GRAVITINO DARK MATTER (& THE ILC)

Laura Covi

DESY HELMHOLTZ | ASSOCIATION

In collaboration with:
C. Berger, S. Kraml and F. Palorini,
J. Hasenkamp, J. Roberts and S. Pokorski

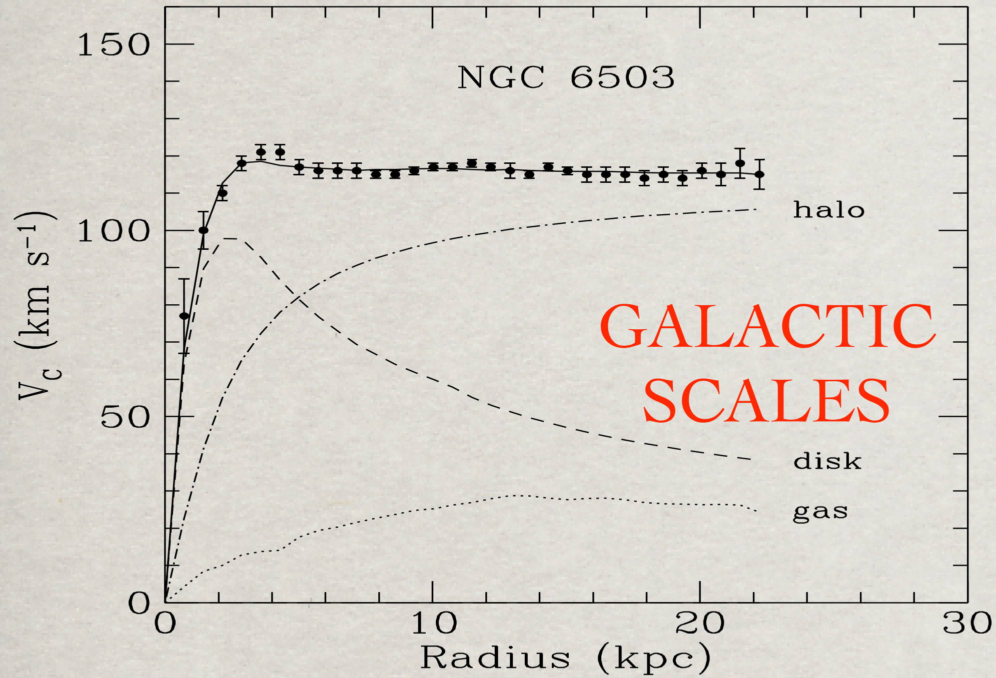
OUTLINE

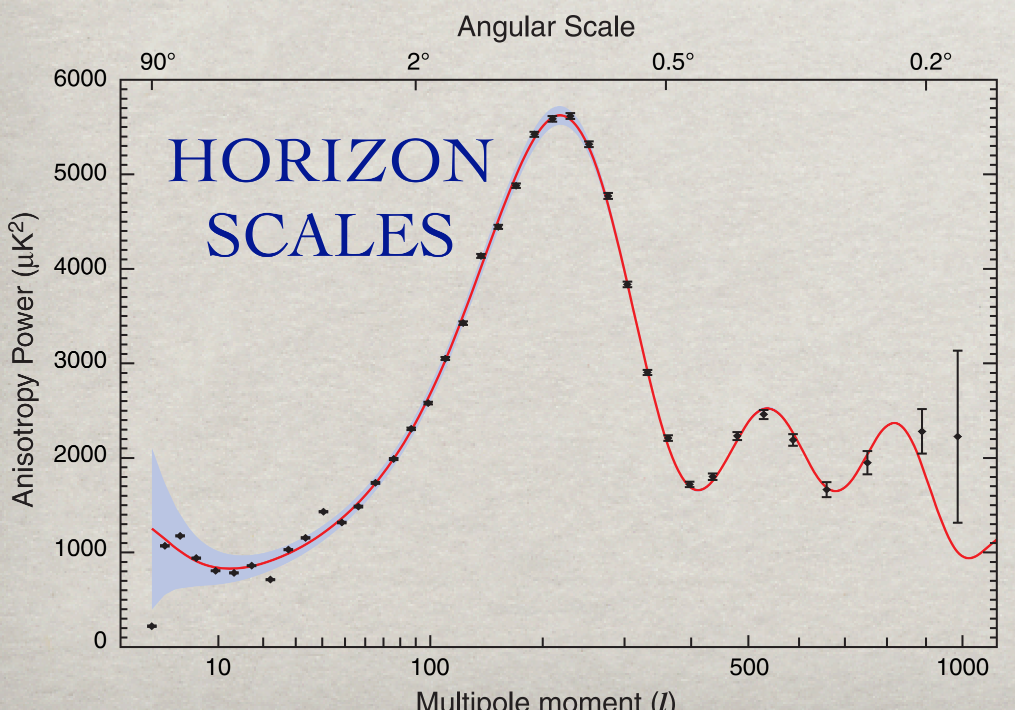
- Introduction: Dark Matter properties
  Why gravitino DM ?
- Cosmological constraints on gravitino DM

- Charged NLSPs: stop
- Revisiting neutralino NLSP:
  Wino and Higgsino @ LHC/ILC ?
- Another neutral NLSP: sneutrino

- Outlook

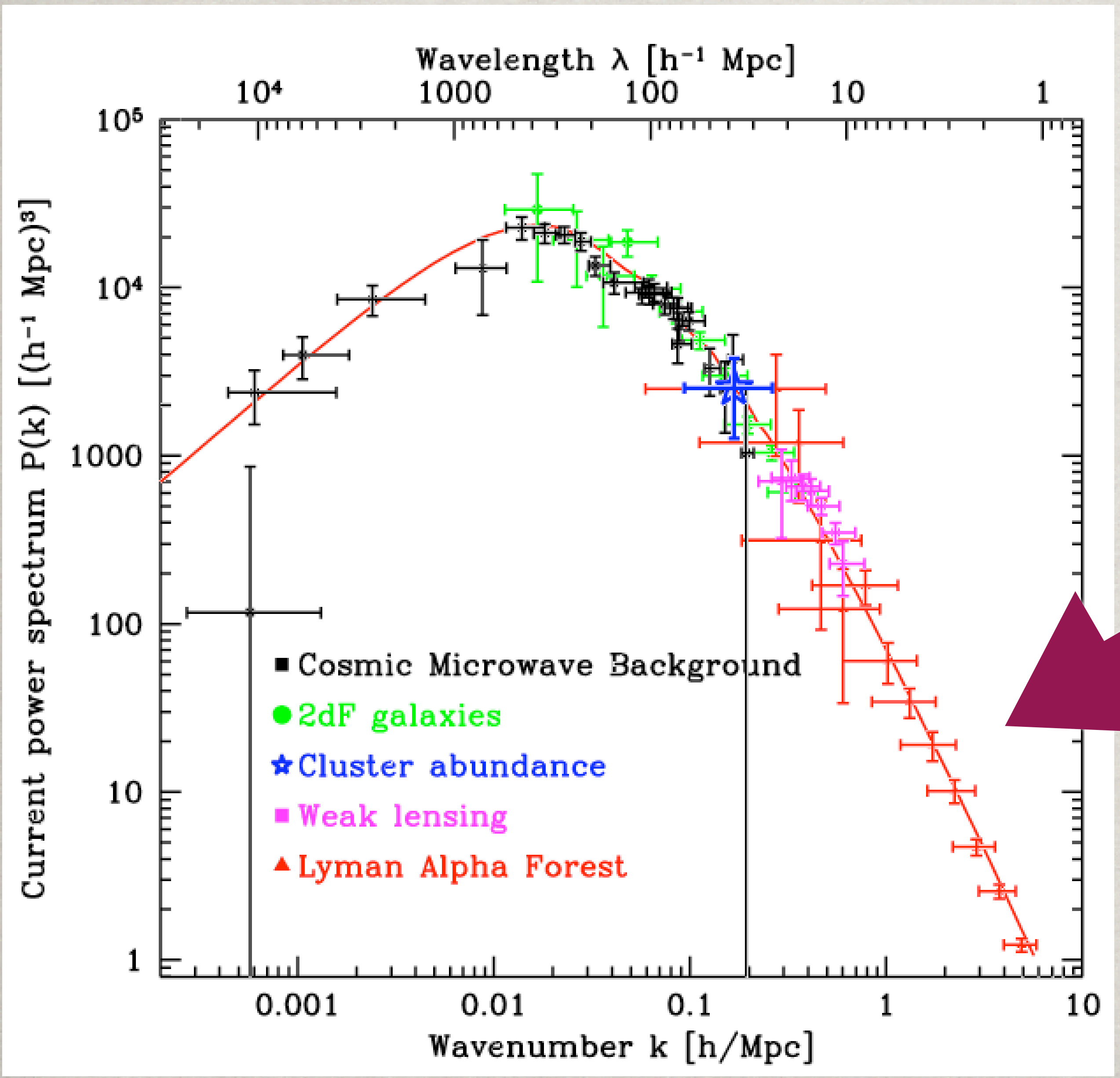
DARK MATTER EVIDENCE





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

WDM & THE POWER SPECTRUM



WARM DM 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]

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral, non-baryonic 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 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 is not strictly necessary...

