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Non-WIMP Dark Matter Candidates

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Outline

- Introduction & DM (gravitational) evidence
- Gravitino Dark Matter & SuperWIMPs
- Axion Dark Matter
- Strongly interacting Dark Matter (?)
- Outlook

Introduction

DARK MATTER EVIDENCE

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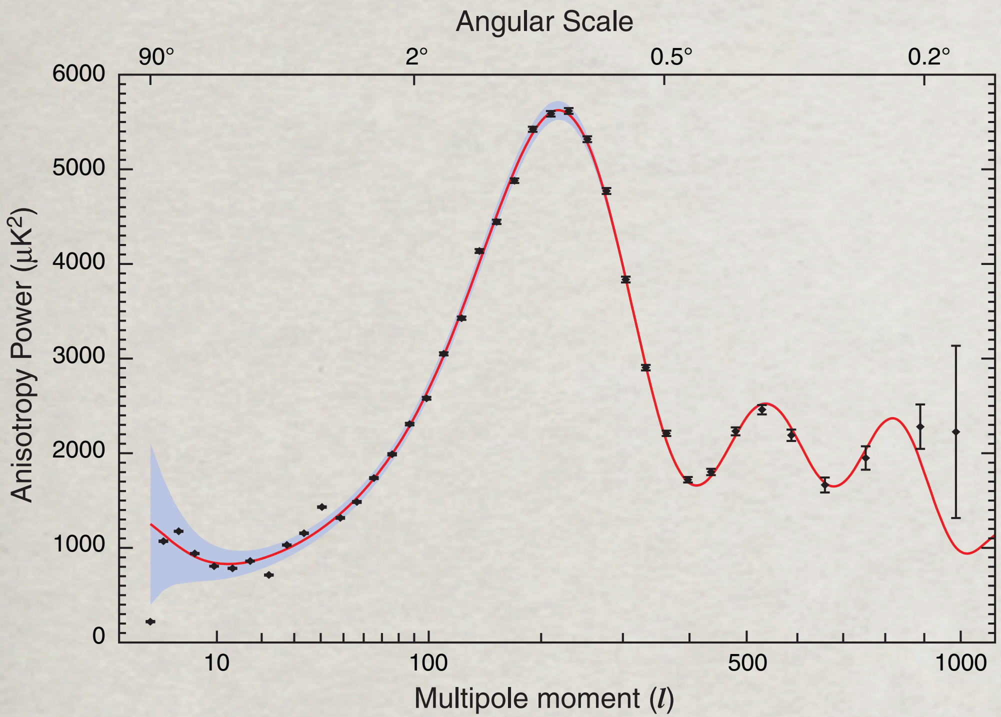
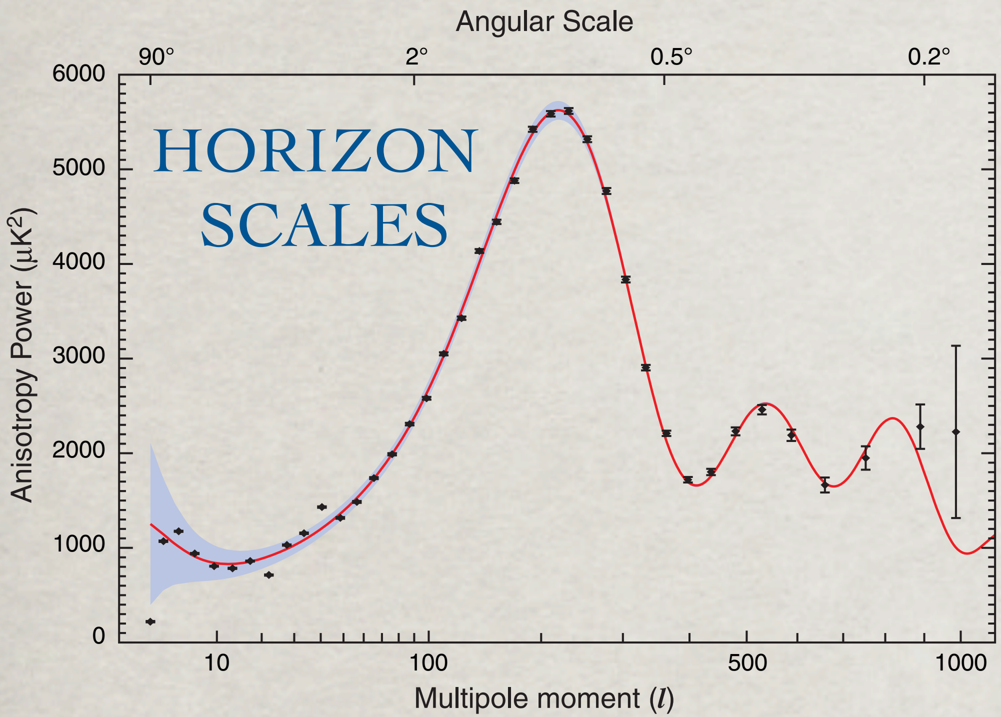
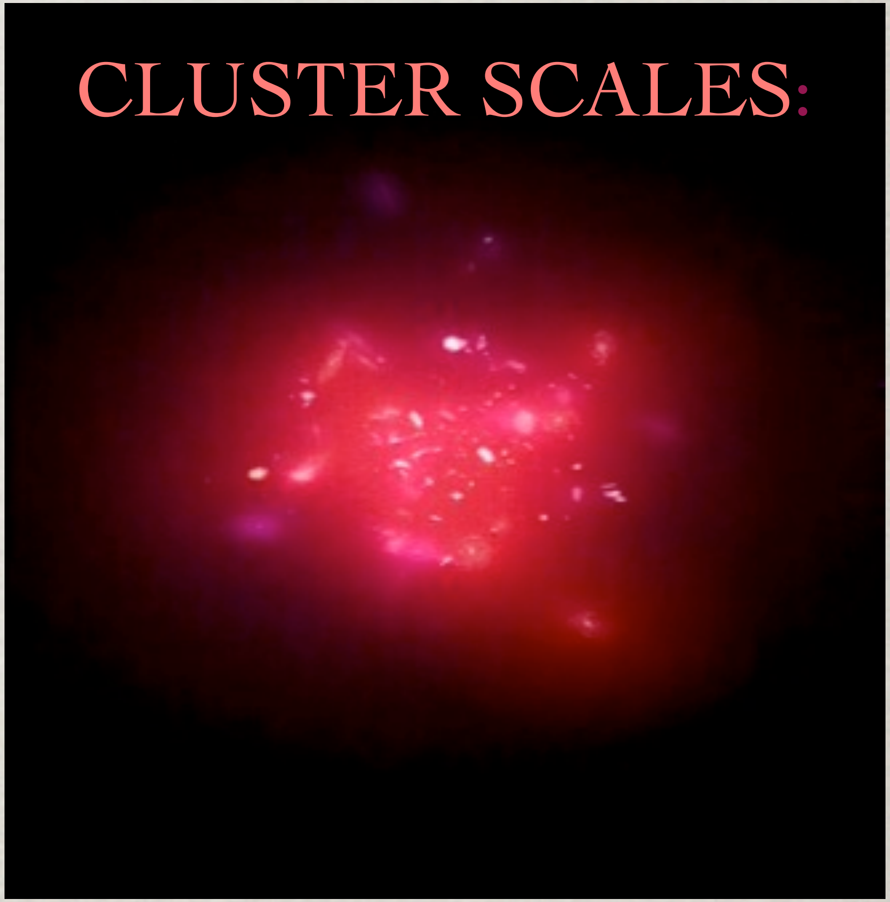


HORIZON SCALES:

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





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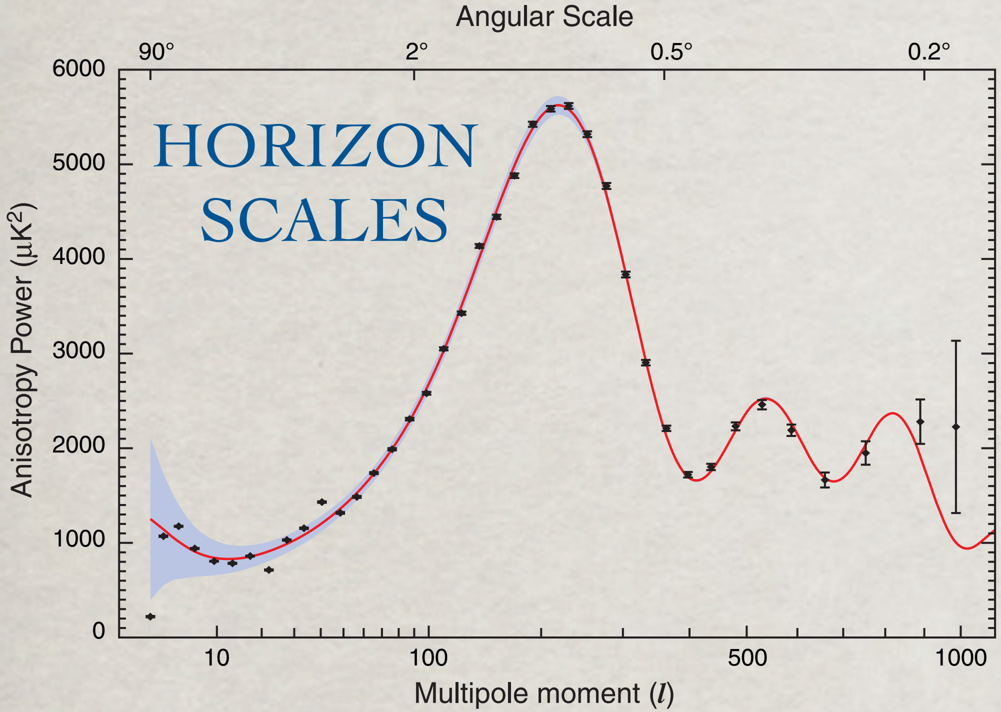

