10th Patras Workshop on Axions, WIMPs and WISPs
CERN, 1st July 2014

From WIMPs to FIMPs/SuperWIMPs

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

in collaboration with Giorgio Arcadi & Federico Dradi

invisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Outline

- Introduction:
  From WIMPs to FIMPs/SuperWIMPs
- Gravitino CDM with stop NLSP — with F. Dradi
- A minimal WIMP/FIMP/SuperWIMP DM scenario at the LHC — with G. Arcadi, G. Arcadi/F. Dradi
- Outlook

From WIMPs to FIMPS & SuperWIMPs

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

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

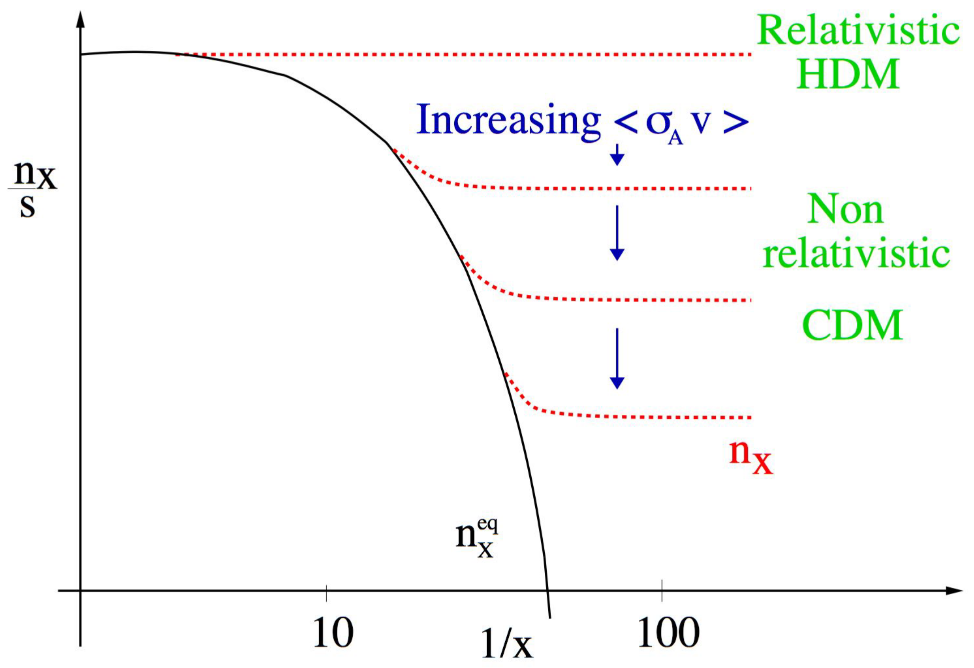
Hubble expansion   Collision integral

The particles stay in thermal equilibrium until the interactions are fast enough, then they freeze-out at $x_f = m_X/T_f$

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

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

Abundance $\Leftrightarrow$ Particle properties



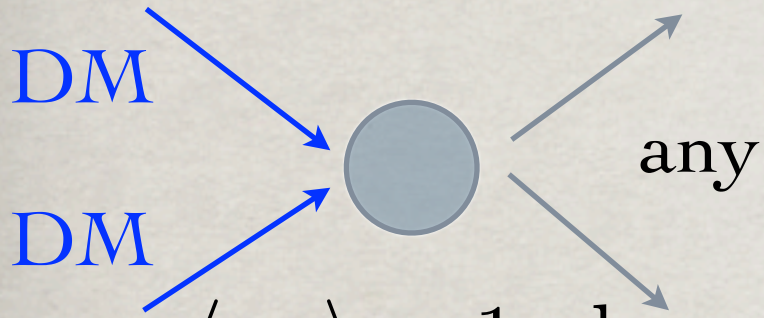
For $m_X \simeq 100$ GeV a WEAK cross-section is needed !

Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

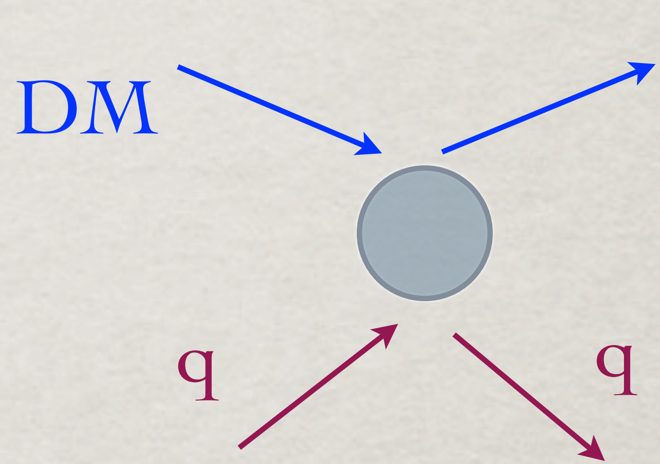
THE WIMP CONNECTION

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



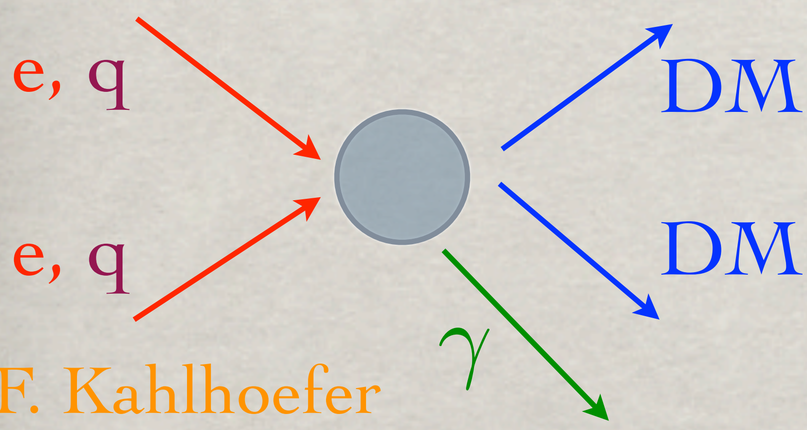
$\langle \sigma v \rangle \sim 1 \text{ pb}$

Direct Detection:



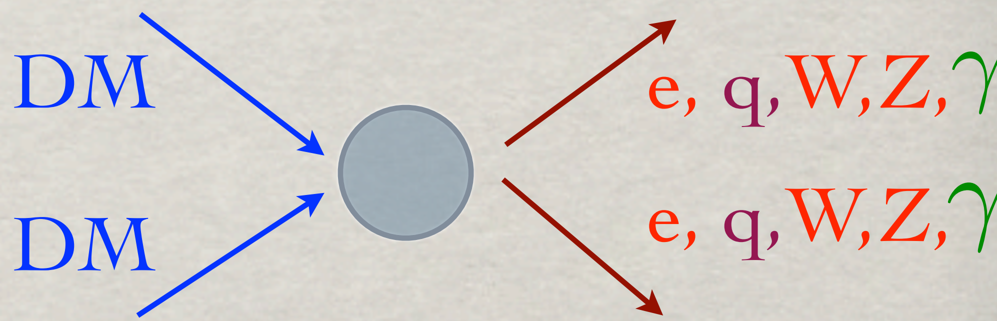
P. Gondolo
Edelweiss,
LUX, Xenon
SuperCDMS

Colliders: LHC/ILC



F. Kahlhoefer

Indirect Detection:



G. Zaharjas

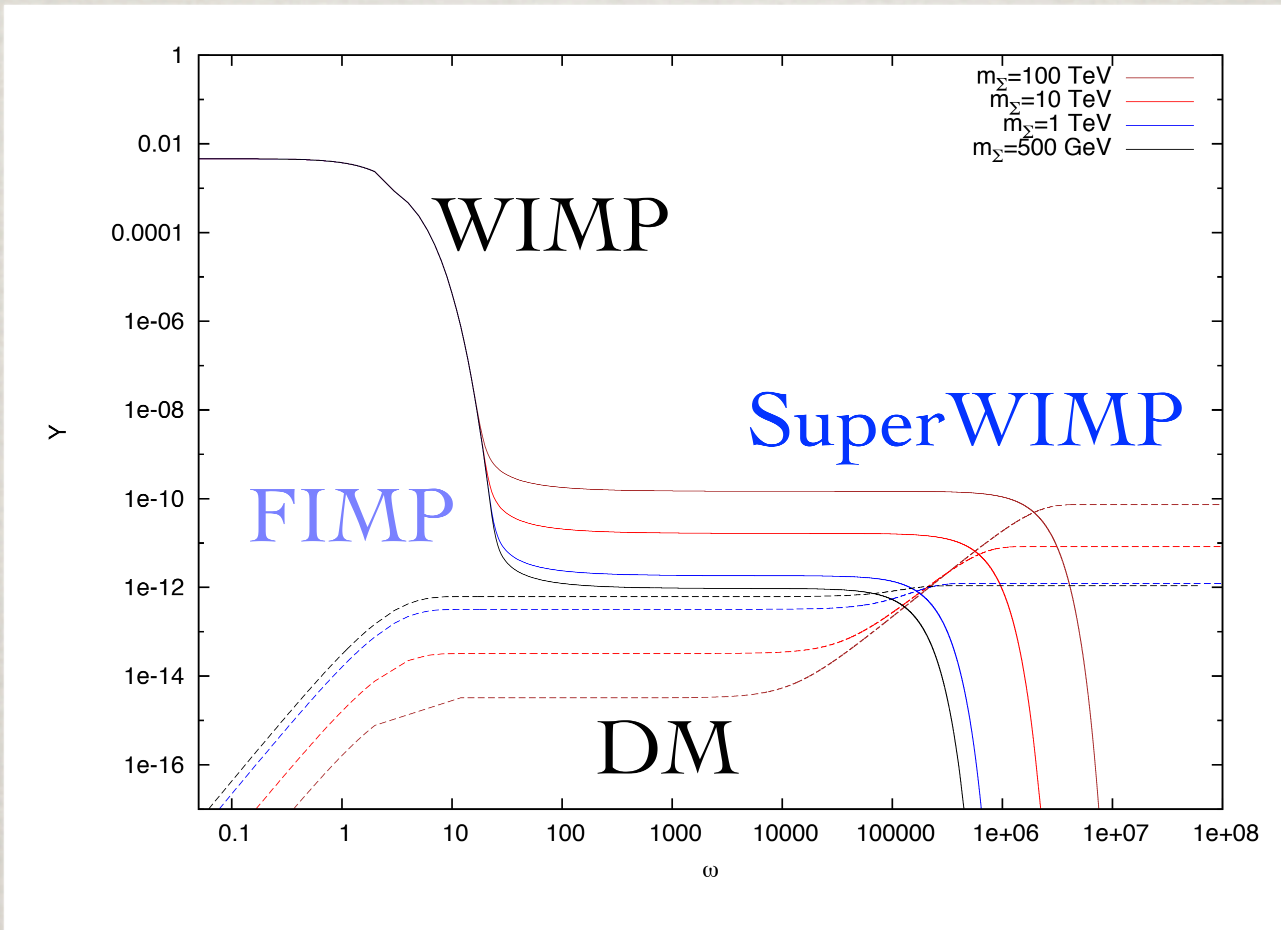
3 different ways to check this hypothesis !!!

SuperWIMP/FIMP paradigms

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

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



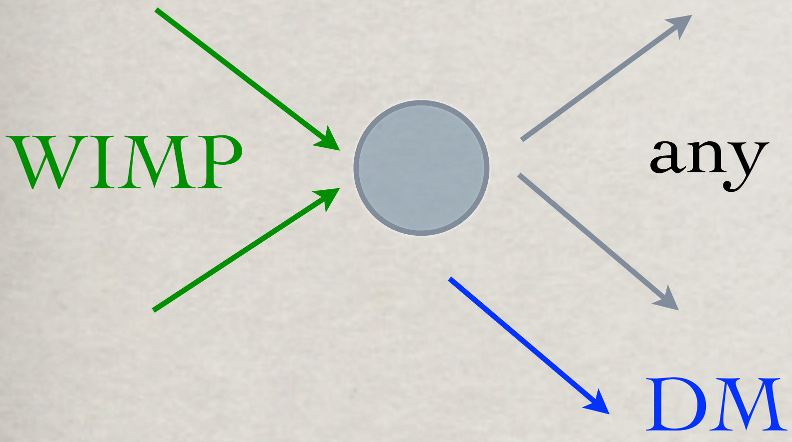
[Feng et al 04]

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

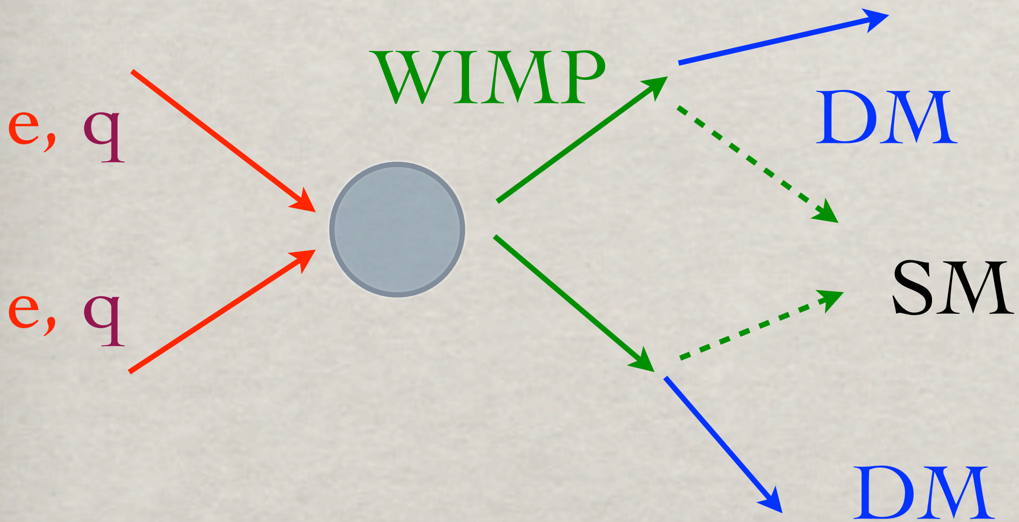
Early Universe: $\Omega_{CDM} h^2$



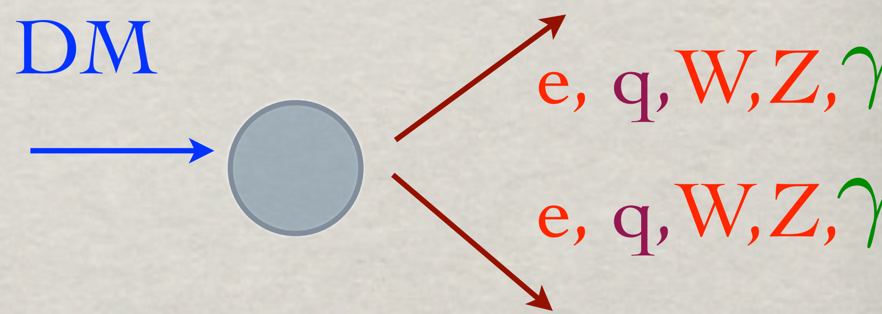
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