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

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

Hubble expansion Collision integral

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

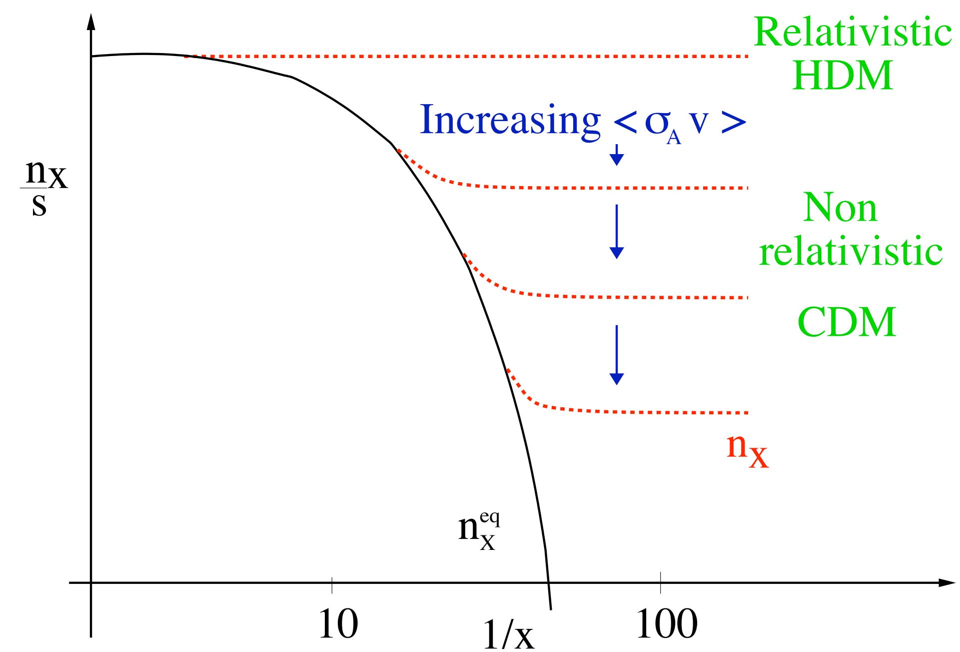
$$n_{eq}\langle \sigma_A v \rangle \sim H \qquad \Rightarrow \qquad \Omega \propto \frac{1}{\langle \sigma_A v \rangle}$$

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 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

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

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

Ω … ${}^2 \propto$ … h^2

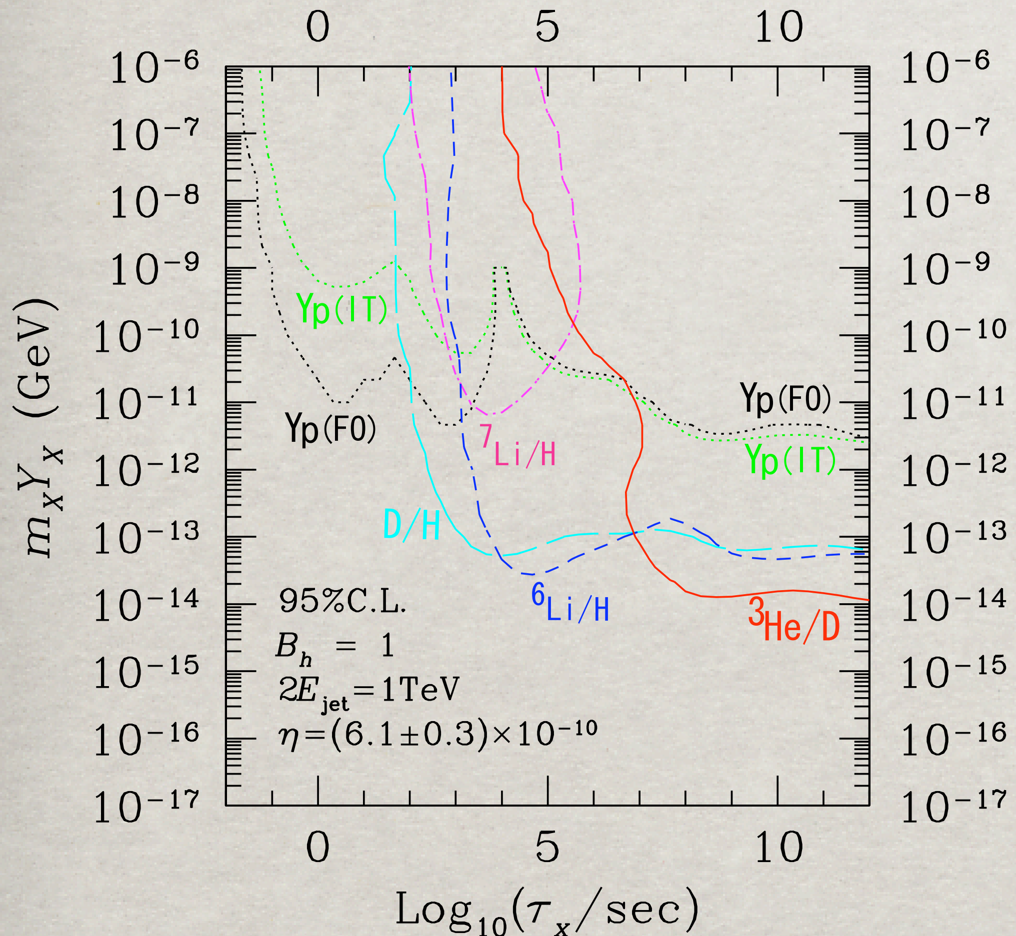
!

DANGER !!!
BBN at risk !

BBN BOUNDS ON NLSP DECAY

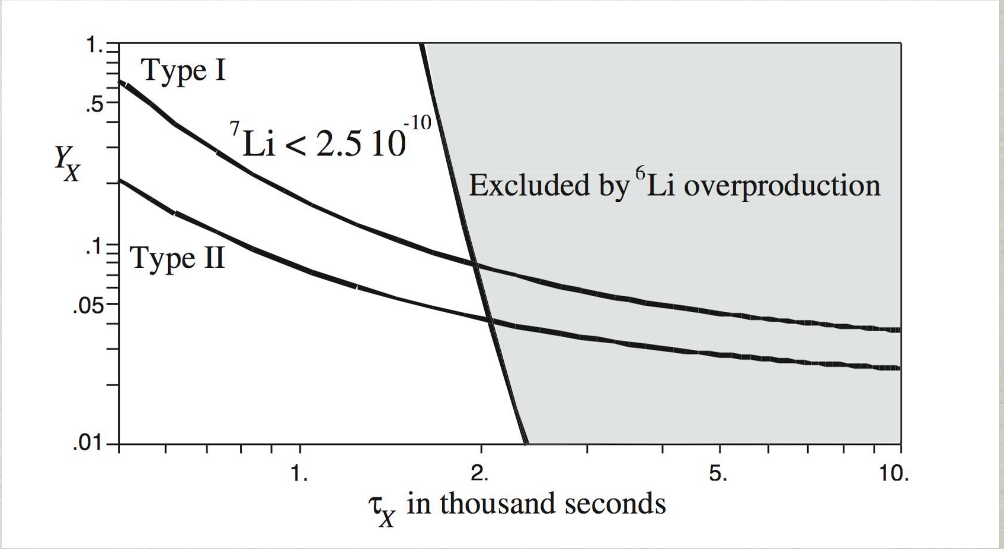
Neutral relics

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



EM charged relics

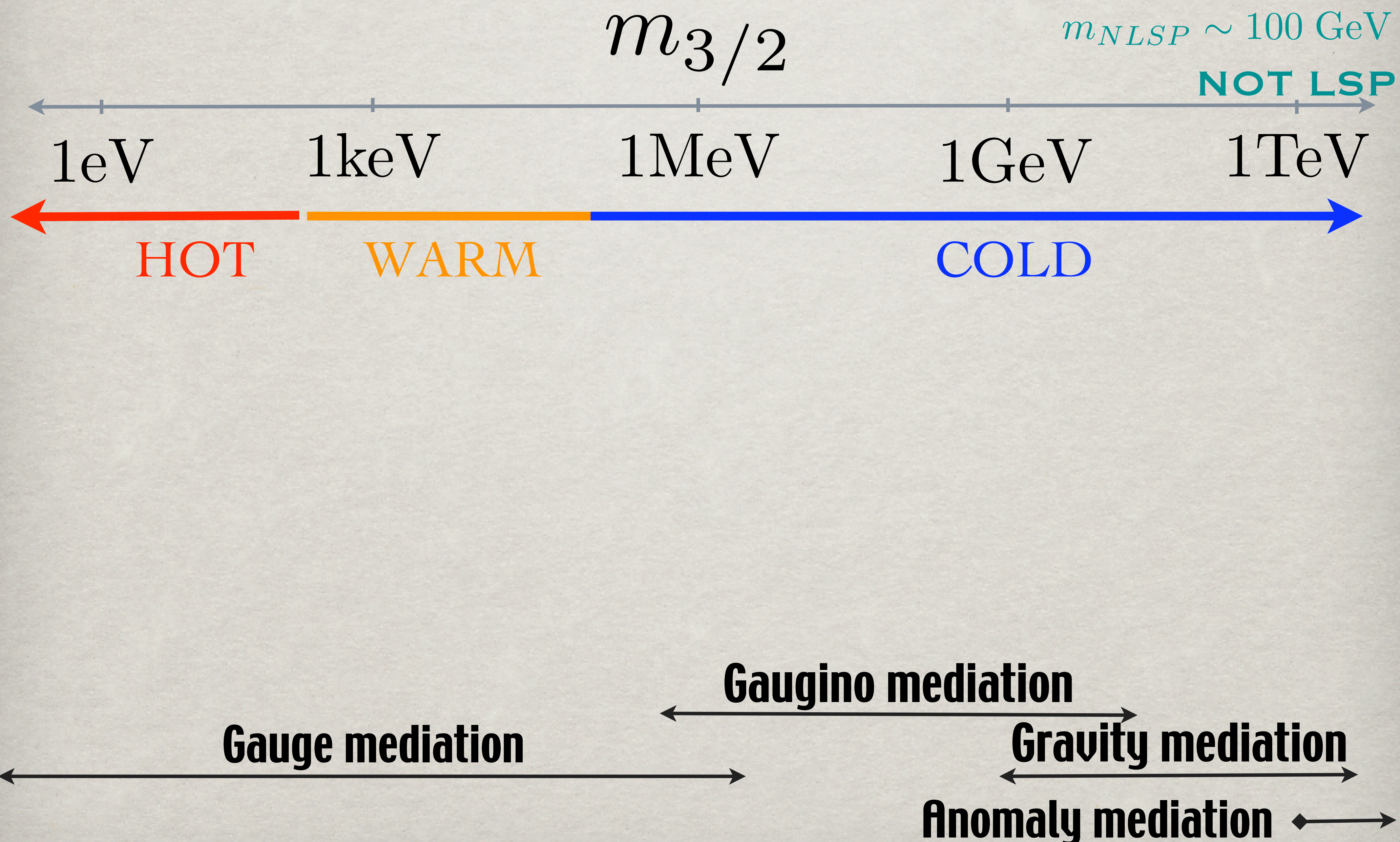
[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]



