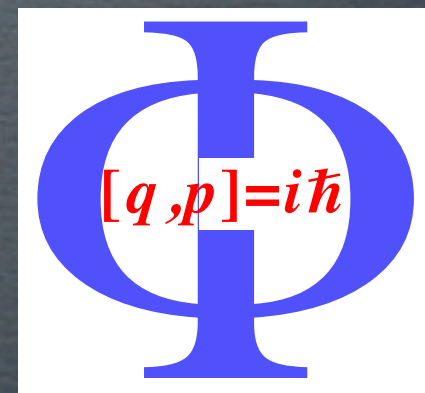# Dark Matter (2/2)

Laura Covi

Institute for Theoretical Physics

Georg-August-University Gottingen
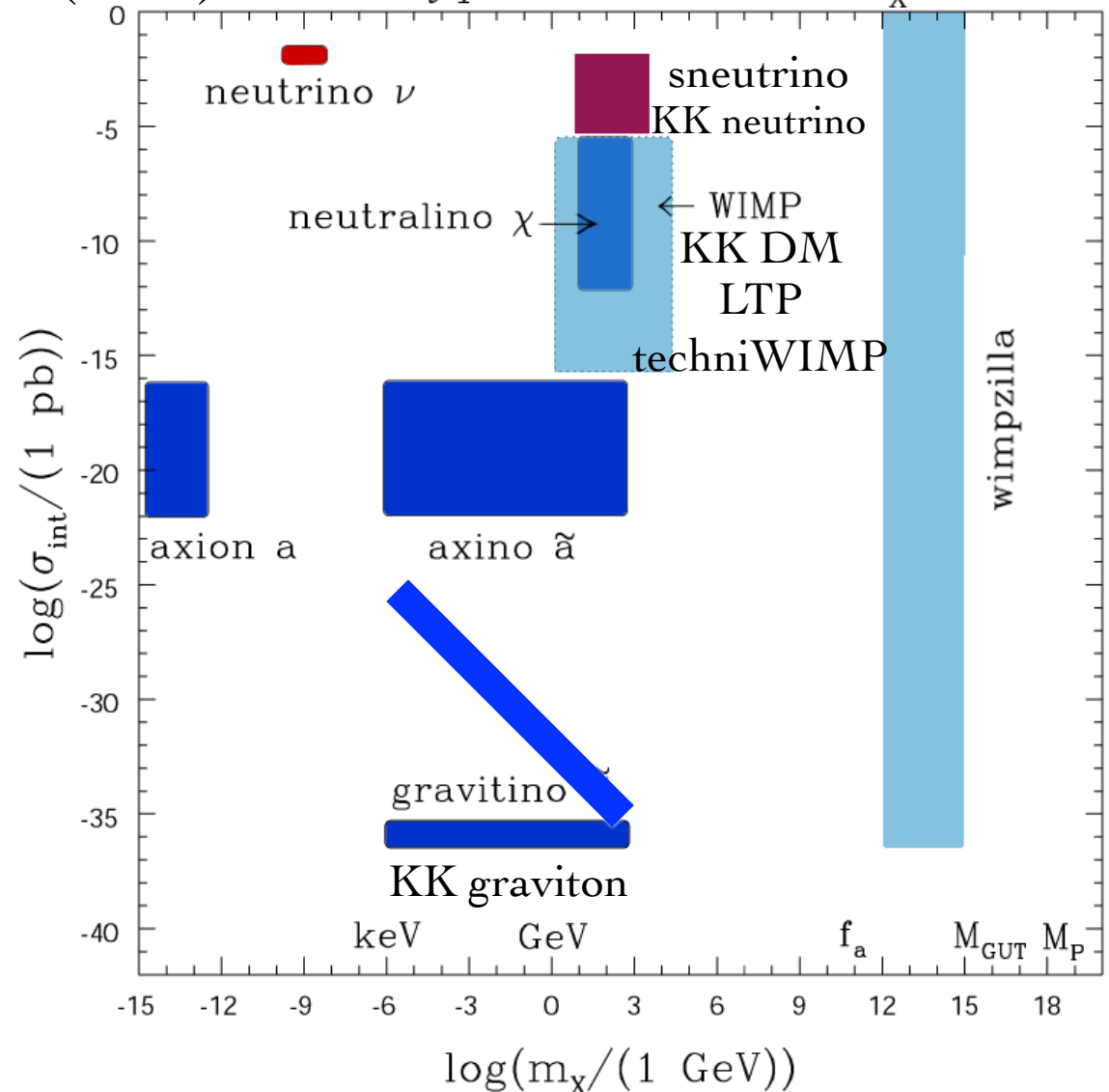
OUTLINE

- Introduction:
  Dark Matter, what we know about it...

- The WIMP mechanism/connection
  and how to detect DM particles...

- Some DM models:
  - SUSY DM: sneutrino, neutralino WIMP ?
  - Gravitino, SuperWIMPs and decaying DM
  - Axion DM

- Outlook

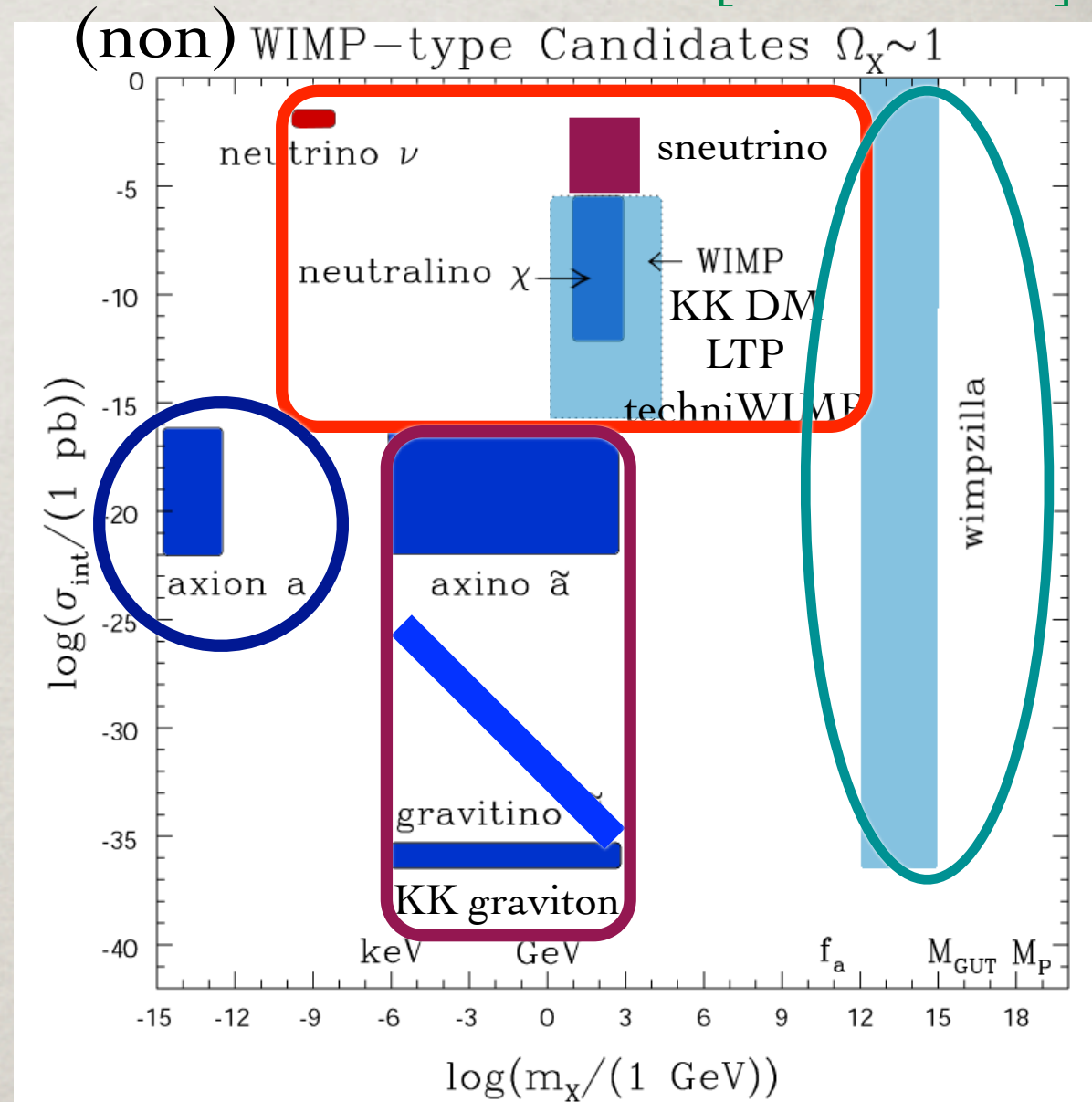# DM models

DARK MATTER CANDIDATES

[Roszkowski 04]

(non) WIMP−type Candidates $\Omega_X \sim 1$

DARK MATTER CANDIDATES

- Thermal relics: WIMPs

- "SuperWIMPs"

- Condensate

- Produced gravitationally

(non) WIMP−type Candidates $\Omega_X \sim 1$

DARK MATTER CANDIDATES

Let us look for candidates in extensions of the Standard Model

SUPERSYMMETRY: boson <-> fermion

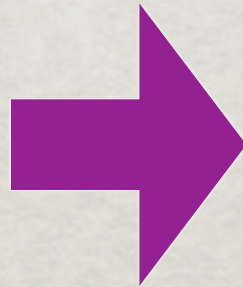| Standard Model	
Matter	Forces
e μ τ	γ
ν_e ν_μ ν_τ	$W^{\pm}, Z$
u c t	g
d s b	G

Lots of new particles... any good one ?

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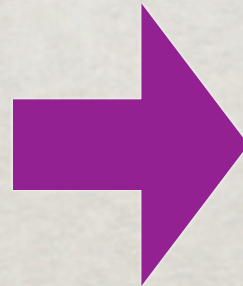| Standard Model	
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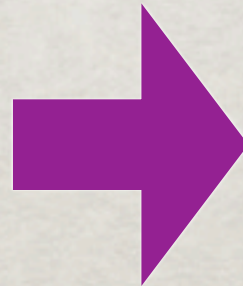| SUSY SM			
SMatter			SForces
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	$\tilde{\gamma}$
$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{W}^\pm, \tilde{Z}$
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SUSY is broken: MASSIVE !
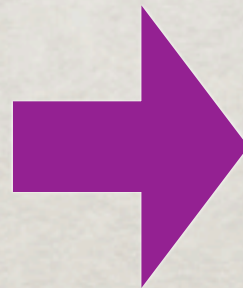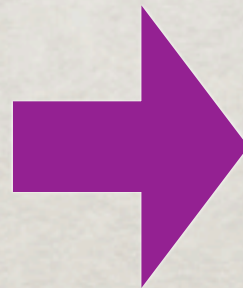
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$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	$\tilde{g}$
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$\tilde{\chi}$

$\psi_{3/2}$

SUSY is broken: MASSIVE !

Lots of new particles... any good one ?

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

MSSM ⟷ ~~SUSY~~ $\langle F \rangle \neq 0$

Mediation

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: $m_{3/2} = \dfrac{\langle F \rangle}{M_P}$.

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 !

