Gravitino & SuperWIMPs in cosmology

Laura Covi

Institute for Theoretical Physics
Georg-August-University Gottingen

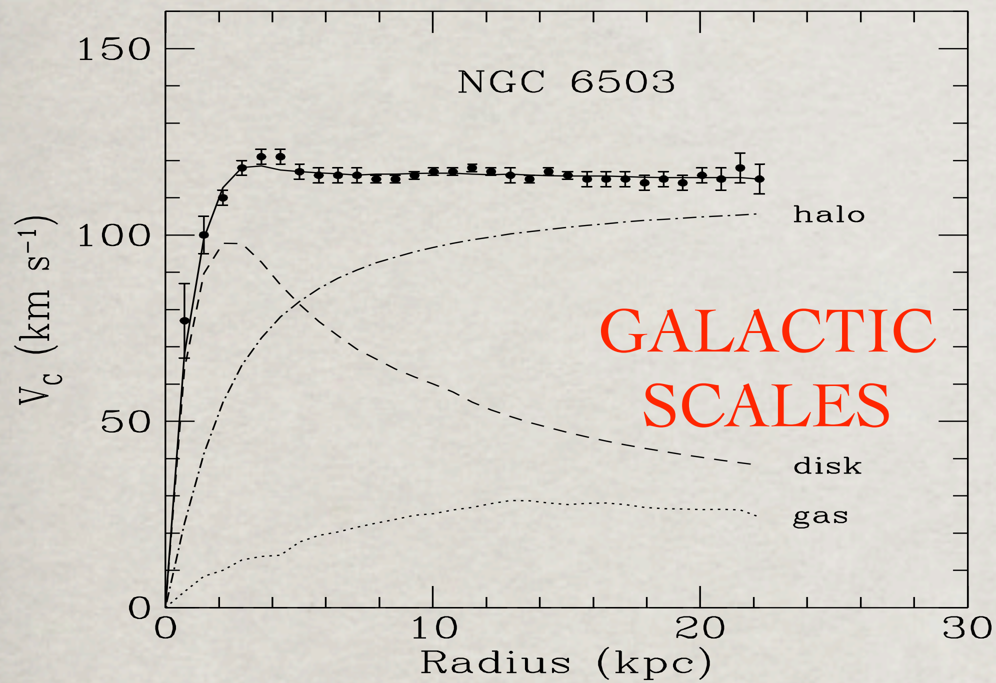
$[q,p]=i\hbar$

Outline

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

Introduction

DARK MATTER EVIDENCE



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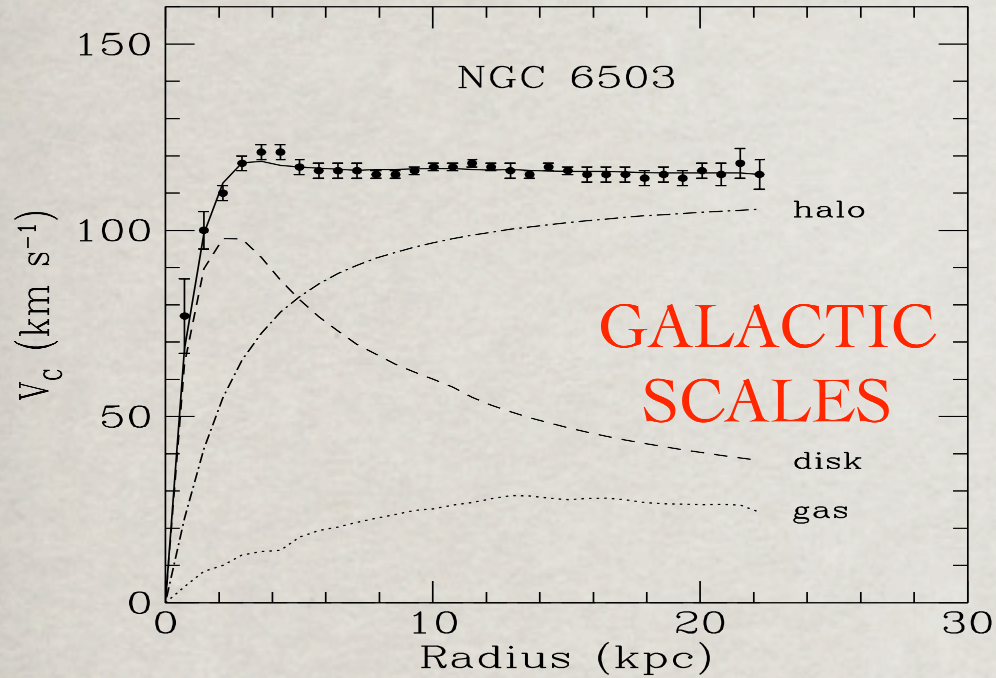

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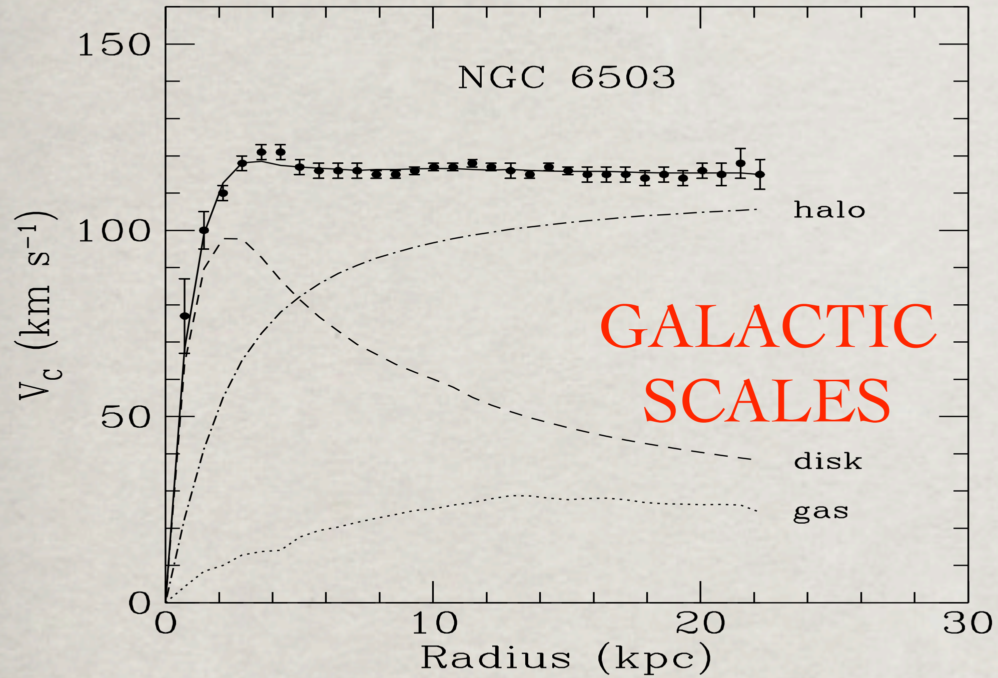

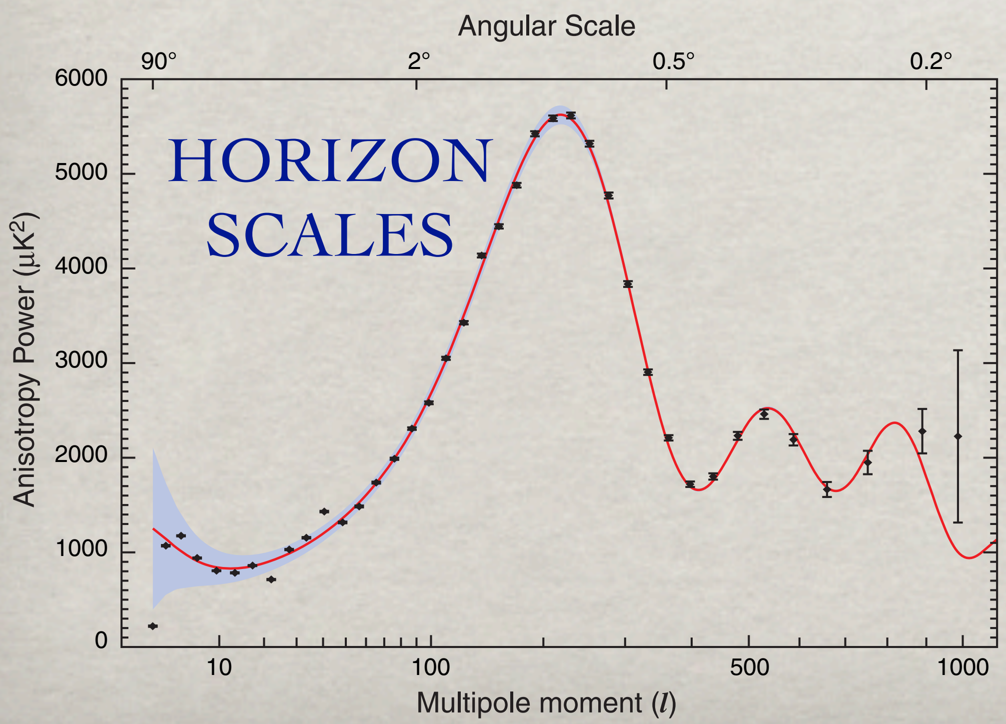

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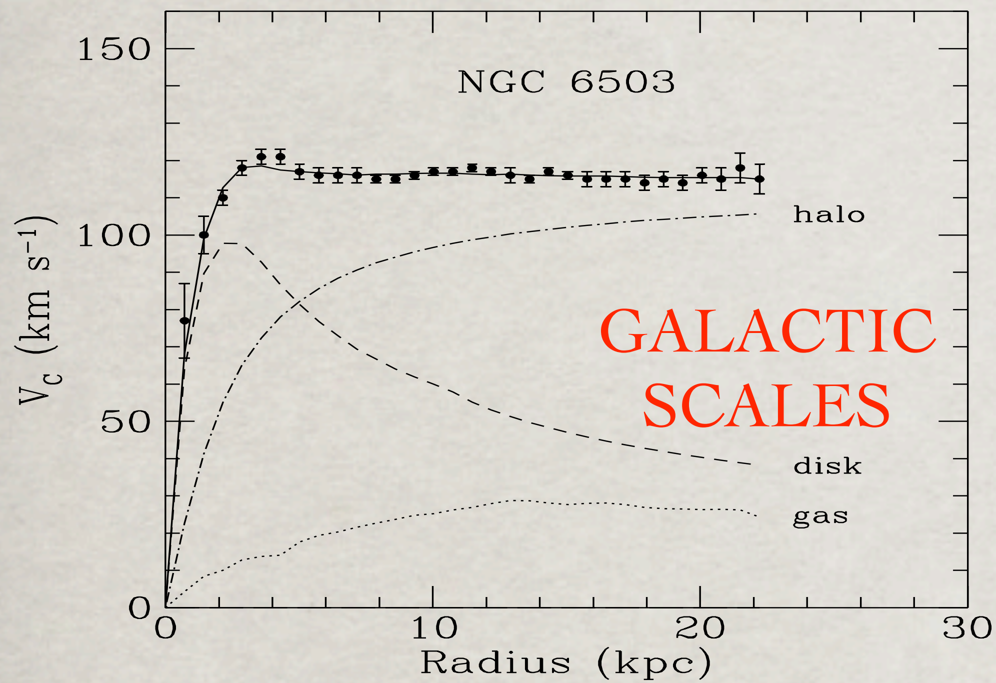
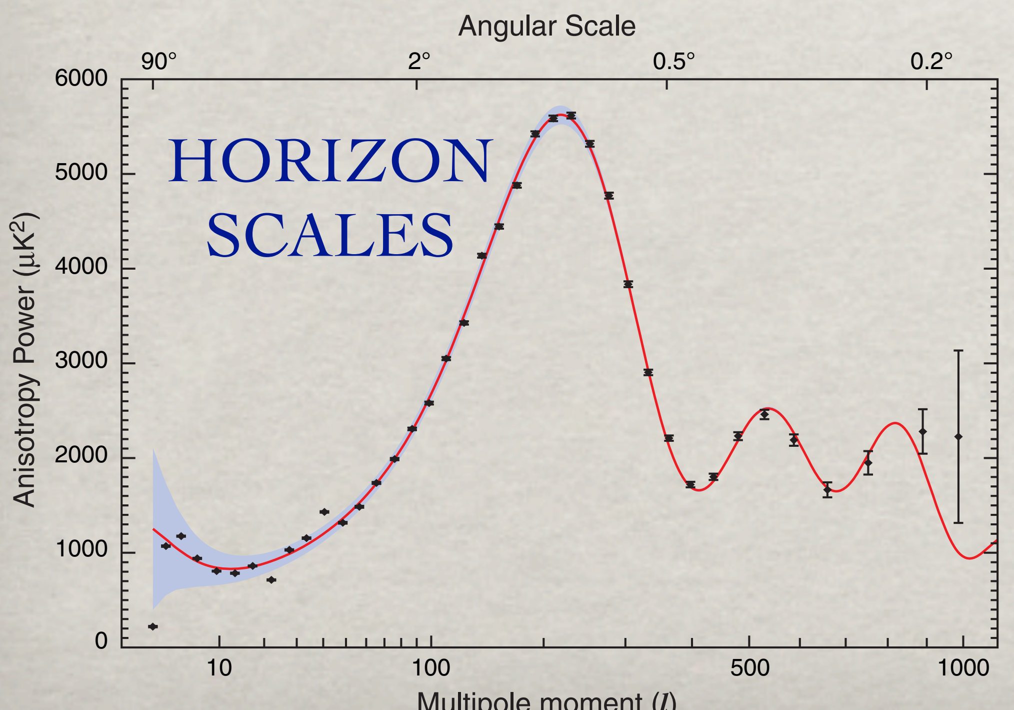




Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

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

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

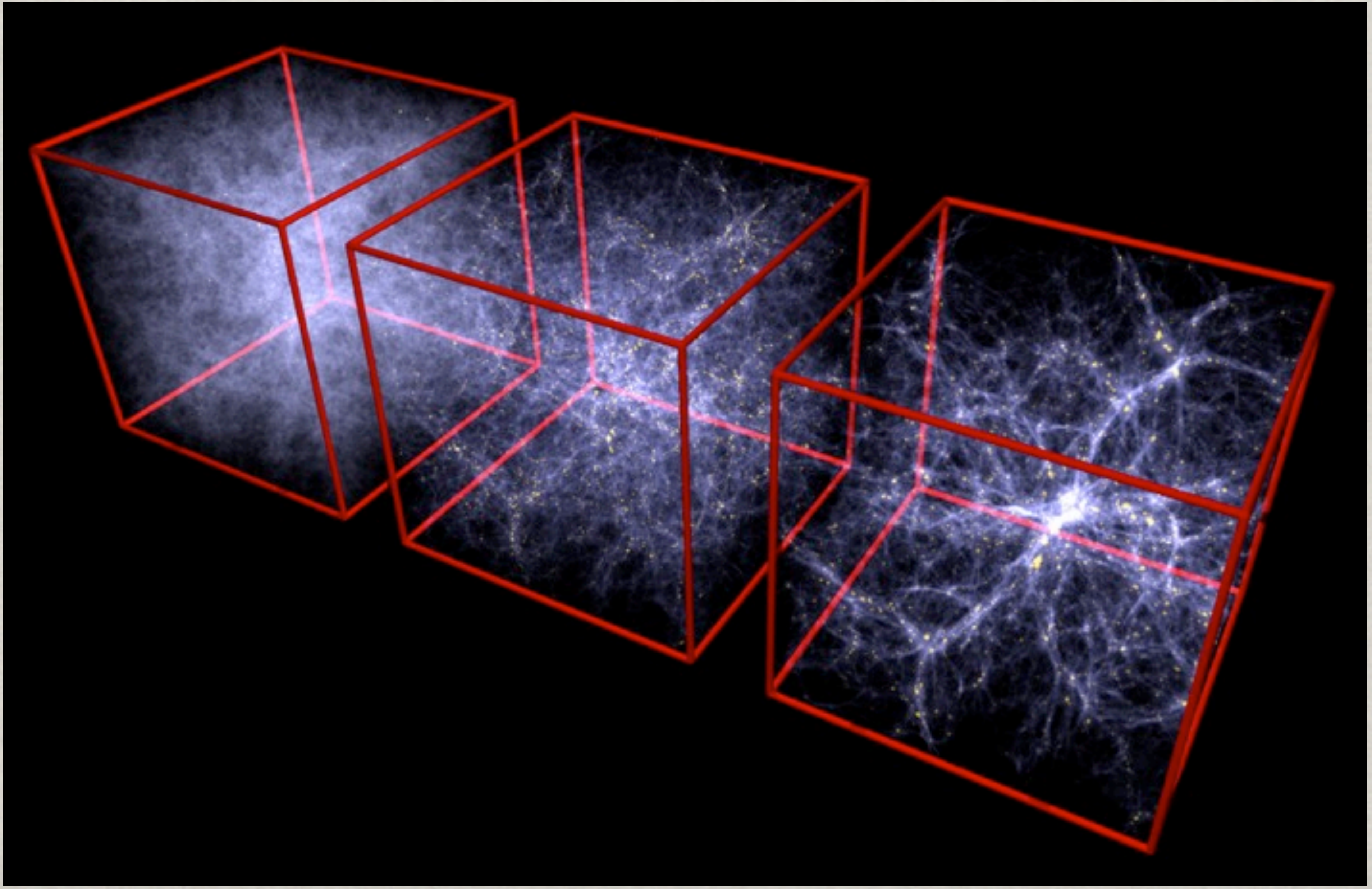
[Markevitch et al 03]

