THE DARK MATTER/BARYOGENESIS CONNECTION

OR

ASYMMETRIC DARK MATTER

PARTICLE PHYSICS AND COSMOLOGY 2011

CERN

STEPHEN WEST

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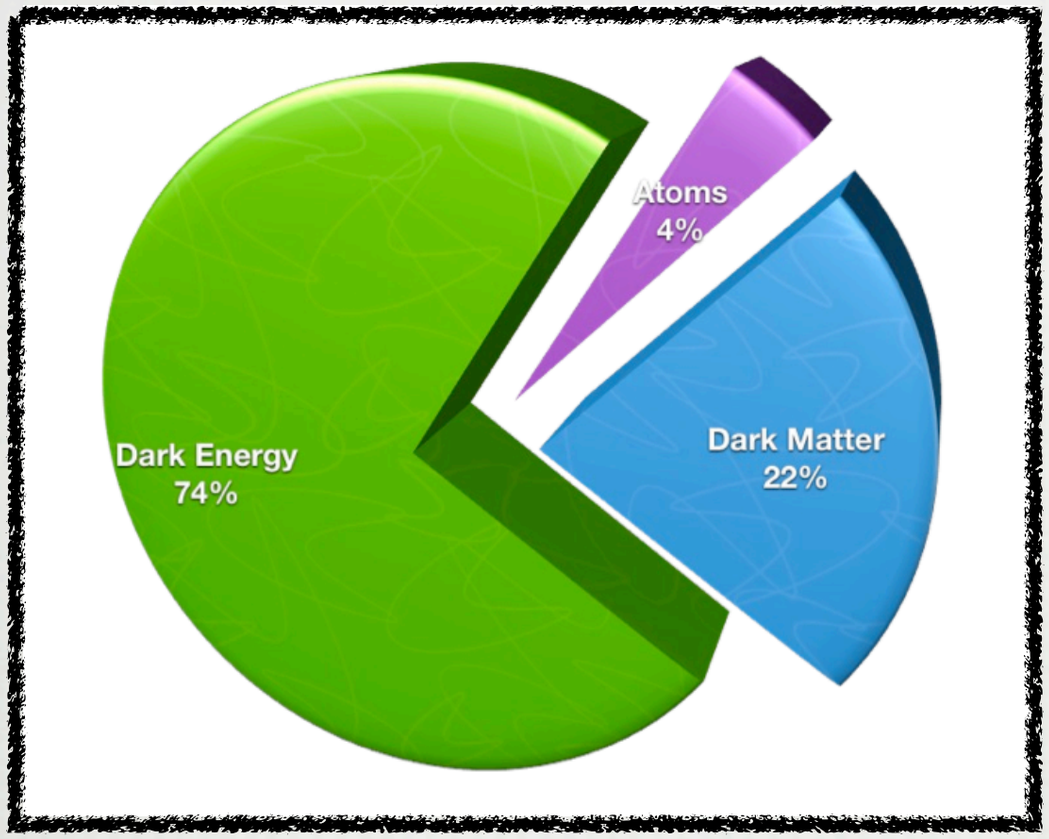
OUTLINE

- ☐ INTRODUCTION
- ☐ CHARACTERISTICS OF ASYMMETRIC DM
- ☐ MODELS OF ASYMMETRIC DM
- ☐ SIGNALS/EXPERIMENTAL CONSEQUENCES
- ☐ CONCLUSIONS

INTRODUCTION

- COMPOSITION OF THE UNIVERSE:



$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

- USUALLY THESE TWO NUMBERS ARE DETERMINED BY INDEPENDENT DYNAMICS

Ω_{dm} BY WIMPS

Ω_b BY BARYOGENESIS/ LEPTOGENESIS

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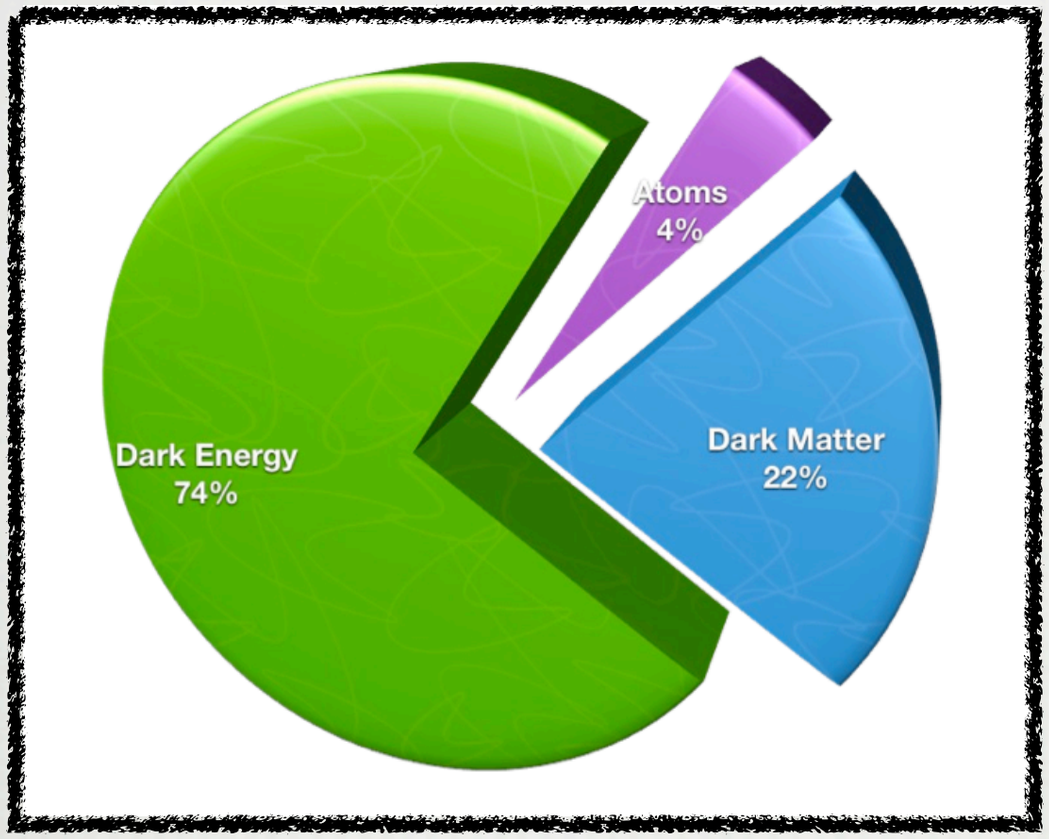

