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GRAVITINO DARK MATTER & COLLIDERS

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OUTLINE

- Introduction: Dark Matter properties
  Why gravitino DM ?
- Cosmological constraints on gravitino DM:
  - production mechanisms
  - cold or warm ?
- BBN constraints on the NLSP
- NLSP Phenomenology at colliders:
  - decaying NLSP
  - (quasi-)stable particles
- Indirect detection and R-parity breaking
- Outlook

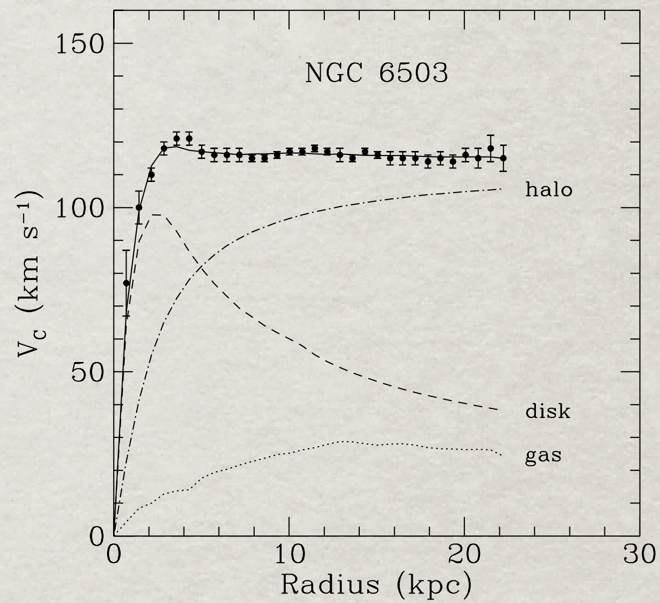
Introduction: DARK MATTER Properties

THE MATTER CONTENT

The clumpy energy density/matter divides into

Particles	$\Omega_i(t_{\text{now}})h^2$ (WMAP)	Type
Baryons	0.0224	Cold
Massive ν	$6.5 \times 10^{-4} - 0.01$	Hot
???	$\sim 0.1 - 0.13$	COLD

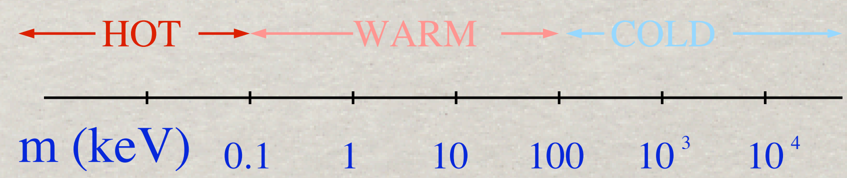
[Begeman, Broeils & Sanders '91]



DARK matter !

Note: DM first discovered in 1933 by F. Zwicki from the rotational curve of the COMA cluster...

Structure formation requires COLD Dark Matter, otherwise the structure formation on scales smaller than its free-streaming length at t_{eq} is suppressed.

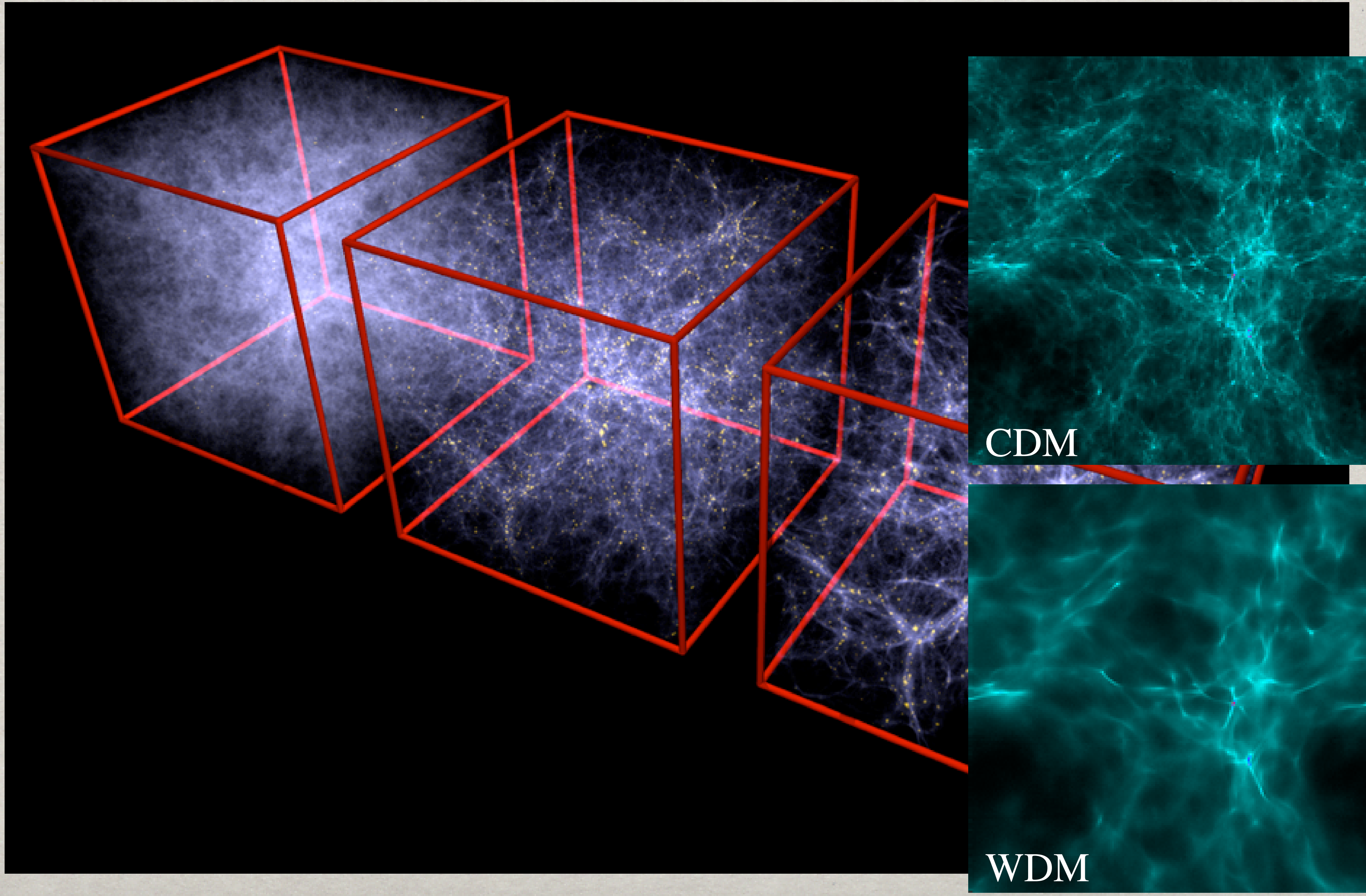


NEED to produce after inflation a large number of particles sufficiently massive, stable and neutral !

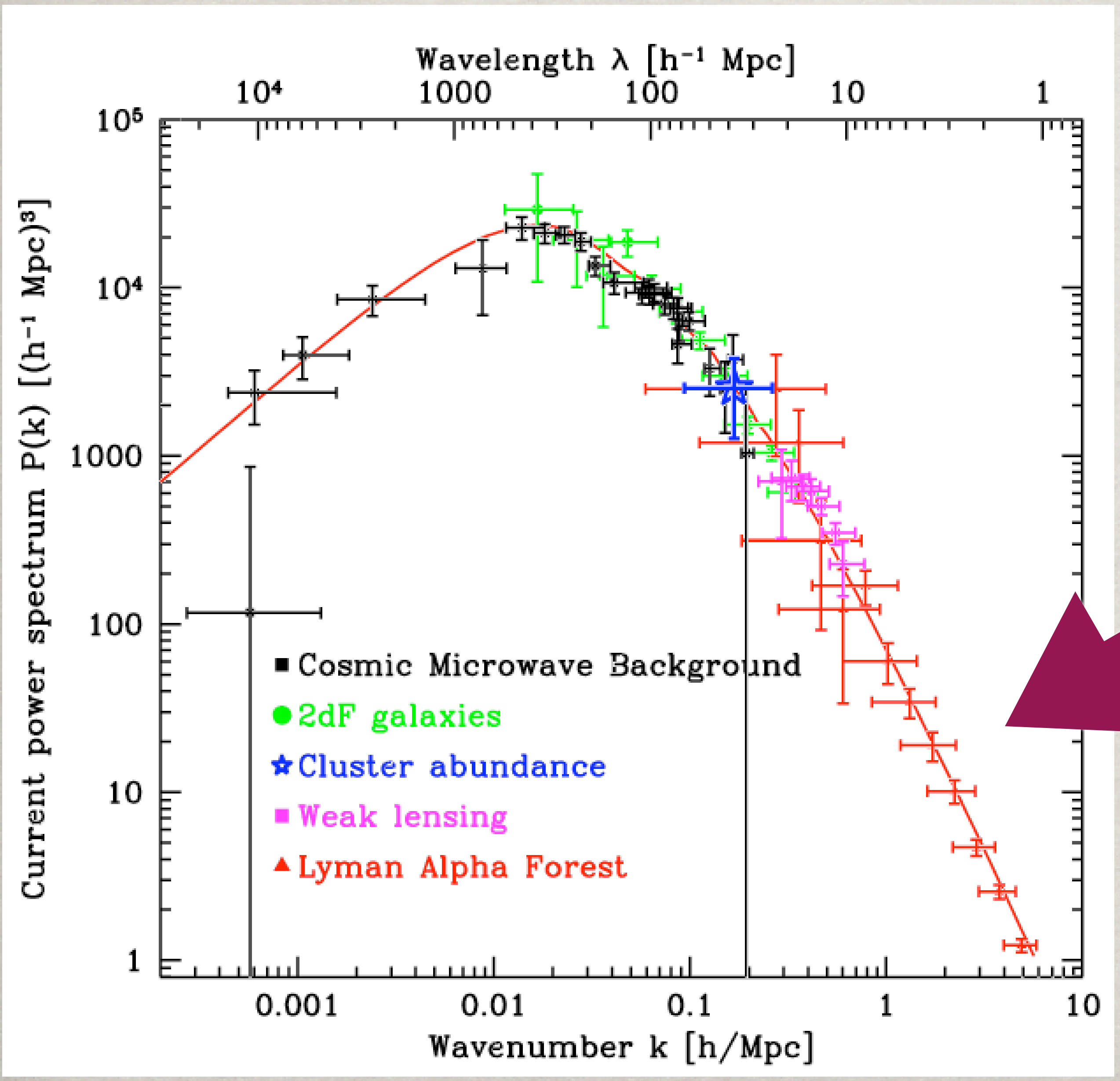
Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



WDM & the Power spectrum



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]

WHY GRAVITINO DM?

- Solves the DM problem within gravity and with sufficiently high reheat temperature.
- Based on supersymmetric extension, i.e. very theoretically attractive: gives gauge unification, solves hierarchy problem, etc...
- Opens up a WINDOW ON SUSY BREAKING !
- Allows for coherent framework, with a “small” number of parameters in the minimal setting apart from the SM ones...
- R-parity conservation provides a stable DM particle, but it is not strictly necessary !

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:

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

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

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

The gravitino gives us direct information on SUSY breaking !

Who is the LSP ???

Which particle is the LSP depends strongly on the SUSY breaking and transmission mechanisms...
If we can single out the LSP, we can already exclude many models and in general already the requirement of a neutral LSP is not trivial !

SUSY mediation	typical LSP
gauge/gaugino	gravitino
gravity	neutralino/slepton/gravitino
anomaly	slepton (tachyonic...)

We can exploit cosmology to constrain the SM extensions !

The gravitino is the lightest in some well-motivated cases....

