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GRAVITINO DARK MATTER

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OUTLINE

- Introduction: Dark Matter properties
  Why gravitino DM ?
- Cosmology of gravitino DM:
  - production mechanisms
  - cold or warm ?
  - BBN constraints on the NLSP
- Neutralino NLSPs
  reducing the number density...
- R-parity breaking and decaying DM
  - indirect detection signals
- Collider signatures
- Outlook

Introduction: DARK MATTER Properties

DARK MATTER EVIDENCE

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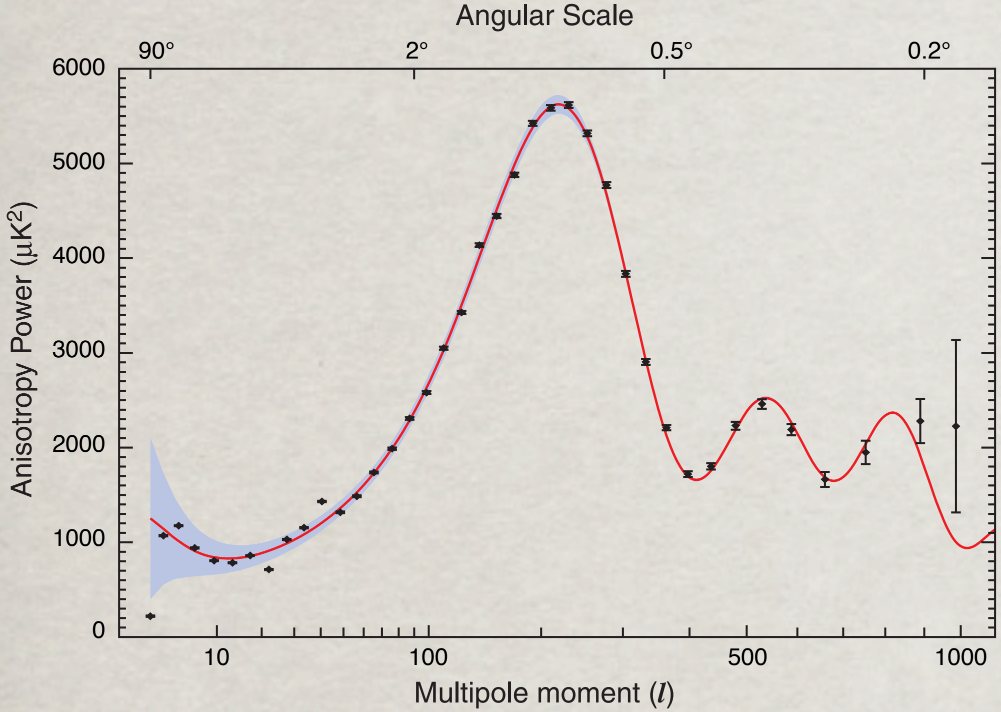
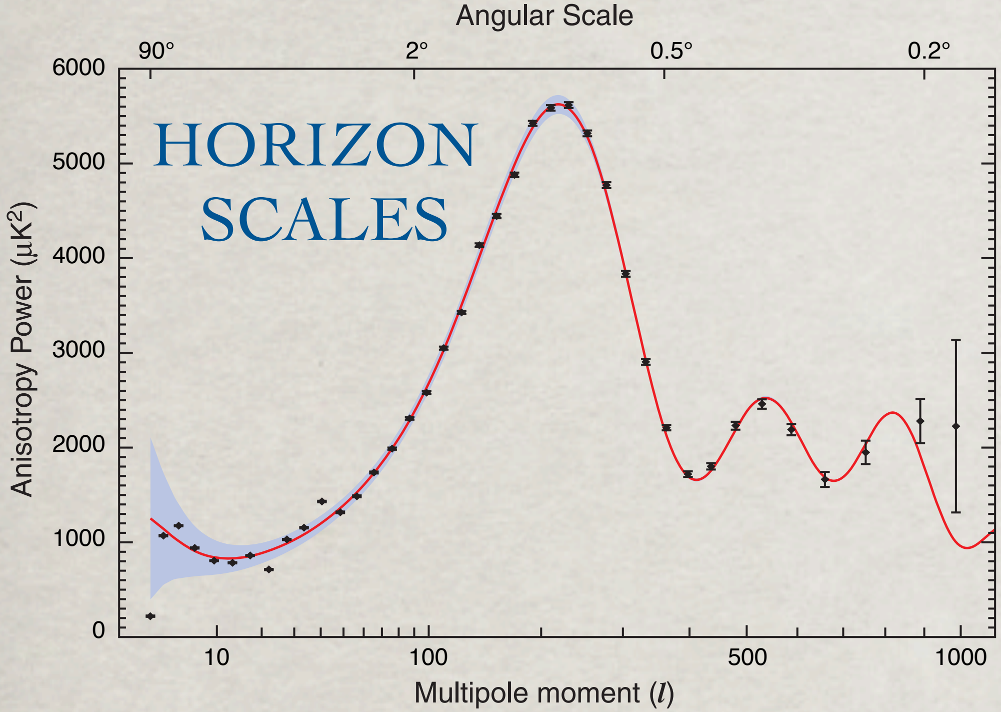


HORIZON SCALES:

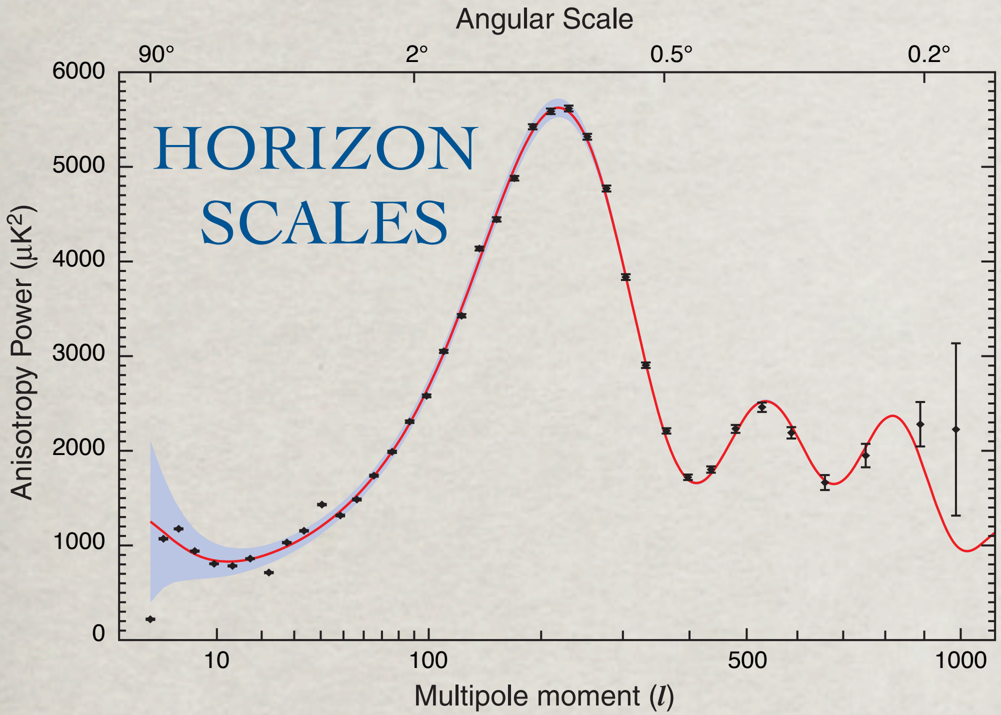
From the position and height of the CMB anisotropy acoustic oscillations peaks we can determine very precisely the curvature of the Universe and other background parameters.

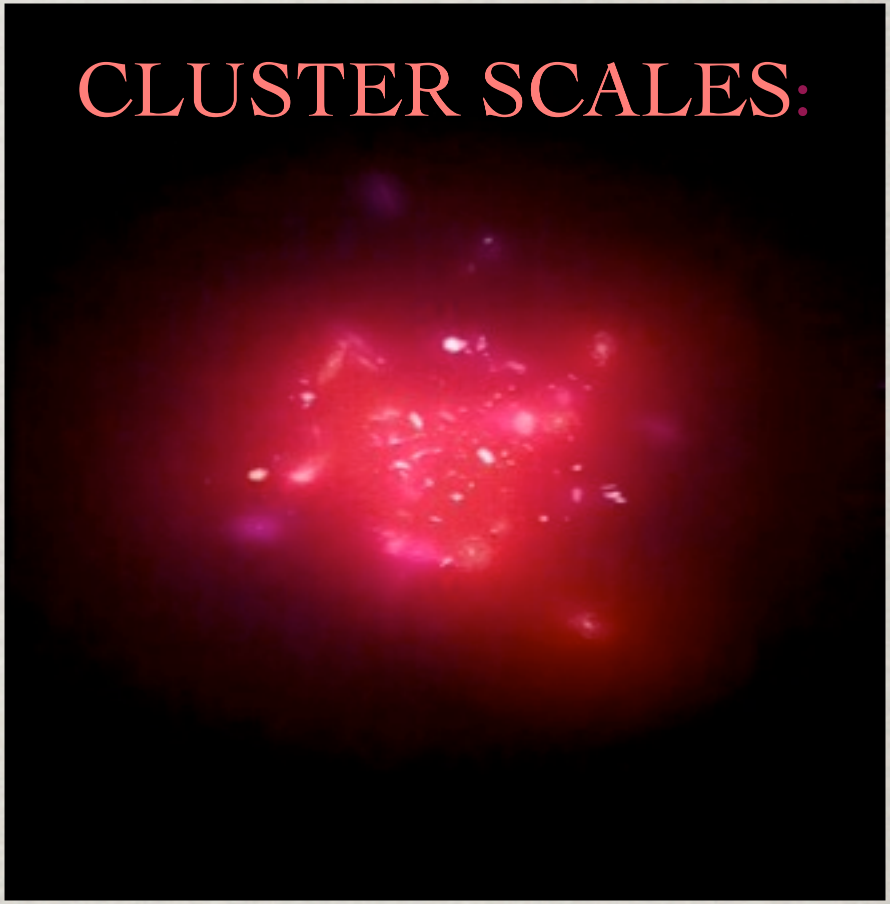
DARK MATTER EVIDENCE

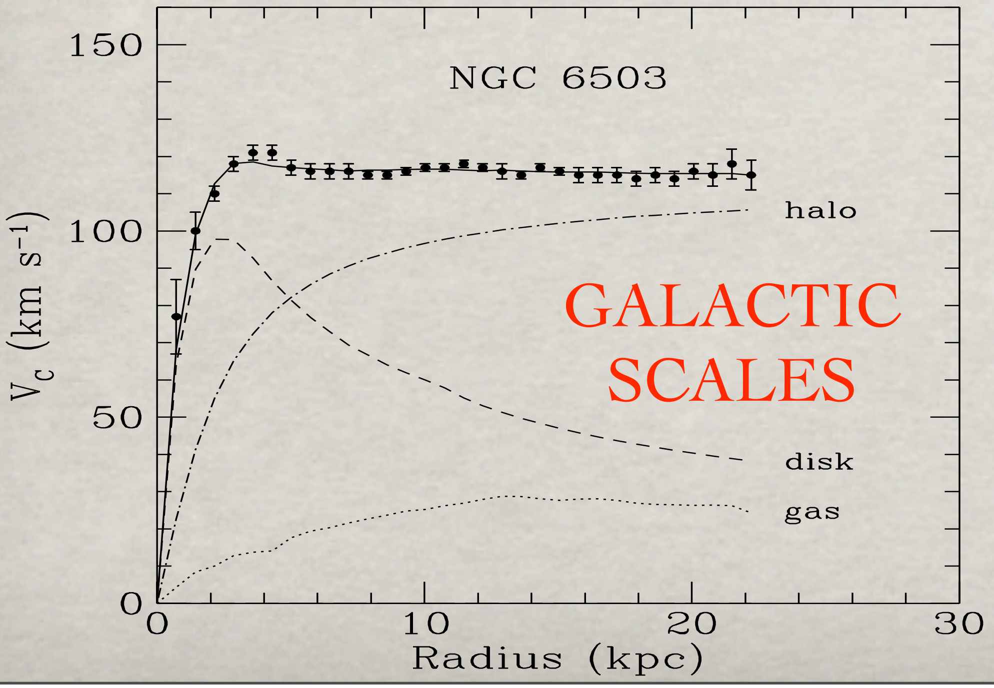


CLUSTER SCALES:

DARK MATTER EVIDENCE







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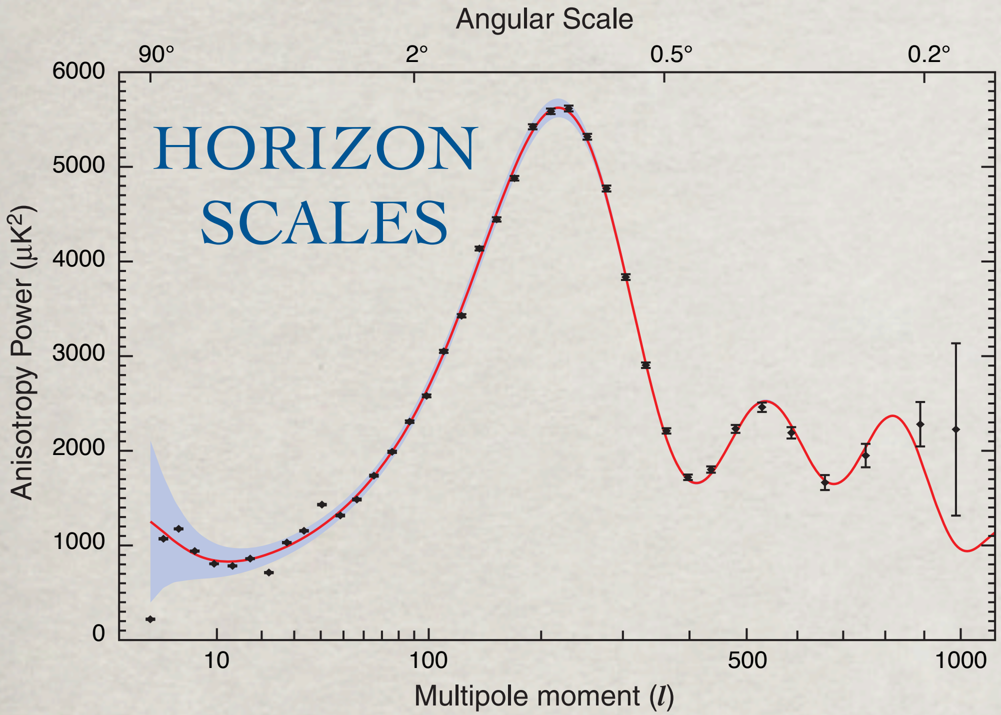
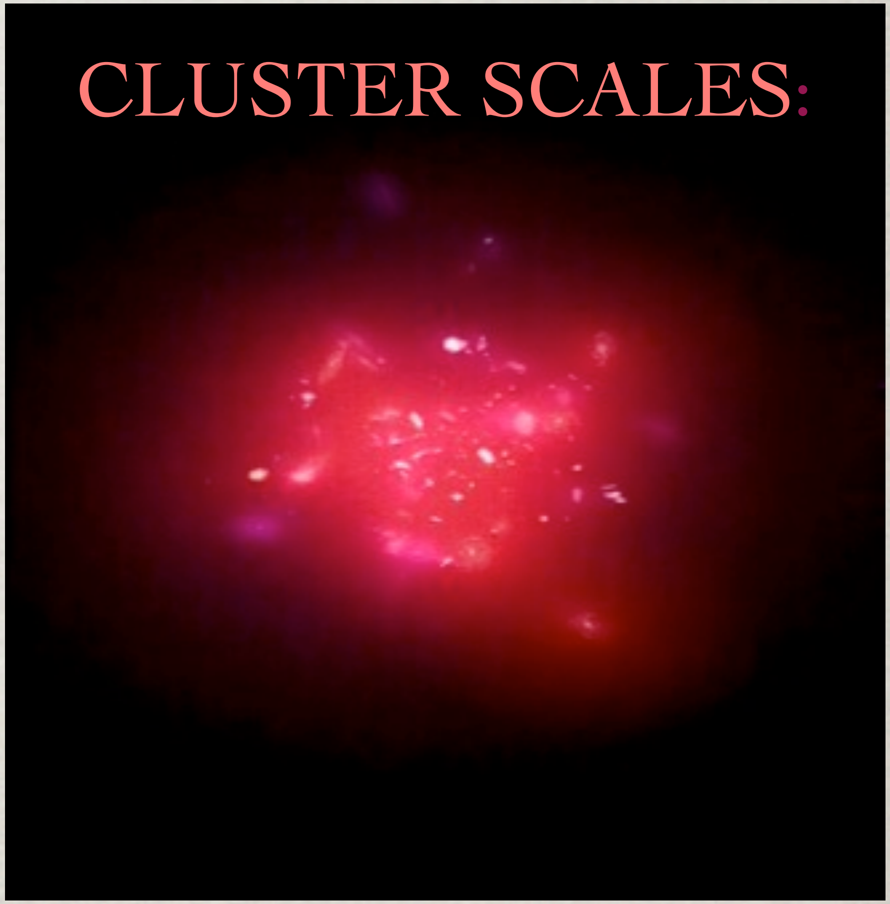
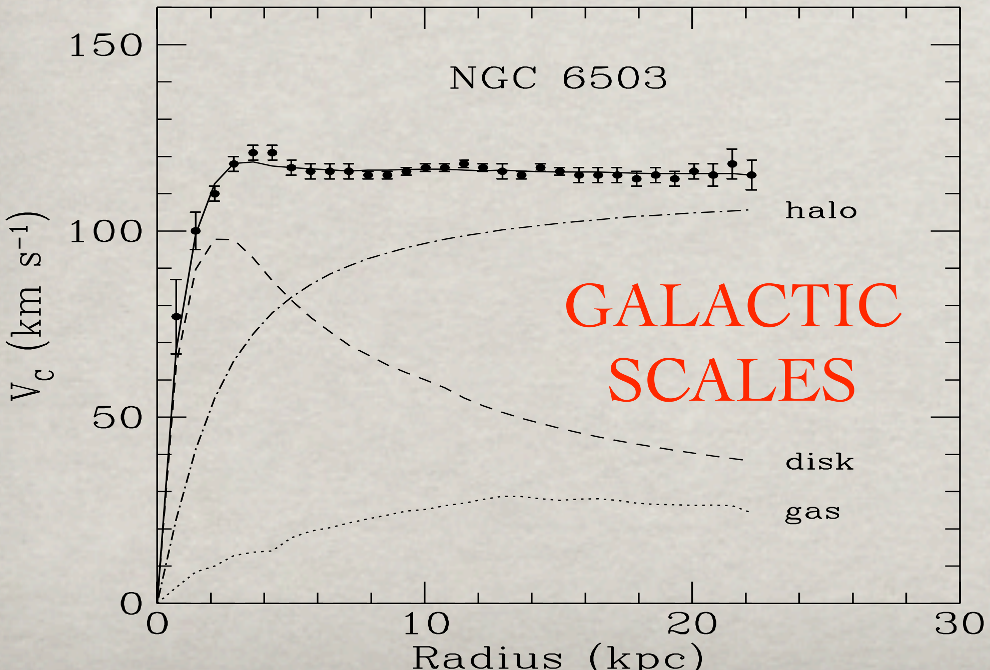




