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Dark Matter theory: Status and news

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neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

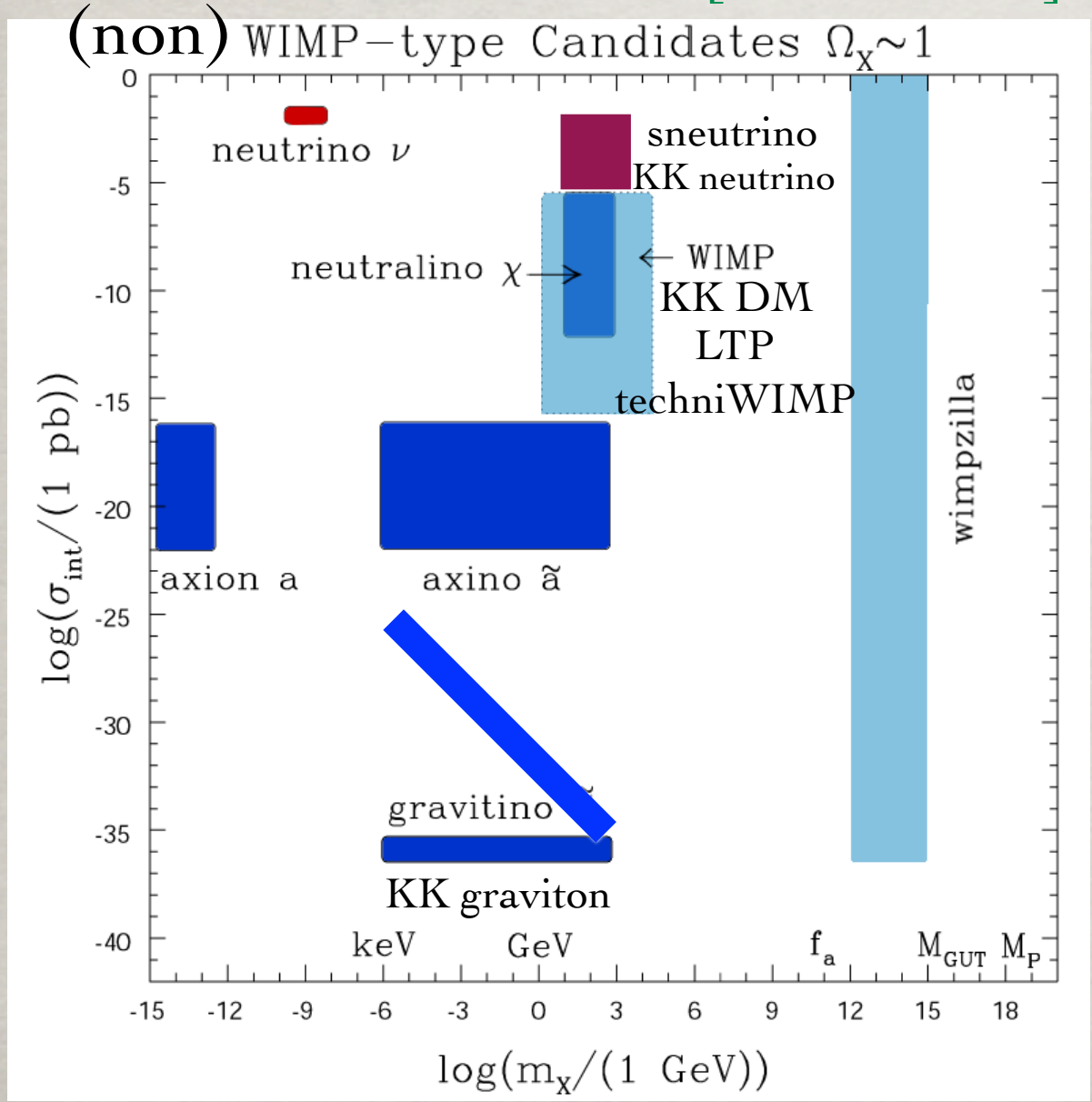
Outline

- Theoretical guiding principle:
  Dark Matter production mechanisms
- WIMP DM:
  from EFT (back) to (simplified)Models
- Decaying DM:
  FIMP/SWIMPs in the sky and LHC
- More than gravity:
  looking for Dark Interactions in structure formation
- Outlook

(Theoretical) guiding principles

DARK MATTER CANDIDATES

[Roszkowski 04]



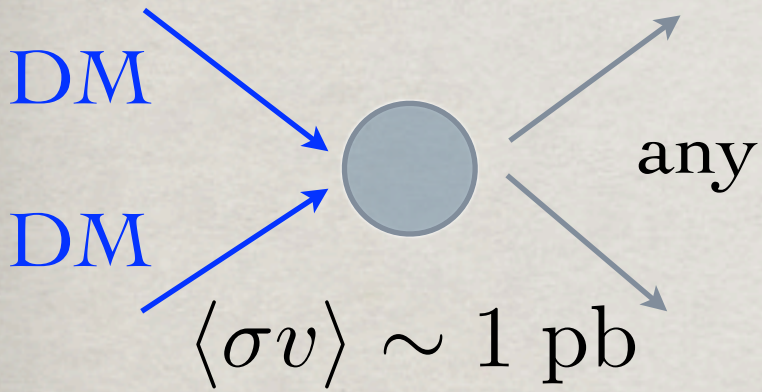
Too many different candidates...

"Standard" DM production paradigms:

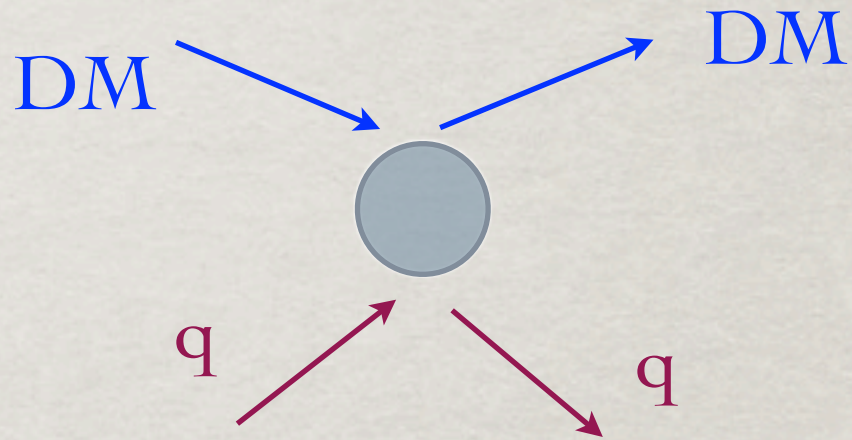
WIMPs
(i.e. neutralino)
&
"FIMP/SuperWIMPs"
(i.e. gravitino)
&
Misalignment
(i.e. axion/condensate)

THE WIMP CONNECTION

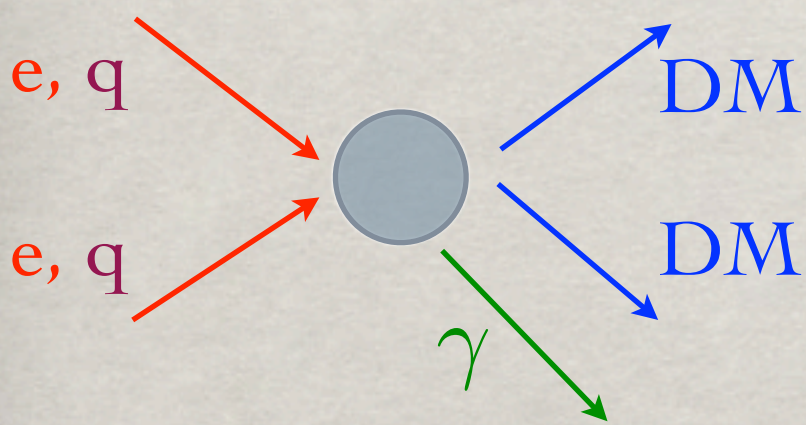
Early Universe: $\Omega_{CDM} h^2$



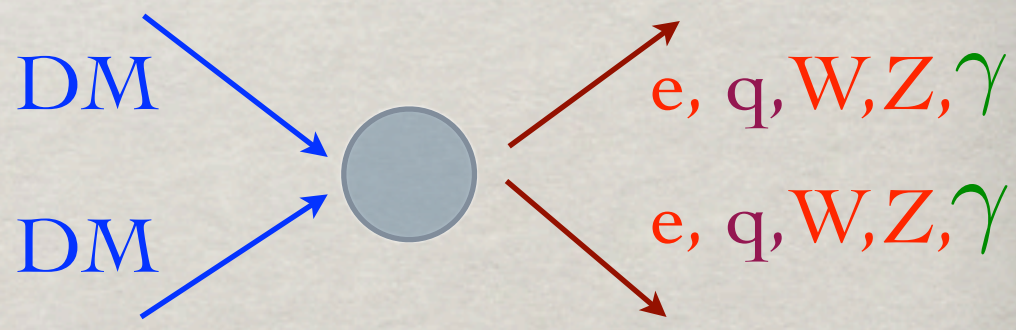
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:



3 different ways to check this hypothesis !!!

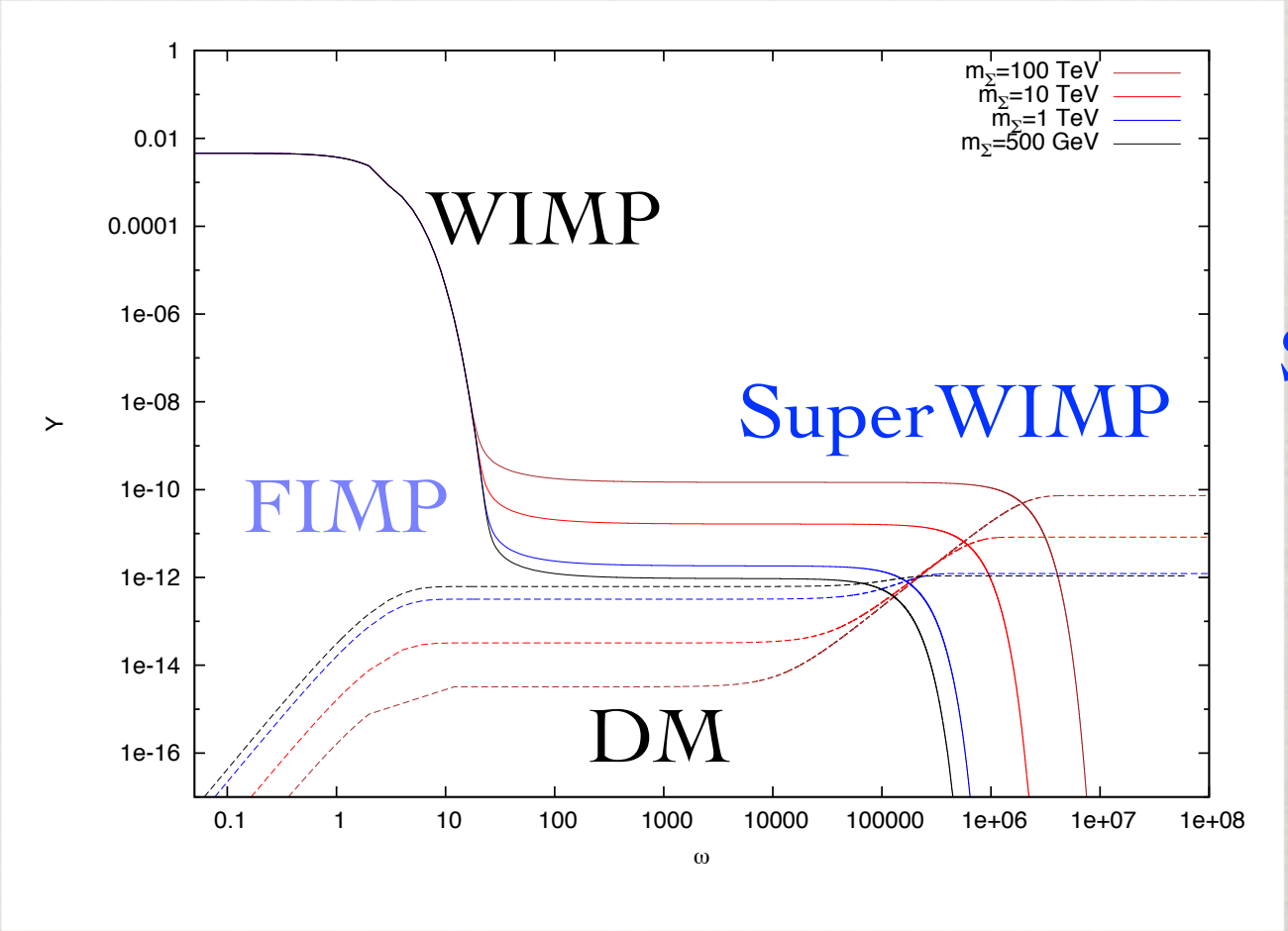
SuperWIMP/FIMP paradigms

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]

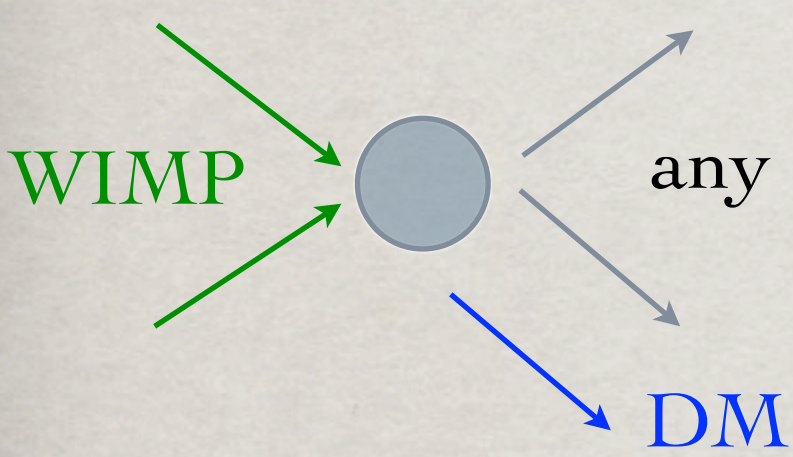
SuperWIMP

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

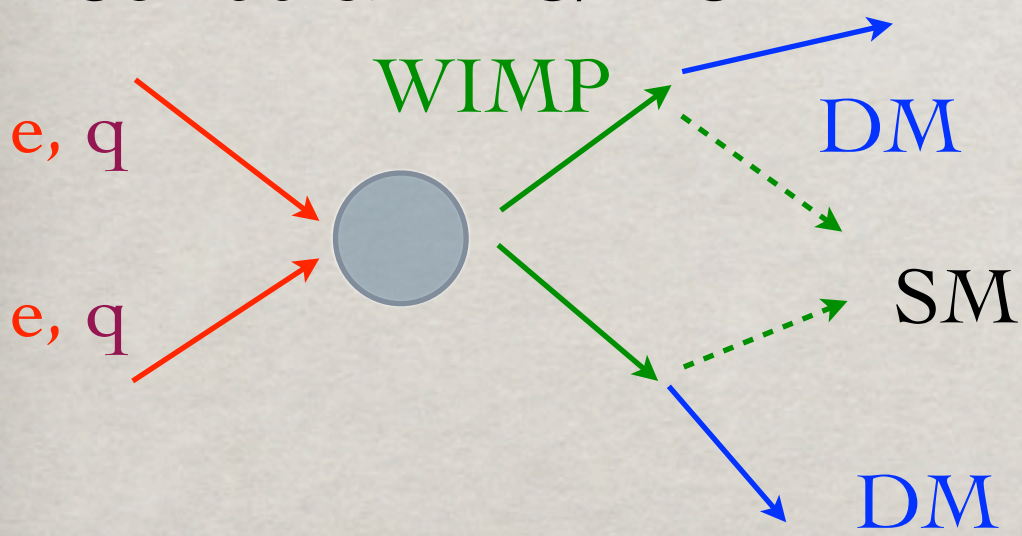
Early Universe: $\Omega_{CDM} h^2$



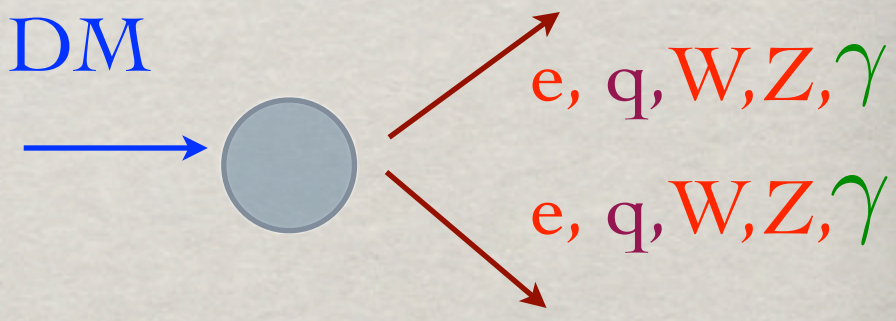
Direct Detection:

NONE...

