Title: Light Moduli: Applications to Dark Matter and Baryogenesis

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Abstract: <p>Moduli fields with Planck suppressed couplings to light species are ubiquitous in string theory and supersymmetry. These scalar fields are expected to dominate the energy budget in the early universe. Their out-of-equilibrium decays can produce dark matter and baryons. Dark matter generated in this non-thermal manner typically has large annihilation rates that are strongly constrained by indirect detection. The resulting bounds on superpartner masses offer dim prospects for collider discovery of supersymmetry. We will discuss extensions of the Minimal Supersymmetric Standard Model (MSSM) that allow low scale supersymmetry accessible by direct searches, while being consistent with astrophysical and cosmological probes. The tension with indirect searches is most easily relieved by allowing the lightest MSSM superpartner to decay into new stable states that play the role of dark matter. We examine the viability of this scenario in models with light Abelian and non-Abelian hidden sectors, and asymmetric dark matter. This latter possibility has a natural connection to theories of baryogenesis.</p>

Light Moduli: Applications to Dark Matter and Baryogenesis

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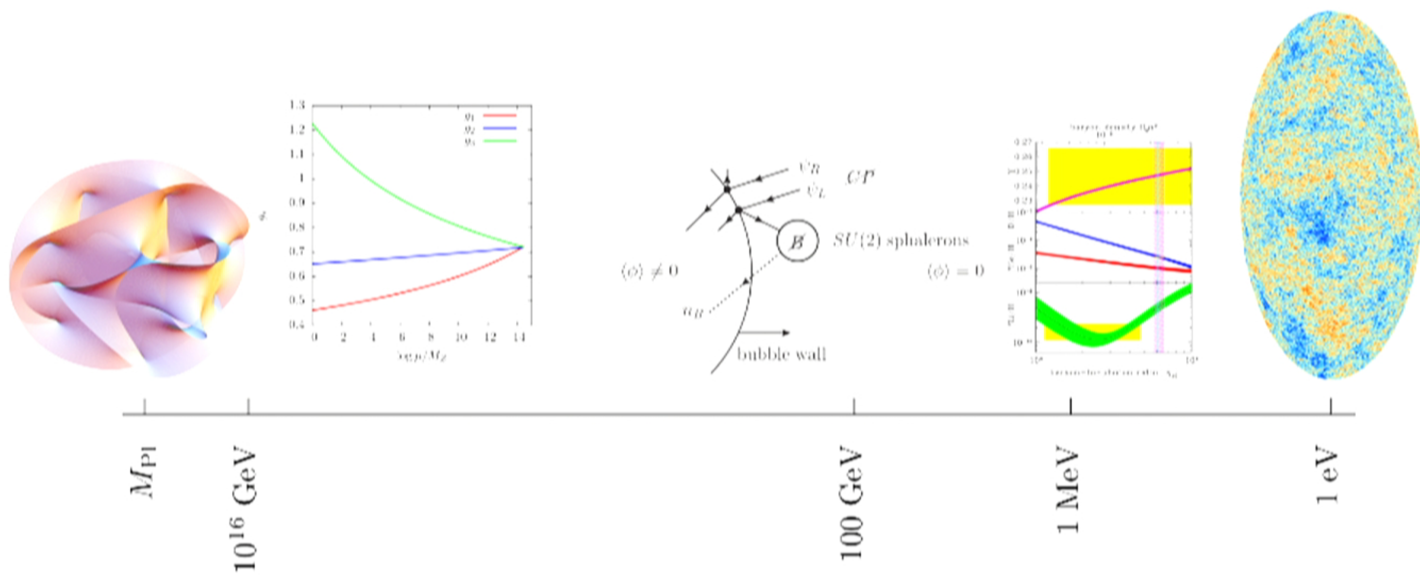
Perimeter Institute, November 28, 2014

Based on:
1409.1222 with David Morrissey, Jonathan Kozaczuk, Arjun Menon
1206.3304 with David Morrissey, Kris Sigurdson and Sean Tulin

History

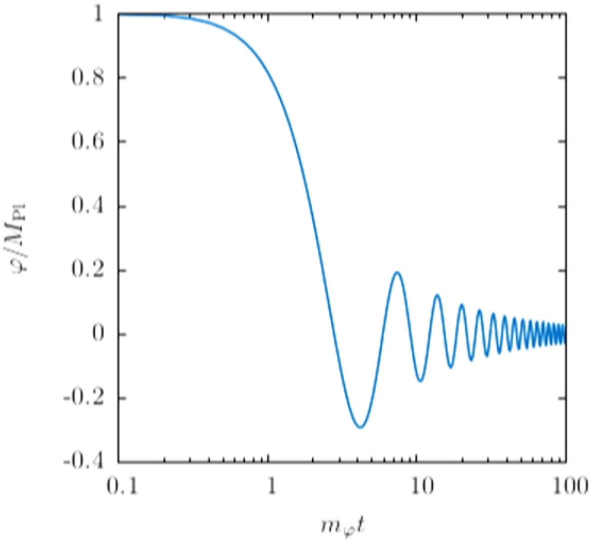


Moduli Fields

- "Heavy" scalars generic in string theories, *e.g.* components of the $10D$ metric g^{MN}
- Initially displaced from potential minimum, with $\varphi \lesssim M_{\rm Pl}$
- Coherent oscillations store energy

$$\ddot{\varphi} + 3H\dot{\varphi} + m_\varphi^2 \varphi = 0 + \ldots$$

$$\rho_\varphi = \langle \dot{\varphi}^2 \rangle \propto a(t)^{-3}$$



- Interactions suppressed by $M_{\rm Pl} = 2.435 \times 10^{18}$ GeV

$$\frac{\varphi}{M_{\rm Pl}} F_{\mu\nu} F^{\mu\nu} \quad \Rightarrow \quad \Gamma_\varphi = \frac{c}{4\pi} \frac{m_\varphi^3}{M_{\rm Pl}^2}$$

