Sussex University, 24th August 2007

DARK MATTER CANDIDATES

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OUTLINE

- Introduction: Dark Matter properties
  Why Supersymmetry ?
- WIMPs: neutralino in the CMSSM
  sneutrino revisited
  non minimal models
- Gravitino/axino: production mechanisms
  BBN and NLSP
  R-parity or not R-parity...
- Other candidates with/out SUSY...
- Outlook

Intoduction: DARK MATTER Properties

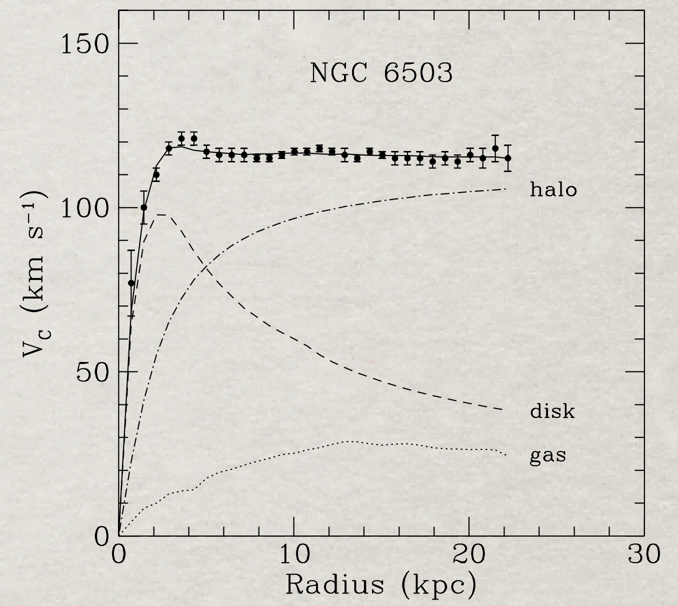
THE MATTER CONTENT

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

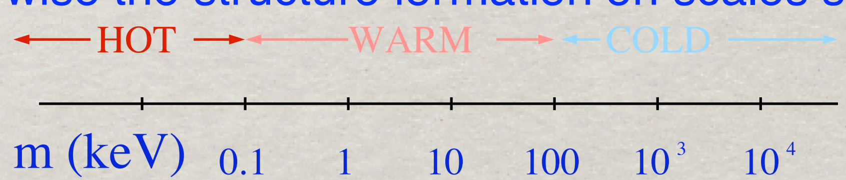
DARK matter !

[Begeman, Broeils & Sanders '91]



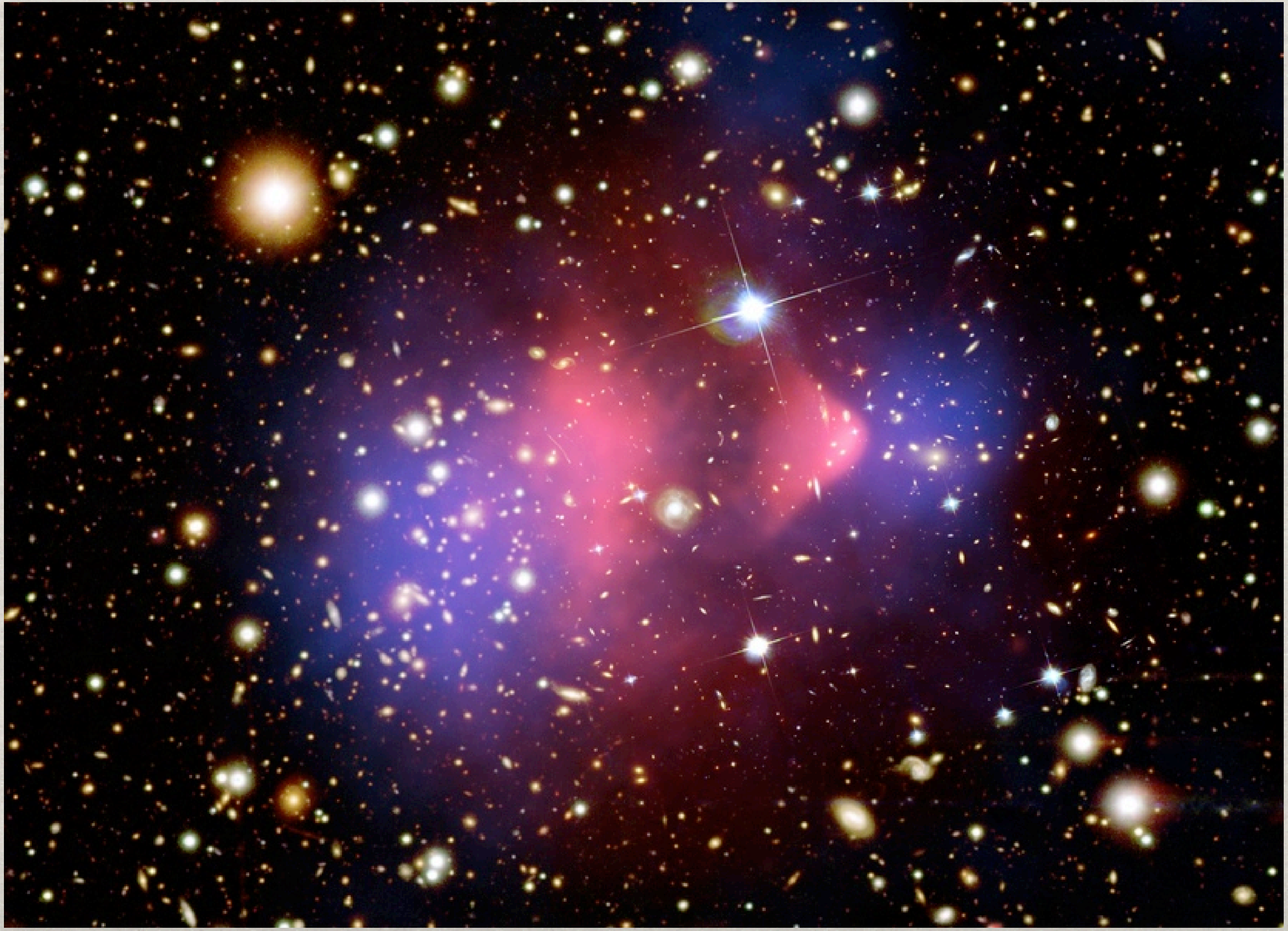
Note: DM first discovered in 1933 by F. Zwicki from the rotational curve of the COMA cluster...

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 !

Nowadays even more impressive evidence...: the BULLET CLUSTER 1E 0657-56



WHY SUPERSYMMETRY ?

- Theoretically attractive: gives gauge unification, solves hierarchy problem, etc...
- Provides a coherent framework to study different signal at colliders & DM experiments
- Has 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...

DARK MATTER
SUSY CANDIDATES

An infinite list...: any new neutral massive particle would do.
But most promising those predicted by minimal extensions...

- neutralino, superpartner of the photon/Z/Higgs
- sneutrino, superpartner of the neutrino
- gravitino, superpartner of the graviton
- axino, superpartner of the axion
- singlino, superpartner of the NMSSM singlet
- modulino, superpartner of the moduli....
- ...

Too many ???

Perhaps, but as theorists we can see it as a challenge: which particle is the LSP depends strongly on the SUSY breaking and trasmission 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 !

