Workshop "From Higgs to DM 2014" - Geilo, 15.12.2014

MINIMAL DECAYING DM AND THE LHC

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arXiv: 1305.6587, arXiv:1408.1005, in progress

inVisibles
neutrinos, dark matter & dark energy physics

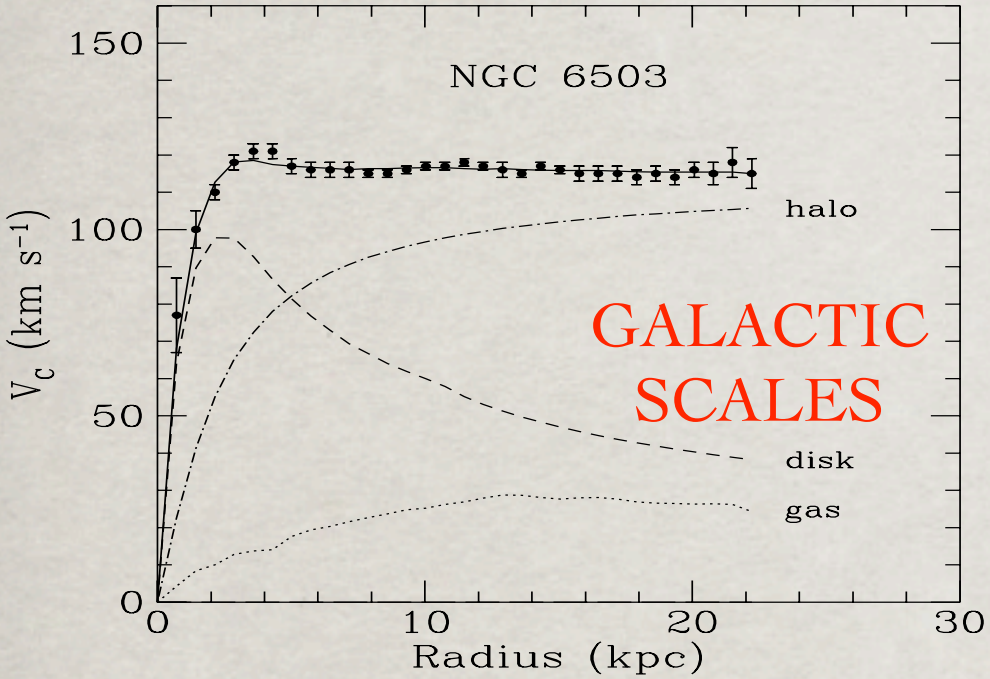
SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS

Outline

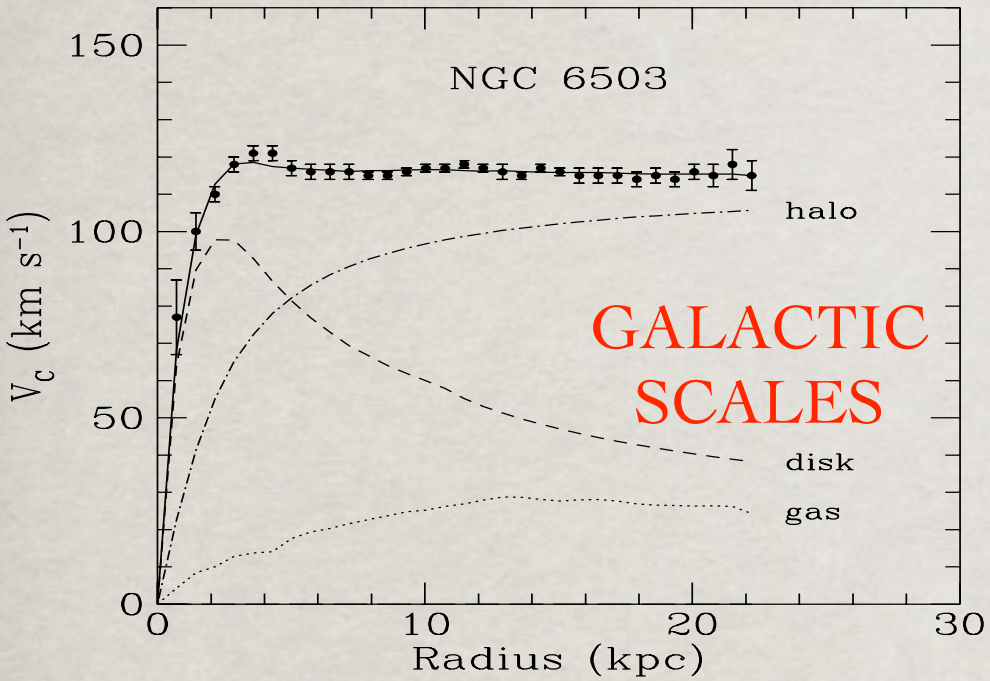
- Introduction:
  From WIMPs to FIMPs/SuperWIMPs
- A minimal decaying DM scenario:
  FIMP/SuperWIMP DM with G. Arcadi
- Prospects at the LHC with G. Arcadi & F. Dradi
- What about the 3.5 keV Line ?
- Outlook

From WIMPs to FIMPs & SuperWIMPs

DARK MATTER EVIDENCE



DARK MATTER EVIDENCE



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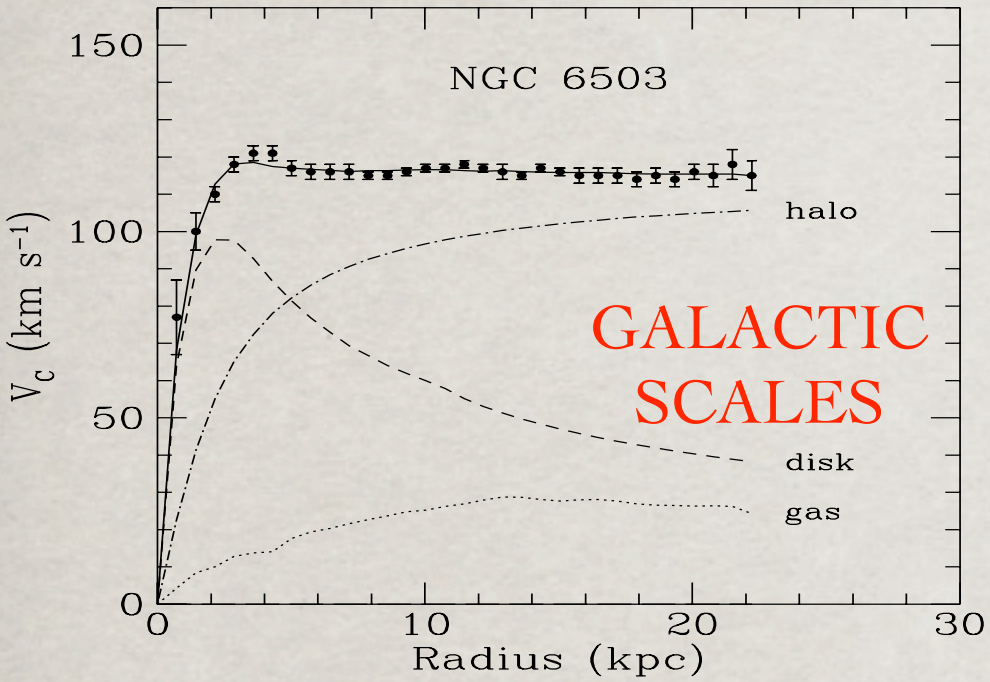

