Inflatable Dark Matter

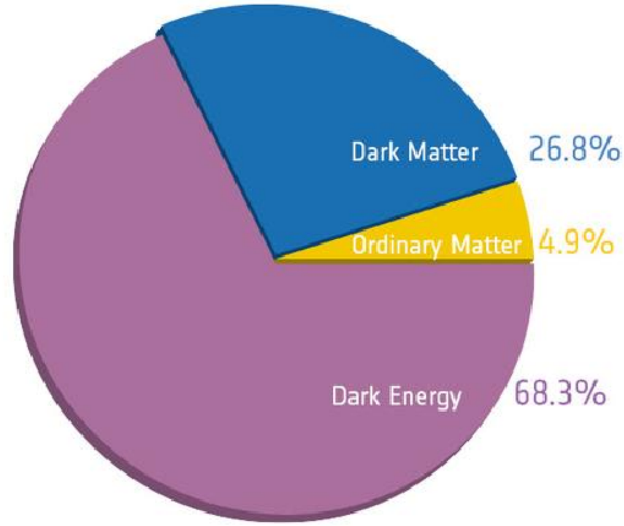
Hooman Davoudiasl

HET Group, Brookhaven National Laboratory

Based on: H. D., D. Hooper and S. D. McDermott, Phys. Rev. Lett. **116**, no. 3, 031303 (2016)
arXiv:1507.08660 [hep-ph]

Warsaw Workshop on Non-Standard Dark Matter, University of Warsaw, June 2-5, 2016

- Dark matter (DM): a new substance
- Something beyond the Standard Model (SM)
- Stable on cosmological time scales
- So far manifested only through gravity
- Generally expected to have other interactions
- Couplings: DM-SM weak; DM-DM not too strong



Planck

★ *Guiding principles needed to narrow multitude of possibilities*

- Is there a bigger picture where DM naturally arises?
- Hierarchy and extended EW sectors $\rightarrow$ WIMP miracle

- Can the same physics address another mystery?
- Strong CP $\rightarrow$ QCD axion DM

- Do observations offer a clue?
- $\Omega_{\rm DM} \sim 5\,\Omega_{\rm baryon}$ $\rightarrow$ Asymmetric DM

DM and SM Extensions

- $\Omega^{\rm th} < \Omega^{\rm meas} \Rightarrow$ Other contributions to $\Omega^{\rm meas} \simeq 0.26$
- Less economical, but does not rule out a model per se

- Generally, models get ruled out when $\Omega^{\rm th} > \Omega^{\rm meas}$
- "Overclosing" the Universe (premised on *standard cosmology*)

Examples:

- Thermal Relic WIMP: $\Omega^{\rm th}_{\rm WIMP} \propto 1/\langle \sigma v \rangle_{\rm ann} \sim M^2/g^4$, with $M \sim$ TeV
- Experimental searches: g gets smaller and/or M gets larger $\Rightarrow \Omega^{\rm th}_{\rm WIMP} > \Omega^{\rm meas}$

- QCD axion good DM if Peccei-Quinn scale $f_{\rm PQ} \lesssim 10^{12}$ GeV
- Assuming "natural" misalignment
- String theory offers multitude of axion candidates ($f_{\rm PQ} \gg 10^{12}$ GeV)
- $\Omega_a \propto f^n_{\rm PQ}$ with $n \approx 1 \Rightarrow$ disfavors natural UV scales $M_{\rm Planck}$, $M_{\rm GUT}$
- Anthropic arguments? Linde, 1988; Wilczek, 2004

This talk: consider diluting DM density through inflation

- Inflation after DM "production"
- Thermal relic freeze-out at $T \lesssim m_{\rm DM}/20$
- Axion oscillation at $T \lesssim \Lambda_{\rm QCD}$ (200 MeV)
- ...

- For illustrative purposes, we focus on *thermal inflation*
- Dilutions of $\mathcal{O}(10 - 1000)$ can be realized in simple models
- Inflation can originate in a "hidden sector" largely decoupled from the SM
- Elusive laboratory signals, yet significant effect on the visible sector cosmology

- Space of viable DM models opens up for "Inflatable DM"

Inflation: Guth 1981; Linde 1982; Albrecht, Steinhardt, 1982

Thermal Inflation: Lyth, Stewart, 1995

Some Background

- Similar effects may obtain from late decay of moduli, massive states

Recent work: Patwardhan, Fuller, Kishimoto, Kusenko, 2015

- Earlier discussions of inflation for axion DM with $f_{\rm PQ} \gg 10^{12}$ GeV

