ASYMMETRIC DARK MATTER

STEPHEN WEST

UNIVERSITY OF SUSSEX

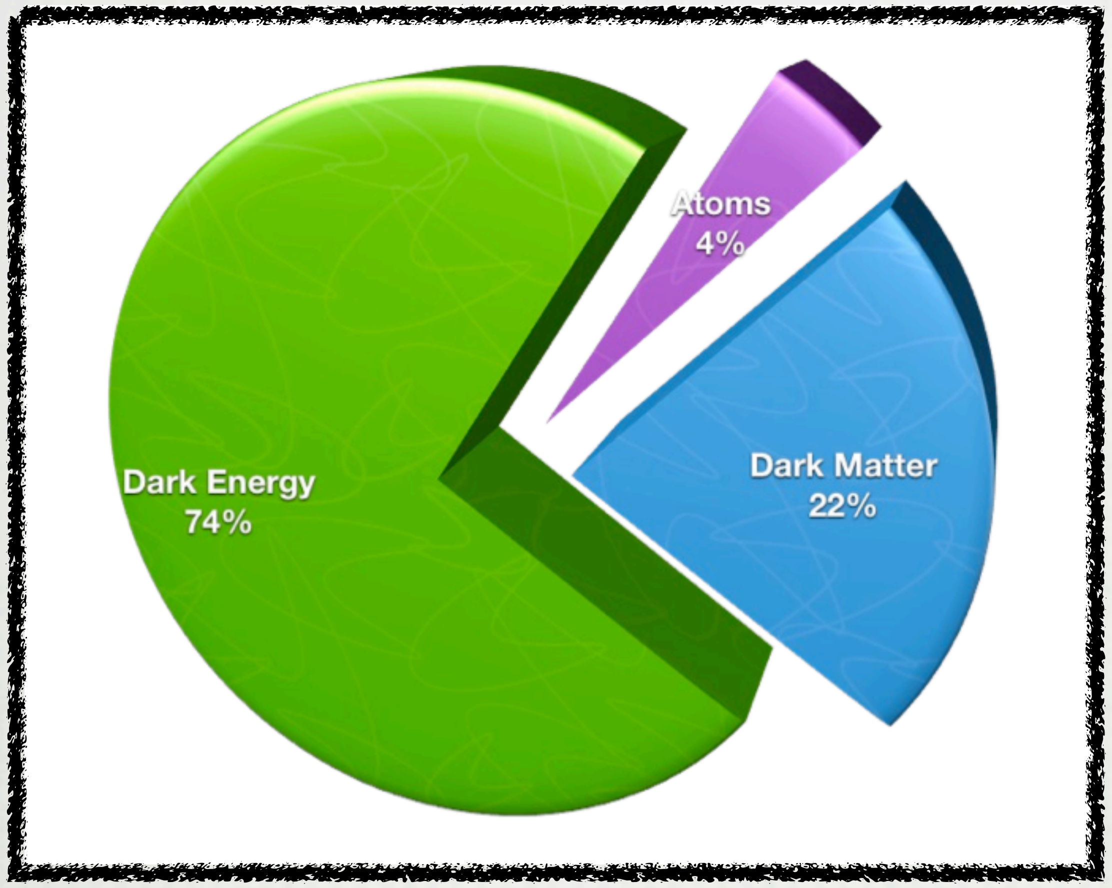
NOVEMBER 28TH 2011

OUTLINE

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

INTRODUCTION

- COMPOSITION OF THE UNIVERSE:



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

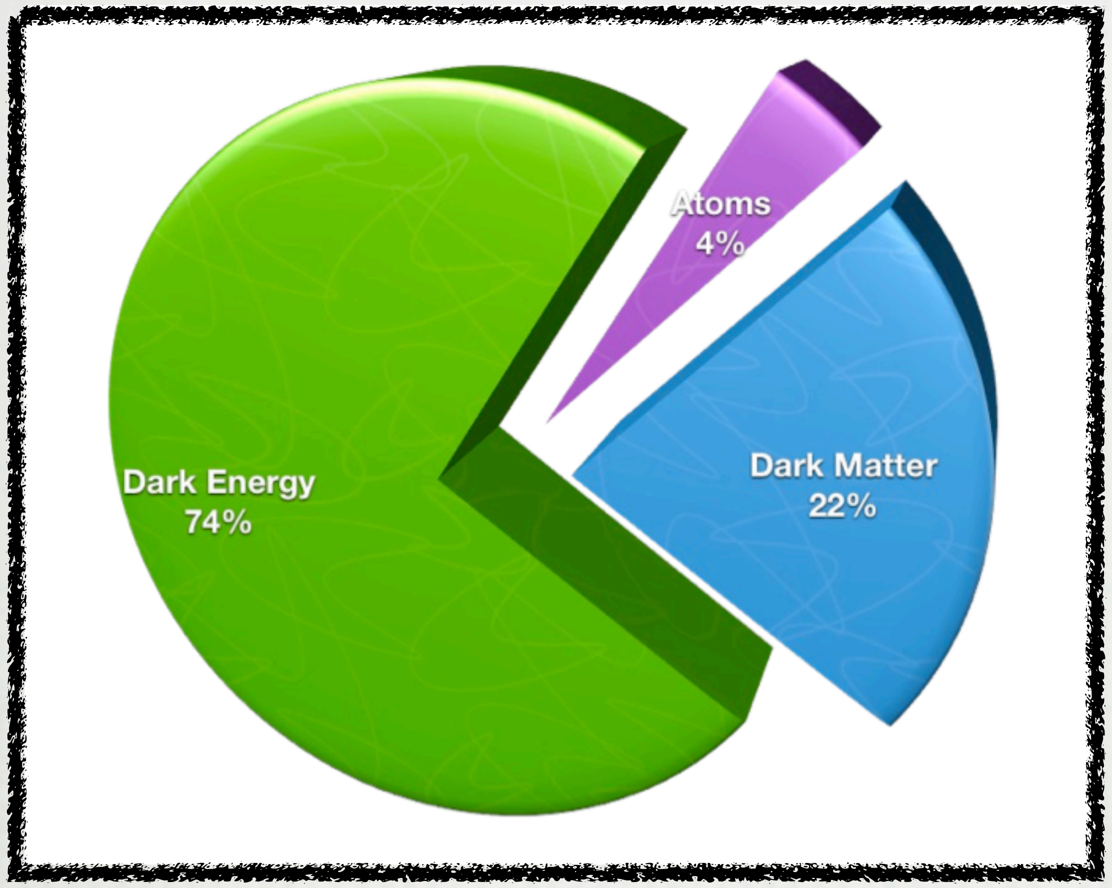
- USUALLY THESE TWO NUMBERS ARE DETERMINED BY INDEPENDENT DYNAMICS

Ω_{dm} BY WIMPS

Ω_b BY BARYOGENESIS/ LEPTOGENESIS

INTRODUCTION

- COMPOSITION OF THE UNIVERSE:



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

- USUALLY THESE TWO NUMBERS ARE DETERMINED BY INDEPENDENT DYNAMICS

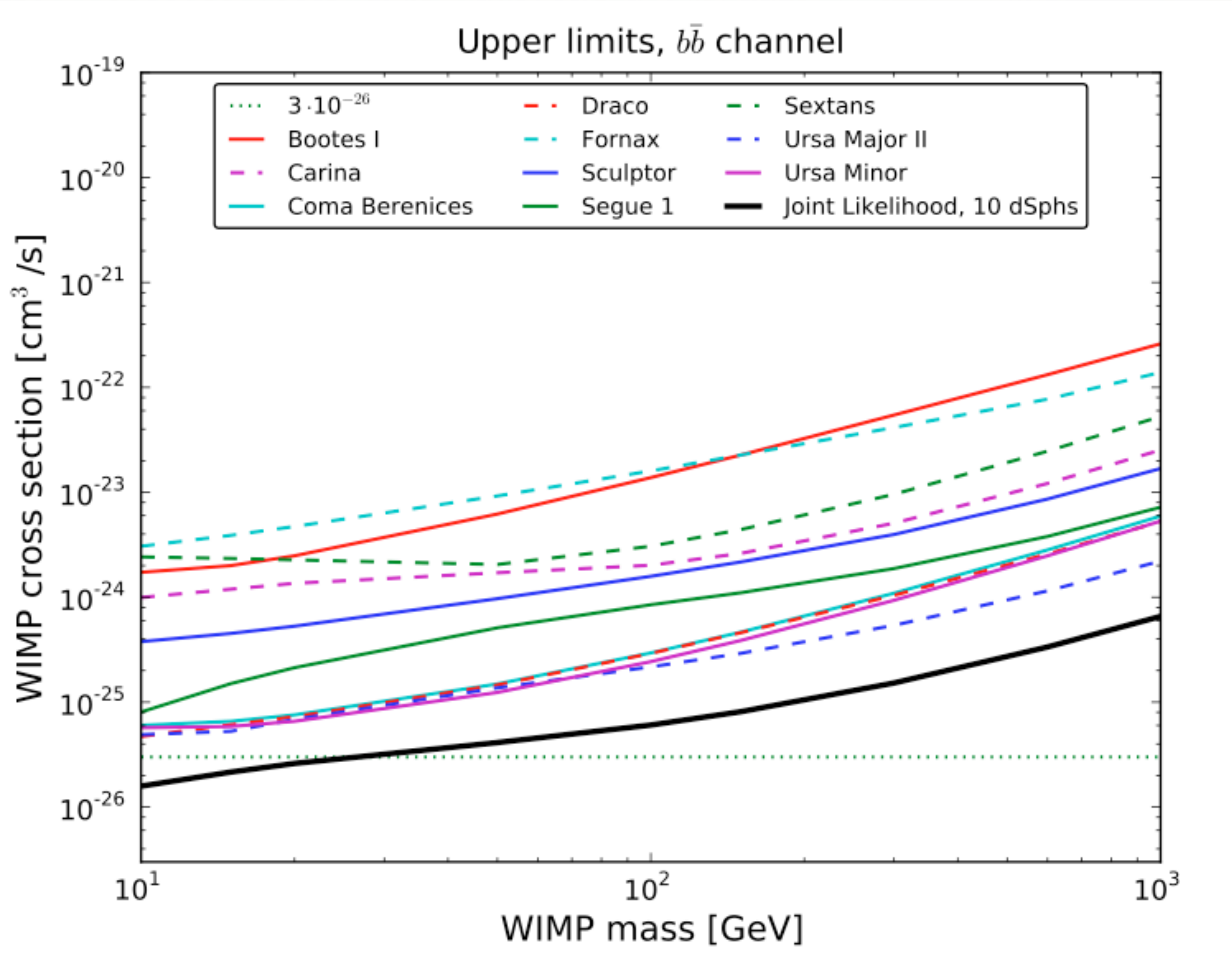
Ω_{dm} BY WIMPS

Ω_b BY BARYOGENESIS/ LEPTOGENESIS

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

...LEADS TO IDEAS OF ASYMMETRIC DM

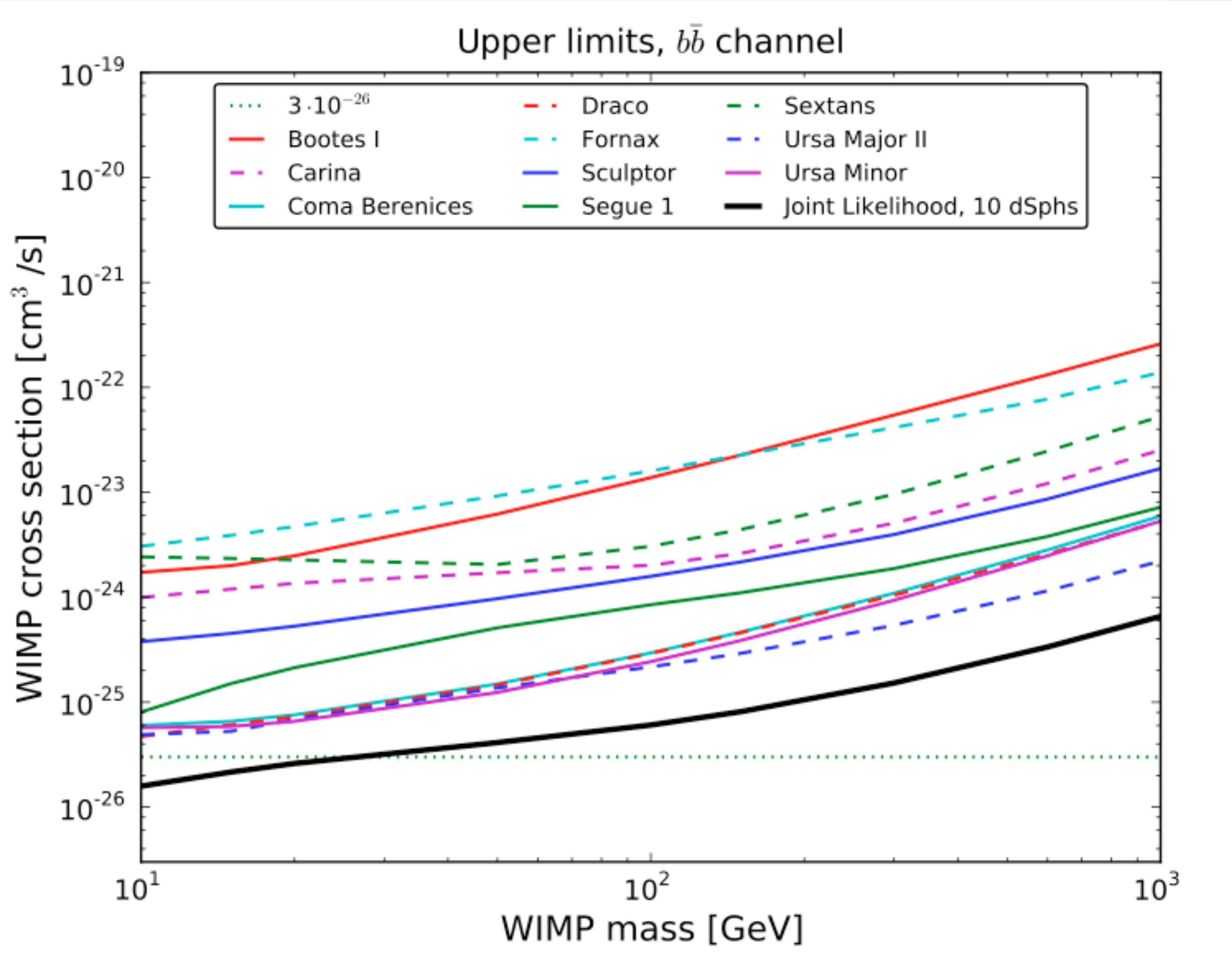
MORE MOTIVATION?



FERMI 2011, EPRINT: 1108.3546

MORE MOTIVATION?