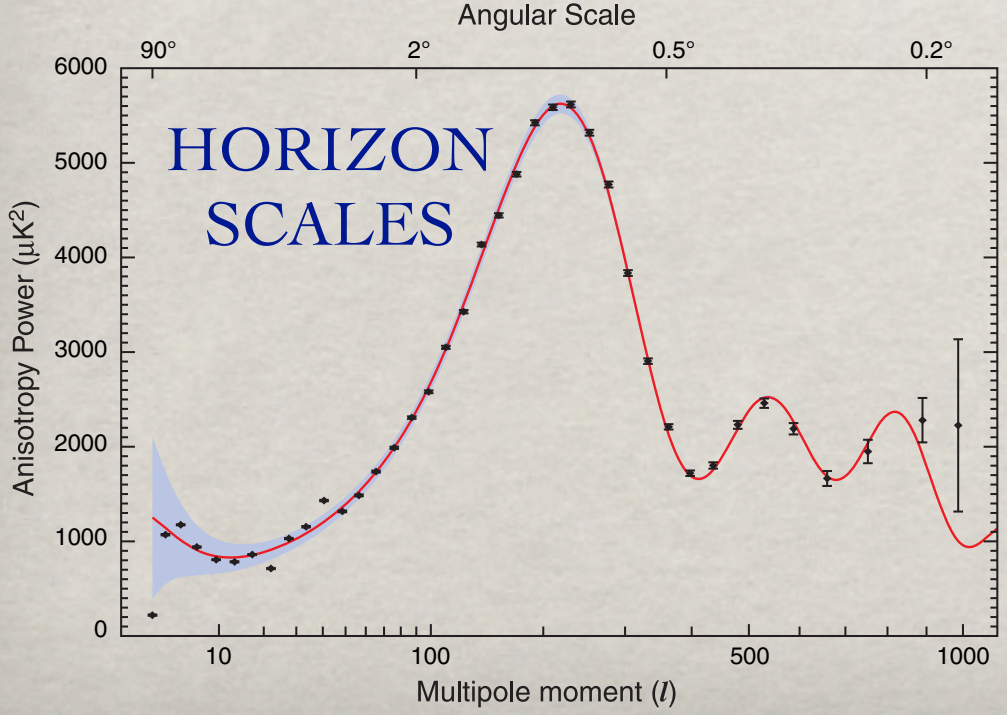

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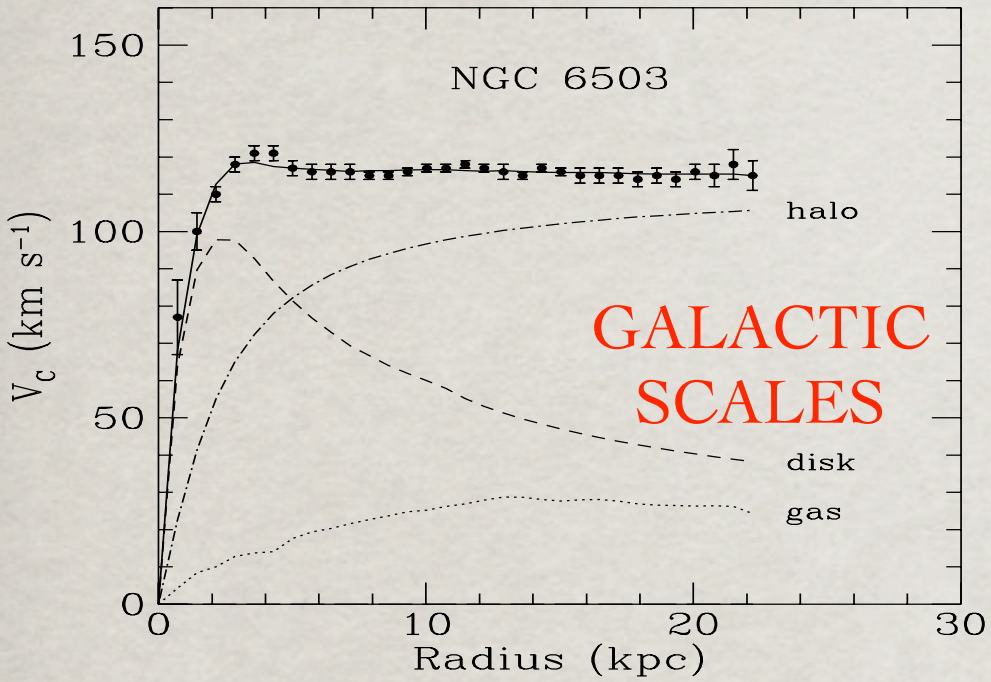
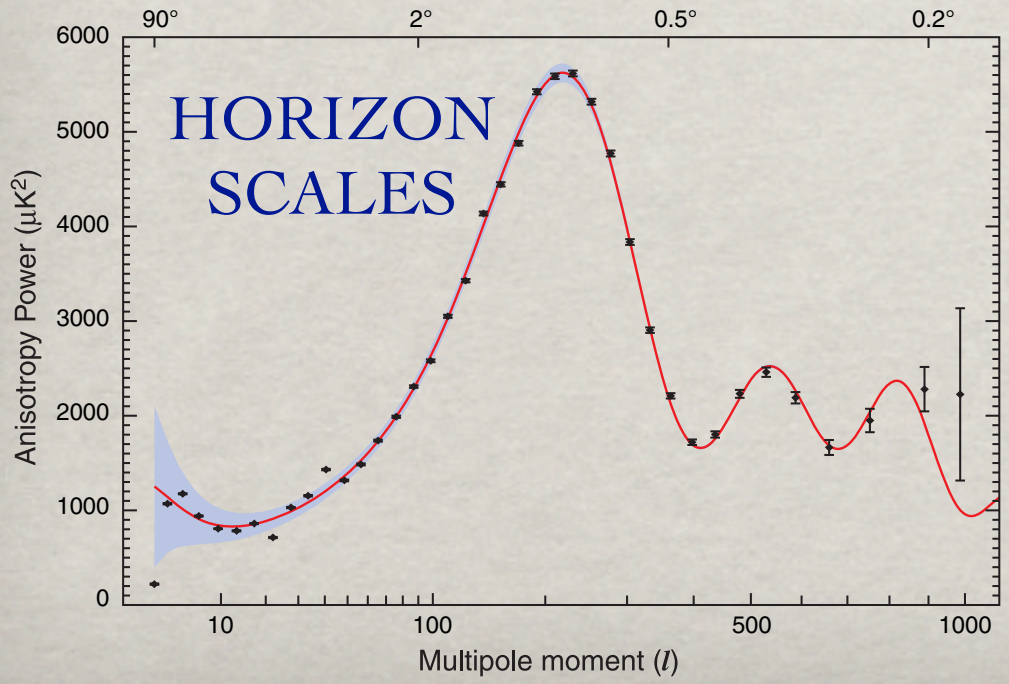




Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	~ 0.11	Cold

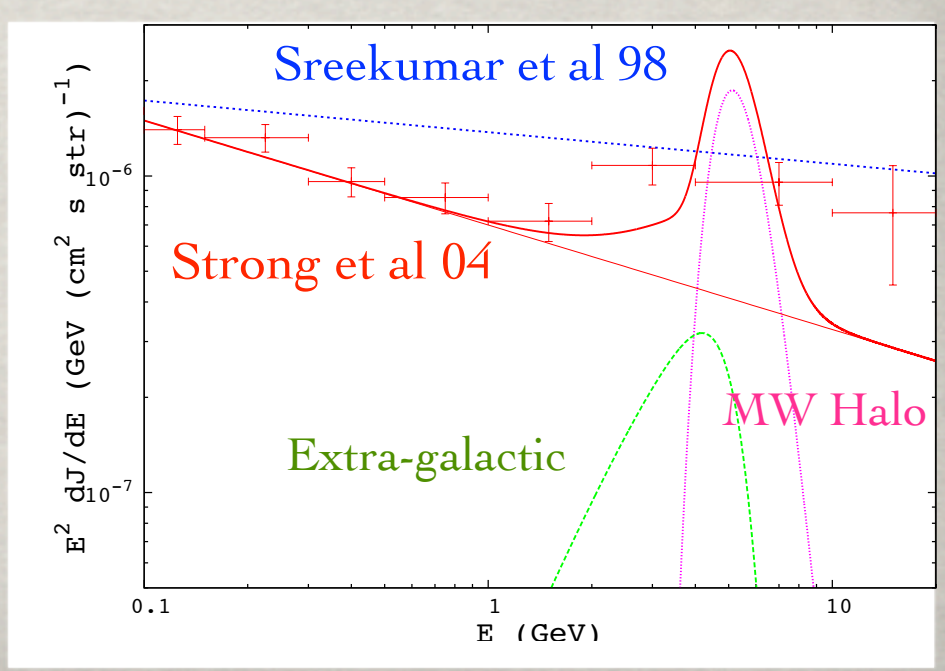
DECAYING DM

- 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...



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

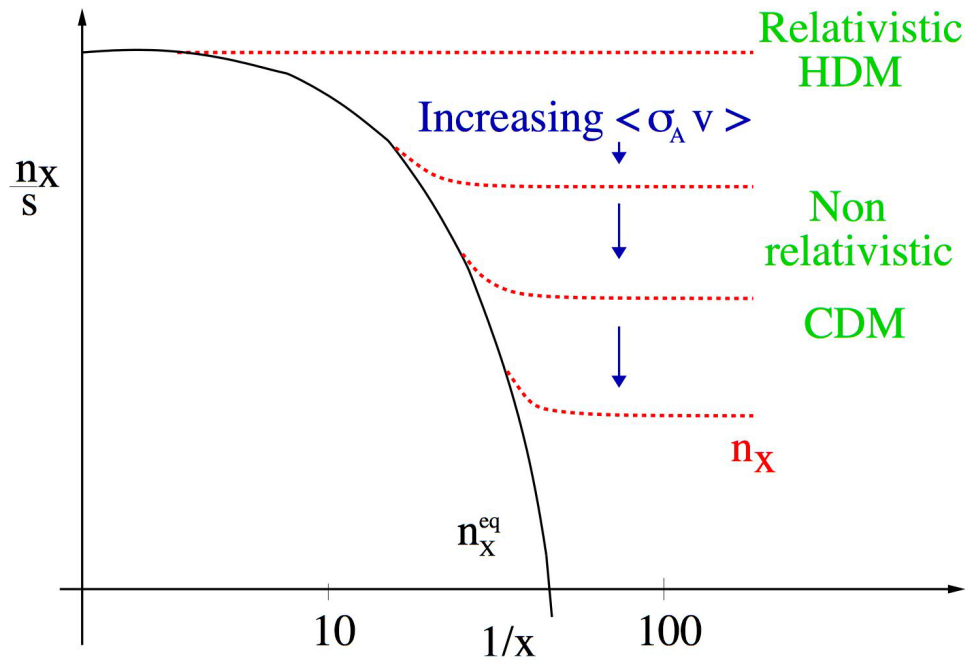
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

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 !

