Beyond the WIMP Miracle

Shufang Su • U. of Arizona

Pitt-PACC LDM workshop

Nov 16, 2011

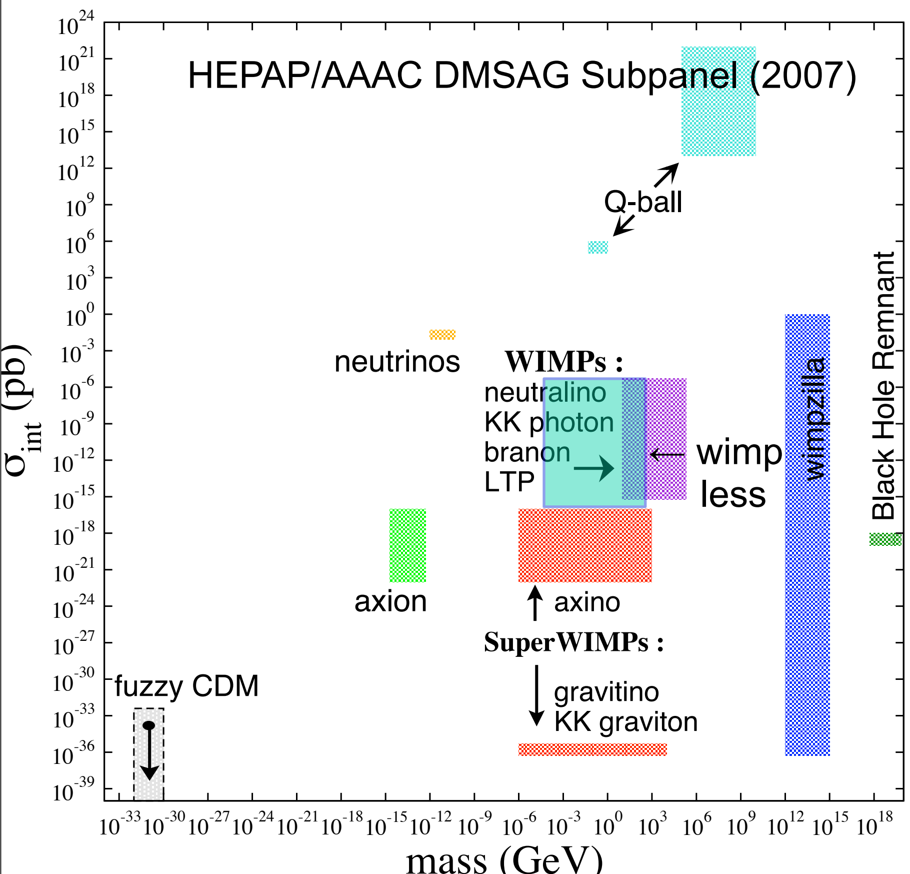
Beyond the WIMP Miracle

- WIMP miracle
- WIMPless
  - ➡ general framework
  - ➡ light dark matter
  - ➡ collider signature
- superWIMP

Zoo of dark matter

mass and interaction strengths span many, many orders of magnitude

Some Dark Matter Candidate Particles



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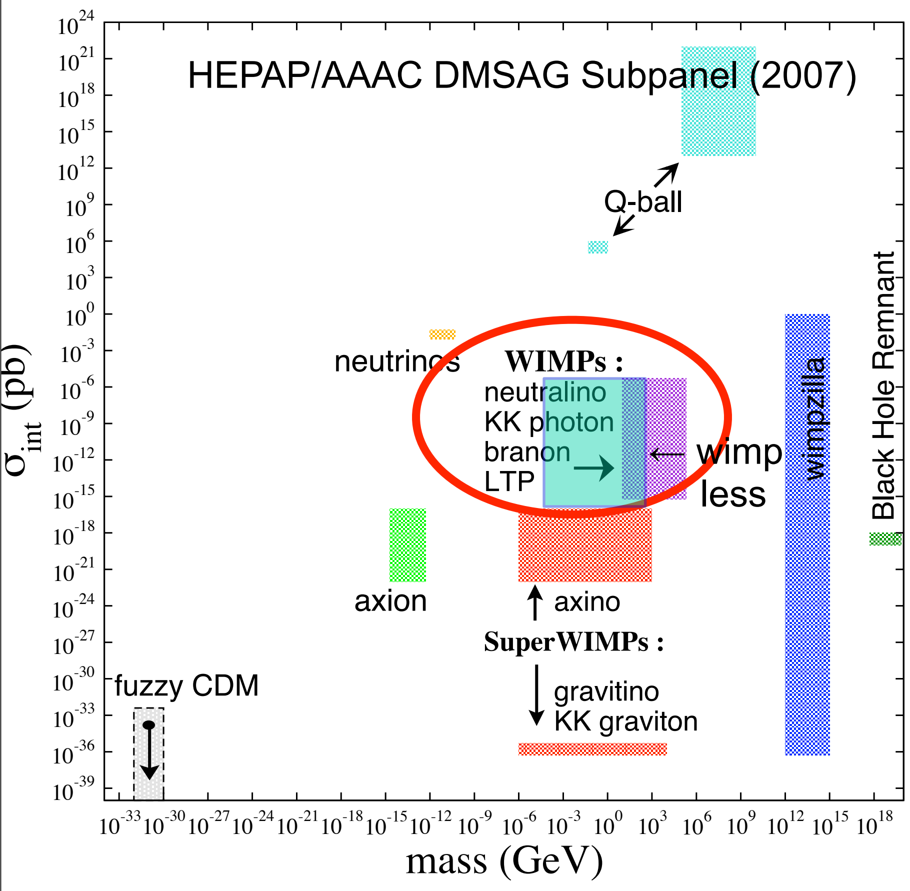

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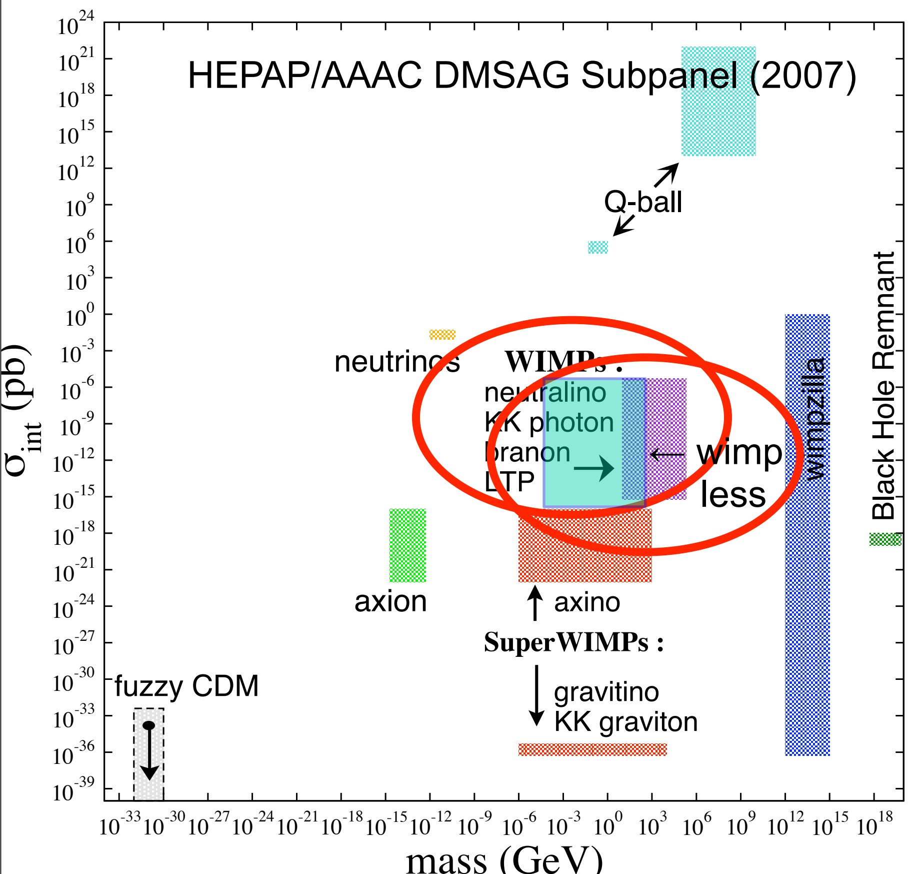

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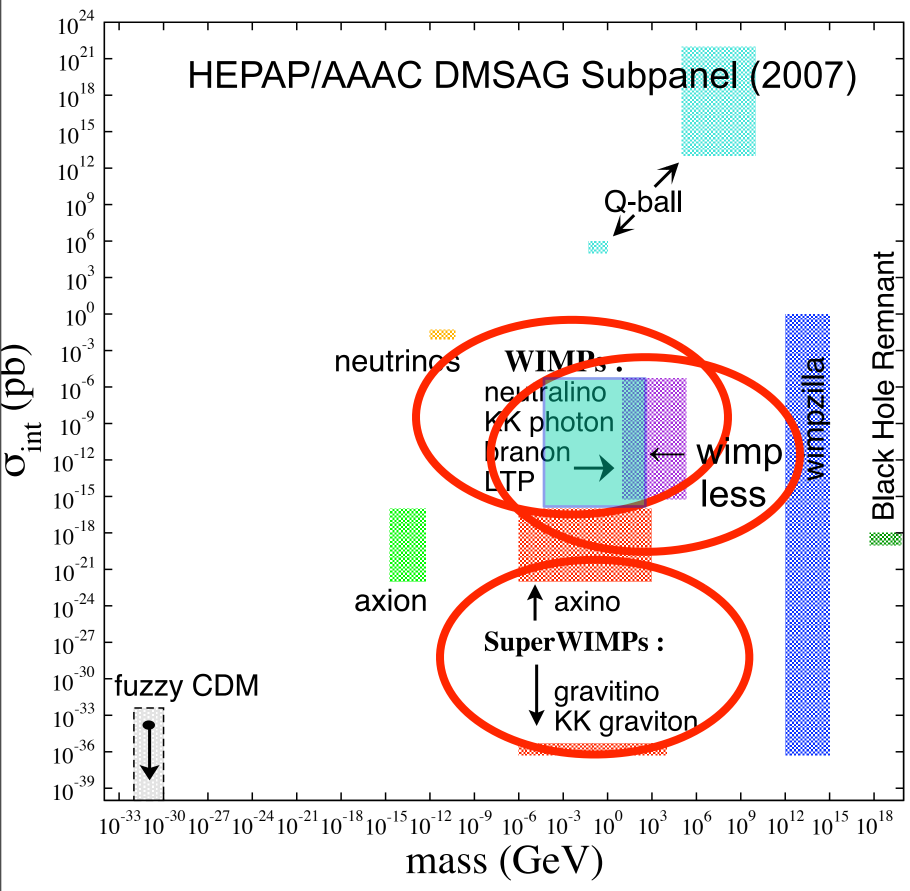

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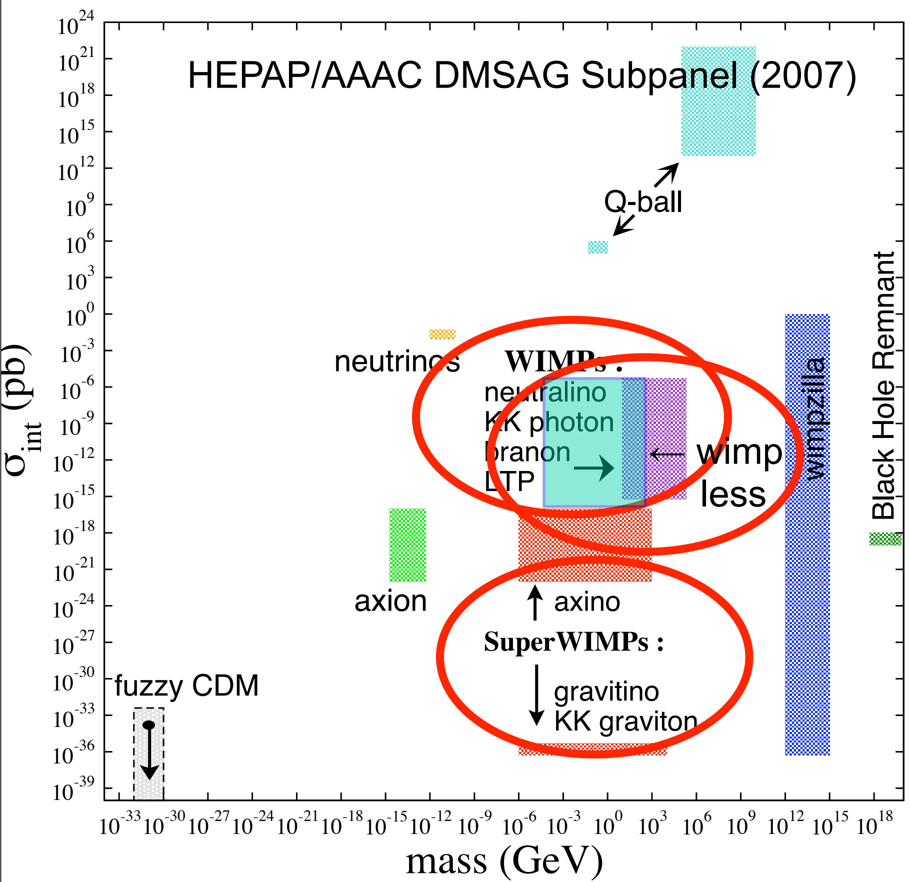

- appear in particle physics models motivated independently by attempts to solve EWSB
- relic density are determined by m_{pl} and m_{weak}
  - naturally around the observed value
  - no need to introduce and adjust new energy scale

WIMP

Weak Interacting Massive Particle

WIMP

- $m_{WIMP} \sim m_{weak}$
- g_{weak}^2

WIMP miracle

WIMP: Weak Interacting Massive Particle

- $m_{WIMP} \sim m_{weak}$
- $\sigma_{an} \sim \alpha_{weak}^2 \, m_{weak}^{-2}$

$$\left.\begin{array}{l} \Omega h^2 \sim \dfrac{2.6 \times 10^{-10}\,\text{GeV}^{-2}}{\langle \sigma_A v \rangle} \\ \langle \sigma_A v \rangle \sim \dfrac{\alpha^2}{m_{weak}^2} 0.1 \sim 10^{-9}\,\text{GeV}^{-2} \end{array}\right\} \Rightarrow \Omega\, h^2 \sim 0.3$$

naturally around the observed value

- WIMP appears in many BSM scenarios
  - lightest supersymmetric particles in SUSY models
  - lightest KK particles in extra dimension models
  - ...

WIMP miracle

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WIMP

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Is it necessary to have both?

WIMP

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Is it necessary to have both?