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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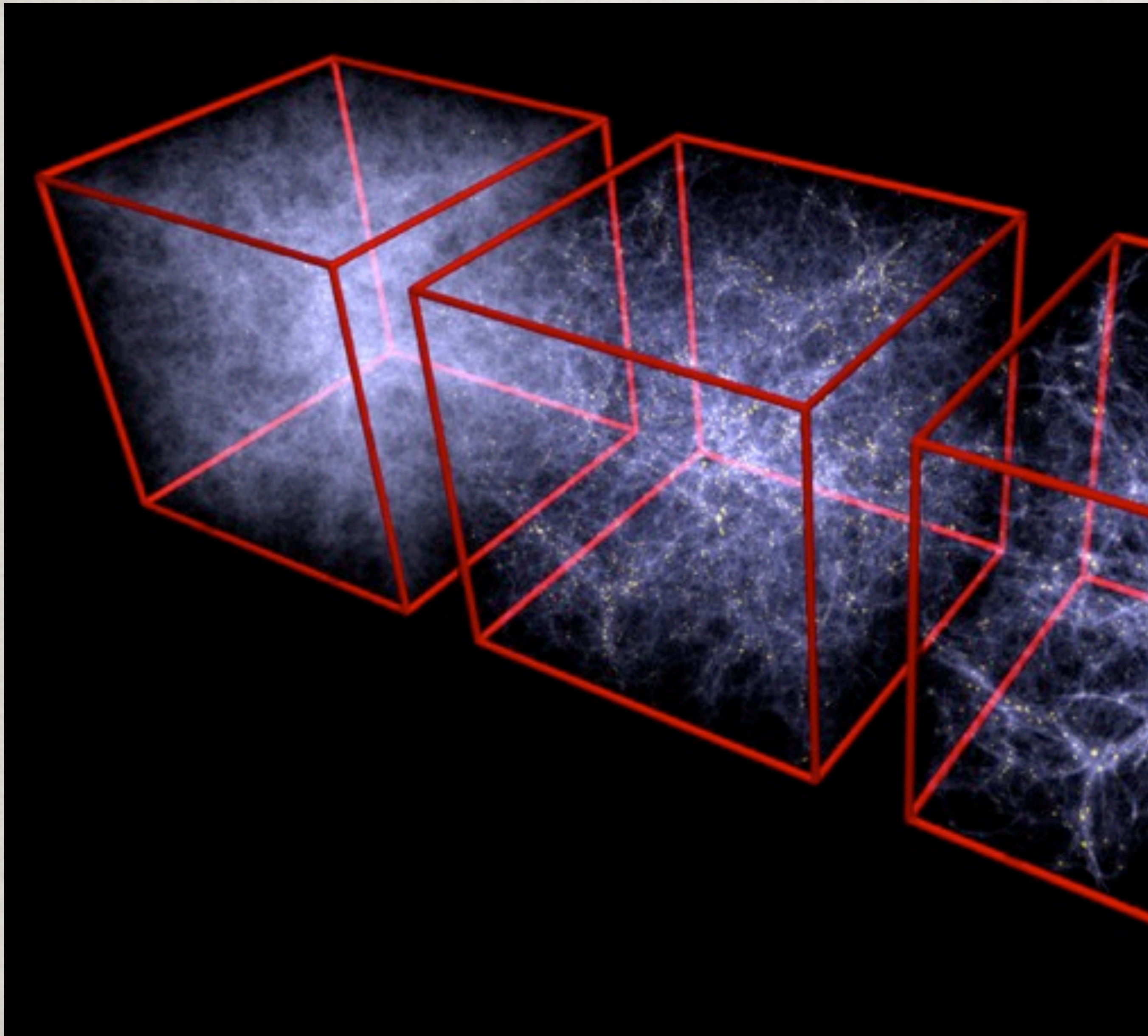
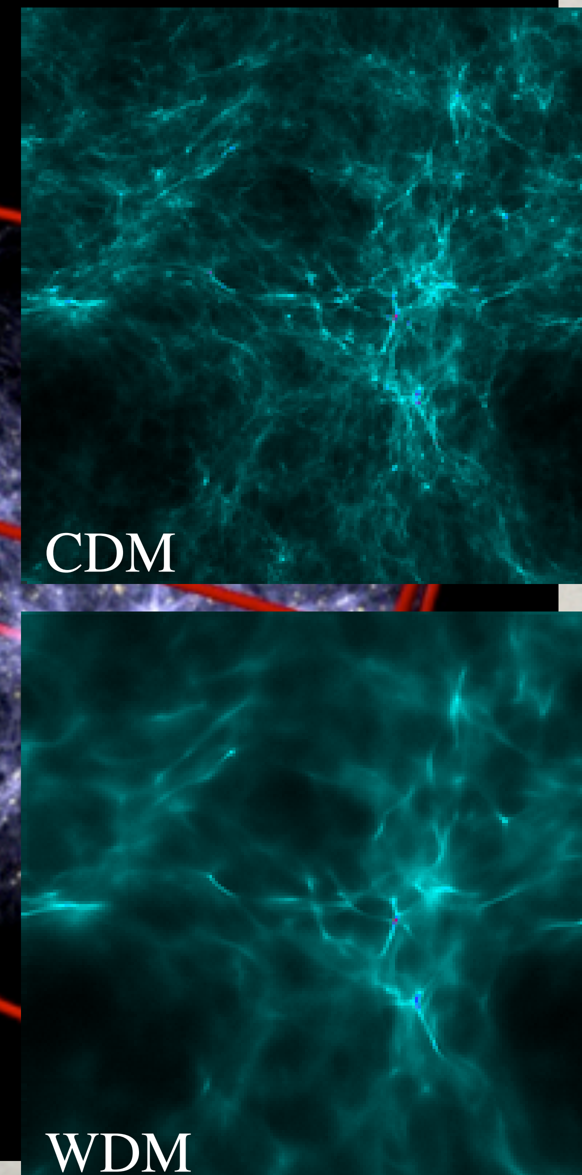
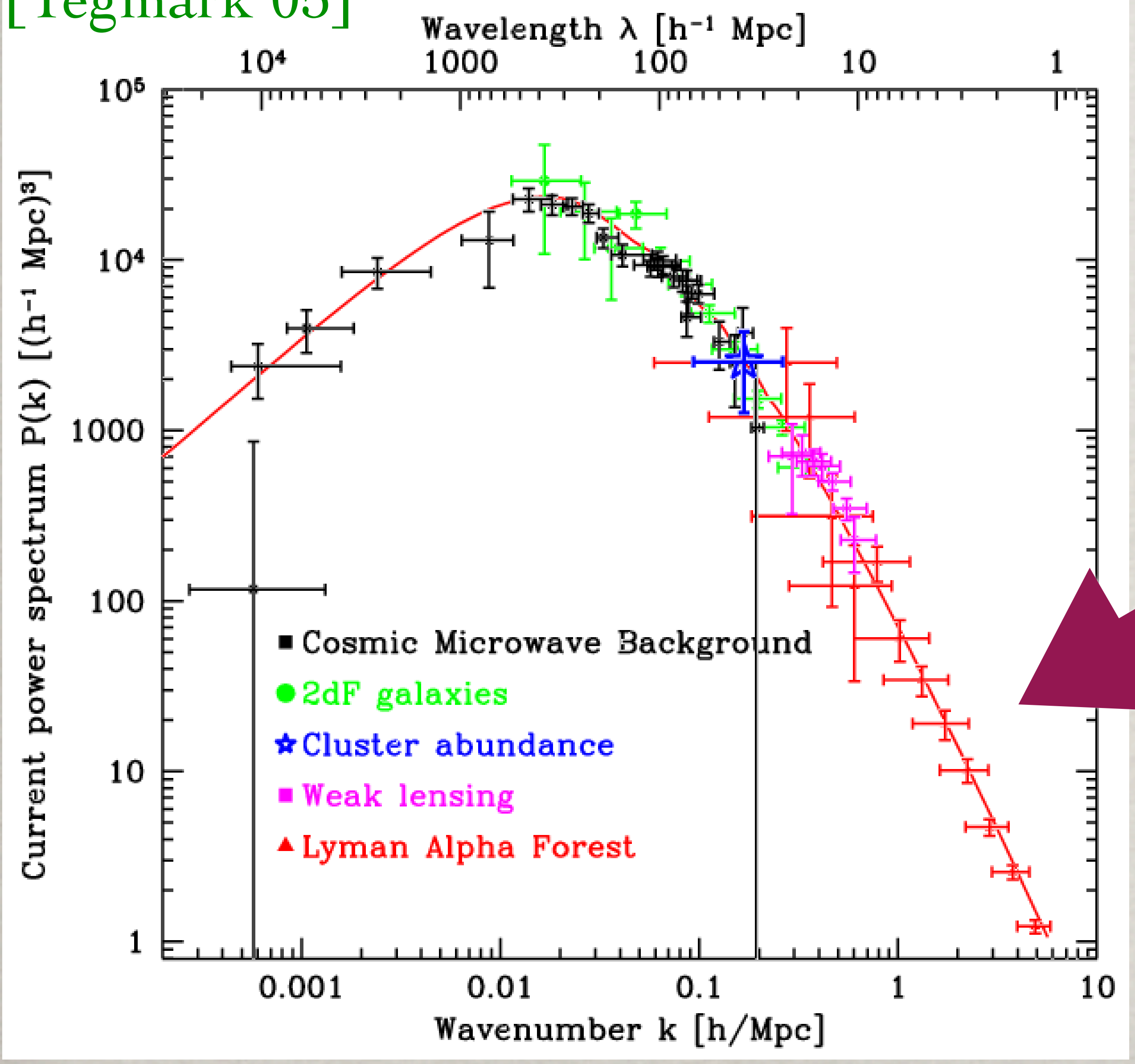




WDM & the Power spectrum

[Tegmark 05]



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

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

Compare with the data:

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

[Viel et al. '07]

All these evidences are just based on the gravitational force: either directly on the attraction of the Dark Matter on the visible matter or on the effect of the Dark Matter energy component on the Universe expansion or on the evolution of the density perturbation...

So there is no doubt:

DARK MATTER
IS GRAVITATING !

But what about other interactions ???

Only upper bounds from Bullet cluster or the shape of halos, at the order σ/m ~ 1-0.04 barn/GeV, but

no lower bound down to gravity !

DM could be a WIMP, but may also be much more weakly interacting, like the candidates I will discuss...

SM and Dark Matter

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

SM and Dark Matter

- Do we have a DM candidate ???

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charged/unstable

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massless

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- Neutrinos seem the only chance... but HDM !

Neutrino as (prototype) DM

- Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93\ \mathrm{eV}}$$

but $m_\nu \leq 2\ \mathrm{eV}$ (Tritium β decay) so $\Omega_\nu h^2 \leq 0.07$

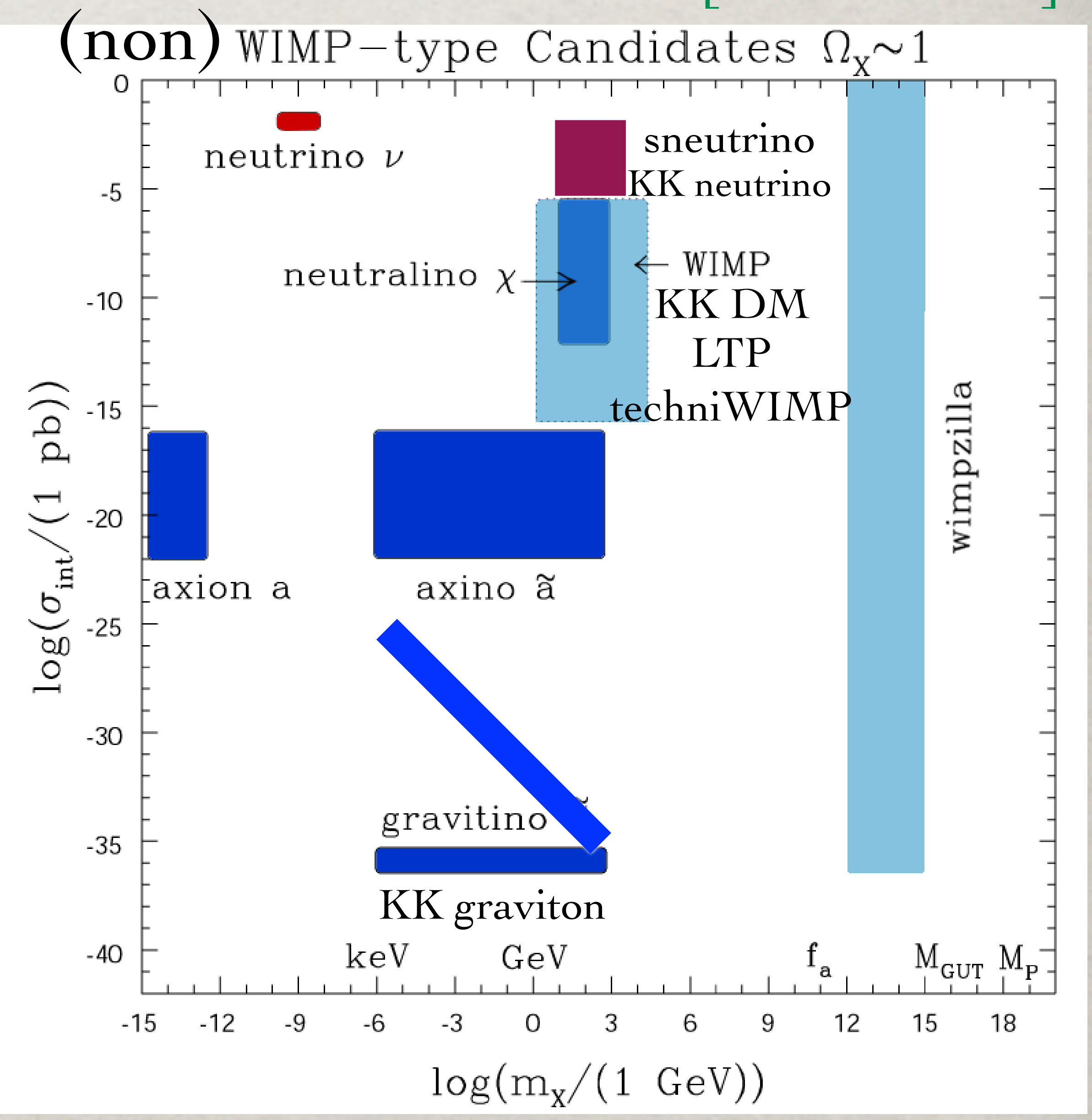
- Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain

$m_\nu \leq 0.27 \sim 1\ \mathrm{eV}$ ➡ $\boxed{\Omega_\nu \ll \Omega_{DM}}$

NEED to go beyond the Standard Model !

DARK MATTER CANDIDATES

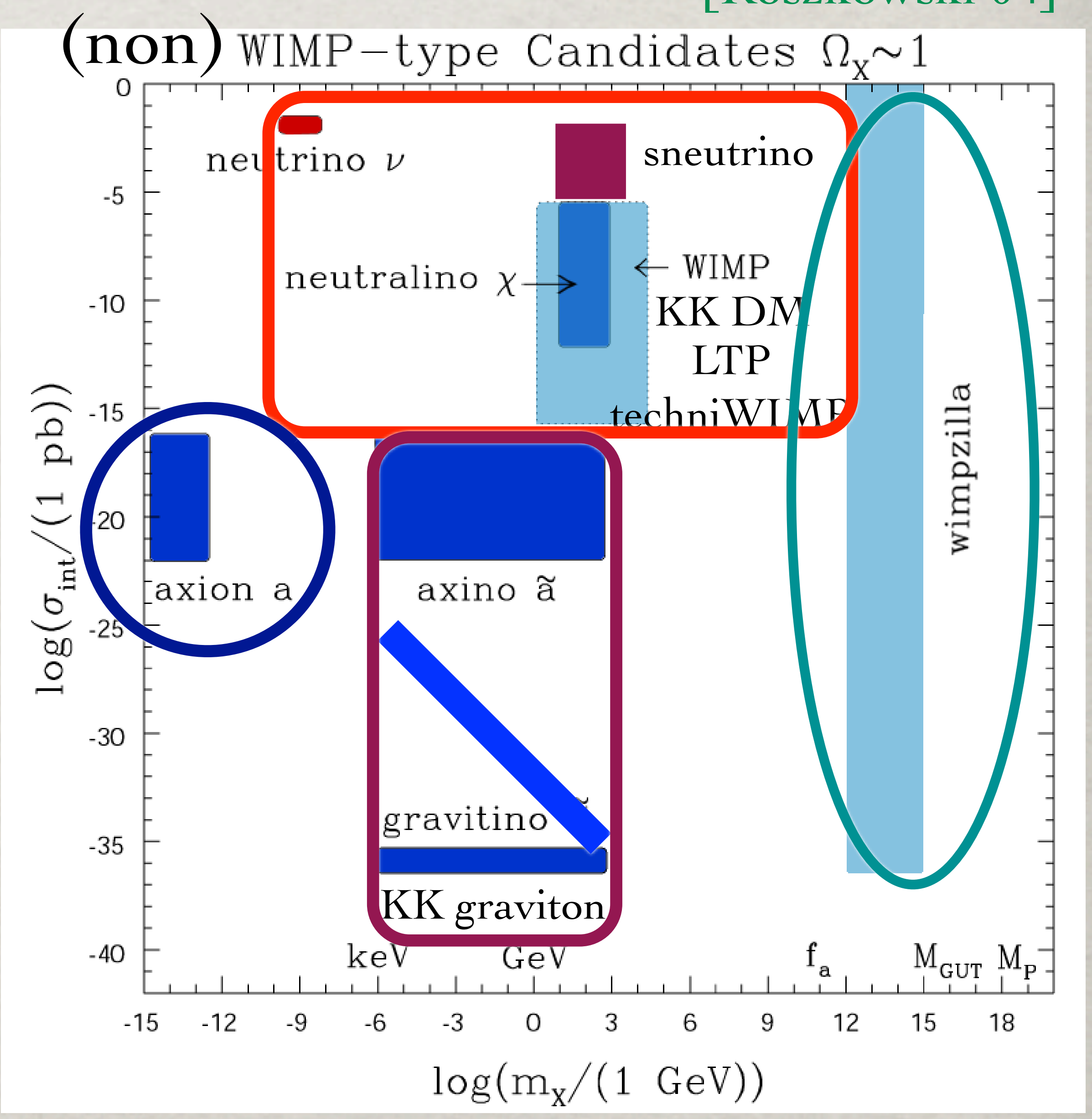
[Roszkowski 04]



DARK MATTER CANDIDATES

- Thermal relics: WIMPs
- "SuperWIMPs"
- Condensate
- Produced gravitationally

[Roszkowski 04]



What are SuperWIMPs ?

- Super/E-WIMPs are particles that are much more weakly interacting than weakly, so there is no hope of direct detection...
- They are usually not a thermal relic since if they are thermal their number density is compatible only with Hot/Warm DM...
- Moreover they do not need to have an exactly conserved quantum number to be sufficiently stable...

Dark Matter may decay !!!

Classical SuperWIMPs:

- Gravitino or axino DM characterised by non-renormalizable interactions;
- Hidden photon/photino DM with interaction suppressed by a small mixing with visible U(1);
- Sterile/RH neutrino/FIMPs with very small Yukawa coupling;
- Hidden sector particles with GUT suppressed non-renormalizable interactions.
- ... any particle with very suppressed interaction

What is supersymmetry?

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

SUPERSYMMETRY: boson <-> fermion

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$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$
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The beauty of SUSY...

- Non-renormalisation theorem for the superpotential, i.e. masses and couplings !

  [Wess & Zumino 1974, Grisaru & Siegel 1982]

- Maximal SUSY is mathematically unique and it is conjectured that 4D maximal SUGRA is actually (perturbatively) finite.

  [Bern, Dixon & Roiban 07]

  ... proven to 4 loops so far...

- Most parameters in common with the Standard Model and minimal field content is given by SM and anomaly considerations (2 Higgs fields...).

