ASYMMETRIC DARK MATTER

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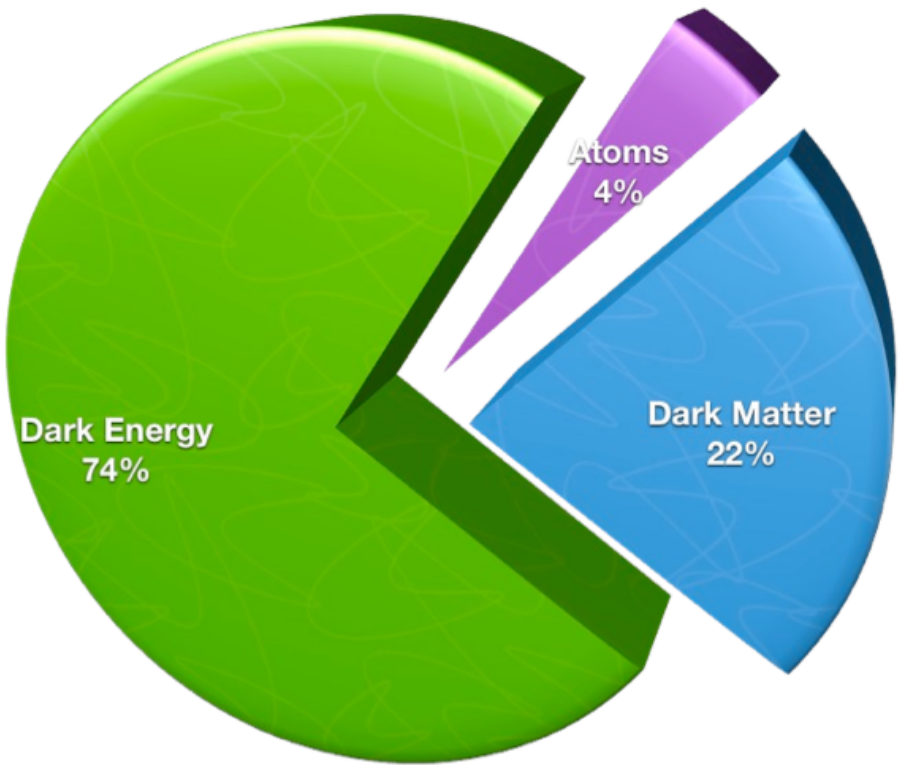
HAP DARK MATTER 2015

OUTLINE

- ADM BASICS
  - SHARING
  - CO-GENESIS
  - HEAVY ADM
- CONSTRAINTS AND SIGNALS
  - REMOVING SYMMETRIC COMPONENT
  - NUCLEAR DM

INTRODUCTION



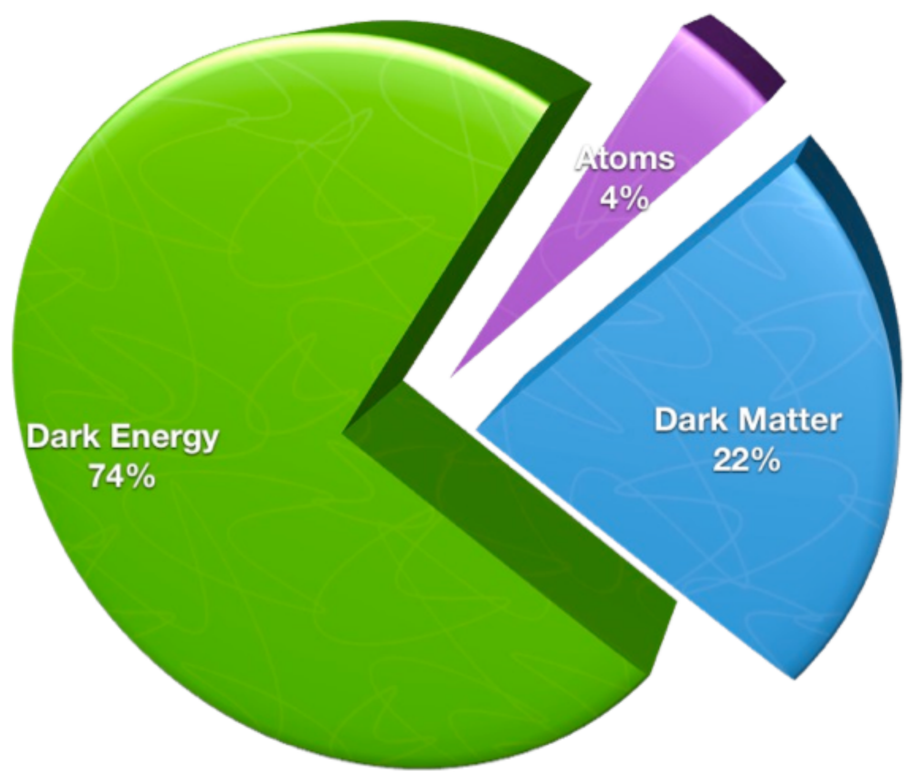
$$\boxed{\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim 5}$$

- STANDARD PICTURE:

$\Omega_{\rm dm}$ WIMP FREEZE-OUT - SET WHEN $\Gamma_{\rm ann} \lesssim H$

$\Omega_{\rm B}$ SET BY CP-VIOLATING, BARYON NUMBER VIOLATING OUT OF EQUILIBRIUM PROCESSES.

Introduction



$$\boxed{\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim 5}$$

- Standard picture:

$\Omega_{\rm dm}$ WIMP freeze-out - set when $\Gamma_{\rm ann} \lesssim H$

$\Omega_{\rm B}$ Set by CP-violating, baryon number violating out of equilibrium processes.

- Given the physics generating each quantity, ratio is a surprise
- If not a coincidence - need to explain the closeness

$\Rightarrow$ Shared dynamics $\Rightarrow$ **Asymmetric Dark Matter**

ADM BASICS

$$\boxed{\eta_{\mathrm{dm}} = n_{\mathrm{dm}} - n_{\overline{\mathrm{dm}}} \neq 0}$$

OR

$$\boxed{\eta_{\mathrm{B}} = n_{\mathrm{B}} - n_{\overline{\mathrm{B}}} \neq 0}$$

OR BOTH

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- RELATE THIS DM ASYMMETRY TO THE BARYON ASYMMETRY
- LEADING TO:

$$\boxed{n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}}} \Rightarrow \quad \eta_{\rm dm} = C\eta_{\rm B}$$

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- Relate this DM asymmetry to the baryon asymmetry
- Leading to:

$$\boxed{n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}}} \Rightarrow \eta_{\rm dm} = C\eta_{\rm B}$$

$$n_{\rm dm} \gg n_{\overline{\rm dm}}$$

$$\boxed{\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{(n_{\rm dm} + n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} + n_{\overline{\rm B}})m_{\rm B}} \sim \frac{(n_{\rm dm} - n_{\overline{\rm dm}})m_{\rm dm}}{(n_{\rm B} - n_{\overline{\rm B}})m_{\rm B}}}$$

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- VALUE OF C IS DETERMINED BY HOW THE ASYMMETRIES ARE SHARED BETWEEN THE TWO SECTORS

ADM BASICS

$$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{\eta_{\rm dm}}{\eta_{\rm B}} \frac{m_{\rm dm}}{m_{\rm B}}$$

IF

$$\eta_{\rm dm} \sim \eta_{\rm B}$$

- Then we get a prediction for the mass of the dark matter

$$\boxed{m_{\rm dm} \sim 5 m_{\rm B} \sim 5 \text{ GeV}}$$

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$$\boxed{m_{\rm dm} \sim 5 m_{\rm B} \sim 5\ \text{GeV}}$$

- This is the "natural" dark matter mass for ADM models.

- Not the only possible mass, more sophisticated models can allow for a large range of ADM masses

$\Rightarrow$ Depends on the way in which the asymmetry is shared (or generated)

ADM BASICS

- In many models, symmetries are introduced that link the baryon and dark matter sectors
- In the dark sector: $U(1)_{\mathrm{X}}$
- In the SM sector: $U(1)_{\mathrm{B-L}}$
- Generically require operators that break these two symmetries down to

$$\boxed{U(1)_{\mathrm{B-L+X}}}$$

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- These operators play a crucial role in transmitting the asymmetry from one sector to another
- They can also lead to signals. E.g. at the LHC, see later...