SUSY WIMP DM

THE WIMP MECHANISM

Primordial abundance of stable massive species

[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 until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

defined by $n_{eq} \langle \sigma_A v \rangle_{x_f} = H(x_f)$ and that gives

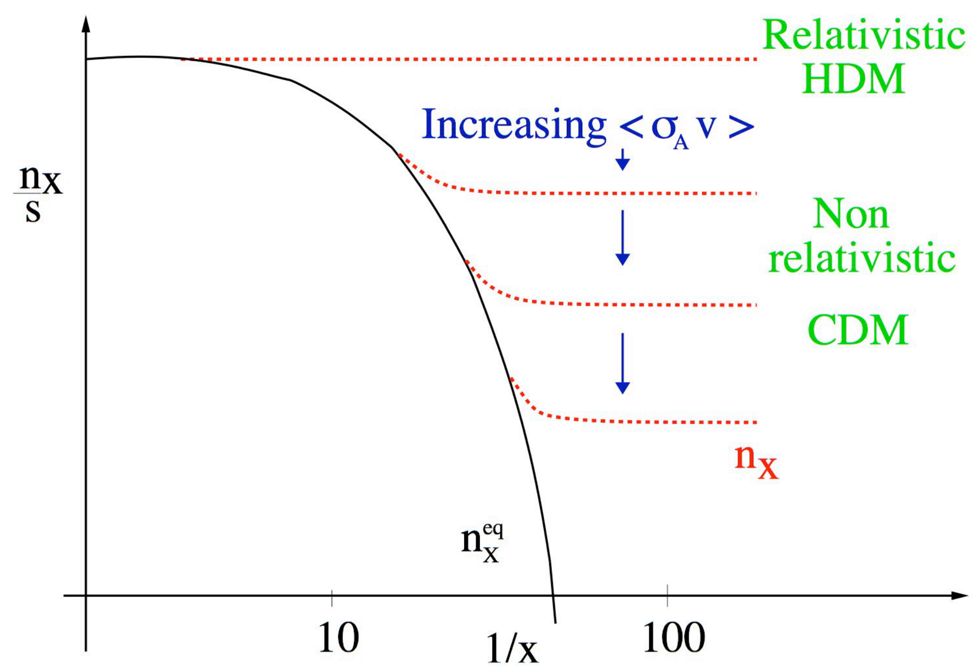
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



NEUTRALINO AS A WIMP

The neutralino is a ”natural” WIMP, but its composition, mass and its couplings change strongly depending on the SUSY breaking parameters and allow to span about 5 orders of magnitude in Ωh^2...

In particular in the CMSSM the neutralino cross-section turns out to be too weak (or its mass is too heavy) in most of the parameter space, apart in four scenarios:

- efficient annihilation into SM fermions (bulk region): needs light sfermions and it is nearly completely excluded by LEP bounds...

- efficient coannihilation with another superparticle, in the CMSSM the lightest stau , but in general also stops, sneutrinos, etc.. Note that in this case the number density is strongly dependent on the mass difference between the two particles (exponentially...);

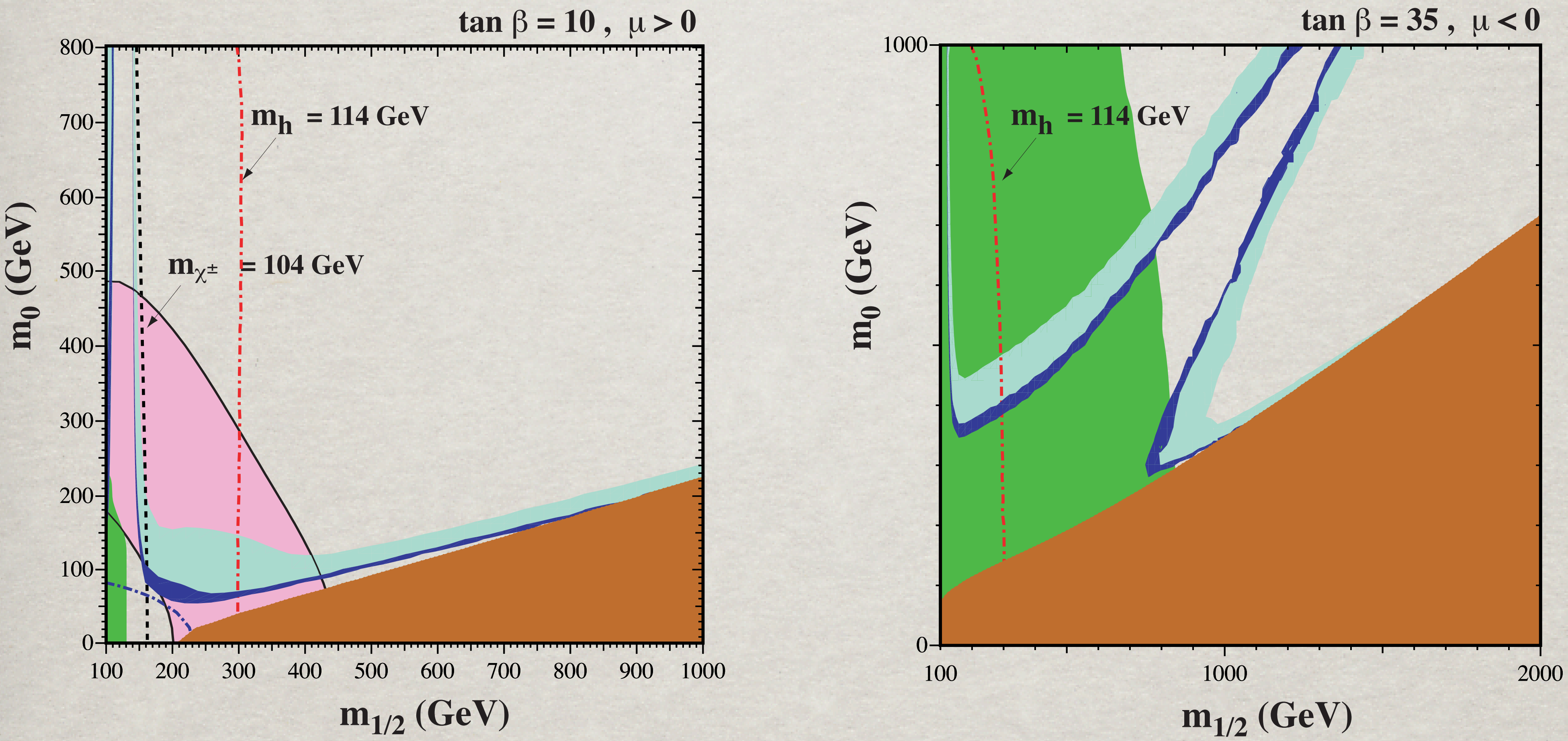
-enhanced annihilation near a Higgs resonance, again the mass of the neutralino has to be very near to e.g. half the A-mass and Ωh^2 strongly depends on the mass difference and Γ_A;

- large Higgsino component (focus point region): then the channel of annihilation into WW is open and reduces the number density sufficiently;

The different allowed regions present completely different particle spectra !

