Flavou Workshop - Anacapri 24.05.2014

FIMPs & SuperWIMPs at the LHC

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invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Outline

- Introduction:
  SuperWeakly Interacting DM & Cosmology

- A minimal WIMP/FIMP/SuperWIMP
  DM scenario at the LHC

  with G. Arcadi,
  G. Arcadi/F. Dradi

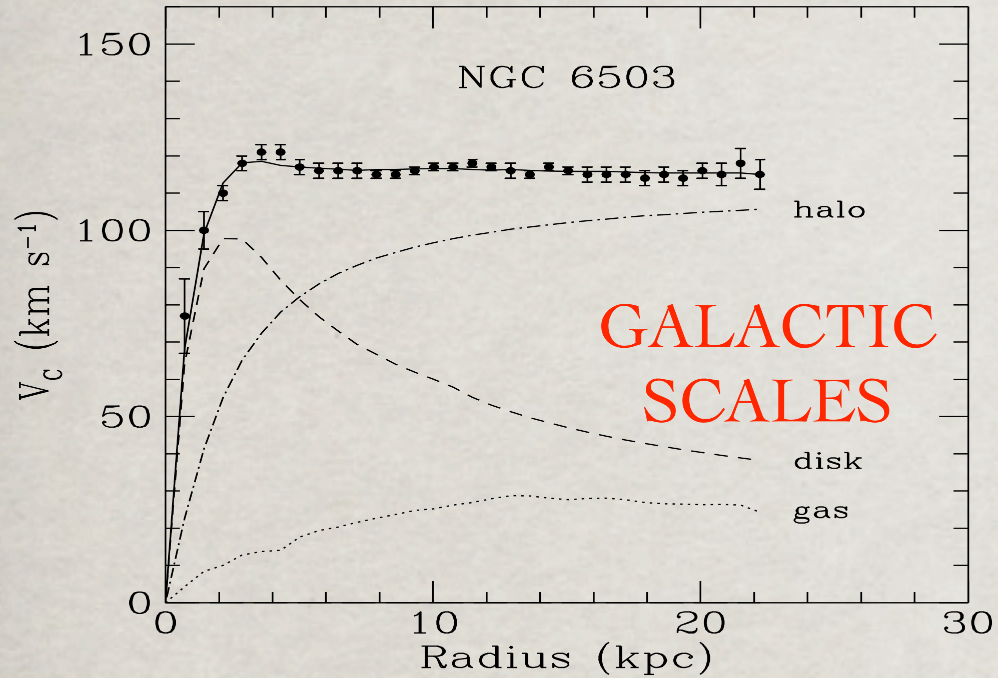
- Gravitino CDM with stop NLSP:
  - cosmological bounds
  - signals at the LHC

  with F. Dradi

- Outlook

Introduction: SuperWIMP & Cosmology

DARK MATTER EVIDENCE



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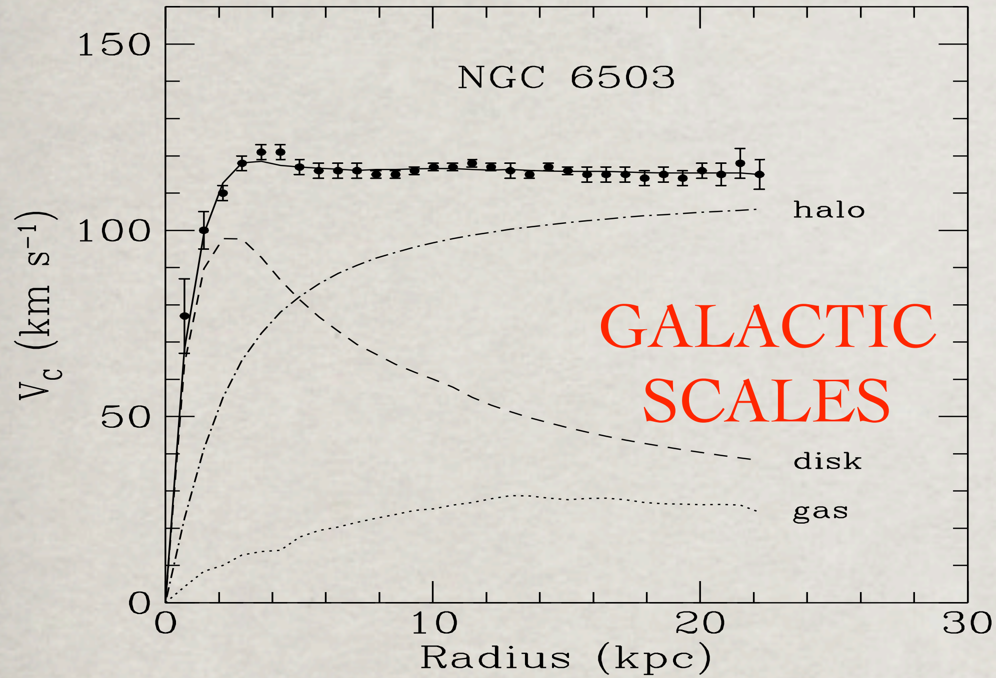

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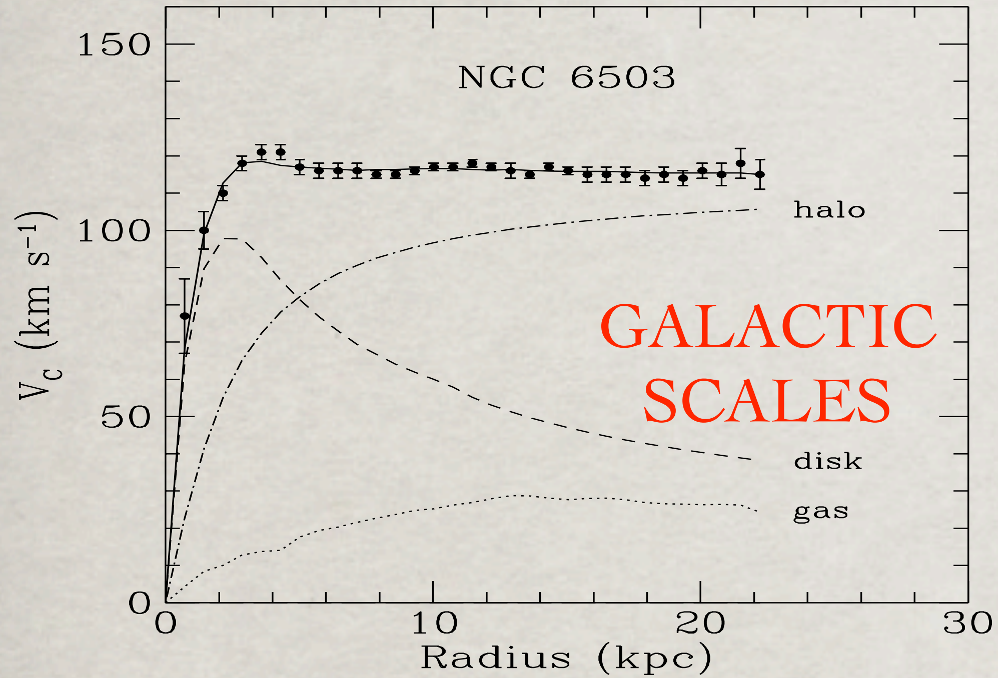

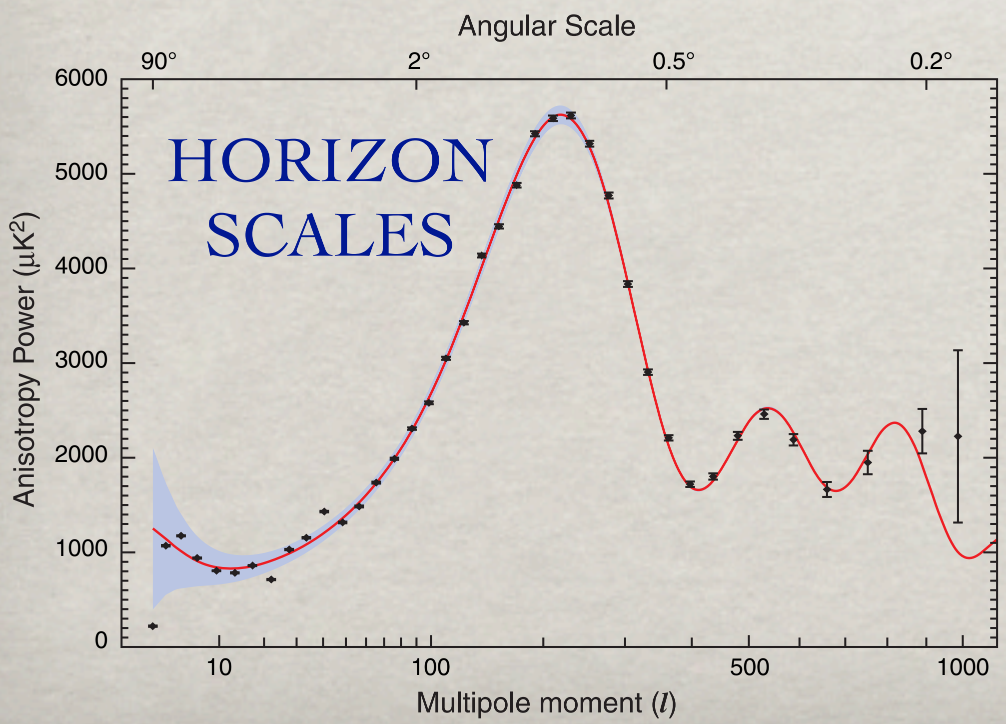

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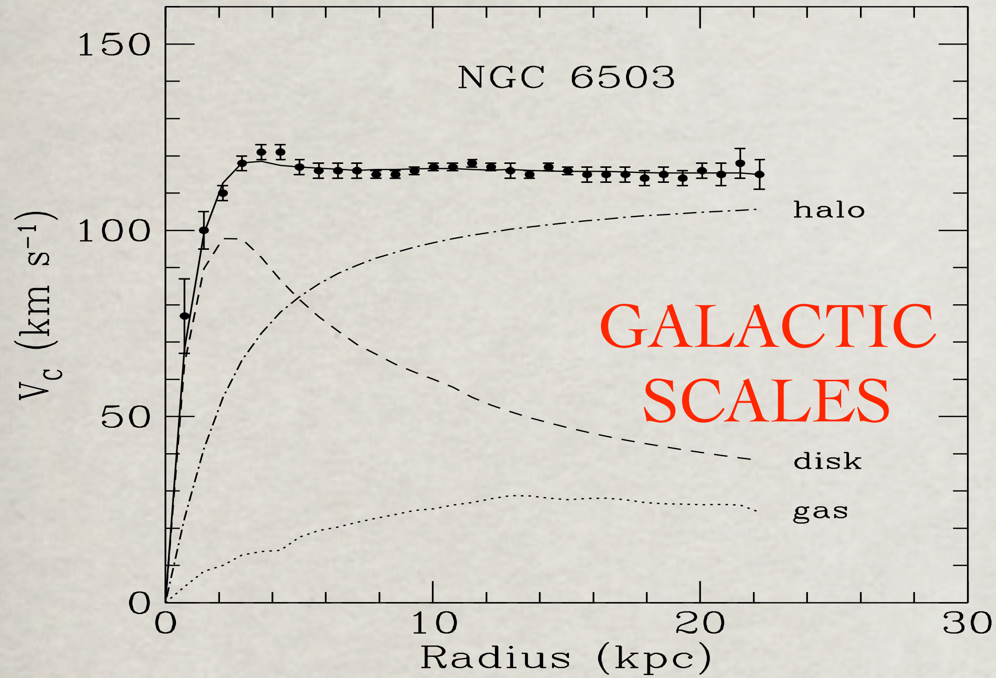
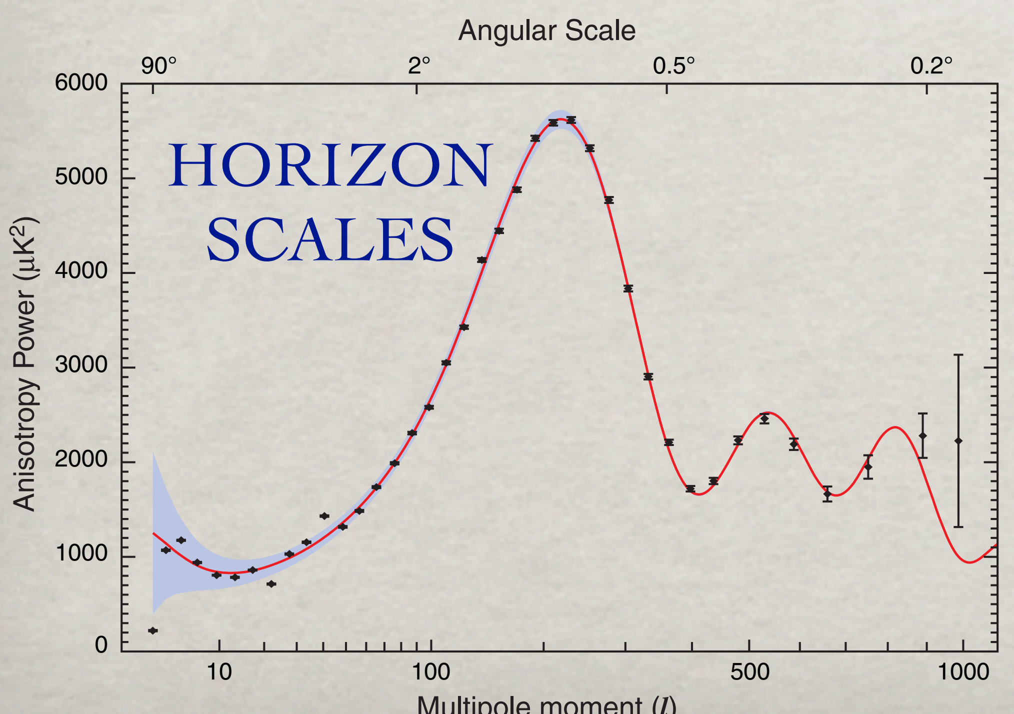




Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	~ 0.11	Cold

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 !