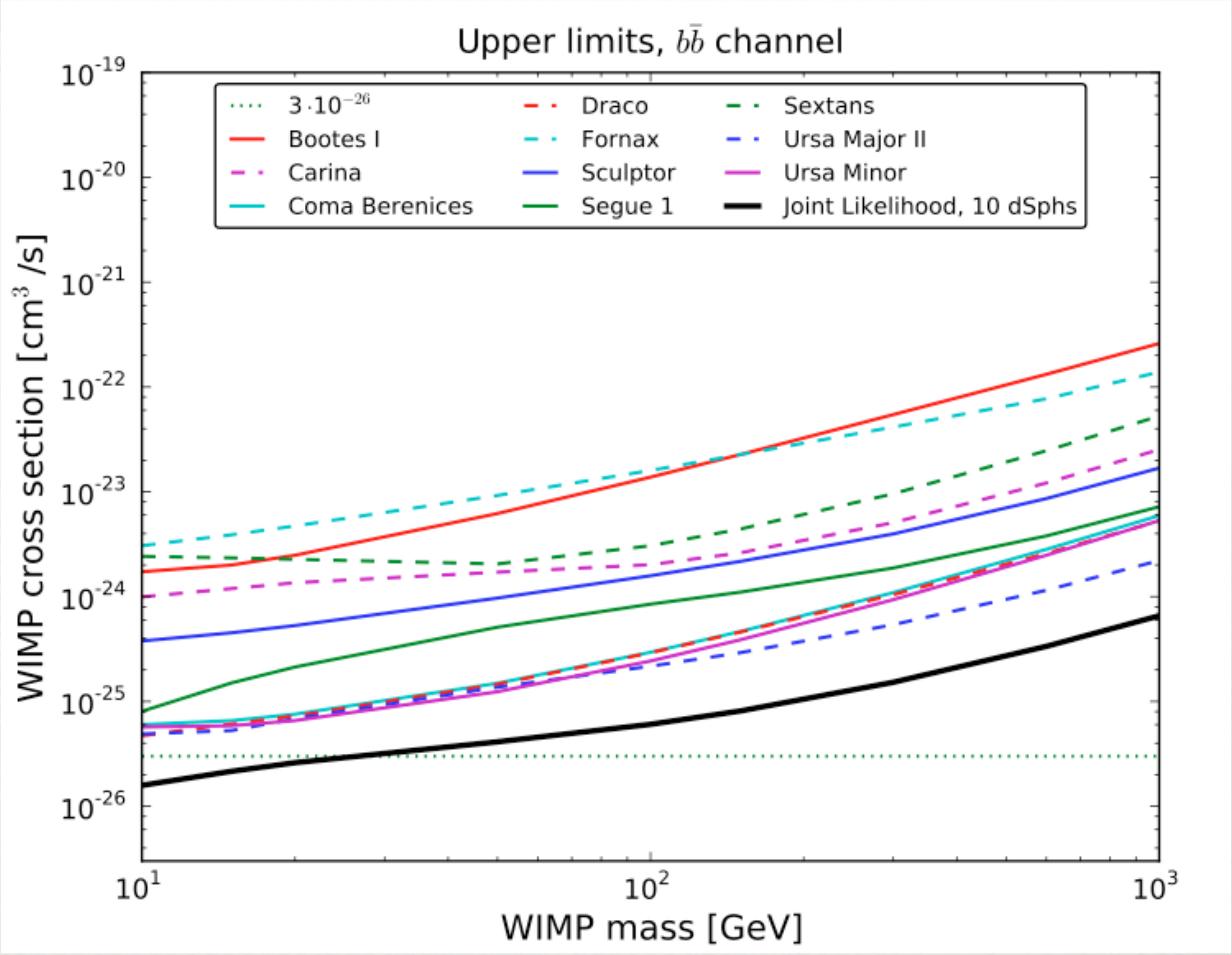
- ☐ DATA FROM FERMI MEASUREMENT OF GAMMA RAYS FROM DWARF SPHEROIDAL SATELLITE GALAXIES



FERMI 2011, EPRINT: 1108.3546

MORE MOTIVATION?

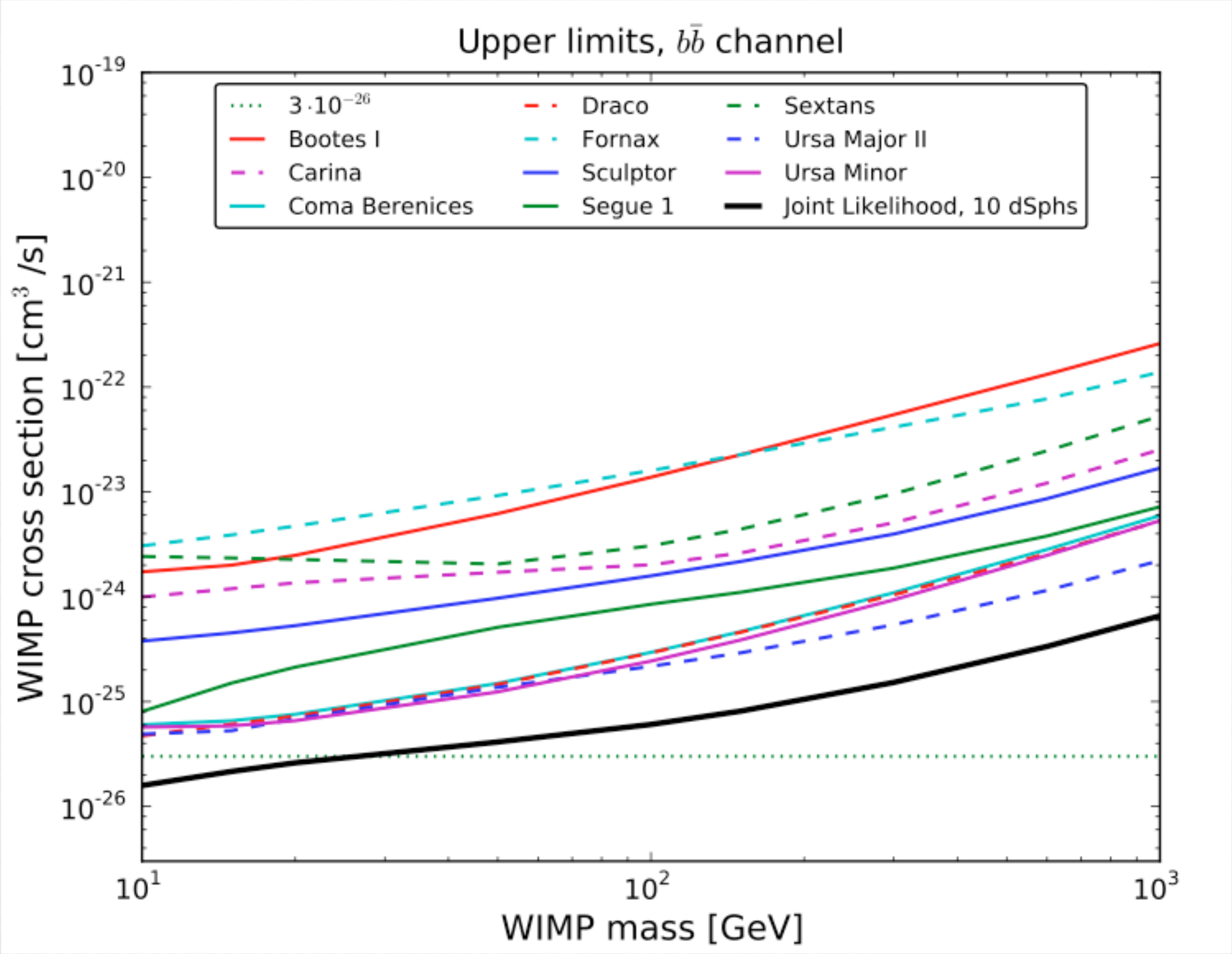
- ☐ DATA FROM FERMI MEASUREMENT OF GAMMA RAYS FROM DWARF SPHEROIDAL SATELLITE GALAXIES
- ☐ PUTS LIMITS ON THE WIMP ANNIHILATION CROSS SECTION
- ☐ GETTING CLOSE TO THE CANONICAL FREEZE-OUT VALUE
- ☐ PLOT ONLY SHOWS LIMITS ON ANNIHILATION RATE TO $b\bar{b}$ (AND IS FOR S-WAVE ONLY!)



FERMI 2011, EPRINT: 1108.3546

MORE MOTIVATION?

- DATA FROM FERMI MEASUREMENT OF GAMMA RAYS FROM DWARF SPHEROIDAL SATELLITE GALAXIES
- PUTS LIMITS ON THE WIMP ANNIHILATION CROSS SECTION
- GETTING CLOSE TO THE CANONICAL FREEZE-OUT VALUE
- PLOT ONLY SHOWS LIMITS ON ANNIHILATION RATE TO $b\bar{b}$ (AND IS FOR S-WAVE ONLY!)



FERMI 2011, EPRINT: 1108.3546

- NO LIMIT ON ASYMMETRIC DM MODELS.

ASYMMETRIC DARK MATTER BASICS

- INTRODUCE AN ASYMMETRY IN DM NUMBER DENSITY (OR THE BARYON SECTOR)

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

ASYMMETRIC DARK MATTER BASICS

- INTRODUCE AN ASYMMETRY IN DM NUMBER DENSITY (OR THE BARYON SECTOR)

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

- 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)

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)

TOY EXAMPLE:

BARYONS HAVE CHARGE q, DARK MATTER HAS CHARGE Q

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)

TOY EXAMPLE:

BARYONS HAVE CHARGE q, DARK MATTER HAS CHARGE Q

CONSERVATION OF GLOBAL CHARGE IMPLIES $Q(n_{dm} - \overline{n}_{dm}) = q(n_b - \overline{n}_b)$

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)

TOY EXAMPLE:

BARYONS HAVE CHARGE q, DARK MATTER HAS CHARGE Q

CONSERVATION OF GLOBAL CHARGE IMPLIES $Q(n_{dm} - \overline{n}_{dm}) = q(n_b - \overline{n}_b)$

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 - SOLUTION TO SOLAR NEUTRINO PROBLEM:
  GELMINI, HALL, LIN (1987); GIUDICE, RABY (1990)

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

ASYMMETRIC DARK MATTER
A (PARTIAL) HISTORY

- 80'S AND 90'S

  COSMIONS AS ~5 GEV ADM - SOLUTION TO SOLAR NEUTRINO PROBLEM:
  GELMINI, HALL, LIN (1987); GIUDICE, RABY (1990)

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

- 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 - LOTS OF OTHERS:

  ~ 5 GEV OR TEV ADM 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

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
- SHARING
  - 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

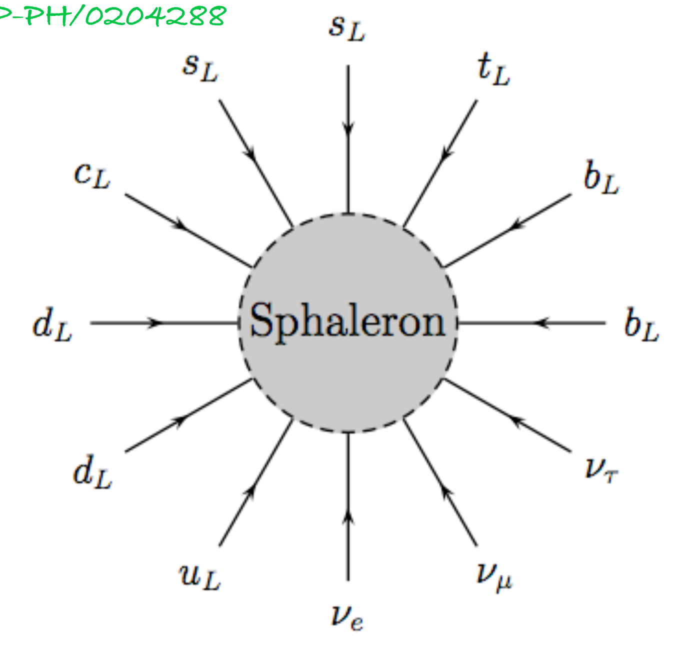
IMPORTANT ASIDE ON THE ELECTROWEAK ANOMALY/SPHALERONS

- HAS AN IMPORTANT INFLUENCE OVER THE DYNAMICS OF ASYMMETRIES IN ANY CHIRAL FERMION CHARGED UNDER $SU(2)_L$

- B+L VIOLATING PROCESS, CONSERVES B-L EFFICIENTLY OPERATE $10^{12}\,\mathrm{GeV} > T \gtrsim 100\,\mathrm{GeV}$ (BELOW EXPONENTIALLY SUPPRESSED)

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

TAKEN FROM BUCHMULLER, HEP-PH/0204288



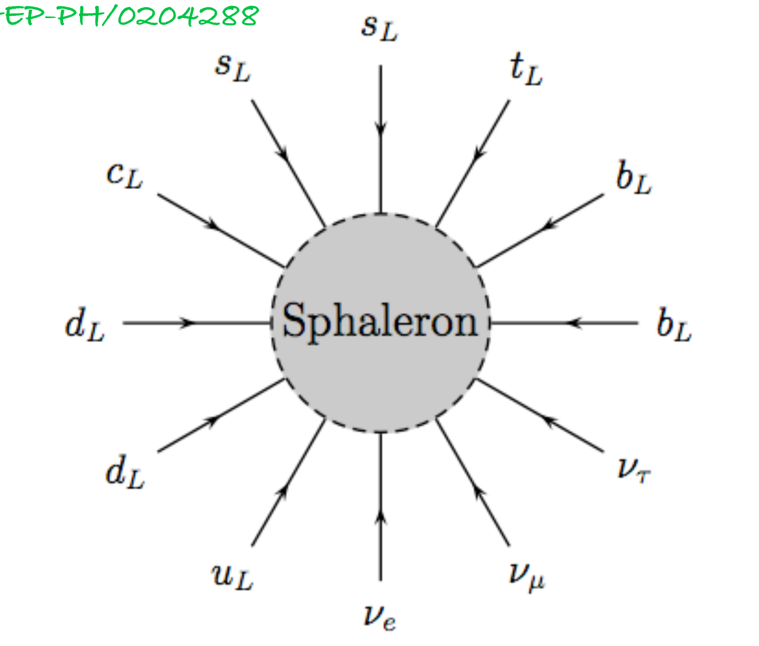
IMPORTANT ASIDE ON THE ELECTROWEAK ANOMALY/SPHALERONS

- HAS AN IMPORTANT INFLUENCE OVER THE DYNAMICS OF ASYMMETRIES IN ANY CHIRAL FERMION CHARGED UNDER $SU(2)_L$

- B+L VIOLATING PROCESS, CONSERVES B-L EFFICIENTLY OPERATE $10^{12}\ \mathrm{GeV} > T \gtrsim 100\ \mathrm{GeV}$ (BELOW EXPONENTIALLY SUPPRESSED)

