Cosmology and Collider Physics

- Focus on Neutralino Dark Matter -

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Plan of the Talk

- Introduction
- Neutralino Dark Matter as Thermal Relic: Standard View
- Non-Thermal Relic Neutralinos: An Alternative
- Summary

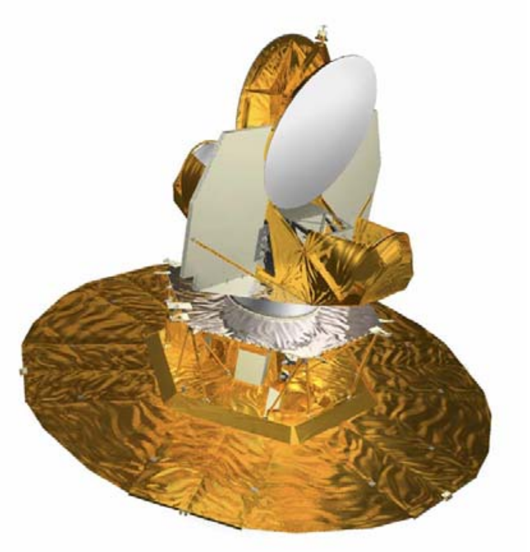
1. Introduction

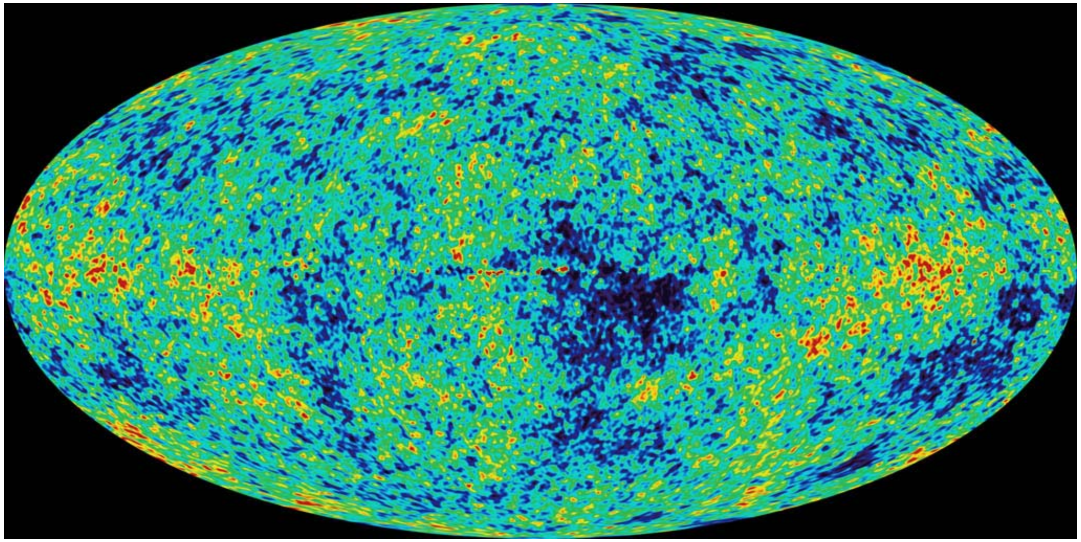
Cosmology in the Post-WMAP Era

Recent Development on observational cosmology:
CMB measurements, SN Ia, 2dF, …..

WMAP

– launch of MAP satellite, June 2001
– Fist data, Feb. 2003 → Precise Information on our Universe





Map of Sky by WMAP

Present Understanding of our Universe

- Inflationary Universe with adiabatic density perturbation
- Mass Components of the Universe
  - Baryons (not anti-baryons) ~ 4%
  - (Cold) Dark Matter ~23%
  - Dark Energy ~73%

None of the components given above is accounted for by the standard model of particle physics.

Call for New Physics beyond the Standard Model

Particle Physics is trying to explore

- Mechanism of Inflation/Seed of Density Perturbation
- Mechanism of baryogenesis
- Nature of dark matter
- Hints on dark energy

In my talk, I will focus on dark matter and discuss interesting connection between cosmology and collider physics in this context.

Cold Dark Matter (CDM)

Dark Matter:

originally introduced as source of gravitational force to explain rotation curves….

