Workshop "Dark Matter Identification: Connecting Theory and Signature Space"
MITP - Mainz, 4th April 2019

Theory II on DM production beyond WIMPs

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neutrinos, dark matter & dark energy physics

Outline

- Introduction:
  -Theoretical guiding principles
  - Cosmology as a probe of particle physics

- FIMP/SuperWIMP/
  Decaying Dark Matter

- Axion Dark Matter (for later…)

- Outlook

Introduction

Which model Beyond the SM ?

weakly coupled ⟷ strongly coupled

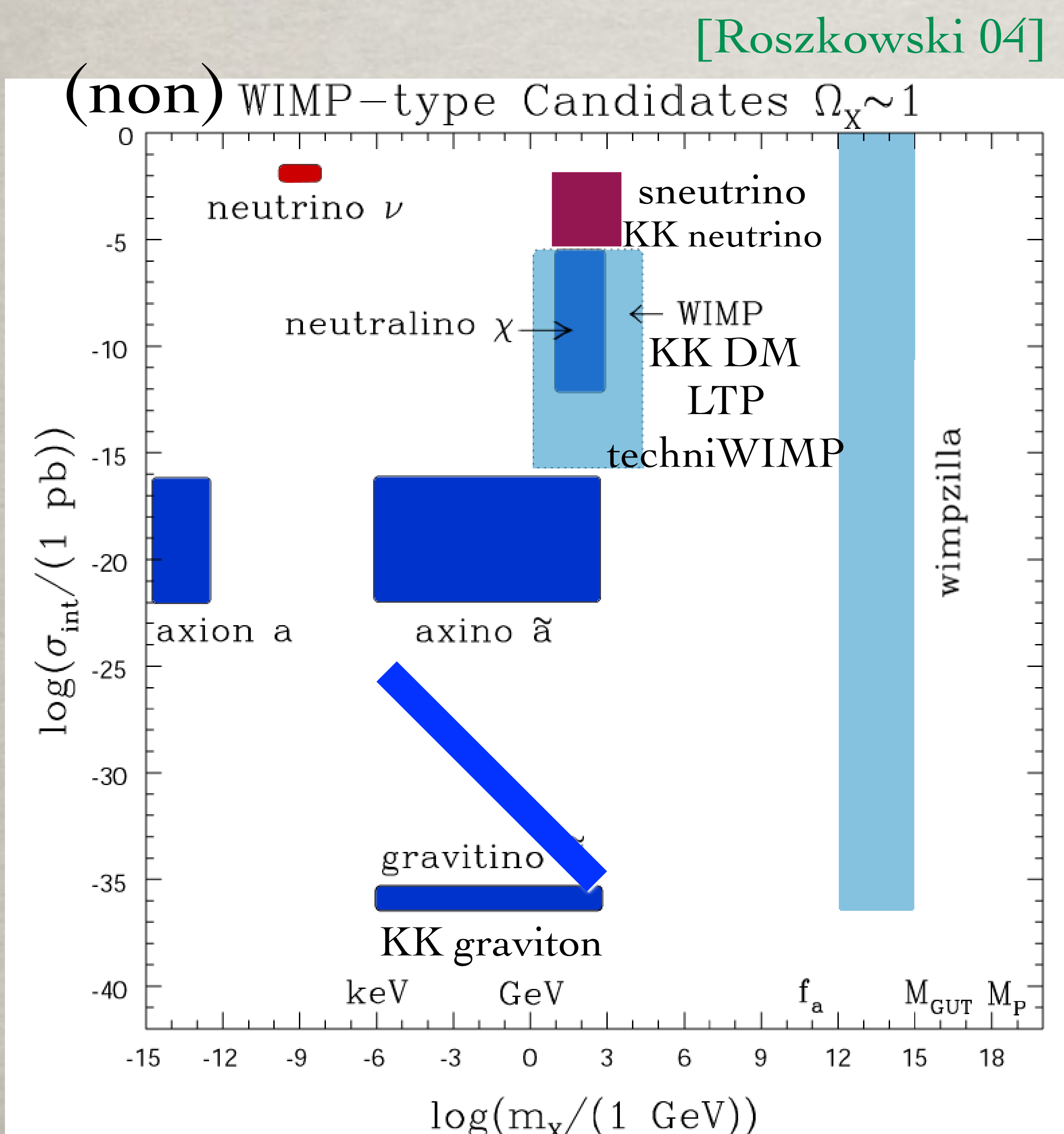
Cosmology

(Collider-based) Particle Physics

To pinpoint the completion of the SM, exploit the complementarity between Cosmology and Particle Physics to explore all the sectors of the theory: the more weakly coupled and the more strongly coupled to the Standard Model fields...

Best results if one has information from both sides, e.g. neutrinos, axions, DM, etc... ???

DARK MATTER CANDIDATES



Too many different candidates...

"Standard" DM production paradigms:

WIMPs
(i.e. neutralino)
&
"FIMP/SuperWIMPs"
(i.e. gravitino)
&
Misalignment
(i.e. axion/condensate)

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

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

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

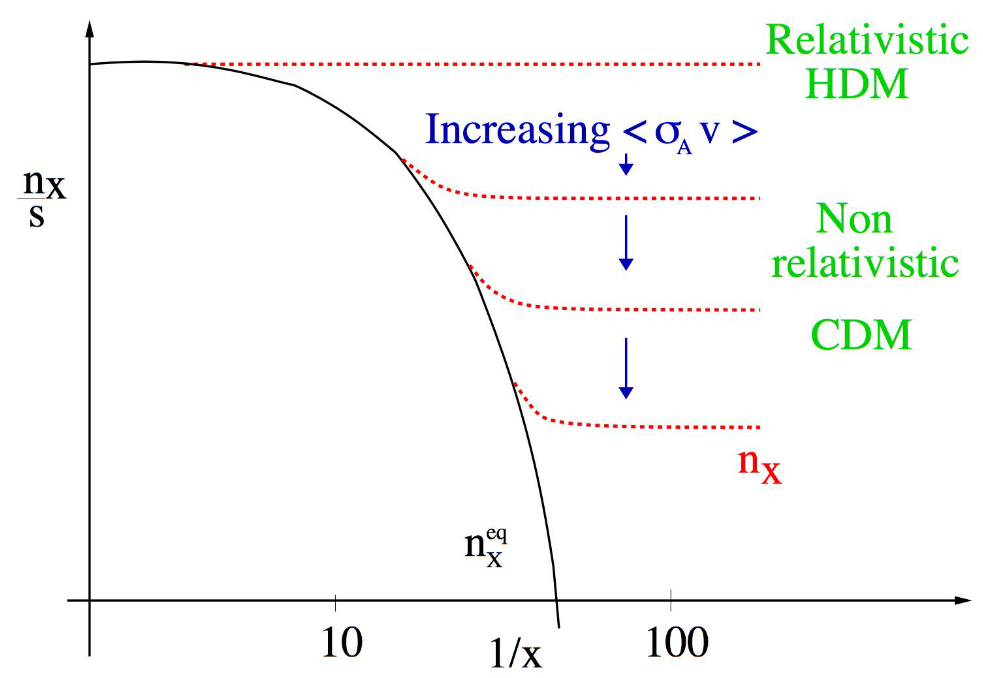
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

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

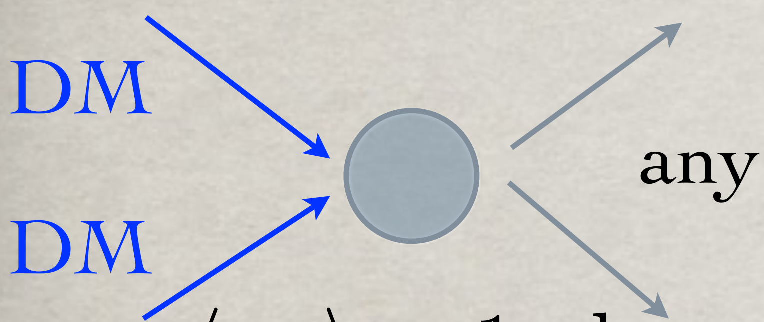
Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !



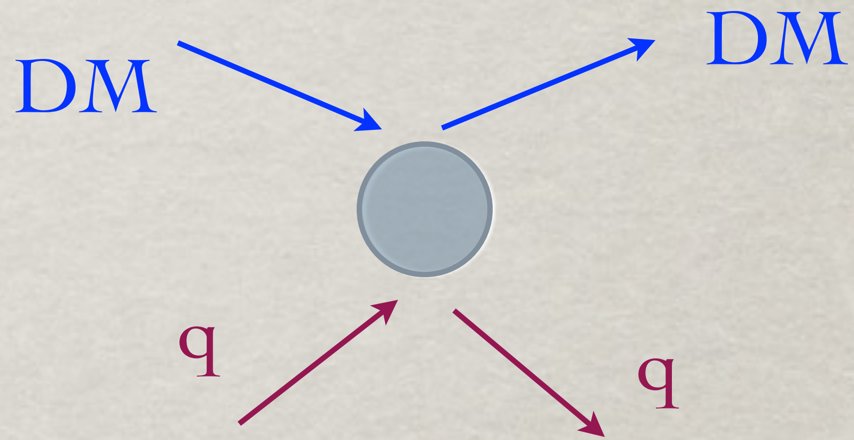
THE WIMP CONNECTION

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

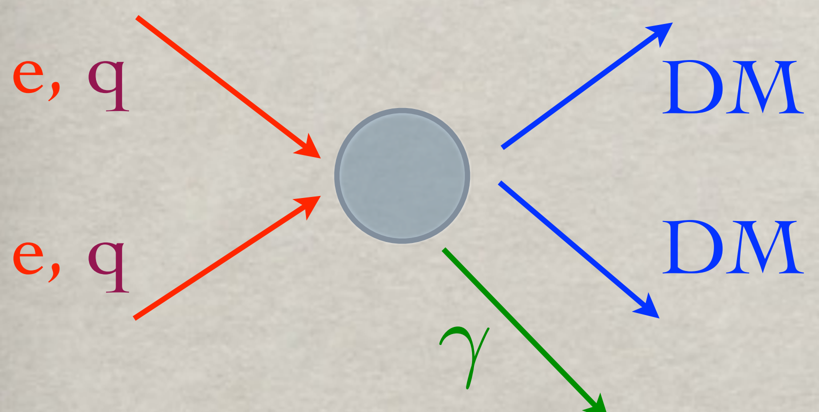


$\langle \sigma v \rangle \sim 1 \text{ pb}$

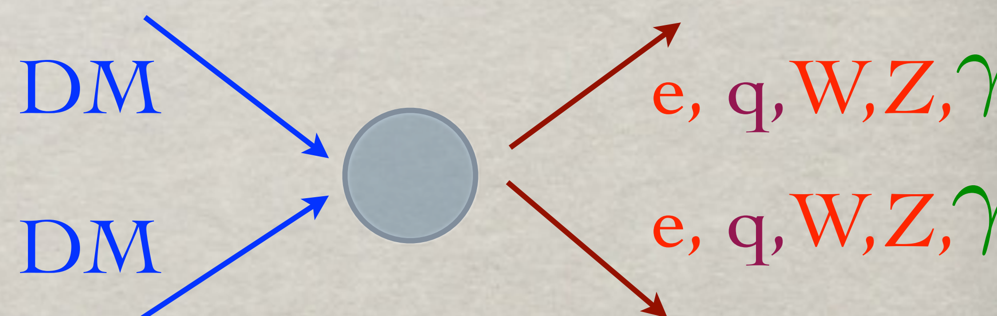
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:

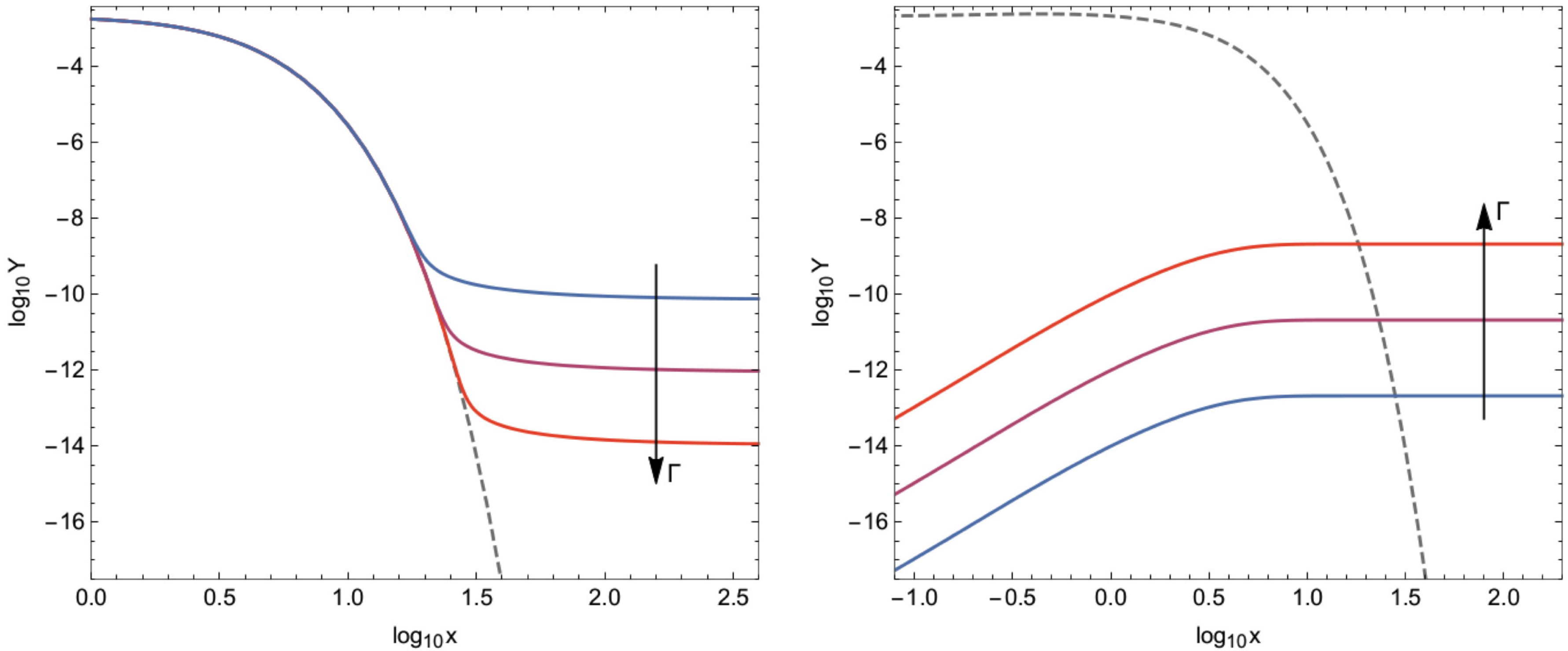


3 different ways to check this hypothesis !!!

SuperWIMP/FIMP paradigms

WIMP vs FIMP Dark Matter

$$\frac{dn_\chi}{dt} + 3\,H\,n_\chi = -\langle v\sigma_\chi\rangle\left[n_\chi^2 - (n_\chi^{\rm eq})^2\right]$$



[Figure from N. Bernal's talk at Invisibles18]

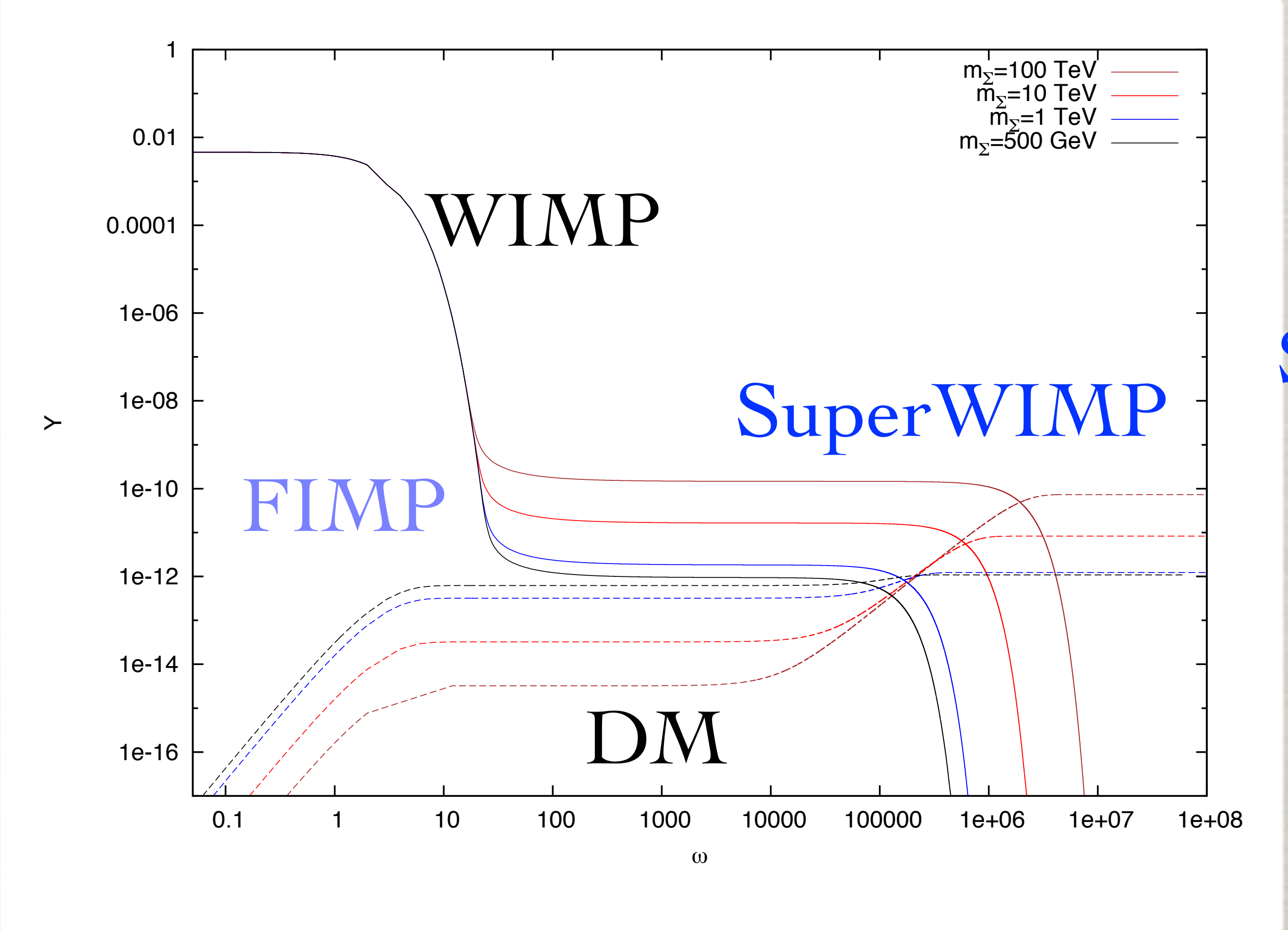
Instead of starting from thermal equilibrium, consider the opposite case: a particle so weakly interacting that is not initially in equilibrium, but it is driven towards it by the interaction with particles in the thermal bath.
Same Boltzmann equation, but different dynamics !

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

FIMP/SWIMP

- The FIMP/SuperWIMP type of Dark Matter production is effective for any mass of the mother and daughter particle !
- Indeed if the mass ratio is large the WIMP-like density of the mother particle gets diluted:

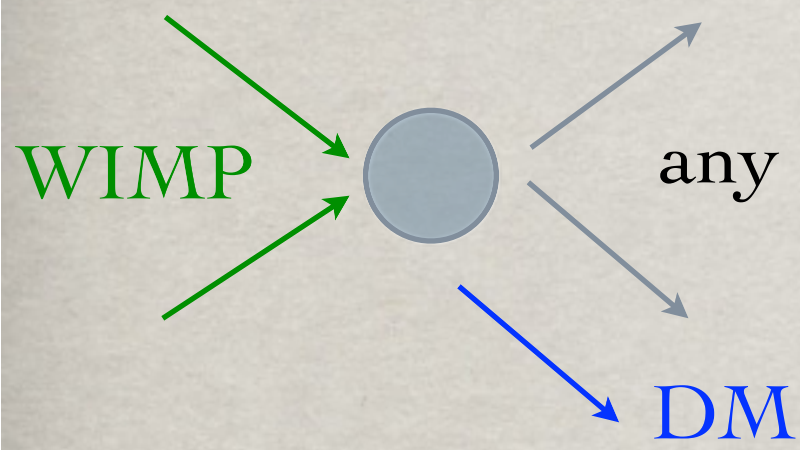
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} \, BR(\Sigma \to \psi) \, \Omega_\Sigma h^2$$

- Moreover also the FIMP production is dependent on the decay rate of the mother particle not just the mass and can work also in different parameter regions…

$$\Omega^{FI} h^2 = 10^{27} \frac{g_\Sigma}{g_*^{3/2}} \, \frac{m_\psi \Gamma(\Sigma \to \psi)}{m_\Sigma^2}$$

F/SWIMP CONNECTION

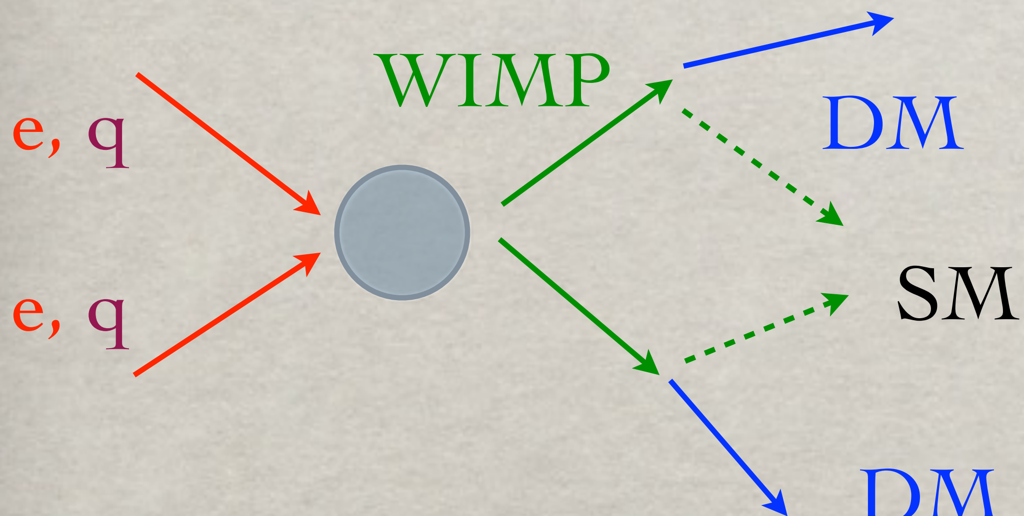
Early Universe: $\Omega_{CDM} h^2$



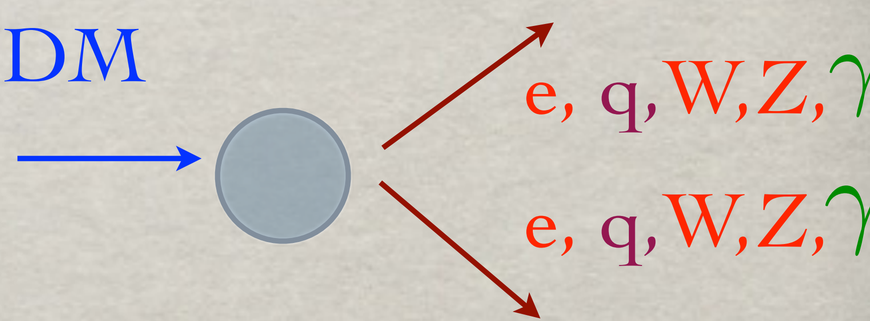
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:

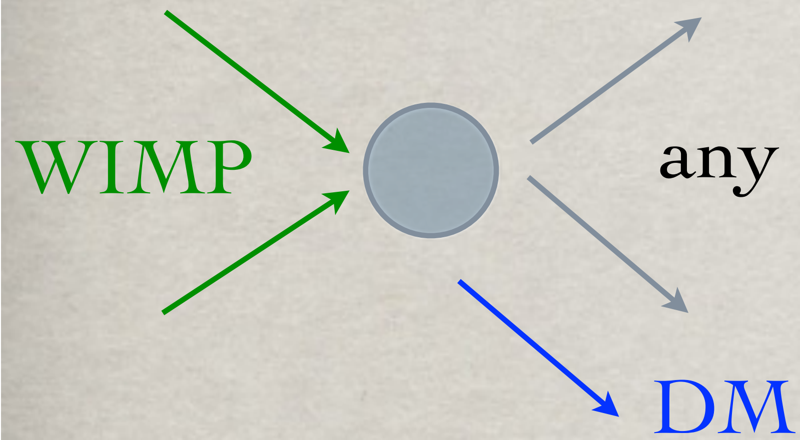


decaying DM !