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- TAKE SERIOUSLY THE CLOSENESS OF THESE VALUES - INVESTIGATE DYNAMICS THAT LINK THE TWO...

...LEADS TO IDEAS OF ASYMMETRIC DM

- INTRODUCE AN ASYMMETRY IN DM NUMBER DENSITY

$$\boxed{n_{dm} - \overline{n}_{dm} \neq 0}$$

- INTRODUCE AN ASYMMETRY IN DM NUMBER DENSITY

$$n_{dm} - \overline{n}_{dm} \neq 0$$

- USE DYNAMICS TO RELATE THIS ASYMMETRY IN DM TO THAT IN BARYONS

$$n_{dm} - \overline{n}_{dm} \propto n_b - \overline{n}_b$$

- LEADING TO

$$\frac{\Omega_{dm}}{\Omega_b} \sim \frac{(n_{dm} - \overline{n}_{dm})m_{dm}}{(n_b - \overline{n}_b)m_b} \sim C\frac{m_{dm}}{m_b}$$

- THE VALUE OF C DEPENDS ON THE DETAILS OF THE DYNAMICS CONNECTING DM AND BARYONS...SEE LATER

ASYMMETRIC DARK MATTER BASICS

- CANDIDATES: COMPLEX SCALARS AND DIRAC FERMIONS (+USUAL REQUIREMENTS FOR DM, NO EM OR COLOUR CHARGE ETC) - CANNOT USE MAJORANA

- NEED A SHARED QUANTUM NUMBER, E.G. A CHARGE ASSOCIATED WITH A GLOBAL U(1)

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BARYONS HAVE CHARGE q, DARK MATTER HAS CHARGE Q

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ASSUME ANNIHILATIONS OF DM ANTI-DM EFFICIENT $n_{dm} \gg \overline{n}_{dm}$

THEN, $n_{dm} = C n_b$ WHERE $C = q/Q$

$$\Rightarrow \quad \frac{\Omega_{dm}}{\Omega_b} \sim C \frac{m_{dm}}{m_b}$$

SEE E.G. HOOPER, MARCH-RUSSELL, SMW (2004)

ASYMMETRIC DARK MATTER
A (PARTIAL) HISTORY

- 80'S AND 90'S

COSMIONS AS ~5 GEV ADM: GELMINI, HALL, LIN (1987); GIUDICE, RABY (1990)

WEAK SCALE ADM: NUSSINOV (1985); BARR, CHIVUKULA, FARHI (1990), BARR (1991); DB KAPLAN (1992); THOMAS (1995);

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- 00'S

  WEAK SCALE ADM: FUJII, YANAGIDA (2002); FARRAR, ZAHARIJAS (2004), HOOPER, MARCH-RUSSELL, SMW (2004); KITANO, LOW (2004); AGASHE, SERVANT (2004); TYTGAT (2006).

- MANY RECENT DEVELOPMENTS - SORRY IF I MISS SOME NAMES

  MURAYAMA, RATZ, KAPLAN (DE), LUTY, ZUREK, COHEN, CAI, FRANDSEN, SARKAR, SCHMIDT-HOBERG, PHALEN, SANNINO, DAVOUDIASL, MORRISSEY, SIGURDSEN, TULIN, HABA, MATSUMOTO, BUCKLEY, RANDALL, CHUN, GU, LINDNER, SARKAR, ZHANG, BLENNOW, DASGUPTA, FERNANDEZ-MARTINEZ, MCDONALD, GRAESSER, SHOEMAKER, VECCHEI, IMINNIYAZ, DREEZE, CHEN, HALL, MARCH-RUSSELL, SMW...MANY MORE

GENERATING THE ASYMMETRY: CO-GENESIS VS SHARING

- CO-GENESIS
  - ASYMMETRIES IN DM AND BARYONS GENERATED SIMULTANEOUSLY
  - DM GENESIS/BARYOGENESIS ALL WRAPPED UP IN ONE MECHANISM
  - POTENTIAL TO TEST BOTH DM GENESIS AND BARYOGENESIS

