Supersymmetric Dark Matter in Cosmology and at Colliders

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Excellence Cluster Universe

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Why is Dark Matter an exciting topic?

Our present picture of the Universe

photons

$\Omega_\gamma = 0.005\ \%$

baryons

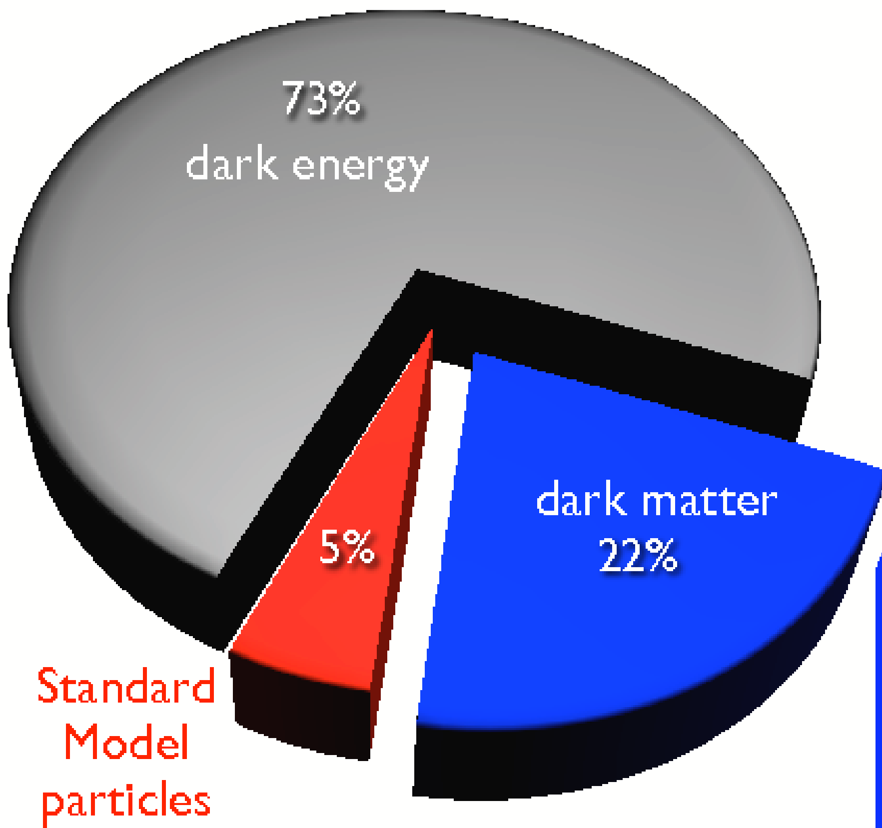
$\Omega_B = 4\ \%$

? baryon asymmetry ?

neutrinos

$0.1\ \% \leq \Omega_\nu \leq 1.5\ \%$

? neutrino mass ?



dark energy

$\Omega_{DE} = 73\ \%$

? vacuum energy ?

dark matter

$\Omega_{DM} = 22\ \%$

? identity ?

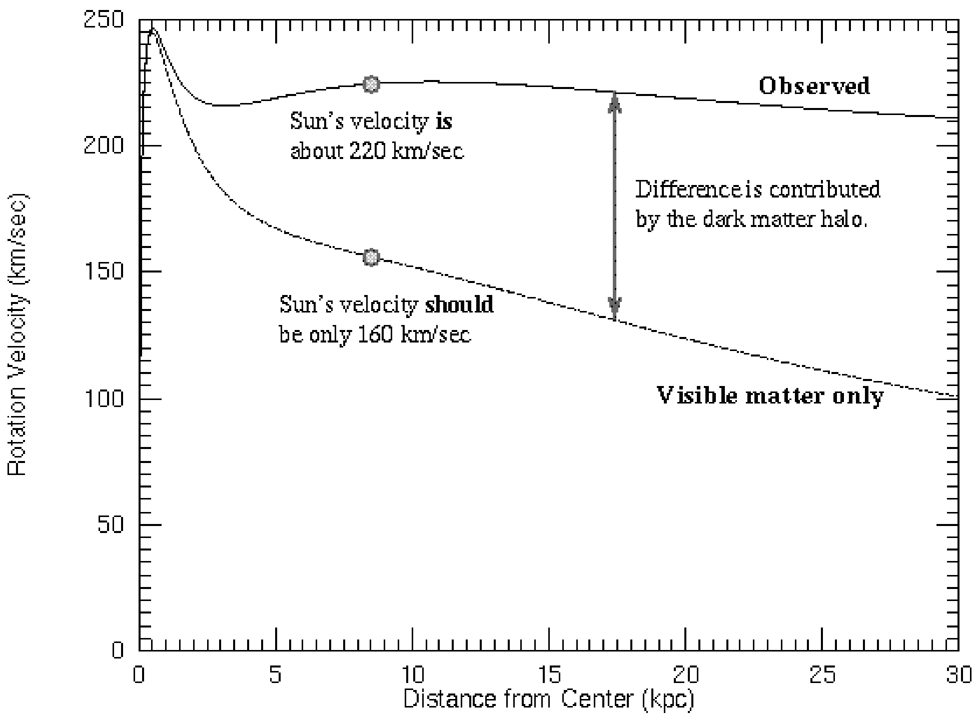
95% of the energy content of the Universe cannot reside in Standard Model particles

There is striking evidence for Dark Matter ...

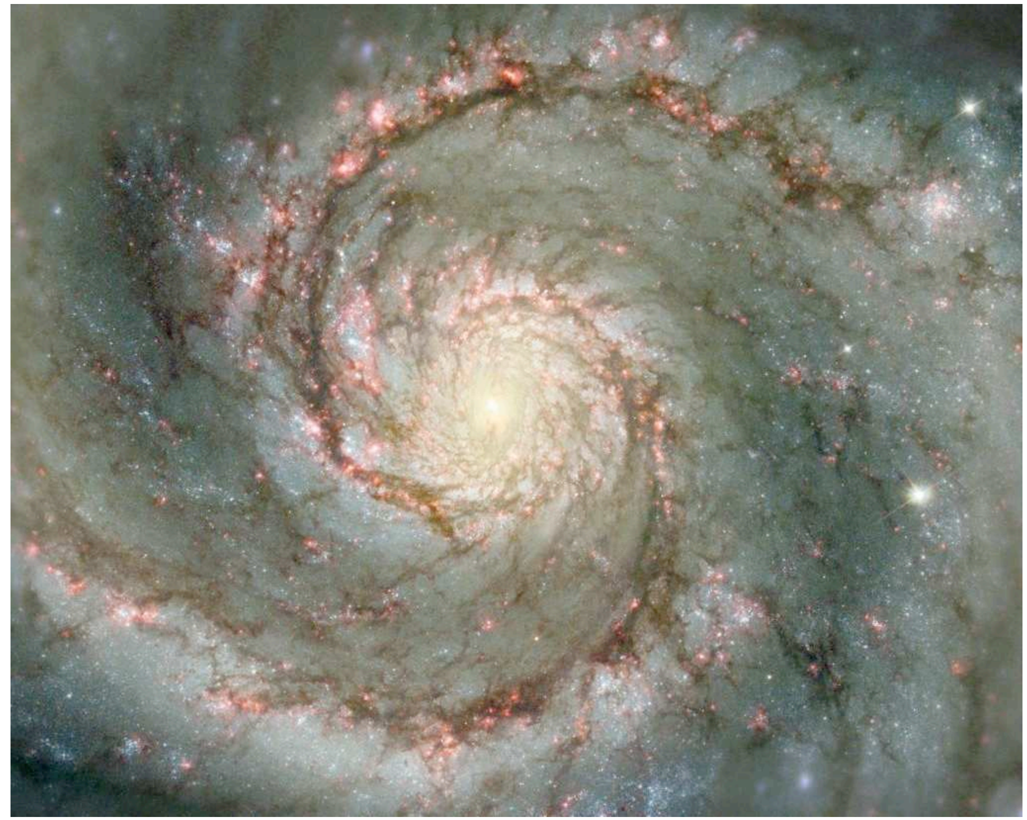
Evidence for Dark Matter in the Universe

□ Spiral Galaxies

 * Rotation Curves

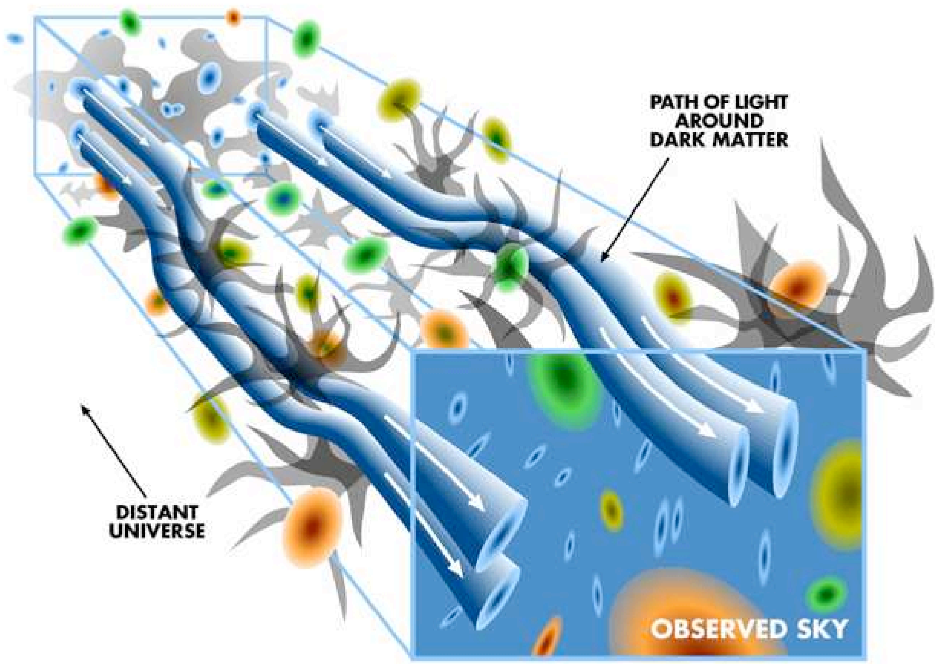


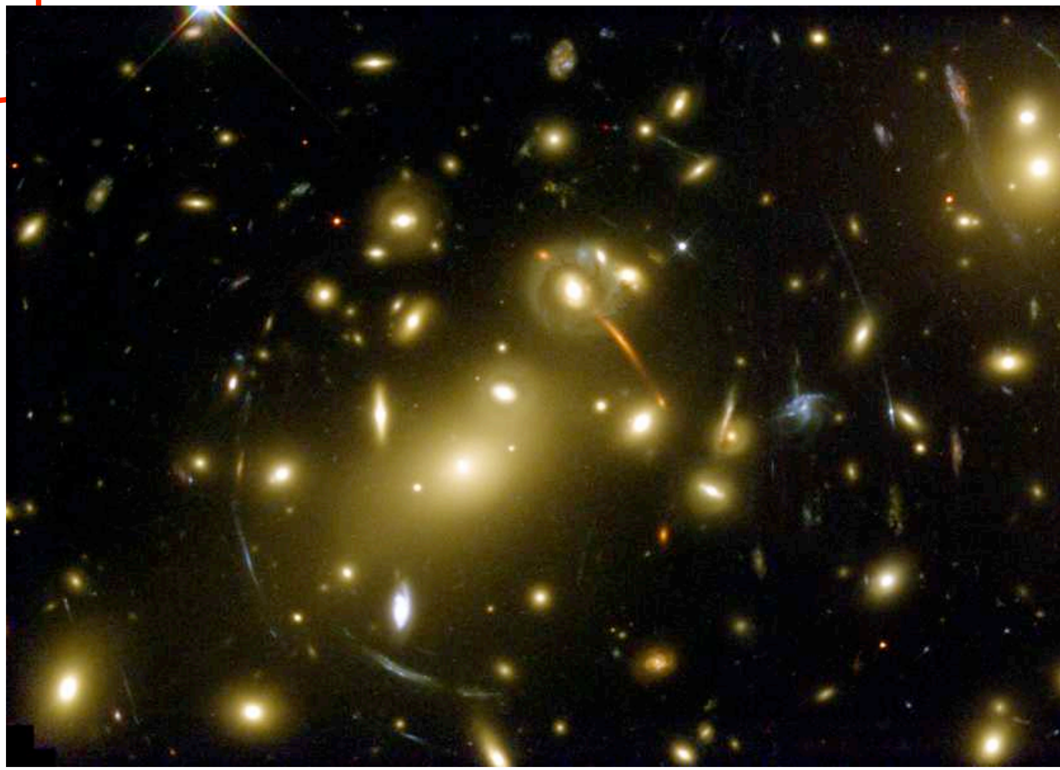
The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two curves is evidence for a **dark matter halo.**



Evidence for Dark Matter in the Universe

- □ Spiral Galaxies
  - * Rotation Curves
- □ (Super-) Clusters of Galaxies
  - * Galaxy Velocities ↔ X-Rays
  - * Weak Gravitational Lensing
  - * Strong Gravitational Lensing





Evidence for Dark Matter in the Universe

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  - * Rotation Curves
- ☐ (Super-) Clusters of Galaxies
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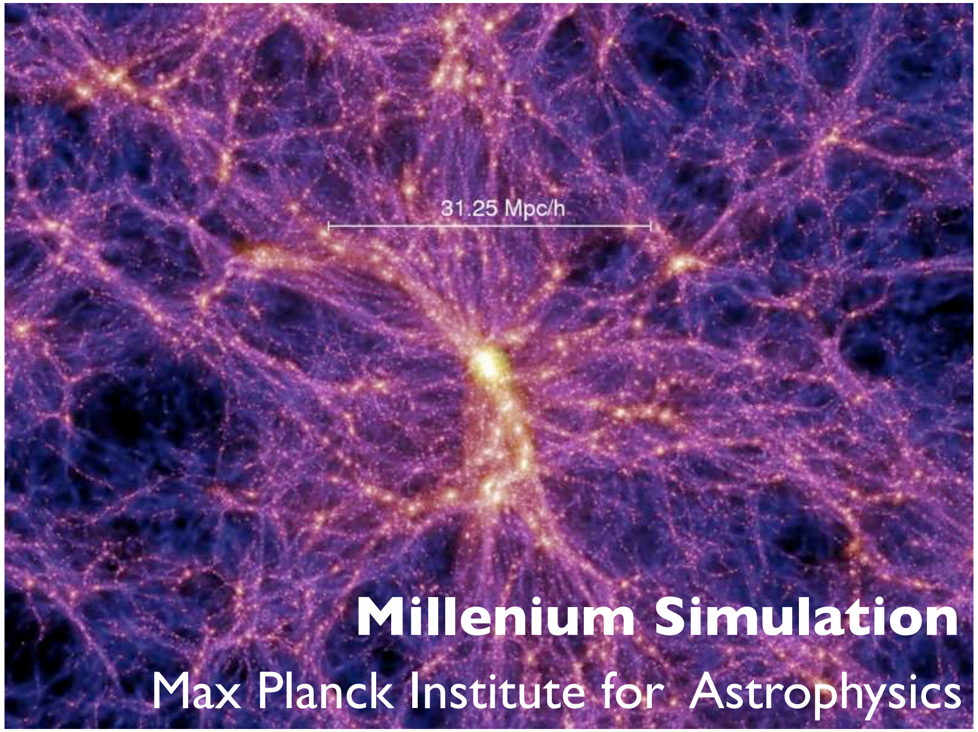
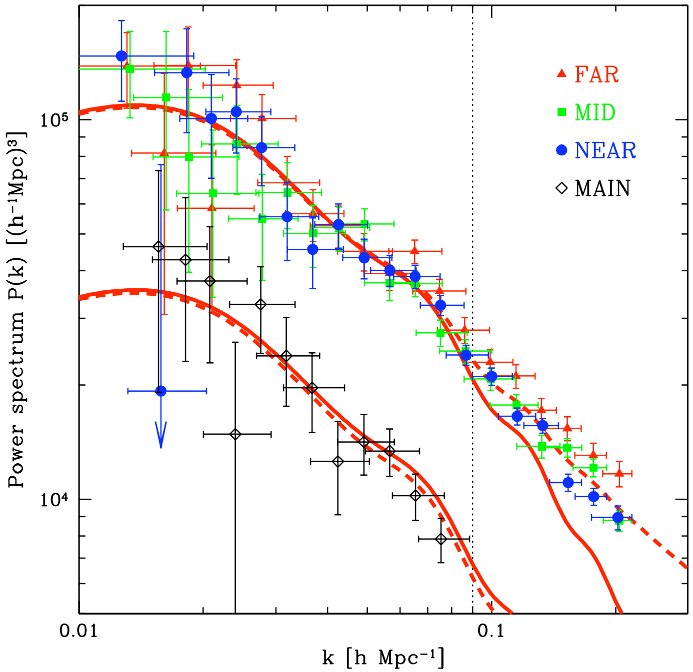
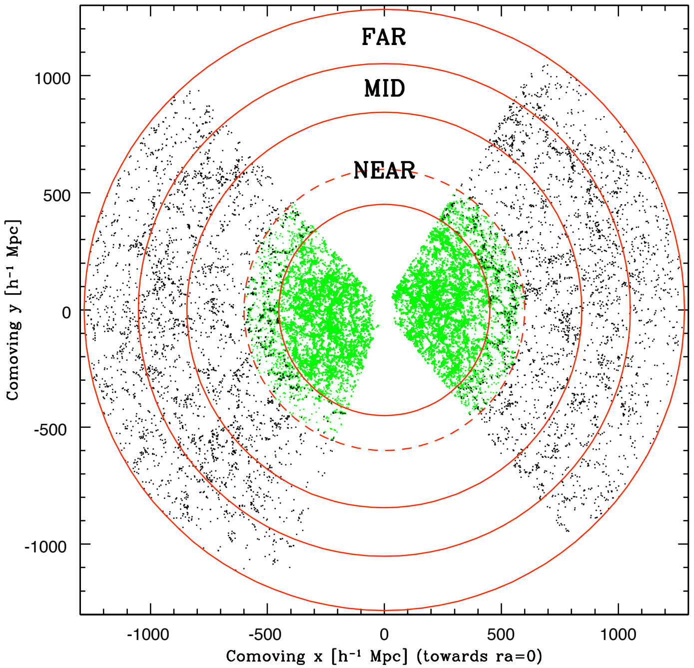
  - * Weak Gravitational Lensing
  - * Strong Gravitational Lensing
- ☐ Large Scale Structure
  - * Structure Formation





SDSS



Evidence for Dark Ma

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  - * Rotation Curves
- (Super-) Clusters of Galaxies
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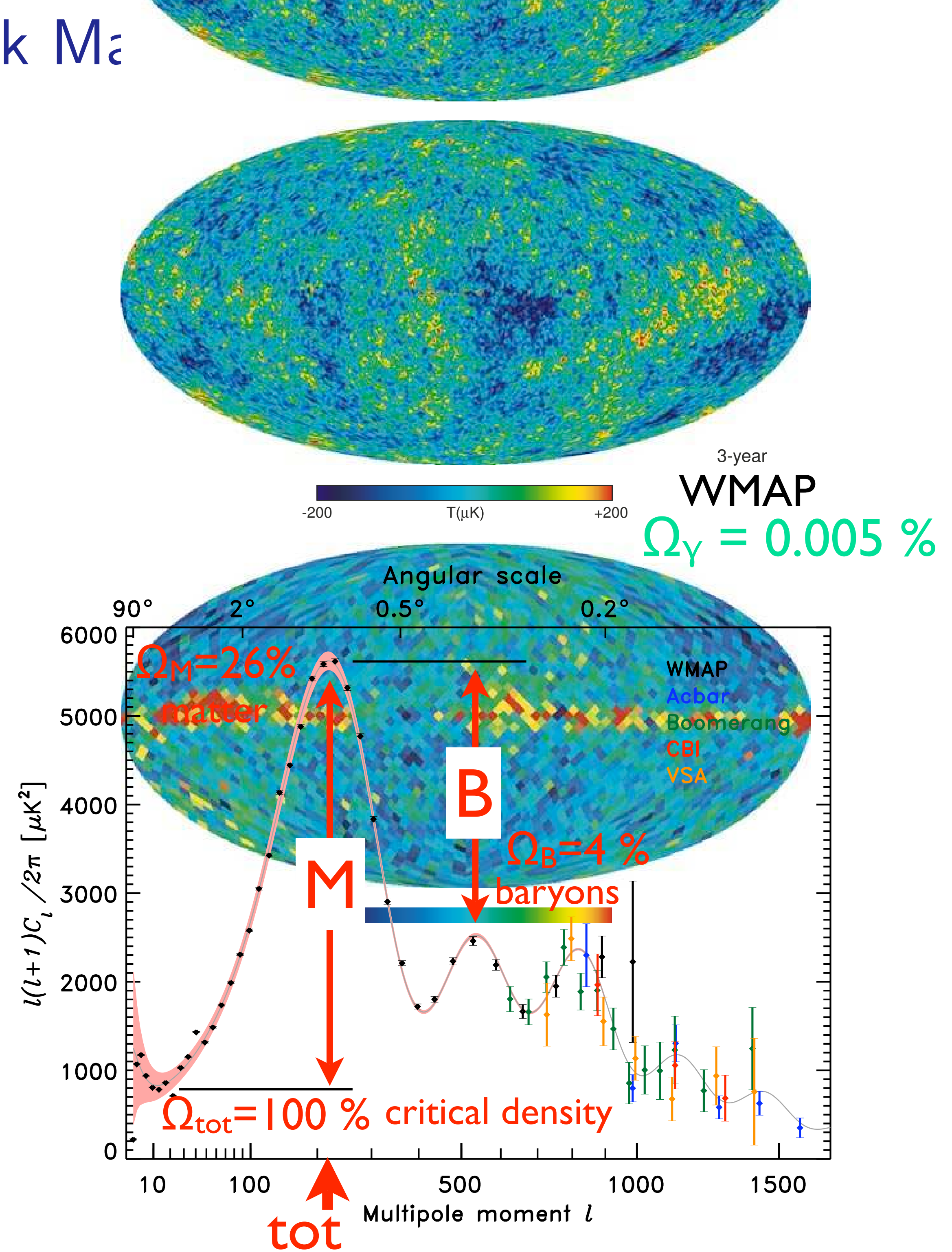
  - * Strong Gravitational Lensing
- Large Scale Structure
  - * Structure Formation
- CMB Anisotropy: WMAP, ...

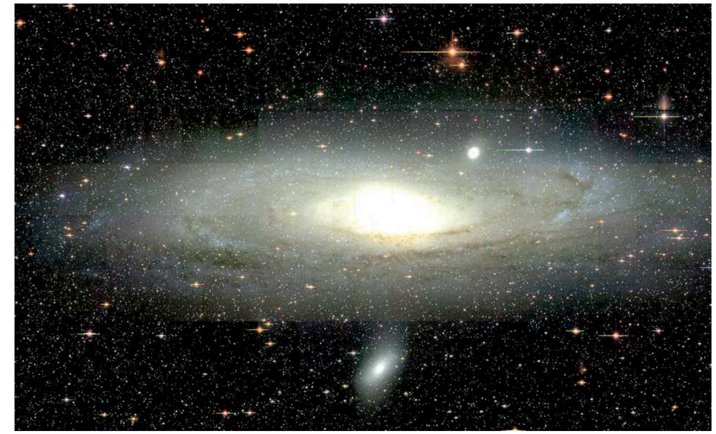
dark matter
Ω_{DM} = 22 %

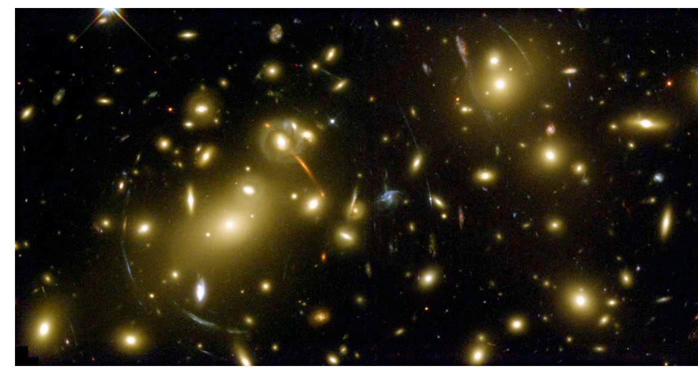


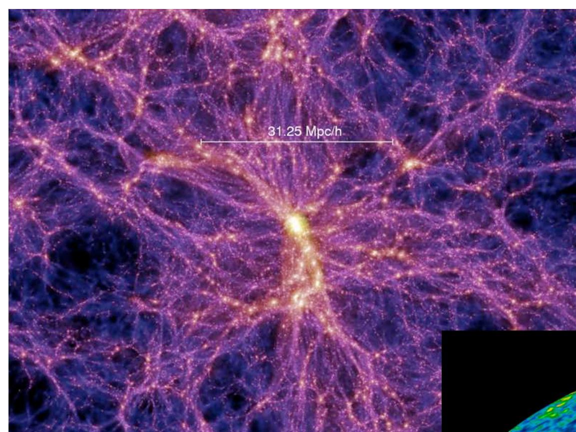
What is the identity of Dark Matter ?

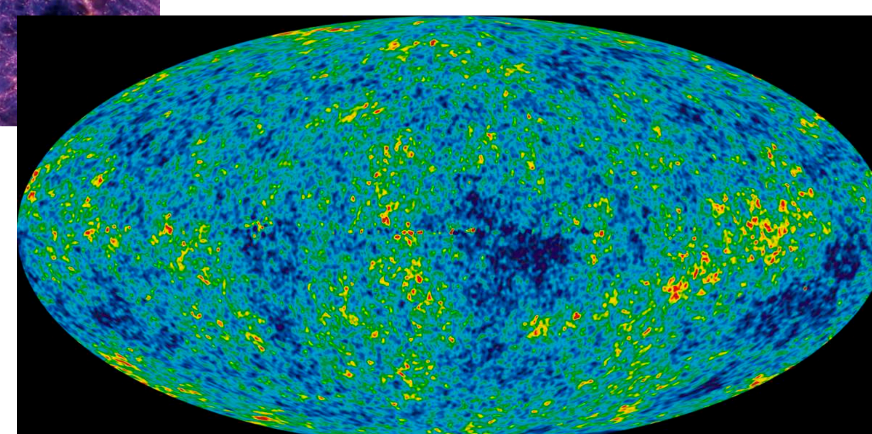
Properties of Dark Matter

- stable or lifetime well above the age of our Universe
- electrically neutral
- clusters →
- “cold”
- dissipationless
- color neutral









The Standard Model

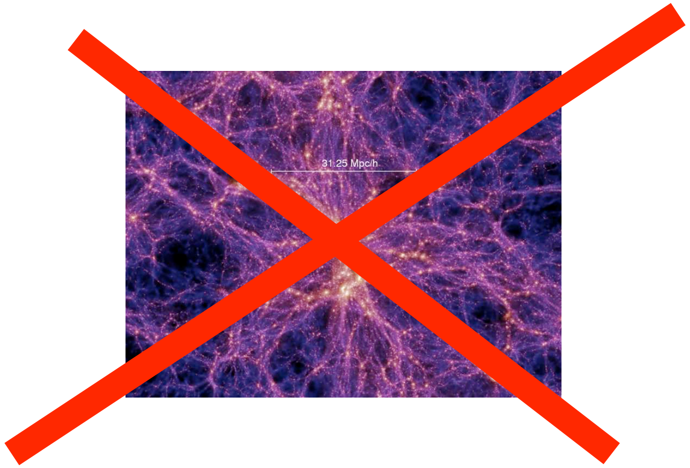
GAUGE	Gauge bosons	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
B-boson	$A_\mu^{(1)} = B_\mu$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons	$A_\mu^{(2)\,a} = W_\mu^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon	$A_\mu^{(3)\,a} = G_\mu^a$	$(\mathbf{8}, \mathbf{1})_0$

MATTER	Fermions	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
leptons $I = 1, 2, 3$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1}, \mathbf{1})_{+2}$
quarks $I = 1, 2, 3$ ($\times$ 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 $\rightarrow \tau_{\rm DM} \gtrsim$ age of our Universe
- clusters $\leftarrow$ gravitation
- fast – "hot"
- electrically neutral
- color neutral



[Yvonne Y.Y. Wong et al.]

$\sum_i m_{\nu_i} \lesssim \mathcal{O}(1\ \mathrm{eV})$

Neutrino Dark Matter = Hot Dark Matter

in conflict with Large Scale Structure

Dark Matter

↓

Physics beyond the Standard Model

Supersymmetry

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

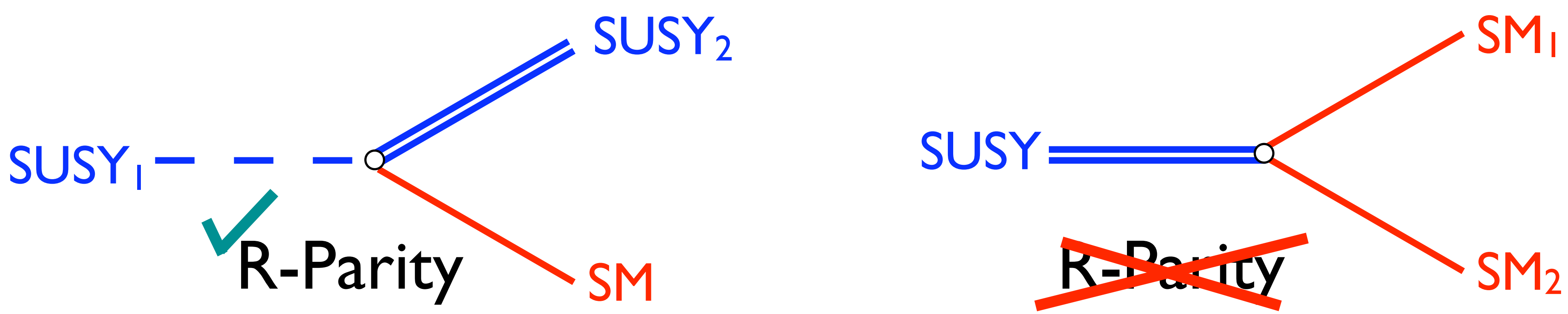
Minimal
Supersymmetric
Extension
of the
Standard Model

Every Particle
of the
Standard Model
has a
Superpartner

Conservation of R-Parity

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

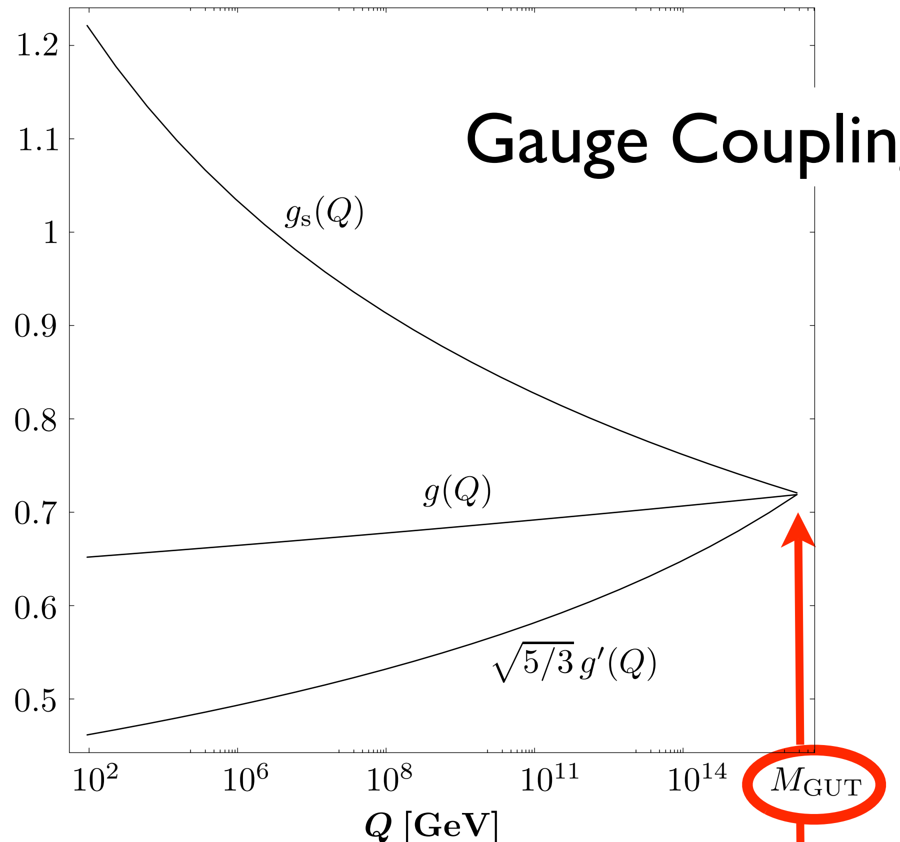
$$P_{\mathrm{R}} = (-1)^{3(B-L)+S} = \begin{cases} +1 & \text{for } \mathrm{SM}, H_u, H_d \\ -1 & \text{for } \widetilde{X} \leftarrow \text{superpartners} \end{cases}$$



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

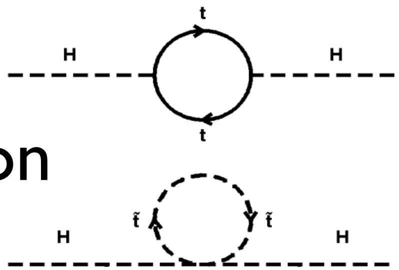
Why Supersymmetry?