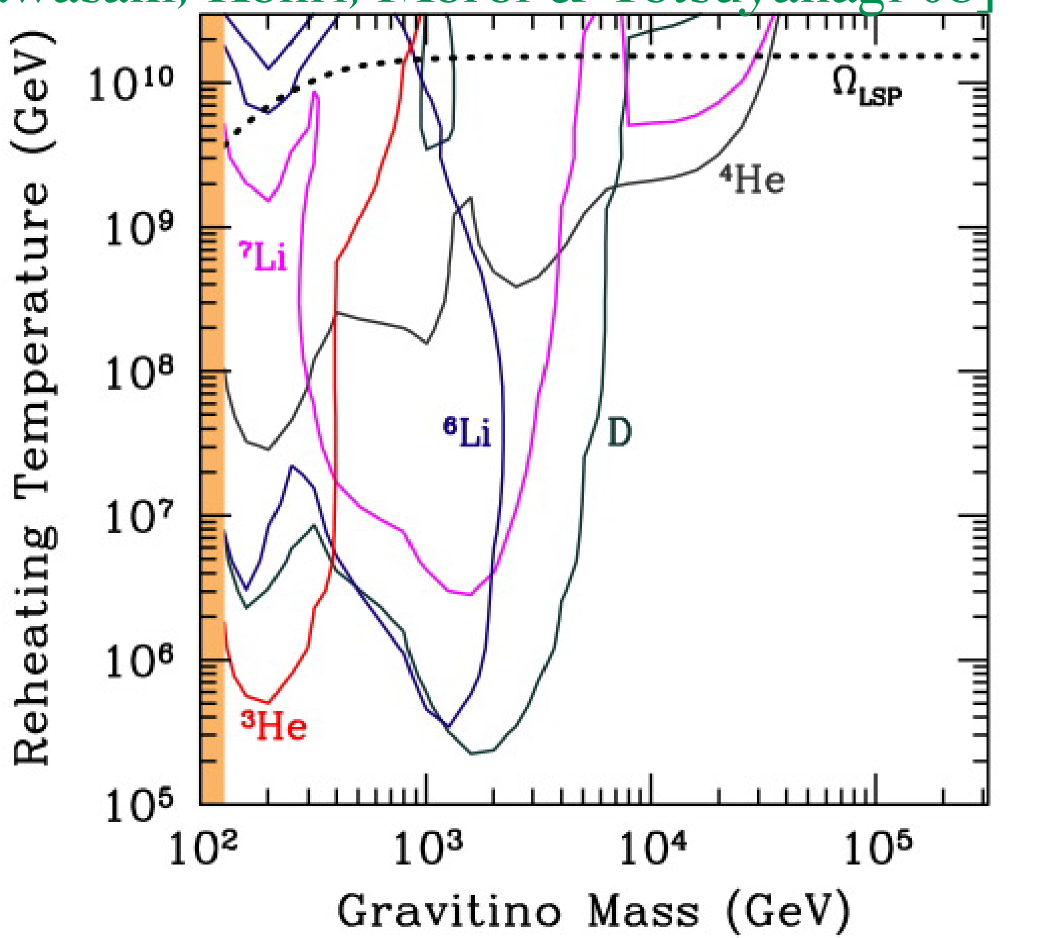
SuperWIMPs/FIMPs

- Typical SuperWIMPs are axino & gravitino, Majorana fermions with spin 1/2 & 3/2. Typical FIMP is a RH sneutrino or some scalar modulus. In some cases similar to sterile neutrino... A. Boyarsky
- 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.

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 small! Indeed due to non-renormalizable coupling

$$\Omega_{3/2} \propto T_R \, M_i^2 / m_{3/2}$$

Gravitino DM with stop NLSP

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

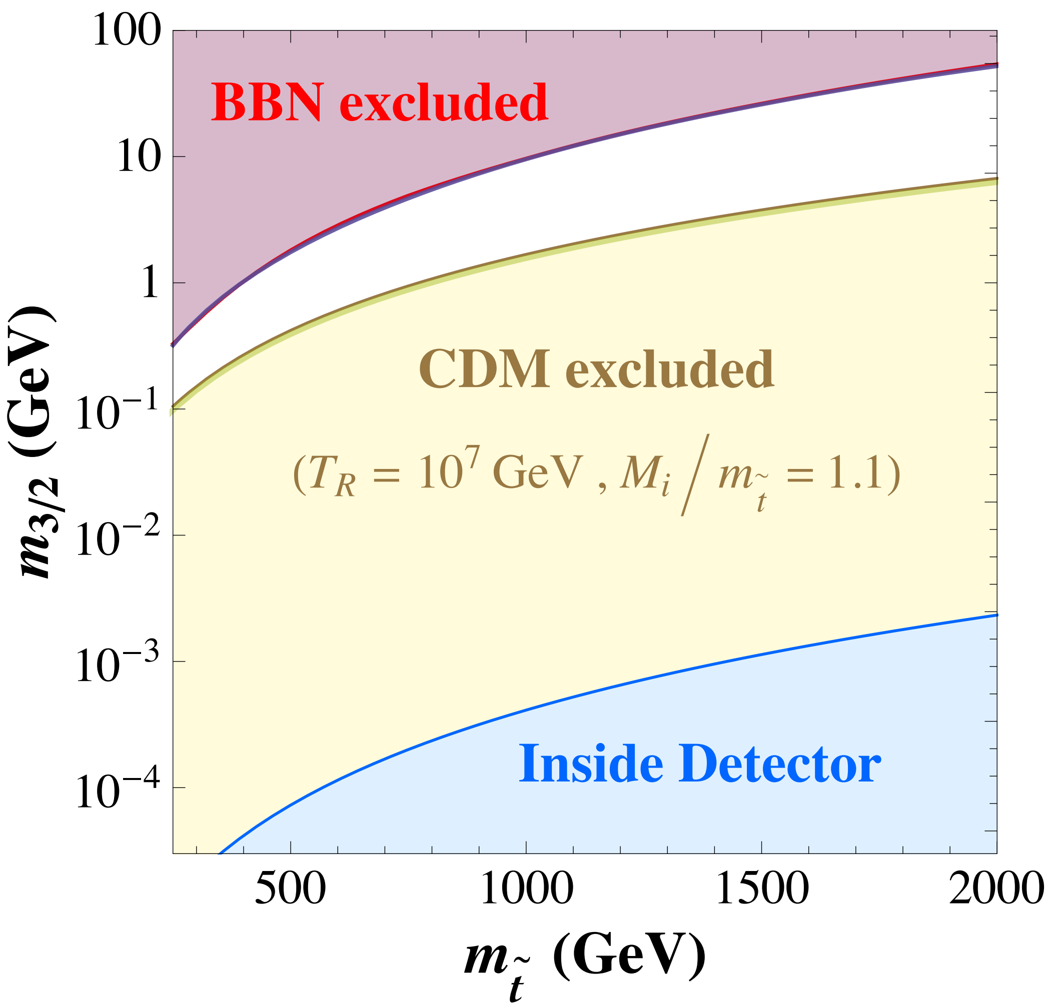
→ stop NLSP scenario

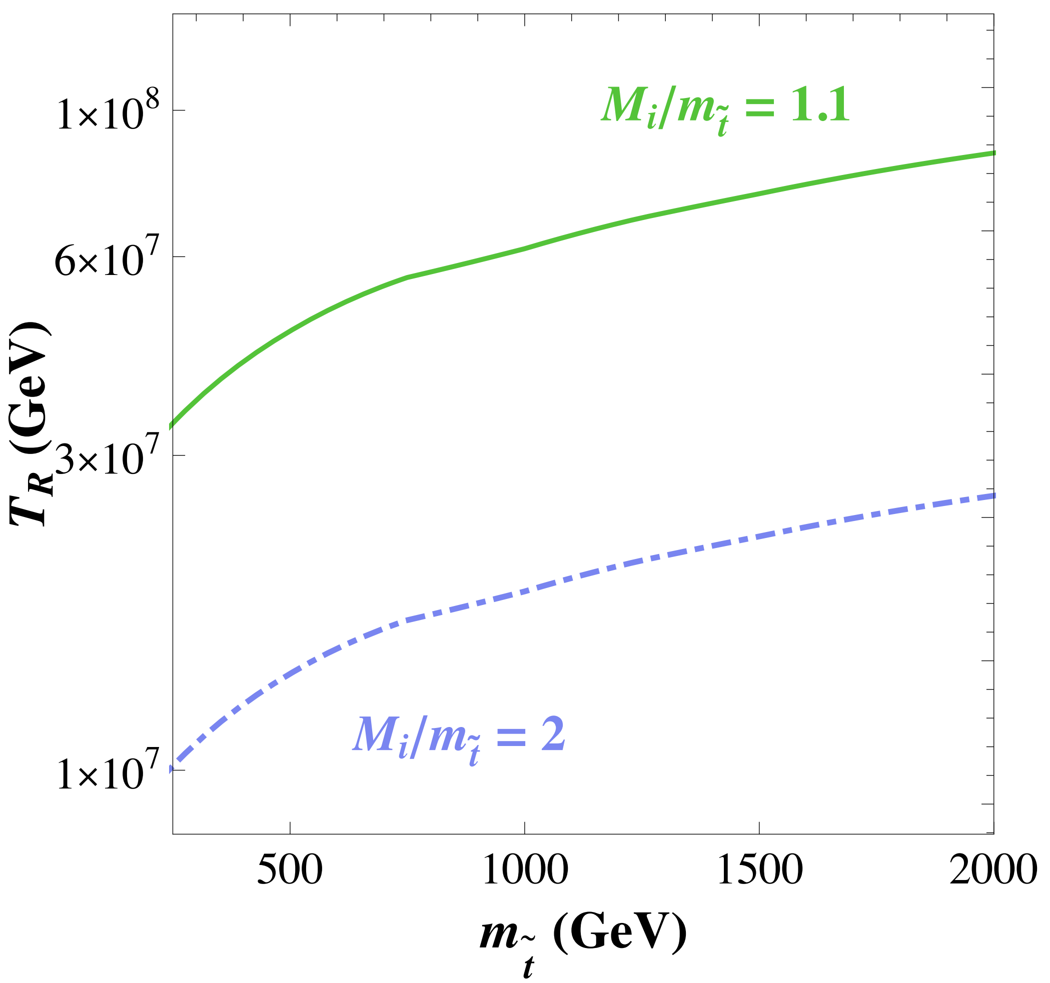
[LC & Federico Dradi 1403.4923]

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 weaker...