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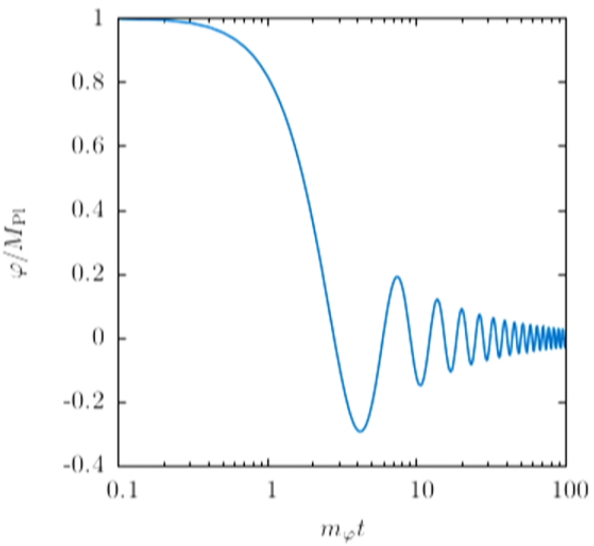

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The Moduli Problem and Reheating

- **At least one modulus with** $m_\varphi \approx m_{3/2} \leftarrow$ **SUSY breaking scale***

  de Carlos, Casas, Quevedo and Roulet (1993), Acharya, Kane and Kumar (2012)

  *For exceptions see *e.g.* Bose, Dine and Draper (2013)

- Because ρ_φ dilutes slower than radiation, φ likely to dominate energy content of the universe

- φ decays when $\Gamma_\varphi \approx H$ and reheats the universe at $T = T_{\rm RH}$

$$T_{\rm RH} \approx 5.5 \text{ MeV} \left(\frac{m_\varphi}{100 \text{ TeV}}\right)^{3/2}, \text{ BBN} \Rightarrow T_{\rm RH} \gtrsim 5 \text{ MeV}$$

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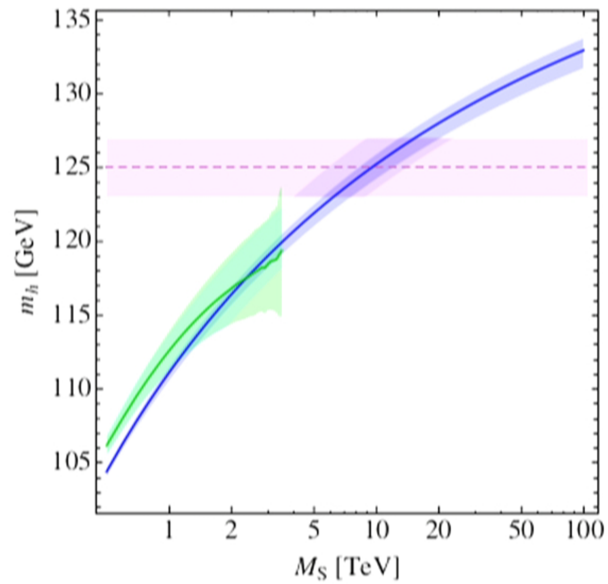
An Aside: Higgs Mass in the MSSM

- To get $m_h = 125.5$ GeV need heavy stops*
- Generally other scalars will be even heavier
- Again this points to a scale $m_{3/2} \sim 100$ TeV



Draper, Meade, Reece, and Shih (2011)

If all superpartners at $m_{3/2} \sim m_\varphi \gtrsim 100$ TeV, bleak prospects for SUSY discovery at LHC

*Assuming $X_t = 0$...

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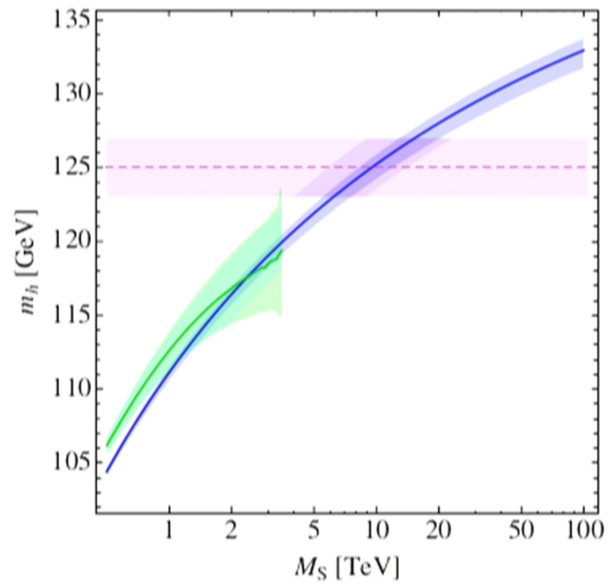

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Anomaly Mediation and Wino DM

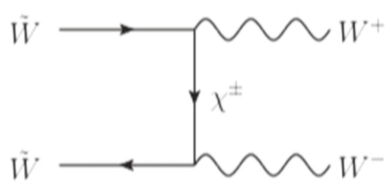
Split spectrum predicted by Anomaly Mediated Supersymmetry Breaking (AMSB)

$$m_\lambda \sim (\text{loop factor}) \times m_{3/2}, \; m_{\tilde{f}} \sim m_{3/2}$$

- Gauginos can be light, despite $m_{3/2} \gtrsim 100$ TeV
- For SM $|M_2| \ll |M_1| \ll |M_3| \Rightarrow$ Wino LSP

Wino DM

- Very efficient annihilation:

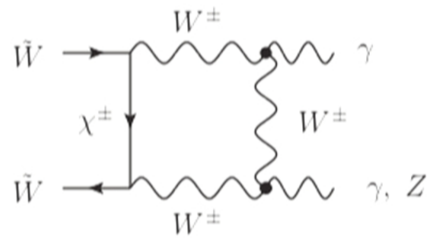


$$\langle \sigma v \rangle \approx 4 \times 10^{-24} \text{ cm}^3/\text{s} \left(\frac{100 \text{ GeV}}{m_{\widetilde{W}}} \right)^2$$

Thermal relic density too small for $m_{\widetilde{W}} < 2.8$ TeV!

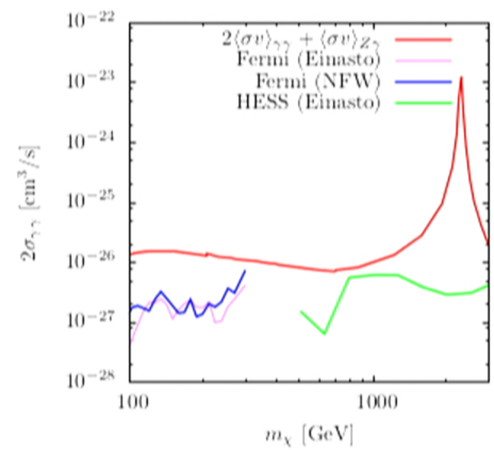
Constraints from Indirect Detection

- Large annihilation cross-section to γ *lines* & continuum γs



- Large expected signal from galactic center
- HESS and Fermi-LAT put bounds on line fluxes
- Continuum constraints from GC
  Hooper, Kelso and Queiroz (2012)

$$\Phi = \frac{\sigma v}{8\pi m_\chi^2} \frac{dN}{dE_\gamma} \int_{\rm los} \rho(l)^2 dl$$



H.E.S.S. (2013) and Fermi-LAT (2013)
Fan and Reece (2013) and Cohen, Lisanti, Pierce and Slatyer (2013)

Ways Out?