Structure formation, CMB perturbation

→ Prefers Cold Dark Matter, not Hot Dark Matter

Amount of CDM is precisely determined by WMAP

→ $\Omega_{CDM}\, h^2 = 0.094 - 0.129$ at 2 σ

(h =~ 0.72 expansion parameter)

(Note $\Omega_{CDM}\, h^2 \sim 0.1\text{-}0.3$ before WMAP)

WIMP: A Promising Candidate for CDM

- Extensions of Standard Model often provide candidates for CDM in the form of a weakly interacting massive particle (WIMP).
  - Mass around weak scale, Interaction comparable to weak interaction
- Collider Physics ←→ WIMP Dark Matter
  - Colliders as WIMP factories
  - Detail Study of WIMP
- I will illustrate this interesting interplay in the context of supersymmetric standard model.

  Neutralino Dark Matter

  - You don’t need to believe SUSY.

    The idea described here will also apply other WIMP candidates.

2. Neutralino Dark Matter as Thermal Relic:

Standard View

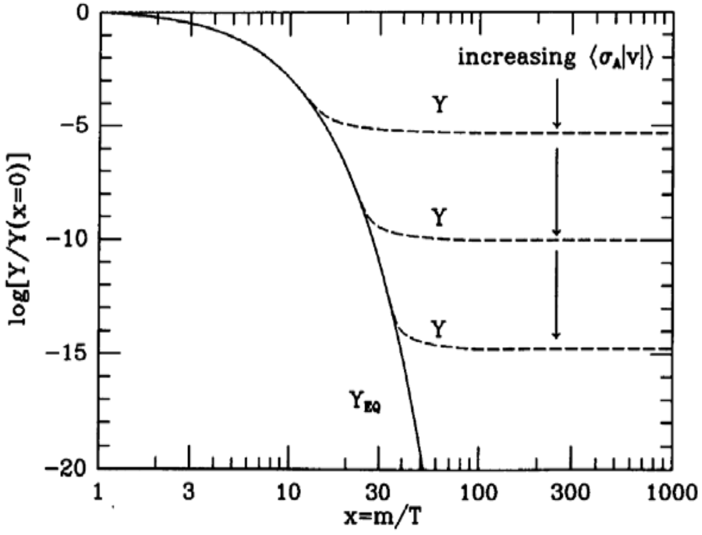
Neutralino Dark Matter: Standard View

- Assumptions:
  - Neutralino LSP:
    - A neutralino (a combination of neutral gauginos and neutral higgsinos) is lightest superparticle (LSP).
  - R-parity conservation → LSP is stable
  - Thermal Relic under Standard Thermal History
    - The Universe gradually cools down from very hot universe (T>100GeV) as the Universe expands. Nothing special (such as huge entropy production) happens.

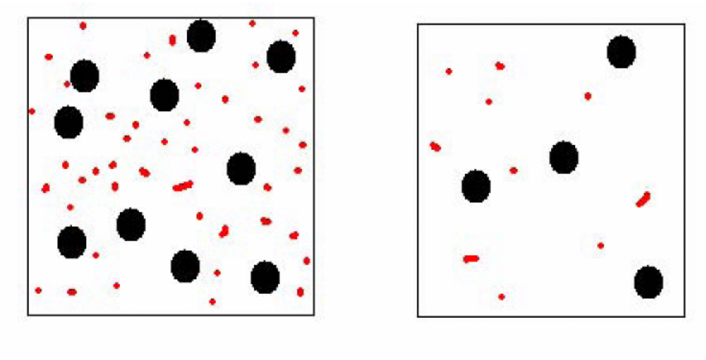
- One can compute the relic abundance of the neutralino LSP. Typically the abundance turns out to be in right order of magnitude $\Omega_\chi h^2 \sim O(1)$

- WMAP requires $\Omega_{CDM} h^2 = 0.094$—0.129 at 2 σ

Thermal Relic Abundance



From
Text Book by
Kolb & Turner



High Temp. Low Temp.

At high T, the neutralinos are in thermal equilibrium. As Universe cools down, the neutralinos get non-relativistic and their abundance is Boltzmann suppressed.

Eventually one neutralino LSP cannot find another neutralino to annihilate each other.