ADM BASICS

- ACHIEVING: $$n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}}$$
- TWO TYPES OF MODELS TO DO THIS

ADM BASICS

- Achieving: $$n_{\rm dm} - n_{\overline{\rm dm}} \propto n_{\rm B} - n_{\overline{\rm B}}$$

- Two types of models to do this

Sharing a pre-existing asymmetry

- Assume a pre-existing asymmetry
  - High scale Leptogenesis or baryogenesis
  - Asymmetry generated via some Dark version of baryogenesis
- Asymmetry transferred/shared between sectors

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Co-generating both asymmetries

- Asymmetries in DM and baryons created simultaneously
- DM genesis and baryogenesis wrapped up in one mechanism
- Potential to test both DM genesis and baryogenesis

ELECTROWEAK ANOMALY

- PLAYS A CRUCIAL ROLE IN MOST BARYOGENESIS/LEPTOGENESIS MODELS

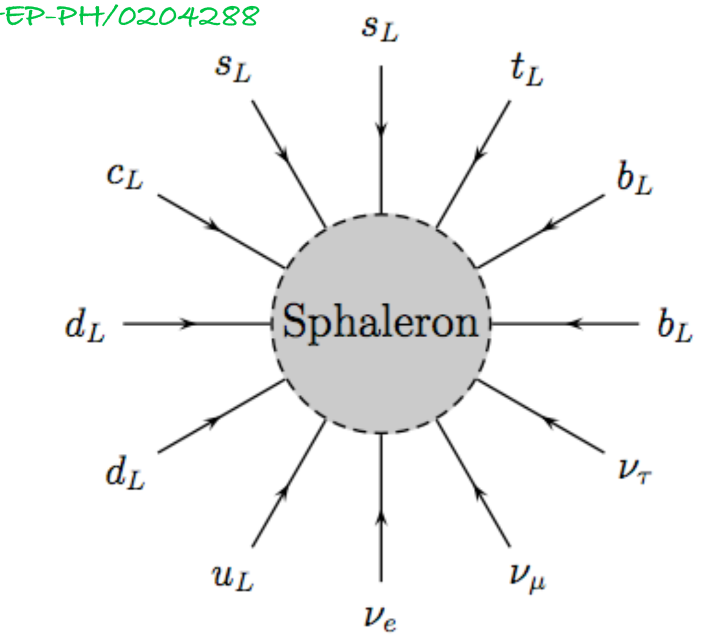
- $\mathrm{B}+\mathrm{L}$ VIOLATING PROCESSES, CONSERVES $\mathrm{B}-\mathrm{L}$

- OPERATES EFFICIENTLY FOR

$$10^{12}\,\mathrm{GeV} > T \gtrsim 100\,\mathrm{GeV}$$

  - BELOW - EXPONENTIALLY SUPPRESSED

TAKEN FROM BUCHMULLER, HEP-PH/0204288



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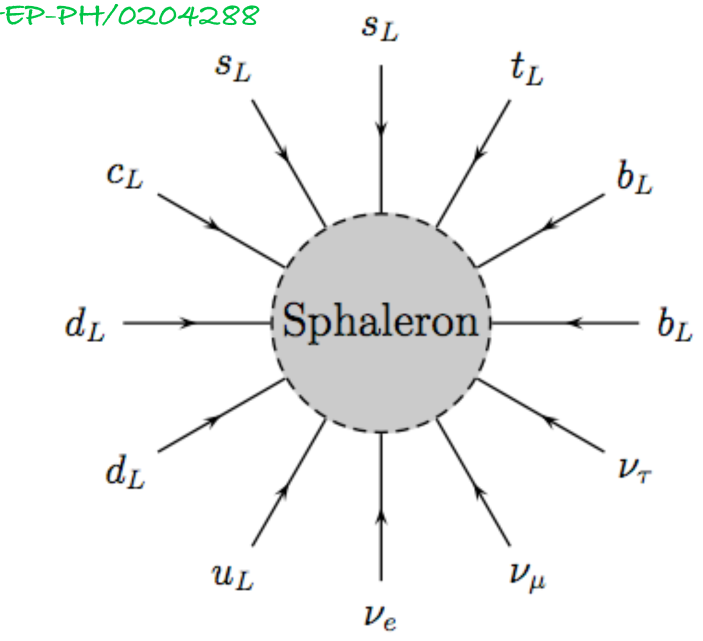
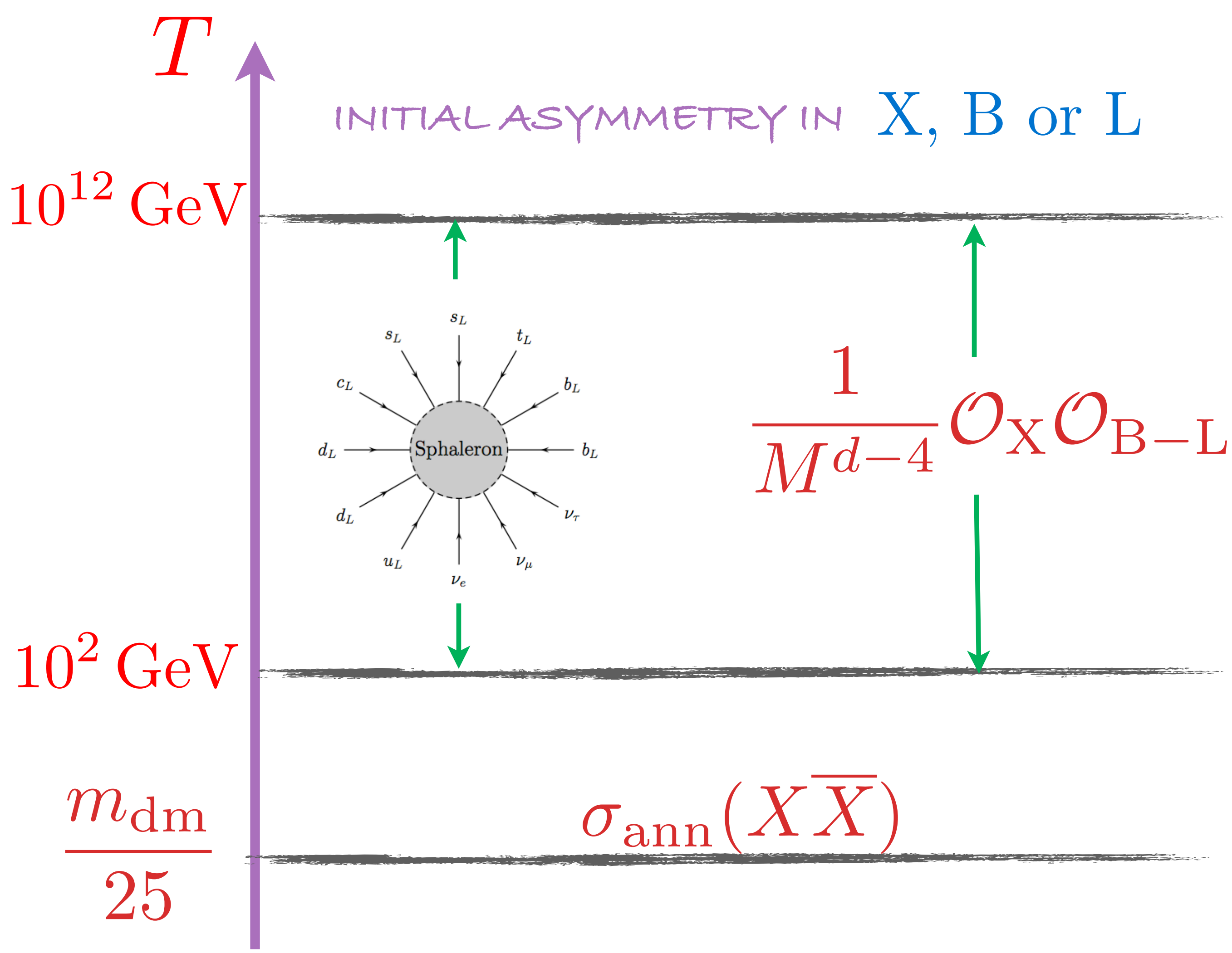


- CAN EFFECTIVELY BE THOUGHT OF AS MULTI-PARTICLE VERTEX INVOLVING $SU(2)_L$ STATES
- IF $\mathrm{B}\neq 0$ AND $\mathrm{L}\neq 0$, BUT $\mathrm{B}-\mathrm{L}=0$, E-WEAK ANOMALY WILL WASH THE ASYMMETRIES OUT
- IF $\mathrm{B}=0$ BUT $\mathrm{L}\neq 0$, $\mathrm{B}-\mathrm{L}\neq 0$, E-WEAK ANOMALY WILL REPROCESS THE L ASYMMETRY INTO A B ASYMMETRY

SHARING

- Assume the presence of a non-zero primordial asymmetry in either dark matter or baryon or Lepton sector



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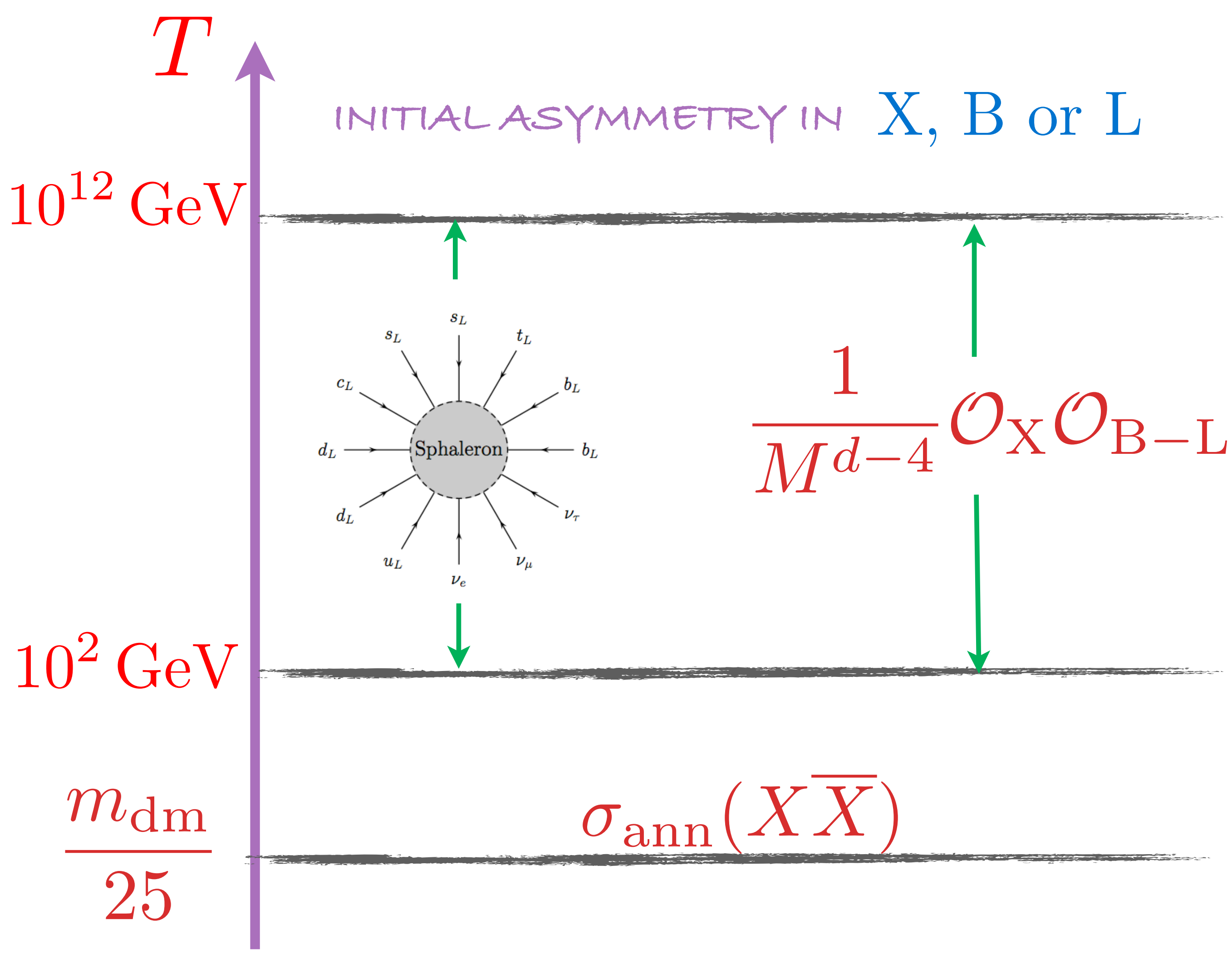