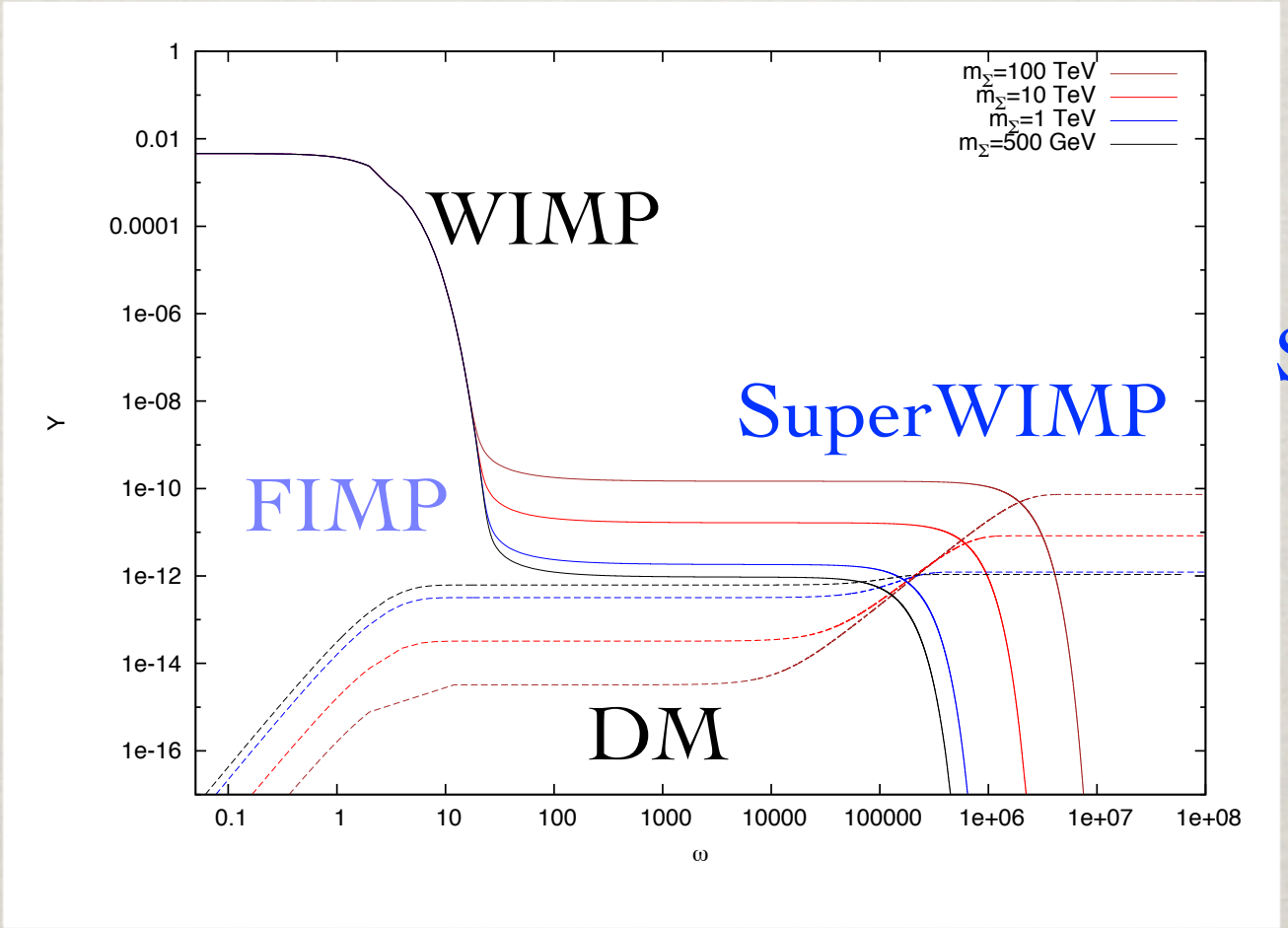


SuperWIMP/FIMP paradigms

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



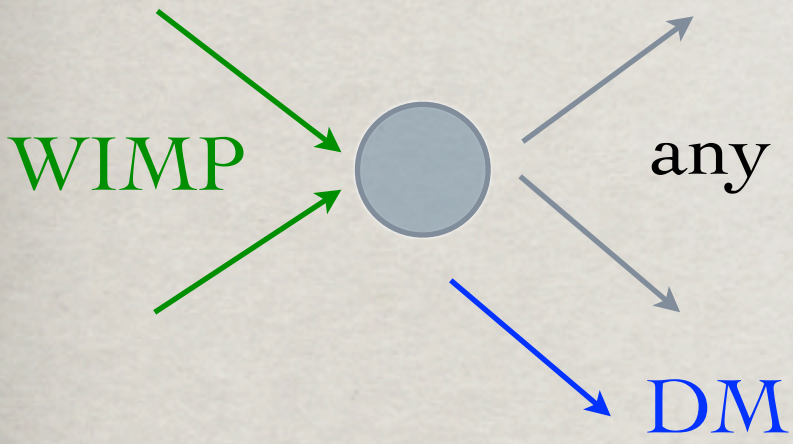
[Feng et al 04]

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

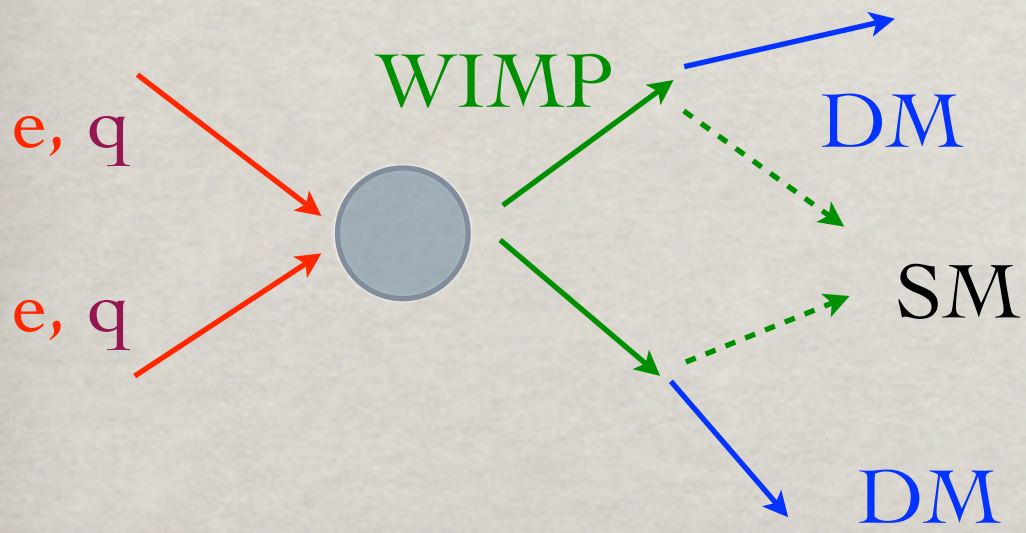
Early Universe: $\Omega_{CDM}h^2$



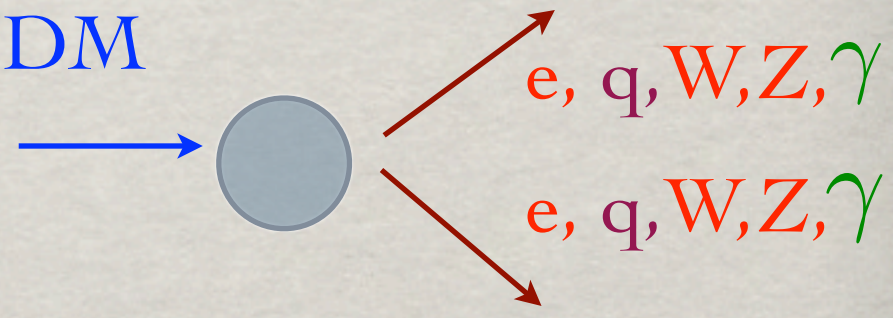
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

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 :

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

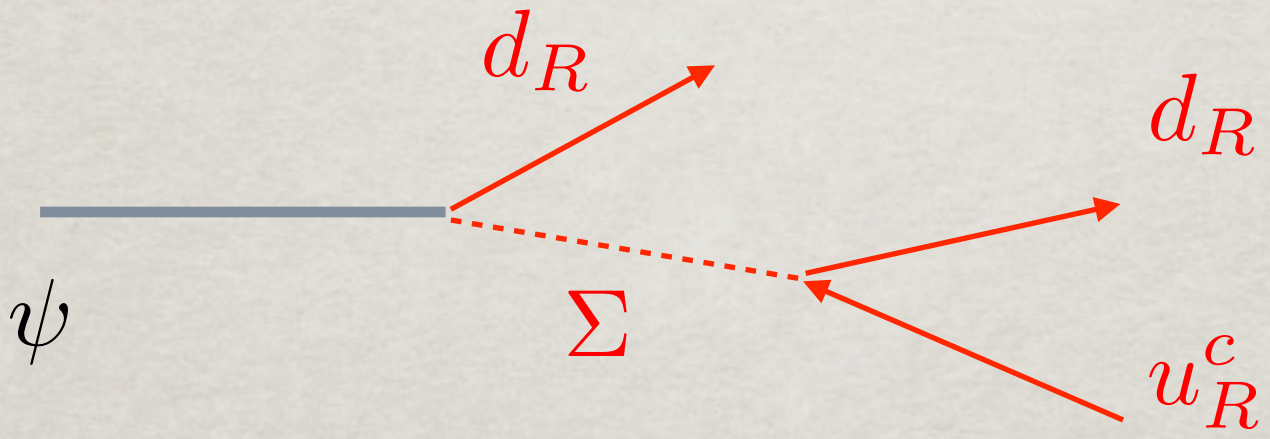
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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

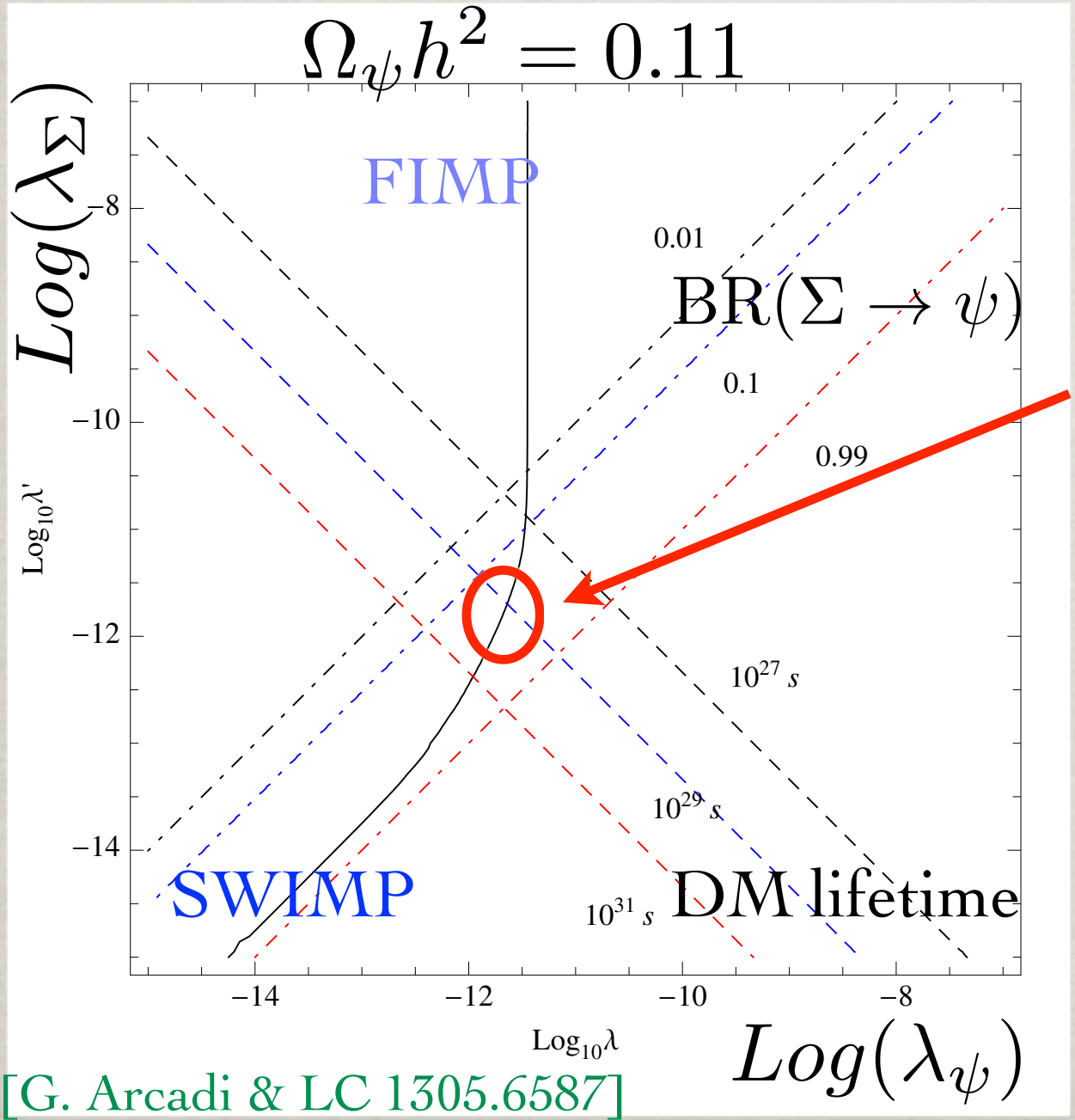
$$\tau_\psi \propto \lambda_\psi^{-2} \lambda_\Sigma^{-2} \frac{m_\Sigma^4}{m_\psi^5} \sim 10^{28} s$$

