Non-thermal Production of Dark Matter: Heavy Axino Cosmology

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Introduction

In this talk we will examine how non-thermal production (NTP) of Dark Matter (DM) can help SUSY models which predict insufficient amounts of DM. We will first examine in general how AMSB models, notorious for having a dearth of DM, can attain cosmologically safe relic densities. We then turn our attention to the details of a specific NTP mechanism: neutralinos ($\tilde{Z}_1$) produced through heavy axino decays ($\tilde{a}$). Finally, we conclude with a few remarks on future directions of research.

Introduction

Publications

- "Neutralino Versus Axion and Axino Cold Dark Matter in Minimal, Hypercharged and Gaugino AMSB", JCAP **1007**, 014 (2010)
  arXiv:1004.3297 [hep-ph]

- "Mixed Axion/Neutralino Cold Dark Matter in the Presence of Heavy Axino Decay"
  arXiv:1103.5413 [hep-ph]

Dark Matter in AMSB Models

Dark Matter in AMSB Models

Consequences of a Wino-like Neutralino

Universe expands

→ Temperature drops

→ Particles fall out of equilibrium ("freeze out")

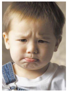
$\boxed{\tilde{Z}_1 \ \& \ \tilde{W}_1}$ nearly degenerate and wino-like.

$$\sigma_{eff} \sim A\ \sigma^{annihilation} + B\ \sigma^{co-annihilation}$$

Co-annihilation interactions keep $\tilde{Z}_1$ in thermal contact.

$\Rightarrow$ Effective annihilations long after "freeze-out"

$\Rightarrow \Omega_{CDM} h^2 \lesssim O(10^{-2} - 10^{-3}) \times \Omega_{CDM}^{WMAP} h^2$

$\Rightarrow$ 

Dark Matter in AMSB Models

Consequences of a Wino-like Neutralino

* Many theories predict very heavy particles in early universe.

Can the decays of these particles affect present abundances?

$\Rightarrow$ Yes! In particular, DM abundance can be augmented in a way that does not interfere with BBN abundances!

Refer to this broadly as "Non-thermal Production" (NTP) of Dark Matter

Dark Matter in AMSB Models

Possible Non-thermal Sources of DM

DM Non-Thermal Production

i. Moduli Decay (ϕ) $\longrightarrow$ Neutralino DM

ii. Gravitino Decay ($\psi_{3/2}$) $\longrightarrow$ Neutralino DM

iii. Neutralino Decay ($\tilde{Z}_1$) $\longrightarrow$ Axino DM + Axion DM

iv. Heavy Axino ($\tilde{a}$) $\longrightarrow$ Neutralino DM + *Axion* DM

Dark Matter in AMSB Models

i. Moduli Decay (ϕ) $\rightarrow$ Neutralino DM

Randall, Moroi, Kane, *etc*.

$$\Omega^{\phi}_{\tilde{Z}_1} h^2 \sim 0.1 \times \left(\frac{m_{\tilde{Z}_1}}{100\ \mathrm{GeV}}\right)\left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{\sigma_0^{int}}{\langle\sigma v\rangle}\right)\left(\frac{100\ \mathrm{TeV}}{m_\phi}\right)^{3/2}$$

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

Assuming:

$m_\phi \sim 100\,TeV$ *and*

$m_{\tilde{Z}_1} \sim$ weak scale mass and

$\sigma_0^{int} \sim 10^{-24}$ cm^3/sec

$\Rightarrow$ Values expected in AMSB scenarios

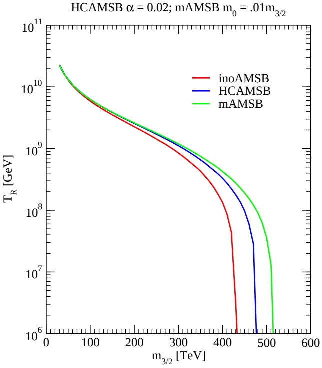
$\Rightarrow$ "Non-thermal Wimp Miracle" - Kane

Dark Matter in AMSB Models

ii. Gravitino Decay ($\psi_{3/2}$) $\rightarrow$ Neutralino DM

$$\Omega_{\tilde{Z}_1} h^2 = \quad \textbf{TP} \quad + \quad \textbf{NTP}$$

$$\Omega^{TP}_{\tilde{Z}_1} h^2 + \frac{m_{\tilde{Z}_1}}{m_{3/2}} \Omega^{TP}_{\psi_{3/2}} h^2$$



T_R *vs.* $m_{3/2}$ plane for wino-like neutralino DM from TP and gravitino NTP.

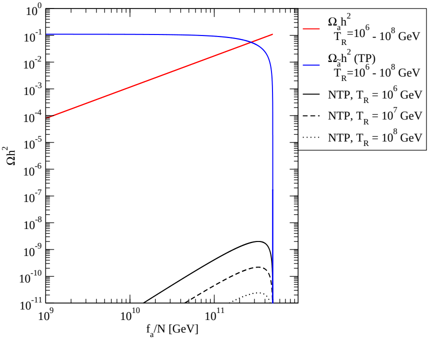
For HCAMSB $\alpha = 0.02$ and for mAMSB $m_0 = 0.01\ m_{3/2}$.

