The Baryon--Dark-Matter Connection

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Oxford University

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Introduction & Motivation

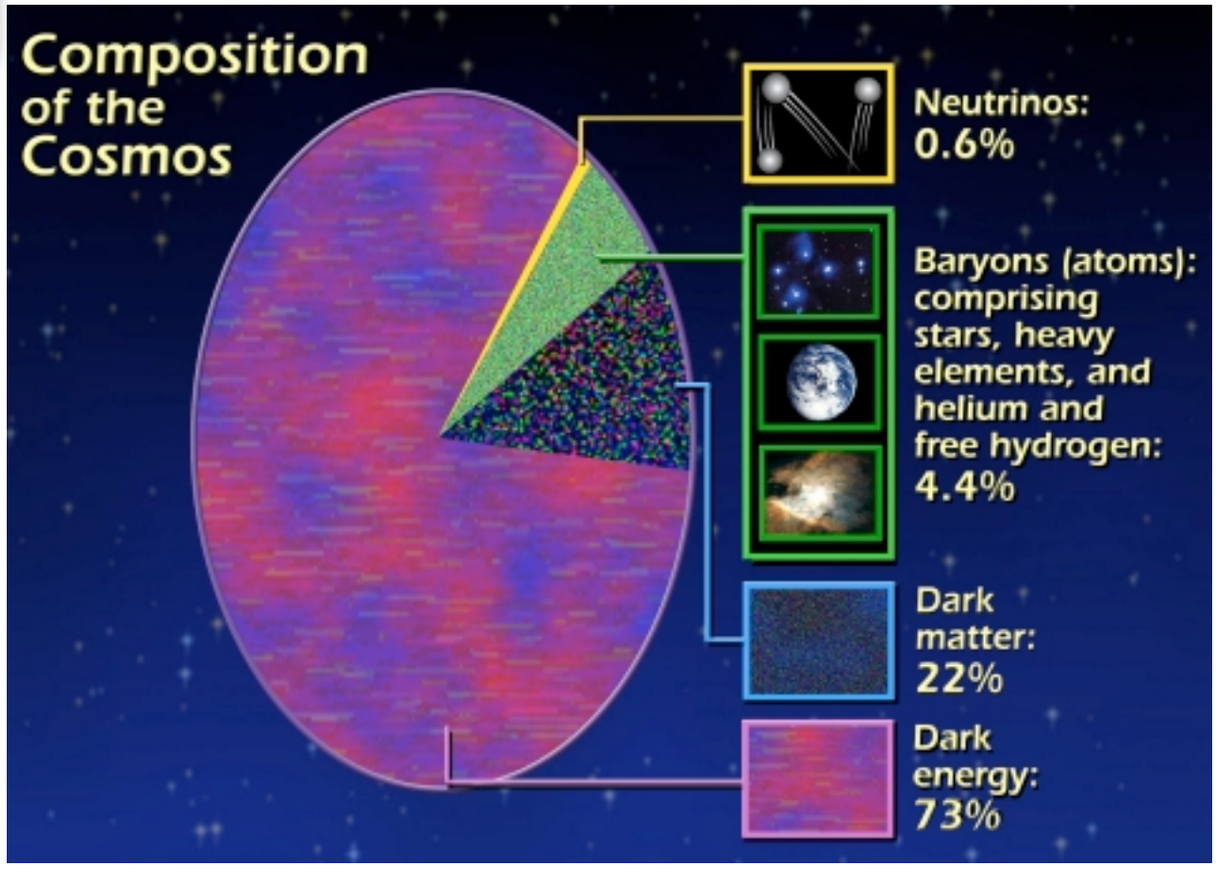
A primary goal of modern physics:

Theory of Particle Interactions
+
Big Bang based on GR

⇓ compute

Contents of Universe

Composition is complex & surprising!



Mario Livio, HSTSI

Introduction & Motivation

Reality is hard to understand

$\left.\begin{array}{r}\Omega_B \\ \Omega_{DM}\end{array}\right\}$ many ideas - can they be tested?

Ω_{DE} remarkable surprise - no good idea (anthropic?)

Introduction & Motivation

Matter genesis - leading ideas

- Dark matter

  WIMPs: Thermal freeze-out with scale v

  Axions: Mis-alignment or thermal production

- Baryons

  GUT baryogenesis - problems with cosmo

  Affleck-Dine - impossible to test?

  Leptogenesis - hard to test, disfavored by cosmo?

  Electroweak baryogenesis - hard to implement b/c CP

...but see "Axion-Assisted Electroweak Baryogenesis," Nathaniel Craig & JMR, arXiv:1007.0019

Introduction & Motivation

★ Unrelated origin, involving very different physics, of baryons & DM, make it hard to understand

$$\Omega_{DM}/\Omega_B \simeq 4.86$$

★ Freeze-out dominates thinking about DM candidates, detection, and collider phenomenology

Are we being misled?

Introduction & Motivation

Alternative view:

similar physics underlies both Ω_B and Ω_{DM}

(Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92; Thomas '95; Hooper, JMR, West '04; explosion in last 2 yrs with work by many people, esp Zurek etal...)