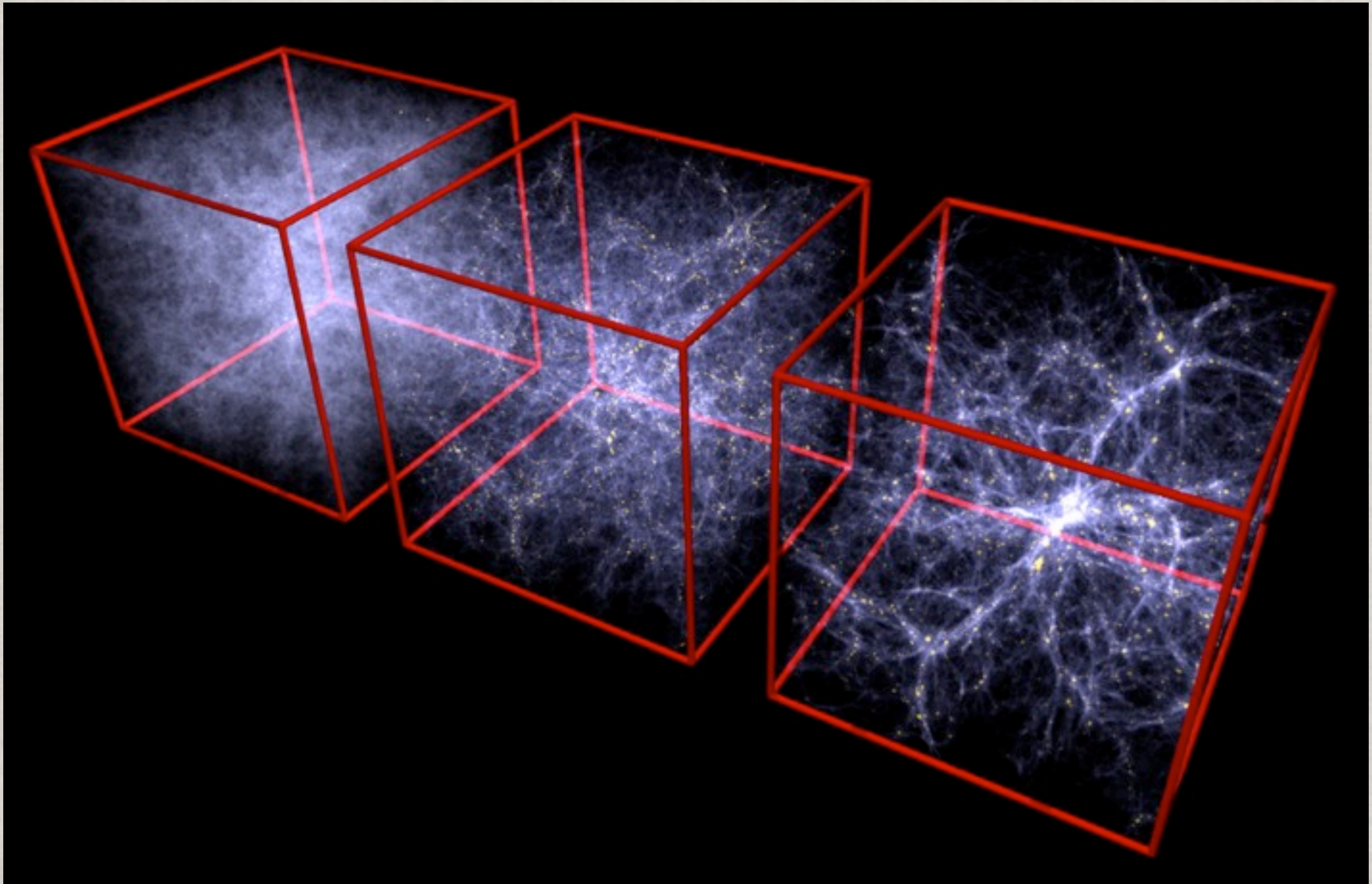


Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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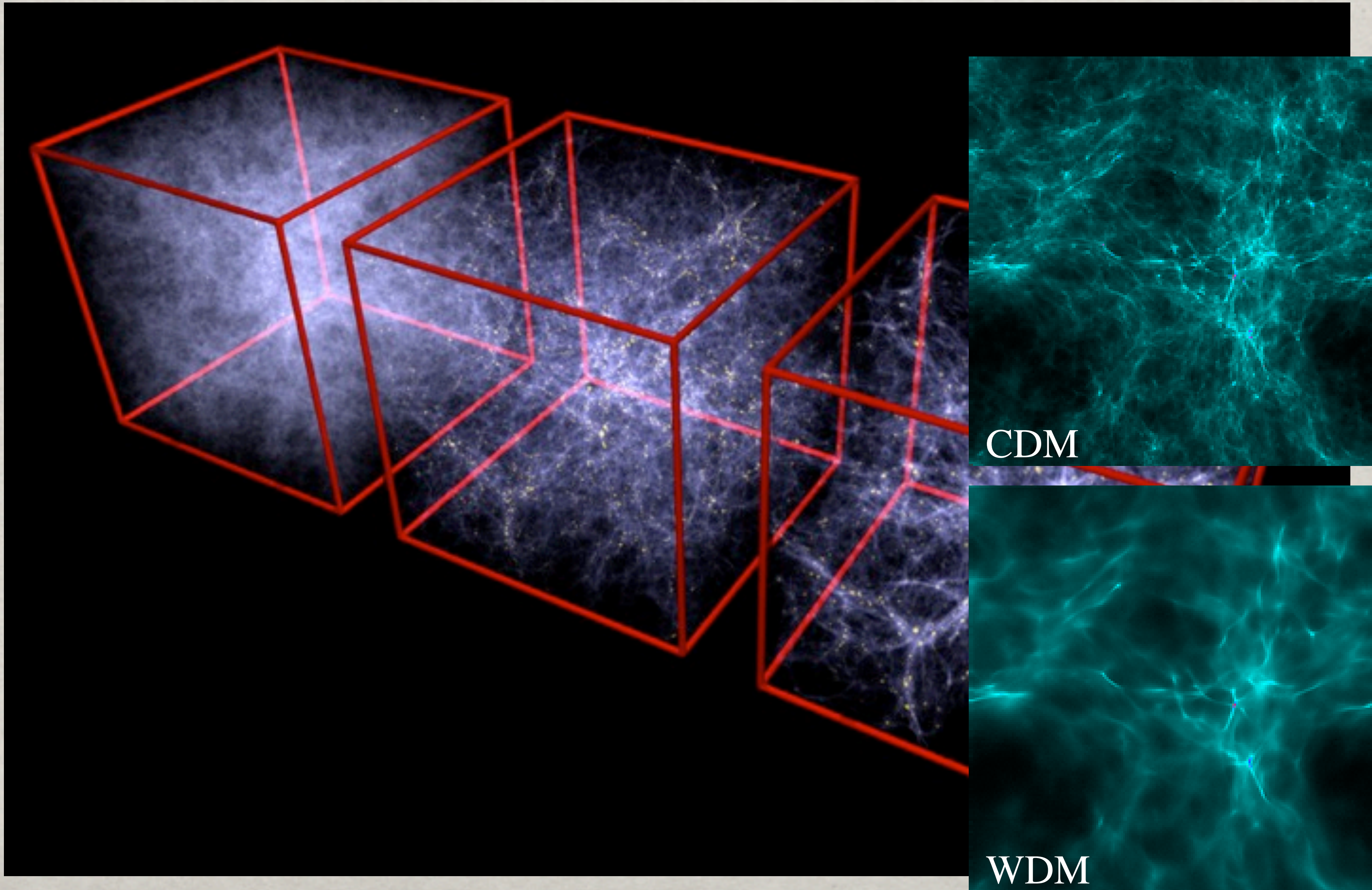
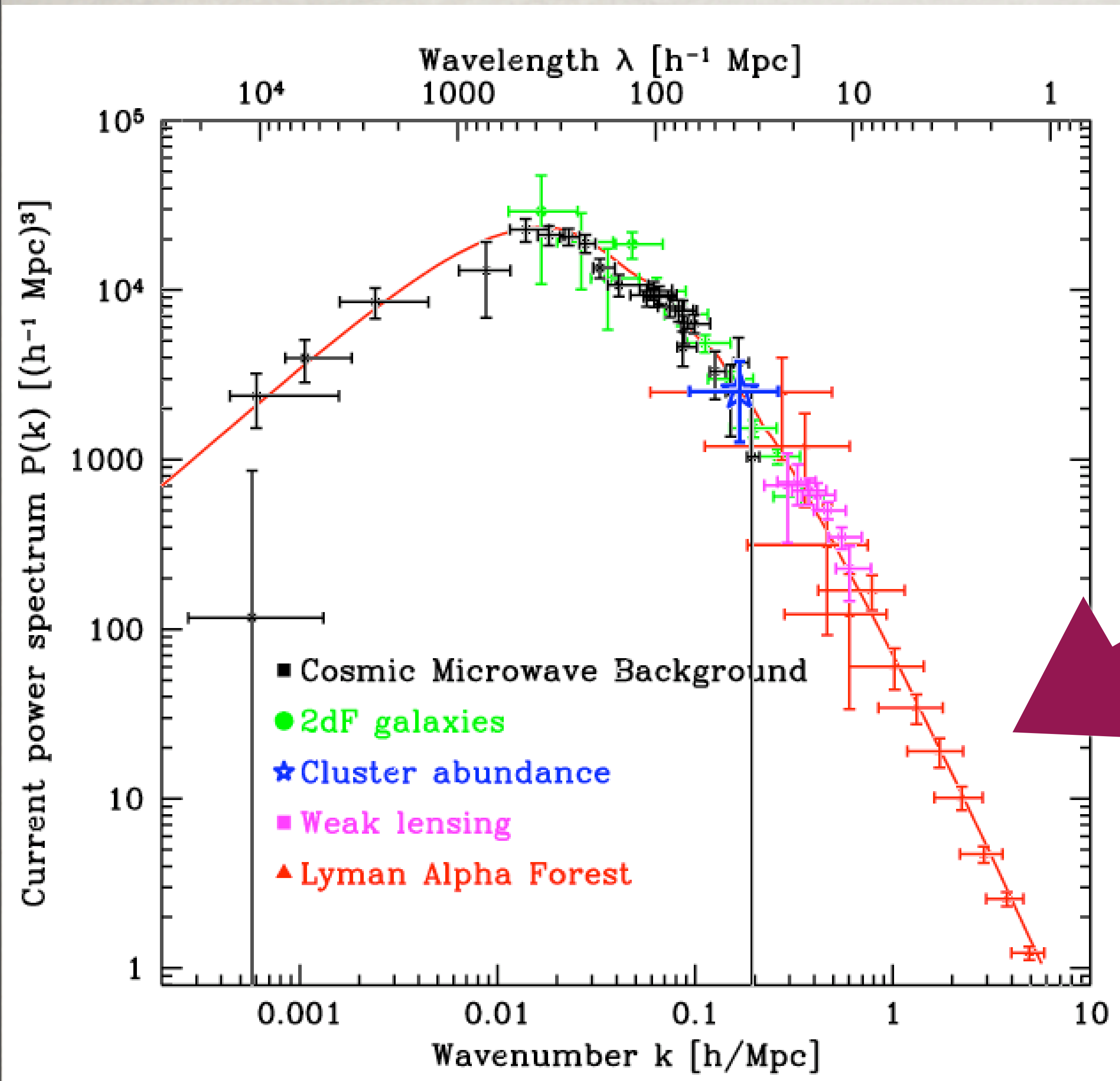


WDM & the Power spectrum



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

$$_{FS} \quad \mathrm{Mpc} \quad \frac{m_{WDM}}{1\mathrm{keV}}$$

Compare with the data:

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

[Viel et al. '07]

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral and decoupled from the primordial plasma !!!)

- It must have the right density profile to "fill in" the galaxy rotation curves.

- No pressure and negligible free-streaming velocity, it must cluster & cause structure formation.

↓

COLD DARK MATTER

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:

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

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

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

The gravitino gives us direct information on SUSY breaking

Cosmological constraints on gravitino DM

CAN THE GRAVITINO BE COLD DARK MATTER ?

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

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

PLASMA SCATTERINGS

$$\Omega_{3/2} h^2 \propto \frac{m_{1/2}^2}{m_{3/2}} T_R$$

NLSP DECAY OUT OF EQUILIBRIUM

$$\Omega_{3/2} h^2 \propto \frac{m_{3/2}}{m_{\rm NLSP}} \Omega_{\rm NLSP} h^2$$

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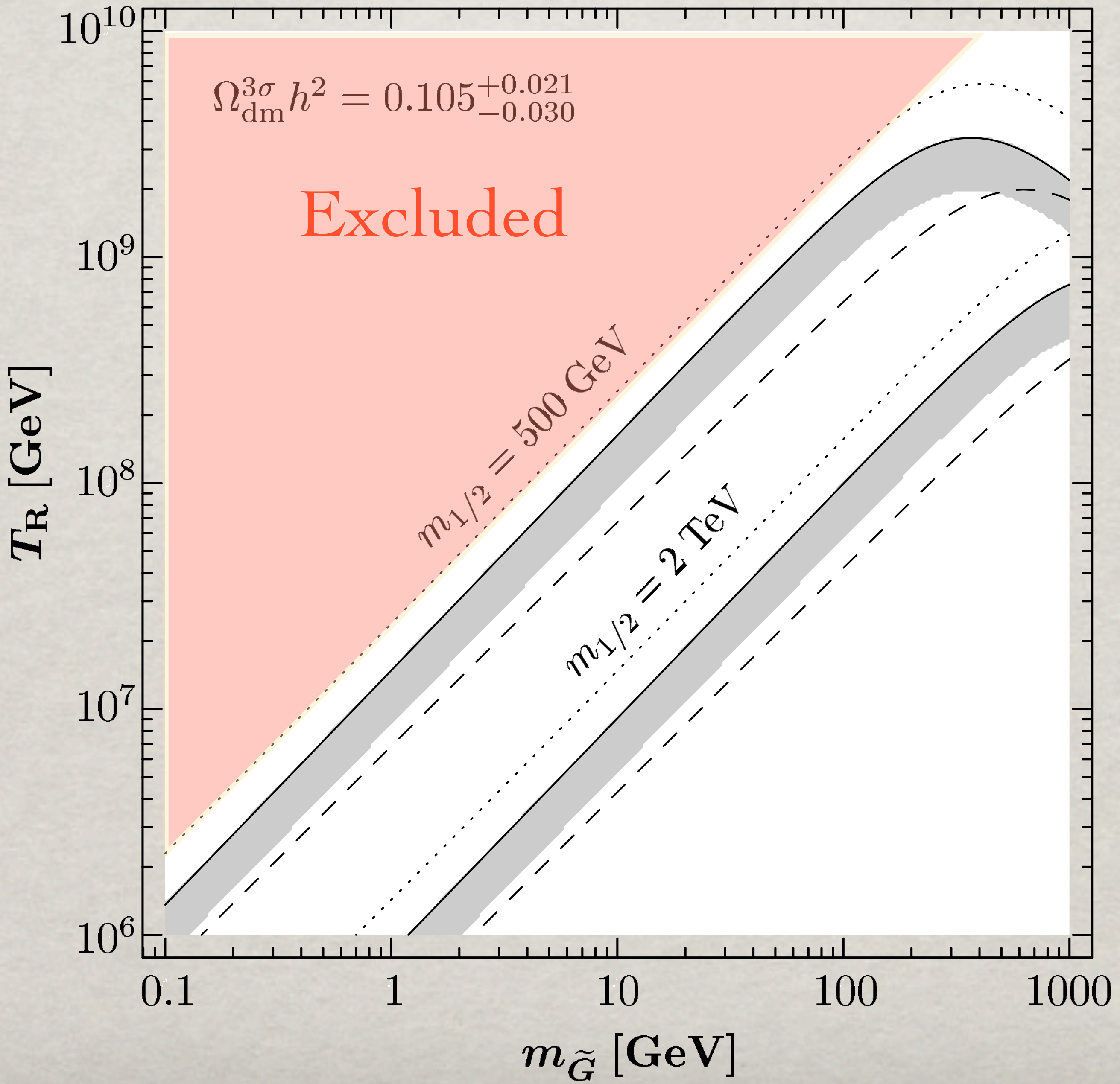
NLSP DECAY OUT OF EQUILIBRIUM

Ω ... $^2 \propto$ ... h^2

DANGER !!!
BBN at risk !