Dark Matter in AMSB Models

iii. Neutralino Decay ($\tilde{Z}_1$) $\rightarrow$ Axino DM + Axion DM

Entire CDM abundance given by sum of TP and NTP parts:

$$\Omega_{a\tilde{a}} h^2 = \Omega_{\tilde{a}}^{NTP} h^2 + \Omega_{\tilde{a}}^{TP} h^2 + \Omega_a h^2 = 0.11.$$



Dark Matter in AMSB Models

iv. Heavy Axino ($\tilde{a}$) $\rightarrow$ Neutralino DM + *Axion* DM

Peccei-Quinn MSSM

Pecci-Quinn Solution to Strong CP Problem	}	axion (a)
Supersymmetry for hierarchy, *etc*.		saxion (s) axino ($\tilde{a}$)

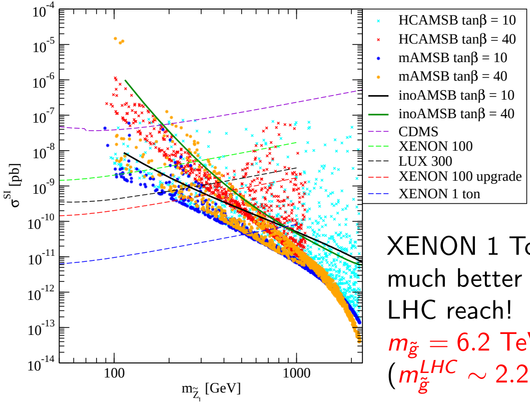
Axino ($\tilde{a}$) mass related to SUSY breaking and mediation mechanism, so very model dependent. Mass can range from 1 keV to larger than $m_{3/2}$.

Axion (a) mass can be tiny: $\sim O(\text{keV})$.

Dark Matter in AMSB Models

Wino DM Direct Detection Rates

Isajet IsaTools Package



XENON 1 Ton reach is much better than the LHC reach!

$m_{\tilde{g}} = 6.2$ TeV

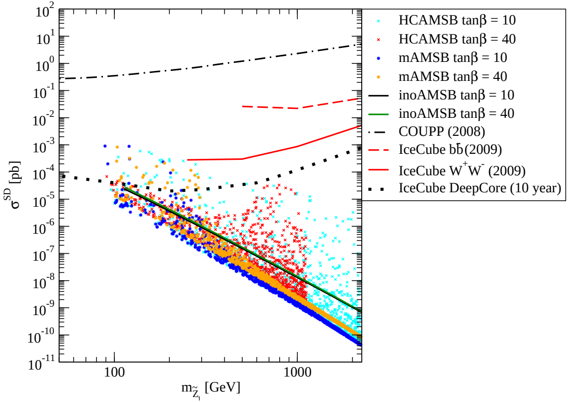
($m_{\tilde{g}}^{LHC} \sim 2.2 - 2.6$ TeV)

Spin-independent $\sigma(\tilde{Z}_1 - p)$ versus $m_{\tilde{Z}_1}$ for the AMSB models. The model parameters have been scanned over. CDMS limit and projected Xenon and LUX sensitivities are shown.

Dark Matter in AMSB Models

Wino DM Direct Detection Rates

Isajet IsaTools Package



Spin-dependent $\sigma(\tilde{Z}_1 - p)$ versus $m_{\tilde{Z}_1}$ for AMSB models. The model parameters have been scanned over. We also show the COUPP and IceCube limits on this cross section.

Heavy Axino Cosmology

Heavy Axino Cosmology

This scenario is of interest because

- two major SM fine-tuning problems avoided: Hierarchy & Strong CP Problems (slide 45)
- the interactions are understood: *tractable*.
- leads to more complex scenarios with multiple decays, *i.e.* of saxion, gravitino, *etc.*.

Goals of this work are:

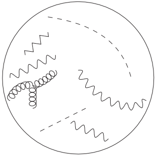
- Present numerical calculations of the relic abundance of **mixed a-$\tilde{\mathbf{Z}}_1$** dark matter.
- Account for CDM abundance as given by the WMAP7 analysis:

  $$\Omega_{DM}h^2 = 0.1123 \pm 0.0035 \text{ at } 68\% \text{ CL.}$$

  Determine which parameter values achieve this.
- Understand relative proportions of axion and $\tilde{Z}_1$ dark matter and determine the detection prospects.

Heavy Axino Cosmology

Axino ($\tilde{a}$) Production



Axinos can be produced in equilibrium early on. They can also be produced in thermal scattering, and how much depends on T_R, f_a/N, and $T^{\tilde{a}-dec}$.

$$Y_{\tilde{a}}^{\mathrm{TP}} = (5.8 \times 10^{-9})\, g_s^4\, F(g_s)\, \frac{T_R}{10^4\ \mathrm{GeV}} \left(\frac{10^{11}}{f_a/N}\right)^2 \quad (Strumia),$$

$$\text{for} \quad T^{\tilde{a}-dec} > T_R \quad \text{and} \quad F(g_s) \sim 20 g_s^2 \ln \frac{3}{g_s}.$$

$$Y_{\tilde{a}}^{\mathrm{TP}} = \frac{135\zeta(3)}{8\pi^4} \frac{g_{\tilde{a}}}{g_*(T^{\tilde{a}-dec})} \text{ for } T_R > T^{\tilde{a}-dec}.$$

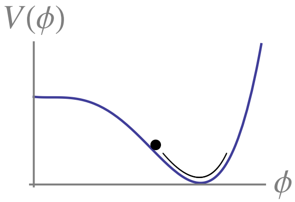
$m_{\tilde{a}}$ can be large compared to the weak scale dependent on the SUSY breaking sector and the mediation mechanism. We take $m_{\tilde{a}}$ to be a free parameter.

Heavy Axino Cosmology

Axion (a) DM Production

Axion EoM implies $<\phi_a>$ stays constant until $\sim$ 1 GeV.

As T $\rightarrow$ 1 GeV, an effective (T-dependent) axion mass turns on. The axion oscillates about a minimum that conserves CP.



