermi predictions

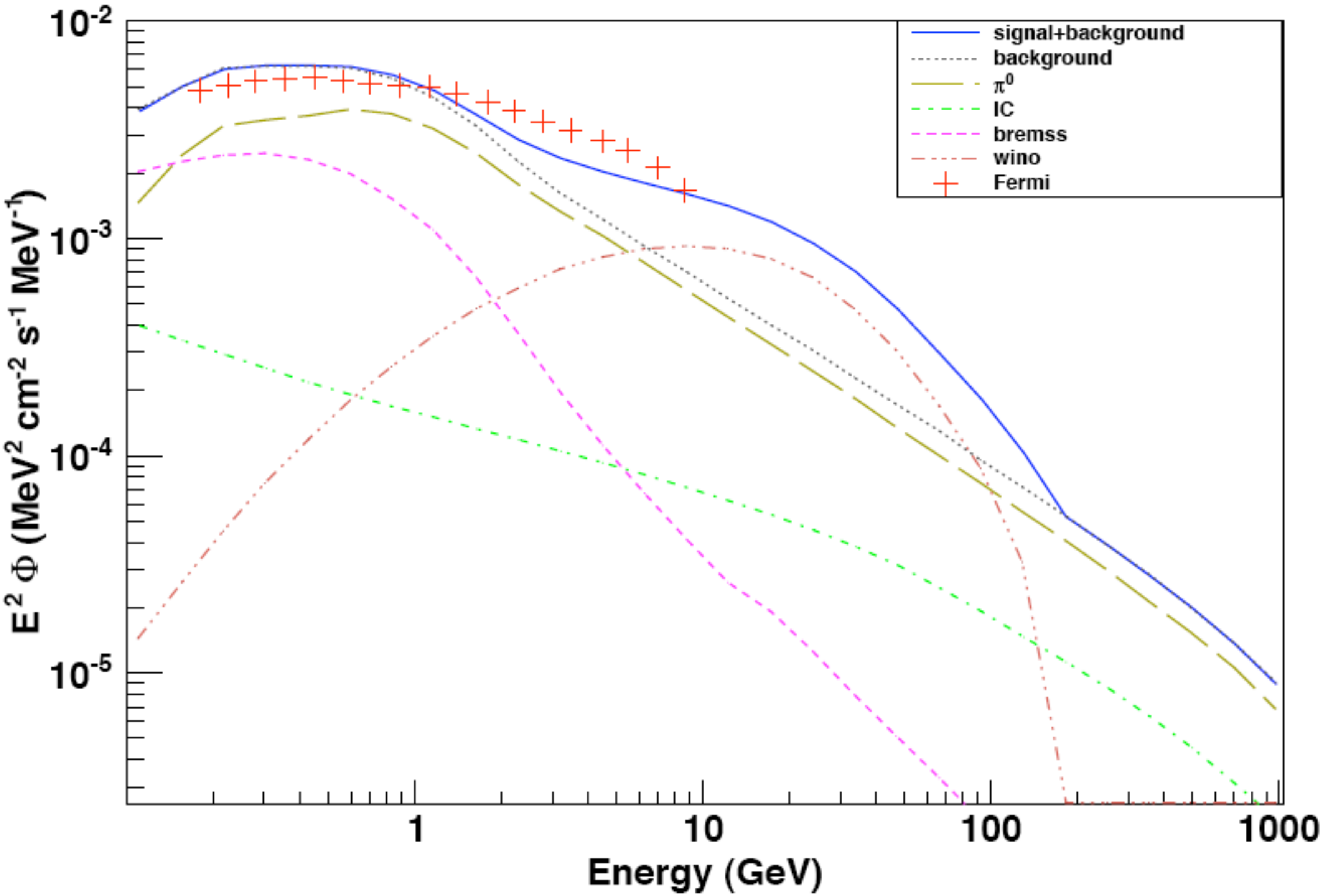
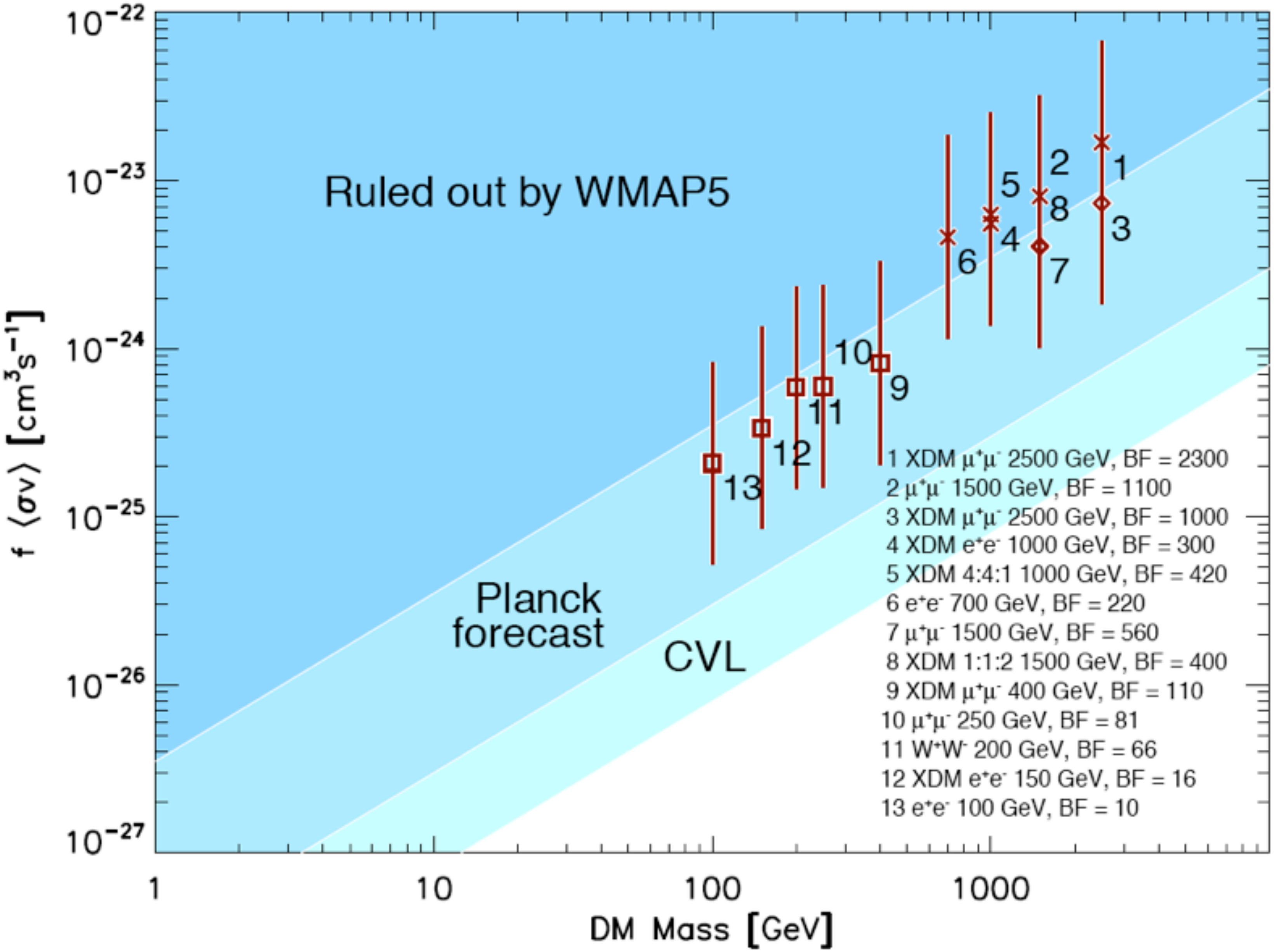