Extension of Space-Time Symmetry



Gauge Coupling Unification

Hierarchy Stabilization



(Super-) Gravity

Consistent String Theory

Dark Matter

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

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: $m_{\widetilde{a}}$, f_a

Dark Matter

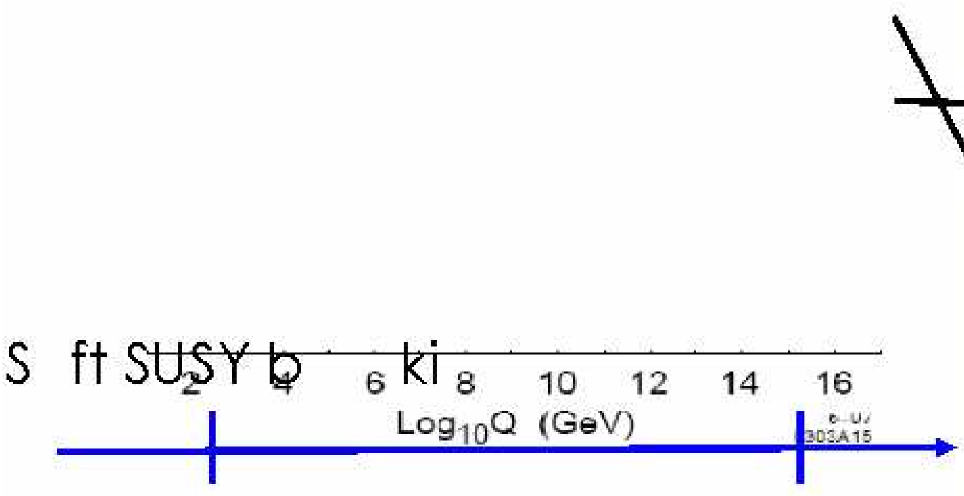
↓

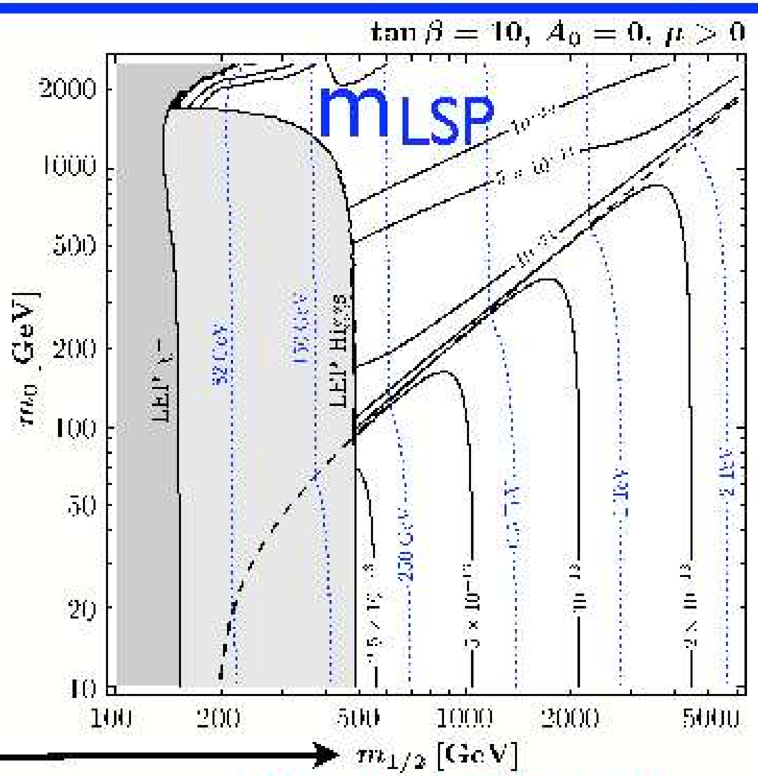
Neutralino LSP

Supersymmetric Dark Matter Candiates

	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

CMSSM



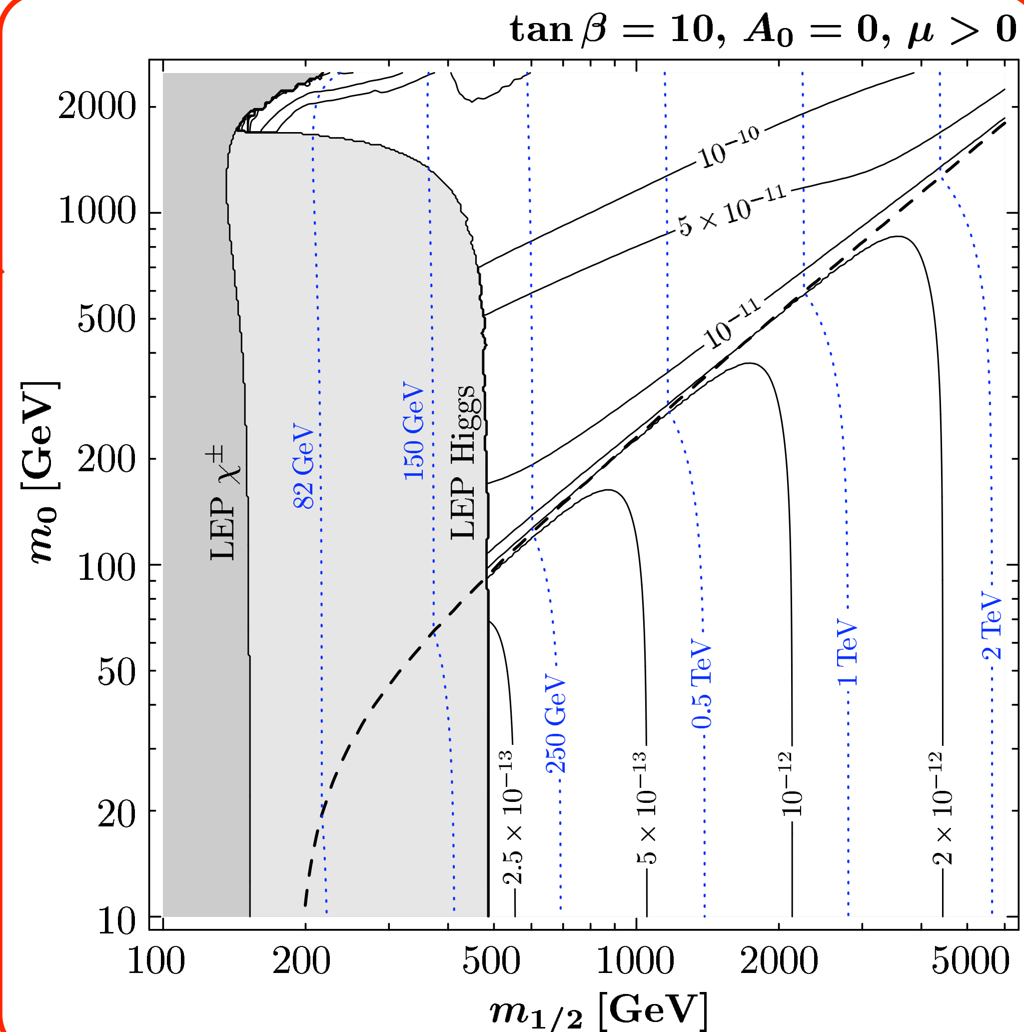


[Pradler, FDS, '07]

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

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

$$\Omega_{\widetilde{\chi}_1^0} h^2 = m_{\widetilde{\chi}_1^0} \, Y^{\rm dec}_{\widetilde{\chi}_1^0} \, s(T_0) \, h^2/\rho_c$$



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

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

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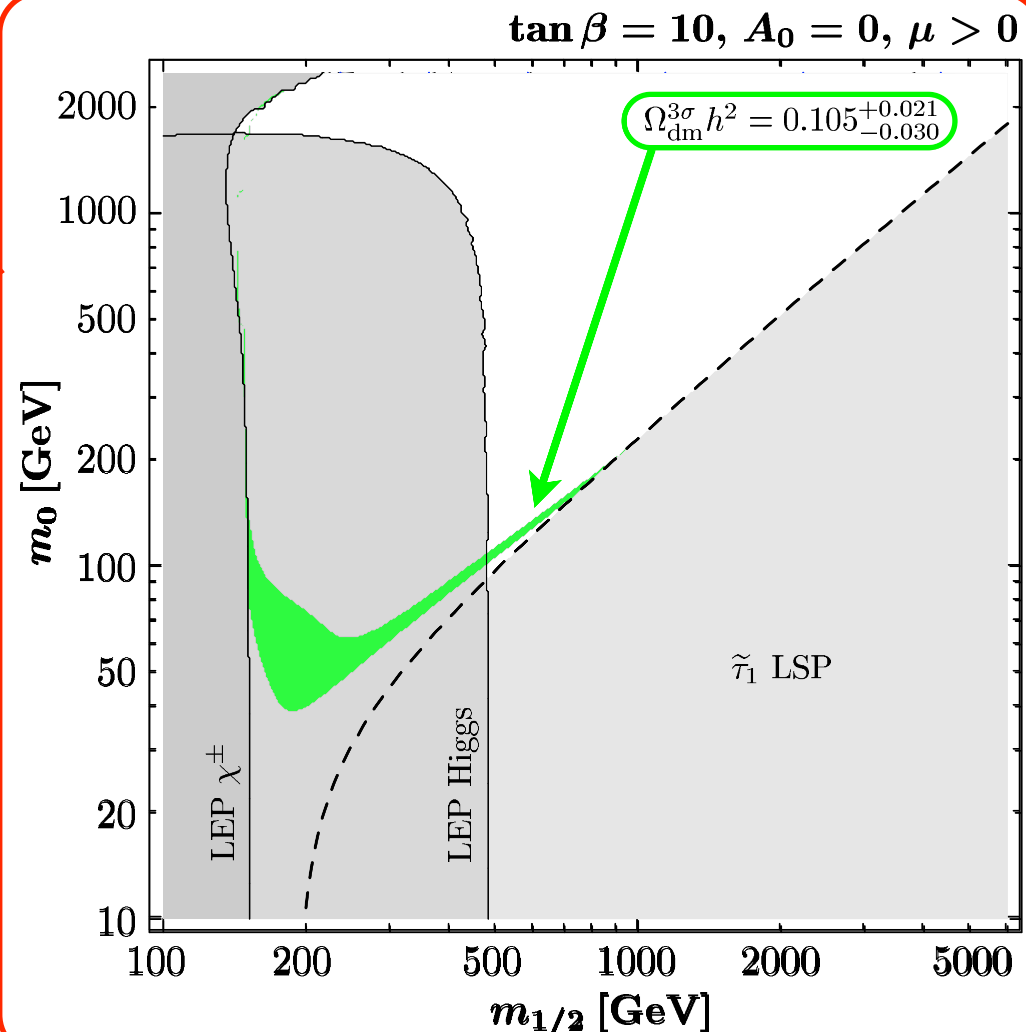

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$\widetilde{\chi}_1^0$	g, g' weak	WIMP ← cold freeze out		

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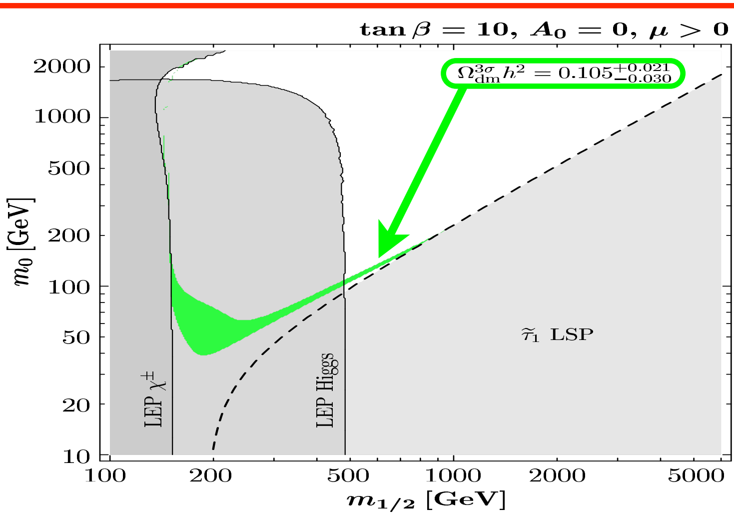
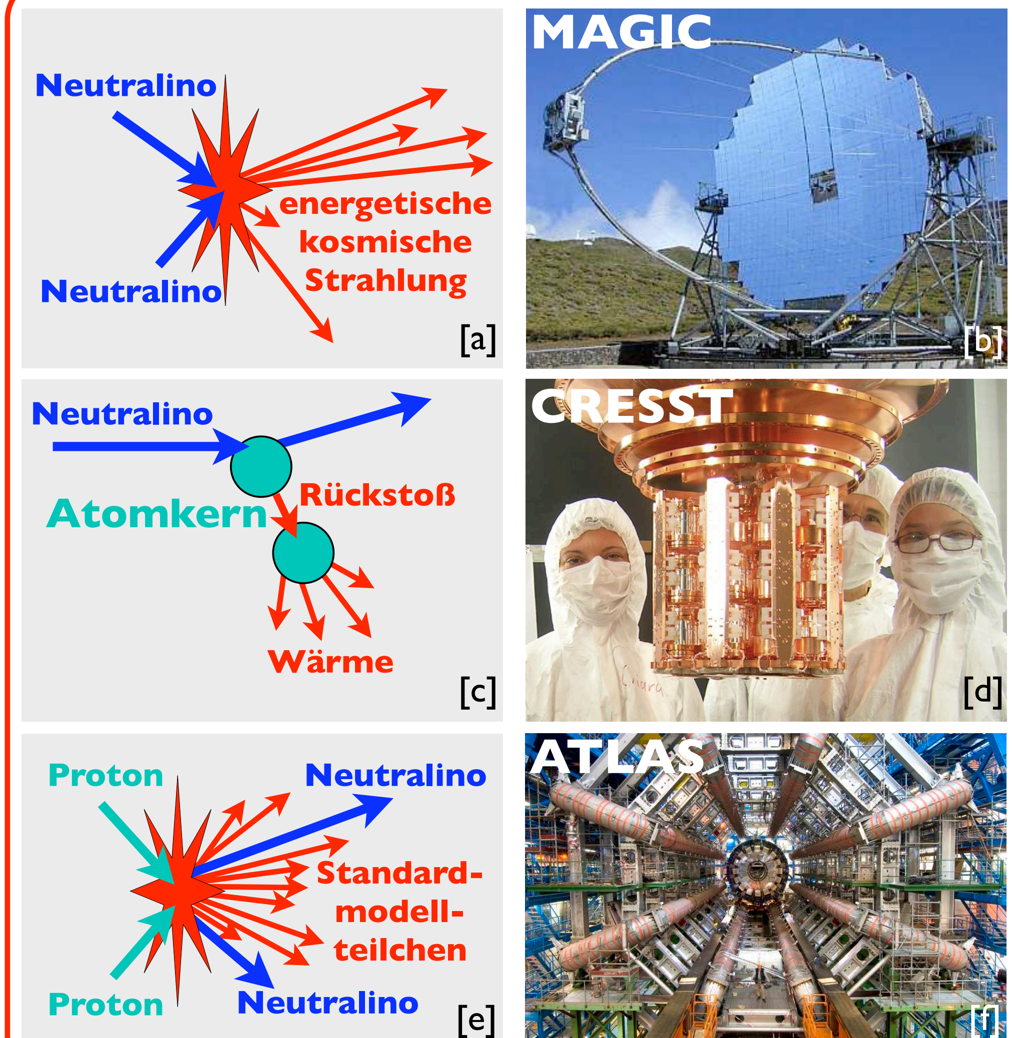
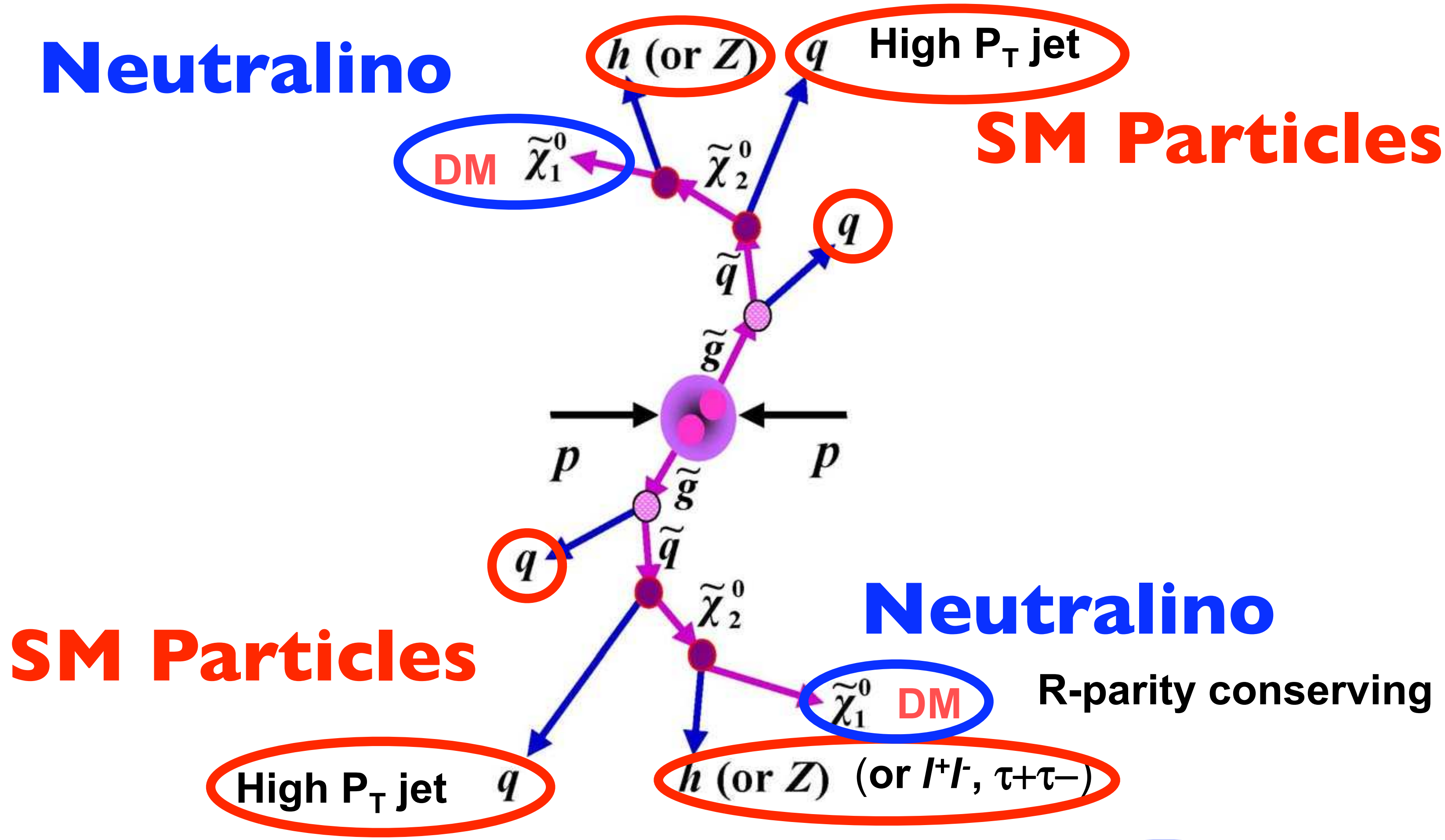




promising experimental prospects

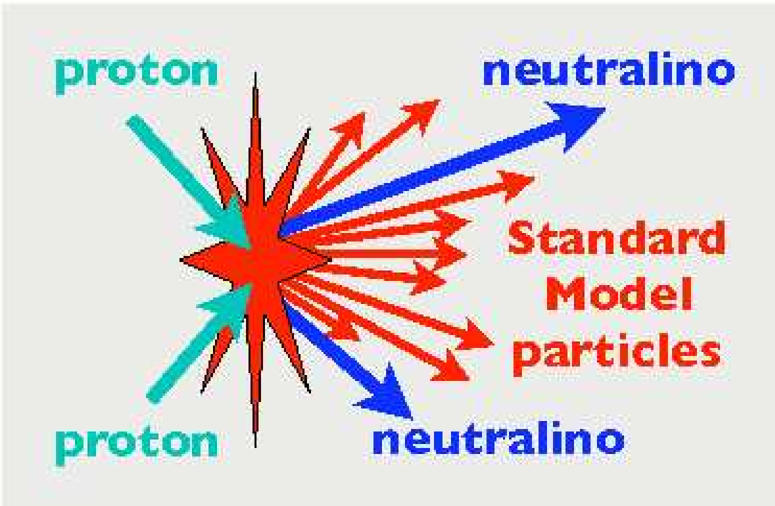
Neutralino DM Production at the LHC



The signal : jets + leptons + missing E_T

[from B. Dutta's Talk, SUSY 2007]

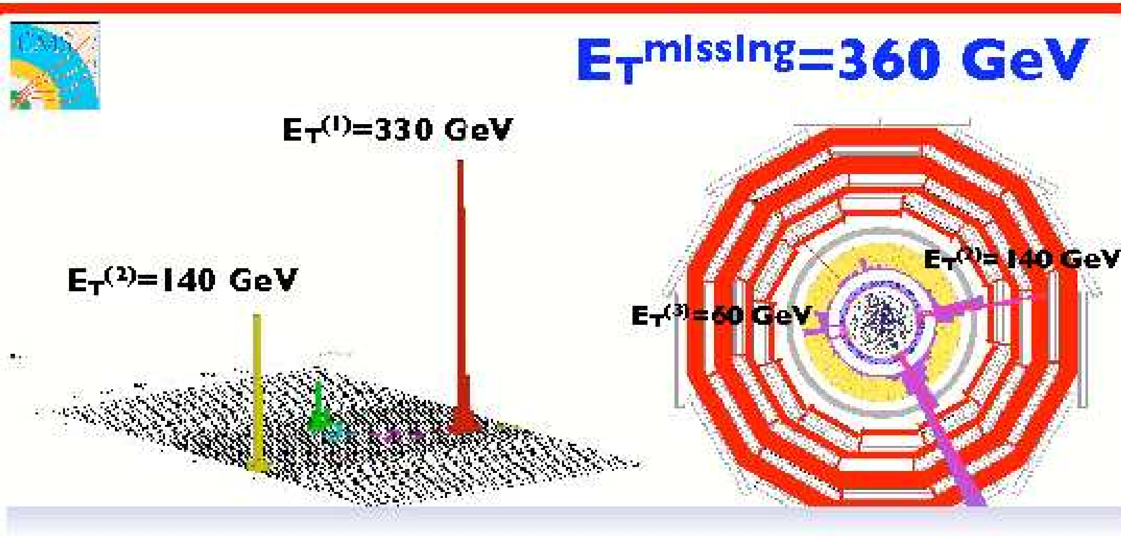
Collider Searches



ongoing searches at Tevatron

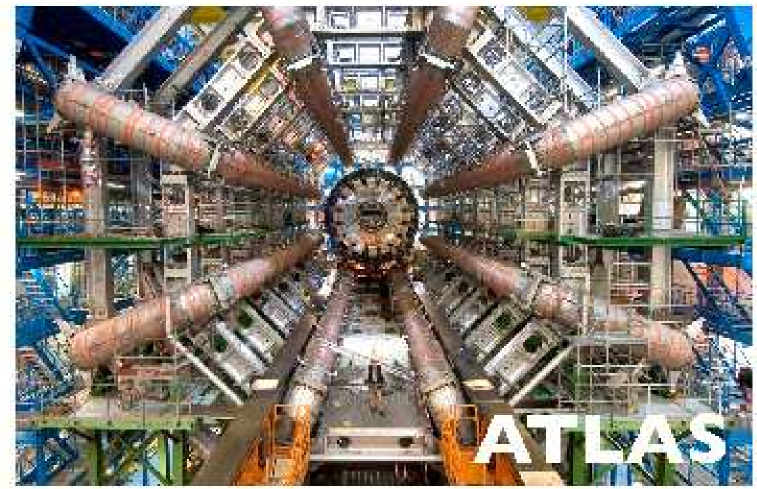
pp @ 2 TeV

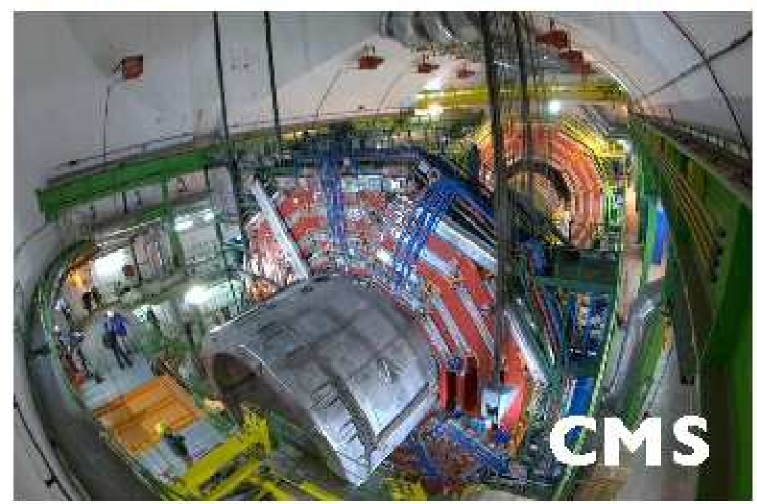
CDF D0



The signal:

jets + leptons + large E_T^{miss}





... however, SUSY phenomenology might look very different ...

Dark Matter

↓

Gravitino LSP

Supersymmetric Dark Matter Candiates

	LSP	ID	spin	mass	interaction
lightest neutralino	$\widetilde{\chi}_1^0$	$\widetilde{B}, \widetilde{W}, \widetilde{H}_u^0, \widetilde{H}_d^0$	$\frac{1}{2}$	$\mathcal{O}(100\text{ GeV})$	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

$$m_{\widetilde{G}} \sim \sum_I \frac{\langle F_I \rangle}{\mathrm{M_{Pl}}} + \sum_A \frac{\langle D_A \rangle}{\mathrm{M_{Pl}}} \sim \frac{M_{\mathrm{SUSY}}^2}{\mathrm{M_{Pl}}}$$

gauge-MSB	gravity-MSB gaugino-MSB	anomaly-MSB mirage-MSB
light gravitino **1 eV-1 GeV**	**weak-scale gravitino** **0.01-1 TeV**	**heavy gravitino** **1-100 TeV**

[Cremmer, Ferrara, Girardello, Van Proeyen, '83]

The Supergravity Lagrangian (N=1, d=4)

$$
\begin{aligned}
\frac{1}{e}\mathcal{L} \quad = \quad & -\frac{M_{\mathsf{P}}^2}{2}R + g_{ij^*}\mathcal{D}_\mu\phi^i\mathcal{D}^\mu\phi^{*j} - \frac{1}{2}g^2\left[(\mathrm{Re}f)^{-1}\right]^{ab}D_aD_b \\
& + i g_{ij^*}\overline{\chi}^j_L\gamma^\mu\mathcal{D}_\mu\chi^i_L + \varepsilon^{\mu\nu\rho\sigma}\overline{\psi}_{L\mu}\gamma_\nu\mathcal{D}_\rho\psi_{L\sigma} \\
& - \frac{1}{4}\mathrm{Re}f_{ab}F^a_{\mu\nu}F^{b,\mu\nu} + \frac{1}{8}\varepsilon^{\mu\nu\rho\sigma}\mathrm{Im}f_{ab}F^a_{\mu\nu}F^b_{\rho\sigma} \\
& + \frac{i}{2}\mathrm{Re}f_{ab}\overline{\lambda}^a\gamma^\mu\mathcal{D}_\mu\lambda^b - e^{-1}\frac{1}{2}\mathrm{Im}f_{ab}\mathcal{D}_\mu\left[e\overline{\lambda}^a_R\gamma^\mu\lambda^b_R\right] \\
& + \Bigg[-\sqrt{2}g\partial_i D_a\overline{\lambda}^a\chi^i_L + \frac{1}{4}\sqrt{2}g\left[(\mathrm{Re}f)^{-1}\right]^{ab}\partial_i f_{bc}D_a\overline{\lambda}^c\chi^i_L \\
& + \frac{i}{16}\sqrt{2}\partial_i f_{ab}\overline{\lambda}^a[\gamma^\mu,\gamma^\nu]\chi^i_L F^b_{\mu\nu} - \frac{1}{2M_{\mathsf{P}}}gD_a\overline{\lambda}^a_R\gamma^\mu\psi_\mu \\
& - \frac{i}{2M_{\mathsf{P}}}\sqrt{2}g_{ij^*}\mathcal{D}_\mu\phi^{*j}\overline{\psi}_\nu\gamma^\mu\gamma^\nu\chi^i_L + \text{h.c.}\Bigg] \\
& - \frac{i}{8M_{\mathsf{P}}}\mathrm{Re}f_{ab}\overline{\psi}_\mu[\gamma^m,\gamma^n]\gamma^\mu\lambda^a F^a_{mn} \\
& - e^{K/2M_{\mathsf{P}}^2}\Bigg[\frac{1}{4M_{\mathsf{P}}^2}W^*\overline{\psi}_{R\mu}[\gamma^\mu,\gamma^\nu]\psi_{L\nu} + \frac{1}{2M_{\mathsf{P}}}\sqrt{2}D_iW\overline{\psi}_\mu\gamma^\mu\chi^i_L \\
& + \frac{1}{2}\mathcal{D}_iD_jW\overline{\chi^c_L}^i\chi^j_L + \frac{1}{4}g^{ij^*}D_{j^*}W^*\partial_i f_{ab}\overline{\lambda}^a_R\lambda^b_L + \text{h.c.}\Bigg] \\
& - e^{K/M_{\mathsf{P}}^2}\left[g^{ij^*}(D_iW)\left(D_{j^*}W^*\right) - 3\frac{|W|^2}{M_{\mathsf{P}}^2}\right] + \mathcal{O}(M_{\mathsf{P}}^{-2})\ .
\end{aligned}
$$

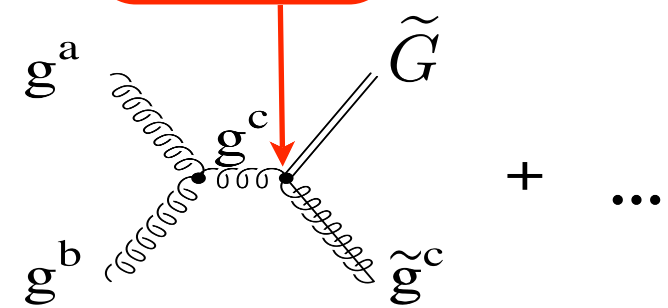
gravitino gaugino gauge boson Planck scale

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, ...)
	$M_{\mathrm{W}} \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M}_{\mathrm{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	**Very Early Hot Universe**
	extremely weak	NLSP decays	$\leftarrow$ warm	
	$\mathrm{M}_{\mathrm{Pl}} = 2.44 \times 10^{18}$ GeV	...		

Very Early Hot Universe

T ~ 10^7 GeV



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

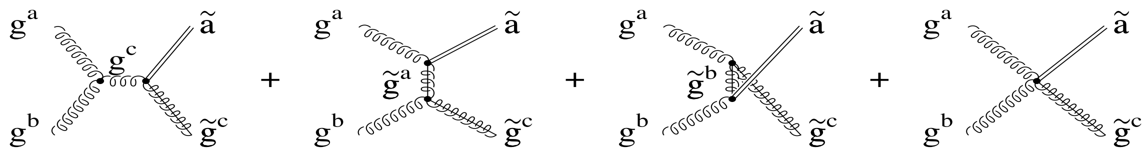
[Pradler, FDS, '06]

[Rychkov, Strumia, '07] (gauge dep.)

