MPIK Seminar - Heidelberg, 9th July 2012

Gravitino & axino Dark Matter

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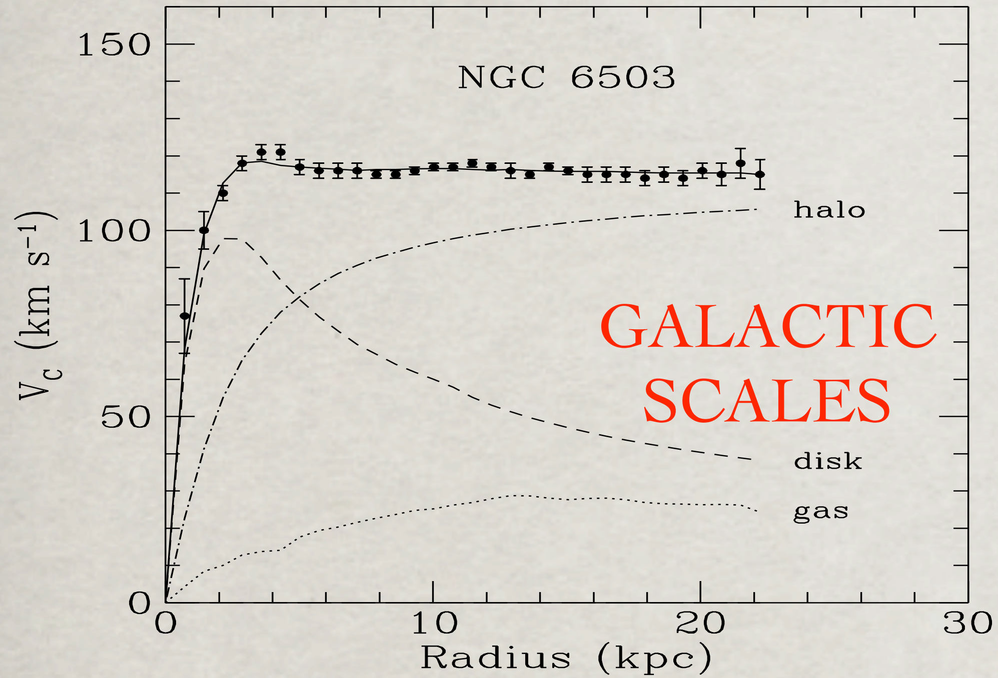
Outline

- Introduction:
  Dark Matter, SUSY & the Gravitino problem
- Stable Gravitino/Axino Cold Dark Matter
- Unstable Gravitino CDM
- Supersymmetric SuperWIMPs @ LHC
- Outlook

Introduction

DARK MATTER EVIDENCE



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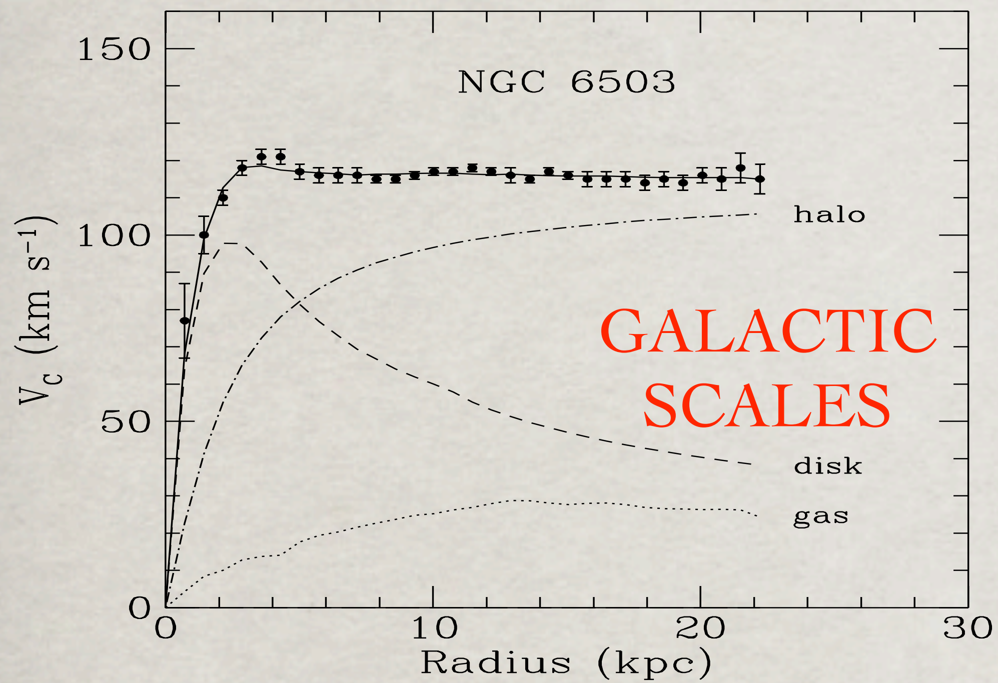

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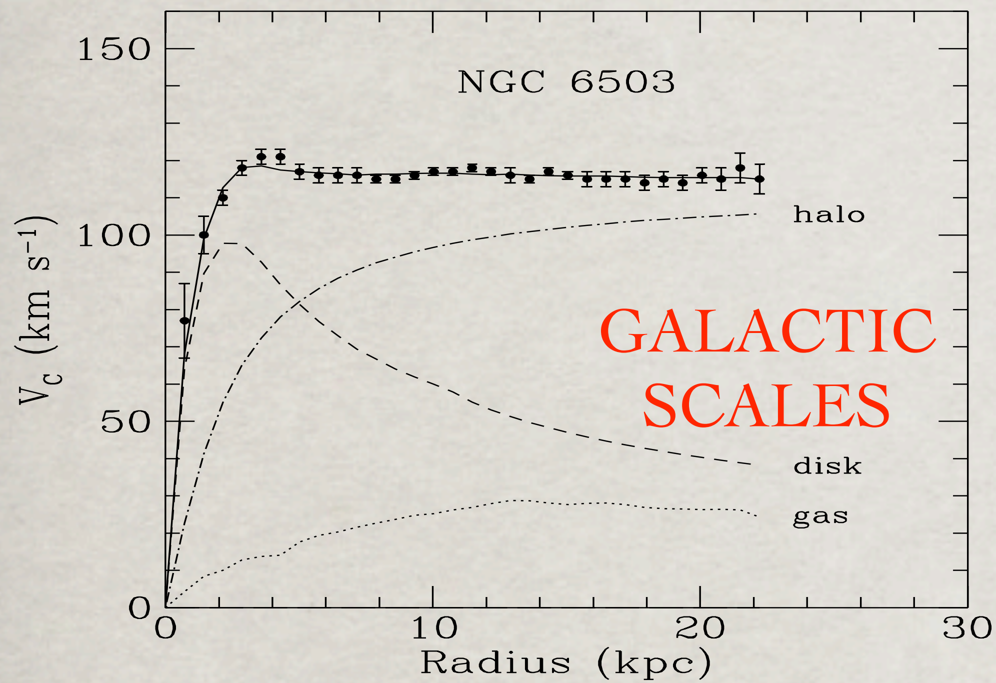

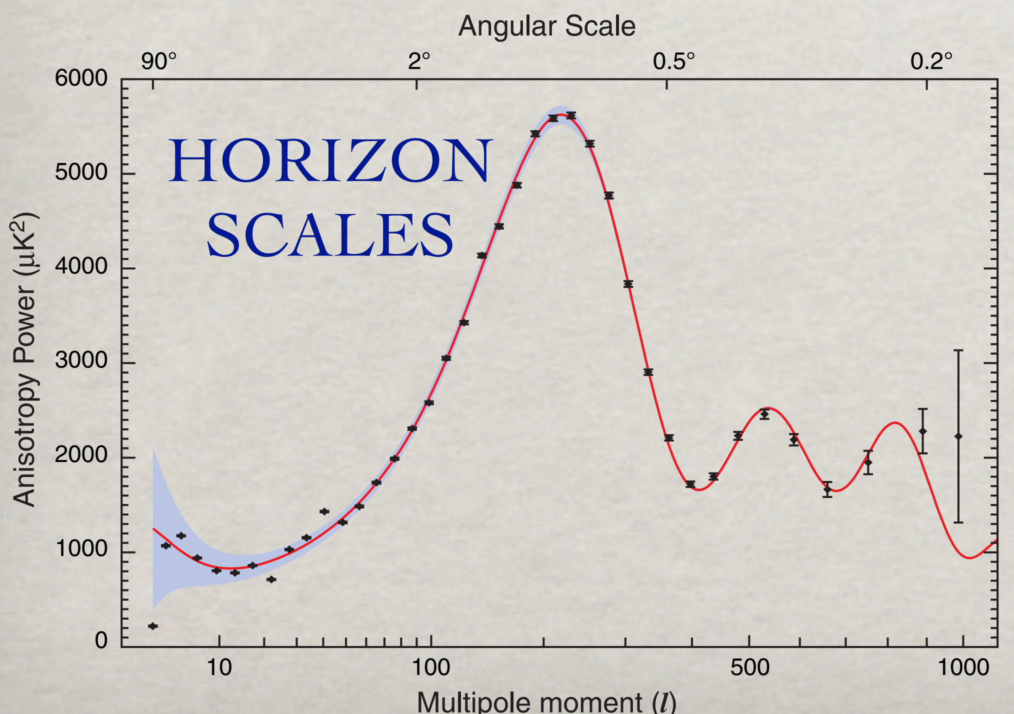

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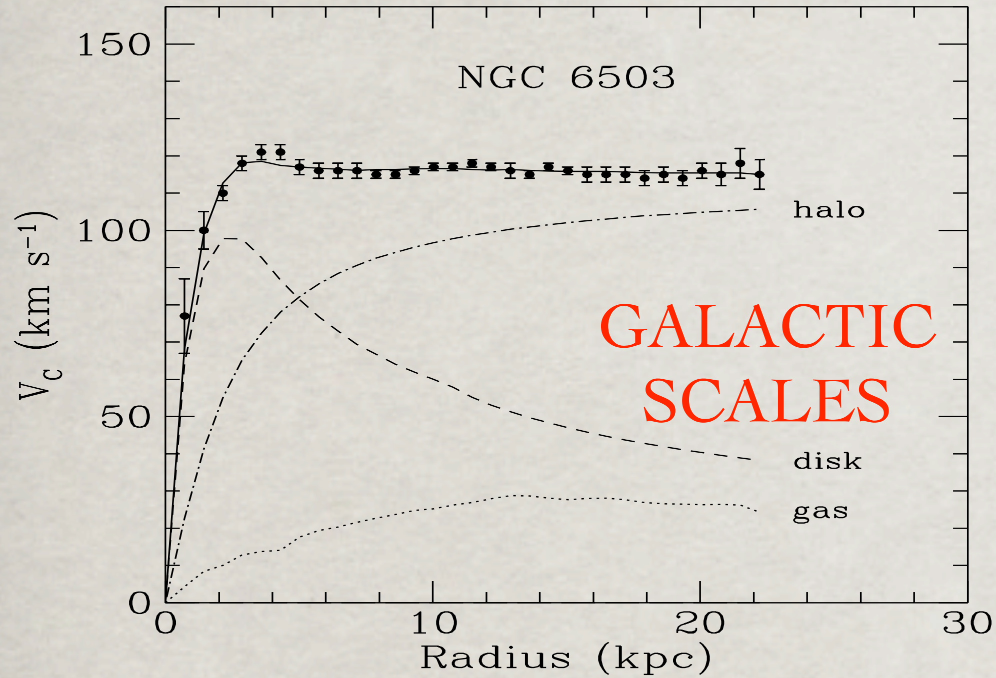
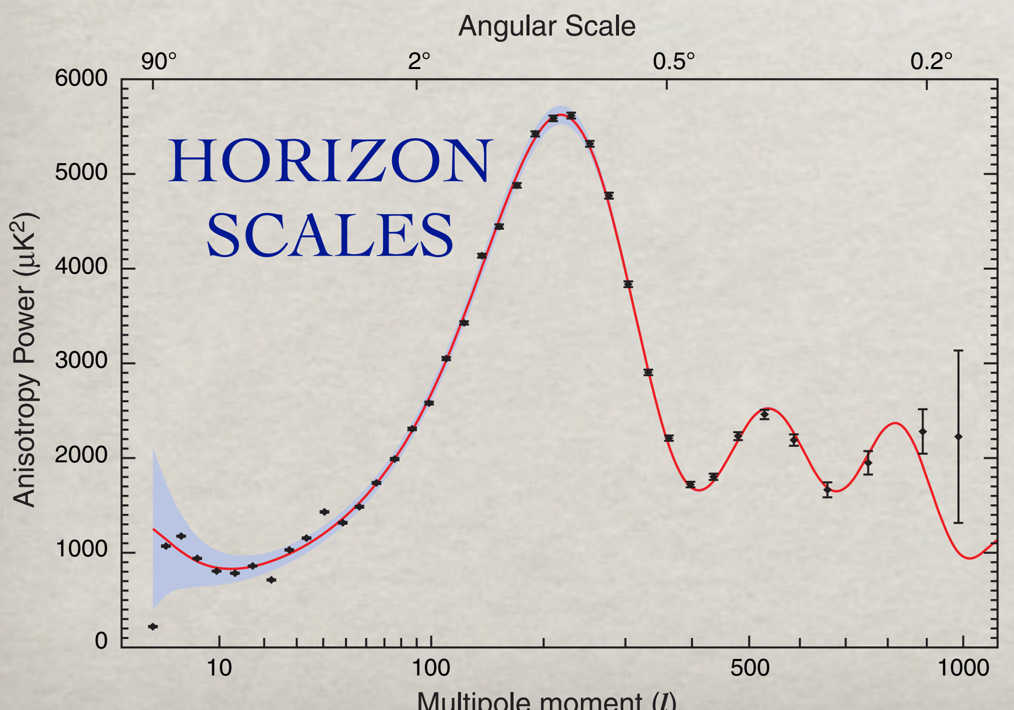




Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

DARK MATTER EVIDENCE

CLUSTER SCALES:

Systems like the Bullett cluster allow to restrict the self-interaction cross-section of Dark Matter to be smaller than the gas at the level

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad \text{for } m \sim 1\text{GeV}$$

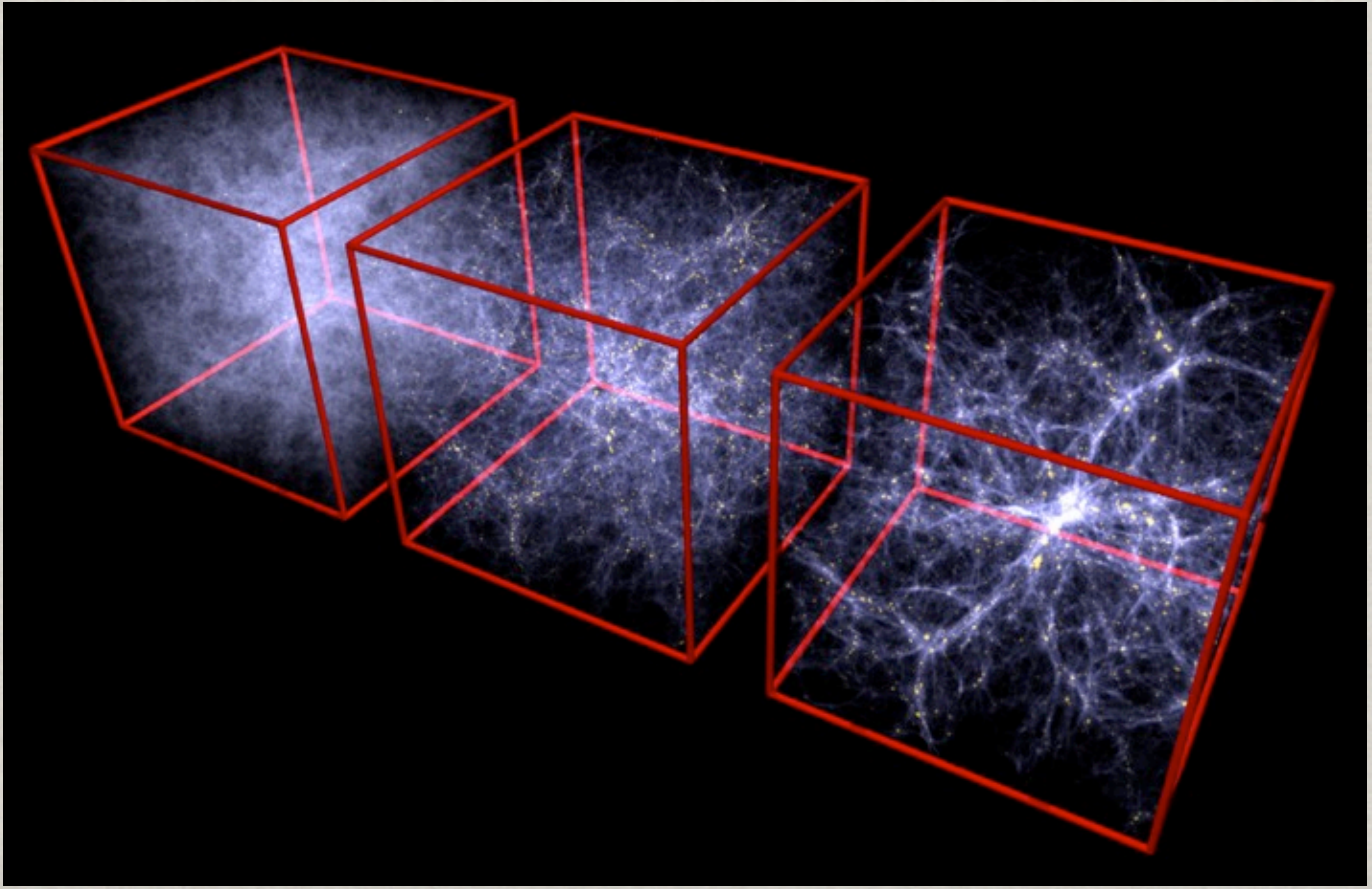
[Markevitch et al 03]

One order of magnitude stronger contraint by required a sufficiently large core... [Yoshida, Springer & White 00]

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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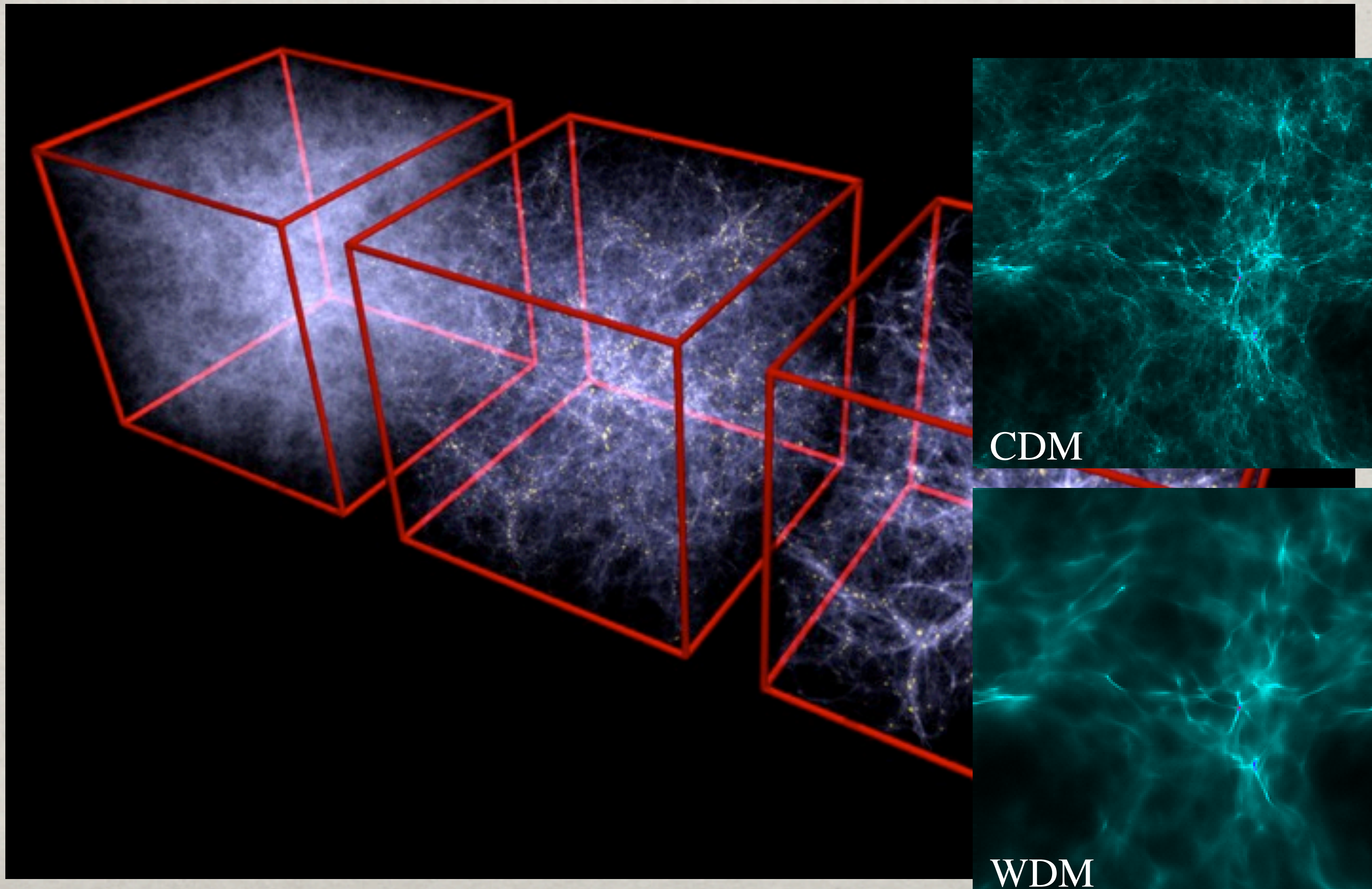
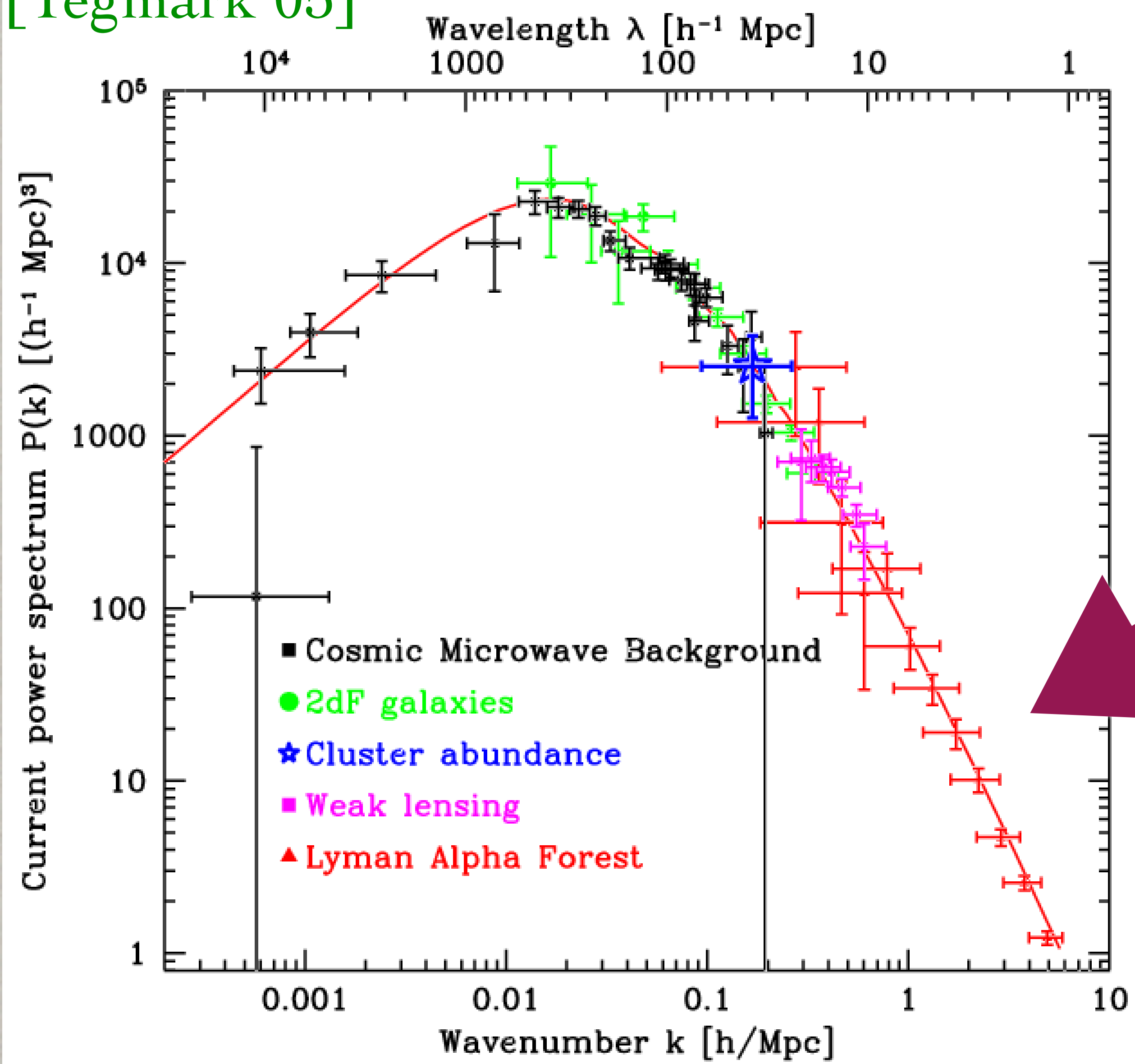