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

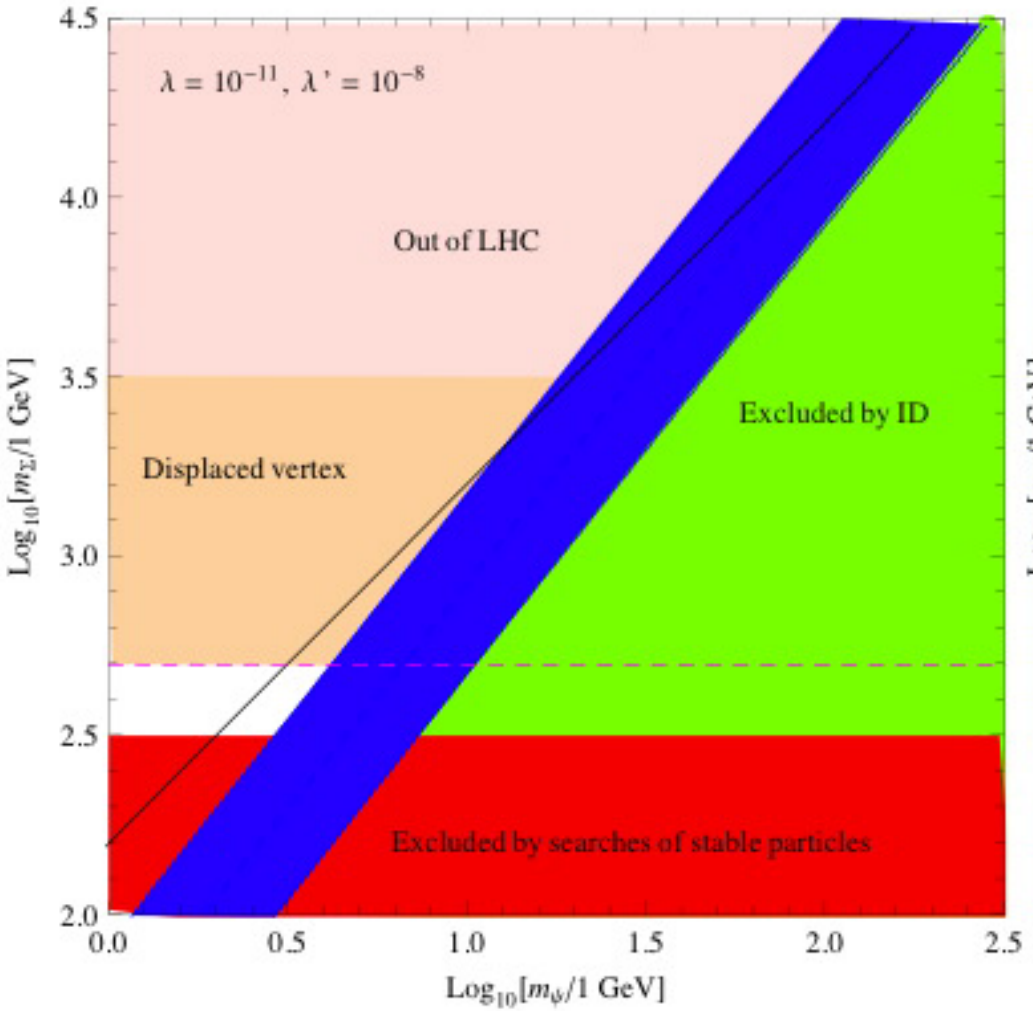
Moreover imposing ID "around the corner" gives

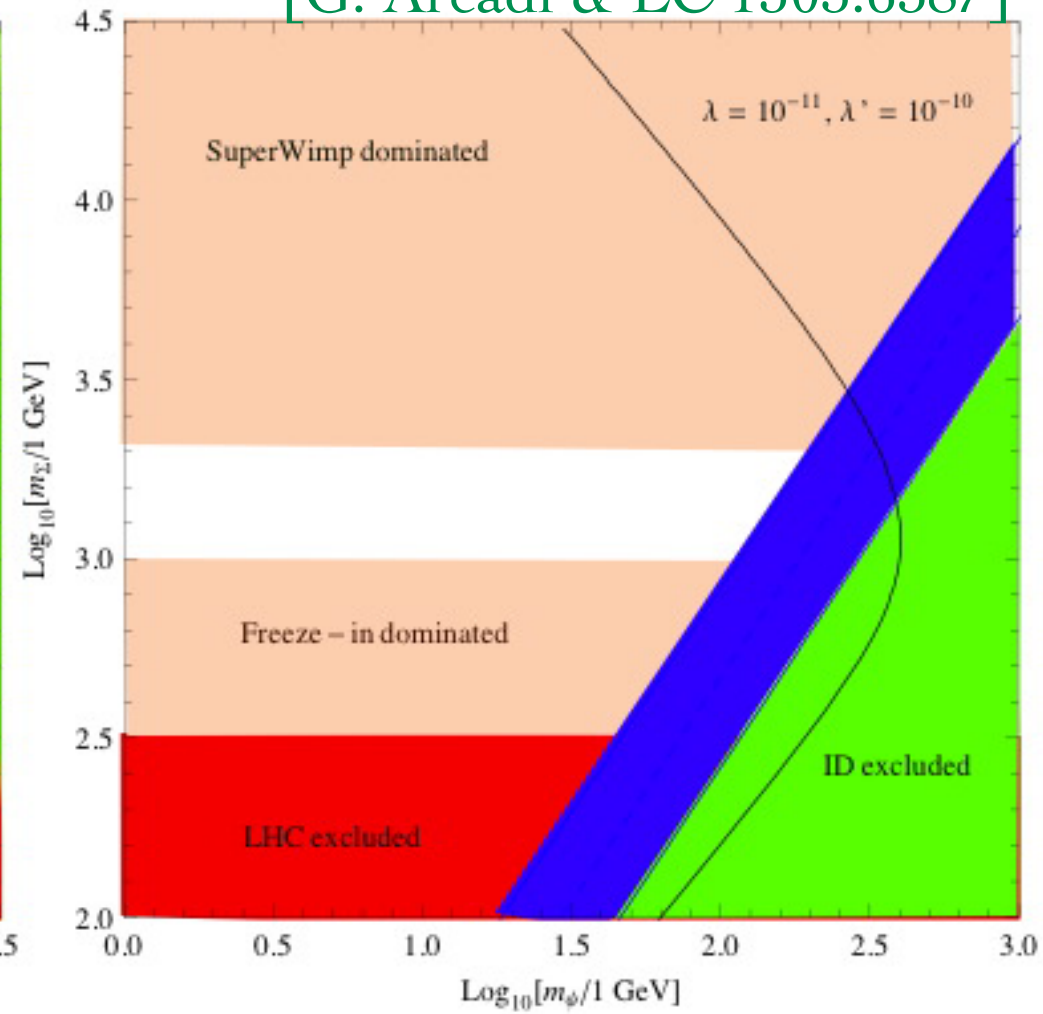
$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\, \frac{1}{g_\Sigma} \left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4} \left(\frac{m_\psi}{10\mathrm{GeV}}\right)^{4} \left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right) \left(\frac{\Omega_{CDM}h^2}{0.11}\right) \left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

FIMP/SWIMP & EW PARTNER

[G. Arcadi & LC 1305.6587]



