Asymmetric Dark MATTER

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OVERWHELMING EVIDENCE for Dark Matter

Evidence for DM OVERWHELMING

All evidence points toward

WHAT DO WE KNOW ABOUT DM? δ^r = δ^p (4) is gauge-invariant and conserved. Indeed this is the entropy per PBH, which should remain constant as long as the universe expands adiabatically (e.g. see Mukhanov et al. 1992). The associated perturbations, generated in this way are isocurvature(or entropy) perturbations, as the curvature at large scales is not (immediately) affected by

• Not modified gravity \mathbf{L} and begin \mathbf{L} and \mathbf{L} vot modified \mathbf{r} models and the data points does not in distribution that the models are models are the models $\overline{}$

- BBN --> not free baryons
- MACHO searches $+Lya$ \rightarrow not bound baryons
- CMB + LSS + Bullet --> not neutrinos as DM

which is also a lower bound on the matter linear power bound on the matter linear power bound on the matter line

of PBHs, Poisson fluctuations and radiation, respectively. Since δ^p in Eq.(1)is observable and constant, one would

^S [≡] ^δPBH [−] ³

the formation of compact objects at small scale.

leads to the following power spectrum

 \mathbf{p} is given in Eq.(2). While \mathbf{p}

PCDM(k) = T ²

^Tiso(k) = ³

[∆]PCDM # ⁹MPBH (1 + ^zeq)²

trum as both P^p and

gives the power offset

 \mathbb{R} we are the present day \mathbb{R} Dark Matter (CDM), the overdensity of CDM is given by

δCDM(k) = Tiso(k)δi, (5) + Tiso(k), (5)

conclude that the quantity

WHAT DO WE KNOW ABOUT DM?

\bullet CMB + LSS -clustering properties

• Weakly interacting

The shaded regions are disfavored by constraints from the Bullet Cluster observations on self-

- With us -- direct detection
- With itself -- halo shape bounds

• Cold

• Which probe is the most constraining? $r \cdot r$ The thermally averaged momentum transfer per unit time is

$$
d\langle \delta p_X^2 \rangle/dt = \sum_{b=e,p} n_b \int d^3v_B d^3v_X f(v_B) f(v_X) d\Omega_* \frac{d\sigma_{Xb}}{d\Omega_*} v_{rel} \delta p_X^2
$$

HOW DARK IS DARK MATTER? HOW DARK IS DARK the constraints we discuss here strongly disfavor such a model as the explanation for these velocity dependence of the scattering cross-section. For example, the Rutherford Scattering irreducible coupling to the photon (and charged SM particles), and, more importantly, the costruction of DM off DM off DM of DM off DM off DM of DM off DM off DM off DM off DM of DM of DM of DM of DM
Photon is the photon is a photon is a photon is a photon in the photon is a photon in the photon is a photon o

• Coupling at CMB epoch is most where mass constraining constraining and DM mass, vrel is the Scattering angle in the scattering angle in the Scattering angle in the scattering angle is the scattering angle in the scattering angle in the scattering angl \sim 1. \sim 1. \sim 1. \sim 1. • Coupling at CMB epoch is most cross-section of DM off DM through a photon is dd
XX $\frac{1}{2}$ most

term. If, on the other hand, the dark photon is massless, kinetic mixing between the dark

(θ∗/2), (1)

signals. In either case, we denote the charge of the DM as !e.

How Dark is Dark MATTER?

• Direct detection is also (potentially) highly constraining

THEORIES OF DARK MATTER

• Axions

- Solve Strong CP
- Correct density of high scale axions via selection

• WIMPs

- Naturally obtain correct density via freeze-out
- Connected to weak scale
- Chemical Potential Dark Matter
	- Naturally obtain correct density via chemical potential
	- Connected to weak scale

Baryon and DM Number Related?

 -20

10

 $x = m/T$

100

Baryon and DM Number Related?

• Accidental, or dynamically related?

 Mechanism $n_{DM} \approx n_b$ Experimentally, $\Omega_{DM} \approx 5\Omega_b$

 $m_{DM} \approx 5 m_p$

Nussinov, Hall, Gelmini, Barr, Chivukula, Farhi, D.B. Kaplan

Chemical Potential Dark **MATTER**

Mechanism $n_{DM} \approx n_b$ Experimentally, $\Omega_{DM} \approx 5\Omega_b$ $m_{DM} \approx 5 m_p$

Use EW sphalerons?

SU(2) carrying dark fields! Barr, Chivukula, Farhi; D.B. Kaplan

Chemical Potential Dark **MATTER**

Mechanism $n_{DM} \approx n_b$ Experimentally, $\Omega_{DM} \approx 5\Omega_b$ $m_{DM} \approx 5 m_p$

Use EW sphalerons?