Colliders: LHC/ILC



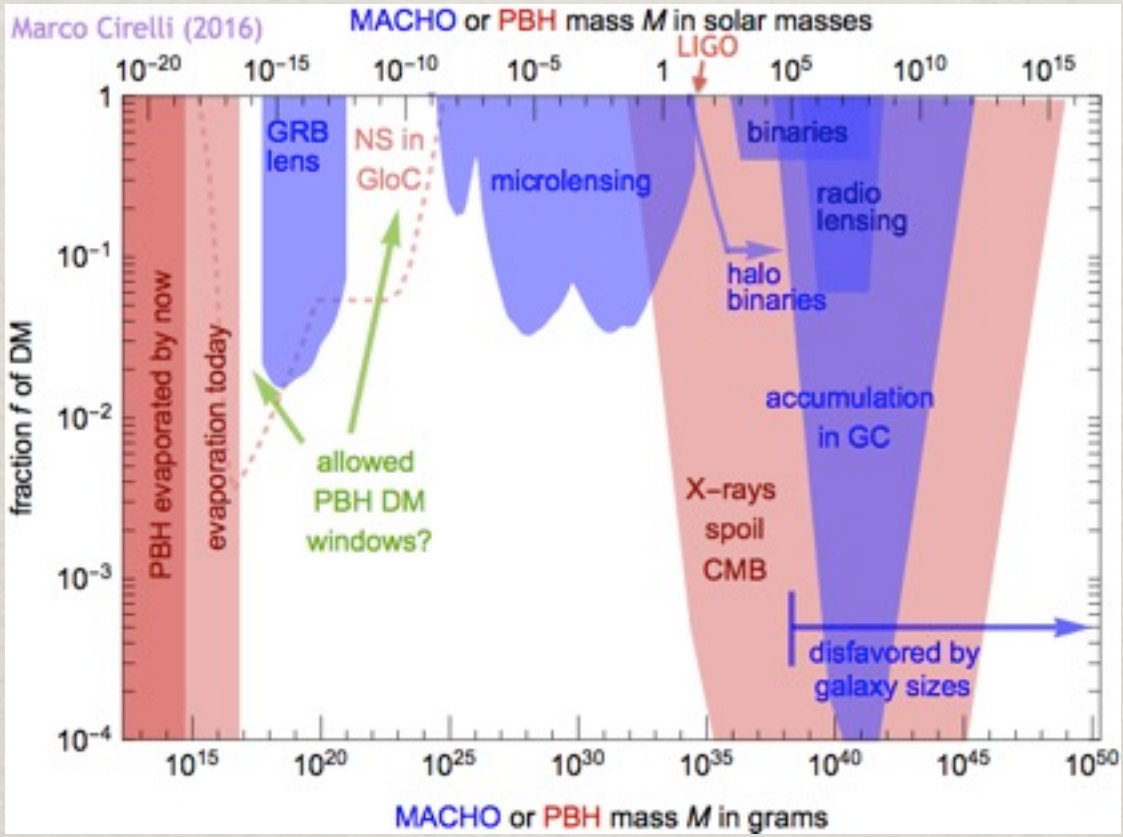
Indirect Detection:



decaying DM !

3 different ways to check this hypothesis !!!

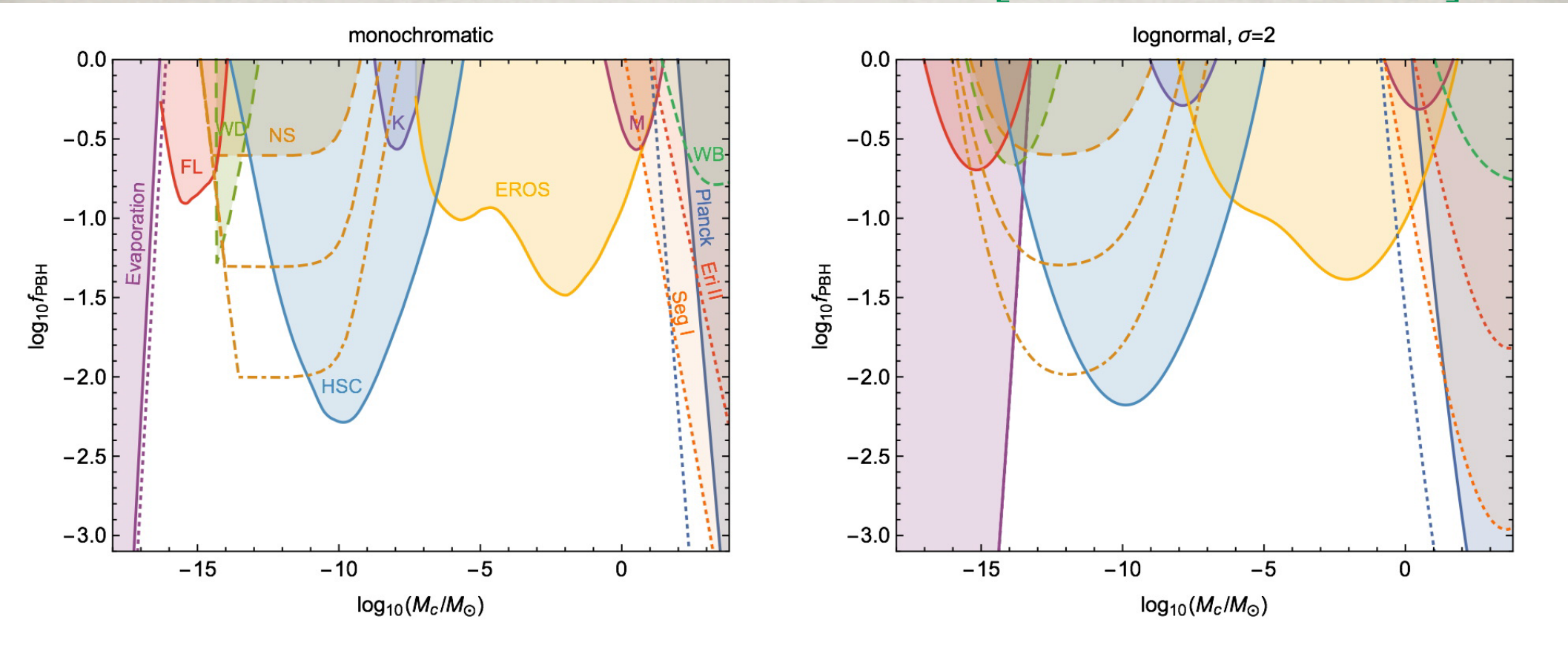
Black Hole DM ?



Not easy to produce them in the Early Universe..., e.g. need funny power spectra from inflation for primordial Black Holes; if they are produced by collapse and mergers, after BBN/CMB then DM still needed...

Black Hole DM ?

[Carr et al. 1705.05567]



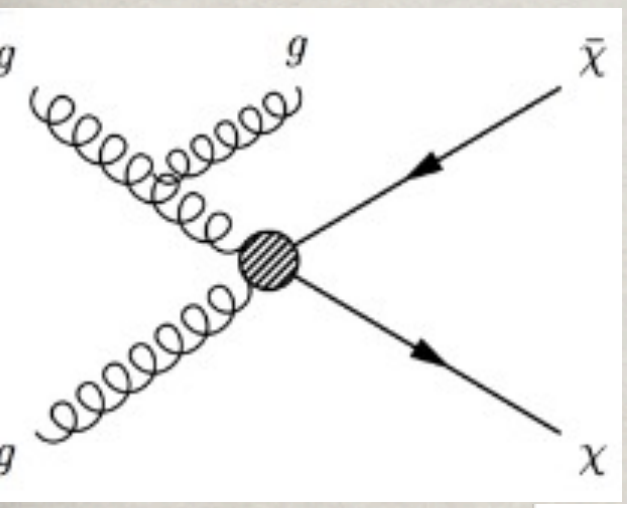
Not easy to produce them in the Early Universe..., e.g. need funny power spectra from inflation for primordial Black Holes; if they are produced by collapse and mergers, after BBN/CMB then DM still needed...

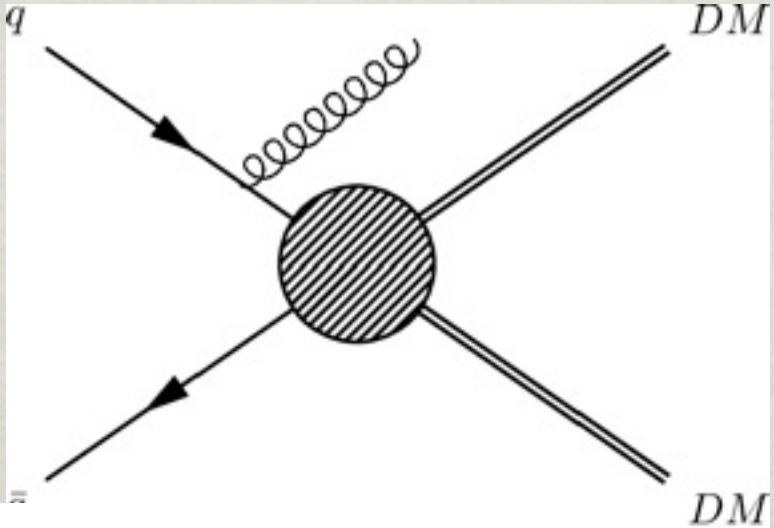
WIMP DM: from EFT to simplified models

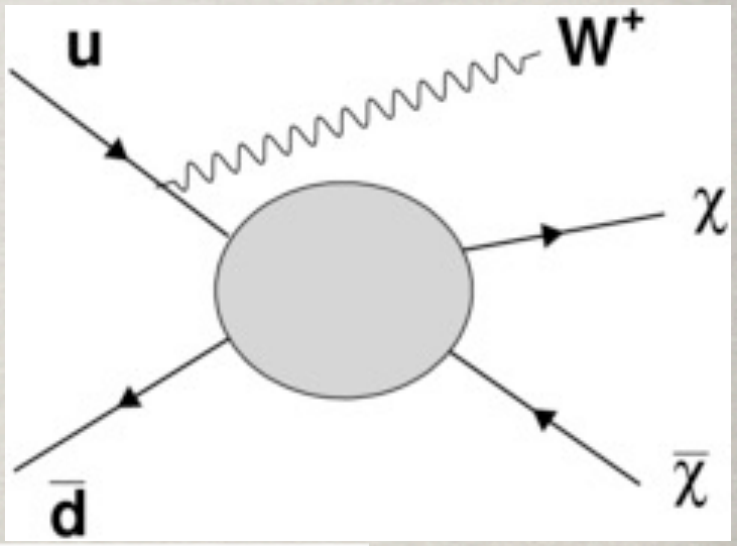
EFT for Dark Matter

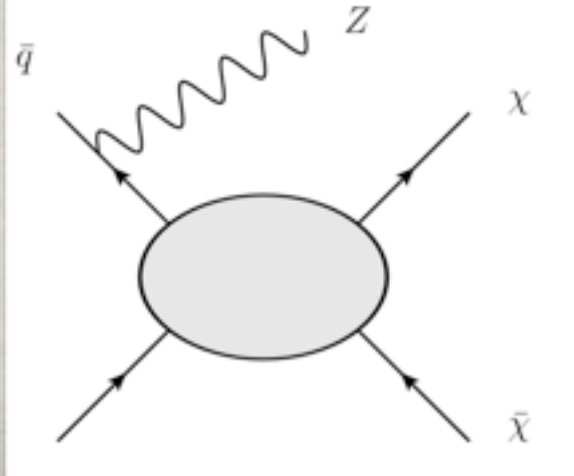
[Beltram et al 2000, Goodman et al 2000 & 2001, Bai et al 2001,....]

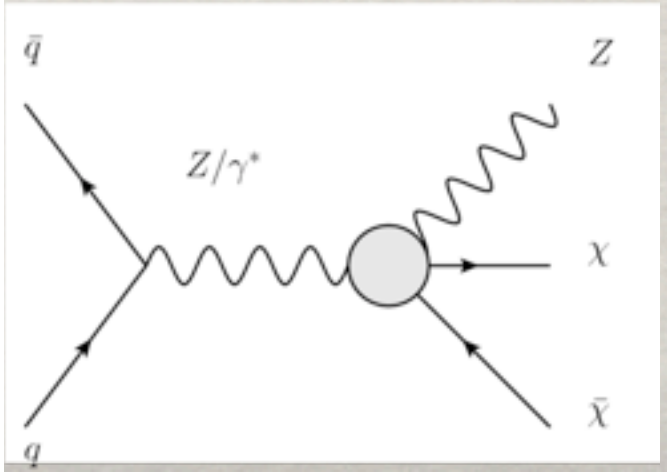
Consider the production of a pair of DM particles together with ISR of a SM particle: gluon, photon, W/Z, top, etc...
EFT: Many different effective operators are possible !









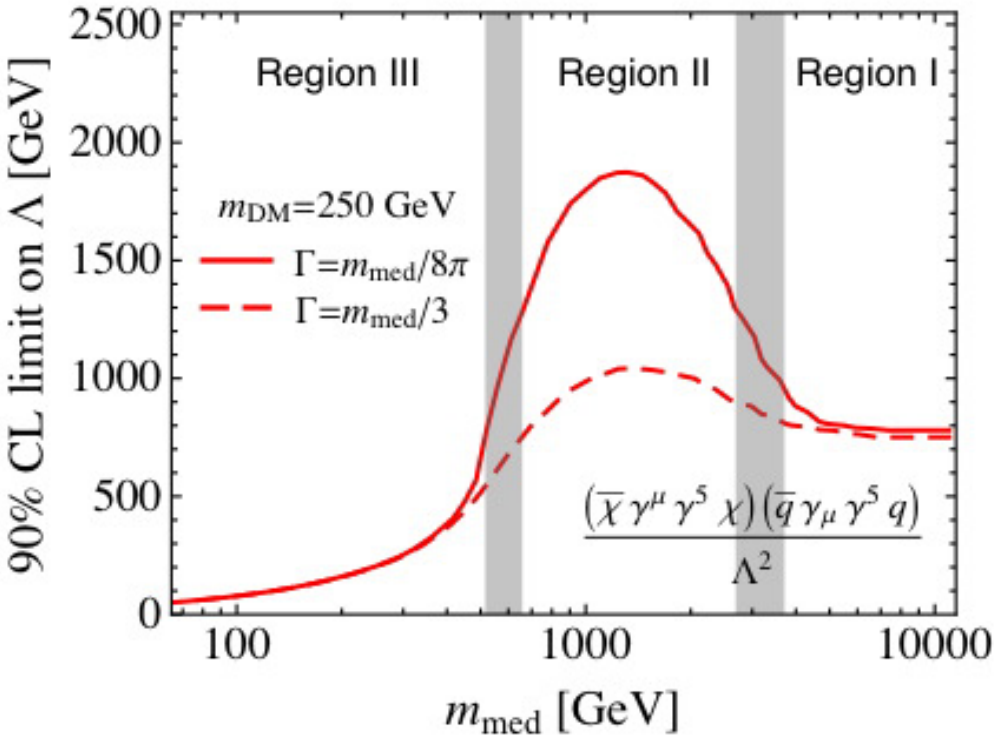


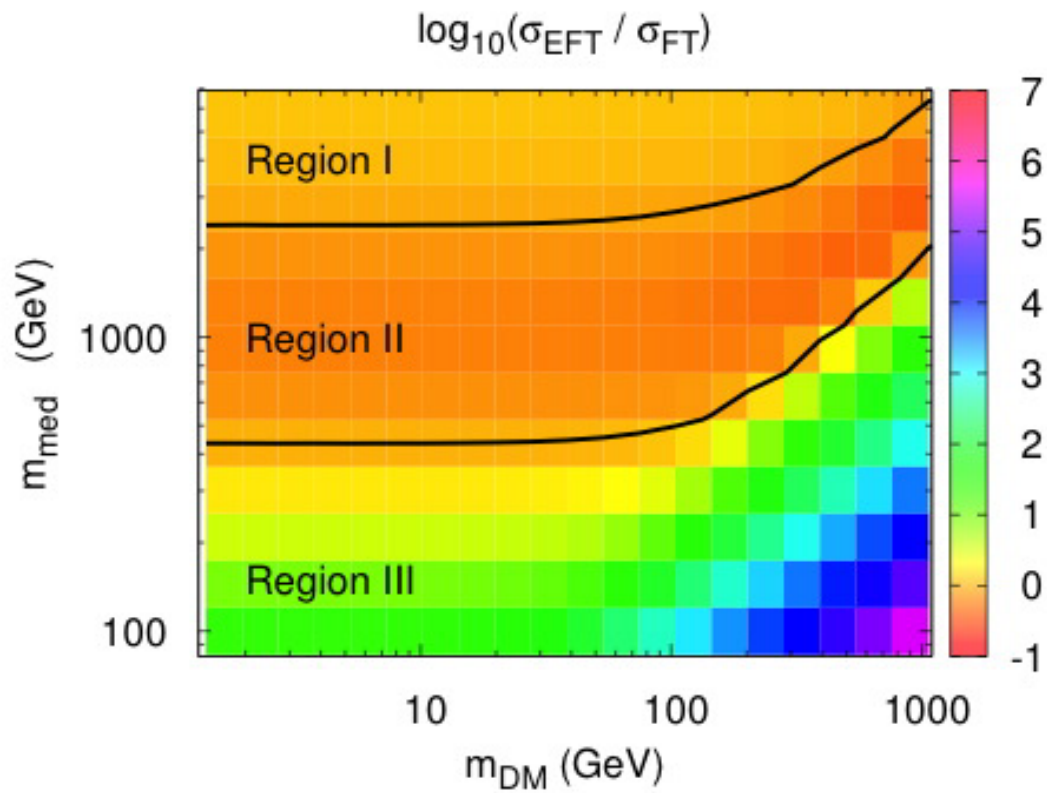
Caveat for the EFT: s

While the use of EFT for the case of non-relativistic scattering with matter in DM direct detection is well-justified, at LHC energies one has to be more careful...