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 that 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" !

- Moreover they do not need to have an exactly conserved quantum number to be sufficiently stable...

Dark Matter may decay !!!

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

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

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

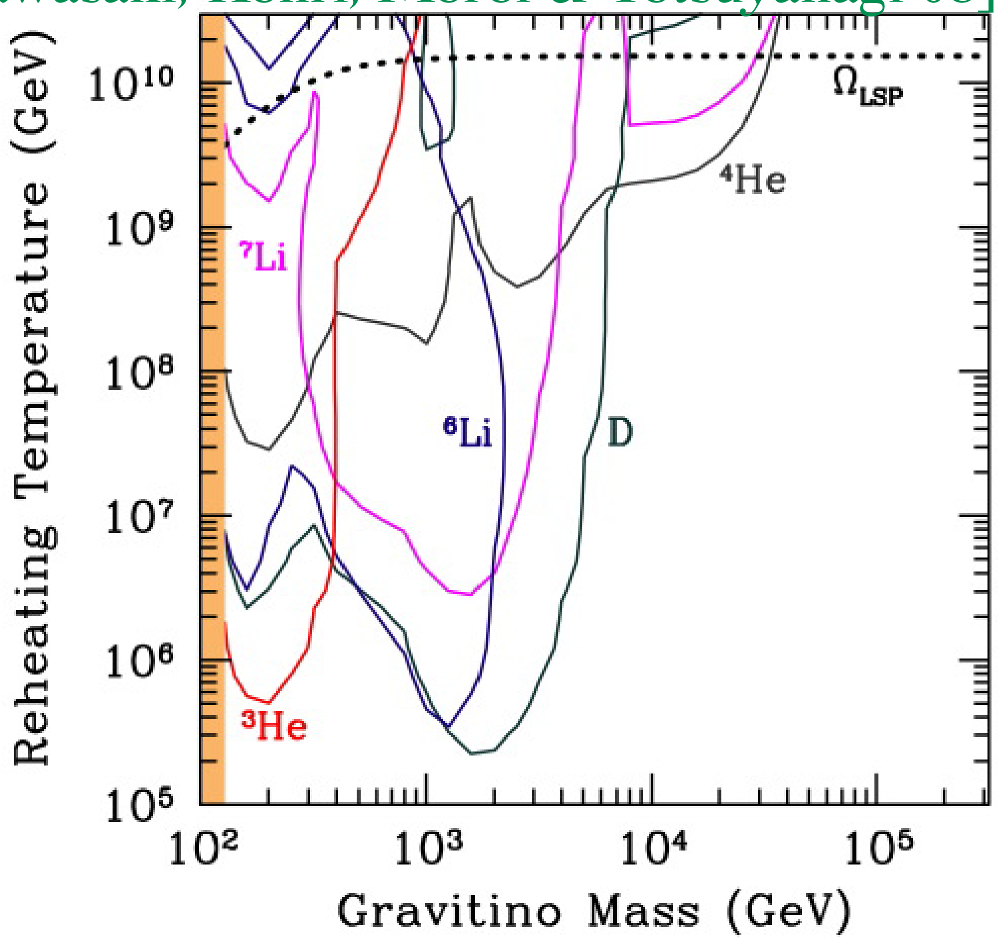
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}} \right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}} \right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}} \right)^2$$

[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]



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

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

A Minimal WIMP/FIMP/SuperWIMP for the LHC

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 Bolzmann equation

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

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

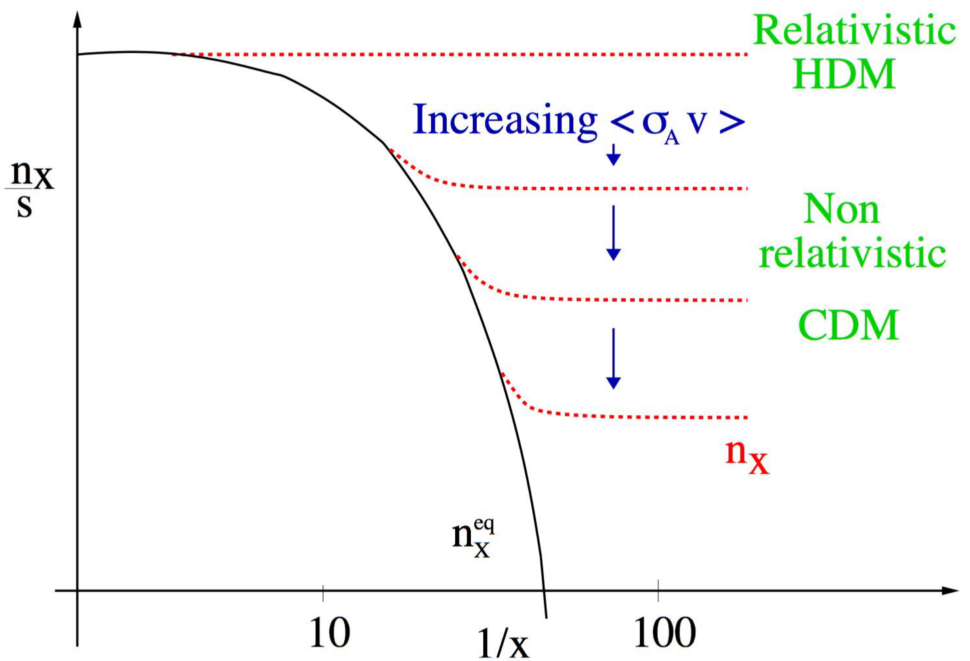
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

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

Weakly Interacting Massive Particle

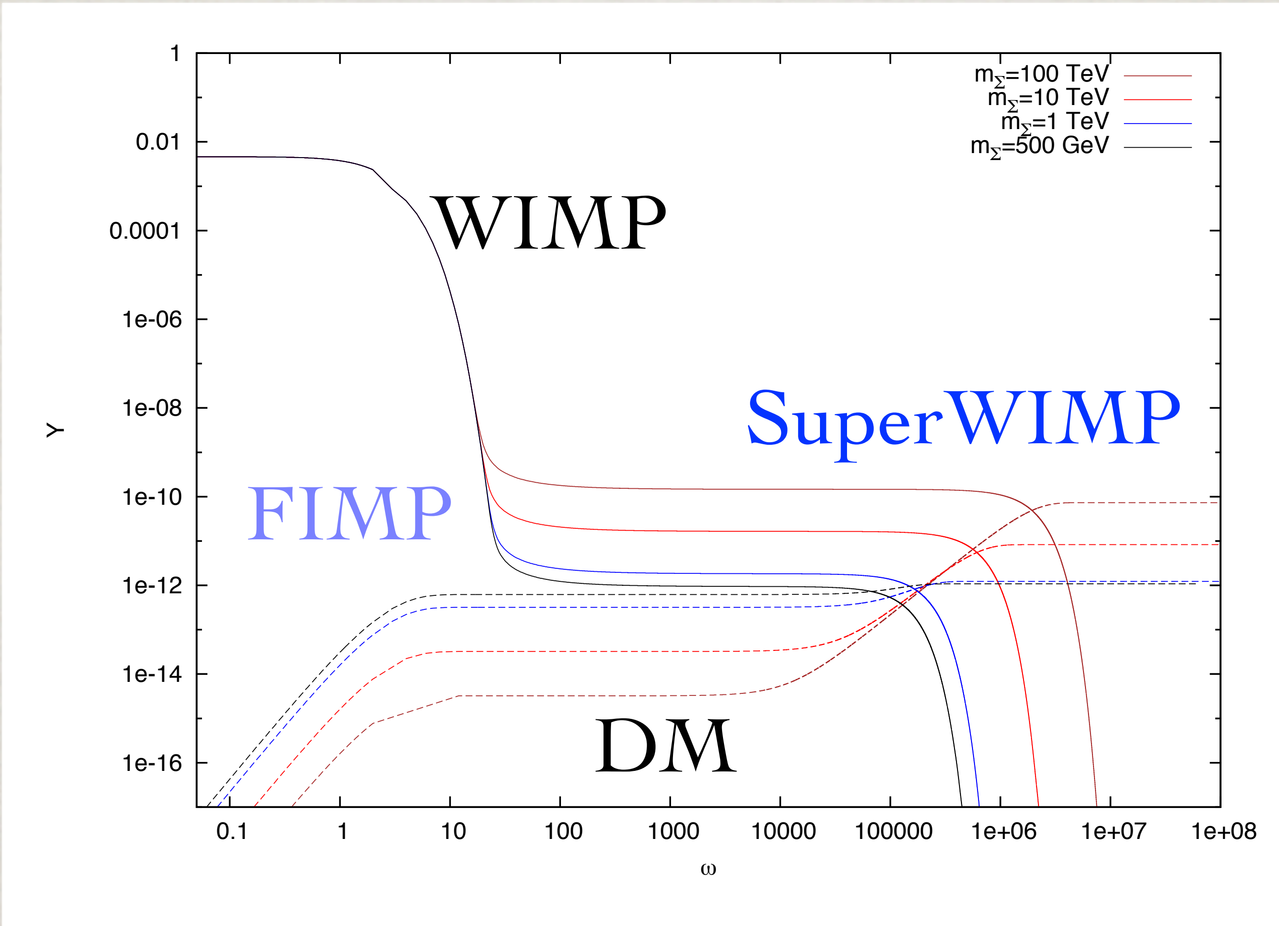
For weaker interactions need lighter masses HOT DM !



SuperWIMP/FIMP paradigms

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

FIMP DM produced by WIMP decay in equilibrium

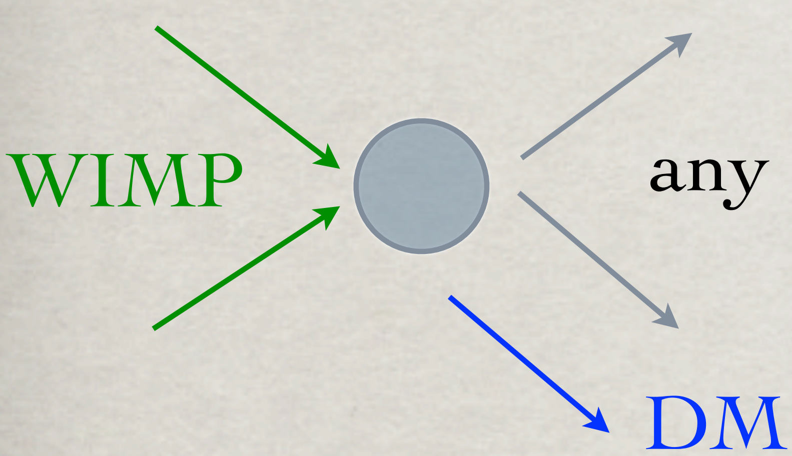


SuperWIMP DM produced by WIMP decay after freeze-out

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

F/SWIMP CONNECTION

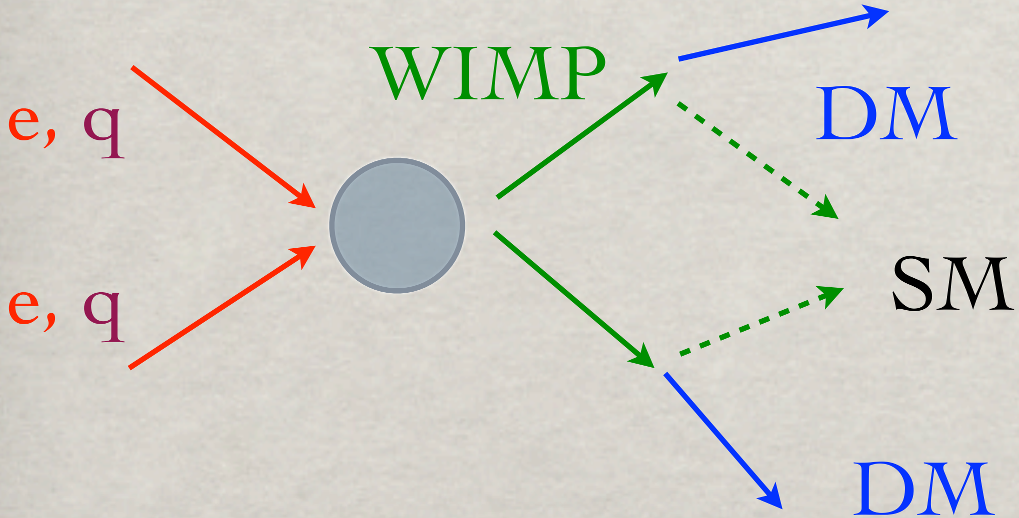
Early Universe: $\Omega_{CDM} h^2$



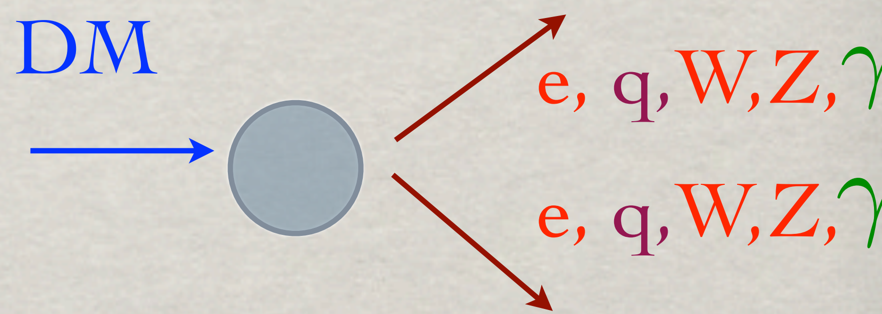
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