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- TRANSFERRING PRIMORDIAL ASYMMETRY
  - ASSUME PRE-EXISTING ASYMMETRY (EITHER IN BARYONS OR DM)
  - ASYMMETRY TRANSFERRED AND SHARED BETWEEN SECTORS
  - OPERATORS FOR TRANSFER COULD BE TESTABLE
  - GENERALLY HARD TO TEST GENERATION OF INITIAL ASYMMETRY
  - MAY LOOSE THE LINK BETWEEN GENERATION OF BARYONS AND DM

CO-GENESIS EXAMPLES - MAKING AN ASYMMETRY IN B AND DM

- E-WEAK BARYOGENESIS (EWB) KAPLAN DB (1992)
  - EXTRA $U(1)_{DM}$ SYMMETRY WITH WEAK ANOMALY
  - STABLE PARTICLES CHARGED UNDER $U(1)_{DM}$ WILL BE PRODUCED IN EWB WITH BARYONS
  - DM STATES CHARGED UNDER $SU(2)_L$
  - MUST ALSO HAVE LIGHT MASSES (SUB 45GEV)

$\Rightarrow$ SIMPLE MODEL RULED OUT BY COUPLINGS TO Z
(DIRECT DETECTION AND INVISIBLE Z-WIDTH

SUBSET OF RELATED: THOMAS, DAVOUDIASL, MORRISSEY, SIGURDSON, TULIN, HALL, MARCH-RUSSELL, SMW, CHUN, BLENNOW, ALLAHVERDI, FALKOWSKI, RUDERMAN, VOLANSKY, ZUREK, CHEUNG

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  - DECAYS VIOLATE CP AND PRODUCE ASYMMETRY IN DM AND LEPTON/BARYON NUMBER

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- ASYMMETRIC FREEZE-IN...MORE LATER

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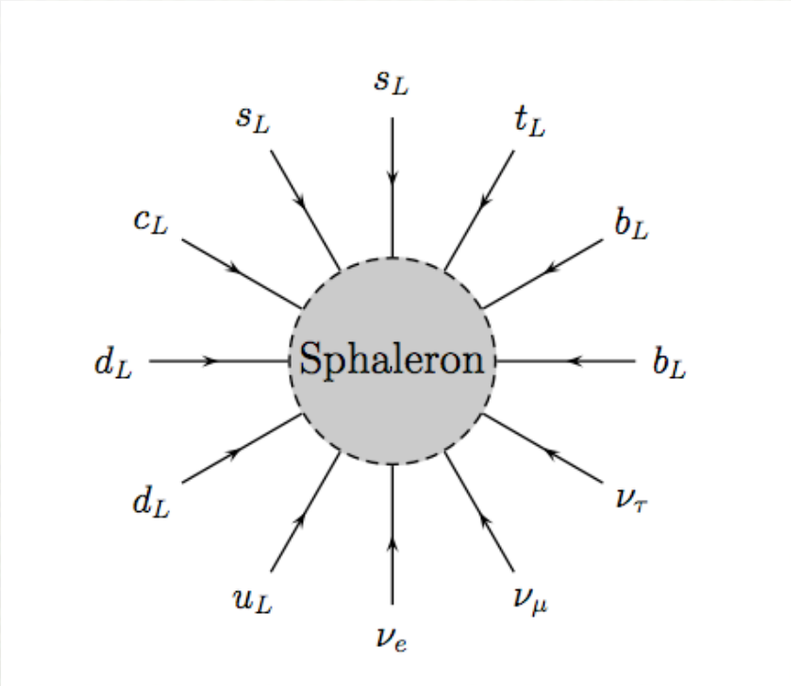
IMPORTANT ASIDE ON THE ELECTROWEAK ANOMALY/SPHALERONS

- B+L VIOLATING PROCESS, CONSERVES B-L EFFICIENTLY OPERATE AT $T_C \sim 100\,\mathrm{GeV}$ (BELOW THIS TEMP EXPONENTIALLY SUPPRESSED)

