The Origin of Cosmic Baryons *and* Displaced Vertices at the LHC

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UC Riverside

PITT PACC workshop
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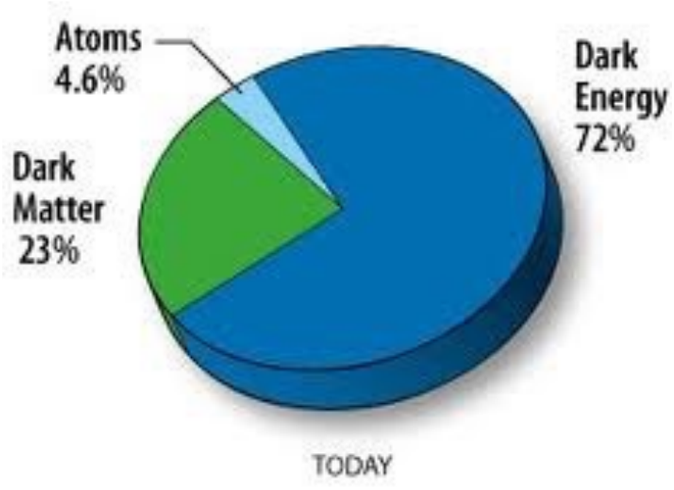
Probing the Origin of Matter with the LHC?

- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{\mathrm{DM}} \approx 23\%$
- **Coincidence/Similarity:** $\Omega_{\mathrm{DM}} \sim \Omega_{\mathrm{B}}$



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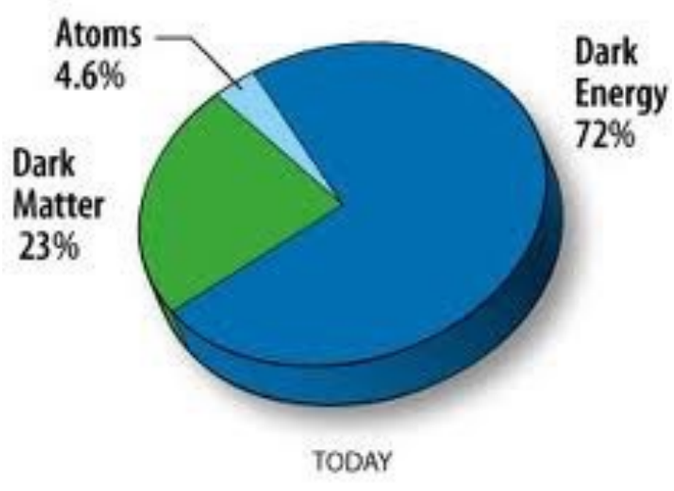

- Familiar/well-studied case: WIMP dark matter (Ω_{DM})
  - Stable, mass ~O(10-100) GeV, can be produced within E_{LHC} =14 TeV
  - Pair produced (Z_2),
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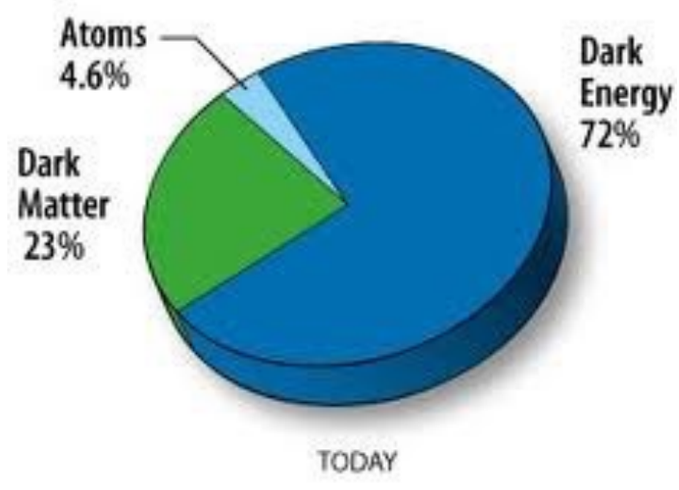

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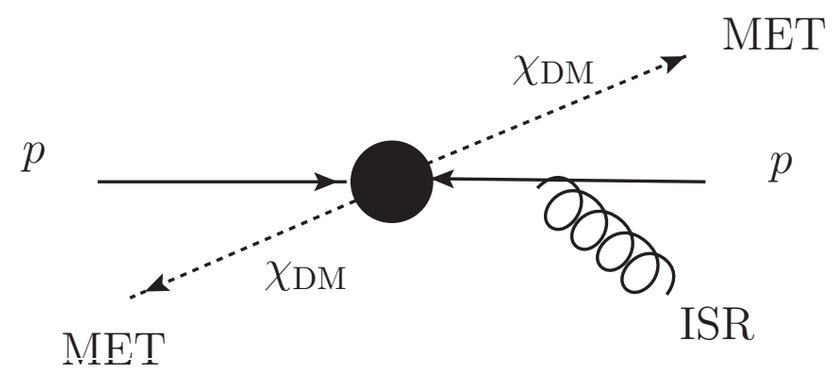

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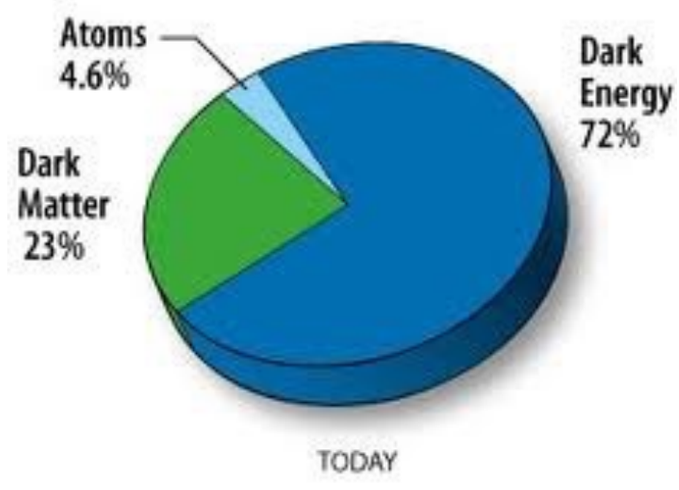

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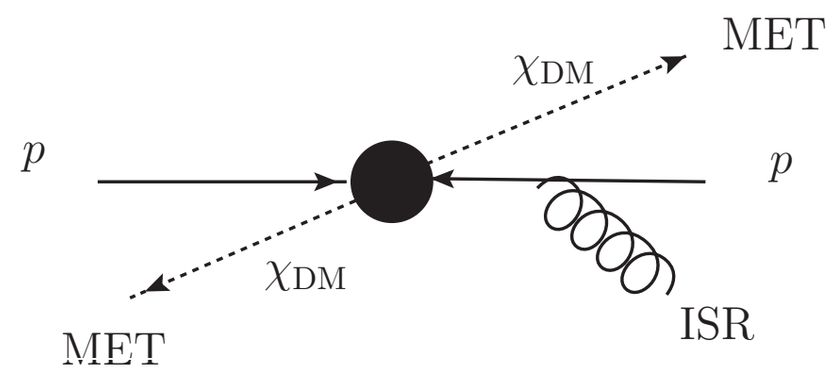


- *Direct* test for $\Omega_{\rm B}$, $\Omega_{\rm B} \sim \Omega_{\rm DM}$ @LHC?
  (challenges: high mass, high T (EWBG) involved)

  Indirect tests for EWBG: see David Morrissey's talk

Probing the Cosmic Origin of Baryons with Displaced Vertices at the LHC

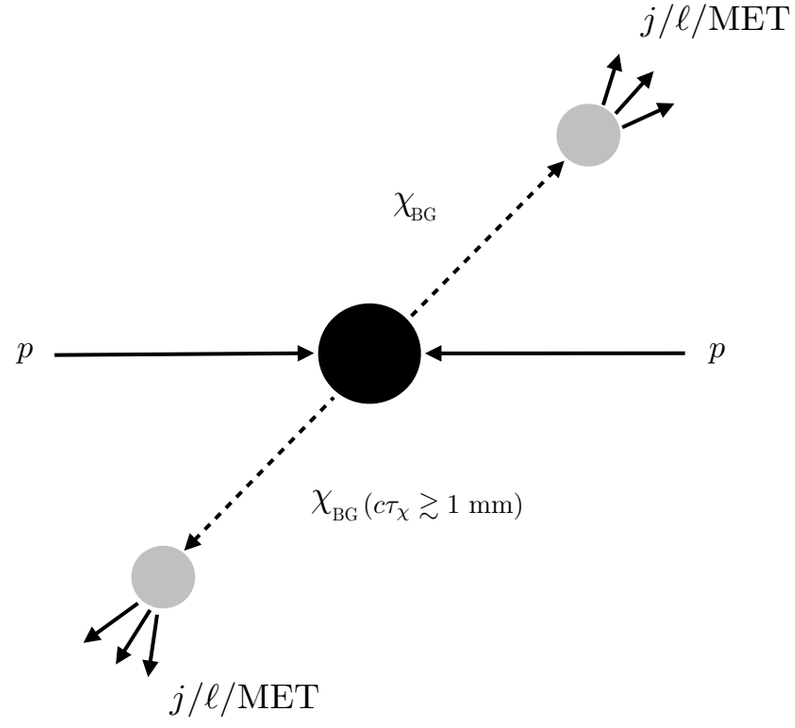
- **New opportunity**: baryogenesis

  (address Ω_B , possibly + $\Omega_B \sim \Omega_{DM}$)

  - New weak scale <u>metastable</u> particle (e.g. long-lived WIMP) as baryon parent
  - Pair produced (approx. Z_2)
  - Displaced decay to $j/\ell/\mathrm{MET}$ by cosmological conditions!

  Generic event topology

  (analogy to WIMP DM search!)



$L_{dec} \gtrsim 1\ mm$

Displaced Vertices at the LHC

- Nearly all SM particles decay **promptly**

  ≲ 100 μm - 1 mm (= *prompt*)

- Ubiquitous predictions from motivated new physics:

  long-lived particles, **displaced decay vertices** from all part of the detector ($L_{dec} \gtrsim 1\ mm$) (SUSY,twin-Higgs,hidden valley, sterile **ν**…)

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Impressive developments, dedicated studies in the past a few years (experimentalists + theorists)!

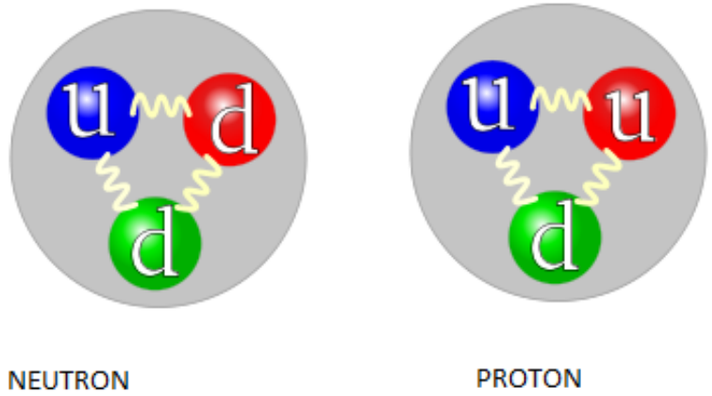
Baryogenesis 101

Baryon $\Omega_B \approx 5\%$

— The Unknown Aspects of the Known

- **Baryon**: proton, neutron ⇨ atoms, stars, ourselves!
- **Where does Ω_B come from?**

= Where do we ourselves come from?



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Quark structure

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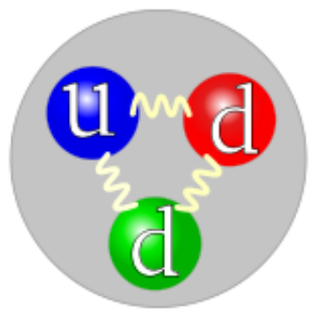

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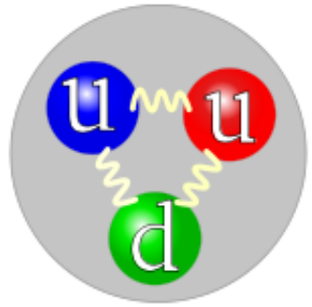

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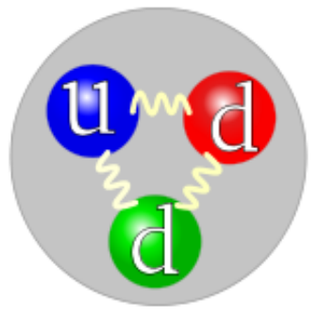

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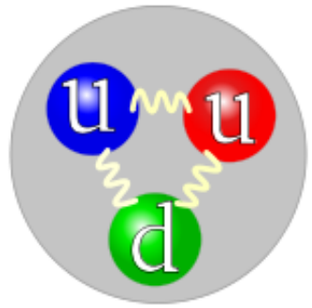

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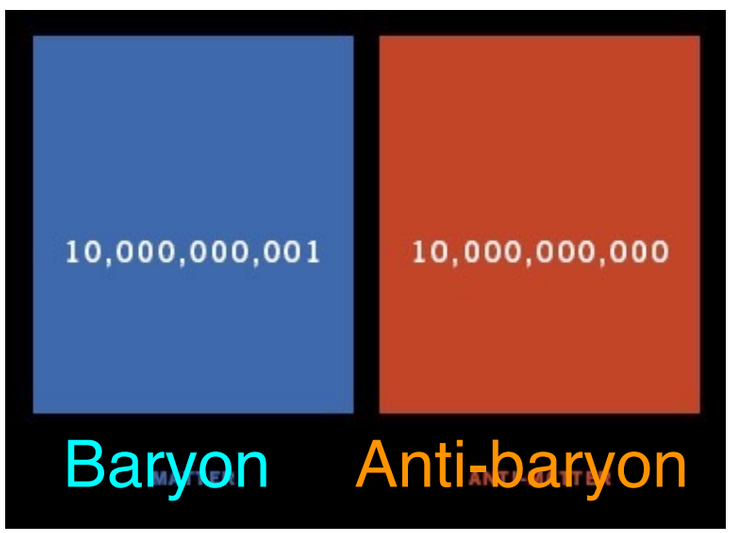
Initial $B - \bar{B}$ asymmetry

$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$



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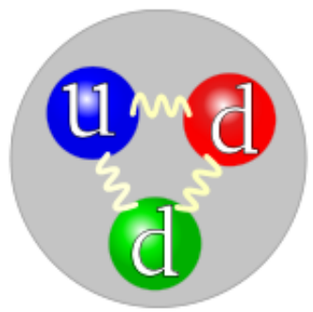