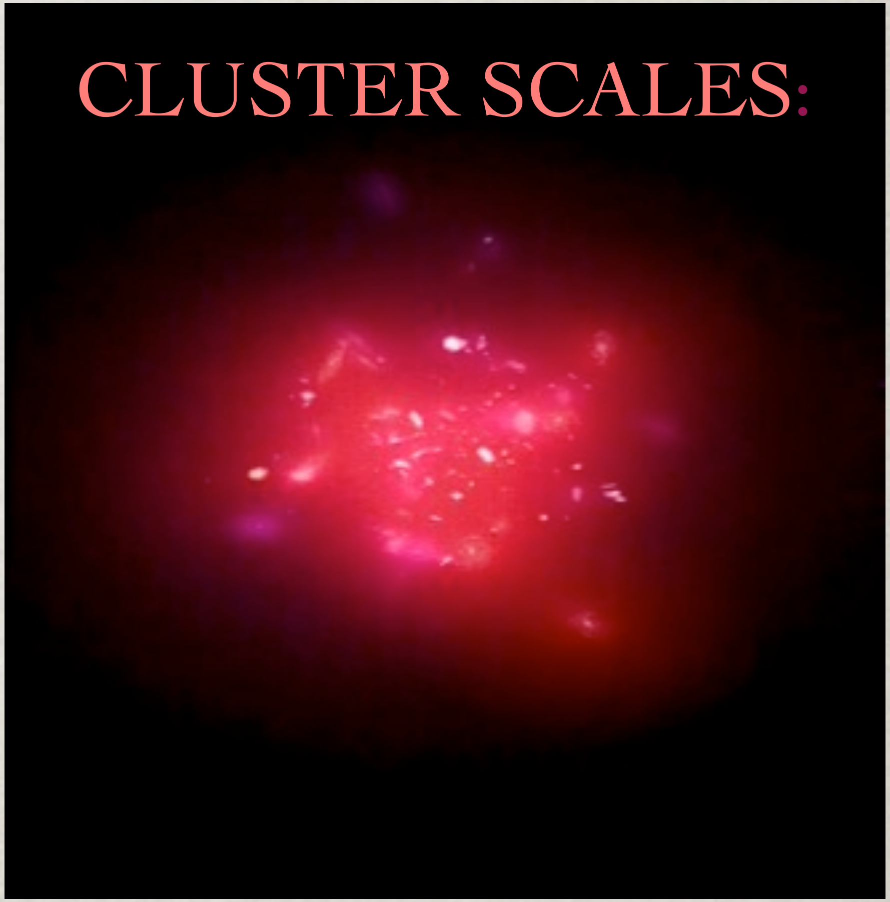

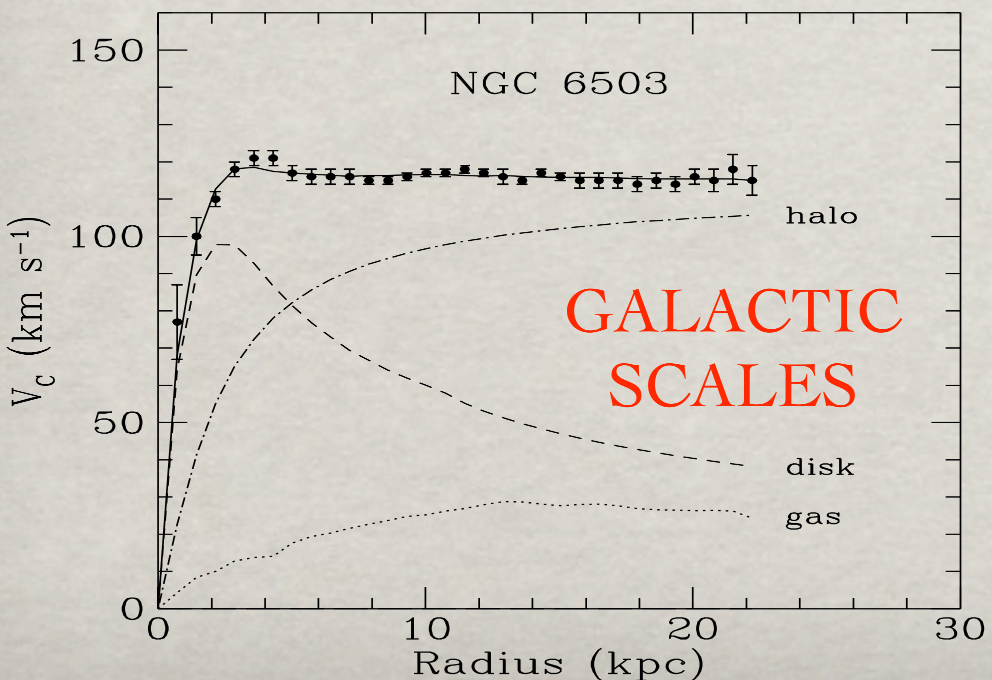

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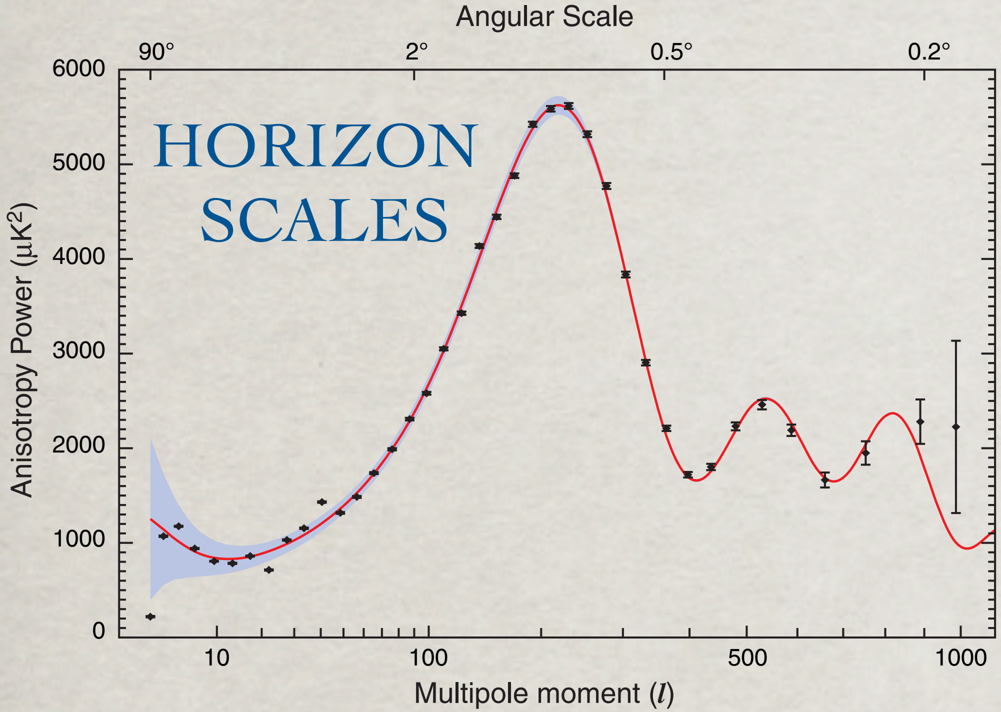
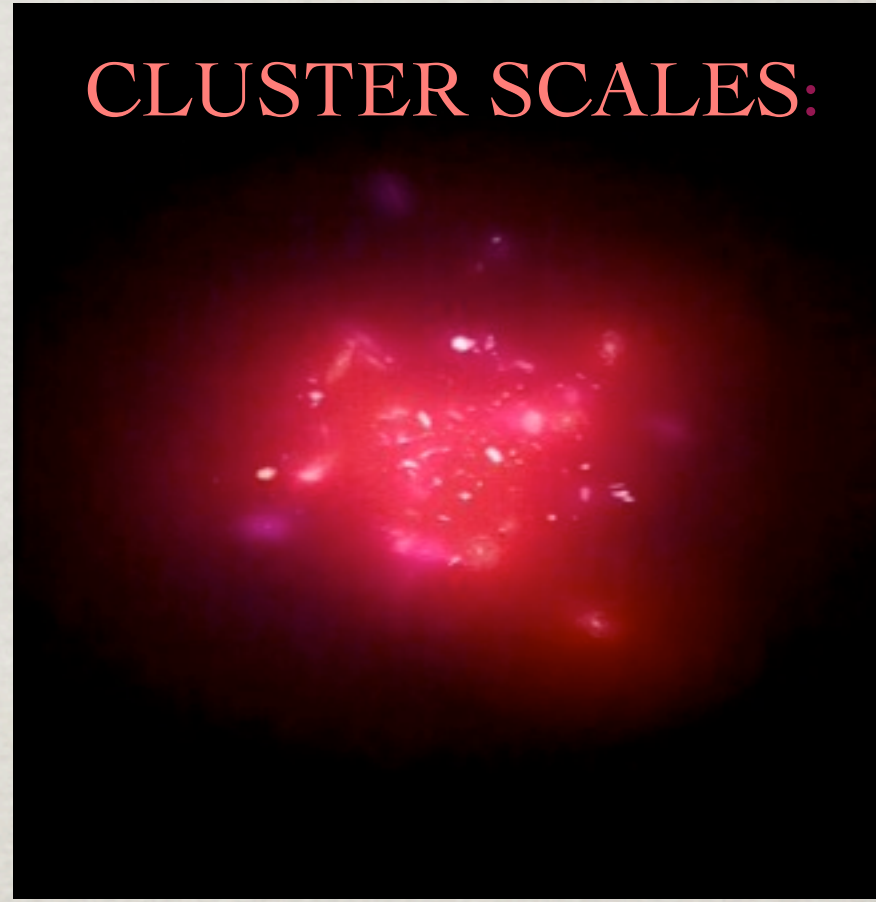
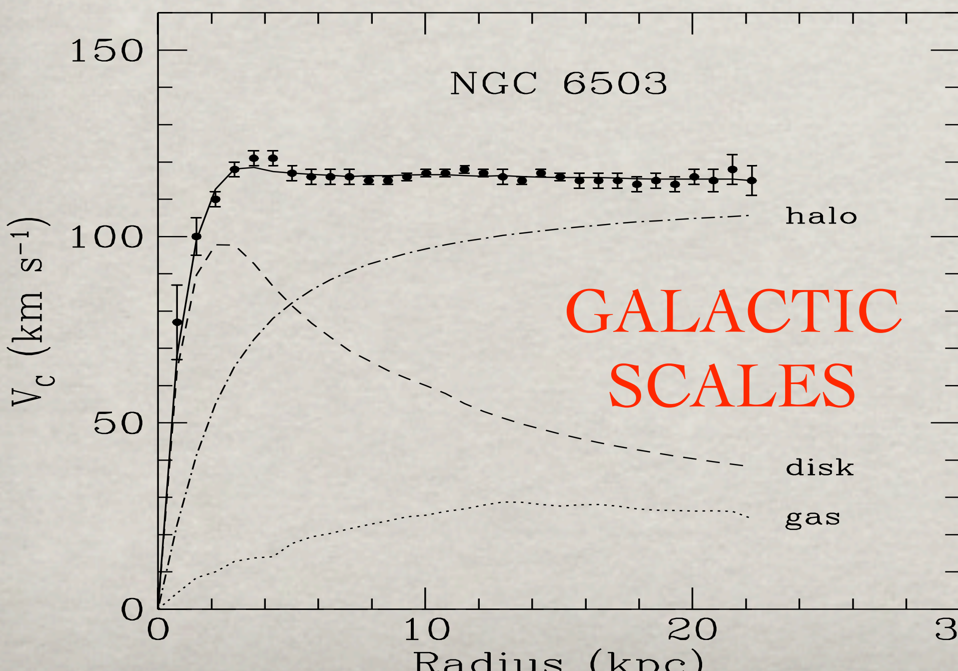




