Dark Matter Candidates

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Excellence Cluster Universe

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CRESST-GERDA-FCD-ZEUS Chat @ MPP

April 24th, 2009

Why is Dark Matter an exciting topic?

Our present picture of the Universe

photons

$\Omega_\gamma = 0.005\ \%$

baryons

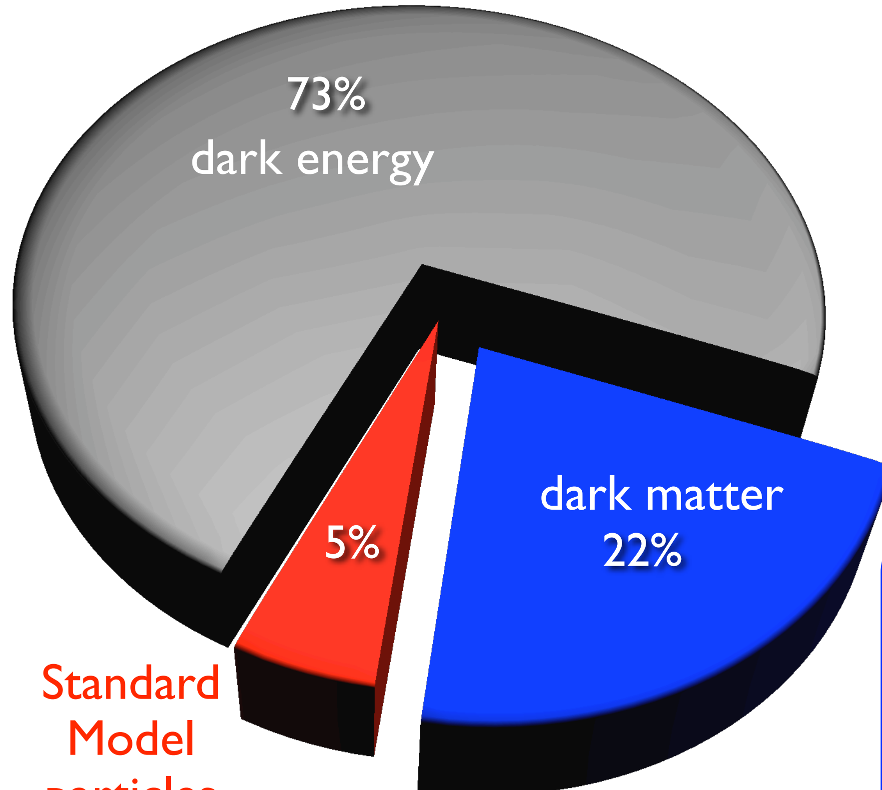
$\Omega_B = 4\ \%$

? baryon asymmetry ?

neutrinos

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

? neutrino mass ?



dark energy

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

? vacuum energy ?

dark matter

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

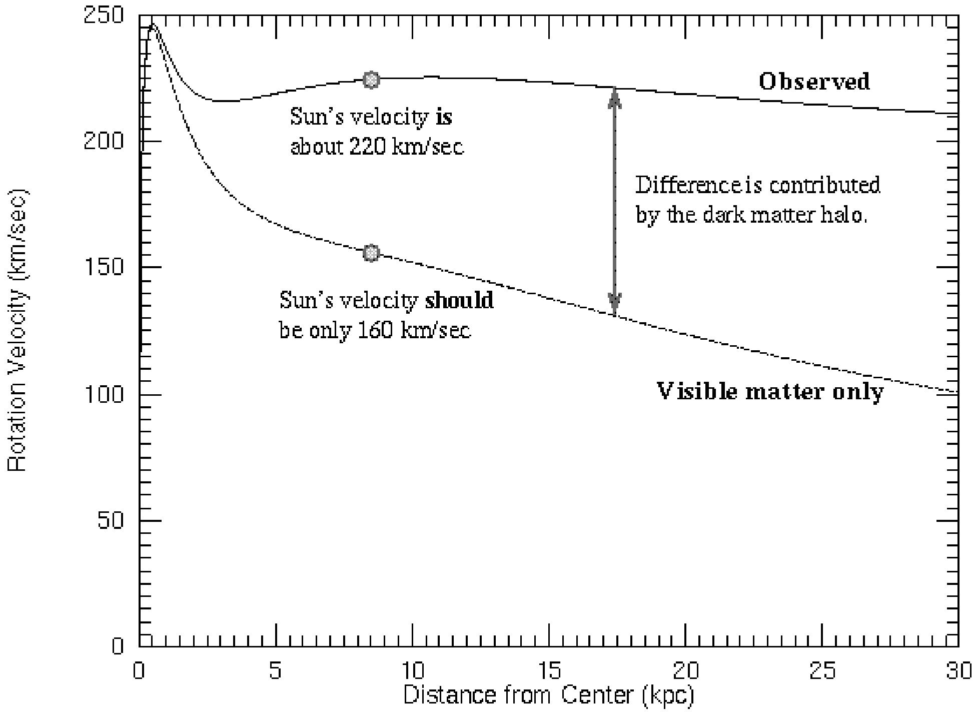
? identity ?

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

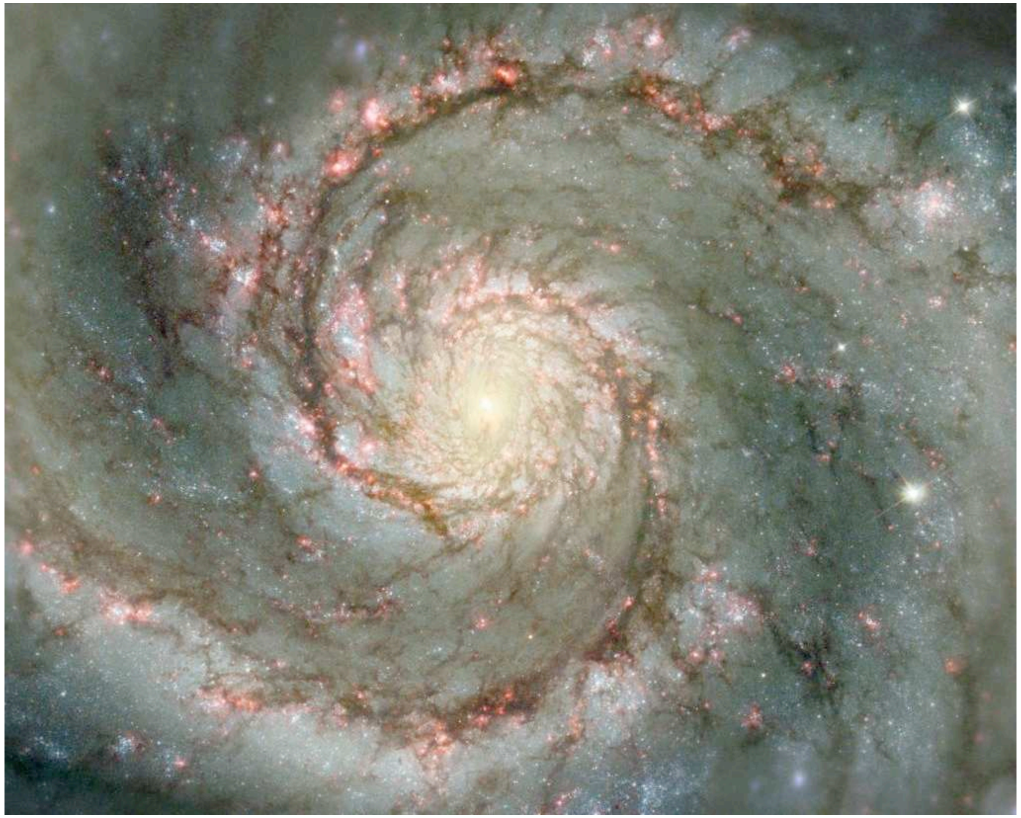
There is striking evidence for Dark Matter ...

Evidence for Dark Matter in the Universe

- Spiral Galaxies
  - * Rotation Curves

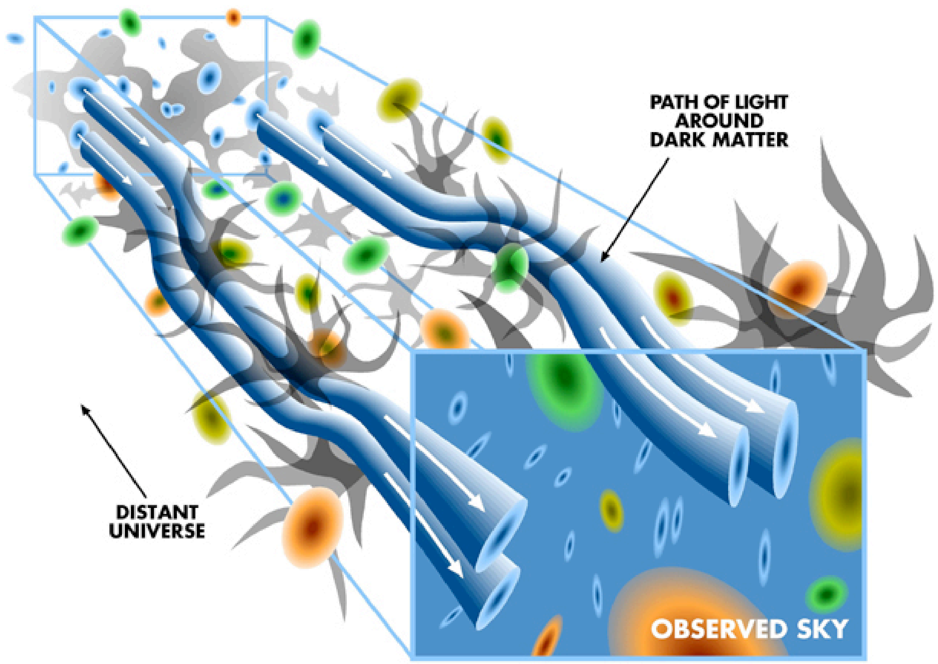


The gravity of the visible matter in the Galaxy is not enough to explain the high orbital speeds of stars in the Galaxy. For example, the Sun is moving about 60 km/sec too fast. The part of the rotation curve contributed by the visible matter only is the bottom curve. The discrepancy between the two 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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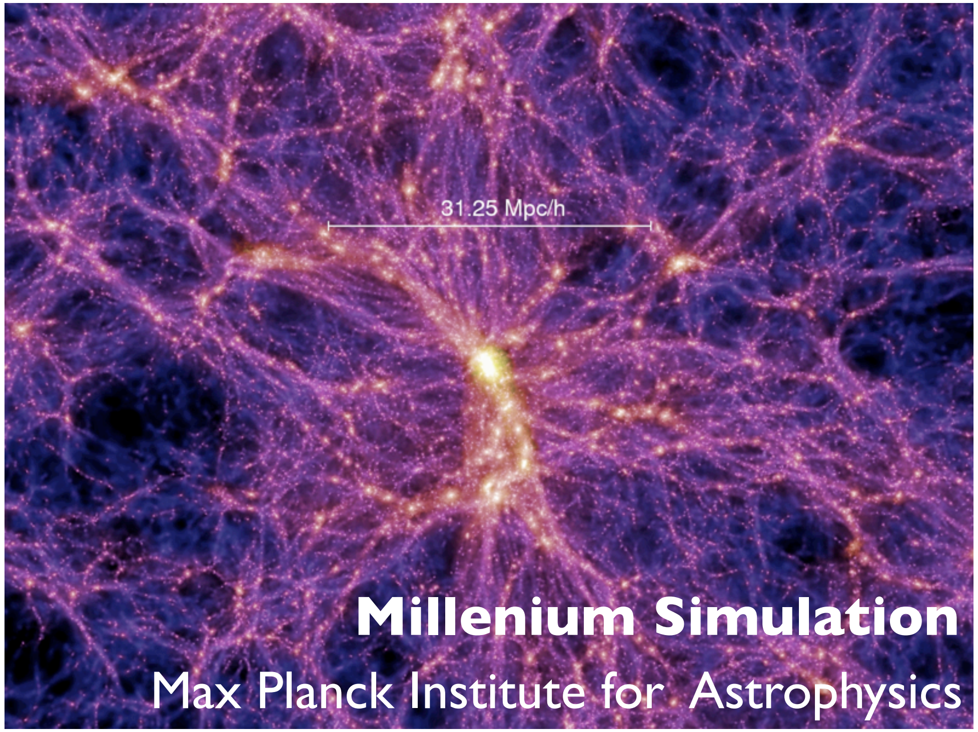
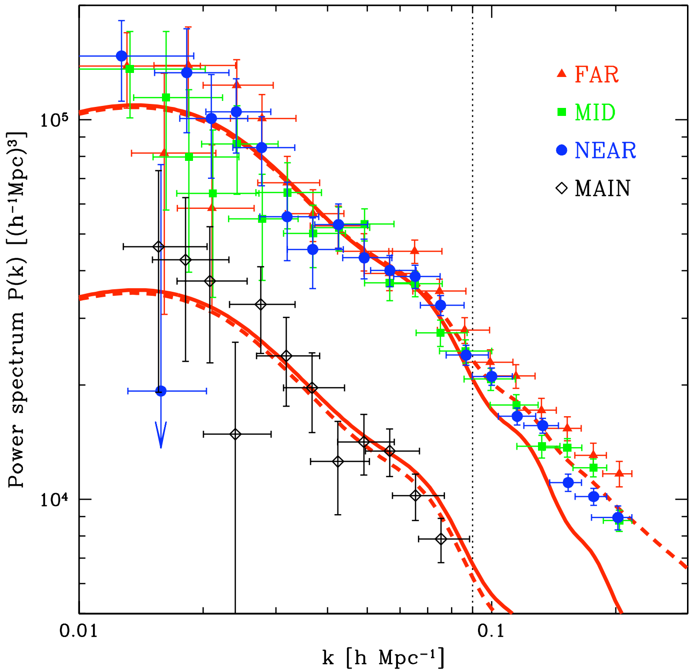
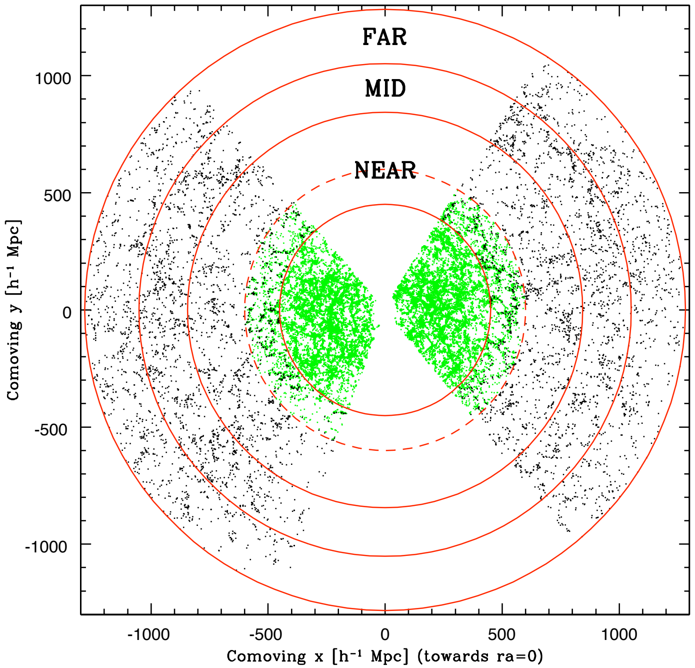
  - * Strong Gravitational Lensing
- ☐ Large Scale Structure
  - * Structure Formation





SDSS



Evidence for Dark Matter in the Universe

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  - * Rotation Curves
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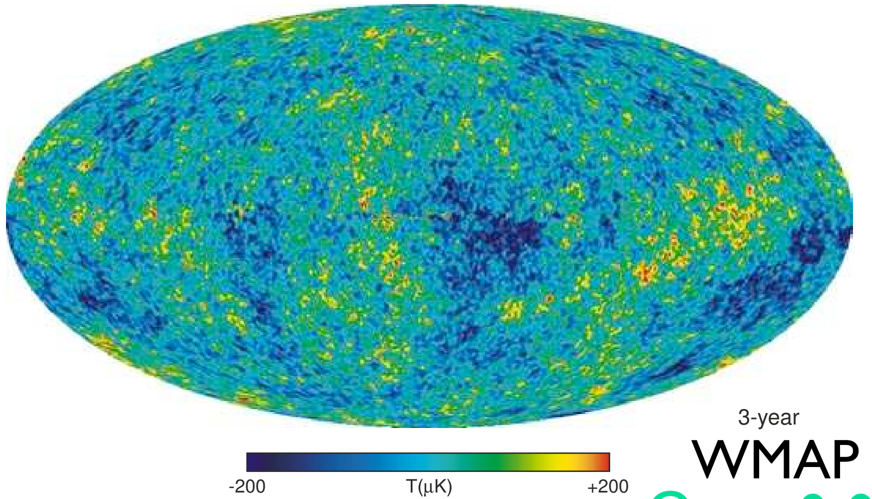
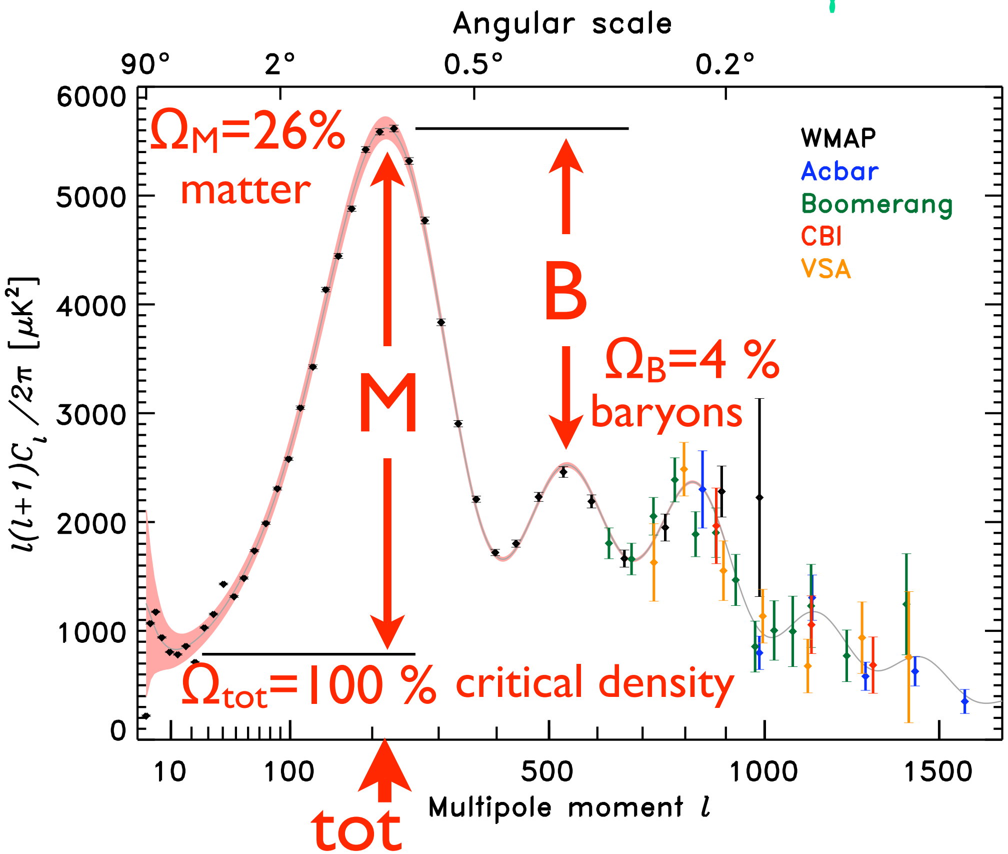
  - * Strong Gravitational Lensing
- □ Large Scale Structure
  - * Structure Formation
- □ CMB Anisotropy: WMAP, ...

dark matter
Ω_{DM} = 22 %

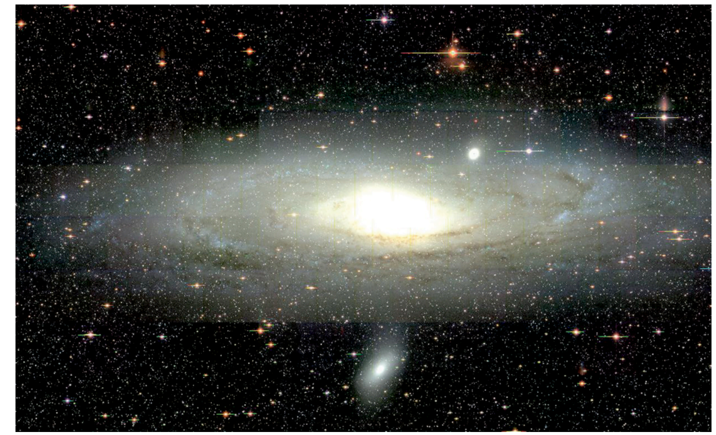


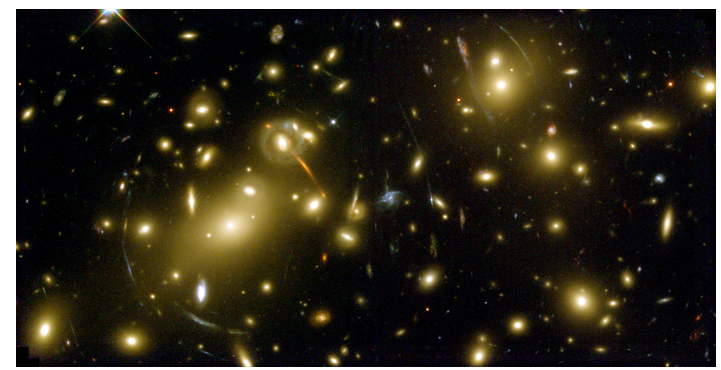
Ω_γ = 0.005 %



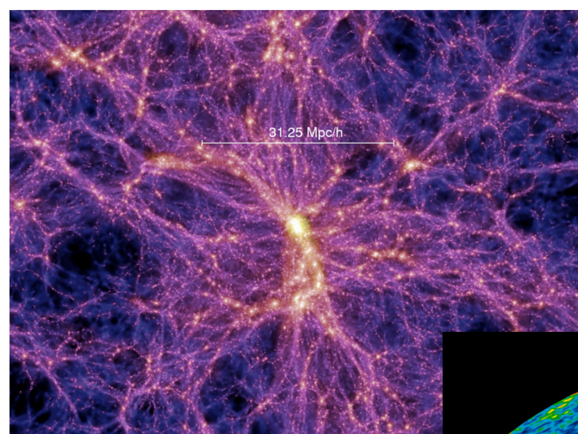
What is the identity of Dark Matter ?

