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Superweakly & not so weakly interacting DM

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with G. Arcadi, F. Dradi, M. Nardecchia, F. Kirk,
Ch. Eckner & M. Gustafsson, T. Binder, A. Kamada, et al.

elusiVes-inVisiblesPlus
neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

Outline

- Introduction:
  From WIMPs to FIMPs/SuperWIMPs

- Superweakly interacting DM:
  - decaying DM @ LHC & ID
  - baryogenesis connection

  with G. Arcadi & F. Dradi,
  Ch. Eckner & M. Gustafsson

  with G. Arcadi & M. Nardecchia,
  G. Arcadi & F. Kirk

- Not so weakly interacting DM:
  - kinetic decoupling and the formation of structure on small scales

  with T.Binder, A.Kamada,
  H.Murayama, T. Takahashi,
  N. Yoshida

- Outlook

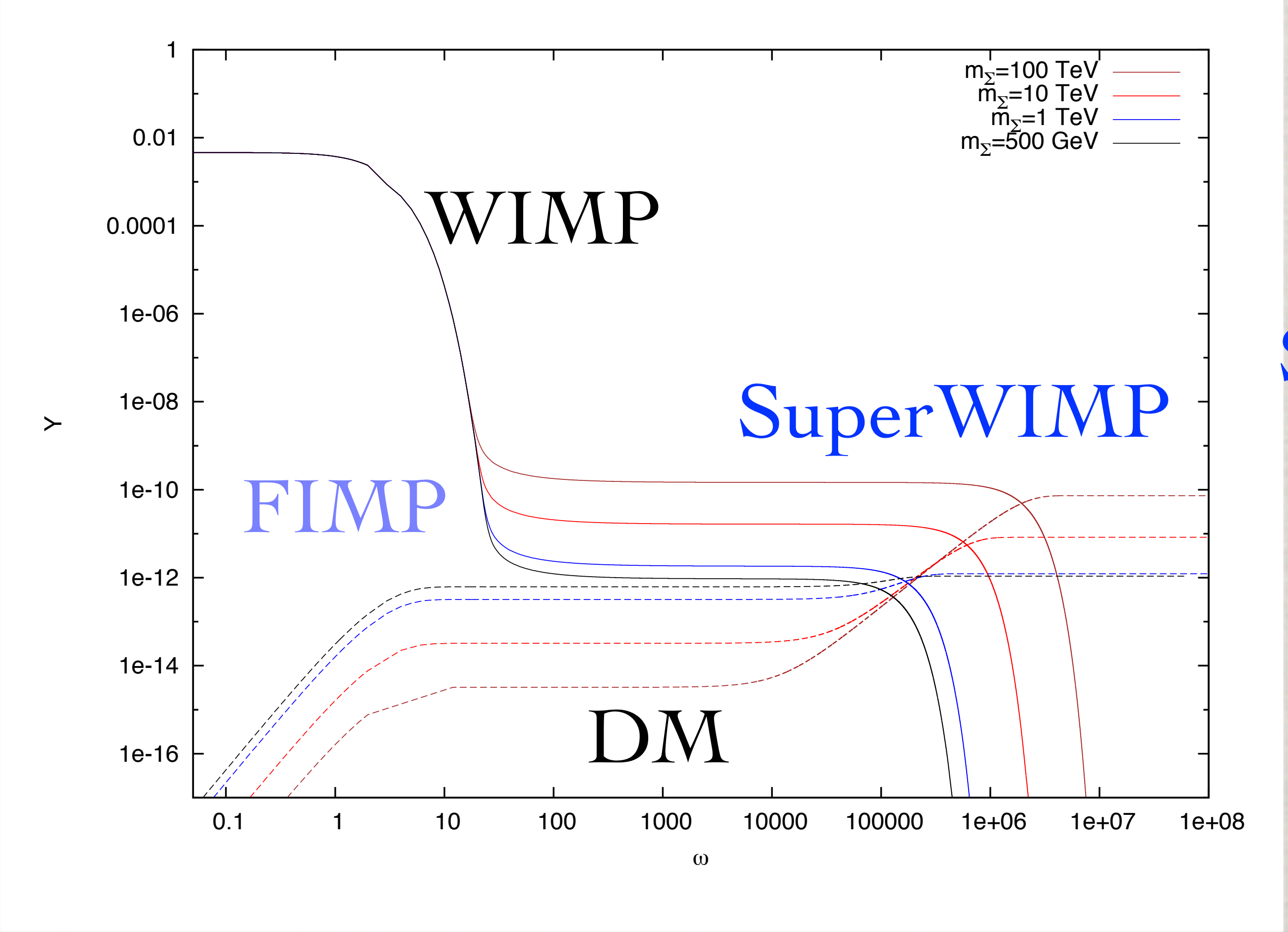
From WIMPs to FIMPS & SuperWIMPs

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



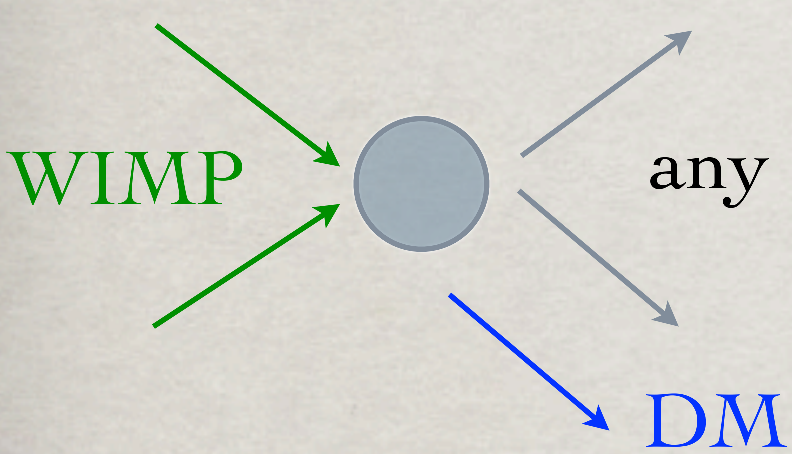
[Feng et al 04]

SuperWIMP DM produced by WIMP decay after freeze-out

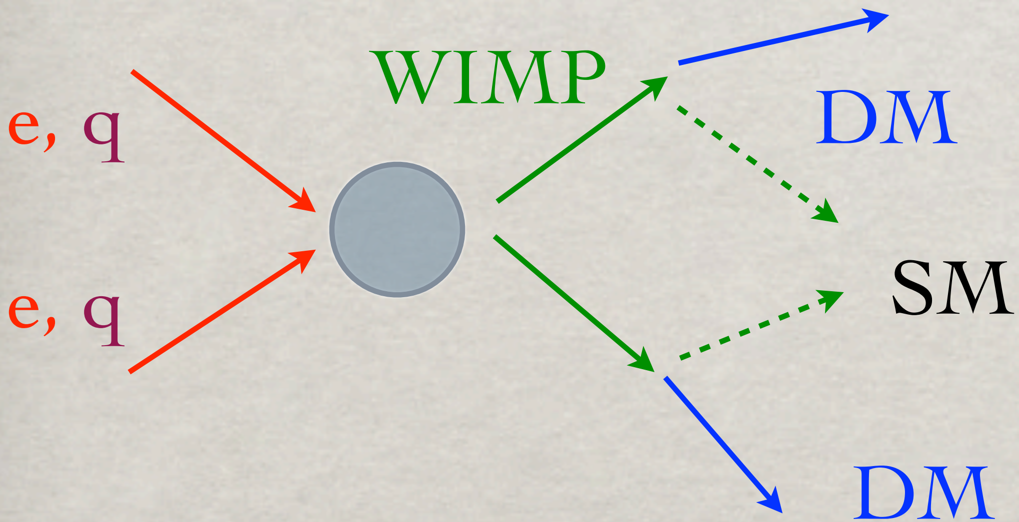
Two mechanism naturally giving "right" DM density depending on WIMP/DM mass & DM couplings