Expected axion relic density from vacuum mis-alignment:

$$\Omega_a h^2 \simeq 0.23 f(\theta_i)\theta_i^2 \left(\frac{f_a/N}{10^{12}\ \mathrm{GeV}}\right)^{7/6},$$

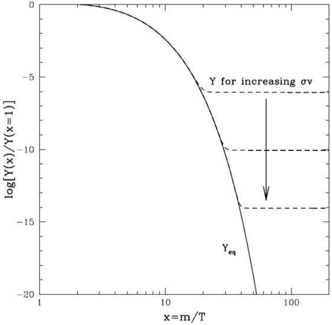
where $f(\theta_i) = \left[\ln\left(\frac{e}{1-\theta_i^2/\pi^2}\right)\right]^{7/6}$. Will have more to say on this...

(slide 45)

Heavy Axino Cosmology

Neutralino ($\tilde{Z}_1$) DM Production

From Kolb & Turner "The Early Universe"



Neutralinos are produced thermally and freeze out as usual.

Neutralinos are also produced from heavy Axino decays.

$$Y^{fr}_{\tilde{Z}_1} + Y^{decay}_{\tilde{Z}_1} = \boxed{Y_{\tilde{Z}_1}(T = T_D)}$$

(T_D = T just after $\tilde{a}$ decay.)

Heavy Axino Cosmology

Neutralino ($\tilde{Z}_1$) DM Production

$$\boxed{\mathrm{H} < \Gamma \sim n_{\tilde{Z}_1} \cdot \langle \sigma_{ann.} v \rangle}$$

If $Y_{\tilde{Z}_1}(T = T_D) > Y^{th}_{\tilde{Z}_1}(T = T_D)$, annihilations re-activated, *i.e.* for

$$Y_{\tilde{Z}_1}(T = T_D) > \left(\frac{90}{\pi^2 g_*} \right)^{1/2} \frac{1}{\langle \sigma_{ann.} v \rangle} \frac{1}{M_P T_D}.$$

The $\tilde{Z}_1$ Boltzmann equation in terms of yield is:

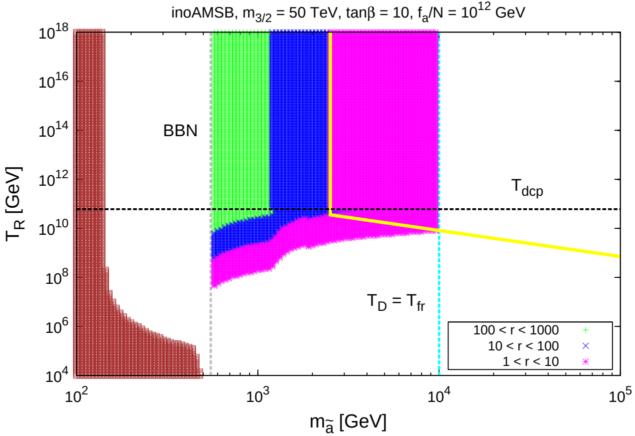
$$\frac{dY_{\tilde{Z}_1}}{dt} = -\langle \sigma_{ann.} v \rangle Y^2_{\tilde{Z}_1} s.$$

Its solution is

$$Y^{-1}_{\tilde{Z}_1}(T) \simeq Y^{-1}_{\tilde{Z}_1}(T_D) + \frac{\langle \sigma_{ann.} v \rangle s(T_D)}{H(T_D)}$$

Heavy Axino Cosmology

Neutralino ($\tilde{Z}_1$) DM Production



brown region: no $\tilde{Z}_1$ annihilation occurs.

Heavy Axino Cosmology

Calculating Scales

Combining ingredients:

- *Inflation*
- *Supersymmetry* : model choice
- *PQ Mechanism* : $\tilde{a}$ super-multiplet

Scales:

f_a/N	–	*PQ scale*
T_R	–	*inflation reheat*
$T^{\tilde{a}-dec}$	–	$\tilde{a}$ *decouples*
$T_{\tilde{a}=rad}$	–	$\rho(\tilde{a}) = \rho(rad)$
T_{fr}	–	$\tilde{Z}_1$ *freeze – out*
T_D	–	$\tilde{a}$ *decays*

Parameters:

$$f_a/N,\ T_R,\ m_{\tilde{a}},\ \theta_i,\ SUSY\ model\ p's$$

mSUGRA : $m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sgn(\mu)$

inoAMSB : $m_0,\ m_{3/2},\ \tan\beta,\ sgn(\mu)$

Heavy Axino Cosmology

Calculating Scales

$$T^{\tilde{a}-dec} = 10^{11}\ \mathrm{GeV}\left(\frac{f_a/N}{10^{12}\ \mathrm{GeV}}\right)^2\left(\frac{0.1}{\alpha_s(T^{\tilde{a}-dec})}\right)^3$$

$$T_{\tilde{a}=rad} = \frac{4}{3}m_{\tilde{a}}Y_{\tilde{a}}(f_a/N, T_R)$$

$$T_{fr} \sim \frac{m_{\tilde{Z}_1}(SUSY\ \ p's)}{20}$$

$$T_D = \sqrt{\Gamma_{\tilde{a}}(m_{axino}, f_a/N)M_P}/(\pi^2 g_*/90)^{1/4}$$

Heavy Axino Cosmology

Calculating Scales

Decay Temperature (T_D):

T_D is the temperature just after axino decays ($t \sim \tau_{\tilde{a}}$). This depends on the strength of it's interactions, *i.e.*, its width.

$$\frac{1}{\tau_{\tilde{a}}} \sim \sum_i \Gamma_i$$

Exponential decay law assumed

$$N_{\tilde{a}} \sim e^{-t/\tau_{\tilde{a}}}$$

Exponential implies no 'reheat', but cooling is slower.

There are a few models for axino couplings and T_D can be computed. We choose the bound $T_D > 2$ MeV to avoid problems with BBN.

