Freeze-in Production of FIMP Dark Matter

Stephen West

Royal Holloway, University of London
and
Rutherford Appleton Laboratory

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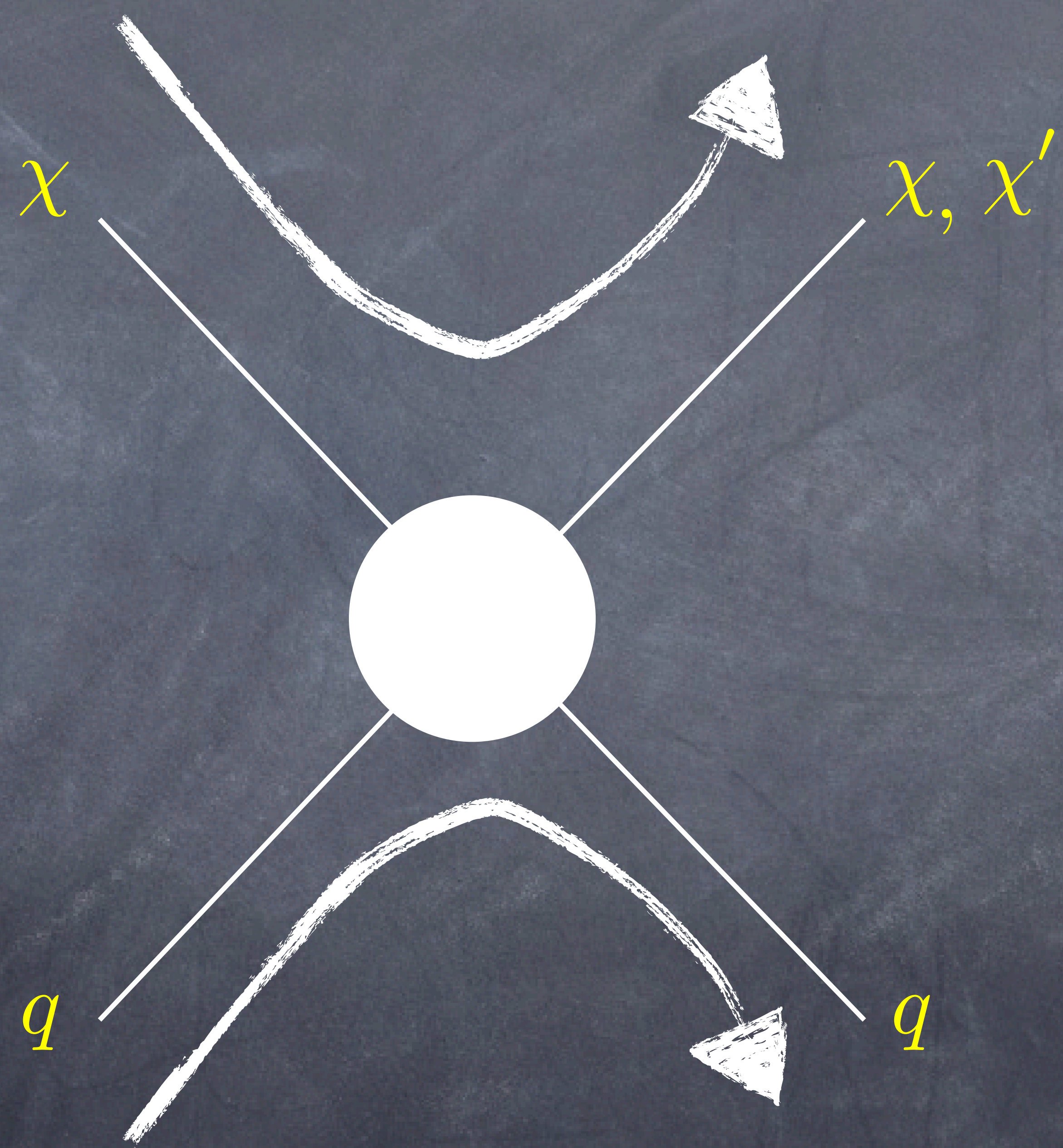
Outline

- Introduction and Motivation
- Freeze-in production of FIMP dark matter
- Experimental Signatures of Freeze-in
- A Unified Theory of Matter Genesis

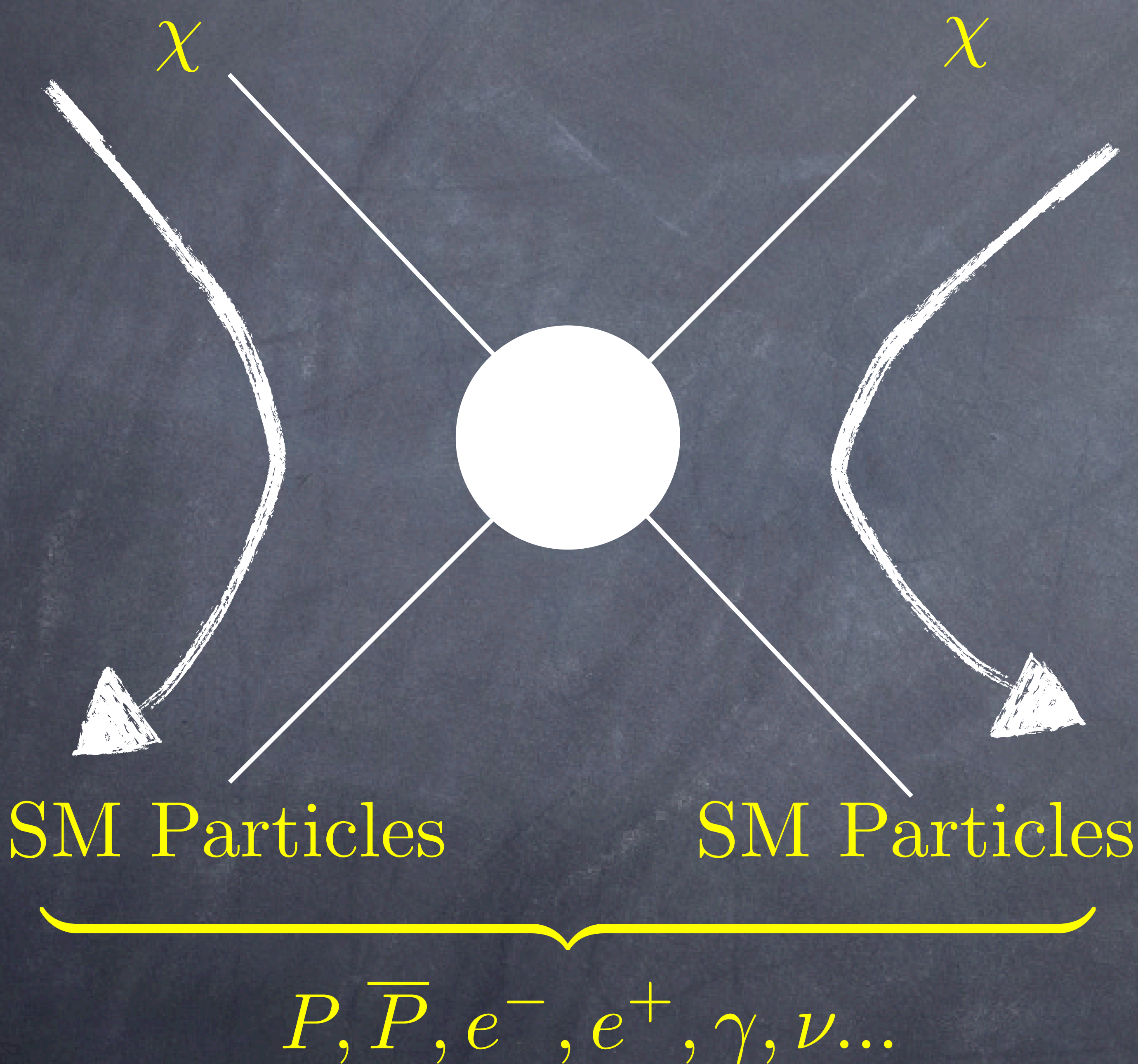
Probing Dark Matter

- Traditional Methods: Direct detection using operator of form $\overline{\chi}\chi\overline{q}q$