F/SWIMP CONNECTION

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



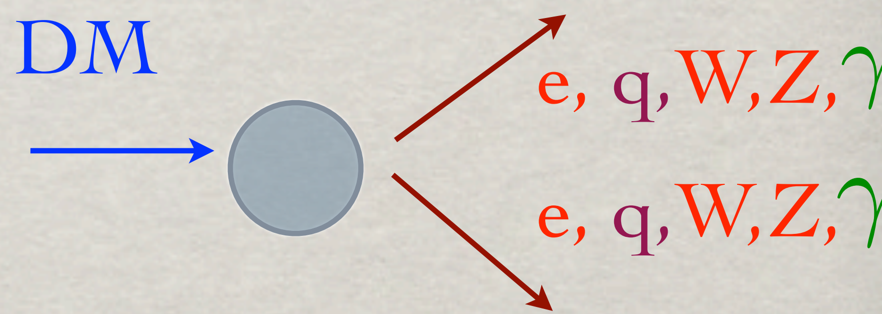
Colliders: LHC/ILC



Direct Detection:

NONE...

Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

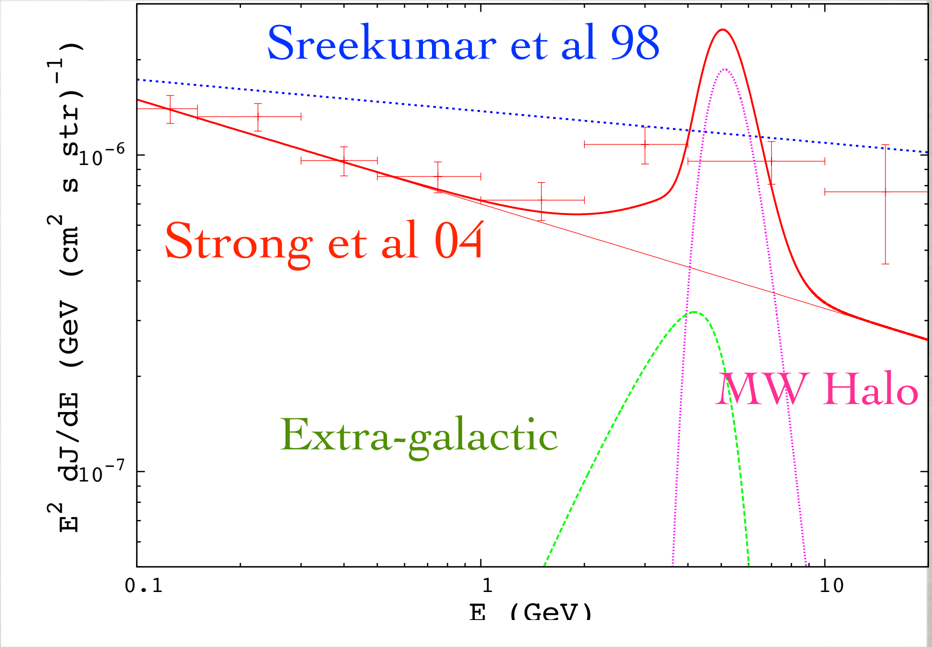
DECAYING DM

- 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 Σ :

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

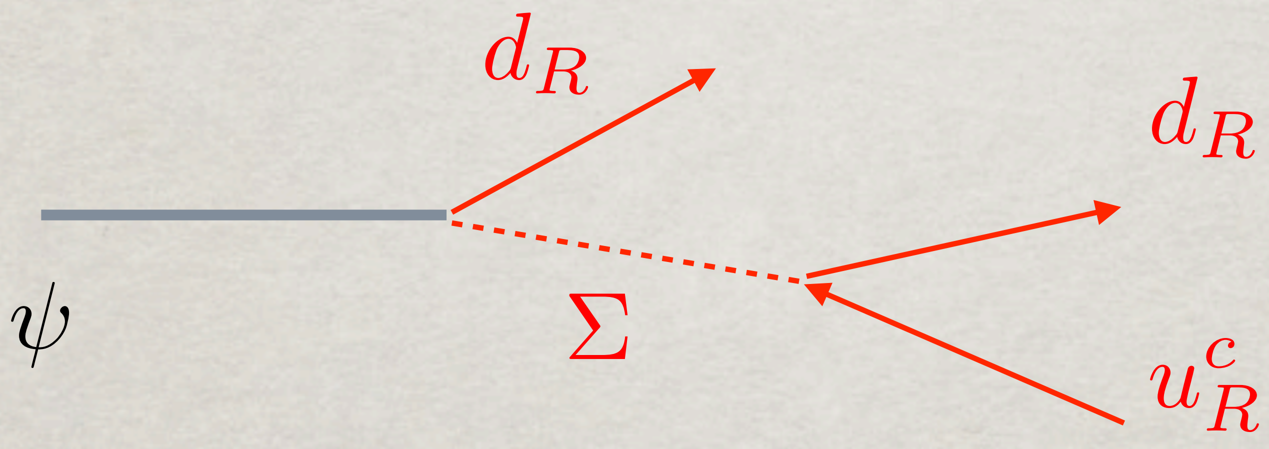
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

$\longrightarrow$ 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 $m_\Sigma \gg m_\psi$:

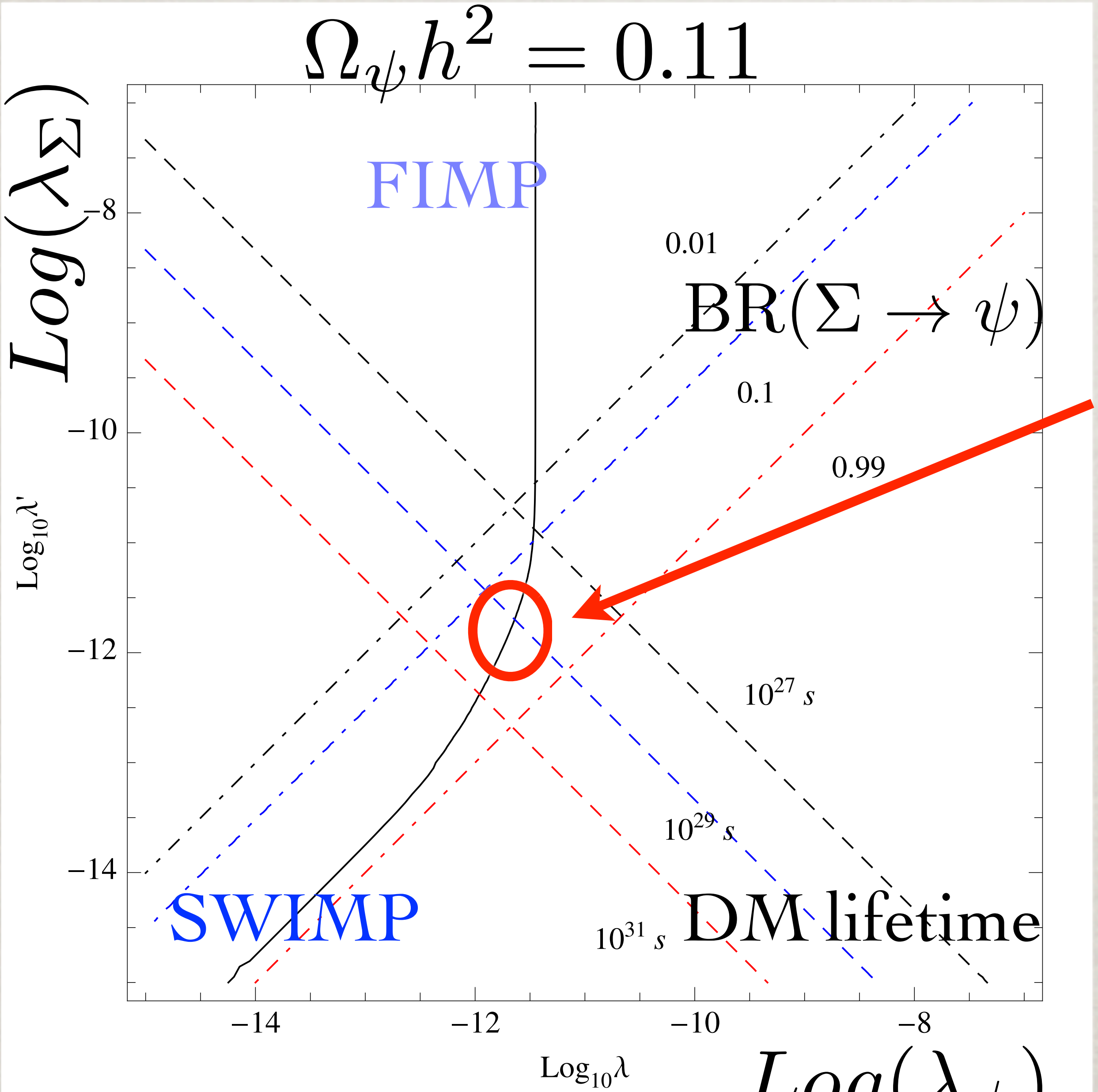


Decay into 3 quarks via both couplings !

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

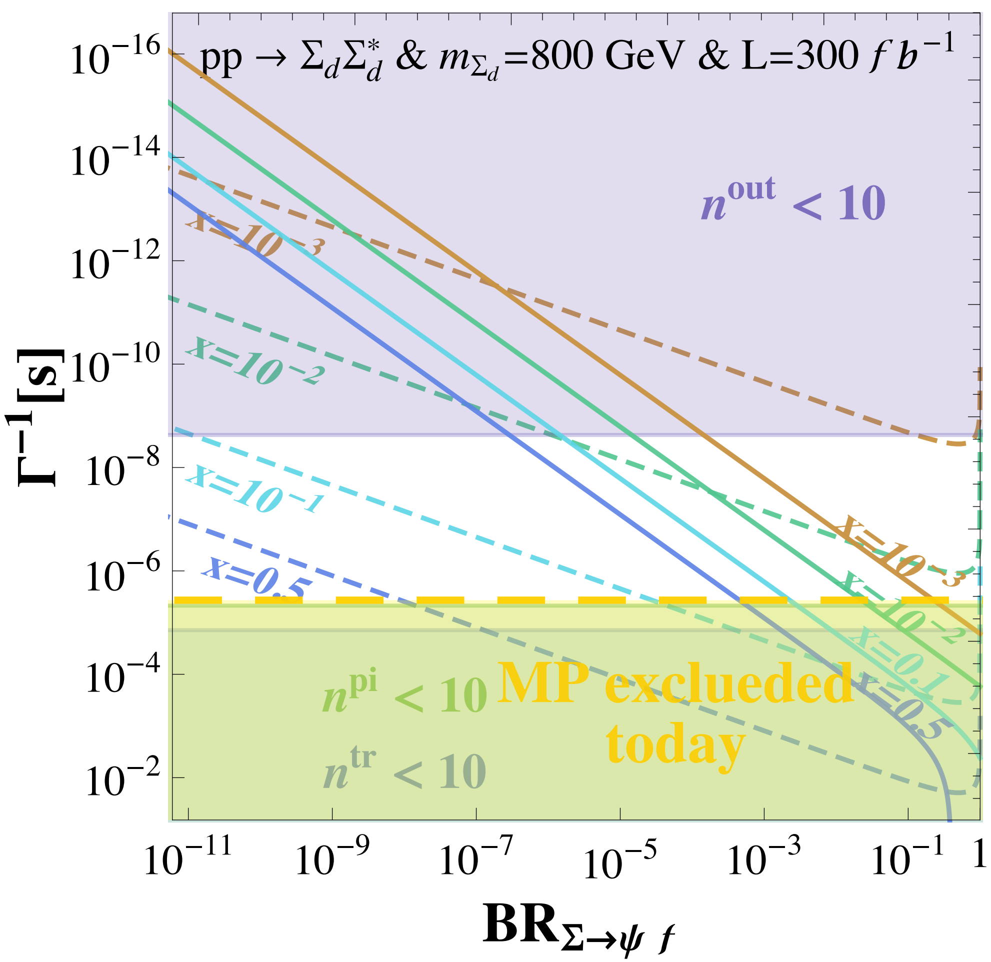
Moreover imposing ID "around the corner" gives

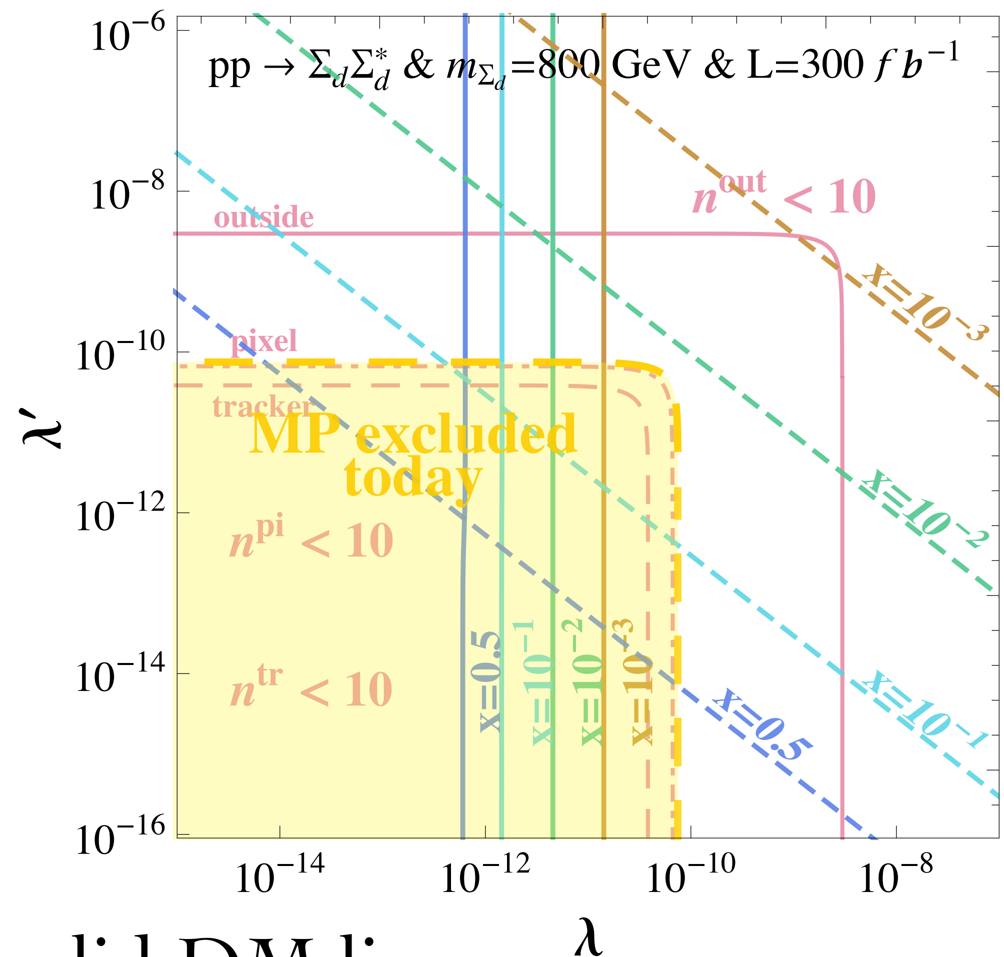
$$l_{\Sigma,SM} \simeq 55\,\mathrm{m}\,\frac{1}{g_\Sigma}\left(\frac{m_{\Sigma_f}}{1\mathrm{TeV}}\right)^{-4}\left(\frac{m_\psi}{10\mathrm{GeV}}\right)^{4}\left(\frac{\tau_\psi}{10^{27}\mathrm{s}}\right)\left(\frac{\Omega_{CDM}h^2}{0.11}\right)\left(\frac{g_*}{100}\right)^{3/2}$$

At least one decay could be visible !!!