[Fox et al 11, Busoni et al 13, O.Buchmuller et al 13, ...]

[O.Buchmuller et al 1308.6799]

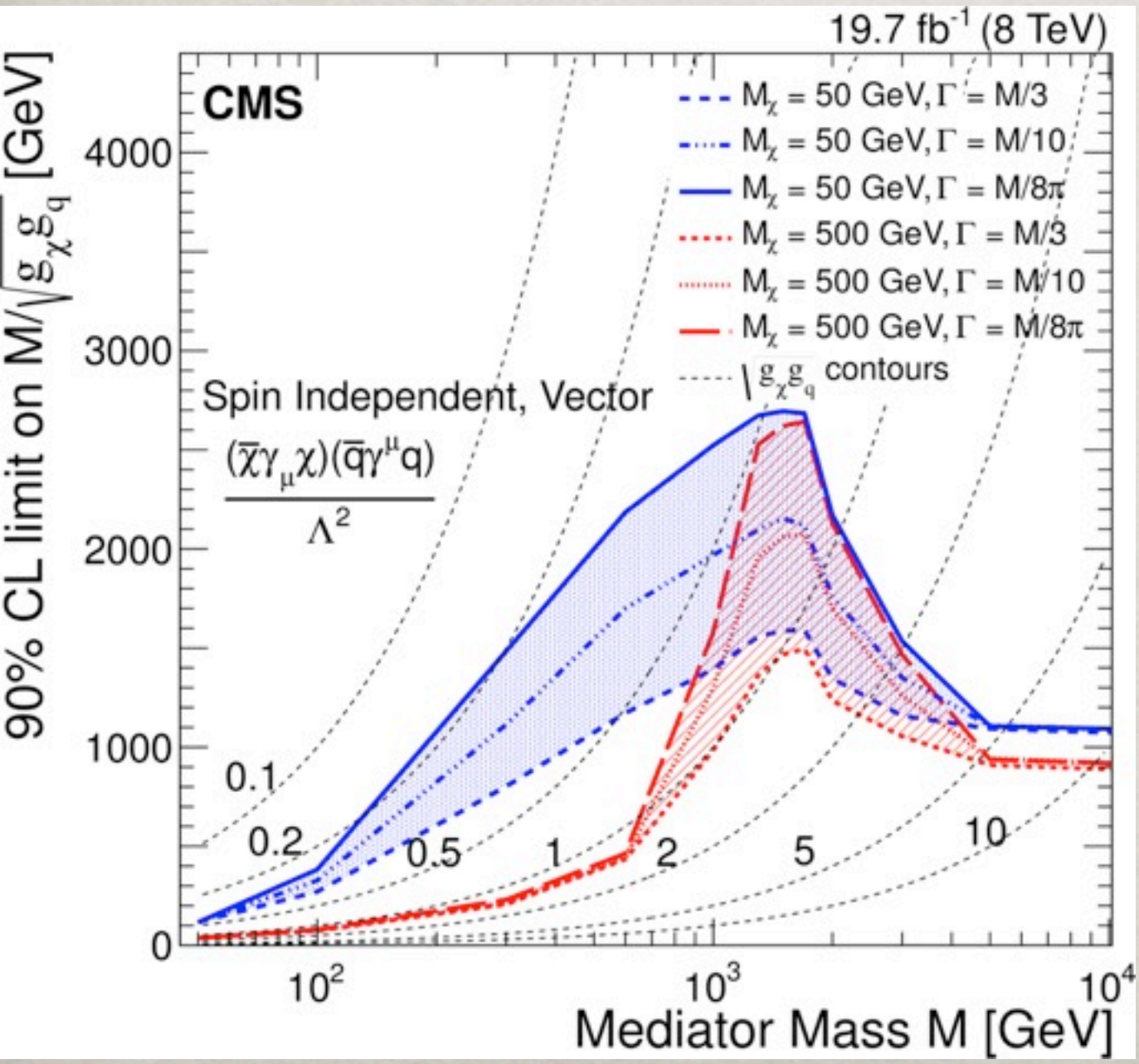




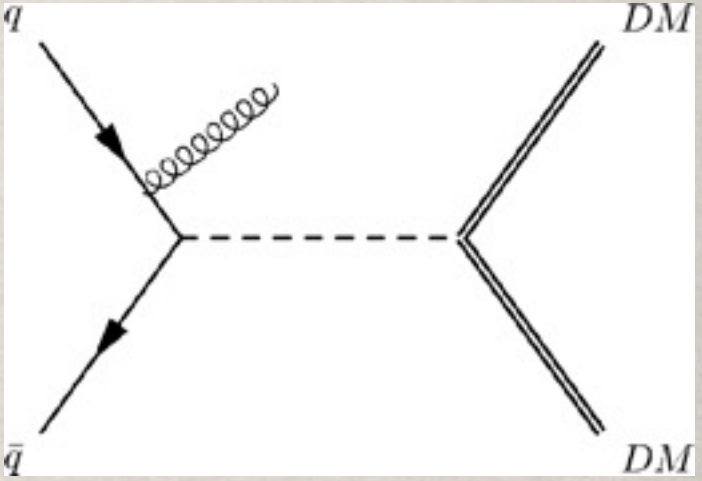
The bound is valid only for large mediator mass !

LHC: simplified models

[CMS collaboration, EPJC 75 (2015) 235]

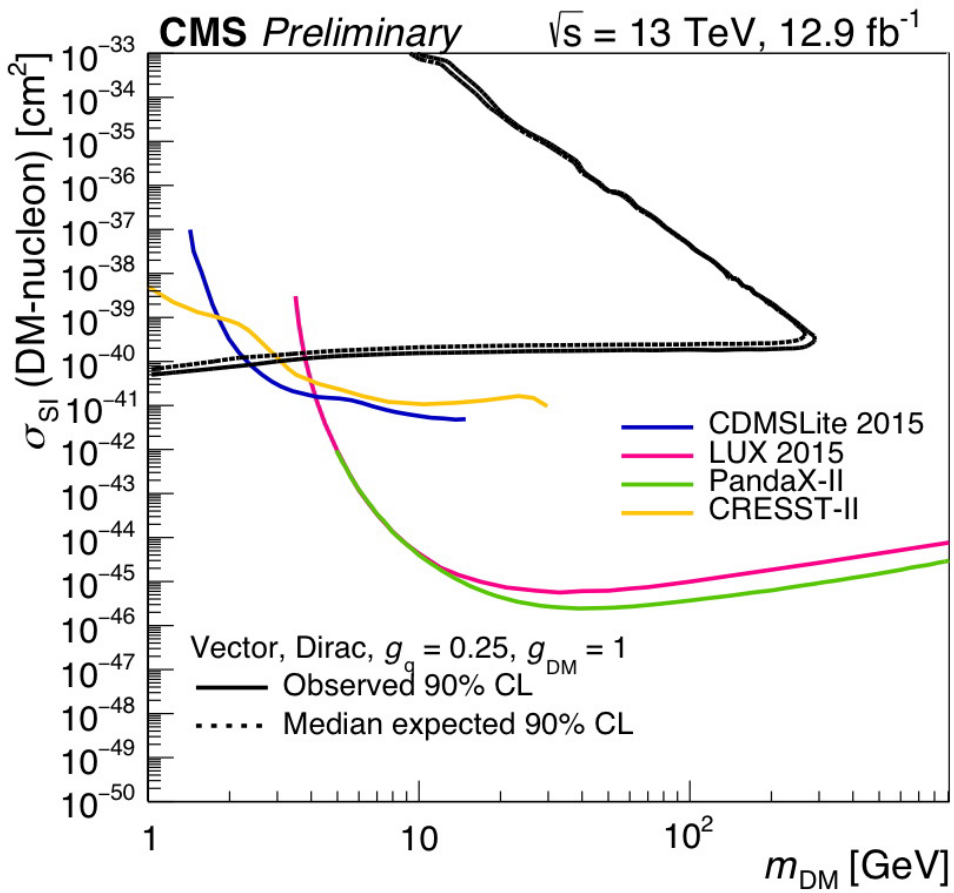


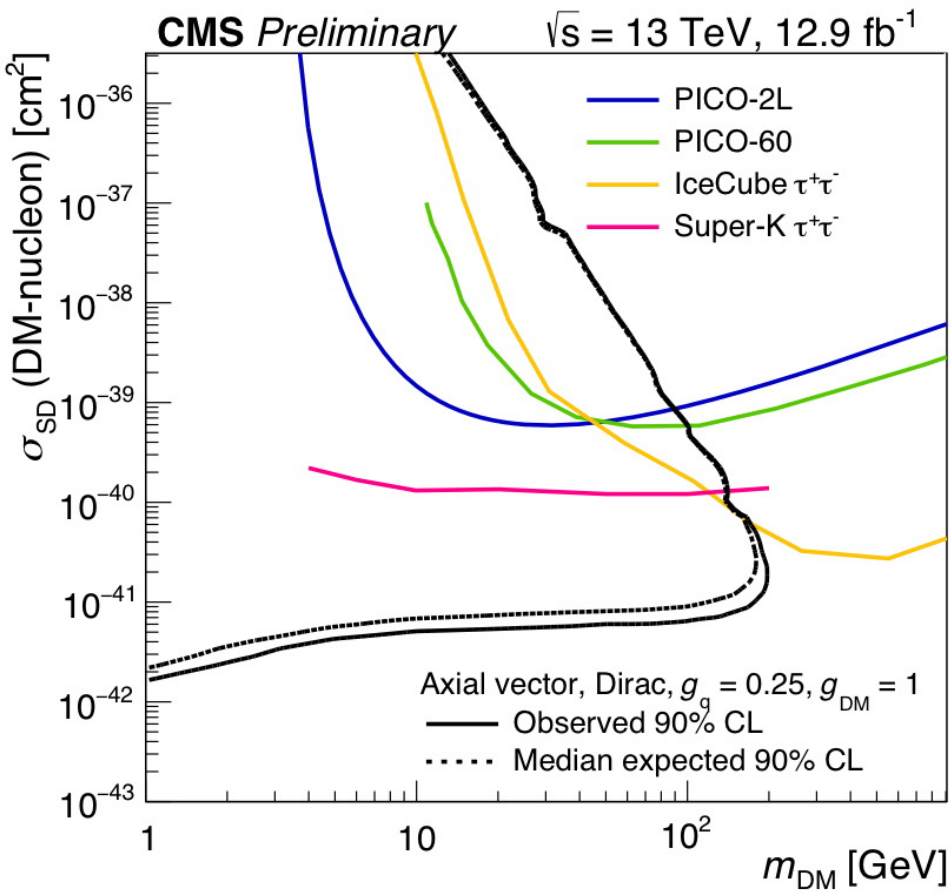
Vector mediator



LHC: simplified models II

[CMS, EXO-16-039-pas]



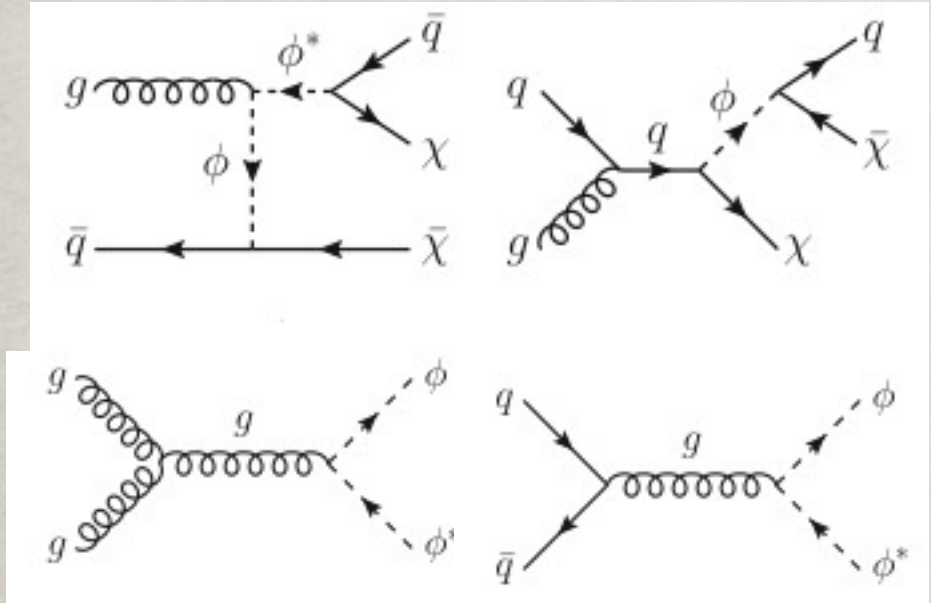


Very strong bounds for the axial vector case !

Caveat for the EFT: t

In the case of t-channel mediation, there is no resonant enhancement, but instead more channels for monojets as well as dijets show up, e.g. for scalar mediator:

[An et al. 2013, Papucci et al 2014]



Mono-jet without ISR

Dijet and MET

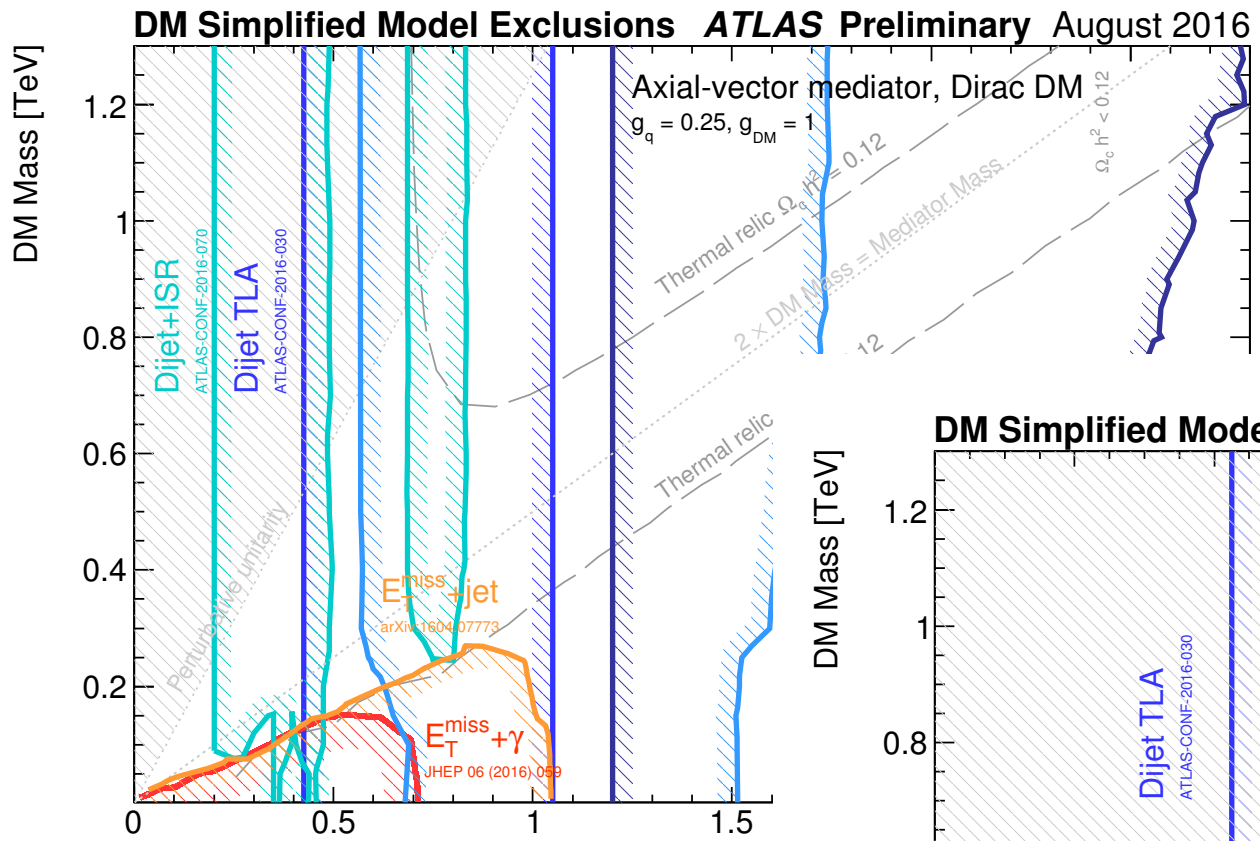
Complementary limits from Mono-jets & Di-jets !