Heavy Axino Cosmology

Calculating Scales

$$\boxed{\mathcal{L}_{\tilde{a}\tilde{g}g} = i\frac{\alpha_s}{16\pi(f_a/N)}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{g}_A F_{A\mu\nu}}$$

$$\boxed{\mathcal{L}_{\tilde{a}\tilde{B}B} = i\frac{\alpha_Y C_{aYY}}{16\pi(f_a/N)}\bar{\tilde{a}}\gamma_5[\gamma^\mu,\gamma^\nu]\tilde{B}B_{\mu\nu}}$$

(Strumia)

$$\Gamma(\tilde{a}\to\tilde{g}g) = \frac{8\alpha_s^2}{128\pi^3(f_a/N)^2}m_{\tilde{a}}^3\left(1-\frac{m_{\tilde{g}}^2}{m_{\tilde{a}}^2}\right)^3$$

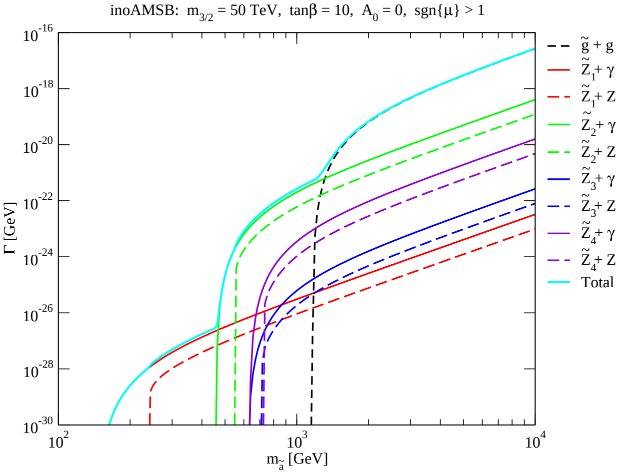
$$\Gamma(\tilde{a}\to\tilde{Z}_i+\gamma) = \frac{\alpha_Y^2 C_{aYY}^2\cos^2\theta_w Z_{iB}^2}{128\pi^3(f_a/N)^2}m_{\tilde{a}}^3\left(1-\frac{m_{\tilde{Z}_i}^2}{m_{\tilde{a}}^2}\right)^3$$

$$\Gamma(\tilde{a}\to\tilde{Z}_i+Z) = \frac{\alpha_Y^2 C_{aYY}^2\sin^2\theta_w Z_{iB}^2}{128\pi^3(f_a/N)^2}m_{\tilde{a}}^3\lambda^{1/2}\left(1,\frac{m_{\tilde{Z}_i}^2}{m_{\tilde{a}}^2},\frac{m_Z^2}{m_{\tilde{a}}^2}\right)$$
$$\cdot\left\{\left(1-\frac{m_{\tilde{Z}_i}^2}{m_{\tilde{a}}^2}\right)^2+3\frac{m_{\tilde{Z}_i}m_Z^2}{m_{\tilde{a}}^3}-\frac{m_Z^2}{2m_{\tilde{a}}^2}\left(1+\frac{m_{\tilde{Z}_i}^2}{m_{\tilde{a}}^2}+\frac{m_Z^2}{m_{\tilde{a}}^2}\right)\right\}$$

Heavy Axino Cosmology

Calculating Scales

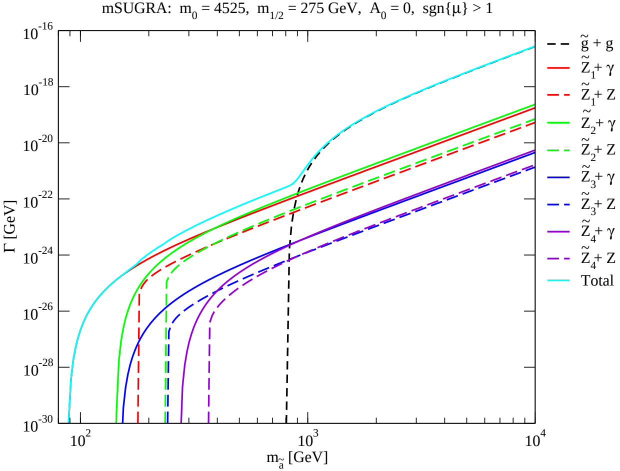
Widths for *inoAMSB* model



Heavy Axino Cosmology

Calculating Scales

Widths for *mSUGRA* model (FP region)



Heavy Axino Cosmology

Time Line

$f_a/N \sim 10^{(10-14)}\, GeV$ — PQ symm. broken

$T^{\tilde{a}-dec} \sim 10^{(8-14)}\, GeV$ — $\tilde{a}$ decouples

$T_R \sim 10^{6-10}\, GeV$ — Universe reheats

determine
$\tilde{a}$ yield, $Y_{\tilde{a}}$
decay temp., T_D
$i.e.$ $\tilde{a}$ production
& decay props