Probing Dark Matter

- Traditional Methods: Indirect detection

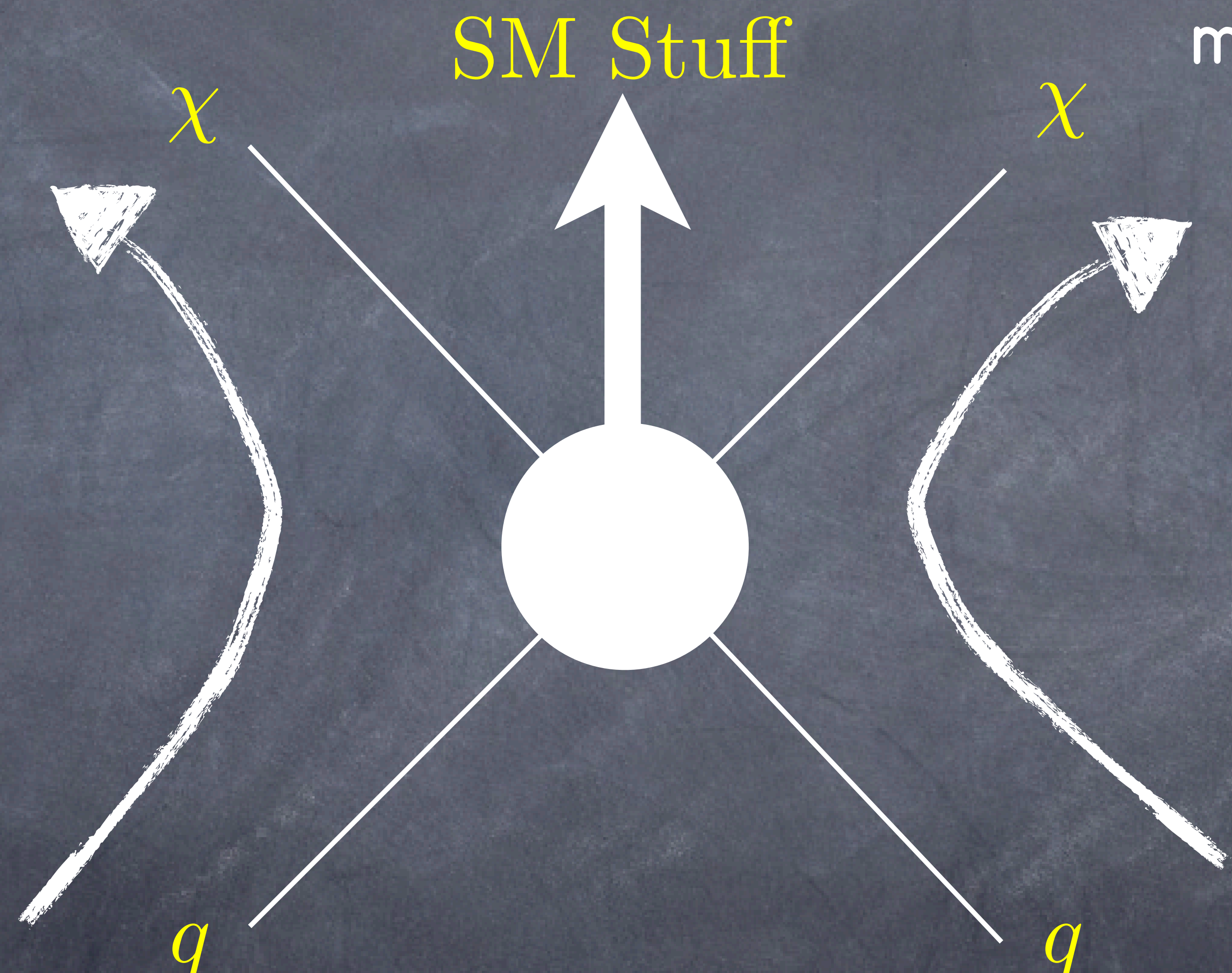


- Experiments: FERMI, PAMELA, HESS, ATIC hint towards an excess in positrons but no excess in anti-protons.
- Difficult to explain in standard dark matter scenarios...need to complicate models
- Excesses can be explained with astrophysics e.g. pulsars

