Alternatives to the Thermal WIMP "Miracle"-- A Top-Down Perspective

Piyush Kumar

Columbia University

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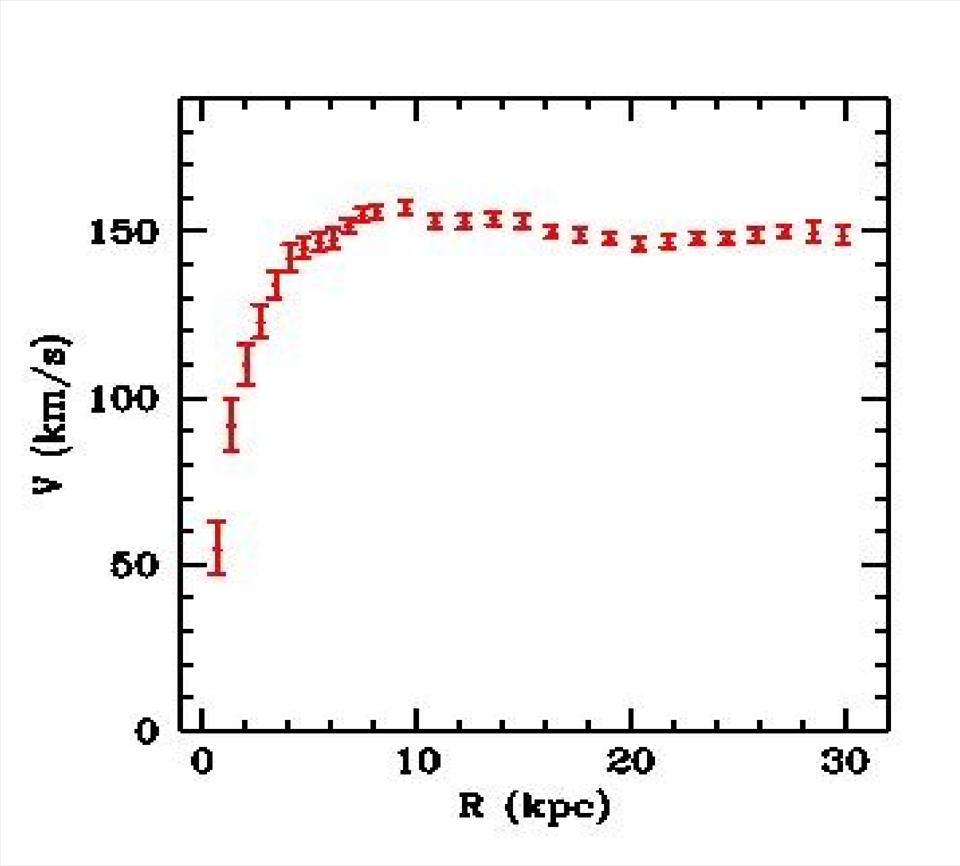
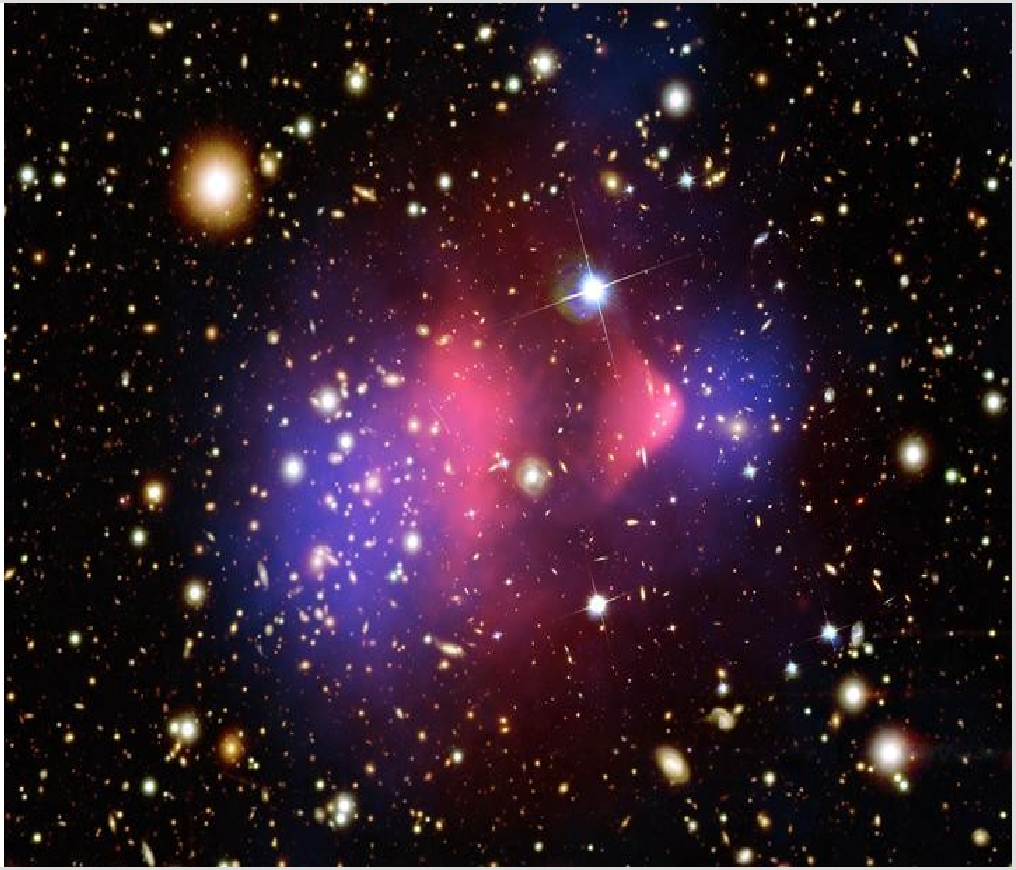
Outline

