Dark Matter and Collider Studies

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TeVPA 08
Beijing

Outline

(Incomplete) review of dark matter candidates

that are relevant for collider studies

Outline

- Dark matter and new physics
- WIMP: (not so) recent development
- WIMPless miracle
- superWIMP: gravitino and axino
  - stable dark matter (RPC)
  - metastable dark matter (RPV)

New physics beyond SM

DM problem provide precise, unambiguous evidence for new physics

Independent motivation for new physics in particle physics

New physics beyond SM

DM problem provide precise, unambiguous evidence for new physics

Independent motivation for new physics in particle physics

- New physics to protect electroweak scale
  - new symmetry: supersymmetry
  - new space dimension: extra-dimension
  - little Higgs, twin Higgs, ...

Dark matter in new physics

Dark Matter: new stable particle

in many theories, dark matter is easier to explain than no dark matter

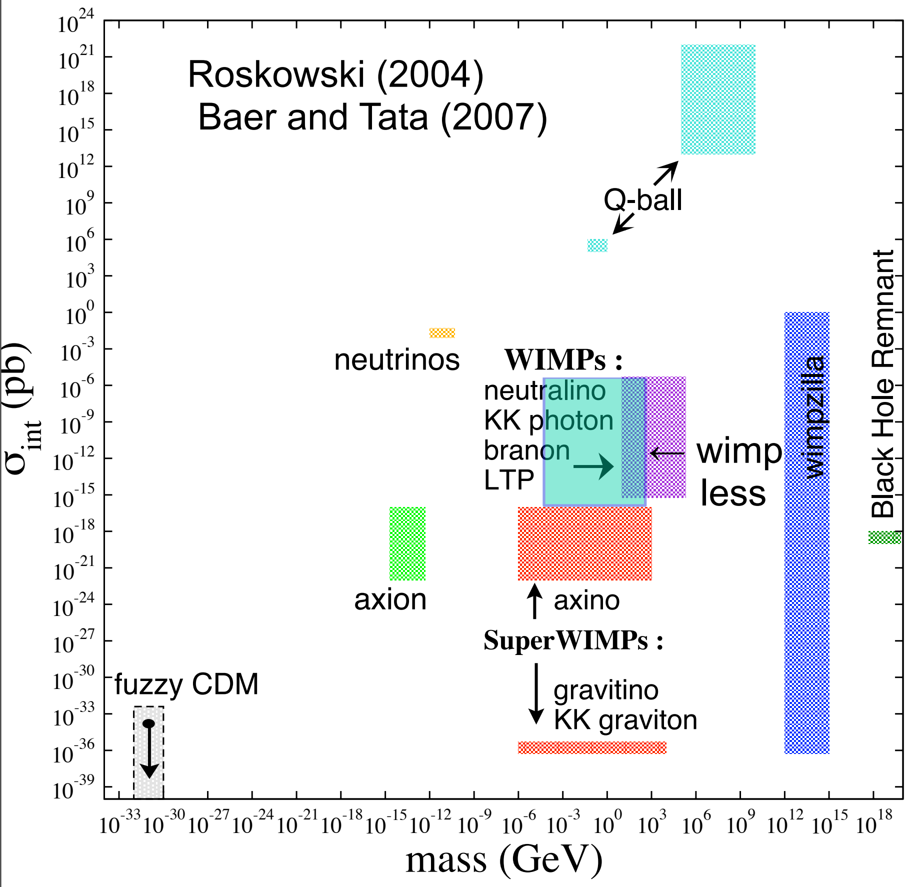
- there are usually many new weak scale particle
- constraints (proton decay, large EW corrections)

↕
discrete symmetry
↕
stability
↕
good dark matter candidate

Zoo of dark matter

mass and interaction strengths span many, many orders of magnitude

Some Dark Matter Candidate Particles



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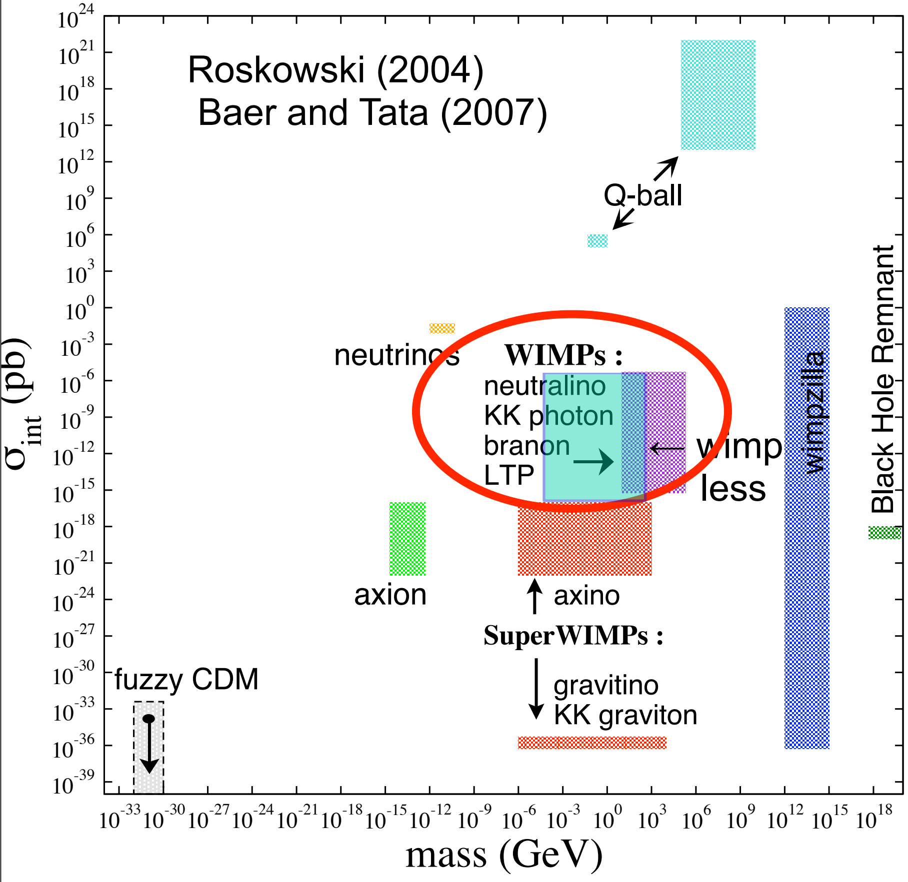

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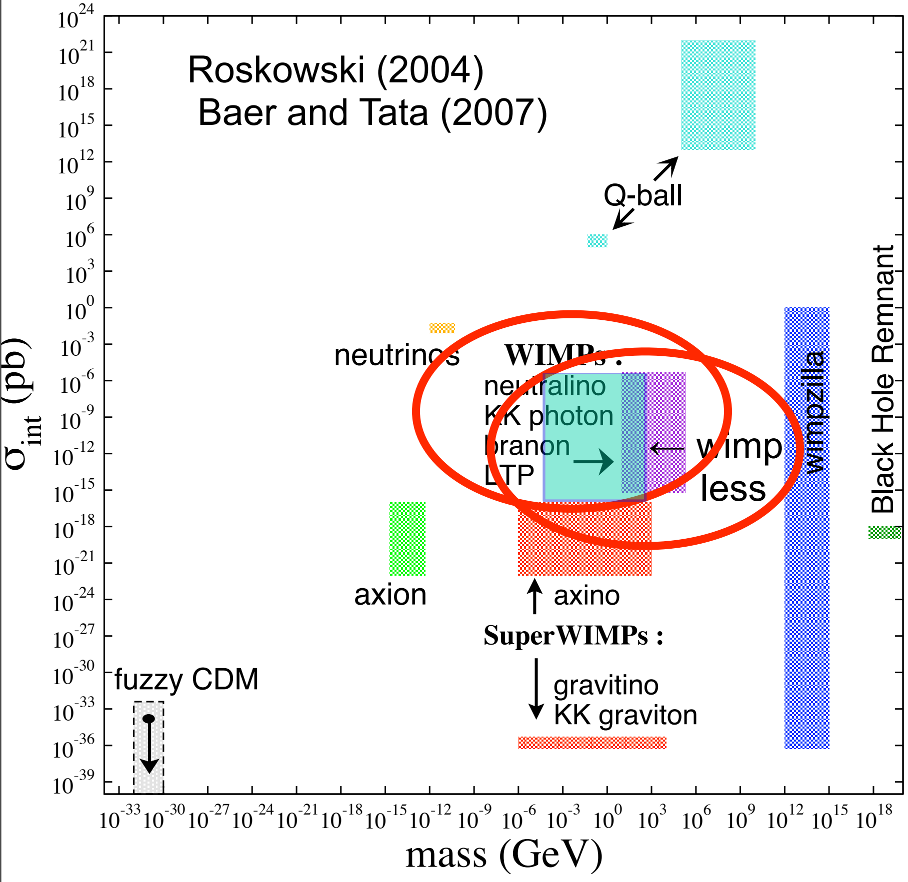

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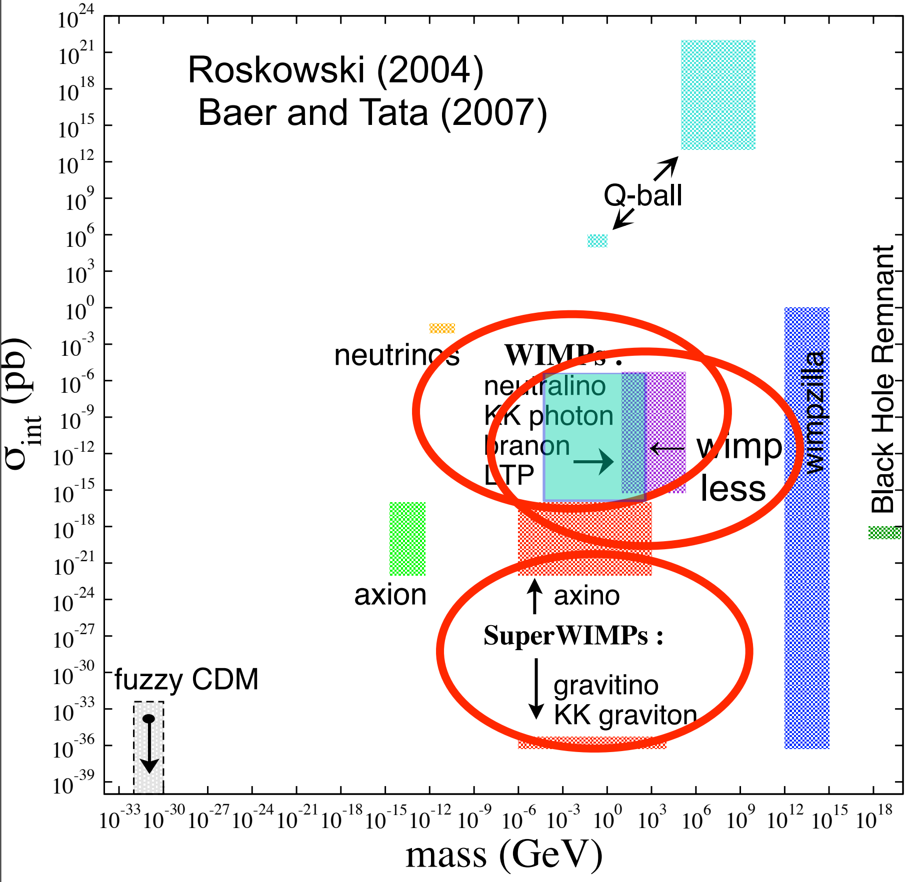

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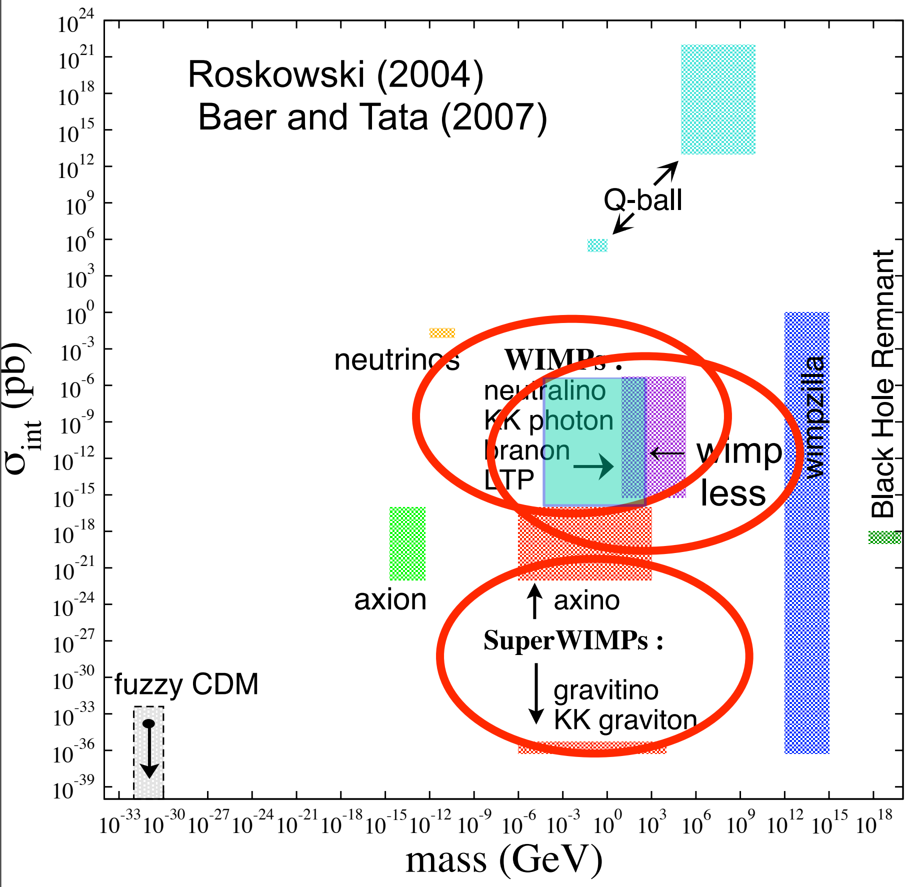


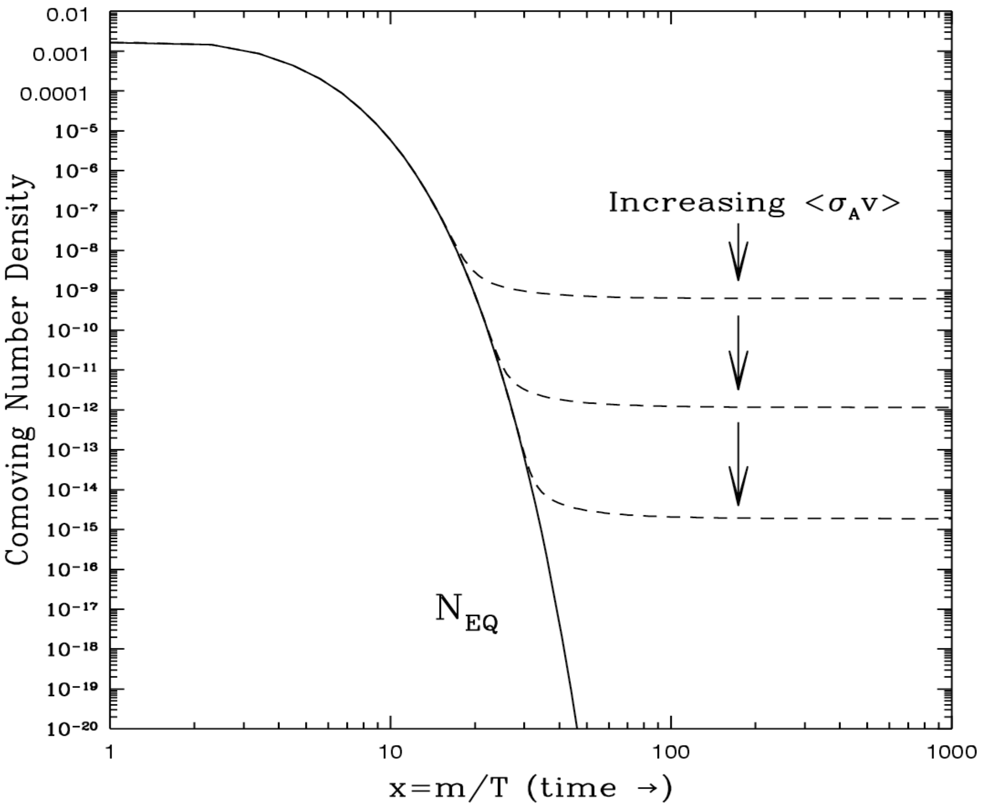
- appear in particle physics models motivated independently by attempts to solve EWSB

- 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 freeze out

Boltzmann equation

$$\frac{\mathrm{d}n}{\mathrm{d}t} + \underbrace{3Hn}_{\text{expansion}} = -\langle \sigma v \rangle (\underbrace{n^2}_{\chi\chi \to ff} - \underbrace{n_{eq}^2}_{ff \to \chi\chi})$$