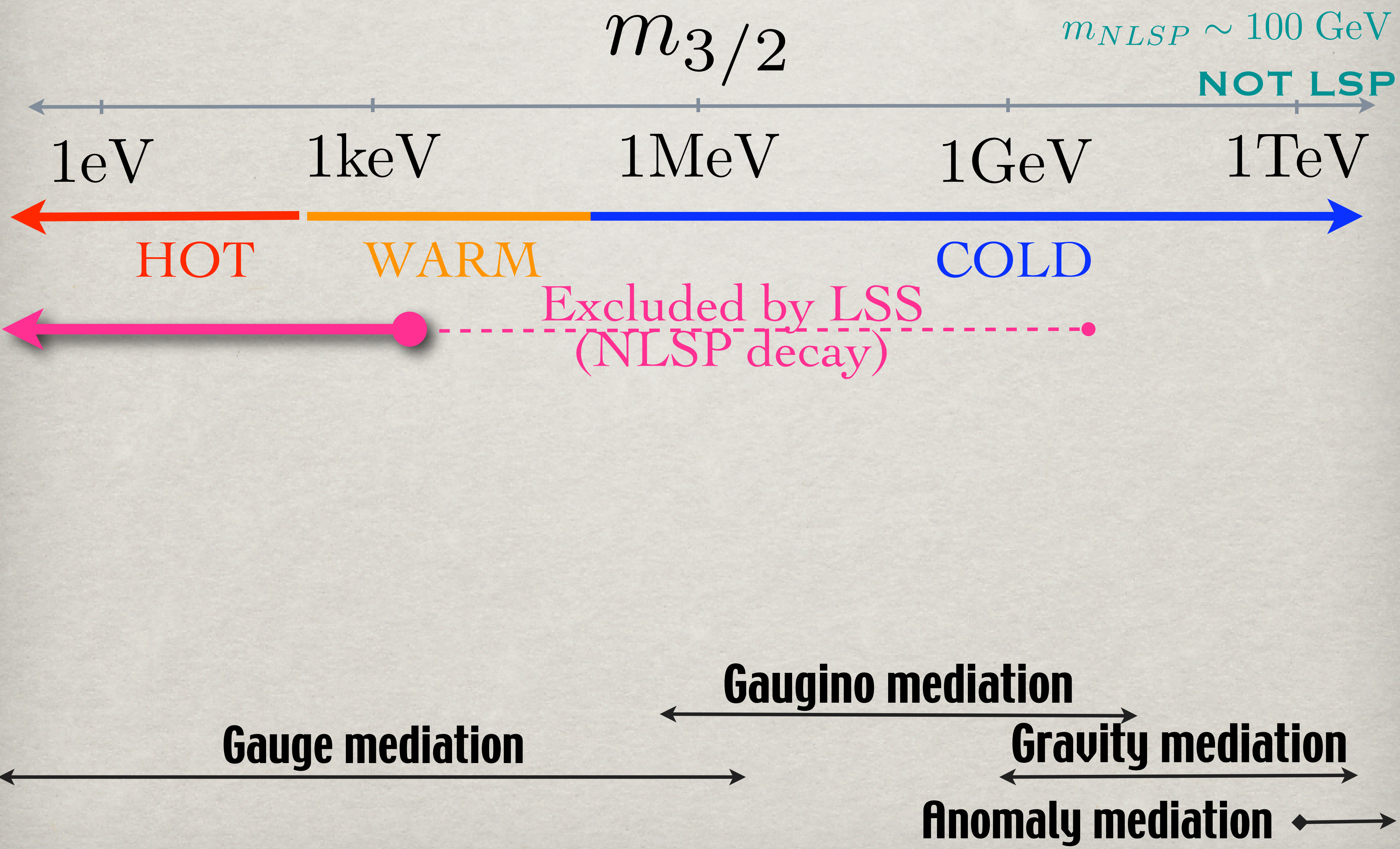
Need short lifetime & low abundance for NLSP

Big problem for gravitino LSP, if the mass is above 1 GeV...