Baryons: $U(1)_B$ $u, d, s...$ p stable $\Omega_B \propto m_B \eta_B$

DM: $U(1)_X$ $X_0, X_1, X_2...$ X_0 stable $\Omega_X \propto m_X \eta_X$

Introduction & Motivation

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DM: $U(1)_X$ $X_0, X_1, X_2...$ X_0 stable $\Omega_X \propto m_X \eta_X$

At some era

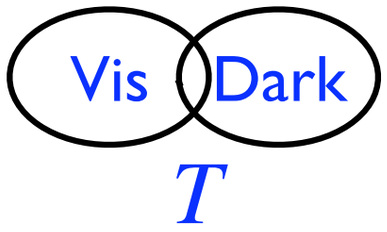
Interactions violate B and X to yield related values for η_B and η_X

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

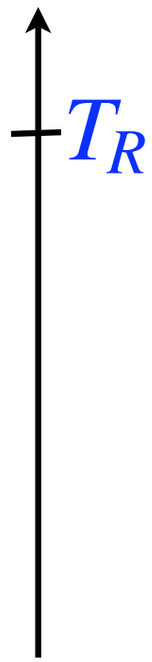
Introduction & Motivation

- Two general categories of theories: "sharing" & "co-generation"

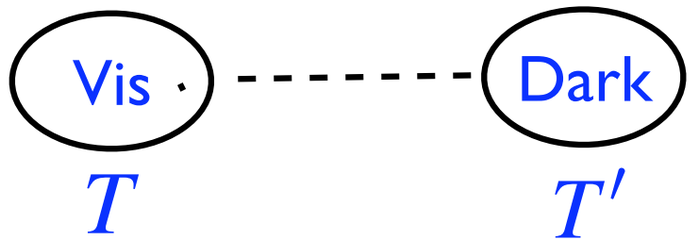
Unspecified primordial generation



$\eta_X \sim \eta_B$ by sharing



Negligible primordial generation



$\eta_X \sim \eta_B$ by co-generation

Co-generation is more ambitious: attempts to explain simultaneous origin of B & X asymmetries (at scale ~ TeV allowing test at LHC...)

Introduction & Motivation

Alternative view (either sharing or co-generation):

- incompatible with SUSY neutralino DM
- alters expected LHC signals of new physics
- changes one or both direct/indirect DM detection

co-generation appears hard as requires B, X violation & out-of-equilibrium condition at TeV scale

requires a new theory of calculable thermal DM production....

"Freeze-In" Production

Hall, Jedamzik, JMR, West, arXiv:0911.1120

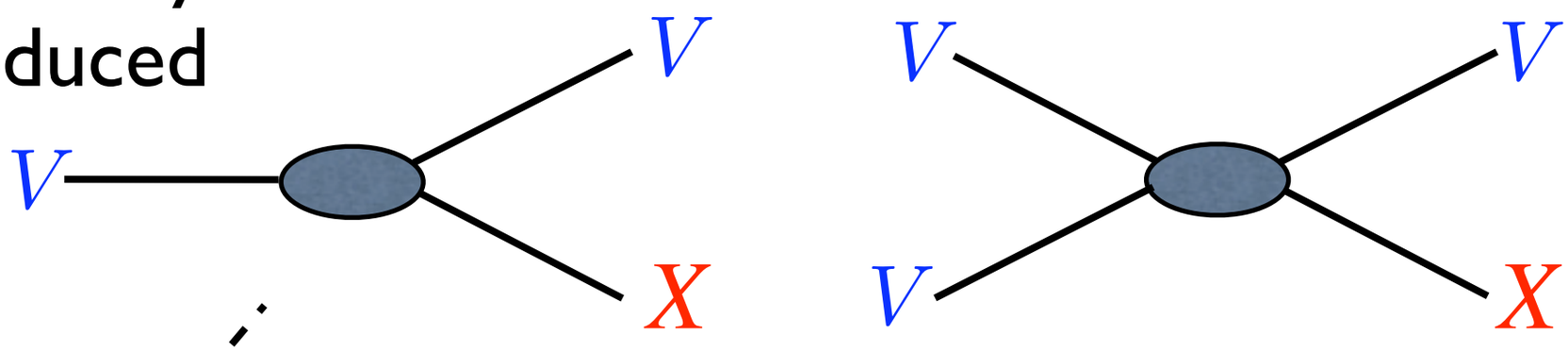
Hall, JMR, West, arXiv:1010.0245

Suppose

- X only feebly coupled to visible-sector thermal bath particles V_i

- X never in thermal equilibrium with SM

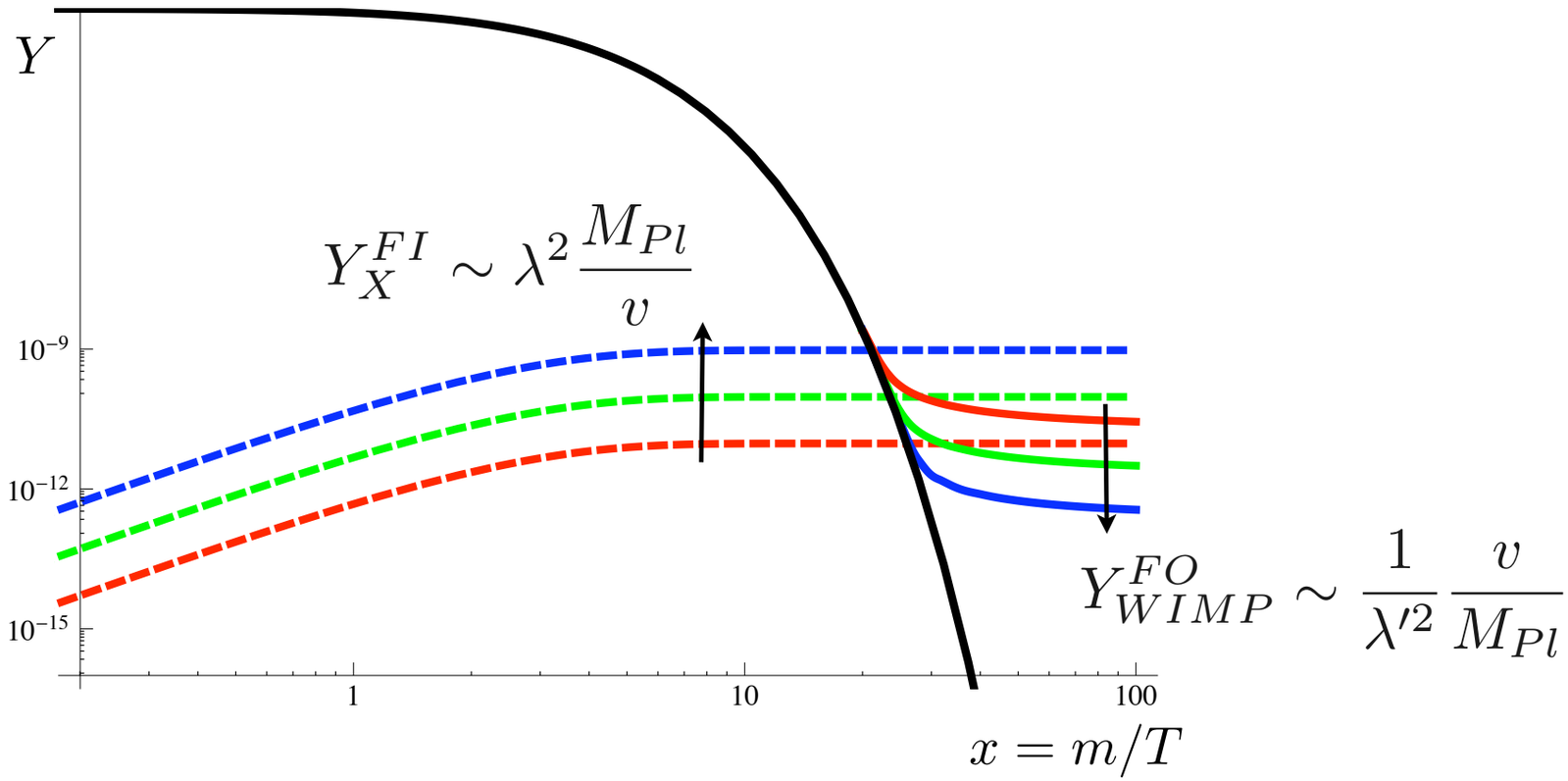
as universe evolves, a tiny X abundance is produced