UPPER BOUND ON T_R

[Pradler & Steffen '06]



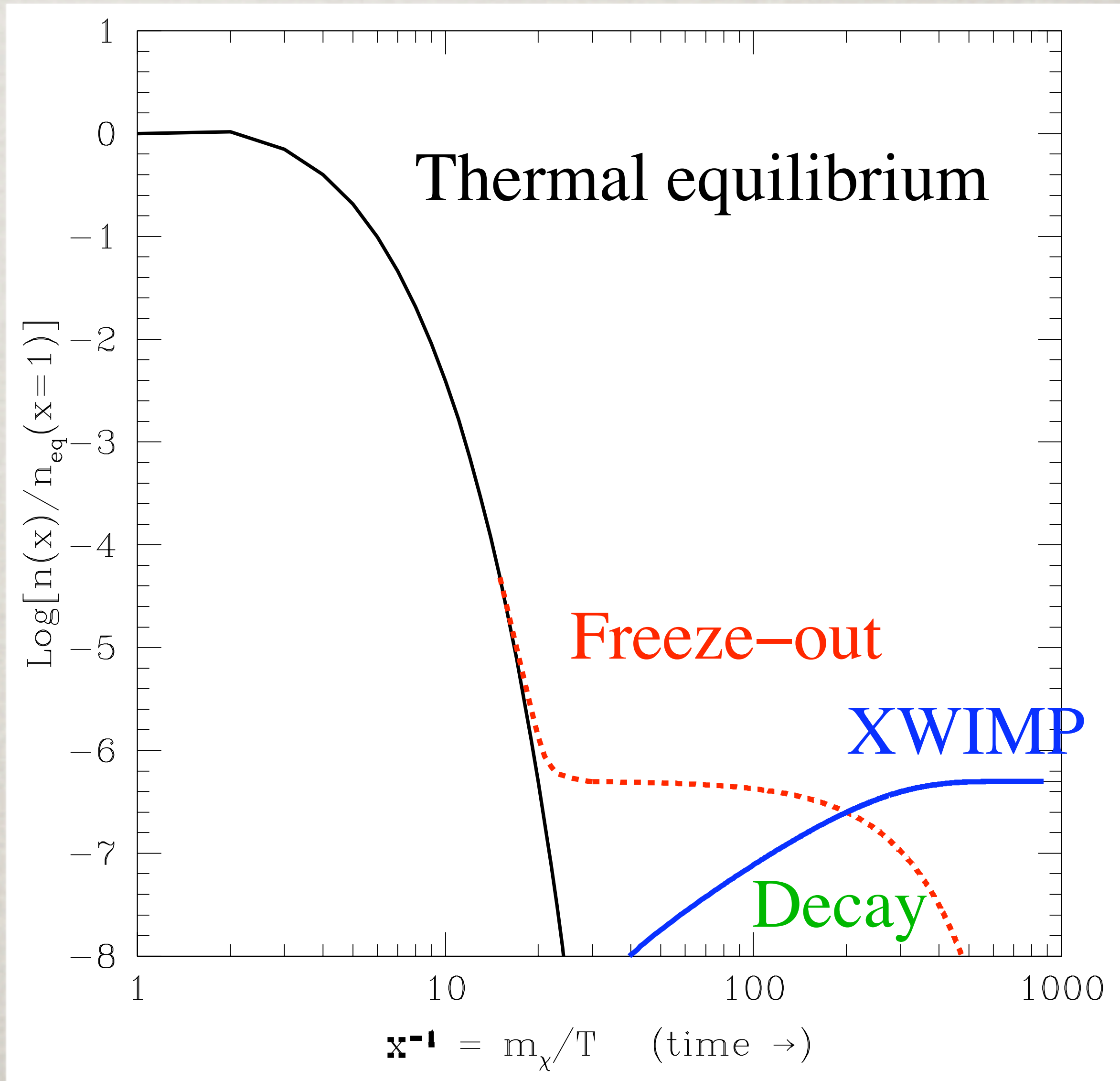
NLSP DECAY

[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 ???

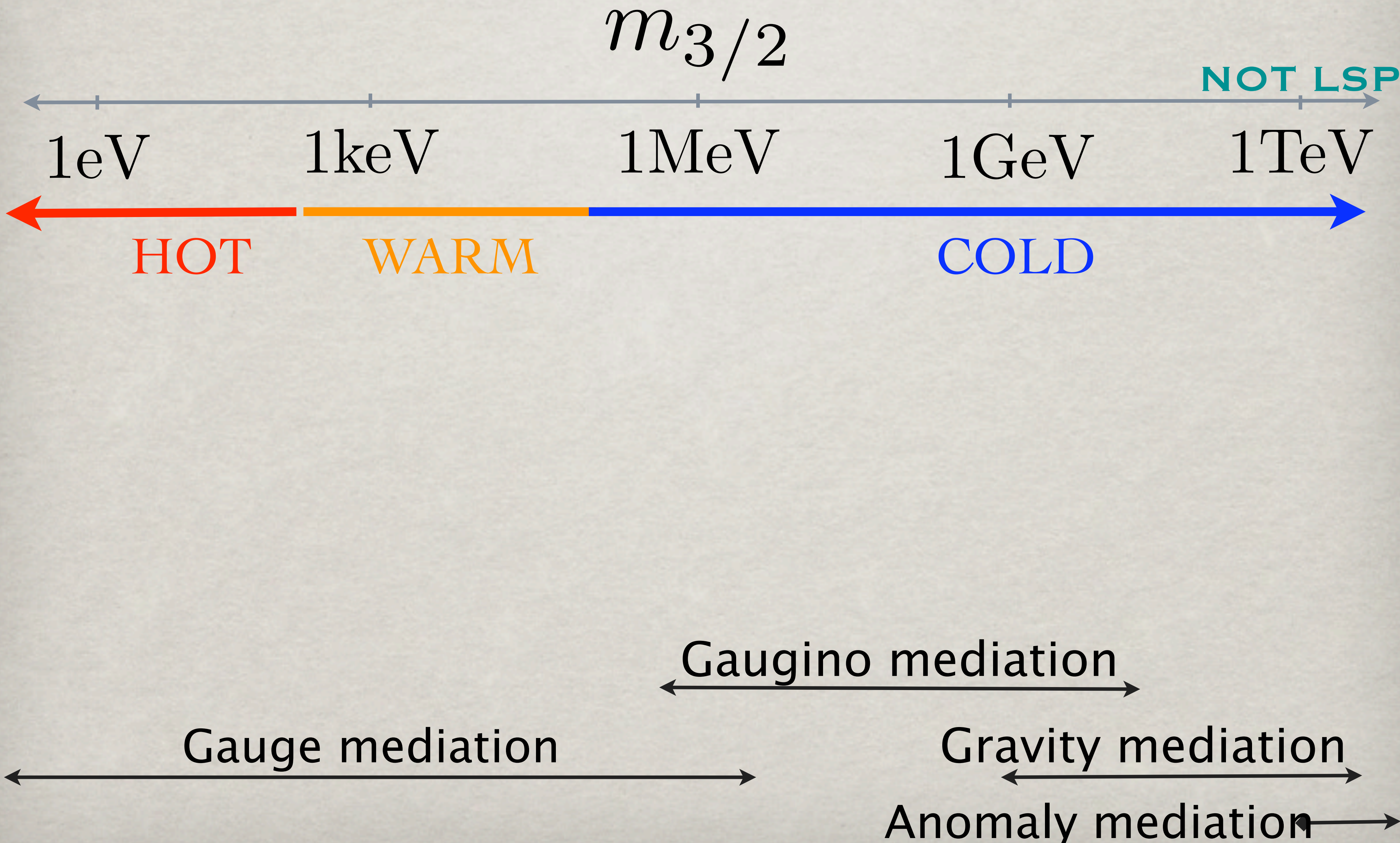
- Gravitinos in thermal equilibrium are HOT DM with mass in the 200-400 eV range;
- Gravitinos from thermal production can be WARM or COLD depending on their mass;
- Gravitinos from NLSP decay are not thermal, but they can behave as WARM DM: their velocity is

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

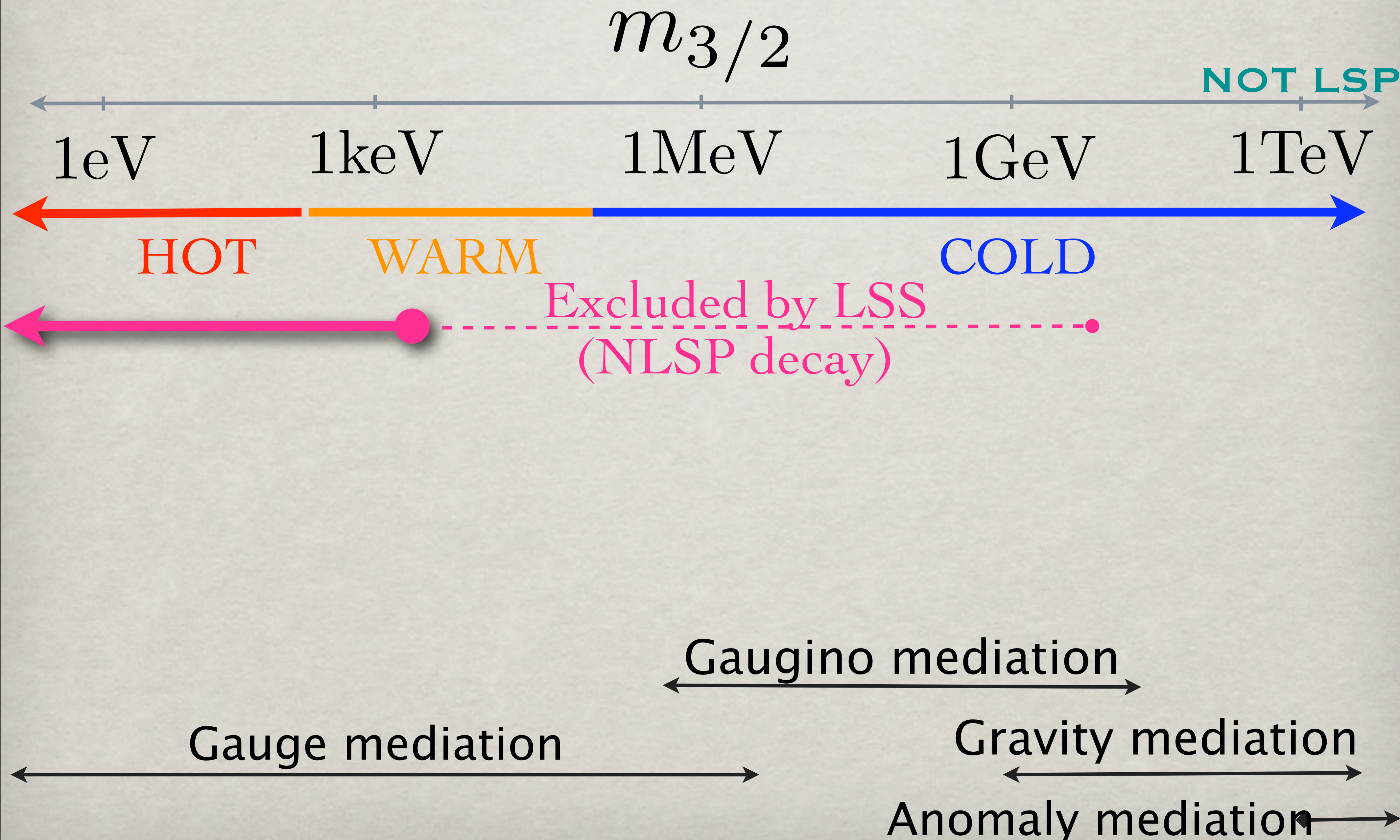
Need probably gravitino masses around 10 GeV or more...

[Jedamzik, Lemoine & Moultaka '05]