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.

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

no p decay

Open window:

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

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

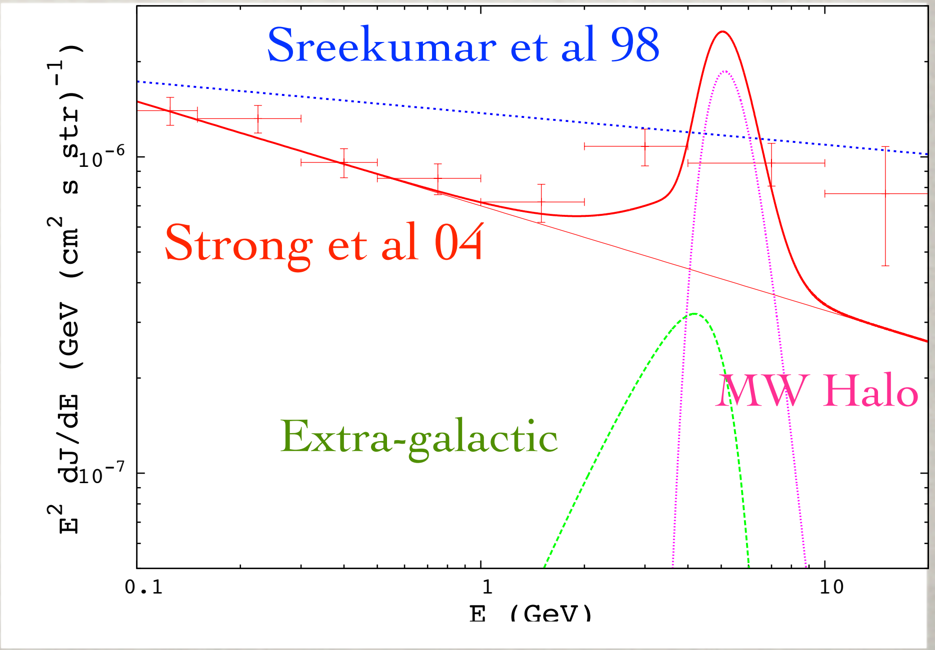
G. Zaharjas,
A. Boyarsky

- 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...

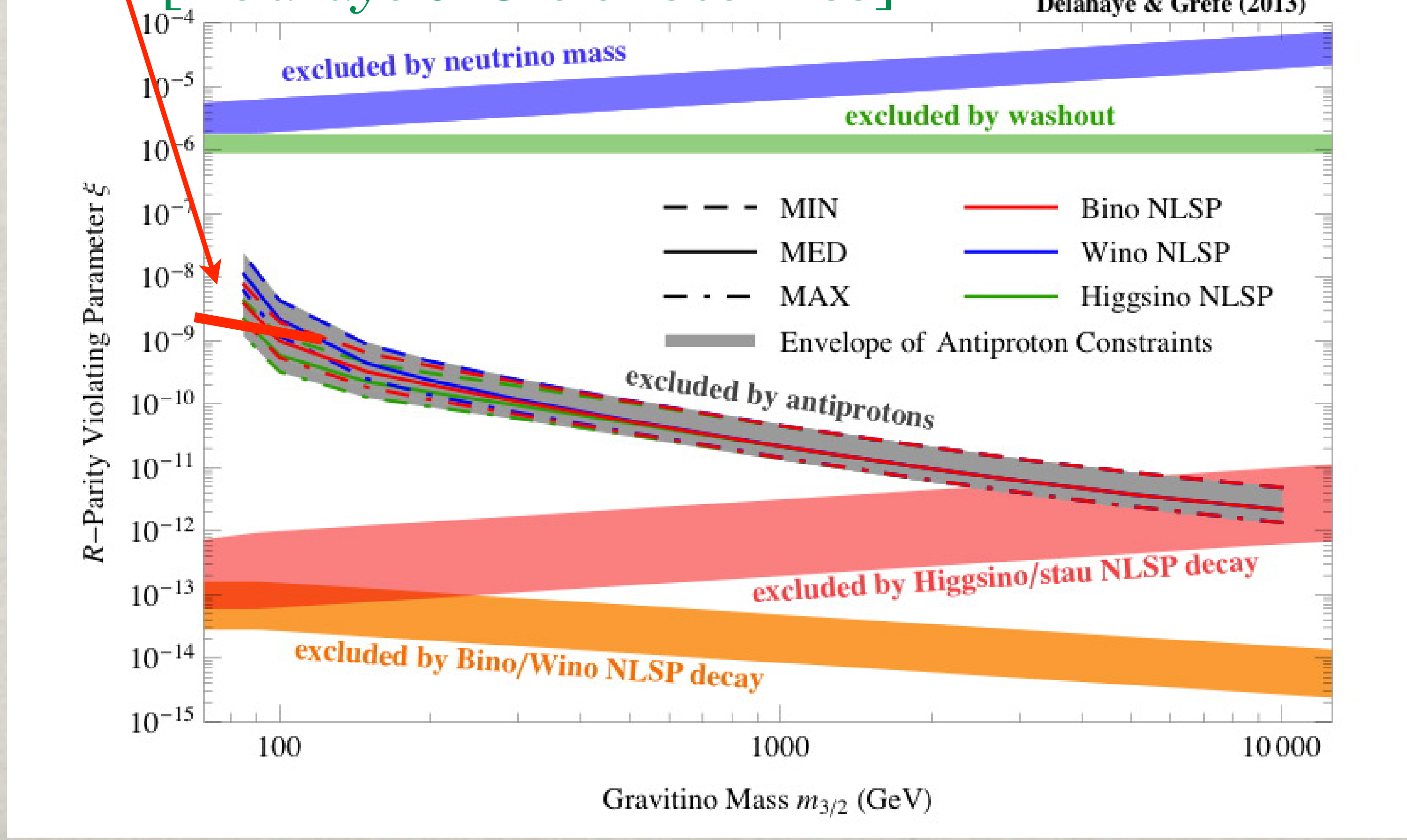


Antiproton constraints

Heavy gravitinos decay into RPV channel in EW gauge boson and lepton, producing gamma-rays and antiprotons. The antiproton constraints already limit strongly the R-parity breaking coupling.