$$Y_X(t) \sim \Gamma_V t$$

“Freeze-In” Production

heading either ‘in’ or ‘out’ of equilibrium



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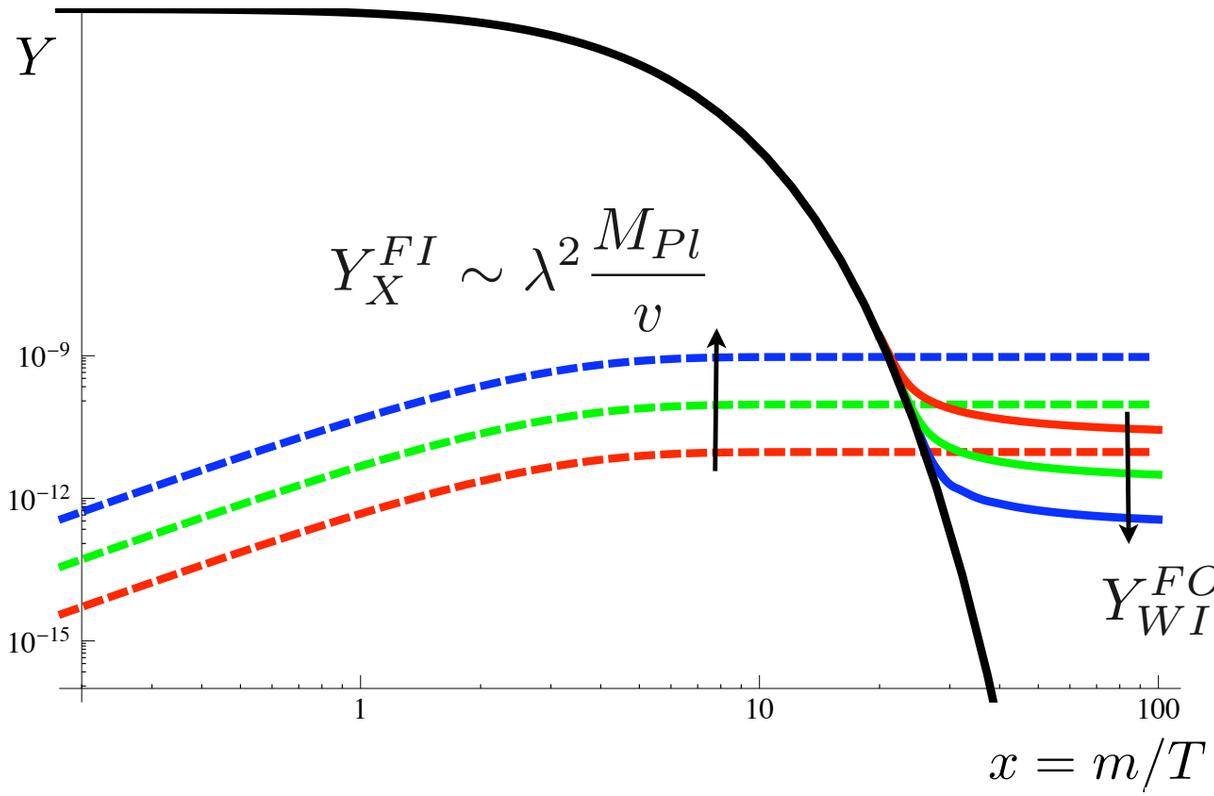
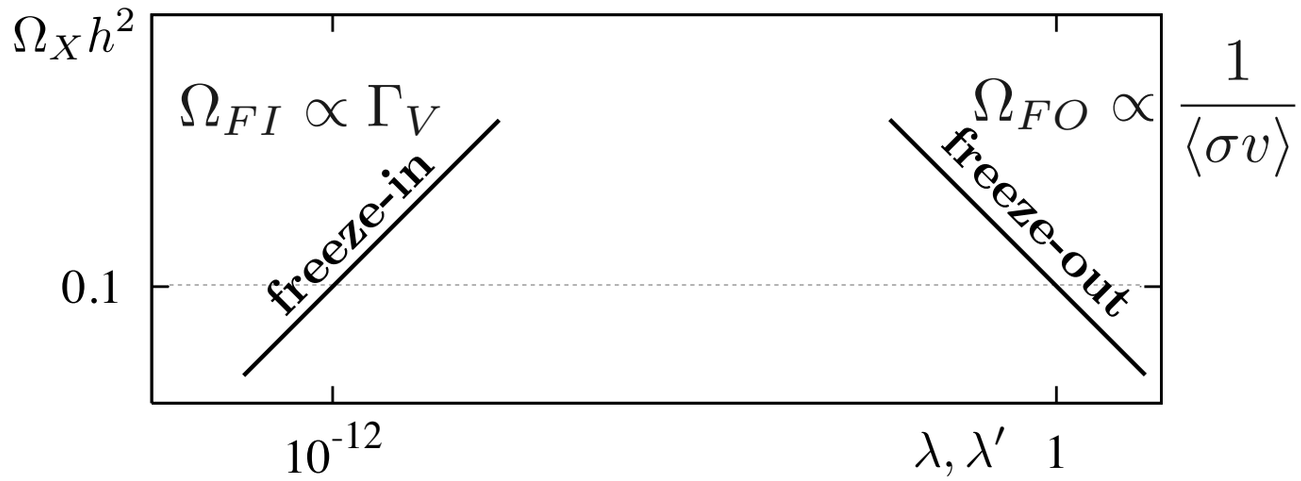