...AND UGLY REALITY:

- SUSY has to be broken since we have not yet seen any superpartner of e.g. electron...
- It can be broken only by marginal operators, which do not modify the UV behaviour, but this introduces a lot of free parameters, including complex phases (CP violation !)
- The proton can decay at tree-level via exchange of a s(calar)quark: introduce R-parity and so make the Lightest SUSY Particle (LSP) stable.

  A neutral LSP can be DM !!!

SUSY BREAKING

Supersymmetry has to be broken, but NOT spontaneously in the visible (MSSM) sector since then $STr\mathcal{M}^2 = 0$, i.e. in a multiplet it is impossible to push up the scalar masses only...

Way out: break SUSY in a hidden sector (where the STr formula holds...) and then transmit it to the MSSM

The mediation interaction can be of different types: renormalizable gauge interaction, non-renormalizable gravitational interaction, etc...

Different mediations give different SUSY spectra !

Note: In the most general case 105 parameters....

SUSY Breaking Masses

Given $\langle F \rangle \neq 0$ and requiring zero cosmological constant in SUGRA the gravitino mass is universal: $m_{3/2} = \frac{\langle F \rangle}{M_P}$.

Gauge mediation: sparticle masses given by loops of the messenger particles via gauge interaction:

$$m_{1/2} \sim \frac{\alpha}{4\pi} \frac{\langle F \rangle}{M_{mes}} \qquad m_0^2 \sim \frac{\alpha^2}{(4\pi)^2} \frac{\langle F^2 \rangle}{M_{mes}^2}$$

Gravity mediation: sparticle masses given by gravitational contact interaction with SUSY breaking sector:

$$m_{1/2} \sim \partial_Z f(Z) \frac{\langle F \rangle}{M_P} \qquad m_0^2 \sim \frac{\langle F^2 \rangle}{M_P^2}$$

Anomaly mediation: loop effect in supergravity:

$$m_{1/2} \sim \frac{\beta_\alpha}{4\pi} \frac{\langle F \rangle}{M_P} \qquad m_0^2 \sim \frac{\beta_m}{4\pi} \frac{\langle F^2 \rangle}{M_P^2}$$

Who is the LSP ?

Depending on the SUSY breaking mediation mechanism, different SUSY particles can be the LSP:

Gauge mediation: gravitino is lighter than the rest as long as the messenger mass is smaller than Planck...

Gravity mediation: for universal boundary conditions on can have either neutralino, RH stau or gravitino as LSP; for non-universal boundary conditions also LH sleptons can be the lightest or Higgsinos

Anomaly mediation: in pure anomaly mediation the leptons are tachyonic, usually a mixed mediation is needed. Then of the neutralinos the Wino is the lightest, while the gravitino is always the heaviest state...

Different LSP and DM in different scenarios !

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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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$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$	
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	$\tilde{G}$	$\psi_{3/2}$

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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

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]

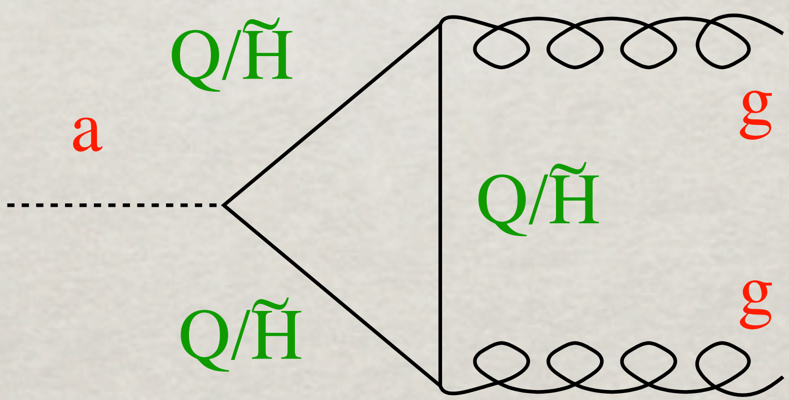
$W = h\, \Phi_a H_u H_d \quad H_u, H_d$ Higgs multiplets

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 & 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

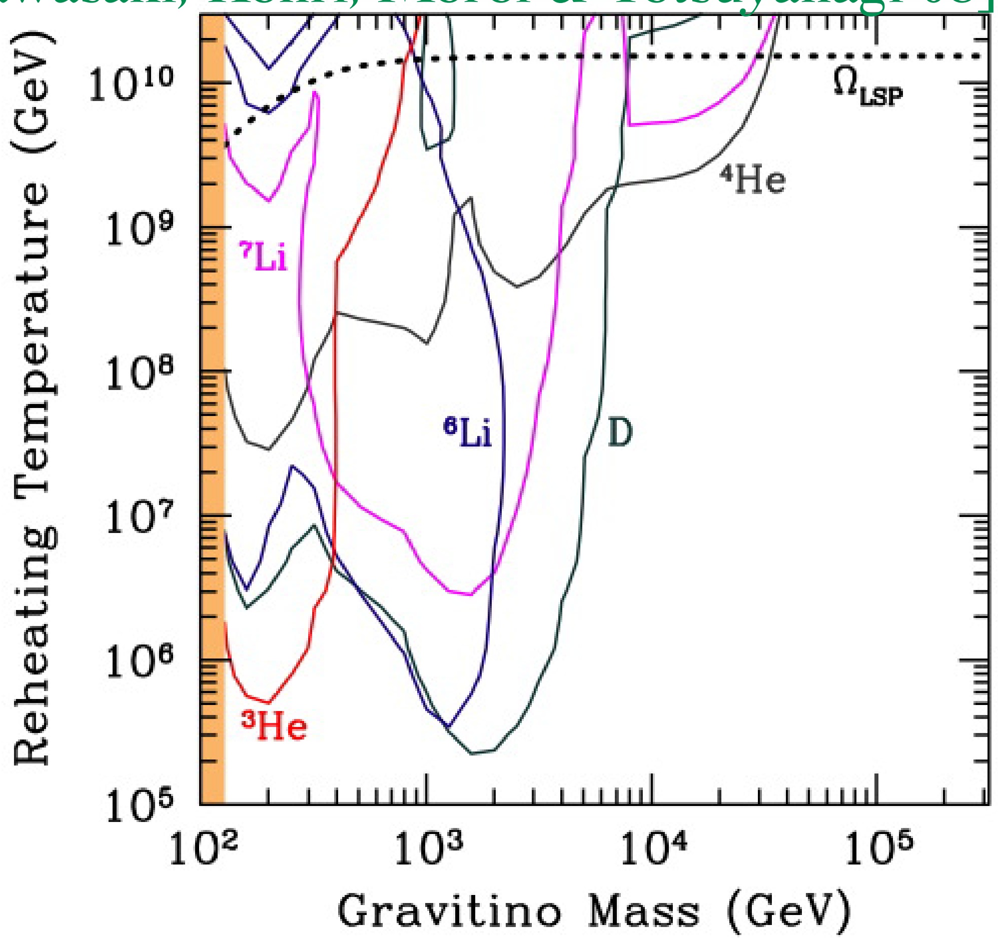
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1 \mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[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]



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

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 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

Ω_{D} ... $\propto$ ... m

!

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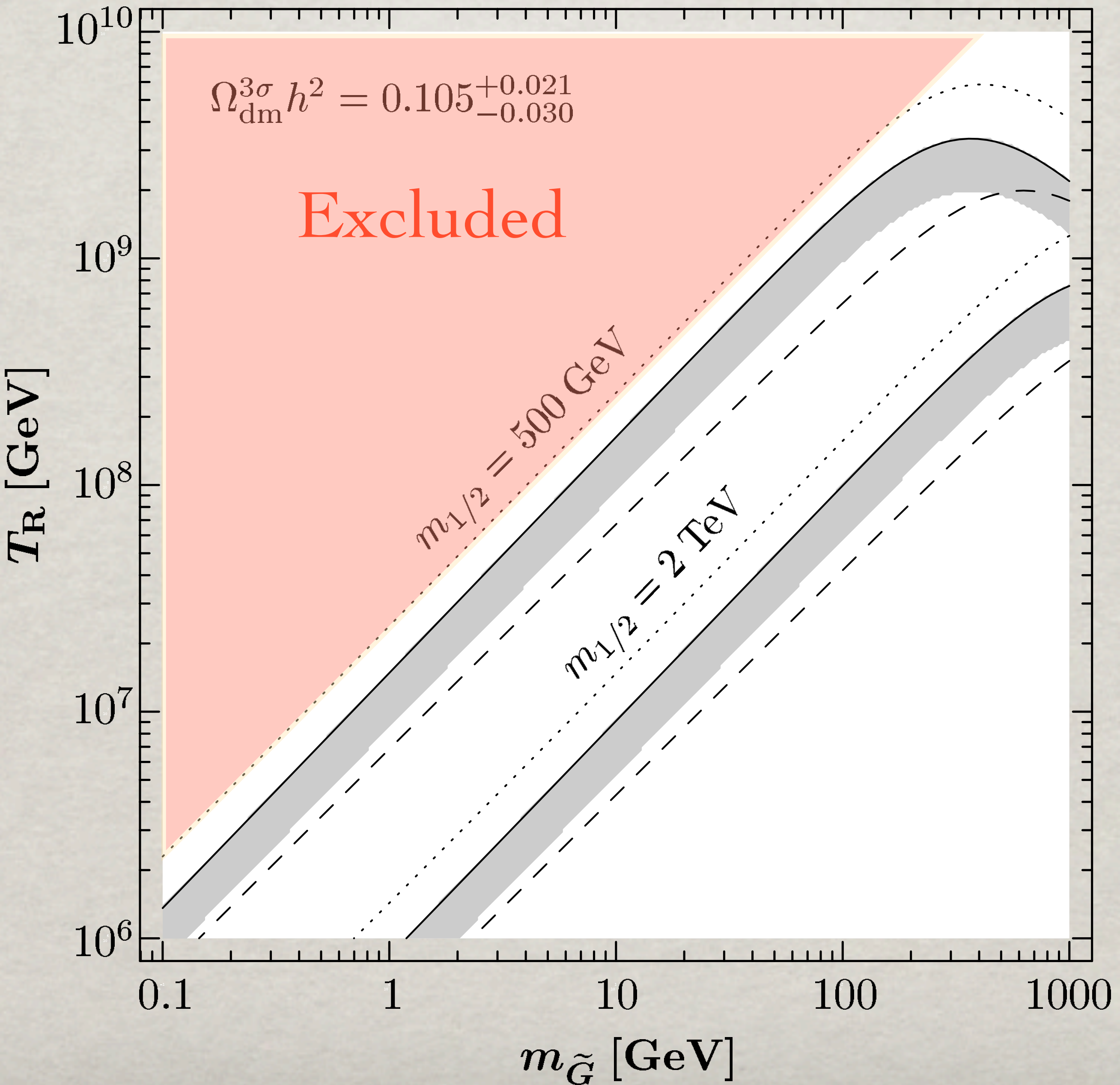
where M_i are the gaugino masses and $c_i \sim 0(1)$

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:

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

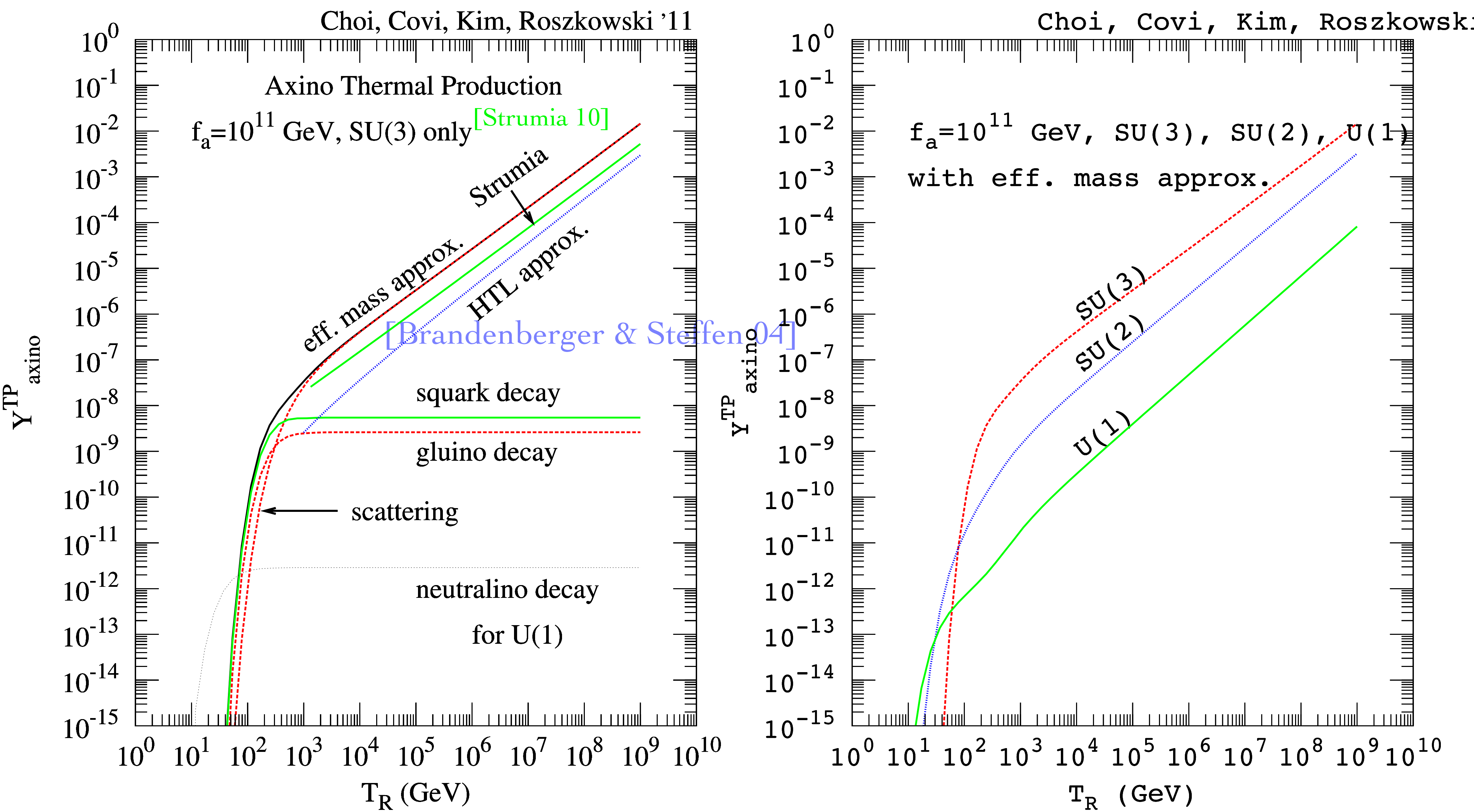
[Strumia 10]

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

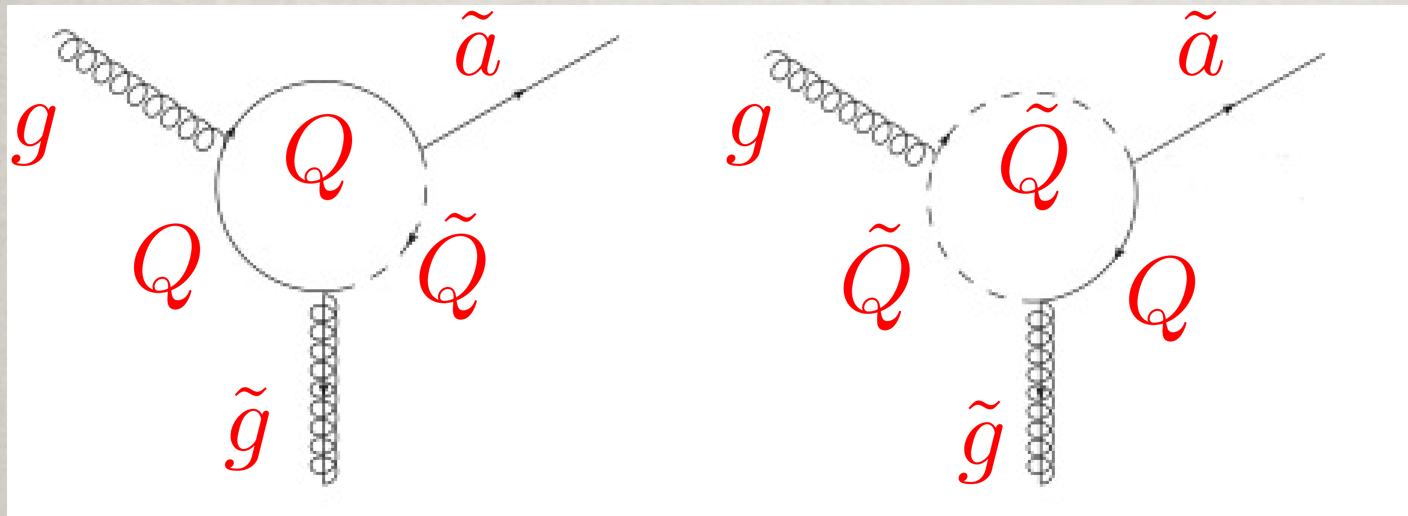
[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]



Do not worry: Perturbation series seems converging...

