Workshop Physics Challenges in the face of LHC-14CERN, IFT, Madrid, 15th September 2014

LHC Prospects for minimal decaying DM

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arXiv: 1305.6587, arXiv:1408.1005

Outline

- Introduction:
  From WIMPs to FIMPs/SuperWIMPs
- A minimal decaying DM scenario:
  FIMP/SuperWIMP DM — with G. Arcadi
- Prospects at the LHC — with G. Arcadi & F. Dradi
- Outlook

From WIMPs to FIMPs & SuperWIMPs

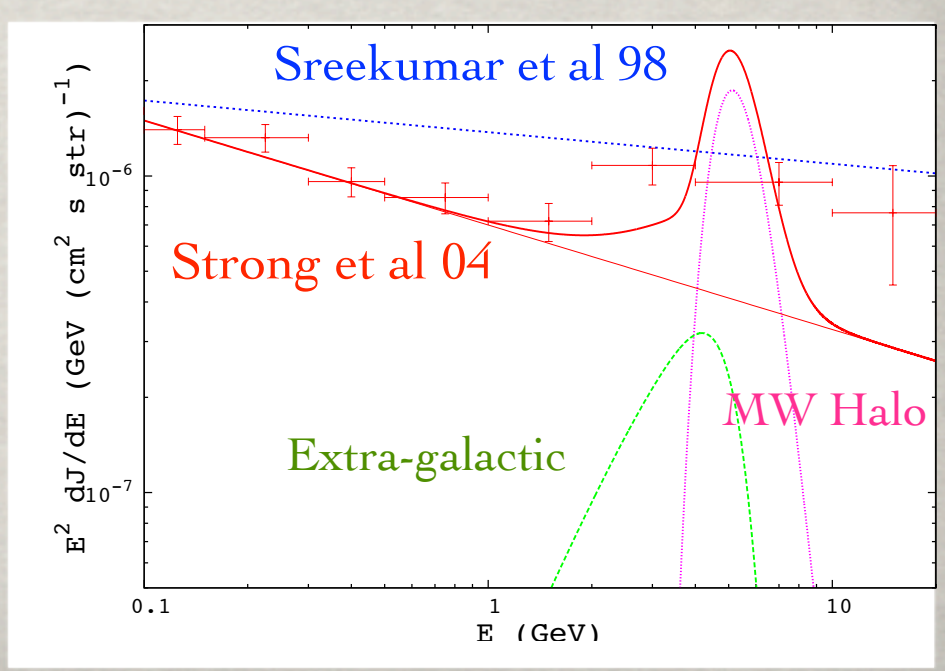
DECAYING DM

- 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...