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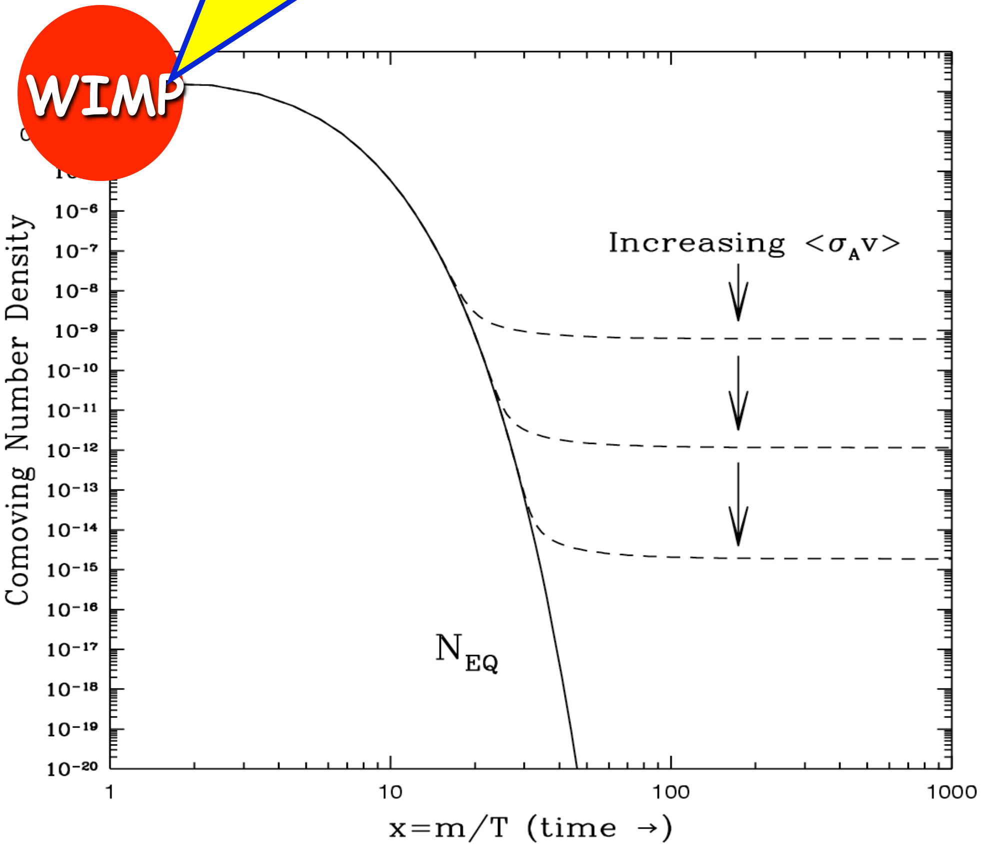
χ → ff

ff → χχ

Thermal equilibrium

χχ ⇔ ff



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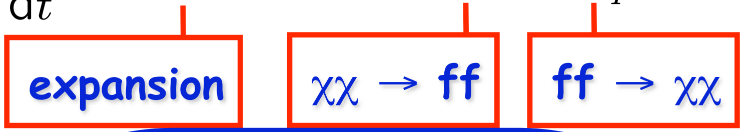
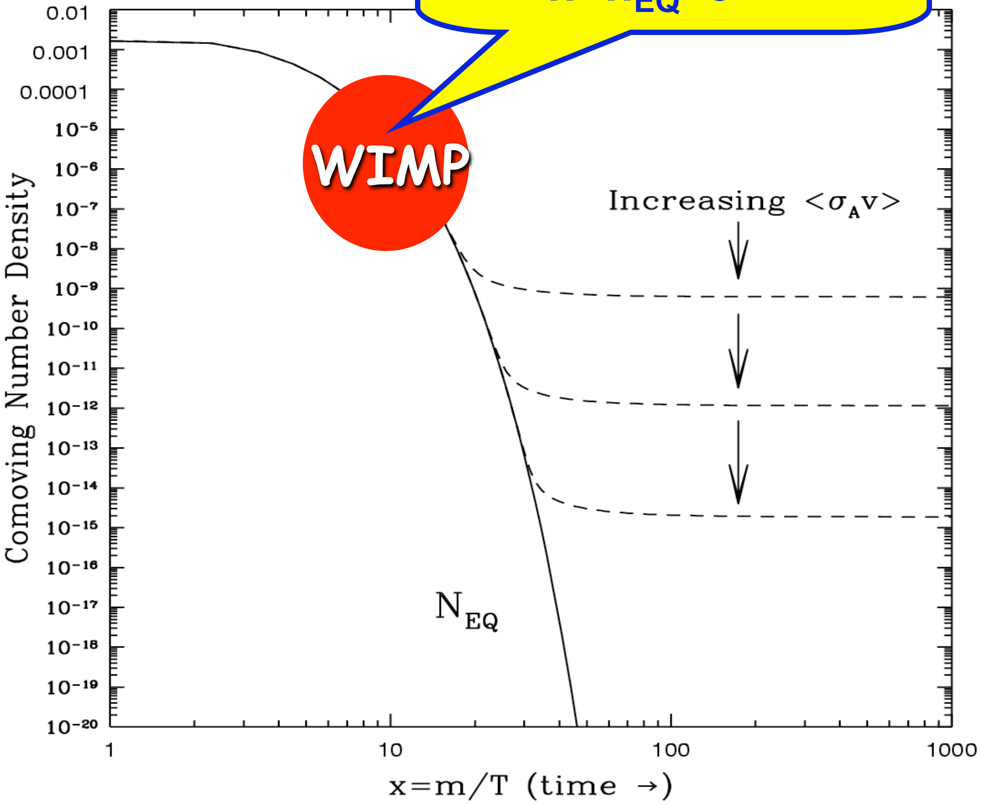


Universe cools:
$n=n_{EQ}\sim e^{-m/T}$



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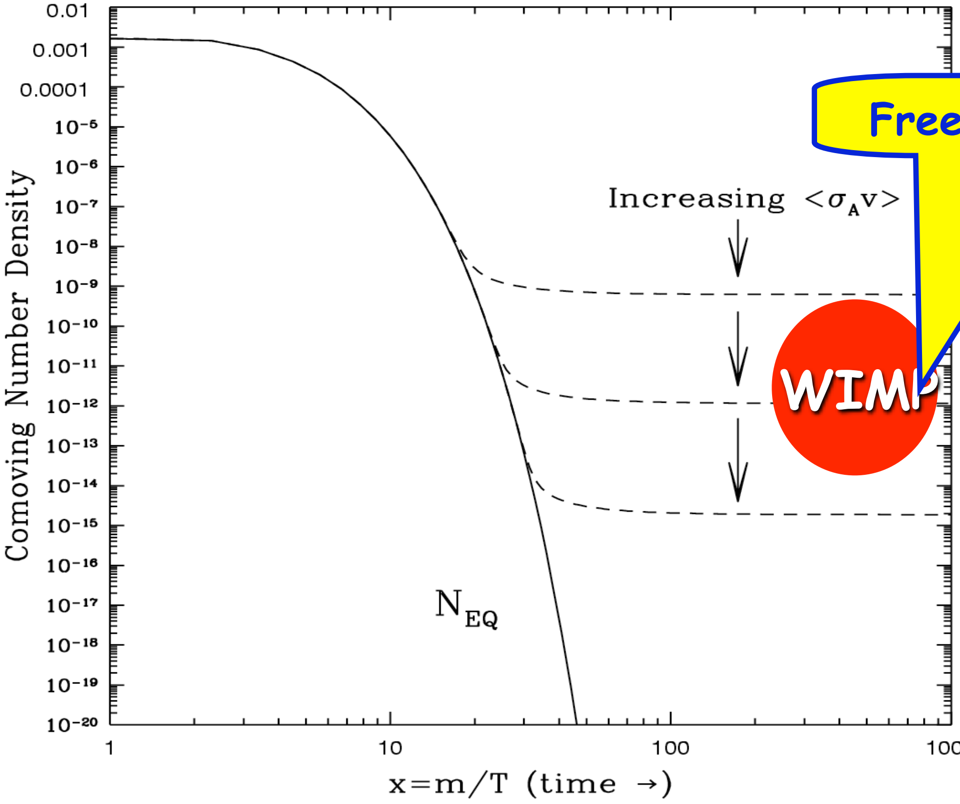

Freeze out, n/s ~ const

WIMP freeze out

Boltzmann equation

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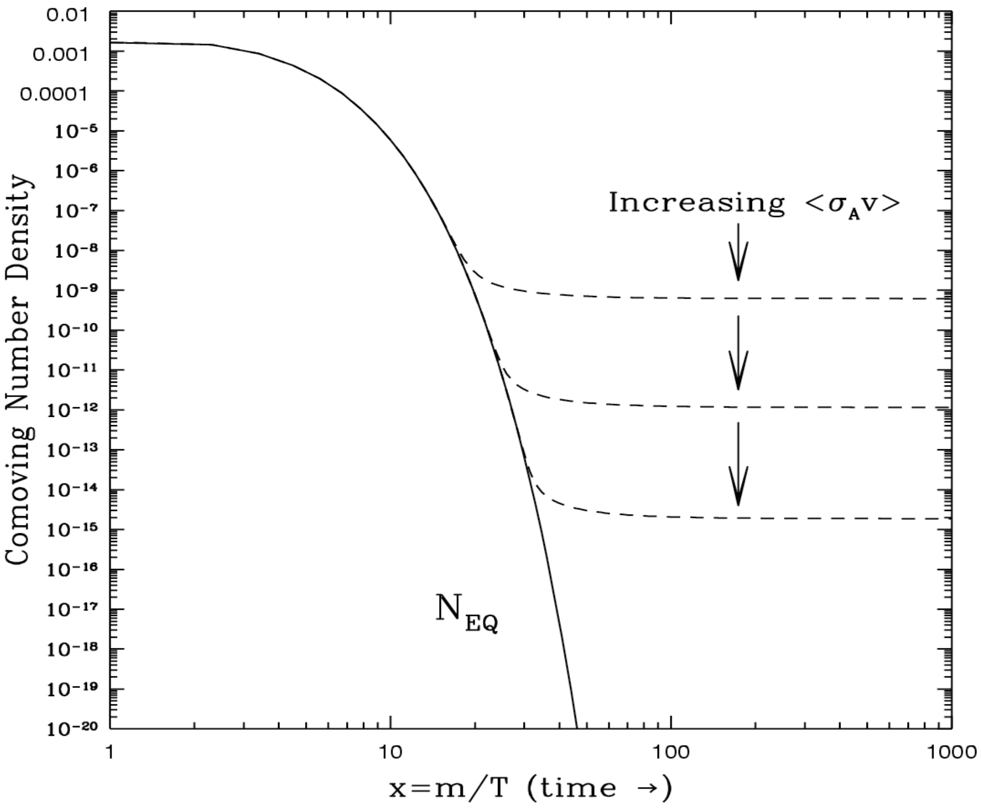


WIMP miracle

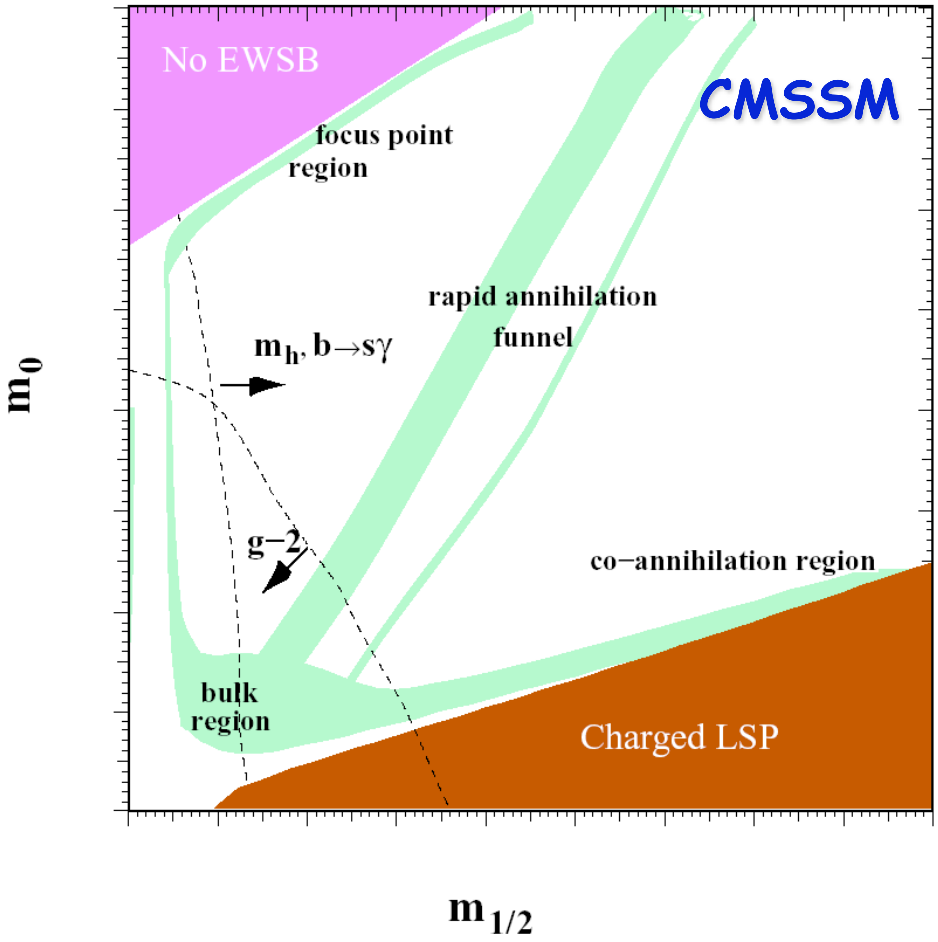
WIMP: Weak Interacting Massive Particle

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

$$\left.\begin{aligned} \Omega h^2 &\sim \frac{2.6\times 10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle} \\ \langle\sigma_A v\rangle &\sim \frac{\alpha^2}{m_{weak}^2}0.1 \sim 10^{-9}\mathrm{GeV}^{-2} \end{aligned}\right\} \Rightarrow \Omega\, h^2 \sim 0.3$$

naturally around the observed value

Neutralino DM and LHC connection



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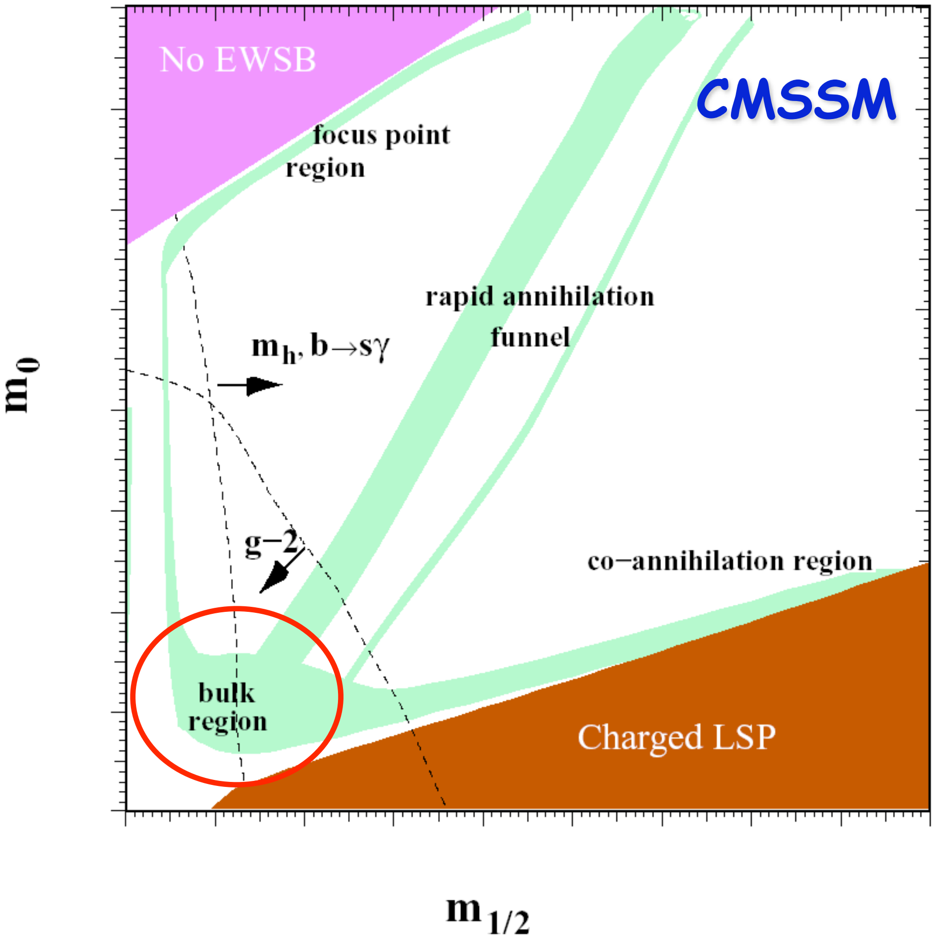

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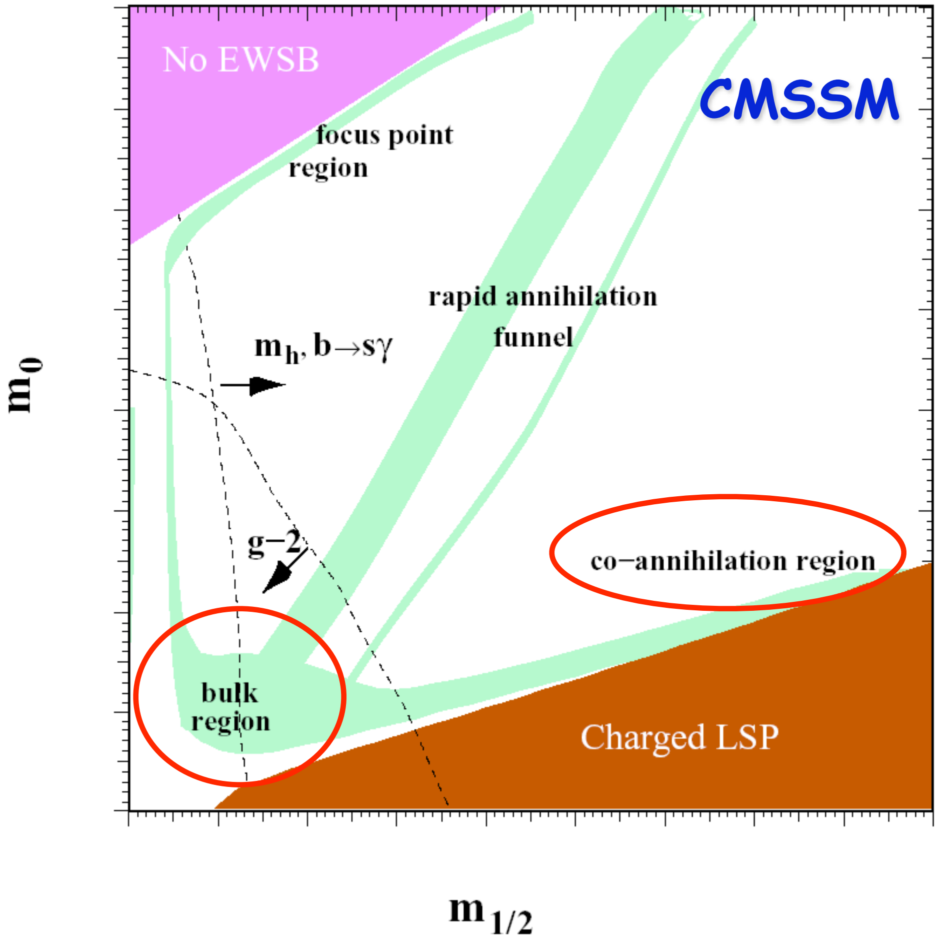