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 Σ :

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

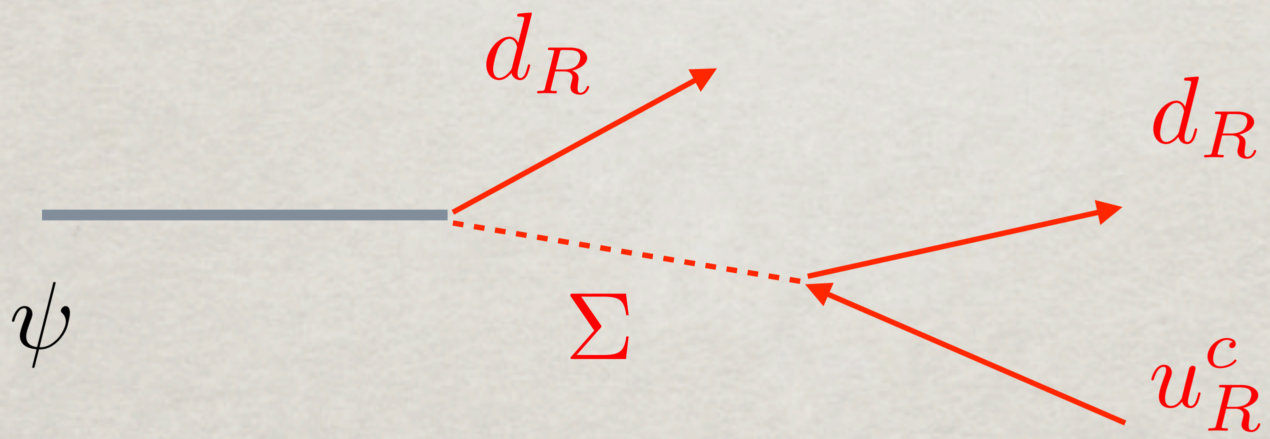
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection. Then the possibility would arise to measure the parameters of the model in two ways !

→ 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

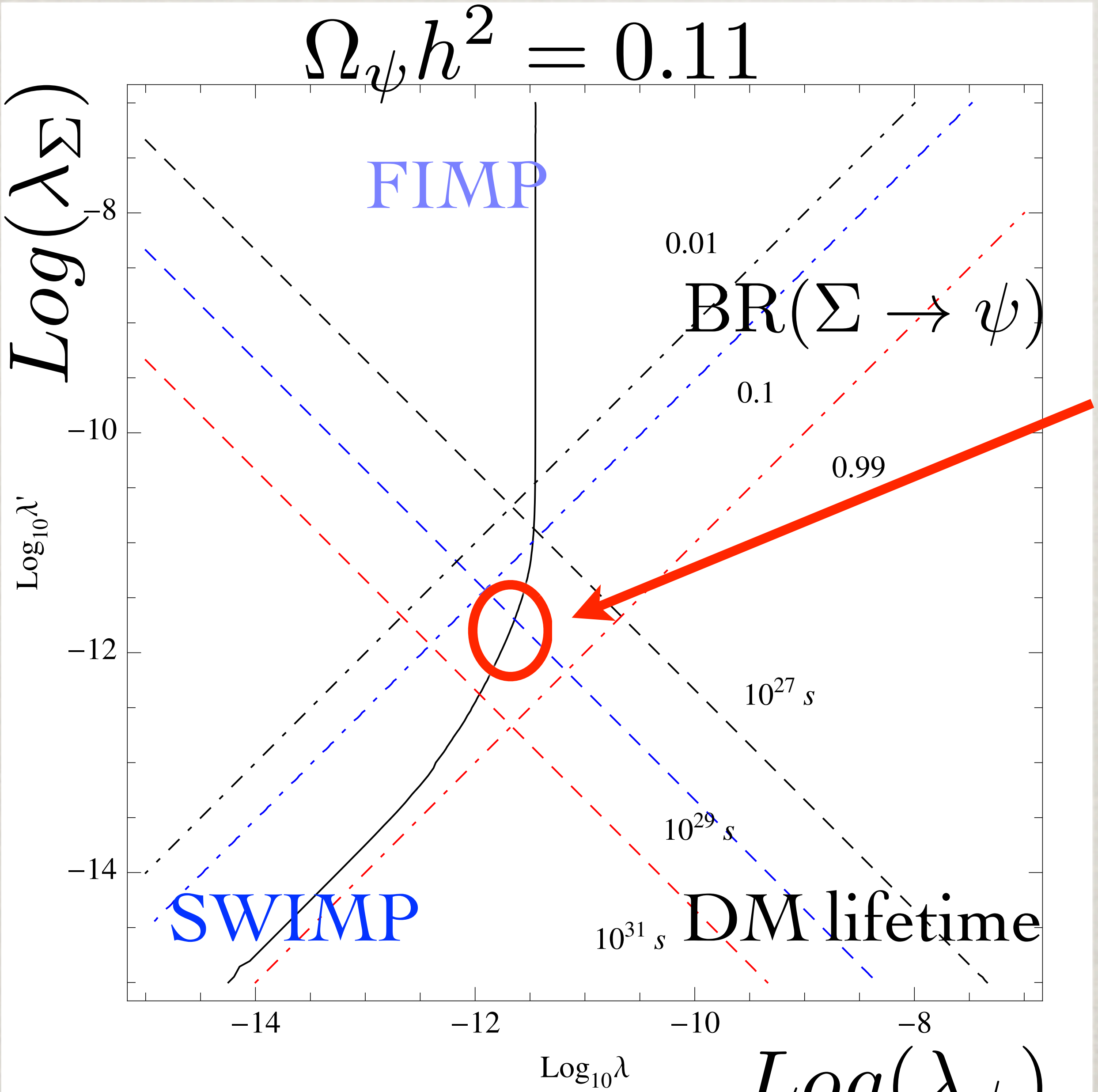
$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \, \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

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 Σ in equilibrium
- $\lambda_\psi < 10^{-12}$: SuperWIMP Dark Matter, produced by the decay of Σ after freeze-out

A simple WIMP/SWIMP model



[G. Arcadi & LC 1305.6587]

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

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

But unfortunately Σ 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 Σ, 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:

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

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

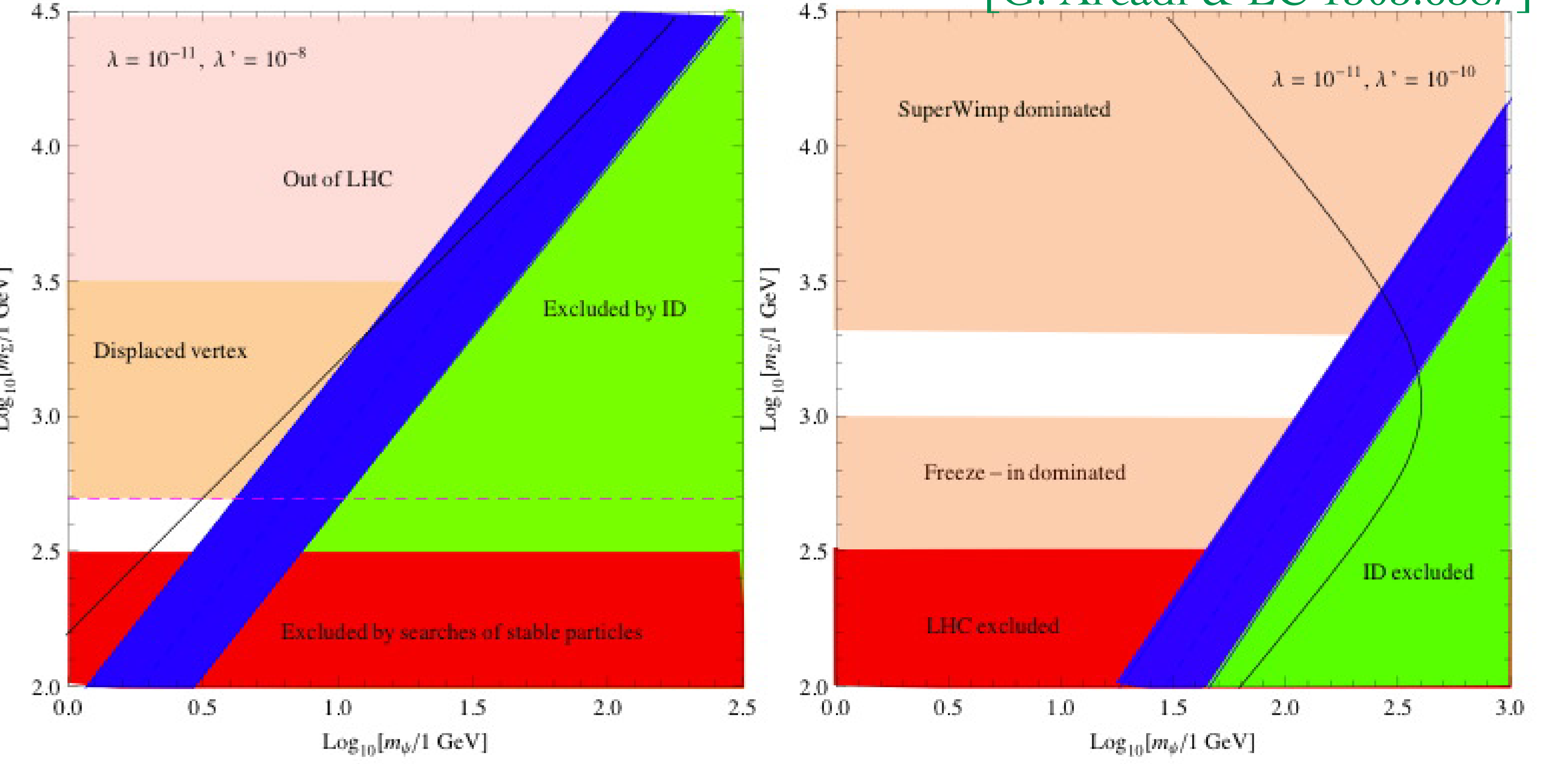
Moreover imposing ID "around the corner" gives

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

At least one decay could be visible !!!