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

TAKEN FROM BUCHMULLER, HEP-PH/0204288



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

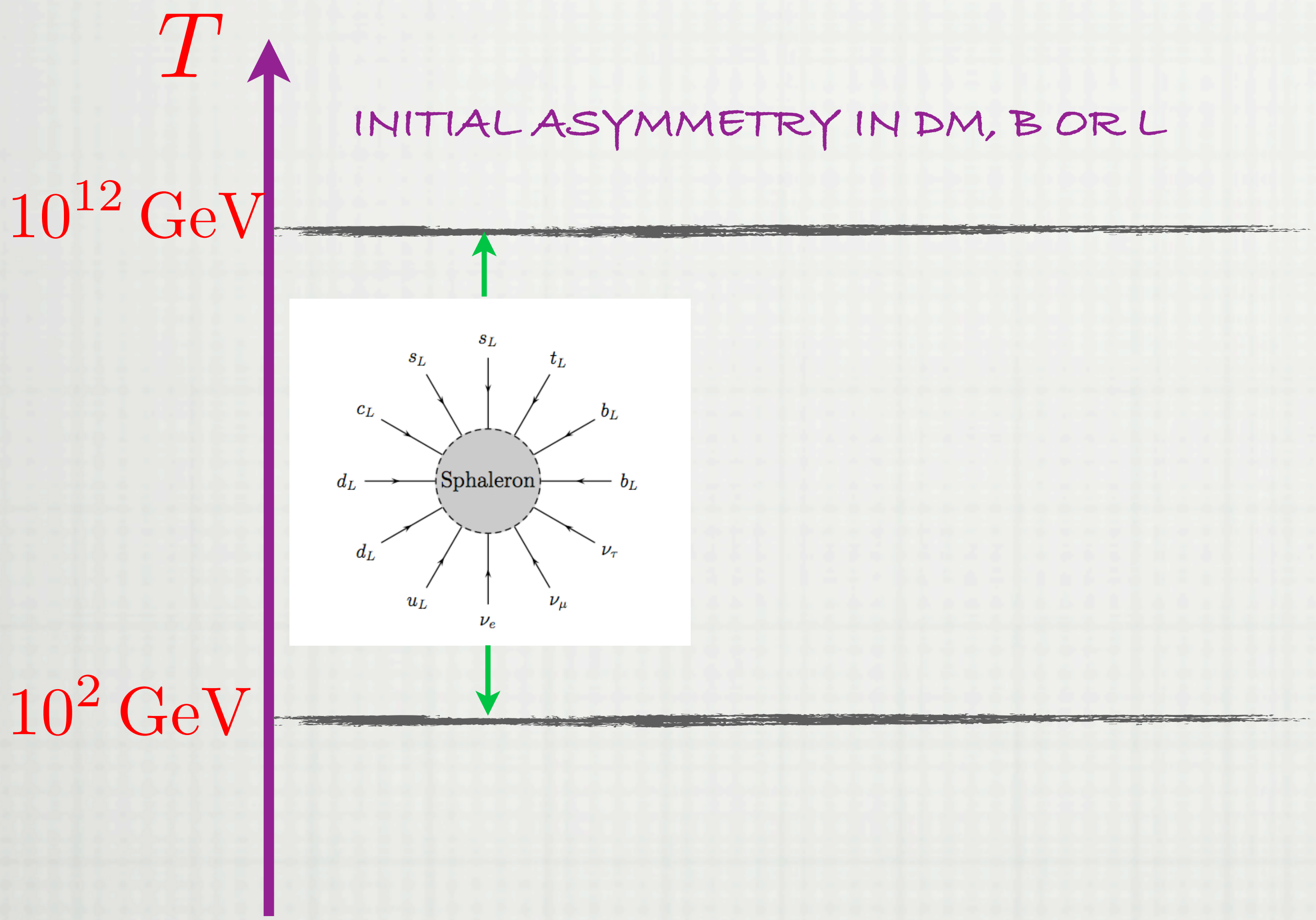
- IF $B \neq 0$, $L \neq 0$ BUT $B\text{-}L=0$, E-WEAK ANOMALY WILL WASH OUT THE ASYMMETRY

SHARING:

- ASSUME THE PRESENCE OF A NON ZERO PRE-EXISTING HIGH SCALE ASYMMETRY IN EITHER DM, B OR L.

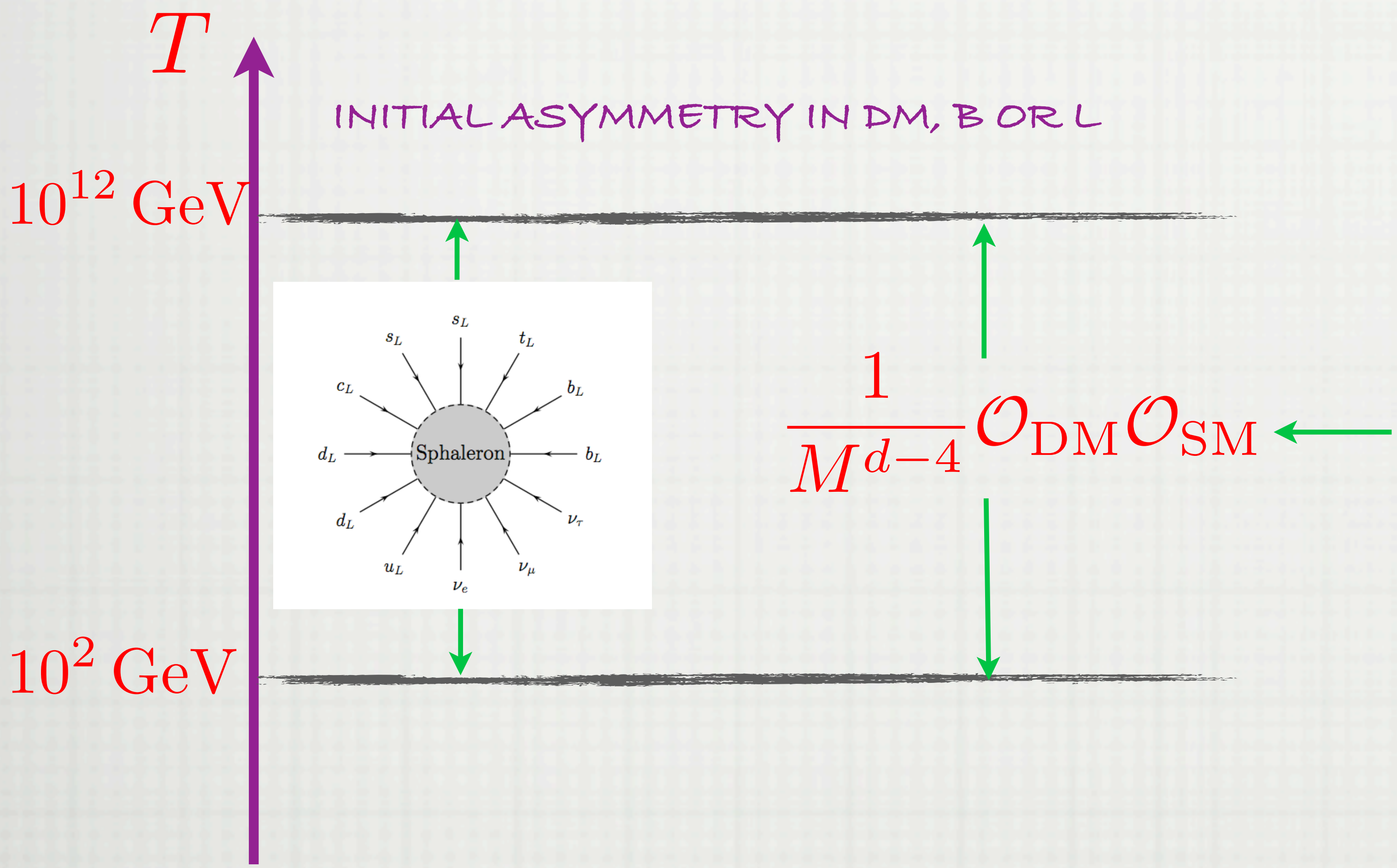
SHARING:

- ASSUME THE PRESENCE OF A NON ZERO PRE-EXISTING HIGH SCALE ASYMMETRY IN EITHER DM, B OR L.



SHARING:

- ASSUME THE PRESENCE OF A NON ZERO PRE-EXISTING HIGH SCALE ASYMMETRY IN EITHER DM, B OR L.



SOME OPERATORS RESPONSIBLE FOR PROCESSES THAT VIOLATE A COMBINATION OF B, L AND DM NUMBER BUT PRESERVE B-L+DM

THIS CAN INCLUDE THE ELECTRO-WEAK ANOMALY. WILL ALWAYS SHARE ASYMMETRIES BETWEEN B AND L

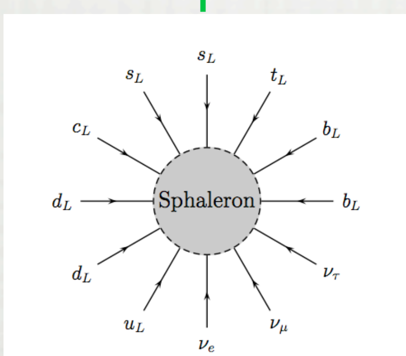
SHARING:

- ☐ ASSUME THE PRESENCE OF A NON ZERO PRE-EXISTING HIGH SCALE ASYMMETRY IN EITHER DM, B OR L.

T

INITIAL ASYMMETRY IN DM, B OR L

10^{12} GeV



$$\frac{1}{M^{d-4}}\mathcal{O}_{\rm DM}\mathcal{O}_{\rm SM}$$

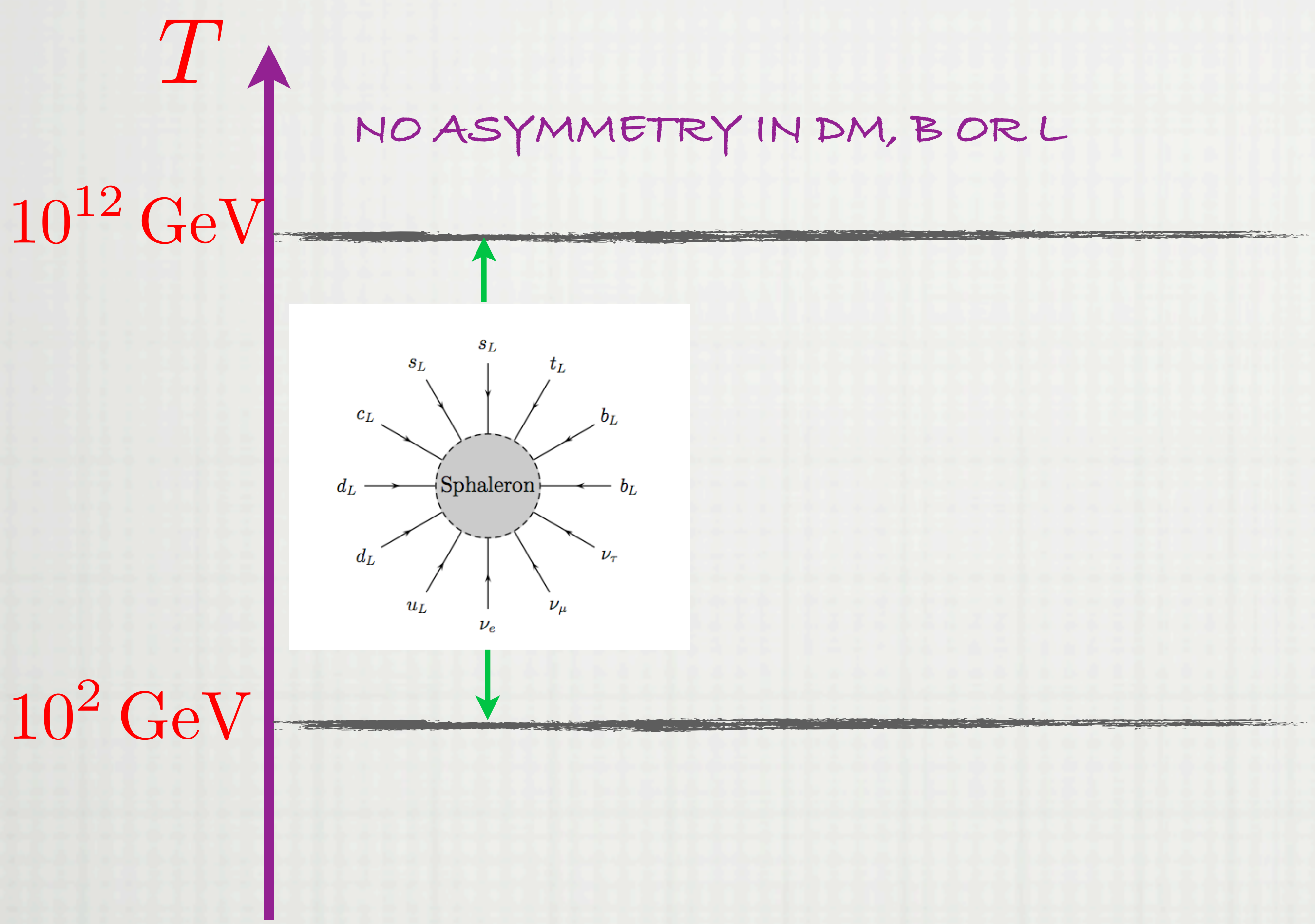
10^{2} GeV

SOME OPERATORS RESPONSIBLE FOR PROCESSES THAT VIOLATE A COMBINATION OF B, L AND DM NUMBER BUT PRESERVE B-L+DM

THIS CAN INCLUDE THE ELECTRO-WEAK ANOMALY. WILL ALWAYS SHARE ASYMMETRIES BETWEEN B AND L

- ☐ CHEMICAL POTENTIALS RELATED THROUGH ALL PROCESS IN THERMAL EQ., NEED TO SOLVE.
- ☐ THE RESULT IS THAT ANY ASYMMETRIES IN B, L OR DM ARE SHARED AND RELATED BY B-L+DM NUMBER - EXAMPLE LATER

CO-GENESIS EXAMPLES - GENERATING AN ASYMMETRY IN B AND DM SIMULTANEOUSLY

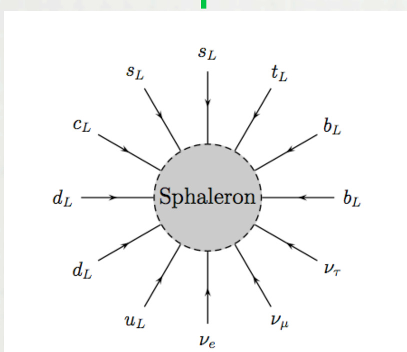


CO-GENESIS EXAMPLES - GENERATING AN ASYMMETRY IN B AND DM SIMULTANEOUSLY

T

NO ASYMMETRY IN DM, B OR L

10^{12} GeV



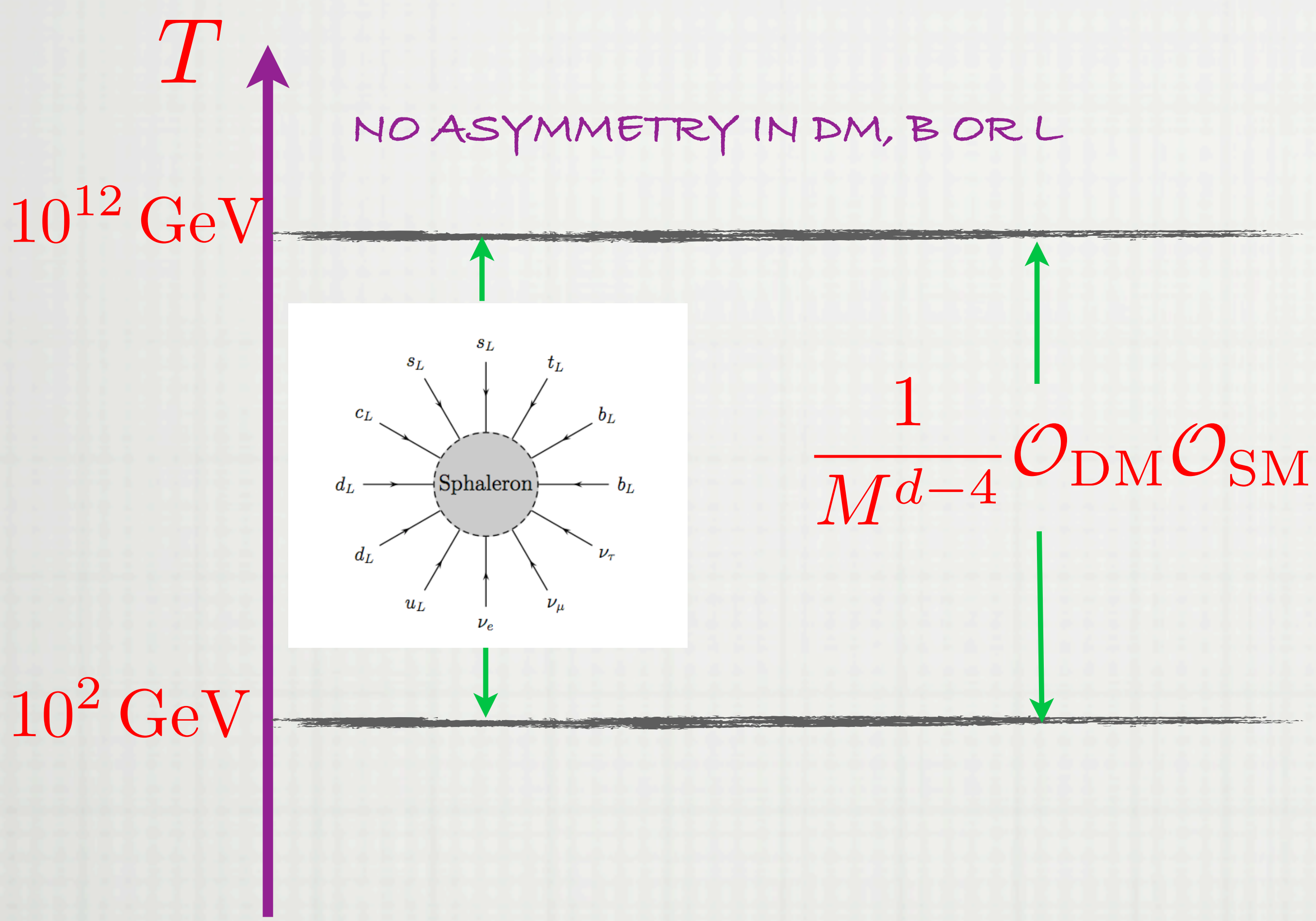
$$\frac{1}{M^{d-4}}\mathcal{O}_{\rm DM}\mathcal{O}_{\rm SM}$$

10^{2} GeV

AGAIN COMBINATION OF B, L AND DM NUMBER VIOLATED AND B-L +DM PRESERVED.

