BSM PARTICLE AND ASTRO-PARTICLE THEORY

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APRIL 2012

INTERESTING TIME IN ASTRO-PARTICLE PHYSICS

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- MY FOCUS IS - DARK MATTER PHYSICS

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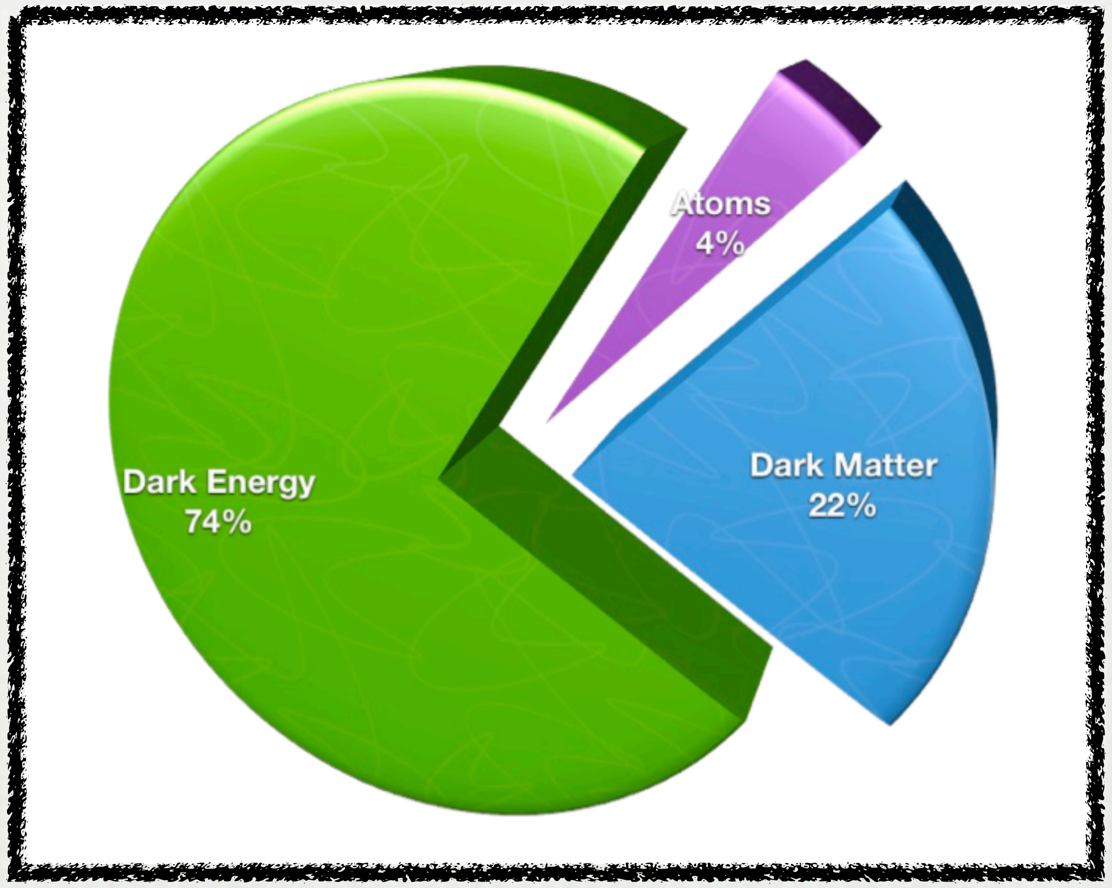
INTRODUCTION

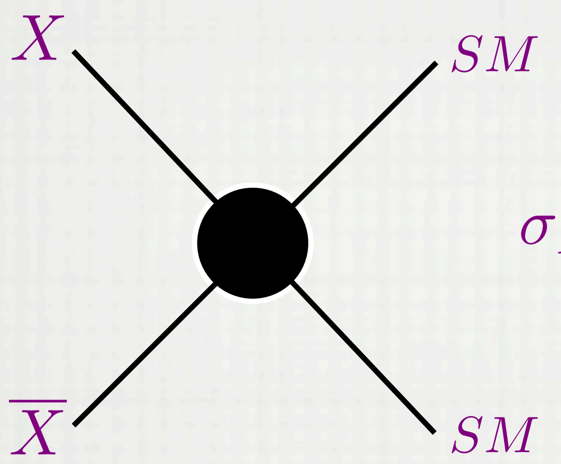
- COMPOSITION OF THE UNIVERSE:

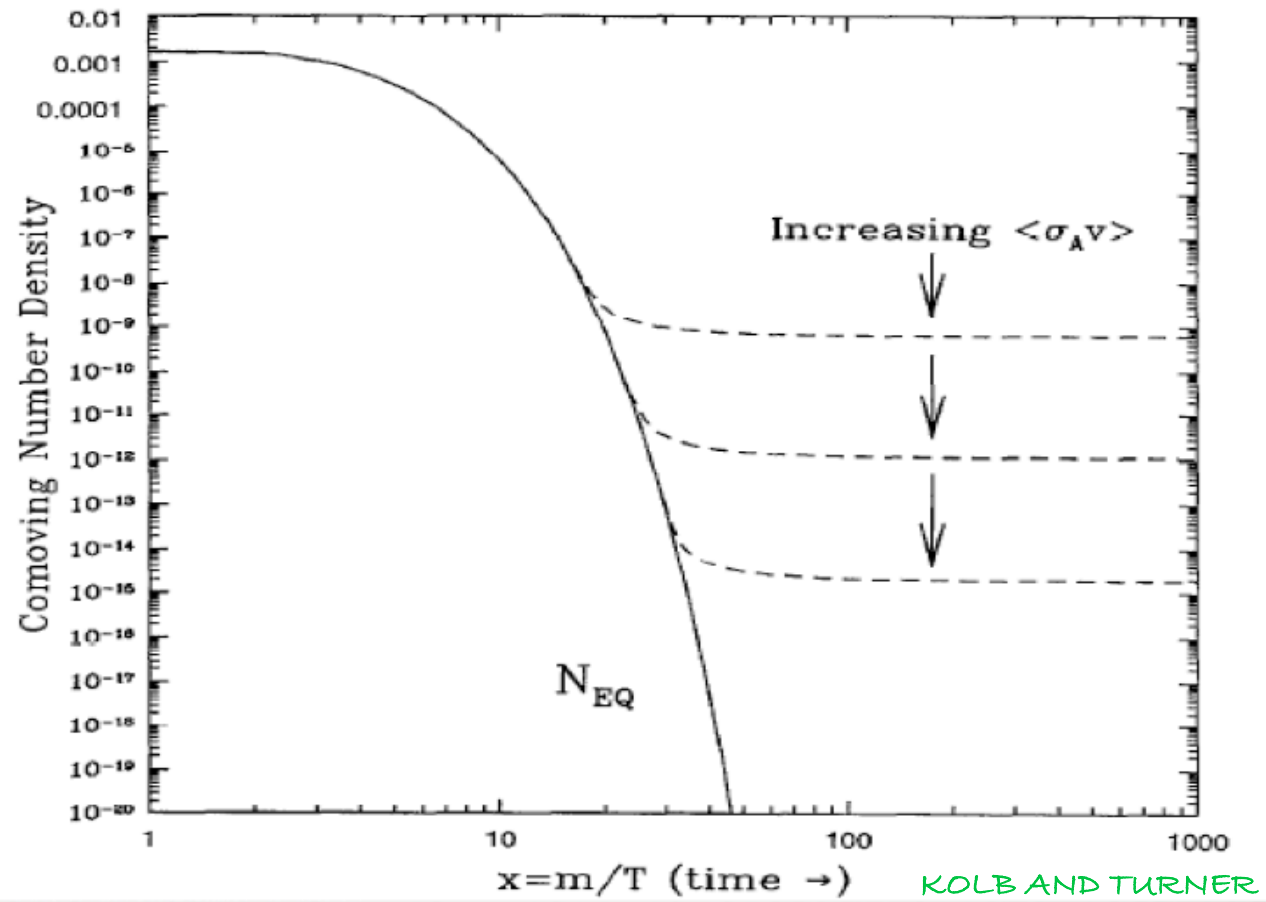


- DARK MATTER IS A MAJOR COMPONENT - DEMANDS INVESTIGATION
- MUCH WORK ALREADY DONE...MUCH DONE IN A FAMILIAR FRAMEWORK

THE "STANDARD PICTURE" - FREEZE-OUT

- ☐ DARK MATTER X INITIALLY IN THERMAL EQUILIBRIUM $T > m_X$





KOLB AND TURNER

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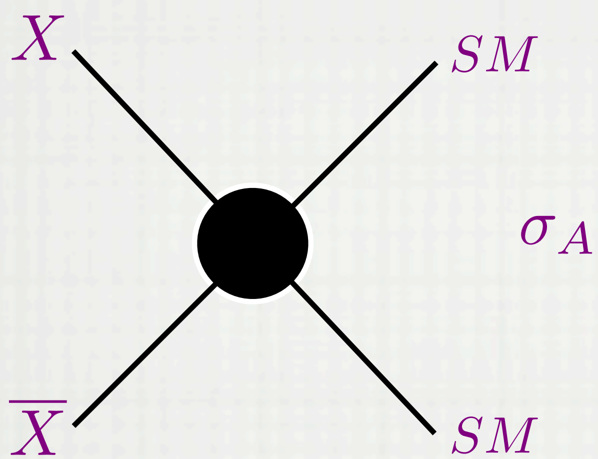

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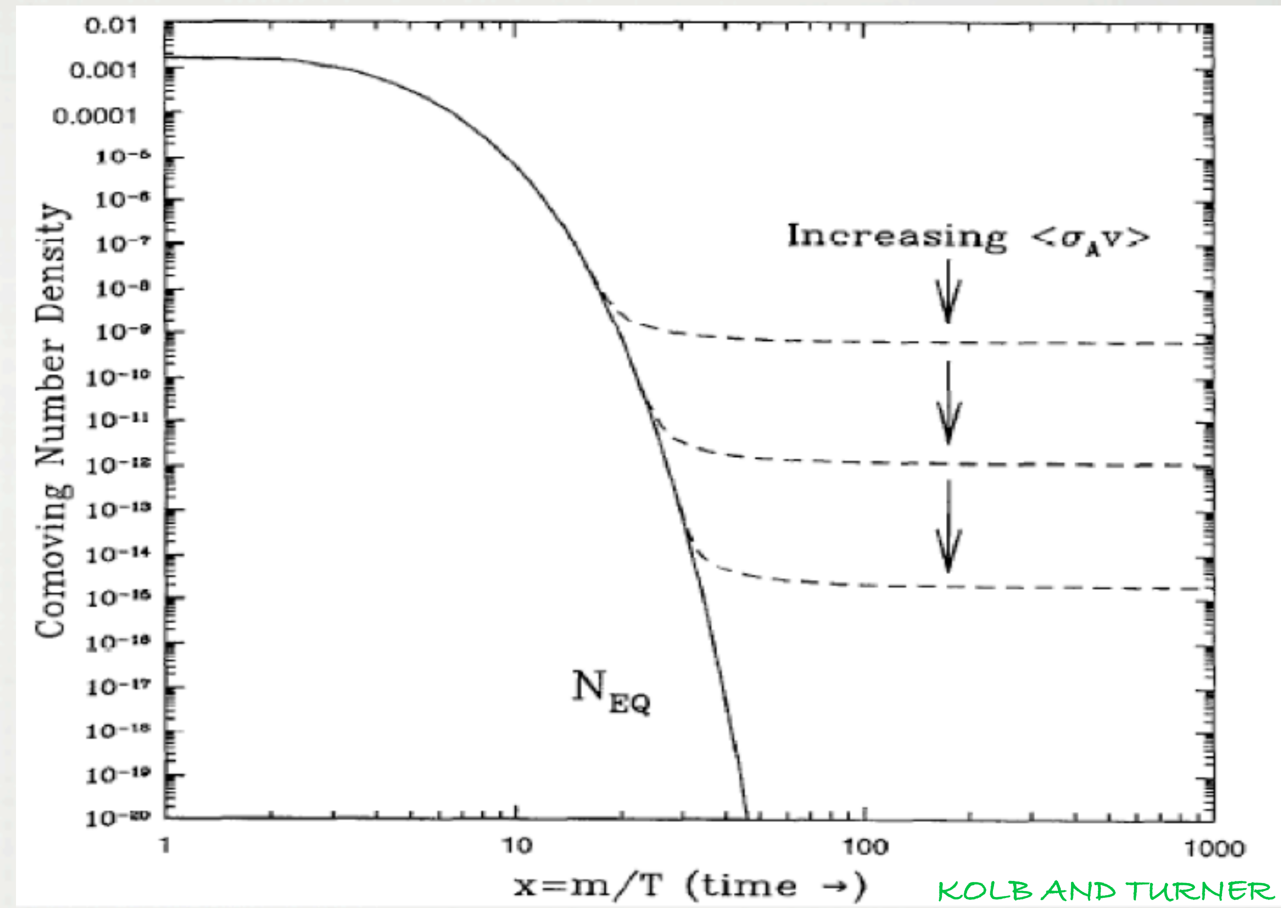

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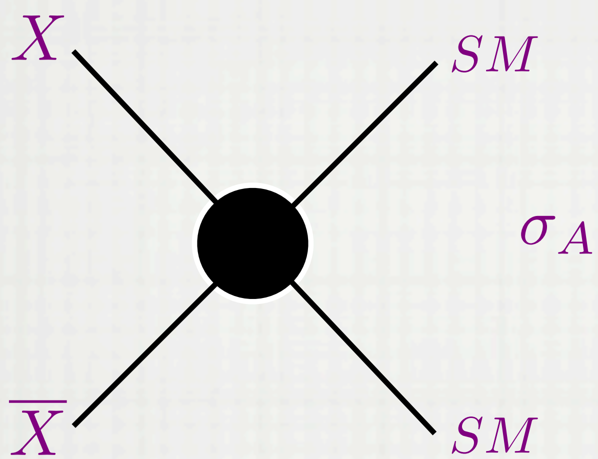

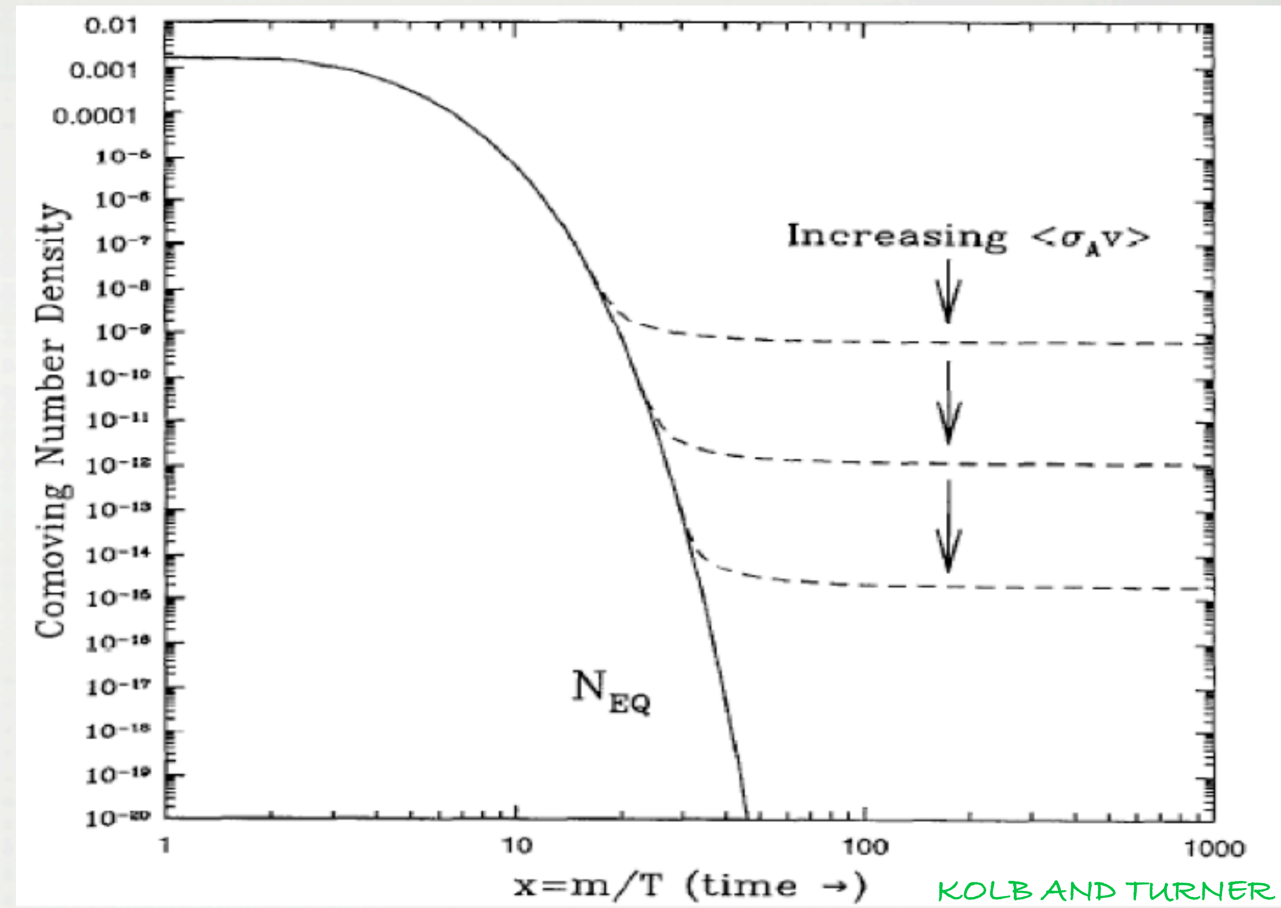

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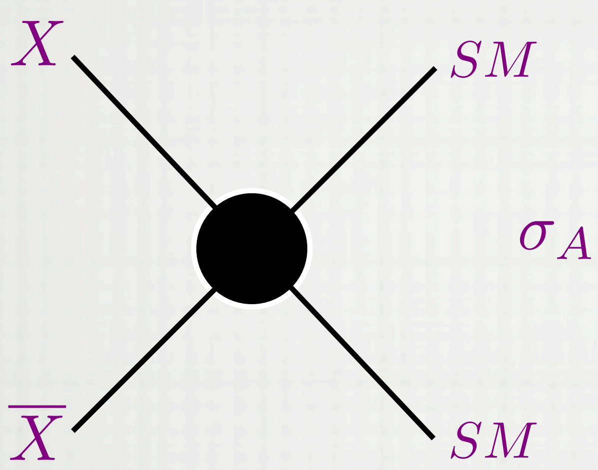
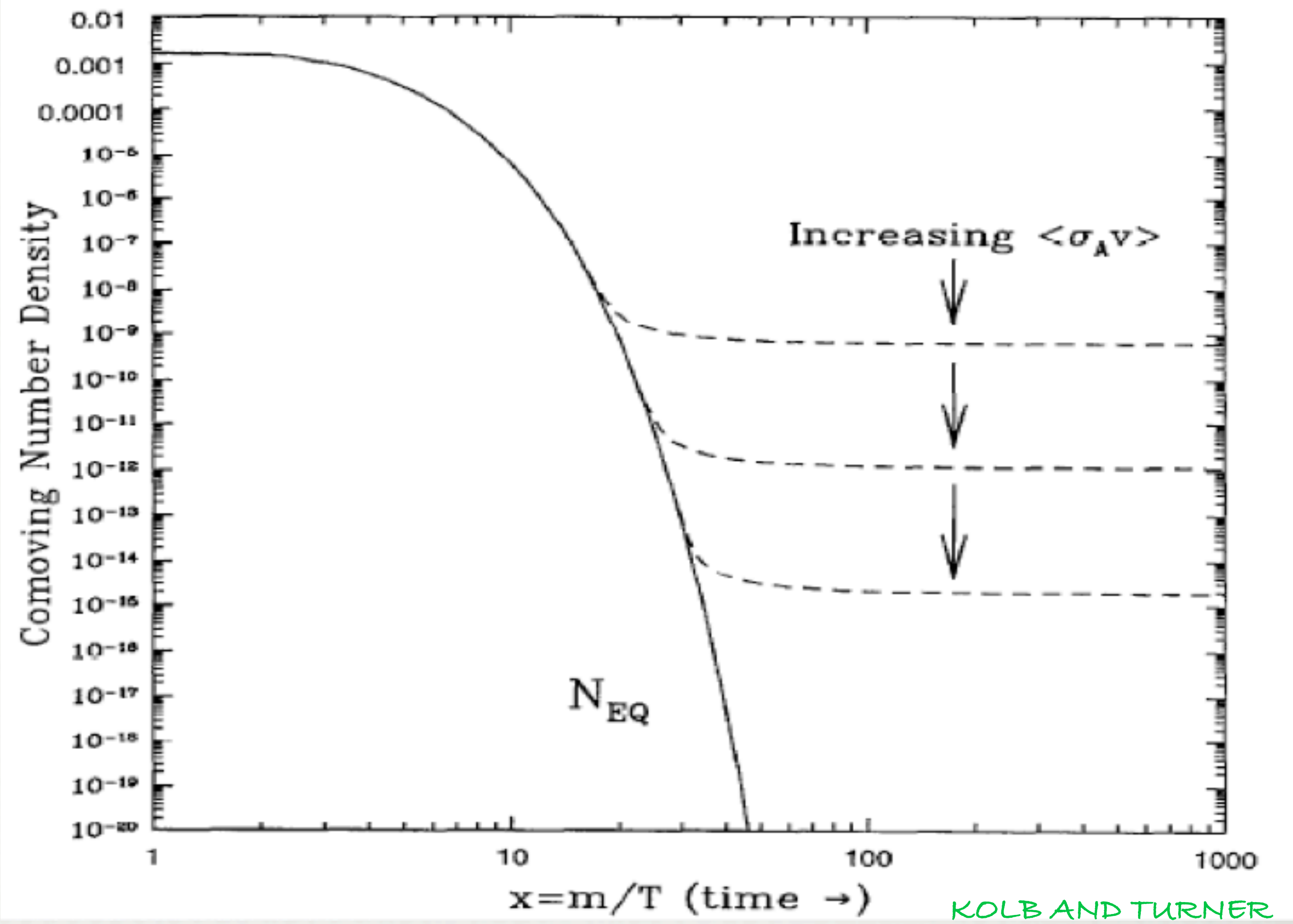
- ☐ ANNIHILATION OF X STILL PROCEEDS, NUMBER DENSITY OF X GIVEN BY

$$n_{X,eq} \approx g_X \left(\frac{m_X T}{2\pi}\right)^{3/2} e^{-m_X/T}$$

$n_{X,eq} \to 0$ as $T \to 0$

☐ DUE TO EXPANSION, DARK MATTER NUMBER DENSITY FREEZES-OUT WHEN: $\Gamma = n_X \langle \sigma_A v \rangle < H$