Properties of Dark Matter

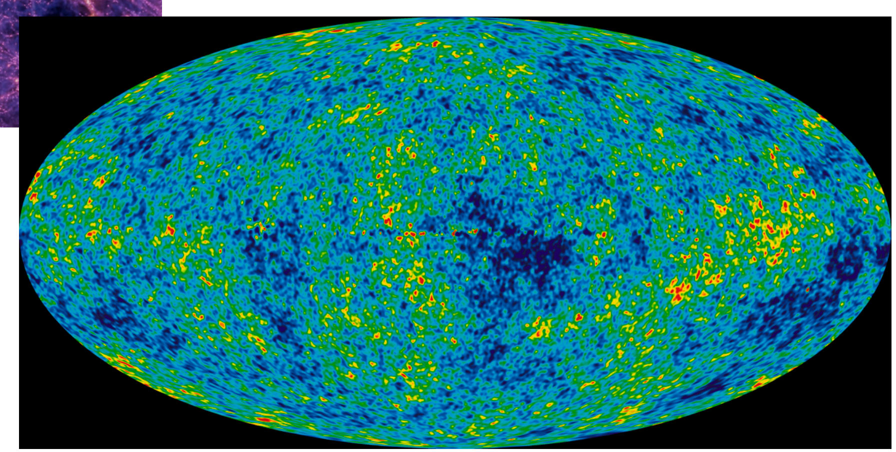




- stable or lifetime well above the age of our Universe
- electrically neutral
- clusters →



- “cold”
- dissipationless
- color neutral



The Standard Model

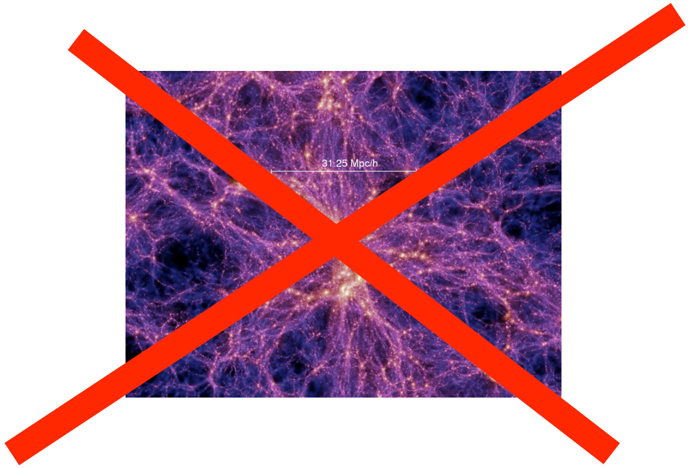
GAUGE	Gauge bosons	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
B-boson	$A_\mu^{(1)} = B_\mu$	$(\mathbf{1}, \mathbf{1})_0$
W-bosons	$A_\mu^{(2)\,a} = W_\mu^a$	$(\mathbf{1}, \mathbf{3})_0$
gluon	$A_\mu^{(3)\,a} = G_\mu^a$	$(\mathbf{8}, \mathbf{1})_0$

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	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
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 $I = 1, 2, 3$	$\widetilde{L}^I = \begin{pmatrix} \widetilde{\nu}_L^I \\ \widetilde{e}_L^{-\,I} \end{pmatrix}$	$L^I = \begin{pmatrix} \nu_L^I \\ e_L^{-\,I} \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$\widetilde{E}^{*I} = \widetilde{e}_R^{-\,*\,I}$	$E^{c\,I} = e_R^{-\,c\,I}$	$(\mathbf{1}, \mathbf{1})_{+2}$
squarks, quarks $I = 1, 2, 3$ ($\times$ 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	$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\widetilde{H}_d = \begin{pmatrix} \widetilde{H}_d^0 \\ \widetilde{H}_d^- \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{-1}$
	$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\widetilde{H}_u = \begin{pmatrix} \widetilde{H}_u^+ \\ \widetilde{H}_u^0 \end{pmatrix}$	$(\mathbf{1}, \mathbf{2})_{+1}$

Minimal Supersymmetric Extension of the Standard Model

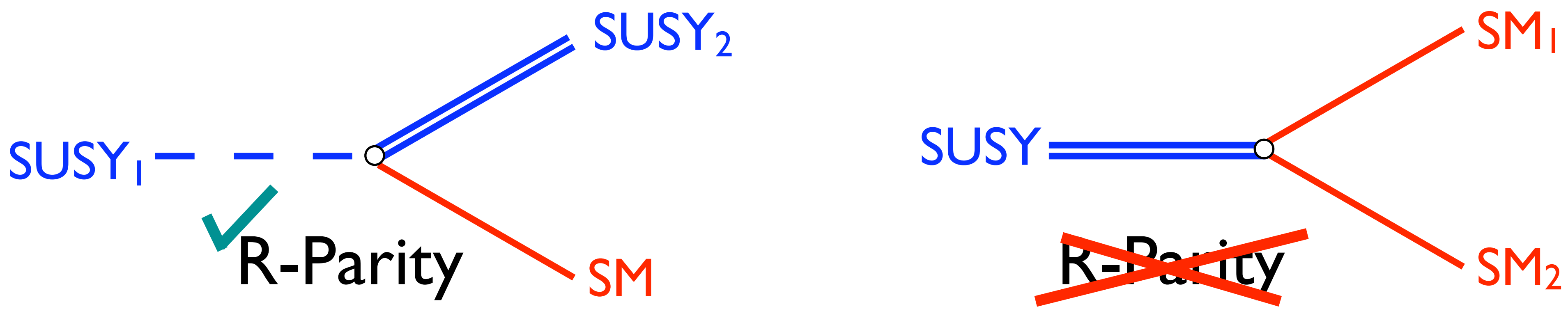
↓

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 $\leftarrow$ multiplicative quantum number

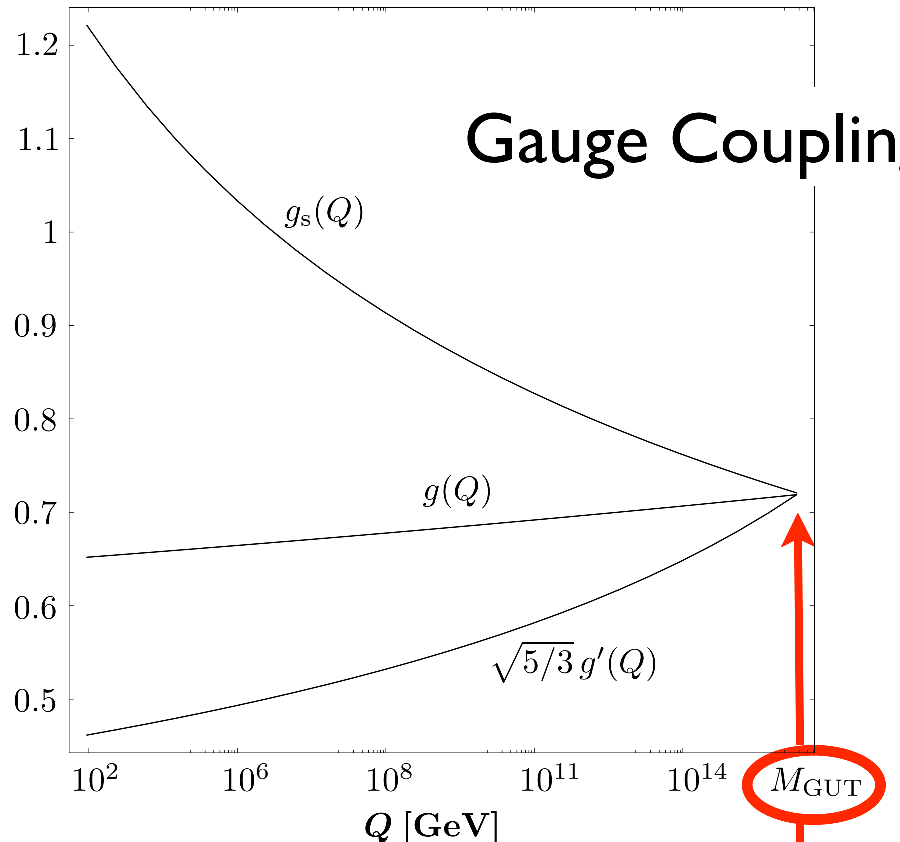
$$P_{\mathrm{R}} = (-1)^{3(B-L)+S} = \begin{cases} +1 & \text{for SM}, H_u, H_d \\ -1 & \text{for } \widetilde{X} \leftarrow \text{superpartners} \end{cases}$$



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

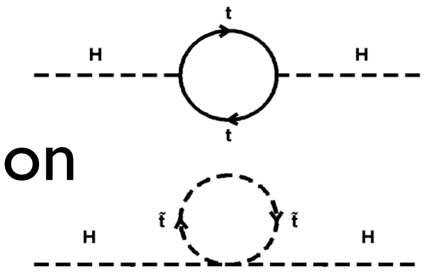
Why Supersymmetry?

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

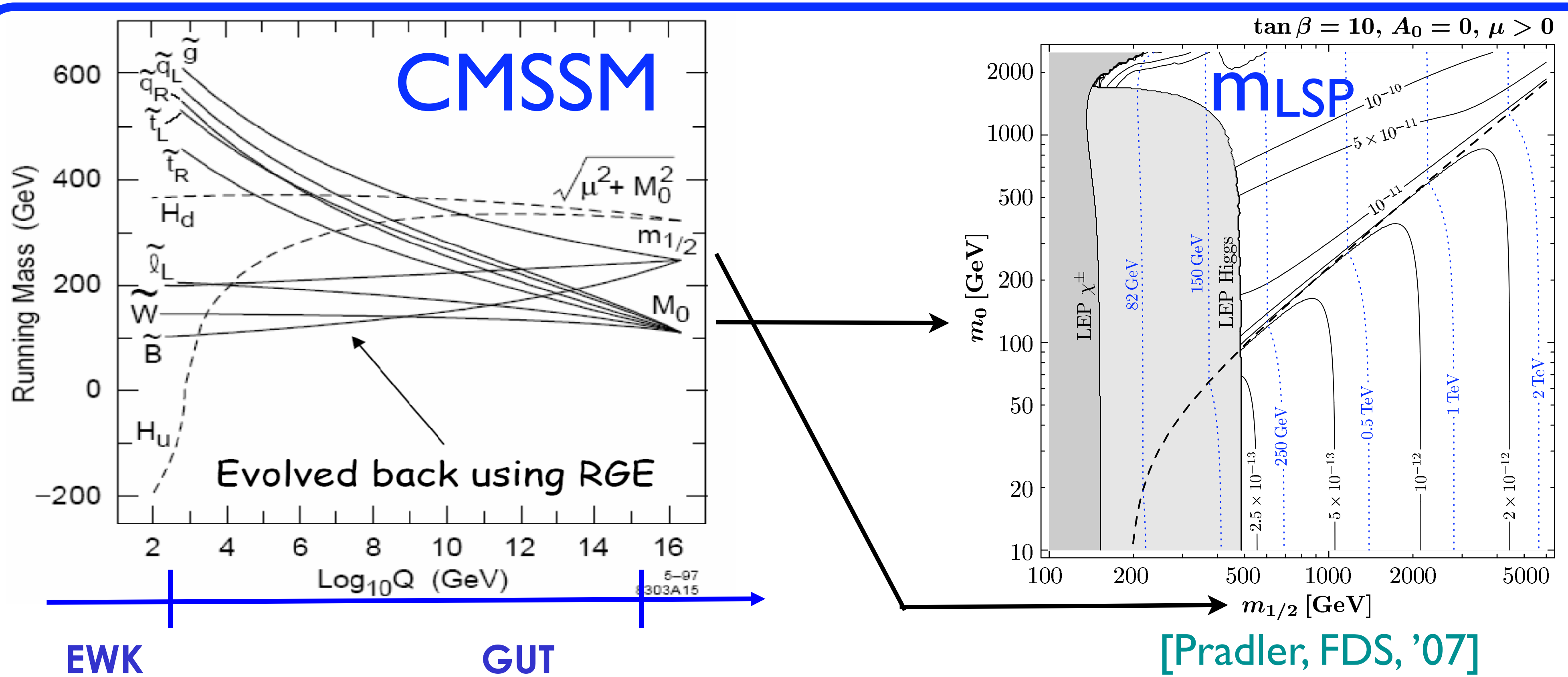
Dark Matter

↓

Neutralino LSP

Supersymmetric Dark Matter Candiates

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

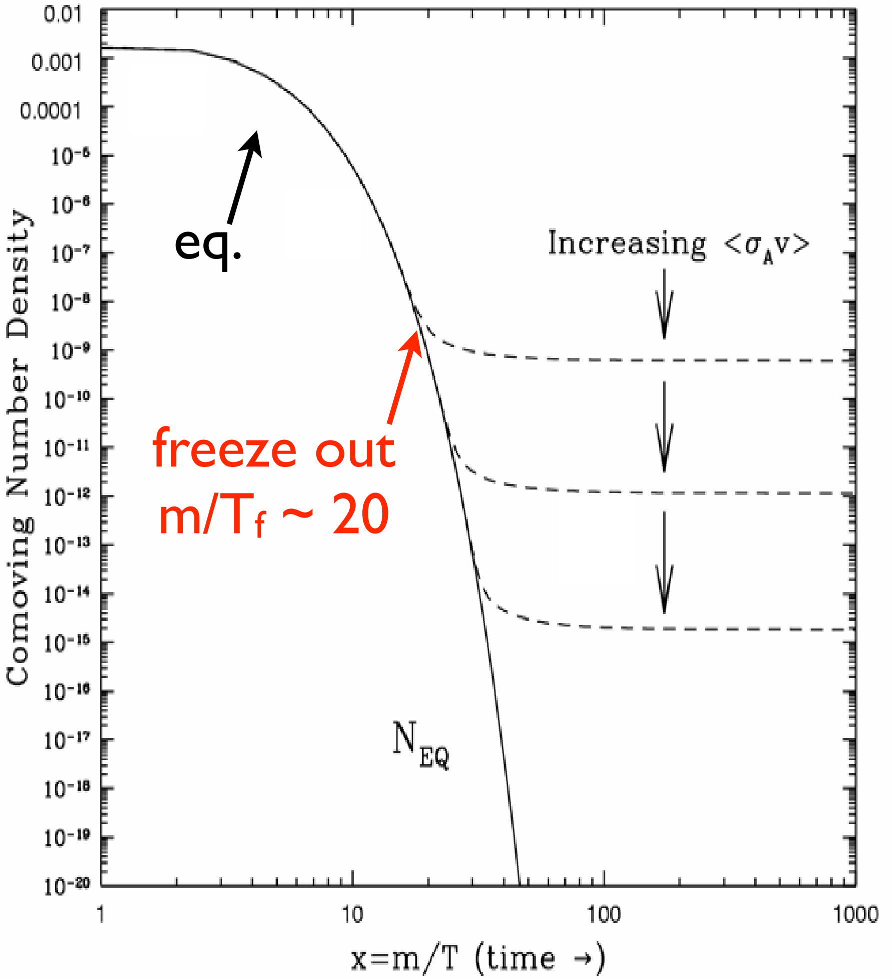


[Pradler, FDS, ’07]

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

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

Cold Thermal Relic



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

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

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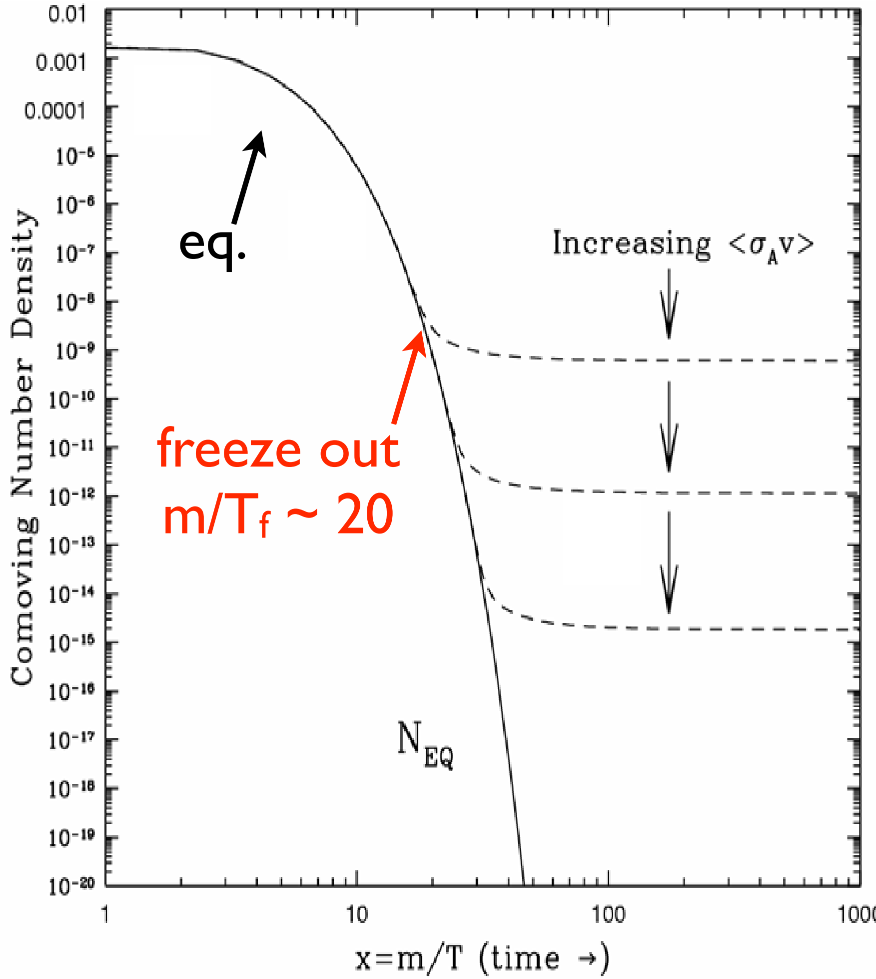
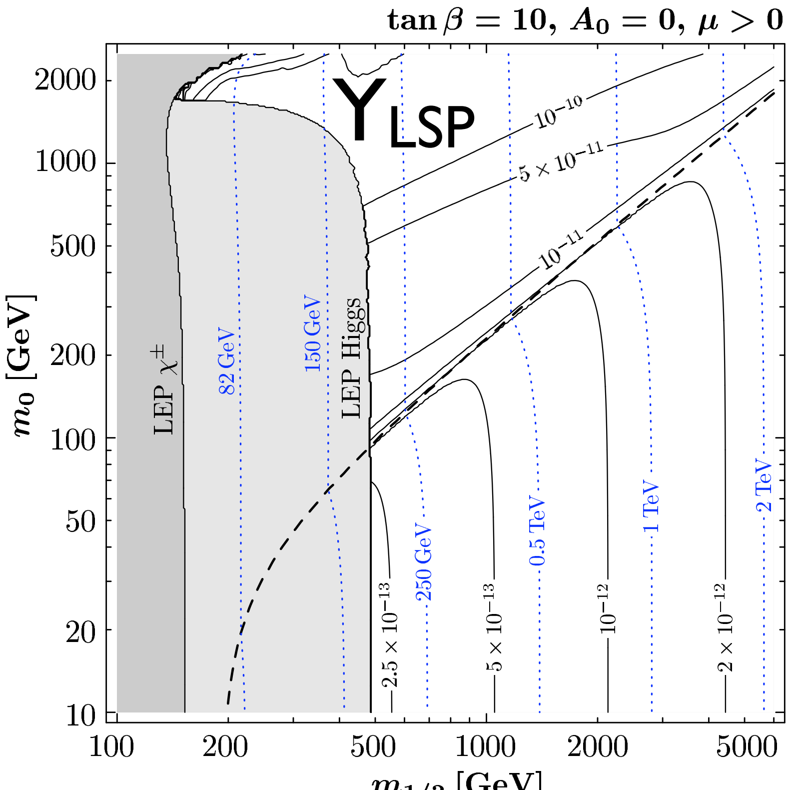


[... , Jungman, Kamionkowski, Griest, '96, ...]

micrOMEGAs 1.37
[Belanger et al., '03 & '06]

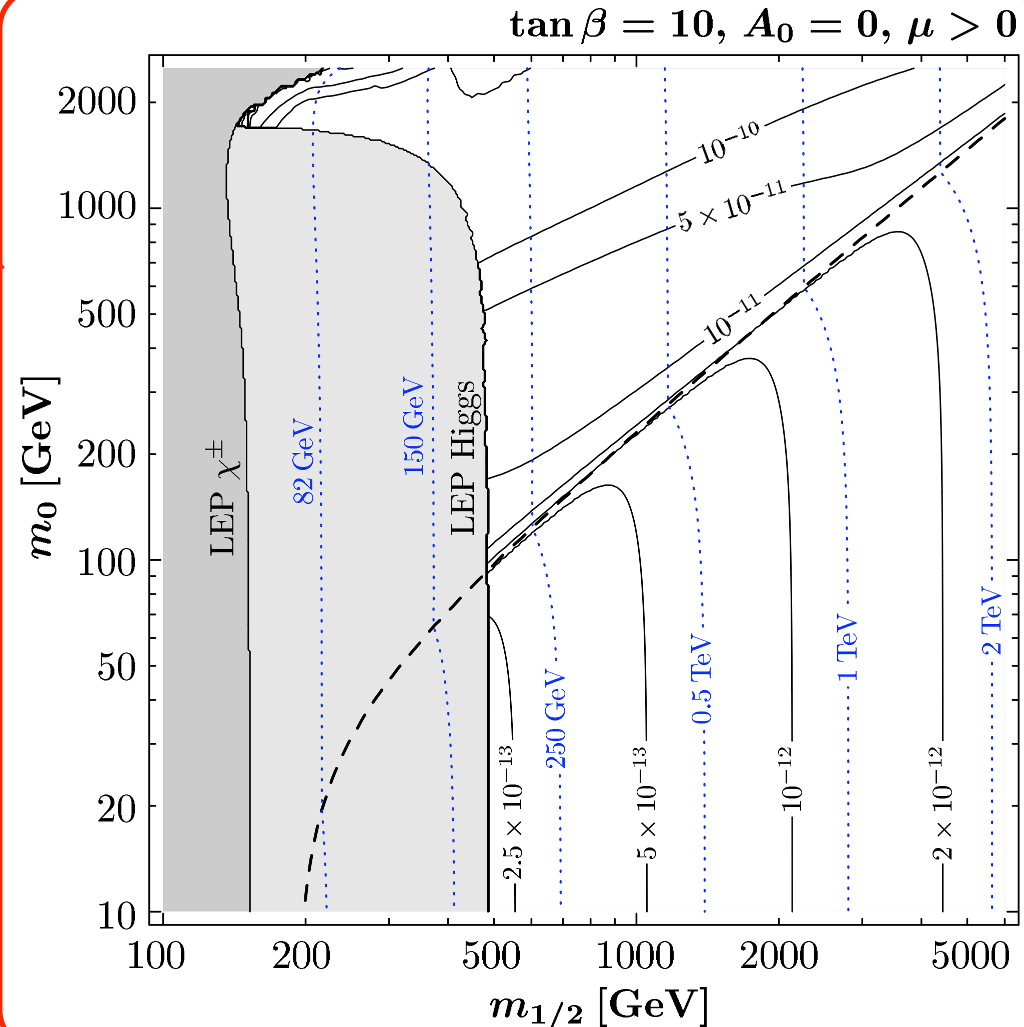
[Pradler, FDS, '07]



