Helmholtz Program days
Matter & the Universe 2021
24-25 November 2021

Dark Matter

Laura Covi

Institute for Theoretical Physics
Georg-August-University Göttingen

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

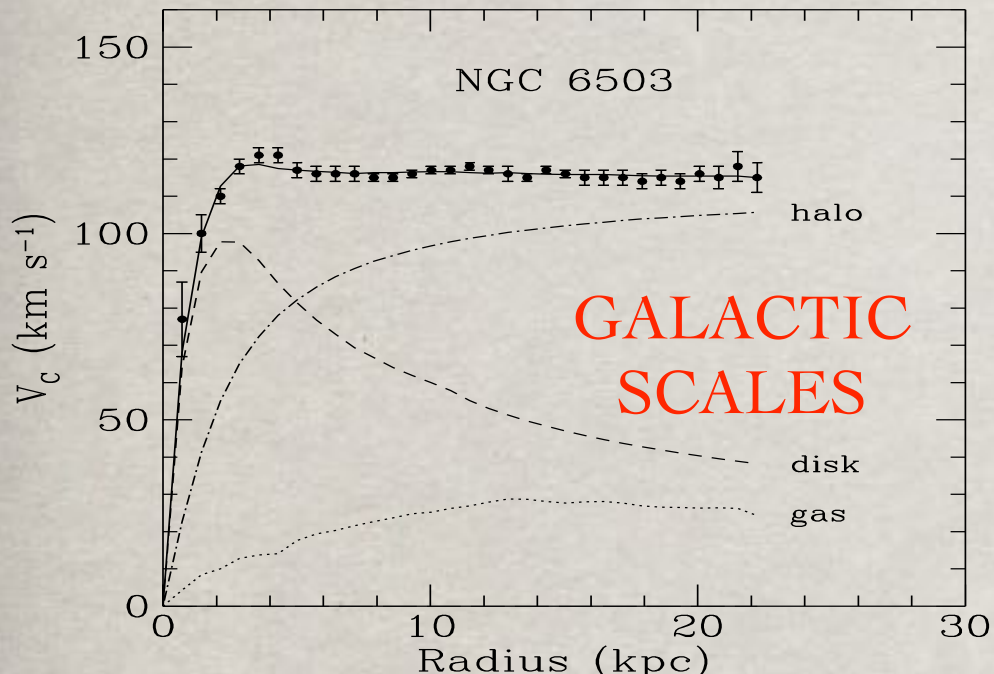
MARIE CURIE ACTIONS

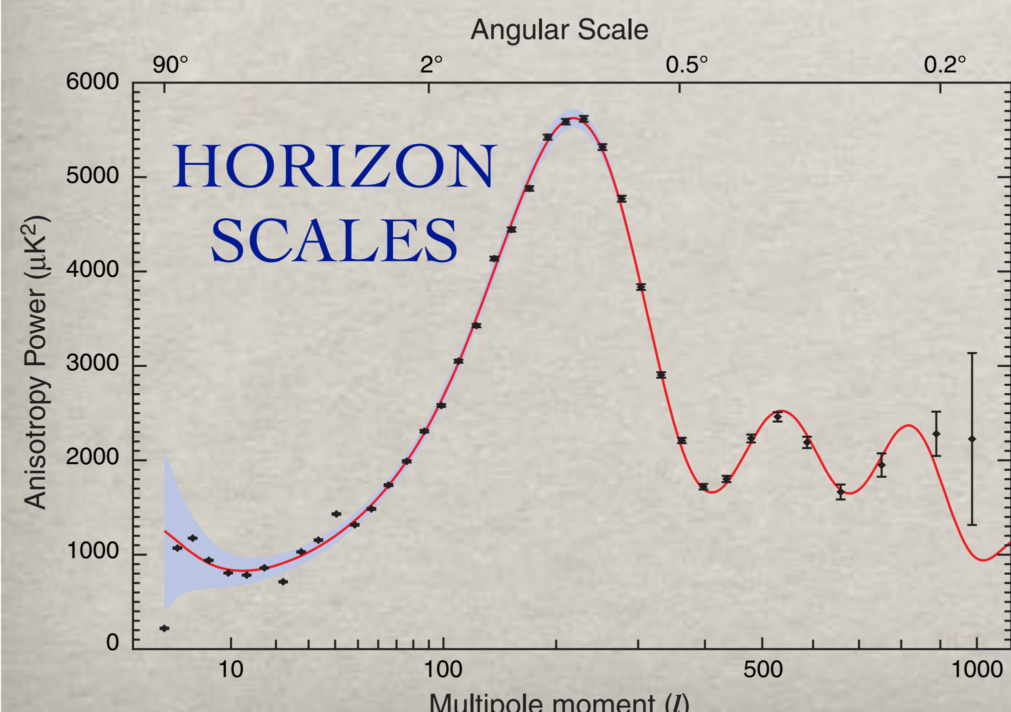
Outline

- Introduction:
  - DM evidence & properties
  - Theoretical guiding principles
- WIMP Dark Matter
- FIMP/SuperWIMP/Decaying Dark Matter
- Axion Dark Matter
- Outlook

Introduction

DARK MATTER EVIDENCE





Particles	Ωh^2	Type
Baryons	0.0224	Cold
Neutrinos	< 0.01	Hot
Dark Matter	0.1-0.13	Cold

DARK MATTER PROPERTIES

- Interacts very weakly, but surely gravitationally (electrically neutral, non-baryonic and decoupled from the primordial plasma !!!)