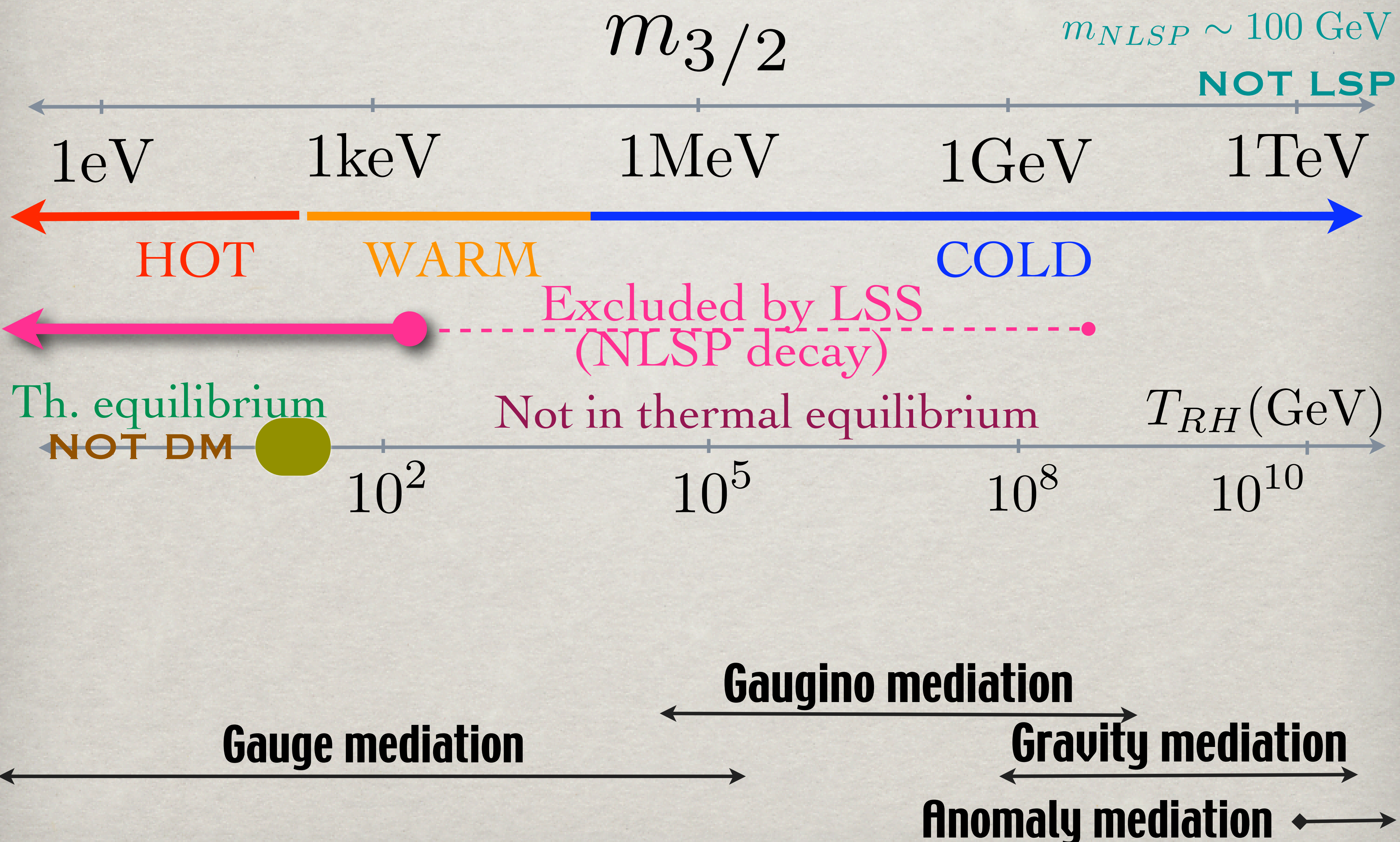
Gravitino DM summary



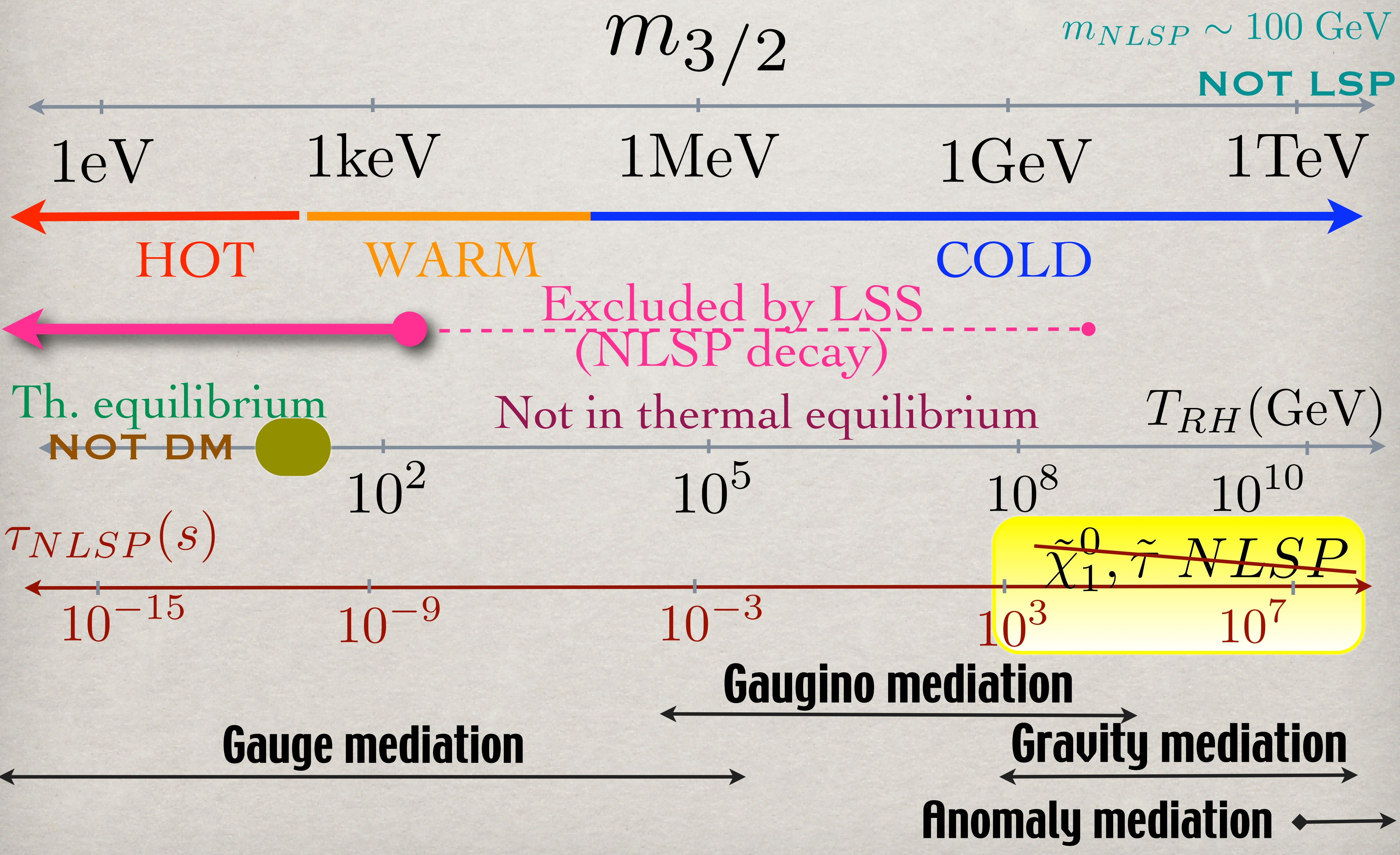
Gravitino DM summary II



Gravitino DM summary II



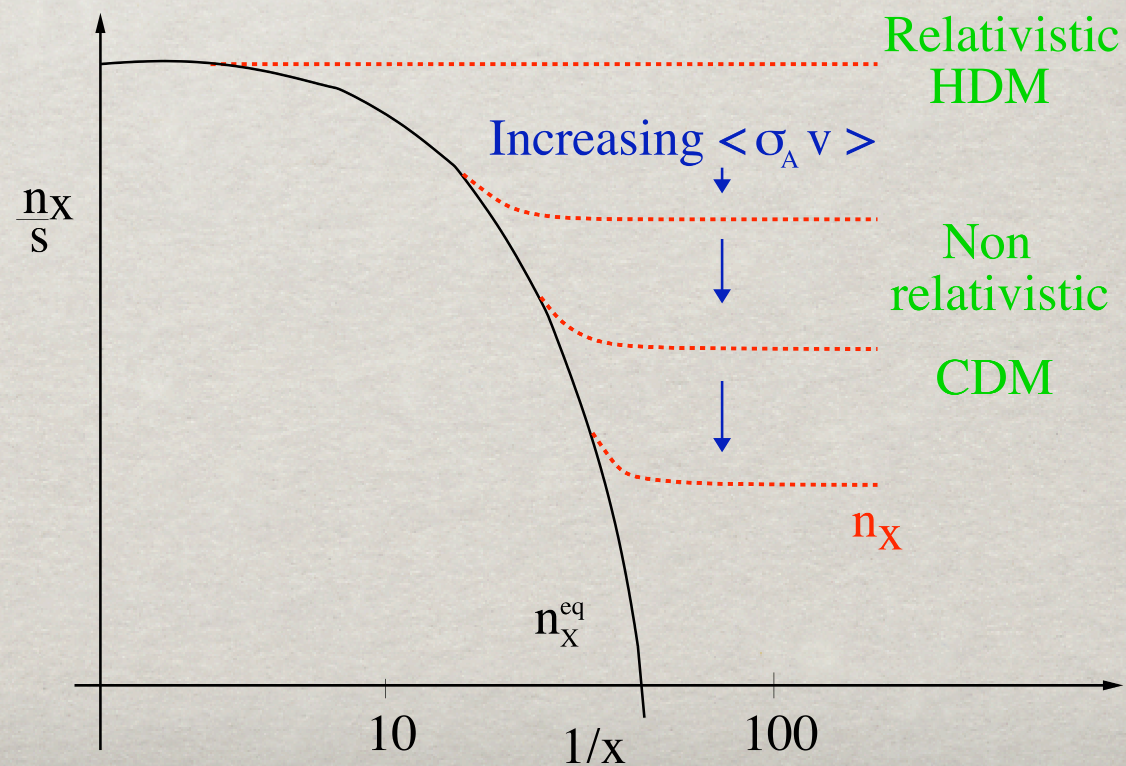
Gravitino DM summary II



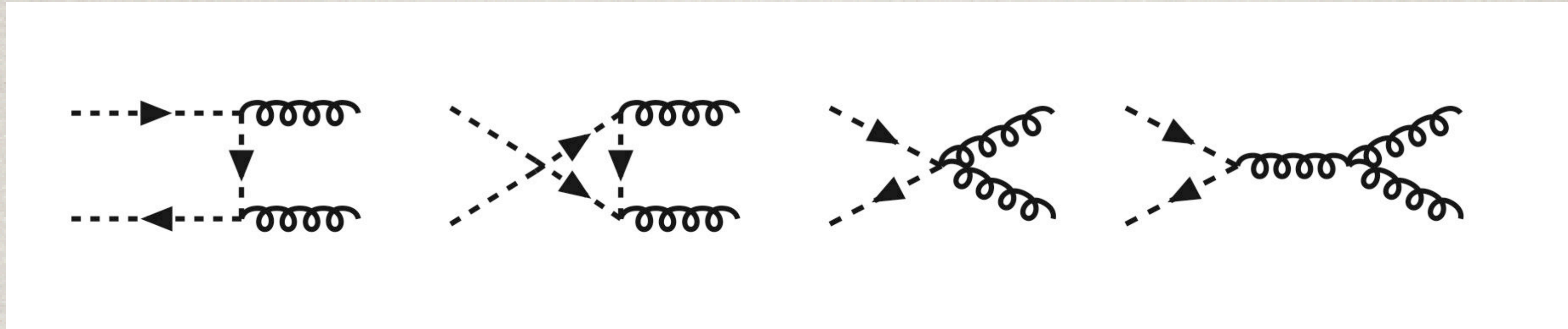
NLSPs @ COLLIDERS

CHARGED RELIC'S DENSITY

- Consider a scalar particle charged under a gauge interaction
- How strong can the annihilation cross-section be ??? Sufficient to reduce the number density to negligible numbers ?
- Classical examples in the MSSM: stau, stop...
- And what about the maximal cross section, the unitary bound ?



Annihilation into gauge bosons



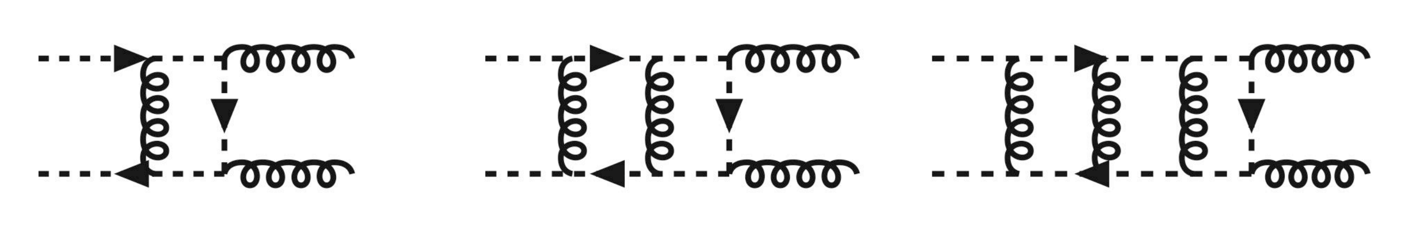
- Take two scalars in the (anti)fundamental representation and just the annihilation into gauge bosons: dominant channel for strong coupling and depending only on the gauge coupling and mass of the relic;
- 4 diagrams contribute for a non-abelian interaction; the result has a symmetric and antisymmetric part in group indices

$$\tilde{\sigma}_{sym}(\beta) = \pi\alpha_N^2 \frac{(N^2-1)(N^2-2)}{N^3}\beta\left[1-\frac{\beta^2}{2}+\frac{1-\beta^4}{4\beta}\log\left(\frac{1-\beta}{1+\beta}\right)\right] \mathcal{O}(\beta)$$

$$\tilde{\sigma}_{as}(\beta) = \pi\alpha_N^2 \frac{(N^2-1)}{N}\beta\left[\frac{3}{2}-\frac{4}{3}\beta^2+\frac{(1-\beta^2)(3+\beta^2)}{4\beta}\log\left(\frac{1-\beta}{1+\beta}\right)\right] \mathcal{O}(\beta^3)$$

Sommerfeld Factor

[Sommerfeld 39, Sakharov 48]



- Consider one particle moving in the Coulomb field produced by 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:

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

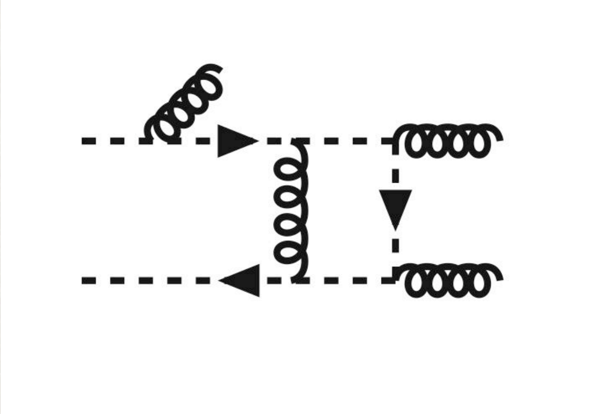
- Large correction for small velocity !!!
  RELEVANT AT FREEZE-OUT ! [Hisano et al 04, 06]

Plasma effects ?

- Plasma screening/Debye thermal mass for the gluon: negligible since $$m_g \sim gT \ll m\beta \sim \sqrt{mT}$$
- Mixing between initial state configurations: the Sommerfeld factor at T=0 depends on the channel, e.g. it is attractive (C>0) for the singlet case, but repulsive (C<0) for the adjoint configuration. In a thermal plasma there is no definite color configuration....

