# Dark Matter Candidates

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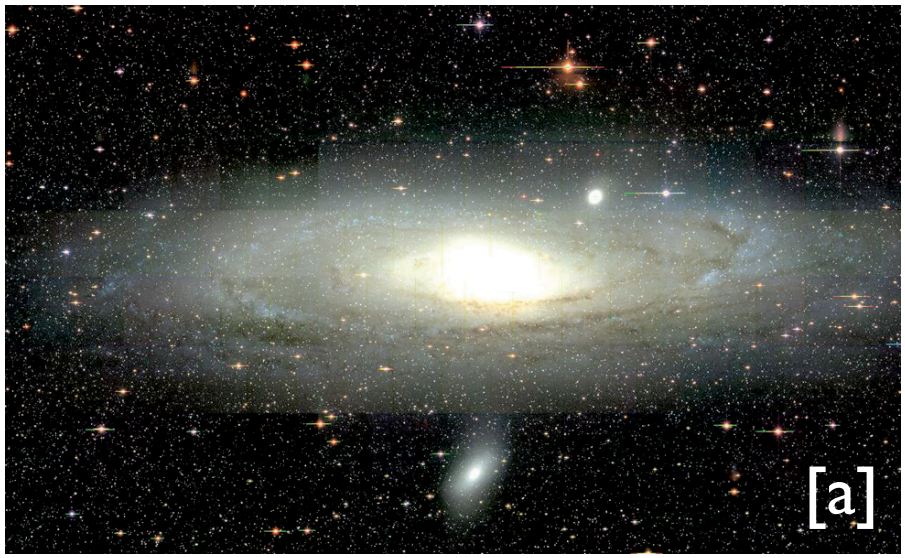
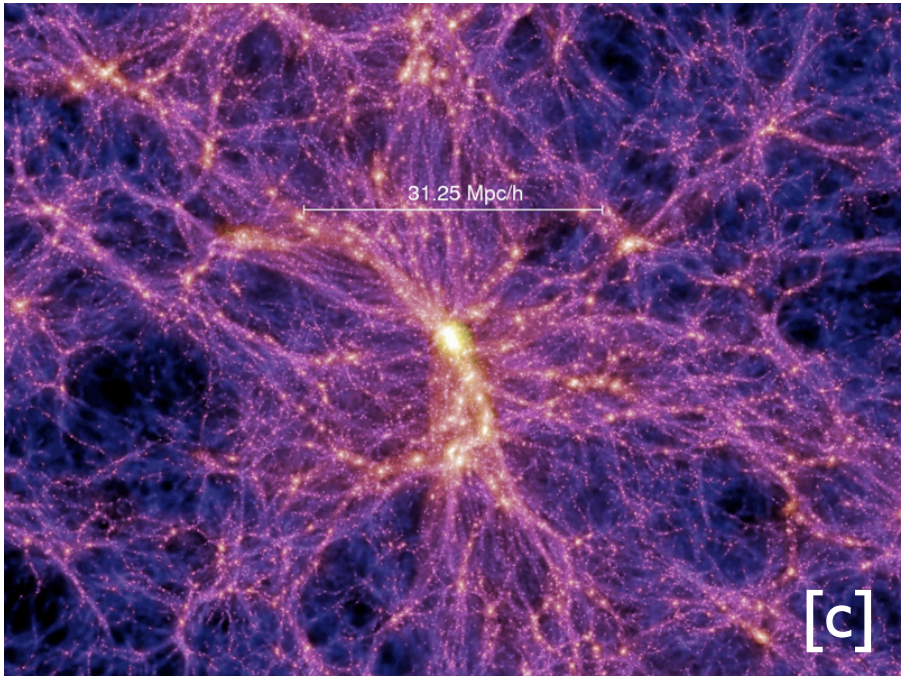
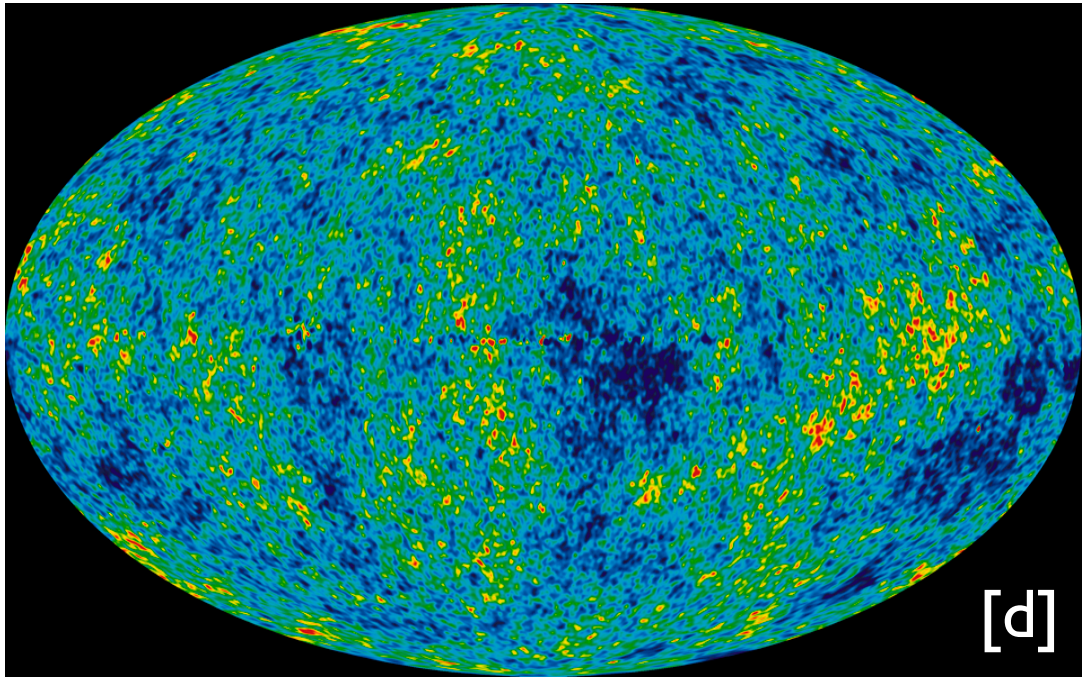
**für Physik**
**(Werner-Heisenberg-Institut)**

# Evidence for Dark Matter in the Universe



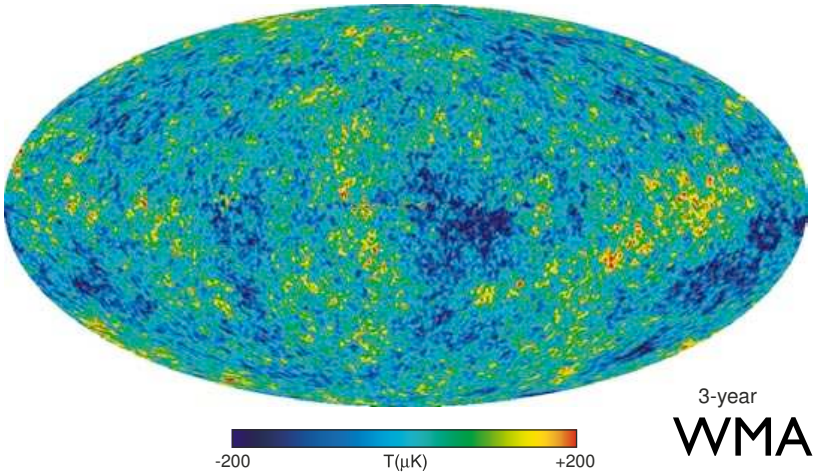


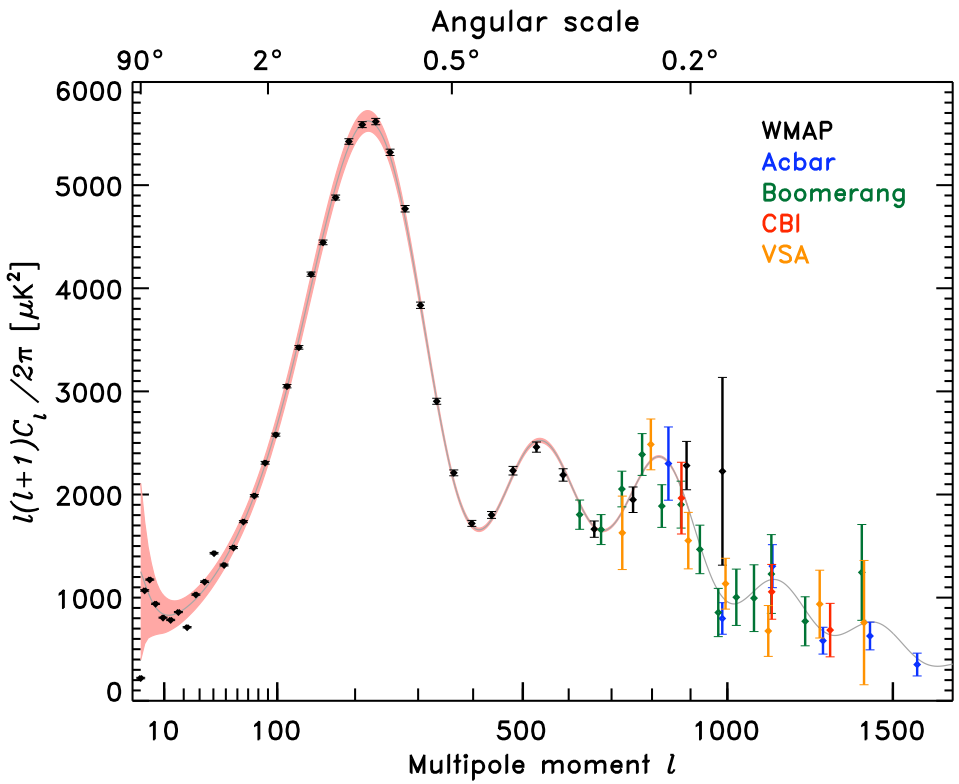



# Evidence for Dark Matter in the Universe

- Spiral Galaxies
  - Rotation Curves
- (Super-) Clusters of Galaxies
  - Galaxy Velocities $\leftrightarrow$ X-Rays
  - Weak Gravitational Lensing
  - Strong Gravitational Lensing
- Large Scale Structure
  - Structure Formation
- CMB Anisotropy: WMAP, ...
  - $\Omega_{\rm tot} = 100\%$
  - $\Omega_{\rm M} = 27\%$
  - $\Omega_{\rm B} = 5\%$

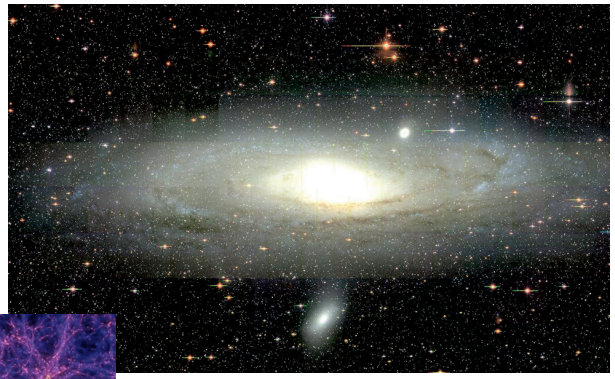
$$\Omega_{\rm DM} \simeq 22\%$$

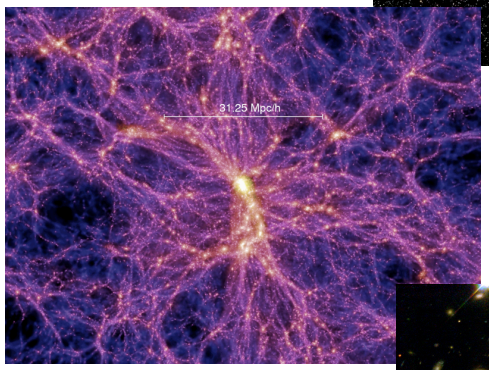


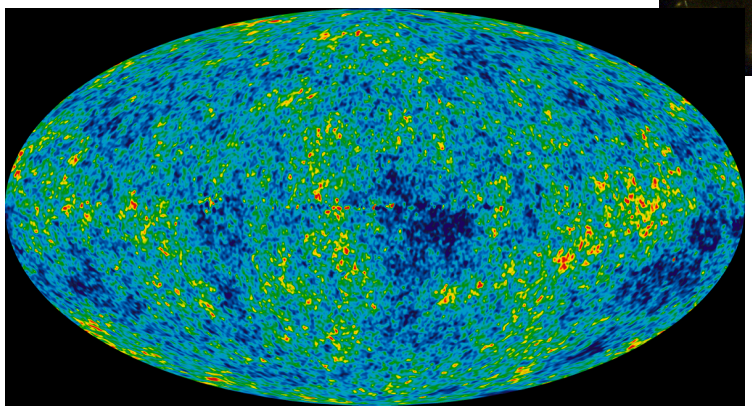



# Properties of Dark Matter

- $\tau_{\mathrm{DM}} \gtrsim$ age of our Universe
- clusters $\leftarrow$ gravitation
- slow – "cold"
- electrically neutral
- color neutral







# The Standard Model

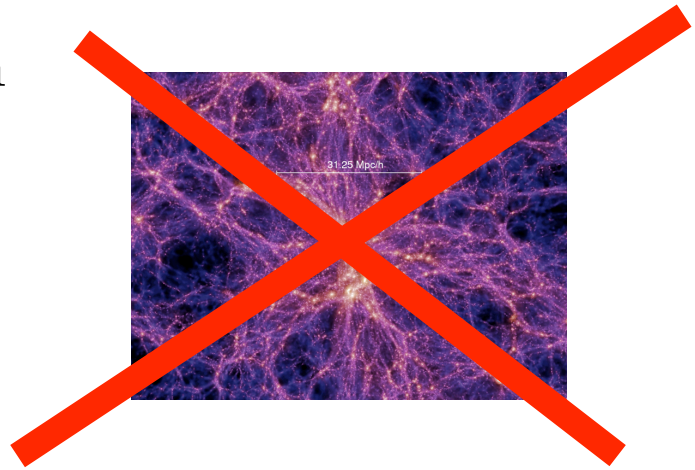
| GAUGE | Gauge bosons | $(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$ |
|---|---|---|
| B-boson | $A_\mu^{(1)} = B_\mu$ | $(\mathbf{1}, \mathbf{1})_0$ |
| W-bosons | $A_\mu^{(2)\,a} = W_\mu^a$ | $(\mathbf{1}, \mathbf{3})_0$ |
| gluon | $A_\mu^{(3)\,a} = G_\mu^a$ | $(\mathbf{8}, \mathbf{1})_0$ |

| MATTER | Fermions | $(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$ |
|---|---|---|
| leptons<br>$I = 1, 2, 3$ | $L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$ | $(\mathbf{1}, \mathbf{2})_{-1}$ |
| | $E^{c\,I} = e_R^{-\,c\,I}$ | $(\mathbf{1}, \mathbf{1})_{+2}$ |
| quarks<br>$I = 1, 2, 3$<br>($\times$ 3 colors) | $Q^I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$ | $(\mathbf{3}, \mathbf{2})_{+\frac{1}{3}}$ |
| | $U^{c\,I} = u_R^{c\,I}$ | $(\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}}$ |
| | $D^{c\,I} = d_R^{c\,I}$ | $(\overline{\mathbf{3}}, \mathbf{1})_{+\frac{2}{3}}$ |

| HIGGS | Higgs Boson | $(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$ |
|---|---|---|
| Higgs | $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ | $(\mathbf{1}, \mathbf{2})_{+1}$ |

# Properties of Neutrino Dark Matter

- stable $\rightarrow \tau_{\mathrm{DM}} \gtrsim$ age of our Universe
- clusters $\leftarrow$ gravitation
- fast – "hot"
- electrically neutral
- color neutral




[Talks by Guido Drexlin, ...]

Neutrino Dark Matter = Hot Dark Matter

in conflict with Large Scale Structure

# Dark Matter

# points to

# Physics

# Beyond the Standard Model

# The Minimal Supersymmetric Standard Model

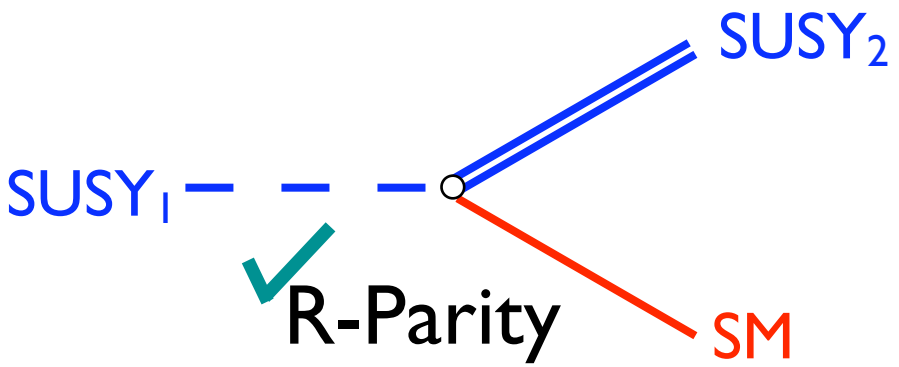
| GAUGE | Gauge bosons | Gauginos | $(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$ |
|---|---|---|---|
| B-boson, bino | $A_\mu^{(1)} = B_\mu$ | $\lambda^{(1)} = \widetilde{B}$ | $(\mathbf{1}, \mathbf{1})_0$ |
| W-bosons, winos | $A_\mu^{(2)\,a} = W_\mu^a$ | $\lambda^{(2)\,a} = \widetilde{W}^a$ | $(\mathbf{1}, \mathbf{3})_0$ |
| gluon, gluino | $A_\mu^{(3)\,a} = G_\mu^a$ | $\lambda^{(3)\,a} = \widetilde{g}^a$ | $(\mathbf{8}, \mathbf{1})_0$ |

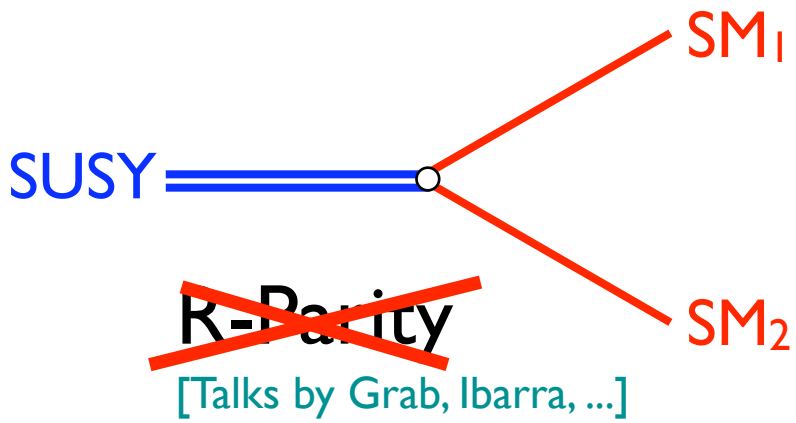
| MATTER | Sfermions | Fermions | $(\mathrm{SU(3)_c}, \mathrm{SU(2)_L})_Y$ |
|---|---|---|---|
| sleptons, leptons<br>$I = 1, 2, 3$ | $\widetilde{L}^I = \begin{pmatrix} \widetilde{\nu}_L^I \\ \widetilde{e}_L^{-\,I} \end{pmatrix}$ | $L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$ | $(\mathbf{1}, \mathbf{2})_{-1}$ |
| | $\widetilde{E}^{*I} = \widetilde{e}_R^{-\,*\,I}$ | $E^{c\,I} = e_R^{-\,c\,I}$ | $(\mathbf{1}, \mathbf{1})_{+2}$ |
| squarks, quarks<br>$I = 1, 2, 3$<br>($\times$ 3 colors) | $\widetilde{Q}^I = \begin{pmatrix} \widetilde{u}_L^I \\ \widetilde{d}_L^I \end{pmatrix}$ | $Q^I = \begin{pmatrix} u_L^I \\ d_L^I \end{pmatrix}$ | $(\mathbf{3}, \mathbf{2})_{+\frac{1}{3}}$ |
| | $\widetilde{U}^{*I} = \widetilde{u}_R^{*I}$ | $U^{c\,I} = u_R^{c\,I}$ | $(\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}}$ |
| | $\widetilde{D}^{*I} = \widetilde{d}_R^{*I}$ | $D^{c\,I} = d_R^{c\,I}$ | $(\overline{\mathbf{3}}, \mathbf{1})_{+\frac{2}{3}}$ |
| Higgs, higgsinos | $H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$ | $\widetilde{H}_d = \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$ | $(\mathbf{1}, \mathbf{2})_{-1}$ |
| | $H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$ | $\widetilde{H}_u = \begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}$ | $(\mathbf{1}, \mathbf{2})_{+1}$ |

# Conservation of R-Parity

- superpotential: $W_{\rm MSSM} \leftarrow W_{\Delta L} + W_{\Delta B}$
- non-observation of $L$ & $B$ violating processes (proton stability, ...)
- postulate conservation of R-Parity ← multiplicative quantum number

$$P_{\rm R} = (-1)^{3(B-L)+S} = \begin{cases} +1 \quad \text{for} \quad \text{SM}, H_u, H_d \\ -1 \quad \text{for} \quad \widetilde{X} \leftarrow \text{superpartners} \end{cases}$$




[Talks by Grab, Ibarra, ...]