FIMP/SWIMP & COLORED Σ

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





solid DM lines

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

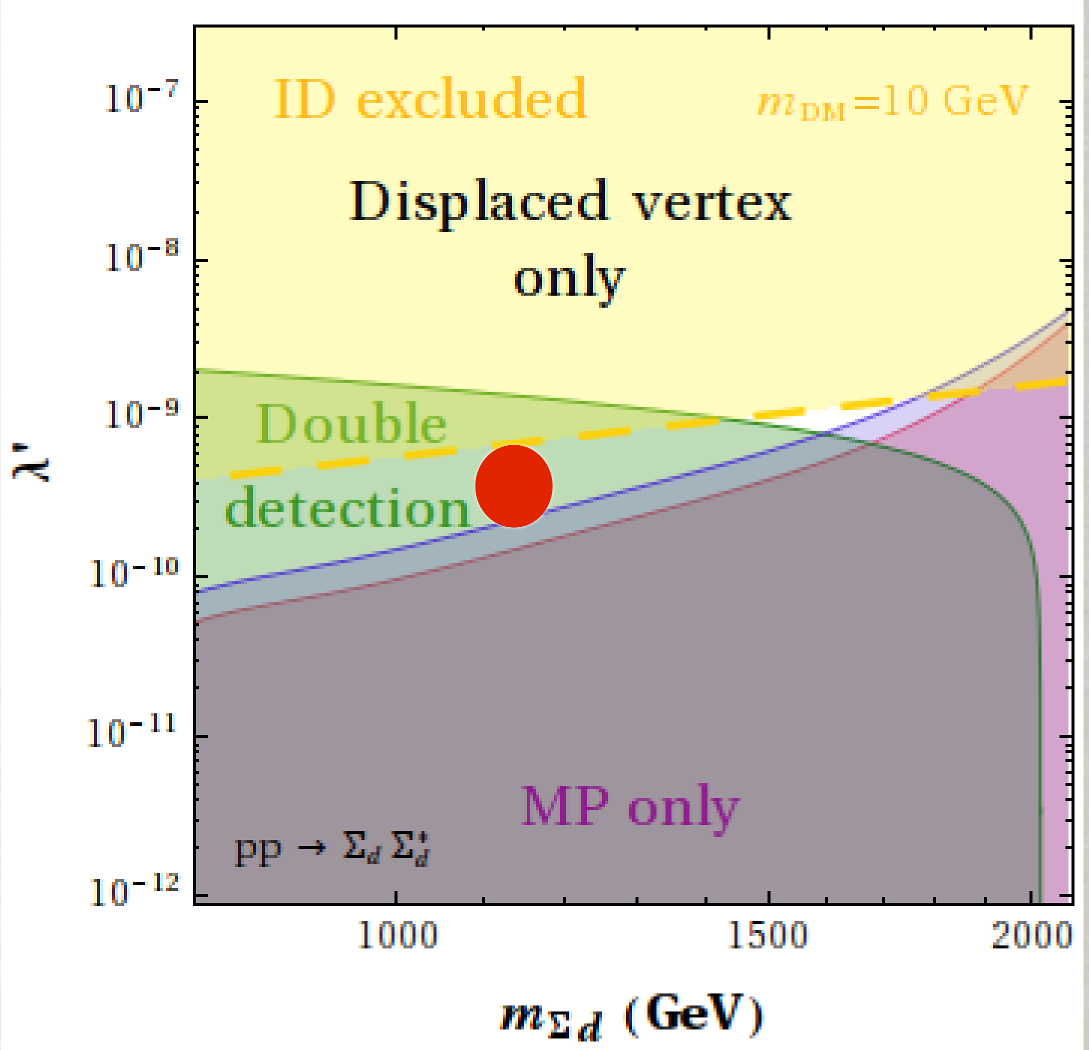
Σ Combined detection

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 1408.1005]



It is possible to over-constraint the model and check the hypothesis of FIMP production !

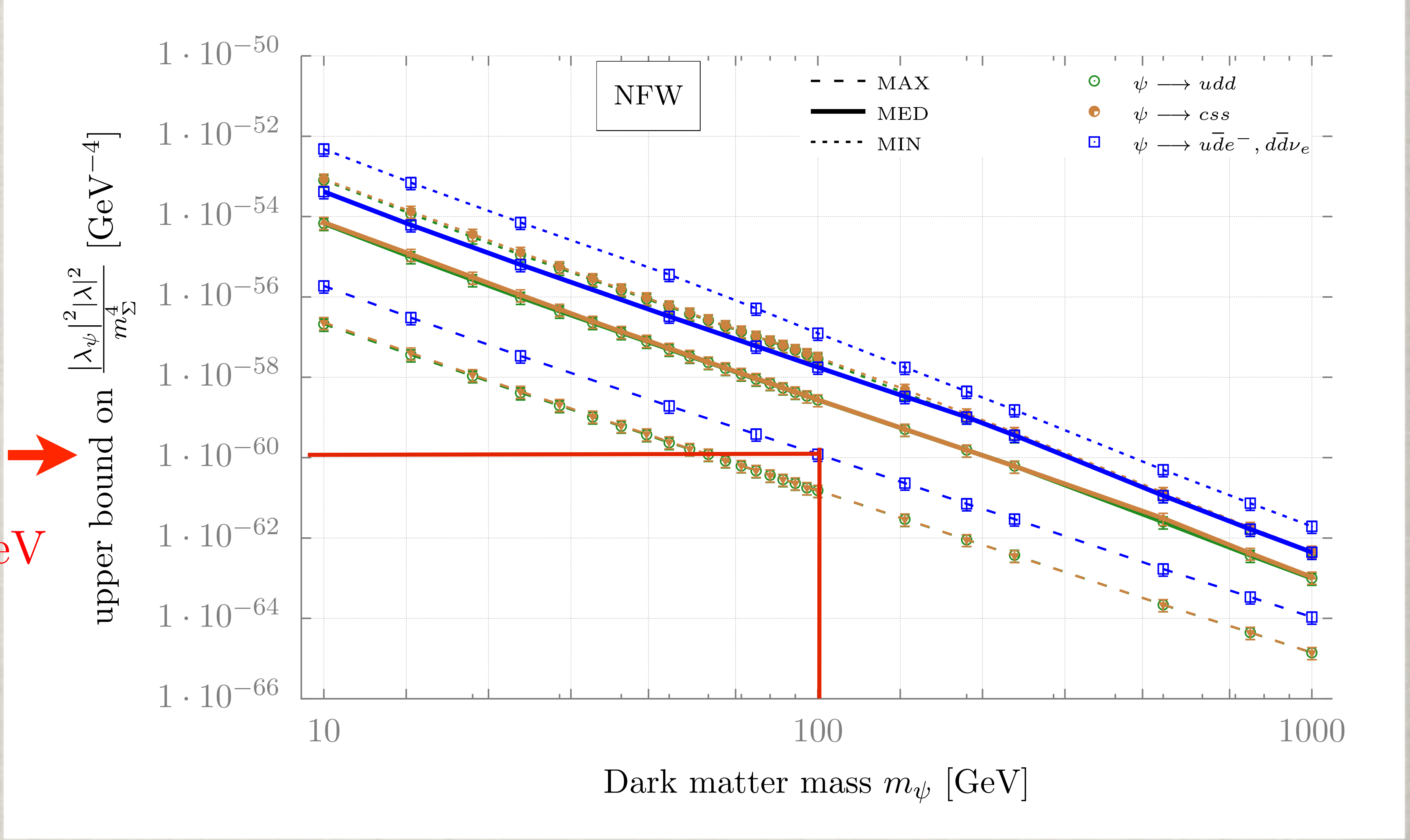
ID of FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]