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

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

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

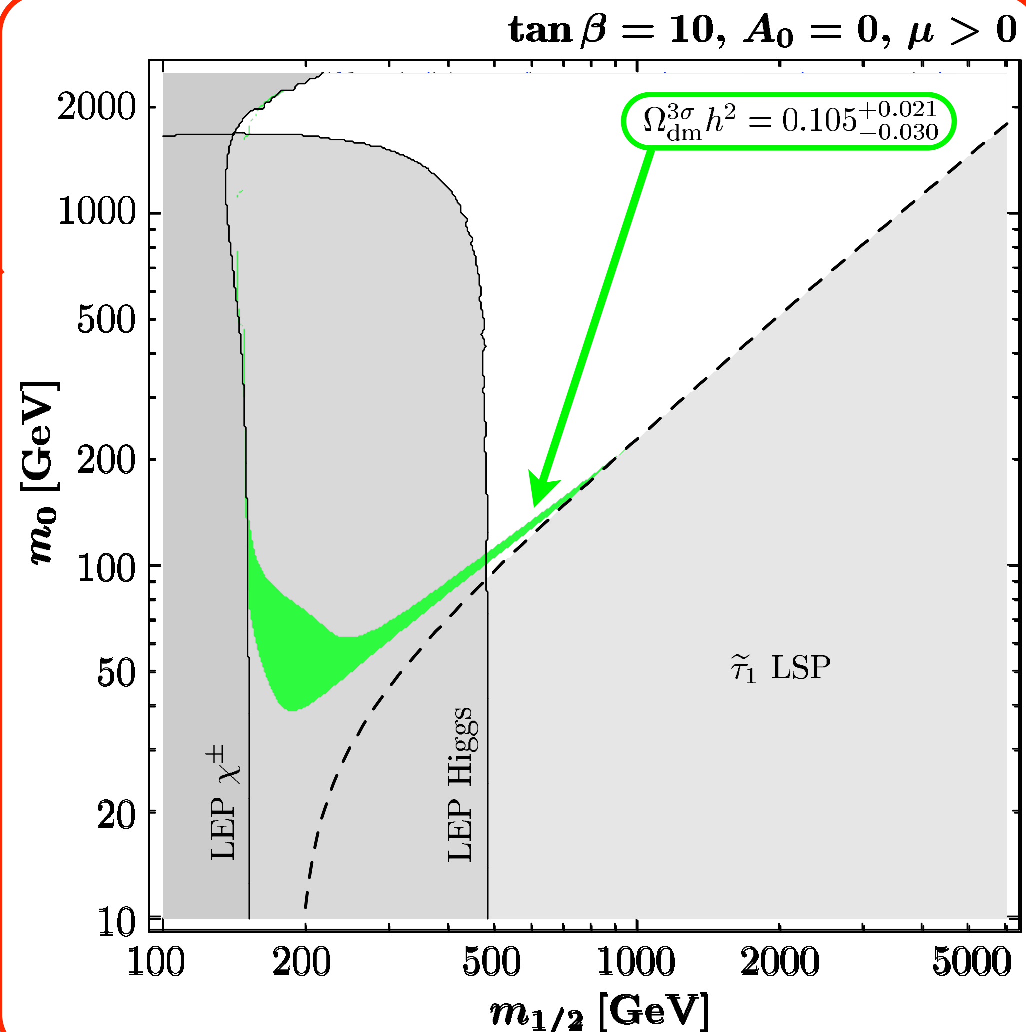


$\Omega_{\widetilde{\chi}^0_1} = \Omega_{\rm DM}$ **is possible!!!**

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

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

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



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

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

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

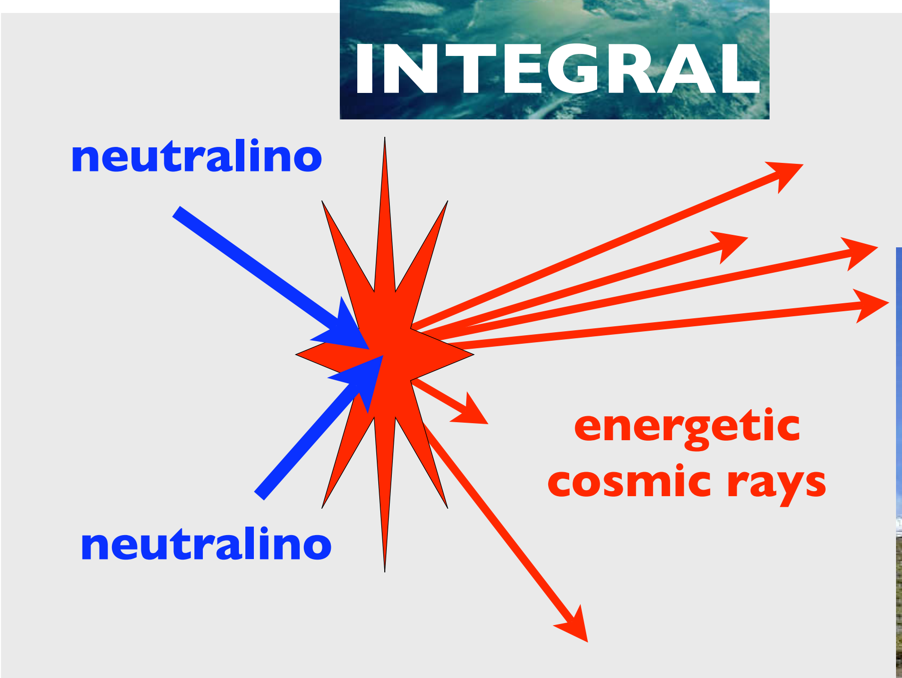
EGRET

AMS02

GLAST

PAMELA

HESS



AMANDA

IceCube

...

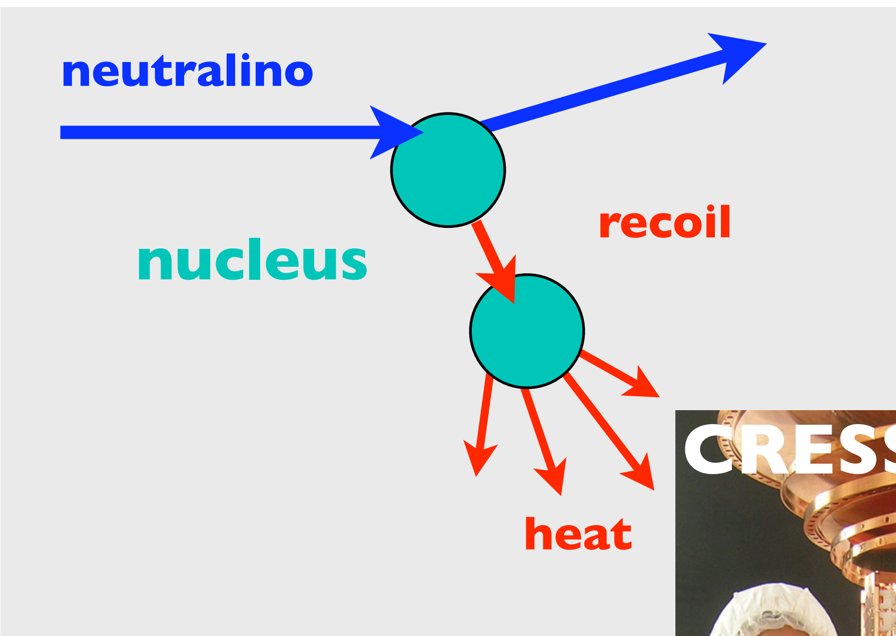
$\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

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

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

elastic neutralino scattering

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



EURECA

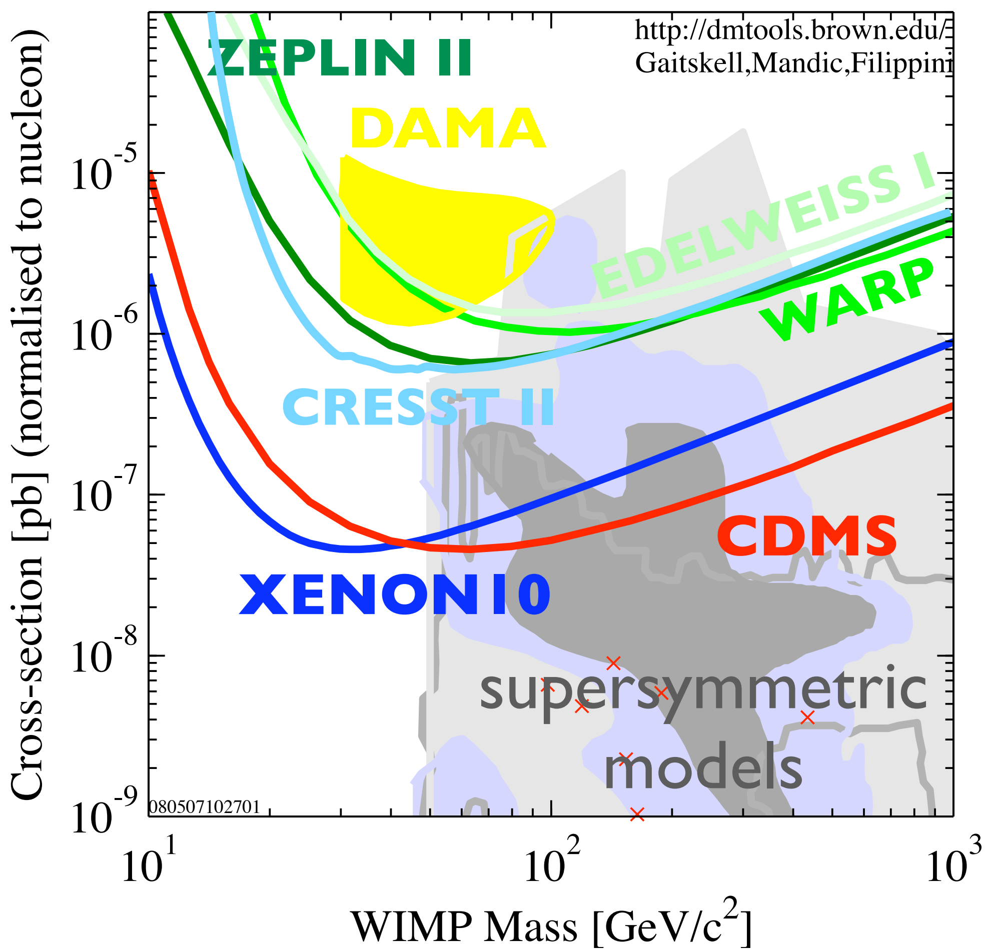
EDELWEISS-2

CDMS II

LUX

XENON10

...



http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
ZEPLIN II
DAMA
EDELWEISS I
WARP
CRESST II
CDMS
XENON10
supersymmetric
models
080507102701
Cross-section [pb] (normalised to nucleon)
WIMP Mass [GeV/c²]

$\widetilde{\chi}_1^0$ 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		

- indirect detection (EGRET, GLAST, ...)

  neutralino pair annihilation

  $\widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \rightarrow \mathrm{SM}_1\,\mathrm{SM}_2$

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

  elastic neutralino scattering

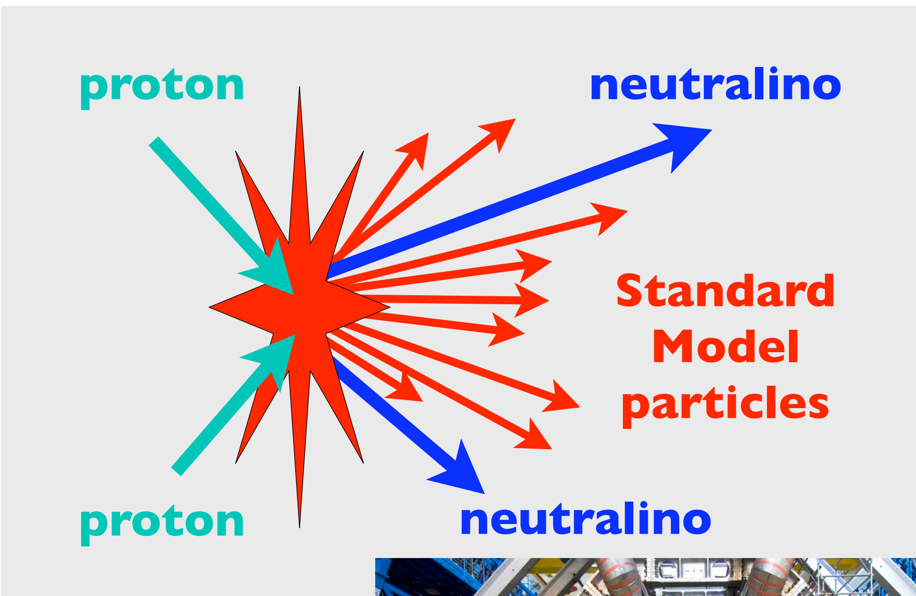
  $\widetilde{\chi}_1^0\,\mathrm{A} \rightarrow \widetilde{\chi}_1^0\,\mathrm{A}$

- prod.@colliders (Tevatron, LHC, ILC, ...)

  neutralino pair production

  $\mathrm{p\,p} \rightarrow \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \ldots$ (Tevatron, LHC)

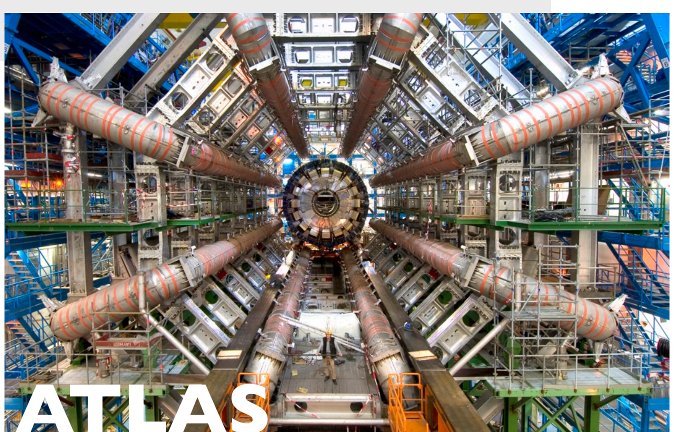
  $e^+\,e^- \rightarrow \widetilde{\chi}_1^0\,\widetilde{\chi}_1^0 \ldots$ (ILC)



CDF

D0

CMS



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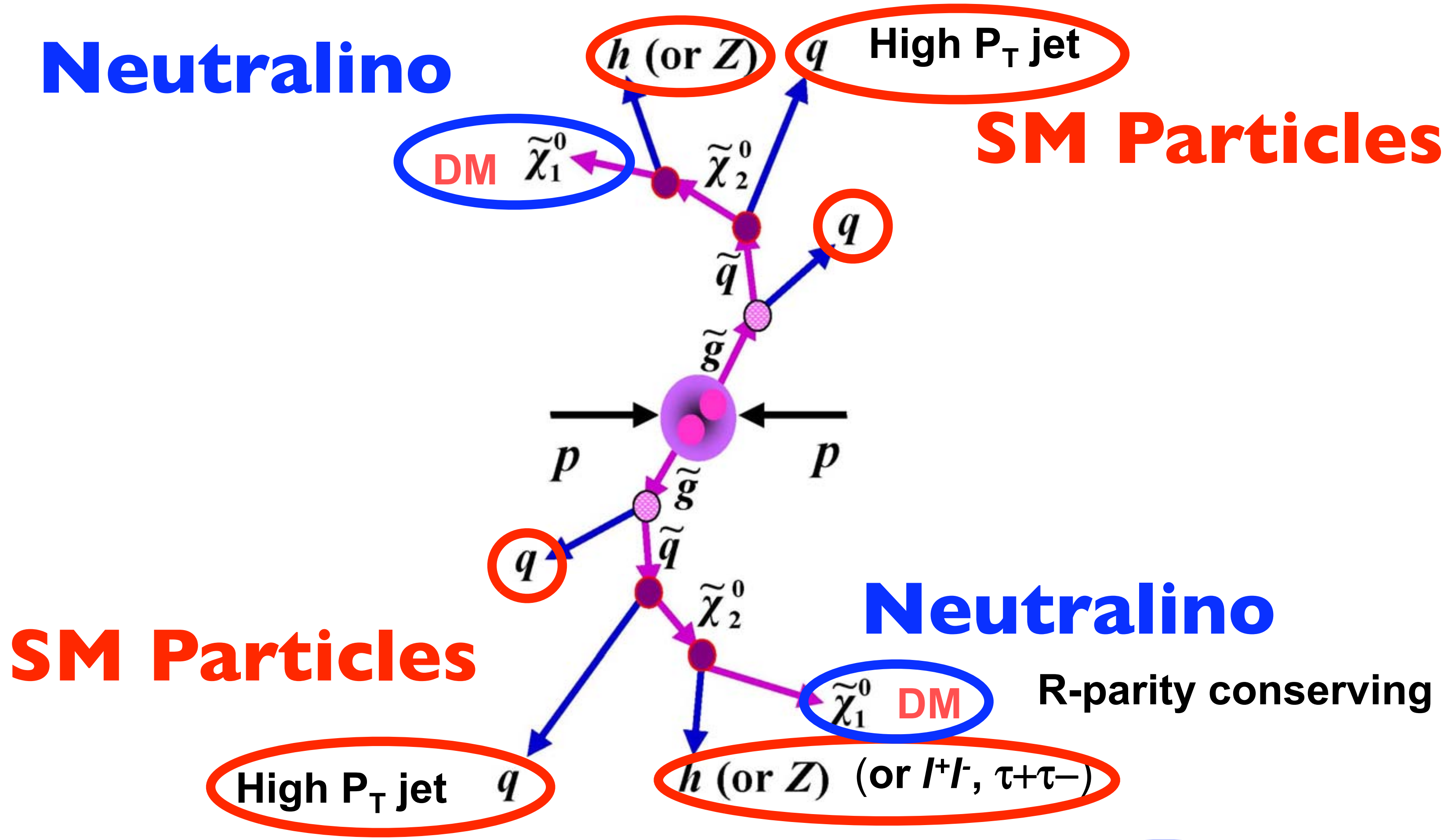
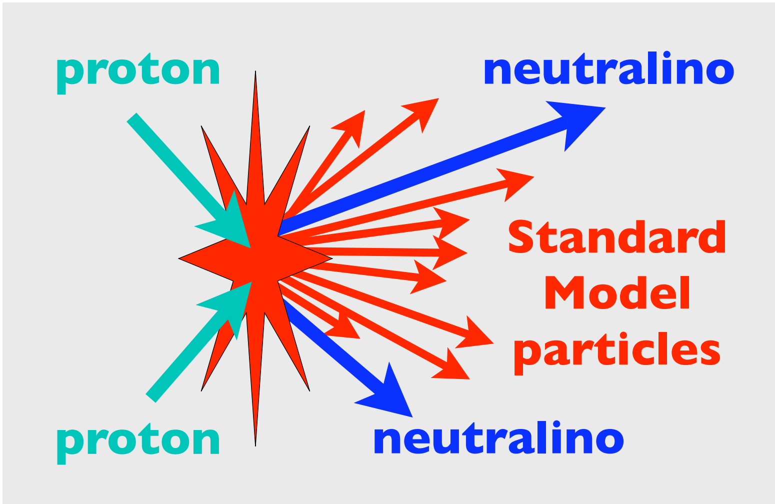
Neutralino DM Production at the LHC



The signal : jets + leptons + missing E_T

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

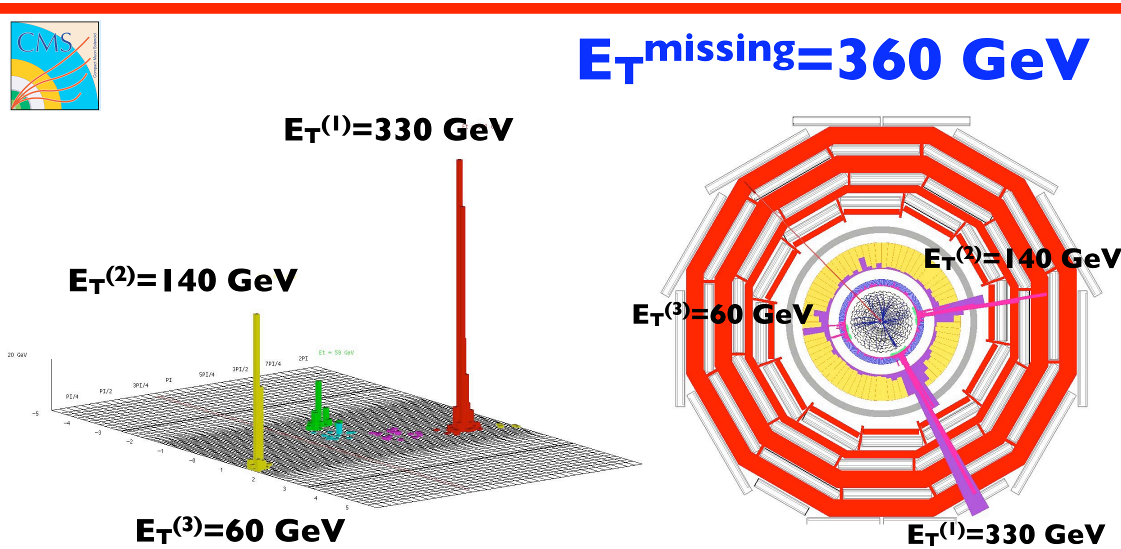
Collider Searches



ongoing searches at Tevatron

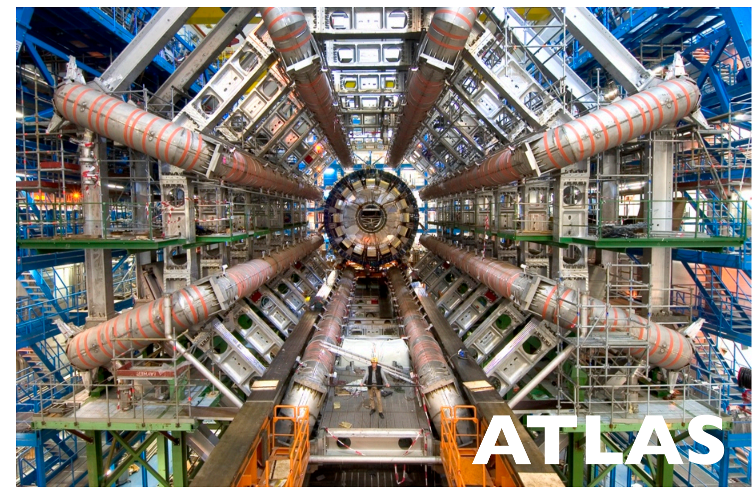
pp @ 2 TeV

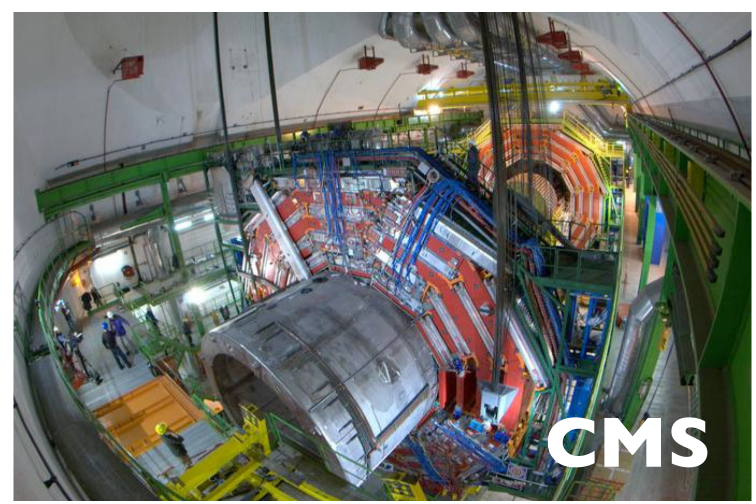
CDF D0



The signal:

jets + leptons + large E_T^{miss}



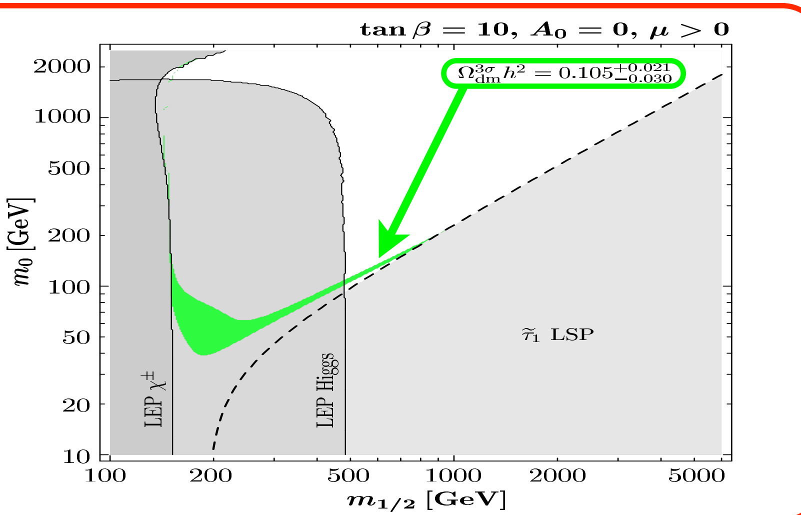


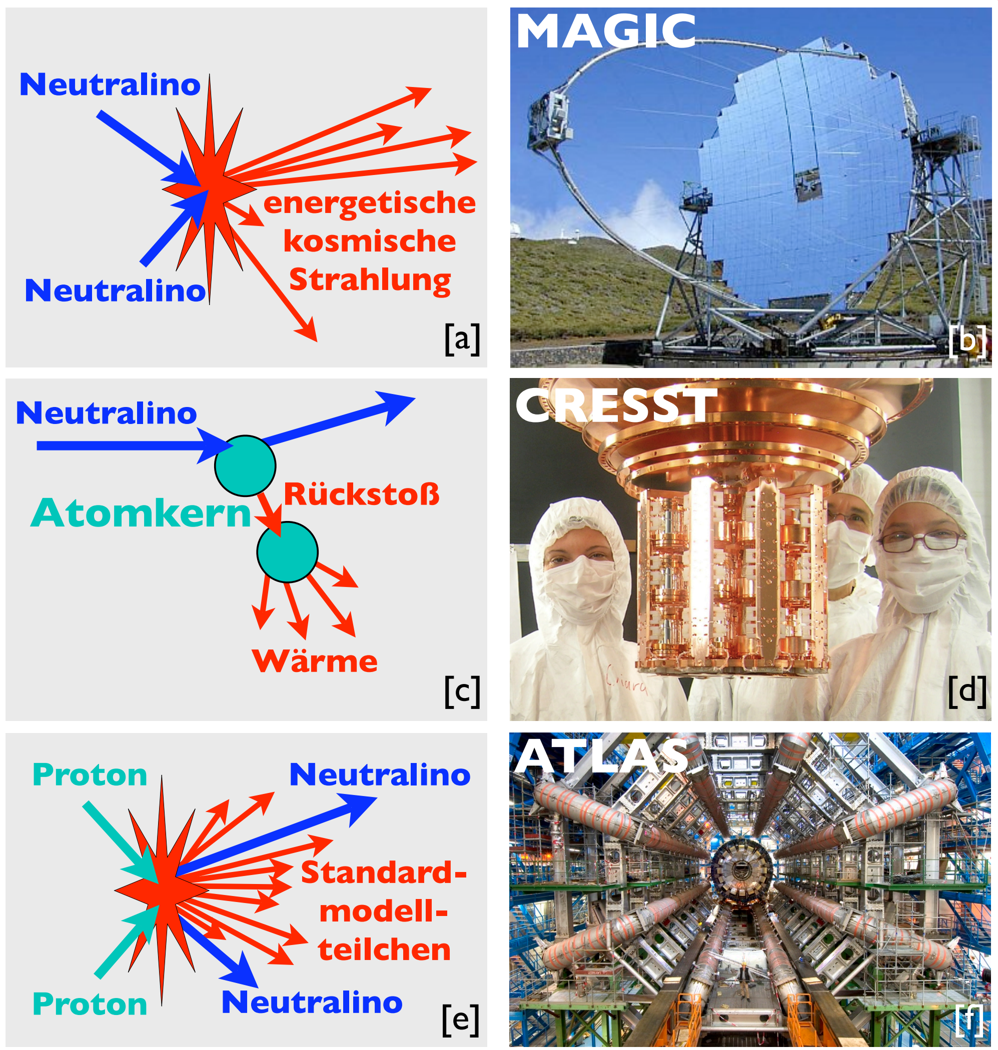
$\widetilde{\chi}_1^0$ LSP Dark Matter: Production, Constraints, Experiments

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

↓

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





promising experimental prospects

... 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	$\left(\frac{p}{\text{M}_{\text{Pl}}}\right)^n$
$*$ gravity		the graviton		SUSY breaking	extremely weak

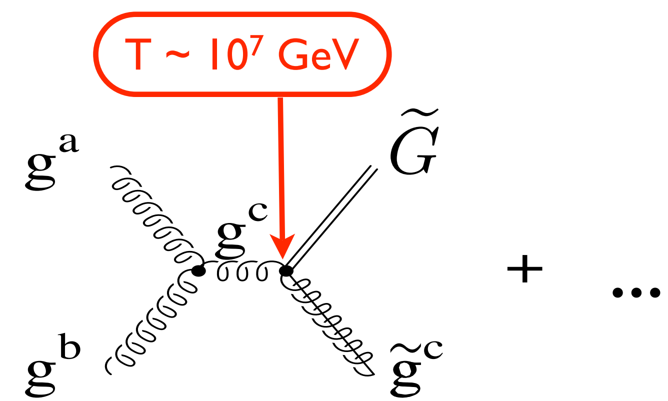
$$m_{\widetilde{G}} \sim \sum_I \frac{\langle F_I \rangle}{\text{M}_{\text{Pl}}} + \sum_A \frac{\langle D_A \rangle}{\text{M}_{\text{Pl}}} \sim \frac{M_{\text{SUSY}}^2}{\text{M}_{\text{Pl}}}$$

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

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

Very Early Hot Universe

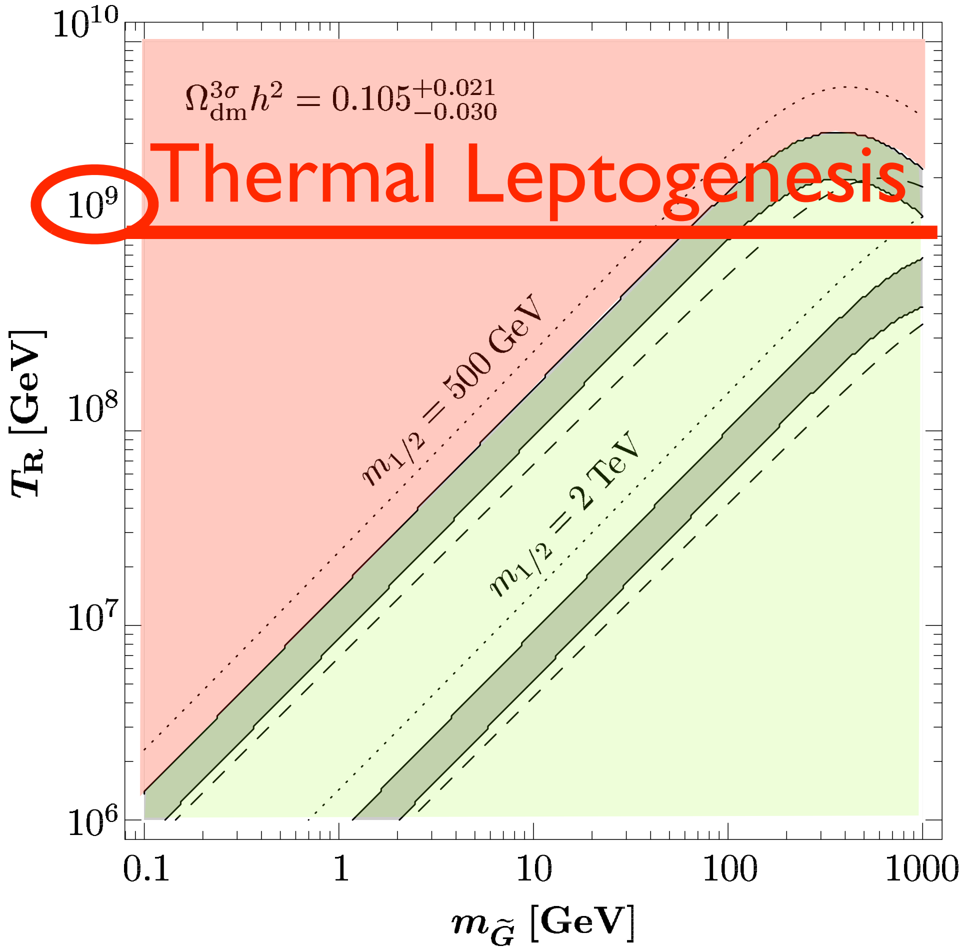


[... ; Bolz, Brandenburg, Buchmüller, '01]

[Pradler, FDS, '06]

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

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]

LSP Dark Matter: Production, Constraints, Experiments

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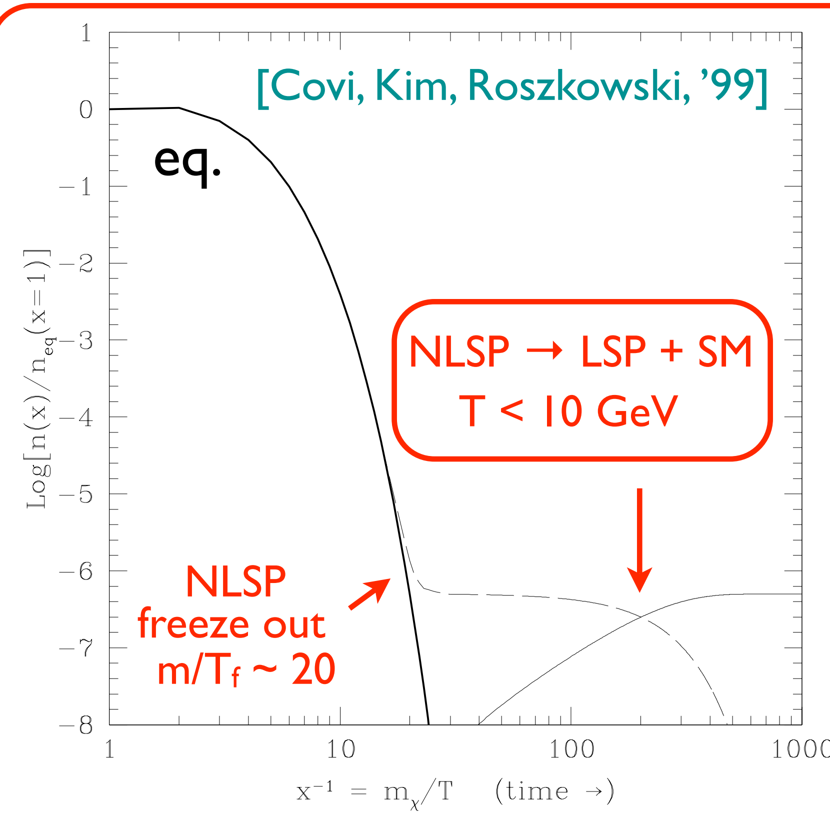
	$M_{Pl} = 2.44 \times 10^{18}$ GeV	...		



NLSP Candidates

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

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
$\widetilde{\chi}_1^0$	g, g'	WIMP	← cold	indirect detection (EGRET, GLAST, ...)
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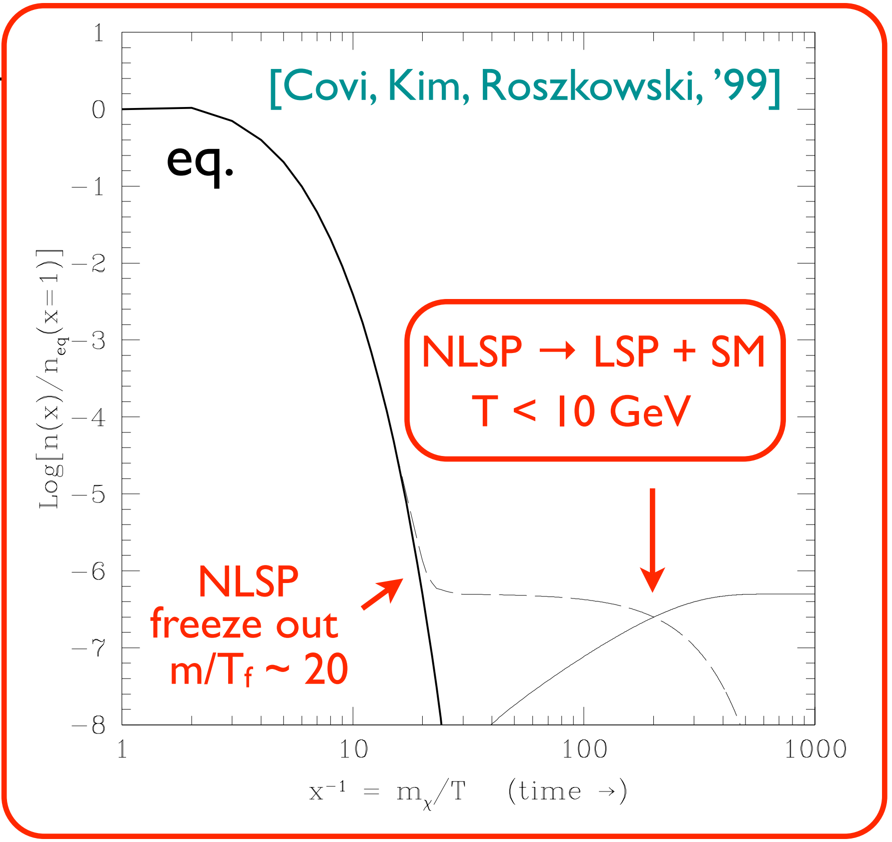
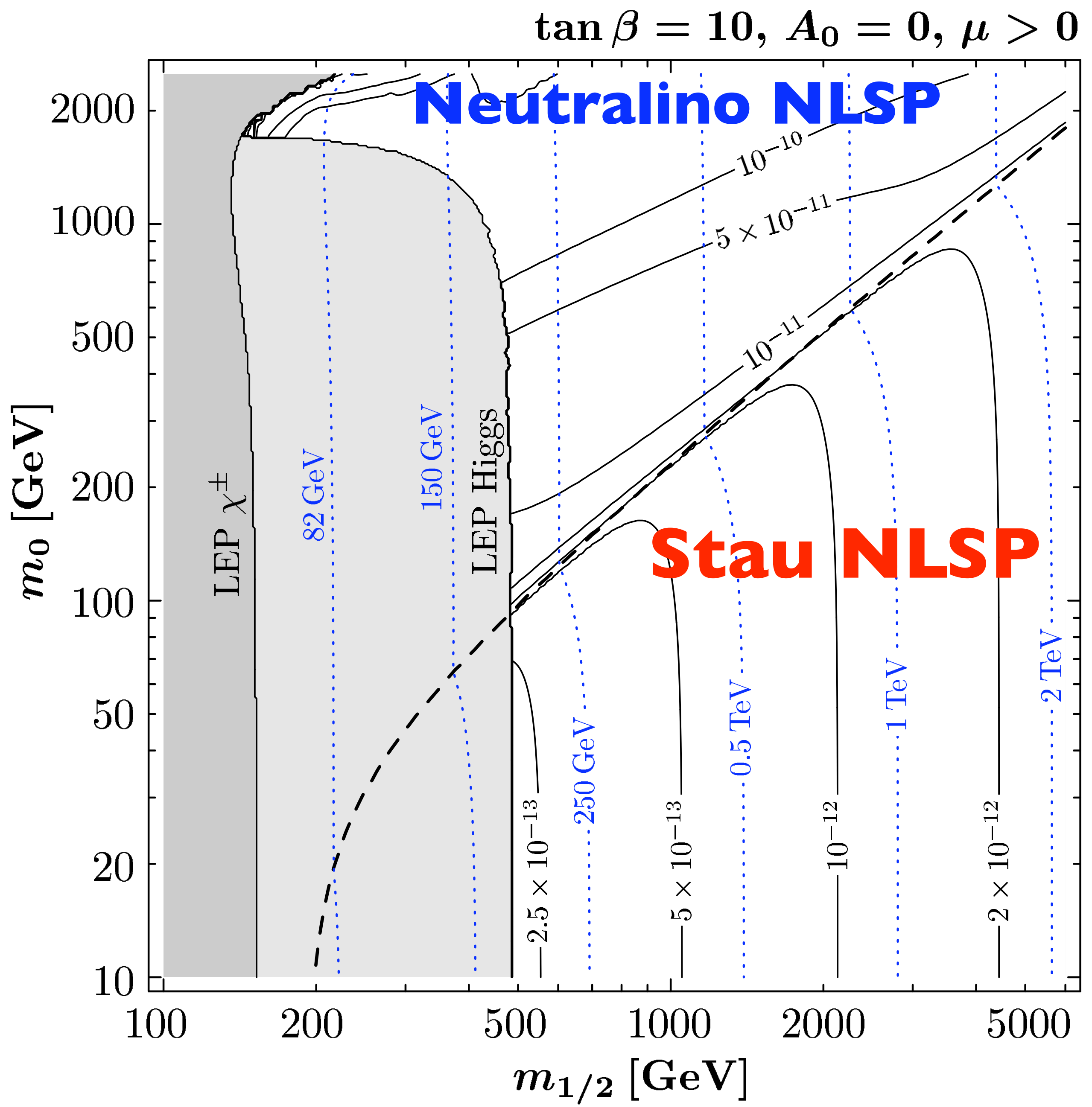


NLSP Candidates

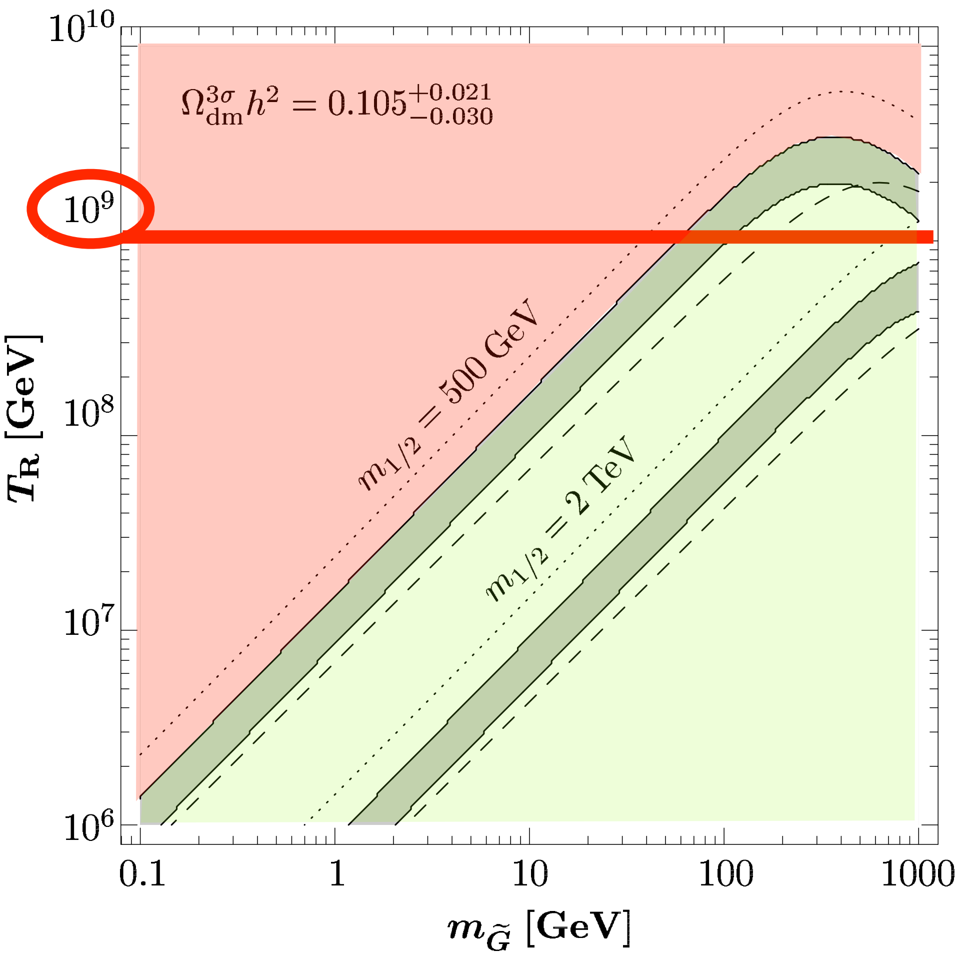
electrically charged →

- **lightest neutralino**
- **lighter stau**
- **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 $\chi^{\pm}$
LEP Higgs
82 GeV
150 GeV
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

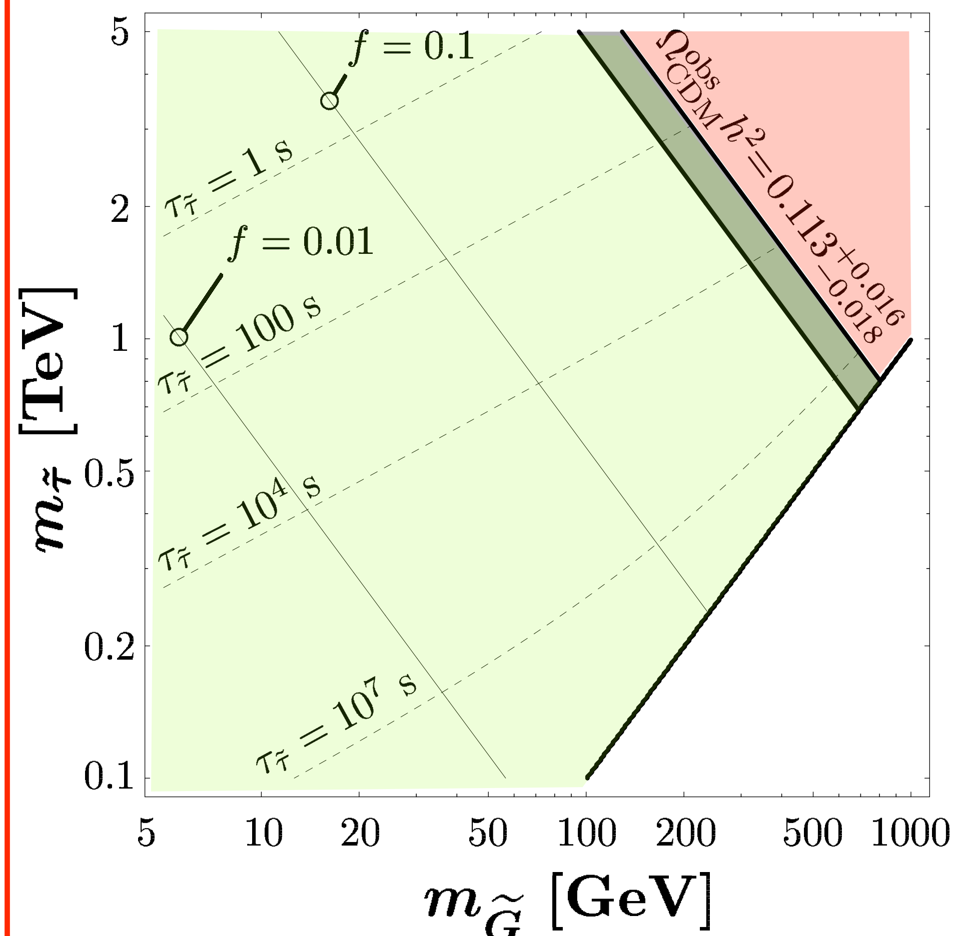
Thermal $\widetilde{G}$ Production



[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

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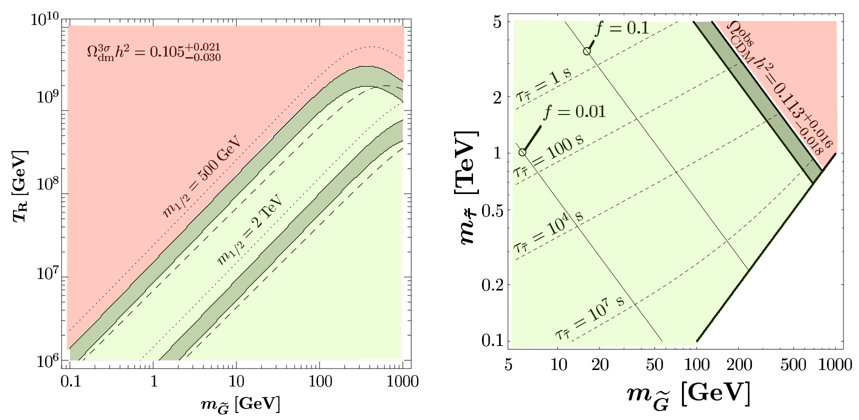
	$M_W \sim 100$ GeV			prod.@colliders (Tevatron, LHC, ILC, ...)
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	
	extremely weak	NLSP decays	$\leftarrow$ warm	
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV	...		