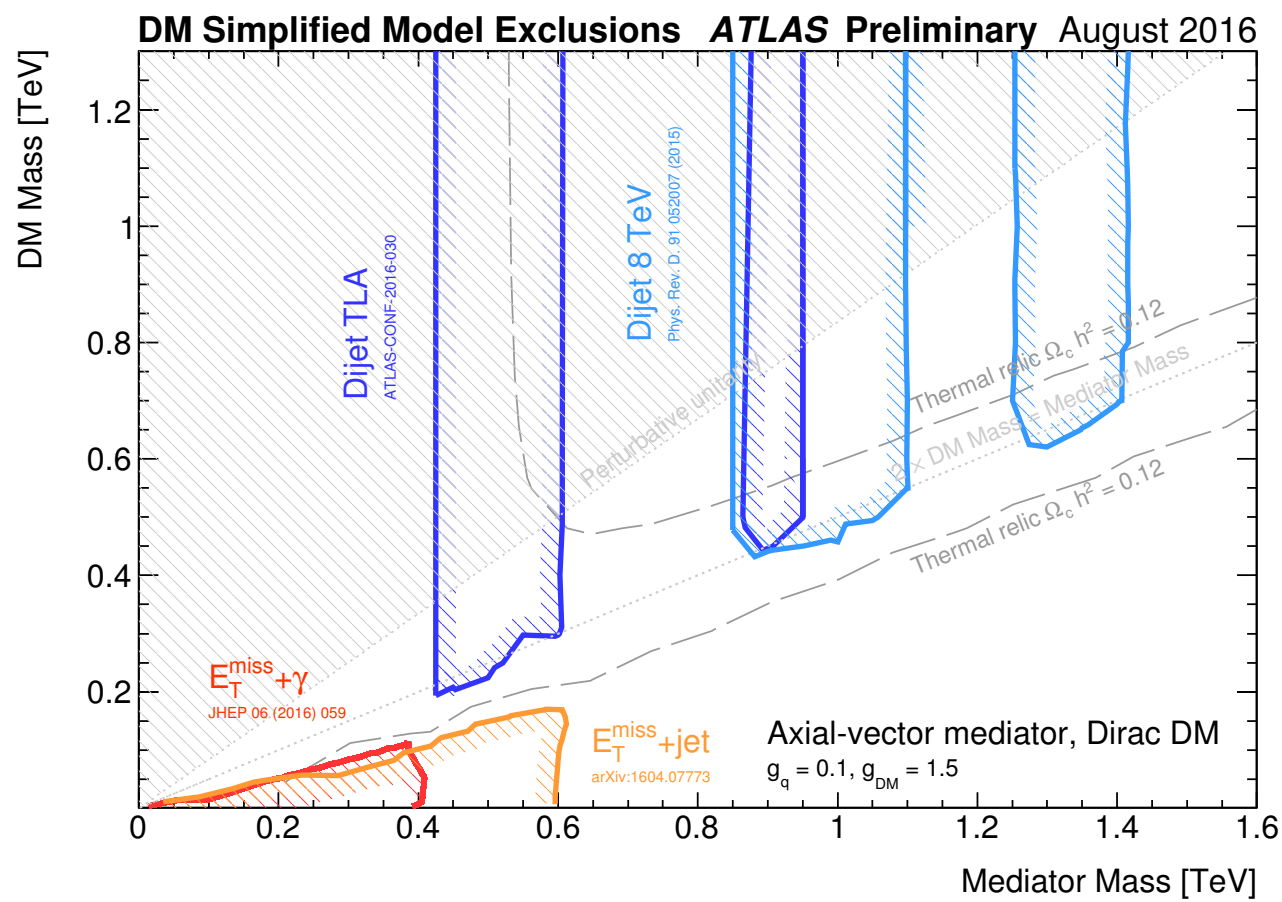
In some cases direct searches for the mediator or di-jets can be more effective than monojets (i.e. also for Z').

[Fradsen et al. 2012, Chala et al. 2015]

LHC limits from dijets

[ATLAS coll. 2016]

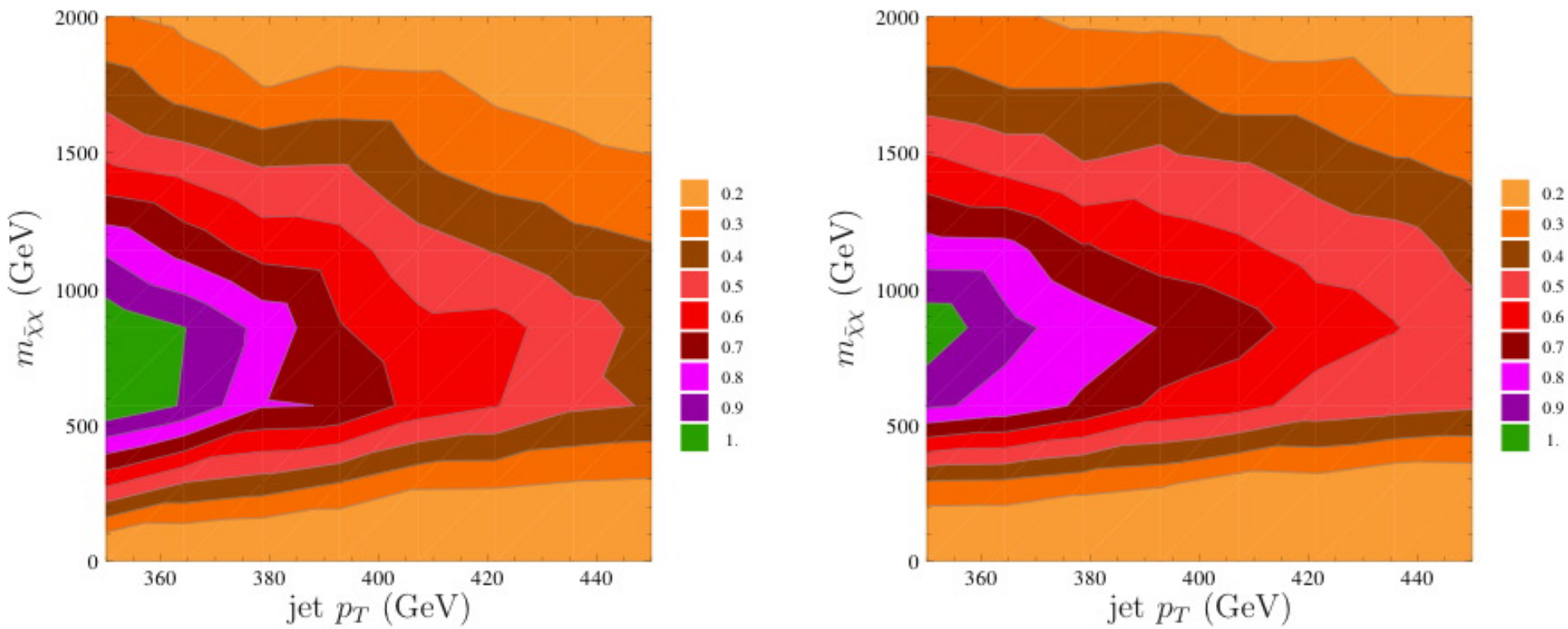




Jet substructure for DM

In case of a positive signal, the jet substructure could help to disentangle the operator and type of coupling:

[Agrawal & Rentala 1312.5325]



(a) Event kinematic distribution for $\mathcal{O}_q$.

(b) Event kinematic distribution for $\mathcal{O}_g$.

Di-jet angular distribution could also vary for loop operators !

[Haisch et al 1311.7131]

Effective Theory for DD

[Riccardo Catena WIN-2015]

- Only 14 linearly independent operators can be constructed, if we demand that they are at most linear in $\hat{\mathbf{S}}_N$, $\hat{\mathbf{S}}_\chi$ and $\hat{\mathbf{v}}^\perp$

- The most general Hamiltonian density is therefore

$$\hat{\mathcal{H}}(\mathbf{r}) = \sum_k c_k \hat{\mathcal{O}}_k(\mathbf{r})$$

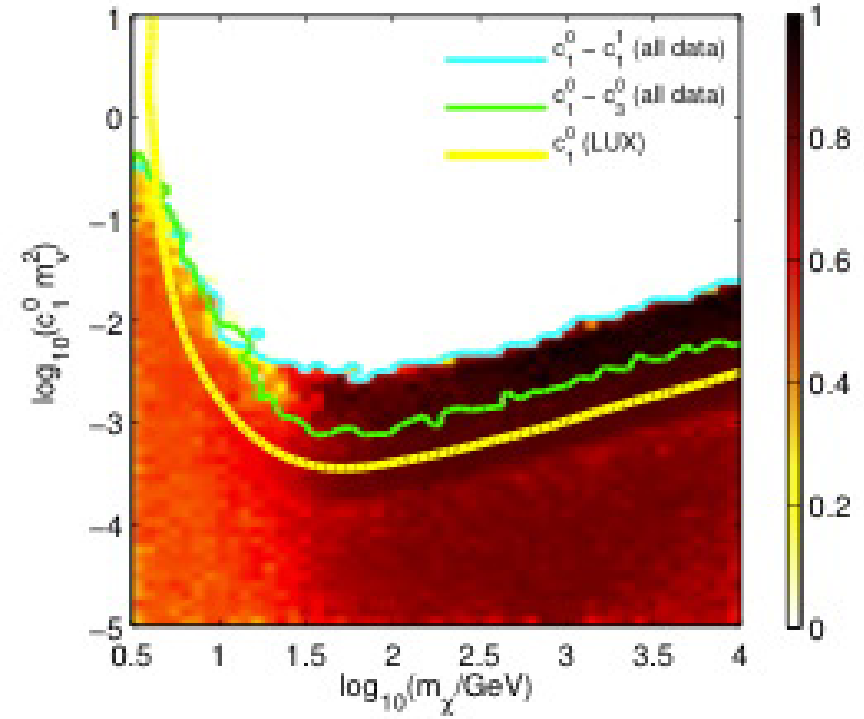
[Fitzpatrick et al. 2012]

$\hat{\mathcal{O}}_1 = \mathbb{1}_{\chi N}$	$\hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$	$\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$
$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right)$	$\hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$	$\hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$
$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$
$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp$	$\hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$

Effective Theory for DD

Interference matters !

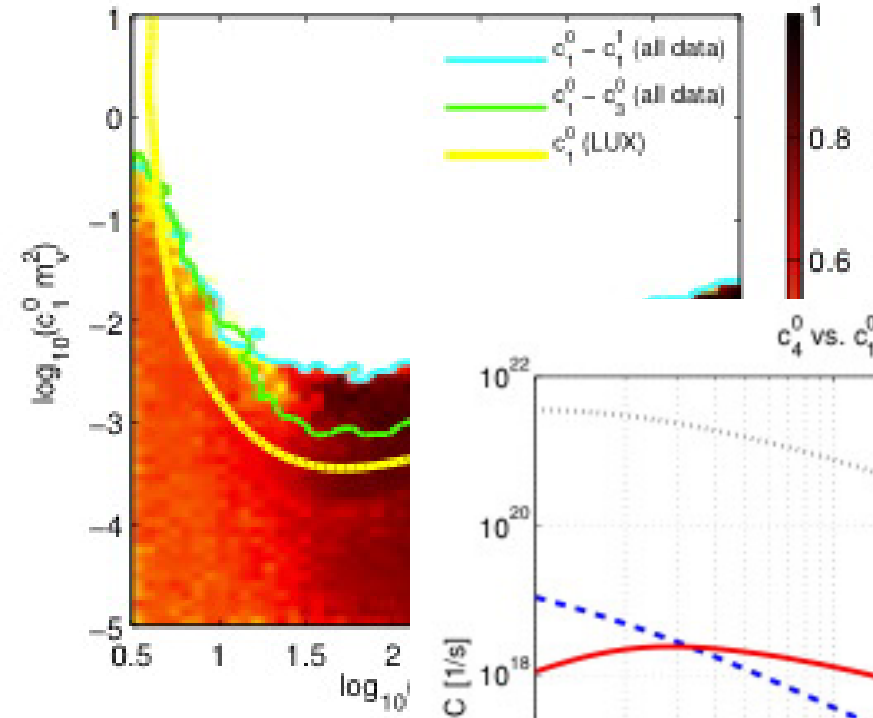
[Catena & Gondolo 2015]

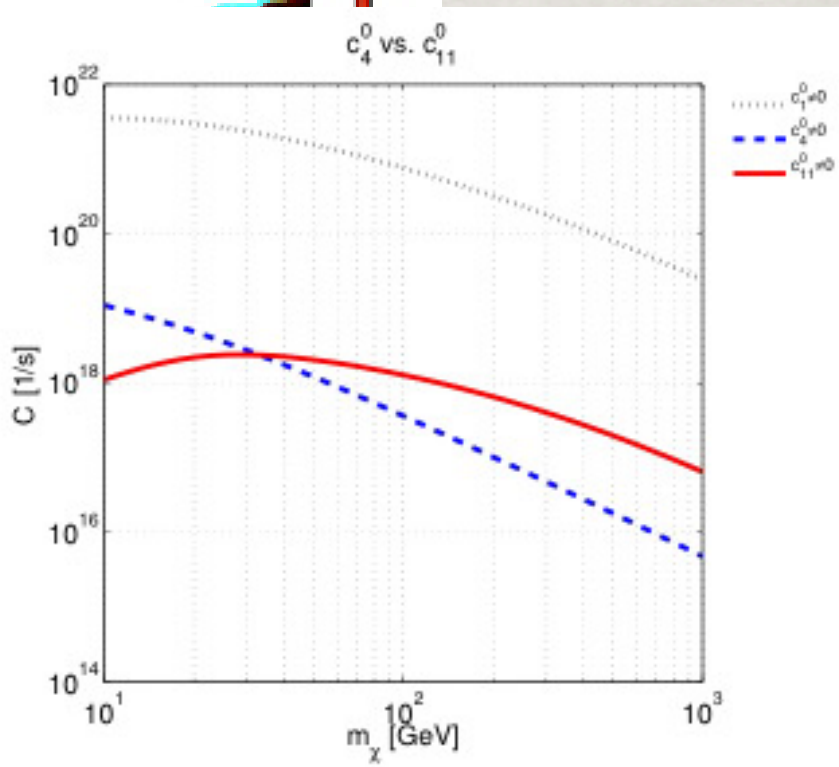


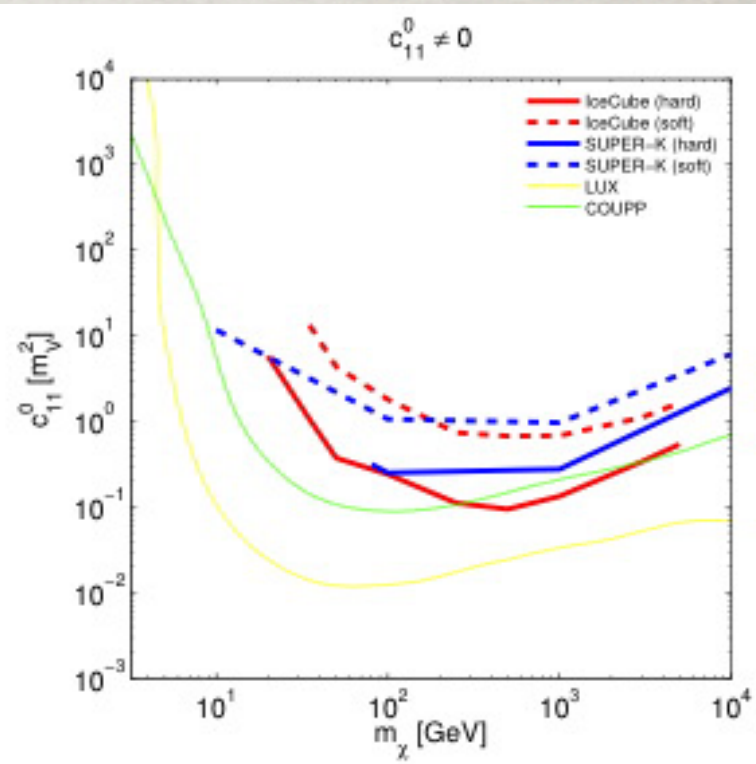
Effective Theory for DD

Interference matters !