3 different ways to check this hypothesis !!!

F/SWIMP CONNECTION

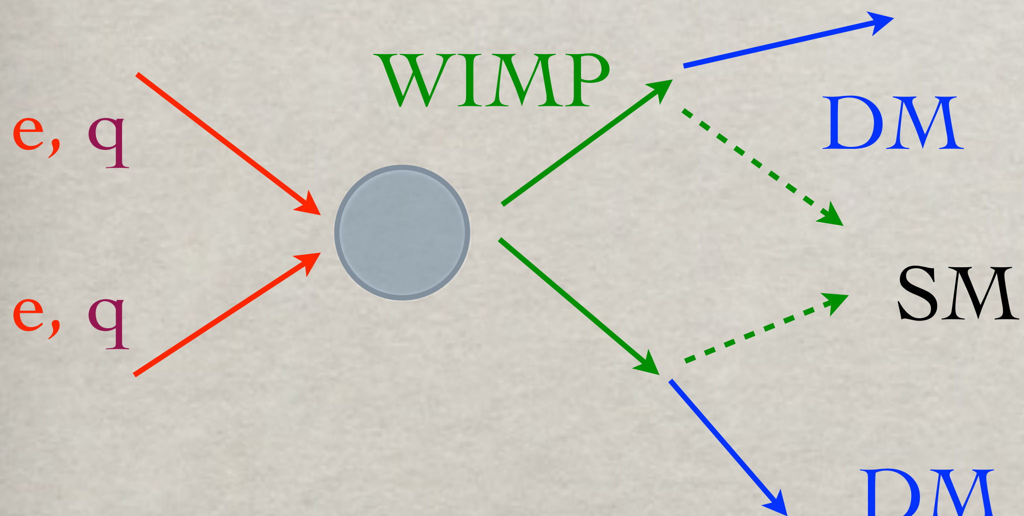
Early Universe: $\Omega_{CDM} h^2$



Direct Detection:

Usually Suppressed, apart if the mediator is light or kinetic mixing is present…

Colliders: LHC/ILC



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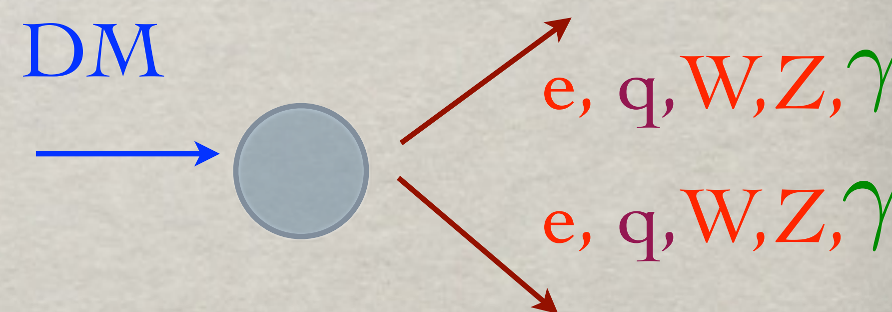

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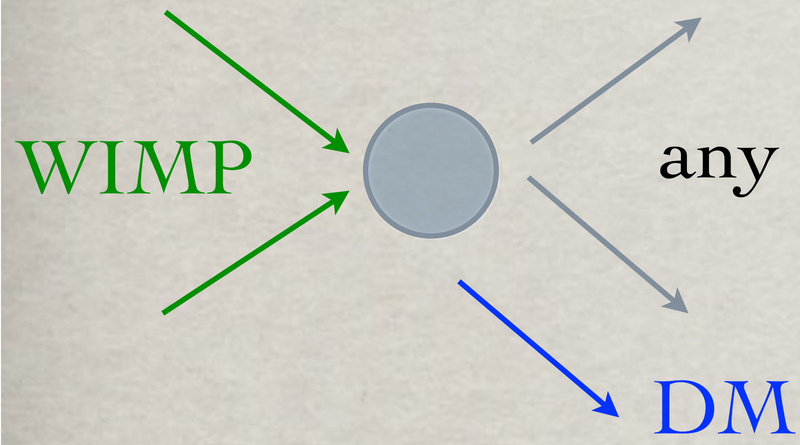

Direct Detection:

Usually Suppressed, apart if the mediator is light or kinetic mixing is present…

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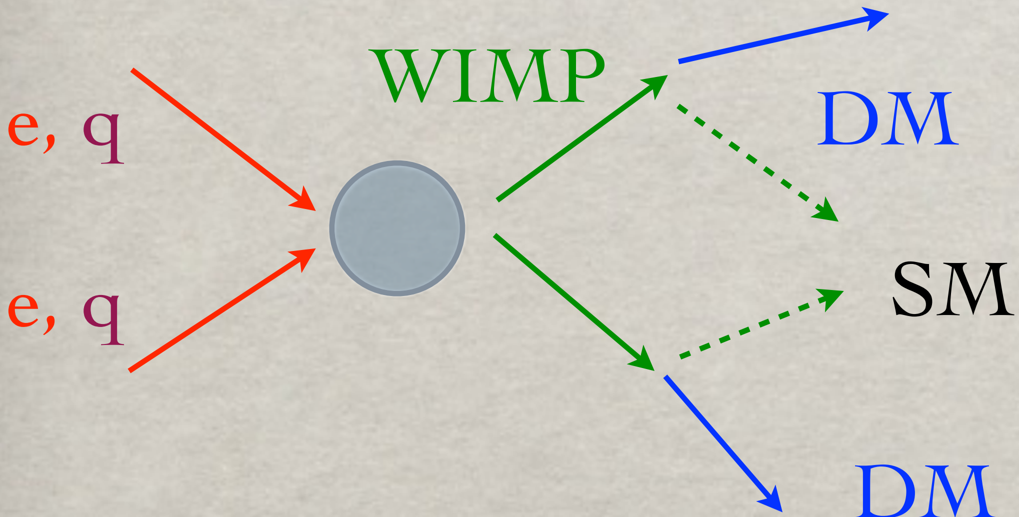
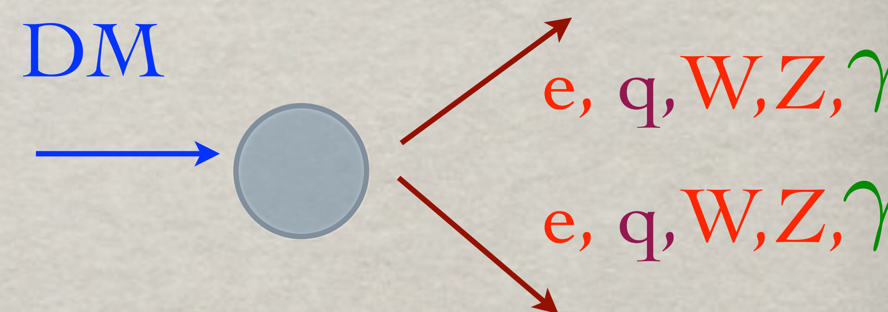


Indirect Detection:



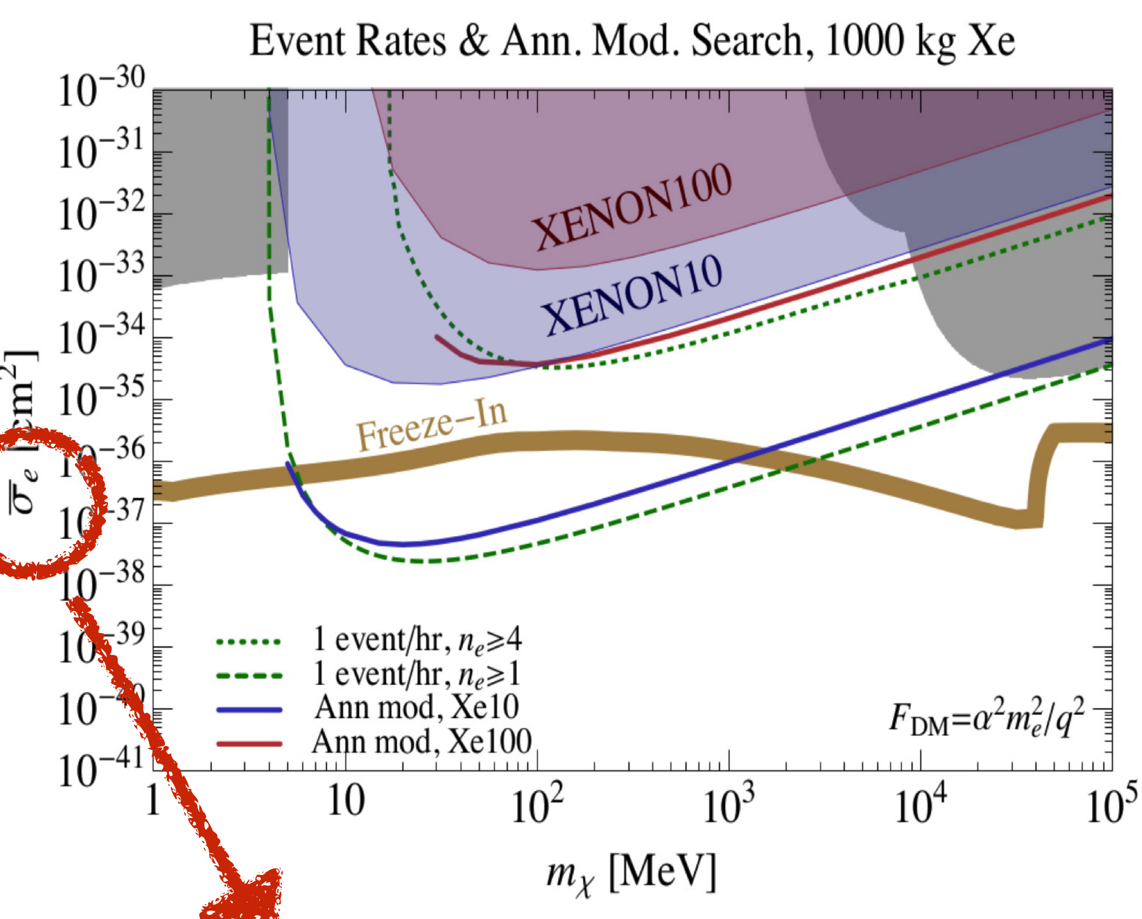
decaying DM !

3 different ways to check this hypothesis !!!

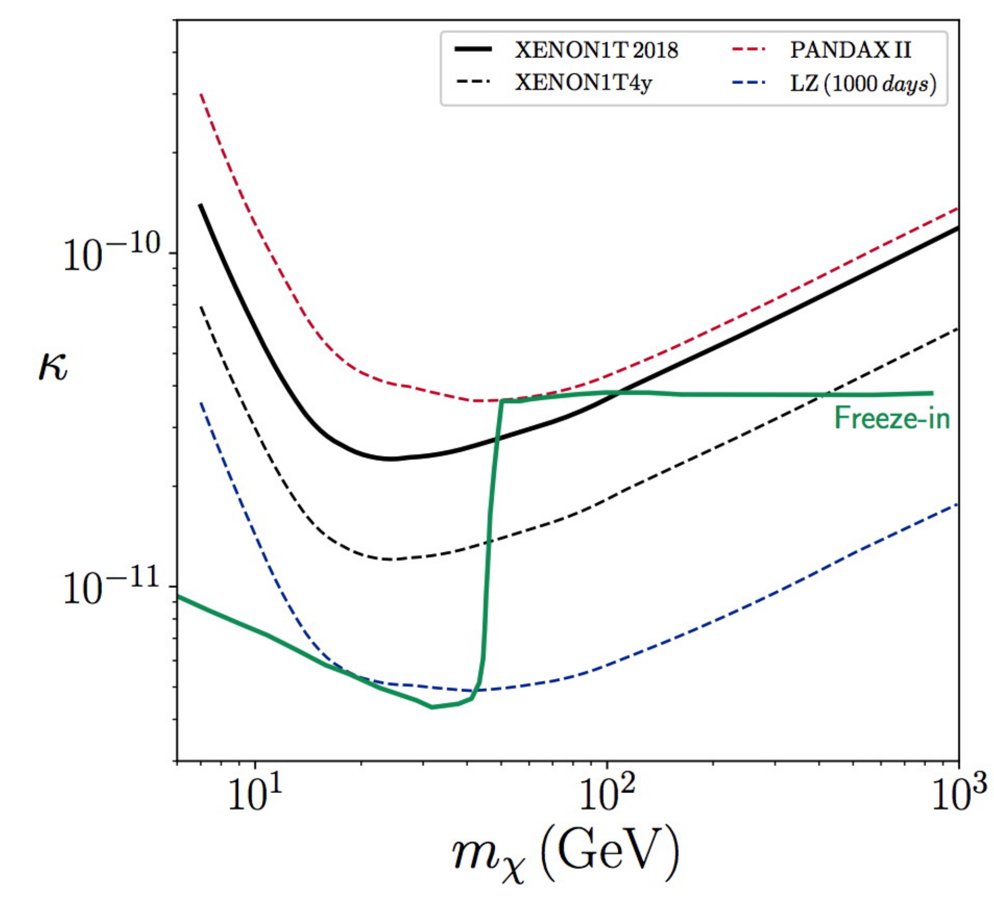
Direct detection of FIMPs

Direct detection experiment start to become sensitive even to tiny couplings, if there is a sufficient enhancement by the number density or a light mediator/Dark Matter !