The lightest supersymmetric particle (LSP) is stable!!!

# Properties of LSP Dark Matter

- stable $\rightarrow \tau_{\mathrm{DM}} \gtrsim$ age of our Universe
- clusters $\leftarrow$ gravitation
- ? slow – "cold"
- electrically neutral
- color neutral
- non-observation in the lab **(so far)**

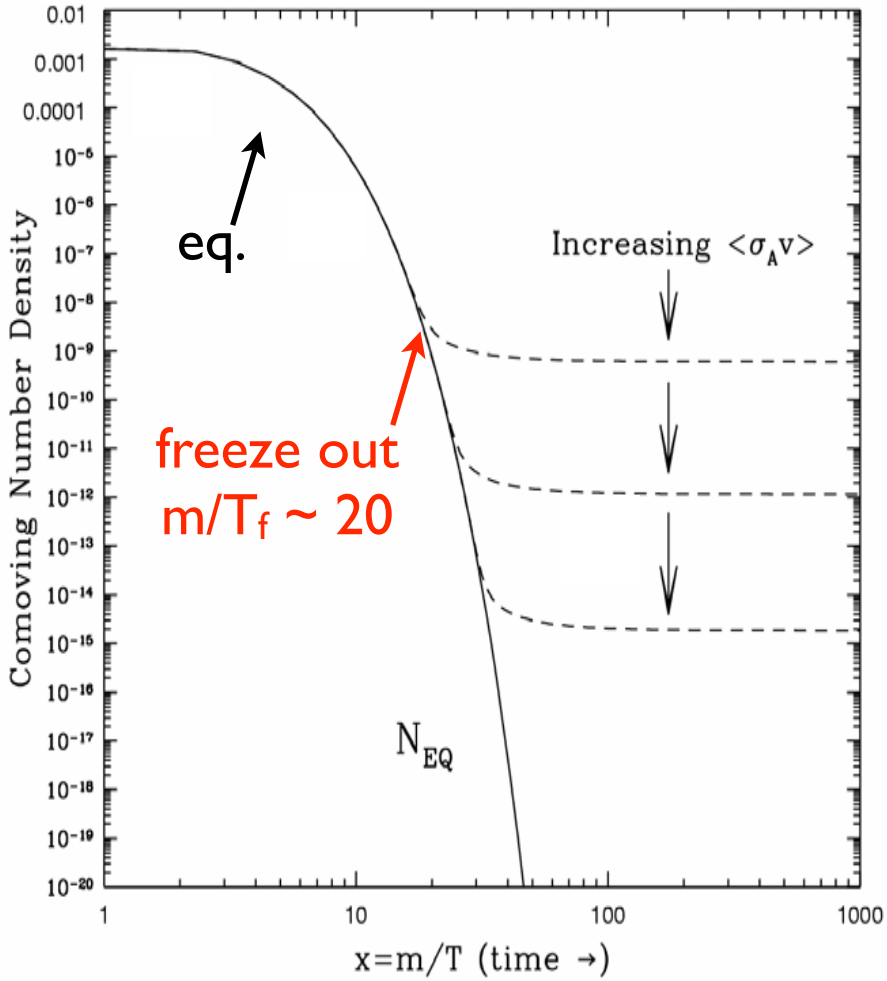
# Supersymmetric Dark Matter Candidates

| | LSP | ID | spin | mass | interaction |
|---|---|---|---|---|---|
| lightest neutralino | $\widetilde{\chi}_1^0$ | $\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$ | $\frac{1}{2}$ | $\mathcal{O}(100\ \mathrm{GeV})$ | g, g' |
| $\in$ MSSM | | mixture | | $M_1, M_2, \mu, \tan\beta$ | weak |

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints |
|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold |
| | weak | freeze out | |

## Cold Thermal Relic




[... , Jungman, Kamionkowski, Griest, '96, ...]

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints |
|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold |
| | weak | freeze out | |

[Talk by Ben Allanach]

**Numerical Treatment for a given SUSY model**

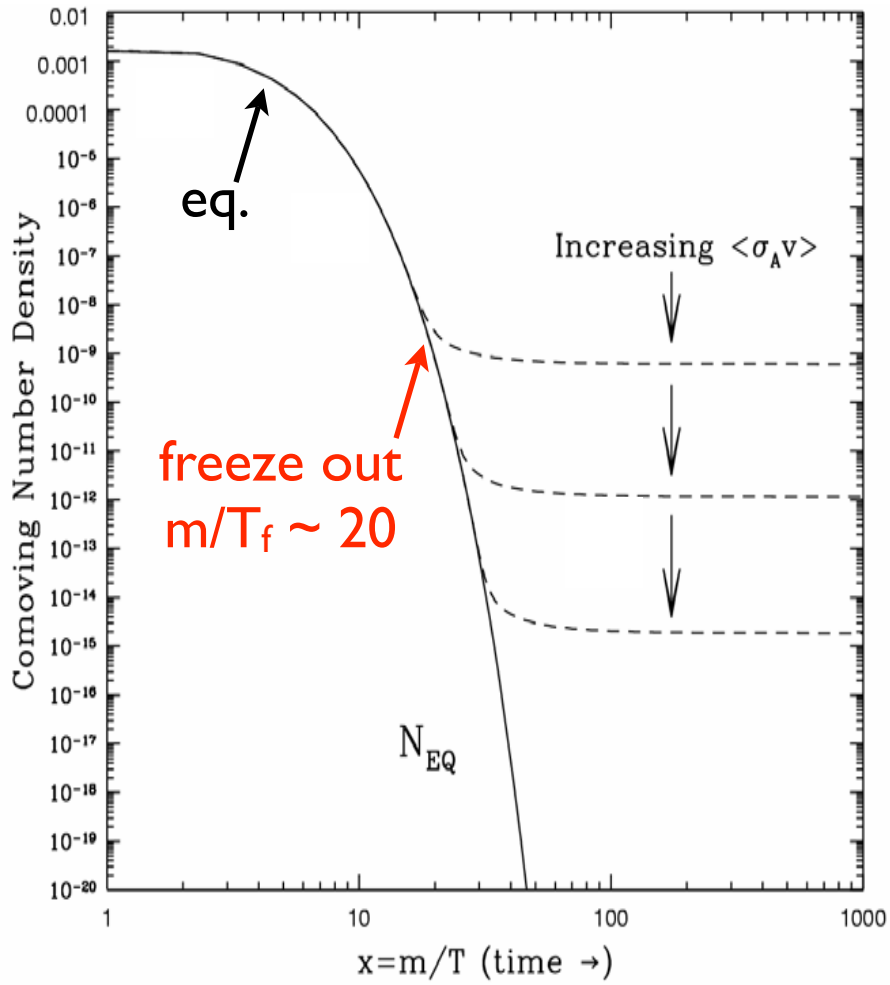
- ...
- DarkSUSY

[Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz, '04]

- micrOMEGAs

[Belanger, Boudjema, Pukhov, Semenov, '03 & '06]

## Cold Thermal Relic




[... , Jungman, Kamionkowski, Griest, '96, ...]

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints |
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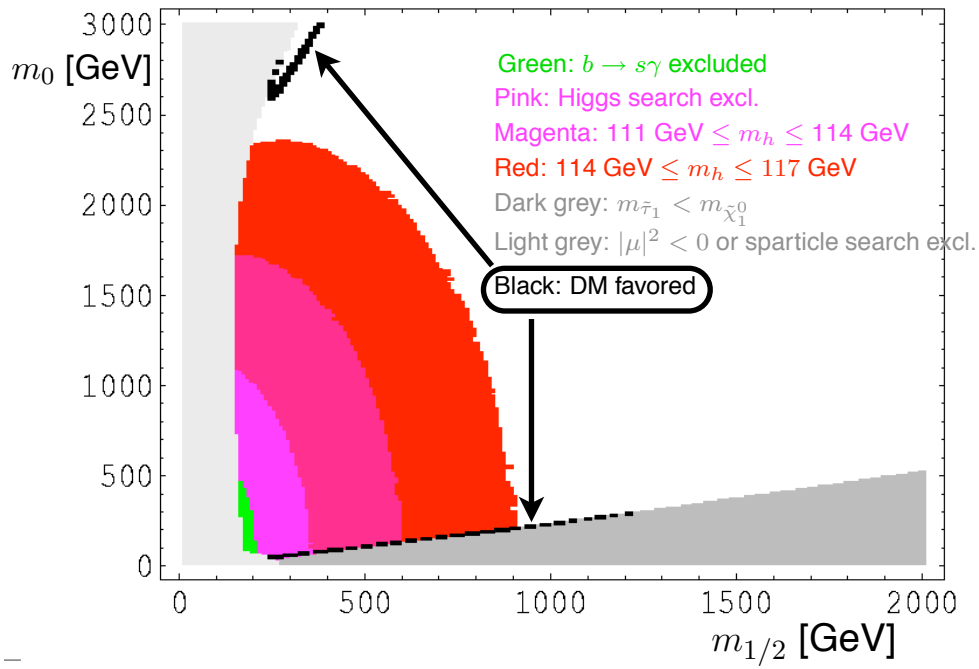
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold |
| | weak | freeze out | |

see also [Talks by Olive, Baer, ...]

**mSUGRA / CMSSM**

**Example:** $m_t = 172.7$ **GeV,** $\tan\beta = 10,\ A_0 = 0,\ \mu > 0$

[Drees, Djouadi, Kneur, '06]




[from M. Drees' Lecture, DESY Theory Workshop 2006]

$\Omega_{\widetilde{\chi}_1^0} = \Omega_{\rm DM}$ is possible!!!

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints |
|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP freeze out | ← cold |
| | weak | | |

see also [Talks by Olive, Baer, ...]

**mSUGRA / CMSSM**

**Example:** $m_t = 172.7$ **GeV,** $\tan\beta = 10,\ A_0 = 0,\ \mu > 0$

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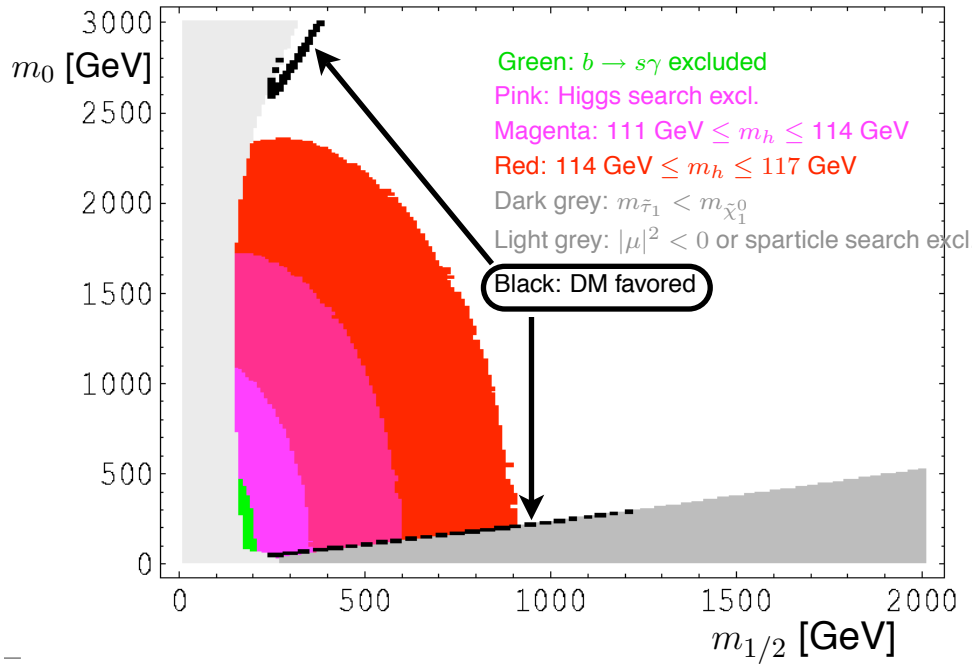



[from M. Drees' Lecture, DESY Theory Workshop 2006]

$\Omega_{\widetilde{\chi}_1^0} = \Omega_{\rm DM}$ **is possible!!!**

**(? natural ?)**

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

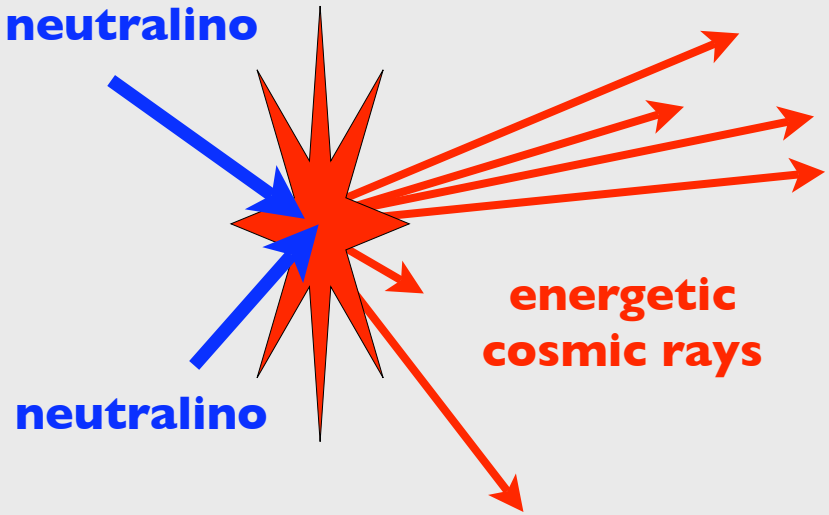
| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold | • indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | neutralino pair annihilation |
| | | | | $\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \to \mathrm{SM}_1\,\mathrm{SM}_2$ |

**EGRET**
[Talks by de Boer, Sander, Weber, Gebauer]

**GLAST**

[Talk by Olzem]
**AMS02**
[Talk by Brun]
**PAMELA**

**HESS**
[Talk by Moulin]



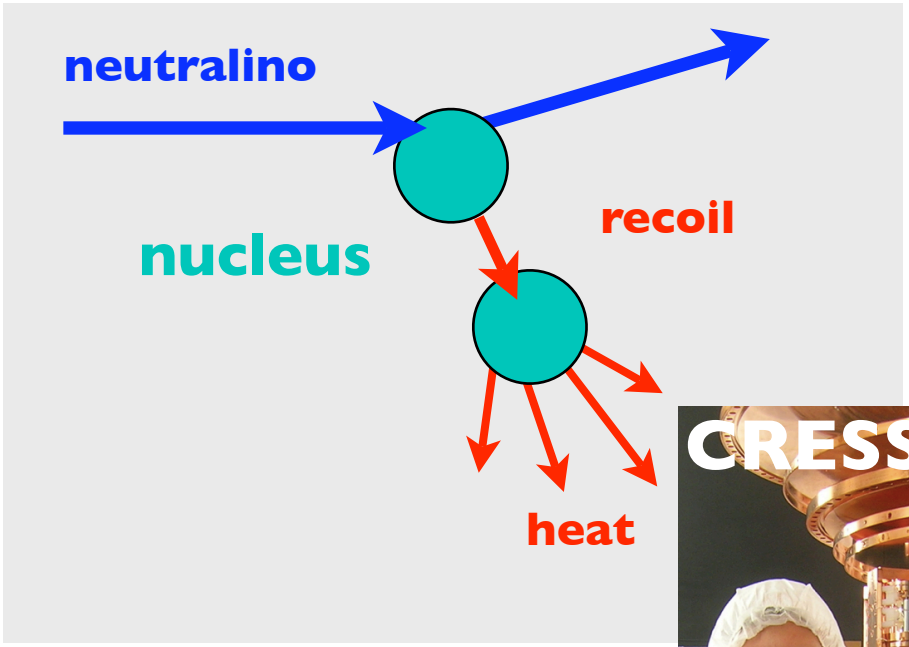
[Talk by Blennow]
**AMANDA**
[Talk by Lim]
**IceCube**
**. . .**

# Indirect DM Searches

Talk by Dan Hooper at 10:00 AM

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

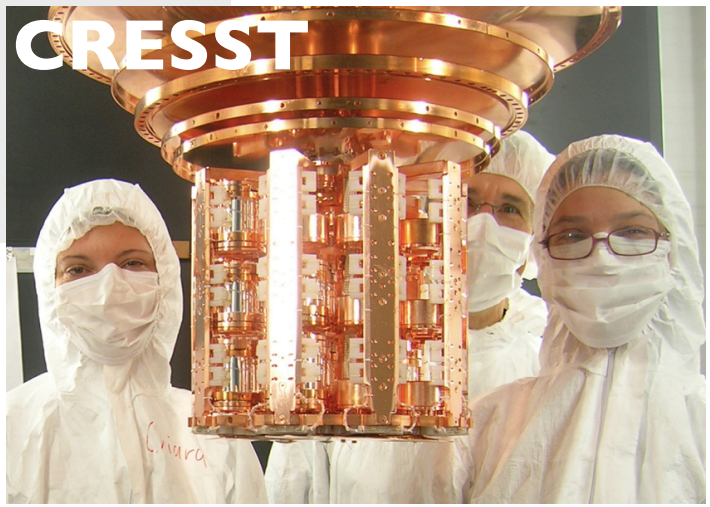
| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold | • indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | neutralino pair annihilation |
| | | | | $\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \to \mathrm{SM}_1\,\mathrm{SM}_2$ |




• direct detection (CRESST, EDELWEISS, ...)

elastic neutralino scattering

$\widetilde{\chi}_1^0\,\mathrm{A} \to \widetilde{\chi}_1^0\,\mathrm{A}$




[Talk by Chung-Lin San]

**EDELWEISS-2**
[Talk by Chantelauze]

**CDMS II**

**XENON10**
[Talk by McKinsey]

**LUX**
[Talk by Tripathi]

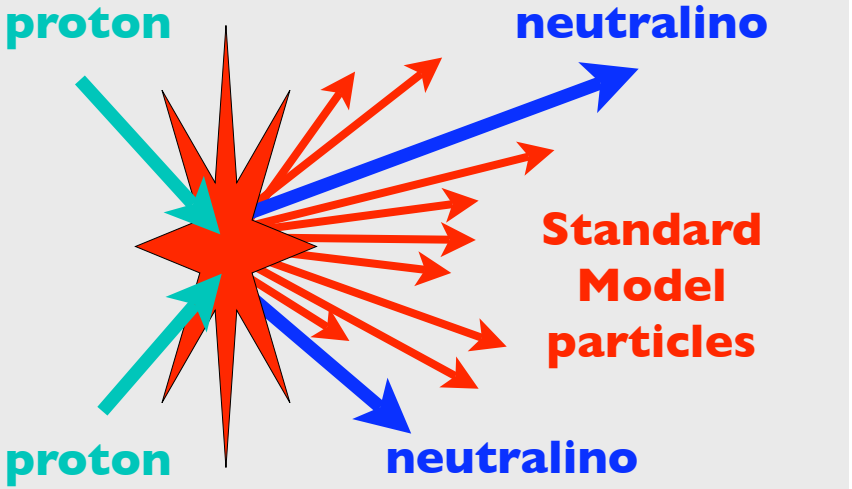
• • •

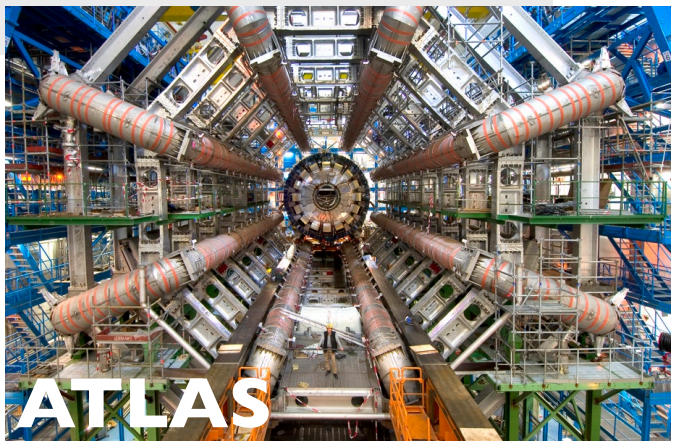
# Direct DM Searches

Talk by Laura Baudis at 9:30 AM

# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold | • indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | neutralino pair annihilation |
| | | | | $\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \to \mathrm{SM}_1\,\mathrm{SM}_2$ |
| | | | | • direct detection (CRESST, EDELWEISS, ...) |
| | | | | elastic neutralino scattering |
| | | | | $\widetilde{\chi}_1^0\,\mathrm{A} \to \widetilde{\chi}_1^0\,\mathrm{A}$ |
| | | | | • prod.@colliders (Tevatron, LHC, ILC, ...) |
| | | | | neutralino pair production |
| | | | | $\mathrm{p\,p} \to \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \ldots$ (Tevatron, LHC) |
| | | | | $e^+\,e^- \to \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \ldots$ (ILC) |

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[very many SUSY2007 Talks]