[Catena & Gondolo 2015]







[Catena 2015]

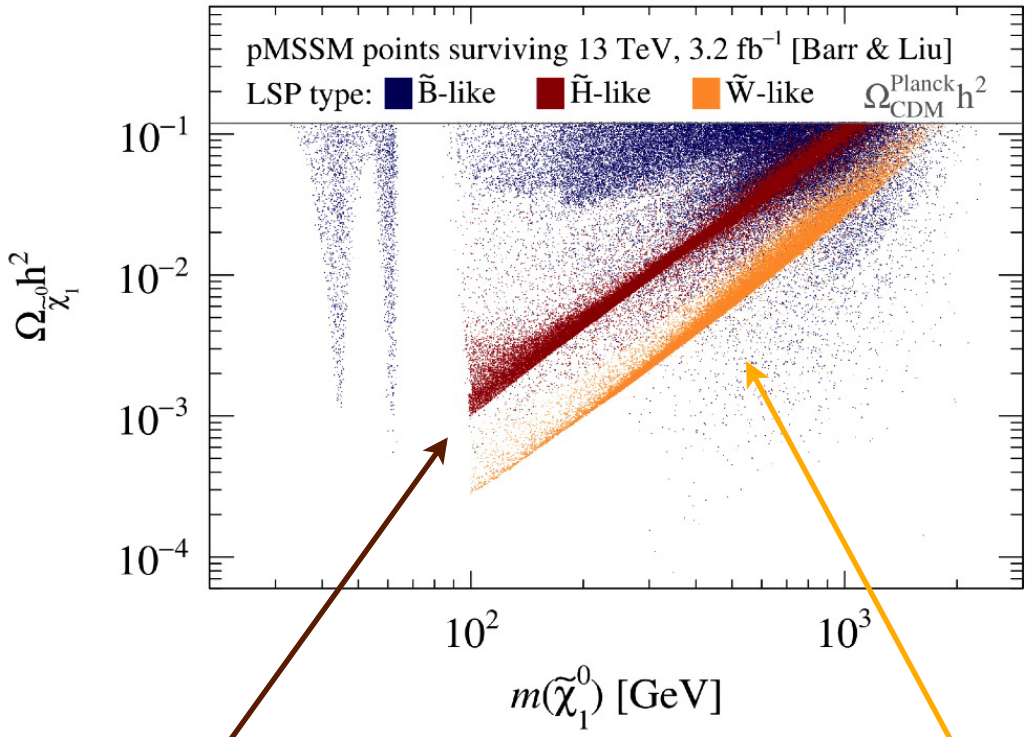
More Ops can contribute to solar capture:

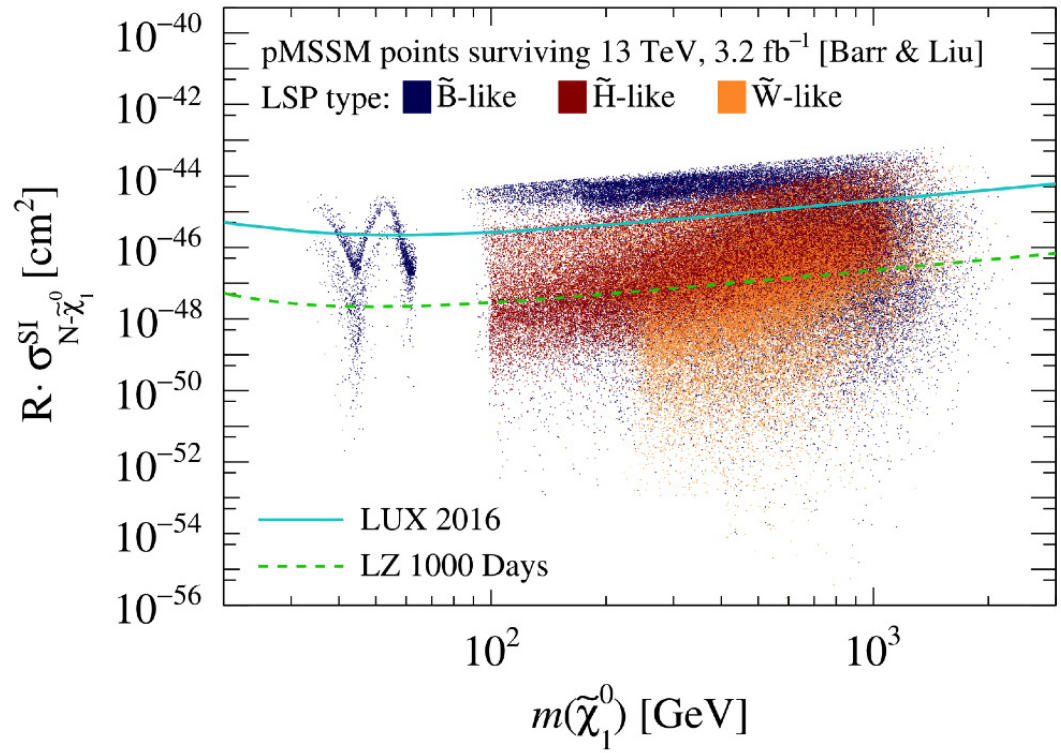
- $\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N$, $\hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{q}}/m_N$

SUSY MODELS STILL ALIVE

pMSSM points surviving after LHC-13 data

[Barr & Liu 2016]





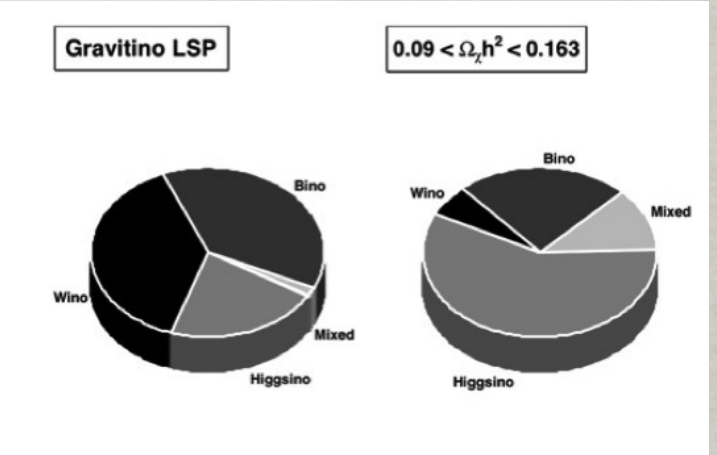
Higgsino band

Wino band

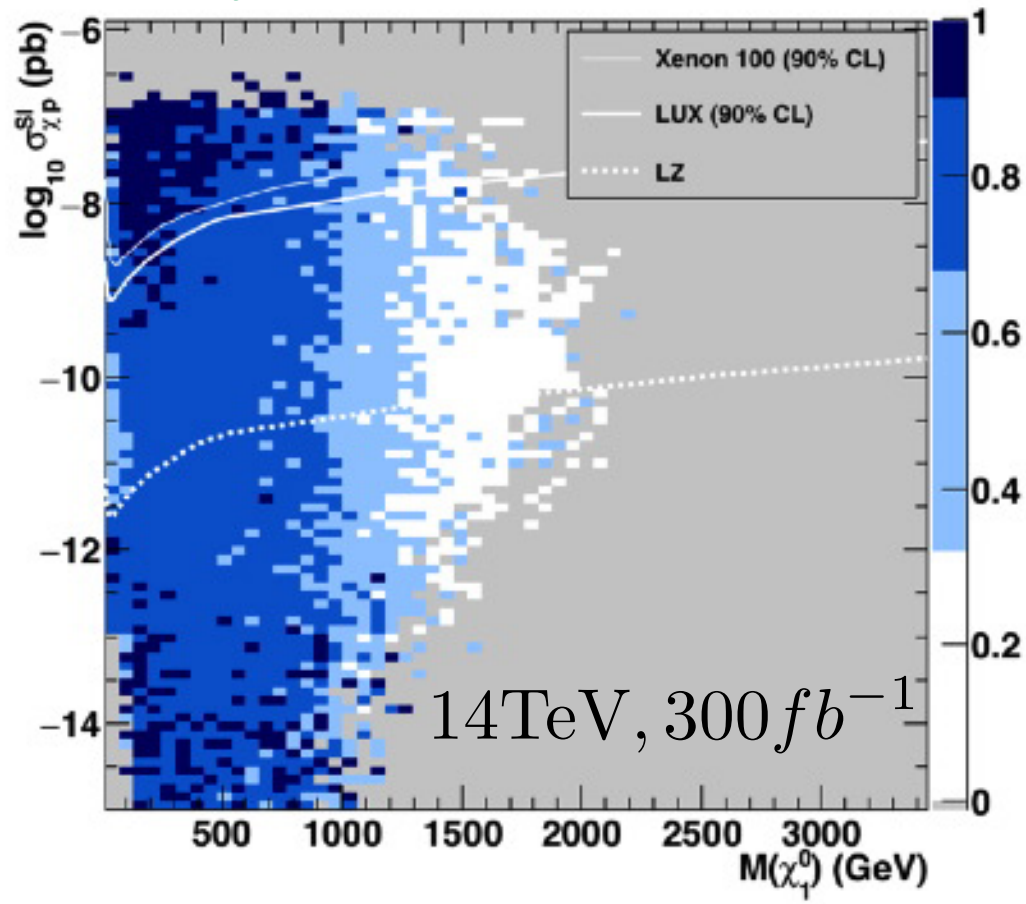
Wino DM challenged by Indirect Detection, but Higgsino parameter space still viable (and also some Bino-like...)

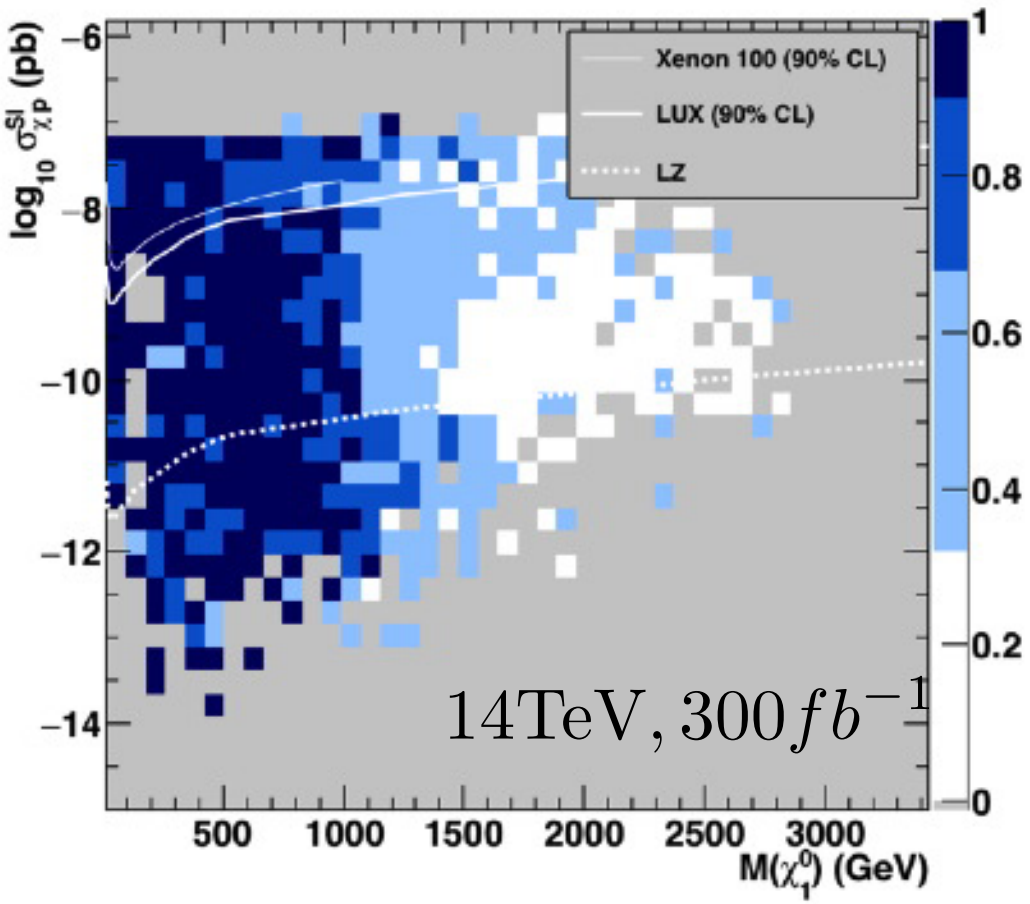
Gravitino vs neutralino DM

The neutralino compositions is very different, so only half the neutralino DM points will be excluded by LHC-14, while 75% of the gravitino DM points...



[Arbey et al. 1505.04595]





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 :

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

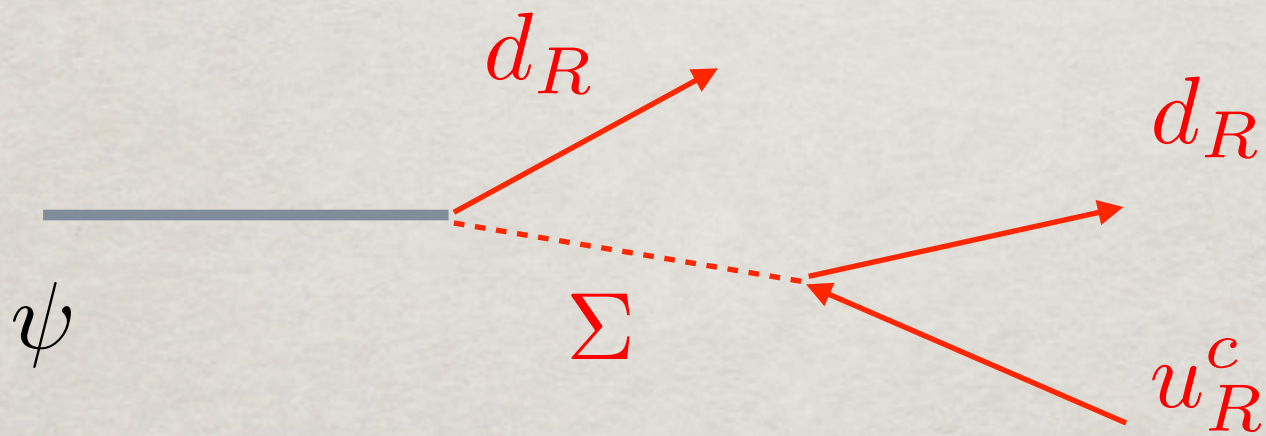
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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 $m_\Sigma \gg m_\psi$:

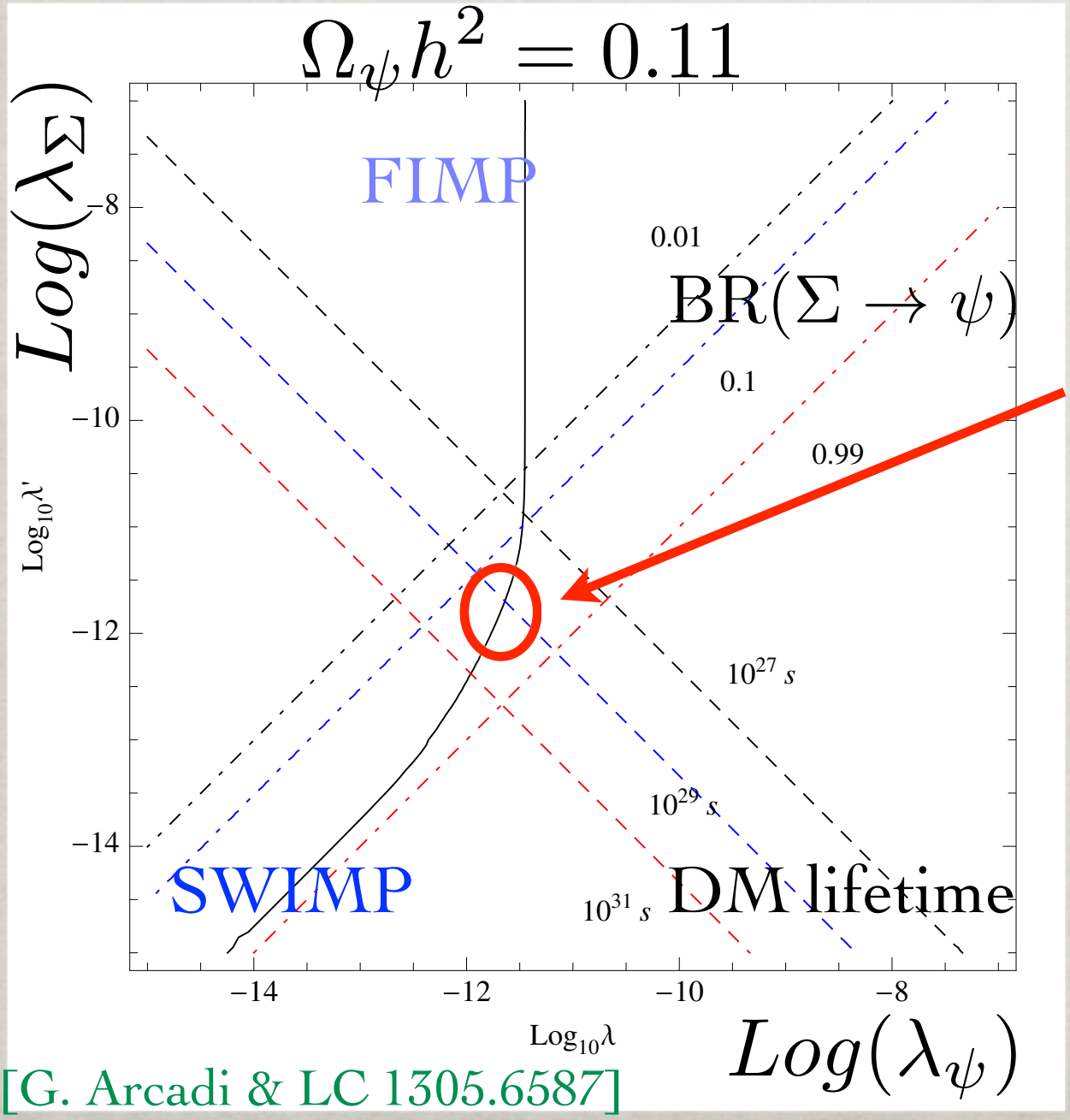


Decay into 3 quarks via both couplings !