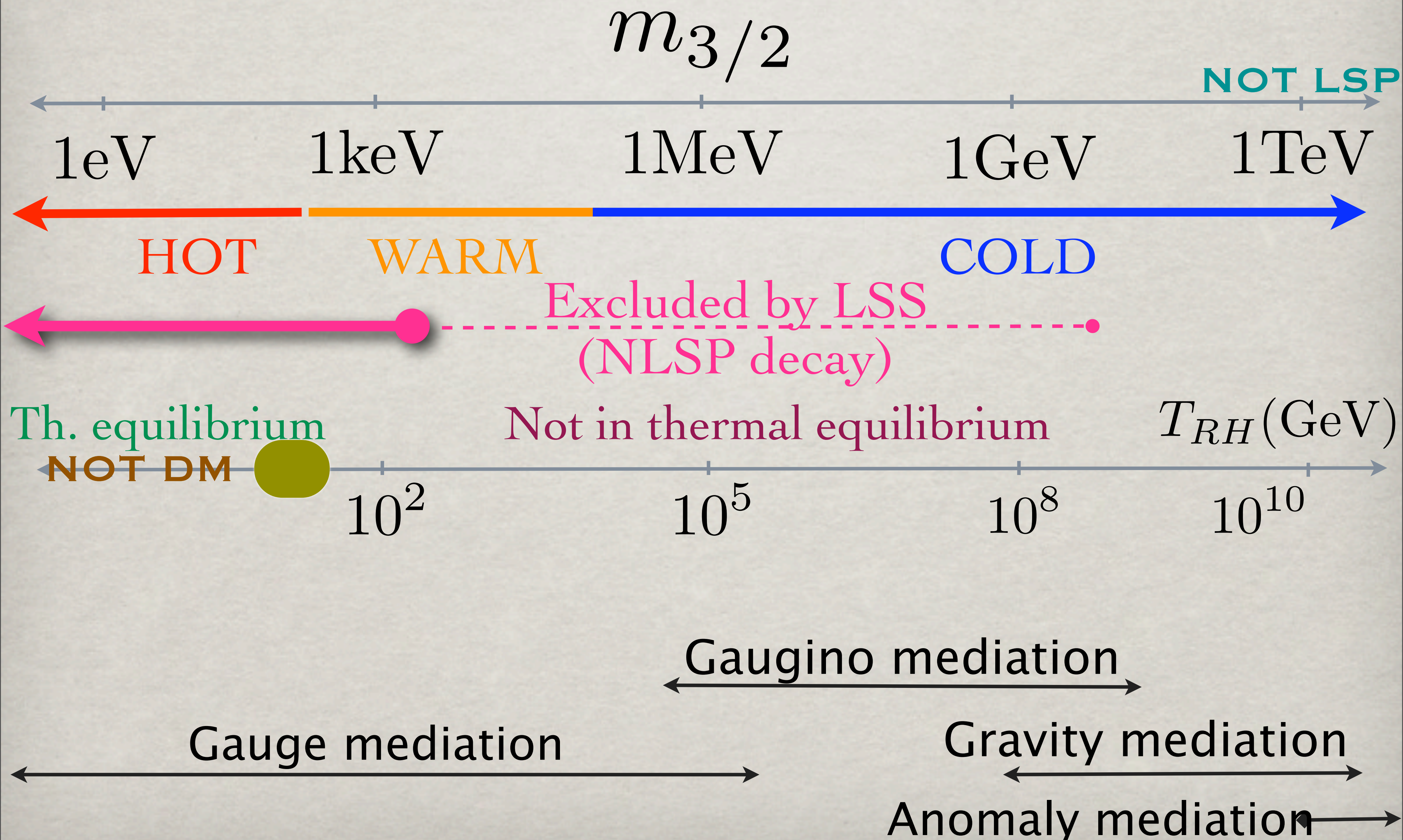
Gravitino DM summary



Gravitino DM summary



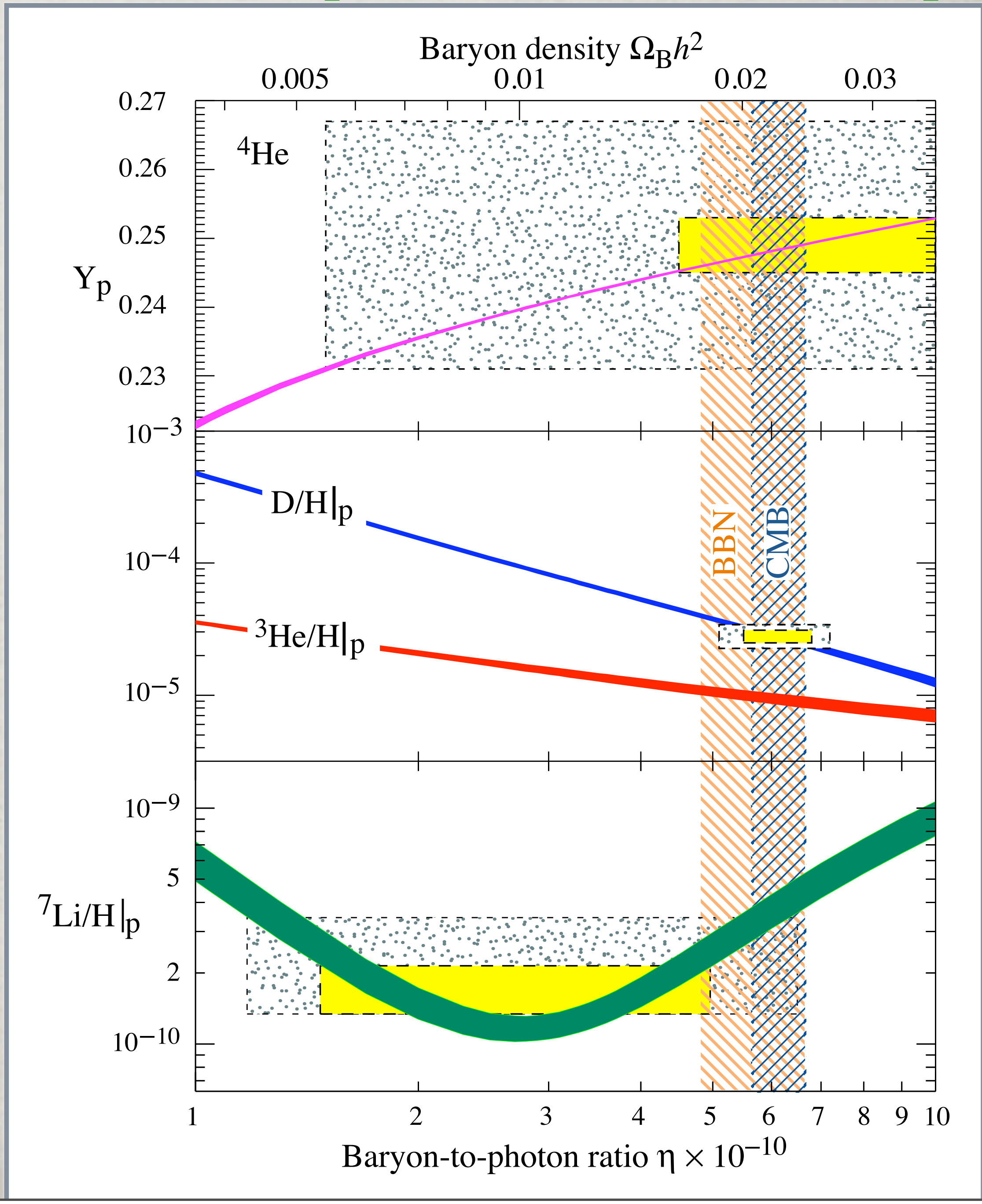
Gravitino DM summary



Big Bang Nucleosynthesis

[Fields & Sarkar PDG 07]

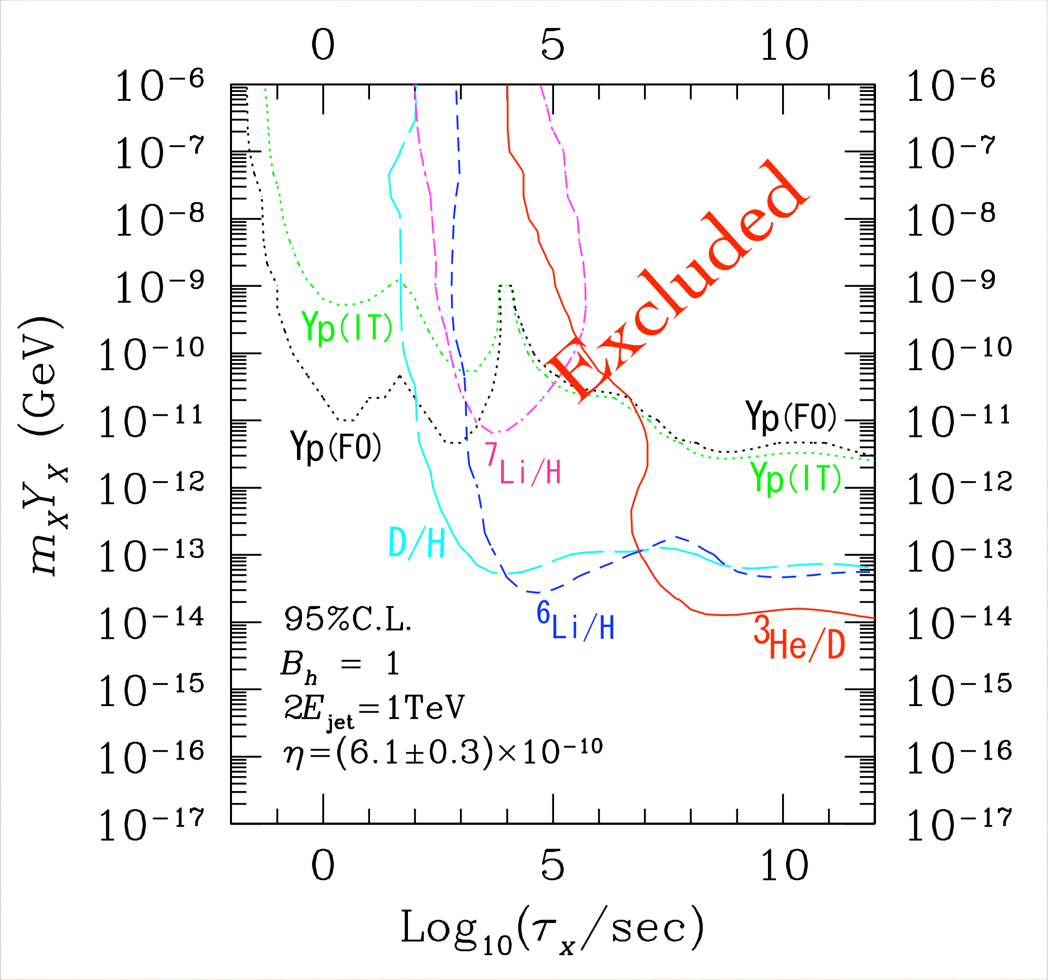
- Light elements abundances obtained as a function of a single parameter $\Omega_B h^2$
- Perfect agreement with WMAP determination
- Some trouble with Lithium 6/7



BBN bounds on NLSP decay

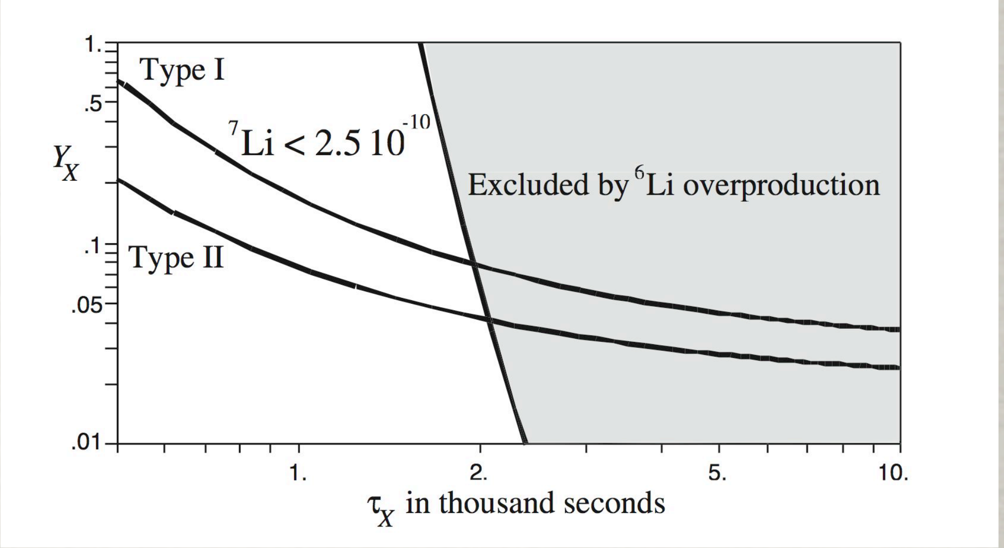
Neutral relics

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



Charged relics

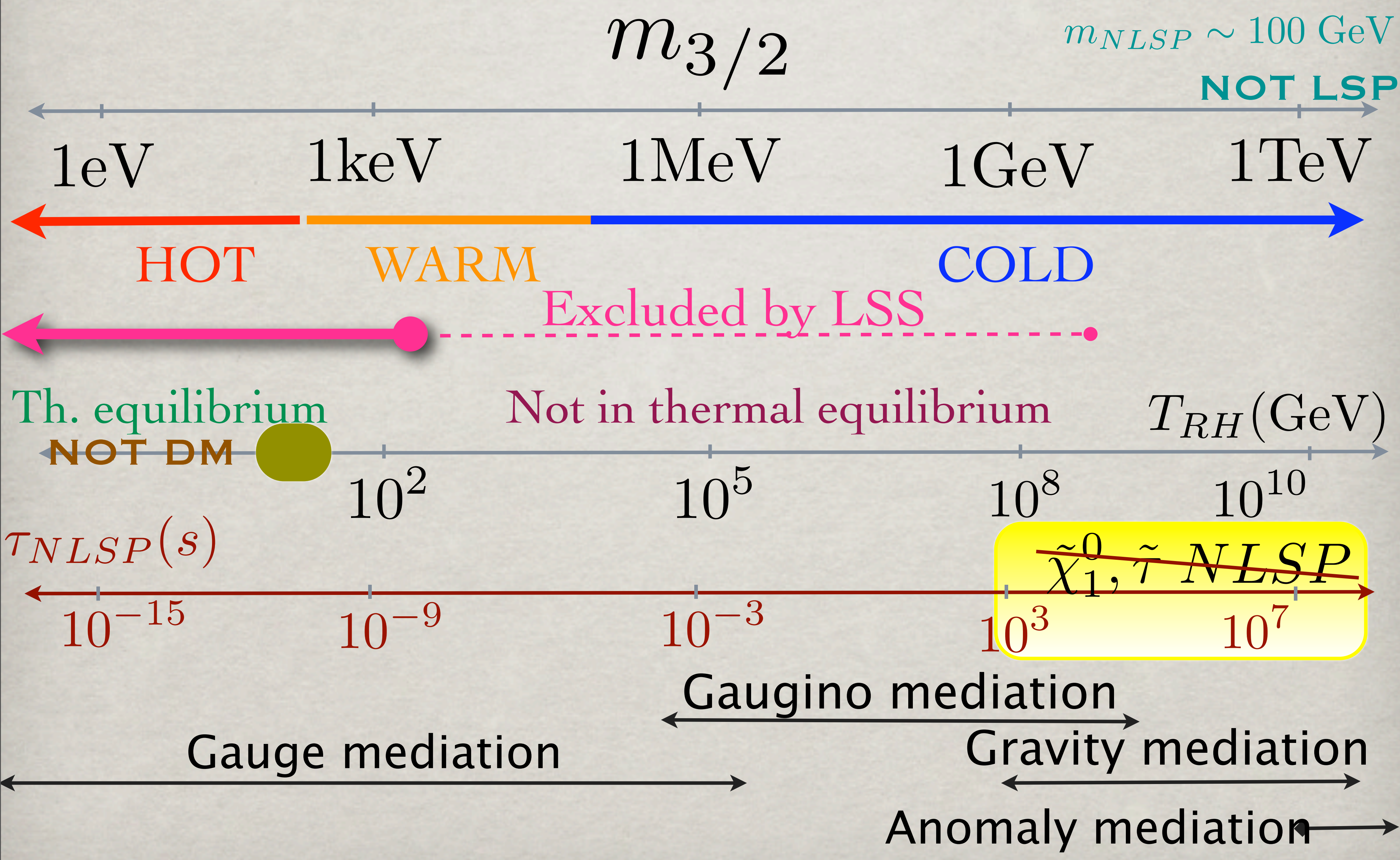
[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]



Need short lifetime & low abundance for NLSP

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

Gravitino DM summary II



Revisiting neutralino NLSP

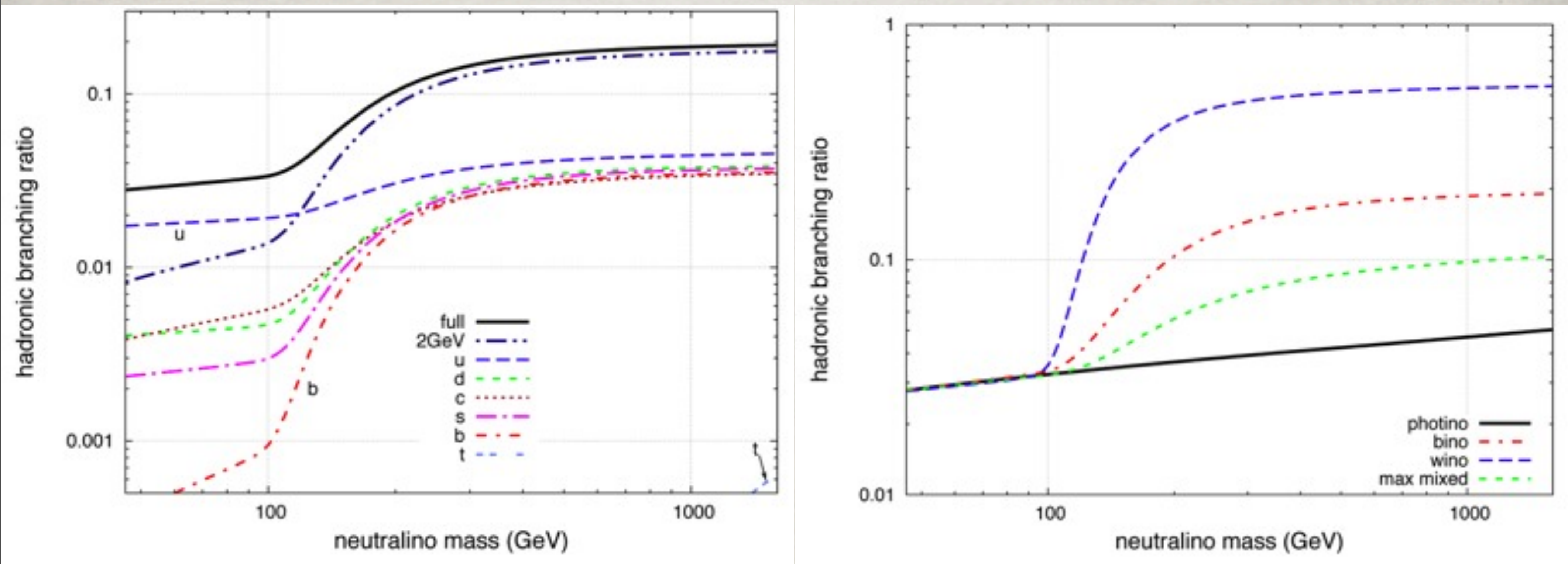
General neutralino NLSP

[LC, Hasenkamp, Roberts & Pokorski 09]

- In the CMSSM the neutralino NLSP is strongly constrained and requires a gravitino mass < 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]