two thermal mechanisms!



"Freeze-In" Production

Comments

- FI yield is IR-dominated for renormalizable interactions

$$Y_X^{FI}(T) \sim \lambda^2 \frac{m^2 M_{Pl}}{T^3}$$

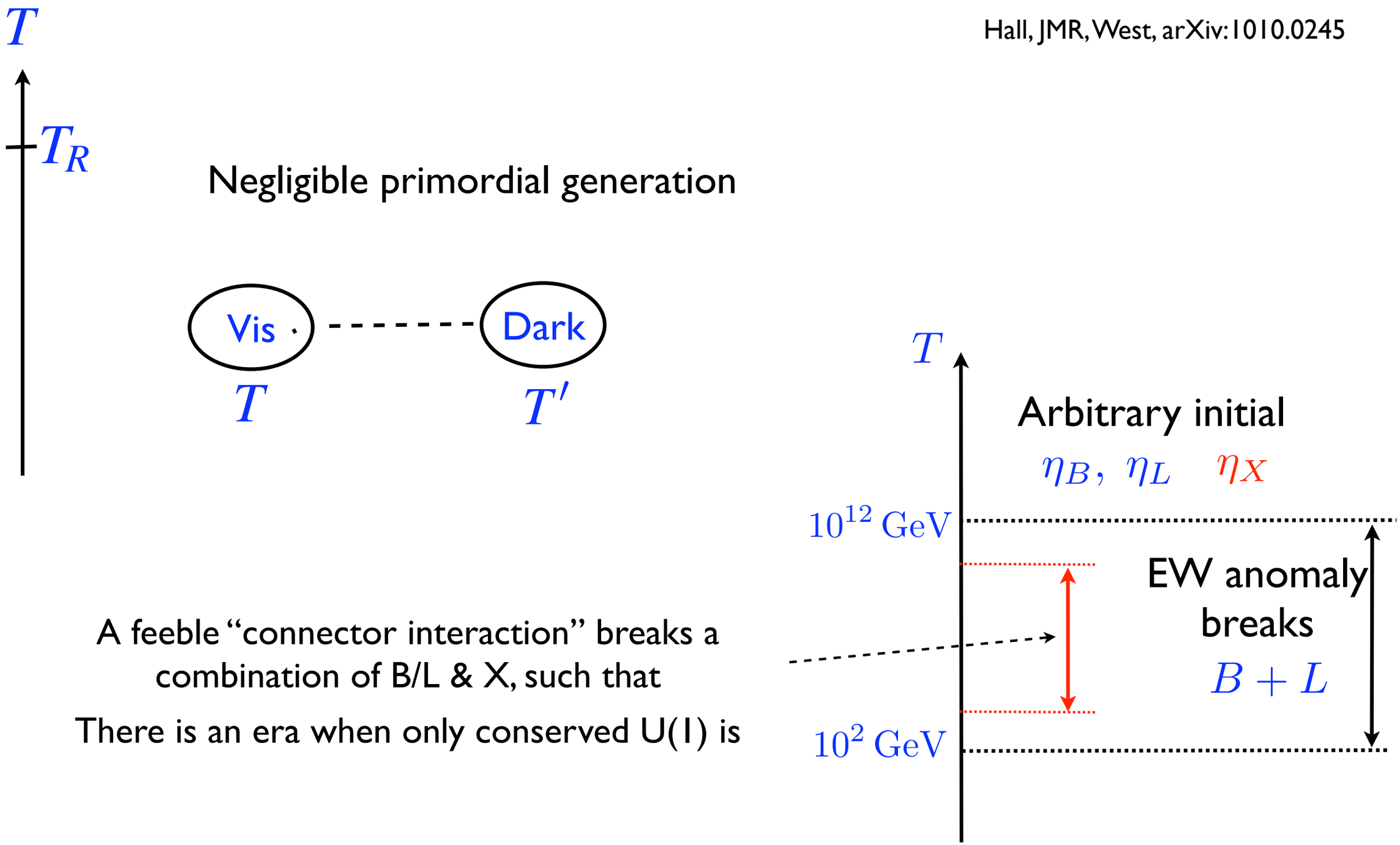
dominant production occurs at $T \sim m$
(heaviest particle in vertex)

$$\Delta L = \lambda X V_1 V_2$$

- The lightest ordinary-sector particle (LOSP) transforming under the X-stabilising symmetry is automatically long-lived