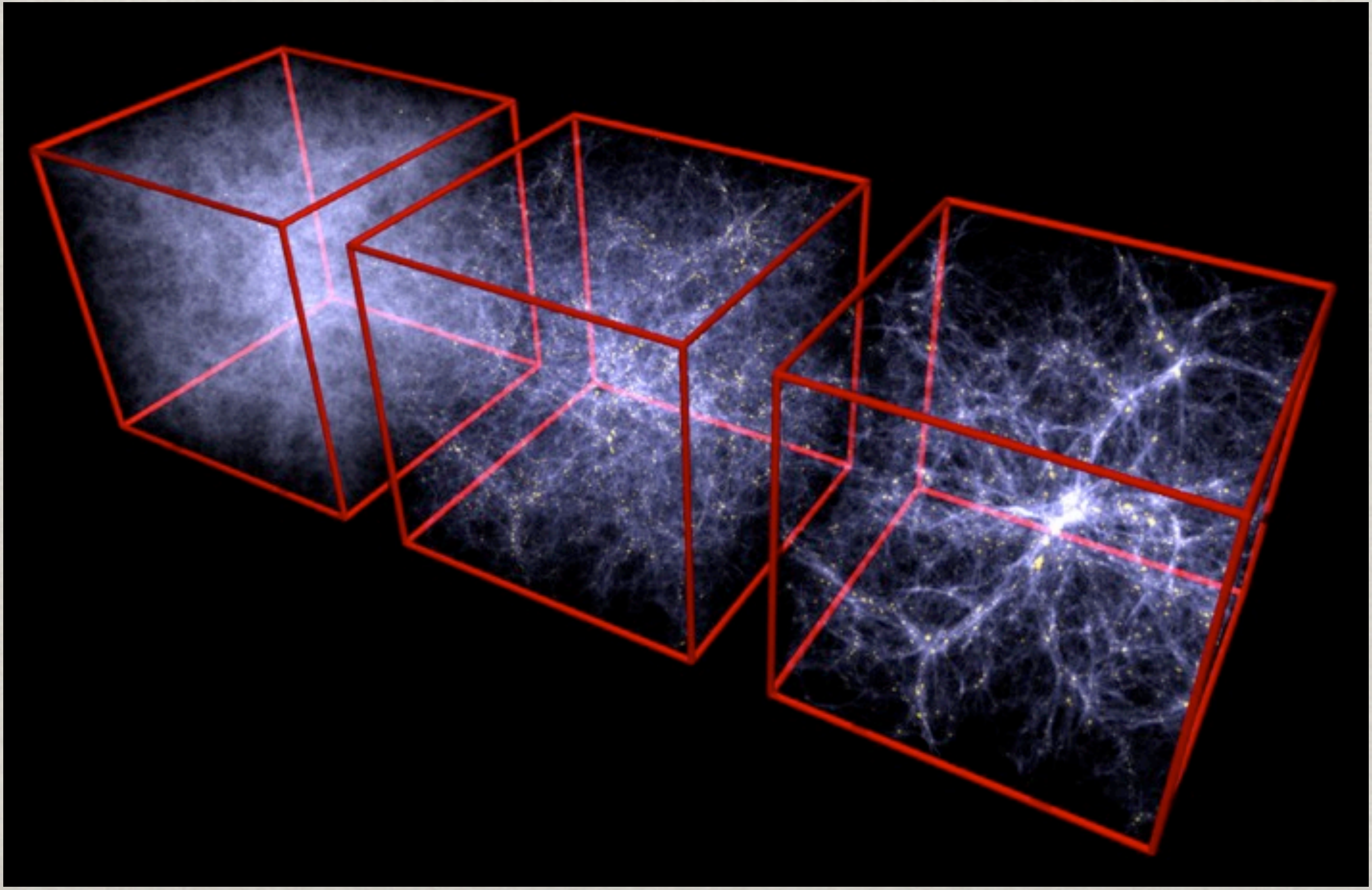


Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

Structure Formation

V. Springel @MPA Munich

Yoshida et al 03



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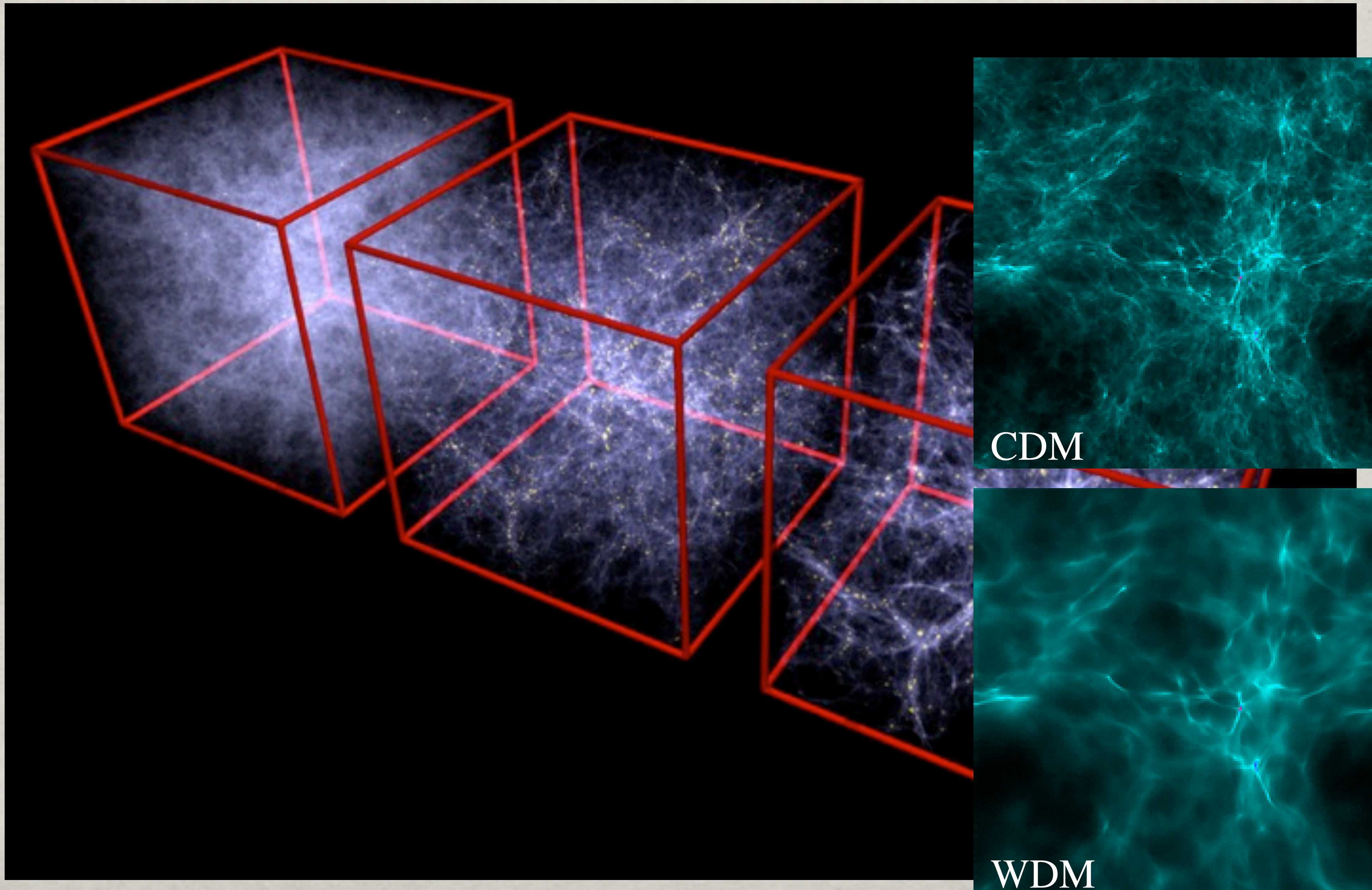
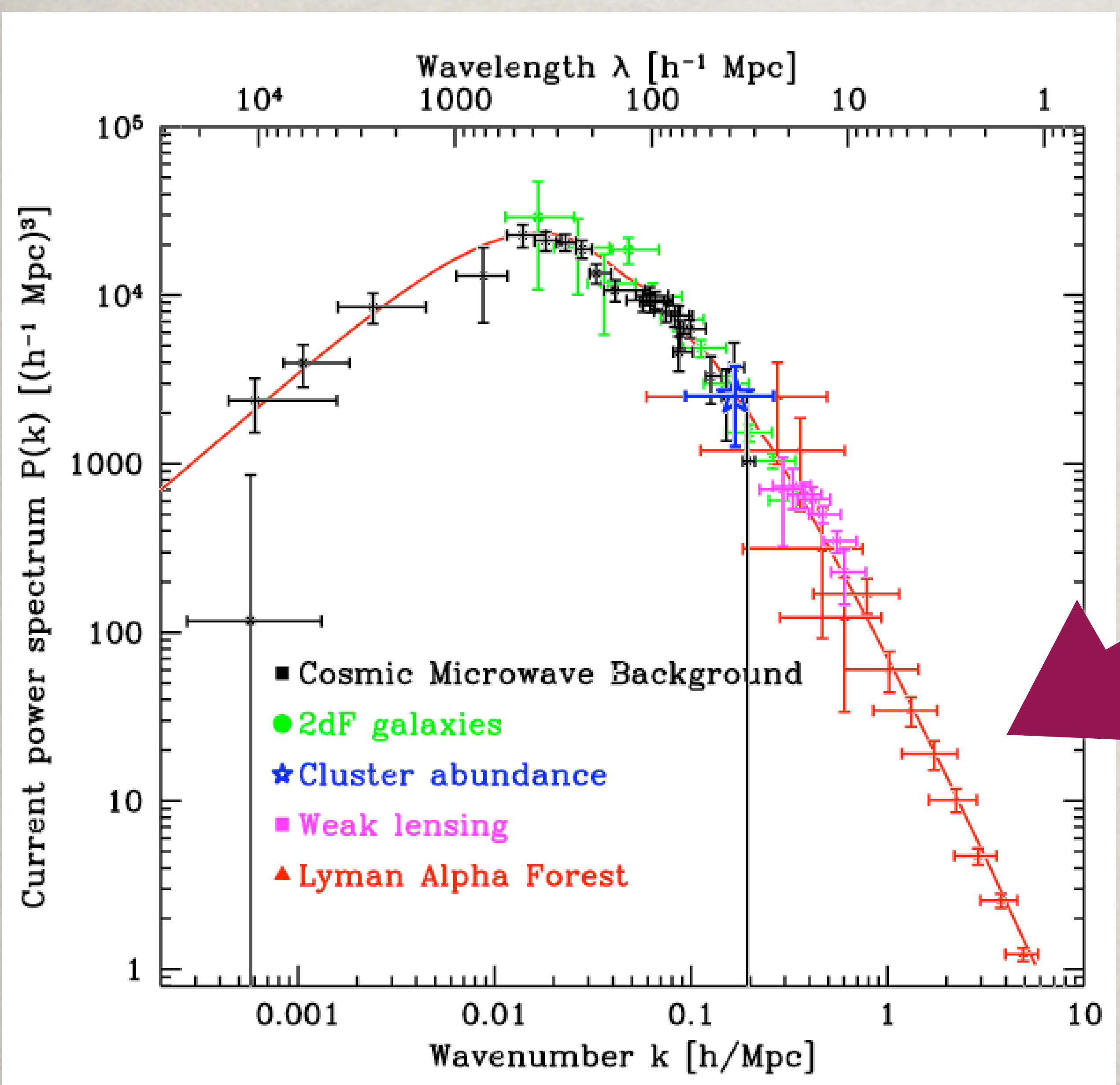


WDM & the Power spectrum



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

$$\lambda_{FS} \sim \text{Mpc} \left(\frac{m_{WDM}}{1\text{keV}} \right)^{-1}$$

Compare with the data:

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

[Viel et al. '07]

All these evidences are just based on the gravitational force: either directly on the attraction of the Dark Matter on the visible matter or on the effect of the Dark Matter energy component on the Universe expansion or on the evolution of the density perturbation...

So there is no doubt:

DARK MATTER
IS GRAVITATING !

But what about other interactions ???

DARK MATTER INTERACTION

CLUSTER SCALES:

Systems like the Bullett cluster allow to restrict the self-interaction cross-section of Dark Matter to be smaller than the gas at the level

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \ \sim 1 \ \text{barn}$$

[Markevitch et al 03]

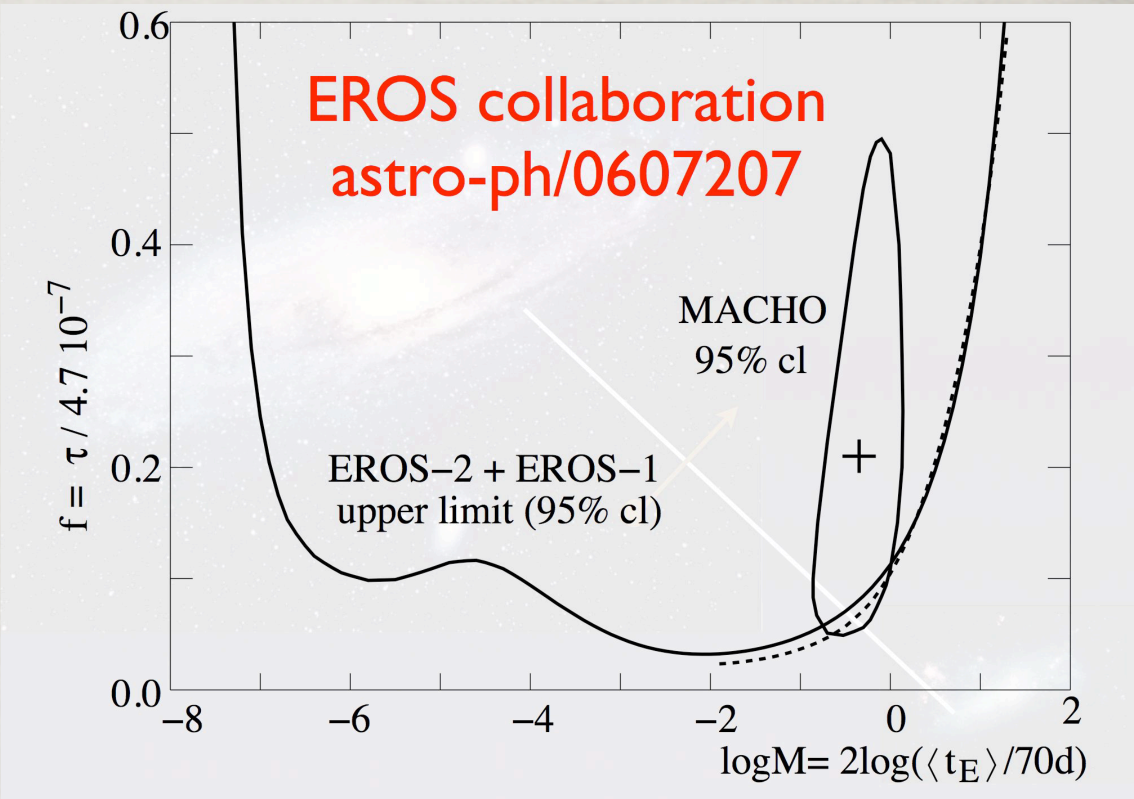
One order of magnitude stronger contraint by required a sufficiently large core... [Yoshida, Springer & White 00]

Not such a strong bound...

Baryonic DARK MATTER ?

Faint planets, MACHOS ?
No evidence in our galaxy found by the EROS collaboration between 10^{-7} and 20 solar masses.

Still clumps of non-baryonic Dark Matter, much less concentrated, may be there...



DARK MATTER LIFETIME?

- The Dark Matter keeps our galaxy together, so it should be longer lived than the Universe:

$$\tau > 10^{17}\ \mathrm{s}$$

- For any visible decay (photons, charged particles, even neutrinos) the limits are actually much stronger

$$\tau > 10^{24} - 10^{28}\ \mathrm{s}$$

Still quite far from the proton lifetime bound...

DARK MATTER PROPERTIES

- Electrically neutral, non-baryonic, possibly electroweak interacting, but could even be only gravitationally interacting.

- It must still be around us: either stable or very very long lived, i.e. it is the lightest particle with a conserved charge (R-, KK-, T-parity, etc...) or its interaction and decay is strongly suppressed !

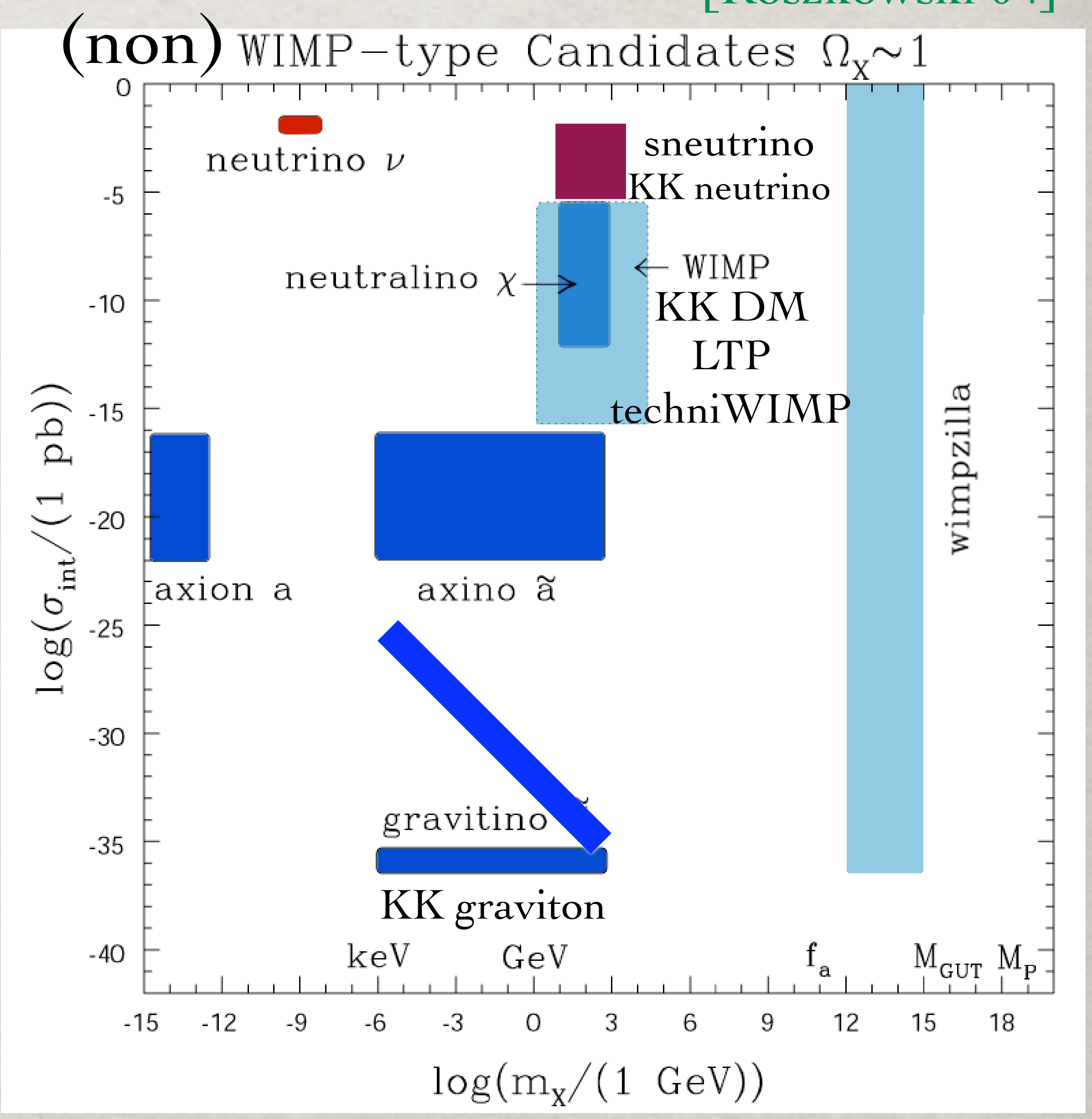
- If it is a thermal relic, must be sufficiently massive to be cold..., but it may even be a condensate...

⬇

LOOK FOR PARTICLE DM CANDIDATES !