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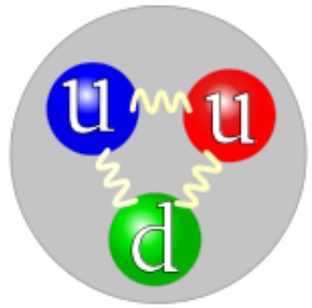

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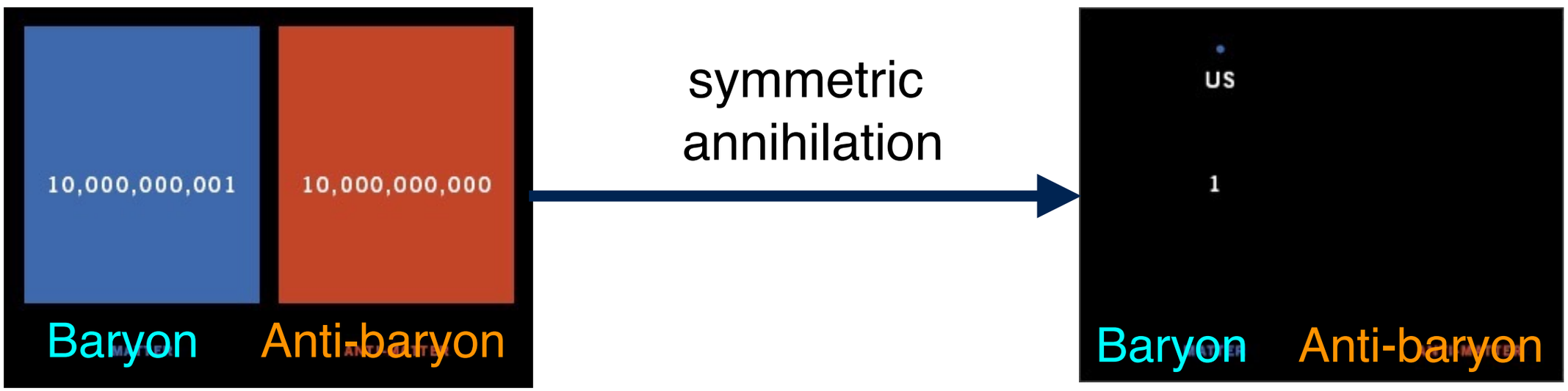

Baryogenesis

- the Origin of the Baryon Asymmetry

The Universe starts with $B = 0$, ? $B \neq 0$

$B - \bar{B}$ asymmetry

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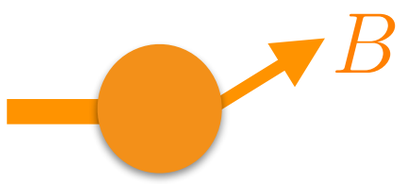

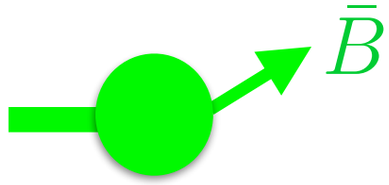

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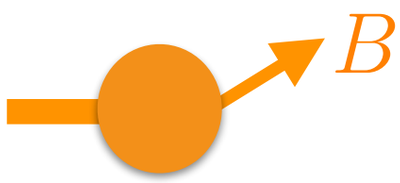

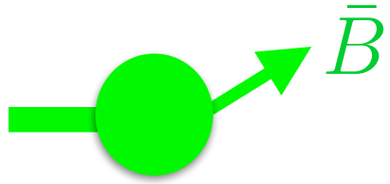

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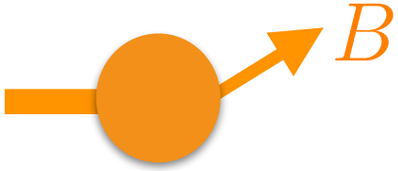

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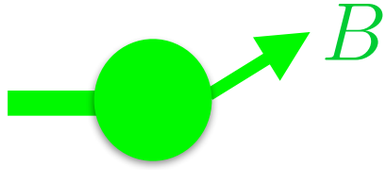

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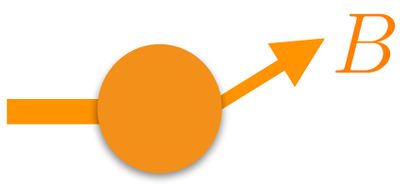

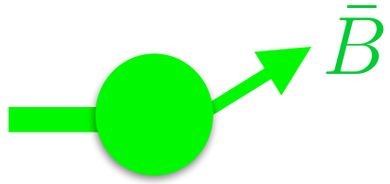

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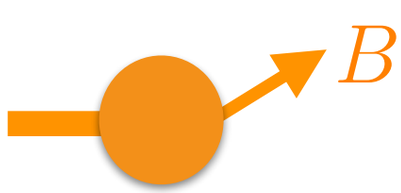

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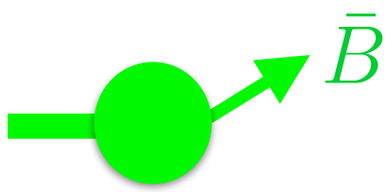

- **Require departure from equilibrium!**

Thermal equilibrium + CPT symmetry

$\Rightarrow$ $n_B^{\rm eq} = n_{\bar{B}}^{\rm eq}$, $\boxed{\langle B \rangle_{\rm eq} = 0}$

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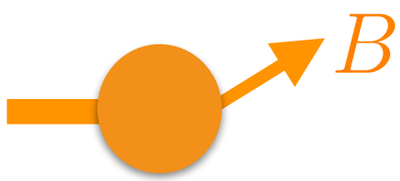

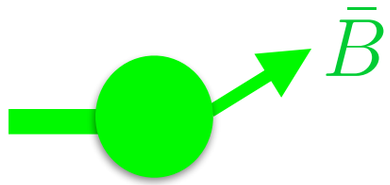

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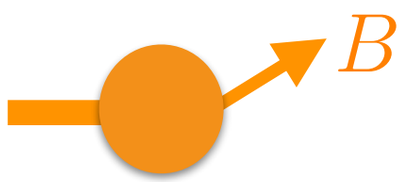

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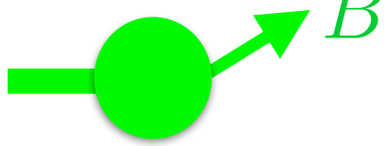

$\Omega_B \approx 5\%$: Need beyond the Standard Model Particle Physics!

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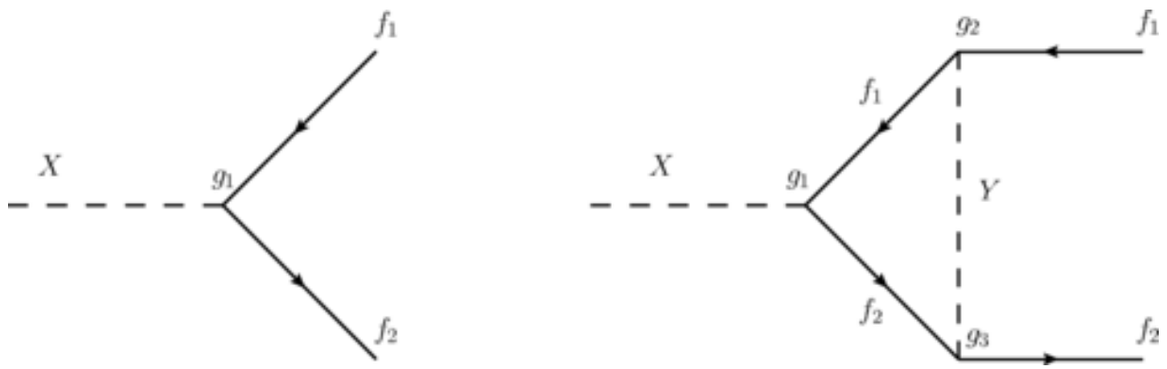
Baryogenesis from Out-of-Equilibrium Decay

A general class of baryogenesis models (e.g. leptogenesis)

- Consider an unstable massive neutral particle χ
- Baryon asymmetry produced in its decay (B-, C-, CP-violating)



$$\Gamma(\chi \to f) \neq \Gamma(\chi \to \bar{f})$$

$$n_f - n_{\bar{f}} \neq 0$$

- Typically, the inverse processes efficiently erase the asymmetry
- But, if χ is long-lived, and decays only after $T_f < M_\chi$:

Inverse decay:
Boltzmann suppressed

$$e^{-M_\chi / T_{\rm decay}}$$

Baryogenesis from Out-of-Equilibrium Decay

☞ **Out-of-equilibrium decay** → Sakharov conditions ✔

An intriguing observation (**YC**, Sundrum; **YC**, Shuve):

If χ has weak scale mass,

$$\Gamma_\chi < H(T = M_\chi) \quad \Longleftrightarrow \quad c\tau_\chi \gtrsim \mathrm{mm}$$

- A **generic connection** between cosmological slow rates at *T ~100 GeV* and displaced vertices at colliders!

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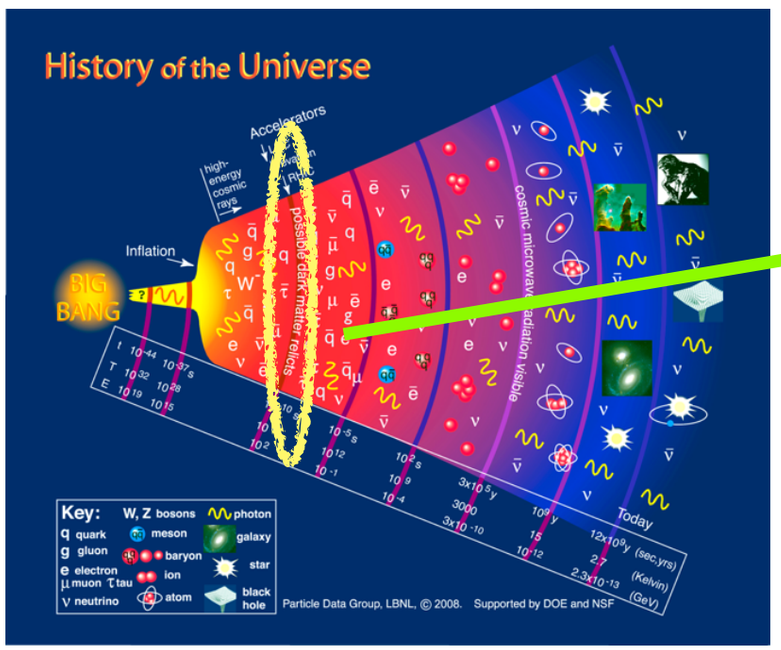


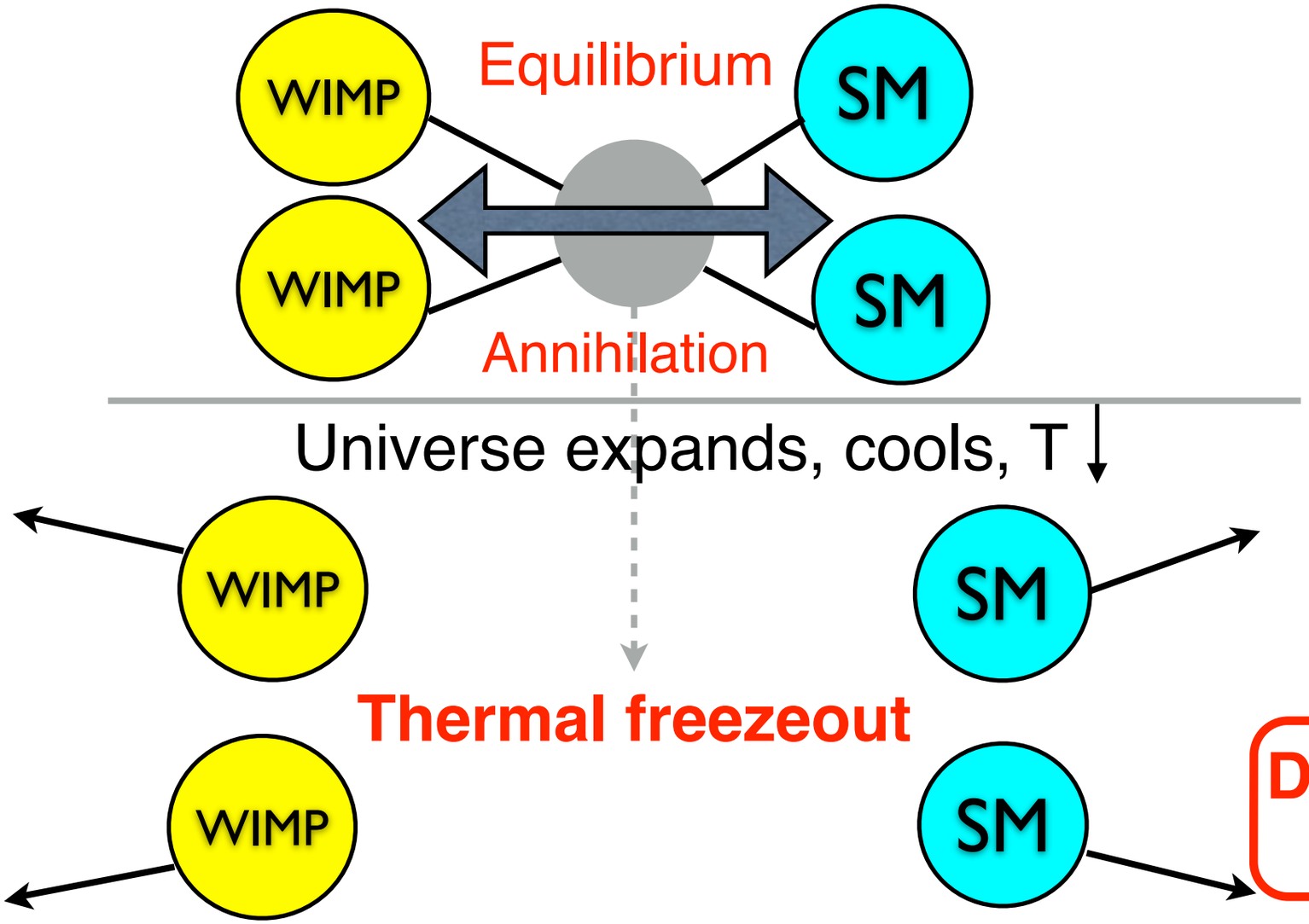
Our universe around EW phase transition was just slightly bigger than LHC tracking resolution!