FIMP/SWIMP & EW PARTNER

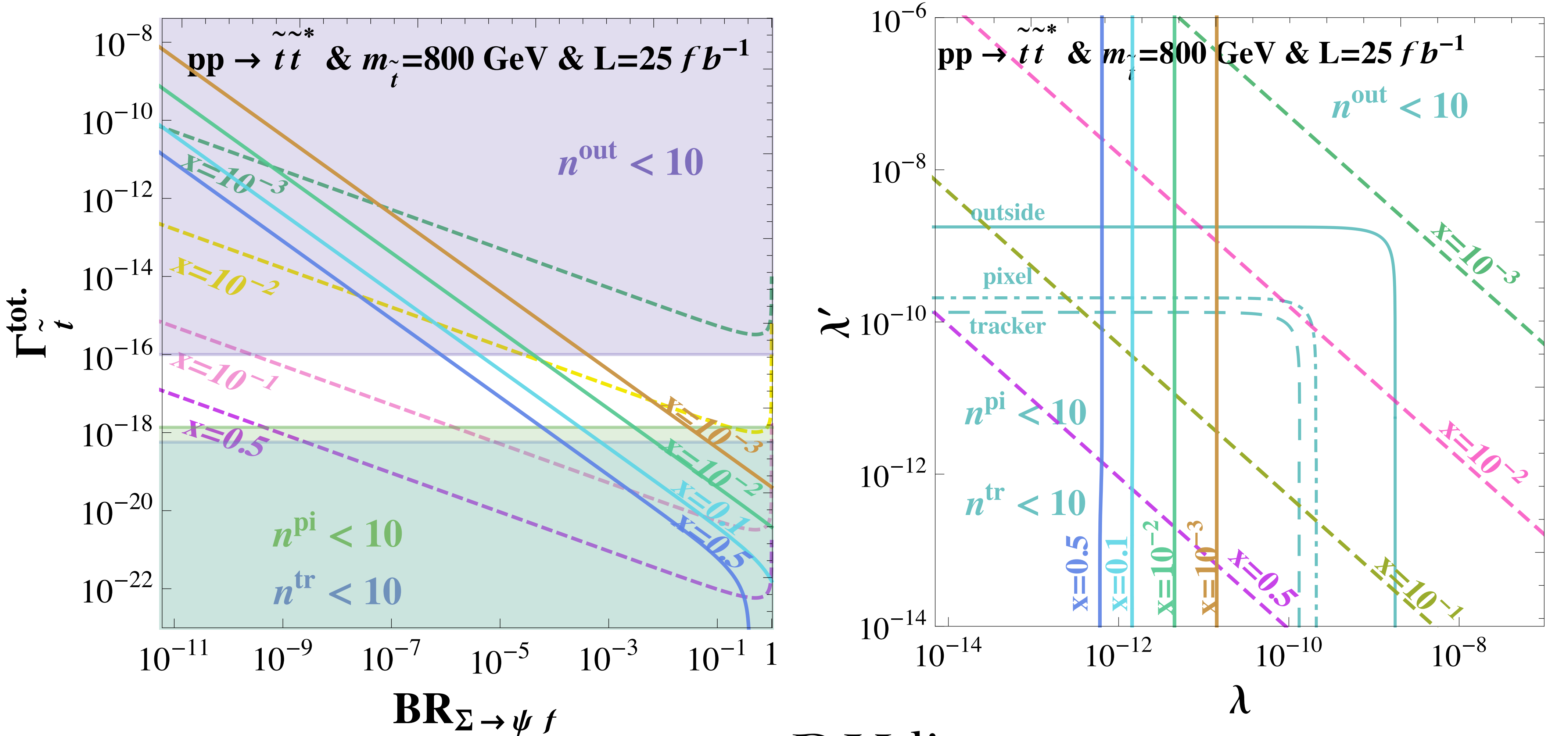
[G. Arcadi & LC 1305.6587]



For Σ SU(2) doublet, FIMP case gives displaced vertices, SuperWIMP gives "stable" charged particle @ LHC

FIMP/SWIMP & COLORED Σ

[G. Arcadi, LC & F. Dradi 1406.xxx]

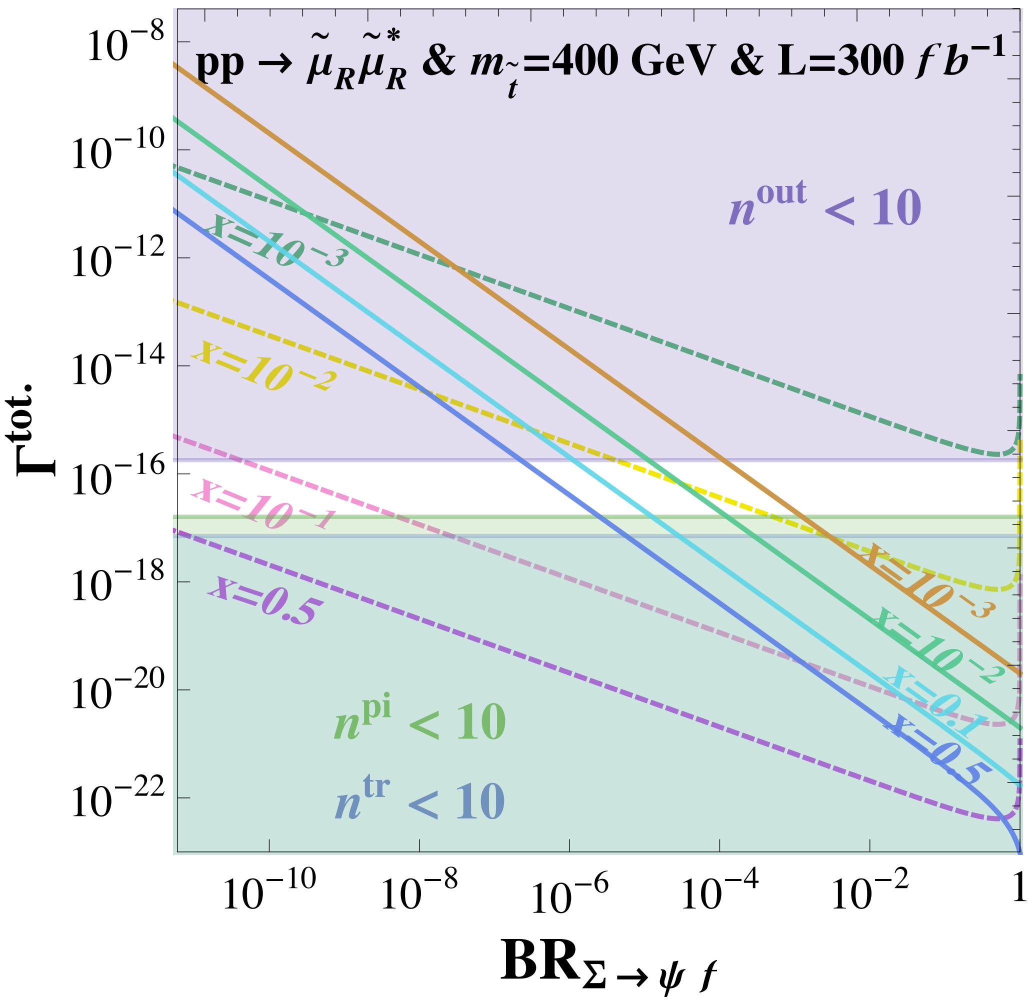


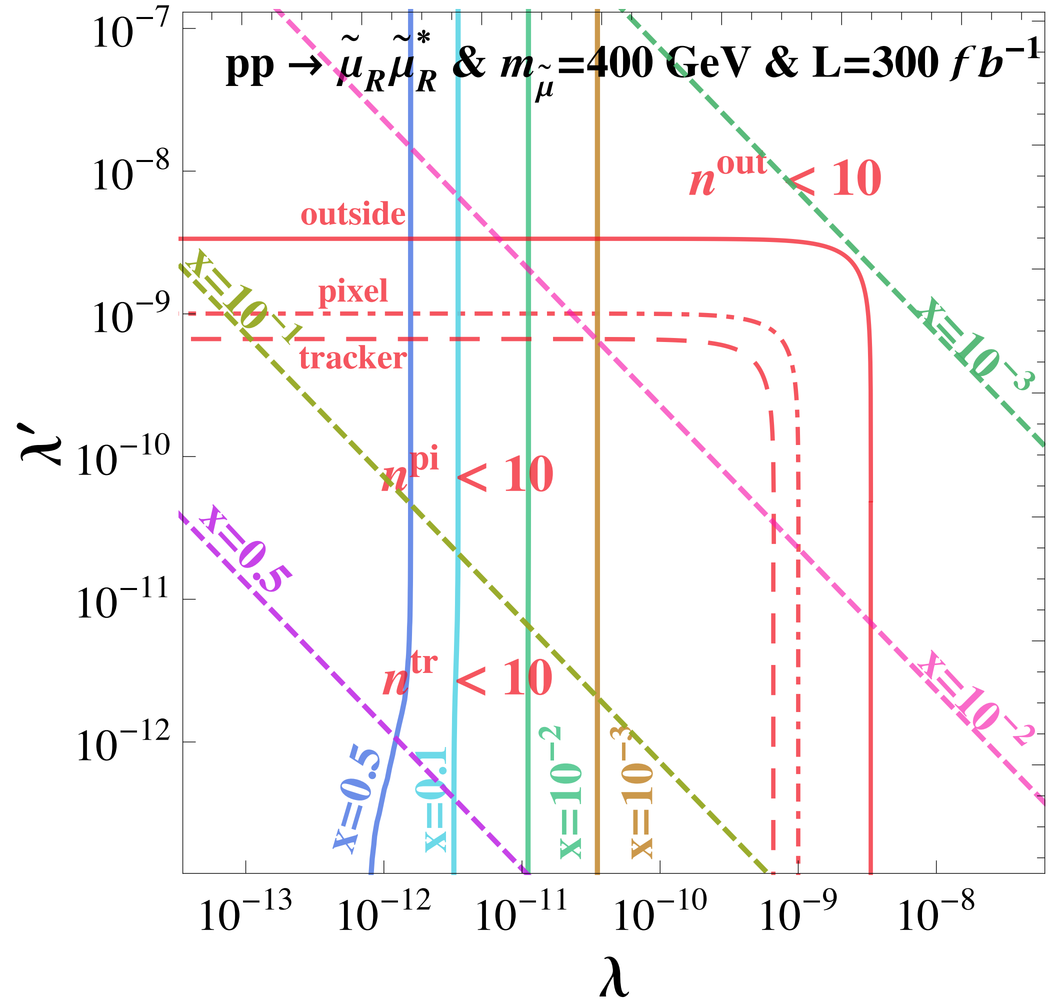
DM lines

Practically pure FIMP production: both displaced vertices & "stable" charged particle @ LHC possible...

FIMP/SWIMP & EW Σ

[G. Arcadi, LC & F. Dradi1406.xxxx]





Production at LHC is much more suppressed !

SWIMP at large x for "stable" charged particle @ LHC

Gravitino Dark Matter with stop NLSP

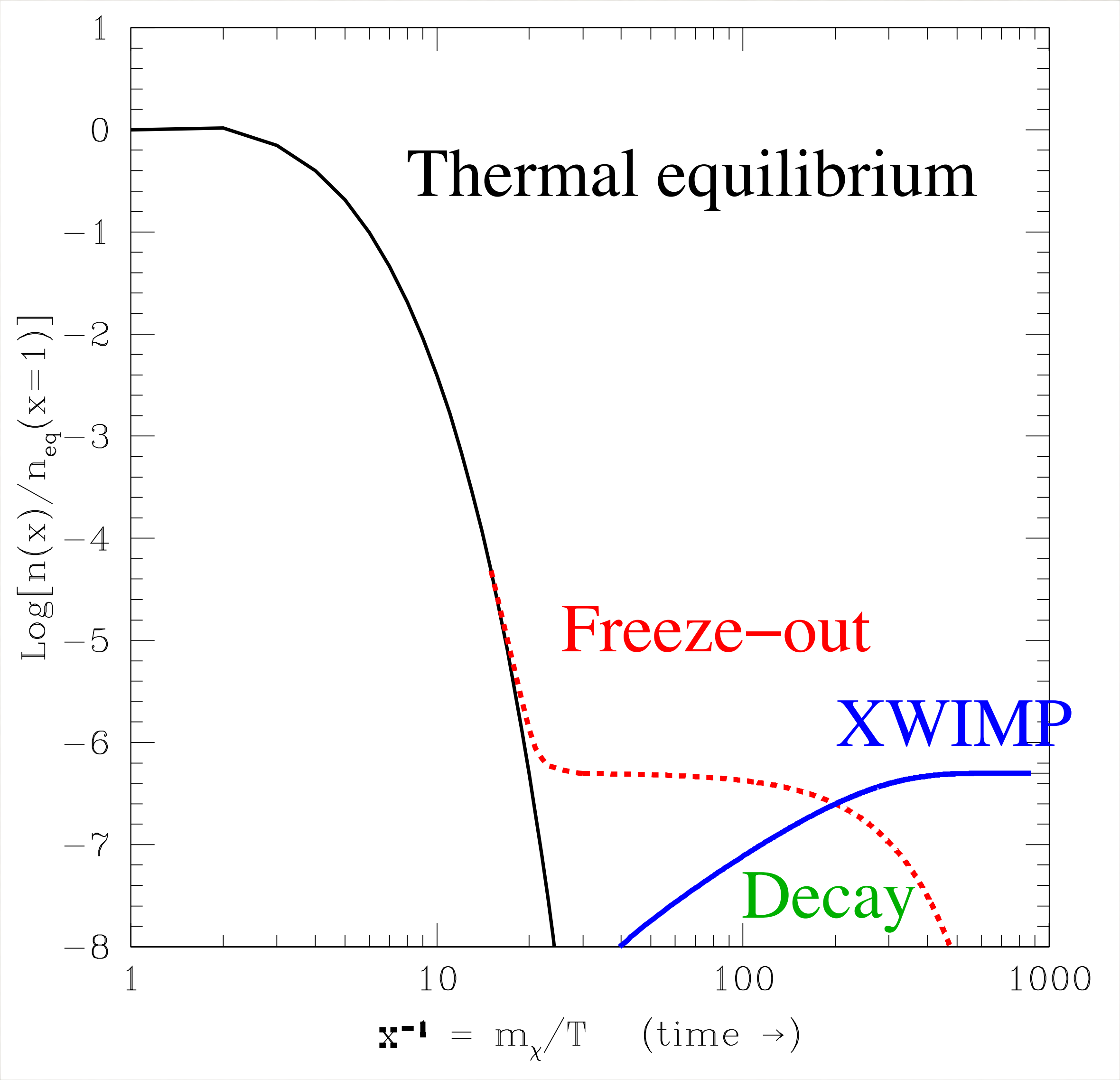
NLSP DECAY

[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?