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

is possible!!!



LSP Dark Matter: Production, Constraints, Experiments

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$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	
	extremely weak	NLSP decays	$\leftarrow$ warm	
			BBN	
			CMB	
			γ rays	

Can we probe Gravitino DM in experiments?

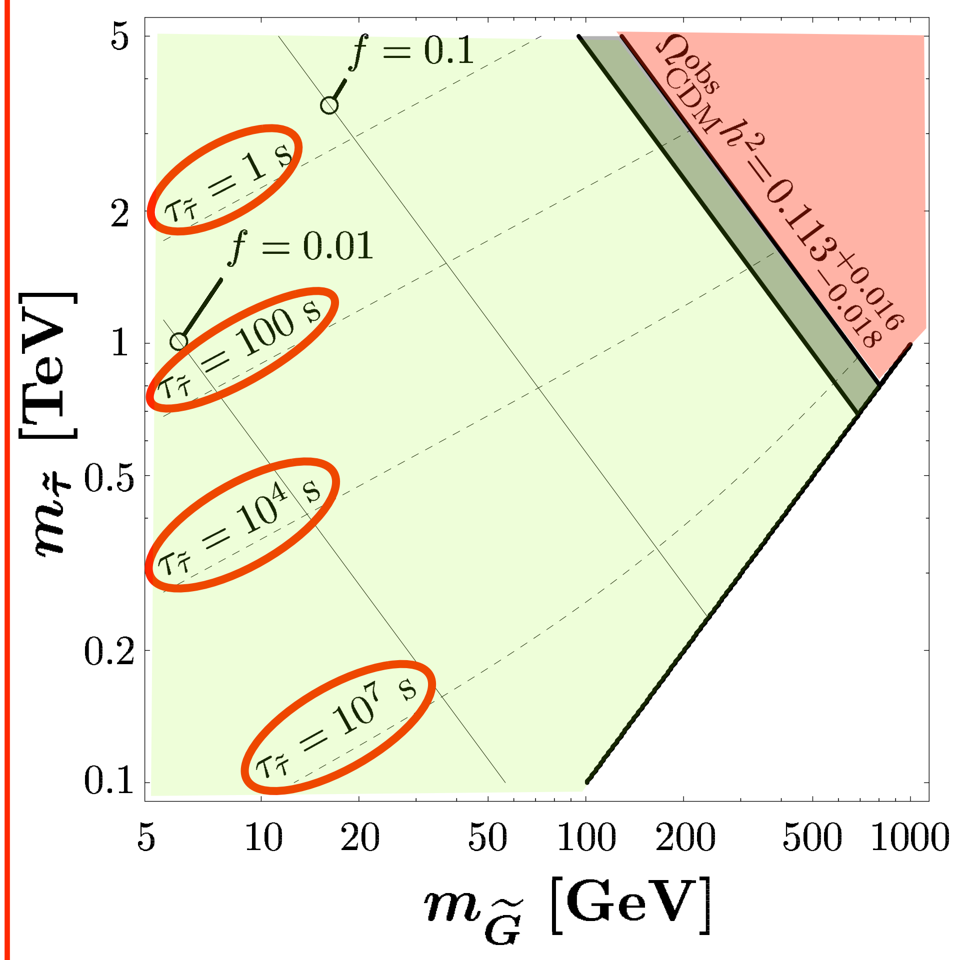
Signatures of Gravitinos in Experiments

– Direct Detection of $\widetilde{G}$

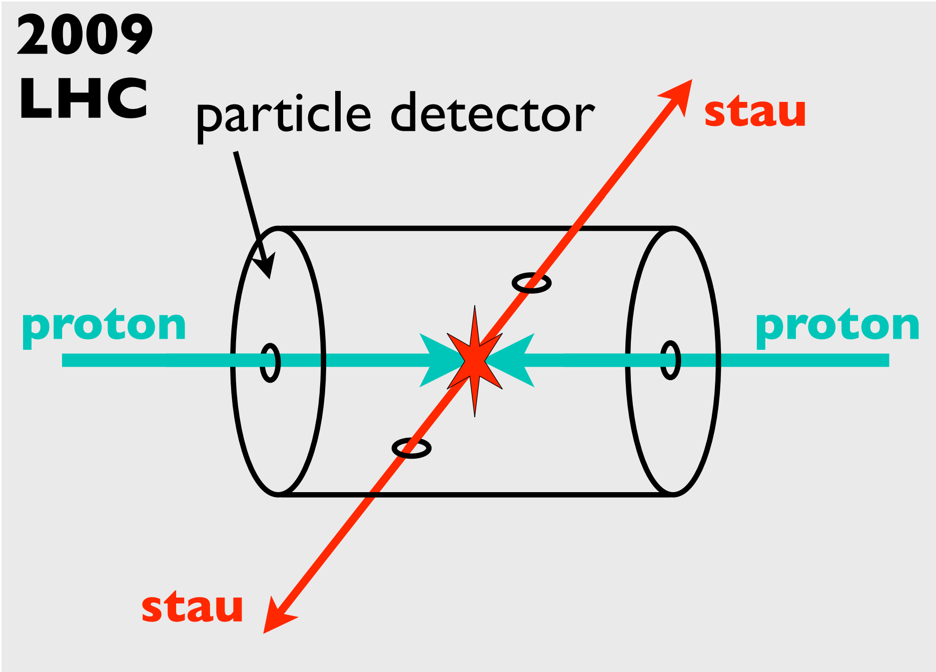
– Direct Production of $\widetilde{G}$

long-lived NLSP

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

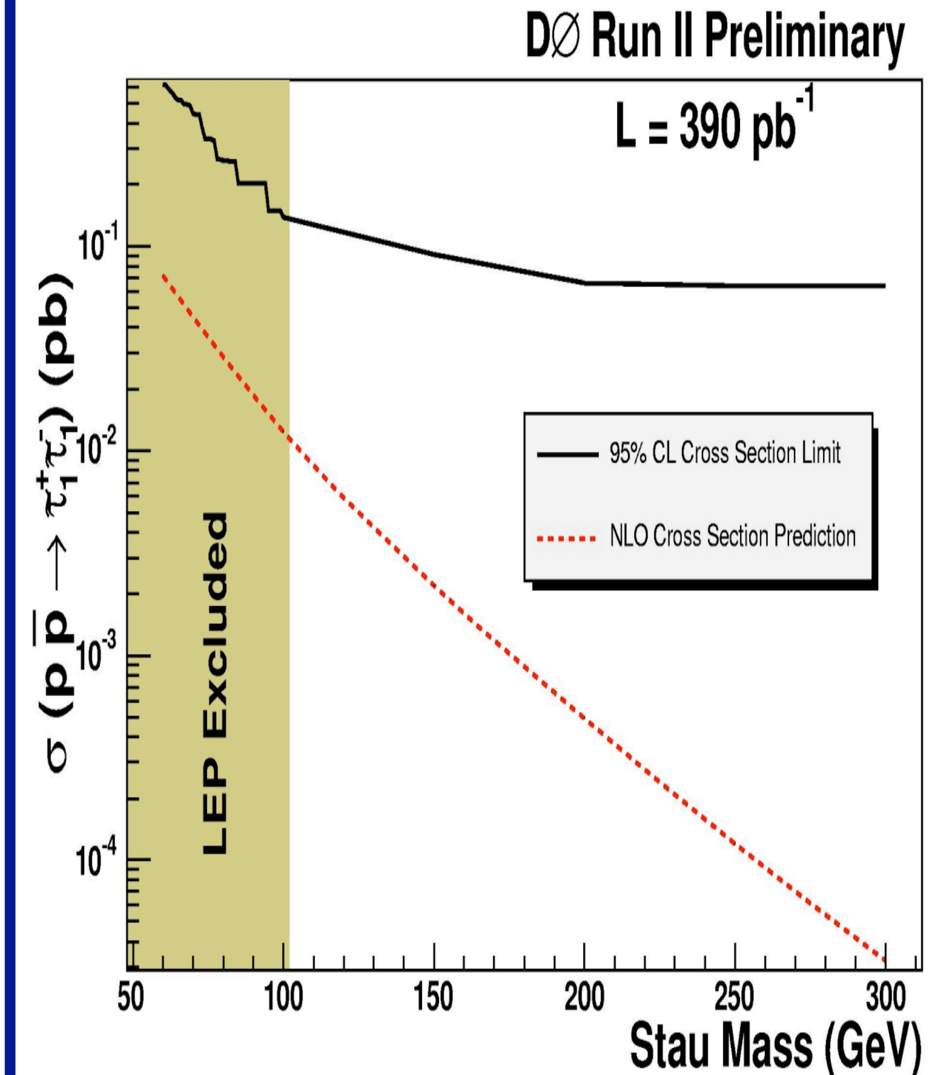


Gravitino DM @ LHC ⟵ Stau NLSP



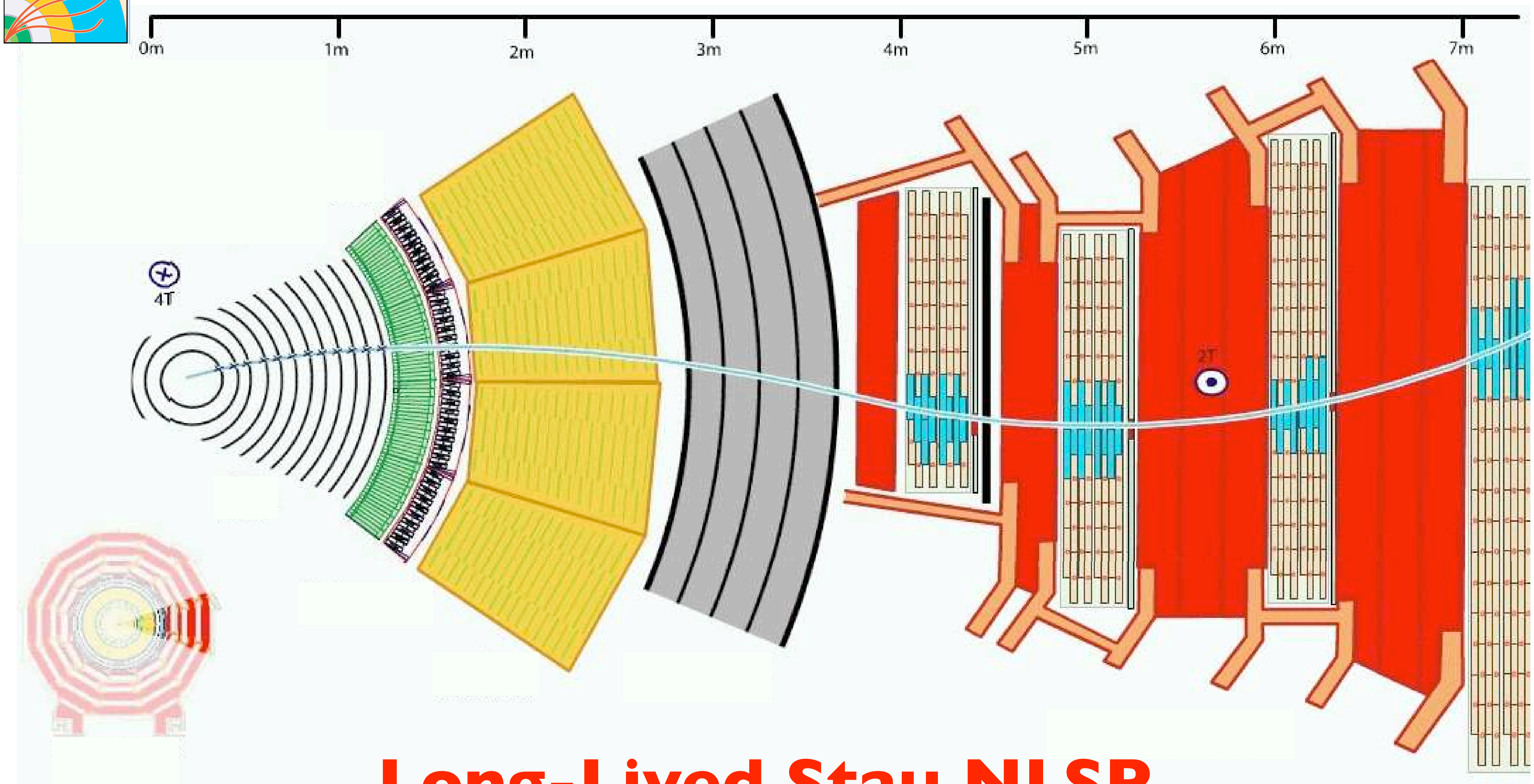
The signal:
jets + leptons
+ 2 “stable” charged particles

Tevatron



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

“Stable” Charged Massive Particle @ LHC



Long-Lived Stau NLSP

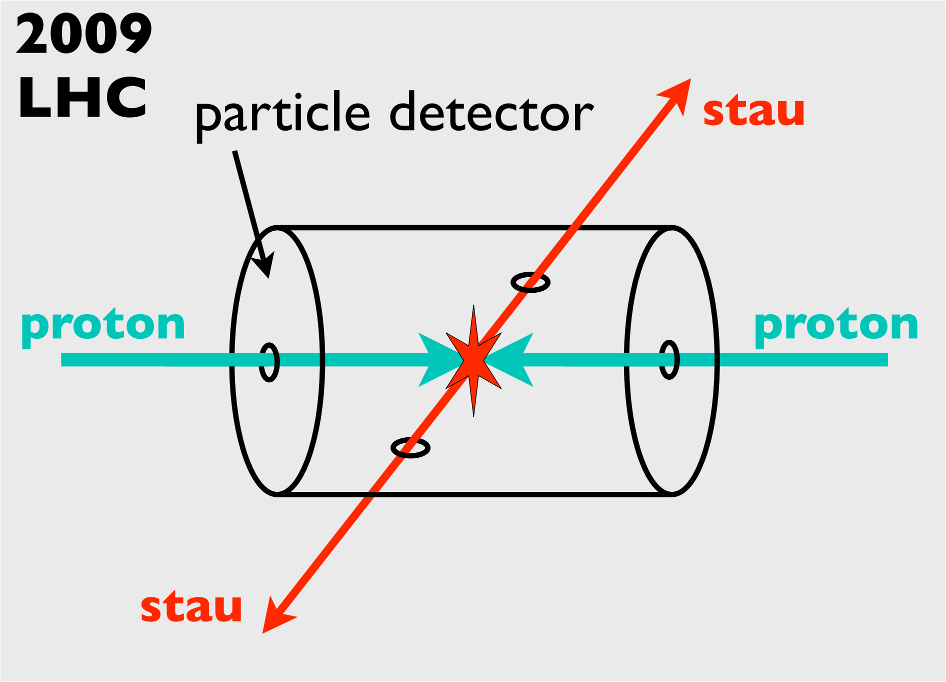
[from P. Zalewski’s Talk, SUSY 2007]

Signatures of Gravitinos in Experiments

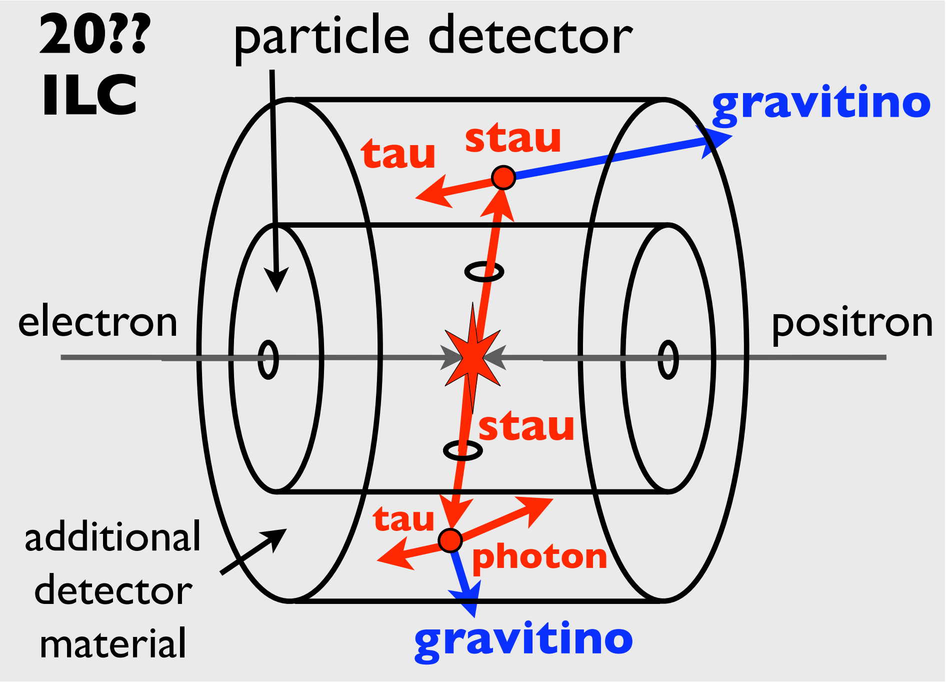
– Direct Detection of $\widetilde{G}$

– 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; ...]

