
# FIMP/SWIMP DM AT THE LHC

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inVisibles
neutrinos, dark matter & dark energy physics

SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS

# Outline

- Introduction:
  From WIMPs to FIMPs/SuperWIMPs

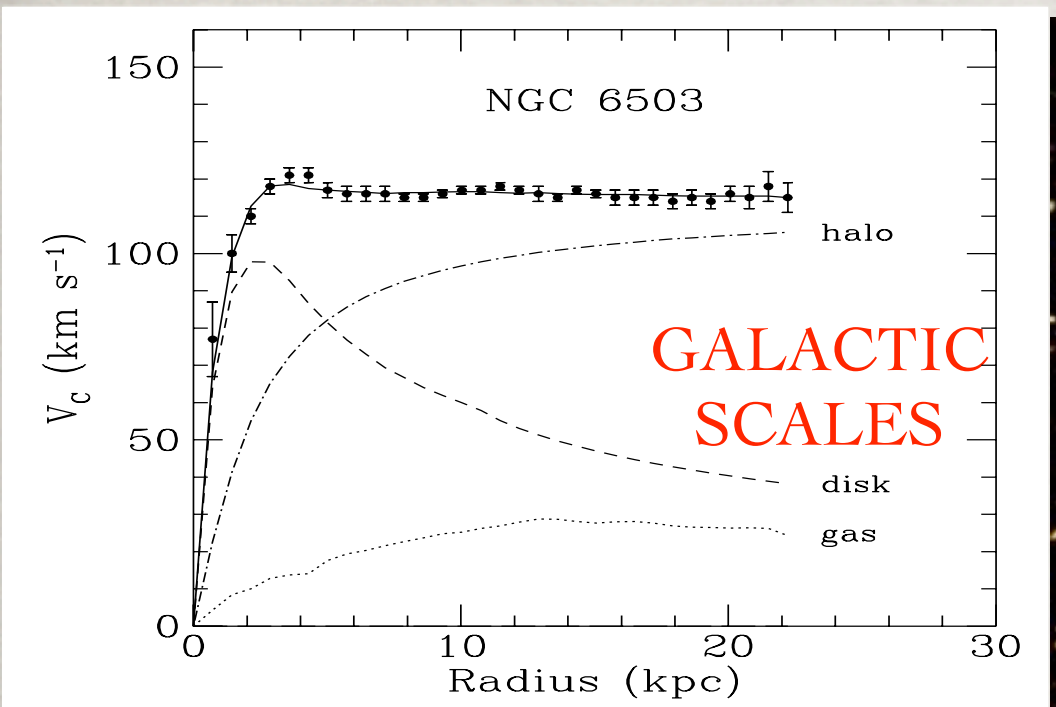
- A minimal decaying DM scenario:
  FIMP @ LHC
  with G. Arcadi & F. Dradi

- Gravitino as a SWIMP:
  - within the pMSSM
  - DM & baryogenesis connection
  with A. Arbey, M. Battaglia, J. Hasenkamp & F. Mahmoudi
  with G. Arcadi & M. Nardecchia

- Outlook

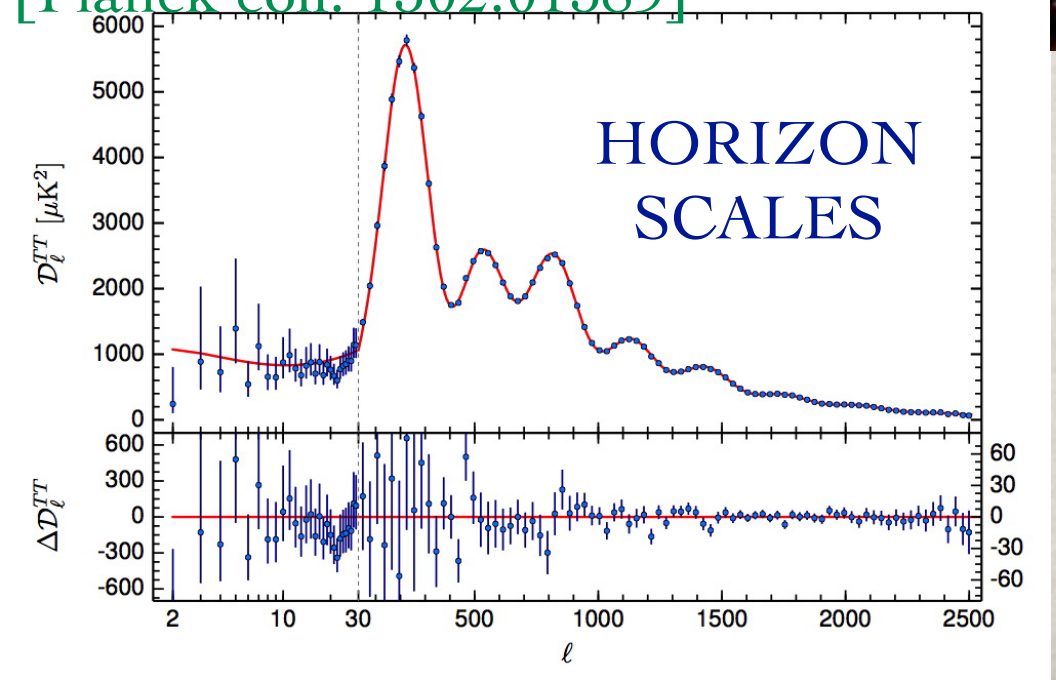
# From WIMPs to FIMPs & SuperWIMPs

# DARK MATTER EVIDENCE





[Planck coll. 1502.01589]



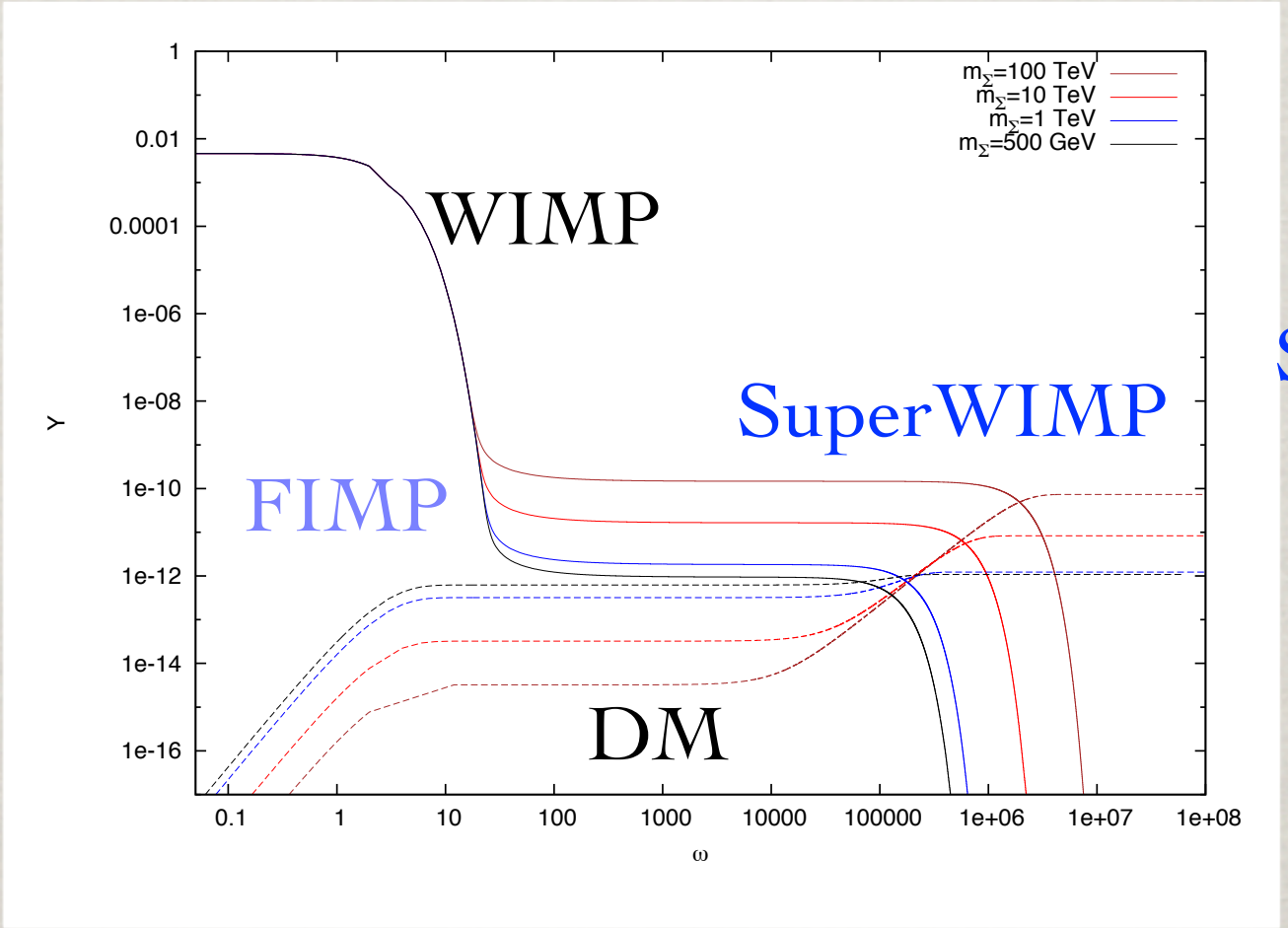

| Particles | $\Omega h^2$ | Type |
|---|---|---|
| Baryons | 0.0224 | Cold |
| Neutrinos | < 0.01 | Hot |
| **Dark Matter** | 0.11-13 | Cold |