WIMPless

WIMPless miracle

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

- only fixes one combination of dark matter mass and coupling
- $m_X/g_X^2 \sim m_{weak}/g_{weak}^2$, $\Omega h^2 \sim 0.3$

could have $m_X \neq m_{weak}$ as long as the relation holds

WIMPless DM

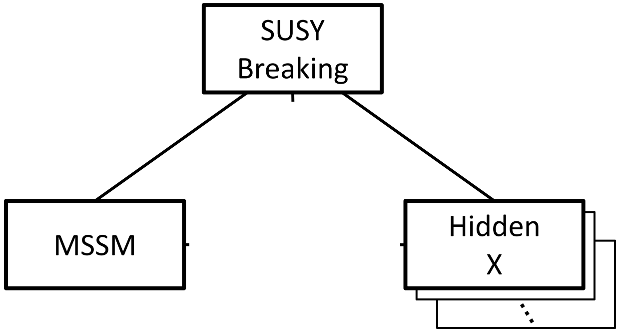
J.L. Feng and J. Kumar, PRL 101, 231301 (2008)
J.L. Feng, H. Tu and H. Yu, JCAP 0810, 043 (2008)
Feng, Shadmi, PRD 83, 095011 (2011)
Feng, Rentala, Surujon, 1108.4689

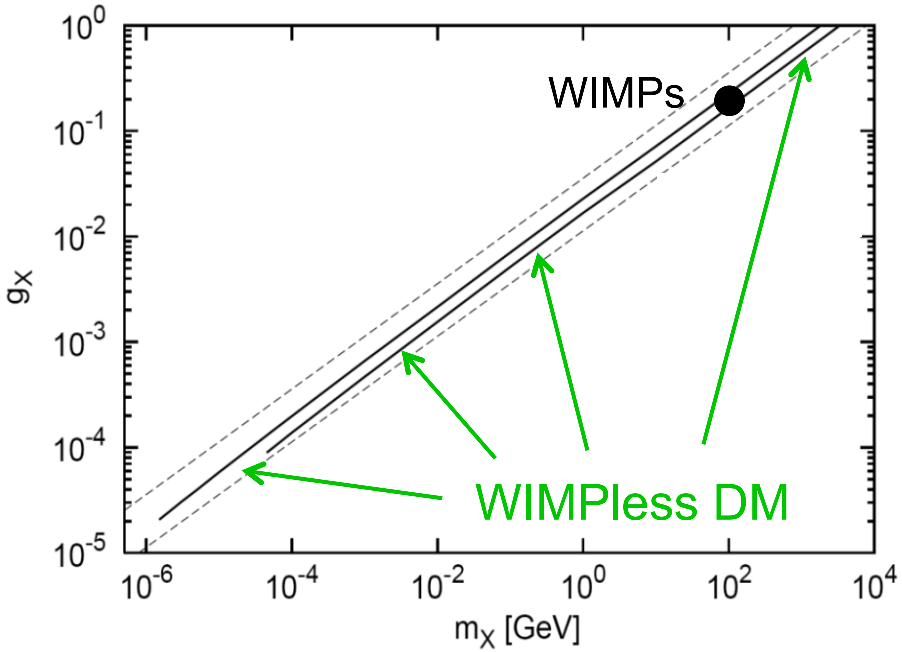
- dark matter: no SM gauge interactions, not WIMP
- naturally obtain right relic density: similar to WIMP

WIMPless miracle

J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

- Dark matter is hidden no SM interactions
- DM sector has its own particle content, mass m_X, coupling g_X
- Connected to SUSY breaking sector





$$\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}$$

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

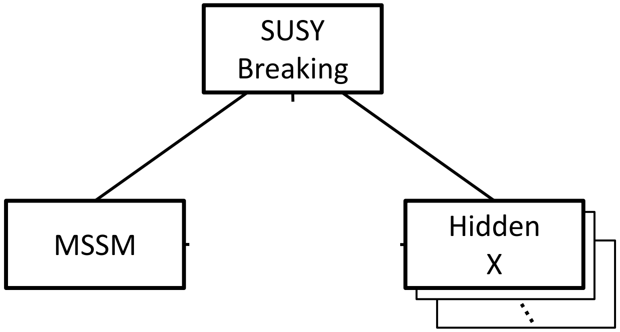
right relic density !
(irrespective of its mass)

S. Su

WIMPless: not hidden

If no direct coupling to SM:

- interact only through gravity
- impact on structure formation
- no direct/indirect/collider signals



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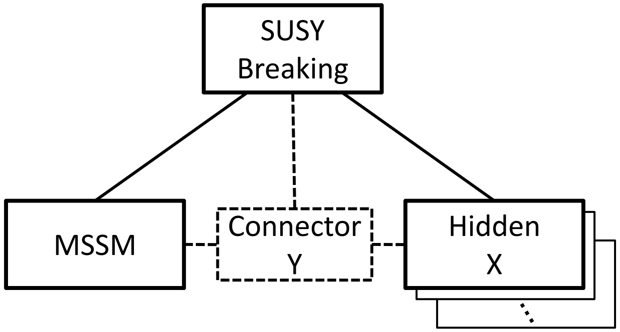

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$m_Y \sim \max(m_{weak}, m_X)$ interaction λ XYf

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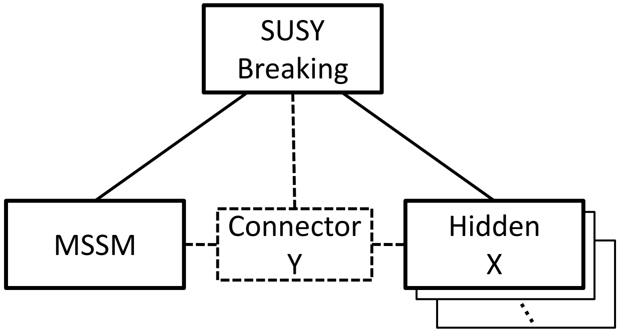

$m_Y \sim \max(m_{weak}, m_X)$ interaction λ XYf

- indirect detection
  $XX \to ff,\ YY$
- direct detection
  $Xf \to Xf$
- collider: 4th generation fermions

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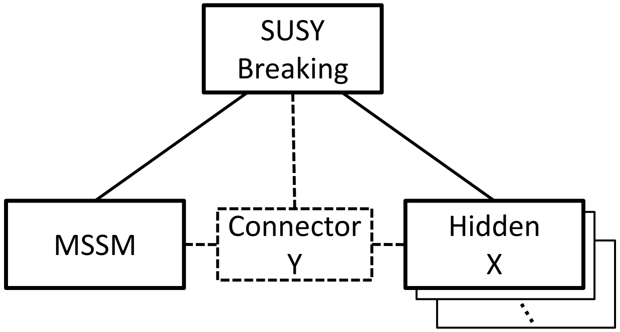

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open new possibility for

- ◉ DM model parameters
- ◉ new experimental search windows

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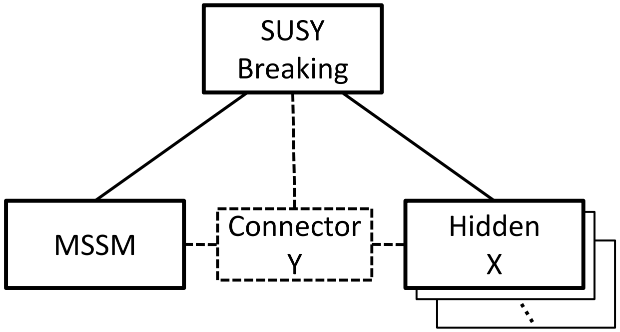

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light dark matter

open new possibility for
- ◉ DM model parameters
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- ◉ indirect detection $XX \rightarrow ff, YY$
- ◉ direct detection $Xf \rightarrow Xf$
- ◉ collider: 4th generation fermions

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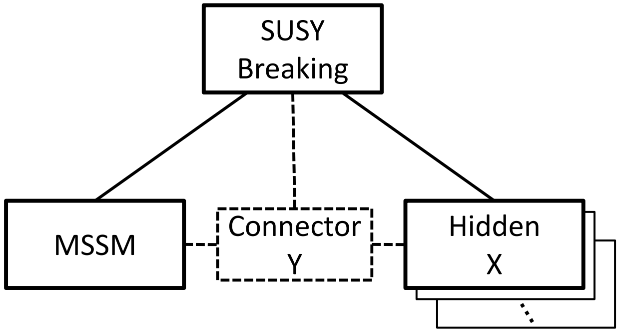

$m_Y \sim \max(m_{weak}, m_X)$

interaction λ XYf

light dark matter

- indirect detection
  XX → ff, YY
- direct detection
  Xf → Xf
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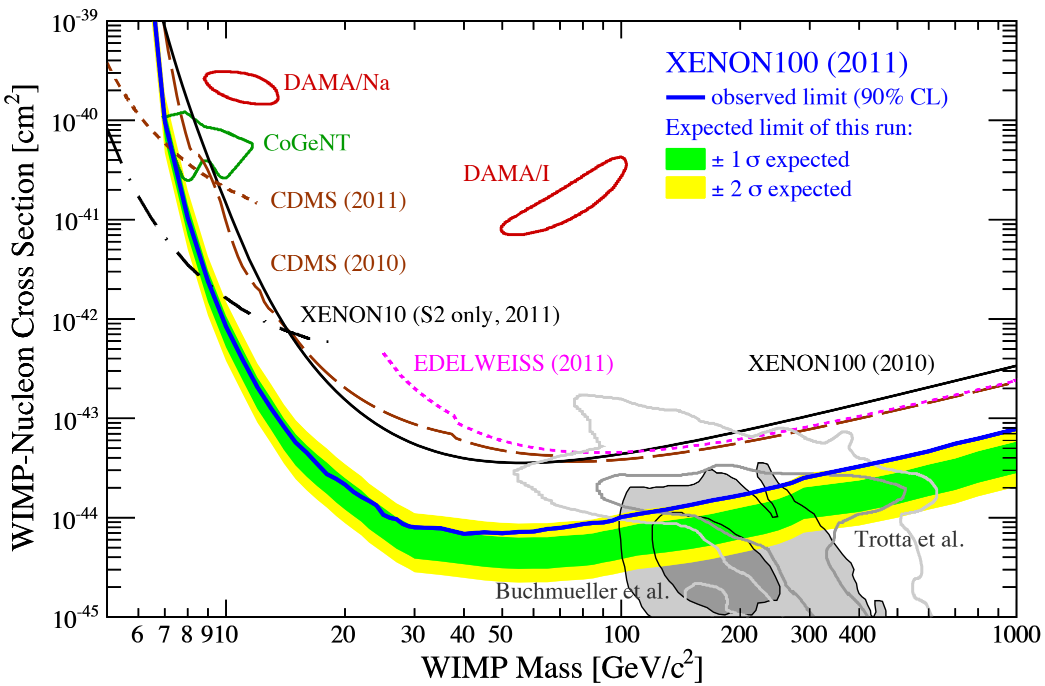
open new possibility for

- DM model parameters
- new experimental search windows

provide a framework that

- guarantee DM relic density
- allow freedom in DM-SM interaction

Light dark matter



XENON 100: 1104.2549

- small mass, large σ_{SI}
- DAMA vs. CoGeNT ?
- reconcile with CDMS/XENON?

Light dark matter

light DM with large σ_{SI}

- not generic in typical WIMP

  σ_{SI} : chirality flip, proportional to Yukawa coupling

A. Bottino, F. Donato, N. Fornengo and S. Scopel, PRD 68, 043506 (2003); PRD 77, 015002 (2008); PRD 78, 083520 (2008).

- can be easily accommodated in WIMPless model with connector Y

J.L. Feng, J. Kumar and L.E. Strigari, PLB 670, 37 (2008)

$$W = \sum_i (\lambda_q^i X Y_{q_L} q_L^i + \lambda_u^i X Y_{u_R} u_R^i + \lambda_d^i X Y_{d_R} d_R^i)$$

$$\begin{array}{lcl} Y_{qL} & : & (3, 2, \frac{1}{6}) \\ Y_{uR} & : & (3, 1, \frac{2}{3}) \\ Y_{dR} & : & (3, 1, -\frac{1}{3}) \quad . \end{array}$$

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not chirality opposite chirality of SM quark

Y_{qL} : $(3, 2, \frac{1}{6})$

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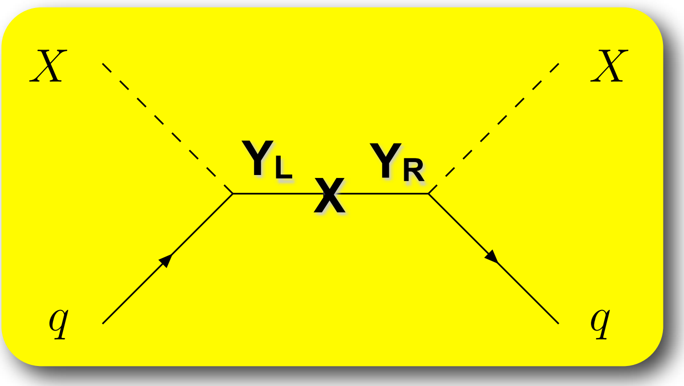
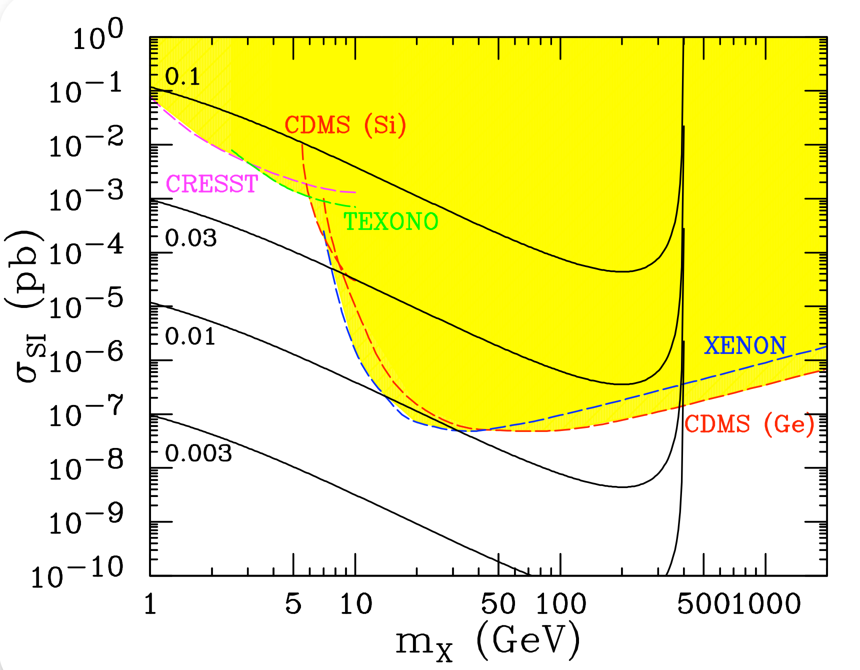
Exotic mirror quarks

Connector couple with first two gen.