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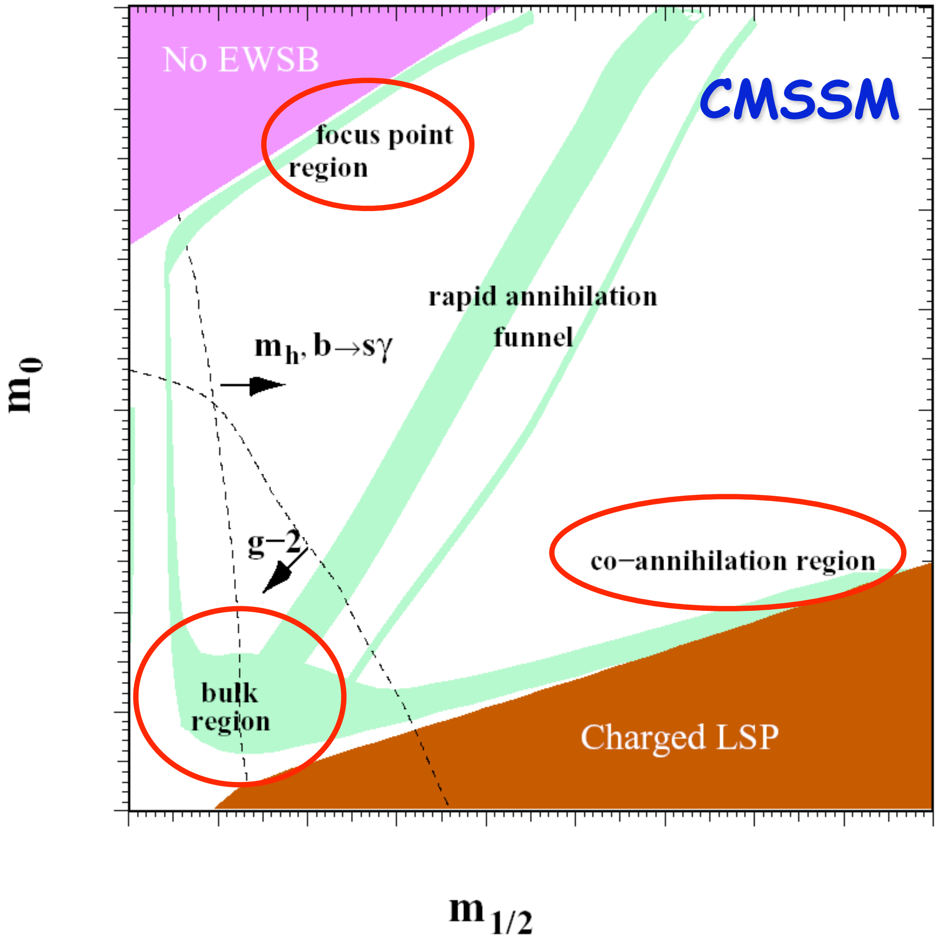

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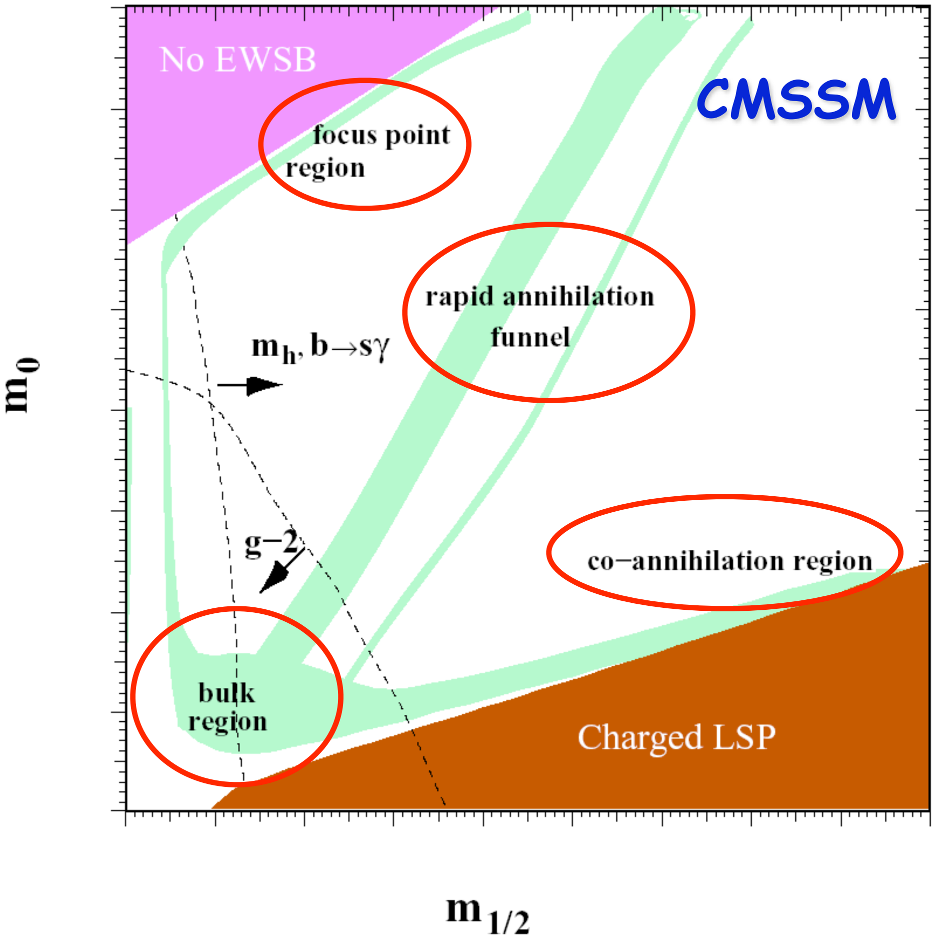

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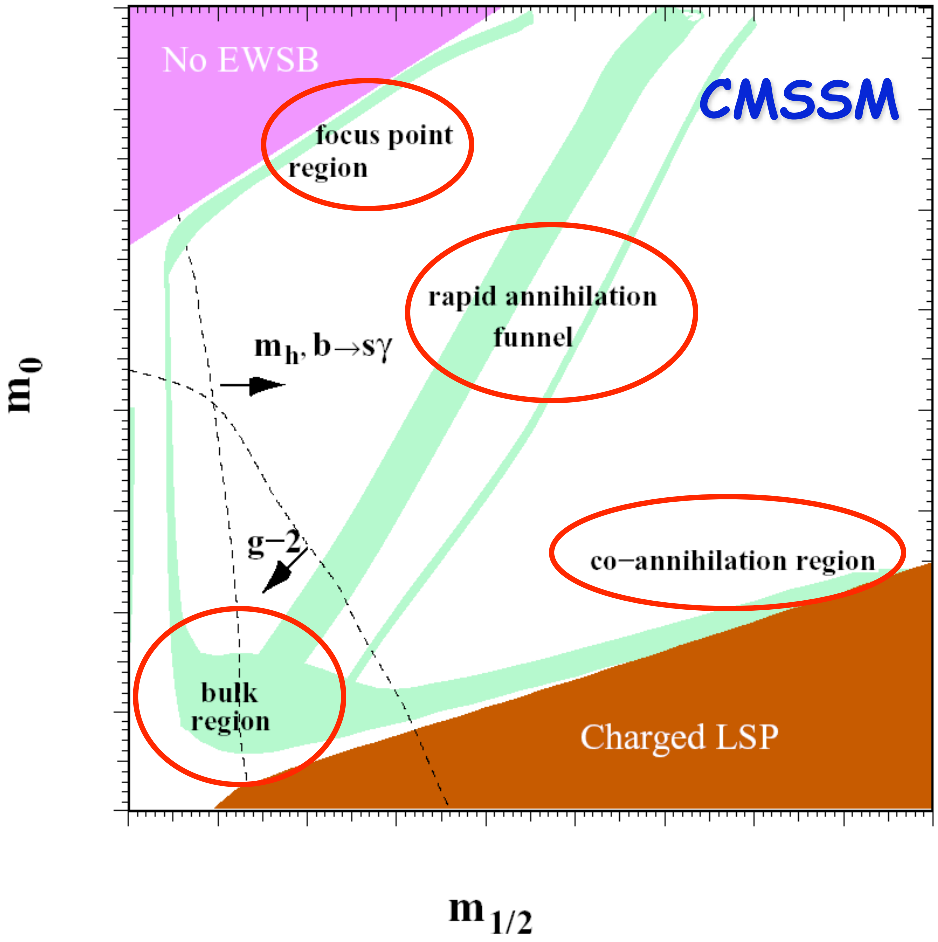

There have been many many studies ...

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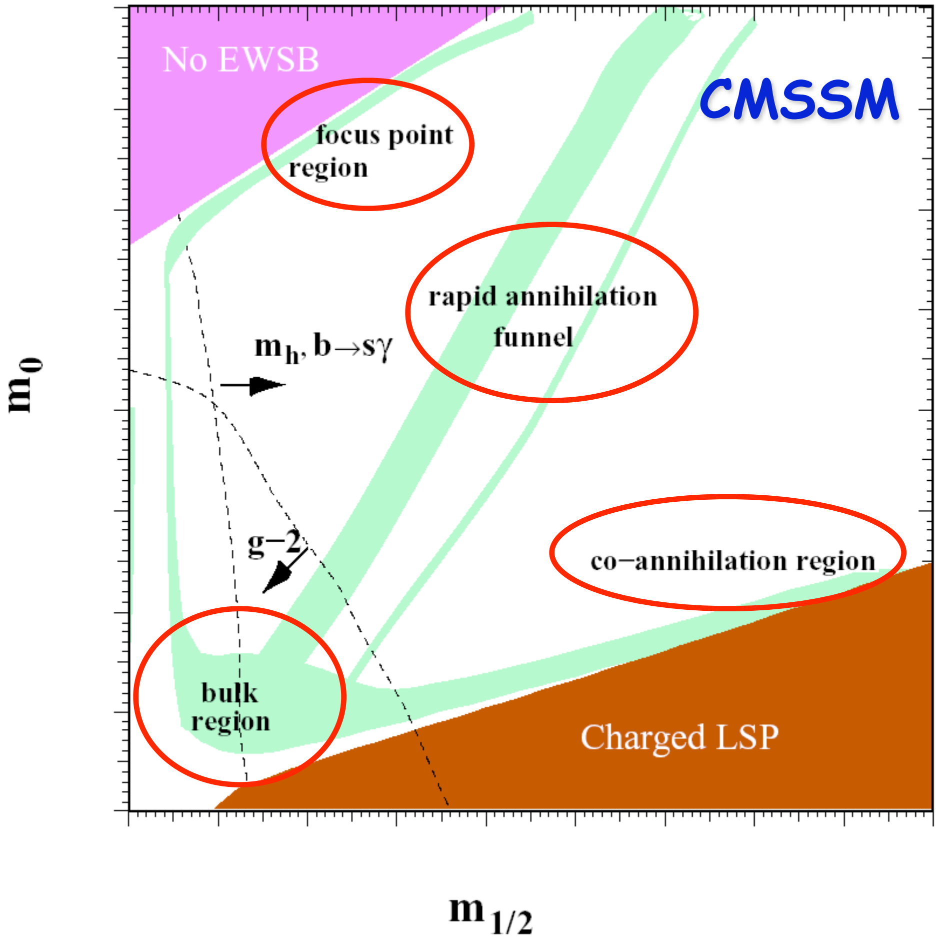

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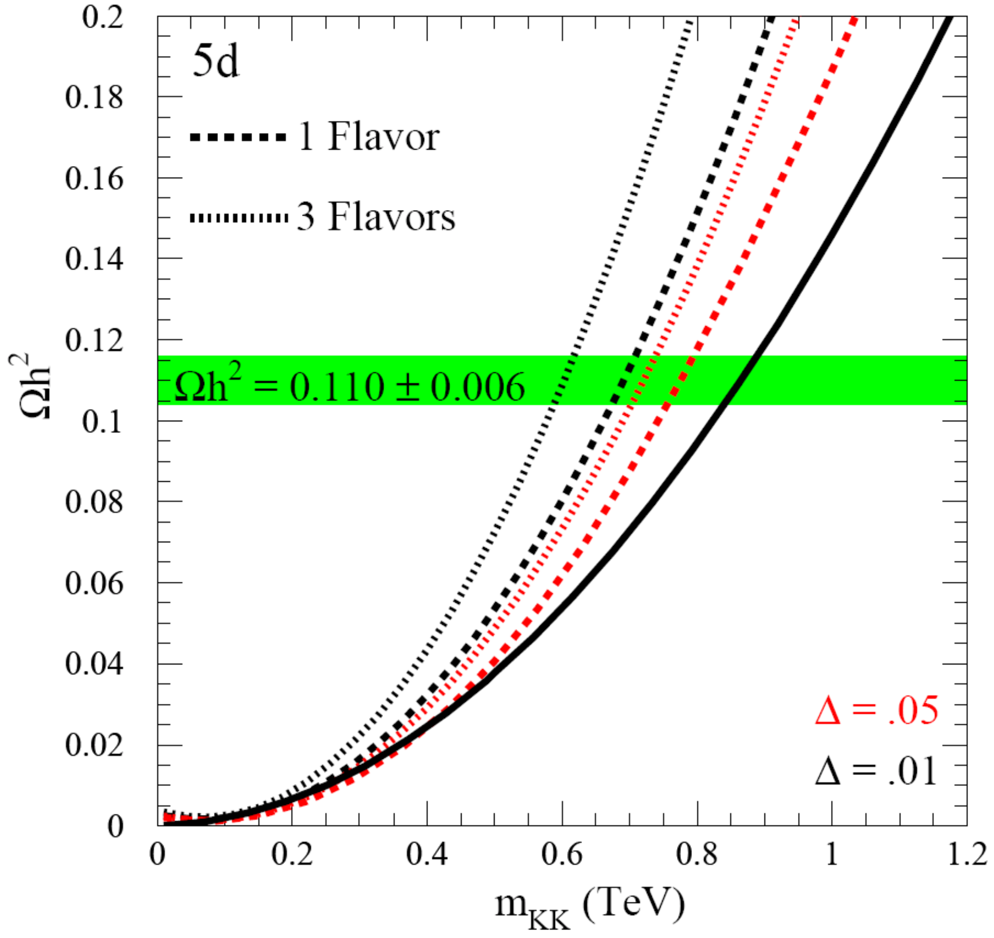
Talk by Bogdan Dobrescu
“LHC and WIMPs”

UED: LKP dark matter

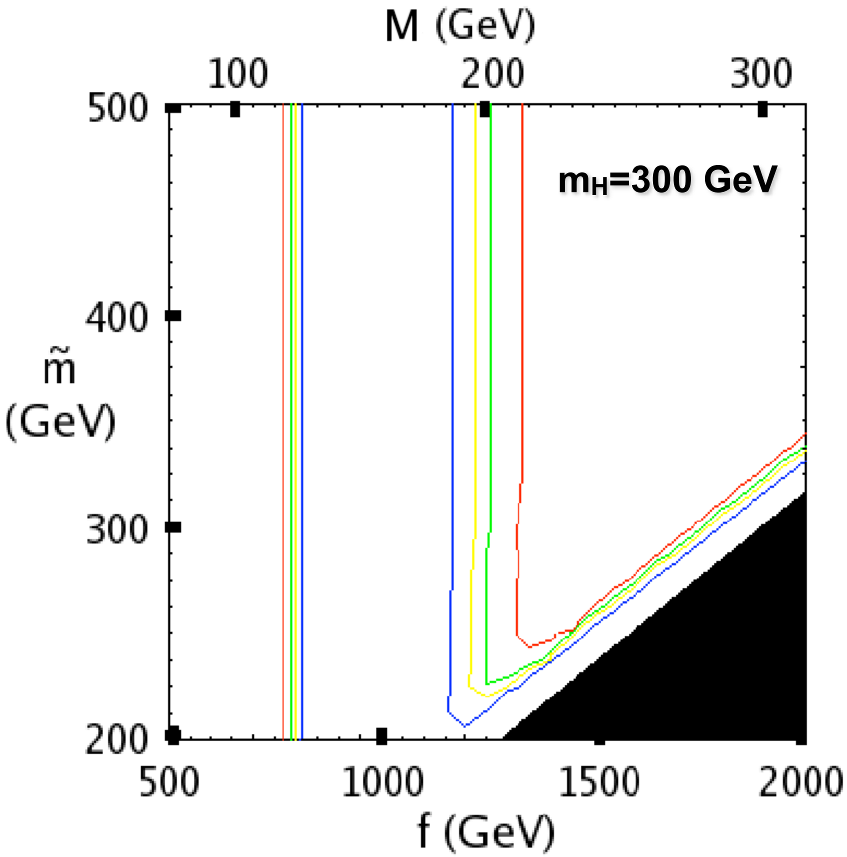
Servant, Tait (2002)