$\lambda\lambda' =$

10^{-24}

$m_\Sigma = 1\text{TeV}$



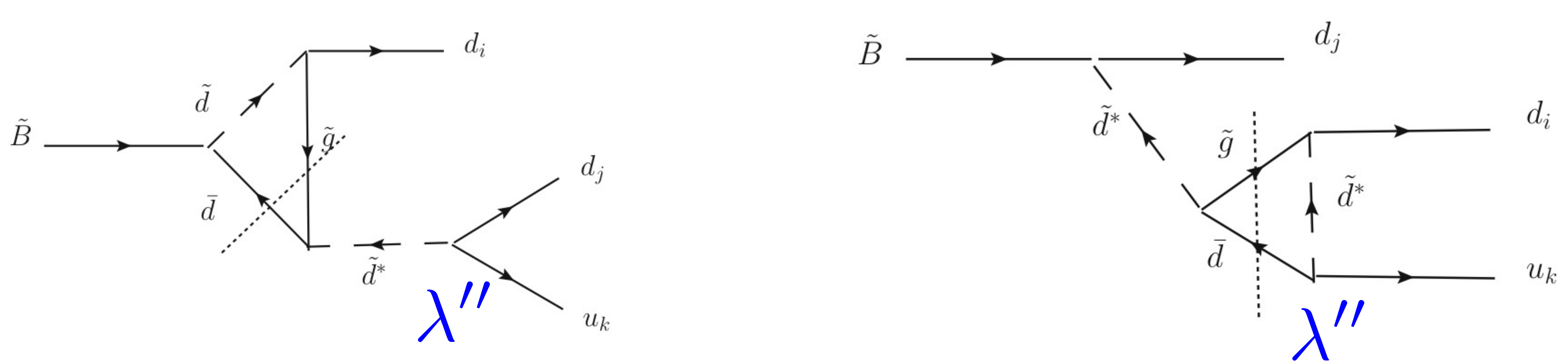
Unfortunately bounds strongly depend on propagation...

The SW DM-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

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

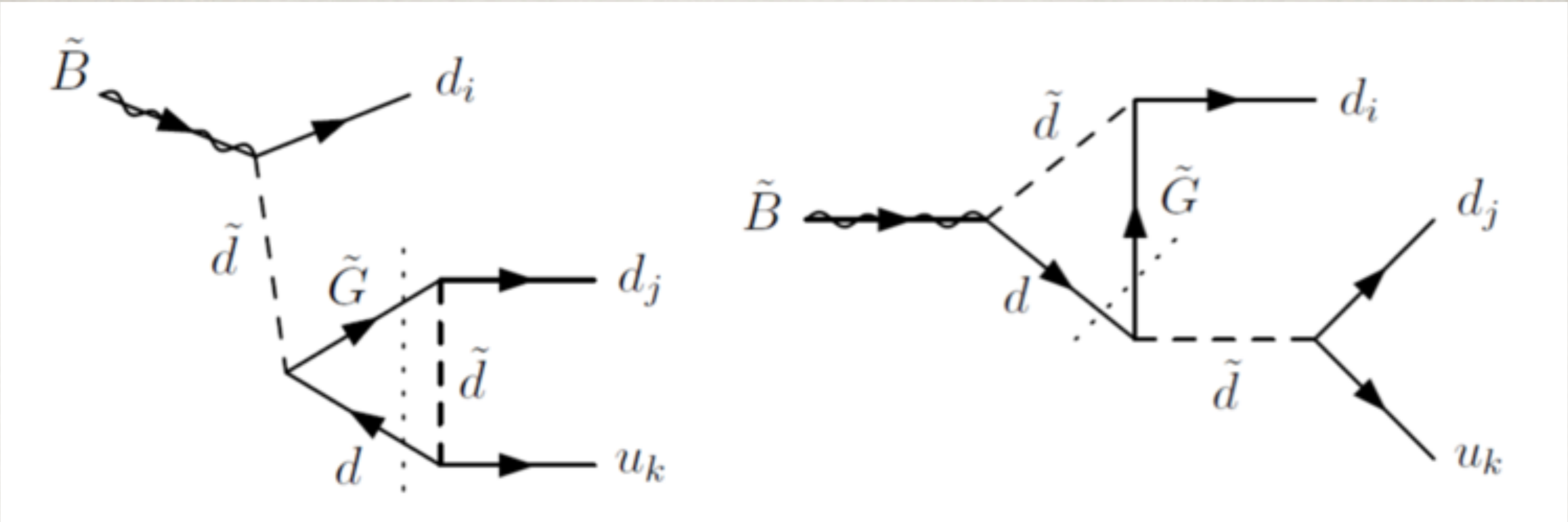
$$\frac{\Omega_{\Delta B}}{\Omega_{DM}} = \frac{m_p}{m_{DM}} \; \frac{\epsilon_{CP}\, BR(\chi \to \not{B})}{BR(\chi \to DM + \text{anything})}$$

independent of Bino density

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

CP violation in RPV SUSY

The loop diagrams contributing to the CP violation are



CP violation can be provided either by a phase difference between the Bino and Gluino masses or by flavour effects in the RPV couplings and CKM-mixing for squarks. The latter suffers unfortunately of GIM-like cancellations for degenerate squarks... Study of full flavour structure with general squark mass spectrum is on-going [G. Arcadi, LC & F. Kirk work in progress]

Baryogenesis in RPV SUSY

Simple scenario with no Flavour Violation: the CP phase comes from the gaugino mass phase difference

$$\Gamma\left(\tilde{B}\to udd+\overline{udd}\right)=\frac{\lambda^2 g_1^2 N_{\rm RPV}}{768\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\Gamma\left(\tilde{B}\to \tilde{g} f\overline{f}\right)=\frac{(g_1 g_3 Q_f)^2 N_{\rm RPC}}{256\pi^3}\frac{m_{\tilde{B}}^5}{m_0^4}$$

$$\longrightarrow \quad \epsilon_{\rm CP}=\frac{8}{3} Im\left[e^{i\phi}\right]\boxed{\frac{m_{\tilde{B}} m_{\tilde{g}}}{m_0^2}}\alpha_s\left(1+\frac{2\pi N_{\rm RPC}\alpha_s}{N_{\rm RPV}\lambda^2}\right)^{-1}$$

Baryon Asymmetry

CP asymmetry is suppressed both for $m_{\tilde{g}}=m_{\tilde{B}}$ or $m_{\tilde{g}}=0$

Neglecting wash-out processes we get

$$\Omega_{\Delta B}\approx 1.3\times 10^{-2}\frac{x_{\rm f.o.}}{A(x_{\rm f.o.})}\left(\frac{m_{\tilde{B}}}{1{\rm TeV}}\right)\left(\frac{\mu}{10^{3/2}m_0}\right)^2\left(\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC}\alpha_s}\right)\left(1+\frac{\lambda^2 N_{\rm RPV}}{\pi N_{\rm RPC}\alpha_s}\right)^{-1}$$