- first two generations,
  tree level scattering $\Rightarrow \lambda \sim 0.03$

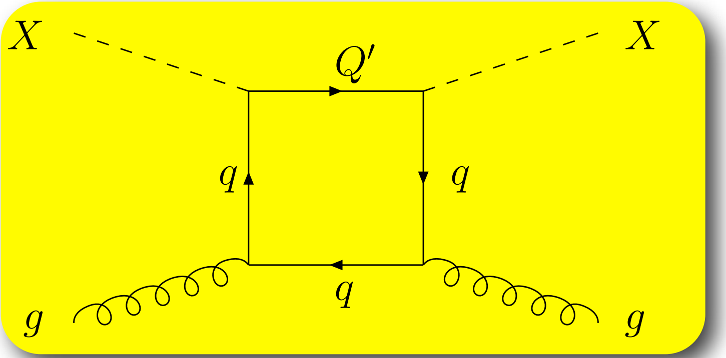


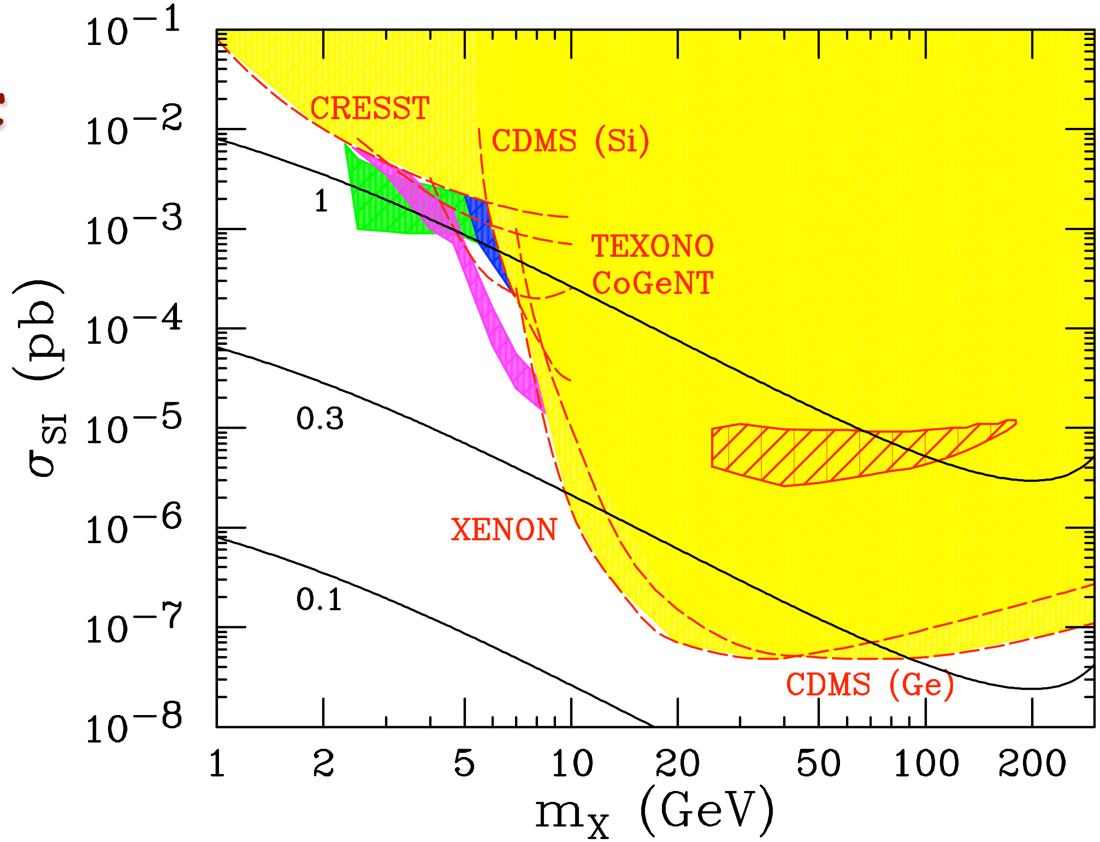


J.L. Feng and J. Kumar, PRL 101, 231301 (2008)

Connector couple with third gen.

- third generation
  - loop level scattering, λ ~ 0.3-1, more natural
  - less constrained by FCNC





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J.L. Feng, J. Kumar and L.E. Strigari, PLB 670, 37 (2008)

Isospin violating dark matter

- DM scattering off a nucleus: coherent

Giuliano (2005);
Chang, Liu, Pierce, Weiner, Yavin (2010)
Feng, Kumar, Marfatia, Sanford (2011)

$$\sigma_A \sim (f_p Z + f_n (A-Z))^2$$

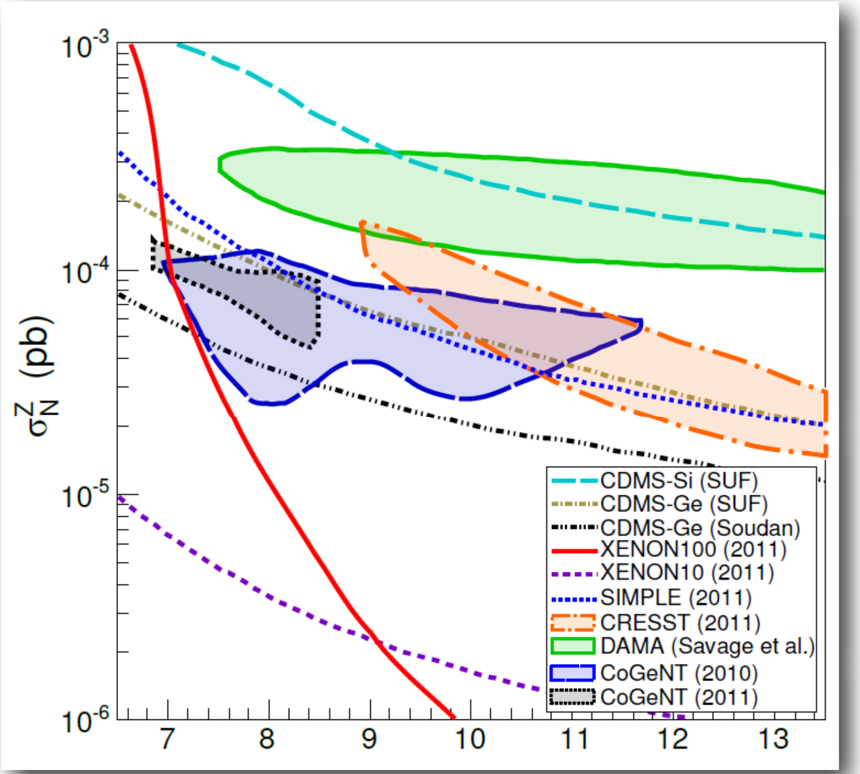
- usual assumptions: $f_p = f_n$
  - $\sigma_A \sim (f_p A)^2$
  - results for various target nuclei in (m, σ_p) plane
  - A^2 scaling

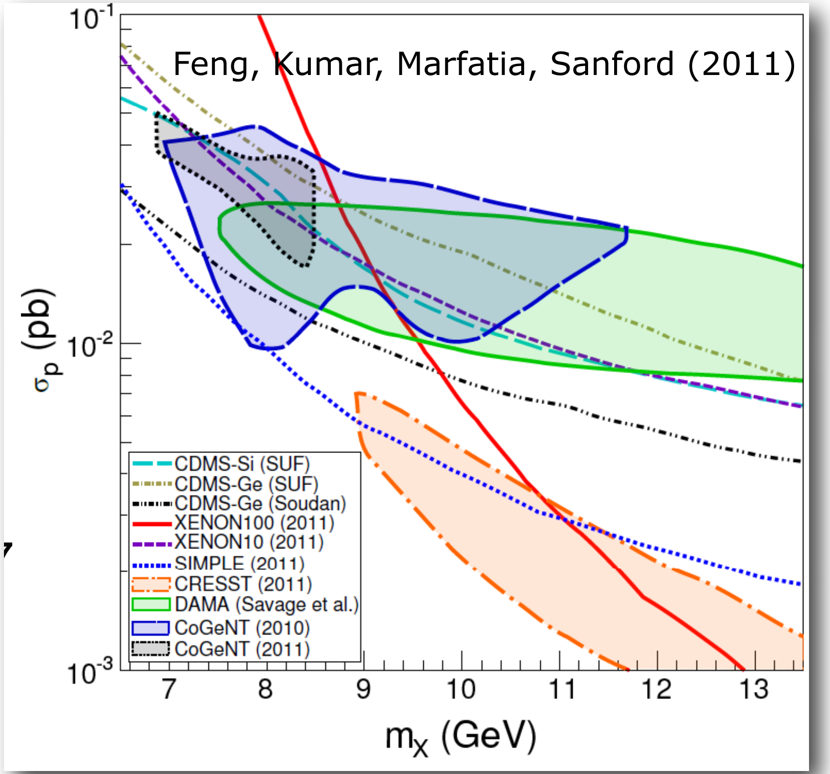
- isospin violation $f_p \neq f_n$
  - could appear in many BSM
  - decouple one exp with $f_n/f_p=-Z/(A-Z)$
  - not exact cancellation due to isotopes

$$\sigma_N^Z = \sigma_p \frac{\sum_{i=iso.} \eta_i \mu_{A_i}^2 \left[Z + \left(f_n/f_p\right)\left(A_i - Z\right)\right]^2}{\sum_i \eta_i \mu_{A_i}^2 A_i^2}$$

Isospin violating dark matter

$f_n / f_p = 1$ $\qquad$ $f_n / f_p = -0.7$

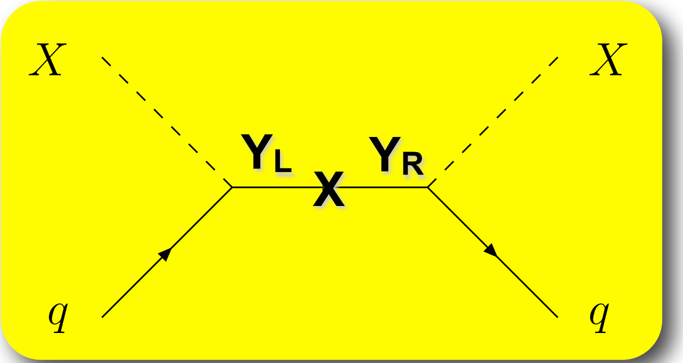




- hard to fit all three signals
- CDMS, CoGeNT both Germanium based
- SIMPLE gets tighter

Realization of IVDM in WIMPless

- at nucleon level: $f_p \neq f_n$
- at quark level: $W = \sum_i (\lambda_q^i X Y_{q_L} q_L^i + \lambda_u^i X Y_{u_R} u_R^i + \lambda_d^i X Y_{d_R} d_R^i)$



- SI operators $\mathcal{O}_i = \lambda_q^i \lambda_u^i X X \bar{u}^i u^i / m_Y + \lambda_q^i \lambda_d^i X X \bar{d}^i d^i / m_Y$
- isospin violating $f_{p,n}/M_*^2 = \sum_i (\lambda_q^i \lambda_u^i B_{u^i}^{p,n} + \lambda_q^i \lambda_d^i B_{d^i}^{p,n}) / (\sqrt{\pi} m_X m_Y)$

$f_n/f_p \sim -0.7$ → $\lambda_u^1 \simeq -1.08\, \lambda_d^1, \qquad 0.013 \lesssim \lambda_q^1 \lambda_d^1 \lesssim 0.024$

Collider constraints

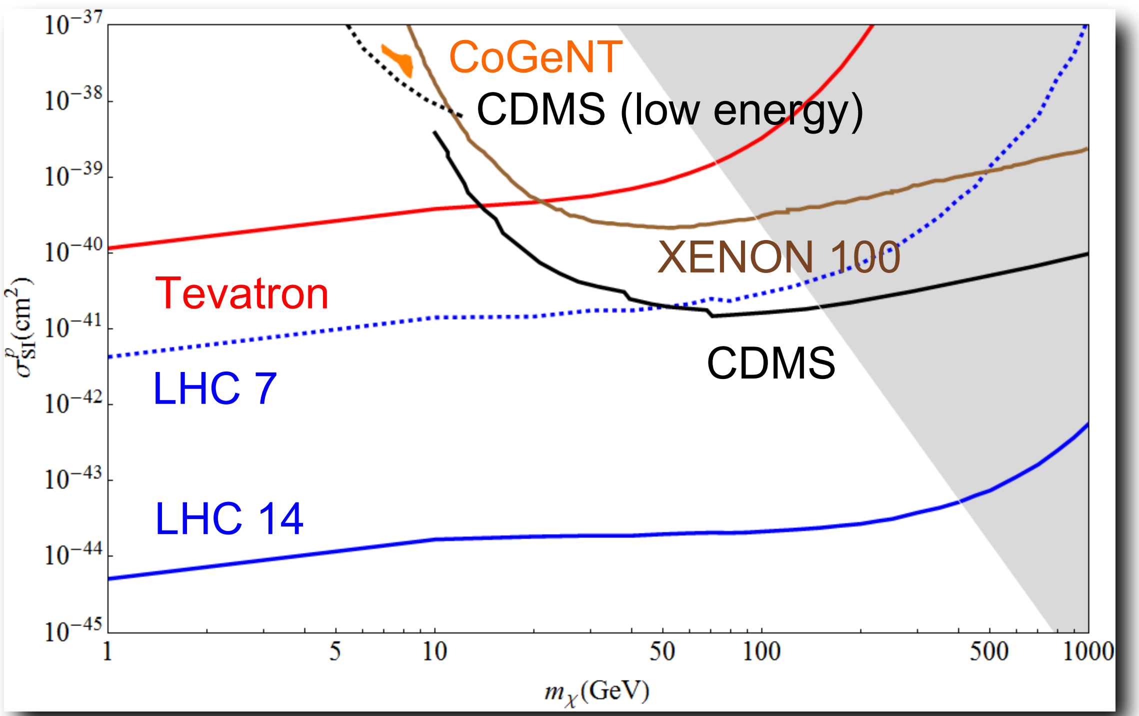
$$\mathcal{O}_i = \lambda_q^i \lambda_u^i X X \bar{u}^i u^i / m_Y + \lambda_q^i \lambda_d^i X X \bar{d}^i d^i / m_Y$$

- **monojet @ Tevatron: $\lambda_q \lambda_{u,d} < 1$, two orders of magnitude too weak**

Feng, Kumar, Marfatia, Sanford, 1102.4331

- **jets+MET @ Tevatron and LHC, 1 fb^{-1}: tension with IVDM**

Rajaramam, Shepherd, Tait, Wijangco, 1108.1196



- **X: fermion (vs. scalar)**
- **minimal flavor violation**

SU(2) breaking term ~ m_q

Collider constraints

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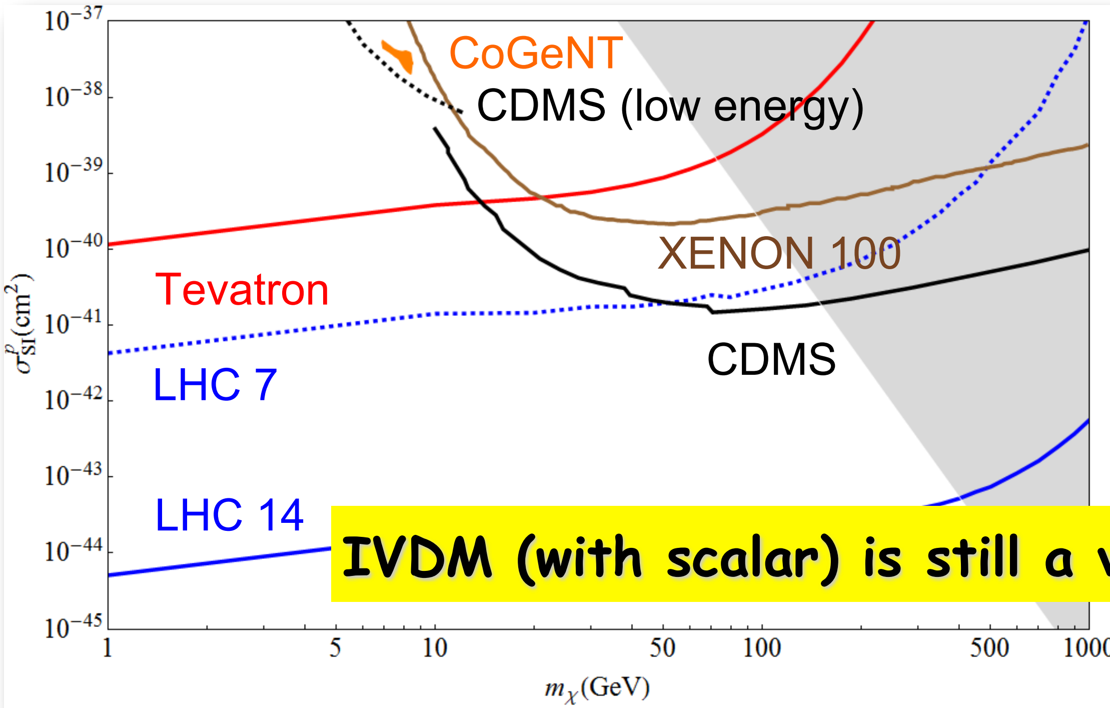

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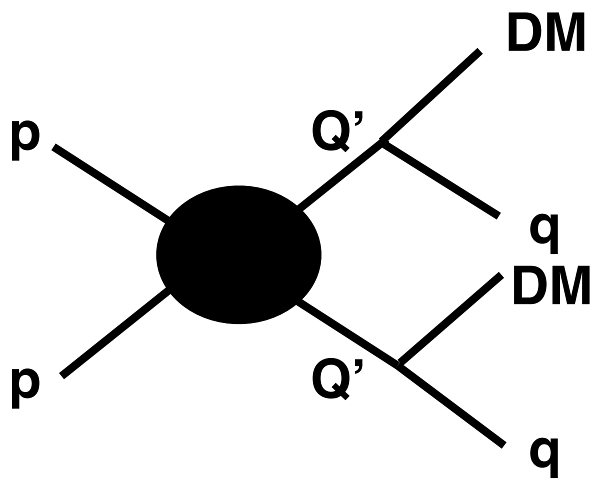
SU(2) breaking term ~ m_q

IVDM (with scalar) is still a viable solution ...

