

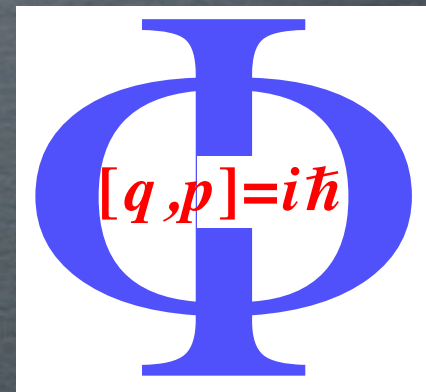
Workshop “New perspective in Dark Matter” - Lyon 24.10.13

# SUPERWIMP DARK MATTER & THE LHC



Laura Covi

Institute for Theoretical Physics  
Georg-August-University Göttingen



inVisibles  
neutrinos, dark matter & dark energy physics



# OUTLINE

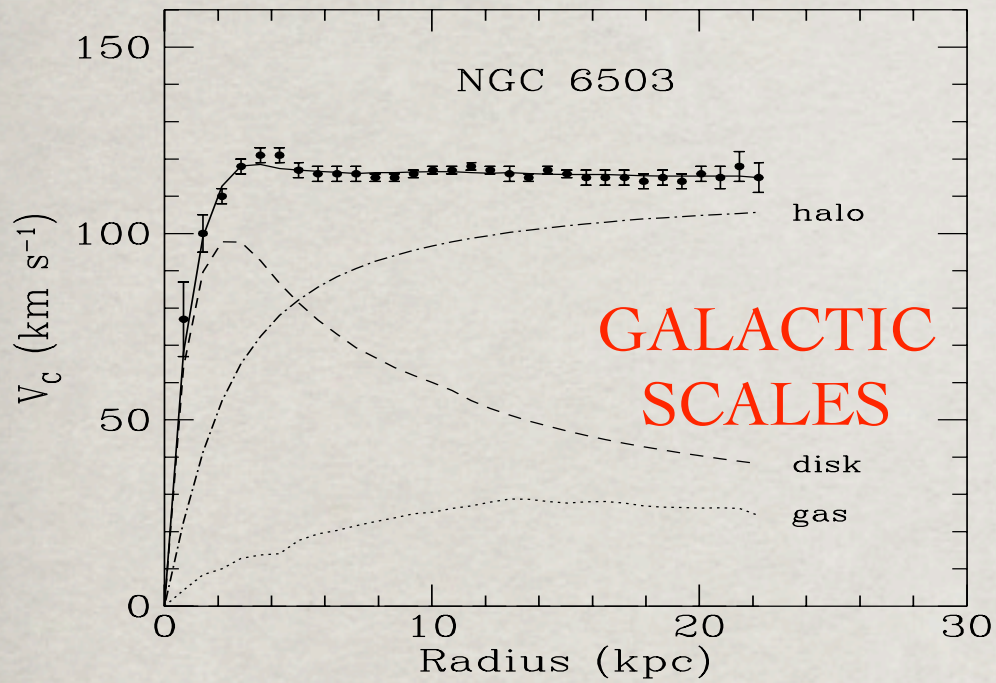
- Introduction:  
SuperWeakly Interacting DM & Cosmology
- Gravitino CDM with stop NLSP:
  - cosmological bounds
  - signals at the LHC

work in progress  
with F. Dradi
- A minimal WIMP/FIMP/SuperWIMP  
DM scenario for LHC

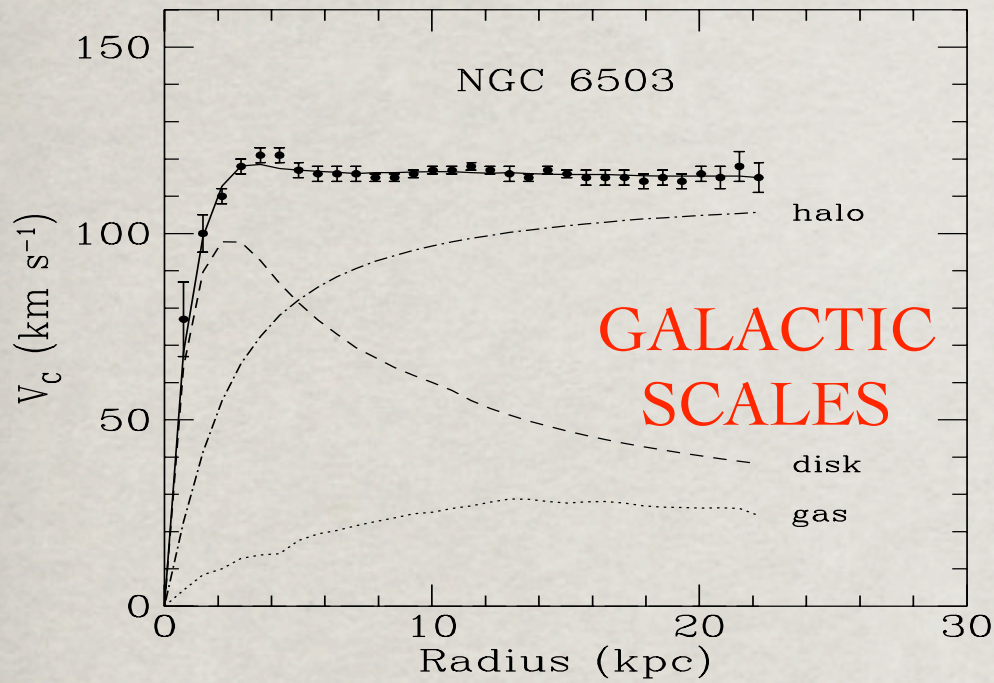
work with G. Arcadi
- Outlook

# INTRODUCTION: SUPERWIMP & COSMOLOGY

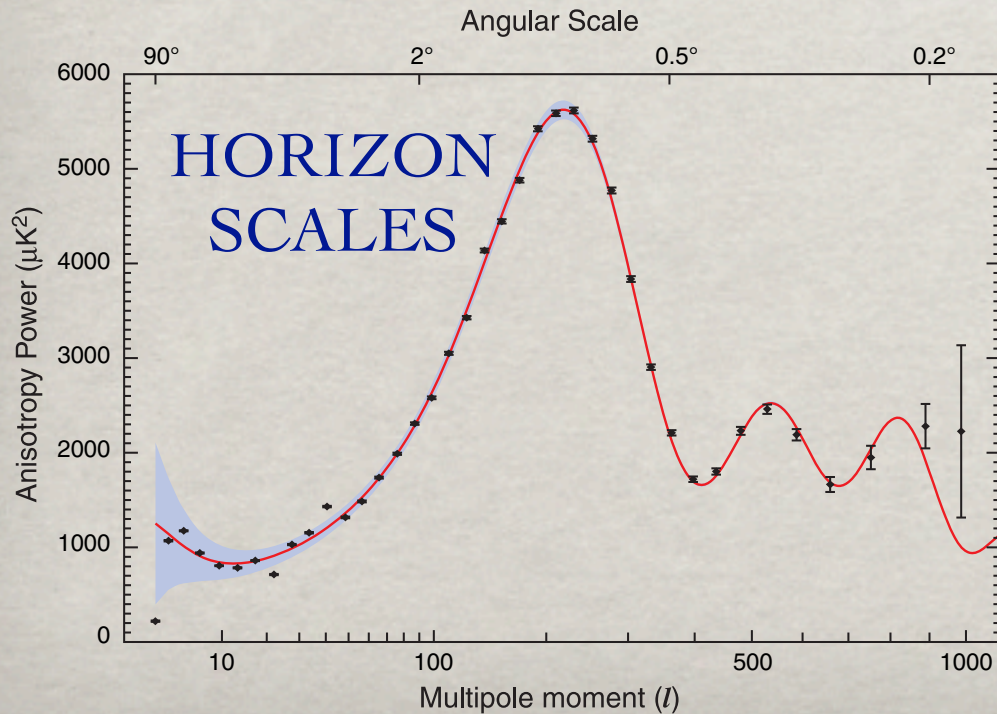
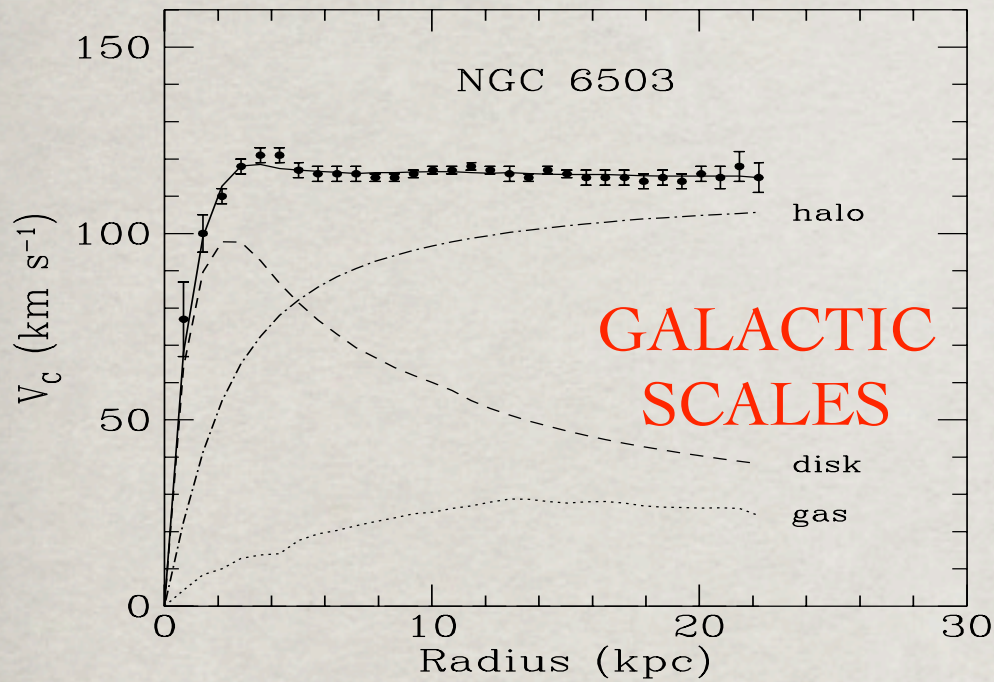
# DARK MATTER EVIDENCE



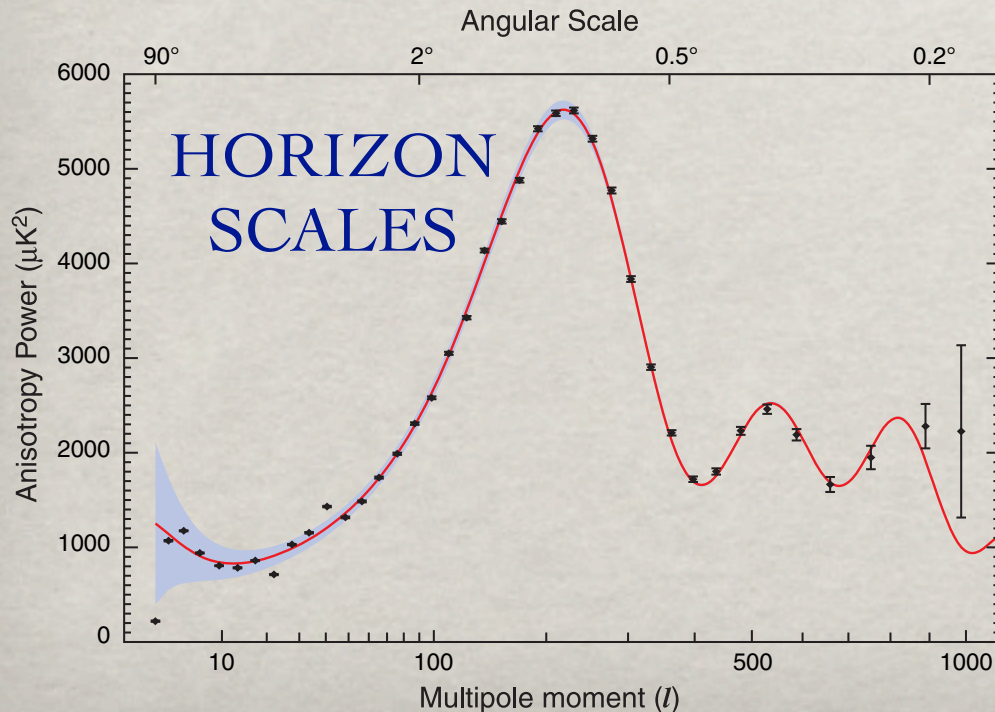
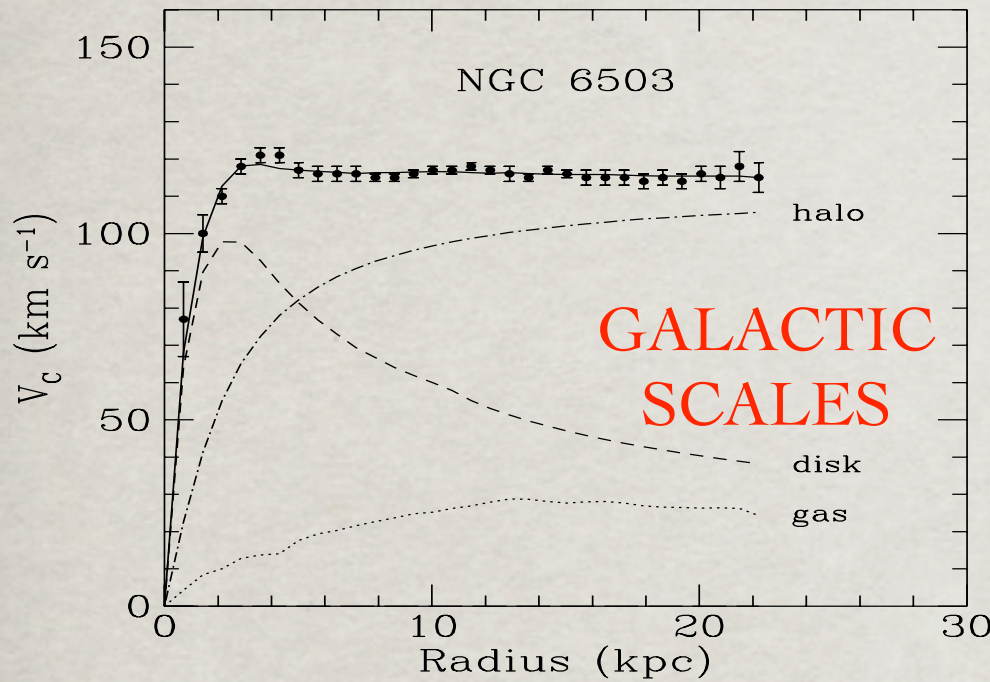
# DARK MATTER EVIDENCE



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# DARK MATTER EVIDENCE



Particles	$\Omega h^2$	Type
Baryons	0.0224	Cold
Neutrinos	$< 0.01$	Hot
Dark Matter	$\sim 0.11$	Cold

# DARK MATTER PARTICLE

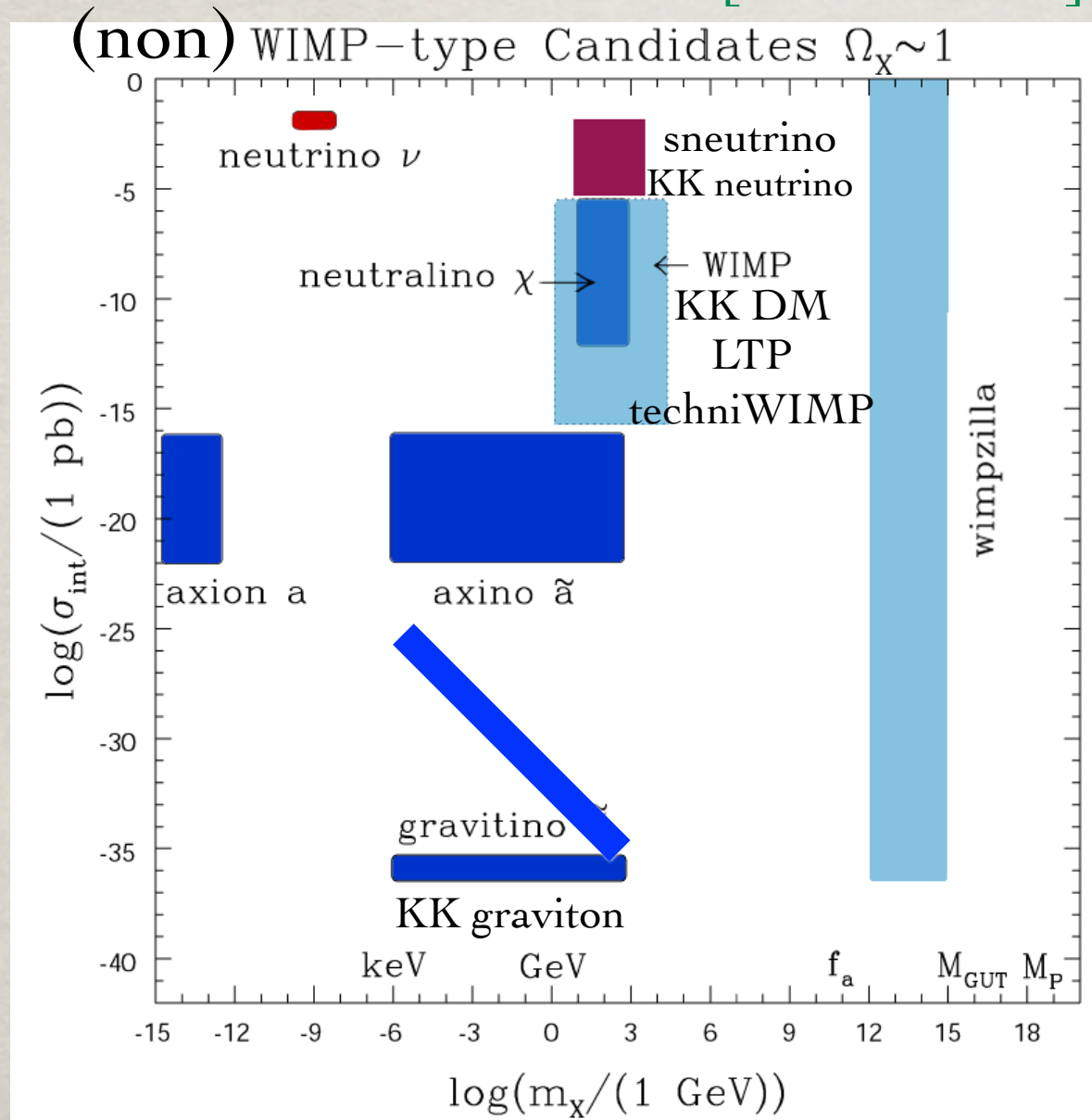
- Electrically neutral, non-baryonic, possibly **electroweak interacting**, but could even be **only gravitationally interacting**.
- It must still be around us: **either stable or very very long lived**, i.e. it may be the lightest particle with a conserved charge (R-, KK-, T-parity, etc...) or its 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...



But NO PARTICLE of this type in the Standard Model !