Allowed regions in the CMSSM after WMAP 1

[Ellis, Olive, Santoso & Spanos 03]

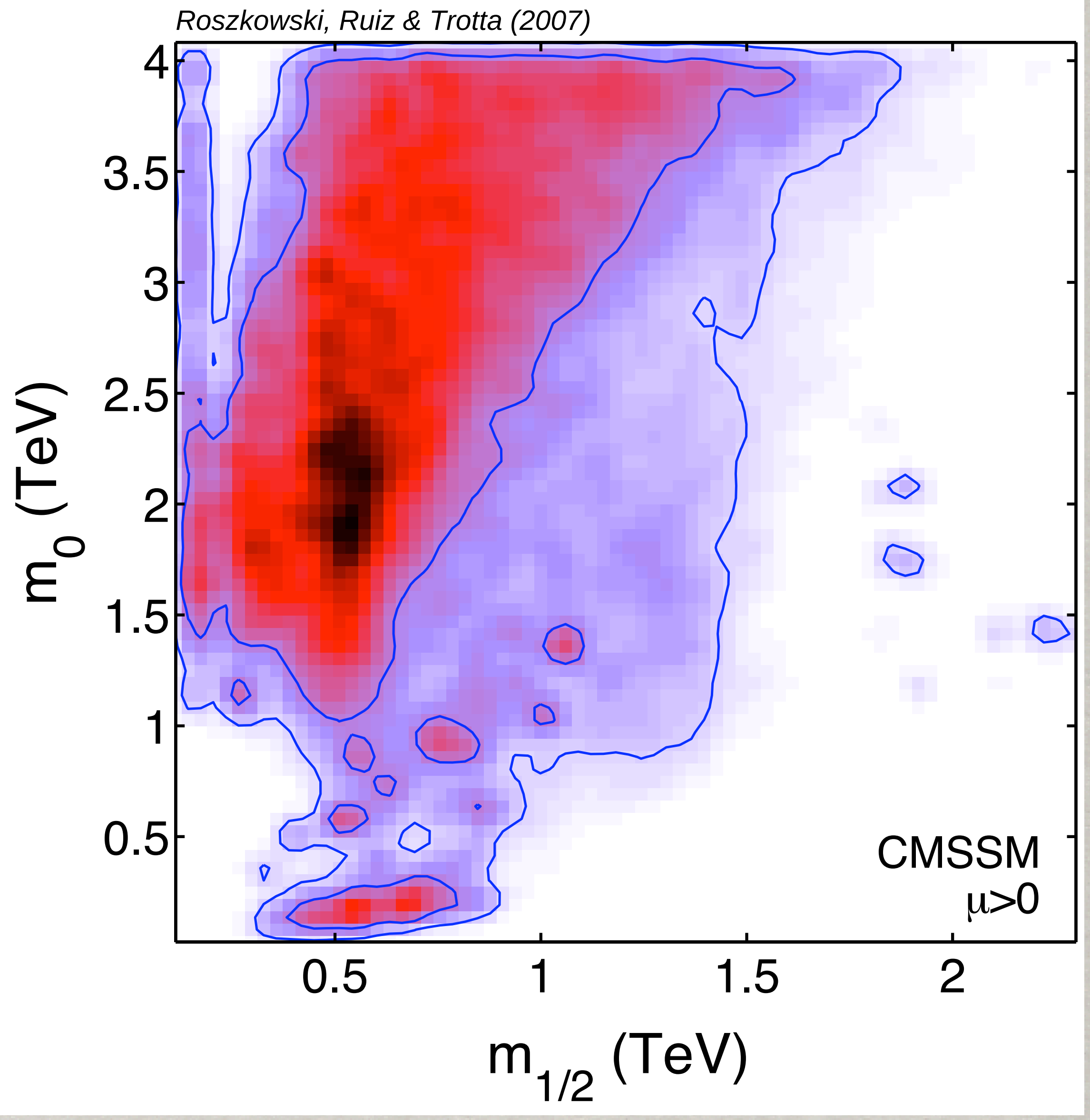


Tiny strips in the parameter space are allowed...
the natural WIMP bulk region is excluded by LEP.

Use instead Bayesian statistics

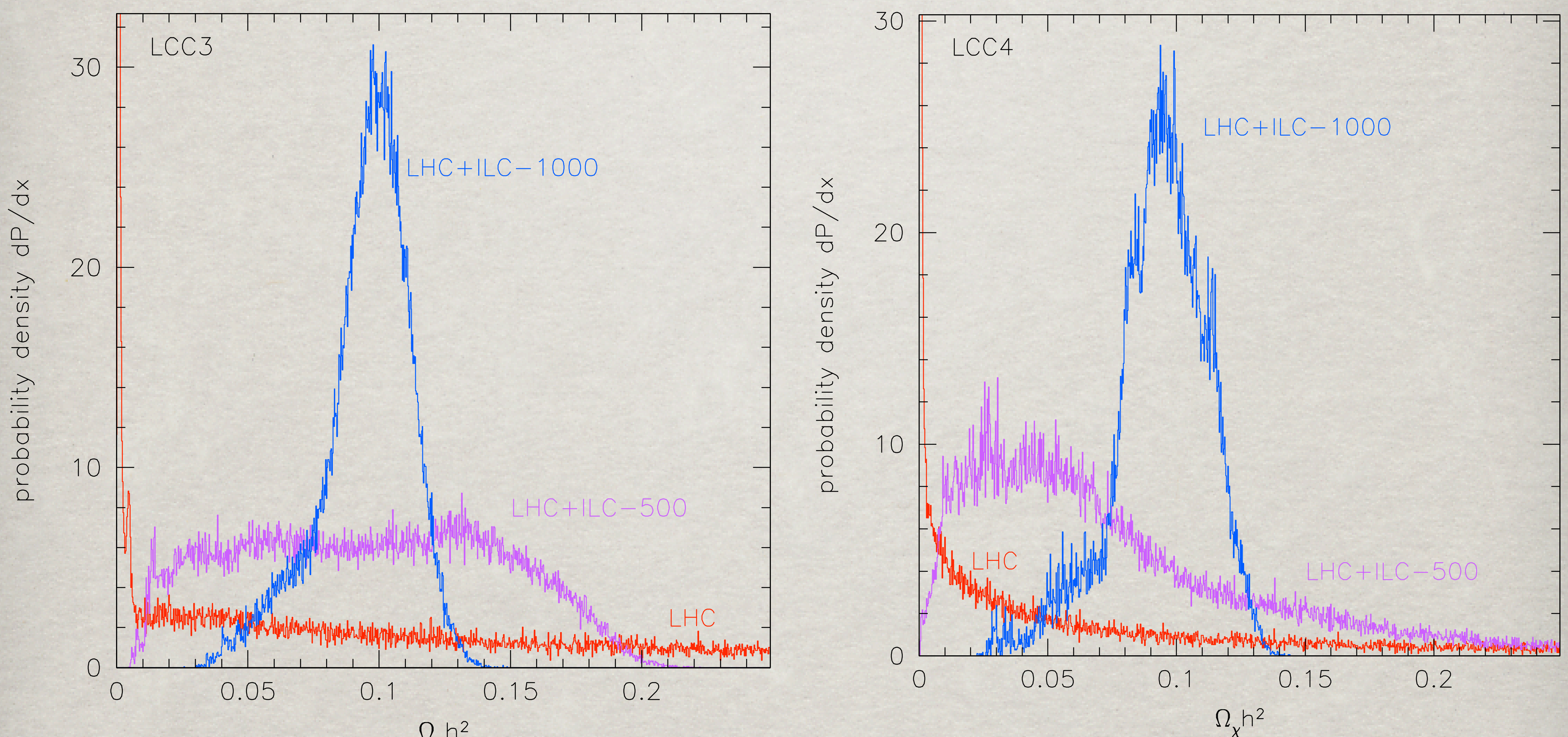
Allanach et al 07, Roszkowski et al 07

- Much wider regions are allowed and LHC could find SUSY nearly anywhere...
- Clearly though tuning of certain parameters is necessary to obtain right DM abundance.
- Unfortunately there is still dependence on the priors.



CAN LHC 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...