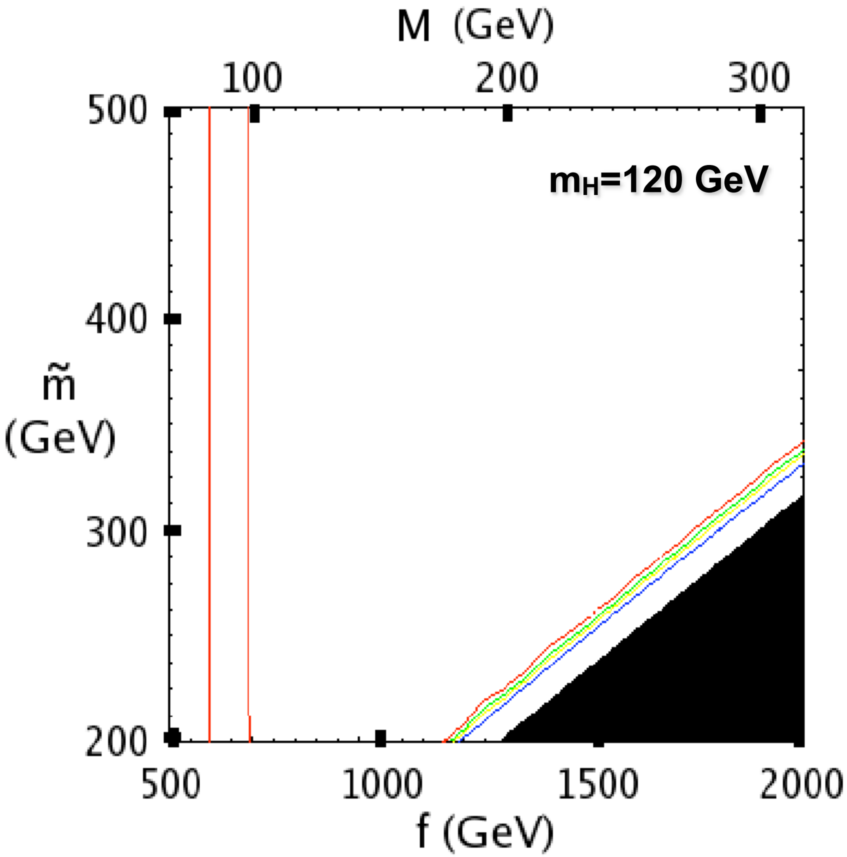


LKP in UED: $B^{(1)}$

Little Higgs with T-parity: LTP

LTP in LH models: B_H

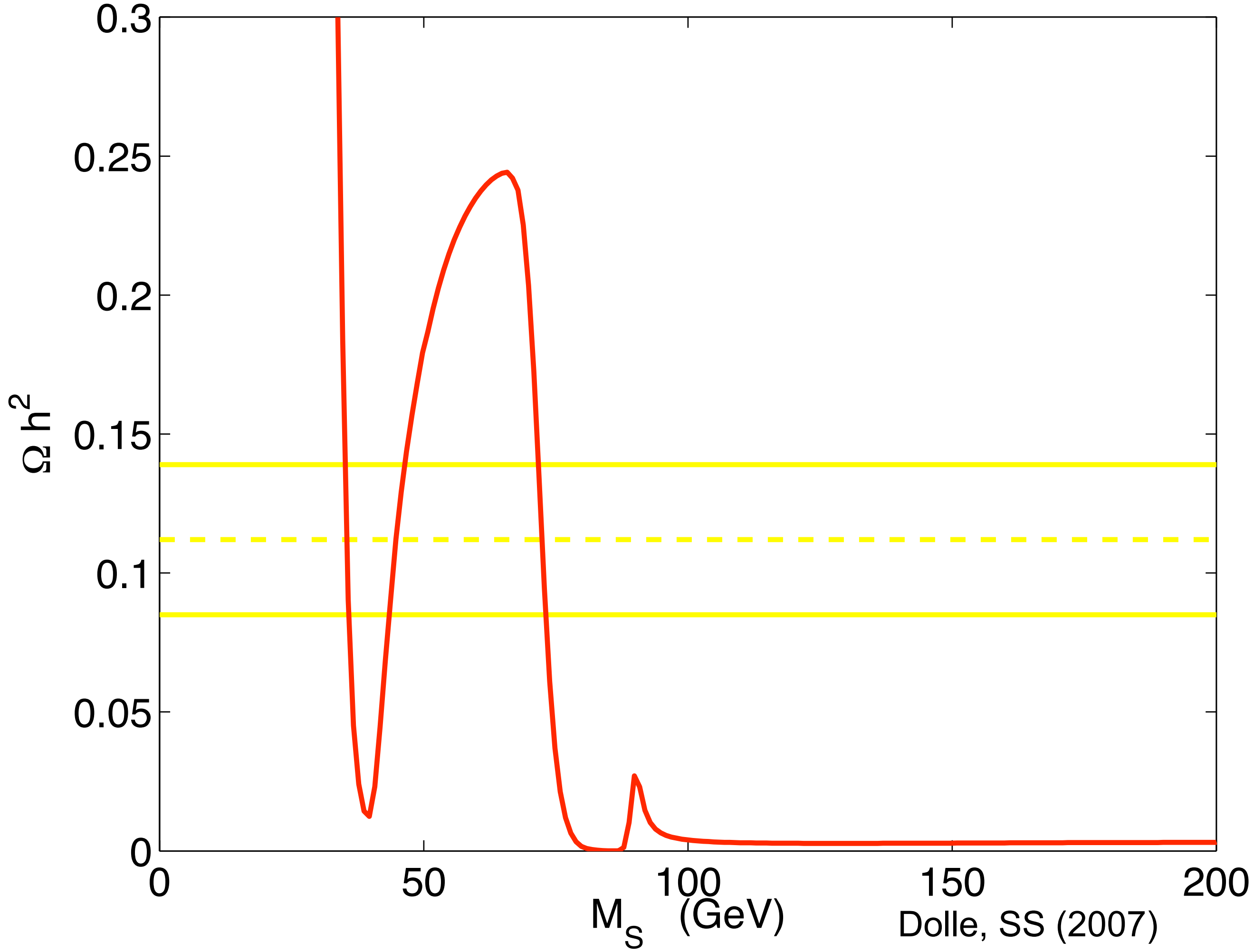




Birkedal, Noble, Perelstein, Spray (2006)

DM in Inert Higgs Doublet Model

$\delta_2 = m_A - m_S = 10$ GeV



Dolle, SS (2007)

SU(2)$_L$ Higgs doublet

$\hat{H}_1^{\pm}$, $\hat{H}_{20}$=S+iA

couple to gauge boson only

Deshpande, Ma,
Barbieri et. al. ,
Cirelli et. al.,
Honorez et. al.,
Gustafsson et. al.,
Majumdar et. al.,
Dolle and Su (2007), ...

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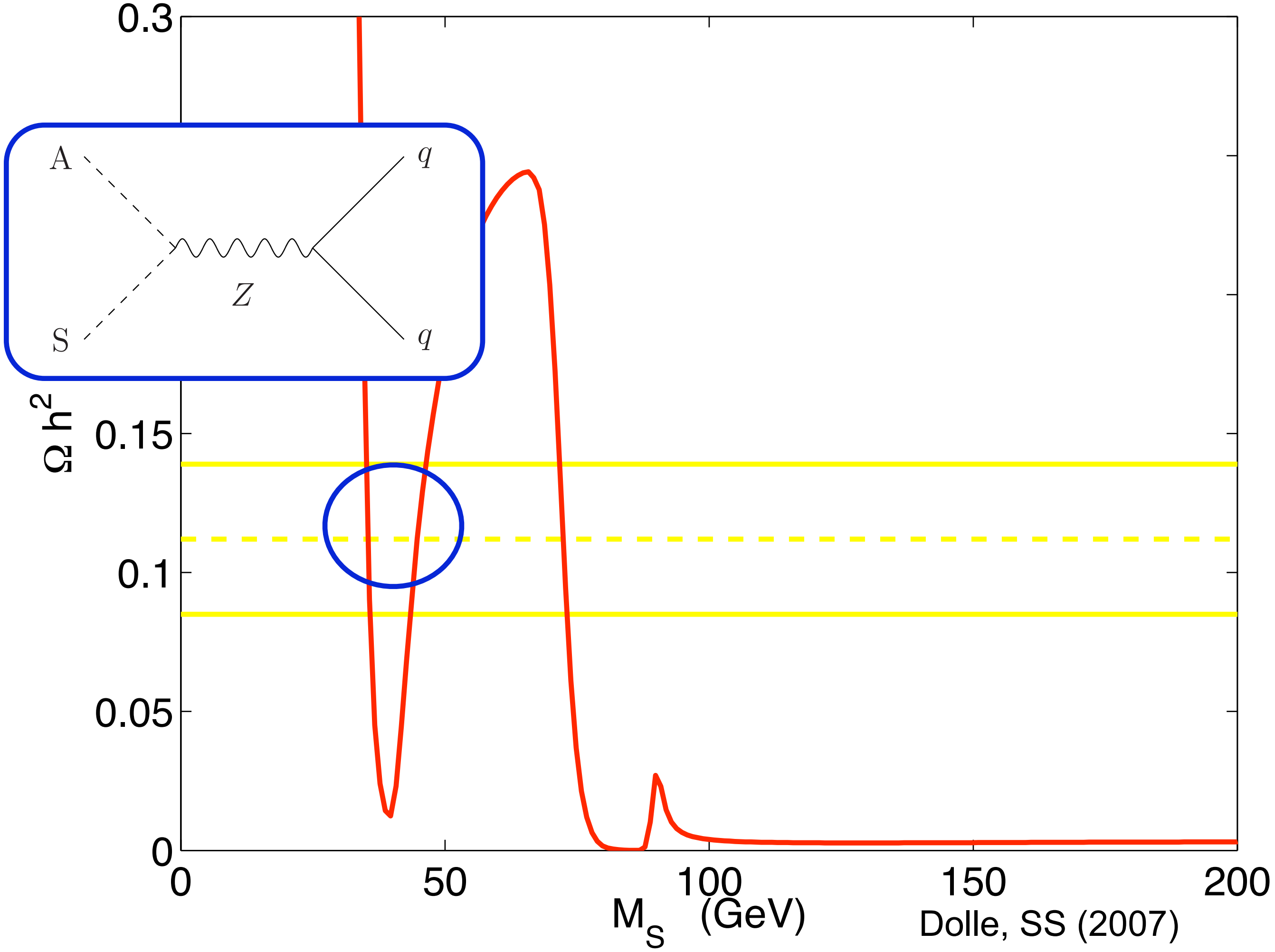

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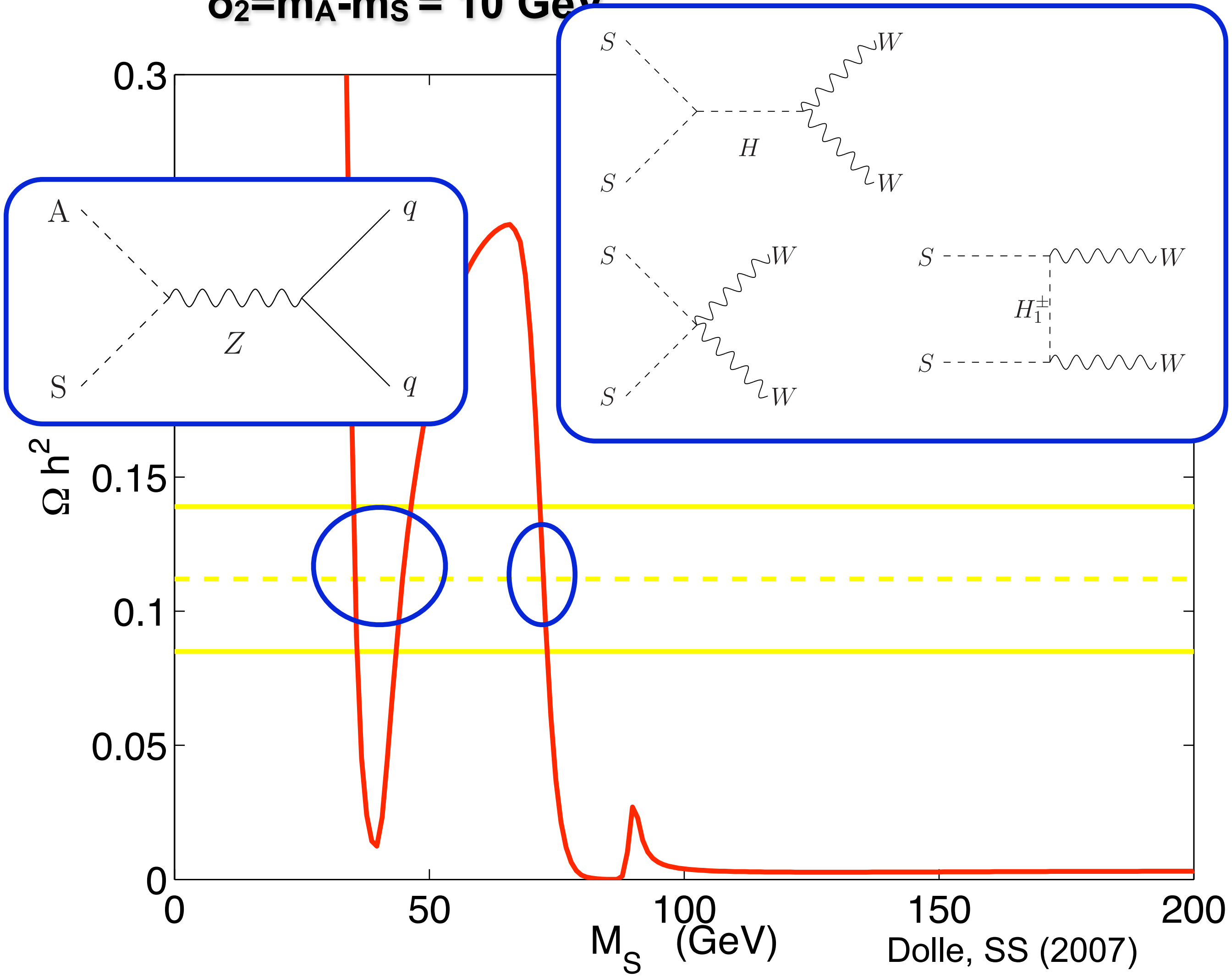

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WIMPless ?

Feng and Kumar (2008)

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

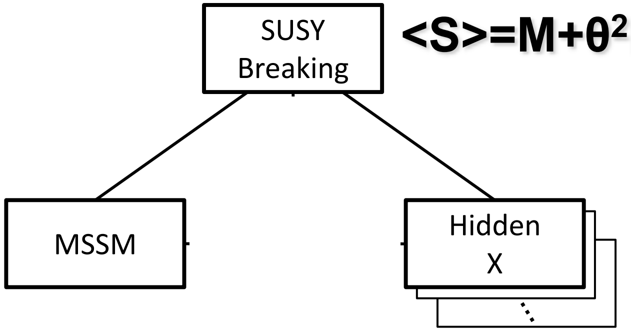
- $(m_X, g_X) \sim (m_{weak}, g_{weak})$, $\Omega h^2 \sim 0.3$
- only fixes one combination of dark matter mass and coupling

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

WIMPless miracle

Feng and Kumar (2008)

SUSY with GMSB



SUSY Breaking

$\langle S\rangle = M + \theta^2 F$

MSSM

Hidden X

March-Russel et. al,
Hooper et. al.,
McDonald et. al,
Kim et. al.,
Krolikowski.

$$W = \lambda \bar{\Phi} S \Phi \qquad\qquad W = \lambda_X \bar{\Phi}_X S \Phi_X$$

messenger F term	$F_m = \lambda F$	$F_{mX} = \lambda_X F$
messenger mass scale	$M_m = \lambda M$	$M_{mX} = \lambda_X M$
superpartner mass	$m \sim \frac{g^2}{16\pi^2}\frac{F_m}{M_m} = \frac{g^2}{16\pi^2}\frac{F}{M}$	$m_X \sim \frac{g_X^2}{16\pi^2}\frac{F_{mX}}{M_{mX}} = \frac{g_X^2}{16\pi^2}\frac{F}{M}$

$$\rightarrow \boxed{\frac{m_X}{g_X^2} \sim \frac{m}{g^2} \sim \frac{F}{16\pi^2 M}} \rightarrow \boxed{\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}}$$

right relic density !
(irrespective of its mass)

WIMPless DM: hidden?