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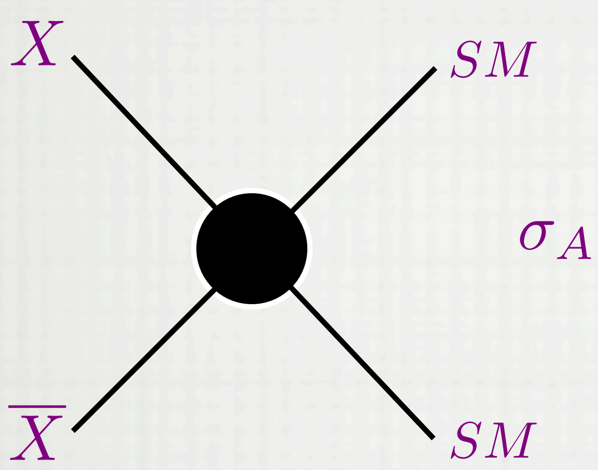
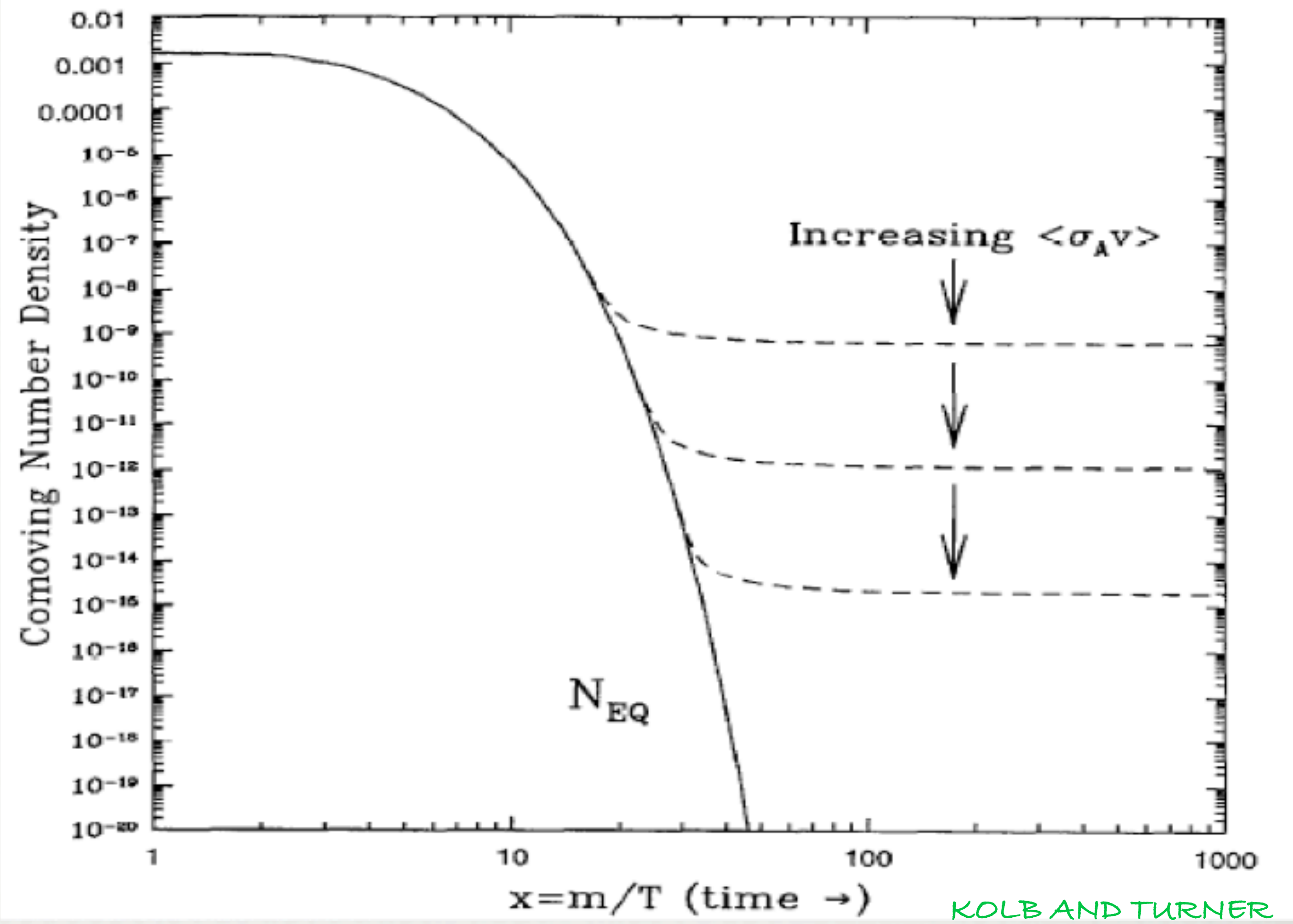




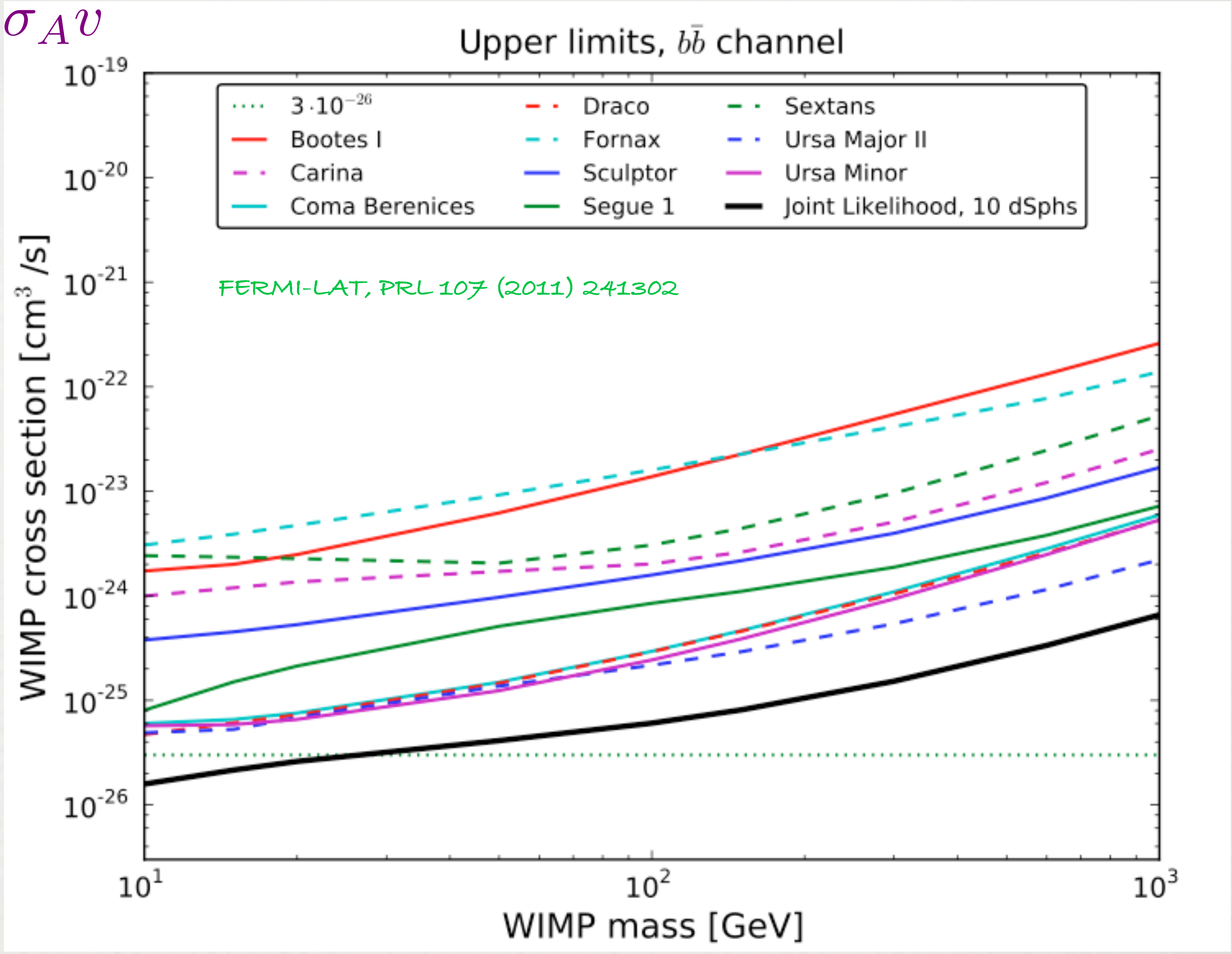
KOLB AND TURNER

☐ FINAL ABUNDANCE:

$$\Omega h^2 \sim 0.1 \frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma_A v \rangle}$$

APPROX. WEAK SCALE CROSS SECTION - WIMPS

INDIRECT DETECTION IN STANDARD PICTURE



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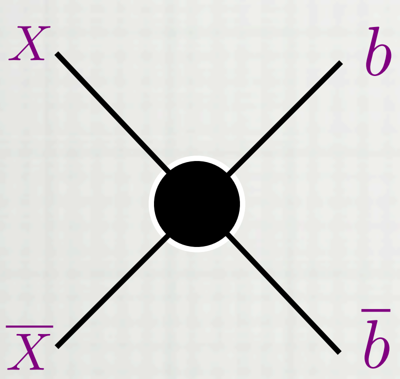

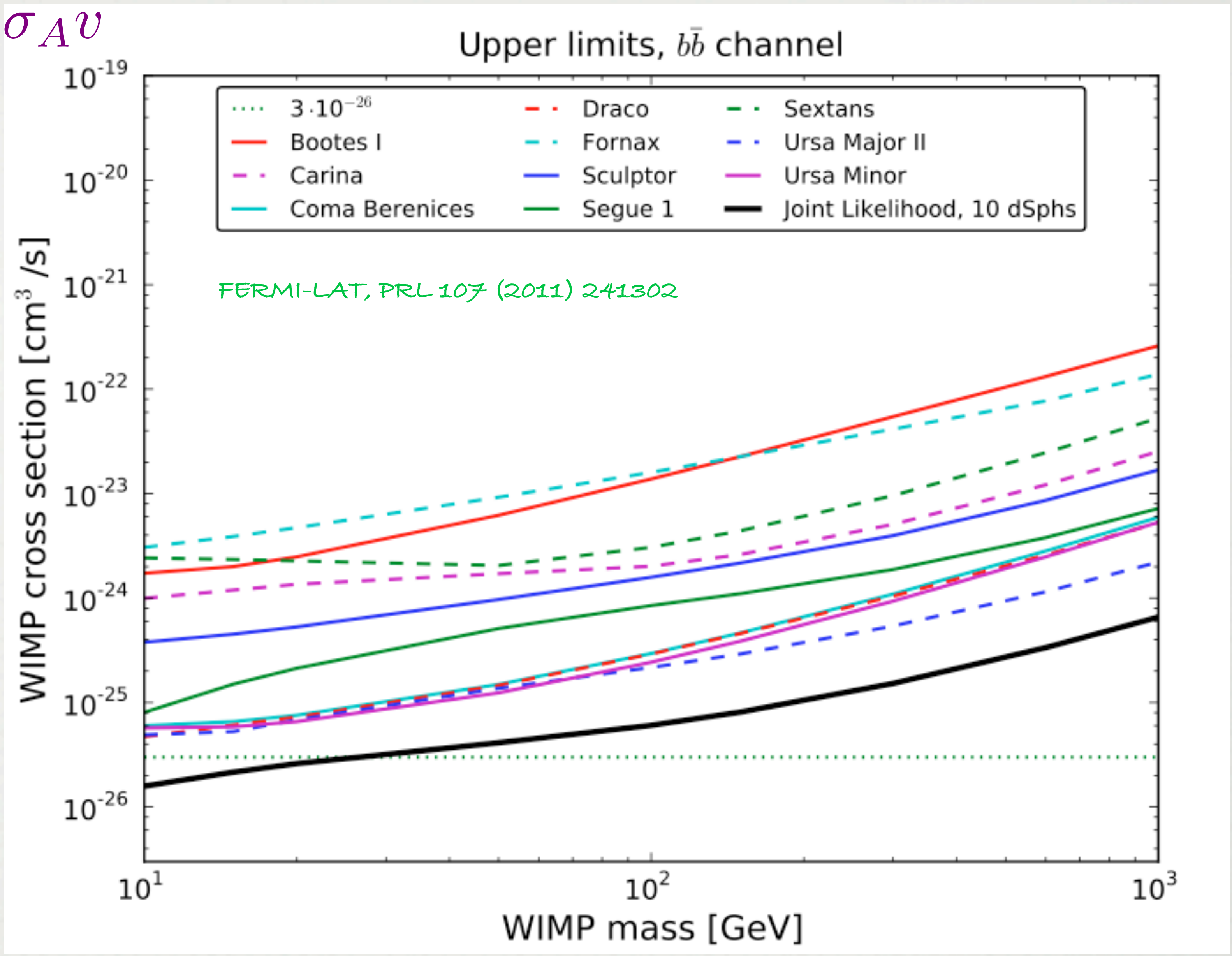

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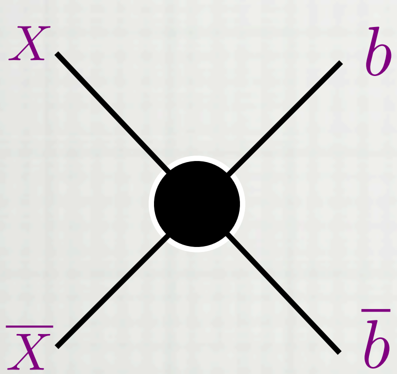

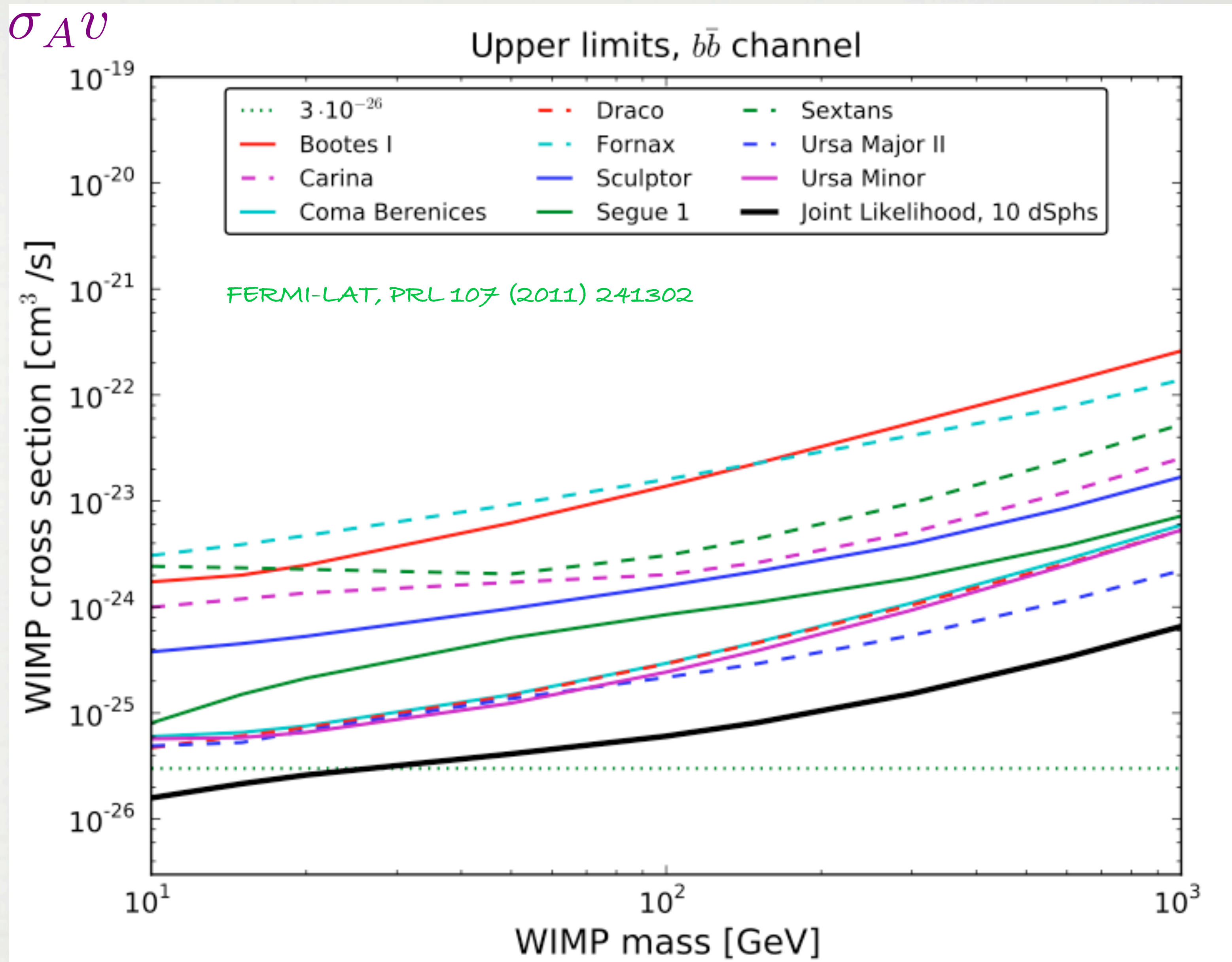

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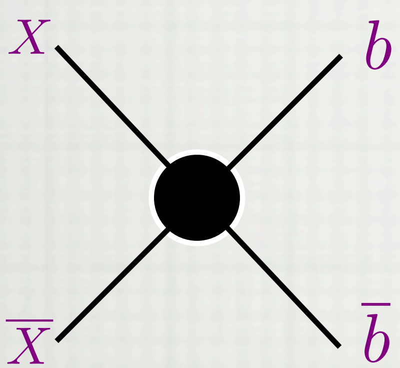

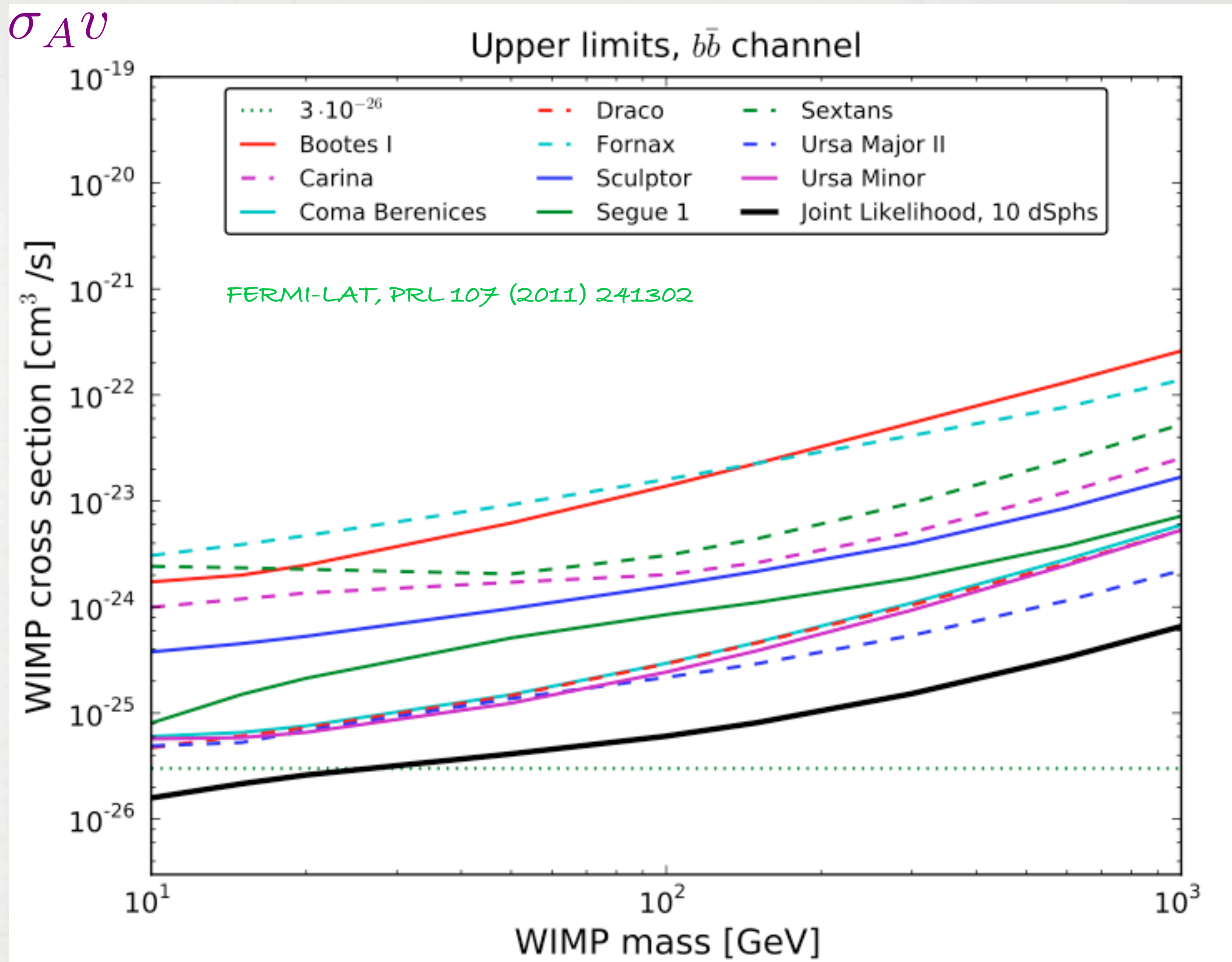

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- IMPROVING ALL THE TIME, STARTING TO IMPINGE ON DM MODELS…SEE PREVIOUS TALK!