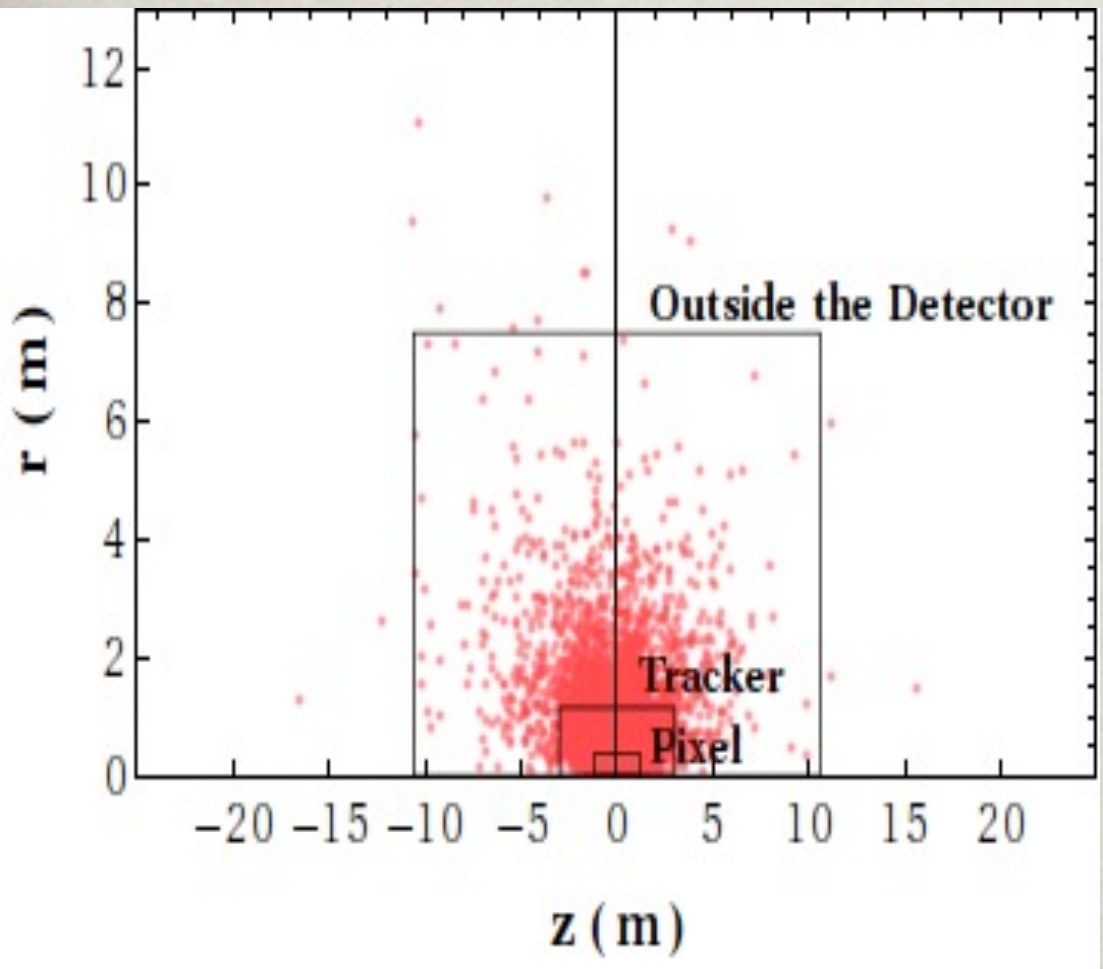


For $\sum$ SU(2) doublet, FIMP case gives displaced vertices, SuperWIMP gives "stable" charged particle @ LHC

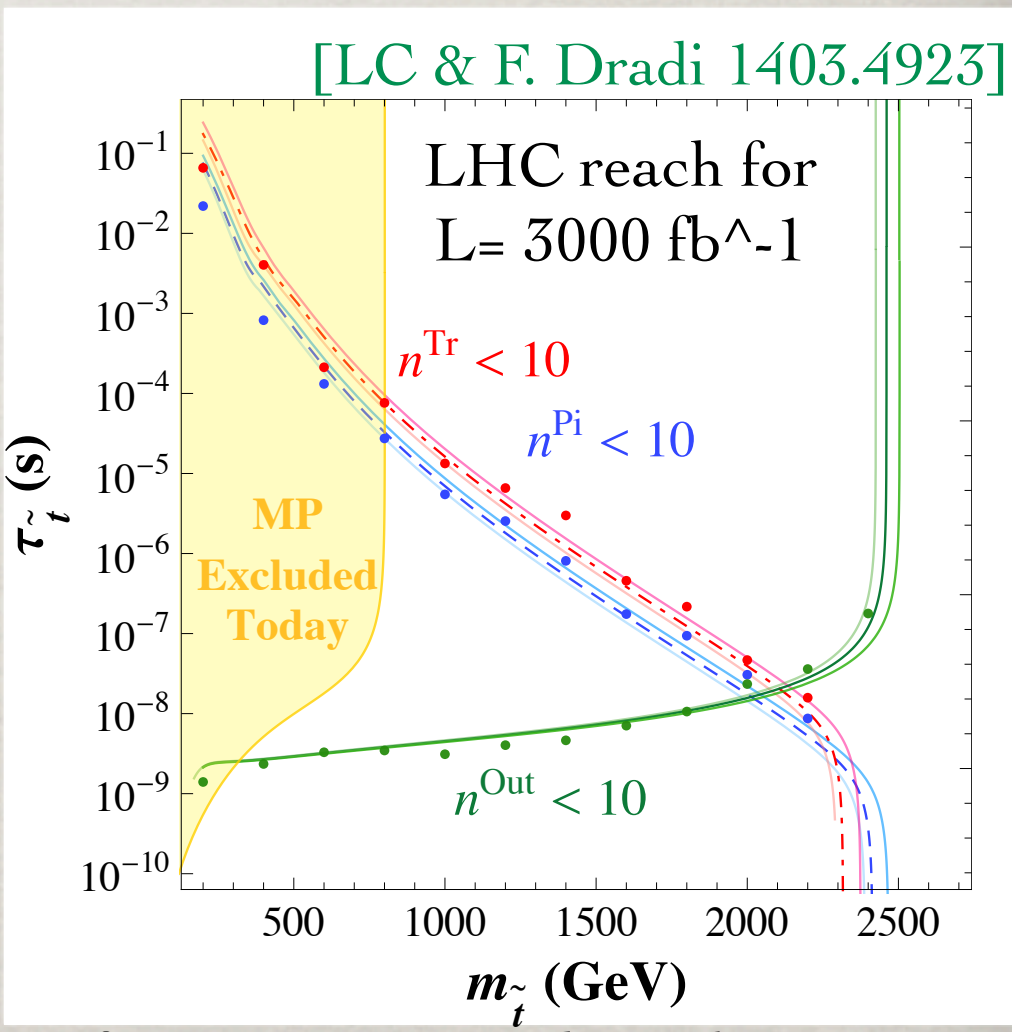
LHC-14 prospects

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:



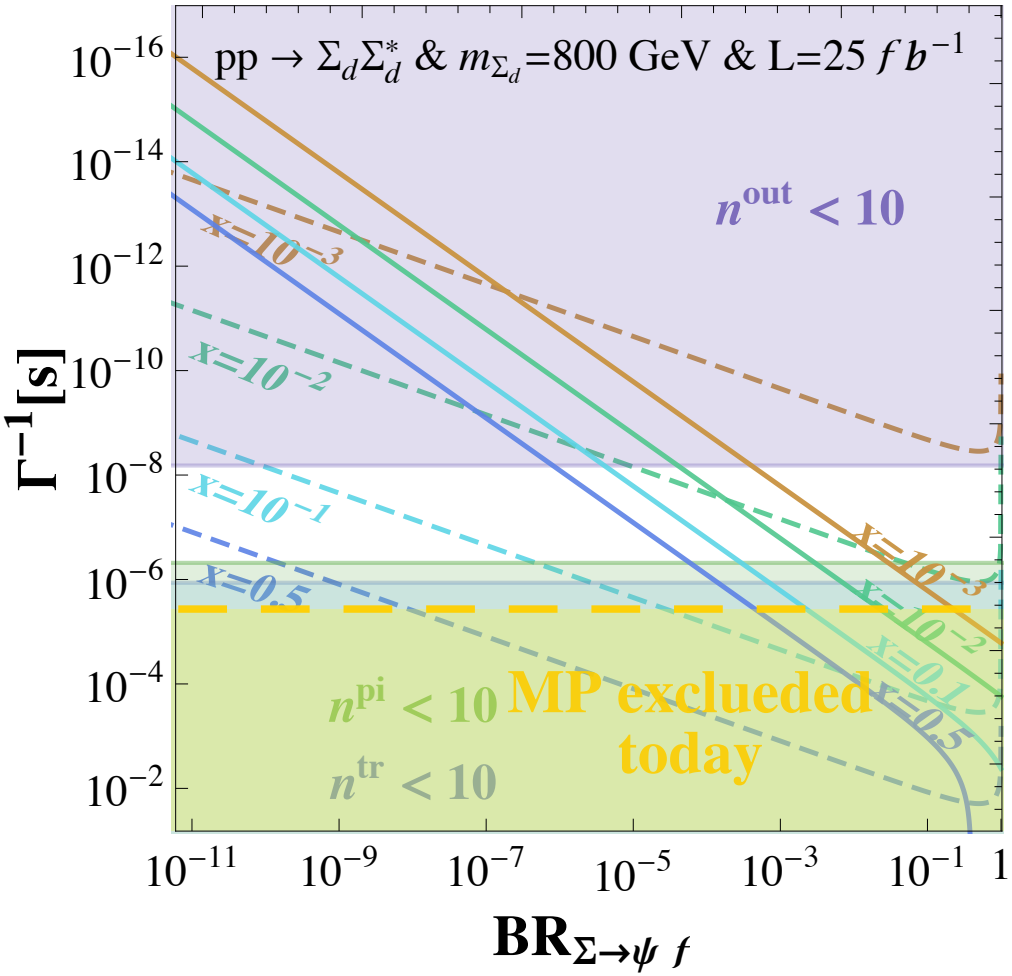
[LC & F. Dradi 1403.4923]