BUT NOW, THESE INTERACTIONS ARE RESPONSIBLE FOR GENERATING THE ASYMMETRY.

CO-GENESIS EXAMPLES - GENERATING AN ASYMMETRY IN B AND DM SIMULTANEOUSLY



AGAIN COMBINATION OF B, L AND DM NUMBER VIOLATED AND B-L +DM PRESERVED.

BUT NOW, THESE INTERACTIONS ARE RESPONSIBLE FOR GENERATING THE ASYMMETRY.

- STILL GET SHARING. E.G ASYMMETRY COULD BE GENERATED IN DM AND L NUMBER BUT THROUGH E-WEAK ANOMALY WILL BE SHARED TO BARYON SECTOR.

POSSIBLE MASSES

SIMPLEST CASES, THERE ARE TWO MASS REGIONS

$m_{dm} \sim 5\,\mathrm{GeV}$ AND $m_{dm} \sim 1\,\mathrm{TeV}$

POSSIBLE MASSES

SIMPLEST CASES, THERE ARE TWO MASS REGIONS

$m_{dm} \sim 5\,\mathrm{GeV}$ AND $m_{dm} \sim 1\,\mathrm{TeV}$

- ☐ IF THE DM IS NOT CHARGED UNDER $SU(2)_L$ AND
- ☐ THERE ARE NO B OR DM NUMBER VIOLATING PROCESSES IN EQUILIBRIUM AS DM FREEZES-OUT

$n_{dm} = C n_b$ WITH $C \sim \mathcal{O}(1)$

$$\Rightarrow \frac{\Omega_{dm}}{\Omega_b} \approx \frac{m_{dm}}{m_b} \qquad \rightarrow m_{dm} \sim 5\,\mathrm{GeV}$$

TEV MASS CASE: TWO SCENARIOS (SAME PHYSICS: "WASH OUT")

TEV MASS CASE: TWO SCENARIOS (SAME PHYSICS: "WASH OUT")

- IF THE DM IS CHARGED UNDER $SU(2)_L$ IT WILL INTERACT VIA SPHALERONS AND WE GET TWO POSSIBILITIES
  - IF $m_{dm} \lesssim T_c$ THEN WE AGAIN FIND THE RESULT - $m_{dm} \sim 5\,\mathrm{GeV}$ (E-WEAK ANOMALY NO LONGER OPERATIONAL AS DM FREEZES-OUT)

TEV MASS CASE: TWO SCENARIOS (SAME PHYSICS: "WASH OUT")

- IF THE DM IS CHARGED UNDER $SU(2)_L$ IT WILL INTERACT VIA SPHALERONS AND WE GET TWO POSSIBILITIES

  - IF $m_{dm} \lesssim T_c$ THEN WE AGAIN FIND THE RESULT - $m_{dm} \sim 5\,\mathrm{GeV}$ (E-WEAK ANOMALY NO LONGER OPERATIONAL AS DM FREEZES-OUT)

  - IF $m_{dm} \gtrsim T_c$ (I.E. E-WEAK ANOMALY STILL OPERATIONAL AS DM FREEZE-OUT) NUSSINOV (1985)

$$\frac{\Omega_{dm}}{\Omega_b} \approx \frac{m_{dm}}{m_b} x^{3/2} e^{-x} \quad \text{WITH} \quad x = \frac{m_{dm}}{T_c}$$

(ACTUALLY ONLY REALLY CORRECT FOR $m_{dm} \gg T_c$)

TEV MASS CASE: TWO SCENARIOS (SAME PHYSICS: "WASH OUT")

- IF THE DM IS CHARGED UNDER $SU(2)_L$ IT WILL INTERACT VIA SPHALERONS AND WE GET TWO POSSIBILITIES
  - IF $m_{dm} \lesssim T_c$ THEN WE AGAIN FIND THE RESULT - $m_{dm} \sim 5\,\mathrm{GeV}$ (E-WEAK ANOMALY NO LONGER OPERATIONAL AS DM FREEZES-OUT)
  - IF $m_{dm} \gtrsim T_c$ (I.E. E-WEAK ANOMALY STILL OPERATIONAL AS DM FREEZE-OUT) NUSSINOV (1985)

$$\frac{\Omega_{dm}}{\Omega_b} \approx \frac{m_{dm}}{m_b} x^{3/2} e^{-x} \quad \text{WITH} \quad x = \frac{m_{dm}}{T_c}$$

(ACTUALLY ONLY REALLY CORRECT FOR $m_{dm} \gg T_c$)

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

TEV MASS CASE: TWO SCENARIOS (SAME PHYSICS: "WASH OUT")

☐ IF THE DM IS CHARGED UNDER $SU(2)_L$ IT WILL INTERACT VIA SPHALERONS AND WE GET TWO POSSIBILITIES

- IF $m_{dm} \lesssim T_c$ THEN WE AGAIN FIND THE RESULT - $m_{dm} \sim 5\,\mathrm{GeV}$ (E-WEAK ANOMALY NO LONGER OPERATIONAL AS DM FREEZES-OUT)

- IF $m_{dm} \gtrsim T_c$ (I.E. E-WEAK ANOMALY STILL OPERATIONAL AS DM FREEZE-OUT) NUSSINOV (1985)

$$\frac{\Omega_{dm}}{\Omega_b} \approx \frac{m_{dm}}{m_b} x^{3/2} e^{-x} \quad \text{WITH} \quad x = \frac{m_{dm}}{T_c}$$

(ACTUALLY ONLY REALLY CORRECT FOR $m_{dm} \gg T_c$)

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

☐ SECOND CASE IS WHERE A PROCESS THAT VIOLATES B OR DM NUMBER IS STILL IN THERMAL EQ. AS DM FREEZES-OUT.

- EXAMPLE BEING THE PROCESS THAT PROVIDES THE SHARING

TEV MASS CASE: TWO SCENARIOS (SAME PHYSICS: "WASH OUT")

- IF THE DM IS CHARGED UNDER $SU(2)_L$ IT WILL INTERACT VIA SPHALERONS AND WE GET TWO POSSIBILITIES

  - IF $m_{dm} \lesssim T_c$ THEN WE AGAIN FIND THE RESULT - $m_{dm} \sim 5\,\mathrm{GeV}$ (E-WEAK ANOMALY NO LONGER OPERATIONAL AS DM FREEZES-OUT)

  - IF $m_{dm} \gtrsim T_c$ (I.E. E-WEAK ANOMALY STILL OPERATIONAL AS DM FREEZE-OUT) NUSSINOV (1985)

$$\frac{\Omega_{dm}}{\Omega_b} \approx \frac{m_{dm}}{m_b} x^{3/2} e^{-x} \quad \text{WITH} \quad x = \frac{m_{dm}}{T_c}$$

(ACTUALLY ONLY REALLY CORRECT FOR $m_{dm} \gg T_c$)

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

- SECOND CASE IS WHERE A PROCESS THAT VIOLATES B OR DM NUMBER IS STILL IN THERMAL EQ. AS DM FREEZES-OUT.

  - EXAMPLE BEING THE PROCESS THAT PROVIDES THE SHARING

  GET A SIMILAR DEPENDENCE AS ABOVE AND A MASS PREDICTION OF A TEV (IF STILL 5 GEV DM, DM ASYMMETRY WILL BE WASHED OUT)

SHARING EXAMPLE

KAPLAN, LUTY, ZUREK (2009)

- GLOBAL SYMMETRY USED IS $U(1)_{B-L-X/2}$
- AT HIGH T, A B-L ASYMMETRY IS GENERATED
- TRANSFER OPERATORS PRESERVE B-L-X/2, E.G.

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

THE X FIELD HAS X=1 CHARGE

SHARING EXAMPLE

KAPLAN, LUTY, ZUREK (2009)

- GLOBAL SYMMETRY USED IS $U(1)_{B-L-X/2}$
- AT HIGH T, A B-L ASYMMETRY IS GENERATED
- TRANSFER OPERATORS PRESERVE B-L-X/2, E.G.

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

THE X FIELD HAS X=1 CHARGE

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

SHARING EXAMPLE

KAPLAN, LUTY, ZUREK (2009)

- GLOBAL SYMMETRY USED IS $U(1)_{B-L-X/2}$
- AT HIGH T, A B-L ASYMMETRY IS GENERATED
- TRANSFER OPERATORS PRESERVE B-L-X/2, E.G.

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

THE X FIELD HAS X=1 CHARGE

- WHEN IN EQUILIBRIUM, THIS OPERATOR TRANSFERS AN L ASYMMETRY INTO THE DM X SECTOR
- NEED TO FIND RELATIONSHIP BETWEEN X ASYMMETRY AND B - NEED TO SOLVE USUAL EQUILIBRATION CONDITIONS

SEE E.G. J. A. Harvey and M. S. Turner, Phys. Rev. D 42, 3344 (1990); T. Inui, T. Ichihara, Y. Mimura and N. Sakai, Phys. Lett. B 325, 392 (1994) [arXiv:hep-ph/9310268].

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

- X ASYMMETRY CAN BE CALCULATED IN TERMS OF B-L

$$X = -\frac{11}{79}(B-L)$$

KAPLAN, LUTY, ZUREK (2009)

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

- X ASYMMETRY CAN BE CALCULATED IN TERMS OF B-L

$$X = -\frac{11}{79}(B-L)$$

- THROUGH THE E-WEAK ANOMALY B-L IS TRANSFERRED INTO B

$$B \approx 0.31(B-L)$$

KAPLAN, LUTY, ZUREK (2009)

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

- ☐ X ASYMMETRY CAN BE CALCULATED IN TERMS OF B-L

$$X = -\frac{11}{79}(B-L)$$

- ☐ THROUGH THE E-WEAK ANOMALY B-L IS TRANSFERRED INTO B

$$B \approx 0.31(B-L)$$

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

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

WHAT ABOUT CO-GENESIS? ASYMMETRIC FREEZE-IN.

FIRST, WHAT IS FREEZE-IN?