→Freeze-out !

Final Abundance is proportional to the inverse of the annihilation cross section.

Annihilation Cross Section

A crude estimate:

$$\Omega h^2 \sim 1 \times (<\sigma_{ann} v>/ 10^{-10}\ \mathrm{GeV}^{-2})^{-1}$$ motivation for WIMPs

A close look:

In generic regions of SUSY parameter space, the calculated relic abundance becomes too large >>0.1

Efficient Annihilation Mechanisms required:

- light neutralino & light slepton: "bulk" annihilation region
  disfavored by Higgs mass bound
- Co-annihilation with next-LSP (eg. stau)
- Annihilation through resonances (e.g. A, H)
- Annihilation into W pair: not suppressed by small fermion mass
  In mSUGRA, this is realized in Focus Point region.
  (high m_0, low $m_{1/2}$, low μ: higgsino component)

→ Tiny and special corners of the parameter space gives the relic abundance consistent with the WMAP data.

Regions preferred by WMAP

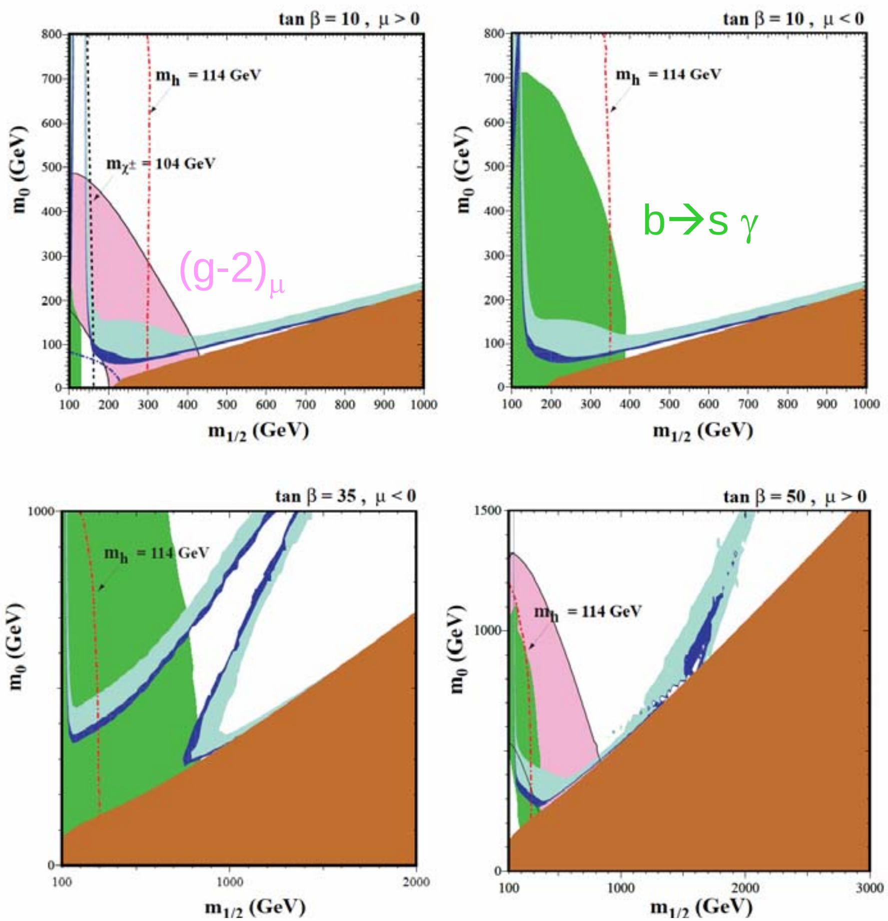


Figure 1: *The* $(m_{1/2}, m_0)$ *planes for (a)* $\tan\beta = 10, \mu > 0$*, (b)* $\tan\beta = 10, \mu < 0$*, (c)* $\tan\beta = 35, \mu < 0$*, and (d)* $\tan\beta = 50, \mu > 0$*. In each panel, the region allowed by the older cosmological constraint* $0.1 \le \Omega_\chi h^2 \le 0.3$ *has medium shading, and the region allowed by the newer cosmological constraint* $0.094 \le \Omega_\chi h^2 \le 0.129$ *has very dark shading. The disallowed region where* $m_{\tilde{\tau}_1} < m_\chi$ *has dark (red) shading. The regions excluded by* $b \to s\gamma$ *have medium (green) shading, and those in panels (a,d) that are favoured by* $g_\mu - 2$ *at the 2-σ level have medium (pink) shading. A dot-dashed line in panel (a) delineates the LEP constraint on the* $\tilde{e}$ *mass and the contours* $m_{\chi^\pm} = 104$ *GeV* ($m_h = 114$ *GeV) are shown as near-vertical black dashed (red dot-dashed) lines in panel (a) (each panel).*