Some operator responsible for processes that violates a combination of B , L and X but preserve $\mathrm{B-L+X}$

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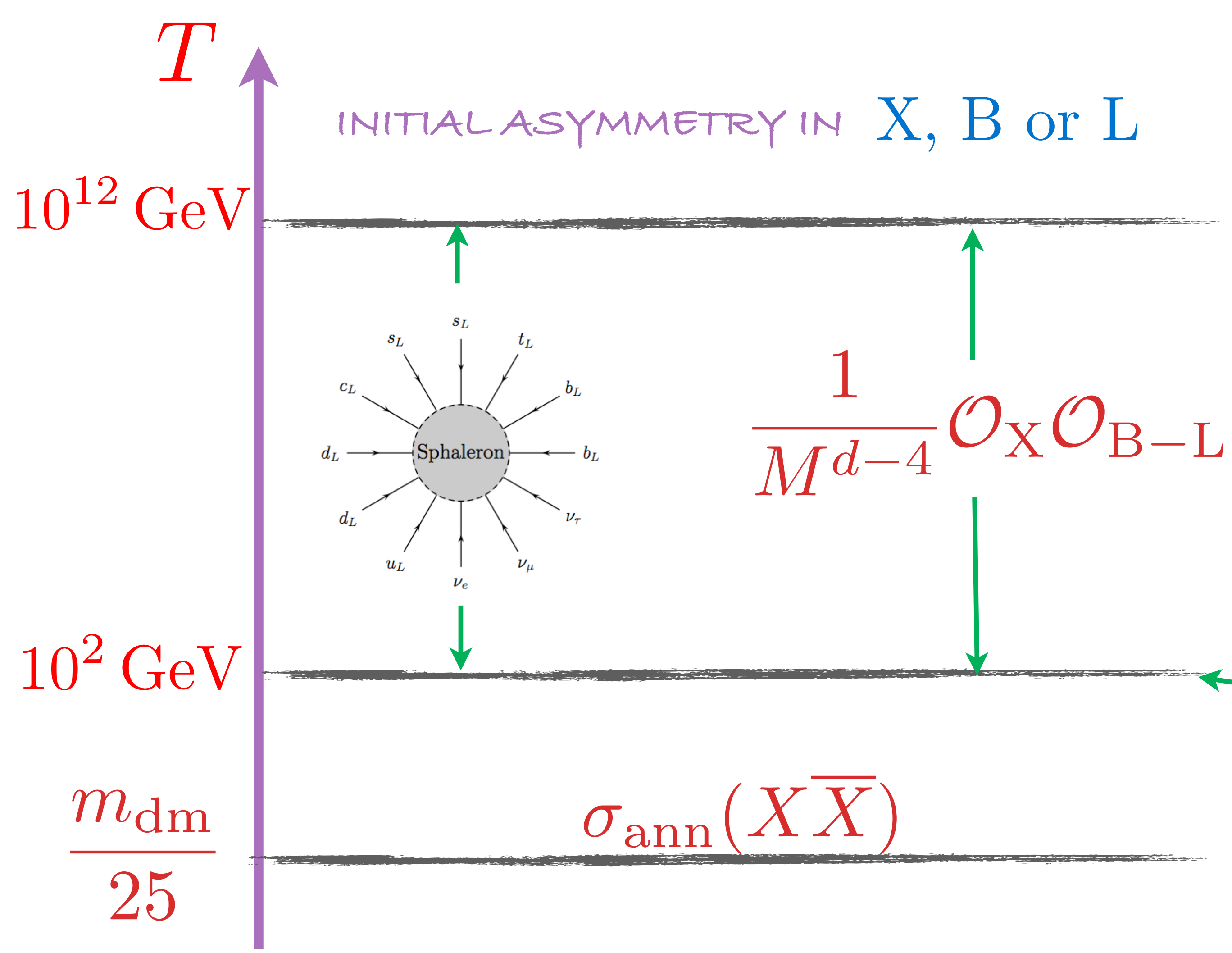

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Crucial X and $\mathrm{B-L}$ violating processes are in-active before DM becomes non-relativistic - fixes the asymmetry in X
(if we want ~5 GeV states)

SHARING

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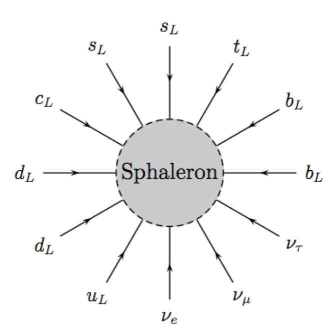
T

Initial asymmetry in X, B or L

10^{12} GeV



$$\frac{1}{M^{d-4}}\mathcal{O}_{\mathrm{X}}\mathcal{O}_{\mathrm{B-L}}$$

Some operator responsible for processes that violates a combination of B, L and X but preserve $\mathrm{B-L+X}$

10^2 GeV

Crucial X and $\mathrm{B-L}$ violating processes are in-active before DM becomes non-relativistic - fixes the asymmetry in X
(if we want ~5 GeV states)

$\frac{m_{\mathrm{dm}}}{25}$

$\sigma_{\mathrm{ann}}(X\overline{X})$

Need sufficient annihilation rate to remove the symmetric component $\Longrightarrow$ Leads to constraints/possible signals

SHARING

- There are a three main options

B or L violating operators

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Electroweak sphalerons

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B or L violating operators

Electroweak sphalerons

dark sphalerons

- Let's look at some examples...

SHARING 1

KAPLAN, LUTY, ZUREK (2009)

- B or L violating operators - Example case
  - Global symmetry $U(1)_{\mathrm{B-L-X/2}}$
  - At high temperatures a $\mathrm{B-L}$ asymmetry is generated
  - Introduce an operator that preserves $\mathrm{B-L-X/2}$, violating $\mathrm{B-L}$ and X (context of SUSY)

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

X has charge $\mathrm{X}=1$

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- B OR L VIOLATING OPERATORS - EXAMPLE CASE
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$$\boxed{\Delta W = \frac{1}{M} \overline{X}^2 L H_u}$$

X HAS CHARGE $\mathrm{X} = 1$

  - WHEN IN THERMAL EQUILIBRIUM, OPERATOR TRANSFERS ASYMMETRY FROM L TO X NUMBER.
  - NEED TO ANALYSE CHEMICAL POTENTIALS TO WORK OUT THE RATIO OF ASYMMETRIES IN X AND B

SEE E.G. HARVEY, TURNER '90

SHARING 1

Kaplan, Luty, Zurek (2009)

- Calculation critically depends on what particles and what interactions are in thermal equilibrium

- Assume that the transfer operator $\Delta W = \frac{1}{M}\overline{X}^2 L H_u$ drops out of thermal equilibrium above the electroweak phase transition.

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- At this point, the asymmetries in X and $\mathrm{B-L}$ are fixed as now $U(1)_{\mathrm{X}}$ and $U(1)_{\mathrm{B-L}}$ are restored (fixing asymmetry in X)

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KAPLAN, LUTY, ZUREK (2009)

- CALCULATION CRITICALLY DEPENDS ON WHAT PARTICLES AND WHAT INTERACTIONS ARE IN THERMAL EQUILIBRIUM

- ASSUME THAT THE TRANSFER OPERATOR $\Delta W = \frac{1}{M}\overline{X}^2 L H_u$ DROPS OUT OF THERMAL EQUILIBRIUM ABOVE THE ELECTROWEAK PHASE TRANSITION.