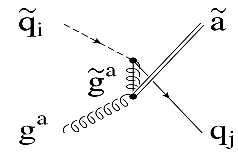
[... ; Bolz, Brandenburg, Buchmüller, '01, Pradler, FDS, '06]

Thermal Gravitino Production in SUSY QCD

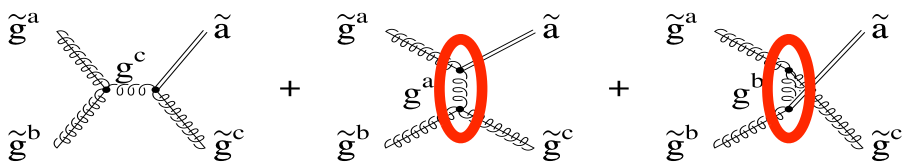
- A: $g^a + g^b \longrightarrow \tilde{g}^c + \widetilde{G}$



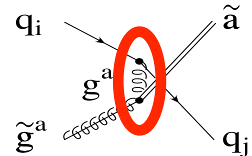
- B: $g^a + \tilde{g}^b \longrightarrow g^c + \widetilde{G}$ (crossing of A)
- C: $\tilde{q}_i + g^a \longrightarrow \tilde{q}_j + \widetilde{G}$



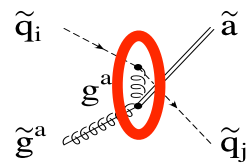
- D: $g^a + q_i \longrightarrow \tilde{q}_j + \widetilde{G}$ (crossing of C)
- E: $\bar{\tilde{q}}_i + q_j \longrightarrow g^a + \widetilde{G}$ (crossing of C)
- F: $\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + \widetilde{G}$



- G: $q_i + \tilde{g}^a \longrightarrow q_j + \widetilde{G}$



- H: $\tilde{q}_i + \tilde{g}^a \longrightarrow \tilde{q}_j + \widetilde{G}$



- I: $q_i + \bar{q}_j \longrightarrow \tilde{g}^a + \widetilde{G}$ (crossing of G)
- J: $\tilde{q}_i + \bar{\tilde{q}}_j \longrightarrow \tilde{g}^a + \widetilde{G}$ (crossing of H)

+ electroweak contributions

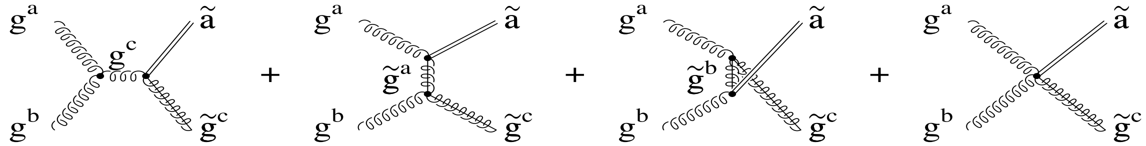
[Pradler, FDS, '06]

[Pradler, Diploma Thesis, '06]

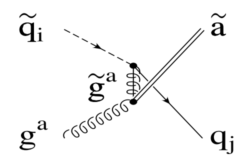
[... ; Bolz, Brandenburg, Buchmüller, '01, Pradler, FDS, '06]

Thermal Gravitino Production in SUSY QCD

- A: $g^a + g^b \longrightarrow \tilde{g}^c + \widetilde{G}$



- B: $g^a + \tilde{g}^b \longrightarrow g^c + \widetilde{G}$ (crossing of A)
- C: $\tilde{q}_i + g^a \longrightarrow \tilde{q}_j + \widetilde{G}$



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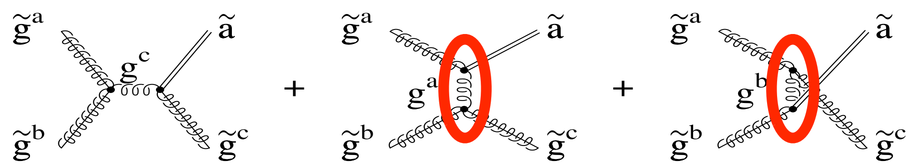
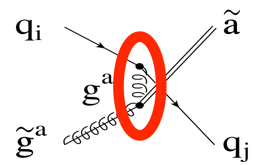
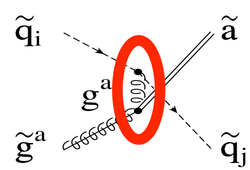
- F: $\tilde{g}^a + \tilde{g}^b \longrightarrow \tilde{g}^c + \widetilde{G}$



- G: $q_i + \tilde{g}^a \longrightarrow q_j + \widetilde{G}$



- H: $\tilde{q}_i + \tilde{g}^a \longrightarrow \tilde{q}_j + \widetilde{G}$



- I: $q_i + \bar{q}_j \longrightarrow \tilde{g}^a + \widetilde{G}$ (crossing of G)
- J: $\tilde{q}_i + \bar{\tilde{q}}_j \longrightarrow \tilde{g}^a + \widetilde{G}$ (crossing of H)

+ electroweak contributions

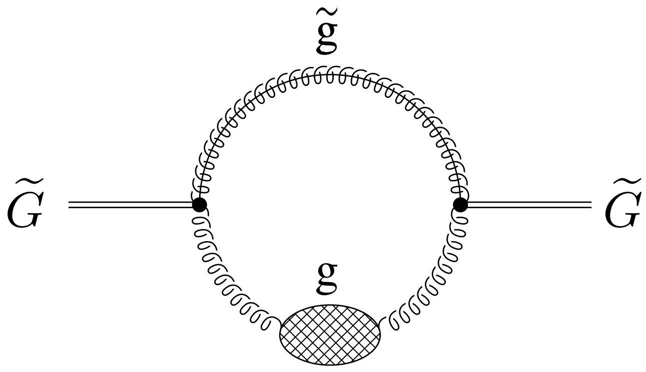
[Pradler, FDS, '06]

[Pradler, Diploma Thesis, '06]

Helmholtz-Nachwuchspreis für Astroteilchen-physik 2006

• Separation of Scales: $gT \ll \Lambda \ll T \quad \leftarrow \quad g \ll 1$ [Braaten, Yuan, 1991]

• Soft Part: $\widetilde{G}$ Self-Energy

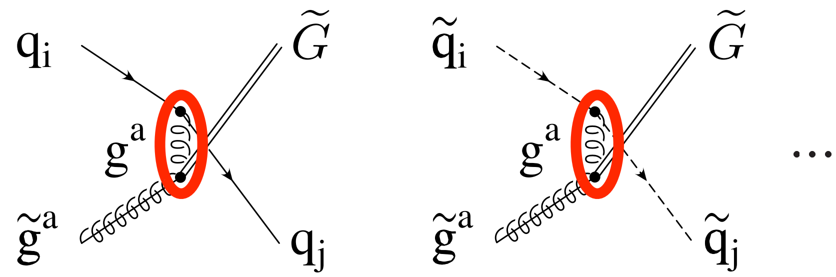


$\rightarrow$ eff. HTL resummed propagator

$$E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\rm soft} = -f_F(E)\,\frac{{\rm Im}\Sigma(E+i\epsilon,\mathbf{p})}{(2\pi)^3}\bigg|_{|\mathbf{p}_1-\mathbf{p}_3|<\Lambda}$$

$$= A_{\rm soft} + B\ln\left[\frac{\Lambda}{gT}\right]$$

• Hard Part: Relativ. Kin. Theory



$\rightarrow$ bare propagator

$$E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\rm hard} = \frac{1}{2}\int\prod_{i=1}^{3}\ldots|M|^2\,\Theta(|\mathbf{p}_1-\mathbf{p}_3|-\Lambda)$$

$$= A_{\rm hard} + B\ln\left[\frac{T}{\Lambda}\right]$$

• Thermal Production Rate: $*$ complete to LO in g , $*$ finite , $*$ indep. of Λ

$$E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{{\rm LO\ in}\ g} = E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\rm soft} + E\,\frac{d\Gamma_{\widetilde{G}}}{d^3p}\bigg|_{\rm hard} = A_{\rm soft} + A_{\rm hard} + B\ln\left[\frac{1}{g}\right]$$

Gravitino Dark Matter from Thermal Production

- Boltzmann Equation

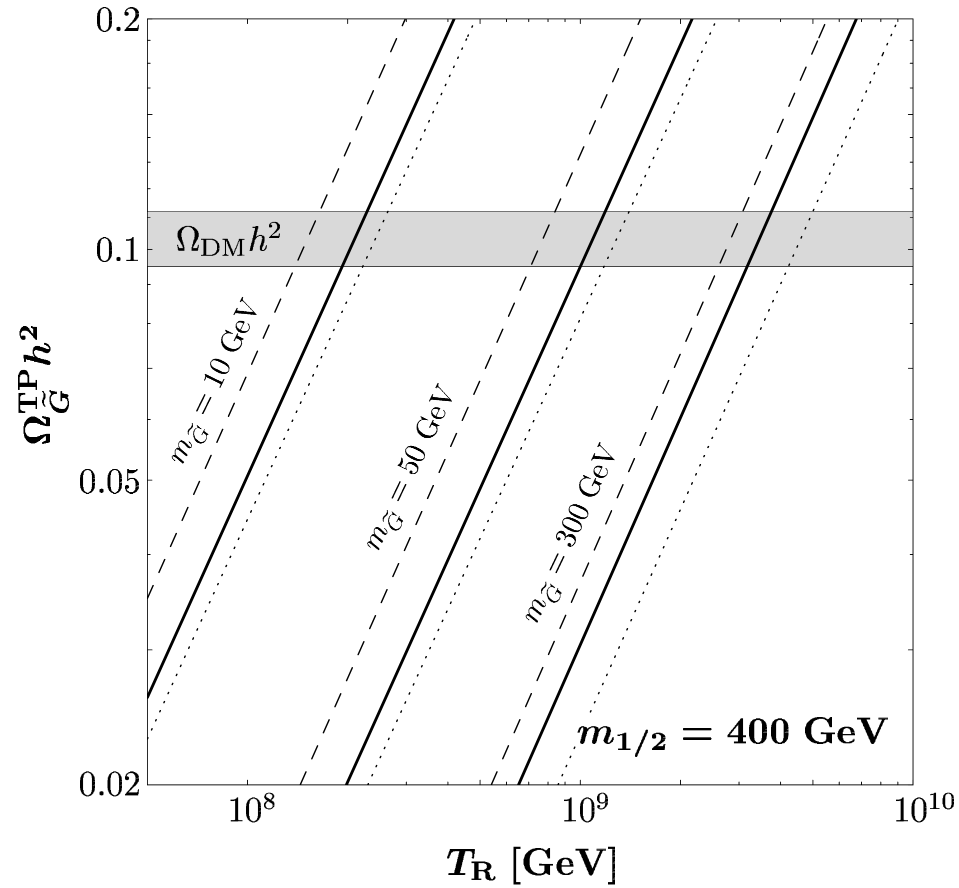
$$\frac{dn_{\widetilde{G}}}{dt} + 3Hn_{\widetilde{G}} = C_{\widetilde{G}}$$

- 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

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



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

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

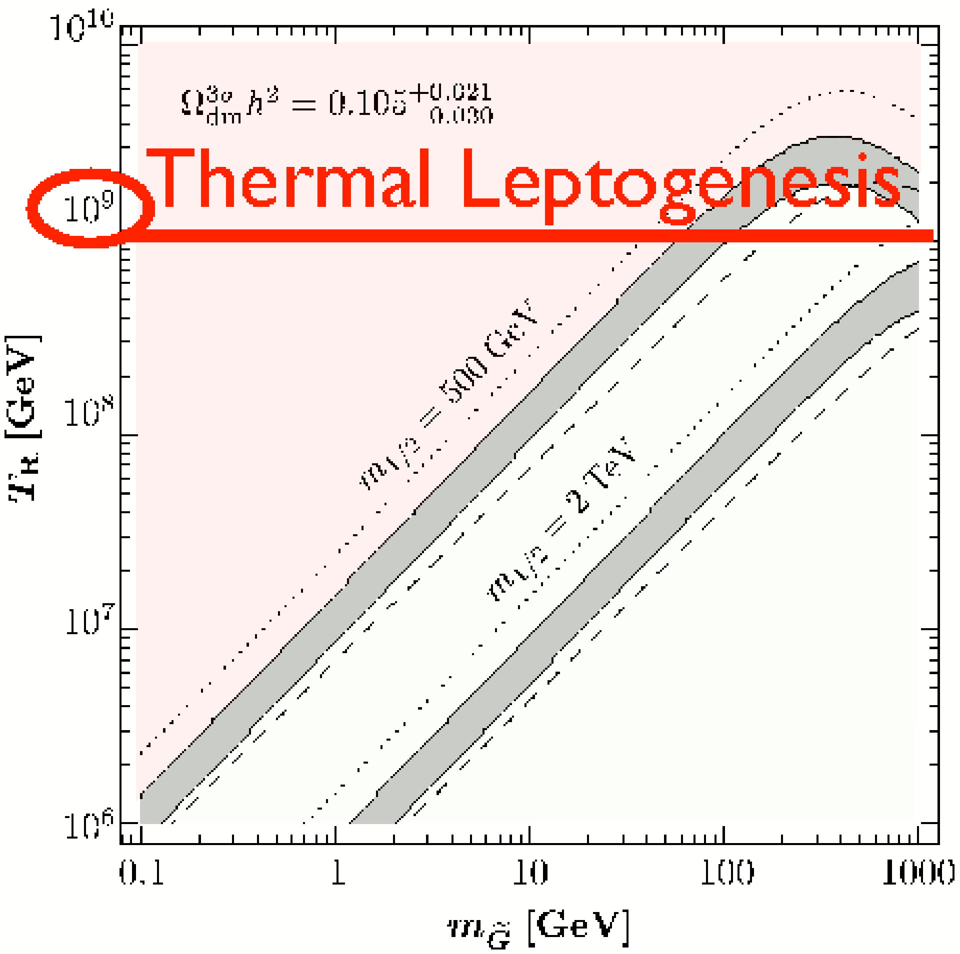
dotted: $M_3 = m_{1/2}$

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

$$c_i = (11, 27, 72)$$
$$k_i = (1.266, 1.312, 1.271)$$
$$\omega_i = (0.018, 0.044, 0.117)$$

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

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]

Definition of the Reheating Temperature

$$\Gamma_\phi = \xi \, H_{\rm rad}(T_{\rm R})$$

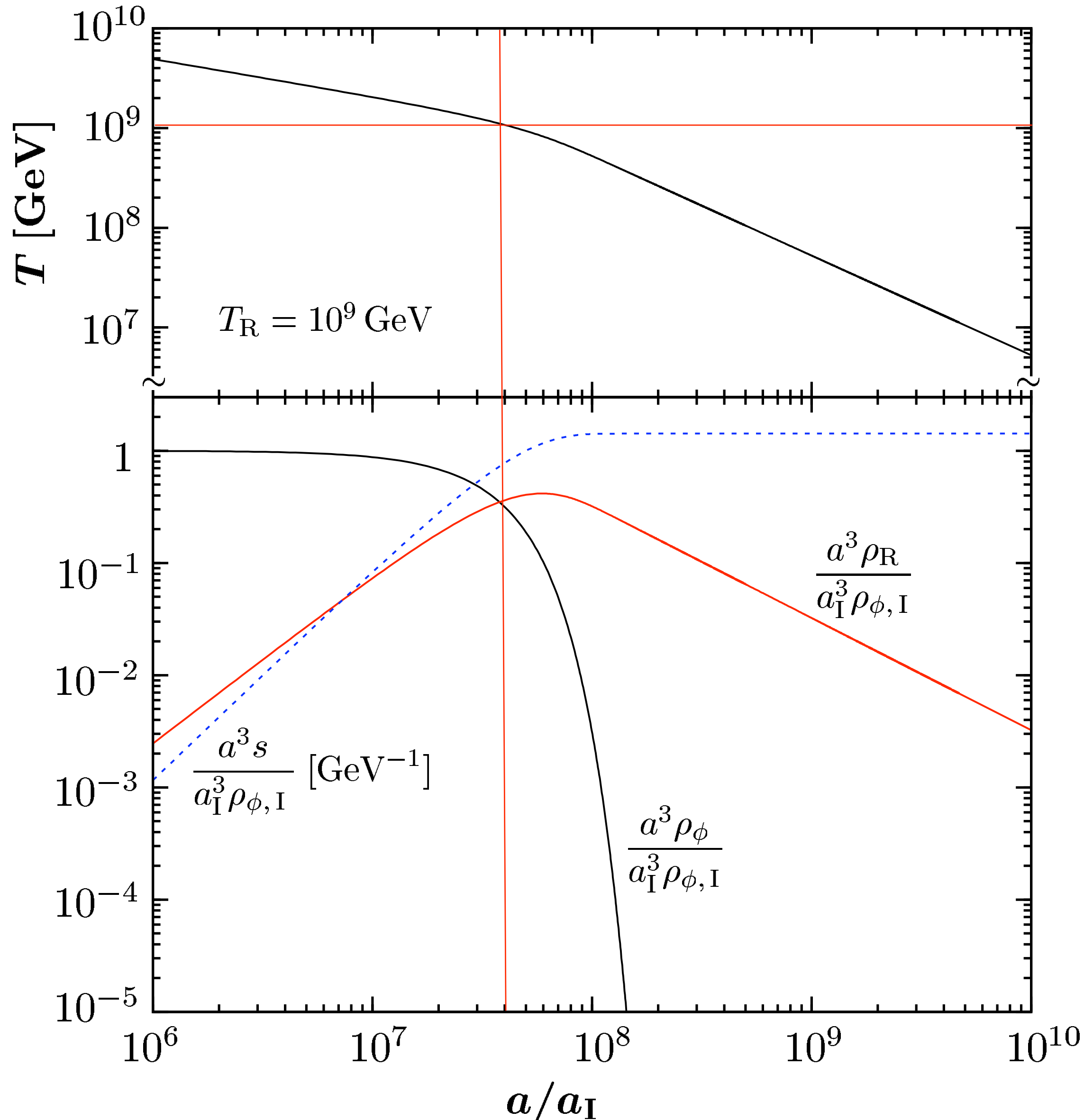
$$T_{\rm R}^{\xi} \equiv \left[\frac{90}{g_*(T_{\rm R})\pi^2}\right]^{1/4} \sqrt{\frac{\Gamma_\phi {\rm M_P}}{\xi}}$$

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\phi \rho_\phi ,$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi ,$$

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

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



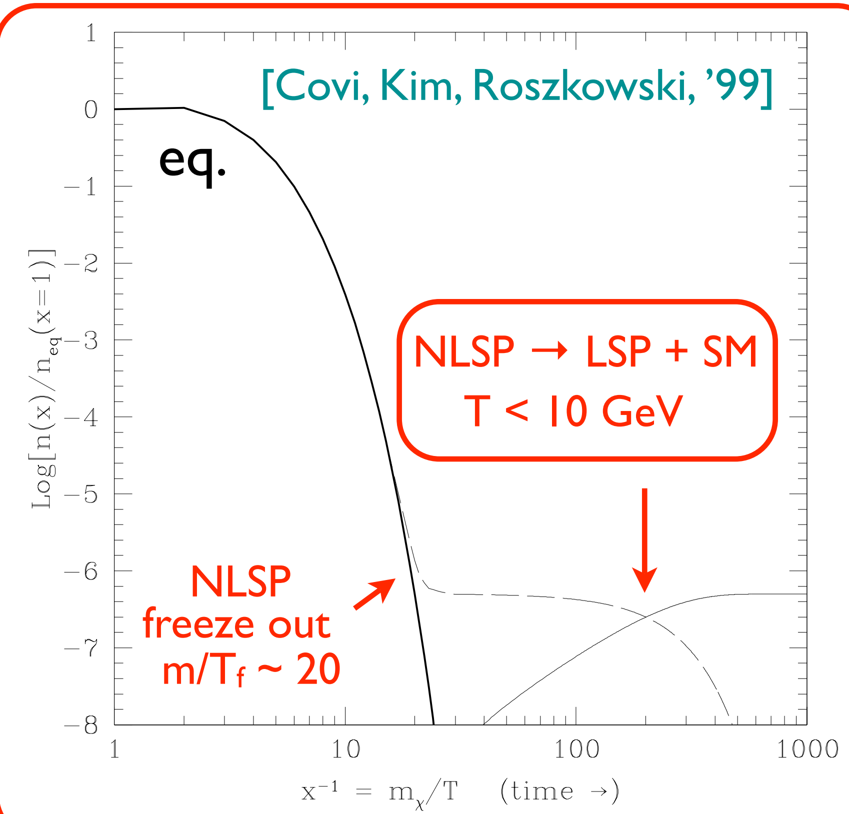
[...; Kawasaki, Kohri, Moroi, '05; Pradler, FDS, '07]

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	...		

NLSP Candidates

- **lightest neutralino**
- **lighter stau**
- **lighter stop**
- **lightest sneutrino**



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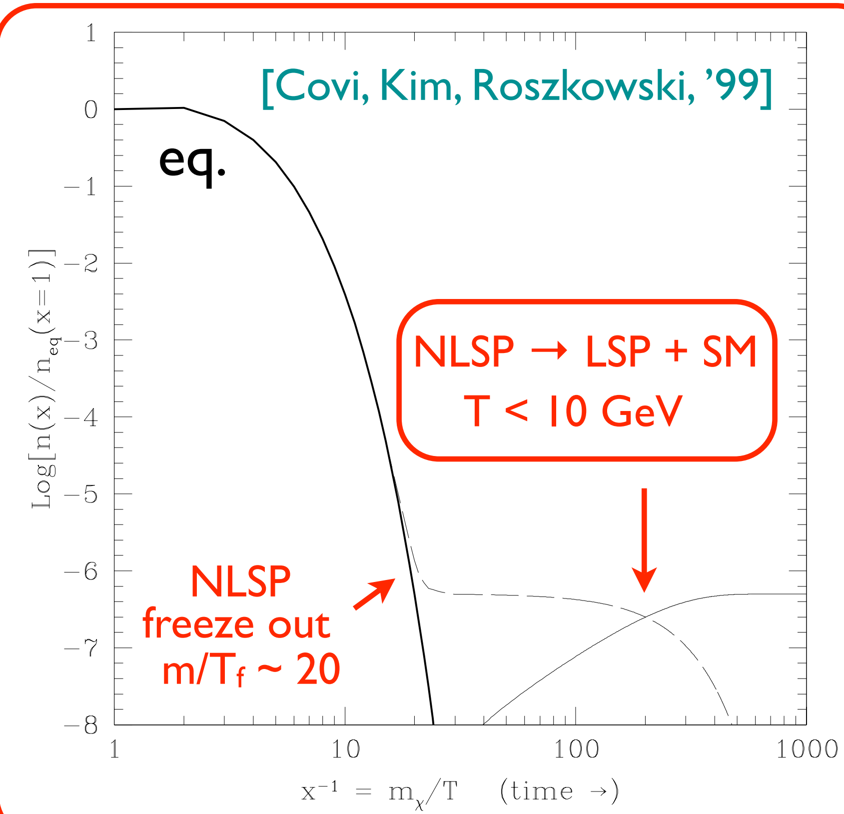
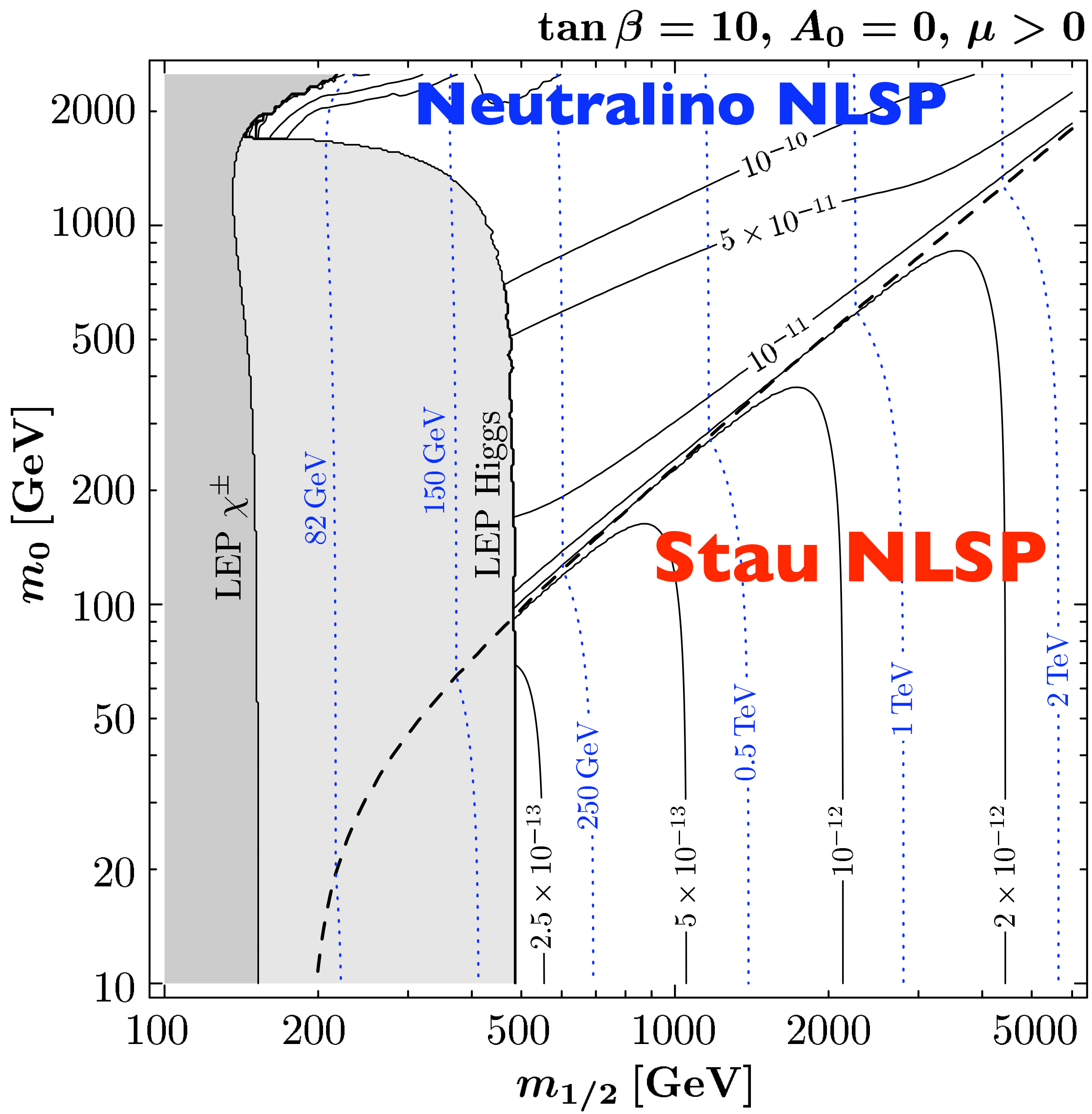
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		

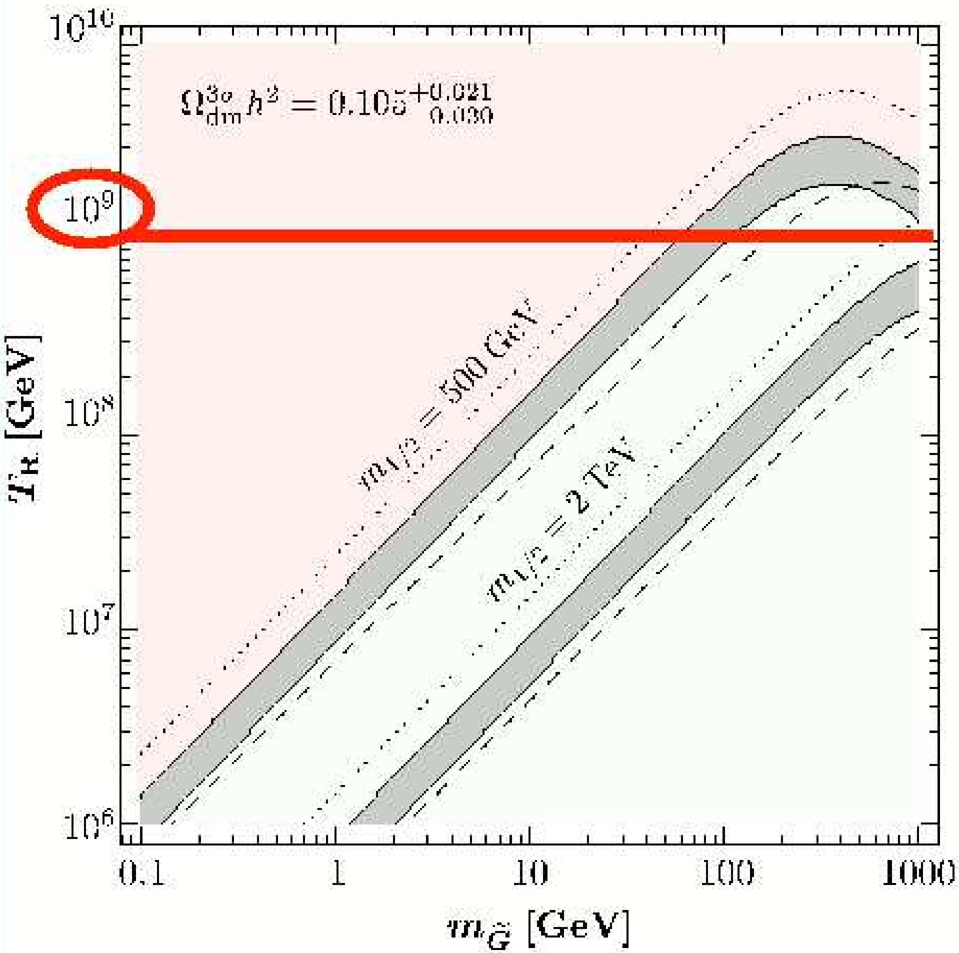
NLSP Candidates

- **lightest neutralino**
- **lighter stau** ← **electrically charged**
- **lighter stop**
- **lightest sneutrino**




$\tan\beta = 10,\ A_0 = 0,\ \mu > 0$
Neutralino NLSP
Stau NLSP
10^{-10}
5×10^{-11}
10^{-11}
2.5×10^{-13}
5×10^{-13}
10^{-12}
2×10^{-12}
LEP $\chi^{\pm}$
82 GeV
150 GeV
LEP Higgs
250 GeV
0.5 TeV
1 TeV
2 TeV
m_0 [GeV]
$m_{1/2}$ [GeV]
2000
1000
500
200
100
50
20
10
100
200
500
1000
2000
5000

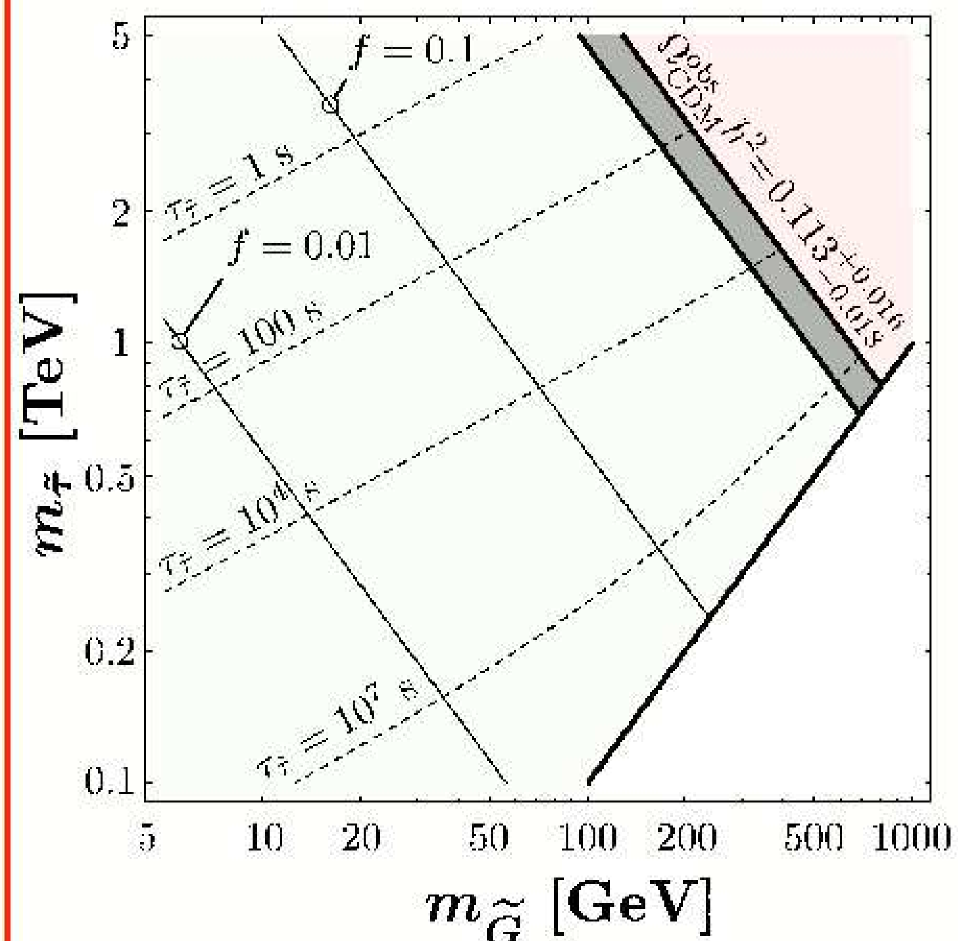
Thermal $\widetilde{G}$ Production



[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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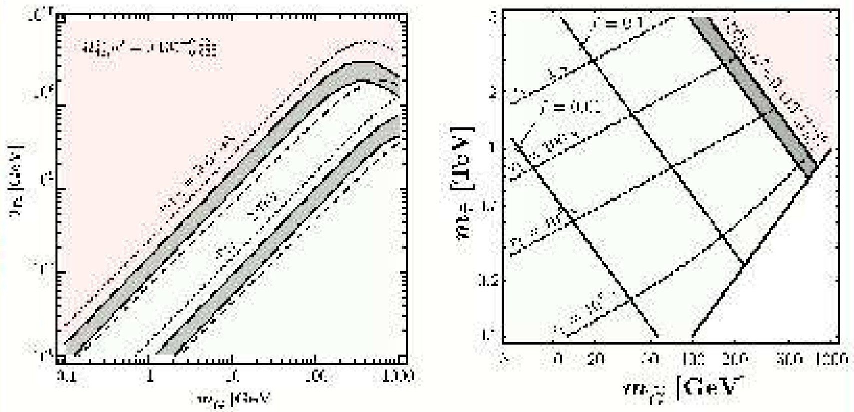
	$M_{\mathrm{W}} \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	
	extremely weak	NLSP decays	$\leftarrow$ warm	
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV	...		

$$\Omega_{\widetilde{G}} = \Omega_{\mathrm{DM}}$$

is possible!!!



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	extremely weak	NLSP decays	← warm	
			BBN	
			CMB	
			γ rays	

Can we probe Gravitino DM in experiments?