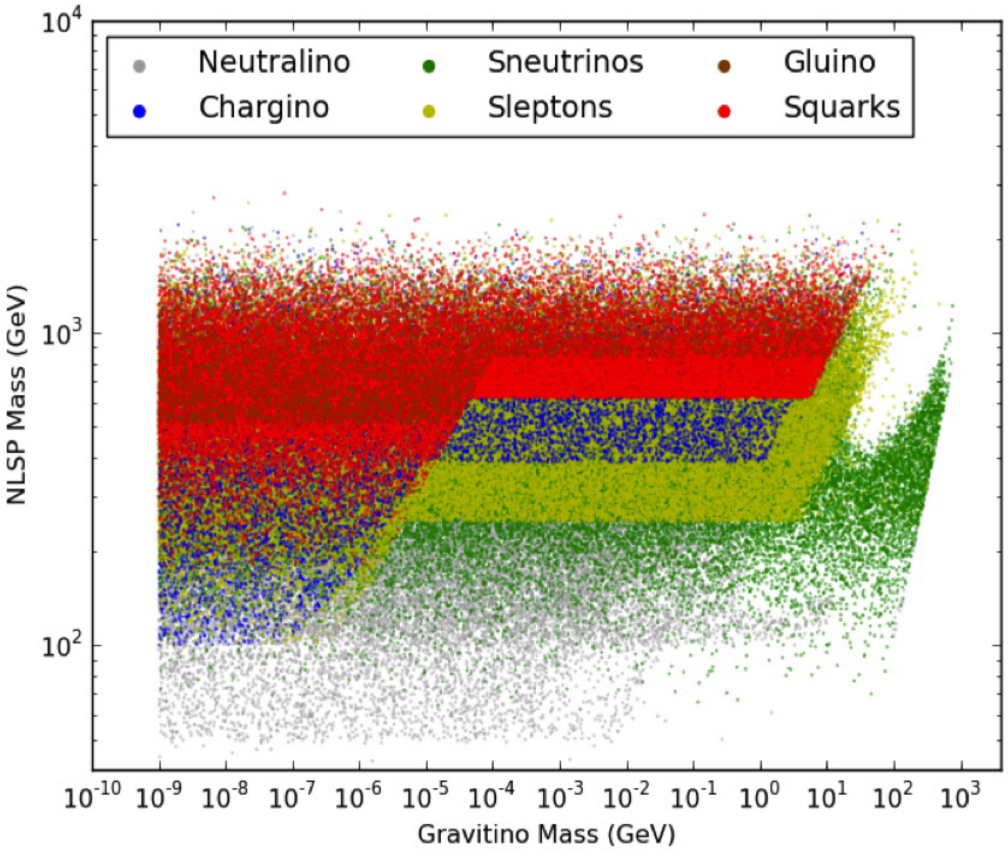
$$\Gamma_{\tilde{B}}^{-1} = 5.7 \times 10^4 \mathrm{s} \left(\frac{m_{\tilde{B}}}{100\ \mathrm{GeV}} \right)^{-5} \left(\frac{m_{\tilde{G}}}{1\ \mathrm{GeV}} \right)^2$$

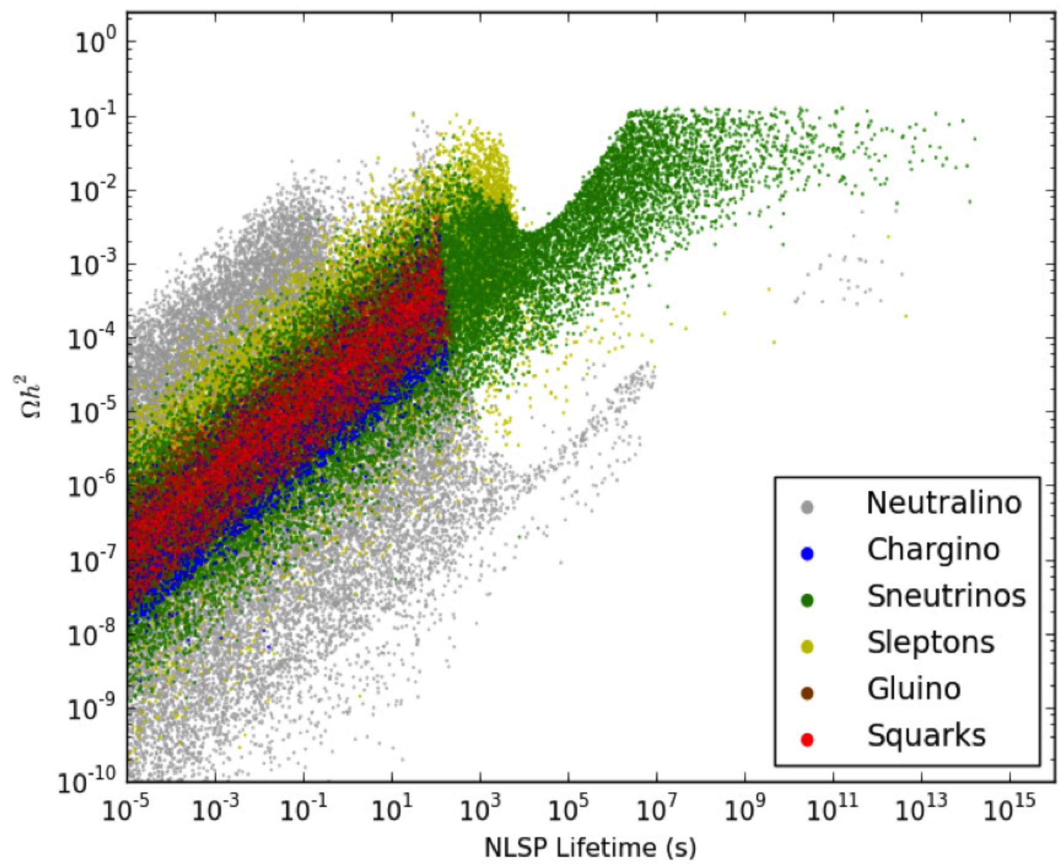
Quite long timescale, apart for heavy neutralino or light gravitino mass... Trouble for a gravitino heavier than 1 GeV !

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

BBN bounds on pMSSM

[Cahill-Rawley 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 naturality reasons and to keep the Higgs light, concentrate on the lightest stop

→ stop NLSP scenario

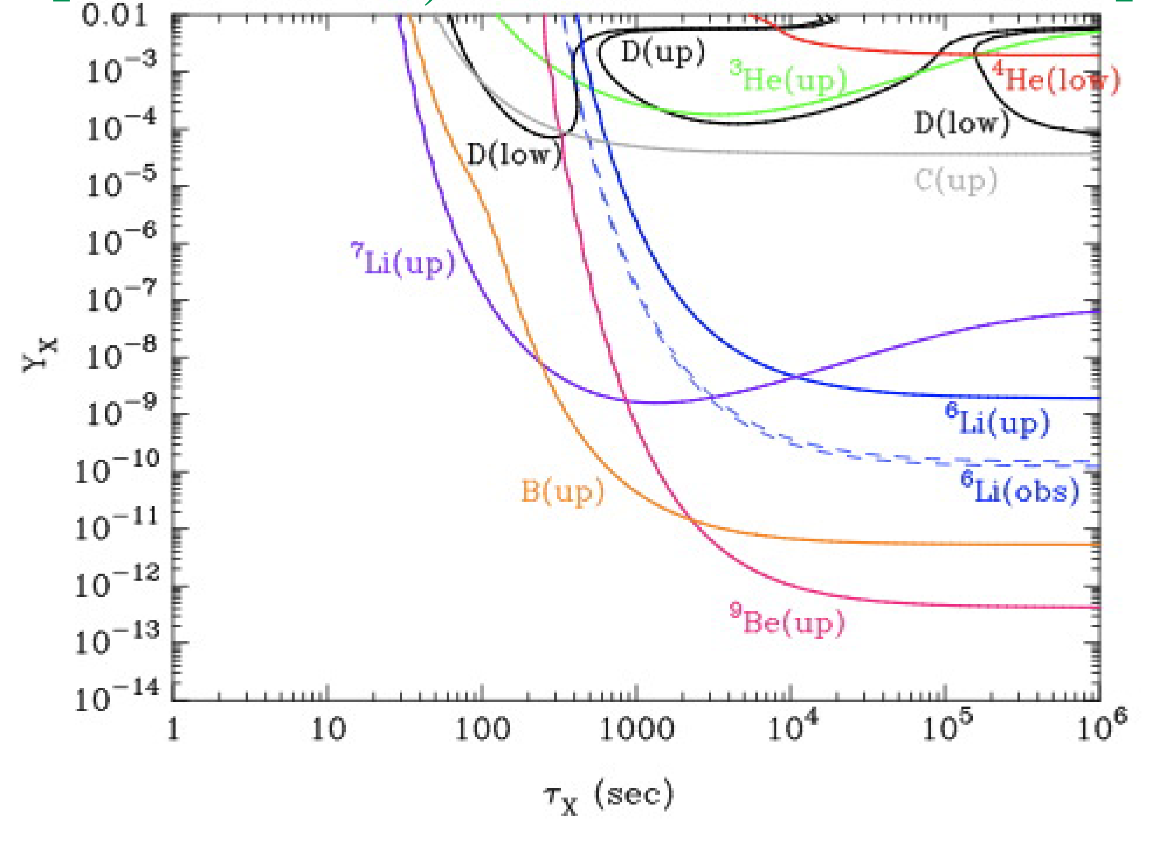
[LC & Federico Dradi 1403.4923]

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...

BBN bounds: colored relics

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

[Kusakabe, Kajino, Yoshida, Mathews 09]



BBN bounds: colored relics

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

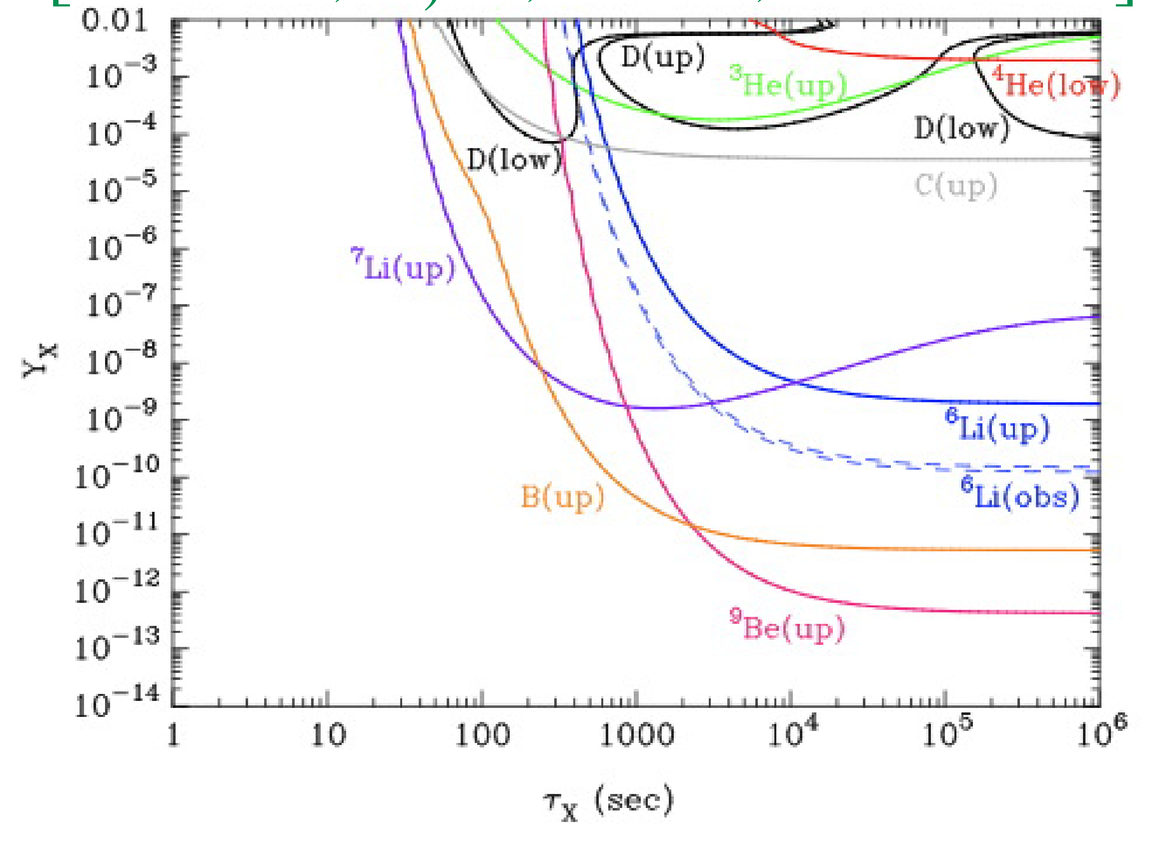
Beware:

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

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

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

[Kusakabe,Kajino,Yoshida, Mathews 09]