If we want superpartners at LHC with AMSB-like spectrum, must suppress Wino abundance or annihilations into photons

Options:

1. **Light hidden sector (HS) with the real LSP:** $\widetilde{W} \to \chi_1^x + \ldots$
   No direct annihilation into SM
2. **Asymmetric DM**
   Annihilations suppressed by small anti-DM density
3. R-parity violation: $\widetilde{W} \to \mathrm{SM} + \overline{\mathrm{SM}}$
4. Dilute Wino component with singlino (NMSSM)?
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$U(1)_x$ Hidden Sector

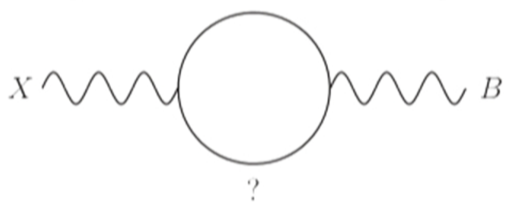
Additional spontaneously broken $U(1)_x$ kinetically mixed with $U(1)_Y$

$$W = W_{\mathrm{MSSM}} + \mu' H H^c; \quad \mathscr{L} \supset \frac{\epsilon}{2} \int d^2\theta X^\alpha B_\alpha$$

Holdom (1986), Pospelov, Ritz and Voloshin (2007)

HS Neutralino, χ_1^x can be lighter than $\widetilde{W}$ and allows for $\widetilde{W} \to X_\mu \chi_1^x$

- Origin of kinetic mixing



$$\epsilon \sim \frac{g_x g_Y}{(4\pi)^2} \log\left(\frac{M}{\mu}\right)$$

- Most important coupling to matter

$$\mathscr{L} \supset -\epsilon e X_\mu J^\mu_{\mathrm{em}}$$

Searching for the Vector Portal

- Fixed target/Beam dump experiments, *e.g.*

$$e^- + N(A, Z) \to X^* \to e^+ e^-$$

- Flavour factory searches for resonances *e.g.*

$$\Upsilon \to \gamma + X^* \to \mu^+ \mu^-$$

- Can also look for friends of X: dark Higgs, DM, ...
  Izaguirre, Krnjaic, Schuster and Toro (2013)
  Morrissey and Spray (2014)
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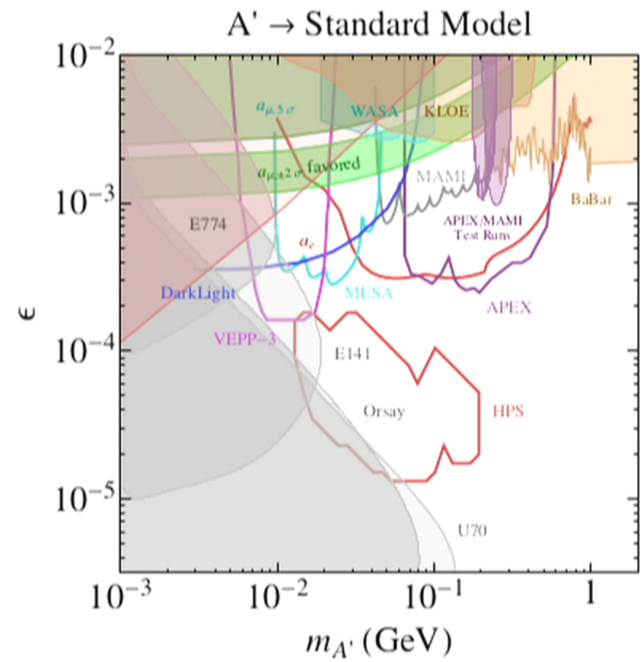

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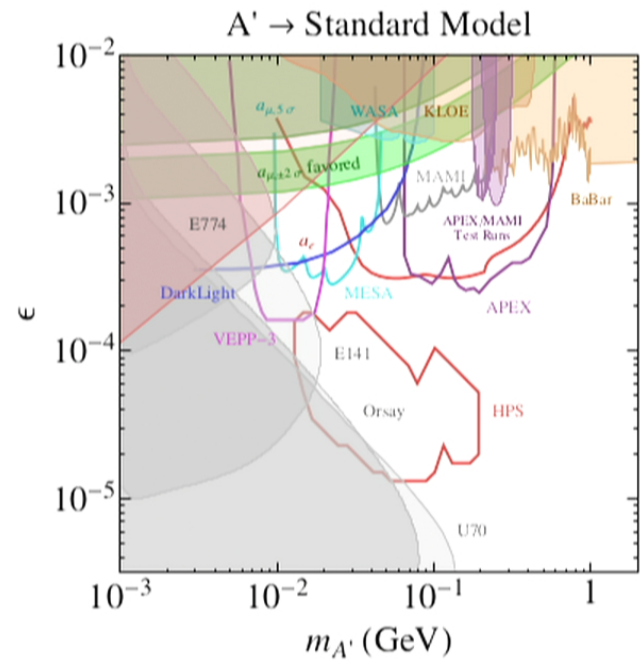

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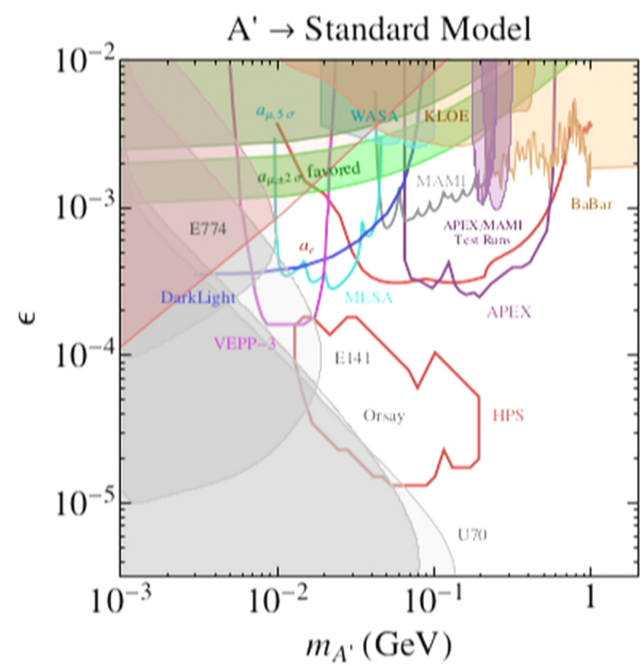

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Particles!