Collider signature: exotic quarks

Y particle appears as exotic mirror quarks Q'



Collider Signal (4th gen)

T'T'→ttXX, B'B' →bbXX

J. Alwall, J.L. Feng, J. Kumar, SS
1002.3366; 1107.2919.

- differ from SUSY searches: cascade decay
- differ from usual 4th generation quark T' → Wb, B' → Wt

Collider Signature: exotic quarks

Collider Signal: T'T'→ttXX, B'B' →bbXX

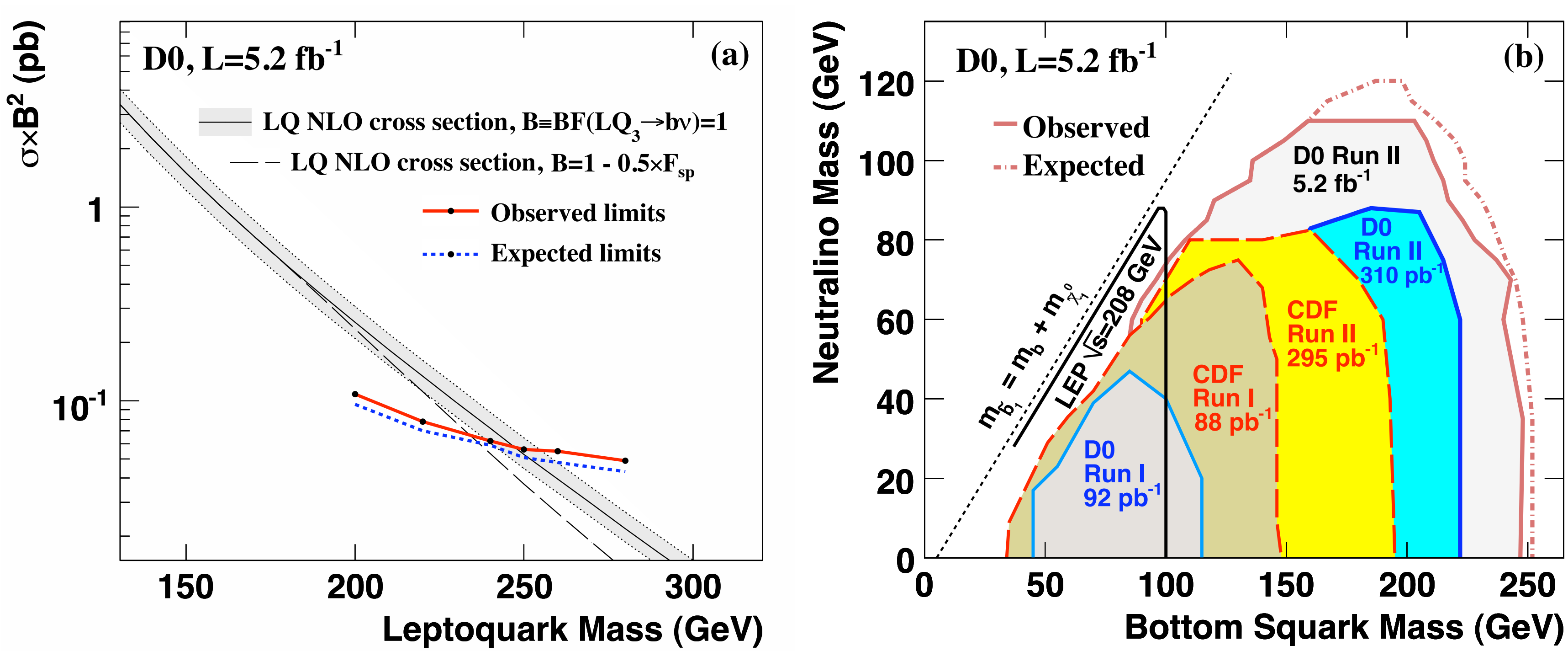
- Connection to solution for Hierarchy problem
  - need top partner
  - the lighter, the more natural
  - decay straight to invisible particles
  - bottom partner
- appears in a general set of new physics scenarios
  - light stop/sbottom
  - asymmetric dark matter — B. Dutta and J. Kumar, arXiv: 1012.1341
  - little Higgs with T-parity — H.C. Cheng and I. Low, JHEP 0408, 061 (2004)
  - baryon and lepton number as gauge symmetry — P. Fileviez Perez and M. B. Wise, arXiv: 1002.1754
  - ...

relevant for re-examine of naturalness based on LHC data, light stop/sbottom signatures.

Constraints

- perturbativity constraints: $m_{Q'} = y_{Q'}\, v$, $m_{Q'} \leq 600$ GeV (if through Yukawa)
- precision electroweak data: $|m_{T'}-m_{B'}| \sim 50$ GeV (for SU(2) doublet)
- direct searches limits

$B'B' \to bbXX$, similar to sbottom pair production with



V. M. Abazov et al. [D0 Collaboration], 1005.2222

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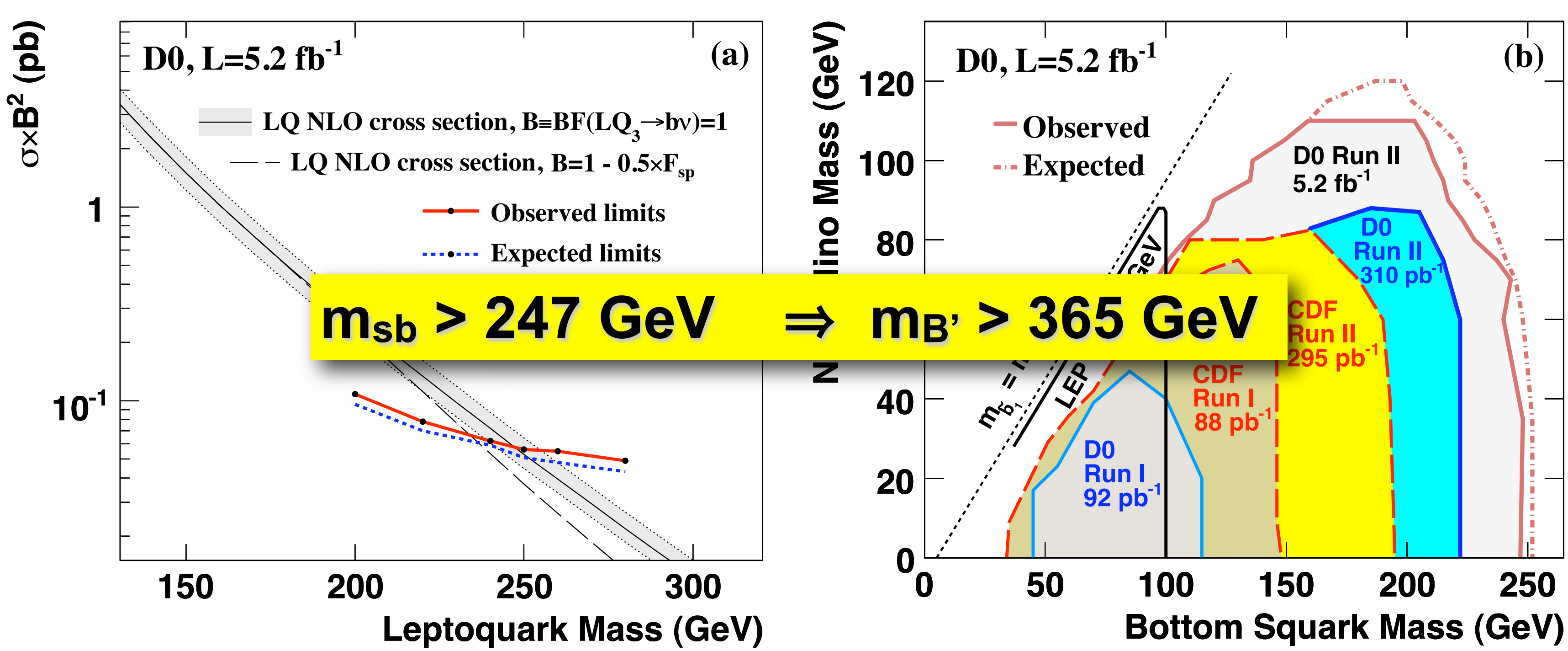

$m_{sb} > 247$ GeV $\Rightarrow$ $m_{B'} > 365$ GeV

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V. M. Abazov et al. [D0 Collaboration], 1005.2222

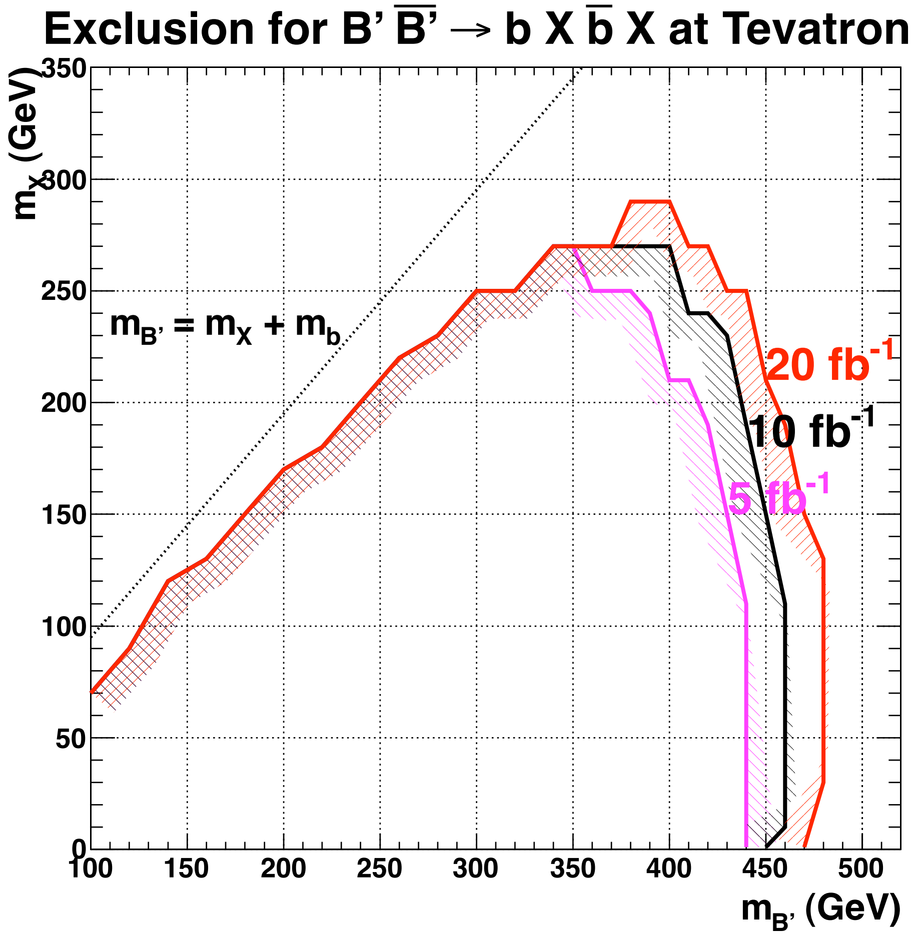
B′: Tevatron Reach

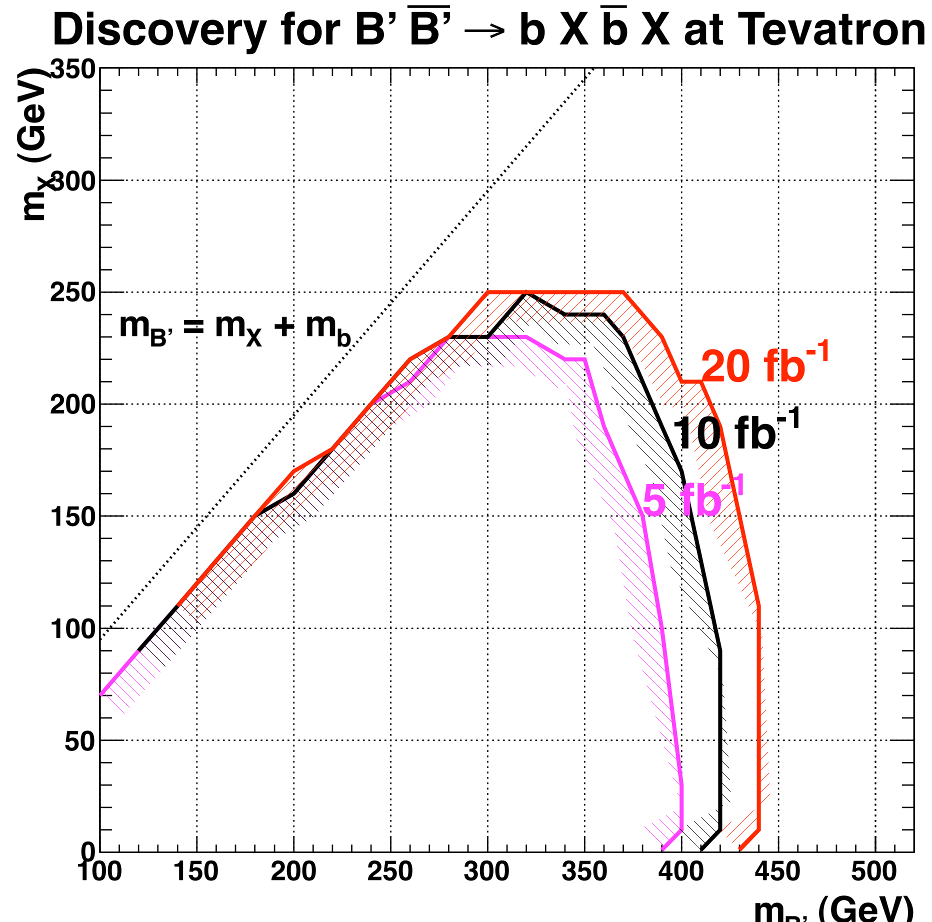
J. Alwall, J.L. Feng, J. Kumar, SS 1107.2919.