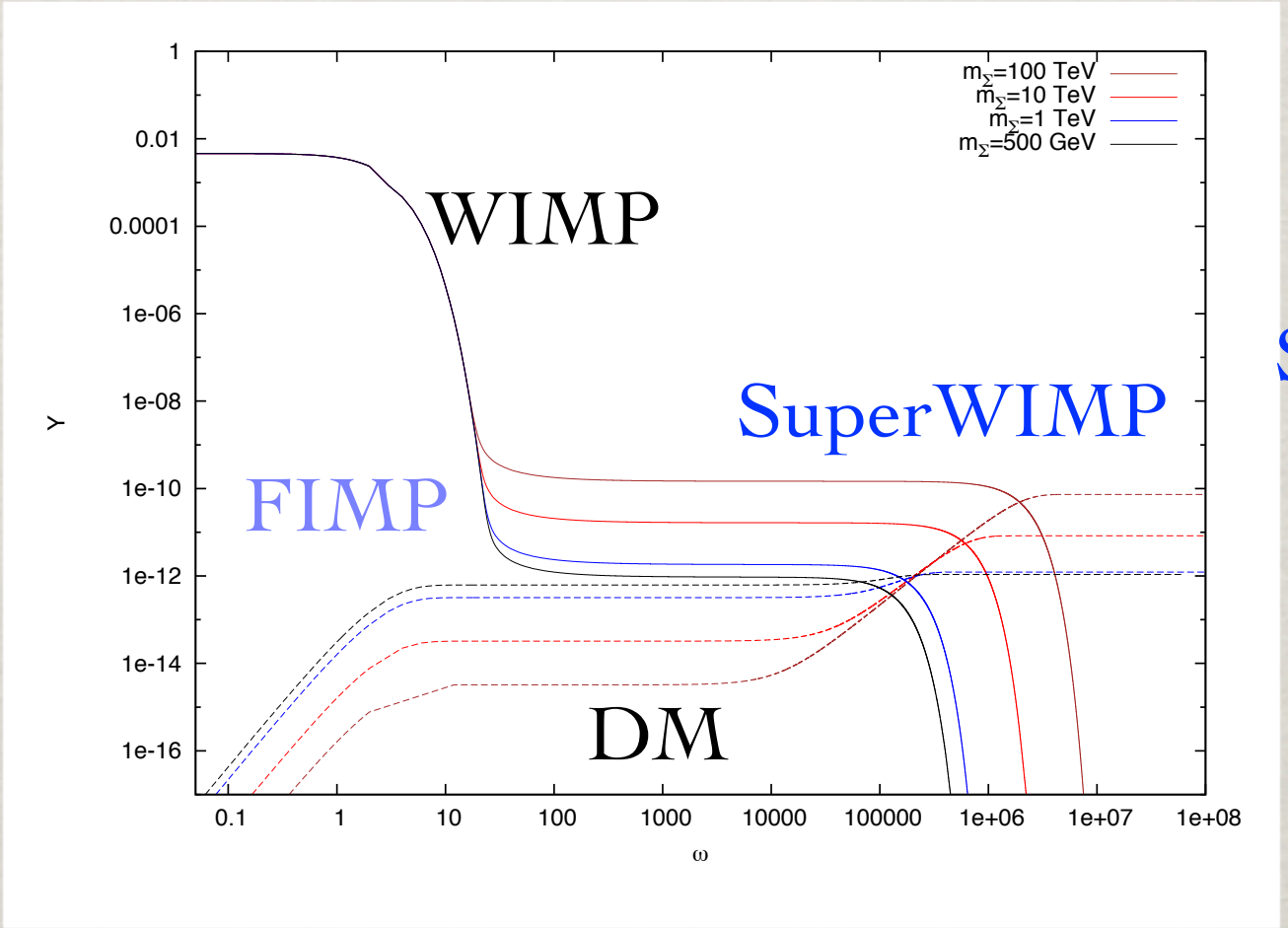


SuperWIMP/FIMP paradigms

Add to the BE a small decaying rate for the WIMP into a much more weakly interacting (i.e. decaying !) DM particle:

[Hall et al 10]

FIMP DM produced by WIMP decay in equilibrium



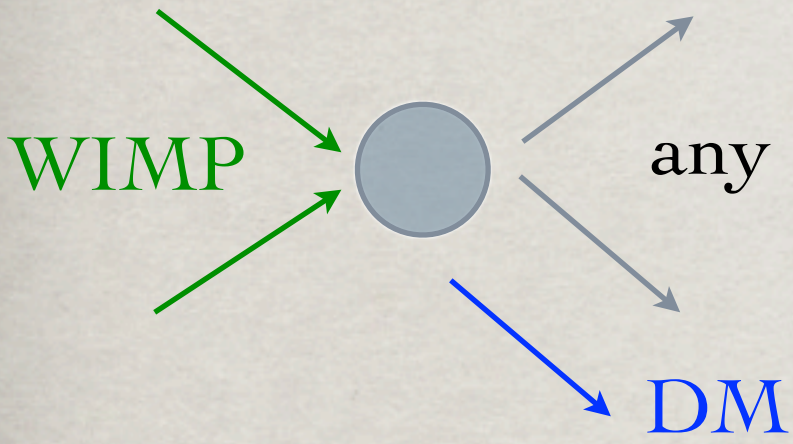
[Feng et al 04]

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

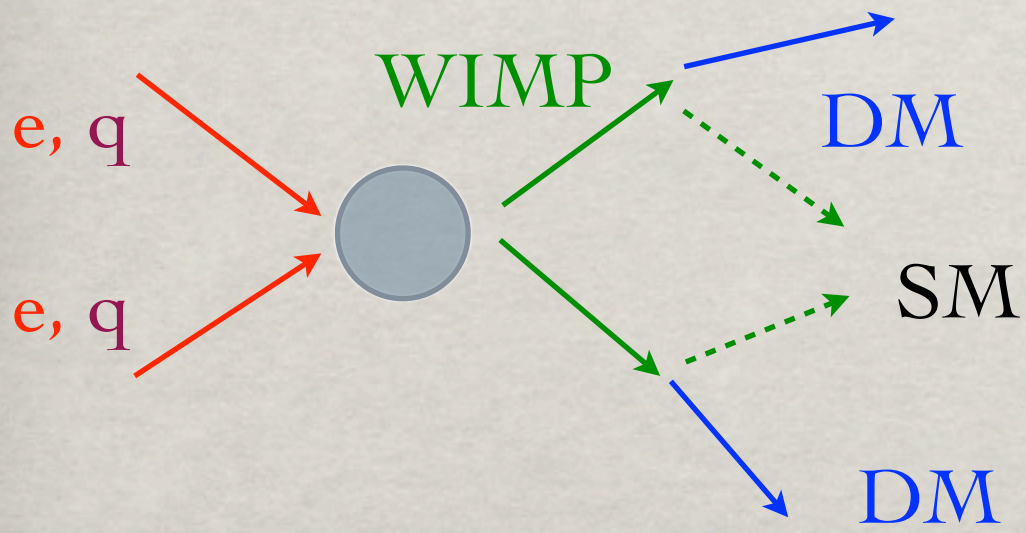
Early Universe: $\Omega_{CDM}h^2$



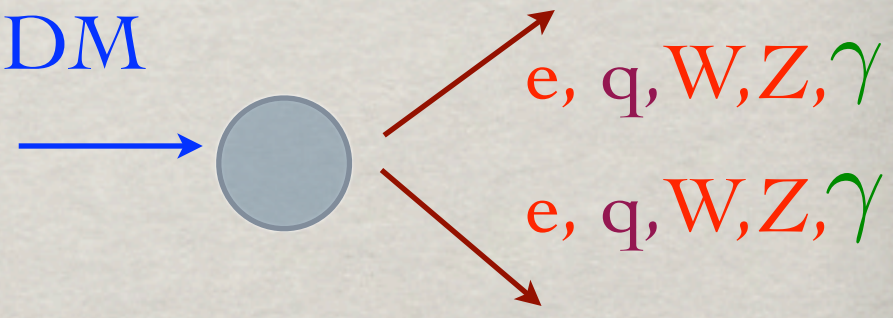
Direct Detection:

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.