# 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



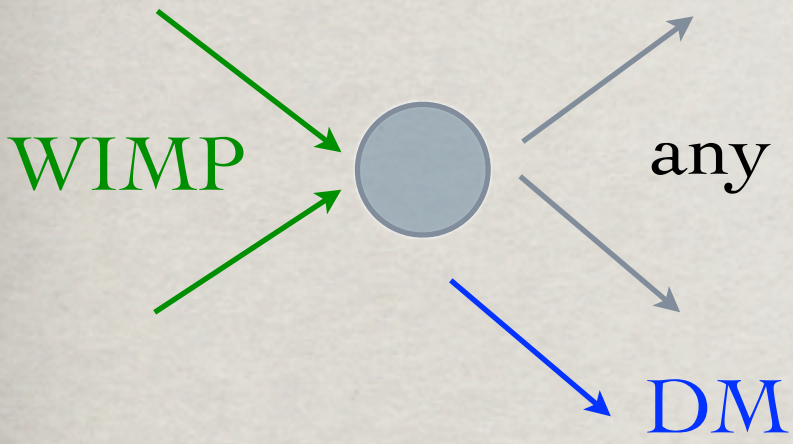

[Feng et al 04]

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

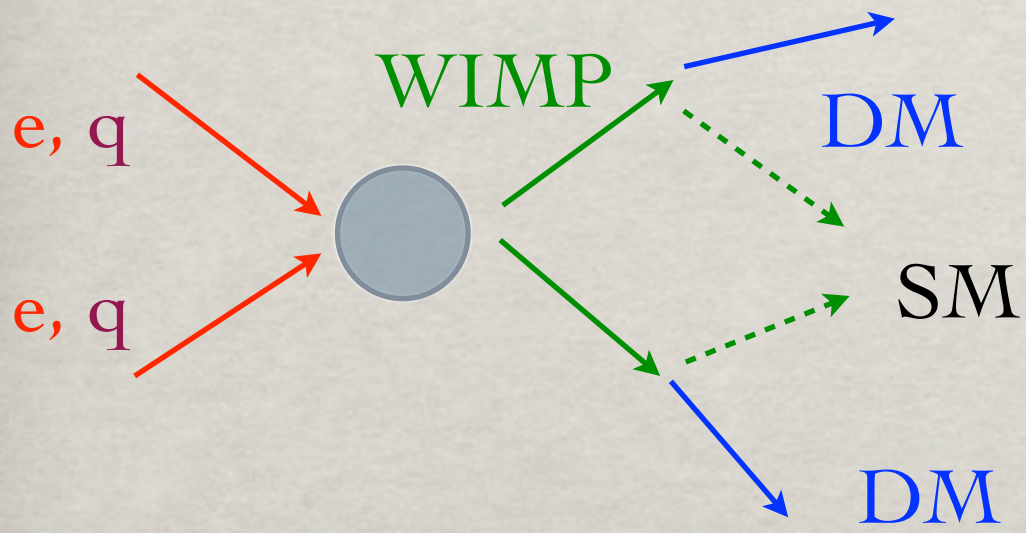
Early Universe: $\Omega_{CDM}h^2$



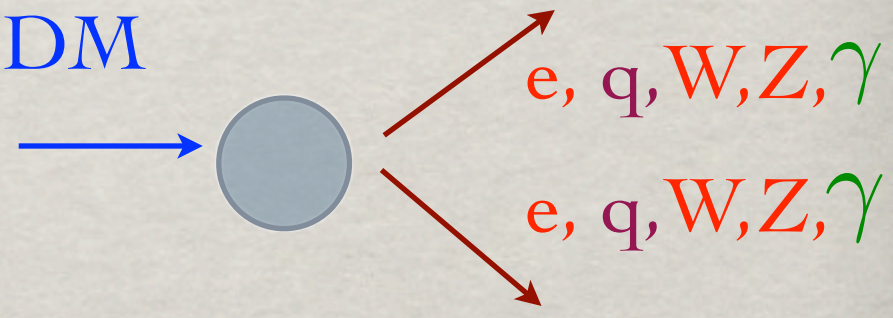

Direct Detection:

NONE...

Colliders: LHC/ILC




Indirect Detection:




decaying DM !

3 different ways to check this hypothesis !!!

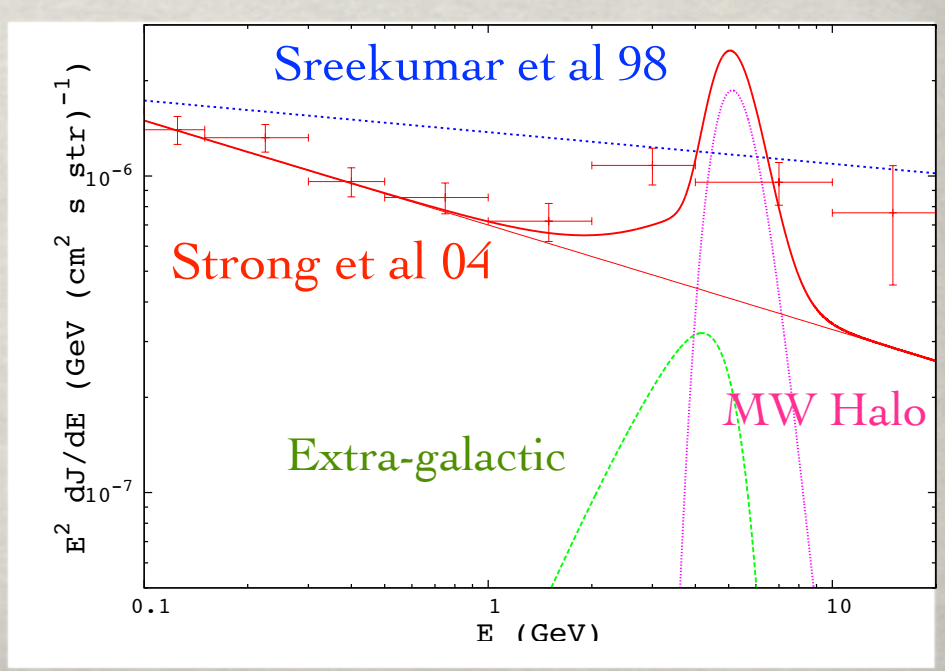
# DECAYING DM

- 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...



# 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 $\Sigma$ :

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

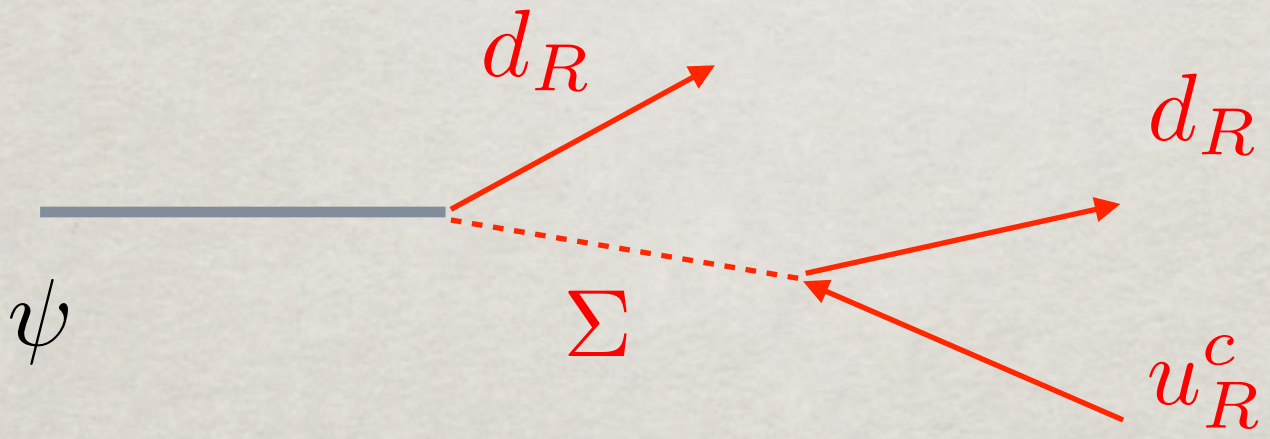
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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 $m_\Sigma \gg m_\psi$ :