Cosmological constraints on gravitino DM

PRODUCTION MECHANISM

Primordial abundance of a thermal relic

[see e.g. Kolb & Turner '90]

The number density of a stable particle X in an expanding Universe is given by the Bolzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = \langle \sigma(X + X \rightarrow \text{anything})v \rangle \left(n_{eq}^2 - n_X^2\right)$$

Hubble expansion   Collision integral

The particles stay in thermal equilibrium as long as the interactions are fast enough, then they freeze-out when

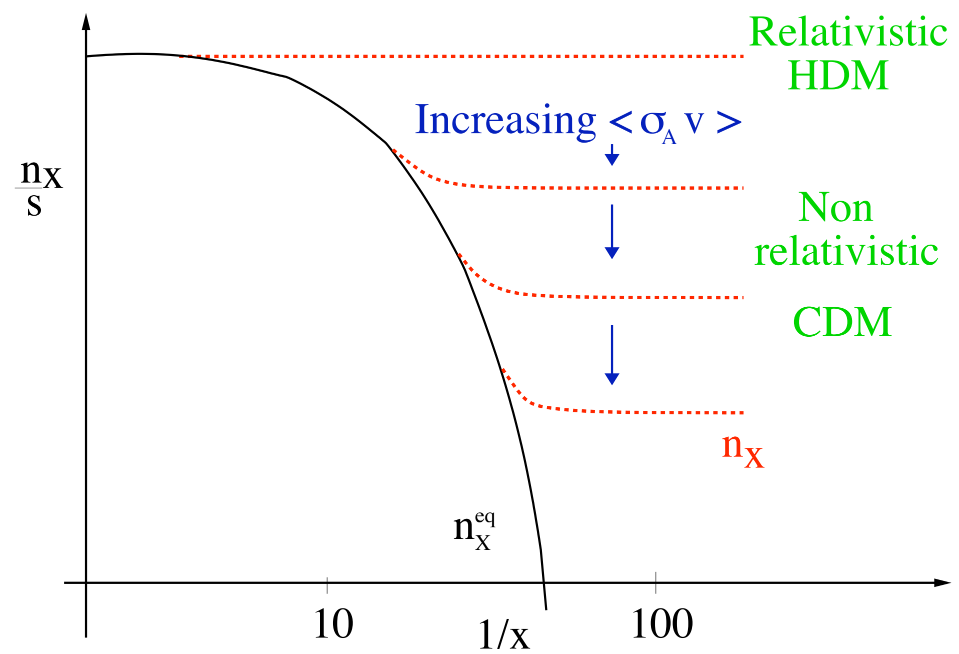
$$n_{eq}\langle\sigma_A v\rangle \sim H \qquad \Rightarrow \qquad \Omega \propto \frac{1}{\langle\sigma_A v\rangle}$$

Particles with very weak interactions decouple when still relativistic, i.e. with $n_X(T_D) \sim n_\gamma(T_D)$ and so

$$m_X \lesssim 10^{-3}\text{keV} \;\; g_\star(T_D)\left(\frac{\Omega_X h^2}{0.15}\right)$$

VERY LIGHT $\longrightarrow$ HOT Dark Matter !

Since we need COLD DM either gravitinos are not DM or they never were in thermal equilibrium !



CAN COLD DM BE MORE WEAKLY INTERACTING THAN A WIMP ?

Yes, if the Universe was never hot enough...,
require a reheat Temperature sufficiently low.

Very weakly interacting particles are produced even in this case, at least by two mechanisms

PLASMA SCATTERINGS

NLSP DECAY OUT OF EQUILIBRIUM

Neglect here other mechanisms, i.e. inflaton decay, etc...

THERMAL PRODUCTION

THERMAL PRODUCTION: At high temperatures, the dominant contribution to the production come from 2-body scatterings with colored states, mediated by non-renormalizable operators:

- gravitino case: $$\Omega_{\tilde{G}}^{TH} h^2 \simeq 0.2 \left(\frac{100\text{GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{\tilde{g}}}{1\text{TeV}}\right)^2 \left(\frac{T_R}{10^{10}\text{GeV}}\right)$$

[Bolz, Brandenburg & Buchmüller '01]

- axino case: $$\Omega_{\tilde{a}}^{TH} h^2 \simeq 0.6 \left(\frac{m_{\tilde{a}}}{0.1\text{GeV}}\right) \left(\frac{10^{11}\text{GeV}}{f_a}\right)^2 \left(\frac{T_R}{10^4\text{GeV}}\right)$$

[LC, HB KIm, JE Kim & Roszkowski '01, Brandenburg & Steffen '04]

NOTE the completely different dependence on the "X"WIMP mass !!! It is due to the fact that the gravitino is produced via its Goldstino component, whose couplings are enhanced by the ratio $\frac{m_{\tilde{g}}}{m_{\tilde{G}}}$!

Technical point: Hard Thermal loop resummation needed to regularize the gluon IR divergences.

For contributions from other gauge groups, top Yukawa and thermal corrections see the recent papers [Pradler & Steffen 06, Rychov & Strumia 07].

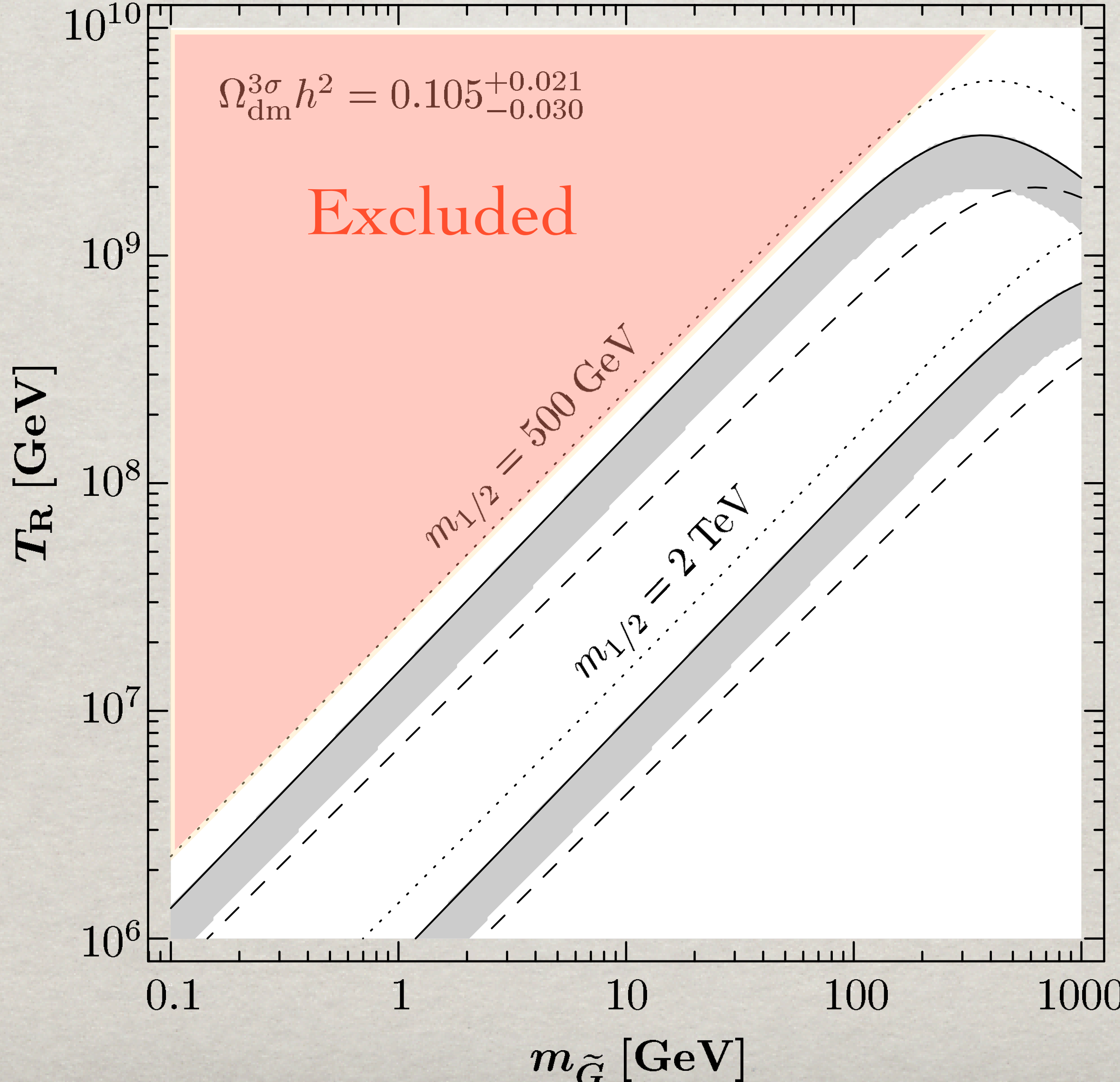
Non thermal production via inflaton decay neglected here...

In general UPPER BOUND on the REHEAT TEMPERATURE !

Special T_{RH} needed to have the observed DM density.

UPPER BOUND ON T_R

[Pradler & Steffen '06]



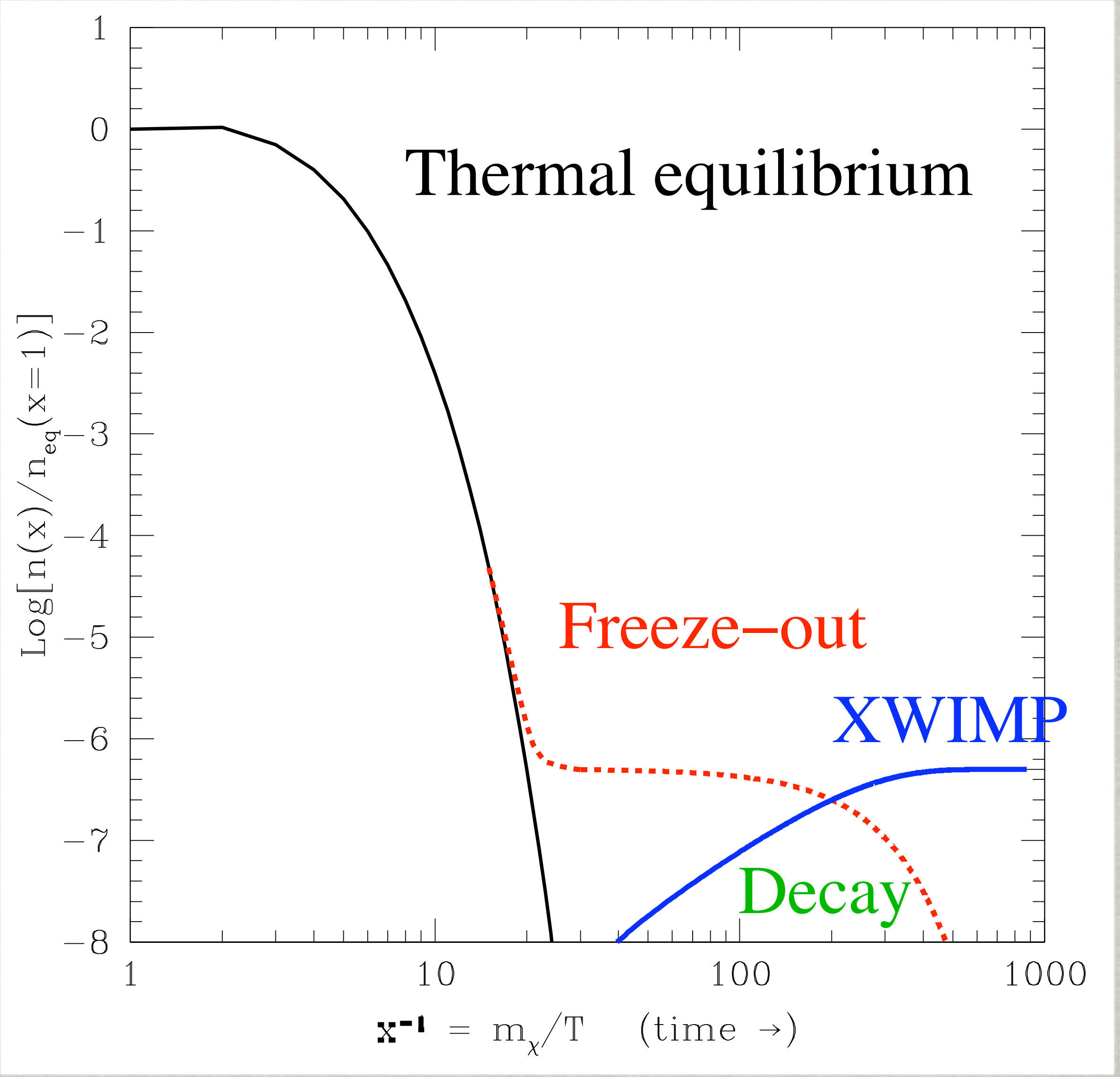
NLSP DECAY

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

- For long lifetime the NLSP decays after freeze-out and R-parity is conserved

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

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



THE TROUBLE OF LATE DECAYING PARTICLES...

- Moduli problem (if they dominate before decay)
- BBN disruption if very energetic hadronic or electromagnetic particles are released after 1 s
- CMB distortion if energetic photons are released after 10000 s or so
- COLD or WARM ? The decaying particles do not have thermal spectrum and have larger velocities then thermal relics...

Hot, Warm or cold ???