Asymmetric "Freeze-In"

Hall, JMR, West, arXiv:1010.0245



$$B - L + X \quad \Longrightarrow \quad \eta_B : \eta_L : \eta_X = N_1 : N_2 : N_3$$

Asymmetric "Freeze-In"

Freeze-in production between the sectors via connector interaction leads to related $\eta_B, \eta_L, \eta_X \neq 0$

if

- temperatures of visible and dark sectors differ (out-of-equilibrium condition)

- CP-violation occurs in decays (and/or scatterings) from visible to dark sectors

Asymmetric "Freeze-In"

One more condition:

If $U(1)_{B-L+X}$ only relevant symmetry then depending on relative proton and X_0 masses

either proton or DM not stable

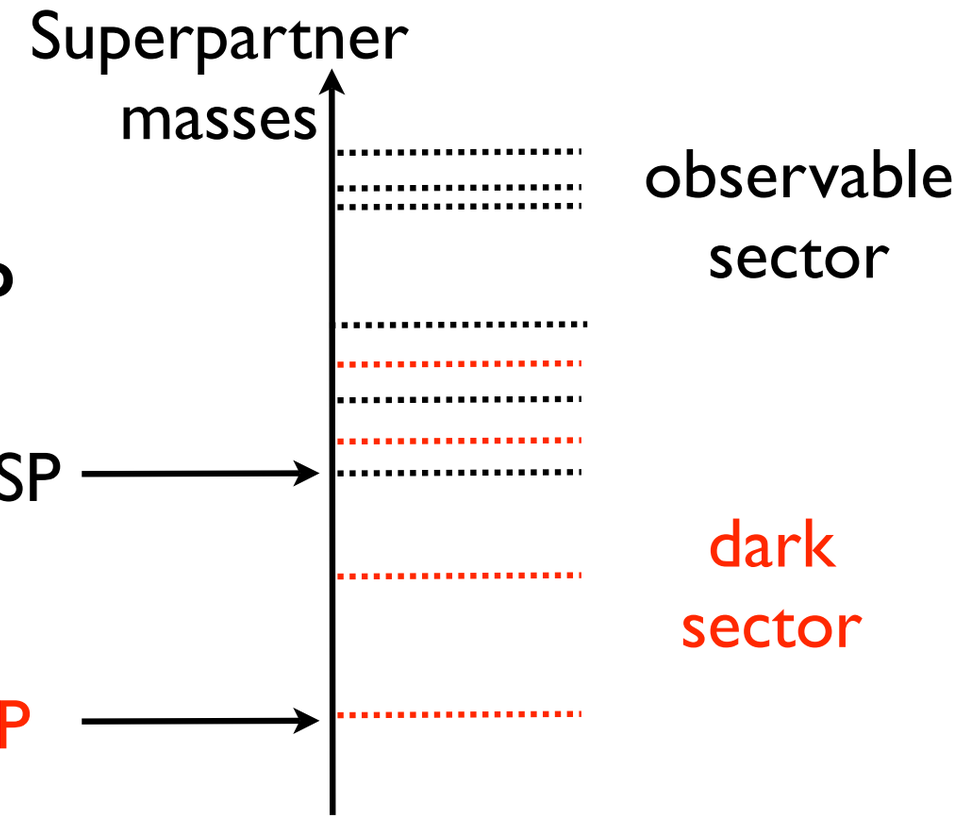
Need additional (discrete) symmetry to stabilise lightest X
- take to be R-parity in SUSY case

Asymmetric "Freeze-In"

Supersymmetric example

connector interaction $\lambda \ll 1$

eg $W = \lambda L H_u X$ with chargino LOSP



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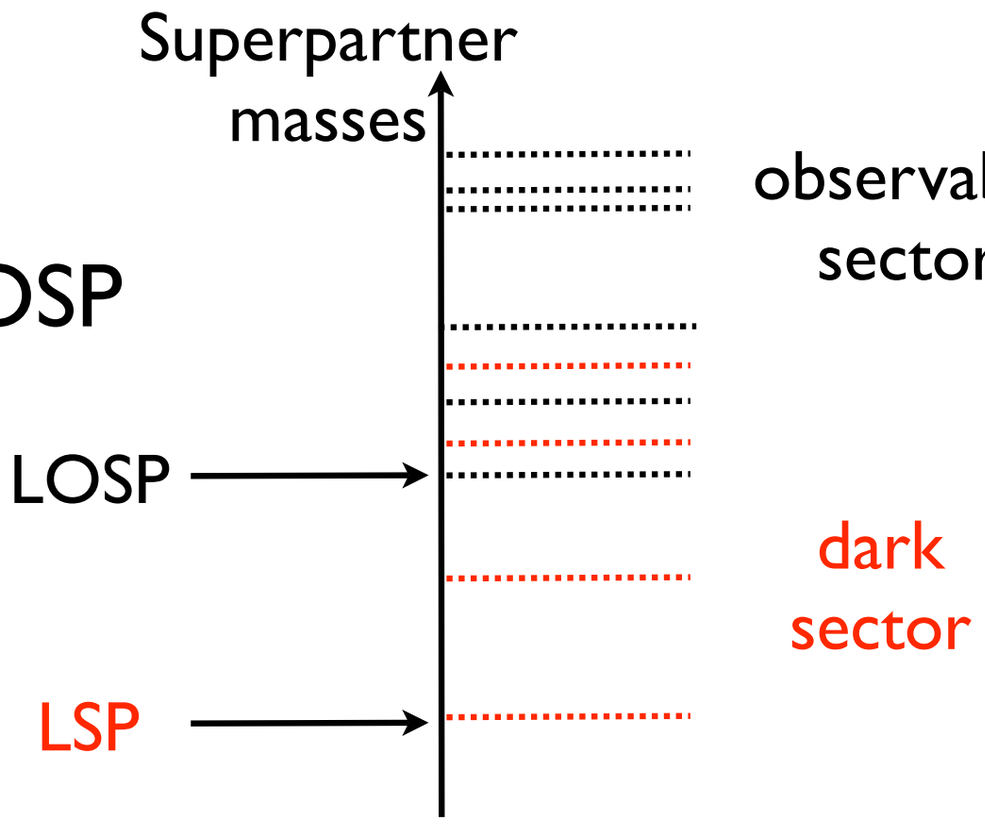