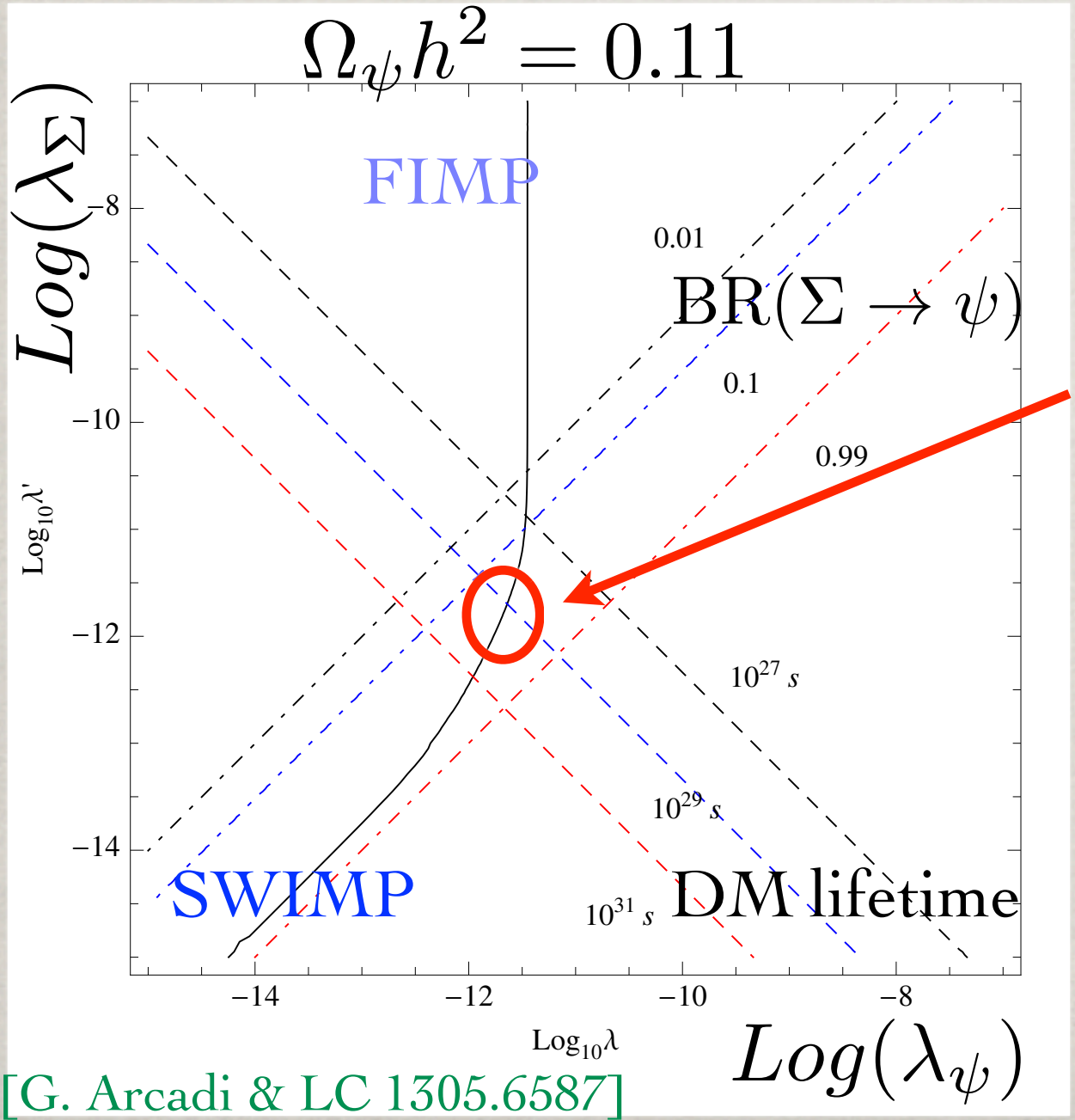



Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

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

# 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 $\Sigma$ 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:

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

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

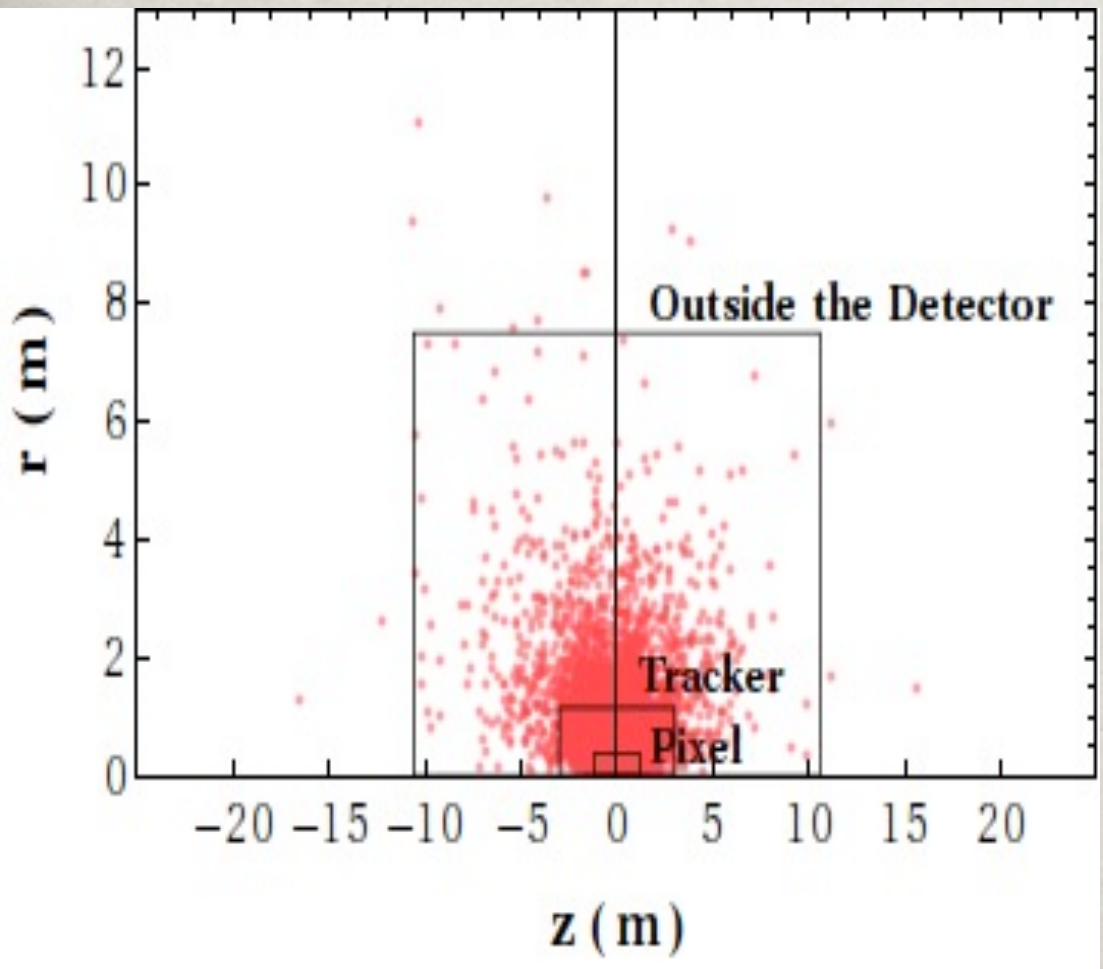
Moreover imposing ID "around the corner" gives

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

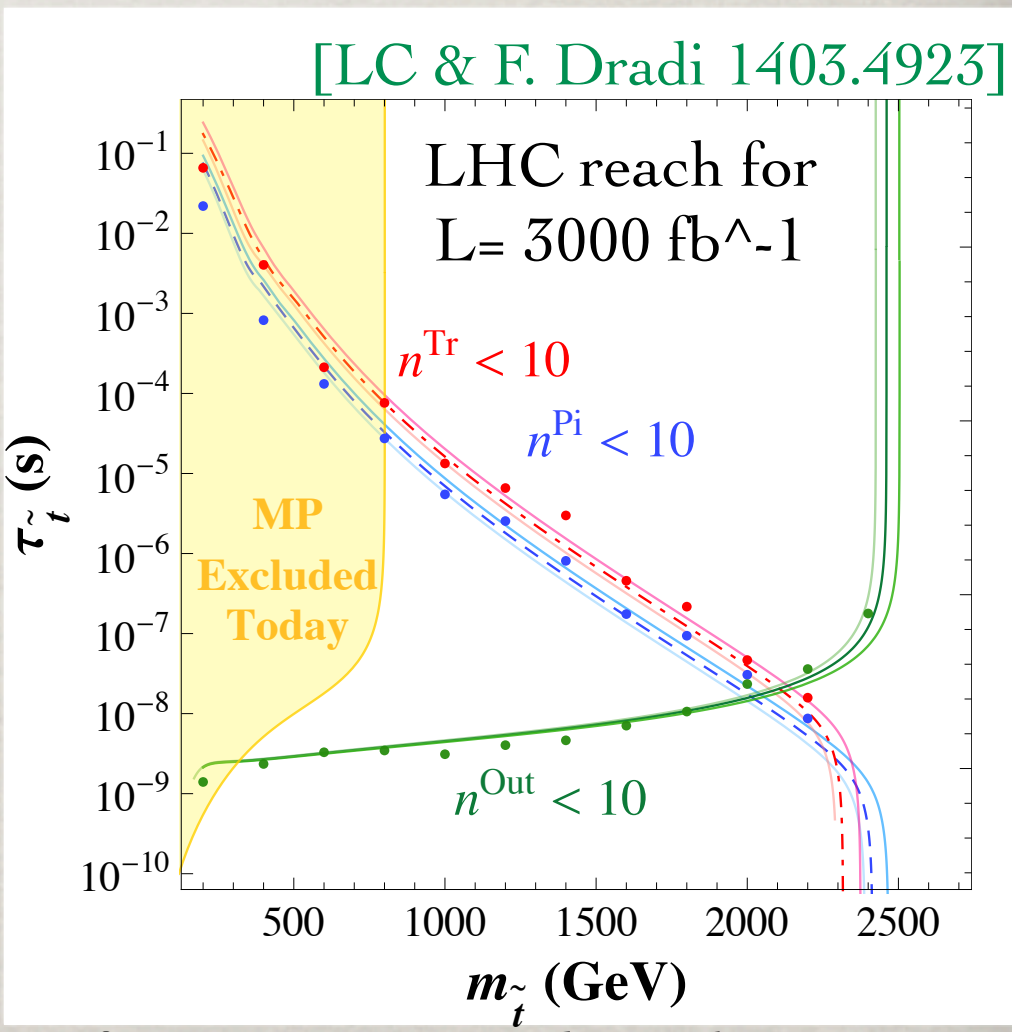
At least one decay could be visible !!!