# DARK MATTER CANDIDATES

[Roszkowski 04]

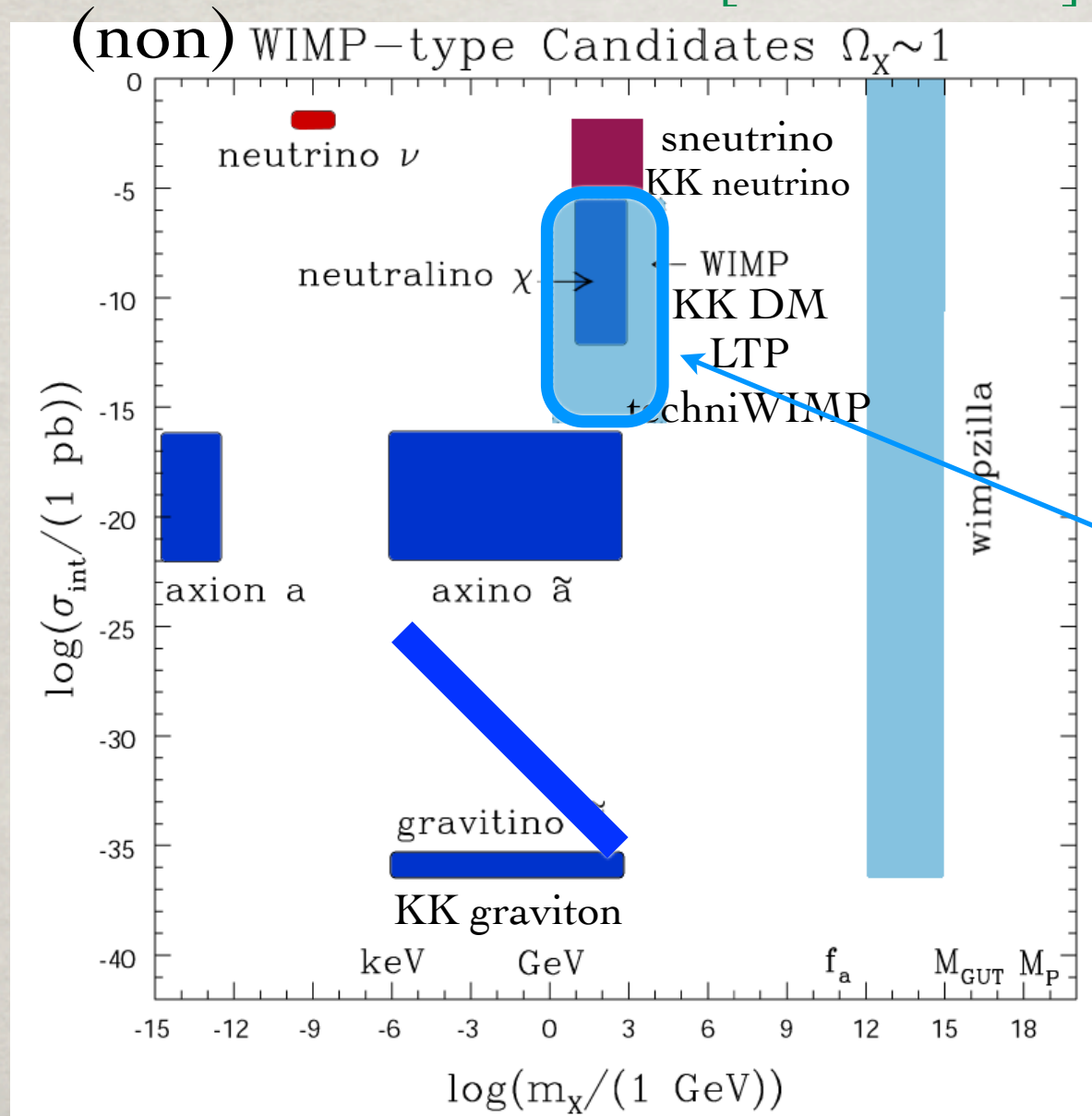


Too many different candidates...

Standard DM production paradigms:  
**WIMPs**  
 (i.e. neutralino)  
 &  
 “FIMP/  
 SuperWIMPs”  
 (i.e. gravitino)

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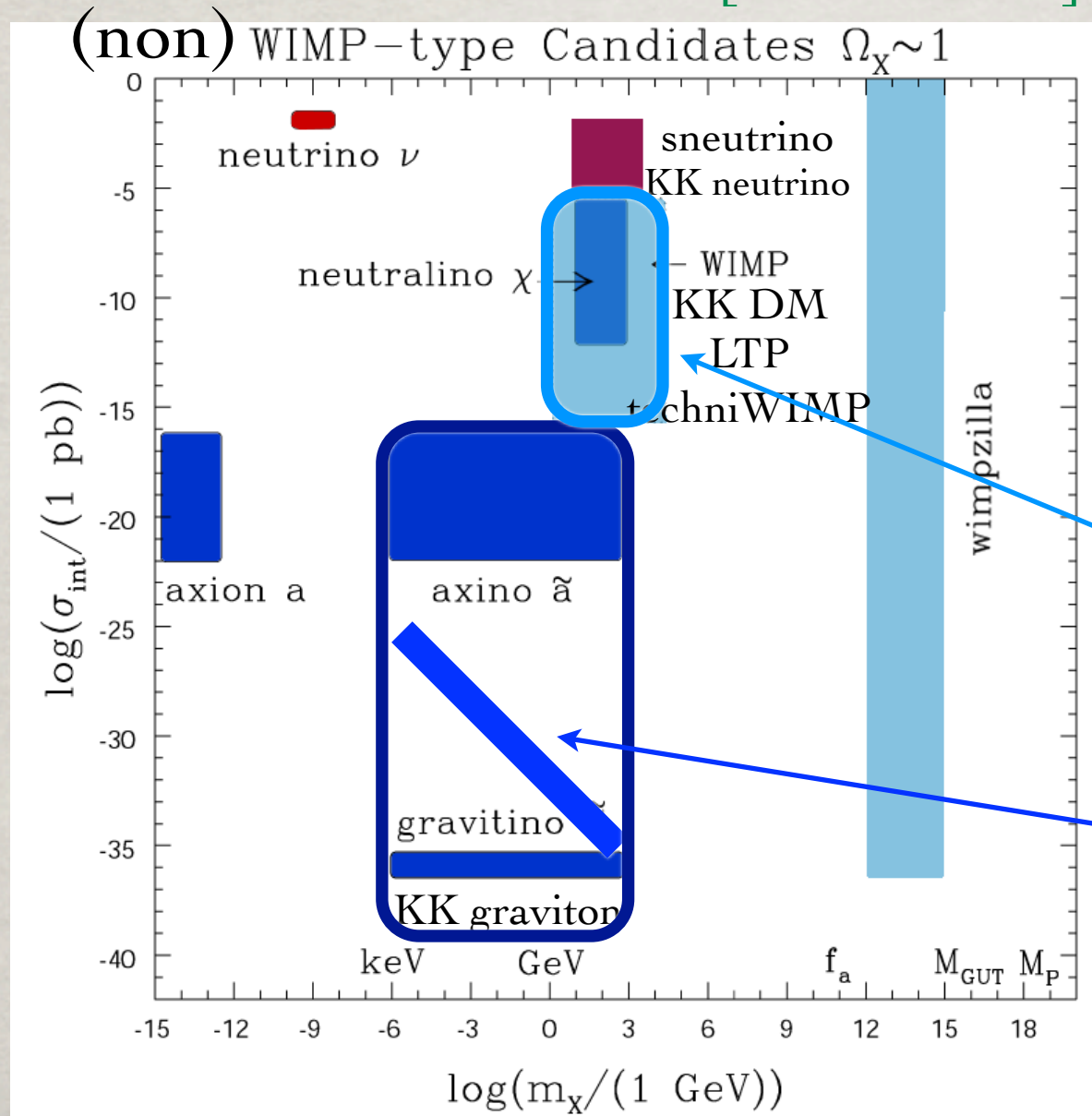


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Standard DM production paradigms:

**WIMPs**  
(i.e. neutralino)

&

“FIMP/  
SuperWIMPs”  
(i.e. gravitino)

# THE WIMP PARADIGM

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 Boltzmann equation

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

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

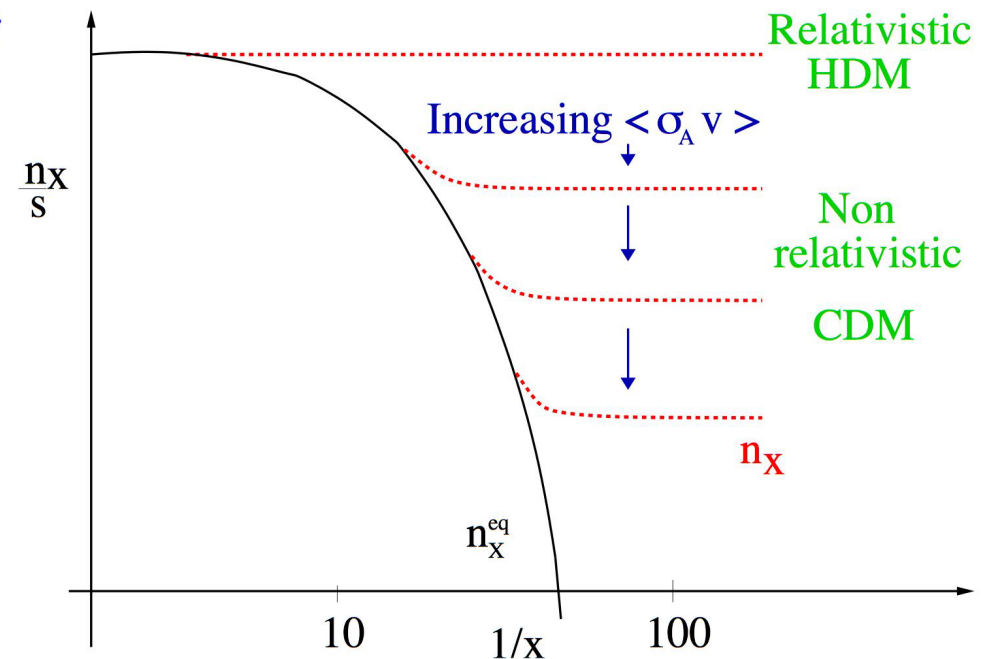
$$\Omega_X = m_X n_X(t_{now}) \propto \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance  $\Leftrightarrow$  Particle properties

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

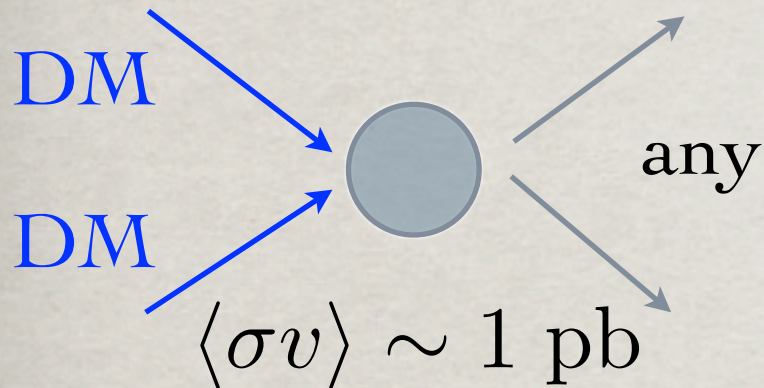
Weakly Interacting Massive Particle

For weaker interactions need lighter masses **HOT DM** !

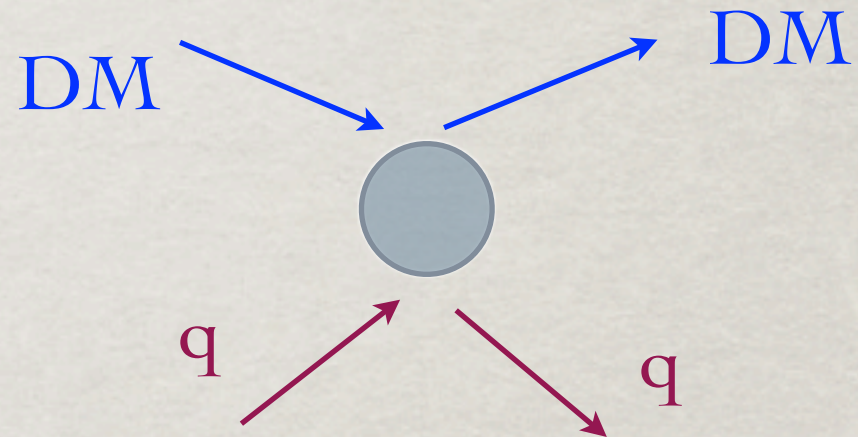


# THE WIMP CONNECTION

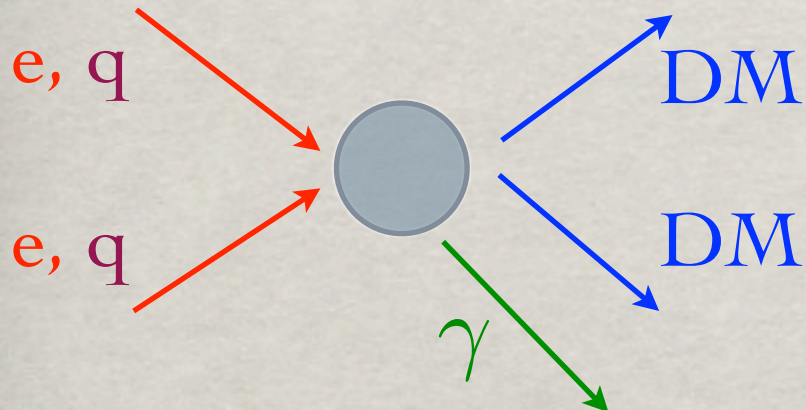
Early Universe:  $\Omega_{CDM} h^2$



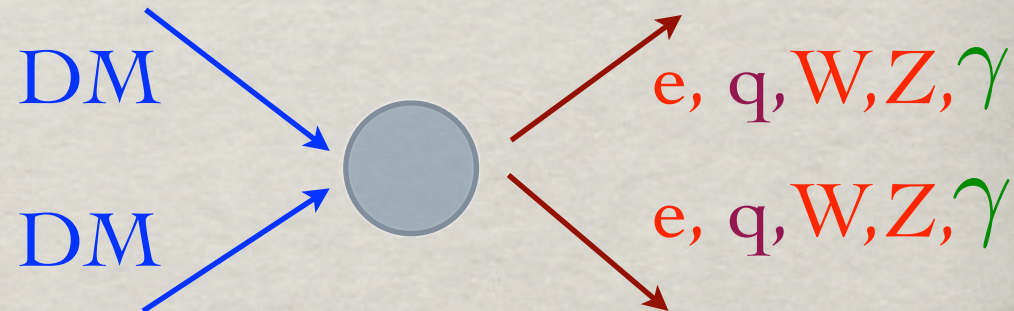
Direct Detection:



Colliders: LHC/ILC



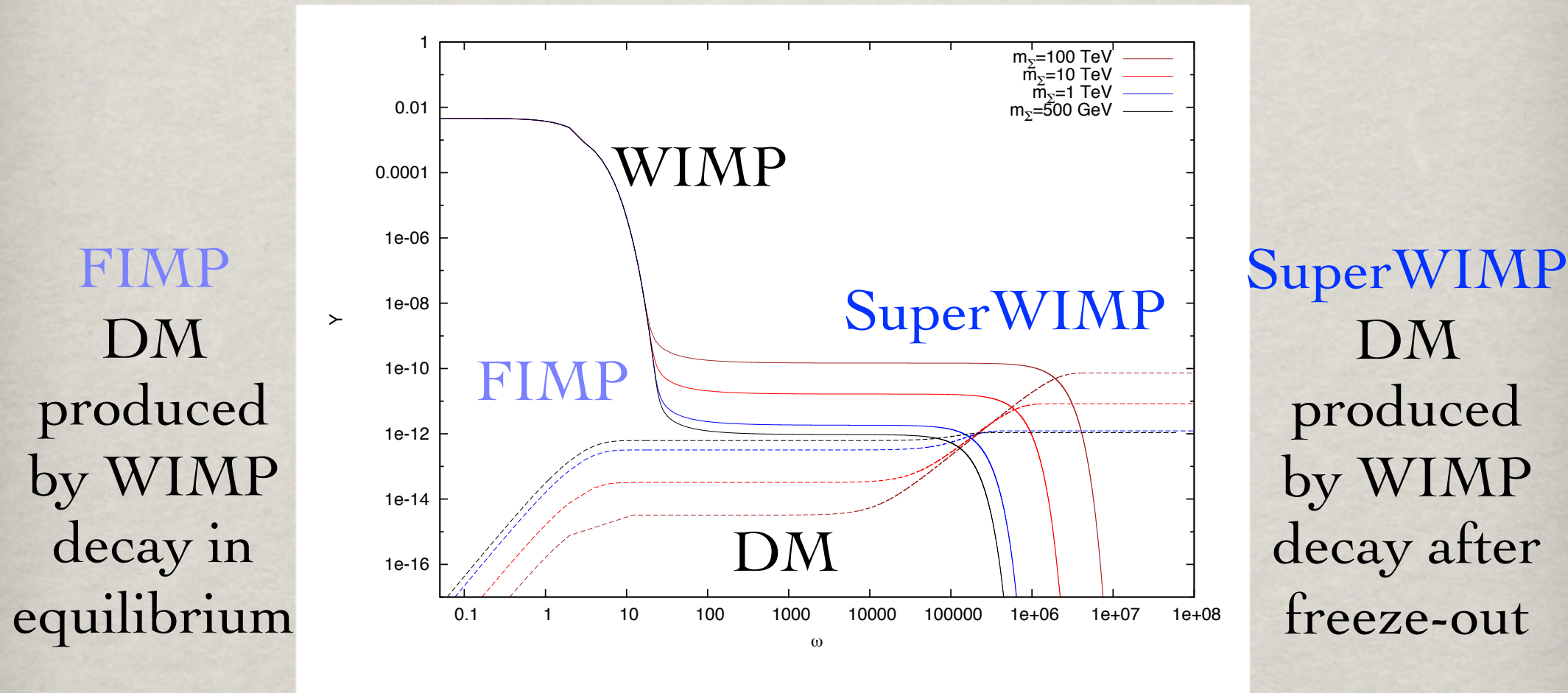
Indirect Detection:



3 different ways to check this hypothesis !!!

# SUPERWIMP/FIMP PARADIGMS

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting DM particle:



Two mechanism naturally giving “right” DM density depending on WIMP/DM mass & DM couplings

# SUPERWIMPs/FIMPs

- Typical SuperWIMPs are axino & gravitino, Majorana fermions with spin  $1/2$  &  $3/2$ . Typical FIMP is a RH sneutrino or some scalar modulus.
- They are particles motivated by symmetry, e.g. SUSY+PQ for the axino and SUGRA for the gravitino, not introduced just to solve the Dark Matter problem.
- They can be much lighter than the rest of the superparticle spectrum (it depends on the SUSY-breaking mechanism...) and so the LSP.

# WHAT HAVE THEY IN COMMON?

- They are particles characterised by (similar) suppressed/non-renormalizable interactions, i.e. much more weakly interacting than WIMPs.
- They are usually not a thermal relic since if they are thermal their number density is compatible only with Hot/Warm DM... They can cause the “gravitino problem” !



# GRAVITINO & COSMOLOGY

Gravitinos can interact very weakly with other particles and therefore cause trouble in cosmology, either because they decay too late, if they are not LSP, or, if they are the LSP, because the NLSP decays too late...