**SUSY at the LHC**

Talks by Dutta & Spiropulu

**SM Backgrounds to SUSY Searches**

Talk by Mangano

**Colliders and Cosmology**

Talk by Keith Olive

• • •

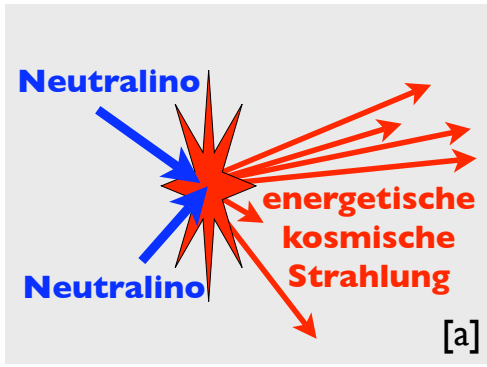
# $\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

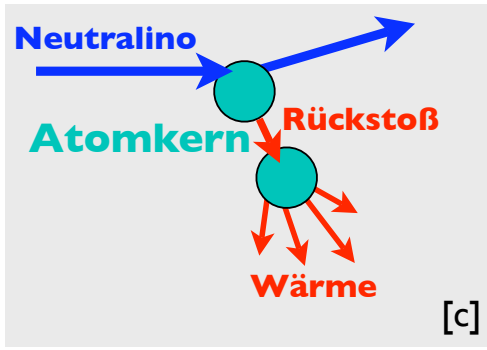
| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|

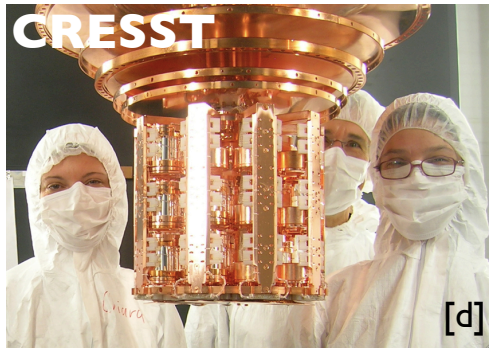
$\widetilde{\chi}_1^0$ g, g' WIMP ← cold

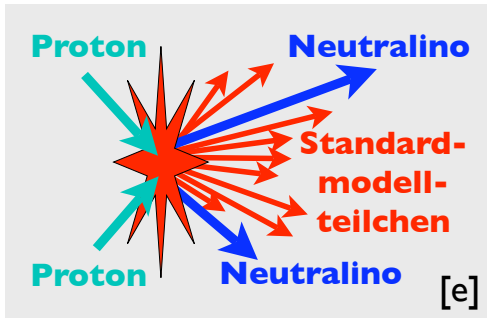
weak freeze out

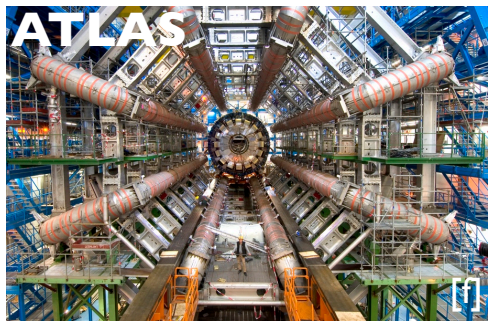
$\Omega_{\widetilde{\chi}_1^0} = \Omega_{\rm DM}$ is possible!!!






**promising experimental prospects**

# Supersymmetric Dark Matter Candidates

| | LSP | ID | spin | mass | interaction |
|---|---|---|---|---|---|
| lightest neutralino | $\widetilde{\chi}_1^0$ | $\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$ | $\frac{1}{2}$ | $\mathcal{O}(100\ \mathrm{GeV})$ | g, g' |
| $\in$ MSSM | | mixture | | $M_1, M_2, \mu, \tan\beta$ | weak |
| gravitino | $\widetilde{G}$ | superpartner of | $\frac{3}{2}$ | eV – TeV | $\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$ |
| $*$ gravity | | the graviton | | SUSY breaking | extremely weak |

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| $*$ gravity | | the graviton | | SUSY breaking | extremely weak |

**gauge-MSB**

**light gravitino**
**1 eV-1 GeV**

[Talks by Ibe, Moultaka, Murayama,...]

**gravity-MSB**
**gaugino-MSB**

**weak-scale gravitino**
**0.01-1 TeV**

[This Talk]

**anomaly-MSB**
**mirage-MSB**

**heavy gravitino**
**1-100 TeV**

[Talks by Nilles, Tata, ...]

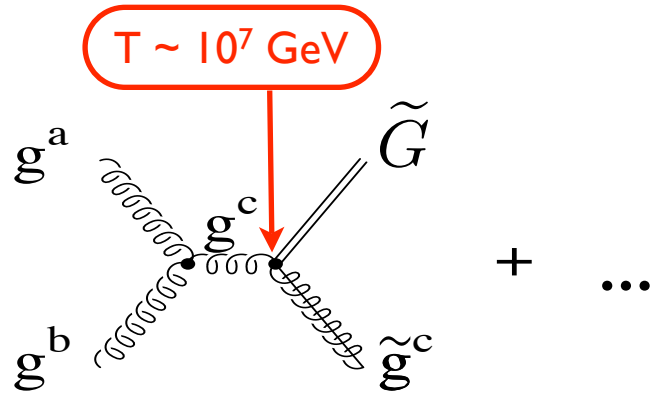
**super heavy gravitino**
**$10^{10}$ TeV**

[Talk by Linde]

# LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | ← cold | indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | direct detection (CRESST, EDELWEISS, ...) |
| | $M_W \sim 100$ GeV | | | prod.@colliders (Tevatron, LHC, ILC, ...) |
| $\widetilde{G}$ | $\left(\frac{p}{M_{Pl}}\right)^n$ | therm. prod. | ← cold | |
| | extremely weak | NLSP decays | ← warm | |
| | $M_{Pl} = 2.44 \times 10^{18}$ GeV | ... | | |

**Very Early Hot Universe**




[... ; Bolz, Brandenburg, Buchmüller, '01]
[Pradler, FDS, '06]
[Rychkov, Strumia, '07] (gauge dep.)

# LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints | experiments |
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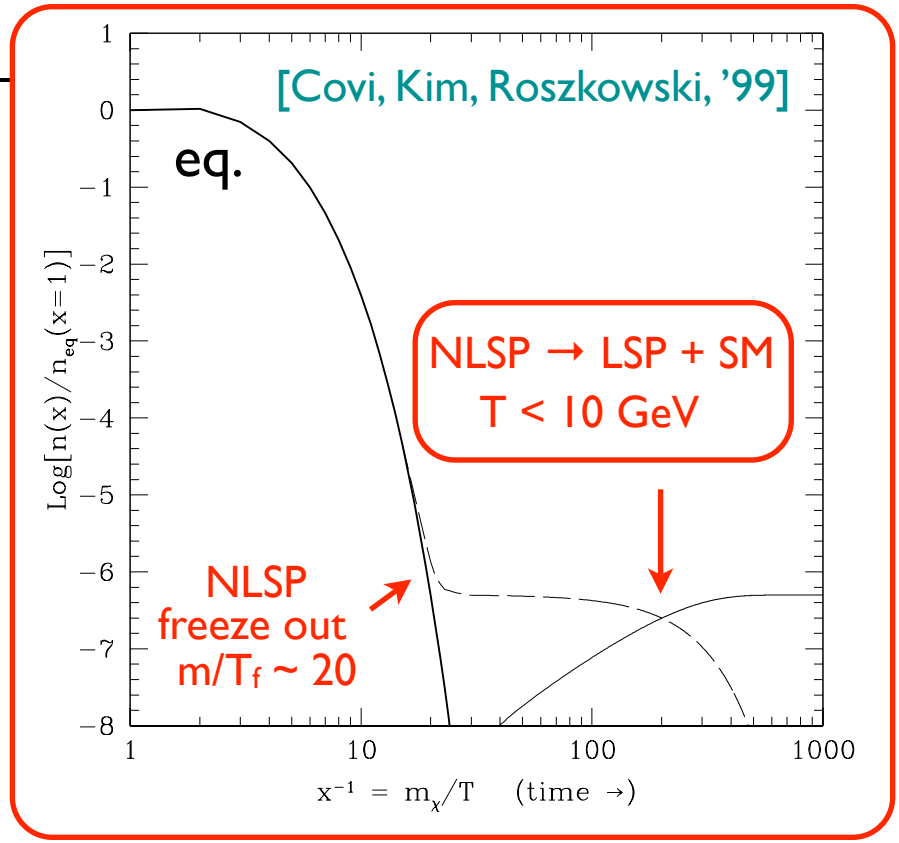

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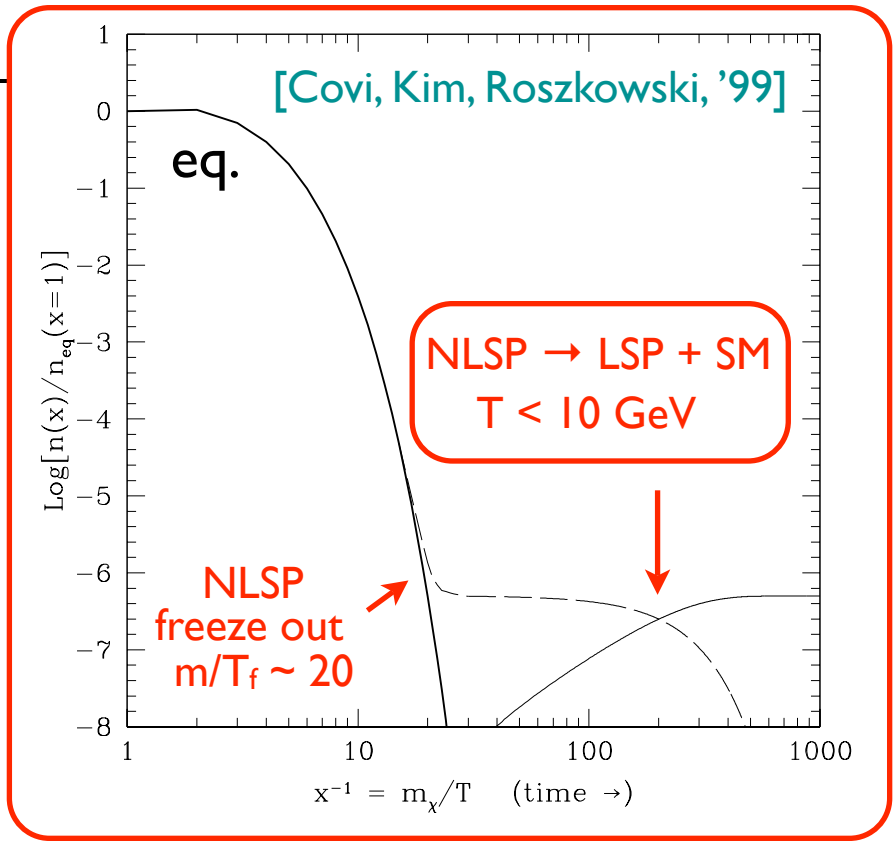
**NLSP Candidates**

- **lightest neutralino**
- **lighter stau**
- **lighter stop** [Talk by Santoso]
- **lightest sneutrino** [Talk by Ishiwata]



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**NLSP Candidates**

**electrically charged** →

- **lightest neutralino**
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- **lighter stop** [Talk by Santoso]
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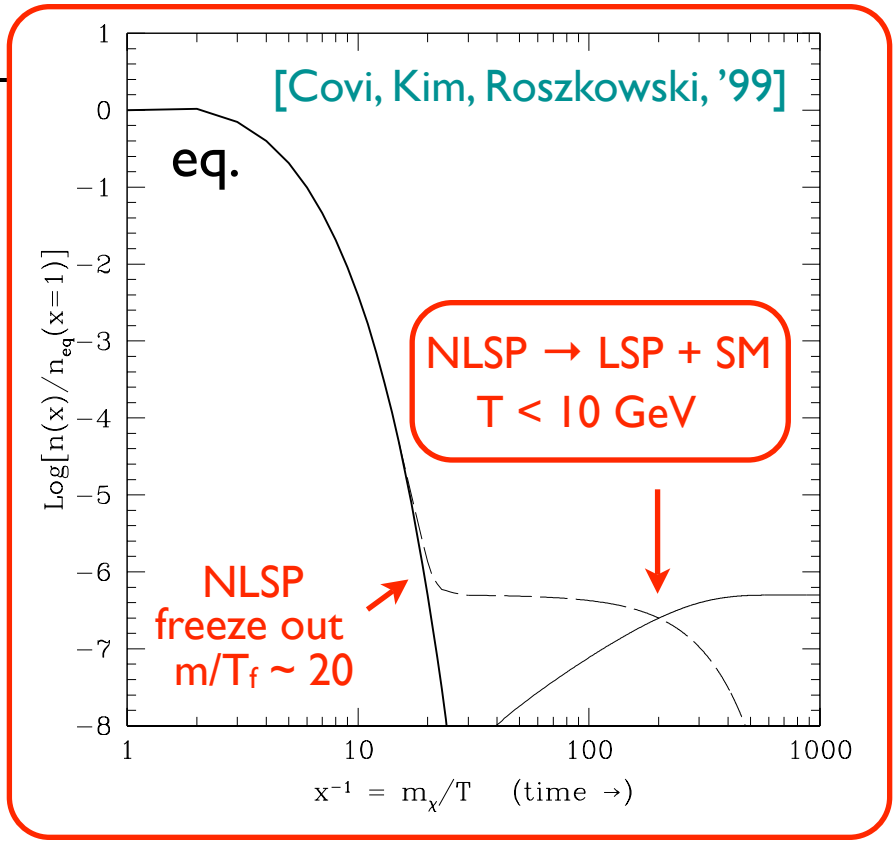
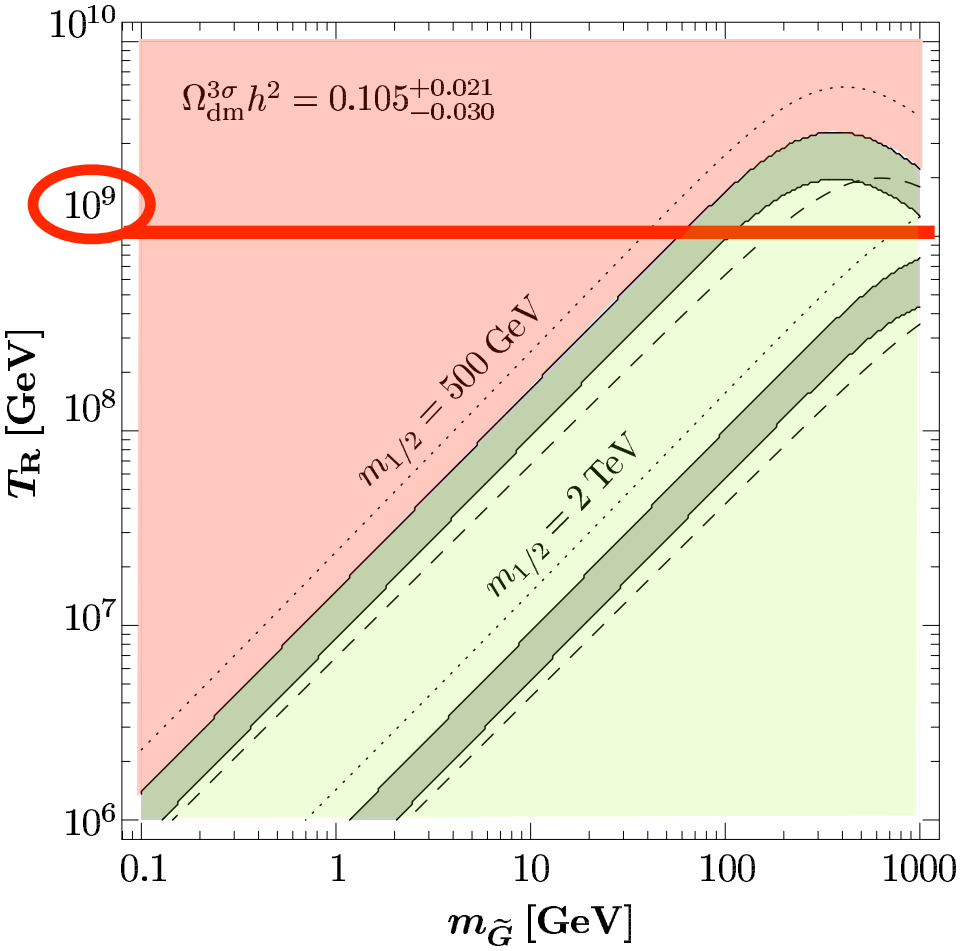


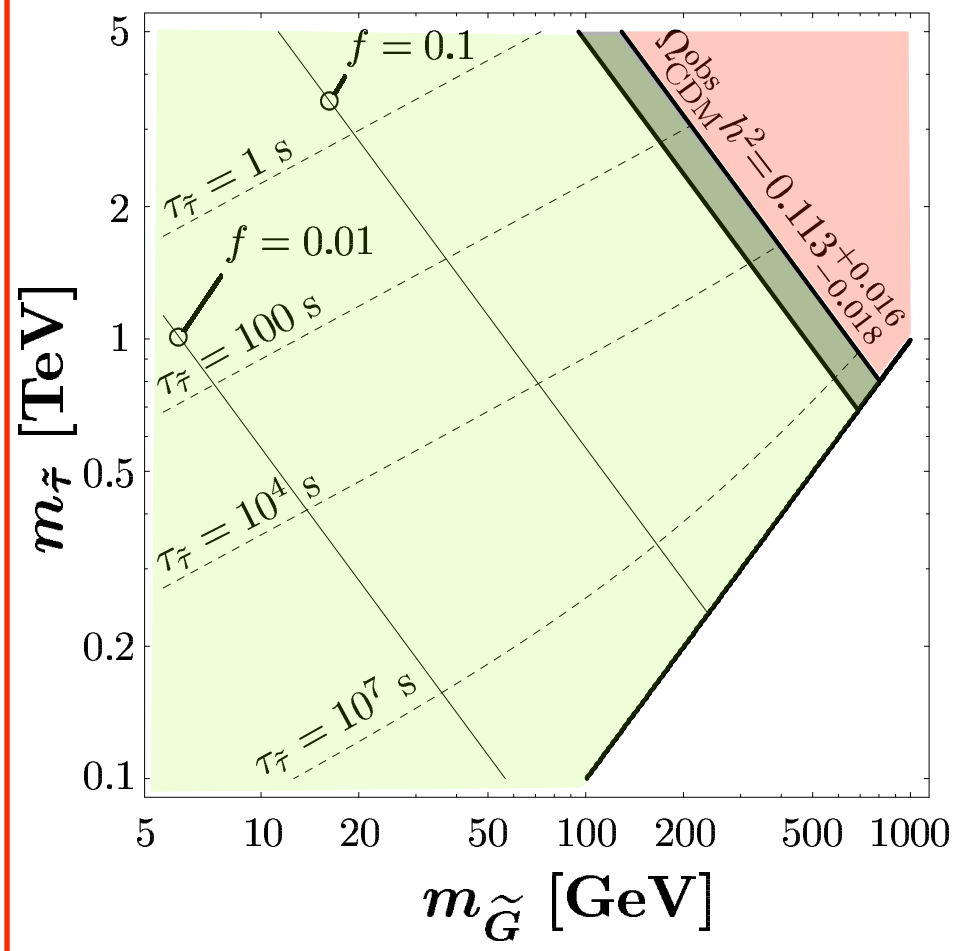
# Thermal $\widetilde{G}$ Production




[Pradler, FDS, '07]

see also [Moroi, Murayama, Yamguchi, '93, Asaka, Hamaguchi, Suzuki, '00, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Rychkov, Strumia, '07]

# $\widetilde{\tau}$ NLSP $\longrightarrow \widetilde{G} + \tau$




[FDS '06]

see also [Borgani, Masiero, Yamguchi, '96, Asaka, Hamaguchi, Suzuki, '00, Ellis et al., '04, Feng, Su, Takayama, '04]

# LSP Dark Matter: Production, Constraints, Experiments

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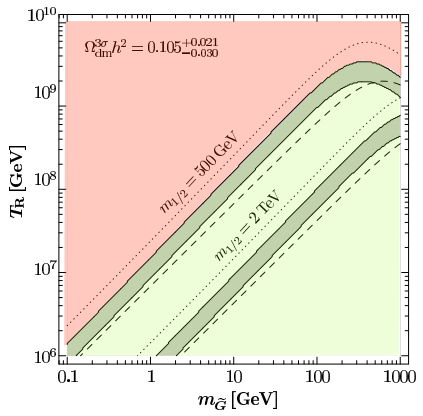
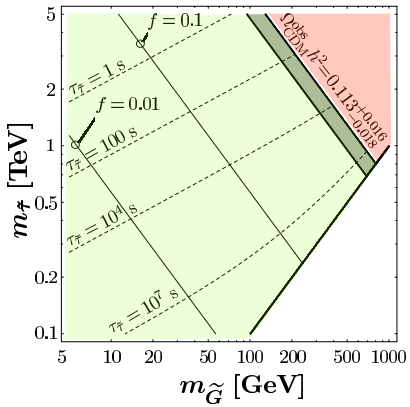
$\Omega_{\widetilde{G}} = \Omega_{DM}$ is possible!!!