Axino effective coupling

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



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

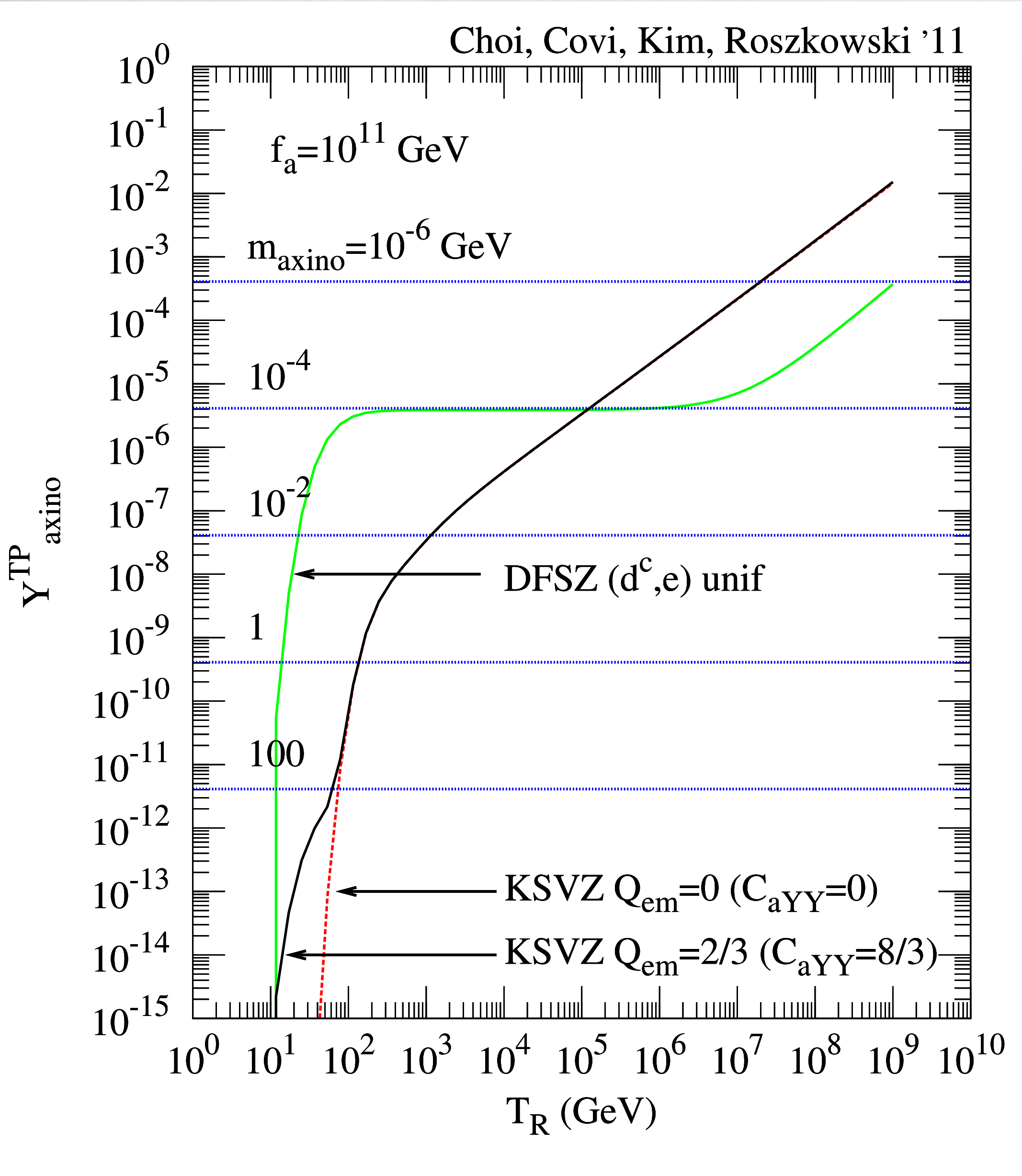
$$\mathcal{A}(p, q, M_Q) \propto \begin{cases} \frac{M_Q^2}{p^2} \ln^2 \left(\frac{M_Q^2}{p^2} \right) & \text{for } \; p^2 >> M_Q^2 \\ 1 - \frac{p^2}{12 M_Q^2} & \text{for } \; p^2 << M_Q^2 \end{cases}$$

Constant vertex only for heavy quarks/squarks !

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

Revisiting axino production

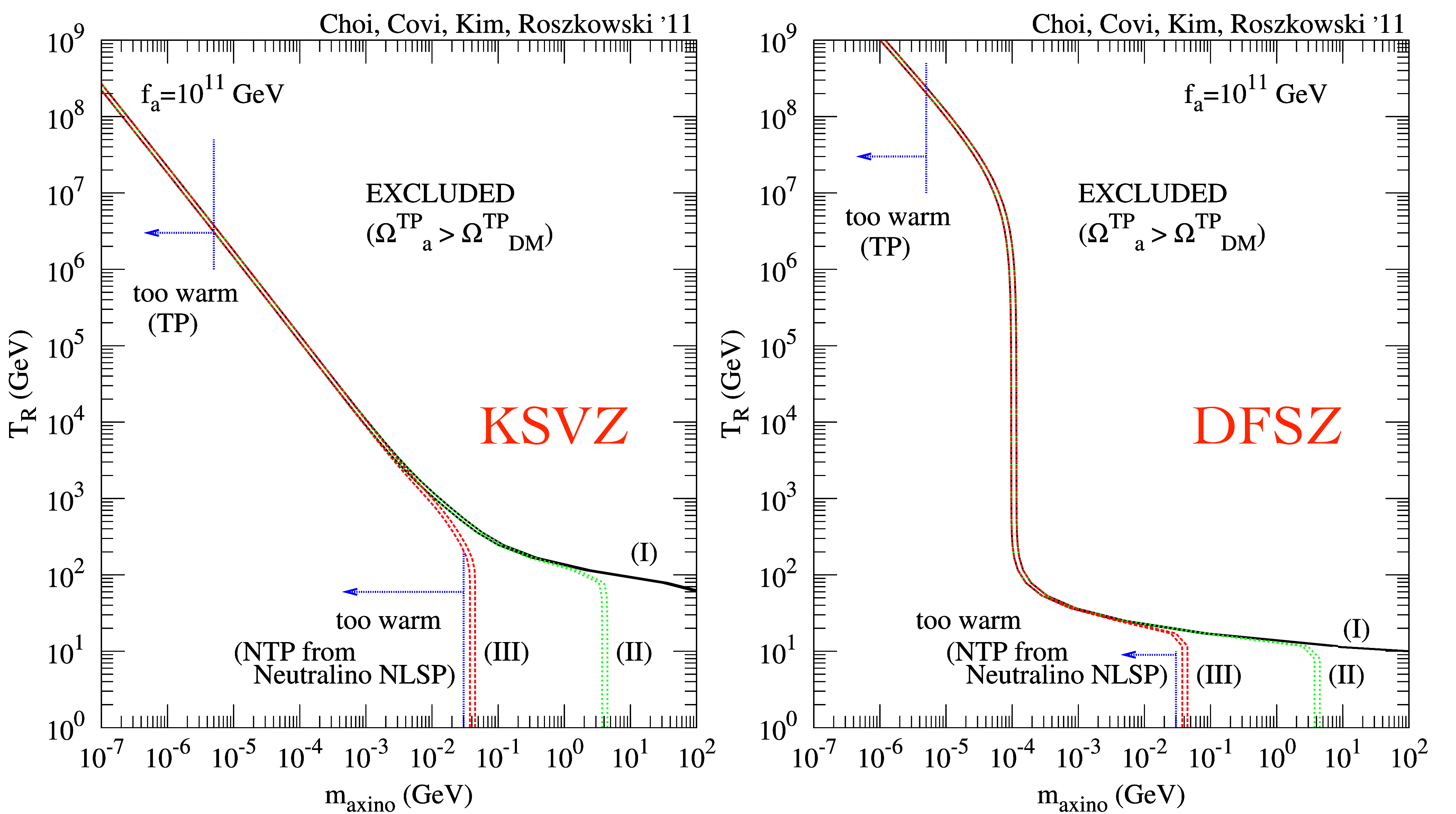
[E.J. Chun 11, Bae, Choi & Im 11]
[K.Y. Choi, LC, J.E. Kim, L. Roszkowski 01]



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...

Revisiting axino production

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



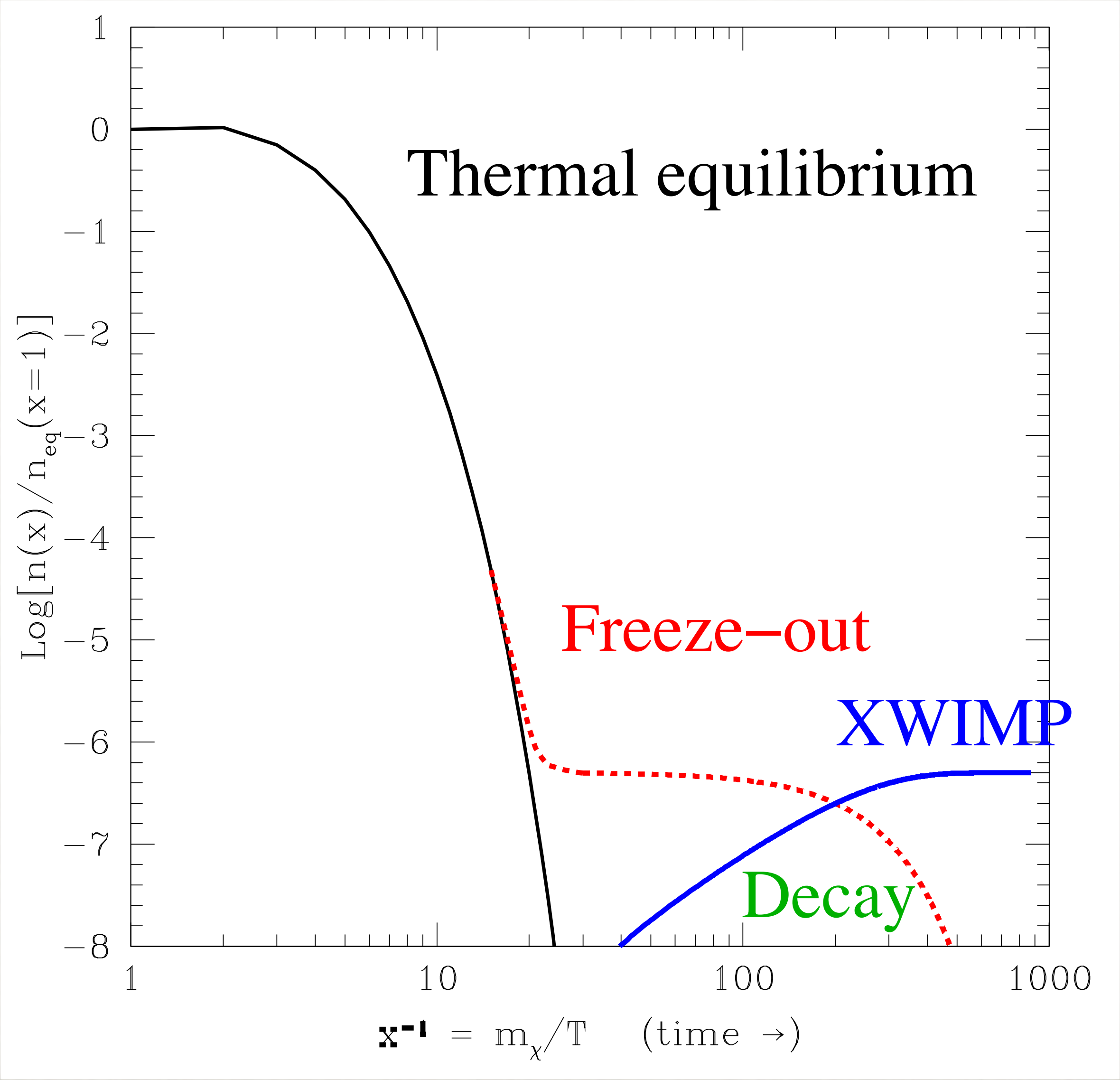
NLSP DECAY

[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:

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

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



Hot, Warm or cold ???

- Gravitinos/axinos in thermal equilibrium are HOT DM with mass in the 200-400 eV range;
- Gravitinos/axinos from thermal production can be WARM or COLD depending on their mass;
- Gravitinos/axinos from NLSP decay are not thermal, but they can behave as WARM DM: in a two-body decay their velocity is

$$v_{3/2} = 5 \times 10^{-5}\ \mathrm{km/s} \frac{m_{NLSP}}{m_{3/2}} \frac{1\ \mathrm{MeV}}{T_{decay}} \quad \leq 0.1\ \mathrm{km/s}$$

[Jedamzik, Lemoine & Moultaka '05]

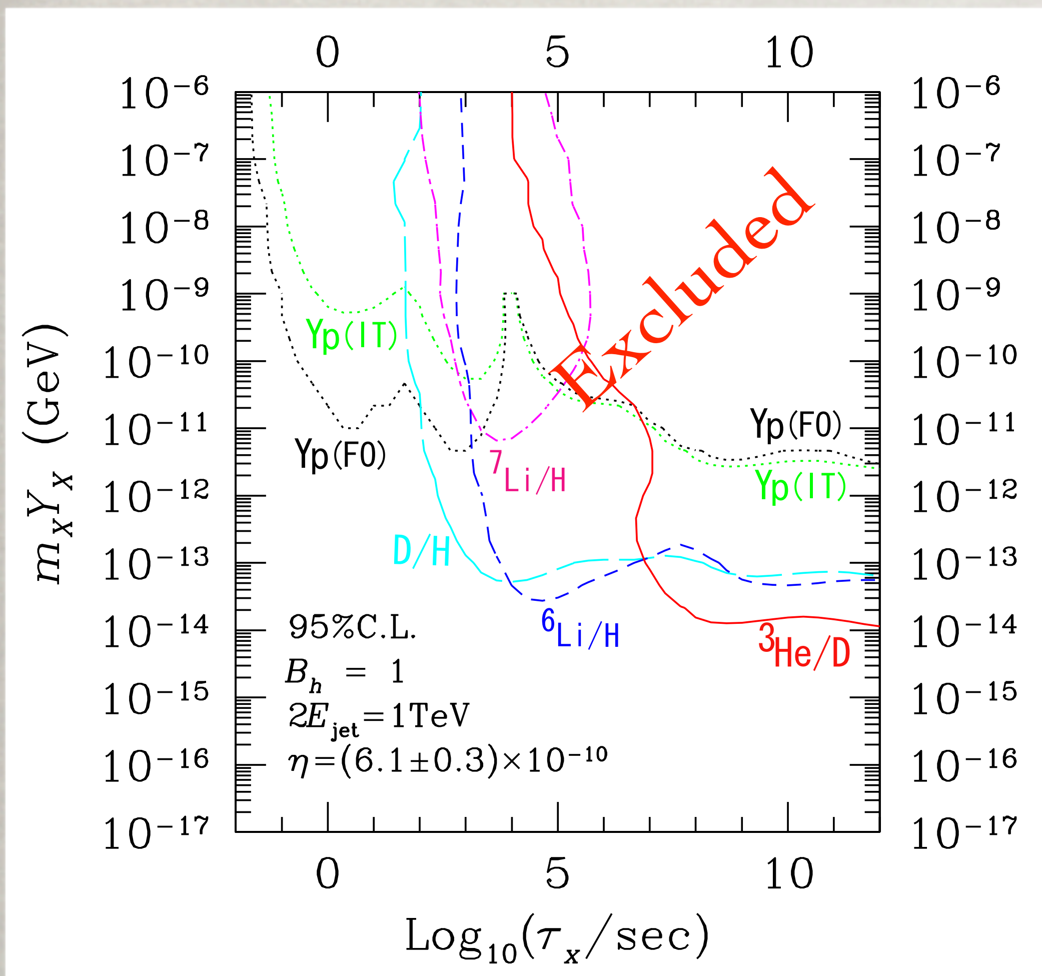
Need probably gravitino masses around 10 GeV or more...
But free-streaming may not be the whole story...

[Maccio` et al. '12]

BBN bounds on NLSP decay

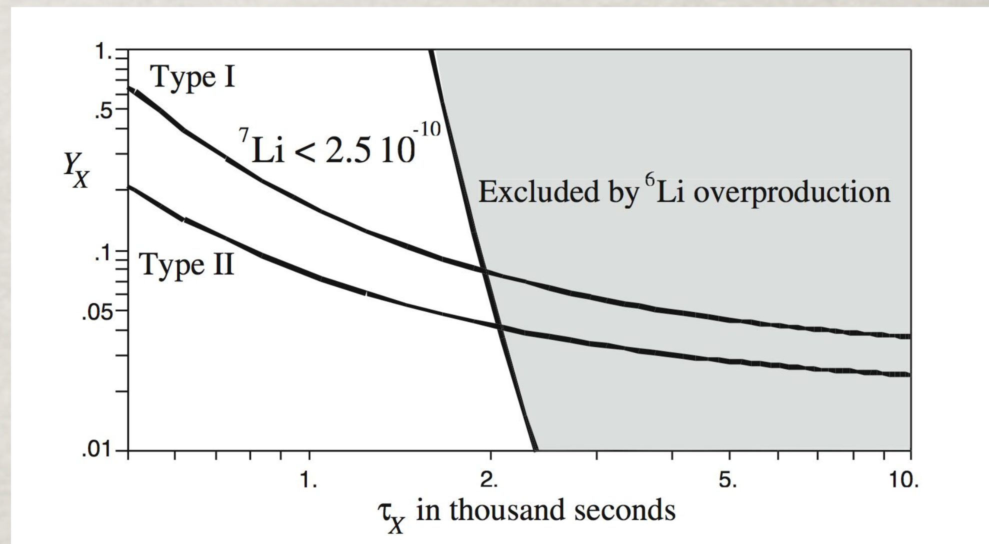
Neutral relics

[...,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:

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

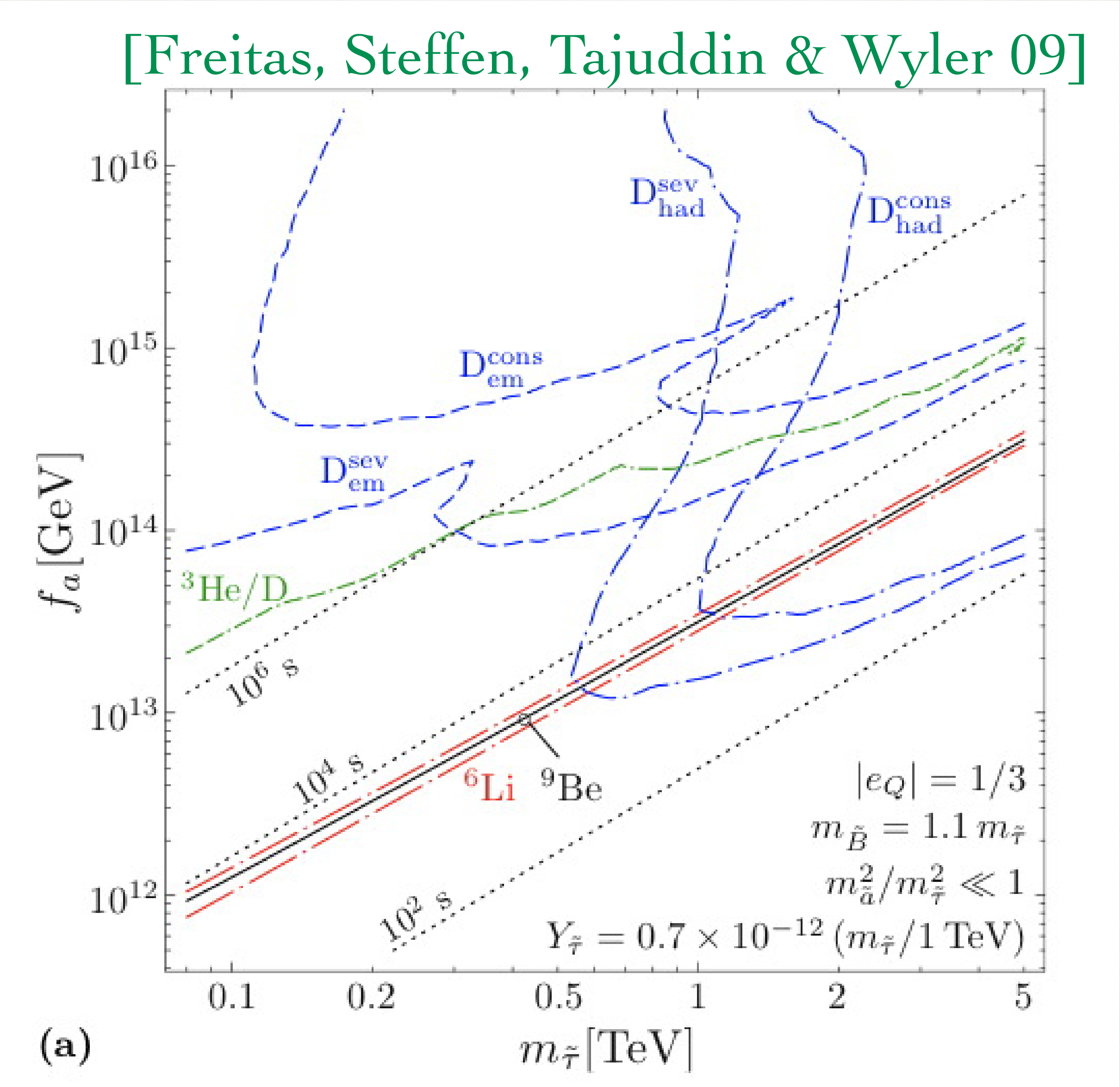
at leading log, where the e.m. charge and mass of the heavy quarks are $e_Q, y f_a$ respectively. It is suppressed by loop factors and large powers of the coupling.