LEP and Precision EW tend to result in problematic models

A simple prescription: ASYMMETRIC DM

- Essential idea is to use higher dimension operators to transfer the asymmetry between sectors
- Avoid problems of precision EW

Luty, Kaplan, KZ '09

ASYMMETRIC DM

symmetric flat directions can also carry DM number. In

Since the baryon and DM asymmetries are produced si-

multaneously, we refer to this mechanism as AD "coge-

equilibrium dynamics, while the DM density arises from

tion, albeit at a low temperature, and chemical equilib-

rium distributes the initial n^X asymmetry among all X

charged states which are sufficiently long-lived to freeze

out. An example of such a state is the lightest X number

charged particle (LXP), which is often meta-stable, but

will in general decay later to B − L charged SM states

via OB−LOX. In this paper, we will assume that the

lightest supersymmetric particle (LSP) carries X num-

ber and it thus attains an asymmetric relic abundance

from the initial X asymmetry. Moreover, because the

lightest observable supersymmetric particle (LOSP) and

the LXP are typically long-lived, this class of theories

generally in Asymmetric DM [3], which relates a present

day asymmetry in baryons and DM via similar symmetry

considerations. However, while in [3] the baryon asym-

metry was assumed initially and then shared with the

DM, in the present work the baryon and DM asym-

accommodates an interesting collider phenomenology.

thermal freeze out.

ASYMMETRIC DM

1. Transfer lepton or baryon asymmetry to DM through higher dimension operator

2. Have asymmetry transferring operator decouple before DM becomes non-relativistic (Otherwise allows DM asymmetry to washout)

3. Annihilate away symmetric abundance of DM $n_X - n_{\bar{X}} \approx 10^{-10} n_X$

ANNIHILATING THERMAL abundance

 $n_{DM} \sim T^3 \to 10^{-10} T^3$

Matter Anti-Matter

Dark

ANNIHILATING THERMAL abundance we of the party of $ABUNDANCE$ TINC THEDMAI

It is also possible that the interactions Eq. (2.1) decouple below the electroweak

. (2.14)

MANY EXAMPLES OF ASYMMETRIC DM

Standard Model

Multiple resonances?

$M_p \sim 1$ GeV \vert Could be complex

Dark forces and dark Higgs mechanism

Constructing ADM **SECTORS**

- Difficult? Highly constrained? Predictive?
- Generate GeV scale dynamically
- Dark photon and dark Higgs provide efficient annihilation mechanism

DYNAMICAL GENERATION OF "LOW" SCALE

• All that's needed is a weak coupling between dark sector and weak scale

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DYNAMICAL GENERATION OF "LOW" SCALE

Cohen, Phalen, Pierce, KZ

$W = \lambda S T H' + S^2 L H$ + Kinetic Mixing $U(1)_X$ $U(1)_d$ $+1-1$ $+1-1$

DYNAMICAL GENERATION OF "LOW" SCALE % &= 0 [21, 23].¹ There is an accidental global symmetry under which *S* = +1 and constitutes the DM. and \$*H*! % &= 0 [21, 23].¹ There is an accidental global symmetry under which *S* = +1 and THE STABLE STATE STATE. THE *NAI*

and hypercharge, respectively, with kinetic mixing #. In the absence of large soft terms in

the hidden sector, this model gives rise to a symmetry breaking pattern where \$*S*% = \$*T*% = 0

and \$*H*!

A Simple Model

- Unbroken global $U(1)_X$ --> stable sterile DM candidate
- Approximately supersymmetric; a workable spectrum

DESTRUCTIVE POWER OF DARK PHOTINOS

MANY QUESTIONS REMAIN

- How to generate the asymmetry? Cheung, KZ '11
- How to dynamically generate DM mass and light states in hidden sector?
- Cosmological implications -- is the asymmetry erased? Impact on astrophysical objects? McDermott, Yu, KZ'12 McDermott, Yu, KZ, '11
- Direct and indirect detection of DM?

Lin, Yu, KZ, '11

Astrophysical Implications

- DM does not annihilate
- It can accumulate in the center of stars

 χ

- Notable case: neutron stars
- Elastically scatter, come to rest in core
- High density!

ADM, Black Hole and Neutron Stars

McDermott, Yu, KZ '11

- Scalar case can lead to BH formation
- DM continues to accumulate until there are enough that they self-gravitate
- OR, they first form Bose-Einstein condensate and then self-gravitate
- Once they self-gravitate, they can collapse to form a BH!

BH Formation W/O BEC BH FORMATION W/C inside a sphere with radius R, they have zero point energy they have zero point energy in the uncertainty of th principle in the relativistic limit. The relativistic limit. The typical energy for a boson in a boson in a sp FQ E ∼ − TI\ R + 1 R. (1988).
R. (1988).
R. (1988). (1988). (1988). (1988). (1988). (1988). $\begin{array}{c} \n\textbf{D} \cup \textbf{F} \cap \textbf{D} \cup \textbf{D} \end{array}$ Note that since we consider scattering off only one nucleon, this scattering can be regarded BH FORMATION W/O

After attaining thermal equilibrium, captured DM particles drift to the center of the start of the center of th
After of the start of the start to the start of the start

scalar ADM follows the thermal distribution in the neutron star. This is only true when tth

10.6 km 2 | 1.44 M

Mⁿ

McDermott, Yu, KZ, '11 Again and the radius cancels in the radius cancels in the critical limit. In this case, the Chandrasekhar limit is calculated in the Chandrasekhar limit is case, the Chandrasekhar limit is case, the Chandrasekhar limit is

$$
E \sim -\frac{GNm^2}{R} + \frac{1}{R}
$$
 $N_{Cha}^{boson} \simeq \left(\frac{M_{pl}}{m}\right)^2 \simeq 1.5 \times 10^{34} \left(\frac{100 \text{ GeV}}{m}\right)^2$