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...

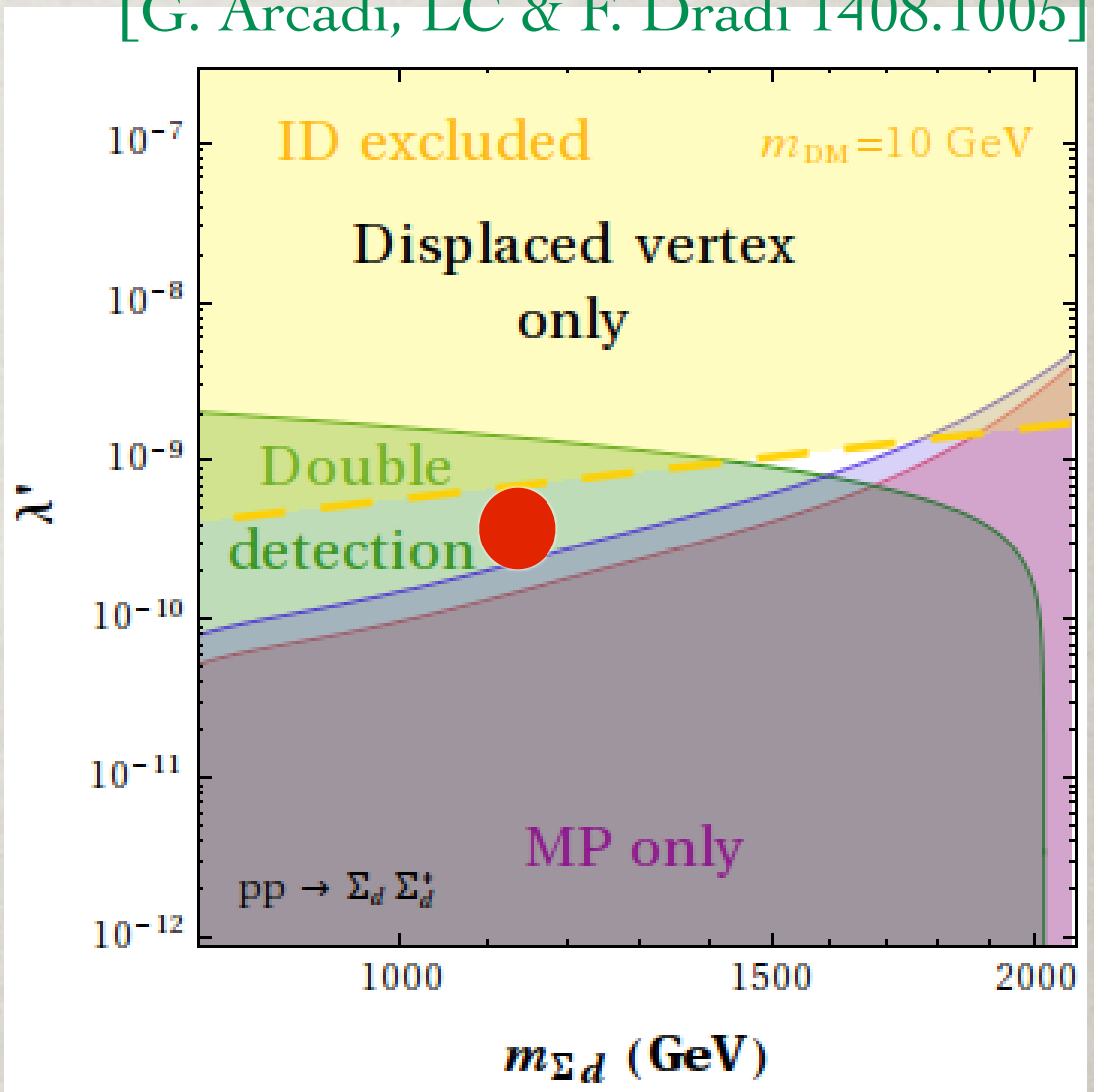
Σ Combined detection

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 !

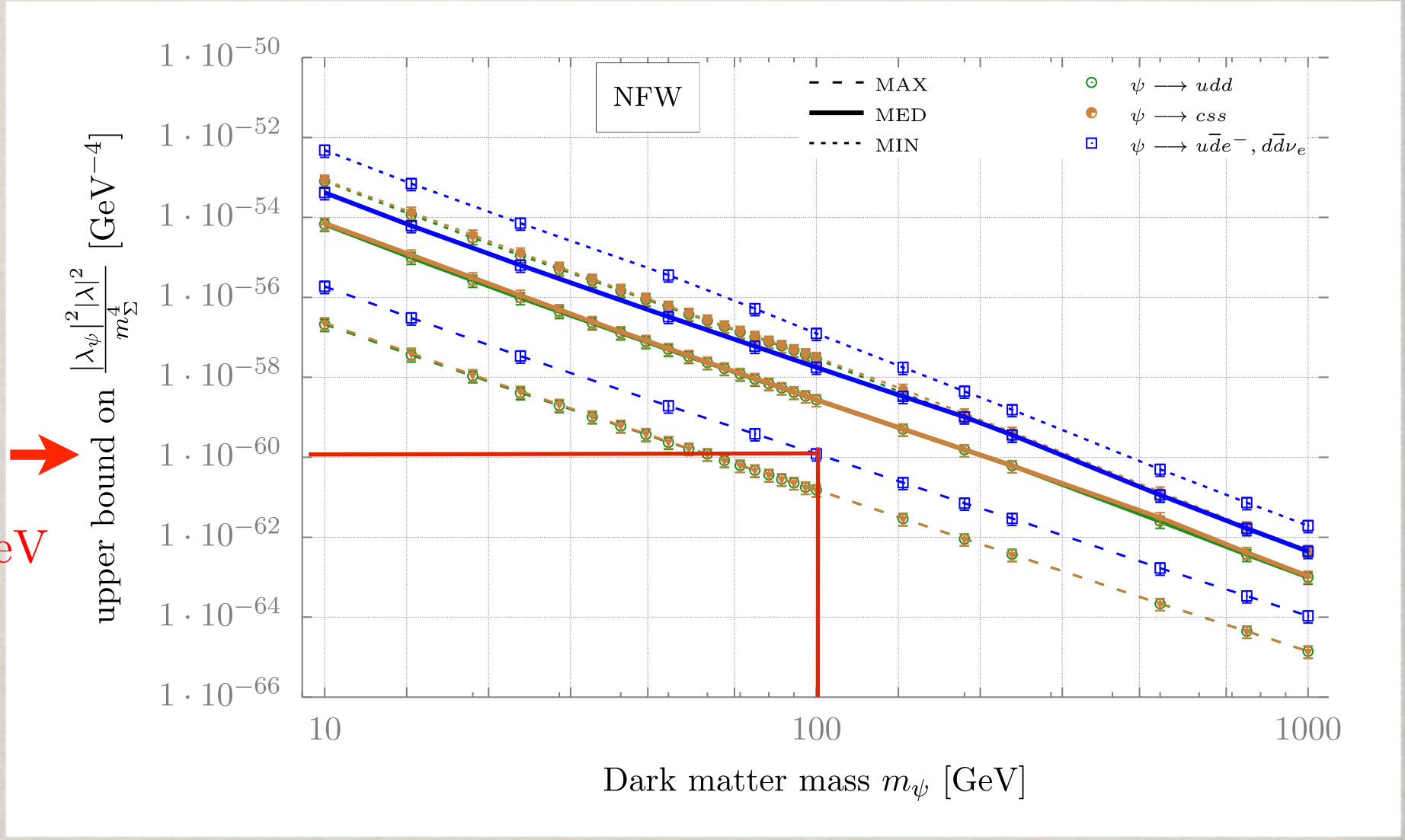
ID of FIMP/SWIMP DM

[LC, Eckner & Gustafsson, work in progress]

$\lambda\lambda' =$

10^{-18}

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

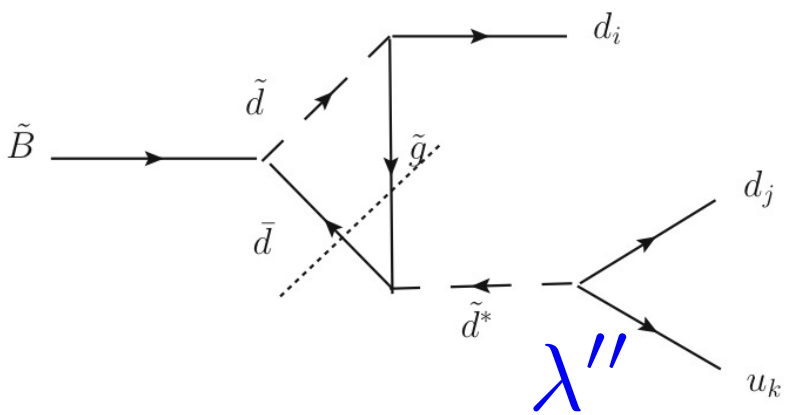


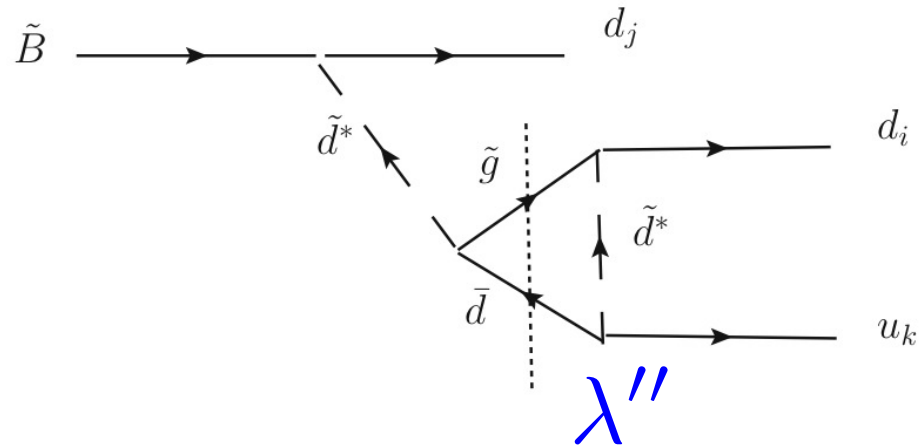
Unfortunately bounds strongly depend on propagation...

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

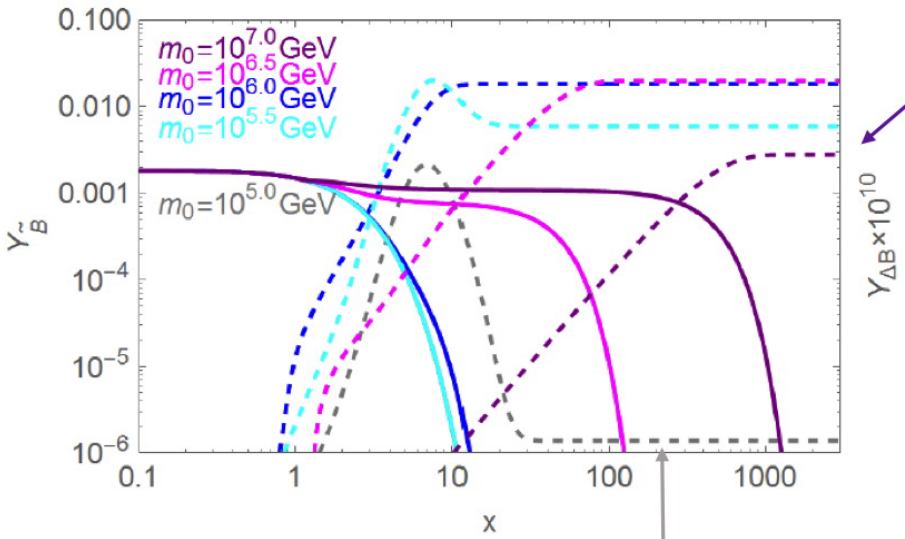
Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

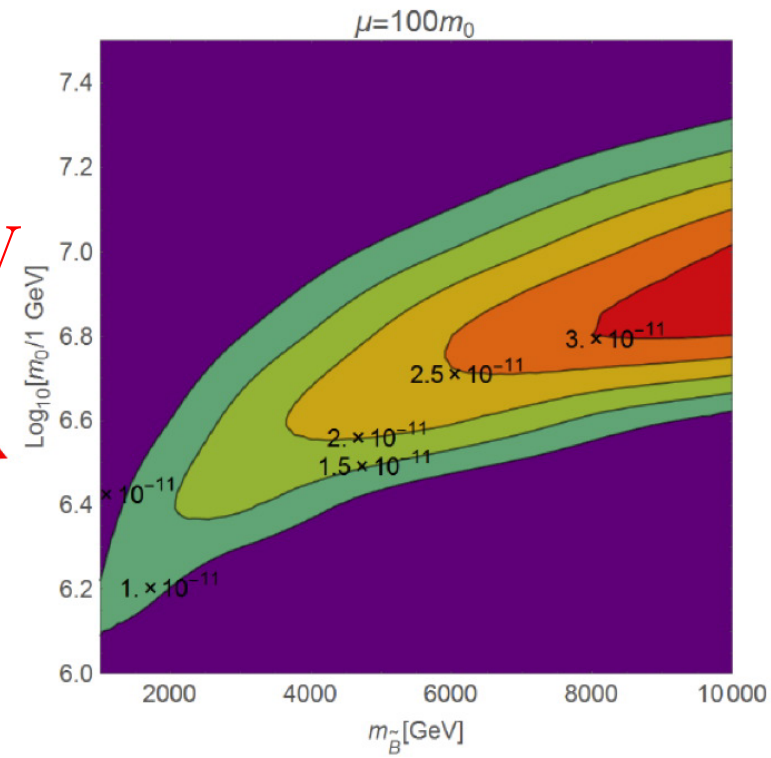
[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC & Kirk work in progress]