LSP Dark Matter: Production, Constraints, Experiments

LSP	interaction	production	constraints	experiments
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	weak	freeze out		direct detection (CRESST, EDELWEISS, ...)
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$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	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	...		+ $\widetilde{\tau}$ decay analysis: $m_{\widetilde{G}}$, $\mathrm{M_{Pl}}$ (?), ...
			BBN	
			CMB	
			γ rays	

LSP Dark Matter: Production, Constraints, Experiments

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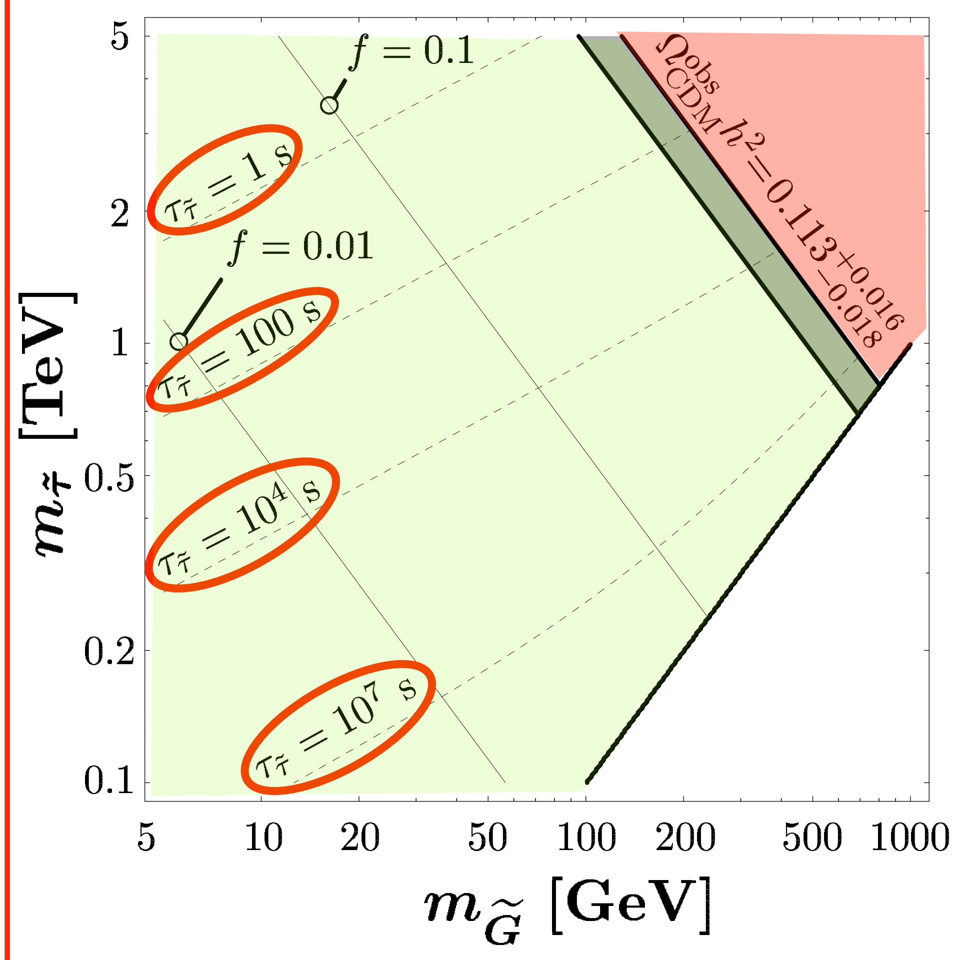
			BBN	
			CMB	
			γ rays	

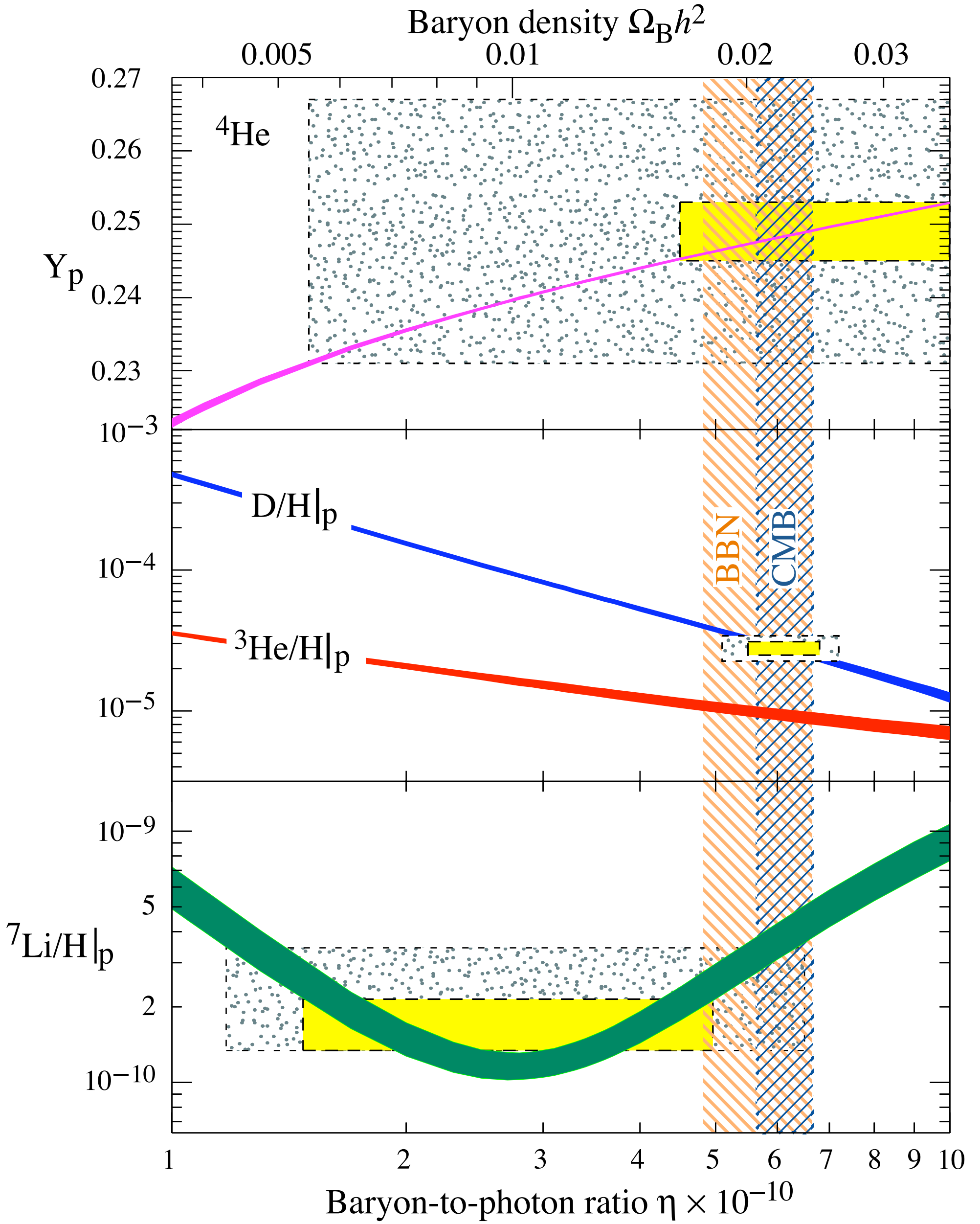
Does your theory allow for successful BBN?

long-lived NLSP

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

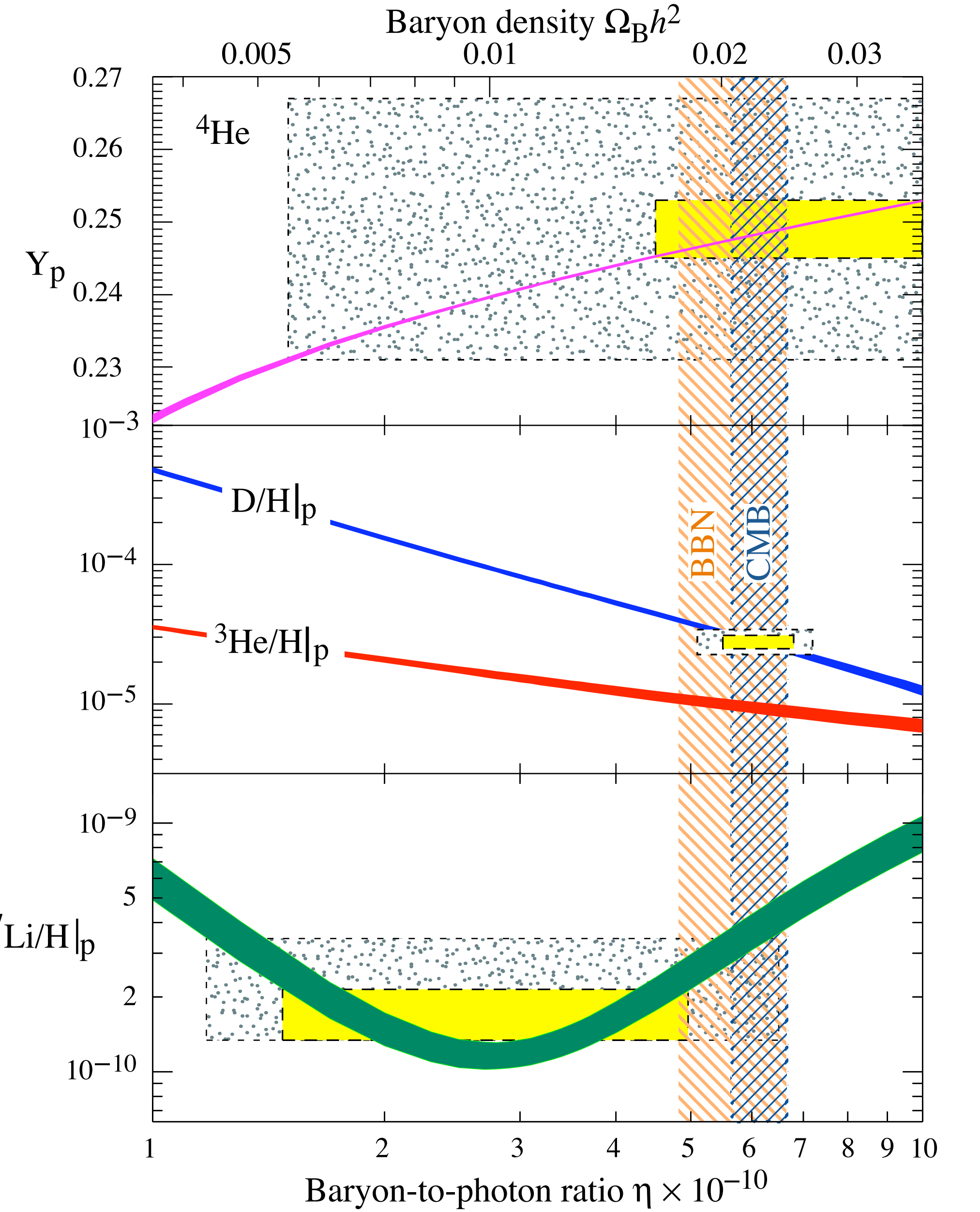


Big-Bang Nucleosynthesis



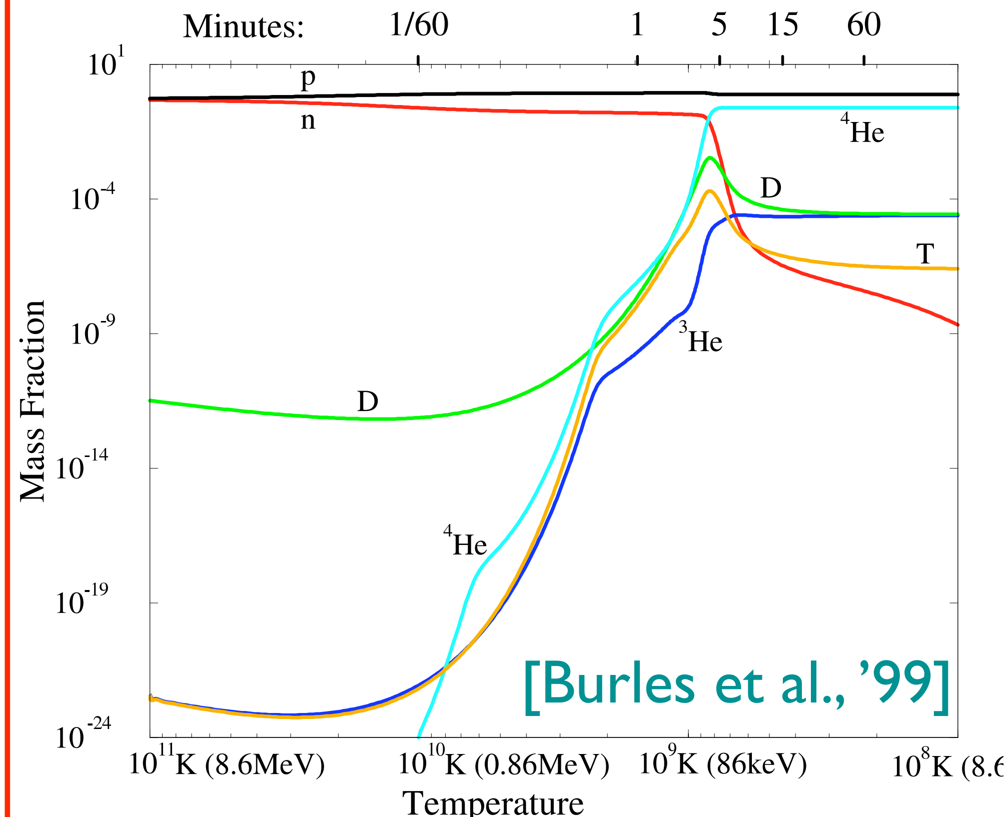
[Particle Data Book 2006]

Big-Bang Nucleosynthesis

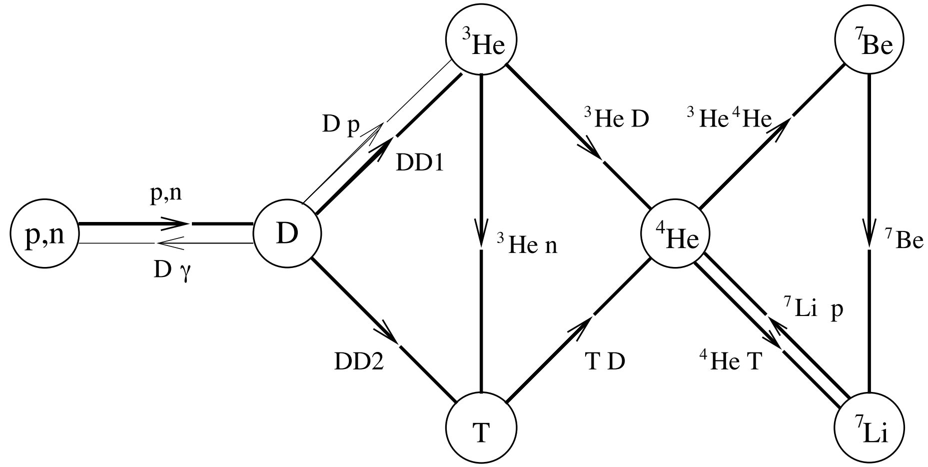


[Particle Data Book 2006]

SBBN

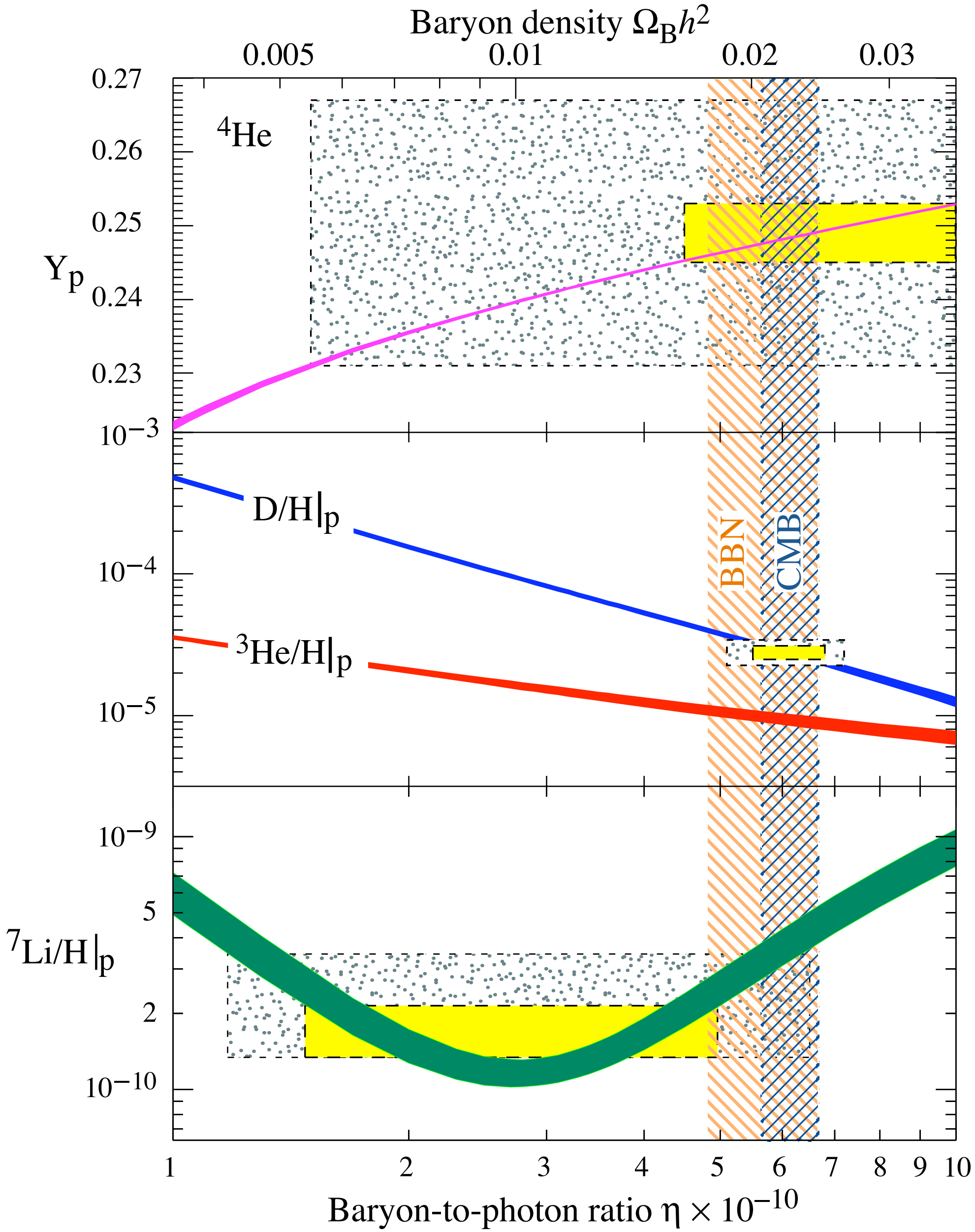


[Burles et al., '99]



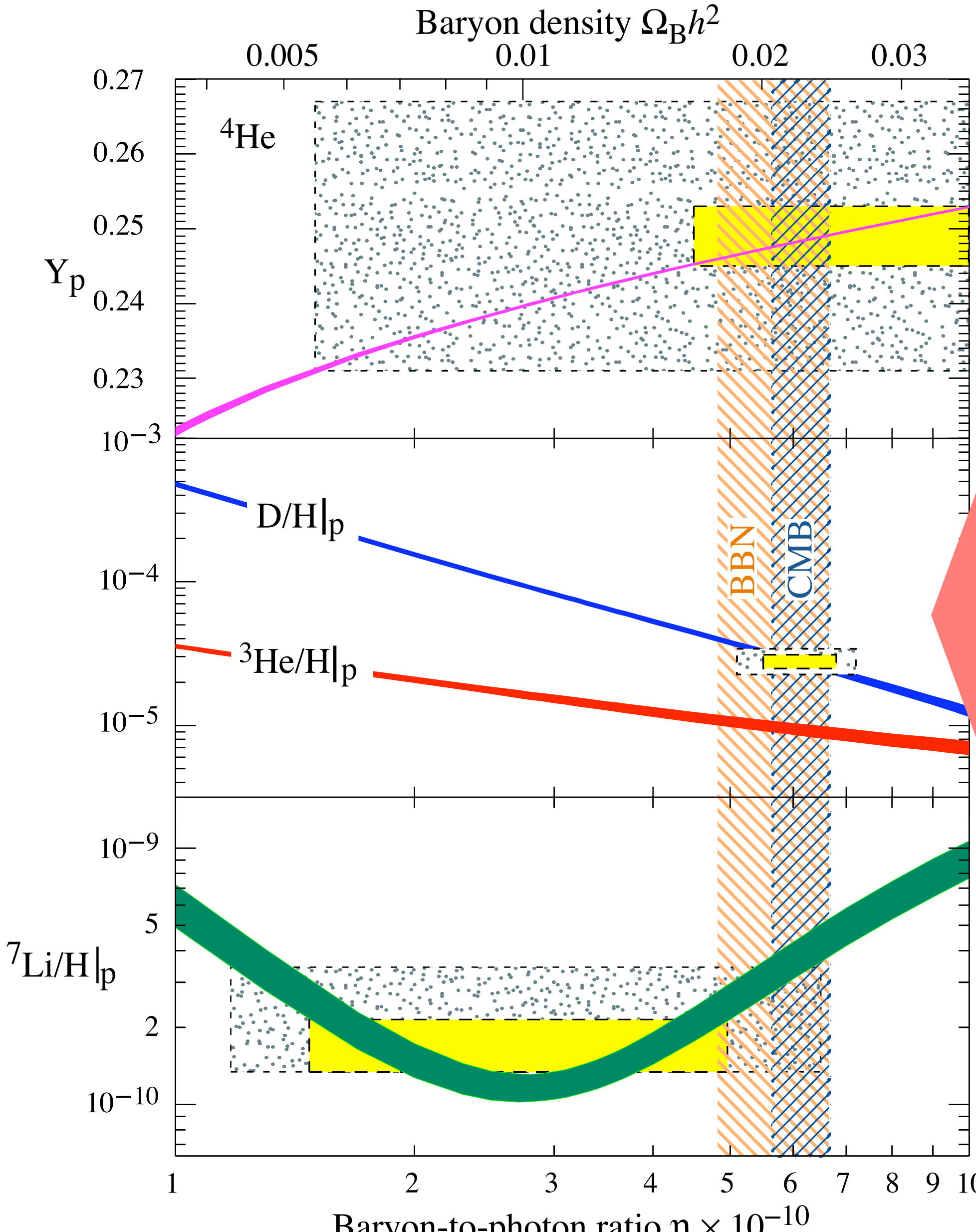
[V. Mukhanov, '04]

Big-Bang Nucleosynthesis

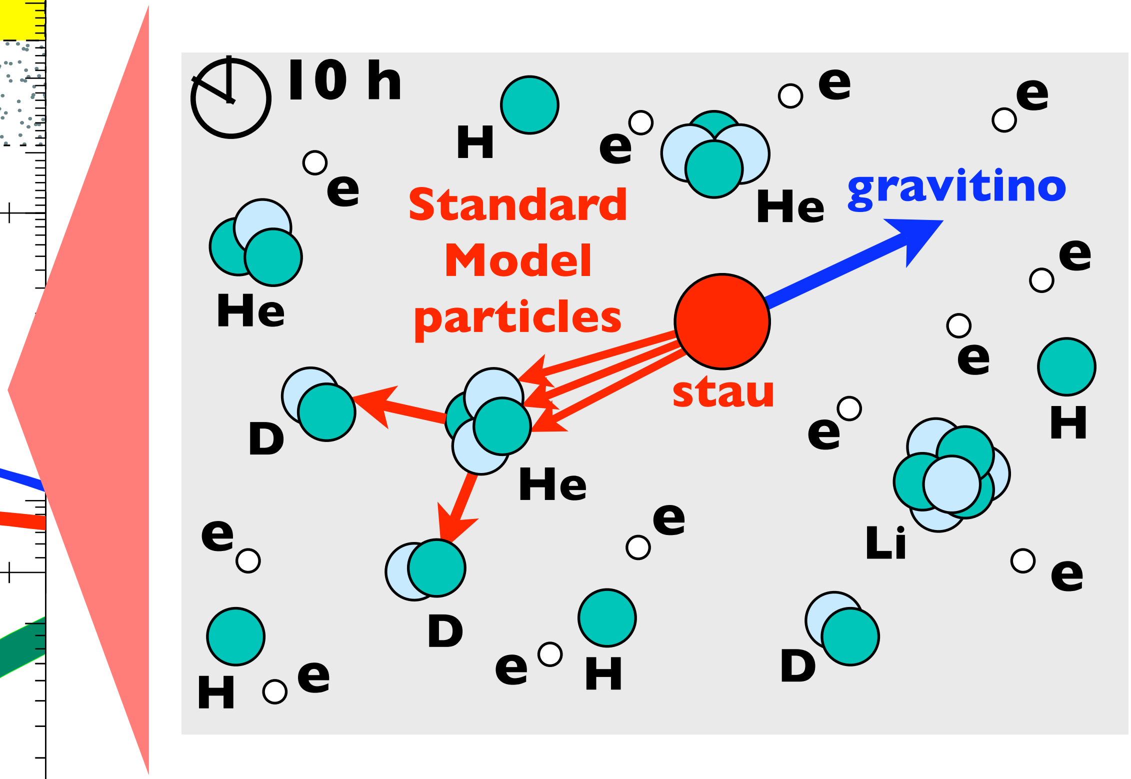


[Particle Data Book 2006]