General neutralino NLSP

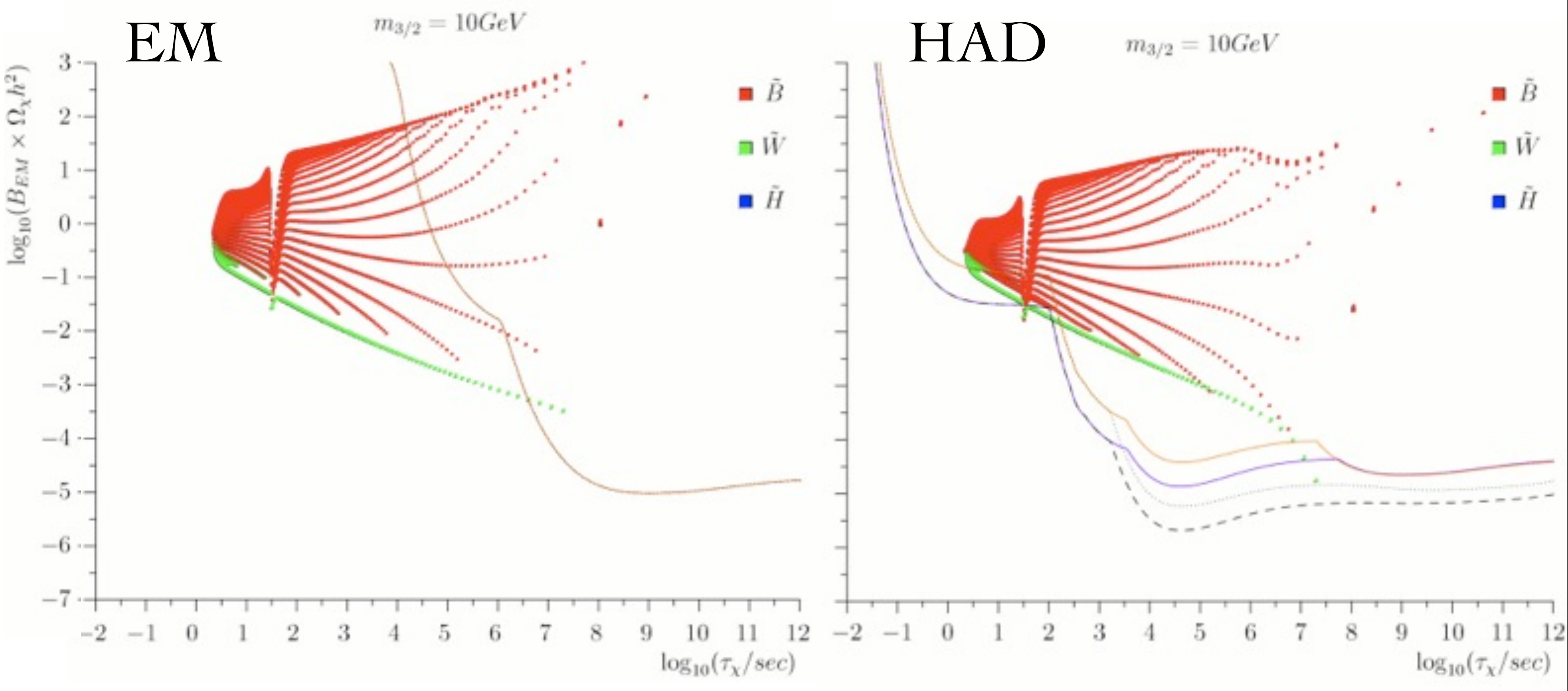
[LC, Hasenkamp, Roberts & Pokorski 09]



Reconsider the neutralino case in the most general terms:
Compute the hadronic branching ratio exactly, including the contribution of intermediate photon, Z, Higgs and squarks....
The hadronic BR is always larger than 0.03, but for large masses it can be suppressed by interference effects...

Bino-Wino neutralino

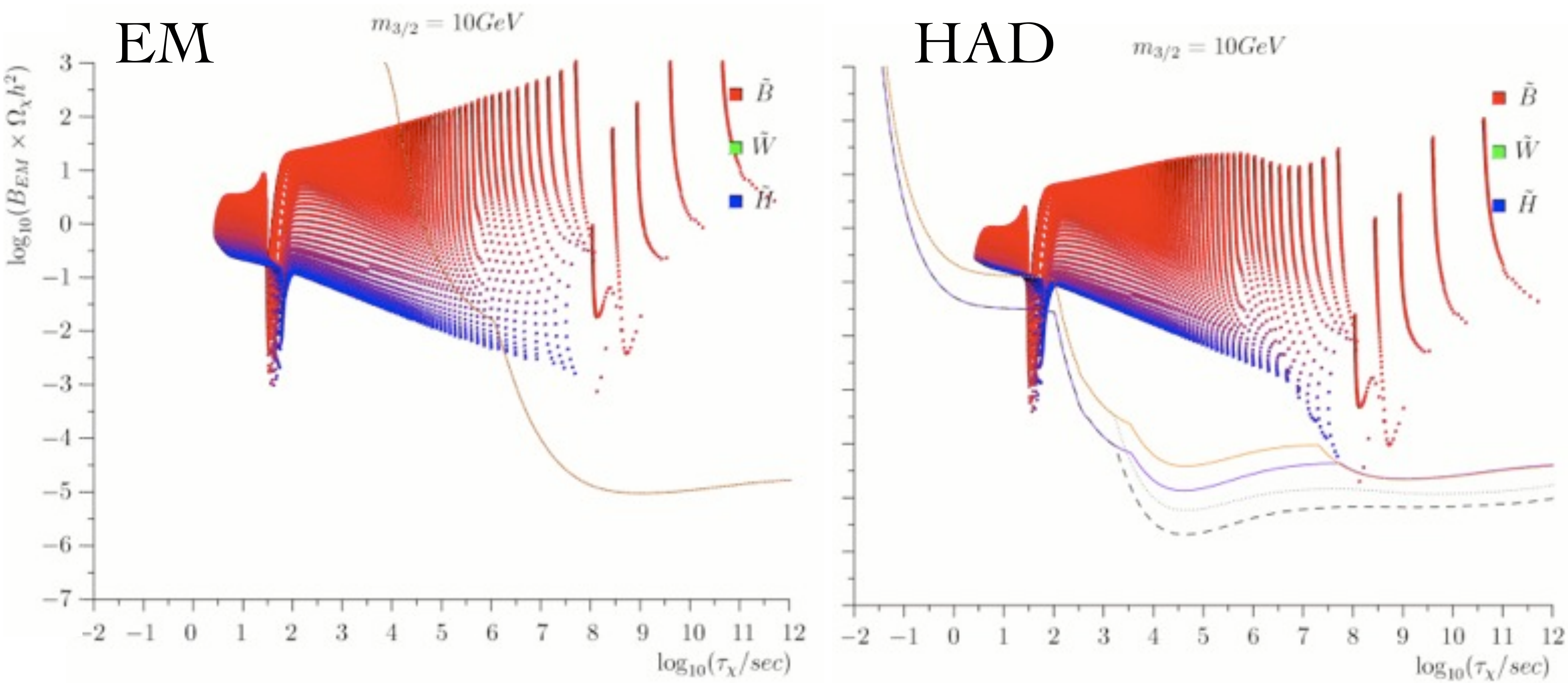
[LC, Hasenkamp, Roberts & Pokorski 09]



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]



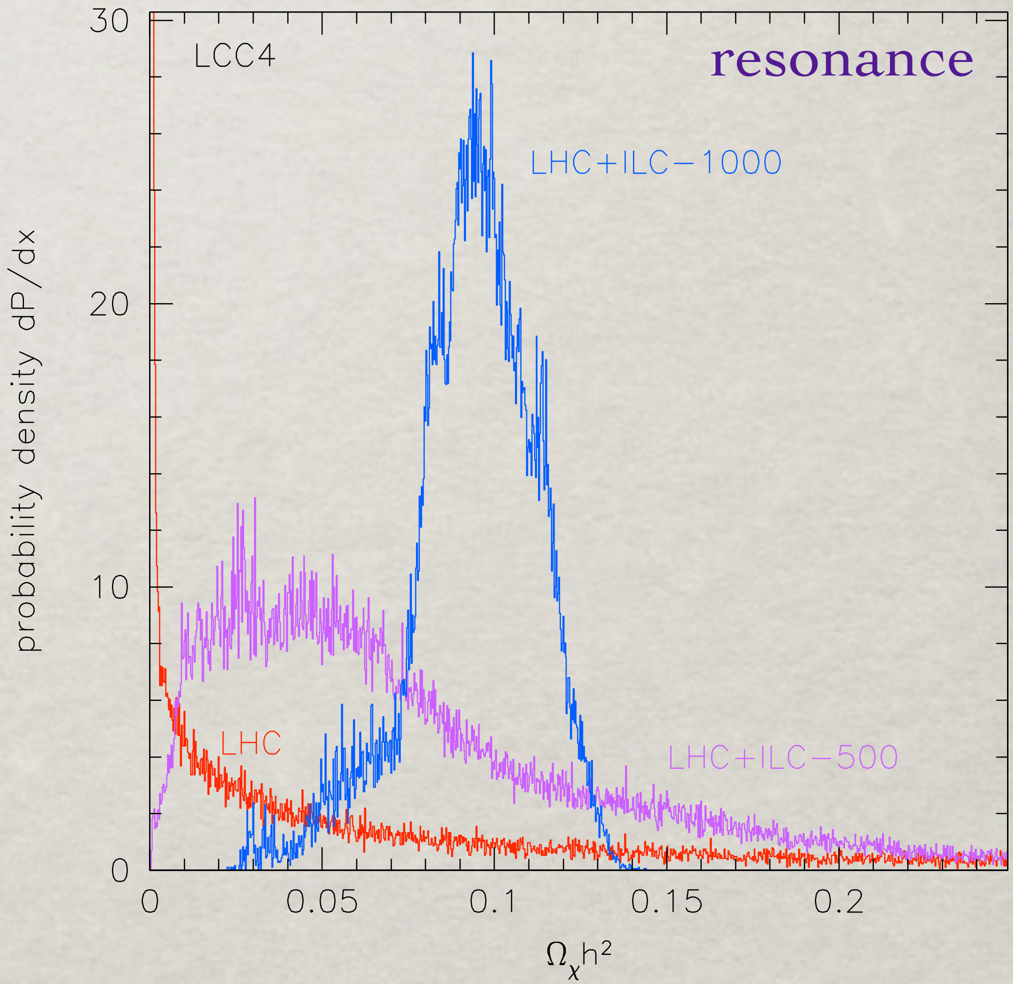
The resonant annihilation into heavy Higgses becomes much more effective ! Allows for a gravitino mass up to 10-70 GeV ! Need strong degeneracy: $2\, m_\chi \sim M_{A/H}$

LHC: MISMATCH IN $\Omega_{DM}h^2$?

Unfortunately it will be difficult to reconstruct precisely the relic density in the resonance case by LHC measurements alone;
still possible perhaps to improve when data are coming...

Need to measure the mass difference between the resonance and twice the neutralino mass with high accuracy: a job for ILC !

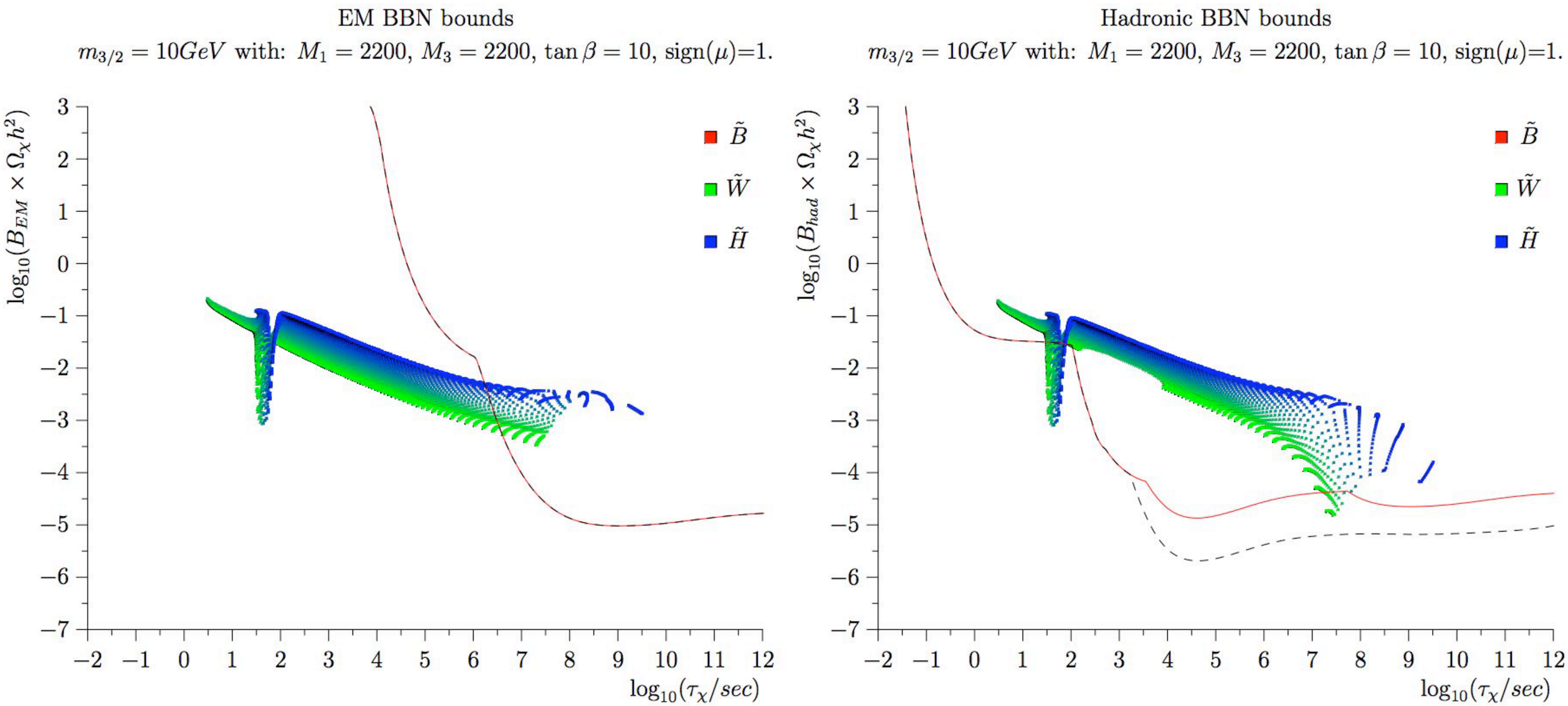
[Baltz, Battaglia, Peskin & Wizanski '06]



$$2\, m_\chi \sim M_{A/H}$$

Wino-Higgsino

[LC, Hasenkamp, Roberts & Pokorski 09]



The Wino case has even stronger annihilation and lower energy density; apart for the resonance region, also a light Wino can allow for 1-5 GeV gravitino masses...

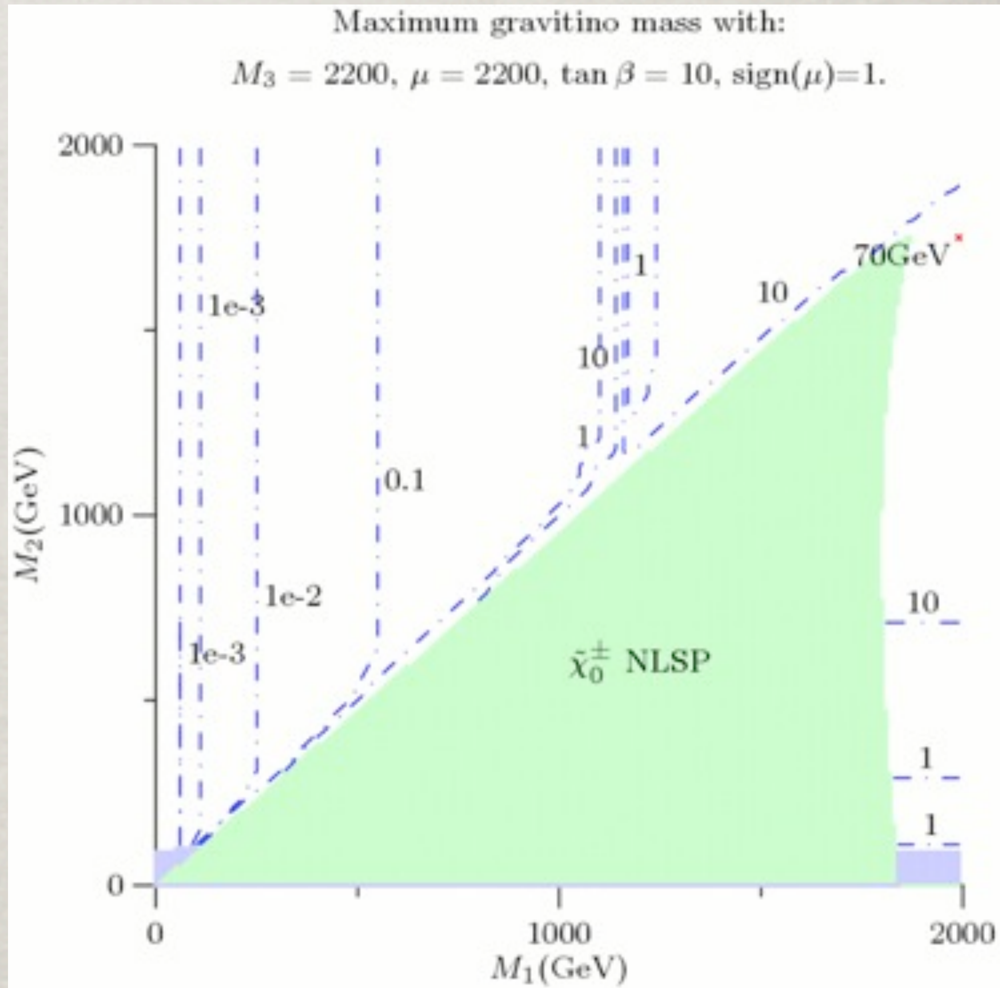
Light Wino window...

This points to a relatively light Wino NLSP, with a nearly degenerate chargino...