SNEUTRINO AS A WIMP

Let us start with one neutral SM superpartners: the sneutrino !
After the neutrino the sneutrino seems an obvious choice...
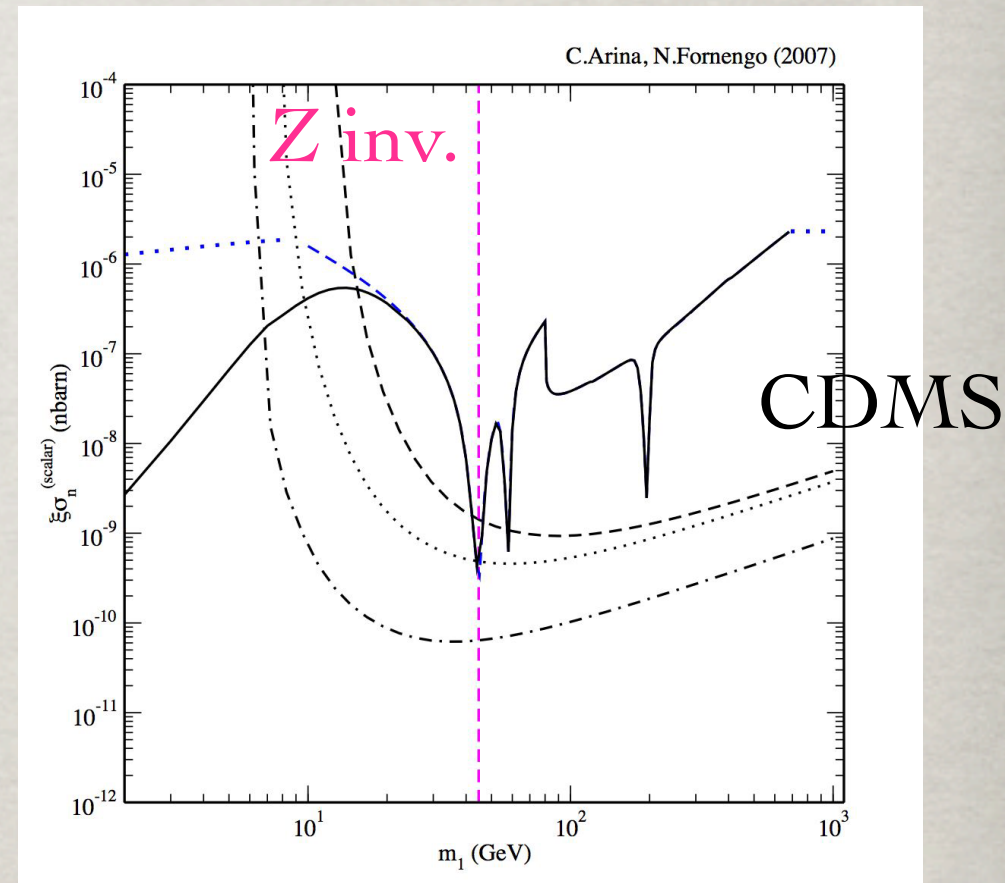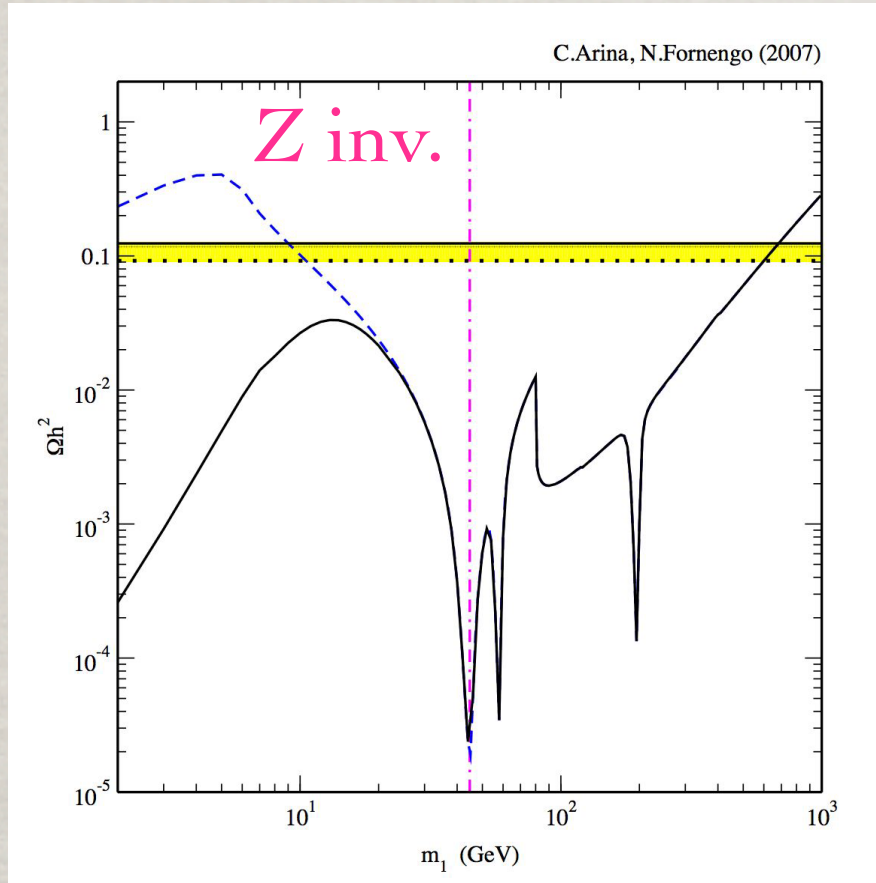
Unfortunately the LH sneutrino interacts too strongly with the Z boson: not a WIMP or already excluded by DD exps. A mixed RH/LH sneutrino is still allowed though.

Is neutralino a WIMP ?

[LC, Hasenkamp, Roberts & Pokorski 09]

$$\Omega_{CDM} h^2 \sim 0.1$$
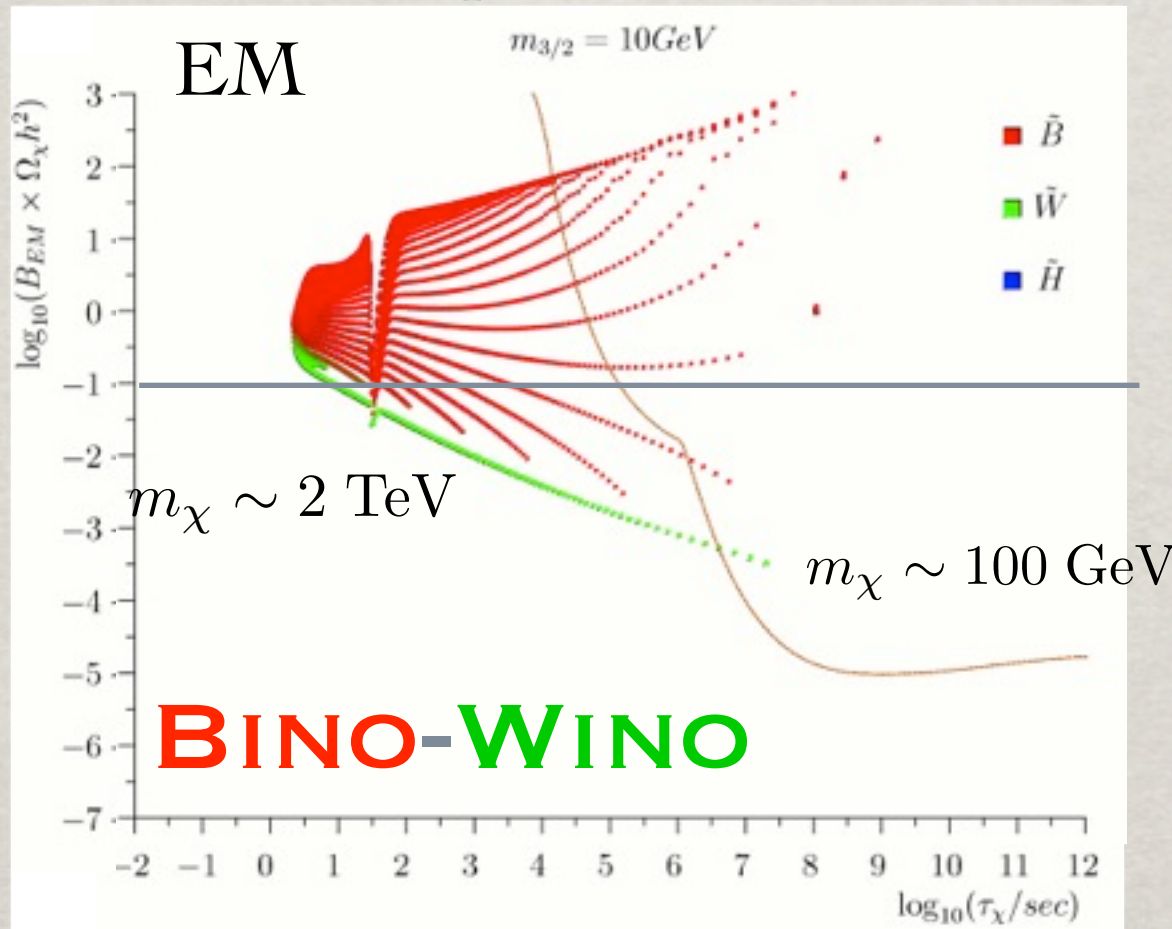
The neutralino energy density shows a strong dependence on the neutralino composition: in general need to tune to obtain the right DM density, Bino (as in CMSSM) usually too abundant...

Neutralino as a WIMP

The neutralino is often described as natural WIMP, but its density can span 5-6 orders of magnitude depending on the SUSY breaking parameters and mass spectra

In general the Bino neutralino has a too large density for 100 GeV mass, while the Higgsino and the Wino too low...
Due to the present limits on sparticles masses, the natural "bulk" region of parameters in the CMSSM is excluded.
An enhancement is needed for the annihilation cross-section:

- Coannihilation with another SUSY particle;

- Resonance in the annihilation;

- Large coupling with W (large higgsino component)