^σmax = 2.¹ [×] ¹⁰[−]⁴⁵ cm²

 $N_X \simeq 2.3 \times 10^{44} \left(\frac{100 \text{ GeV}}{m_X}\right) \left(\frac{100}{10^3}\right)$ m GeV/cm^3 / χ 2.1 \times 10⁻⁴⁵ ((100 GeV) (100 GeV) $N_X \simeq 2.3 \times 10^{44} \left(\frac{100 \text{ GeV}}{m_X}\right) \left(\frac{\rho_X}{10^3 \text{ GeV/cm}^3}\right) \left(\frac{100 \text{ GeV}}{2.1}\right)$ m_X \bigwedge | ρ_X $10^3 \text{ GeV}/\text{cm}^3$ \bigwedge σ_{XB} 2.1×10^{-45} cm² $N_X \simeq 2.3 \times 10^{44} \left(\frac{100 \text{ GeV}}{m_X} \right) \left(\frac{\rho_X}{10^3 \text{ GeV/cm}^3} \right) \left(\frac{\sigma_{XB}}{2.1 \times 10^{-45} \text{ cm}^2} \right) \left(\frac{t}{10^{10} \text{ years}} \right)$

- Rapidly accumulate enough DM to exceed Chandrasekhar number obeys Bose-Einstein statistics will experience gravitational collapse much more readily than than the DM-neutron scattering cross section. Since bose-Einstein section. Since bose-Einstein smaller Chandrasekhara experience a particle that obeys Fermi-Dirac statistics. \sim 11 decays to a black hole and decays the captured DM particles collapse to a black hole and destroy the captured DM particles collapse to a black hole and decays the captured DM particles collapse to a black hole and holy accumulate enough Divi to eed Chandrasekhar number limits on bosonic DM. In this work, we have a limit of the United Stronger limits on \mathbf{D} ∴ 11 \mathbf{L} 1 GeV, the degeneracy effect on the capture process is \mathbf{L} GeV, the capture process is \mathbf{L} • Rapidly accumulate er exceed Chandrasekhar number 2.1 × 10−45 cm2
- Rapidly thermalize \mathbf{D}_{max} : $\mathbf{11}_{\text{max}}$ of $\mathbf{1}$ number $\mathbf{1}$ in a neutron star surpasses the surpasses of $\mathbf{1}$ is a neutr Rapidly dictinanze $\frac{1}{4}$ $\frac{1}{4}$ $\frac{1}{4}$ $\frac{1}{4}$ \bullet Rapidly thermalize $r = r \cdot 11 \cdot 11$ $1Z$.
1980 - Από το Παρακολογίου (1980), ο Παρακολογίου (1980), ο Παρακολογίου (1980), ο Παρακολογίου (1980), ο Παρ
1980 - Αντιλιάνδρος το Παρακολογίου (1980), ο Παρακολογίου (1980), ο Παρακολογίου (1980), ο Παρακολογίου (198

Now we discuss bosons. Similar to the fermion case, the gravitational collapse occurs when

particles are relativistic. But the bosonic system is significantly different from the fermionic

principle in the relativistic limit. Therefore, the typical energy for a boson in a sphere of

 $A_{\rm eff}$ and the radius cancels in the critical limit. In this case, the Chandrasekhar limit is case, the $C_{\rm eff}$

• Then need to self-gravitate! host neutron star. Therefore, observations of old neutron stars can be used to constrain \bullet Then need to self-oravitatel $\mathbf C$ the DM. Now we estimate the DM mass scale below which the evaporation is relevant. Since $\mathbf C$ T_{beam} mead to celf-gravitatel then in

$$
N_{self} \simeq 4.8 \times 10^{41} \left(\frac{100 \text{ GeV}}{m_X}\right)^{5/2} \left(\frac{T}{10^5 \text{ K}}\right)^{3/2}
$$

4

ρ
B = 1.4 × 1.4 × 1.4
S = 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4 × 1.4

Nboson

BH Formation W/BEC DU L 2 2π 3 JRMAI 195 Ka λ the ground state and form a BEC. relatively low central temperature as indicated by Eqs. (16) and (17) . star. In this way, the introduction of more DM particles into the thermal radius essentially forces the formation of a BEC ground state. Before and after the mini black hole forms, the neutron star continuously captures ADM particles. All of the captures ADM particles will of the capture of the c

, and the set of \mathcal{L} , and \mathcal{L}

ADM particles follow an isothermal distribution with a radius rth. As discussed above, the

#3

 \mathbf{r} , $\mathbf{r} \in \mathbb{R}$, $\mathbf{r} \in \mathbb{R}$, $\mathbf{r} \in \mathbb{R}$

\$³/² 4πr³

th

where we have used Eq. (22). The total number of captured ADM in the total number of captured ADM in the total

For T , the BEC for T , the BEC forms and the number of T and T are condensed ground state in the condensed ground state is T

! ¹.⁰ [×] ¹⁰³⁶ # ^T

\$3

, some of captured ADM particles will go

, (27)

. (28)

. (29)

• With BEC, DM becomes dense fast! to the ground state and form a BEC. This condition can be satisfied for a neutron star with \bullet With BF(11) M be Γ , the BEC forms and the BEC forms and the number of particles in the condensed ground state is the condensed ground state is Γ $S_n = S_n$ petulites delise that: b VVIIII DEC, DIVI DECOHIES DENSE IDSU.