WDM & the Power spectrum

[Tegmark 05]



WDM suppresses perturbations on scales smaller than its free-streaming length:

$$\lambda_{FS} \sim \text{Mpc} \left(\frac{m_{WDM}}{1\text{keV}} \right)$$

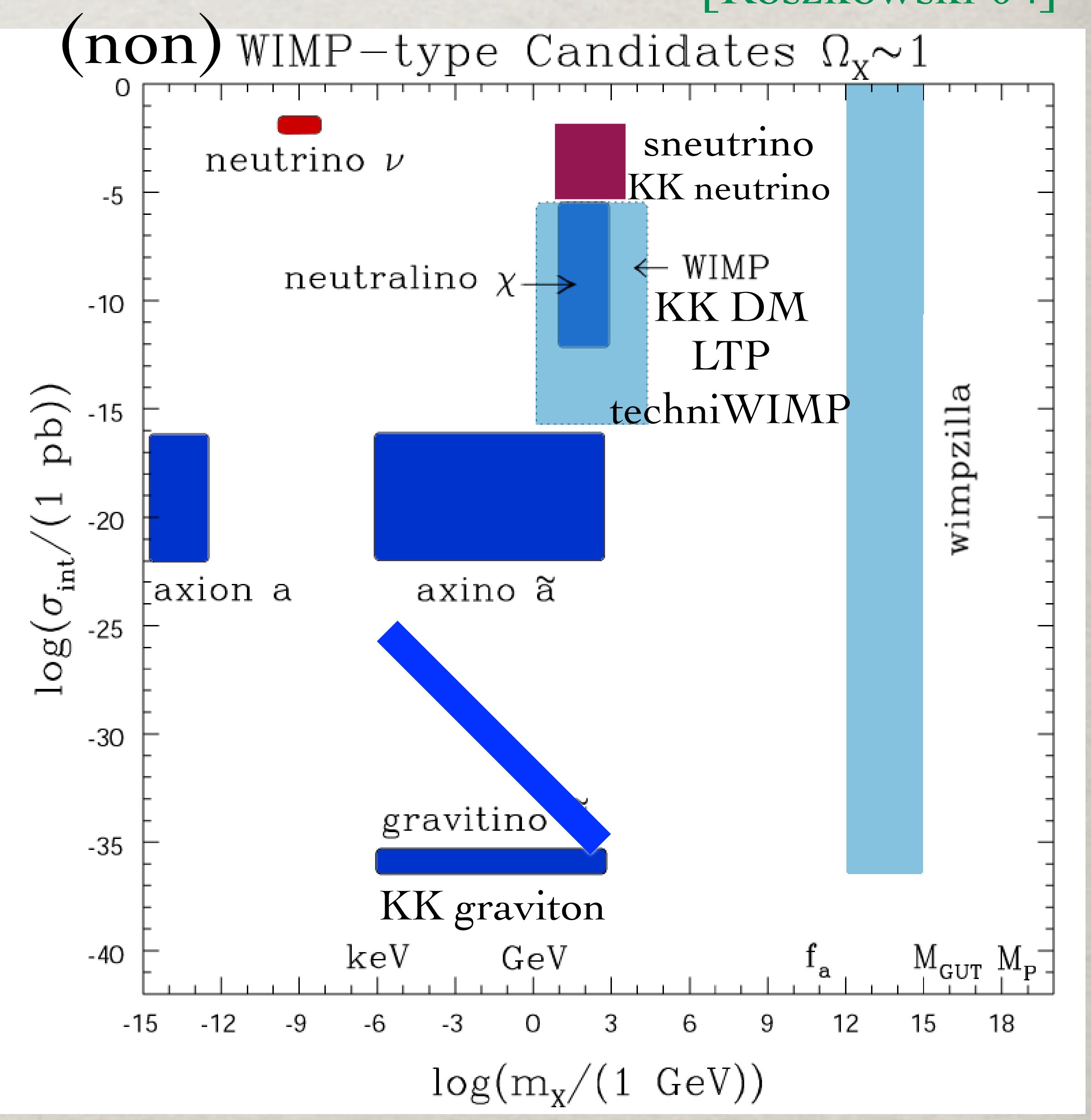
Compare with the data:

$$m_{WDM} > 4 \text{ keV}$$

[Viel et al. '07]

DARK MATTER CANDIDATES

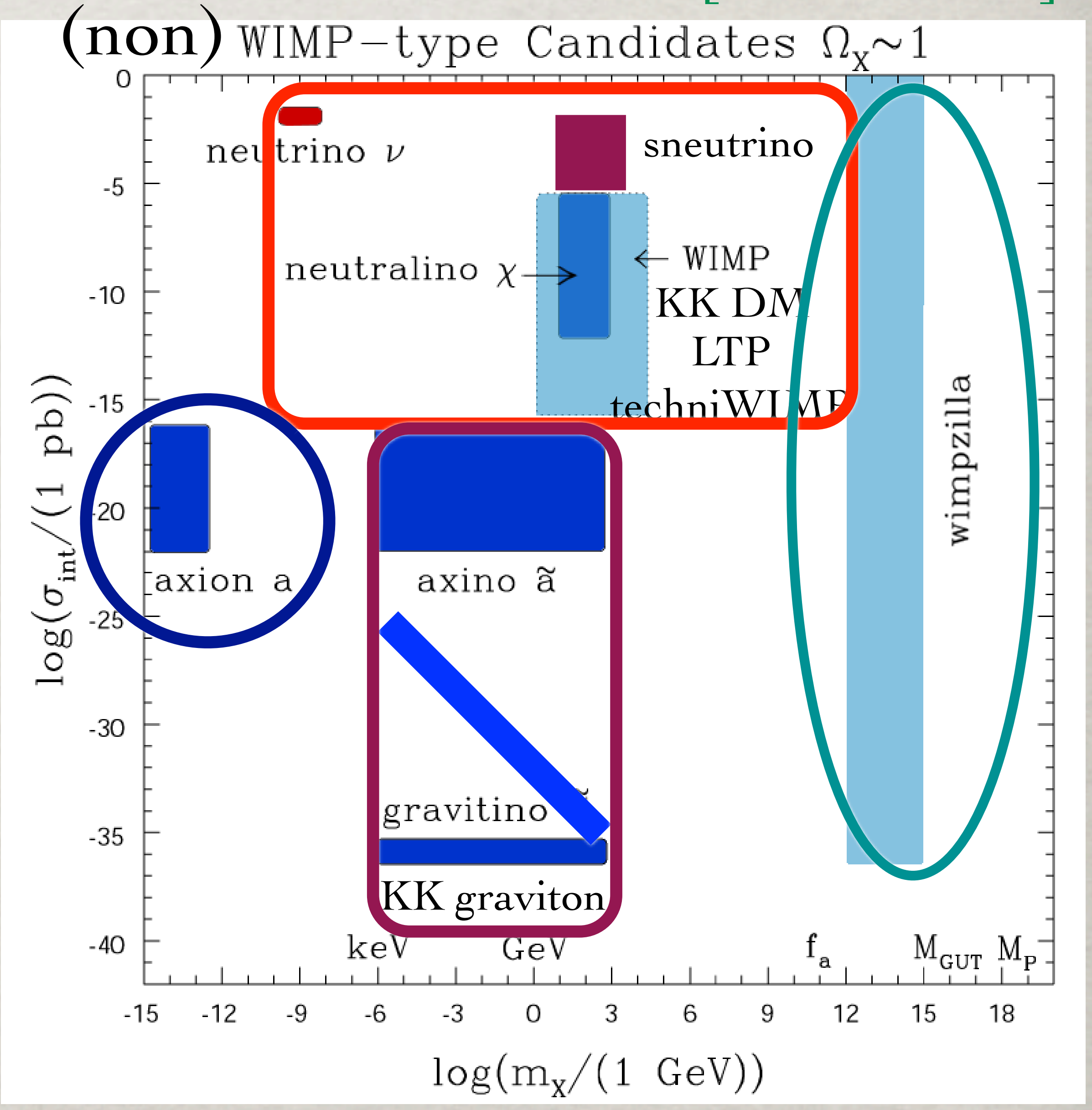
[Roszkowski 04]



DARK MATTER CANDIDATES

- Thermal relics: WIMPs
- “SuperWIMPs”
- Condensate
- Produced gravitationally

[Roszkowski 04]



What is supersymmetry?

Its generators are fermionic operators, building a graded Lie algebra together with the generators of the Poincare` group:

SUPERSYMMETRY: boson <-> fermion

Standard Model			
Matter			Forces
e	μ	τ	γ
ν_e	ν_μ	ν_τ	$W^\pm, Z$
u	c	t	g
d	s	b	G

SUSY SM			
SMatter			SForces
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\gamma}$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$
$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$
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SUSY is broken: MASSIVE !

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Lots of massive new particles... any good one for DM ?

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$\tilde{\chi}$

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$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$	$\tilde{\chi}$
$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$	
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$	$\psi_{3/2}$

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AXION:

STRONG CP problem $\Rightarrow$ PQ symmetry [Peccei & Quinn 1977]

$\theta_{QCD} < 10^{-9}$ axion a

Introduce a global $U(1)_{PG}$ symmetry broken at f_a, then θ becomes the dynamical field a,

a pseudogoldstone boson with interaction:

$$\mathcal{L}_{PQ} = \frac{g^2}{32\pi^2 f_a} a \, F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a$$

A small axion mass is generated at the QCD phase transition by instanton's effects

$$m_a = 6.2 \times 10^{-5} \text{eV} \left(\frac{10^{11}\ \text{GeV}}{f_a} \right)$$

Axion physics constrains

$$5 \times 10^9\ \text{GeV} \leq f_a \leq 10^{12}\ \text{GeV}$$

SN cooling $\Omega_a h^2 \leq 1$ [Raffelt '98]

ADD SUSY: $a \Rightarrow \Phi_a \equiv (s + ia, \tilde{a})$ with $W_{PQ} = \frac{g^2}{16\sqrt{2}\pi^2 f_a} \Phi_a W^\alpha W_\alpha$

[Nilles & Raby '82]

[Frére & Gerard '83]

AXINO couplings equal mostly to those of the axion

AXINO mass depends on SUSY breaking : free parameter

Possibility of mixed axino/axion DM depending on f_a !

AXION and AXINO MODELS

KSVZ

[Kim '79], [Shifman, Vainstein & Zakharov '80]

$W = h_H \Phi_a \bar{Q} Q$ $\quad \bar{Q}, Q$ heavy quarks

SM fields are not charged under $U(1)_{PQ}$

$$m_Q = h_H f_a$$

$$h_H \simeq \mathcal{O}(1)$$

DFSZ

[Dine, Fischler & Srednicki '81], [Zhitnitskii '80]

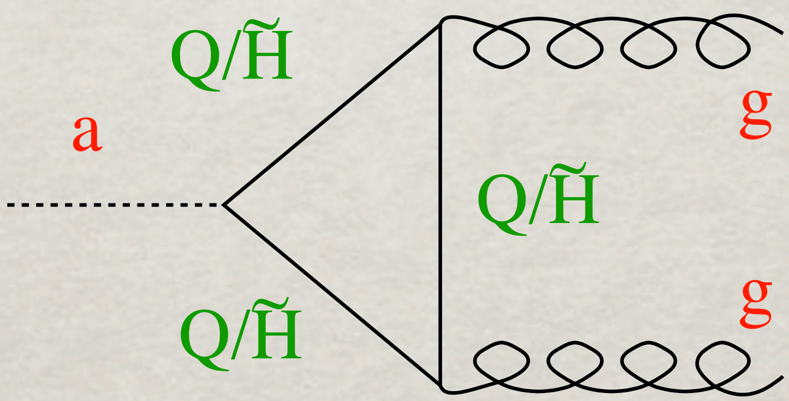
$W = h\, \Phi_a H_u H_d$ $\quad H_u, H_d$ Higgs multiplets

SM fields are charged under $U(1)_{PQ}$

$h f_a = \mu$ $\quad \mu$-term

$$\rightarrow h \ll 1$$

~ NMSSM



While the axion/axino couplings to QCD are model independent, the couplings to matter, quarks and leptons, and also Higgses, are model-dependent.

GRAVITINO properties: completely fixed by SUGRA !

Gravitino mass: set by the condition of "vanishing" cosmological constant

$$m_{\tilde{G}} = \langle W e^{K/2} \rangle = \frac{\langle F_X \rangle}{M_P}$$

~~SUSY~~

It is proportional to the SUSY breaking scale and varies depending on the mediation mechanism, e.g. gauge mediation can accomodate very small $\langle F_X \rangle$ giving $m_{\tilde{G}} \sim$ keV, while in anomaly mediation we can even have $m_{\tilde{G}} \sim$ TeV (but then it is not the LSP...).

Gravitino couplings: determined by masses, especially for a light gravitino since the dominant piece becomes the Goldstino spin 1/2 component: $\psi_\mu \simeq i\sqrt{\frac{2}{3}}\frac{\partial_\mu \psi}{m_{\tilde{G}}}$. Then we have:

$$-\frac{1}{4M_P}\bar{\psi}_\mu \sigma^{\nu\rho}\gamma^\mu \lambda^a F^a_{\nu\rho} - \frac{1}{\sqrt{2}M_P}\mathcal{D}_\nu \phi^* \bar{\psi}_\mu \gamma^\nu \gamma^\mu \chi_R - \frac{1}{\sqrt{2}M_P}\mathcal{D}_\nu \phi \bar{\chi}_L \gamma^\mu \gamma^\nu \psi_\mu + h.c.$$

$$\Rightarrow \quad \frac{-m_\lambda}{4\sqrt{6}M_P m_{\tilde{G}}}\bar{\psi}\sigma^{\nu\rho}\lambda^a F^a_{\nu\rho} + \frac{i(m^2_\phi - m^2_\chi)}{\sqrt{3}M_P m_{\tilde{G}}}\bar{\psi}\chi_R \phi^* + h.c.$$

Couplings proportional to SUSY breaking masses and inversely proportional to $m_{\tilde{G}}$!

The gravitino gives us direct information on SUSY breaking

Gravitino & Cosmology

Gravitinos can interact very weakly with other particles and therefore cause trouble in cosmology, either because they decay too late, if they are not LSP, or, if they are the LSP, because the NLSP decays too late...

If gravitinos are in thermal equilibrium in the Early Universe, they decouple when relativistic with number density given by

$$\Omega_{3/2} h^2 \simeq 0.1 \left(\frac{m_{3/2}}{0.1\mathrm{keV}} \right) \left(\frac{g_*}{106.75} \right)^{-1}$$

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

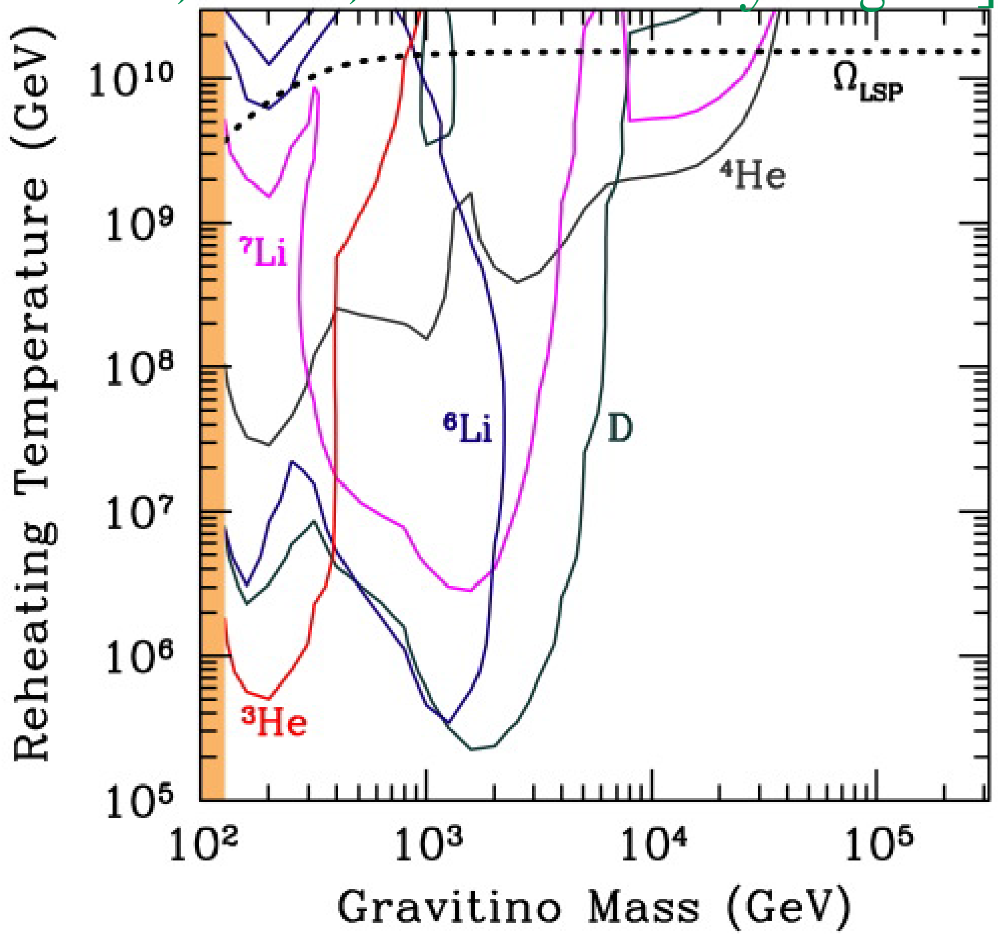
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[Bolz, Brandenburg & Buchmuller 01],
[Pradler & Steffen 06, Rychkov & Strumia 07]

THE GRAVITINO PROBLEM

The gravitino, the spin 3/2 superpartner of the graviton, interacts only "gravitationally" and therefore decays or "is decayed into" very late on cosmological scales.

[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]



$$\tau_{3/2} = 6 \times 10^7 \text{s} \left(\frac{m_{3/2}}{100\text{GeV}} \right)^{-3}$$

BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is much smaller than that required for leptogenesis !

Stable gravitino/axino Dark Matter

CAN THE AXINO/GRAVITINO BE COLD DARK MATTER ?

YES, if the Universe was never hot enough
for axino/gravitinos to be in thermal equilibrium...

Very weakly interacting particles as the axino & gravitino
are produced even in this case, at least by two mechanisms

PLASMA SCATTERINGS

$$\Omega_{DM} h^2 \propto T_R \begin{cases} \dfrac{m_{\tilde{a}}}{f_a^2} \\ \dfrac{m_{\tilde{g}}^2}{m_{\tilde{G}} M_P^2} \end{cases}$$

NLSP DECAY OUT OF EQUILIBRIUM

$$\Omega_{DM} h^2 \propto \frac{m_{DM}}{m_{NLSP}} \Omega_{NLSP} h^2$$

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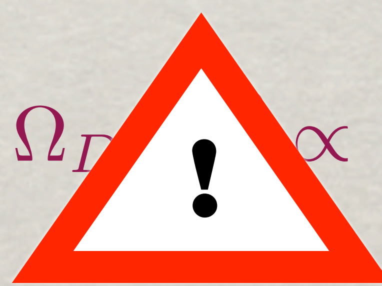
NLSP DECAY OUT OF EQUILIBRIUM

$\Omega_D \propto$



DANGER !!!
BBN at risk !