Dimopoulos, Hall, 1988; Fox, Pierce, Thomas, 2004

- Thermal inflation has been invoked to address cosmological problems (gravitinos, baryogenesis, moduli)

Lazarides, Panagiotakopoulos, Shafi, 1986; Yamamoto, 1986; Lyth, Stewart, 1995

- Inflation from first order QCD phase transition with $\mathcal{O}(1)$ baryon asymmetry

Kämpfer, 1986; Borghini, Cottingham, Vinh Mau, 2000; Boeckel, Schaffner-Bielich, 2009

Inflation: A period of exponential expansion

- Driven by energy density with negative pressure

- Happens whenever $\rho_\Lambda \, g_{\mu\nu}$ dominates cosmic $\langle \Theta_{\mu\nu} \rangle$

- ρ_Λ: scalar potentials, confining dynamics, cosmological constant

- "Inflation" can then be quite generic during cosmological evolution
- Apparently happened at the beginning ($\gtrsim 60$ e-folds) and happening right now!
- Moderate amounts of inflation easy to achieve

We entertain the possibility that the radiation dominated era may have been punctuated by brief inflationary interludes.

- We consider $T \gtrsim 1$ MeV to avoid conflict with BBN data

A Toy Model

- Simple inflationary sector: scalar ϕ and fermions f

$$\mathcal{L} \supset -\frac{1}{2}\mu_\phi^2\phi^2 + \sum_f y_f \bar{f} f \phi + \frac{1}{4!}\lambda_\phi \phi^4$$

- These fields do not need to carry any SM charges (hidden sector)

- Similar to SM; not very exotic!

- $v_\phi = \langle \phi \rangle = \mu_\phi \sqrt{6/\lambda_\phi}$; $m_\phi^2 = 2\mu_\phi^2$

- For simplicity, assume $(\phi, \forall f)$ in thermal equilibrium with SM

- For example, from a small degree of mixing via $\phi^2 H^\dagger H$

- Similar physics may arise from non-trivial (QCD-like) dynamics

- Estimates requires non-perturbative analysis (lattice)

- Thermal Potential

$$V(\phi) = V_0 + \frac{1}{4!}\lambda_\phi \phi^4 + \frac{1}{2}\left[\frac{1}{12}\left(\sum_f \mathrm{g}_f y_f^2 + \frac{1}{2}\lambda_\phi\right) T^2 - \mu_\phi^2\right]\phi^2$$

- $V_0 = 3\mu_\phi^4/2\lambda_\phi$; $V(v_\phi) = 0$
- $\mathrm{g}_f = 1(2)$ for a Majorana (Dirac) f with $m_f \lesssim T$
- Cubic term forbidden by $\mathbb{Z}_2$ at $T = 0$, and higher order for $T \neq 0$ (λ_ϕ small)

- Inflation starts when $V_0 > \rho_R(T)$ $\rho_R(T) = \pi^2 g_{\text{eff}}(T)\, T^4/30$

$$T_s \simeq \mu_\phi \left(\frac{45}{\pi^2 g_s \lambda_\phi}\right)^{1/4}$$

- Inflation ends upon phase transition (thermal mass < 0)

$$T_{pt} = \sqrt{\frac{12}{\sum_f \mathrm{g}_f y_f^2 + \lambda_\phi/2}}\ \mu_\phi$$

See also: Cohen, Morrissey, Pierce, 2008

- Inflation possible if $T_s \gtrsim T_{pt}$, implies bound on $\lambda_\phi \lesssim \lambda_c$

- For perturbative branch (N_D Dirac fermions, $y_f = y$):

$$\boxed{\lambda_c \equiv \frac{5}{16\pi^2 g_s}\left(\sum_f \mathrm{g}_f y_f^2\right)^2 \simeq \frac{N_D^2 y^4}{790} \times \left(\frac{100}{g_s}\right)}$$

$(\lambda_\phi \ll 2\sum_f \mathrm{g}_f y_f^2)$

- Quantum loops:

$$\boxed{\delta\left(\lambda_\phi\right)_f \sim -(3\sum_f y_f^4/2\pi^2)\log(\phi^2/v_\phi^2)}$$