To a 2000

where \tilde{R} is the Riemann-Zeta function, \tilde{R} is the Riemann-Zeta function, \tilde{R} and \tilde{R}

 \mathbb{R}^2 , \mathbb{R}^2 , \mathbb{R}^2

likely it is that the captured ADM will form a BEC in the neutron star, we can estimate the

where we have used Eq. (22). Therefore, if the total number of captured ADM in the total number of captured ADM in

state itself may become self-gravitating. The critical number for the self-gravity of the DM

$$
N_X^0 = N_X \left[1 - \left(\frac{T}{T_c}\right)^{3/2} \right] \simeq N_X - 1.0 \times 10^{36} \left(\frac{T}{10^5 \text{ K}}\right)^3 \qquad r_{BEC} = \left(\frac{3}{8\pi G m_X^2 \rho_B}\right)^{1/4} \simeq 1.5 \times 10^{-5} \text{ cm} \left(\frac{100 \text{ GeV}}{m_X}\right)^{1/2}
$$

• Have to worry about evaporation \blacksquare and ve to worry about evap requiring the zero point energy equal the gravitational energy This is much smaller than rth, which indicates a much higher DM density. Thus, the ground Haye to worry about evaporation riave to worry about evaporation

is given by ^λ^s = (1/2)(γ+1)/(2γ−2)[(5 [−] ³γ)/4][−](5−3γ)/(2γ−2) = 0.25 [40].

$$
\frac{dM_{BH}}{dt} \simeq 4\pi\lambda_s \left(\frac{GM_{BH}}{v_s^2}\right)^2 \rho_B v_s - \frac{1}{15360\pi G^2 M_{BH}^2} + \left(\frac{dM_{BH}}{dt}\right)_{DM}
$$

$$
\left(\frac{dM_{BH}}{dt}\right)_{DM} \simeq 2.3 \times 10^{36} \text{ GeV/year} \left(\frac{\rho_X}{10^3 \text{ GeV/cm}^3}\right) \left(\frac{\sigma_{XB}}{2.1 \times 10^{-45} \text{ cm}^2}\right)
$$

critical ADM number as

neutron star is larger than 1.0 \times 1.0 \times 1.0 \times 1.0 \times 1.0 \times

ADM, Black Hole and **NEUTRON STARS**

F igure 2. Regions (colored) excluded by the nearby pulsars $\mathcal{I}/\mathcal{I}/\mathcal{I}/\mathcal{I}$

Friday, April 27, 2012

LIGHT DARK MATTER $m_X < 10$ GeV

- What are the cosmological constraints?
- Assume thermalized hidden sector
	- Relic density + LHC
	- Halo shapes
	- CMB and ADM

Halo Shapes

- Need new light states
- New light states can mediate scattering

Figure 3: Lower limit on the mediator mass from combining relic density and DM self-interaction constraints. We show the case of a vector mediator; the result for a scalar mediator is similar and is given in Eq. (32). We consider DM self-interaction constraints from Bullet cluster observations, elliptical cluster shapes, and elliptical halo shapes. The dashed red line indicates the bound on the mass if CMB bounds are also applied, assuming efficiency f ≈ 1.

If g^f is less than the bound given in Eq. (26), the DM sector can have a different temperature from the SM sector and the standard freezeout calculation can be modified in a number of ways. We have checked

CMB: Light DM Prefers an Asymmetry 1.1115 1.1115 1.1115 1.1115 1.1115 1.1115 1.1115 1.1115 1.1115 TABLE I: Constraints on the annihilation parameter pann and on the cosmological parameters that are more degenerate with it, i. e. the scalar spectral index ns, the scalar spectral index ns, the dark matter density $\mathcal{L}(\mathcal{M})$ data and WMAP7+ACT data. The constraints on pann are upper bound at 95% c.l., which for the other parameters w the marginalized value and their errors at 68% c.l. The last two columns reports the value of the cosmological parameters in the standard ΛCDM case with no annihilation, as found by the WMAP7 team [24] and the ACT team [25].

 \mathcal{F}_1 , which denotes the DM annihilation constraints on the DM annihilation and mass for asymmetric data matter \mathcal{F}_2 and s-wave annihilation. We show constraints for various values of r = r[∞] = ΩX¯ /ΩX, the anti-DM to DM ratio at the present time. The shaded region (blue) is excluded by the WMAP7 data, with different shades corresponding to different r∞. Along the horizontal contours of constant r are the values of !σv" where the correct relic density can be obtained for an efficiency factor f = 1. The turnover around m^X ∼ 10 GeV comes from the drop in SM degrees of freedom when the universe has temperature ∼ 1 GeV. The solid red line is the intersection of the WMAP7 and relic density contours: it indicates the minimum !σv" needed to obtain the observed relic density and satisfy CMB

[−]0.⁰⁵⁶ 2.214 ± 0.050

100 ± 0.057 ± 0.057 ± 0.057

DIRECT DETECTION

• Couplings (freeze-out)

sions. Constraints from past experiments and from neu-

trino emission by SN 1987A are presented in Section III.