ASYMMETRIC DM MOTIVATION

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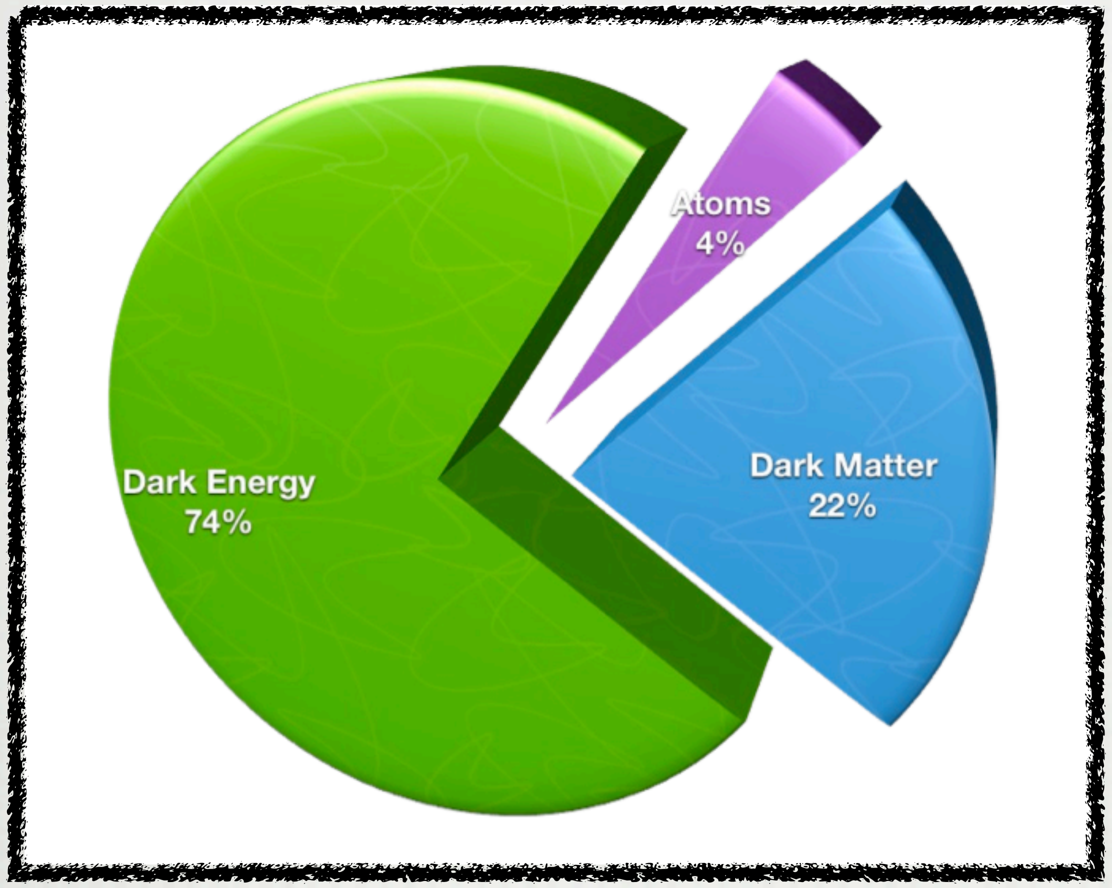

- USUALLY THESE TWO NUMBERS ARE DETERMINED BY INDEPENDENT DYNAMICS

Ω_{dm} BY FREEZE-OUT OF WIMPS

Ω_b BY BARYOGENESIS/ LEPTOGENESIS

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

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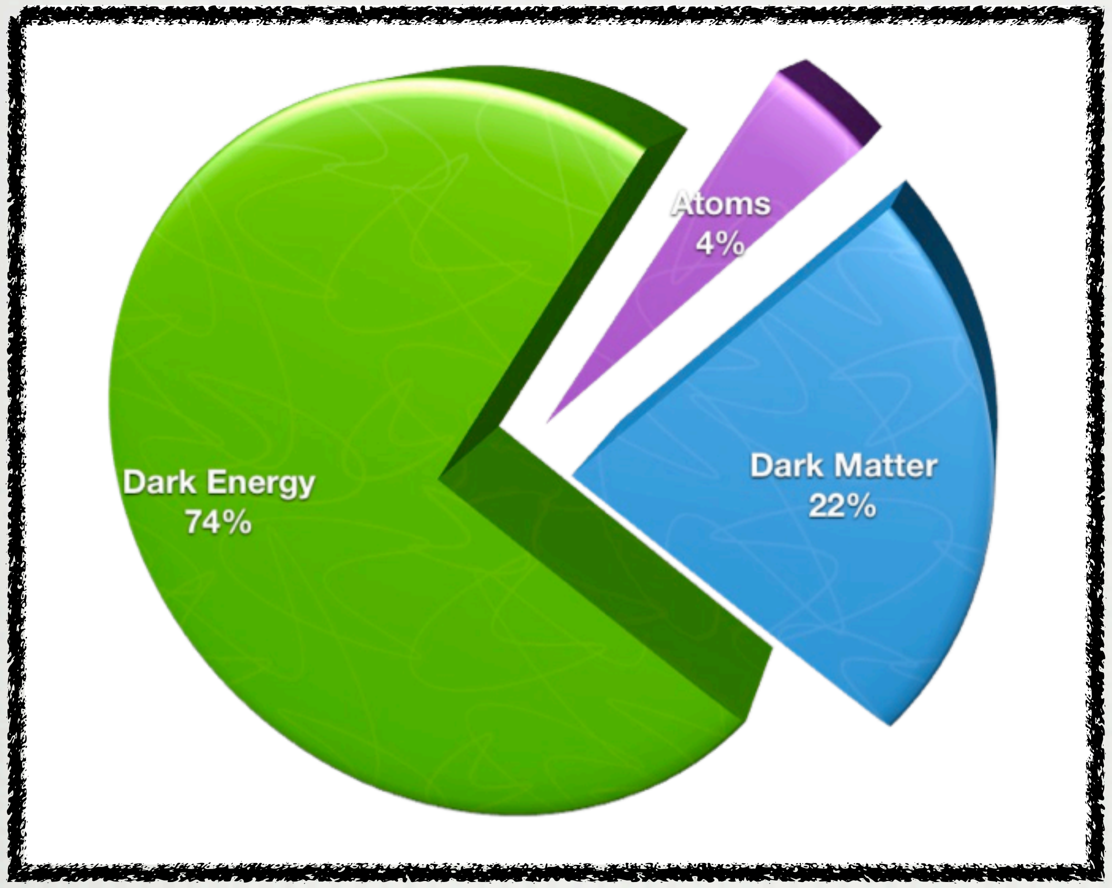

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- TAKE SERIOUSLY THE CLOSENESS OF THESE VALUES - INVESTIGATE DYNAMICS THAT LINK THE TWO...

...LEADS TO IDEAS OF ASYMMETRIC DM

ASYMMETRIC DARK MATTER BASICS

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

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- ☐ THE VALUE OF C DEPENDS ON THE DETAILS OF THE DYNAMICS CONNECTING DM AND BARYONS...A SHARED SYMMETRY

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

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

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)

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  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
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- 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

POSSIBLE MASSES

SIMPLEST CASES, THERE ARE TWO MASS REGIONS

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

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WITH $x = \dfrac{m_{dm}}{T_d}$ CORRECT RATIO FOR

$m_{dm} \sim 1\,\mathrm{TeV}$

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

SHARING EXAMPLE

KAPLAN, LUTY, ZUREK (2009)

- AT HIGH T, A B-L ASYMMETRY IS GENERATED
- TRANSFER OPERATORS PRESERVE A GLOBAL CHARGE (COMBINATION OF DM AND LEPTON NUMBER)

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

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- 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].

KAPLAN, LUTY, ZUREK (2009)

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

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

$$\eta_X = -\frac{11}{79}(\eta_B - \eta_L)$$

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

$$\eta_B \approx 0.31(\eta_B - \eta_L)$$

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

$$m_X \approx \frac{\eta_B}{\eta_X}\frac{\Omega_X}{\Omega_b} \approx 11\,\mathrm{GeV}$$

CONSTRAINING/TESTING ADM

CONSTRAINING/TESTING ADM

- TWO MAIN AVENUES:

REMOVING SYMMETRIC DM COMPONENT	LHC LIMITS - MONOJETS, MONOPHOTONS DIRECT DM DETECTION HEAVY QUARKONIUM DECAYS BBN, CMB PERTURBATIONS?

CONSTRAINING/TESTING ADM

- TWO MAIN AVENUES:

REMOVING SYMMETRIC DM COMPONENT

- LHC LIMITS - MONOJETS, MONOPHOTONS
- DIRECT DM DETECTION
- HEAVY QUARKONIUM DECAYS
- BBN, CMB PERTURBATIONS?

PROBING ASYMMETRY SHARING OPERATORS

- LHC LIMITS - LONG LIVED STATES

REMOVING THE SYMMETRIC CPT

BUCKLEY; MARCH-RUSSELL, UNWIN, SMW

$$\frac{\Omega_X}{\Omega_b} \sim \frac{\eta_X}{\eta_B} \frac{m_X}{m_b}$$

THIS IS TRUE ONLY IF THE X DENSITY IS DETERMINED BY THE ASYMMETRY

REMOVING THE SYMMETRIC CPT

BUCKLEY; MARCH-RUSSELL, UNWIN, SMW

$$\frac{\Omega_X}{\Omega_b} \sim \frac{\eta_X}{\eta_B} \frac{m_X}{m_b}$$

THIS IS TRUE ONLY IF THE X DENSITY IS DETERMINED BY THE ASYMMETRY

OTHERWISE: $$\frac{\Omega_X}{\Omega_b} \sim \frac{n_X + n_{\overline{X}}}{n_B} \frac{m_X}{m_b}$$

LOOSE RELATIONSHIP BETWEEN ABUNDANCES

NEED: $$n_X + n_{\overline{X}} \approx n_X - n_{\overline{X}}$$

- [ ] NEED TO ANNIHILATE AWAY THE SYMMETRIC COMPONENT...

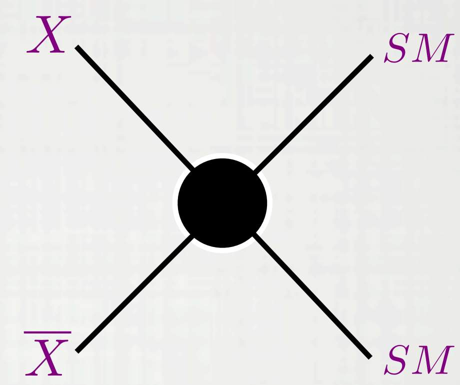
REMOVING THE SYMMETRIC CPT

REMOVING THE SYMMETRIC CPT

- THREE OPTIONS...

1) ANNIHILATE DIRECTLY TO SM STATES

INTERESTING EXISTING LIMITS ...SEE LATER



HALL, MARCH-RUSSELL, SMW

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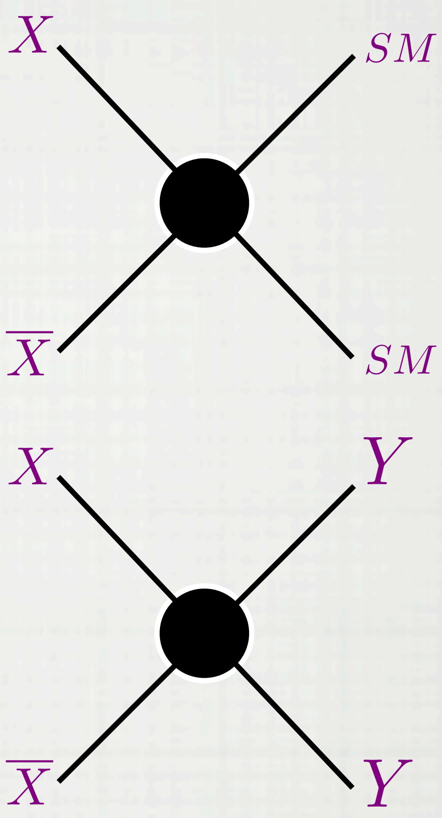
POSSIBLE LONG RANGE DM FORCES



HALL, MARCH-RUSSELL, SMW

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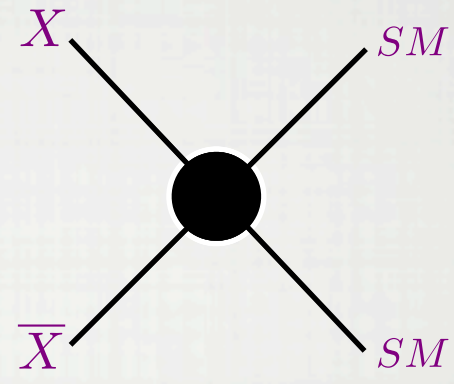

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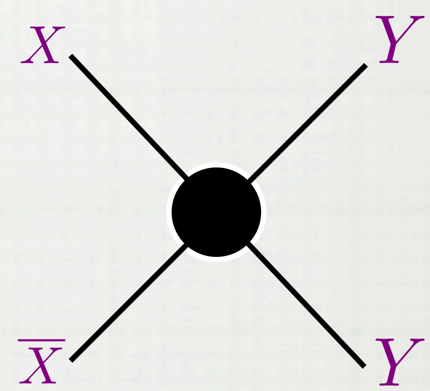
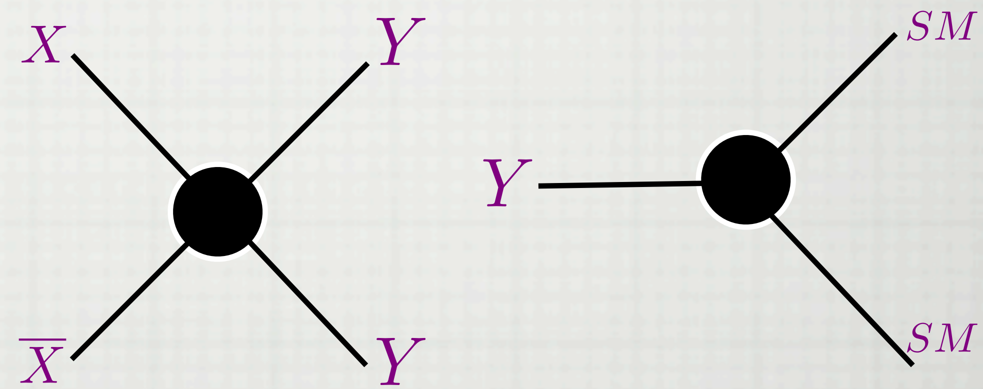


POSSIBLE LONG RANGE DM FORCES

3) ANNIHILATE TO VERY LIGHT HIDDEN SECTOR STATES THAT LATER DECAY TO SM



LATE TIME ENERGY INJECTION IN EARLY UNIVERSE

HALL, MARCH-RUSSELL, SMW

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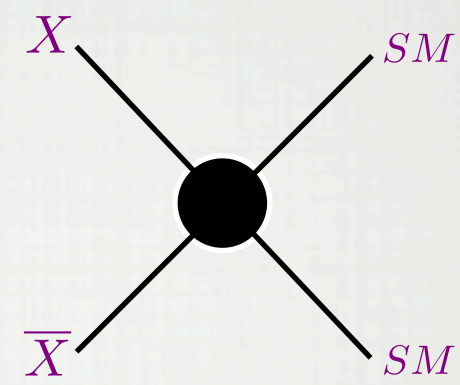

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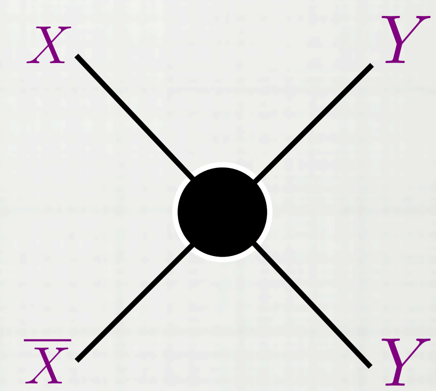

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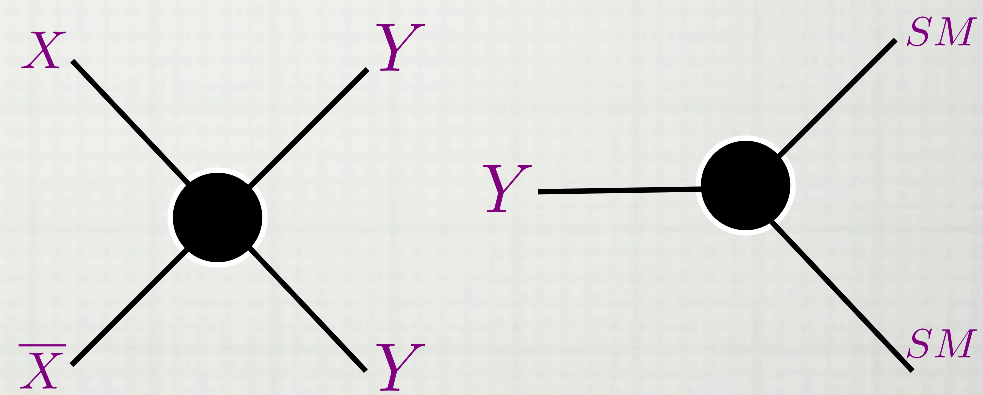


HALL, MARCH-RUSSELL, SMW

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

ASYMMETRIC FREEZE-OUT

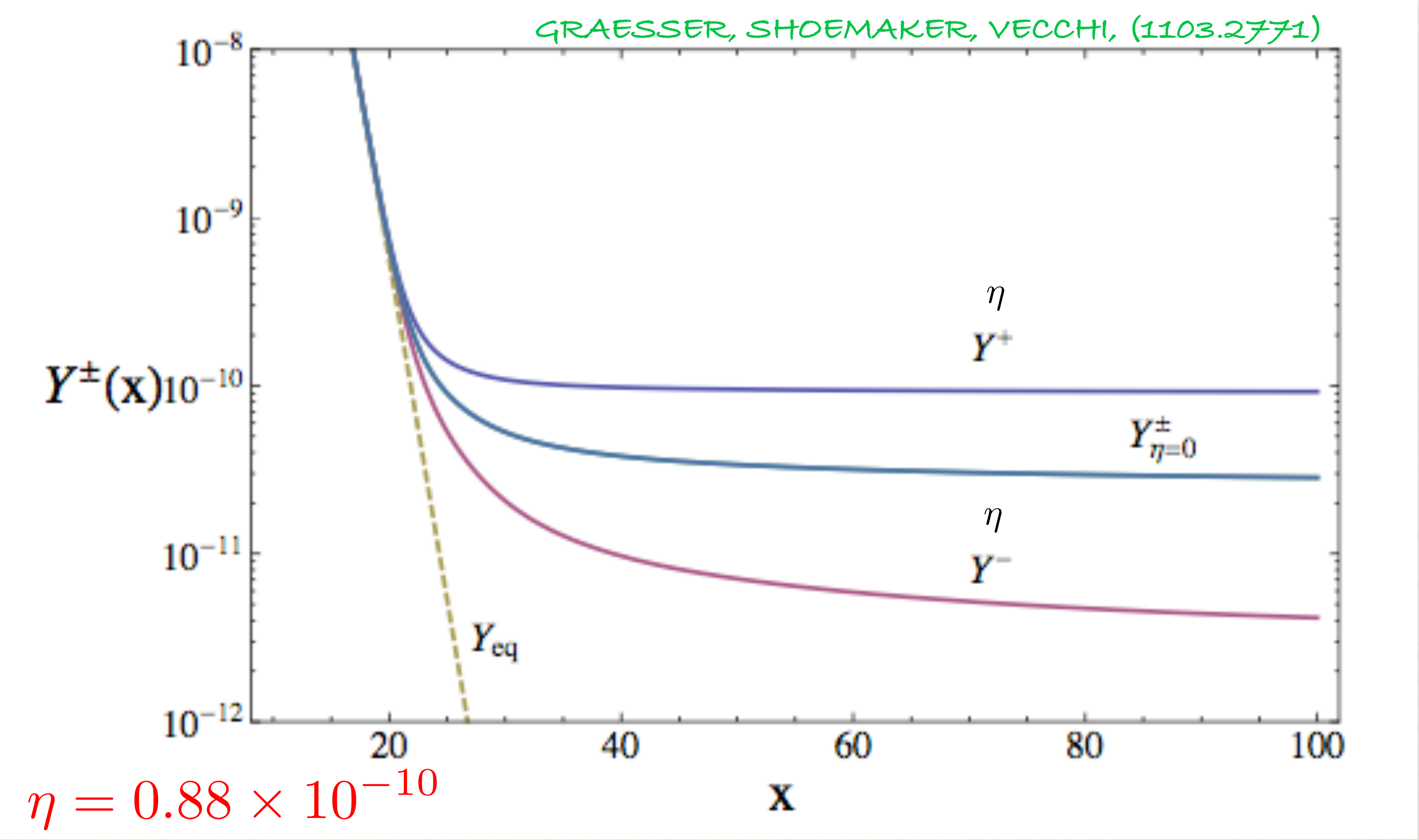
FOR MORE DETAILS SEE IMINNIYAZ, DREES, CHEN (1104.5548); GRAESSER, SHOEMAKER, VECCHI, (1103.2771)