Allowed regions in the constrained MSSM

[Ellis, Olive, Santoso & Spanos 03]
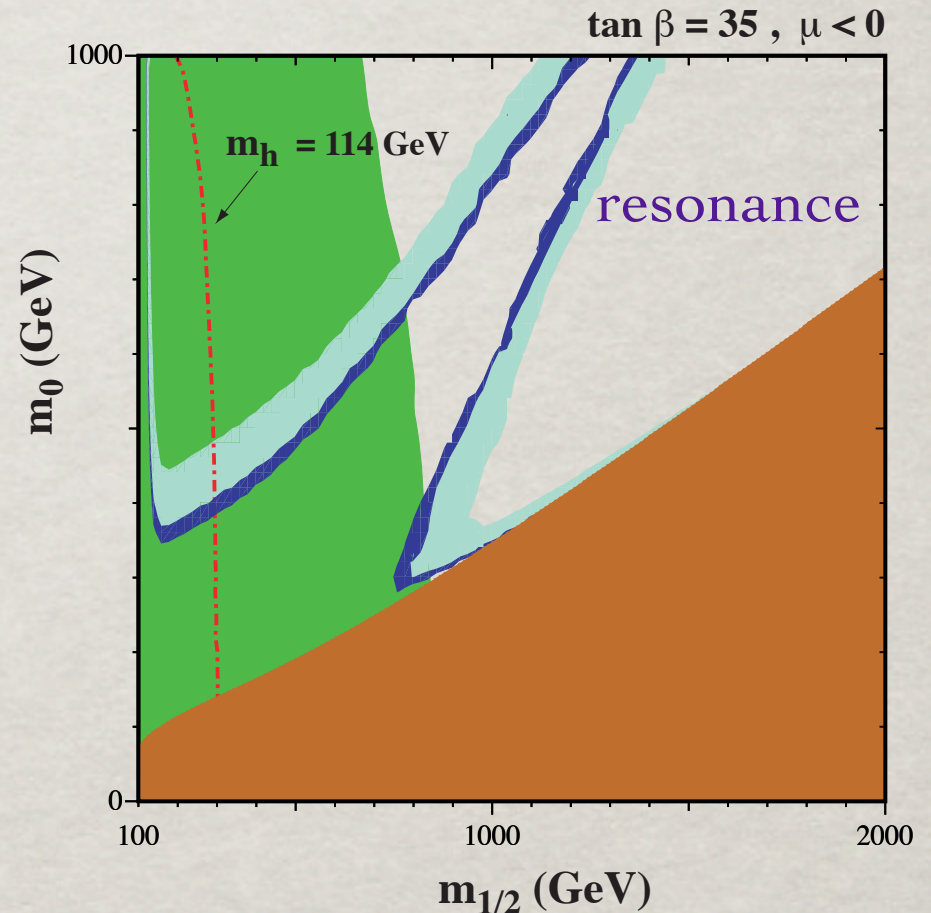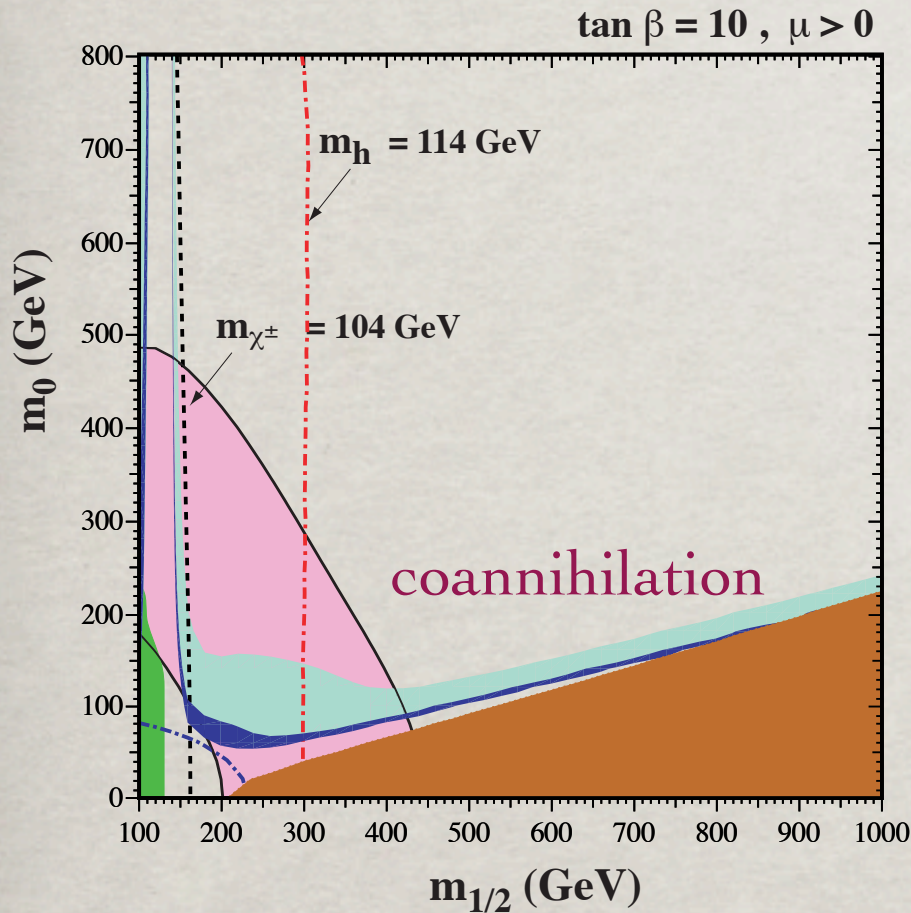
Tiny strips in the parameter space are allowed...
also in most of them the relation between annihilation and
elastic scattering cross-section (direct detection) is lost !
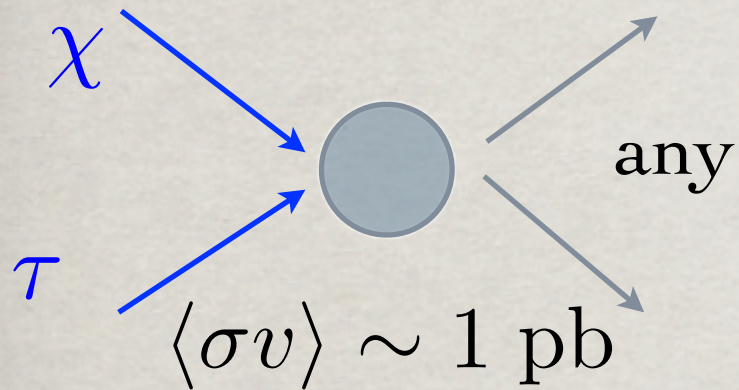
THE WIMP CONNECTION ?
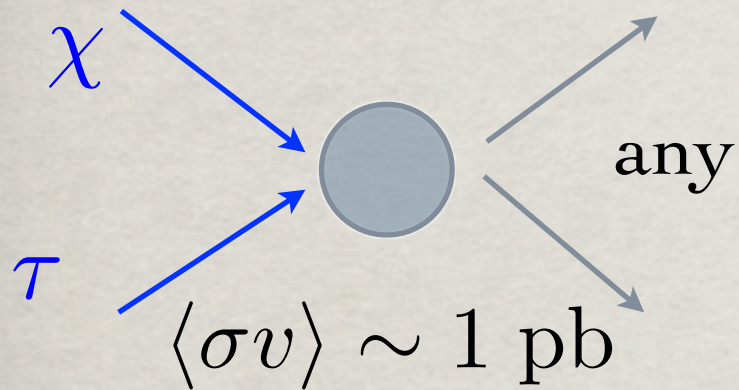
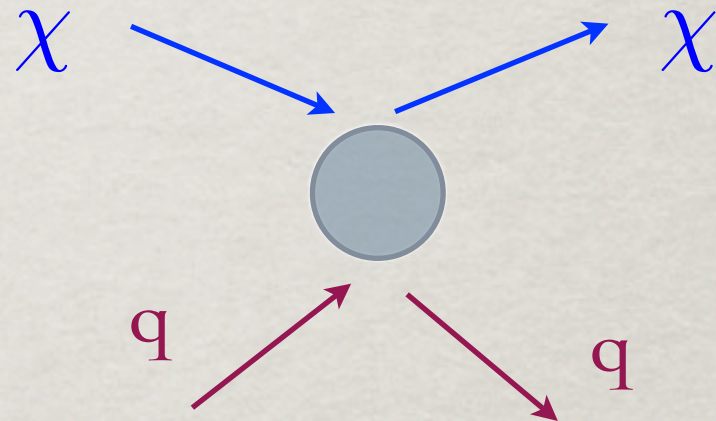Early Universe: $\Omega_{CDM}h^2$ Direct Detection:
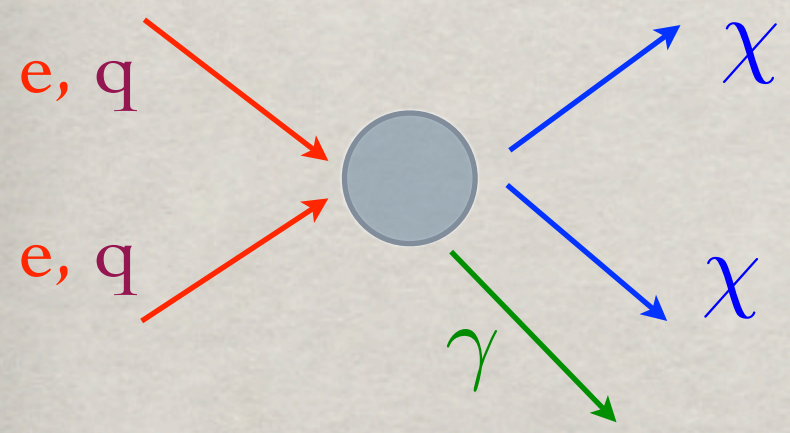
$$\neq$$
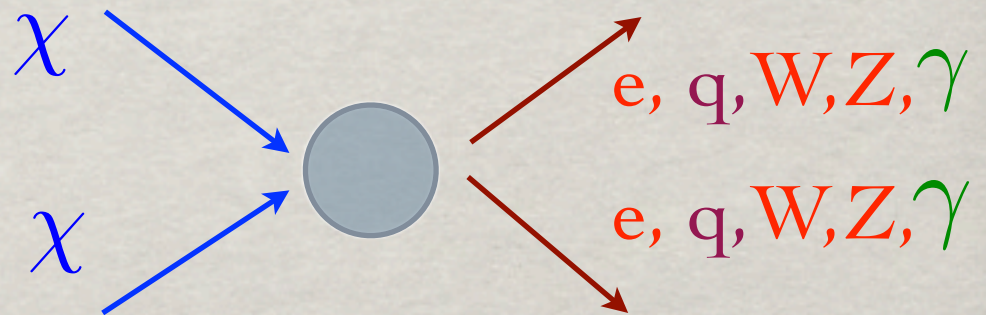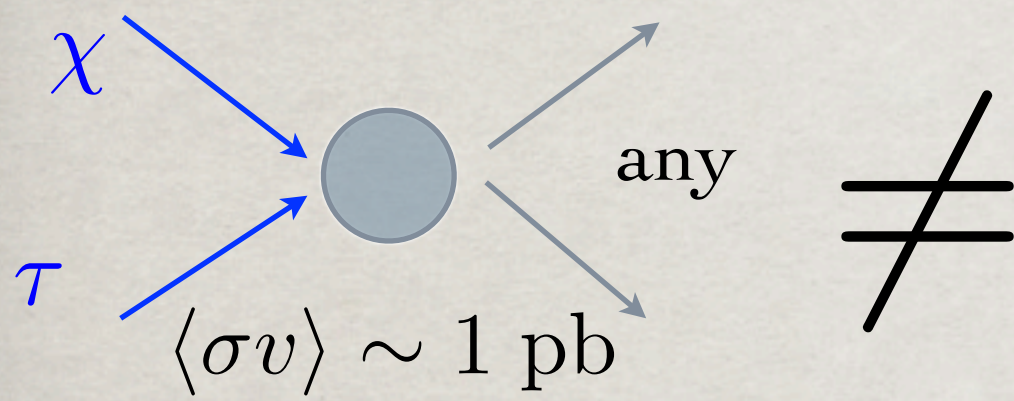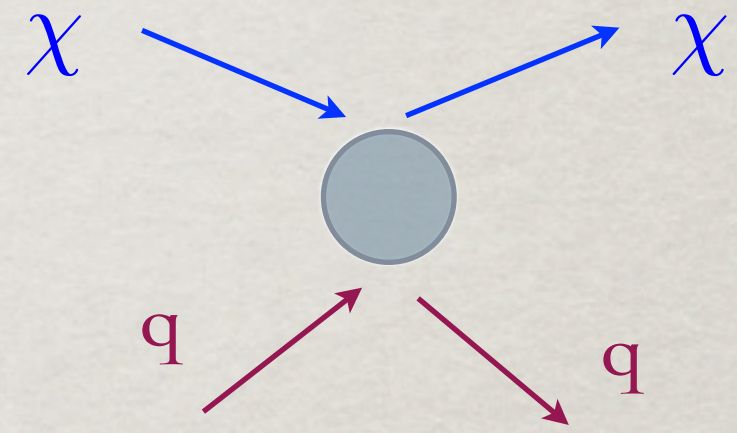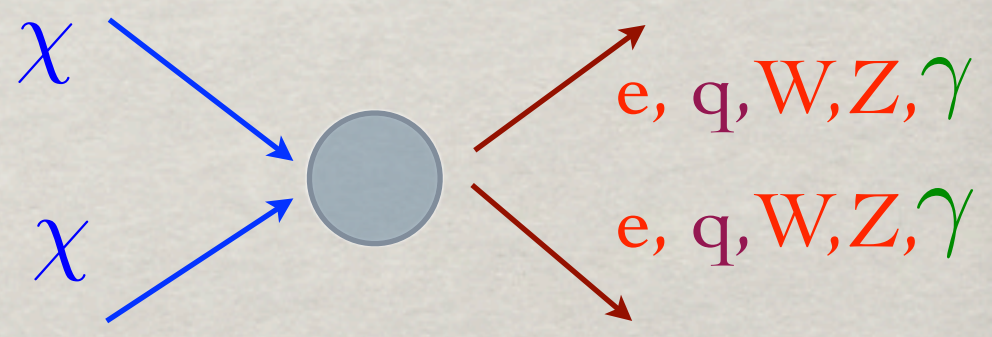
THE WIMP CONNECTION ?

Early Universe: $\Omega_{CDM}h^2$

χ

τ

any

$\langle \sigma v \rangle \sim 1\,\mathrm{pb}$

$\neq$

Direct Detection:

χ χ

q q

Indirect Detection:

χ

χ

e, q,W,Z,γ

e, q,W,Z,γ
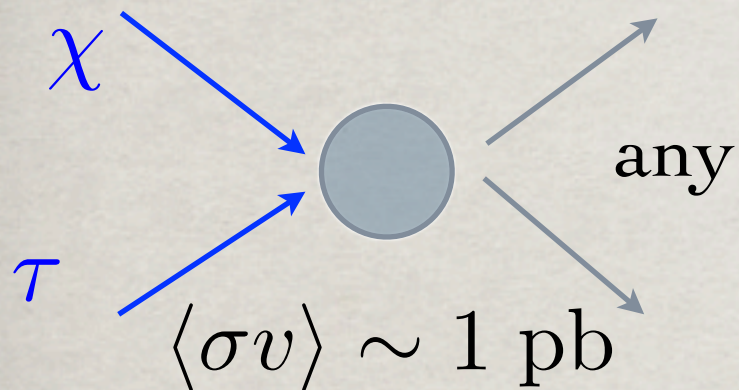
THE WIMP CONNECTION ?

Early Universe: $\Omega_{CDM} h^2$

χ

τ

$\langle \sigma v \rangle \sim 1 \text{ pb}$

any

$\neq$

Direct Detection:

χ χ

q   q

Colliders: LHC/ILC

e, q

e, q

χ

χ

γ

Indirect Detection:

χ

χ

e, q, W,Z, γ

e, q, W,Z, γ

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Early Universe: $\Omega_{CDM} h^2$

χ

τ

any

$\langle \sigma v \rangle \sim 1 \text{ pb}$

$\neq$

Direct Detection:

χ χ

q   q

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χ

χ

γ

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χ

e, q, W, Z, γ

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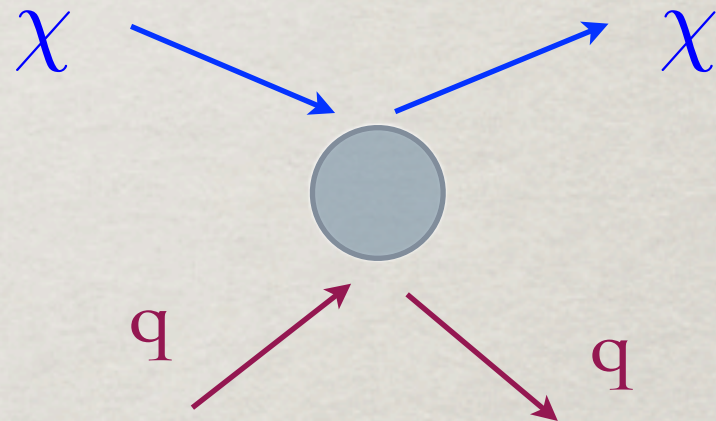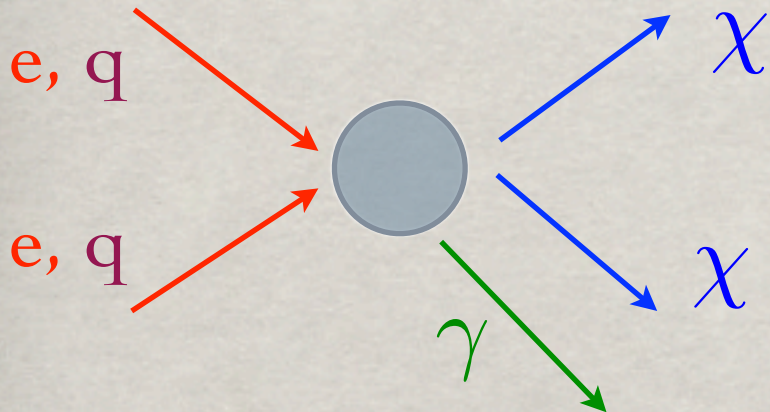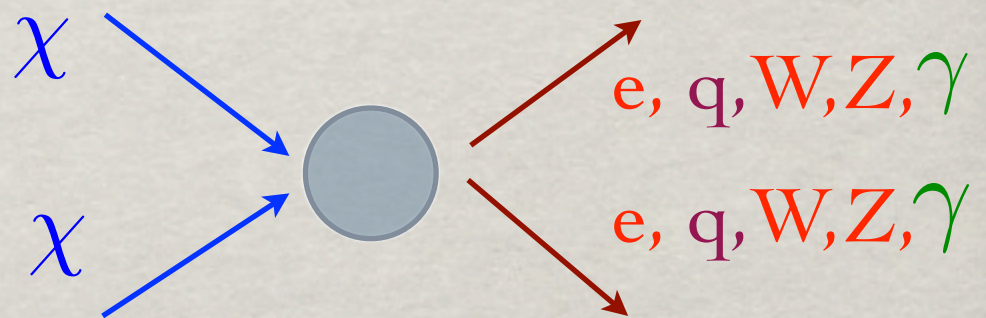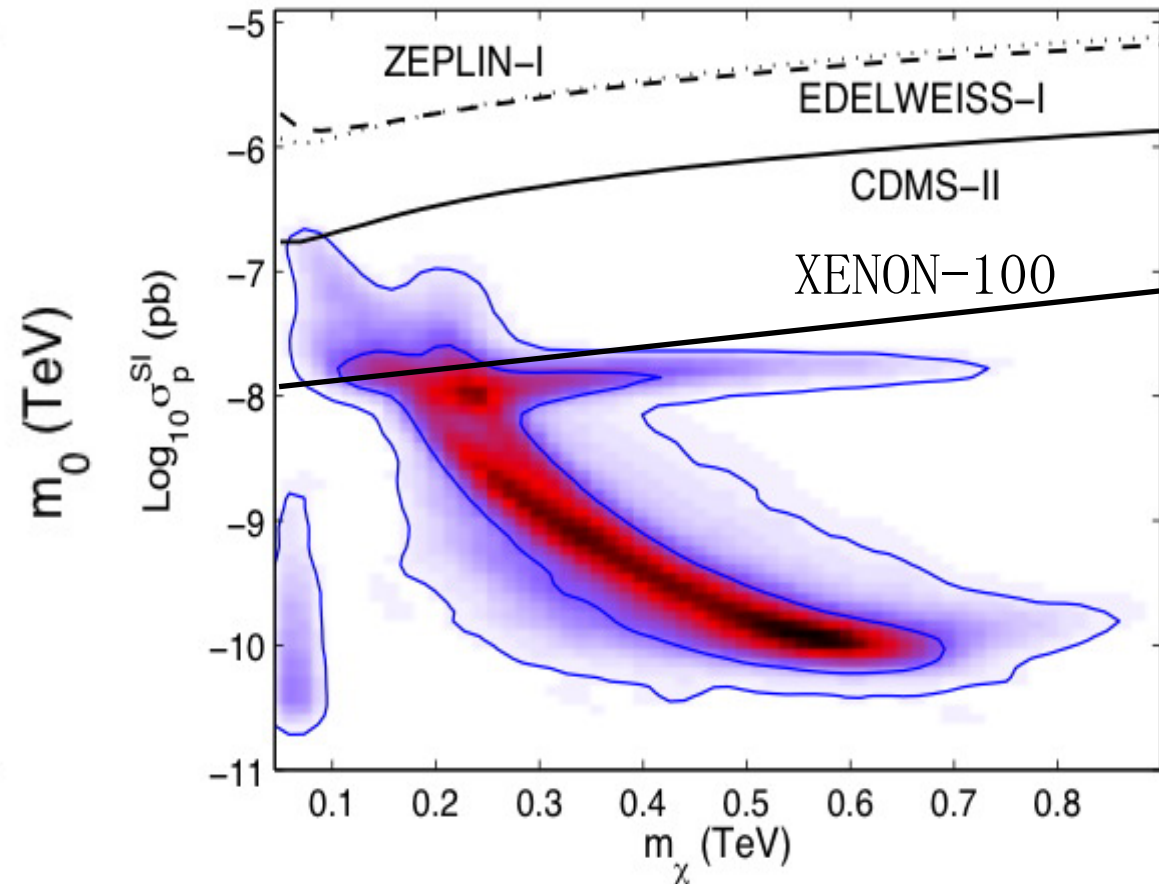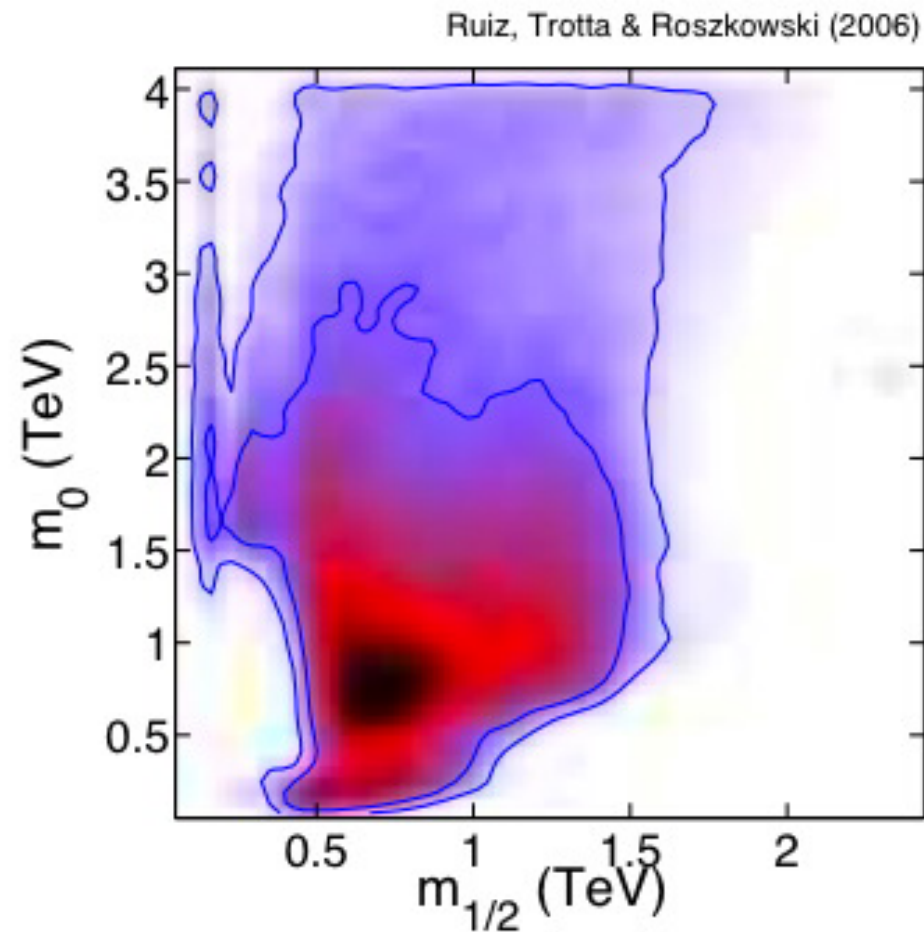
But luckily we have other channels & we know the full model !
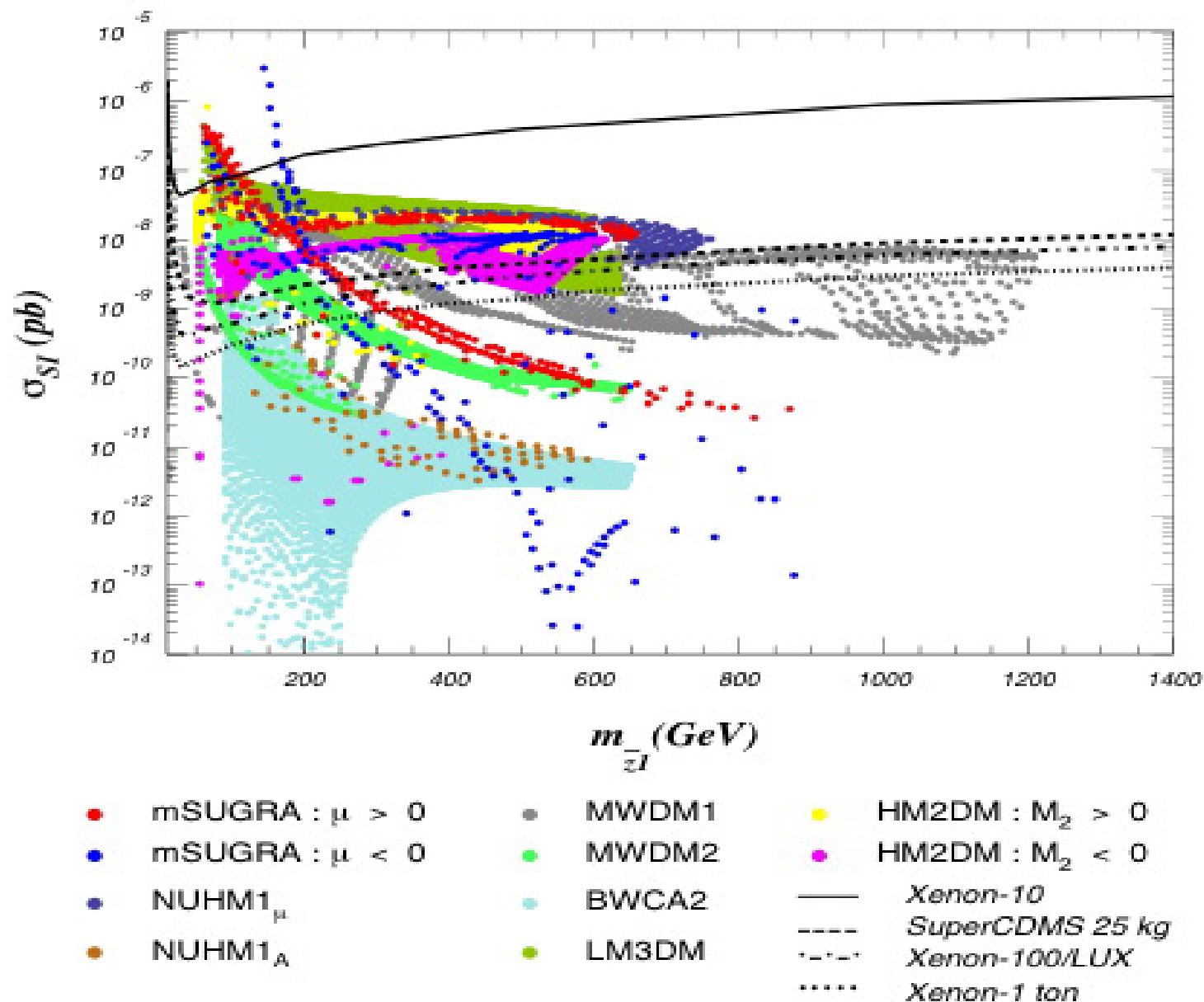
With a BAYESIAN APPROACH strips disappear...

Ruiz, Trotta & Roszkowski (2006)

Tiny strips becomes extended regions if one integrates on the other parameters (including SM ones...), but still in coannihilation/resonance regions the DD rate is low.

It is quite different away from the CMSSM...

Spin-independent Direct Detection [Baer 10]

THE HOPE: PRODUCE DM !

- At the LHC at CERN or other future colliders, in the case of neutralino DM the production is increased thanks to the presence of colored states in the spectrum.

- If R-parity is conserved, a SUSY particle decays in another SUSY particle and the lightest one is stable! Then any (colored) superparticle cascade-decays into the neutralino, which escapes...   -> missing energy !

- The missing energy can be measured only in the transverse plane and ALL the other particles have to be precisely reconstructed.

- Still one needs confirmation from direct/indirect detection that such particles are really Dark Matter...