- CAN EFFECTIVELY BE THOUGHT OF AS MULTI-PARTICLE VERTEX INVOLVING $SU(2)_L$ CHARGED STATES



TAKEN FROM BUCHMULLER, HEP-PH/0204288

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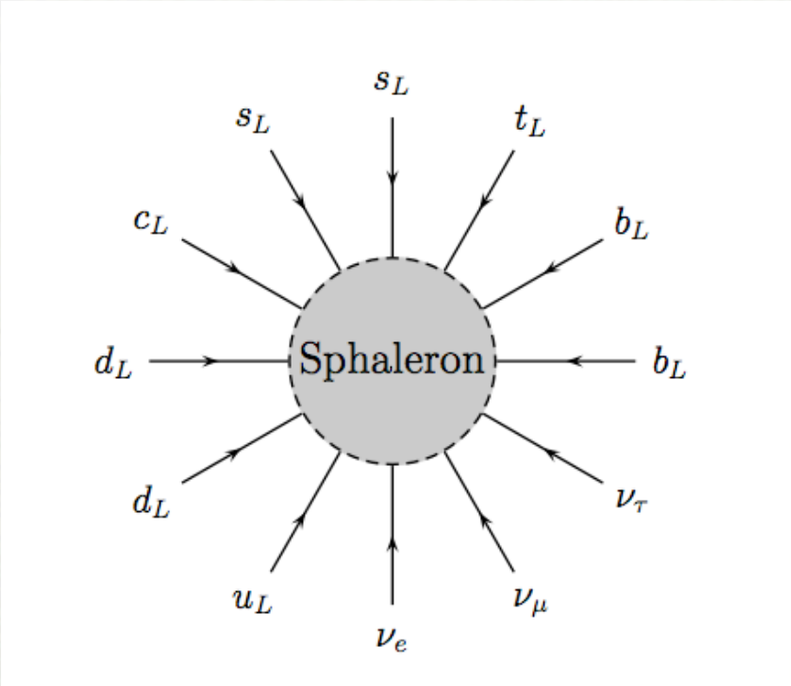

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- MUST HAVE ASYMMETRY IN B-L NUMBER BEFORE SPHALERONS REPROCESS ASYMMETRY

- E.G. IF $L \neq 0$, $B=0$ SPHALERONS WILL REPROCESS L ASYMMETRY INTO B NUMBER

- IF $B \neq 0$, $L \neq 0$ BUT $B-L=0$, E-WEAK ANOMALY WILL WASH OUT THE ASYMMETRY

TRANSFER OF PRE-EXISTING ASYMMETRY

- ☐ PRE-EXISTING ASYMMETRY IN BARYON OR DM SECTOR
- ☐ ASYMMETRY NEEDS TO BE TRANSFERRED (ASSUMING NOT CHARGED UNDER $SU(2)_L$)

SEE E.G. KAPLAN, LUTY, ZUREK (2009)

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- ☐ REQUIRE OPERATORS THAT LEAD TO INTERACTIONS CAPABLE OF TRANSFERRING ASYMMETRY

E.G.

$$\boxed{\mathcal{L} \sim \frac{1}{M^{d-4}} \mathcal{O}_{dm} \mathcal{O}_{sm}}$$

d = DIMENSION OF COMBINED OPERATOR

$\mathcal{O}_{sm}$ AND $\mathcal{O}_{dm}$ INDIVIDUALLY CHARGED UNDER GLOBAL $U(1)$, BUT COMBINED OPERATOR IS INVARIANT UNDER $U(1)$

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- ☐ IF ASYMMETRY EXISTS IN EITHER SM OR DM SECTOR, THESE OPERATORS WILL SHARE THIS WITH THE OTHER SECTOR

- ☐ OPERATORS MUST BE IN THERMAL EQUILIBRIUM ABOVE $T = m_{dm}$

- ☐ HOWEVER, THEY MUST DROP OUT OF THERMAL EQUILIBRIUM ABOVE DM FREEZE-OUT OTHERWISE THEY WILL WASH OUT THE ASYMMETRY

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SHARING EXAMPLE KAPLAN, LUTY, ZUREK (2009)

- GLOBAL SYMMETRY USED IS $U(1)_{B-L}$
- AT HIGH T, A B-L ASYMMETRY IS GENERATED
- TRANSFER OPERATORS PRESERVE B-L, E.G.

$$\boxed{\Delta W = \frac{1}{M}\overline{X}^2 L H_u}$$

THE X FIELD HAS $L = \frac{1}{2}$

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- WHEN IN EQUILIBRIUM, THIS OPERATOR TRANSFERS AN L ASYMMETRY INTO THE DM X SECTOR, THIS LEADS TO

$$2(n_X - \overline{n}_X) \approx (n_L - \overline{n}_L)$$

KAPLAN, LUTY, ZUREK (2009)

- ASSUMING TRANSFER PROCESS DROPS OUT OF THERMAL EQUILIBRIUM ABOVE E-WEAK PHASE TRANSITION

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- FINALLY BY INVERTING $\frac{\Omega_X}{\Omega_b} \sim \frac{X}{B}\frac{m_X}{m_b}$ A PREDICTION FOR

$$m_X \approx \frac{B}{X}\frac{\Omega_X}{\Omega_b} \approx 11\,\mathrm{GeV}$$

POSSIBLE MASSES

SIMPLEST CASES, THERE ARE TWO MASS REGIONS

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CORRECT RATIO FOR $m_{dm} \sim 1\,\mathrm{TeV}$

ASYMMETRIC FREEZE-OUT

- IN ALL THESE MODELS A LARGE ABUNDANCE OF SYMMETRIC DM MUST BE ANNIHILATED AWAY
- FREEZE-OUT OPERATES AS USUAL VIA ANNIHILATIONS BUT NOW THE DM HAS AN ASYMMETRY - THIS CHANGES THE FREEZE-OUT DETAILS

FOR MORE DETAILS SEE IMINNIYAZ, DREES, CHEN (1104.5548); GRAESSER, SHOEMAKER, VECCHI, (1103.2771)