Probing Dark Matter

- Traditional Methods: Collider experiments

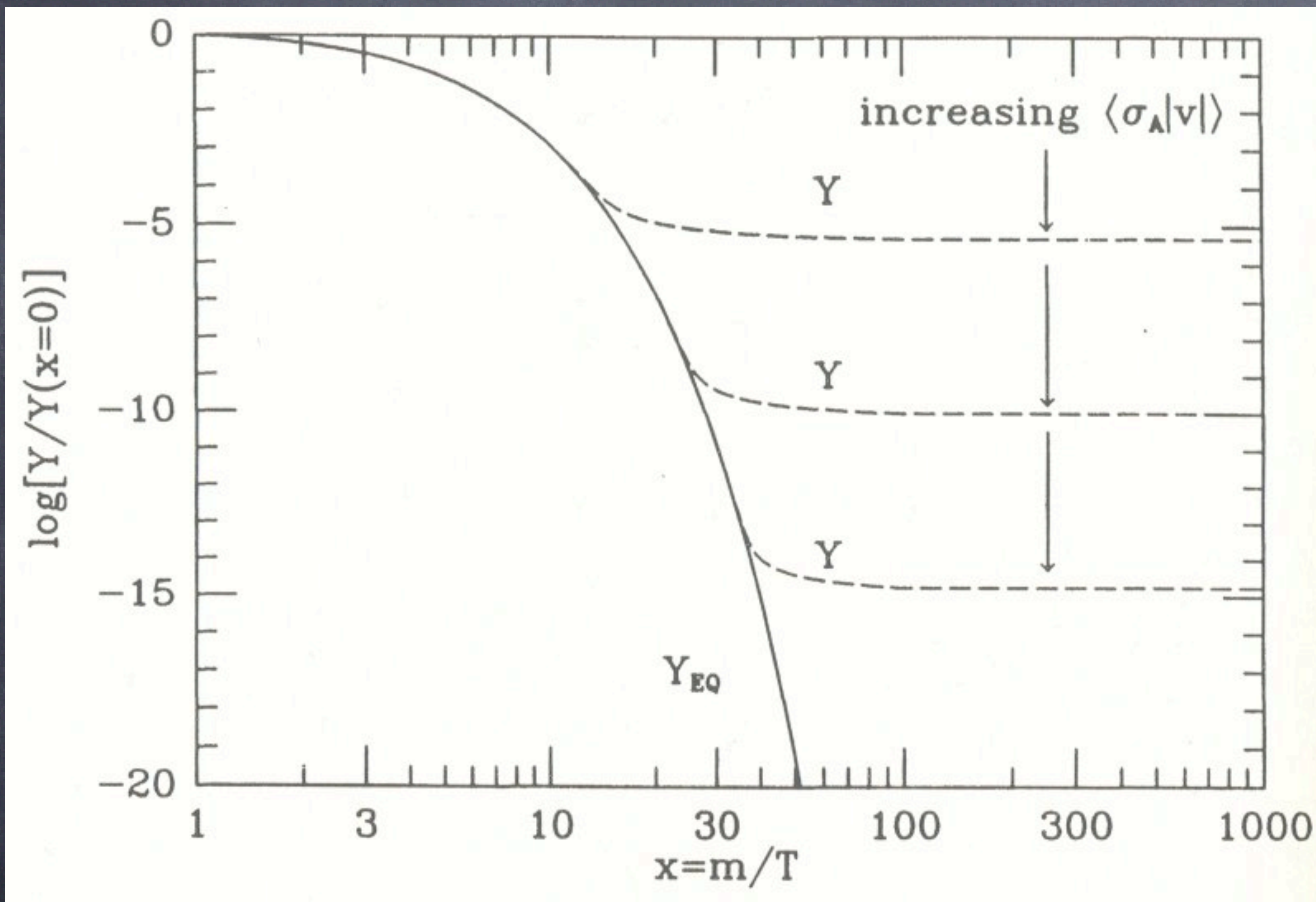
Look for the missing energy



Large backgrounds, very messy

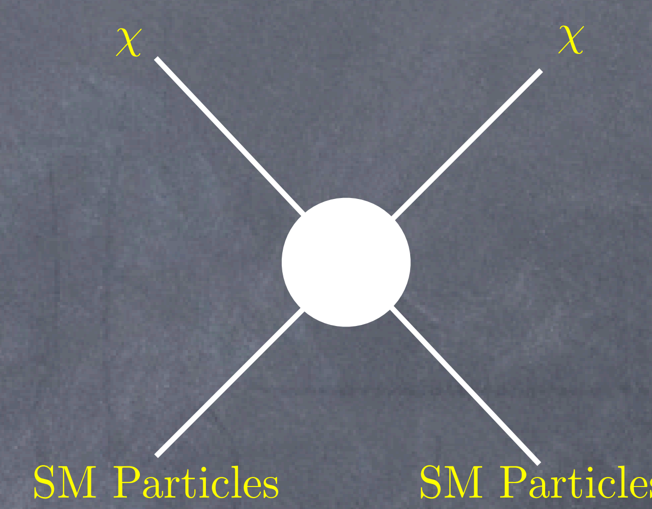
Dark Matter Genesis - Standard Picture

- Freeze-out



See Kolb and Turner

- Dark Matter initially in thermal equilibrium



- Due to expansion, dark matter number density freezes-out when

$$\Gamma = n_{dm}\,\langle \sigma v \rangle < H$$

- Final abundance:

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

Note: Not large enough to explain FERMI/PAMELA etc...

Dark Matter Genesis - A New Picture

Freeze-in

Highlights...

In collaboration with John March-Russell, Lawrence Hall and Karsten Jedamzik
arXiv: 0911:112 [hep-ph] JHEP 1003:080,2010
+ more to come...

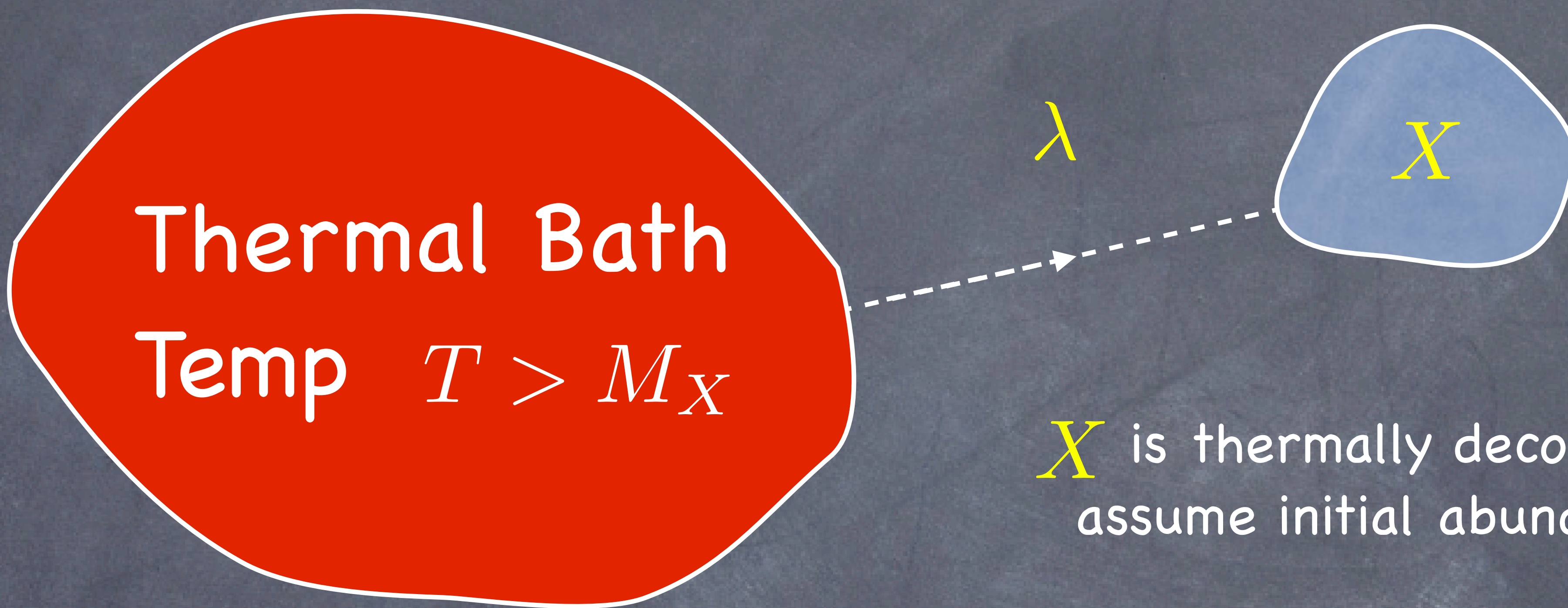
- New genesis mechanism - New DM candidates
- Displaced vertices at LHC
- Consequences for BBN
- Boosts for indirect detection
- New testable mechanism for Baryogenesis

Hall, March-Russell, SMW
arXiv: 1010:0245 [hep-ph]