$$N \times \bar{N} = S + A$$

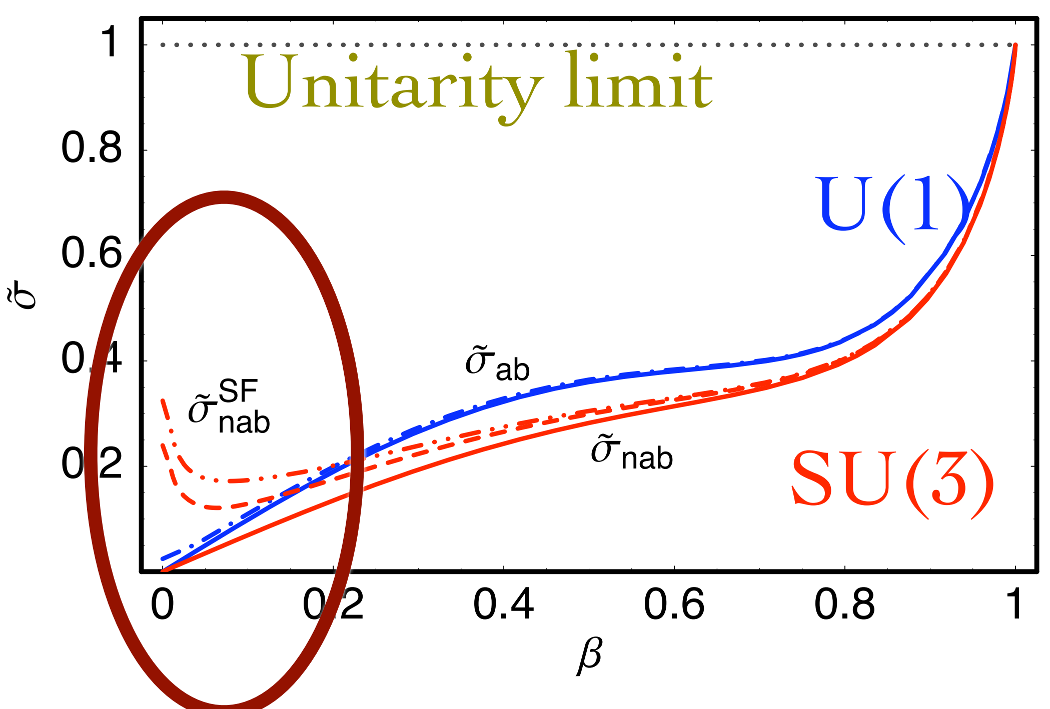
$$S \leftrightarrow A + g$$

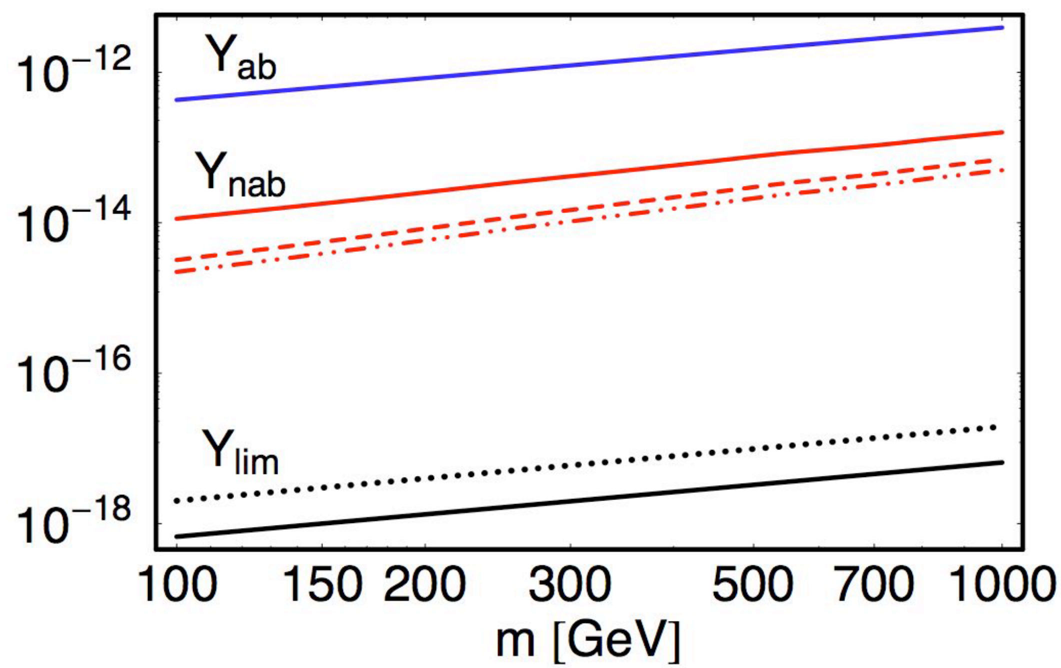


We consider both T=0 and average case (equal at one loop)

ENHANCED CROSS-SECTION

[Berger, LC, Kraml, Palorini 08]





The Sommerfeld enhancement is very small for a U(1), but strong for non-abelian SU(3): note both sum and average SF give a larger cross-section at small beta !

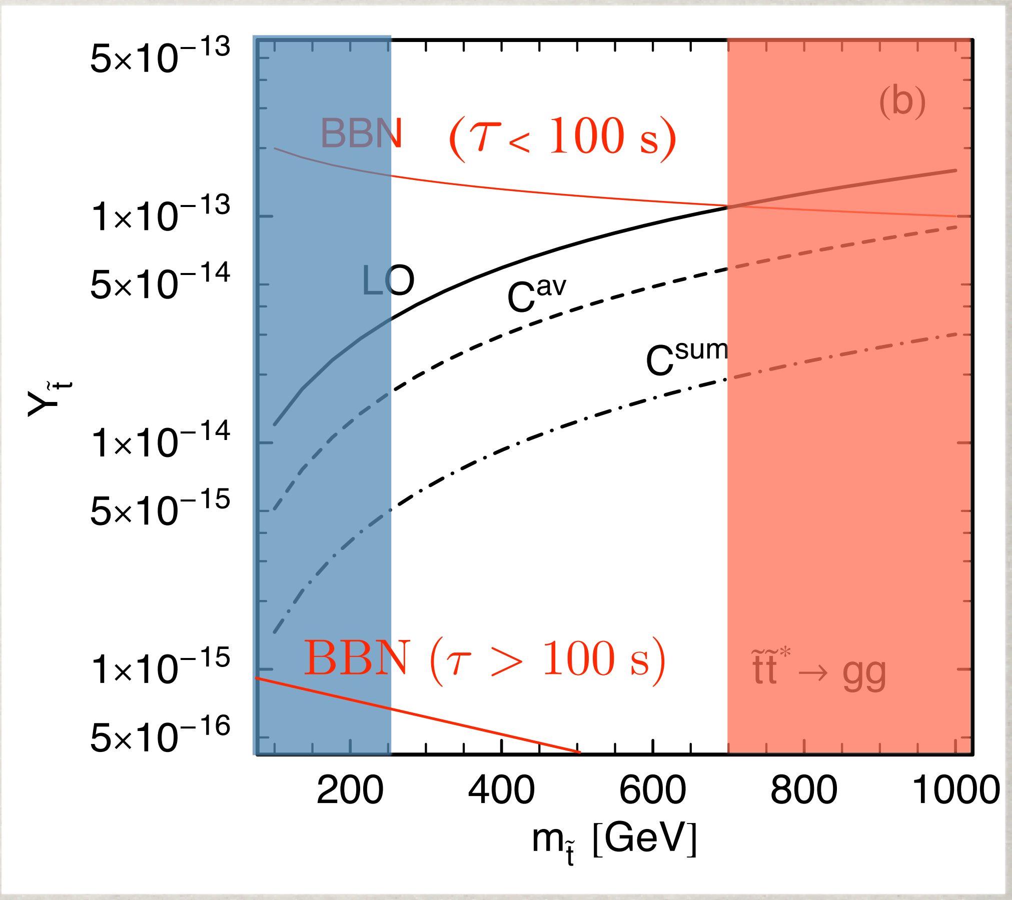
This gives a factor 2/3 reduction in the relic abundance, after being convoluted with Maxwell-Boltzmann !

STOP NLSP

- 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 and evade the BBN bounds for $\tau < 10^7 s$ up to m< 700 GeV, if the annihilation approches the unitarity limit, no need to invoke $\sigma \propto 1/\Lambda^2_{QCD}$ from bound state effects as in [Kang, Luty & Nasri 06]

[Berger, LC, Kraml, Palorini 08]



Excluded by Tevatron

STOP HADRONIZATION

[Gates & Lebedev 00]

- At the QCD phase transition, stops hadronize with the quarks and produce mesinos and shadrons:

$$S^{+} = \frac{1}{\sqrt{2}}(\tilde{t}(ud - du))$$

$$T^{0,+} = (\tilde{t}\bar{u}), (\tilde{t}\bar{d})$$

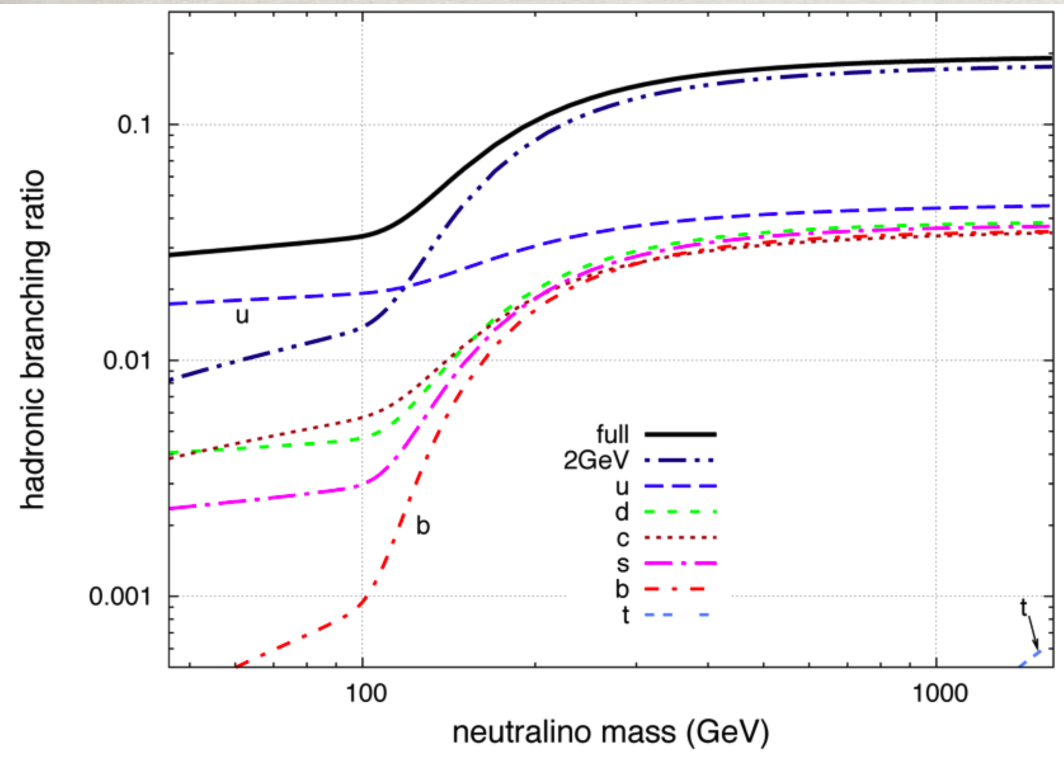
$$V^{++,+,0} = (\tilde{t}uu), (\tilde{t}ud), (\tilde{t}dd)$$