Edge Mass measurement

- Compute the invariant mass distribution of the visible particles e,d

- The maximal value is given when by
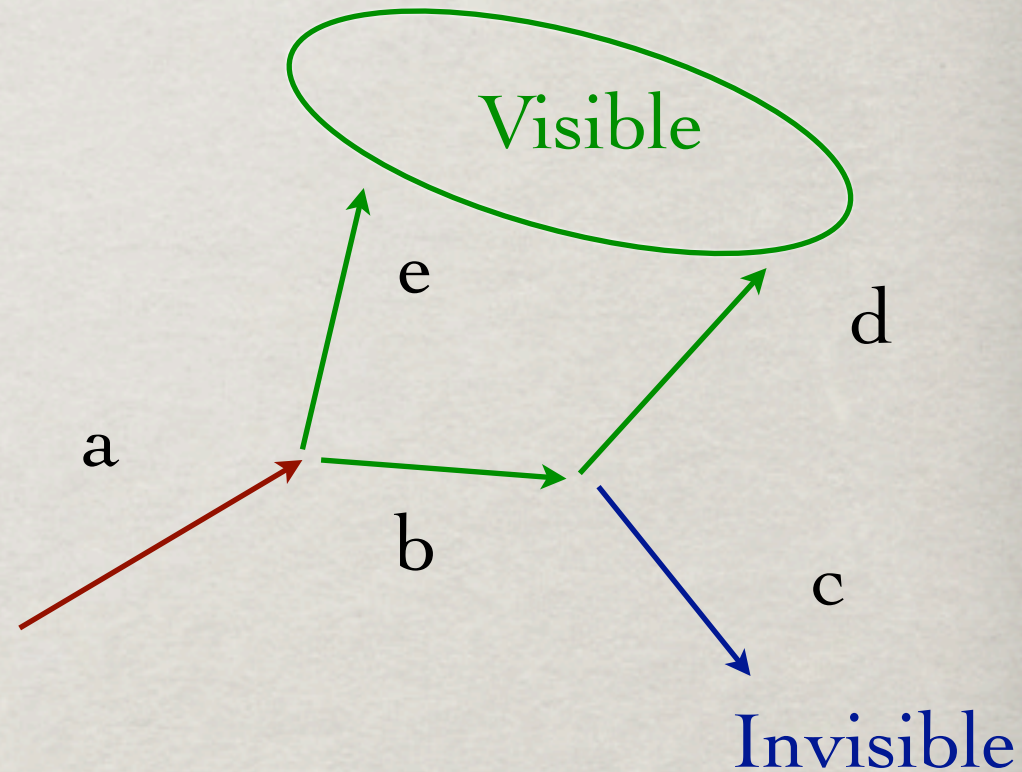
$$(m_{de}^{max})^2 = \frac{(m_a^2 - m_b^2)(m_b^2 - m_c^2)}{m_c^2}$$

Visible

e

d

a

b

c

Invisible

Mass differences !

Longer chains give more constraints !

NB: assumes 2-body decay chain and no degenerate masses

LHC DM CHALLENGE

- Try to measure the masses in different decay chains using invariant mass edges and/or possibly also the shape of the distributions

- Reconstruct the mass differences (~ 1% error) between the new particles in this way and from the frequency of certain chains restrict as well some of the couplings. The DM candidate mass only determined up to ~ 10% error...

- Use the extracted information to reconstruct the density of the DM candidate as a thermal relic.
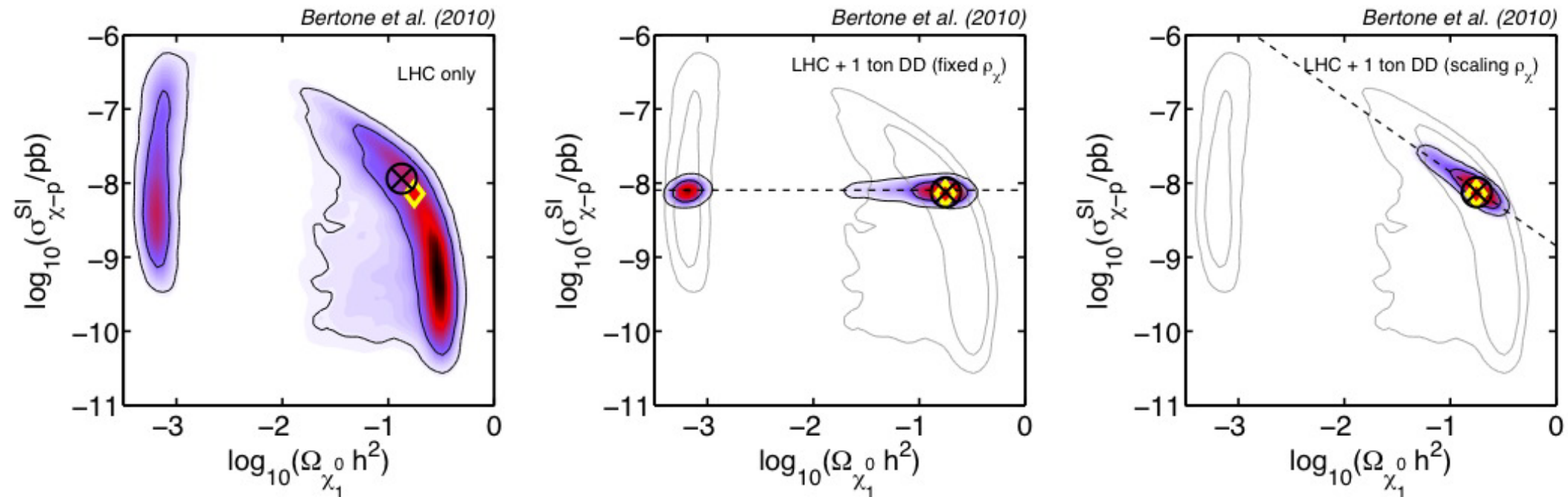
RECONSTRUCTING $\Omega_{DM}h^2$

[Baltz, Battaglia, Peskin & Wizanski '06]
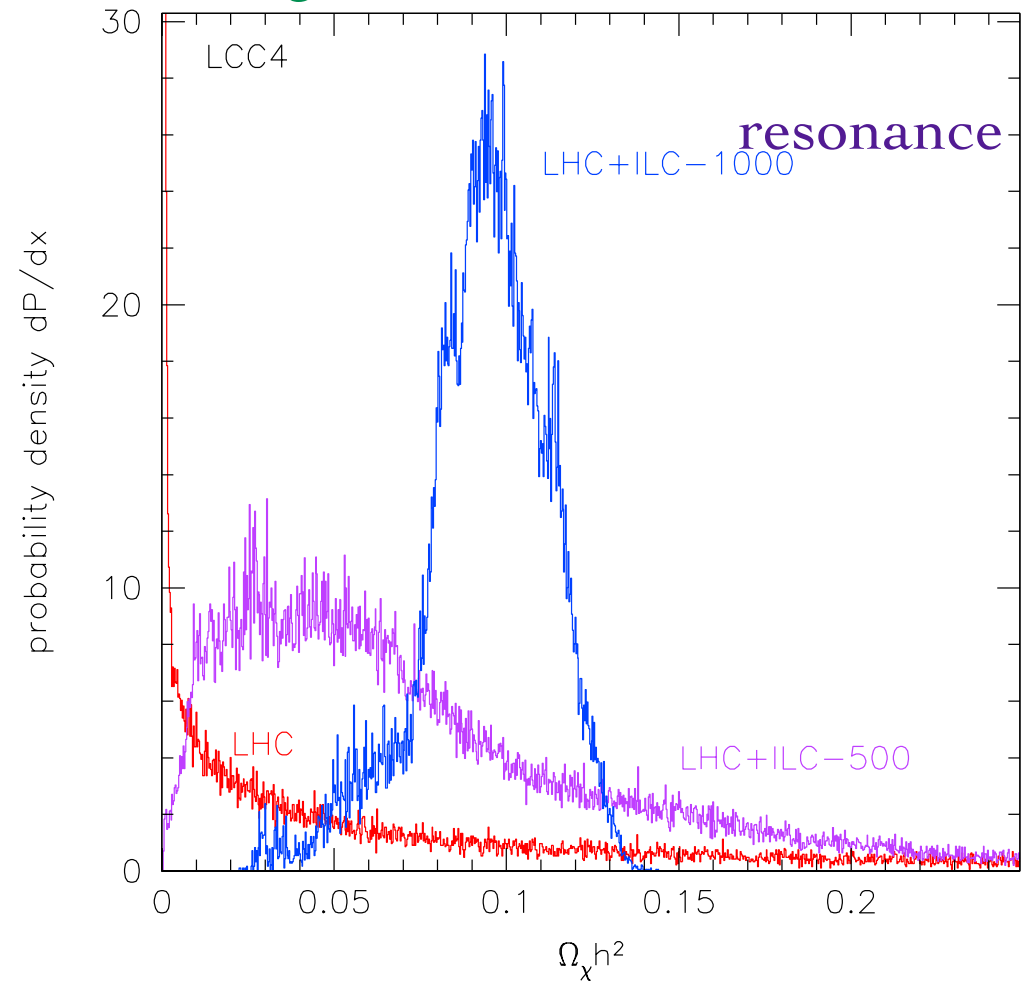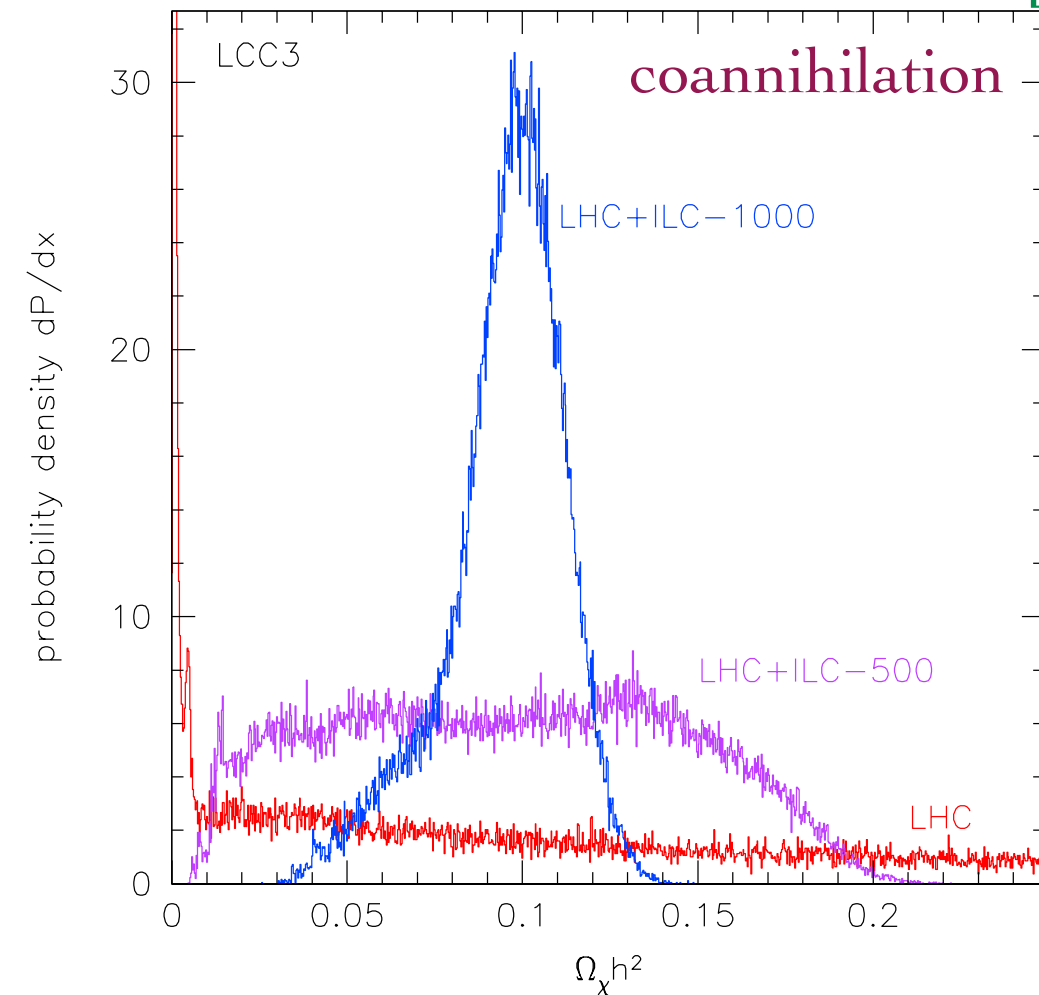
Pretty difficult by LHC alone in coannihilation/resonance case; still possible perhaps to improve when data are coming…

Reconstructing $\Omega_{DM}h^2$

In some cases even multiple peaks in the likelihood arise...,
not clear if the escaping particle can be DM or a thermal relic.

The inclusion of direct detection data in the analysis can lift
degeneracies and single out the right solution...
In such analysis it can also be checked if the DM is a thermal
relic or if other production mechanisms must be at work.