At the LHC and future colliders, precision measurements, EDMs

Freeze-in overview

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

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

Freeze-in via 2-2 scattering, decays or inverse decays

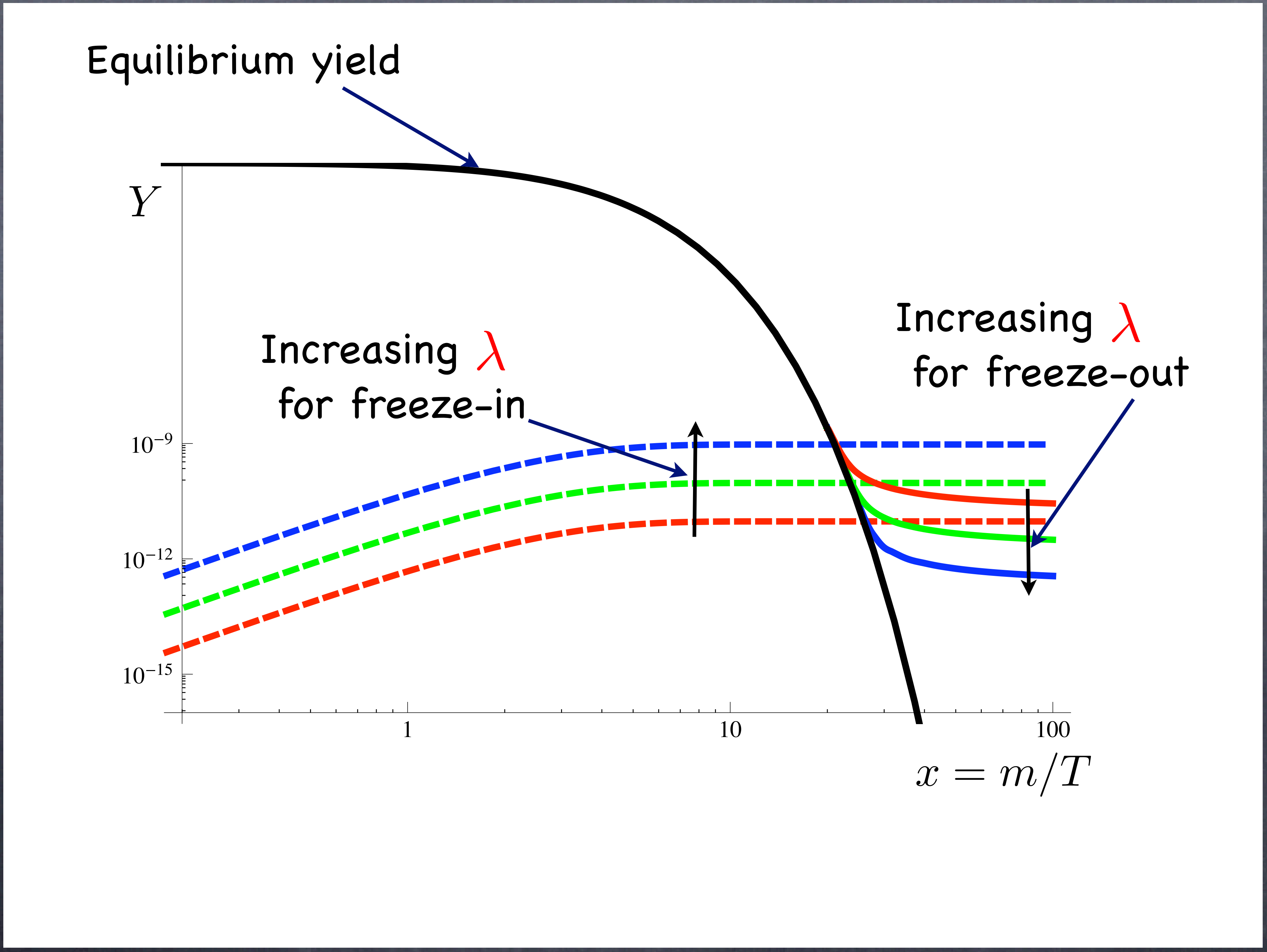
Coupling strength λ

m mass of heaviest particle in interaction

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

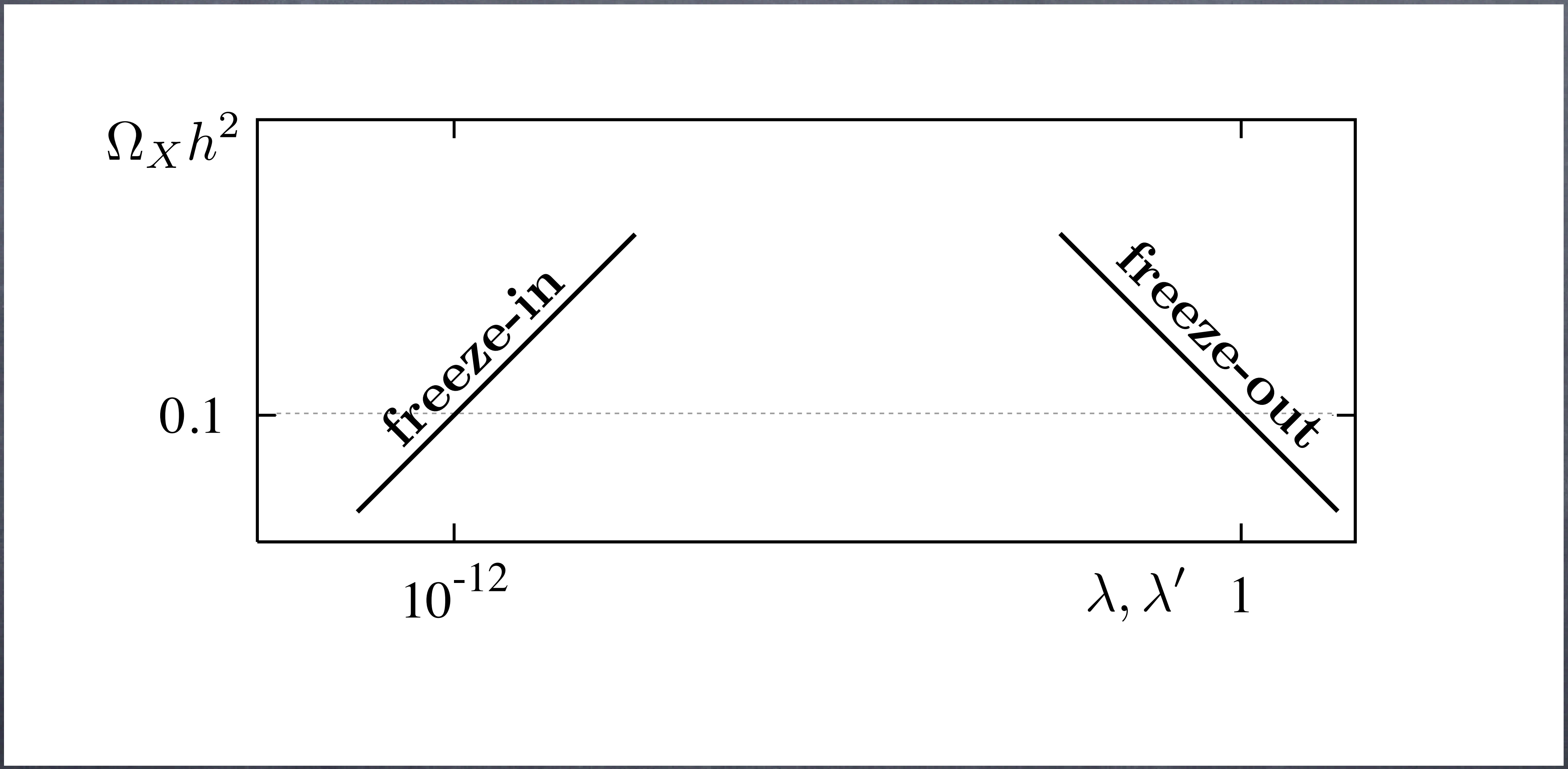
Freeze-in vs Freeze-out

- As T drops below mass of relevant particle, DM abundance is heading towards (freeze-in) or away from (freeze-out) thermal equilibrium



Freeze-in vs Freeze-out

- For a TeV scale mass particle we have the following picture.



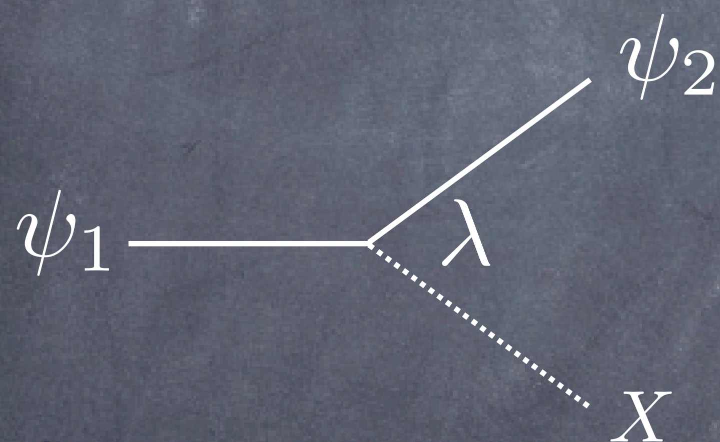
Example Toy Model

- FIMPs can be DM or can lead to an abundance of the Lightest Ordinary Supersymmetric Particle (LOSP)
- Consider FIMP X coupled to two bath fermions ψ_1 and ψ_2

$$\boxed{L_Y = \lambda \psi_1 \psi_2 X}$$

- Let ψ_1 be the LOSP

- First case FIMP DM: $m_{\psi_1} > m_X + m_{\psi_2}$



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

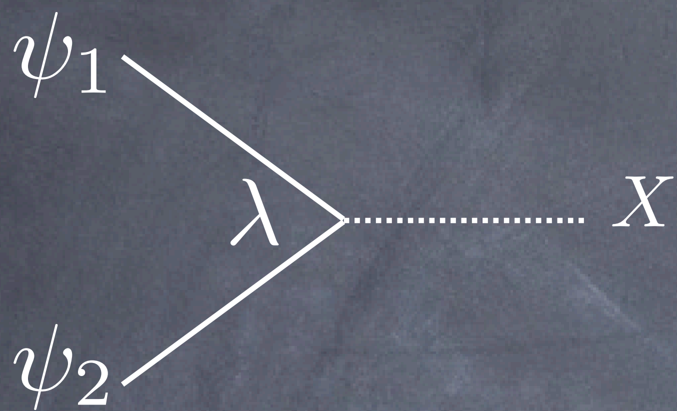
Using $\Gamma_{\psi_1} \sim \frac{\lambda^2 m_{\psi_1}}{8\pi} \Rightarrow$ $$\boxed{\Omega_X h^2 \sim 10^{23} \lambda^2 \frac{m_X}{m_{\psi_1}}}$$

For $\frac{m_X}{m_{\psi_1}} \sim 1$ need $\lambda \sim 10^{-12}$ for correct DM abundance

- Lifetime of LOSP is long - signals at LHC, BBN...