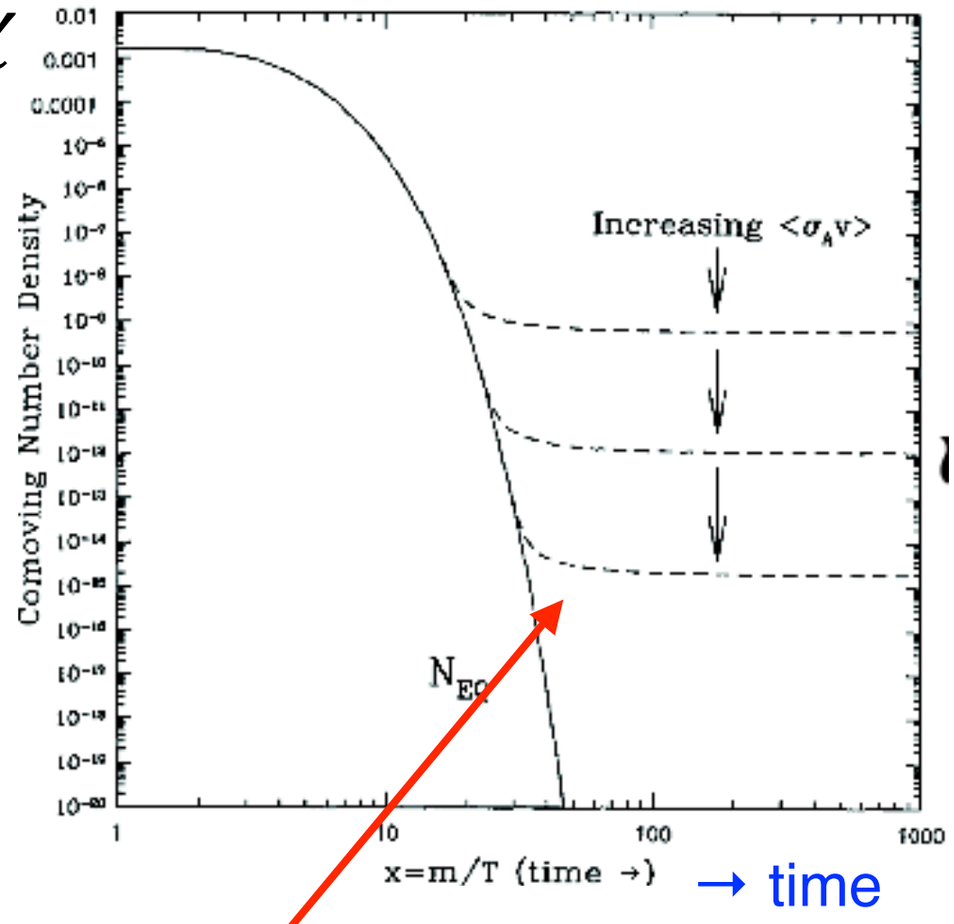
Baryogenesis from WIMPs

— A New Proposal to Address Ω_B, $\Omega_B \sim \Omega_{DM}$

- YC and Raman Sundrum, Phys.Rev. D87 (2013) 11
- YC, JHEP 1312 (2013) 067

· Cosmic Evolution of a <u>stable</u> WIMP χ





Departure from equilibrium: key to Ω_{WIMP} !

(recall Ω_B?)

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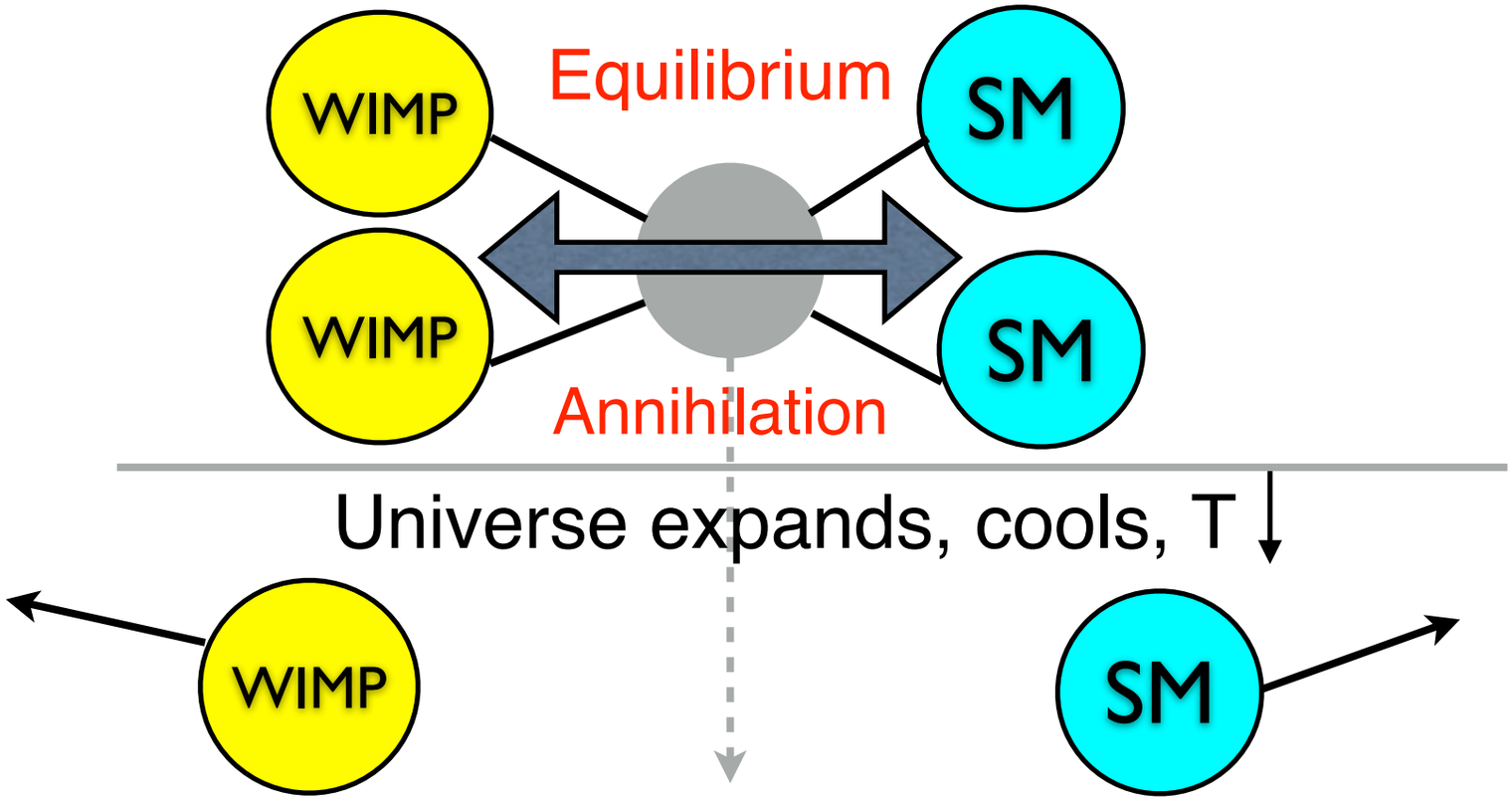
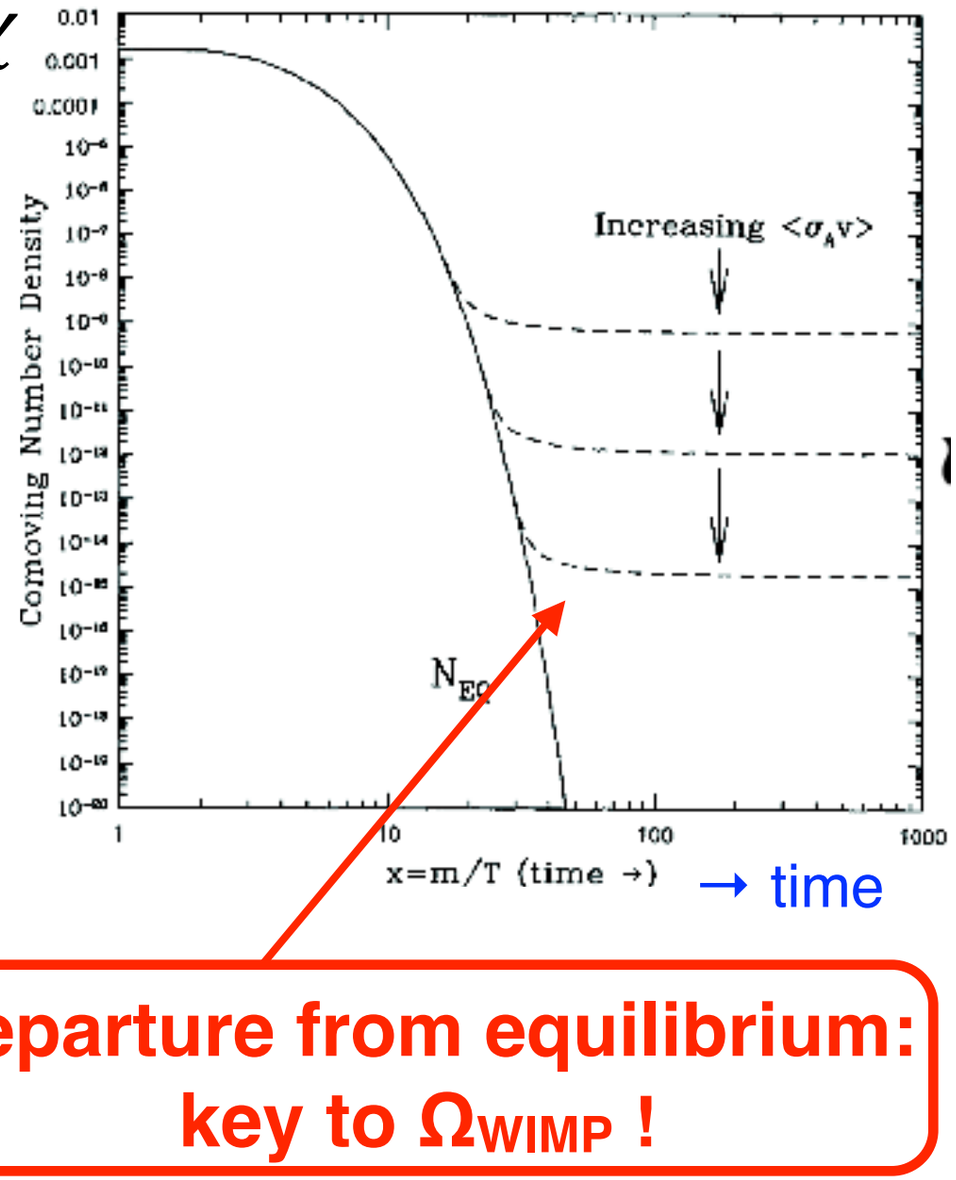




(recall Ω_B?)

- **Relic abundance:**

$$\Omega_\chi \propto \langle \sigma_{\rm ann} v \rangle^{-1}$$

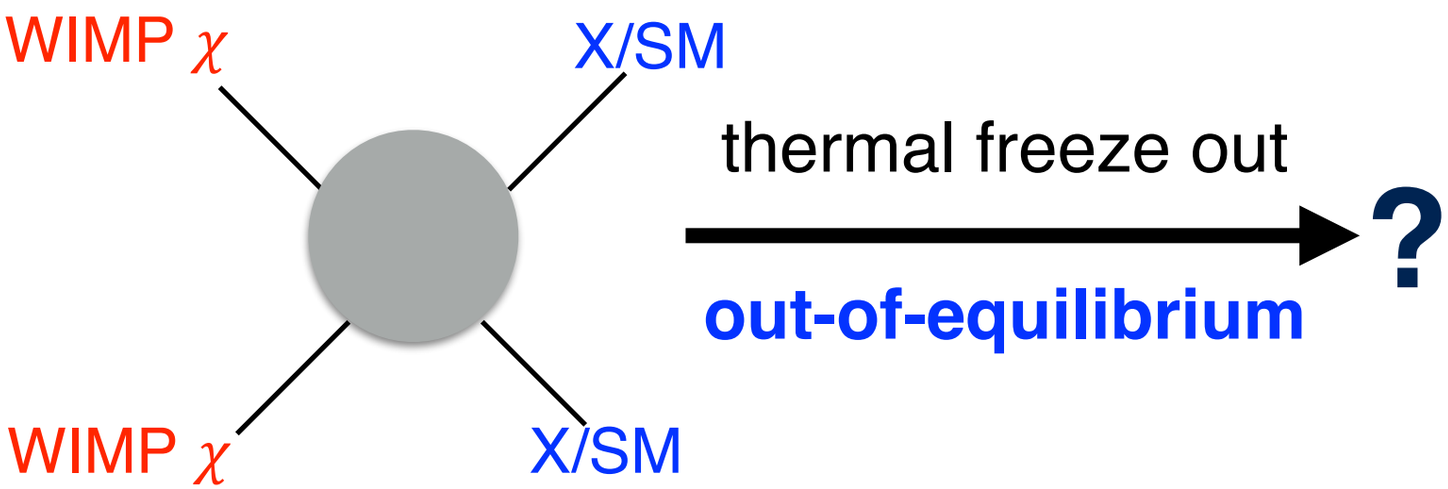
$$\sim \boxed{0.1} \left(\frac{G_{\rm Fermi}}{G_\chi} \right)^2 \left(\frac{M_{\rm weak}}{m_\chi} \right)^2$$

☞ **WIMP Miracle!**

WIMP Miracle for Baryons?