- AT THIS POINT, THE ASYMMETRIES IN X AND $\mathrm{B-L}$ ARE FIXED AS NOW $U(1)_{\mathrm{X}}$ AND $U(1)_{\mathrm{B-L}}$ ARE RESTORED (FIXING ASYMMETRY IN X)

- SOLVING THE CHEMICAL POTENTIAL EQUATIONS WE ARRIVE AT

$$\mathrm{X} = -\frac{11}{79}(\mathrm{B-L}) \quad \text{WITH} \quad \mathrm{B} \approx 0.31(\mathrm{B-L})$$

$$\frac{\Omega_{\mathrm{dm}}}{\Omega_{\mathrm{B}}} \sim \frac{\mathrm{X}}{\mathrm{B}}\frac{m_{\mathrm{dm}}}{m_{\mathrm{B}}} \Rightarrow \boxed{m_{\mathrm{dm}} \approx \frac{\mathrm{B}}{\mathrm{X}}\frac{\Omega_X}{\Omega_B} \approx 11\,\mathrm{GeV}}$$

Sharing 2

Barr, Chivukula, Fahri, '90, Barr '91, Kaplan '92, also see e.g. Foadi, Frandsen, Sannino'09, Kribs, Roy, Terning, Zurek '09

- Dark mater states are charged under $SU(2)_L$ and $U(1)_{\rm X}$
  - $U(1)_{\rm X}$ symmetry constructed to have a chiral anomaly under $SU(2)_L$, just like $\rm B - L$ in the SM

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    The combination $\boxed{\mathrm{B}+\mathrm{L}+\frac{N_{\rm X}}{N_G}\mathrm{X}}$ is violated, where

    $N_{\rm X}$ is the number of dark states charged under $SU(2)_L$

    N_G is the number of generations carrying $\rm B$ and $\rm L$

The combinations $N_1 = \mathrm{B} - \dfrac{N_G}{N_{\rm X}}\mathrm{X}$ $\quad N_2 = \mathrm{B}-\mathrm{L}$ are preserved

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    The combinations $N_1 = \mathrm{B} - \frac{N_G}{N_X}\mathrm{X} \quad N_2 = \mathrm{B} - \mathrm{L}$ are preserved

  - If a primordial asymmetry exists such that either N_1 or N_2 are non-zero, asymmetry will be shared by the electroweak anomaly

  - For a 5 GeV state charged under $SU(2)_L$, this is highly constrained by electroweak precision measurements - we will come back to this...

Sharing 3

See e.g. Buckely, Randall '11

- Dark version of electroweak sphalerons

  - Introduce a hidden non-abelian gauge symmetry, e.g. $SU(2)_R$, and a $U(1)_{\mathrm{X}}$ which has a chiral $SU(2)_R$ anomaly.

  - Standard model states also charged under the $SU(2)_R$, with B or L also having a chiral $SU(2)_R$ anomaly

  - As with the electroweak anomaly, an asymmetry in either X, B or L will be transferred to the others

SHARING 3

SEE E.G. BUCKELY, RANDALL '11

- DARK VERSION OF ELECTROWEAK SPHALERONS

- INTRODUCE A HIDDEN NON-ABELIAN GAUGE SYMMETRY, E.G. $SU(2)_R$, AND A $U(1)_X$ WHICH HAS A CHIRAL $SU(2)_R$ ANOMALY.

- STANDARD MODEL STATES ALSO CHARGED UNDER THE $SU(2)_R$, WITH B OR L ALSO HAVING A CHIRAL $SU(2)_R$ ANOMALY

- AS WITH THE ELECTROWEAK ANOMALY, AN ASYMMETRY IN EITHER X ,B OR L WILL BE TRANSFERRED TO THE OTHERS

- HARD TO JUSTIFY A 5 GEV DARK STATE AND AVOID LIMITS ON RIGHT HANDED GAUGE BOSONS - COME BACK TO THIS ALSO...

HEAVY ADM

SEE E.G. BARR 91, BUCKELY, RANDALL '11

- CAN HAVE ADM WITH HEAVY MASSES
- X NUMBER VIOLATING PROCESSES ONLY DECOUPLE AFTER DM HAS BECOME NON-RELATIVISTIC

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- X NUMBER VIOLATING PROCESSES ONLY DECOUPLE AFTER DM HAS BECOME NON-RELATIVISTIC

$\Rightarrow$ DARK MATTER ASYMMETRY GETS BOLTZMANN SUPPRESSED

$$\boxed{\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \approx \frac{m_{\rm dm}}{m_{\rm B}} x^{3/2} e^{-x}}$$

WITH $x = \dfrac{m_{\rm dm}}{T_d}$

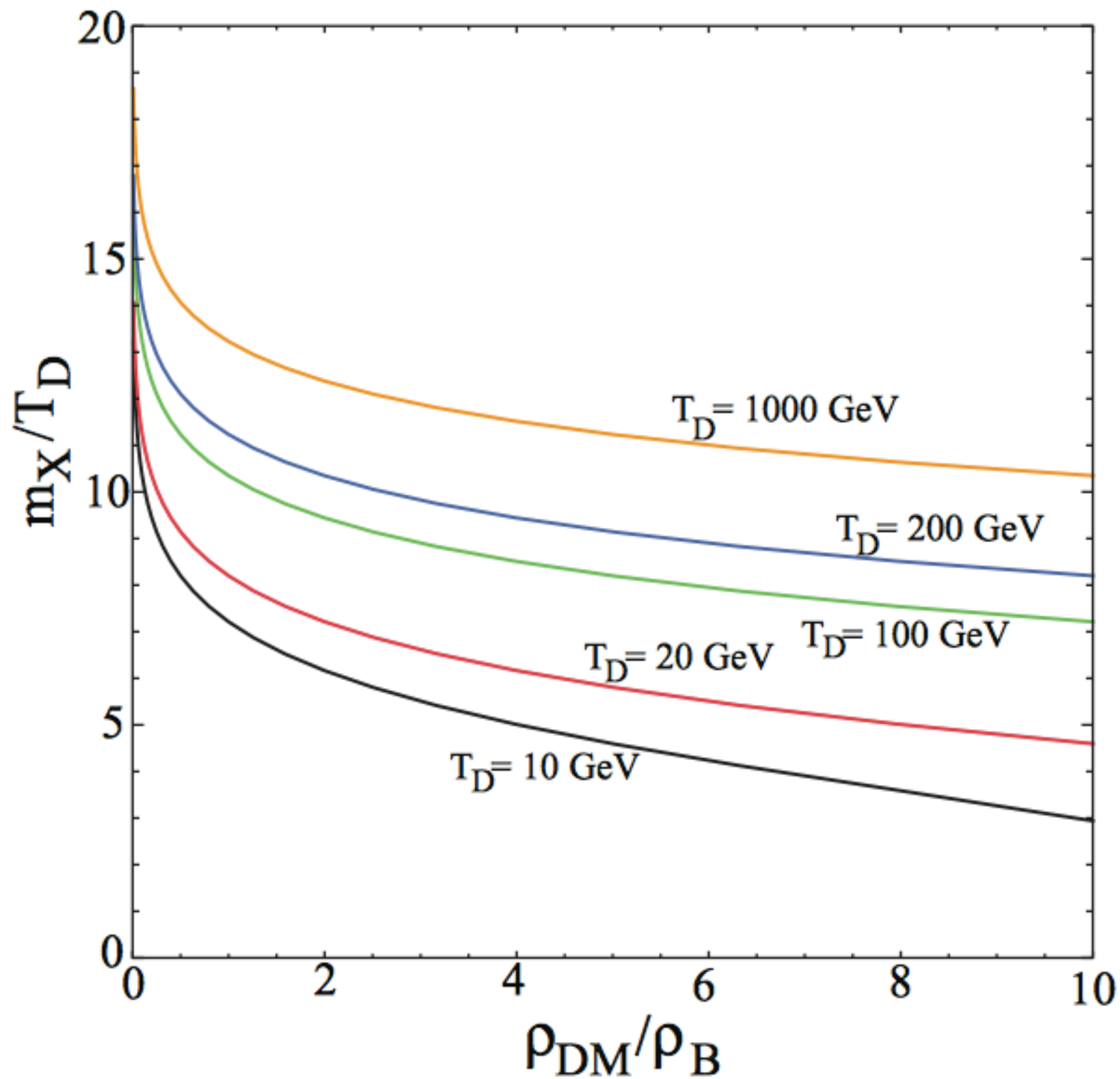
T_d DECOUPLING TEMP OF X-NUMBER VIOLATING INTERACTIONS

- ACTUAL SUPPRESSION IS MORE COMPLICATED - SEE BARR '91

Heavy ADM

Buckley, Randall; (2010)

- Large range of possible masses



HEAVY ADM

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- TWO SHARING EXAMPLES CAN WORK IN THIS REGIME...

- DARK MATER STATES ARE CHARGED UNDER $SU(2)_L$ AND $U(1)_X$

    - EASIER TO AVOID ELECTROWEAK PRECISION CONSTANTS WITH HEAVIER DARK MATTER

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  - MASS SCALES OF DARK MATTER STATES CAN NOW BE LARGE AND ARISE MORE NATURALLY IN A MODEL WITH HEAVY $SU(2)_R$ GAUGE BOSONS
- ALSO OPENS UP MORE POSSIBILITIES WITH TRANSFER OPERATORS... SEE E.G. KRIBS, ROY, TERNING, ZUREK '09; BUCKELY, RANDALL '11

GENERATING AN ASYMMETRY

- High scale leptogenesis or baryogenesis - SM sector

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- Dark sector generates asymmetry

  - Dark version of electroweak baryogenesis

    Dutta, Kumar '10; Shelton, Zurek '10; Petraki, Trodden, Volkas '12; Walker '12

  - Spontaneous Dark Baryogenesis

    Cohen, Kaplan '87 '88; March-Russell, McCullough

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- Co-genesis

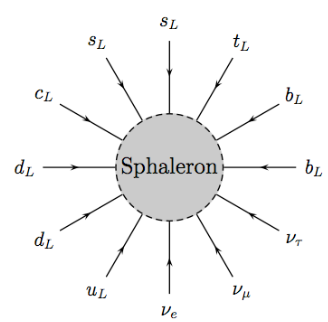
    - Generate both dark matter and baryon asymmetry at the same time

CO-GENESIS

T

NO INITIAL ASYMMETRY IN X, B or L

10^{12} GeV



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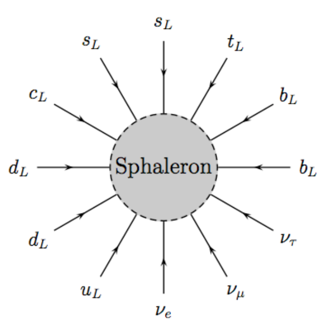

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10^2 GeV

$$\sigma_{\mathrm{ann}}(X\overline{X})$$

$\dfrac{m_{\mathrm{dm}}}{25}$

AGAIN COMBINATION OF B , L AND X NUMBER VIOLATED AND $\mathrm{B}-\mathrm{L}+\mathrm{X}$ PRESERVED.