R-parity-odd ops are precisely those that carry B/L - any will do

Asymmetric "Freeze-In"

Supersymmetric example

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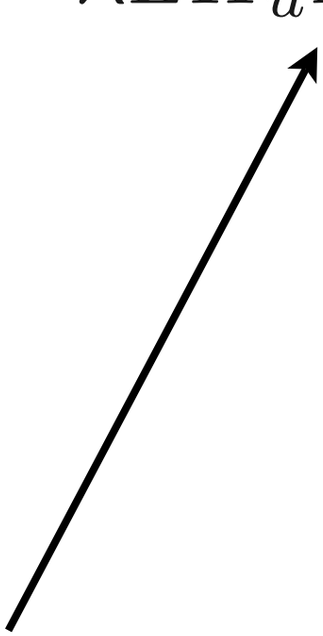
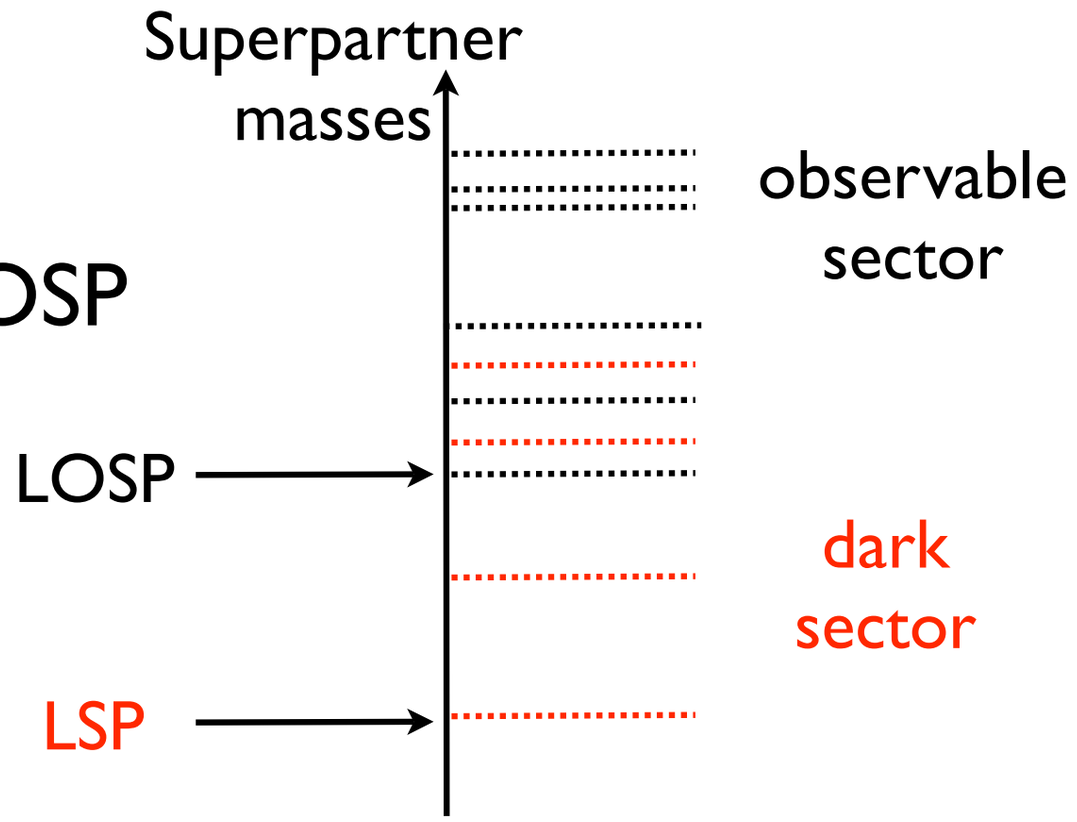
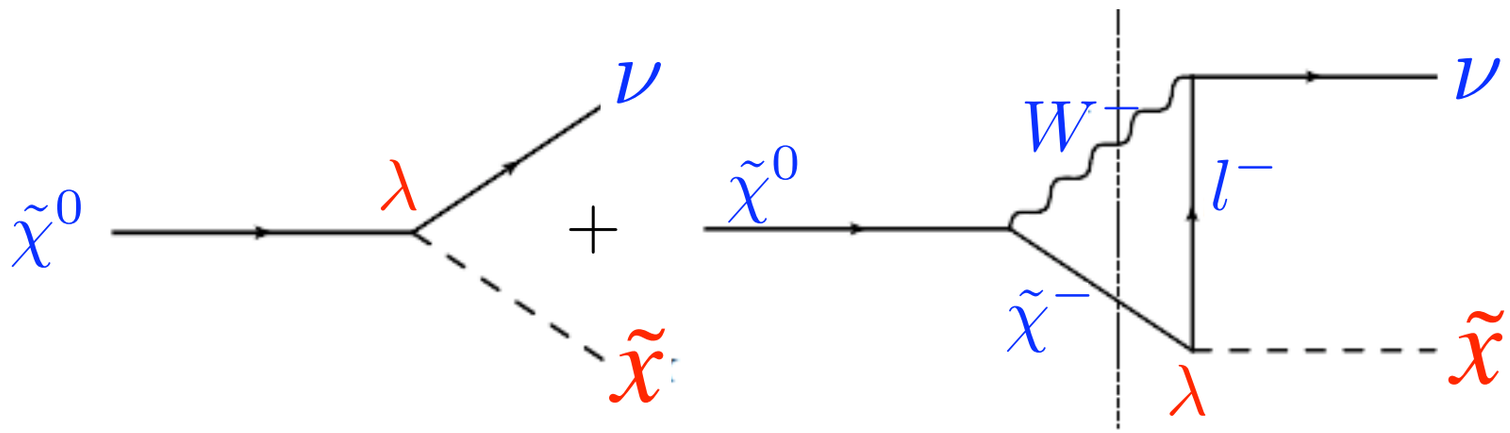




linearity in X is not necessary - other choices change collider & especially DM detection signals