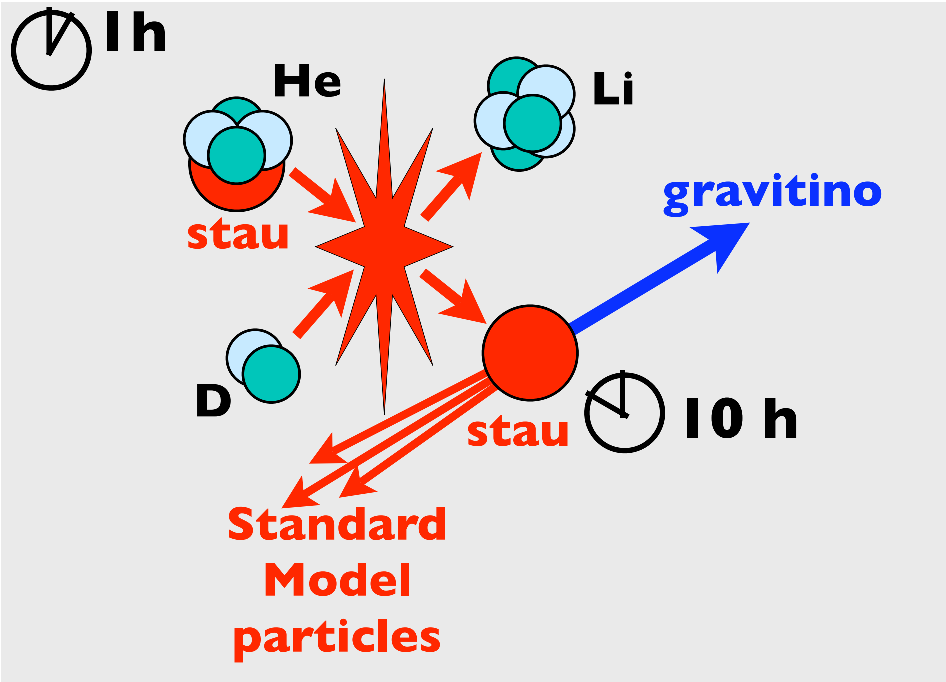
Big-Bang Nucleosynthesis



[Particle Data Book 2006]



Catalyzed BBN [Pospelov, '06]

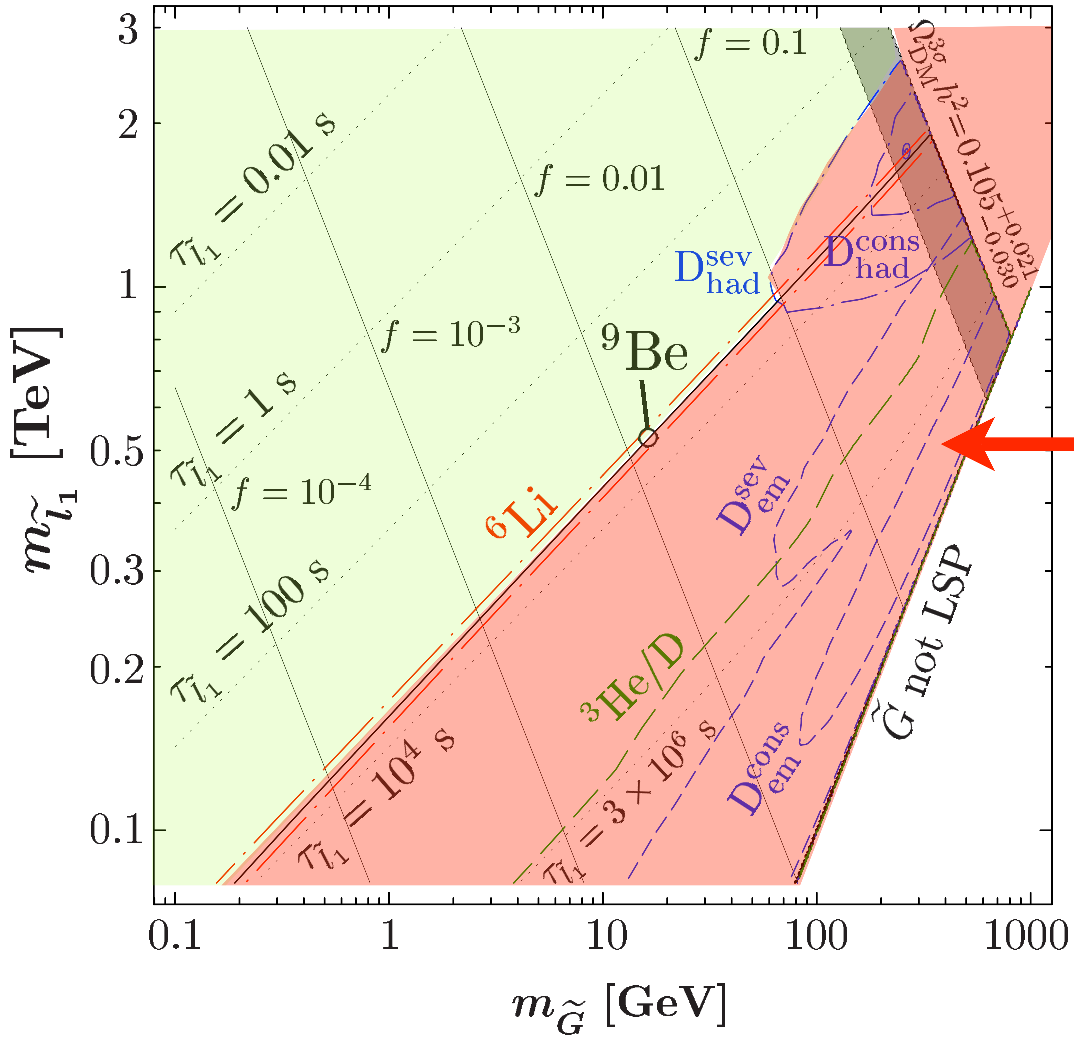


[Cyburt et al., '06; FDS, '06; Pradler, FDS, '07; Hamaguchi et al., '07; Kawasaki, Kohri, Moroi, '07; Takayama, '07; Jedamzik, '07; Pradler, FDS, '08]

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

[Pospelov, Pradler, FDS, '08]

Current Status of (C)BBN Constaints

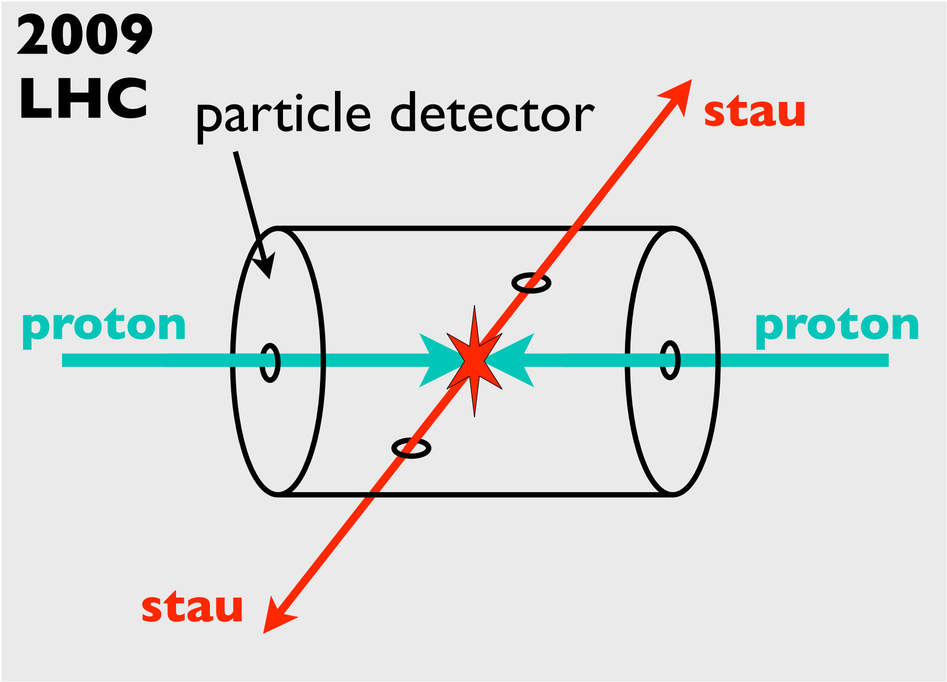


disfavored by cosmological constraints

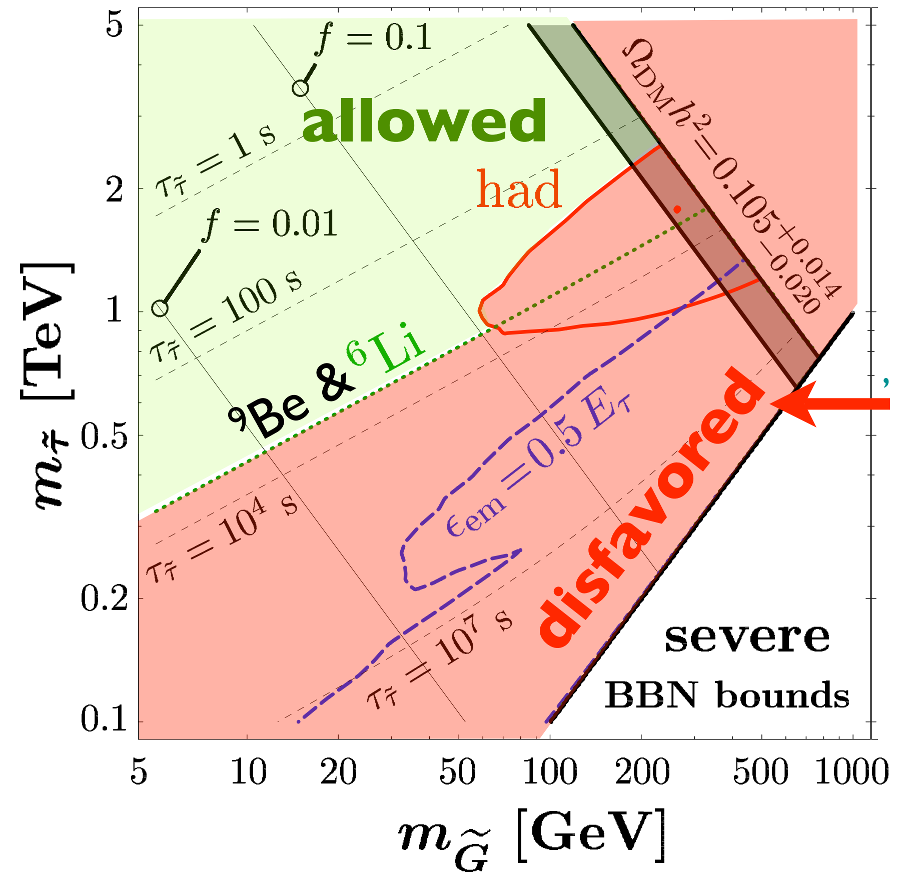
see also [FDS, hep-ph/0611027]

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

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	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$
* gravity		the graviton	SUSY breaking	extremely weak
* local SUSY				$\mathrm{M_{Pl}} = 2.44 \times 10^{18}\ \mathrm{GeV}$
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

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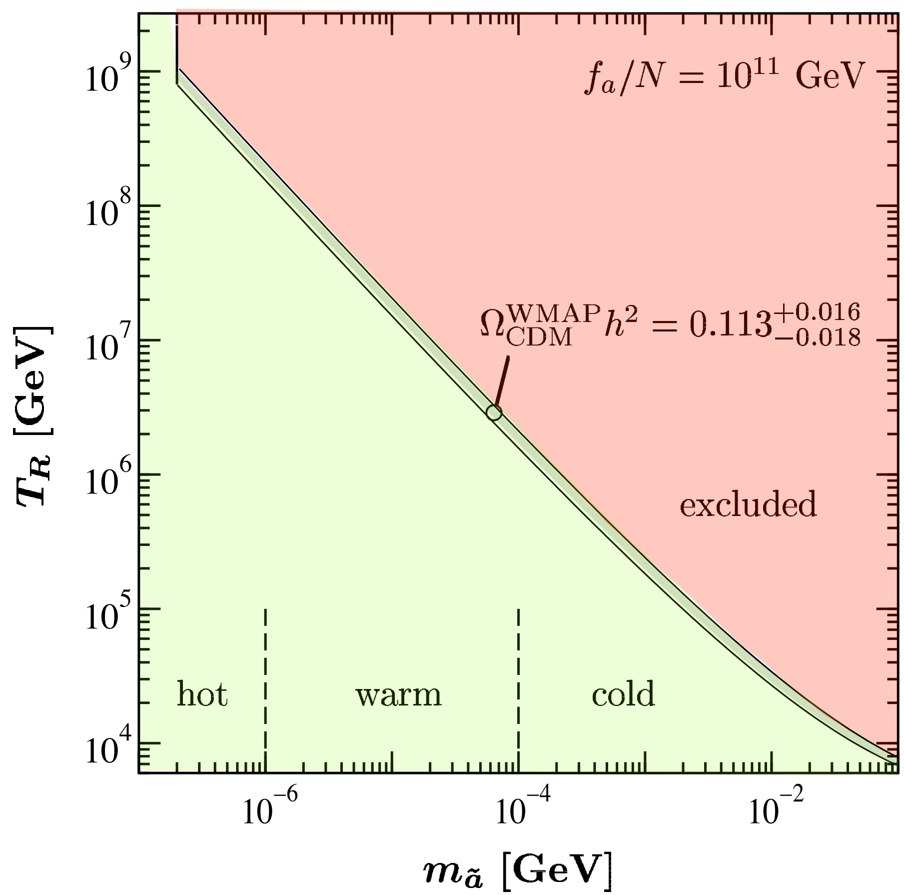
$\widetilde{G}$	$\left(\frac{p}{\mathrm{M_{Pl}}}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	$\leftarrow$ warm	+ $\widetilde{\tau}$ collection
	$\mathrm{M_{Pl}} = 2.44 \times 10^{18}$ GeV	...	BBN	+ $\widetilde{\tau}$ decay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

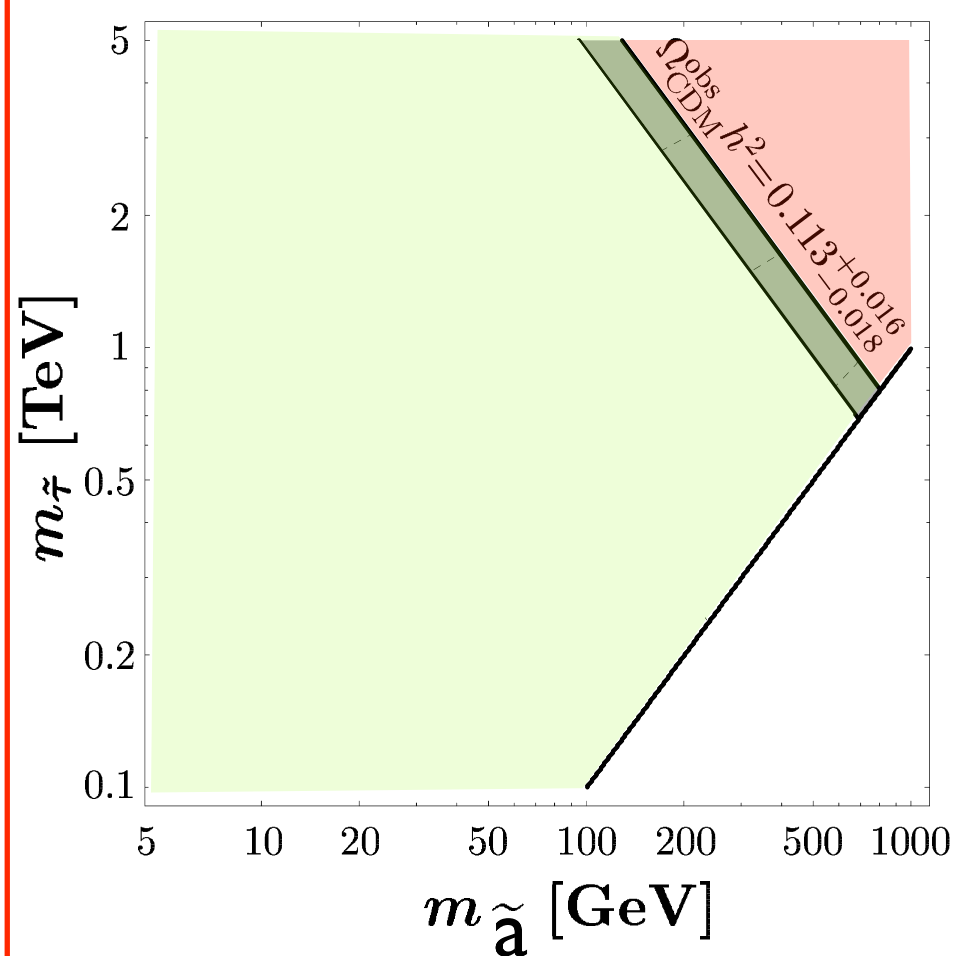
Thermal $\tilde{a}$ Production



[Brandenburg, FDS, '04]

see also [Covi et al., '01]

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



identical to the gravitino case

LSP Dark Matter: Production, Constraints, Experiments

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$\widetilde{a}$	$\left(\frac{p}{f_a}\right)^n$	therm. prod.	$\leftarrow$ cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
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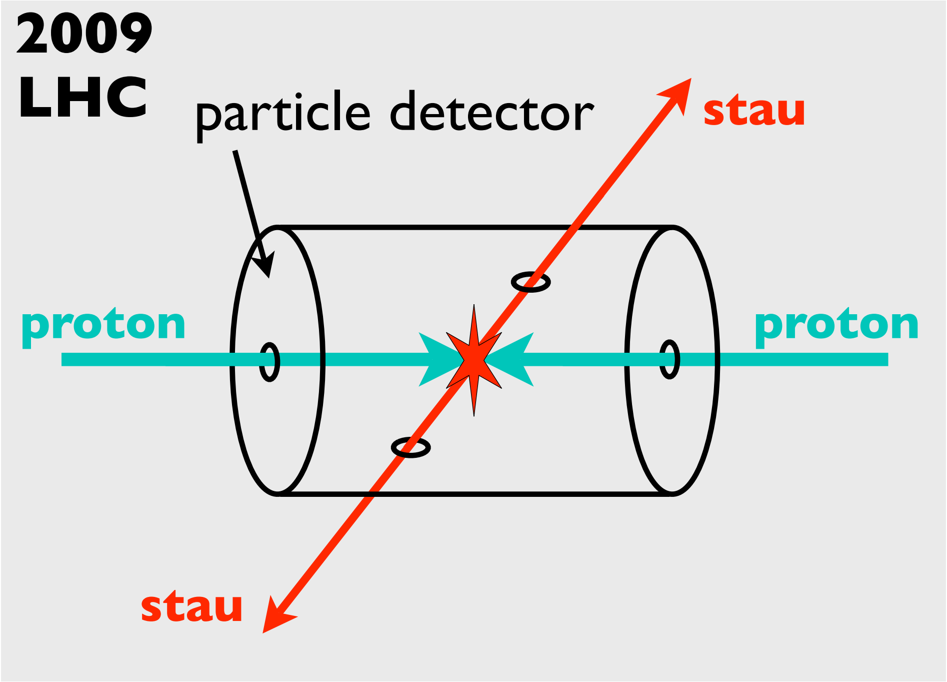
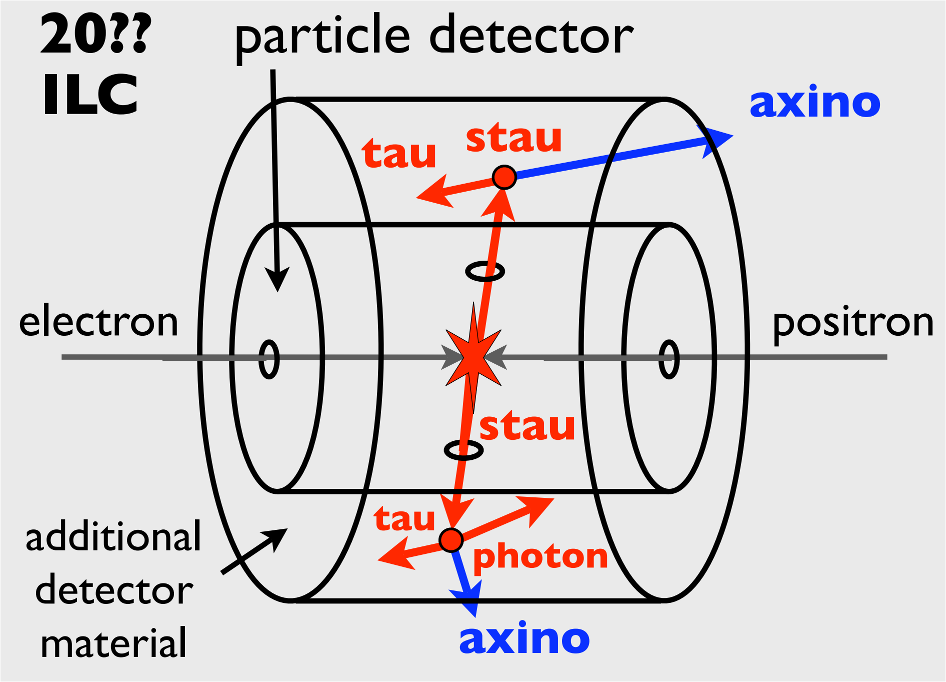

2009
LHC
particle detector
stau
proton
proton
stau


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?