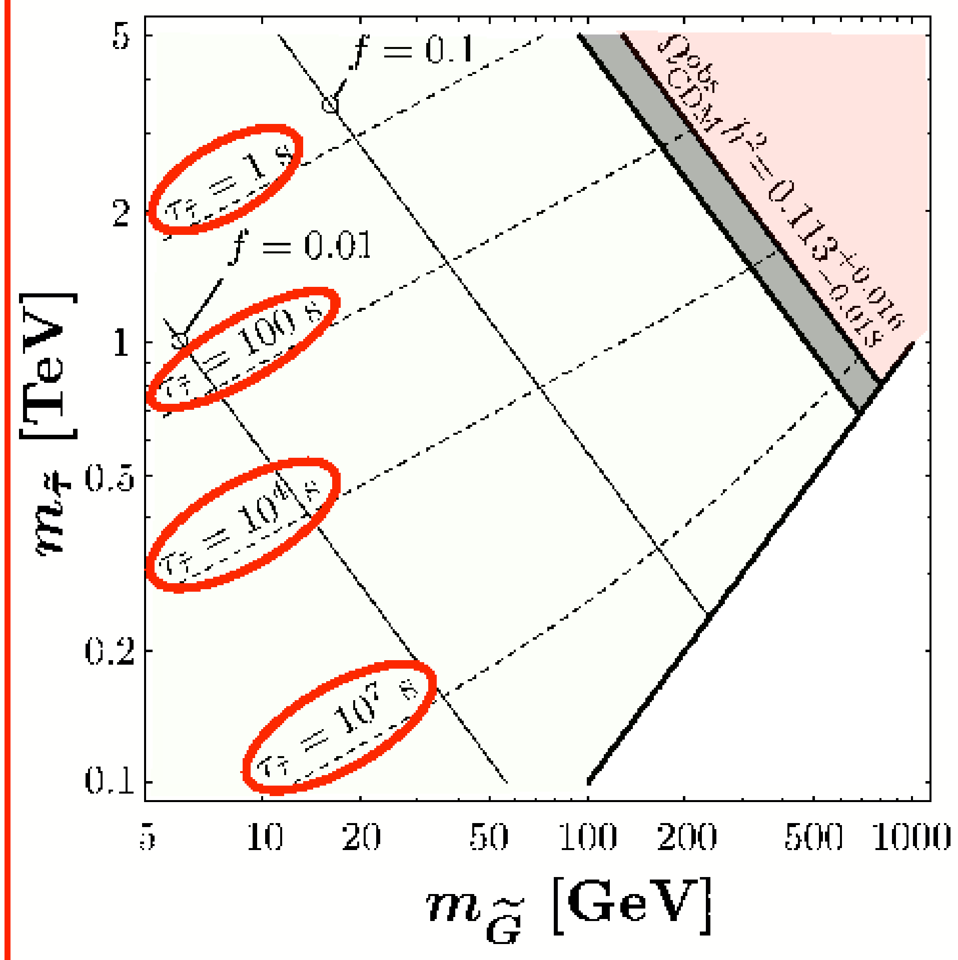
Signatures of Gravitinos in Experiments

– Direct Detection of $\widetilde{G}$

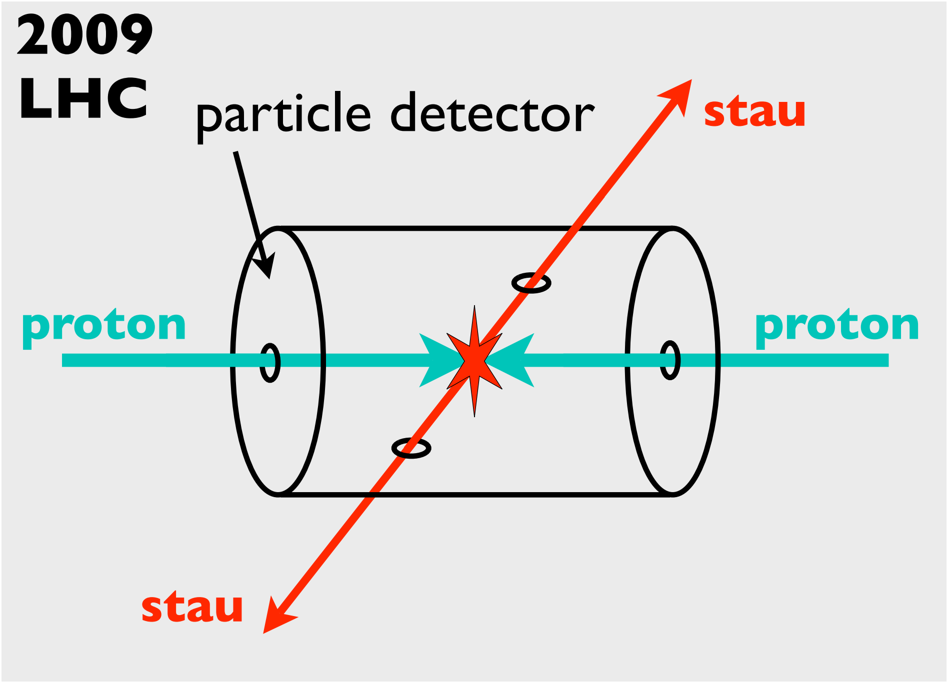
– Direct Production of $\widetilde{G}$

long-lived NLSP

$\tilde{\tau}$ NLSP $\longrightarrow \tilde{G} + \tau$



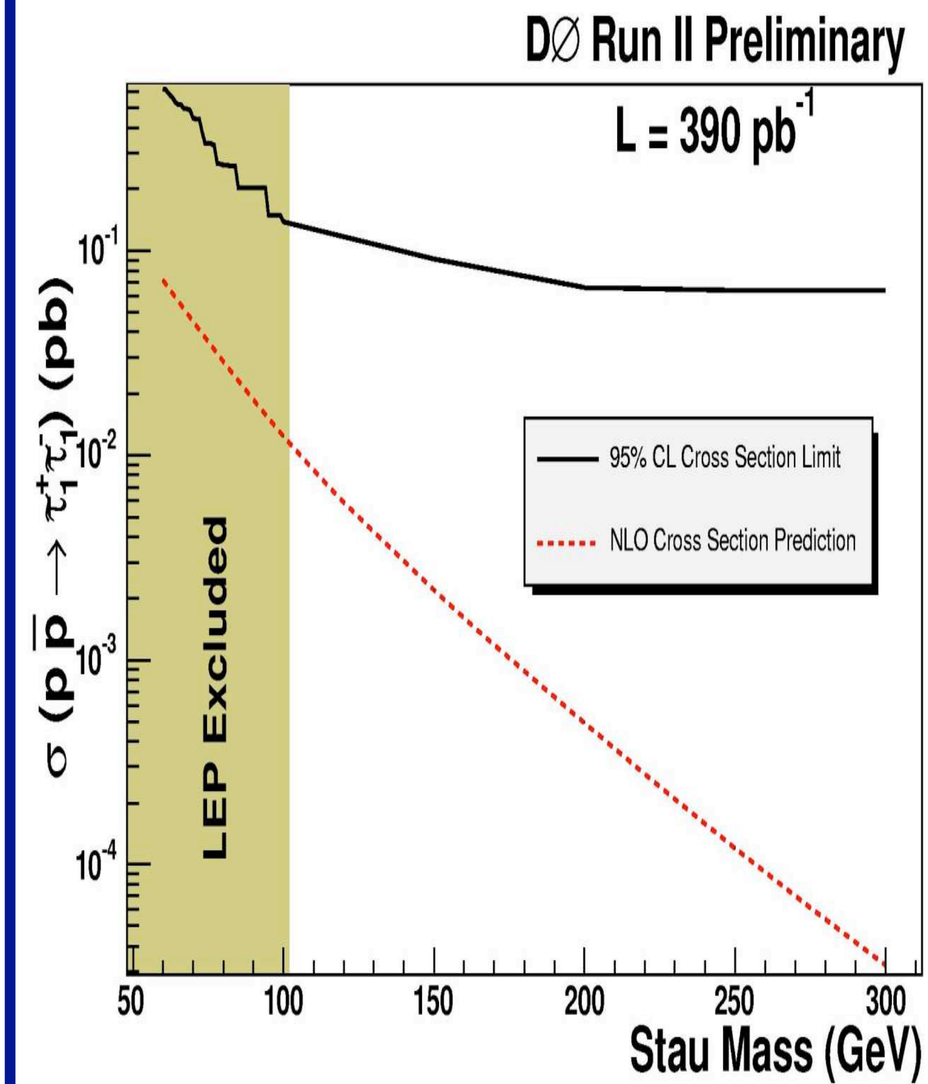
Gravitino DM @ LHC ⟵ Stau NLSP



The signal:
jets + leptons

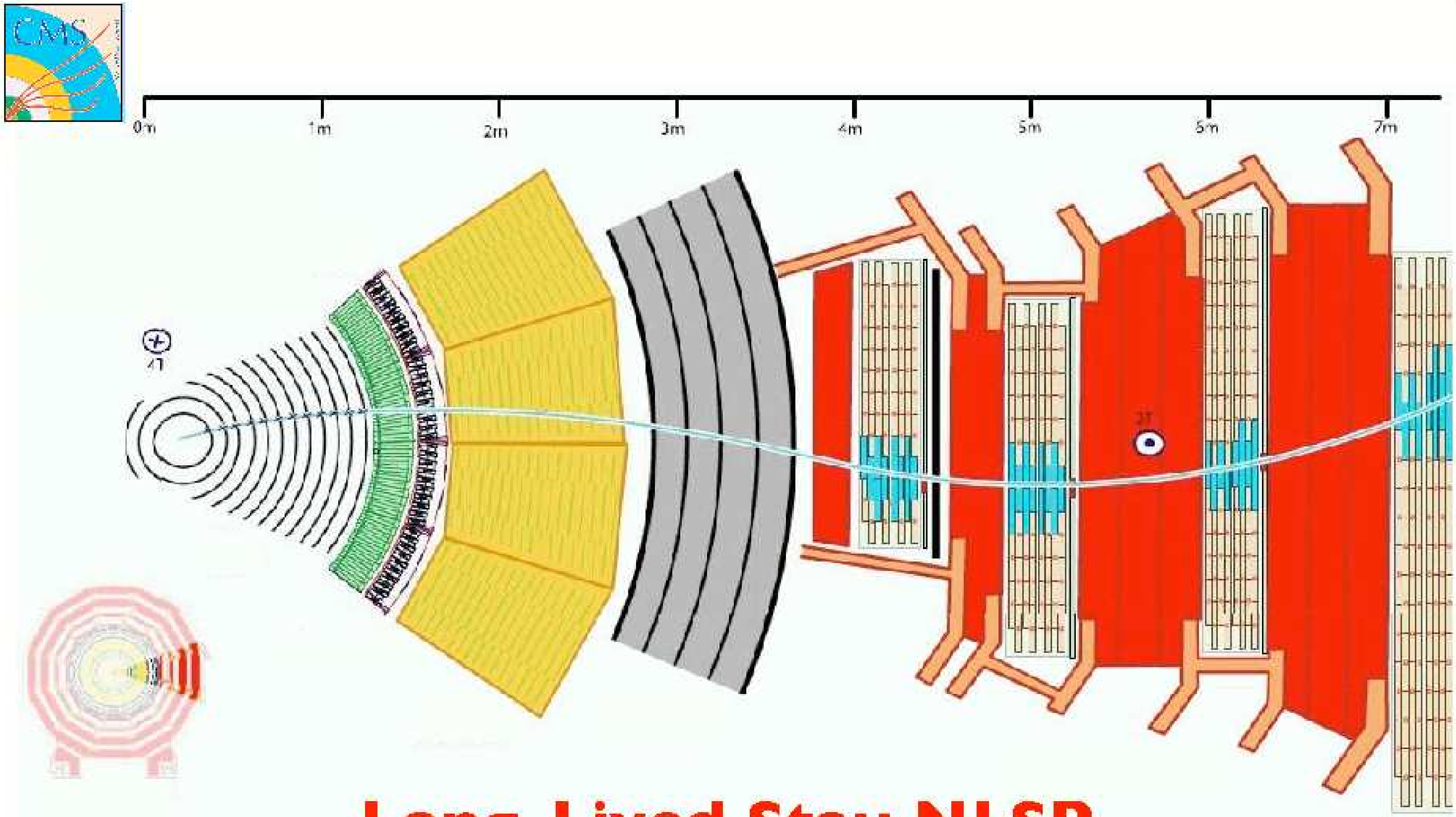
+ 2 “stable” charged particles

Tevatron



Very different from the large E_T^{miss} signal of Neutralino DM

“Stable” Charged Massive Particle @ LHC



Long-Lived Stau NLSP

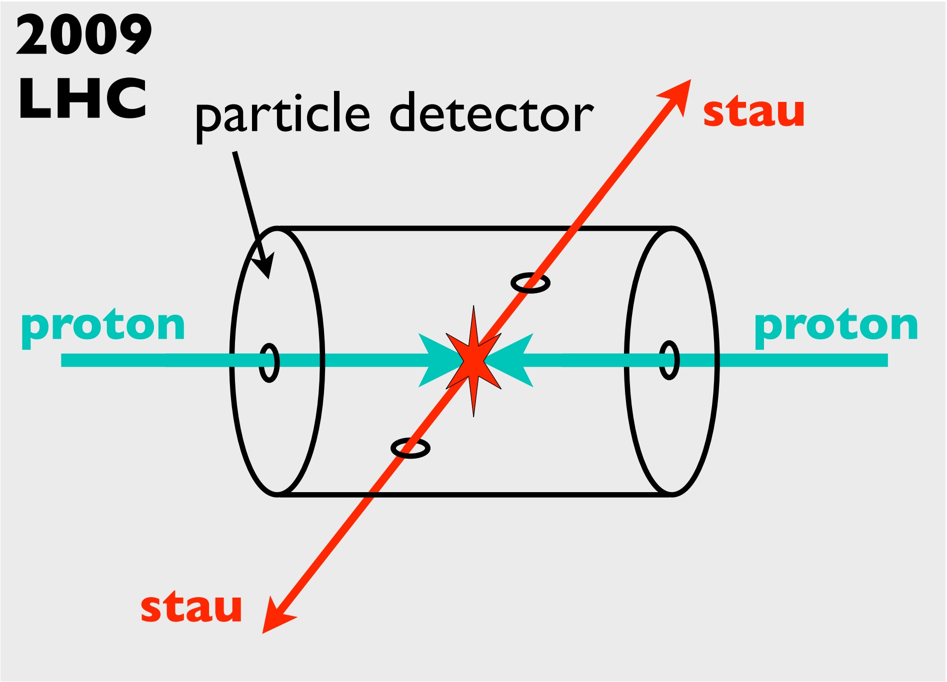
[from P. Zalewski’s Talk, SUSY 2007]

Signatures of Gravitinos in Experiments

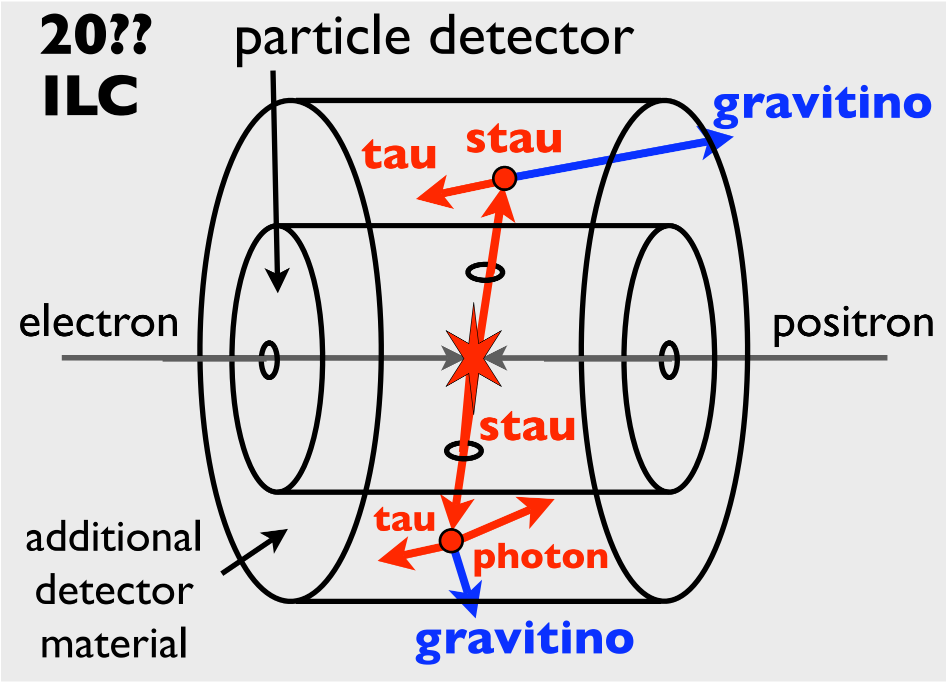
– Direct Detection of $\widetilde{G}$

– Direct Production of $\widetilde{G}$

⁎ "stable" charged sparticles



⁎ long-lived charged sparticles



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

For prospects
on stopping and analyzes of staus
at the LHC

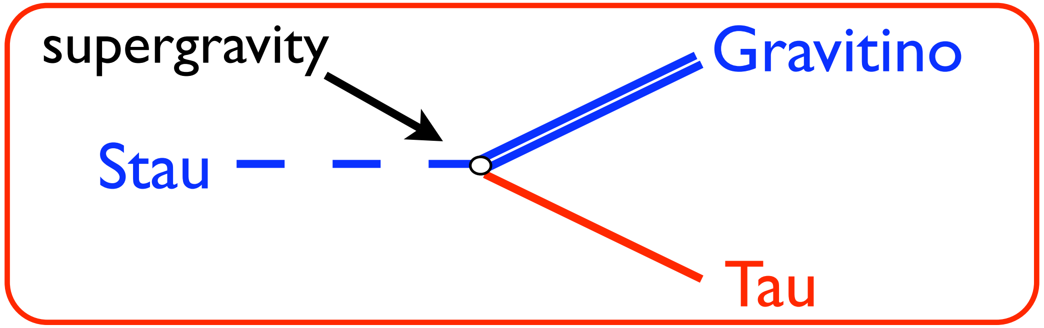
↓

[Hamaguchi, Nojiri, de Roeck, ’07]

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

$\widetilde{G}$ LSP $\longrightarrow$ Planck Scale $\mathrm{M_{Pl}}$ & Gravitino Mass $m_{\widetilde{G}}$

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



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

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

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

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

- Gravitino Mass $m_{\widetilde{G}} = \sqrt{m_{\widetilde{\tau}}^2 + m_{\tau}^2 - 2 m_{\widetilde{\tau}} E_{\tau}}$ $\longleftarrow$ Kinematics

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	extremely weak	NLSP decays	$\leftarrow$ warm	+ $\widetilde{\tau}$ collection
	$\rm M_{Pl} = 2.44 \times 10^{18}$ GeV	...		+ $\widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $\rm M_{Pl}$ (?), ...
			BBN	
			CMB	
			γ rays	

LSP Dark Matter: Production, Constraints, Experiments

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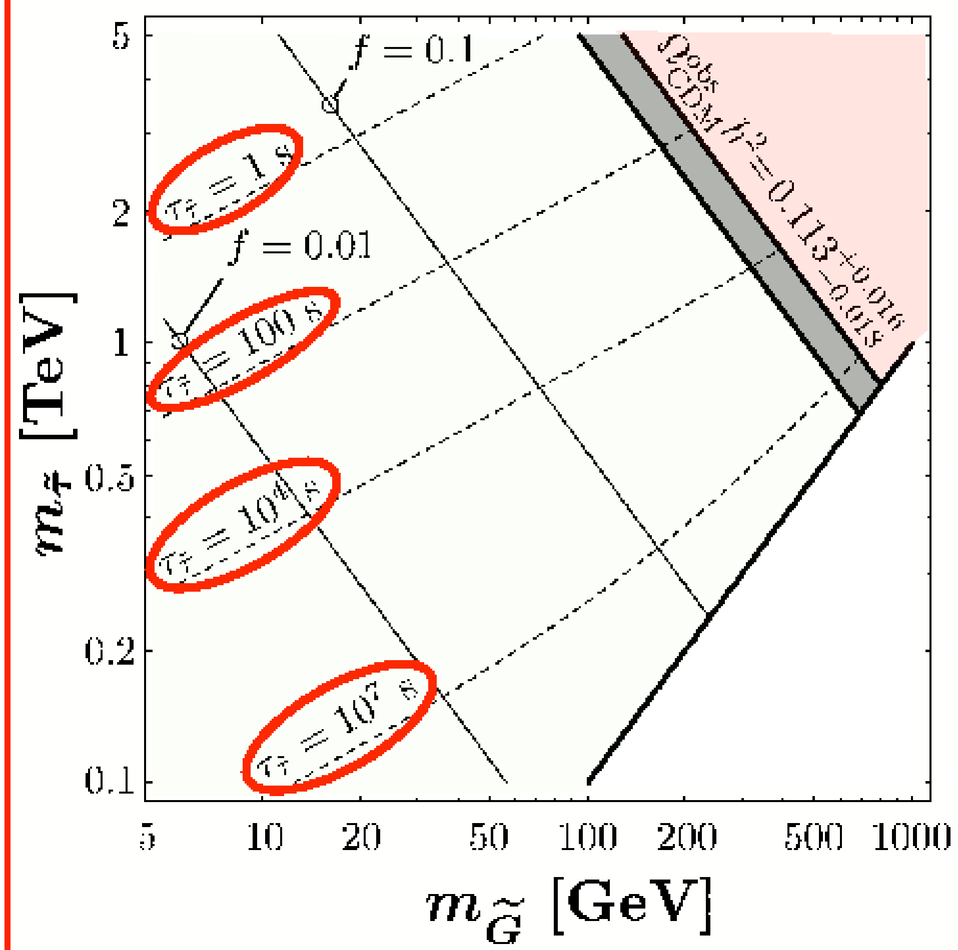
			BBN	
			CMB	
			γ rays	

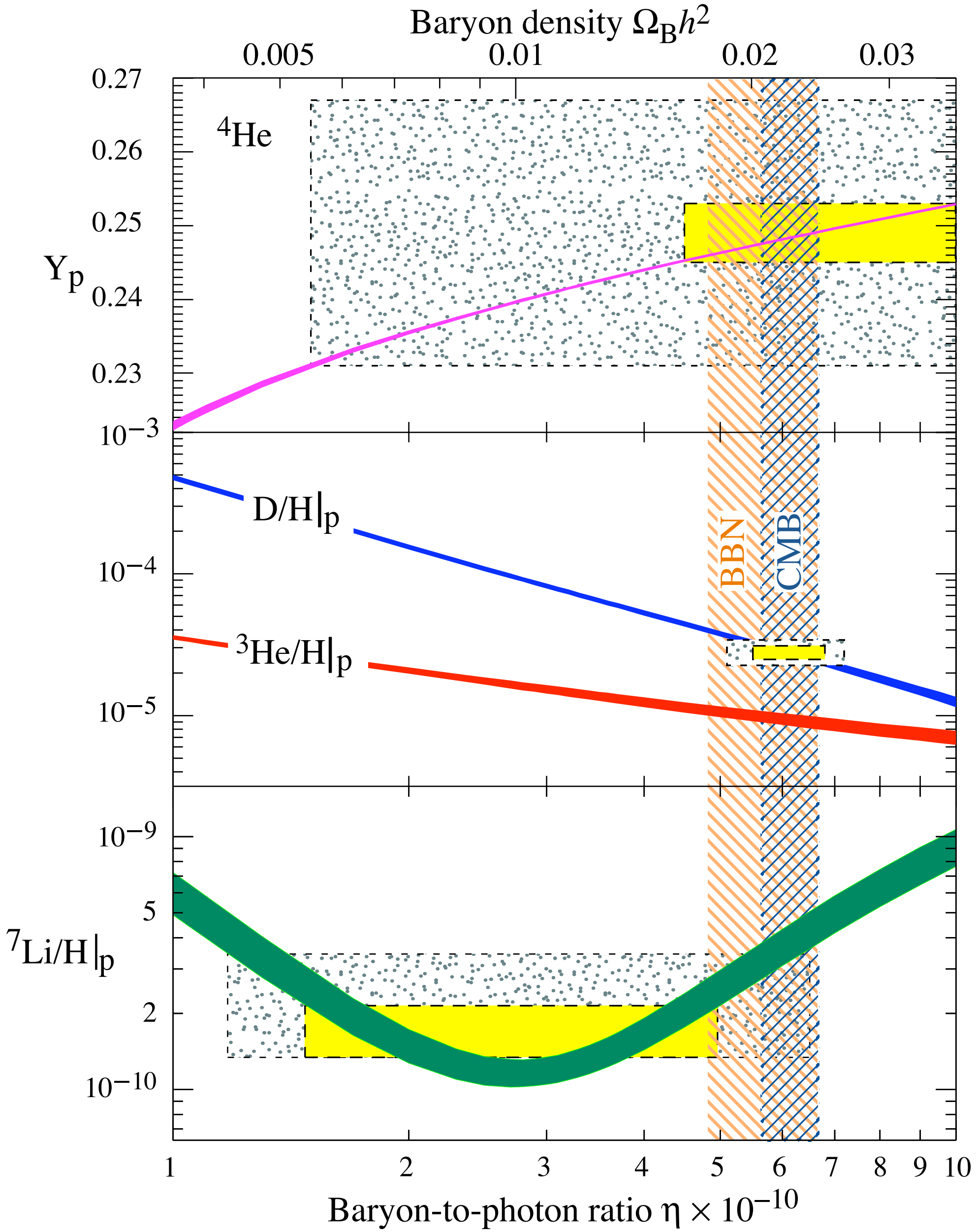
Does your theory allow for successful BBN?

long-lived NLSP

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

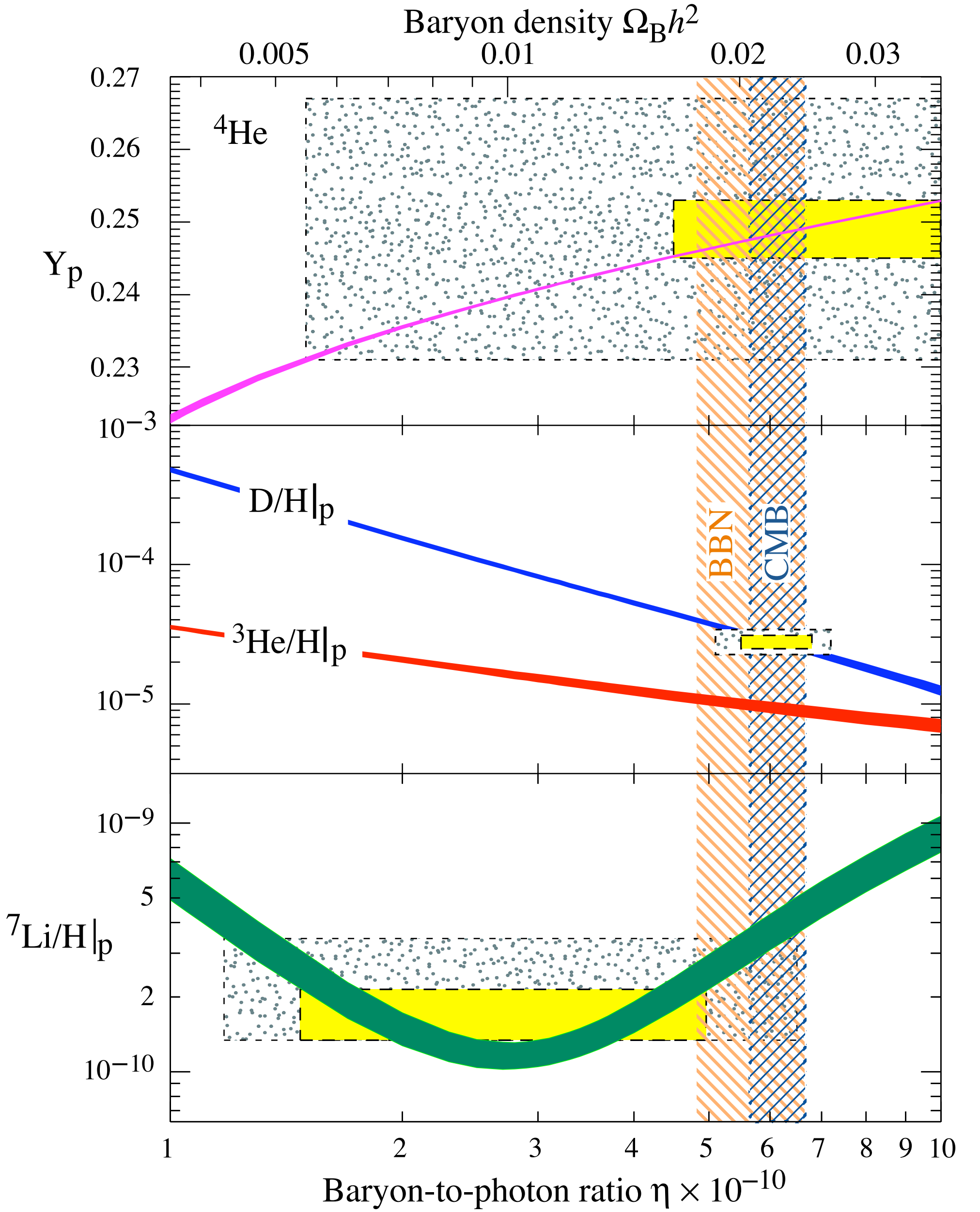


Big-Bang Nucleosynthesis



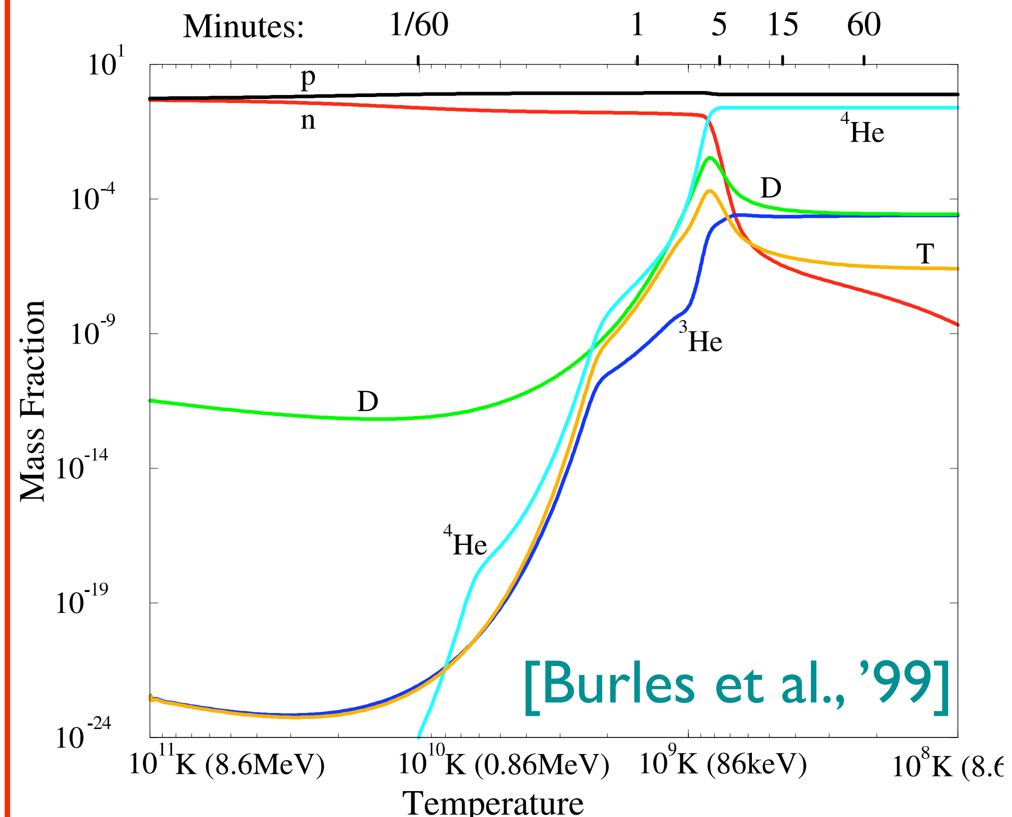
[Particle Data Book 2006]

Big-Bang Nucleosynthesis

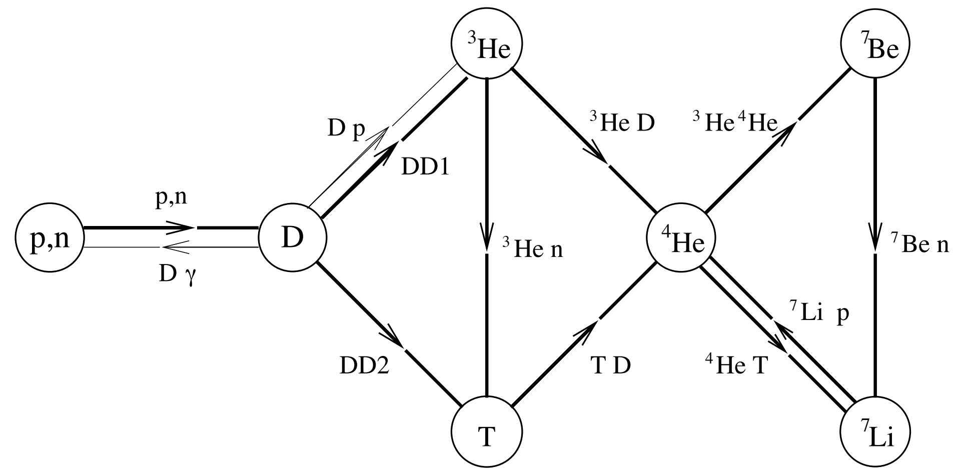


[Particle Data Book 2006]

SBBN

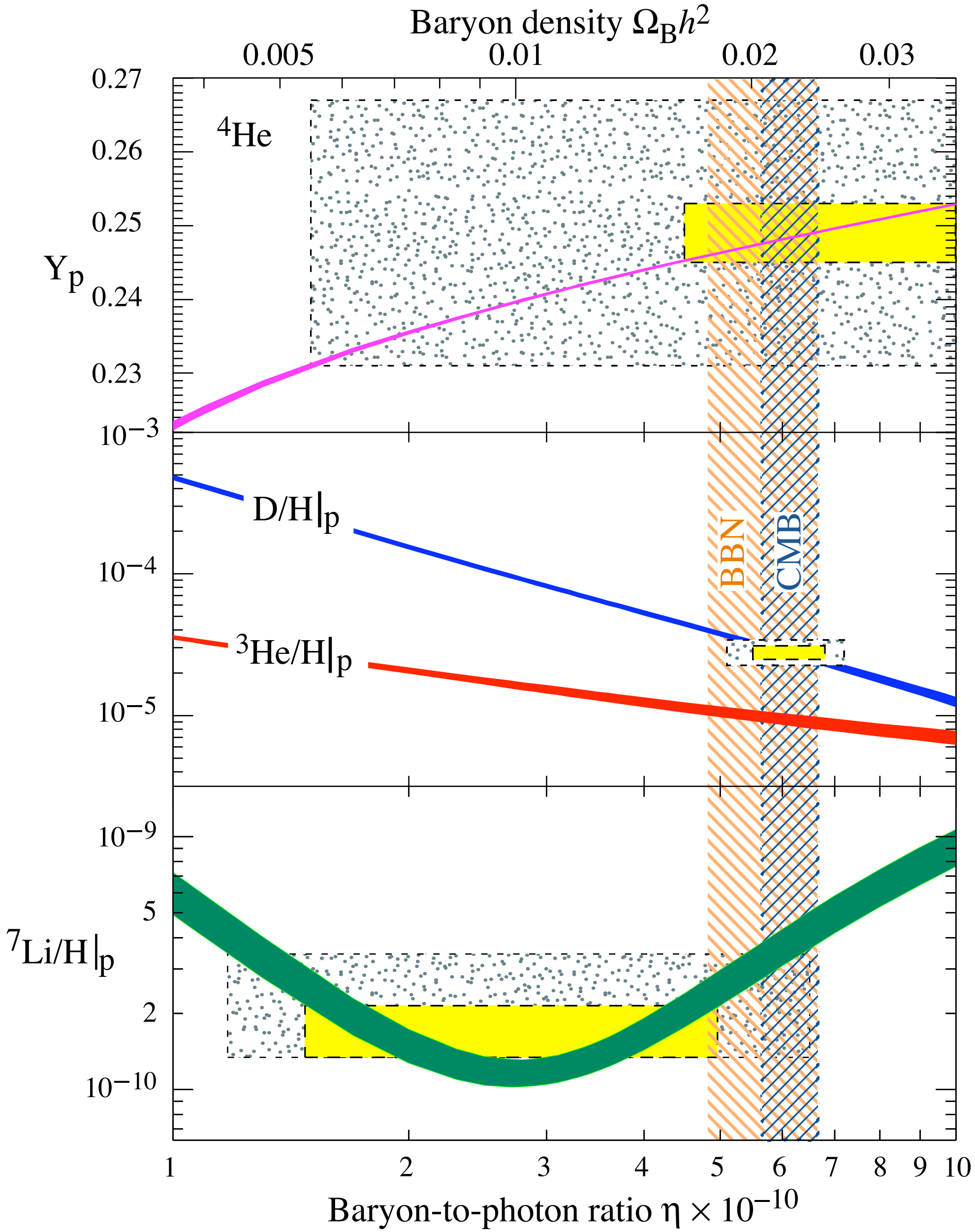


[Burles et al., '99]