THERMAL PRODUCTION

At high temperatures, the dominant gravitino production is due to 2-to-2 scatterings with the gauge sector, mostly QCD:

$$\Omega_{3/2}h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{T_R}{10^{10}\ \mathrm{GeV}}\right)\sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}}\right)^2$$

[Bolz,Brandenburg & Buchmuller 01],
[Pradler & Steffen 06, Rychkov & Strumia 07]

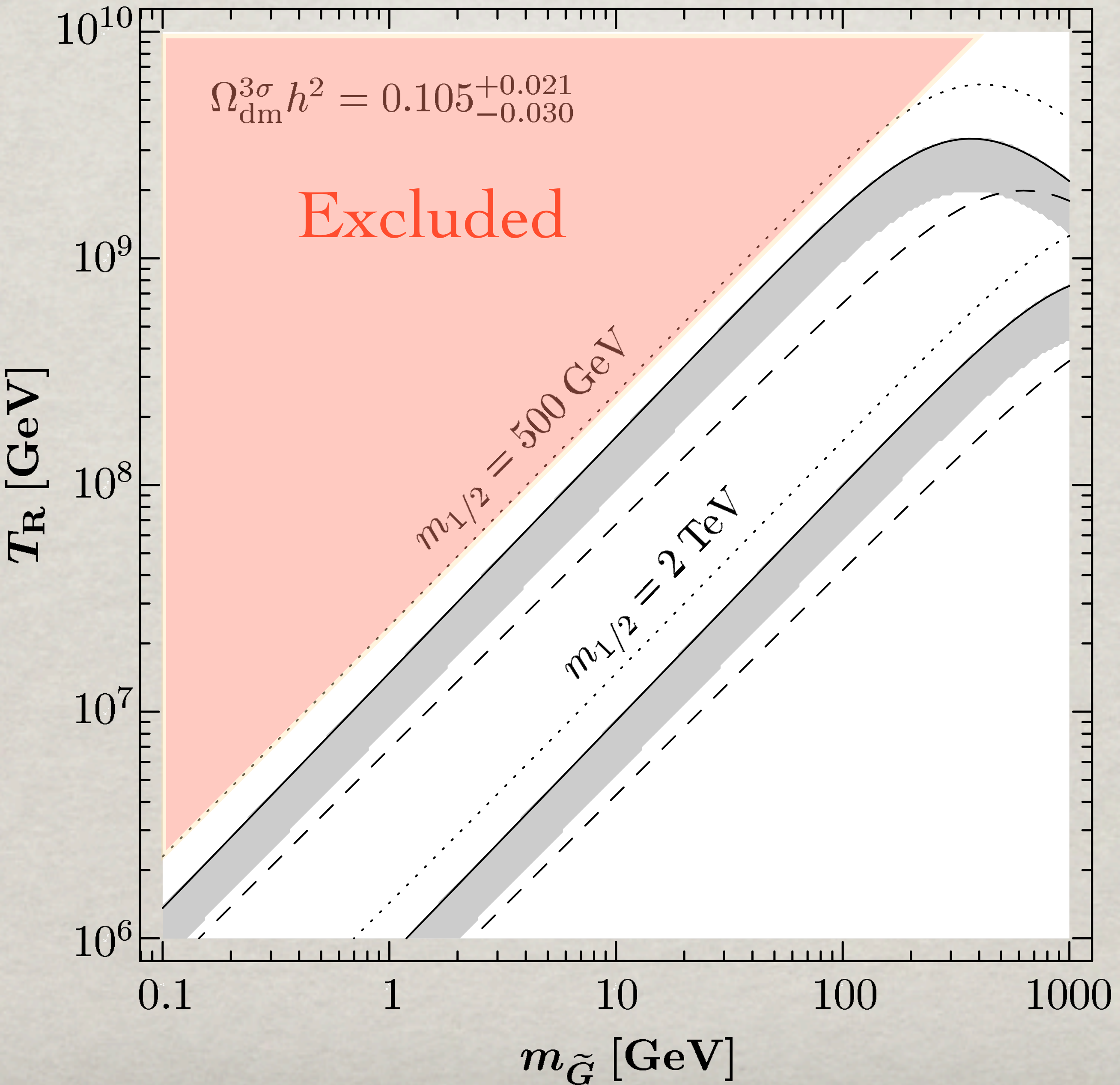
where M_i are the gaugino masses and $c_i \sim 0(1)$

So in general there is always a bound on the reheat temperature and such temperature has to take a specific value in order to match the DM density. Note that the smaller $m_{3/2}$, the smaller the temperature has to be.

Tension with thermal leptogenesis for small gravitino masses !

UPPER BOUND ON T_R

[Pradler & Steffen '06]



THERMAL PRODUCTION

Similarly for the axino, but the couplings are not enhanced by a small axino mass. Recently a new computation by Strumia exploiting the similarity between axino & gravitino gives:

$$\Omega h^2 \simeq 2.72 \left(\frac{m_{\tilde{a}}}{0.1\mathrm{GeV}}\right) \left(\frac{T_R}{10^4\mathrm{GeV}}\right) \left(\frac{10^{11}\mathrm{GeV}}{f_a}\right)^2$$

[Strumia 10]

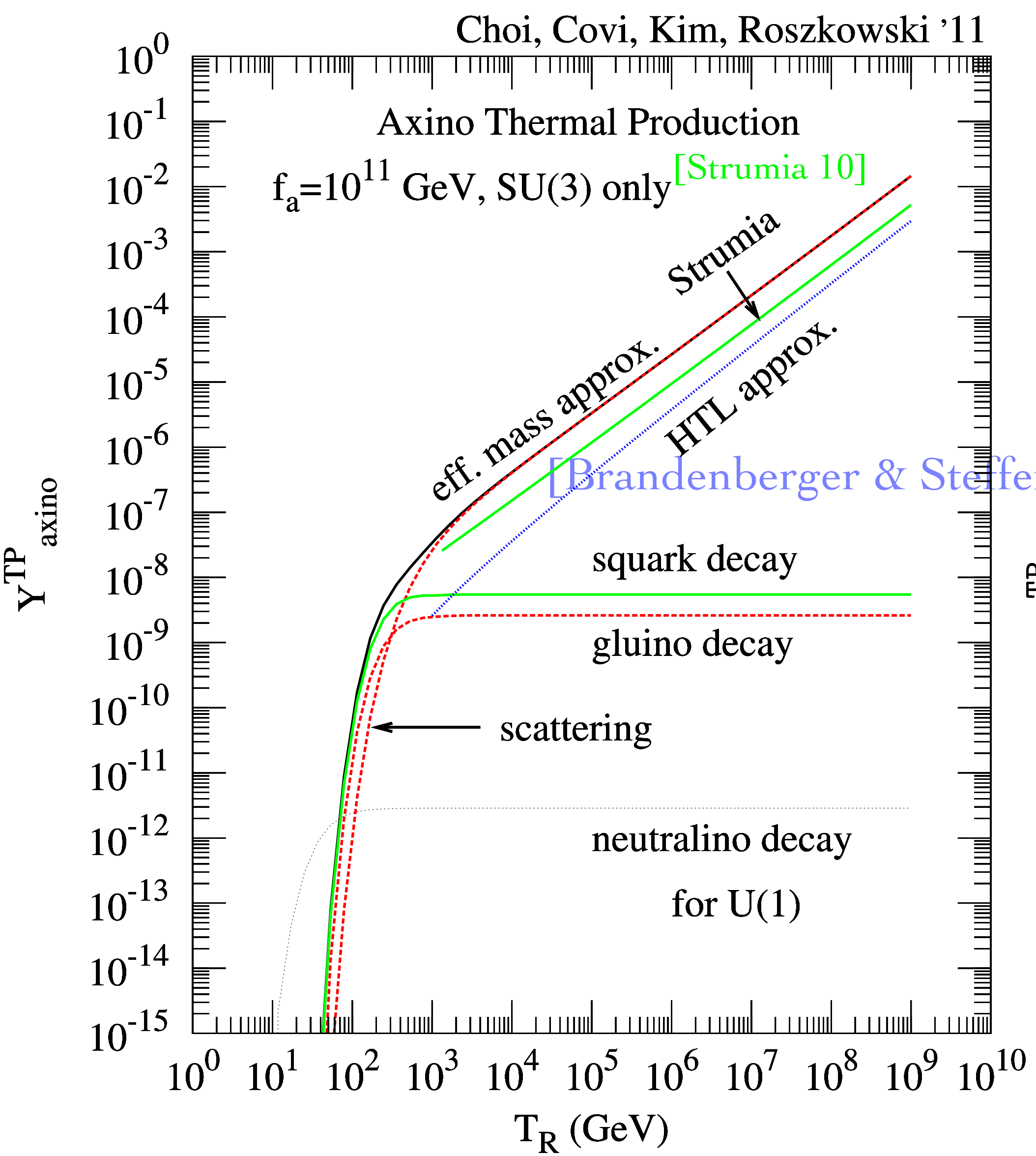
This includes a D-term contribution previously neglected and the effect of (thermally massive) gluon decay.

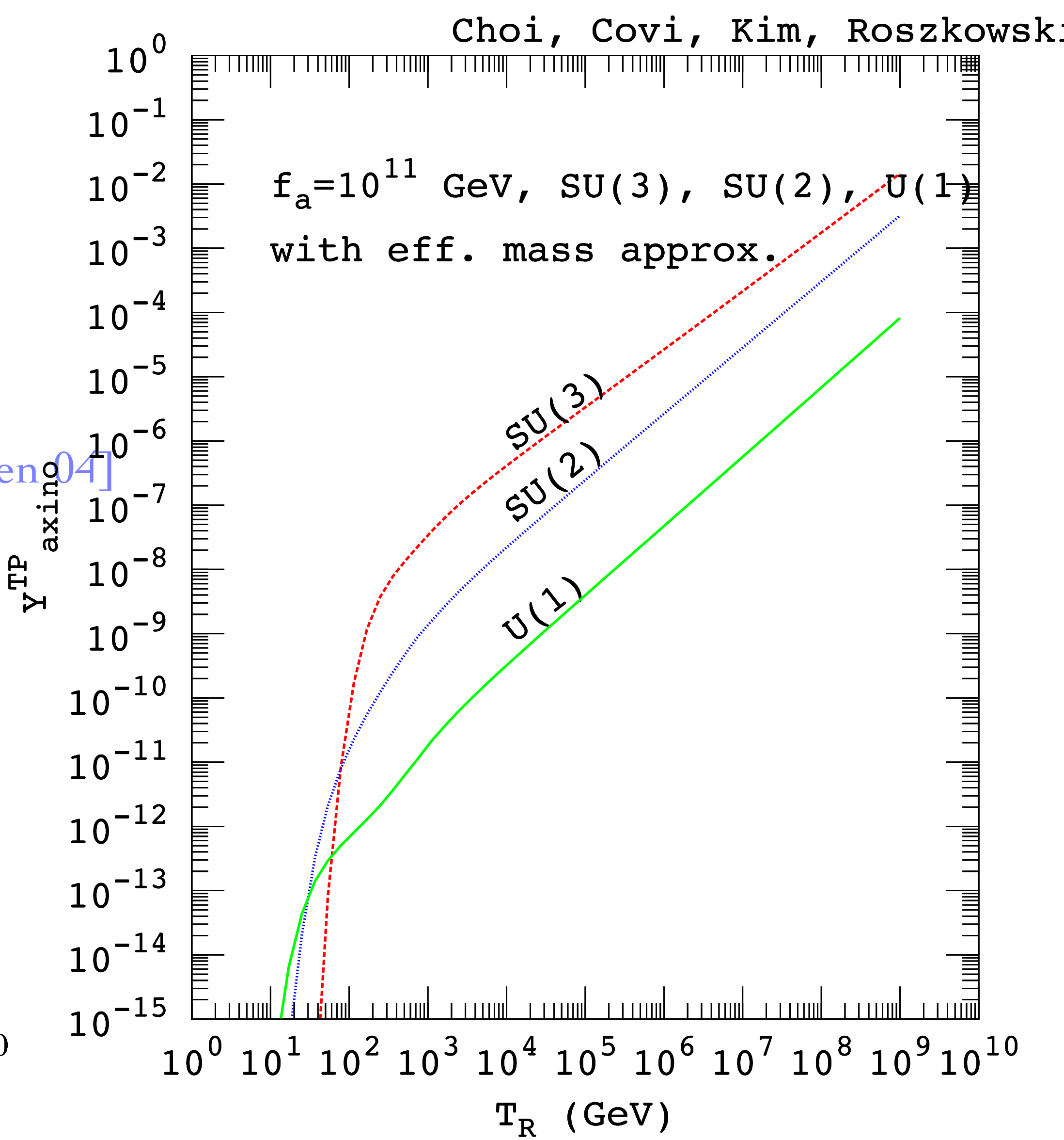
This is a factor ~ 2-3 larger than [Brandenberger & Steffen 04] and nearly equal to our earlier one with a gluino thermal mass introduced per hand [LC, HB Kim, JE Kim & Roszkowski 01].

Tension with thermal leptogenesis is stronger, even for small axino masses ! Non-thermal leptogenesis ? [Baer et al...]

Revisiting axino production

[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]

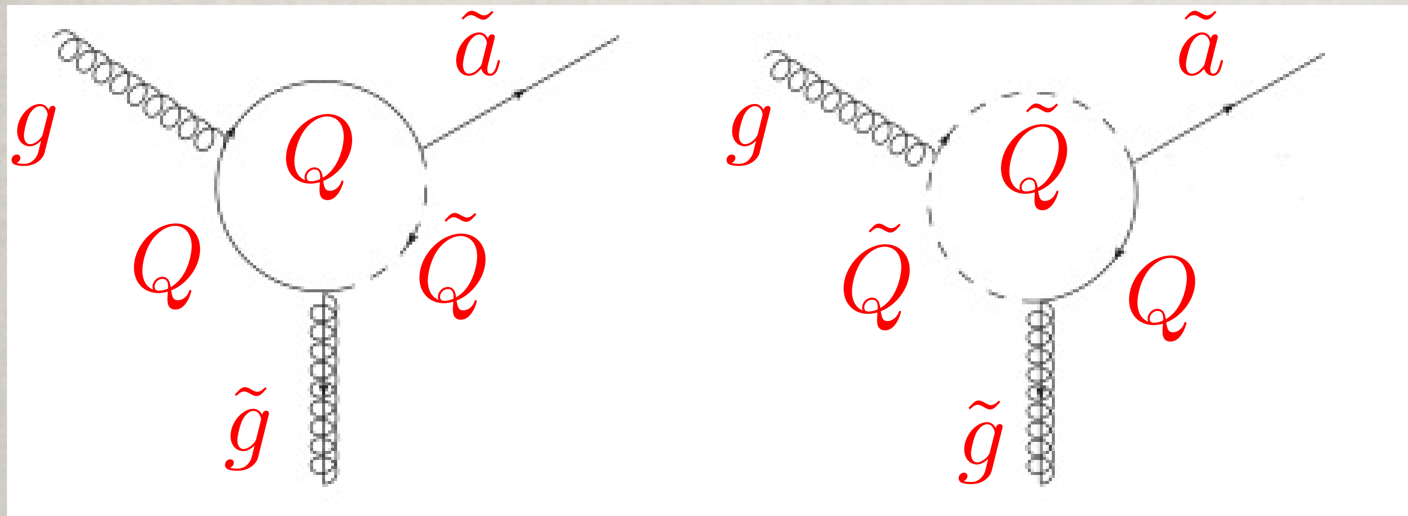




Do not worry: Perturbation series seems converging...

Axino effective coupling

Recent full computation of effective vertex: [Bae, Choi & Im 11]



$$\mathcal{A}(p, q, M_Q)$$

$$\mathcal{A}(p, q, M_Q) \propto \begin{cases} \frac{M_Q^2}{p^2} \ln^2\left(\frac{M_Q^2}{p^2}\right) & \text{for } \; p^2 >> M_Q^2 \\ 1 - \frac{p^2}{12 M_Q^2} & \text{for } \; p^2 << M_Q^2 \end{cases}$$

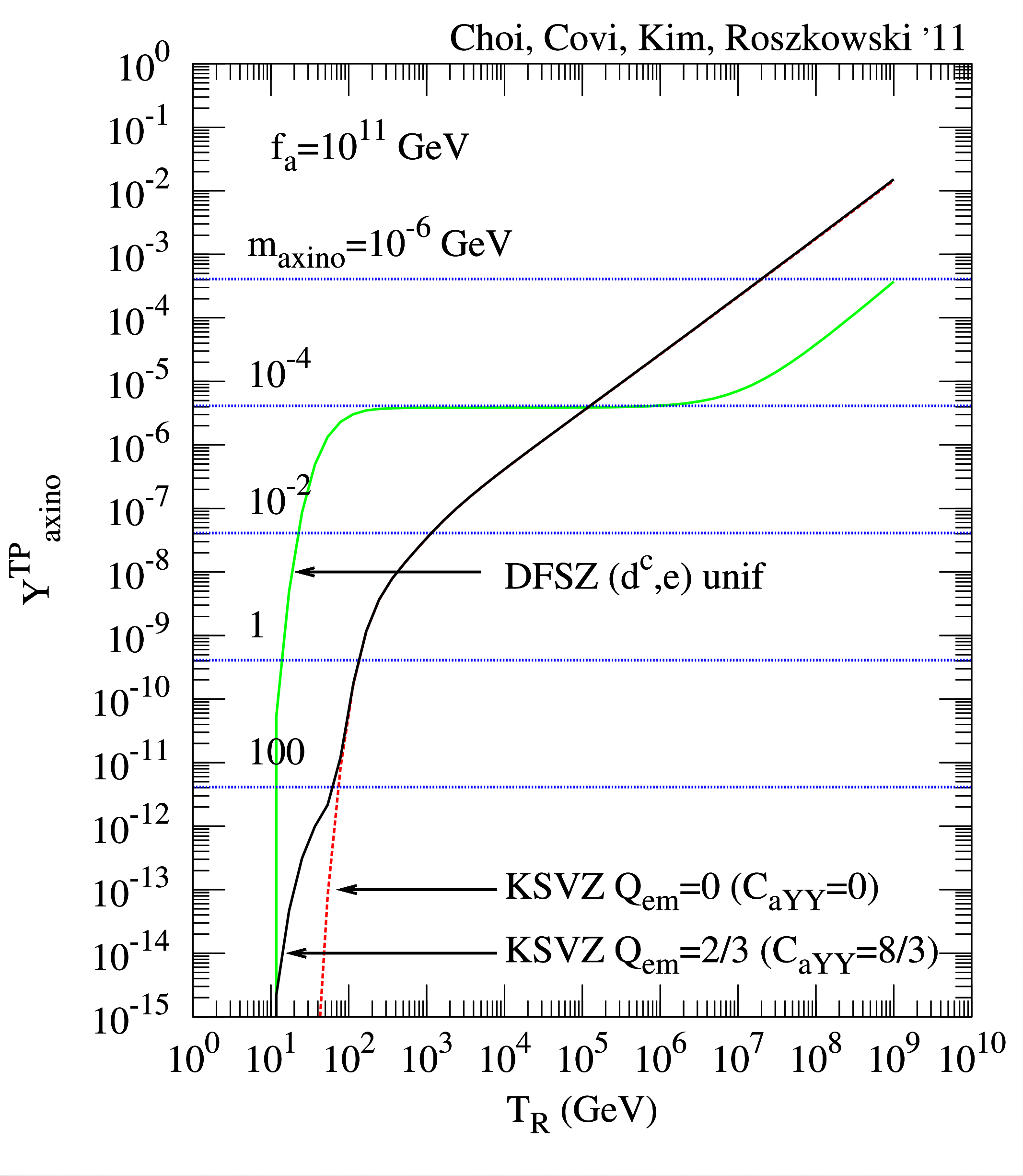
Constant vertex only for heavy quarks/squarks !

OK for KSVZ with $M_Q \sim f_a$. But for DFSZ ?

Revisiting axino production

[E.J. Chun 11, Bae, Choi & Im 11]

[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]



Actually for the DFSZ case, there is a direct coupling to the Higgses : so the Higgsino decay channel dominates over the other production channels, e.g. SU(2) coupling...

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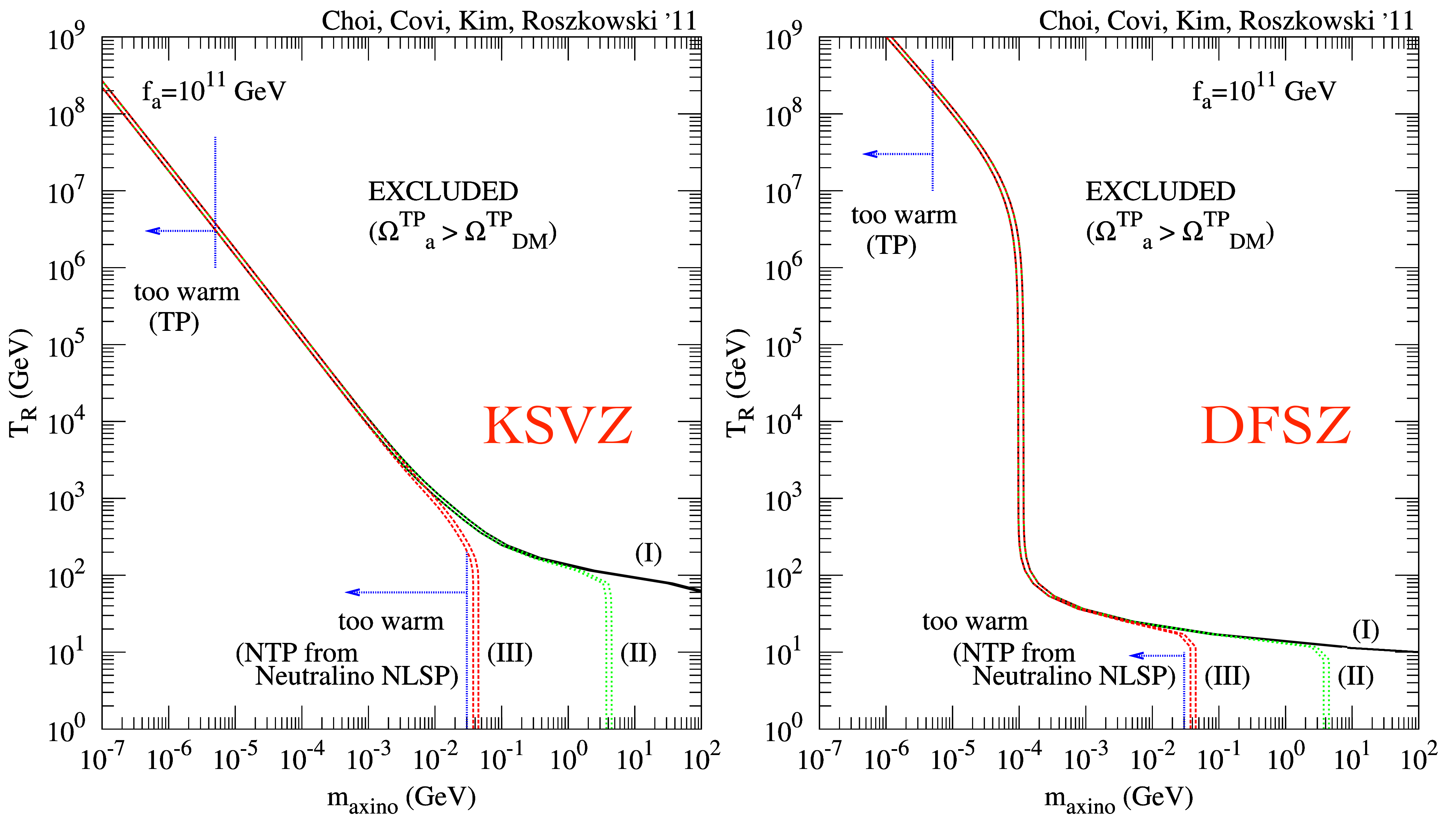