- Another variation of WIMP miracle

(**YC,** w/Sundrum)



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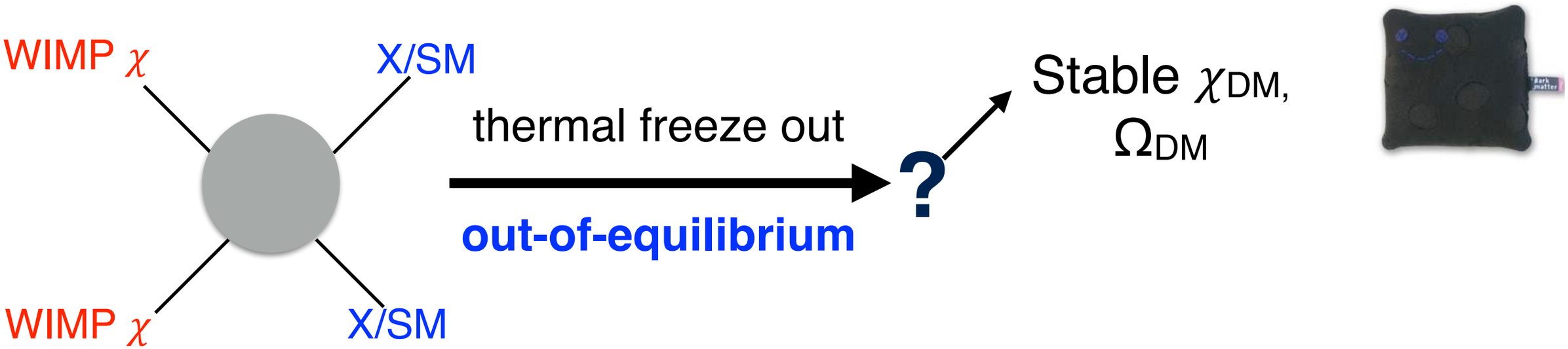

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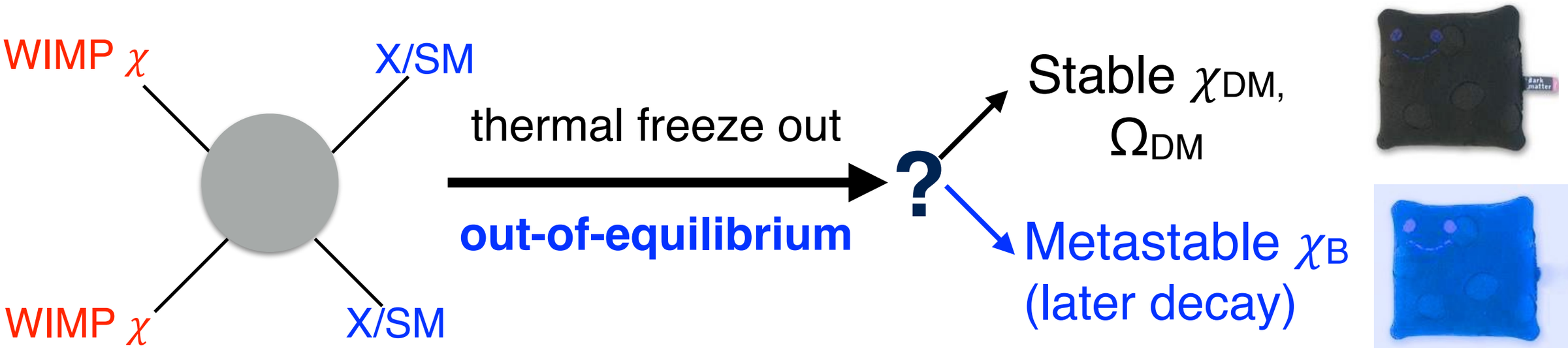

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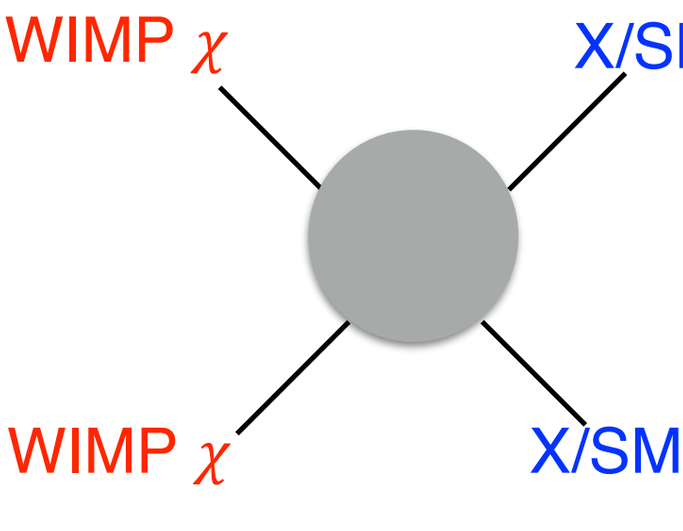


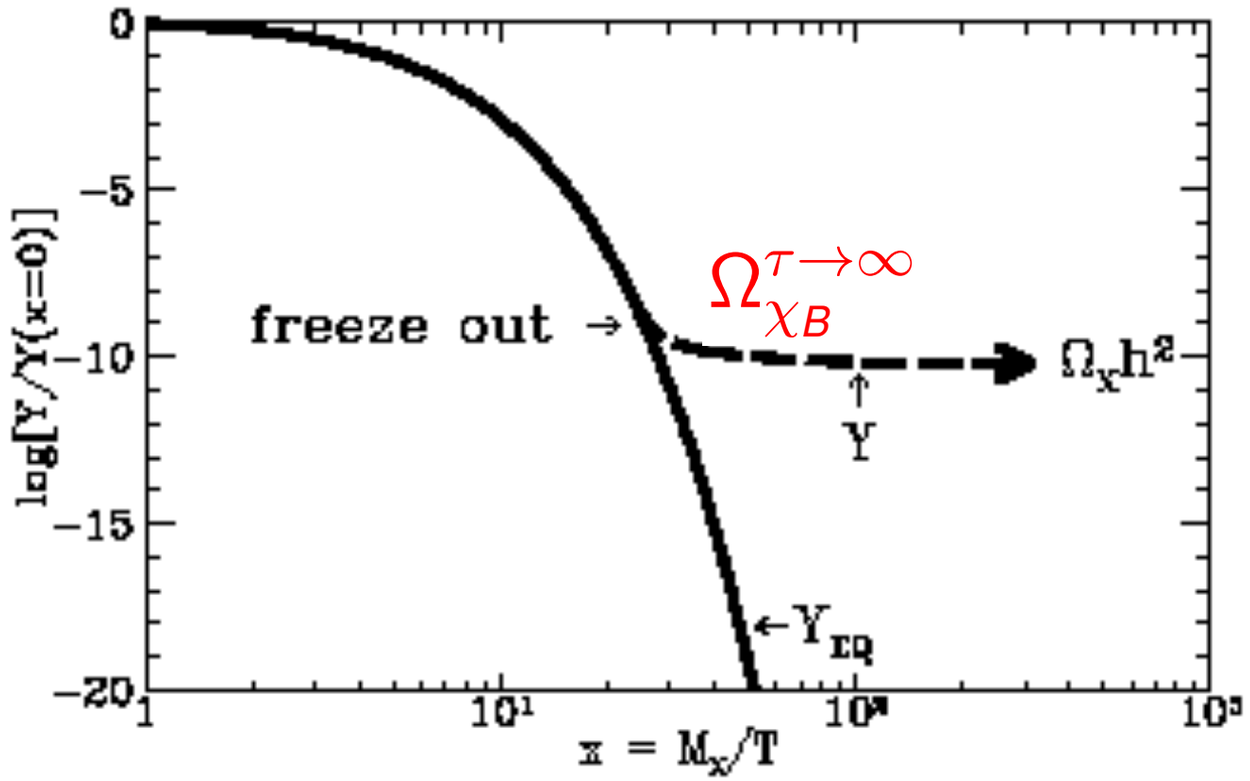
thermal freeze out

out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

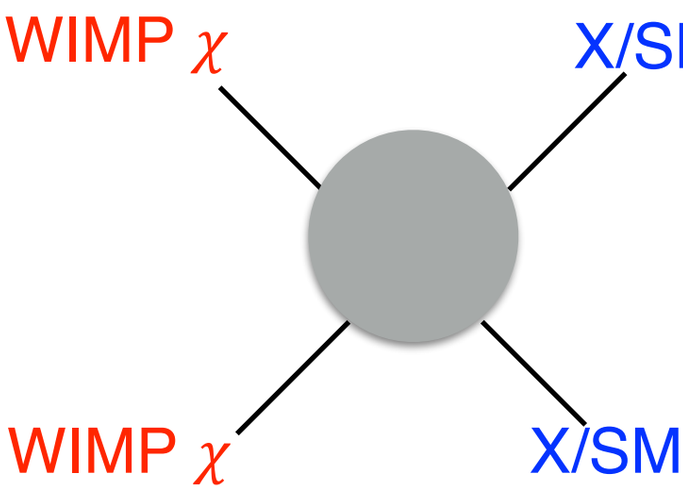
Metastable χ_B (later decay)



WIMP Miracle for Baryons?

- Another variation of WIMP miracle

(**YC,** w/Sundrum)



thermal freeze out

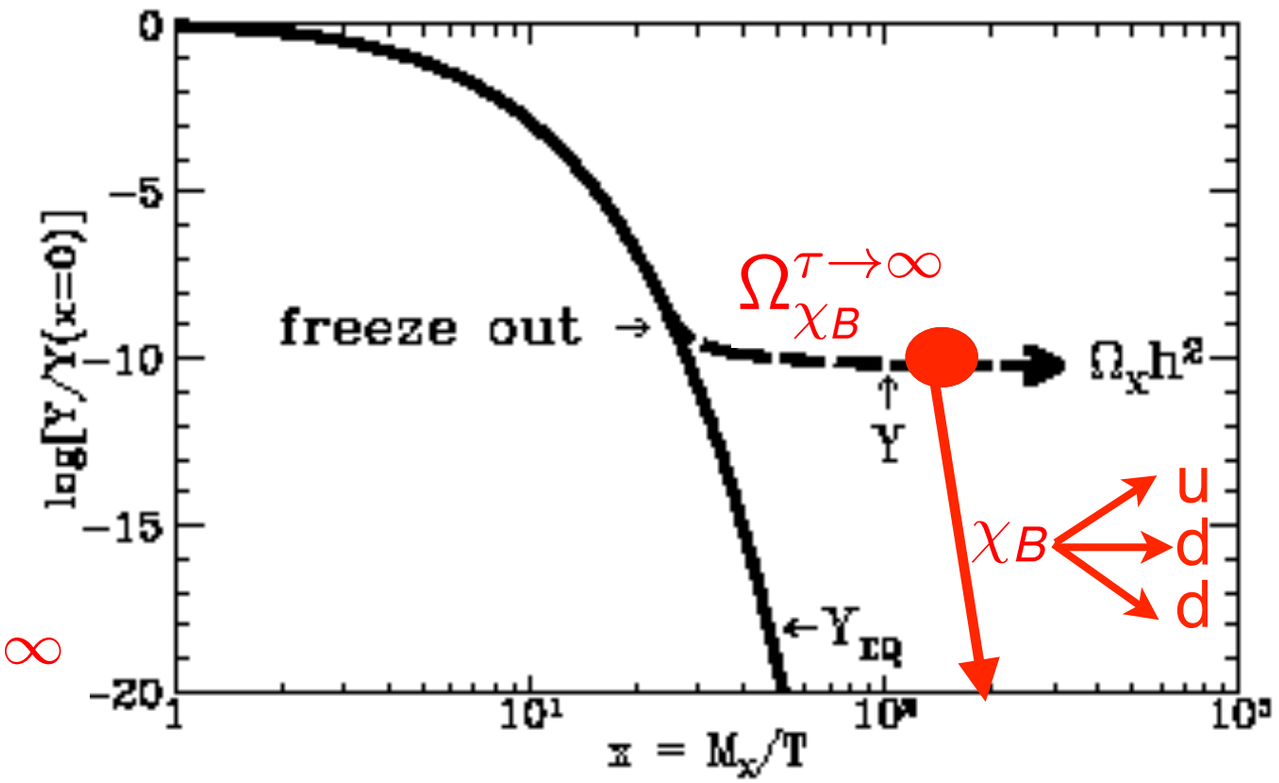
out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

Metastable χ_B (later decay)

$$\Omega_B = \epsilon_{CP} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau \to \infty}$$



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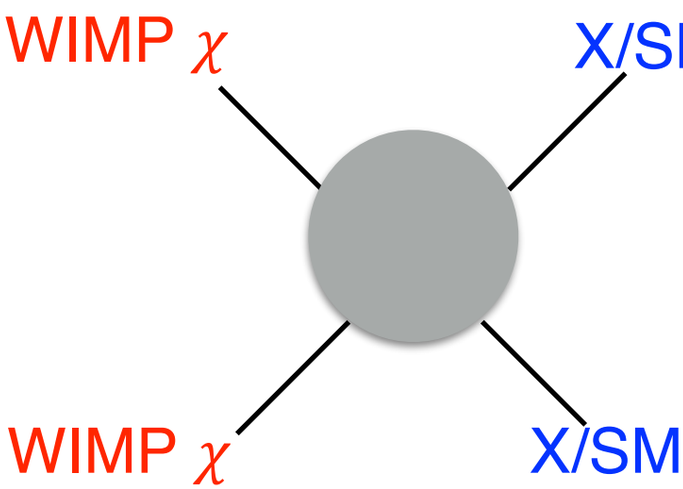


thermal freeze out

out-of-equilibrium

?