- Introduction.
- Assumption of the Thermal WIMP Miracle.
- Checking assumptions within String-motivated Frameworks.
- Some alternatives to the Thermal WIMP Miracle.
- Testing the Ideas – Issues & Challenges.
- Conclusions

Introduction

- Origin of DM remains a deep mystery.
- Only know about the existence of DM via its gravitational effects:





Observationally, very little known about DM

- Mass of DM can lie in an immense range :

  <~ 10^{-20} eV (Axions) to >> TeV (Exotic particles)

- Nature of DM equally uncertain (wide variety of candidates)

  -- Axions
  -- WIMPs
  -- super-WIMPs (Gravitino, Axinos, Goldstini,...)
  -- FIMPs
  -- Exotics (Baryons in the Hidden/Messenger sector)
  -- Topological Defects
  -- Significant warm component (neutrinos or similar)
  -- Who knows???

Still, High-energy community quite hopeful of discovering DM

- Primary reason for this stems from the so-called “WIMP Miracle”.
- Quite Beautiful and Predictive. If DM is a WIMP:

-- Parametrically get the right abundance for weak scale masses & cross-sections.

-- Moreover, possible to reconstruct the cosmology by measurements in: a) Colliders.
b) Direct-Detection.
c) Indirect-Detection (Cosmic Rays)

However, depends on some crucial assumptions:

- DM has a thermal distribution
  (Radiation dominated Universe)
- DM is a WIMP.
- DM shares appreciable interactions with the visible sector.

Thermal Freezeout → WIMP Miracle

Assumptions: How reasonable or restrictive from a Top-Down Perspective?

- Will assume that the top-down perspective is provided from String Theory.

For concreteness,

- Focus on compactifications to 4-dim with stabilized moduli and low-scale supersymmetry.

Assumption 1: DM with Thermal Distribution

- This depends on the cosmological evolution after the end of Inflation to the beginning of BBN.

- Traditionally assumed that Universe reheated to a high-enough temperature after Inflation,

→ A radiation dominated Universe all the way until BBN and Mat.-Rad. Equality.

- However, assumes no other (important) source of energy density or entropy production during this vast era..

– A string compactification → Moduli Fields,

Scalar fields parameterizing the size and shape of extra dimensions

Must be stabilized and given large enough masses to escape fifth force constraints.

Depending on their mass, affect cosmological evolution very differently?

Q: What is the state-of-the-art regarding moduli stabilization in string theory?

- Only give a sketch of the results. *(More in B. Acharya's & C. Scrucca's Talks Also, S. Watson's & K. Bobkov's Talks)*

- Note that low energy theory of any 4D compactification is N=1, d=4 SUGRA (with stringy and quantum corrections)

- Generically, a set of moduli will be stabilized at ~ KK scale. For example, by fluxes, wilson lines, etc.

$$M_{heavy} \sim \alpha'/R^3 \quad \sim M_{KK}{}^3 / M_{st}{}^2$$

- The scalar potential : $V \sqsupset K^i K_i |W|^2 / m_p{}^2 \;\sim\; m_{3/2}{}^2 X^i X_i$

$$X_i = \{\text{Moduli, Charged Matter Scalar, Higgs}\}$$

where, $m_{3/2} = e^{K/2} W / m_p{}^2 = F^i F_i / m_p$

Generically, a set of moduli (scalars) has mass $m_\Phi \sim m_{3/2}$

proved in generality and rigor by Gomez-Reino, Scrucca (th/0606273,0706.2785)
Acharya, Kane,Kuflik (1006.3272 [ph])

Gauge Mediation

- 10^{-3} eV <~ M_{moduli} ~ $M_{3/2}$ <~ 1 GeV
- Charged Matter scalars much heavier because of messengers.
- Can there be exceptions? i.e. can M_{moduli} >> GeV possible?