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

[Delahaye & Grefe 1305.7183]



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

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

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

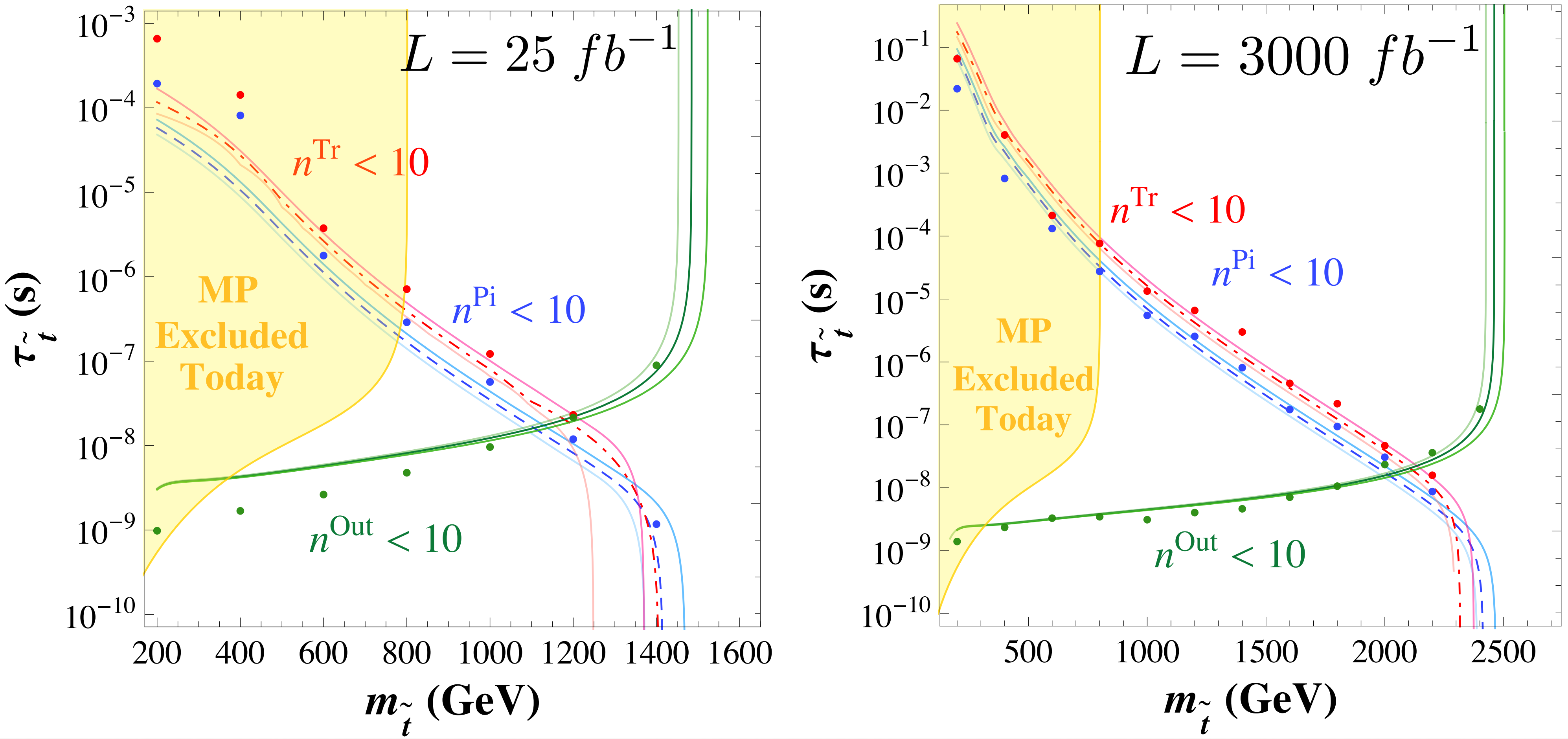
$$\tau_{\tilde{t}_1} \sim 10^{-4} \text{ s} \left(\frac{m_{\tilde{t}_1}}{500\text{GeV}} \right)^{-1} \left(\frac{\epsilon \sin\theta_{\tilde{t}}}{10^{-9}} \right)^{-2}$$

The usual searches looking for prompt decay do not apply !

LHC: 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:

[LC & F. Dradi 1403.4923]

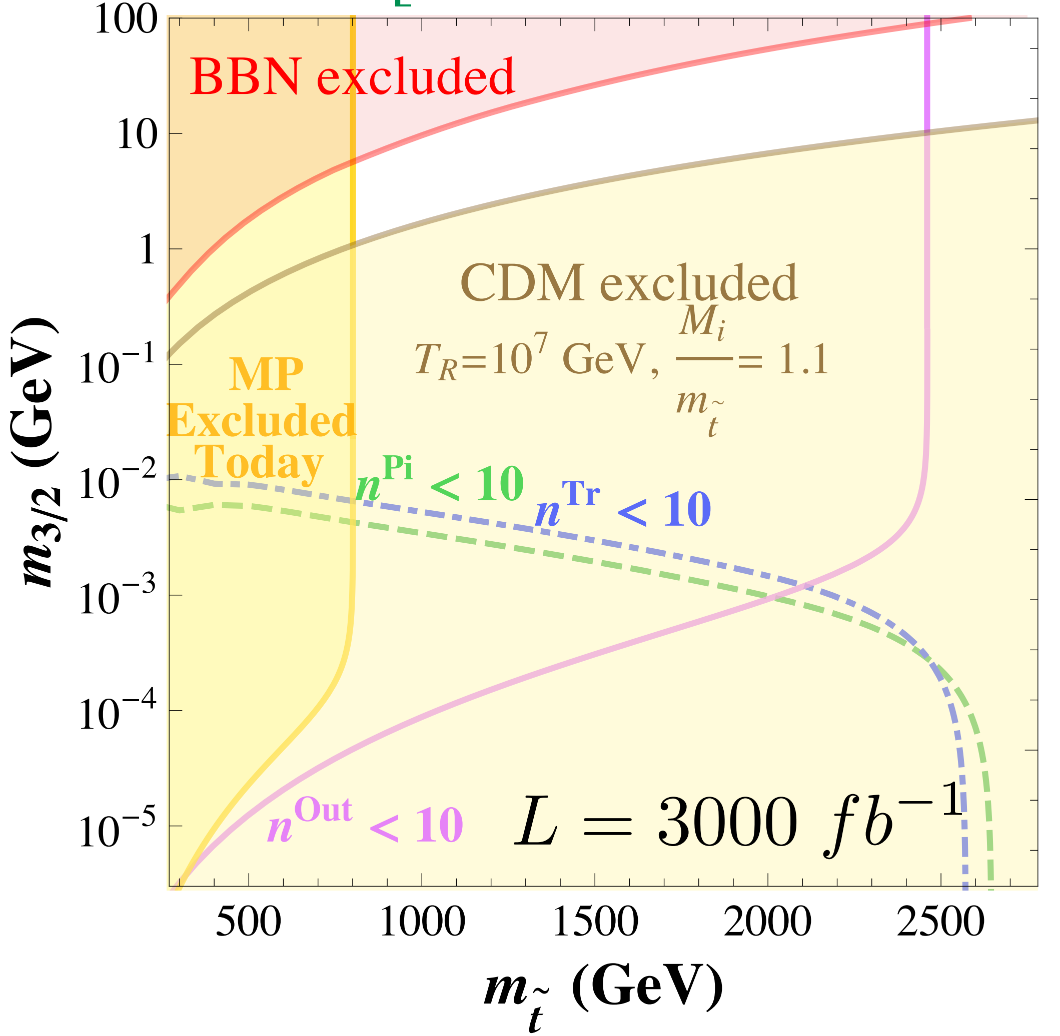


Band is the +/- 1 sigma fluctuation for a Poisson distribution..

LHC: STOP ?