- It must have the right density profile to "fill in" the galaxy rotation curves, i.e. non-dissipative.

- No pressure and negligible free-streaming velocity, it must cluster & cause structure formation.

⬇

COLD DARK MATTER

But unfortunately too many realizations !

Which model Beyond the SM ?

weakly coupled ⟷ strongly coupled

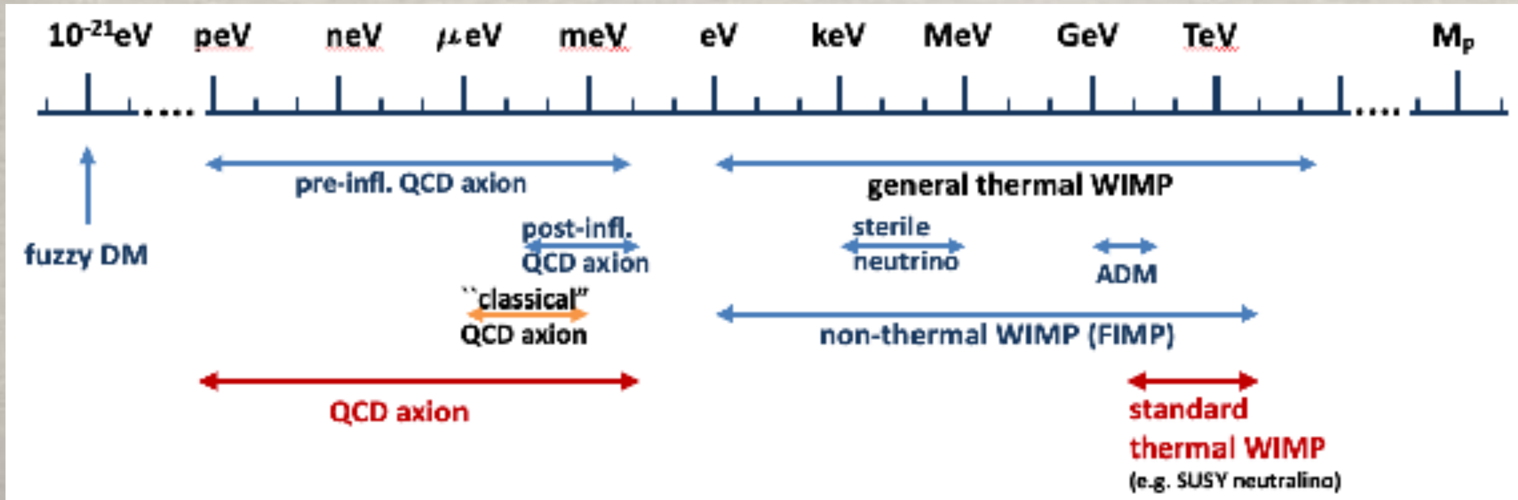
Cosmology

(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... ???