If Kahler & Super-Potential such that **ALL** moduli stabilized supersymmetrically. (R-symmetric dynamics)

Gravity Mediation

- All scalars (M_{moduli}, M_{matter}) ~ $M_{3/2}$ > 100 GeV

Axions

- All (geometric) moduli pair up with pseudoscalars to form N=1 chiral superfields: Z = s+i a.

Generic Compactification → O(100) moduli, O(100) axions

- What about masses of Axions?

Axions have a shift symmetry ---> Get mass only after symmetry broken.

Two Possibilities :

- 1) Shift symmetry broken by classical/pert. Effects in string theory.

Example: KKLT, Large Volume compactifications,.....

$$M_{axions} \sim M_{moduli} \sim M_{3/2}$$

- 2) If symm. only broken by non-pert. Effects, then

Acharya, Bobkov, Kane, PK, Shao th/0701034

Bobkov,Braun, PK, Raby 1003.1982

$$M_{axion} \sim \text{Exp}[-2\pi V]\, M_{3/2} <<< M_{3/2}$$

- Since V can differ by O(1), exponential Hierarchy among axion masses

→ String Axiverse

Proposed in Arvanitaki, Dimopoulos, Dubovsky, Kalojper, March-Russell (0905.4720)

Realized in Acharya, Bobkov, P.K. (1004.5138)

See K. Bobkov's Talk for details.

- Also showed that one of these axions could naturally be the QCD axion

→ Solution to Strong-CP solution in String Theory

Axions also provide significant contribution to Dark Matter

So, what about cosmology in a string compactification with Moduli & Axions?

- Crucially depends on Hubble parameter during Inflation

- Traditional slow-roll Inflation models:

  $H_{inf} >> TeV$ ⟹ (Light) Moduli displaced during Inflation
  Start oscillating when $H \sim M_{moduli}$
  Quickly dominate the Energy Density
  Moduli dominated until BBN.

- $H_{inf} <\sim TeV$ ⟹ possible in Hybrid Inflation
  Moduli not displaced,
  "Standard" Radiation Dom. Cosmology possible.

Assumption 2: DM Candidates

- Hard to know how natural it is to have exotic forms of DM such as
  a) Topological Defects
  b) "Baryons" in Hidden/Messenger sector
  c) etc.

  in String Theory. So, will not comment on these.

- **DM candidates natural within string constructions** :

  a) **Model-Independent (always there, could be DM) :**

  1. Axions (if believe in strong-CP solution within String Theory)
  2. Moduli & Modulinos (FIMPs)
  3. Gravitino (thermal, super-WIMP, FIMP)

- **b) Model-Dependent: WIMPs**

  many semi-realistic string constructions give rise to SSM with R-parity (or extension thereof)

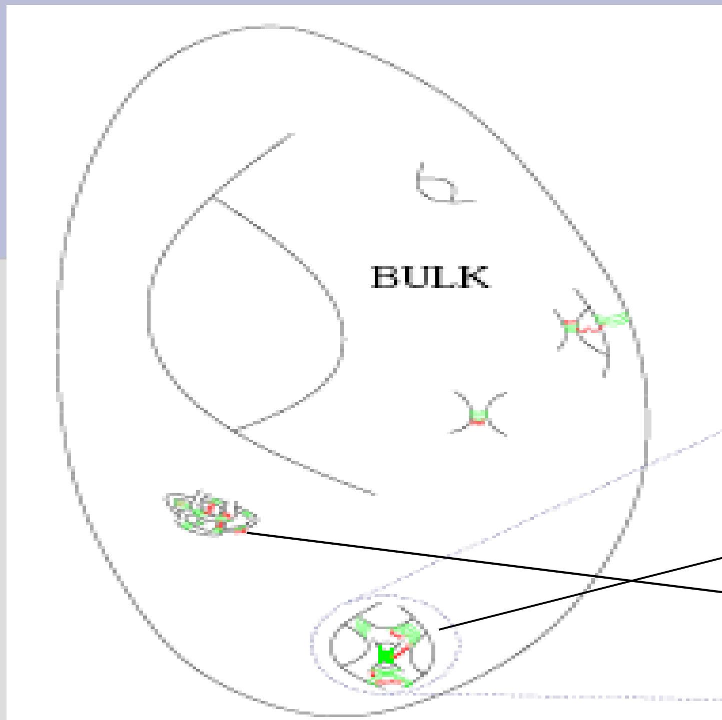
  Seems reasonable

In general, expect more than one non-trivial component of DM

Assumption 3: DM Shares appreciable interactions with visible sector

- Axion Fraction of DM : Not satisfied.
- FIMP fraction of DM (Modulino) : Not satisfied.
- For WIMP fraction of DM : Satisfied if DM is the LSP in Visible Sector.