Asymmetric "Freeze-In"

Decays of NLOSP via on shell LOSP then generate simultaneous L (and thus B) and X asymmetries



$$\eta_L = \eta_X = \epsilon Y_X = \epsilon \Gamma_{\chi^0} \frac{M_{Pl}}{m^2_{\chi^0}}$$

$\epsilon = (\text{loop factor}) \times \sin\phi$ **gives fractional CP asymm in decay**

Consequences

DM state can no longer be a real scalar or Majorana fermion

$\Longrightarrow$ if DM is the LSP it must be in the dark sector

$\Longrightarrow$ must append MSSM with new states and interactions

both very natural from a higher-theory perspective

Observable sector LSP (the LOSP) can be any one of

chargino, squark, slepton, neutralino, sneutrino,...

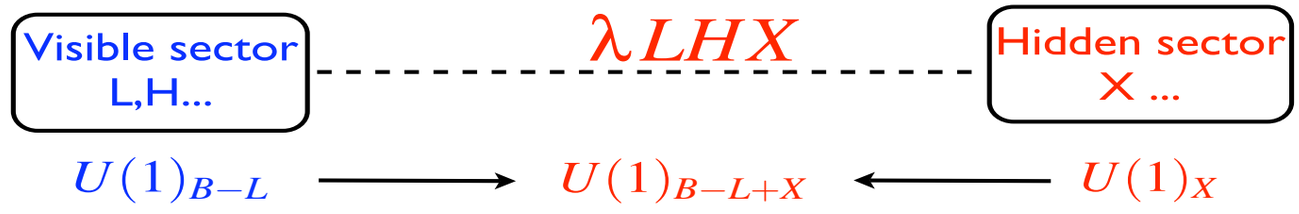
Subject of study at Les Houches, "Physics at TeV Colliders", summer 2011

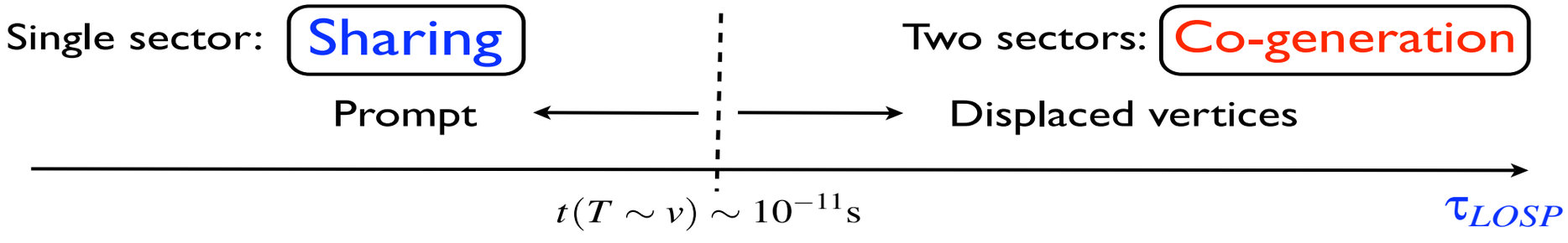
Consequences

ϵ is an important parameter

- can be correlated with/deduced from EDM and SUSY-spectrum measurements (work in progress, Hall, JMR, Unwin, West,...)
- determines LOSP lifetime measurable at LHC