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

CO-GENESIS

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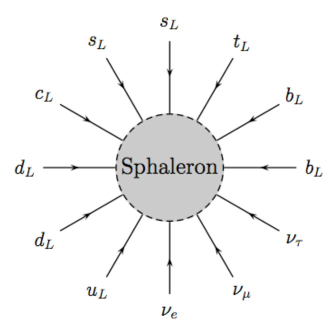


$$\frac{1}{M^{d-4}}\mathcal{O}_{\mathrm{X}}\mathcal{O}_{\mathrm{B-L}}$$

AGAIN COMBINATION OF B , L AND X NUMBER VIOLATED AND $\mathrm{B-L+X}$ PRESERVED.

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

10^2 GeV

$\frac{m_{\mathrm{dm}}}{25}$

$\sigma_{\mathrm{ann}}(X\overline{X})$

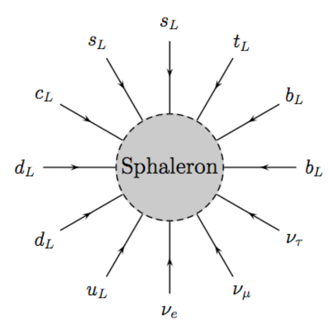
AGAIN NEED SUFFICIENT ANNIHILATION RATE TO REMOVE THE SYMMETRIC COMPONENT

CO-GENESIS

T

NO INITIAL ASYMMETRY IN X, B or L

10^{12} GeV



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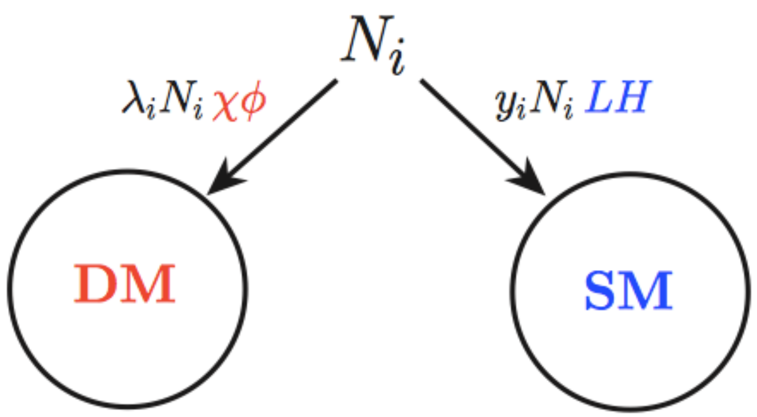
- SOME INTERESTING EXAMPLES ON THE MARKET

CO-GENESIS

- DECAYING STATES

SEE E.G. FALKOWSKI, RUDERMAN, VOLANSKY '11

EXTEND LEPTOGENESIS:



SIMULTANEOUSLY GENERATES ASYMMETRY IN DM AND LEPTONS

DEPENDS ON COUPLINGS AND PHASES IN EACH SECTOR

CO-GENESIS

- DECAYING STATES

SEE E.G. FALKOWSKI, RUDERMAN, VOLANSKY '11

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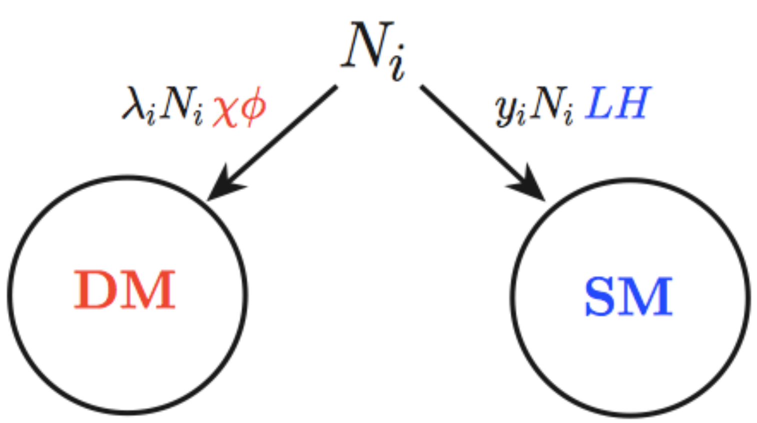

SIMULTANEOUSLY GENERATES ASYMMETRY IN DM AND LEPTONS

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- AFFLECK-DINE

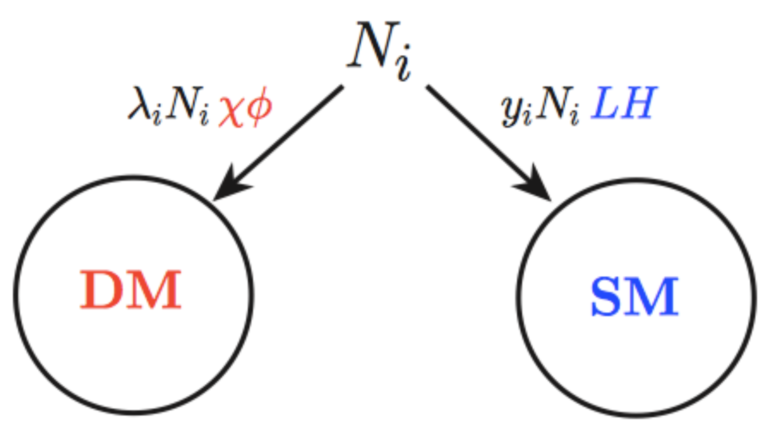
AFFLECK, DINE '85; DINE, KUSENKO '04; CHEUNG, ZUREK '12

EXTEND AFFLECK-DINE MECHANISM - FLAT DIRECTIONS USED CARRY BOTH $\mathrm{B-L}$ AND X NUMBER

CO-GENESIS

- DECAYING STATES — SEE E.G. FALKOWSKI, RUDERMAN, VOLANSKY '11

EXTEND LEPTOGENESIS:



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EXTEND AFFLECK-DINE MECHANISM - FLAT DIRECTIONS USED CARRY BOTH $\mathrm{B-L}$ AND X NUMBER

- ELECTROWEAK CO-GENESIS — CHEUNG, ZHANG '13

EXTENSION OF ELECTROWEAK BARYOGENESIS, 2 HIGGS DOUBLETS AND 2 DARK SCALAR CARRYING $U(1)_X$ CHARGES ARE REQUIRED.

UTILISES 1ST ORDER EW PHASE TRANSITION.

CONSTRAINTS AND SIGNALS

CONSTRAINTS AND SIGNALS

REMOVING SYMMETRIC DM COMPONENT

LHC LIMITS - MONOJETS, MONOPHOTONS

DIRECT DM DETECTION

HEAVY QUARKONIUM DECAYS

BBN, CMB PERTURBATIONS

CONSTRAINTS AND SIGNALS

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PROBING ASYMMETRY SHARING OPERATORS

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DIRECT DM DETECTION

HEAVY QUARKONIUM DECAYS

BBN, CMB PERTURBATIONS

PROBING ASYMMETRY SHARING OPERATORS

LHC LIMITS - LONG LIVED STATES

OTHER POSSIBILITIES

DM-ANTI DM OSCILLATIONS

ADM COULD DECAY VIA SHARING OPERATORS

ADM CAN COLLECT IN STARS

COULD FORM DARK NUCLEI -
SEE LATER IF TIME

IMPORTANT: CAN HAVE DIRECT DETECTION

REMOVING SYMMETRIC CPT

BUCKLEY; MARCH-RUSSELL, UNWIN, SMW

$$\boxed{\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{\eta_{\rm X}}{\eta_{\rm B}} \frac{m_{\rm dm}}{m_{\rm B}}}$$

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

OTHERWISE: $$\frac{\Omega_{\rm dm}}{\Omega_{\rm B}} \sim \frac{n_{\rm dm} + n_{\overline{\rm dm}}}{n_{\rm B}} \frac{m_{\rm dm}}{m_{\rm B}}$$

LOOSE RELATIONSHIP BETWEEN ABUNDANCES

NEED: $$n_{\rm dm} + n_{\overline{\rm dm}} \approx n_{\rm dm} - n_{\overline{\rm dm}}$$

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LOOSE RELATIONSHIP BETWEEN ABUNDANCES

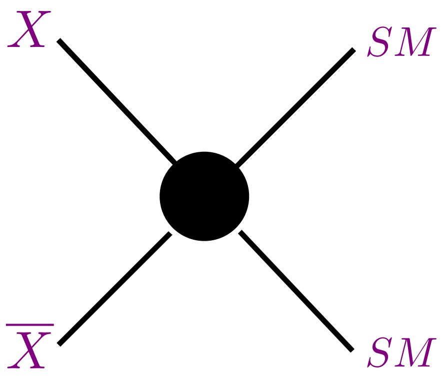
NEED: $$n_{\rm dm} + n_{\overline{\rm dm}} \approx n_{\rm dm} - n_{\overline{\rm dm}}$$