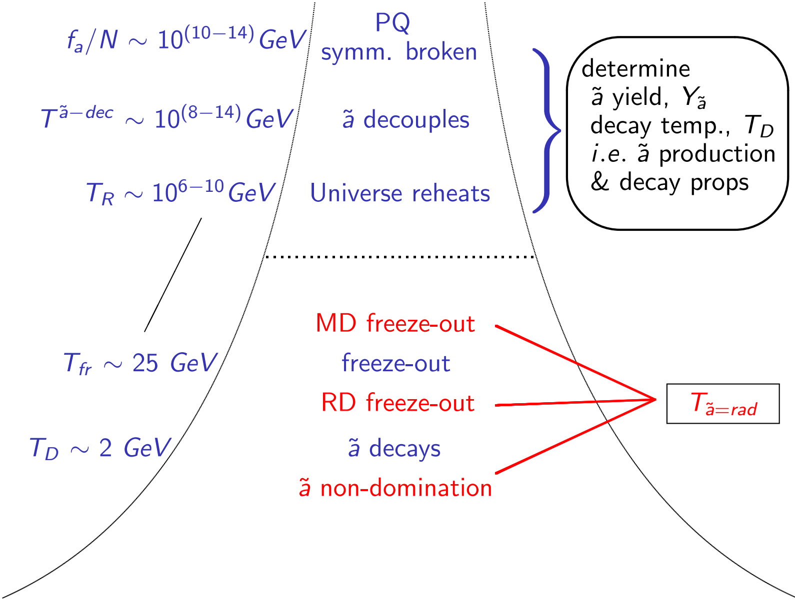
$T_{fr} \sim 25\ GeV$ — freeze-out

$T_D \sim 2\ GeV$ — $\tilde{a}$ decays

$T_{\tilde{a}=rad}$

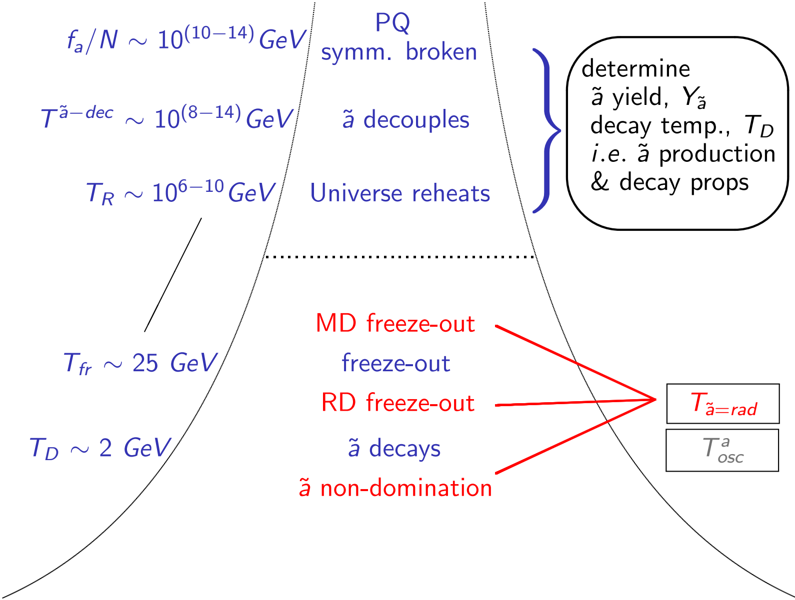
Heavy Axino Cosmology

Time Line



Heavy Axino Cosmology

Time Line



Heavy Axino Cosmology

Time Line

MD freeze-out

freeze-out

RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$

Heavy Axino Cosmology

Time Line

Usual expression for $\tilde{Z}_1$ freeze-out changed b/c freeze occurs during MD, *i.e.* during $\tilde{a}$-domination

MD freeze-out

freeze-out

RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$

$$Y^{fr}_{\tilde{Z}_1}(DPDC) \equiv Y^{\tilde{a}D}_{\tilde{Z}_1} = \left(\frac{g_*(T_D)}{g_{*S}(T_D)}\right) \frac{(90/\pi^2 g_{fr})^{1/2}}{4\langle\sigma_{ann.}v\rangle m_{pl} T^{\tilde{a}D}_{fr}} \cdot \frac{15}{4} \left(\frac{g_D}{g_{fr}}\right)^{1/2} \left(\frac{T_D}{T^{\tilde{a}D}_{fr}}\right)^3$$

$$T^{\tilde{a}D}_{fr} = m_{\tilde{Z}_1} / \log\left(\frac{8\sqrt{2}\langle\sigma_{ann.}v\rangle g_*^{\frac{1}{2}}(T_D) T_D^2 m_{\tilde{Z}_1}^{1/2} m_{pl}}{g_*(T^{\tilde{a}D}_{fr})\pi^{5/2} T^{\tilde{a}D\,\frac{3}{2}}_{fr}}\right)$$

Heavy Axino Cosmology

Time Line

Usual expression for $\tilde{Z}_1$ freeze-out changed b/c freeze occurs during MD, *i.e.* during $\tilde{a}$-domination

MD freeze-out

freeze-out

RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$

$$Y^{fr}_{\tilde{Z}_1}(DPDC) \equiv Y^{\tilde{a}D}_{\tilde{Z}_1}$$

$$= \left(\frac{g_*(T_D)}{g_{*S}(T_D)}\right) \frac{(90/\pi^2 g_{fr})^{1/2}}{4\langle\sigma_{ann.} v\rangle m_{pl} T^{\tilde{a}D}_{fr}} \cdot \frac{15}{4} \left(\frac{g_D}{g_{fr}}\right)^{1/2} \left(\frac{T_D}{T^{\tilde{a}D}_{fr}}\right)^3$$

$$Y_{\tilde{Z}_1} = Y^{\tilde{a}D}_{\tilde{Z}_1} + Y^{decay}_{\tilde{Z}_1}$$

Heavy Axino Cosmology

Time Line

Usual expression for $\tilde{Z}_1$ freeze-out changed b/c freeze occurs during MD, *i.e.* during $\tilde{a}$-domination

MD freeze-out

freeze-out

RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$

$$Y^{fr}_{\tilde{Z}_1}(DPDC) \equiv Y^{\tilde{a}D}_{\tilde{Z}_1}$$

$$= \left(\frac{g_*(T_D)}{g_{*S}(T_D)}\right) \frac{(90/\pi^2 g_{fr})^{1/2}}{4\langle\sigma_{ann.} v\rangle m_{pl} T^{\tilde{a}D}_{fr}} \cdot \frac{15}{4} \left(\frac{g_D}{g_{fr}}\right)^{1/2} \left(\frac{T_D}{T^{\tilde{a}D}_{fr}}\right)^3$$

- further annihilations?
- entropic *dilution*?