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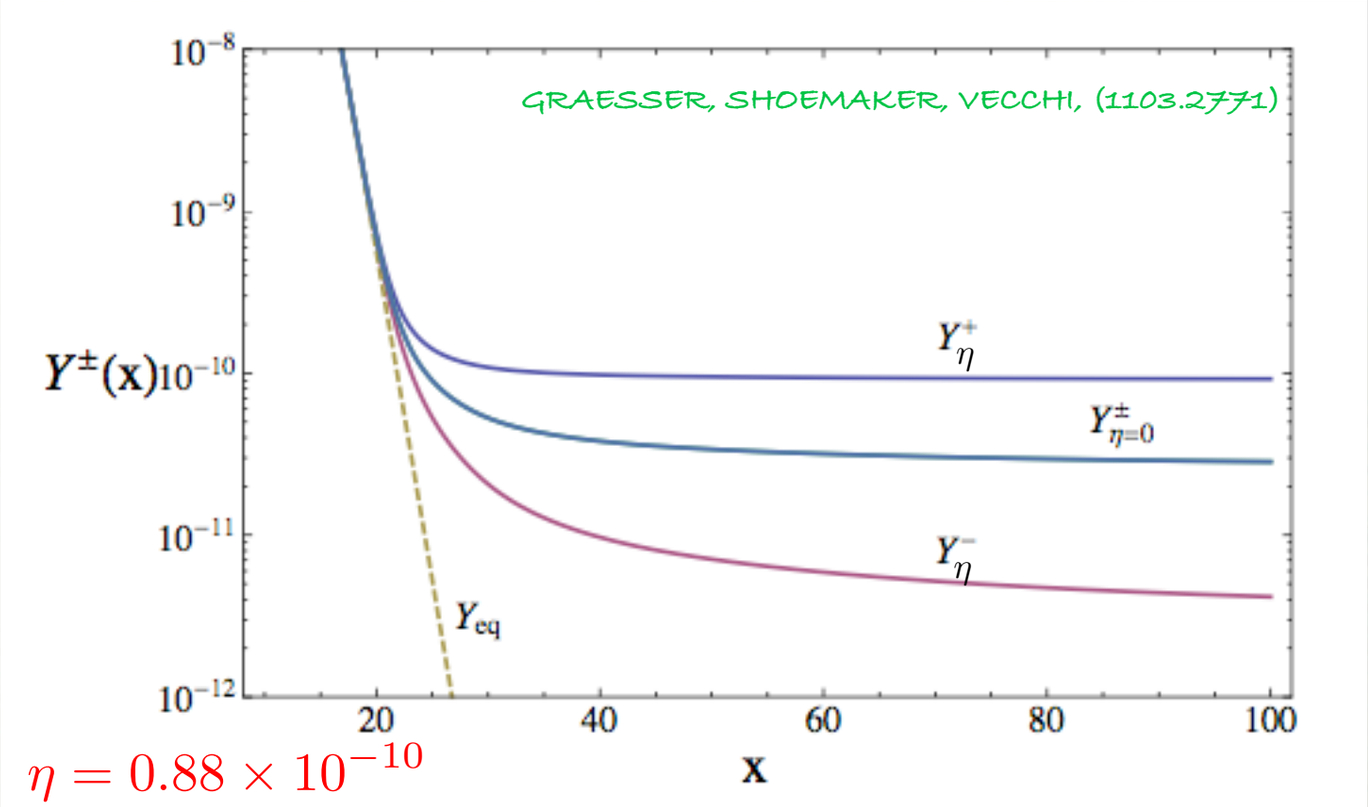
ASYMMETRIC AND SYMMETRIC DM FREEZE-OUT, WITH THE SAME ANNIHILATION RATE AND MASS

ANTI-PARTICLES ANNIHILATE EFFICIENTLY

PARTICLES ARE DEPLETED LESS THAN SYMMETRIC CASE

ACTUALLY NEED LARGER ANNIHILATION RATE, APPROX FACTOR OF 2-3 LARGER



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AN ASIDE ON FREEZE-IN

- FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED TO THE THERMAL BATH, CALL THEM FIMPS (FEEBLY INTERACTING MASSIVE PARTICLES)

HALL, JEDAMZIK, MARCH-RUSSELL, SMW, ARXIV:0911.1120

- OPERATORS GENERATING COUPLING CAN BE RENORMALISABLE OR NON-RENORMALISABLE.