Sneutrino DM revisited

The sneutrino is also a WIMP candidate within the MSSM, but in the classical setting it is excluded, either by the Z invisible decay width or by DM direct searches.

If the coupling of the sneutrino to the Z is suppressed by mixing, those bounds are relaxed and it could still be possible to have sneutrino LSP as DM candidate.

[Hall, Moroi & Murayama 97]

If the neutrino is purely Dirac with a tiny Yukawa coupling, also a pure RH sneutrino could be DM as a very weakly interacting candidate, not a WIMP.

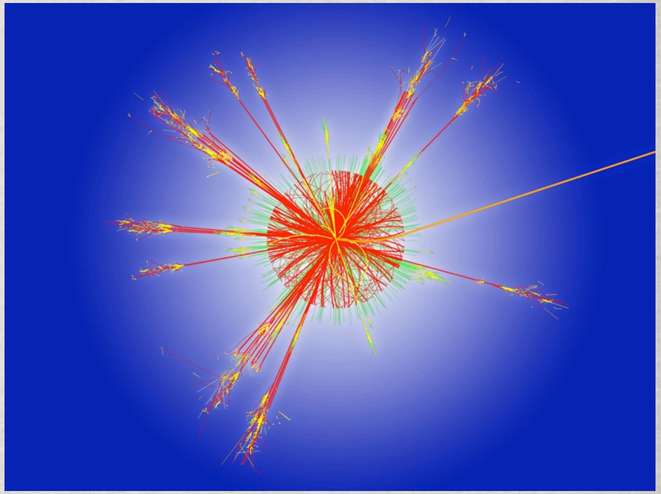
[Asaka et al, Gopalakrishna et al,...]

More general models:

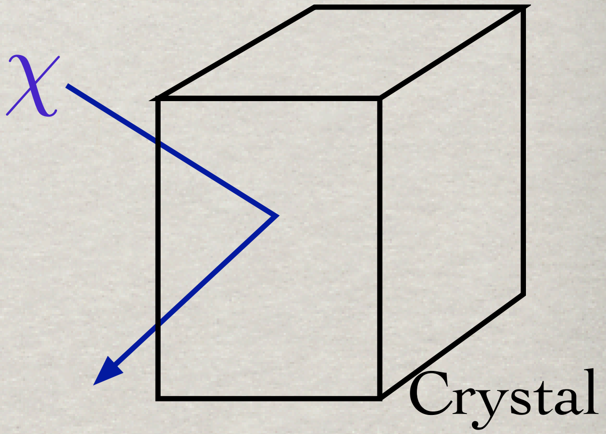
- NMSSM or nMSSM
  [Carena et al, Belanger et al,..]
- MSSM with CP violation [Scopel et al,..]
- Mirage mediation/compressed SUSY, i.e. low unification scale
  [Baer et al, S. Martin, Sandick et al]
- Non Universal Higgs Masses
  [Ellis et al, Wells et al,..]
- .....

THE HOPE:
DETECT DM IN MORE WAYS !

- At future colliders like the LHC at CERN or the ILC somewhere in the world... If it is a neutralino it is possible !



- In direct experimental searches in various underground laboratories or indirectly by looking at photons, cosmic rays or neutrinos



STAY TUNED: WE WILL KNOW MORE SOON...

gravitino/axino Dark Matter

GRAVITINO properties: completely fixed by SUGRA !

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

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

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 $m_{\tilde{G}}$!

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

CAN CDM 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

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.

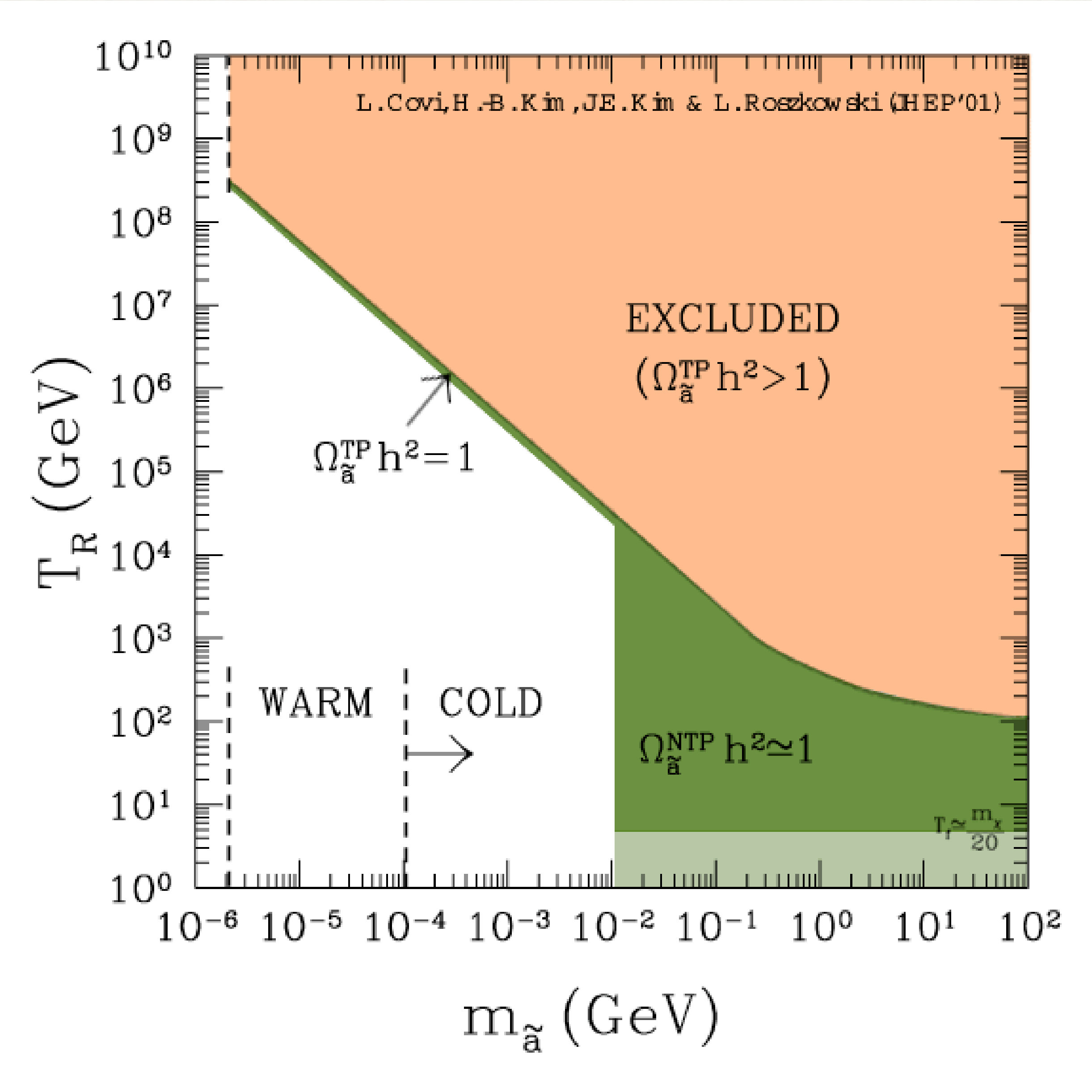
For contributions from other gauge groups, top Yukawa and thermal corrections see the recent papers [Pradler & Steffen 06, Rychov & Strumia 07].