Can there be broader frameworks motivated from String Theory in which assumption 3 not true, even for WIMP DM?



- In D-Brane constructions, Tadpole Cancellation often ⇒

  Complicated set of D-brane configs.

  a) One set could comprise visible sector.

  b) Other set could comprise hidden sector.

- If ~~SUSY~~ gravity mediated, naturally obtain:

  $M_{vis} \sim M_{hid} \sim M_{3/2}$ with two sectors very weakly coupled suppressed by $\sim 1/M_{KK}$ interactions

  $T \neq T'$

- If stabilization symmetry (R-parity) acts globally, then LSP either in a) visible sector (m' > m) b) hidden sector (m > m')

Alternatives to the Thermal WIMP Miracle

-- which could follow naturally
from above considerations.

- Briefly describe some of them:

  -- Moduli Decay to DM (Non-thermal WIMP "Miracle")
  -- Axion DM
  -- FIMP DM.
  -- Freezeout & Decay (to DM in Hidden sector)
  -- Freeze-In (to DM in Hidden sector)

- May be others as well.

Moduli Decay to DM (Non-thermal WIMP Miracle)

B. Acharya's Talk

- a) $H_{inf} >> M_{3/2}$;
  b) Significant fraction of DM : WIMP (part of visible sector) ;
  c) Hidden sectors not relevant.

- Gravity Mediation : $M_{3/2}$ ~ TeV typically, but this leads to moduli and gravitino problems.

Simple Solution -- Increase $M_{3/2}$ to 10-100 TeV.

Superpartner spectrum – Generically all superpartner scalars ~ $M_{3/2}$ (Heavy)

Gauginos can be light (sub-TeV) due to approx. R-symmetry in gauge sector. ($F_{X\alpha} << F_{dominant}$)

Conlon, Quevedo; JHEP 0606:029,2006 (Type IIB)

Acharya, Bobkov, Kane, PK, Shao; Phys.Rev.D78:065038,2008 (M-theory)

Moduli oscillate → decay to superpartners → LSP

- For weak scale masses and cross-sections, typically BR to DM such that

$$n_\chi \quad > \; n_\chi^{crit} = 3\,H/ \langle \sigma\, v \rangle \mid T = T_{RH}\,(X_0)$$

- Relic Density fixed at $n_\chi^{crit}\,(T{=}T_{RH}\,(X_0))$

- $\Omega_{DM} = \Omega_{DM}$ (standard) $(T^{freezeout}_{\chi} \,/\, T_{RH}\,(X_0))$

With M_{moduli} ~ 10-100 TeV (Simple solution to Moduli Problem)

Weak scale masses and SU(2) cross-section,

Obtain parametrically the correct abundance

First explored in Moroi, Randall (ph/9906527)

In Acharya, Kane, Watson, P.K.(0908.2430), showed that quite natural within string theory.

Axion DM

- As mentioned earlier,

  Axion solution to strong CP problem in string theory

  ⇨ Axions form a significant fraction of DM .

  (see K. Bobkov's Talk)

- Axion Relic Abundance within “Standard” and “Non-standard” cosmologies different.

  computed in Acharya, Bobkov, P.K. (1004.5138) .

- Can be distinguished from each other by future observations

  -- comment later.

FIMP DM (Modulus, Modulino, Axino,~ν_R...)

See L. Hall's Talk

Also, T. Moroi's Talk

- $H_{inf} <\sim M_{3/2}$;
- Significant fraction of DM : FIMP
- Hidden sectors not relevant

- In this case, FIMP has negligible initial abundance

- Very weakly coupled to visible sector via **marginal** couplings.

- Abundance arises from "Freeze-In" mechanism
  $Y_{FI} \sim \Gamma t \sim \Gamma M_{pl} / T^2 \sim \Gamma M_{pl} / m^2$ (dominant support at T ~ m)

Yield sensitive to IR physics if no higher dim. Operators involved. *Hall et al (0911.1120), Ishiwata et al (0912.0781)*

Freezeout & Decay (FO&D) and Freeze-In (FI)

for details, see L. Hall's Talk

Setup

- DM stable due to a symmetry shared by both sectors.
- Mass of DM X': m' < m, the mass of lightest superpartner in visible sector X.
- m, m' ~ weak scale – natural in Gravity Mediation.
- $H_{inf} < \sim M_{3/2}$, so radiation dominated cosmology until BBN.