DARK MATTER CANDIDATES

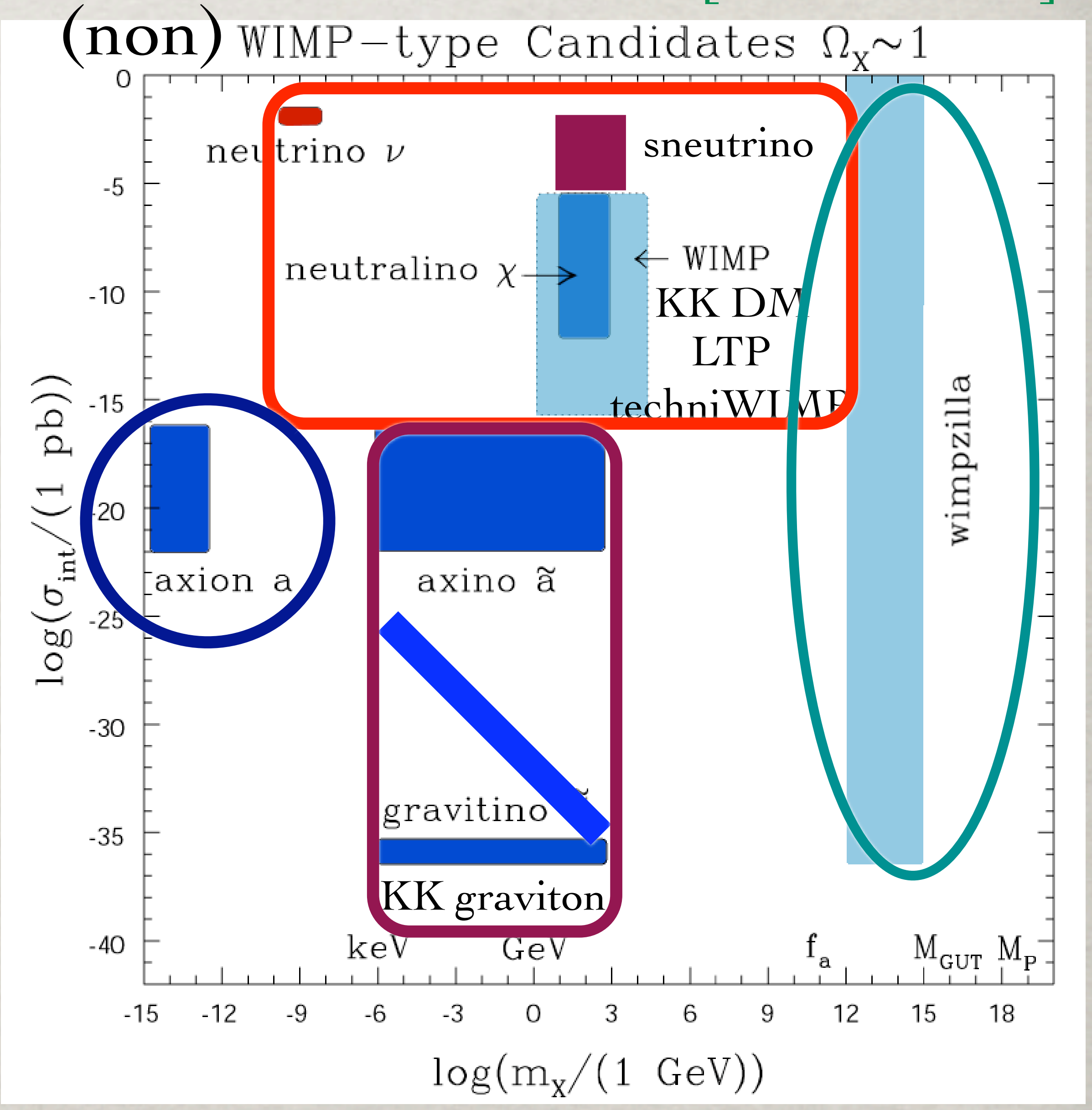
[Roszkowski 04]



DARK MATTER CANDIDATES

[Roszkowski 04]

- Thermal relics: WIMPs
- "SuperWIMPs"
- Condensate
- Produced gravitationally



Gravitino & 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

GRAVITINO properties: completely fixed by SUGRA !

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

$$m_{3/2} = \langle W e^{K/2} \rangle = \frac{\langle F_X \rangle}{M_P}$$

~~SUSY~~ scale

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 $m_{3/2} \sim$ keV, while in anomaly mediation we can even have $m_{3/2} \sim$ 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: $\psi_\mu \simeq i\sqrt{\frac{2}{3}} \frac{\partial_\mu \psi}{m_{3/2}}$. Then we have:

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

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

Couplings proportional to SUSY breaking masses and inversely proportional to $m_{3/2}$.

SUSY breaking mechanism determines which particle is the LSP and the gravitino couplings !

The gravitino gives us direct information on SUSY breaking and can be stable or unstable depending on R-parity...

Stable Gravitino

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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PLASMA SCATTERINGS

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

NLSP DECAY OUT OF EQUILIBRIUM

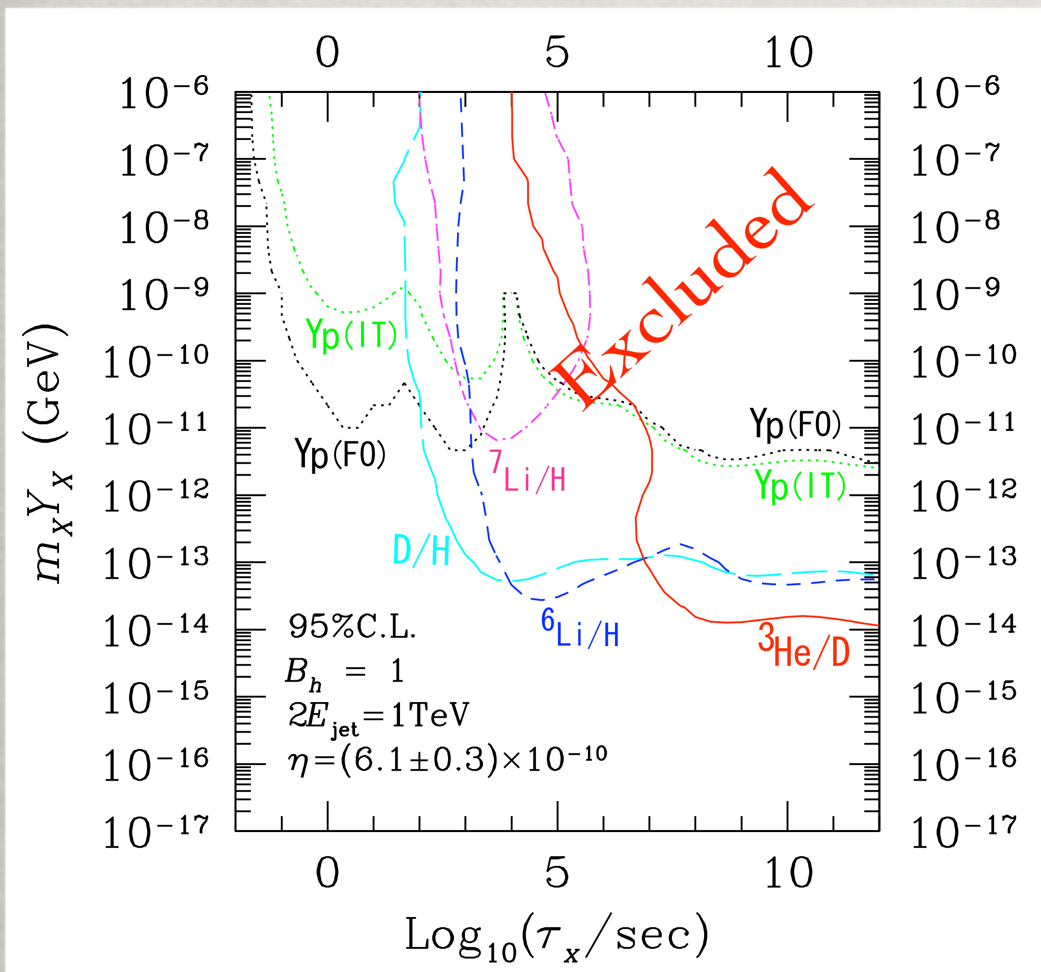
Ω ^{2} $\propto$ h^2

DANGER !!!
BBN at risk !

BBN bounds on NLSP decay

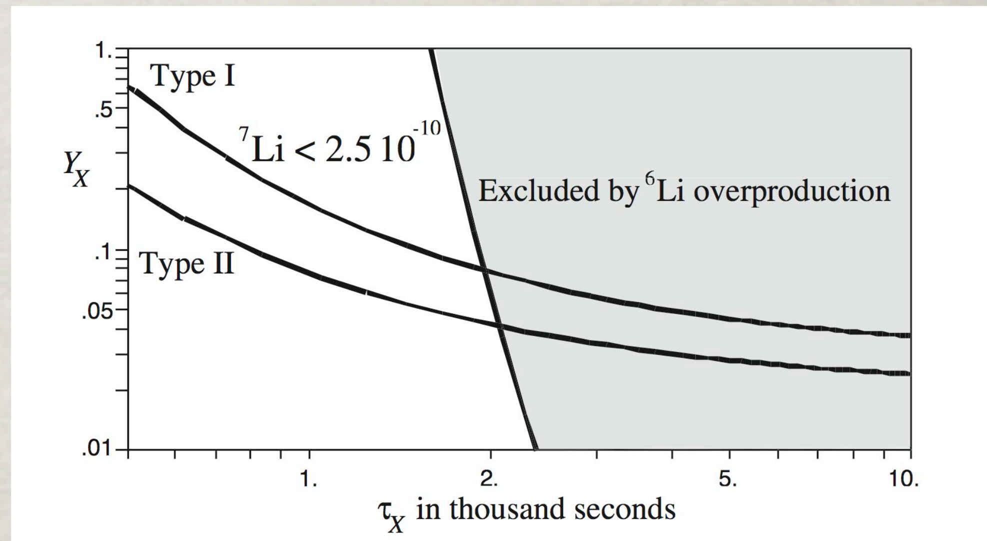
Neutral relics

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



Charged relics

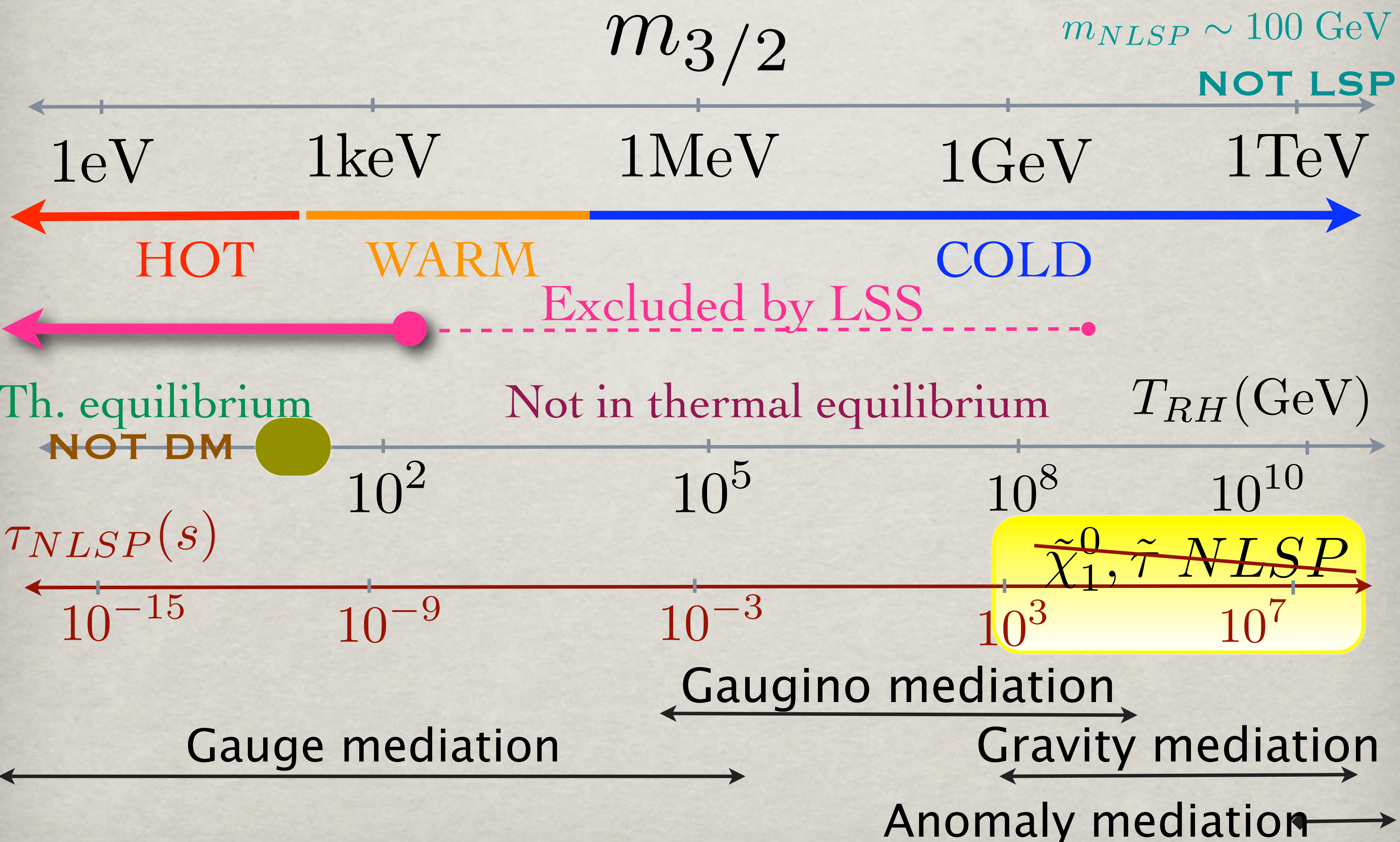
[Pospelov 05, Kohri & Takayama 06, Cyburt at al 06, Jedamzik 07,...]