Stable χ_{DM}, Ω_{DM}

Metastable χ_B (later decay)

- **Novel baryogenesis**

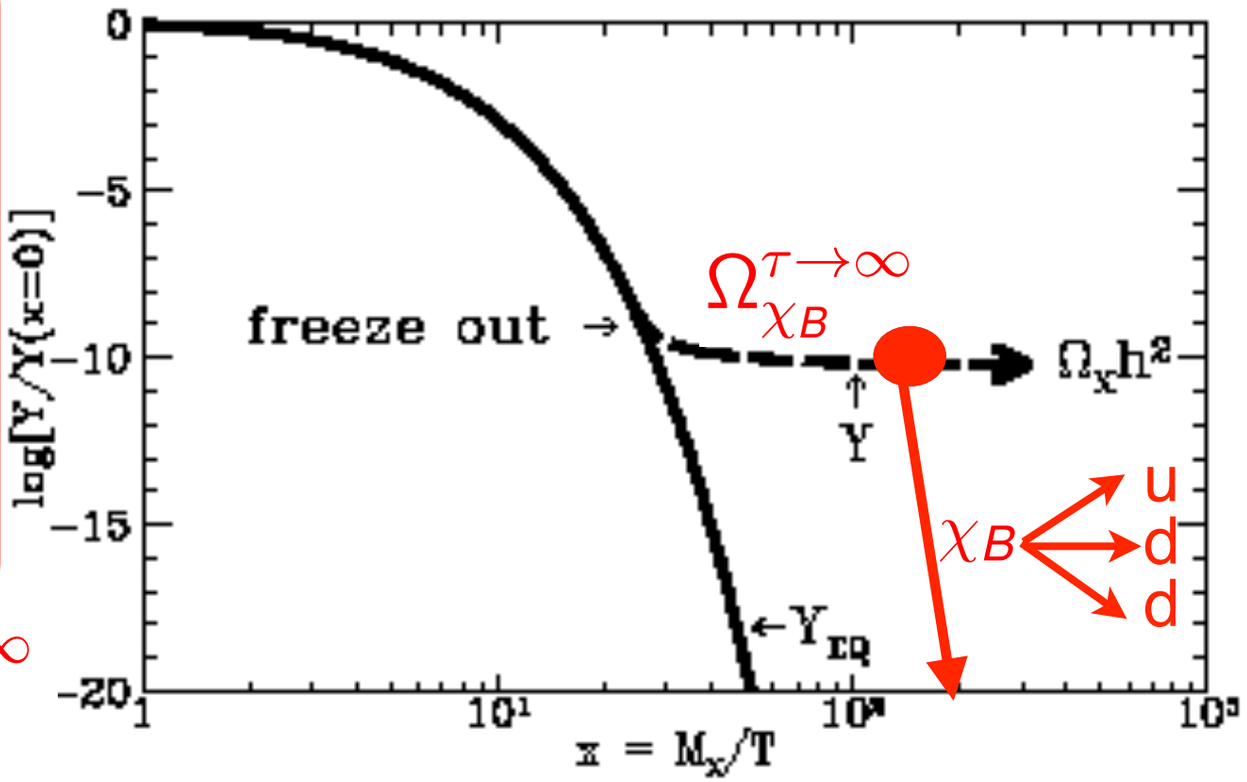
  Ω_B ✅

- **Generalized WIMP miracle**

  (+ stable WIMP DM Ω_{DM} ✅)

  $\Omega_B \sim \Omega_{DM}$ ✅

$$\Omega_B = \epsilon_{CP} \frac{m_p}{m_{\chi_B}} \Omega_{\chi_B}^{\tau \to \infty}$$



A Minimal Model Example

(Phys.Rev. D87 (2013) 11, **YC** w/Sundrum)

- BSM CP-, B-violating Lagrangian:

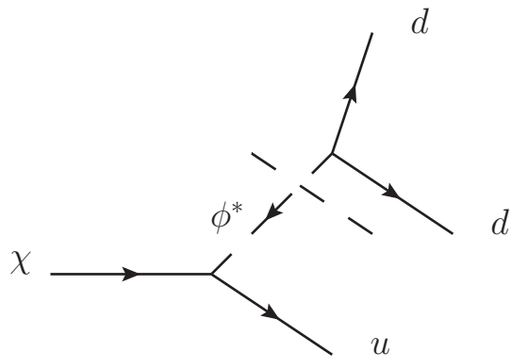
$$\begin{aligned}\Delta\mathcal{L} &= \lambda_{ij}\phi d_i d_j + \varepsilon_i \chi \bar{u}_i \phi + M_\chi^2 \chi^2 + y_i \psi \bar{u}_i \phi + M_\psi^2 \psi^2 \\ &+ \alpha \chi^2 S + \beta |H|^2 S + M_S^2 S^2 + \text{h.c.}\end{aligned}$$

ϕ: di-quark scalar w/same charges as SM u-quark;

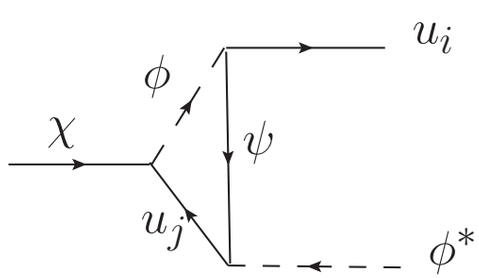
χ, ψ: SM singlet Majorana fermions;

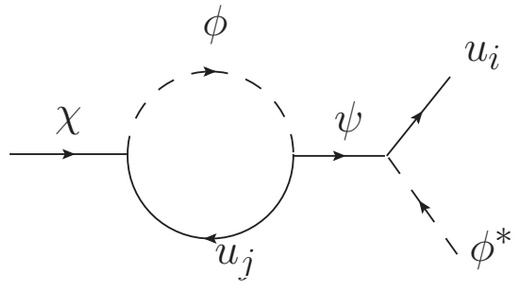
ε: small breaking of a χ-parity → long-lived χ (baryon parent)

CP asymmetry from:



interfere w/





- Easy embedding in RPV natural SUSY (+ singlet)! ($\phi \to \tilde{t}$)
- Late-time baryogenesis; a remedy for a potential cosmological crisis with RPV SUSY: RPV washout of existing Ω_B
  (e.g. Barry, Graham, Rajendran 2013)

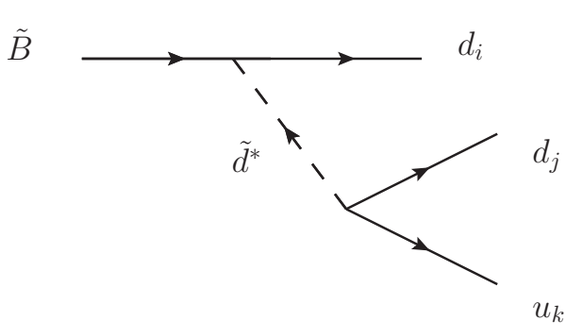
Embedding in Mini-split SUSY

(**YC**, JHEP 1312 (2013) 067)

Baryogenesis with Minimal SUSY model (MSSM+RPV)!

Bino $\tilde{B} \to \Delta B$!

- Sakharov#1: out-of equilibrium ✔
  Split spectrum→ automatic late decay of gauginos
- Sakharov#2, 3: CP-, B-(L-)violations, rich sources in RPV SUSY ✔
- Bino as baryon parent ("would-be" over-abundance desirable for Ω_B)
- Nanopoulos-Weinberg theorem→ extra BV source in loop: $\tilde{W}$, $\tilde{g}$!



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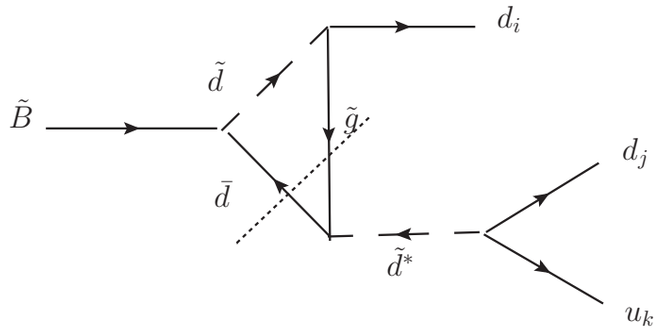
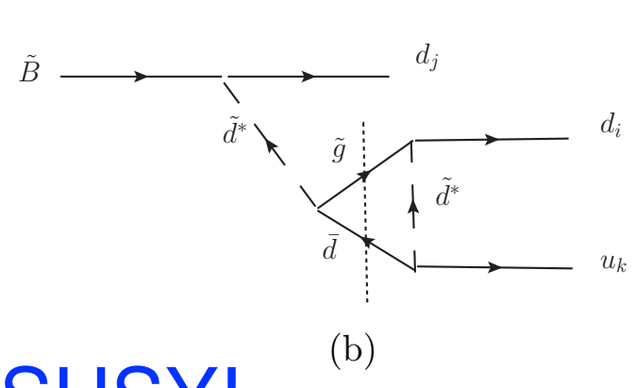




(b)

Cosmological motivation for mini-split SUSY!

Baryogenesis from Out-of-equlibrium Decays

— Collider Phenomenology

YC and Shuve, JHEP 1502 (2015) 049

(**YC** and Okui, Yunesi, Phys.Rev. D94 (2016))

★*Strategies/results generally applicable to other new physics searches via displaced vertices*

Reproduce Baryogenesis at the LHC!

(**YC** w/Sundrum; w/Shuve)

- WIMP $m_\chi \sim O(100\ GeV)$ can be produced within E_{LHC}=14 TeV!
- **Cosmological condition for baryogenesis:**

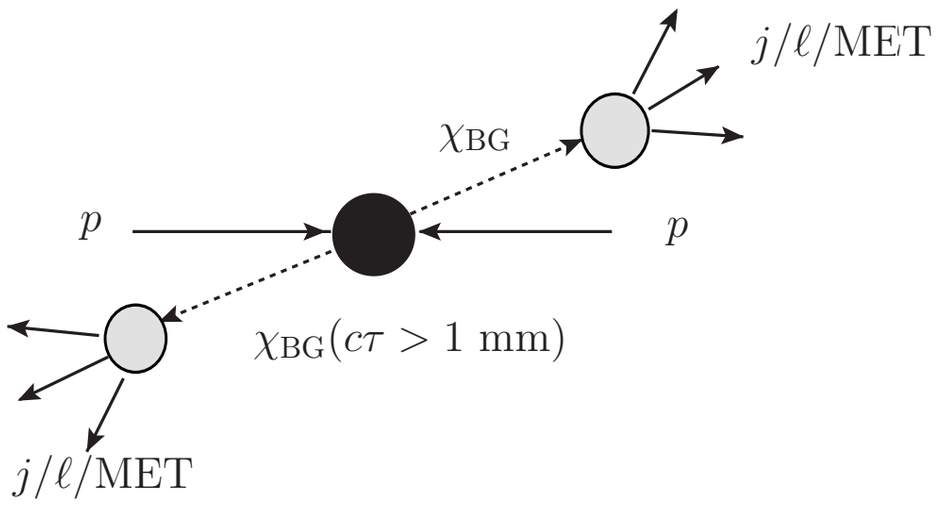
χ lives beyond its thermal freeze out time

$$\Gamma_\chi < H_{\rm fo} \quad \Longleftrightarrow \quad c\tau_\chi \gtrsim {\rm mm}$$

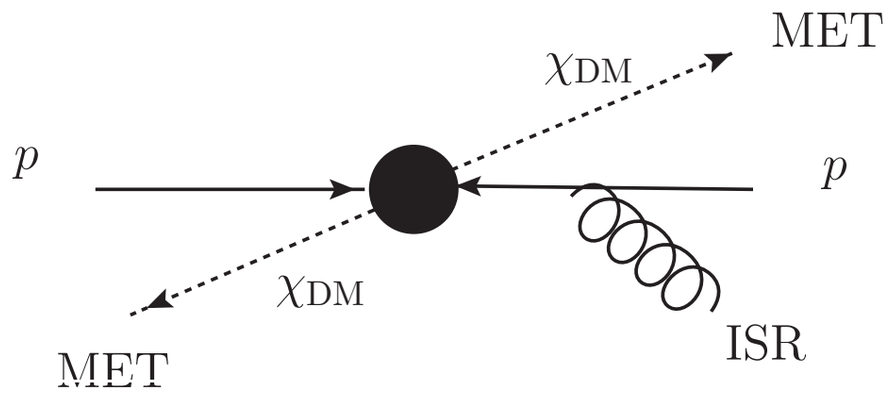
LHC tracking resolution!

- **Distinctive signal**: displaced decay vertex inside detectors

—not well-covered, low bkg search channel, rising interest!



Metastable WIMP baryon parent@LHC: displaced vertex



Stable WIMP DM@LHC: missing energy (analogy)

Simplified Model Approach for LHC Pheno

(**YC** and Shuve arxiv:1409.6729, JHEP)

- Classify production modes (analogy to DM search @LHC!)

- Classify decay modes (unlike DM search)

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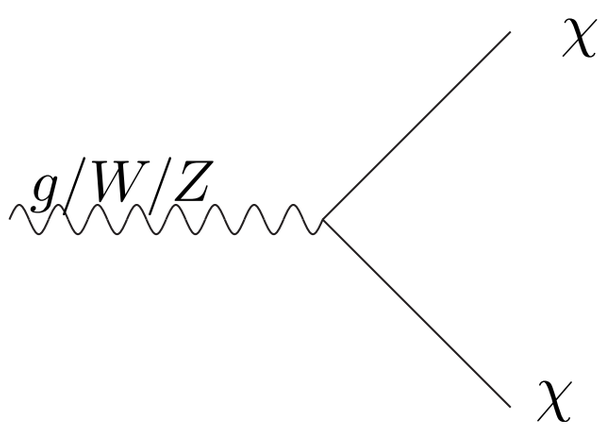
Charged under SM gauge interactions:

wino/gluino-like (state in interference loop)



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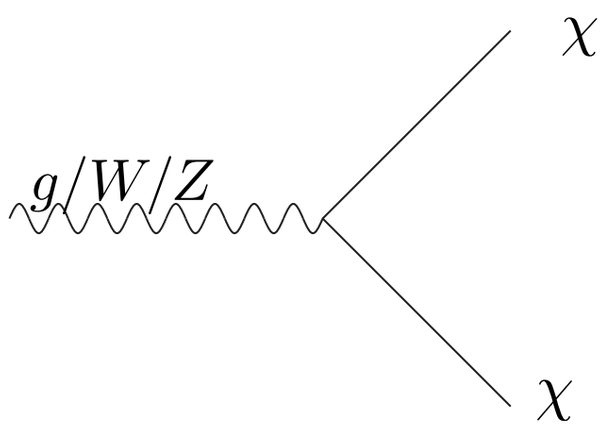
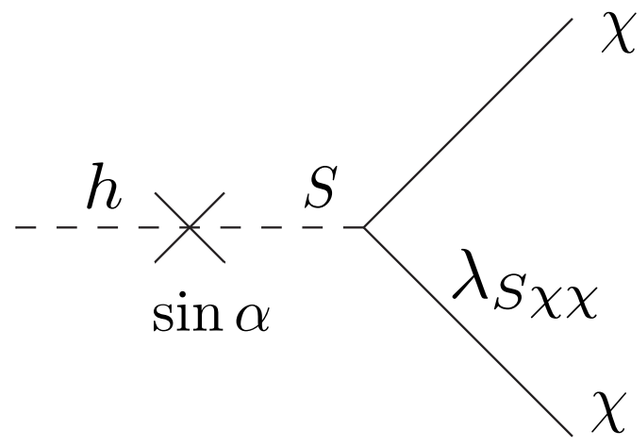


Higgs portal:

singlet-like (e.g. $M_\chi = 150$ GeV)