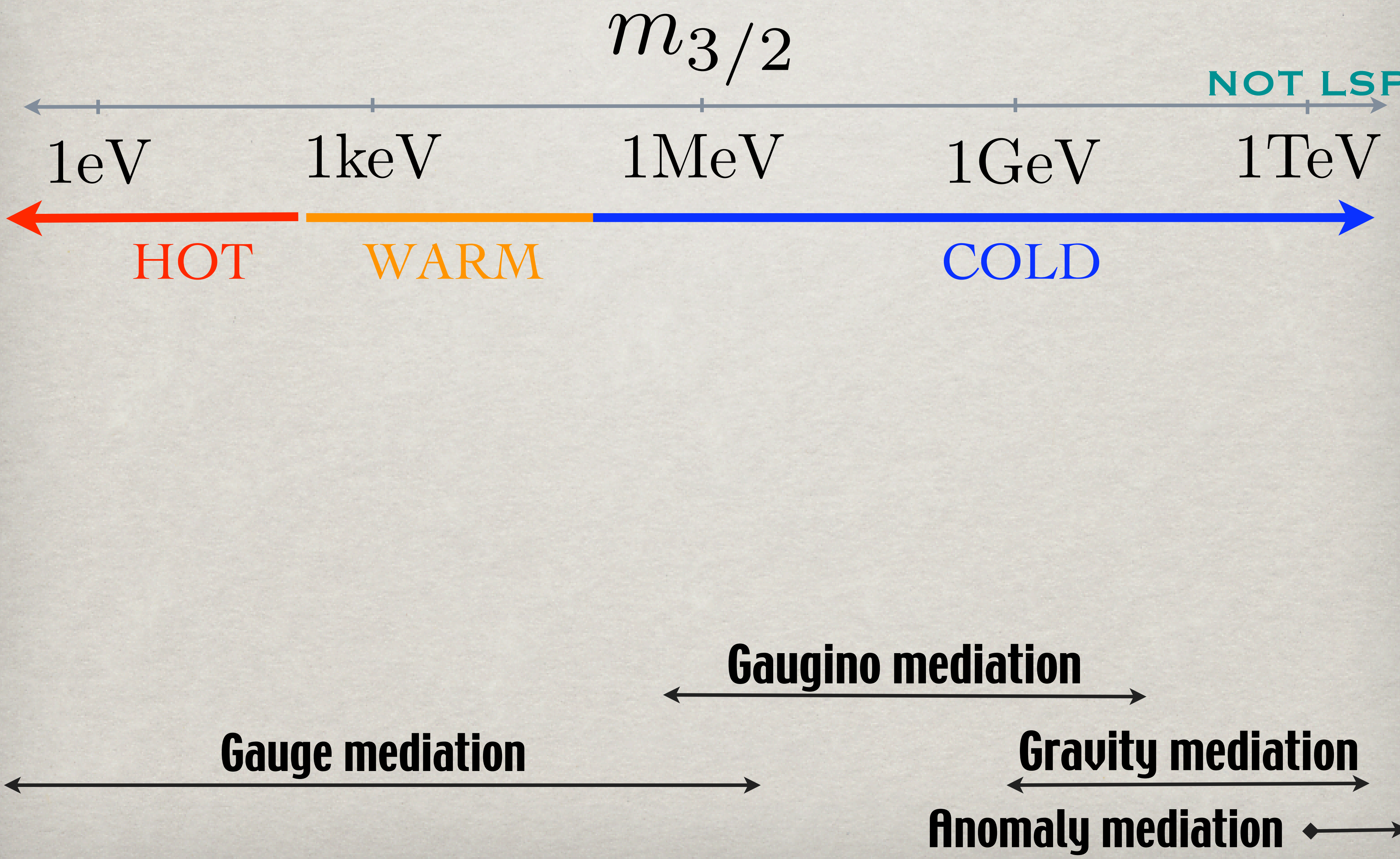
- Gravitinos in thermal equilibrium are HOT DM with mass in the 200-400 eV range;
- Gravitinos from thermal production can be WARM or COLD depending on their mass;
- Gravitinos from NLSP decay are not thermal, but they can behave as WARM DM: their velocity is

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

Need probably gravitino masses around 10 GeV or more...

[Jedamzik, Lemoine & Moultaka '05]

Gravitino DM summary



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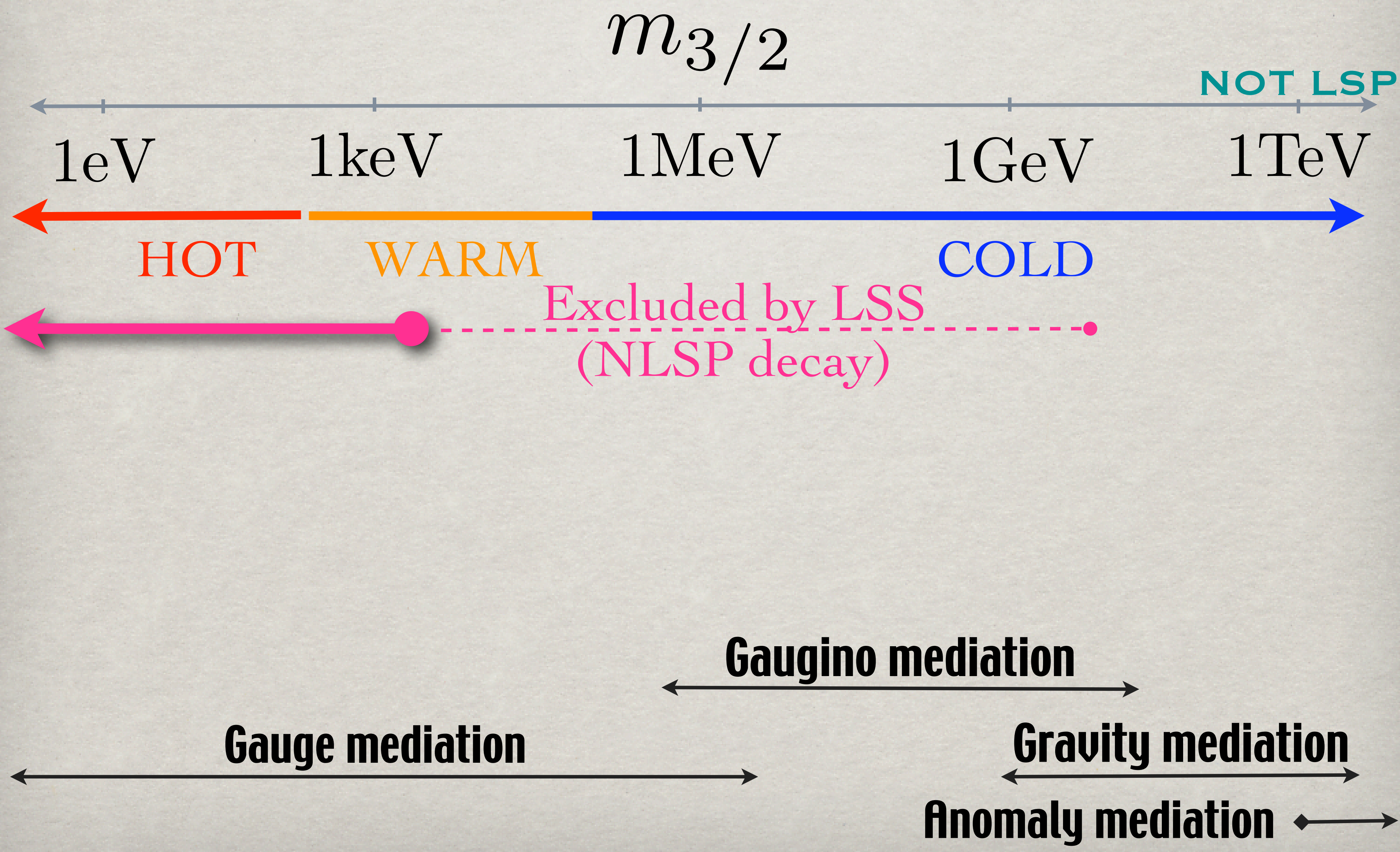
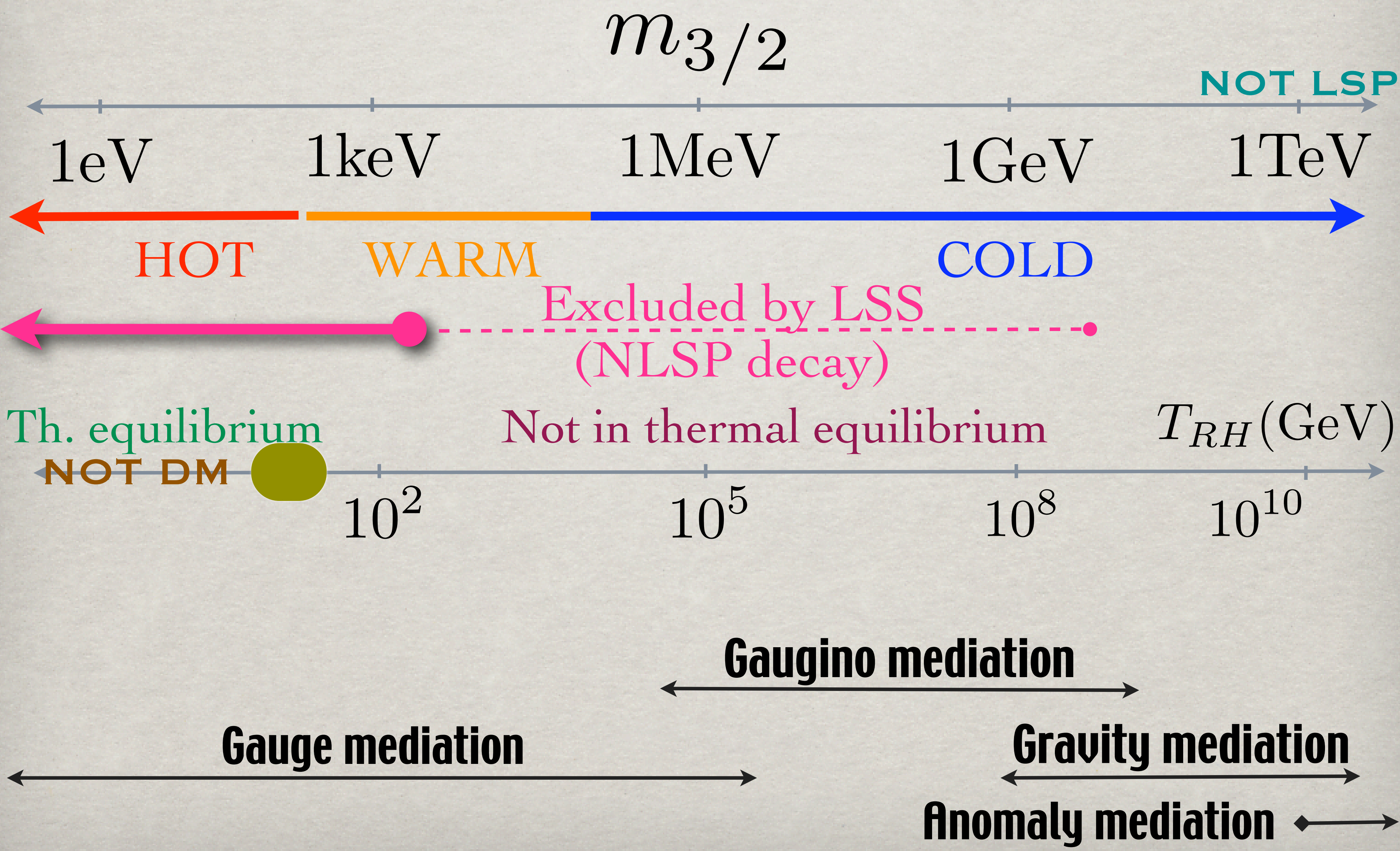