# LHC: 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:



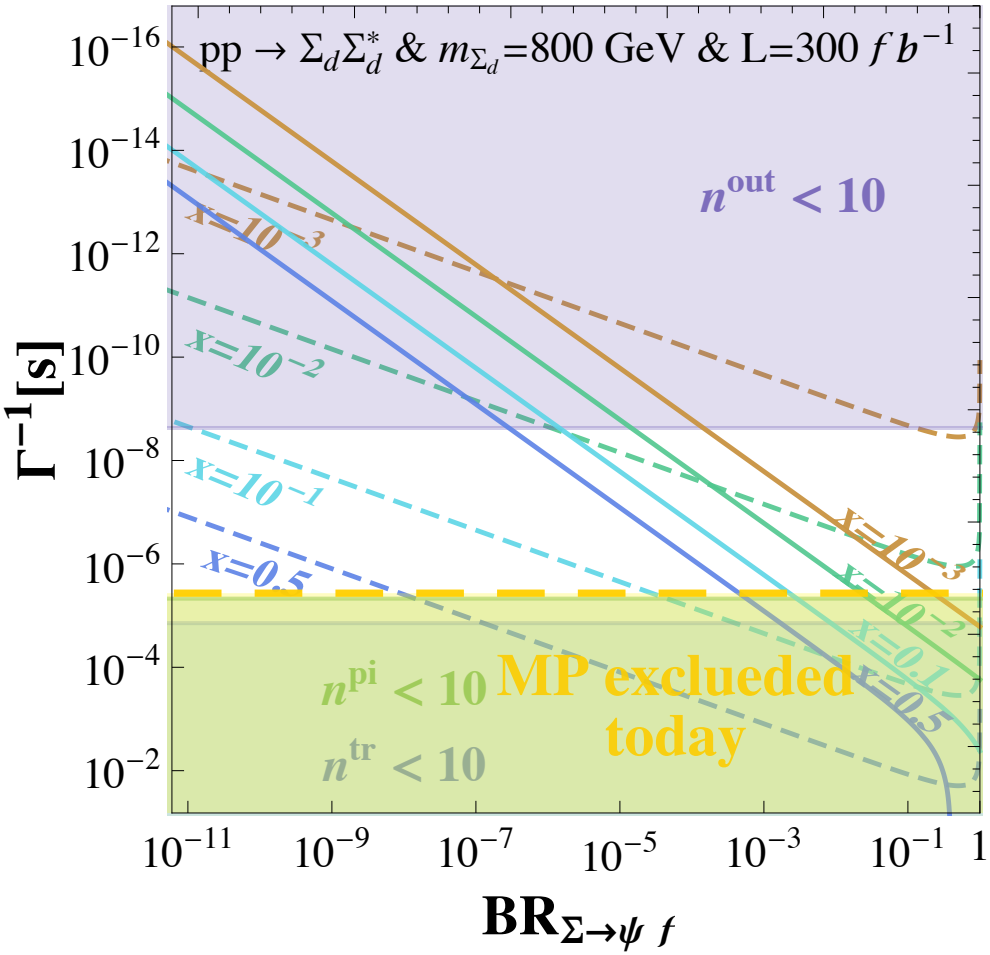

[LC & F. Dradi 1403.4923]

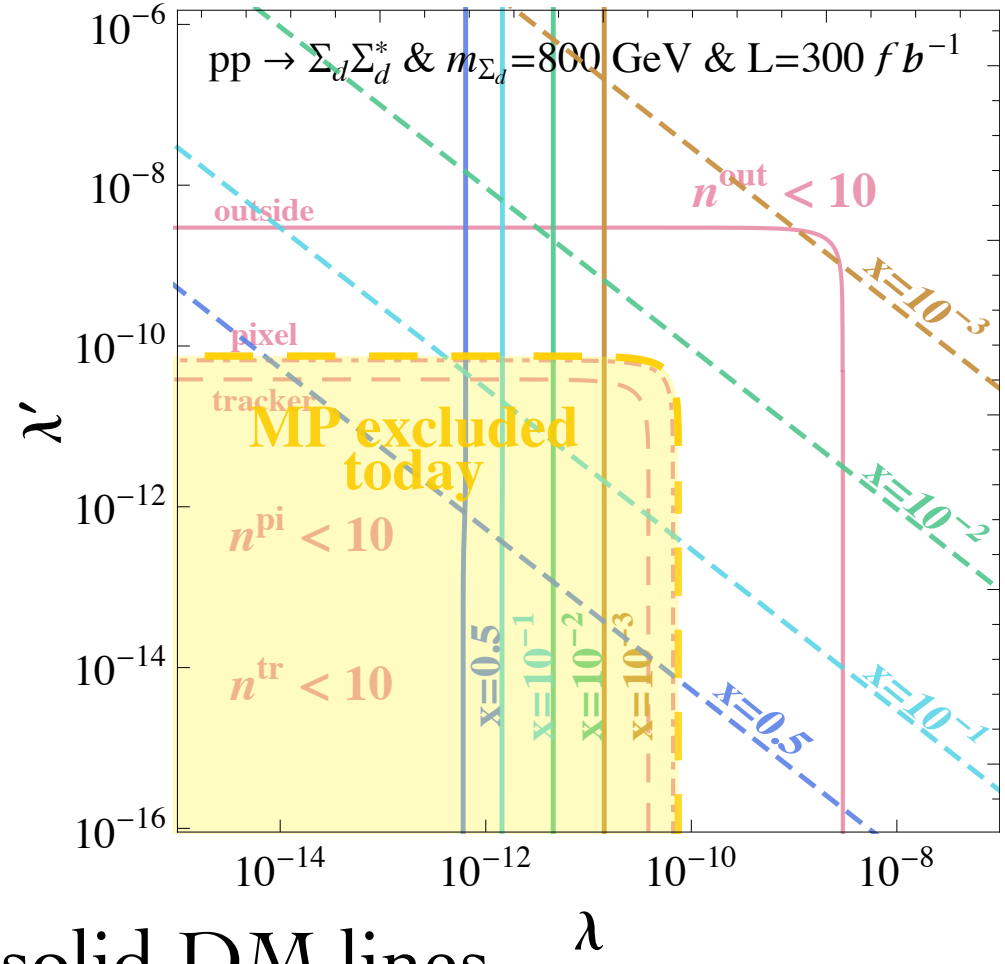



Band is the +/- 1 sigma fluctuation for a Poisson distribution..