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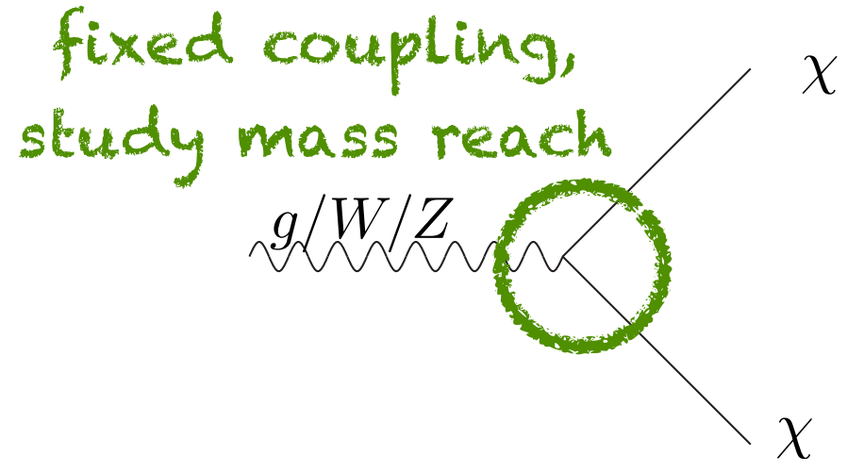

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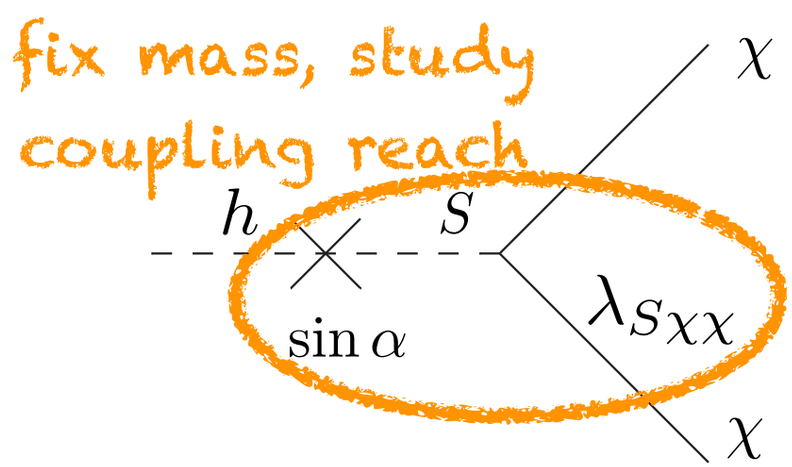

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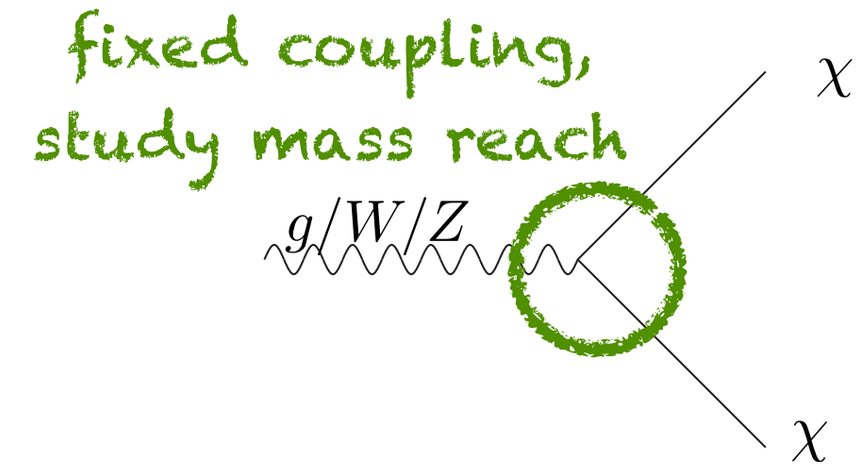

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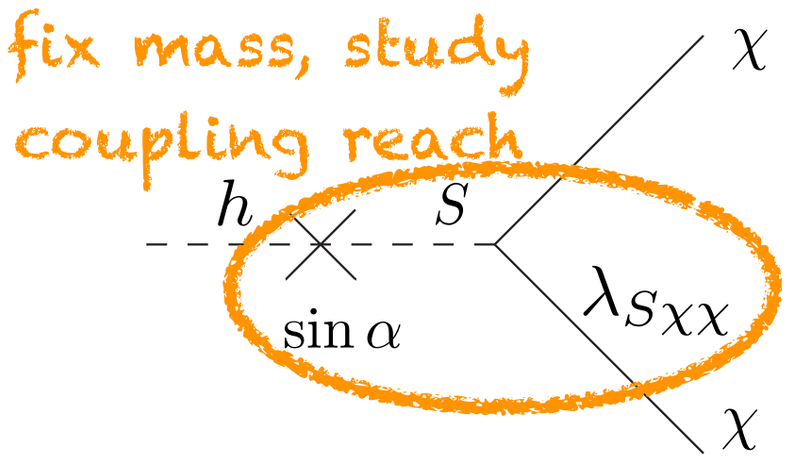

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Baryon number violating:

$$\chi \to u_i d_j d_k$$

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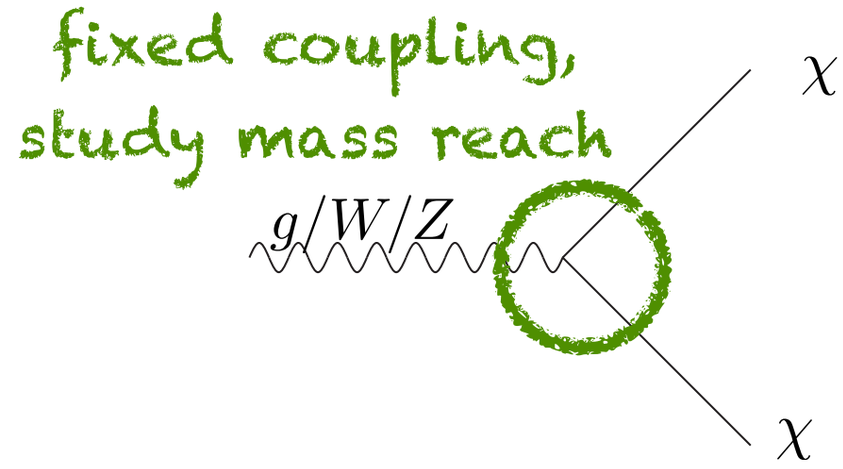

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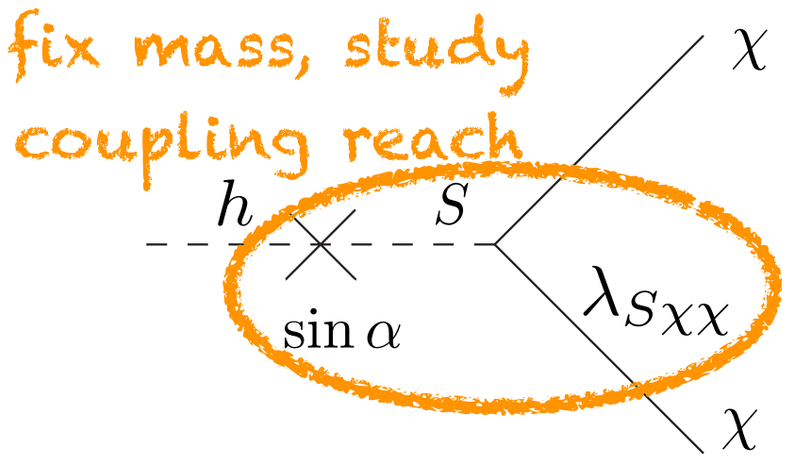

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Baryon number violating:

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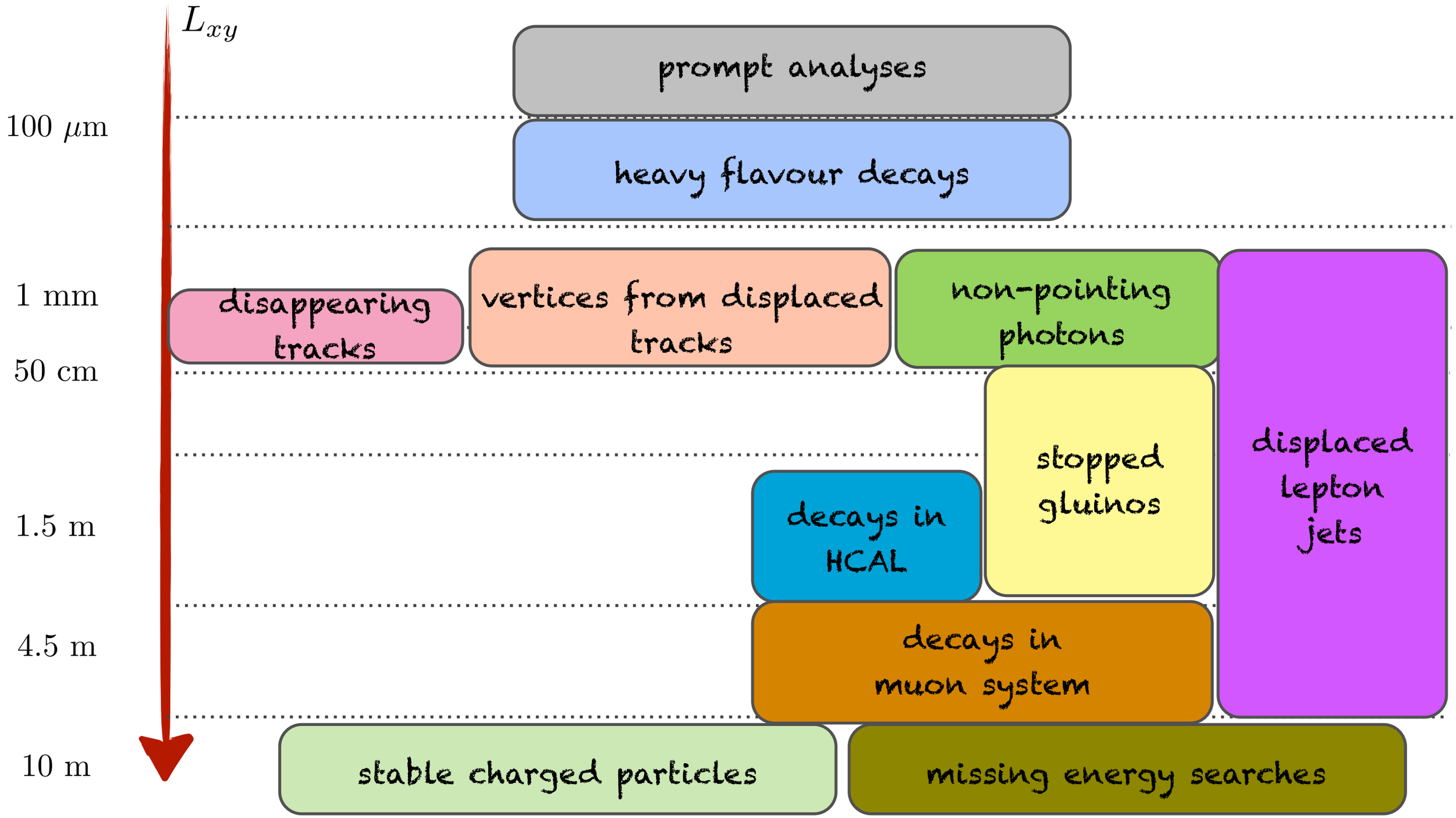
Lepton number violating:

$$\chi \to L_i Q_j \bar{d}_k$$
$$\chi \to L_i L_j \bar{E}_k$$

LHC DV Search Possibilities



New detector: Mathusla? (Chou, Curtin, Lubatti +others)

Recast Existing LHC Searches

- Focus on displaced decay in tracking volume

  Near lower bound $c\tau_\chi \gtrsim \mathrm{mm}$, better sensitivity to wide lifetime range, easier to model with theorists' tools!

  (decay in other parts of detector important too!)

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- Two concrete examples (light-flavour only):

<u>Baryon number violating</u>:

$$\chi \to 3q$$

displaced jets (all-hadronic)

CMS, arXiv:1411.6530

<u>Lepton number violating</u>:

$$\chi \to \ell + 2q$$

displaced muon + tracks

ATLAS-CONF-2013-092

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ATLAS-CONF-2013-092

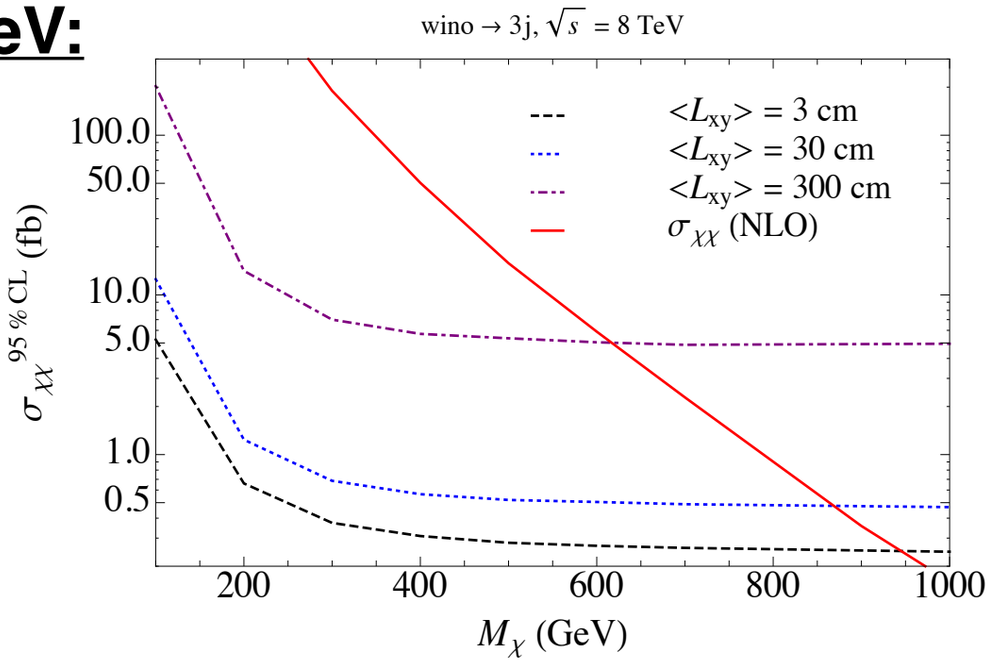
- **Goal of our analysis:**
  - What is the coverage for our simplified models based on benchmarks chosen by the collaborations?
  - What advice can we provide for general experimental improvement?