$$X \to X' + SM \quad \text{(long lifetime)}$$

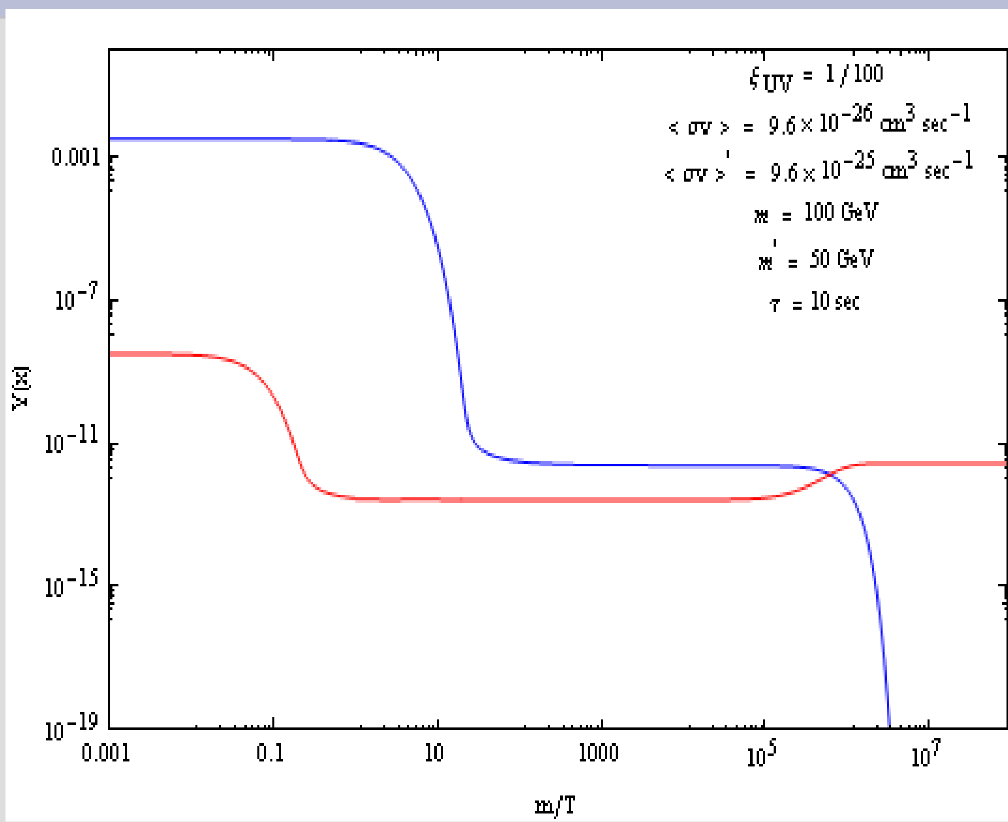
Relic Abundance determined by only a few parameters in general:

$$\{m, m', <\sigma v>, <\sigma v>', \tau, \xi\}; \quad \xi = T'/T$$

Based on Cheung, Elor, Hall, P.K. (1010.0022 & 1010.0024) [ph]

FO&D

for details, see L. Hall's Talk



If coupling very small:

$$Y'_{FO\&D} = Y_{FO}$$

Since m' < m,

$$\Omega_{DM} = \Omega_{FO}\,(m' / m)$$

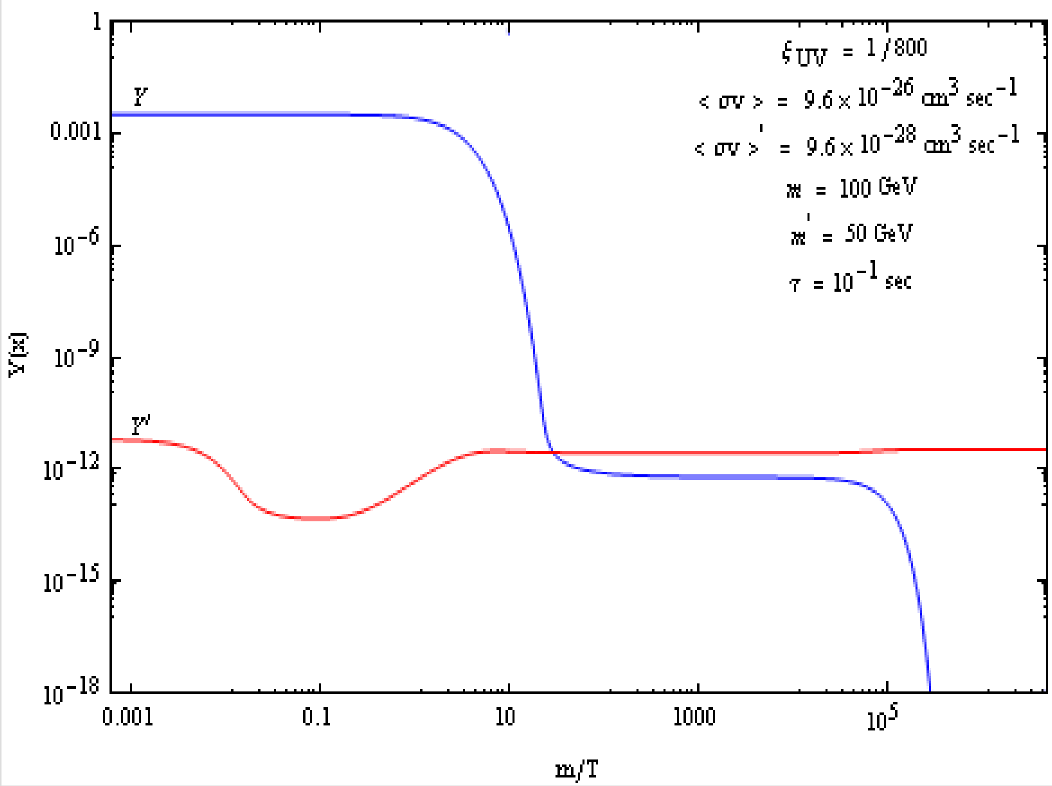
Want theories of FO which naturally overproduce.