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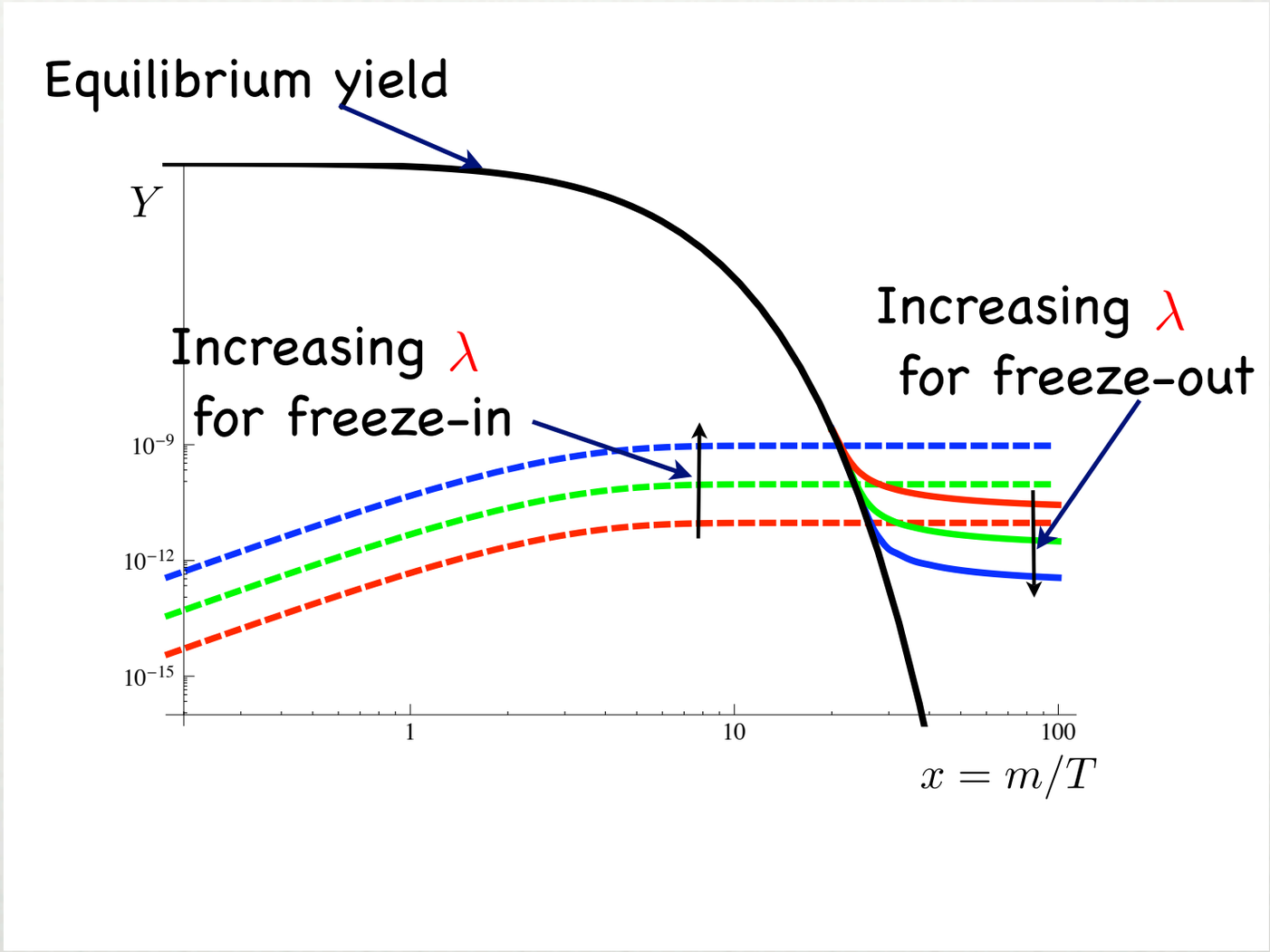
SIMPLE PICTURE FOR A RENORMALISBLE FEEBLE COUPLING

PRODUCTION IS IR DOMINATED

FUNCTION OF COUPLINGS AND MASSES



ASIDE ON FREEZE-IN CONT...

- CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS

$$L_Y = \lambda \psi_1 \psi_2 X \qquad m_{\psi_1} > m_X + m_{\psi_2}$$

ASIDE ON FREEZE-IN CONT...

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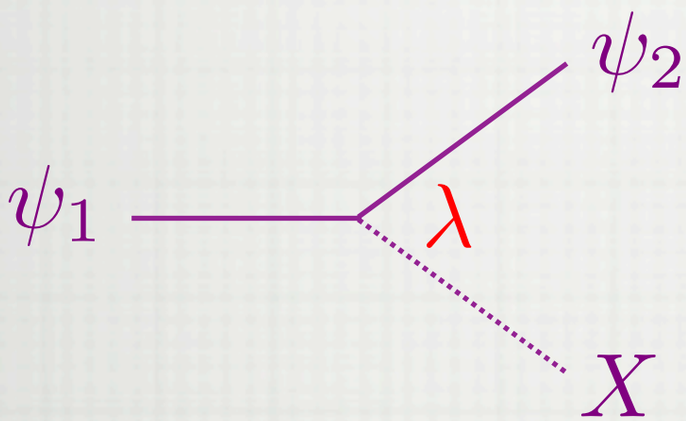


$$\Omega_X h^2 \sim 10^{24} \frac{m_X \Gamma_{\psi_1}}{m_{\psi_1}^2}$$

ABUNDANCE GOES AS λ^2

CORRECT ABUNDANCE

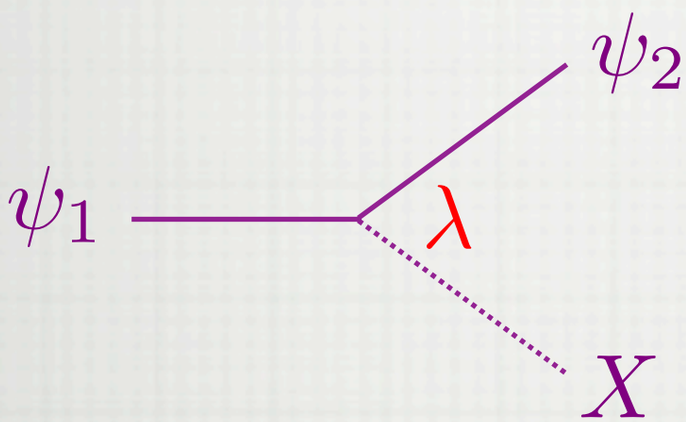
FOR $m_X \sim m_{\psi_1}$

$\Rightarrow \lambda \sim 10^{-11}$

ASIDE ON FREEZE-IN CONT...

- CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS

$$L_Y = \lambda \psi_1 \psi_2 X \qquad m_{\psi_1} > m_X + m_{\psi_2}$$



$$\Omega_X h^2 \sim 10^{24} \frac{m_X \Gamma_{\psi_1}}{m_{\psi_1}^2}$$

ABUNDANCE GOES AS λ^2

CORRECT ABUNDANCE

FOR $m_X \sim m_{\psi_1}$

$\Rightarrow \lambda \sim 10^{-11}$

- INTERESTING POSSIBILITIES FOR NEW DM GENESIS MECHANISM
- GIVES LONG LIVED DECAYS AT LHC, IMPLICATIONS FOR BBN
- WHAT ABOUT ASYMMETRIC DM IN THIS SCENARIO?

ASYMMETRIC FREEZE-IN

HALL, MARCH-RUSSELL, SMW, ARXIV:1010:0245

- FREEZE-IN PROCESSES COULD BE CP- AND B-L NUMBER VIOLATING
- THESE PROCESSES ALREADY CONTAIN OUT-OF-EQUILIBRIUM PROCESSES - FIMP IS NOT IN THERMAL EQUILIBRIUM
- ASYMMETRY COULD BE PRODUCED THROUGH INTERFERENCE OF TREE AND LOOP-LEVEL PROCESSES

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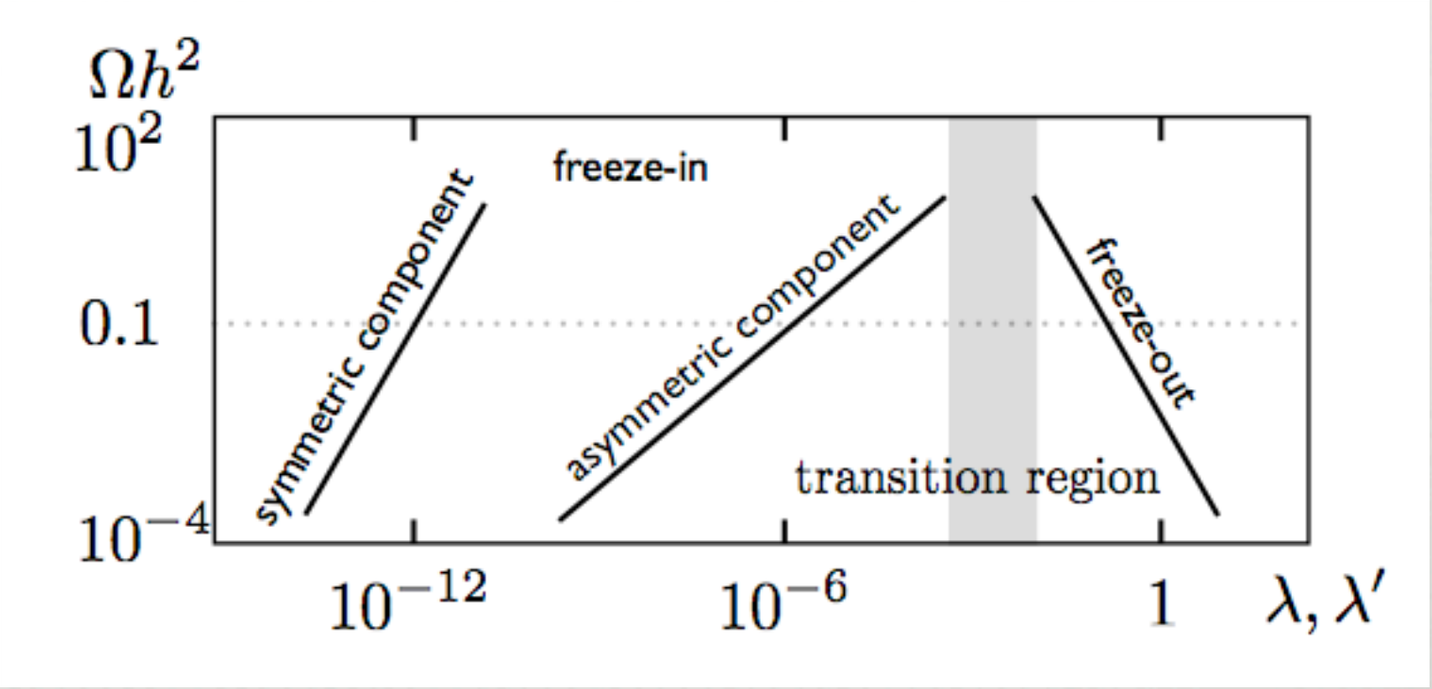
- INITIALLY IT WAS THOUGHT THAT AN ASYMMETRY AT λ^2 COULD BE GENERATED. TURNS OUT, LOWEST ORDER IS λ^3 HOOK, ARXIV:1105:3728