$$\tau_{LOSP} \sim 10^{-3} \epsilon\, r \quad \text{sec}$$



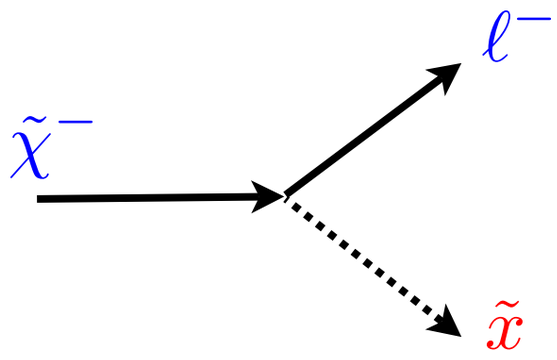


Note that $10^{-2} \gtrsim \epsilon \gtrsim 10^{-8}$ so sectors don't thermalise

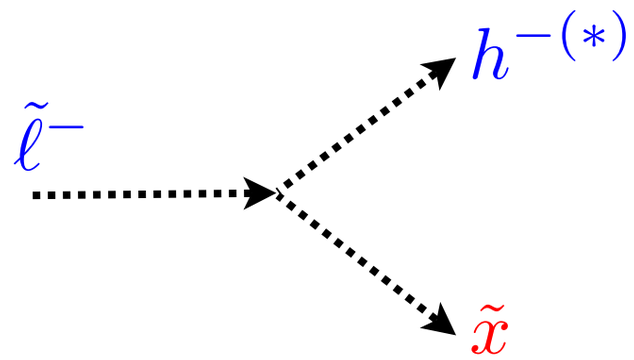
Consequences

Observable sector LSP (the LOSP) will decay in a B/L-violating way

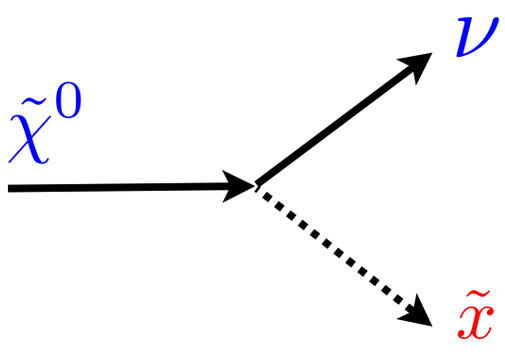
eg, chargino LOSP



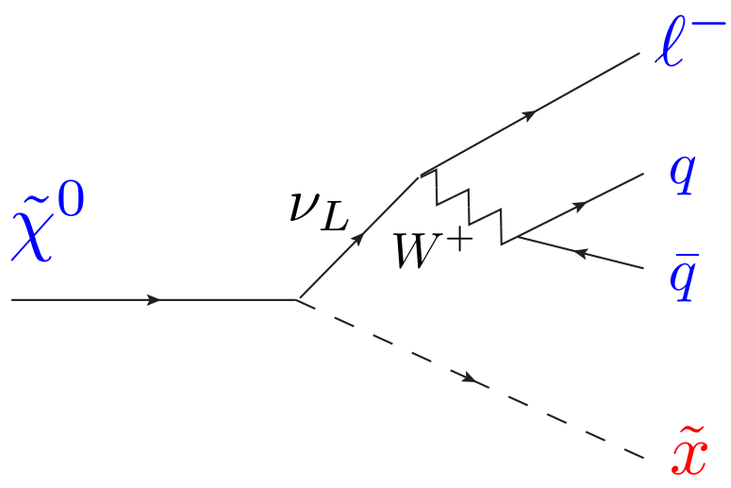
eg, slepton LOSP



eg, neutralino LOSP



but



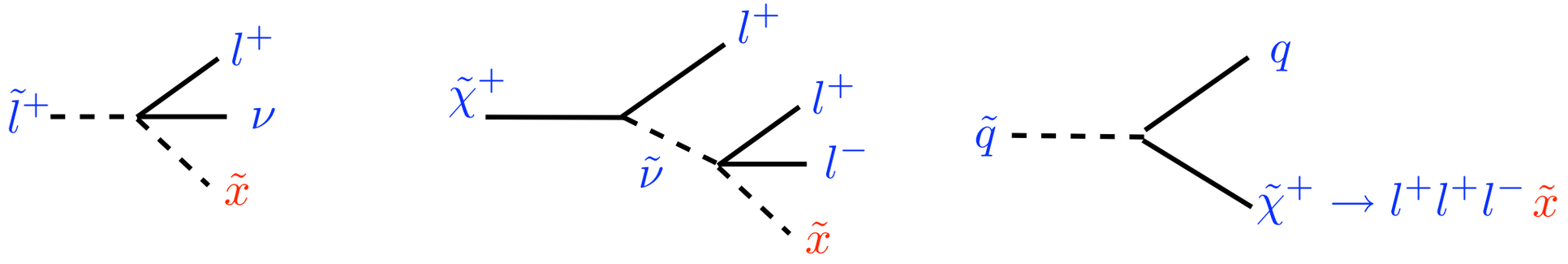
(where we ID the quantum #s of the decaying state by earlier part of cascade chain)

Consequences

Observable sector LSP (the LOSP) will decay in a B/L-violating way

similarly for other connector operators

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



eg, $W = \frac{1}{M} U^c D^c D^c X$

$(\tilde{\chi}^\pm, \tilde{\chi}^0) \to jjj \qquad (\tilde{\ell}^\pm, \tilde{\nu}) \to \ell^\pm jjj$

much harder as involves jets in final state and must distinguish $j_q j_q j_q$ from $j_q j_{\bar{q}} j_g$

by measuring LOSP mass and lifetime can determine λ

Consequences

Crucial challenge - can we measure $m_{\tilde{x}}$?

Since $\Omega_{DM}/\Omega_B \simeq 4.86$ and $\dfrac{\Omega_X}{\Omega_B} = \dfrac{\eta_X}{\eta_B}\dfrac{m_X}{m_B}$

$$m_{\tilde{x}} \simeq 4.86 m_p \frac{\eta_X}{\eta_B} \sim 0.5 \div 5 \text{ GeV}$$

depending on the computable asymmetry ratio which is SUSY-spectrum-dependent if connector interaction involves leptons

LHC can bound, but precision of LC likely needed to confirm

Consequences

Consequences for DM searches

- light DM ~ few GeV is strongly favoured

- "sharing" allows normal direct detection, but "co-generation" by asymmetric FI kills direct detection signals (but see JMR+McCullough)

- indirect detection strongly modified - DM can't annihilate to photons but can give rise to anti-B/L final states (see Hall, JMR, Unwin, West,...)

Consequences

Other generic astro signals

both sharing and co-generation generate an initially dominant symmetric $(X + \bar{X})$ component

$$\text{eg} \quad Y_X + Y_{\bar{X}} \sim \frac{Y_X - Y_{\bar{X}}}{\epsilon}$$

must be efficiently removed - most simply by late annihilation/ decay to SM states via light X-sector states

Hall, JMR, West, arXiv:1010.0245
& cf Buckley arXiv:1104.1429

$\Longrightarrow$ late-time energy injection (neutrinos, photons, hadronic all possible)

$\Longrightarrow$ large-scale structure, CMBR, big-bang nucleosynthesis signals

(work in progress, Ferreira, Hall, Jedamzik, JMR, Marsh, Unwin, West,...)

Conclusions

Related baryonic & DM asymmetries, either in sharing or co-generation regime, provides route to understand

$$\Omega_{DM}/\Omega_B \simeq 4.86$$

Asymmetric DM, & especially frozen-in ADM leads to striking collider signals and astro search opportunities

There exists an equally motivated, calculable, and testable mechanism of DM genesis: 'freeze-in'