(Bino, Slepton$_{RH}$)

- No bound on T_{RH} in contrast to that for super-WIMPs.

FI

for details, see L. Hall's Talk



Increase coupling, at some point

A new mechanism, FI, dominates

DM (X') abundance from X decays while X in thermal eqb.

$$Y'_{FI} \propto \Gamma\, t \propto \Gamma\, M_{pl} / m^2$$

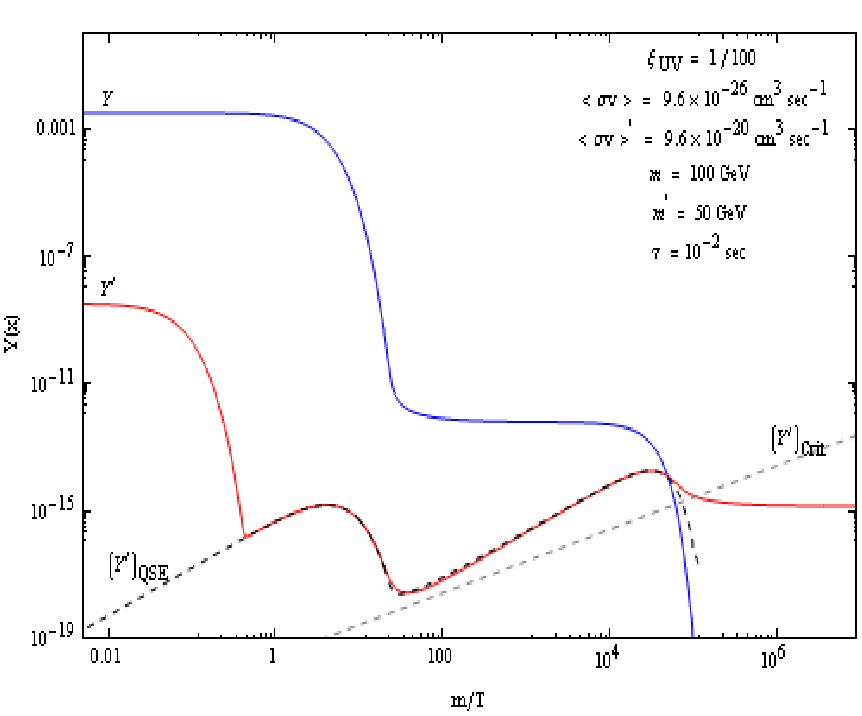
$$\Omega_{DM} \propto m' M_{pl} / m^2 \tau$$