- Need to annihilate away the symmetric component

REMOVING SYMMETRIC CPT

1) ANNIHILATE DIRECTLY TO SM STATES

SEVERE LIMITS FOR HEAVY MEDIATORS



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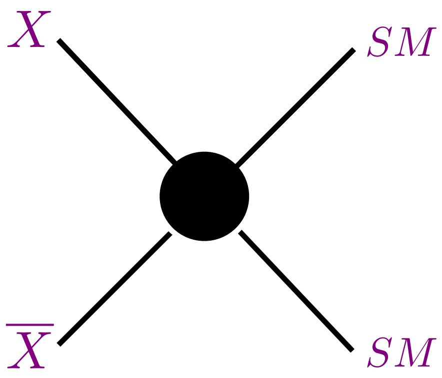
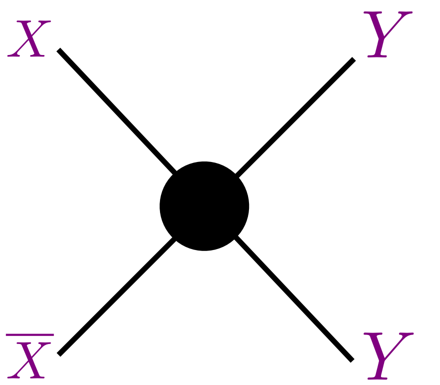


2) ANNIHILATE DIRECTLY TO LIGHT HIDDEN SECTOR STATES

POSSIBLE CONTRIBUTION TO DARK RADIATION



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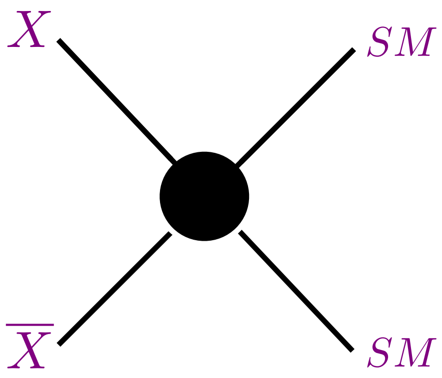

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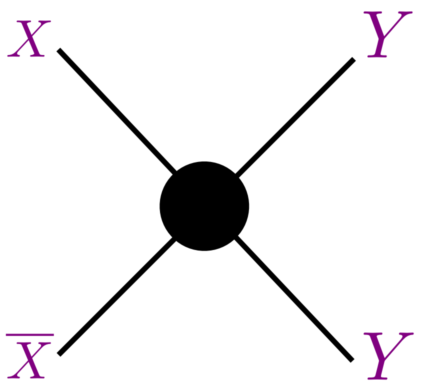
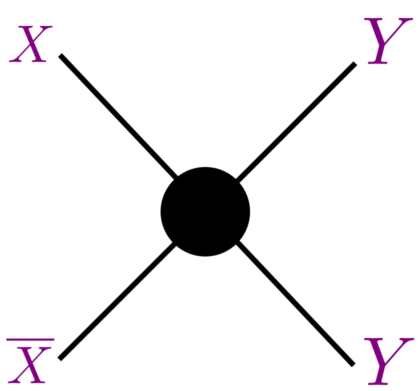
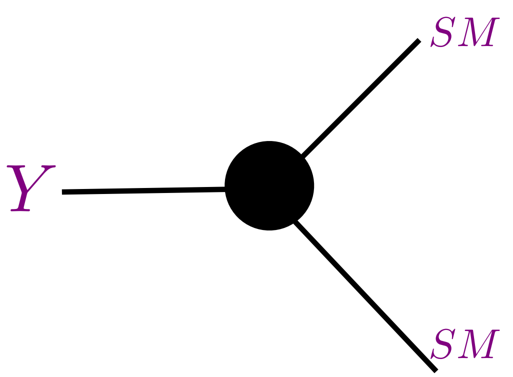


3) ANNIHILATE TO VERY LIGHT HIDDEN SECTOR STATES THAT LATER DECAY TO SM

LATE TIME ENERGY INJECTION IN EARLY UNIVERSE





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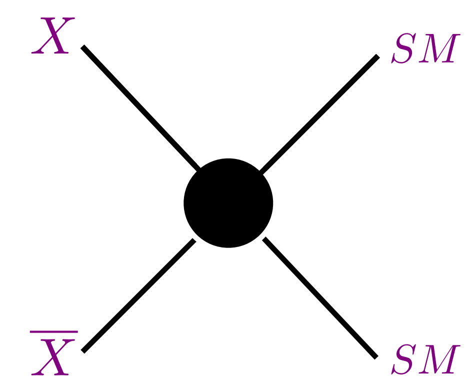

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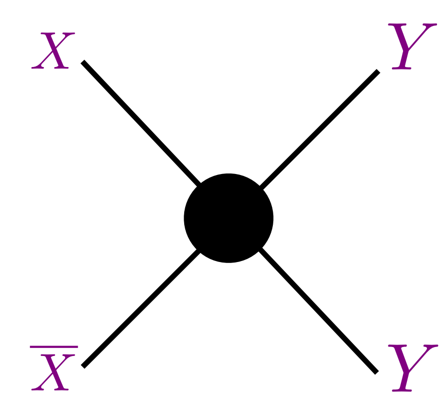

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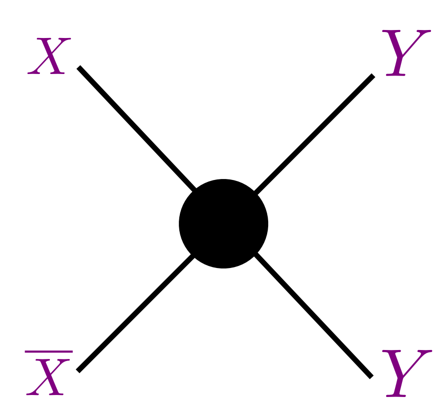
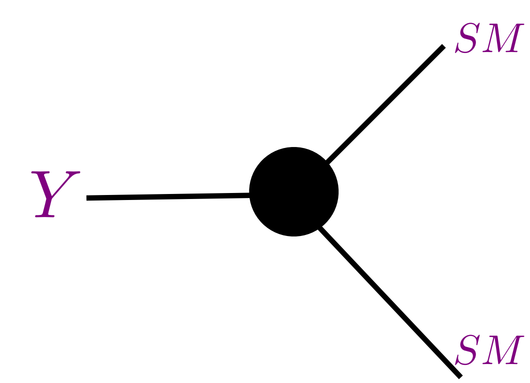
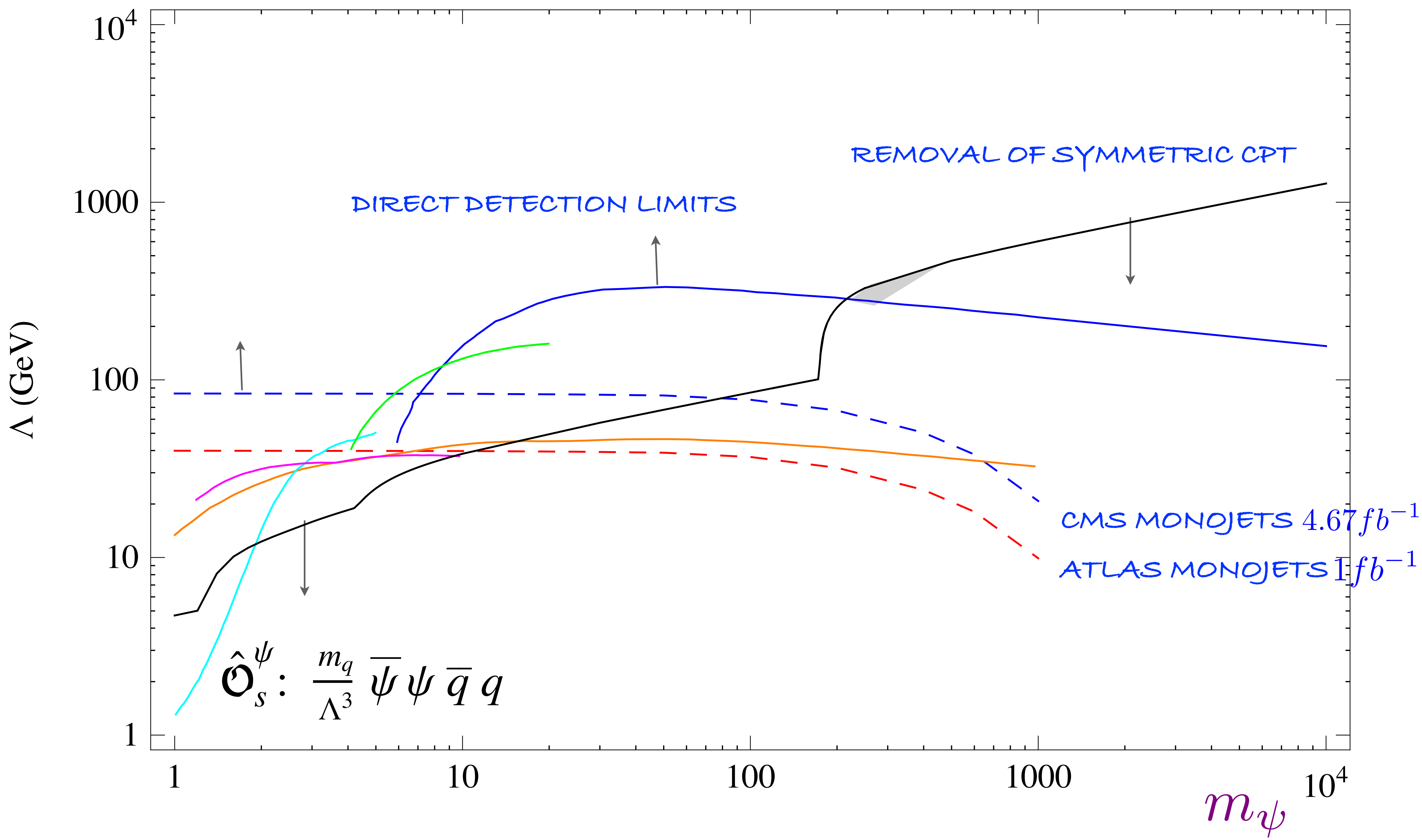