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

Asymmetry suppressed by the high scalars



10^7GeV



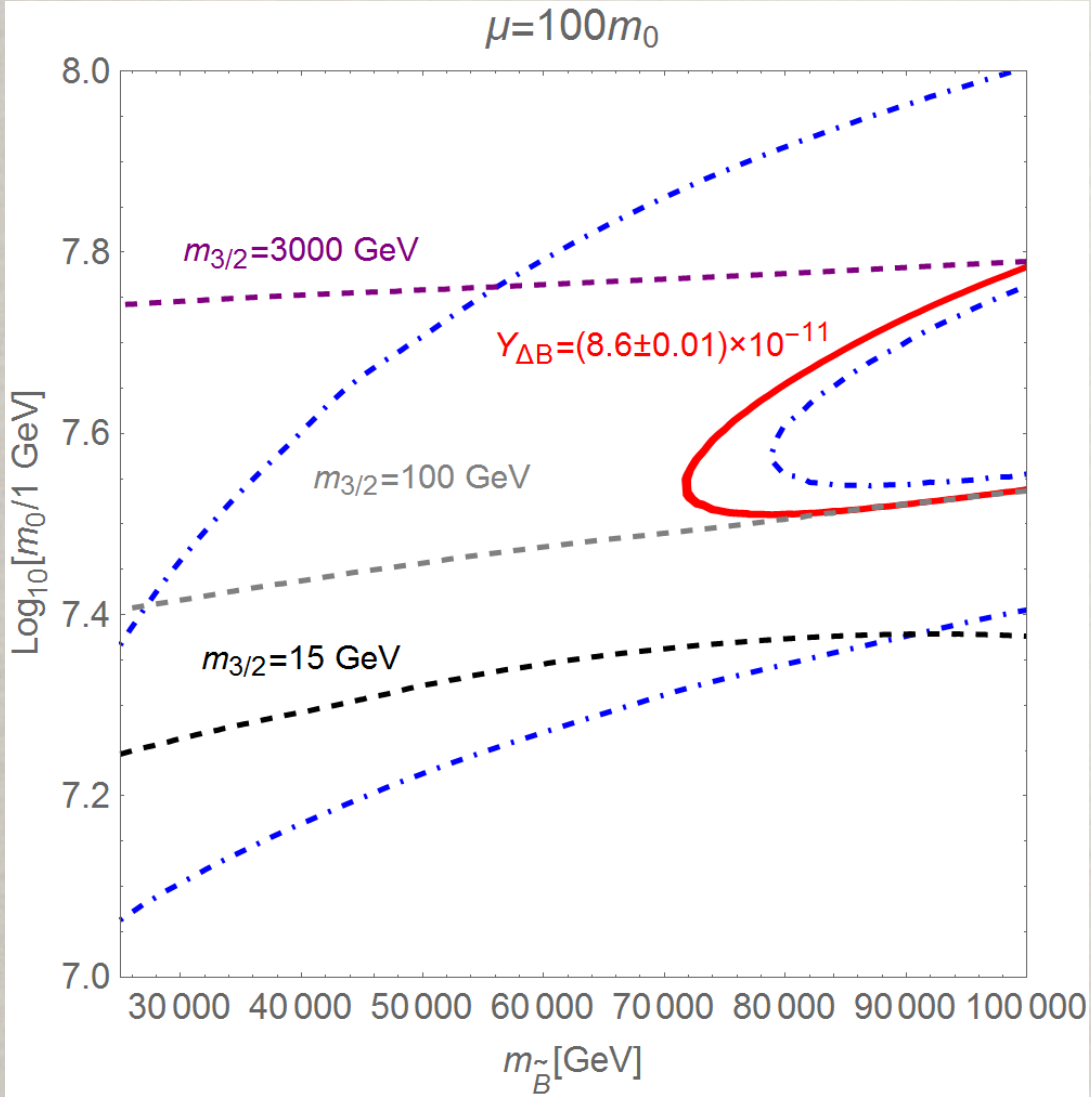
Asymmetry suppressed by wash-out

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

G. Arcadi

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



But the large scalar mass suppresses the branching ratio into gravitinos, i.e.

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

Need a large gravitino mass to compensate & obtain

$$\Omega_{DM} \sim 5\, \Omega_B$$

not so simple explanation after all..., but still possible with $m_{3/2} < m_{\tilde{g}}$.

Possible signatures: gravitino decay in DM Indirect Detection for high mass and long-lived gluino with mass above 7 TeV

Looking for Dark Interactions

10+Billion$ Question: How does Dark Matter interact apart GR ?

We detected DM so far only through its gravitational effects, which are universal and do not tell us what DM is !
BUT probably we some other interaction is needed to produce DM since gravity is not very effective.

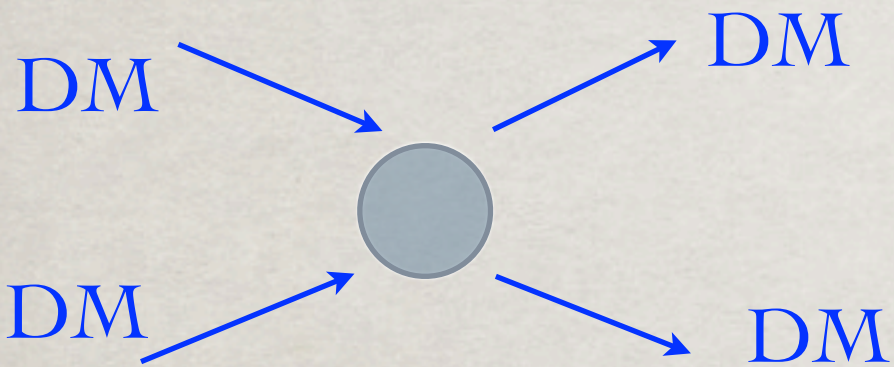
Moreover the standard CDM simulations do not fare so well on the small scales...: the missing satellites, core vs cusp in dwarves galaxies, too big to fail problems may be a hint that we need to go beyond the CDM/WIMP paradigms !

[Klypin et al 1999, Moore et al 1999], [Moore 1994, Flores & Primack 1994], [Bolyan-Kolchin, Bullock & Kaplinghat 2011+2011]

Of course there is also a chance that baryons solve it all...

DM-DM INTERACTION

Self-interaction:



Bullett cluster bound on self-interaction:

$$\sigma \leq 1.7 \times 10^{-24} cm^2 \sim 10^9 pb \quad (m = 1 \text{ GeV})$$

[Markevitch et al 03]

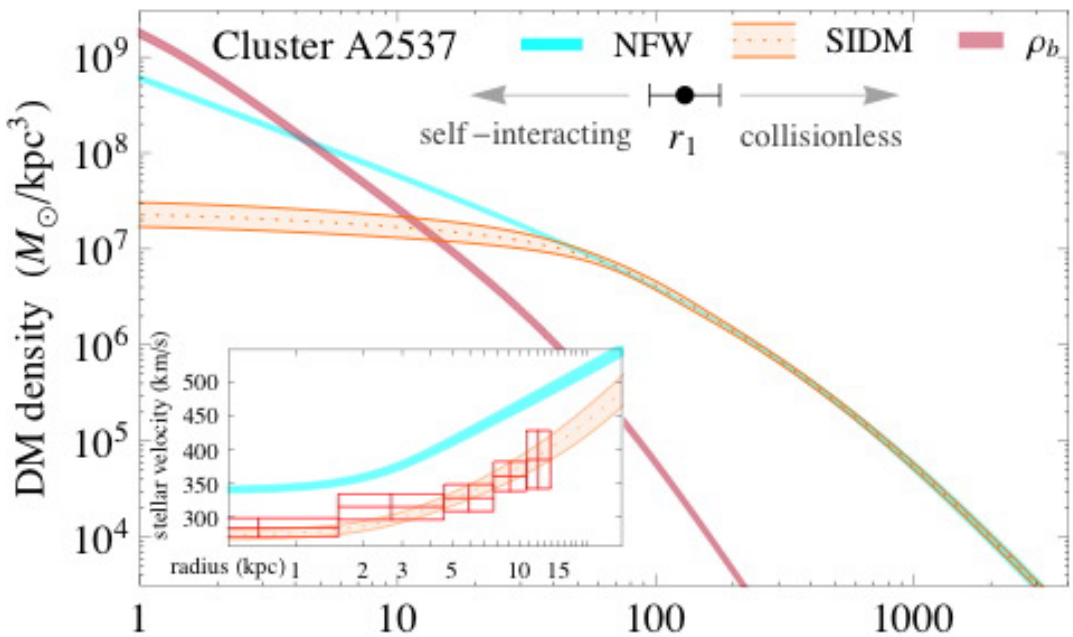
Slightly stronger constraint by requiring a sufficiently large core & from sphericity of halos... [Yoshida, Springer & White 00]

But at the boundary maybe some effect on small scales:

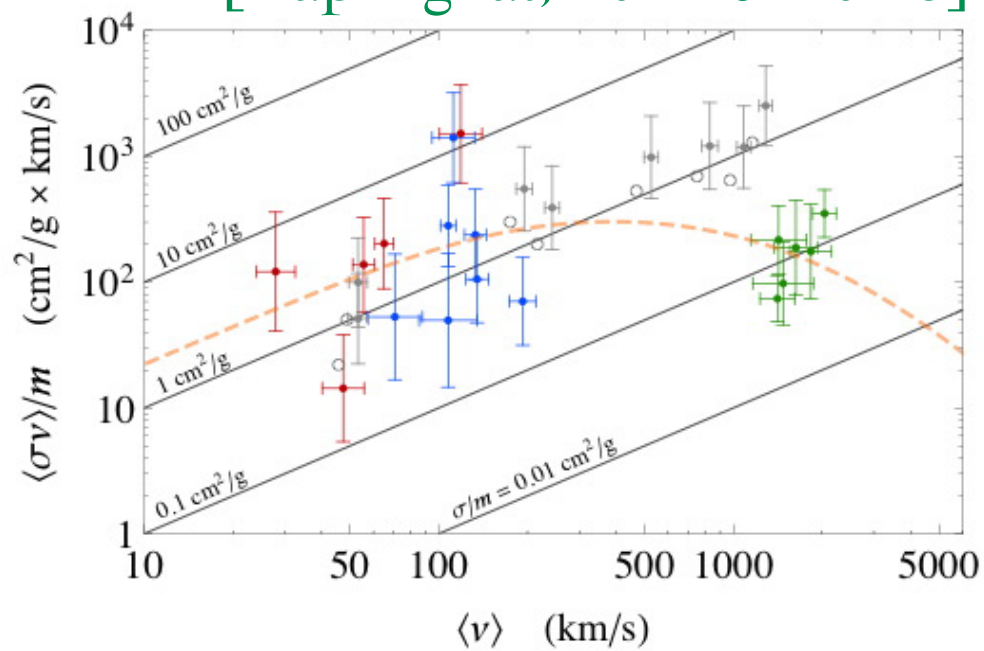
Strongly Interacting Massive Particle [Spergel & Steinhardt 99]

DM-DM INTERACTION

SIMP Dark Matter can relax some of the tensions at small scales and flatten the density in the centre:



[Kaplinghat, Tulin & Yu 15]

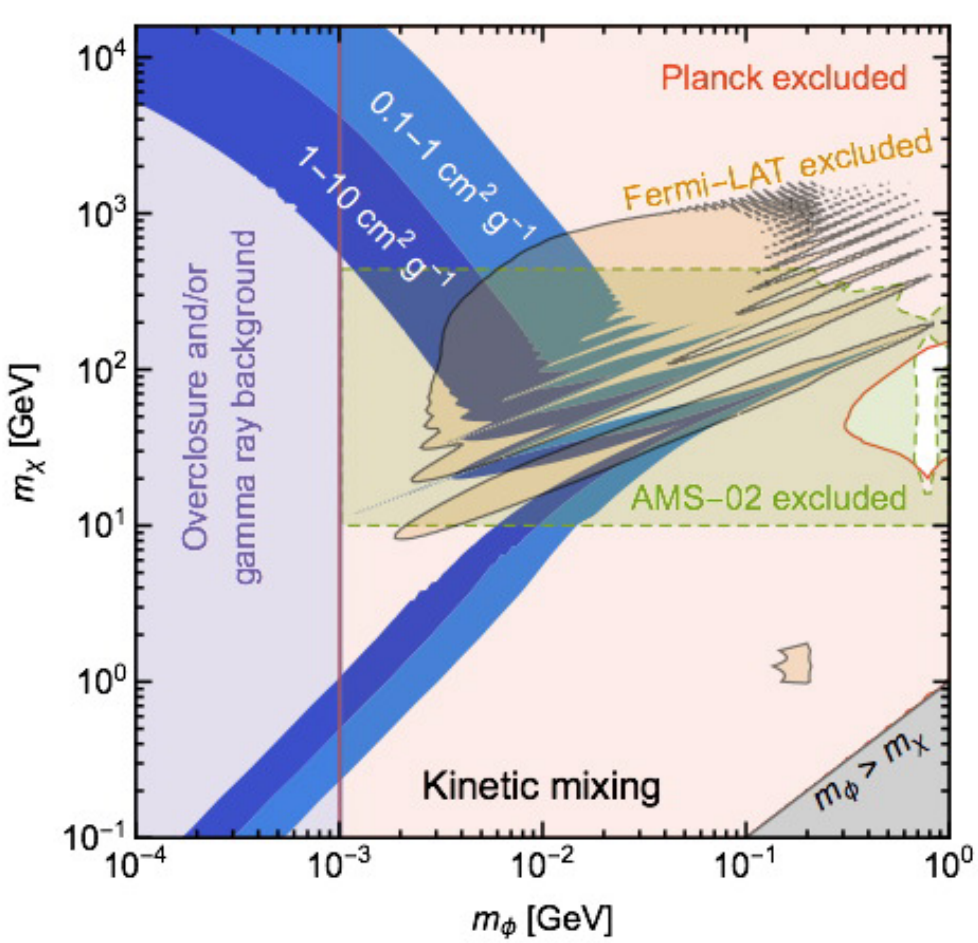


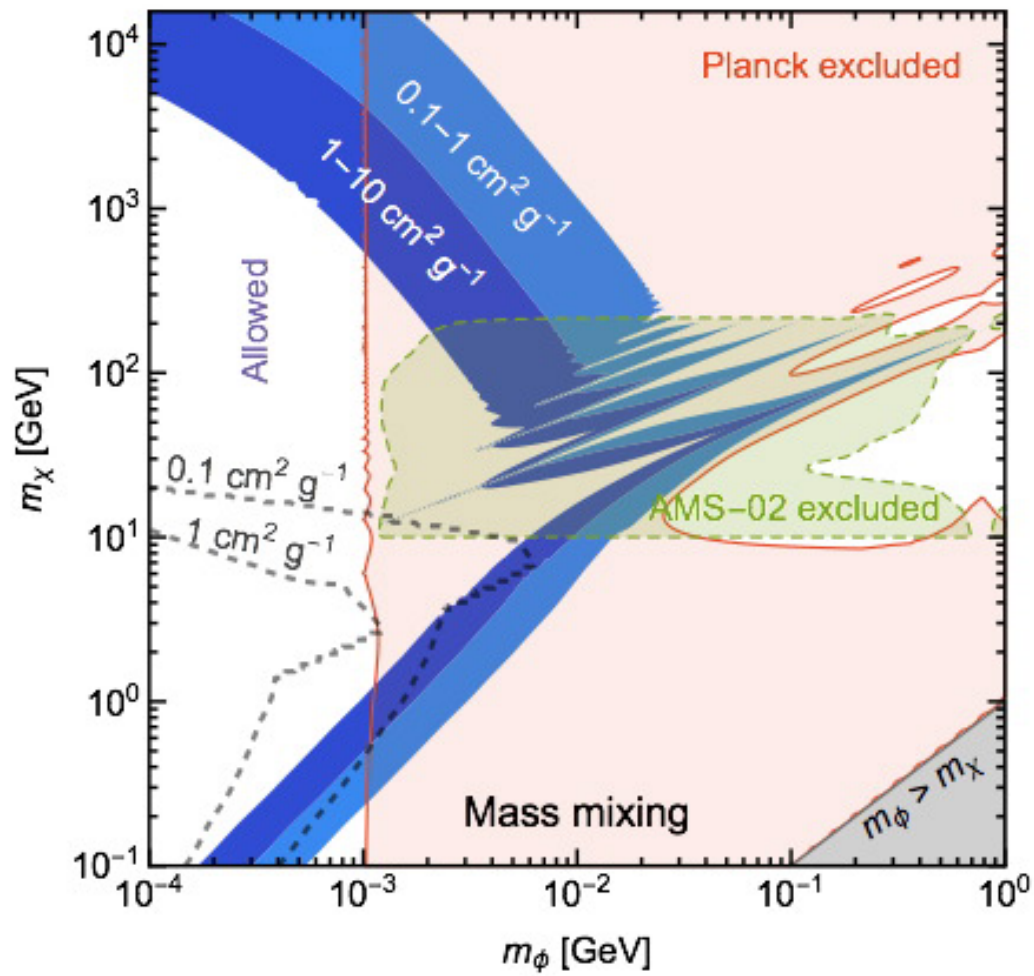
On the other hand it looks that larger cross-sections are needed at dwarves galaxies/low surface brightness galaxies compared to cluster scales...