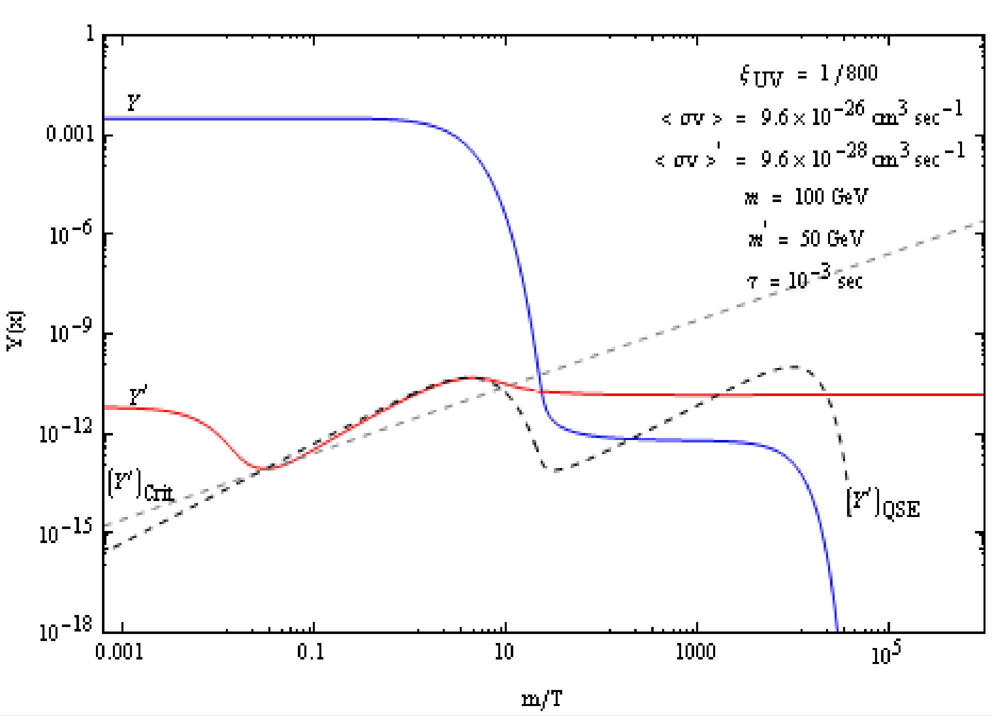
- Want theories in which FO naturally underproduces. ($\tau \sim 10^{-2}$ s)

  → *Picks out every superpartner **other** than bino, slepton$_{RH}$*

FO&D$_r$ and Fi$_r$ (Re-annihilations)

- Until now, X' annihilations **NOT** taken into account.
- If Non-thermal production too large ⟶ X's start re-annihilating
- Final Relic Abundance depends on <σ v>' -- in the hidden sector.





Testing Different Ideas for DM
Issues & Challenges

- Suppose see superpartners at the LHC:

- **If find signals with large missing energy & no displaced vertices**,

  → provide a strong hint that stable LSP produced which could be DM.

  -- By measuring properties (mass, couplings), compute FO abundance

  If gives correct abundance, TRIUMPH for the Thermal WIMP Miracle !

- **But what if does NOT match up?**

  a) FO abundance too small.

  b) FO abundance too large.

a) FO Abundance too small

- Another (non-thermal) mechanism for DM abundance, OR
- Another component of DM (not relevant at colliders), OR
- Both.

Example 1: Moduli decay to DM ($Y_{DM} > Y_{crit}$) with $H_{inf} > m_{3/2}$

$$\Omega_{DM} = \Omega_{DM}\,(\text{std})\ \left(T^{freezeout}_{\chi} \,/\, T_{RH}\,(X_0)\right)$$

Know T_{RH}, or decay time τ of moduli

Since Moduli typically much heavier than DM → DM produced with significant velocity.

- Phase space distribution different than standard thermal distribution.
- Could have effects on structure formation ⇒ **Challenging to test**

Example 2:

- Also consistent with Freeze-In to DM in Hidden sector with neutral LOSP. ($H_{inf} <\sim M_{3/2}$)
- Since lifetime of LOSP large for FI ($\tau \sim 10^{-2}$ s) and LOSP is neutral, would escape detector, have usual missing energy.
- Direct Detection may help in distinguish this scenario from previous one.

  -- No signal for Direct Detection in this case, whereas

  -- Signal should be seen for previous case.

FO abundance too large

- In this case, Relic Density has to be diluted by entropy production.
- **Example :** Moduli decay could give rise to this case, but now with

$$Y_{DM} < Y_{crit}$$

- To confirm that this is the mechanism, would have to look at effects on astrophysical observables again.

Suppose signals found with displaced vertices:

- Would imply that LOSP is unstable, and decays to DM.
- Many mechanisms could be relevant:

  -- FO&D to super-WIMP or DM in Hidden sector.

  -- FI to FIMP or DM in Hidden Sector.

  -- FO&D or FI with Re-annihilations.

  -- Asymmetric Dark Matter, *(Kaplan et al 0901.4117; Chang et al 0906.5013)*

  -- etc.
- Need data from Colliders, Direct-detection, Indirect detection & Astrophysical Observables to break degeneracy.

  --- Quite Challenging in general.

Last, but not the least !