[Essig, Volansky & Yu 2017]



[Hambye et al. 1807.05022]



Note: here electron scattering !!!

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

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

Warm DM !

[Pagels & Primack 82]

If the gravitinos are NOT in thermal equilibrium instead

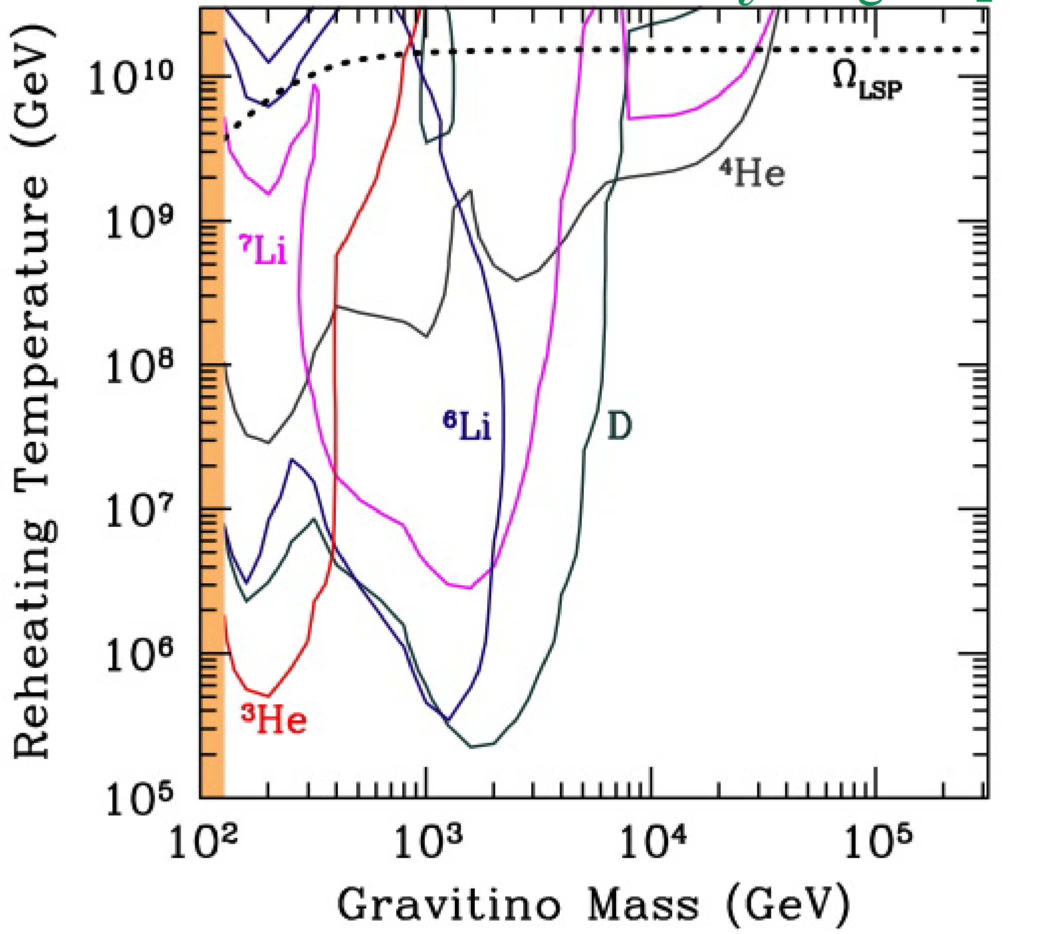
$$\Omega_{3/2} h^2 \simeq 0.3 \left(\frac{1\mathrm{GeV}}{m_{3/2}}\right) \left(\frac{T_R}{10^{10}\ \mathrm{GeV}}\right) \sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}}\right)^2$$

[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

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

FIMP/SuperWIMP/ Decaying Dark Matter

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 :

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

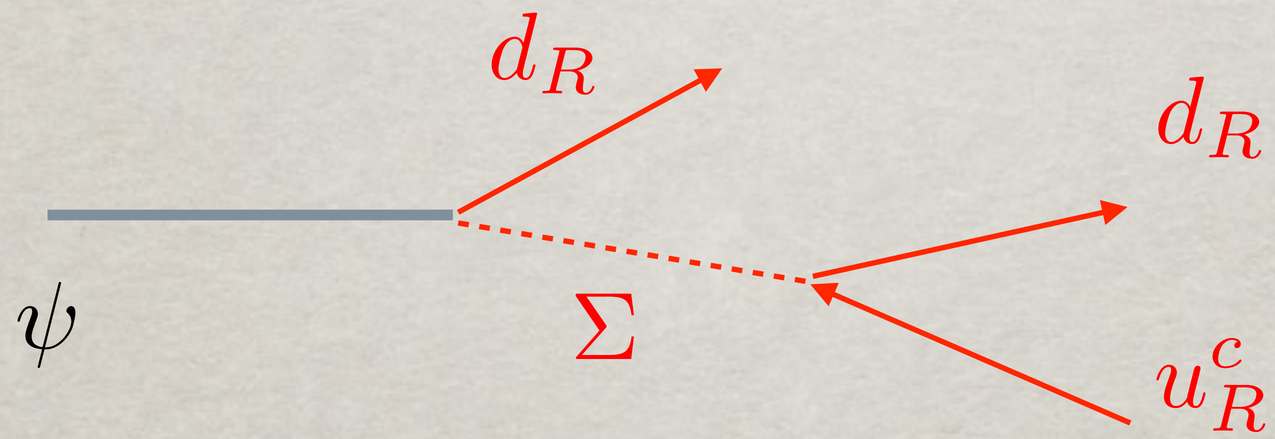
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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 $m_\Sigma \gg m_\psi$:

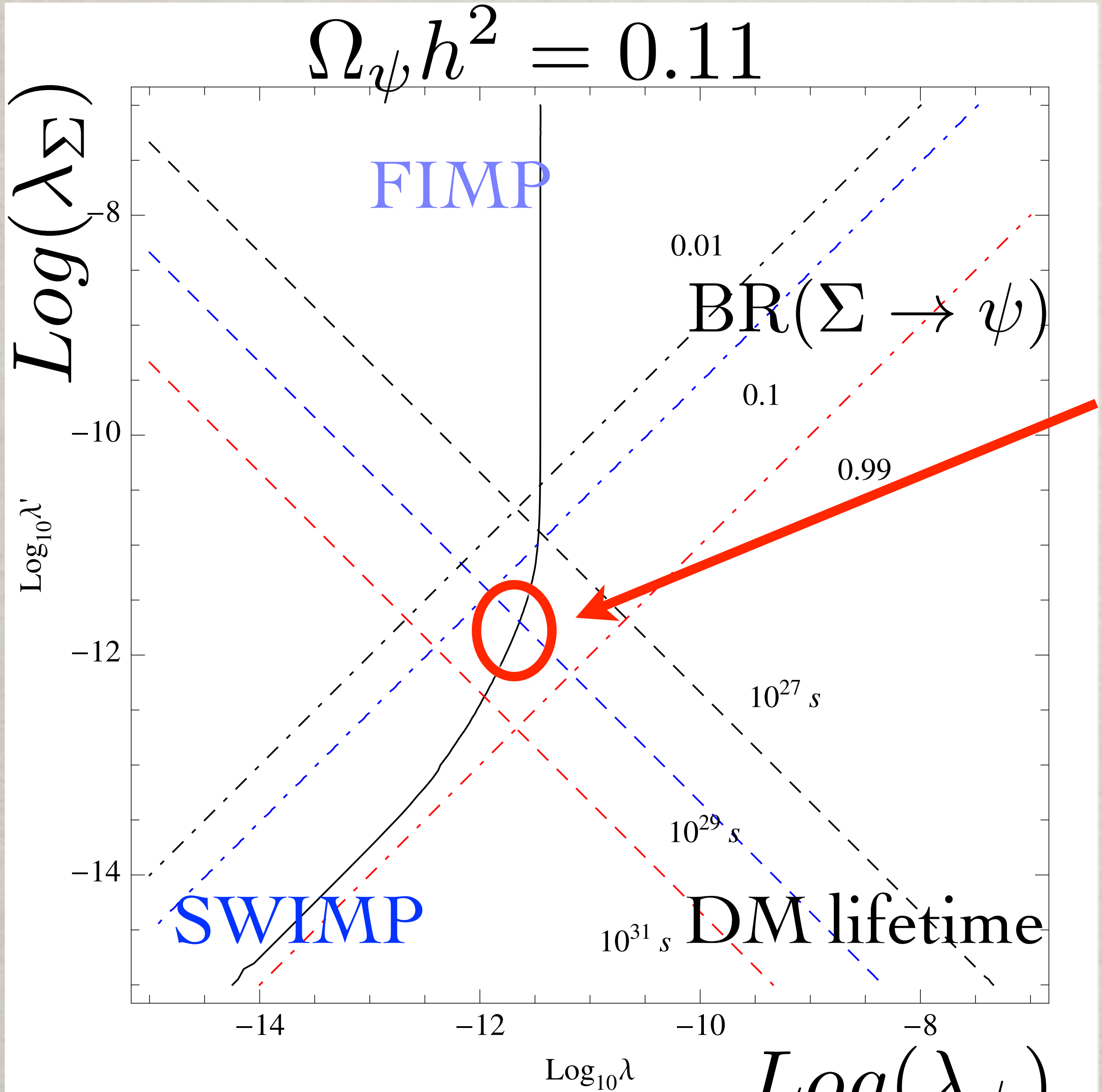


Decay into 3 quarks via both couplings !