Guiding principles 4 DM

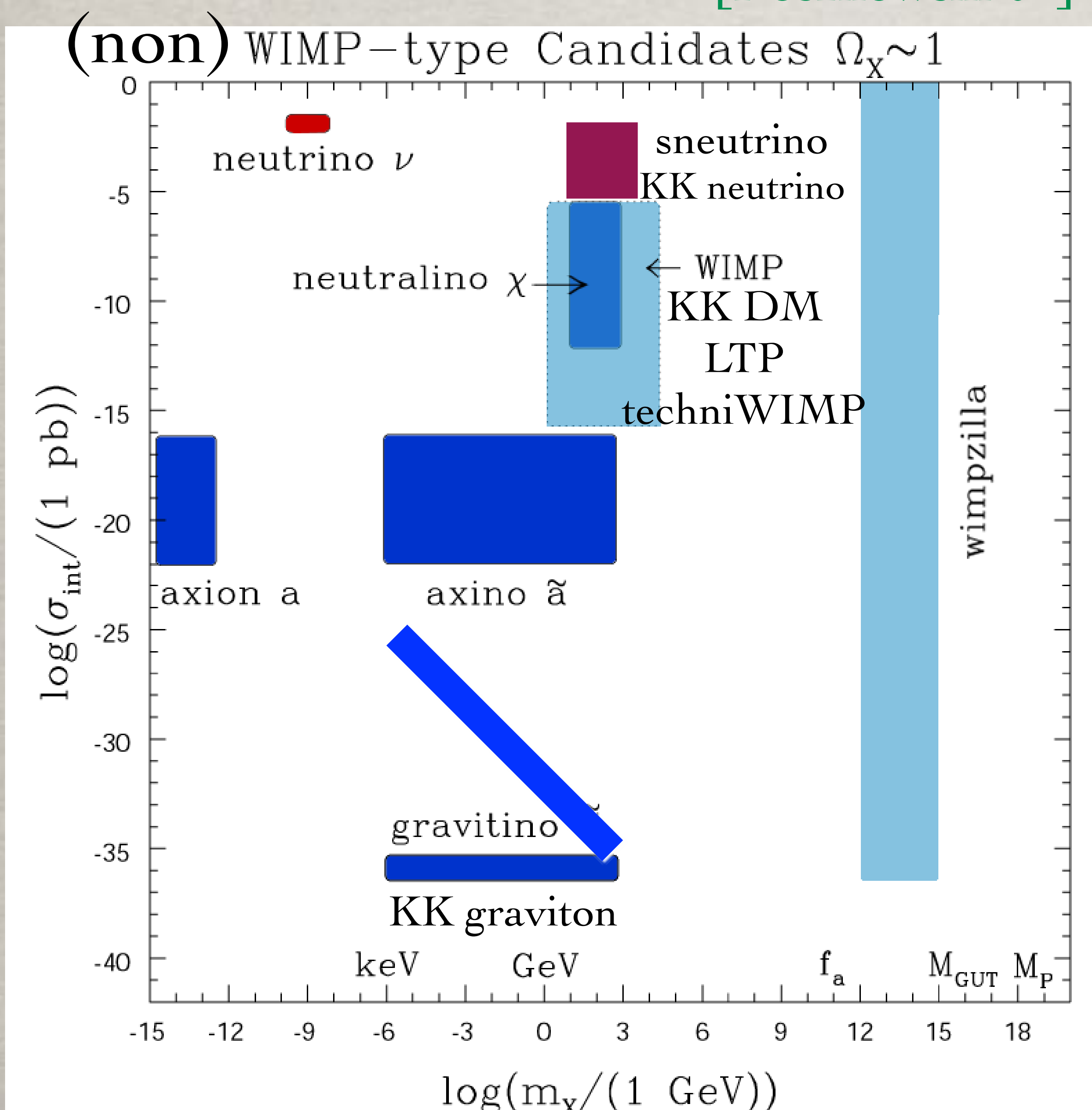
- An effective DM production mechanism should be present, possibly independent from initial conditions.
- The DM particle or the DM sector should fit into a BSM model solving more than the DM problem, e.g. hierarchy, neutrino masses, strong CP problem, etc…
- Possibly detectable Dark sector in the near future.



DARK MATTER paradigms

DARK MATTER CANDIDATES

[Roszkowski 04]