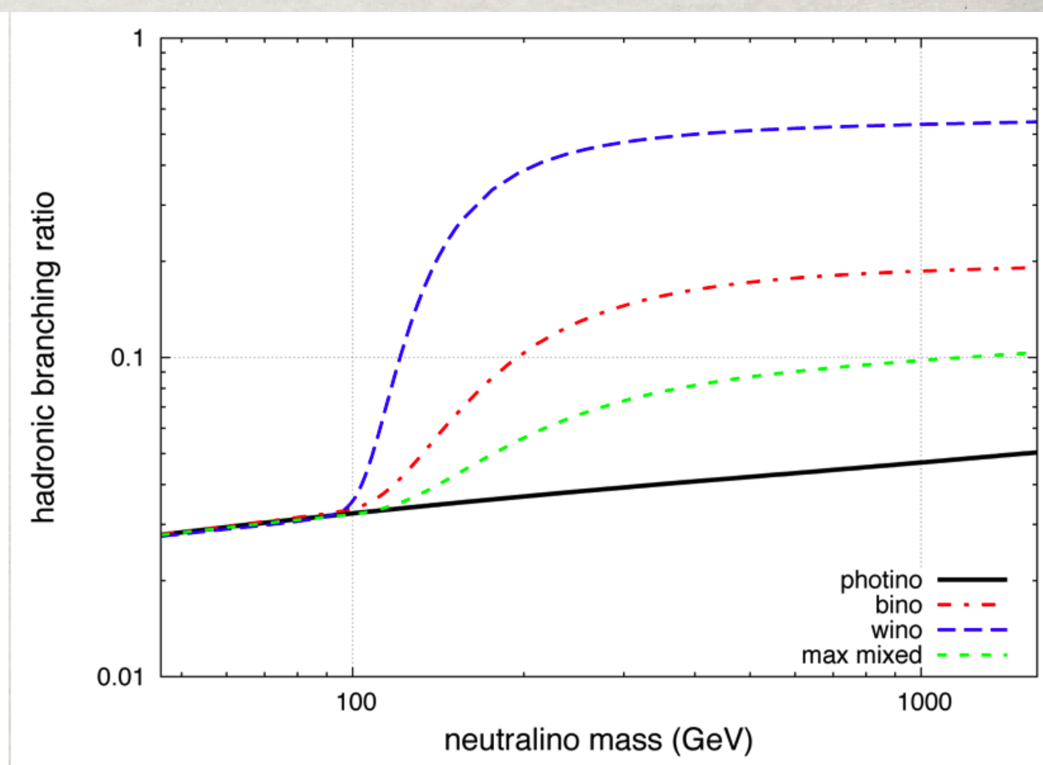
- $T^0, \bar{T}^0$ mixing a la $B^0, \bar{B}^0$ gives the lightest mesino mass eigenstate as the neutral T^1
- The lightest shadrons should be S^+ with a mass difference of 300-400 MeV to V's. It carries baryon number and cannot decay, but could get interconverted with p/n.
- But note: the density of stops for unitary cross-section is ~ three orders of magnitude below the BBN bounds

LHC should see a long-lived stop mesino/shadron !

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...

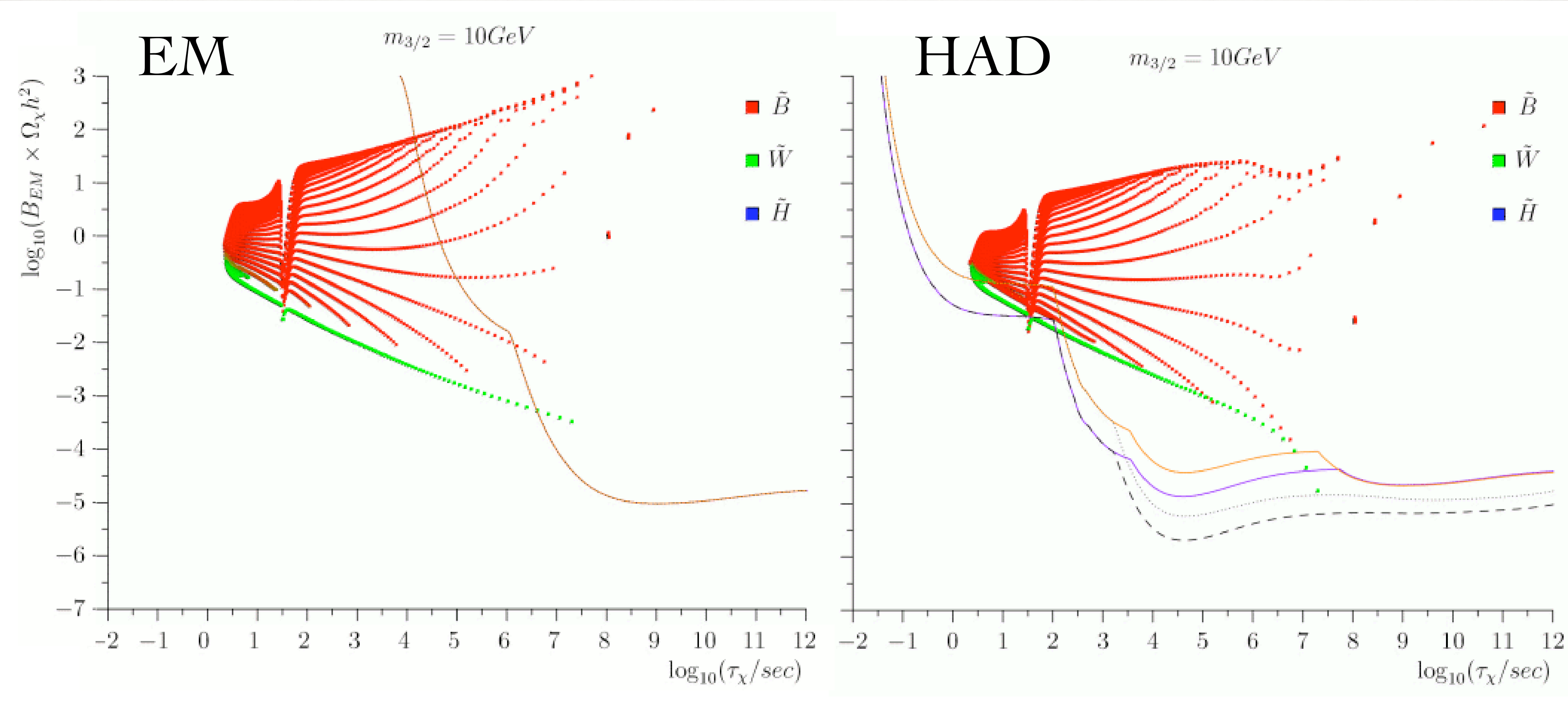
General neutralino NLSP

[LC, Hasenkamp, Roberts & Pokorski 09]

- 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 do not include the Sommerfeld enhancement in this case, since it becomes effective only at very large (Wino) masses above 2 TeV [Hisano et al 04, 06]
- 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

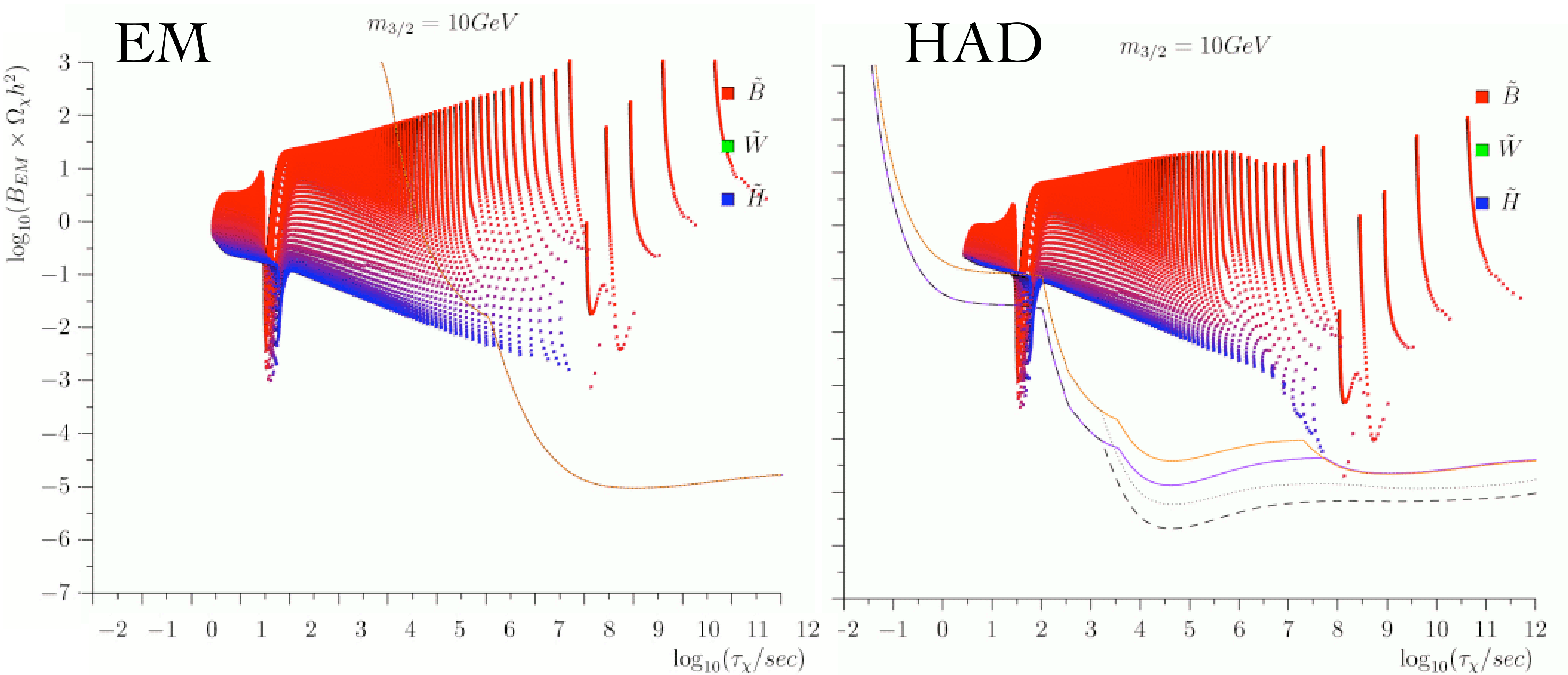
[LC, Hasenkamp, Roberts & Pokorski 09]



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]