A minimal decaying DM 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 :

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

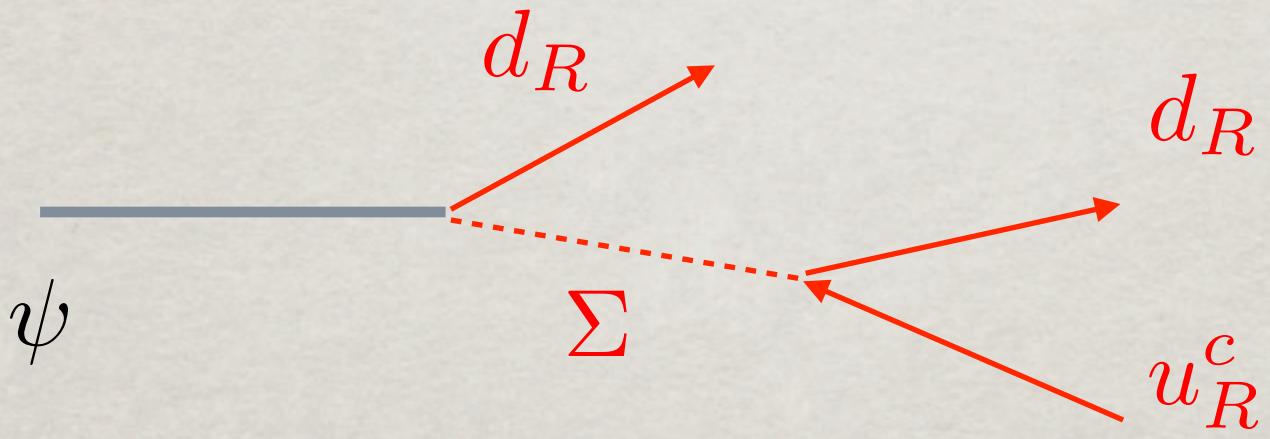
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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

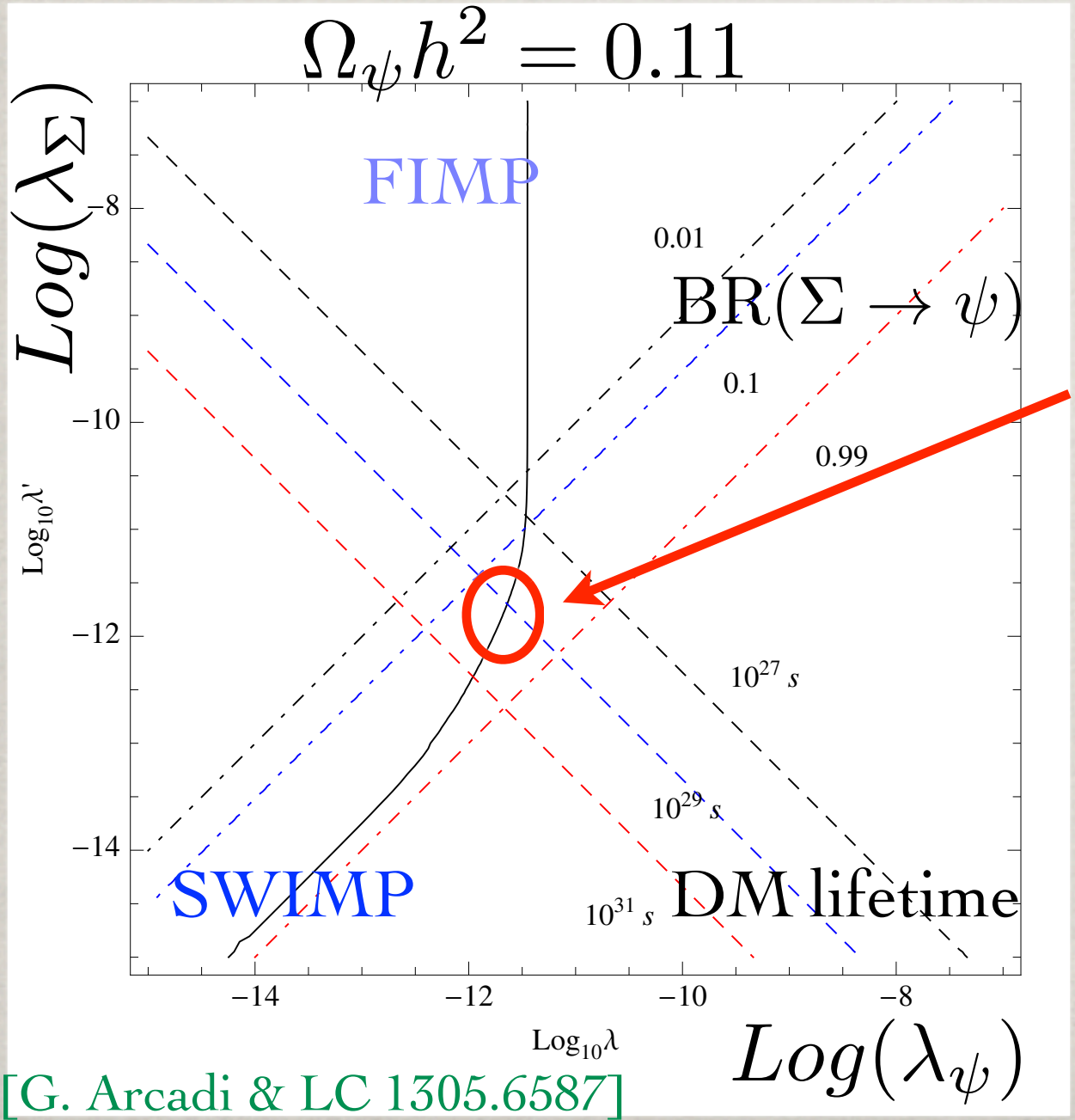
$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