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



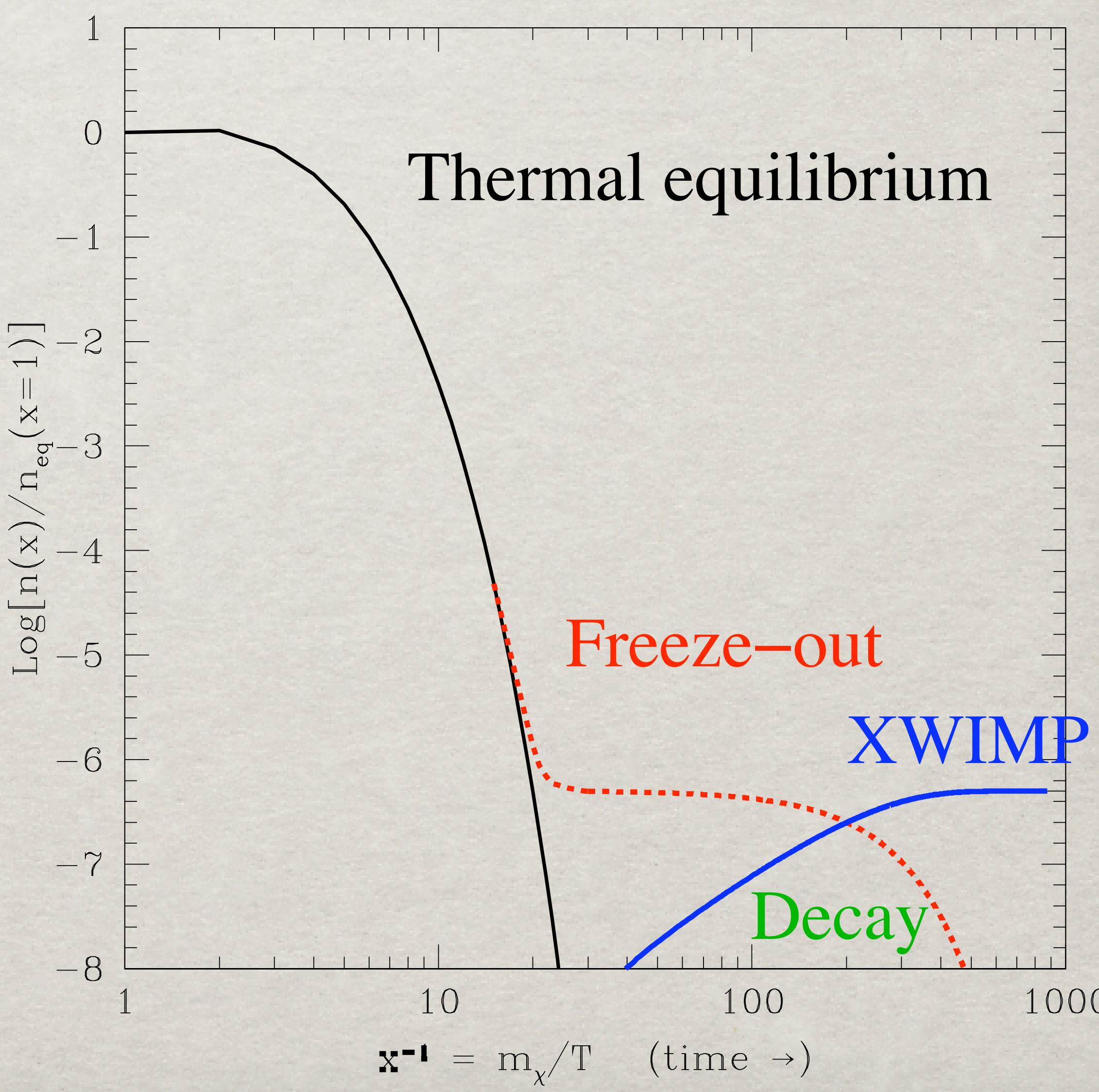
NLSP DECAY

[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

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

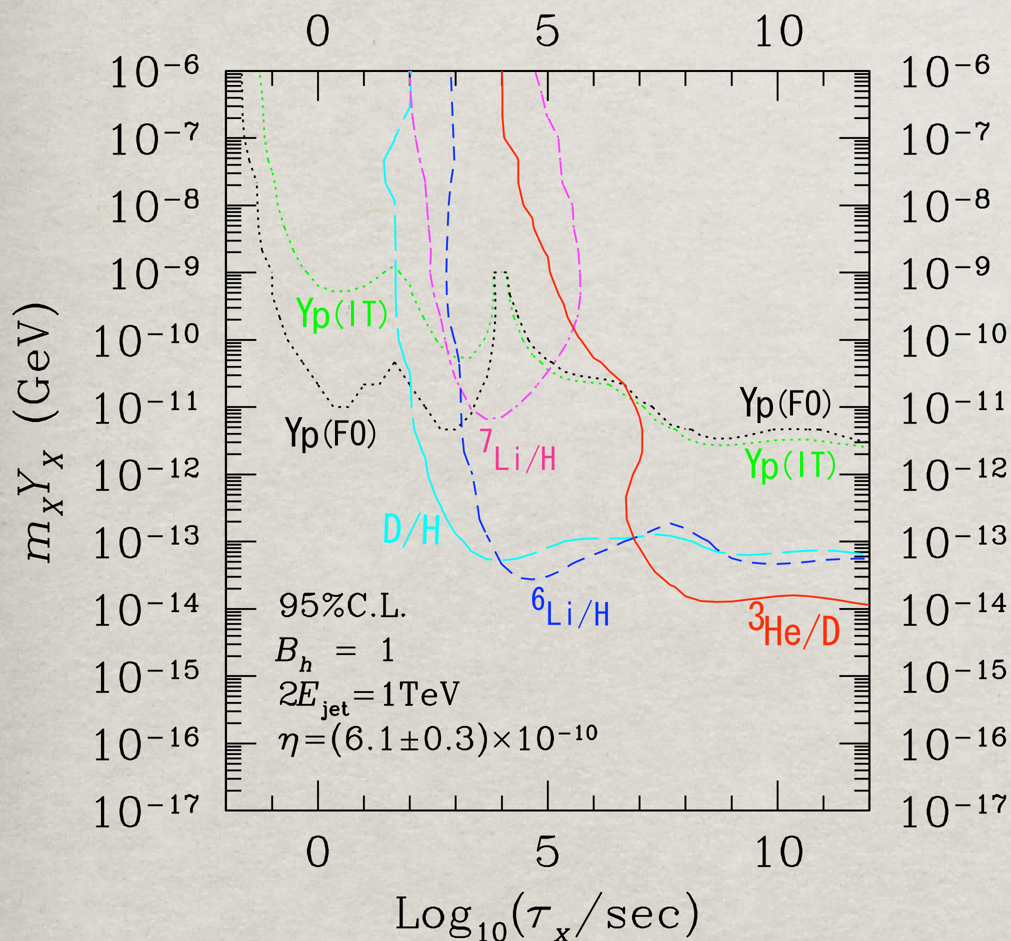
- The LSP is not thermal
- Other energetic particles are produce in the decay: beware of BBN...