SuperWIMP DM

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
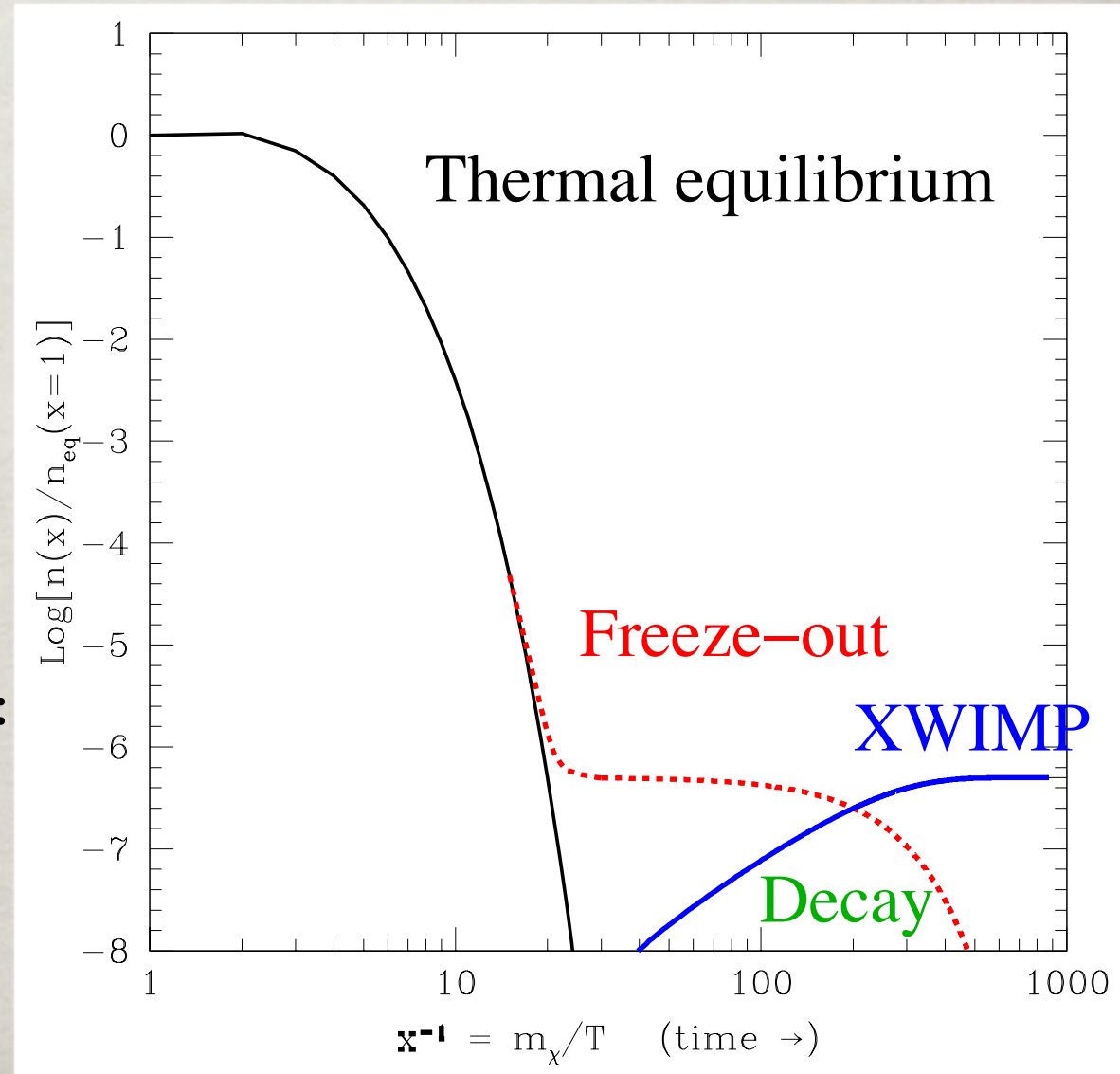
NLSP DECAY

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

- For long lifetime the NLSP decays after freeze-out and due to R-parity conservation:

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

- Other energetic particles are produced in the decay: beware of BBN...

WAY OUT: break R-parity so that the NLSP decays earlier !

Thermal equilibrium

Freeze-out

XWIMP

Decay

$x^{-1} = m_\chi/T \quad (\text{time} \rightarrow)$

$\text{Log}[n(x)/n_{eq}(x=1)]$

R-PARITY OR NOT R-PARITY

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.

$$W_{R\!\!\!/p} = \mu_i L_i H_u + \lambda LLE^c + \lambda' LQD^c + \lambda'' U^c D^c D^c$$

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

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For the NLSP to decay before BBN

To avoid wash-out of lepton number

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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.
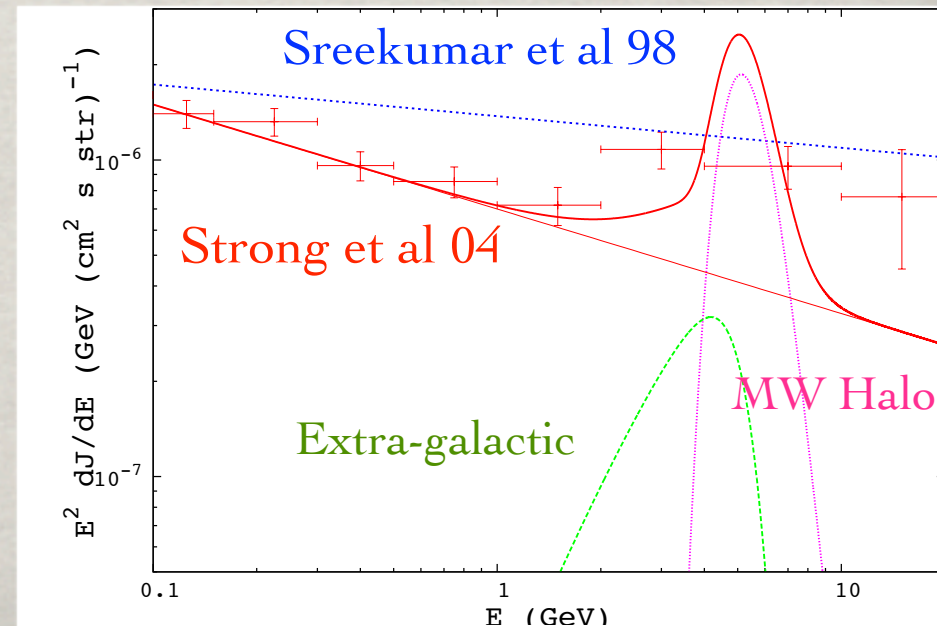
DECAYING DM

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

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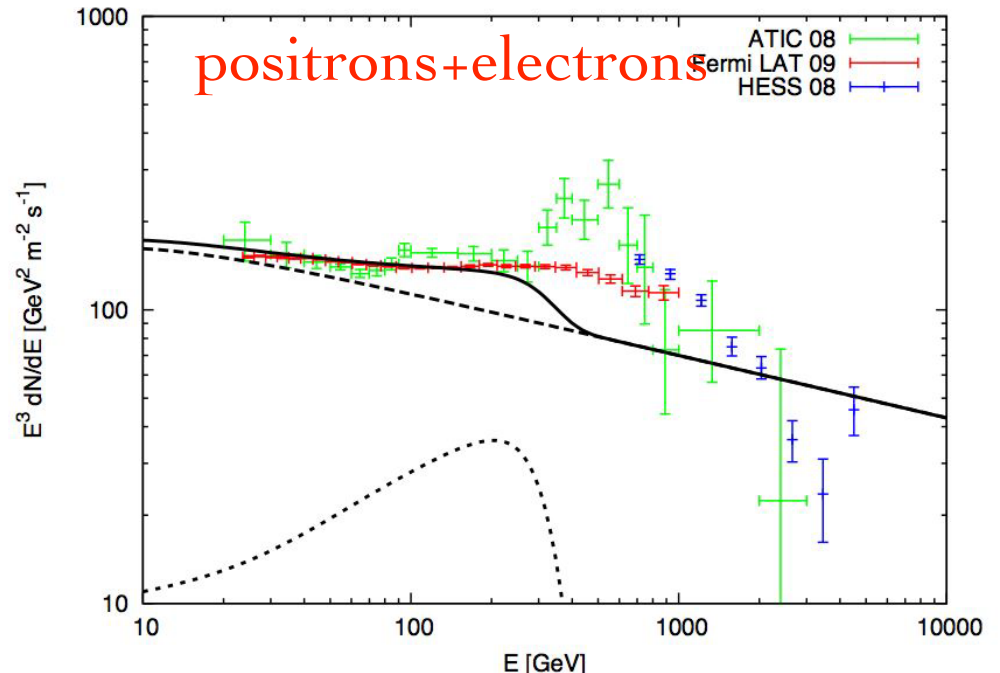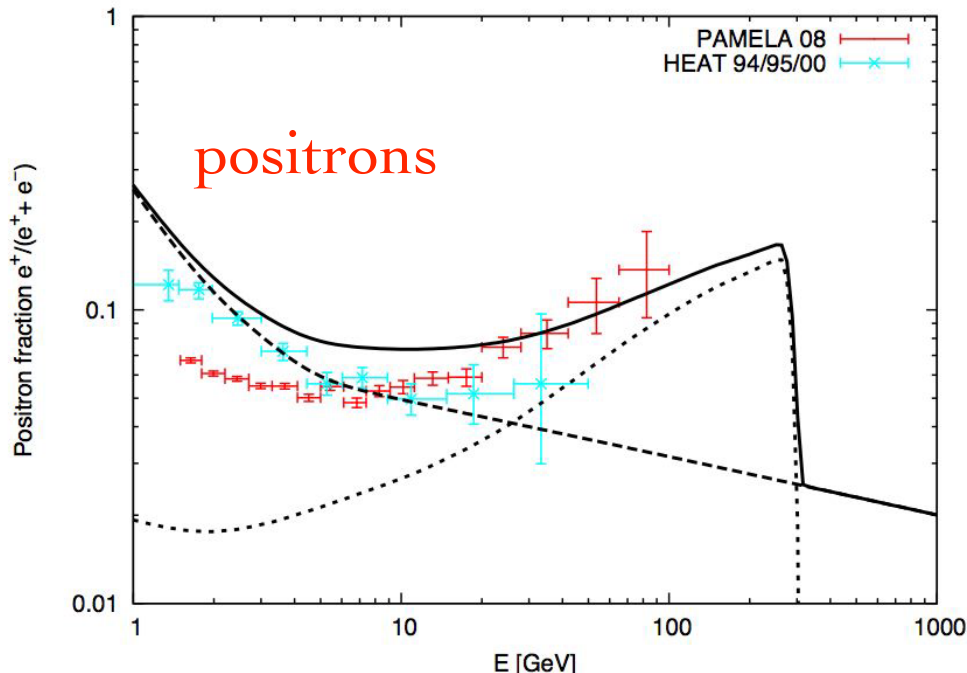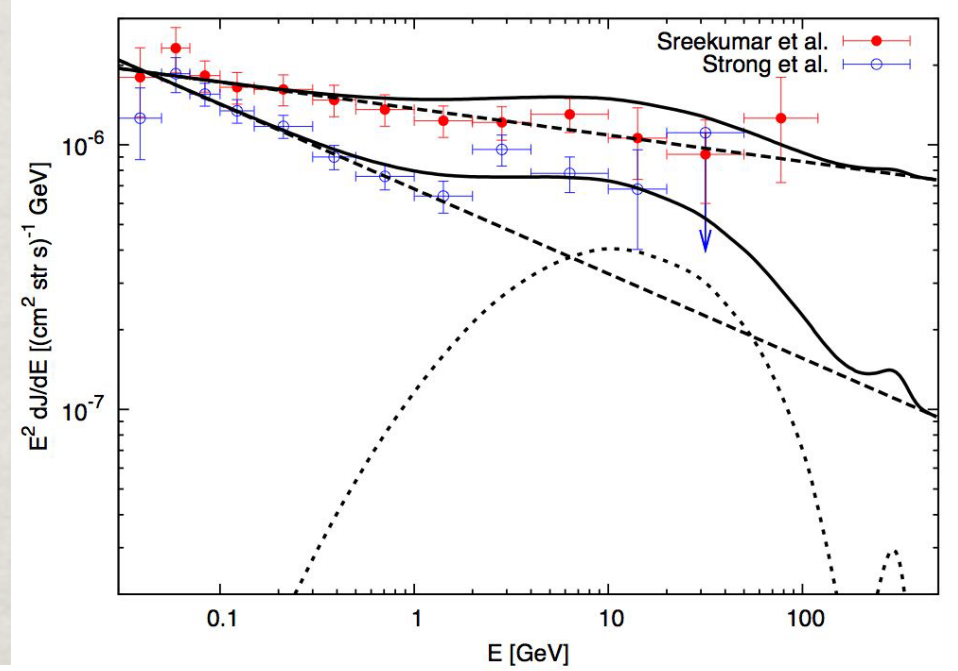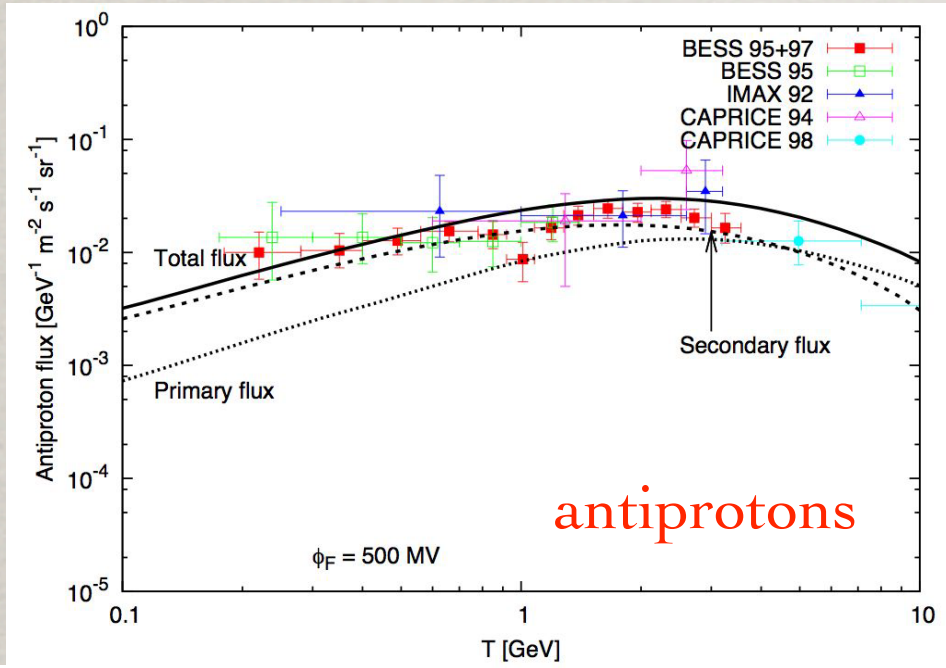
Particle Physics   Halo property

- 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...