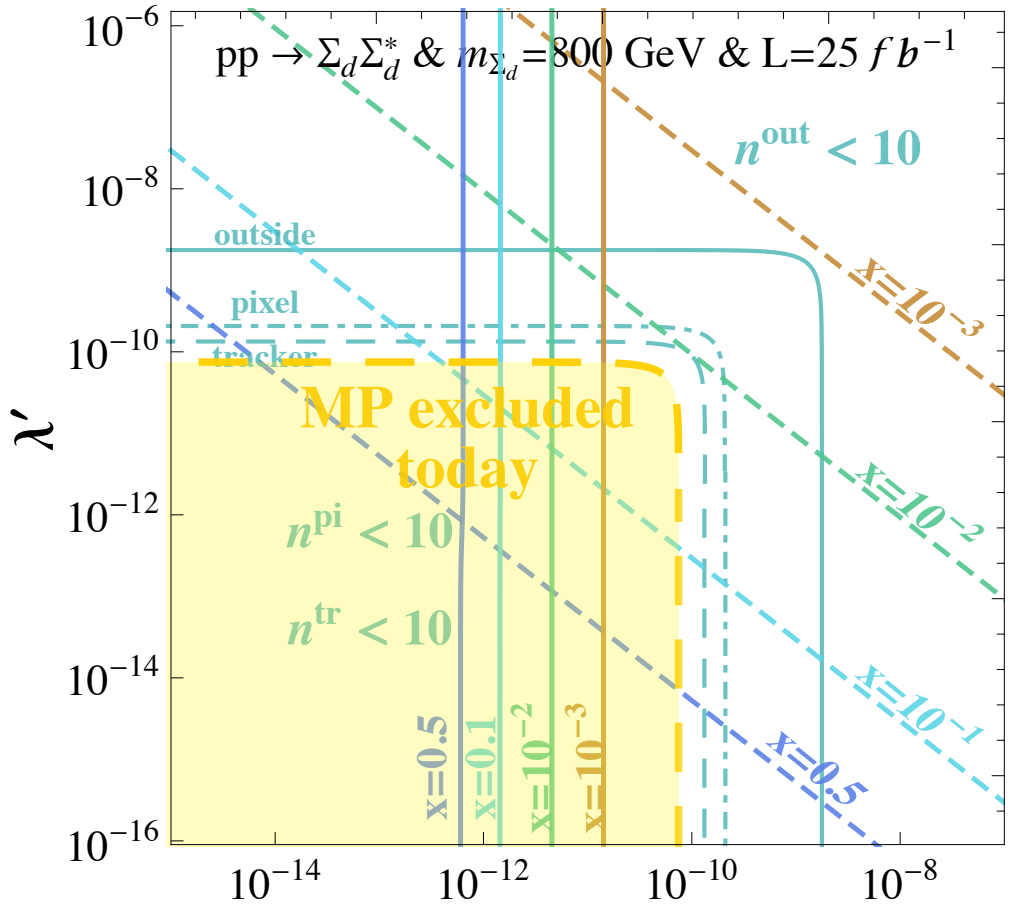


Band is the +/- 1 sigma fluctuation for a Poisson distribution..