Gravitino DM summary

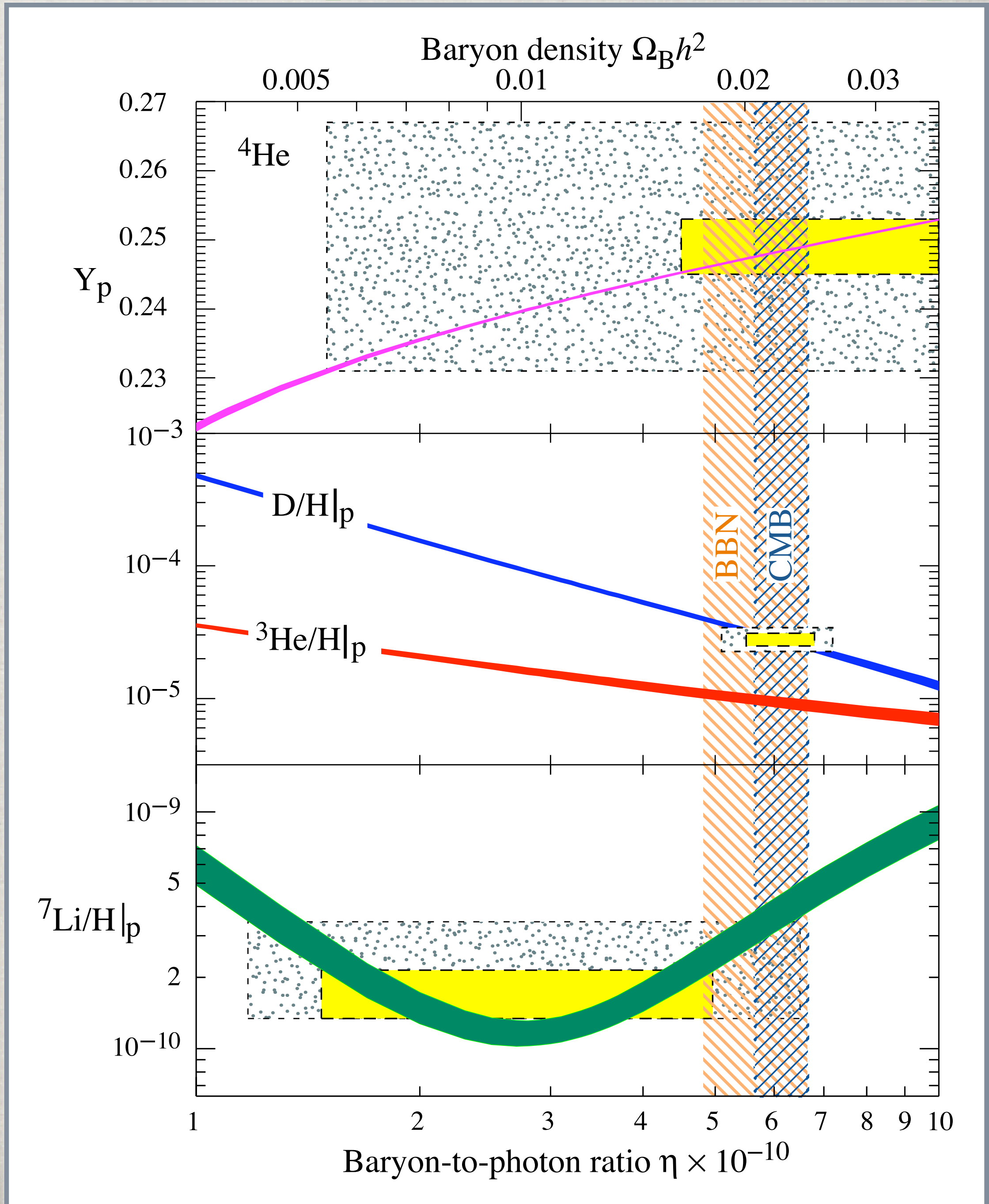


BBN constraints on the NLSP

Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

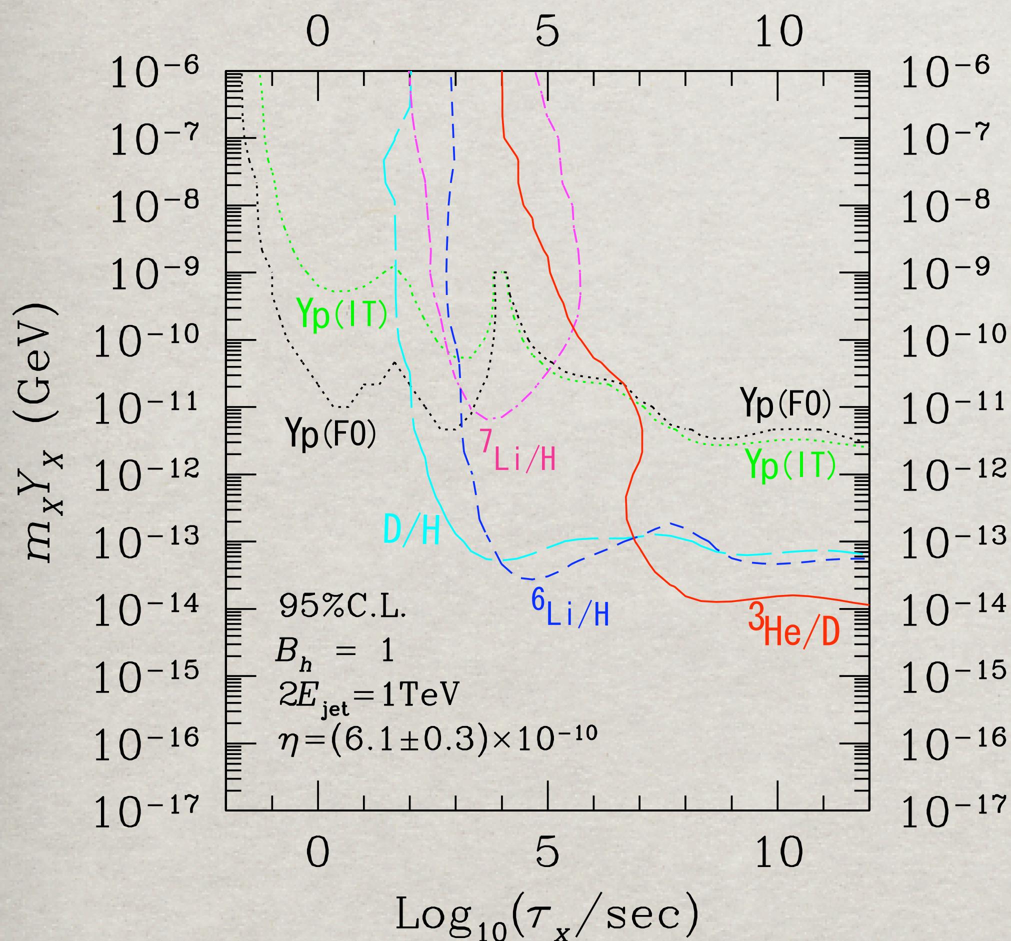
- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7



BBN bounds on NLSP decay

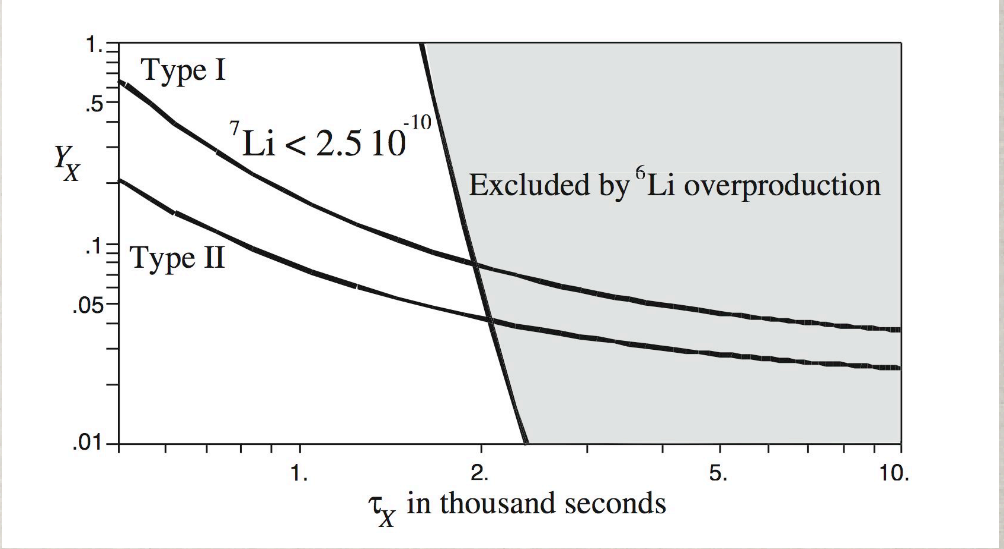
Neutral relics

[...,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, if the mass is above 1 GeV...

HOW TO EVADE BOUNDS

- Make the lifetime shorter:
  heavy(er) NLSP or light(er) gravitino LSP

$$\tau_{NLSP} \sim 10^5 s \left(\frac{m_{NLSP}}{200GeV}\right)^{-5} \left(\frac{m_{3/2}}{10GeV}\right)^2$$

  axino LSP

$$\tau_{NLSP} \sim 1s \left(\frac{m_{NLSP}}{200GeV}\right)^{-3} \left(\frac{f_a}{10^{11}GeV}\right)^2$$

  violate R-parity

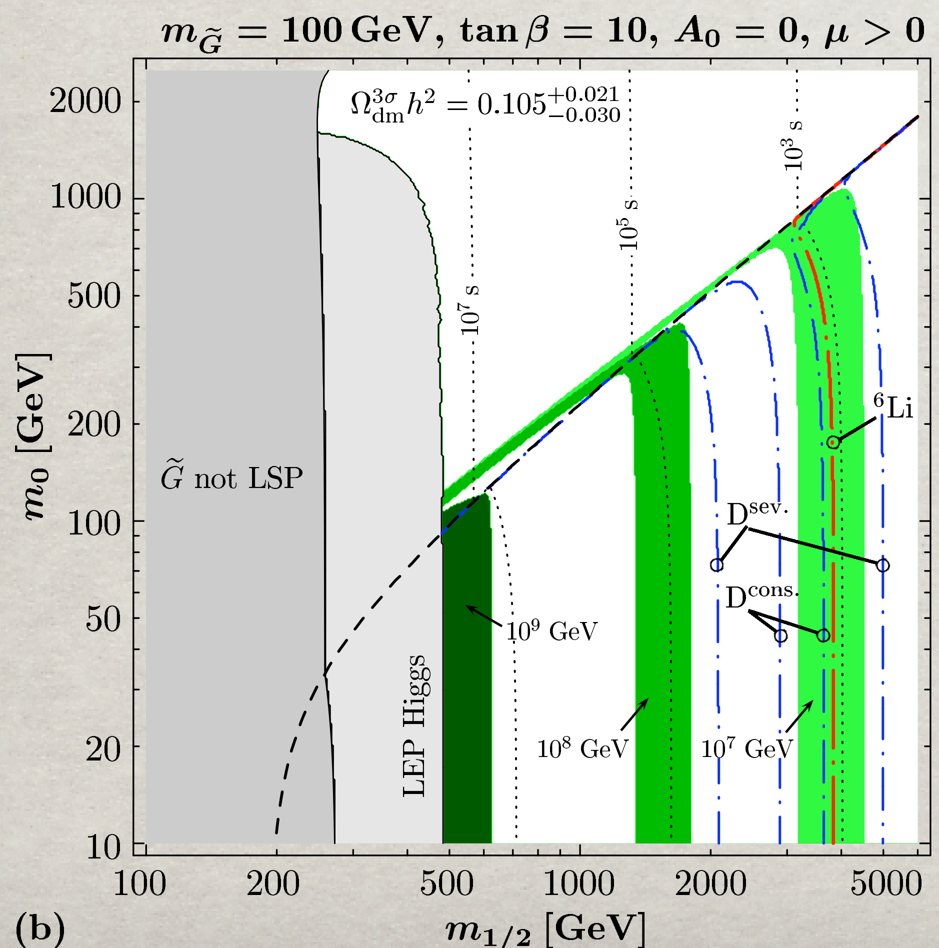
- Choose a harmless NLSP:
  sneutrino LH or RH (weaker bounds...) [LC, S. Kraml 07]
  stop (low abundance and annihilation at QCD transition)
  [Diaz-Cruz, Ellis, Olive & Santoso et al. 07]
  [Berger, LC, Kraml & Palorini 08]

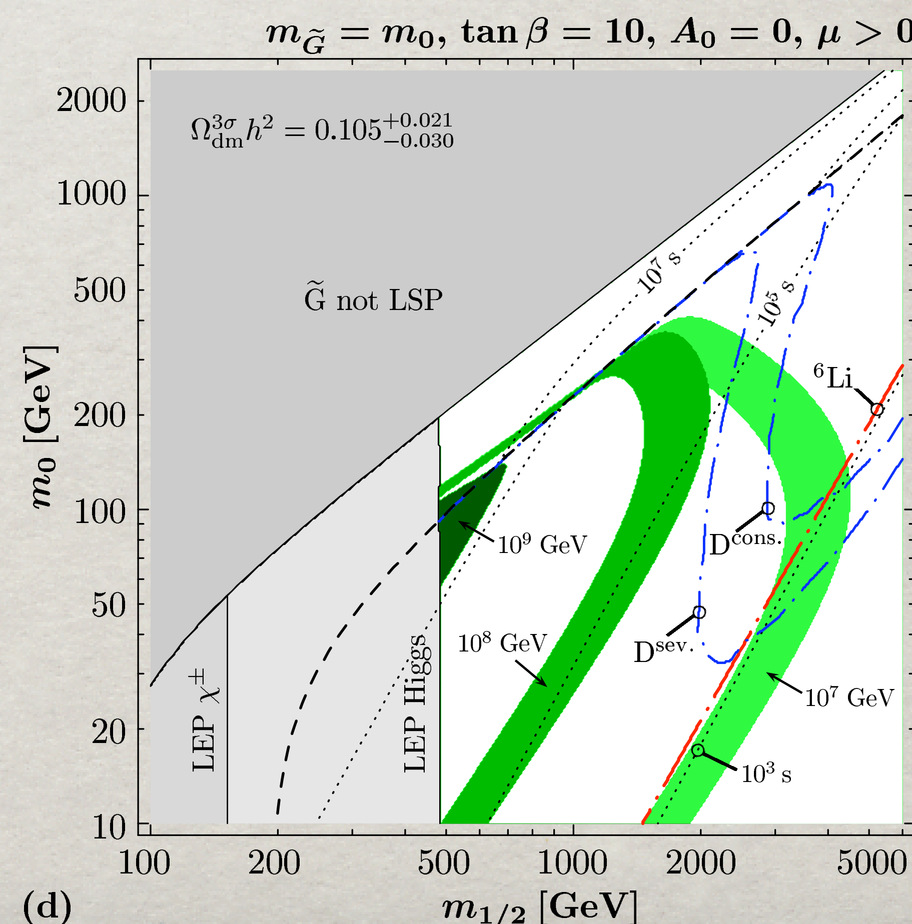
- dilute the NLSP abundance with entropy production
  [Buchmuller et al 05, Hamaguchi et al 07...]