Ellis, Olive, Santoso & Spanos ‘03

Dark blue region: most preferred by WMAP Data

$0.094<\Omega_\chi h^2<0.129$

(light blue region

$0.1<\Omega_\chi h^2<0.3$

before WMAP)

Regions with $\Omega_\chi h^2<0.129$ are allowed by WMAP

See also talk by Nihei @ this workshop

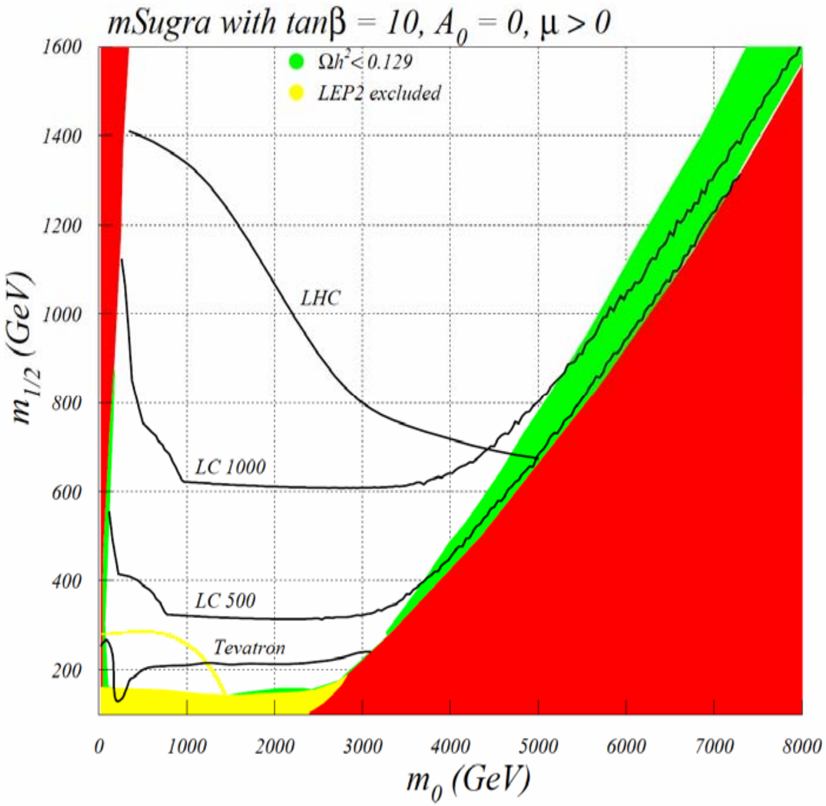
New Benchmark Points in Post-WMAP Era

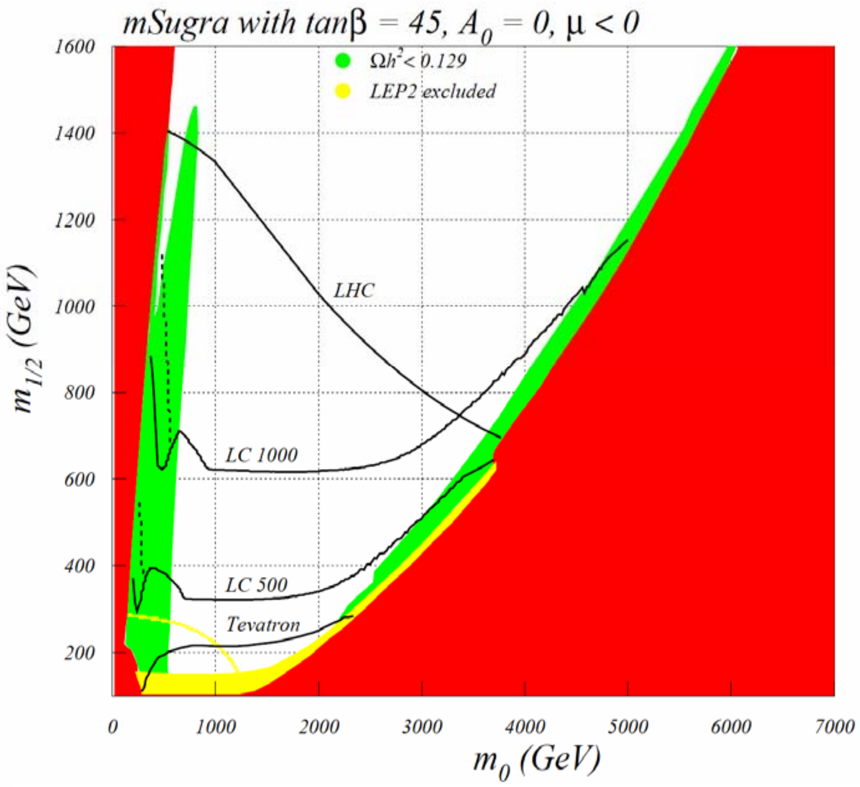
Battaglia,De Roeck, Ellis, Gianotti, Olive & Pape, '03

Model	A'	B'	C'	D'	E'	F'	G'	H'	I'	J'	K'	L'	M'
$m_{1/2}$	600	250	400	525	300	1000	375	935 (1500)	350	750	1300 (1150)	450	1840 (1900)
m_0	120 (140)	60 (100)	85 (90)	110 (125)	1530 (1500)	3450	115 (120)	245 (419)	175 (180)	285 (300)	1000	300 (350)	1100 (1500)
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	121	125	123	121	124	120	124	120	123	120	118	122	117
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175
Masses													
$\lvert\mu(m_Z)\rvert$	741	333	503	634	205	496	471	1026	439	843	1317	540	1764
h	115	113	116	117	114	118	117	122	116	121	118	118	124
H	884	375	578	736	1532	3491	523	1185	452	883	1176	489	1652
A	882	375	578	735	1533	3491	523	1185	451	883	1176	489	1663
$H^\pm$	886	383	584	740	1535	3492	529	1188	459	887	1180	496	1654
χ_1	252	98	163	220	115	430	153	402	143	320	573	187	821
χ_2	480	181	310	424	182	522	289	774	270	615	1105	358	1583
χ_3	761	346	519	655	221	523	489	1068	464	897	1413	588	1994