It may be difficult to produce at LHC, apart if the SUSY spectrum is compressed (favored by leptogenesis...).

But this should be a very good channel at ILC: the chargino decays into neutralino and off-shell W

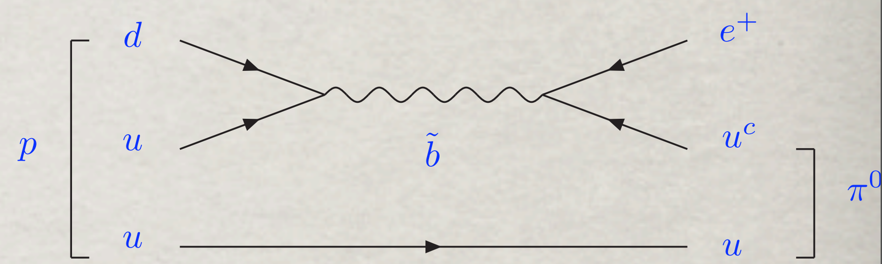
[LC, Hasenkamp, Roberts & Pokorski 09]



R-parity violation
&
indirect DM detection

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:



$$W = \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c + \mu_i L_i H_2$$

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

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

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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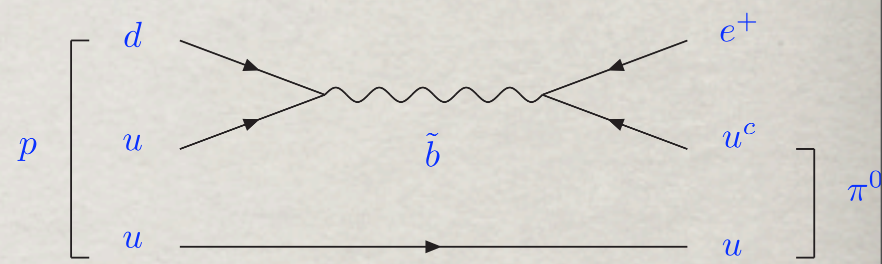

$\Rightarrow$ Dimension 4 proton decay operators $\propto \frac{\lambda' \lambda''}{m_{\tilde{q}}^2}$

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

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$\Rightarrow$ GRAVITINO CDM WITH R-parity VIOLATION

A SIMPLE MODEL with (suppressed) BROKEN R-PARITY

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

R-parity is usually not a fundamental symmetry of the MSSM completion. Our idea is to tie the R-parity breaking to the $B-L$ breaking: the v.e.v. of a single field Φ generates both the Majorana mass for RH neutrinos and bilinear R-parity breaking $\mu_i L_i H_u$:

$$W_{B-L} = X(NN^c - \Phi^2) + \frac{NNN_i^c N_j^c}{M_P} \quad \Rightarrow \quad \langle N \rangle = \langle N^c \rangle = \langle \Phi \rangle = v_{B-L}$$

$$\delta K_1 = \left[\frac{(a_i Z + a_i' Z^\dagger)\Phi^\dagger N^c}{M_P^3} + \frac{(c_i Z + c_i' Z^\dagger)\Phi N^\dagger}{M_P^3} \right] H_u L_i \quad \Rightarrow \quad \delta W_1 = \mu_i H_u L_i$$

Then we have

$$M_3 = \frac{v_{B-L}^2}{M_P} \qquad \mu_i \propto m_{3/2} \frac{v_{B-L}^2}{M_P^2}$$

The charge of Φ is such that the other R-parity breaking terms are generated only with higher powers of $\left(\frac{v_{B-L}}{M_P}\right)^{4+n}$ and are harmless.

	$\mathbf{16}_i$	H_u	H_d	N	N^c	Φ	X	Z
R	1	0	0	0	-2	-1	4	0

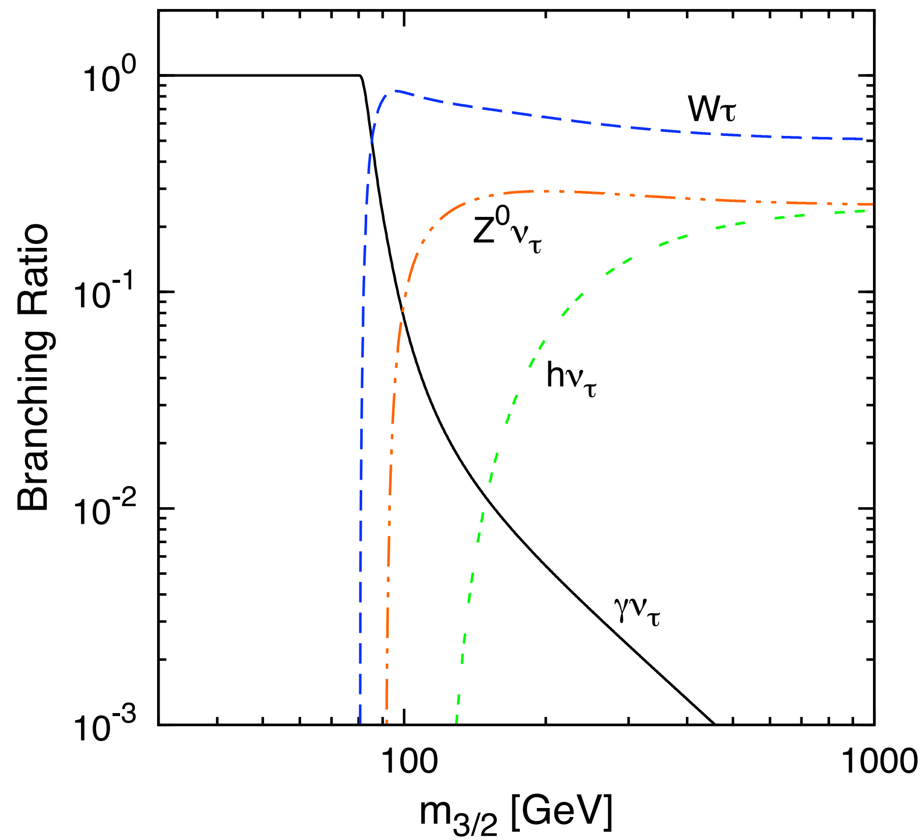
Effectively a model with bilinear R-parity violation, but with a coupling smaller than those usually discussed in the literature...

$$\epsilon_i = \frac{\mu_i}{\mu} \leq 10^{-7}$$

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]

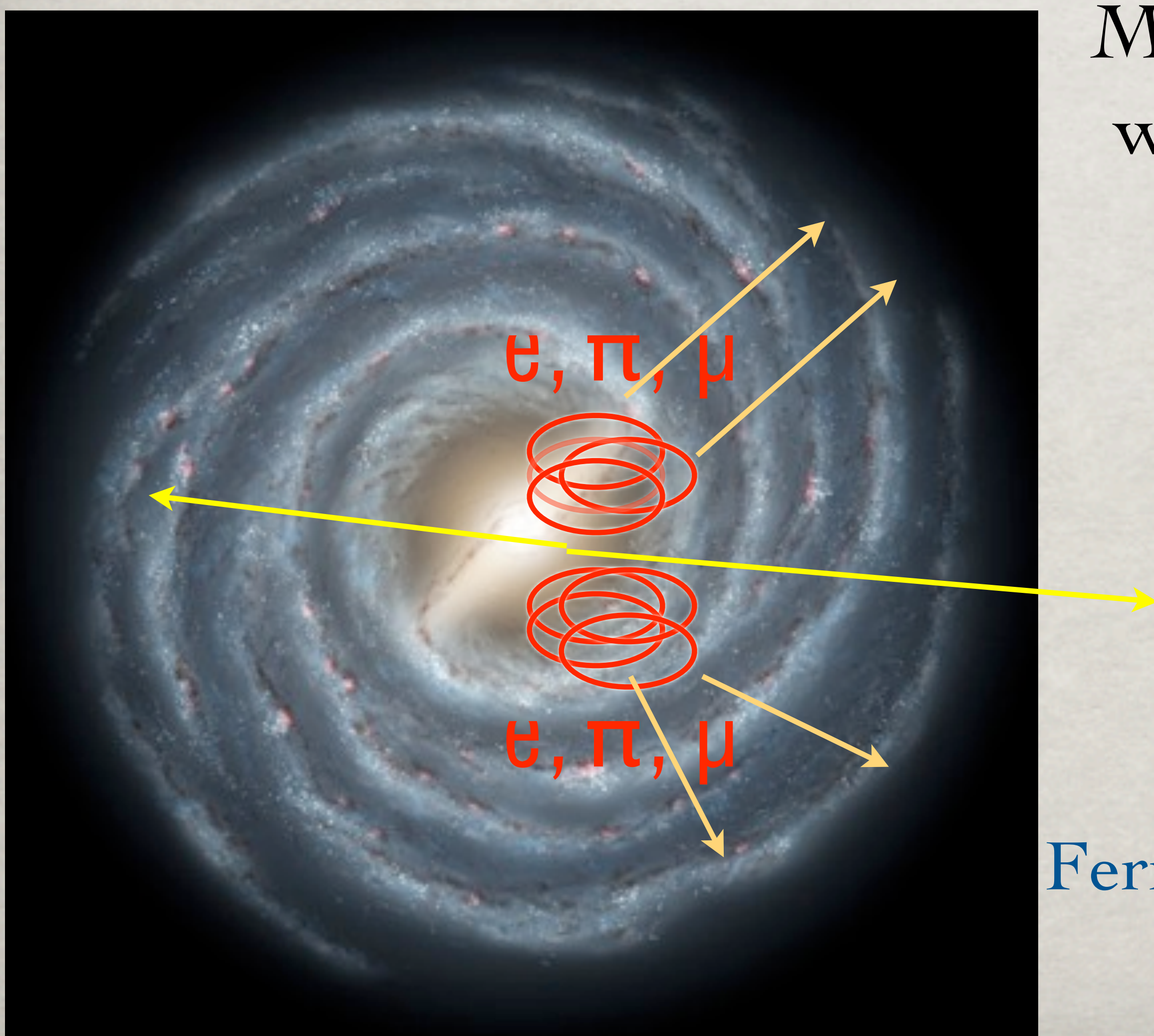


The lifetime is very long, suppressed by M_P and the small mixing between neutrinos and gauginos:

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

THE HOPE: DETECT DM !

- Look for decay signal from the Milky Way, other galaxies, clumps of DM, etc...



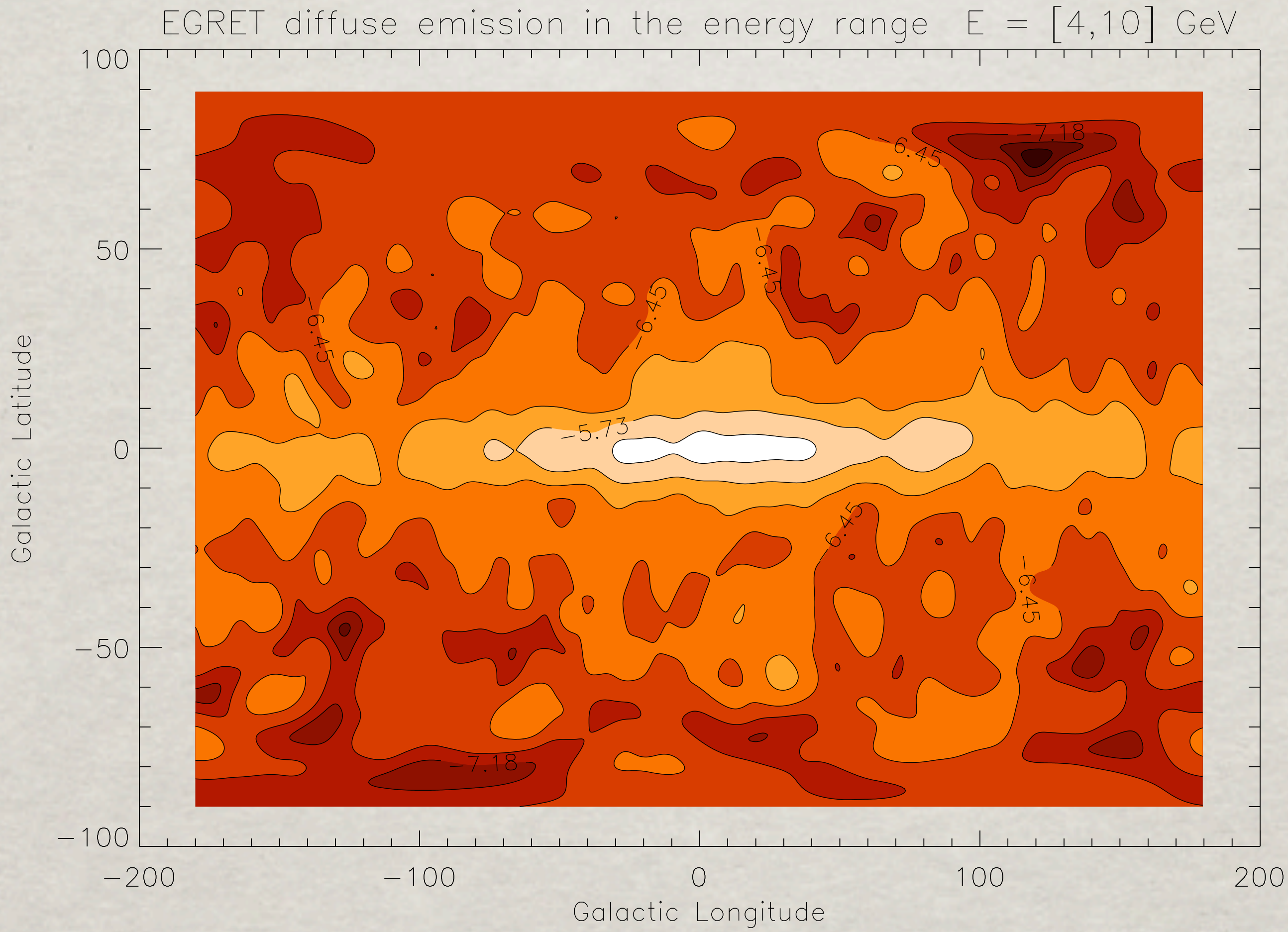
Measure the decay products with balloons or satellites !