Gravitino DM in the CMSSM Difficult to see at LHC ?

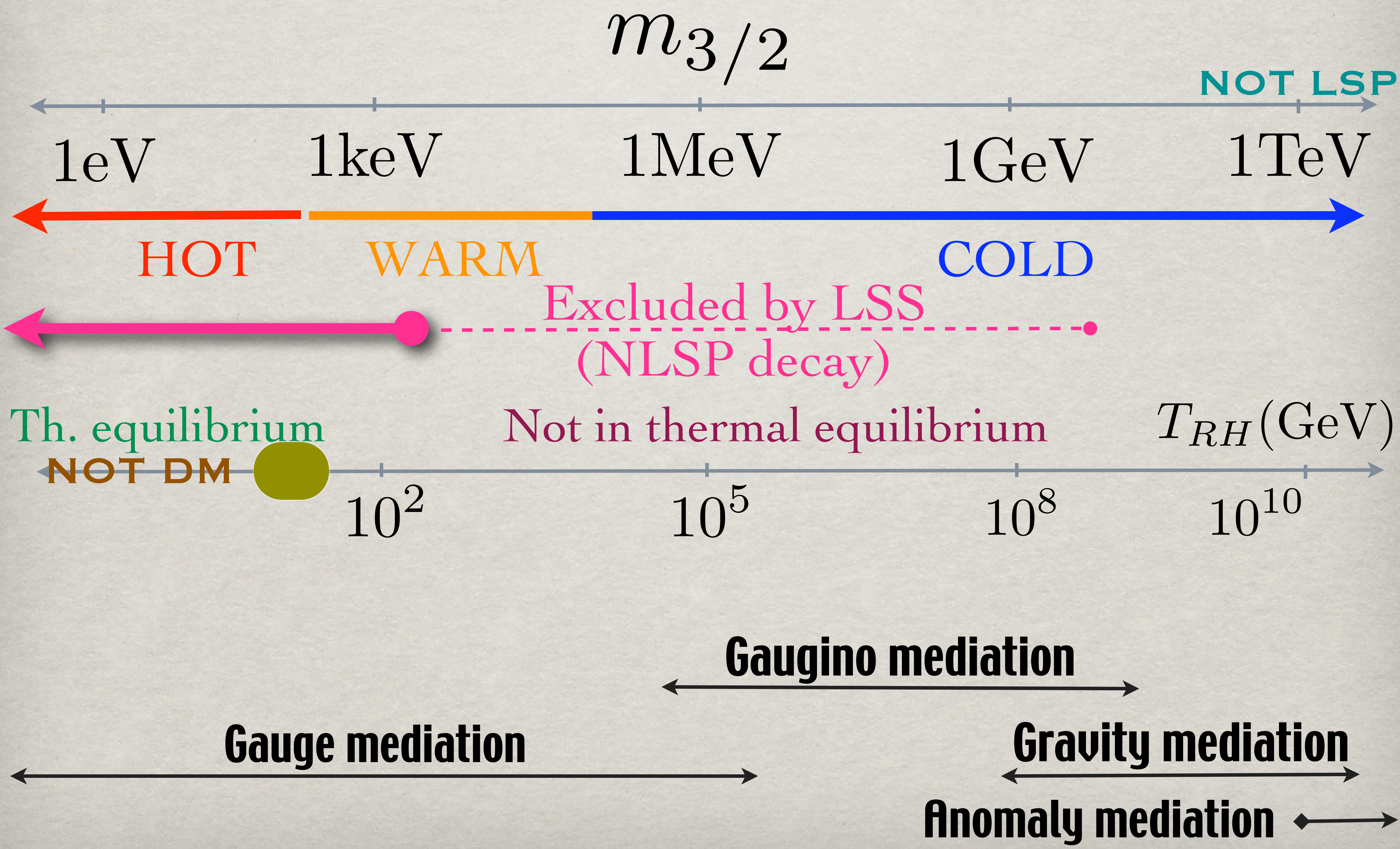
Only the large stau mass region > 1 TeV is still allowed in the CMSSM for gravitino LSP...

[Pradler & Steffen '06]

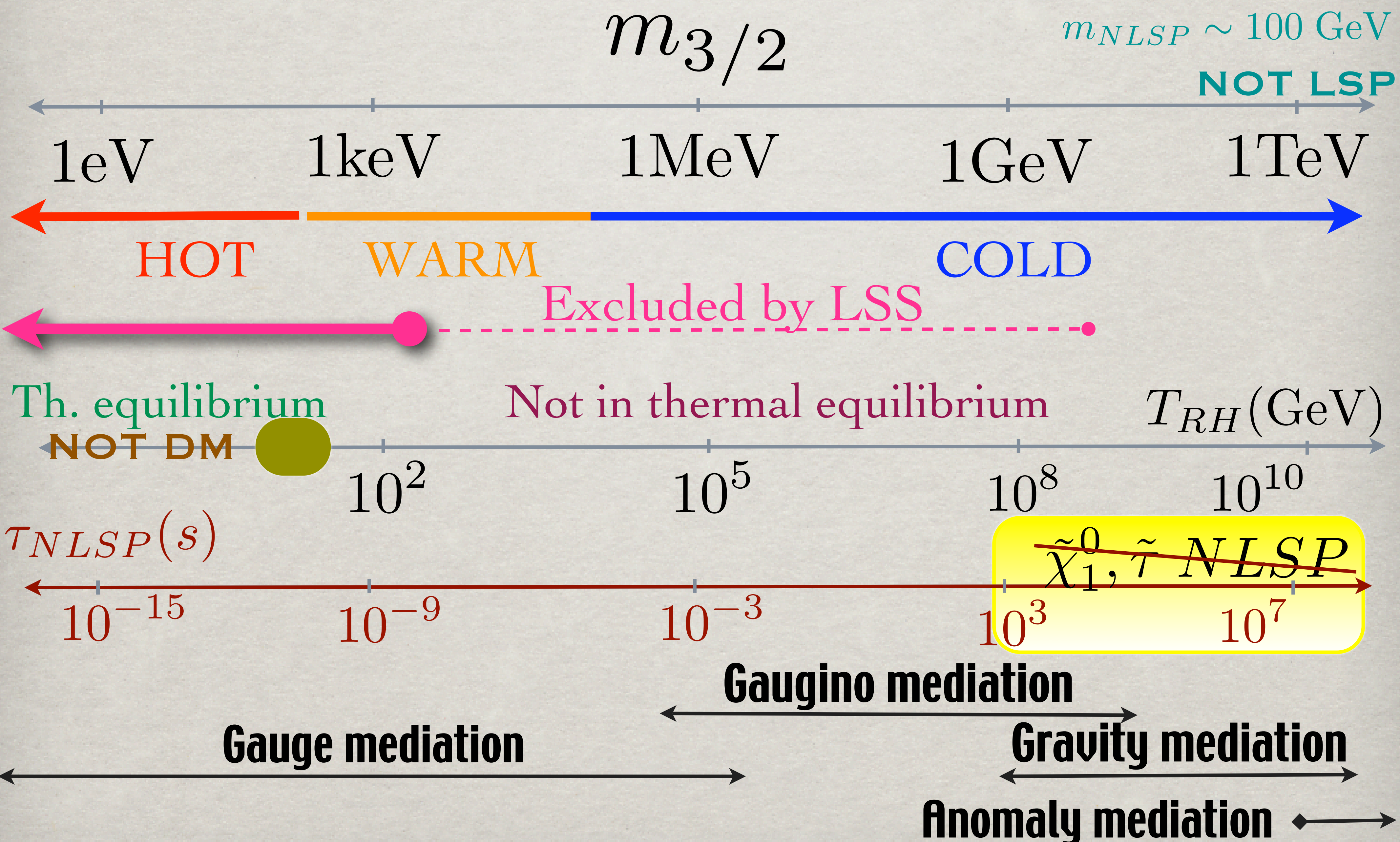




Gravitino DM summary



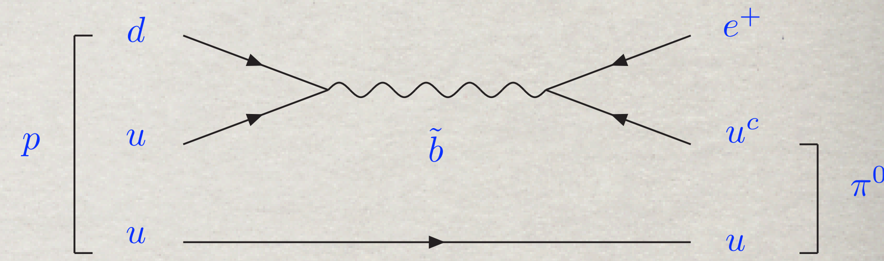
Gravitino DM summary II



(R-parity or not R-parity ?)

R-parity or not R-parity ?

R-parity is imposed by hand in the MSSM in order to avoid fast proton decay due to renormalizable couplings explicitly violating B and L:



$$W = \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

$\Rightarrow$ Dimension 4 proton decay operators $\propto \frac{\lambda'\lambda''}{m_{\tilde{q}}^2}$

R-parity = $(-1)^{3B+L+2s}$ forbids these terms $\Rightarrow$ No dimension 4 proton decay (and LSP is stable)!

Proton decay can be avoided also if only B violating couplings λ'' are forbidden. So do we really need R-parity to have gravitino DM ? NO: the decay rate of the gravitino is doubly suppressed by M_P and the R-parity breaking couplings:

$$\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(\prime)}}{10^{-7}}\right)^2 \left(\frac{m_{3/2}}{10\mathrm{GeV}}\right)^{-3}$$

It is sufficient to have $\lambda, \lambda' < 10^{-7}$ for the gravitinos to live long enough. Such small value also gives sufficient suppression to L violating wash out processes and allows for leptogenesis. On the other hand, requiring the NLSP to decay before BBN just gives $\lambda, \lambda' > 10^{-14}$.

ANY NLSP is allowed if R-parity is broken and still we can have supersymmetric DM !

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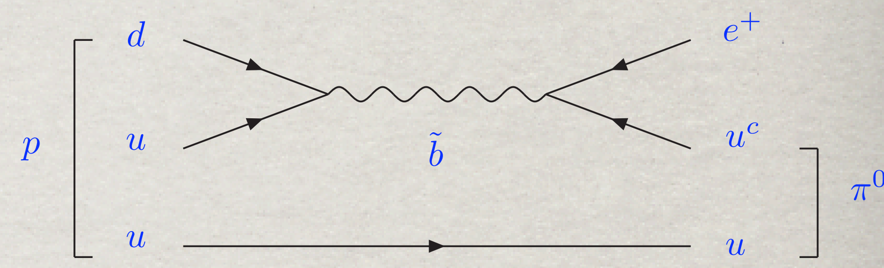

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$$\tau_{3/2} \simeq 10^{26} s \left(\frac{\lambda^{(\prime)}}{10^{-7}}\right)^2 \left(\frac{m_{3/2}}{10\mathrm{GeV}}\right)^{-3} \gg H_0^{-1} \sim 10^{17}\mathrm{s}$$

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GRAVITINO CDM WITH R-parity VIOLATION

NLSP @ COLLIDERS

Different signals...

- NLSP decaying within the detector... Need

$$\tau_{NLSP} \leq 10^{-7}\ \mathrm{s} \quad \Rightarrow \quad m_{3/2} \leq 10\ \mathrm{keV}$$

or R-parity breaking at the level larger than 10^{-7}

- Charged meta-stable NLSP: $\tilde{\tau}_R$
- Colored meta-stable NLSP: $\tilde{t}_R$
- Neutral meta-stable NLSP: χ_1^0 vs $\tilde{\nu}_L$

(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...

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

$$\tau_{3/2} > 10^{27} \text{ s}$$

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

$$\tau_{NLSP} > 10^{-9} \text{ s}$$

DISPLACED VERTICES... perhaps even too much !

Metastable charged (N)LSP

- Typical signal of a metastable stau is a highly ionized track leaving the detector (like a heavier muon...)

- Impossible to miss ! It would immediately exclude neutralino Dark Matter

- But not possible to say which scenario is realized without seeing the decay channels...

  ... stop the staus and wait for them to decay !

  Many proposals in the literature: [Hamaguchi et al.'04, Feng & Smith '04, de Roeck et al '05 ...]

  Studying the decay will allow us to distinguish !

HOW TO DISTINGUISH AXINO FROM GRAVITINO LSP ???

Possible if the NLSP is charged and can be stopped and stored to observe its decays...

see e.g. [Hamaguchi, Kuno, Nakaya & Nojiri '04] and [Feng & Smith '04] for proposals about stopping long-lived $\tilde{\tau}$ around the LHC/ILC.