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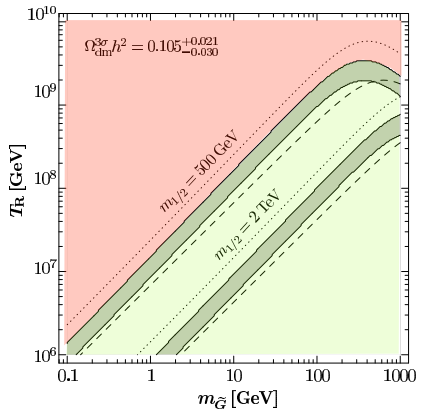
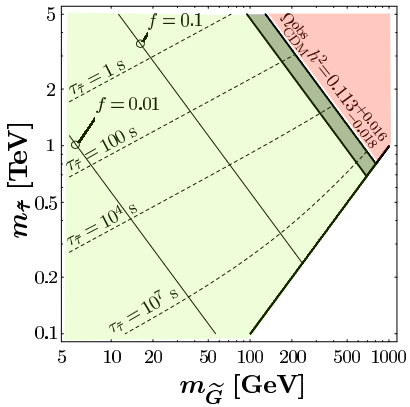
[Talks by Endo & Takahashi]

**Gravitinos from Inflaton Decays**

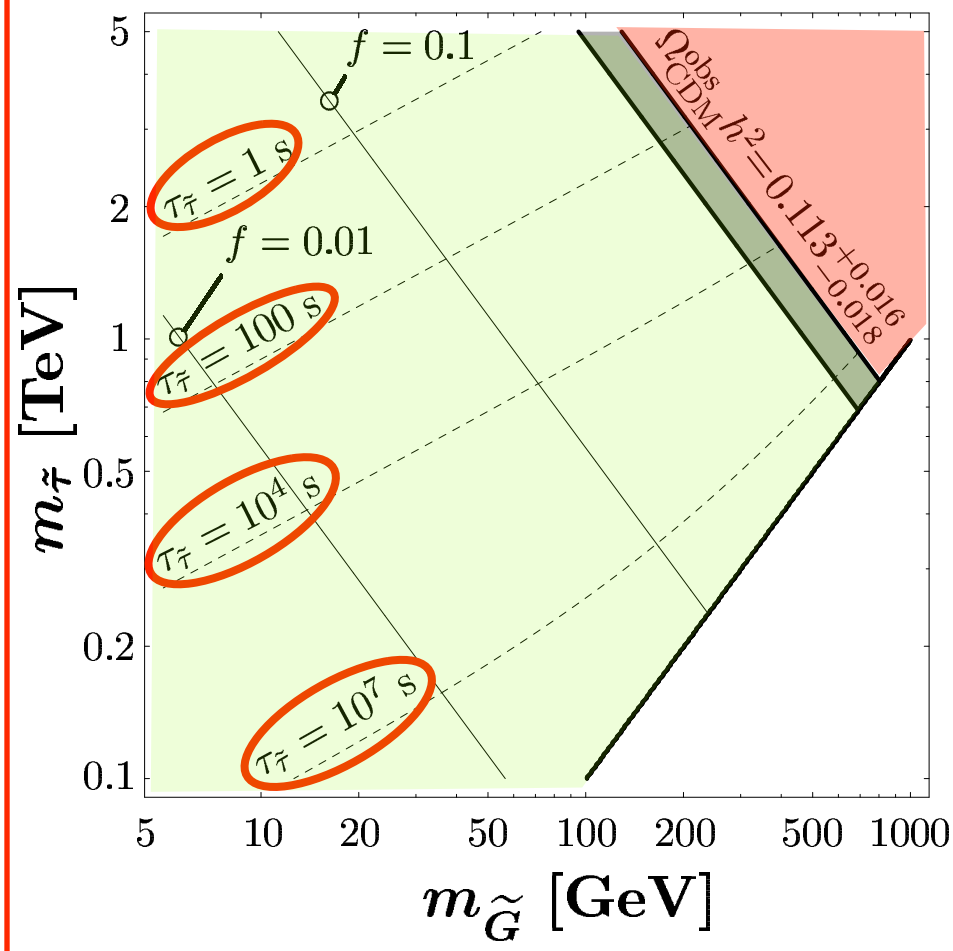



$\Omega_{\widetilde{G}} = \Omega_{\rm DM}$ is possible!!!

**long-lived NLSP**

## $\widetilde{\tau}$ NLSP $\longrightarrow \widetilde{G} + \tau$



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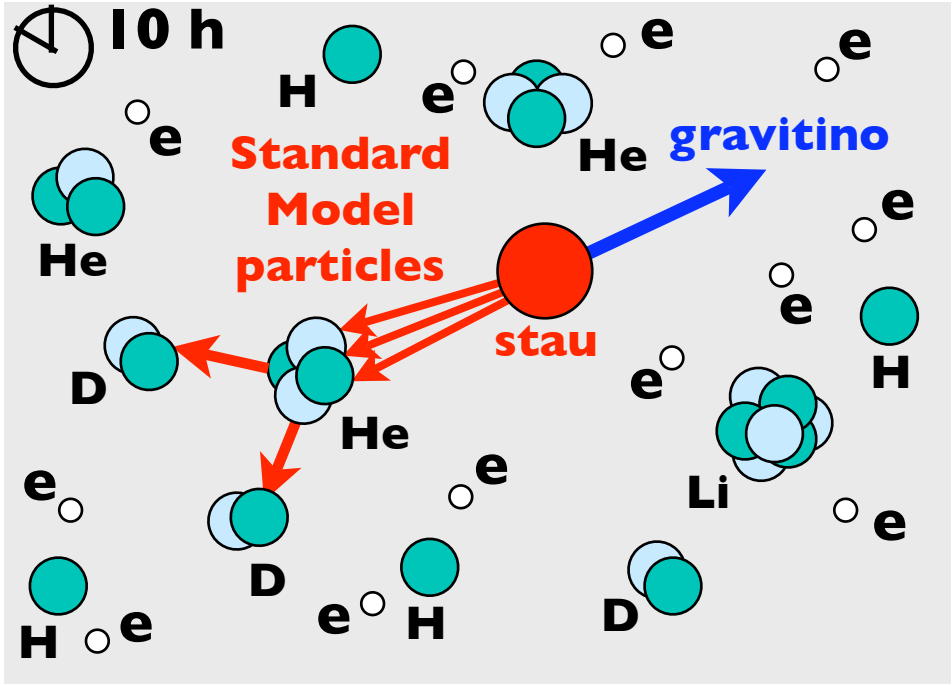
**long-lived NLSP**

**NLSP $\rightarrow \widetilde{G}$ + SM**

BBN

CMB

$\gamma$ rays



# LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|

[..., Reno, Seckel, '88, Dimopoulos et al., '88 & '89, ... Ellis et al., '04, Jedamzik, '04, Kawasaki, Kohri, Moroi, '05, Feng, Su, Takayama, '04, Roszkowski et al., '05, Cerdeno et al., '06, FDS '06, Jedamzik, '06]

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| $\widetilde{G}$ | $\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$ | therm. prod. | $\leftarrow$ cold |
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$\mathrm{M_{Pl}} = 2.44 \times 10^{18}\,\mathrm{GeV}$ ...

**long-lived NLSP**

**NLSP $\rightarrow \widetilde{G} + \mathrm{SM}$**

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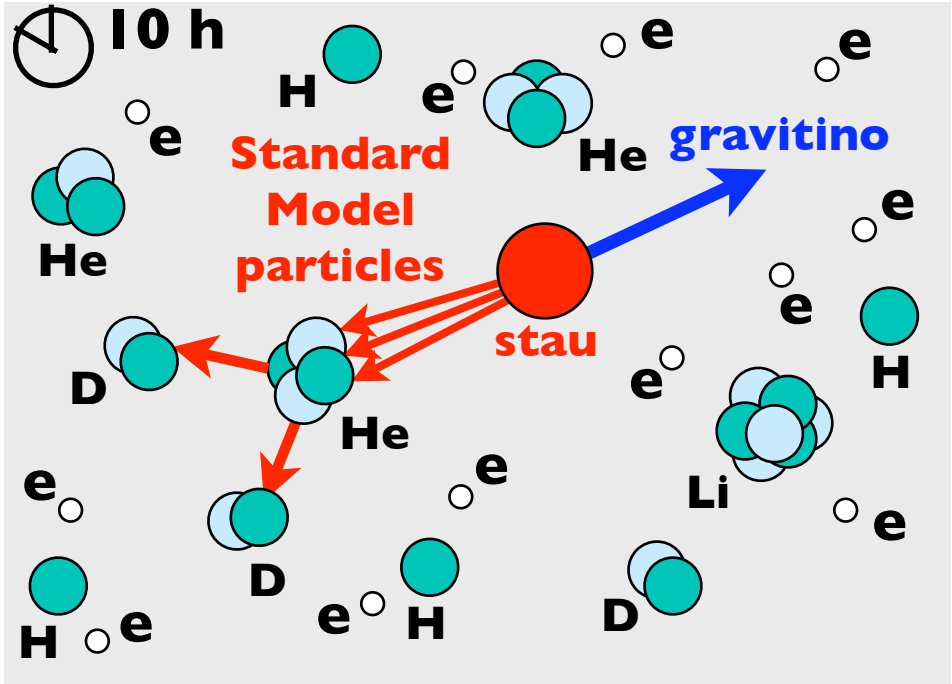
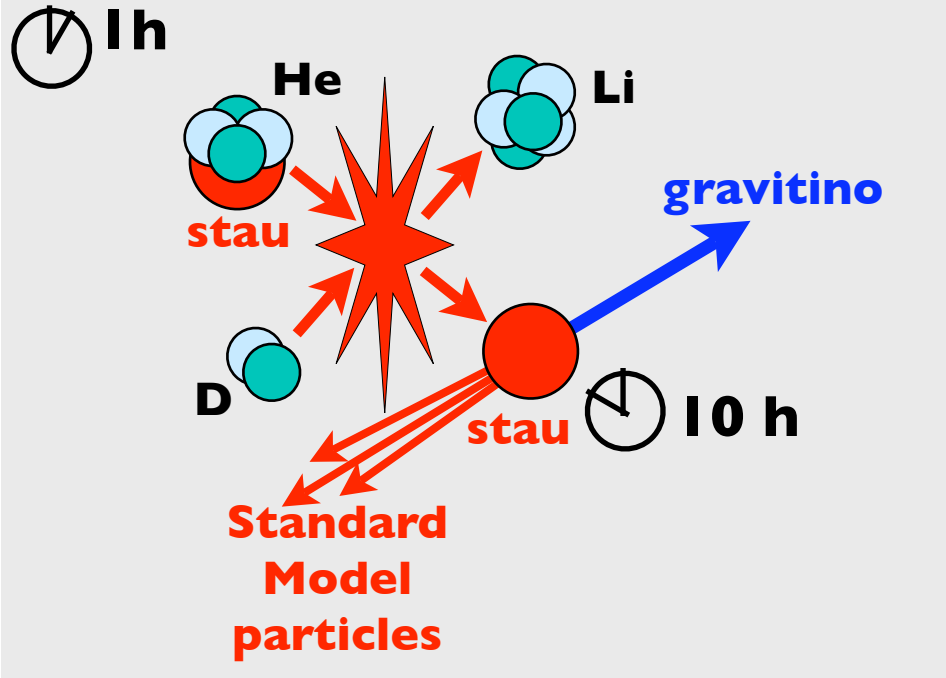


# Catalyzed BBN [Pospelov, 06]



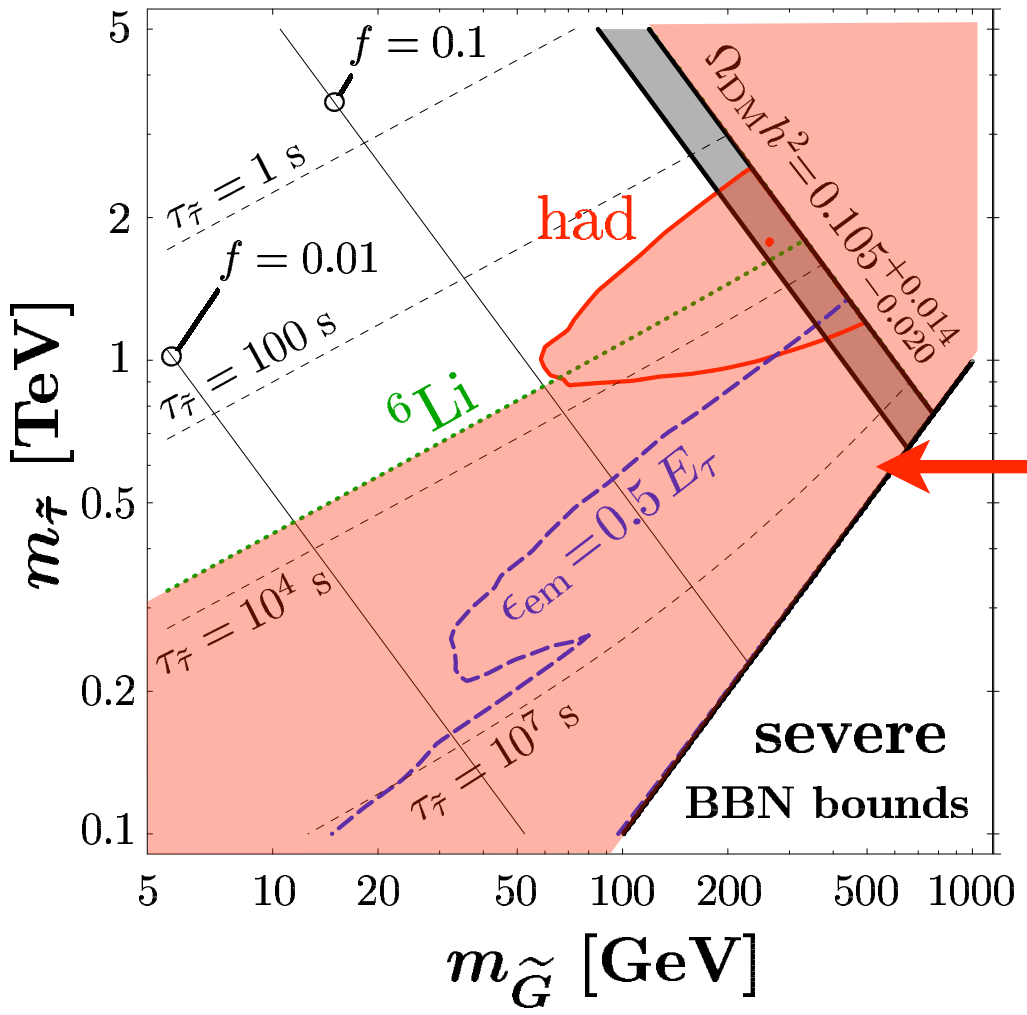

Recent Result: [Hamaguchi et al., 07]

[Cyburt et al., '06, FDS, '06, Pradler, FDS, '07, Kawasaki, Kohri, Moroi, '07, Takayama, '07]

[Talks by Ibarra, Pradler, Spanos, Takayama, ...]

[FDS, hep-ph/0611027]

# Cosmological Constraints — $\Omega_{\rm DM}$ & BBN




**disfavored by cosmological constraints**

[FDS, hep-ph/0611027]

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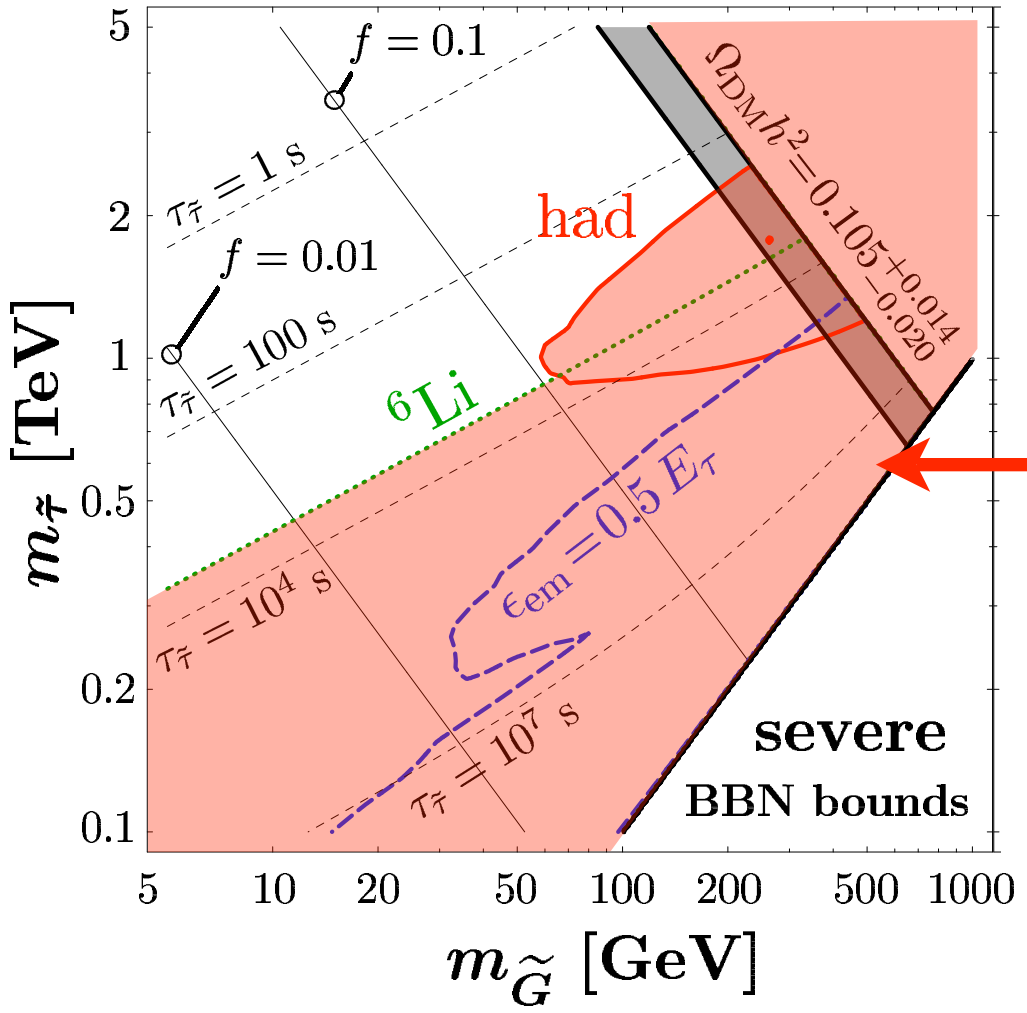


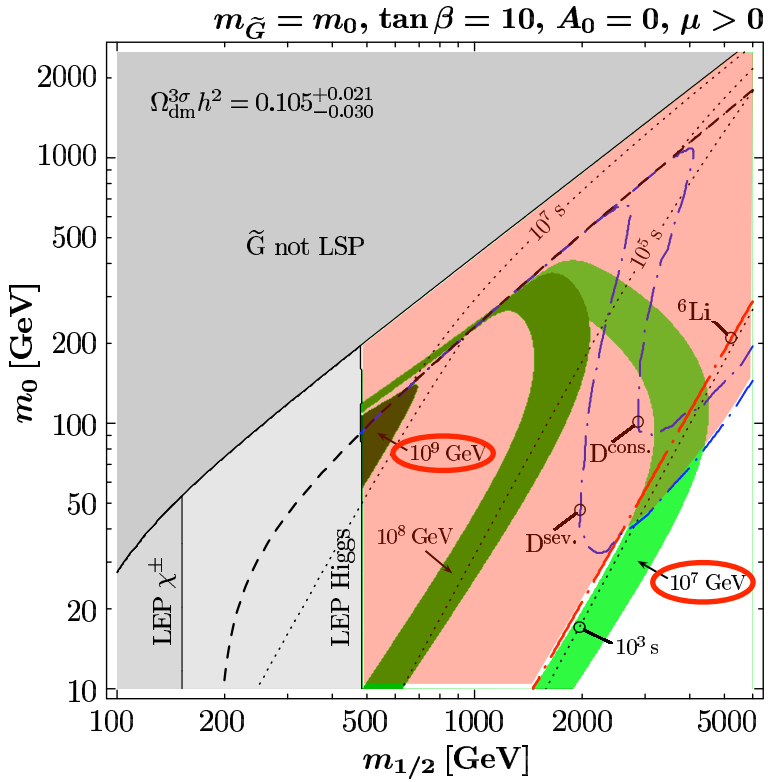

**disfavored by cosmological constraints**

two weeks ago → [Jedamzik, 07]

[Josef Pradler, FDS, hep-ph/0612291]

# Upper Bounds on $T_R$ in the CMSSM with $\widetilde{G}$ Dark Matter

[Talk by Josef Pradler]




$$T_R \lesssim 10^7\,\text{GeV}$$

**Thermal Leptogenesis requires T >10⁹ GeV**

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**Can we probe Gravitino DM in experiments?**

# Signatures of Gravitinos in Experiments

- Direct Detection of $\widetilde{G}$
- Direct Production of $\widetilde{G}$

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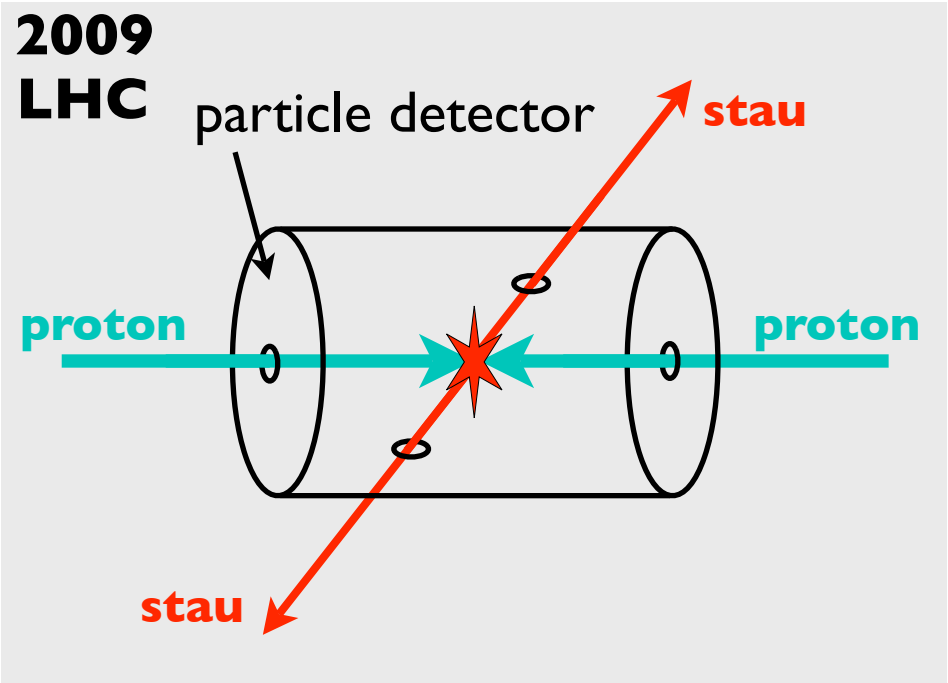
[Drees, Tata, '88, Nisati, Petrarca, Salvini, '97, Ambrosanio, Kribs, Martin, '97, Feng, Moroi, '98, Martin, Wells, '99, Ambrosanio et al., '01, ...]