Signal: B'B' →bbXX

Bg: W(lv)jj, Z(vv) jj,WZ, ttbar, single top.

- optimal cuts (after precuts)
- S/B > 0.1, more than 2 events
- Poisson statistics





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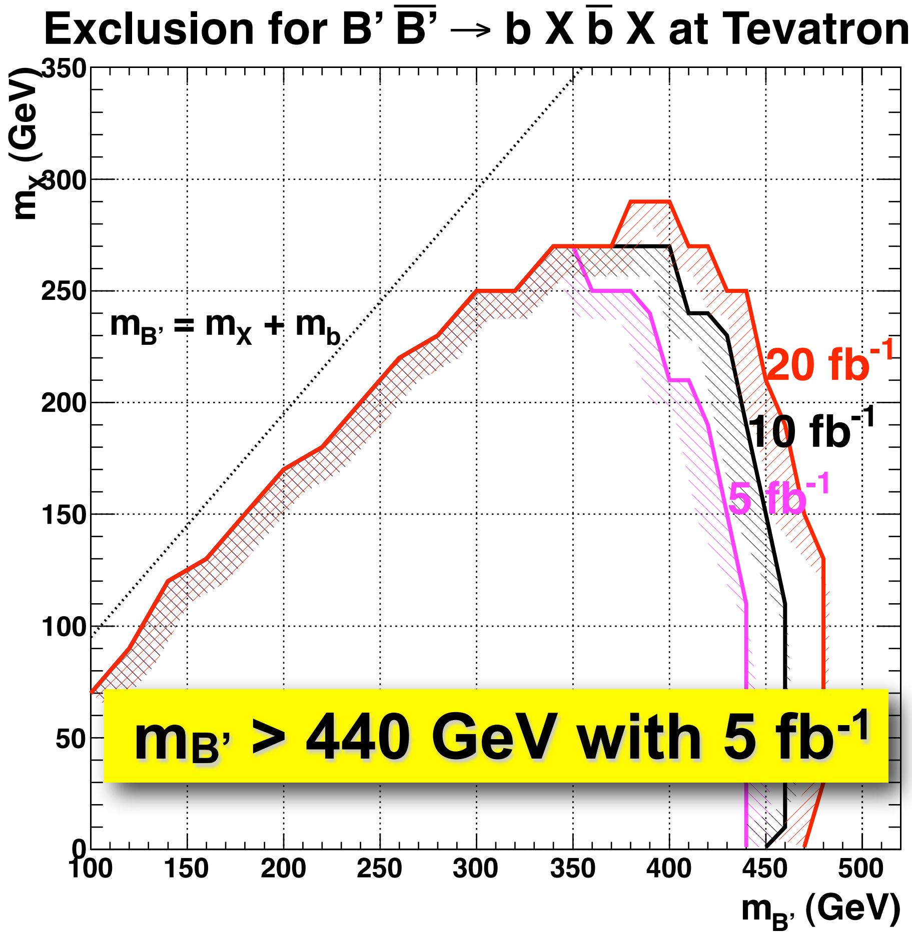

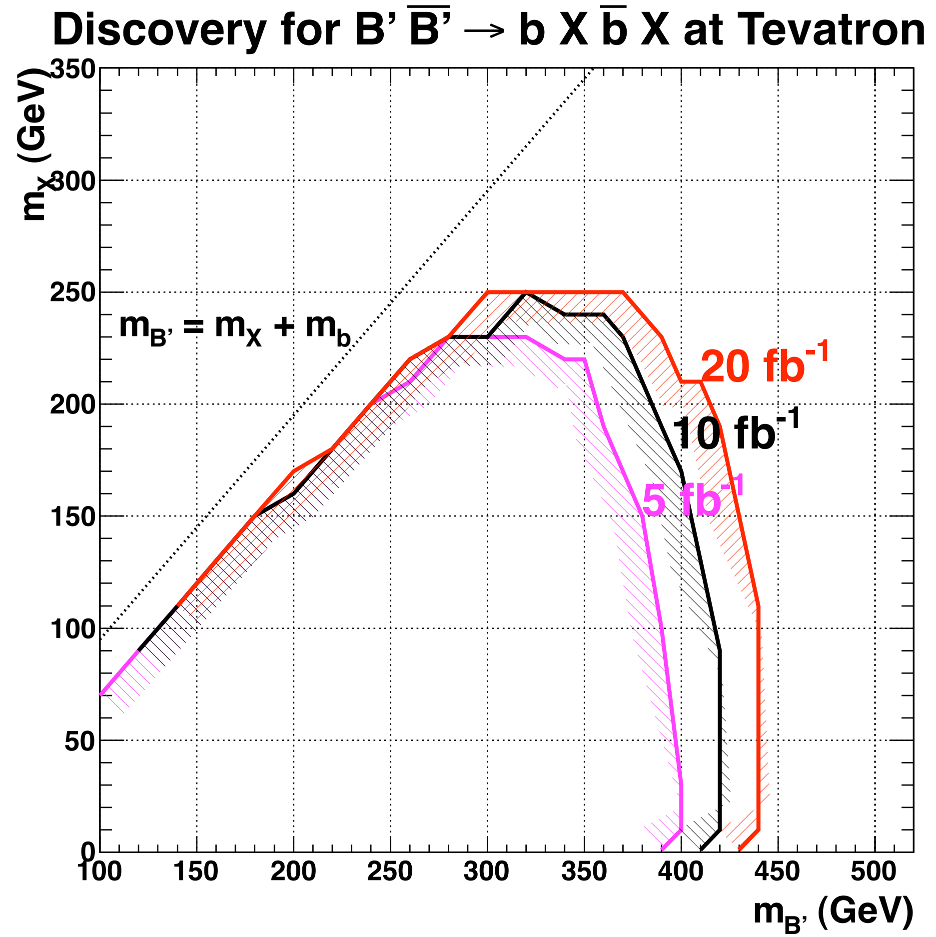

LHC reach

J. Alwall, J.L. Feng, J. Kumar, SS
1107.2919.

B'B' →bbXX

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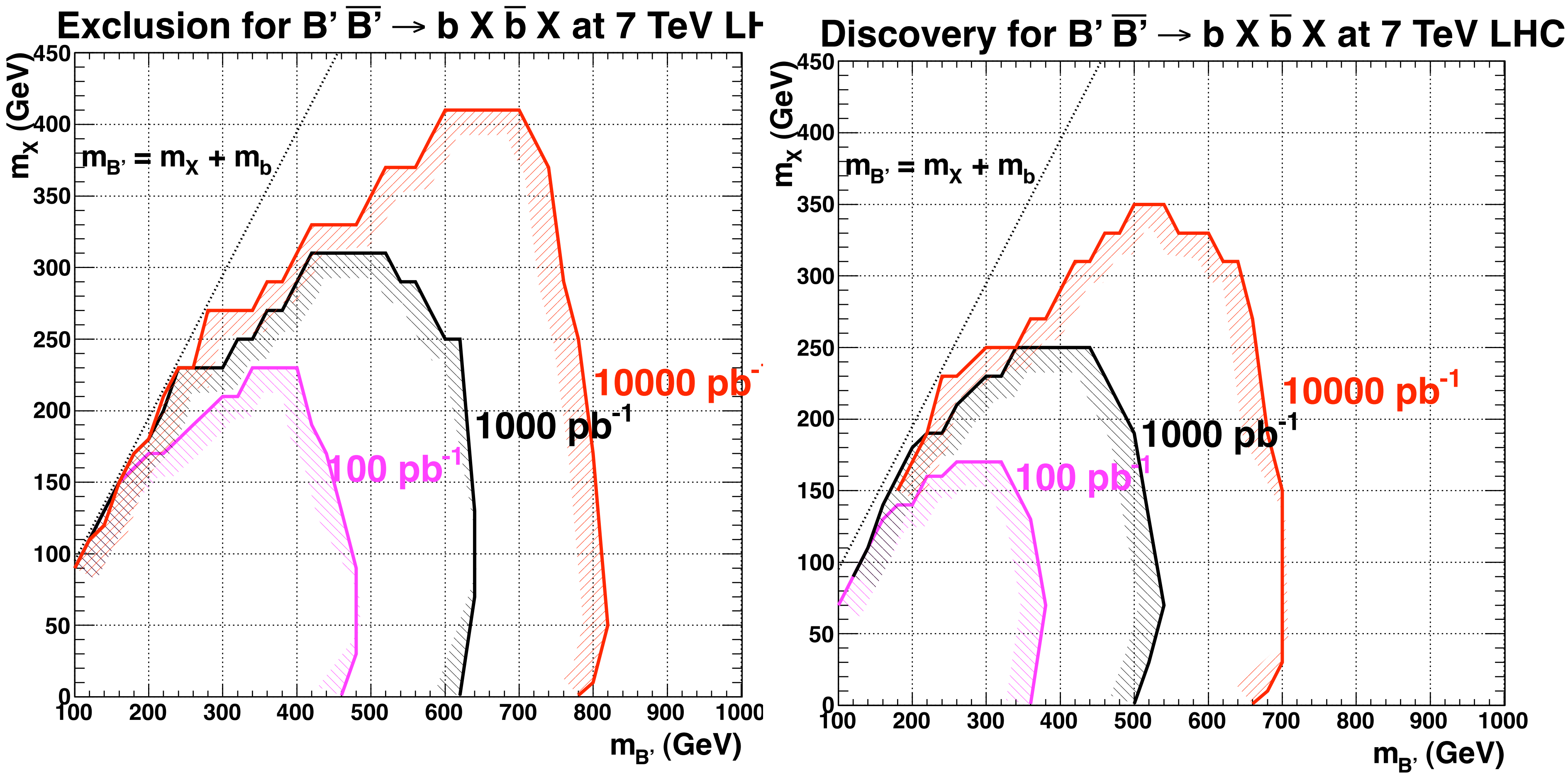


Simulation

MadGraph - Pythia - PGS

Signal: $T'\bar{T}' \to t^{(*)} X \bar{t}^{(*)} X \to bW^+ X \bar{b} W^- X$

- hadronic channel: large cross section
  - SM backgrounds, tt, W, have MET with lepton
  - irreducible background: Z→ νν + jets
- semi-leptonic channel: isolated lepton, suppress QCD background
- purely leptonic channel: suppressed cross section

Similar analyses in the literature

- semileptonic mode, high mass, large luminosity

  T. Han, R. Mahbubani, D. G. E. Walker and L. T. E. Wang, JHEP 0905, 117 (2009)

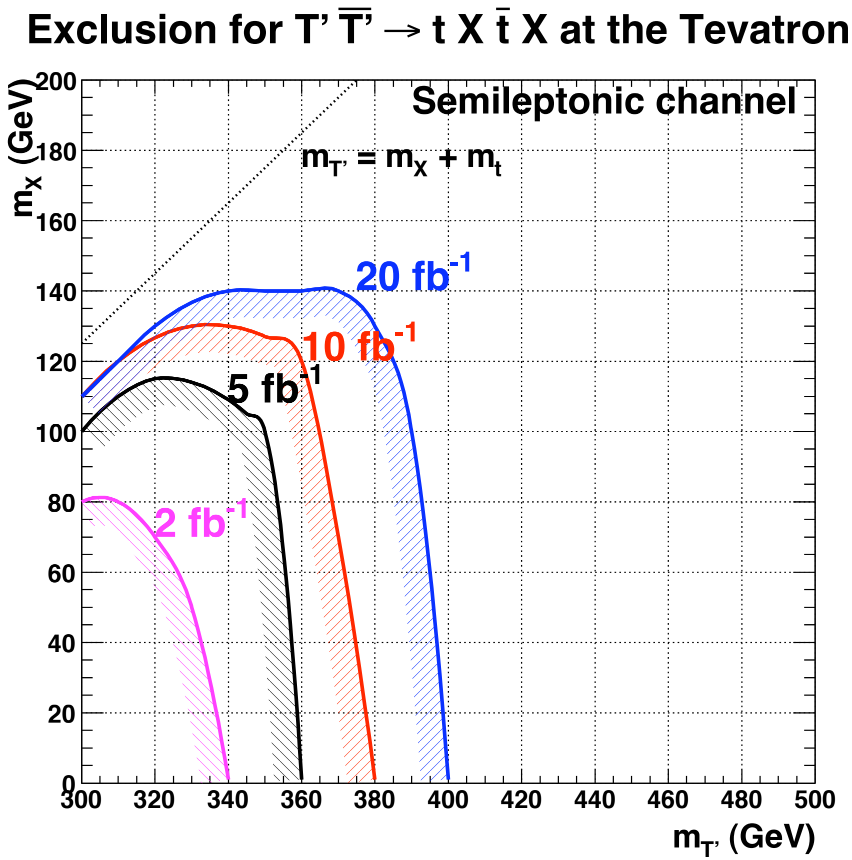
- hadronic mode, spin and mass determination

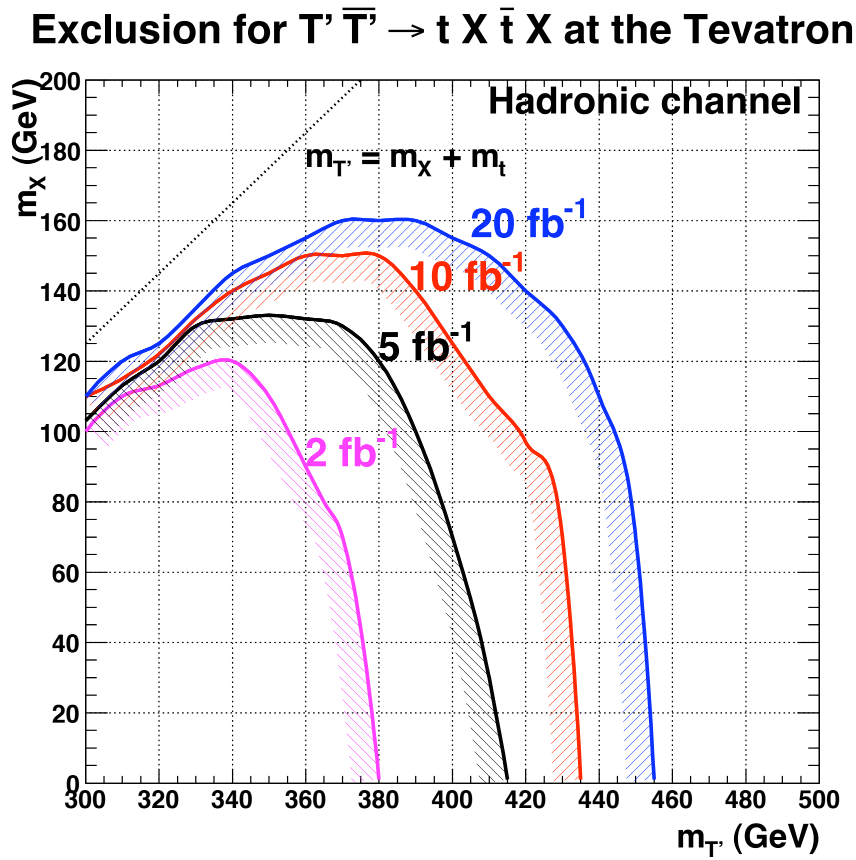
  P. Meade and M. Reece, Phys. Rev. D 74, 015010 (2006).