Need short lifetime & low abundance for NLSP

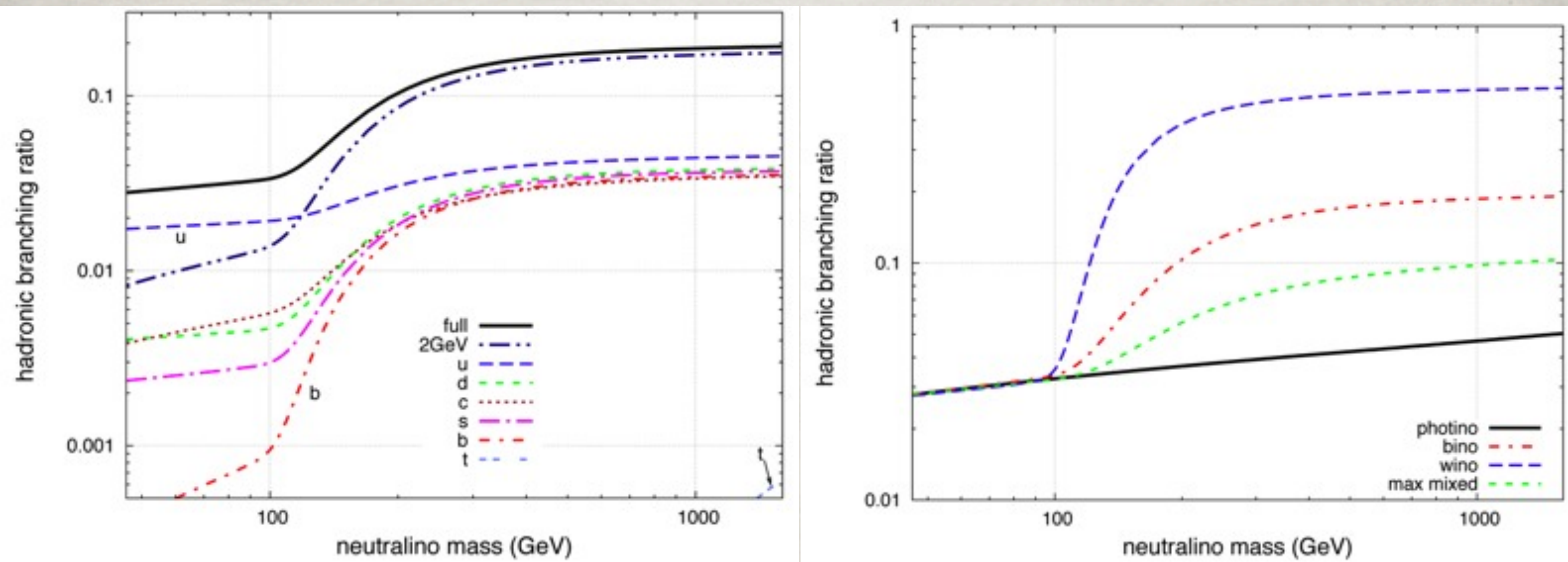
Big problem for gravitino LSP with 10-100 GeV mass...

Gravitino DM summary



General neutralino NLSP

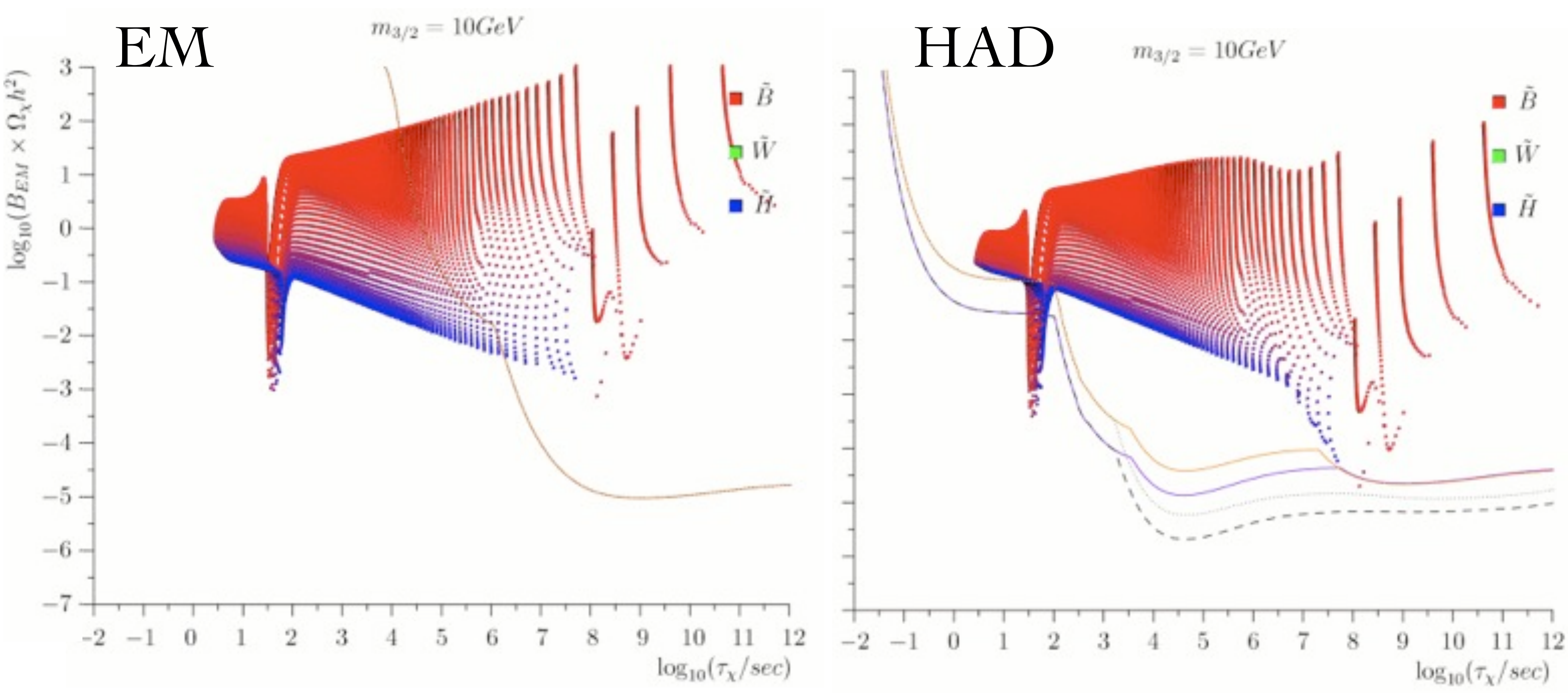
[LC, Hasenkamp, Roberts & Pokorski 09]



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-Higgsino

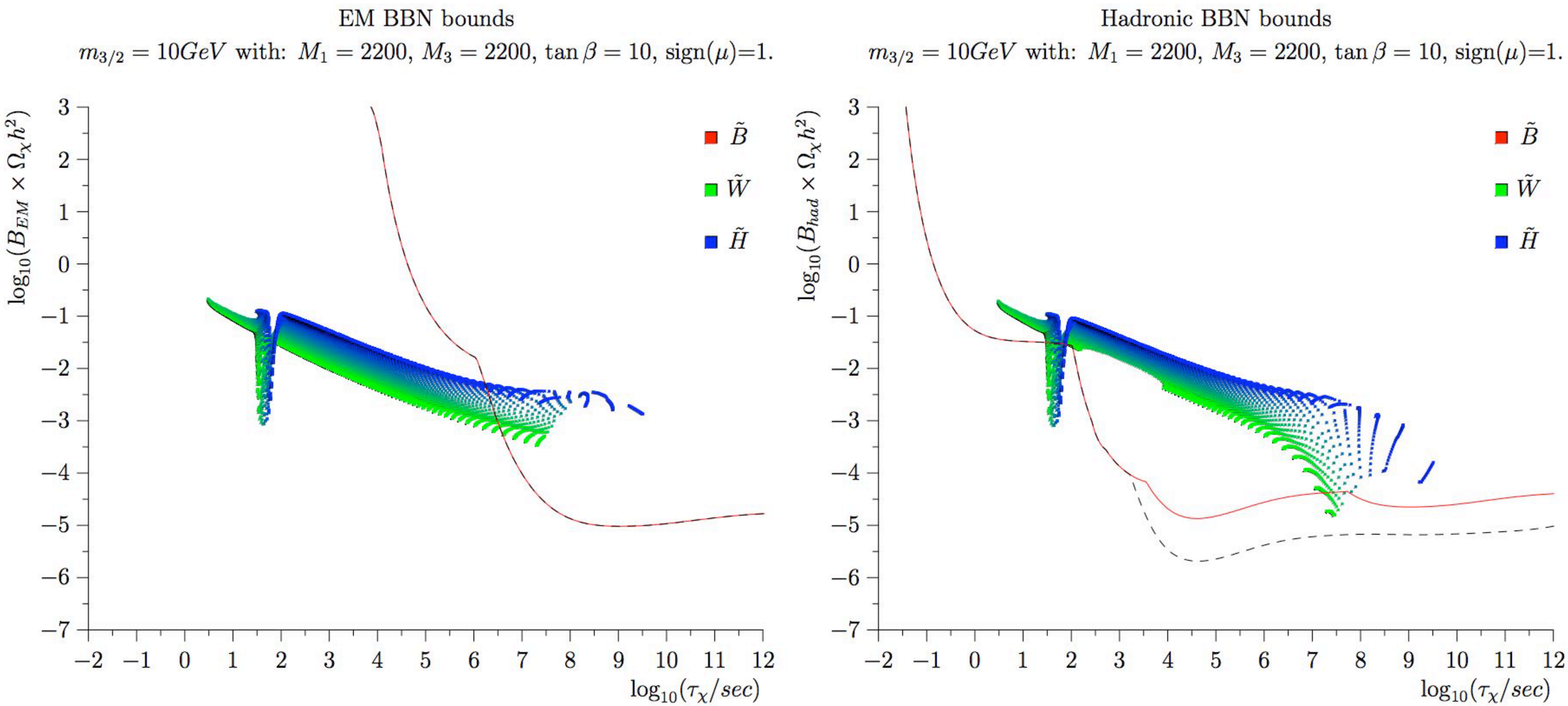
[LC, Hasenkamp, Roberts & Pokorski 09]



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

Wino-Higgsino

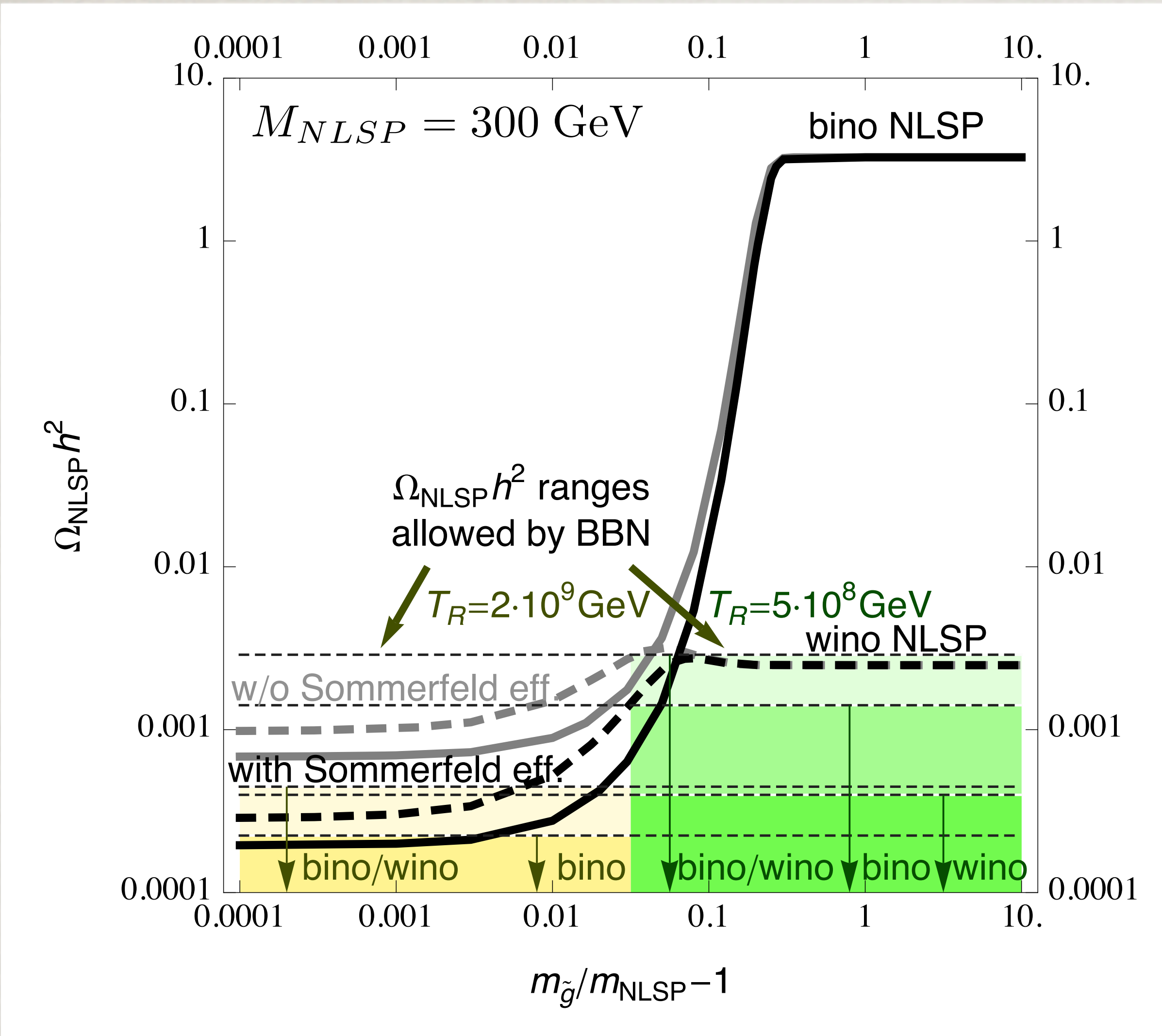
[LC, Hasenkamp, Roberts & Pokorski 09]



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...

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski, Wells ....]