# FIMP/SWIMP & COLORED $\Sigma$

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



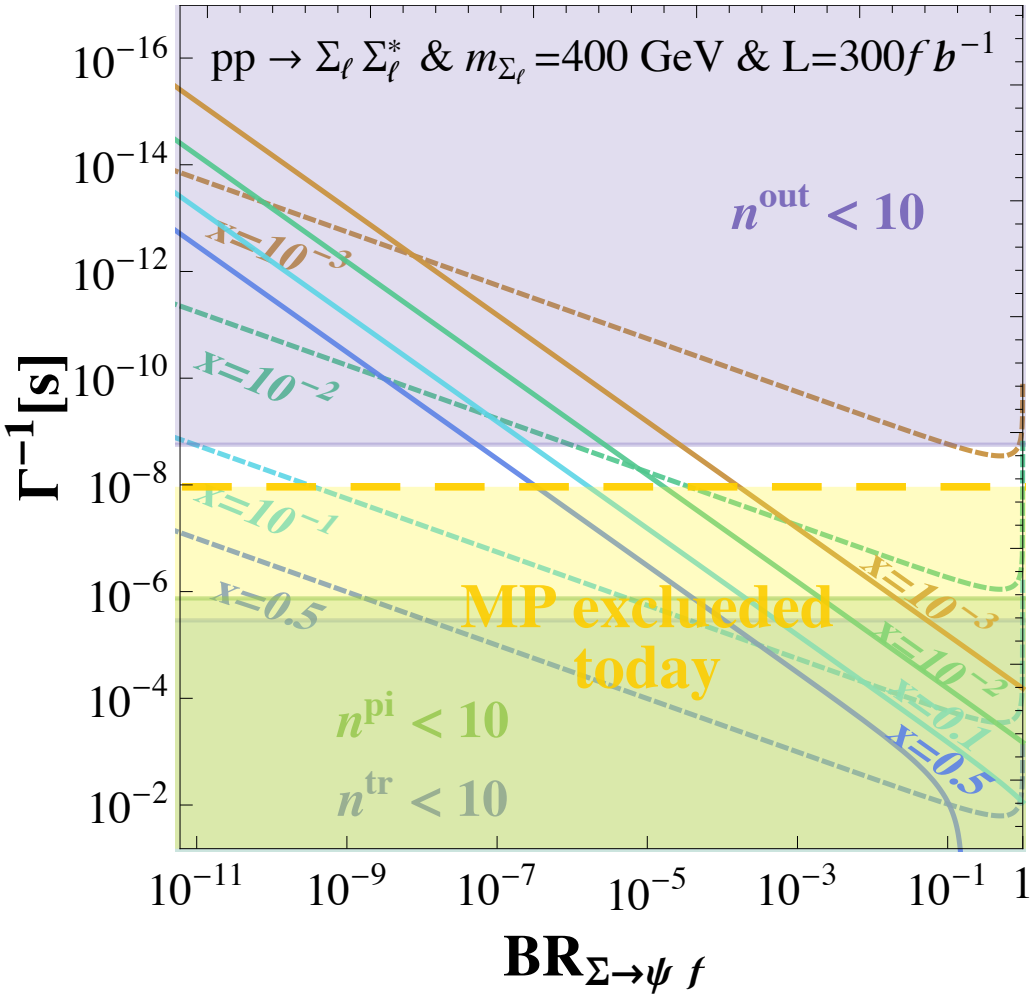



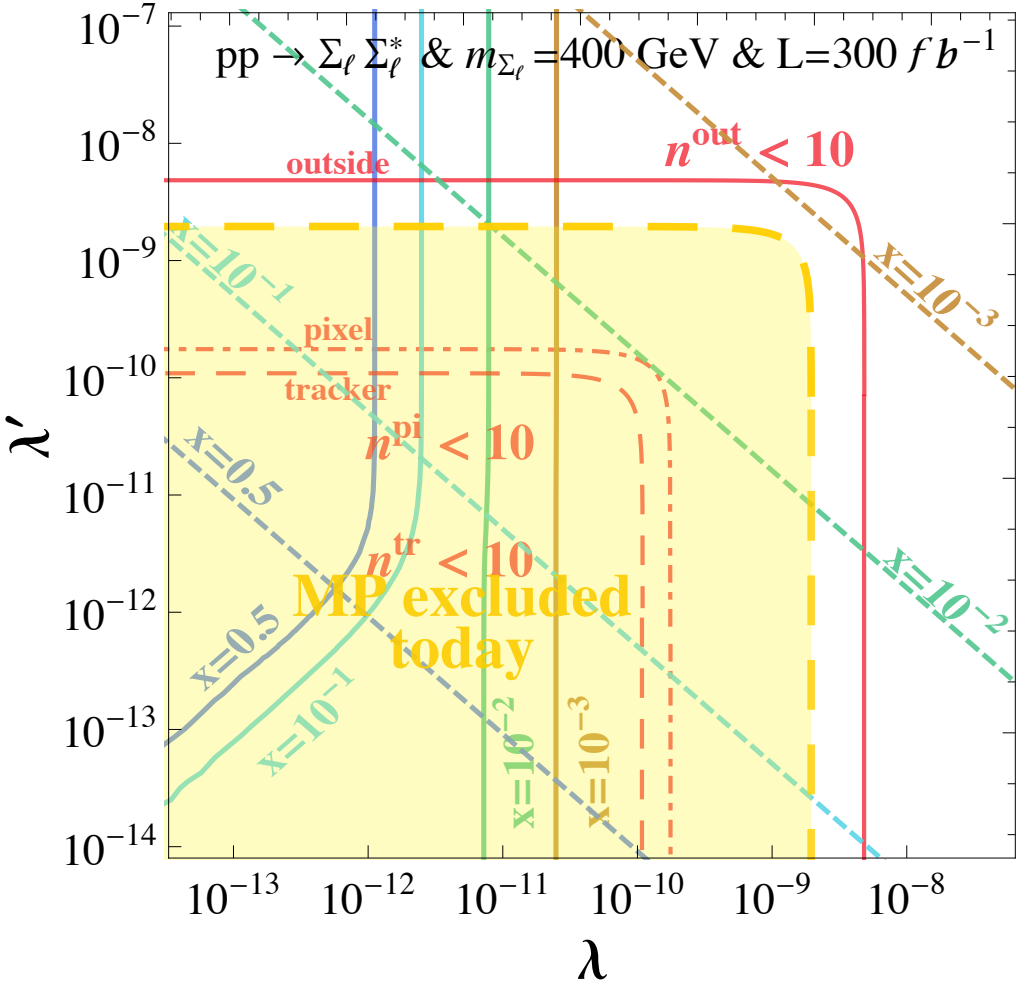

solid DM lines

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

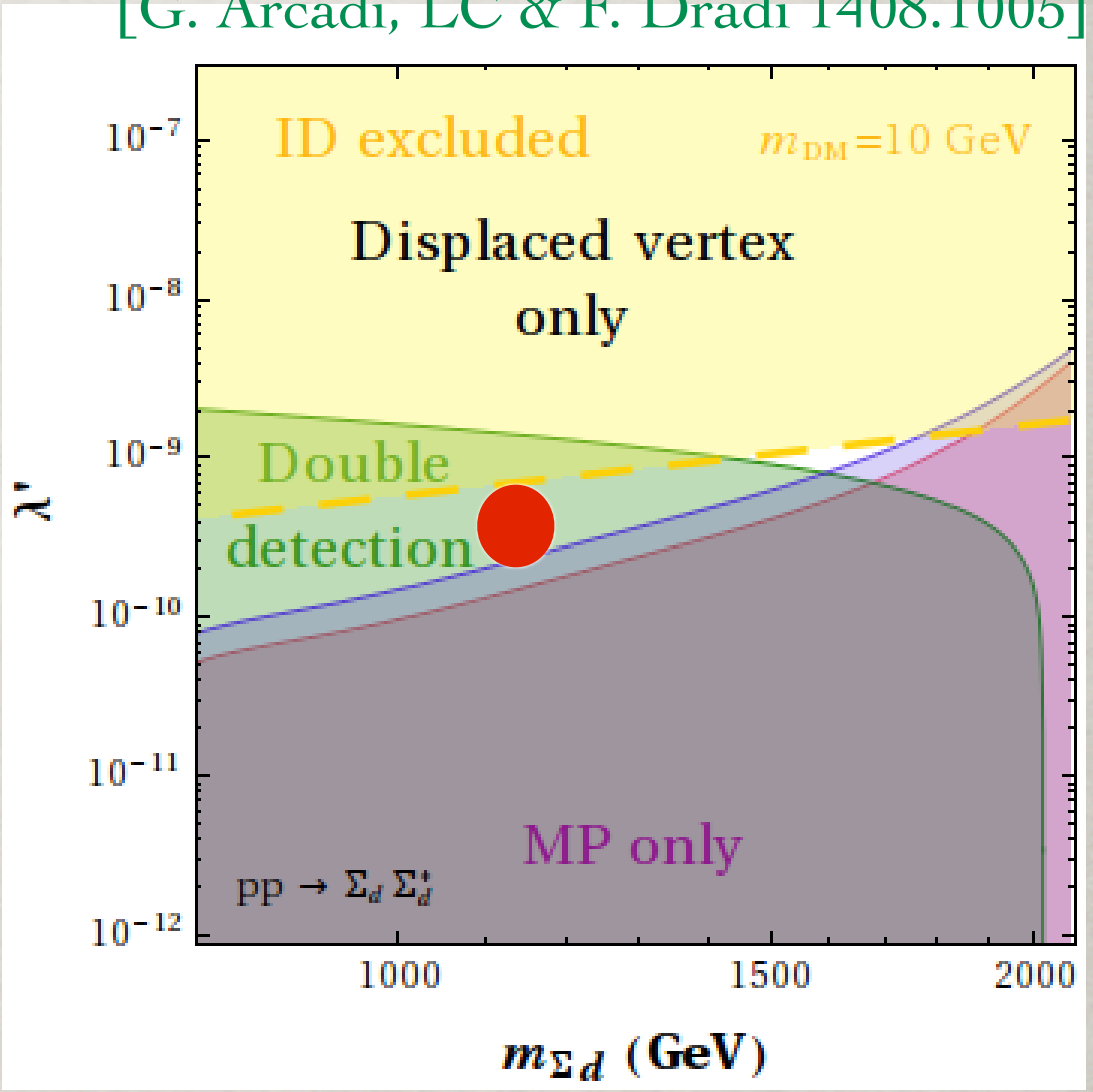
# $\sum$ Combined detection

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 !

# Gravitino DM in the pMSSM

# 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

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

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

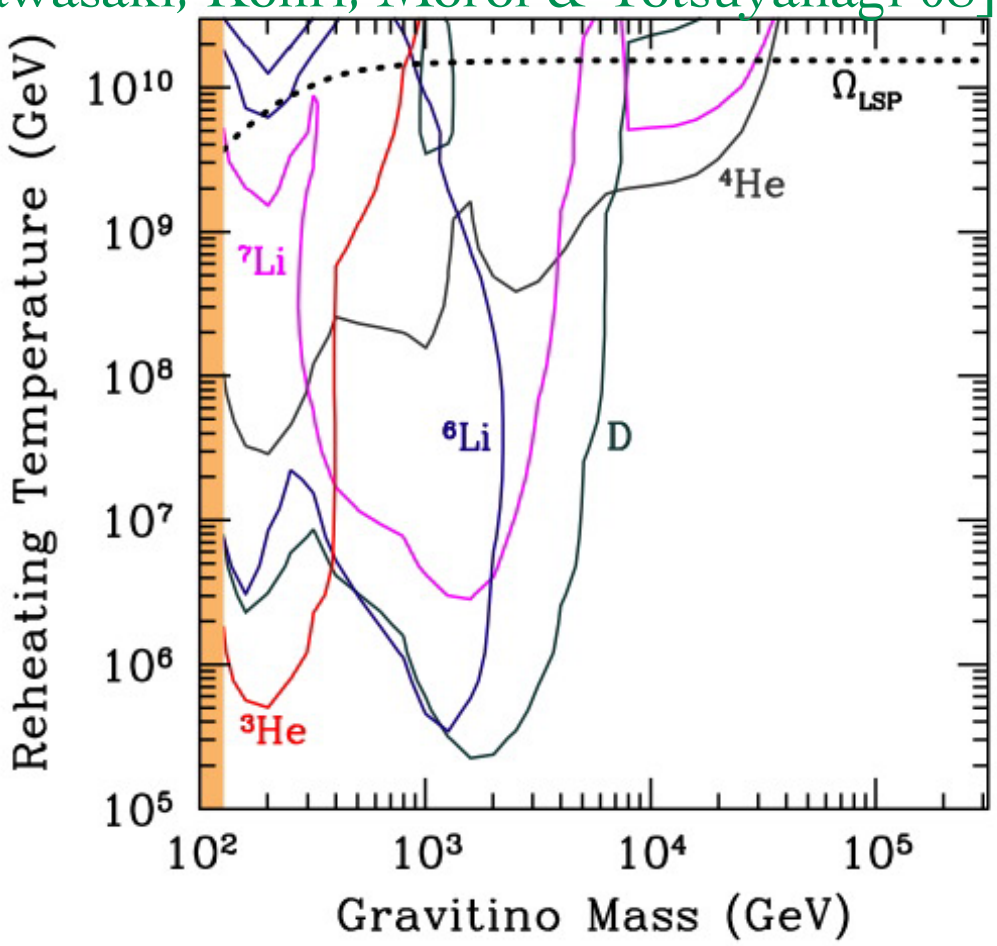
$$\Omega_{3/2}h^2 \simeq 0.3 \left(\frac{1\text{GeV}}{m_{3/2}}\right)\left(\frac{T_R}{10^{10}\text{ GeV}}\right)\sum_i c_i \left(\frac{M_i}{100\text{ GeV}}\right)^2$$