SUSY Hidden Sector gives:

- 1 Vector X_μ with mass m_x
- 2 CP-even Scalars h_a^x
- 1 CP-odd Scalar A_x
- 3 HS Neutralinos χ_i^x

All masses can be near m_x. SUSY can explain small m_x

Morrissey, Poland, and Zurek (2009)

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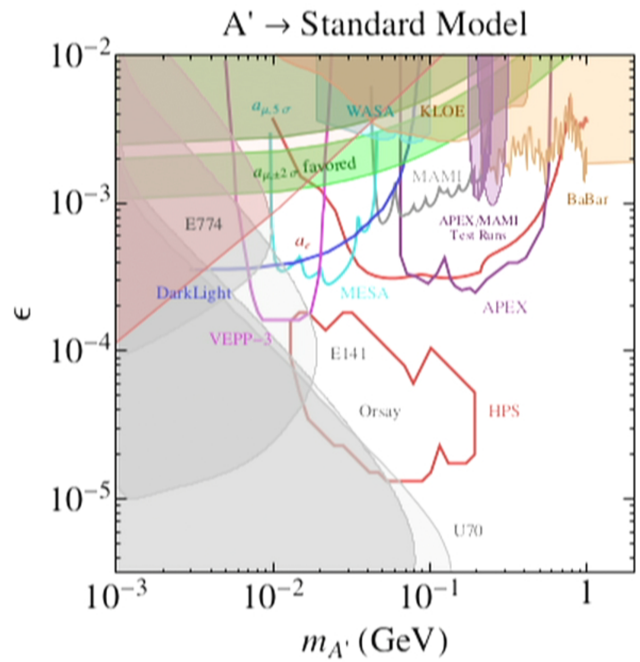

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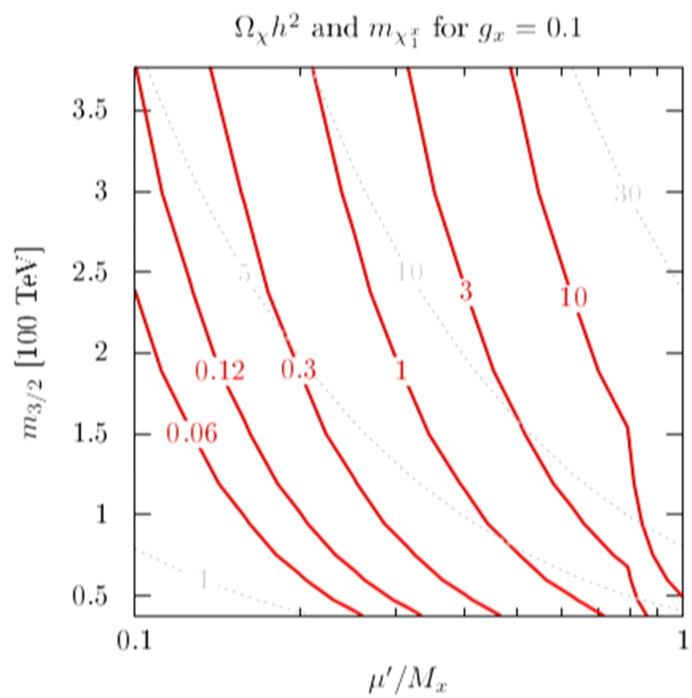
Hidden Sector Dark Matter

- χ_1^x annihilates directly to HS
- Non-thermal WIMP miracle can be realized with χ_1^x
- **On-shell annihilation products decay into SM**

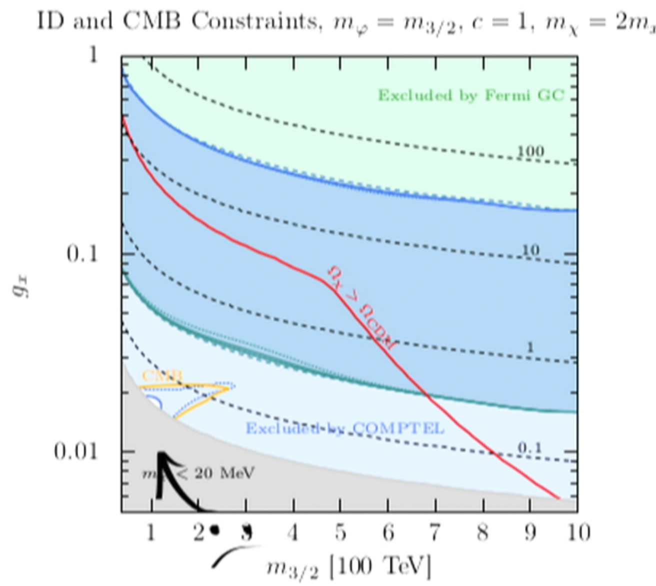
$$\Gamma(X \to \overline{\mathrm{SM}}\ \mathrm{SM}) \propto \frac{1}{3}\alpha\epsilon^2 m_x$$



Indirect Detection and Cosmology Constraints

- SM decay products generally produce HE photons from hadronization and radiation
- γ lines also possible, but the rate is negligible
- Annihilations during recombination at $z \sim 1000$ distorts surface of last scattering

  Hütsi, Chluba, Hektor & Raidal (2011), Galli, Iocco, Bertone & Melchiorri (2011)