Tevatron exclusion

- optimal cuts (after precuts)
- S/B > 0.1, more than 2 events
- Poisson statistics

J. Alwall, J.L. Feng, J. Kumar, SS, 1002.3366





Tevatron exclusion

- optimal cuts (after precuts)
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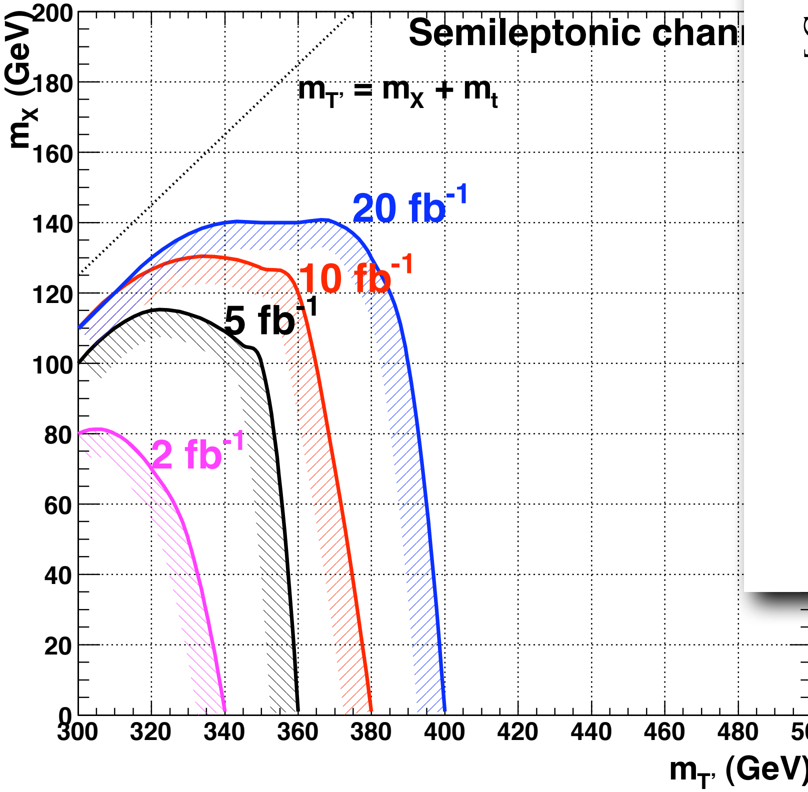
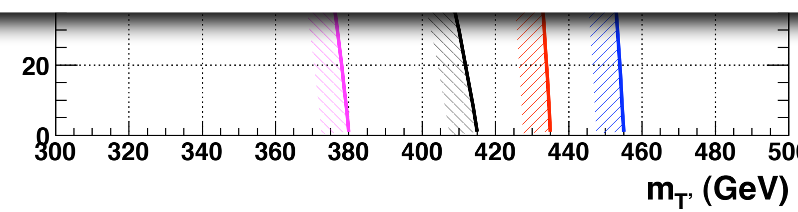
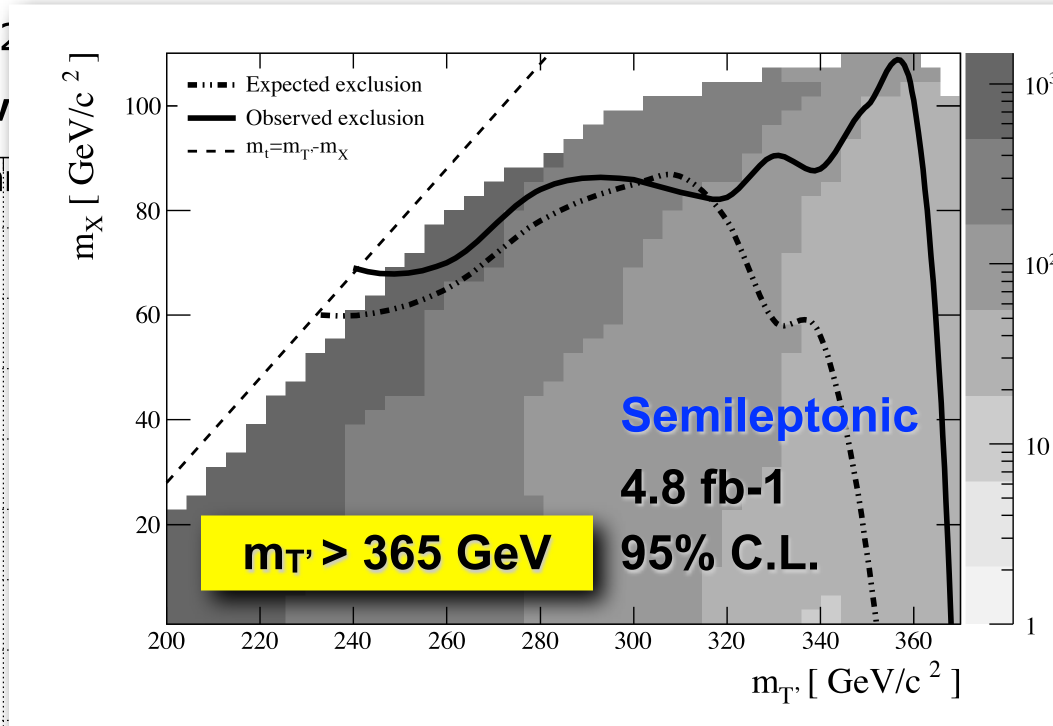
T. Aaltonen et al. [CDF Collaboration], arXiV:1103.2482

J. Alwall, J.L. Feng, J. Kumar, SS, 1002

Exclusion for T' $\overline{\text{T}}$' → t X $\bar{\text{t}}$ X at the Tev

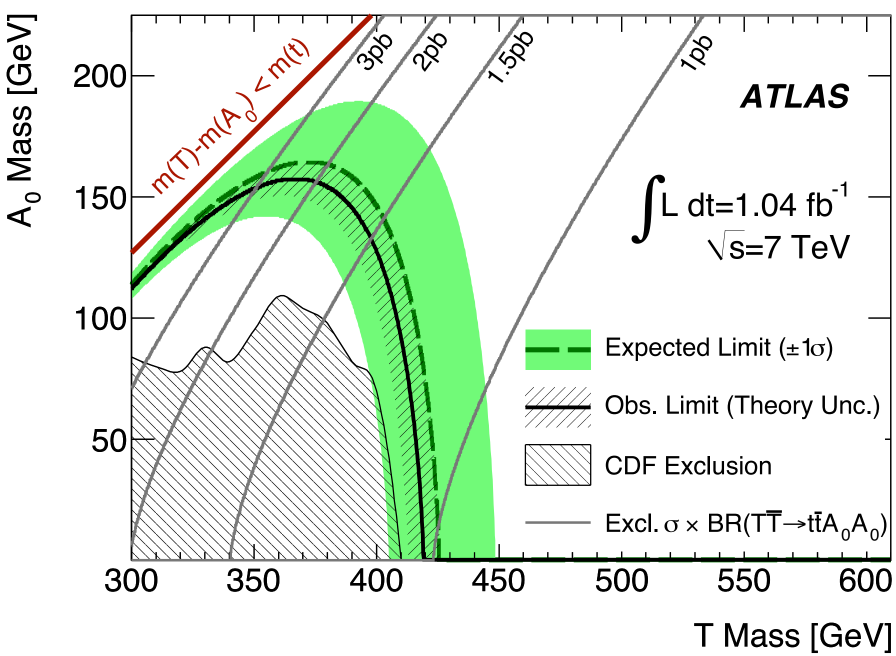


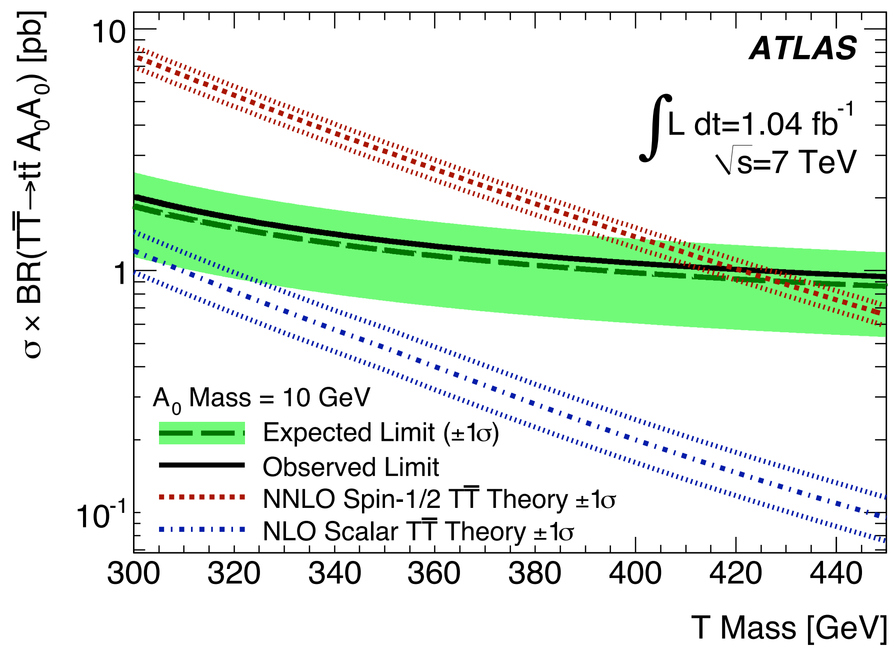




Constraints: direct search

ATLAS, 1.04 fb^{-1}, ttbar+MET , 1 lepton, >=4 j , + MET





ATLAS, 1109.4725

$m_{T'}$ > 420 GeV for mX<10 GeV

$m_{T'}$ > 370 GeV for mX<140 GeV

WIMP

- $m_{WIMP} \sim m_{weak}$
- g_{weak}^2

WIMP

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- g_{weak}^2

WIMPLESS

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

follow WIMP relation

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Not follow WIMP relation, DM interaction << Weak interaction. Possible?

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WIMPLESS

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

follow WIMP relation

Not follow WIMP relation, DM interaction << Weak interaction. Possible?

superWIMP

SuperWIMP / Extremely WIMP

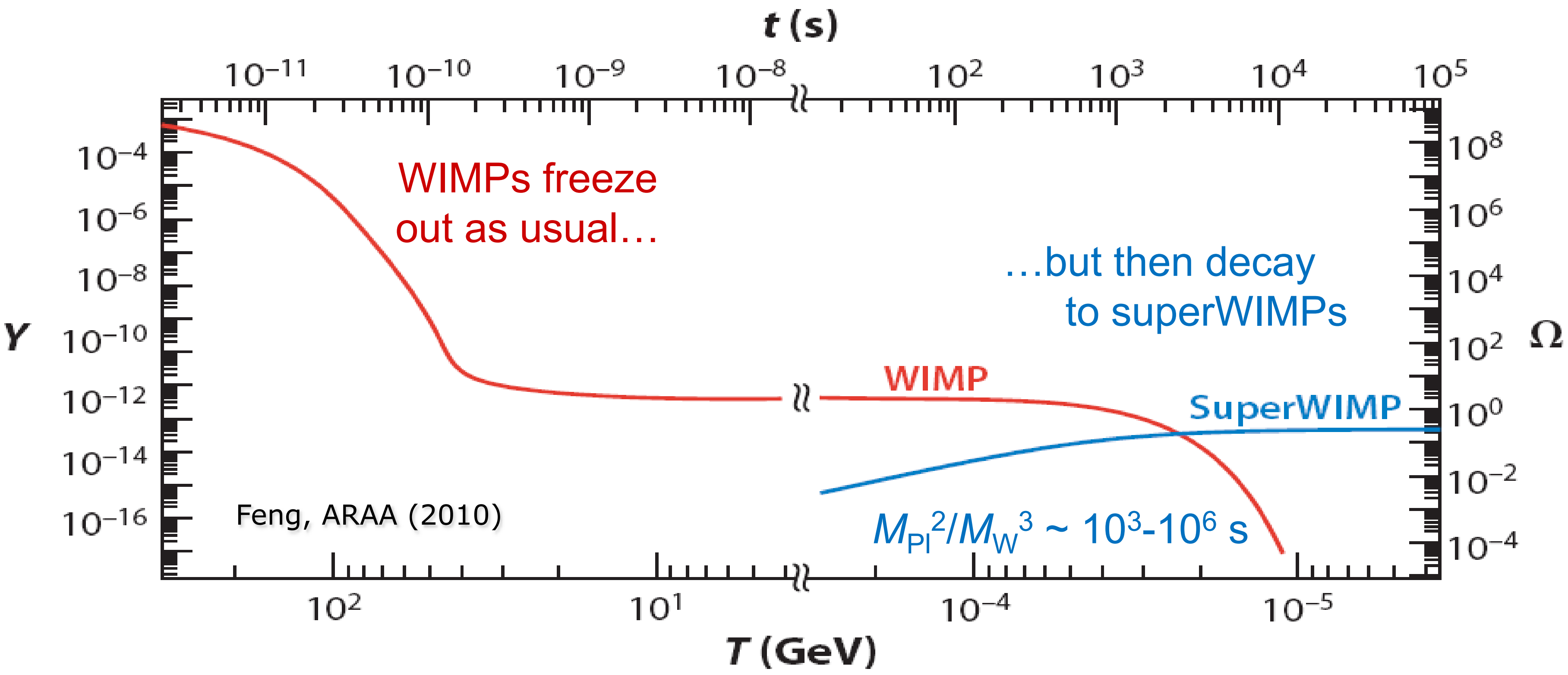
Not follow WIMP relation, DM interaction << Weak interaction. Possible?