To avoid bounds from the antiproton flux require then

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

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

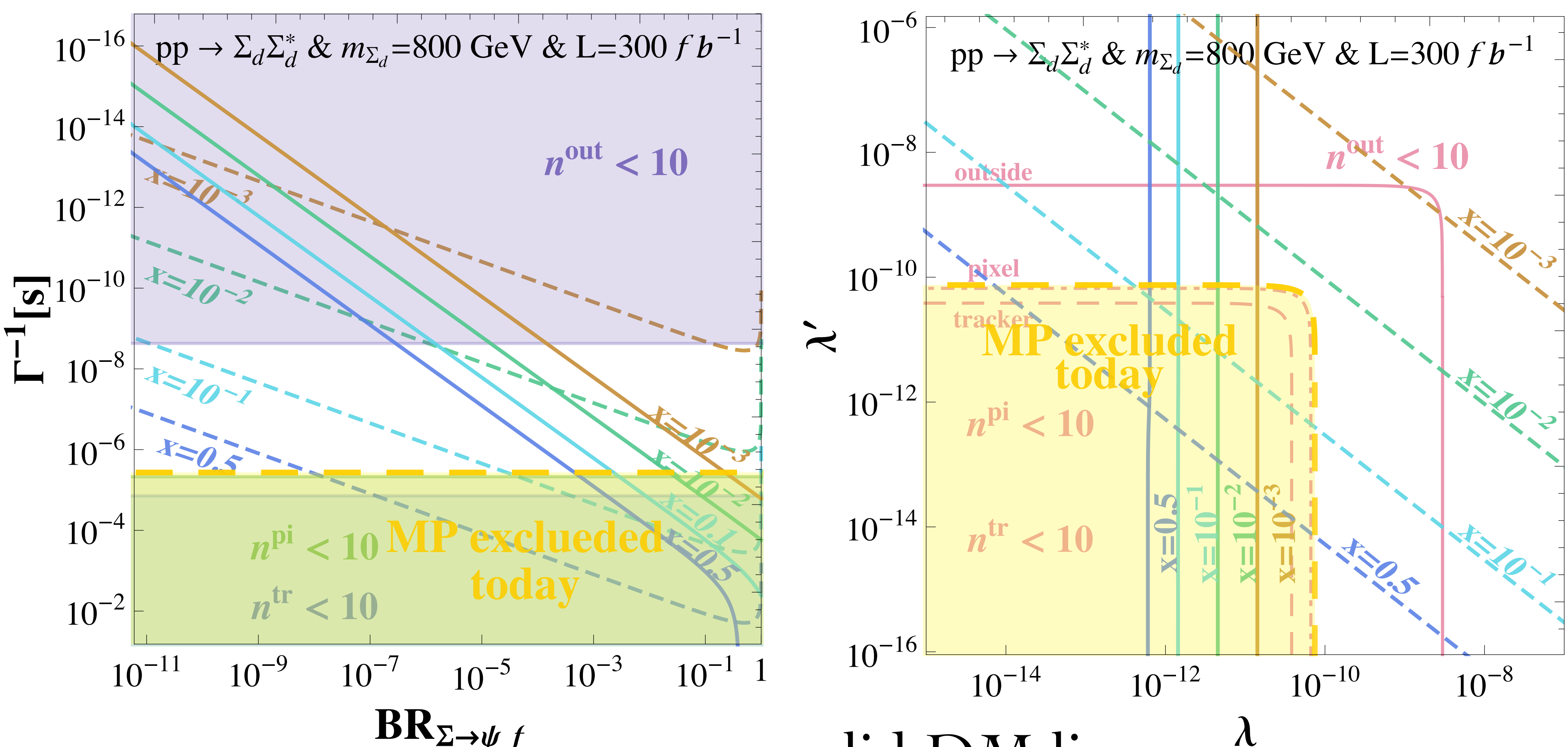
Moreover imposing ID "around the corner" gives

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

At least one decay could be visible !!!

FIMP/SWIMP & COLORED Σ

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

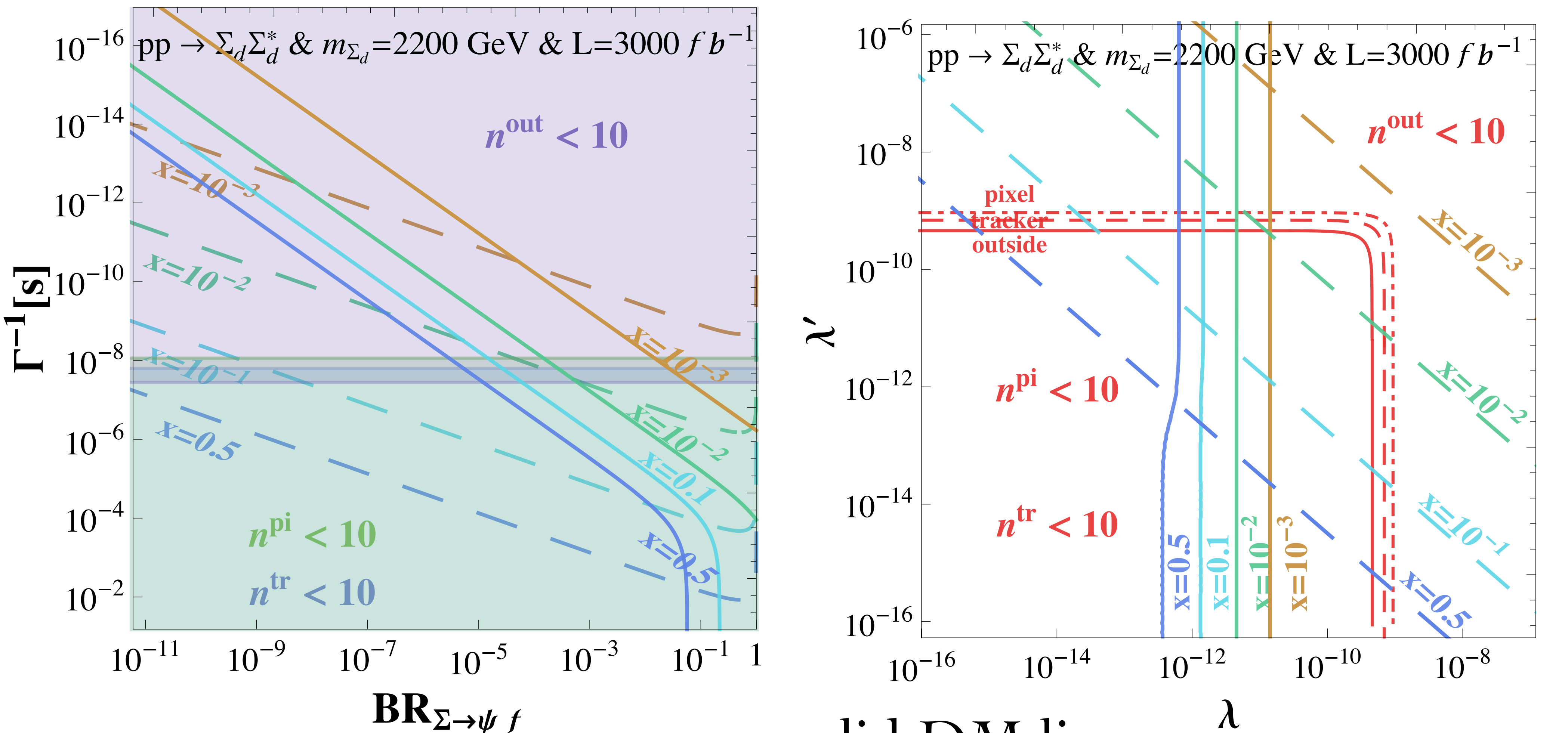


solid DM lines

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

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...

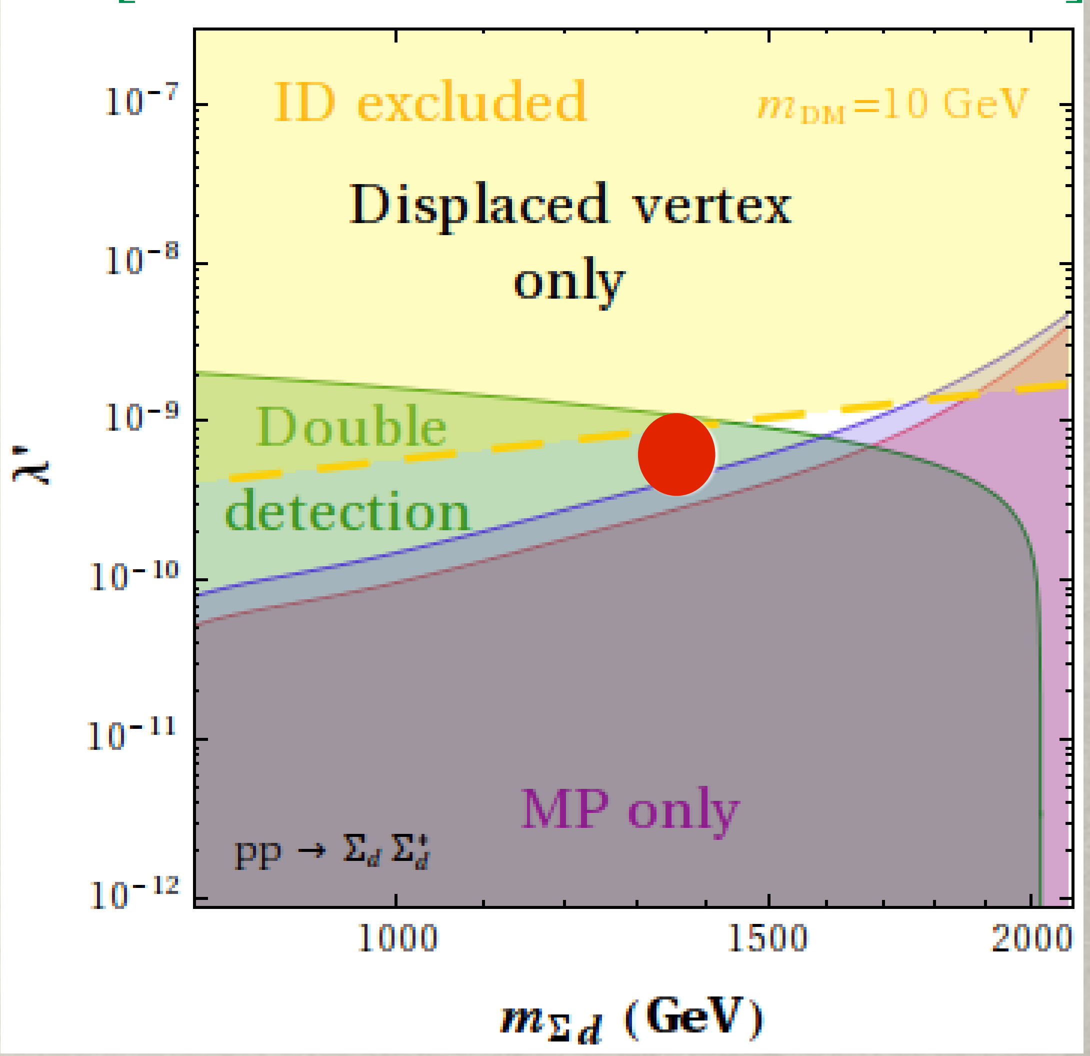
Σ Combined detection

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 !

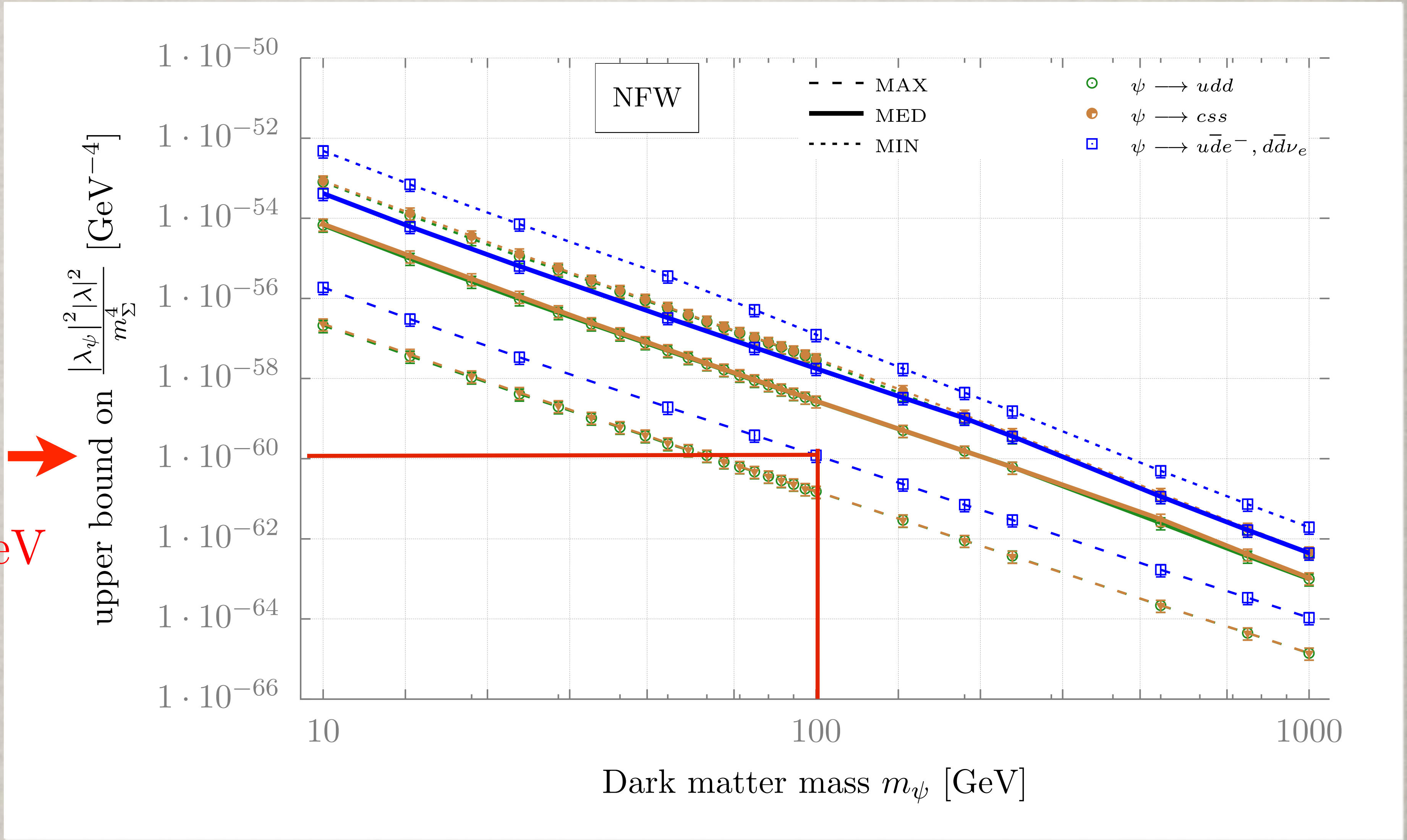
ID of FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]