Heavy Axino Cosmology

Time Line

Usual expression for $\tilde{Z}_1$ freeze-out changed b/c freeze occurs during MD, *i.e.* during $\tilde{a}$-domination

MD freeze-out

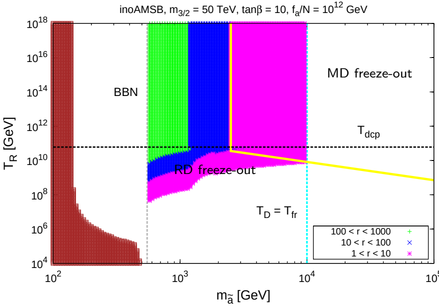
freeze-out

RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$



Heavy Axino Cosmology

Time Line

MD freeze-out

freeze-out

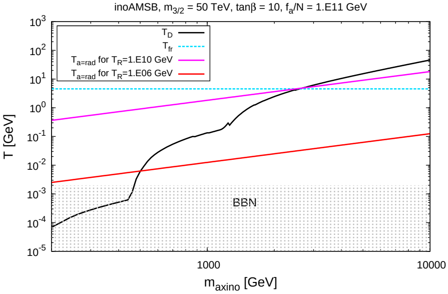
RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$

Usual expression for $\tilde{Z}_1$ freeze-out is used in this case.



(*bigger slide 47)

$$Y^{fr}_{\tilde{Z}_1} = \frac{(90/\pi^2 g_*(T_{fr}))^{1/2}}{4\langle\sigma_{ann.}v\rangle m_{pl} T_{fr}}$$

- further annihilations?
- entropic *dilution*?

$$Y^{decay}_{\tilde{Z}_1} = Y_{\tilde{a}}/(S_f/S_0)$$

($\tilde{Z}_1$ inherits $\tilde{a}$ yield, but diluted by entropy.)

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Time Line

MD freeze-out

freeze-out

RD freeze-out

$\tilde{a}$ decays

$\tilde{a}$ non-domination

$T_{\tilde{a}=rad}$

Again use usual expression for RD-freeze again.

$$Y_{\tilde{Z}_1}^{decay} = Y_{\tilde{a}} \text{ (no dilution)}$$

$$Y_{\tilde{Z}_1} = Y_{\tilde{Z}_1}^{th} + Y_{\tilde{Z}_1}^{decay}$$

- further annihilations?
- entropic dilution?

Heavy Axino Cosmology

Entropy

Crucial: entropy evolution (Boltzmann) equation:

$$\frac{ds}{dt} = -3Hs + \frac{\Gamma_{\tilde{a}}\rho_{\tilde{a}}}{T}$$

source term represents entropy *non*-conservation and changes the R (scale factor) $\leftrightarrow$ T relationship.

$\Rightarrow$ *final yields* ($Y_i \equiv \frac{n_i}{s}$) *are also altered.*

To quantify this effect use the quantities

$$T_{\tilde{a}=rad} = \frac{4}{3} m_{\tilde{a}} Y_{\tilde{a}} \quad \text{and}$$

$$T_D = \sqrt{\Gamma_{\tilde{a}} m_{pl}}/(\pi^2 g_*/90)^{1/4}.$$

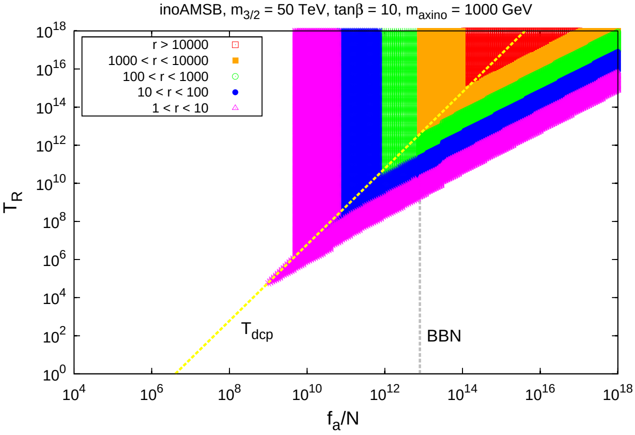
When $T_{\tilde{a}=rad} > T_D$ $\tilde{a}$ can dominate the Universe. The ratio of the entropy before and after $\tilde{a}$ decay, r, is calculated:

$$r \equiv \frac{S_f}{S_0} \simeq T_{\tilde{a}=rad}/T_D = \frac{4 m_{\tilde{a}} Y_{\tilde{a}}}{3 T_D}$$

Heavy Axino Cosmology

Entropy

$$r \equiv \frac{S_f}{S_0} \simeq T_{\tilde{a}=rad} / T_D = \frac{4 m_{\tilde{a}} Y_{\tilde{a}}}{3 T_D}$$



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Entropy

$$r \equiv \frac{S_f}{S_0} \simeq T_{\tilde{a}=rad}/T_D = \frac{4m_{\tilde{a}}Y_{\tilde{a}}}{3T_D}$$

*Yield of any out of equilibrium particle will be "diluted" by entropy injection by a factor $\frac{1}{r}$ in the cases where $r > 1$. Otherwise if $r < 1$ (non-domination), $\tilde{Z}_1$ and a yields will not be diluted by entropy.

Then dilution possibly applies to

$Y^{fr}_{\tilde{Z}_1}$ ($\tilde{Z}_1$ yield from freeze-out), and

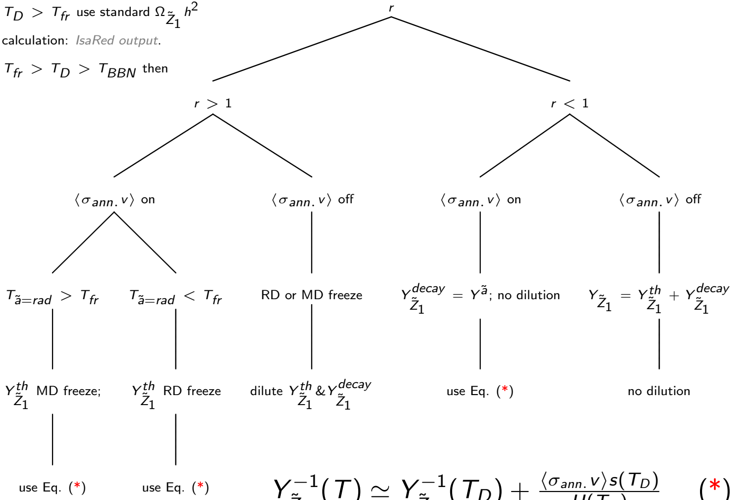
Y_a (the axion yield)

depending on the particular case. There are several cases...