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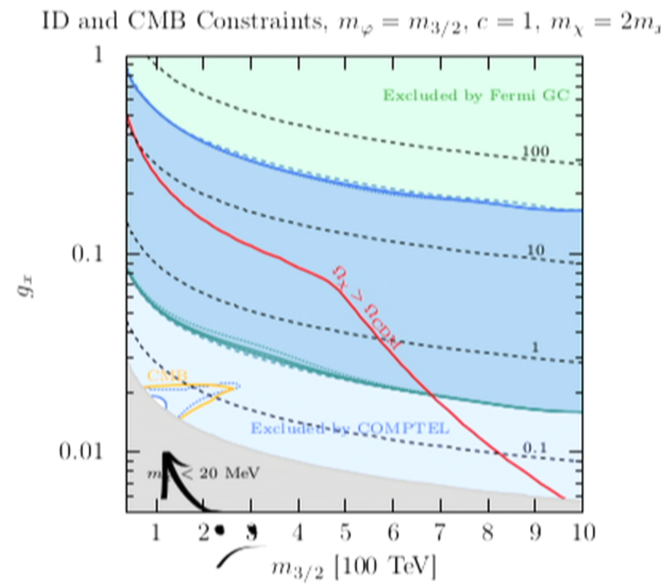


Asymmetric Dark Matter

Asymmetric Dark Matter solves the late-time annihilation problem, while allowing $\widetilde{W}$ decay into the HS

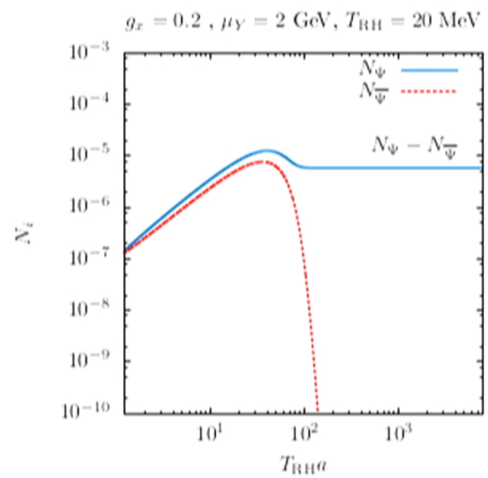
- Dirac fermion or complex scalar Y with $n_Y \gg n_{\overline{Y}}$ at late times

Kaplan, Luty, & Zurek (2009)

- Efficient annihilation required to deplete $n_{\overline{Y}}$

$$\langle \sigma v \rangle \gg 3 \times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$

- Light mediators needed $\Rightarrow$ reuse the $U(1)_x$ HS



Challenges for ADM+$U(1)_x$

1. Annihilation is not fully efficient, some anti-DM remains:

   Energy injection during recombination ⇒ CMB constraints

$$2f \sum_{i=\Psi,\Phi} \left(\frac{\Omega_i + \Omega_{\bar{i}}}{\Omega_{\rm cdm}} \right)^2 \frac{R_i}{(1+R_i)^2} \frac{\langle \sigma v \rangle_i}{m_i} \quad < \quad \frac{2.42 \times 10^{-27}\ {\rm cm}^3/{\rm s}}{\rm GeV}.$$

   Lin, Yu and Zurek (2011)

   Indirect detection

2. A light mediator ⇒ Spin-independent scattering off nuclei
   Stringent constraints from direct (non) detection, even at low masses: LUX (2013), XENON S2 (2011), CDMSLite (2013) and CRESST-Si (2002)

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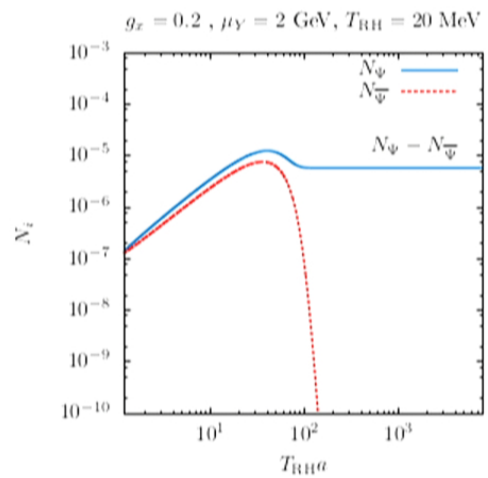

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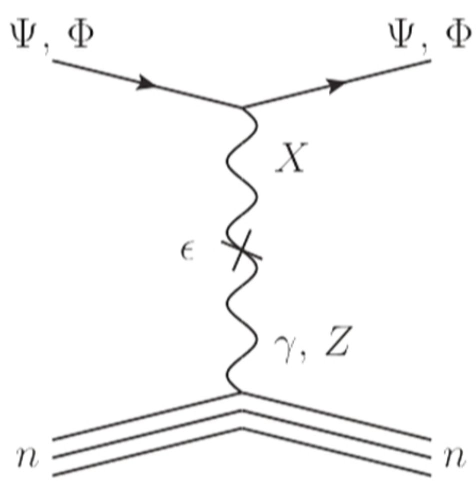
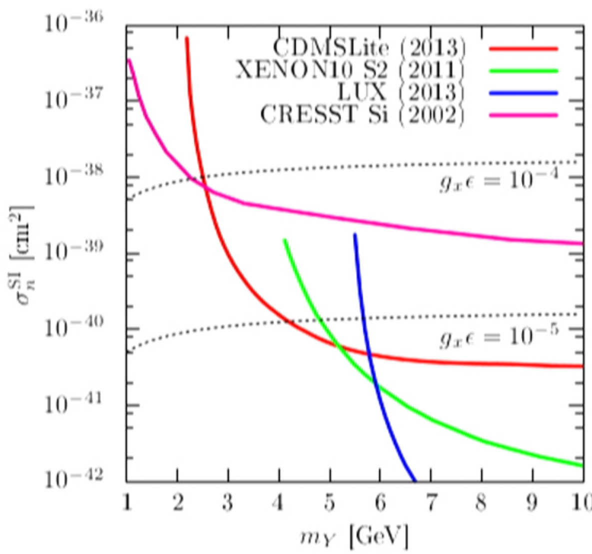
Direct Detection

$$\tilde{\sigma}_n \approx 2 \times 10^{-38}\ \mathrm{cm}^2 \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{g_x}{0.1}\right)^2 \left(\frac{\mu_n}{1\ \mathrm{GeV}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_x}\right)^4 .$$

Note: ϵ cannot be arbitrarily small - $\widetilde{W}$ must decay before BBN, maintain kinetic equilibrum between HS and MSSM