$\lambda\lambda' =$

10^{-18}

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



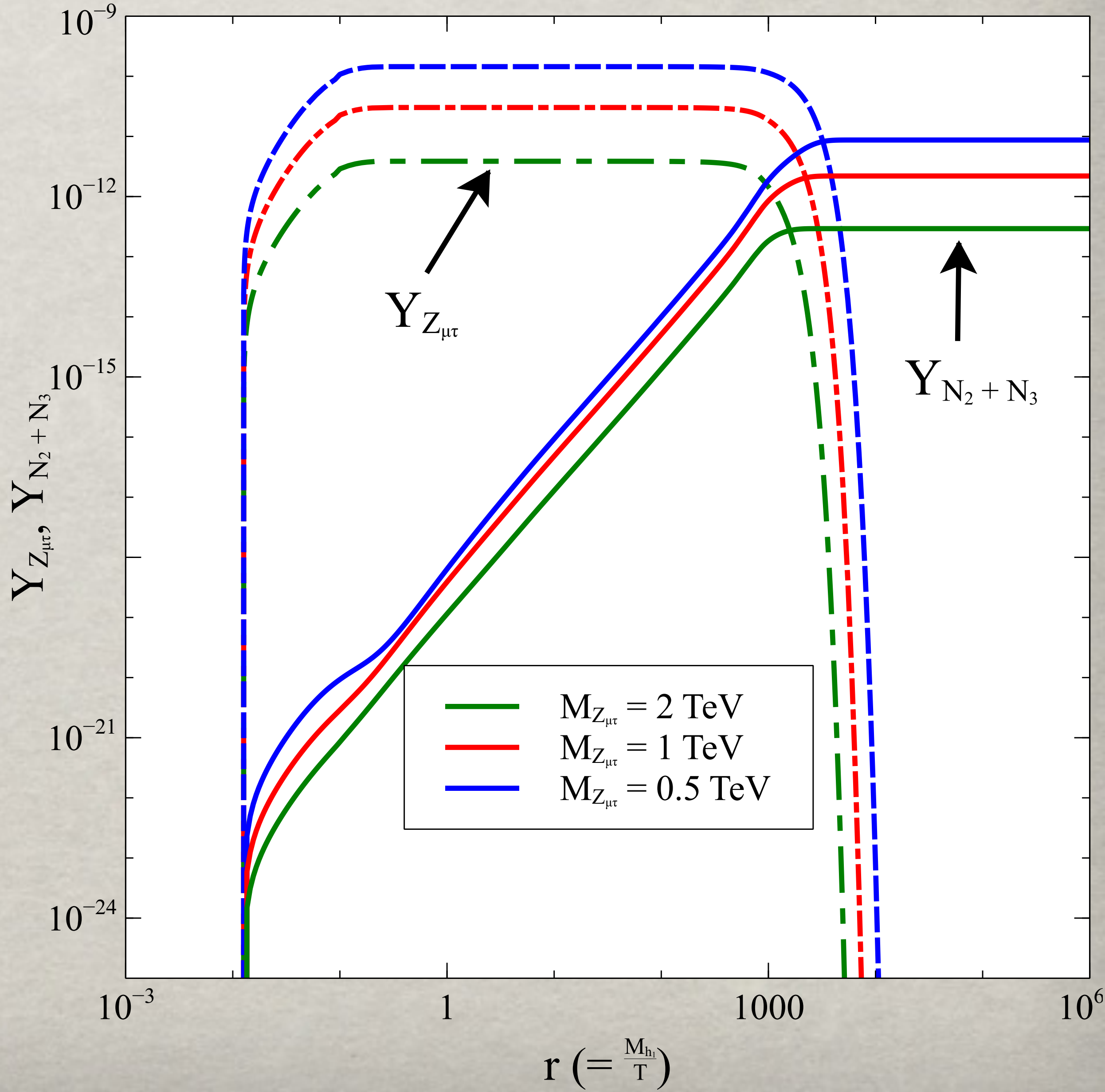
Unfortunately bounds strongly depend on propagation...

FIMP from a FIMP

[A. Biswas, S. Choubey, LC & S. Khan 2017]

Note: more complex models are possible, e.g. a gauged $U(1)_{L_\mu - L_\tau}$ where the neutrino masses are generated radiatively and two RH neutrinos are FIMP DM produced from the gauge boson, itself a FIMP… Need though a very small gauge coupling:

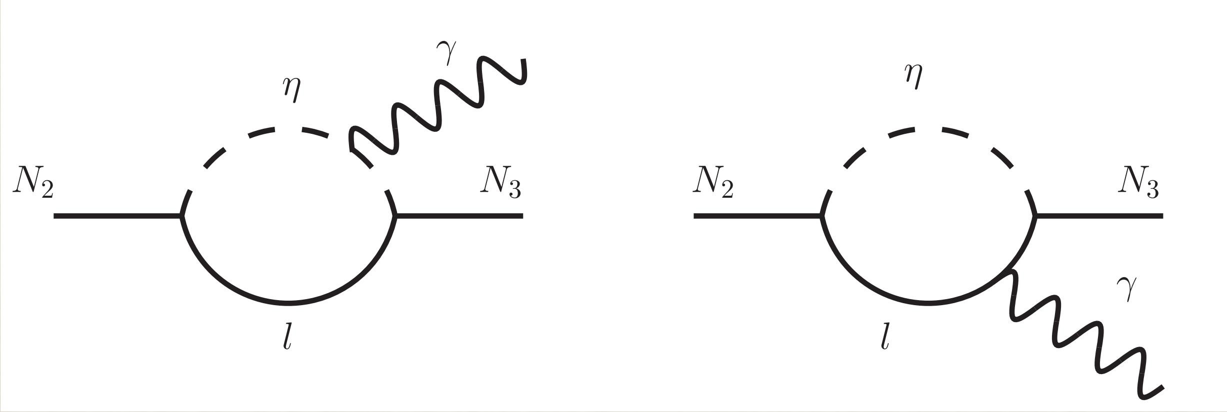
$$g_{\mu\tau} \sim 10^{-11}$$



Decaying FIMP from a FIMP

[A. Biswas, S. Choubey, LC & S. Khan 2017]

In this case the mass splitting between the RH neutrinos is small due to the $U(1)_{L_\mu - L_\tau}$ and the heavier can decay into the lighter one giving rise to a keV line if the mass splitting is in that range…



The right lifetime is obtained for masses of the RH neutrinos in the 100 GeV range and inert scalars in the 10^6 GeV range.

Difficult to test at collider due to tiny coupling/heavy scalars !

Baryogenesis in RPV SUSY

RPV superpotential includes couplings that violate baryon number and can be complex, i.e.

$$W = \lambda''_{ijk} U_i D_j D_k$$

Possible to generate a baryon asymmetry from out-of-equilibrium decay of a superparticle into channels with different baryon number, e.g. for a neutralino

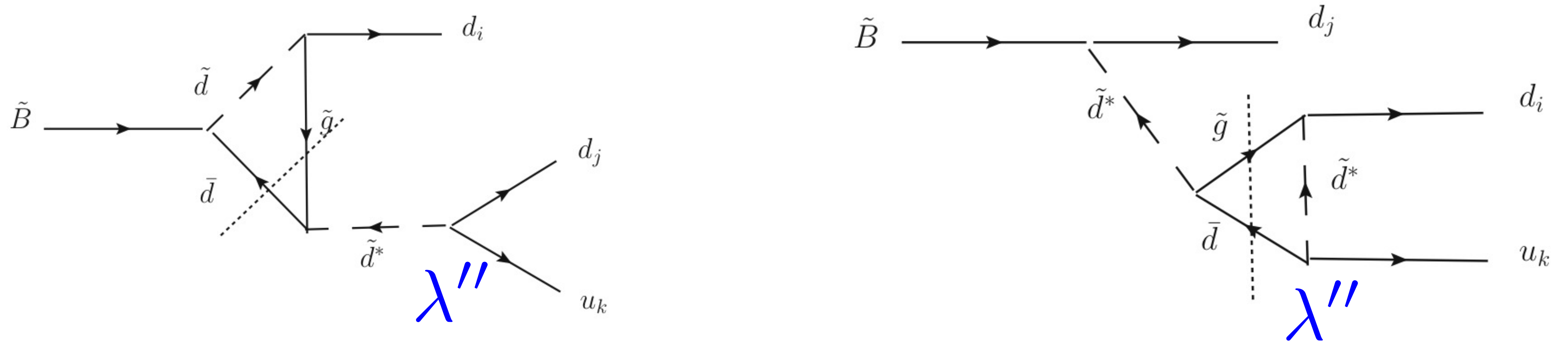
$$\tilde{B} \to udd,\ \bar{u}\bar{d}\bar{d},\ \tilde{g}\bar{q}q$$

Initial density of neutralino can arise from usual WIMP mechanism, since the decay rate is very suppressed !

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

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

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

independent of Bino density

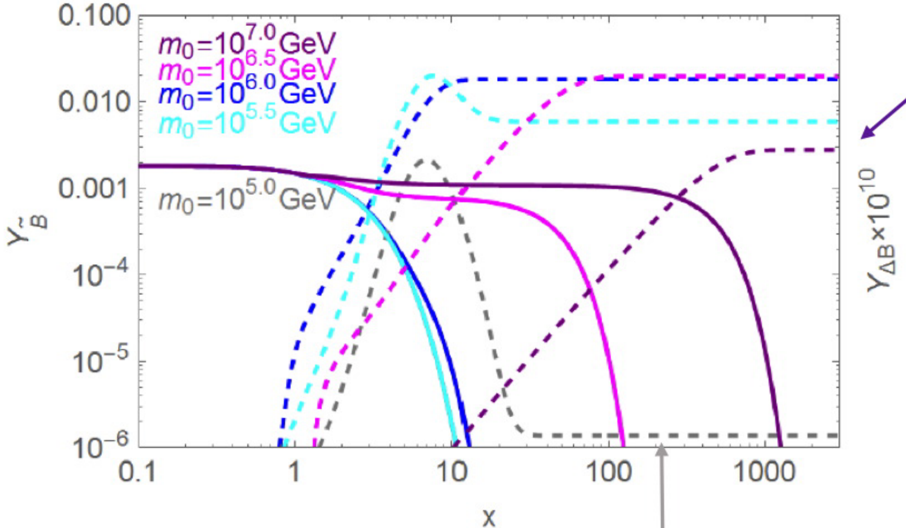
Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

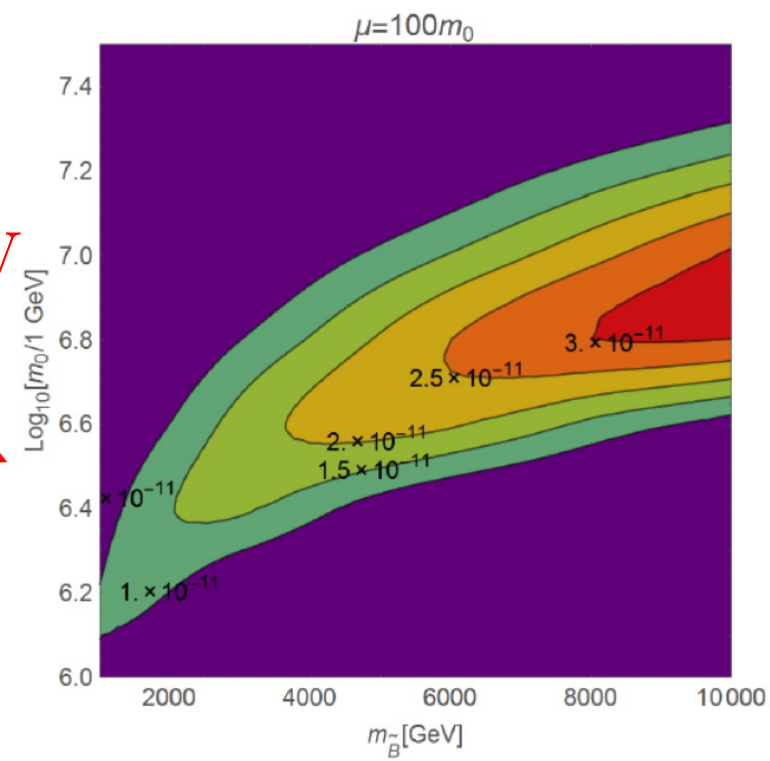
Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Asymmetry suppressed by the high scalars