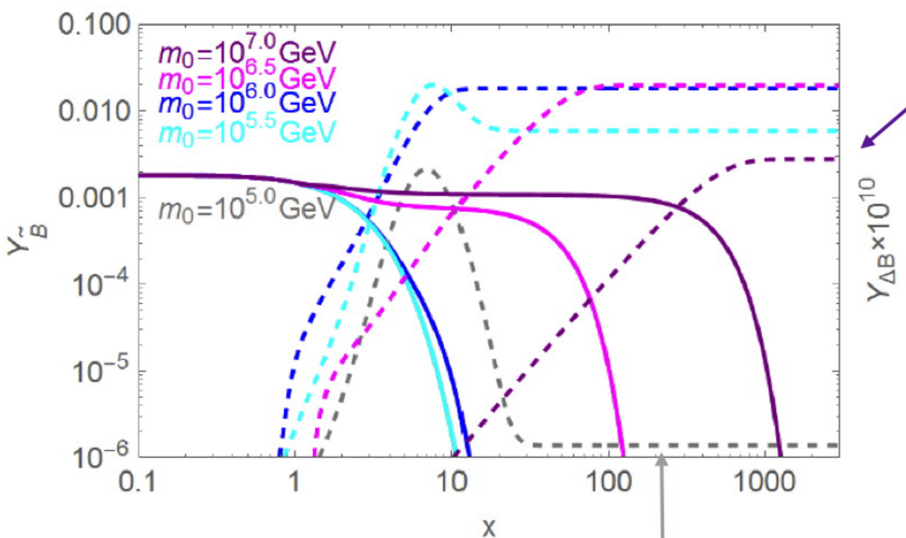
Need a very heavy spectrum to realize the scenario !

Baryogenesis in RPV SUSY

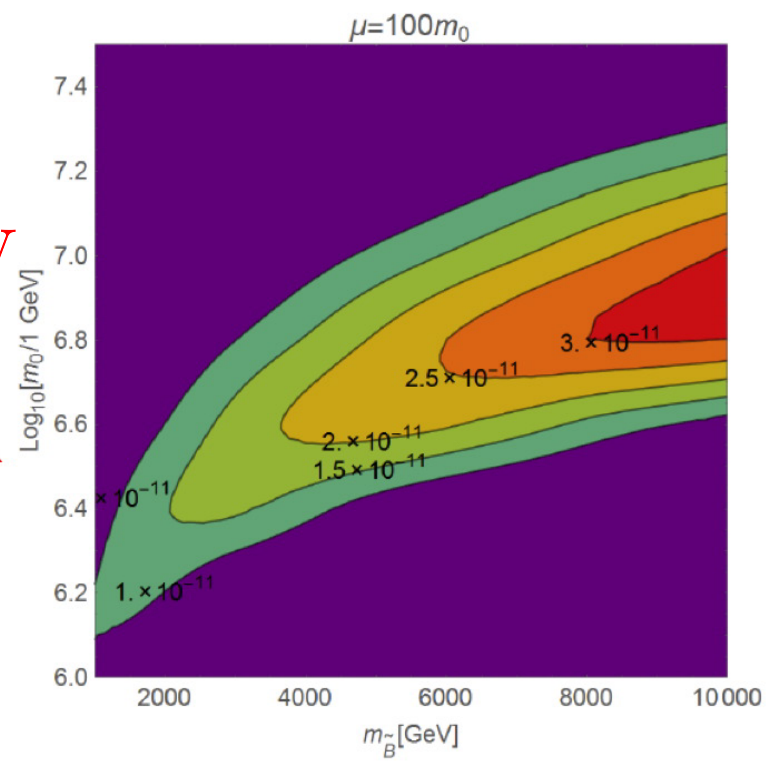
[Arcadi, LC & Nardecchia 1507.05584]

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

Asymmetry suppressed by the high scalars



$10^7\,\mathrm{GeV}$

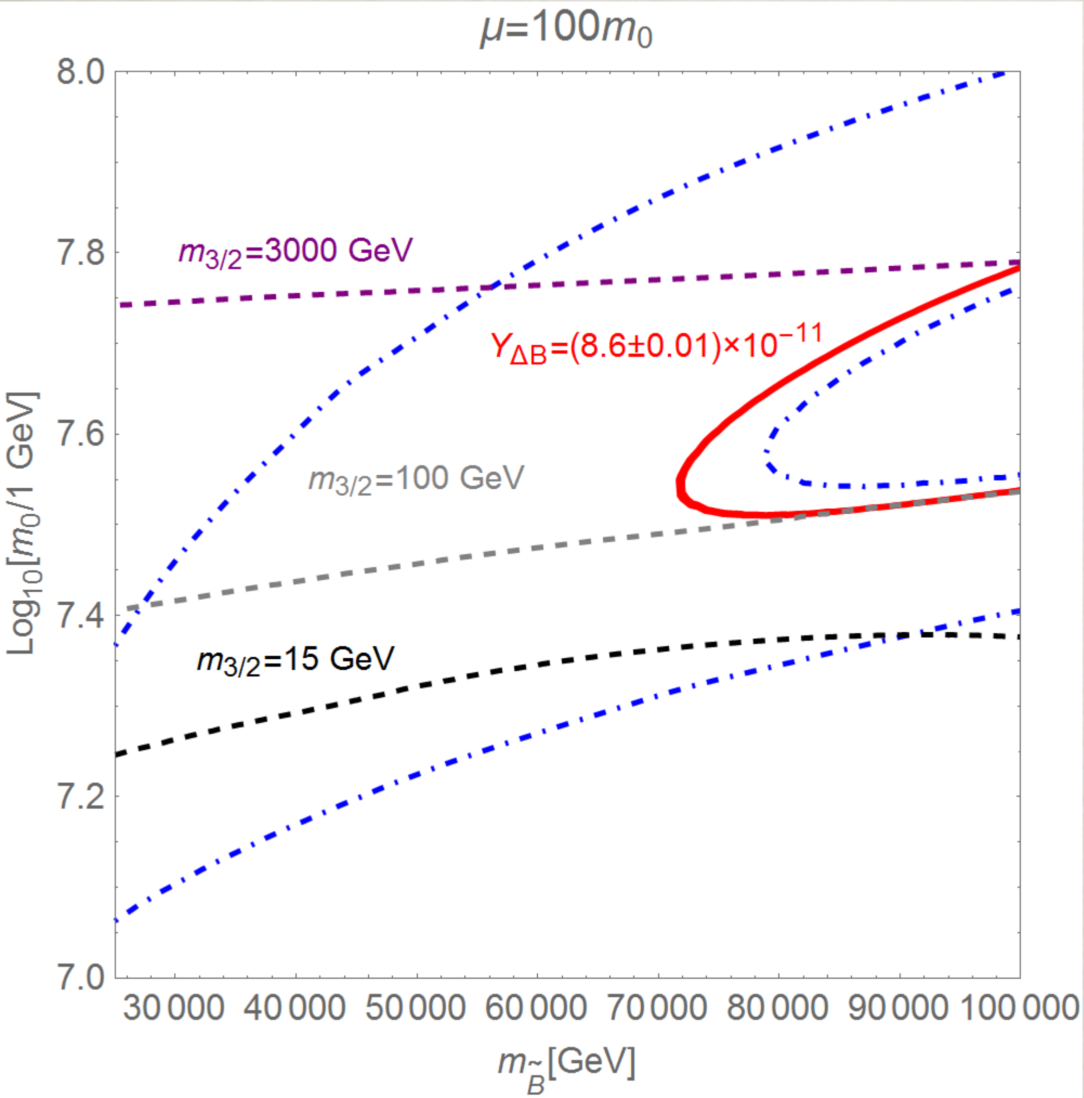


Asymmetry suppressed by wash-out

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

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



Moreover the large scalar mass suppresses the branching ratio into gravitinos too much...

$$BR(\tilde{B} \rightarrow \psi_{3/2} + \text{any}) << \epsilon_{CP}$$

Need a large gravitino mass to compensate & obtain $\Omega_{DM} \sim 5\,\Omega_B$, not so simple explanation after all..., but still possible with $m_{3/2} < m_{\tilde{g}}$.