CDM requirements

- Stable
- Non-baryonic
- Neutral
- Cold (massive)
- Correct density
- Gravitational interacting (much weaker than weak interaction)

Non-thermal production: WIMP decay

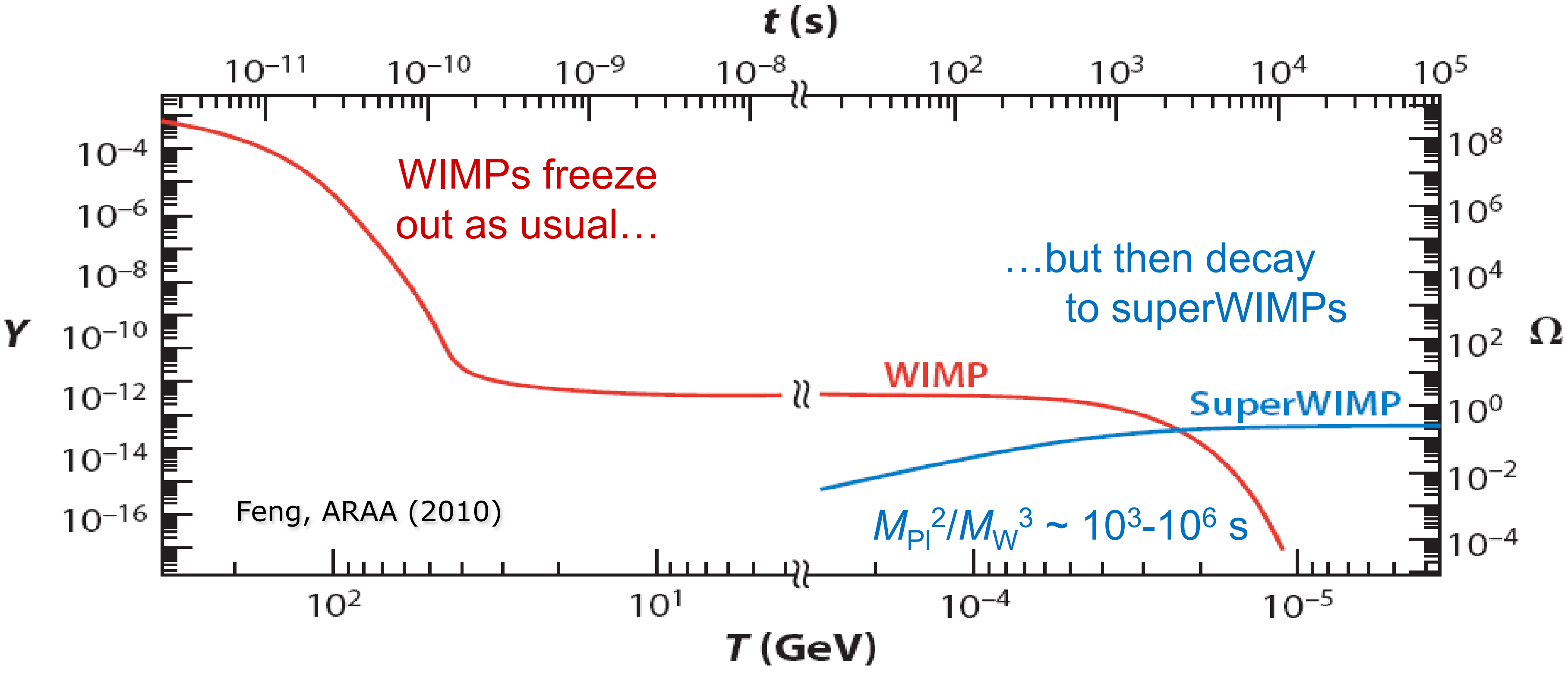
WIMP → superWIMP + SM particles



Non-thermal production: WIMP decay

WIMP → superWIMP + SM particles

$$\Omega_{SWIMP} = \frac{m_{SWIMP}}{m_{WIMP}} \Omega_{WIMP}$$



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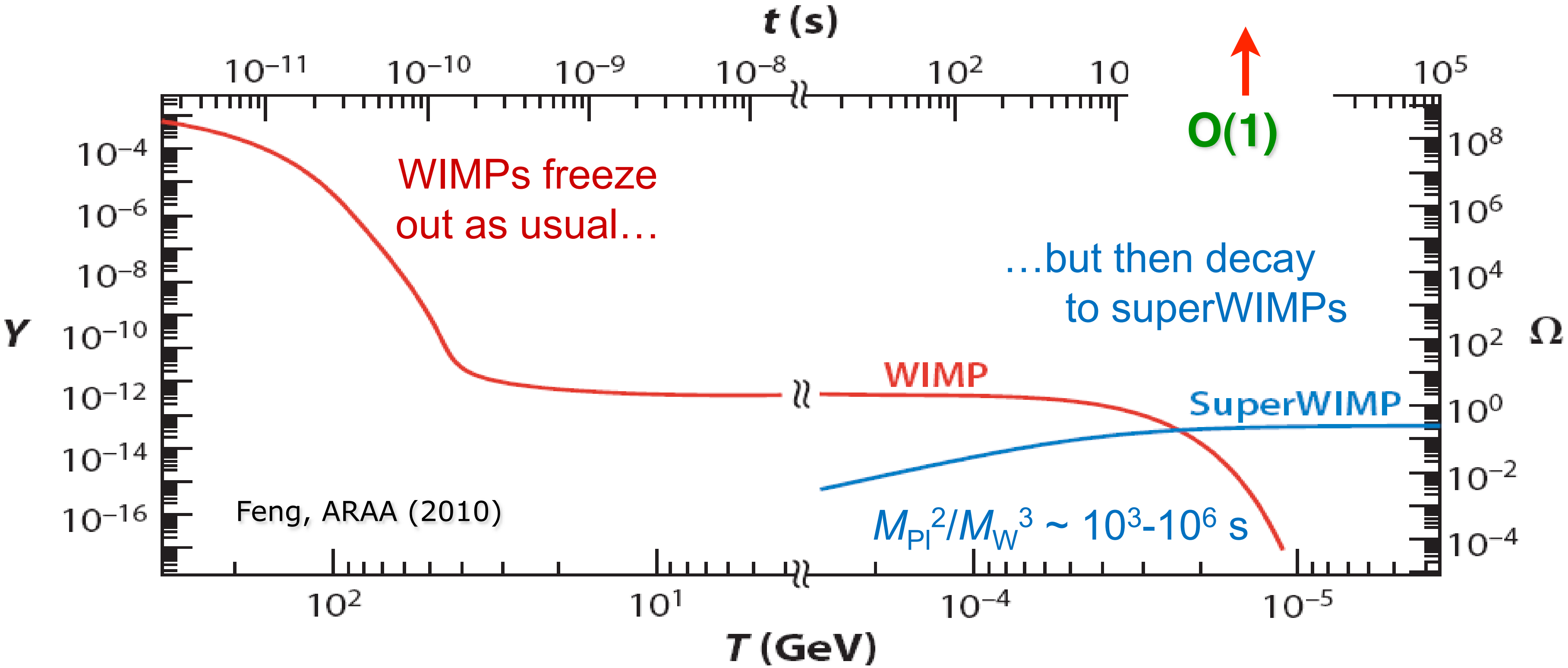

Non-thermal production: WIMP decay

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Feng, Rajaraman, Takayama (2003);
Bi, Li, Zhang (2003);
Ellis, Olive, Santoso, Spanos (2003);
Wang, Yang (2004);
Feng, Su, Takayama (2004);
Buchmuller, hamaguchi, Ratz, Yanagida (2004);
Roszkowski, Ruiz de Austri, Choi (2004);
Brandeburg, Covi, hamaguchi, Roszkowski, Steffen (2005);
...

superWIMP

e.g. Gravitino LSP
LKK graviton
axino

WIMP

- neutral
- charged

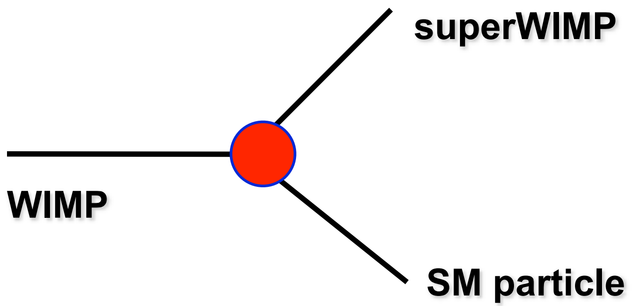
superWIMP in SUSY

Feng, Rajaraman, Takayama (2003)
Feng, SS, Takayama (2004)

SUSY case

WIMP → superWIMP + SM particles

WIMP	superWIMP
Charged slepton Superpartner of lepton	Gravitino Superpartner of graviton



$\sim \frac{1}{m_{pl}}$

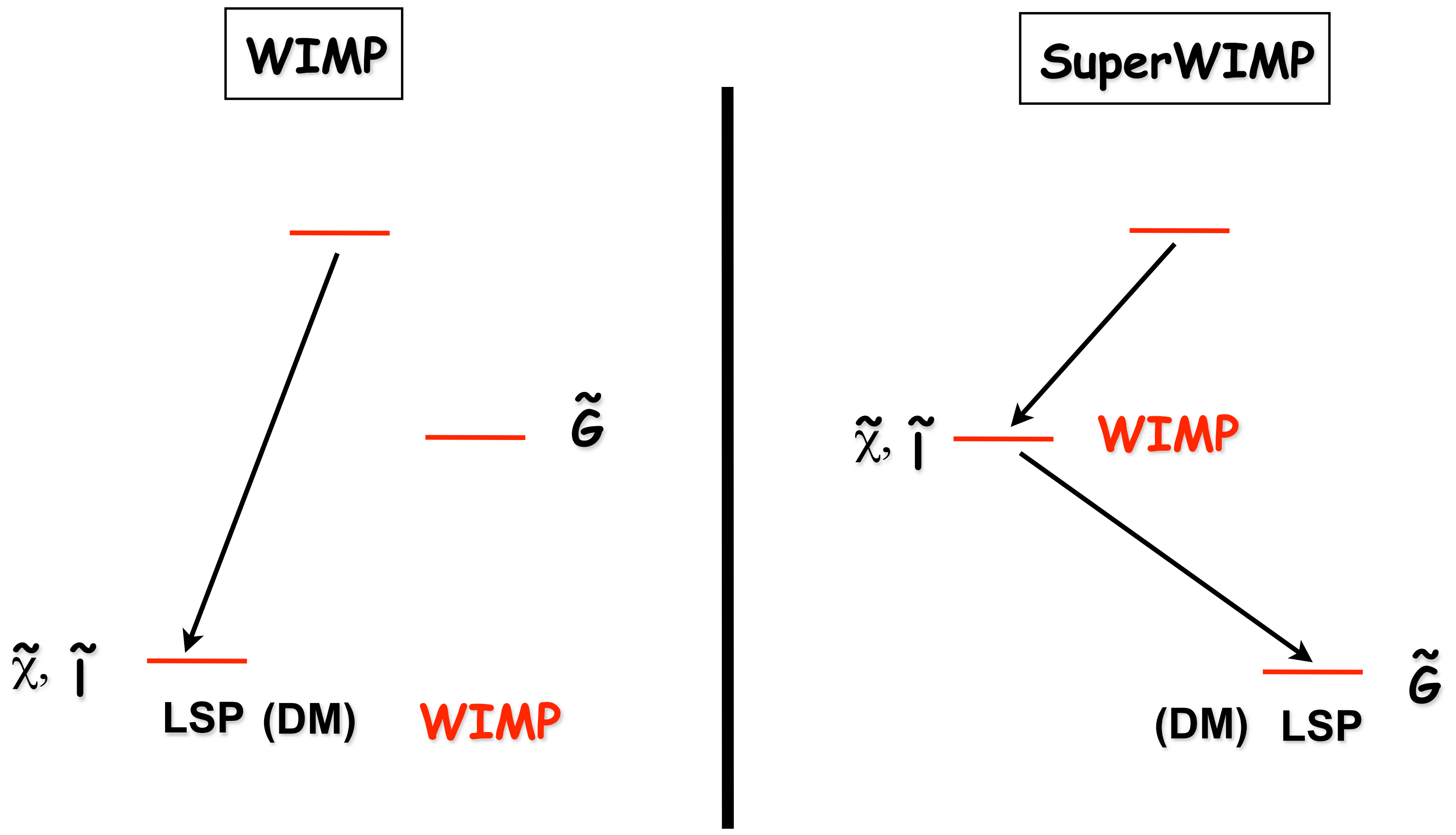
Decay lifetime $\propto m_{pl}^2/m_{\tilde{G}}^3$

EM, had. cascade

- ⇒ change CMB spectrum
- ⇒ change light element abundance predicted by BBN

Strong constraints !

Neutralino LSP vs. gravitino LSP



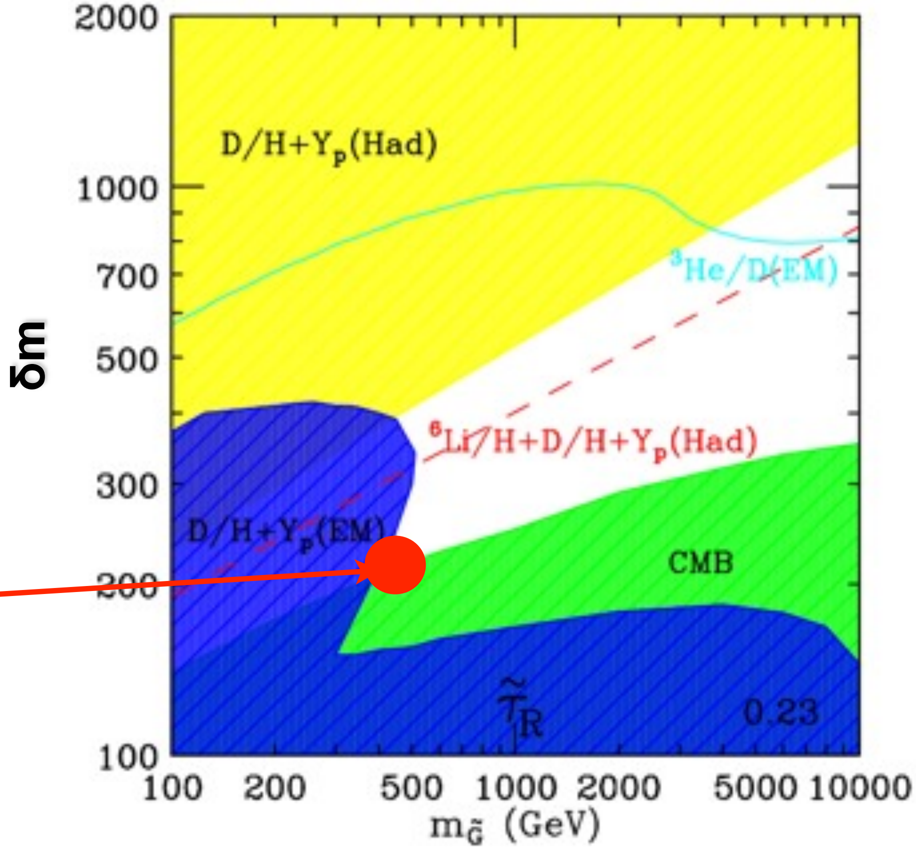
stau NLSP

$$Y_{NLSP} = \frac{n_{NLSP}}{n_\gamma} \simeq 3.0 \times 10^{-12} \left[\frac{\text{TeV}}{m_{\tilde{G}}}\right] \left[\frac{\Omega_{\tilde{G}}}{0.23}\right]$$