FREEZE-IN OVERVIEW

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

- FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X

FREEZE-IN OVERVIEW

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

- ☐ FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X

THERMAL BATH

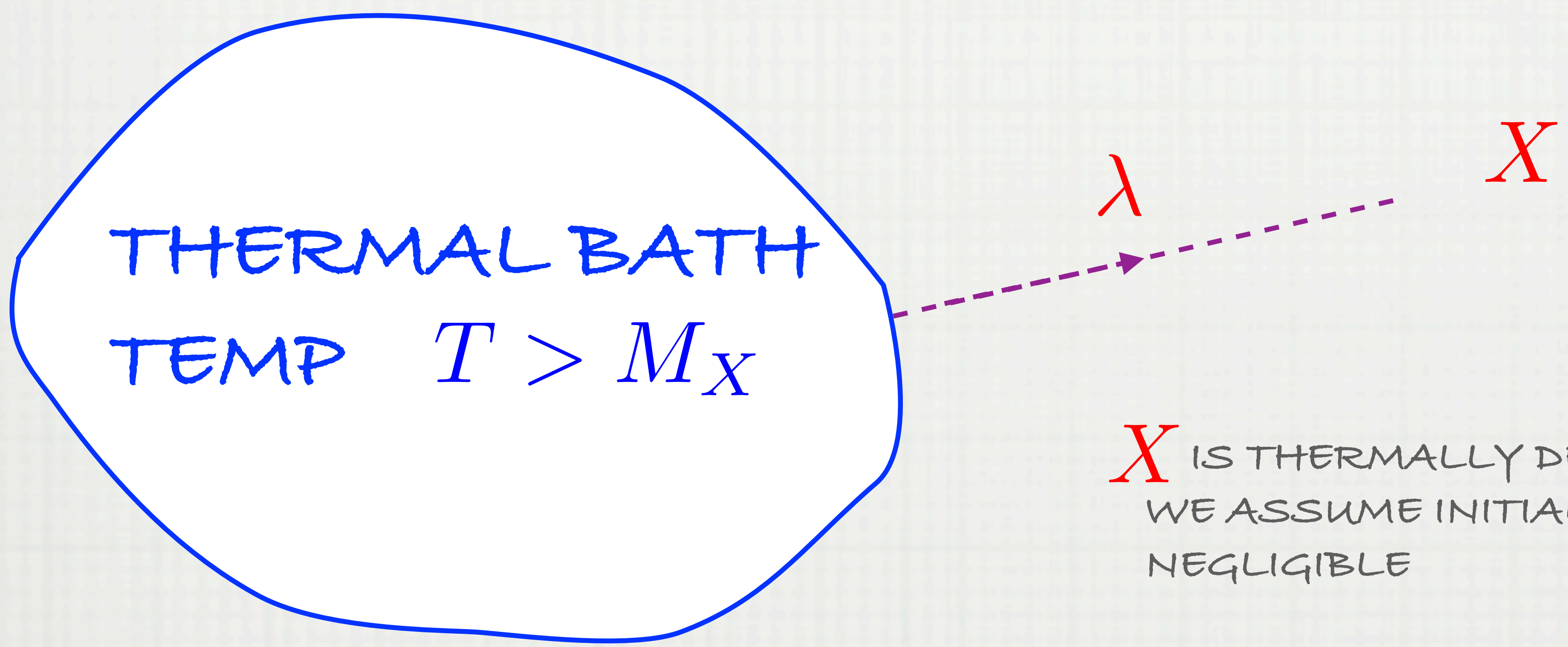
TEMP $T > M_X$

X IS THERMALLY DECOUPLED AND WE ASSUME INITIAL ABUNDANCE NEGLIGIBLE

FREEZE-IN OVERVIEW

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

- ☐ FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X



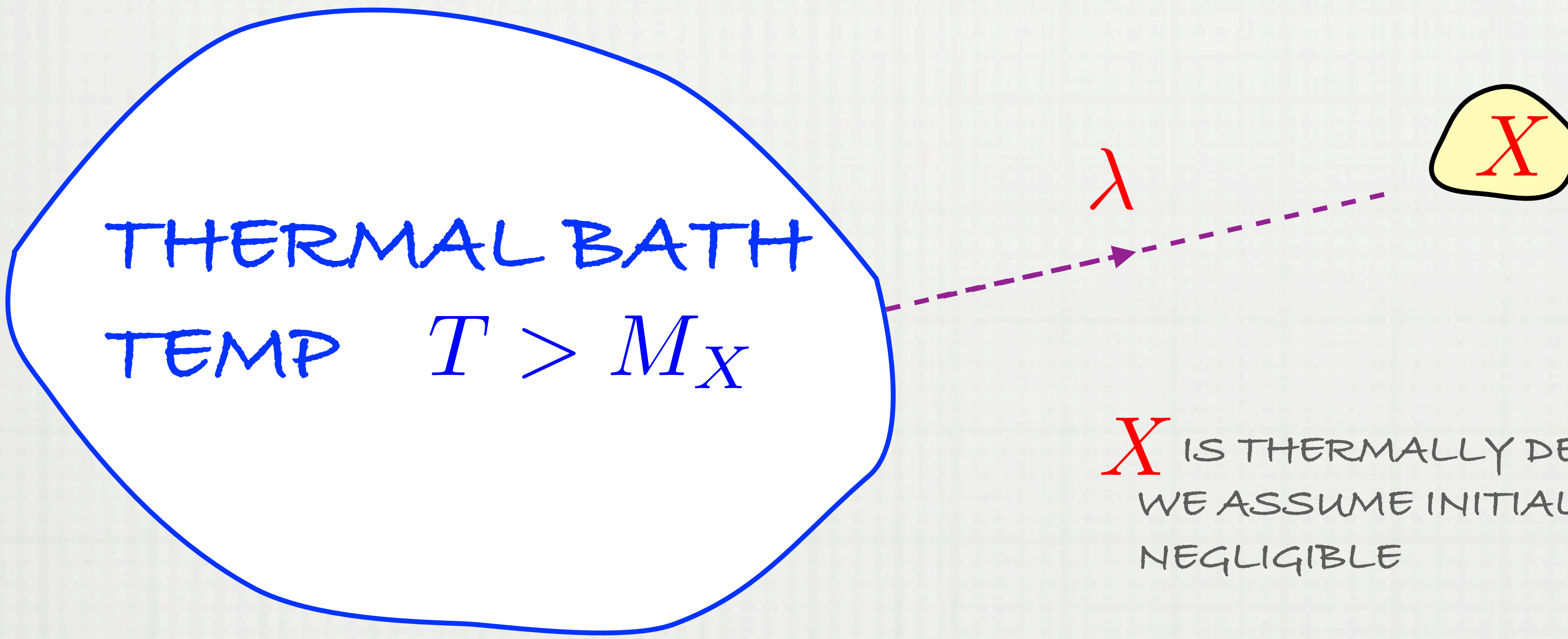
X IS THERMALLY DECOUPLED AND WE ASSUME INITIAL ABUNDANCE NEGLIGIBLE

- ☐ ALTHOUGH INTERACTION ARE FEEBLE THEY LEAD TO SOME X PRODUCTION

FREEZE-IN OVERVIEW

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

- FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X



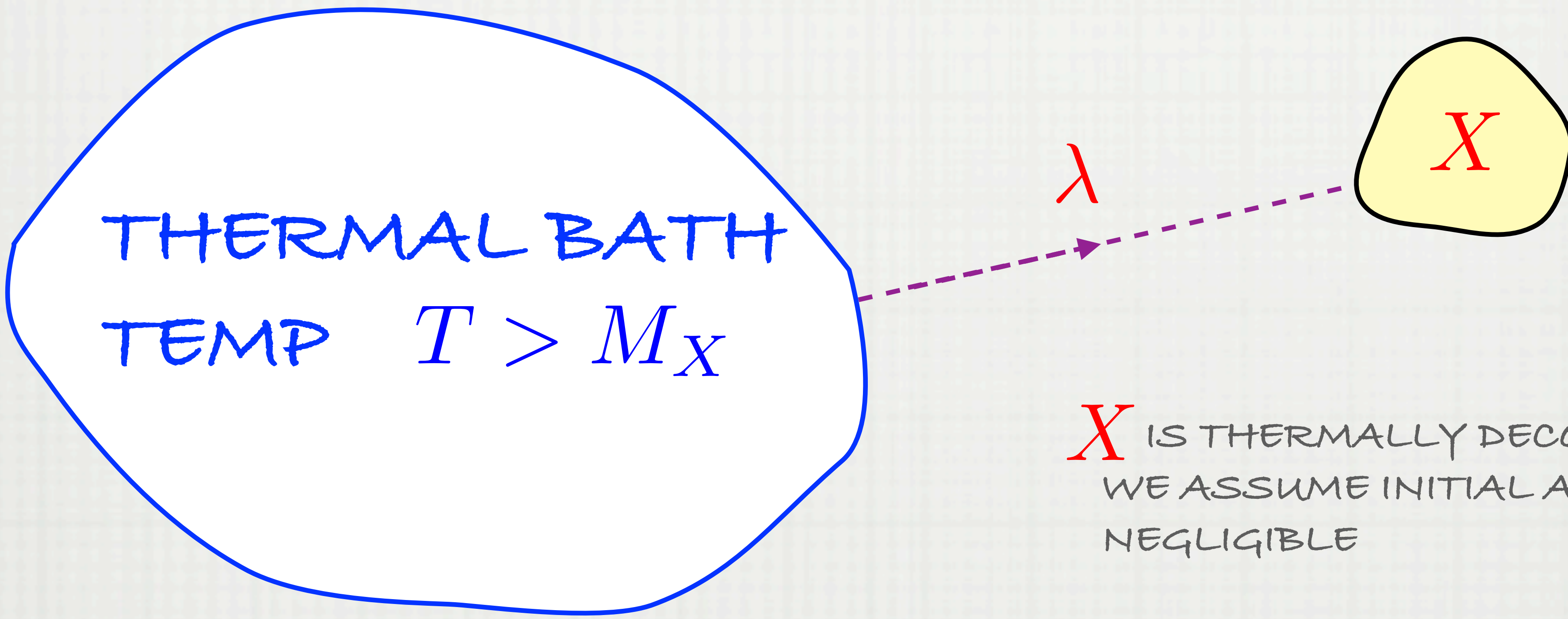
X IS THERMALLY DECOUPLED AND WE ASSUME INITIAL ABUNDANCE NEGLIGIBLE

- ALTHOUGH INTERACTION ARE FEEBLE THEY LEAD TO SOME X PRODUCTION

FREEZE-IN OVERVIEW

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

- ☐ FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X



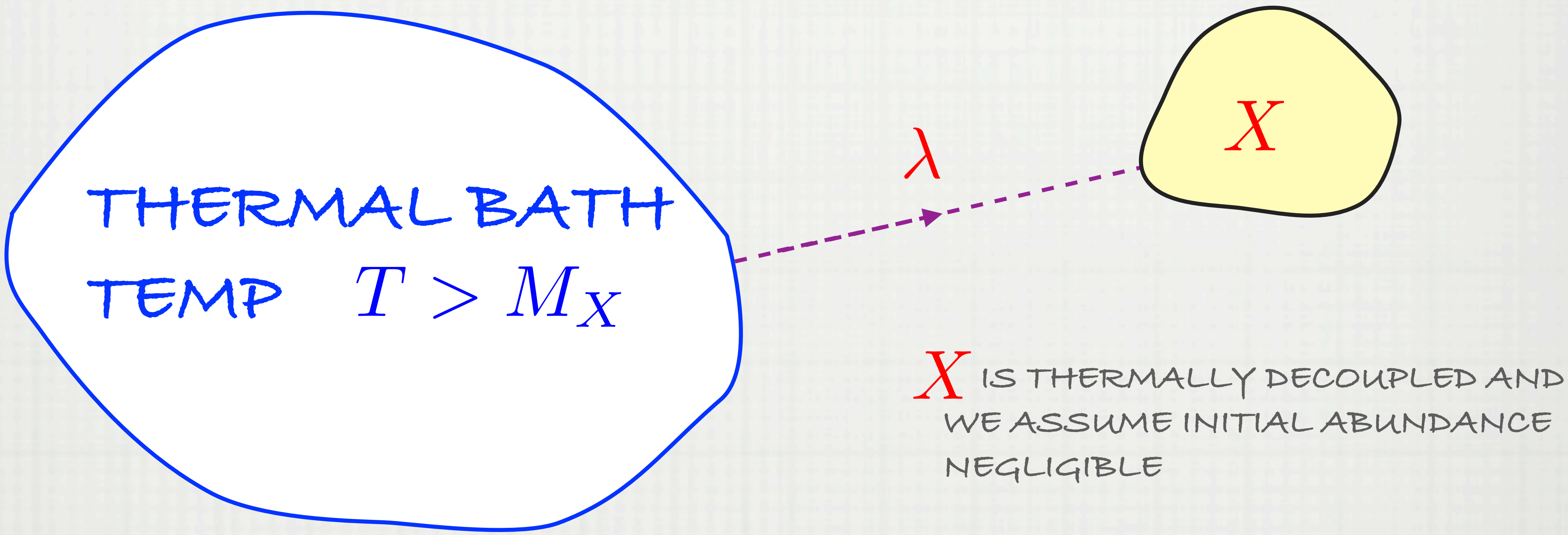
X IS THERMALLY DECOUPLED AND WE ASSUME INITIAL ABUNDANCE NEGLIGIBLE

- ☐ ALTHOUGH INTERACTION ARE FEEBLE THEY LEAD TO SOME X PRODUCTION

FREEZE-IN OVERVIEW

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

- ☐ FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X

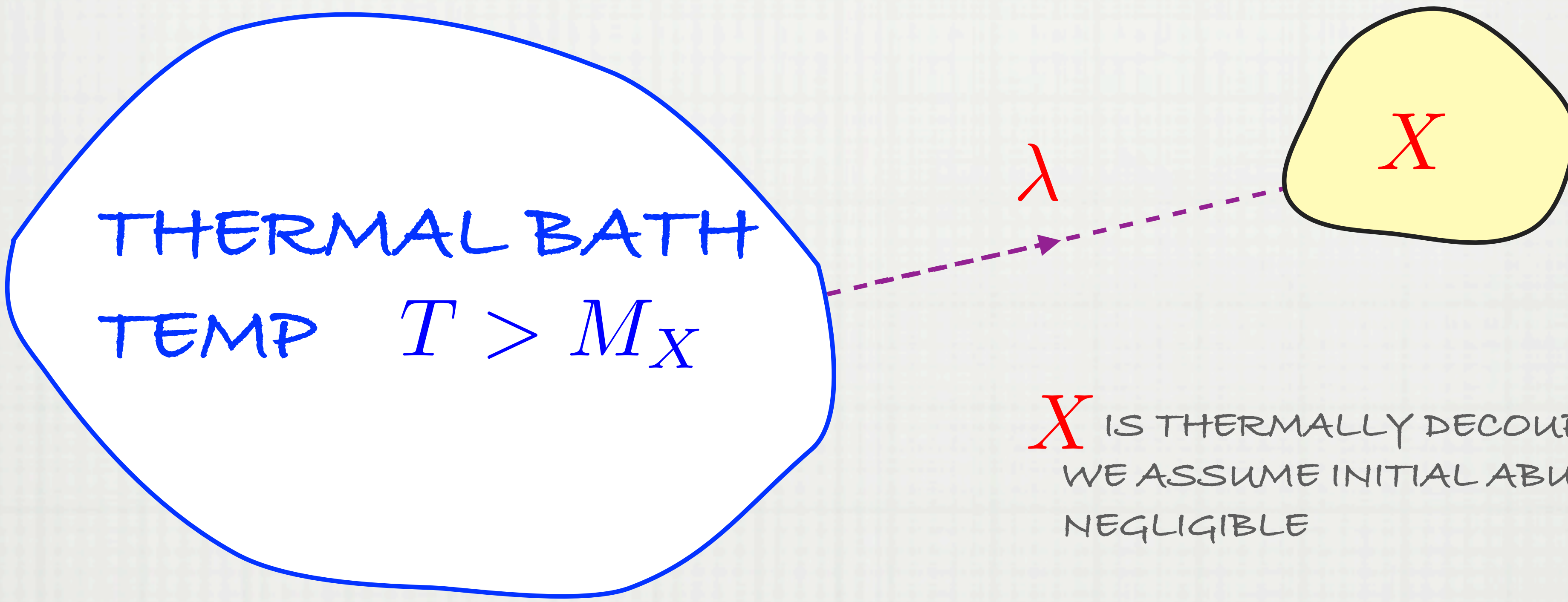


- ☐ ALTHOUGH INTERACTION ARE FEEBLE THEY LEAD TO SOME X PRODUCTION

FREEZE-IN OVERVIEW

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

- FREEZE-IN IS RELEVANT FOR PARTICLES THAT ARE FEEBLY COUPLED (VIA RENORMALISABLE COUPLINGS) - λ
  FEEBLY INTERACTING MASSIVE PARTICLES - FIMPS X



X IS THERMALLY DECOUPLED AND WE ASSUME INITIAL ABUNDANCE NEGLIGIBLE

- ALTHOUGH INTERACTION ARE FEEBLE THEY LEAD TO SOME X PRODUCTION
- DOMINANT PRODUCTION OF X OCCURS AT $T \sim M_X$ - IR DOMINANT
- INCREASING THE INTERACTION STRENGTH INCREASES THE YIELD