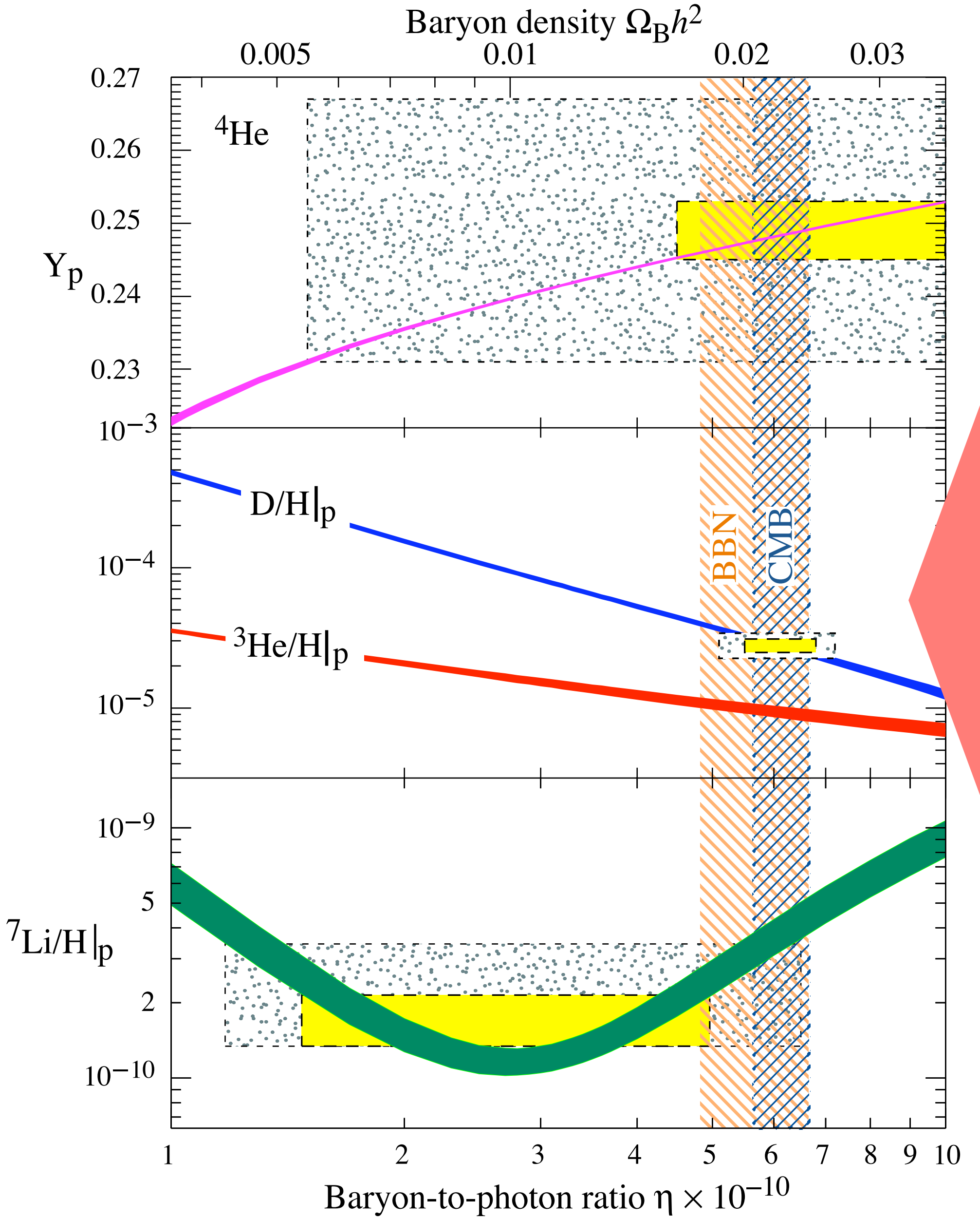
[V. Mukhanov, '04]

Big-Bang Nucleosynthesis

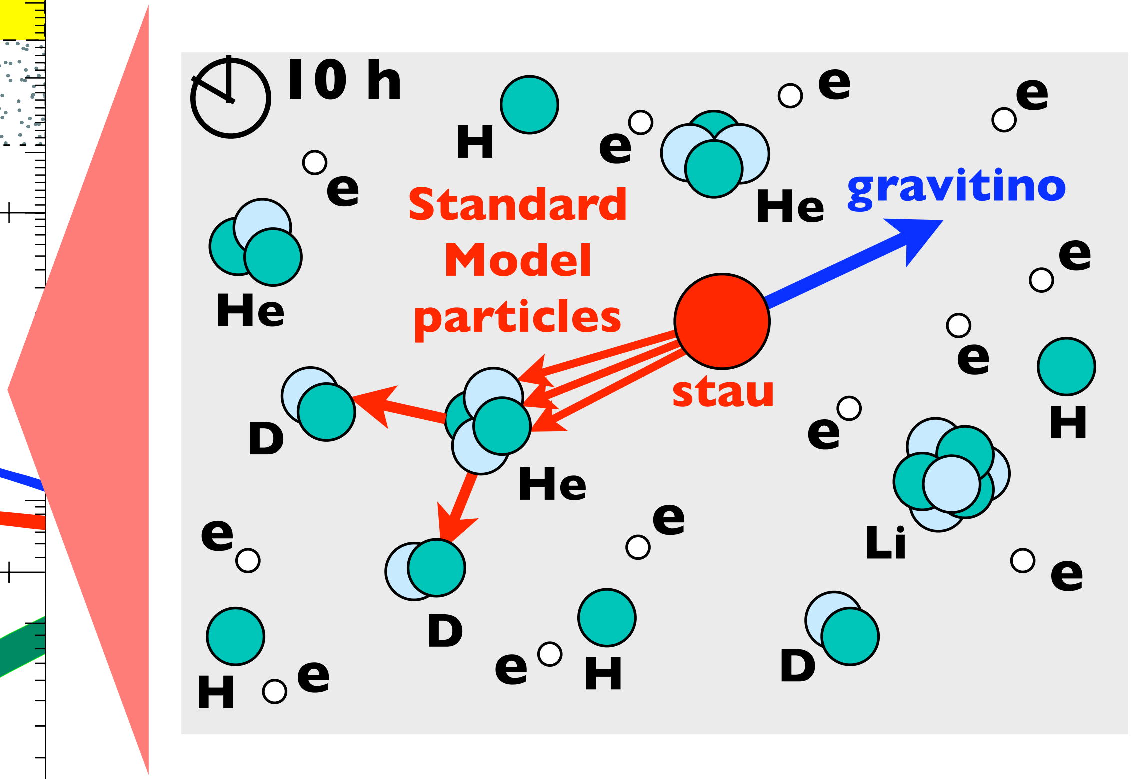


[Particle Data Book 2006]

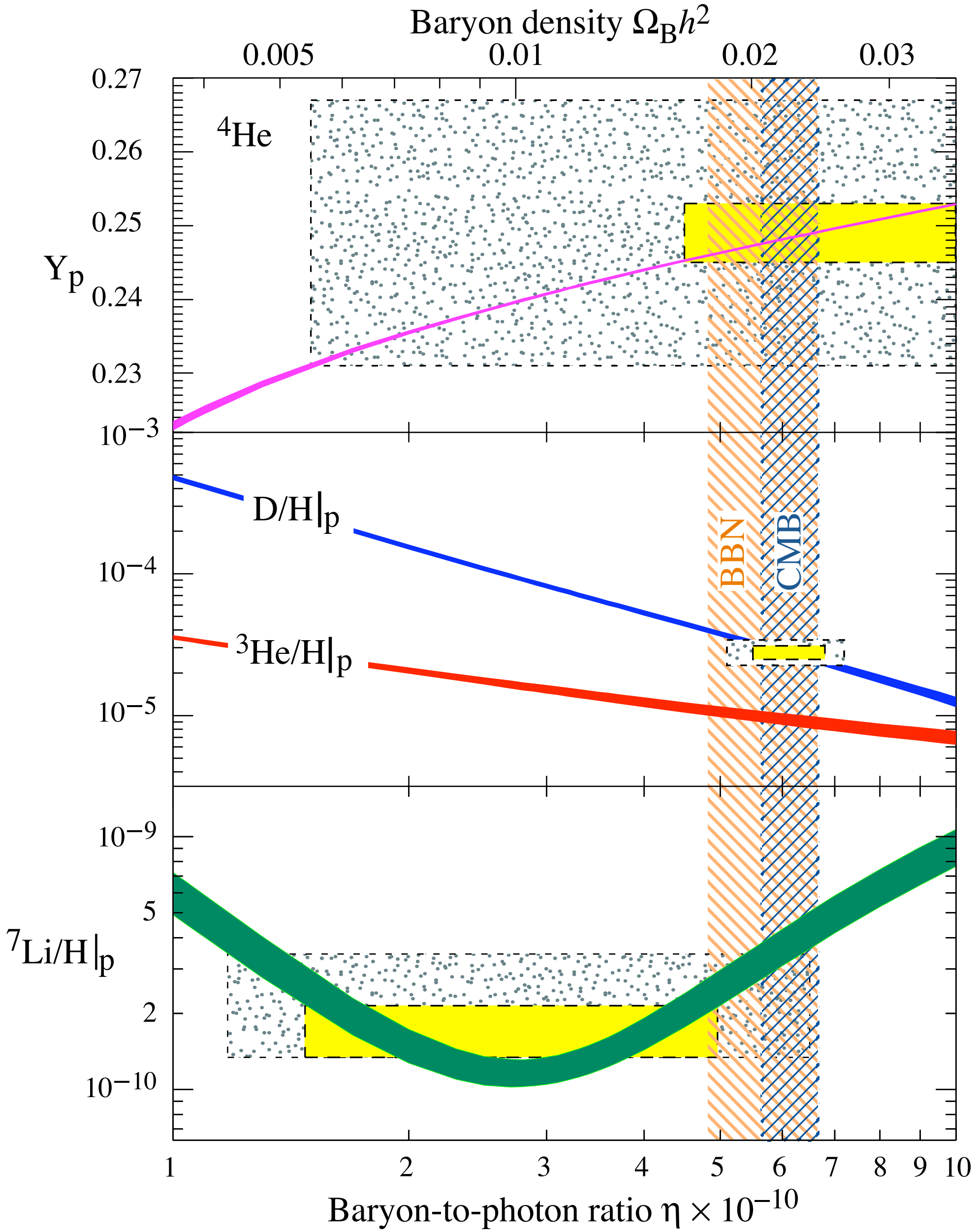
Big-Bang Nucleosynthesis



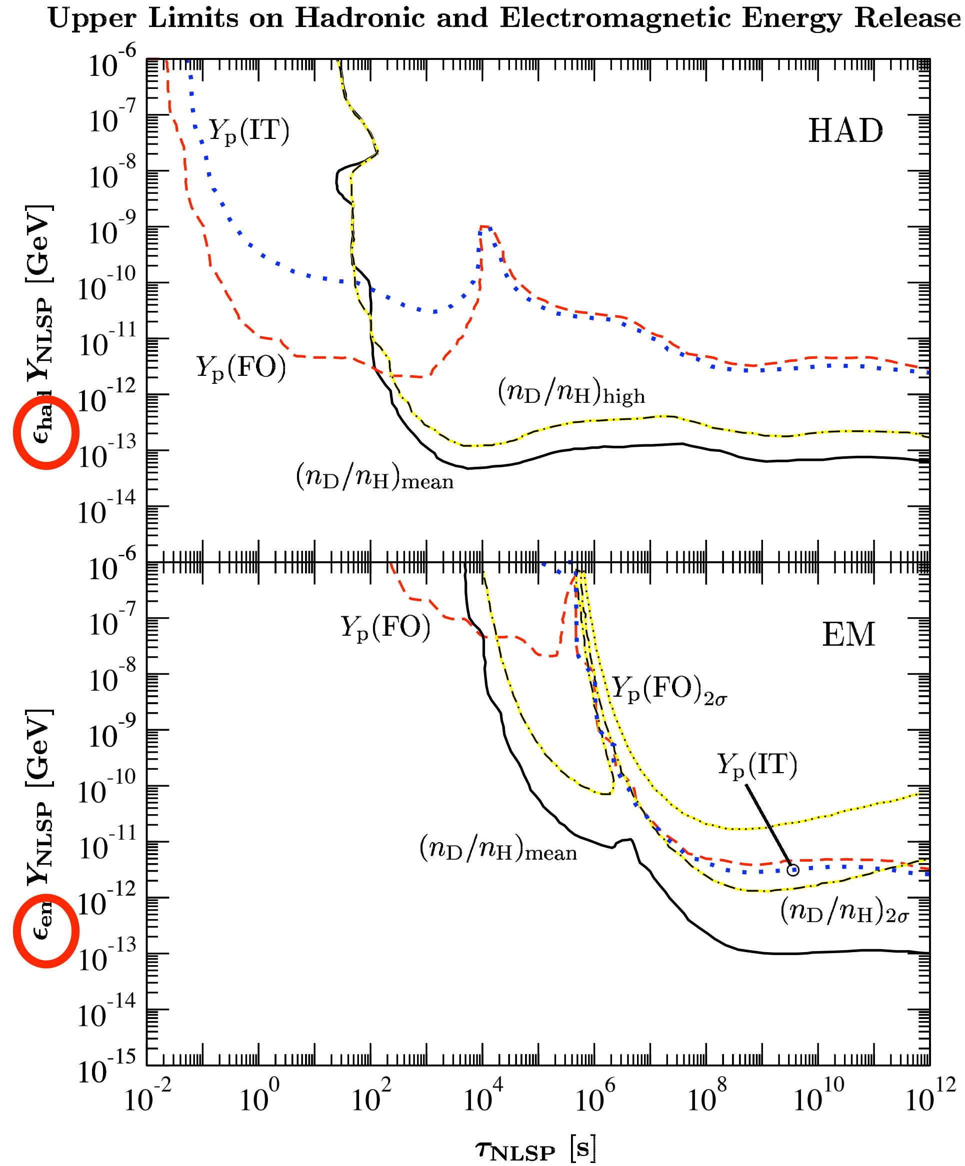
[Particle Data Book 2006]



Big-Bang Nucleosynthesis



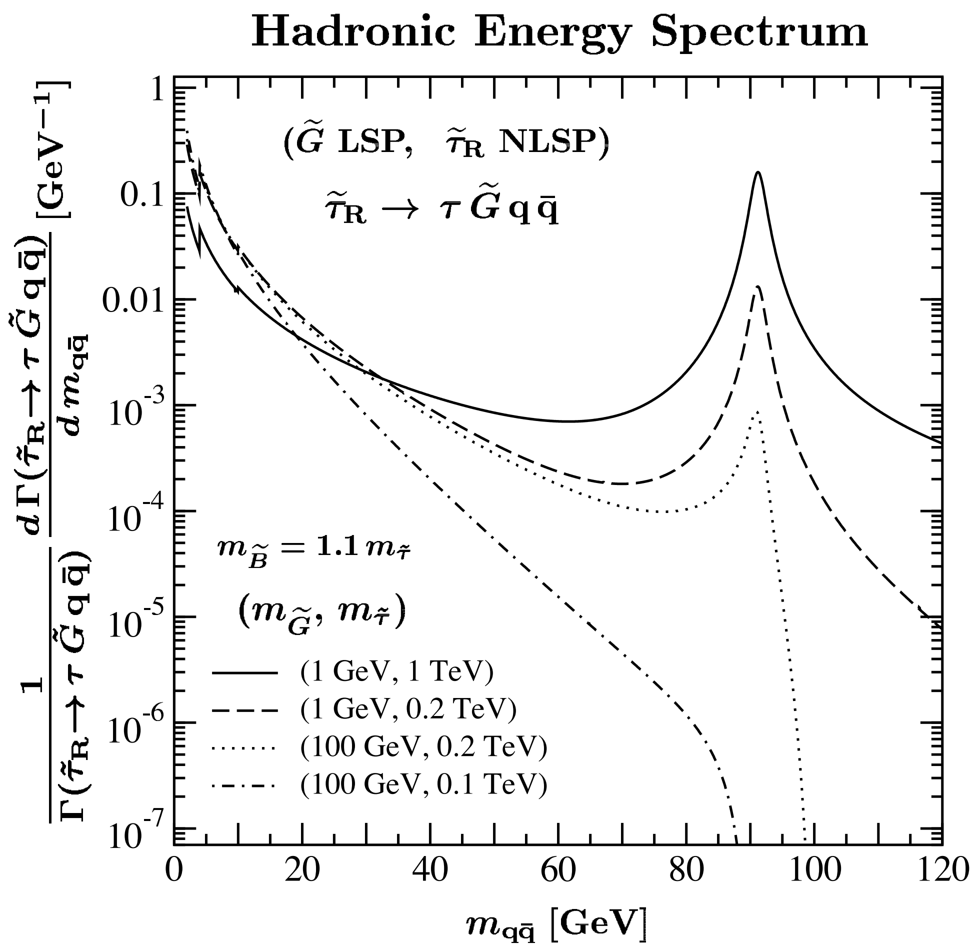
[Particle Data Book 2006]

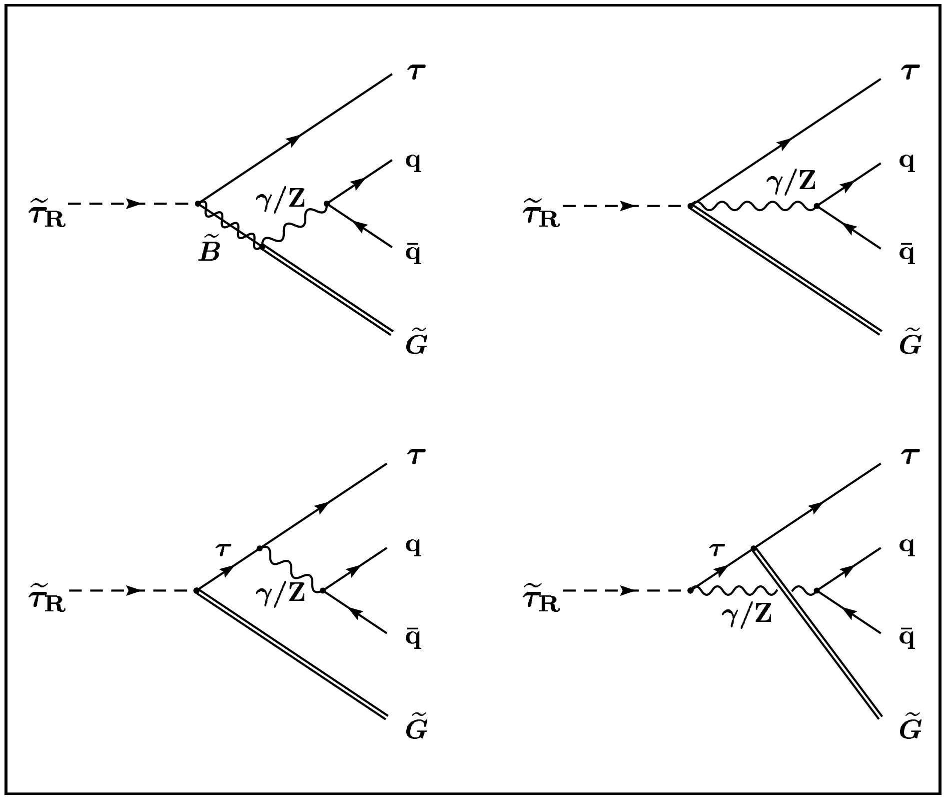


[Kawasaki, Kohri, Moroi, '05; Cyburt et al., '03]

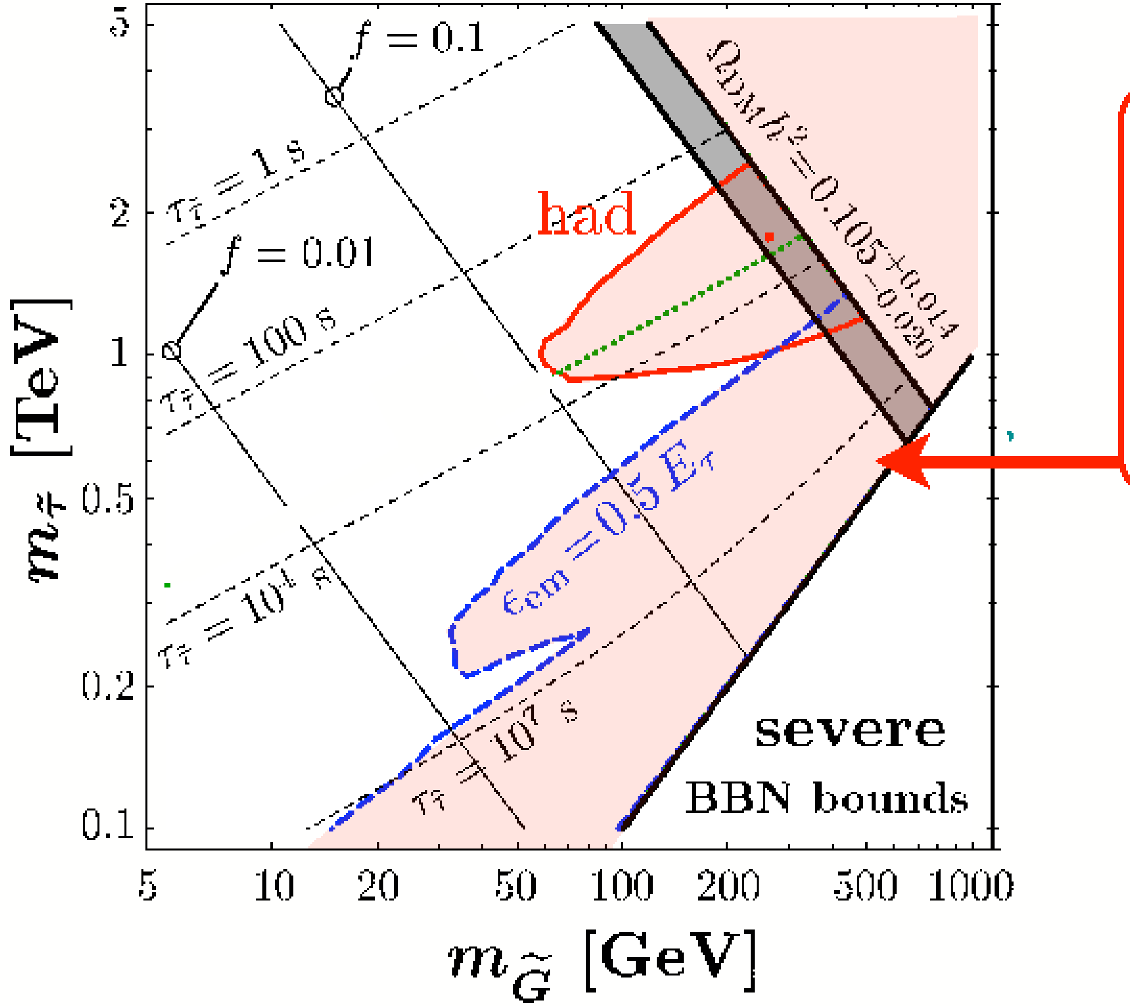
[FDS, '06]

The 4-Body Decay of the Stau NLSP into Hadrons





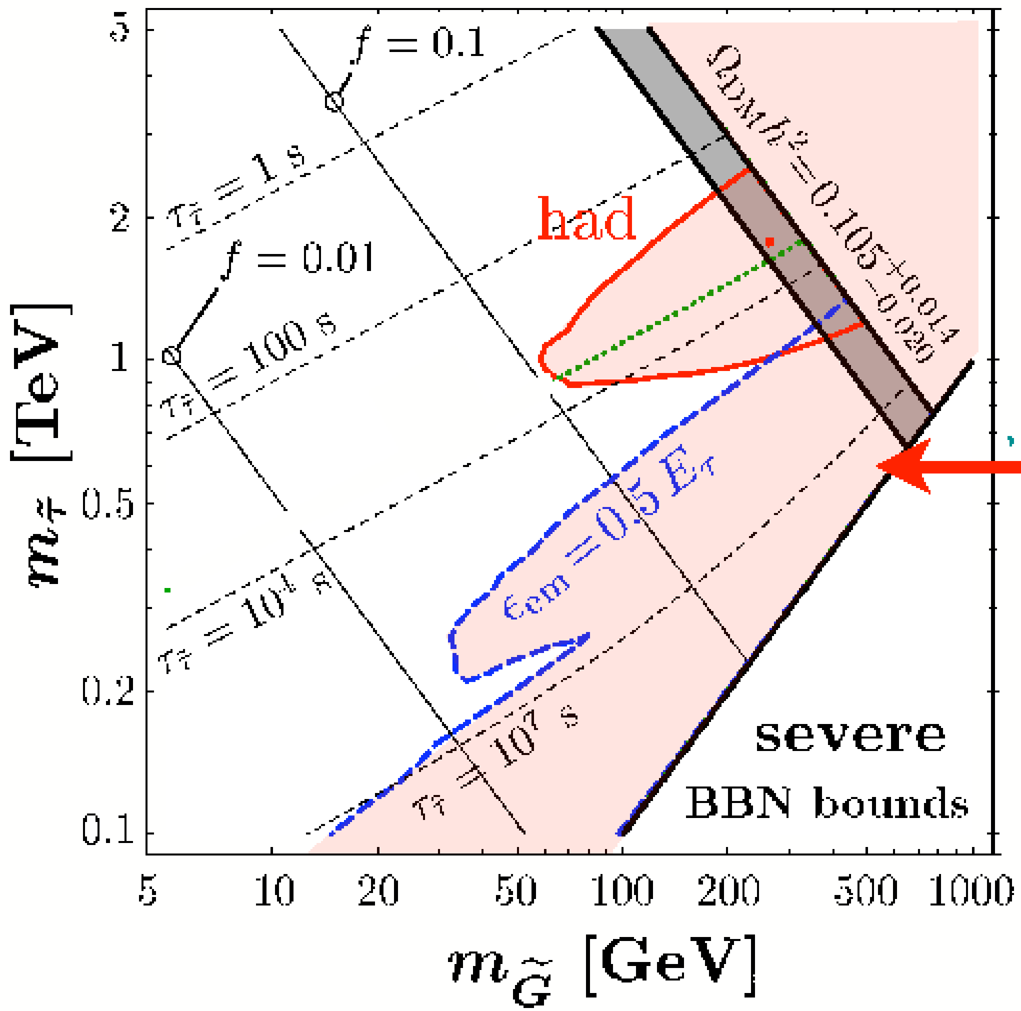
Cosmological Constraints — $\Omega_{\rm DM}$ & BBN



disfavored by cosmological constraints

[FDS, '06]

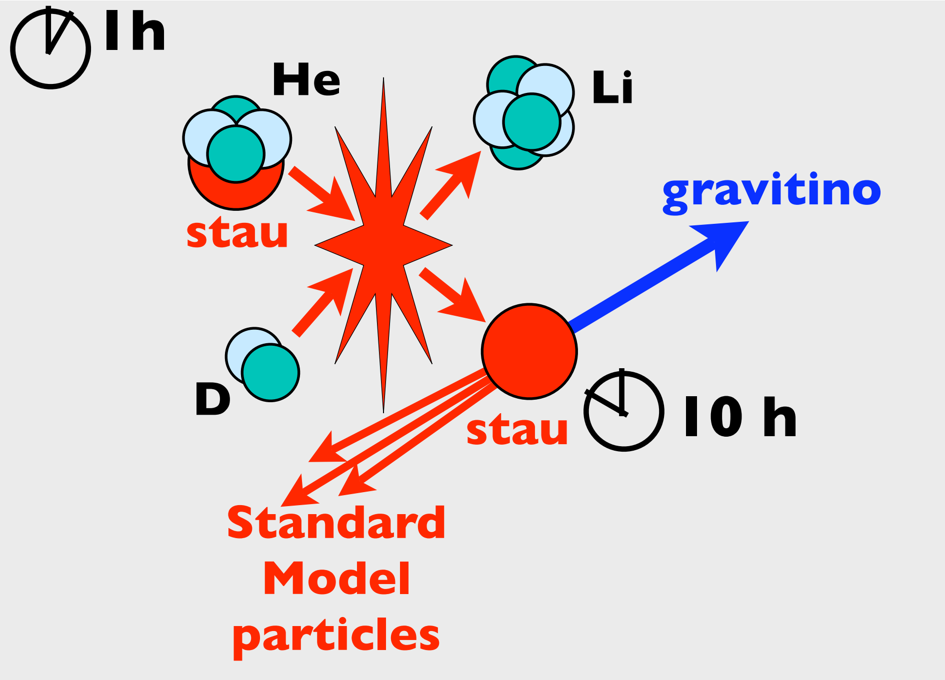
Cosmological Constraints — $\Omega_{\rm DM}$ & BBN



disfavored by cosmological constraints

Picture until May 2006 ...

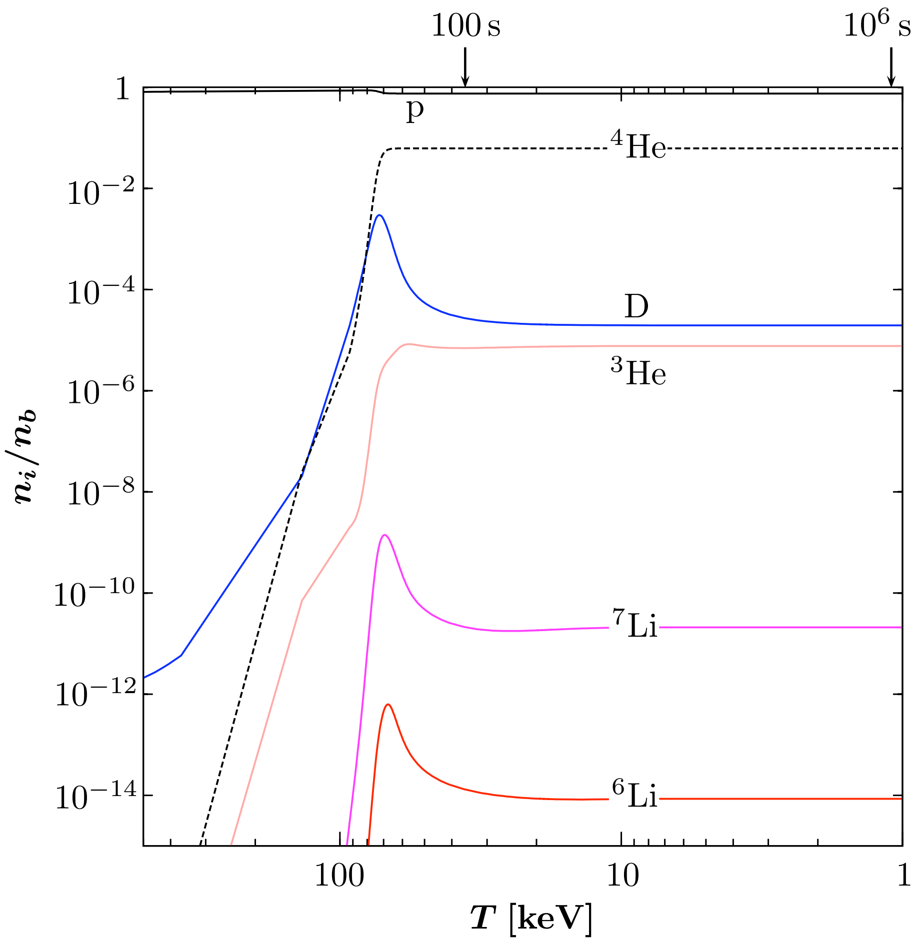
Catalyzed BBN [Pospelov, '06]



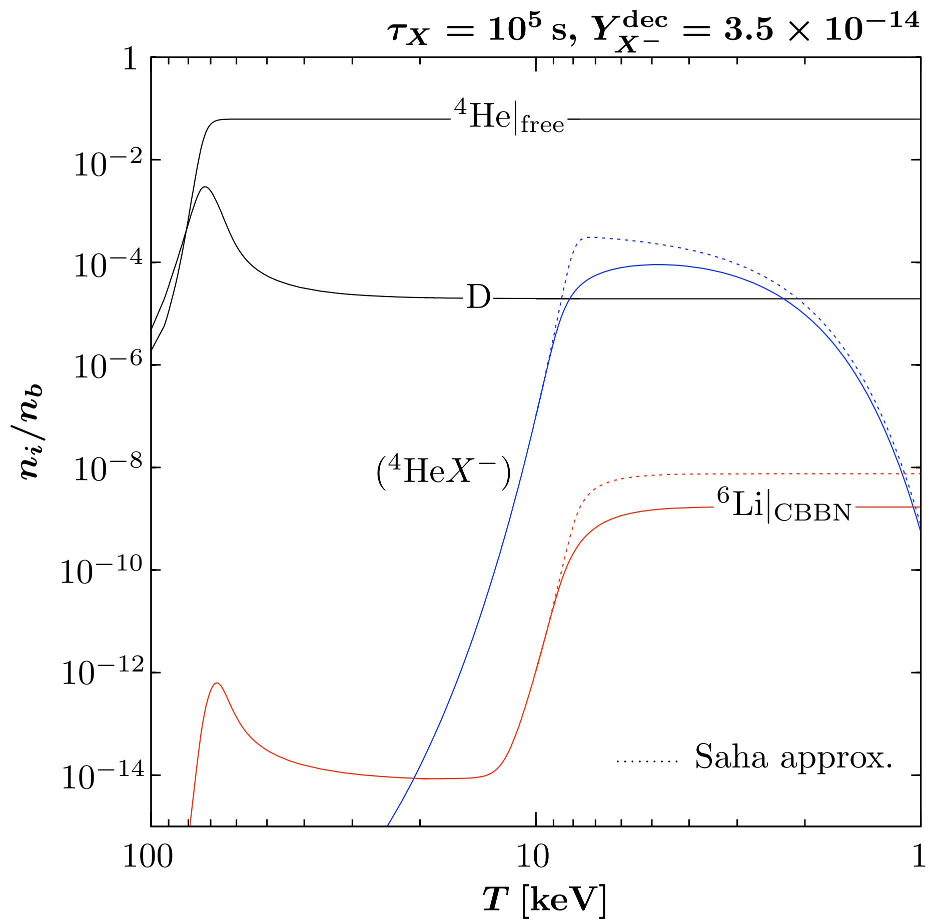
[Cyburt et al., '06; FDS, '06; Pradler, FDS, '07; Hamaguchi et al., '07; Kawasaki, Kohri, Moroi, '07; Takayama, '07; Jedamzik, '07; Pradler, FDS, '08]

CBBN of 9Be: [Pospelov, '07; Pospelov, Pradler, FDS, '08]

Standard BBN



Catalyzed BBN



[Pradler, FDS, arXiv:0710.2213]

Catalyzed Big Bang Nucleosynthesis (CBBN)

$$({}^4\mathrm{He}X^-) + \mathrm{D} \rightarrow {}^6\mathrm{Li} + X^-$$

$$\frac{dY_{\mathrm{BS}}}{dt} = \langle\sigma_{\mathrm{r}} v\rangle s Y_\delta - \Gamma_{X^-} Y_{\mathrm{BS}} - \langle\sigma_{\mathrm{C}} v\rangle s Y_{\mathrm{BS}} Y_{\mathrm{D}},$$

$$\frac{dY_{X^-}}{dt} = -\langle\sigma_{\mathrm{r}} v\rangle s Y_\delta - \Gamma_{X^-} Y_{X^-} + \langle\sigma_{\mathrm{C}} v\rangle s Y_{\mathrm{BS}} Y_{\mathrm{D}},$$

$$\frac{dY_{^4\mathrm{He}}}{dt} = -\langle\sigma_{\mathrm{r}} v\rangle s Y_\delta + \Gamma_{X^-} Y_{\mathrm{BS}},$$

$$\frac{dY_{^6\mathrm{Li}}}{dt} = \langle\sigma_{\mathrm{C}} v\rangle s Y_{\mathrm{BS}} Y_{\mathrm{D}},$$

$$\frac{dY_{\mathrm{D}}}{dt} = -\langle\sigma_{\mathrm{C}} v\rangle s Y_{\mathrm{BS}} Y_{\mathrm{D}}.$$