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

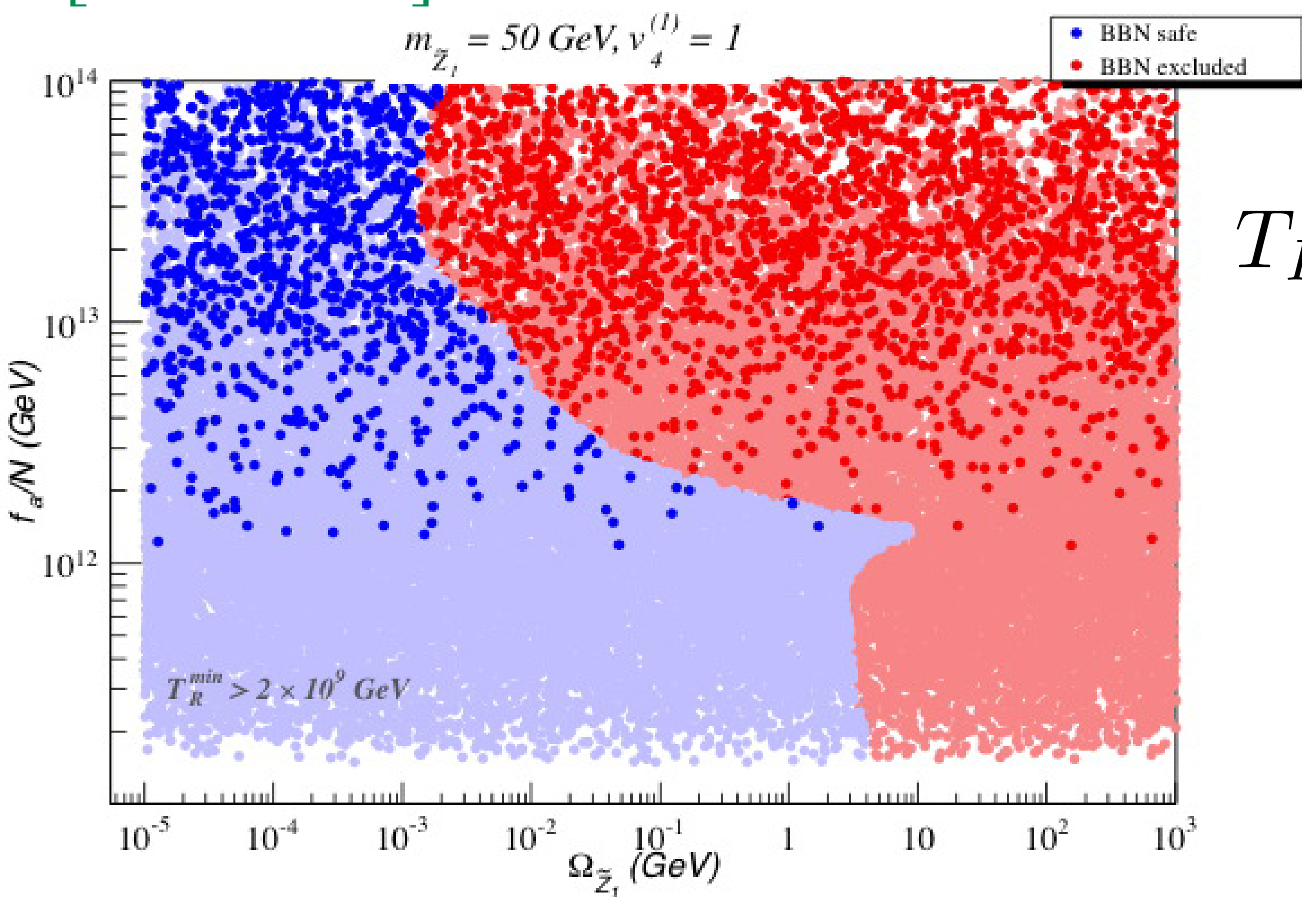
For τ_R NLSP



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.

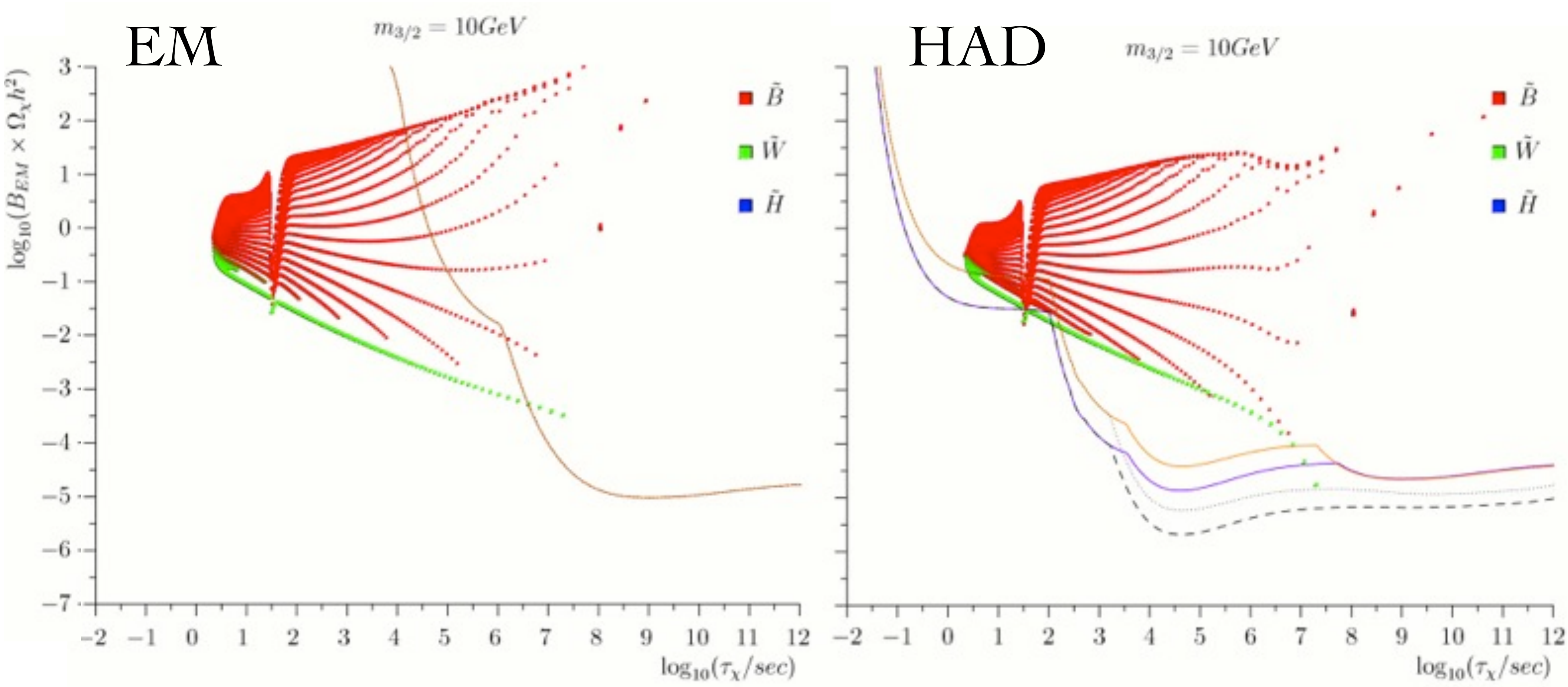
Gravitino: neutralino NLSP

[LC, Hasenkamp, Roberts & Pokorski 09]

- In the CMSSM the neutralino NLSP is strongly constrained and requires a gravitino mass < 0.1 GeV. Check which regions are still open in the general case and how light the gravitino has to be...
- Important parameter is the neutralino branching ratio into hadrons e.g. via 3 body decay.
- The other important parameter for BBN constraints is the number density: We compute it with Micromegas 2.0 by [Belanger et al. 06] in the general mixed case.
- We compare our results with the BBN bounds for neutral relics given for the pure electromagnetic decays and also for different values of the hadronic branching ratios by [K. Jedamzik 06]

Bino-Wino neutralino

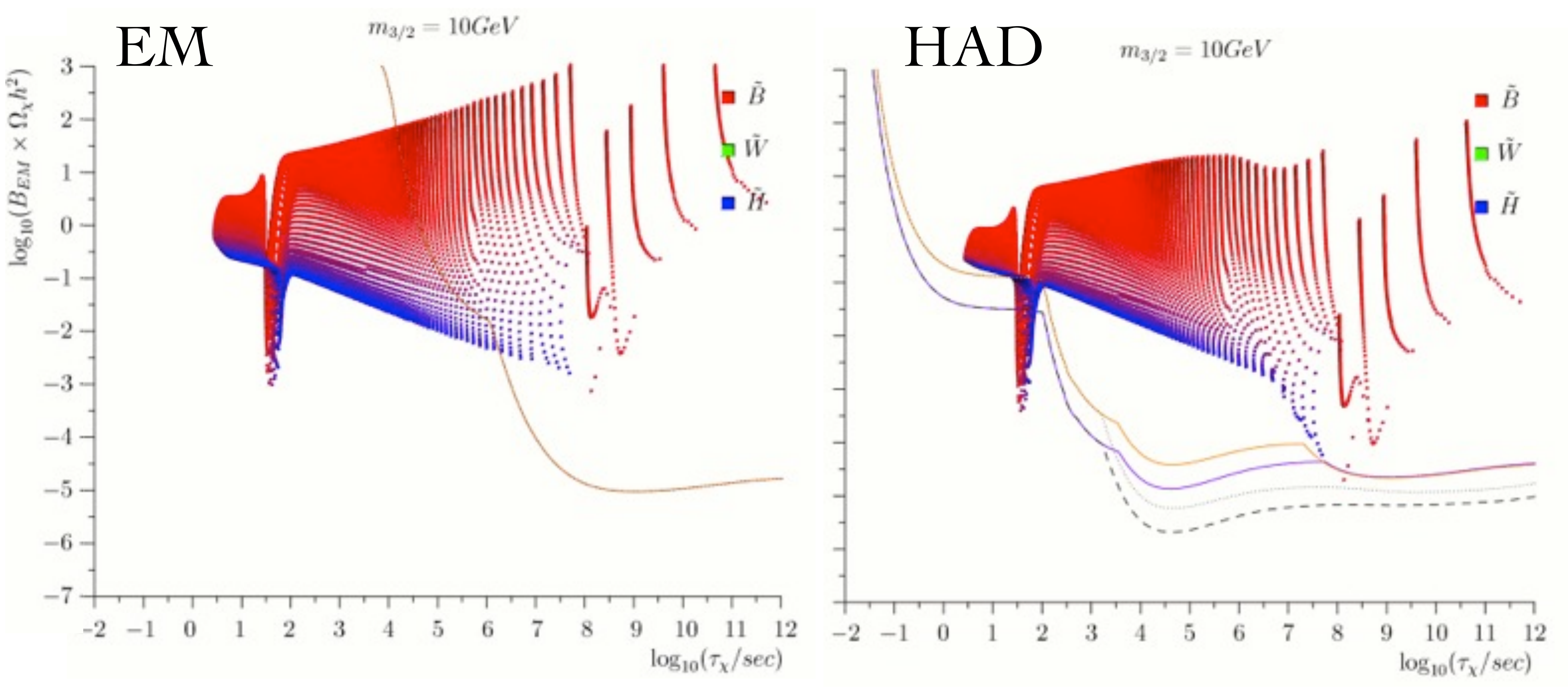
[LC, Hasenkamp, Roberts & Pokorski 09]



Not much room for Bino-Wino neutralino, even when the branching ratio is reduced by interference...
Still for low Wino masses the EM constraints are stronger !

Bino-Higgsino

[LC, Hasenkamp, Roberts & Pokorski 09]



The resonant annihilation into heavy Higgses becomes much more effective & reduces the density by 4 orders of magnitude !

MAXIMAL T_R

Look again at the thermal production yield:

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

Best case scenario, all gaugino masses M_i equal and as light as possible..., while $m_{3/2}$ as large as possible.

→ light degenerate gaugino spectrum
as it is possible in general gauge mediation

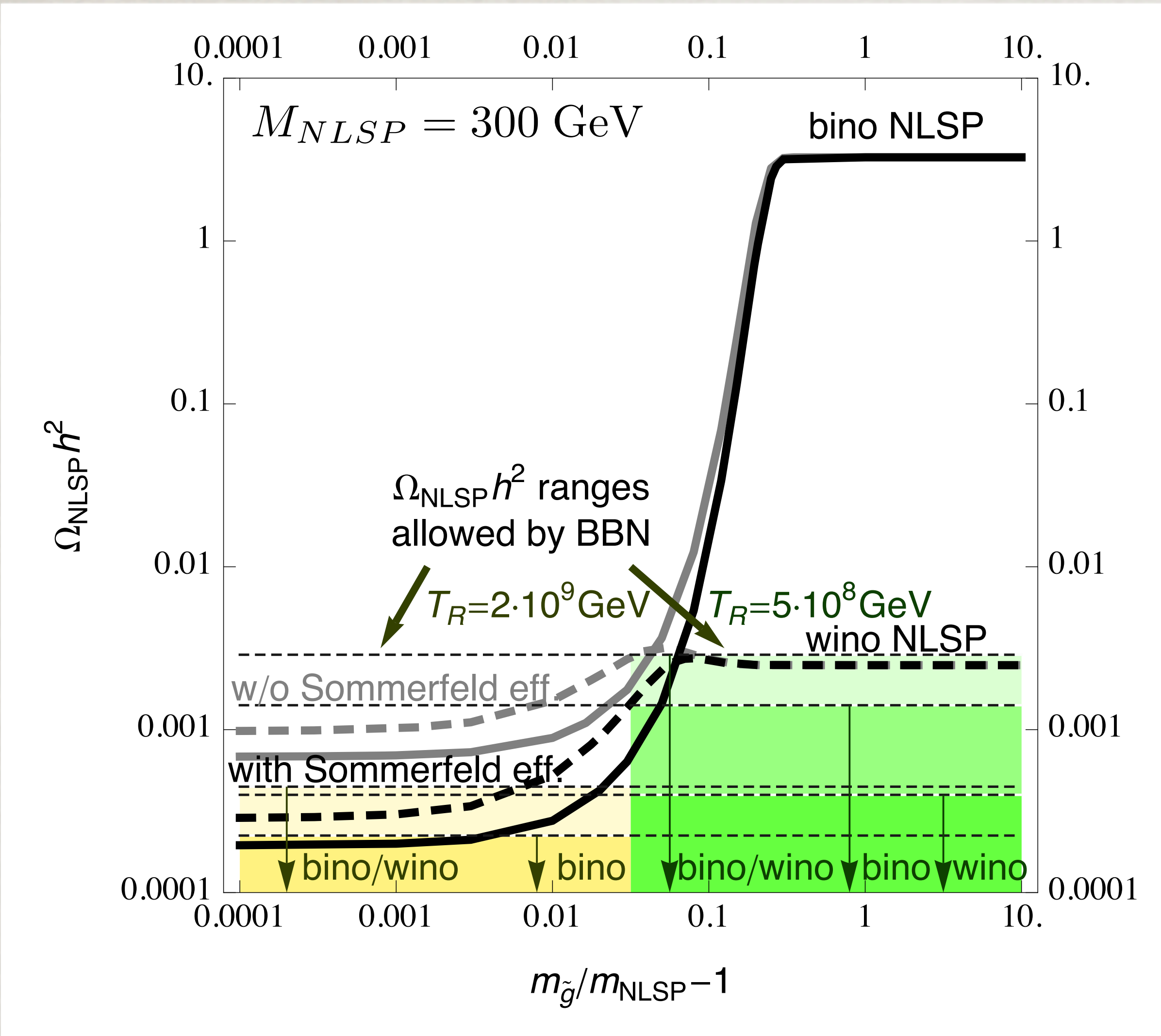
[Olechowski, Pokorski, Turzynski,Wells 09]

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

Other advantage of degenerate masses at the low scale: coannihilation helps reducing the NLSP density !