fix $\Omega_{\tilde{G}} = 0.23$

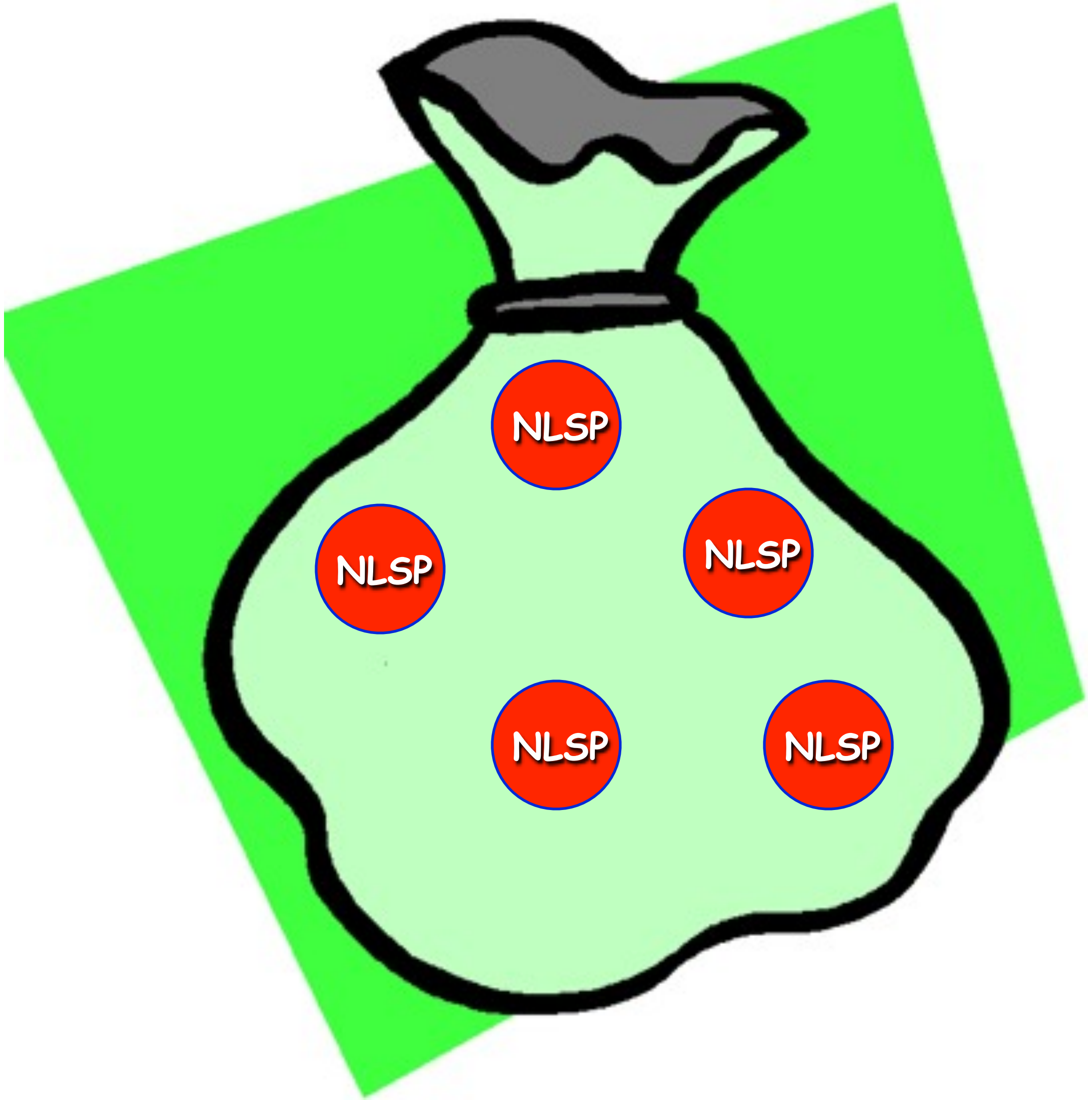
200 GeV ≲ δm ≲ 400 ~1500 GeV
$m_{\tilde{G}}$ ≲ 200 GeV

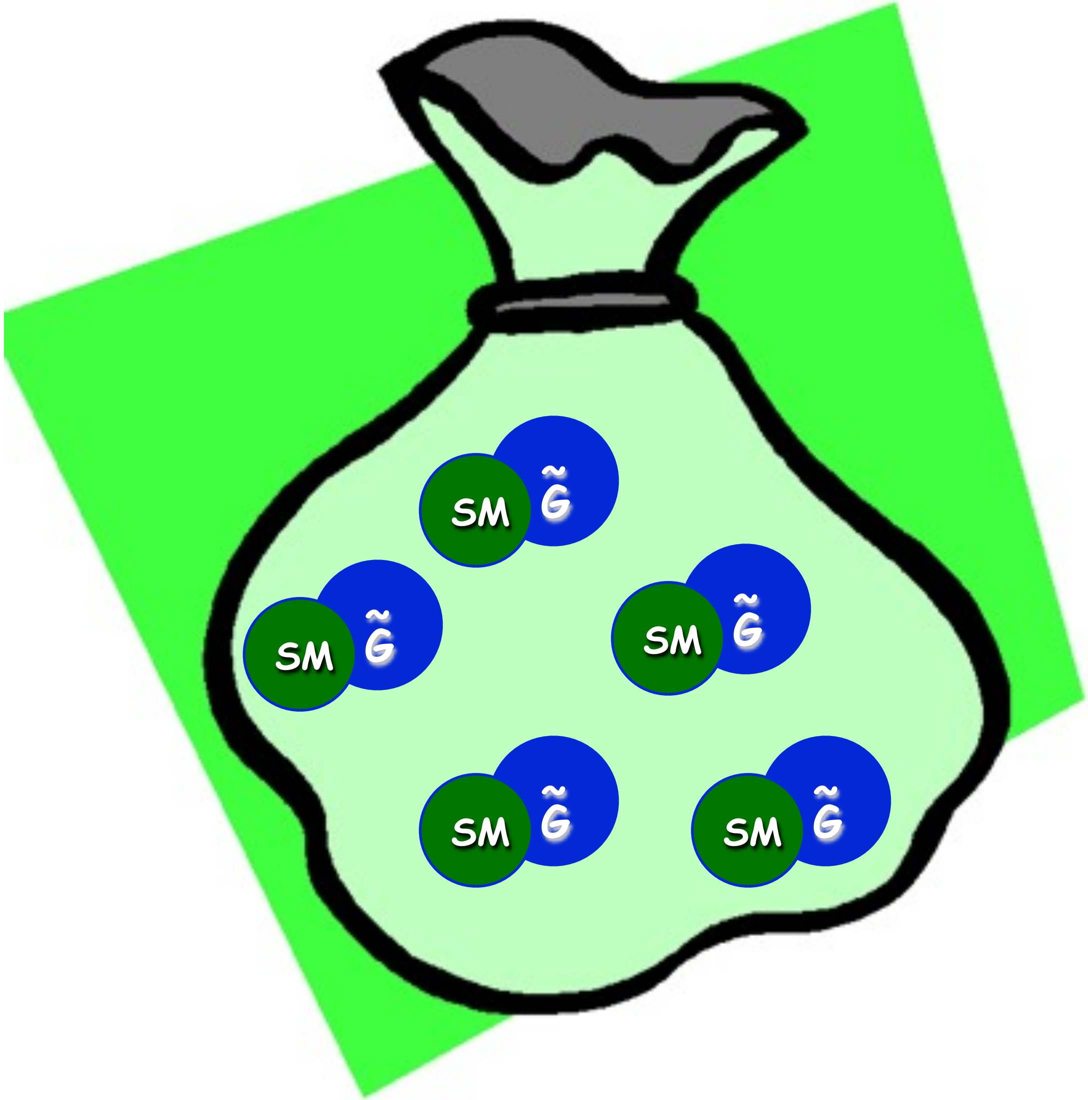
solve ^{7}Li anomaly

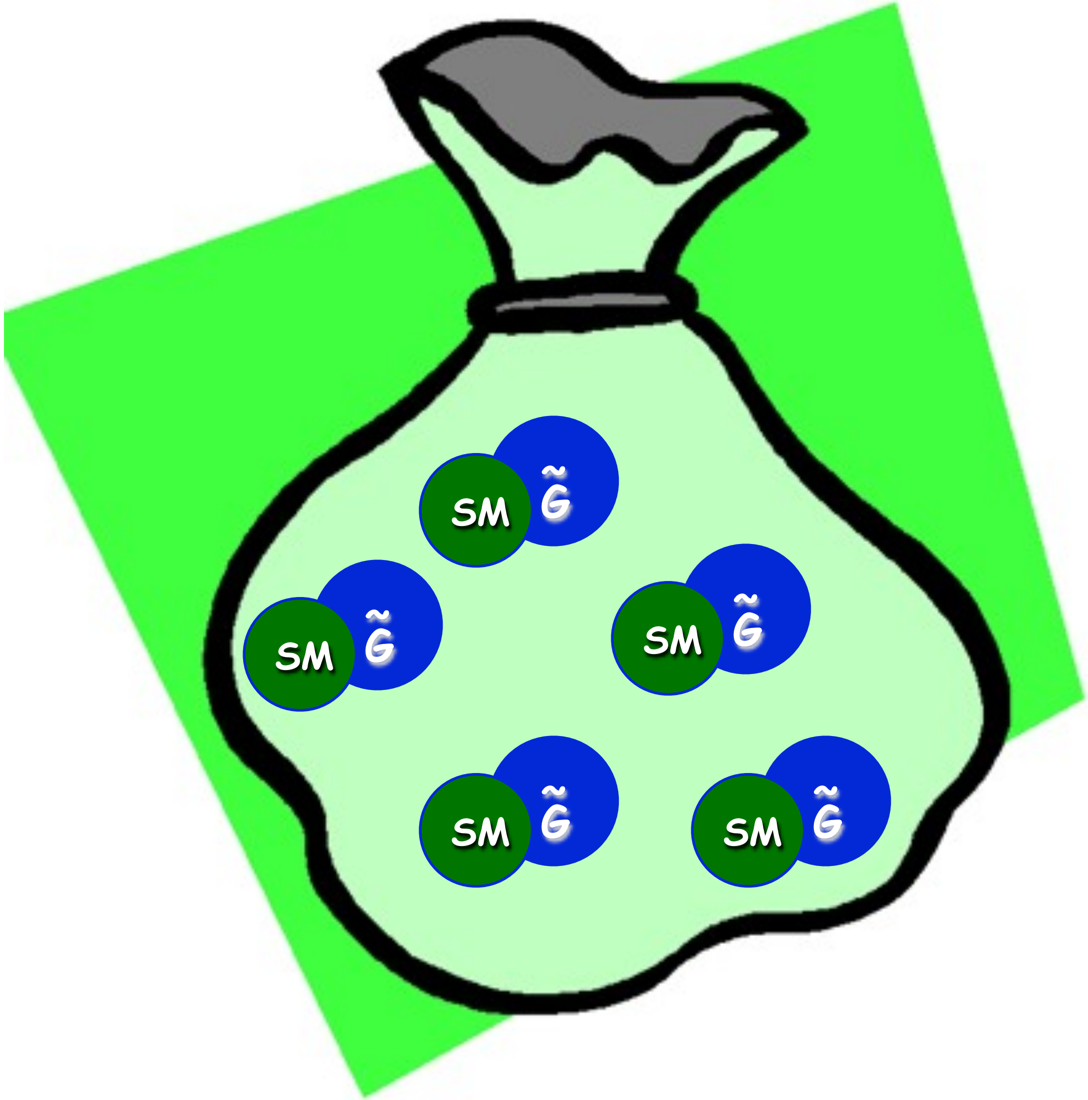


S. Su

J. Feng, SS, F. Takayama (2004)


NLSP
NLSP
NLSP
NLSP
NLSP

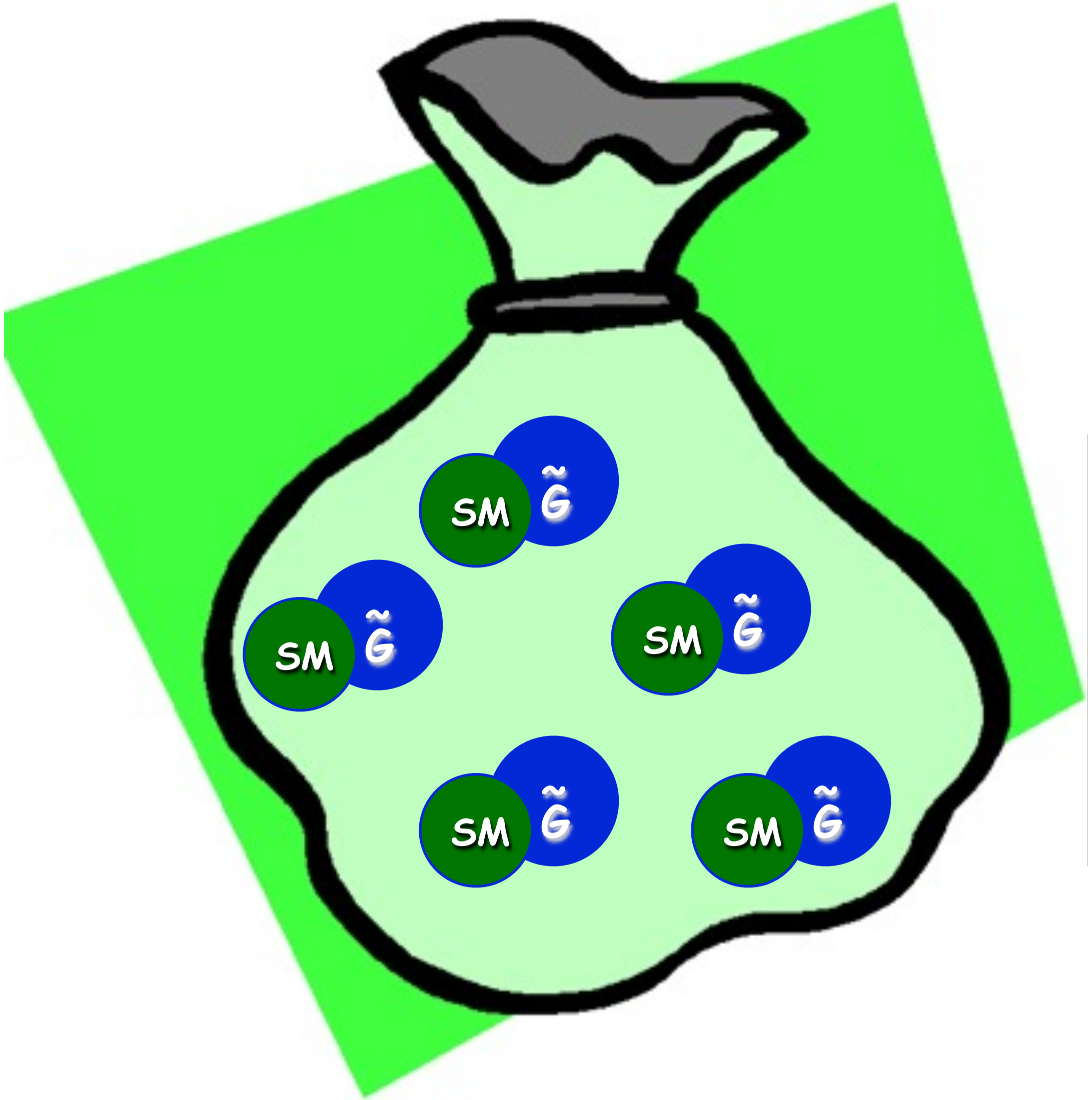

SM
G̃
SM
G̃
SM
G̃
SM
G̃
SM
G̃



- Decay life time
- SM particle energy/angular distribution …

  $\Rightarrow m_{\tilde{G}}$

  $\Rightarrow m_{pl}$ …



- Decay life time
- SM particle energy/angular distribution …

  ⇒ $m_{\tilde{G}}$

  ⇒ m_{pl} …

- Probes gravity in a particle physics experiments!
- BBN, CMB in the lab
- Precise test of supergravity: gravitino is a graviton partner

Conclusion

- dark matter candidates naturally obtain relic density

$\Rightarrow$ WIMP, WIMPless, superWIMP, ...

- WIMPless miracle:
  - hidden sector dark matter with $m_X/g_X^2 \sim m_{weak}/g_{weak}^2$
  - with connector fields, allow DM-SM interactions
  - direct detection: light dark matter, IVDM,...
  - collider signatures: 4th generation quarks, T', B'

- superWIMP: WIMP $\rightarrow$ superWIMP + SM particles

$$\Omega_{\mathrm{SWIMP}} = \frac{m_{\mathrm{SWIMP}}}{m_{\mathrm{WIMP}}} \Omega_{\mathrm{WIMP}}$$