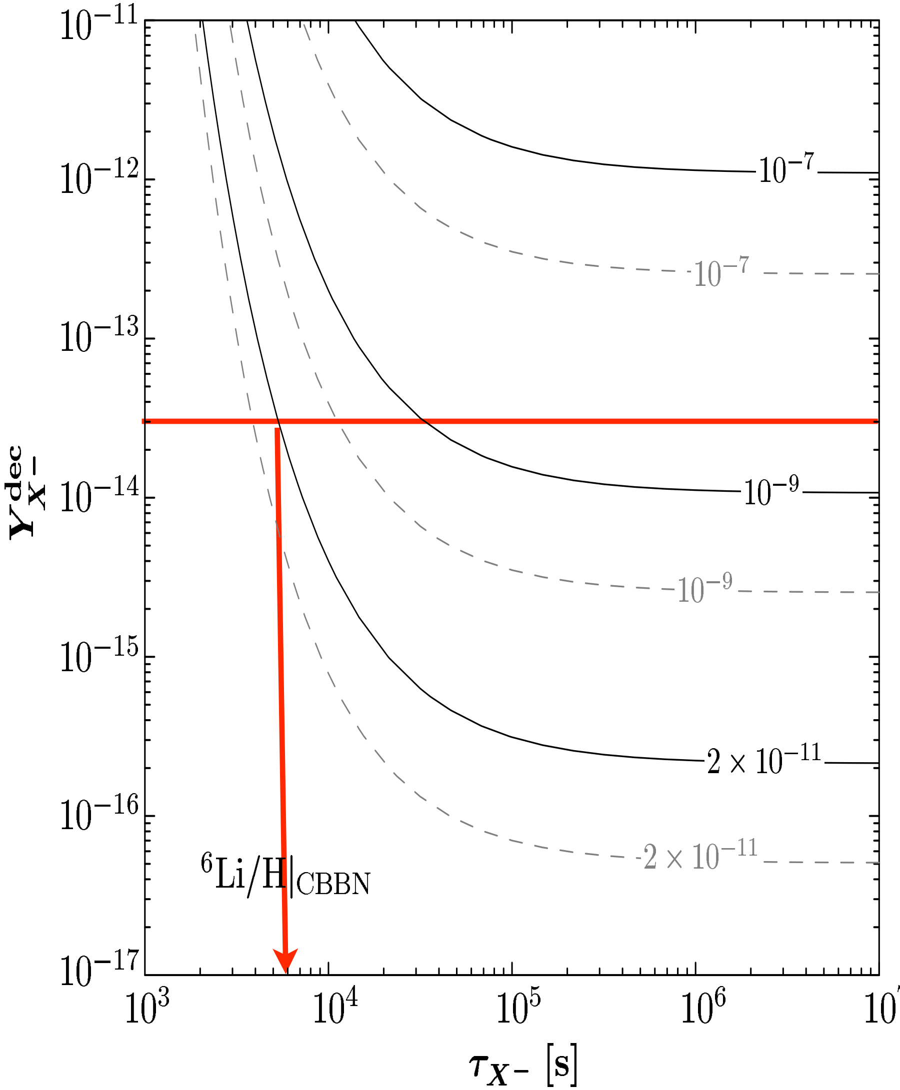
$$\langle\sigma_{\mathrm{C}} v\rangle = 2.37\times 10^8\,(1-0.34T_9)\,T_9^{-2/3} e^{-5.33 T_9^{-1/3}}$$

[Hamaguchi et al., '07]

$$\langle\sigma_{\mathrm{r}} v\rangle = \frac{2^9 \pi\alpha Z_\alpha^2\sqrt{2\pi}}{3e^4}\,\frac{E_{\mathrm{b}}}{m_\alpha^2\sqrt{m_\alpha T}}$$

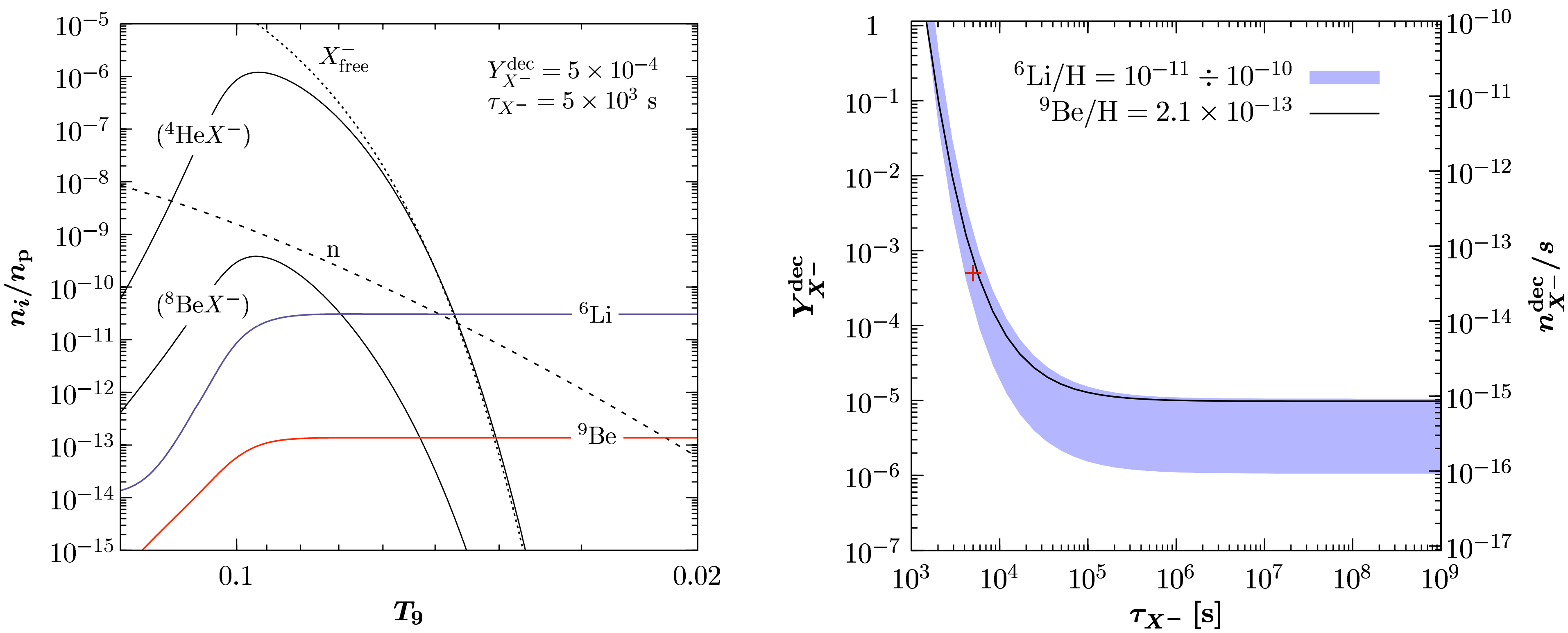
$$Y_\delta \equiv (Y_{X^-} Y_{^4\mathrm{He}} - Y_{\mathrm{BS}}\widetilde{Y}_\gamma)$$

$E_{\mathrm{b}} = 337.33\,\mathrm{keV}$ $\widetilde{n}_\gamma \equiv n_\gamma(E > E_{\mathrm{b}})$



[Pospelov, Pradler, FDS, '08]

Catalyzed BBN of Lithium-6 and Beryllium-9



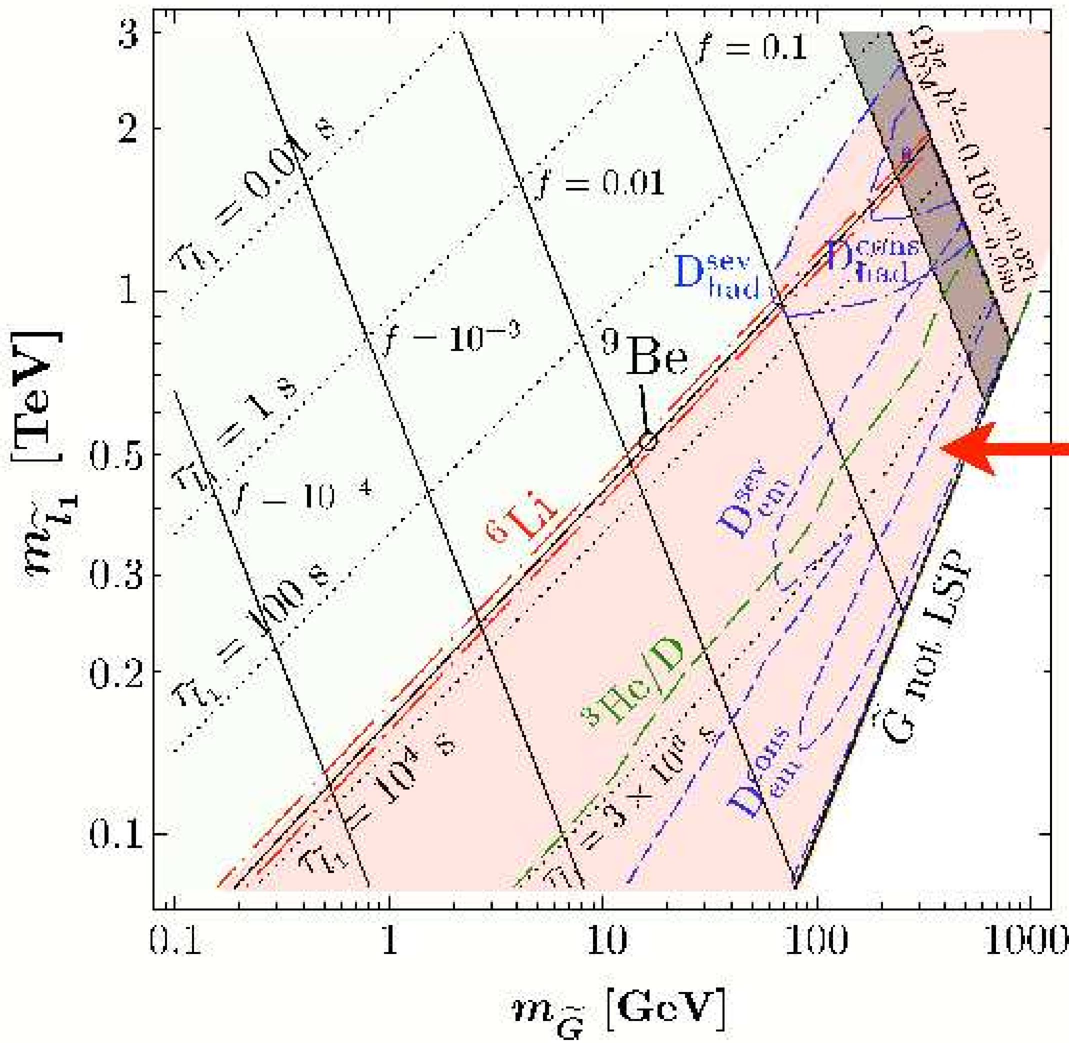
$$(^4{\rm He}X^-) + {\rm D} \rightarrow {}^6{\rm Li} + X^-$$ [Pospelov, '06; ...]

$$^4{\rm He} + (^4{\rm He}X^-) \rightarrow (^8{\rm Be}X^-) + \gamma$$ [Pospelov, '07] &

$$(^8{\rm Be}X^-) + n \rightarrow {}^9{\rm Be} + X^- \ .$$ [Pospelov, Pradler, FDS, '08]

[Pospelov, Pradler, FDS, '08]

Current Status of (C)BBN Constaints

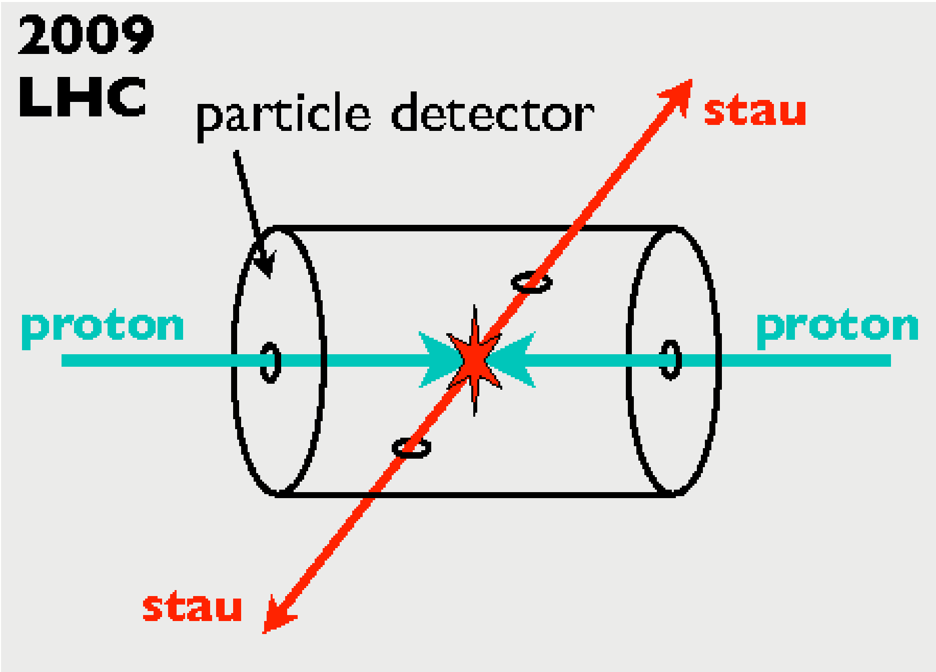


disfavored by cosmological constraints

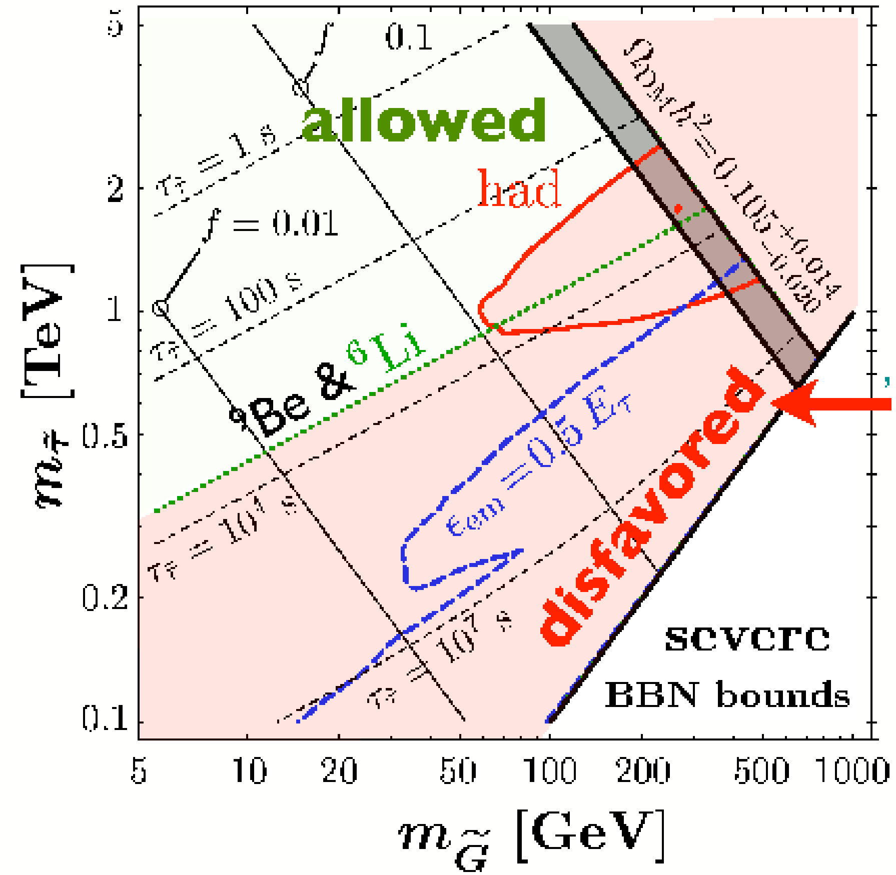
see also [FDS, hep-ph/0611027]

Why are the cosmological constraints so important?

Gravitino DM @ LHC ⟵ Stau NLSP



The signal:
jets + leptons
+ 2 “stable” charged particles



Cosmological Constraints

[FDS, ’06, FDS, hep-ph/0611027]
[Pradler, FDS, arXiv:0710.4548]
[Pospelov, Pradler, FDS, arXiv:0807.4287]

Very different from the large E_T^{miss} signal of Neutralino DM

The gravitino can become a problem ...

Upper Limits on the Reheating Temperature

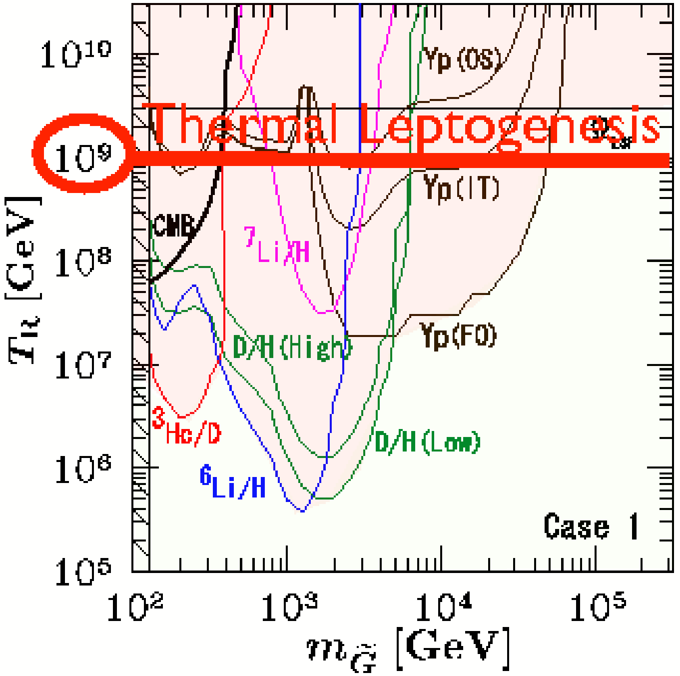
Neutralino LSP

Late Decaying Gravitinos from Thermal Production

$$Y_{\widetilde{G}}^{\rm TP}(T_{\rm low}) \equiv \frac{n_{\widetilde{G}}^{\rm TP}(T_{\rm low})}{s(T_{\rm low})} \approx \frac{C_{\widetilde{G}}(T_{\rm R})}{s(T_{\rm R})H(T_{\rm R})}$$
$$= \sum_{i=1}^{3} y_i g_i^2(T_{\rm R}) \left(1 + \frac{M_i^2(T_{\rm R})}{3m_{\widetilde{G}}^2}\right) \times \ln\left(\frac{k_i}{g_i(T_{\rm R})}\right)\left(\frac{T_{\rm R}}{10^{10}\,{\rm GeV}}\right),$$

[Pradler, FDS, '07]

Unstable Gravitino



BBN constraints

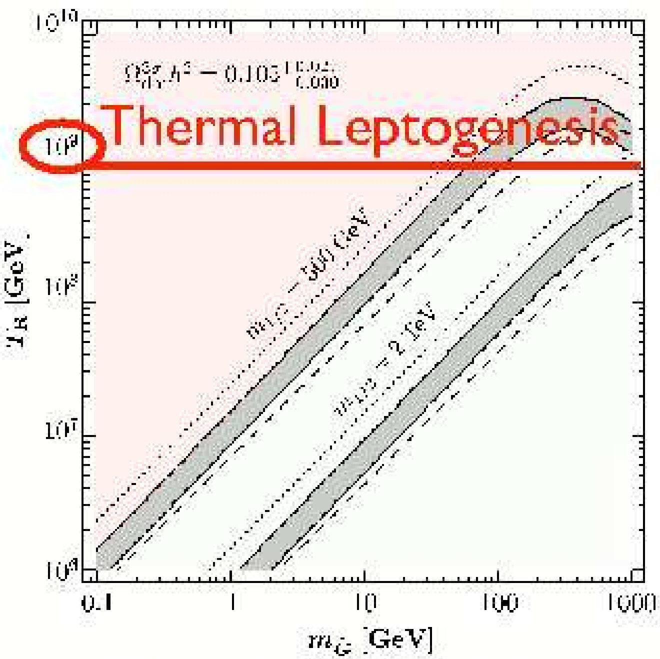
+ Ω_{DM} constraint for neutralino DM

[Kohri, Moroi, Yotsuyanagi, '05]

Thermal Leptogenesis requires T >10^9 GeV

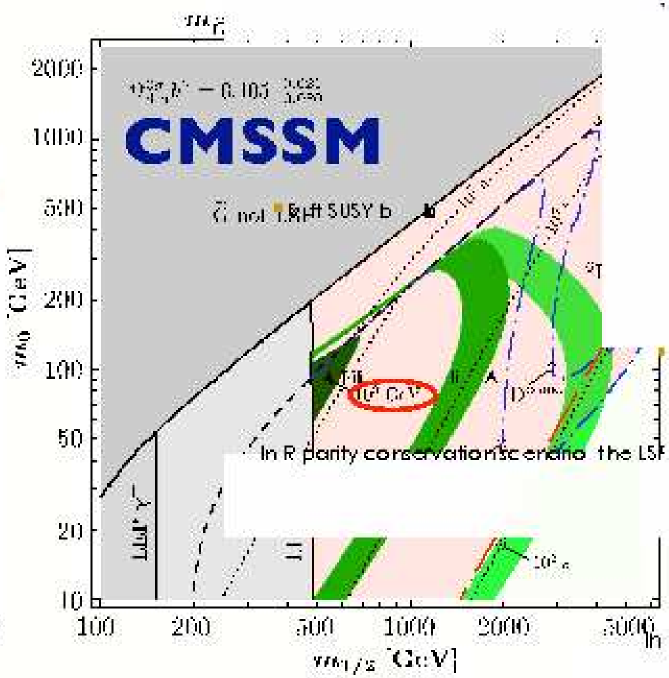
Upper Limits on the Reheating Temperature

Stable Gravitino



Ω_{DM} constraint for gravitino DM

[Pradler, FDS, '07]

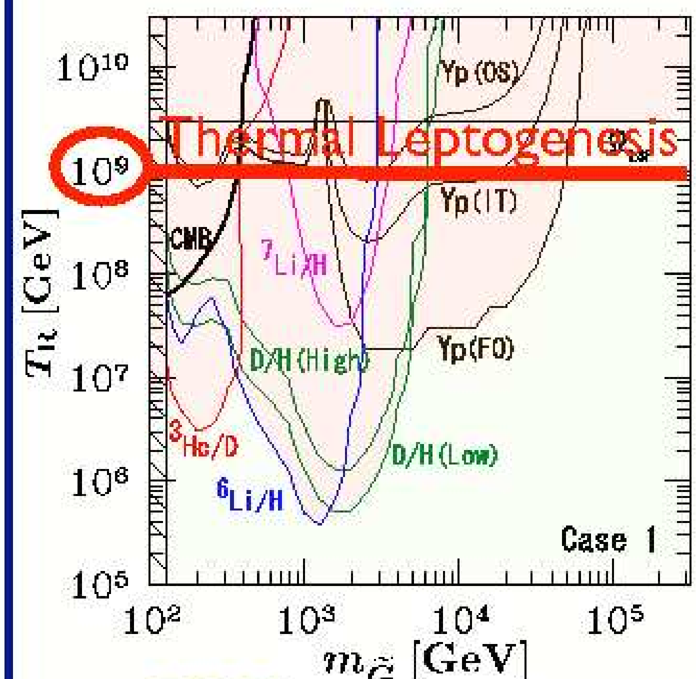


+ BBN constraints

$$T_R \lesssim 4.9 \times 10^7 \text{ GeV} \left(\frac{m_{\widetilde{G}}}{10 \text{ GeV}}\right)^{1/5}$$

[Pradler, FDS, arXiv:0710.2213]

Unstable Gravitino



BBN constraints

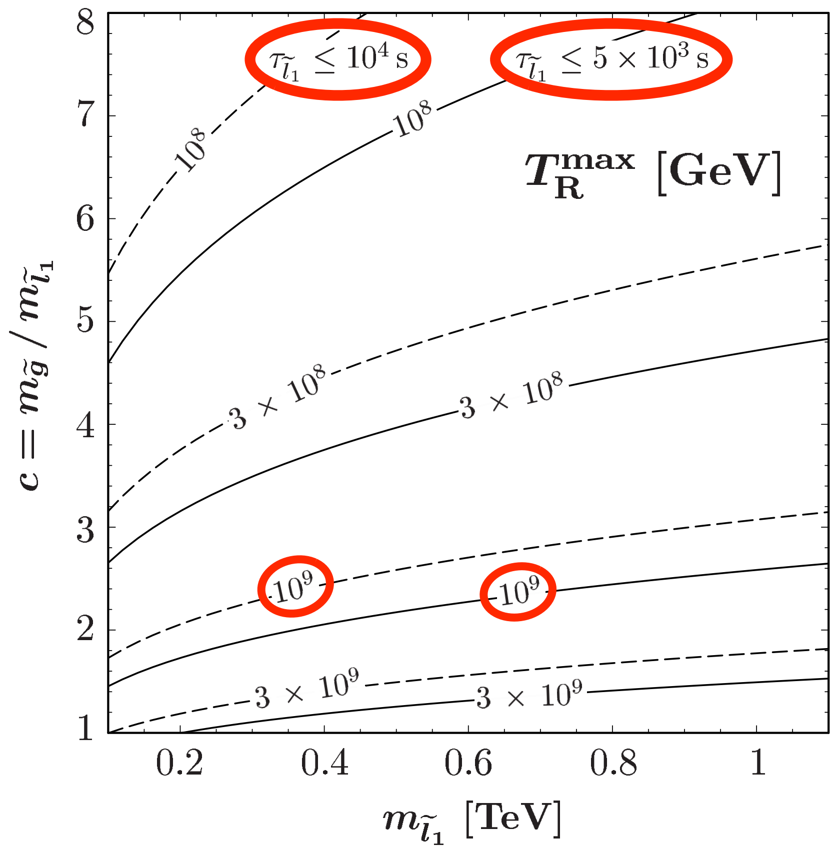
+ Ω_{DM} constraint for neutralino DM

[Kohri, Moroi, Yotsuyanagi, '05]

Thermal Leptogenesis requires T > 10^9 GeV

[FDS, '08]

Probing T_R at Colliders and with BBN



Collider Prediction of Thermal Leptogenesis

Dark Matter

↓

Axino LSP

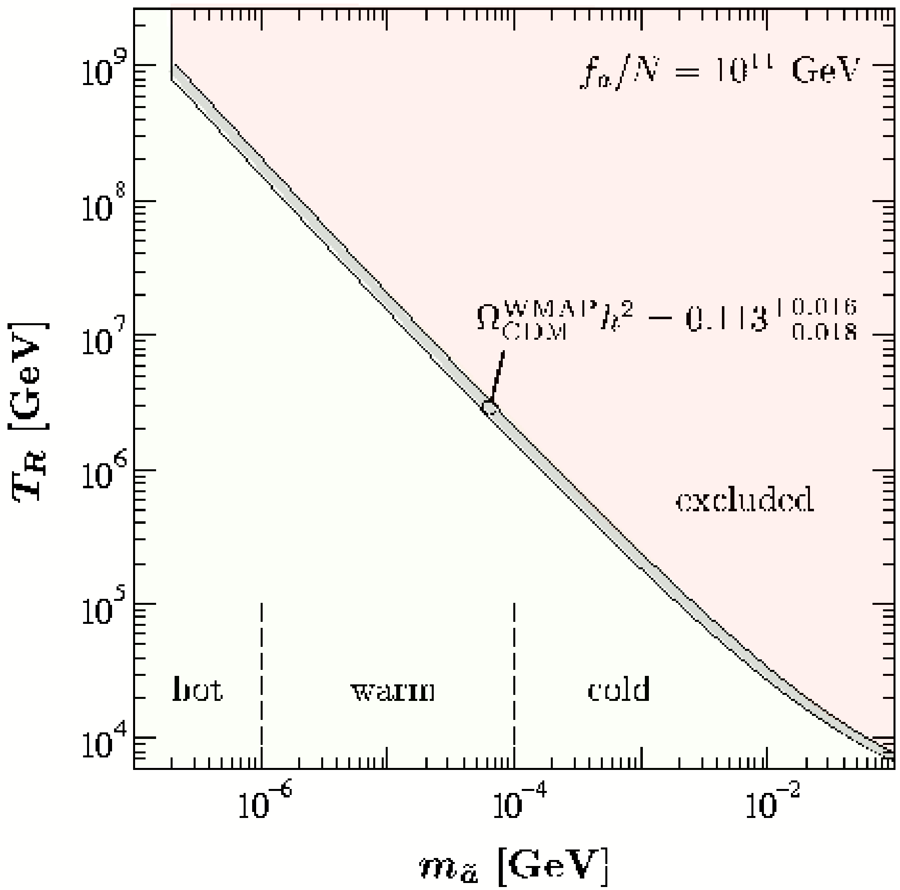
Supersymmetric Dark Matter Candiates

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

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\widetilde{\chi}^0_1$	g, g'	WIMP	← 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.	← cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	← 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.	← cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	← warm	+ $\widetilde{\tau}$ collection
	$f_a \gtrsim 10^9$ GeV	...	BBN	+ $\widetilde{\tau}$ decay analysis: $m_{\widetilde{a}}$, f_a

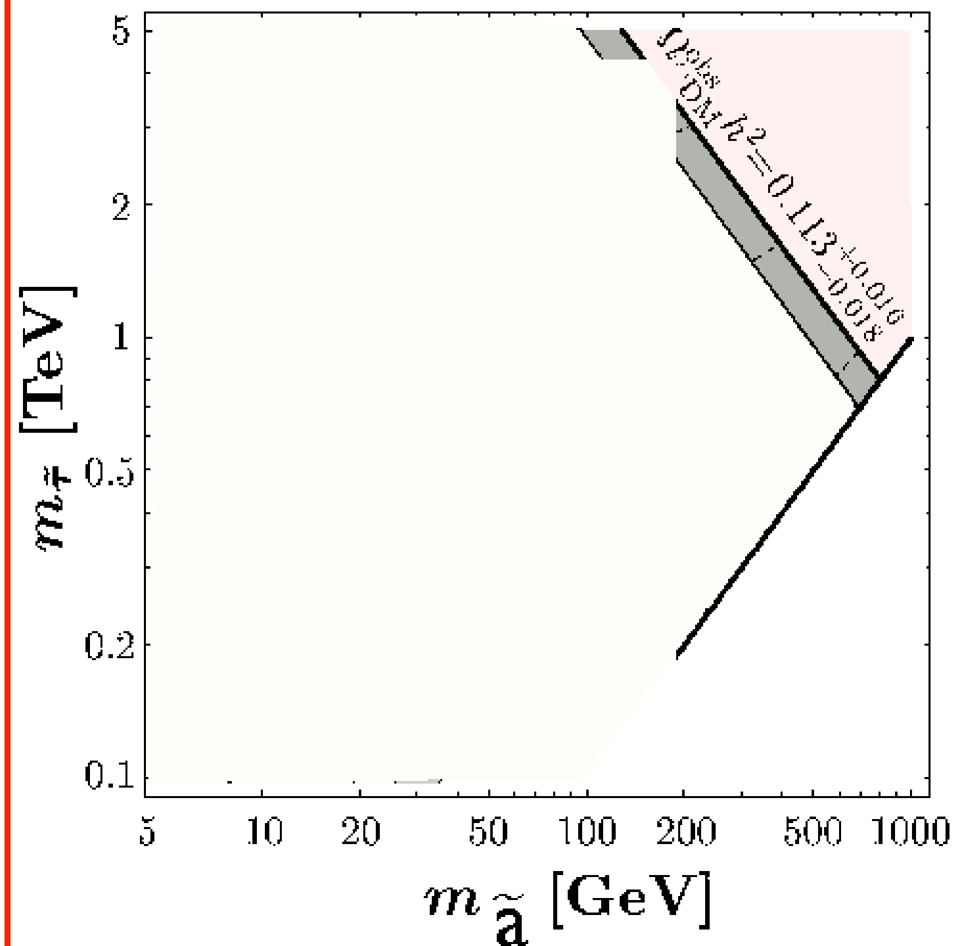
Thermal $\widetilde{a}$ Production



[Brandenburg, FDS, '04]

see also [Covi et al., '01]

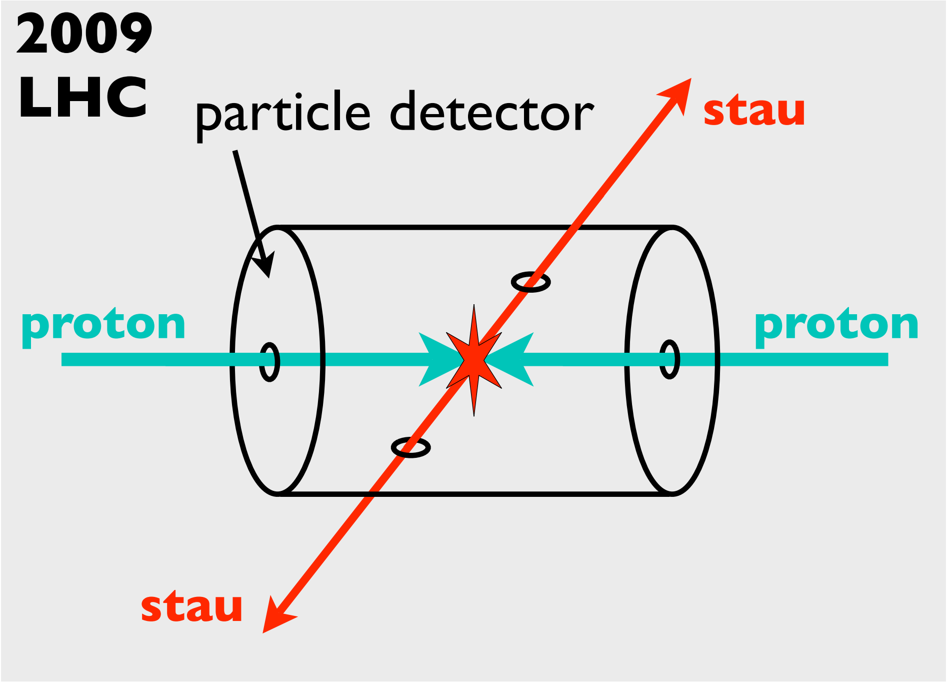
$\widetilde{\tau}$ NLSP $\longrightarrow$ $\widetilde{a} + \tau$

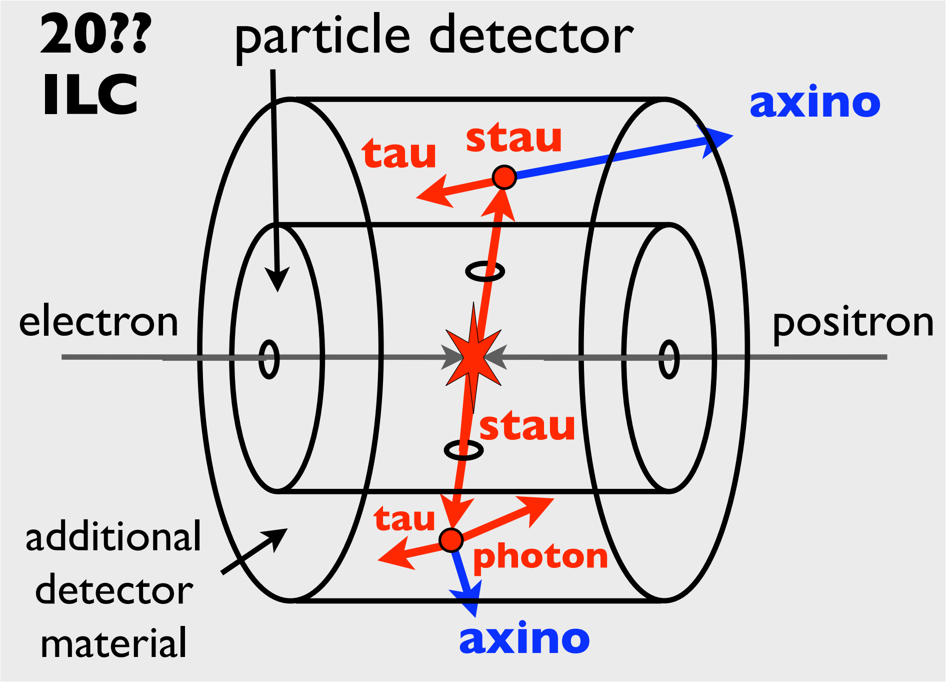


identical to the gravitino case

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, ...)
	$M_{\mathrm{W}} \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M}_{\mathrm{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	$+\ \widetilde{\tau}$ collection
	$\mathrm{M}_{\mathrm{Pl}} = 2.44 \times 10^{18}$ 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: $m_{\widetilde{a}}$, f_a


2009
LHC
particle detector
stau
proton
proton
stau


20??
ILC
particle detector
axino
tau
stau
electron
positron
stau
tau
photon
additional
detector
material
axino

Can one distinguish between

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

experimentally?