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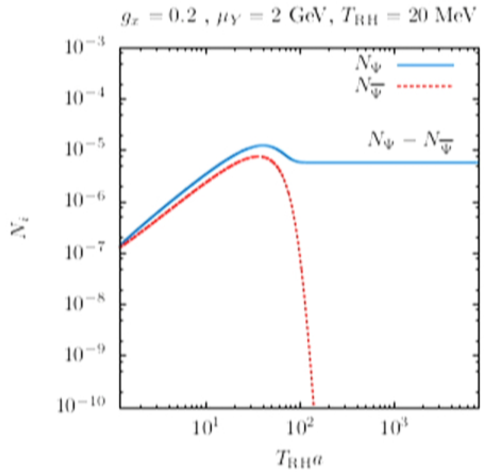
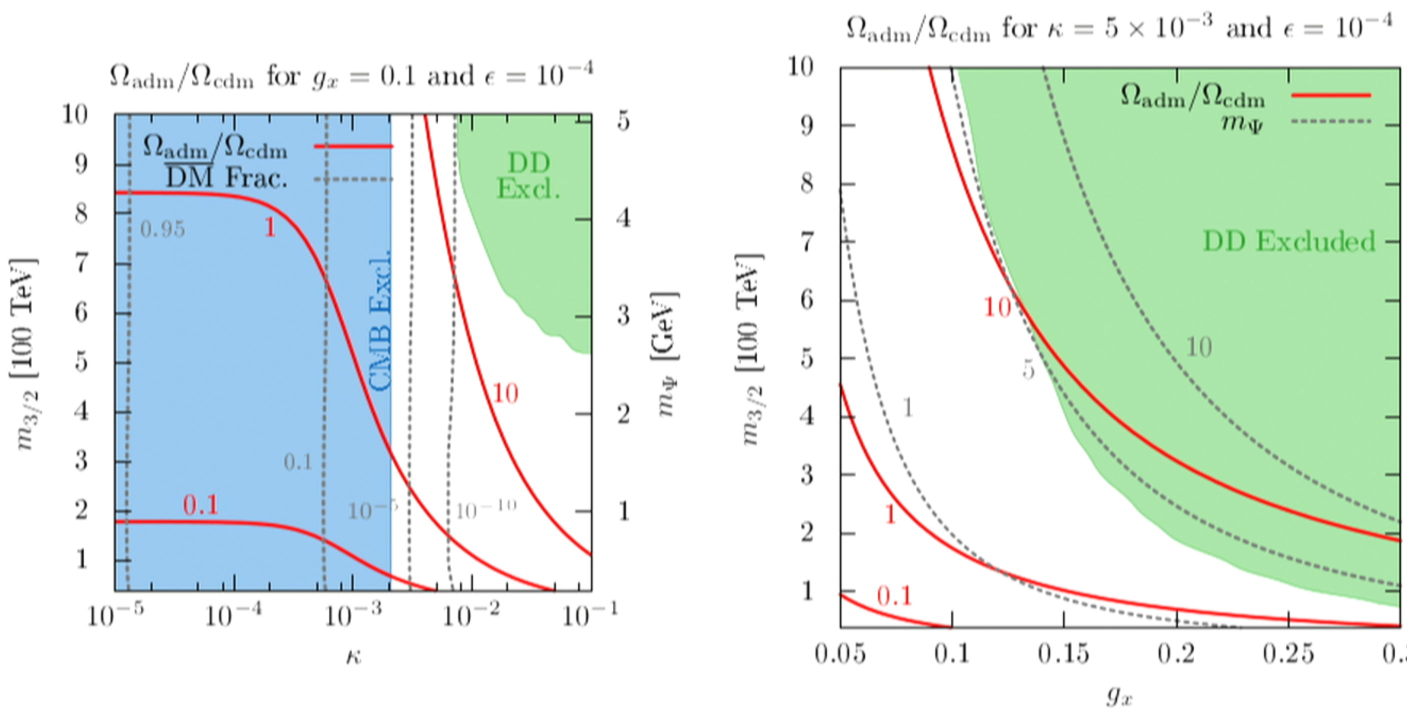


ADM Works!



Production rates for $\Phi, \Phi^* \sim (1 \pm \kappa/2)\Gamma$

Observations So Far

- An Abelian HS (with or without ADM) can solve the moduli induced MSSM (Wino) LSP problem (or at least relieve tension with ID)
- Both cases considered require light $\sim$ GeV scale scalars

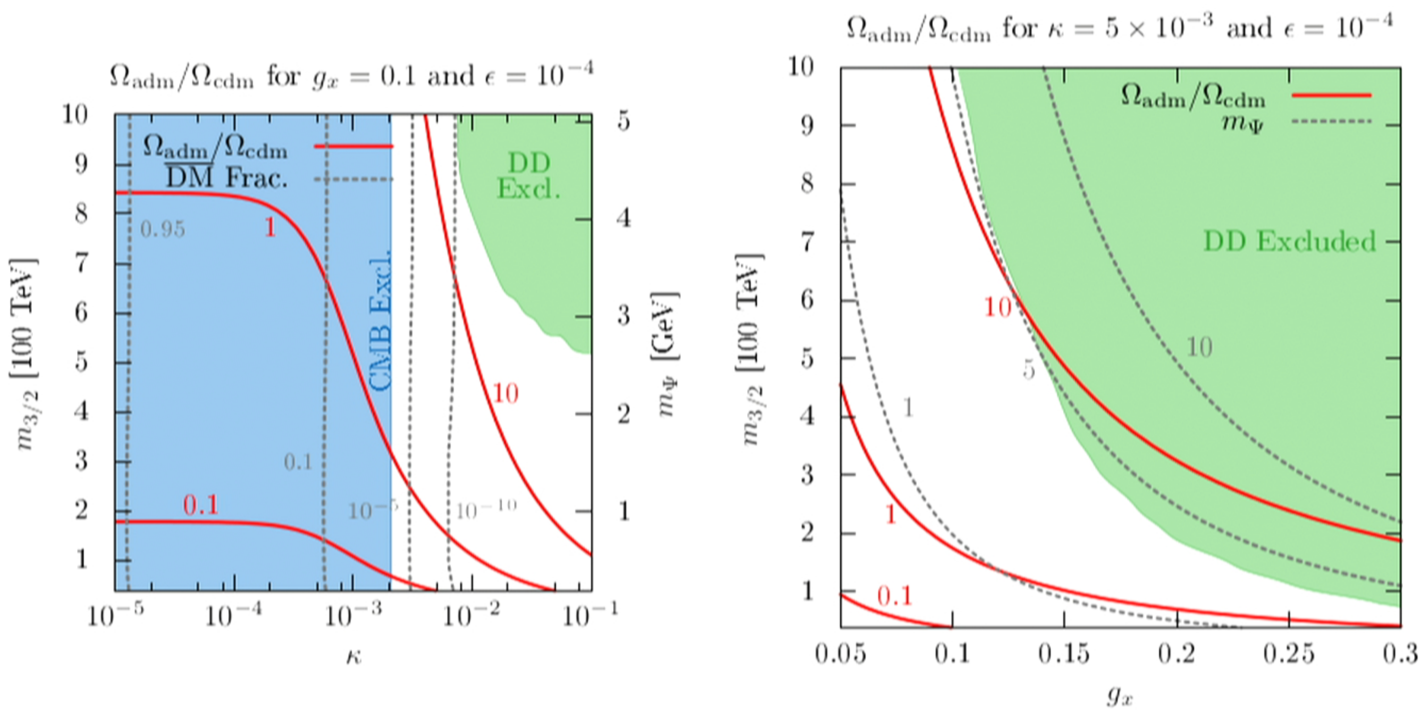
  e.g. light HS vector needs a Higgs with a $\mathcal{O}(\text{GeV})$ VEV