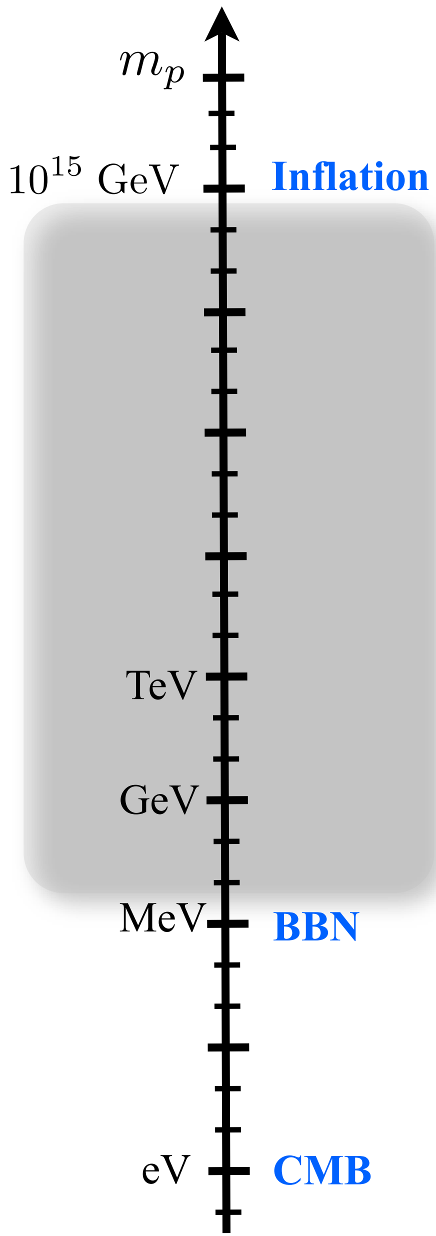
Figure by Ran Lu (grad student MCTP)