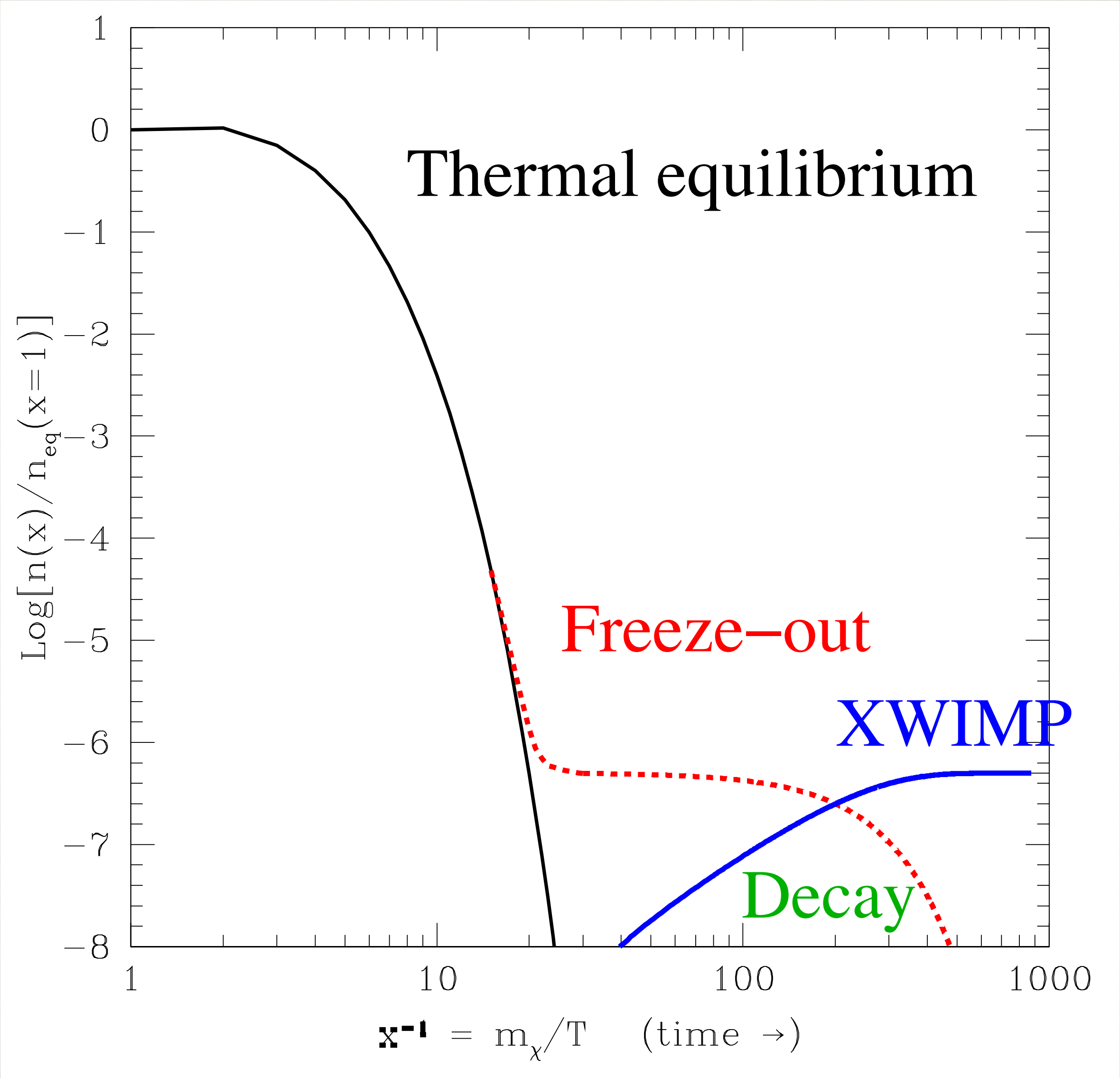
NLSP DECAY

[JE Kim, Masiero, Nanopoulos '84]
[LC, JE Kim, Roszkowski '99], [Feng et al '04]

- If R-parity is conserved, the NLSP decays after freeze-out into the superWIMP:

$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

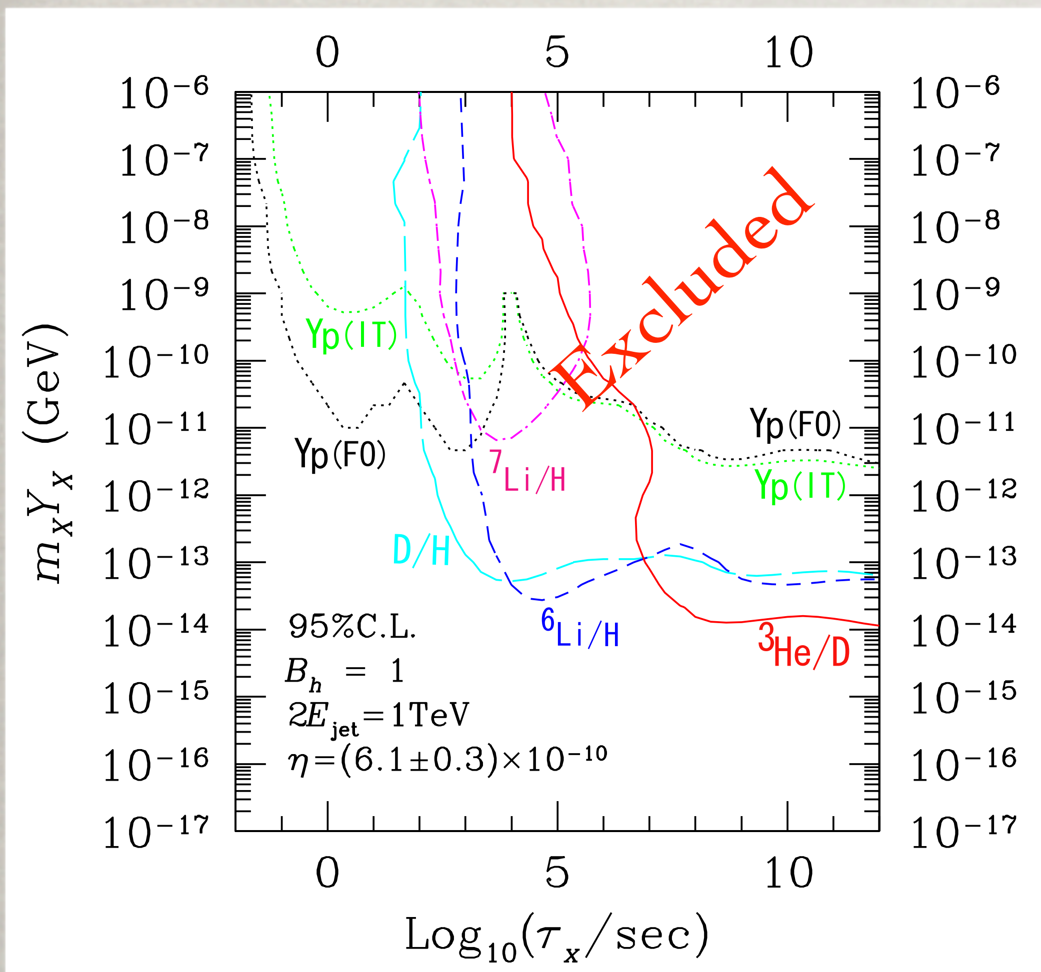
- The LSP is not thermal
- Other energetic particles are produced in the decay: beware of BBN...



BBN bounds on NLSP decay

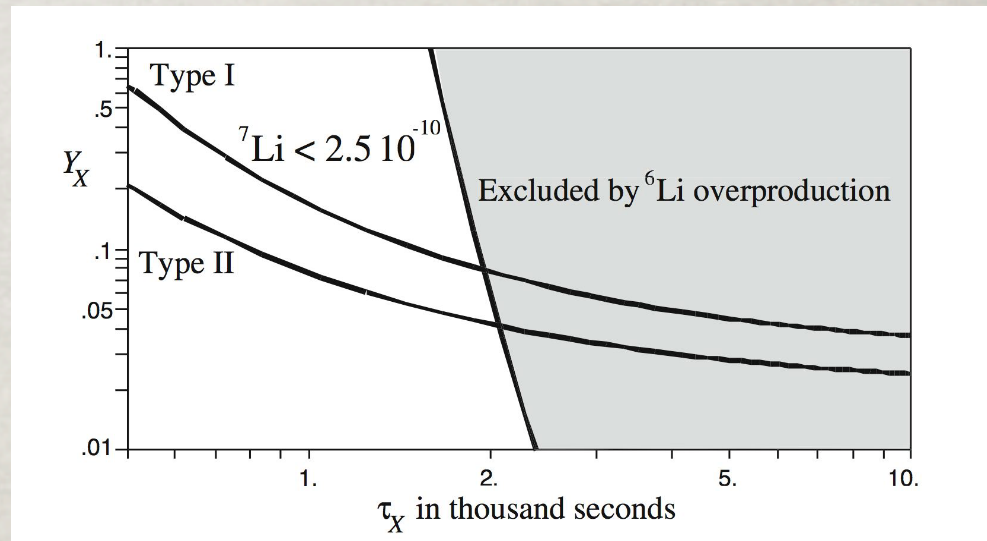
Neutral relics

[...,Kohri, Kawasaki & Moroi 04]



Charged relics

[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]



Need short lifetime & low abundance for NLSP

Big problem for gravitino LSP with 10-100 GeV mass...

A MATTER OF LIFETIME...

Due to the suppressed couplings, the NLSP decays slowly into an axino/gravitino and a SM particle.
Consider a Bino neutralino NLSP and R-parity conservation.
What is its lifetime for axino or gravitino LSP?

For an axino LSP:

$$\Gamma_{\tilde{B}}^{-1} = 0.25\,\mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-3} \left(\frac{f_a}{10^{11}\ \mathrm{GeV}} \right)^2$$

For a gravitino LSP:

$$\Gamma_{\tilde{B}}^{-1} = 5.7 \times 10^4 \mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-5} \left(\frac{m_{\tilde{G}}}{1\ \mathrm{GeV}} \right)^2$$

Quite different timescale, apart for large f_a or small gravitino mass... Trouble for a gravitino heavier than 1 GeV !
Is there a way out apart light gravitino/heavy NLSP ???

Axino-stau coupling

The full two-loop computation of the axino couplings to sleptons-lepton and quark-squarks in the hadronic axion models, done by [Freitas, Steffen, Tajuddin & Wyler 09], gives:

$$\Gamma(\tilde{\tau}_R \to \tau \tilde{a}) = \frac{81\, \alpha^4 e_Q^4}{128 \pi^5 \cos^8 \theta_W} \frac{m_{\tilde{\tau}} m_{\tilde{B}}^2}{f_a^2} \ln^2\left(\frac{y f_a}{m_{\tilde{\tau}}}\right)$$

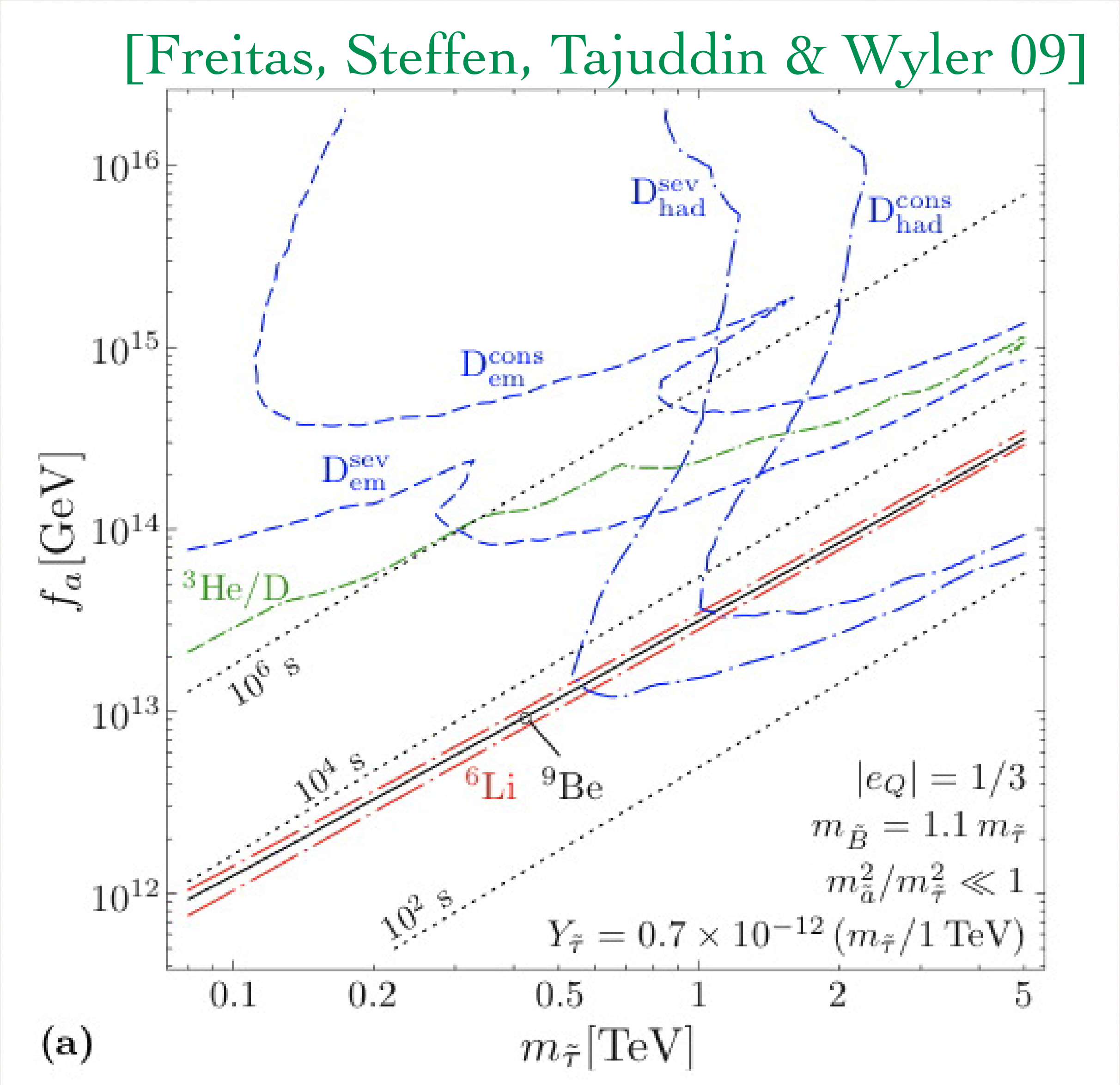
at leading log, where the e.m. charge and mass of the heavy quarks are $e_Q, y f_a$ respectively. It is suppressed by loop factors and large powers of the coupling.

It gives ~ 20% correction to the previous computation using an effective one loop approximation [LC, L. Roszkowski, M. Small, 02]

This is important for computing the stau NLSP lifetime !

UPPER BOUND ON f_a

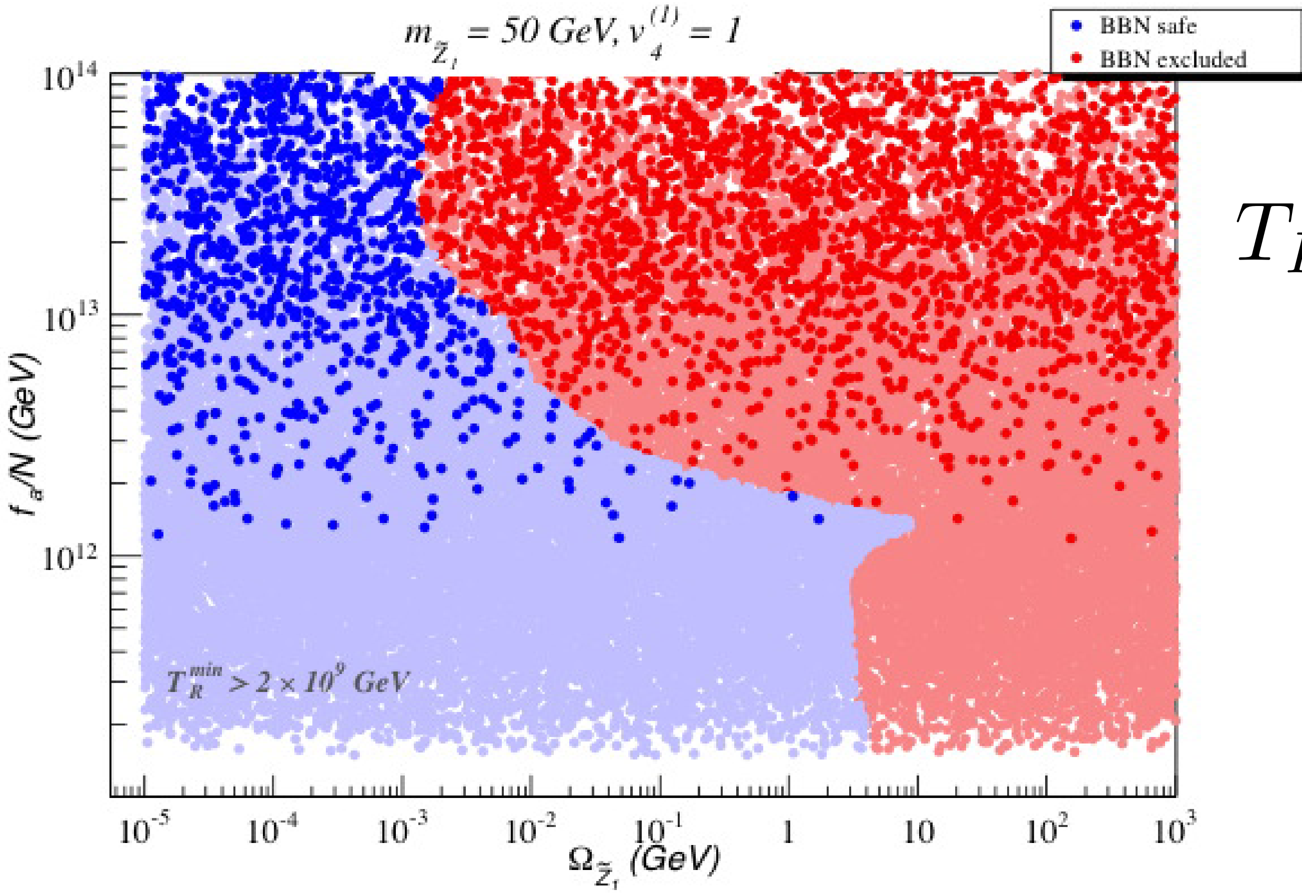
For τ_R NLSP



More stringent bounds than for neutralino NLSP [H. Baer et al]

Mixed Axino/axion DM

[Baer et al 10]



$$T_{RH} > 2 \times 10^9 \text{ GeV}$$

needs large

$$f_a/N$$

With mixed axion/axino DM high reheat temperature is possible also in the PQ case for small axino mass.

Reduce NLSP density

Try to reduce the NLSP density to evade BBN bounds:

- require degenerate masses at the low scale to have coannihilation with a stronger interacting NNLSP:

→ light degenerate gaugino spectrum
as it is possible in general gauge mediation,
it helps also to make T_R maximal !

[LC, Olechowski, Pokorski, Turzynski, Wells 10]

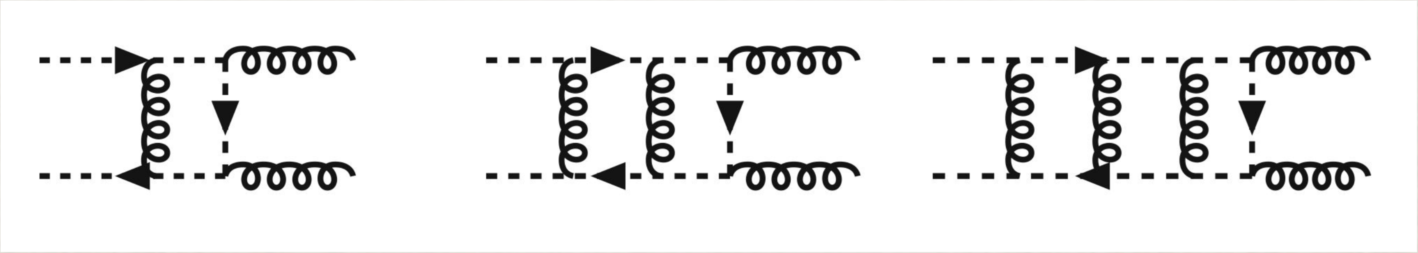
- take a colored NNLSP with strong Sommerfeld enhancement in the annihilation cross-section

→ colored NNLSP like gluino and stop

Light and degenerate gaugino or "compressed susy" also ameliorates the fine-tuning problem, while heavy scalar superpartners help with the flavour problem/Higgs mass...