REMOVING SYMMETRIC CPT

MARCH-RUSSELL, UNWIN, SMW '12



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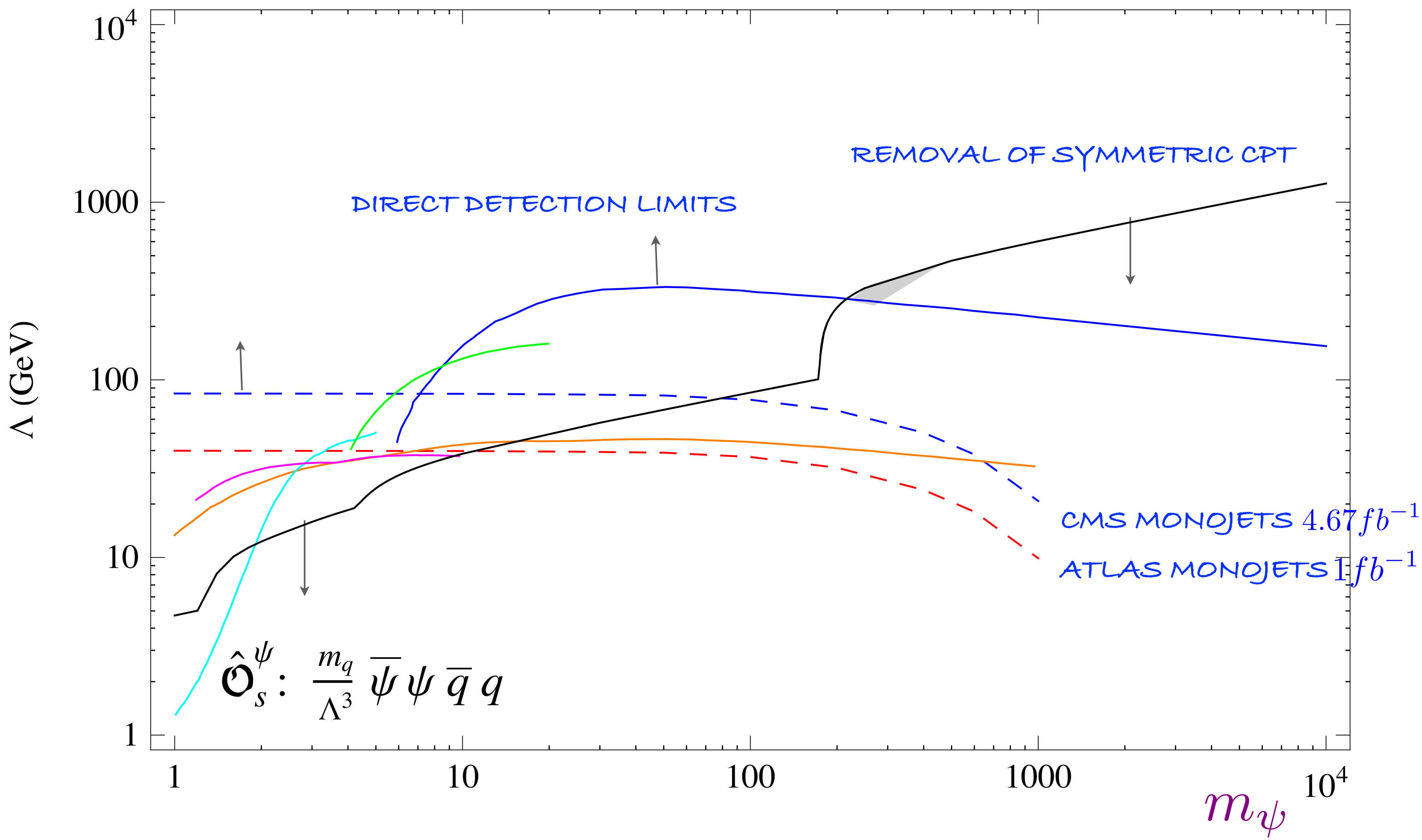

- NEED TO CONSIDER LIGHT MEDIATORS...LOTS OF PHYSICS

NUCLEAR DARK MATTER

- INTERESTING POSSIBILITY THAT ADM COULD BIND TOGETHER TO FORM LARGE COMPOSITE STATES
- CAN WE HAVE THE ANALOGY TO THE SM IN TERMS OF BUILDING UP LARGE COMPOSITE STATES OF DM - BUT LARGE DARK NUCLEI FORM IN DARK VERSION OF BIG BANG NUCLEOSYNTHESIS

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- CAN WE HAVE THE ANALOGY TO THE SM IN TERMS OF BUILDING UP LARGE COMPOSITE STATES OF DM - BUT LARGE DARK NUCLEI FORM IN DARK VERSION OF BIG BANG NUCLEOSYNTHESIS
- OLD EXAMPLES OF BOUND STATES OF DARK MATTER ARE:
    - WIMPONIUM (BOUND STATE OF TWO DM PARTICLES)

      M. Pospelov and A. Ritz '08; March-Russell, SW '08; Shepherda, Tait, Zaharijasb '09; Panotopoulos '10, Laha '13 '15; Von Harling, Petraki '14, Petraki, Postma, Wiechers '15

    - ATOMIC DARK MATTER

      Kaplan, Krnjaic, Rehermann, Wells '09, '11

- CAN WE GO BIGGER?

NUCLEAR DARK MATTER

G. Krnjaic and K. Sigurdson '14; Hardy, Lasenby, March-Russell, SW '14, '15

- Propose DM has short-ranged strong "nuclear" binding force with hard core repulsion - analogy with the SM

NUCLEAR DARK MATTER

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- PROPOSE DM HAS SHORT-RANGED STRONG "NUCLEAR" BINDING FORCE WITH HARD CORE REPULSION - ANALOGY WITH THE SM

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- NO COULOMB FORCE - BINDING ENERGY PER NUCLEON DOES NOT TURN OVER AT LARGE DNN

NUCLEAR DARK MATTER

G. Krnjaic and K. Sigurdson '14; Hardy, Lasenby, March-Russell, SW '14, '15

- Propose DM has short-ranged strong "nuclear" binding force with hard core repulsion - analogy with the SM
- DM or "dark nucleons" posses approximately conserved quantum number, dark nucleon number (DNN) - analogous to baryon number
- Assume dark nucleons present only - asymmetric
- For minimality, only one type of dark nucleon present and no dark version of the Coulomb force
- No Coulomb force - binding energy per nucleon does not turn over at large DNN
- Dark nuclei exist with a range of DNNs, forming post freeze-out via dark nucleosynthesis

NUCLEAR DARK MATTER

- RELATED WORKS
  - QCD-LIKE MODEL - NUCLEI WITH SMALL NUMBERS OF DARK NUCLEONS:

    Detmold, McCullough, Pochinsky '14

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  - YUKAWA INTERACTIONS BETWEEN DARK NUCLEONS LEADING TO DARK NUCLEI (OR NUGGETS) WITH LARGE NUMBER NUCLEONS. NO HARD CORE REPULSION LEADING TO INTERESTING RADIUS VS DNN BEHAVIOUR

    WISE AND ZHANG '14

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    WISE AND ZHANG '14
  - EARLY EXAMPLES IN TERMS OF Q-BALLS
    FRIEMAN, GELMINI, GLEISER, KOLB '88; FRIEMAN, OLINTO, GLEISER, AND C. ALCOCK '89 KUSENKO, SHAPOSHNIKOV '97;

NUCLEAR DARK MATTER

- INTERESTING POSSIBILITIES:
  - THERMALLY PRODUCED DARK MATTER WITH MASSES IN EXCESS OF THE USUAL UNITARITY BOUND GRIEST, KAMIONKOWSKI '90

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  - POTENTIALLY PRODUCE STATES WITH VERY LARGE SPIN

NUCLEAR DARK MATTER IN DIRECT DETECTION

- SEVERAL INTERESTING POINTS
  - MOMENTUM DEPENDENT SCATTERING DUE TO DARK NUCLEI FORM FACTOR
  - FOR A LARGE RANGE OF THE MOMENTUM TRANSFER , ELASTIC SCATTERING (AND POSSIBLY INELASTIC) WILL BE COHERENTLY ENHANCE BY k^2
    - HOWEVER, OVERALL RATE WILL INCREASE AS k DUE TO $1/k$ DECREASE IN NUMBER DENSITY
  - DUE TO COHERENCE EFFECTS, UNDERLYING SIZE OF INDIVIDUAL DARK NUCLEON-QUARK INTERACTION REDUCED - - CONSEQUENCE FOR SEARCHES AT COLLIDERS

SUMMARY

- FREEZE-OUT IS BY NO MEANS THE ONLY WAY TO GENERATE DM IN THE EARLY UNIVERSE
- ADM IS A WELL MOTIVATED AND RICH WAY TO EXPLAIN

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

- ADM UTILISES A SHARED SYMMETRY BETWEEN THE DARK AND STANDARD MODEL STATES
- PRIMORDIAL ASYMMETRIES CAN BE TRANSFERRED FROM ONE SECTOR TO THE OTHER OR BOTH ASYMMETRIES CAN BE CO-GENERATED,
- NUCLEAR DM POSSIBILITY EXTENDS THE ADM SET-UP. MANY EXCITING CONSEQUENCES FOR A WIDE RANGE OF EXPERIMENTS