The dominant decay mode is in both cases $\tilde{\tau}_R \to \tau \;\; \tilde{a}/\tilde{G}$ and the lifetime can vary considerably:

$\tilde{a}$: the lifetime is independent of the axino mass for $m_{\tilde{a}} \ll m_{\tilde{\tau}}$ and can range from 0.01 sec to 10 h depending on $f_a, m_{\tilde{\tau}}$:

$$\Gamma \sim (25\text{sec})^{-1} \left(\frac{m_{\tilde{\tau}_R}}{100\text{GeV}}\right) \left(\frac{m_{\tilde{B}}}{100\text{GeV}}\right)^2 \left(\frac{10^{11}\text{GeV}}{f_a}\right) \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{\tau}_R}^2}\right);$$

$\tilde{G}$: the lifetime is strongly dependent on the gravitino mass and can range within 10^{-7} sec to 15 yrs depending on $m_{\tilde{G}}, m_{\tilde{\tau}}$:

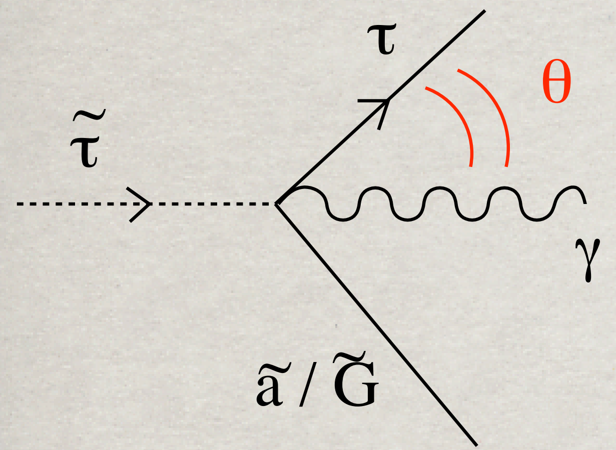
$$\Gamma \sim (6\text{sec})^{-1} \left(\frac{m_{\tilde{\tau}_R}}{100\text{GeV}}\right)^5 \left(\frac{10\text{MeV}}{m_{\tilde{G}}}\right)^2 \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_R}^2}\right)^4.$$

$\Rightarrow$ difficult to distinguish in the overlapping region. Need to see the STAU DECAY MODES !

That would allow also to distinguish from R-parity violation.

GRAVITINO VS AXINO LSP?

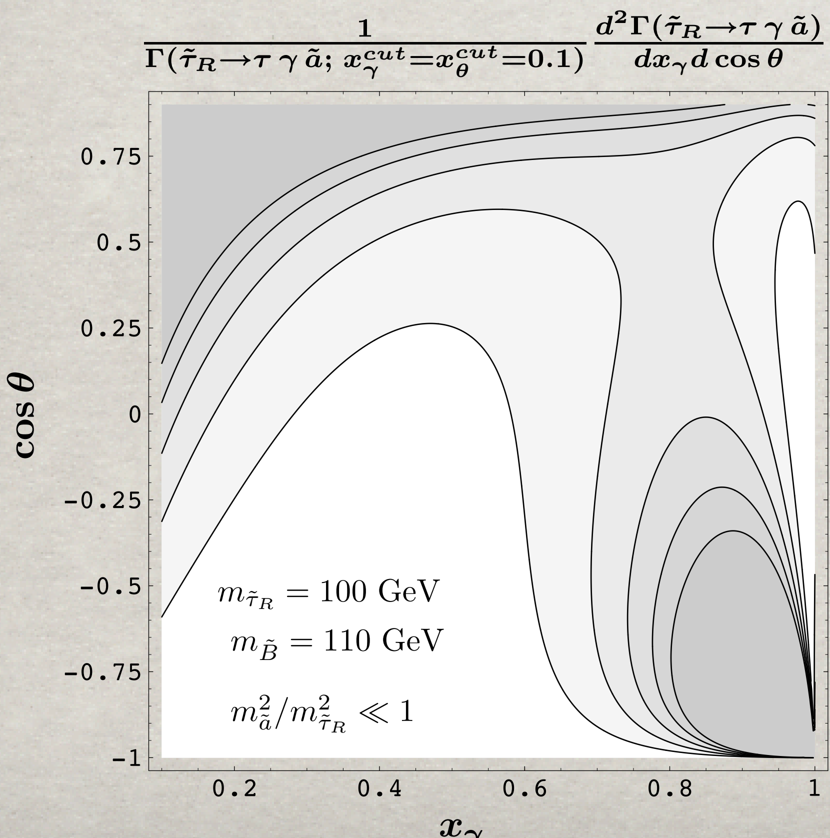
[Buchmuller et al 04, Brandenburg et al 05]



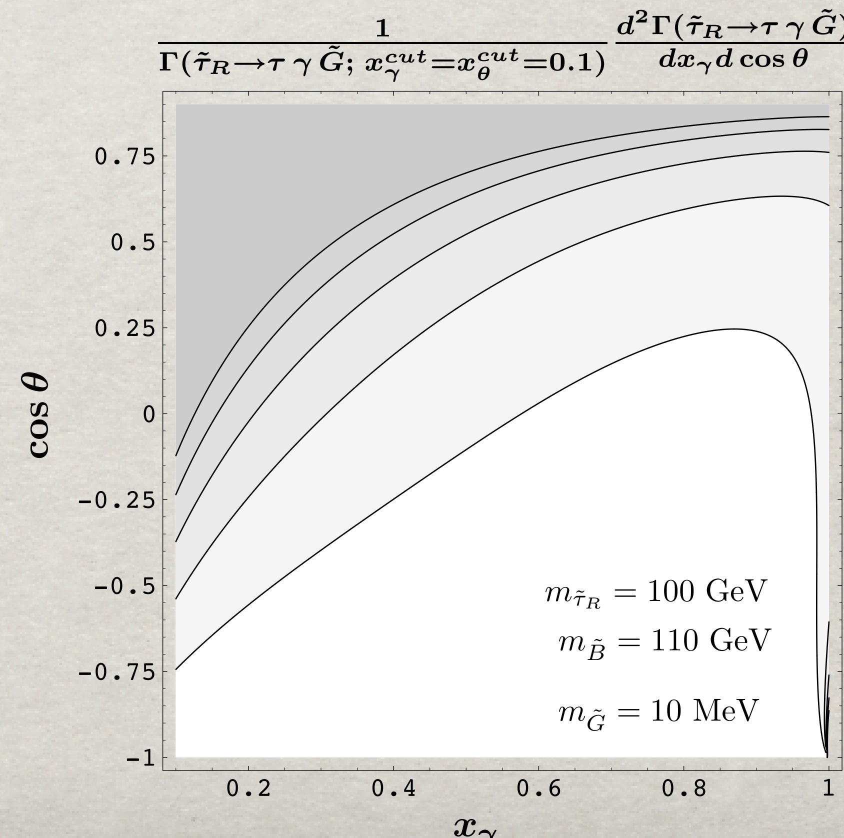
$$x_\gamma = \frac{E_\gamma}{2m_{\tilde{\tau}}}$$

Look at the angular distribution in the radiative decay and/or its branching ratio

Axino LSP Scenario



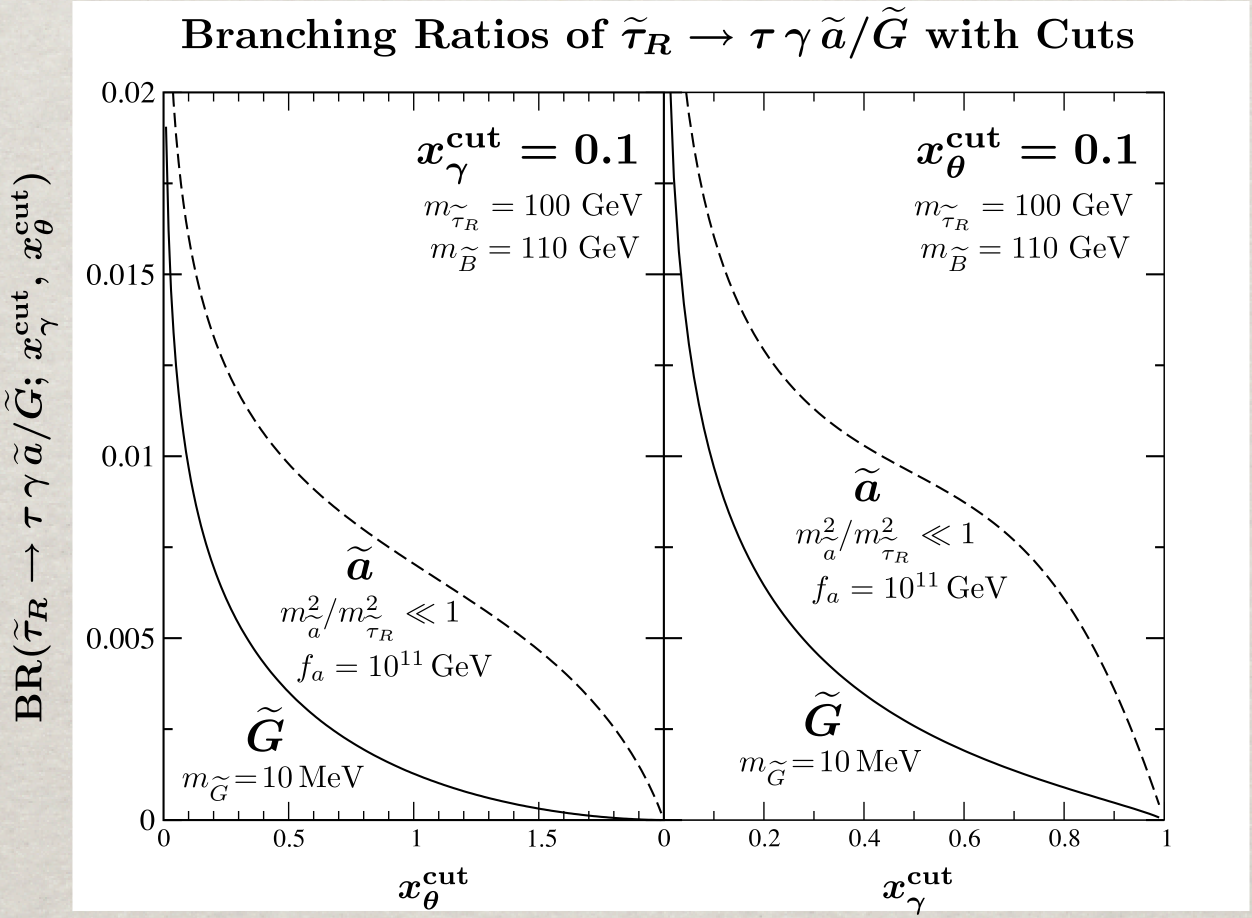
Gravitino LSP Scenario



Need just ~200 staus...

The branching ratios in two or three body are different

[Brandenburg, LC, Hamaguchi, Roszkowski & Steffen ’05]



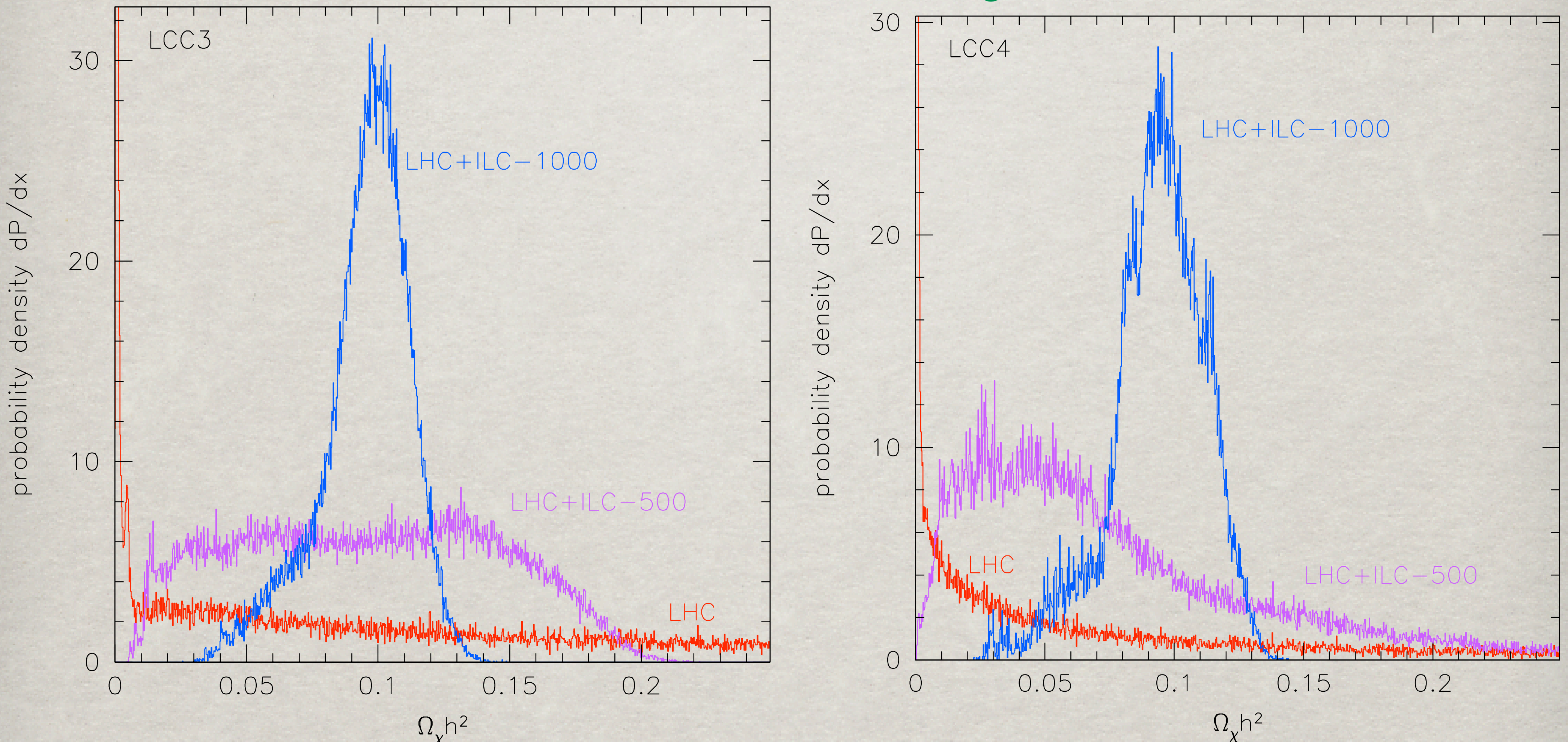
Both decays suffer from IR divergencies and we need to have a cut in the photon energy and in the cosine of the opening angle.