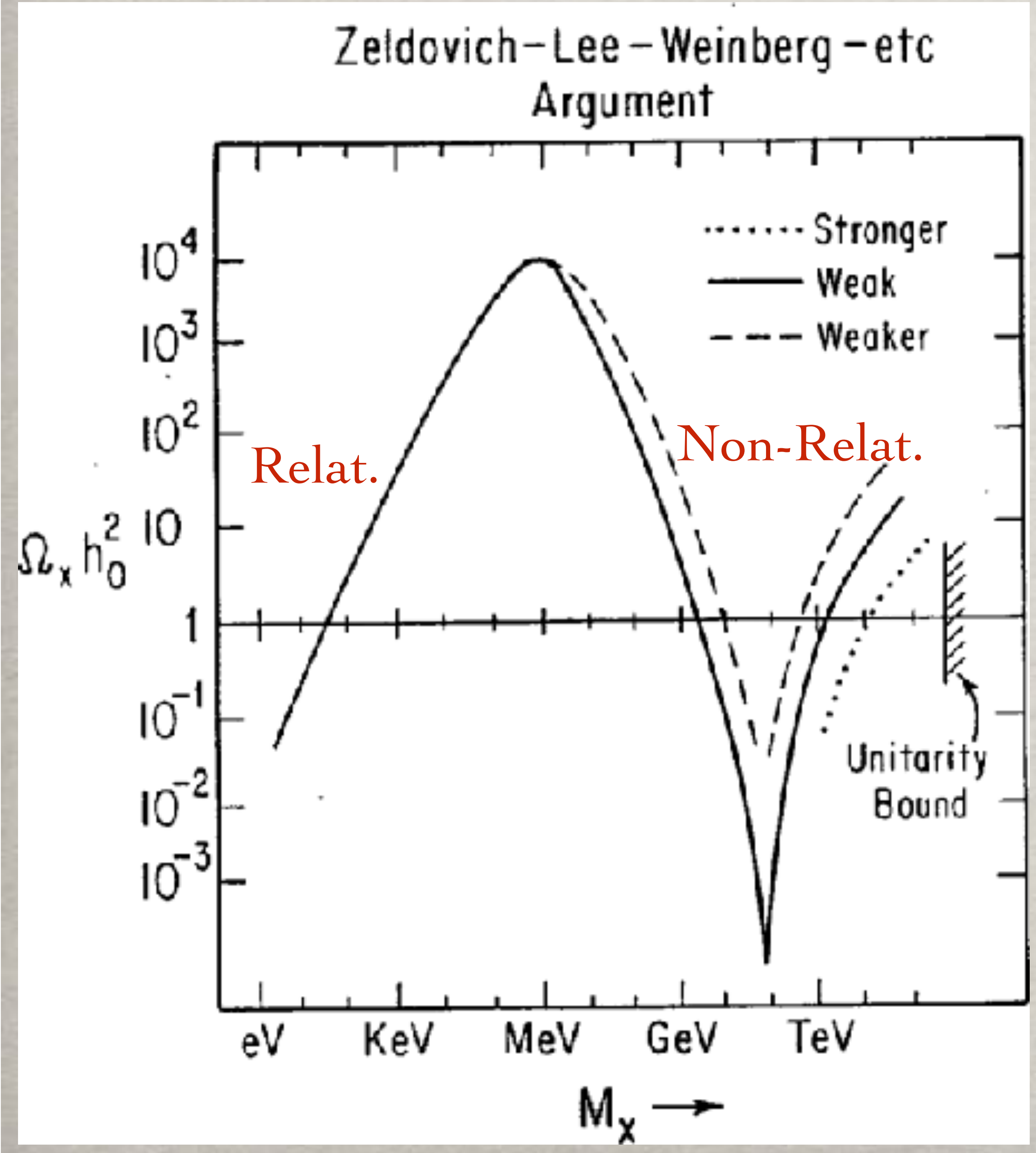


Multidimensional space !

DM production paradigms:
WIMPs
(e.g. neutralino)
&
"FIMP/SuperWIMPs"
(e.g. gravitino)
&
Misalignment
(e.g. axion/condensate)

WIMP
Dark Matter

Zeldovich-Lee-Weinberg bound



Two possibilities for obtaining the “right” value of $\Omega_\nu h^2$: decoupling as relativistic species or as non-relativistic ! In-between the density is too large !

$$m_\nu > 4(12)\mathrm{GeV}$$

for Dirac (Majorana)

Neutrino as (prototype) DM

- Massive neutrino is one of the first candidates for DM discussed; for thermal SM neutrinos:

$$\Omega_\nu h^2 \sim \frac{\sum_i m_{\nu_i}}{93\ \mathrm{eV}}$$

but $m_\nu \leq 2\ \mathrm{eV}$ (Tritium β decay) so $\Omega_\nu h^2 \leq 0.07$

- Unfortunately the small mass also means that neutrinos are HOT DM... Their free-streaming is non negligible and the LSS data actually constrain

$m_\nu \leq 0.27 \sim 1\ \mathrm{eV}$ → $\Omega_\nu \ll \Omega_{DM}$

NEED to go beyond the Standard Model !

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

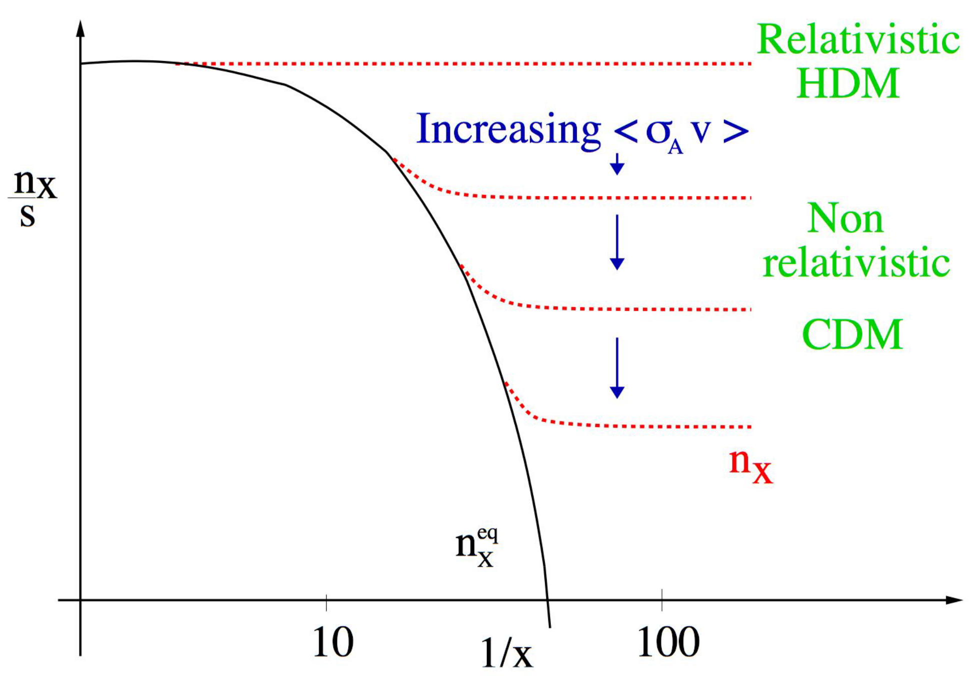
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle \sigma_A v \rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