*** "stable" charged sparticles**




**Tevatron**

[Talks by Krutelyov, Gershtein, ...]

**LHC**

[Talks by Bressler, Zalewski]

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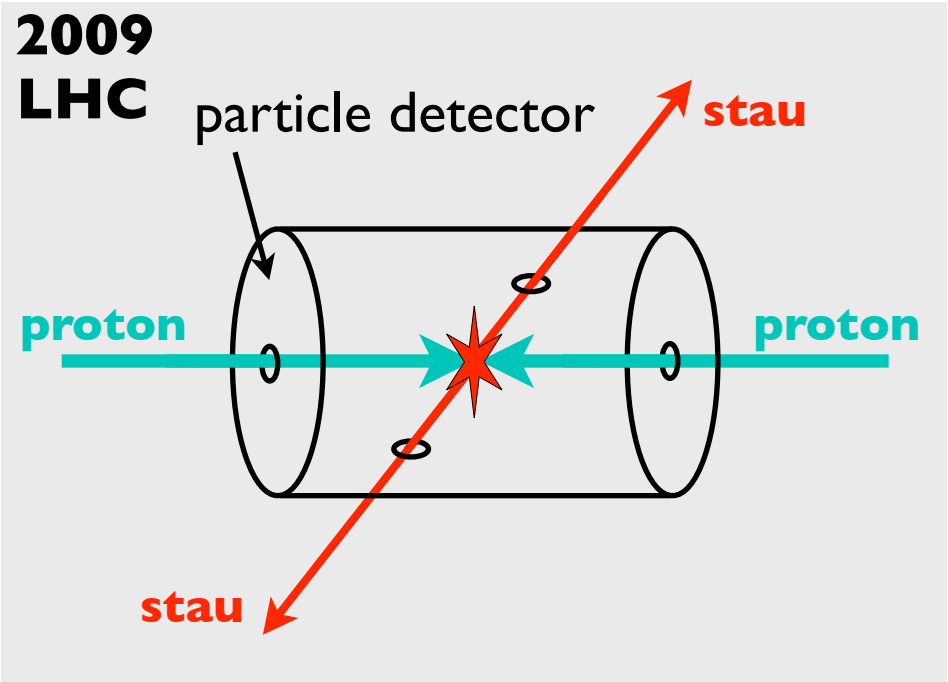


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[Talks by Krutelyov, Gershtein, ...]

**LHC**

[Talks by Bressler, Zalewski]

Talk by John Ellis at 11:30 AM

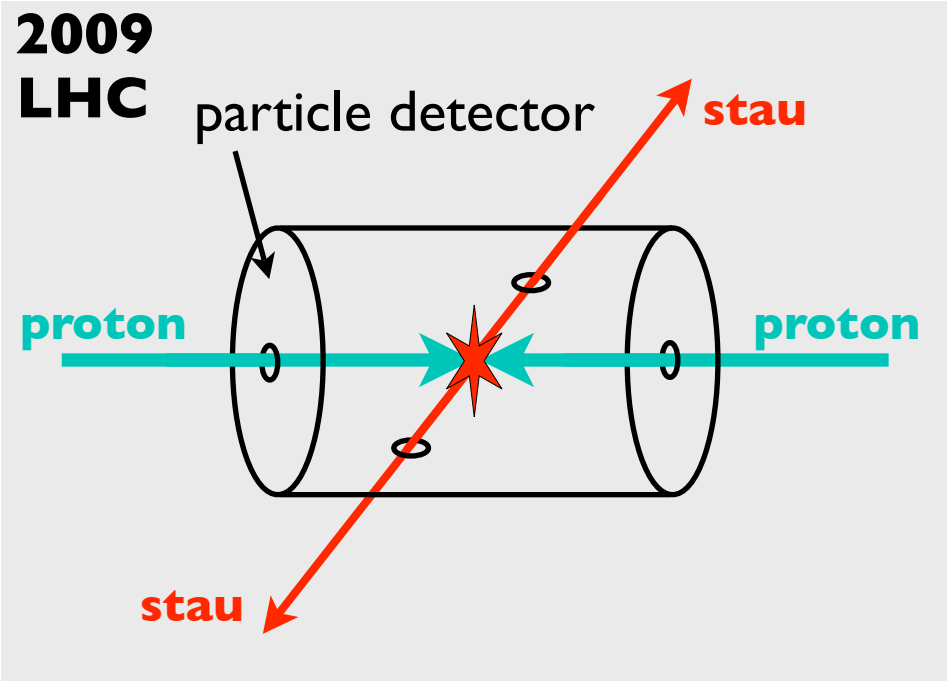
# Signatures of Gravitinos in Experiments

– Direct Detection of $\widetilde{G}$

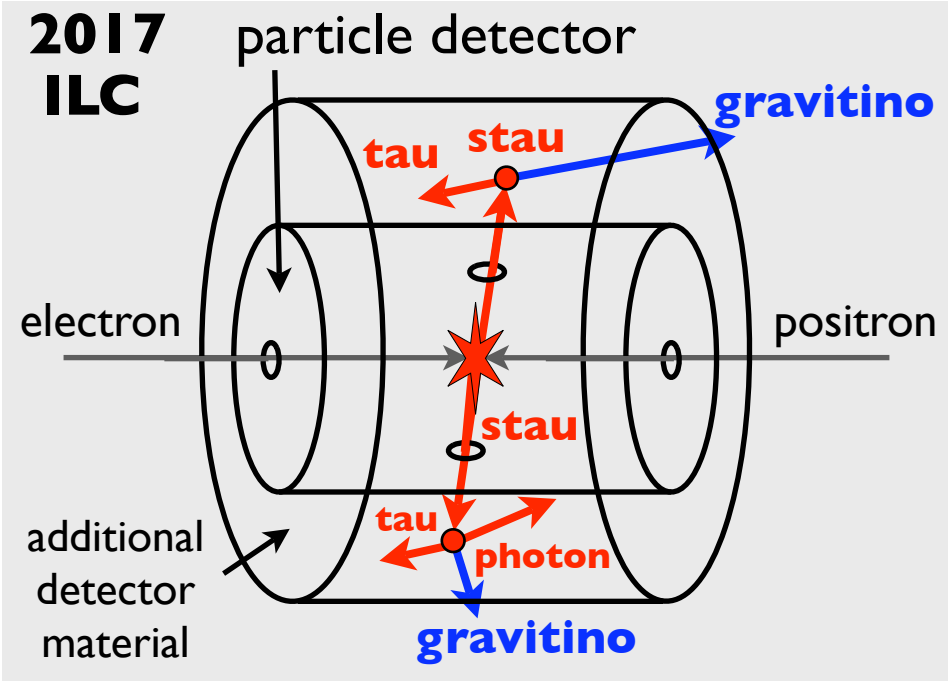
– Direct Production of $\widetilde{G}$

[Talk by Martyn]

∗ **"stable" charged sparticles**




∗ **long-lived charged sparticles**



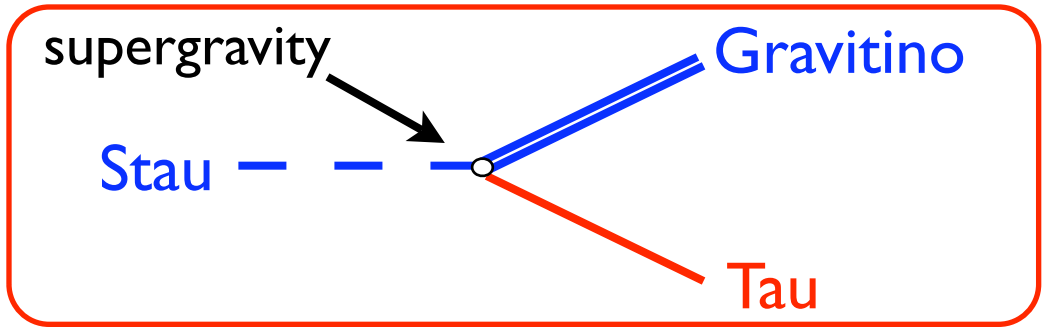

[... ; Buchmüller et al., '04; Hamaguchi et al., '04; Feng, Smith, '05; Martyn, '06; ...]

# Assumptions:

- LSP = Gravitino
- NLSP = Stau $\widetilde{\tau}_{\mathrm{R}}$
- Analyses of $\widetilde{\tau}_{\mathrm{R}}$ Decays

[Buchmüller, Hamaguchi, Ratz, Yanagida, '04]

# $\widetilde{G}$ LSP $\rightarrow$ Planck Scale $\mathbf{M_{Pl}}$ & Gravitino Mass $m_{\widetilde{G}}$




- Assumption: $\widetilde{\tau}_R$ NLSP

- 2-Body Decay $\widetilde{\tau}_R \rightarrow \tau + \widetilde{G}$

$$\Gamma(\widetilde{\tau}_{\mathrm{R}} \rightarrow \tau\, \widetilde{G}) = \frac{m_{\widetilde{\tau}}^5}{48\pi\, m_{\widetilde{G}}^2\, \mathrm{M}_{\mathrm{Pl}}^2} \left(1 - \frac{m_{\widetilde{G}}^2}{m_{\widetilde{\tau}}^2}\right)^4$$

[Buchmüller, Hamaguchi, Ratz, Yanagida, '04]

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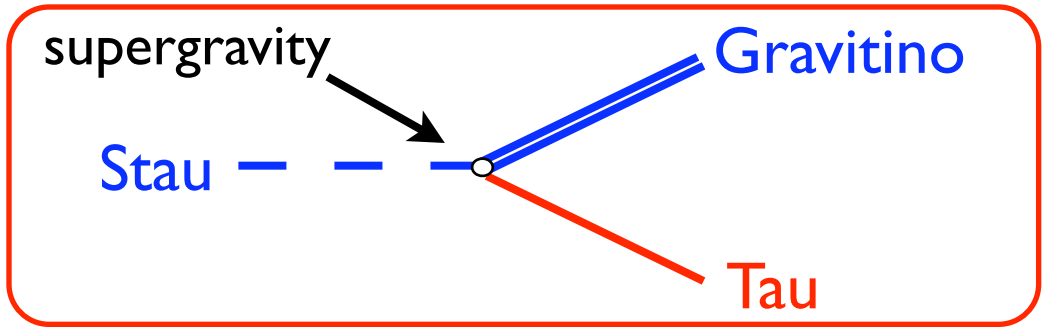


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[Buchmüller, Hamaguchi, Ratz, Yanagida, '04]

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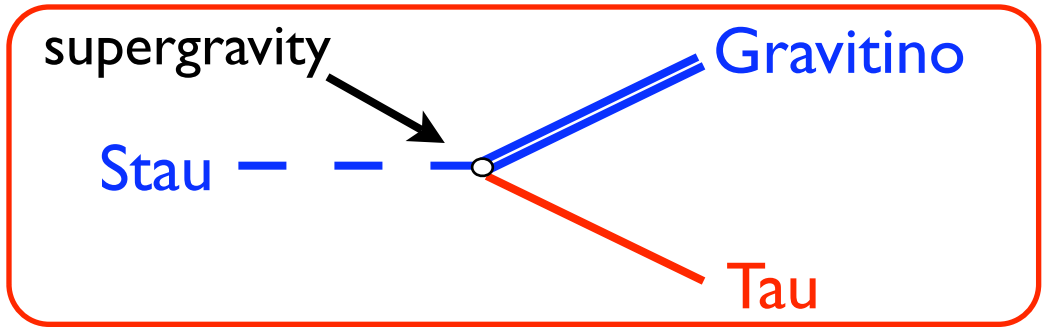


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- Planck Scale $\mathrm{M_{Pl}}$ $\longleftarrow$ NLSP Lifetime $\tau_{\widetilde{\tau}} \approx 1/\Gamma(\widetilde{\tau}_R \rightarrow \tau\, \widetilde{G})$

$$\mathrm{M}_{\mathrm{Pl}}^2 = \frac{\tau_{\widetilde{\tau}}}{48\pi} \frac{m_{\widetilde{\tau}}^5}{m_{\widetilde{G}}^2} \left(1 - \frac{m_{\widetilde{G}}^2}{m_{\widetilde{\tau}}^2}\right)^4 \quad \overset{???}{\longleftrightarrow} \quad \mathrm{M}_{\mathrm{Pl}}^2 = \frac{1}{8\pi\, G_N} = (2.44 \times 10^{18}\,\mathrm{GeV})^2$$

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# Can one identify

# the gravitino LSP

# experimentally?

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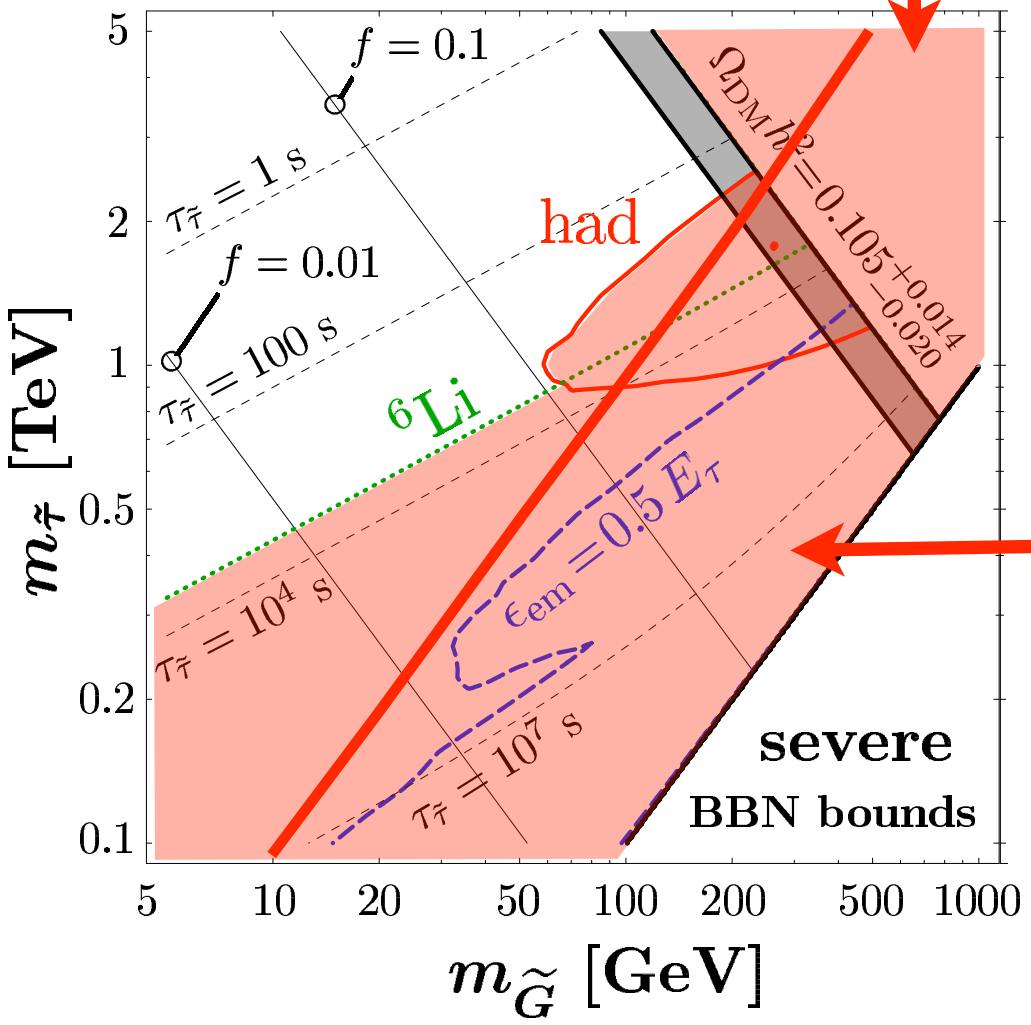
## experimentally?