Toy Model continued...

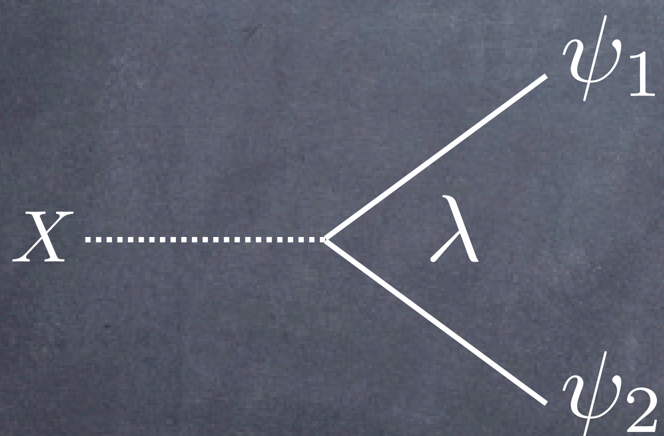
- Second case LOSP (=LSP) DM: $m_X > m_{\psi_1} + m_{\psi_2}$



$$\boxed{\Omega_X h^2 \sim 10^{24} \frac{\Gamma_X}{m_X} \sim 10^{23} \lambda^2}$$

Using $\Gamma_X \sim \frac{\lambda^2 m_X}{8\pi}$

- BUT X is unstable...



giving $$\boxed{\Omega_{\psi_1} h^2 = \frac{m_{\psi_1} \Omega_X h^2}{m_X} \sim 10^{23} \lambda^2 \frac{m_{\psi_1}}{m_X}}$$

Again for $\frac{m_X}{m_{\psi_1}} \sim 1$ need $\lambda \sim 10^{-12}$ for correct DM abundance

- X lifetime can be long - implications for BBN, indirect DM detection

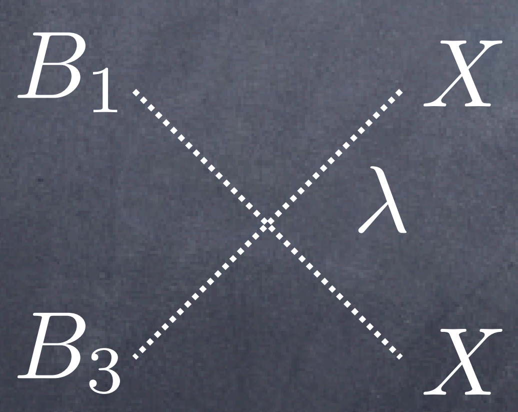
Another source of boost factors

Example Model II

- Many applications and variations of the Freeze-in mechanism
- Assume FIMP is lightest particle carrying some stabilising symmetry - FIMP is the DM
- Consider quartic coupling of FIMP with two bath scalars

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

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



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

For correct DM abundance $\Rightarrow \lambda \sim 10^{-11}$

- NOTE: Abundance in this case is independent of the FIMP mass

FIMP miracle vs WIMP miracle

- WIMP miracle is that for $m' \sim v \quad \lambda' \sim 1$

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

- FIMP miracle is that for $m \sim v \quad \lambda \sim v/M_{Pl}$

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

FIMP Candidates and generating tiny λ

- Any long lived particle that is coupled to the thermal bath with a feeble coupling - needs to be a SM gauge singlet

- Hidden sector feebly coupled to MSSM

- Moduli and Modulinos associated with SUSY breaking

$$m_{susy}^2(T)\,\phi^\dagger\phi = m_{susy}^2\left(1+\frac{T}{M}\right)\phi^\dagger\phi \qquad \lambda \sim \frac{m_{susy}}{M}$$

- Dirac neutrino masses with SUSY - RH sneutrino FIMPs

$$\mathcal{L}_{\mathrm{Dirac}} = \lambda_\nu L H_u N \qquad \lambda_\nu \sim 10^{-12}$$

See Moroi *et al* **for related**

- FIMPs from kinetic mixing: hidden sector particles coupling to the MSSM via mixing of $U(1)_Y$ and hidden U(1) feeble mixing feeble coupling
- Others...Gravitino, RH neutrino...

Experimental Signatures

- Long lived LOSPs at the LHC: FIMPs frozen in by decay of LOSP - LOSP produced at LHC will be long lived could be electrically charged or even coloured

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

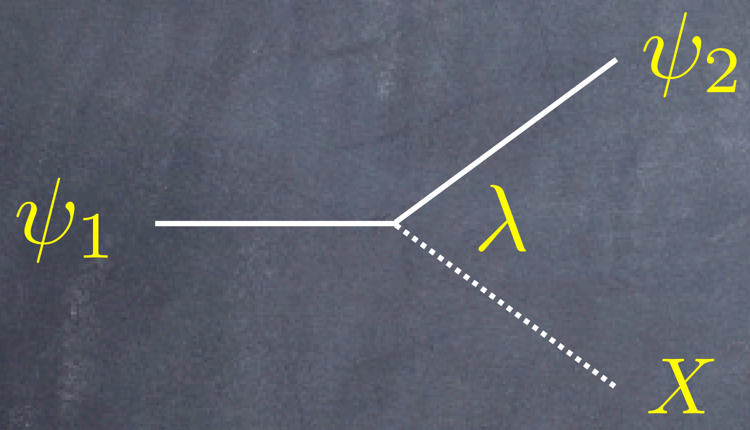
- Signals for BBN: FIMPs or LOSPs decaying late could have implications for BBN

- Enhanced indirect and direct detection: Relic abundance and DM annihilation cross section no longer related. Freeze-in dominantly produces DM abundance annihilation cross section must be large - freeze-out abundance is small

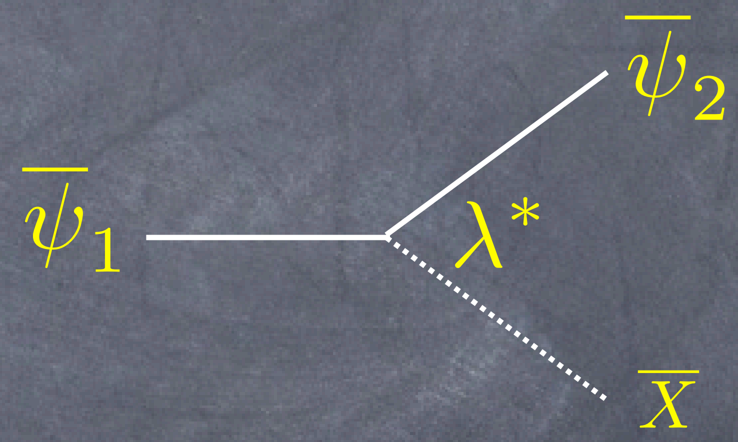
Can we do baryogenesis with this mechanism?