META-STABLE NEUTRAL (N)LSP

- It could be the DM itself... How to distinguish it ???
- If it is a neutralino probably need to reconstruct the energy density and compare to the DM one
- If it is NOT a neutralino, perhaps easier..., the sneutrino is excluded by DM direct detection !
  But can we distinguish a sneutrino from a neutralino at the LHC ???

Not easy for neutralino NLSP need to measure $\Omega_{DM}h^2$

Baltz, Battaglia, Peskin & Wizanski '06



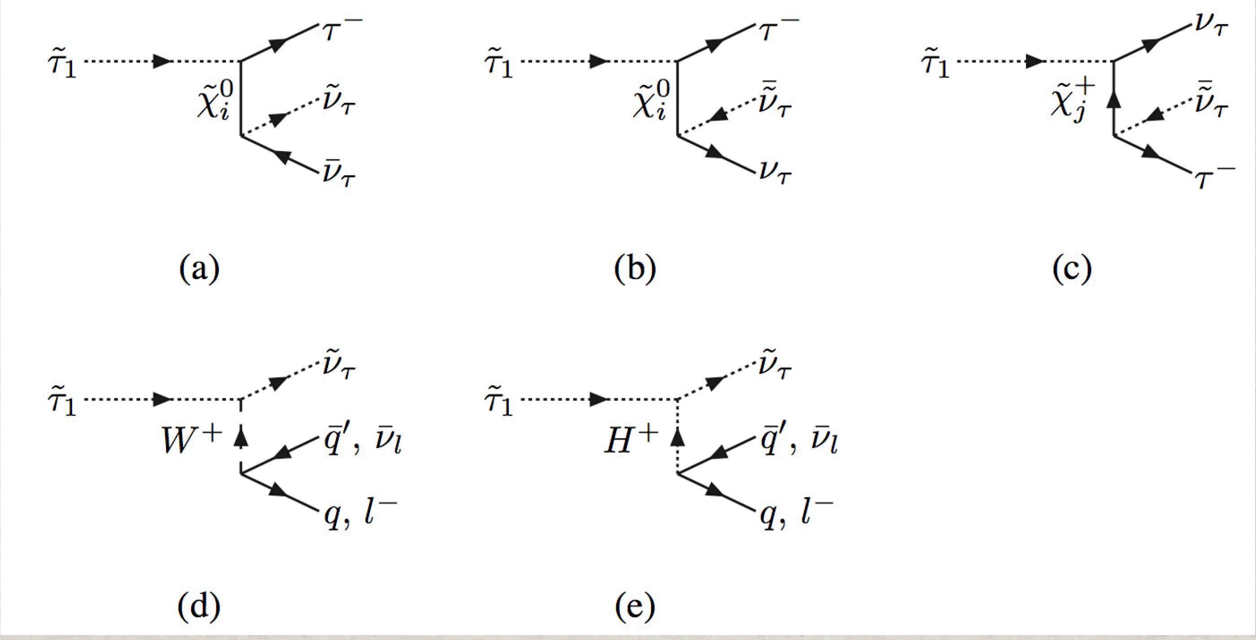
Pretty difficult by LHC alone in coannihilation/resonance case; still possible perhaps to improve when data are coming...

Neutralino vs sneutrino:

Sneutrino NLSP at colliders

[LC & Kraml 07]

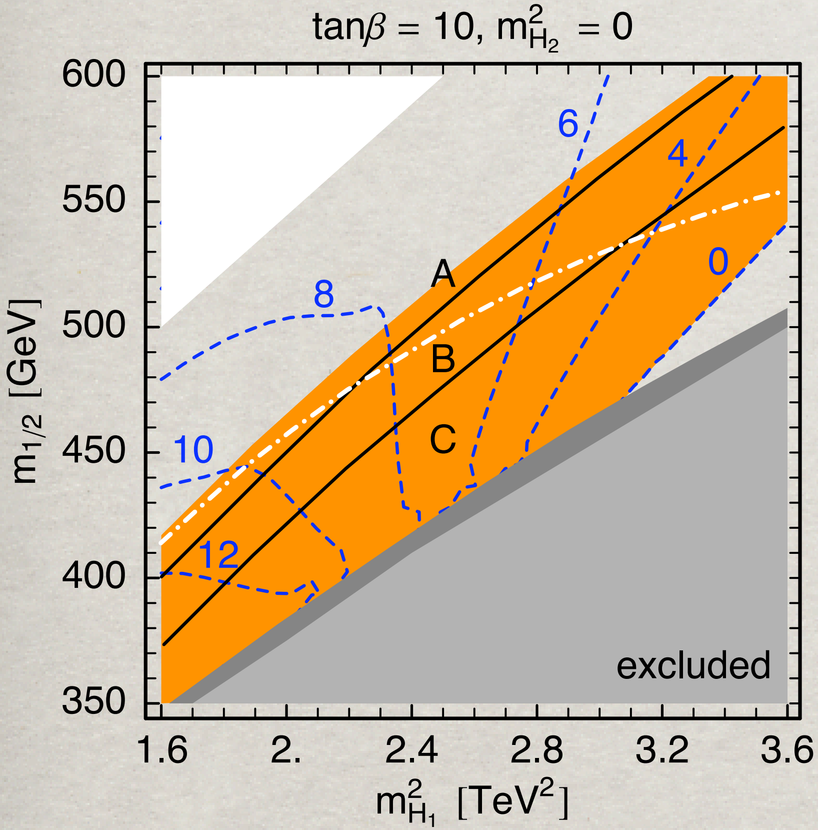
In general it is very difficult to identify if the missing neutral particle is a neutralino or a sneutrino..., but for gaugino mediation there is also another smoking gun: the sleptons are nearly degenerate and if the neutralino is heavier than the stau, the last decay of the chain is a three-body decay with (mostly) an off-shell W and produces soft leptons.



Unfortunately the decay time is too short to give a displaced vertex...: $\Gamma_{\tilde{\tau}}^{-1} \sim 10^{-17}$s

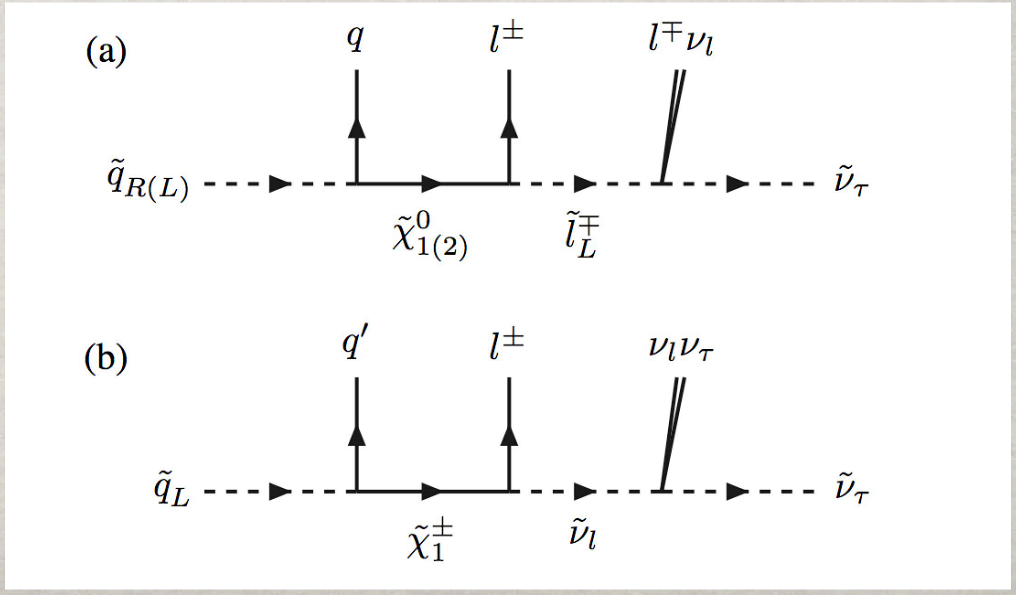
How to measure sneutrino NLSP in gaugino mediation

[LC & S. Kraml 07]



Very strong degeneracy in the spectrum between $\tilde{\nu}, \tilde{\tau}, \tilde{e}, \tilde{\chi}^0$

- NNLSP decays via 3-body
- Different decay chains
- Many soft leptons produced



ILC could allow also to study chargino decay and ISR in $e^- e^+ \to \tilde{\nu}\tilde{\nu}\gamma$

R-parity violation
&
indirect DM detection

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.

$$\tilde{G} \to \gamma\nu \qquad \tilde{G} \to \ell_L \bar{\ell}_L e_R \quad \tilde{G} \to \ell_L \bar{q}_L d_R$$

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

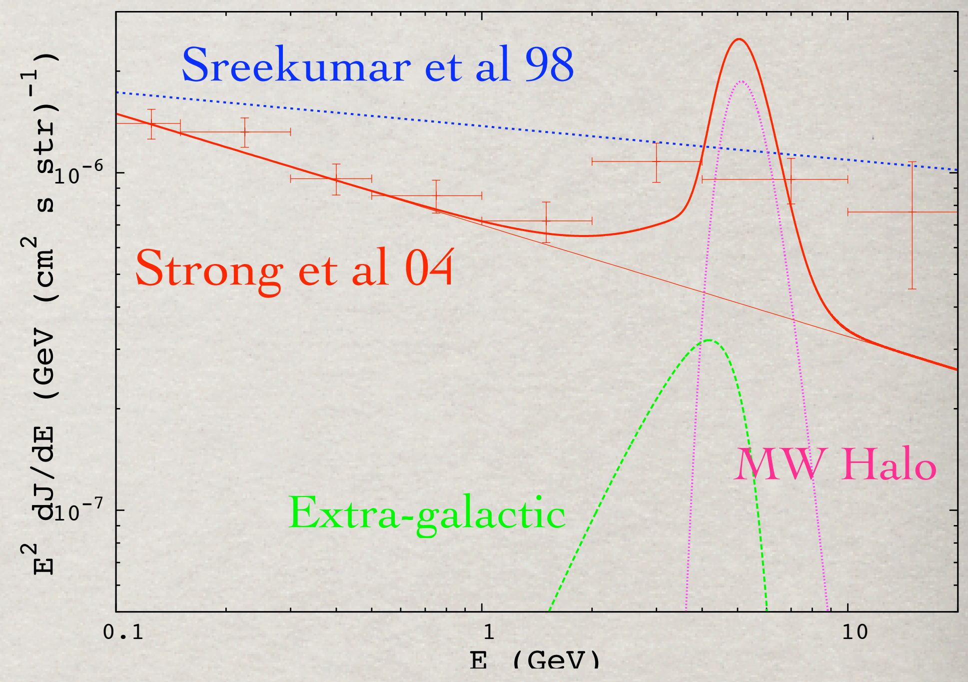
$$\tau_{\tilde{G}} = 4 \times 10^{27} s \left(\frac{U_{\tilde{\gamma}\nu}}{10^{-8}} \right)^2 \left(\frac{m_{\tilde{G}}}{10\mathrm{GeV}} \right)^{-3}$$

Recently [Lola, Osland & Raklev 07] computed also the 2-body one-loop decay and found it also important with respect to the 3-body one for most parameter space.