Heavy Axino Cosmology

Algorithm for Calculating $\tilde{Z}_1$ DM Yield

- If $T_D < T_{BBN} \sim 2$ MeV excluded.
- If $T_D > T_{fr}$ use standard $\Omega_{\tilde{Z}_1} h^2$ calculation: *IsaRed output*.
- If $T_{fr} > T_D > T_{BBN}$ then



$$Y^{-1}_{\tilde{Z}_1}(T) \simeq Y^{-1}_{\tilde{Z}_1}(T_D) + \frac{\langle \sigma_{ann.} v \rangle s(T_D)}{H(T_D)} \qquad (*)$$

Heavy Axino Cosmology

Adding Axion (a) DM Yield

Following procedure similar to **Visinelli & Gondolo PRD 81, 063508** to add in axion abundance.

PQ-symmetry breaks $\Rightarrow$ $a(x)$ (backup 45)

Oscillations begin when

$$\boxed{3H(T_{osc}) = m(T_{osc})}.$$

Moreover the mass is T-dependent:

$$m(T) = \begin{cases} m_a & T \lesssim \Lambda_{QCD} \\ b m_a (\Lambda/T)^4 & T \gtrsim \Lambda_{QCD}. \end{cases}$$

Oscillations can occur in different phases depending on value of T_{osc}, and the relic axion abundance can vary by orders of magnitude (implicitly depending on f_a/N).

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* $3H(T_{osc}) = m(T_{osc})$

$T_{\tilde{a}=rad} > T > T_S$

MD phase ($H \propto T^{3/2}$)

$T_S > T > T_D$

MD decaying phase

($H \propto T^4$)

$T_D > T$

RD phase ($H \propto T^2$)

→ *oscillations*

This leads to many more T-dependent cases. These formulae are not very illuminating.

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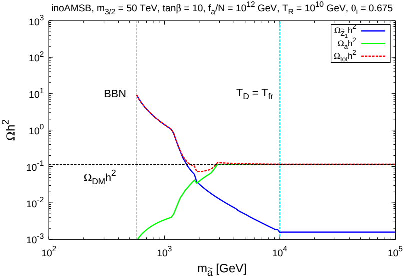
→ *oscillations*

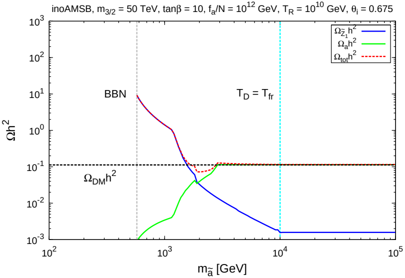
In the end we consider again axion entropy dilution as in $\tilde{Z}_1$ case.

And finally $\boxed{\Omega h^2 = \Omega_{\tilde{Z}_1} h^2 + \Omega_a h^2}$.

Heavy Axino Cosmology

Total $a\tilde{Z}_1$ DM Abundance





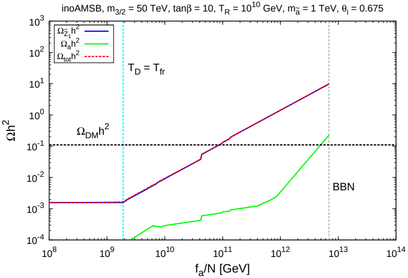
When $m_{\tilde{a}}$ is low, T_D smallish as well.

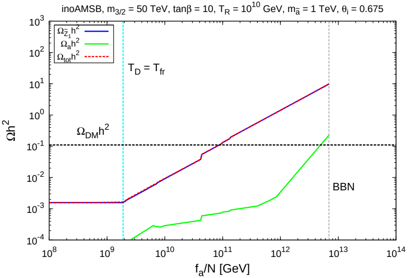
Re-annihilation effect gives $\Omega_{\tilde{Z}_1} \propto T_D^{-1}$

- $\Omega_{\tilde{Z}_1} \uparrow$ for $m_{\tilde{a}} \downarrow$.
- Ω_a experiences dilution where $r > 1$ and $T_D < T_{osc}^a$.

Heavy Axino Cosmology

Total $a\tilde{Z}_1$ DM Abundance





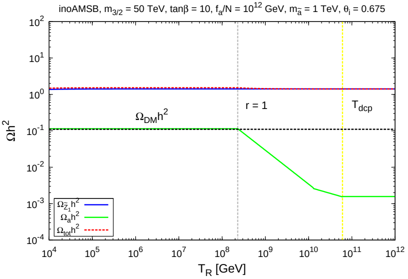
When f_a/N is low, $\Gamma_{\tilde{a}}$ is large $\Rightarrow T_D > T_{fr}$ $\Rightarrow \Omega^{std}_{\tilde{Z}_1} \sim 10^{-2} - 10^{-3}$

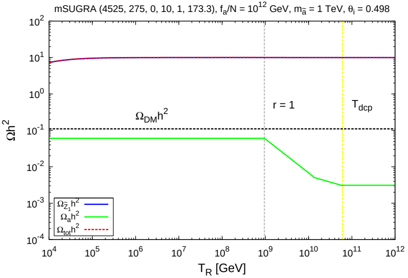
$\Omega_{\tilde{Z}_1} \propto T_D^{-1}$ for $T_D < T_{fr}$

- $\Omega_{\tilde{Z}_1} \uparrow$ as $f_a/N \uparrow$.
- $\Omega_a \uparrow$ as $f_a/N \uparrow$ except where $r > 1$ and $T_D < T^a_{osc}$, *i.e.* dilution turns on.