[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]




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

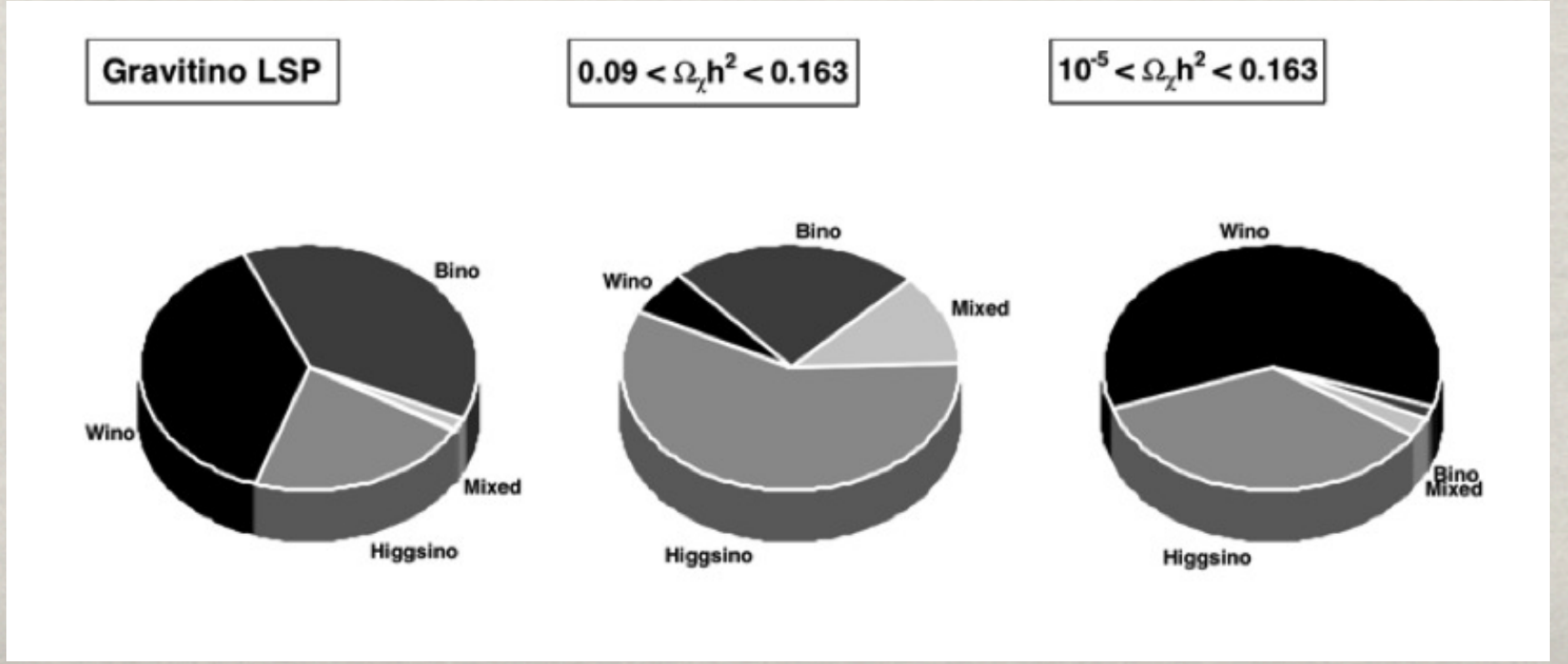
BBN is safe only if the gravitino mass is larger than 40 TeV, i.e. the lifetime is shorter than ~ 1 s, or if the reheating temperature is small! Indeed due to non-renormalizable coupling

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

# Gravitino DM in pMSSM

[Arbey et al. 1505.04595]

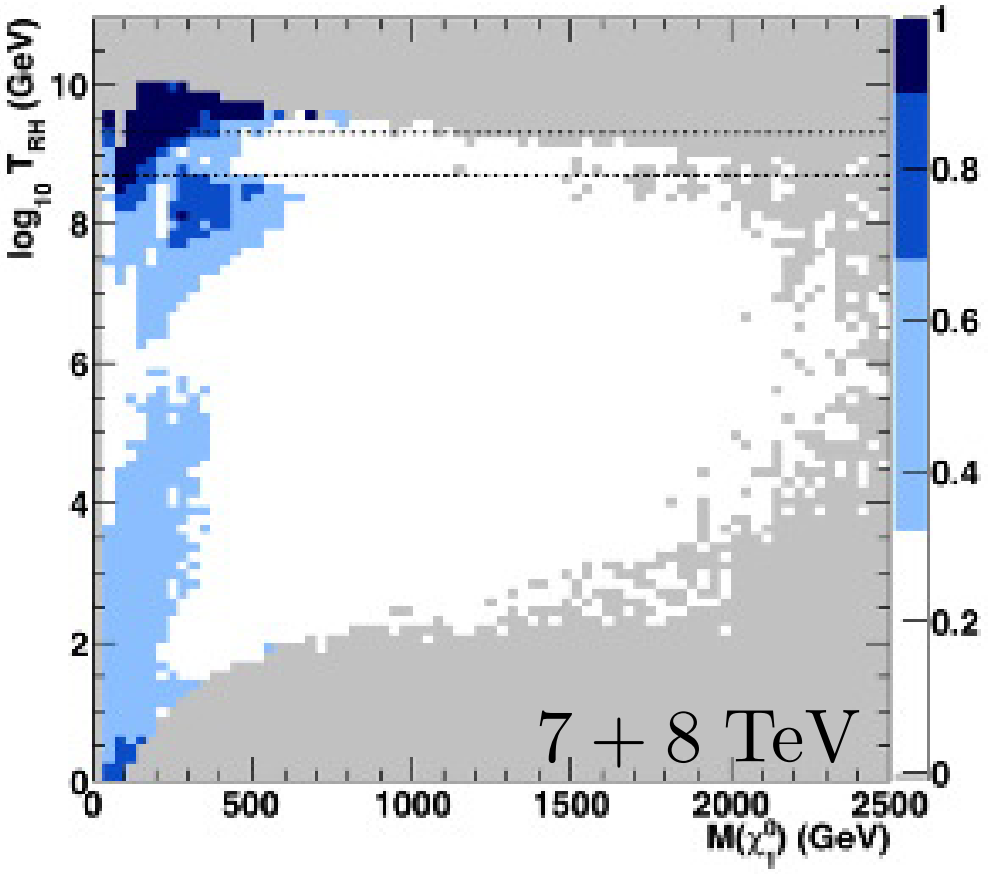
Let us consider gravitino DM with neutralino NLSP within the RPC pMSSM with 19+1 parameters, i.e. no unification assumption, flavour & CP conserving SUSY breaking. Impose all constraints from low energy, flavour observables, LHC SUSY searches and monojets, as well as DM density and BBN limits on neutralino NLSP...