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

Moreover imposing ID "around the corner" gives

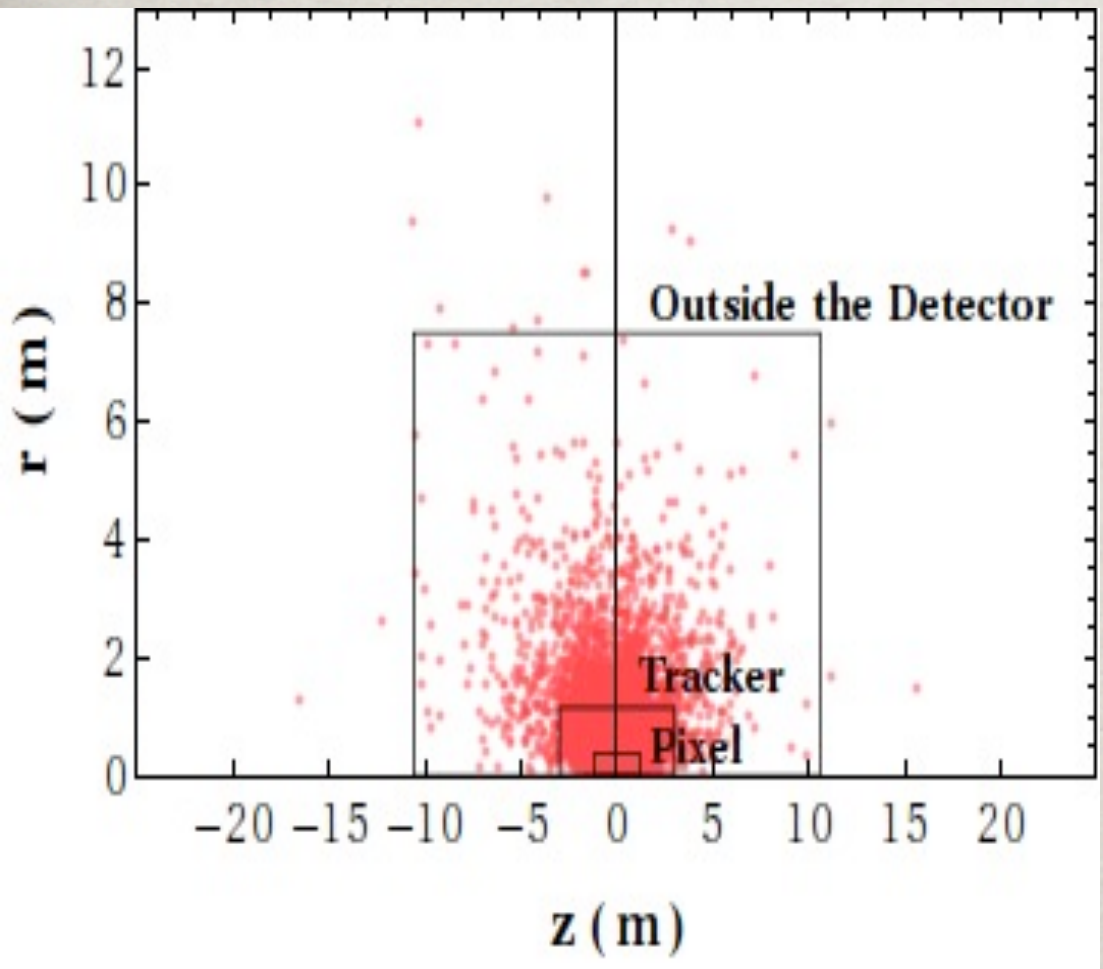
$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\, \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\mathrm{GeV}}\right)^{4} \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right) \left(\frac{\Omega_{CDM}h^2}{0.11}\right) \left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