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

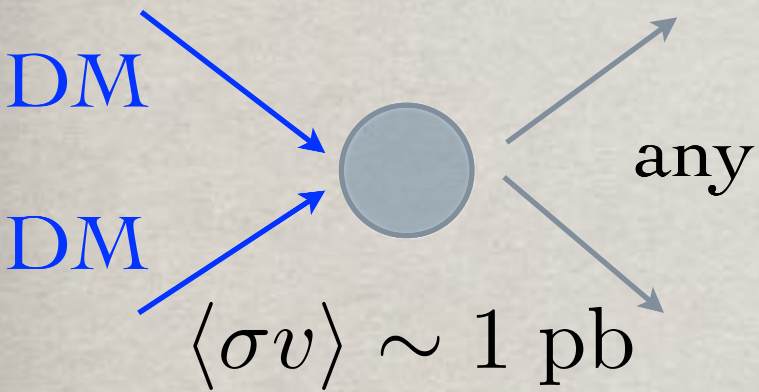
Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

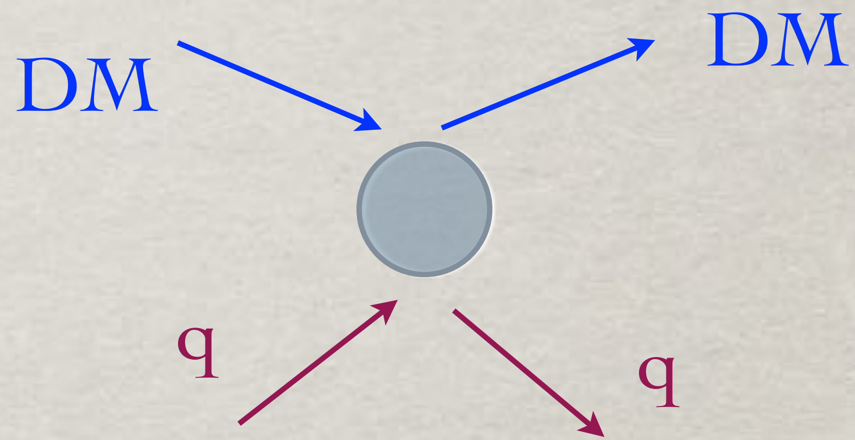


THE WIMP CONNECTION

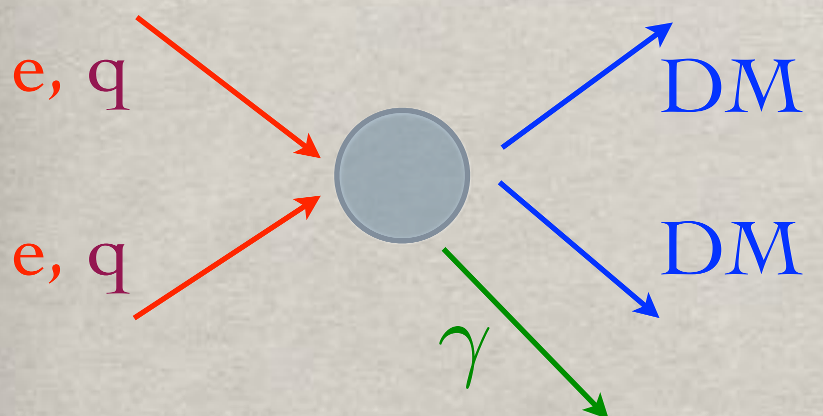
Early Universe: $\Omega_{CDM} h^2$



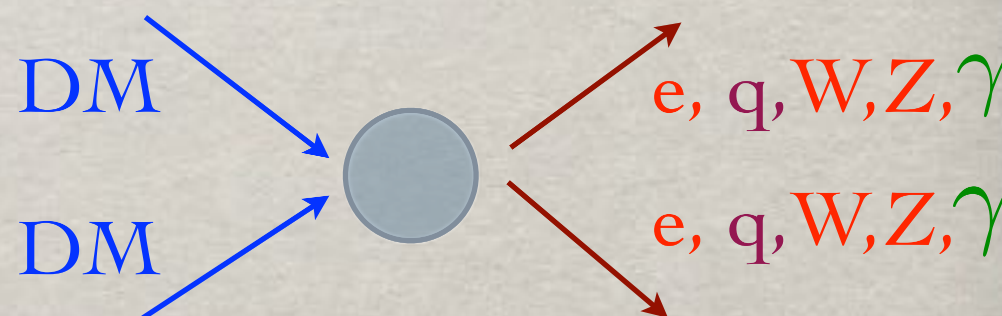
Direct Detection:



Colliders: LHC/ILC



Indirect Detection:

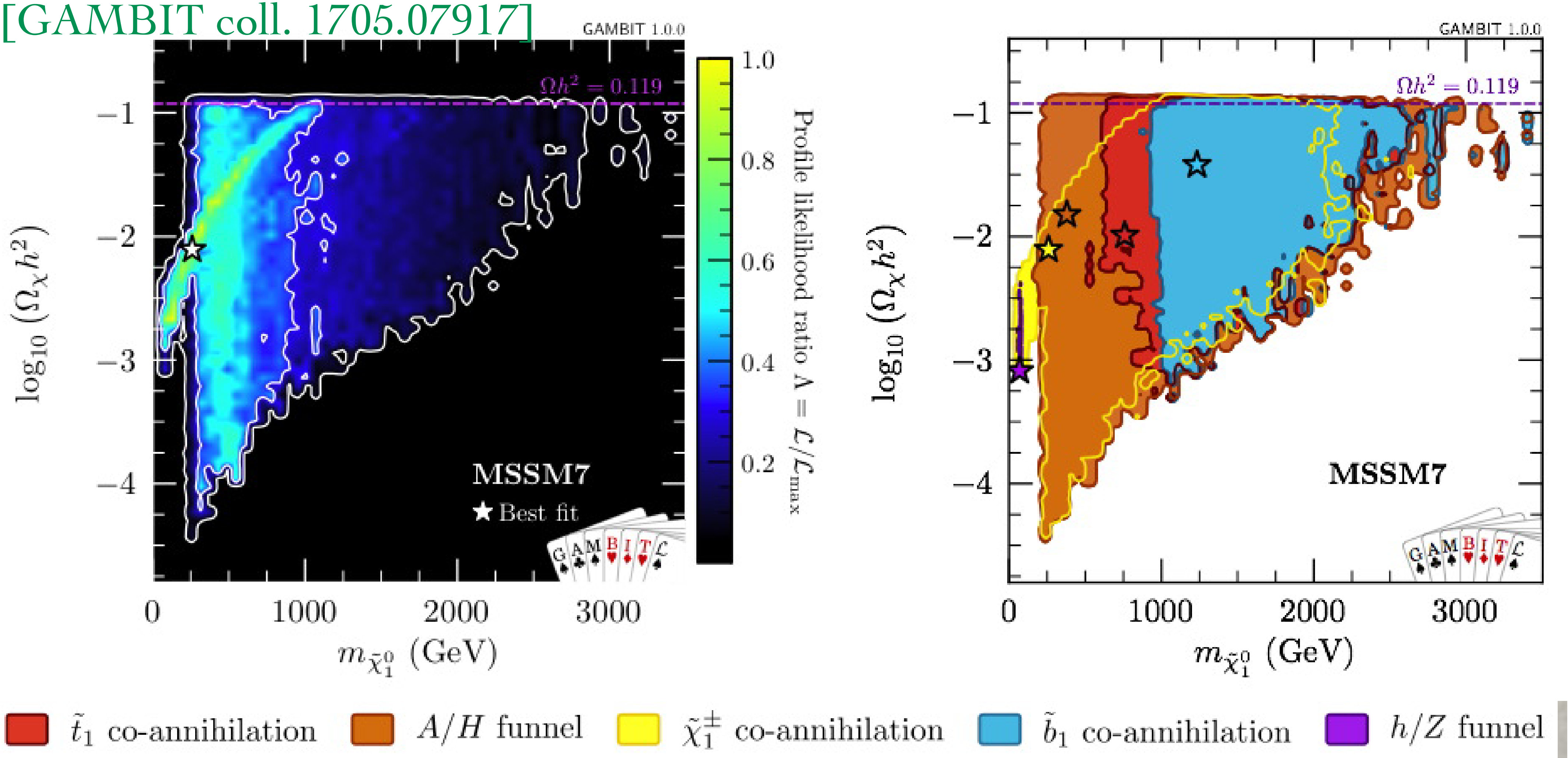


3 different ways to check this hypothesis !!!

MSSM-7 Dark Matter

With more parameters, more mechanism are possible, i.e. in the MSSM with 7 parameters: both Bino & Higgsino DM !

[GAMBIT coll. 1705.07917]