FIMP/SWIMP & COLORED Σ

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



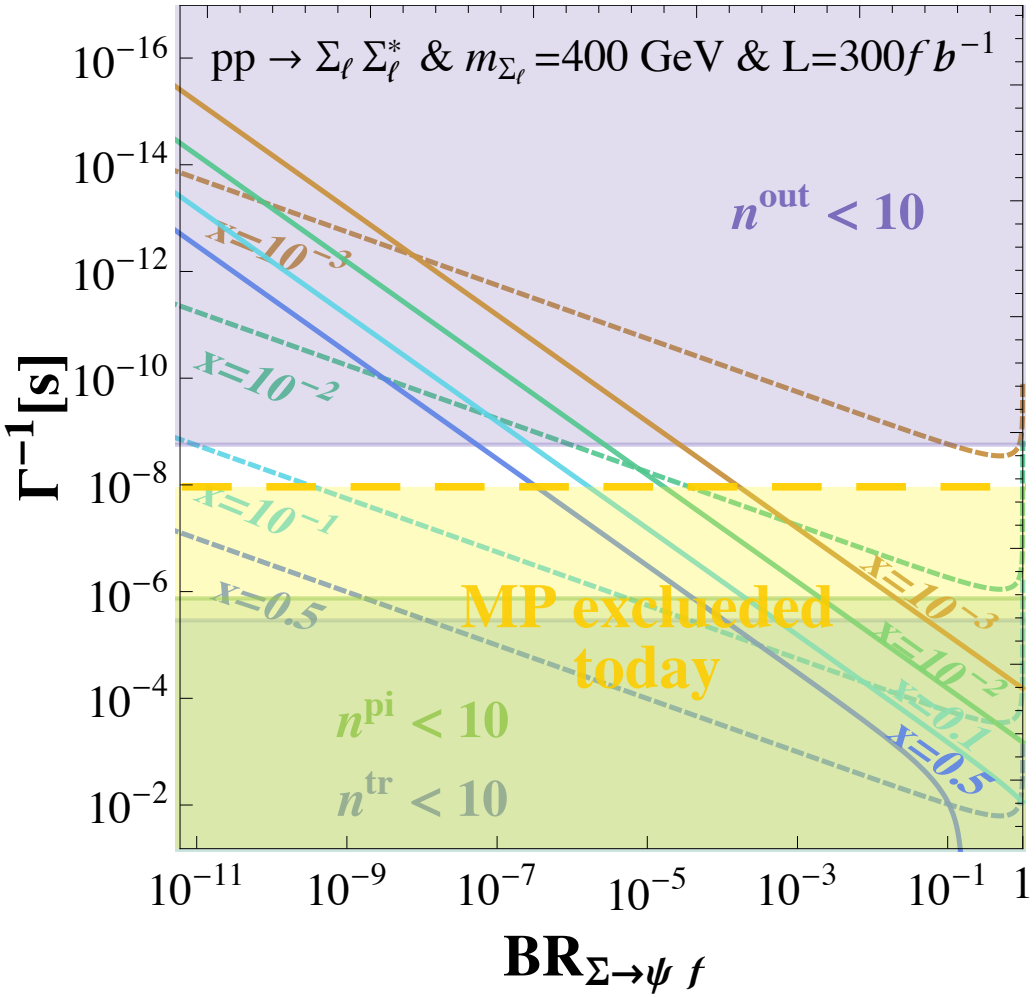


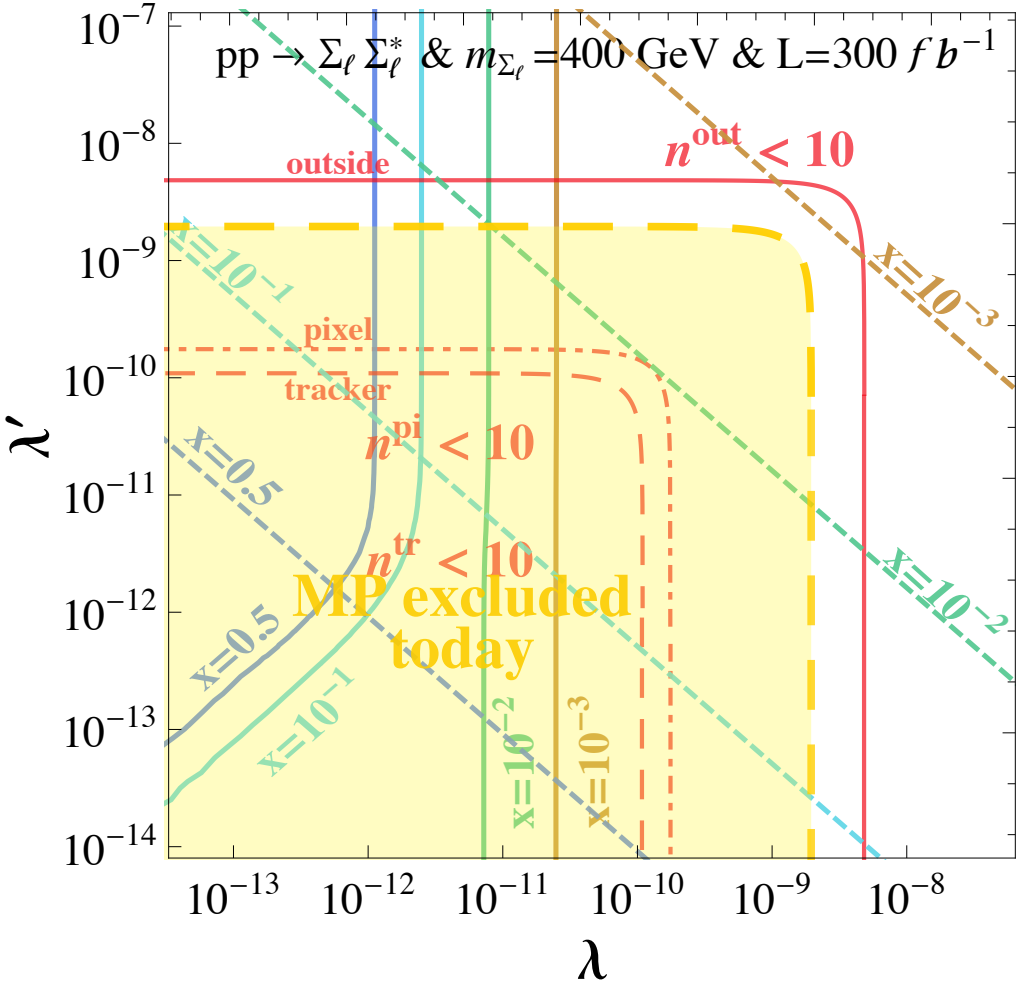
solid DM lines

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

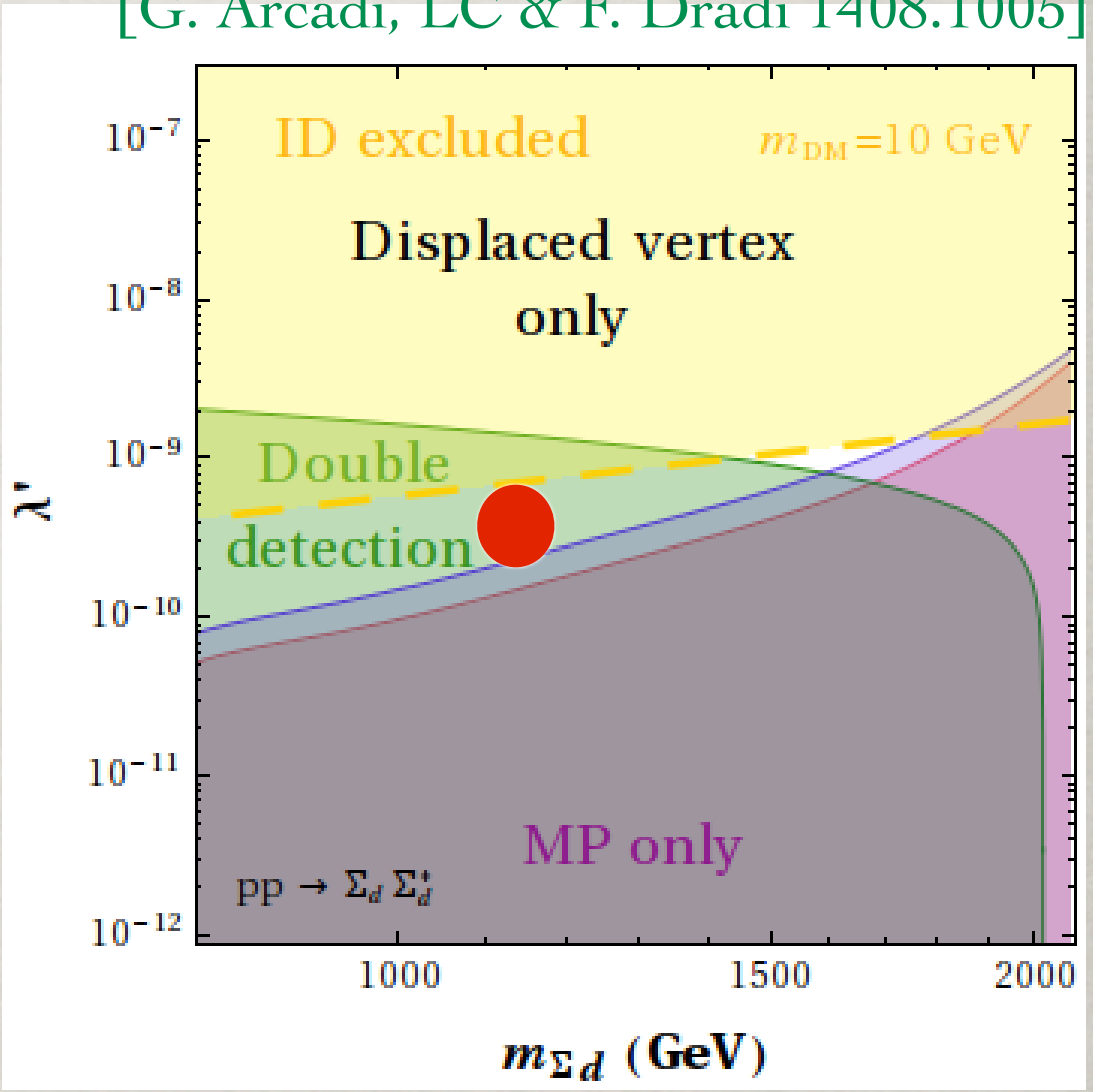
$\sum$ Combined detection

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 over-constraint the model and check the hypothesis of FIMP production !

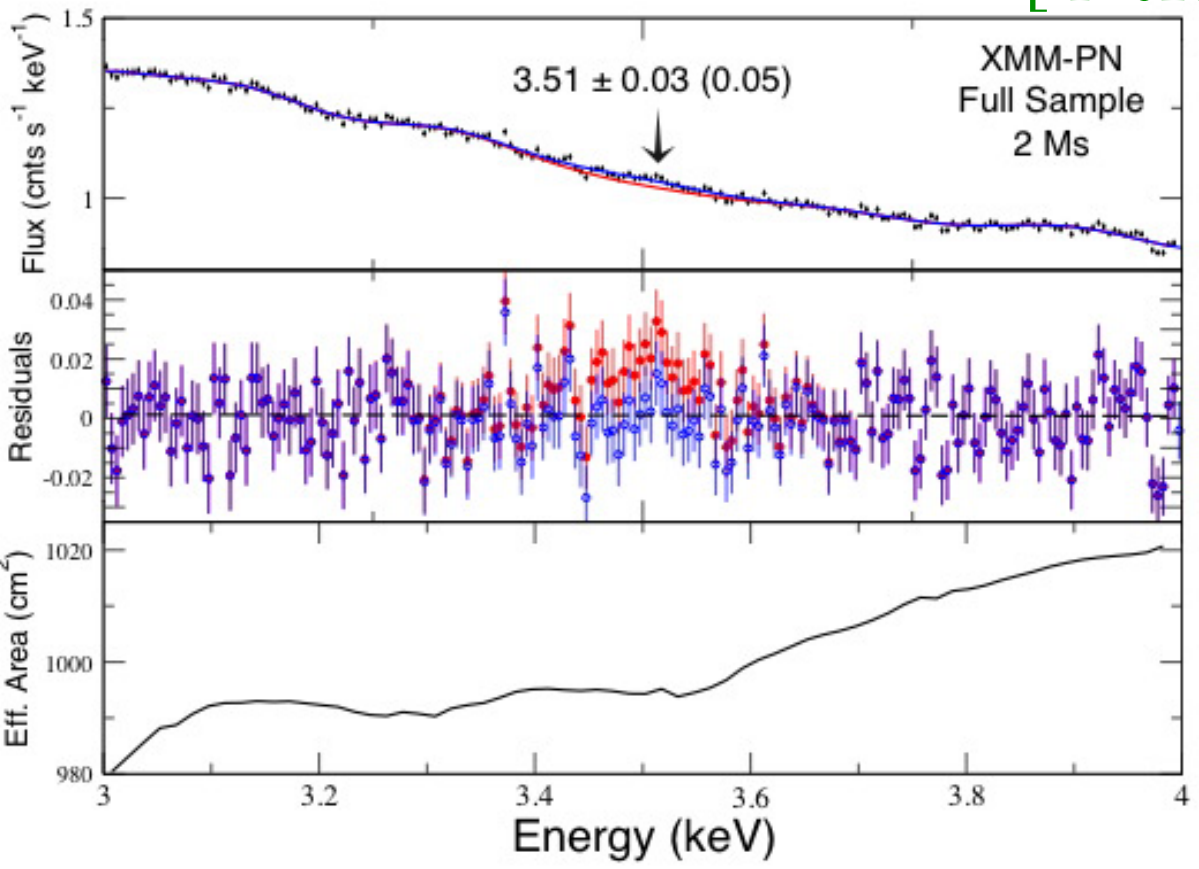
What about the 3.55 keV line ?

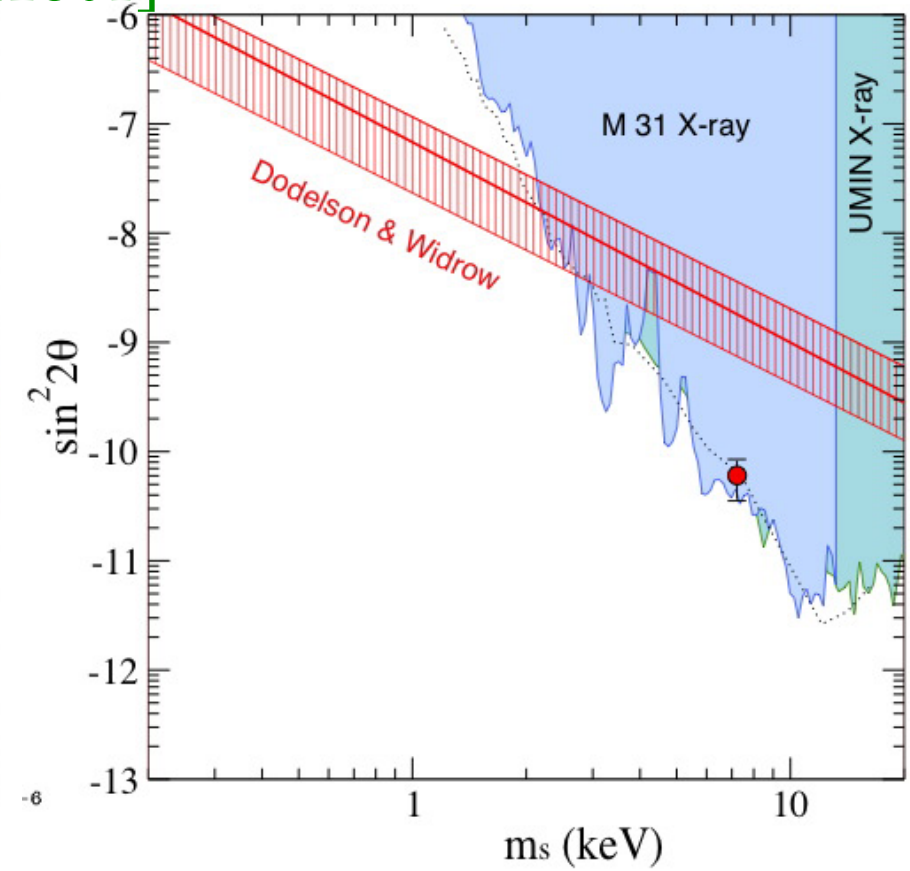
ν EWS FROM THE SKY

Possible new line in X-ray data at about 3.5 keV !
Seen both in stacked clusters and in Andromeda/Perseus.
[1402.2301, 1402.4119]

Not seen in Virgo or centre of Milky Way... [1405.7943]

[1402.2301]





Is it a real signal ?

Instrumental line ?

Probably not, seen in both XMM & Chandra.
Also at slightly different energy depending on the cluster due to red-shift.

Atomic line ?

Not clear: possible contribution of Chlorine and Potassium debated recently. [1408.1699, 1409.4143]
On the other hand, it is seen in Andromeda, where there is no hot gas...