- LHC null searches imply a split spectrum (heavy scalars) in the visible sector

Wells (2004), Hall and Nomura (2011), Arvanitaki *et al* (2012)

Is there a viable solution with split hidden sector?

ADM Works!



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Mini-Split With a Non-Abelian Hidden Sector

Pure $U(1)_x$ does not work: HS neutralino cannot annihilate (no coupling to gauge bosons!)
$\therefore$ Consider a hidden $SU(N)_x$

Feng and Shadmi (2011)

Boddy, Feng, Kaplinghat and Tait (2014)

- Spectrum contains $N^2 - 1$ (unconfined) massless gluons and massive gluinos (DM)

$$M_x = r_x \frac{g_x^2}{(4\pi)^2} m_{3/2} ,$$

- MSSM LSP must decay to HS via high-dimension operators
  $\Rightarrow$ matter charged under SM gauge group and $SU(N)_x$ at some high scale
- Two sectors never thermalize: HS gluons another radiation bath and set of massless d.o.f.s

Back to Asymmetric Dark Matter

- ADM provides a viable solution to the moduli-induced LSP problem
- DM and baryons are in principle generated by completely different mechanisms, BUT

$$\Omega_{\rm cdm}/\Omega_b \approx 5,$$

  so why are their abundances so similar?
- Goal of hylogenesis* ("matter"-genesis): Unify production of DM and the baryon asymmetry in one mechanism

* Not to be confused with xogenesis, higgsogenesis, pangenesis, darkogenesis, aidnogenesis, cladogenesis...

Moduli Decays and Baryon Production

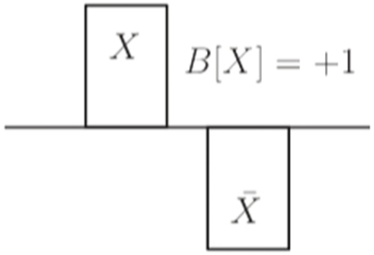
- Sakharov conditions for baryon asymmetry production:
  1. B violation
  2. C and CP-violation
  3. *departure from thermal equilibrium*

Sakharov (1967)

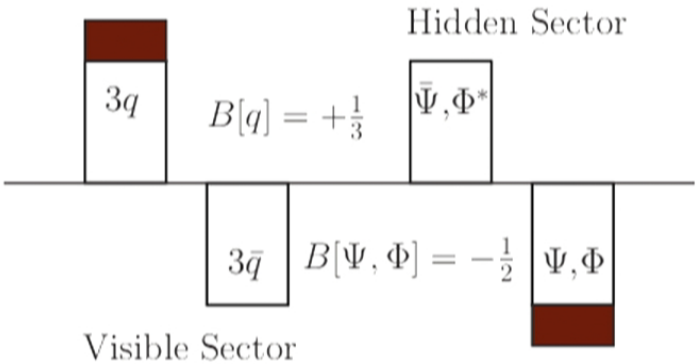
Moduli decays naturally occur far out of equilibrium

Hylogenesis (I)

1. A symmetric density of heavy particles X, $\bar{X}$ is generated out of equilibrium ($T \ll M_X$) via moduli decay



2. X, $\bar{X}$ decay to baryons and DM, producing equal and opposite asymmetries in the two sectors (total B is conserved)



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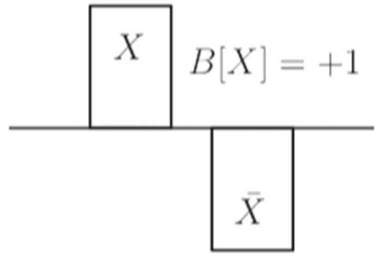

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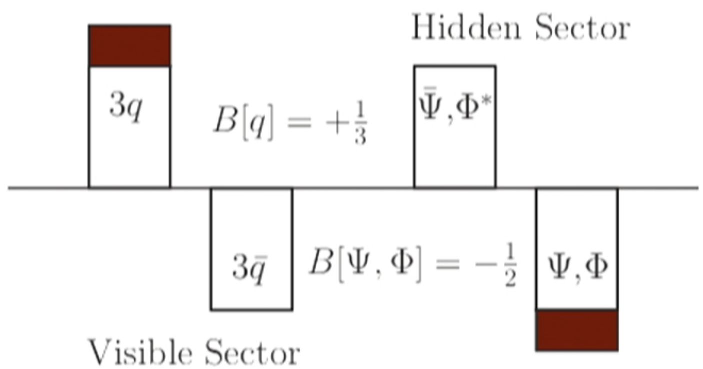

Hylogenesis (II)

3. Symmetric densities annihilate away

Davoudiasl, Morrissey, Sigurdson and Tulin (2010)

- DM consists of a fermion Ψ and a scalar Φ
- To get correct DM abundance need

$$m_\Phi + m_\Psi \approx (\Omega_{\rm cdm}/\Omega_b) m_p \approx 5\,\mathrm{GeV}$$

- To ensure stability of DM and nucleons, masses must satisfy

$$|m_\Phi - m_\Psi| < m_p + m_e < m_\Phi + m_\Psi\,,$$

kinematically forbidding processes like $p \to \Phi^* + \bar{\Psi} + e^+$.