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

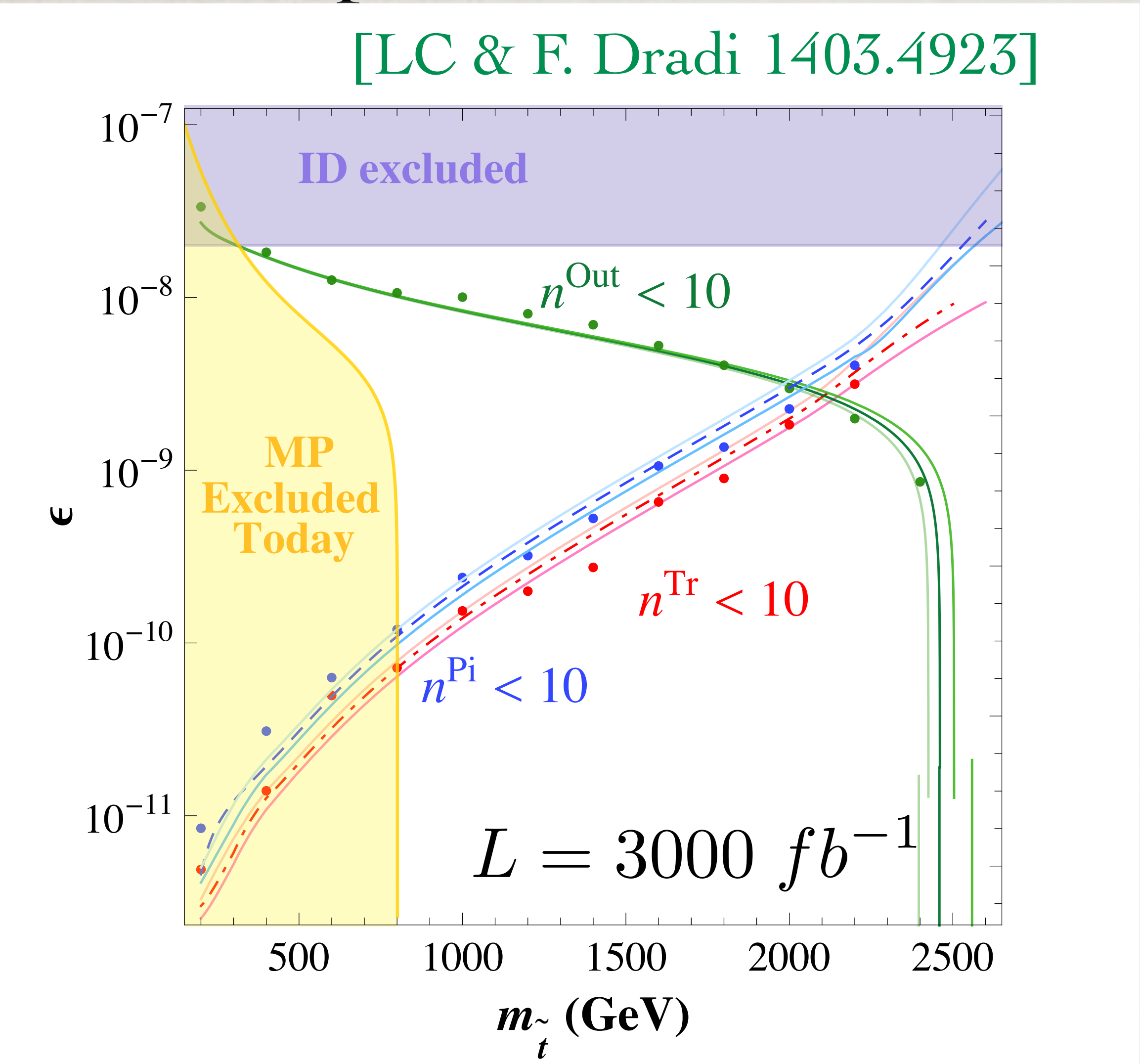
[LC & F. Dradi 1403.4923]



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...



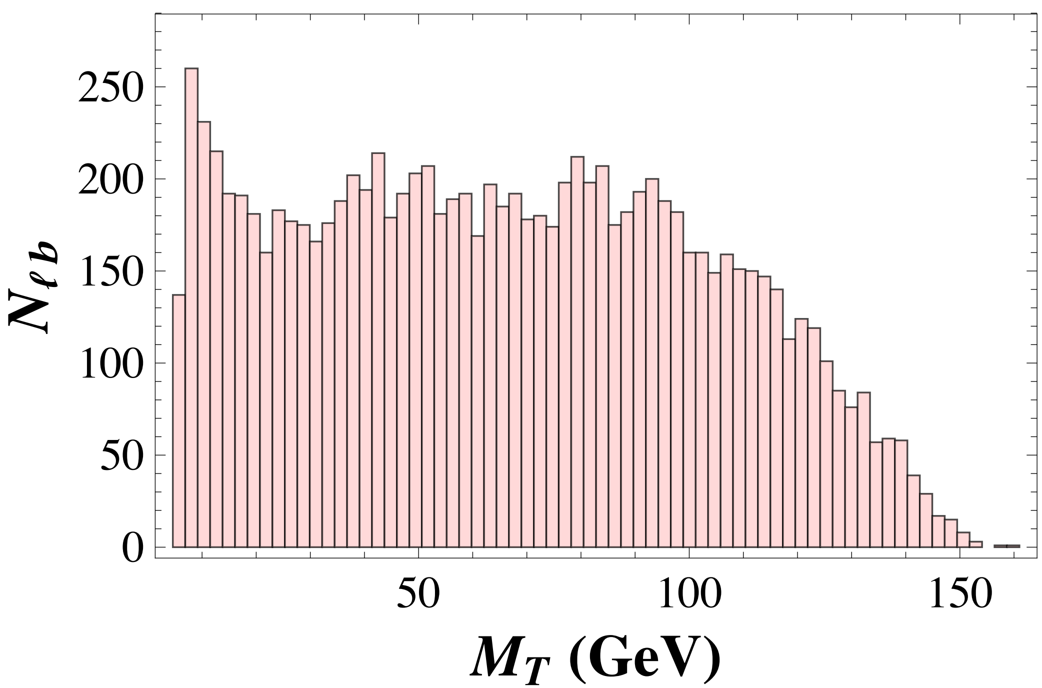
Possibility of displaced vertices is still open ! Using both measurement possible to cover all parameter space up to stop mass of ~ 2 TeV

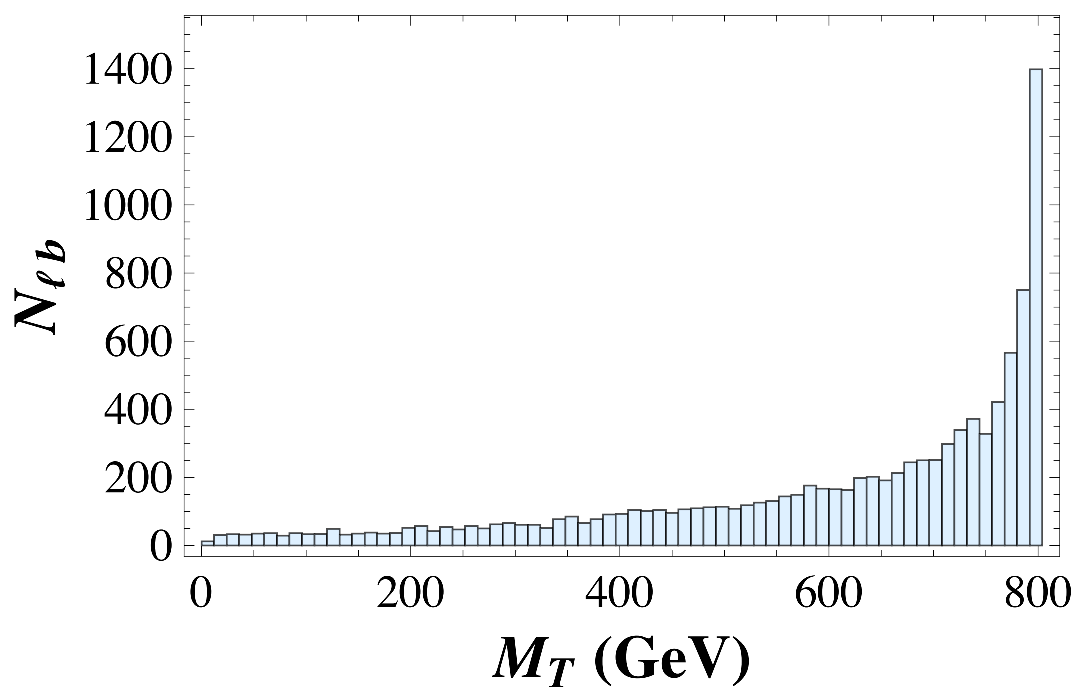
LHC can cover regions beyond Indirect Detection !

LHC: WHICH STOP DECAY ?

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 !