MPI Measurement

... requires $\boxed{m_{\tilde{G}} > 0.1 m_{\tilde{\tau}}}$ [Talk by Martyn]

... requires $m_{\tilde{G}} > 0.1 m_{\tilde{\tau}}$




**disfavored by cosmological constraints**

[FDS, hep-ph/0611027]

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| $\widetilde{G}$ | $\left(\frac{p}{M_{Pl}}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | $+ \widetilde{\tau}$ collection |
| | $M_{Pl} = 2.44 \times 10^{18}$ GeV | ... | | $+ \widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $M_{Pl}$ (?), ... |
| | | | BBN | |
| | | | CMB | |
| | | | $\gamma$ rays | |

# Supersymmetric Dark Matter Candidates

| | LSP | ID | mass | interaction |
|---|---|---|---|---|
| lightest neutralino | $\widetilde{\chi}_1^0$ | $\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$ | $\mathcal{O}(100\ \text{GeV})$ | g, g' |
| $\in$ MSSM | | mixture | $M_1, M_2, \mu, \tan\beta$ | weak |
| | | | | $M_{\text{W}} \sim 100\ \text{GeV}$ |
| gravitino | $\widetilde{G}$ | superpartner of | eV – TeV | $\left(\frac{p}{\text{M}_{\text{Pl}}}\right)^n$ |
| * gravity | | the graviton | SUSY breaking | extremely weak |
| * local SUSY | | | | $\text{M}_{\text{Pl}} = 2.44 \times 10^{18}\ \text{GeV}$ |
| axino | $\widetilde{a}$ | superpartner of | ??? | $\left(\frac{p}{f_a}\right)^n$ |
| * strong CP | | the axion [Talk by Wilczek] | model | extremely weak |
| | | | | $f_a \gtrsim 10^9\ \text{GeV}$ |

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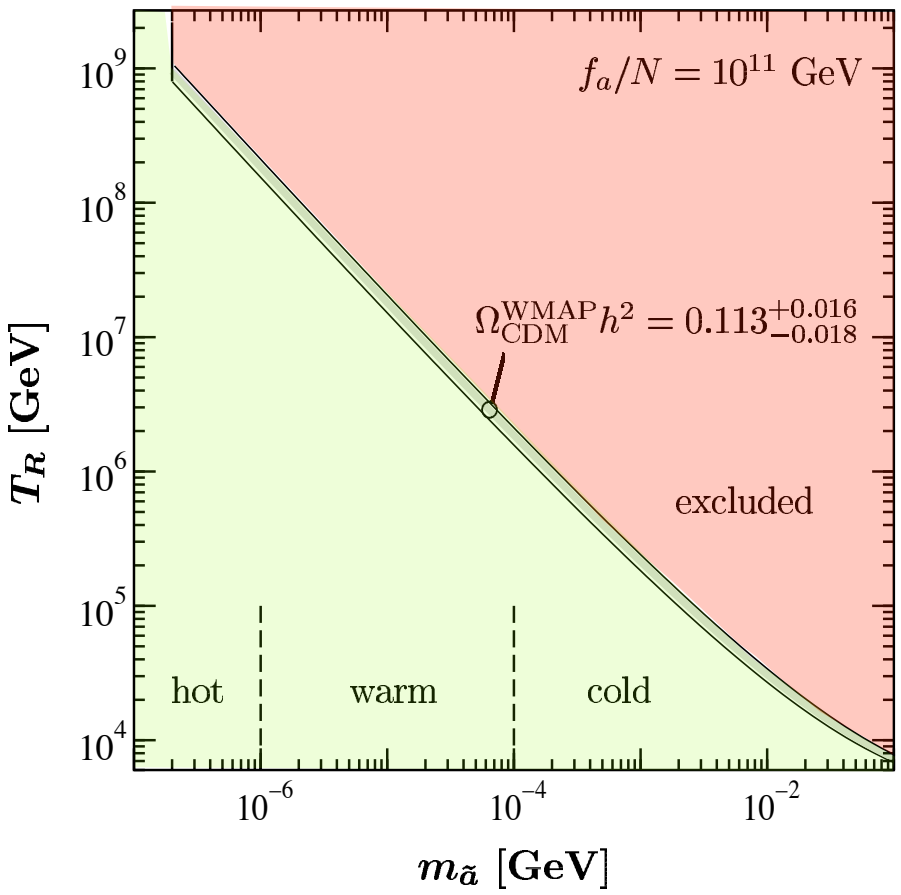
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | $\leftarrow$ cold | indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | direct detection (CRESST, EDELWEISS, ...) |
| | $M_W \sim 100$ GeV | | | prod.@colliders (Tevatron, LHC, ILC, ...) |
| $\widetilde{G}$ | $\left(\frac{p}{M_{Pl}}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | + $\widetilde{\tau}$ collection |
| | $M_{Pl} = 2.44 \times 10^{18}$ GeV | ... | BBN | + $\widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $M_{Pl}$ (?) |
| $\widetilde{a}$ | $\left(\frac{p}{f_a}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | + $\widetilde{\tau}$ collection |
| | $f_a \gtrsim 10^9$ GeV | ... | BBN | + $\widetilde{\tau}$ decay analysis: $m_{\tilde{a}}$, $f_a$ |

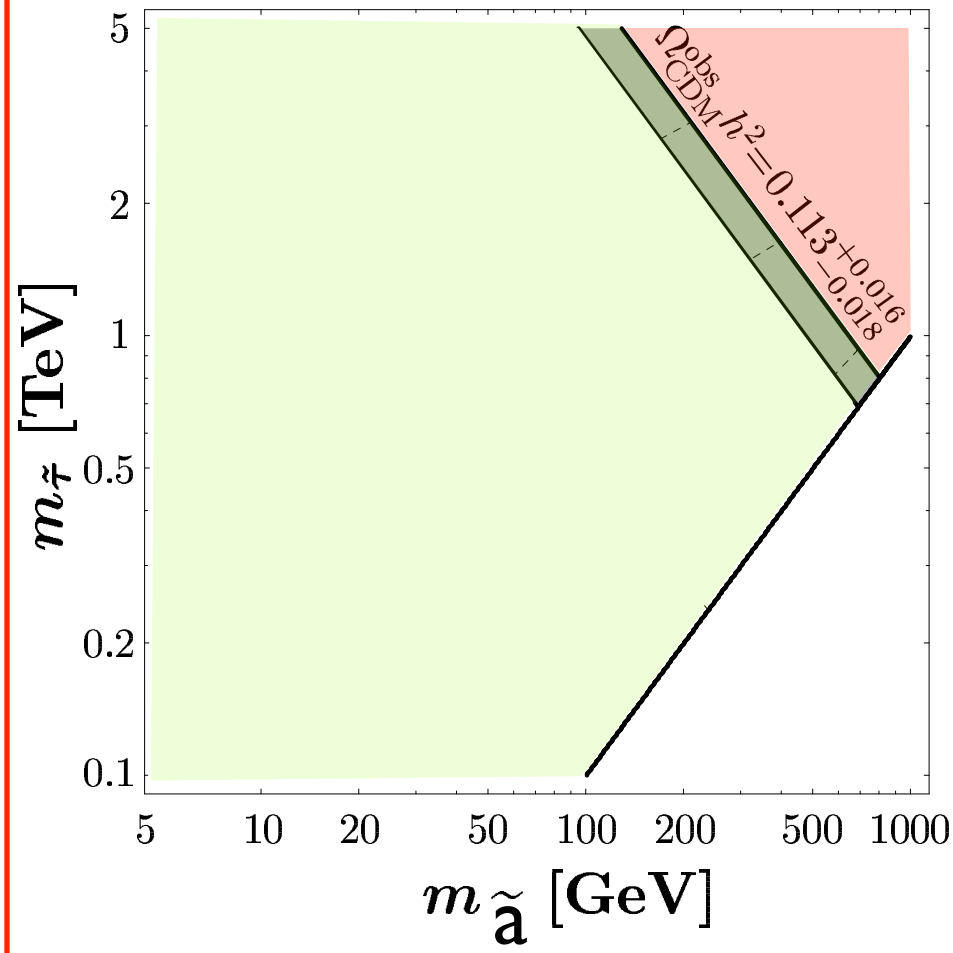
# Thermal $\widetilde{a}$ Production




[Brandenburg, FDS, '04]

see also [Covi et al., '01]

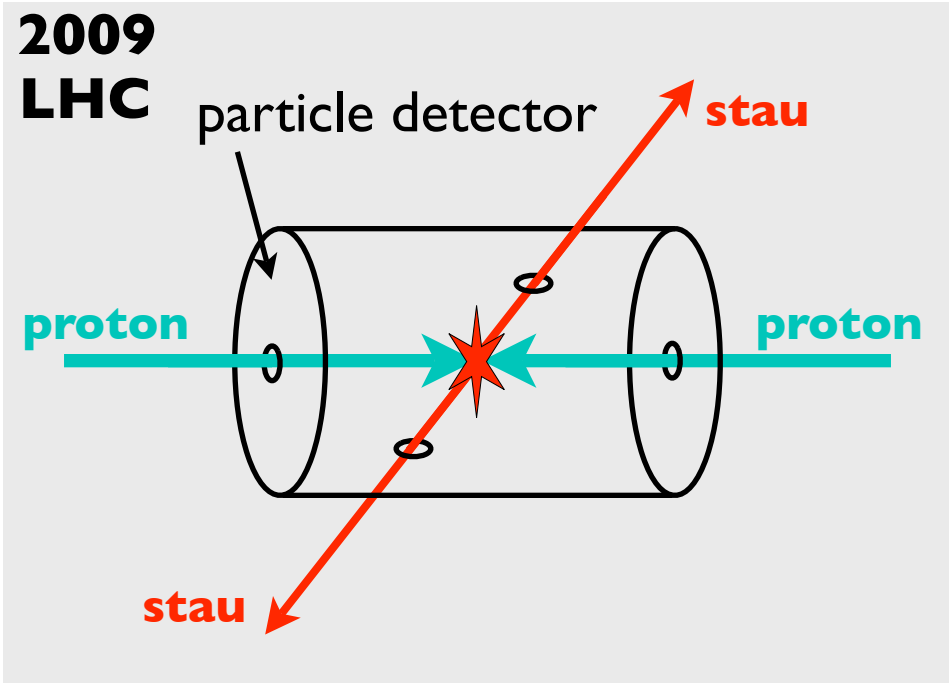
# $\widetilde{\tau}$ NLSP $\longrightarrow$ $\widetilde{a} + \tau$

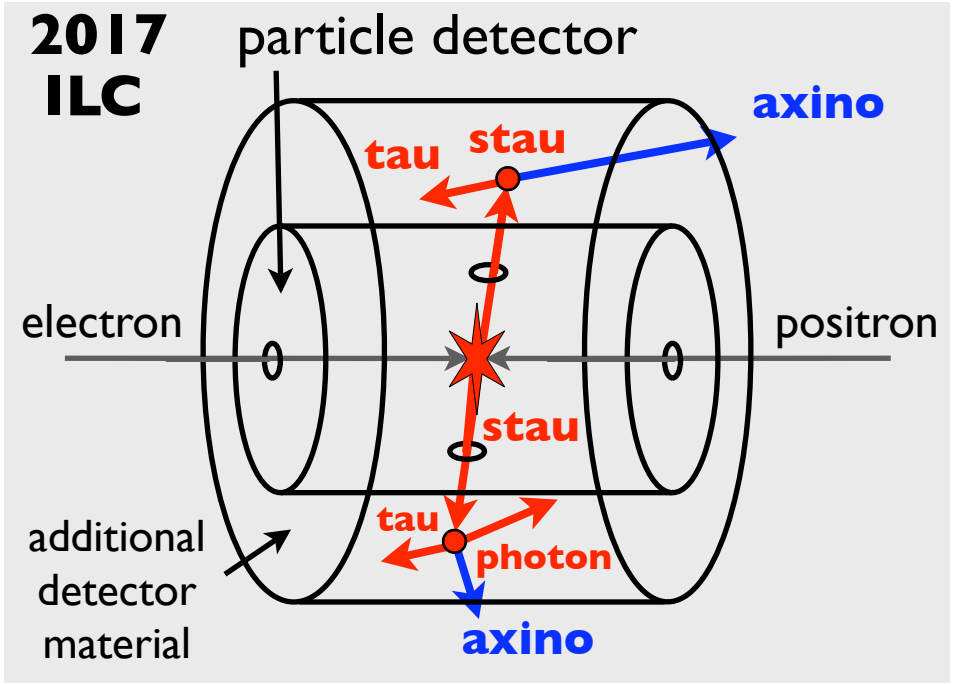



identical to the gravitino case

# LSP Dark Matter: Production, Constraints, Experiments

| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | $\leftarrow$ cold | indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | direct detection (CRESST, EDELWEISS, ...) |
| | $M_W \sim 100$ GeV | | | prod.@colliders (Tevatron, LHC, ILC, ...) |
| $\widetilde{G}$ | $\left(\frac{p}{M_{Pl}}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | + $\widetilde{\tau}$ collection |
| | $M_{Pl} = 2.44 \times 10^{18}$ GeV | ... | BBN | + $\widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $M_{Pl}$ (?) |
| $\widetilde{a}$ | $\left(\frac{p}{f_a}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | + $\widetilde{\tau}$ collection |
| | $f_a \gtrsim 10^9$ GeV | ... | BBN | + $\widetilde{\tau}$ decay analysis: $m_{\tilde{a}}$, $f_a$ |

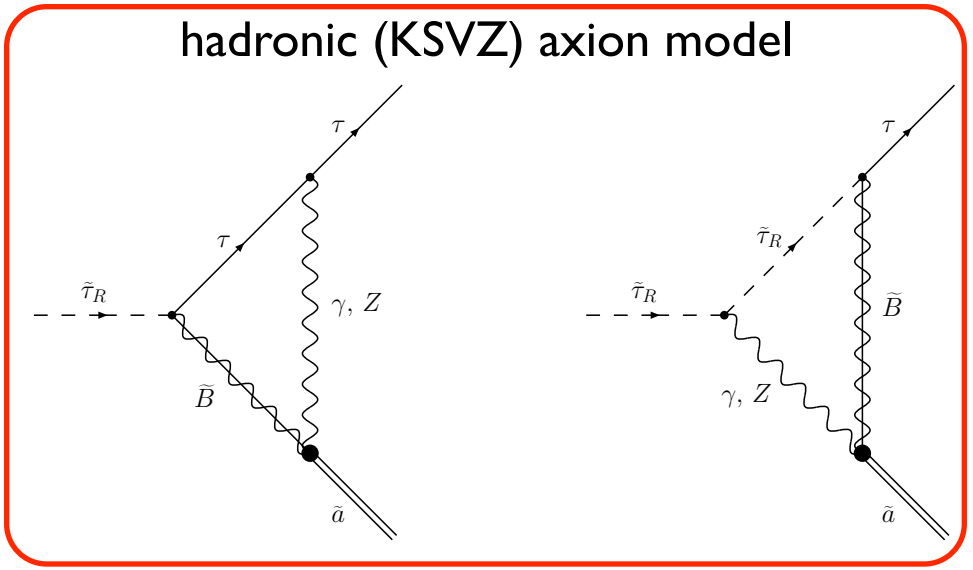

2009
LHC
particle detector
stau
proton
proton
stau


2017
ILC
particle detector
axino
tau
stau
electron
positron
stau
tau
photon
additional
detector
material
axino

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

# $\tilde{a}$ LSP $\rightarrow$ Peccei–Quinn Scale $f_a$ & Axino Mass $m_{\tilde{a}}$

hadronic (KSVZ) axion model




□ Assumption: $\widetilde{\tau}_R$ NLSP & $\widetilde{\chi}^0 \simeq \widetilde{B}$

- 2-Body Decay $\widetilde{\tau}_R \rightarrow \tau + \tilde{a}$

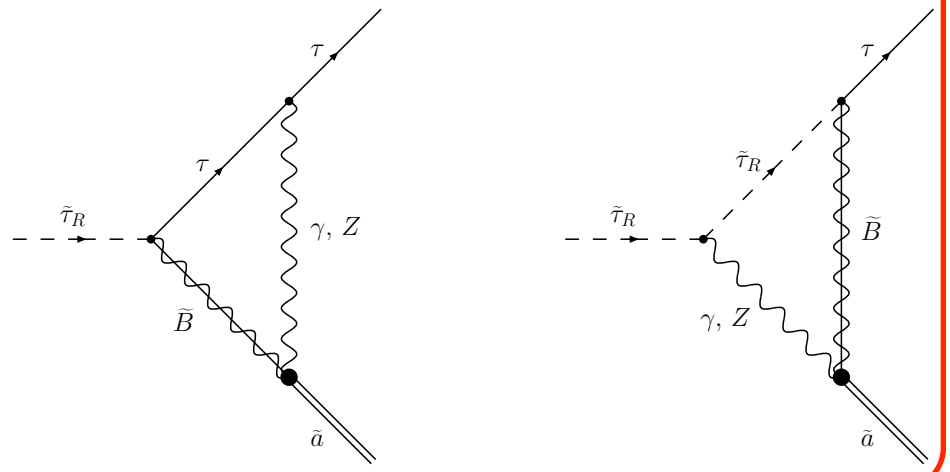
$$\Gamma(\widetilde{\tau}_{\rm R} \rightarrow \tau \widetilde{a}) \simeq \xi^2 \, (25\,{\rm sec})^{-1} C_{\rm aYY}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right) \left(\frac{m_{\widetilde{\tau}}}{100\,{\rm GeV}}\right) \left(\frac{10^{11}\,{\rm GeV}}{f_a}\right)^2 \left(\frac{m_{\widetilde{B}}}{100\,{\rm GeV}}\right)^2$$

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

# $\tilde{a}$ LSP $\longrightarrow$ Peccei–Quinn Scale $f_a$ & Axino Mass $m_{\tilde{a}}$

□ Assumption: $\widetilde{\tau}_R$ NLSP & $\widetilde{\chi}^0 \simeq \widetilde{B}$

hadronic (KSVZ) axion model




- 2-Body Decay $\widetilde{\tau}_R \to \tau + \tilde{a}$

$$\Gamma(\widetilde{\tau}_{\rm R} \to \tau \widetilde{a}) \simeq \xi^2\,(25\,{\rm sec})^{-1} C^2_{\rm aYY} \left(1 - \frac{m^2_{\widetilde{a}}}{m^2_{\widetilde{\tau}}}\right) \left(\frac{m_{\widetilde{\tau}}}{100\,{\rm GeV}}\right) \left(\frac{10^{11}\,{\rm GeV}}{f_a}\right)^2 \left(\frac{m_{\widetilde{B}}}{100\,{\rm GeV}}\right)^2$$

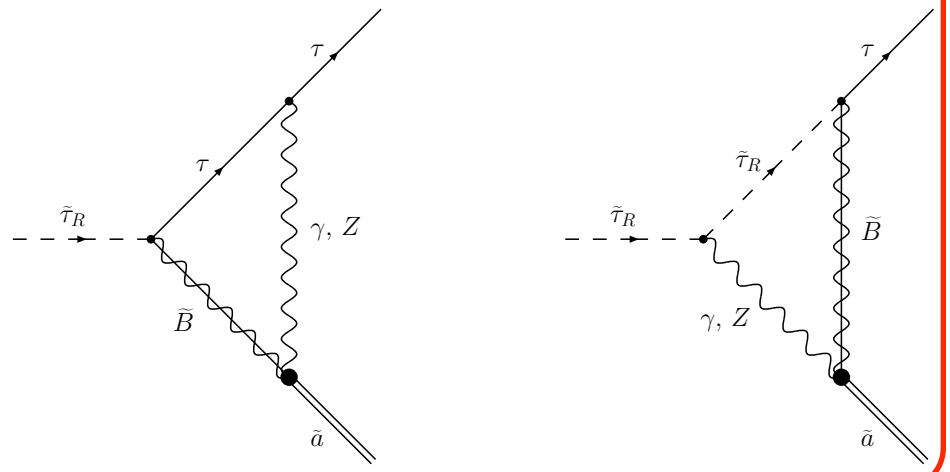
- Axino Mass $m_{\tilde{a}} = \sqrt{m^2_{\widetilde{\tau}} + m^2_{\tau} - 2 m_{\widetilde{\tau}} E_{\tau}}$ $\longleftarrow$ Kinematics

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

# $\tilde{a}$ LSP $\longrightarrow$ Peccei–Quinn Scale $f_a$ & Axino Mass $m_{\tilde{a}}$

□ Assumption: $\widetilde{\tau}_R$ NLSP & $\widetilde{\chi}^0 \simeq \widetilde{B}$

hadronic (KSVZ) axion model




- 2-Body Decay $\widetilde{\tau}_R \to \tau + \tilde{a}$

$$\Gamma(\widetilde{\tau}_{\rm R} \to \tau \widetilde{a}) \simeq \xi^2\,(25\,{\rm sec})^{-1} C_{\rm aYY}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right) \left(\frac{m_{\widetilde{\tau}}}{100\,{\rm GeV}}\right) \left(\frac{10^{11}\,{\rm GeV}}{f_a}\right)^2 \left(\frac{m_{\widetilde{B}}}{100\,{\rm GeV}}\right)^2$$

- Peccei–Quinn Scale $f_a$ $\longleftarrow$ NLSP Lifetime $\tau_{\widetilde{\tau}} \approx 1/\Gamma(\widetilde{\tau}_R \to \tau\,\tilde{a})$

$$f_a^2 \simeq \left(\frac{\tau_{\widetilde{\tau}}}{25\ {\rm sec}}\right) \xi^2\, C_{\rm aYY}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right) \left(\frac{m_{\widetilde{\tau}}}{100\,{\rm GeV}}\right) \left(\frac{m_{\widetilde{B}}}{100\,{\rm GeV}}\right)^2 (10^{11}\,{\rm GeV})^2$$

- Axino Mass $m_{\tilde{a}} = \sqrt{m_{\widetilde{\tau}}^2 + m_\tau^2 - 2 m_{\widetilde{\tau}} E_\tau}$ $\longleftarrow$ Kinematics

# Can one distinguish between

# $\tilde{a}$ LSP and $\tilde{G}$ LSP

# experimentally?

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

# Can one distinguish between the $\tilde{a}/\widetilde{G}$ LSP Scenarios?

- Lifetime of the NLSP $\longleftarrow$ Assumption: $\widetilde{\tau}_R = \text{NLSP}$ & $\widetilde{\chi}^0 \approx \widetilde{B}$

$\tilde{a} = \text{LSP}$

$\tau_{\widetilde{\tau}}^{\tilde{a}\,\text{LSP}} \longleftarrow m_{\widetilde{\tau}}, m_{\widetilde{B}}, m_{\tilde{a}}, f_a$

$\mathcal{O}(0.01\ \text{sec}) \lesssim \tau_{\widetilde{\tau}}^{\tilde{a}\,\text{LSP}} \lesssim \mathcal{O}(10\ \text{h})$