Superpotential and Field Content (Vector Model)

- SUSY hylogenesis superpotential

$$W = W_{\rm MSSM} + W_{\rm trans} + W_{\rm HS},$$

- $W_{\rm trans}$ transfers baryon number between hidden and visible sectors

$$W_{\rm trans} = \sum_{a=1,2} \frac{\lambda_a}{M} \epsilon^{\alpha\beta\gamma} X_a U_\alpha{}^c D_\beta{}^c S_\gamma{}^c \ ,$$

- The Hidden Sector (HS) interactions are described by $W_{\rm HS}$:

$$W_{\rm HS} = \sum_{a=1,2} \zeta_a X_a Y_1^2 + \bar{\zeta}_a X_a^c (Y_1^c)^2 + \gamma Y_1 Y_2^c H + \bar{\gamma} Y_1^c Y_2 H^c$$
$$+ \mu_{X_a} X_a X_a^c + \mu_{Y_a} Y_a Y_a^c + \mu_H H H^c \ ,$$

- The X kinetically mixes with the MSSM hypercharge to allow for efficient annihilation of HS states

$$-\mathscr{L} \supset \frac{\epsilon}{2} \int d^2\theta \ B^\alpha X_\alpha + \text{h.c.}$$

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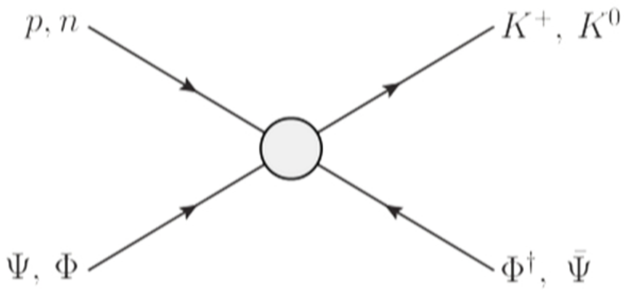
Induced Nucleon Decay (IND)

- DM in the halo can scatter with nucleons, destroying them and producing a meson:

$$\Psi N \to \Phi^\dagger M,\ \Phi N \to \bar{\Psi} M,$$

  where $N = (p, n)$ and $M = (K^+, K^0)$.
- For $m_{\Psi_1} \neq m_{\Phi_1}$ up- and down-scattering is possible
- Current bound on proton lifetime:

$$\tau_p \gtrsim 10^{33}\,\text{years}$$



Davoudiasl, Morrissey, Sigurdson and Tulin (2011)

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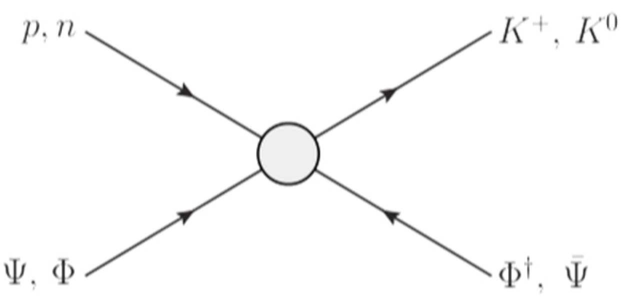


Davoudiasl, Morrissey, Sigurdson and Tulin (2011)

Induced Nucleon Decay (IND)

- Effective nucleon lifetime in the presence of IND

$$\tau_N^{-1} = n_{\rm dm}(\sigma v)_{\rm IND} \approx (10^{32}\,{\rm years})^{-1}\left(\frac{(\sigma v)_{\rm IND}}{10^{-39}\,{\rm cm}^3/{\rm s}}\right)$$

- Kinematics of daughter meson different from standard nucleon decay (SND) searches. For example,

Decay Mode	$p_M^{\rm SND}$ (MeV)	$p_M^{\rm IND}$ (MeV) up	$p_M^{\rm IND}$ (MeV) down
$p \to K^+ + \ldots$	340	< 680	$680 - 1360$

- IND events in *current* nucleon decay searches may be missed due to kinematic cuts!

Conclusion, Part II

- Hylogenesis provides a unified explanation for the baryon asymmetry and dark matter abundance
- The model can be embedded in a SUSY theory, fixing scalar mass fine-tuning and providing a connection with a viable extension of SM
- Interesting cosmological evolution due to SUSY interactions
- Induced Nucleon Decay provides a unique experimental signature

Conclusion, Part III

- Moduli decays lead to non-thermal cosmologies
- DM is generally over produced, or in conflict with indirect detection

  The simplest scenarios are ruled out by ID!
- Asymmetric DM evades ID constraints and provides connection to baryogenesis (?)

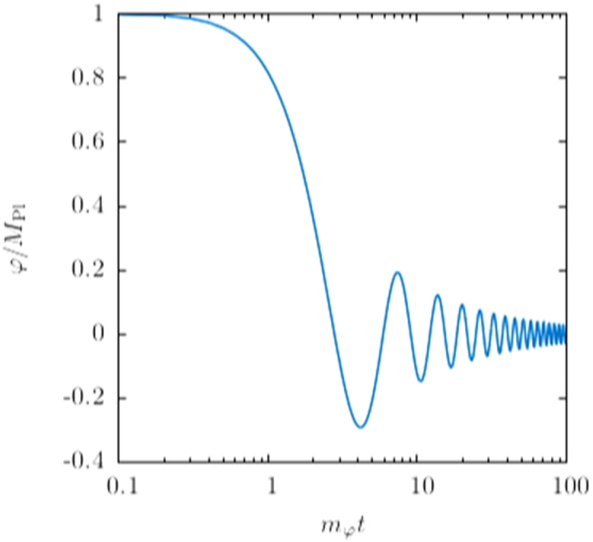
Thank you!

Moduli Fields

- "Heavy" scalars generic in string theories, *e.g.* components of the $10D$ metric g^{MN}
- Initially displaced from potential minimum, with $\varphi \lesssim M_{\rm Pl}$
- Coherent oscillations store energy

$$\ddot{\varphi} + 3H\dot{\varphi} + m_\varphi^2 \varphi = 0 + \ldots$$

$$\rho_\varphi = \langle \dot{\varphi}^2 \rangle \propto a(t)^{-3}$$



- Interactions suppressed by $M_{\rm Pl} = 2.435 \times 10^{18}$ GeV

$$\frac{\varphi}{M_{\rm Pl}} F_{\mu\nu} F^{\mu\nu} \quad \Rightarrow \quad \Gamma_\varphi = \frac{c}{4\pi} \frac{m_\varphi^3}{M_{\rm Pl}^2}$$