ASYMMETRIC FREEZE-OUT

- 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

NEED LARGER ANNIHILATION RATE
NEEDS TO BE APPROX FACTOR OF 2-3 LARGER



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

REMOVING THE SYMMETRIC COMPONENT

SEE BUCKLEY FOR A FIRST ATTEMPT

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- FOR OPTION 1), ANNIHILATING DIRECTLY INTO THE SM, WE CAN PARAMETERISE THE INTERACTIONS IN TERMS OF EFFECTIVE OPERATORS ASSUMING SOME HEAVY MEDIATOR

- E.G. DIRAC FERMION DM ψ

$$\frac{m_q}{\Lambda^3}\overline{\psi}\psi\bar{q}q$$

$$\overline{\psi}\psi \to \bar{q}q$$

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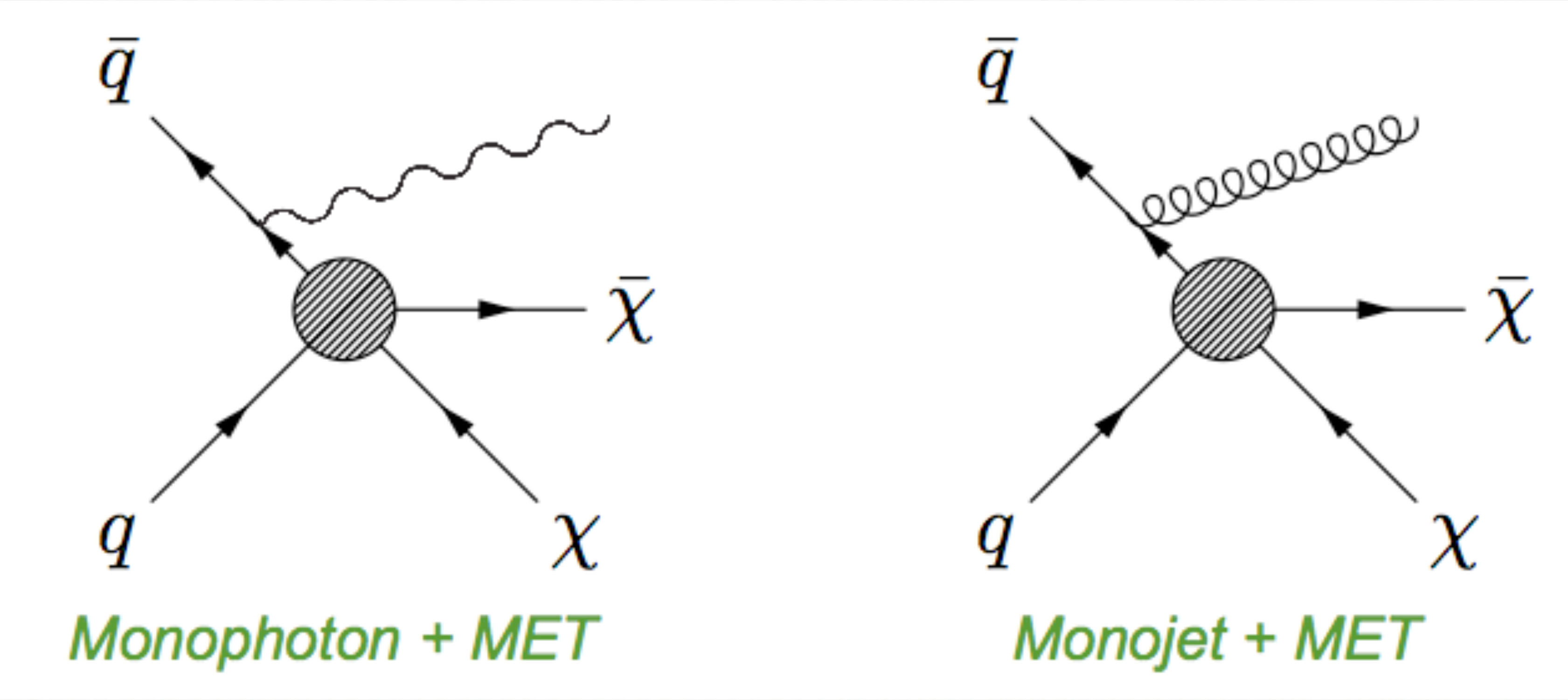
HEAVY QUARKONIUM DECAY $\bar{q}q \to \overline{\psi}\psi \quad \bar{q}q \to \gamma\overline{\psi}\psi$

(NOT TOO RESTRICTIVE IN MOST CASES)

MONOJET/MONOPHOTON LIMITS: MODEL INDEPENDENT LIMITS ON DM

STEVE WORM TALK AT MORIOND 2012



E.G. BAI,FOX AND HARNIK, JHEP 1012:048 (2010); GOODMAN, IBE, RAJARAMAN,SHEPHERD, TAIT,YU, PHYS.REV.D82:116010

ATLAS: ATLAS-CONF-2011-096 (2011)

LATEST CMS: EXO-11-059, EXO-11-096, HTTPS://TWIKI.CERN.CH/TWIKI/BIN/VIEW/CMSPUBLIC/PHYSICSRESULTSEXO

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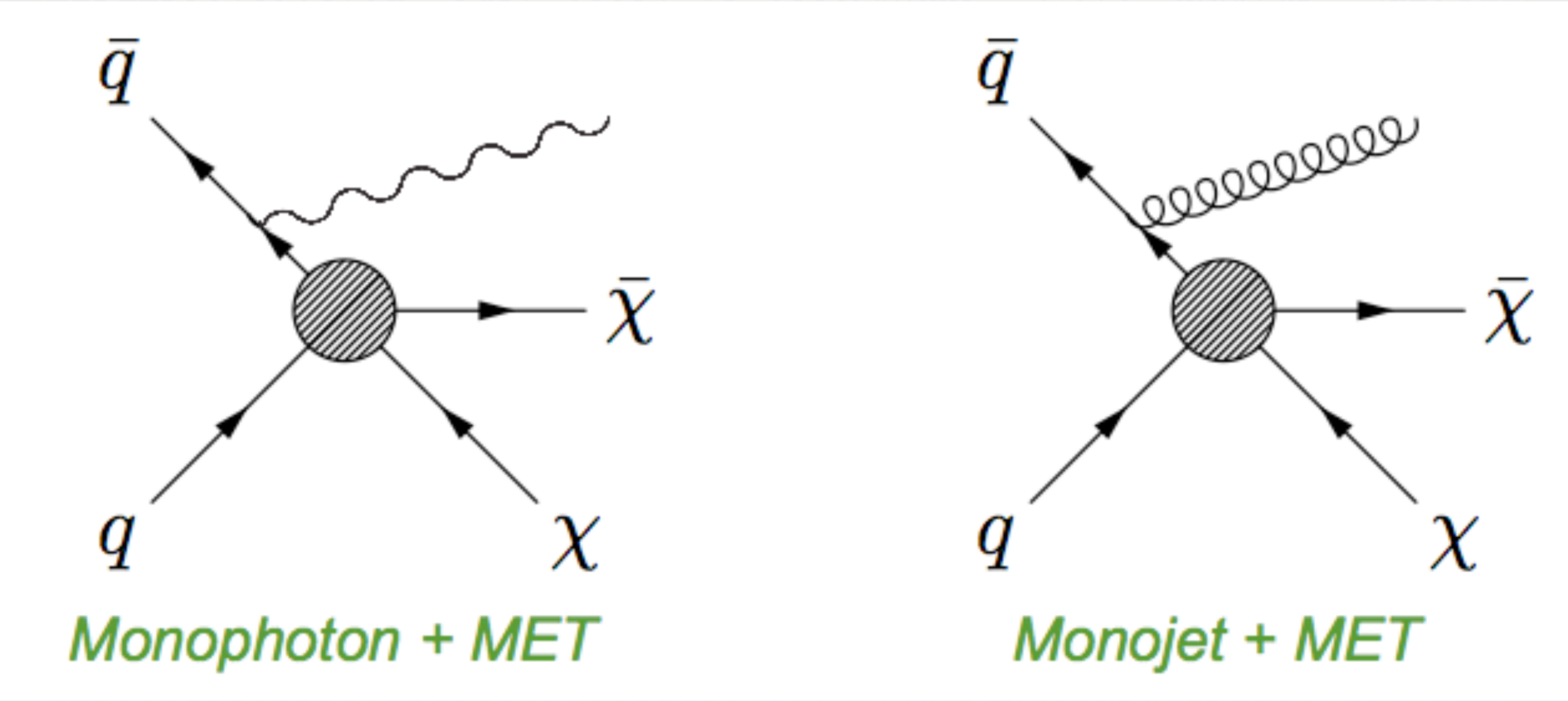

- ATLAS AND CMS HAVE UPPER LIMITS ON THESE PROCESSES - RECENTLY UPDATED

E.G. BAI,FOX AND HARNIK, JHEP 1012:048 (2010); GOODMAN, IBE, RAJARAMAN,SHEPHERD, TAIT,YU, PHYS.REV.D82:116010

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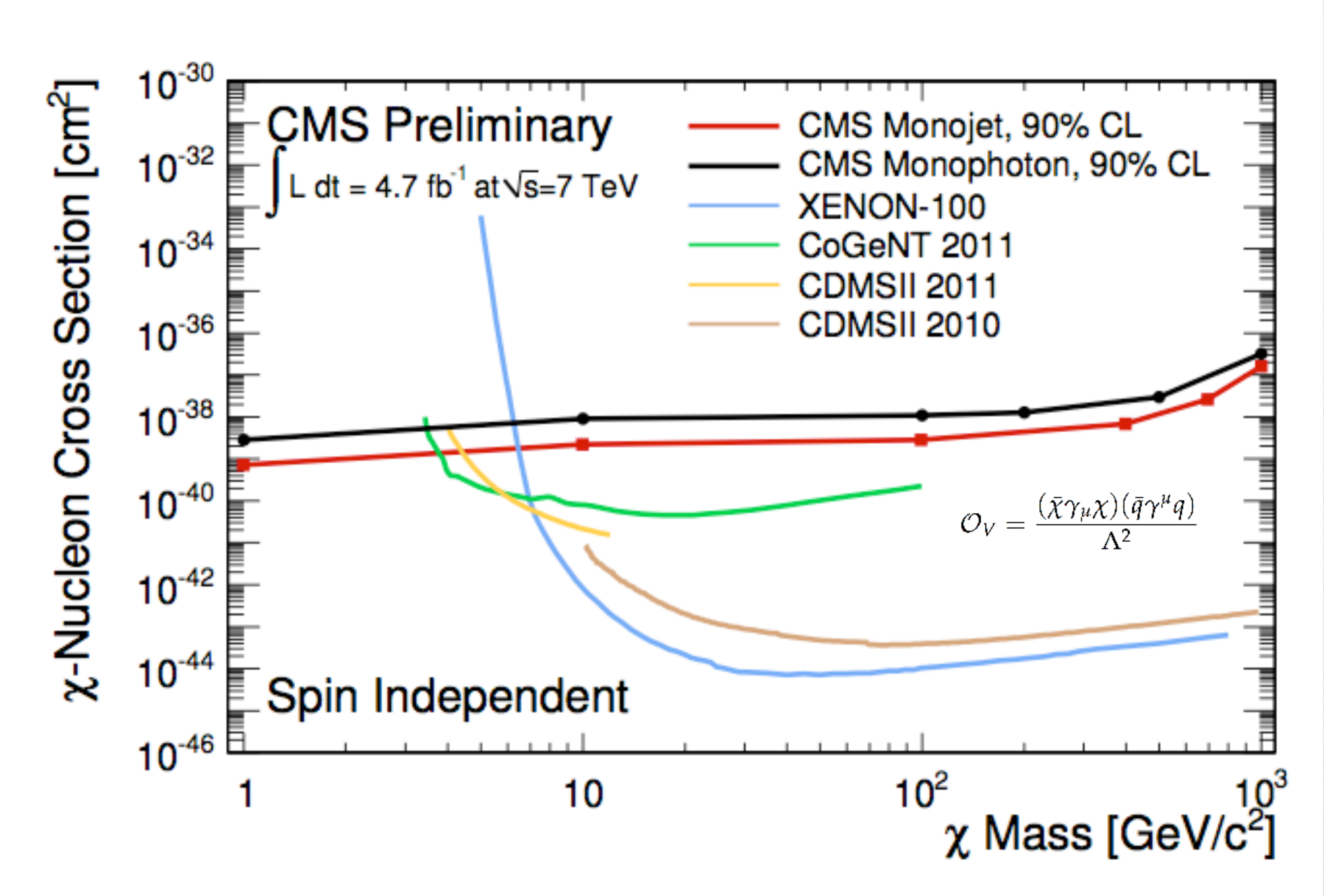

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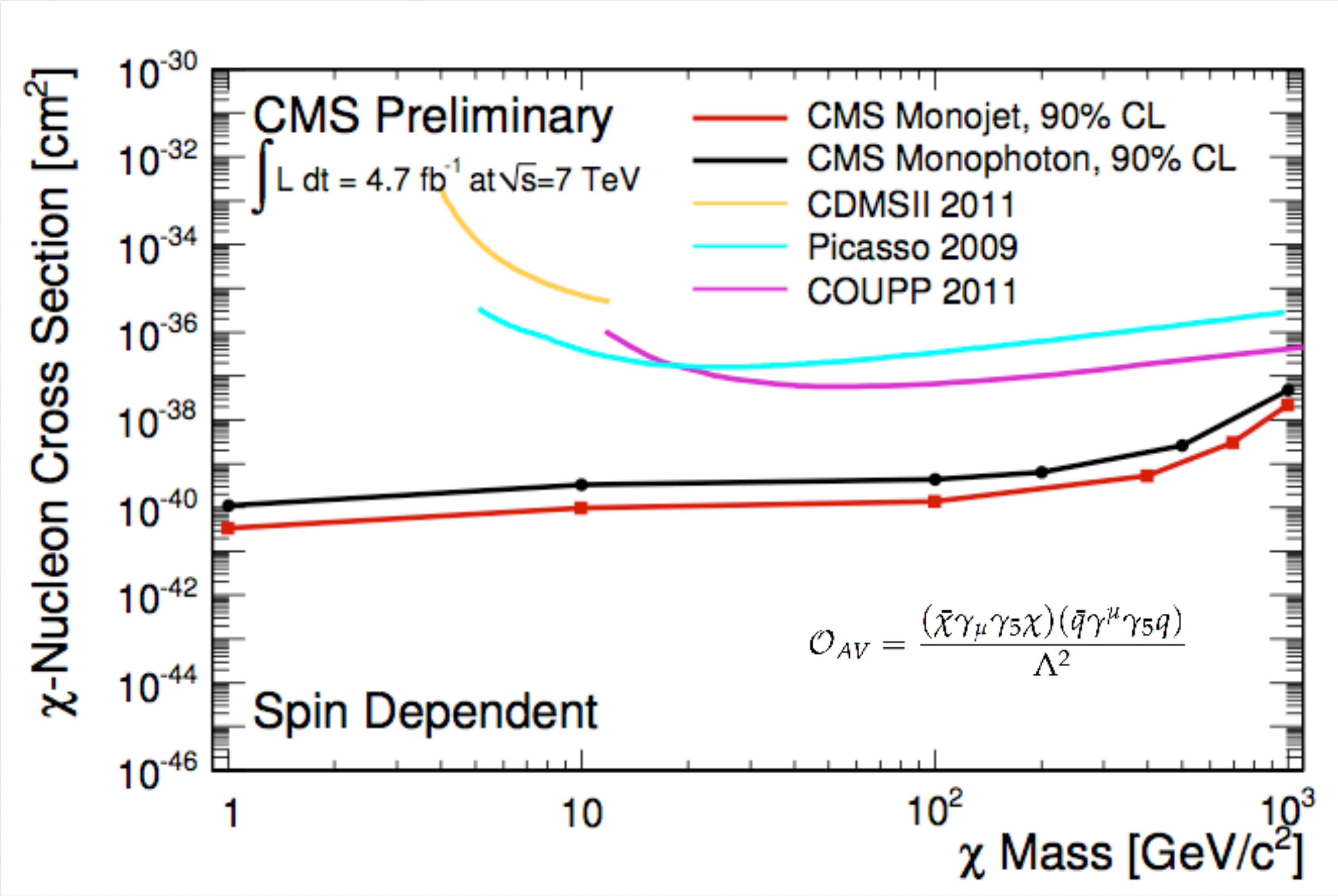

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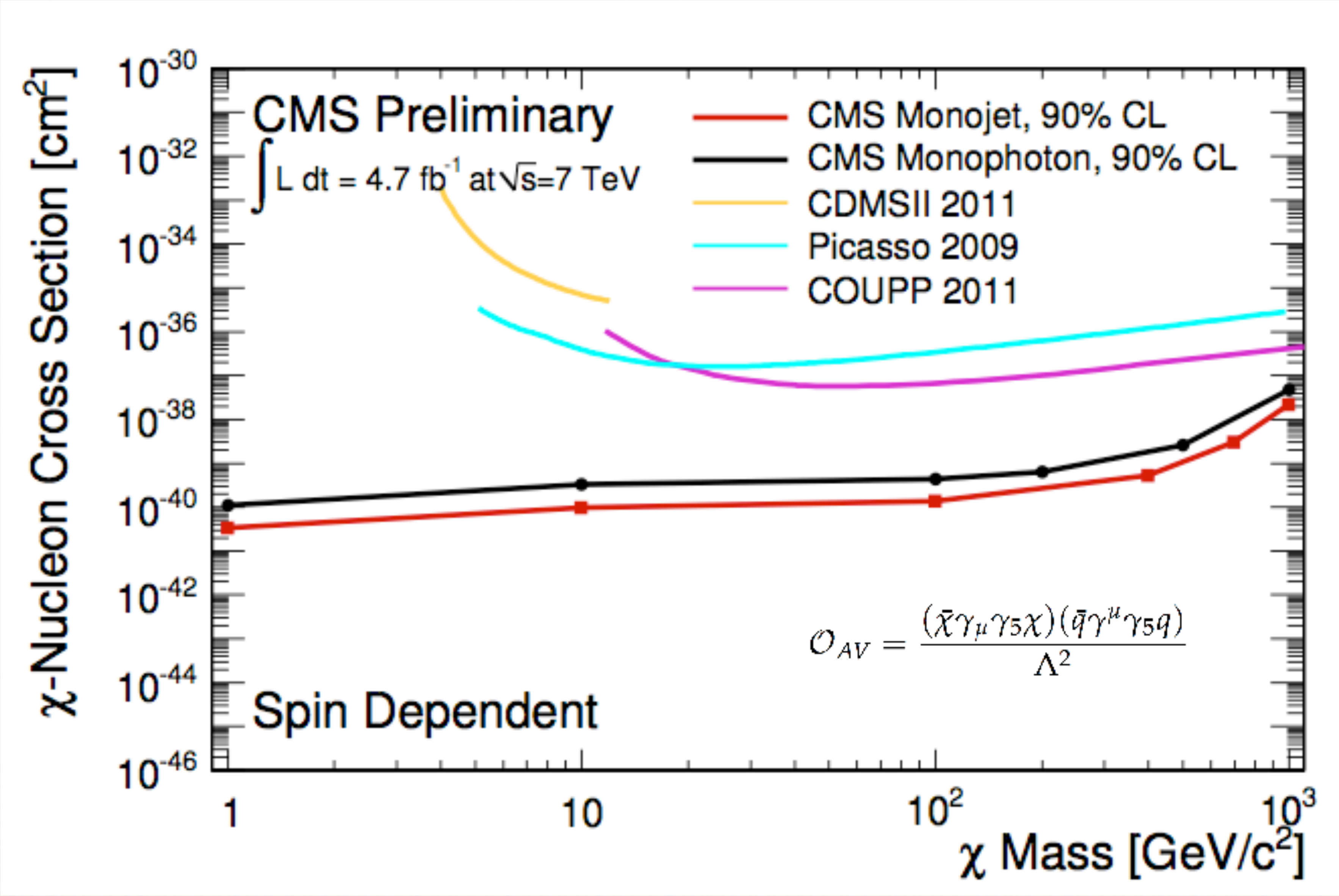

- MUST BE CAREFUL WITH THESE LIMITS - NOT ALWAYS CORRECT TO USE EFFECTIVE THEORY DESCRIPTION

LATEST CMS: EXO-11-059, EXO-11-096, HTTPS://TWIKI.CERN.CH/TWIKI/BIN/VIEW/CMSPUBLIC/PHYSICSRESULTSEXO

THE CONCERN WITH EFFECTIVE OPERATOR APPROACH

M_χ (GeV/c^2)	Spin-dependent σ(cm^2)	Spin-dependent Λ(GeV)	Spin-independent σ(cm^2)	Spin-independent Λ(GeV)
1	3.37×10^{-41}	730	7.20×10^{-40}	776
10	9.83×10^{-41}	744	2.12×10^{-39}	789
100	1.33×10^{-40}	718	2.65×10^{-39}	776
400	5.14×10^{-40}	514	6.66×10^{-39}	619
700	2.95×10^{-39}	332	2.62×10^{-38}	440
1000	2.15×10^{-38}	202	1.57×10^{-37}	281