χ_4	775	365	535	662	304	885	504	1078	478	906	1421	599	1999
$\chi_1^\pm$	480	180	309	424	174	511	290	774	270	615	1105	358	1583
$\chi_2^\pm$	775	367	535	664	304	886	505	1079	479	907	1422	600	1999
$\tilde{g}$	1715	715	1145	1495	869	2914	1075	2681	999	1593	3716	994	5262
e_L, μ_L	425	188	289	375	1544	3512	285	673	300	581	1319	430	1635
e_R, μ_R	261	121	180	232	1535	3471	189	433	224	405	1114	348	1300
ν_e, ν_μ	418	171	278	367	1542	3511	273	669	289	575	1317	422	1633
τ_1	258	112	172	225	1522	3443	162	403	155	323	971	200	920
τ_2	425	192	291	376	1538	3498	291	670	310	573	1268	420	1511
ν_τ	418	187	277	366	1542	3497	270	661	277	555	1261	386	1502
u_L, c_L	1202	546	834	1064	1644	3908	792	1808	755	1493	2602	965	3491
u_R, c_R	1151	527	803	1021	1635	3867	762	1730	723	1429	2494	930	3332
d_L,s_L	1205	552	838	1067	1646	3909	797	1810	758	1429	2603	968	3492
d_R, s_R	1144	526	799	1016	1634	3861	759	1718	723	1495	2479	925	3309
t_1	896	393	618	807	1050	2580	587	1380	553	1131	1935	710	2630
t_2	1143	573	819	1013	1387	3330	777	1677	731	1372	2237	891	3054
b_1	1101	502	765	976	1379	3323	717	1645	659	1325	2173	815	2998
b_2	1144	528	798	1011	1622	3834	756	1695	711	1377	2242	880	3062

Discovery Reach at LCs/LHC/Tevatron

Baer, Belyaev, Krupovnickas & Tata '03





New selection cuts are proposed to extend the reach of LCs in FP region (upper right).