Hall, March-Russell, SMW
arXiv: 1010:0245 [hep-ph]

- Can we 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)

Can we do baryogenesis with this mechanism?

- We also need to violate B-L if we want to generate a baryon asymmetry (need B-L as the electroweak anomaly will remove an asymmetry generated in B+L)

- Perfect example (for me at least), consider the following operators

$$L_i H_u, \quad L_i L_j \overline{E}_k, \quad L_i Q_j \overline{D}_k, \quad \overline{U}_i \overline{D}_j \overline{D}_k, \quad L_i H_d^\dagger$$

- Includes the usual operators forbidden by R-parity
- Dress these with FIMP superfield - assign odd under R parity
- Striking example is

$$\text{Feeble Coupling} \longrightarrow \boxed{\lambda_i L_i H_u X}$$

- Through this operator get linked asymmetries between L and X
- Overall we have a symmetry $U(1)_{B-L+X}$
- Allows transfer of asymmetries into baryon number

What do we get out of this?
- Unified theory of Matter Genesis

- Unifying dark matter (DM) genesis and baryogenesis
    - ✳ DM is now a hidden sector field

- Linking the X (DM) asymmetry to B-L asymmetry we can hope to explain $\Omega_{dm}/\Omega_b \sim 5$

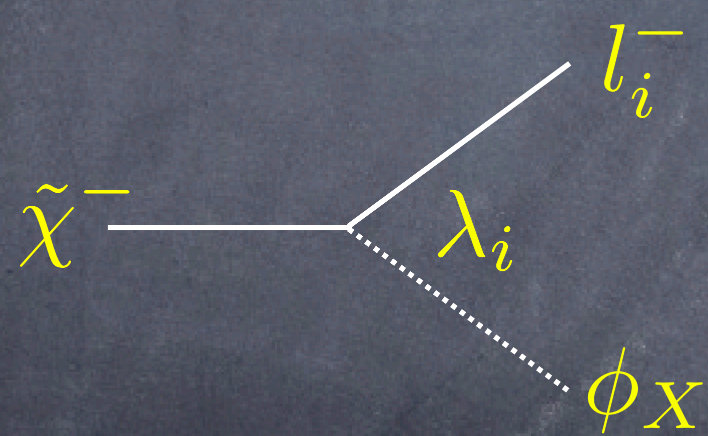
- In fact we find calculable, linked asymmetries in baryon number and dark matter number produced by feeble interaction between SM and FIMP.

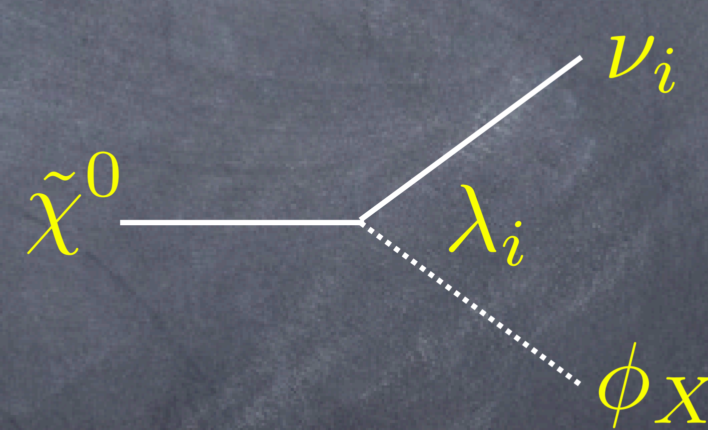
Back to Example Model

$$\boxed{\Delta W = \lambda_i L_i H_u X}$$

- Renormalisable term $\Rightarrow$ freeze-in yield is IR dominated

- Most interesting case is freeze-in via $\tilde{\chi}^-$ and $\tilde{\chi}^0$ decay





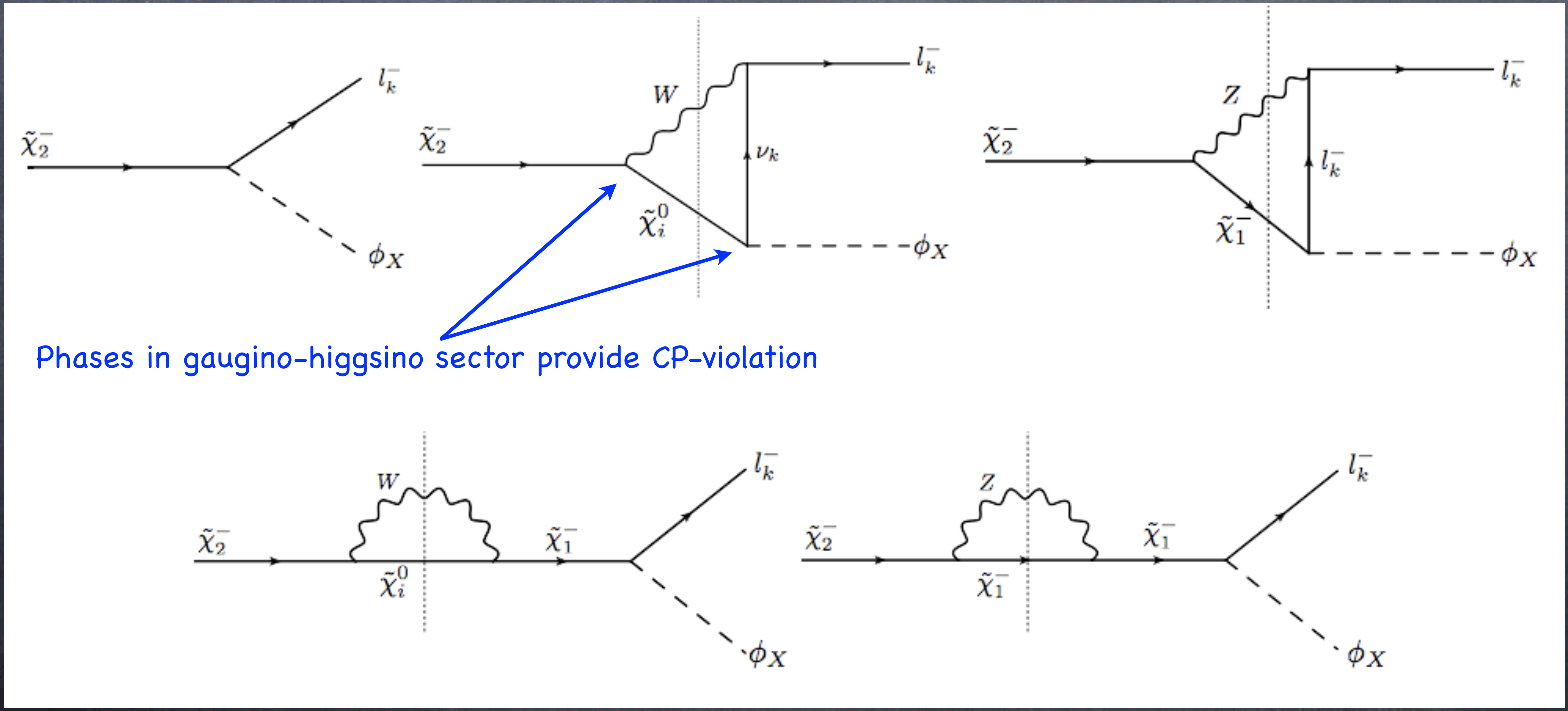
- Phases in the Higgsino-gaugino (i.e. neutralino/chargino sector) provide the CP-violation.