Asymmetry suppressed by wash-out

10^7GeV

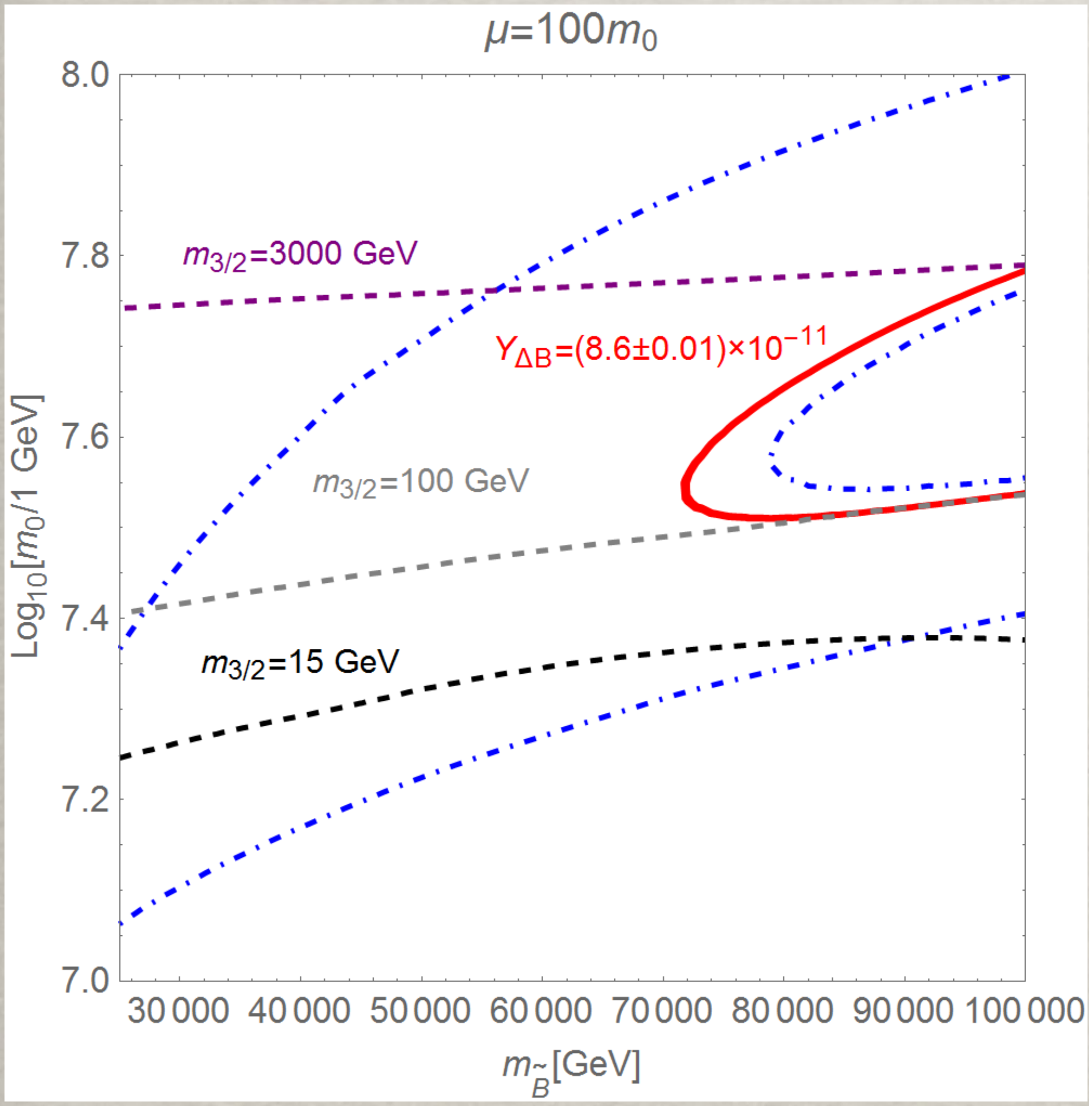


Rather definite prediction for range of scalar masses

Heavy !!!

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



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

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

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...

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.

Axion
Dark Matter

Strong CP & the Axion

The QCD vacuum has a non trivial structure, as a superposition of different topological configurations, giving rise to strong CP problem from the term:

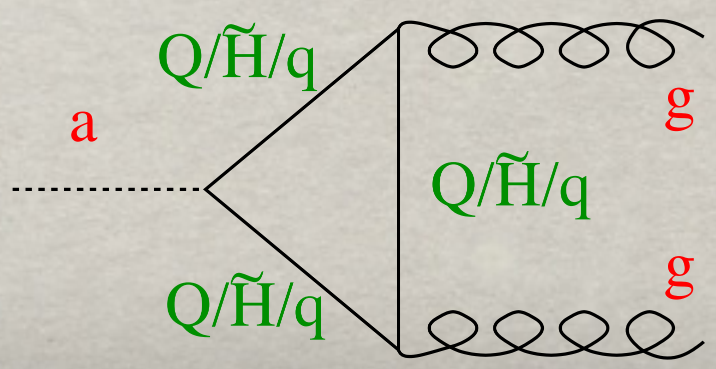
['t Hooft 76]

$$\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$

But from the bounds on neutron el. dipole moment $\theta < 10^{-9}$

Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a , leaving the axion, a pseudo-Goldstone boson, interacting as

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a} a F^b_{\mu\nu} \tilde{F}^{\mu\nu}_b$$



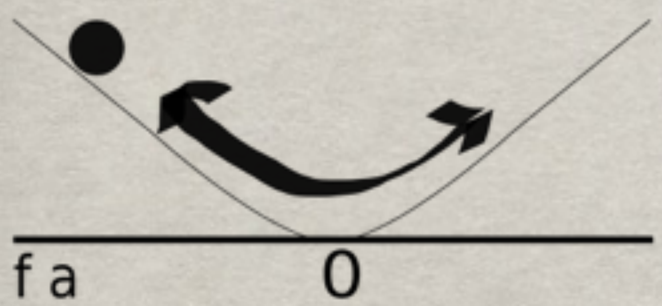
Axions as Dark Matter

The axion is also a very natural DM candidate, but in this case in the form of a condensate, e.g. generated by the misalignment mechanism:

Before the QCD phase transition the potential for the axion is flat

After the QCD phase transition a potential is generated

$$V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$

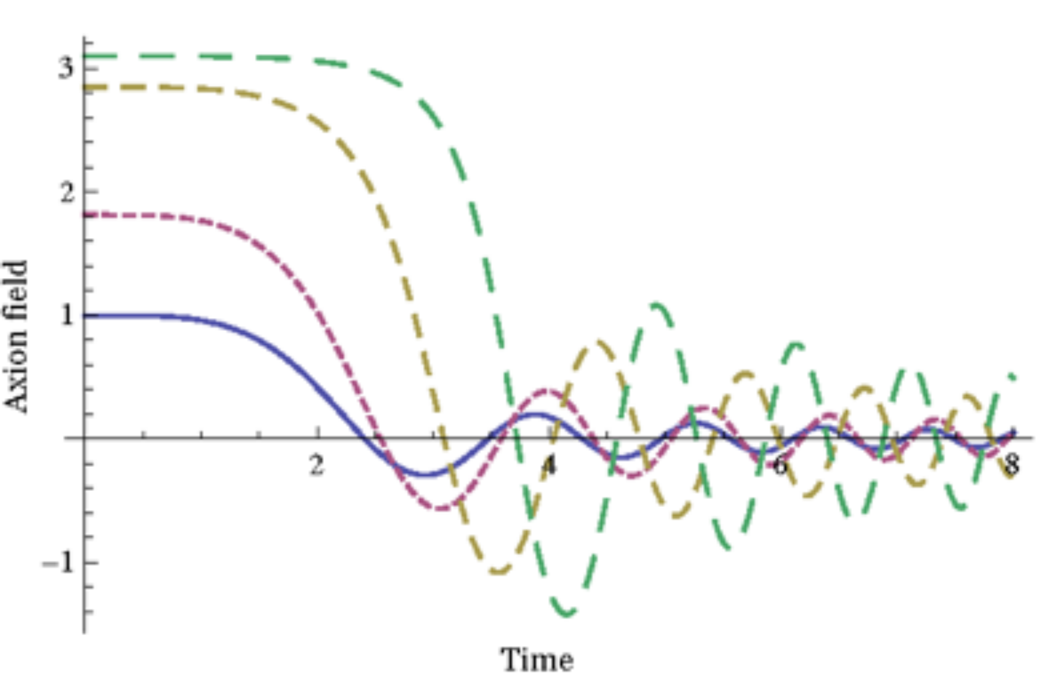


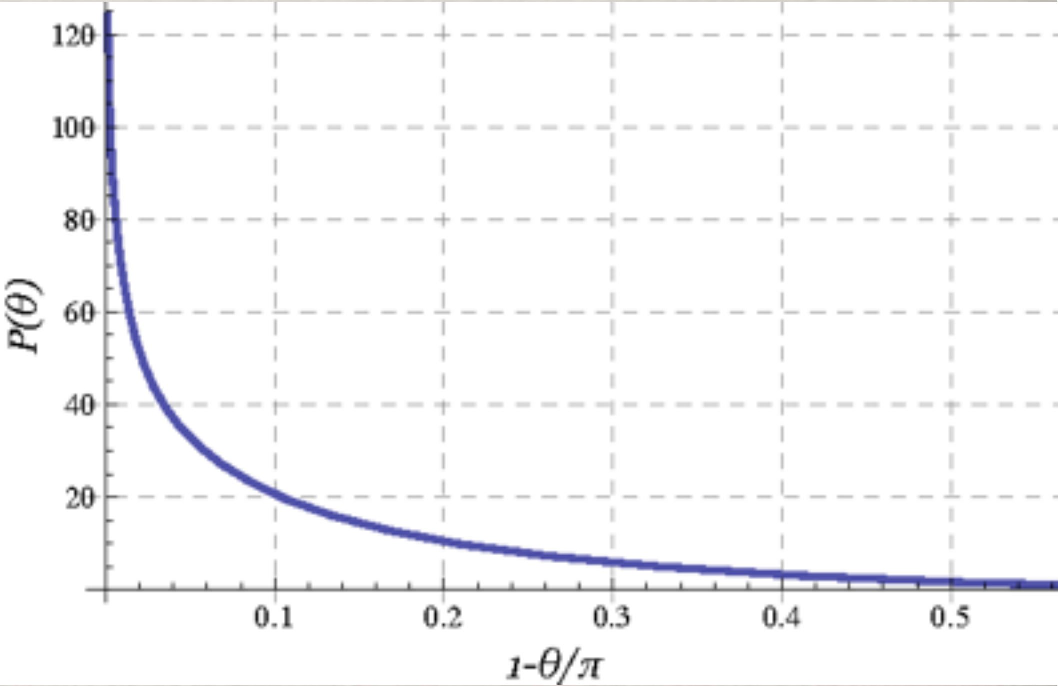
by instanton's effects and the axion starts to oscillate coherently around the minimum:

zero momentum particles >> CDM !

Axion's dynamics

[Arvanitaki, Dimopoulos et al. 2009]





The axion starts to oscillate after the QCD phase transition and depending on the initial condition θ_i (including non-harmonic effects), different axion densities survive.