BBN bounds on NLSP decay

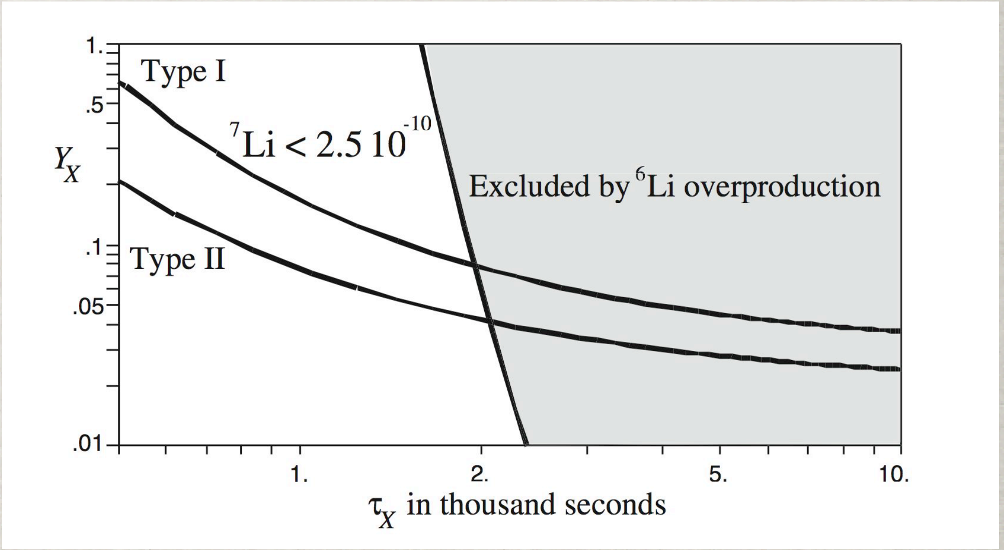
Neutral relics

[Kohri, Kawasaki & Moroi 04]



Charged relics

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



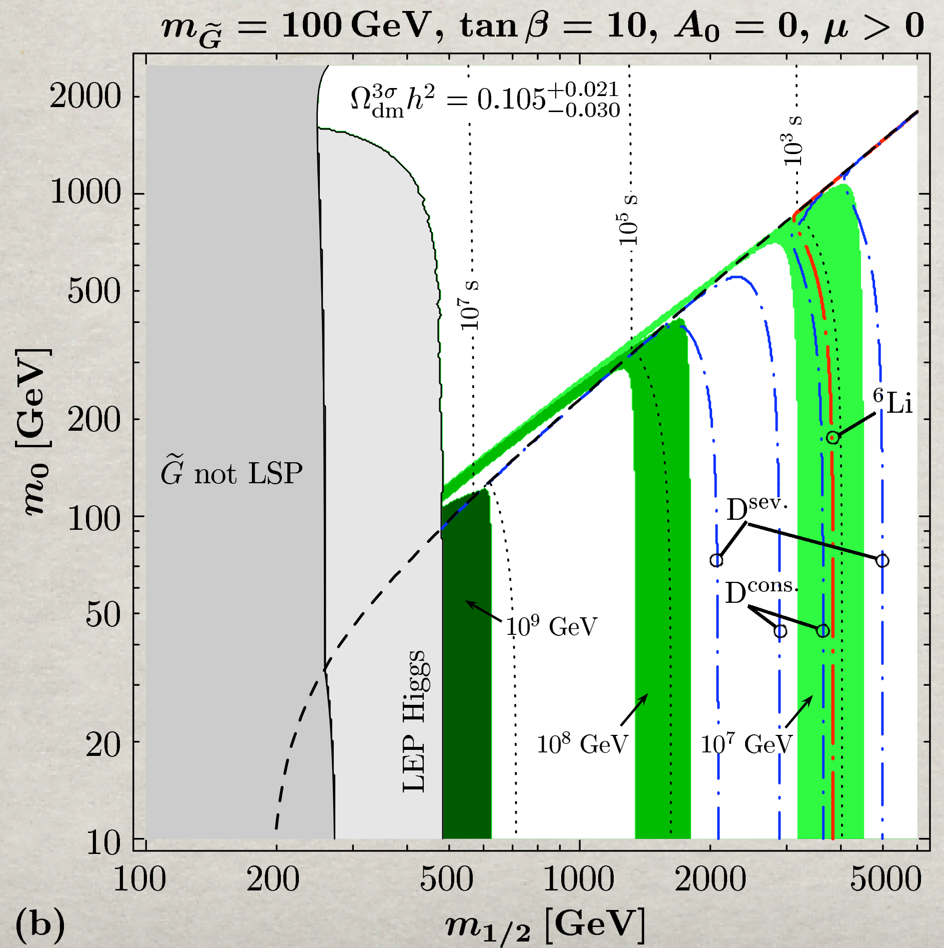
Need short lifetime & low abundance for NLSP

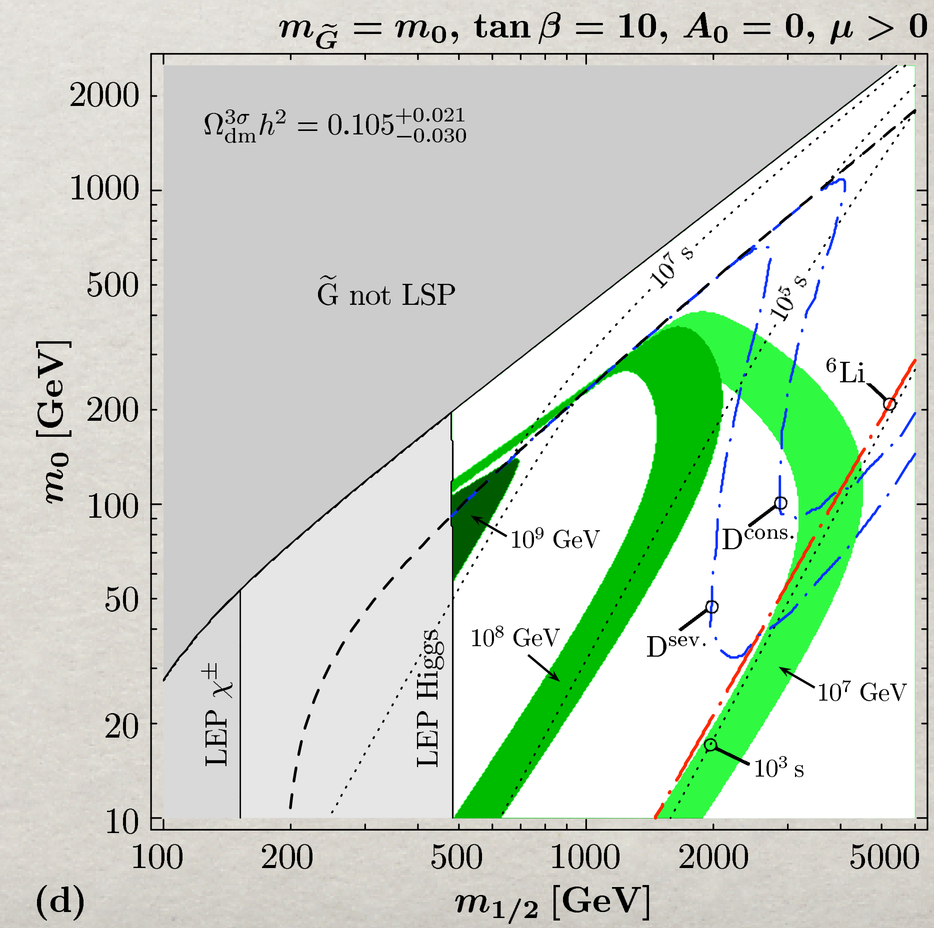
Big problem for gravitino LSP, not so much for the axino...