In Section IV, we describe the five new experimental sce-

narios and estimate the limiting backgrounds. We con-

clude in Section V with a summary of the prospects for

new experiments. More detailed formulas, which we use

to calculate our expected search reaches, and a more de-

tailed discussion of some of the backgrounds, are given

II. THE PHYSICS OF NEW *U*(1) VECTORS IN

• Mediator masses (halo shapes)

0.01 0.1 1

mA'!GeV

0.01 0.1 1

DIRECT DETECTION

- Couplings (freeze-out)
- Mediator masses (halo shapes)

Figure 4: (Left) Nucleon scattering through a vector mediator. The green shaded region indicates the allowed parameter space of direct detection cross sections. The lighter green region imposes the bound of thermal coupling

Oscillating ADM WE ADM ν¯ oscillations can be neglected for the parameters of interest). It is important that the

- Any violation of X number can lead to dark - anti - dark oscillations, e.g. $m_M X^2$ on of X number can lead to the Hubble rate at all times. rative doctriation, c.g. n_{M+1}
- What are the conditions for this to happen? t_{max} discussed in section 4.1, for generating large cosmic ray fluxes at the section 4.1, for generating large cosmic ray fluxes at the section 4.1, for generating large cosmic ray fluxes at the section 4.1, ϵ e contaition In order to verify that DM does not oscillate too soon, we briefly review the formalism for treating particle oscillations in the expanding universe [36, 37, 38]. Consider a generic

Oscillation time scale $m_M > H$ Scattering time scale $\frac{dY_{\beta}}{dz}$

 $m_M > H$ *dz* = $\frac{z}{2}\left\langle P_{\alpha\rightarrow\beta}\left(t\right)\right\rangle \frac{\Gamma_{\alpha}}{H_{1}}$ $(Y_{\alpha} - Y_{\beta})$

The χ Majorana mass, *µ*χ, leads to DM particle/antiparticle oscillations χ ↔ χ˜. Similarly,

the DM-neutrino mass mixing, *participal mass mixing, and neutrino oscillations, χ ντ, με το προσ*

oscillations do not turn on until after DM annihilations decouple, because otherwise the xinger DM annihilatio
The xinger DM annihilations decouple, because otherwise the xinger of the xinger of the xinger of the xinger o

asymmetry, resulting from leptogenesis, is erased. As a consequence, we shall now see that α

discuss how these oscillations can modify the cosmological history of this model.

• True results more subtle where *P*^α→^β (*t*) is the probability that α oscillates into β after time *t*, Γ^α is the total inthe more subtle $\mathbf x$ and $\mathbf x$ is an arbitrary more subtle

Halkowski, Rudermann, Volansky '10 **Direlli, Panci, Servant, Zaharijas '11** Cohen, KZ '09 Buckley, Profumo '11

are in equilibrium whenever *P*Γ (*H* and are frozen out whenever *P*Γ) *H*. The general

Boltzmann Eq from FIRST PRINCIPLES BOLTZMANN EQ FROM In the Appendix, we derive the appendix, we derive the derivers we derive the device of the density matrix principles using the deriversity of the deriversity of the deriversity matrix equation from first principles using 1 $\overline{\mathbf{N}}$ BULIZMANN EQ FROM THRST LATHERS TO BE THAT THE SPECIES Ψ mentum k. The diagonal elements F¹¹ and F²² correspond to occupation numbers of X and XC states, respectively, respectively, which the off-diagonal components governors governors governors and

Lfermion =

2ω^k

Tulin, Yu, KZ '12 Tulin, Yu, KZ $'12$

m^M m^X

 \mathbb{R}^2

^M m²

k (* 1892)

2s + 1

$$
\frac{\partial \mathcal{F}_k}{\partial t} - Hk \frac{\partial \mathcal{F}_k}{\partial k} = -i [\mathcal{H}_k, \mathcal{F}_k] + C_k [\mathcal{F}]
$$

\n
$$
X \quad X^C
$$

\n
$$
M = \begin{pmatrix} m_X & m_M \\ m_M & m_X \end{pmatrix} \qquad \mathcal{H}_k = \sqrt{k^2 + M^2} = \omega_k \mathbb{1} + \frac{m_X \delta m}{\omega_k} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}
$$

 $\delta m \sim m_M > H$ $\sum_{i=1}^{n} \frac{1}{n}$ $\delta m \sim m_M > H$

^Ψ¯ (i∂/ [−] ^M)^Ψ ⁺ ^Lint , M ⁼

"flavor-blind."

^kbk#

 \mathbb{P}^1

The model now appears to be that of two species Ψ1,² that mix via flavor off-diagonal mass

none quilibrium field theory. For a spatially homogeneous and isotropic expanding Universe, and isotropic expan
Theory. For a spatially homogeneous and isotropic expanding Universe, and is one of the spatial development of

In the Appendix, we derive the density matrix equation from first principles using

terms.