Sommerfeld Factor

[Sommerfeld 39, Sakharov 48]



- Consider one particle moving in the Coulomb field of the other... In Feynman diagrams it correspond to resumming over all ladder diagrams with soft gluons.
- The cross-section factorizes; for a massless gauge boson:

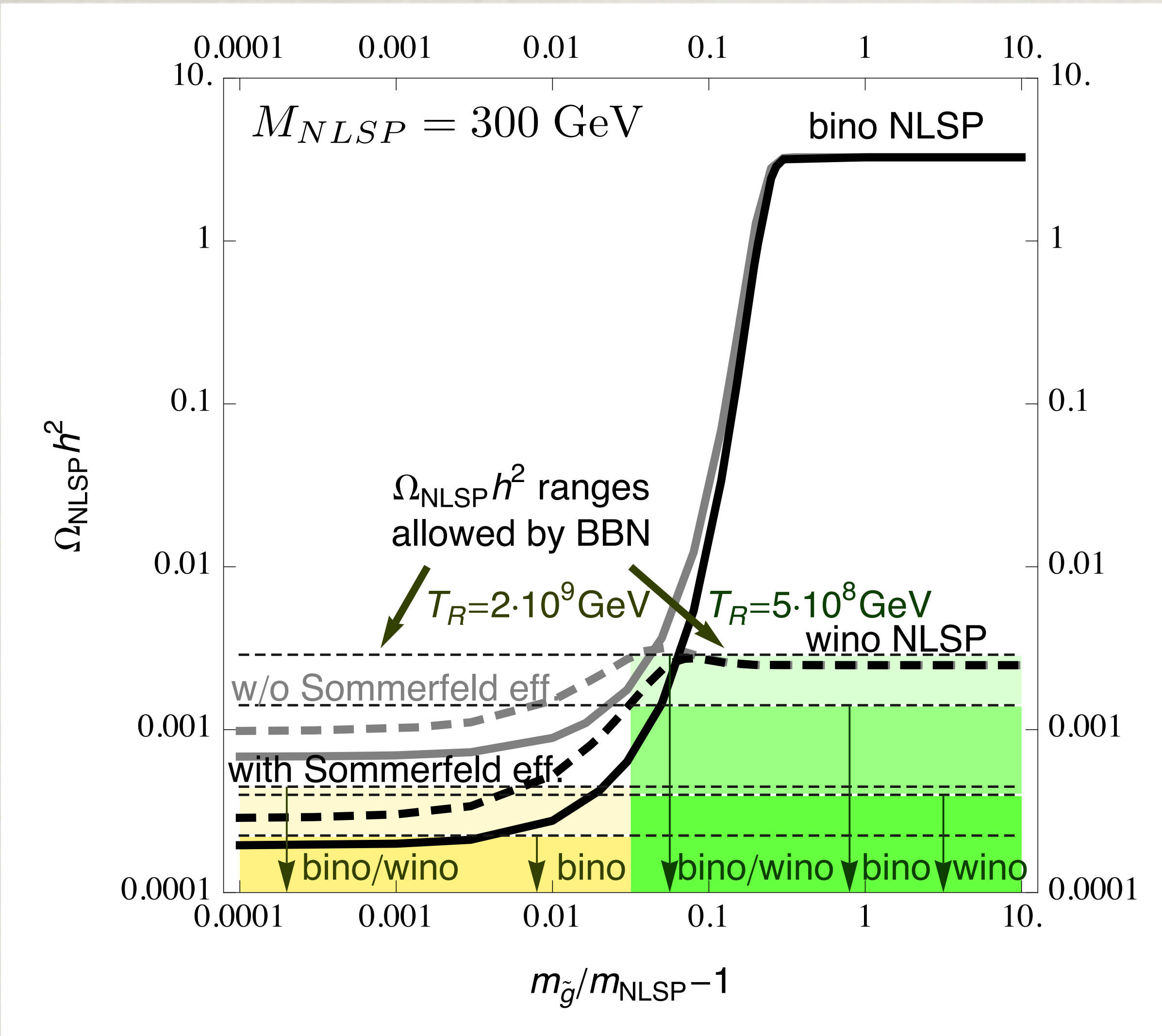
$$\sigma_S = \sigma_0 \times E_S(\beta) \qquad E_S(\beta) = \frac{z}{1 - e^{-z}} \quad \text{with} \quad z = \frac{C\pi\alpha_N}{\beta}$$

- Large correction for small velocity β !!!

IMPORTANT AT FREEZE-OUT ! [Hisano et al 04, 06...]

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski, Wells 10]



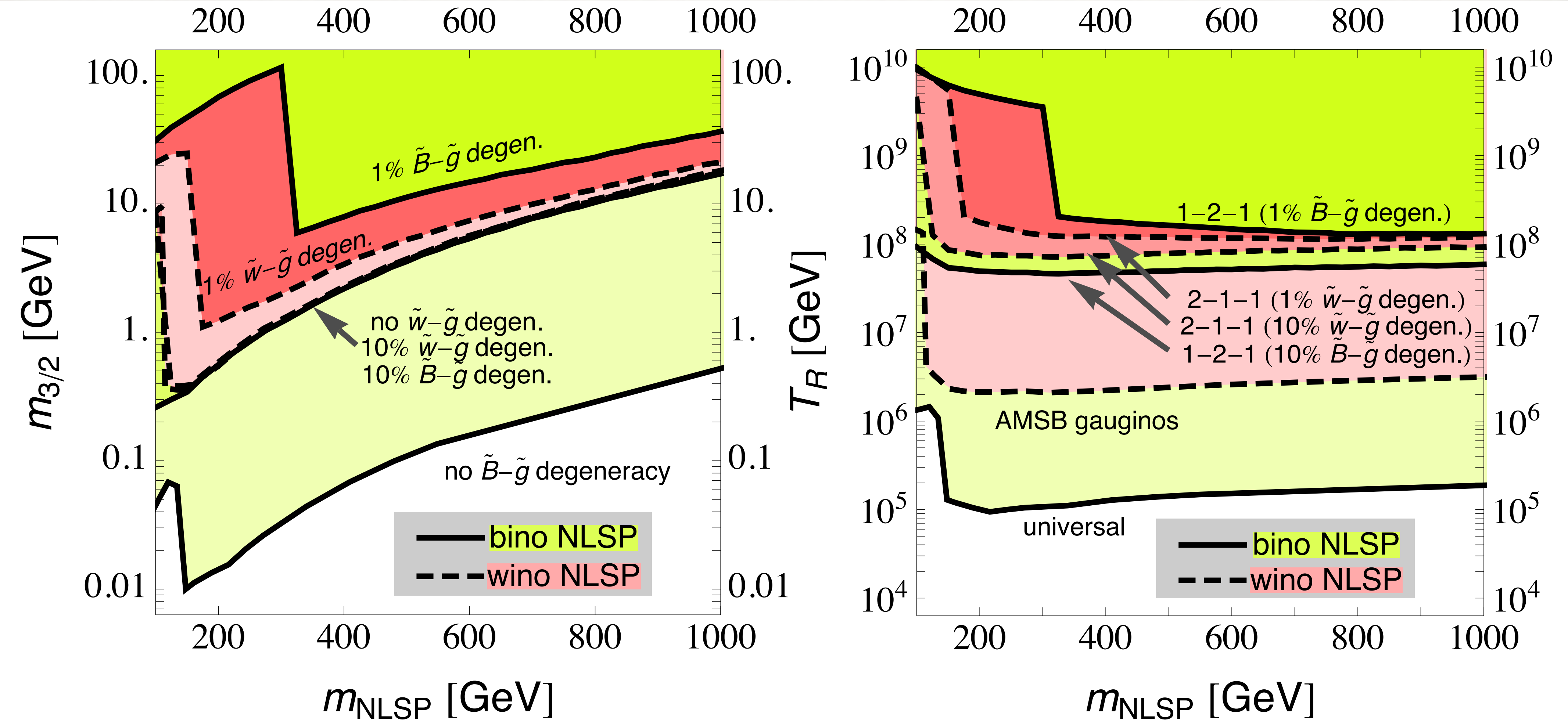
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

On the other hand they can help the other neutralinos NLSP.

The coannihilation with gluinos has a very strong effect on the Bino, even for just 10% degeneracy. Weaker effect for the Wino.

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski,Wells 10]



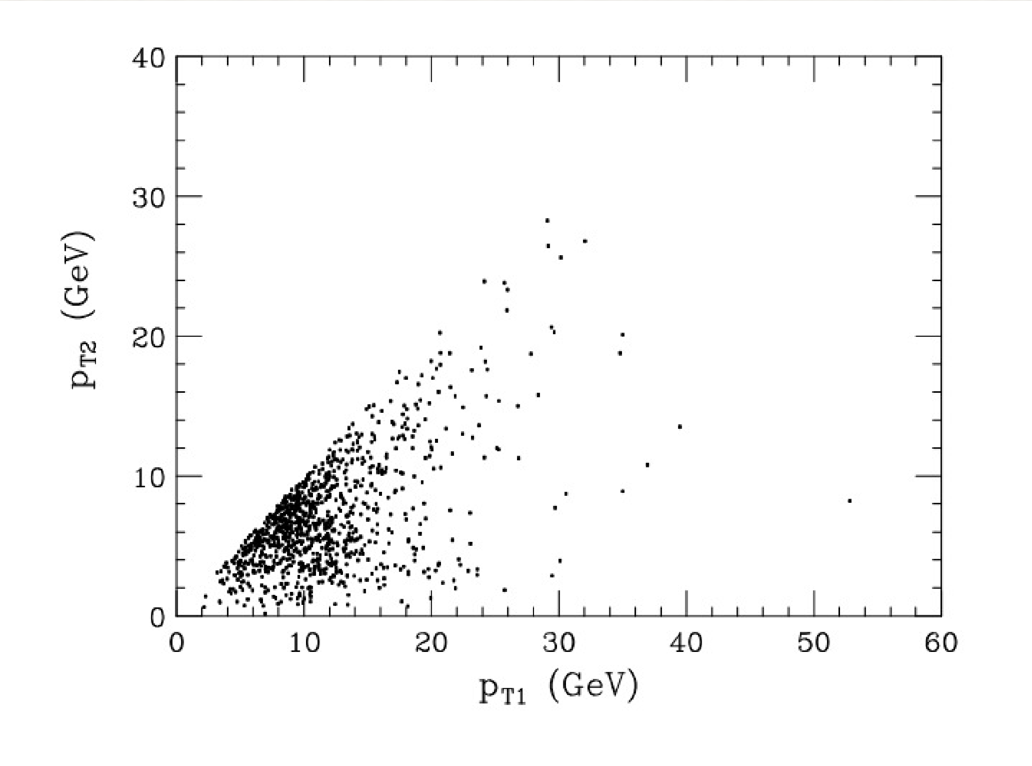
The coannihilation with gluinos allows to reach large T_R, but with very strong degeneracy and light masses...

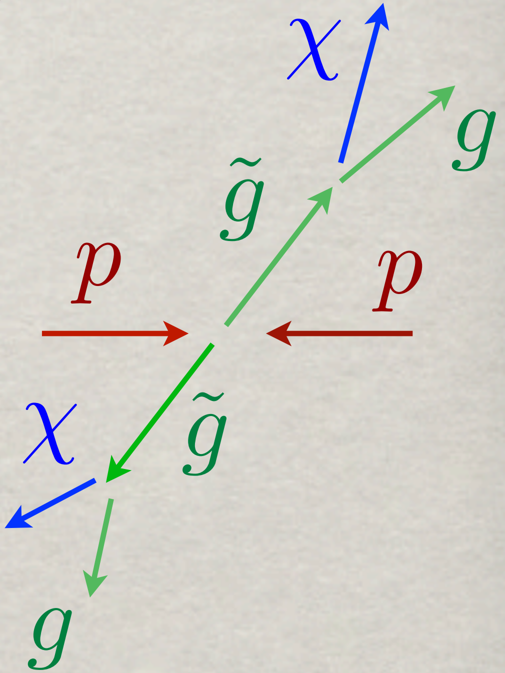
LHC: DEGENERATE GAUGINOS?

In this scenario of maximal T_R and stable gravitino DM we expect light gauginos with 1-10% degeneracy between Bino NLSP and gluino NNLSP.
The largest cross-section at LHC is gluino pair production, but if they decay dominantly into gluon and neutralino, the arising jets are possibly too soft to trigger on...

$$m_{\tilde{g}} = 309$$
$$m_{\tilde{B}} = 300$$

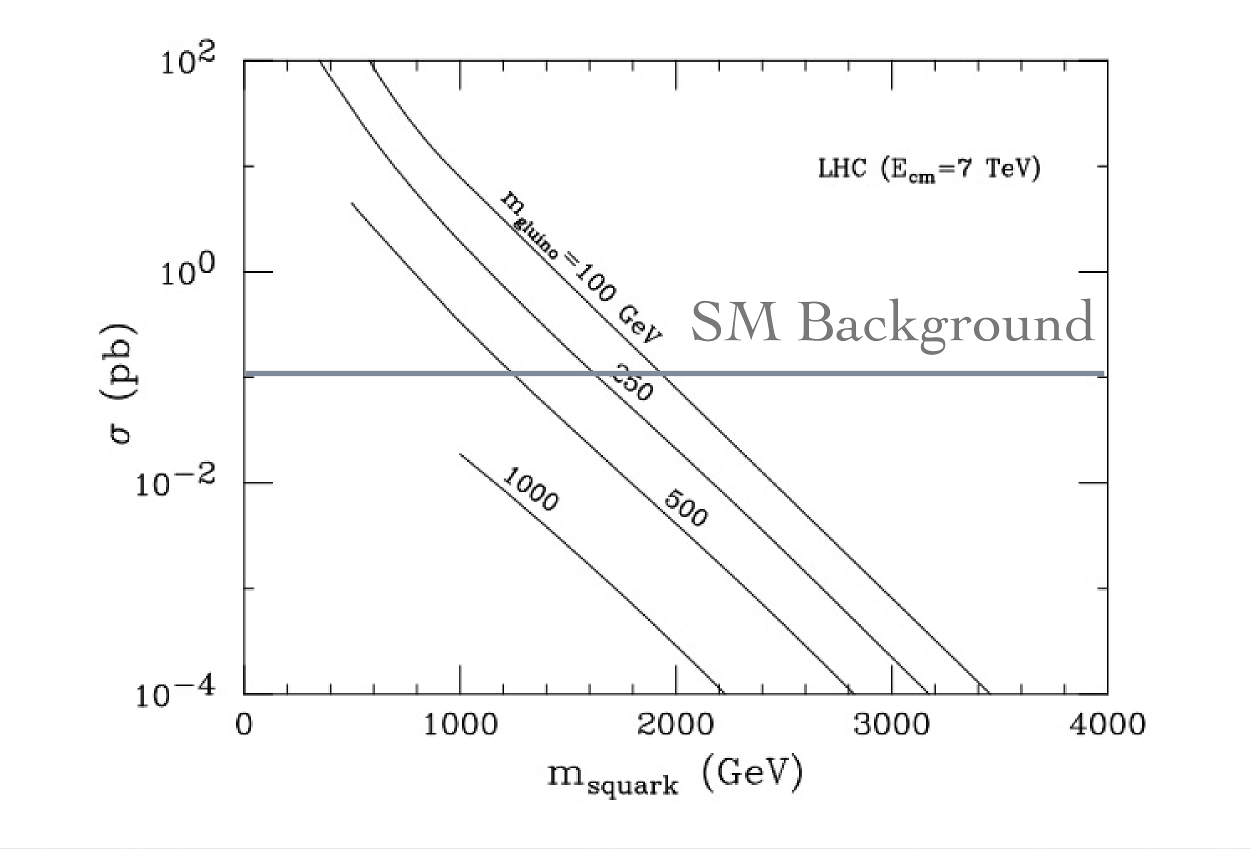
to low p_T !

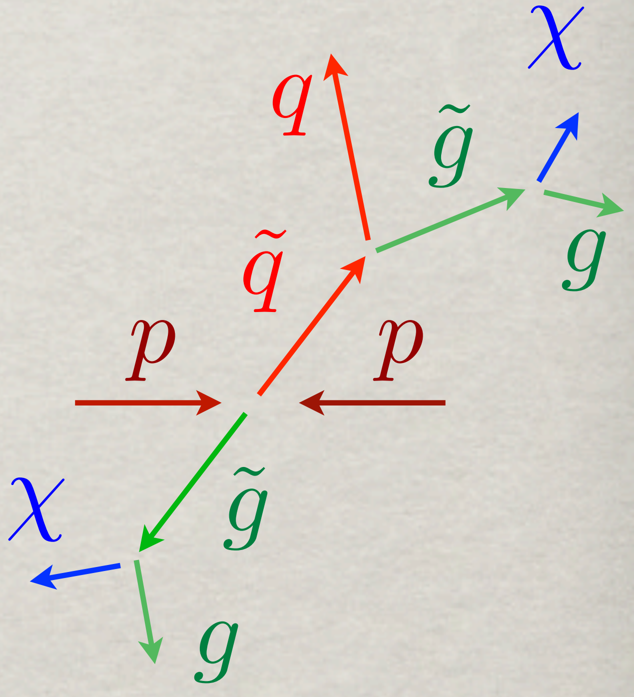




LHC: Mono-jet signature

More promising perhaps the squark-gluino channel, where the squark decays into quark and gluino (= missing Energy !). Since the other gluino also decays invisibly, the signal is a mono-jet and large missing transverse momentum.



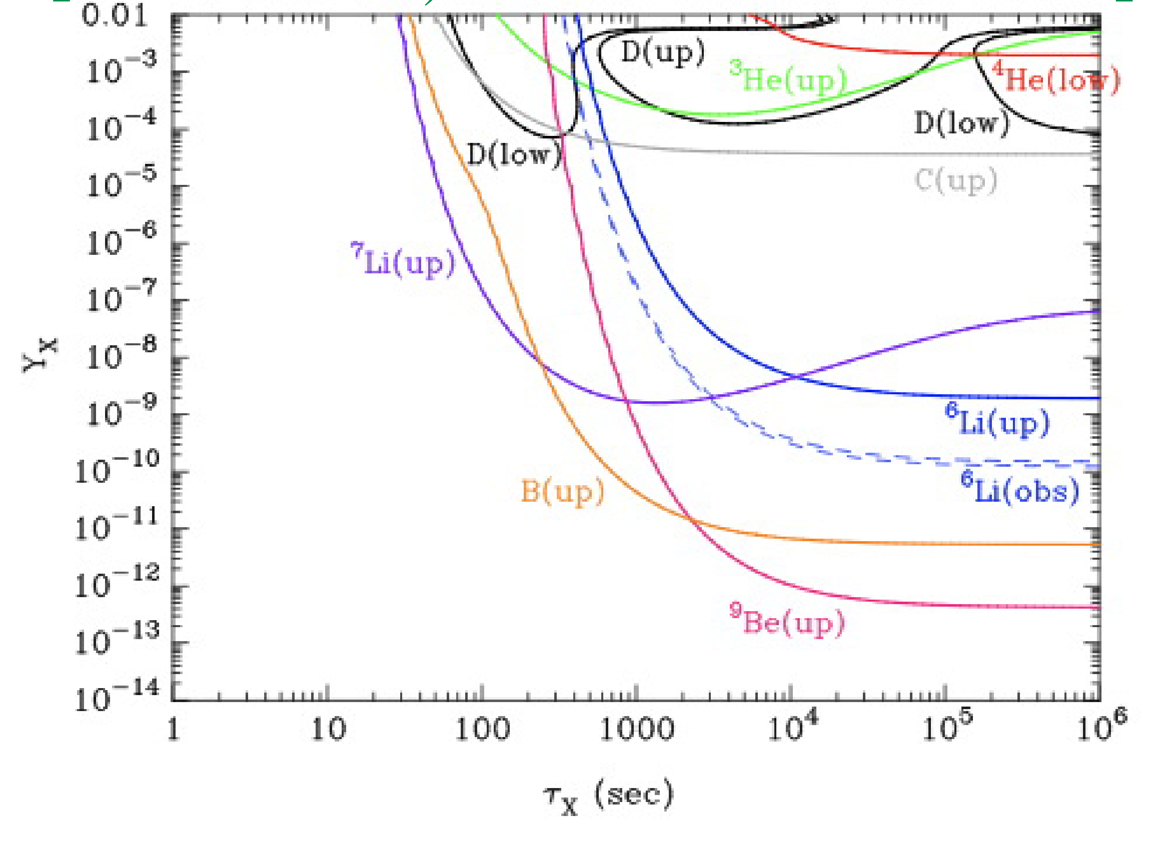


Detectable in the 1st LHC phase up to 1.8 TeV squark mass !

BBN bounds: colored relics

Colored relics: even stronger BBN bound state effects...

[Kusakabe, Kajino, Yoshida, Mathews 09]



BBN bounds: colored relics

Colored relics: even stronger BBN bound state effects...

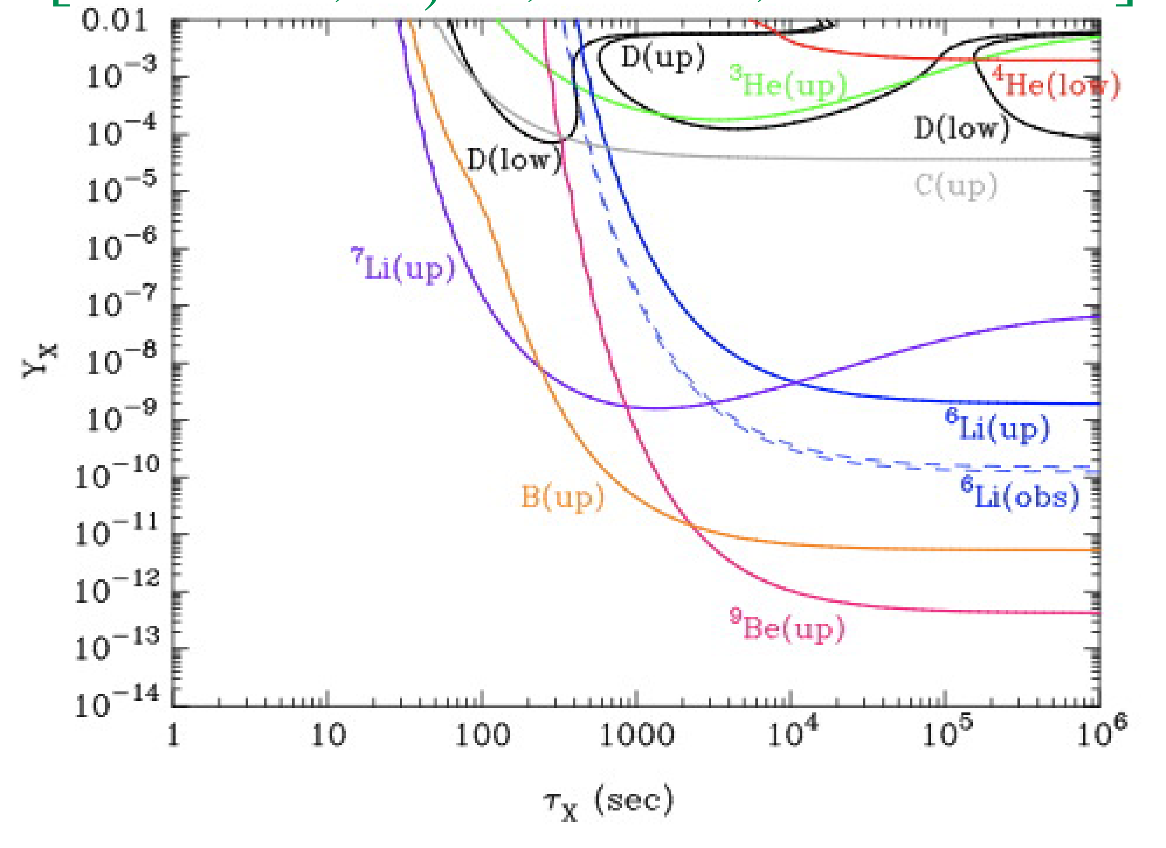
Beware:

$$Y_X^{BBN} = \frac{n_X}{n_b} \sim 10^{-9}\, Y_X$$

$$\rightarrow 0.02\, \frac{m_X}{GeV} \text{ in } \Omega h^2$$

Bounds so strong that even strong interaction is not strong enough...