Fully hadronic displaced vertices

CMS displaced dijet, arXiv:1411.6530

wino

8 TeV:



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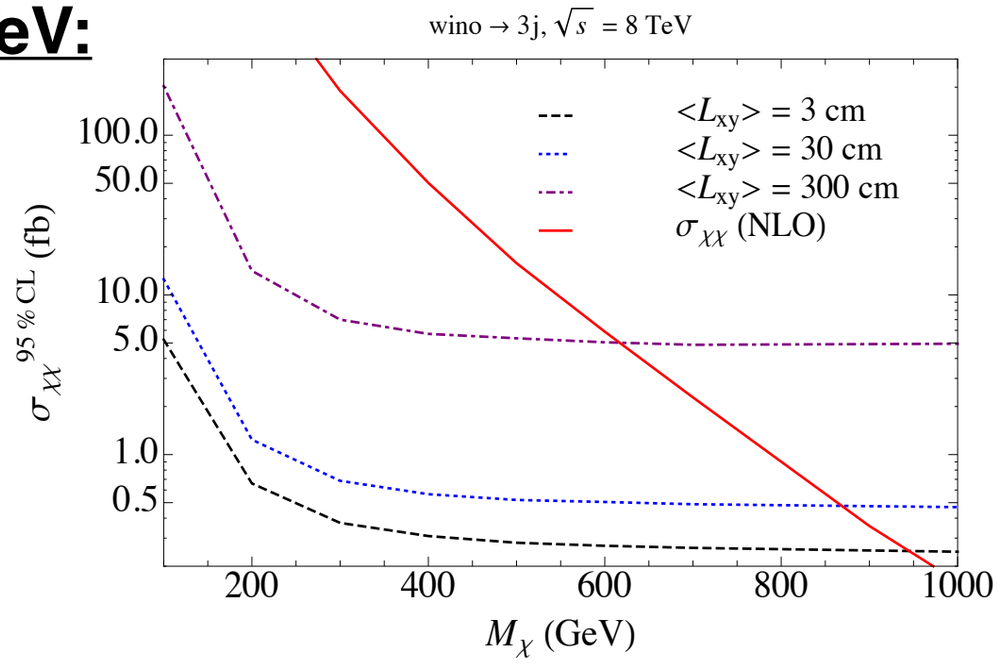

singlet-like (Higgs portal)

We studied a challenging case:
M_χ = 150 GeV, moderately off-shell!

No bound @ 8 TeV 20 fb^{-1}!

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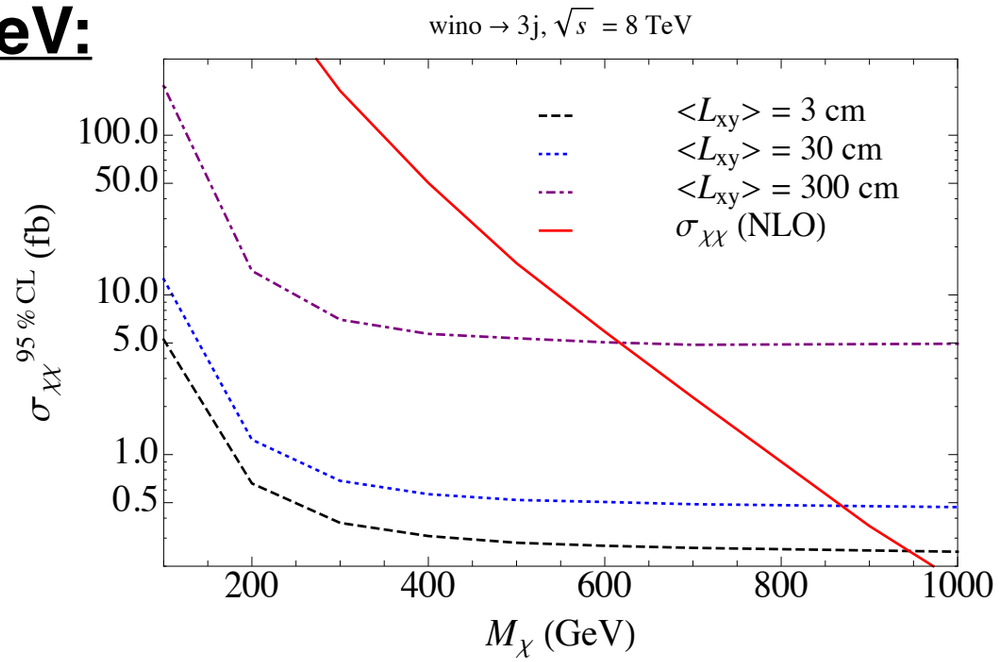
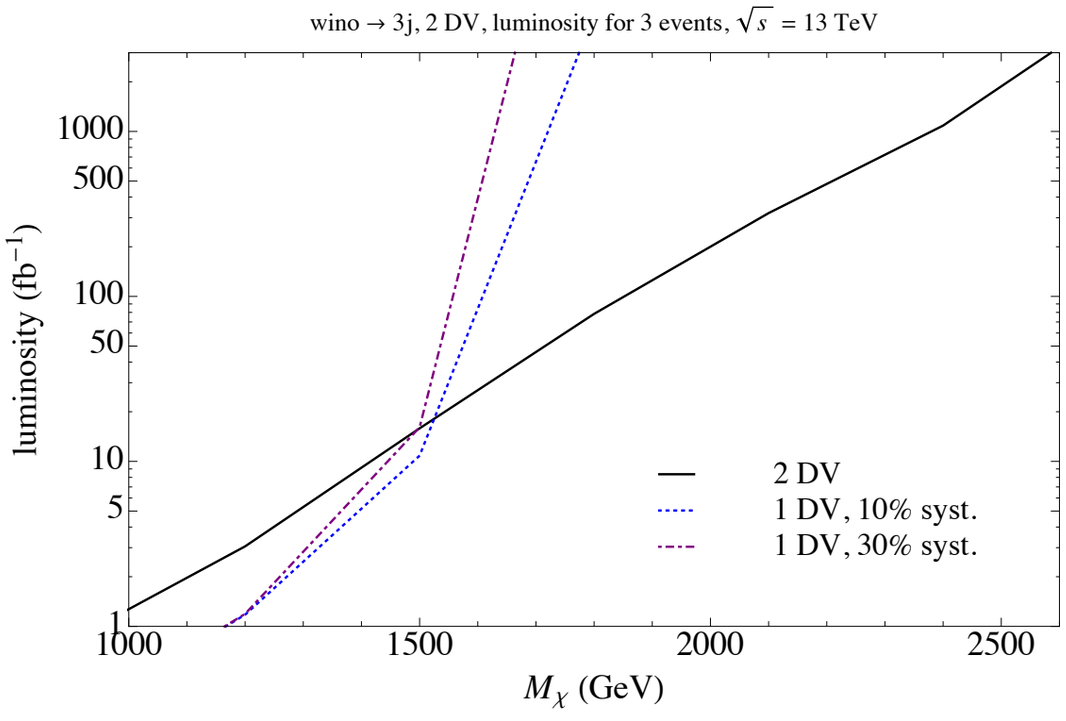


13 TeV:



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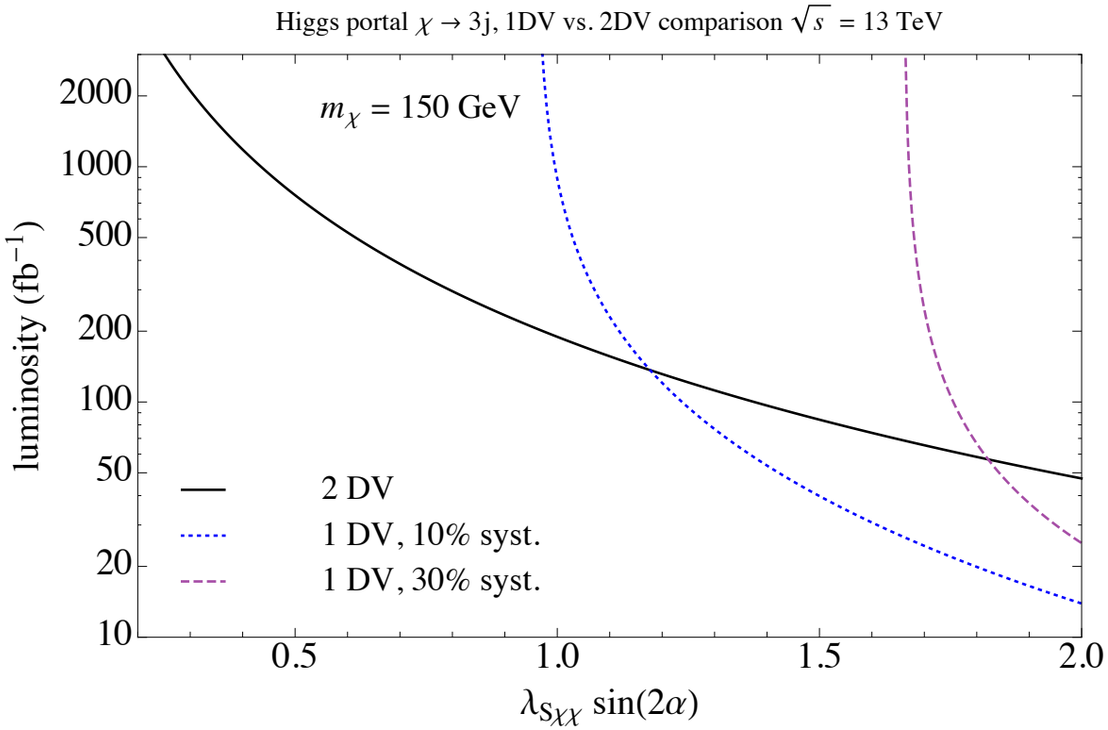
***L_{xy}* = 3 cm**



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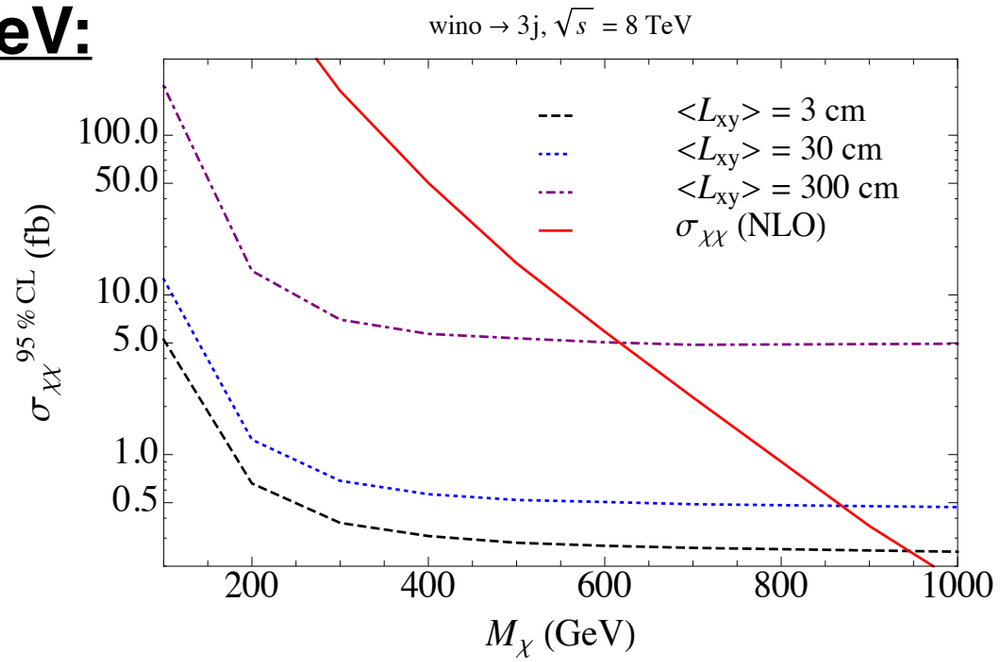

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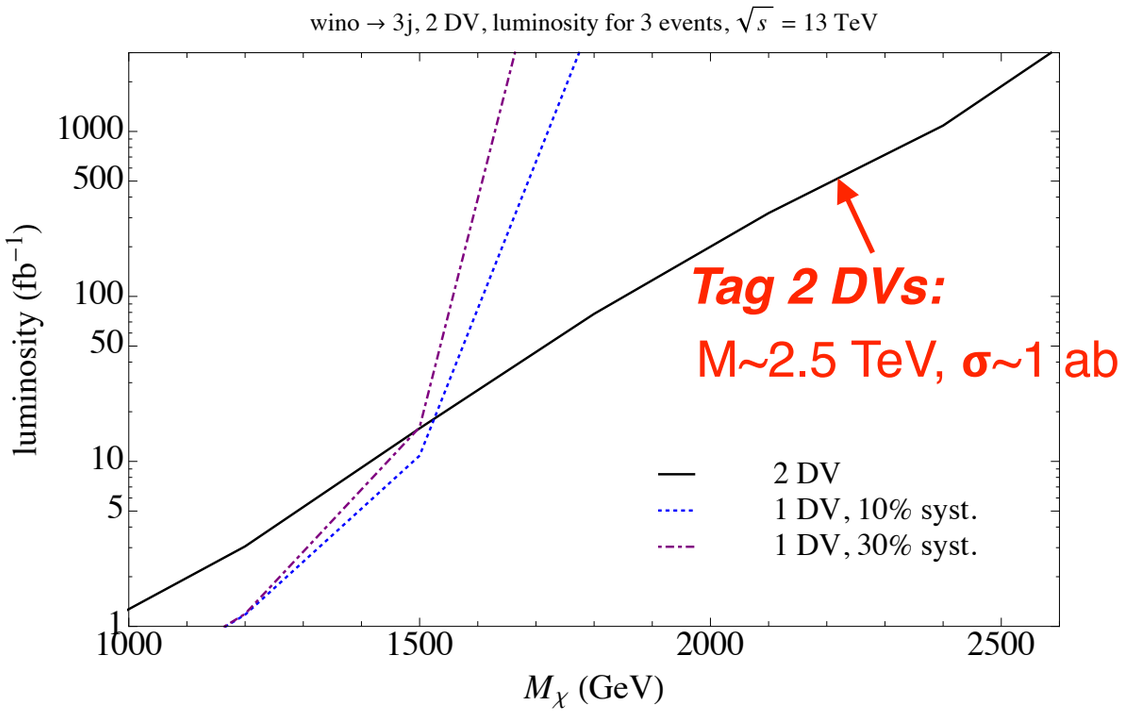