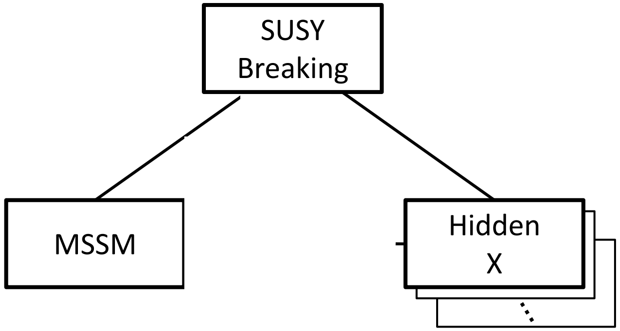
$$10^{-3} \lesssim \; g_X \; \lesssim 3$$
$$10 \text{ MeV} \lesssim m_X \lesssim 10 \text{ TeV}$$

thermal relic non-relativistic at freeze out

unitarity bound

- if no direct coupling to SM: interact only through gravity
- impact on structure formation
- no direct/indirect/collider signals

WIMPless DM: not hidden



SUSY Breaking

MSSM

Hidden X

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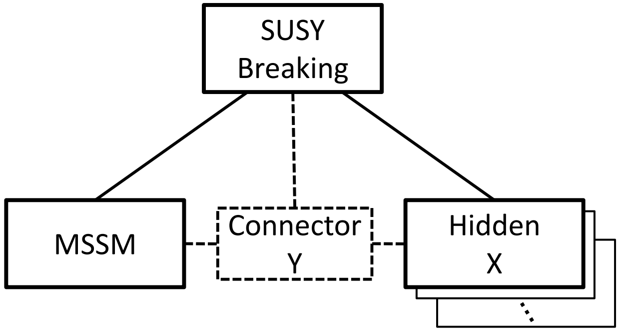

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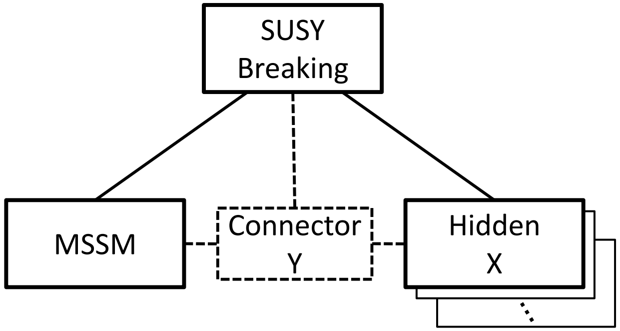


SUSY Breaking

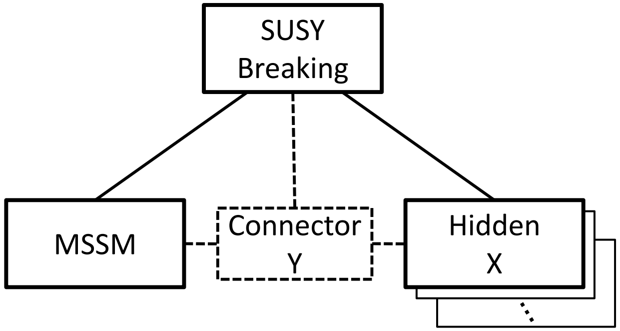
MSSM

Connector Y

Hidden X

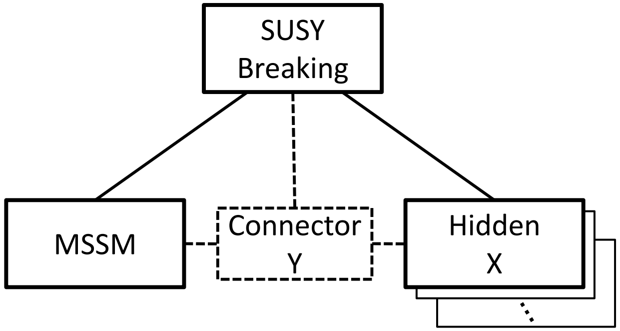
$m_Y \sim \max(m_{weak}, m_X)$

WIMPless DM: not hidden



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

WIMPless DM: not hidden

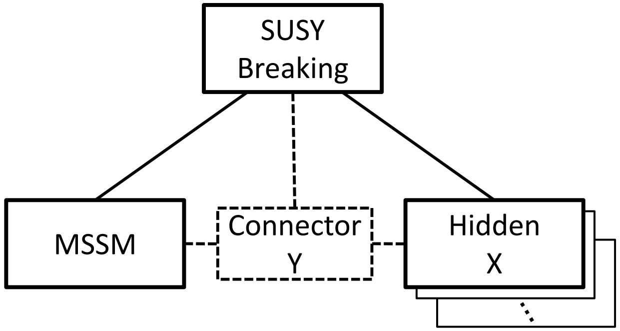


$m_Y \sim \max(m_{weak}, m_X)$

interaction λ XYf

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

WIMPless DM: not hidden



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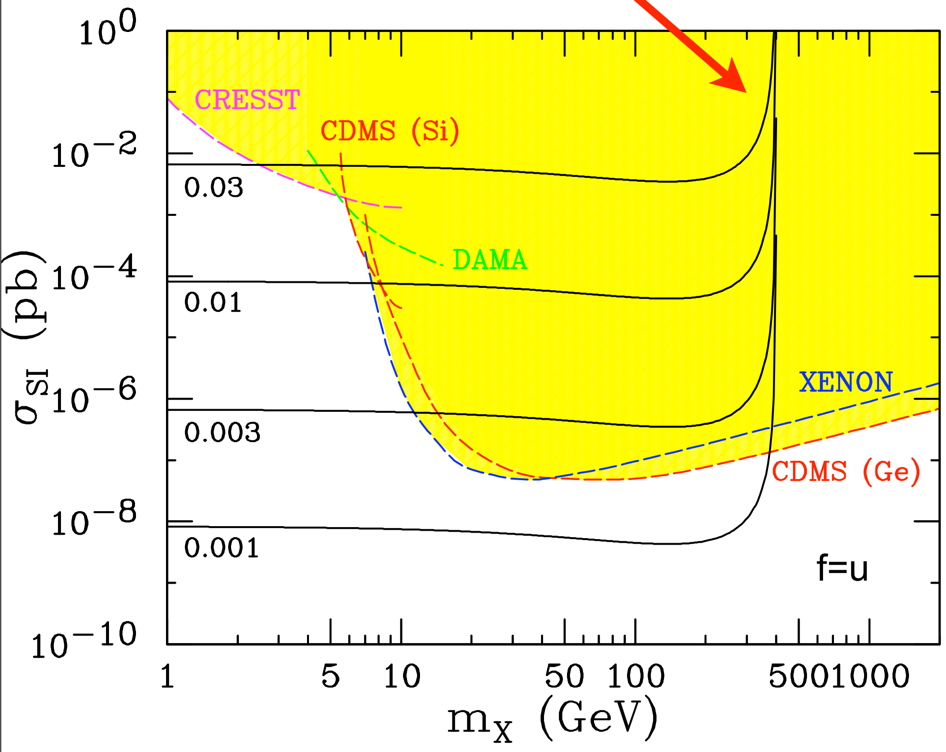
- light DM: $m_X << m_{weak}$
- $\Omega = n\, m$: m↓, n↑

⇒ enhanced indirect detection

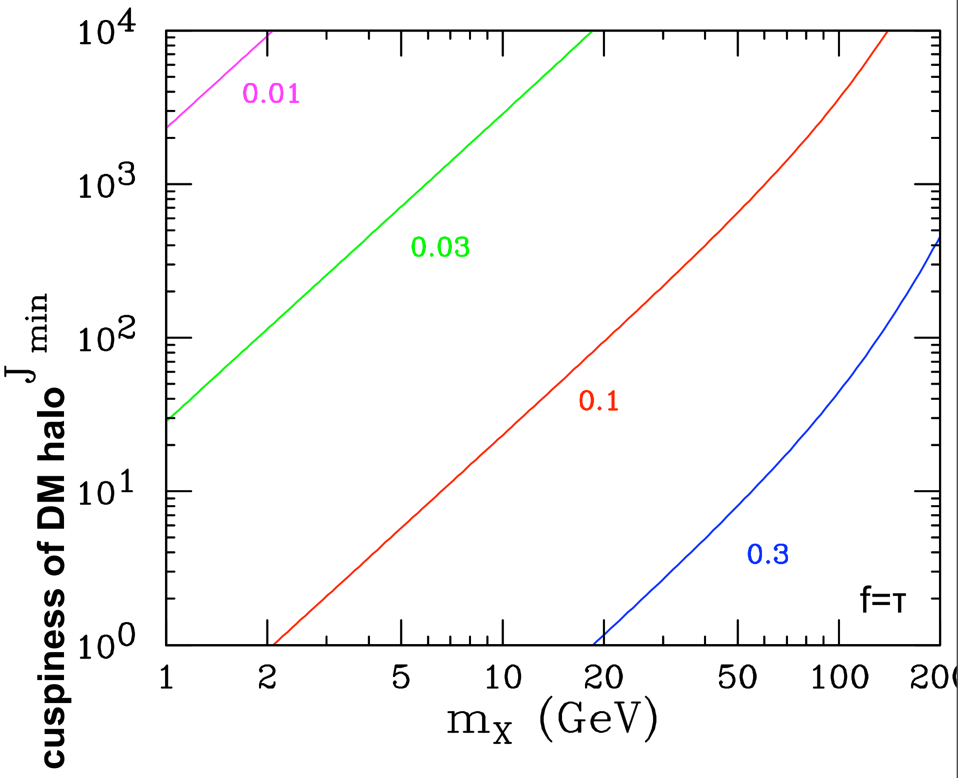
m_{weak}^2/m_X^2 over WIMP signal

WIMPless DM

resonance enhancement



Gamma ray: GLAST



SuperWIMP / Extremely WIMP

DM interaction << Weak interaction. Possible?

CDM requirements

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

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for super-weak coupling

- $\langle\sigma v\rangle$ too small
- Ω_{DM} too big

overclose the Universe

SuperWIMP / Extremely WIMP

if the Universe is never hot enough, low T_R

Thermal production:
plasma scattering

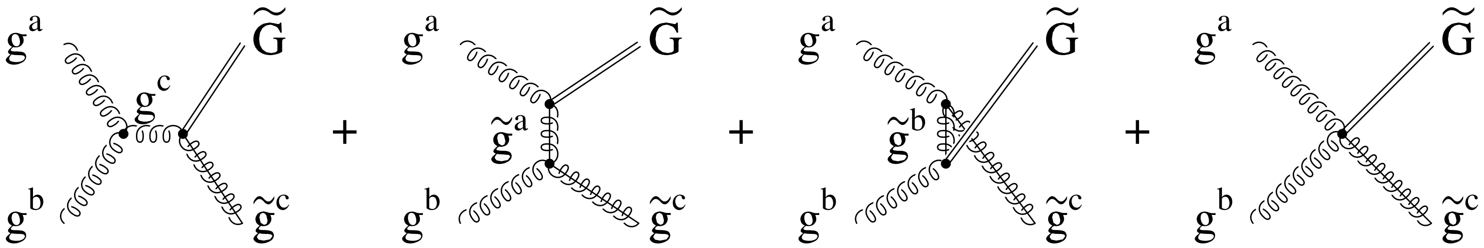
Non-thermal process:
WIMP decay out of equilibrium

	gravitino DM $\tilde{G}$	axino DM $\tilde{a}$
	spin 3/2 superpartner of graviton	spin 1/2 superpartner of axion
mass	GeV - TeV	eV - GeV
interaction	$\propto m_{pl}^{-1}$, $m_{pl} \sim 10^{19}$ GeV	$\propto f_a^{-1}$, $f_a \geq 5 \times 10^9$ GeV

Thermal production

Gravitino

Bolz, Brandenburg and buchmuller (2001)



$$\boxed{\Omega_{\tilde{G}}^{\rm Thermal} \approx 0.2 \left(\frac{100\ {\rm GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\ {\rm TeV}}\right)^2\left(\frac{T_R}{10^{10}\ {\rm GeV}}\right)}$$

- $\Omega \Rightarrow$ upper bound on T_R
- Leptogenesis: $T_R > 10^9$ GeV $\Rightarrow m_{3/2} > 10$ GeV

$m_{3/2}^{\rm min} \sim T_R\, m_{\rm gluino}^2$

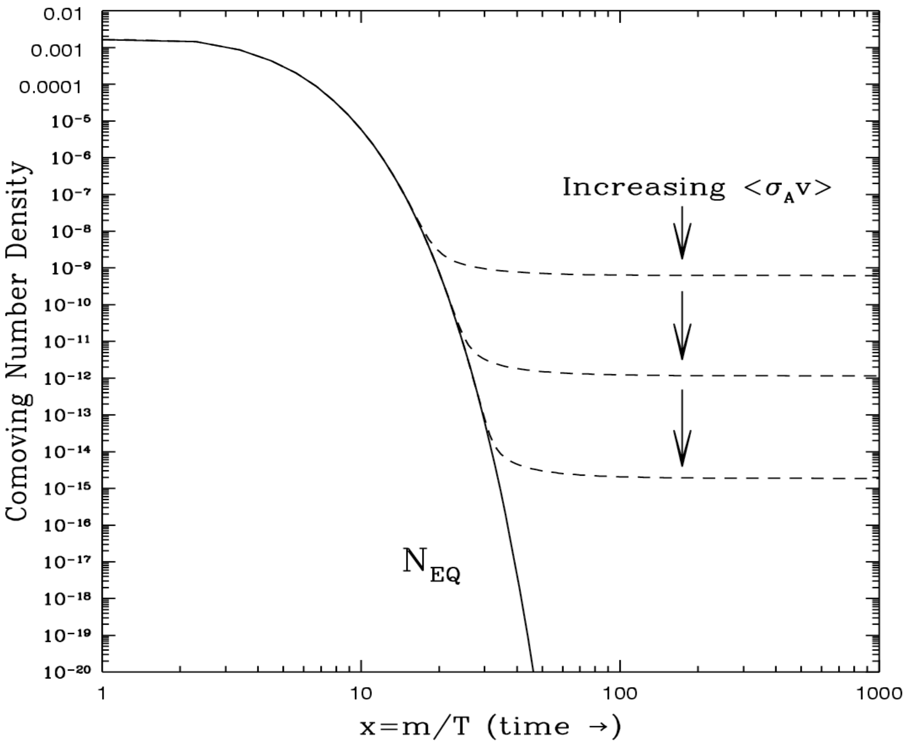
Axino

Covi, Kim, Kim and Roszkowski (2001); Brandenburg and Steffen (2004)

$$\boxed{\Omega_{\tilde{a}}^{\rm Thermal} \approx 0.6 \left(\frac{m_{\tilde{a}}}{0.1\ {\rm GeV}}\right)\left(\frac{10^{11}\ {\rm GeV}}{f_a}\right)^2\left(\frac{T_R}{10^{4}\ {\rm GeV}}\right)}$$

Non-thermal production: WIMP decay

WIMP → superWIMP + SM particles



Kim, Masiero, Nanopoulos (1984)
Covi, Kim, Roszkowski (1999)
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);
...

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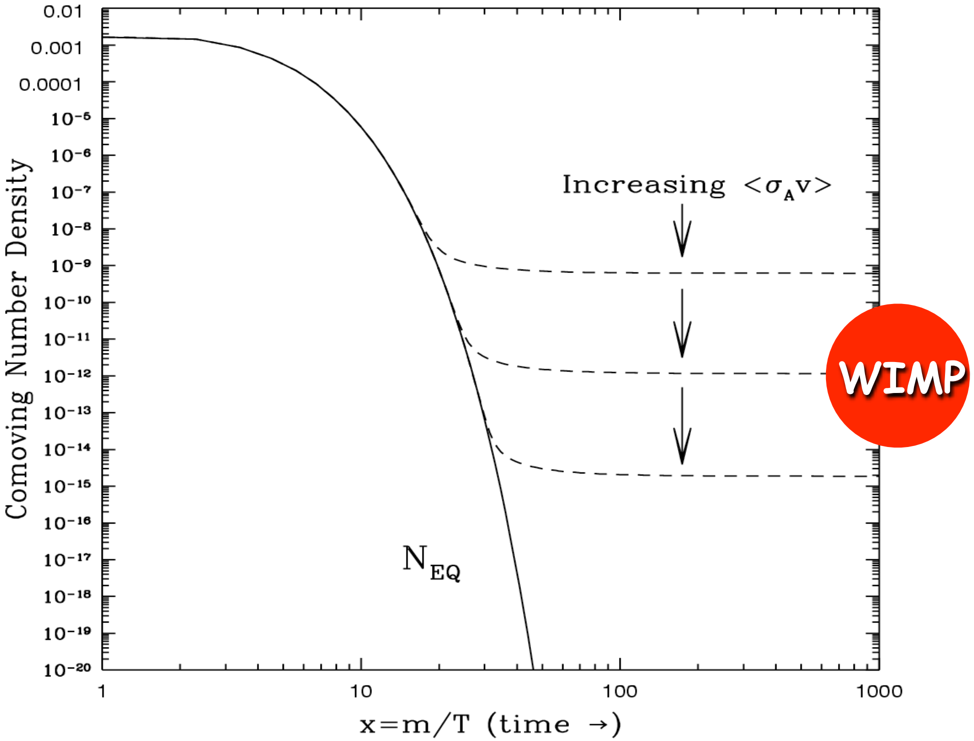

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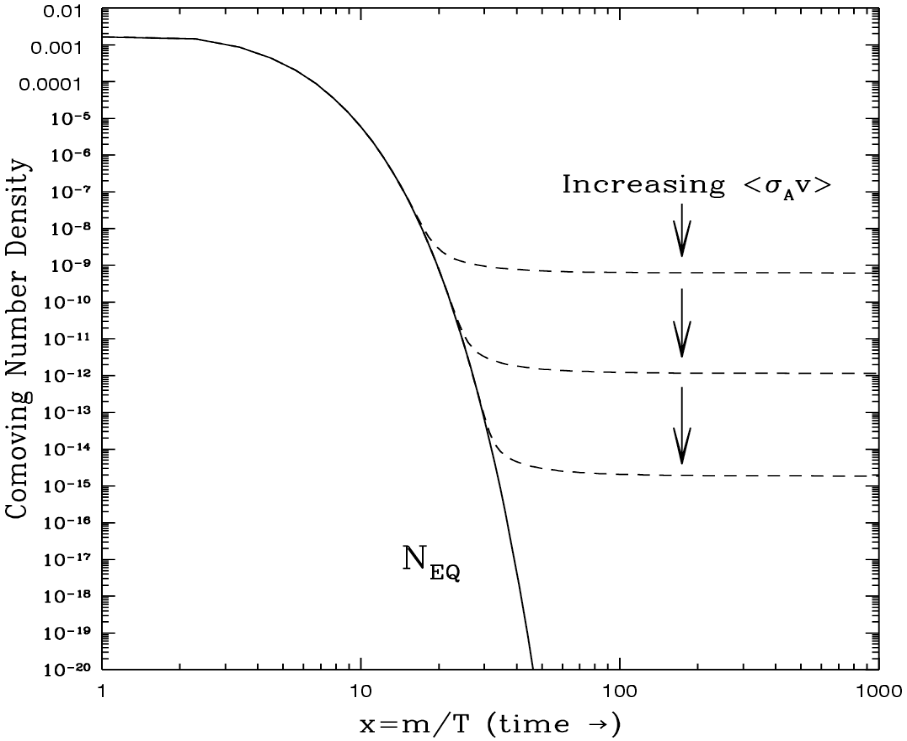