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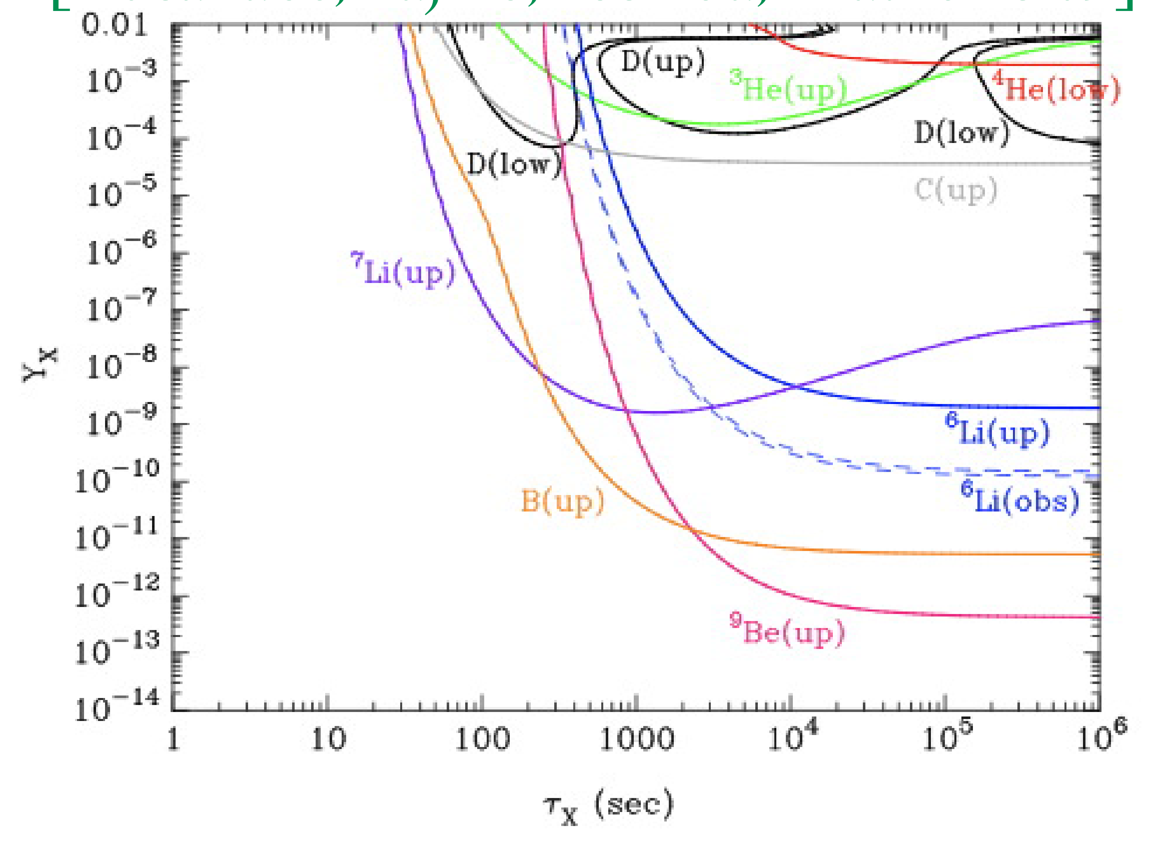
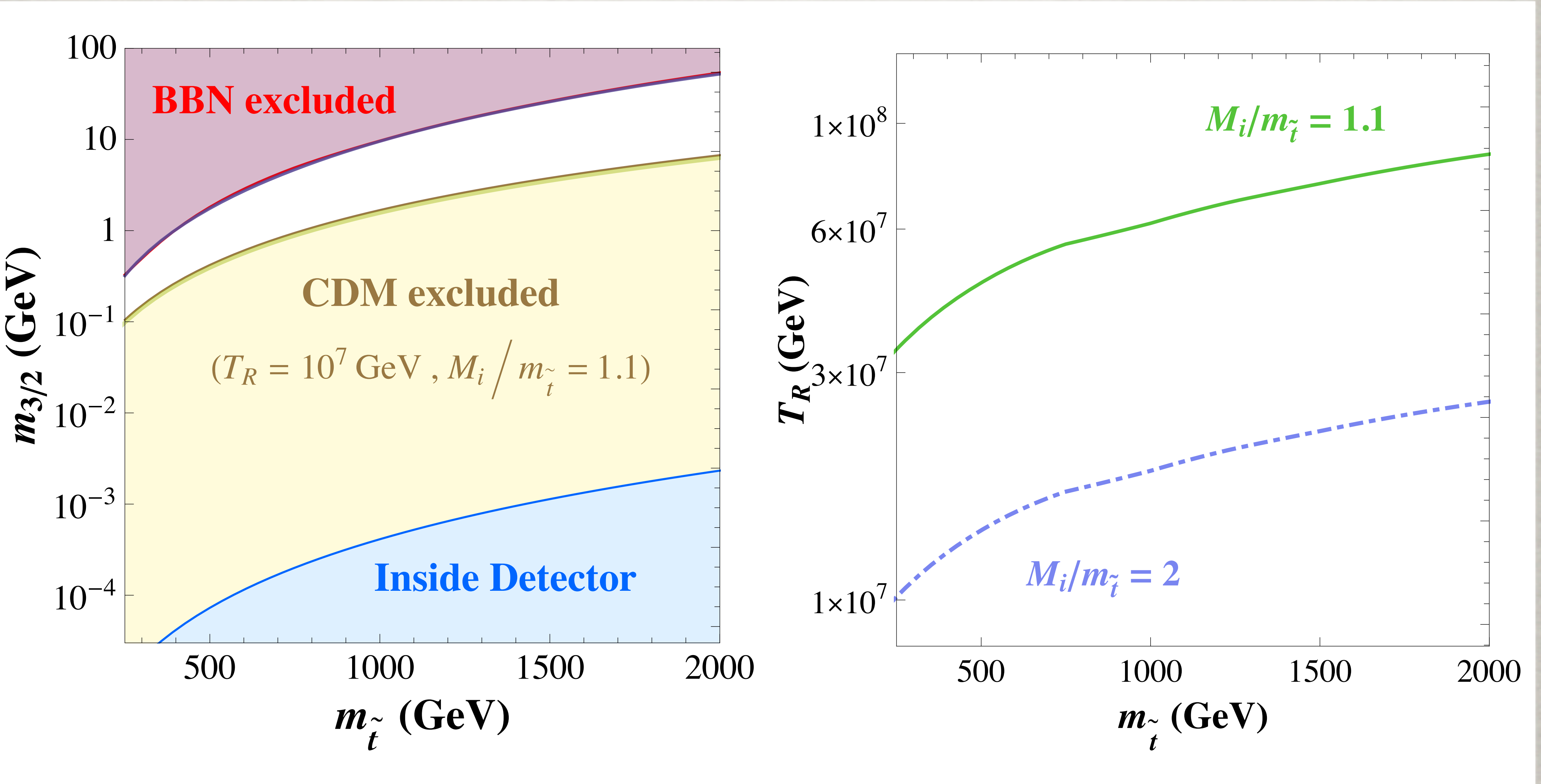


Only short lifetime for colored NLSP allowed:

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

STOP NLSP & BBN

[LC & F. Dradi 1403.4923]



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

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:

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

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For the NLSP to decay before BBN

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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.

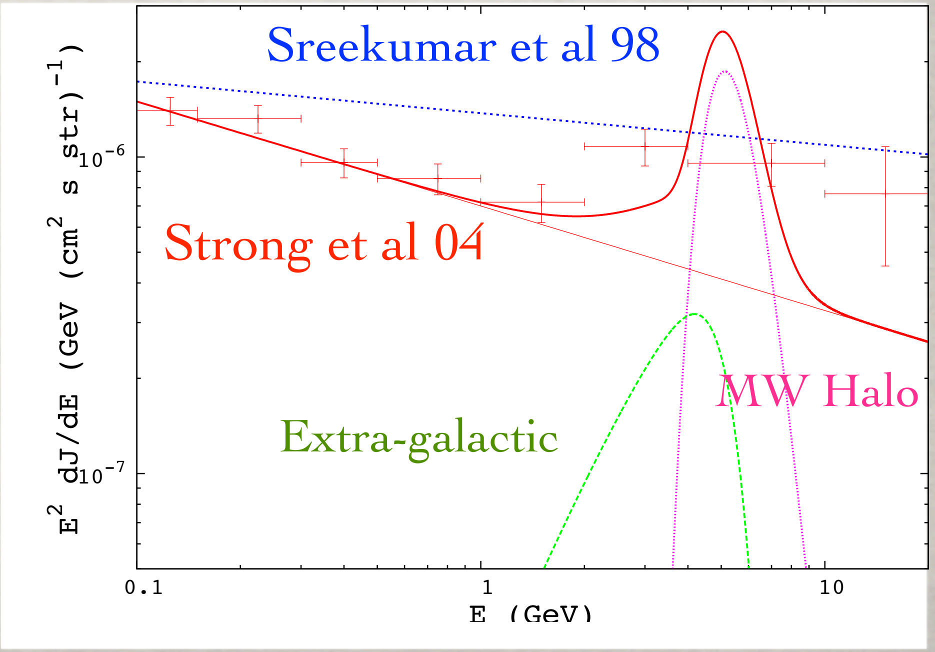
DECAYING DM

- 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...

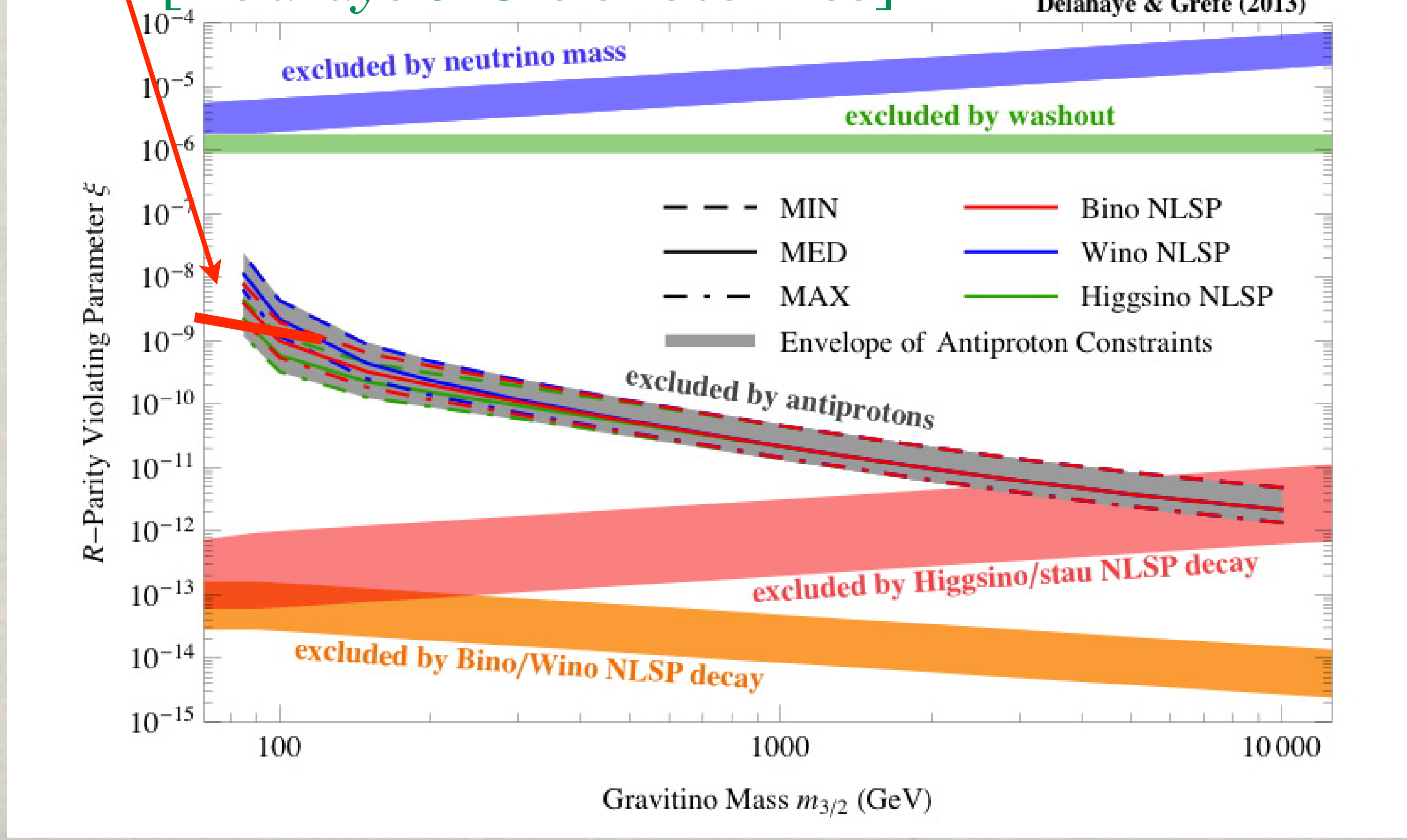


Antiproton constraints

Very important for future the AMS-02 expected antiproton data !
E.g. see a new analysis of the antiproton constraints for decaying gravitino DM limiting the R-parity breaking coupling.