Generating The Asymmetry

- Decays must violate CP, achieved by interference of 1-loop diagrams

$$\epsilon_a^- = \sum_k \frac{\Gamma(\tilde{\chi}_a^- \to l_k^- \phi_X) - \Gamma(\tilde{\chi}_a^+ \to l_k^+ \phi_X^*)}{\Gamma(\tilde{\chi}_a^- \to l_k^- \phi_X) + \Gamma(\tilde{\chi}_a^+ \to l_k^+ \phi_X^*)}$$

- Asymmetry generated in L+X number



The form of the asymmetry

- Simple case where only one physical phase in gaugino-Higgsino sector - Put phase on gaugino mass M_2

- Physical phase really is $\phi_2 = \mathrm{Arg}[\mu M_2 Sin(2\beta)]$

- Parametrically the asymmetry has the dependence

$$\boxed{\epsilon = \epsilon_0 \alpha_w \sin\phi_2}$$

where $\epsilon_0 \sim 10^{-1} - 10^{-3}$ and depends on the details of the neutralino masses and mixing

- Size of the phase is restricted by EDMs (depending on mass spectrum of SUSY particles)
- Final asymmetry can in principle be in the range:

$$\boxed{\epsilon \sim 10^{-3} - 10^{-9}}$$

(Can be smaller but lower limit comes from insisting two sectors do not equilibrate and that we get correct dark matter abundance)

DM and baryon abundances

- Finally the relic abundance of dark matter

$$\boxed{\eta_X = \epsilon Y_X}$$

$$Y_X \propto \Gamma_a m_{pl}/m_a^2$$

"a" labels the decaying particle

- Due to electro-weak anomaly an asymmetry generated in B-L gets transferred to a final asymmetry in B (and L)

$$\boxed{\eta_B = c\eta_{B-L} = c\eta_X}$$

where c is a spectrum dependent number

- This gives

$$\boxed{\frac{\Omega_{dm}}{\Omega_b} = \frac{m_X}{cm_p}}$$

- We get a prediction for the mass of X, depends on spectrum of SUSY particles (i.e. on c) but around 1.5 GeV

At the LHC...

- We have that $$\boxed{\Omega h^2_{dm} \propto \epsilon\, \Gamma}$$

- As $\epsilon \ll 1$ the size of the decay width must be larger than standard freeze-in

- Assume LOSP is χ_1^-, decay is $\chi_1^- \to l^- \phi_X$ with length in this case

$$\boxed{L \approx 10m \left(\frac{\gamma}{2}\right)\left(\frac{\epsilon_a}{10^{-5}}\right)\left(\frac{m_X}{GeV}\right)\left(\frac{(10^2 GeV)^2}{m_{LOSP} m_a}\right)\left(\frac{g_a}{2}\right)\left(\frac{10^2}{g_*}\right)^{3/2}}$$

- In realistic models we may expect ϵ_a to be even smaller due to mixing angles

$\Rightarrow$ Can Expect decay lengths to be $\boxed{\sim 10cm}$

- Very clean signal - will have two of these for every SUSY event.

- Can use kinematics to deduce mass of X particle (to some degree)

Other Signals and complications

- There are a number of subtle details

– We freeze-in a large symmetric component of X DM

$\Rightarrow$ Need to annihilate away this symmetric part, therefore need a more complicated hidden sector

$\Rightarrow$ Implications for BBN

- Another subtlety

– The decaying particle cannot be the LOSP due to on-shell conditions

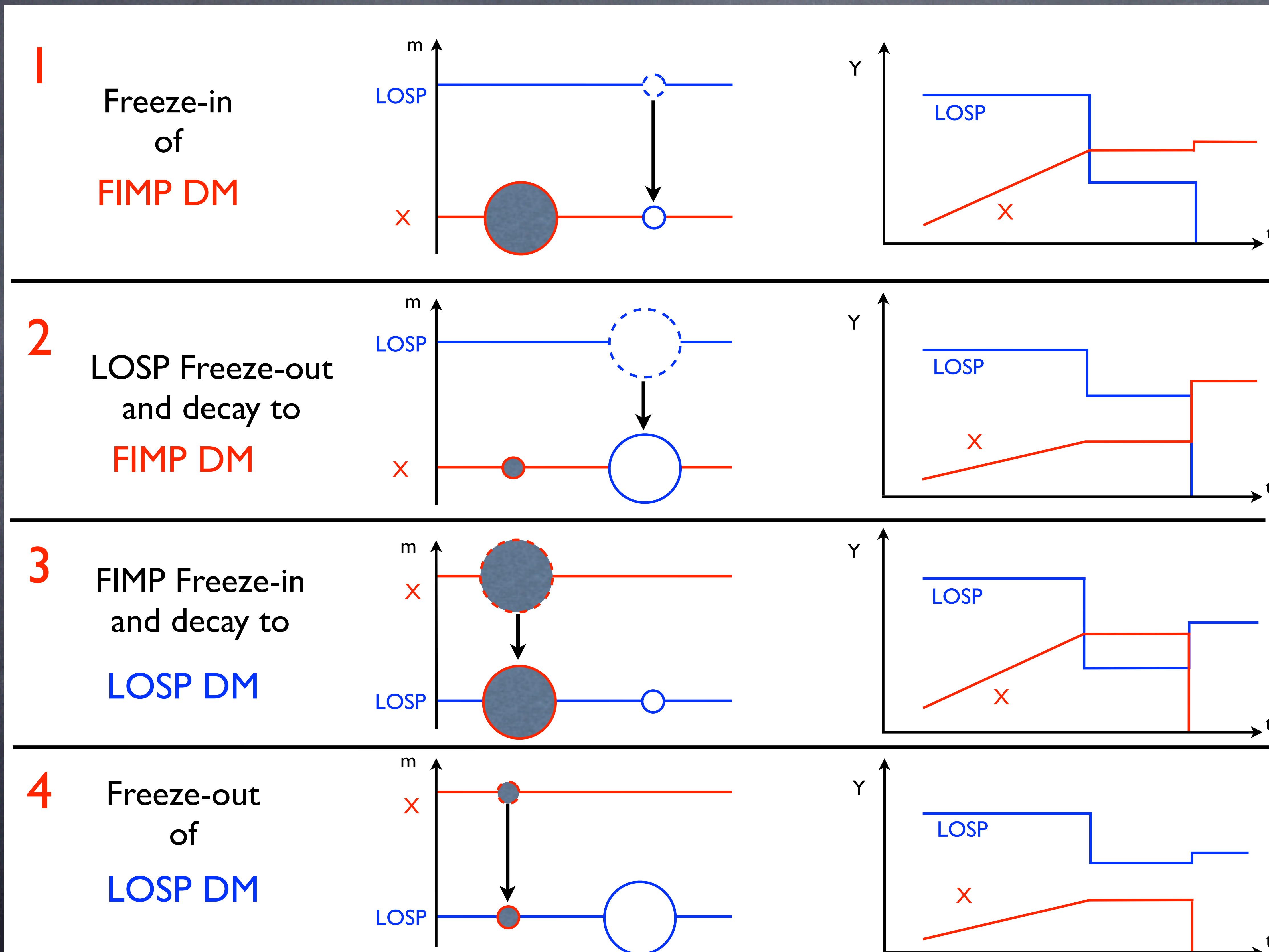
–Decay length at LHC still easily related to freeze-in yield

Conclusions and Outlook

- Freeze-in can provide attractive alternative to Freeze-out
- It is an IR dominated process and in simple scenarios relic abundance can be found analytically
- Experimental implications of Freeze-in include: potentially spectacular signals at the LHC, signals at BBN and boosts factors for indirect DM detection
- New baryogenesis mechanism that is potentially fully testable
- Even more spectacular, lepton number/baryon number violating decays at LHC
- Phases involved potentially testable at edm experiments