Axions as Dark Matter

Their energy density by misalignment is

$$\Omega_a h^2 = 0.5 \left(\frac{f_a}{10^{12}\text{GeV}} \right)^{7/6} \theta_i^2 \quad \rightarrow P(\theta_i)$$

Axions can contribute to star/SN cooling and so

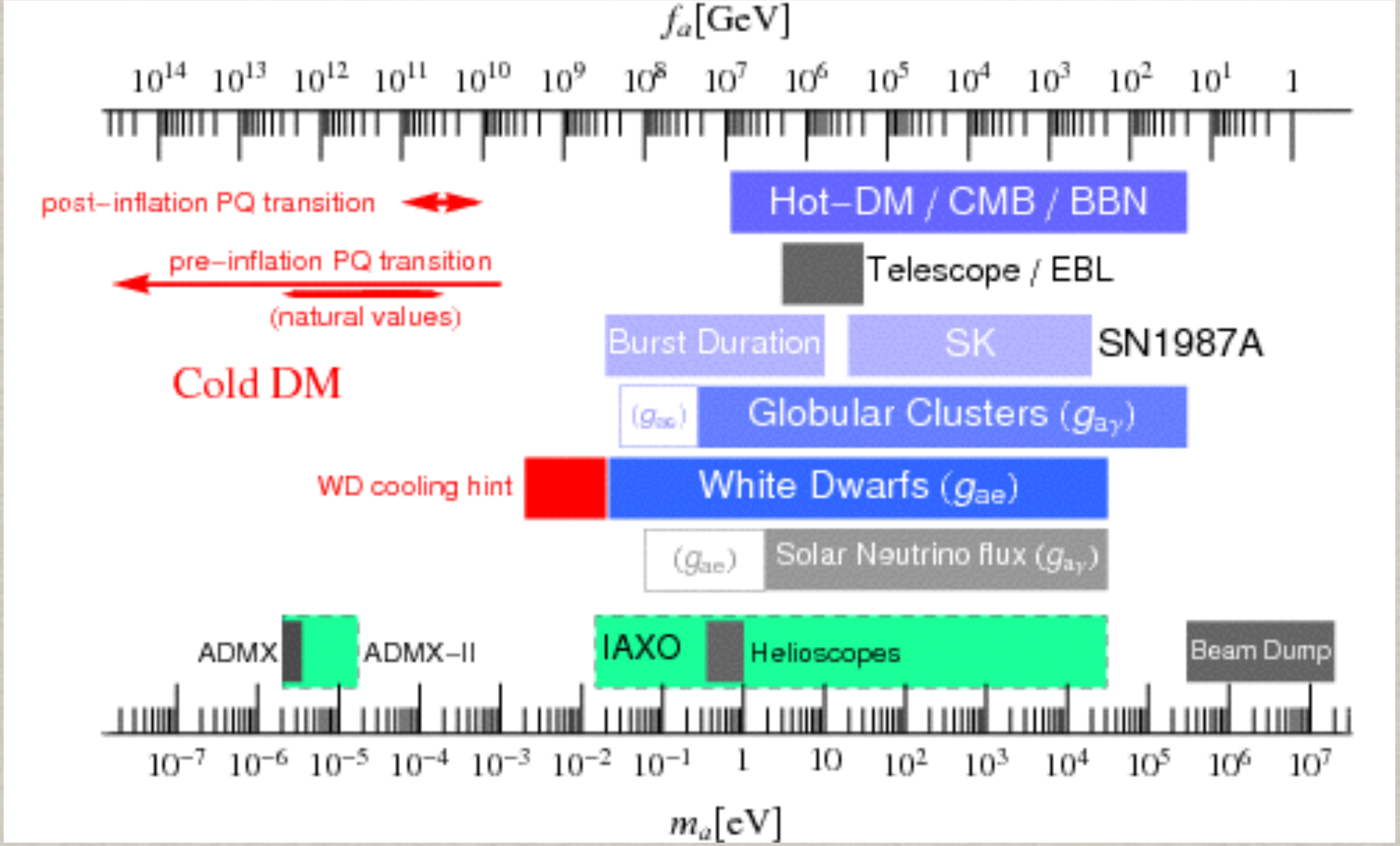
$$0.5 \times 10^{10}\text{GeV} \leq f_a \leq 10^{12}\text{GeV}$$

[Raffelt 98]

Therefore the mass for axion DM is very small:

$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\text{eV} \left(\frac{f_a}{10^{11}\text{GeV}} \right)^{-1}$$

Axion's constraints



[CERN Report]

AXION DM SEARCHES

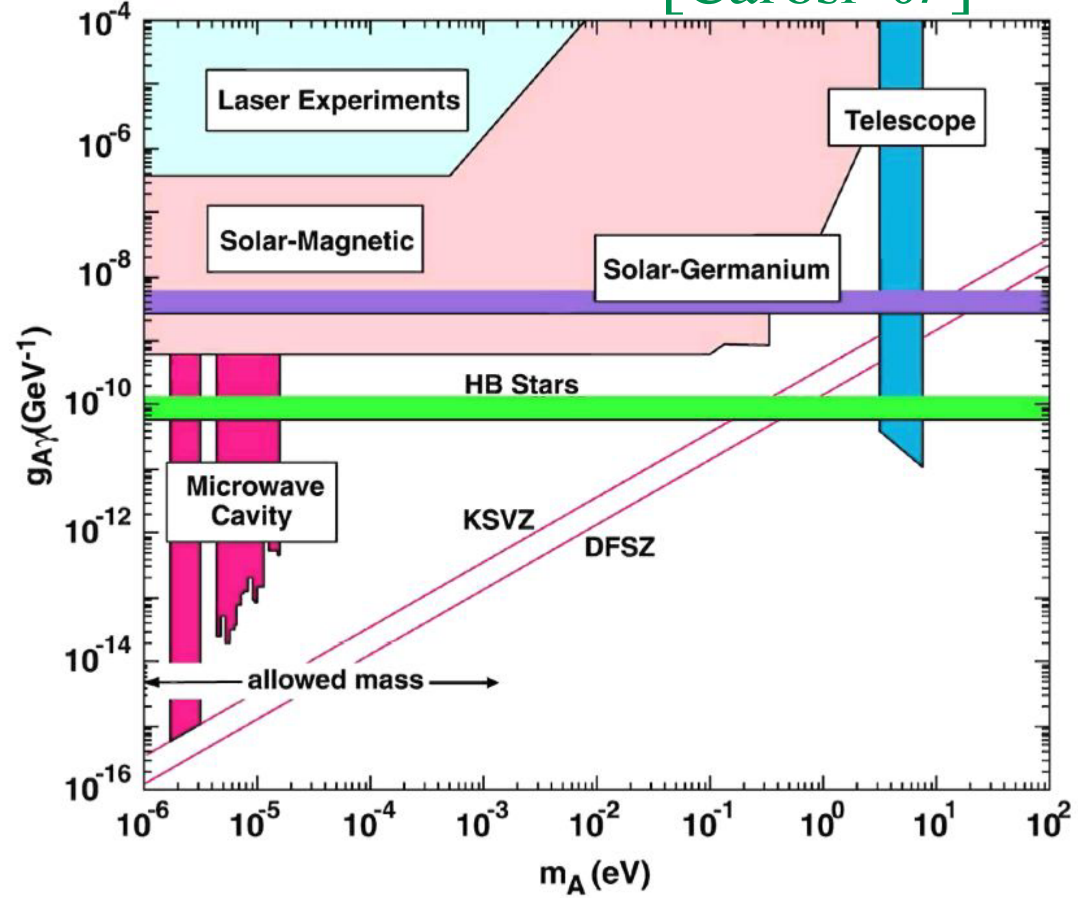
The right abundance can be obtained if the Peccei-Quinn scale is of the order of 10^{11-12} GeV and the mass in the μ eV.

ADMX is finally touching the expected region.

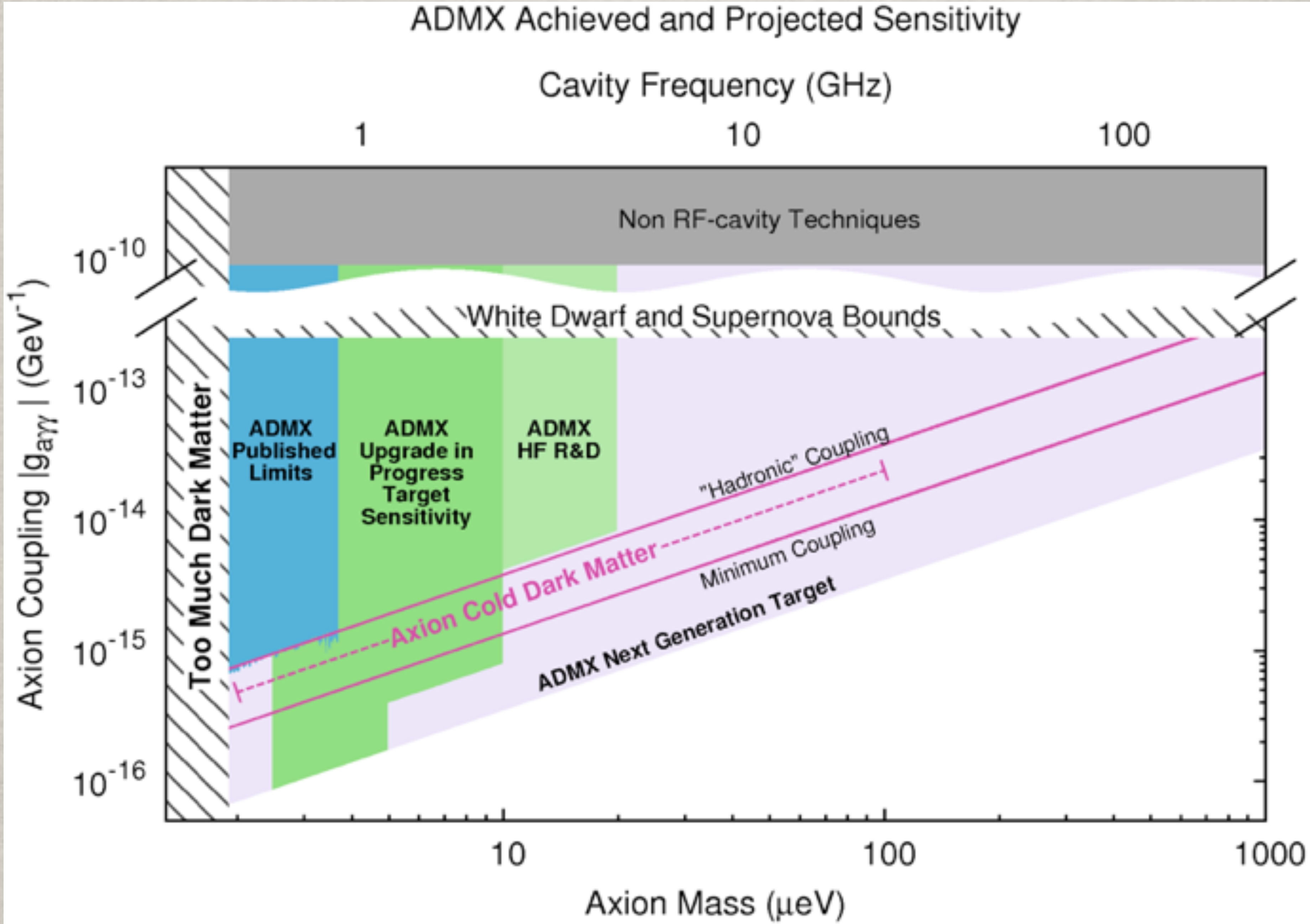
But it could be much wider for non-standard cosmologies...

[Gondolo et al 09]

[Carosi '07]



AXION DM SEARCHES



http://www.phys.washington.edu/groups/admx/home.html

Other evidence of axion DM?

- Axion DM may give rise to a different caustics shapes as Cold DM due to the BEC rotational properties... [Sikivie et al. '07, '08]
- Axion DM is a decaying DM candidate !!!
  The axion decays to 2 photons like the pion, but the lifetime is quite long $\tau_a \geq 10^{46} s$ and the photon energy very low …
  Maybe SKA could see it [Caputo, Pena Garay & Witte '18]
- In the axion/axino mixed DM case, some collider signal are expected, see e.g. [Baer et al. '08,…'18]

Outlook

Outlook

- From the theoretical perspective, we have a few "natural" DM production mechanisms, not only the WIMP, but also the FIMP/SuperWIMP mechanisms or misalignment for axions.
- The FIMP/SuperWIMP framework is quite general and could point to heavy metastable particles or displaced vertices at LHC with different decay channels.
- Supersymmetric models are still alive and actually heavi(er) than expected SUSY may give some advantages in cosmology, e.g. baryogenesis in SUSY via RPV
- Finally experiments are exploring the axion frontier and finally reaching the predicted axion band !
- Also on the WIMP front, we are making progress in modelling the Sommerfeld enhancement at finite temperature !

Stay tuned, the race is still open, also for dark horses…