If gravitinos are in thermal equilibrium in the Early Universe, they decouple when relativistic with number density given by

$$\Omega_{3/2} h^2 \simeq 0.1 \left( \frac{m_{3/2}}{0.1 \text{keV}} \right) \left( \frac{g_*}{106.75} \right)^{-1} \quad \text{Warm DM !}$$

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

$$\Omega_{3/2} h^2 \simeq 0.3 \left( \frac{1 \text{GeV}}{m_{3/2}} \right) \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \sum_i c_i \left( \frac{M_i}{100 \text{ GeV}} \right)^2$$

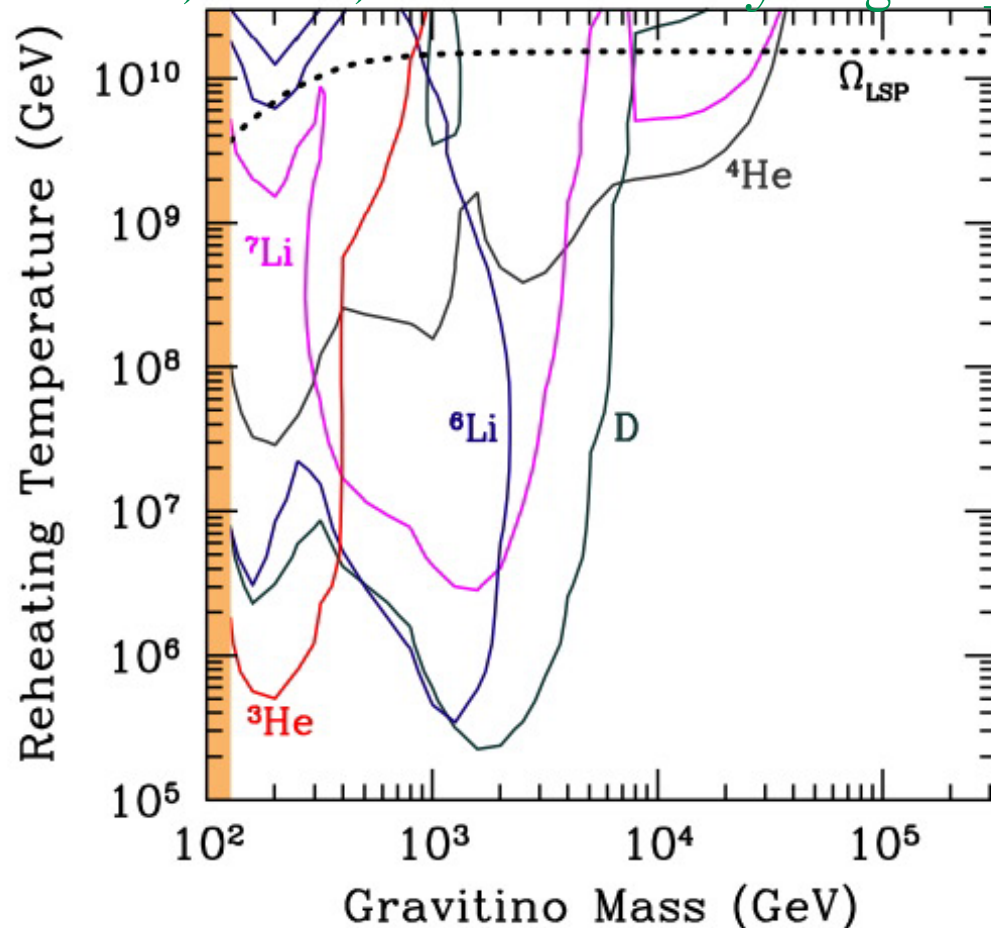
[Bolz, Brandenburg & Buchmuller 01],  
[Pradler & Steffen 06, Rychkov & Strumia 07]

# THE GRAVITINO PROBLEM

The gravitino, the spin 3/2 superpartner of the graviton, interacts only “gravitationally” and therefore decays (or “is decayed into”) very late on cosmological scales.

[Kawasaki, Kohri, Moroi & Yotsuyanagi 08]

$$\tau_{3/2} = 6 \times 10^7 \text{ s} \left( \frac{m_{3/2}}{100 \text{ GeV}} \right)^{-3}$$



BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than  $\sim 1$  s, or if the reheating temperature is much smaller than that required for leptogenesis !

# WHAT HAVE THEY IN COMMON?

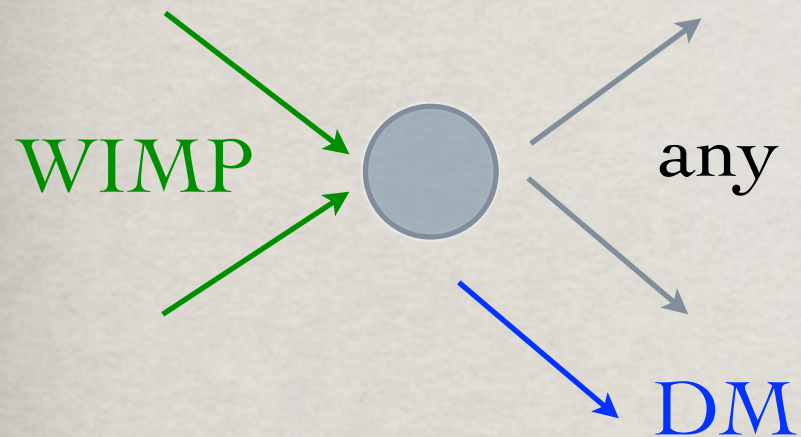
- They are particles characterised by (similar) suppressed/non-renormalizable interactions, i.e. much more weakly interacting than WIMPs.
- They are usually not a thermal relic since if they are thermal their number density is compatible only with Hot/Warm DM... They can cause the “gravitino problem” !
- Moreover they do not need to have an exactly conserved quantum number to be sufficiently stable...

Dark Matter may decay !!!

# F/SWIMP CONNECTION

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

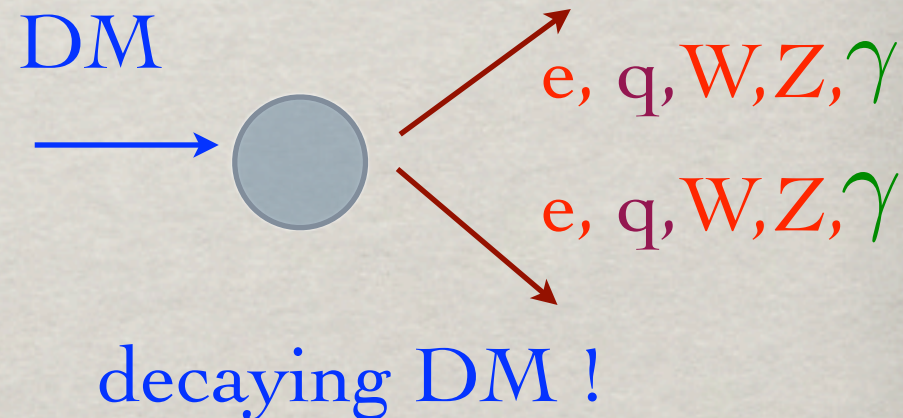
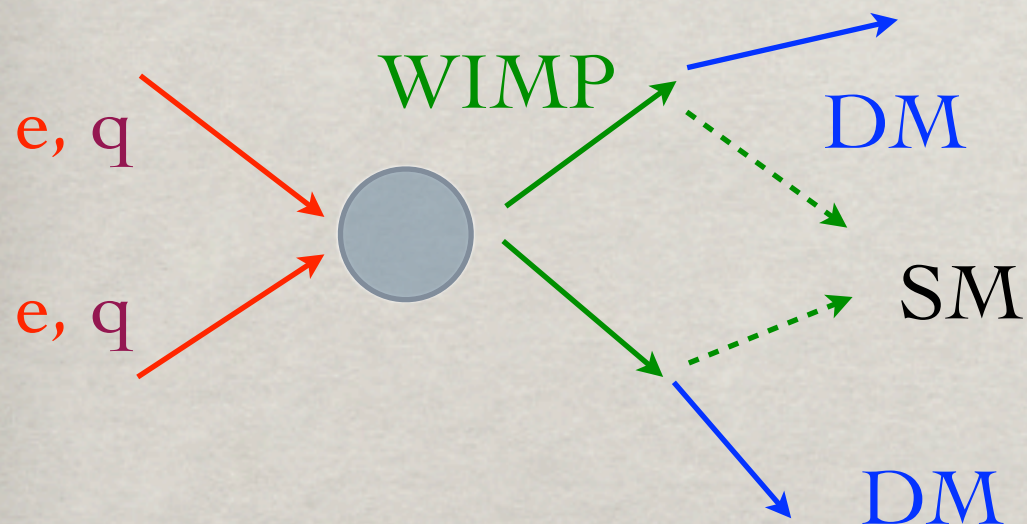
Direct Detection:



NONE...

Colliders: LHC/ILC

Indirect Detection:



3 different ways to check this hypothesis !!!

**GRAVITINO  
DARK MATTER  
WITH STOP NLSP**

# THERMAL PRODUCTION

At high temperatures, the dominant gravitino production is due to 2-to-2 scatterings with the gauge sector, mostly QCD:

$$\Omega_{3/2} h^2 \simeq 0.3 \left( \frac{1 \text{ GeV}}{m_{3/2}} \right) \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \sum_i c_i \left( \frac{M_i}{100 \text{ GeV}} \right)^2$$

[Bolz, Brandenburg & Buchmuller 01],  
[Pradler & Steffen 06, Rychkov & Strumia 07]

where  $M_i$  are the gaugino masses and  $c_i \sim 0(1)$

**Note:** dimension 5 operator result is UV sensitive  $\propto T_{RH}$

So in general there is always a bound on the reheat temperature and such temperature has to take a specific value in order to match the DM density. Note that the smaller  $m_{3/2}$ , the smaller the temperature has to be.

**Tension with thermal leptogenesis for small gravitino masses !**

# NLSP DECAY

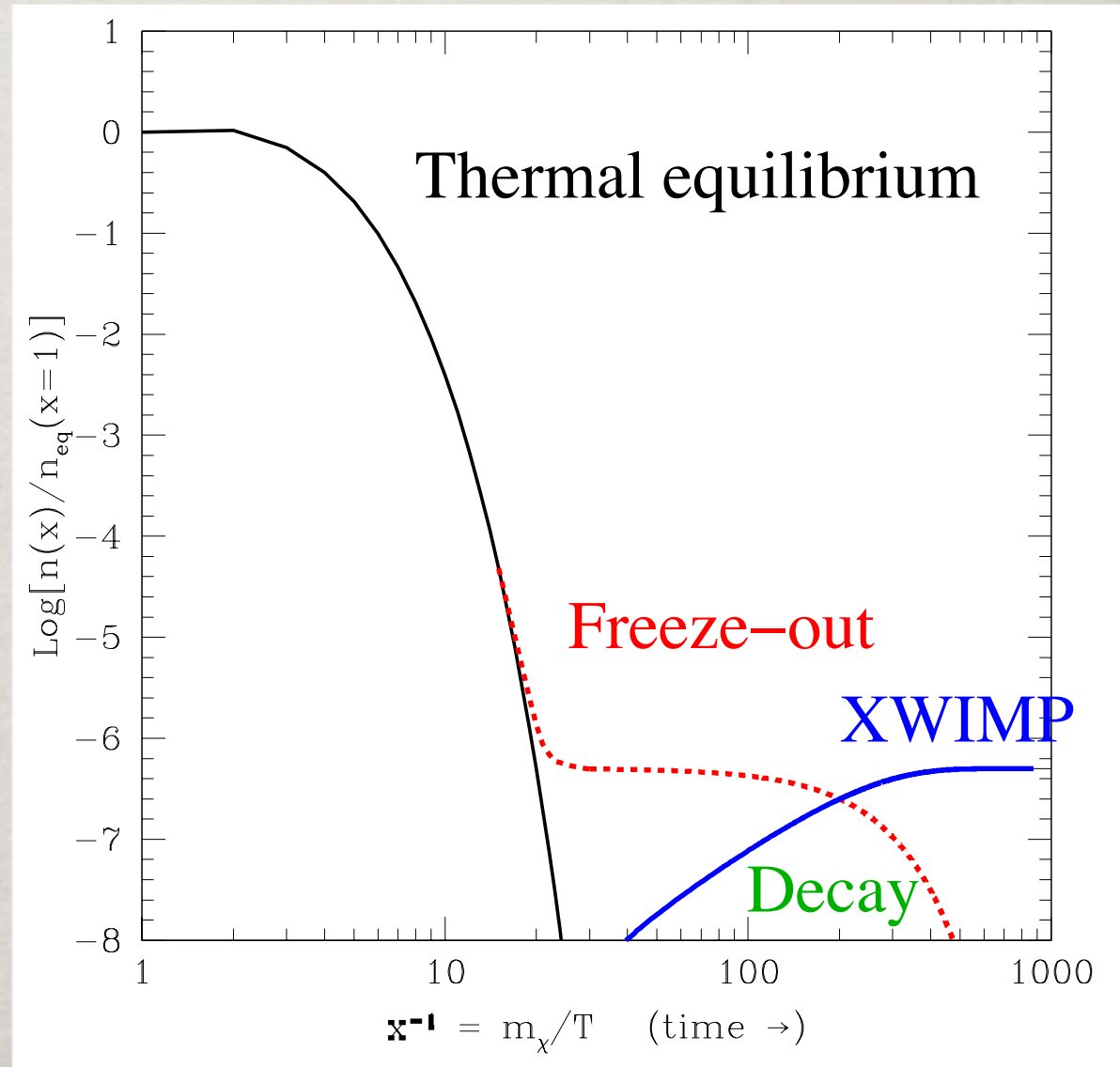
[JE Kim, Masiero, Nanopoulos '84]

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

- If R-parity is conserved, the NLSP decays after freeze-out gravitino (SuperWIMP):

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

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



# A MATTER OF LIFETIME...

Due to the suppressed couplings, the NLSP decays slowly into a gravitino and a SM particle.

Consider a Bino neutralino NLSP and R-parity conservation.  
What is its lifetime for gravitino LSP?

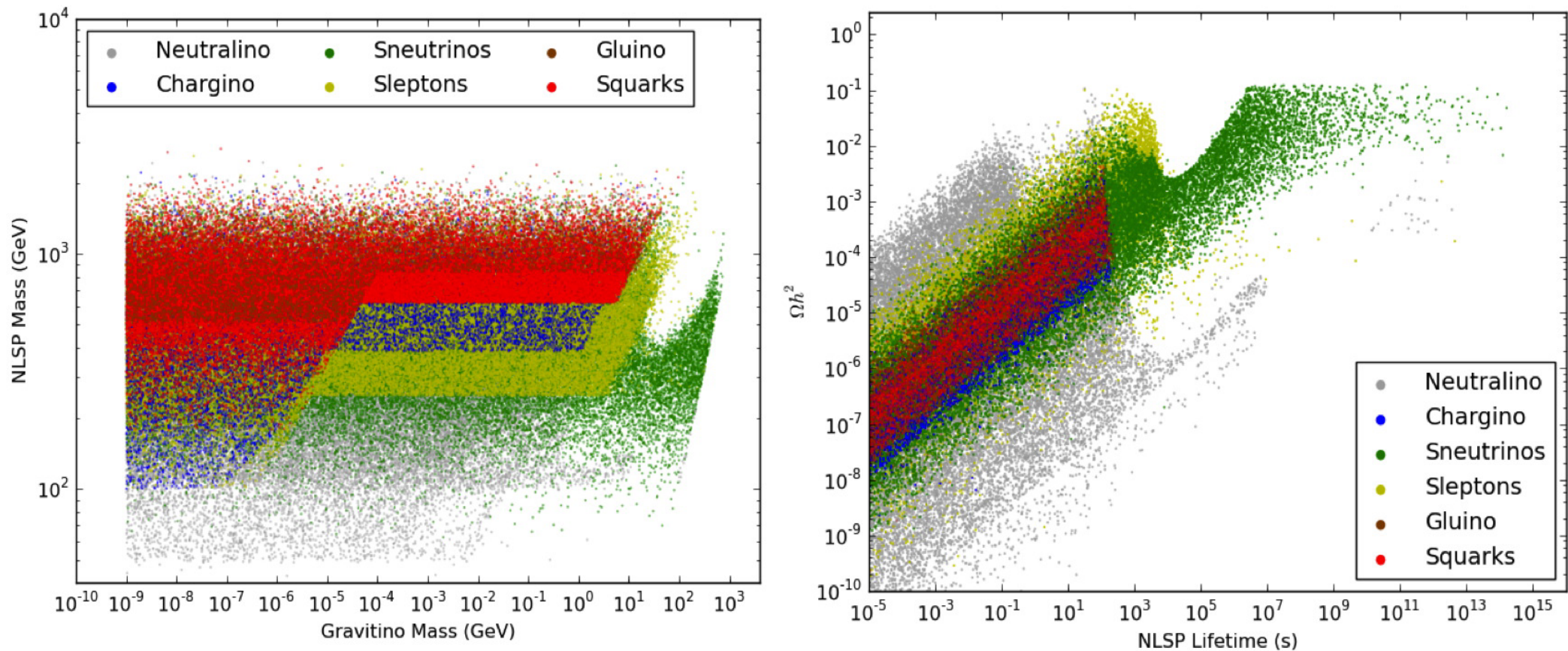
$$\Gamma_{\tilde{B}}^{-1} = 5.7 \times 10^4 \text{s} \left( \frac{m_{\tilde{B}}}{100 \text{ GeV}} \right)^{-5} \left( \frac{m_{\tilde{G}}}{1 \text{ GeV}} \right)^2$$

Quite long timescale, apart for heavy neutralino or light gravitino mass... Trouble for a gravitino heavier than 1 GeV !

$$\left[ \text{N.B.: } c\Gamma_{\tilde{B}}^{-1} = 17 m \left( \frac{m_{\tilde{B}}}{100 \text{ GeV}} \right)^{-5} \left( \frac{m_{\tilde{G}}}{1 \text{ keV}} \right)^2 \right]$$

# BBN BOUNDS ON PMSSM

[Cahill-Rowley et al 12]



Many points for various NLSPs excluded by BBN: only the sneutrino survives to large gravitino masses.  
Heavy NLSP is actually preferred !