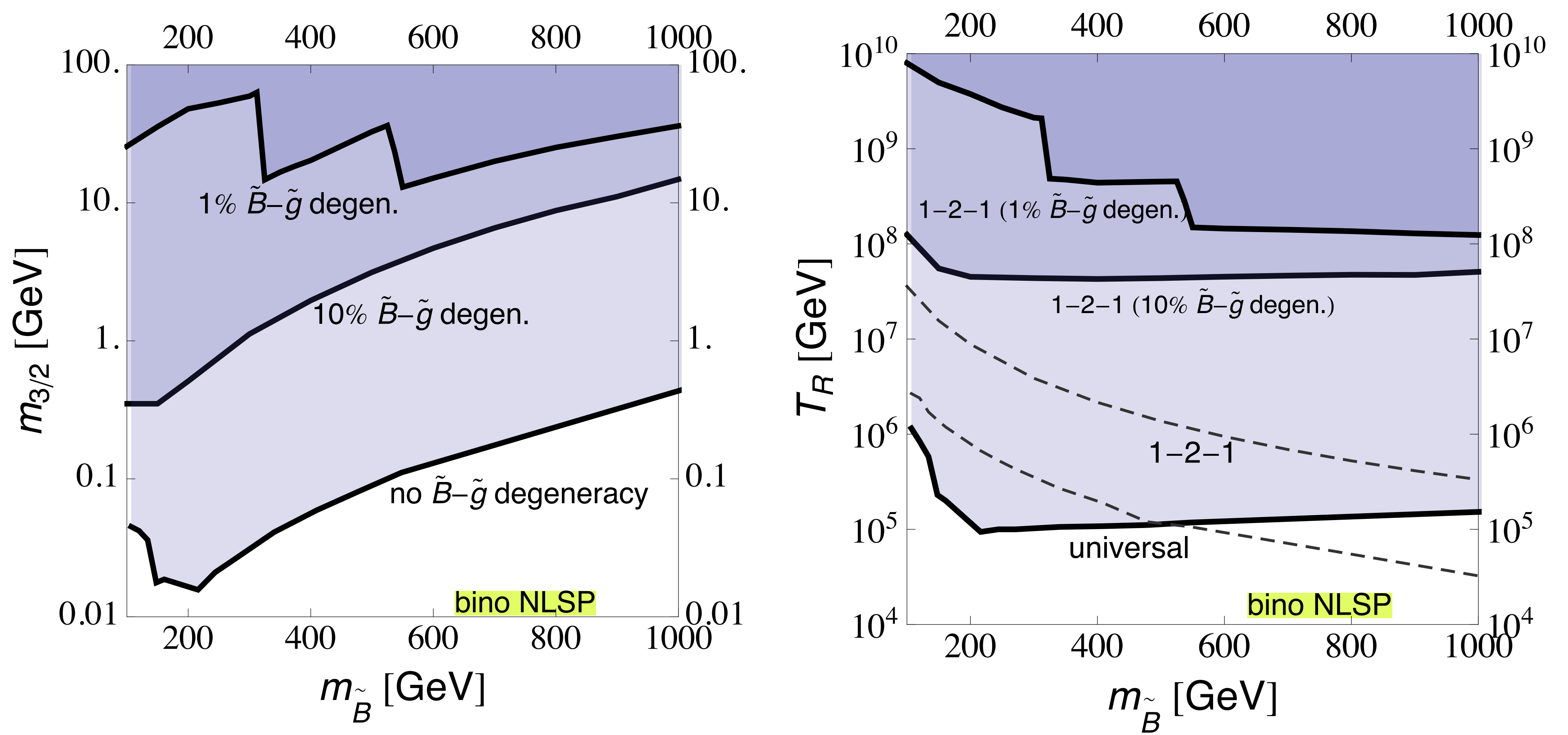
Gluinos annihilate most efficiently, but are a bad NLSP due to BBN bound state effects...

On the other hand they can help the other neutralinos NLSP.

The coannihilation with gluinos has a very strong effect on the Bino, even for just 10% degeneracy. Less effect for Wino.

Degenerate gauginos NLSP

[LC, Olechowski, Pokorski, Turzynski, Wells ....]



The coannihilation with gluinos allows to reach gravitino masses in the 10 GeV range (high T_R), but with very strong degeneracy...

Other ways out:

- Dilute the NLSP abundance with entropy production

  [Buchmuller et al 05, Hamaguchi et al 07...]

- Reduce the energy released during BBN by making the gravitino mass nearly equal to the NLSP mass...

  $\longrightarrow$ degenerate gravitino scenario [Boubekeur et al 09]

- Choose a relatively harmless NLSP, e.g. sneutrino

  [LC & Kraml 07, Santoso et al. 08, ...]

- Make the NLSP lifetime shorter:

  heavy(er) NLSP or light(er) gravitino LSP or breaking R-parity and allowing the NLSP decay to SM.

  But then the gravitino DM is unstable !!!

Unstable Dark Matter

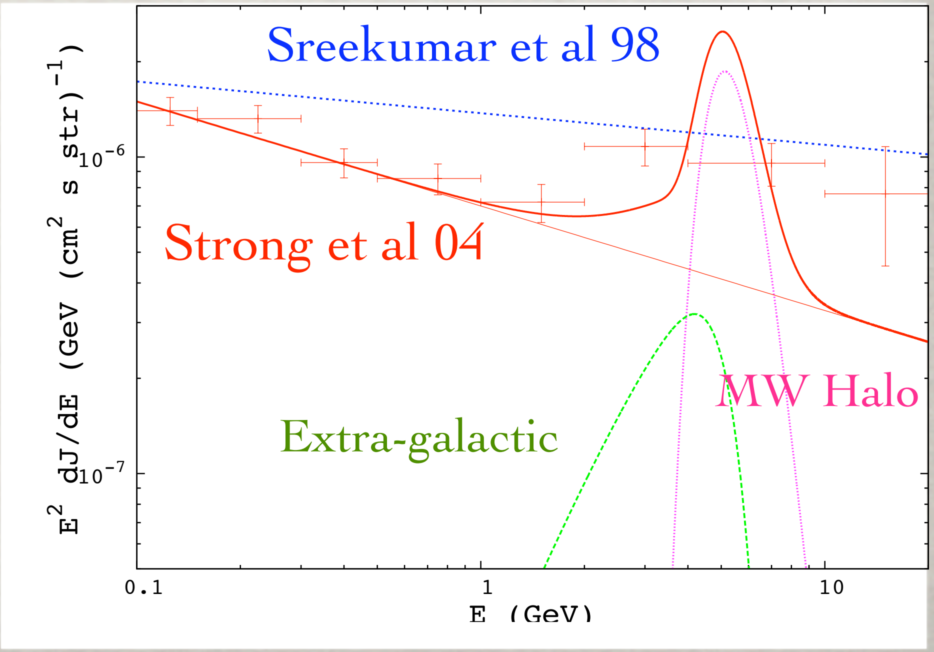
DECAYING DM

- 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

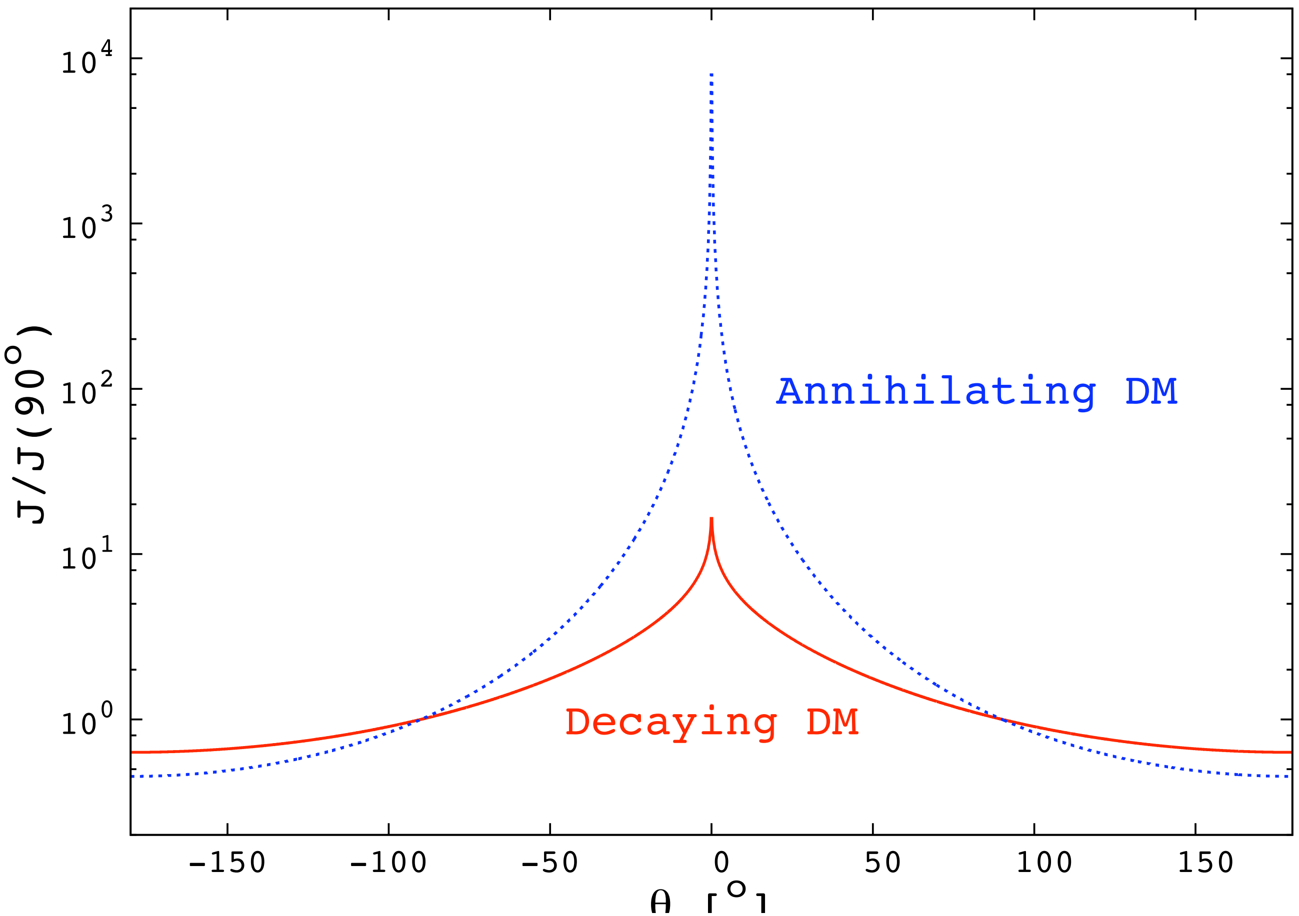
- Very weak dependence on the Halo profile; key parameter is the DM lifetime...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...
- Galactic/extragalactic signal are comparable...



Decaying vs annihilating

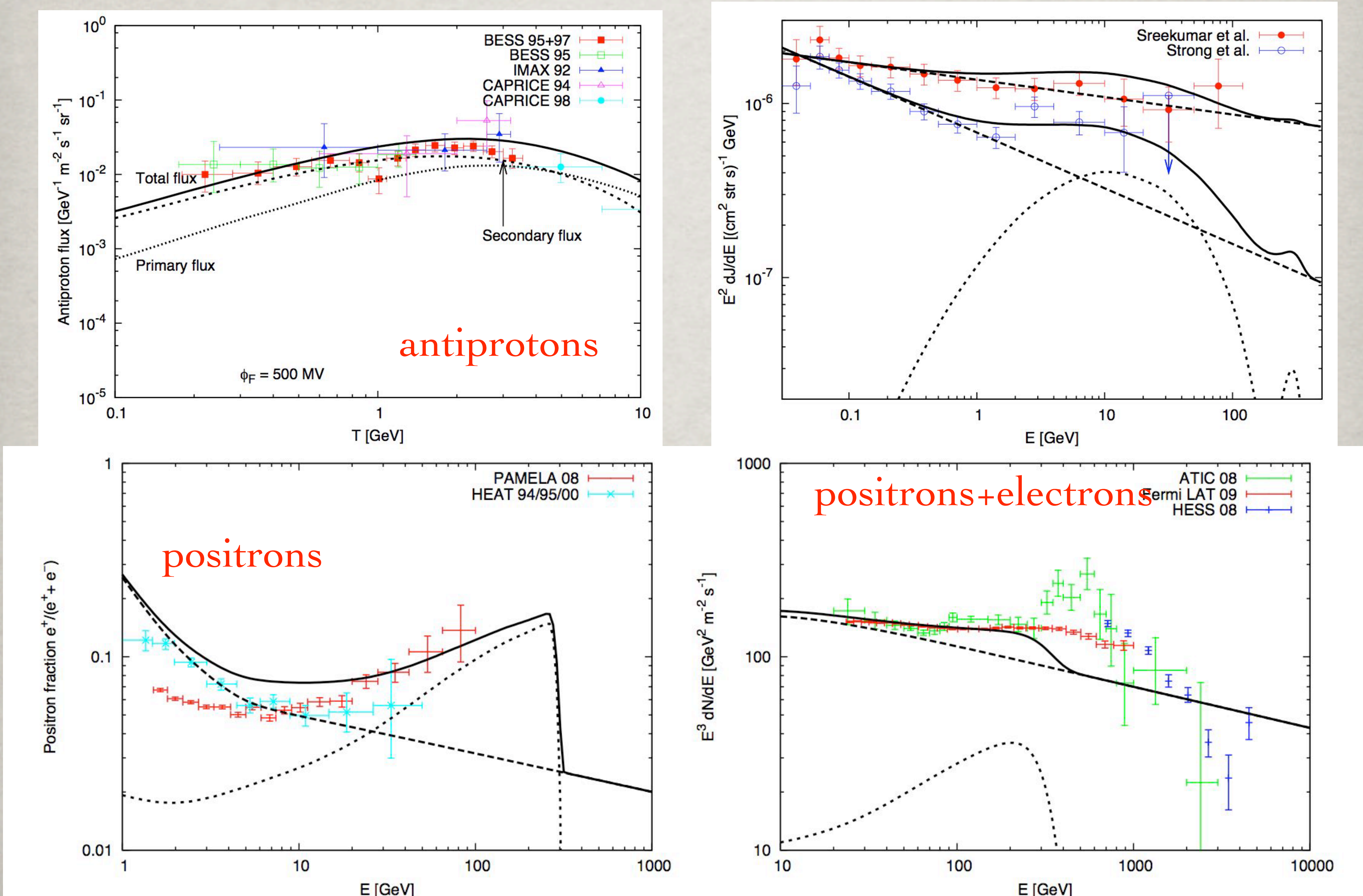
The galactic signal in photon or neutrinos follows either the density for decay or the density squared for annihilating DM: the angular profiles may allow to distinguish the two !