- $\lambda_c < |\delta\left(\lambda_\phi\right)_f|$: Model is fine-tuned

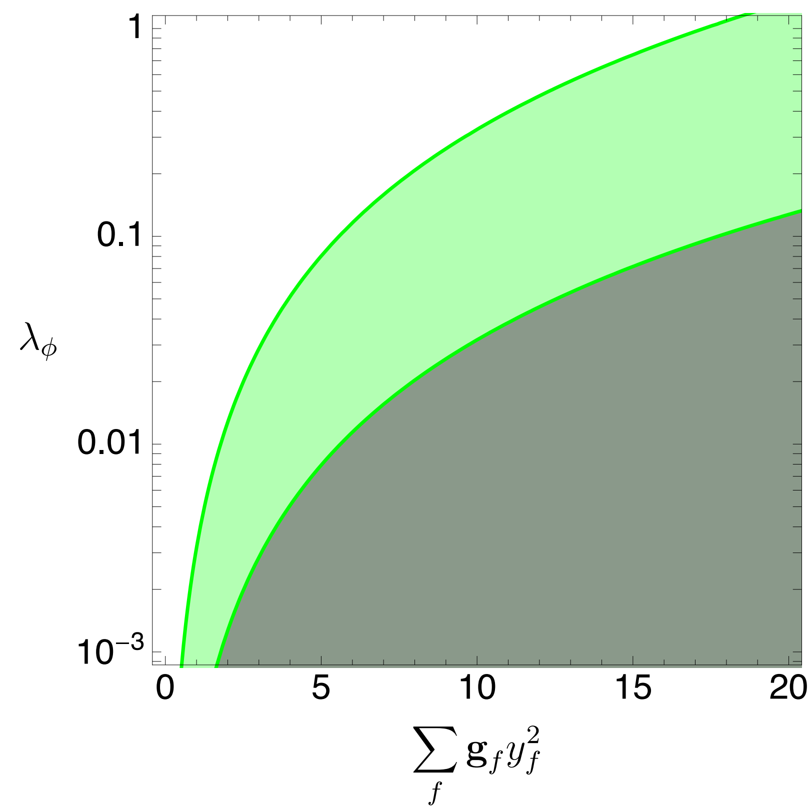
- Instability for $\lambda_\phi < 0$

⋆ Live in a long-lived meta-stable universe

⋆ Or:

- Use only scalars
- Add scalars in the UV model

\- Can be above $\sim T_s$, thermally decoupled



Green (gray) $g_s = 10\,(100)$

- Thermal potential turns off as Universe inflates, ϕ rolls to $\langle\phi\rangle$

- ϕ oscillates and decays (instantaneous), reheating to $T = T_{\rm RH}$

- Large entropy release, dilution of DM density by $\Delta = s_{\rm RH}/s_{pt}$

- Toy model:

$$\Delta_\phi = \frac{g_{\rm RH}}{g_{pt}}\left(\frac{T_{\rm RH}}{T_{pt}}\right)^3 = \left[\left(\frac{g_{\rm RH}}{g_{pt}}\right)^{1/3} + \frac{g_{\rm RH}^{1/3} g_s}{g_{pt}^{4/3}}\frac{\lambda_c}{\lambda_\phi}\right]^{3/4}$$

Δ_ϕ commensurate with fine-tuning

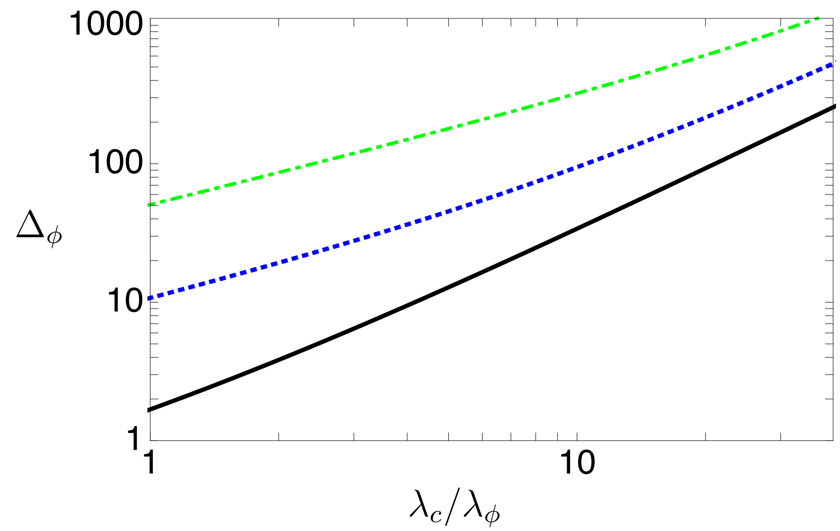
Cohen, Morrissey, Pierce, 2008

Using conservation of energy

$\rho_R(T_{\rm RH}) = \rho_R(T_{pt}) + \rho_\phi$

$\rho_\phi = \rho_R(T_s)$

$\boldsymbol{g_{\rm RH}/g_{pt} = 1, 10, 50;\ \ g_s = g_{\rm RH}}$



Thermal DM benchmark models:

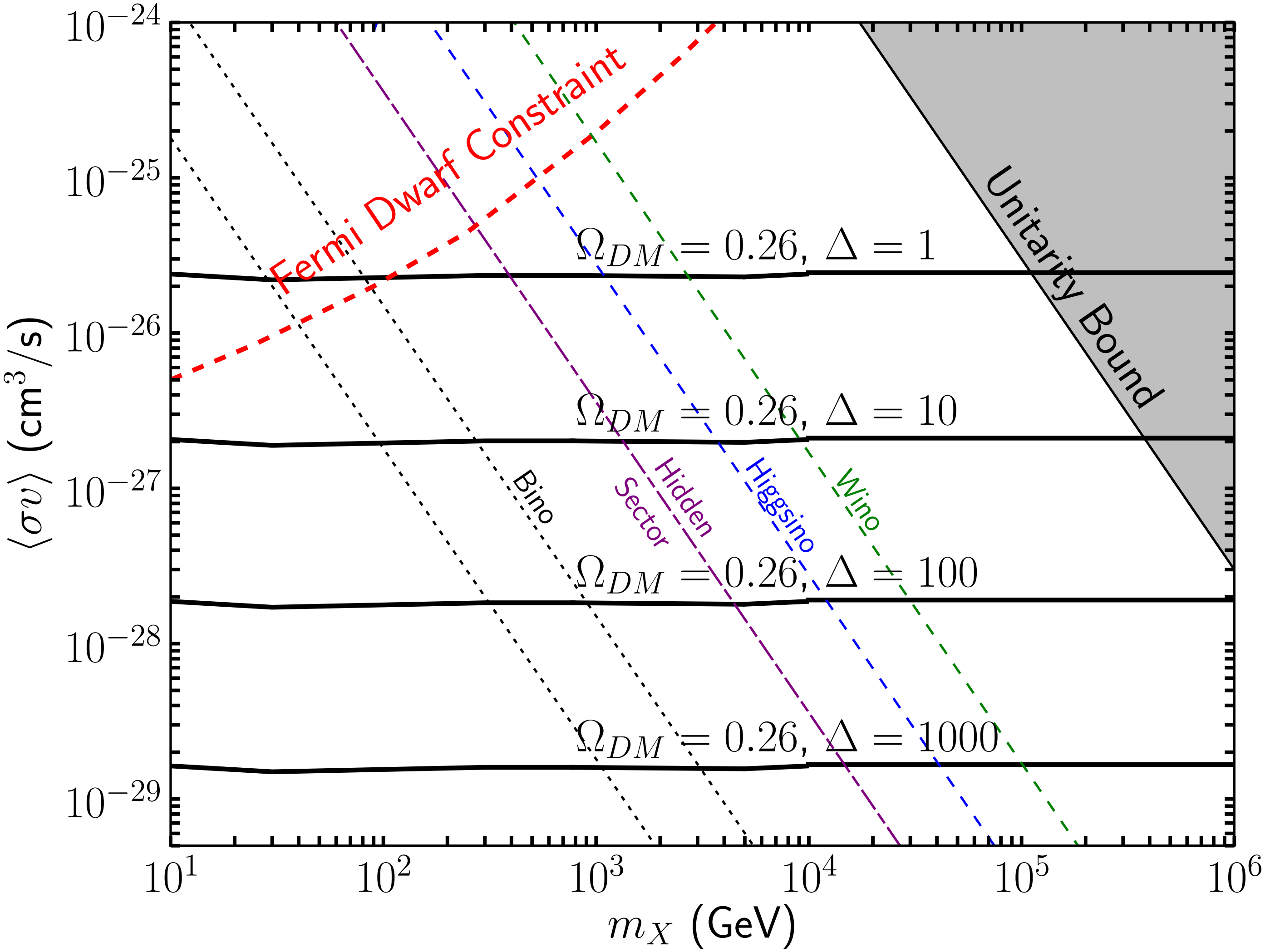
- **Pure bino**: Annihilate largely via t-channel sfermion exchange. If significantly lighter than squarks, right-handed charged sleptons will be the most efficient mediator. LHC and LEP constrain slepton masses, reducing bino annihilation cross section and thus increasing its minimal relic abundance (we will consider $m_{\tilde{l}_R}/m_\chi = 1.2,\ 3$).

- **Pure higgsino**: The μ parameter sets the masses of four quasi-degenerate higgsinos which annihilate and coannihilate in t-channel, largely to gauge boson pairs, with modest Sommerfeld enhanced annihilation at freeze-out.