Heavy Axino Cosmology

Total $a\tilde{Z}_1$ DM Abundance





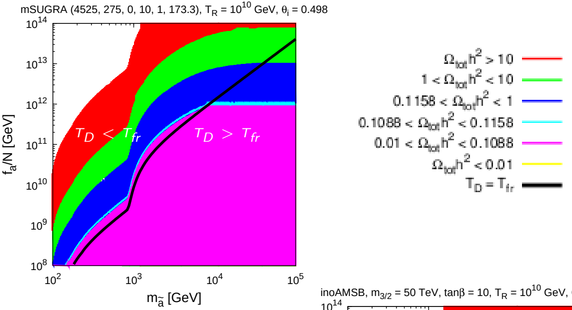
$\Omega_{\tilde{Z}_1}$ depends *little* on T_R and much more on $T_D \sim m_{\tilde{a}}^{3/2}/(f_a/N)$ which is fixed here.

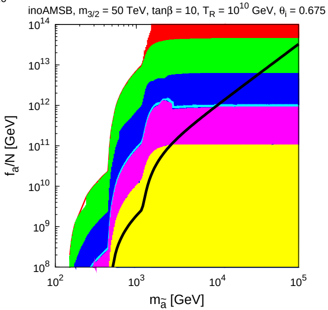
- $\Omega_{\tilde{Z}_1}$ mainly fixed in T_R.
- Ω_a not connected to reheat process, but dilution occurs for $r > 1$.

Best to look in $f_a/N - m_{\tilde{a}}$ plane.

Heavy Axino Cosmology

Total $a\tilde{Z}_1$ DM Abundance





Heavy Axino Cosmology

Forward Direction

Include the saxion (s):

- spin-0, *R-parity* even, real scalar
- as with $\tilde{a}$, s produced in thermal scatterings or in equilibrium, or additionally through coherent oscillations.
- $s \to gg, \tilde{g}\tilde{g}, \ \tilde{Z}_i\tilde{Z}_j, \ \gamma\gamma$
- s may co-dominate with $\tilde{a}$.
- *more complicated analysis:* need precise Boltzmann solutions and will likely need to include gravitino decays as well (high T_R).

Summary

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We have seen that models that predict *under-abundances* of DM should be aided by extra *non-thermal* sources. As a result, such models can account for WMAP in addition to having good prospects for detection.

I've given a flavor for the types of calculations encountered. When considering the full spectrum of NTP sources the Boltzmann equations become ever-increasingly complex.

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Thank you

Backup Slides

CP Problem and the Axion

Owing to non-trivial gauge configurations of the QCD vacuum and electroweak effects involving quark masses, an unwanted CP-violating non-perturbative term appears in the QCD Lagrangian:

$$\mathcal{L}_{QCD} \ni \bar{\Theta} \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{a\mu\nu},$$

where $\bar{\Theta} = \Theta + Arg\ det\mathcal{M}$.

Vacuum structure supported by solution to $U(1)_A$ problem.

However the electric dipole moment of the neutron constrains $\bar{\Theta} \lesssim 10^{-10}$, but there is no reason for $\bar{\Theta}$ to be so small since Θ and $\mathcal{M}$ come from completely different sources.

axion intro, slide 17

axion yield, slide 36

CP Problem and the Axion

Peccei and Quinn (1977) introduced anomolous $U(1)_{PQ}$. The symmetry is broken at the scale f_a and a Nambu-Goldstone boson, the axion (a), is produces another term in the QCD Lagrangian

$$\mathcal{L}_{QCD} \ni \bar{\Theta} \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{a\mu\nu} + \frac{C_a a}{f_a} \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{a\mu\nu}.$$

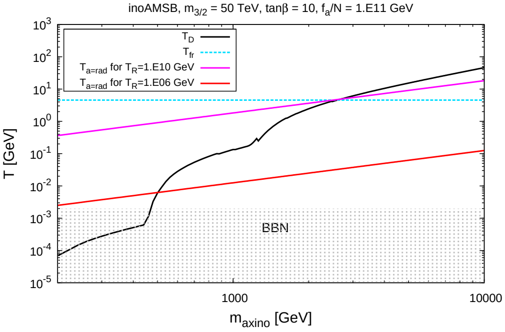
The two terms amount to a potential for the axion which is minimized for

$$\langle a \rangle = -\frac{\bar{\Theta} f_a}{C_a},$$

and the $G\tilde{G}$ term vanishes at the minimum.

axion intro, slide 17

axion yield, slide 36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Tfr
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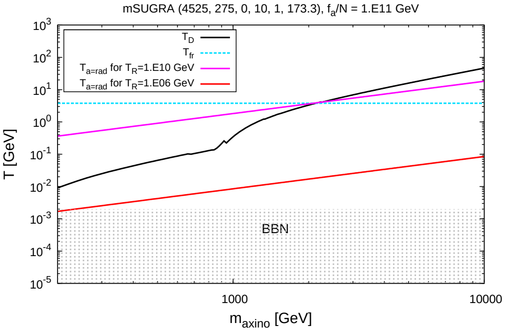
Ta=rad for TR=1.E06 GeV
BBN
T [GeV]
maxino [GeV]
1000
10000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TD
Tfr
Ta=rad for TR=1.E10 GeV
Ta=rad for TR=1.E06 GeV
BBN
T [GeV]
maxino [GeV]
1000
10000

(* to slide 30)