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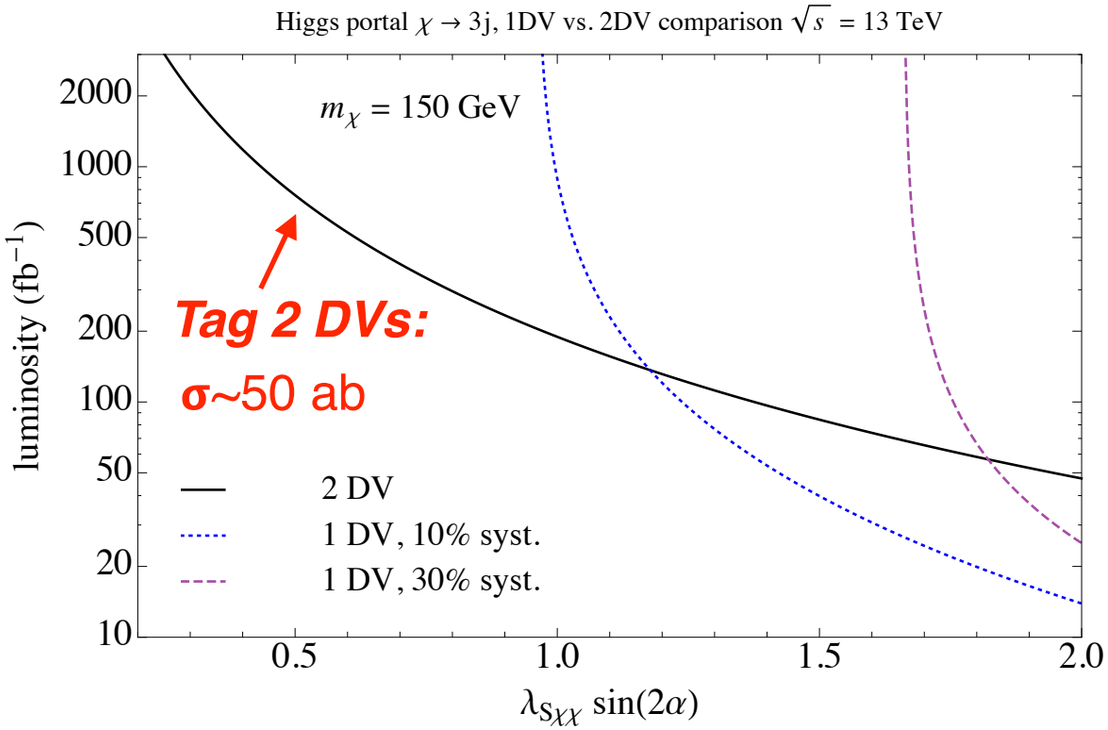
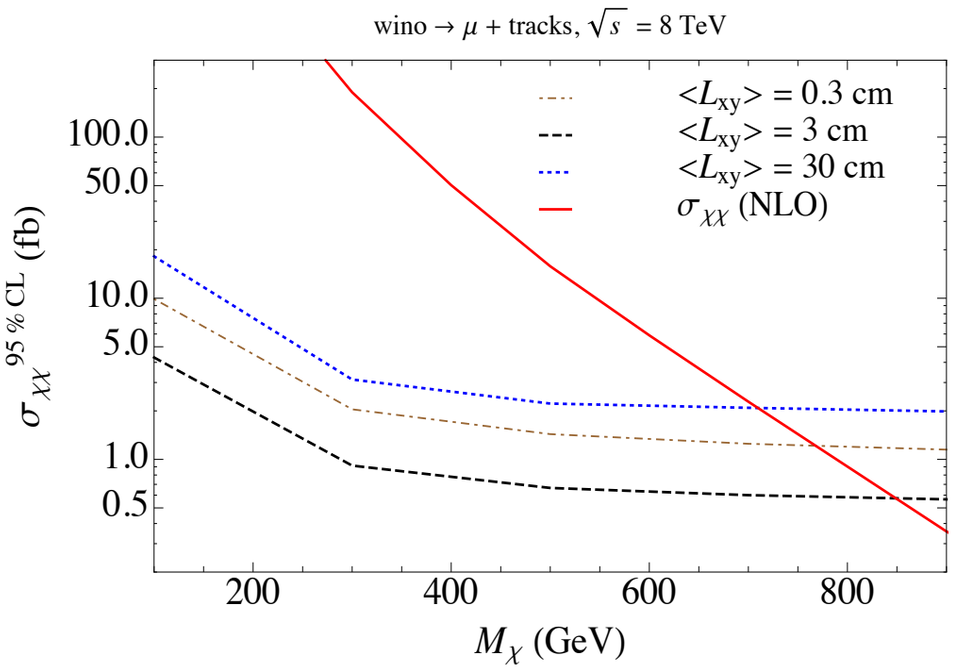


Displaced muon + Tracks

ATLAS-CONF-2013-092

wino

8 TeV

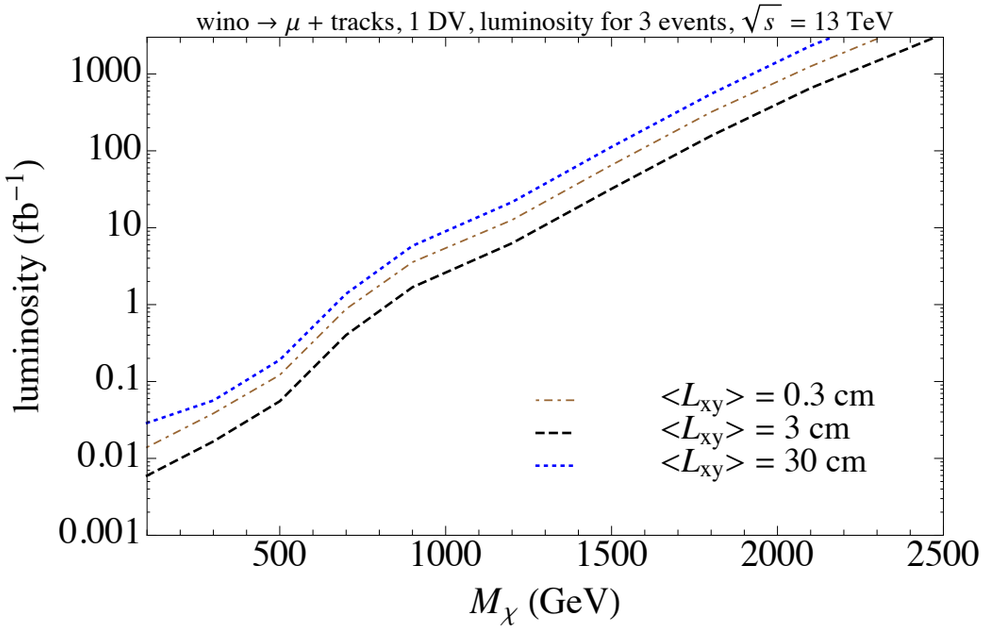


13 TeV:

Tag 1 DV

M~2.5 TeV

(lower bkg than all-hadronic)



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ATLAS-CONF-2013-092

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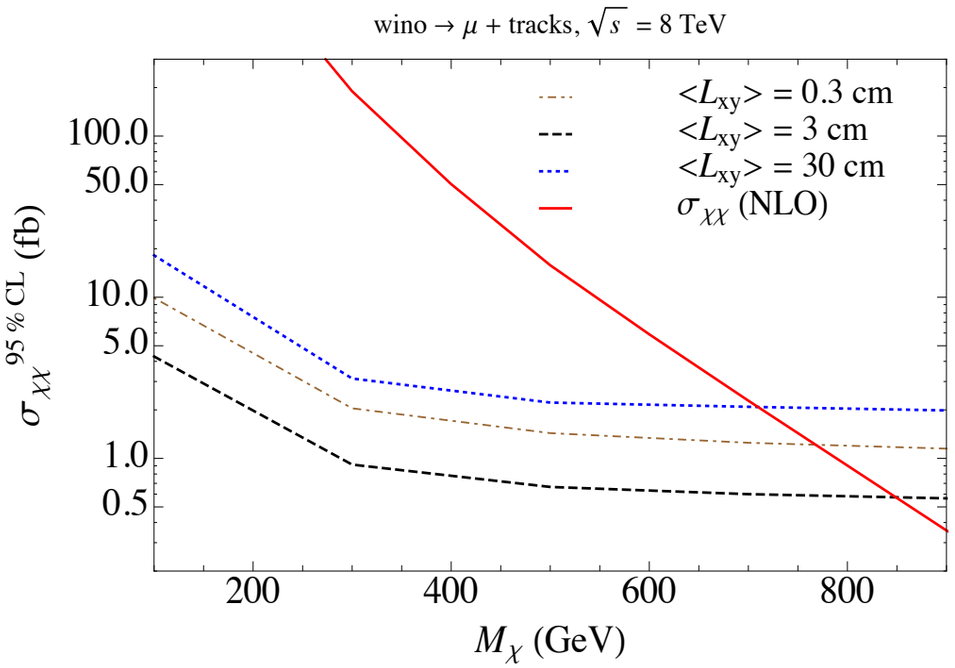

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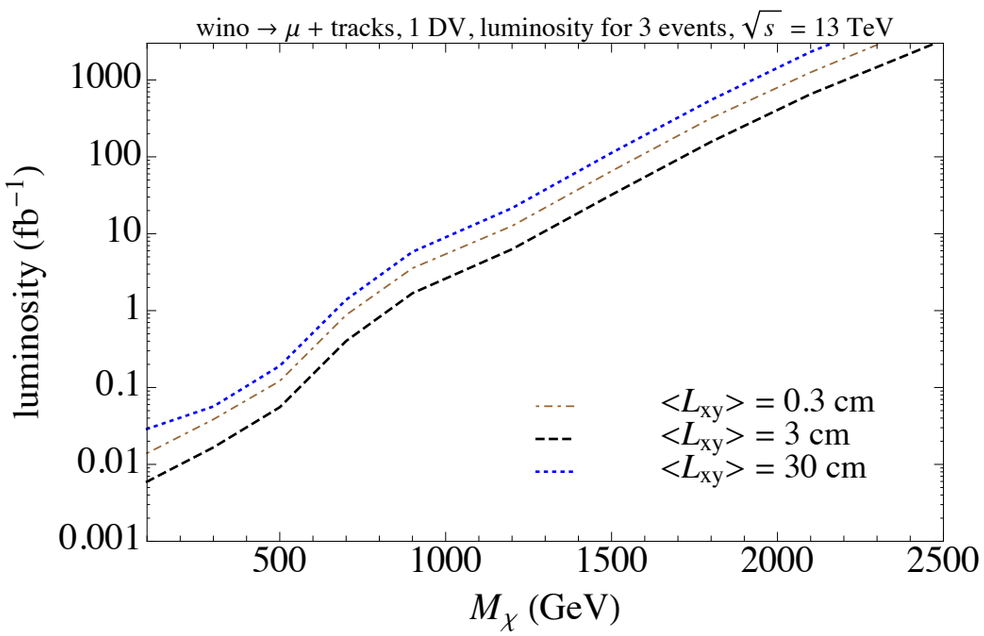

singlet (Higgs portal)

(singlet-like, $M_\chi = 150$ GeV)

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- 13 TeV: σ_S~50 ab for L_{xy}~1 cm

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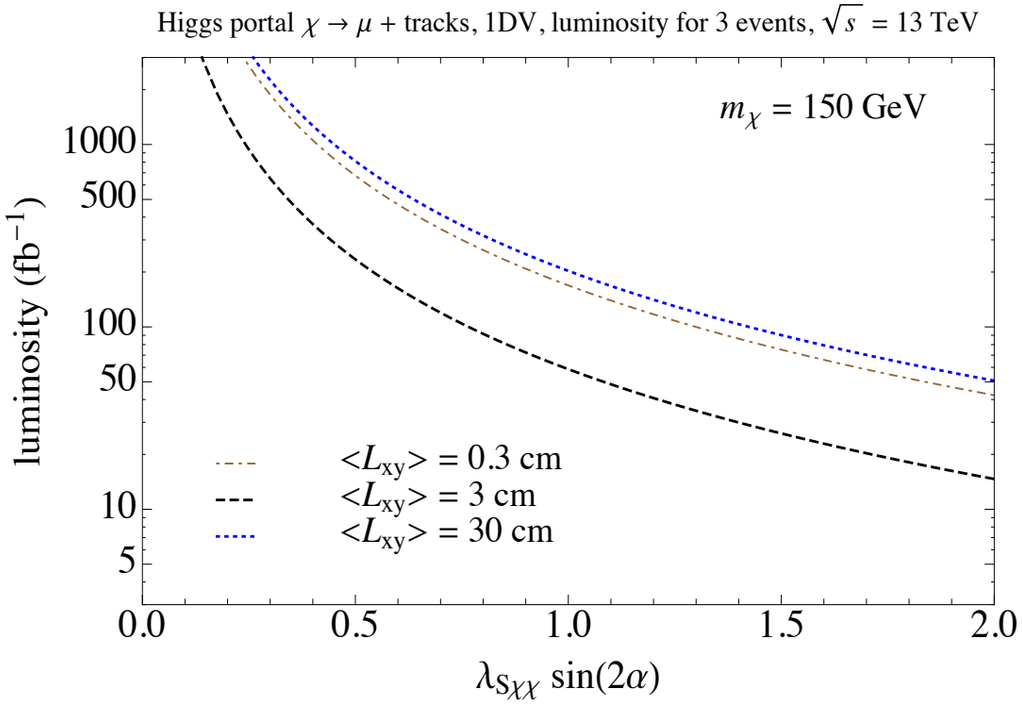

Summary/Outlook

- **Baryogenesis from metastable weak scale particle decay:**
  - A **robust cosmological motivation** for DV searches
  - Reproduce/study early universe BG @ LHC! (cf. WIMP DM search)
- **WIMP baryogenesis:** a motivated example, new mechanism addressing Ω_B (+) $\Omega_B \sim \Omega_{DM}$, natural embedding in SUSY

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- **Simplified models for LHC pheno:** signal generator for **general** DV searches *(cooperation with ATLAS displaced jets group, officially approved as a new benchmark for Run-2 analysis)*
- **Further pheno explorations:**
  - Other signal channels: diphoton resonance, multi-b/t events (YC and Okui, Yunesi arxiv:1605.08736, JHEP)
  - Challenging case for DV search: Light WIMP ($\lesssim$*100 GeV*), longer lifetime, hadronic decay (sphaleron turned off)… ?