[Bertone, Buchmuller, LC, Ibarra '07]

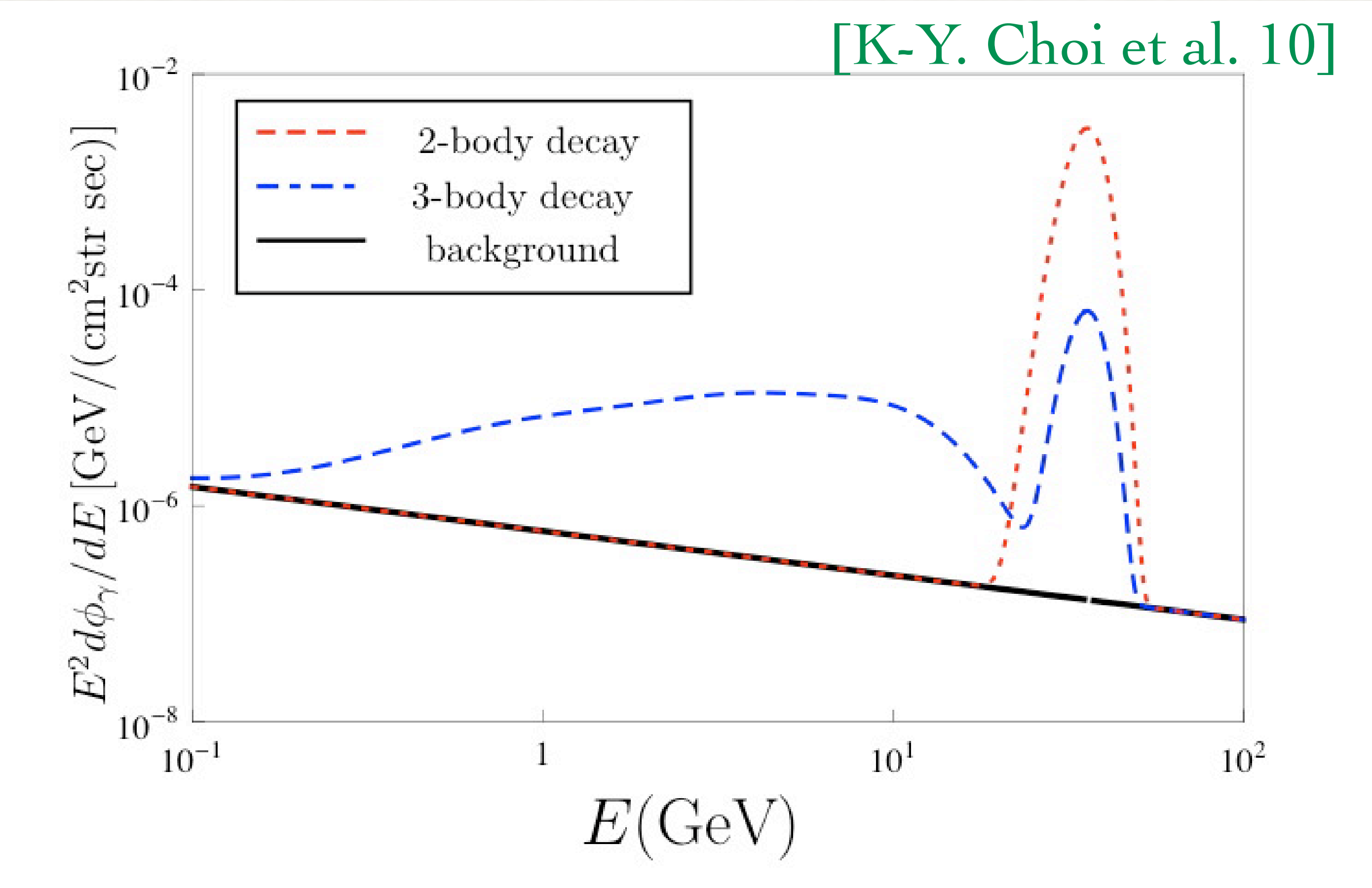


Gravitino DM without R_p

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



Below M_W also 3-body

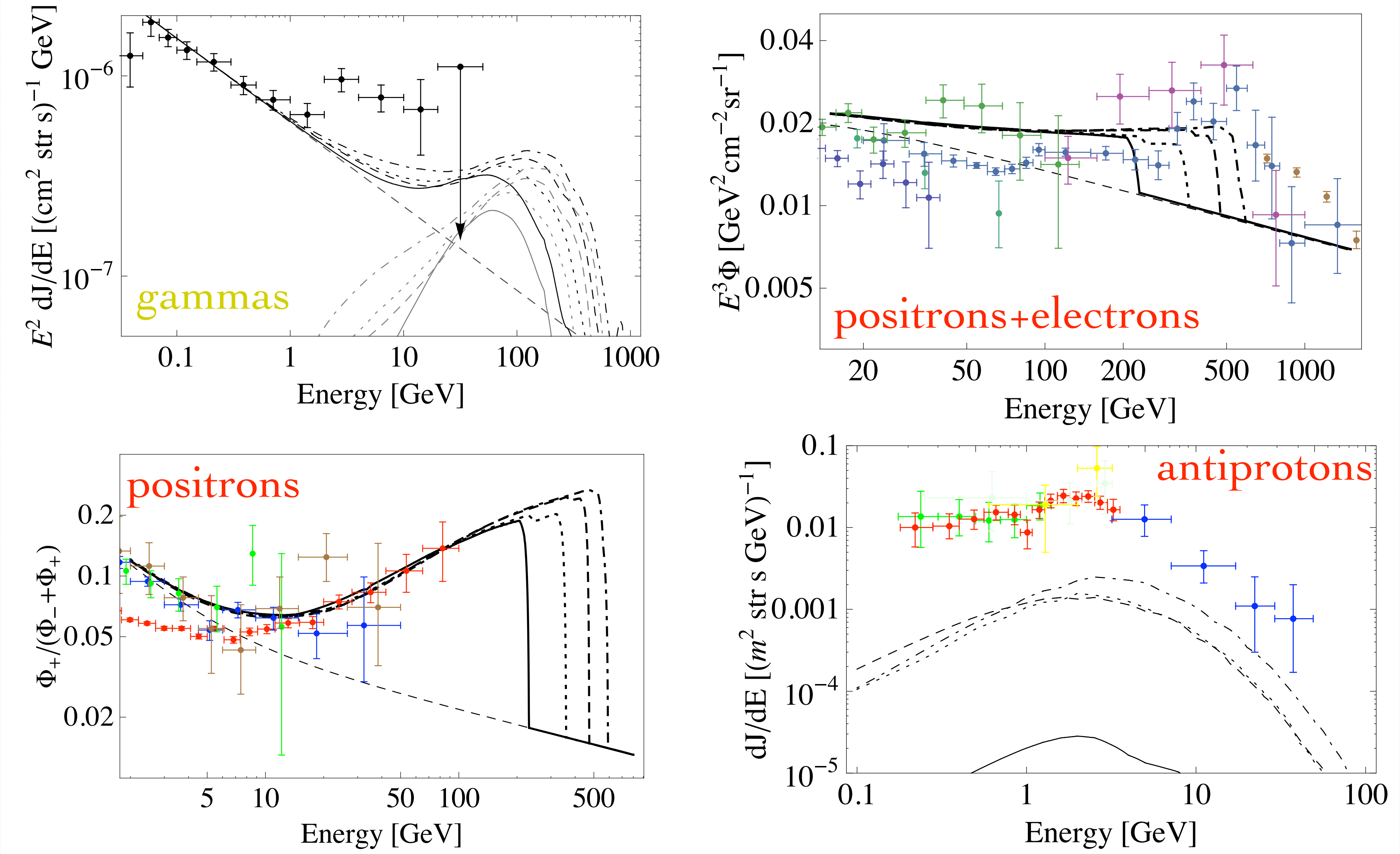


For bilinear R-parity breaking, the gravitino decays mostly into lepton and gauge boson... Below the W/Z threshold though, also the 3-body decay via virtual W/Z are important because the photon channel can be suppressed... [K-Y. Choi & Yaguna 10]

Constrained by FERMI gamma-line search: $\tau \geq 10^{29}$s

Hidden Photino Dark Matter

[Ibarra, Ringwald, Weniger 09]



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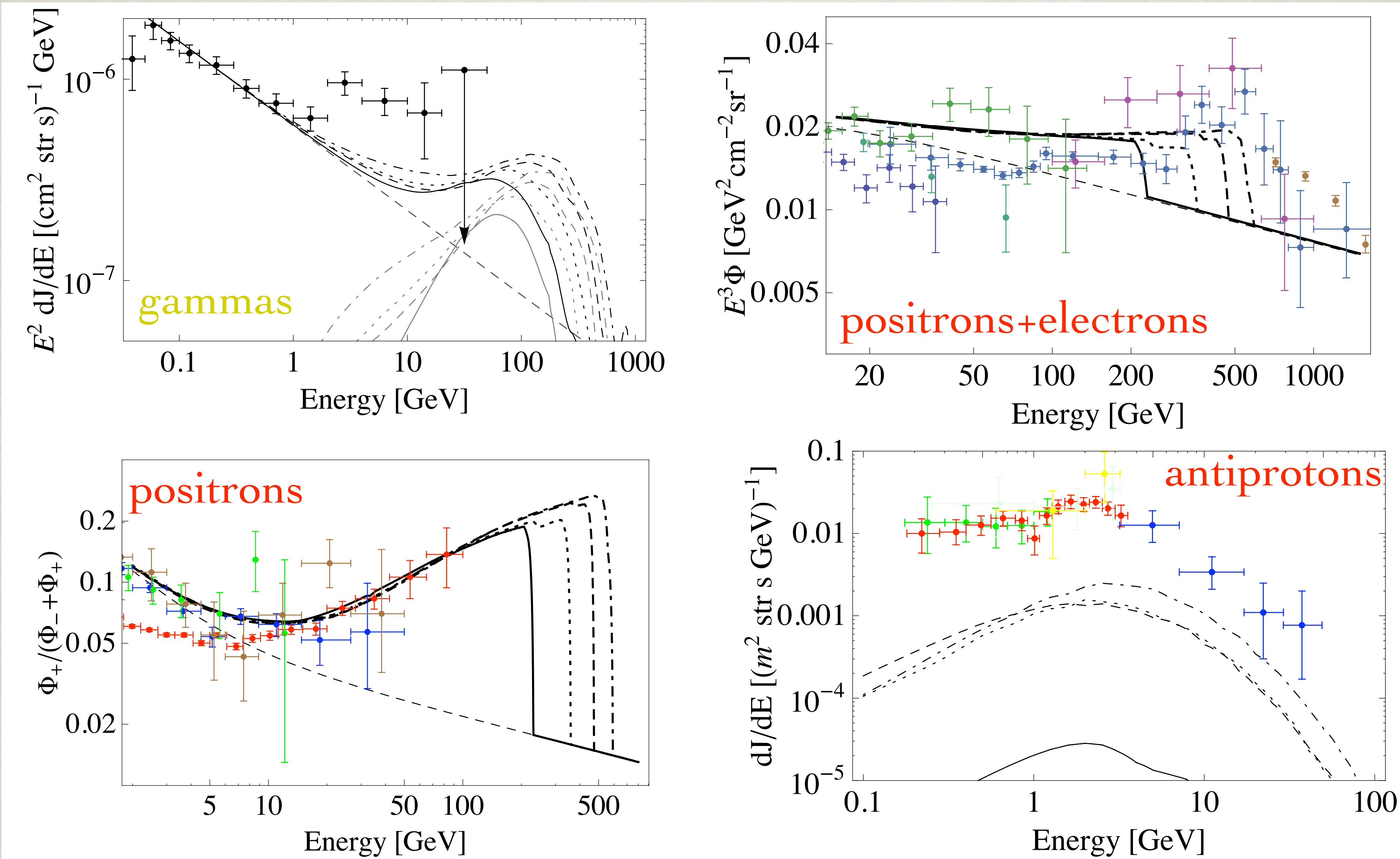
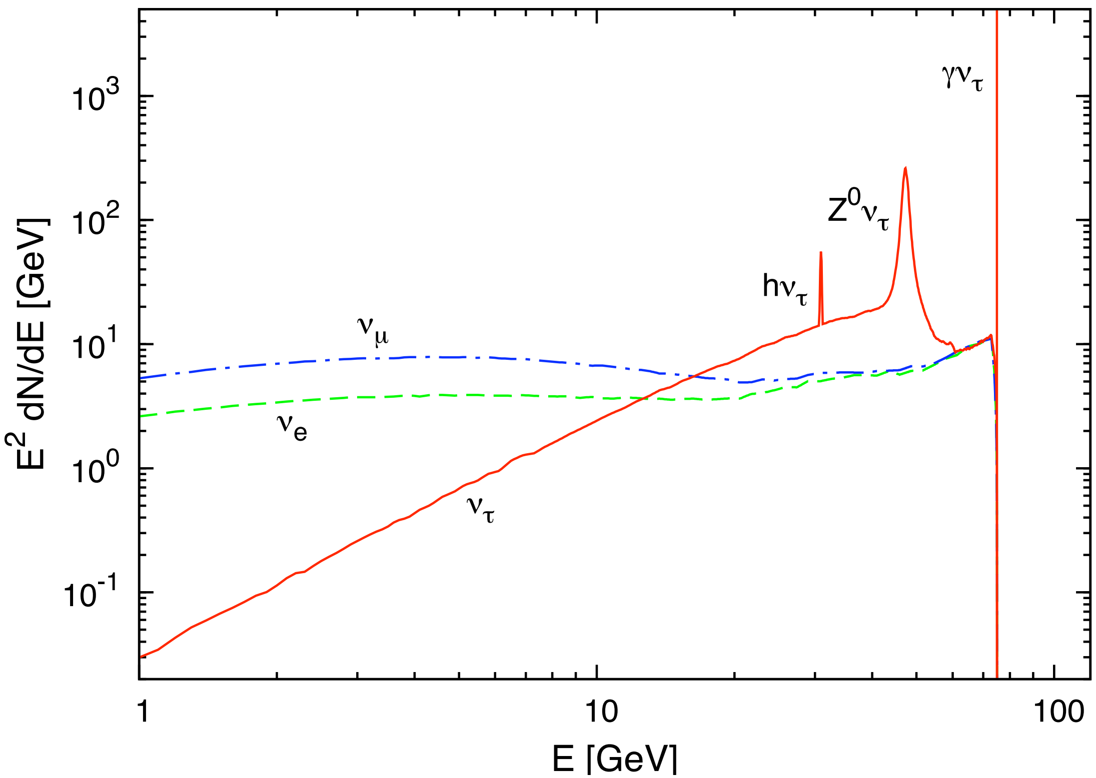