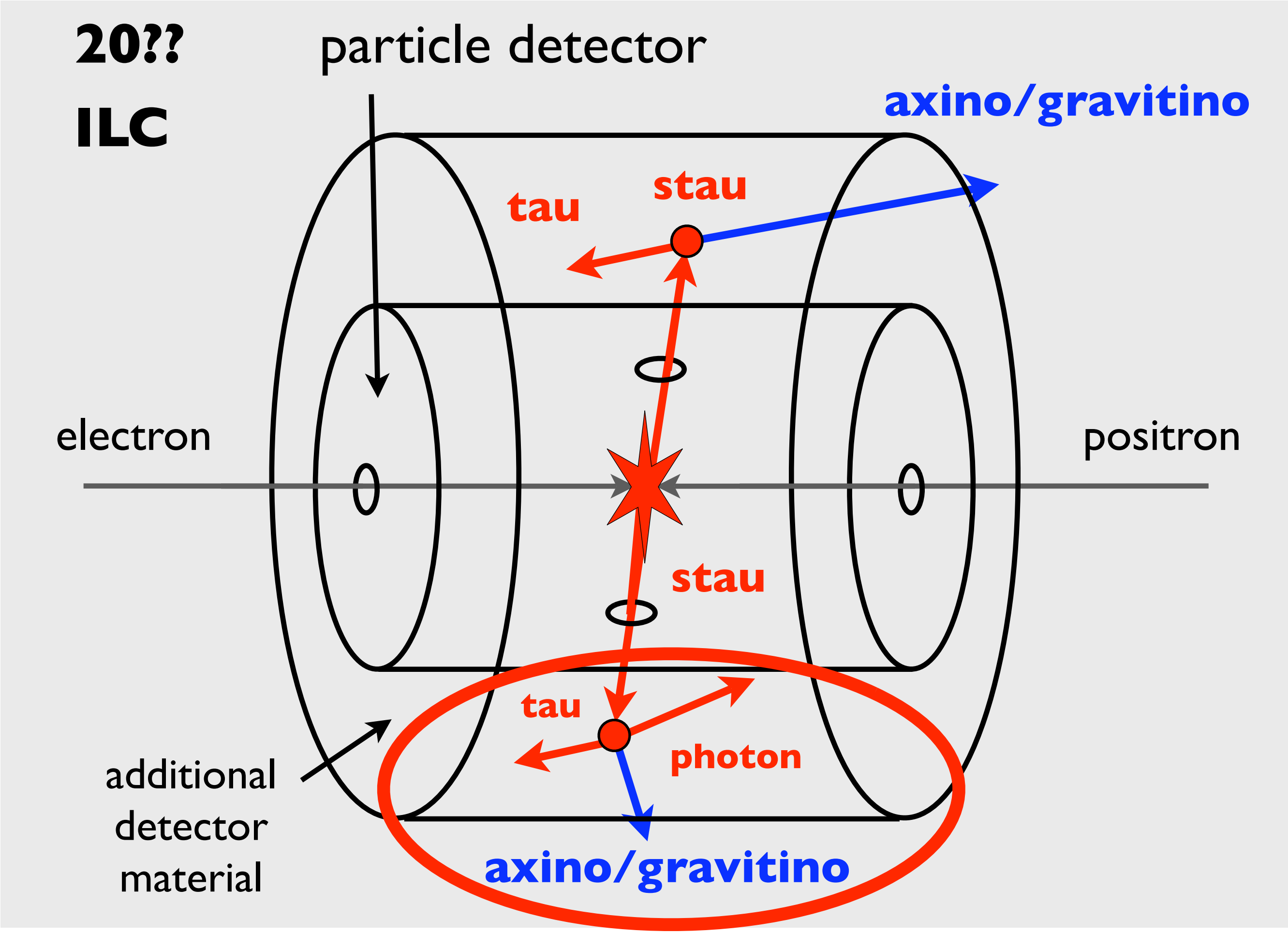
[Brandenburg, Covi, Hamaguchi, Roszkowski, FDS, '05]

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

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

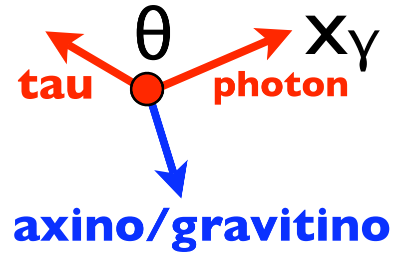
$\tilde{a}$ = LSP	$\widetilde{G}$ = LSP
$\tau_{\widetilde{\tau}}^{\tilde{a}\,\mathrm{LSP}} \longleftarrow m_{\widetilde{\tau}}, m_{\widetilde{B}}, m_{\tilde{a}}, f_a$	$\tau_{\widetilde{\tau}}^{\widetilde{G}\,\mathrm{LSP}} \longleftarrow m_{\widetilde{\tau}}, m_{\widetilde{B}}, m_{\widetilde{G}}$
$\mathcal{O}(0.01\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

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

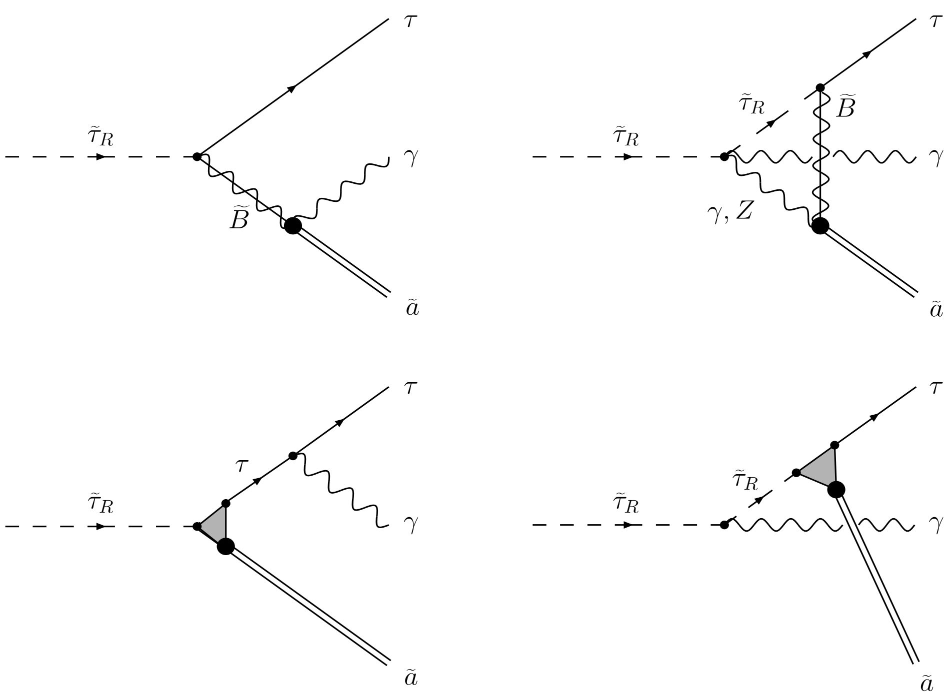


3-Body Decays

The 3-Body Decays

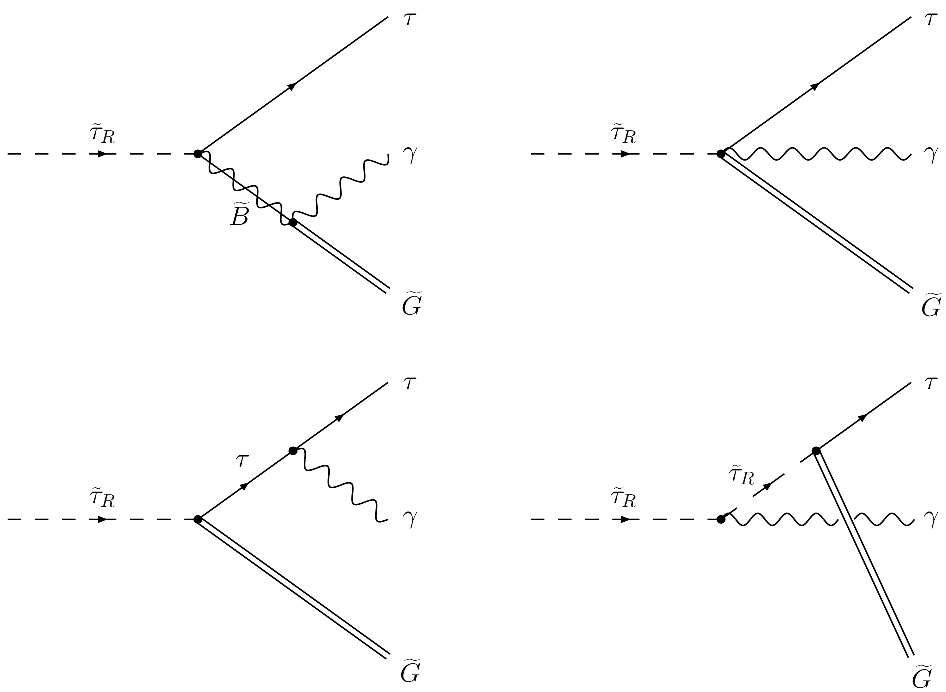


$\tilde{a} = \text{LSP}: \quad \tilde{\tau}_R \to \tau + \gamma + \tilde{a}$



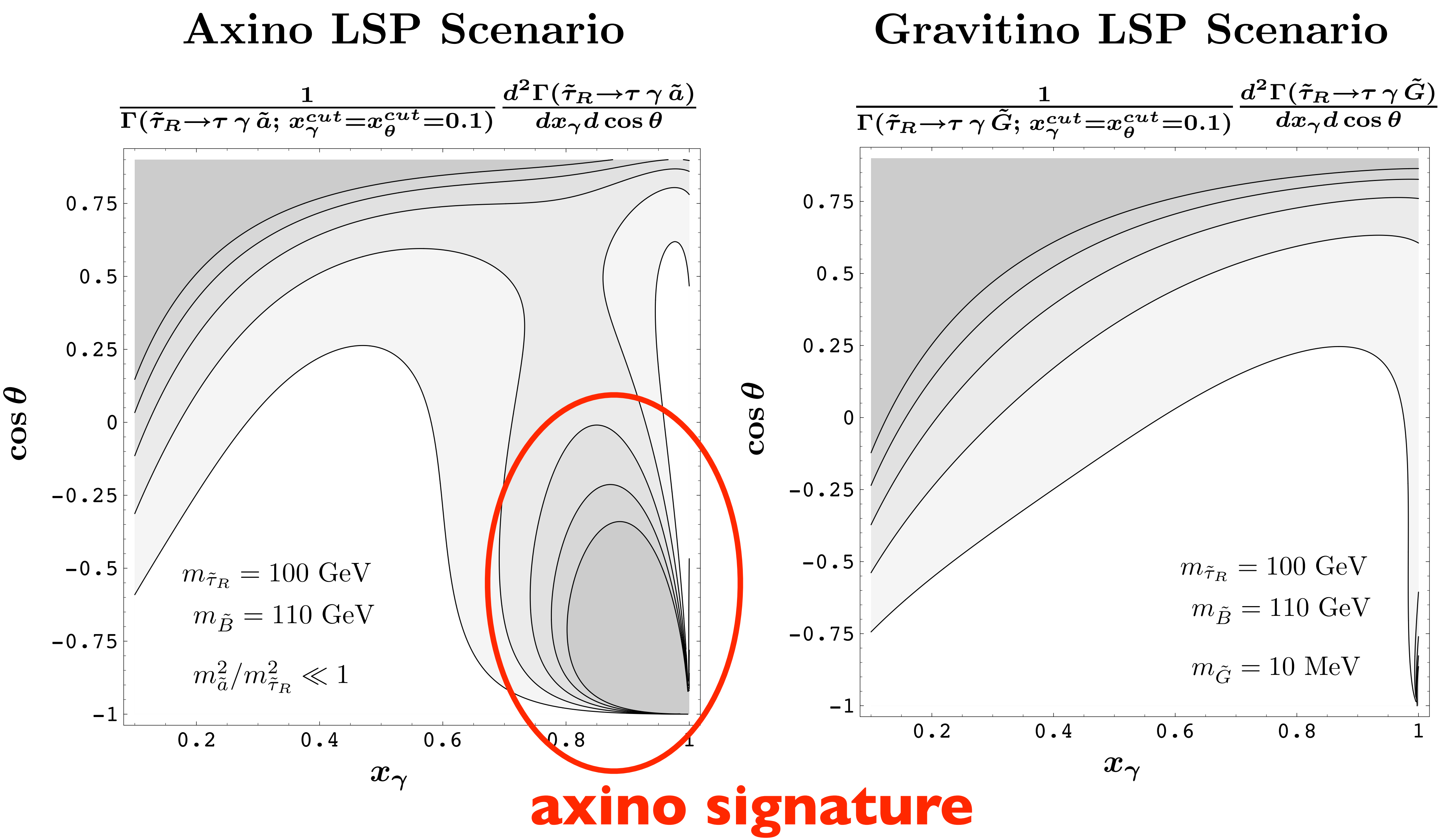
$$\frac{d^2\Gamma(\widetilde{\tau}_{\rm R} \to \tau\, \gamma\, \widetilde{a})}{dx_\gamma\, d\cos\theta} = \ldots$$

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



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

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



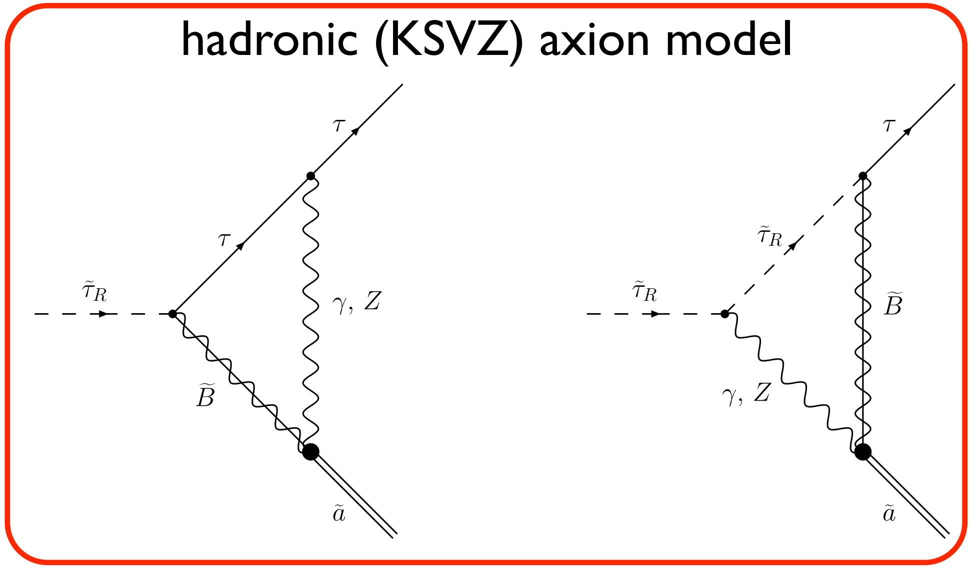
Differential Distribution of the Visible Decay Products

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

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

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

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



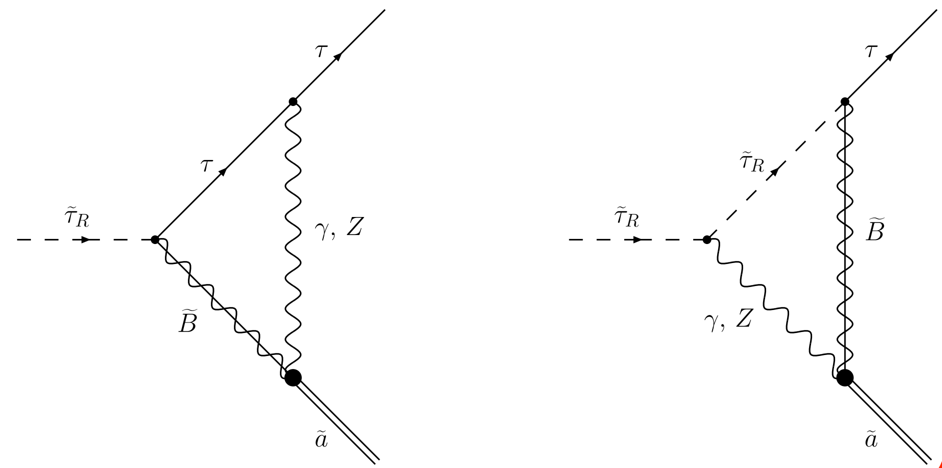
$$\Gamma(\widetilde{\tau}_R \rightarrow \tau \widetilde{a}) \simeq \xi^2 \, (25 \, \mathrm{sec})^{-1} C_{\mathrm{aYY}}^2 \left(1 - \frac{m_{\widetilde{a}}^2}{m_{\widetilde{\tau}}^2}\right) \left(\frac{m_{\widetilde{\tau}}}{100 \, \mathrm{GeV}}\right) \left(\frac{10^{11} \, \mathrm{GeV}}{f_a}\right)^2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

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

$\tilde{a}$ 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



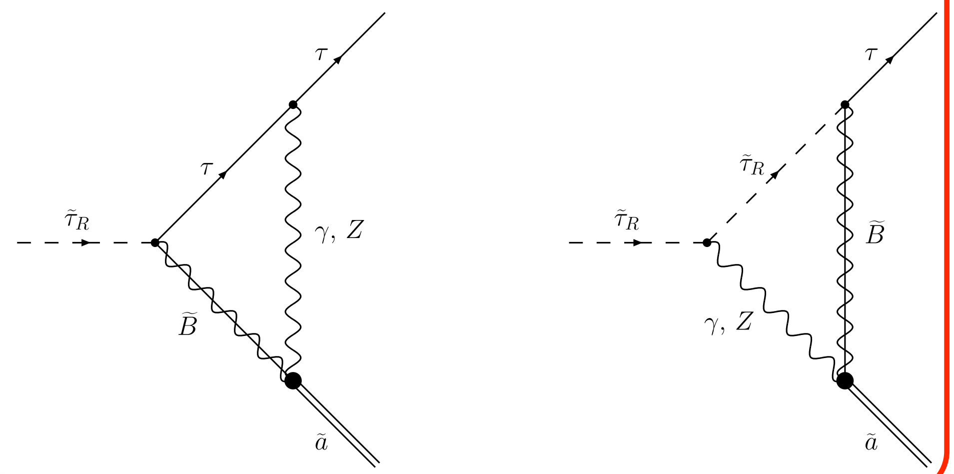
- 2-Body Decay $\widetilde{\tau}_R \rightarrow \tau + \tilde{a}$

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

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

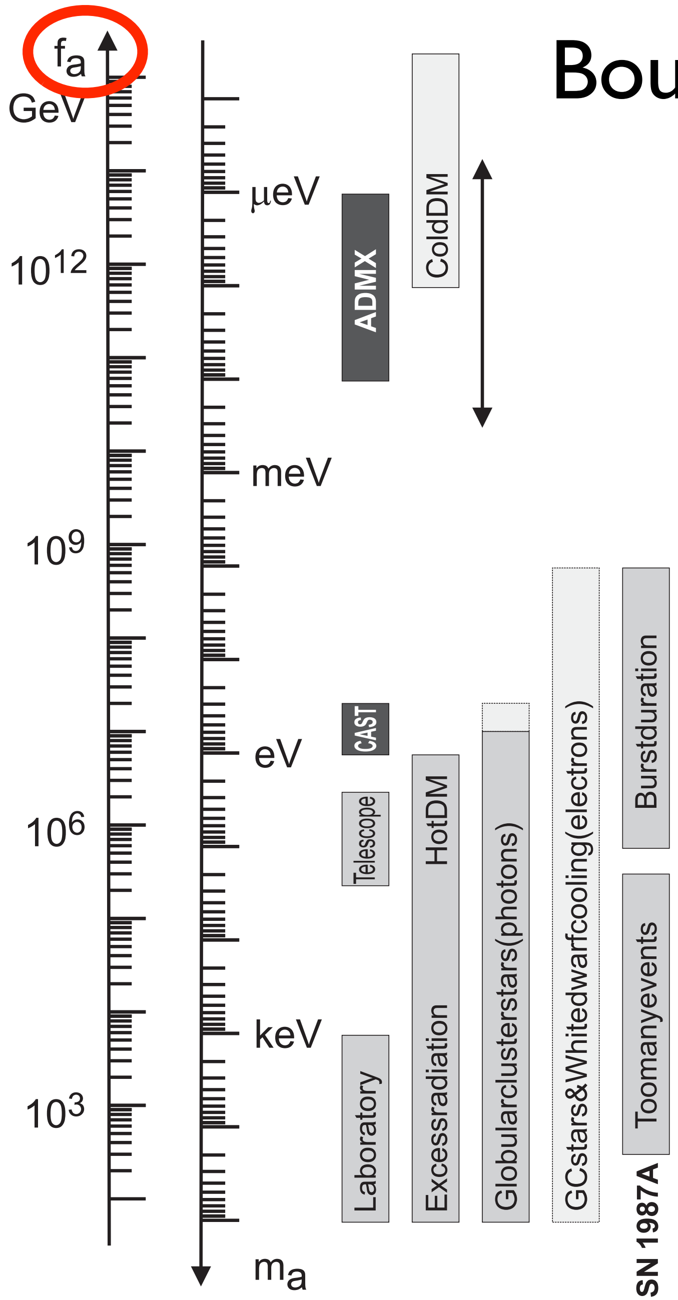
$$\Gamma(\widetilde{\tau}_{\rm R} \rightarrow \tau \widetilde{a}) \simeq \xi^2 \, (25\,\text{sec})^{-1} C^2_{\rm aYY} \left(1 - \frac{m^2_{\widetilde{a}}}{m^2_{\widetilde{\tau}}}\right) \left(\frac{m_{\widetilde{\tau}}}{100\,\text{GeV}}\right) \left(\frac{10^{11}\,\text{GeV}}{f_a}\right)^2 \left(\frac{m_{\widetilde{B}}}{100\,\text{GeV}}\right)^2$$

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

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

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

Bounds on the Peccei-Quinn Scale



Bounds from Axion Searches

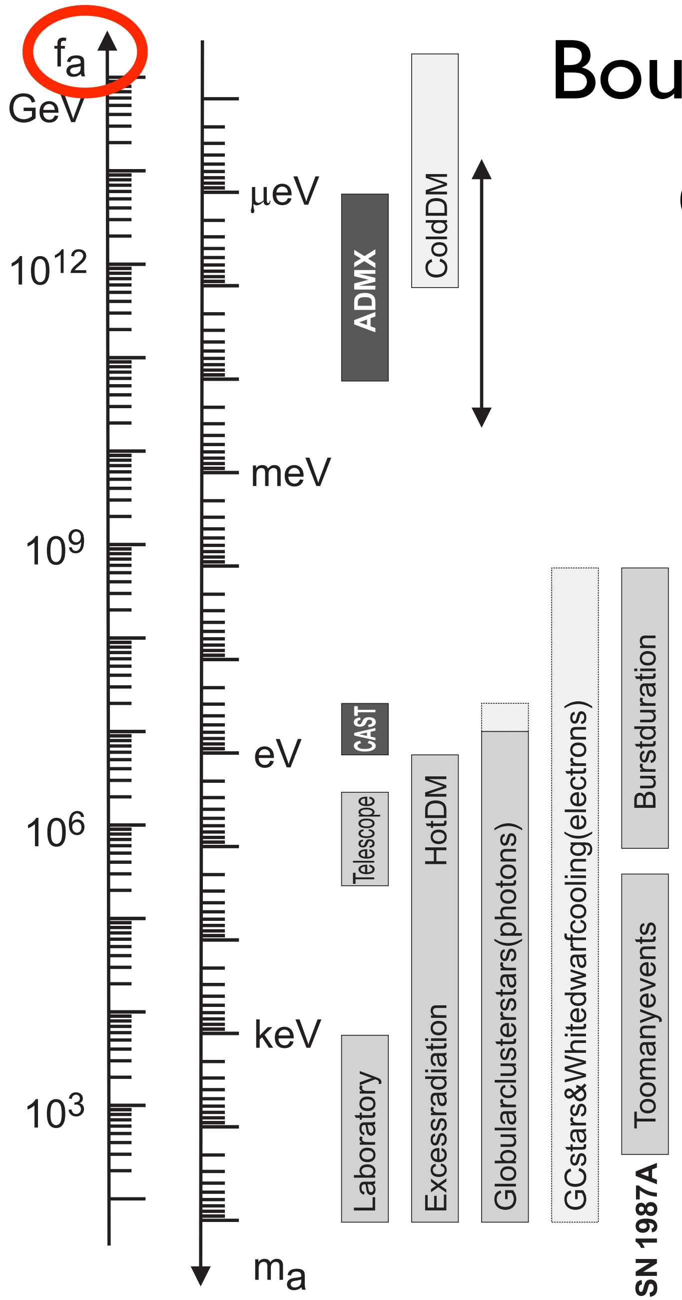
Cosmological Axion Bounds

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	← 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.	← cold	$\widetilde{\tau}$ prod. at colliders (LHC, ILC, ...)
	extremely weak	NLSP decays	← 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.	← 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: $m_{\tilde{a}}$, f_a