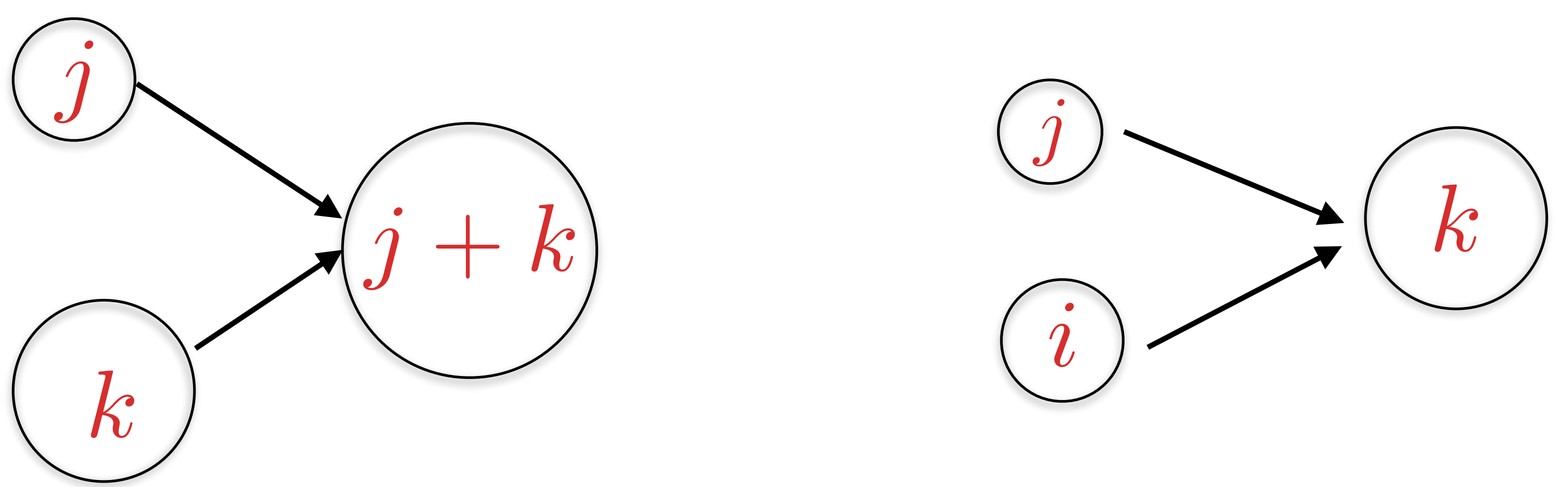
LOTS OF POSSIBILITIES TO INVESTIGATE!

NUCLEAR DARK MATTER

HARDY, LASENBY, MARCH-RUSSELL, SW '14, '15

- AGGREGATION PROCESS - NEGLECTING DISSOCIATIONS

$$\frac{dn_k(t)}{dt} + 3H(t)n_k(t) = -\sum_{j=1}^{\infty}\langle\sigma v\rangle_{j,k}n_j(t)n_k(t) + \frac{1}{2}\sum_{i+j=k}\langle\sigma v\rangle_{i,j}n_i(t)n_j(t)\,,$$



- REWRITING $y_k = Y_k / Y_0$ AND $\langle \sigma v \rangle_{i,j} = \sigma_1 v_1 K_{i,j}$ WHERE

Y_0	IS TOTAL YIELD OF DARK NUCLEONS
$K_{i,j}$	PARAMETERISES RELATIVE RATES OF DIFFERENT FUSION PROCESSES
σ_1	GEOMETRICAL CROSS SECTION OF INDIVIDUAL DARK NUCLEON
v_1	VELOCITY OF SINGLE NUCLEON

$$\Rightarrow \quad \frac{dy_k}{dw} = -y_k \sum_j K_{j,k} y_j + \frac{1}{2} \sum_{i+j=k} K_{i,j} y_i y_j$$

WHERE WE CAN DEFINE A DIMENSIONLESS TIME VARIABLE

$$\frac{dw}{dt} = Y_0 \sigma_1 v_1(t) s(t)$$

- APPROXIMATING

$$K_{i,j} \approx (i^{2/3} + j^{2/3}) \left(\frac{1}{i^{1/2}} + \frac{1}{j^{1/2}} \right)$$

RELATED TO GEOMETRICAL SIZE

RELATED TO RELATIVE VELOCITY

$$v^2 \sim T/m$$

- APPROXIMATING

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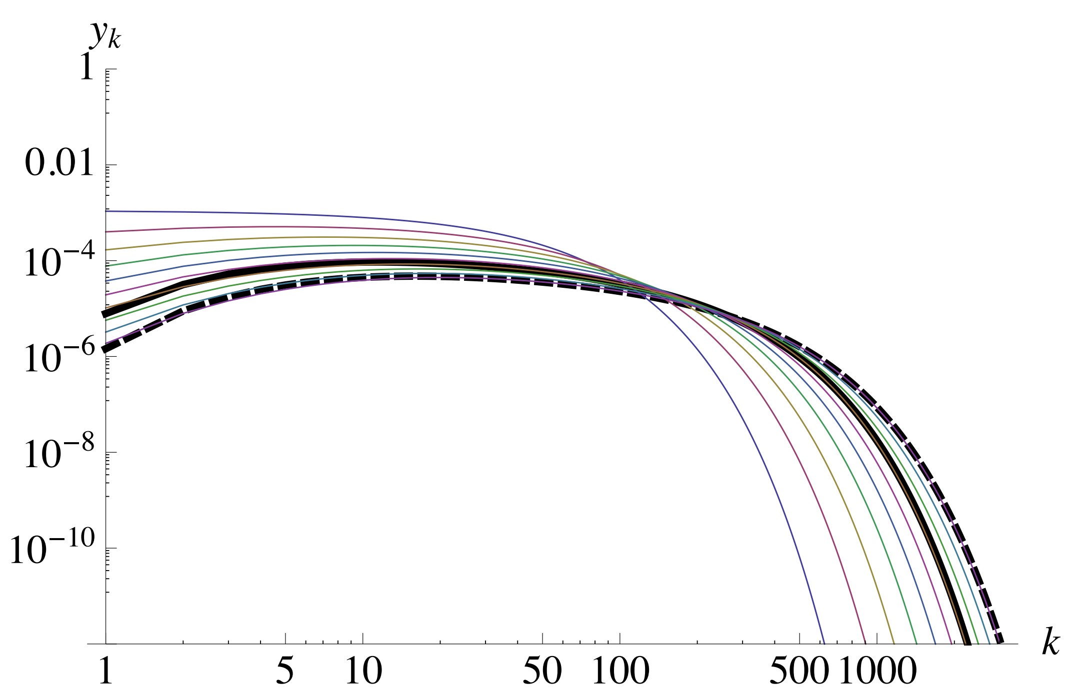
RELATED TO GEOMETRICAL SIZE

RELATED TO RELATIVE VELOCITY

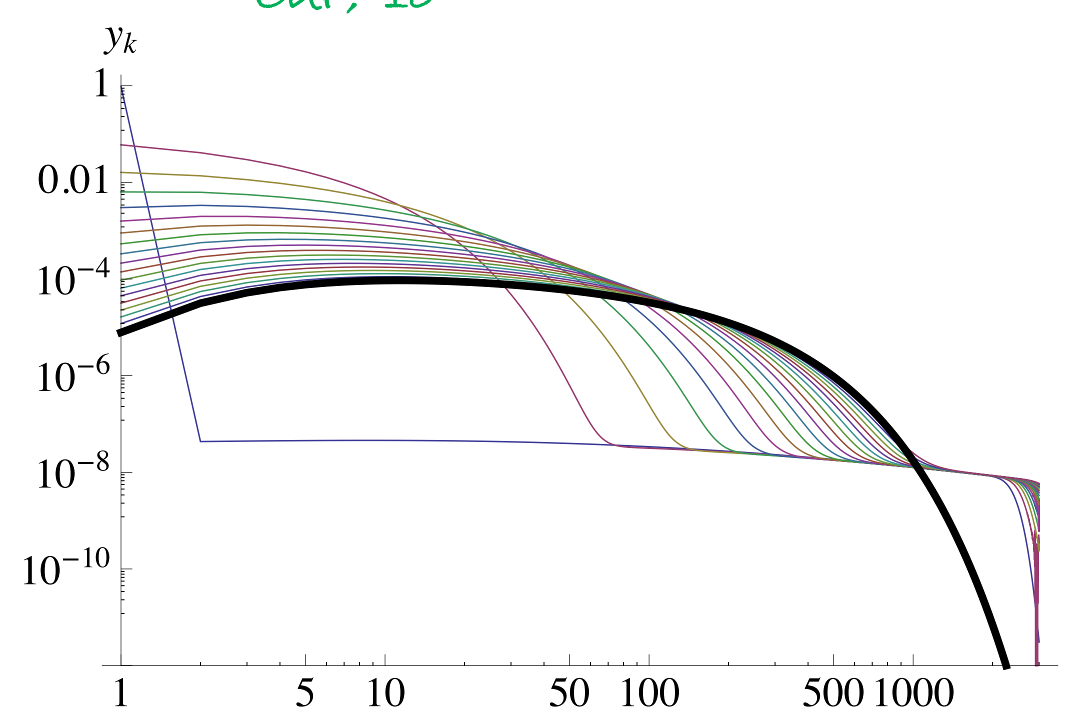
$$v^2 \sim T/m$$

- FOR THIS CASE THERE IS AN ATTRACTOR SCALING SOLUTION FOR LARGE DNN (VALID FOR ALL INITIAL CONDITIONS WE CONSIDER)

SEE E.G. KRAPIVSKY, REDNER, BEN-NAIM, A KINETIC VIEW OF STATISTICAL PHYSICS, CUP, '10



$$y_k(0) = e^{-k/30}$$



INITIAL CONDITIONS: MOSTLY IN SINGLE NUCLEONS, BUT WITH A SUB-DOMINANT TAIL

NUCLEAR DARK MATTER IN DIRECT DETECTION

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