# STOP NLSP

Try to reduce the NLSP density to evade BBN bounds:

- require a strongly interacting NLSP to increase the annihilation cross-section, including as well the Sommerfeld enhancement

→ colored NLSP like stop & gluino

- for naturalness reasons and to keep the Higgs light, concentrate on the lightest stop

→ stop NLSP scenario

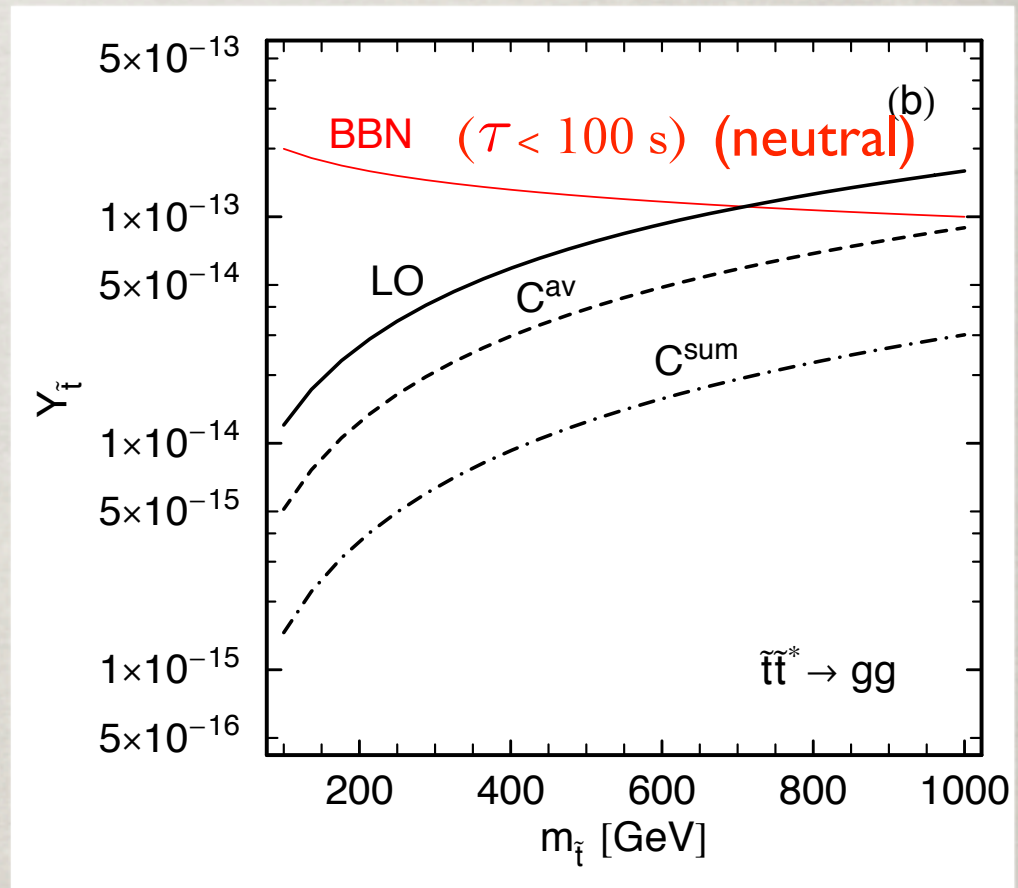
[LC & Federico Dradi xx]

Of course stop has also the advantage of a relatively small production cross-section compared to gluinos/other squarks such that the LHC bounds are less strong...

# 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, see e.g. [Kang, Luty & Nasri 06], but still difficult to bypass bound state effect BBN bound...

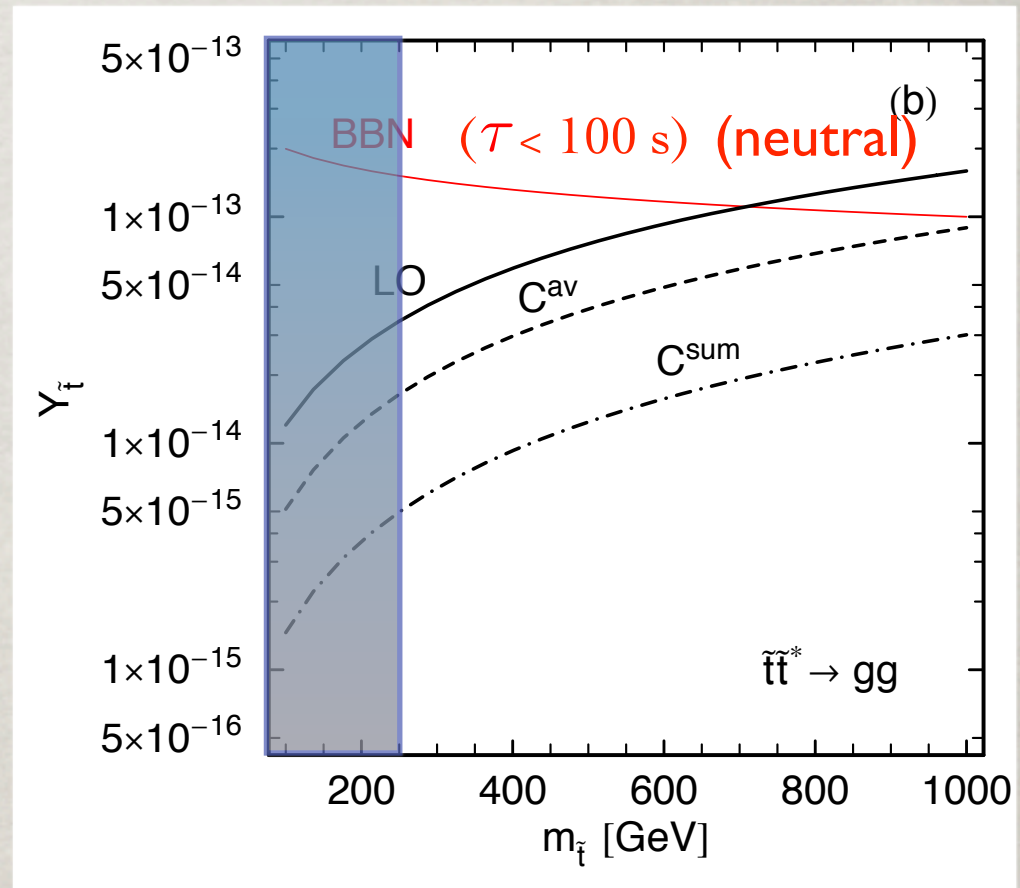
[Berger, LC, Kraml, Palorini 08]



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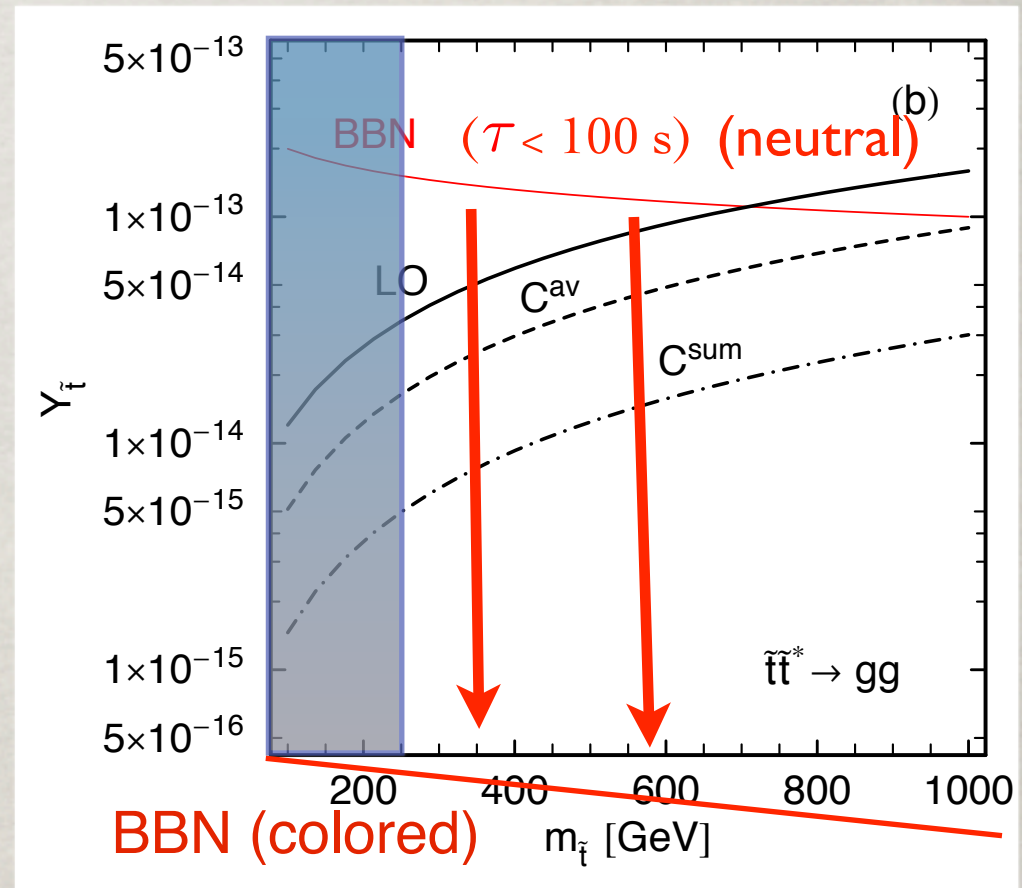


Excluded by Tevatron

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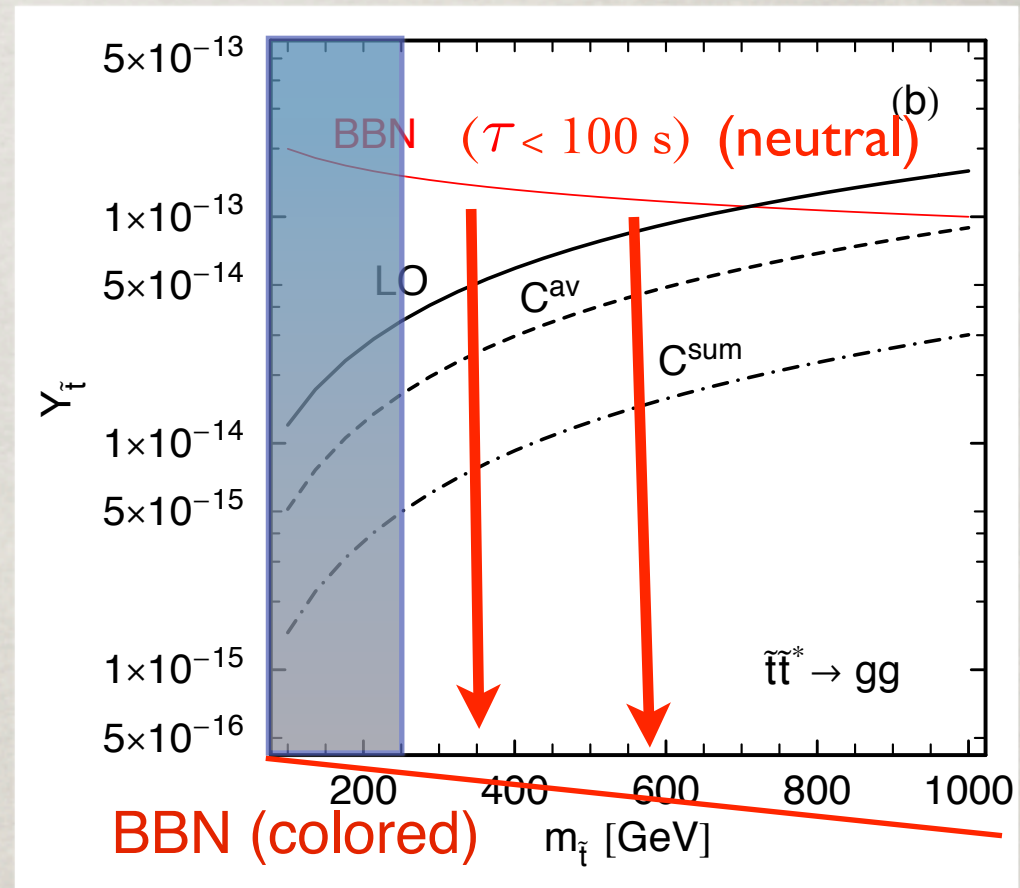


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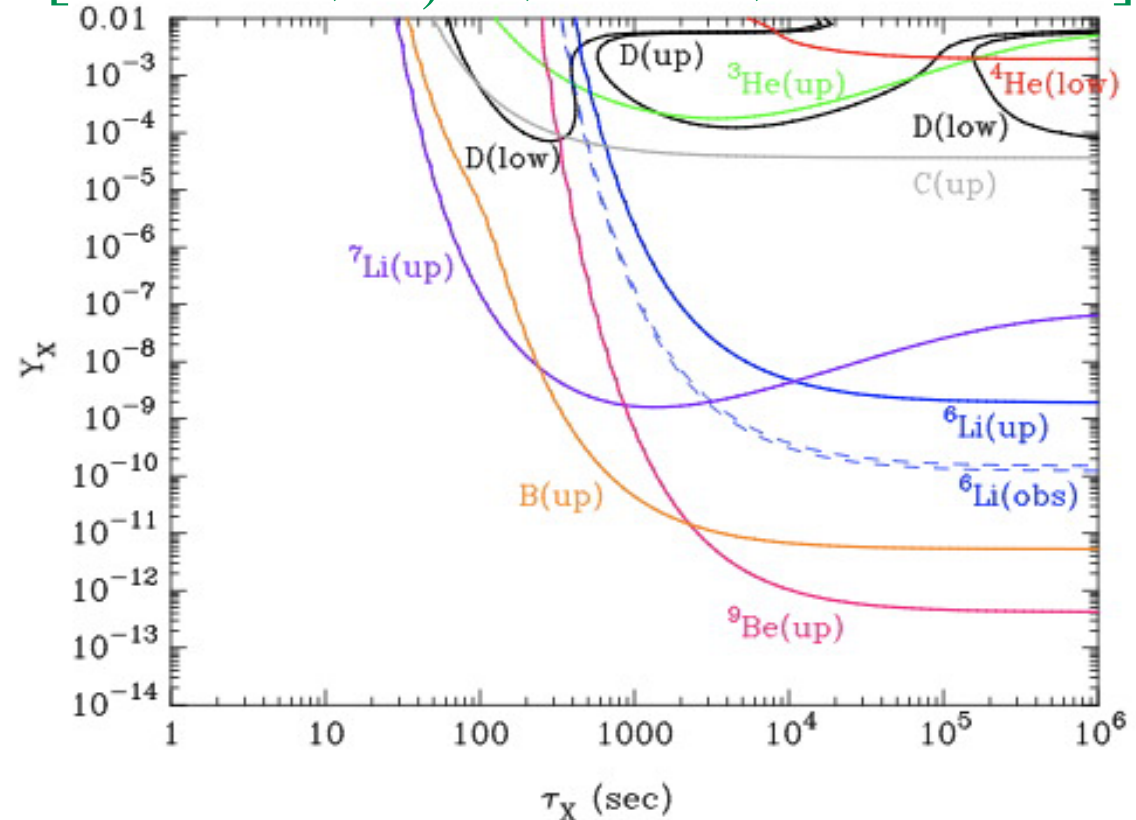
Excluded by Tevatron

Colored NLSP case is very constrained..., or not ?

# BBN BOUNDS: COLORED RELICS

Colored relics: even stronger BBN bound state effects...

[Kusakabe, Kajino, Yoshida, Mathews 09]



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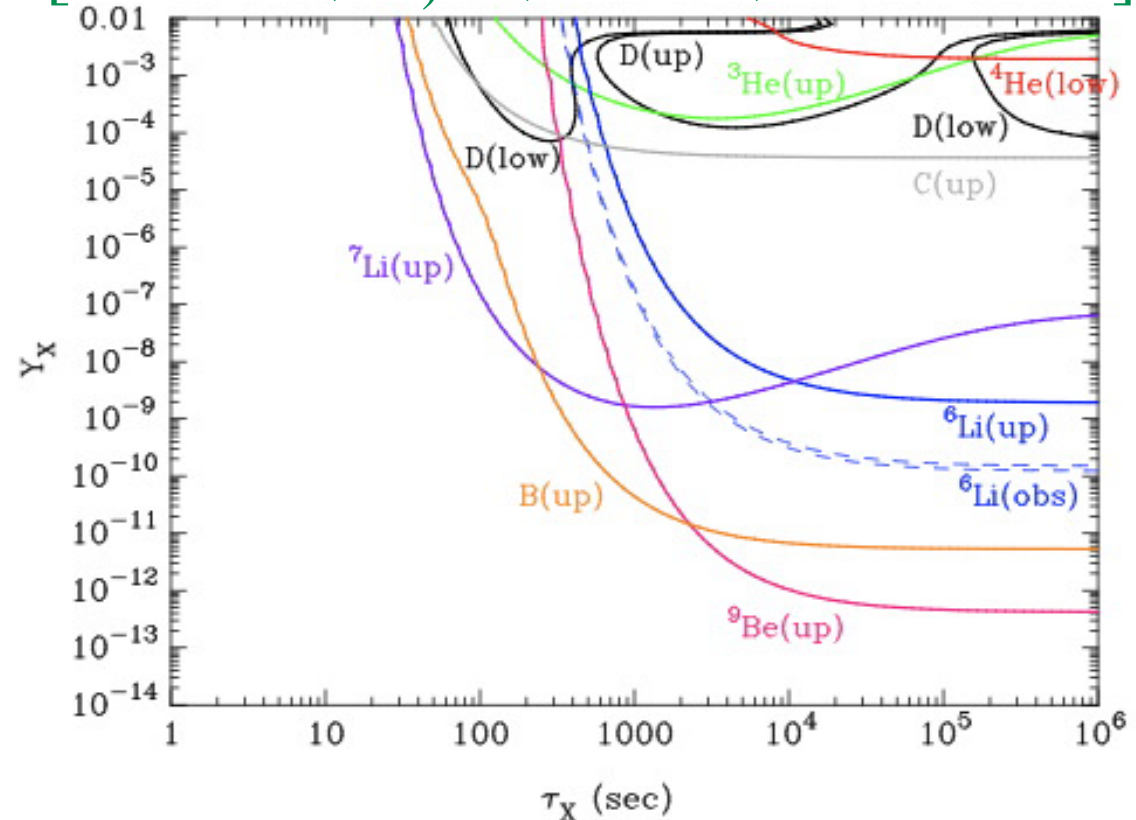
Beware:

$$Y_X^{BBN} = \frac{n_X}{n_b} \sim 10^{-9} Y_X$$

$$\rightarrow 0.02 \frac{m_X}{\text{GeV}} \text{ in } \Omega h^2$$

Bounds so strong that even strong interaction is not strong enough...