- ANALYSIS BECOMES MODEL DEPENDENT - MUST BE CAREFUL

LATEST CMS: EXO-11-059, EXO-11-096, HTTPS://TWIKI.CERN.CH/TWIKI/BIN/VIEW/CMSPUBLIC/PHYSICSRESULTSEXO

MONOJET + DIRECT DETECTION VS ADM

- PLACES A LOWER LIMIT ON Λ FOR LARGE CUT OFF ONLY

$$\sigma_{\rm mono} \propto \frac{1}{\Lambda^6}$$

$$\frac{m_q}{\Lambda^3}\overline{\psi}\psi\overline{q}q$$

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- CAN ALSO CONVERT LIMITS ON THE SPIN INDEPENDENT ELASTIC SCATTERING CROSS SECTION TO A LOWER LIMIT ON Λ

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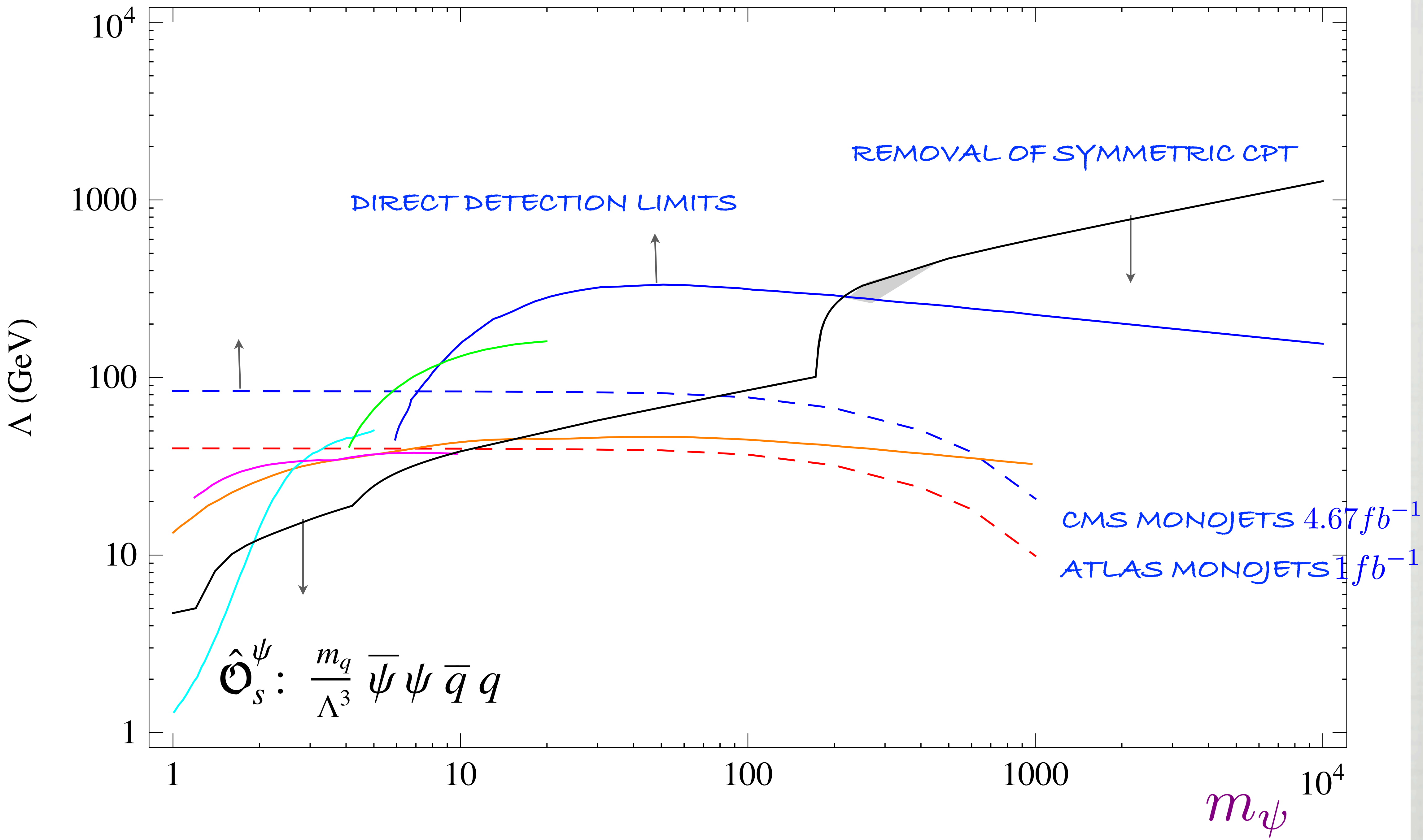
- NEEDING TO ANNIHILATE AWAY SYMMETRIC CPT GIVES A MAXIMUM Λ

$$\sigma_{ann} \propto \frac{1}{\Lambda^6}$$

MONOJET + DIRECT DETECTION VS ADM



LIGHT MEDIATORS

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- ☐ FOR LOW CUT OFF/MEDIATOR, EFFECTIVE THEORY NO LONGER APPROPRIATE
- ☐ NEED TO TAKE ACCOUNT OF A REAL MEDIATOR BETWEEN DM AND SM SECTOR

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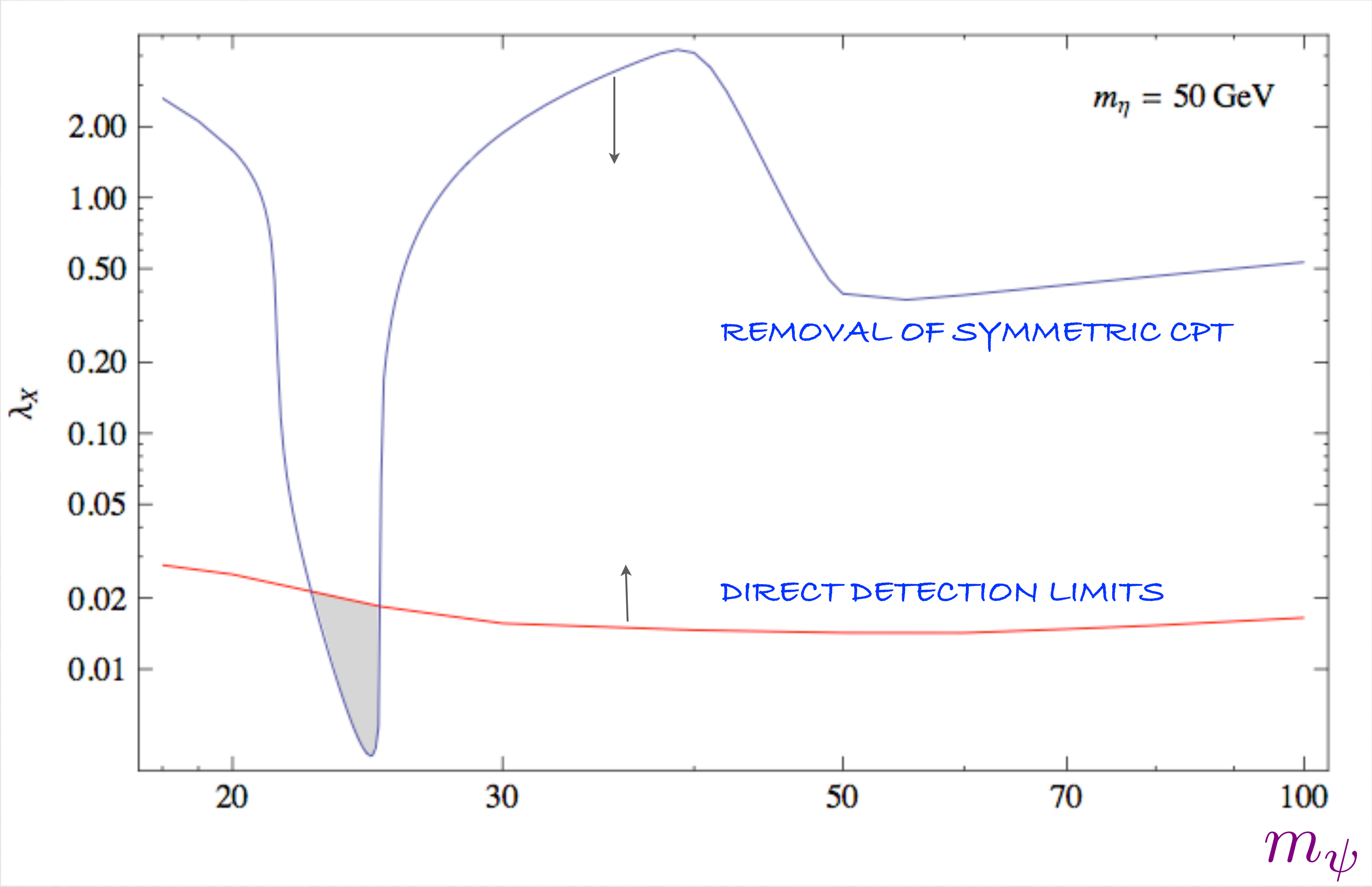
- SIMPLE EXAMPLE FERMION DM : $\mathcal{L} = \lambda_X \eta \overline{X} X + \lambda'_q \bar{q} q \eta$
- FIXING THE SIZE OF THE QUARK COUPLING TO THE MEDIATOR WE FIND THE VALUE OF λ_X THAT GIVES A LARGE ENOUGH ANNIHILATION RATE TO REMOVE SYMMETRIC PART
- WE CAN APPLY DIRECT DETECTION CONSTRAINTS AS BEFORE

LIGHT MEDIATORS



- ☐ MOST MEDIATOR MASSES, ONLY IN THE RESONANT REGION IS IT POSSIBLE
- ☐ POSSIBILITIES FOR PSEUDO-SCALAR MEDIATOR...MORE TO COME

BOTTOM LINE FOR DIRECT ANNIHILATION TO SM STATES

- IT IS VERY CONSTRAINED - POSSIBILITIES FOR LIGHT PSEUDO-SCALAR MEDIATOR, OTHERWISE UNLIKELY

$\Rightarrow$ NEED A MORE COMPLICATED HIDDEN SECTOR

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2) ANNIHILATE DIRECTLY TO LIGHT HIDDEN SECTOR STATES

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SHARING OPERATORS - 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

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

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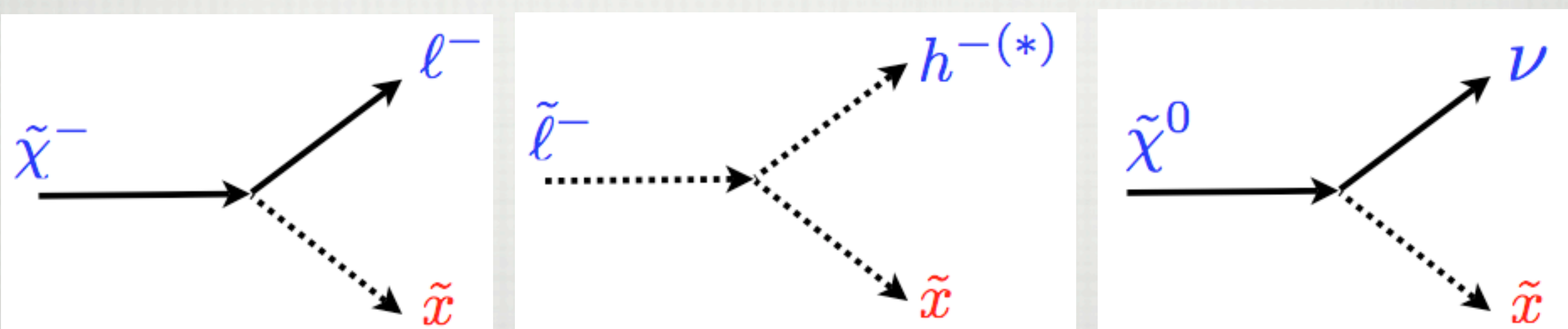
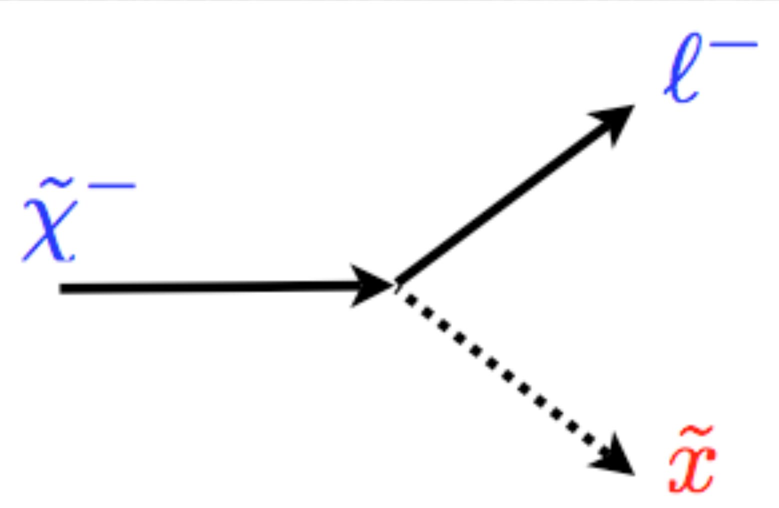
- ☐ INTRODUCES THE FOLLOWING INTERACTIONS:



☐ DEPENDING ON WHAT IS THE LIGHTEST ORDINARY SUSY PARTICLE WE WILL GET THE FOLLOWING AT THE END OF SUSY DECAY CHAIN:

CHARGINO LOSP



CHARGED TRACK, WITH A KINK

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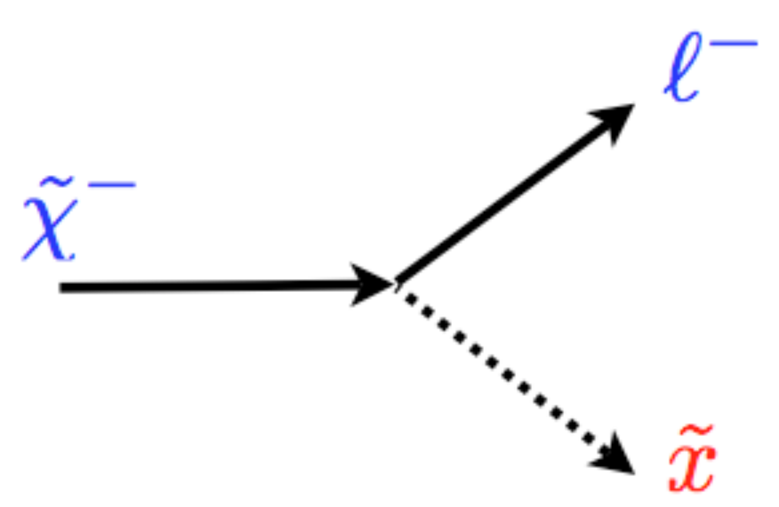

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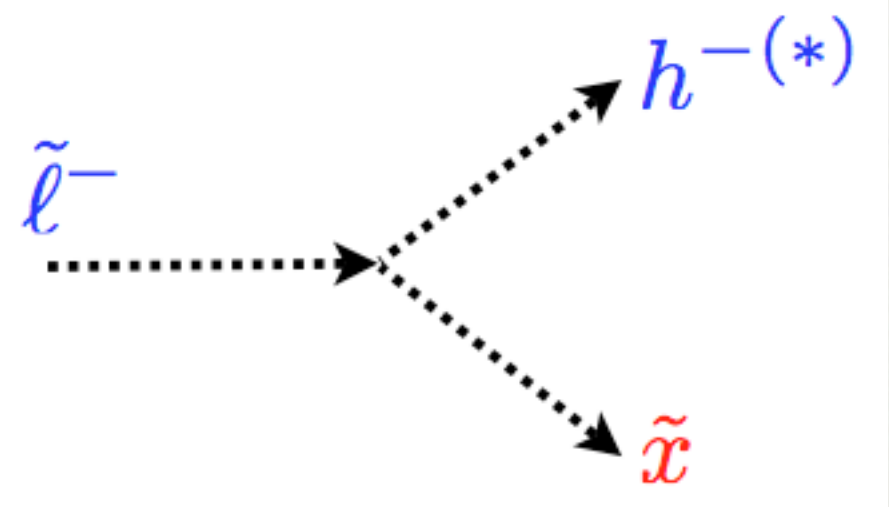

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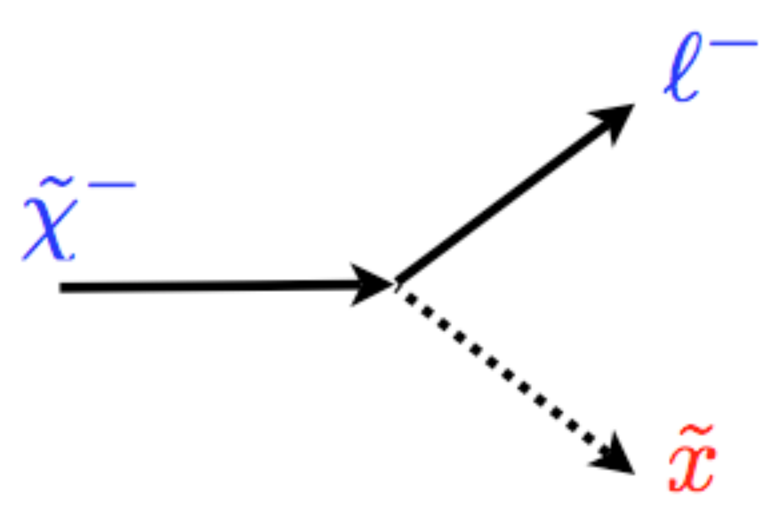

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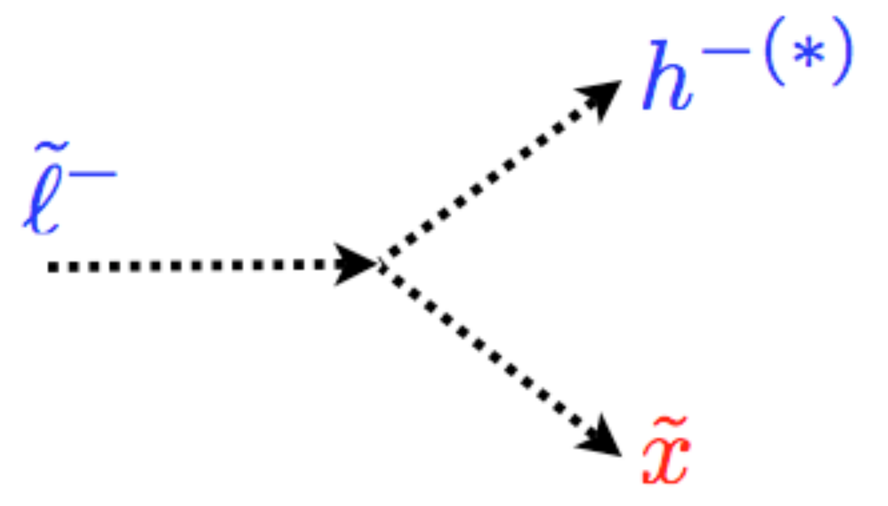
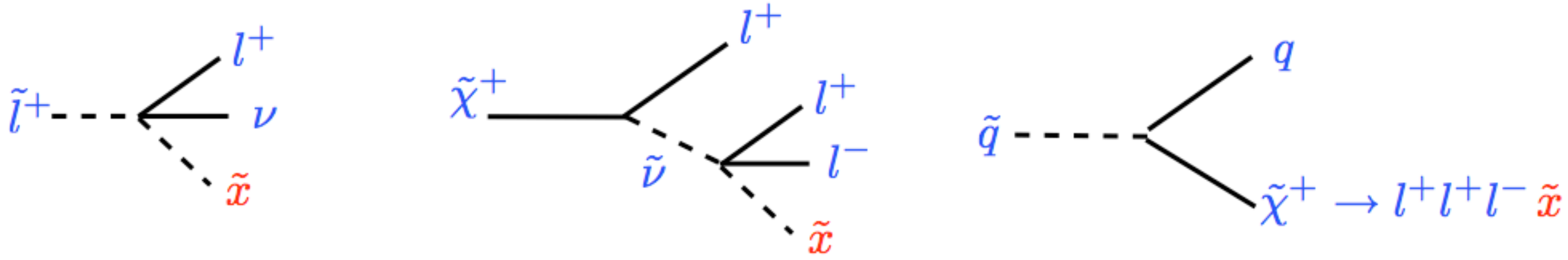


- REMEMBERING THAT THE SHARING OPERATORS MUST DROP OUT OF THERMAL EQUILIBRIUM BEFORE FREEZE-OUT - COUPLING MUST BE SMALL

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

eg, $W = \frac{1}{M} L L E^c X$

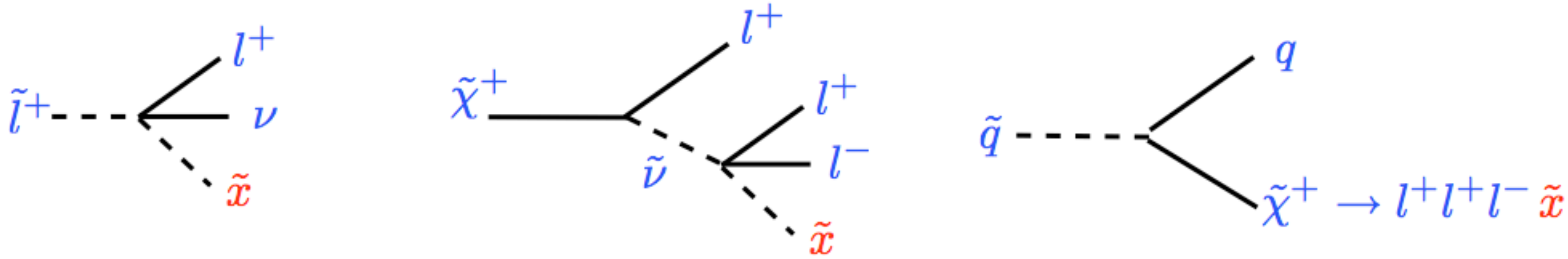


HALL, MARCH-RUSSELL, SMW

ANOTHER EXAMPLE

MARCH-RUSSELL TALK ,HEIDELBERG 2011

eg, $W = \frac{1}{M} L L E^c X$



- NOTE: EACH SUSY DECAY CHAIN WILL END IN THIS DECAY
- ALL DECAYS FORM SHARING OPERATORS VIOLATE B OR L
- NEED A COMBINATION OF LIMITS ON PROMPT EVENT AND DISPLACED VERTEX

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
- MANY CONSTRAINTS ON ADM, ESPECIALLY REMOVAL OF SYMMETRIC COMPONENT
- LHC PHENOMENOLOGY OF SHARING OPERATORS- LONG LIVED EXOTICS
- LOTS MORE TO INVESTIGATE...