WIMP

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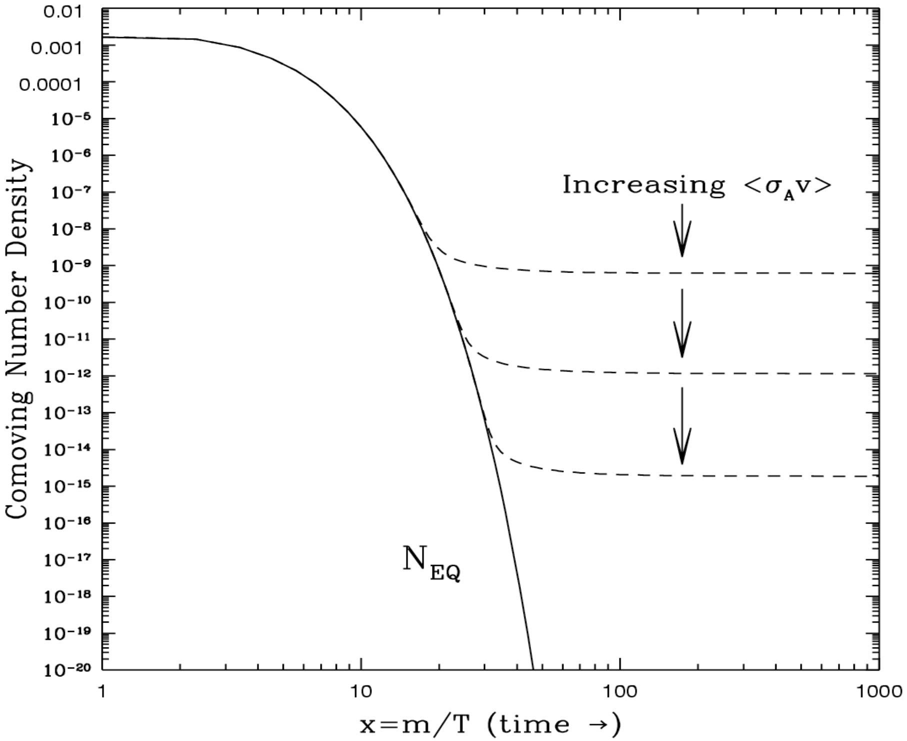


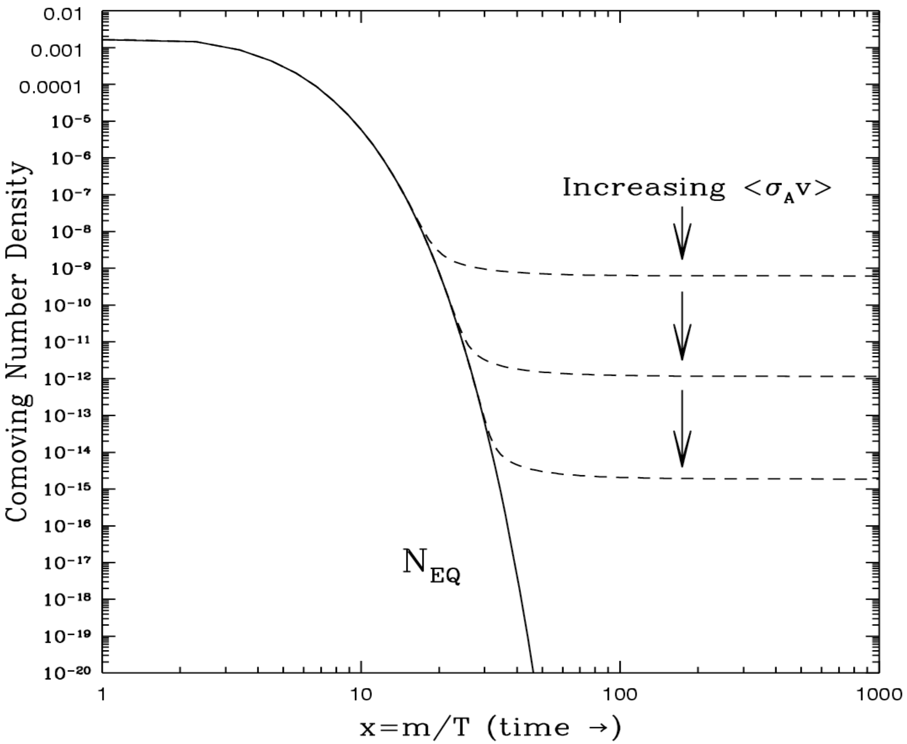
SWIMP

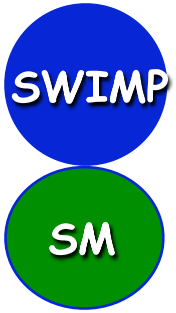
SM

Non-thermal production: WIMP decay

WIMP → superWIMP + SM particles

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





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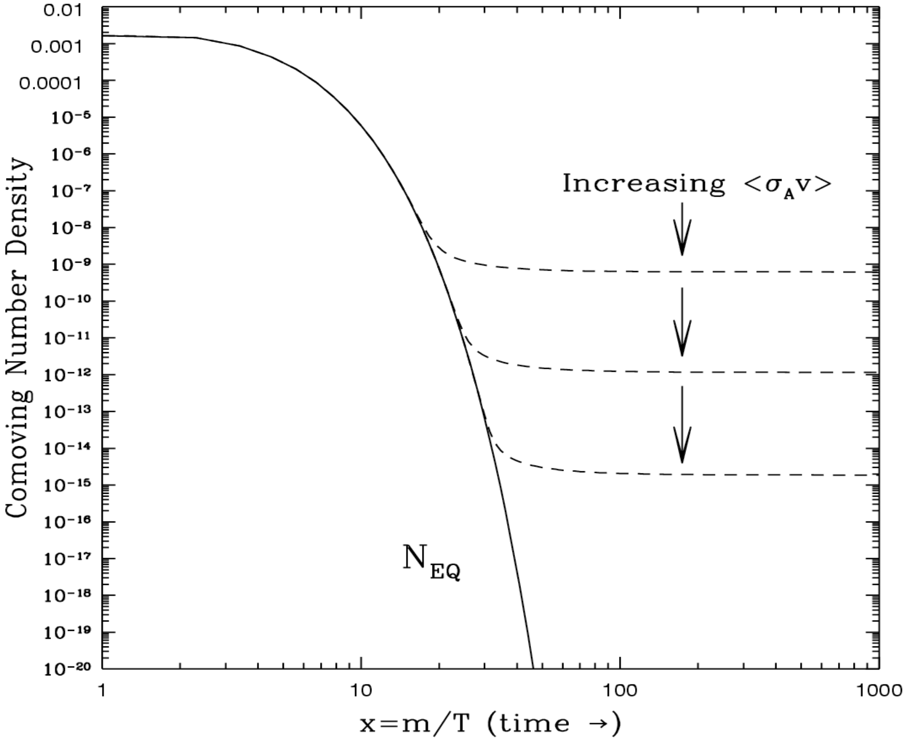
WIMP → superWIMP + SM particles

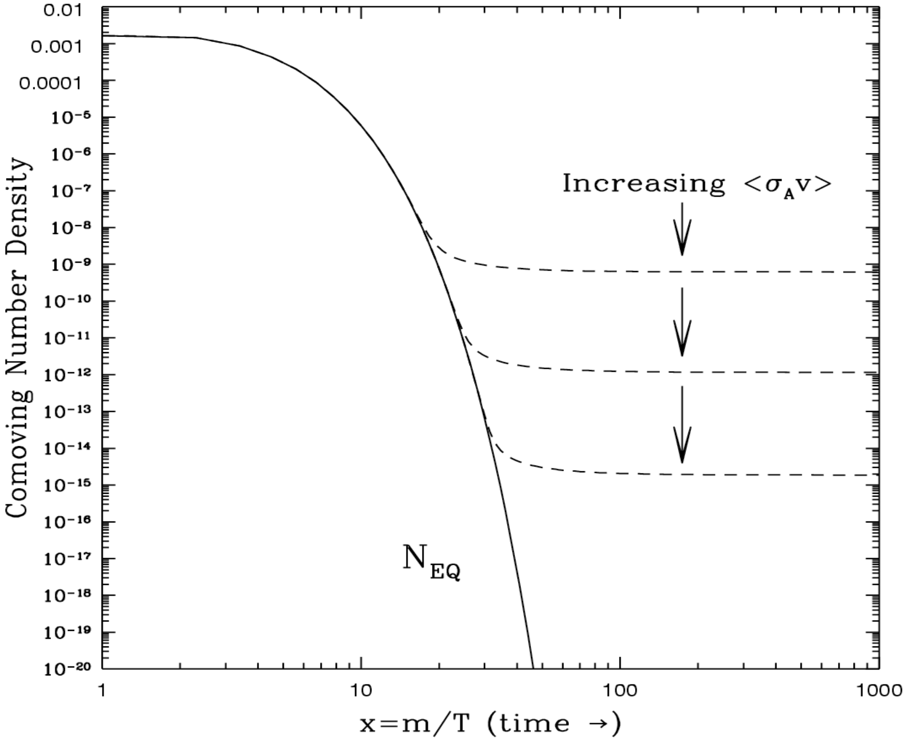
$$\Omega_{\mathrm{SWIMP}} = \frac{m_{\mathrm{SWIMP}}}{m_{\mathrm{WIMP}}} \Omega_{\mathrm{WIMP}}$$



Non-thermal production: WIMP decay

WIMP → superWIMP + SM particles

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



superWIMP

e.g. Gravitino LSP

LKK graviton

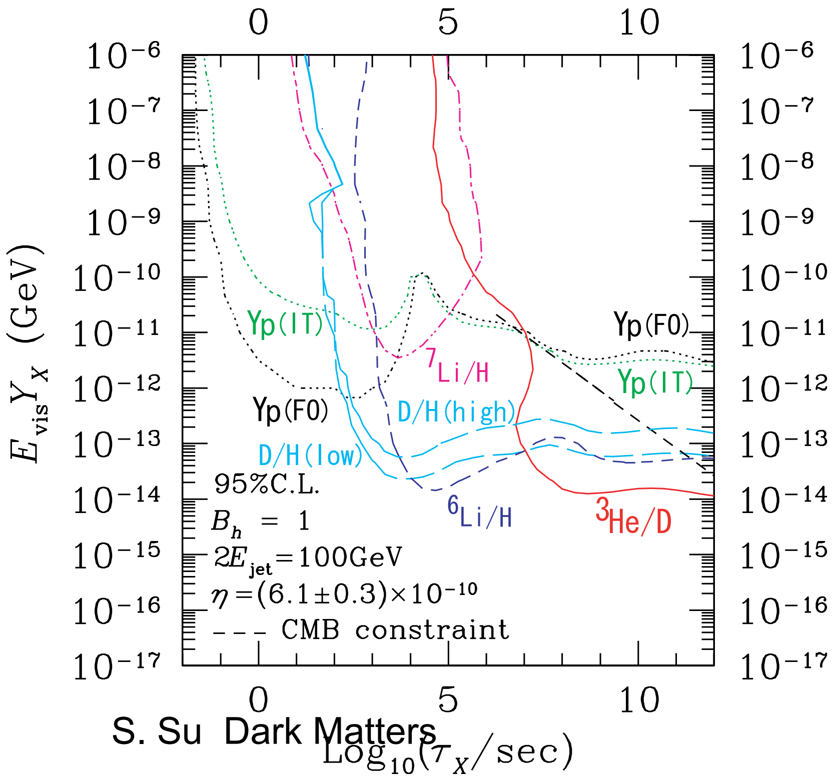
axino

WIMP

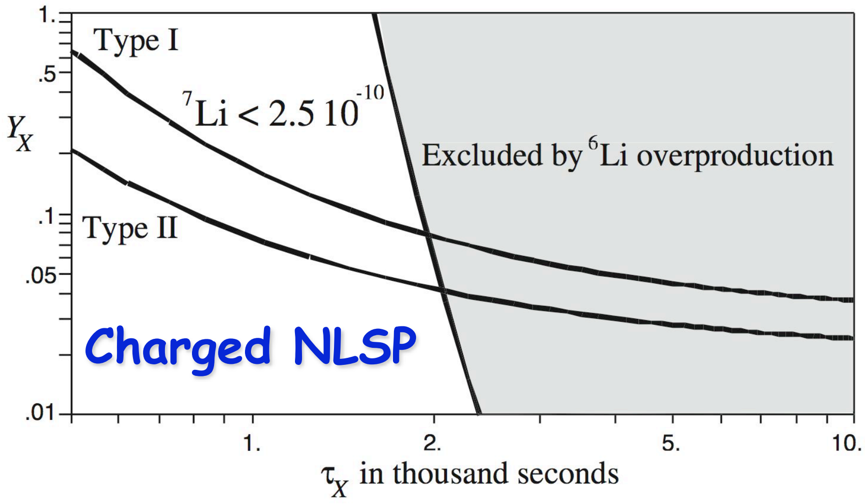
- neutral
- charged

superWIMP DM

	gravitino DM	axino DM
lifetime	10^4 sec - 15 years for $m_{3/2}$: 1 GeV - 50 GeV	O(0.01 sec)-O(10 h) for f: 5×10^9 - 5×10^{12} GeV
BBN constraints	severe	mild



Kohri, Kawasaki, Moroi (2004)



Charged NLSP

Pospelov (2005), Kohri and Takayama (2006), Cyburt et al (2006), Jedamzik (2007), ...

BBN constraints

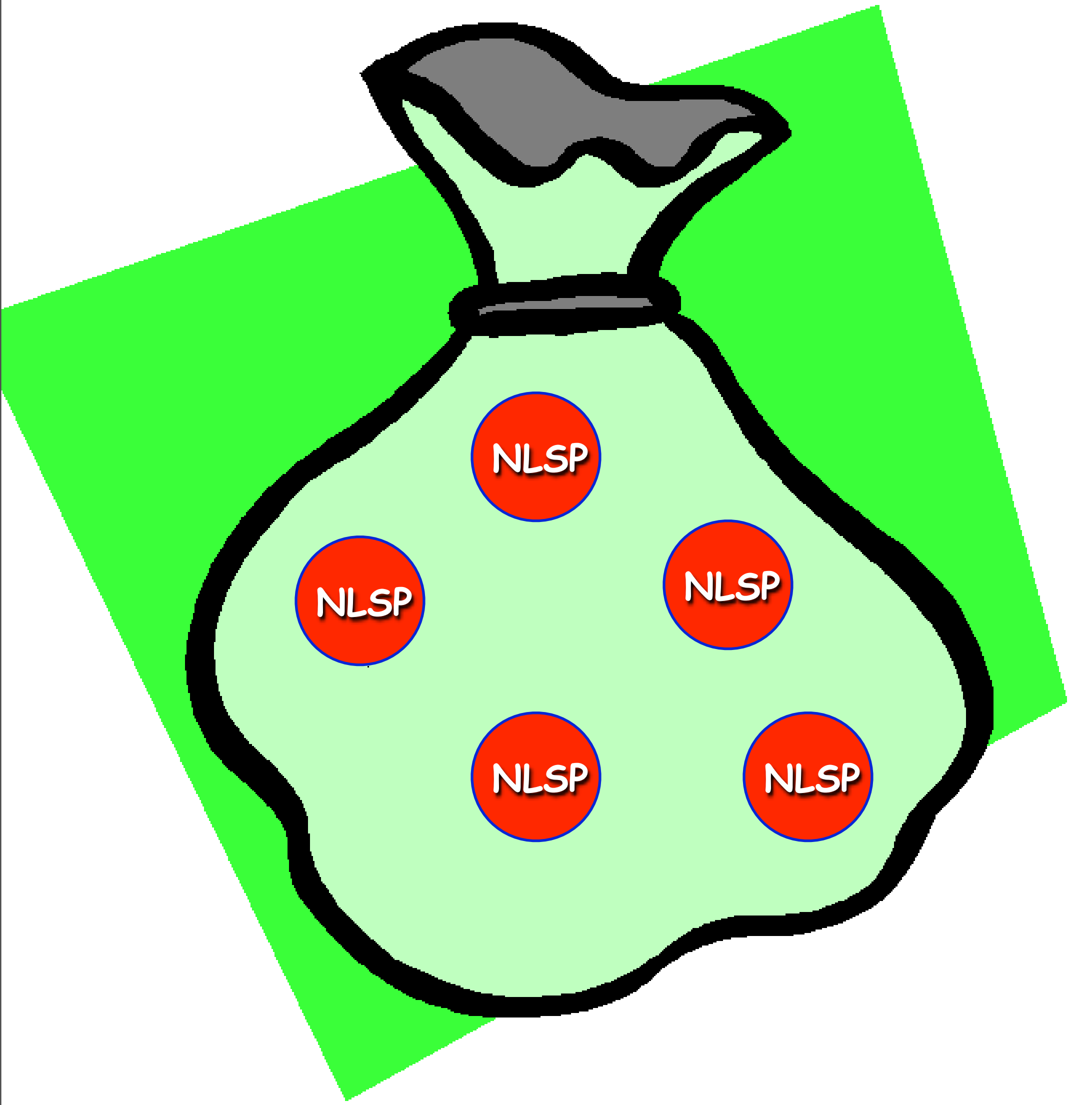
charged NLSP (stau)	neutralino NLSP	sneutrino NLSP
EM, had BBN	EM, had BBN	$Br_{had} < 10^{-3}$
$\tau \lesssim 10^3 \sim 10^4$ sec $m_{3/2} < 1$ GeV	$\tau \lesssim 10^2$ sec smaller mass	longer lifetime larger $m_{3/2}$
strongly constrained	strongly constrained	viable
Pospelov, Cyburt et. al., Kohri et. al., Kaplinghat et. al., Kawasaki et. al., Feng et. al., Steffen...	Kawasaki et. al., Feng et. al., Steffen	Kawasaki et. al., Feng et. al., Steffen

- harmless NLSP: sneutrino
- dilute with entropy production Buchmuller et. al. (2006)