A minimal FIMP/SuperWIMP scenario

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 :

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

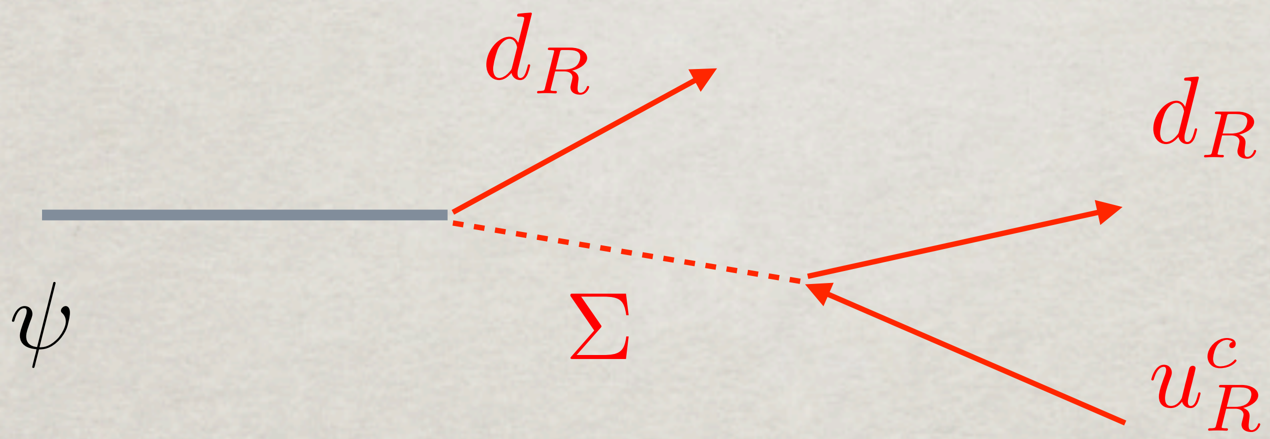
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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

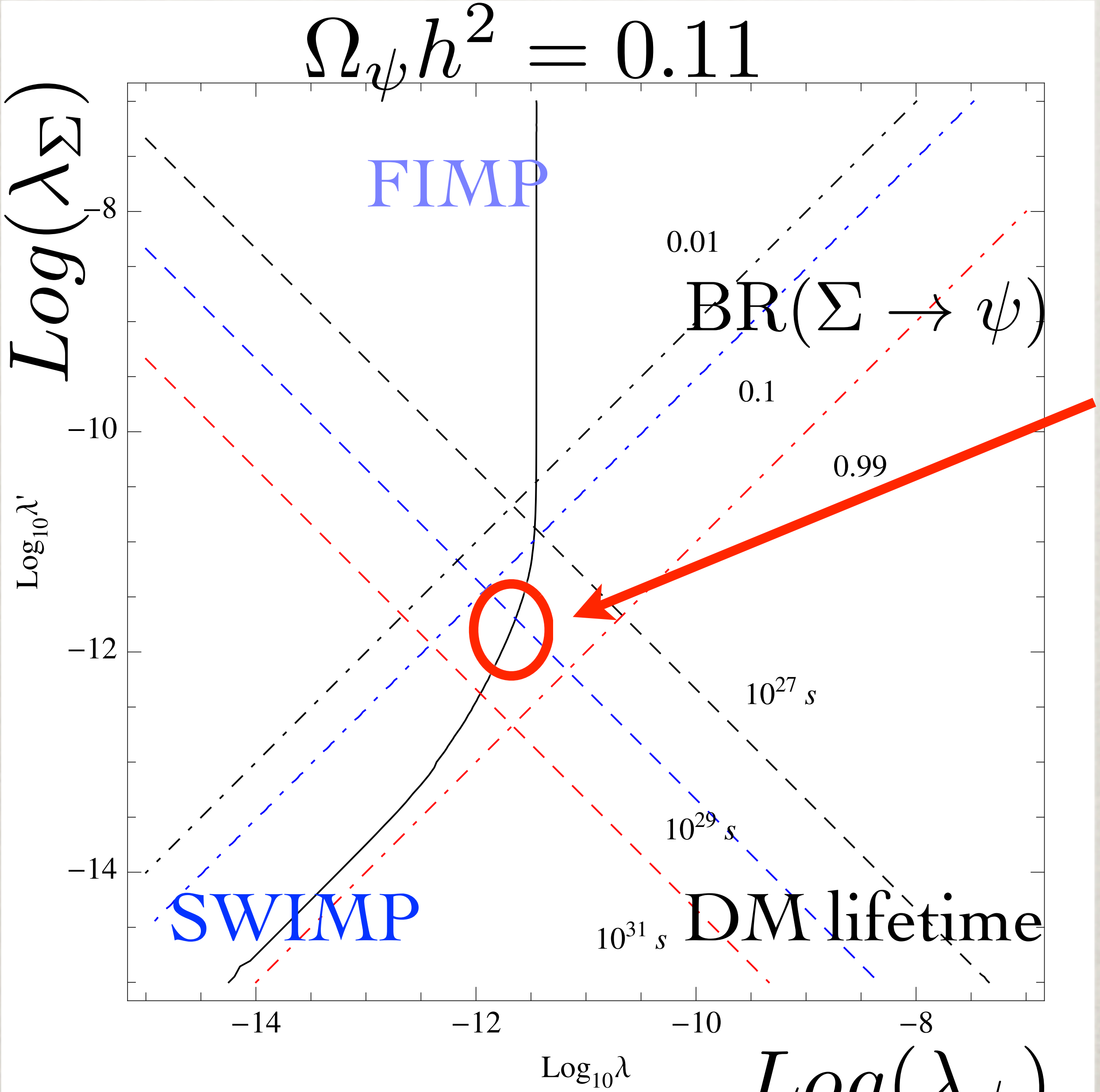
$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \, \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

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. $x = \frac{m_{DM}}{m_{\Sigma_f}} \ll 1$

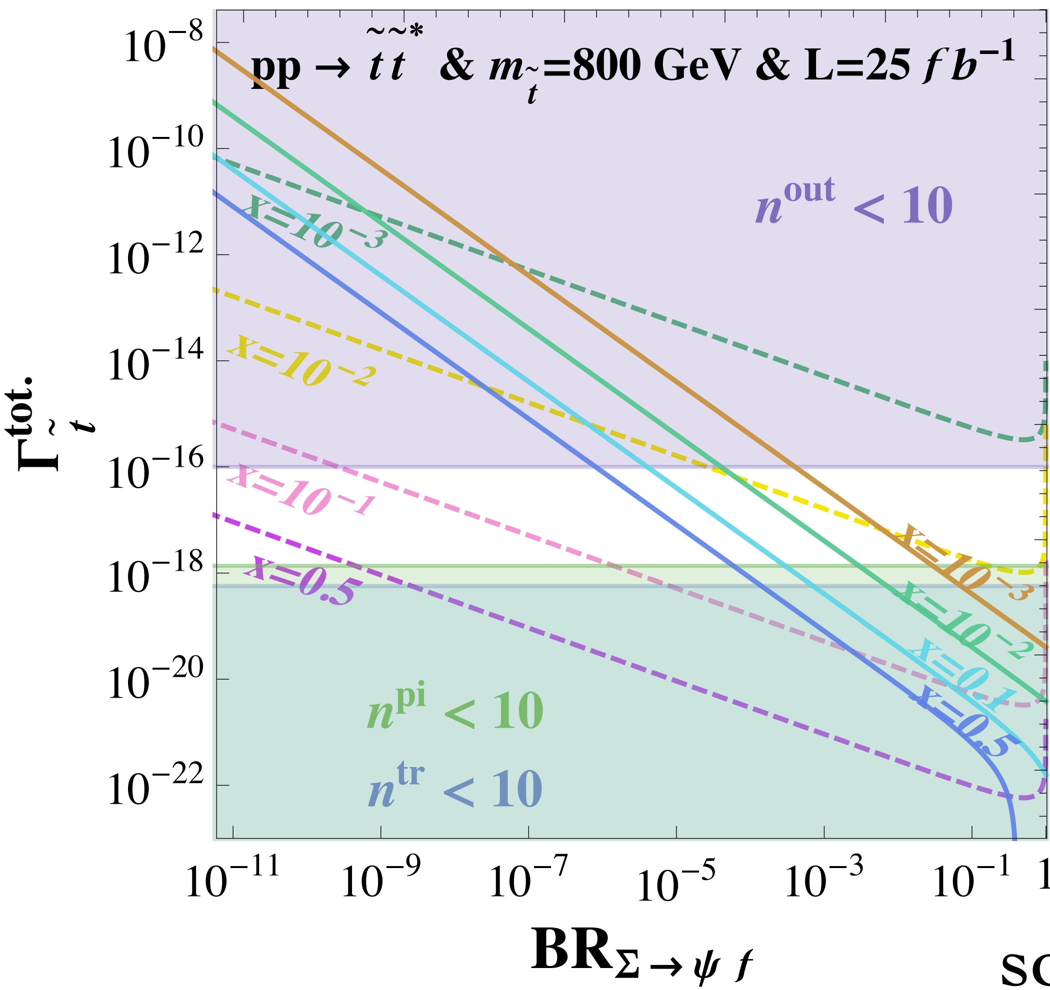
Moreover imposing ID "around the corner" gives