Photon-baryon heating during ionization from dark matter annihilation



Slatyer, Padmanabhan and Finkbeiner 0906.1197

Conclusions



Non-thermal cosmology provides a viable alternative to the well motivated thermal scenario.

Unlike the thermal case, a non-thermal history would imply a direct connection to fundamental theory and an observational window on the properties of the early universe.

Working directly with fundamental theories non-thermal models can lead to predictions which are falsifiable in current and near term experiments.

The New York Times

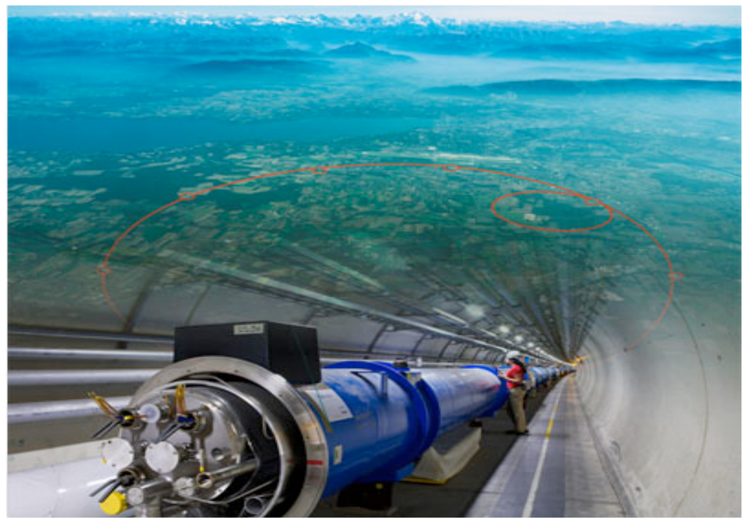
April 1, 2011

New York Partly Cloudy 42°F

Obama Solves Global Financial Crisis and Brings World Peace

by Paul Krugman

President Obama addressed the nation today acknowledging that although his administration has successfully resolved the global financial crisis, restored the confidence of the American housing market, and brought world peace, that there is still much left to be accomplished. The president has promised to turn to more mundane issues such as establishing a legitimate college football playoff,



Experimental Result Leads to Excitement and Controversy

by Dennis Overbye

$$\Omega_{cdm} = 0.002$$

To the physicist, the above expression succinctly summarizes the recent surprising results coming from the Large Hadron Collider (LHC) located in Geneva, Switzerland. The equation symbolically represents the amount of dark matter in the universe, which from the initial findings of the experiment seem to fall short of expectations coming from cosmological observation.

OPINION »

Op-Ed: Restore the Senate's Treaty Power

America needs to maintain its sovereignty, write John R. Bolton and John Yoo.

- Krugman: Stimulus Plan
  Comments (418)
- Kristol: Why Israel Fights
  Comments (368)
- Cohen: Penn's Dangers
  Comments (130)
- Editorial: Drug Money
  Comments (69)

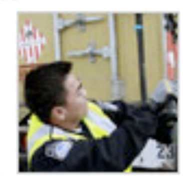
ARTS »

A Leitmotif of Love, Memories and Secrets

Jayne Anne Phillips's novel fuses disparate influences into something utterly original.

Protecting Borders and Other Pursuits

A reality series about policing the borders is more homage than reportage.



MARKETS » At close 01/05/2009

S.&P. 500	Dow	Nasdaq
9927.45	19927.45	8927.45
–4.35	–81.80	–4.18
–0.47%	–0.91%	–0.26%

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