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

Thanks to the large gravitino mass, the squark mass suppression is partially compensated and a visible gravitino decay is possible:

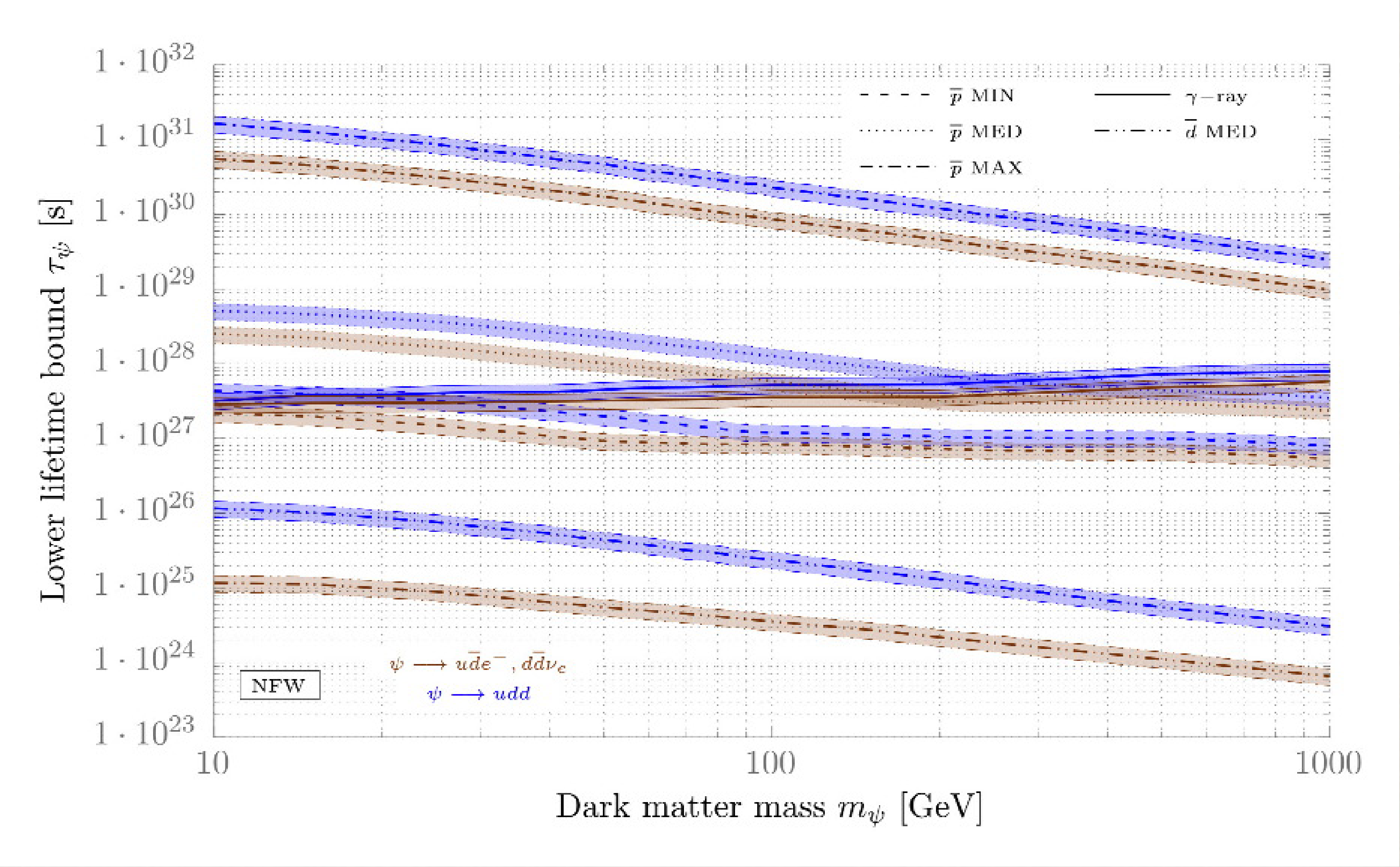
$$\Gamma(\psi_{3/2} \to u_k d_i d_j) = \frac{3\lambda^2}{124\pi^3} \frac{m_{3/2}^7}{m_0^4 M_P^2}$$

$$\tau_{3/2} = 0.26 \times 10^{28}\mathrm{s} \left(\frac{\lambda}{0.4}\right)^{-2} \left(\frac{m_{3/2}}{1\mathrm{TeV}}\right)^{-7} \left(\frac{m_0}{10^{7.5}\mathrm{GeV}}\right)^{4}$$

Right ballpark for indirect DM detection, but strongly dependent on the gravitino mass...

ID of FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]



Same decay channel as before..., possibly observable !!!

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.

Not so weakly interacting DM

Interacting Dark Matter

Apart for chemical decoupling of DM, also the kinetic decoupling is important as it sets the cut-off in the power spectrum at small scales. ANY interaction of the DM, even with a hidden (relativistic) Dark Sector can influence the DM kinetic decoupling.

A delayed decoupling may be important in solving the present small-scale problems of ΛCDM, if other possible effects, e.g. baryonic feedback, are not sufficient.

[Hofmann, Schwarz & Stecker 2001, Green, Hofmann & Schwarz 2005, Bringmann & Hofmann 2007, ...]

Consider then a Dirac fermion DM coupling with a massless hidden neutrino through a scalar or vector mediator and compute its kinetic decoupling expanding the collision integral in the momentum transfer.

Interacting Dark Matter

[J.Kasahara PhD Thesis 2009, Binder et al. 1602.07624]

Let us have a look at the collision integral for the process:

DM(1) + Particle(2) < - > DM (3) + Particle(4)

$$C[f_1] = \frac{1}{2}\sum_{s_3}\int \frac{d^3\mathbf{p}_3}{(2\pi)^3 2E_3}\left[-S^{\mathrm{eq}}(p_1,p_3)f_1(1\mp f_3) + S^{\mathrm{eq}}(p_3,p_1)f_3(1\mp f_1)\right]$$

Both terms have the same matrix element (no CP violation!)

$$S^{\mathrm{eq}}(p_1,p_3) = \sum_{s_2}\int \frac{d^3\mathbf{p}_2}{(2\pi)^3 2E_2}\sum_{s_4}\int \frac{d^3\mathbf{p}_4}{(2\pi)^3 2E_4}(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)$$
$$\times\overline{|\mathcal{M}(1+2\to 3+4)|^2}\, f_2^{\mathrm{eq}}(1\mp f_4^{\mathrm{eq}})\,,$$

$$S^{\mathrm{eq}}(p_3,p_1) = \sum_{s_2}\int \frac{d^3\mathbf{p}_2}{(2\pi)^3 2E_2}\sum_{s_4}\int \frac{d^3\mathbf{p}_4}{(2\pi)^3 2E_4}(2\pi)^4\delta^4(p_3+p_4-p_1-p_2)$$
$$\times\overline{|\mathcal{M}(3+4\to 1+2)|^2}\, f_4^{\mathrm{eq}}(1\mp f_2^{\mathrm{eq}})\,,$$

Interacting Dark Matter

[J.Kasahara PhD Thesis 2009, Binder et al. 1602.07624]

In the non-relativistic limit for DM, one can expand these expression for small (but not vanishing !) momentum transfer:

$$C[f_1] = m_1 \frac{\partial}{\partial \mathbf{p}_{1i}} \left[\gamma \left(m_1 T \frac{\partial f_1}{\partial \mathbf{p}_{1i}} + (\mathbf{p}_{1i} - m_1 \mathbf{u}_i) f_1 \right) \right]$$

where we defined

$$\gamma = \frac{1}{6 m_1 T} \sum_{s_2} \int \frac{d^3 \mathbf{p}_2}{(2\pi)^3} f_2^{\mathrm{eq}} (1 \mp f_2^{\mathrm{eq}}) \int_{-4\mathbf{p}_2^2}^{0} dt (-t) \frac{d\sigma}{dt} v$$

t-averaged cross-section

Fokker-Planck equation for the DM momentum distribution function, which can be recast into the Boltzmann hierarchy for density, bulk velocity, pressure and anisotropic stress,...