Boltzmann Eq from FIRST PRINCIPLES BOI TZMANN FO FROM BOLTZMANN FQ ⊥IVUM $\frac{1}{\sqrt{2}}$ mx $\frac{1}{\sqrt{2}}$ # THE DRINCIPLES expected during and after freeze-out. The usual prescription is to be usual prescription in the single flavor case is to be usual prescription in the single flavor case is to be usual present for the single flavor case is

neq

neq

$$
n \equiv (2s+1) \int \frac{d^3k}{(2\pi)^3} \mathscr{F}_k = \left(\begin{array}{c} n_{11} & n_{12} \\ n_{21} & n_{22} \end{array}\right) \,, \quad \bar{n} \equiv (2s+1) \int \frac{d^3k}{(2\pi)^3} \mathscr{\bar{F}}_k = \left(\begin{array}{c} n_{22} & n_{12} \\ n_{21} & n_{11} \end{array}\right)
$$

$$
\frac{\partial n}{\partial t} + 3Hn = -i[\mathcal{H}_0, n] - \frac{\Gamma_{\pm}}{2} [O_{\pm}, [O_{\pm}, n]] - \langle \sigma v \rangle_{\pm} \left(\frac{1}{2} \{n, O_{\pm} \bar{n} O_{\pm}\} - n_{\text{eq}}^2\right)
$$

Y and the other while the other fields unteractions unteractions unter sensitive interactions H⁰ = Coherence broken only through flavor sensitive interactions , α , α , β , α , β , $\$

 $+$ 3Hn $+$ 3Hn $-$

%

^H0, n&

 $-$

%

 $\mathbb{E}[\mathcal{E}]$

%

 $\mathcal{L}(\mathcal{L})=\mathcal{L}(\mathcal{L})$

'1 (

n, O[±] n O¯ [±]

)

 $\frac{1}{2}$

eq*

. (20)
Andre Stadt Britain
Andre Stadt Britain

this case has O+.

Boltzmann Eq from FIRST PRINCIPLES BOI TZMANN FO FROM BOLTZMANN FQ ⊥IVUM $\frac{1}{\sqrt{2}}$ mx $\frac{1}{\sqrt{2}}$ # THE DRINCIPLES expected during and after freeze-out. The usual prescription is to be usual prescription in the single flavor case is to be usual prescription in the single flavor case is to be usual present for the single flavor case is

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$$

$$
\frac{\partial n}{\partial t} + 3Hn = -i[\mathcal{H}_0, n] - \frac{\Gamma_{\pm}}{2} [O_{\pm}, [O_{\pm}, n]] - \langle \sigma v \rangle_{\pm} \Big(\frac{1}{2} \{n, O_{\pm} \bar{n} O_{\pm}\} - n_{\text{eq}}^2\Big)
$$

 $X \mapsto \mathcal{X} \mapsto$

 $\mathcal{L}(\mathcal{L})=\mathcal{L}(\mathcal{L})$

'1 (

 2 Doly flavor blind interactions source annihilations: where the transforms source all finders controls. Flavor blind interactions source annihilations; havoi bilitu litteractions source difficulturations. Only flavor blind interactions source annihilations:

 $+$ 3Hn $+$ 3Hn $-$

%

^H0, n&

 $-$

%

 $\mathbb{E}[\mathcal{E}]$

%

this case has O+.

$$
\frac{1}{2}\{Y, O_{+}\bar{Y}O_{+}\} = \begin{pmatrix} Y_{11}Y_{22} + Y_{12}Y_{21} & Y_{11}Y_{12} + Y_{12}Y_{22} \\ Y_{21}Y_{11} + Y_{22}Y_{21} & Y_{11}Y_{22} + Y_{12}Y_{21} \end{pmatrix}
$$

$$
\frac{1}{2}\{Y, O_{-}\bar{Y}O_{-}\} = \begin{pmatrix} Y_{11}Y_{22} - Y_{12}Y_{21} & 0 \\ 0 & Y_{11}Y_{22} - Y_{12}Y_{21} \end{pmatrix}
$$

First, we consider the annihilation term; expanding the anticommutator, we have⁴

The two types of interactions couple very differently to Yij . However, in the absence of

coherence (Y12, Y²¹ → 0), both interactions give the same (usual) result proportional to

YX IXIX . The distinction between flavor-blind and flavor-blind and flavor-sensitive is only relevant in the d

If oscillations turn on after freeze-out, one naï α is annihilation to be reactivated annihilation to be reactive

n, O[±] n O¯ [±]

)

 $\frac{1}{2}$

eq*

. (20)
Andre Stadt Britain
Andre Stadt Britain

. (23b)

3 exposure to the control of

neq

Numerical Results

- Vector interactions
- But scattering off
- Oscillations turn on, no depletion of DM density

Numerical Results

Numerical Results

 $V_{xx} + V_{-}$

- Scalar interactions
- Oscillations turn on

 $Flavor$ *sensitive* $\kappa = 0$

 $\mathbf{F}^{\dagger}_{\pm}$

Posc

 10^{-17}

1000

 \sim

 10^{-12}

 10^{-7}

Rate (eV)

0.01

1000

 $10⁸$

 10^{8}

1000

 \sim

Friday, April 27, 2012

Flavor ϵ *sensitive,* ϵ ϵ ϵ 10⁻⁴

New Avenues for **BARYOGENESIS**

• B and DM number violation simultaneously

 $W = Xu^c d^c d^c$

- Coupled oscillators
- Generates equal and opposite B and DM number -- cogenesis!