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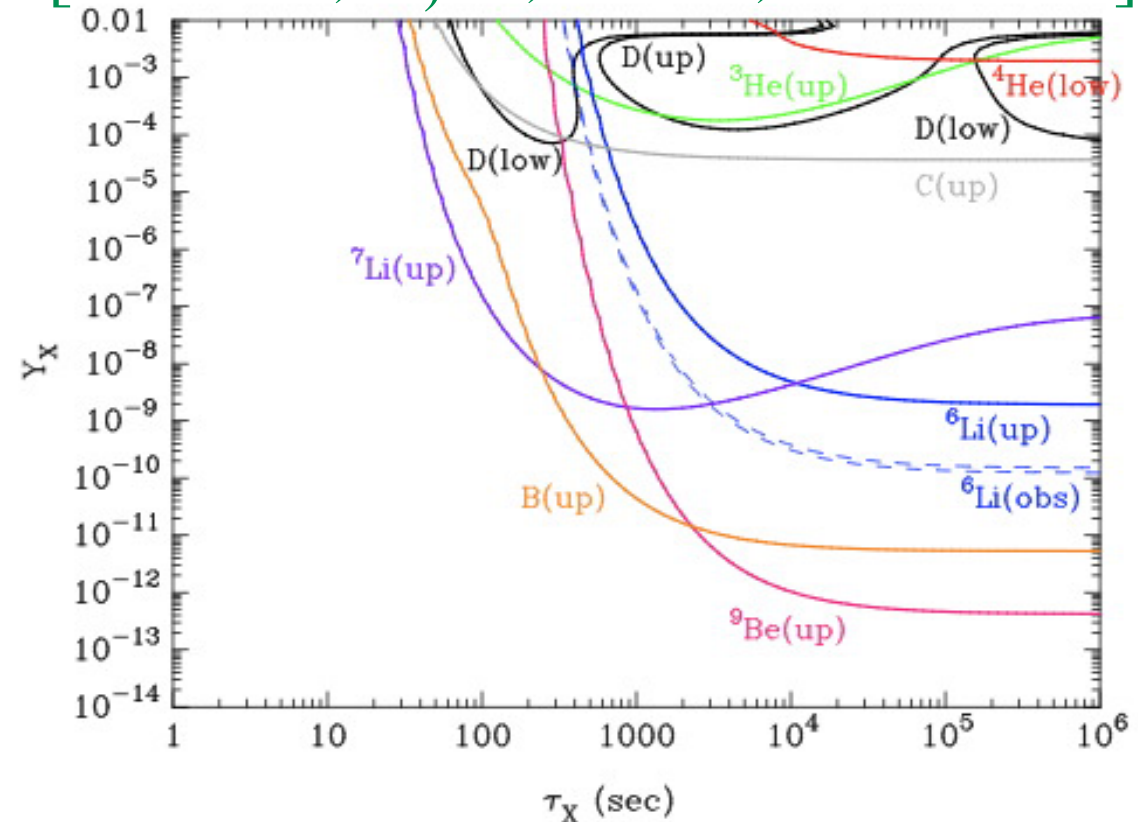
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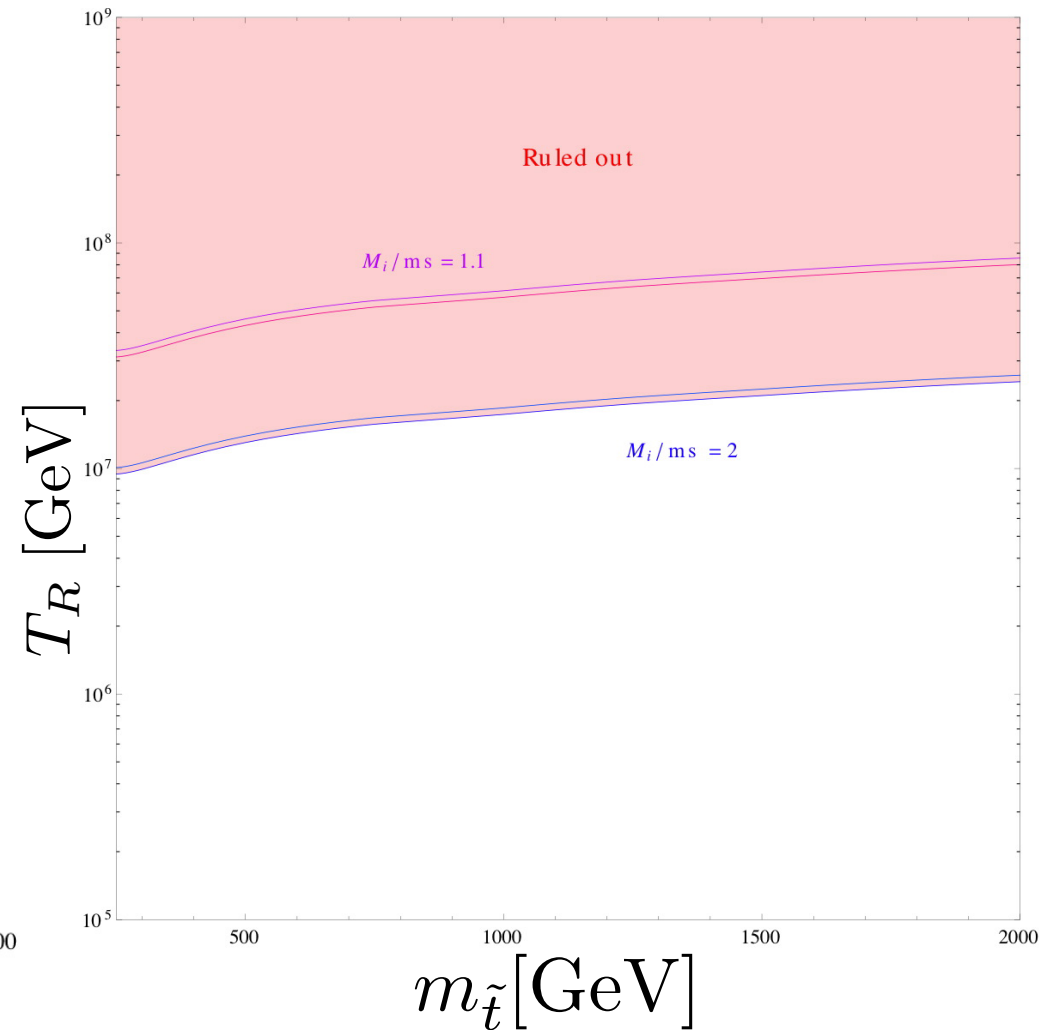
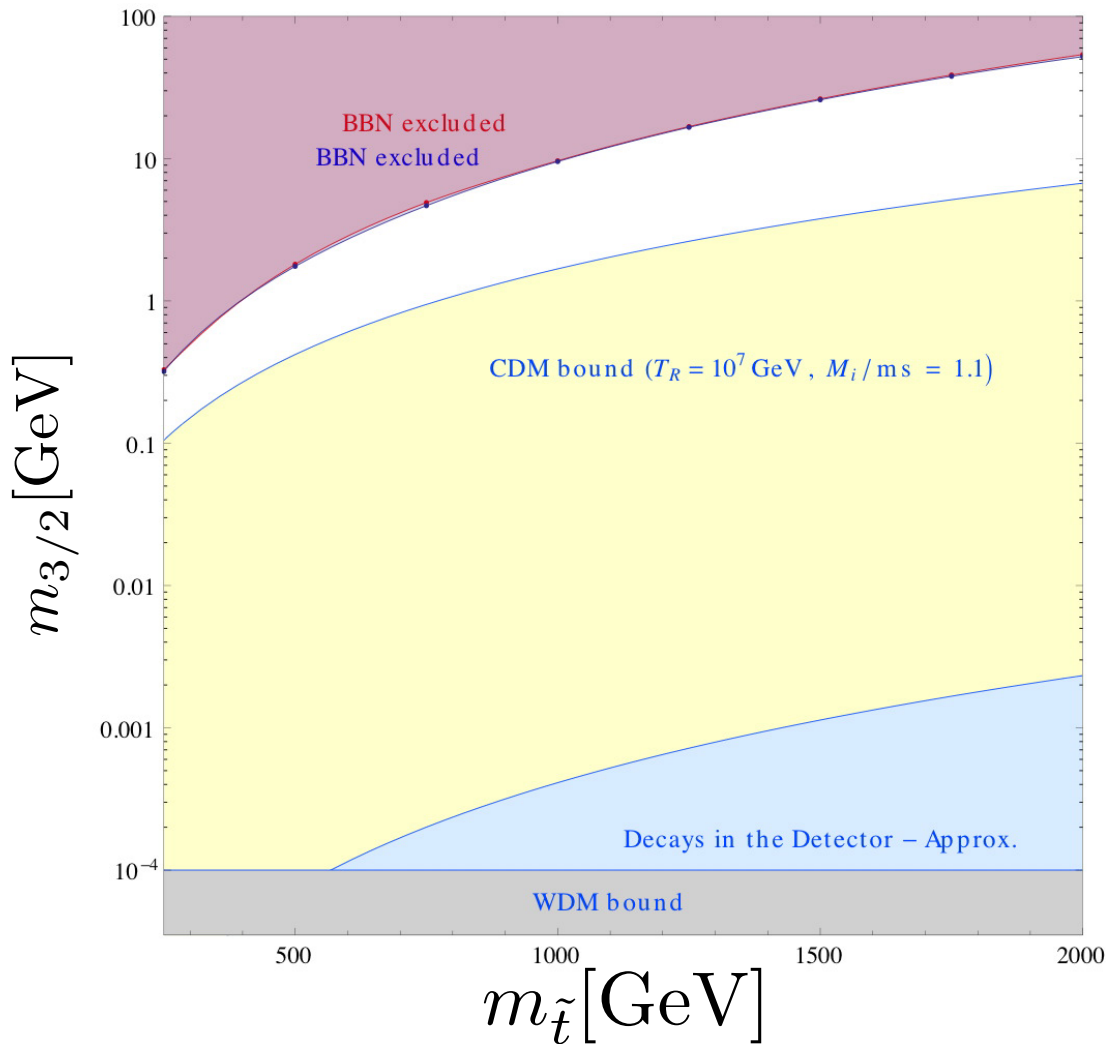


Only short lifetime for colored NLSP allowed:

$$\tau_{\tilde{g}, \tilde{t}} < 200 \text{ s} \quad \rightarrow \quad m_{\tilde{g}, \tilde{t}} > 800 \text{ GeV} \left( \frac{m_{3/2}}{10 \text{ GeV}} \right)^{2/5}$$

# STOP NLSP & BBN

[LC & F. Dradi xx]



Sommerfeld enhancement does not make a difference...  
The BBN constraints allow only for  $T_R$  about few  $10^7$  GeV

# R-PARITY OR NOT R-PARITY

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

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.

$$W_{R/p} = \mu_i L_i H_u + \lambda L L E^c + \lambda' L Q D^c + \lambda'' U^c D^c D^c$$

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Open window:

$$10^{-12-14} < \left| \frac{\mu_i}{\mu} \right|, |\lambda|, |\lambda'| < 10^{-6-7}$$

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For the NLSP to  
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Explicit bilinear R-parity breaking model which ties R-parity breaking to B-L breaking and explains the small coupling.

# DECAYING DM

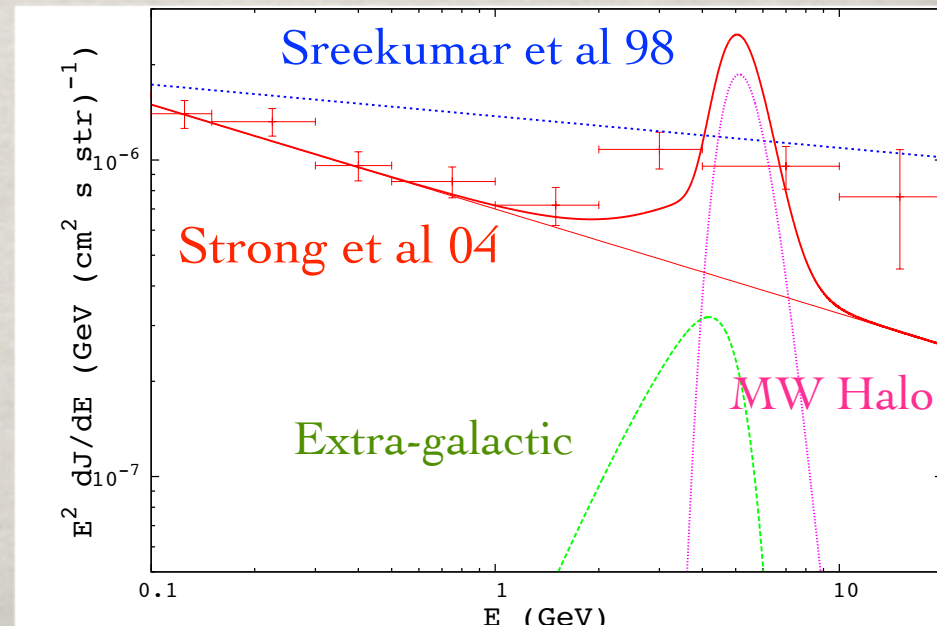
- The flux from DM decay in a species  $i$  is given by

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

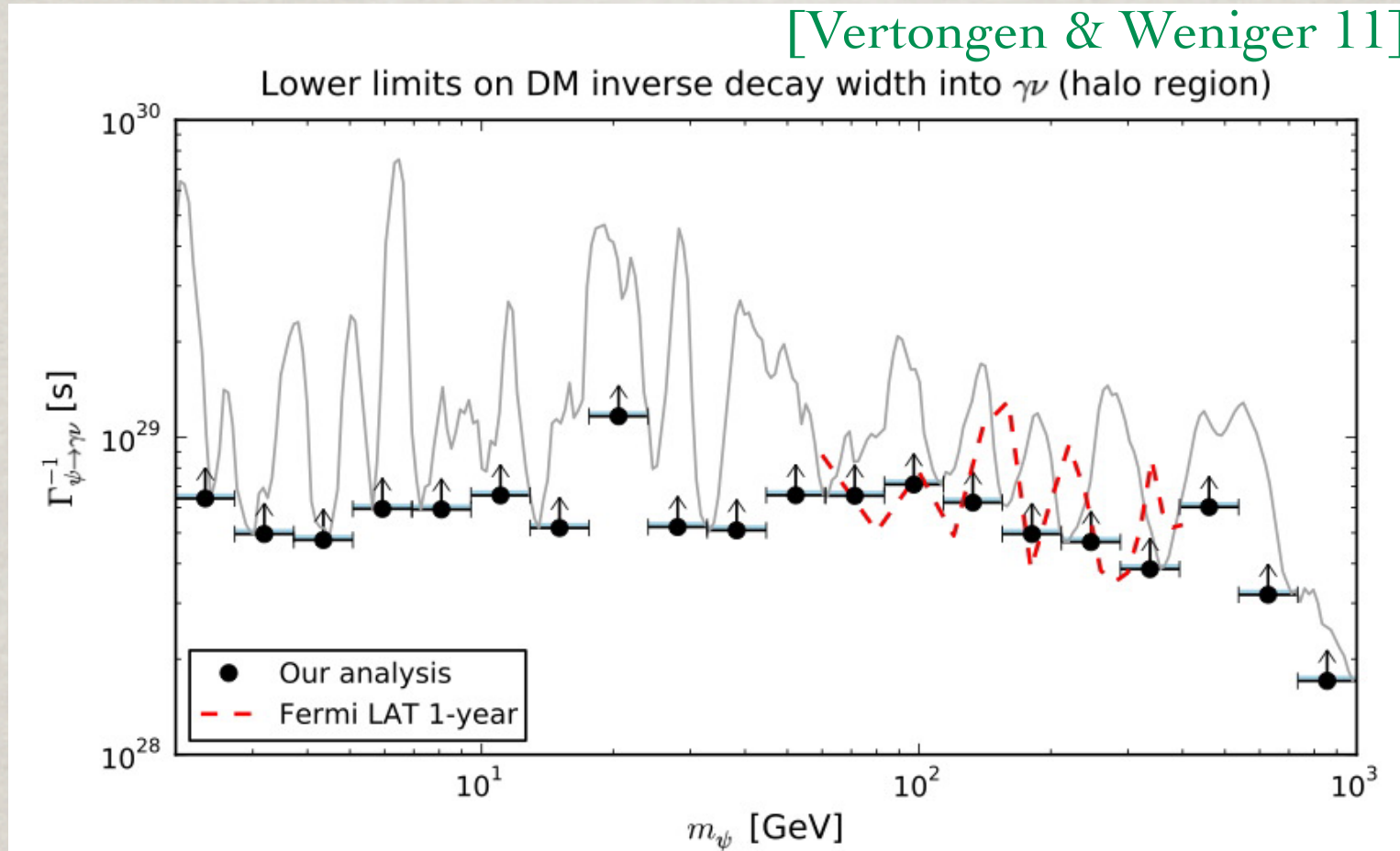
Particle Physics

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...



# FERMI LINE CONSTRAINTS

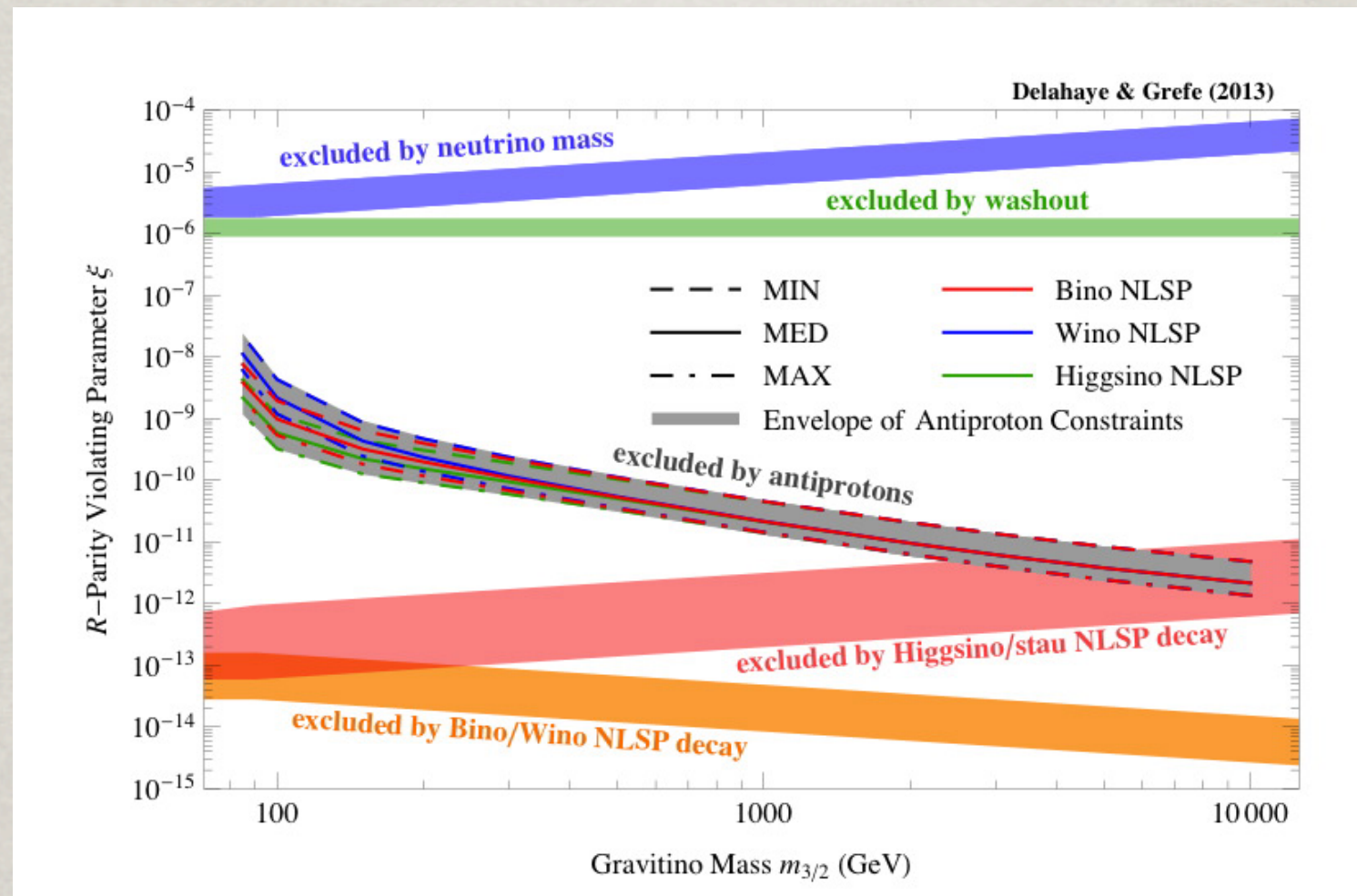


Vertongen & Weniger extended the FERMI line search for energies to 500 GeV, i.e. masses between 1-1000 GeV

From the FERMI gamma-line search:  $\tau \geq 6 \cdot 10^{28} \text{ s} @ 95\% \text{ CL}$

# ANTIPROTON CONSTRAINTS

[Delahaye & Grefe 1305.7183]



Very recently, a new analysis of the antiproton constraints has appeared, limiting the R-parity breaking coupling for large masses.