Much of the regions allowed by WMAP will be probed by these colliders.

Reconstruction of SUSY DM: Consistency Check

Detail Study of SUSY @ Future Collider Experiments will enable us to determine building block to compute relic abundance:

- Masses and components of neutralinos & charginos
- Slepton & Squark Masses
- Higgs Masses

→ Compute Annihilation Cross section

→ Reconstruct SUSY DM by computing $\Omega_\chi h^2$

Comparison with the WMAP value : Consistency Check!

- If $\Omega_\chi h^2 \sim 0.10\text{-}0.13$ → Establishing the standard view of SUSY DM
- If $\Omega_\chi h^2 > 0.13$ → Failure of the standard view

Precise determination of SUSY parameters is needed. LCs will be able to do this job.

Establishing the Standard View of SUSY DM

If the comparison is consistent, i.e. $\Omega_\chi h^2 \sim 0.10\text{-}0.13$

Strong evidence for the neutralino DM scenario

- Should be confirmed by direct/indirect detection of relic neutralinos

→

Identification of the nature of the Dark Matter: Solves the long standing puzzle in cosmology!

Furthermore,

Understanding the thermal history of the Universe up to Temp. $\sim$ 10 - 100 GeV (t $\sim 10^{-9}$ -10^{-11} sec after big bang)

- At present, we know the thermal history only below 1MeV(t>1 sec).

Failure of the Standard SUSY DM

What if the comparison is inconsistent, i.e. $\Omega_\chi h^2 > 0.13$?

At least one of the standard assumptions on SUSY DM is wrong.

- 1) R-parity → R-parity violation
  Generally needs another DM candidate
- 2) Neutralino LSP → lighter LSP(eg. gravitino) SuperWIMPs
- 3) Thermal Relic → Non-thermal Relic

In the following we will discuss the case 3). This seems quite plausible in superstring-inspired models.

3. Non-Thermal Relic Neutralinos:

An Alternative

Motivations for Non-Thermal Relic Neutralinos

Two Tensions in SUSY Cosmology:

- 1) Fear of Neutralino Over-Closure
  - In generic regions of SUSY parameter space, the thermal relic abundance of neutralinos tends to be too large.
- 2) Gravitino Problem
  - Gravitino Abundance, if unstable, is severely constrained by big-bang nucleosynthesis. The constraints get severer when effects of hadronic shower are included.

Hope: Dilution by Moduli Fields

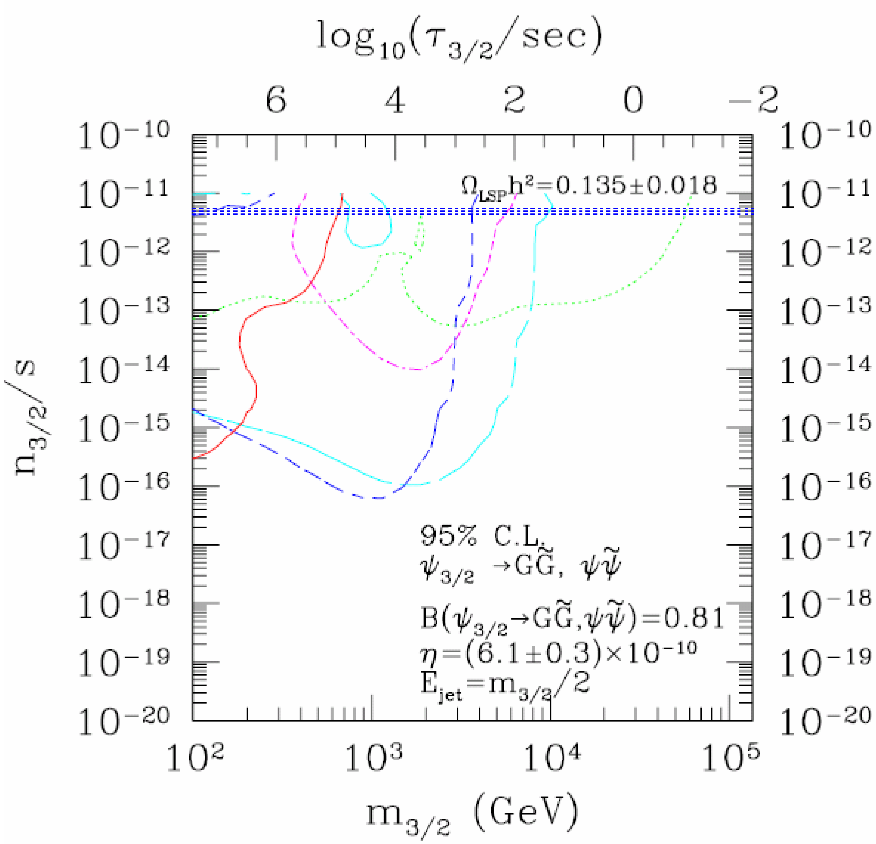
- Moduli Fields whose existence is suggested by superstring/supergravity will dilute thermal relic neutralinos and gravitinos when they decay with huge entropy production.