Consider the signal real and interpret it as decaying DM:

$\tau_{DM} \sim 10^{28}\mathrm{s}$ $\qquad$ $m_{DM} \sim 7\ \mathrm{keV}$

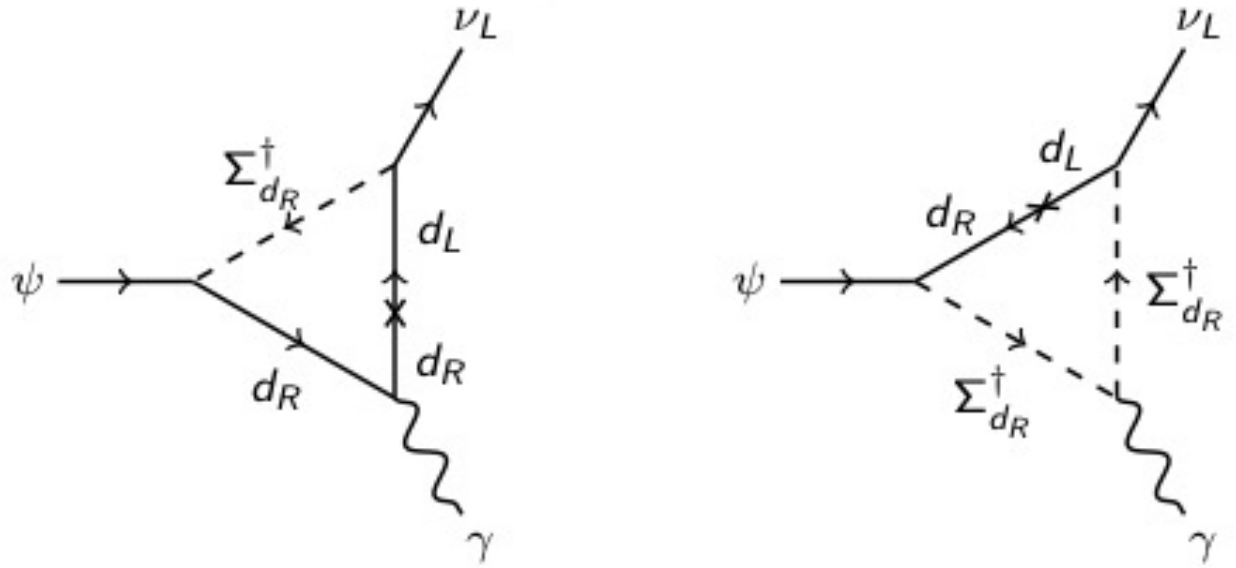
X-RAY LINE IN MDDM

For such a low DM mass, all the 3-body decays are kinematically closed (even $e^+e^-\nu$). Therefore the DM decays via one-loop diagrams in $\gamma\ \nu$

Feynman diagrams:

(H. Haber, D. Wyler - Nucl. Phys. B 323 (1989) 267)

[Garny et al, 1011.3786]



Lifetime:

$$\tau(\psi \to \gamma\nu) \simeq 10^{-12}\,\mathrm{s}\left(\frac{1\,\mathrm{keV}}{m_\psi}\right)\left(\frac{m_\Sigma^2 - m_d^2}{m_\psi m_d}\right)^2\left[1 + \frac{m_\Sigma^2}{m_\Sigma^2 - m_d^2}\ln\left(\frac{m_d^2}{m_\Sigma^2}\right)\right]^{-2}(\lambda'\lambda)^{-2}$$

X-RAY LINE IN MDDM

[Arcadi, LC, Dradi, xxxx]

Keeping still the FIMP production mechanism fixes again one of the couplings as before, but with a lower DM mass

$$\lambda \sim 0.8 \times 10^{-8} \left(\frac{m_{DM}}{7\text{keV}}\right)^{-1/2} \left(\frac{m_\Sigma}{1\text{TeV}}\right)^{1/2} \left(\frac{\Omega_{DM} h^2}{0.11}\right)^{1/2}$$

weak dependence on mass: the coupling is a just a bit larger...

On the other hand to match the DM lifetime need

$$\lambda' \sim 3 \times 10^{-3} \left(\frac{m_{DM}}{7\text{keV}}\right)^{-3/2} \left(\frac{m_\Sigma}{1\text{TeV}}\right)^{2} \left(\frac{\tau_{DM}}{10^{28}\ \text{s}}\right)^{-1/2}$$

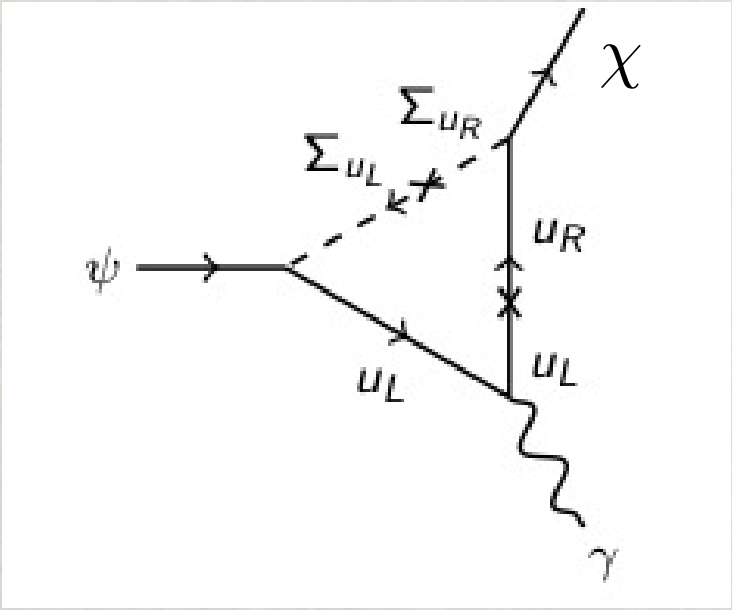
strong dependence on mass: the coupling is much larger !

Prompt decays at the LHC !

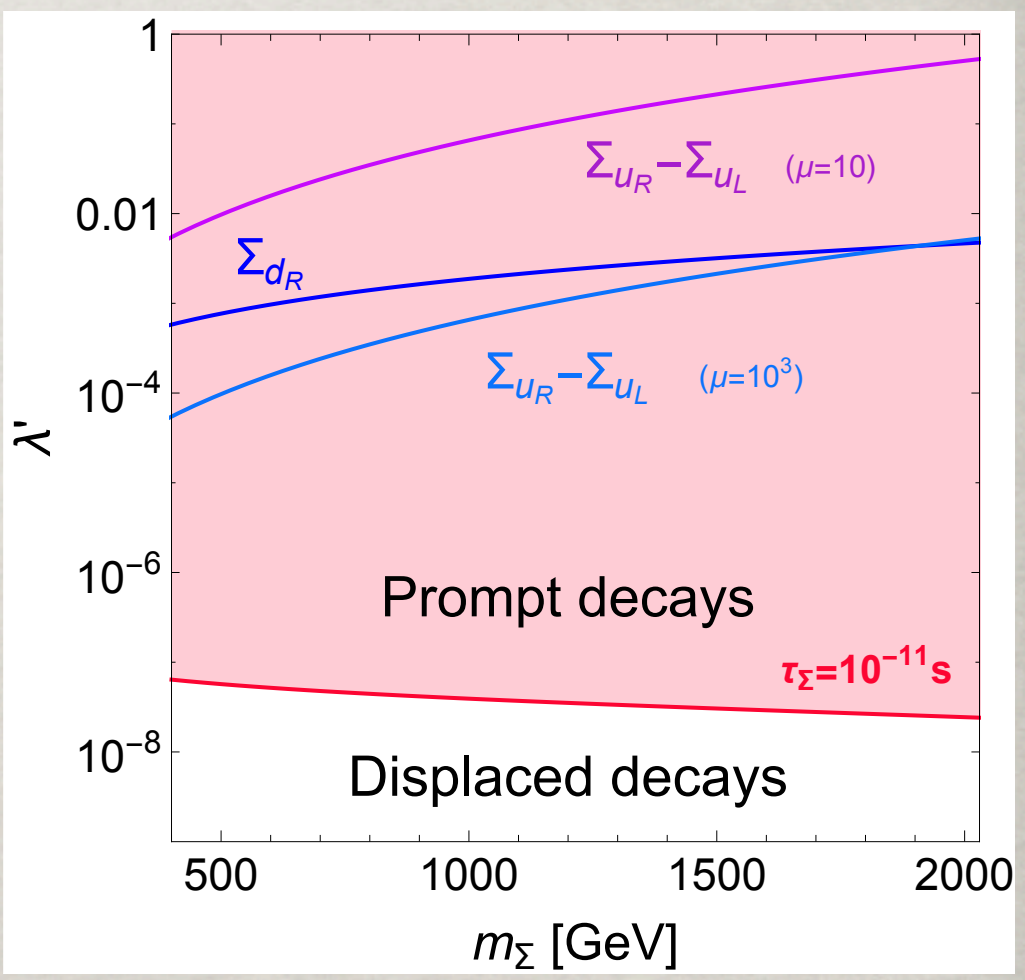
X-RAY LINE IN MDDM

[Arcadi, LC, Dradi, xxxx]

Play around with more scalar fields at the same time with mixing via Higgs..., conclusions very similar:



Chirality flip with top possible !



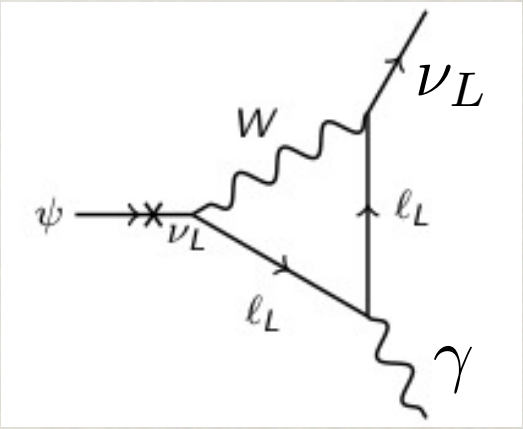
Prompt decays at the LHC via λ' coupling!

X-RAY LINE IN MDDM

[Arcadi, LC, Dradi, xxxx]

Otherwise mix the DM with the neutrino "a` la sterile ν_s", then the DM decay depends only on the new mixing and not on the couplings λ, λ'...

$$\tilde{\lambda}\, \bar{\psi} \nu_L H_u \rightarrow \tilde{\lambda} v_u\, \bar{\psi} \nu_L$$



Still they are not forbidden help produce the right DM density without invoking neutrino oscillations (Dodelson-Widrow production is too low and Shi-Fuller needs L ~ O(0.1)...).

Then for similar values of $\lambda' \sim \lambda$ displaced vertices can appear at the LHC and both decay could be measurable.

Possible to have displaced vertices at the LHC and to probe the DM production mechanism !

Outlook

Outlook

- The search for a DM particle continues on all fronts: WIMP DM is not the only DM paradigm tested, another attractive possibility 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...
- The scenario can also explain the recently observed 3.5 keV X-ray line, but then prompt decays at LHC are expected, as long as the mixing with neutrino does not dominate.