Fermi Gamma-Ray Space Telescope

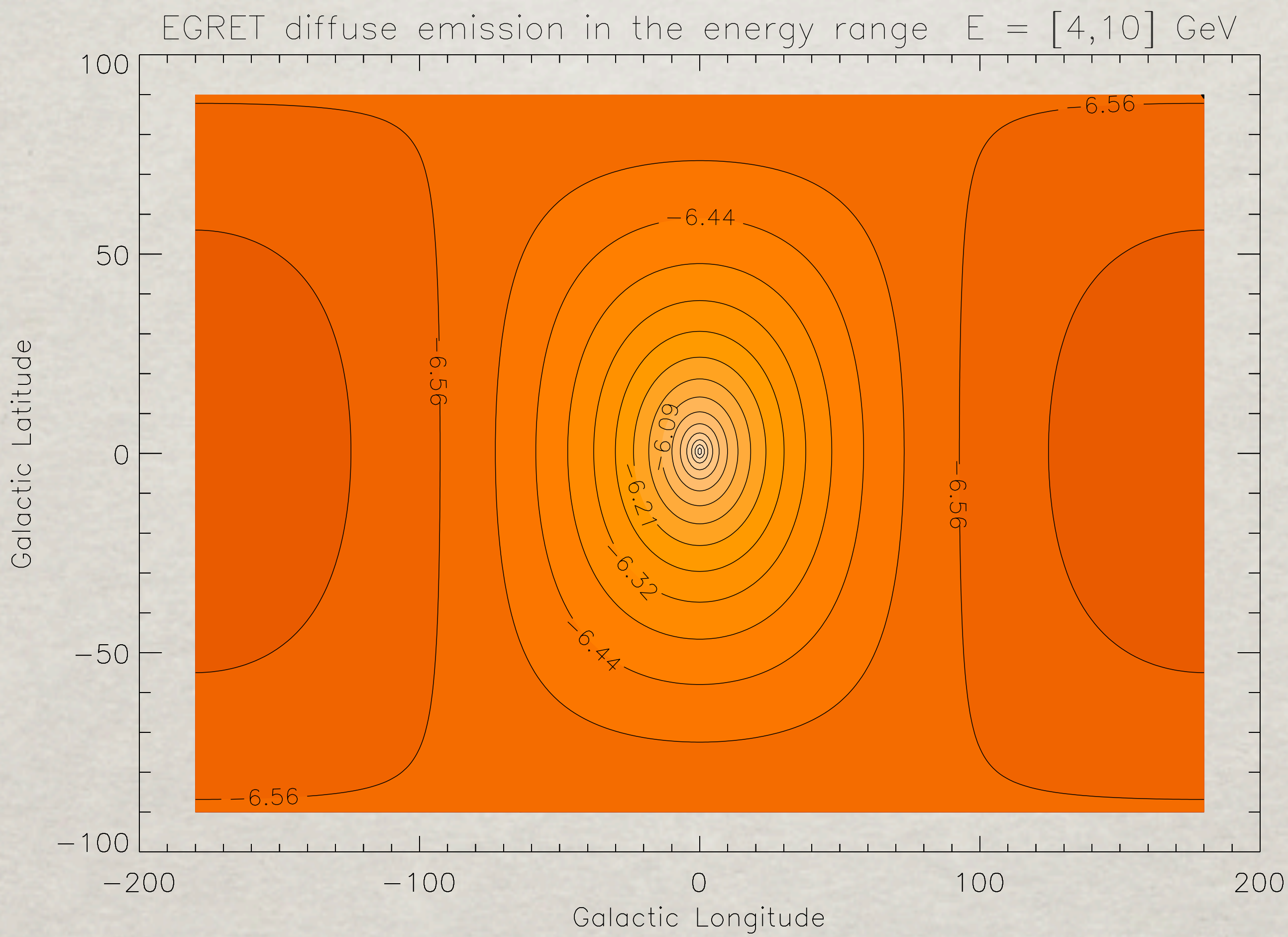
PAMELA

The Milky Way signal in gamma-ray

The Milky Way signal in gamma-ray

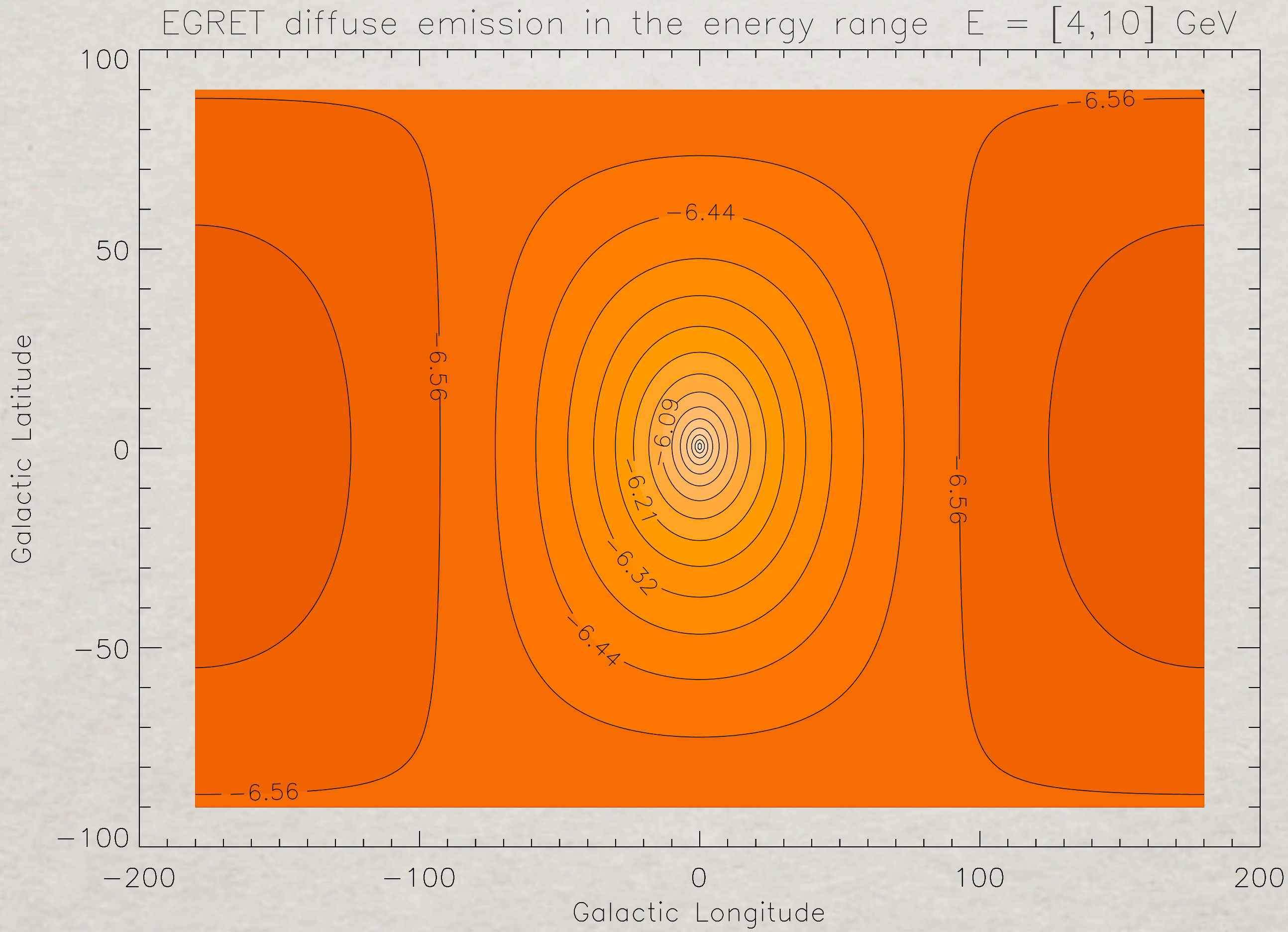


The Milky Way signal in gamma-ray



[Bertone, Buchmuller, LC & Ibarra 07]

The Milky Way signal in gamma-ray

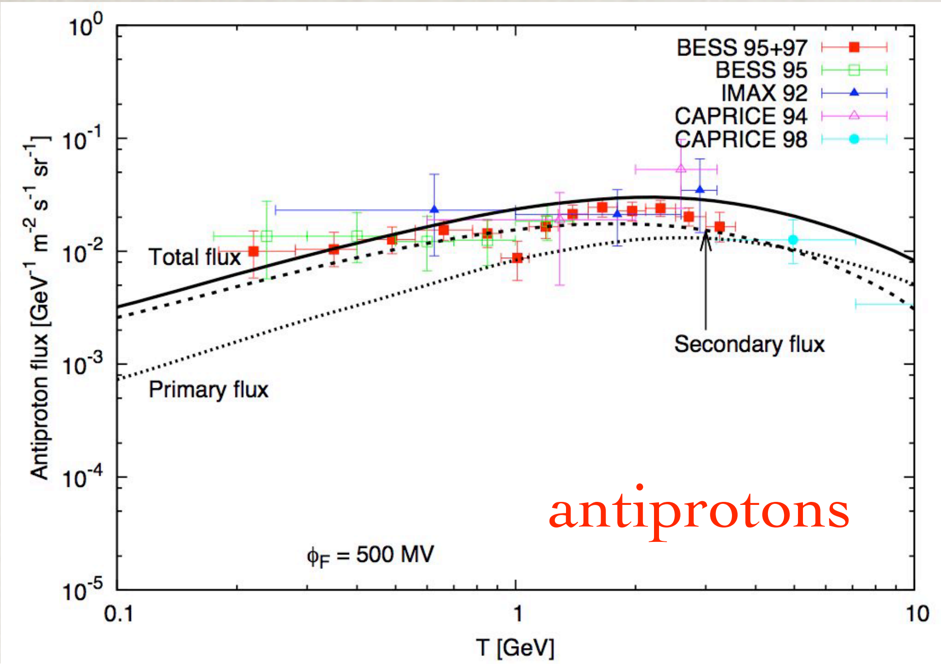


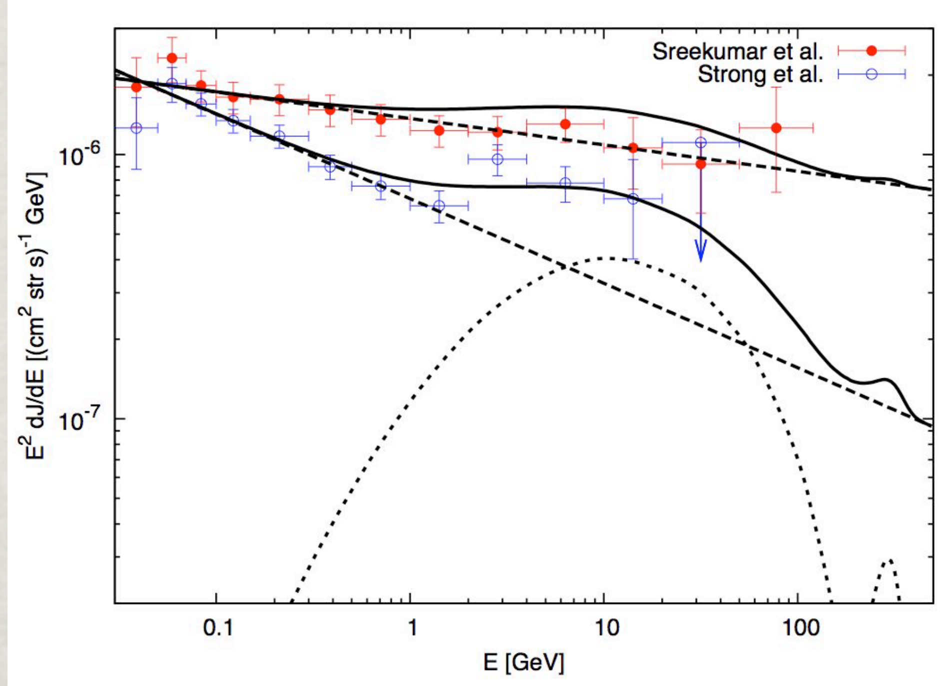
[Bertone, Buchmuller, LC & Ibarra 07]

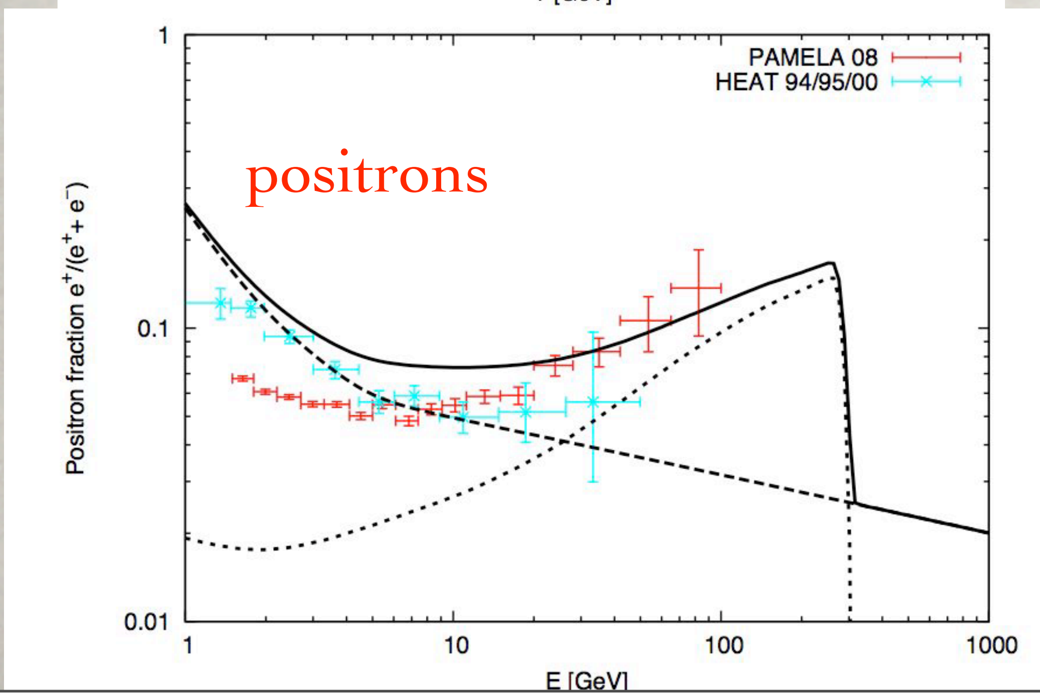
Hopefully the FERMI telescope will be able to see it !

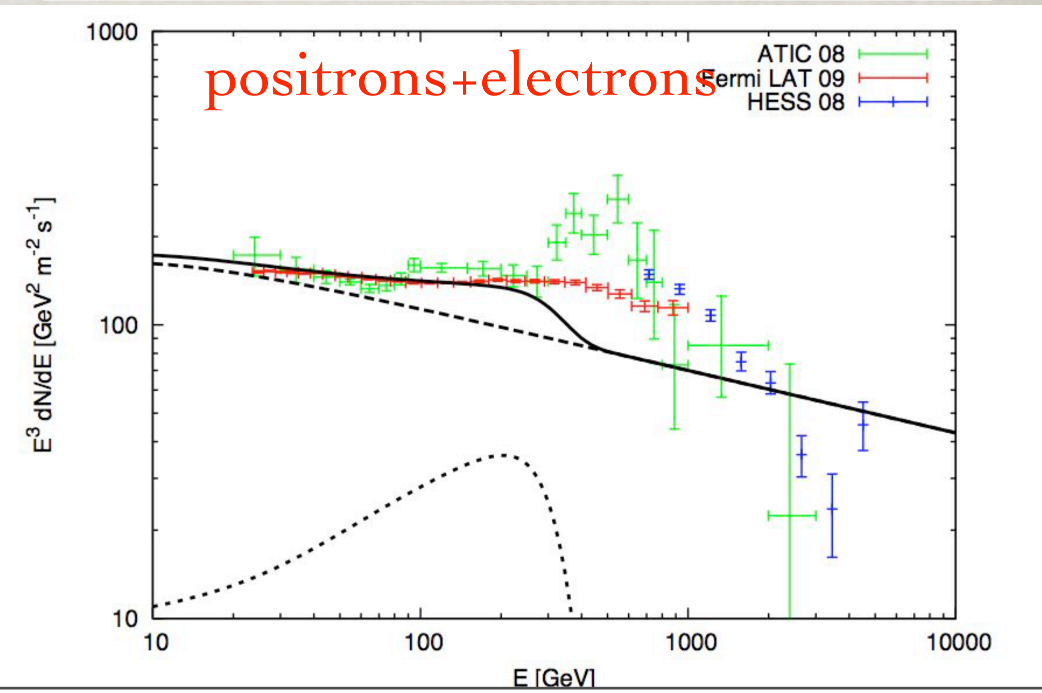
Gravitino DM without R_p

[Buchmuller, Ibarra, Shindou, Takayama, Tran 09]



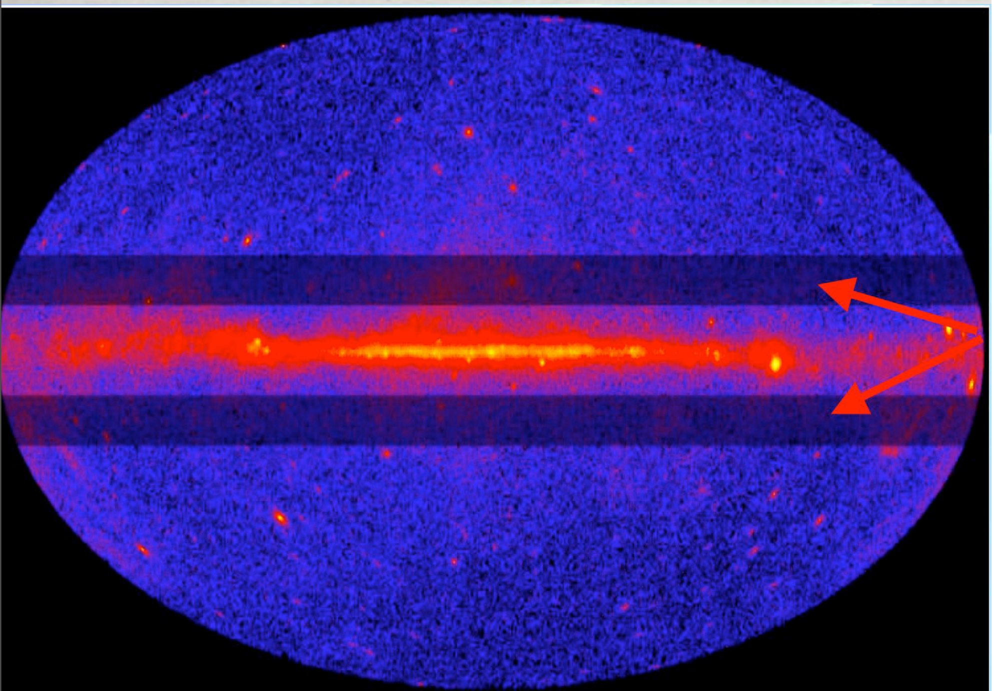




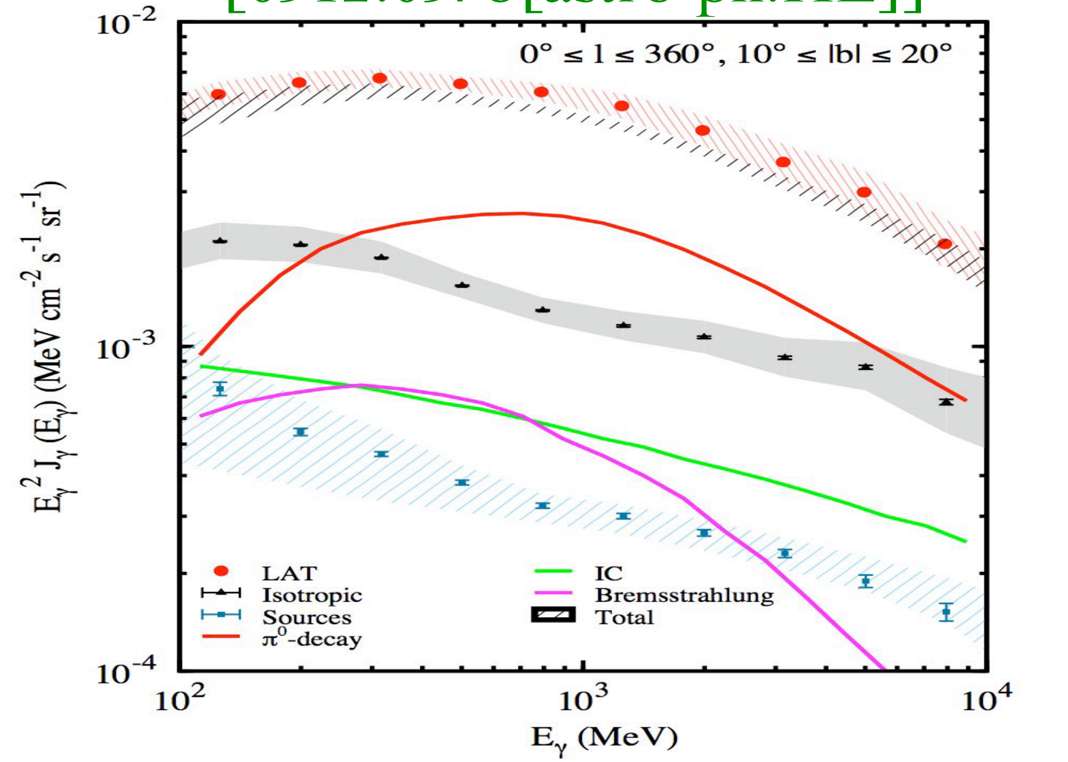


News from the sky

The FERMI satellite has new results on the gamma-ray emissions around the galactic centre in the strip |b|=10-20