Non-Thermal Neutralinos:

- In this case, the neutralinos may be produced in non-thermal way.

Gravitino Problem

Upper-bound on gravitino abundance from BBN constraint



Longevity of gravitinos would spoil big-bang nucleosynthesis (BBN) when gravitino decay produces electromagnetic/hadronic showers.

→ Gravitino abundance is severely constrained. Weinberg 82

Recent Development:

Effect of hadronic shower is included.
Much severer constraint is obtained.

Kawasaki, Kohri & Moroi 04

Entropy Production by Moduli Fields

- Existence of Moduli Fields: implied by supergravity/superstring
  - Mass: close to weak scale
  - Interaction: as weak as gravitational interaction

- Fate of a modulus field:
  - Its damped coherent oscillation dominates the energy density of the Universe.
  - Subsequent decay produces huge entropy, drastically changing the thermal history of the Universe.
  - Disaster if the life time is longer than 1 sec.
  - For relatively heavy moduli, the life time becomes shorter. Moduli decay can dilute the unwanted relics.

A Successful Scenario

Kohri, MY & Yokoyama,
PRD '04 & in preparation

Suppose moduli mass ~10^4 TeV
gravitino mass ~10^2 TeV
neutralino mass ~100 GeV

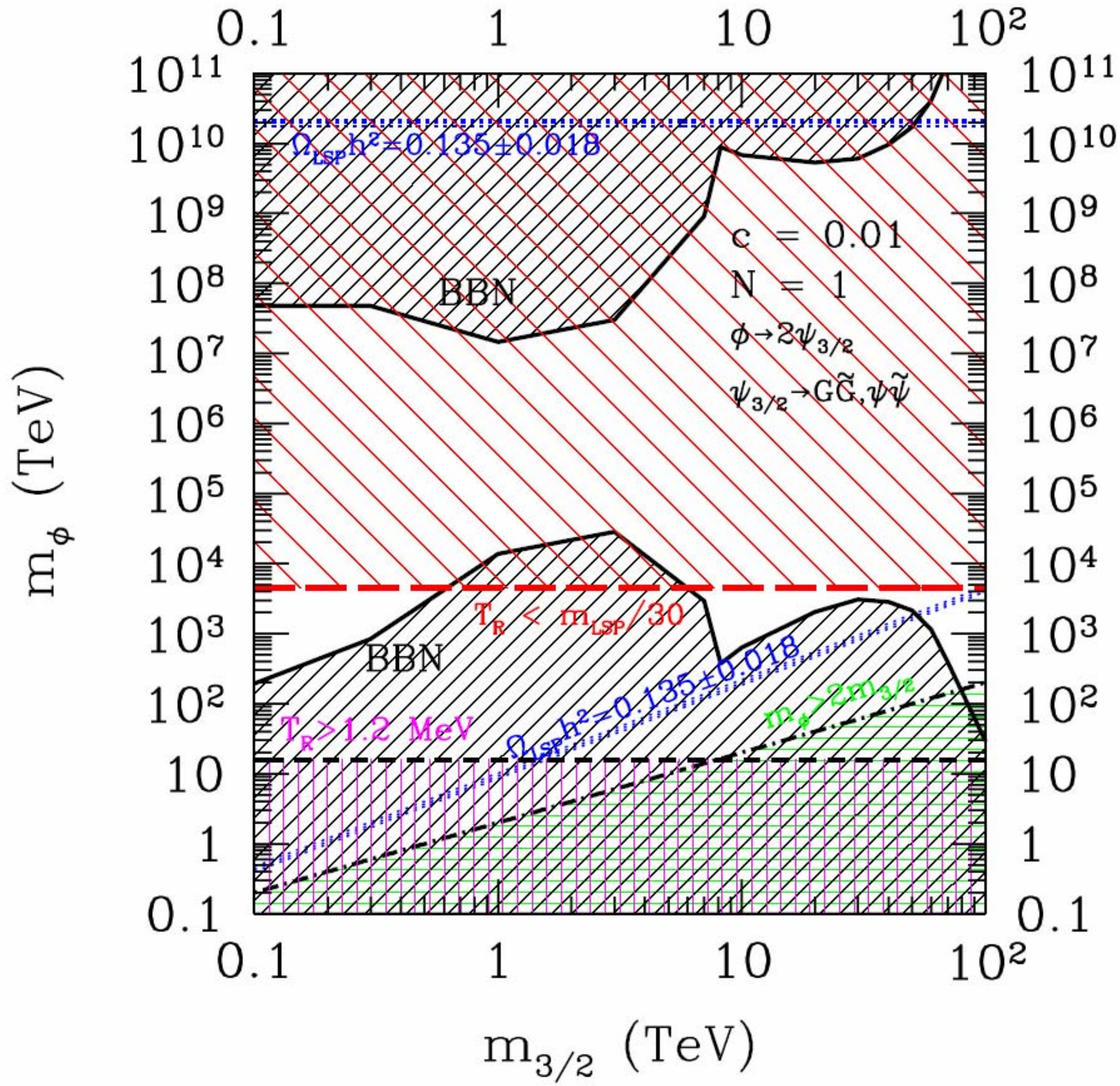
– A small hierarchy: easy to be realized in SUGRA models

Non-Standard Thermal History:

1) Moduli Oscillation dominates energy density.
2) Moduli decay with huge entropy production.
   - Primordial Gravitinos and neutralinos are all diluted. Regeneration of neutralinos in thermal bath is suppressed due to low reheat temp. ~1 GeV.
   - A small fraction of gravitinos are produced by moduli decay. Can satisfy the constraint from BBN