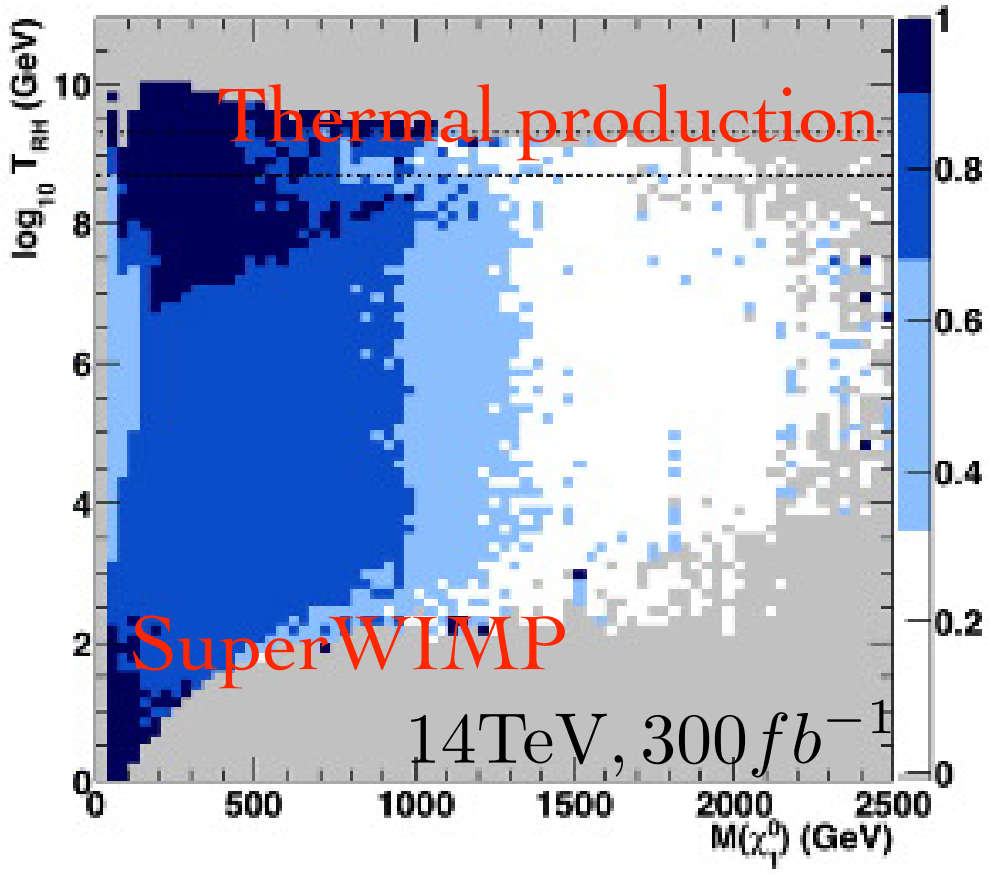


# Gravitino DM in pMSSM

[Arbey et al. 1505.04595]

Interplay between gravitino production and gaugino masses very strong: high $T_{RH}$ region corresponds to light gauginos and it is more easily tested as well as SuperWIMP region !

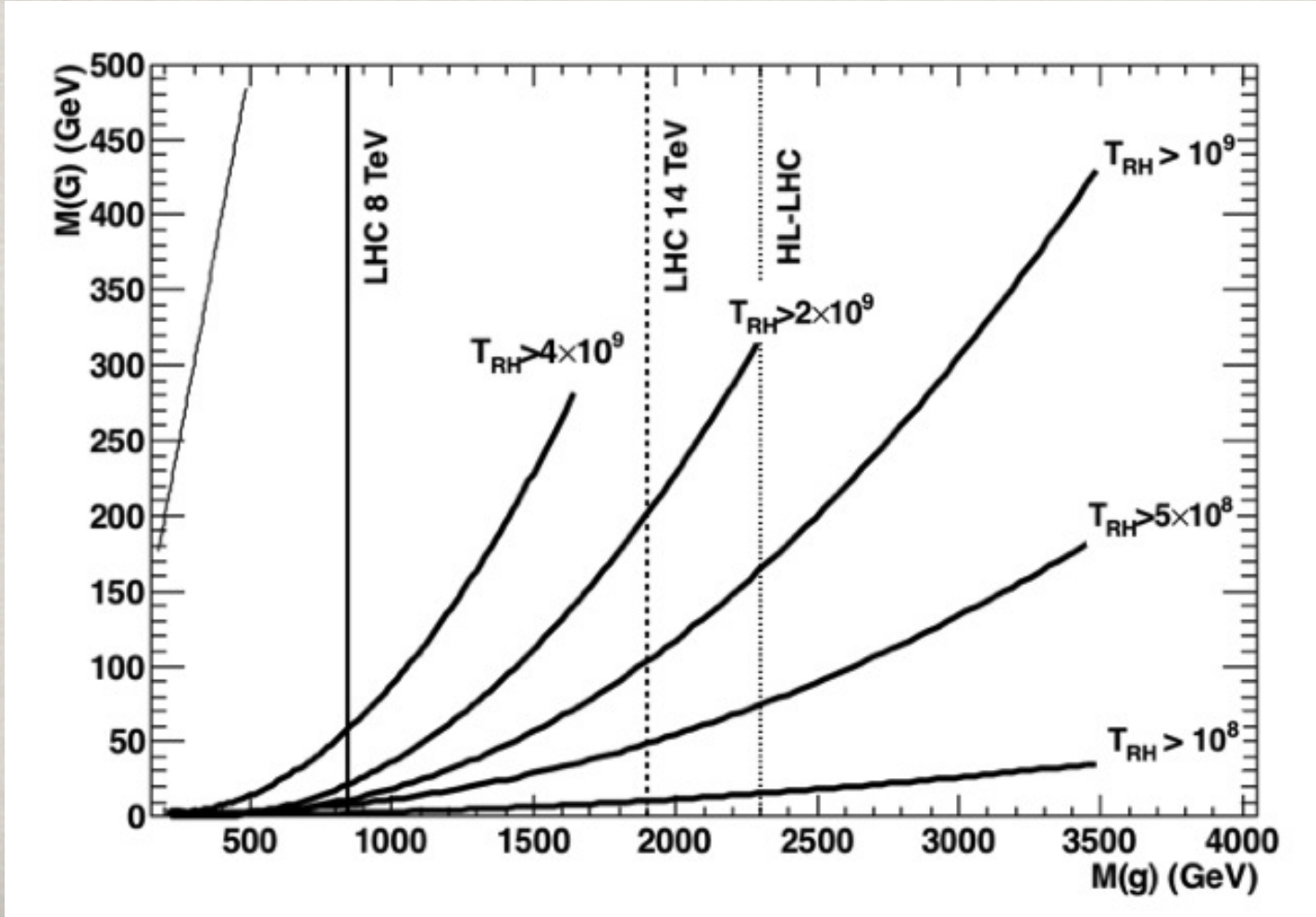


# Gravitino DM & gluino

[Arbey et al. 1505.04595]

Gluino mass is an important parameter in gravitino thermal production: the next LHC run will probe the parameter space compatible with classical (no-flavour) thermal leptogenesis.




Minimal gravitino mass such that $\Omega_{\tilde{G}} h^2 < 0.12$ is given by

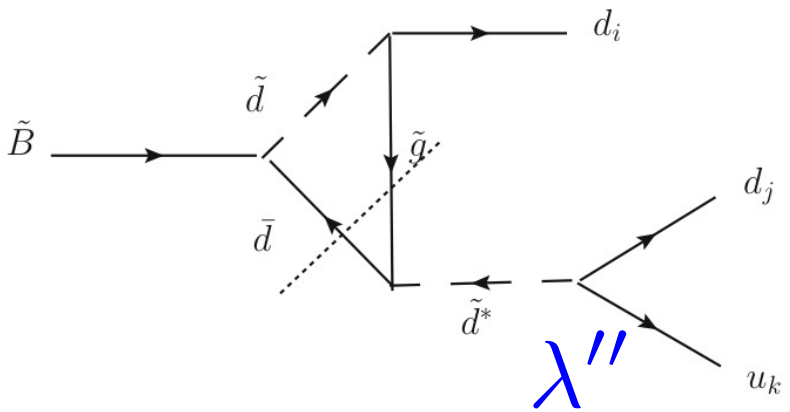
$$m_{\tilde{G}} \propto m_{\tilde{g}}^2$$

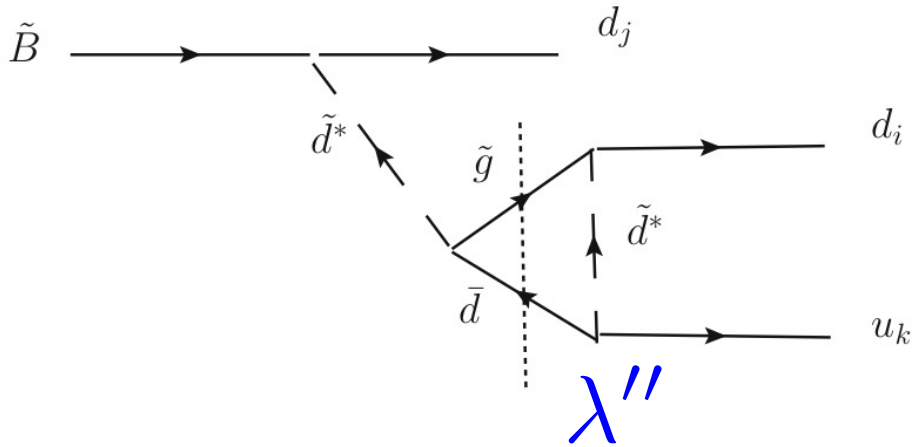
# The Dark Matter-baryogenesis connection

# Baryogenesis in RPV SUSY

[Sundrum & Cui 12, Cui 13, Rompineve 13, ...]

Realization of good old baryogenesis via out-of-equilibrium decay of a superpartner, possibly WIMP-like, e.g. in the model by Cui with Bino decay via RPV B-violating coupling.




CP violation arises from diagrams with on-shell gluino lighter than the Bino. To obtain right baryon number the RPC decay has to be suppressed, i.e. due to heavy squarks, the RPV coupling large and the Bino density very large...