[0912.0973[astro-ph.HE]]



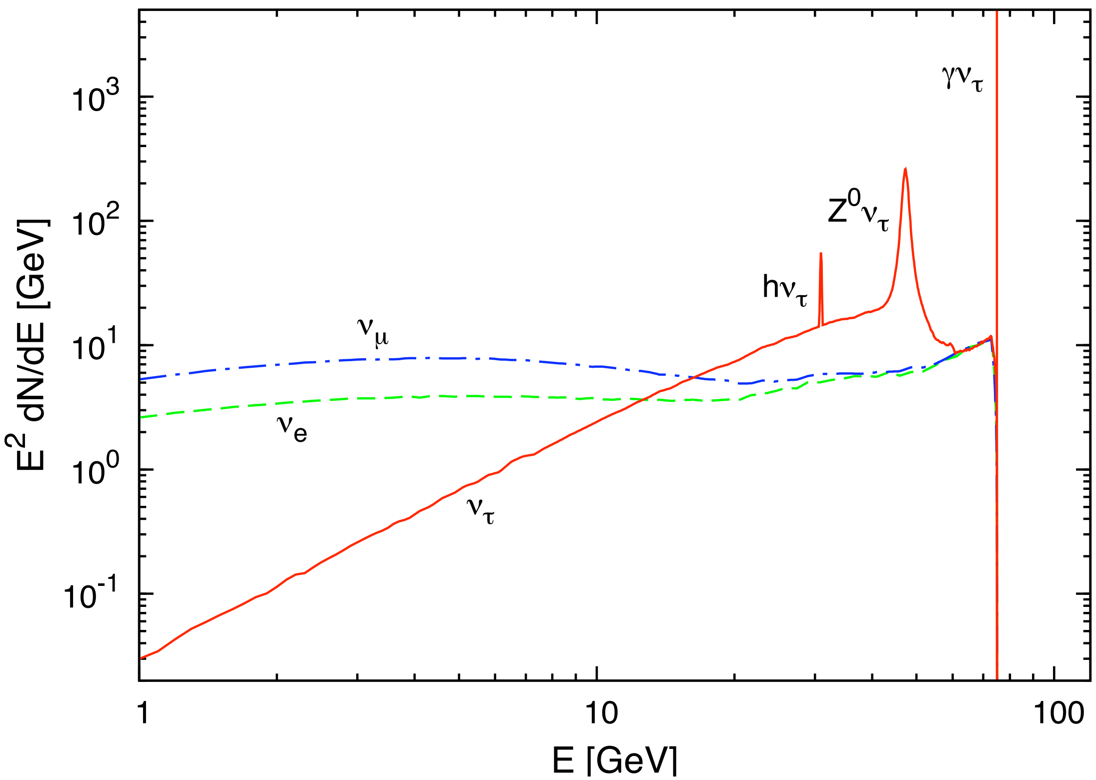
The spectrum seems perfectly consistent with “non-optimized” model of the background, no need of any DM signal there...

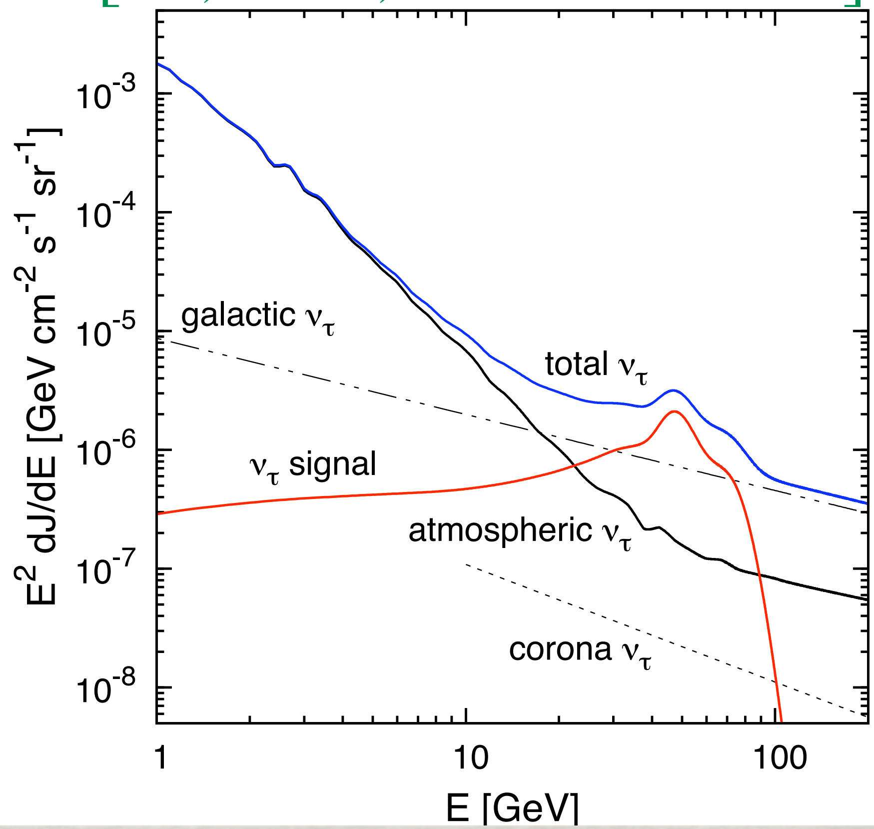
Also recently no lines found between 30-200 GeV...

What about neutrinos ?

For light gravitino, wonderful signal with 3 peaks..., but neutrino detector's resolution not sufficient to see them

[LC, Grefe, Ibarra & Tran 08]



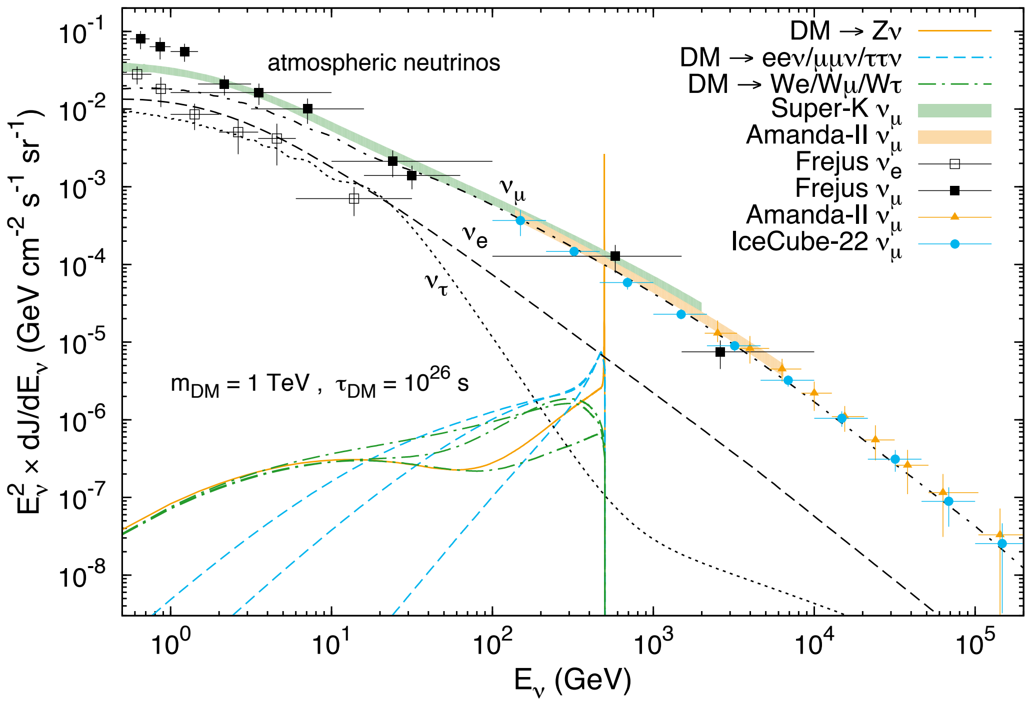


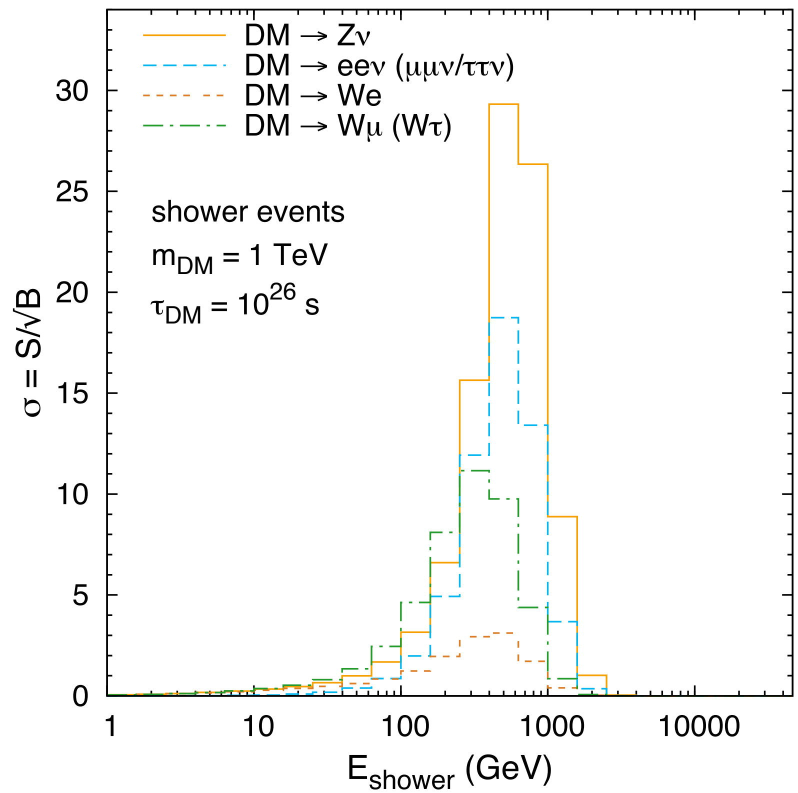
Best signal to background ratio for a tau neutrino looking up...

General decaying DM

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

[LC, Grefe, Ibarra & Tran 09]





Best signal to background ratio for cascade/shower events

Possible to detect in IceCube ?

Collider signatures

Different signals @ LHC depending on the NLSP...

- 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}

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

(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	R-parity violated
$\chi^0 \to \psi_{3/2}\,\gamma$	$\chi^0 \to \tau W, \nu Z, b\bar{b}\nu$
$\tilde{\tau} \to \psi_{3/2}\,\tau$	$\tilde{\tau} \to \tau\nu_\mu, \mu\nu_\tau, \bar{b}bW$

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

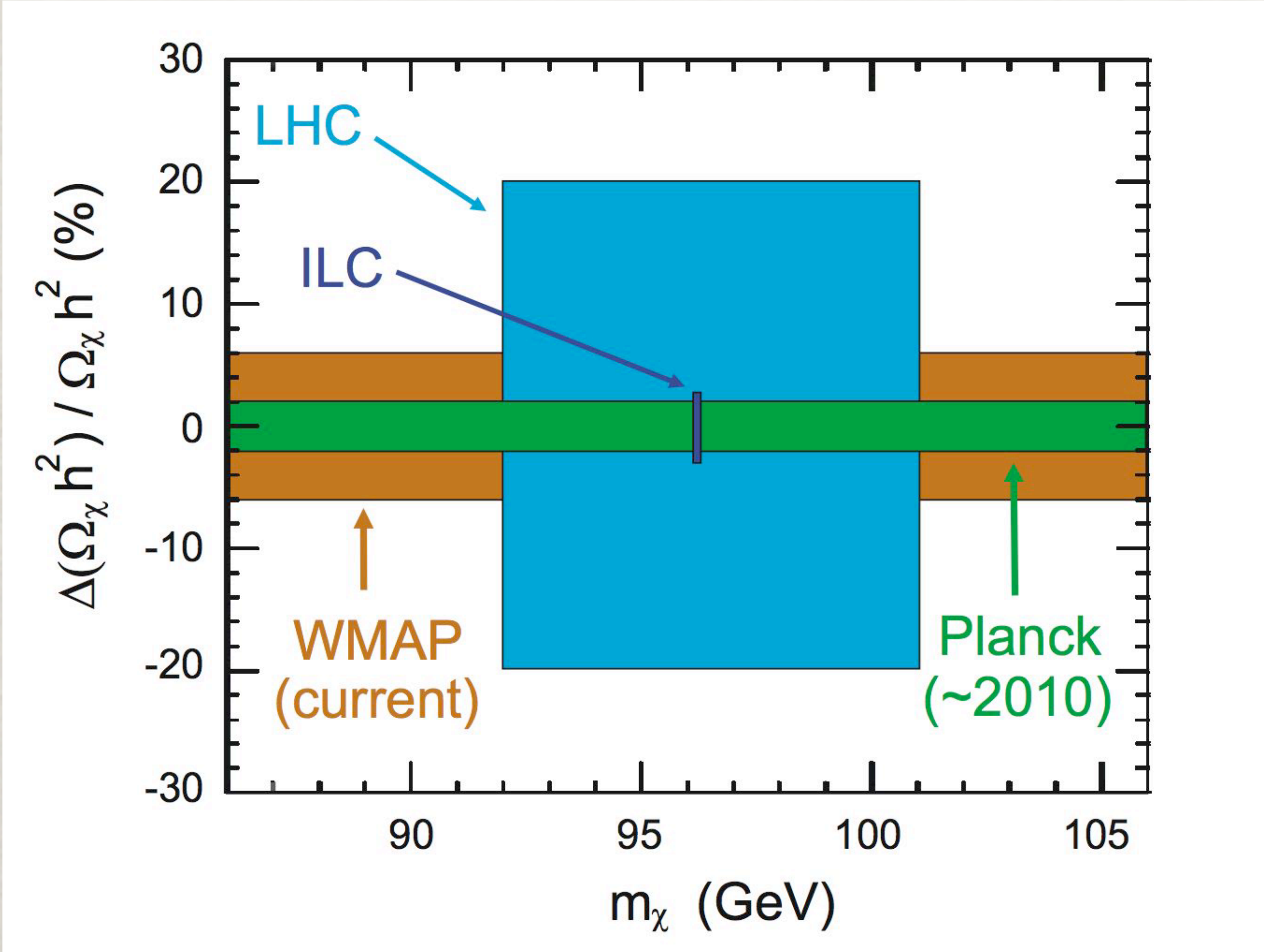
$$m_{3/2} > 4\ \mathrm{keV} \qquad\qquad \tau_{3/2} > 10^{27}\ \mathrm{s}$$

$$\tau_{NLSP} > 10^{-13}\ \mathrm{s}\left(\frac{m_{NLSP}}{2\mathrm{TeV}}\right)^{-5} \qquad \tau_{NLSP} > 10^{-9}\ \mathrm{s}$$

DISPLACED VERTICES... perhaps even too much !

$\Omega_{DM}h^2$ FROM LHC/ILC & CMB

ILC RDR



Probably need ILC to match Planck precision and check neutralino DM density, but LHC may be sufficient to compare neutralino DM vs neutralino NLSP....

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 !

Outlook

- Gravitinos LSPs may be quite naturally DM, but some care is needed with Nucleosynthesis bounds. Tuning a neutralino NLSP to Wino/Higgsino can ease these constraints, but not evade them completely.
- R-parity is not necessary to have gravitino DM, actually a slight breaking solves many cosmological problems !
  Moreover if R-parity is not too weakly broken, we could see soon photons or neutrinos from DM decay.
- There is a good chance that we will know soon !

Stay tuned !