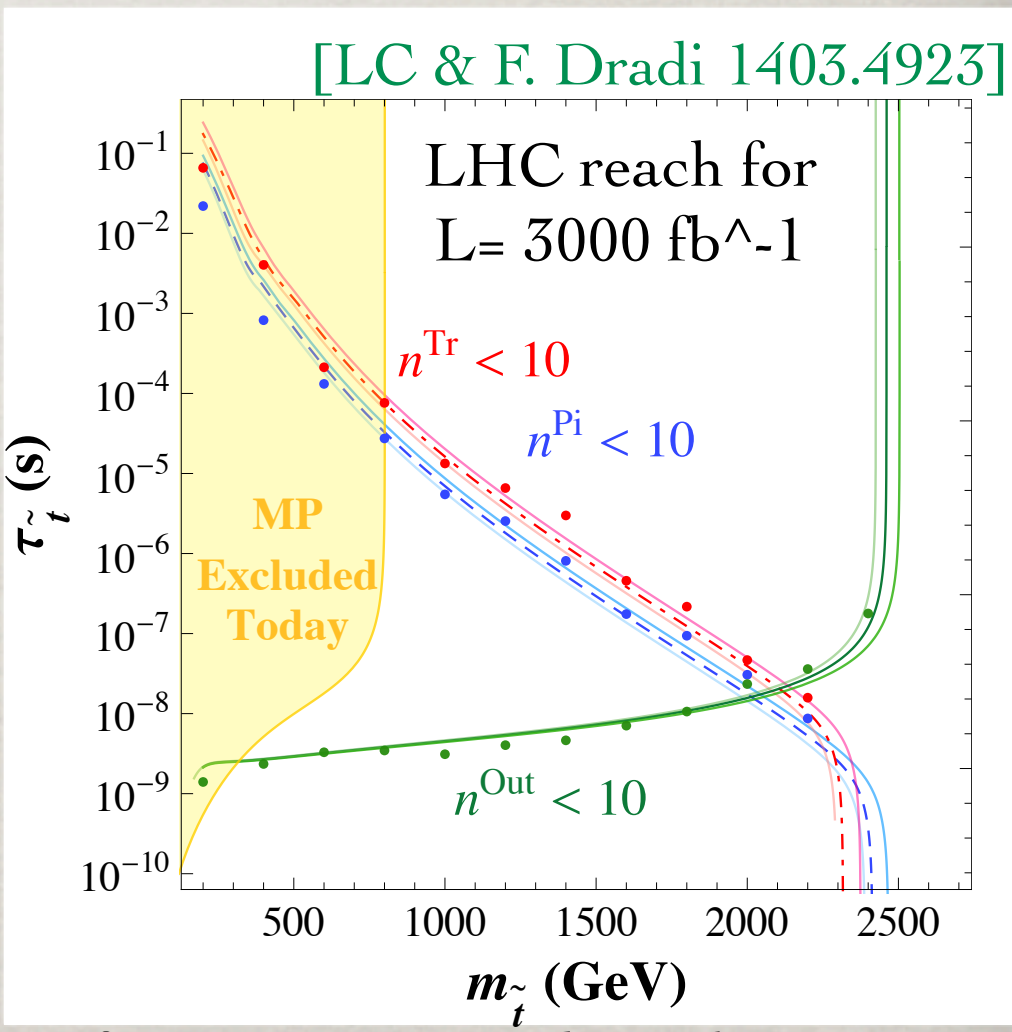
LHC-14 prospects

LHC: LONG-LIVED STOP

Best strategy: combine searches for metastable particles (out) and displaced decay vertices in tracker or pixel (here in CMS). Draw the lines for 10 events of any type to be conservative:



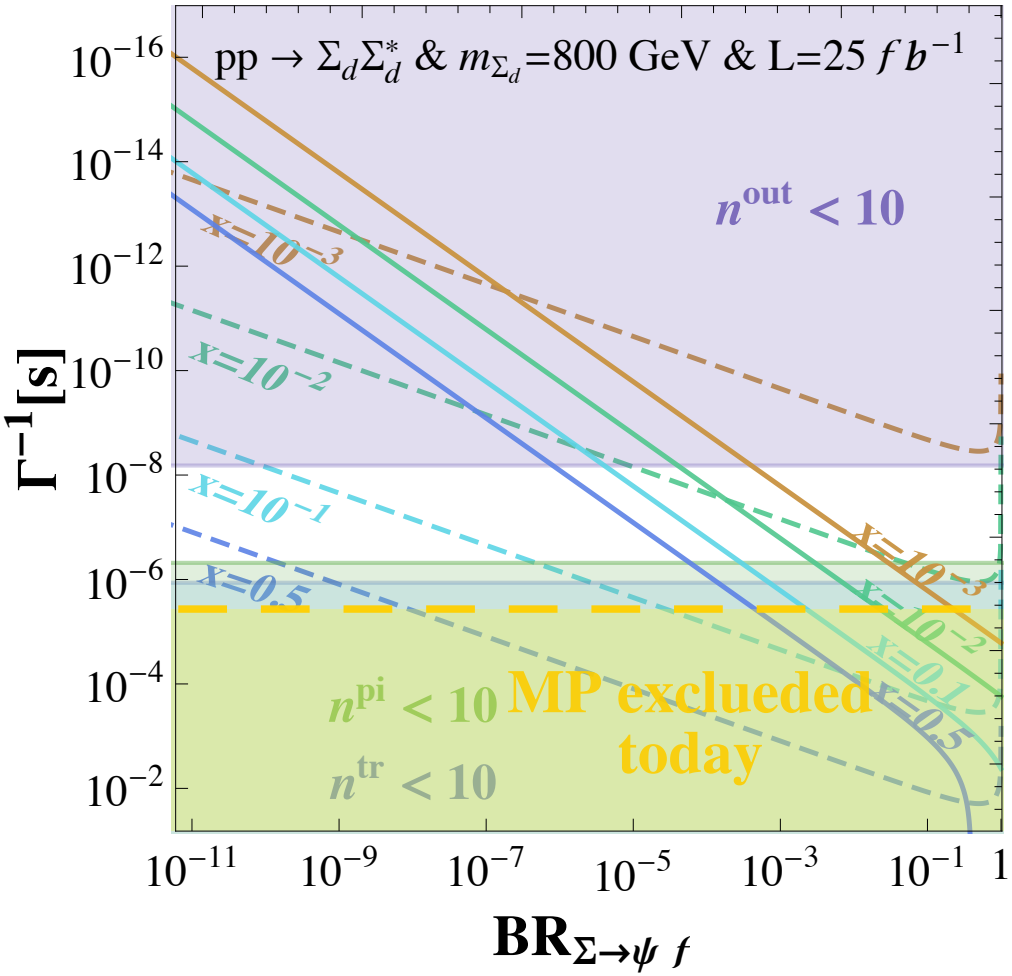
[LC & F. Dradi 1403.4923]