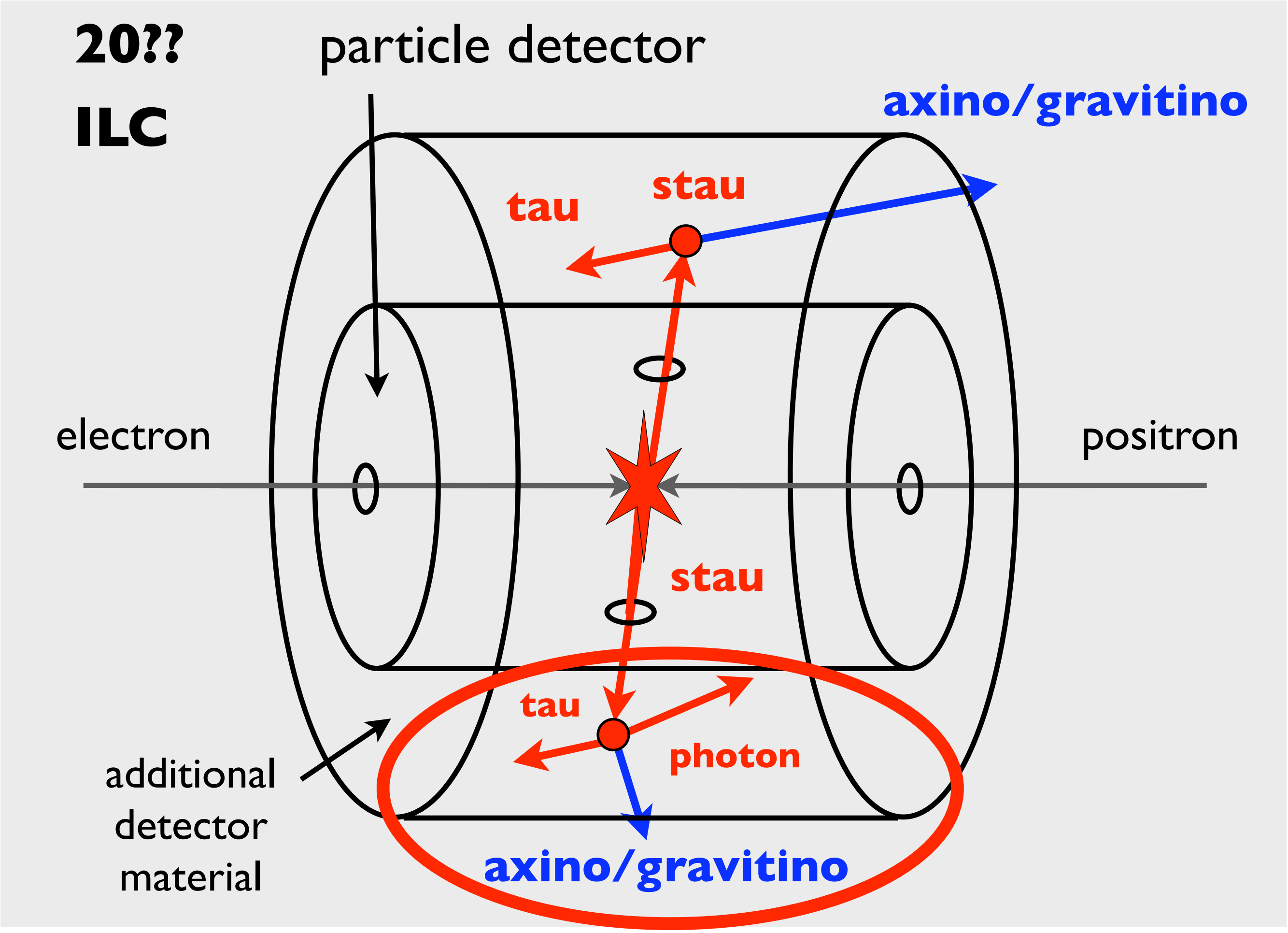
[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

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

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

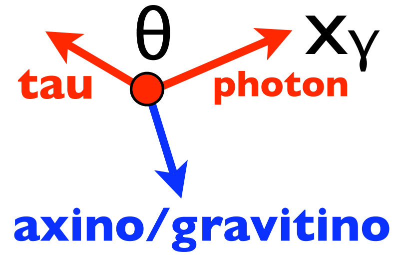
$\tilde{a} =$ LSP	$\widetilde{G} =$ LSP
$\tau_{\widetilde{\tau}}^{\tilde{a}\,\mathrm{LSP}} \longleftarrow m_{\widetilde{\tau}}, m_{\widetilde{B}}, m_{\tilde{a}}, f_a$	$\tau_{\widetilde{\tau}}^{\widetilde{G}\,\mathrm{LSP}} \longleftarrow m_{\widetilde{\tau}}, m_{\widetilde{B}}, m_{\widetilde{G}}$
$\mathcal{O}(0.01\ \mathrm{sec}) \lesssim \tau_{\widetilde{\tau}}^{\tilde{a}\,\mathrm{LSP}} \lesssim \mathcal{O}(10\ \mathrm{h})$	$\mathcal{O}(10^{-8}\ \mathrm{sec}) \lesssim \tau_{\widetilde{\tau}}^{\widetilde{G}\,\mathrm{LSP}} \lesssim \mathcal{O}(15\ \mathrm{y})$
$\uparrow$ $f_a \sim 10^9$ GeV (lower bound); $\uparrow$ $f_a \sim 10^{12}$ GeV (upper bound)	$\uparrow$ $m_{\widetilde{G}} \sim 1$ keV (lower bound); $\uparrow$ $m_{\widetilde{G}} \sim 50$ GeV (upper bound)

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

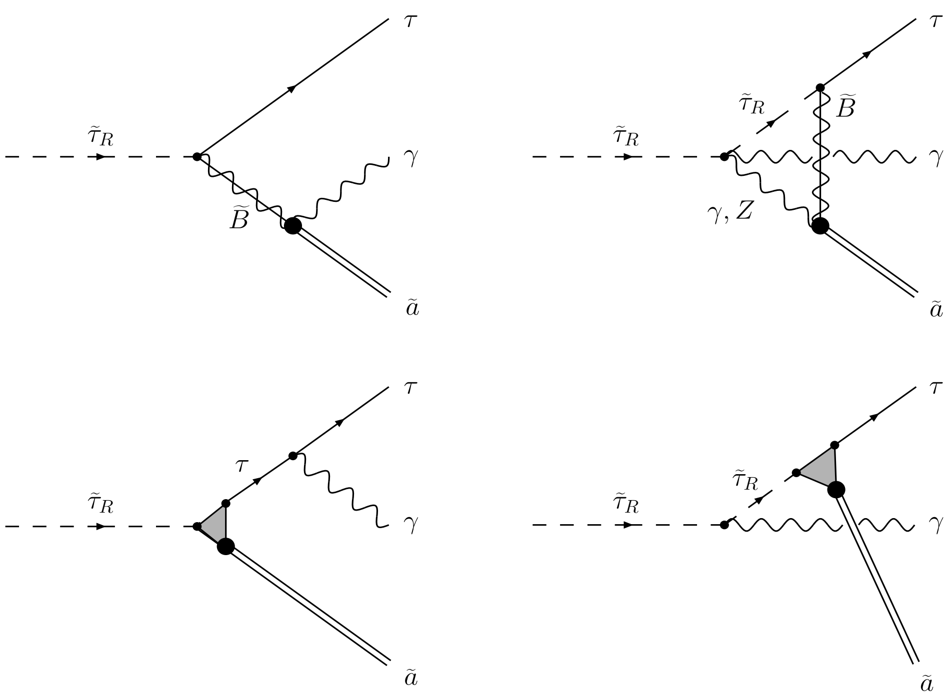


3-Body Decays

The 3-Body Decays

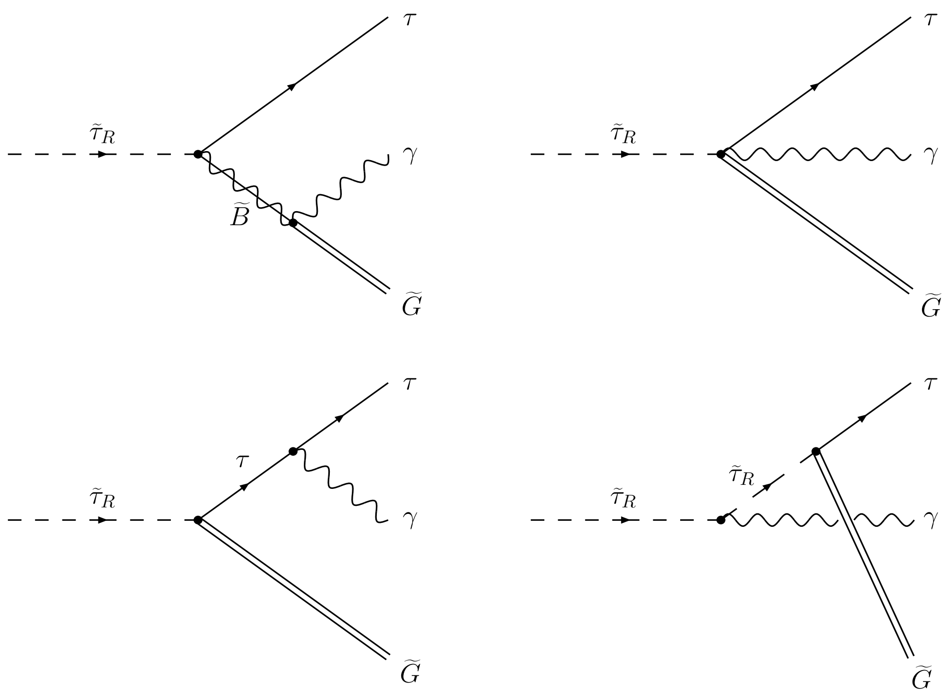


$$\tilde{a} = \text{LSP:} \quad \widetilde{\tau}_R \to \tau + \gamma + \tilde{a}$$



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

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



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

$\tilde{a}$ LSP $\longrightarrow$ The Differential Decay Rate for $\widetilde{\tau}_R \longrightarrow \tau + \gamma + \tilde{a}$

$$\frac{d^2\Gamma(\widetilde{\tau}_{\rm R} \to \tau\,\gamma\,\widetilde{a})}{dx_\gamma\, d\cos\theta} = \frac{m_{\widetilde{\tau}}}{512\pi^3}\, \frac{x_\gamma(1 - A_{\widetilde{a}} - x_\gamma)}{[1 - (x_\gamma/2)(1-\cos\theta)]^2} \sum_{\rm spins} |\mathcal{M}(\widetilde{\tau}_{\rm R} \to \tau\,\gamma\,\widetilde{a})|^2\ ,$$

where

$$\sum_{\rm spins} |\mathcal{M}(\widetilde{\tau}_{\rm R} \to \tau\,\gamma\,\widetilde{a})|^2 \quad = \quad \frac{\alpha^3\, C_{\rm aYY}^2}{\pi \cos^4\theta_W}\, \frac{m_{\widetilde{\tau}}^2}{f_a^2}\, F_{\rm diff}^{(\widetilde{a})}(x_\gamma, \cos\theta, A_{\widetilde{a}}, A_{\widetilde{B}})\ ,$$

with

$$x_\gamma \equiv \frac{2E_\gamma}{m_{\widetilde{\tau}}}\ , \qquad A_{\widetilde{a}} \equiv \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\ , \qquad A_{\widetilde{B}} \equiv \frac{m_{\widetilde{B}}^2}{m_{\widetilde{\tau}}^2}\ ,$$

and

$$F_{\rm diff}^{(\widetilde{a})}(x_\gamma, \cos\theta, A_{\widetilde{a}}, A_{\widetilde{B}}) = \frac{x_\gamma^2(1 - A_{\widetilde{a}} - x_\gamma)[1 + \cos\theta + A_{\widetilde{a}}(1-\cos\theta)][1 + \cos\theta + A_{\widetilde{B}}(1-\cos\theta)}{\{x_\gamma(1+\cos\theta) + 2A_{\widetilde{a}} - A_{\widetilde{B}}[2 - x_\gamma(1-\cos\theta)]\}^2}$$

$$+\ \frac{3\alpha}{\pi\cos^2\theta_W}\,\xi\log\left(\frac{f_a}{m}\right)\left\{\frac{\sqrt{A_{\widetilde{a}}A_{\widetilde{B}}}(1+\cos\theta)(1 - A_{\widetilde{a}} - x_\gamma)}{x_\gamma(1+\cos\theta) + 2A_{\widetilde{a}} - A_{\widetilde{B}}[2 - x_\gamma(1-\cos\theta)]}\right.$$

$$\left. +\ \frac{A_{\widetilde{B}}\,[(1+\cos\theta)(1-A_{\widetilde{a}}) + A_{\widetilde{a}}x_\gamma(1-\cos\theta)]}{x_\gamma(1+\cos\theta) + 2A_{\widetilde{a}} - A_{\widetilde{B}}[2 - x_\gamma(1-\cos\theta)]}\right\}$$

$$+\ \frac{9\alpha^2}{4\pi^2\cos^4\theta_W}\,\xi^2\log^2\left(\frac{f_a}{m}\right) A_{\widetilde{B}}\left\{\frac{1+\cos\theta + A_{\widetilde{a}}(1-\cos\theta)}{(1-\cos\theta)(1-A_{\widetilde{a}}-x_\gamma)} + \frac{2(1+\cos\theta)(1-A_{\widetilde{a}})}{x_\gamma^2(1-\cos\theta)}\right.$$

$\widetilde{G}$ LSP $\rightarrow$ Diff. Decay Rate $\widetilde{\tau}_R \rightarrow \tau + \gamma + \widetilde{G}$

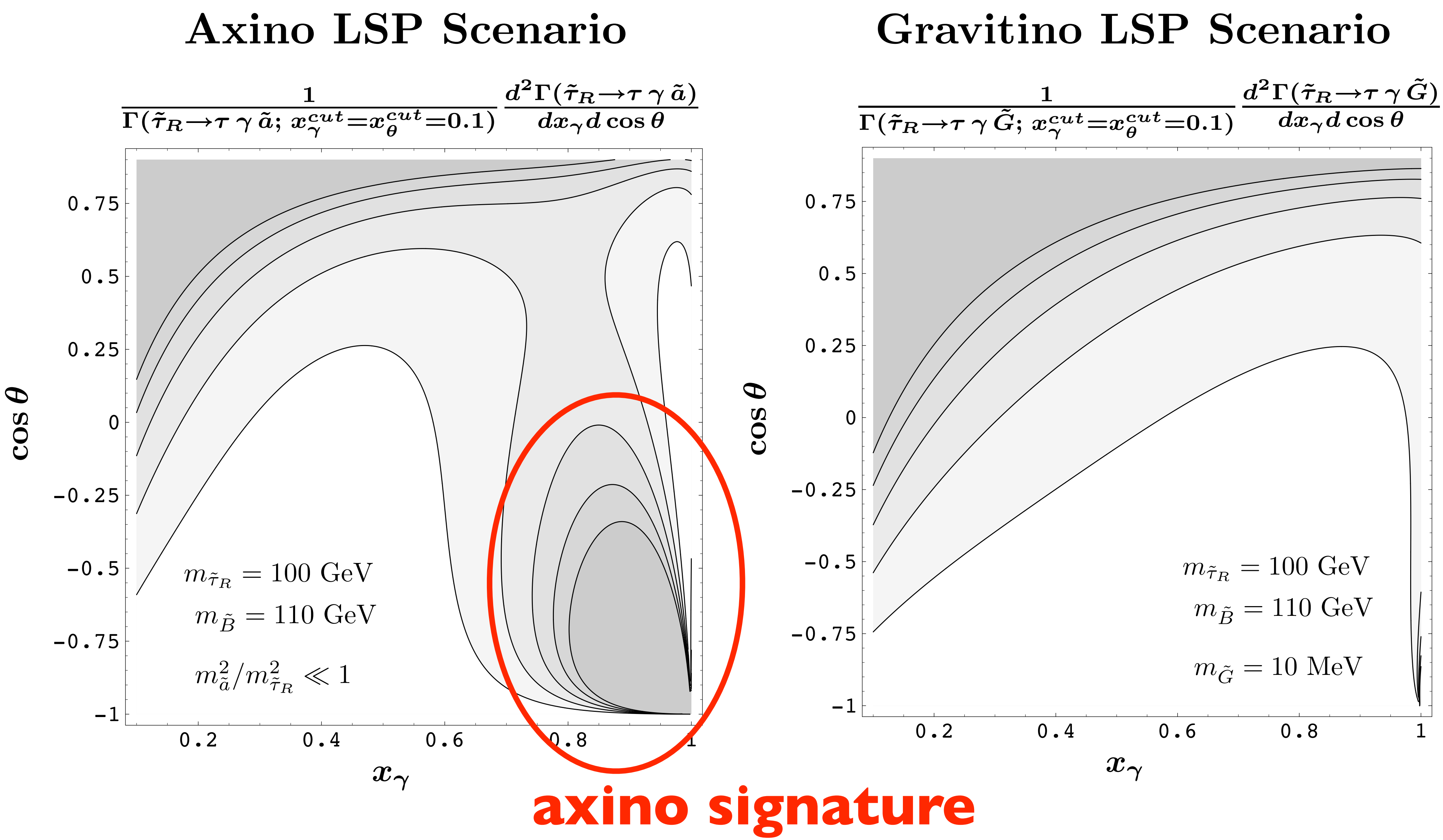
$$\frac{d^2\Gamma(\tilde{\tau}_R \to \tau\,\gamma\,\tilde{G})}{dx_\gamma\, d\cos\theta} = \frac{m_{\tilde{\tau}}}{512\pi^3} \frac{x_\gamma(1 - A_{\widetilde{G}} - x_\gamma)}{[1 - (x_\gamma/2)(1-\cos\theta)]^2} \sum_{\rm spins} |\mathcal{M}(\tilde{\tau}_R \to \tau\,\gamma\,\tilde{G})|^2,$$

where $\sum_{\rm spins} |\mathcal{M}(\tilde{\tau}_R \to \tau\,\gamma\,\tilde{G})|^2 = \frac{8\pi\alpha}{3} \frac{m_{\tilde{\tau}}^2}{M_{\rm Pl}^2 A_{\widetilde{G}}} F^{(\widetilde{G})}_{\rm diff}(x_\gamma, \cos\theta, A_{\widetilde{G}}, A_{\widetilde{B}})$

with $x_\gamma \equiv \frac{2E_\gamma}{m_{\tilde{\tau}}}$, $A_{\tilde{a}} \equiv \frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}}^2}$, $A_{\widetilde{B}} \equiv \frac{m_{\widetilde{B}}^2}{m_{\tilde{\tau}}^2}$, $A_{\widetilde{G}} \equiv \frac{m_{\widetilde{G}}^2}{m_{\tilde{\tau}}^2}$,

$$\begin{aligned}
F^{(\widetilde{G})}_{\rm diff}(x_\gamma, \cos\theta, A_{\widetilde{G}}, A_{\widetilde{B}}) &= -3A_{\widetilde{G}}^2 - 7x_\gamma A_{\widetilde{G}} + \frac{2(2-5\cos\theta)A_{\widetilde{G}}}{1-\cos\theta} - \frac{x_\gamma(1+\cos\theta)}{(1-\cos\theta)} \\
&- \frac{(1+\cos\theta)(3+\cos\theta)}{(1-\cos\theta)^2} + \frac{2(1-A_{\widetilde{G}})^3(1+\cos\theta)}{x_\gamma^2(1-\cos\theta)} + \frac{A_{\widetilde{G}}(1-A_{\widetilde{G}})^2}{1-A_{\widetilde{G}}-x_\gamma} \\
&+ \frac{(1-A_{\widetilde{G}})^2(1+\cos\theta)}{(1-A_{\widetilde{G}}-x_\gamma)(1-\cos\theta)} - \frac{4\left[1+\cos\theta+A_{\widetilde{G}}(1-\cos\theta)\right]^2}{[2-x_\gamma(1-\cos\theta)]^2\,(1-\cos\theta)^2} \\
&+ \frac{2\left\{3+\cos\theta\left[4-\cos\theta+2A_{\widetilde{G}}(1-\cos\theta)\right]\right\}\left[1+\cos\theta+A_{\widetilde{G}}(1-\cos\theta)\right]}{[2-x_\gamma(1-\cos\theta)]\,(1-\cos\theta)^2} \\
&+2(1-A_{\widetilde{G}}-x_\gamma)\left\{\frac{1+x_\gamma-x_\gamma^2-2A_{\widetilde{G}}(1+3x_\gamma-2x_\gamma^2)+A_{\widetilde{G}}^2(1+5x_\gamma)}{x_\gamma(1-A_{\widetilde{B}})(1-A_{\widetilde{G}}-x_\gamma)}\right. \\
&- \frac{2\left[1+x_\gamma(2+A_{\widetilde{B}})-x_\gamma^2+2A_{\widetilde{G}}(1-x_\gamma)\right]}{x_\gamma\,[2-x_\gamma(1-\cos\theta)]} + \frac{4(1-A_{\widetilde{G}}-x_\gamma)}{[2-x_\gamma(1-\cos\theta)]^2} \\
&- \frac{\sqrt{A_{\widetilde{B}}A_{\widetilde{G}}}\left[2(1+\cos\theta)(1-A_{\widetilde{G}})+3x_\gamma A_{\widetilde{G}}(1-\cos\theta)\right]}{x_\gamma(1+\cos\theta)+2(A_{\widetilde{G}}-A_{\widetilde{B}})+A_{\widetilde{B}}x_\gamma(1-\cos\theta)} \\
&- \frac{2\left\{A_{\widetilde{G}}^2\left[-3-6x_\gamma+A_{\widetilde{B}}(2+x_\gamma)\right]+4A_{\widetilde{B}}A_{\widetilde{G}}(1+x_\gamma-x_\gamma^2)\right\}}{x_\gamma(1-A_{\widetilde{B}})\left[x_\gamma(1+\cos\theta)+2(A_{\widetilde{G}}-A_{\widetilde{B}})+A_{\widetilde{B}}x_\gamma(1-\cos\theta)\right]} \\
&\left.+ \frac{2A_{\widetilde{B}}^2\left[(1-x_\gamma)(1+2A_{\widetilde{G}}+x_\gamma)+x_\gamma A_{\widetilde{B}}\right]}{x_\gamma(1-A_{\widetilde{B}})\left[x_\gamma(1+\cos\theta)+2(A_{\widetilde{G}}-A_{\widetilde{B}})+A_{\widetilde{B}}x_\gamma(1-\cos\theta)\right]}\right\} \\
&+(1-A_{\widetilde{G}}-x_\gamma)\left\{\frac{(-1+3A_{\widetilde{G}})(1-A_{\widetilde{G}})}{(1-A_{\widetilde{B}})} + \frac{2\left[2-x_\gamma-2(A_{\widetilde{G}}-A_{\widetilde{B}})\right]}{2-x_\gamma(1-\cos\theta)}\right. \\
&- \frac{4(1-A_{\widetilde{G}}-x_\gamma)}{[2-x_\gamma(1-\cos\theta)]^2} - \frac{2(A_{\widetilde{G}}-A_{\widetilde{B}})\left[3A_{\widetilde{G}}(2-2A_{\widetilde{G}}-x_\gamma)+A_{\widetilde{B}}(2-2A_{\widetilde{B}}+x_\gamma)\right]}{(1-A_{\widetilde{B}})\left[x_\gamma(1+\cos\theta)+2(A_{\widetilde{G}}-A_{\widetilde{B}})+A_{\widetilde{B}}x_\gamma(1-\cos\theta)\right]} \\
&\left.+ \frac{4(1-A_{\widetilde{G}}-x_\gamma)(3A_{\widetilde{G}}+A_{\widetilde{B}})(A_{\widetilde{G}}-A_{\widetilde{B}})^2}{(1-A_{\widetilde{B}})\left[x_\gamma(1+\cos\theta)+2(A_{\widetilde{G}}-A_{\widetilde{B}})+A_{\widetilde{B}}x_\gamma(1-\cos\theta)\right]^2}\right\}
\end{aligned}$$

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



Differential Distribution of the Visible Decay Products

For prospects of this distinction

between axino LSP and gravitino LSP

at the LHC

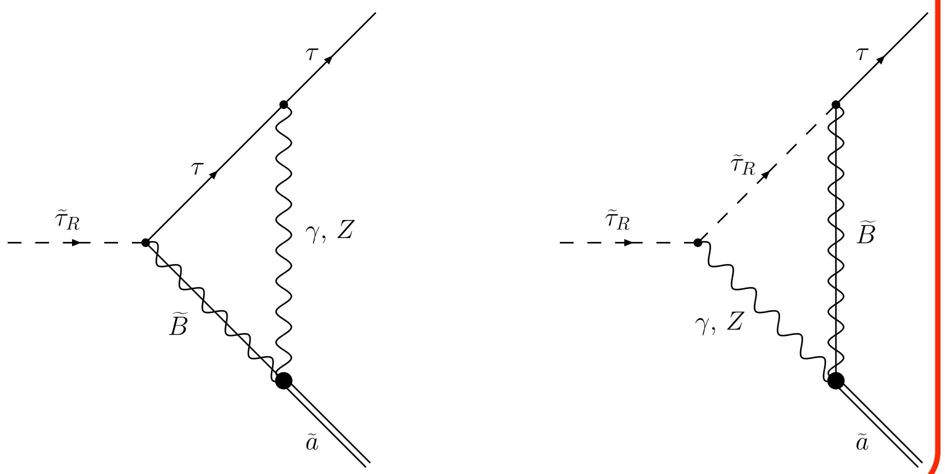
↓

[Hamaguchi, Nojiri, de Roeck, ’07]

[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 & $\widetilde{\chi}^0 \simeq \widetilde{B}$

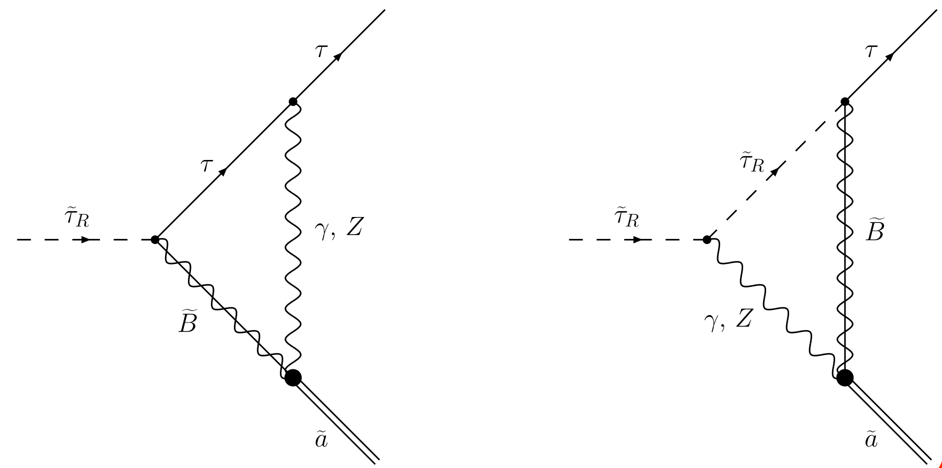
- 2-Body Decay $\widetilde{\tau}_R \rightarrow \tau + \tilde{a}$

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

$\tilde{a}$ LSP $\rightarrow$ 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



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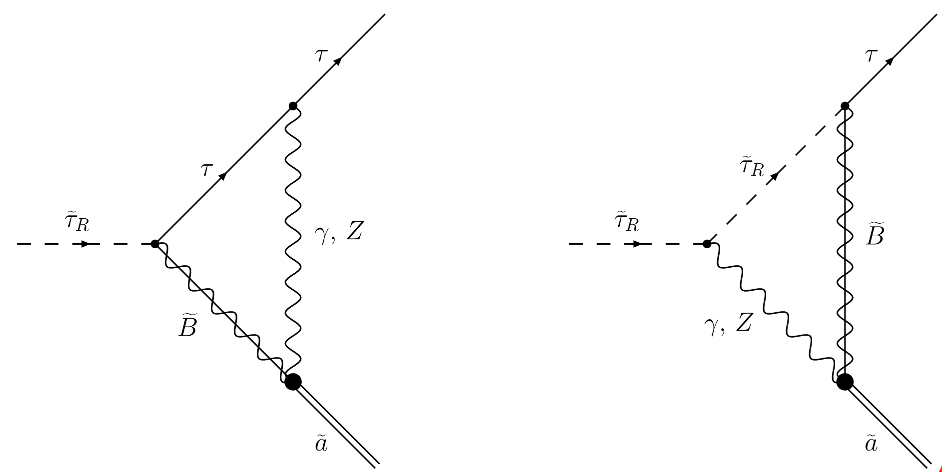
$$\Gamma(\widetilde{\tau}_{\rm R} \rightarrow \tau \widetilde{a}) \simeq \xi^2 \, (25\,\mathrm{sec})^{-1} C_{\rm aYY}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right)\left(\frac{m_{\widetilde{\tau}}}{100\,\mathrm{GeV}}\right)\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^2\left(\frac{m_{\widetilde{B}}}{100\,\mathrm{GeV}}\right)^2$$

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

$\tilde{a}$ 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 $\widetilde{\tau}_R \rightarrow \tau + \tilde{a}$

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

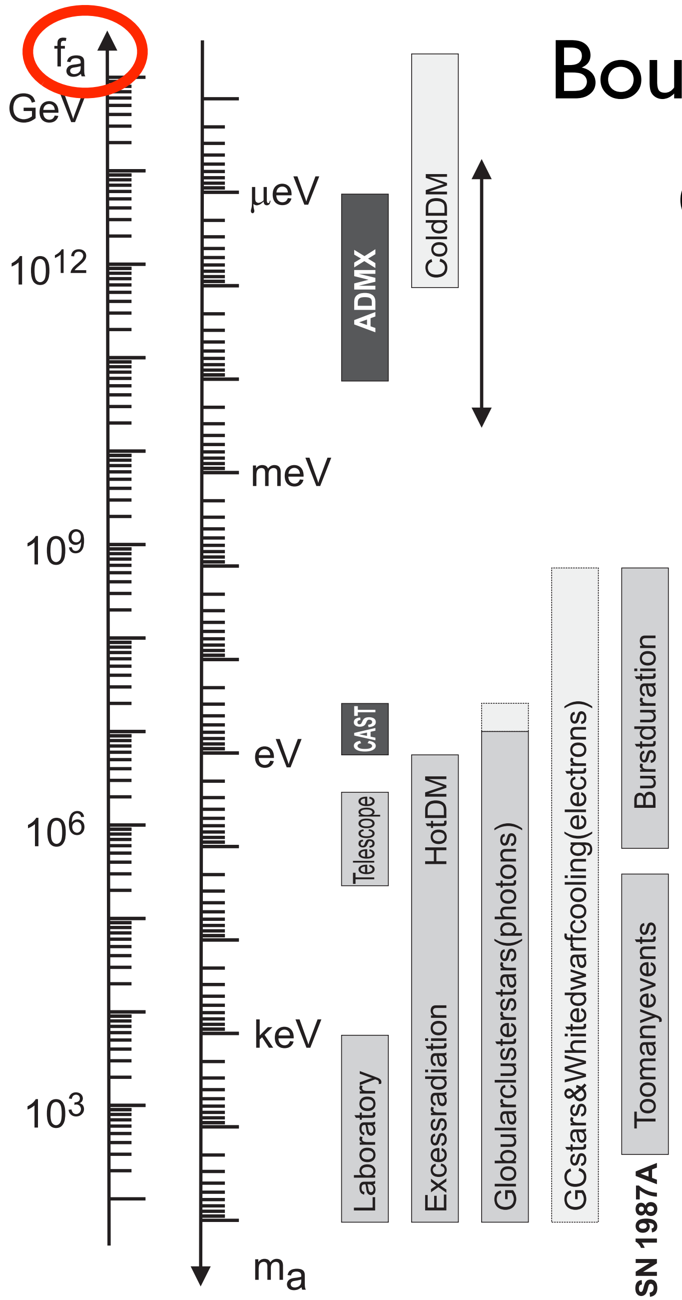
- Peccei–Quinn Scale f_a $\longleftarrow$ NLSP Lifetime $\tau_{\widetilde{\tau}} \approx 1/\Gamma(\widetilde{\tau}_R \rightarrow \tau\, \tilde{a})$

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

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

[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

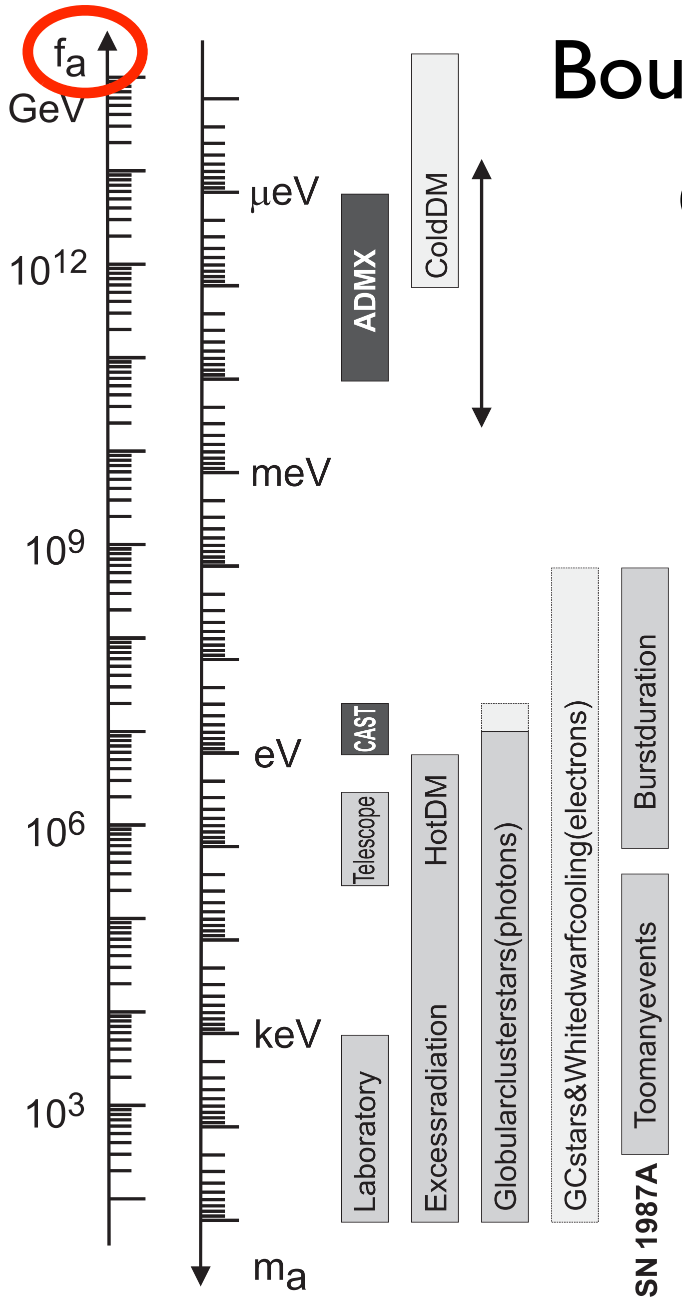
Cosmological Axion Bounds

Astrophysical Axion Bounds

Is the value of the Peccei-Quinn scale inferred from axino searches consistent with astrophysical axion bounds and results from axion searches?