 $n_{B-L} = -n_X$

COGENESIS IN THE EARLY UNIVERSE the Hubble parameter because supersymmetry is broken by the vacuum energy of the universe during inflation. Indeed, Hubble dependent potential terms should IINIVERSE and D-terms. Here Vsoft will vary explicitly in time via ken by the vacuum energy of the universe during inflation. Indeed, Hubble dependent potential terms should be present as a consequence of interactions between the

• To see how it works, map to simple mechanical analog: pseudo-particle in 2-dimensions 20 asymmetry at the end of inflation $\mathbf{1}$ − To see now it works, map to s mochanical analogue poqueda n mechanical analog. Pseudo-pa namics. The presence of these Hubble induced interac t pless that the scalar that the scalar than t fields are critically damped during the inflationary phase 1CIe 11 condense it would man to gi **CELL is required in order to see how it works, map to si** \sim system on the system on \sim 1 and 2 mechanical analog: pseudo-particle in $\frac{1}{2}$ \mathbf{S} \int e [12, 13].

$$
\phi = \frac{1}{\sqrt{2}} r_{\phi} e^{i\theta_{\phi}}
$$

the collider phenomenology of these theories in Sec. V.

$$
n_{\phi} = j^0 = i(\phi \phi^{\dagger} - \phi^{\dagger} \phi) = r_{\phi}^2 \theta_{\phi}
$$

where V^F and V^D arise from supersymmetric F-terms

where VF and VD arise from supersymmetric F-terms and VD arise from supersymmetric F-terms are supersymmetric

be present as a consequence of interactions between the

scalar fields and the inflaton induced by Planck scale dy-

scalar fields and the inflaton induced by Planck scale dy-

namics. T he presence of these Hubble induced interac-

tions along with Hubble friction implies that the scalar

 $\mathcal{G}(\mathcal{G})$ is possible that b $\mathcal{G}(\mathcal{G})$ is possible that b $\mathcal{G}(\mathcal{G})$

roll away from the origin and be stabilized at φ-breaking

 α tachyon is induced for α during inflation, causing α

roll away from the origin and be stabilized at φ-breaking

 $W_{\rm eff}$ showled also expect a contribution to the potential μ

• B-L and X asymmetry: torque on mechanical analog o B-I and X acymmotry torque $t_n = \frac{1}{2}$ particle in the dimension $\mathbf{1}$ is the Hubble parameter. The dimensionless parameter $\mathbf{1}$ rameters a^φ and b^φ are generated by the couplings of the field φ to the goldstino and the inflaton, respectively. In p D dina A di mechanical analog MSS during inflation as a system of coupled pseudorameters a^φ and b^φ are generated by the couplings of the field φ to the goldstino and the inflaton, respectively. In $\mathcal{G}_\mathcal{G}$ is possible that b $\mathcal{G}_\mathcal{G}$ is possible that b $\mathcal{G}_\mathcal{G}$ α tachyon is induced for α during inflation, causing α

Cogenesis in the Early UNIVERSE

- Two ingredients for successful Affleck-Dine Cogenesis
	- Stabilization: non-zero B-L and X vevs

• Torque: non-zero angular momentum

Cogenesis -- Natural for ADM! symmetry carried by MSSM fields and a U(1)X symmetry carried by MSSM fields and a U(1)X symmetry carried by MS
A U(1)X symmetry carried by MSSM fields and a U(1)X symmetry carried by MSSM fields and a U(1)X symmetry carri COGENESIS -- NATURAL operator where OB−^L and O^X are gauge invariant products of chiral superfields which can relightest supersymmetric particle (LSP) carries X num-COGENESIS -- NATURAL from the initial X asymmetry. Moreover, because the ing the S-term of this transition, the ADM! the LXP are typically long-lived, theories of the LXP are typically long-lived, theories of theories of theori served baryon asymmetry nor a viable DM candidate. Distributed baryon asymmetry nor a viable DM candidate. Dis
Distributed baryon asymmetry nor a viable DM candidate. Distributed by the DM candidate. Distributed by the DM both, albeit through unrelated mechanisms. The baryon is the baryon of the baryon of the baryon in the baryon o
The baryon is the baryon of the baryon in the baryon of the baryon of the baryon is the baryon of the baryon o $\mathbb{L}_\mathcal{P}$, the resulting asymmetry has $\mathcal{P}_\mathcal{P}$ vanishing B − L + X number, so $\begin{array}{c} \n\text{[The image shows the image shows a function of the image with a function of the image.}\n\end{array}$

particular, we consider a setup with the usual U(1)B−^L

 \mathcal{O}_{B-L} $\mathcal{O}_{B-L}\mathcal{O}_X$ $\mathcal{O}_{B-L} \;=\; LH_u, LLE^c, QLD^c, U^cD^cD^c$ $\frac{1}{2}$ \mathcal{O}_{E} is a gradient different dynamic dynamics, \mathcal{O}_{E} is an arbitrary \mathcal{O}_{E} . t_{D-D} freezes out. $\mathcal O_{B-L}$ = LLE^c , QLD^c , $U^c D^c D^c$ and $O_x = X, X²$