} ⇒ RPC scenario

- NLSP decay earlier ⇒ RPV scenario

RPC superWIMP DM with charged slepton NLSP



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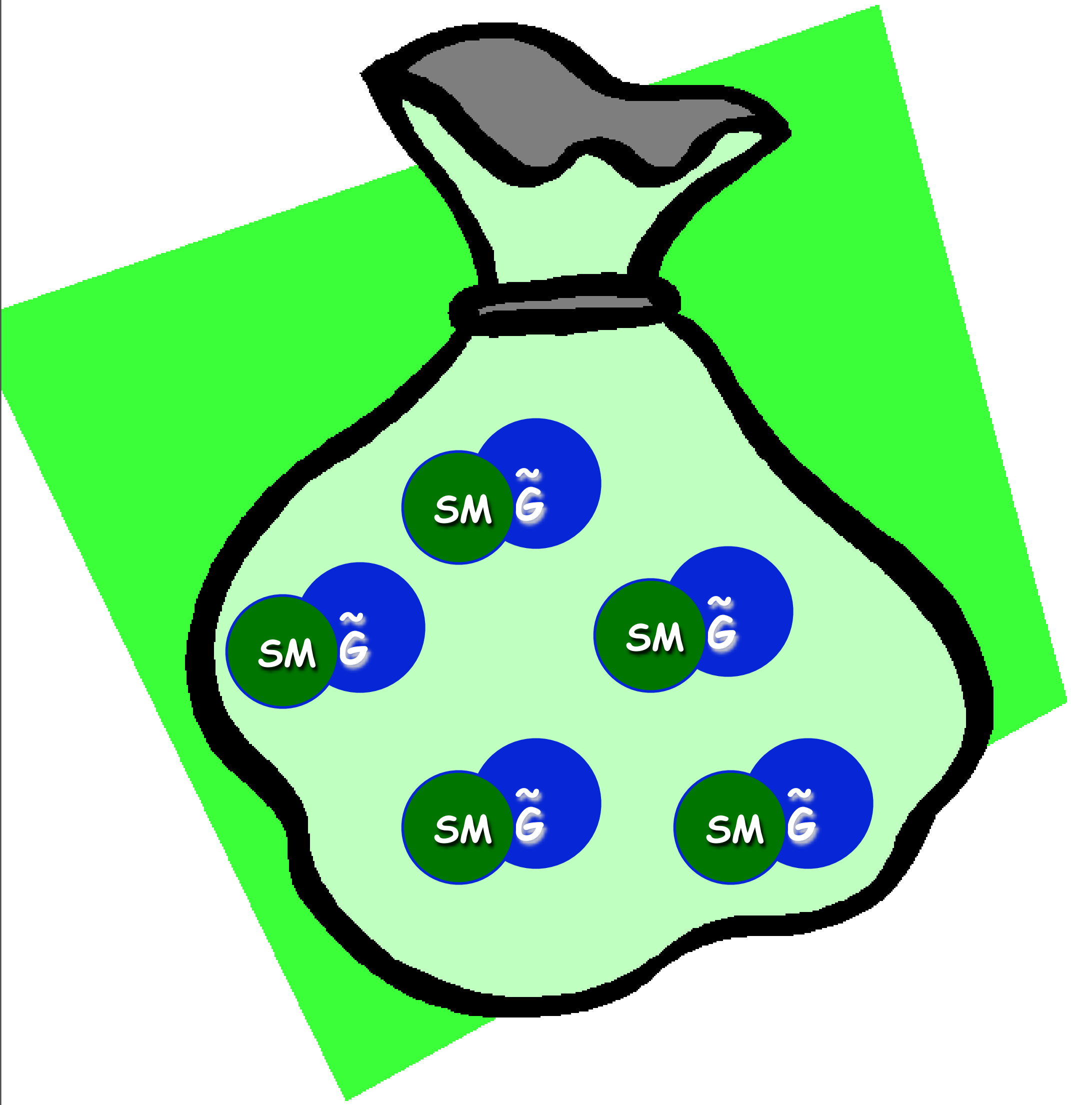

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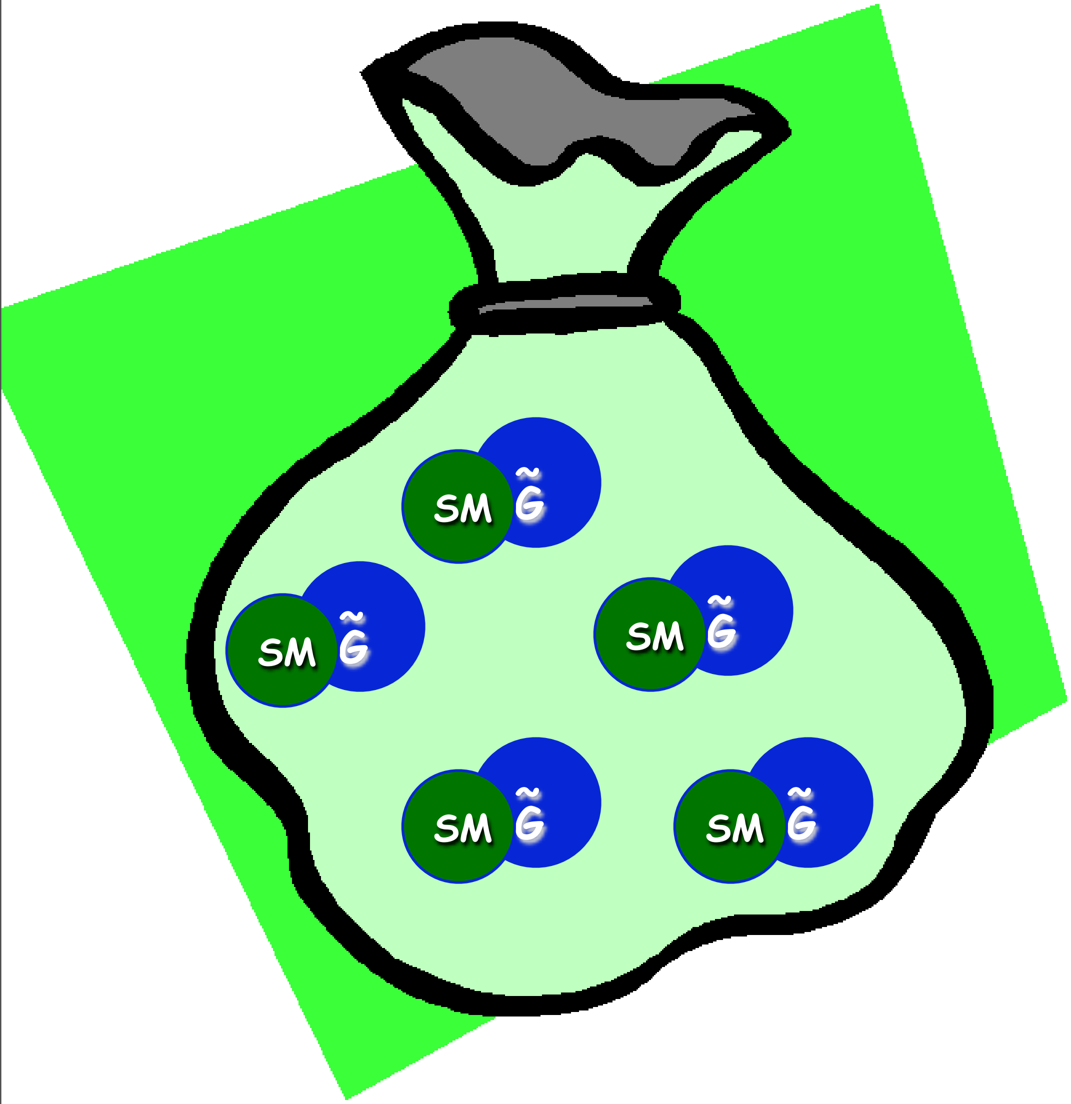

- Probes gravity in a particle physics experiments!
- Precise test of supergravity or Peccei-Quinn scale

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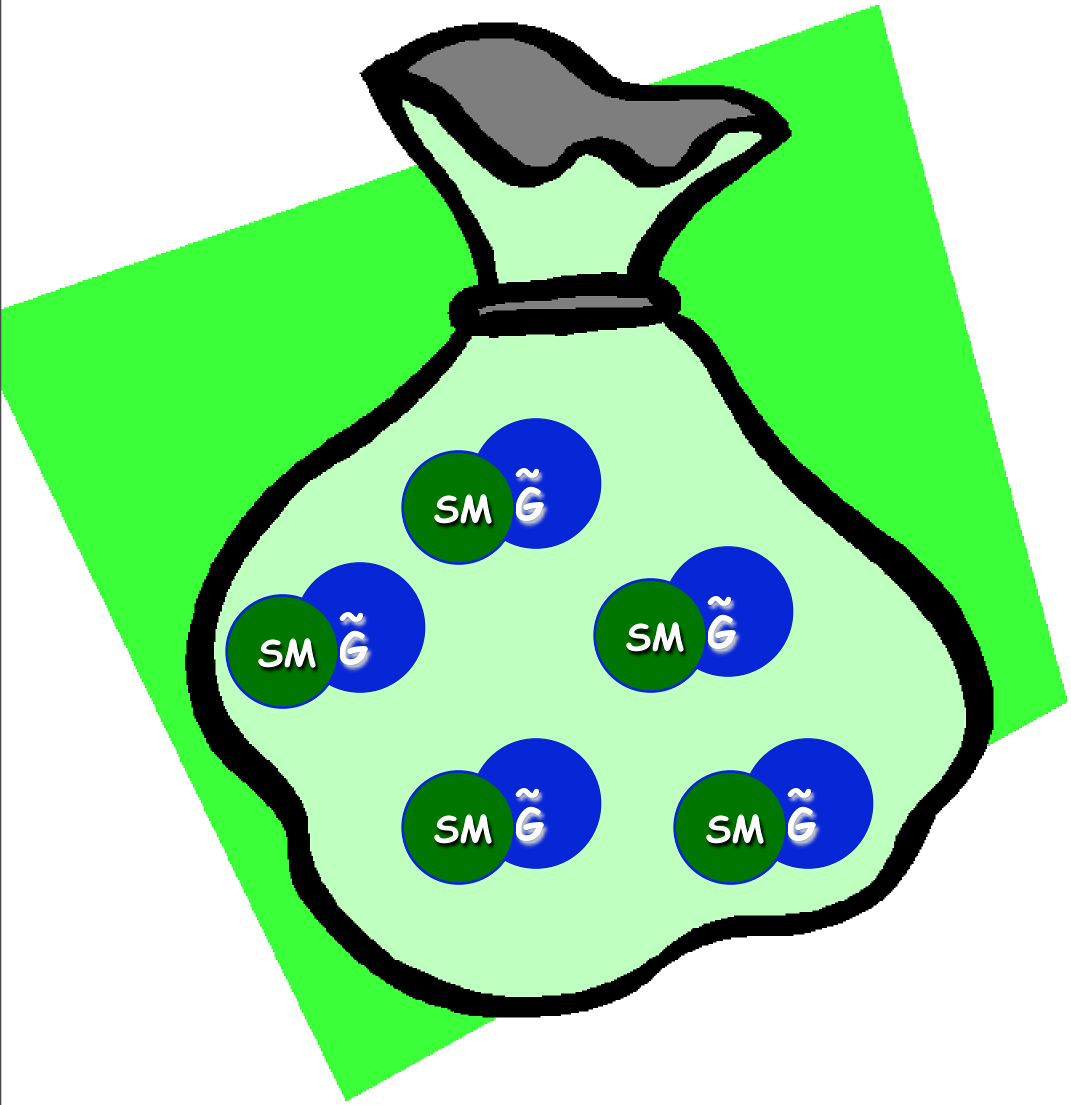

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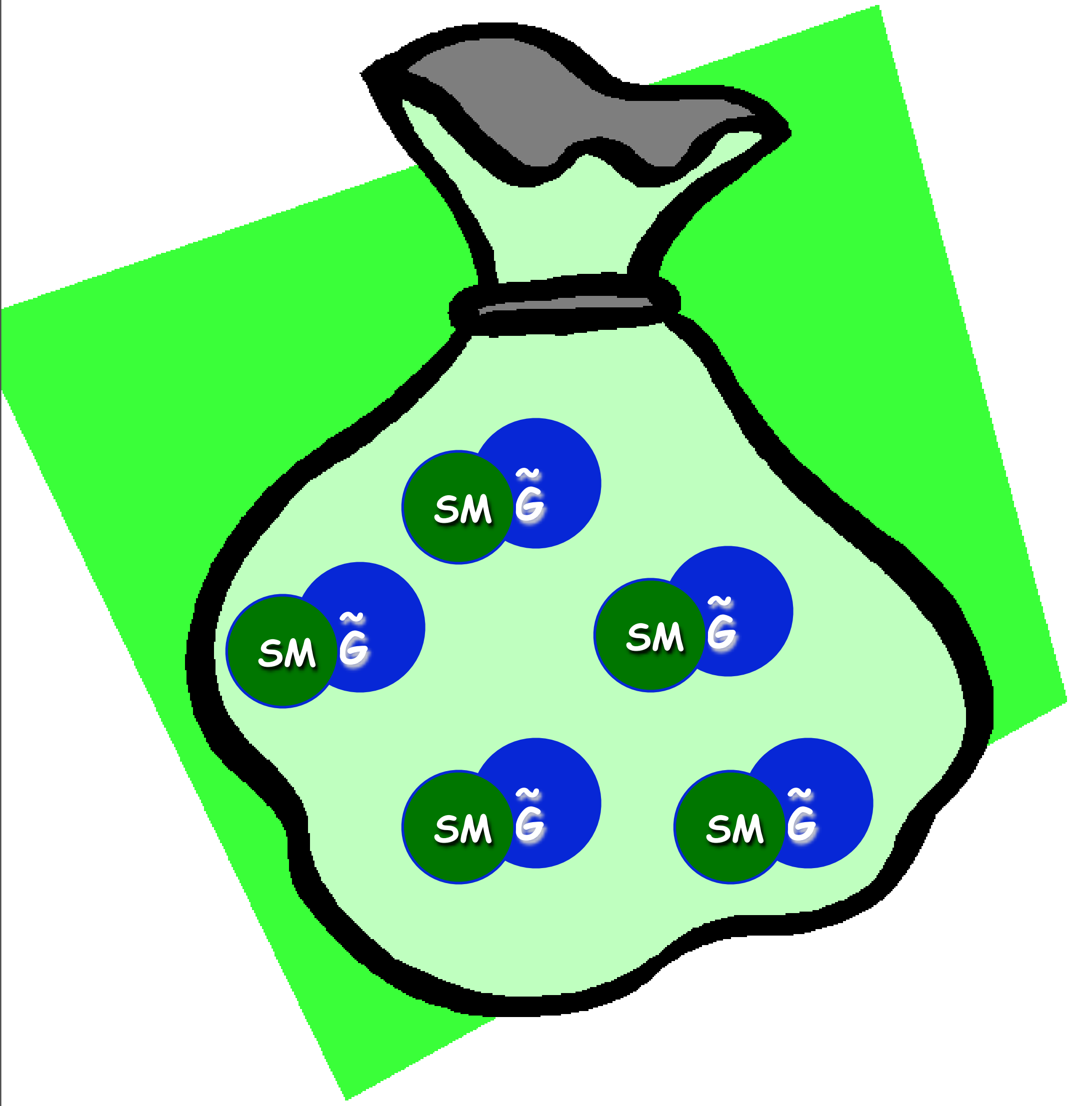
How to trap charged slepton?

RPC superWIMP DM with charged slepton NLSP



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How to trap charged slepton?

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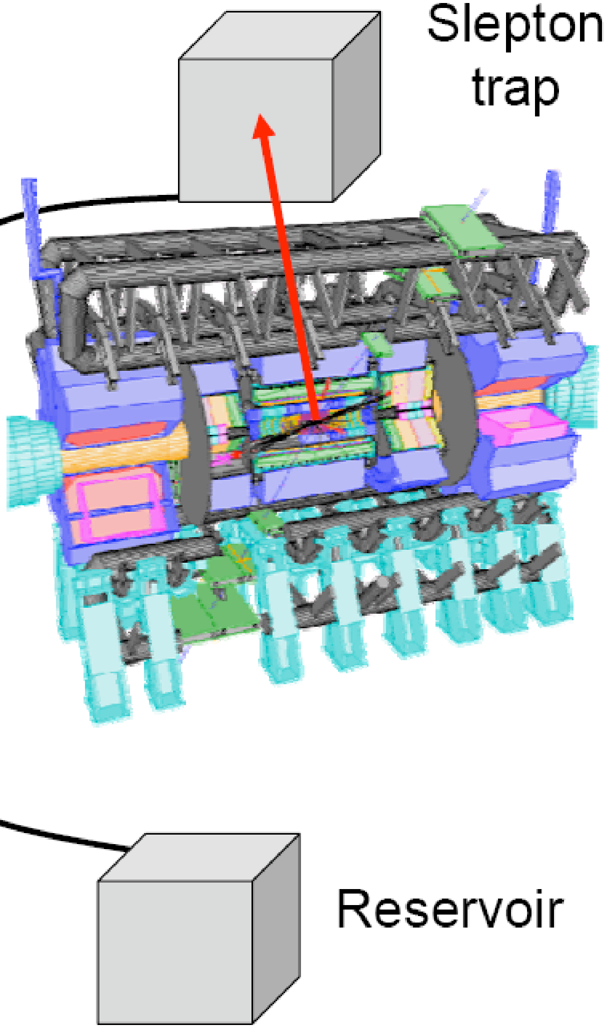
Feng and Smith, (2004)
De Roeck et. al., (2005)

Charged slepton trapping

Feng and Smith (2004)

Slepton could live for a year, so can be trapped then moved to a quiet environment to observe decays



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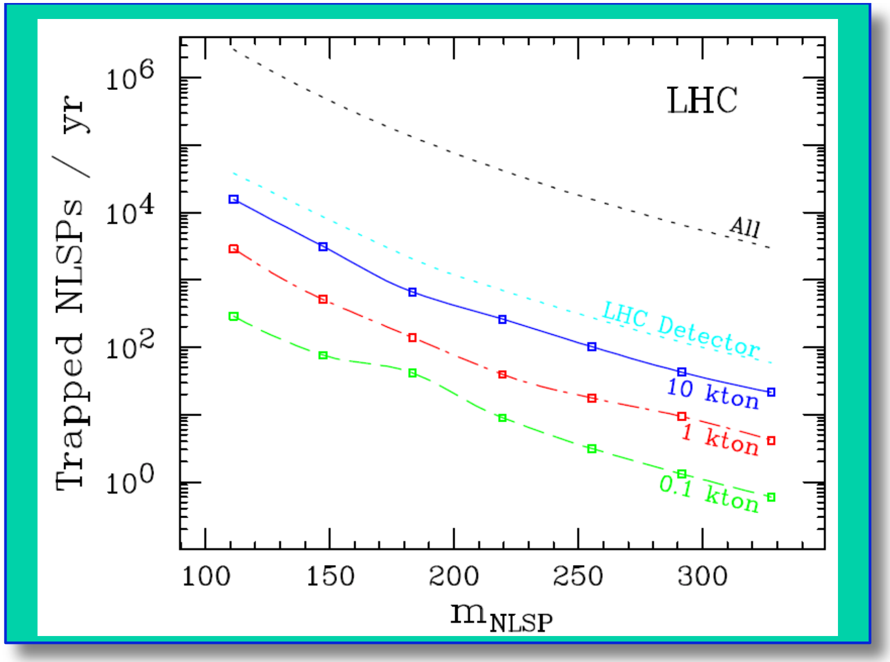