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]





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

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

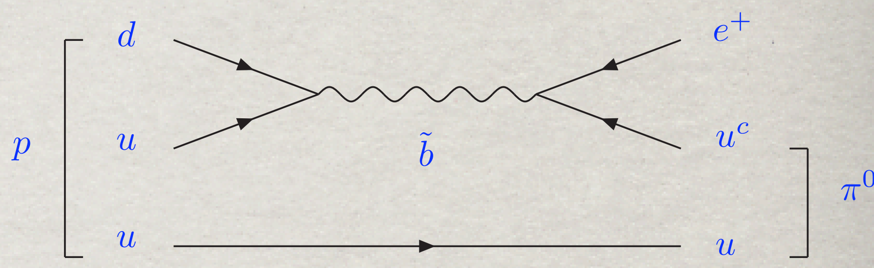
  violate R-parity

- Choose a harmless NLSP:
  sneutrino (weaker bounds...)
  stop (low abundance and annihilation at QCD transition)
  very long lived with abundance such to destroy $^6Li,^7Li$

- dilute the NLSP abundance with entropy production

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 $\lambda, \lambda' > 10^{-14}$.

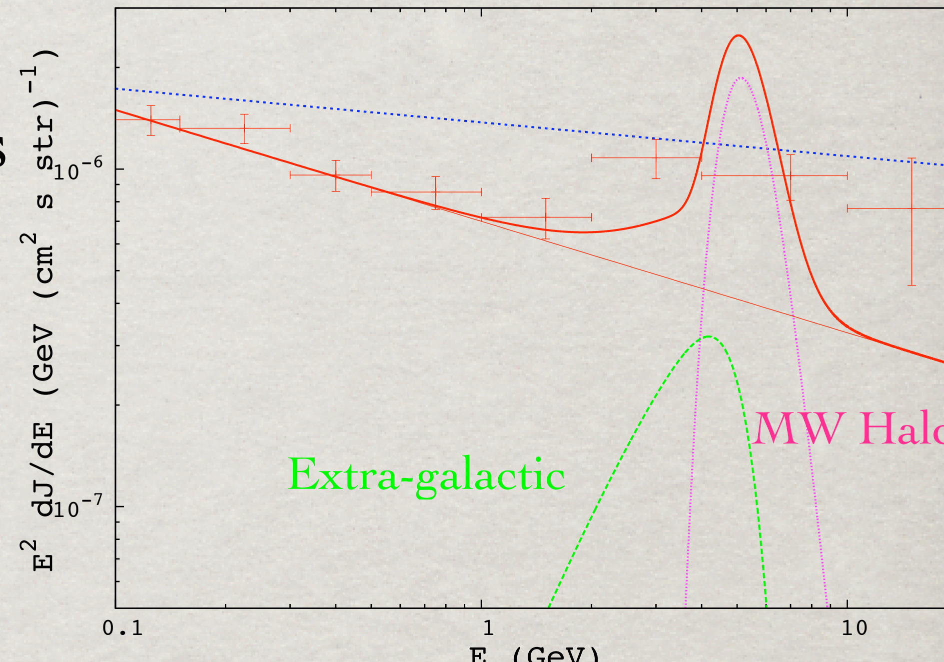
ANY NLSP is allowed if R-parity is broken and still we can have supersymmetric DM !

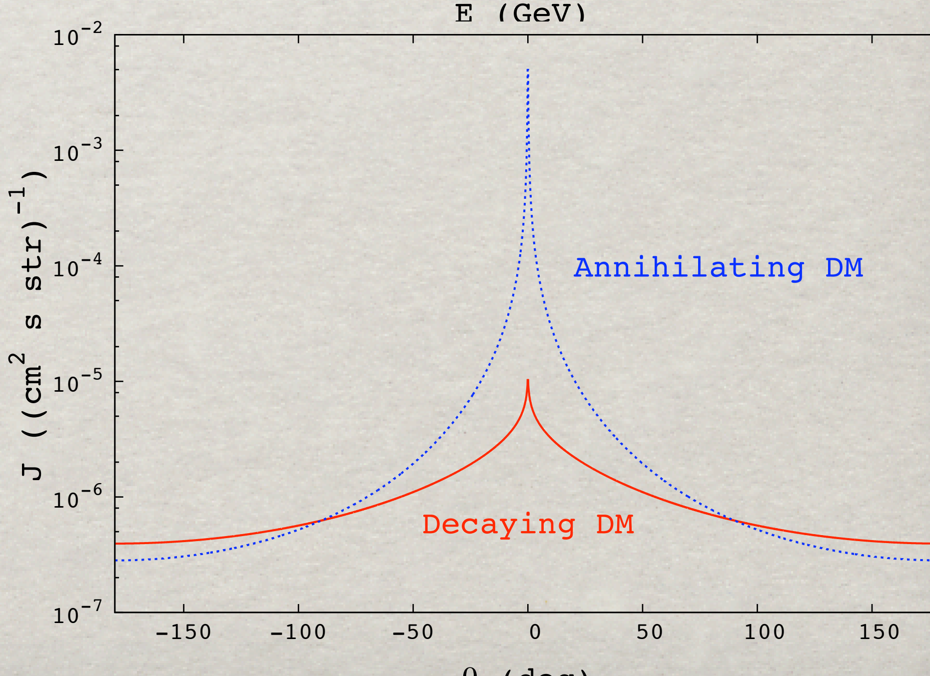
GRAVITINO CDM WITH R-parity VIOLATION

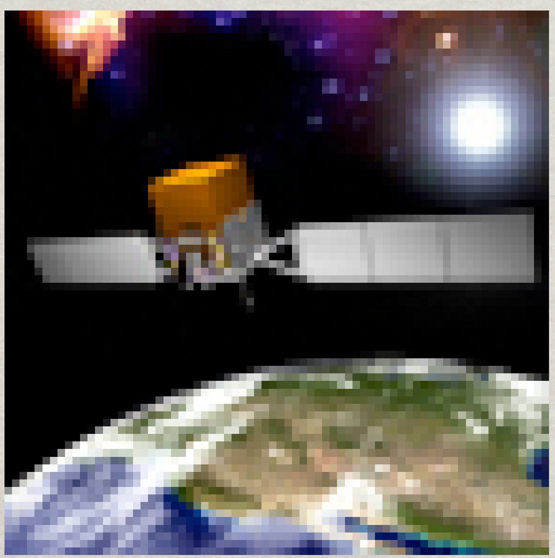
How to see the gravitino

For bilinear R-parity breaking, the gravitino decays into photon and neutrino of energy $\frac{m_{3/2}}{2}$

Look at the photons with GLAST or AMS-02 !







[Bertone,Buchmüller,LC &Ibarra]

But this is not all...:

Clearer signal at colliders: metastable charged NLSP !

The typical signal is a (meta)stable charged particle that escapes the detector leaving a highly ionized track (a heavier μ...).

Very difficult to miss and it would immediately tell us that the neutralino is not the LSP and not DM.

Note that if R-parity breaking is "maximal", $\epsilon_i \sim 10^{-7}$, the NLSP will decay inside the detectors at LHC with $c\tau_{\tilde{\tau}} \sim 30$ cm and give a striking signal !

Unfortunately if the stau does not decay in the detector, it is not possible to identify which is the LSP and if it is stable. We need to measure the decay in order to check if R parity is conserved or not and which is the LSP. There are infact also more "X"WIMP candidates...

$$\tilde{\tau} \to \quad \tau\psi_{3/2}, \tilde{a}, \ldots \quad \text{R-parity conserved}$$

$$\tilde{\tau} \to \quad \tau\nu_\mu, \mu\nu_\tau, 2\text{jets} \quad \text{R-parity broken}$$

See e.g. [Hamaguchi, Kuno, Nakaya & Nojiri 04] , [Feng & Smith 04] ,[Hamaguchi, Nojiri & de Roeck 06] for proposals about stopping long-lived $\tilde{\tau}$ around the LHC/ILC.

If the NLSP is a neutralino more difficult to disentangle...