3) Gravitinos eventually decay to neutralinos, yielding neutralino dark matter.

Numerical Results

Kohri, MY, Yokoyama, in preparation



←Region satisfying all requirements really exists!

In this non-thermal scenario, neutralino abundance is not directly related to properties of neutralinos.

A way out from the WMAP constraint.

Warning to SUSY Study at Colliders!

Smoking Gun Signal:

Heavy Gravitino → SUSY Spectrum:

(Gravity Mediation)+(Anomaly Mediation)

- Significant deviation from mSUGRA spectrum

Mass spectrum is testable at future colliders!

→ Another interplay between cosmology and collider physics

4. Summary

Interplay between cosmology and collider physics was illustrated in the context of SUSY dark matter.

- WMAP already constrains allowed regions of SUSY parameter space under some standard assumptions.
- Discovery Reach to WMAP preferred region
- Precise determination of SUSY parameters at future colliders →Crucial hints in our understanding of the Universe

- Non-Thermal Relic Neutralinos: an alternative
- Interesting interplay between cosmology and collider physics also in this case

You don't need to believe SUSY!

Similar arguments discussed here can also apply to other WIMP candidates.

- eg. lightest KK mode in TeV compactification

Other Connections

Baryogenesis

- Electroweak Baryogenesis in SUSY
  - Light Stop, Higgses, CP phases: can be tested in collider experiments
- Affleck-Dine mechanism:
  - scalar condensate in SUSY SM.
  - Collider physics will give us some hints to this scenario.

Dark Energy! ???????

A lot of things to be explored!

Collider Physics and Cosmology will reveal   Wonderful New Paradigm!

Thank   you !