# Baryogenesis & SW DM

[Arcadi, LC & Nardecchia 1312.5703]

In such scenario it is also possible to get gravitino DM via the SuperWIMP mechanism and the baryon and DM densities can be naturally of comparable order due to the suppression by the CP violation and Branching Ratio respectively...

$$\Omega_{\Delta B} = \frac{m_p}{m_\chi} \epsilon_{\rm CP} BR\left(\chi \to \not{B}\right) \Omega_\chi^{\tau \to \infty}$$

Small numbers

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{m_\chi} BR\left(\chi \to DM + \text{anything}\right) \Omega_\chi^{\tau \to \infty}$$

$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \frac{\epsilon_{CP}\, BR(\chi \to \not{B})}{BR(\chi \to DM + \text{anything})}$$

independent of Bino density

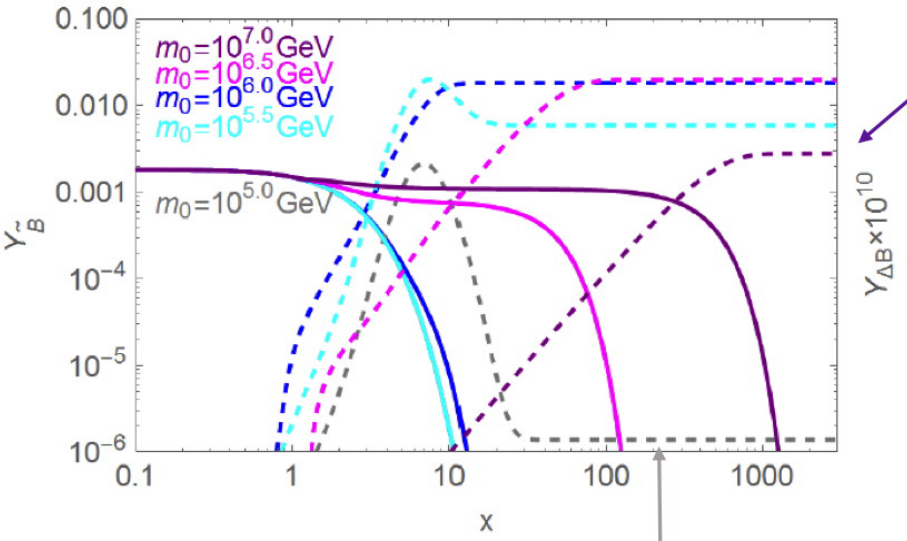
Gravitino DM: BR is naturally small and DM stable enough !

# Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

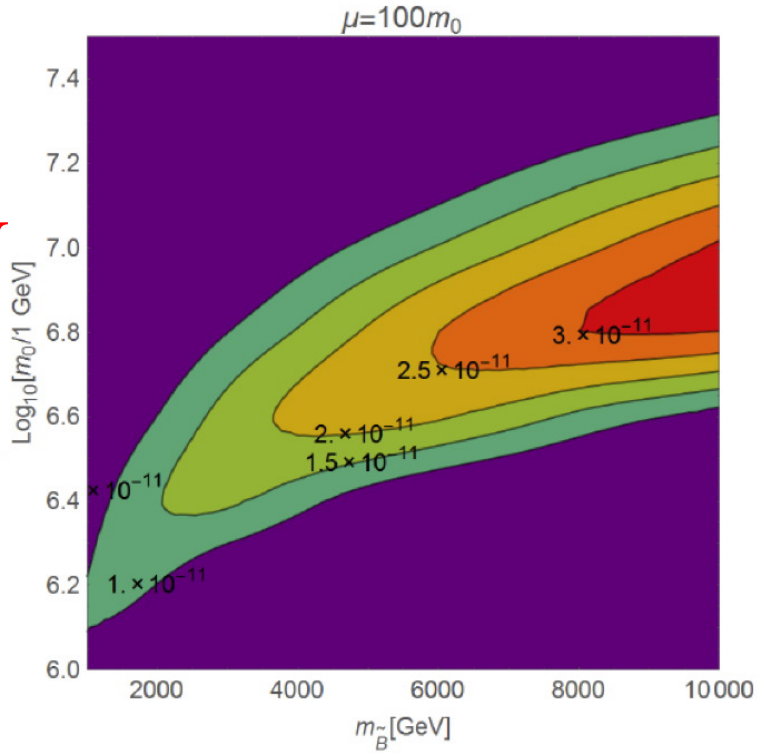
Asymmetry suppressed by the high scalars







$10^7$ GeV



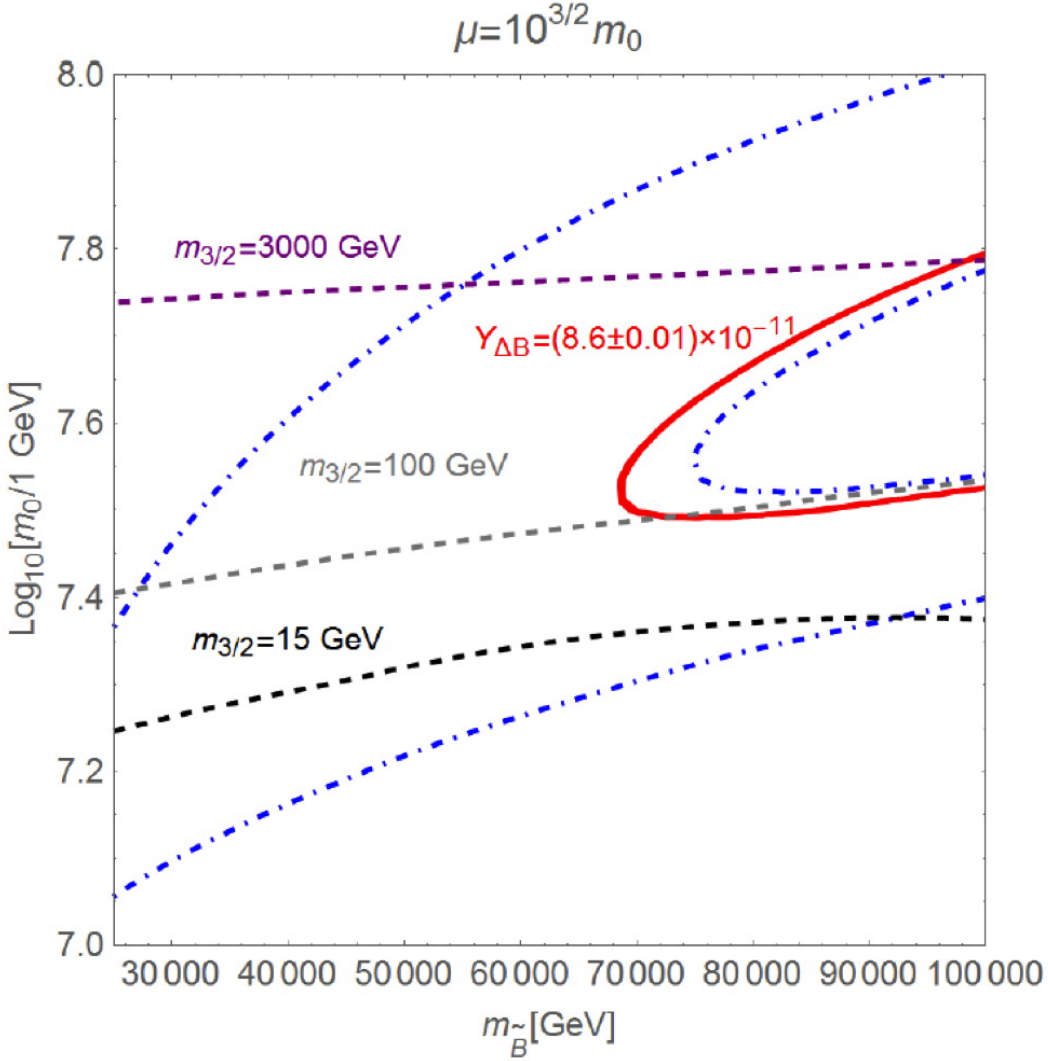

Asymmetry suppressed by wash-out

Rather definite prediction for range of scalar masses Heavy !!!

# Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

But the large scalar mass increases the branching ratio into gravitinos... Need a pretty large gravitino mass to compensate !




Correct baryon density compatible with DM relic density for gravitino masses O(100 GeV-few TeV)

$$\Gamma\left(\tilde{\psi}_{3/2}\to udd\right)=N_c\frac{\lambda^2}{6144\pi^3}\frac{m_{3/2}^7}{m_0^4M_{\rm Pl}^2}$$

$$\tau_{3/2}\approx\frac{4.6}{N_c}\times10^{28}\mathrm{s}\left(\frac{\lambda}{0.4}\right)^{-2}\left(\frac{m_0}{10^{7.5}\mathrm{GeV}}\right)^{4}\left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)^{-7}$$

Lifetime of the gravitino within the sensitivity of AMS.

# Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

The gluino is in this scenario the lightest SUSY particle and may be produced at colliders; but it should be not too much lighter than the Bino, i.e. $m_{\tilde{g}} \sim 0.1 - 0.4\, m_{\tilde{B}} \sim 7 - 28$ TeV, possibly in the reach of a 100 TeV collider.

$$c\tau_{\tilde{g}} \sim 1,5 \text{ cm} \left(\frac{\lambda''}{0.4}\right)^{-2} \left(\frac{m_0}{4 \times 10^7 \text{GeV}}\right)^{4} \left(\frac{m_{\tilde{g}}}{7 \text{ TeV}}\right)^{-5}$$

The heavy squarks give displaced vertices for the gluino decay via RPV, even for RPV coupling of order 1.
Gluino decay into gravitino DM is much too suppressed to be measured.

# 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 points to heavy metastable particles or displaced vertices at LHC with different decay channels !
- A combined detection of displaced vertices/metastable tracks and DM Indirect Detection within the cosmologically favored region is possible in the next run of LHC for a colored scalar. More limited reach for the EW case...
- Gravitino DM with large $T_{RH}$ will be tested in the next LHC run, at low $T_{RH}$ also gravitino SuperWIMP & baryogenesis from Bino decay are feasible with a "mini-split" SUSY spectrum and may give signals in DM indirect detection.