From the FERMI gamma-line search:  $\tau \geq 6 \cdot 10^{28} \text{ s} @ 95\% \text{ CL}$

# STOP NLSPs WITH R\_P

[LC & F. Dradi xxx]

Avoid BBN constraints: introduce a small R-parity violation, e.g. bilinear R-parity violation. Then the stop decays before BBN via the LH component as

$$\tilde{t}_1 \rightarrow b \ell_i$$

The lepton flavour in the decay gives information on the flavour of the bilinear R-parity breaking

Possible to see the decay at the LHC ?

Use MADGRAPH to compute the production rate and also the decay distributions and see what signal is expected...

Already from analytical computations we know that the stops have a large decay lengths !

# STOP NLSPs AT LHC

[LC & F. Dradi xxx]

We have for the lightest stop always relatively long lifetimes,  
both for R-parity conservation or violation...

$$\text{RPC: } \tilde{t}_1 \rightarrow t \tilde{G} \rightarrow b W^+ \tilde{G} \rightarrow b \ell^+ \nu \tilde{G}$$

$$\tau_{\tilde{t}_1} \sim 19 \text{ s} \left( \frac{m_{\tilde{t}_1}}{500 \text{ GeV}} \right)^{-5} \left( \frac{m_{3/2}}{1 \text{ GeV}} \right)^2$$

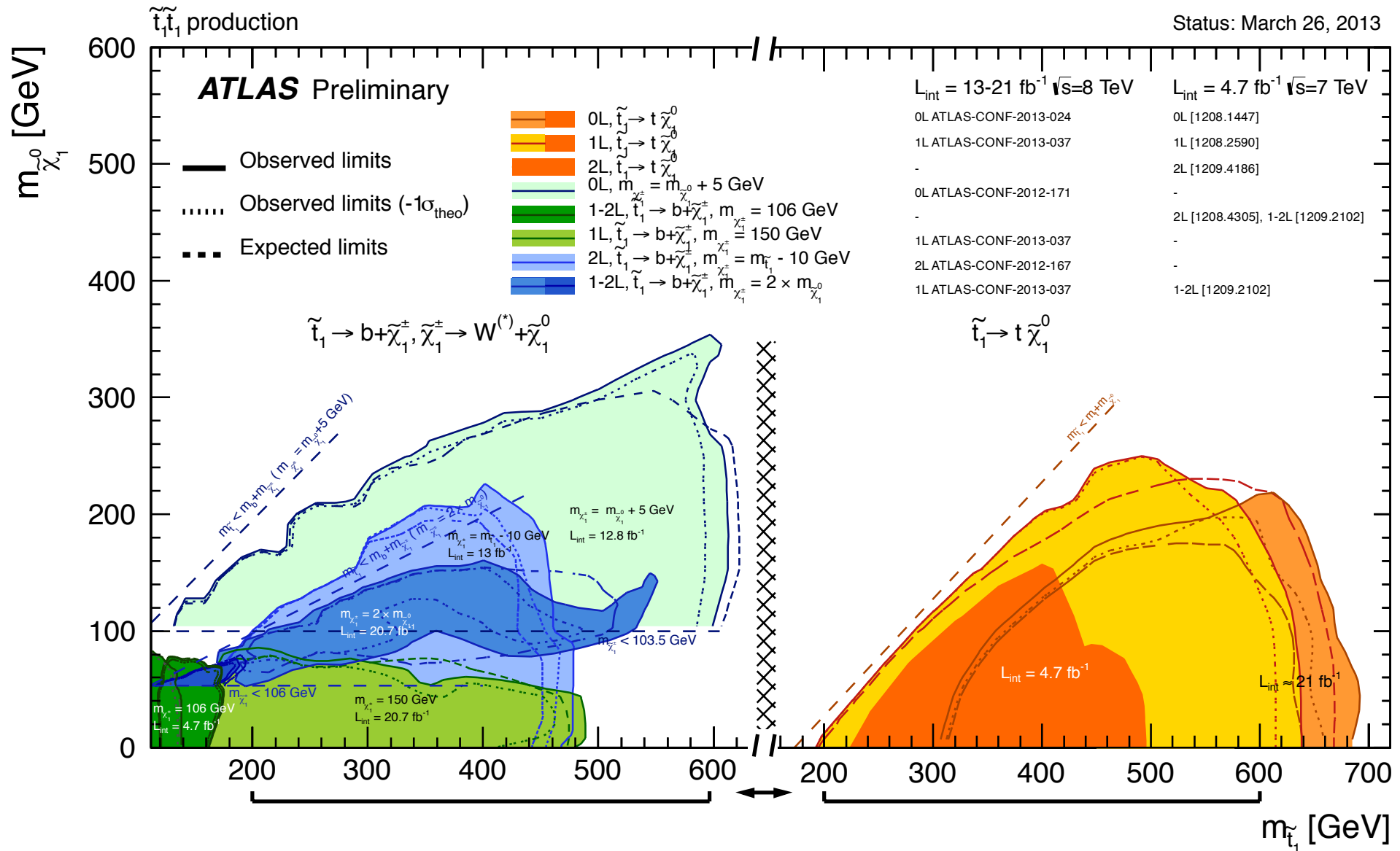
$$\text{RPV: } \tilde{t}_1 \rightarrow b \ell^+$$

$$\tau_{\tilde{t}_1} \sim 10^{-4} \text{ s} \left( \frac{m_{\tilde{t}_1}}{500 \text{ GeV}} \right)^{-1} \left( \frac{\epsilon \sin \theta_{\tilde{t}}}{10^{-9}} \right)^{-2}$$

The usual searches looking for prompt decay do not apply !

# LHC: STOP ?

A light stop is now intensively searched for at LHC...



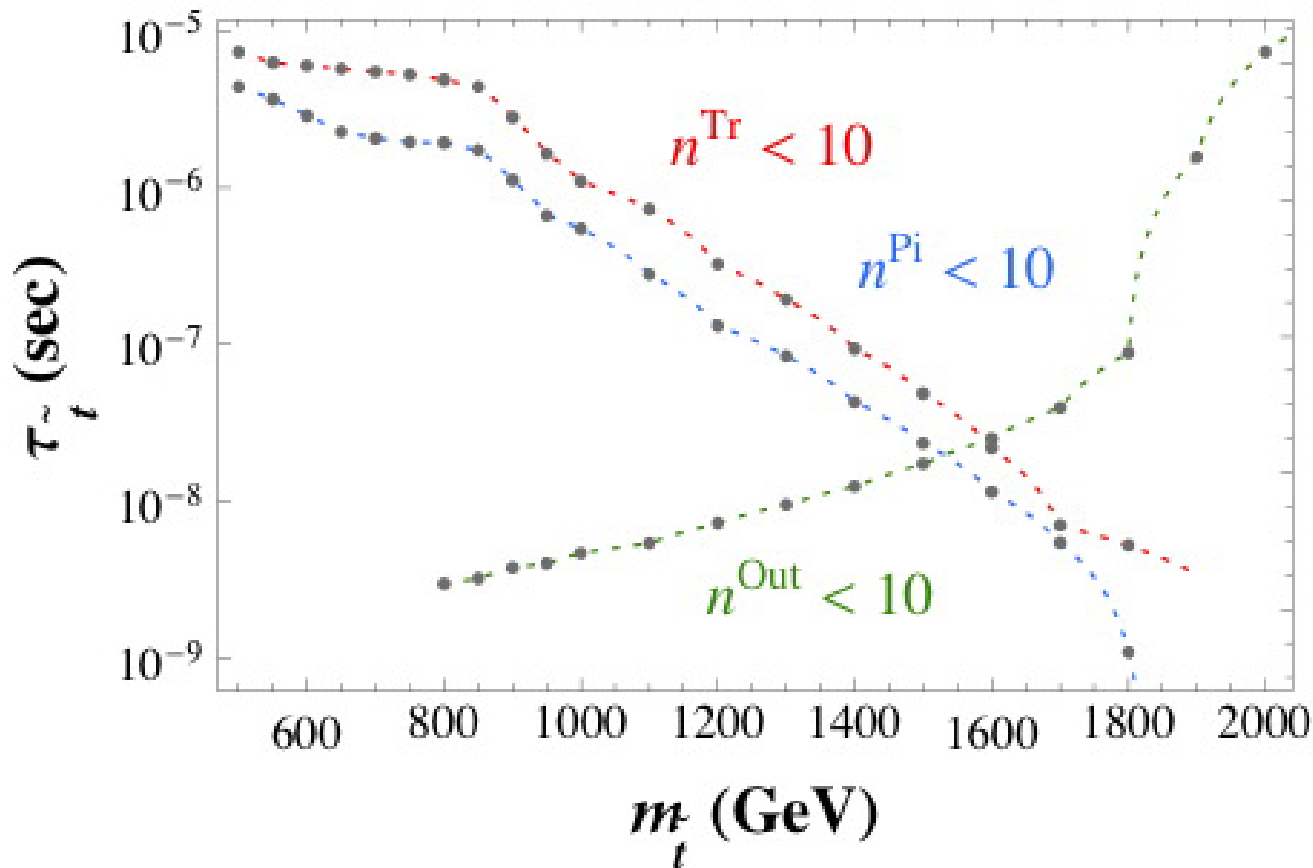
... but in different channels !

# LHC: STOP ?

Best strategy: combine searches for metastable particles (out) and displaced decay vertices in tracker or pixel CMS detector.

Draw the lines for 10 events of any type to be conservative:

$$L = 3000 \text{ fb}^{-1}$$

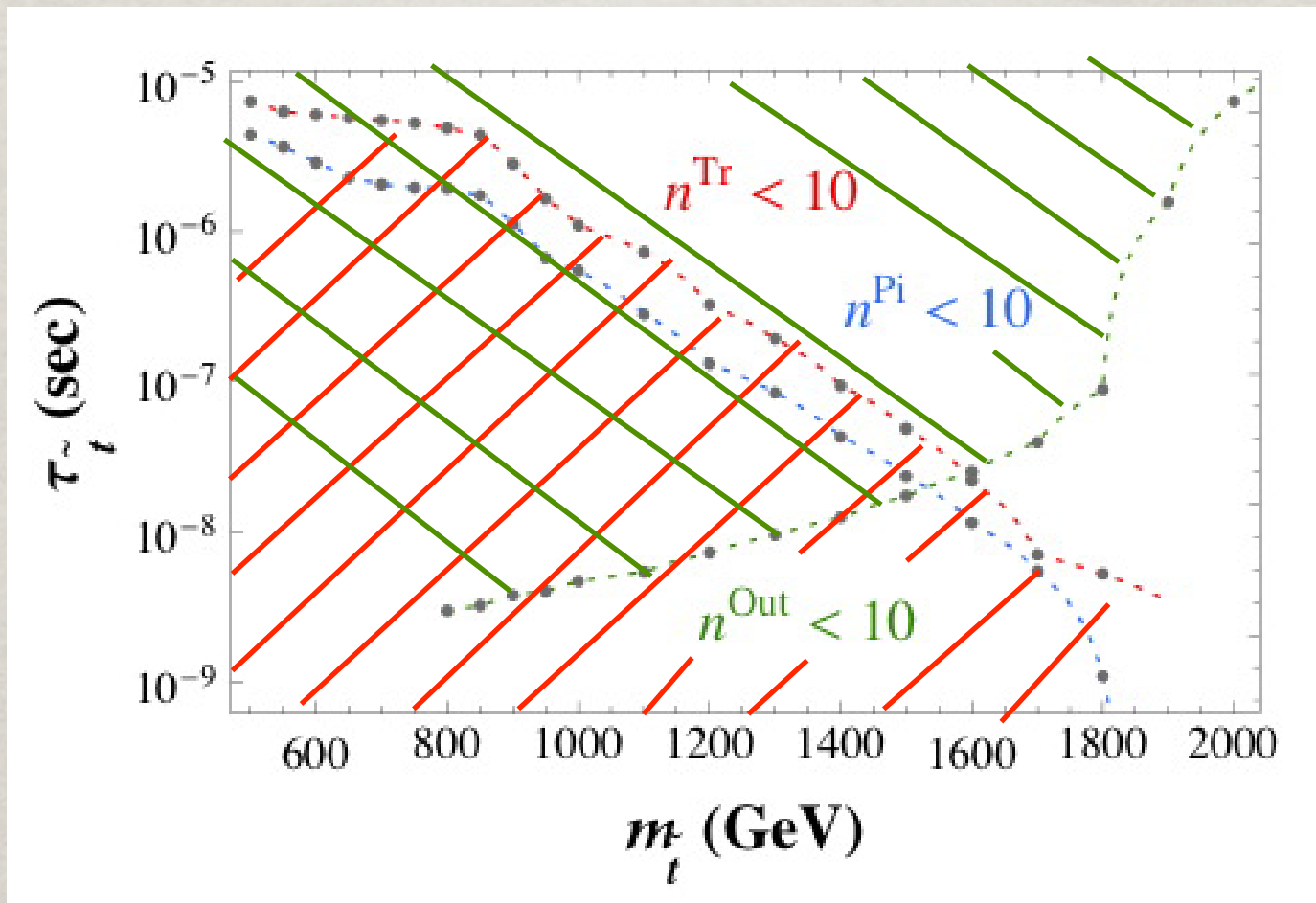


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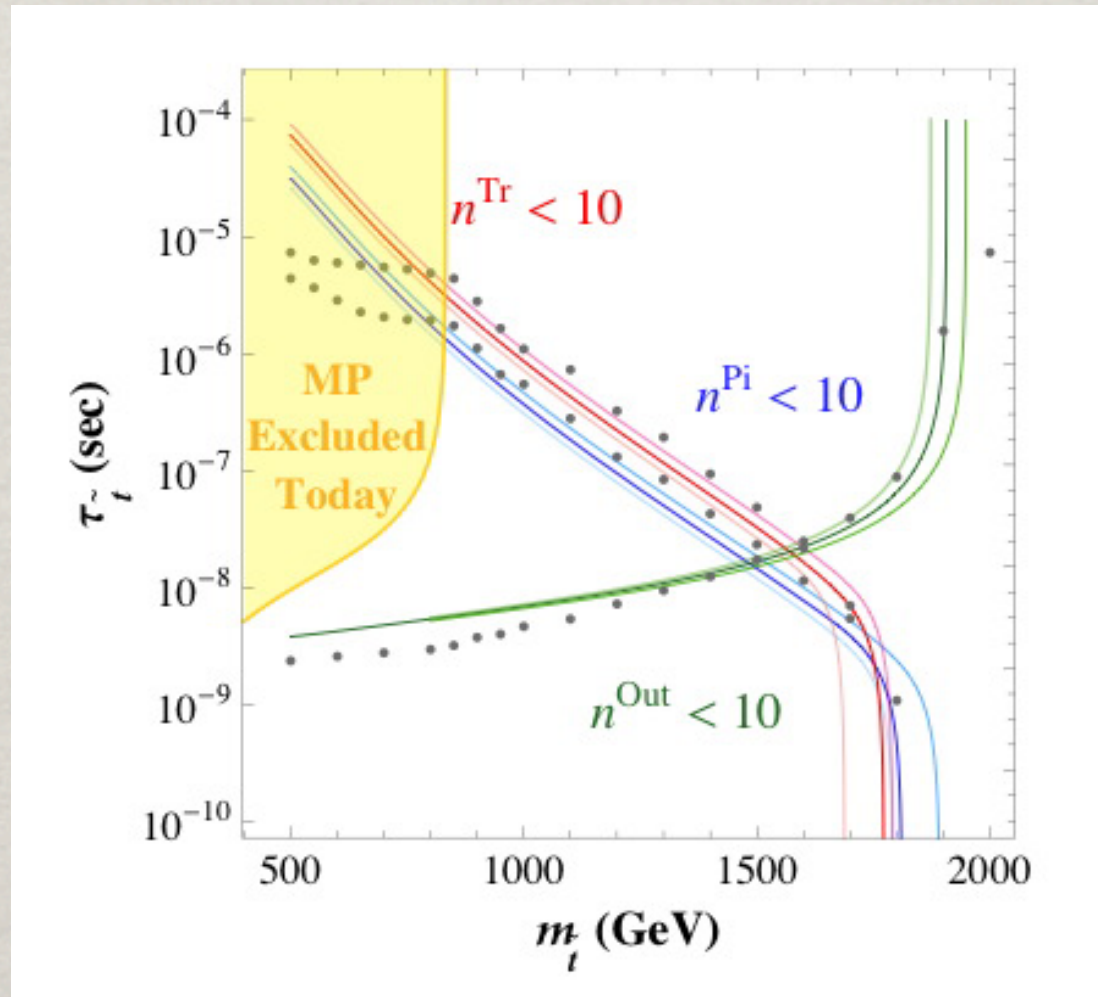


Complementary signals ! Covering masses up to 1600 GeV...