- **Pure wino**: The wino mass parameter M_2 sets the masses of neutral and charged winos, which annihilate and coannihilate (largely to gauge boson pairs) via t-channel, with significant Sommerfeld enhancements at freeze-out.

- **A simple hidden sector model**: Dirac fermion DM that annihilates into a pair of light SM singlet gauge bosons; $\langle \sigma v \rangle \sim 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \left(\frac{g_X}{0.35}\right)^4 \left(\frac{400\ \mathrm{GeV}}{m_X}\right)^2$.

- Supersymmetric cross sections: Arkani-Hamed, Delgado, Giudice 2006
- Sommerfeld enhancement: Hisano, Matsumoto, Nagai, Saito, Senami, 2007
- Hidden sector model: *E.g.*, Pospelov, Ritz, Voloshin, 2008



- Unitarity: $\sigma v \lesssim 3 \times 10^{-22}$ cm^3/s$\times$ $(2J+1)\,(\mathrm{TeV}/m_X)^2 \to m_X \lesssim 120\mathrm{TeV} \times \sqrt{2J+1}$

Griest, Kamionkowski, 1990

Recent work: *e.g.*, Betre, El Hedri, Walker, 2014; Cahill-Rowley, El Hedri, Shepherd, Walker, 2015

★ Inflatable DM can cover a wide range of masses

- Very Heavy DM (disfavored by "naturalness" or unitarity)

- Distinct possibility if LHC does not uncover new physics

- Can become viable with moderate inflation

- Light DM at $\mathcal{O}$(GeV) scales

- Conflict with CMB observations, unless p-wave suppressed
Madhavacheril, Sehgal, Slatyer, 2014

- $\Delta > 1$ allows smaller $\langle \sigma\, v \rangle$ at freeze-out $\Rightarrow$ suppressed CMB era signals

- Difficult to detect via nuclear recoil, but may be probed at fixed target experiments
Batell, Pospelov, Ritz, 2009; Izaguirre, Krnjaic, Schuster, Toro, 2013

- Ultra light DM: QCD Axion with $f_{\text{PQ}} \gg 10^{12}$ GeV ($M_{\text{GUT}}, M_{\text{Planck}}$)

- Typically, a tuned misalignment angle assumed

- For $T_s \lesssim \Lambda_{\text{QCD}}$: correct density (without tuning, depending on the model)

- Potentially detectable via time varying CP odd nuclear moments
Budker, Graham, Ledbetter, Rajendran, Sushkov, 2013 (CASPEr)

★ Mild inflation could arise within some typical models

- Hidden sector DM with a $U(1)$ dark force

- Low mass "dark photons" (also possible resolution of $g_\mu - 2$ anomaly)
- $U(1)$ breaking via a dark Higgs with $\langle\phi\rangle \lesssim \mathcal{O}(\text{GeV})$
- $V(\phi, T)$ may support a brief period of inflation

- Inflation could result from hidden non-trivial dynamics

- No need for light scalars
- "Dark QCD" of twin Higgs models Chacko, Goh, Harnik, 2005
- Hidden valleys models Strassler, Zurek, 2006
- Gravity waves generated by inflation from first order phase transition

Grojean, Servant, 2006; Schwaller, 2015

Asymmetric DM: See, for example, Kaplan, Luty, Zurek, 2009

- Usually requires stronger than "weak" symmetric annihilation

- Depending on the setup, asymmetric DM can be inflatable

- Initial asymmetries, annihilation cross section, reheat

Example:

- Initial baryon and DM asymmetries larger than typical values
- T_{RH} below that of symmetric annihilation freeze-out (and asymmetry generation)
- "Weak" annihilation of symmetric population may then be sufficient

- Mild inflation could open up new avenues for asymmetric DM

- A number of variations possible, *e.g.*, "asymmetric reheating"

- Implications for baryogenesis in general

Conclusions

- Theoretical expectations of DM abundance premised on cosmological history

  - *Otherwise interesting models may be deemed disfavored with a standard history*

- Brief inflation from a "Hidden Sector" can dramatically change conclusions

- The "Inflatable DM" scenario may be realized through very simple models

  - *Can be largely decoupled from the visible sector*

- Some well-studied extensions of SM may in principle give rise to inflation

  - *Dark sector scalar condensation (massive dark photon models)*

  - *Non-trivial dynamics: Twin QCD, Hidden Valleys*

- Many typical inflatable DM scenarios require inflationary sectors below $\mathcal{O}$(GeV)

  - *Additional targets for low energy intensity frontier searches*