From the FERMI gamma-line search: $\tau < 1 - 4 \times 10^{29} s \quad 95\%$ CL

[Delahaye & Grefe 1305.7183]



STOP NLSPs WITH R_P

[LC & F. Dradi 1403.4923]

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

$$\tilde{t}_1 \to b\, \ell_i$$

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 1403.4923]

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

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

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

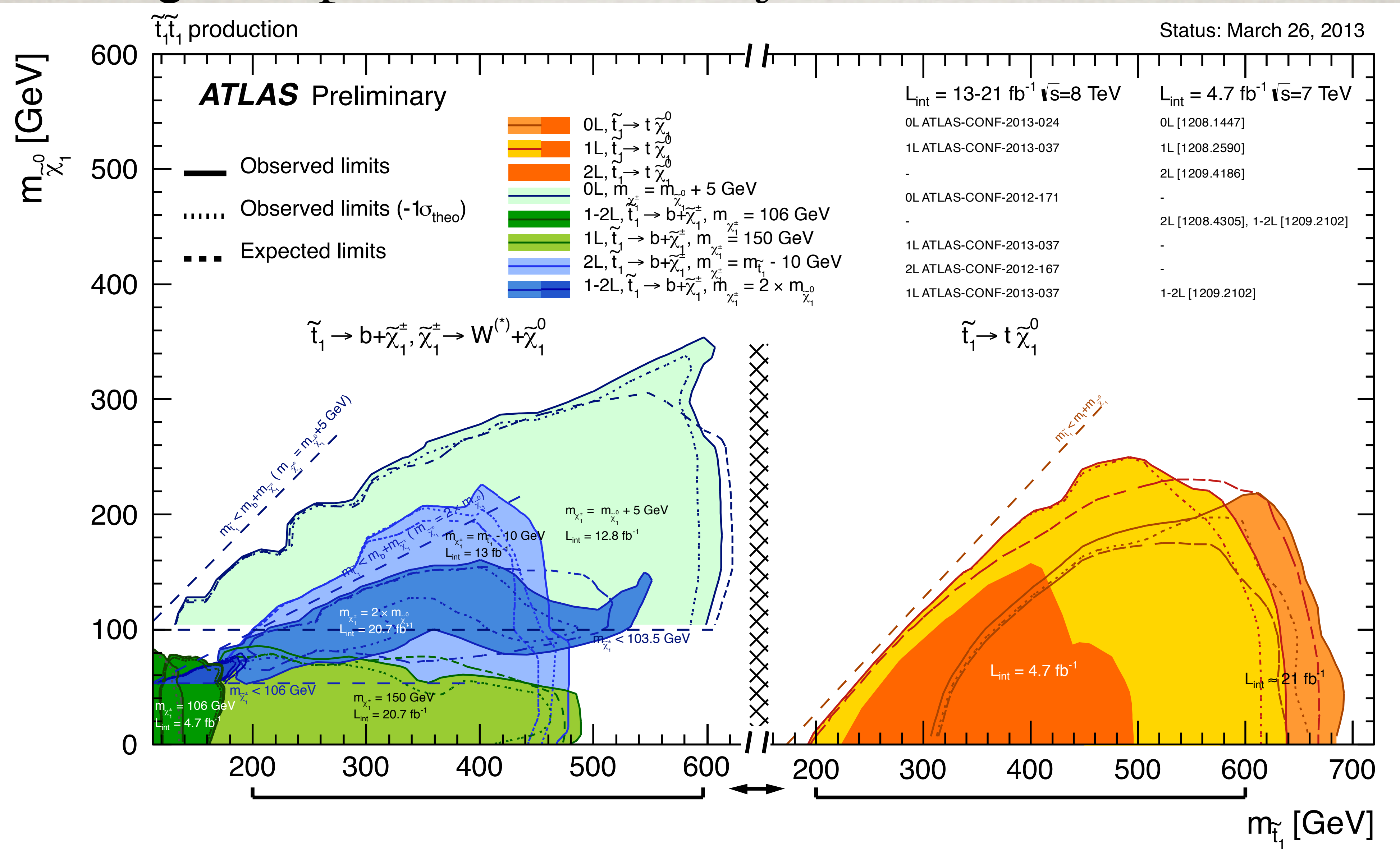
RPV: $\tilde{t}_1 \to b\,\ell^+$

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

The usual searches looking for prompt decay do not apply !

LHC: STOP ?

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

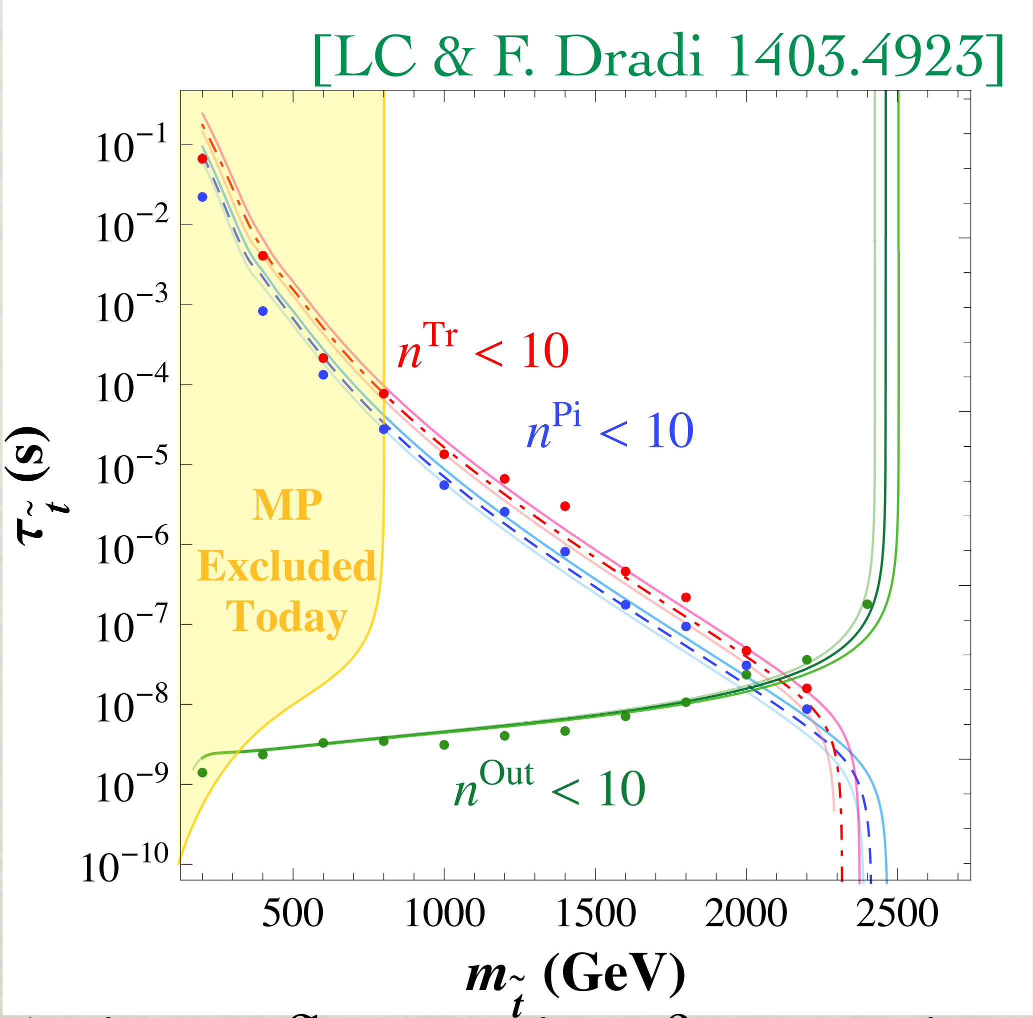


... but in different channels !

LHC: LONG-LIVED 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:

LHC reach for L= 3000 fb^-1

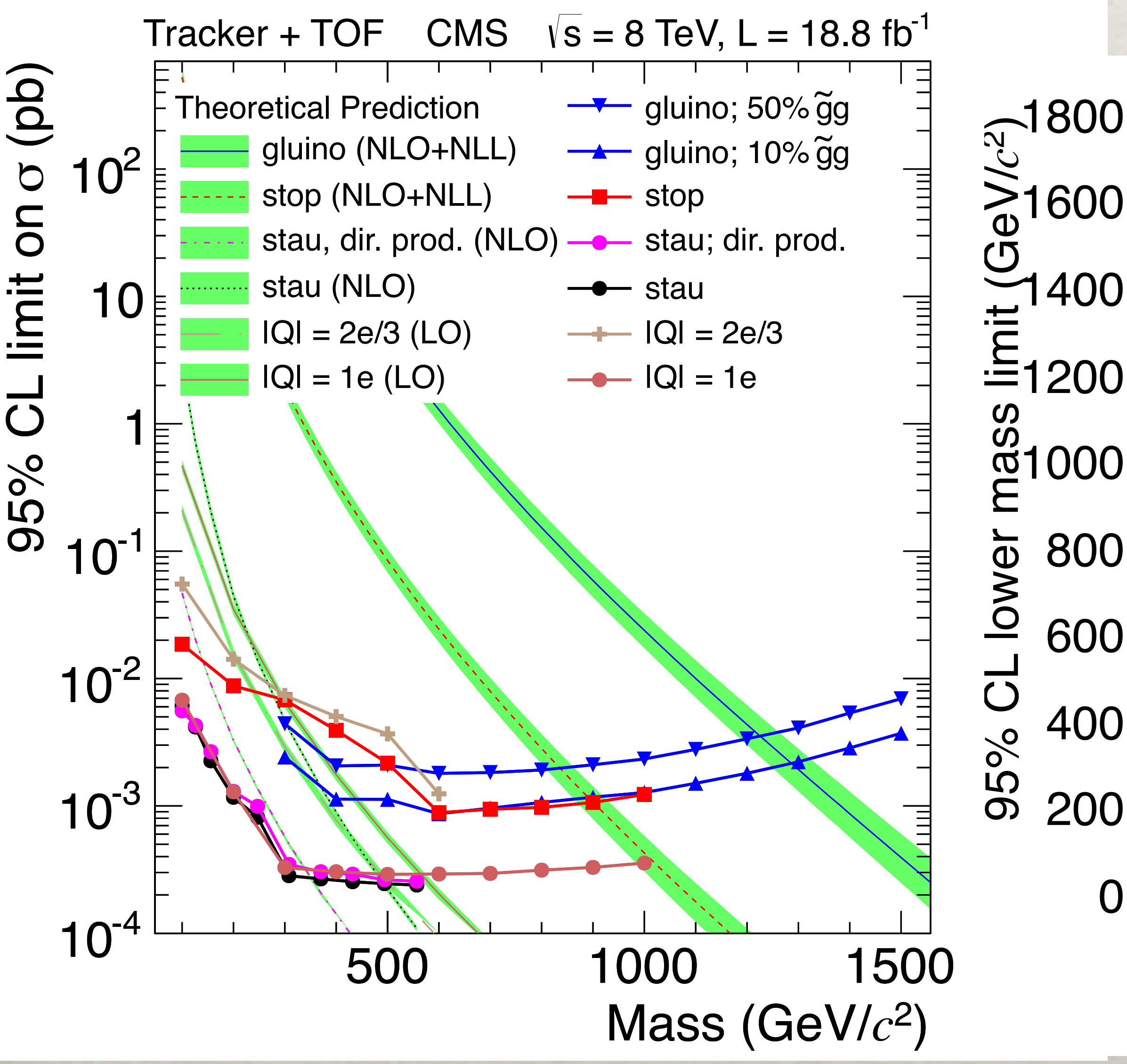


Band is the +/- 1 sigma fluctuation for a Poisson distribution..