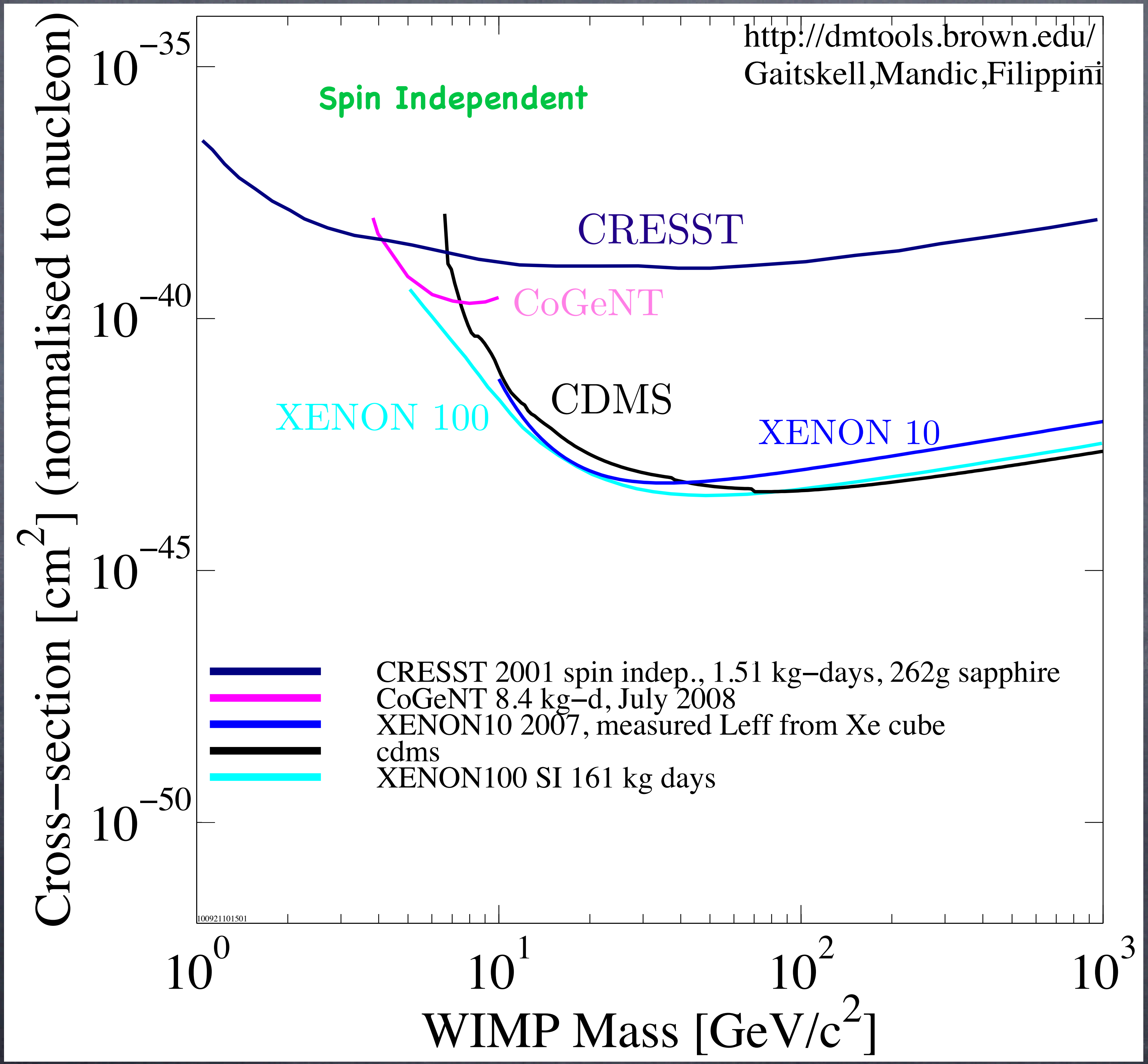
Back up slides....

Summary of Scenarios

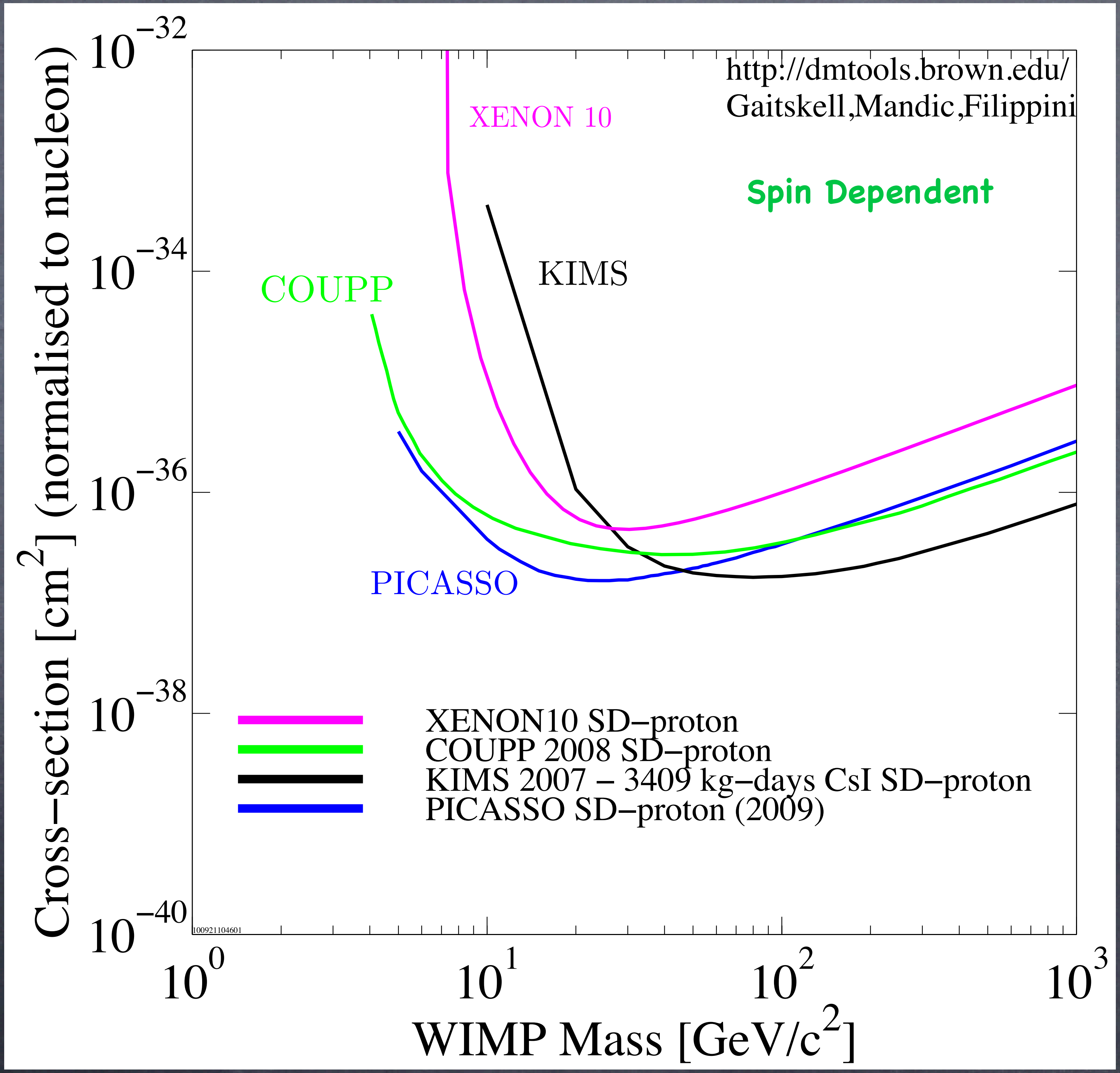


Motivating Dark Matter

Direct detection limits - Spin Independent



Direct detection limits - Spin dependent



Satisfying Sakharov's conditions

- $B-L$ number is effectively broken due to Feeble interactions

- CP-violation from CP-violating phases arising in visible sector
  - ✳ See later

- Out of equilibrium condition for baryogenesis is provided by the different temperatures of the SM and FIMP sectors
  - ✳ final state X particles are out of equilibrium