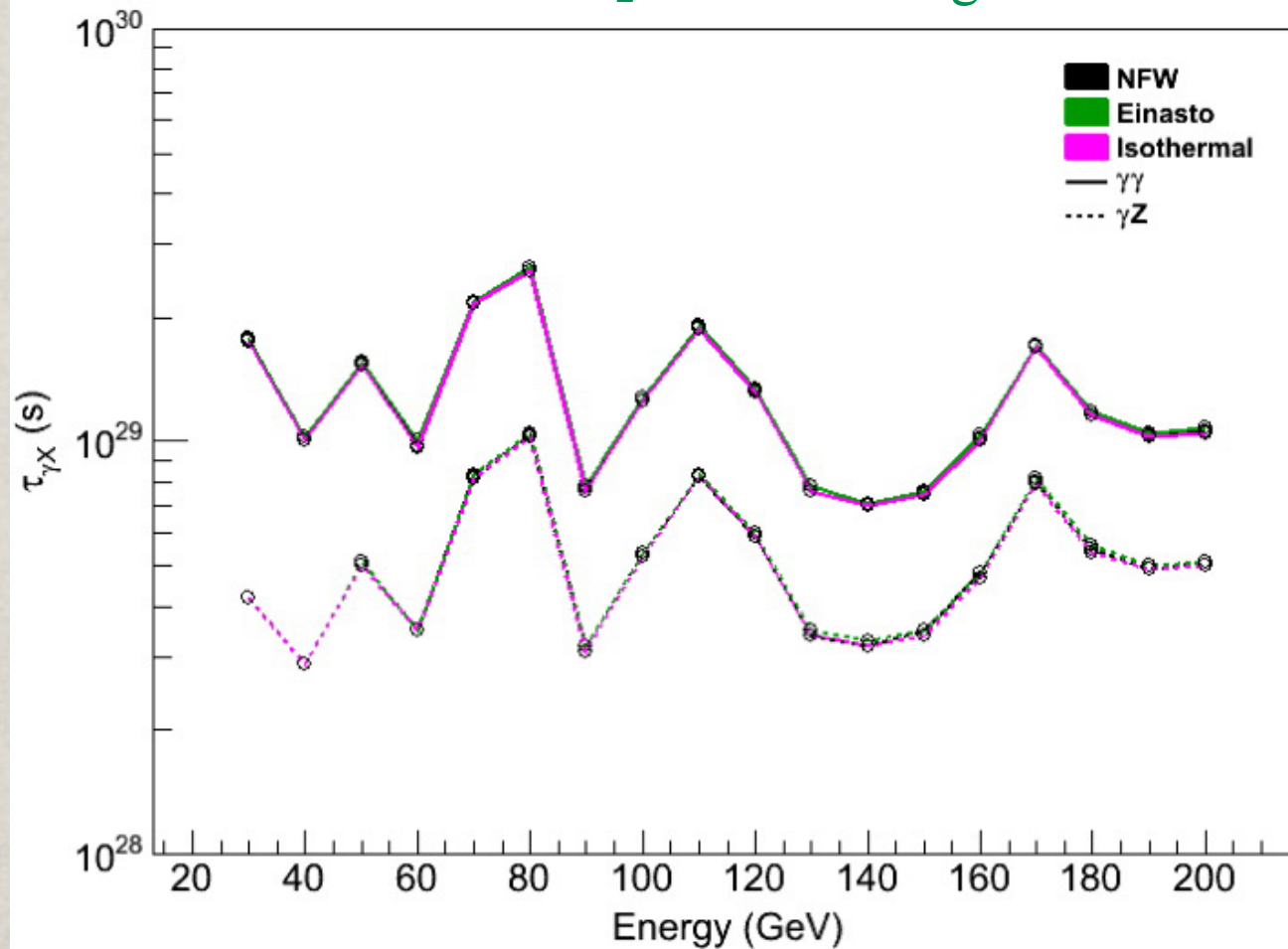- Galactic/extragalactic signal are comparable...

Gravitino DM without R_p

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

antiprotons

positrons

positrons+electrons
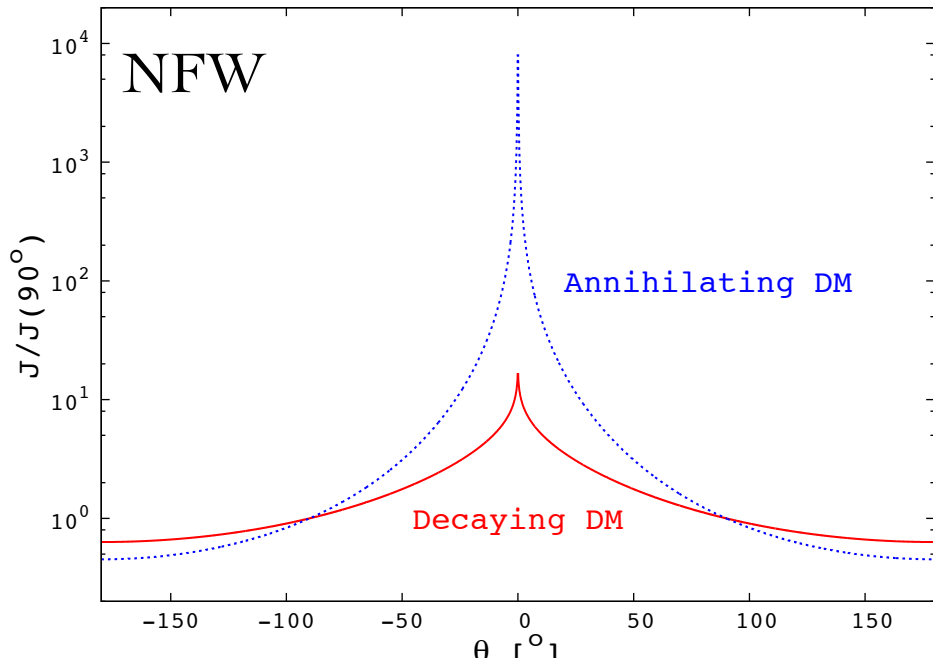
FERMI LINE CONSTRAINTS

[from S. Murgia @ GGI-2010]

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
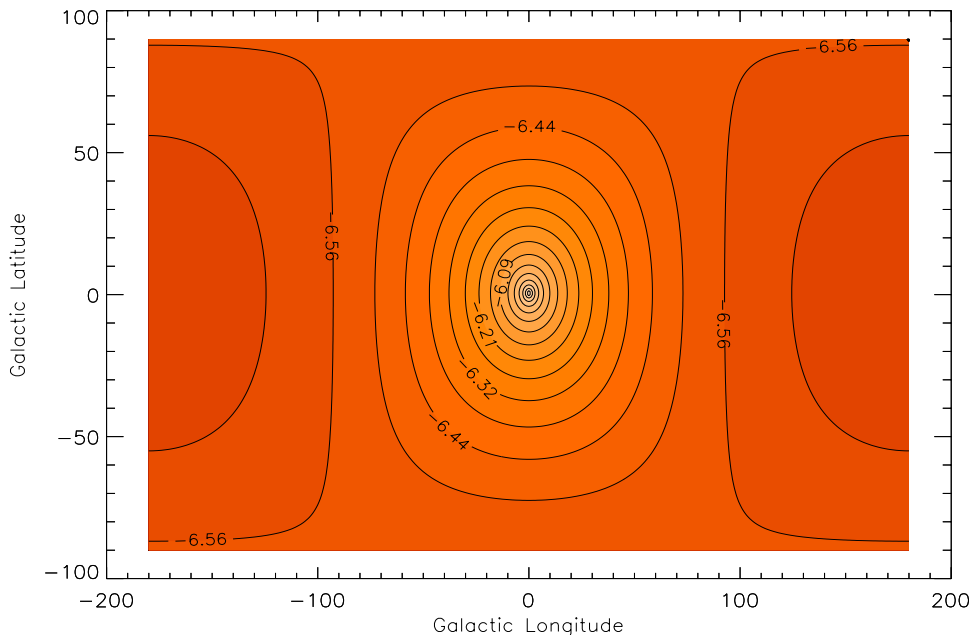
DECAYING DM II