Axions could provide a significant fraction of DM

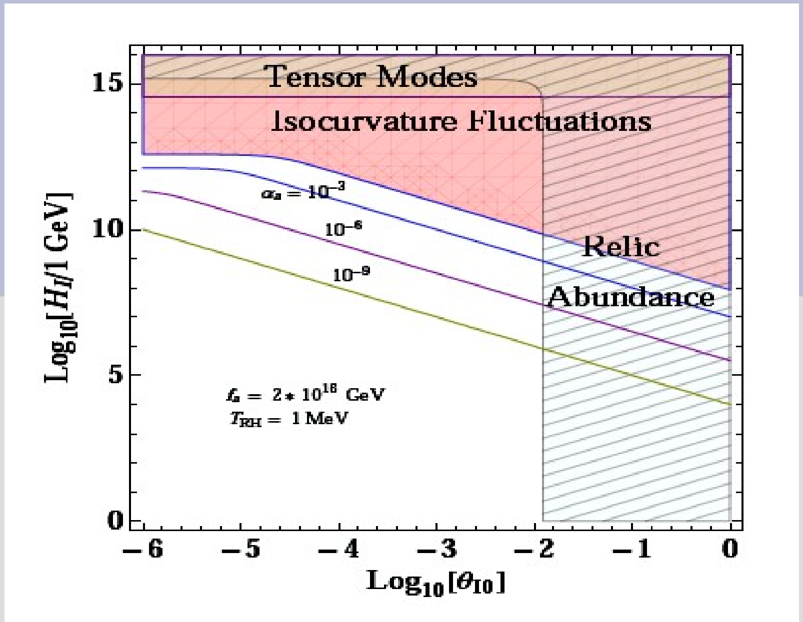
- Not relevant for Colliders, Direct or Indirect Detection (cosmic rays), **BUT**
- Could have important astrophysical effects: *(Arvanitaki et al 0905.4720)*

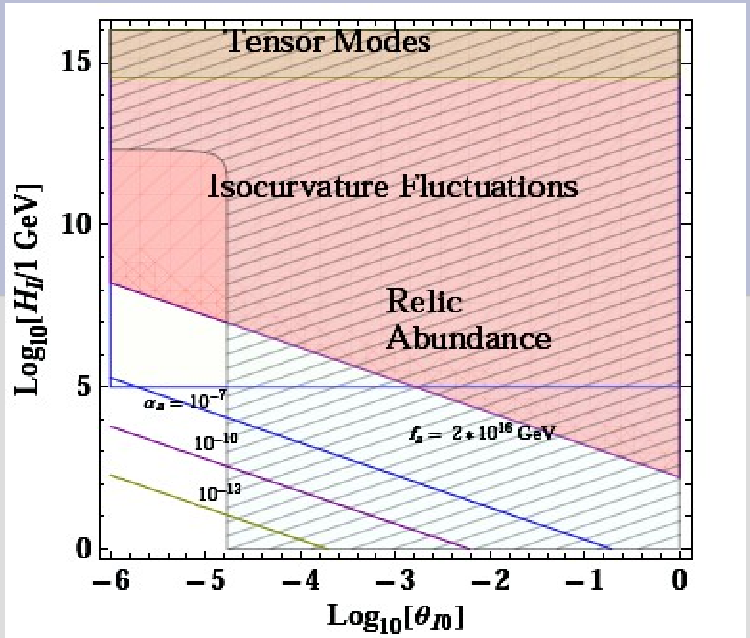
  -- Suppression of Matter Power spectrum at small scales.

  -- Super-radiance of Black Holes (Grav. Waves at LISA)

  -- Rotation of CMB Polarization (in special cases).

- Very interesting aspect of Axion Physics





- *Acharya, Bobkov, PK (1004.5138)*
- A) Non-thermal Cosmology B) Standard Cosmology

One Axion in each e-folding between ~10^{-33} eV to ~ 1 eV
(H_0)

- Tuning in $\langle\theta_I\rangle$ for (A) (percent level) much smaller than that for (B).

generalization of old results for the entire Axiverse

- Isocurvature Fluctuations can easily distinguish between the TWO cases.

Conclusions

- **String Theory provides a natural framework for many alternatives to the Thermal WIMP miracle.**

- **Many of these ideas could be probed by a combination of experiments :**

  Colliders, Direct Detection, Indirect Detection, Astrophysical observables (Structure Formation, Grav. Waves, CMB,...)

- **However, full reconstruction of DM cosmology extremely challenging.**

Extra Slides

- **Note that within gauge mediation**,

a) $H_{inf} >> M_{3/2}$ Severe Moduli Problem

τ(moduli) > 10 yrs

Astro. Problems: Structure formation,..

b) $H_{inf} <\sim M_{3/2}$ Means H_{inf} extremely small (< GeV)

Even smaller for Low-scale Gauge mediation

Does NOT seem natural.

So, Gauge Mediation disfavored from this point of view

UNLESS moduli dynamics extremely special.