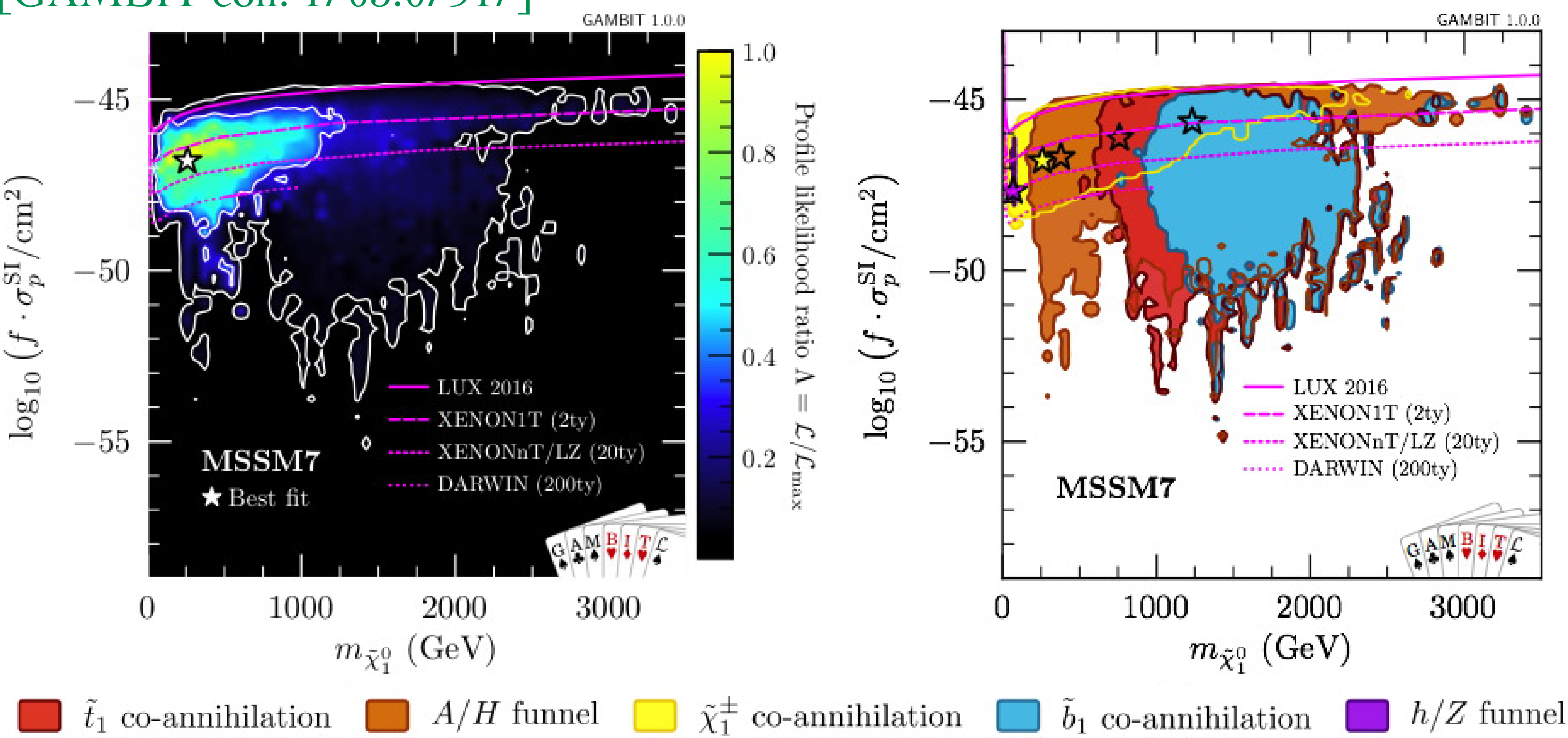


For Higgsino coannihilation with charginos is always present !

Higgsino Dark Matter

The Higgsino DM region mostly covered by Direct Detection:

[GAMBIT coll. 1705.07917]