OPPOSITE TO FREEZE-OUT

FREEZE-OUT VS FREEZE-IN

$$Y_{FO} \sim \frac{1}{\langle \sigma v \rangle \, M_{Pl} \, m'}$$

USING $\langle \sigma v \rangle \sim \lambda'^2 / m'^2$

$$Y_{FO} \sim \frac{1}{\lambda'^2} \left(\frac{m'}{M_{Pl}} \right)$$

FREEZE-OUT VS FREEZE-IN

$$Y_{FO} \sim \frac{1}{\langle \sigma v \rangle \, M_{Pl} \, m'}$$

USING $\langle \sigma v \rangle \sim \lambda'^2 / m'^2$

$$Y_{FO} \sim \frac{1}{\lambda'^2} \left(\frac{m'}{M_{Pl}} \right)$$

FREEZE-OUT VS FREEZE-IN

$$Y_{FO} \sim \frac{1}{\langle \sigma v \rangle \, M_{Pl} \, m'}$$

USING $\langle \sigma v \rangle \sim \lambda'^2 / m'^2$

$$Y_{FO} \sim \frac{1}{\lambda'^2} \left(\frac{m'}{M_{Pl}} \right)$$

FREEZE-IN VIA 2-2 SCATTERING, DECAYS OR INVERSE DECAYS

COUPLING STRENGTH λ

m MASS OF HEAVIEST PARTICLE IN INTERACTION

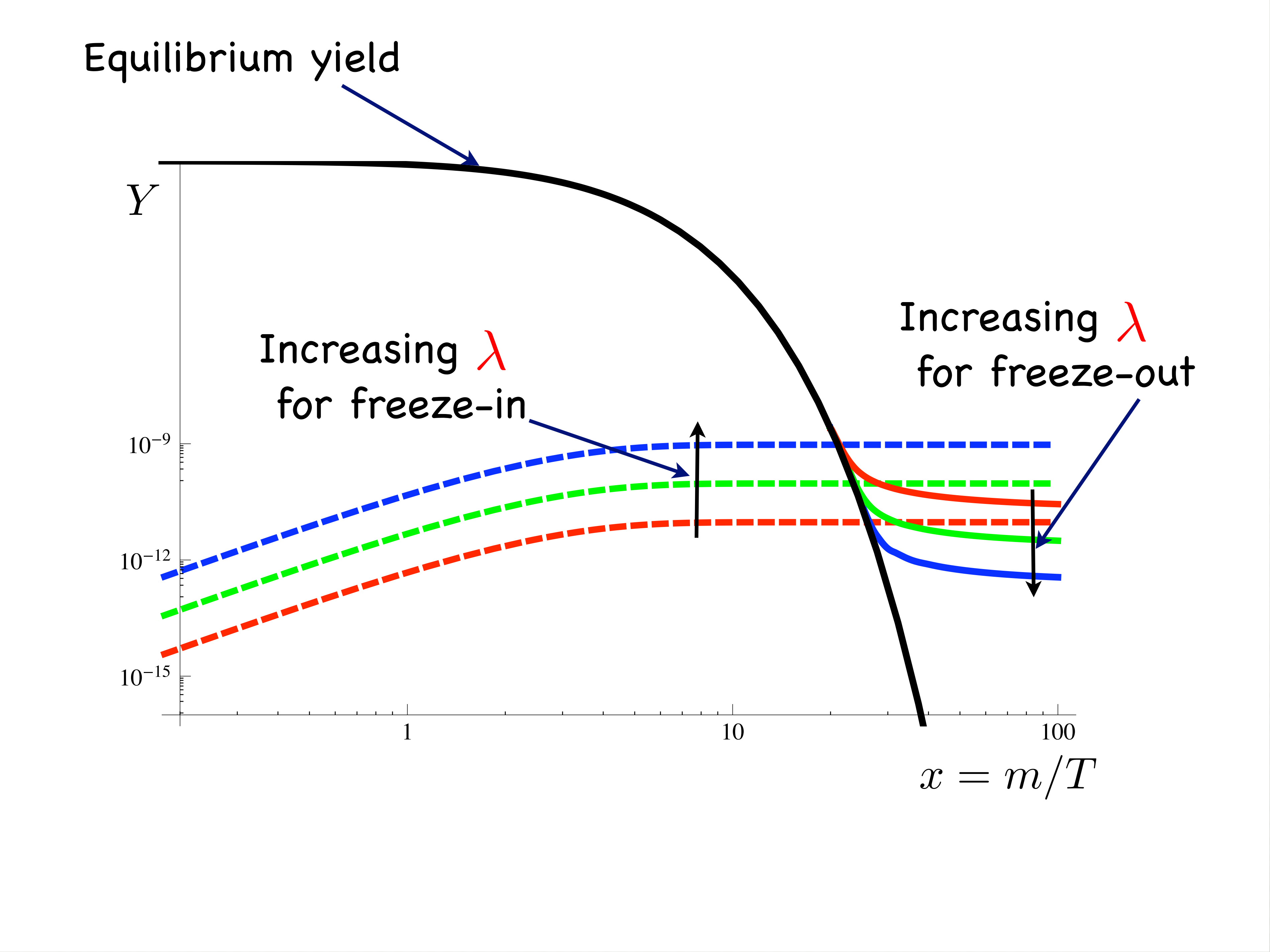
$$Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m} \right)$$

FREEZE-OUT VS FREEZE-IN

- AS TEMP DROPS BELOW MASS OF RELEVANT PARTICLE, DM ABUNDANCE IS HEADING TOWARDS (FREEZE-IN) OR AWAY FROM (FREEZE-OUT) THERMAL EQUILIBRIUM

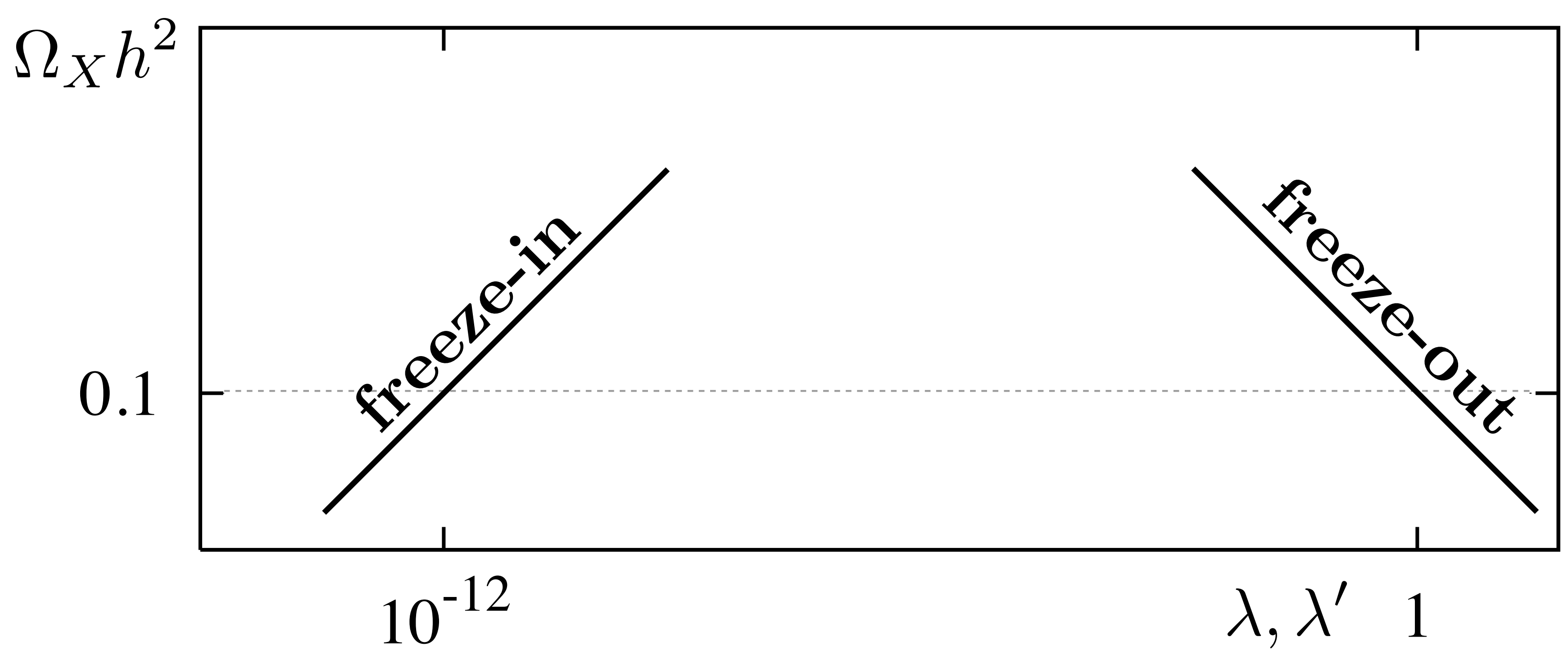
FREEZE-OUT VS FREEZE-IN

- AS TEMP DROPS BELOW MASS OF RELEVANT PARTICLE, DM ABUNDANCE IS HEADING TOWARDS (FREEZE-IN) OR AWAY FROM (FREEZE-OUT) THERMAL EQUILIBRIUM



FREEZE-OUT VS FREEZE-IN

- FOR A TEV SCALE PARTICLE WE HAVE THE FOLLOWING PICTURE



FIMP MIRACLE VS WIMP MIRACLE

- WIMP MIRACLE IS THAT FOR $m' \sim v \quad \lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

FIMP MIRACLE VS WIMP MIRACLE

- WIMP MIRACLE IS THAT FOR $m' \sim v \quad \lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

FIMP MIRACLE VS WIMP MIRACLE

- ☐ WIMP MIRACLE IS THAT FOR $m' \sim v \quad \lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

- ☐ FIMP MIRACLE IS THAT FOR $m \sim v \quad \lambda \sim v/M_{Pl}$

$$Y_{FI} \sim \lambda^2\left(\frac{M_{Pl}}{m}\right) \sim \frac{v}{M_{Pl}}$$

EXAMPLE MODEL I

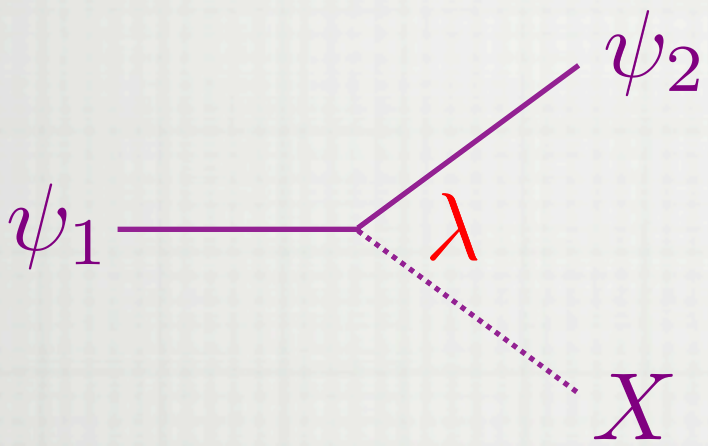
- CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS, FIMP IS LIGHTEST STATES CARRYING SOME STABILISING SYMMETRY - FIMP IS DM

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

EXAMPLE MODEL I

- CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS, FIMP IS LIGHTEST STATES CARRYING SOME STABILISING SYMMETRY - FIMP IS DM

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



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

ABUNDANCE GOES AS λ^2

CORRECT ABUNDANCE

FOR $m_X \sim m_{\psi_1}$

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

- GIVES LONG LIVED DECAYS AT LHC, IMPLICATIONS FOR BBN

- MASS OF FIMP DOES NOT HAVE TO BE SAME SCALE AS BATH PARTICLES, COULD HAVE MUCH SMALLER MASS

EXAMPLE MODEL II

- CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS B_1 B_2
- AGAIN ASSUME FIMP IS LIGHTEST PARTICLE UNDER SOME STABILISING SYMMETRY - FIMP IS DM
- CONSIDER SOME QUARTIC INTERACTION OF FIMP WITH TWO BATH SCALARS

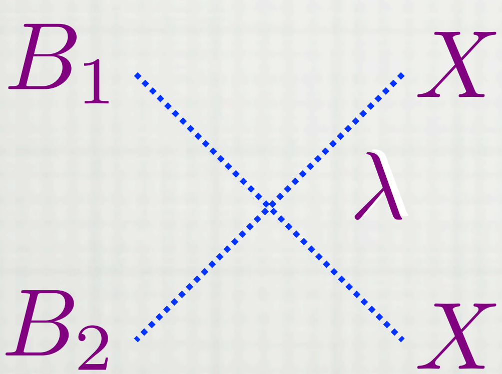
EXAMPLE MODEL II

- ☐ CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS B_1 B_2
- ☐ AGAIN ASSUME FIMP IS LIGHTEST PARTICLE UNDER SOME STABILISING SYMMETRY - FIMP IS DM
- ☐ CONSIDER SOME QUARTIC INTERACTION OF FIMP WITH TWO BATH SCALARS

$$\mathcal{L}_Q = \lambda X^2 B_1 B_2$$

ASSUMING

$$m_X \gg m_{B_1}, m_{B_2}$$



EXAMPLE MODEL II

- CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS B_1 B_2

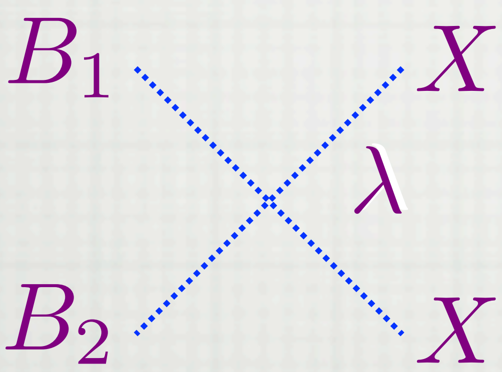
- AGAIN ASSUME FIMP IS LIGHTEST PARTICLE UNDER SOME STABILISING SYMMETRY - FIMP IS DM

- CONSIDER SOME QUARTIC INTERACTION OF FIMP WITH TWO BATH SCALARS

$$\mathcal{L}_Q = \lambda X^2 B_1 B_2$$

ASSUMING

$$m_X \gg m_{B_1}, m_{B_2}$$



$$\Omega h^2_X \approx 10^{21} \lambda^2$$

FOR CORRECT ABUNDANCE $\Rightarrow \lambda \sim 10^{-11}$

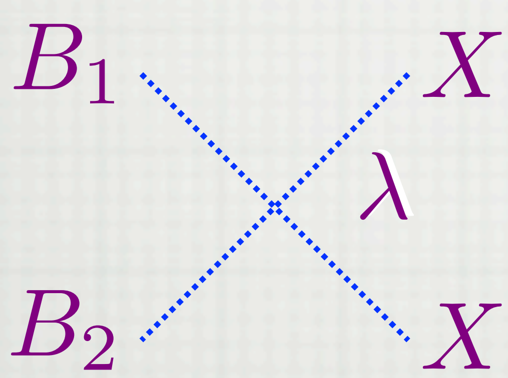
EXAMPLE MODEL II

- ☐ CONSIDER FIMP X COUPLED TO TWO BATH FERMIONS B_1 B_2
- ☐ AGAIN ASSUME FIMP IS LIGHTEST PARTICLE UNDER SOME STABILISING SYMMETRY - FIMP IS DM
- ☐ CONSIDER SOME QUARTIC INTERACTION OF FIMP WITH TWO BATH SCALARS

$$\mathcal{L}_Q = \lambda X^2 B_1 B_2$$

ASSUMING

$$m_X \gg m_{B_1}, m_{B_2}$$



$$\Omega h_X^2 \approx 10^{21} \lambda^2$$

FOR CORRECT ABUNDANCE $\Rightarrow \lambda \sim 10^{-11}$

- ☐ NOTE: ABUNDANCE IN THIS CASE IS INDEPENDENT OF THE FIMP MASS, FIMPZILLA?