OB−LOX, (1) OB−LOX,

vides neither enough CP video to generate the observer enough CP violation to generate the observer and obe-controlled the observer and t

 $\mathcal{O}_X = X, \; X^2$ \mathcal{O}_Y $\overline{X^2}$ multaneously, we refer to this mechanism as AD "coge-

via OB−LOX. In this paper, we will assume that the

to generate B and X as you and X and X as you as you and X as you are the the-the-the-the-the-the-

 \mathcal{A}_max will see, the DM sector is the DM sector is the DM sector is the DM sector is the DM sector infla-

lightest observable supersymmetric particle (LOSP) and

the LXP are typically long-lived, the LXP are typically long-lived, theories of the class of the class of the
Theories of the class of the cla

 \mathcal{L}_X

, (2)

Cheung, KZ '11

- Affleck-Dine works by utilizing flat directions with non-zero <B-L> Where OB are gauge in the OX and \mathcal{L}_B \bullet Affleck-Dine works this convention, OB number directions with non-ANCCHOID WILL HOID \det considerations. However, while in [3] the baryon asym $mR_{\rm I}$ DM, in the present work the baryon and DM asym- $B-L \times \Lambda$ \bullet Affleck-Dine works by utilizing $\frac{1}{2}$ dine otions with non zone \overline{R} I. Symmetric directions with hold zero $>$ D-L/ nesis." The relation in Eq. (3) can be modified in the \mathbf{t} additional operators which separately violately viol the standard model (SM). In particular, the SM provides neither enough CP violation to generate the observed baryon asymmetry nor a viable DM candidate. $fflack$ -Dine works by utilizing $flat$ $\frac{1}{100}$ org present B and the resulting and the resulting asymmetry as a set of the resulting asymmetry as \sim
- Note there is a symmetry which generates \mathbf{S} spectively. In general, we are interested in a spectrum of \mathbf{S} Note the δ CHCLAICS $\mu_{B-L} - \mu_X \neq 0$ breaking effects proportional to the Hubble parameter parameter parameters proportional to the Hubble parameter
The Hubble parameters parameters parameters parameters and the Hubble parameters and the Hubble parameters and ● Note there is a symn values in the early universe. As the universe cools, these which generates $-n_{B-L} = n_X \neq 0$. metries are generated dynamically and simultaneously. $fry ||(1)_P$ $f(x)$ $J = \sqrt{D - D + A}$ particular, we consider $\frac{1}{100}$ s in the calculate by a symmetry $U(1)_{B-}$ lectively as the DM sector. Typically, there exists an tion, albeit at a low temperature, and chemical equilibrium distributes the initial n^X asymmetry among all X charged states which are sufficiently long-lived to freeze out. An example of such a state is the lightest X number On the other hand, supersymmetry can accommodate both, albeit through unrelated mechanisms. The baryon asymmetry is set by new CP violating phases and out of ote there is a symmetry $U(1)_{B-}$ $U(1)_{B-L+X}$
- At low temperature, symmetry breaks when $\mathcal{O}_{B-L}\mathcal{O}_X$ decouples, separately freezing in the asymmetries whom 0 charge decoupled conomitaly when $\mathcal{O}_{B-L}\mathcal{O}_X$ decouples, separately $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ $\frac{1}{(1)}$ where the Ox are and other are and other the original products of the original products of the contracts of the α $U(1)_{P-I+Y} \rightarrow U(1)_{P-I}$ e aks \mathbf{z} via OB−LOX. In this paper, we will assume that the lightest supersymmetric particle (LSP) carries X number and it the unit of the intervals and it the set of th equilibrium dynamics, while the DM density arises from In this paper we unify the production of baryon and DM number through a simple extension of the Affleck-Dine mechanism [1, 2] which exploits the fact that super- $\lim_{n \to \infty} \mathcal{O}_v$ decouples separately nesis." The relation is the relation in the relation in the model presence of additional operators which separately violate B − L and X.

 $U(1)_{B-L+X} \to U(1)_{B-L} \times U(1)_X$ $\mathcal{O}(1)B-L+X \rightarrow \mathcal{O}(1)B-L$ $f(1)_X$

As we will see the DM see, the DM sector is the DM sector is the DM sector is the DM sector is the DM sector i

breaking effects proportional to the Hubble parameter proportional to the Hubble parameter parameter parameter
The Hubble parameter parameter parameter parameter parameter parameter parameter parameter parameter parameter

operator

the form

ter (DM) are key pieces of evidence for physics beyond

symmetric flat directions can also carry DM number. In

DM: WHERE ARE WE?

• The Nature of the DM remains one of the most

important open problems in physics

- It's an auspicious time
- Indirect detection -approaching thermal cross-sections in some mass regions \mathbf{m} e put tension on ~10 GeV models with

thermal relic density of the state of
The state of the state of th

DM: WHERE ARE WE?

- Direct detection reaching the Higgs pole. Ton scale experiments should surpass it
- In a position to rule out or observe "standard" WIMP

$$
\sigma_n \sim 10^{-45-46} \text{ cm}^2
$$

DM: WHERE ARE WE?

- DM anomalies?
- Other candidates
- Asymmetric Dark Matter gives rise to a distinctive phenomenology to explore