BACK UPS AND OLD SLIDES

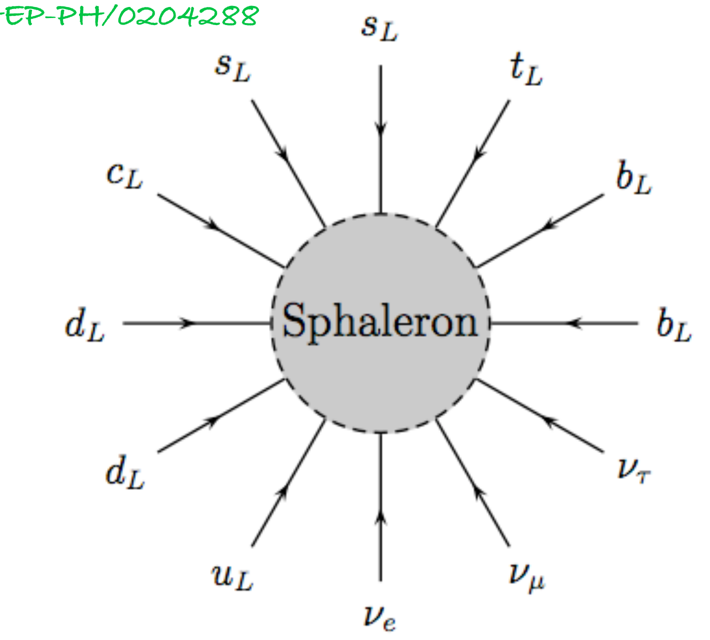
IMPORTANT ASIDE ON THE ELECTROWEAK ANOMALY/SPHALERONS

- 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



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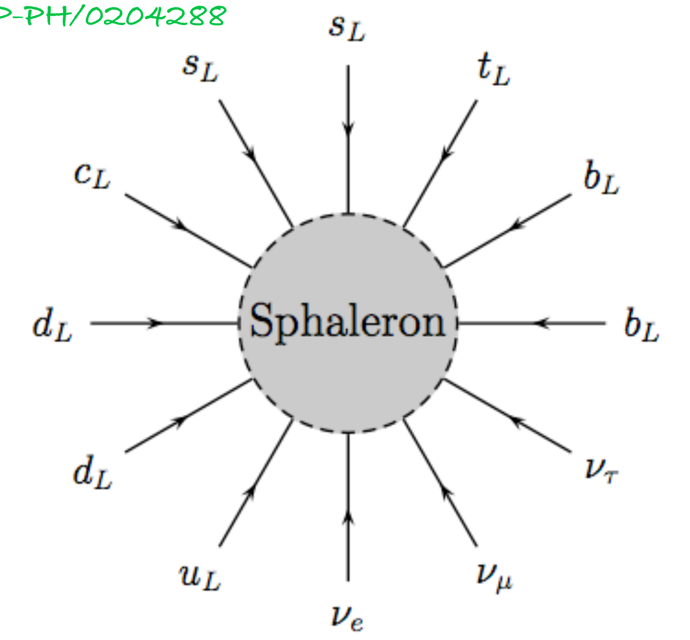

- ☐ IF L≠0, B=0 SPHALERONS WILL REPROCESS L ASYMMETRY INTO B NUMBER

- ☐ IF B≠0, L≠0 BUT B-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.

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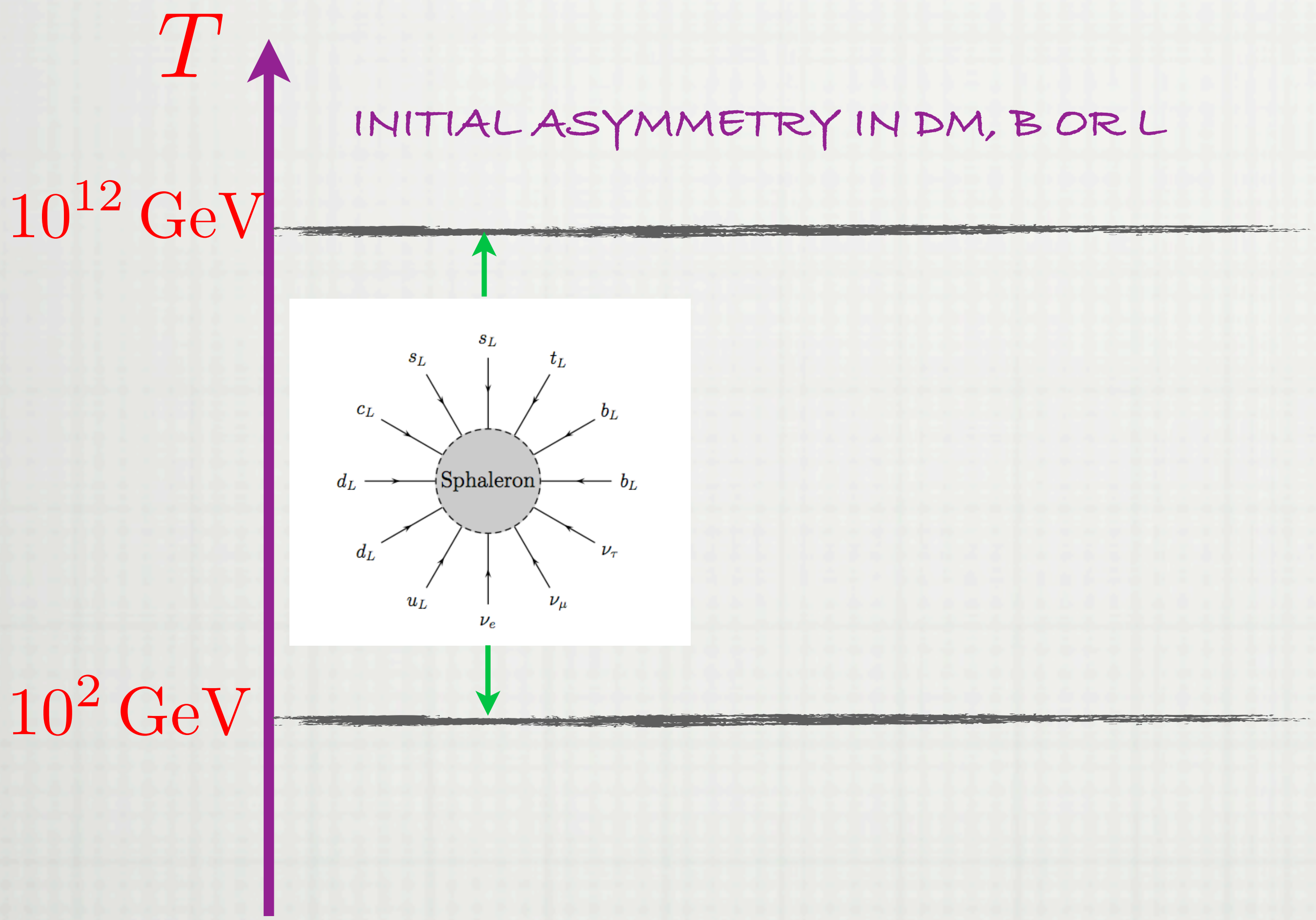

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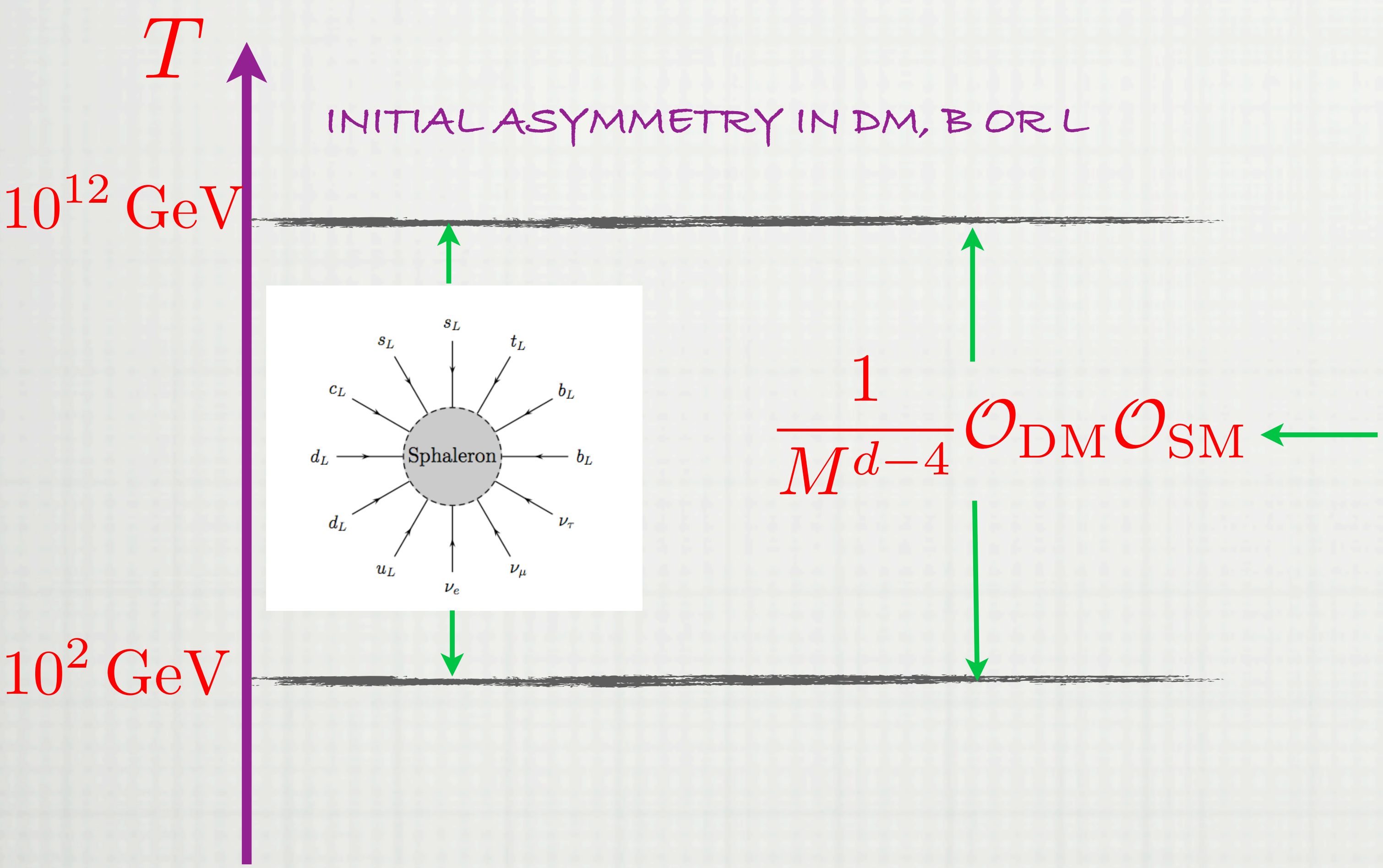

SOME OPERATORS RESPONSIBLE FOR PROCESSES THAT VIOLATE A COMBINATION OF B, L AND DM NUMBER BUT PRESERVE B-L+DM

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

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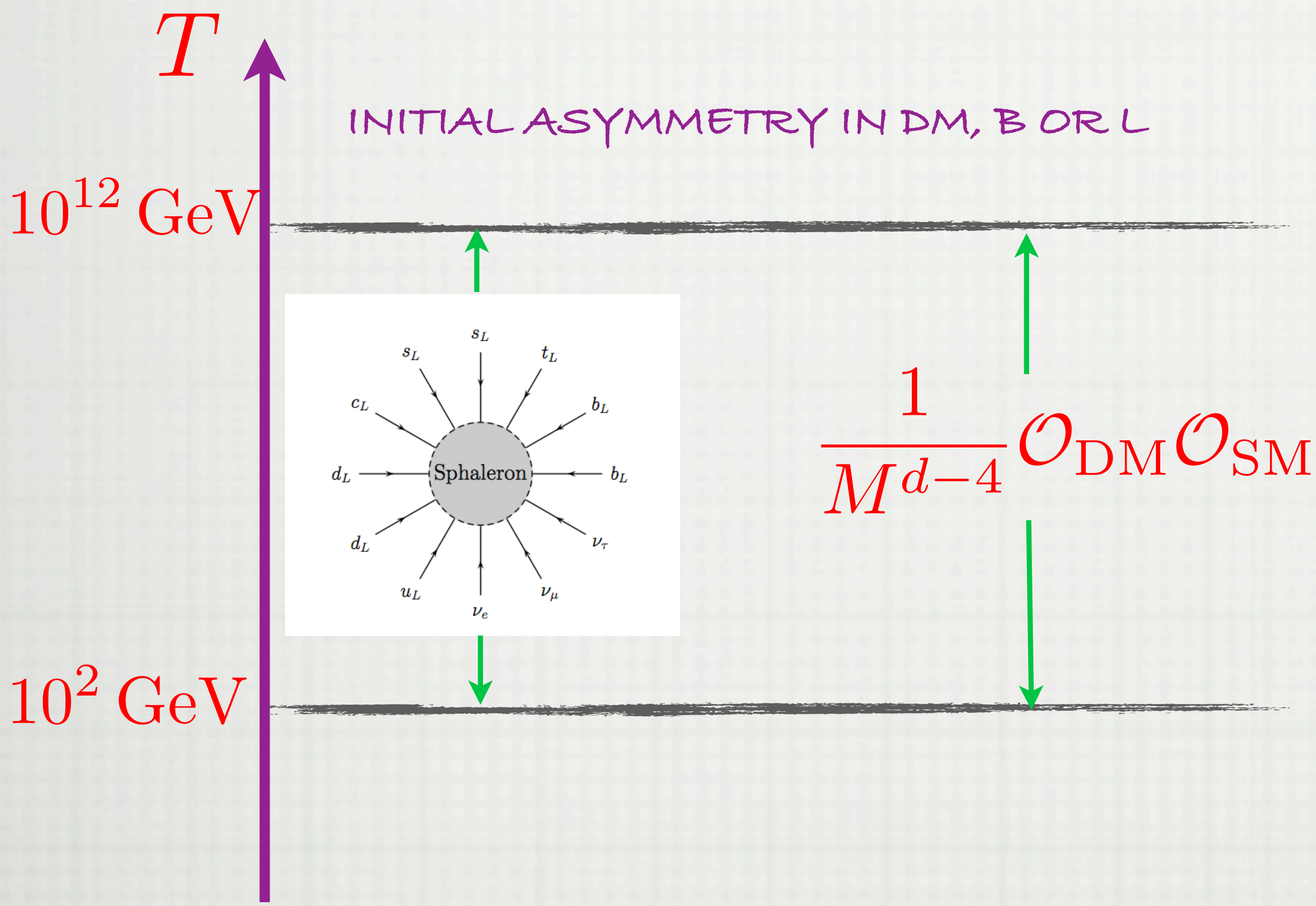

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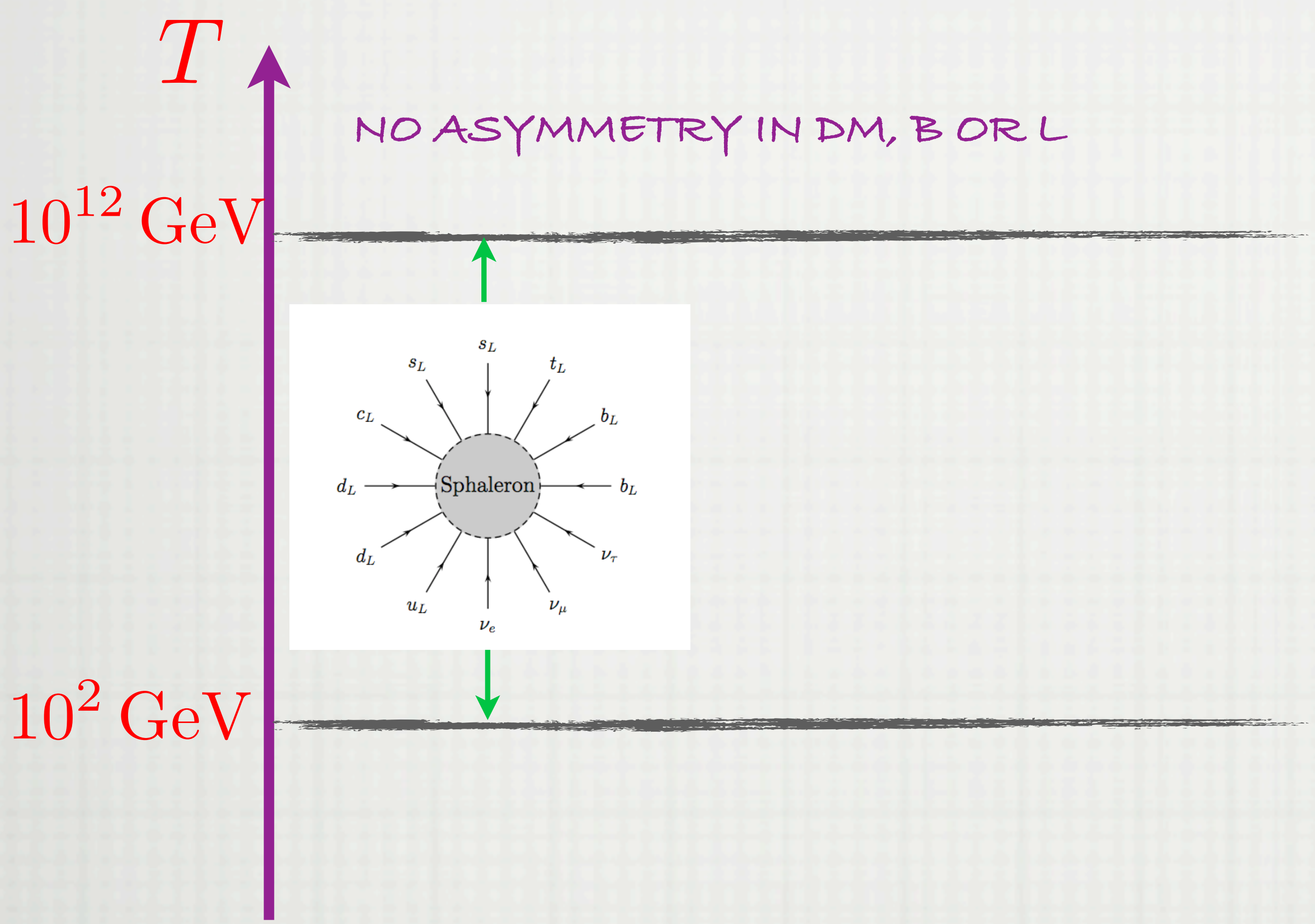
- ☐ THE RESULT IS THAT ANY ASYMMETRIES IN B, L OR DM ARE SHARED AND RELATED BY B-L+DM NUMBER - EXAMPLE LATER

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

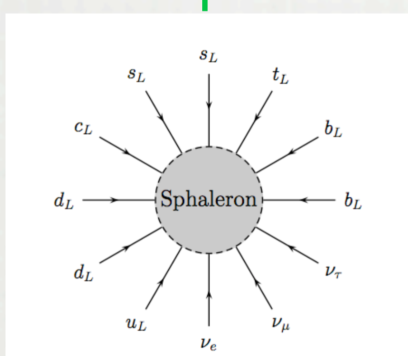


CO-GENESIS EXAMPLES - GENERATING AN ASYMMETRY IN B AND DM SIMULTANEOUSLY

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.