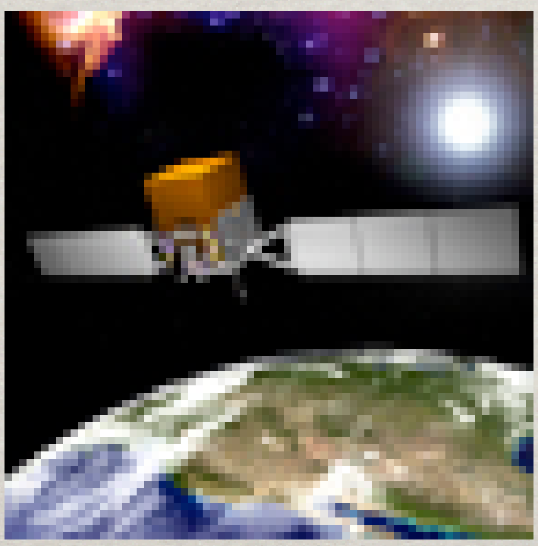
How to see the gravitino

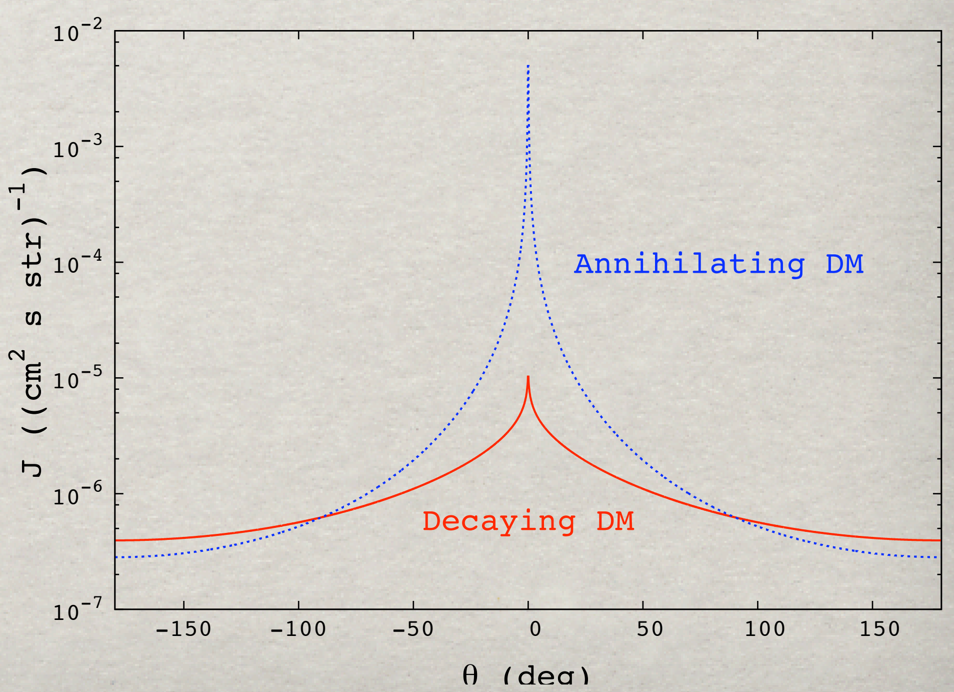
For bilinear R-parity breaking, the gravitino decays into photon and neutrino with flux:

$$J \sim 10^{-7} (\mathrm{cm}^2 \mathrm{s\ str})^{-1} \left(\frac{\tau_{DM}}{10^{27} s}\right)^{-1} \left(\frac{m_{DM}}{10\mathrm{GeV}}\right)^{-1}$$



Look at the photons with GLAST





Bertone, Buchmuller, LC, Ibarra ‘07

How to see the gravitino

For bilinear R-parity breaking,
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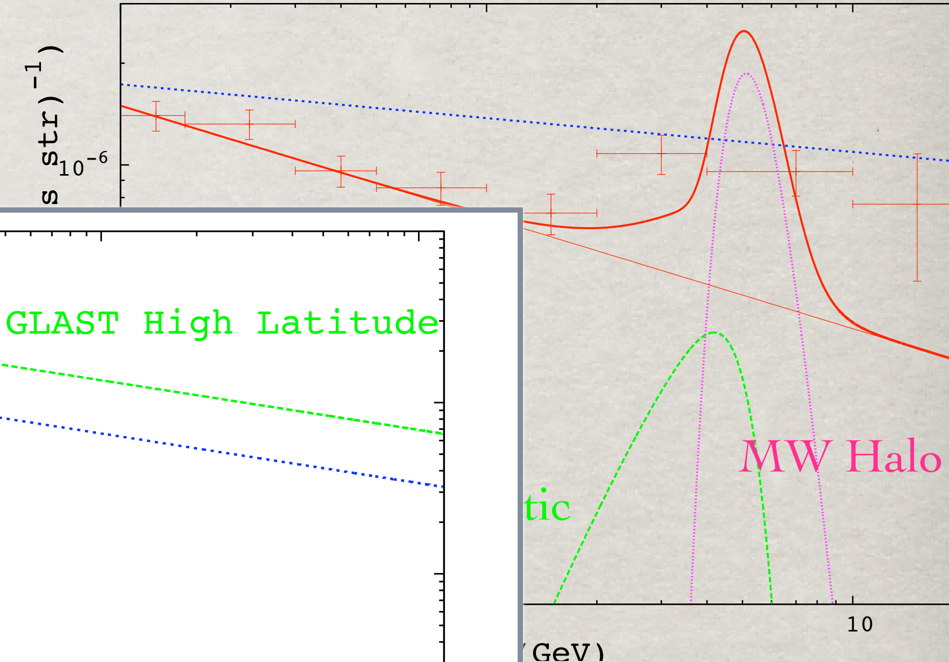

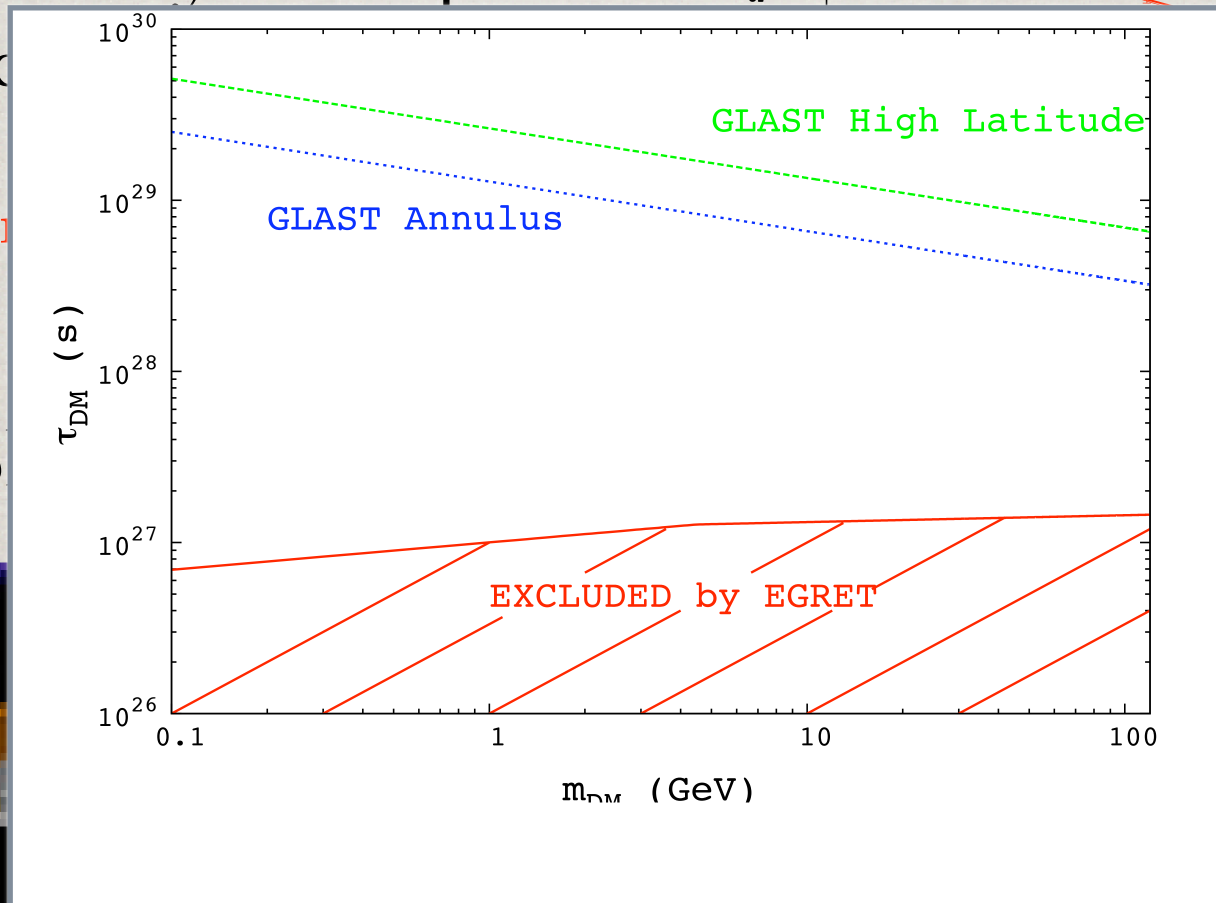

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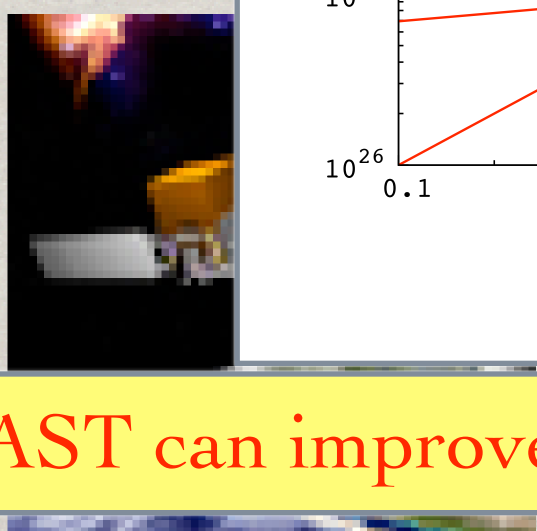

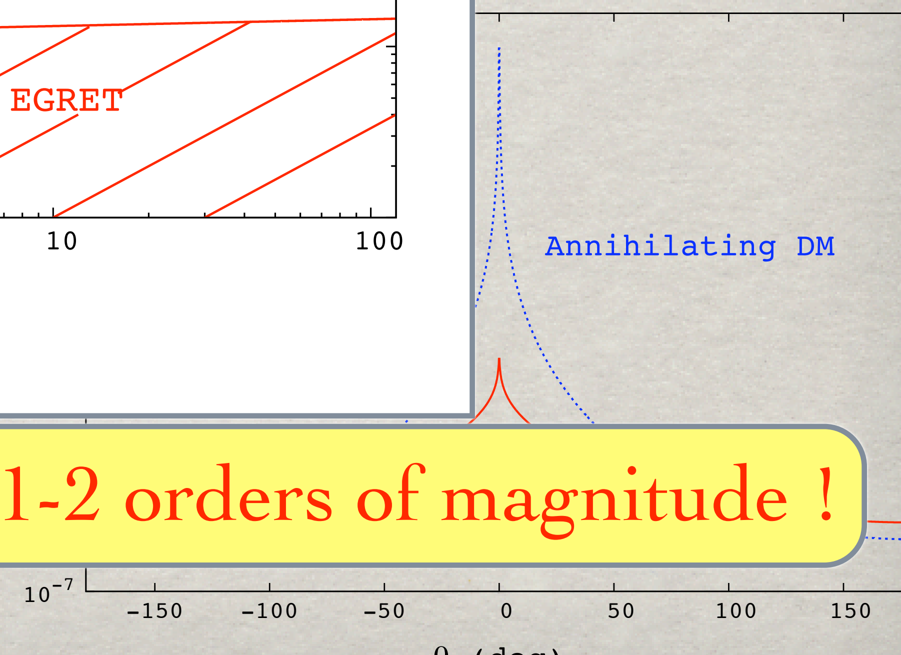

GLAST can improve the limit by 1-2 orders of magnitude !

[Bertone,Buchmüller,LC &Ibarra]

Outlook

- Gravitino DM is pretty natural if such particle is the LSP; probably substantial thermal production is needed to obtain DM abundance & avoid BBN bounds for the gravitino, i.e. $T_R \sim 10^{10}\mathrm{GeV}$

- If the gravitino is Dark Matter, clear signals are expected at colliders, different than for neutralino Dark Matter, both if the NLSP is charged or neutral...

- R-parity is not necessary to have gravitino DM. If R-parity is not too weakly broken, we could also see soon photons from DM decay.

- There is a good chance that we will know soon !

  A very exciting time ahead !