[Kusakabe, Kajino, Yoshida, Mathews 09]



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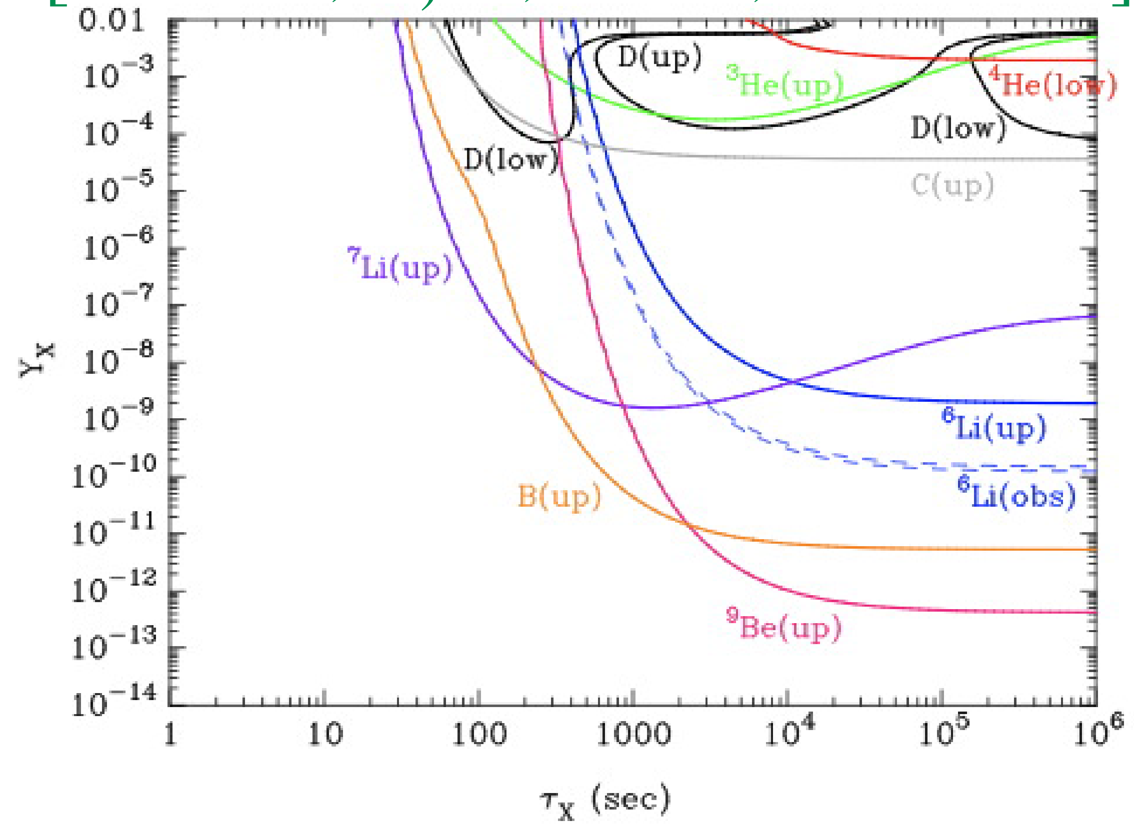

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Bounds so strong that even strong interaction is not strong enough...

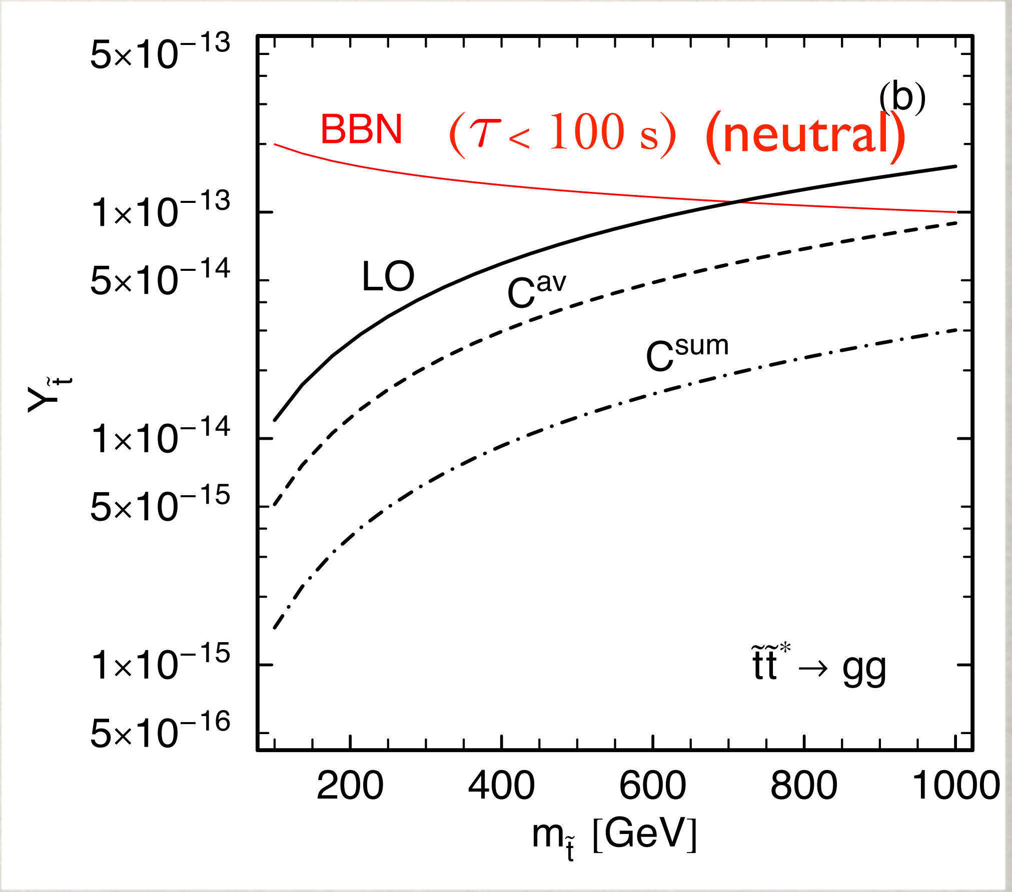
Only short lifetime for colored NLSP allowed:

$$\tau_{\tilde{g},\tilde{t}} < 200 \text{ s} \quad \rightarrow \quad m_{\tilde{g},\tilde{t}} > 800 \text{ GeV} \left(\frac{m_{3/2}}{10 \text{ GeV}}\right)^{2/5}$$

STOP NLSP

[Berger, LC, Kraml, Palorini 08]

- The stop number density is highly reduced thanks to the strong coupling and to non-perturbative effects, like the Sommerfeld enhancement !
- Late annihilations after the QCD phase transition can reduce the yield further, see e.g. [Kang, Luty & Nasri 06], but still difficult to bypass bound state effect BBN bound...



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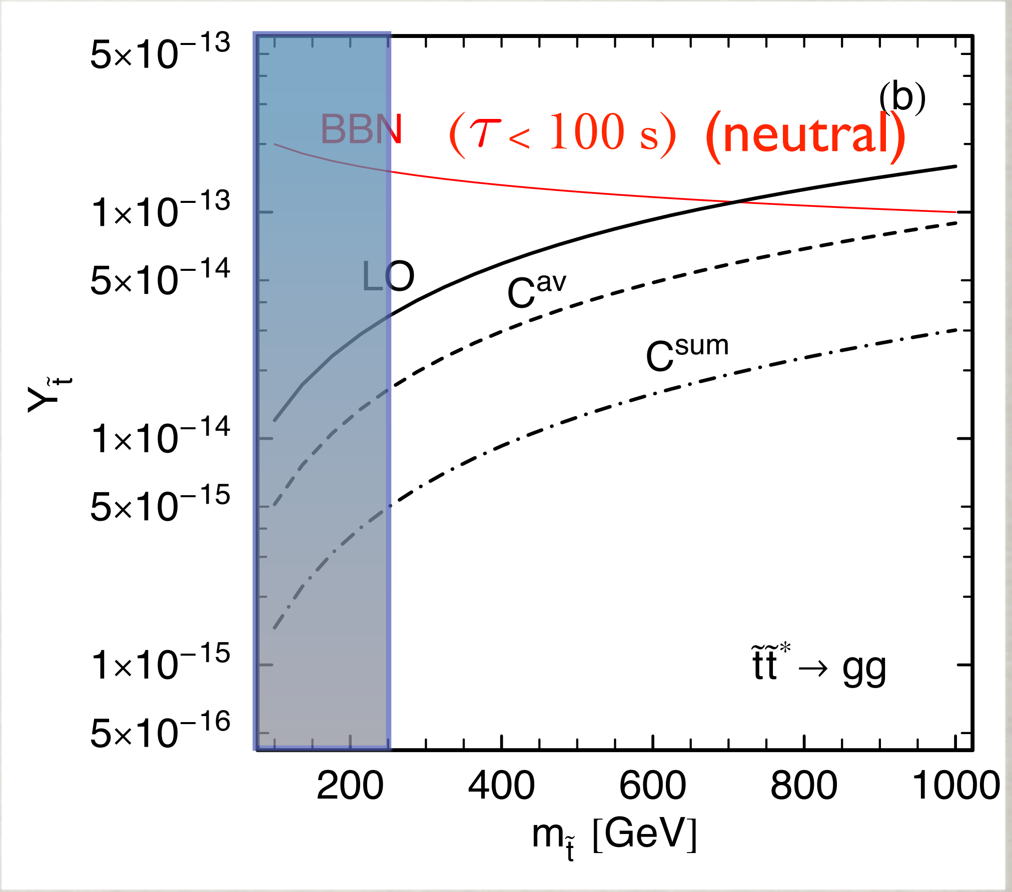

Excluded by Tevatron

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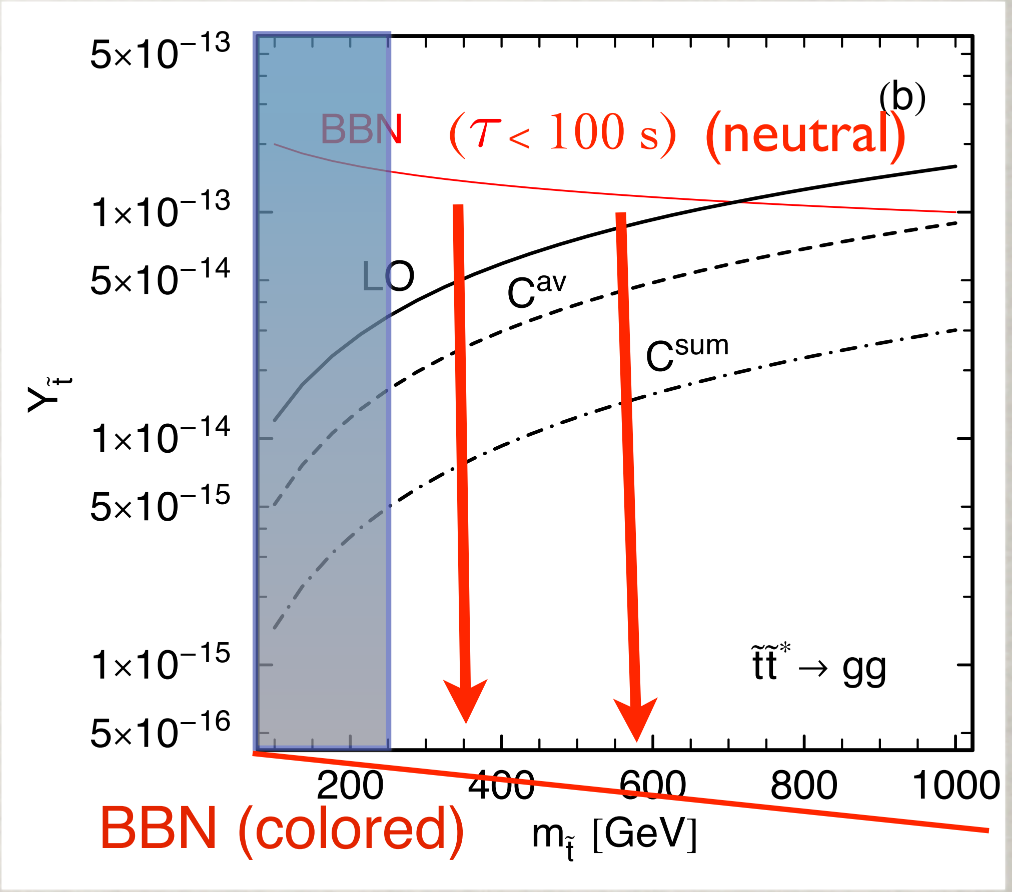

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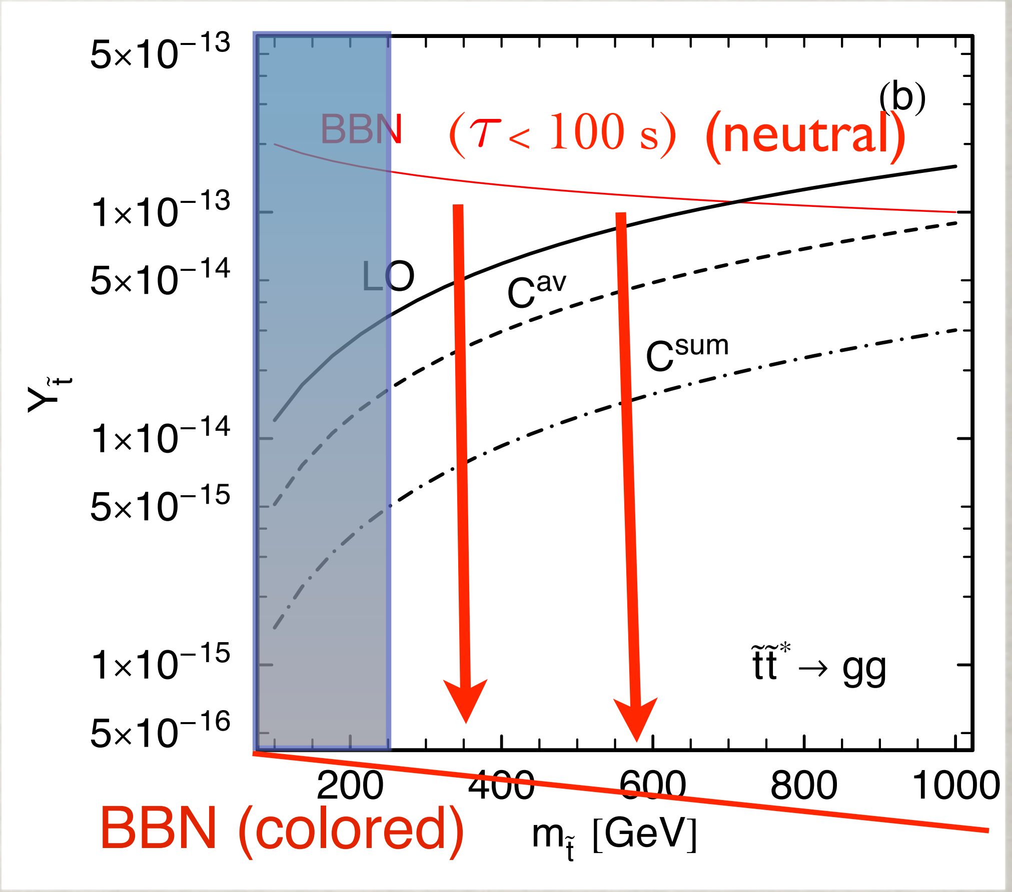
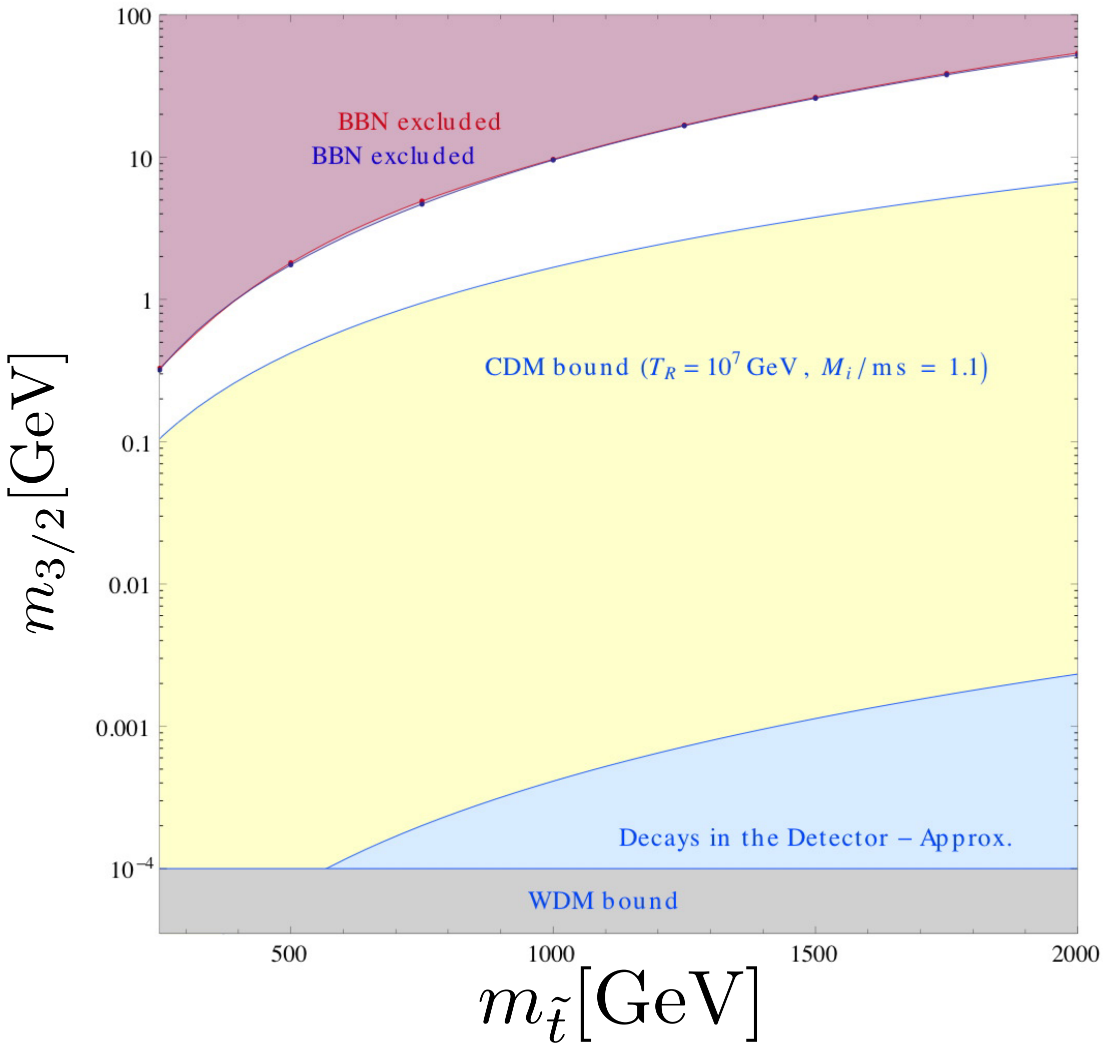


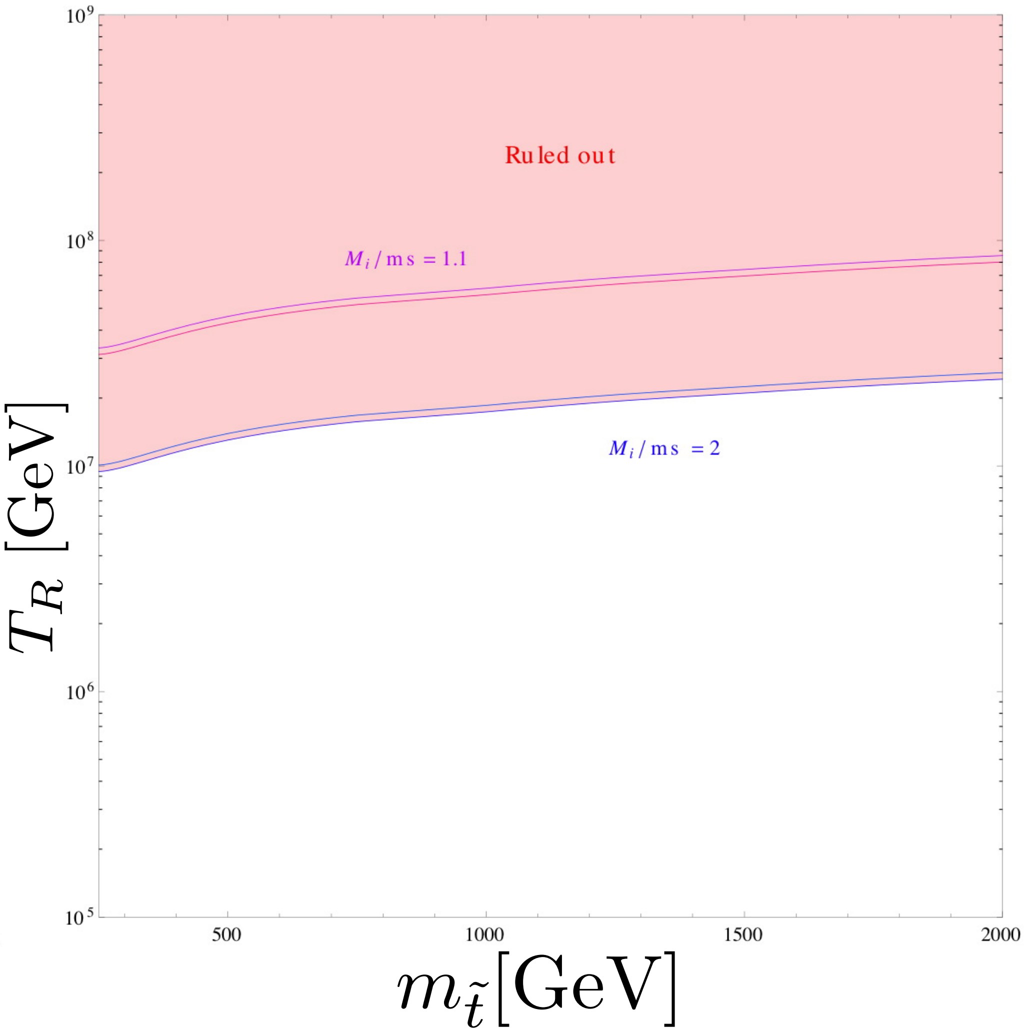
Excluded by Tevatron

Colored NLSP case is very constrained..., or not ?

COLORED NLSPs

[LC & F. Dradi xxx]





The BBN constraints allow only for T_R about few 10^7GeV

Unstable gravitino Dark Matter

R-parity or not R-parity

[Buchmuller, LC, Hamaguchi, Ibarra & Yanagida 07]

Actually there is a simple way to avoid BBN constraints: break R-parity a little... ! Then the NLSP decays quickly to SM particles before BBN and the cosmology returns standard.

$$W_{R\!\!\!/p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$

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no p decay

Open window:

$$10^{-12-14} < |\frac{\mu_i}{\mu}|, |\lambda|, |\lambda'| < 10^{-6-7}$$

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For the NLSP to decay before BBN

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For the NLSP to decay before BBN

To avoid wash-out of lepton number

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For the NLSP to decay before BBN

To avoid wash-out of lepton number

Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

Decaying axino/gravitino?