# LHC: STOP ?

Compare with semianalytical formula for the decay and with the present LHC bounds on metastable particles (MP):

$$L = 3000 \text{ fb}^{-1}$$

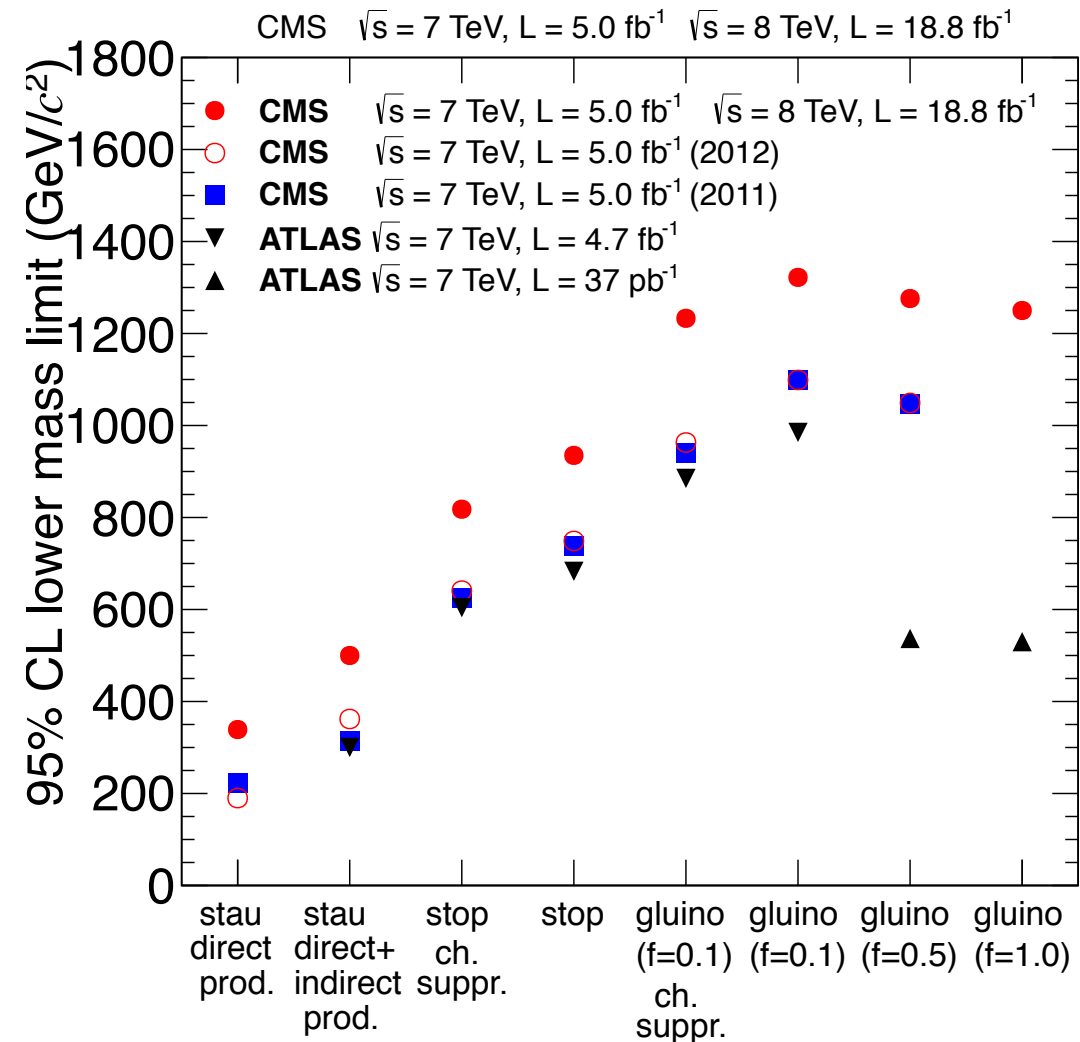
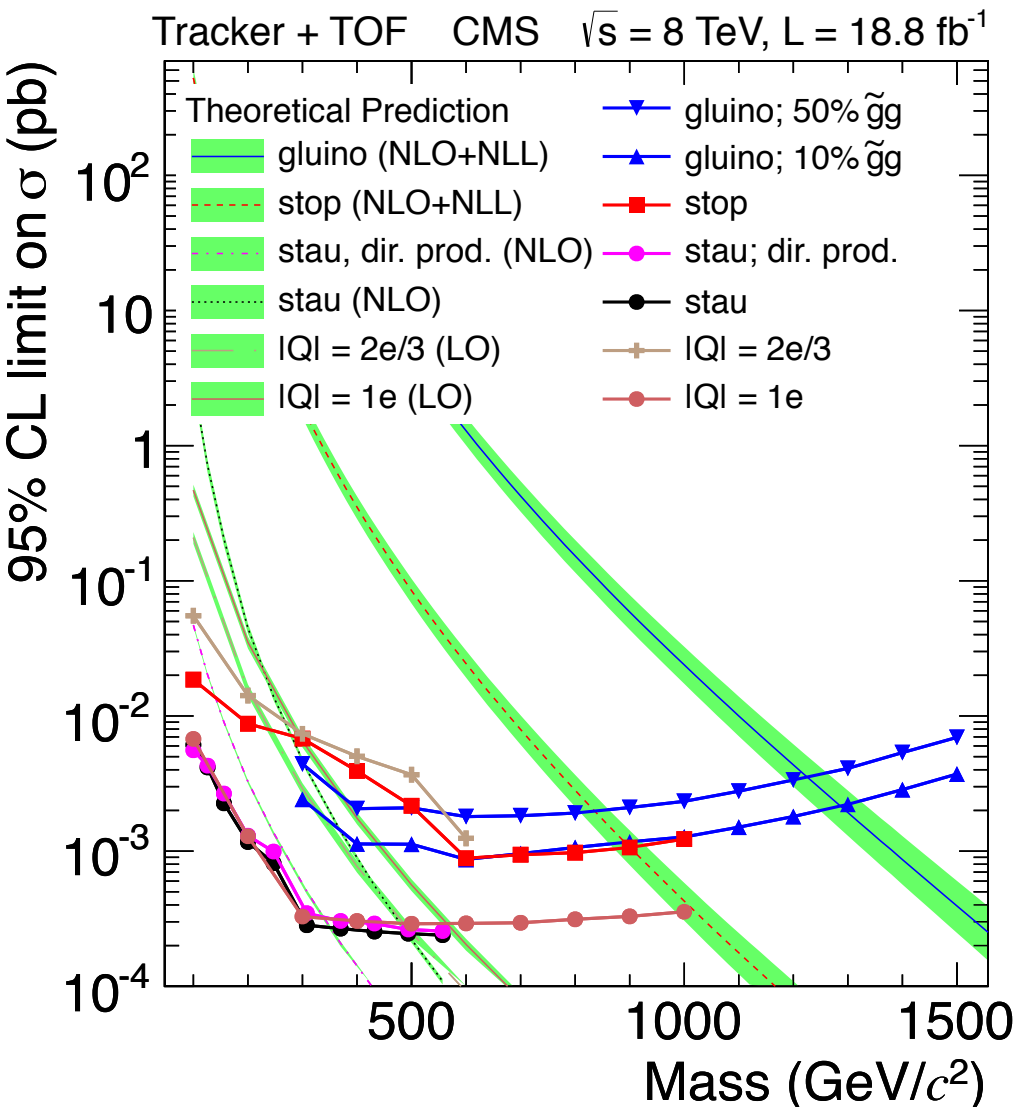


Band is the  $\pm 1$  sigma fluctuation for a Poisson distribution..

# LHC: METASTABLE PARTICLES

Recent results from CMS for metastable SUSY particles:  
at the moment no significant excess found....

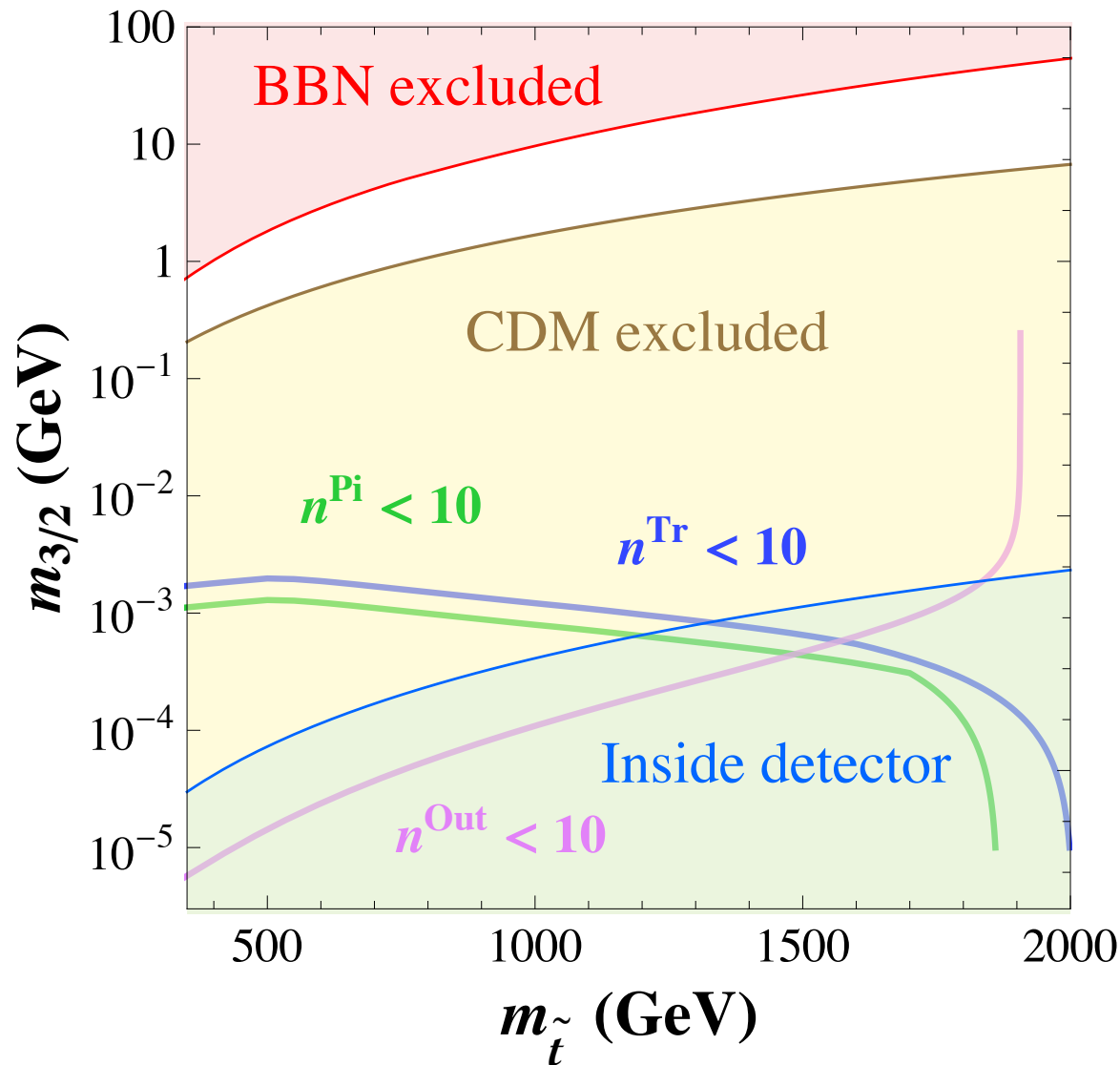
[CMS-EXO-12026]



# LHC: STOP ?

From the previous plot, we can get the LHC reach in parameter space both for RPC and RPV decay...

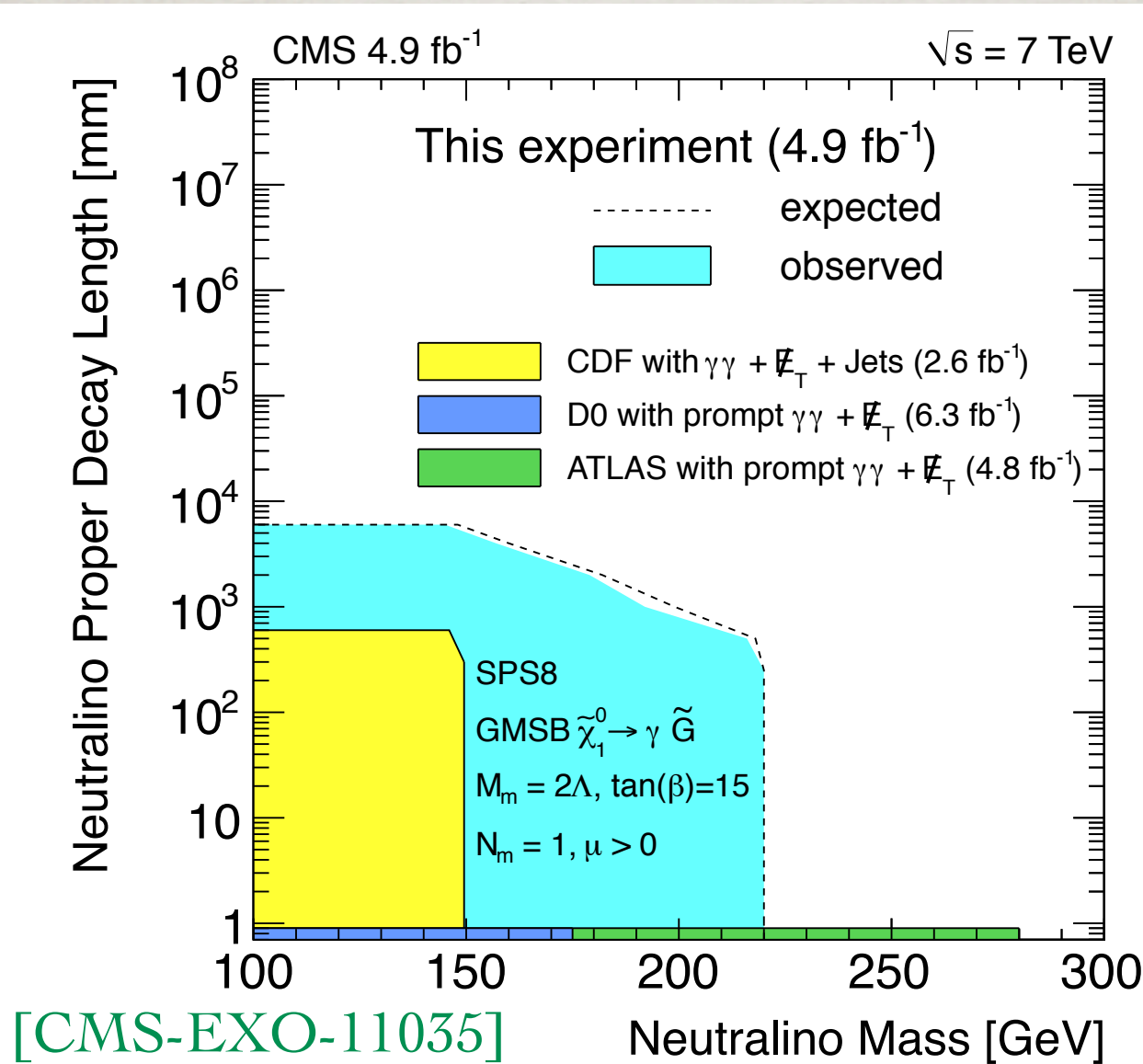
[LC & F. Dradi xxx]



The allowed region at high reheat temperature correspond to metastable NLSP !

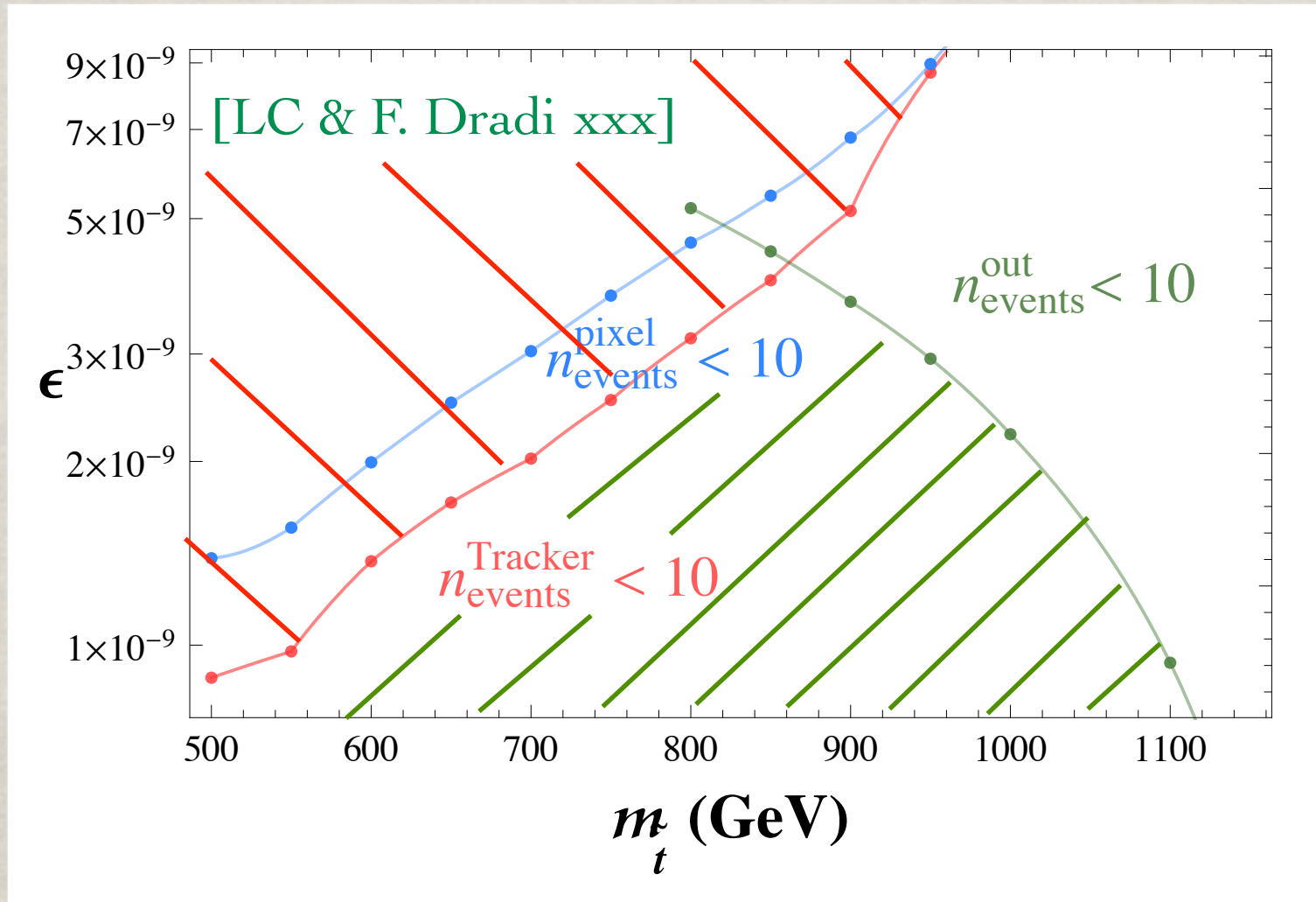
# LHC:NLSP DECAY LENGTH

Conserved  $R_p$ : LHC sets first limits on neutralino decay for very small gravitino masses  $\sim 1$  keV



# LHC: STOP ?

From the previous plot, we can get the LHC reach in parameter space both for RPC and RPV decay...