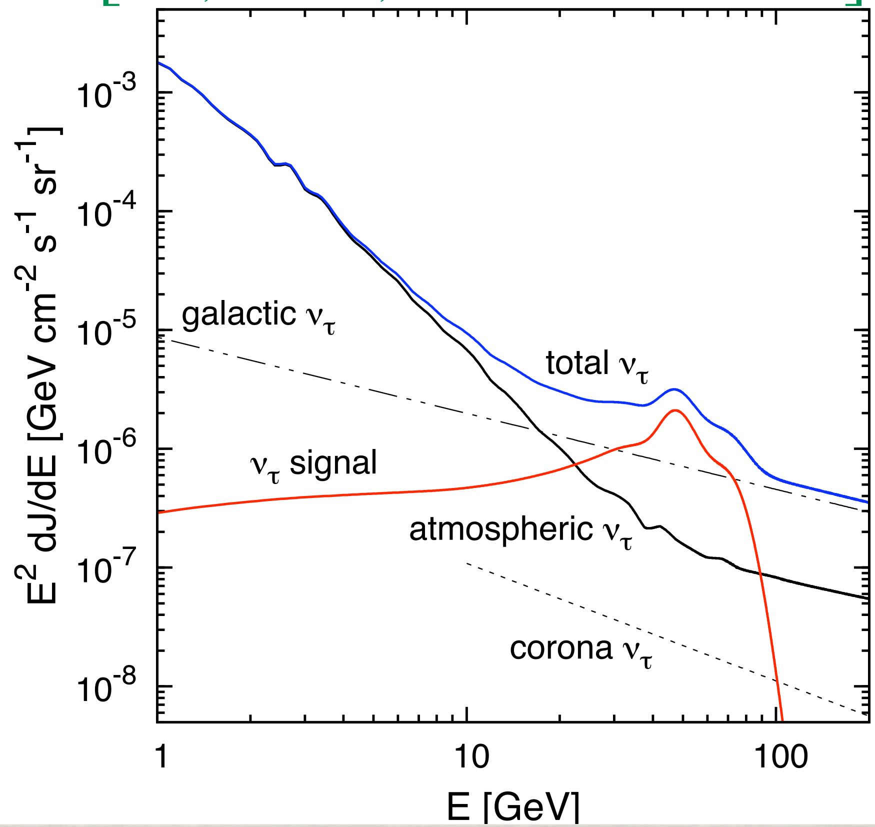
CONSISTENT with PAMELA, but no edge in FERMI...

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]

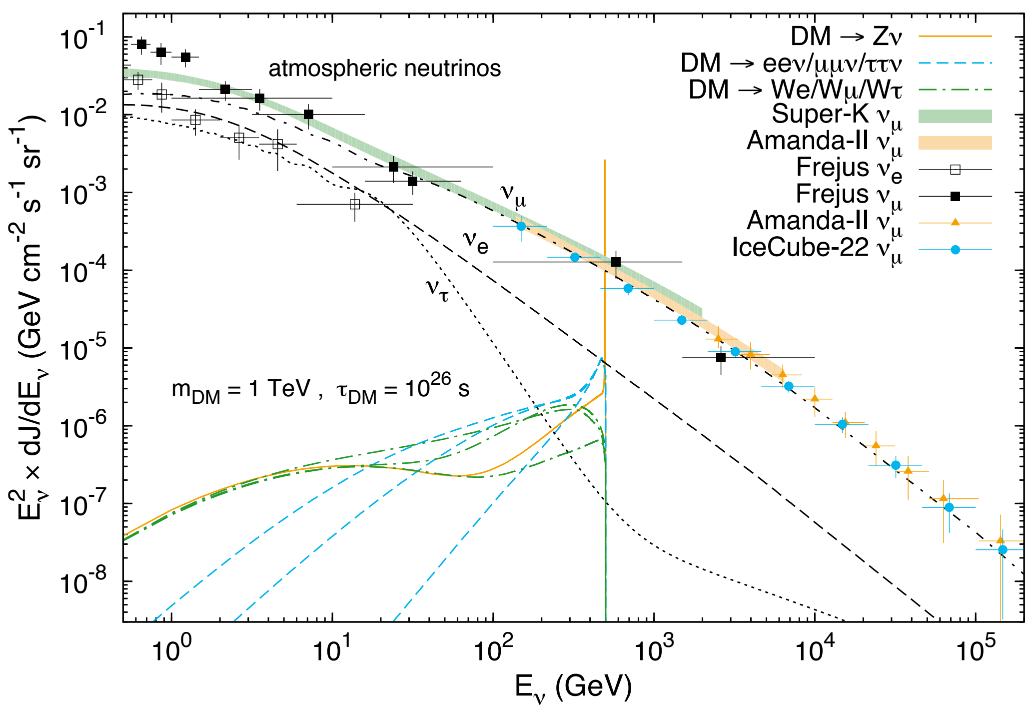


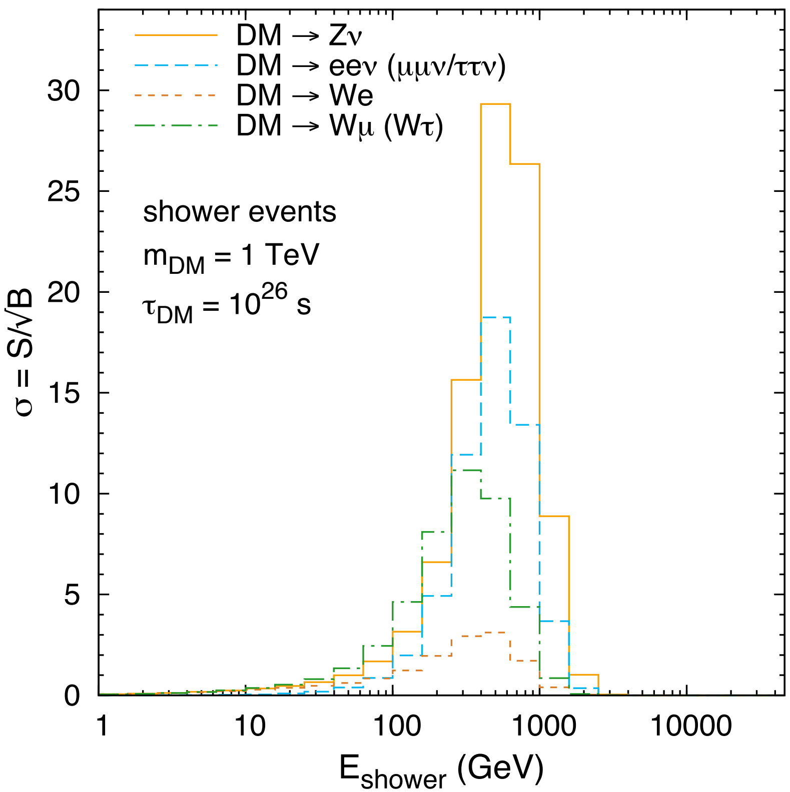
Best signal to background ratio for a tau neutrino looking up...

General decaying DM

For heavy 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]





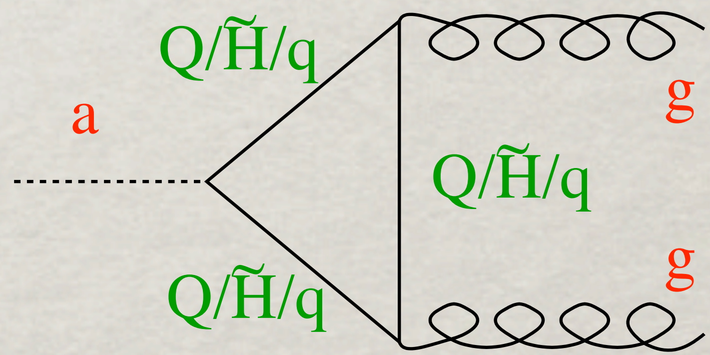
Best significance for cascade/shower events
Possible to detect in IceCube ?

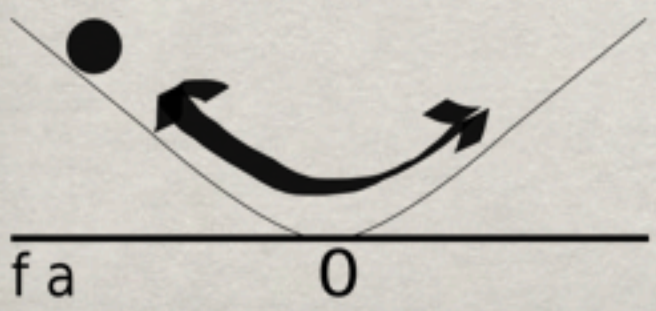
Axion
Dark Matter

Axions as Dark Matter

The axion is also a very natural DM candidate, but in this case it is in the form of a condensate...
The axion is a pseudoGoldstone boson, arising in the Peccei-Quinn solution to the strong CP problem

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





The axion receives a mass and a potential only after the QCD phase transition and then starts to oscillate coherently:
zero momentum particles >> CDM !

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
Possibility of mixed axino/axion DM depending on f_a !

AXION DM SEARCHES

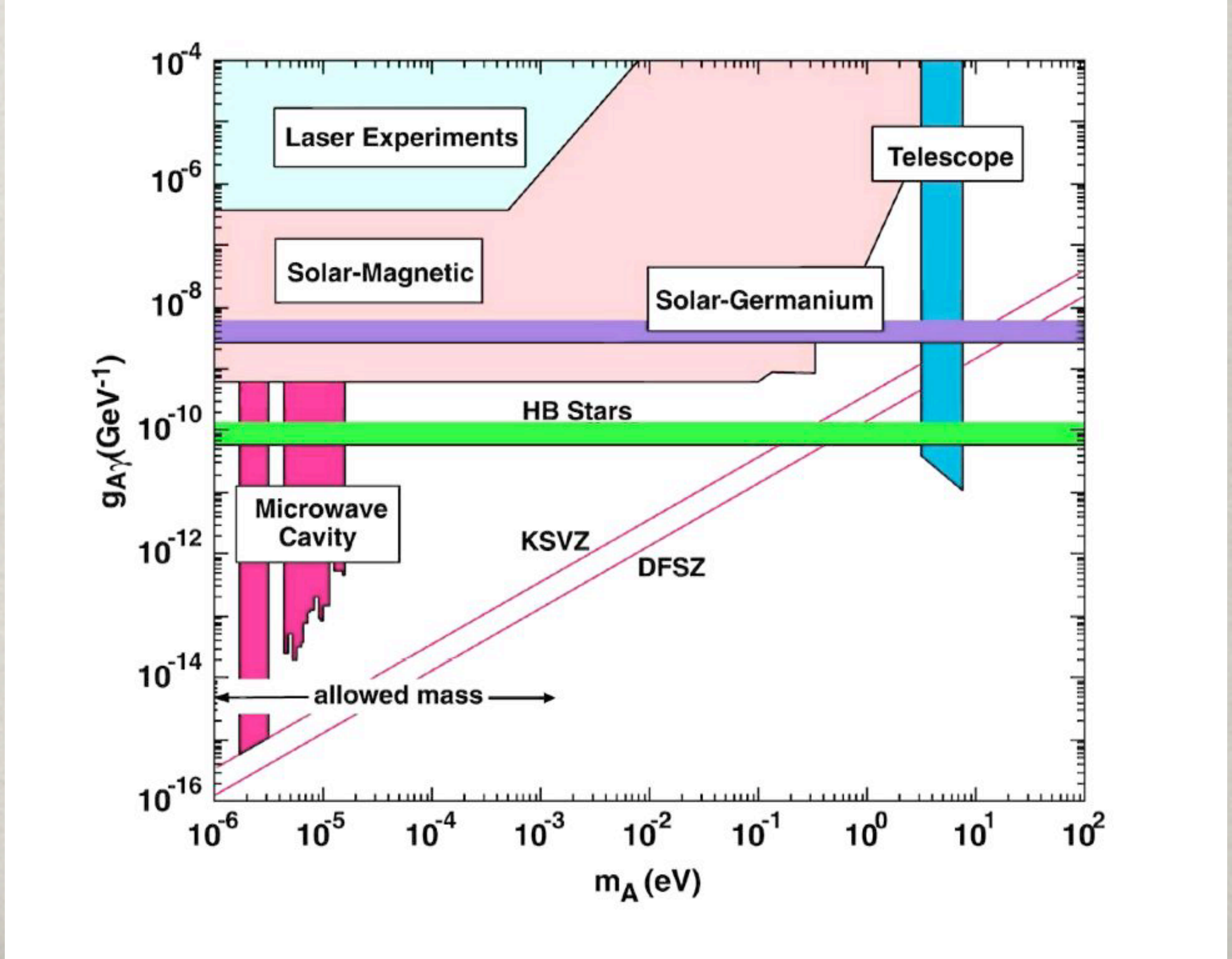
The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μ eV.

[Carosi '07]

ADMX at Livermore is finally touching the expected region.

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

[Gondolo et al 09]



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 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...

Strongly interacting DM ?

Can DM interact strongly?

- Yes, but not via QCD... QCD charged relics are strongly constrained by BBN bound state effects and by searches of exotic nuclei !

- Nevertheless DM could be strongly interacting under a hidden section and be a composite object...

- In that case it can be a very massive "baryon" with unitary cross-section or a techni-WIMP or even a SuperWIMP...

It may decay or annihilate !!!

OPEN questions & Outlook

Outlook

Since the discovery of F. Zwicky, we have learned a lot about Dark Matter, in particular what it is not: not baryonic, not hot, not made of neutrinos, etc...

The next decade hopefully should bring us some more clear answers:

- Many non-WIMP candidates still in good shape ! They will be probed by future accelerator or DM search experiments...

- Indirect detection may discover if DM in the halo is annihilating or decaying, i.e. a WIMP or not...

EXCITING TIMES ARE JUST BEGINNING...