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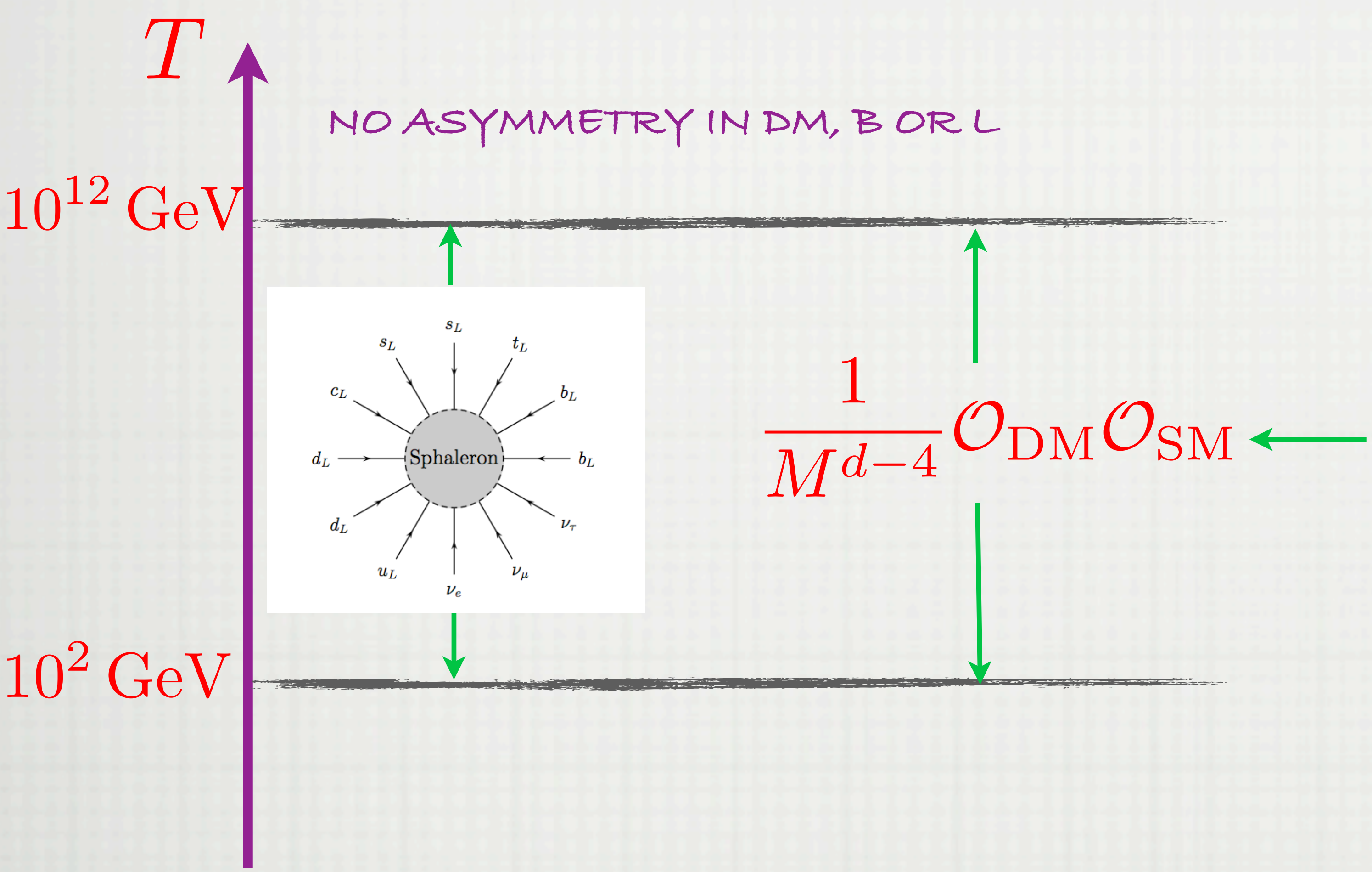

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- MUCH MORE ELEGANT AND TESTABLE - BUT HARD TO BUILD A WORKING MODEL

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.

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- ASYMMETRIC FREEZE-IN...MORE LATER

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- ☐ 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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E.G.

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

d =DIMENSION OF COMBINED OPERATOR

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

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

BARYON ASYMMETRY

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☐ EARLY UNIVERSE COSMOLOGY SUCCESSFULLY PREDICTS THE ABUNDANCE OF LIGHT ELEMENTS (IN THE MOST PART) IF

$$\xi = \frac{n_B}{n_\gamma} \approx (1.5 - 6.3) \times 10^{-10} \qquad n_\gamma \sim 400/cm^3$$

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$$n_\gamma \sim 400/cm^3$$

- NO SIGNIFICANT ANTI-MATTER IN THE UNIVERSE

$$\eta_B = Y_B - Y_{\overline{B}} = \frac{n_B - n_{\overline{B}}}{s} = \frac{\xi}{7}$$

$$s \approx 3 \times 10^3/cm^3$$

$\Rightarrow \qquad \Omega_b h^2 \approx 0.02$

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- ☐ WHERE DOES THE ASYMMETRY COME FROM? LEPTOGENESIS? BARYOGENESIS?

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- WHERE DOES THE ASYMMETRY COME FROM? LEPTOGENESIS? BARYOGENESIS?

- MOREOVER WE NOTE:

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

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

...LEADS TO IDEAS OF ASYMMETRIC DM

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

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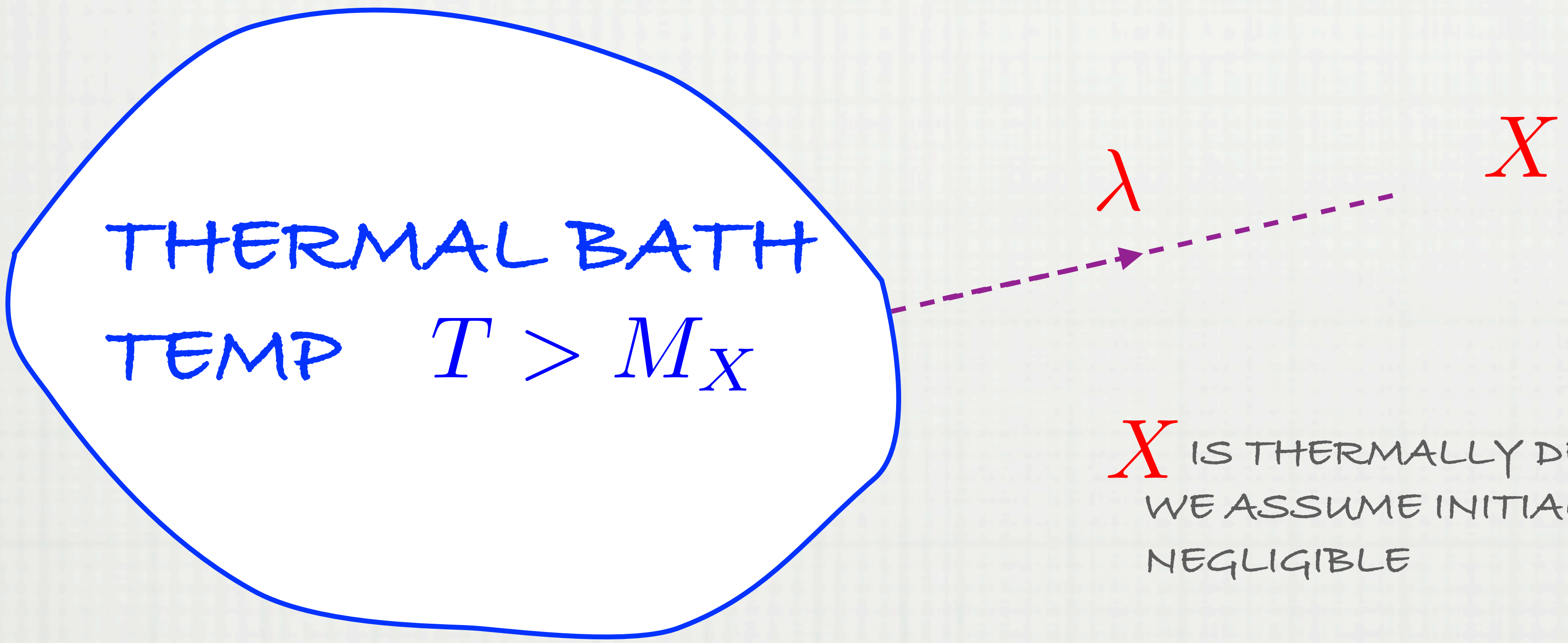

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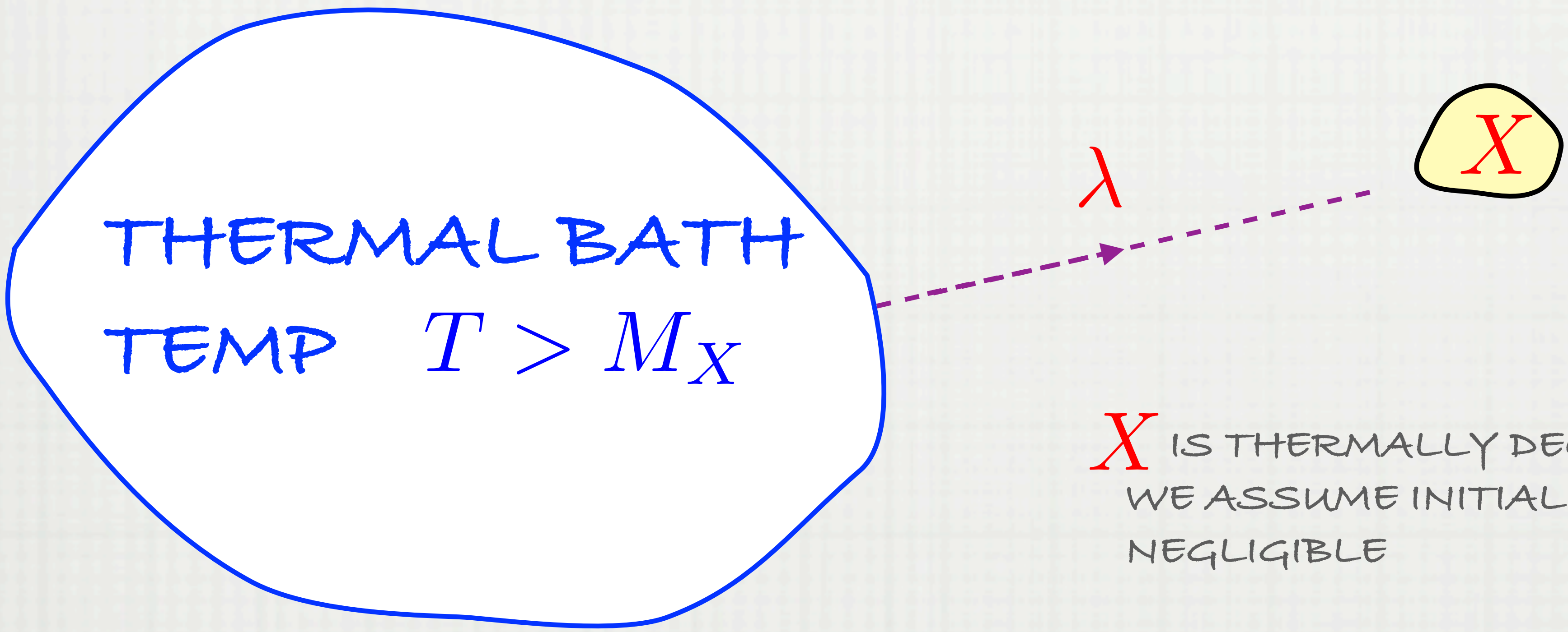

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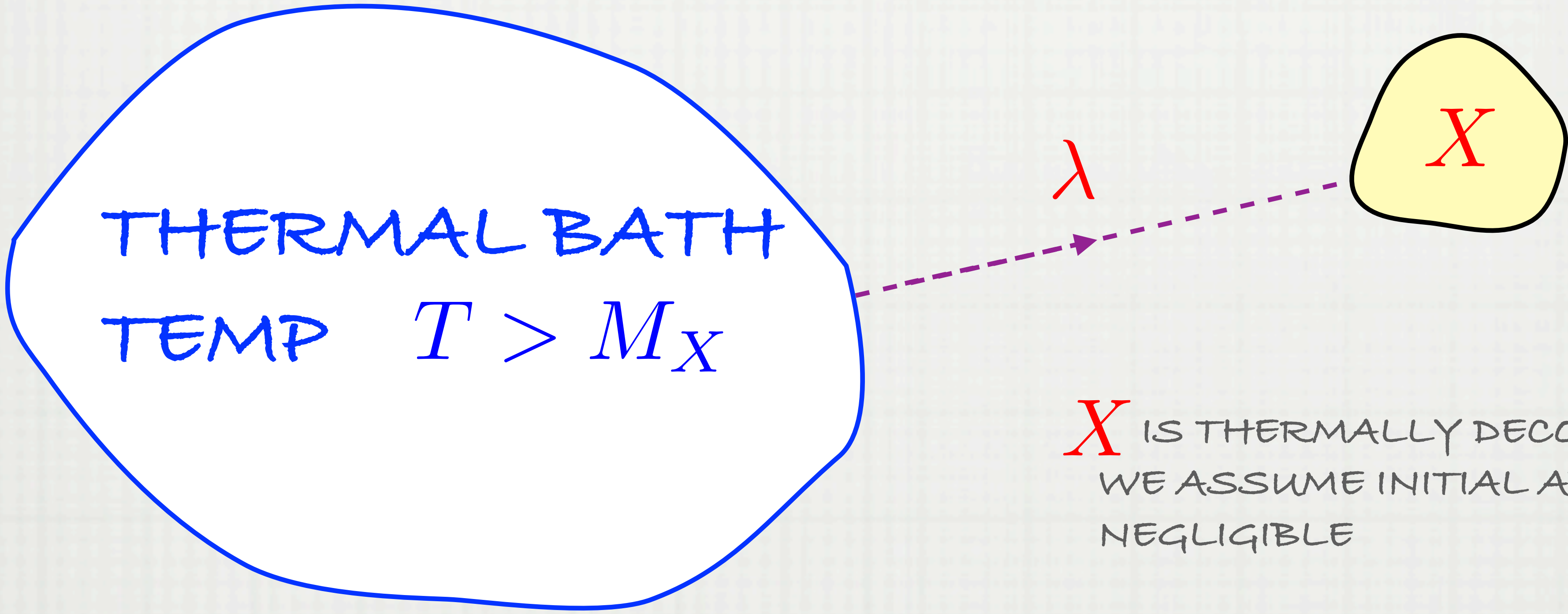

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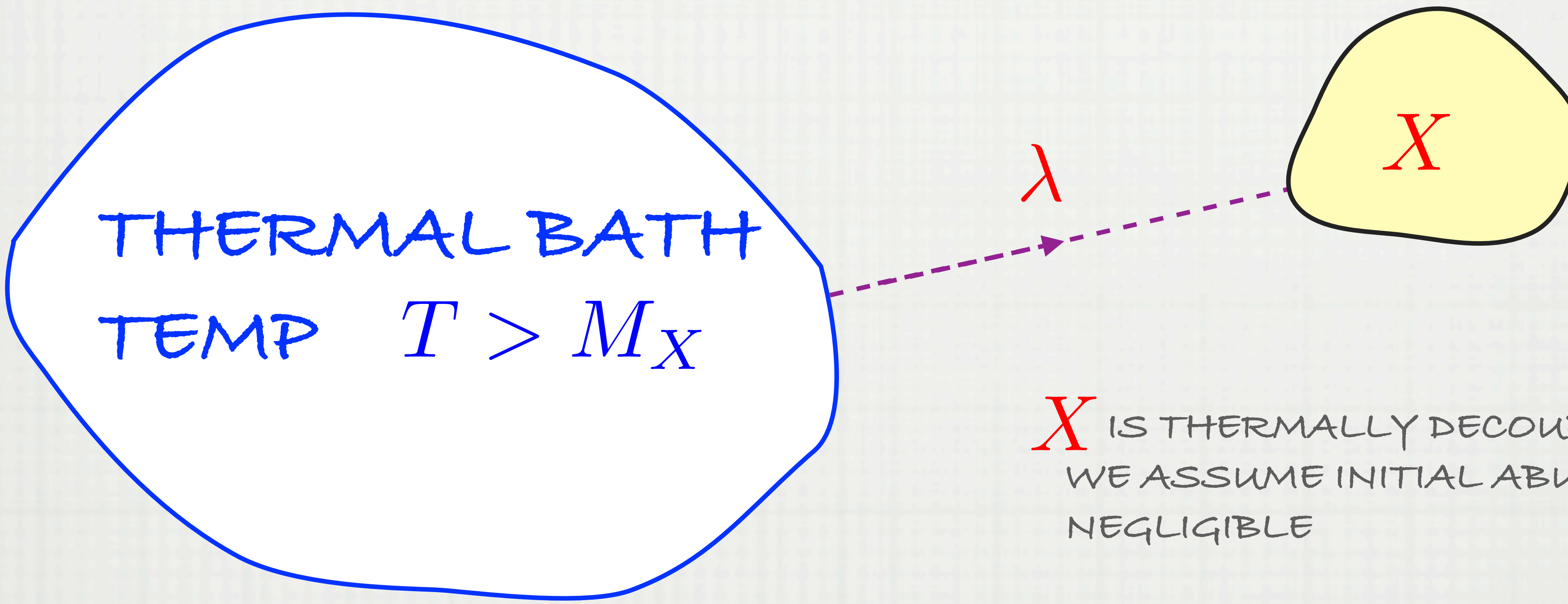

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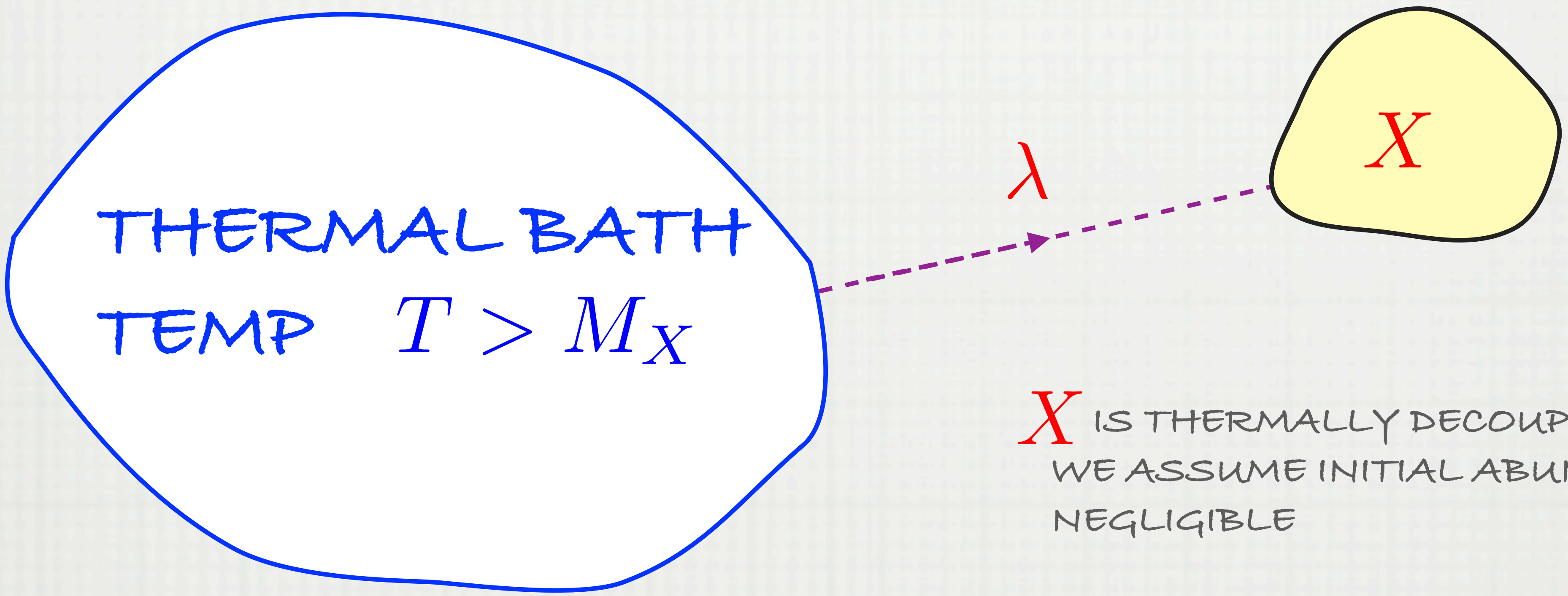

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- ALTHOUGH INTERACTION ARE FEEBLE THEY LEAD TO SOME X PRODUCTION
- DOMINANT PRODUCTION OF X OCCURS AT $T \sim M_X$ - IR DOMINANT
- INCREASING THE INTERACTION STRENGTH INCREASES THE YIELD