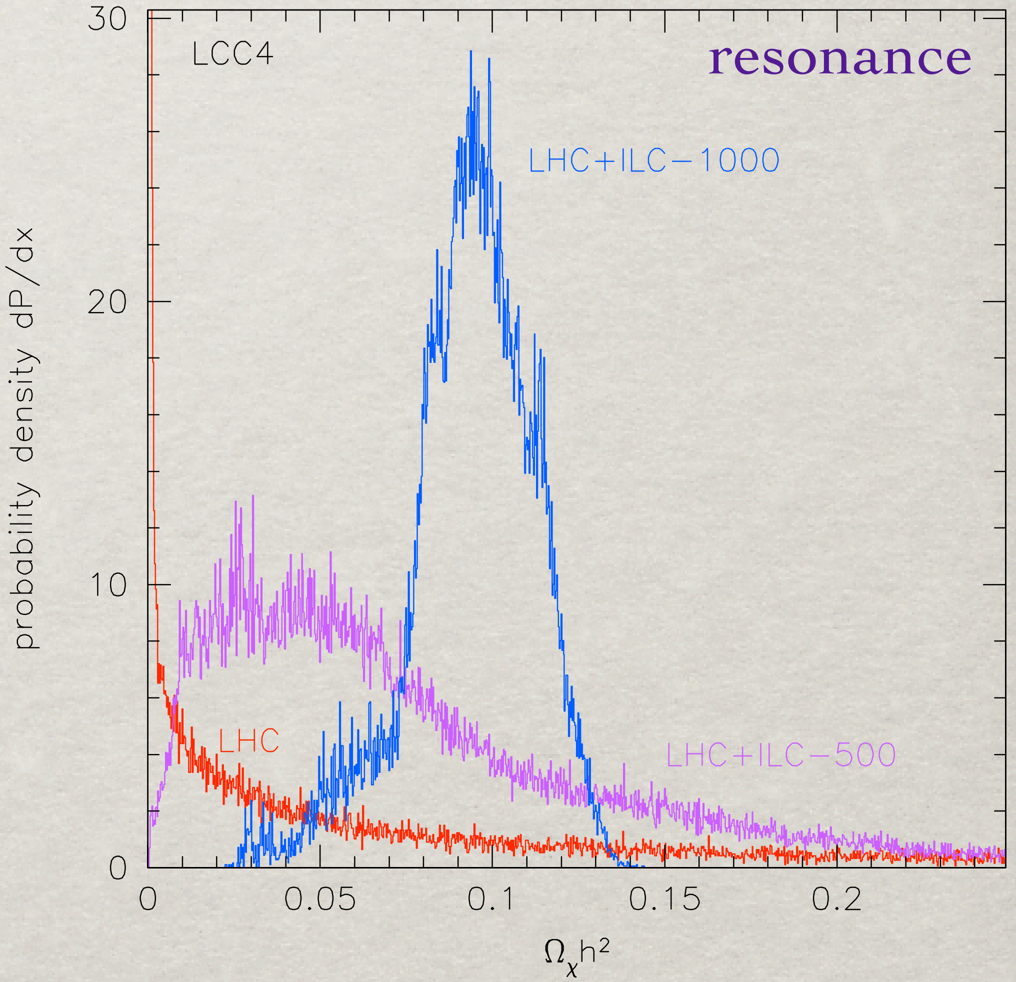
The resonant annihilation into heavy Higgses becomes much more effective ! Allows for a gravitino mass up to 10-70 GeV ! Need strong degeneracy: $2\, m_\chi \sim M_{A/H}$

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 !

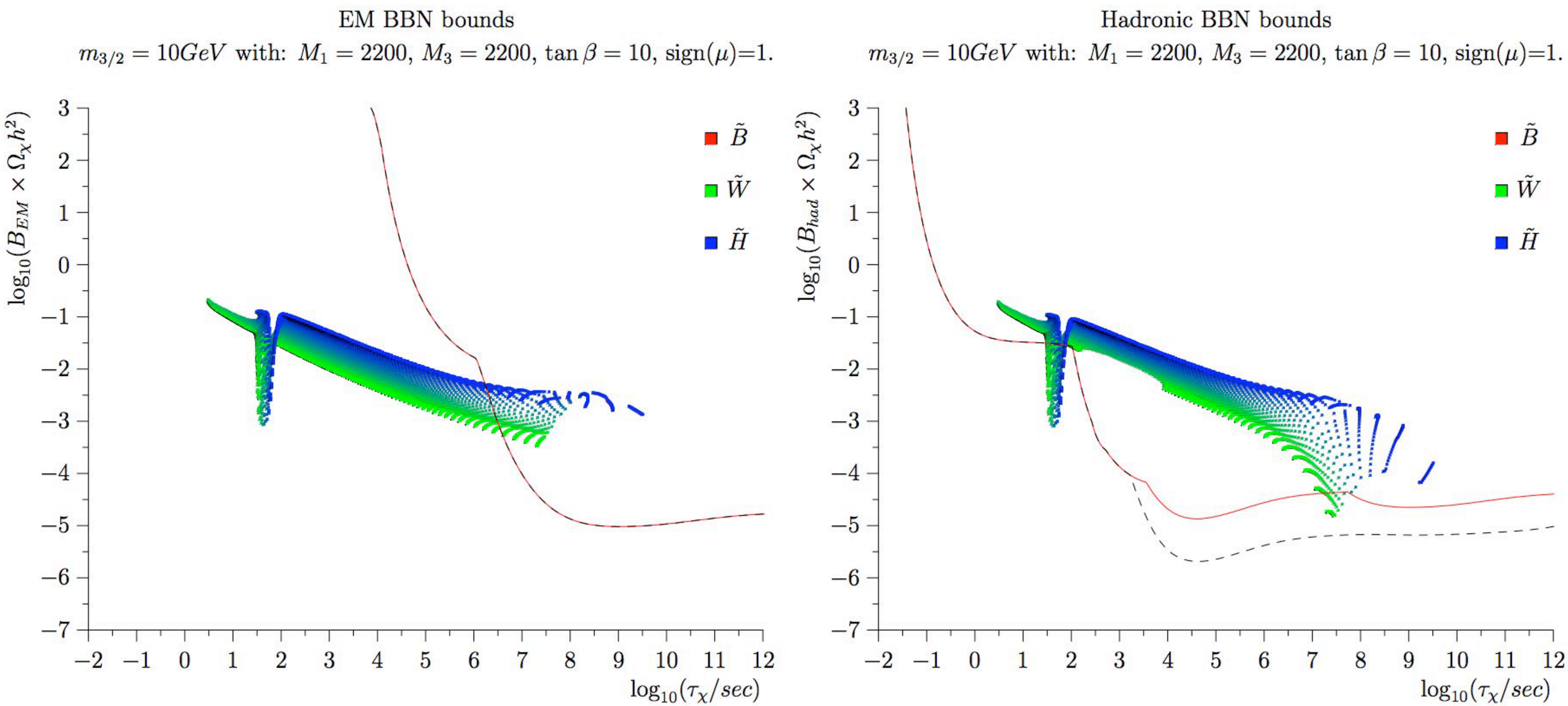
[Baltz, Battaglia, Peskin & Wizanski '06]



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

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...

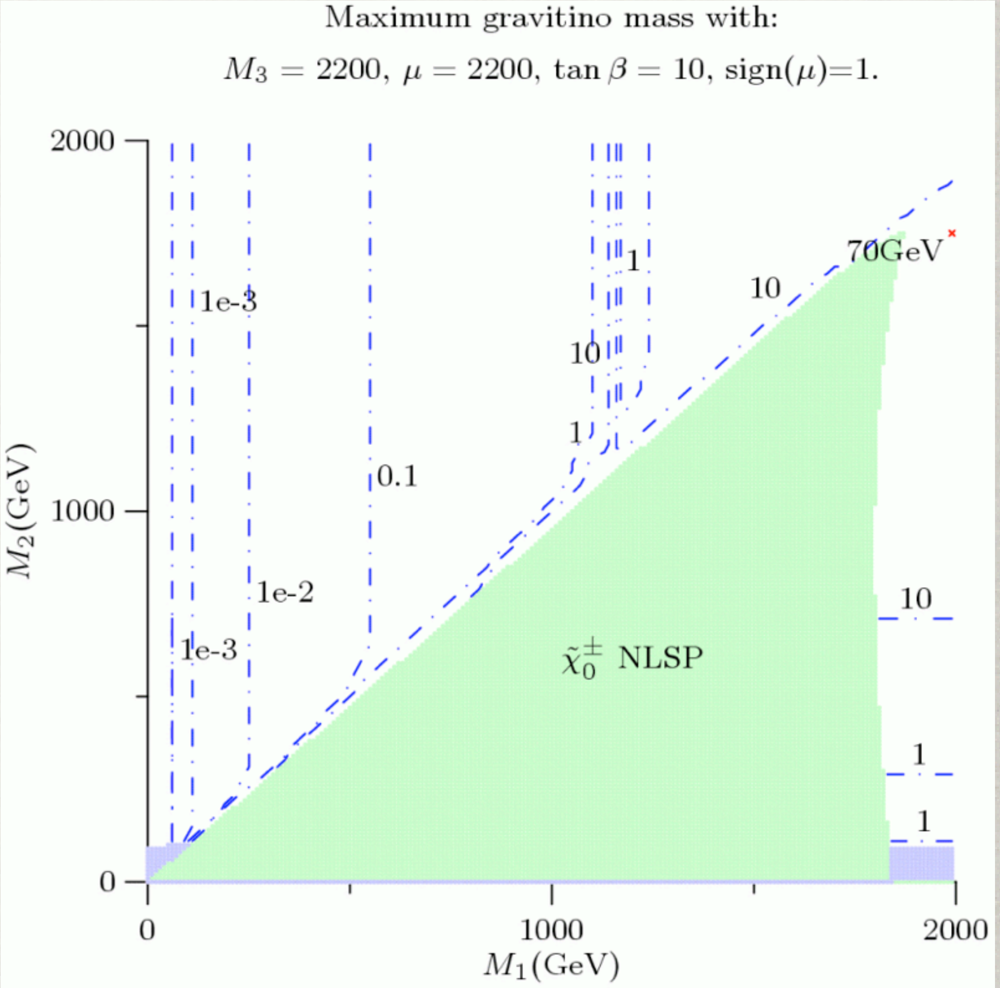
Light Wino window...