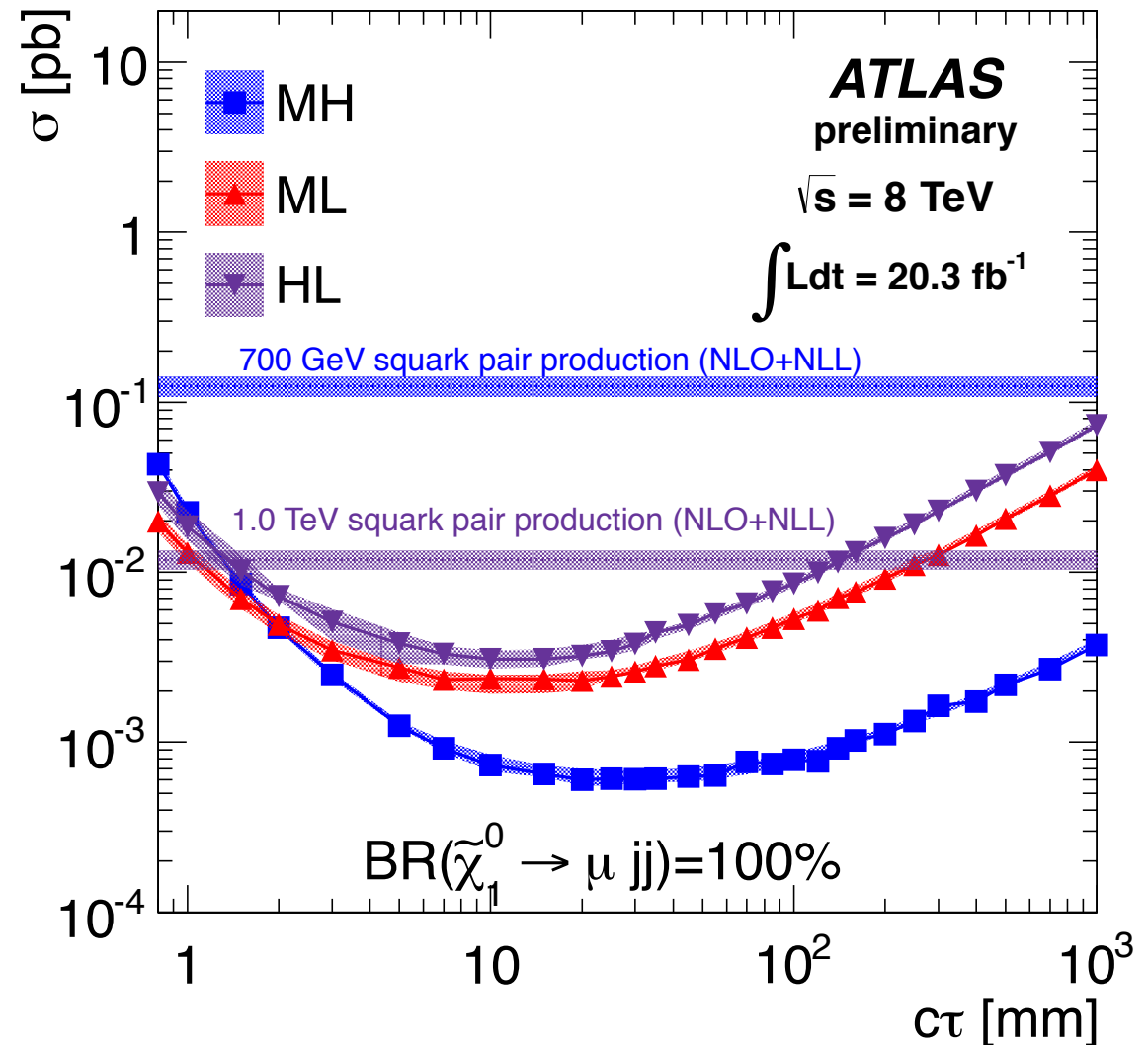
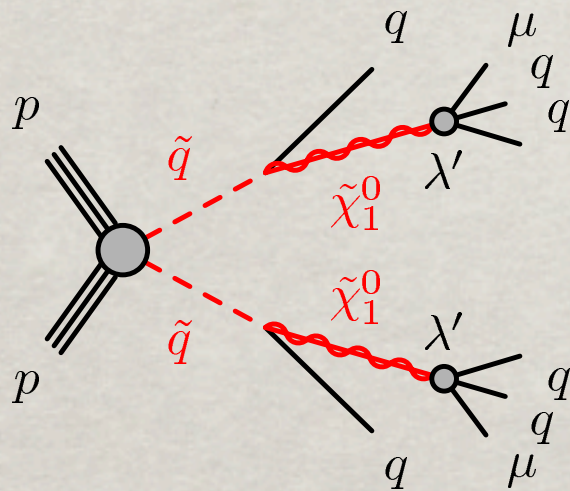


LHC can cover regions beyond Indirect Detection !

# LHC:NLSP DECAY LENGTH

Broken Rp: LHC sets first limits on neutralino decay with a muon displaced vertex

[ATLAS-CONF-12013-092]



# FROM WIMP TO FIMP/SUPERWIMP FOR THE LHC

# A SIMPLE WIMP/SWIMP MODEL

[G. Arcadi & LC 1305.6587]

Consider a simple model where the Dark Matter, a Majorana SM singlet fermion, is coupled to the colored sector via a renormalizable interaction and a new colored scalar  $\Sigma$  :

$$\lambda_\psi \bar{\psi} d_R \Sigma + \lambda_\Sigma \bar{u}_R^c d_R \Sigma^\dagger$$

Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.

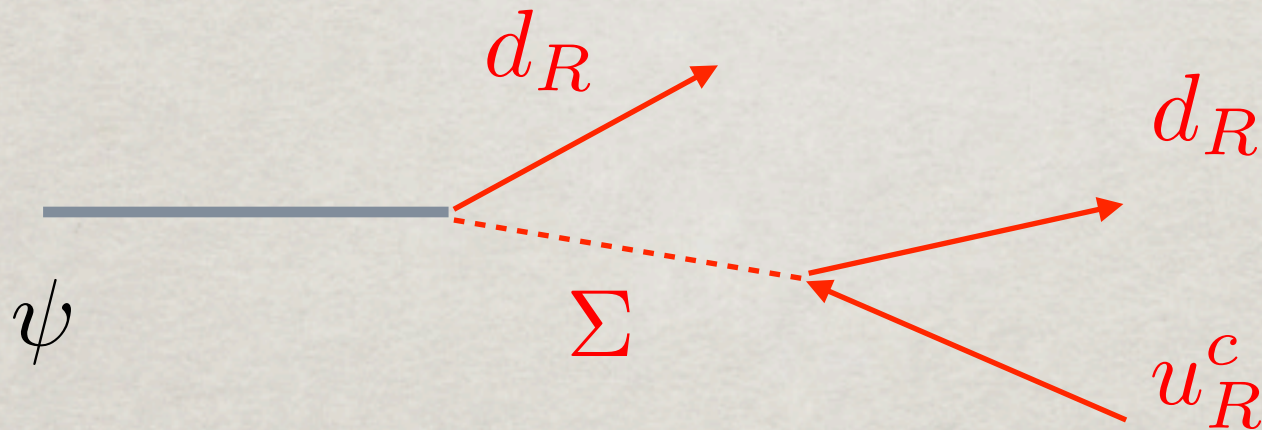
Then the possibility would arise to measure the parameters of the model in two ways !

→ FIMP/SWIMP connection

# A SIMPLE WIMP/SWIMP MODEL

[G. Arcadi & LC 1305.6587]

No symmetry is imposed to keep DM stable, but the decay is required to be sufficiently suppressed. For  $m_\Sigma \gg m_\psi$  :



Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

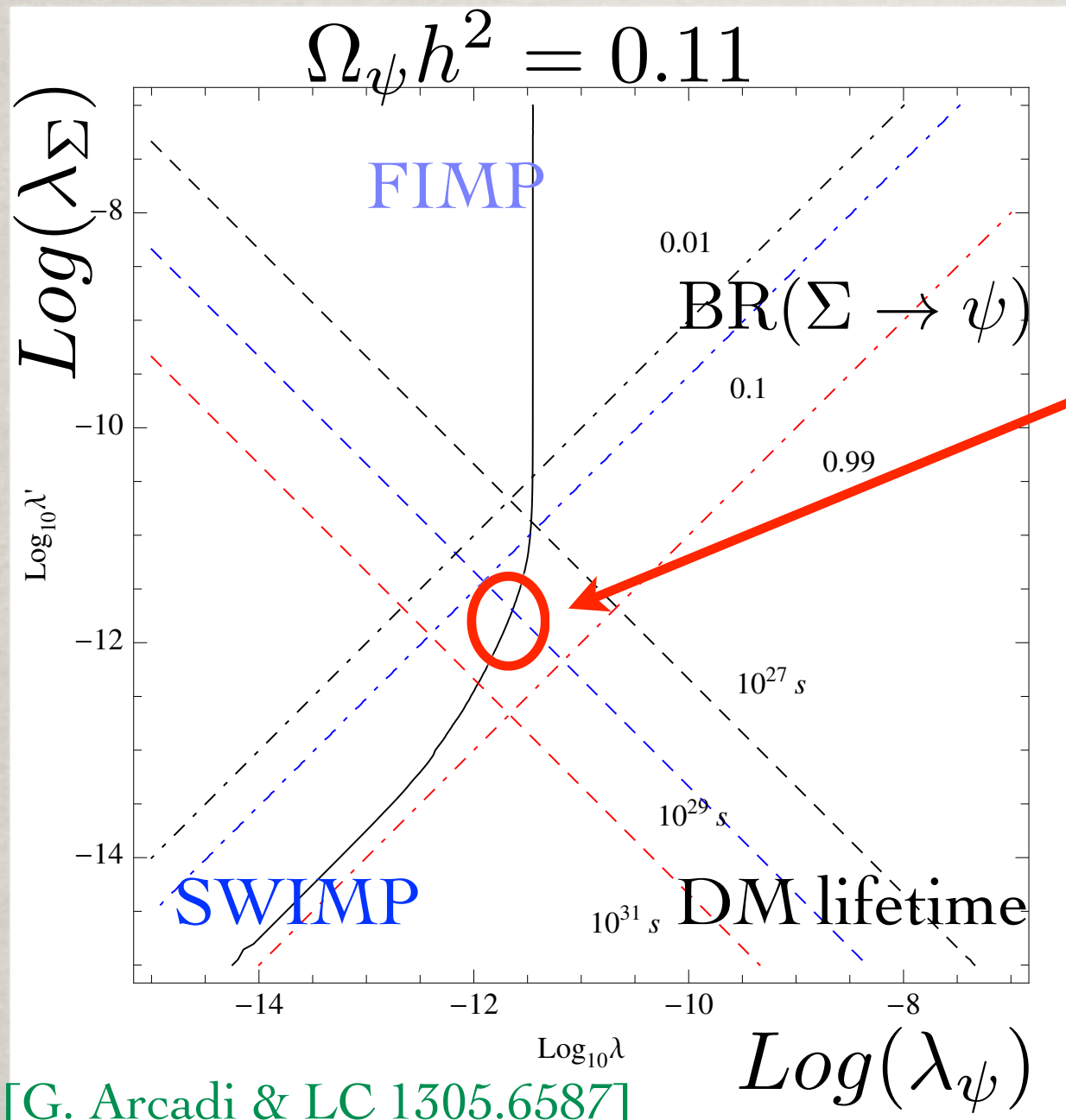
$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

# DM PRODUCTION

Depending on the couplings different mechanisms can play a role:

- $\lambda_\psi \sim 1$  : classical WIMP DM, possibly already excluded by LHC/Direct detection
- $10^{-7} < \lambda_\psi \ll 1$  : relativistic relic, i.e. **HDM**
- $\lambda_\psi \sim 10^{-12}$  : FIMP Dark Matter, produced by the decay of  $\Sigma$  in equilibrium
- $\lambda_\psi < 10^{-12}$  : SuperWIMP Dark Matter, produced by the decay of  $\Sigma$  after freeze-out

# A SIMPLE WIMP/SWIMP MODEL



DM decay observable  
in indirect detection  
& right abundance  
& sizable BR in DM

$$\lambda_\psi \sim \lambda_\Sigma$$

But unfortunately  
 $\Sigma$  decays outside  
the detector @ LHC!

Perhaps visible  
decays with a bit of  
hierarchy...

# FIMP/SWIMP AT LHC

At the LHC we expect to produce the heavy charged scalar  $\Sigma$ , as long as the mass is not too large... In principle the particle has two channels of decay with very long lifetimes.

Fixing the density by FIMP mechanism we have:

$$l_{\Sigma,DM} = 2.1 \times 10^5 \text{m} g_{\Sigma} x \left( \frac{m_{\Sigma_f}}{1\text{TeV}} \right)^{-1} \left( \frac{\Omega_{CDM} h^2}{0.11} \right)^{-1} \left( \frac{g_*}{100} \right)^{-3/2}$$

Very long apart for small DM mass, i.e.  $x = \frac{m_{DM}}{m_{\Sigma_f}} \ll 1$

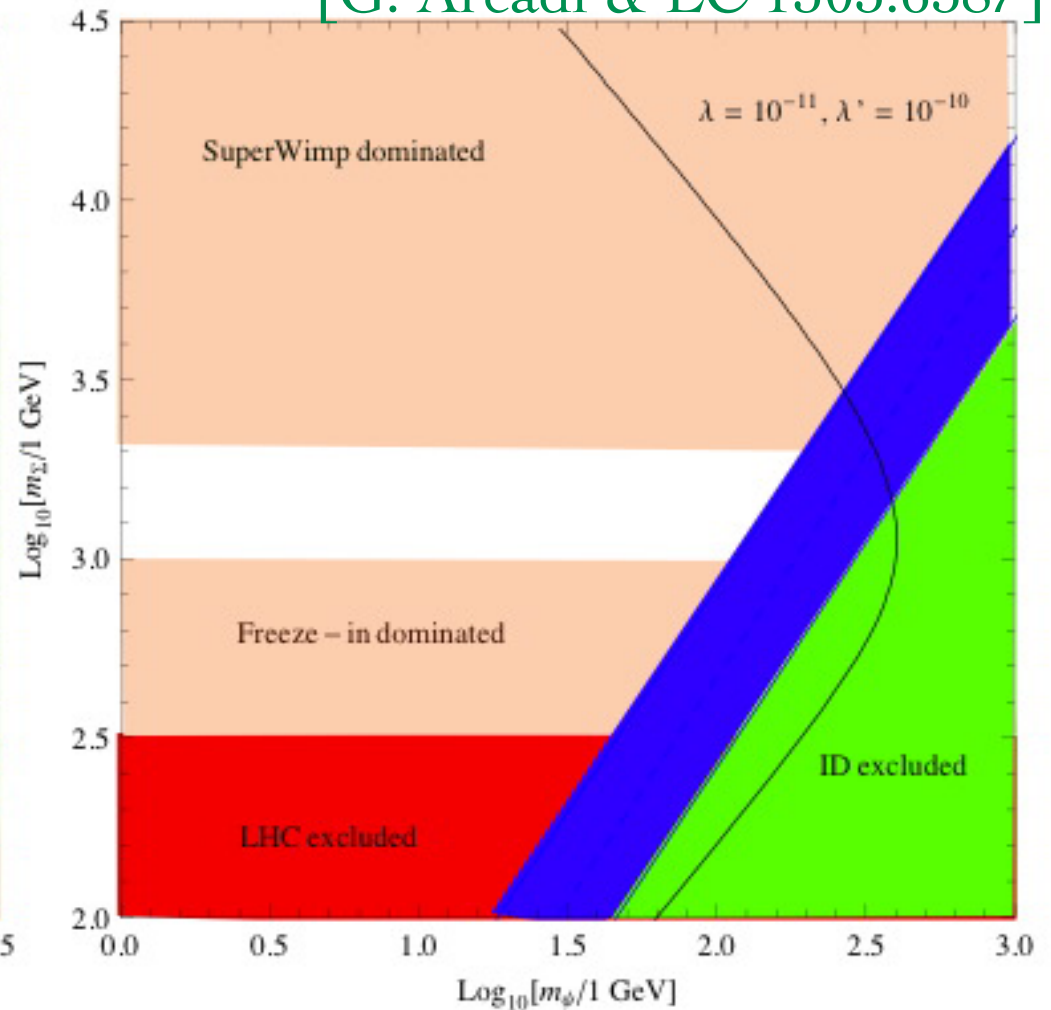
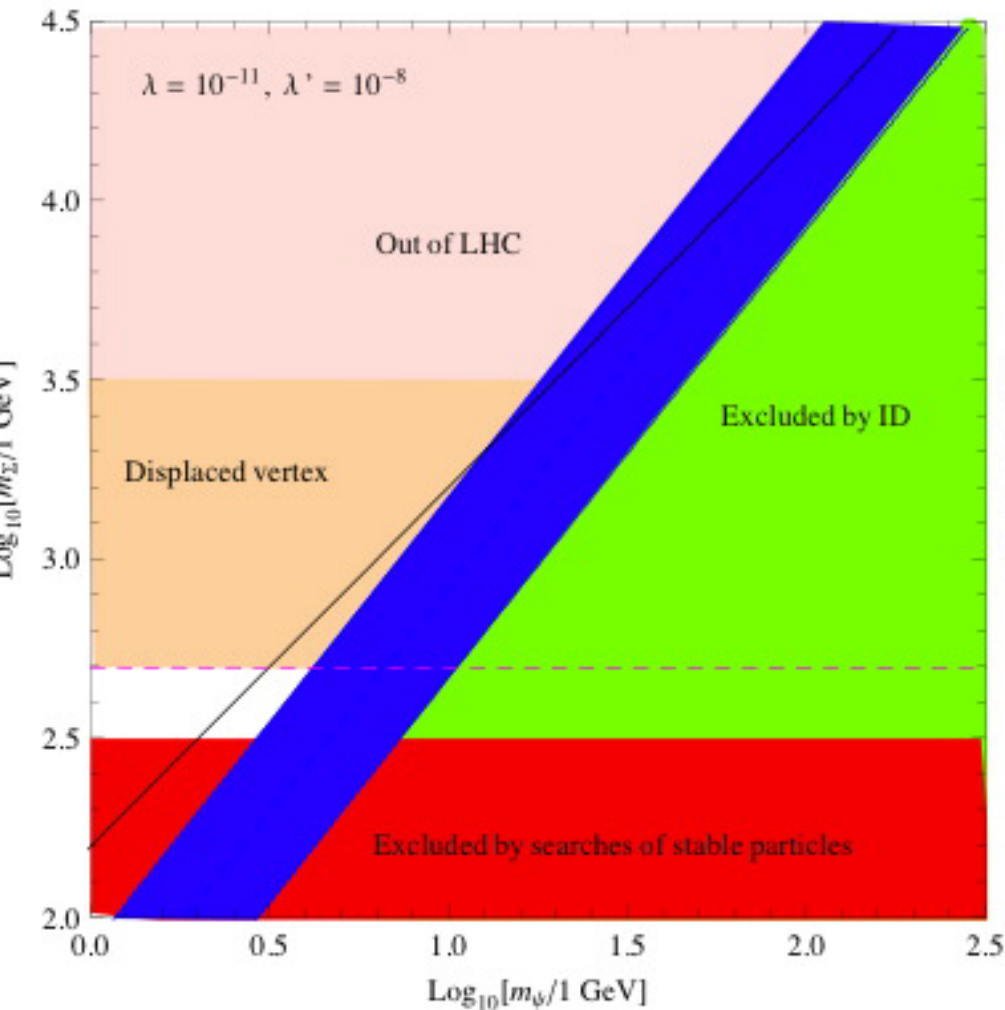
Moreover imposing ID “around the corner” gives

$$l_{\Sigma,SM} \simeq 55 \text{m} \frac{1}{g_{\Sigma}} \left( \frac{m_{\Sigma_f}}{1\text{TeV}} \right)^{-4} \left( \frac{m_{\psi}}{10\text{GeV}} \right)^4 \left( \frac{\tau_{\psi}}{10^{27}\text{s}} \right) \left( \frac{\Omega_{CDM} h^2}{0.11} \right) \left( \frac{g_*}{100} \right)^{3/2}$$

At least one decay could be visible !!!

# A FIMP/SWIMP SUMMARY

[G. Arcadi & LC 1305.6587]



For  $\Sigma$  SU(2) doublet, FIMP case gives displaced vertices,  
 SuperWIMP gives “stable” charged particle @ LHC

# OUTLOOK

# OUTLOOK

- The search for a DM particle continues on all fronts: at LHC, at direct detection experiments and in indirect detection !
- WIMP DM is not the only DM paradigm: in particular in SUGRA the gravitino is an attractive SuperWIMP DM candidate !
- Gravitinos can survive as DM also for broken R-parity, but then indirect DM searches set limits on the parameters. Stop and other NLSPs are being probed at the LHC !
- The FIMP/SuperWIMP framework is more general and could point to heavy metastable charged particles at LHC with different decay channels ! Work in progress: realisations of the scenario and discovery reach.