OPPOSITE TO FREEZE-OUT

FREEZE-OUT VS FREEZE-IN

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

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

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

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

COUPLING STRENGTH λ

m MASS OF HEAVIEST PARTICLE IN INTERACTION

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

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

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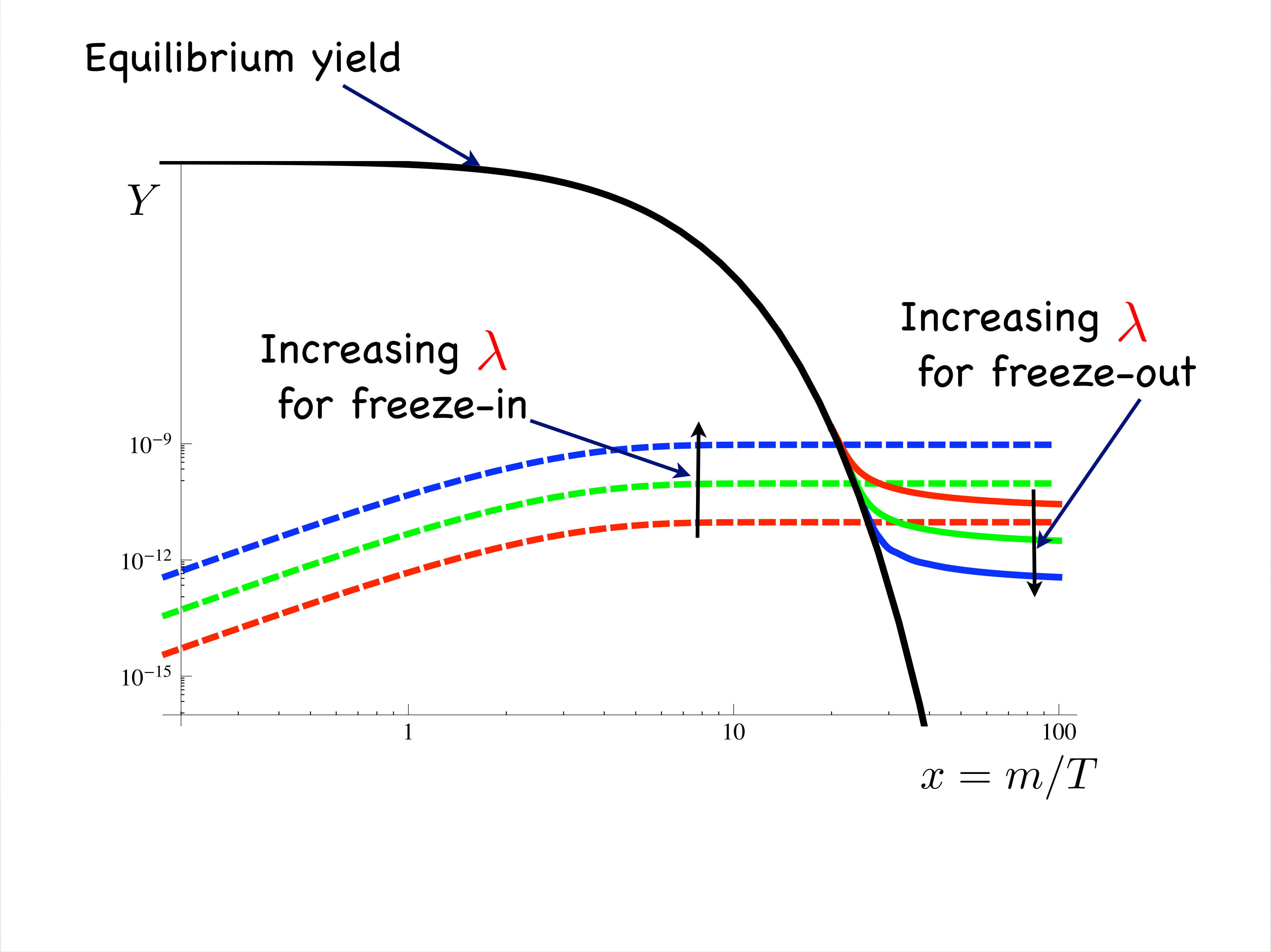
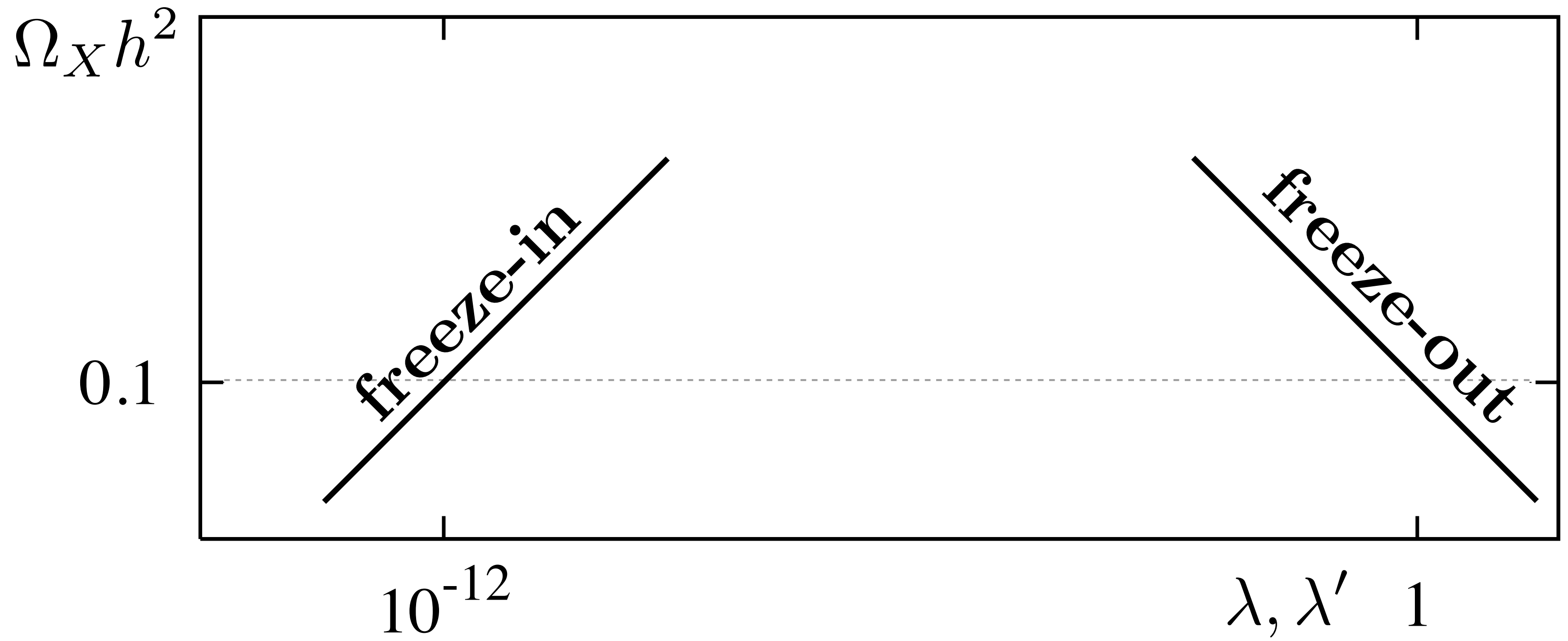


FREEZE-OUT VS FREEZE-IN

- FOR A TEV SCALE PARTICLE WE HAVE THE FOLLOWING PICTURE



FIMP MIRACLE VS WIMP MIRACLE

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

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EXAMPLE MODEL I

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

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

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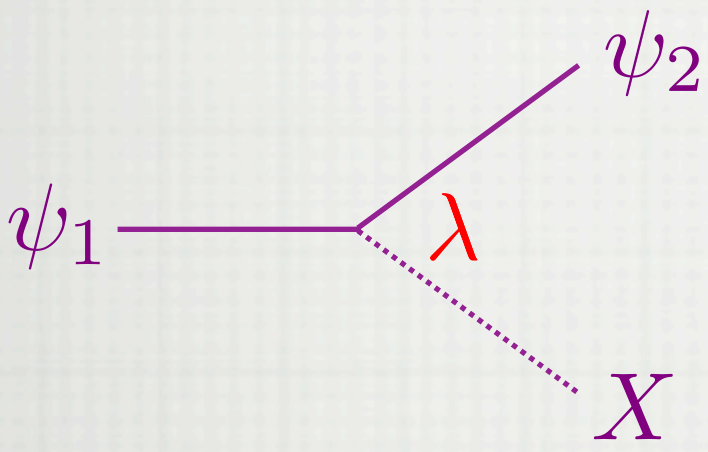

$$\Omega_X h^2 \sim 10^{24} \frac{m_X \Gamma_{\psi_1}}{m_{\psi_1}^2}$$

ABUNDANCE GOES AS λ^2

CORRECT ABUNDANCE

FOR $m_X \sim m_{\psi_1}$

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

- ☐ 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

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ASSUMING

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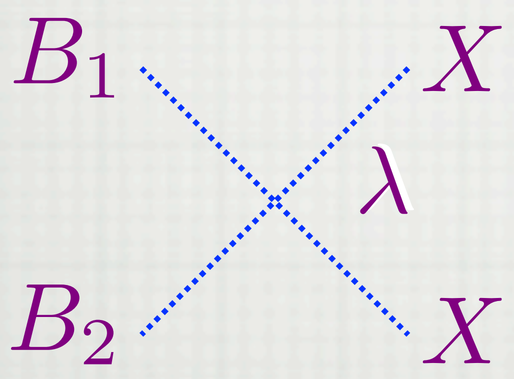

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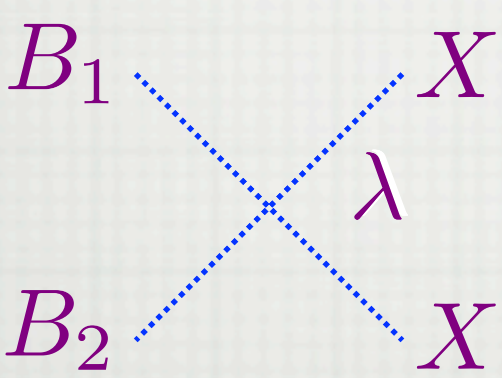


$$\Omega h_X^2 \approx 10^{21} \lambda^2$$

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

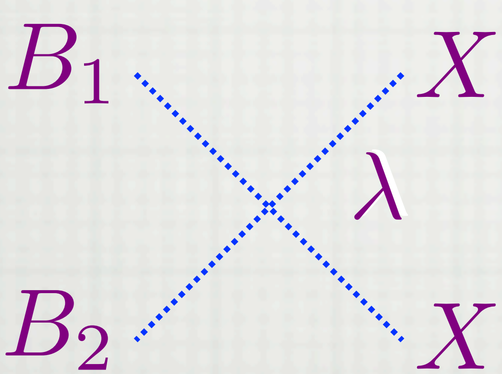
EXAMPLE MODEL II

- 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

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



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- 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
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- 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

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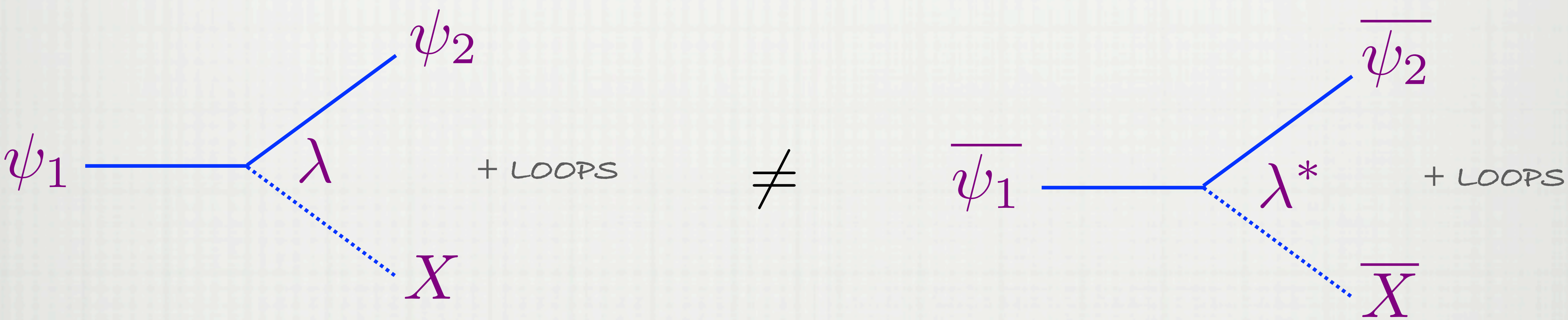

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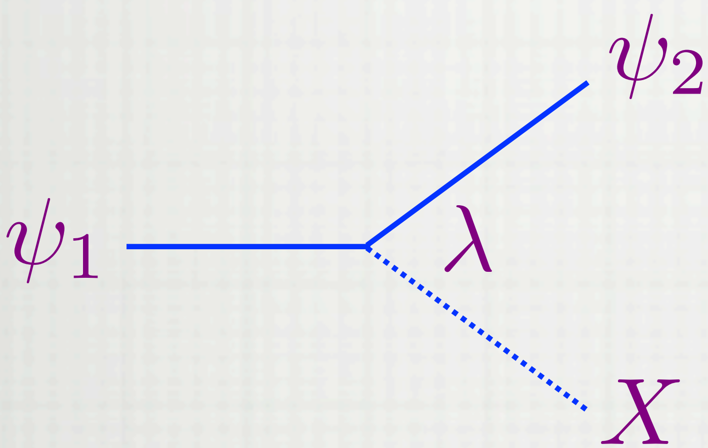
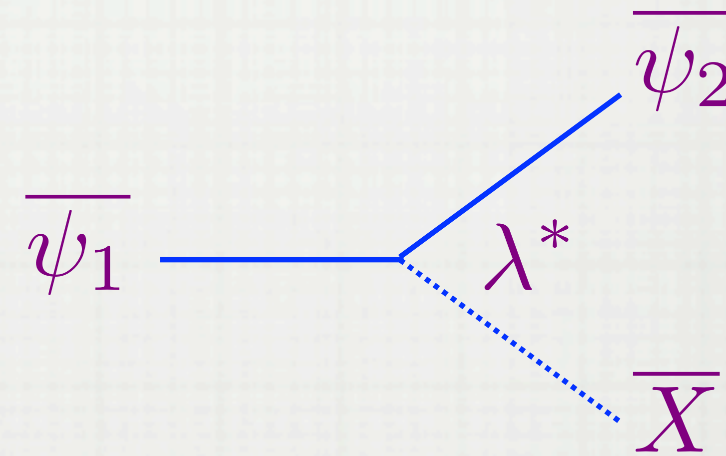


+ LOOPS $\neq$



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

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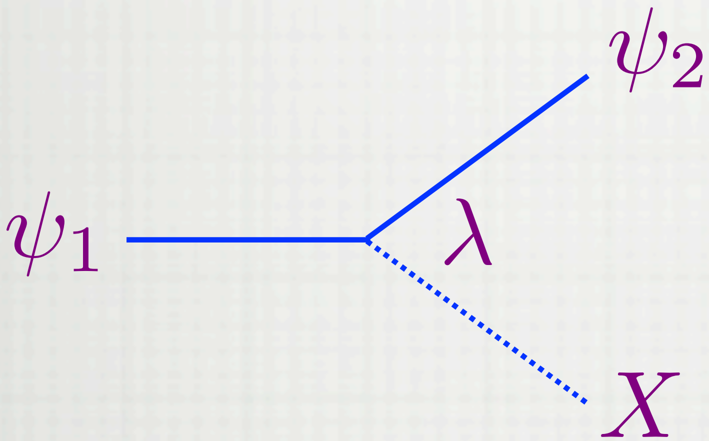

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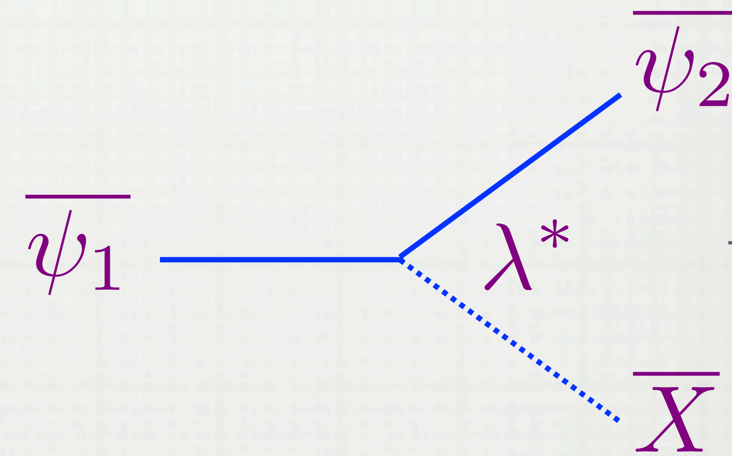

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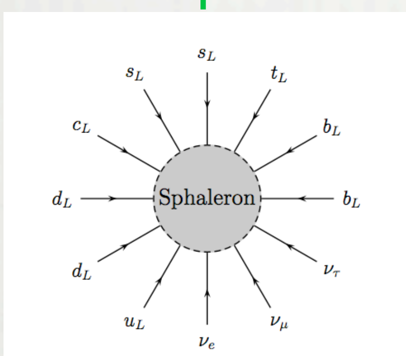
- ☐ WE NEED CP VIOLATION (AND LOOP DIAGRAMS TO INTERFERE WITH THE TREE LEVEL DIAGRAMS)

ASYMMETRIC FREEZE-IN EXAMPLE

T

NO ASYMMETRY IN DM, B OR L

10^{12} GeV

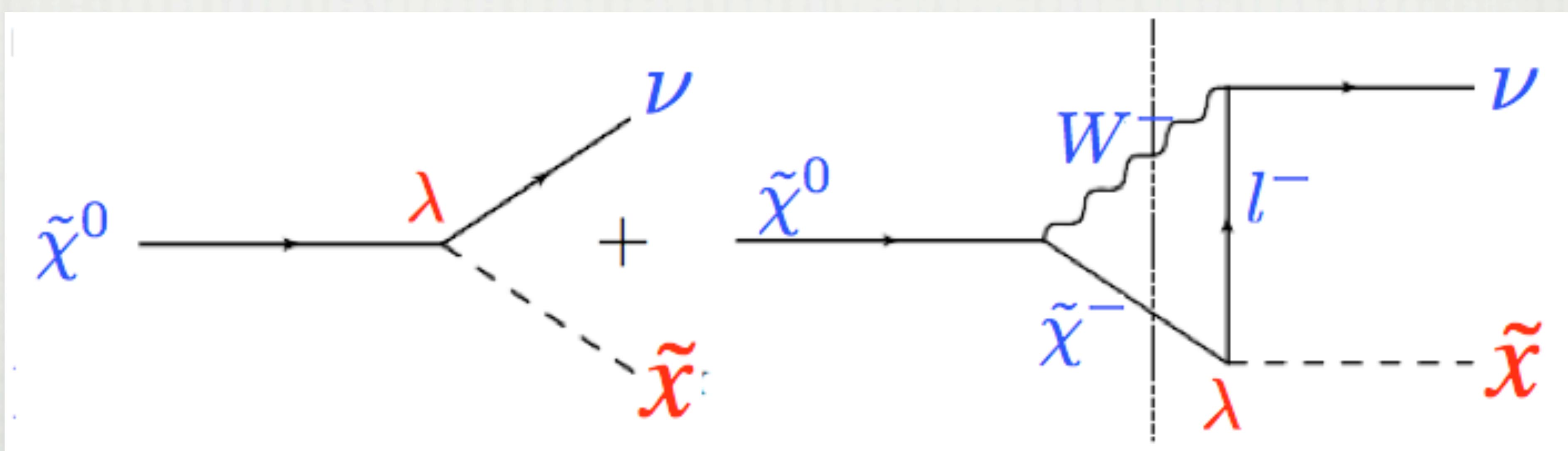


10^2 GeV

$$\lambda_i L_i H_u X$$

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

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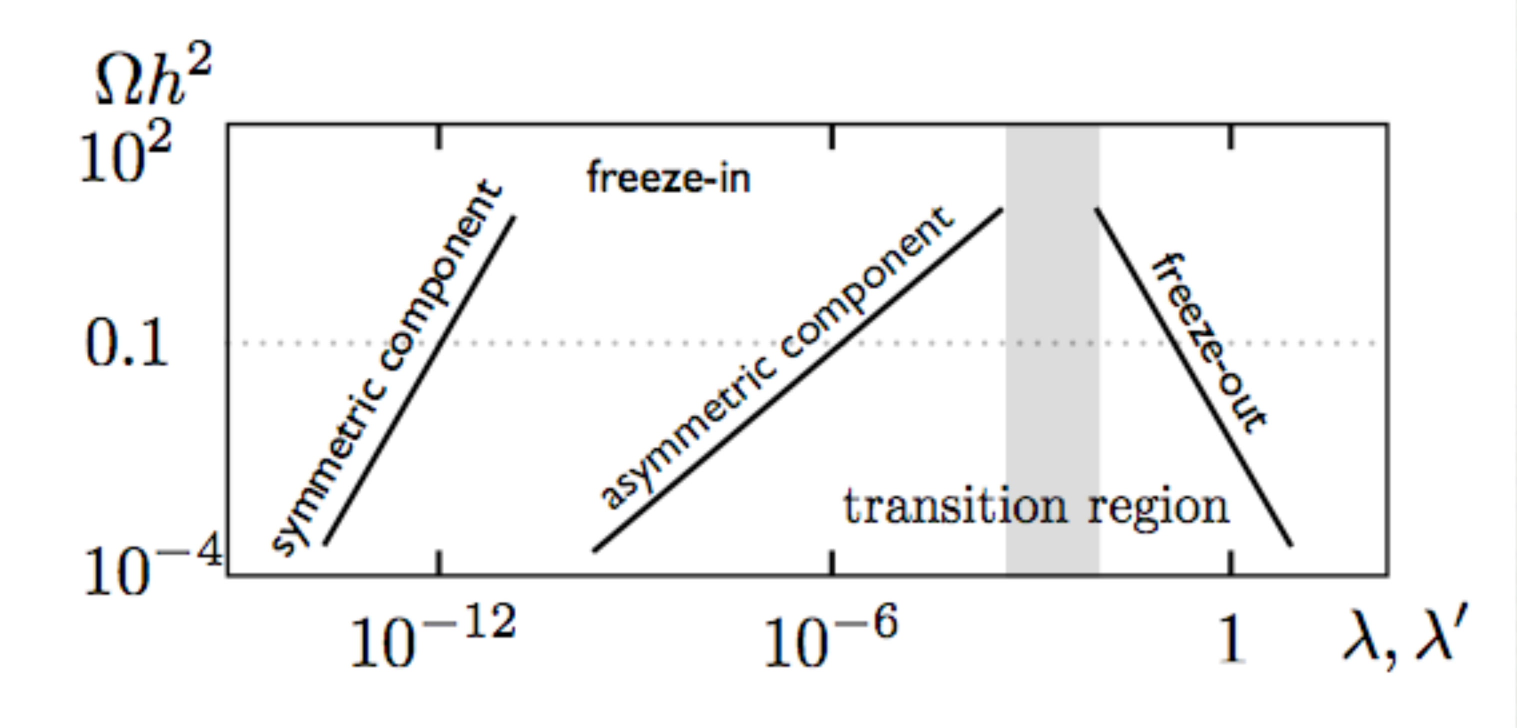
- ASYMMETRY APPEARS AT λ^2
- CP VIOLATION COULD COME FROM GAUGINO - HIGGSINO SECTOR

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