- If R-parity is broken the NLSP decays fast to SM particles, but axino & gravitino are much longer-lived

$$\tau_{\tilde{G}} \sim 10^{27}\mathrm{s} \left(\frac{\epsilon}{10^{-7}}\right)^{-2} \left(\frac{M_1}{100\mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}}\right)^{-3}$$

$$\tau_{\tilde{a}} \sim 10^{27}\mathrm{s} \left(\frac{\epsilon}{10^{-10}}\right)^{-2} \left(\frac{M_1}{100\mathrm{GeV}}\right)^2 \left(\frac{m_{\tilde{a}}}{10\mathrm{GeV}}\right)^{-3} \left(\frac{f_a}{10^{11}\mathrm{GeV}}\right)^2$$

- For bilinear R-parity breaking, they decay similarly to gauge boson/Higgs and neutrino

[Takayama &Yamaguchi 00, Buchmuller et al '07, LC & JE Kim 09]

For trilinear R-parity breaking, the 3-body decays into leptons can dominate and give a leptophilic DM
[Bomark et al 09, LC & JE Kim 09, Bajc et al 10]

Gravitino LSP decay

[Takayama & Yamaguchi 00, Buchmuller et al 07]

If R-parity is broken, the gravitino can decay into photon and neutrino via neutralino-neutrino mixing or via a one-loop diagram or into 3 SM fermions via the trilinear couplings.

$$\tilde{G} \to \gamma\nu, Z\nu, W^{\pm}\ell^{\mp} \qquad \tilde{G} \to \ell_L \bar{\ell}_L e_R \quad \tilde{G} \to \ell_L \bar{q}_L d_R$$

For bilinear R-parity breaking the 2-body channel dominates:

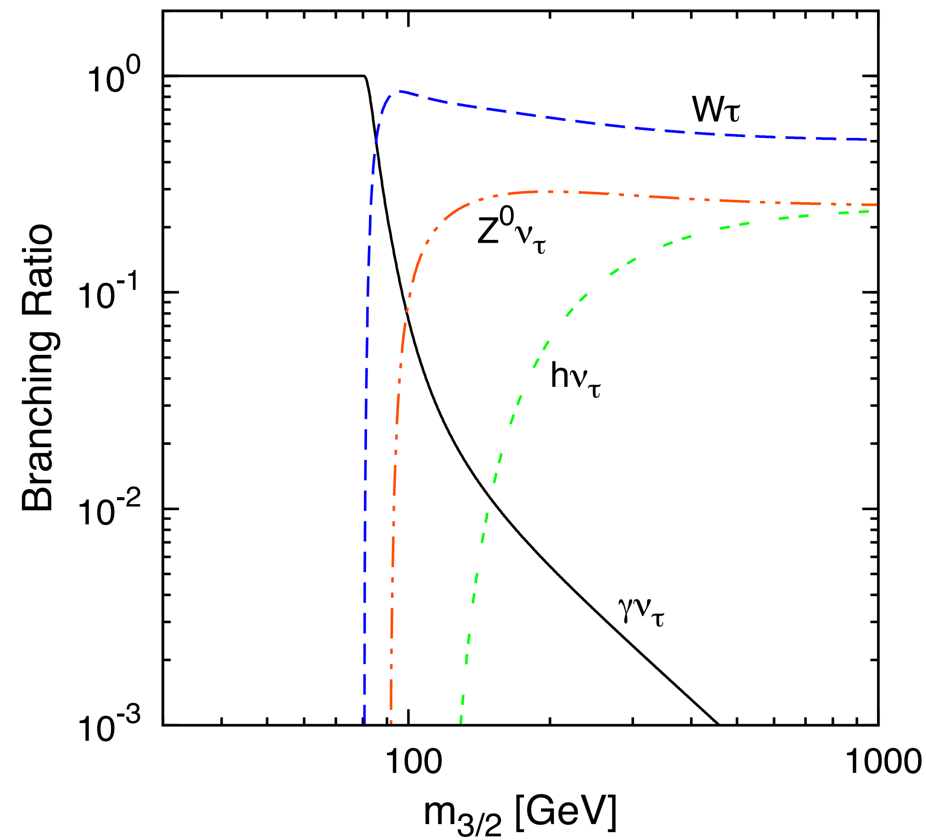
$$\tau_{\tilde{G}} = 4 \times 10^{27} s \left(\frac{U_{\tilde{\gamma}\nu}}{10^{-8}} \right)^2 \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}} \right)^{-3}$$

[Lola, Osland & Raklev 07] computed also the 2-body one-loop decay and found it also important for most parameter space. For heavy gravitino the decays prefers to go into EW gauge boson final states. [Ibarra & Tran 07]

Gravitino decay modes

For bilinear R-parity violation, the gravitino decays into neutrino and (gauge) boson: photon, W, Z or Higgs
or via trilinear couplings into neutrino and 2 leptons

[LC, Grefe, Ibarra & Tran 08]



The lifetime is very long, suppressed by M_P and the small mixing between neutrinos and gauginos:

$$\tau_{\tilde{G}} = 4 \times 10^{27} s \left(\frac{U_{\tilde{\gamma}\nu}}{10^{-8}} \right)^2 \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}} \right)^{-3}$$

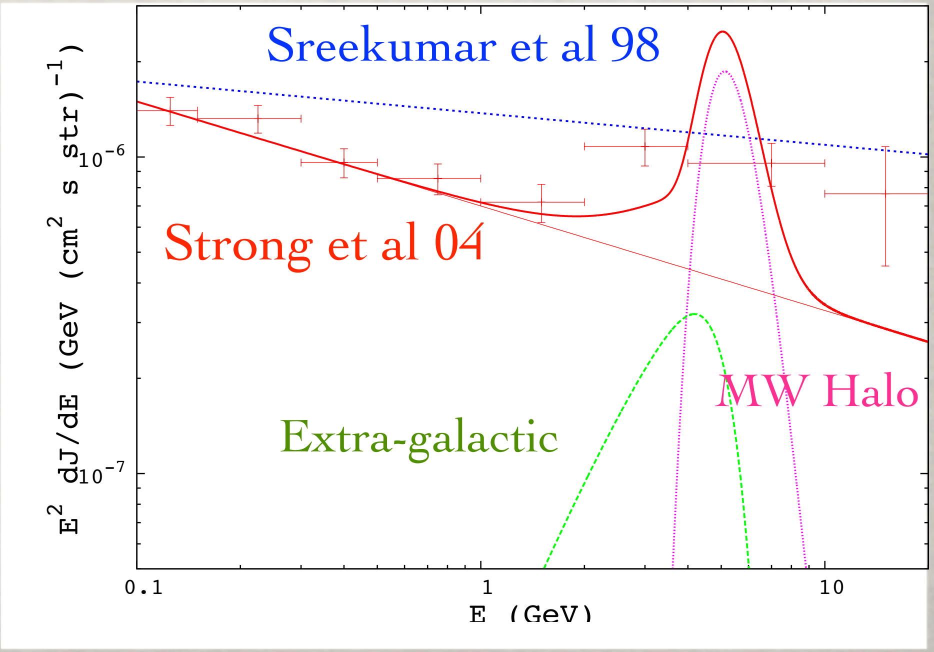
DECAYING DM

- The flux from DM decay in a species i is given by

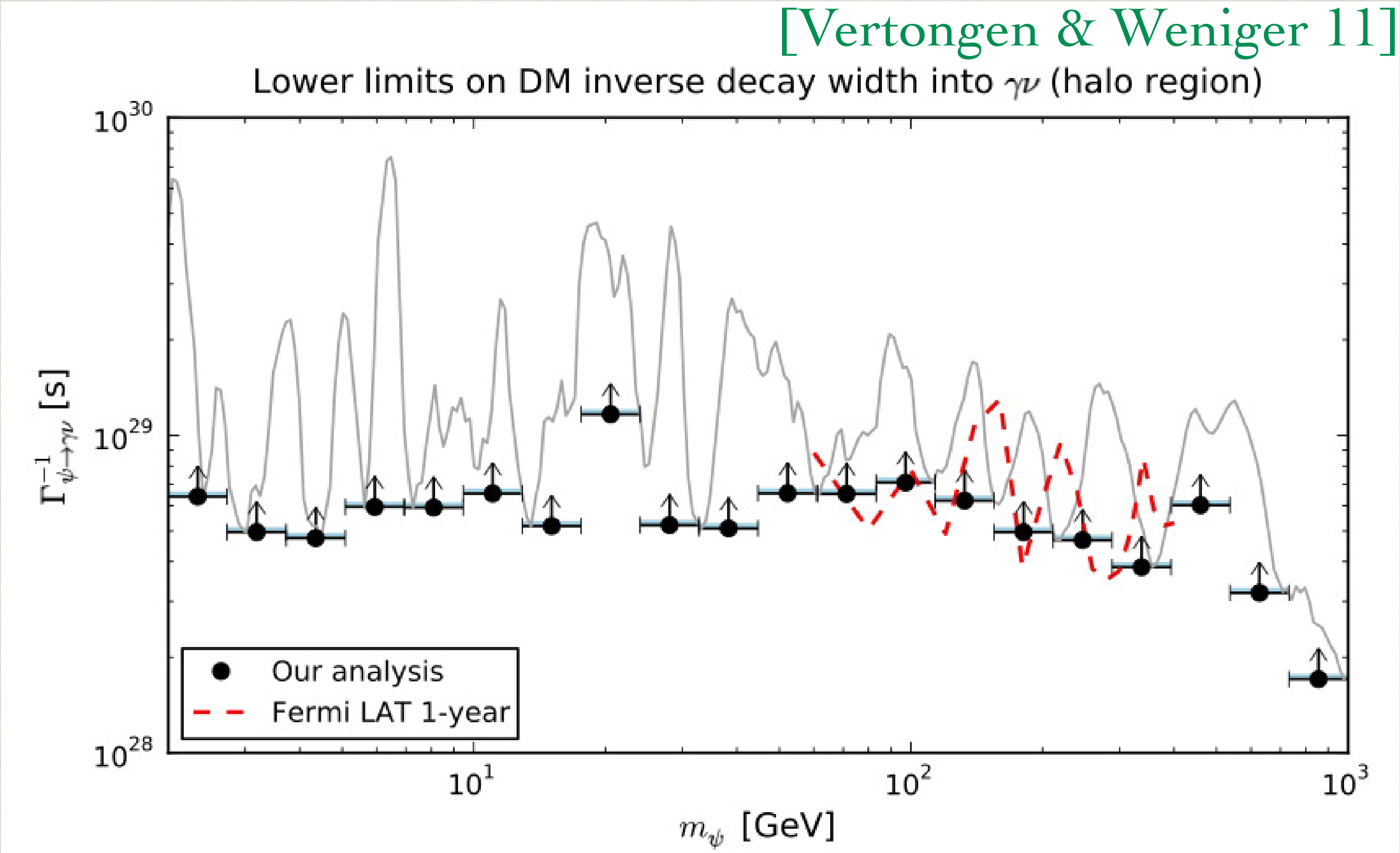
$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\ \rho(r(s,\theta))$$

Particle Physics   Halo property

- Very weak dependence on the Halo profile; key parameter is the DM lifetime...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...
- Galactic/extragalactic signal are comparable...



FERMI LINE CONSTRAINTS

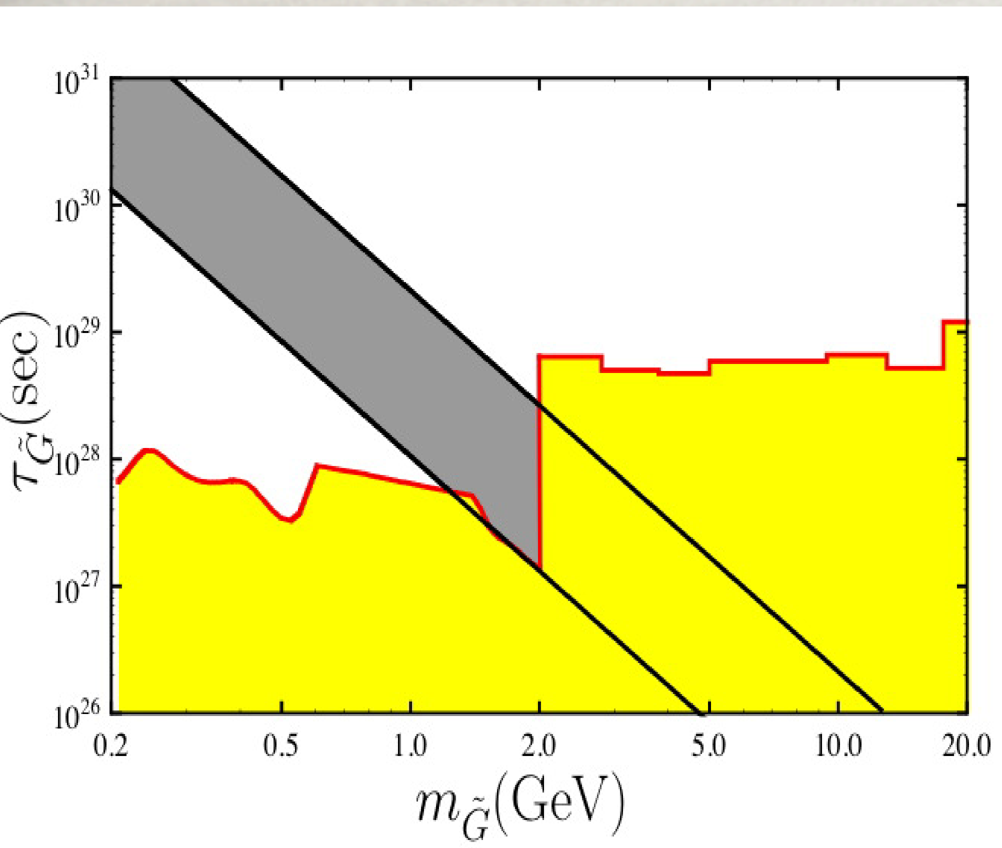


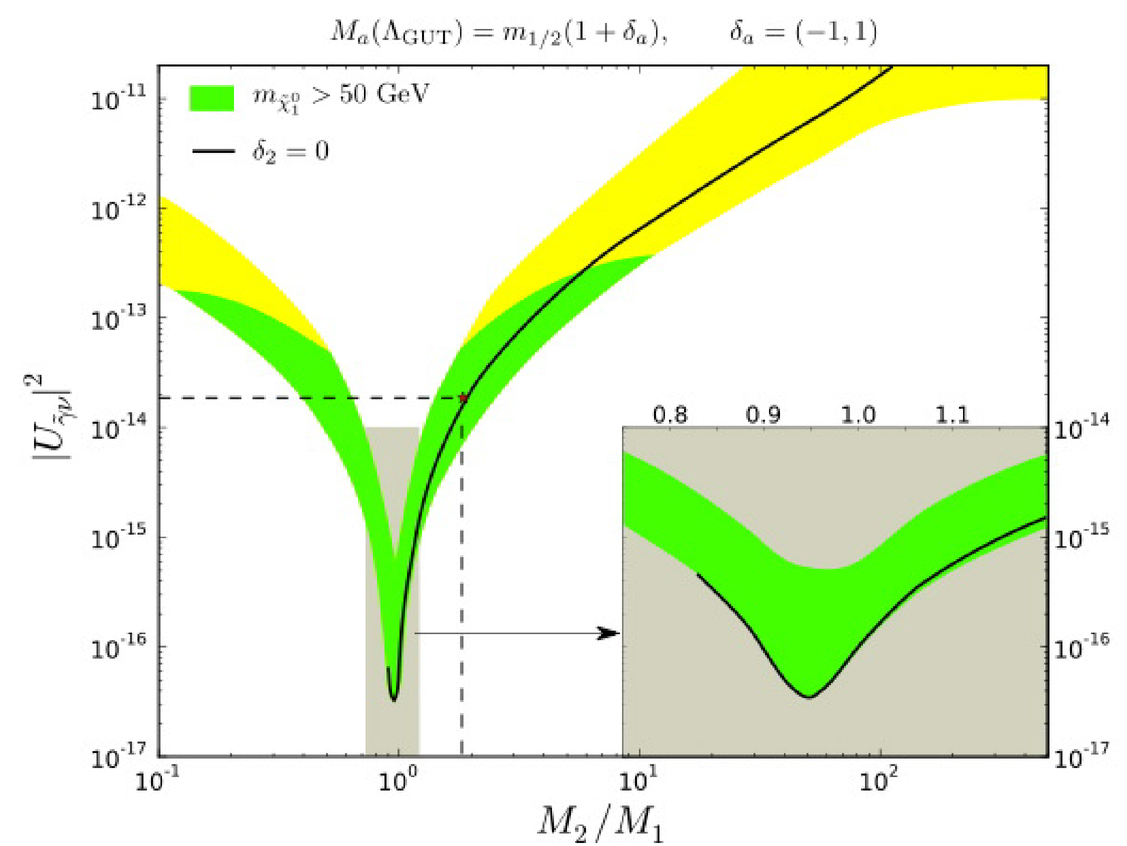
A recent analysis extends the FERMI line search in a wider mass region, for energies to 500 GeV, i.e. masses between 1-1000 GeV

From the FERMI gamma-line search: $\tau \geq 6\ 10^{28}$ s @ 95% CL

R_p and neutrino masses

For smaller gravitino masses the gamma constraints become weaker and allows for R_p breaking in the range explaining the observed neutrino masses [Restrepo, Taoso, Valle & Zapata.12]





Moreover, for non-universal gaugino also a mass suppression for the gamma decay channel is possible

SuperWIMPs
@ the LHC

(N)LSP decay at colliders

Same signals as in classical gauge mediation/R-parity breaking scenarios, the main decay channels for neutralino or stau are

R-parity conserved

$$\chi^0 \to \psi_{3/2}\,\gamma/\tilde{a}\,\gamma$$
$$\tilde{\tau} \to \psi_{3/2}\,\tau/\tilde{a}\,\tau$$

R-parity violated

$$\chi^0 \to \tau W, \nu Z, b\bar{b}\nu$$
$$\tilde{\tau} \to \tau\nu_\mu, \mu\nu_\tau, \bar{b}bW$$

but with longer lifetimes than expected if gravitino is DM...

$$m_{3/2} > 4 \text{ keV}$$

$$\tau_{3/2} > 6 \times 10^{28} \text{ s}$$

$$\tau_{NLSP} > 10^{-13} \text{ s} \left(\frac{m_{NLSP}}{2\text{TeV}}\right)^{-5}$$

$$\tau_{NLSP} > 10^{-8} \text{ s}$$

DISPLACED VERTICES... perhaps even too much !

LHC: Displaced vertices or charged tracks ?

Conserved Rp Gravitino: The decays happen within the detector for gravitino masses below 10 keV. Nevertheless thank to the sizable fraction of boosted NLSP it may be possible to reach even 0.1-1 MeV. [Ishiwata, Ito & Moroi 08]

[Chang & Luty 09, Meade, Reed & Shih 10]

Broken Rp Gravitino: The decays may also happen within the detector with a sufficient number of events. Possible discovery or exclusion down to couplings $\epsilon \sim 10^{-9} - 10^{-10}$ if the colored states are accessible at LHC.

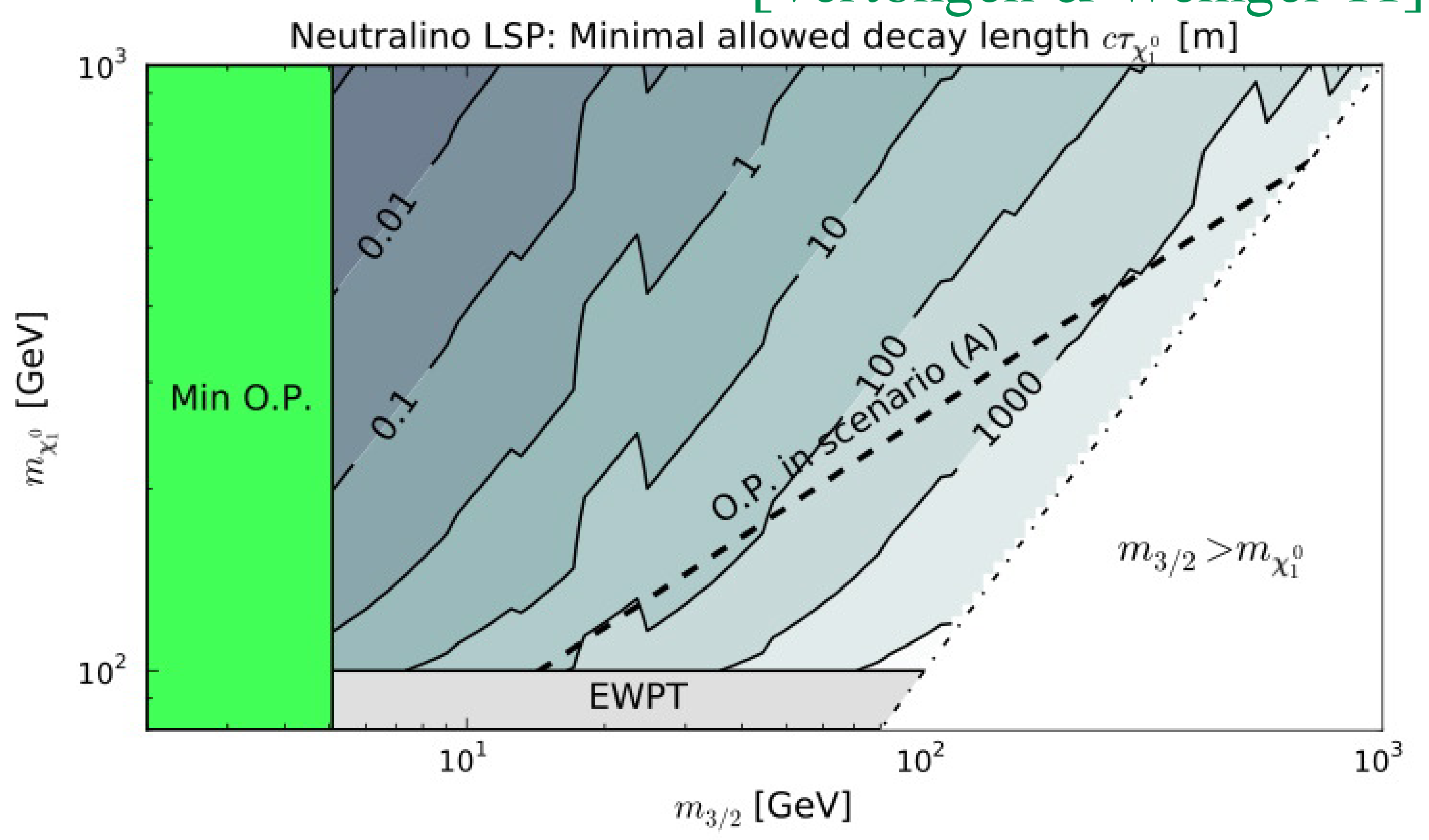
[Bobrovskyi, Buchmuller, Hajer & Schmidt 11]

Axino: The NLSP always decays outside the detector in both cases..., but a "light" metastable stau NLSP leaving a highly ionized track at the LHC is possible !