EXPERIMENTAL IMPLICATIONS

- ☐ LONG LIVED "LOSPS" AT THE LHC: FIMPS FROZEN-IN BY DECAY OF LOSP
--- LOSP PRODUCED AT LHC WILL BE LONG LIVED
- ☐ LOSP COULD BE CHARGED

EXPERIMENTAL IMPLICATIONS

- ☐ LONG LIVED "LOSPS" AT THE LHC: FIMPS FROZEN-IN BY DECAY OF LOSP
- --- LOSP PRODUCED AT LHC WILL BE LONG LIVED
- ☐ LOSP COULD BE CHARGED

$$\tau_{\rm LOSP} = 7.7 \times 10^{-3}{\rm sec} \left(\frac{m_X}{100\,{\rm GeV}}\right) \left(\frac{300\,{\rm GeV}}{m_{\rm LOSP}}\right)^2 \left(\frac{10^2}{g_*(m_{\rm LOSP})}\right)^{3/2}$$

EXPERIMENTAL IMPLICATIONS

- LONG LIVED "LOSPS" AT THE LHC: FIMPS FROZEN-IN BY DECAY OF LOSP

--- LOSP PRODUCED AT LHC WILL BE LONG LIVED

- LOSP COULD BE CHARGED

$$\tau_{\rm LOSP} = 7.7 \times 10^{-3} {\rm sec} \left(\frac{m_X}{100 \,{\rm GeV}} \right) \left(\frac{300 \,{\rm GeV}}{m_{\rm LOSP}} \right)^2 \left(\frac{10^2}{g_*(m_{\rm LOSP})} \right)^{3/2}$$

- SIGNALS FOR BBN: FIMPS AND LOSPS DECAYING LATE

- ENHANCED INDIRECT AND DIRECT DETECTION: RELIC ABUNDANCE NO LONGER LINKED TO DM ANNIHILATION RATE

ASYMMETRIC FREEZE-IN

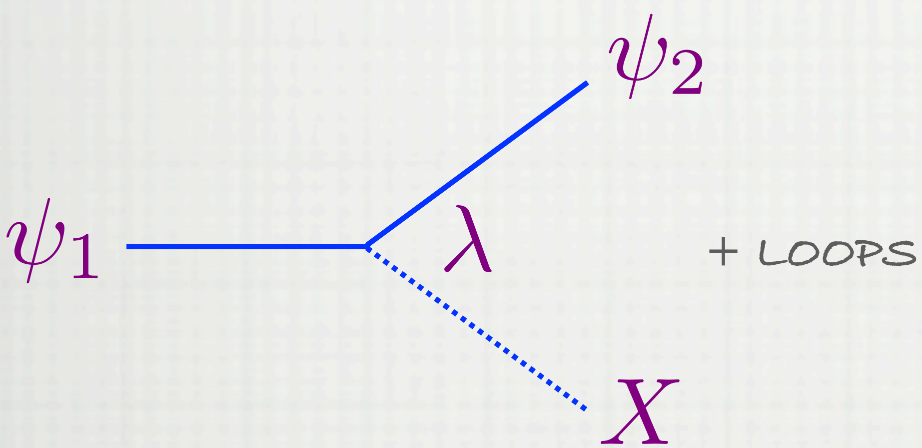
HALL, MARCH-RUSSELL, SMW
ARXIV: 1010:0245 [HEP-PH]

- WE CAN INTRODUCE CP AND B-L VIOLATION IN THE DECAYS THAT FREEZE-IN OUR DARK MATTER

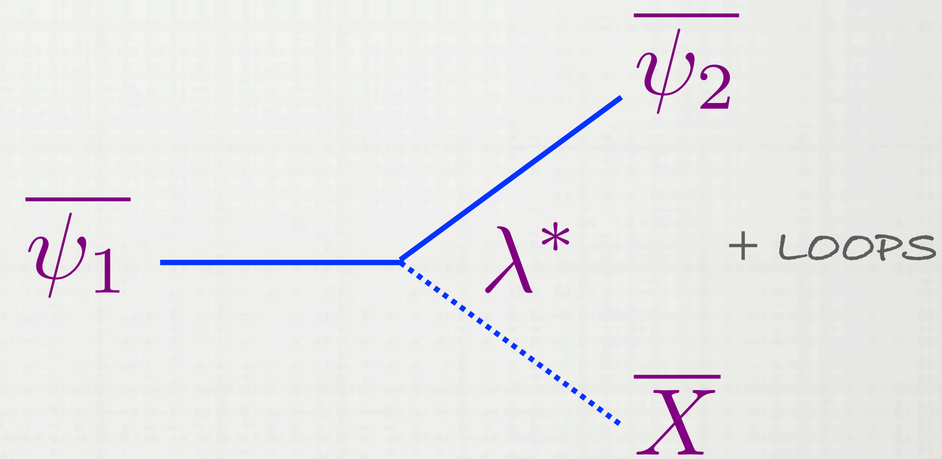
ASYMMETRIC FREEZE-IN

HALL, MARCH-RUSSELL, SMW
ARXIV: 1010:0245 [HEP-PH]

- ☐ WE CAN INTRODUCE CP AND B-L VIOLATION IN THE DECAYS THAT FREEZE-IN OUR DARK MATTER



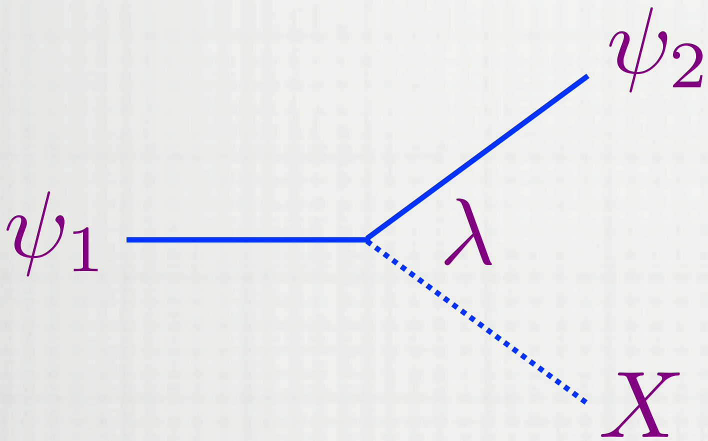
$\neq$



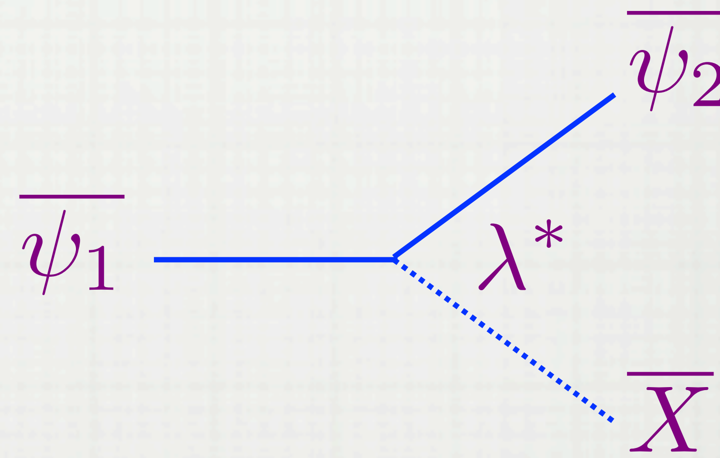
ASYMMETRIC FREEZE-IN

HALL, MARCH-RUSSELL, SMW
ARXIV: 1010:0245 [HEP-PH]

- WE CAN INTRODUCE CP AND B-L VIOLATION IN THE DECAYS THAT FREEZE-IN OUR DARK MATTER



+ LOOPS $\neq$



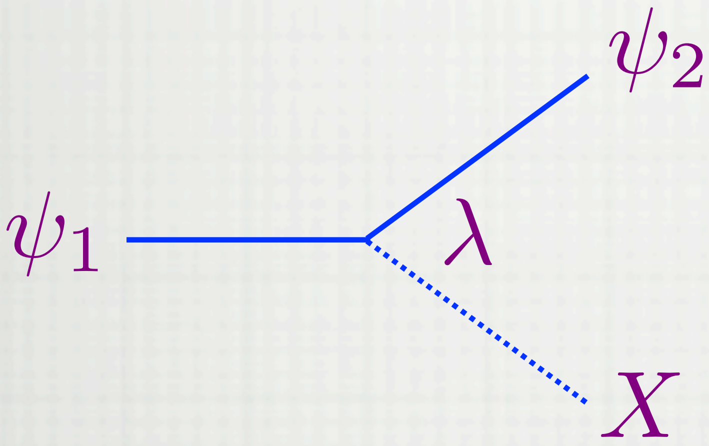
+ LOOPS

$$\Gamma(\psi_1 \to \psi_2 X) \neq \Gamma(\overline{\psi}_1 \to \overline{\psi}_2 \overline{X})$$

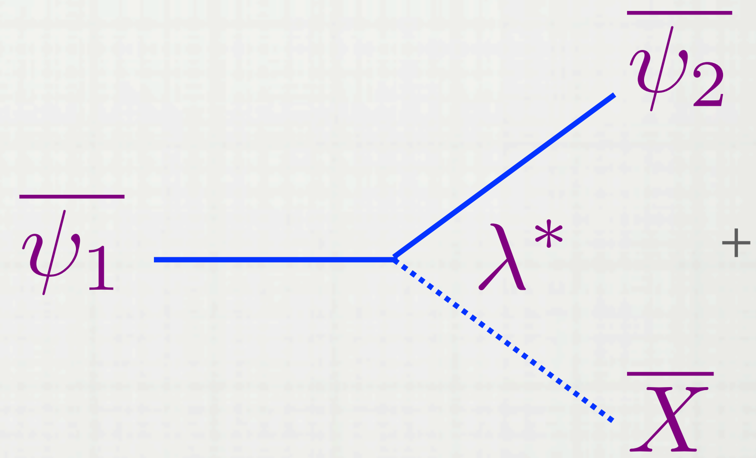
ASYMMETRIC FREEZE-IN

HALL, MARCH-RUSSELL, SMW
ARXIV: 1010:0245 [HEP-PH]

- WE CAN INTRODUCE CP AND B-L VIOLATION IN THE DECAYS THAT FREEZE-IN OUR DARK MATTER



+ LOOPS $\neq$



+ LOOPS

$$\Gamma(\psi_1 \to \psi_2 X) \neq \Gamma(\overline{\psi}_1 \to \overline{\psi}_2 \overline{X})$$

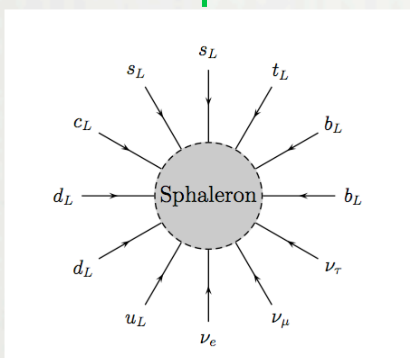
- WE NEED CP VIOLATION (AND LOOP DIAGRAMS TO INTERFERE WITH THE TREE LEVEL DIAGRAMS)

ASYMMETRIC FREEZE-IN EXAMPLE

T

NO ASYMMETRY IN DM, B OR L

10^{12} GeV

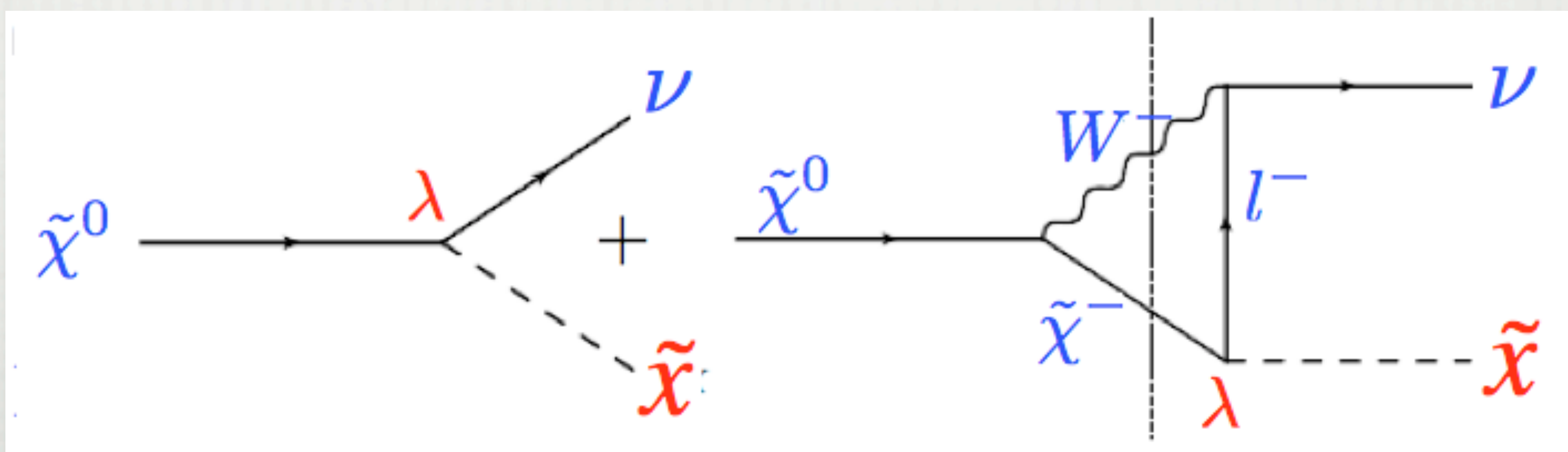


10^2 GeV

$$\lambda_i L_i H_u X$$

THIS OPERATOR NOW HAS A SMALL COUPLING AND IS RESPONSIBLE FOR THE ASYMMETRY

HAS A SYMMETRY $U(1)_{B-L+X}$



ASYMMETRIC FREEZE-IN EXAMPLE

- THESE PROCESSES ALREADY CONTAIN OUT-OF-EQUILIBRIUM PROCESSES - FIMP IS NOT IN THERMAL EQUILIBRIUM, IN FACT ALL YOU NEED IS A DIFFERENCE IN TEMPERATURE BETWEEN FIMP AND SM SECTOR

ASYMMETRIC FREEZE-IN EXAMPLE

- THESE PROCESSES ALREADY CONTAIN OUT-OF-EQUILIBRIUM PROCESSES - FIMP IS NOT IN THERMAL EQUILIBRIUM, IN FACT ALL YOU NEED IS A DIFFERENCE IN TEMPERATURE BETWEEN FIMP AND SM SECTOR
- ASYMMETRY NAIVELY GIVEN BY

$$\eta_L = \eta_X = \epsilon Y_X = \epsilon \Gamma_{\chi^0} \frac{M_{pl}}{m_{\chi^0}^2}$$

$$\epsilon = (\text{loop factor}) \sin\phi \qquad \Gamma_{\chi^0} \sim \frac{\lambda^2 m_{\chi^0}}{8\pi}$$

ASYMMETRIC FREEZE-IN EXAMPLE

- THESE PROCESSES ALREADY CONTAIN OUT-OF-EQUILIBRIUM PROCESSES - FIMP IS NOT IN THERMAL EQUILIBRIUM, IN FACT ALL YOU NEED IS A DIFFERENCE IN TEMPERATURE BETWEEN FIMP AND SM SECTOR
- ASYMMETRY NAIVELY GIVEN BY

$$\eta_L = \eta_X = \epsilon Y_X = \epsilon \Gamma_{\chi^0} \frac{M_{pl}}{m_{\chi^0}^2}$$

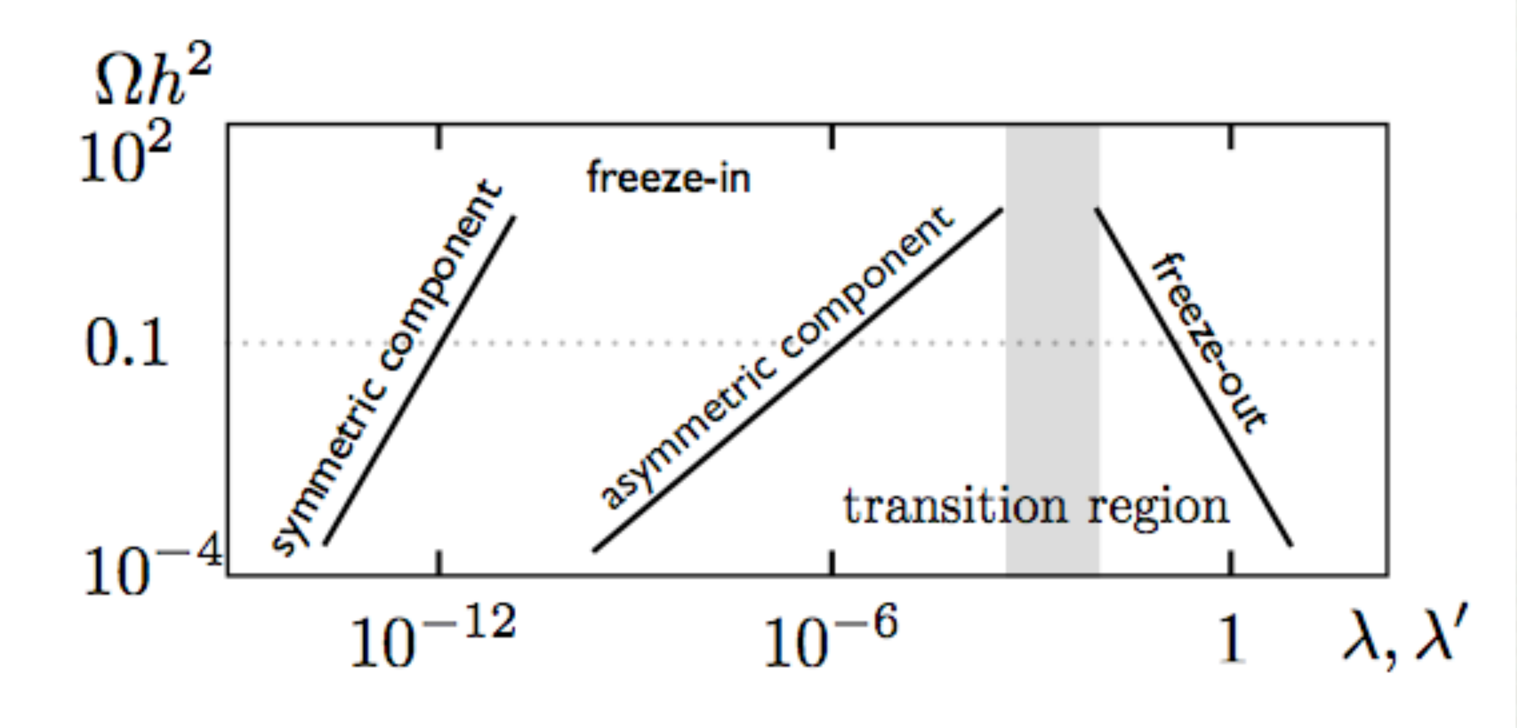
$$\epsilon = (\text{loop factor}) \sin\phi \qquad \Gamma_{\chi^0} \sim \frac{\lambda^2 m_{\chi^0}}{8\pi}$$