$\uparrow$ $\qquad\qquad$ $\uparrow$

$f_a \sim 10^9\,\text{GeV} \qquad f_a \sim 10^{12}\,\text{GeV}$

$\widetilde{G} = \text{LSP}$

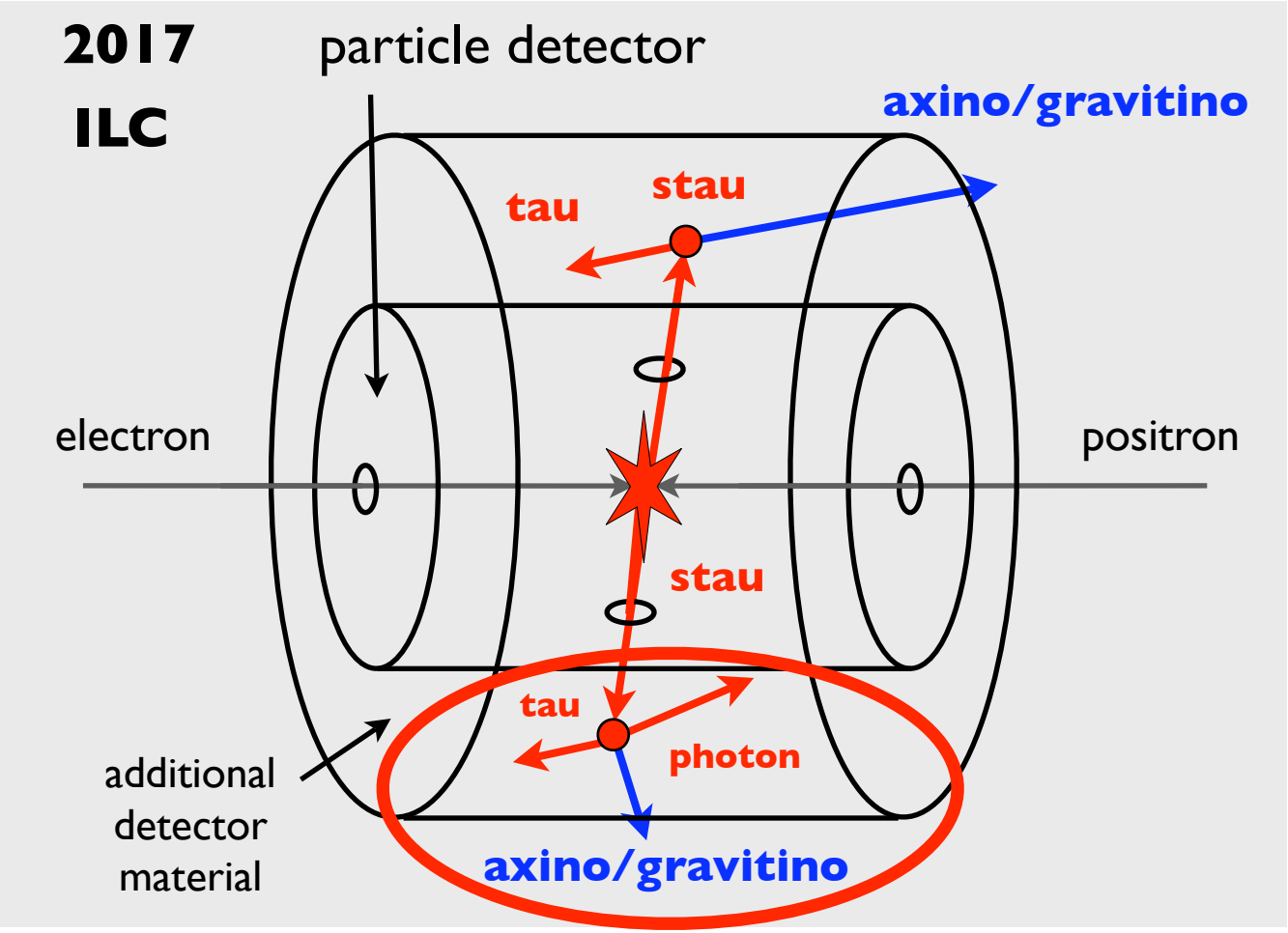
$\tau_{\widetilde{\tau}}^{\widetilde{G}\,\text{LSP}} \longleftarrow m_{\widetilde{\tau}}, m_{\widetilde{B}}, m_{\widetilde{G}}$

$\mathcal{O}(10^{-8}\ \text{sec}) \lesssim \tau_{\widetilde{\tau}}^{\widetilde{G}\,\text{LSP}} \lesssim \mathcal{O}(15\ \text{y})$

$\uparrow$ $\qquad\qquad$ $\uparrow$

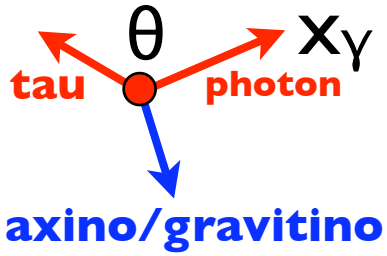
$m_{\widetilde{G}} \sim 1\,\text{keV} \qquad m_{\widetilde{G}} \sim 50\,\text{GeV}$

## Very Short/Very Long Lived NLSP $\rightarrow \widetilde{G}$ LSP Scenario

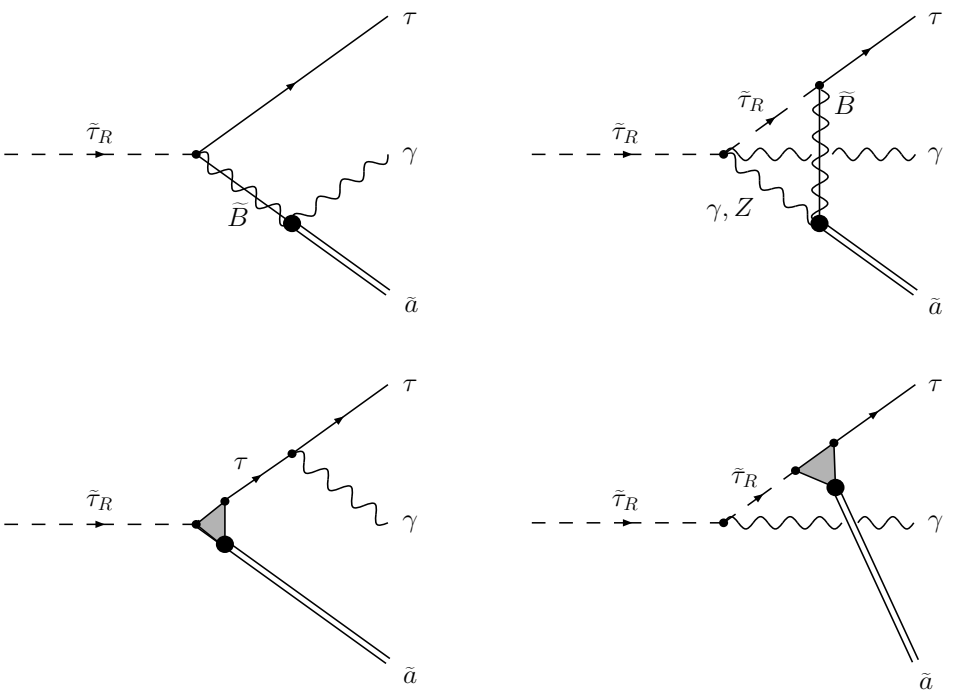



# 3-Body Decays

# The 3-Body Decays

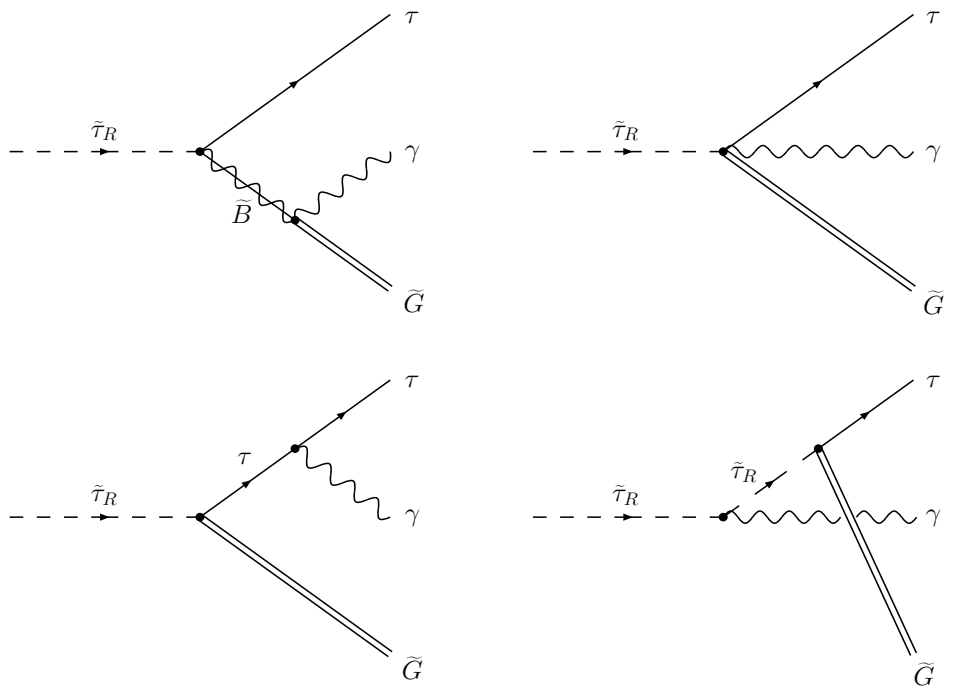



$\tilde{a} = \text{LSP}: \quad \widetilde{\tau}_R \to \tau + \gamma + \tilde{a}$




$$\frac{d^2\Gamma(\widetilde{\tau}_\mathrm{R} \to \tau\,\gamma\,\widetilde{a})}{dx_\gamma\, d\cos\theta} = \ldots$$

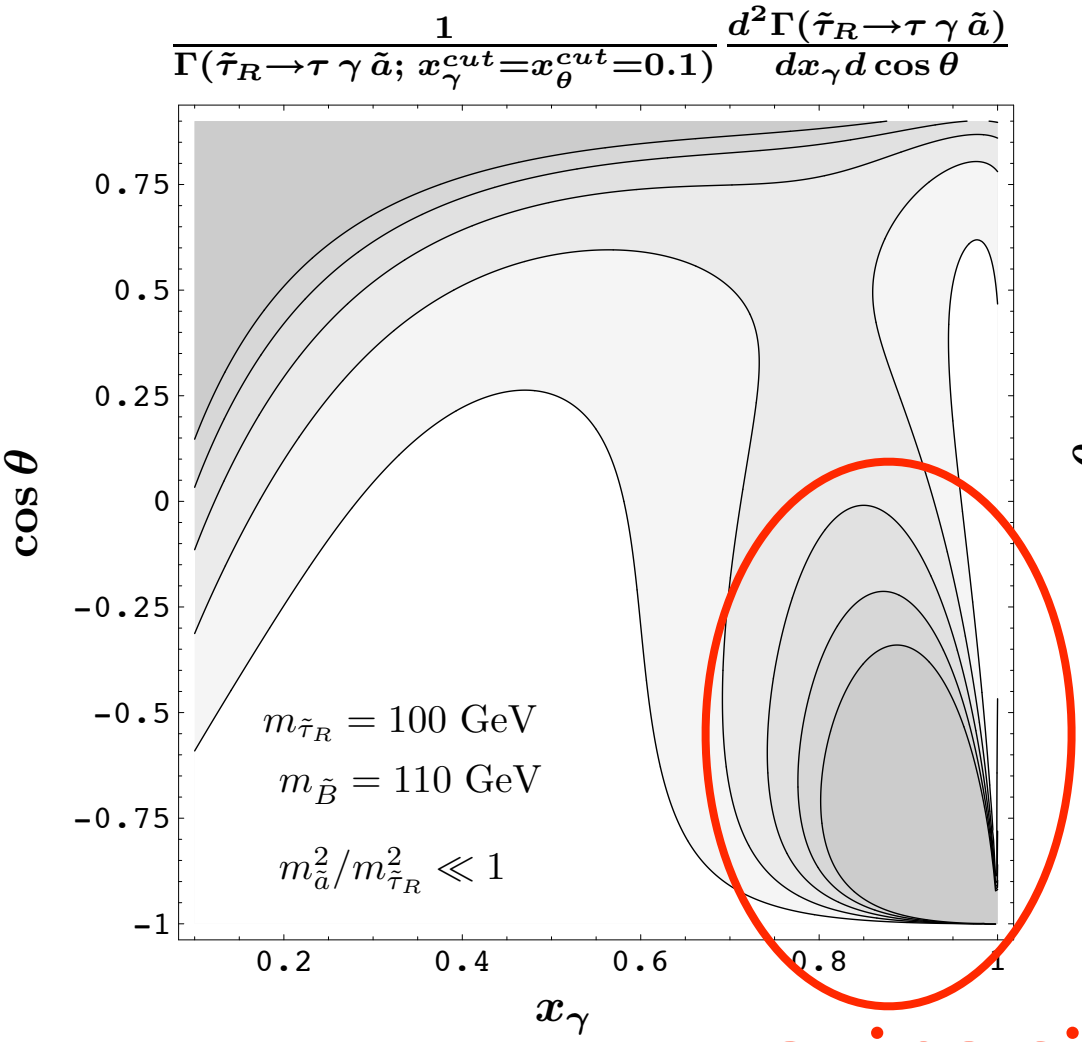
$\widetilde{G} = \text{LSP}: \quad \widetilde{\tau}_R \to \tau + \gamma + \widetilde{G}$



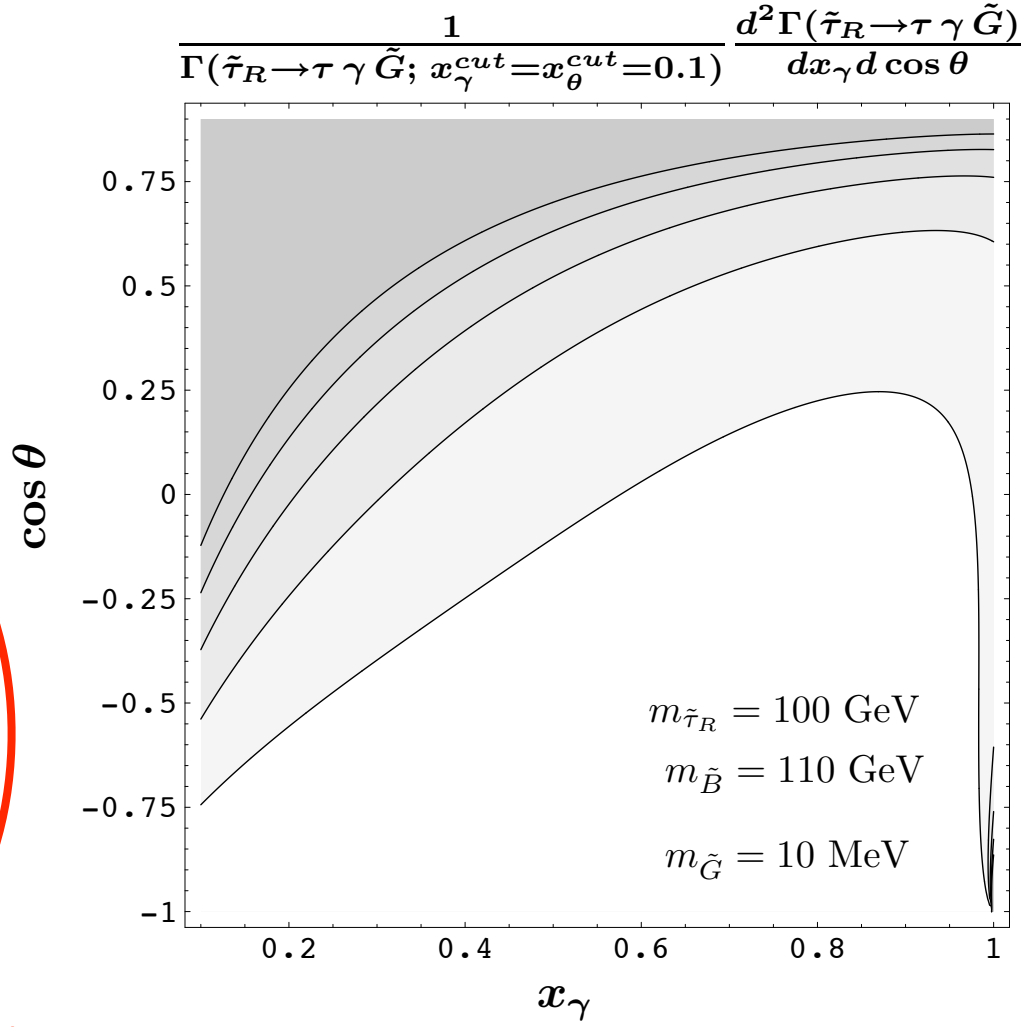

$$\frac{d^2\Gamma(\widetilde{\tau}_\mathrm{R} \to \tau\,\gamma\,\widetilde{G})}{dx_\gamma\, d\cos\theta} = \ldots$$

[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

## Axino LSP Scenario




## Gravitino LSP Scenario




**axino signature**

# Differential Distribution of the Visible Decay Products

# Supersymmetric Dark Matter Candidates

| LSP | interaction | production | constraints | experiments |
|---|---|---|---|---|
| $\widetilde{\chi}_1^0$ | g, g' | WIMP | $\leftarrow$ cold | indirect detection (EGRET, GLAST, ...) |
| | weak | freeze out | | direct detection (CRESST, EDELWEISS, ...) |
| | $M_{\mathrm{W}} \sim 100$ GeV | | | prod.@colliders (Tevatron, LHC, ILC, ...) |
| $\widetilde{G}$ | $\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | $+\ \widetilde{\tau}$ collection |
| | $\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV | ... | BBN | $+\ \widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $\mathrm{M_{Pl}}$ (?) |
| $\widetilde{a}$ | $\left(\frac{p}{f_a}\right)^n$ | therm. prod. | $\leftarrow$ cold | $\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...) |
| | extremely weak | NLSP decays | $\leftarrow$ warm | $+\ \widetilde{\tau}$ collection |
| | $f_a \gtrsim 10^9$ GeV | ... | BBN | $+\ \widetilde{\tau}$ decay analysis: $m_{\tilde{a}}$, $f_a$ |

**22% of the energy content of our Universe**

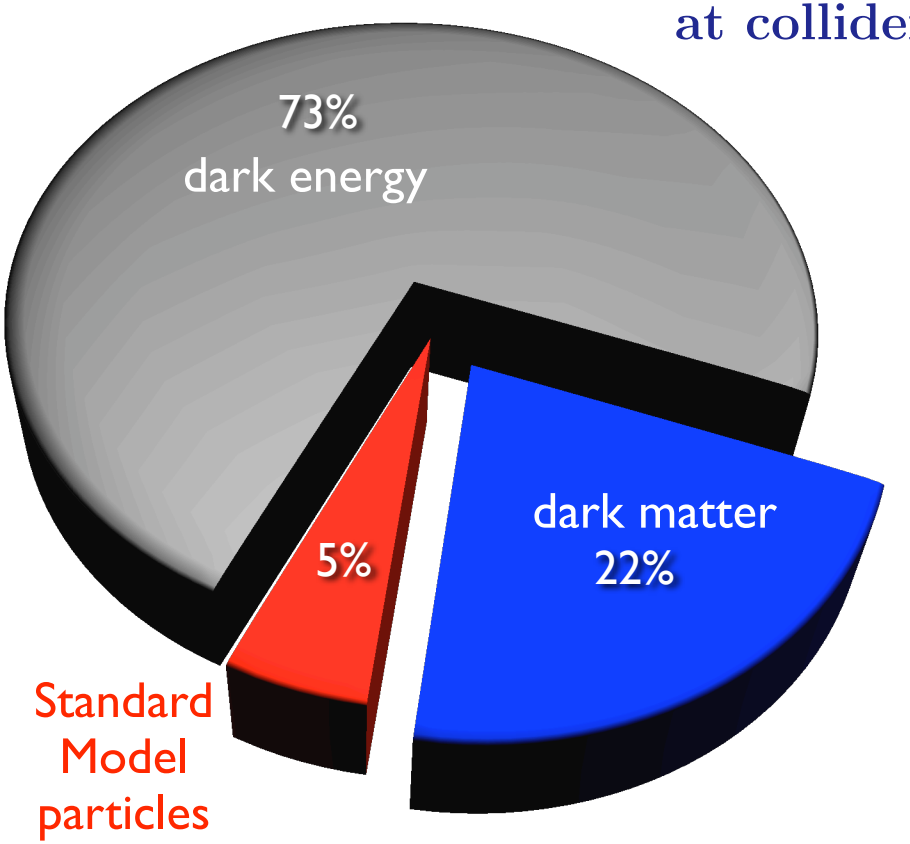
**could be provided**

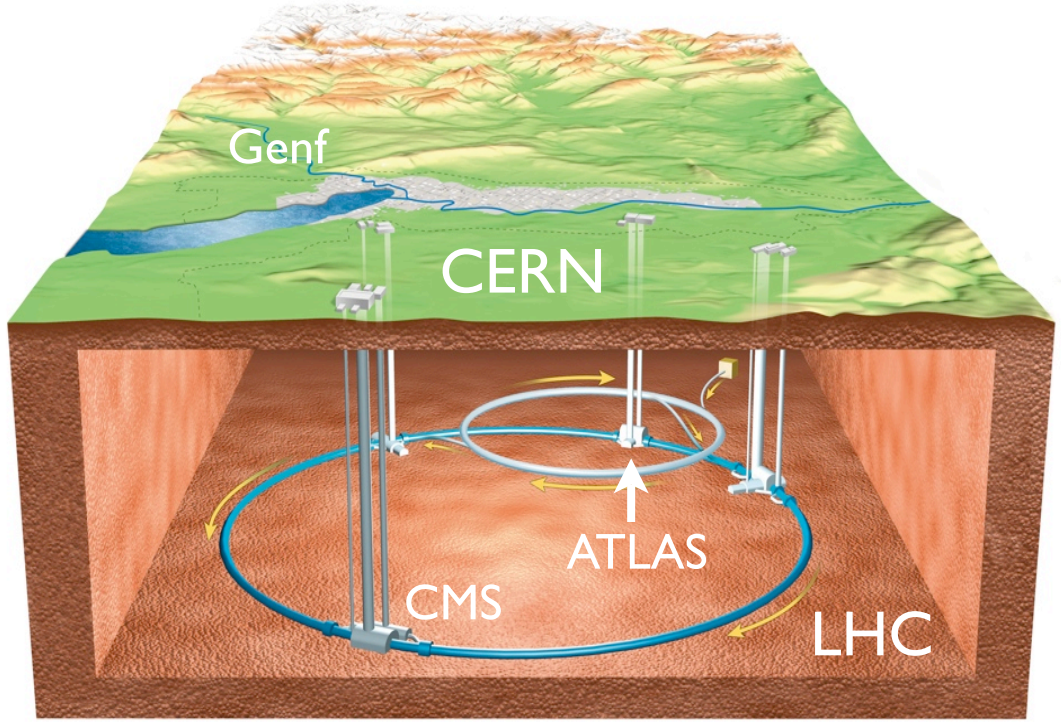
**by the lightest supersymmetric particle**