Degenerate gauginos NLSP

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



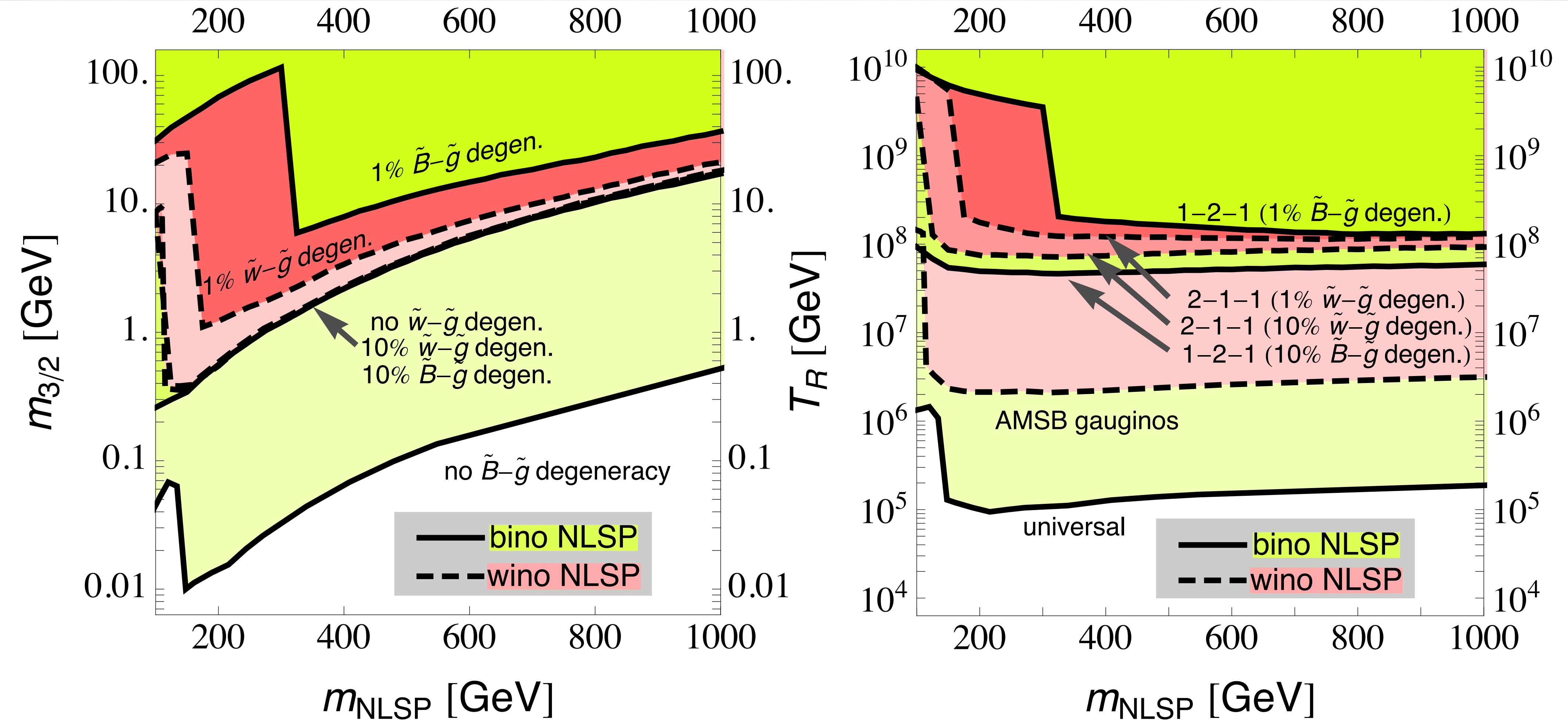
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

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...

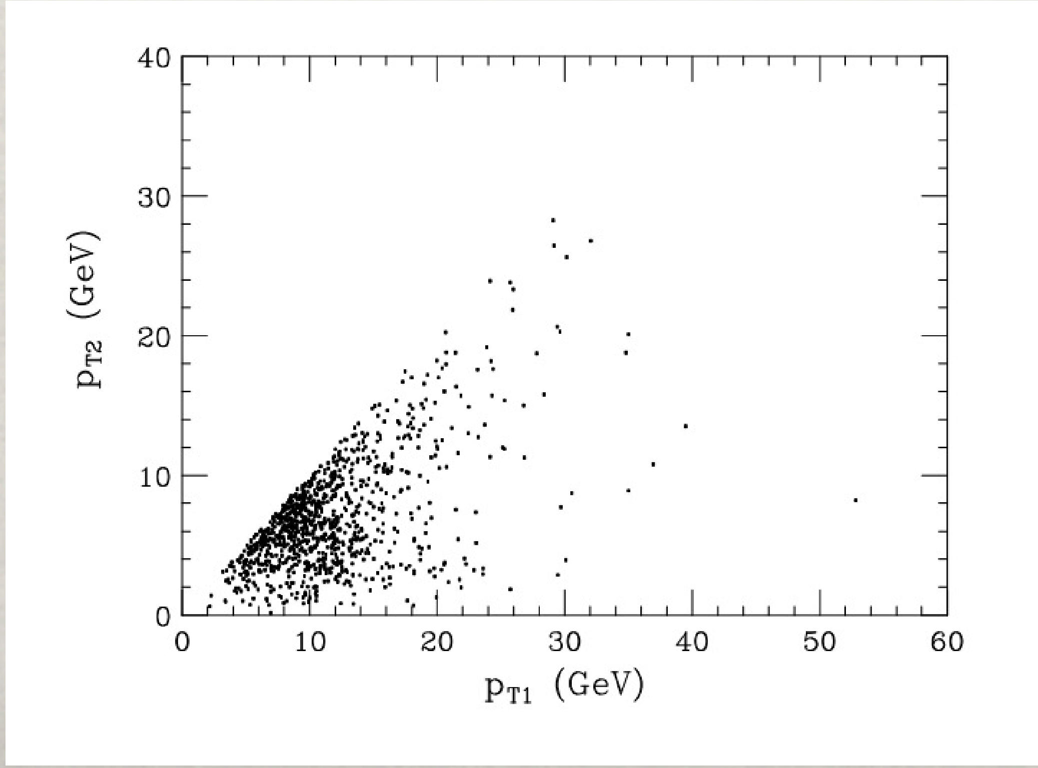
LHC: DEGENERATE GAUGINOS?

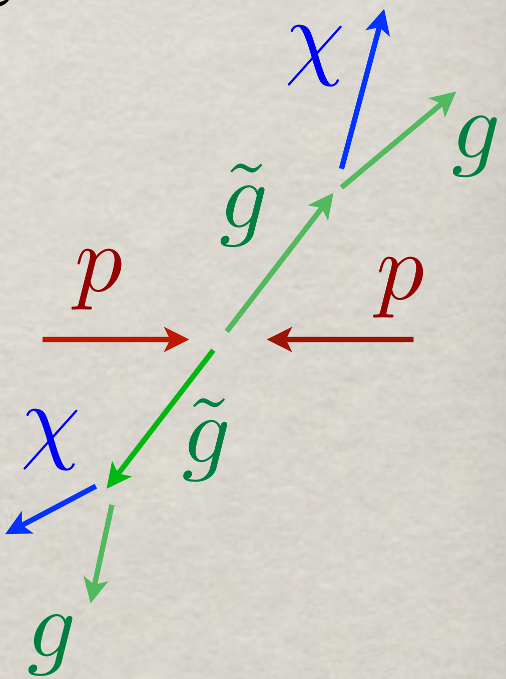
In this scenario of maximal T_R and stable gravitino DM we expect light gauginos with 1-10% degeneracy between Bino NLSP and gluino NNLSP.

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...

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

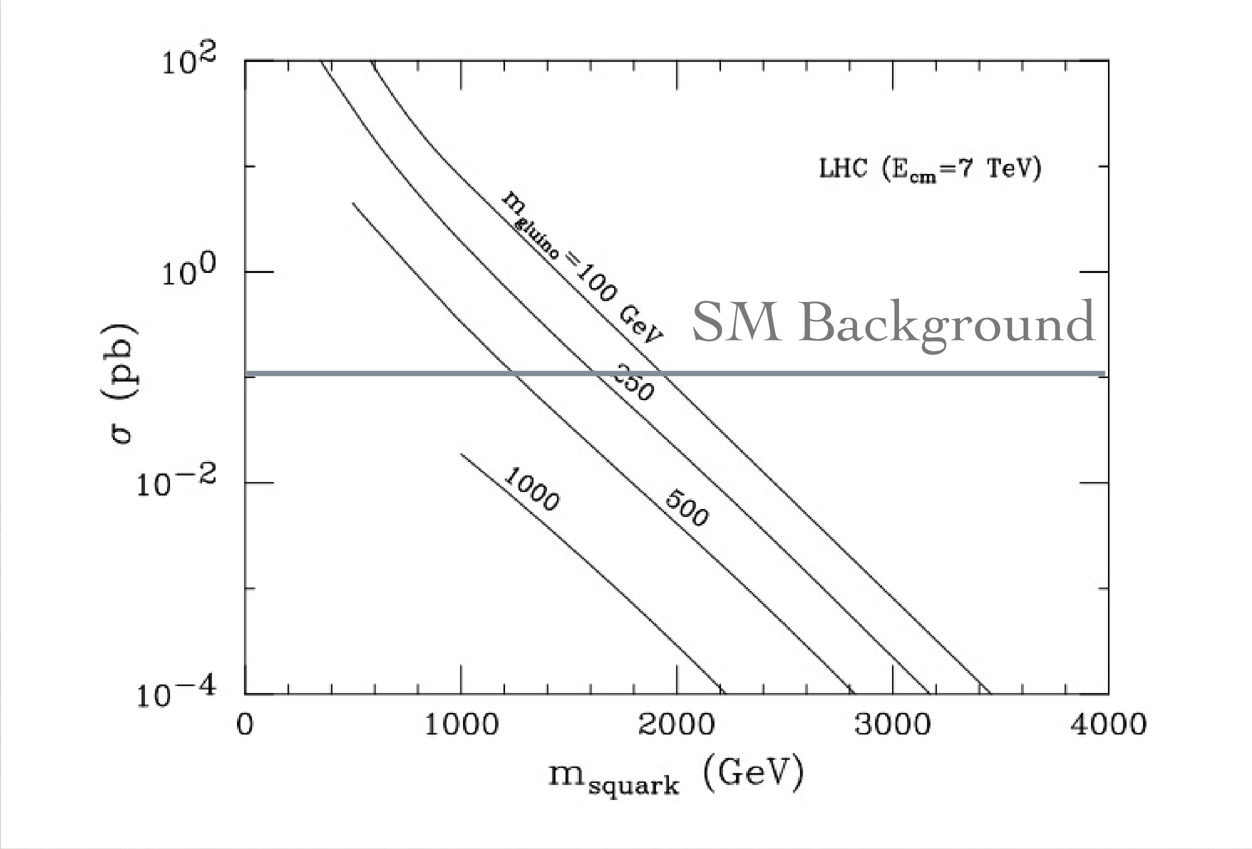
to low p_T !

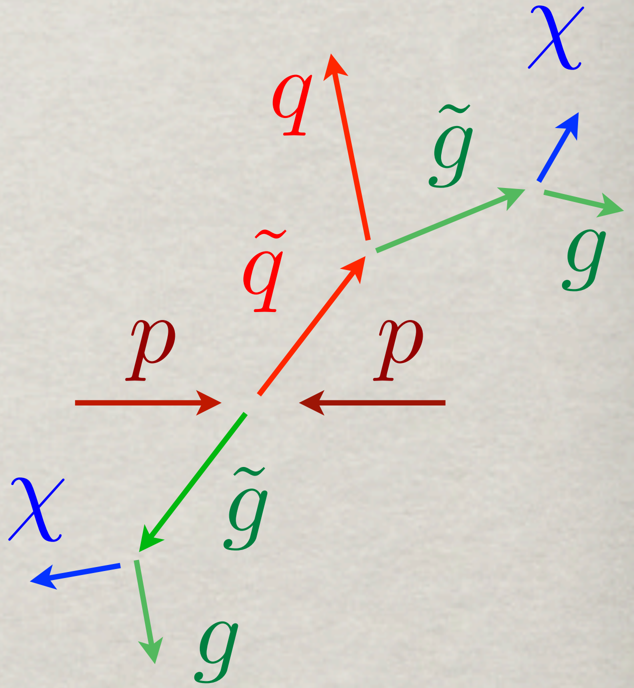




LHC: Mono-jet signature

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 !

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

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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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Open window:

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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]

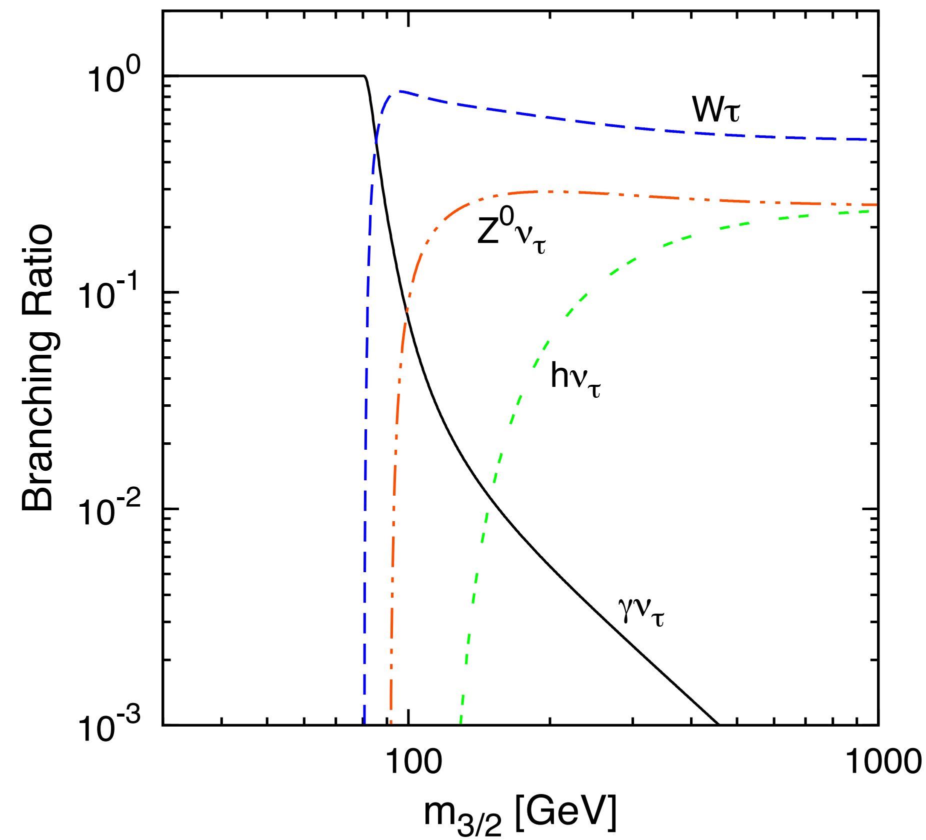
For trilinear R-parity breaking, the 3-body decays into leptons can dominate and give a leptophilic DM
[Bomark et al 09, LC & JE Kim 09, Bajc et al 10]

Gravitino 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

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

[LC, Grefe, Ibarra & Tran 08]



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

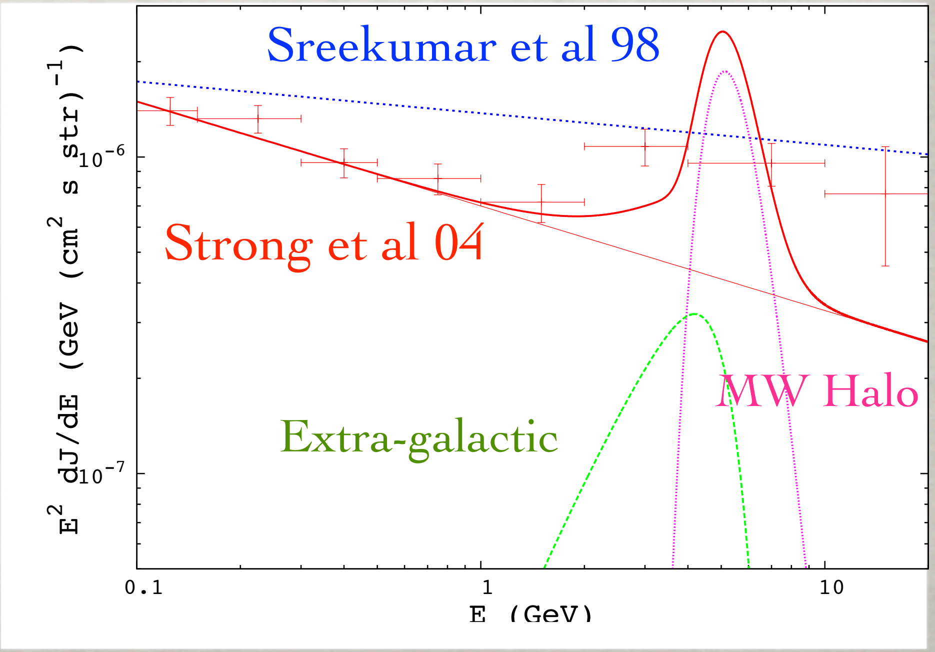
DECAYING DM

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

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

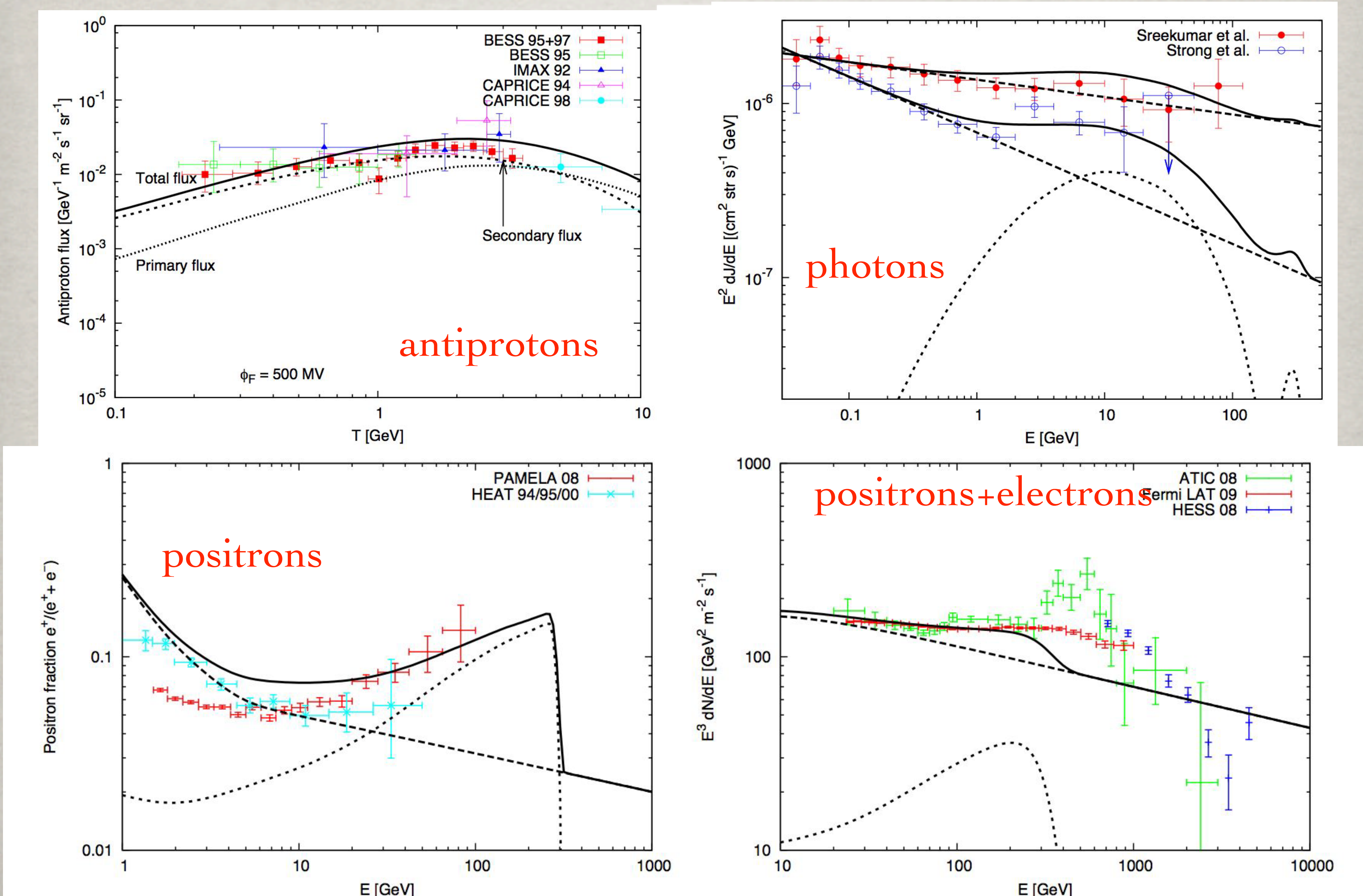
Particle Physics　　　　Halo property

- 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...