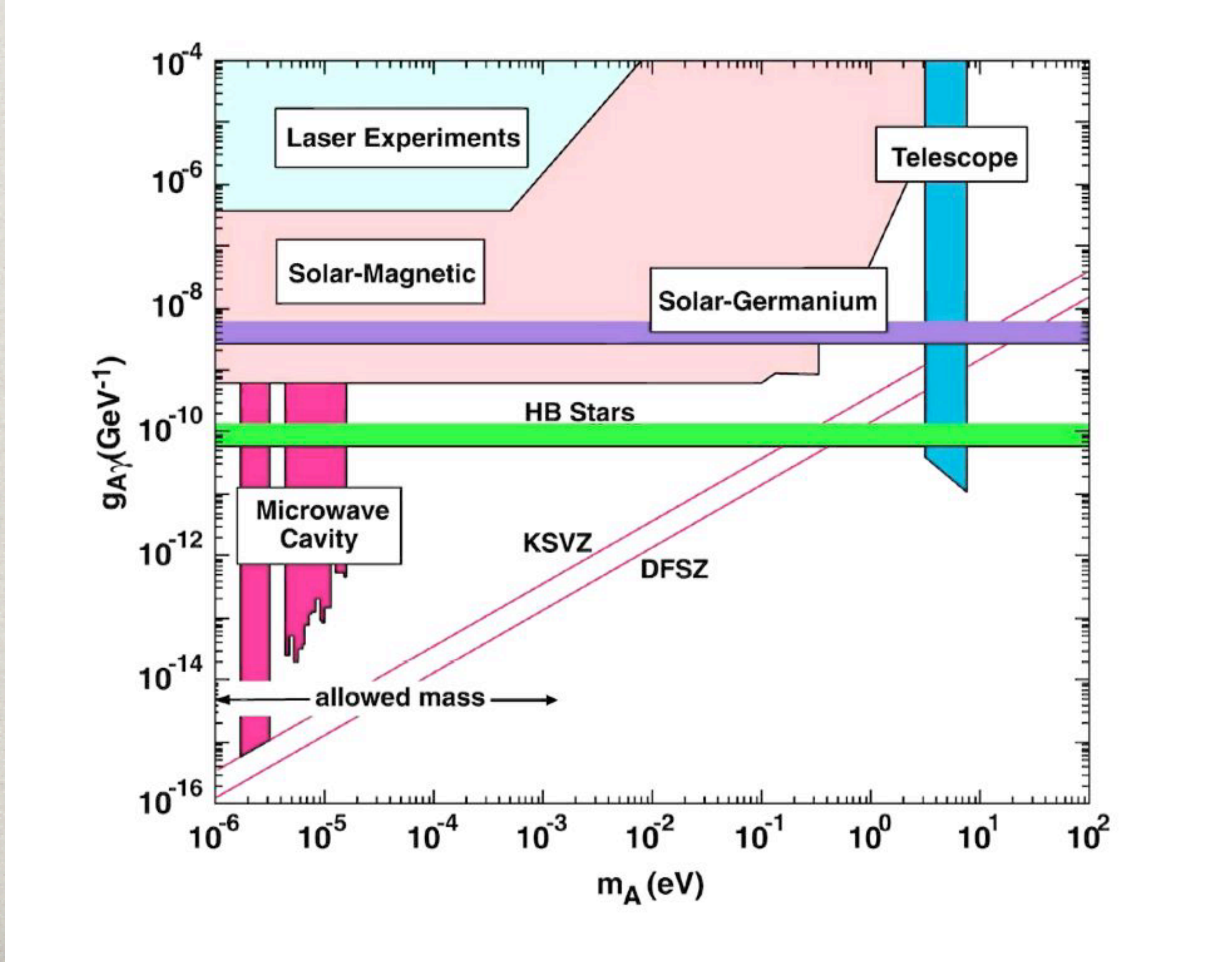
Other Dark Matter Candidates

AXION DARK MATTER

The axion is still a very good DM candidate. The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV.

[Carosi '07]

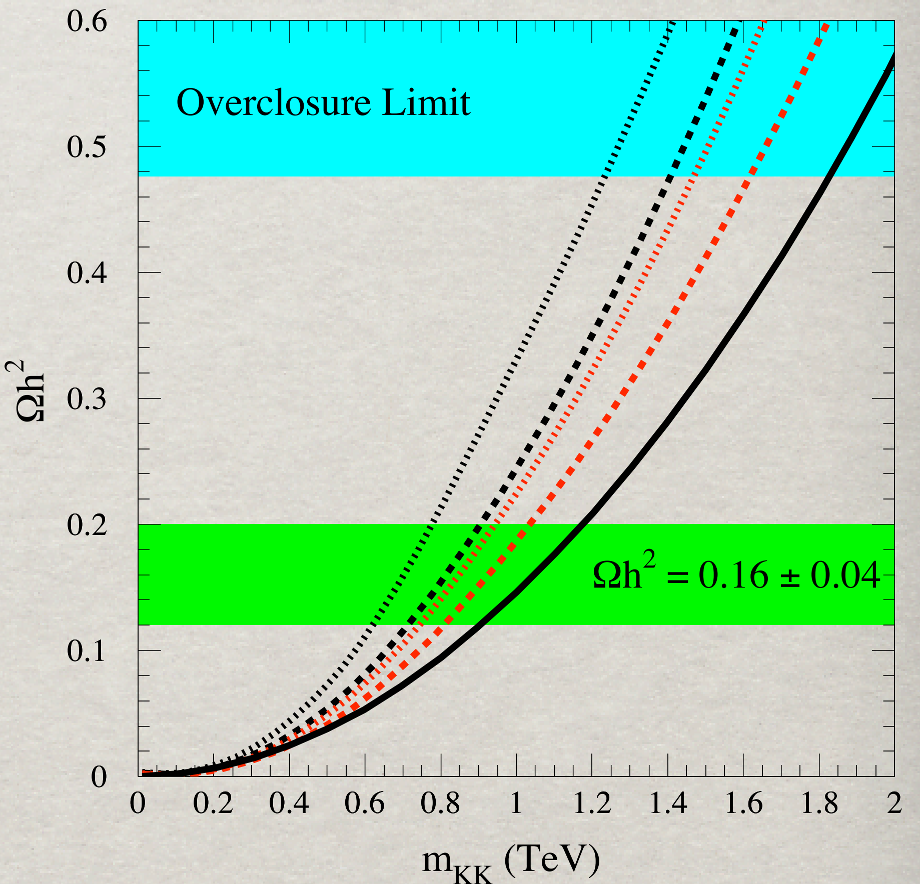
The ADMX experiment at Livermore is finally touching the expected region.



KK DARK MATTER

[Servant & Tait 02, March-Russel et al ....]

- The lightest Kaluza Klein state in LED stable due to KK parity is often the first Bino KK mode → WIMP



- But since the KK modes are degenerate, coannihilation effect are always important
- Difficult to predict the density and highly dependent on the mass splittings at one loop

Many more candidates as we heard here

- Sterile neutrinos A. Slosar
- Technicolor WIMPs J. Virkajaervi
- Inflaton condensate A. Liddle
- Antisymmetric tensor field T. Prokopec
- ...

Outlook

The next decade will bring us some answers:

- If the neutralino is DM the hope is not only to detect it at colliders, but in direct and indirect detection DM experiment and cross-check the results.
- If the gravitino or the axino are Dark Matter, the main signal is expected at colliders, but it would not be impossible to see indirect detection as well if R-parity is broken.
- There is good change that we will know soon !

A very exciting time ahead !