- ASYMMETRY APPEARS AT λ^2
- CP VIOLATION COULD COME FROM GAUGINO - HIGGSINO SECTOR

ASYMMETRIC FREEZE-IN

ASYMMETRIC FREEZE-IN

- TURNS OUT, THROUGH NON-TRIVIAL CANCELLATIONS IN THE BOLTZMANN EQUATIONS THE ASYMMETRY APPEARS AT λ^3 HOOK, ARXIV:1105:3728



- MAKES THE MODEL VERY PREDICTIVE - NOT MUCH PARAMETER SPACE

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

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

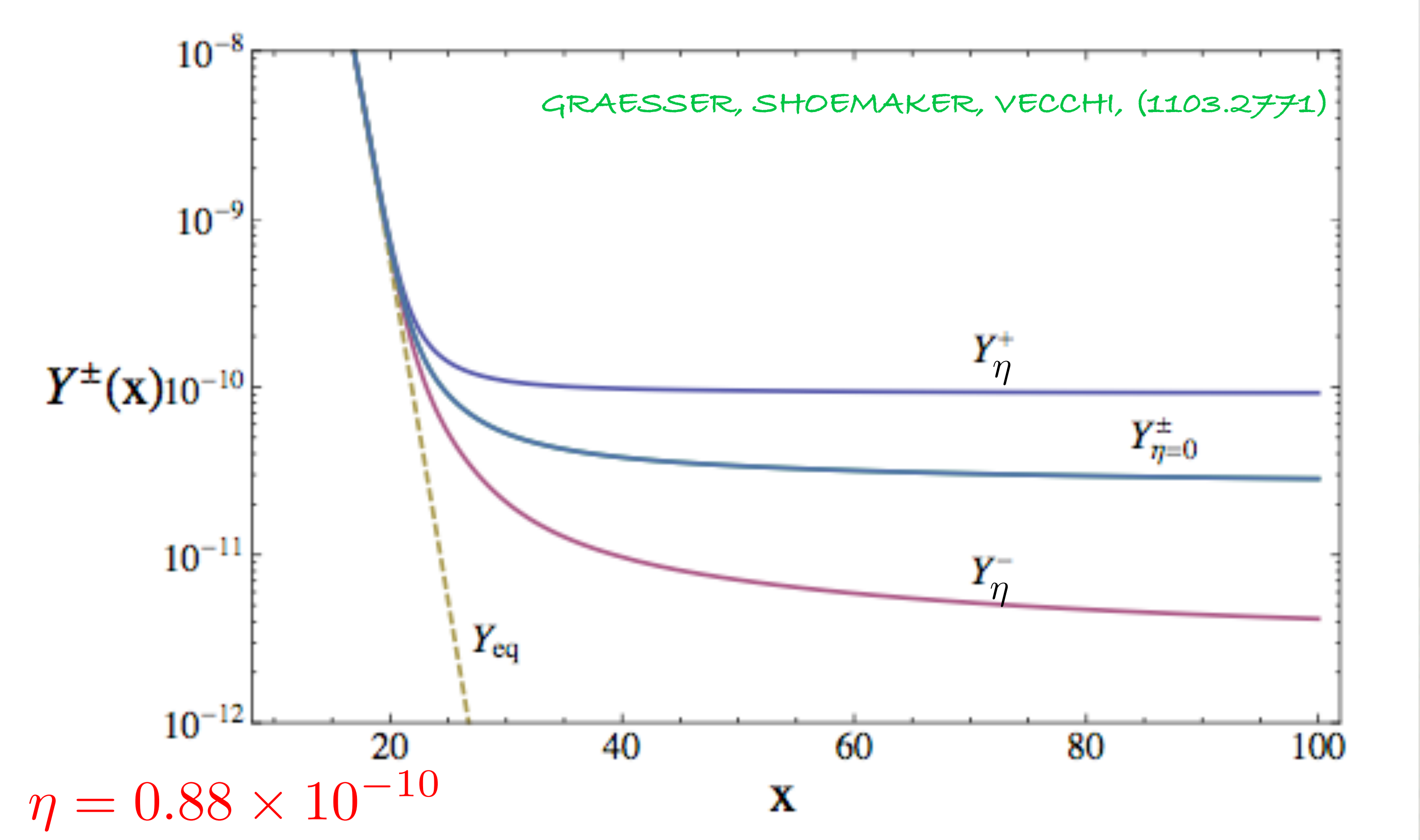
FOR MORE DETAILS SEE IMINNIYAZ, DREES, CHEN (1104.5548); GRAESSER, SHOEMAKER, VECCHI, (1103.2771)

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

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

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



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

REMOVING THE SYMMETRIC COMPONENT

- TRADITIONAL INDIRECT SIGNALS WILL BE SUPPRESSED...ANY OTHERS?
- LARGE SYMMETRIC ABUNDANCE OF DM NEEDS TO ANNIHILATE AWAY

REMOVING THE SYMMETRIC COMPONENT

- TRADITIONAL INDIRECT SIGNALS WILL BE SUPPRESSED...ANY OTHERS?
- LARGE SYMMETRIC ABUNDANCE OF DM NEEDS TO ANNIHILATE AWAY
- THREE OPTIONS TO DO THIS:
  - 1) USE FURTHER CONNECTOR OPERATORS IN ANNIHILATIONS DIRECTLY, THESE MUST NOT TRANSFER AN ASYMMETRY BUCKLEY, 1104.1429

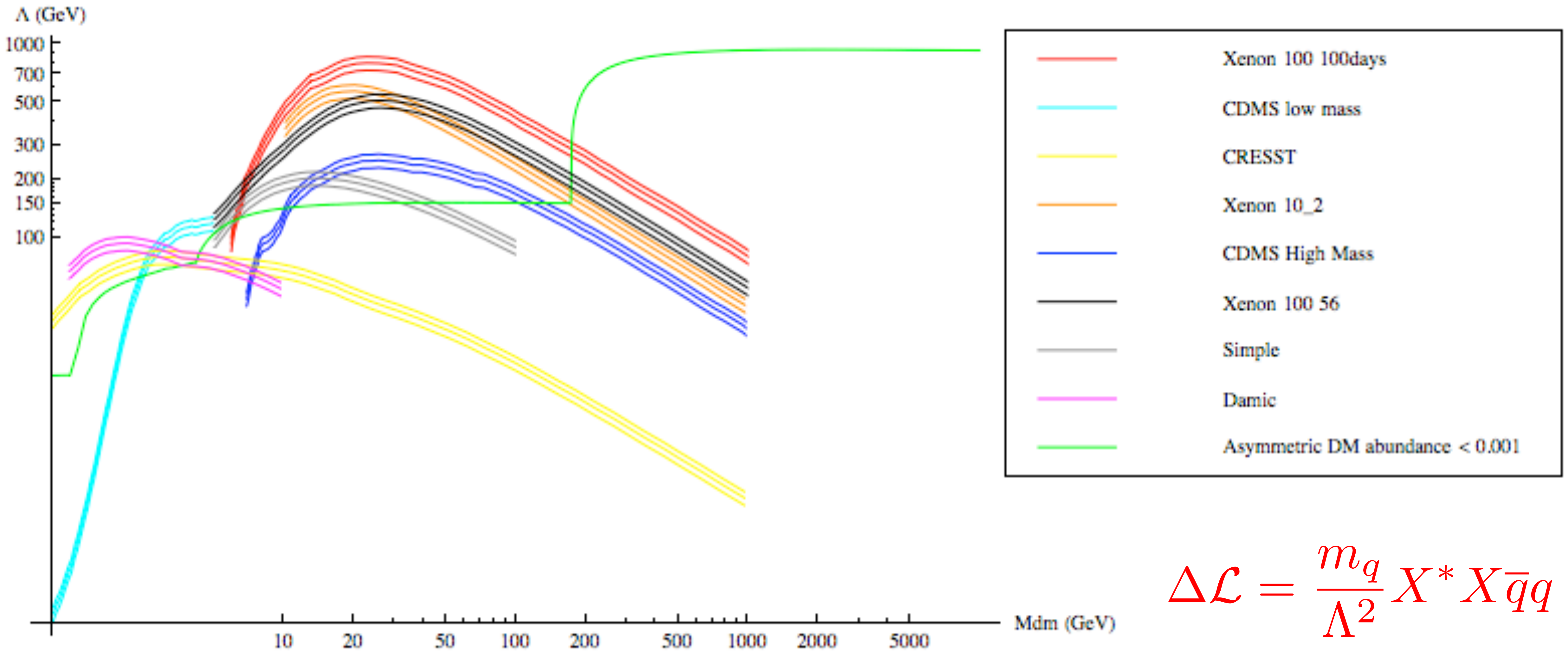
E.G.

$$\Delta\mathcal{L} = \frac{m_q}{\Lambda^2} X^* X \bar{q} q$$

CONSTRAINTS FROM DIRECT DETECTION, COLLIDERS ETC

REMOVING THE SYMMETRIC COMPONENT

- TRADITIONAL INDIRECT SIGNALS WILL BE SUPPRESSED...ANY OTHERS?



$$\Delta\mathcal{L} = \frac{m_q}{\Lambda^2} X^* X \bar{q} q$$

REMOVING THE SYMMETRIC COMPONENT

- TRADITIONAL INDIRECT SIGNALS WILL BE SUPPRESSED...ANY OTHERS?
- LARGE SYMMETRIC ABUNDANCE OF DM NEEDS TO ANNIHILATE AWAY
- THREE OPTIONS TO DO THIS:
  - 1) USE FURTHER CONNECTOR OPERATORS IN ANNIHILATIONS DIRECTLY, THESE MUST NOT TRANSFER AN ASYMMETRY BUCKLEY, 1104.1429

E.G.

$$\Delta\mathcal{L} = \frac{m_q}{\Lambda^2} X^* X \bar{q} q$$

CONSTRAINTS FROM DIRECT DETECTION, COLLIDERS ETC

REMOVING THE SYMMETRIC COMPONENT

- TRADITIONAL INDIRECT SIGNALS WILL BE SUPPRESSED...ANY OTHERS?
- LARGE SYMMETRIC ABUNDANCE OF DM NEEDS TO ANNIHILATE AWAY
- THREE OPTIONS TO DO THIS:
  - 1) USE FURTHER CONNECTOR OPERATORS IN ANNIHILATIONS DIRECTLY, THESE MUST NOT TRANSFER AN ASYMMETRY BUCKLEY, 1104.1429

E.G. $$\Delta\mathcal{L} = \frac{m_q}{\Lambda^2} X^* X \bar{q} q$$

CONSTRAINTS FROM DIRECT DETECTION, COLLIDERS ETC

  - 2) AND 3)USE ADDITIONAL STATES IN DARK SECTOR - FREEZE-OUT IN THIS SECTOR TO SOME VERY LIGHT STABLE STATE OR UNSTABLE STATE, WHICH DECAYS BACK TO SM SECTOR

SEE E.G. HALL, MARCH-RUSSELL, SMW, ARXIV:1010:0245
AND MARCH-RUSSELL, UNWIN, SMW TO APPEAR

REMOVING THE SYMMETRIC COMPONENT

- TRADITIONAL INDIRECT SIGNALS WILL BE SUPPRESSED...ANY OTHERS?
- LARGE SYMMETRIC ABUNDANCE OF DM NEEDS TO ANNIHILATE AWAY
- THREE OPTIONS TO DO THIS:
  - 1) USE FURTHER CONNECTOR OPERATORS IN ANNIHILATIONS DIRECTLY, THESE MUST NOT TRANSFER AN ASYMMETRY BUCKLEY, 1104.1429

E.G.

$$\Delta\mathcal{L} = \frac{m_q}{\Lambda^2} X^* X \bar{q} q$$

CONSTRAINTS FROM DIRECT DETECTION, COLLIDERS ETC

  - 2) AND 3)USE ADDITIONAL STATES IN DARK SECTOR - FREEZE-OUT IN THIS SECTOR TO SOME VERY LIGHT STABLE STATE OR UNSTABLE STATE, WHICH DECAYS BACK TO SM SECTOR
  - POSSIBLY VERY INTERESTING SCENARIO - CONSTRAINTS COMING FROM BBN AND CMBR DEPENDING ON LIFETIME OF UNSTABLE STATE

SEE E.G. HALL, MARCH-RUSSELL, SMW, ARXIV:1010:0245
AND MARCH-RUSSELL, UNWIN, SMW TO APPEAR

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

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

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

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

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

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

- 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

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

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

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

- 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...

BACK UPS AND OLD SLIDES

CO-GENESIS IS HARD: SOME EXAMPLES

- 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

$\Rightarrow$ GENERALLY DIFFICULT TO TEST, HIGH SCALE DYNAMICS

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

CO-GENESIS IS HARD: SOME EXAMPLES

- 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

- OUT OF EQUILIBRIUM DECAYS
  - DECAYS OF PARTICLES OR SUSY FLAT DIRECTIONS
  - DECAYS VIOLATE CP AND PRODUCE ASYMMETRY IN DM AND LEPTON/BARYON NUMBER

$\Rightarrow$ GENERALLY DIFFICULT TO TEST, HIGH SCALE DYNAMICS

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

CO-GENESIS IS HARD: SOME EXAMPLES

- 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

- OUT OF EQUILIBRIUM DECAYS
  - DECAYS OF PARTICLES OR SUSY FLAT DIRECTIONS
  - DECAYS VIOLATE CP AND PRODUCE ASYMMETRY IN DM AND LEPTON/BARYON NUMBER

  $\Rightarrow$ GENERALLY DIFFICULT TO TEST, HIGH SCALE DYNAMICS

- ASYMMETRIC FREEZE-IN...MORE LATER

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

SHARING EXAMPLE

- ☐ 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)

SHARING EXAMPLE

- ☐ PRE-EXISTING ASYMMETRY IN BARYON OR DM SECTOR

- ☐ ASYMMETRY NEEDS TO BE TRANSFERRED (ASSUMING NOT CHARGED UNDER $SU(2)_L$)

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

E.G.

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

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)

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

SHARING EXAMPLE

- PRE-EXISTING ASYMMETRY IN BARYON OR DM SECTOR
- ASYMMETRY NEEDS TO BE TRANSFERRED (ASSUMING NOT CHARGED UNDER $SU(2)_L$)
- REQUIRE OPERATORS THAT LEAD TO INTERACTIONS CAPABLE OF TRANSFERRING ASYMMETRY

E.G.

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

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)

- 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 HEAVILY SUPPRESS THE ASYMMETRY - ACTUALLY LEADS TO TEV SCALE POSSIBILITY - SEE LATER

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