Gravitino DM without R_p

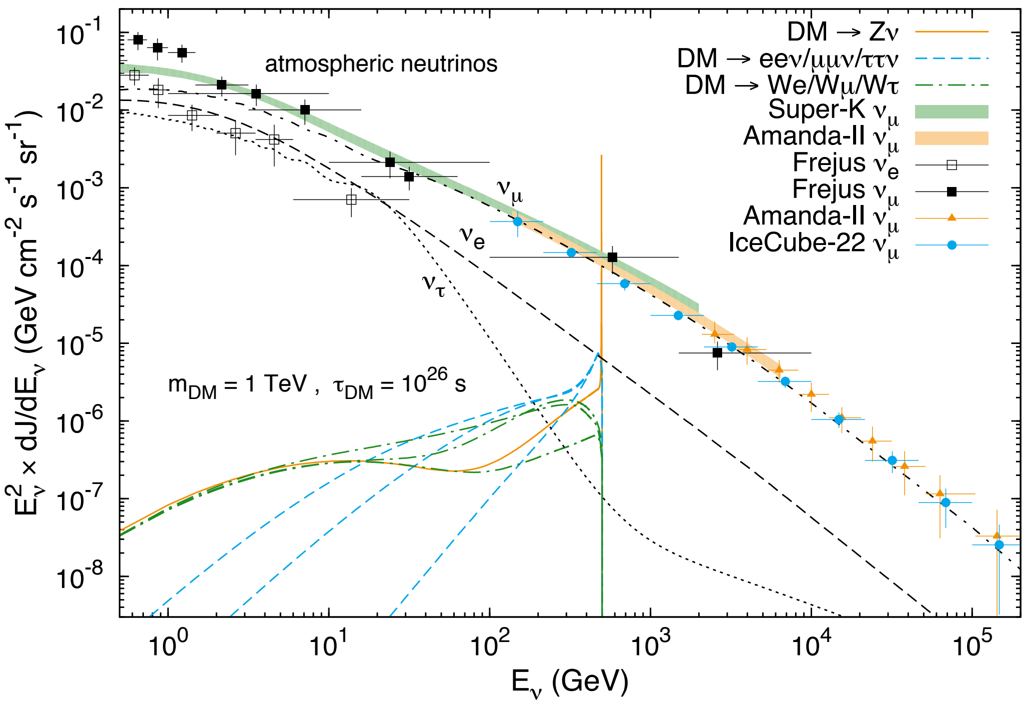
[Buchmuller, Ibarra, Shindou, Takayama, Tran 09] ([Ishiwata, Matsumoto & Moroi 08])

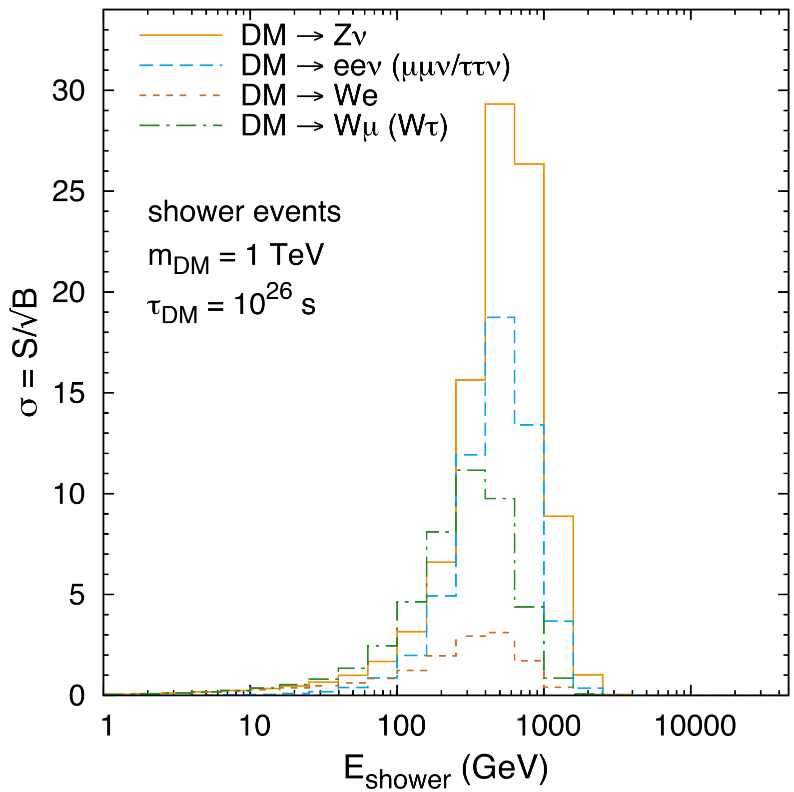


Heavy decaying DM

For heavy decaying DM, the atmospheric neutrino background is large, but still the signal is detectable at km3 detectors like IceCube, esp. if showers may be measured:

[LC, Grefe, Ibarra & Tran 09]

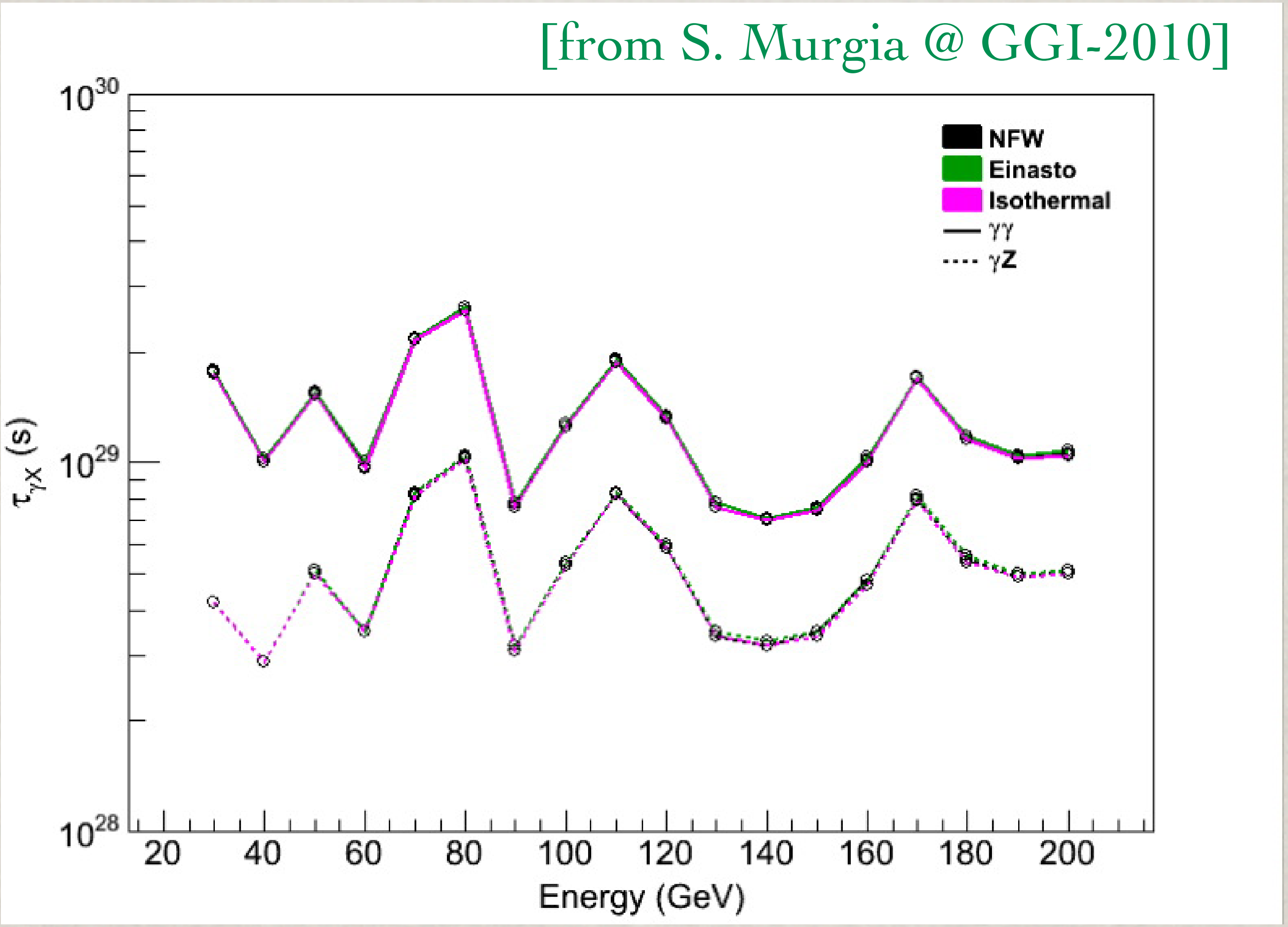




Best significance for cascade/shower events

Possible to detect in IceCube ?

FERMI LINE CONSTRAINTS

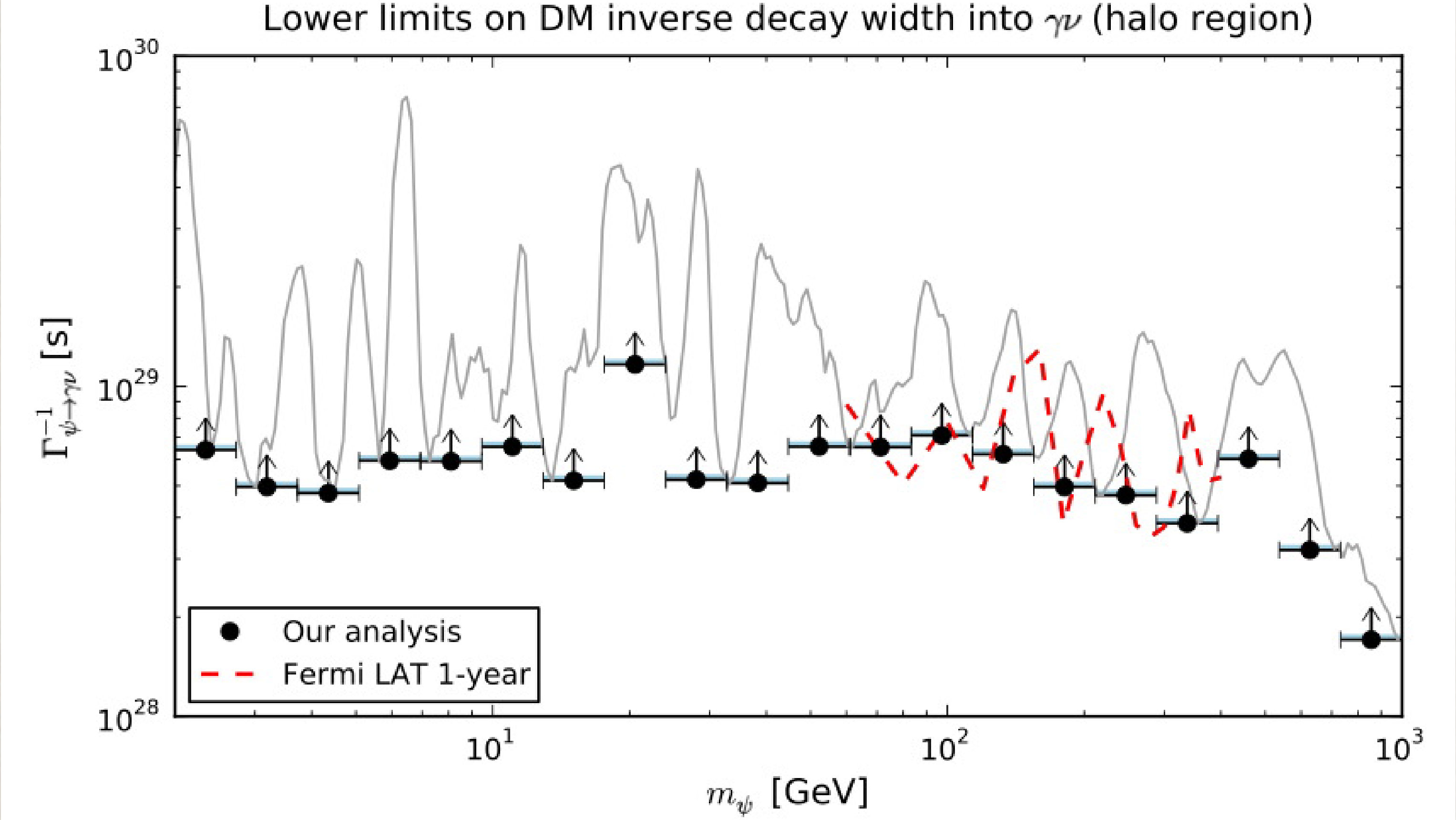


The FERMI space telescope looks for lines in the galactic emissions in the energy range 30-200 GeV and gives the stronger constraint for gravitinos below 400 GeV:

From the FERMI gamma-line search: $\tau \geq 5\ 10^{28}$s @ 95% CL

FERMI LINE CONSTRAINTS

[Vertongen & Weniger 11]



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

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

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

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...

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

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

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

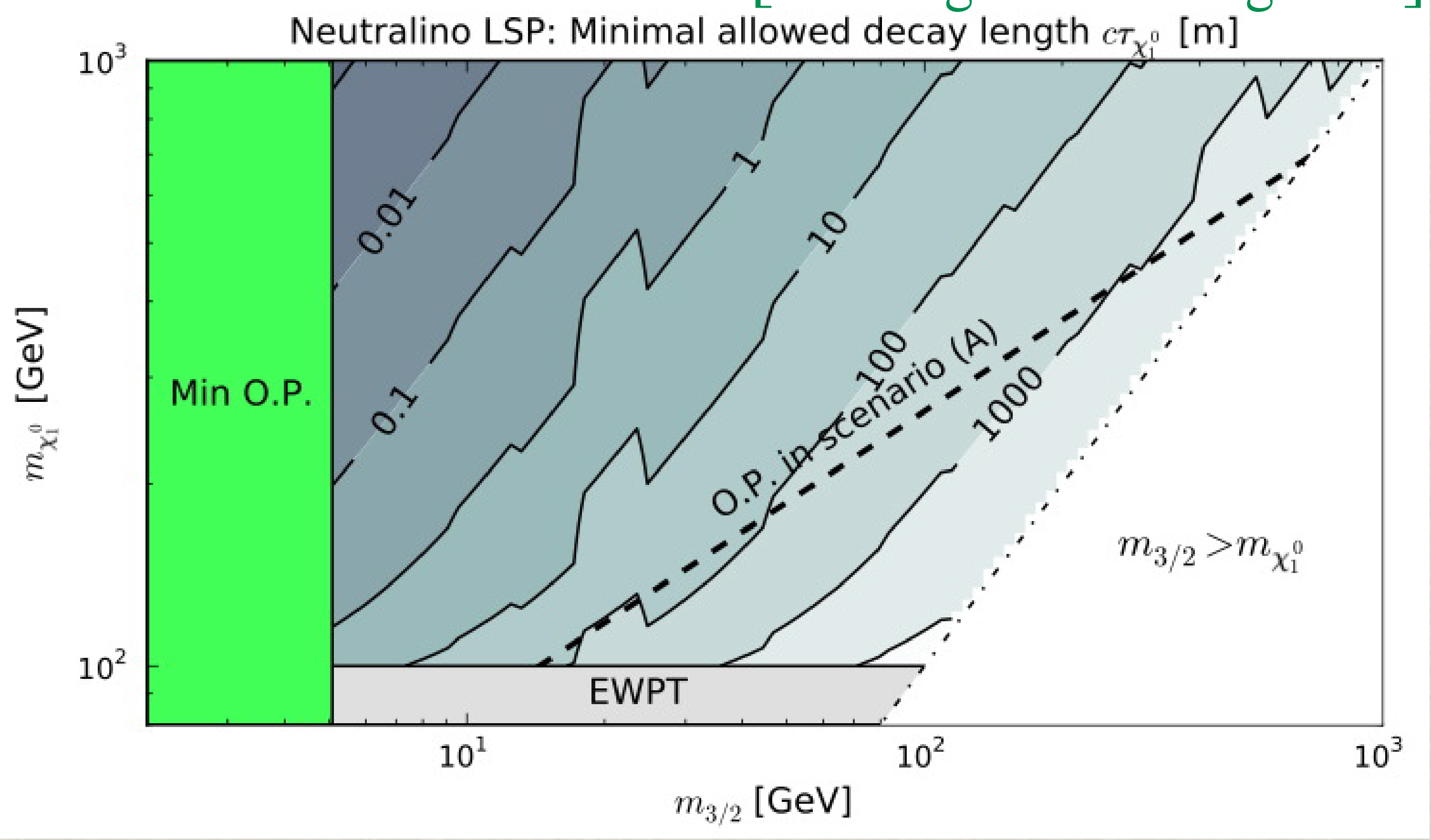
$$\tau_{NLSP} > 10^{-8}\text{ s}$$

DISPLACED VERTICES... perhaps even too much !

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: 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.