- LHC: 10^6 slepton/yr possible, but most are fast.
Catch 100/yr in 1 kton water

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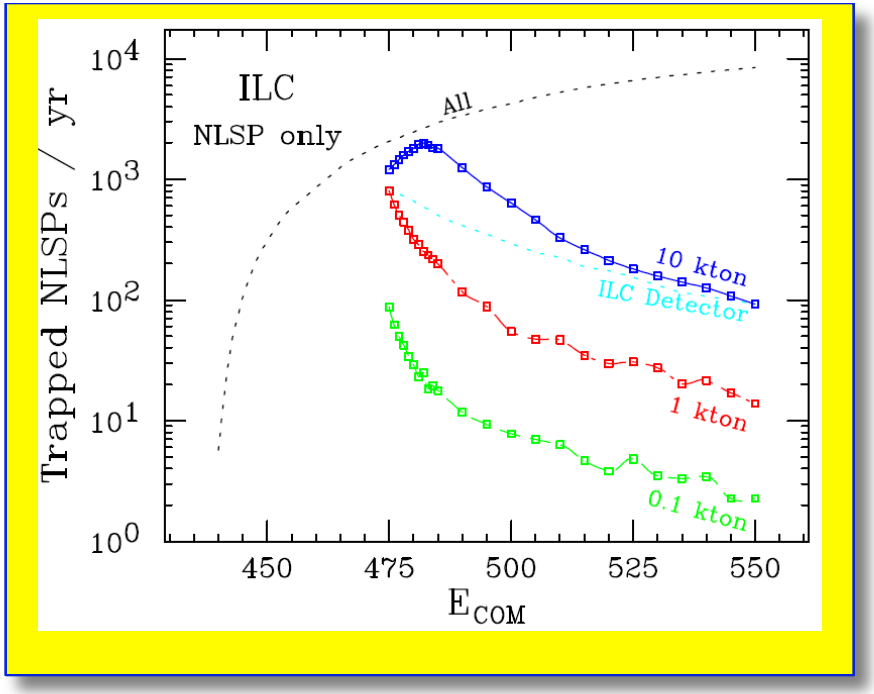
- LHC: 10^6 slepton/yr possible, but most are fast.
  Catch 100/yr in 1 kton water

- LC: tune beam energy to produce slow sleptons,
  can catch 1000/yr in 1 kton water



S. Su Dark Matters

Microscopic determination of M_{pl}, f_a

RPC gravitino DM with long lived stau

Buchmuller, Hamaguchi,
Ratz and Yanagida (2004)

$\tilde{\tau} \to \tau + \tilde{G}$

$$\Gamma_{\tilde{\tau}}^{2-\mathrm{body}} = \frac{m_{\tilde{\tau}}^5}{48\pi\, m_{3/2}^2\, M_{\mathrm{P}}^2} \times \left(1 - \frac{m_{3/2}^2}{m_{\tilde{\tau}}^2}\right)^4$$

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measured at collider

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small: ignored. large: from kinematics

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Axino vs. Gravitino

Brandenburg, Covi, Hamaguchi, Roszkowski and Steffen (2005)

	axino DM	gravitino DM
lifetime	$\propto f_a^2/m_{stau}\, m_{bino}^2$	$\propto m_{pl}^2 m_{3/2}^2/m_{stau}^5$
	O(0.01 sec)-O(10 h) for f_a: 5x10^9 - 5x 10^{12} GeV	10^{-8} sec - 15 years for $m_{3/2}$: 1 keV - 50 GeV
	$\tilde{\tau}_R \to \tau_R + \tilde{a} + \gamma$	$\tilde{\tau}_R \to \tau_R + \tilde{G} + \gamma$
Br_{3body}	large	small
angular distri	different	

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	axin	DM
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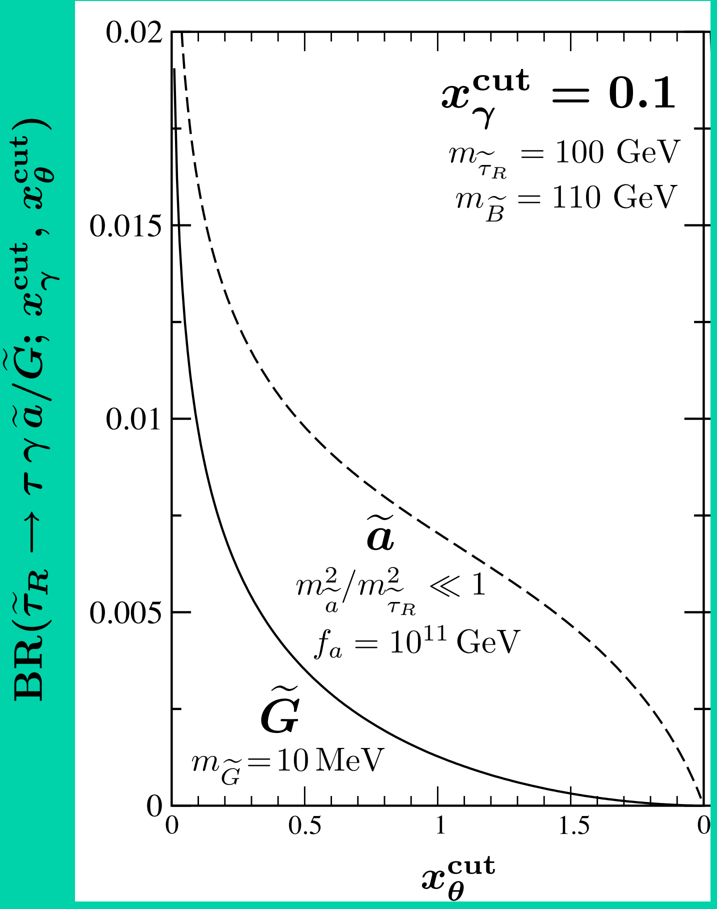

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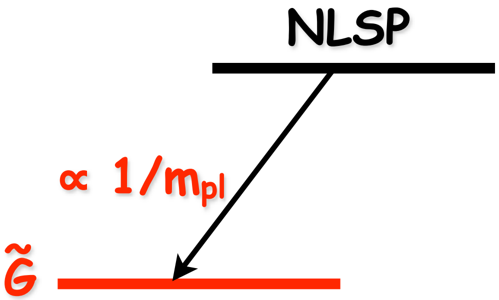
RPV Gravitino DM

Buchmuller, Covi, Hamaguchi, Ibarra and Yanagida (2007)

avoid BBN constraints, NLSP decay earlier



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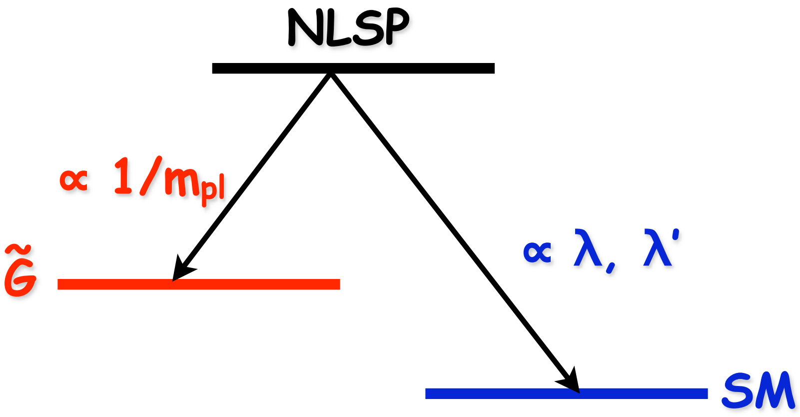

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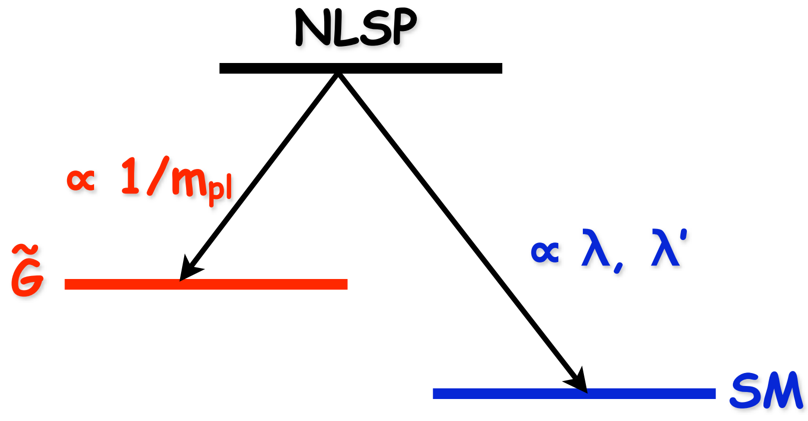

$$W_{\Delta L=1} = \lambda_{ikj} l_i e_j^c l_k + \lambda'_{kji} d_i^c q_j l_k$$

$$\tau_{\rm NLSP} \simeq 10^3 {\rm s} \left(\frac{\lambda}{10^{-14}}\right)^{-2} \left(\frac{m_{\rm NLSP}}{100\ {\rm GeV}}\right)^{-1}$$

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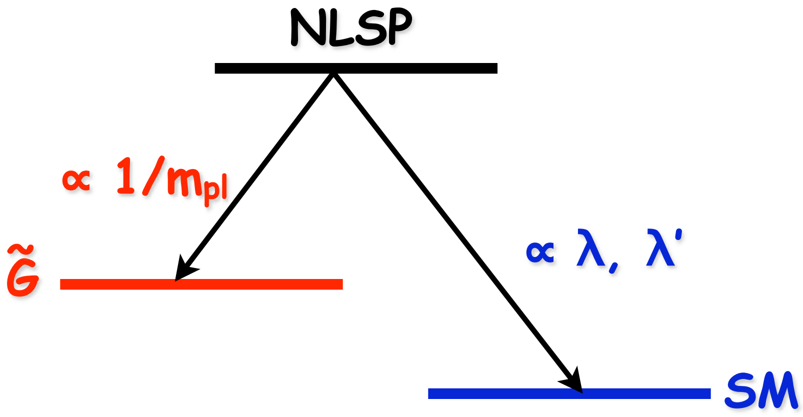

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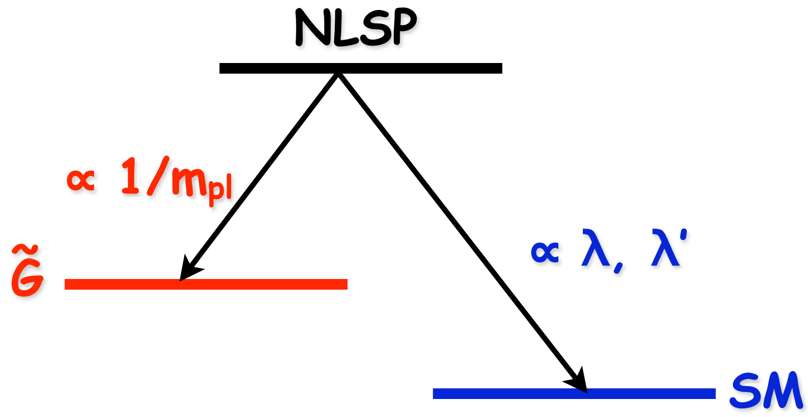

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>> age of the Universe: 10^{17} sec

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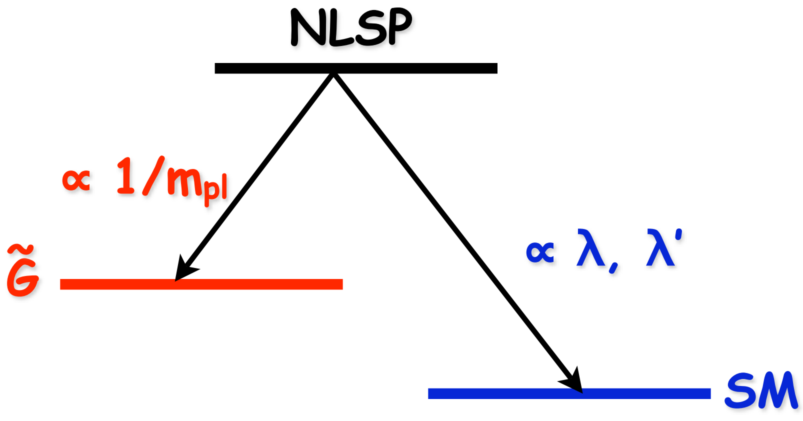

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- Thermal production

$$\Omega_{3/2}h^2 \ \approx \ 0.27 \left(\frac{T_R}{10^{10}\ {\rm GeV}}\right) \left(\frac{100\ {\rm GeV}}{m_{3/2}}\right) \left(\frac{m_{\tilde{g}}}{1\ {\rm TeV}}\right)^2$$

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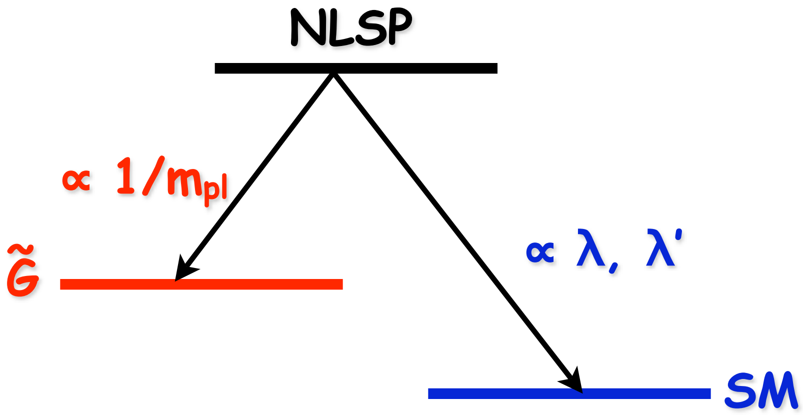

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primordial nucleosynthesis, thermal leptogenesis, gravitino DM consistent

$$10^{-14} < \lambda, \lambda' < 10^{-7}$$

Collider signature: RPV gravitino DM

Buchmuller, Covi, Hamaguchi, Ibarra and Yanagida (2007)

stau NLSP

- $\tilde{\tau}_R \to \tau\nu_\mu,\ \mu\nu_\tau$

$$c\tau_{\tilde{\tau}}^{lep} \sim 30 \text{ cm} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\epsilon_2}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2}$$

baryogenesis: $\epsilon_2 < 10^{-6}$

⇒ charged track longer than 3 mm

Signal: heavily ionizing charged track, followed by a lepton or a jet and $\not{E}_T$

- $\tilde{\tau}_L \to bt$

$$c\tau_{\tilde{\tau}}^{had} \sim 1.4 \text{ m} \left(\frac{m_{\tilde{\tau}}}{200\text{GeV}}\right)^{-1} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2} \left(\frac{\cos\theta_\tau}{0.1}\right)^{-2}$$

Signal: heavily ionizing charged track, followed by two jets, one lepton and $\not{E}_T$

RPV vs. RPC

distinguish from RPC decay

$\tilde{\tau}_R \to \tau\ \tilde{G}$

$$c\tau_{\tilde{\tau}}^{3/2} \sim 40\ \mathrm{cm} \left(\frac{m_{3/2}}{1\ \mathrm{keV}}\right)^{2} \left(\frac{m_{\tilde{\tau}}}{200\ \mathrm{GeV}}\right)^{-5}$$

decay inside the detector if $m_{3/2} < 10$ keV

Signal: heavily ionizing charged track, followed by a lepton or jet and $\not{E}_T$

For RPV case,

- similar branching ratio of $\tilde{\tau}_R \to \tau\nu_\mu$, $\mu\nu_\tau$
- stau decaying into jets

RPV gravitino DM: neutralino NLSP

neutralino NLSP

Mukhopadhyaya et. al (1998)
Chun and Lee (1999)
Dreiner and Ross (1991)

- $\chi_1^0 \to \tau W$, bbν: jets in the events

$$c\tau^{2-\text{body}}_{\chi_1^0} \sim 20\ \text{cm} \left(\frac{m_{\chi_1^0}}{200\ \text{GeV}}\right)^{-3} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{2},$$

$$c\tau^{3-\text{body}}_{\chi_1^0} \sim 600\ \text{m} \left(\frac{m_{\tilde{\nu}_L}}{300\ \text{GeV}}\right)^{4} \left(\frac{m_{\chi_1^0}}{200\ \text{GeV}}\right)^{-5} \left(\frac{\epsilon_3}{10^{-7}}\right)^{-2} \left(\frac{\tan\beta}{10}\right)^{-2}$$

- comparing to RPC: $\chi_1^0 \to \gamma\tilde{G}$: photon plus missing energy

$$c\tau^{3/2}_{\chi_1^0} \sim 80\ \text{cm} \left(\frac{m_{3/2}}{1\ \text{keV}}\right)^{2} \left(\frac{m_{\chi_1^0}}{200\ \text{GeV}}\right)^{-5}$$

Conclusion

- We now know the composition of the Universe
- No known particle in the SM can be DM

  ⇒ precise, unambiguous evidence for new physics
- New physics

  ⇒ new stable particle as DM candidate
- many WIMP candidates

  How to do precision cosmology at colliders

  synergy between cosmology and particle physics
- WIMPless miracle: DM mass/coupling vary
- superWIMP: RPC or RPV? Collider studies
- Other dark matter scenarios? Collider connections?