DM-DM INTERACTION

New constraints for light mediator from ID and CMB:

[Bringmann, Kahlhoefer, Schmidt-Hoberg and Walia 16]



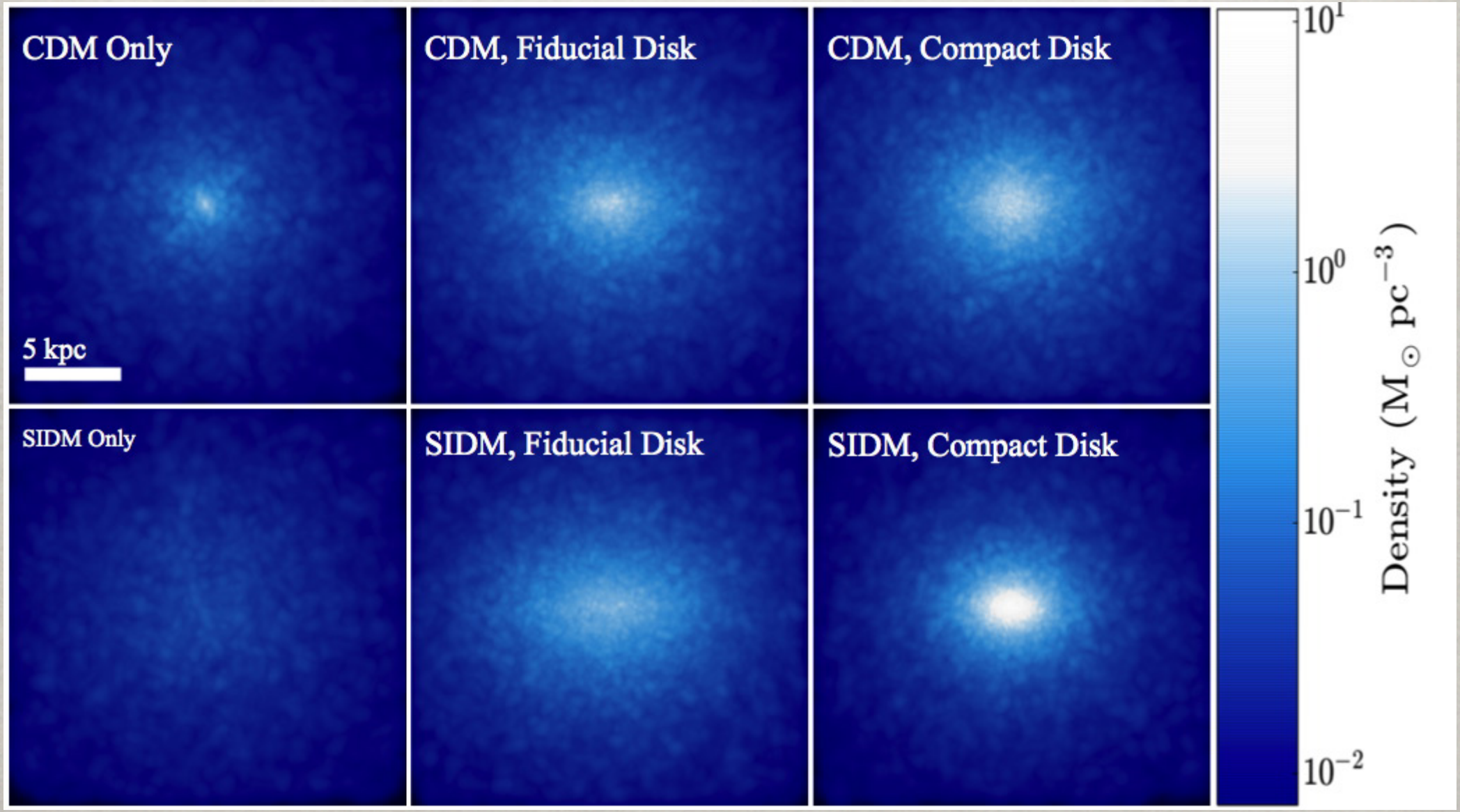


S-wave annihilation into Vector with Sommerfeld effect, weaker bounds on p-wave annihilation

DM-DM INTERACTION

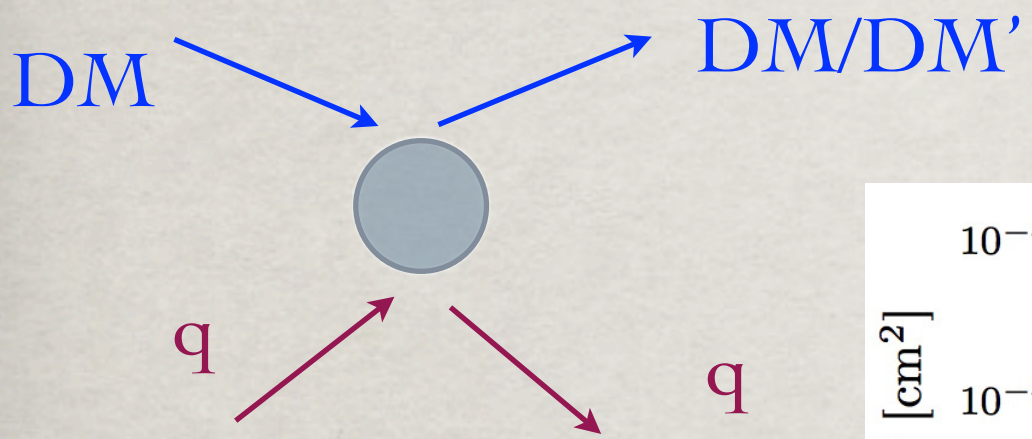
First simulations with SIMP and baryons:

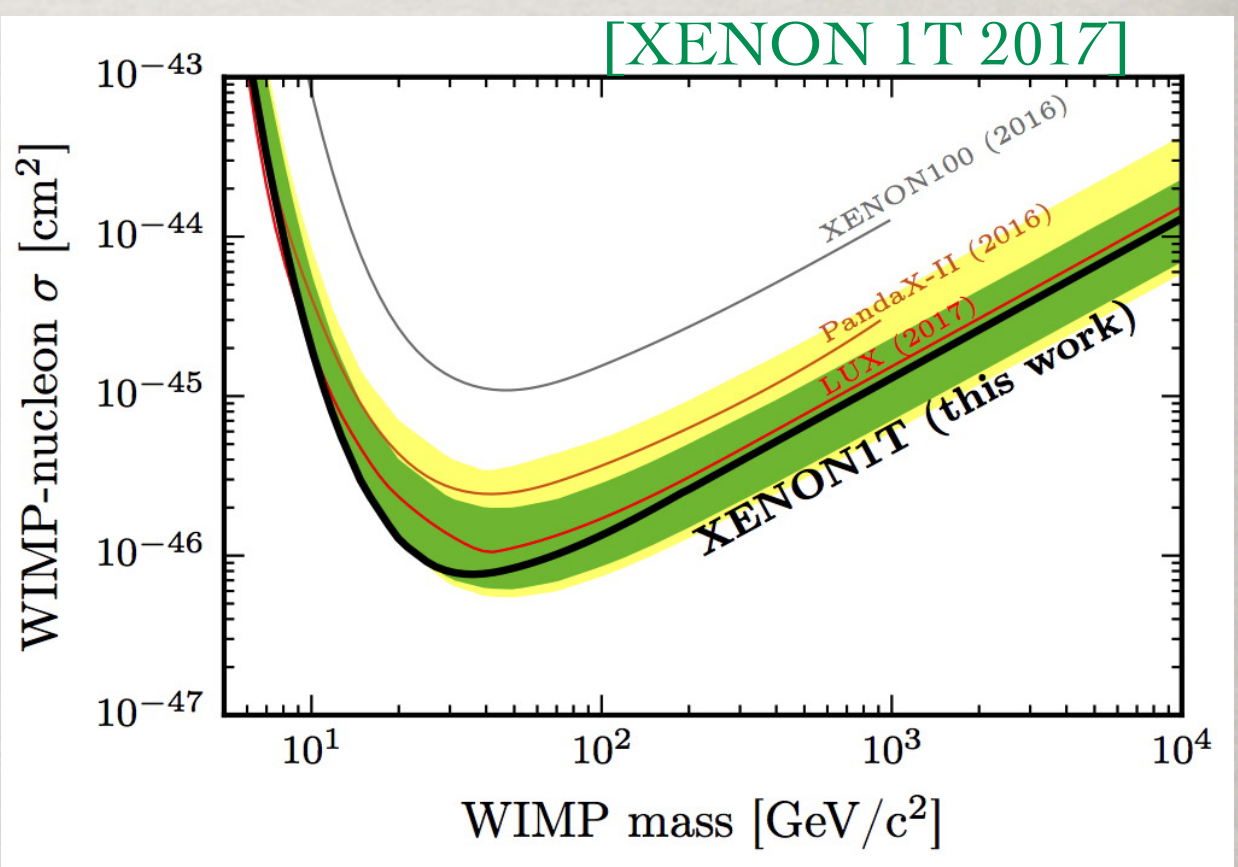
[Elbert et al.16]



DM-Matter Interaction

Elastic/inelastic scattering





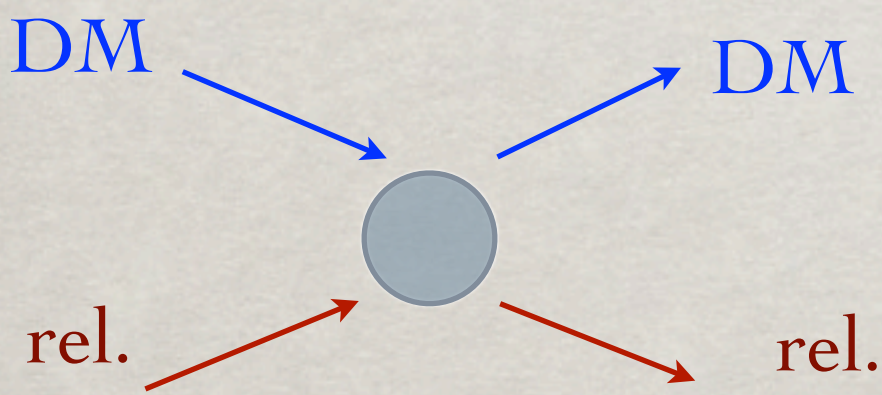
Direct detection:
elastic spin independent
cross-section

But also other interactions can be tested, e.g. with SM neutrinos or ANY relativistic species !!!

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 and structure formation at small scales.

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



Probes ANY interaction with a relativistic species !

A lot of activity for different interactions/mediators !
Not clear if it can always resolve the small scale crises, though...

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

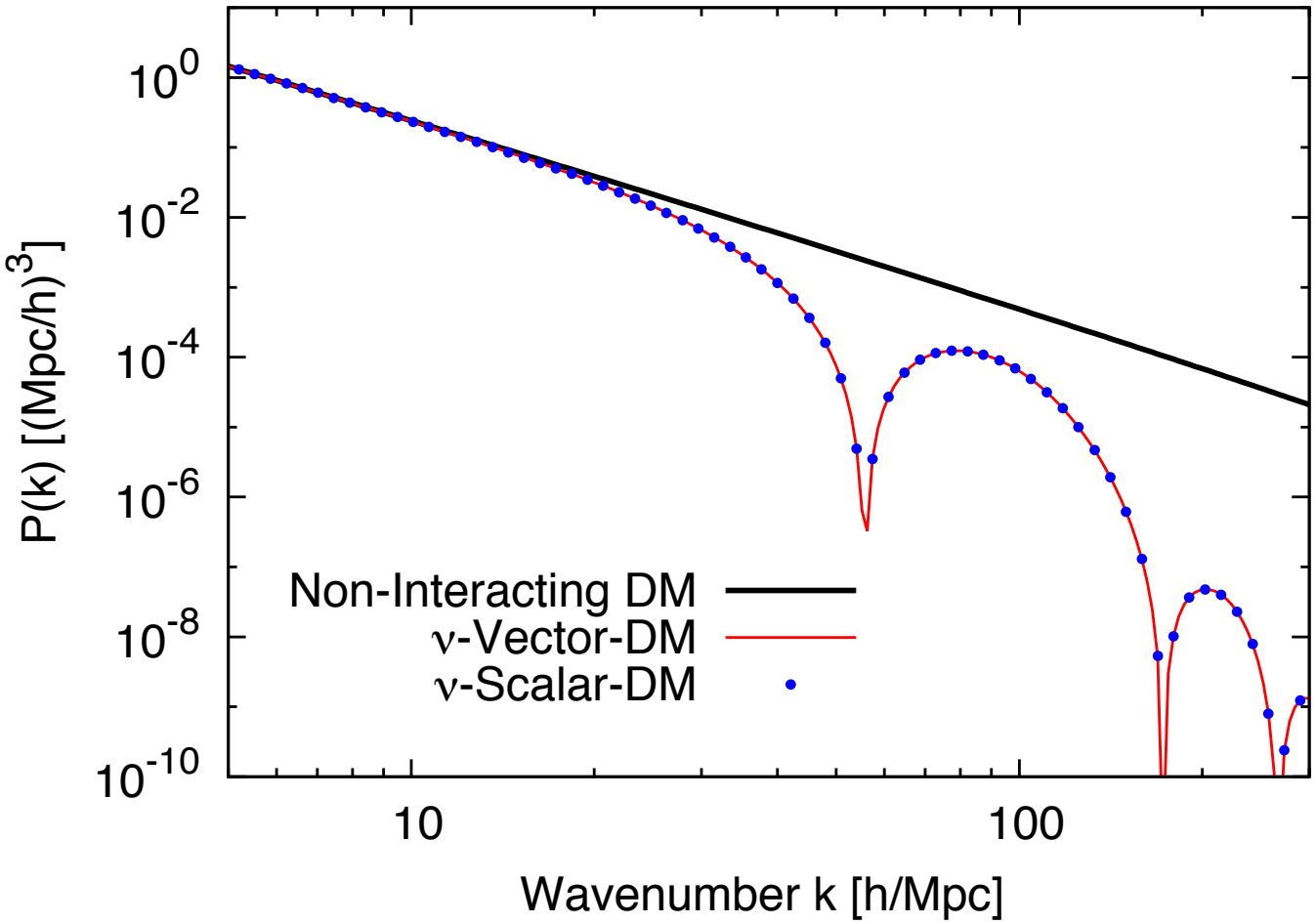
$$\gamma = \frac{1}{6 m_1 T} \sum_{s_2} \int \frac{d^3\mathbf{p}_2}{(2\pi)^3} f_2^{\mathrm{eq}} (1 \mp f_2^{\mathrm{eq}}) \int_{-4\mathbf{p}_2^2}^{0} dt (-t) \frac{d\sigma}{dt} v$$

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 et al. 1602.07624]



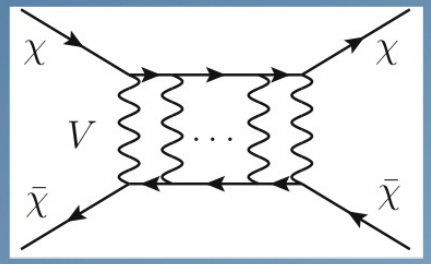
$$M^{\rm cut} = 10^9 M_\odot \left(\frac{N_\nu \alpha_\nu \alpha_\chi}{2\times 10^{-4}}\right)\left(\frac{m_\chi}{1TeV}\right)^{-3/4}\left(\frac{m_\phi}{1MeV}\right)^{-3}$$

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

ETHOS PROJECT

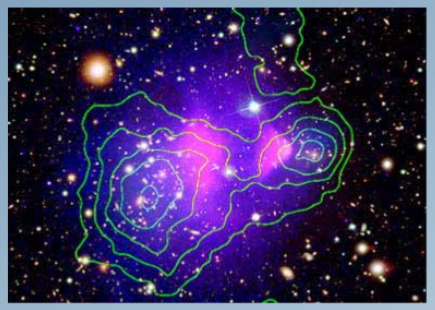
[Bringmann et al., 1512.05344,1512.05349,1603.04884]

From theory to observations



step 1

step 2



particle model	cosmological simulations	astrophysical observables
input: masses, spins, coupling constants	**input:** consistent initial conditions, non-gravitational forces between "particles"	**input (for interpretation of data):** output from simulations

- The first step can be demanding, the second in addition computationally very expensive
- But expect large degeneracies, so very inefficient…
- **Idea of ETHOS**: introduce effective parameters and provide maps for each of those steps (⇝ no need to re-compute each model!)

Cyr-Racine+, PRD'16, Vogelsberger+, *MNRAS'16*

Outlook

Outlook

- Theoretical understanding of the interplay between LHC and the other DM searches has progressed in the last years:
  - improved treatment of LHC bounds via simplified models gives us a consistent framework for all experiments;
  - we can apply such framework beyond WIMP to other types of models like decaying Dark Matter.
- Supersymmetry like pMSSM is still alive even after LHC-13, and heavy SUSY with RPV can offer good cosmological scenarios connecting DM and baryogenesis.
- We are still exploring the parameter space of Dark Matter non-gravitational interactions, and through structure formation we can probe the self-coupling and also the coupling to hidden sectors !
  Systematic studies in both directions are on the way !