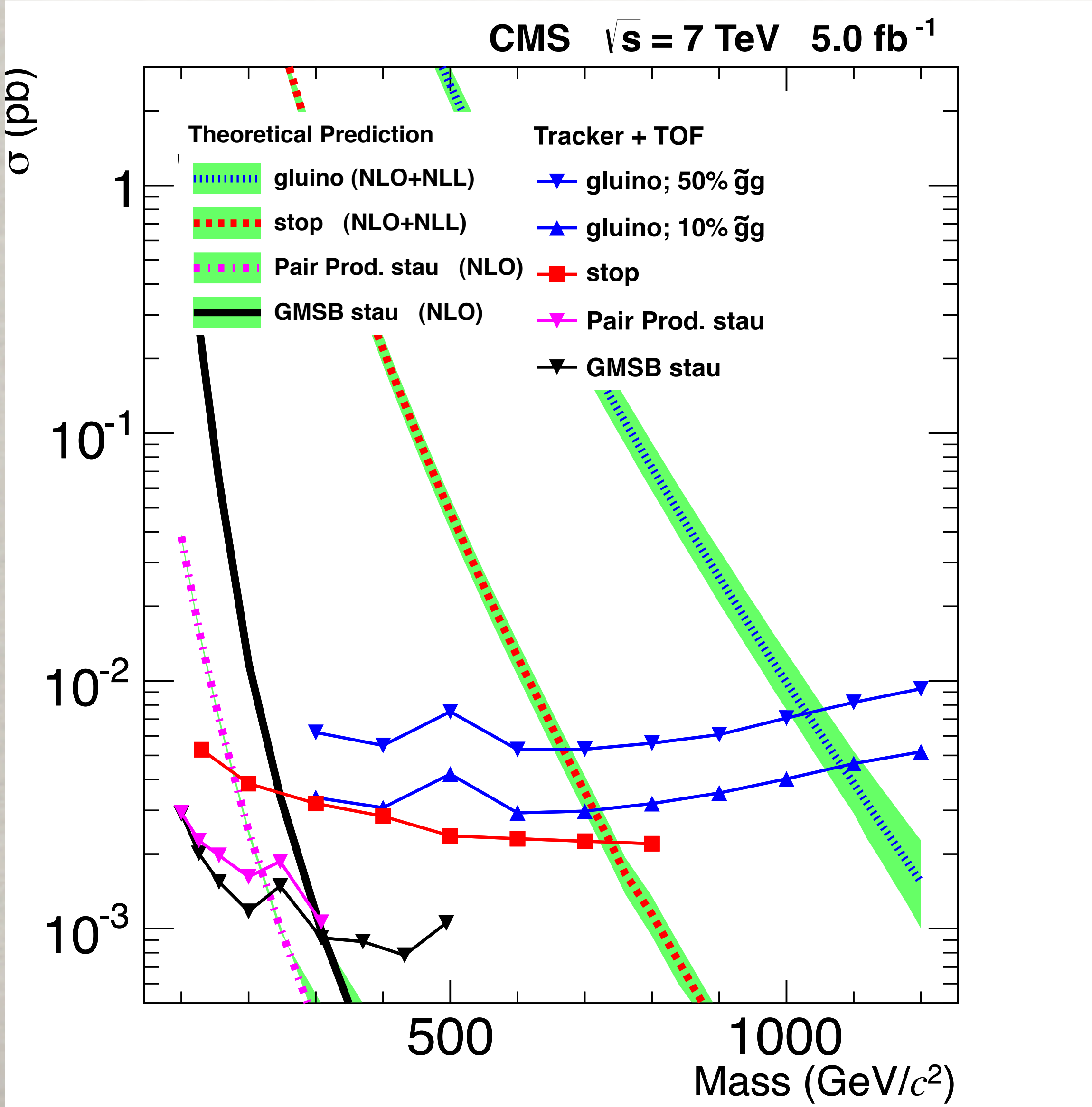
[Bobrovskyi, Buchmuller, Hajer & Schmidt 11]

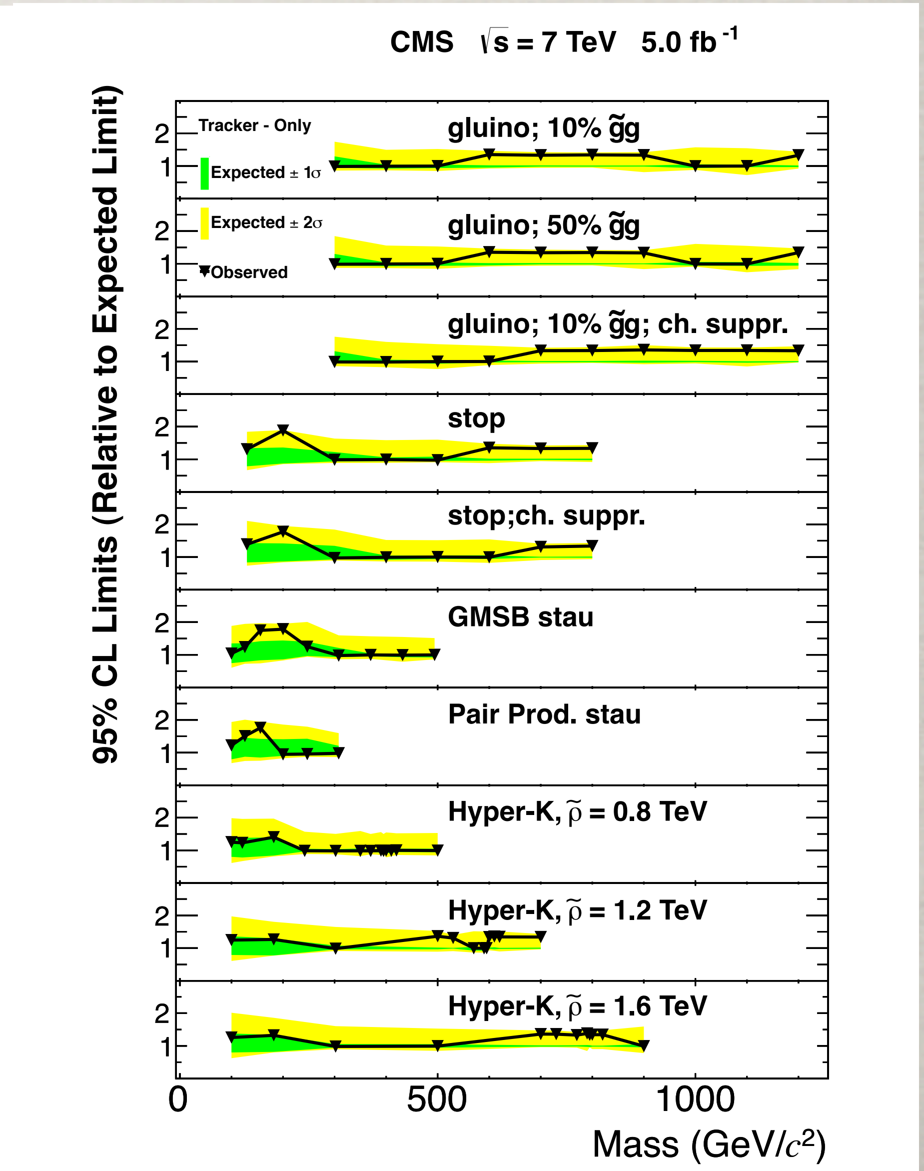
Axino: The NLSP always decays outside the detector in both cases..., but a "light" metastable stau NLSP leaving a highly ionized track at the LHC is possible !

LHC: metastable particles

Recent results from CMS for metastable SUSY particles:

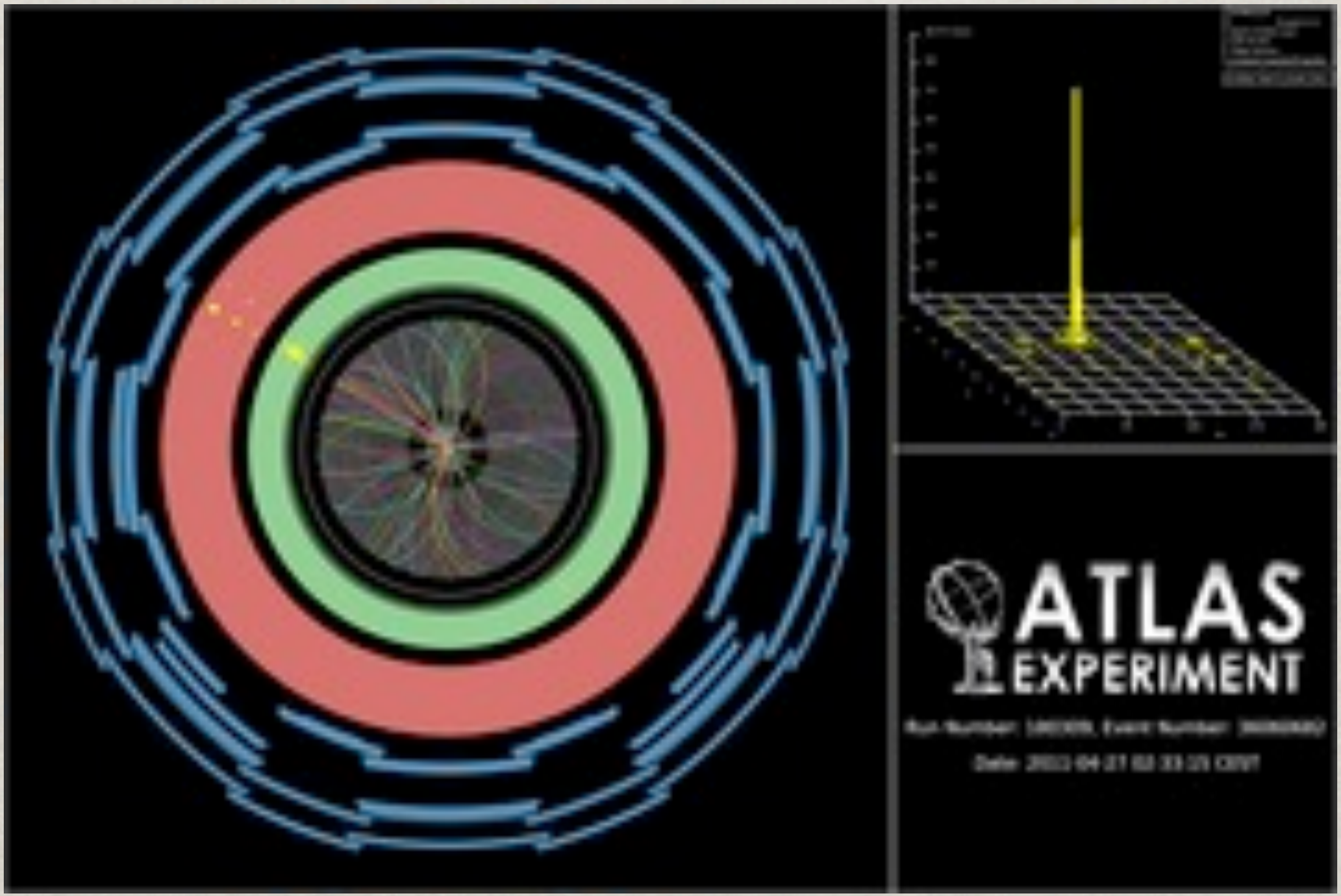
at the moment no significant excess found....





LHC: Monojets ?

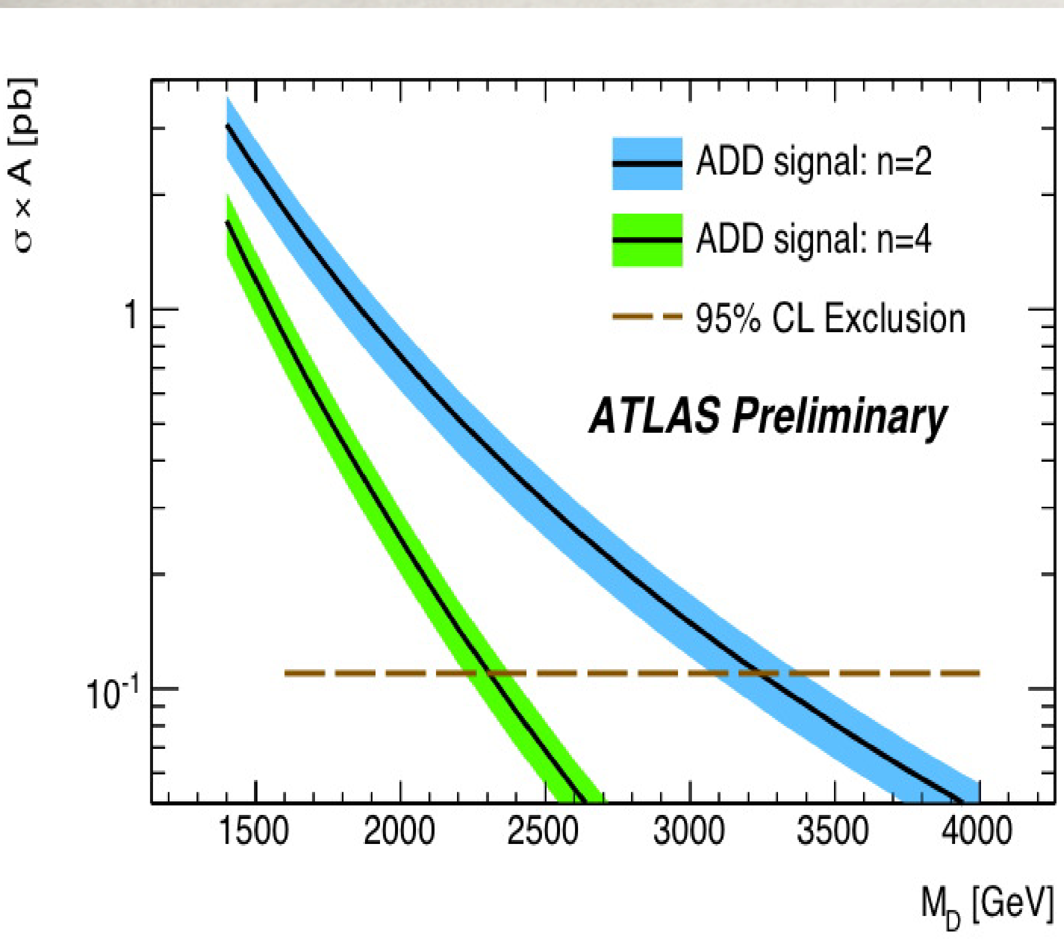
The compressed light neutralino spectrum is already being tested at LHC...

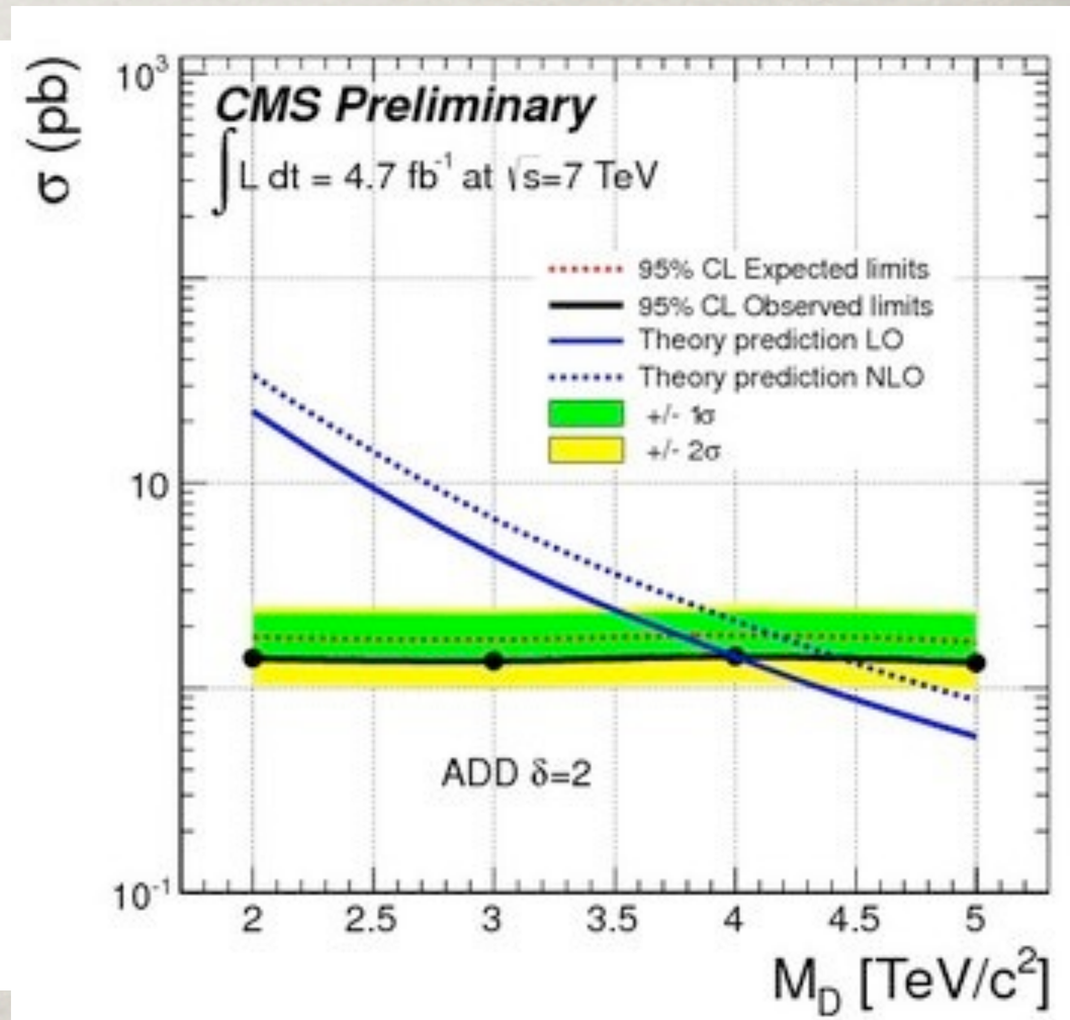


Monojet candidate event !

LHC: Monojets ?

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





Not clear if excluded yet...

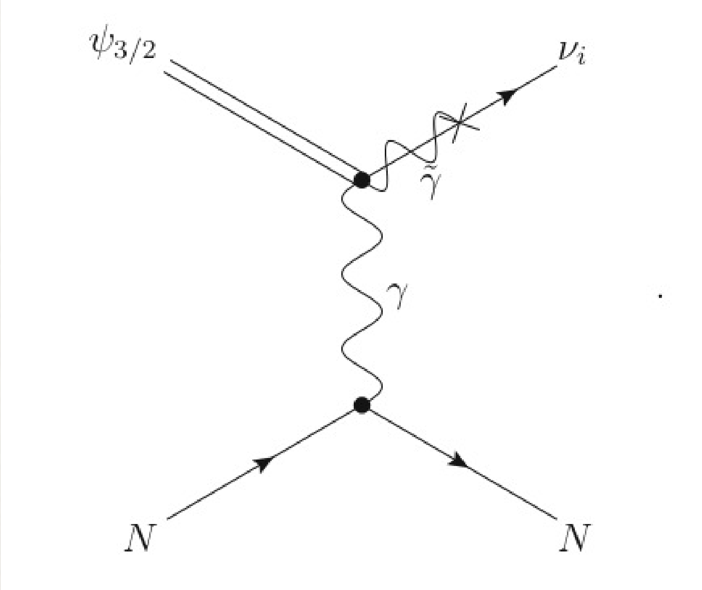
Gravitino Direct detection ?

Gravitino Direct Detection

[Grefe PhD thesis 11], [LC, Grefe 12]

For R-parity breaking a new channel for inelastic scattering opens up for the gravitino/axino: photon exchange !

Need gravitino mass in the 1-100 MeV range to have recoil energies in the 1-100 keV



Similar to Exothermic DM

Simple coupling to the charge of the nucleus !

Unfortunately the rate is way too small for detection...

$$\sigma_p \sim 3.4 \times 10^{-43} pb \left(\frac{\xi_i}{10^{-7}} \right)^2$$

Outlook

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- 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 !