DEPENDING ON THE MODEL, ASYMMETRIC FREEZE-IN MAY ALLOW "FULL" PROBE OF BARYOGENESIS - DM CONNECTION



EXPERIMENTAL SIGNATURES FOR ADM

- ☐ LHC SIGNALS
- ☐ INDIRECT DETECTION SIGNALS
- ☐ IMPLICATIONS FOR BBN AND BEYOND
- ☐ CONSTRAINTS FROM THE SUN
- ☐ DIRECT DETECTION

LHC SIGNALS

- MANY ASYMMETRY TRANSFER OPERATORS CAN LEAD TO LONG LIVED PARTICLES AT THE LHC
- FOR EXAMPLE, IN SUSY MODELS THE LOSP CAN BE LONG LIVED IF IT HAS A SMALL DECAY WIDTH TO THE DM STATE THROUGH A CONNECTOR OPERATOR

$$\Delta W = \lambda L H_u X$$

$$\chi^- \to l^- X$$

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- LOSP IN THIS SIMPLE EXAMPLE IS A CHARGINO
- GIVES CHARGED TRACK PLUS LEPTON PLUS MISSING
- NOTE: EACH SUSY EVENT WILL END IN THIS DECAY - OVERALL EVENT IS TWO LEPTONS PLUS MISSING (WITH TWO CHARGE TRACKS)
- DECAY LENGTH OF THE CHARGINO DEPENDS ON SCENARIO, BUT COULD BE

$$c\tau \sim \text{ primary vertex - many meters}$$

INDIRECT SIGNALS

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  - USE FURTHER CONNECTOR OPERATORS IN ANNIHILATIONS DIRECTLY, THESE MUST NOT TRANSFER AN ASYMMETRY BUCKLEY, 1104.1429

E.G.

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    CONSTRAINTS FROM DIRECT DETECTION, COLLIDERS ETC
  - USE ADDITIONAL STATES IN DARK SECTOR - FREEZE-OUT IN THIS SECTOR TO SOME VERY LIGHT OR UNSTABLE STATE, WHICH DECAYS BACK TO SM SECTOR SEE E.G. HALL, MARCH-RUSSELL, SMW, ARXIV:1010:0245
  - POSSIBLY VERY INTERESTING SCENARIO - CONSTRAINTS COMING FROM BBN AND CMBR DEPENDING ON LIFETIME OF UNSTABLE STATE

CONSTRAINTS FROM THE SUN

- ☐ IF DM HAS LARGE SPIN-DEPENDENT SCATTERING CROSS SECTION OR SELF INTERACTING, DM CAN ACCUMULATE IN THE SUN
- ☐ OLD IDEA TO SOLVE SOLAR NEUTRINO PROBLEM - COSMIONS/LOW MASS DM IN THE SUN TRANSPORTS ENERGY AWAY FROM CORE
- ☐ DM WITH AN ASYMMETRY NEEDED SO THAT ABUNDANCE BUILT UP
- ☐ CHANGES TEMP PROFILE,WHICH AFFECTS THE NEUTRINO FLUXES - - OF COURSE NOW SOLVED BY OSCILLATIONS

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- ☐ IN NEW MODELS OF ADM, THE COSMION CONDITIONS COULD BE REPRODUCED
- ☐ CAPTURE OF ADM BY THE SUN, COULD THEN BE CONSTRAINED BY THE PROPERTIES OF THE SUN OR MAY EVEN ALLEVIATE POTENTIAL ISSUES WITH THE STANDARD SOLAR MODEL

SERENLLI, BASU, FERGUSON (2009), ASPLUND, GREVESSE, SAUVAL (2004, 2009)

ADM/COSMION PAPERS: FAULKNER, GILLILAND (1985); SPERGEL, PRESS (1985); GILLILAND , FAULKNER, PRESS, SPERGEL (1986); GELMINI, HALL, LIN (1987); GIUDICE, RABY (1990); LOPES, SILK, HANSEN, BERTONE (2002) FRANDSEN, SARKAR (2010); CUMBERBATCH, GUZIK, SILK, WATSON, SMW (2010); TAOSO, IOCCO, MEYNET, BERTONE, EGGENBERGER (2010)

CONCLUSIONS

- ADM IS AN INTERESTING AND WELL MOTIVATED DM SCENARIO TO EXPLAIN

$$\frac{\Omega_{dm}}{\Omega_b} \sim 5$$

- REQUIRE A SHARED (GLOBAL) QUANTUM NUMBER BETWEEN DM AND SM

- TWO MAIN SCENARIOS, CO-GENESIS (DM AND B ASYMMETRY GENERATED SIMULTANEOUSLY) AND SHARING WHERE A PRE-EXISTING ASYMMETRY IS TRANSFERRED BETWEEN DM AND SM SECTORS

- RICH PHENOMENOLOGY POSSIBLE AT COLLIDERS, IN DIRECT AND INDIRECT DM SIGNALS, IMPLICATIONS FOR BBN AND EVEN THE SUN.

- LOTS MORE TO INVESTIGATE...