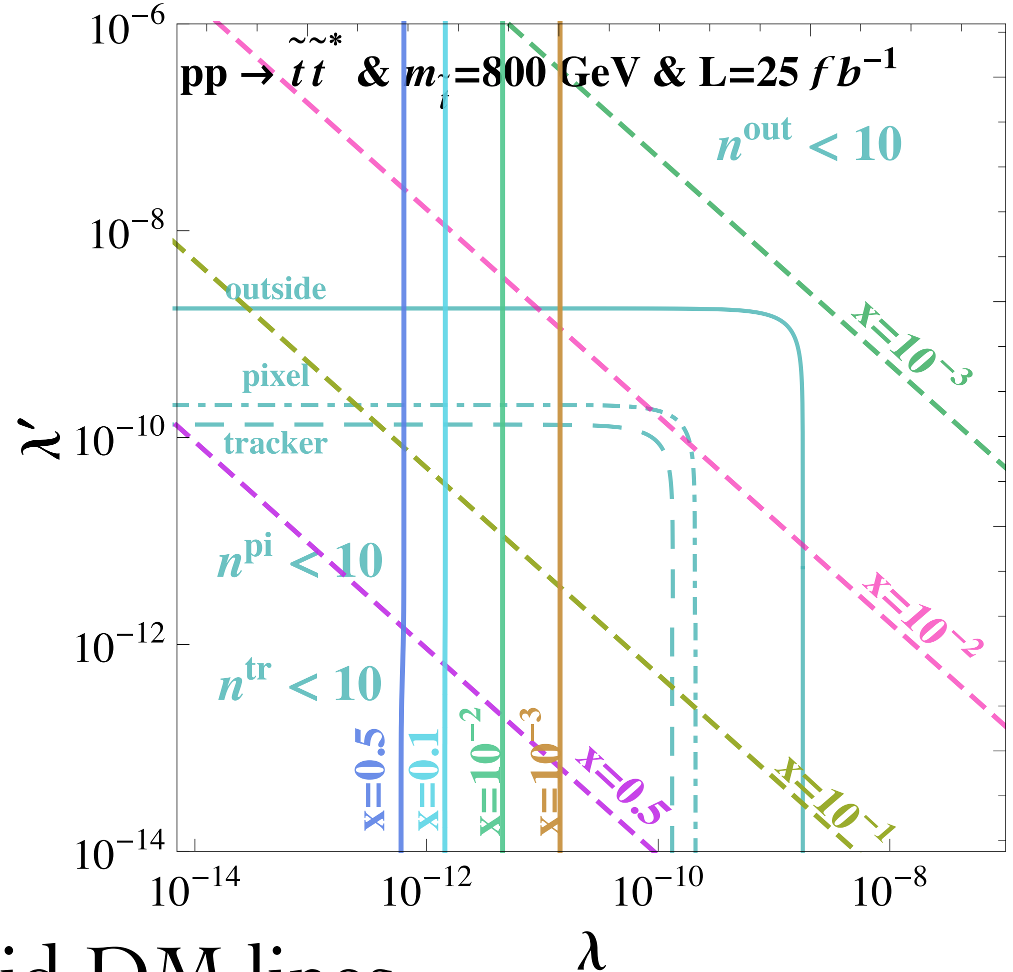
$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\, \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\mathrm{GeV}}\right)^4 \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right) \left(\frac{\Omega_{CDM} h^2}{0.11}\right) \left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

FIMP/SWIMP & COLORED Σ

[G. Arcadi, LC & F. Dradi 1407.xxx]





solid DM lines

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

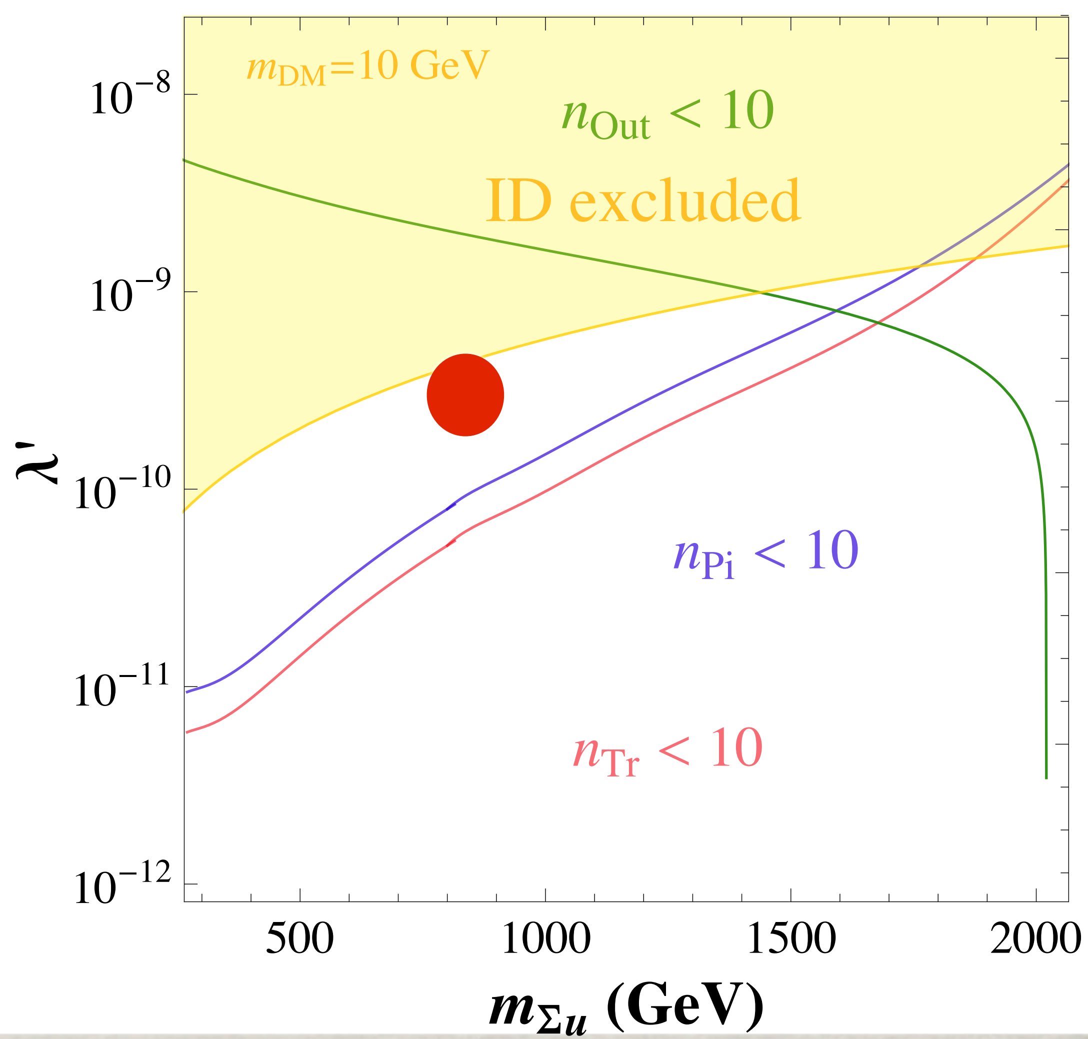
Σ Combined detection

Still possible to have multiple detection of

- DM decay:
  $m_\psi \quad \Gamma_\psi \to \lambda\lambda'$
- displaced vertices
  $m_\Sigma \quad \Gamma_{\Sigma,SM} \to \lambda'$
- metastable tracks
  $m_\Sigma \quad \Gamma_{\Sigma,SM} < X \to \lambda'$

with stopped tracks maybe both $\Gamma_{\Sigma,SM}, \Gamma_{\Sigma,DM}$

[G. Arcadi, LC & F. Dradi 1407.xxxx]



It is possible to overconstrain the model and check the hypothesis of FIMP production !

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 !
- 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 !
- The FIMP/SuperWIMP framework is more general and could point to heavy metastable particles or displaced vertices at LHC with different decay channels ! Work in progress: realisations of the scenarios and discovery reach at LHC.