[Raffelt, '06]

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

Cosmological Axion Bounds

Astrophysical Axion Bounds

Agreement between Axion & Axino Searches

↓

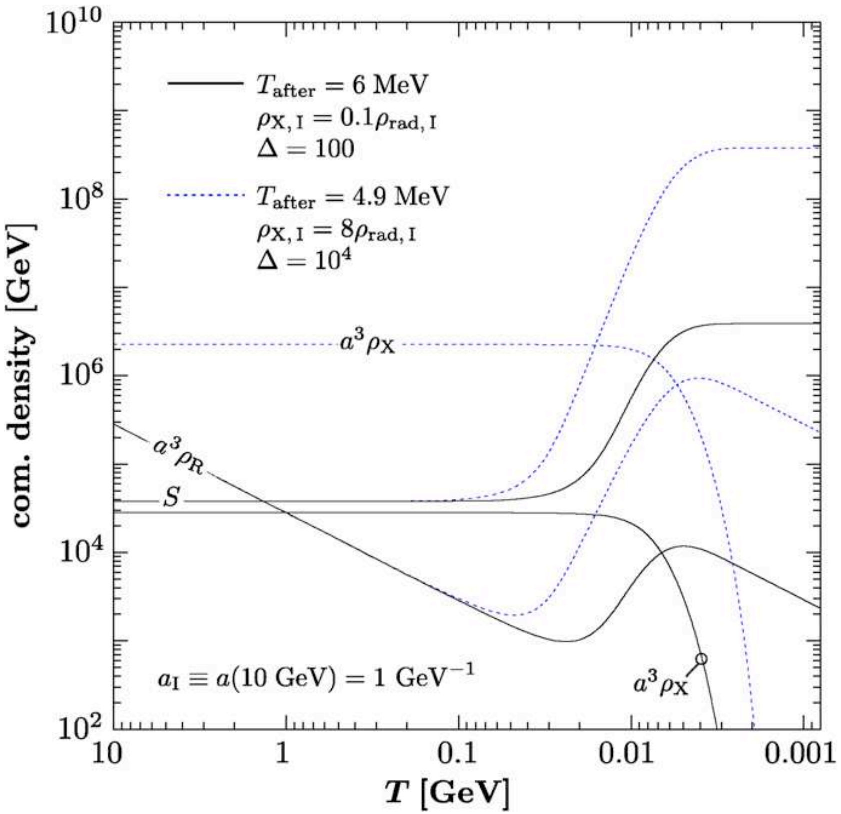
Strong Hint for the Axino LSP

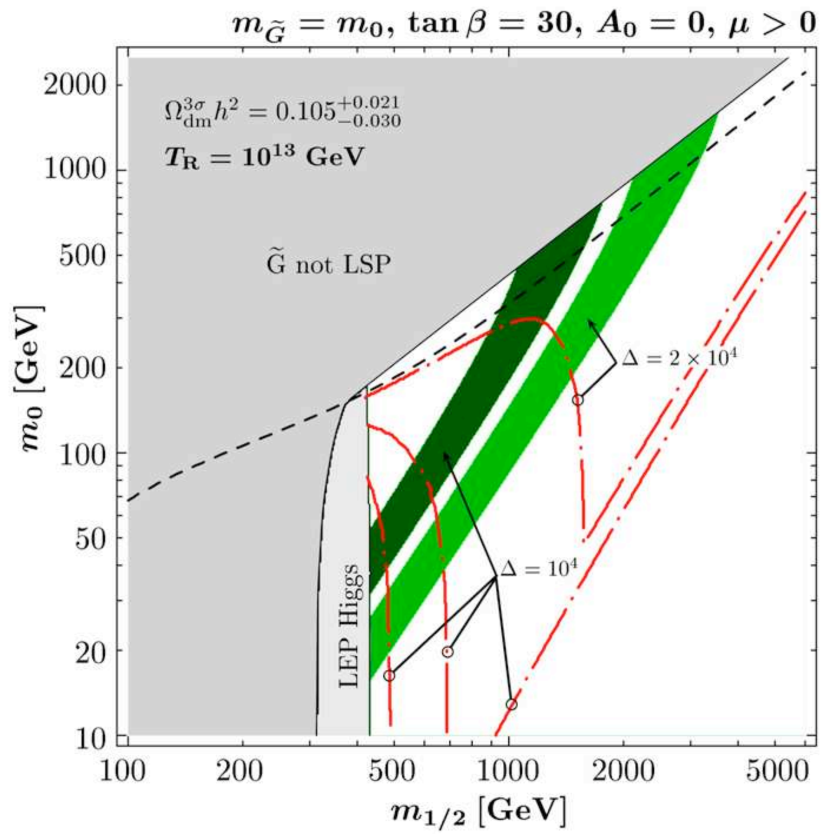
Supersymmetric Dark Matter Candidates

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, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M}_{\mathrm{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	+ $\widetilde{\tau}$ collection
	$\mathrm{M}_{\mathrm{Pl}} = 2.44 \times 10^{18}$ 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

Can one get rid of the Gravitino problem?

Late-Time Entropy Production





$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_\phi \rho_\phi,$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi,$$

$$\frac{dS}{dt} = \frac{\Gamma_X \rho_X a^3}{T} = \left(\frac{2\pi^2}{45} g_*\right)^{1/3} \Gamma_X \rho_X a^4 S^{-1/3}$$

$$Y^{\rm TP}_{\widetilde{G}}(T_0) = \frac{1}{\Delta} Y^{\rm TP}_{\widetilde{G}}(T_{\rm low}),$$

$$Y_{\rm NLSP}(T_0) = \frac{1}{\Delta} Y_{\rm NLSP}(T_{\rm low})$$

$$\eta(T_{\rm after}) = \frac{1}{\Delta}\eta(T_{\rm before}).$$

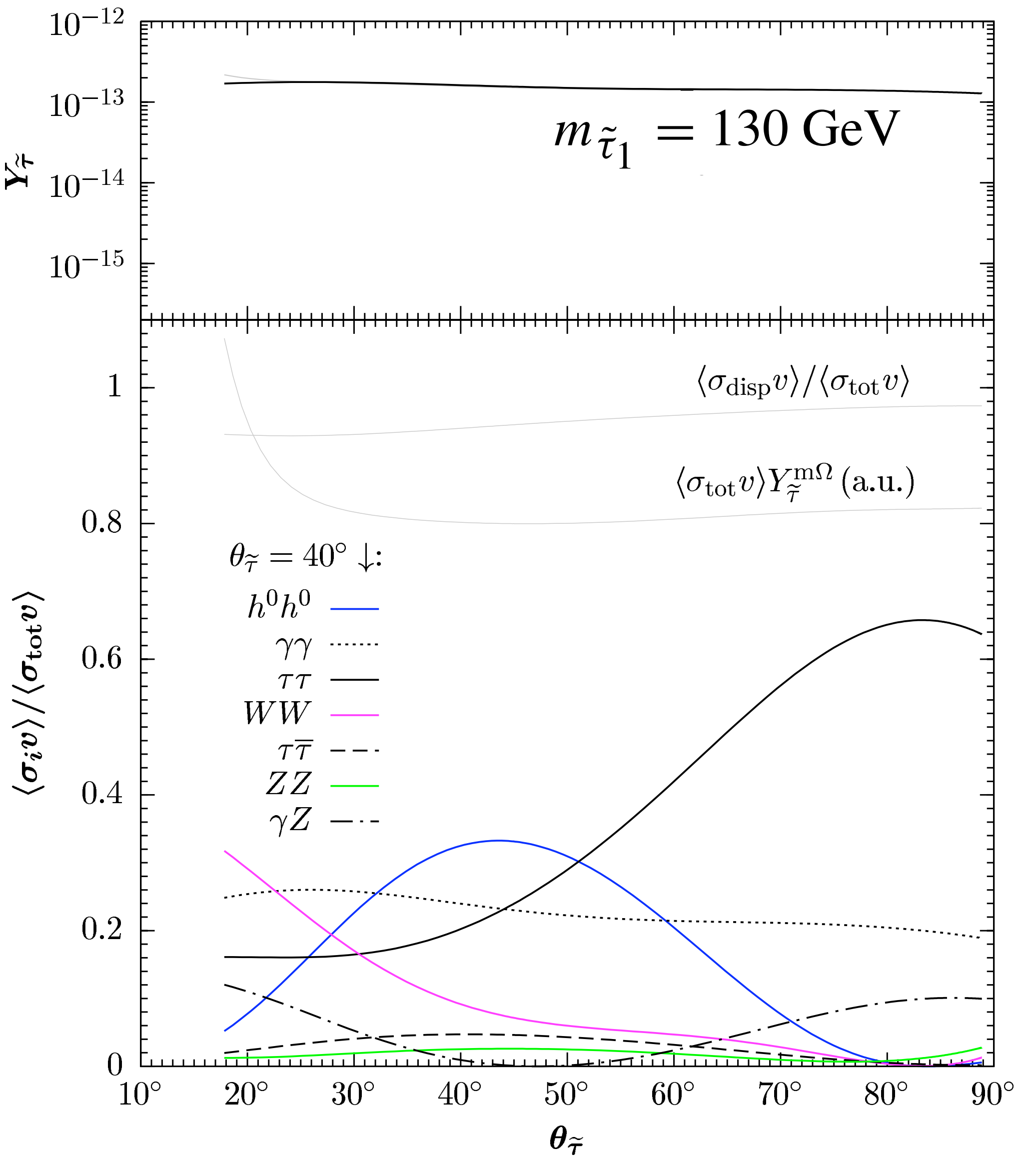
Thermal Relic Stau Abundance

$\tilde{\tau}_1^{(*)}\tilde{\tau}_1^{(*)} \to$	Final state	s-channel	$t(u)$-channel	Contact
	$\tau\tau\ (\bar{\tau}\bar{\tau})$	–	$\tilde{\chi}^0_{1,\ldots,4}$	–
$\tilde{\tau}_1\tilde{\tau}_1^* \to$	Final state X[a]	s-channel	$t(u)$-channel	Contact
	$\mu\bar{\mu}$, $e\bar{e}$	h^0, H^0, γ, Z	–	–
	$\tau\bar{\tau}$	h^0, H^0, γ, Z	$\tilde{\chi}^0_{1,\ldots,4}$	–
	$\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$	Z	–	–
	$\nu_\tau\bar{\nu}_\tau$	Z	$\tilde{\chi}^\pm_{1,2}$	–
	$q_k\bar{q}_k$	h^0, H^0, γ, Z	–	–
	$\gamma\gamma$, γZ	–	$\tilde{\tau}_1$	✓
	ZZ	h^0, H^0	$\tilde{\tau}_{1,2}$	✓
	W^+W^-	h^0, H^0, γ, Z	$\tilde{\nu}_\tau$	✓
	γh^0, γH^0	–	$\tilde{\tau}_1$	–
	Zh^0, ZH^0	Z	$\tilde{\tau}_{1,2}$	–
	ZA^0	h^0, H^0	$\tilde{\tau}_2$	–
	$W^\mp H^\pm$	h^0, H^0	$\tilde{\nu}_\tau$	–
	h^0h^0, h^0H^0, H^0H^0	h^0, H^0	$\tilde{\tau}_{1,2}$	✓
	A^0A^0	h^0, H^0	$\tilde{\tau}_2$	✓
	h^0A^0, H^0A^0	Z	$\tilde{\tau}_2$	–
	H^+H^-	h^0, H^0, γ, Z	$\tilde{\nu}_\tau$	✓

[a] $k = u, d, c, s, t, b$.

[Pradler, FDS, arXiv:0808.2462]

The Effect of Stau-L-R Mixing



$\tan\beta = 10$, $m_{A^0} = M_S = M_3 = -A = 1$ TeV, and $6M_1 = M_2 = \mu = 1$ TeV

$$\begin{pmatrix} \tilde{\tau}_1 \\ \tilde{\tau}_2 \end{pmatrix} = R_{\tilde{\tau}} \begin{pmatrix} \tilde{\tau}_{\rm L} \\ \tilde{\tau}_{\rm R} \end{pmatrix} \quad \text{with } R_{\tilde{\tau}} = \begin{pmatrix} \cos\theta_{\tilde{\tau}} & \sin\theta_{\tilde{\tau}} \\ -\sin\theta_{\tilde{\tau}} & \cos\theta_{\tilde{\tau}} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{\tau}} = \begin{pmatrix} m_\tau^2 + m_{\rm LL}^2 & m_\tau X_\tau^* \\ m_\tau X_\tau & m_\tau^2 + m_{\rm RR}^2 \end{pmatrix} = (R_{\tilde{\tau}})^\dagger \begin{pmatrix} m^2_{\tilde{\tau}_1} & 0 \\ 0 & m^2_{\tilde{\tau}_2} \end{pmatrix} R_{\tilde{\tau}},$$

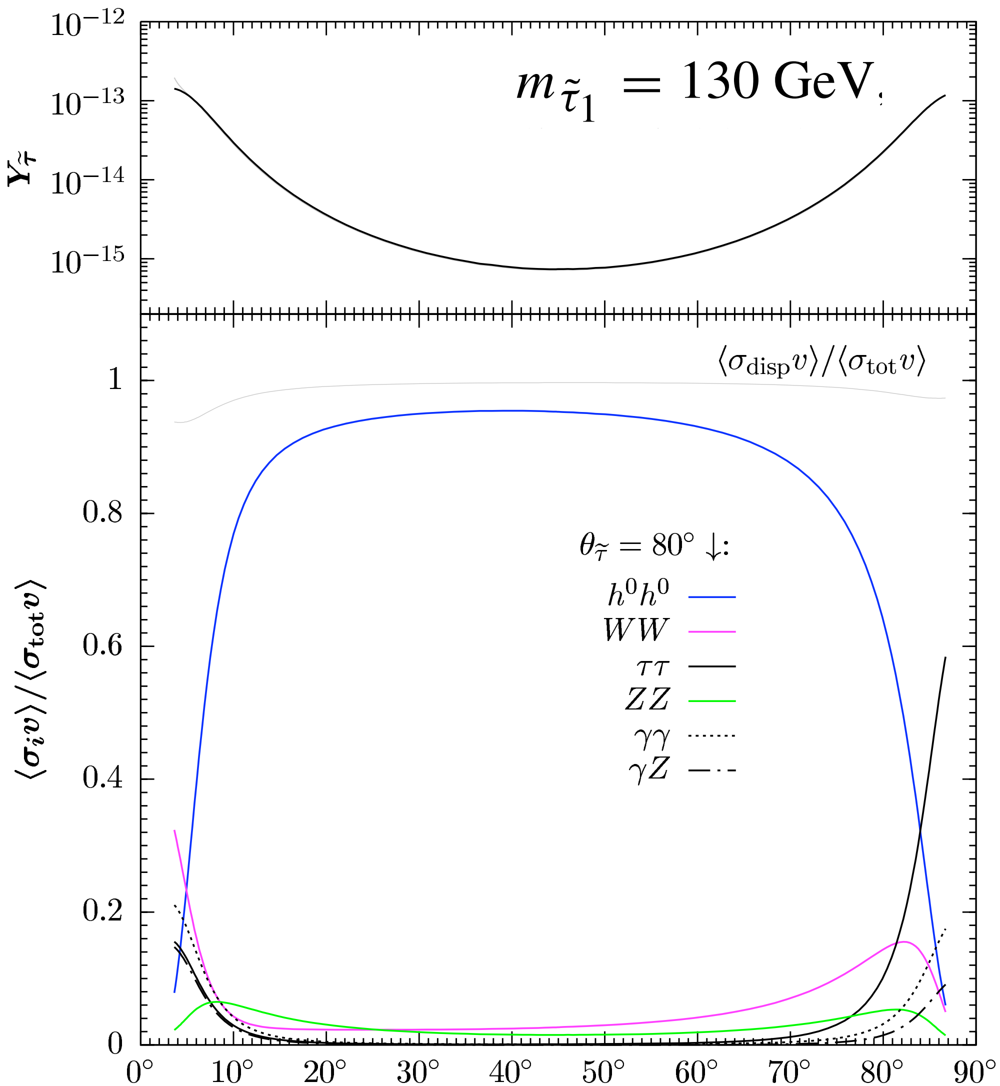
$$m_{\rm LL}^2 = m_{\tilde{\tau}_{\rm L}}^2 + \left(-\frac{1}{2} + \sin^2\theta_W\right) M_Z^2 \cos 2\beta,$$
$$m_{\rm RR}^2 = m_{\tilde{\tau}_{\rm R}}^2 - \sin^2\theta_W M_Z^2 \cos 2\beta,$$
$$X_\tau = A_\tau - \mu^* \tan\beta.$$

$$m^2_{\tilde{\tau}_{1,2}} = m_\tau^2 + m_{\rm RR}^2 + \frac{1}{2}\left[\delta \mp \sqrt{\delta^2 + 4 m_\tau^2 {X_\tau}^2}\right]$$

$\tan\beta = 50,\ m_{A^0} = \mu = M_S = 6M_1 = M_{2,3} = -A = 1$ TeV

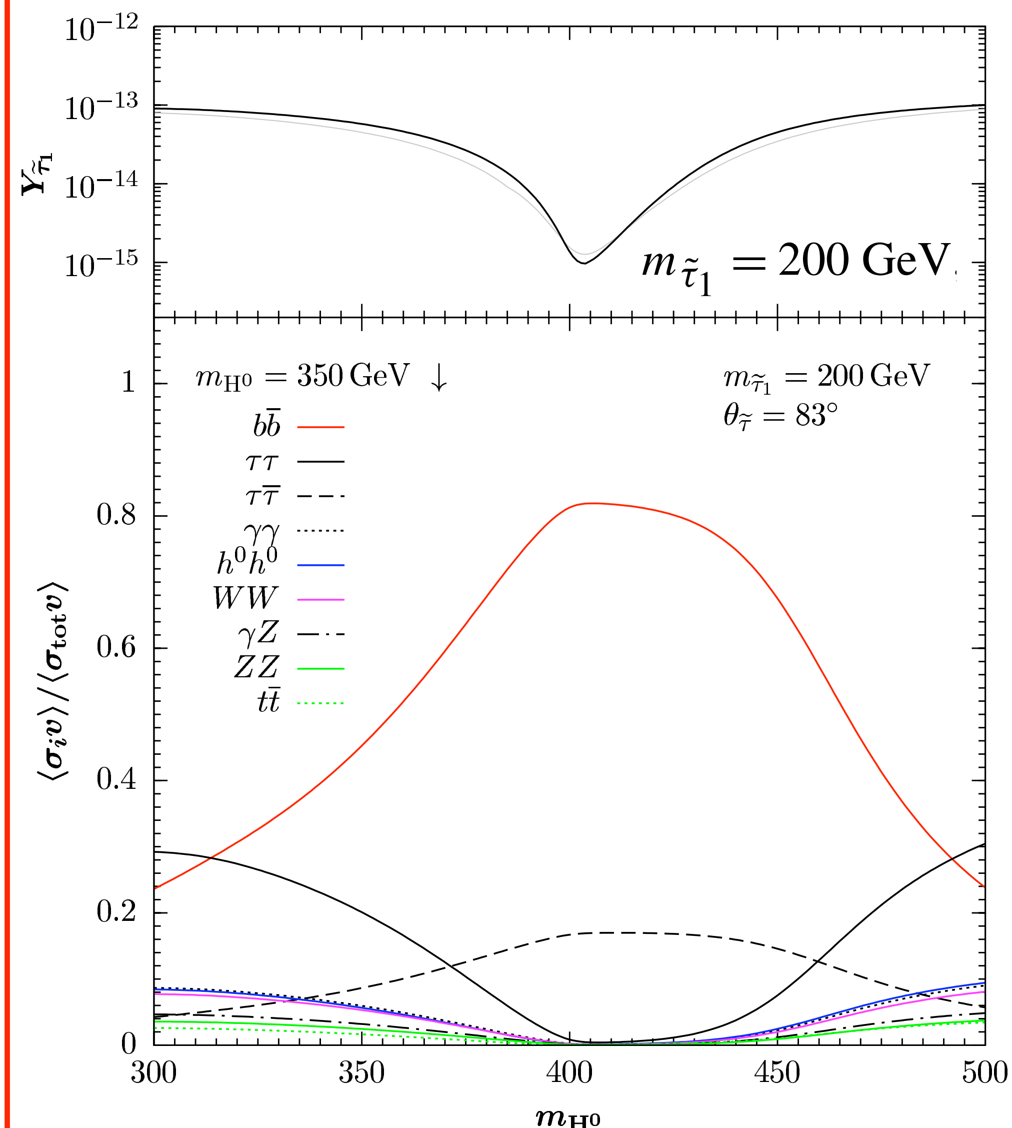
$\theta_{\tilde\tau} = 83^\circ$, $\tan\beta = 40$, and $-A = \mu = 4M_1 = M_{2,3} = M_S = 1$ TeV

Enhanced Stau-Higgs Coupling



[Ratz et al., arXiv:0808.0829; Pradler, FDS, arXiv:0808.2462]

Resonant Stau Annihilation



[Pradler, FDS, arXiv:0808.2462]

$$\mathcal{L}_{\text{MSSM}} \ni \frac{g}{M_{\text{W}}} \sum_{\alpha,\beta=\text{L,R}} \tilde{\tau}^*_\alpha \tilde{C}[\tilde{\tau}^*_\alpha, \tilde{\tau}_\beta, \mathcal{H}] \tilde{\tau}_\beta \mathcal{H}$$

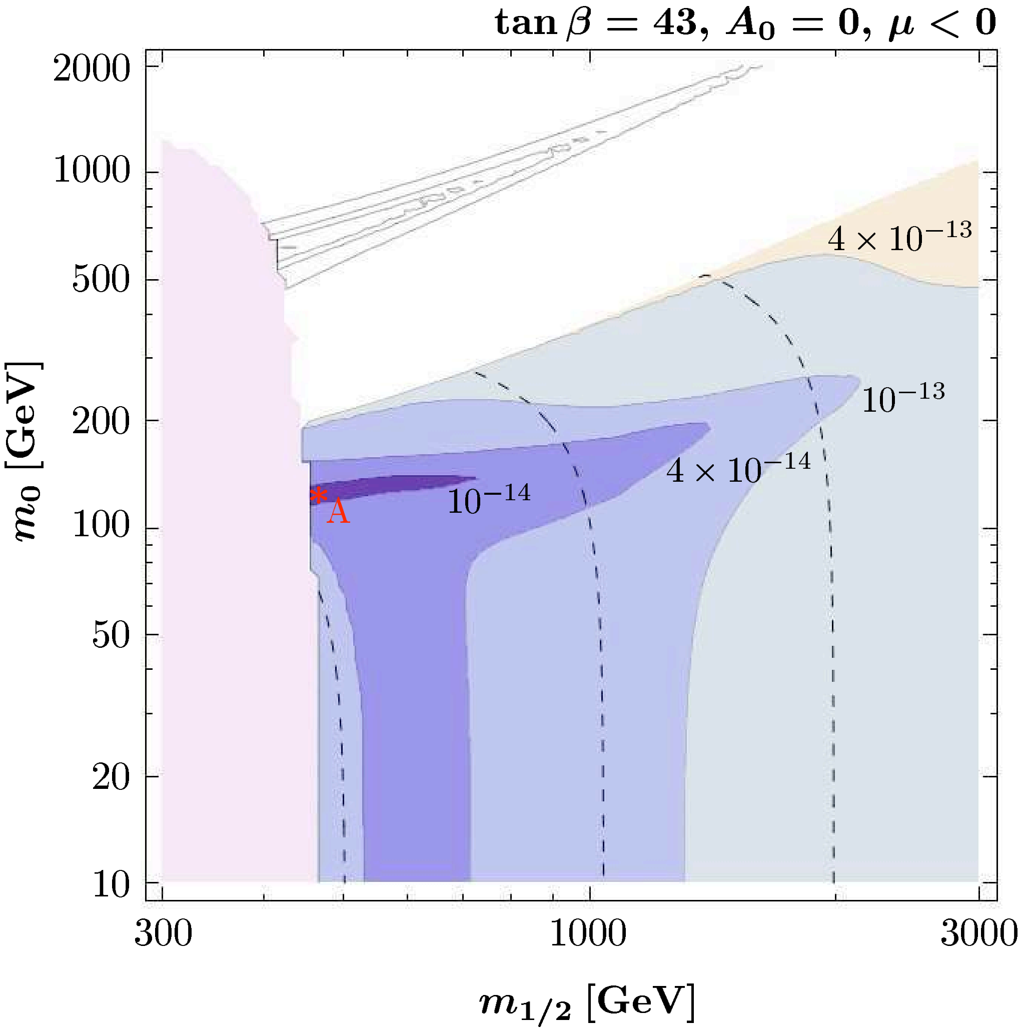
$$\tilde{C}\left[\tilde{\tau}^*, \tilde{\tau}, h^0\right] = \begin{pmatrix} \left(-\frac{1}{2} + s_W^2\right) M_Z^2 s_{\alpha+\beta} + m_\tau^2 \frac{s_\alpha}{c_\beta} & \frac{m_\tau}{2}\left(A_\tau \frac{s_\alpha}{c_\beta} + \mu \frac{c_\alpha}{c_\beta}\right) \\ \frac{m_\tau}{2}\left(A_\tau \frac{s_\alpha}{c_\beta} + \mu \frac{c_\alpha}{c_\beta}\right) & -s_W^2 M_Z^2 s_{\alpha+\beta} + m_\tau^2 \frac{s_\alpha}{c_\beta} \end{pmatrix},$$

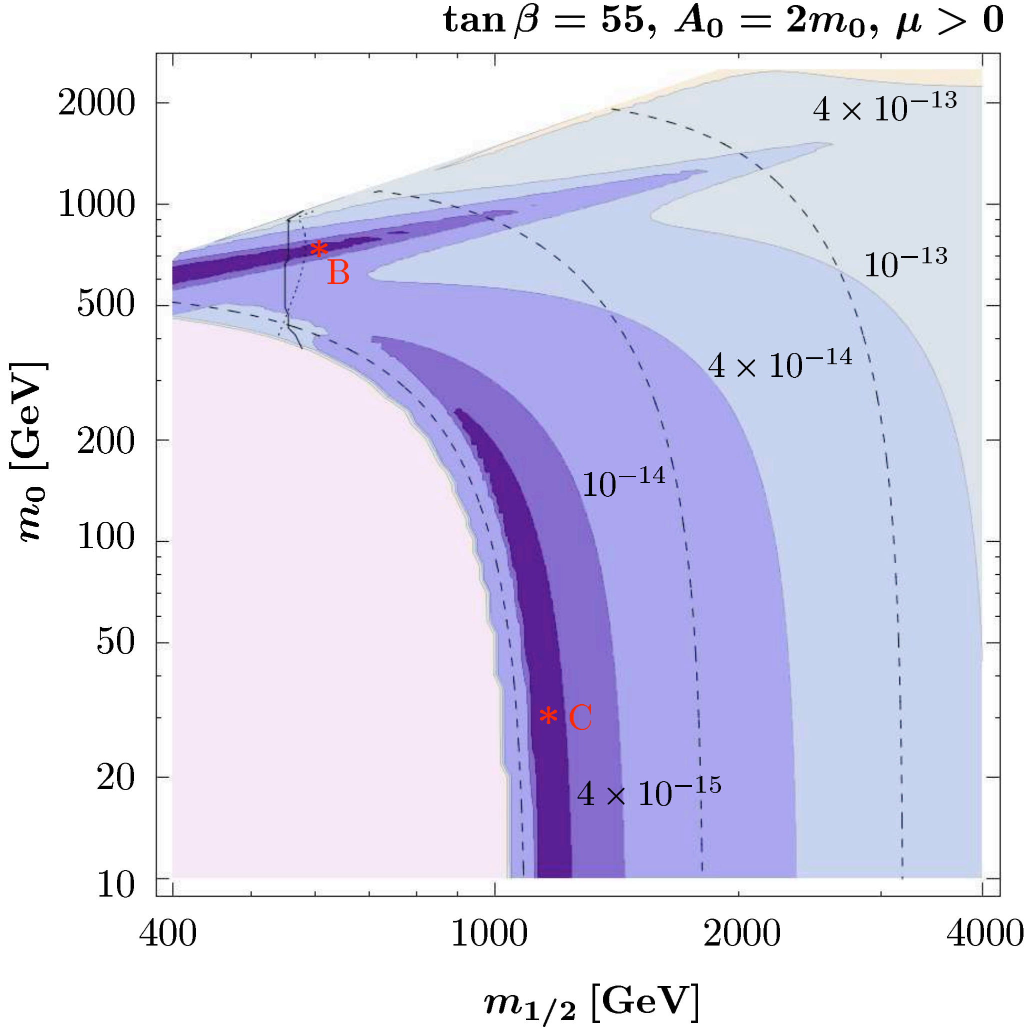
$$\tilde{C}\left[\tilde{\tau}^*, \tilde{\tau}, A^0\right] = \begin{pmatrix} 0 & +i\,\frac{m_\tau}{2}(A_\tau \tan\beta + \mu) \\ -i\,\frac{m_\tau}{2}(A_\tau \tan\beta + \mu) & 0 \end{pmatrix},$$

$$C^{\text{DL}}\left[\tilde{\tau}_1^*, \tilde{\tau}_1, h^0\right] \simeq \left(\frac{1}{2} c^2_{\theta_{\tilde{\tau}}} - s_W^2 c_{2\theta_{\tilde{\tau}}}\right) M_Z^2 c_{2\beta} - m_\tau^2 - \frac{m_\tau}{2} X_\tau s_{2\theta_{\tilde{\tau}}}$$

$$X_\tau = A_\tau - \mu^* \tan\beta$$

Exceptionally Small Thermal Relic Stau Abundances





Exceptionally Interesting Benchmark Scenarios

Point		A	B	C
$m_{1/2}$	[GeV]	456	600	1138
m_0	[GeV]	124	748	30
$\tan\beta$		43	55	55
$m_{\tilde{\tau}_1}$	[GeV]	130	197	127
$m_{\tilde{\tau}_2}$	[GeV]	352	673	739
$\theta_{\tilde{\tau}}$		114	80	75
m_{h^0}	[GeV]	114.6	115	117.9
m_{H^0,A^0}	[GeV]	265	390	799
Γ_{H^0}	[GeV]	9.6	22	41
μ	[GeV]	-565	666	1262
A_τ	[GeV]	-63	473	-164
$m_{\tilde{g}}$	[GeV]	1052	1375	2446
$m_{\tilde{t}_1}$	[GeV]	740	1091	1757
$b\bar{b}$	[%]	76	87	< 1
h^0h^0	[%]	10	< 1	90
$\tau\bar{\tau}$	[%]	9	11	< 1
WW	[%]	2	< 1	6
x_f		30	30	32
$Y_{\tilde{\tau}}$	$[10^{-15}]$	4.2	2.5	2.2
$m_{\tilde{G}}$	[GeV]	100 (50)	100 (50)	100 (50)
$\tau_{\tilde{\tau}_1}$	[s]	5.7×10^9 (7.5×10^7)	6.5×10^7 (6.4×10^6)	8.5×10^9 (8.7×10^7)
$\Omega_{\tilde{G}}^{\mathrm{NTP}}h^2$	$[10^{-4}]$	1.2 (0.58)	0.7 (0.35)	0.64 (0.32)
$T_{\mathrm{R}}^{\mathrm{max}}$	[GeV]	1.9×10^9 (9.5×10^8)	1.1×10^9 (5.5×10^8)	3.1×10^8 (1.5×10^8)

There could be

- gravitino DM
- no gravitino problem
- CBBN explanation of Li-6
- promising prospects for SUSY and Higgs phenomenology at the LHC and the ILC

To be continued ...