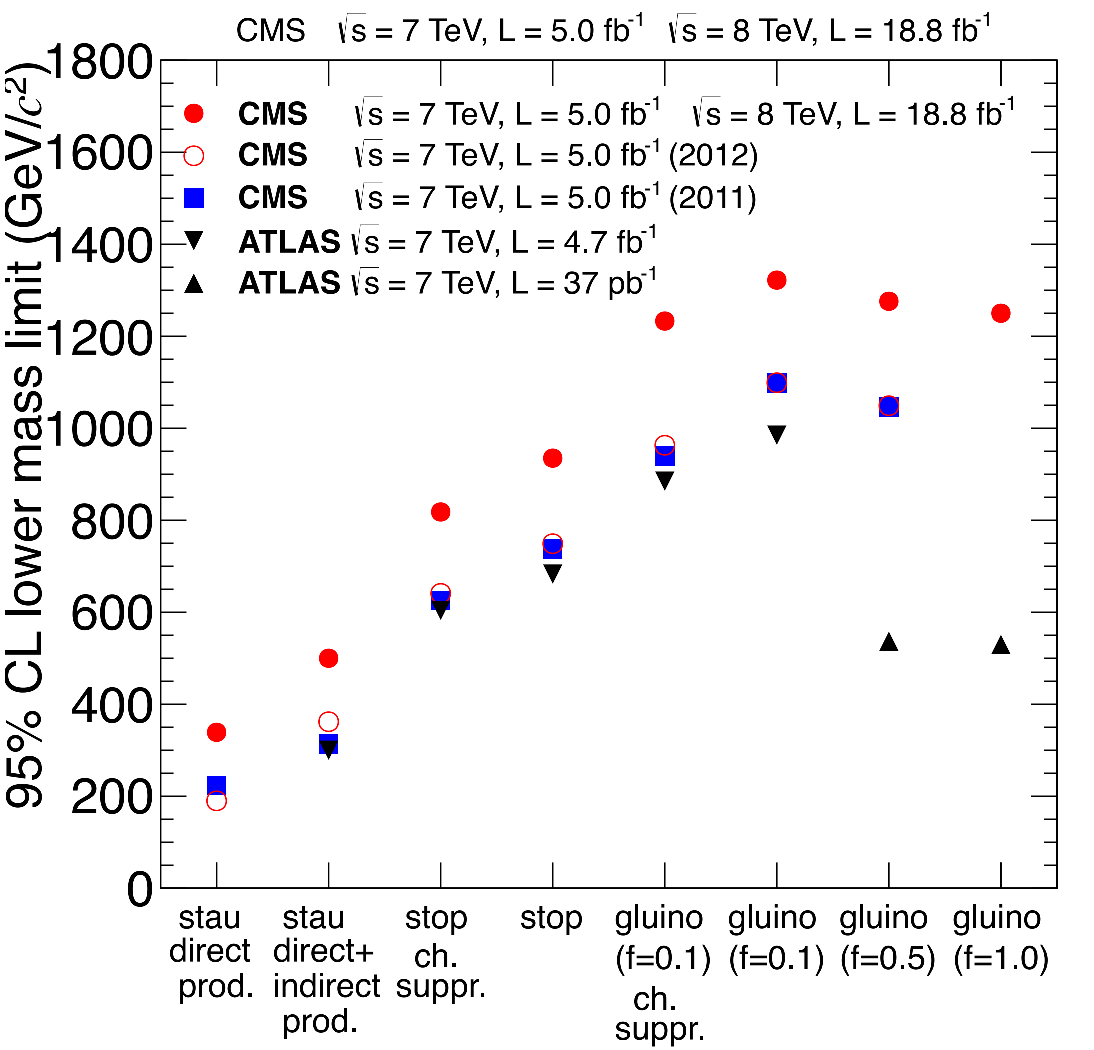
LHC: METASTABLE PARTICLES

Recent results from CMS for metastable SUSY particles:

at the moment no significant excess found....

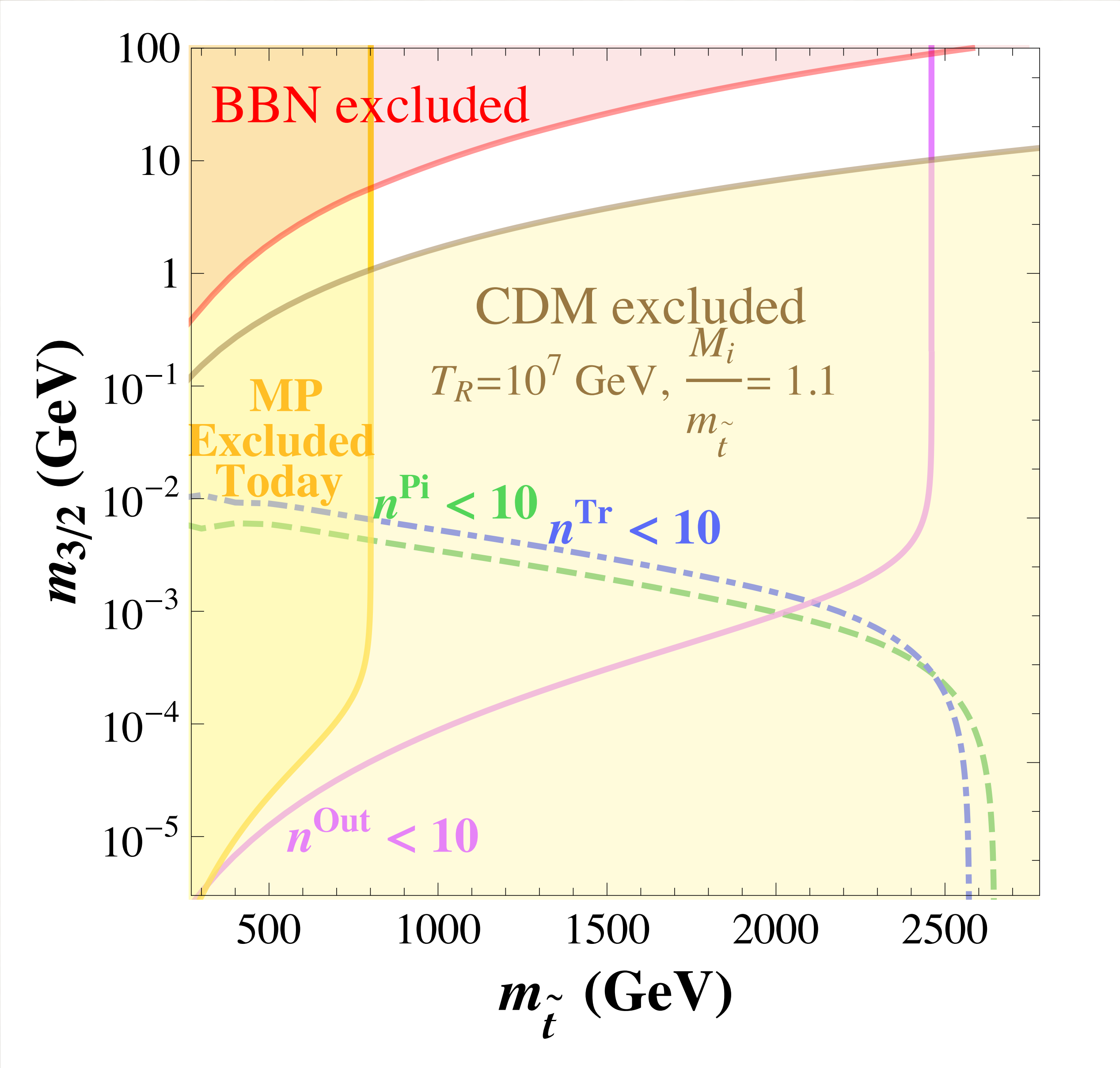


[CMS-EXO-12026]



LHC: STOP ?

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



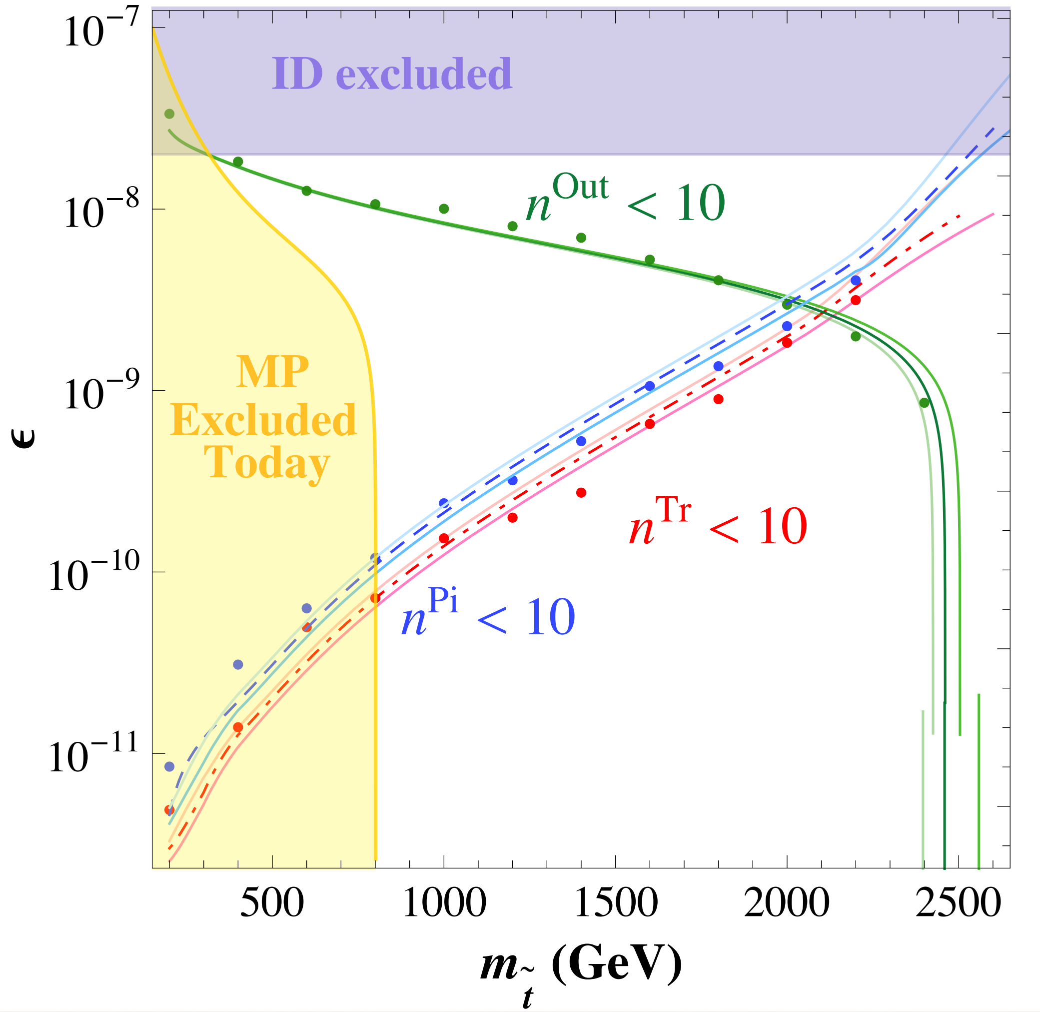
[LC & F. Dradi 1403.4923]

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

LHC: STOP ?

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

[LC & F. Dradi 1403.4923]

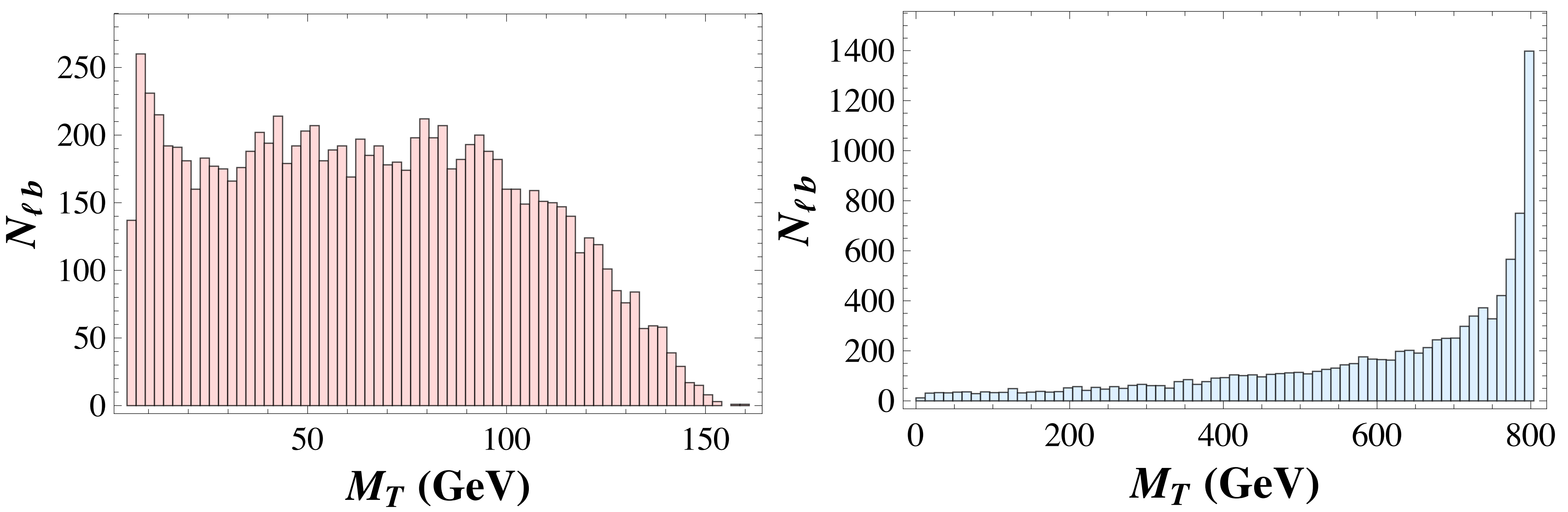


LHC can cover regions beyond Indirect Detection !

LHC: which channel?

If the stop decays inside the detector, the momentum distributions allow to distinguish RPC and RPV decays...

[LC & F. Dradi 1403.4923]



It should be easy to disentangle 2-body from 4-body decay !

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 another attractive candidate is FIMP/SuperWIMP DM !
- The FIMP/SuperWIMP framework is more general and could point to heavy metastable charged particles at LHC with different lifetimes & decay channels ! Work in progress: realisations of the scenarios and discovery reach at LHC.
- Gravitinos can survive as DM also for broken R-parity, but then indirect DM searches set limits on the parameters. LHC can cover most of such parameter space by combining displaced vertices and metastable states searches !