LHC:NLSP DECAY LENGTH

Broken Rp: The limits from the search for gamma-lines require a relatively large decay length for the neutralino NLSP:

[Vertongen & Weniger 11]

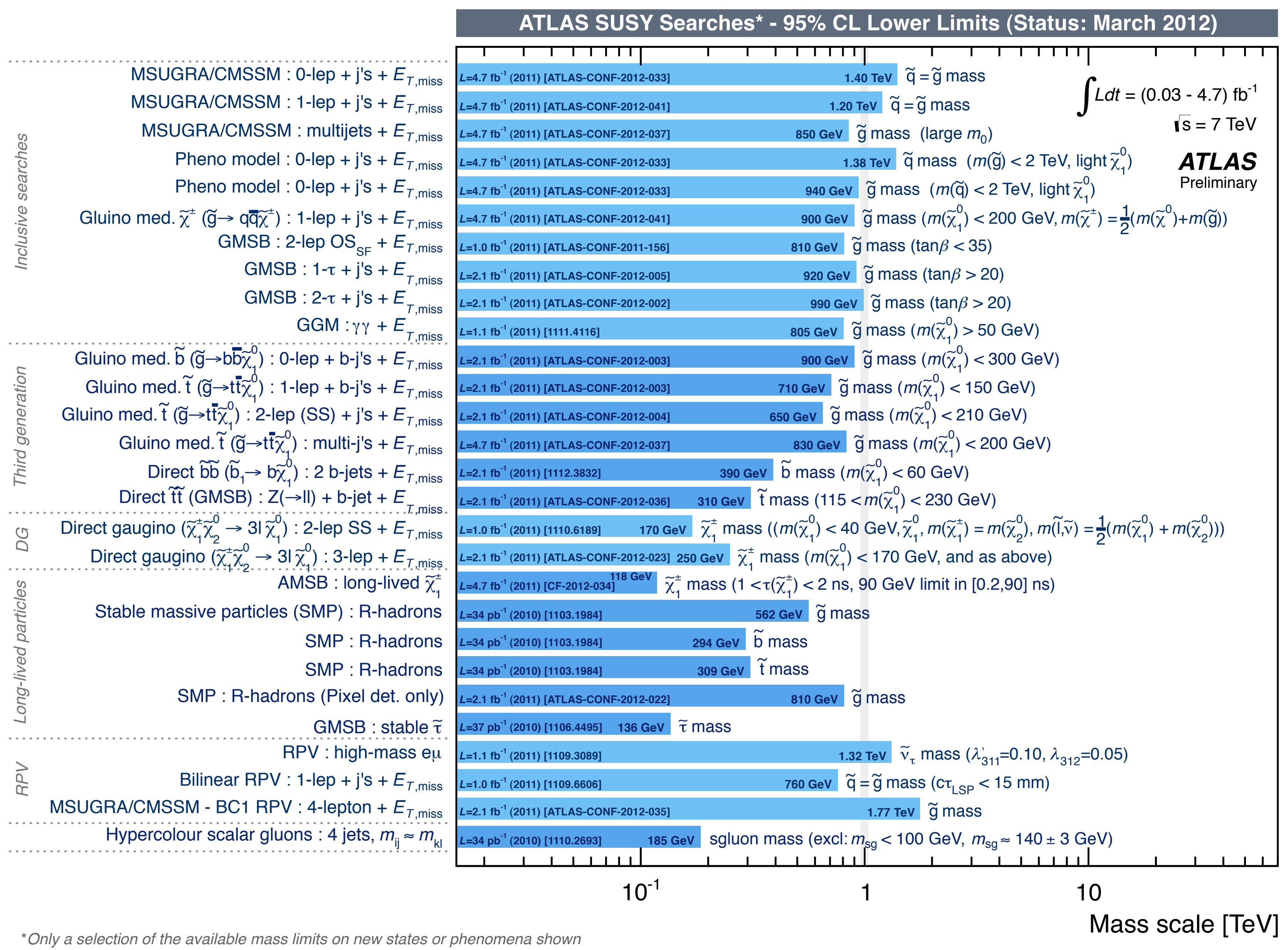


But no definite prediction on decay length for stau NLSP...

[Bobrovskyi, Buchmuller, Hajer & Schmidt 10]

LHC news: SUSY search

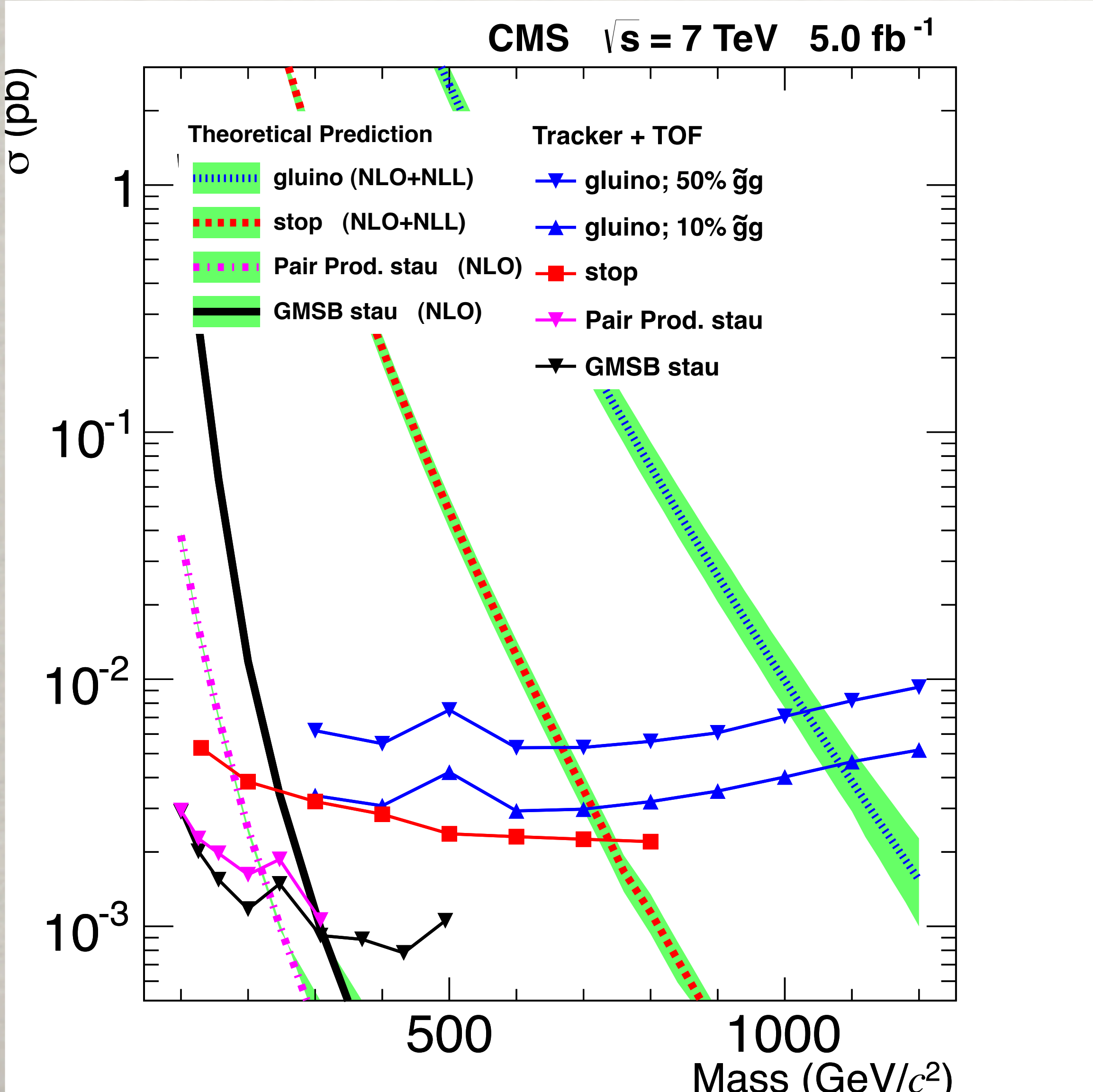
At the moment no significant excess found....

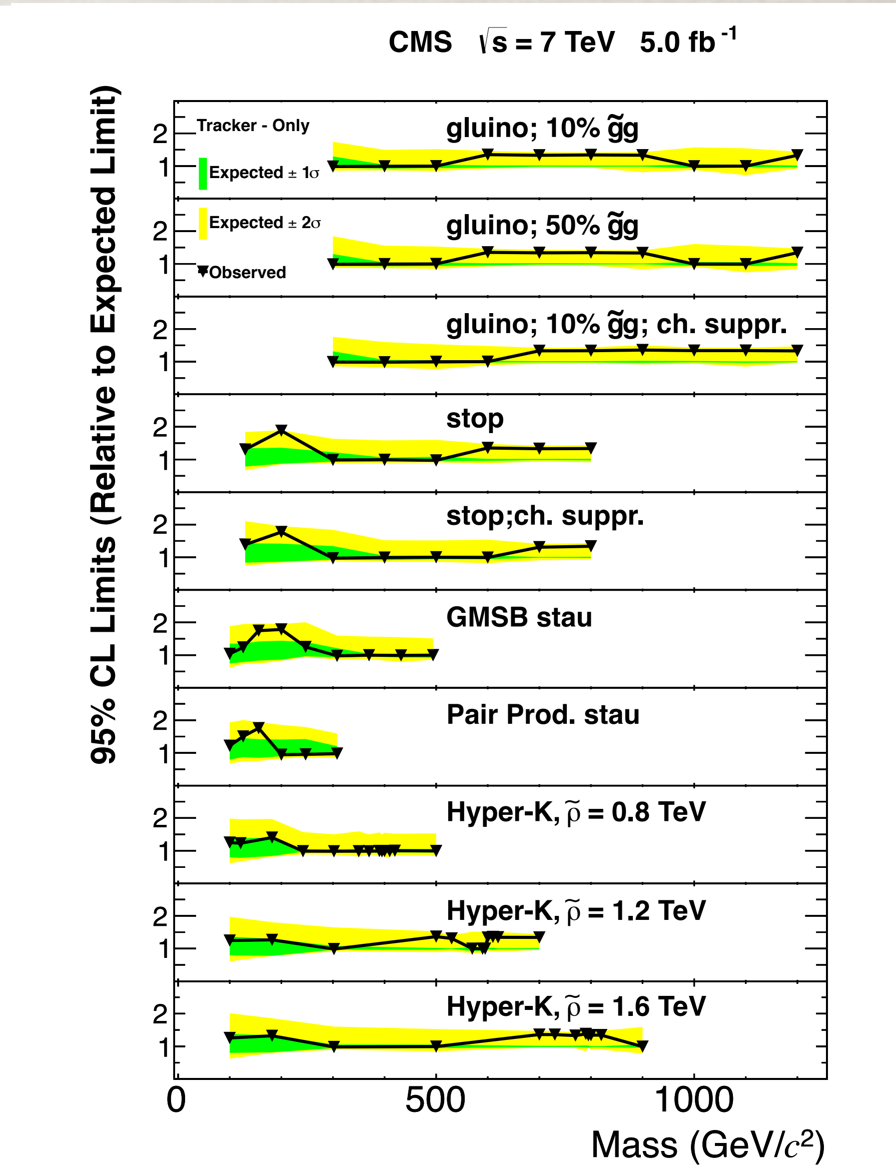


LHC: METASTABLE PARTICLES

Recent results from CMS for metastable SUSY particles:

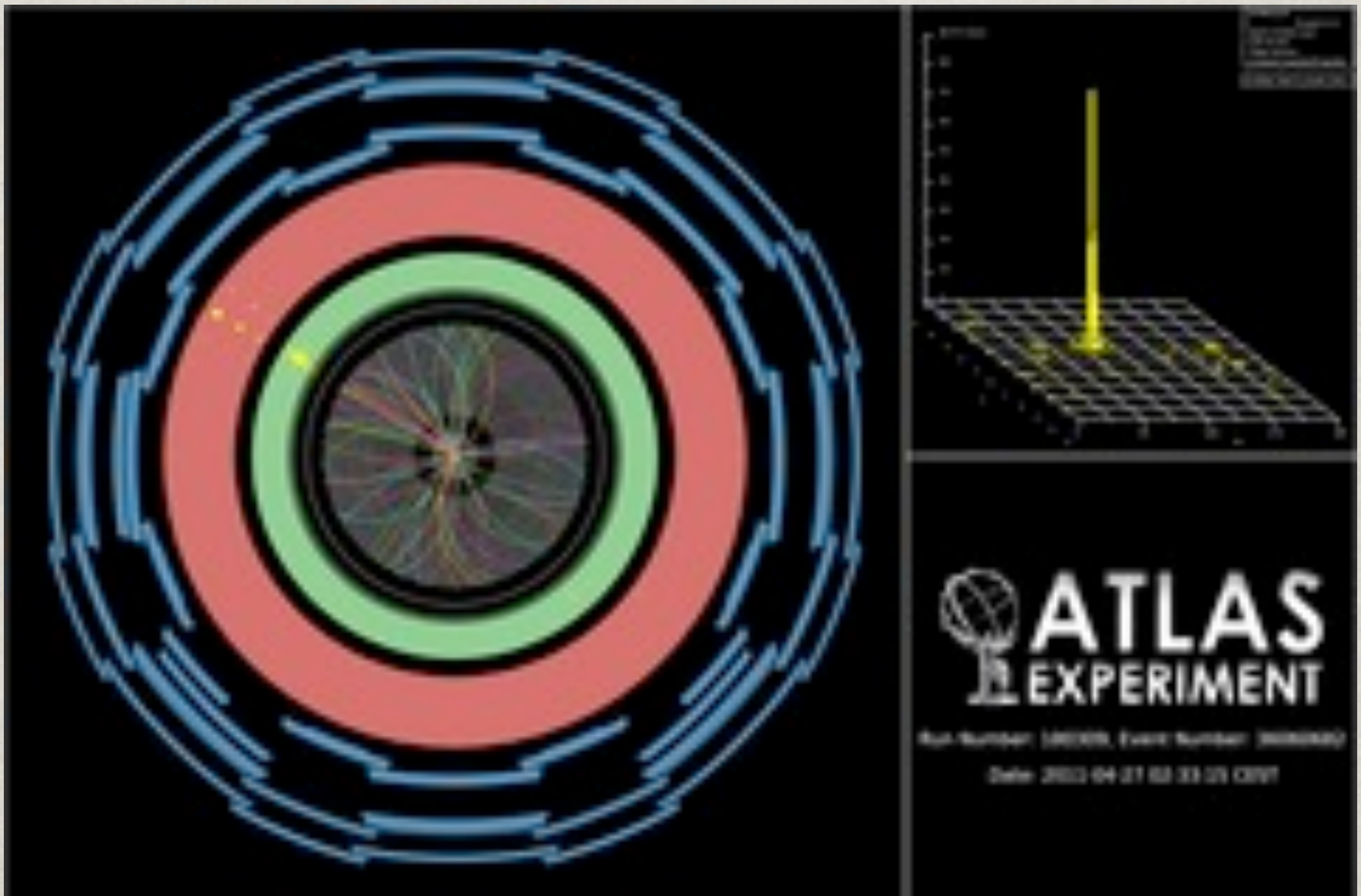
at the moment no significant excess found....





LHC: Monojets ?

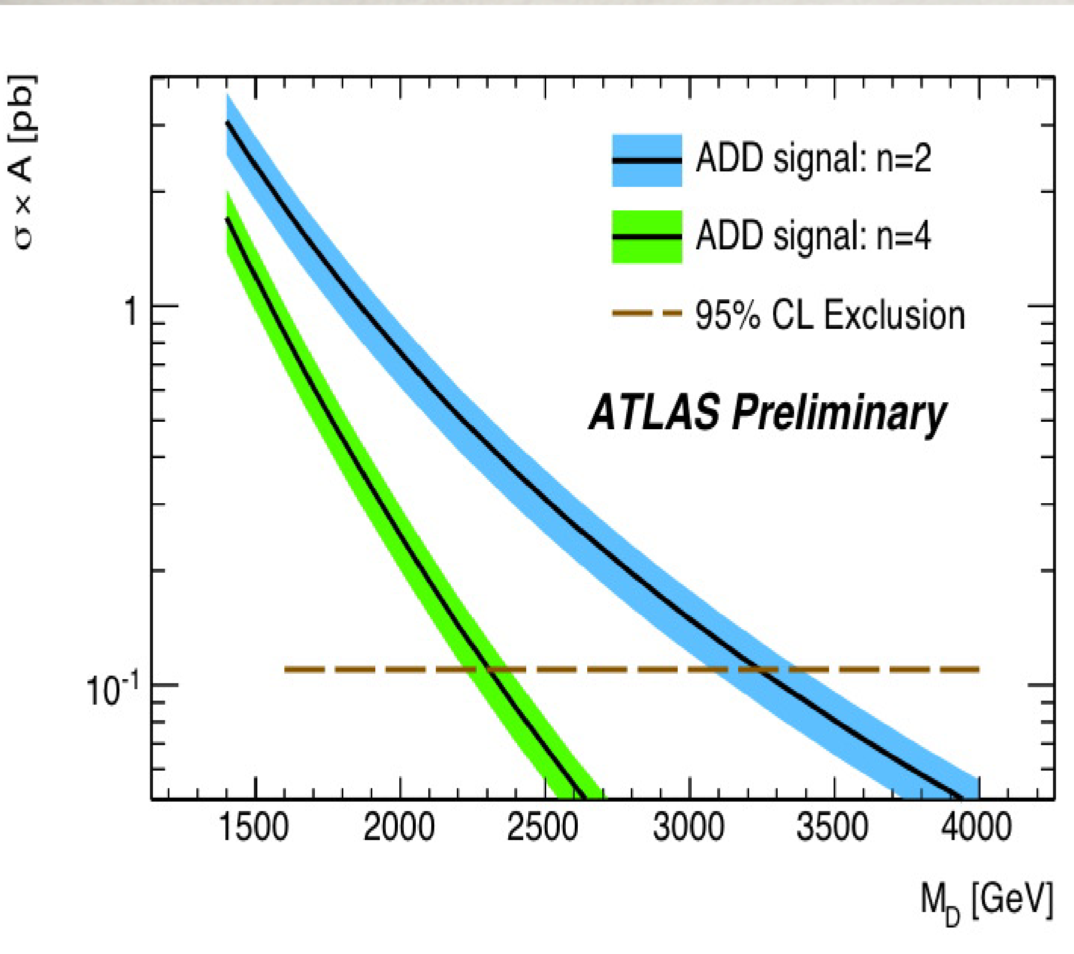
The compressed light neutralino spectrum is already being tested at LHC...

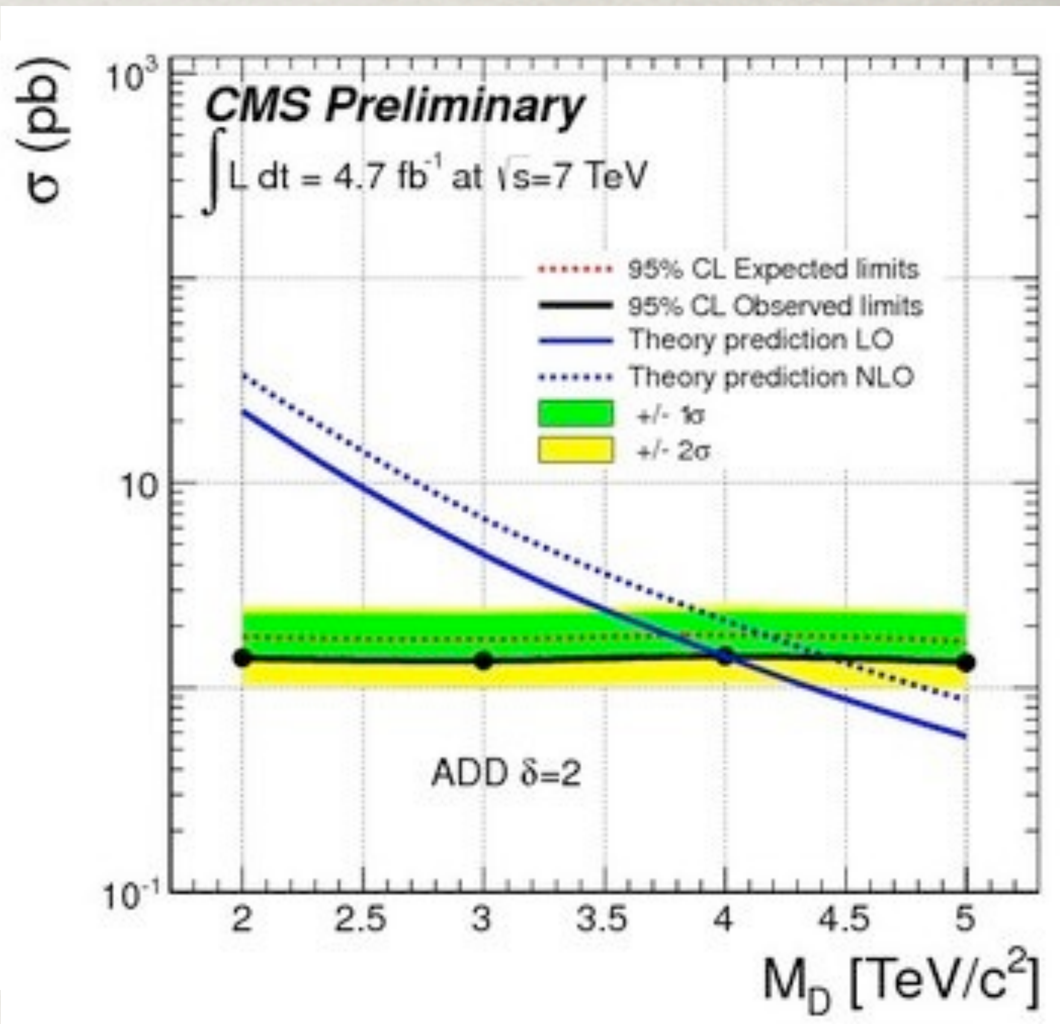


Monojet candidate event !

LHC: Monojets ?

For larger gravitino masses the compressed light neutralino spectrum is already being tested at LHC...





Not clear if excluded yet...

Outlook

Outlook

- SuperWIMPs are an alternative to WIMPs as CDM candidates and can be realized in many different scenarios. In supersymmetry in particular there is the possibility of gravitino and axino DM & LSP.
- BBN puts constraints on the lifetime and density of the NLSP and may point to particular compressed spectrum or large NLSP masses (and/or light gravitino masses...).
- SuperWIMPs gravitino/axino can survive as DM even for broken R-parity, but the breaking has to be suppressed. Indirect DM searches already set limits on these scenarios.
- Different signals are possible at the LHC: displaced vertices, missing energy or metastable charged particles:

  Let us hope for a signal soon !