**(e.g., $\widetilde{\chi}_1^0$, $\widetilde{G}$, or $\tilde{a}$)**

**which could be produced and identified**

**at colliders in the near future**



# Thank you

## for your attention

## and

## the exciting conference

# Bonus Material

# Gravitino Dark Matter from Thermal Production

- Boltzmann Equation

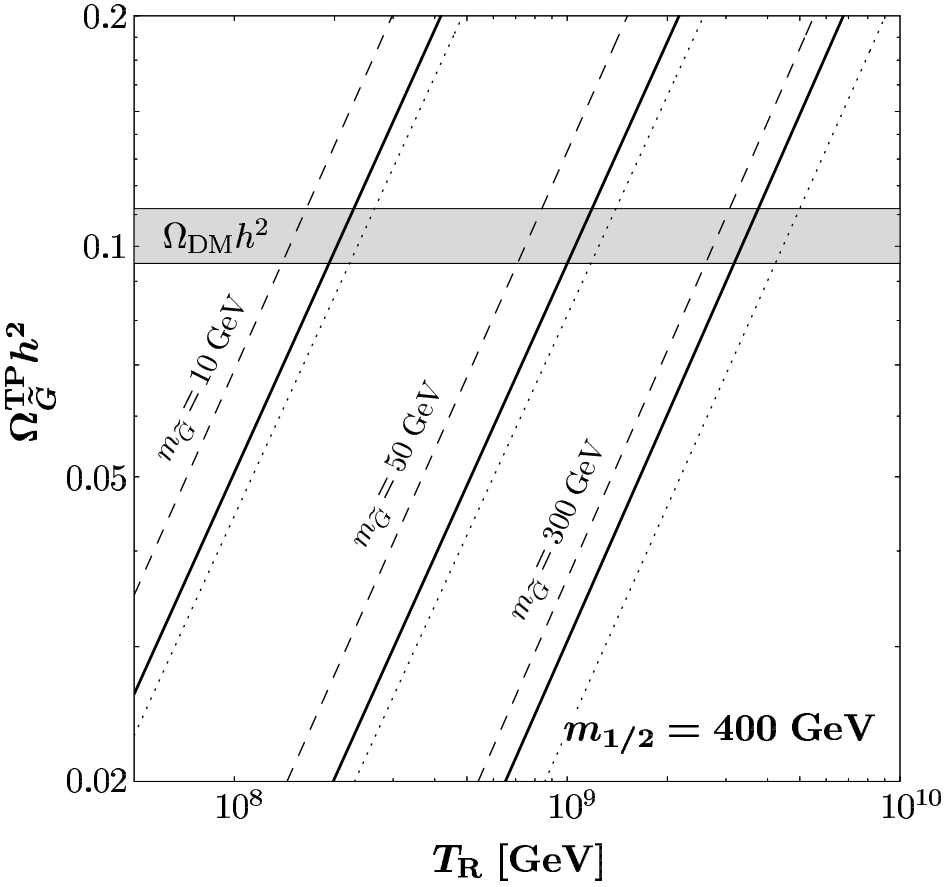
$$\frac{dn_{\widetilde{G}}}{dt} + 3Hn_{\widetilde{G}} = C_{\widetilde{G}}$$

- Collision Term

$$C_{\widetilde{G}} = \sum_{i=1}^{3} \frac{3\zeta(3)T^6}{16\pi^3 \mathrm{M}_{\mathrm{Pl}}^2} \left(1 + \frac{M_i^2}{3m_{\widetilde{G}}^2}\right) c_i\, g_i^2 \ln\left(\frac{k_i}{g_i}\right)$$

- Gravitino Density

$$\Omega_{\widetilde{G}}^{\mathrm{TP}} h^2 = \sum_{i=1}^{3} \omega_i\, g_i^2 \left(1 + \frac{M_i^2}{3m_{\widetilde{G}}^2}\right) \ln\left(\frac{k_i}{g_i}\right) \times \left(\frac{m_{\widetilde{G}}}{100\ \mathrm{GeV}}\right) \left(\frac{T_{\mathrm{R}}}{10^{10}\ \mathrm{GeV}}\right)$$




- $\mathrm{U(1)_Y \times SU(2)_L \times SU(3)_c}$

$$\begin{aligned} c_i &= (11, 27, 72) \\ k_i &= (1.266, 1.312, 1.271) \\ \omega_i &= (0.018, 0.044, 0.117) \end{aligned}$$

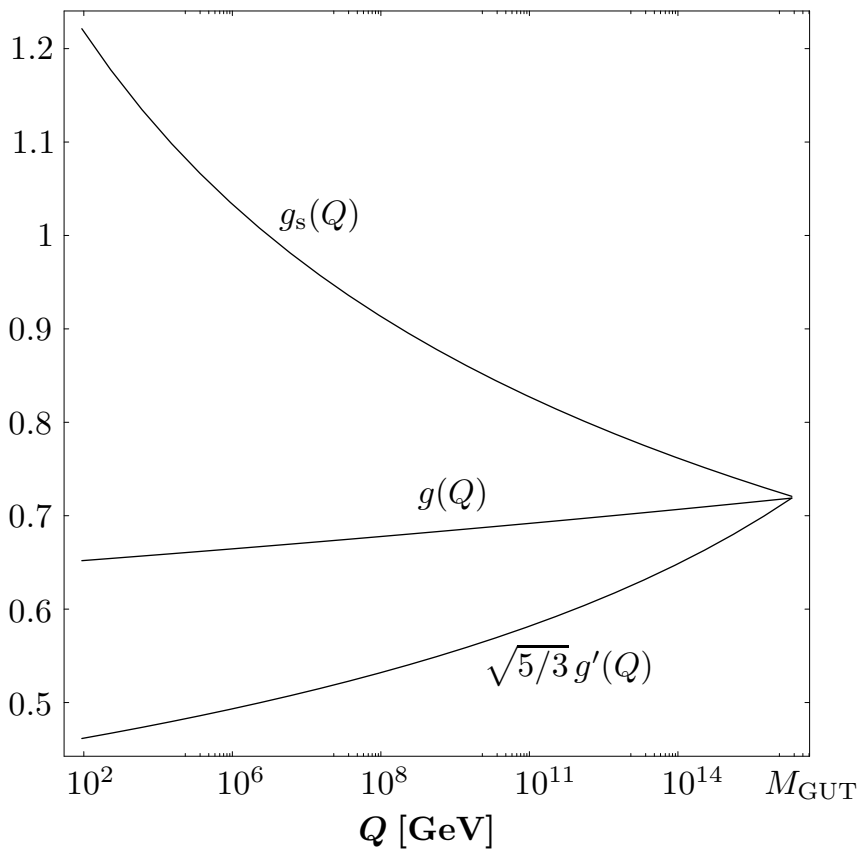
solid: $M_{1,2,3} = m_{1/2}$

dashed: $0.5\, M_{1,2} = M_3 = m_{1/2}$

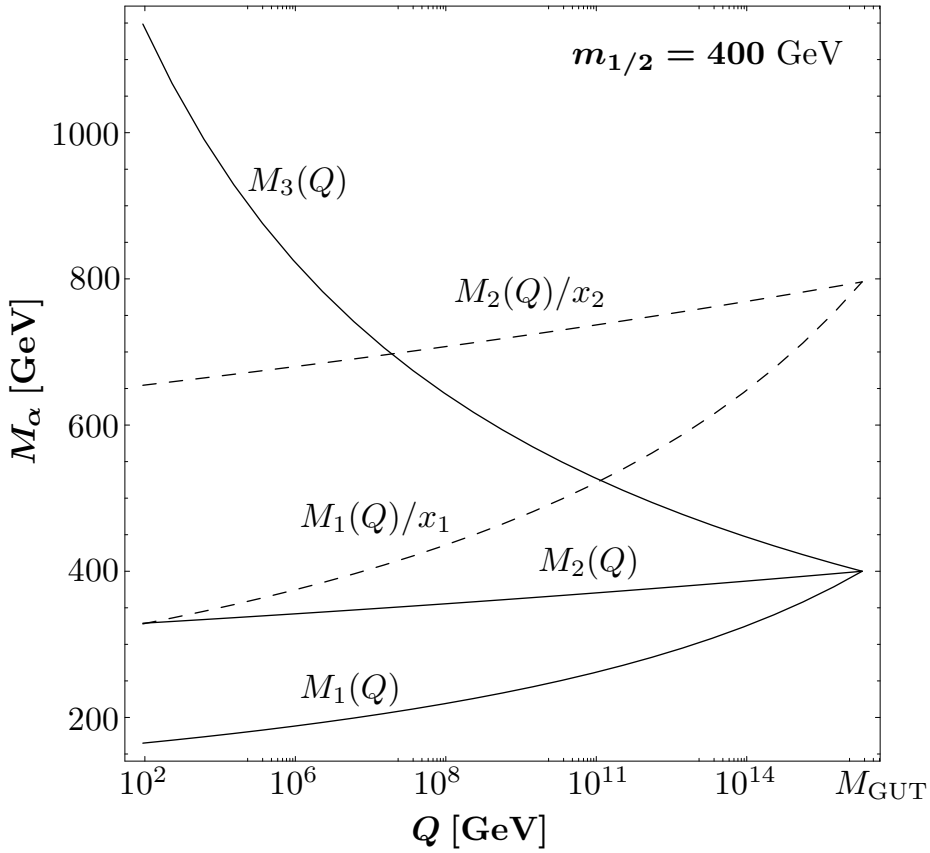
dotted: $M_3 = m_{1/2}$

[ ... ; Bolz, Brandenburg, Buchmüller, '01; Pradler, FDS, '07]

# Gauge Couplings

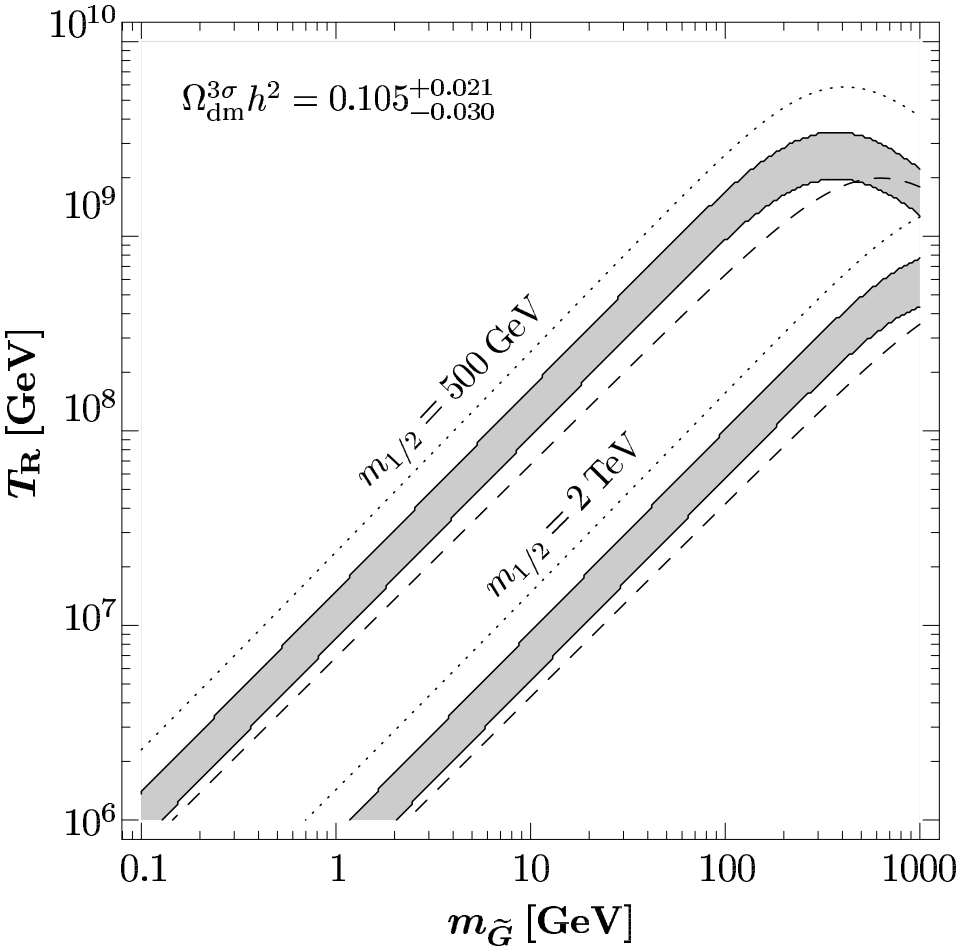



# Gaugino Mass Parameters




## Gauge Coupling Unification at $M_{GUT} \simeq 2 \times 10^{16}\,\mathrm{GeV}$

# Thermal $\widetilde{G}$ Production




[...; Bolz, Brandenburg, Buchmüller, '01]

[Pradler, FDS, '06]

# Constraints from Observ./Simul. of Cosmic Structures

| Probe/Observable | $m_{\rm WDM}^{\rm min}$ | $(v_{\rm FS}^{\rm rms,0})_{\rm WDM}^{\rm max}$ | Ref. |
|---|---|---|---|
| Dwarf spheroidal galaxies | 0.7 keV | 0.06 km/s | [Dalcanton et al., '00] |
| Lyman-$\alpha$ forest at $z \simeq 3$ | 0.75 keV | 0.05 km/s | [Narayanan et al., '00] |
| Lyman-$\alpha$ forest at $z \simeq (2-3)$ | 0.55 keV | 0.08 km/s | [Viel et al., '05] |
| Supermassive black hole at $z \simeq 5.8$ | 0.5 keV | 0.09 km/s | [Barkana et al., '01] |
| Cosmological reionization by $z \simeq 5.8$ | 0.75 keV | 0.05 km/s | [Barkana et al., '01] |
| (Cosmological reionization at $z \simeq 17$ | 10 keV | 0.002 km/s | [Yoshida et al., '03]) |

Collisionless CDM $\longrightarrow$ Too Much Power on Small Scales ($\lesssim 1$ Mpc)

- excess in the number of low mass halos
- overdensity of halo cores

# Free Streaming of Gravitinos from Stau NLSP Decays

□ Comoving Free-Streaming Scale

$$\lambda_{\rm FS}^{\tau_{\tilde\tau}\ll t_{\rm eq}} \simeq \int_0^{t_{\rm eq}} dt\,\frac{v(t)}{a(t)}$$

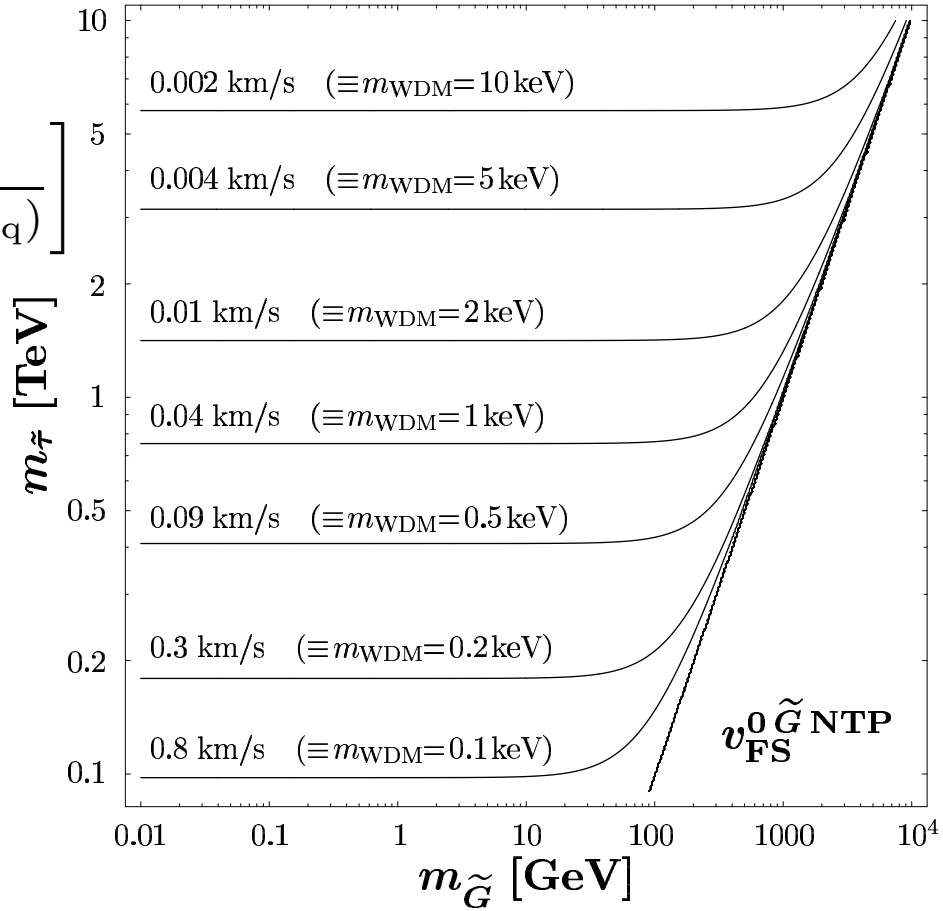
$$= v_0 t_{\rm eq}(1+z_{\rm eq})^2 \ln\left[\sqrt{1+\frac{1}{v_0^2(1+z_{\rm eq})^2}}+\frac{1}{v_0(1+z_{\rm eq})}\right]$$

□ Present Free-Streaming Velocity

$$v_{\rm FS}^{0\,\widetilde G\,\rm NTP} = 0.024\,\frac{\rm km}{\rm s}\left(\frac{g_*(t_i=\tau_{\tilde\tau})}{3.36}\right)^{1/4} \times\left(\frac{m_{\tilde\tau}}{1\ \rm TeV}\right)^{-3/2}\left(1-\frac{m_{\widetilde G}^2}{m_{\tilde\tau}^2}\right)^{-1}$$

$$\boxed{|\vec p_{\widetilde G}(t_i)| = \frac{m_{\tilde\tau}^2 - m_{\widetilde G}^2 - m_\tau^2}{2\,m_{\tilde\tau}}}$$

**Present Velocity of Gravitinos from $\tilde\tau \to \tau\widetilde G$**




Collisionless WDM $\longrightarrow$ Solution of Small Scale ($\lesssim$ 1 Mpc) Structure Problems

[Borgani et al., '96; Kaplinghat, '05; Cembranos et al., '05; Jedamzik et al., '05]

# Free Streaming of Gravitinos from Thermal Production

□ Comoving Free-Streaming Scale

$$\lambda_{\rm FS}^{t_{\rm i}\ll t_{\rm eq}} \simeq \int_0^{t_{\rm eq}} dt\,\frac{v(t)}{a(t)} = v_0\,t_{\rm eq}\,(1{+}z_{\rm eq})^2\,\ln\left(\sqrt{1+\frac{1}{v_0^2\,(1{+}z_{\rm eq})^2}}+\frac{1}{v_0\,(1{+}z_{\rm eq})}\right)$$

□ Present Free-Streaming Velocity $\qquad v_0 = v_{\rm FS}^{\rm rms,0}$

- Gravitinos from Thermal Production

$$(v_{\rm FS}^{\rm rms,0})^{\widetilde{G}\,\rm TP} = 5.8\times10^{-6}\,\frac{\rm km}{\rm s}\left(\frac{10\ {\rm MeV}}{m_{\widetilde{G}}}\right)\left(\frac{230}{g_{*S}(T_R)}\right)^{1/3}$$

- Warm Dark Matter — Hot Thermal Relics

$$(v_{\rm FS}^{\rm rms,0})_{\rm WDM} = 0.77\,\frac{\rm km}{\rm s}\left(\frac{\Omega_{\rm WDM}h^2}{0.113}\right)^{1/3}\left(\frac{100\ {\rm eV}}{m_{\rm WDM}}\right)^{4/3}$$

$$\Omega_{\rm WDM}h^2 = 0.115\left(\frac{100}{g_{*S}(T_{\rm f})}\right)\left(\frac{m_{\rm WDM}}{100\ {\rm eV}}\right)$$