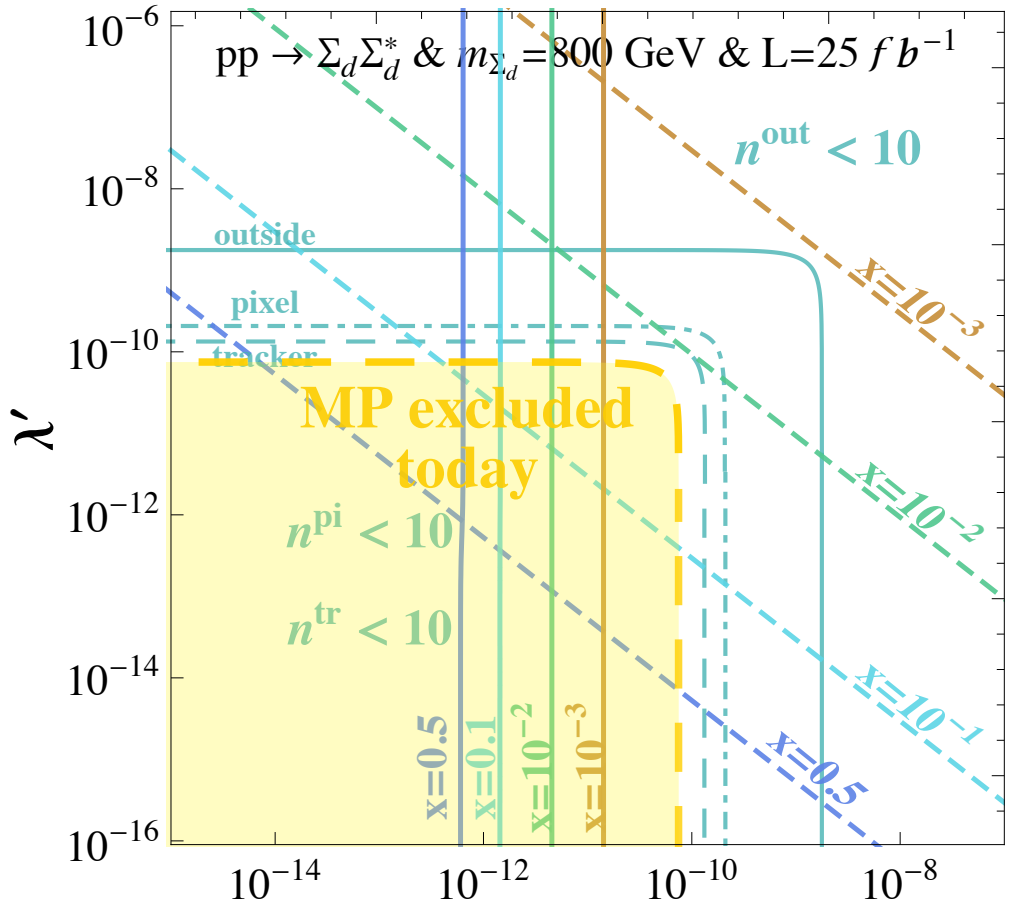


Band is the +/- 1 sigma fluctuation for a Poisson distribution..

FIMP/SWIMP & COLORED Σ

[G. Arcadi, LC & F. Dradi 1408.1005]