NFW

Annihilating DM

Decaying DM

Note that the spectra do not allow to distinguish between annihilating and decaying Dark Matter !
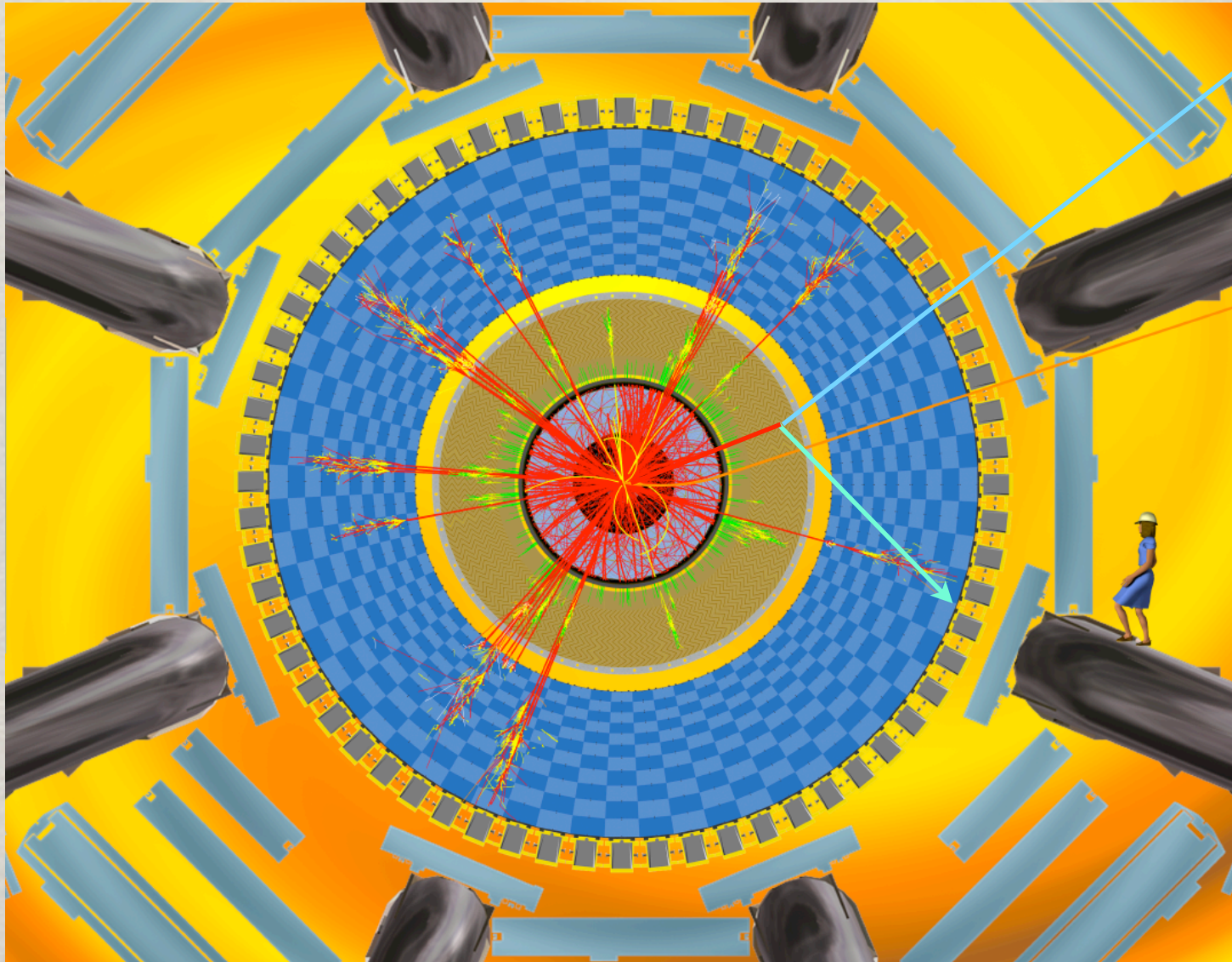
But the anisotropy in the flux does: the annihilating DM signal is proportional to the density squared and therefore much stronger in the centre.
Decaying DM gives instead a much less anisotropic flux.
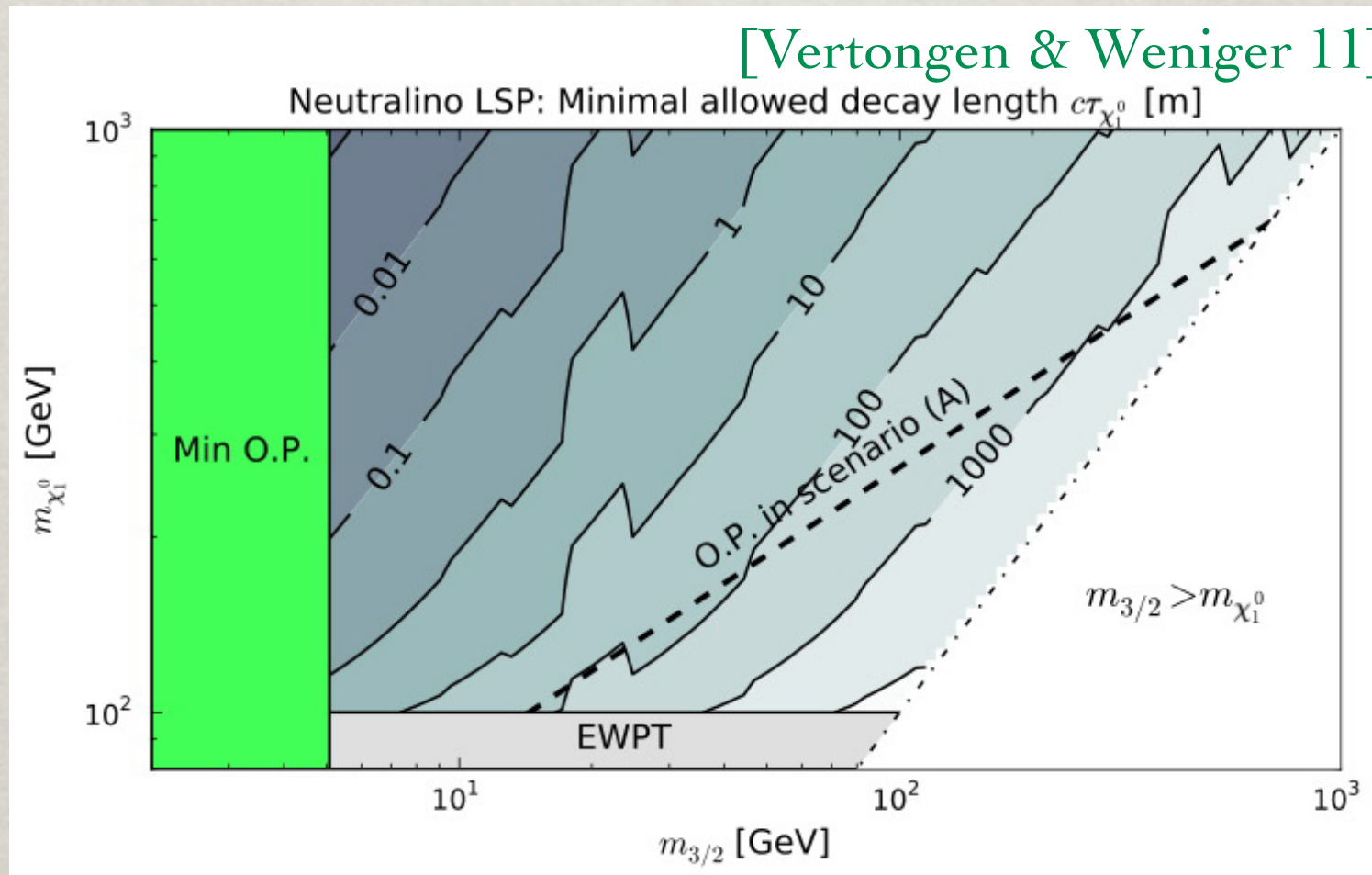
LHC: Displaced vertices ?

The NLSP decay may happen in the detector:

Key question again: missing energy or not ???

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 some neutralinos may be "slow" and decay in the detector...

Axion
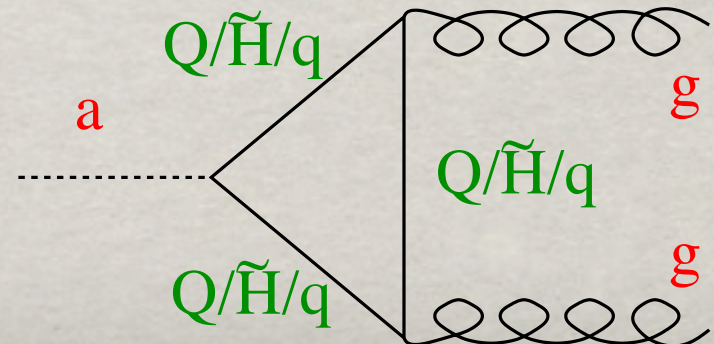# Dark Matter

Strong CP & the Axion

The QCD vacuum has a non trivial structure, as a superposition of different topological configurations, giving rise to strong CP problem from the term:

$$\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$

['t Hooft 76]

But from the bounds on neutron el. dipole moment $\boxed{\theta < 10^{-9}}$

Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a, leaving the axion, a pseudo-Goldstone boson, interacting as

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$

a

Q/H̃/q   g

Q/H̃/q

Q/H̃/q   g

Axions as Dark Matter

The axion is also a very natural DM candidate, but in this case in the form of a condensate, e.g. generated by the misalignment mechanism:
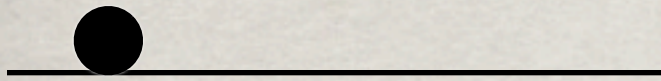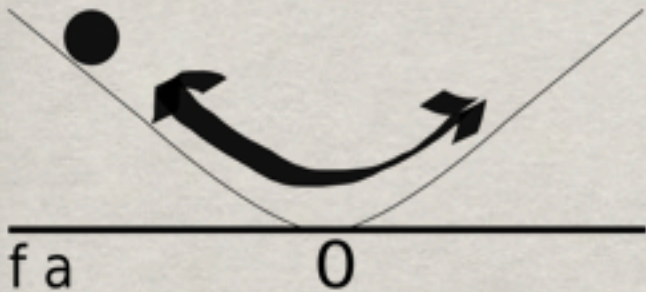

Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

$$V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\theta + \frac{a}{f_a} \right) \right)$$

by instantons effects and the axion starts to oscillate coherently around the minimum:

zero momentum particles >> CDM !

Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12} \text{GeV}} \right)^{7/6} \theta_i^2$$

Axions can contribute to star/SN cooling and so

$$0.5 \times 10^{10} \text{GeV} \leq f_a \leq 10^{12} \text{GeV}$$

[Raffelt 98]

Therefore the mass for axion DM is very small:

$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5} \text{eV} \left(\frac{f_a}{10^{11} \text{GeV}} \right)^{-1}$$
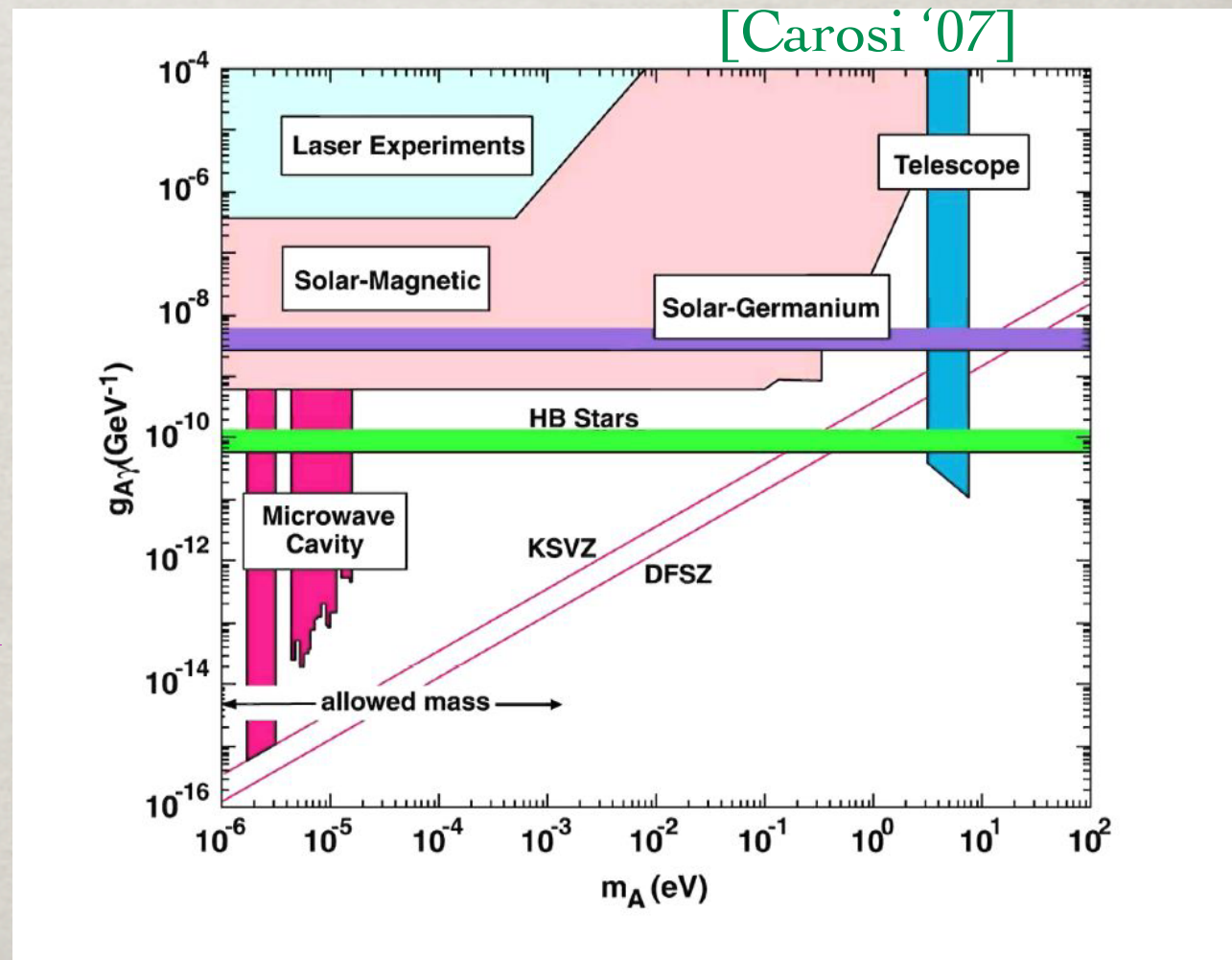
Axion DM Searches

The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μ eV.

ADMX at Livermore is finally touching the expected region.

But it could be much wider for non-standard cosmologies...

[Gondolo et al 09]

[Carosi '07]

OTHER EVIDENCE OF AXION DM?

- Axion DM may give rise to a different caustics shapes as Cold DM due to the BEC rotational properties... [Sikivie et al. 07, 08]

- Axion DM is a decaying DM candidate !!! The axion decays to 2 photons like the pion, but unfortunately the lifetime is beyond reach $\tau_a \geq 10^{46} s$ and the photon energy very low ...

- In the axion/axino mixed DM case, some collider signal are expected, see e.g. [Baer et al. 08, 09,...]

- Other condensates are also possible, but need to be so long-lived and not overclose the universe...

Outlook

Conclusions & Outlook

- In specific models, we can exploit the connection between signals even if it not as direct as in the simple(st) WIMP scenario...

- If Dark Matter is a neutralino, we should see it soon at LHC, and maybe in direct detection and in indirect detection: Consistency check !

- If Dark Matter is something else, still there are some chances of a signal, but it depends strongly on the model...

EXCITING TIMES ARE JUST BEGINNING...

NOT COVERED:

- Inelastic and asymmetric Dark Matter

- Dark Matter in non-standard cosmologies

- Non-thermal Dark Matter

- KK Dark Matter, Inert Doublet DM, Technicolor DM, etc...

- Indirect detection with neutrinos

- ......

Ask me in the discussion time if interested !