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

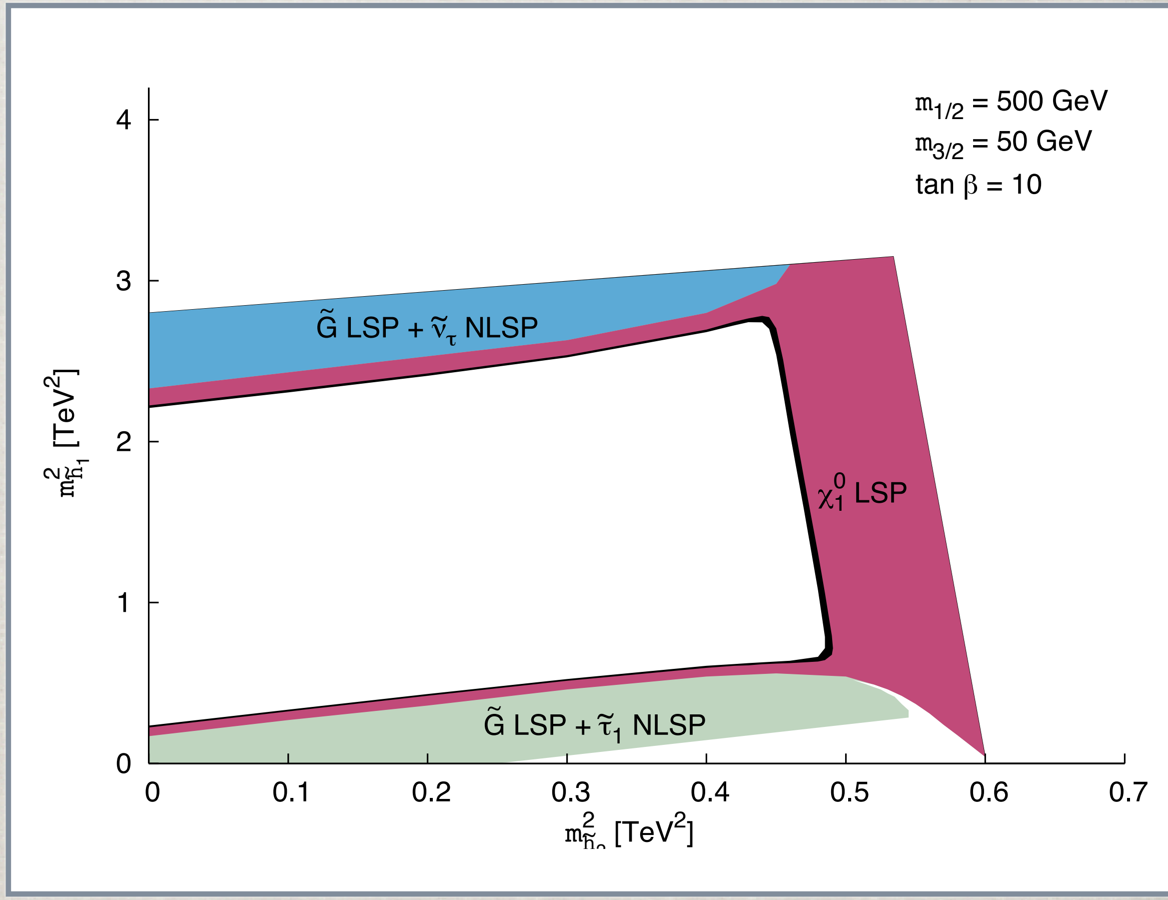
[LC, Hasenkamp, Roberts & Pokorski 09]



Gaugino mediation & DM

[Buchmuller, LC, Kersten & Schmidt-Hoberg 06]

- Non Universal Higgs masses driving the RGE evolution
- Vanishing other scalar masses and trilinear couplings
- ONLY viable DM: neutralino LSP
  gravitino LSP with sneutrino NLSP



Stau NLSP region restricted by bound state constraints

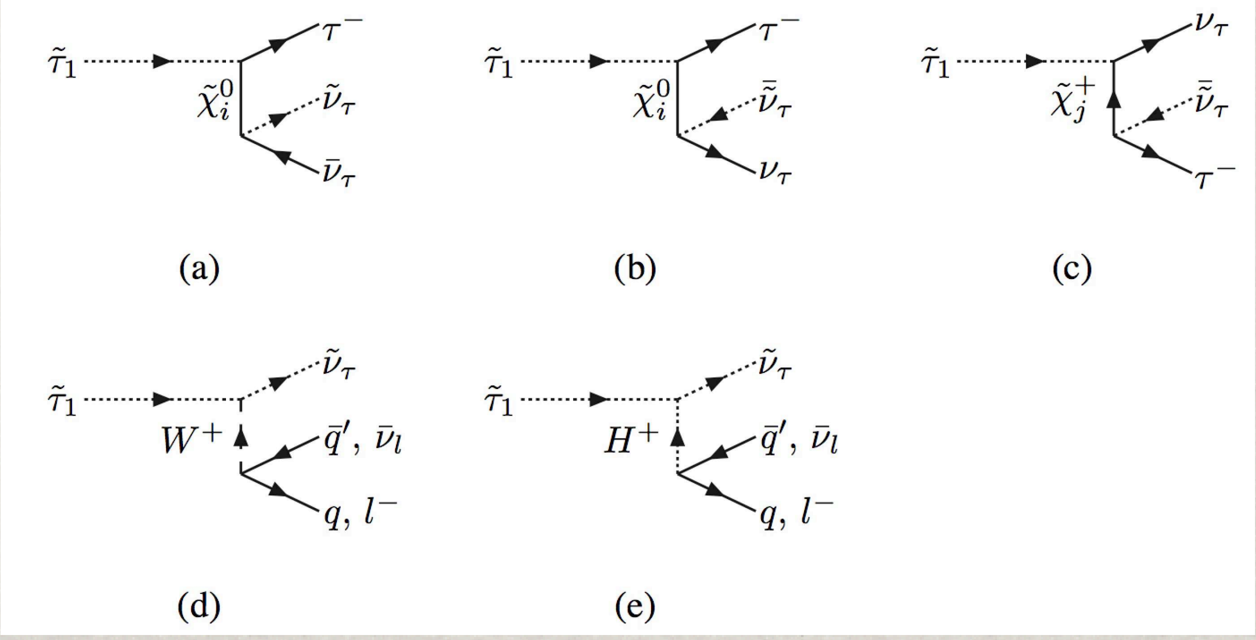
[Kersten & Schmidt-Hoberg 08]

Neutralino vs sneutrino:

Sneutrino NLSP at colliders

[LC & Kraml 07]

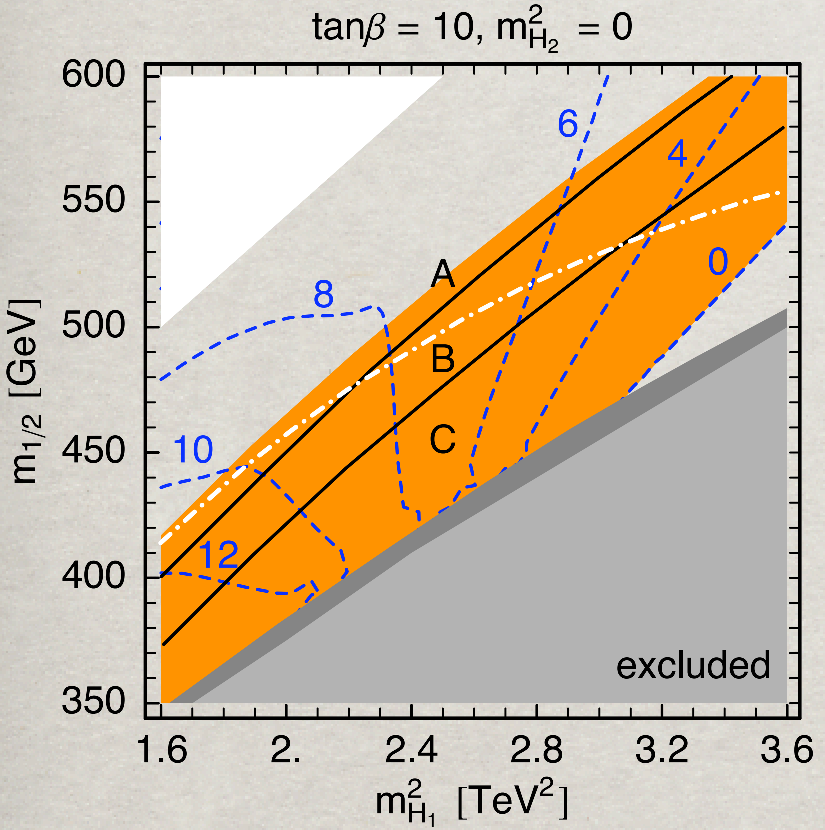
In general it is very difficult to identify if the missing neutral particle is a neutralino or a sneutrino..., but for gaugino mediation there is also another smoking gun: the sleptons are nearly degenerate and if the neutralino is heavier than the stau, the last decay of the chain is a three-body decay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

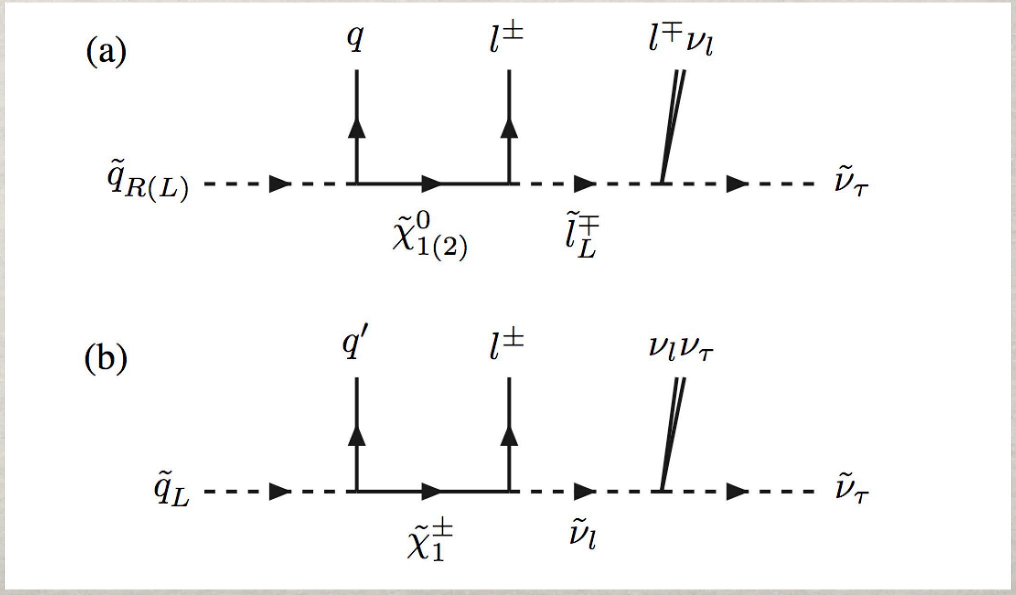
How to measure sneutrino NLSP in gaugino mediation

[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 $e^- e^+ \to \tilde{\nu}\tilde{\nu}\gamma$

Outlook

- Gravitino DM is pretty natural if such particle is the LSP and allows for relatively large $T_R \sim 10^{10}\mathrm{GeV}$ if the gravitino is not light... BBN constrains strongly the nature of the NLSP and favours efficiently annihilating particles or harmlessy decaying ones (if R-parity is conserved...).

- Collider experiments can shed light also on very weakly interacting DM: for the gravitino with mass larger than 1 GeV, clear signals are expected: e.g. a metastable stop NLSP or a neutral Wino/Higgsino with large annihilation cross-section or a sneutrino !

- In many of these cases the SUSY particles are nearly mass degenerate and ILC precision may be needed to disentangle different scenarios.