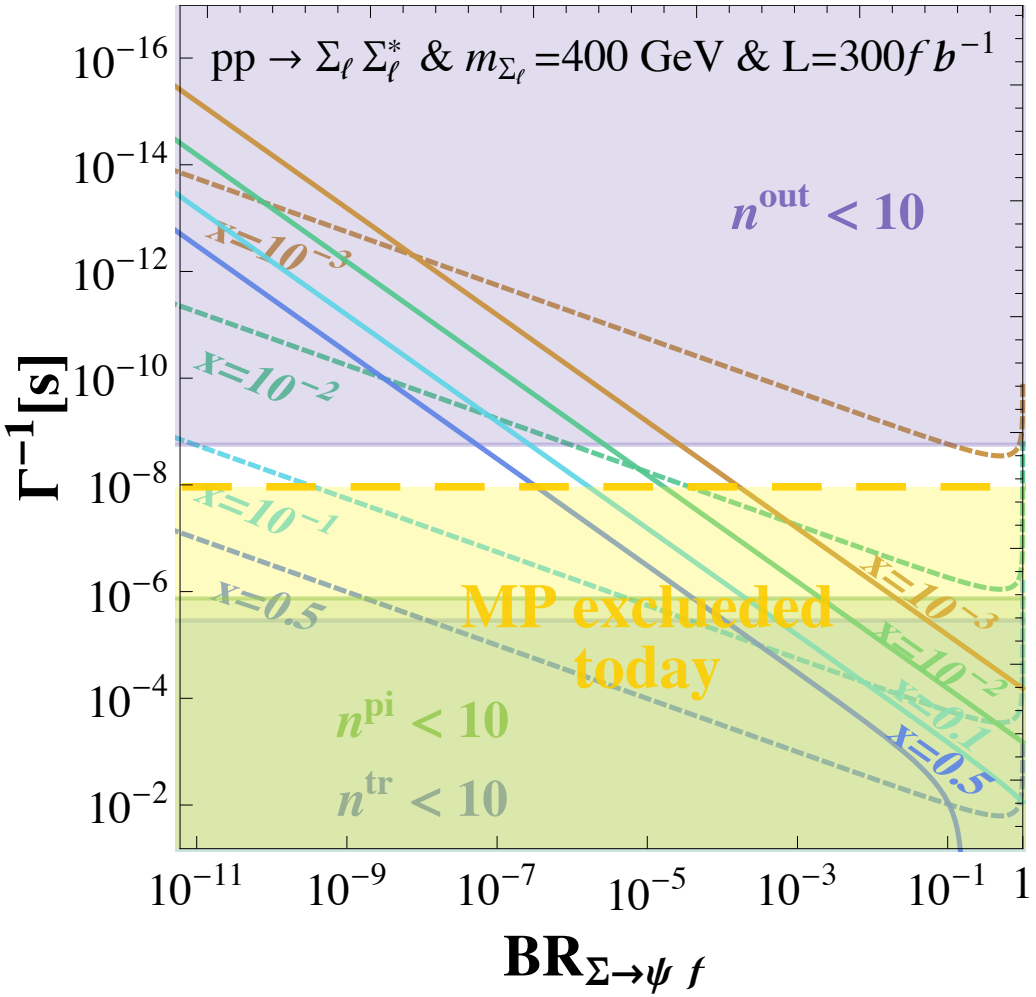


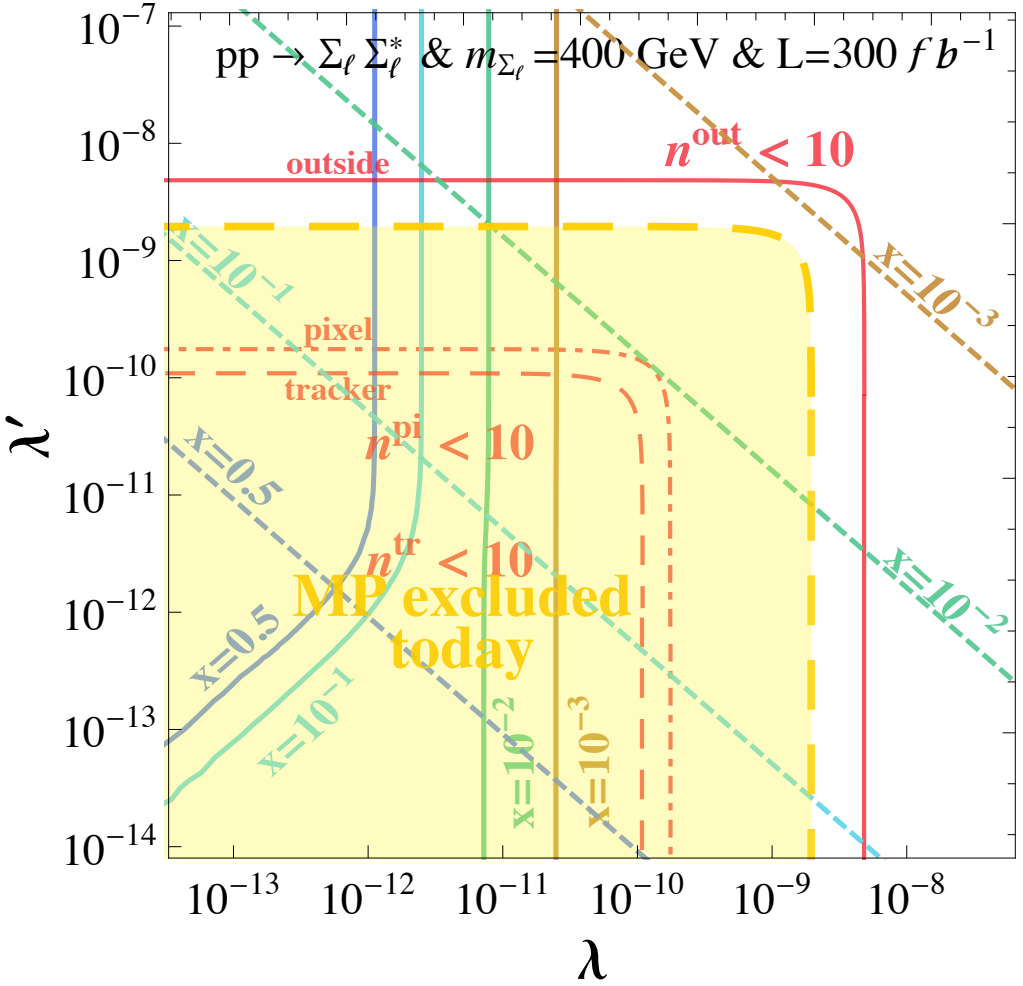
solid DM lines

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

FIMP/SWIMP & EW $\sum$

[G. Arcadi, LC & F. Dradi1408.1005]





Production at LHC is much more suppressed !

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

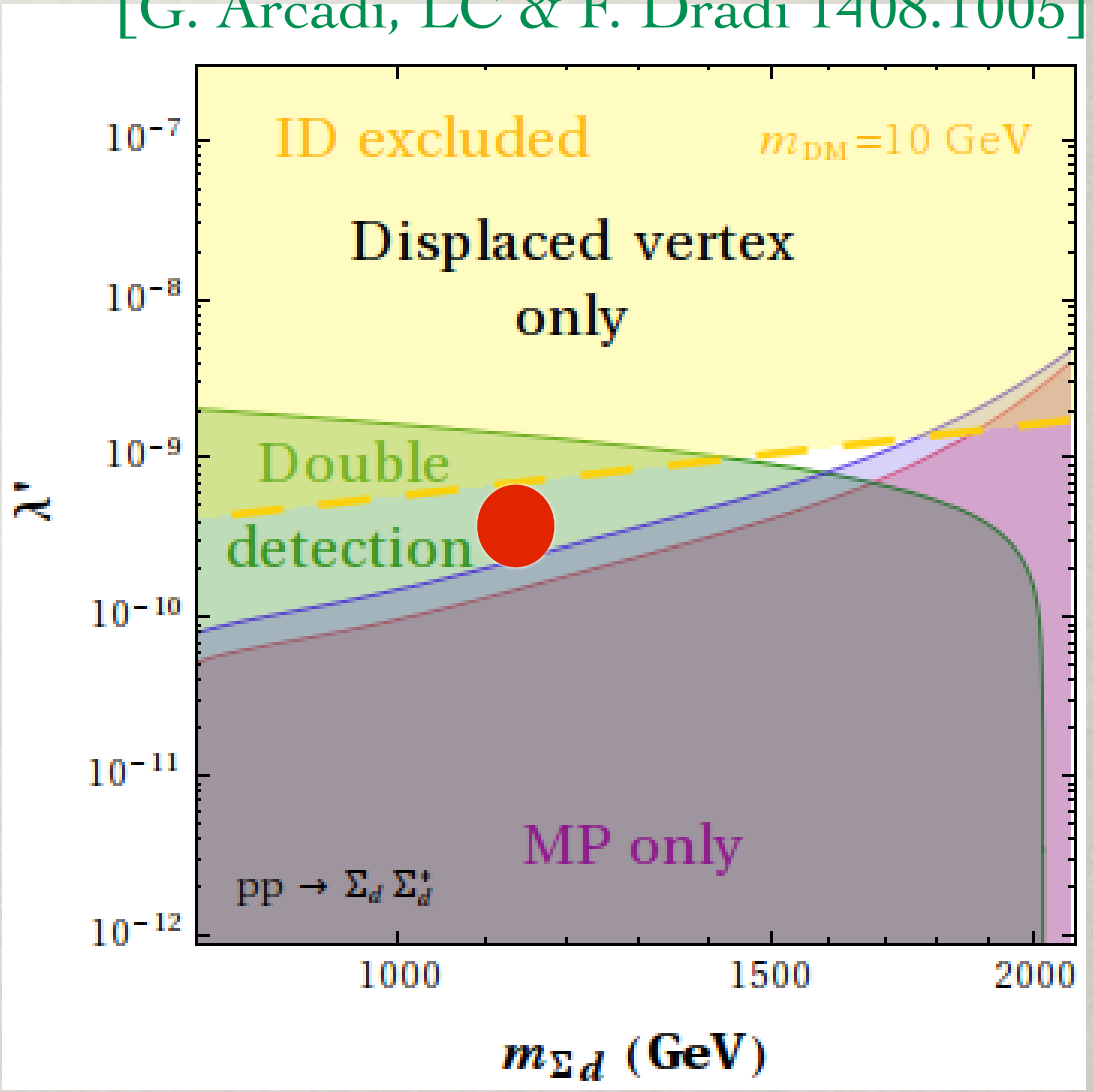
$\sum$ Combined detection

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 1408.1005]



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 decaying FIMP/SuperWIMP DM !
- The FIMP/SuperWIMP framework is quite general and could point to heavy metastable particles or displaced vertices at LHC with different decay channels !
- A combined detection of displaced vertices and metastable tracks within the cosmologically favored region is still possible in the next run of LHC for a colored scalar. More limited reach for the EW case...