Interacting Dark Matter

[Binder, LC, Kamada, Murayama, Takahashi & Yoshida 1602.07624]

Consider a simple Dirac fermion DM interacting with a "dark neutrino" via a massive mediator:

$$g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu + g_\nu \bar{\nu}\gamma^\mu \nu \phi_\mu \qquad \text{vector}$$

$$g_\chi \bar{\chi}\phi\chi + g_\nu \bar{\nu}\phi\nu \qquad \text{scalar}$$

The matrix elements are:

$$|\mathcal{M}|^2 = g_\chi^2 g_\nu^2 \frac{8\left(8E_\nu^2 m_\chi^2 + 4E_\nu m_\chi t + t(2m_\chi^2 + t)\right)}{(t - m_\phi^2)^2}$$

$$|\mathcal{M}|^2 = g_\chi^2 g_\nu^2 \frac{4t(t - 4m_\chi^2)}{(t - m_\phi^2)^2} \,.$$

Interacting Dark Matter

[Binder, LC, Kamada, Murayama, Takahashi & Yoshida 1602.07624]

Consider a simple Dirac fermion DM interacting with a "dark neutrino" via a massive mediator:

$$g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu + g_\nu \bar{\nu}\gamma^\mu \nu \phi_\mu \qquad \text{vector}$$

$$g_\chi \bar{\chi}\phi\chi + g_\nu \bar{\nu}\phi\nu \qquad \text{scalar}$$

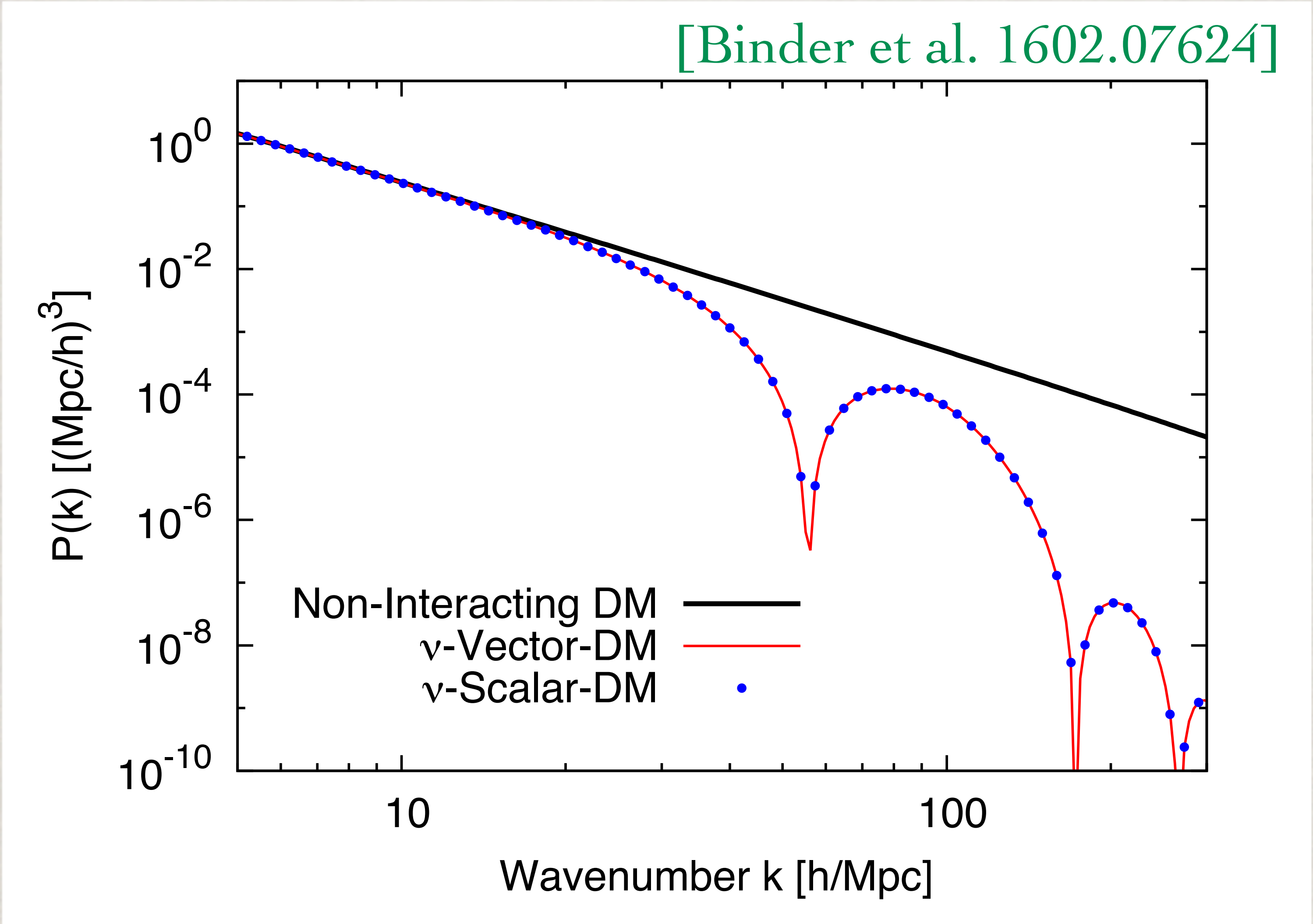
The matrix elements are:

$$|\mathcal{M}|^2 = g_\chi^2 g_\nu^2 \frac{8\left(8E_\nu^2 m_\chi^2 + 4E_\nu m_\chi t + t(2m_\chi^2 + t)\right)}{(t-m_\phi^2)^2}$$

$$|\mathcal{M}|^2 = g_\chi^2 g_\nu^2 \frac{4t(t-4m_\chi^2)}{(t-m_\phi^2)^2} \, .$$

Scalar interaction seems suppressed compared to vector one..., but the t-averaged cross-section is quite similar !

Interacting Dark Matter



$$M^{\rm cut} = 10^9 M_\odot \left(\frac{N_\nu \alpha_\nu \alpha_\chi}{2\times 10^{-4}}\right)\left(\frac{m_\chi}{1TeV}\right)^{-3/4}\left(\frac{m_\phi}{1MeV}\right)^{-3}$$

Similar results from ETHOS group [Bringmann et al. 1603.04884]

Outlook

Outlook

- The search for a DM particle continues on all fronts, not only WIMPs but 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 !
- Gravitino SuperWIMP & baryogenesis from Bino decay are feasible with a “mini-split” SUSY spectrum and may give signals in DM indirect detection or a 100 TeV collider. Analysis of full flavour structure is in progress...
- Also DM interactions with the “Dark Sector” can play a role in structure formation, delaying the kinetic decoupling, both via scalar or vector mediator.