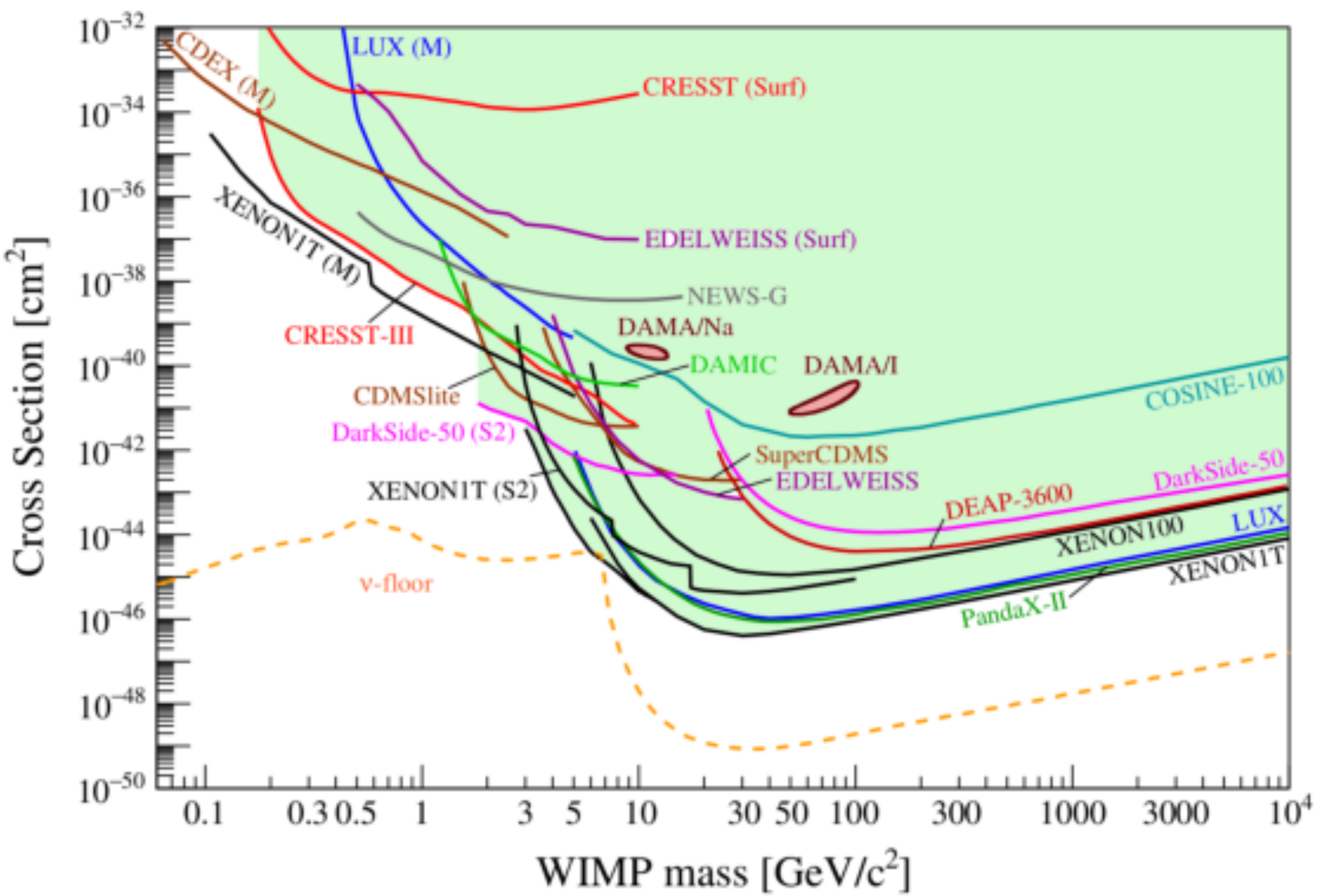


Nevertheless for other compositions low cross-section is possible

Direct detection

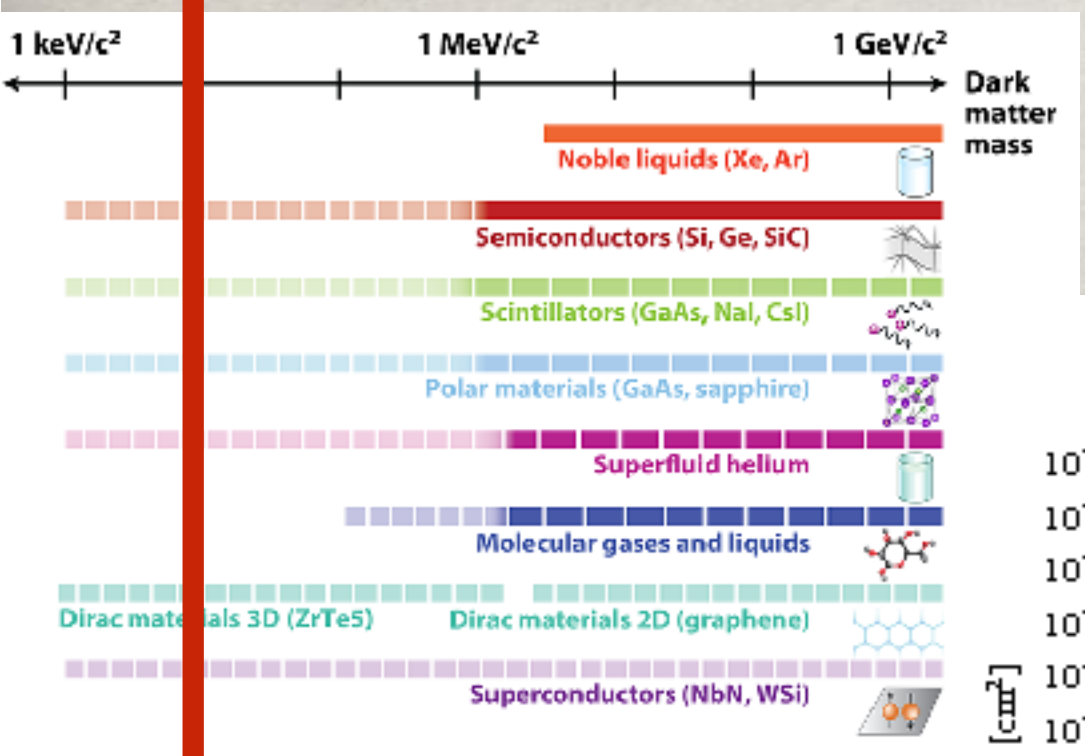
The constraints are moving towards the neutrino floor, with new frontiers at low masses:

[Billard et al. 2104.07634]



Low mass WIMPs

The DD searches are being extended to low masses via new technologies and sensitivity to electron scatterings:

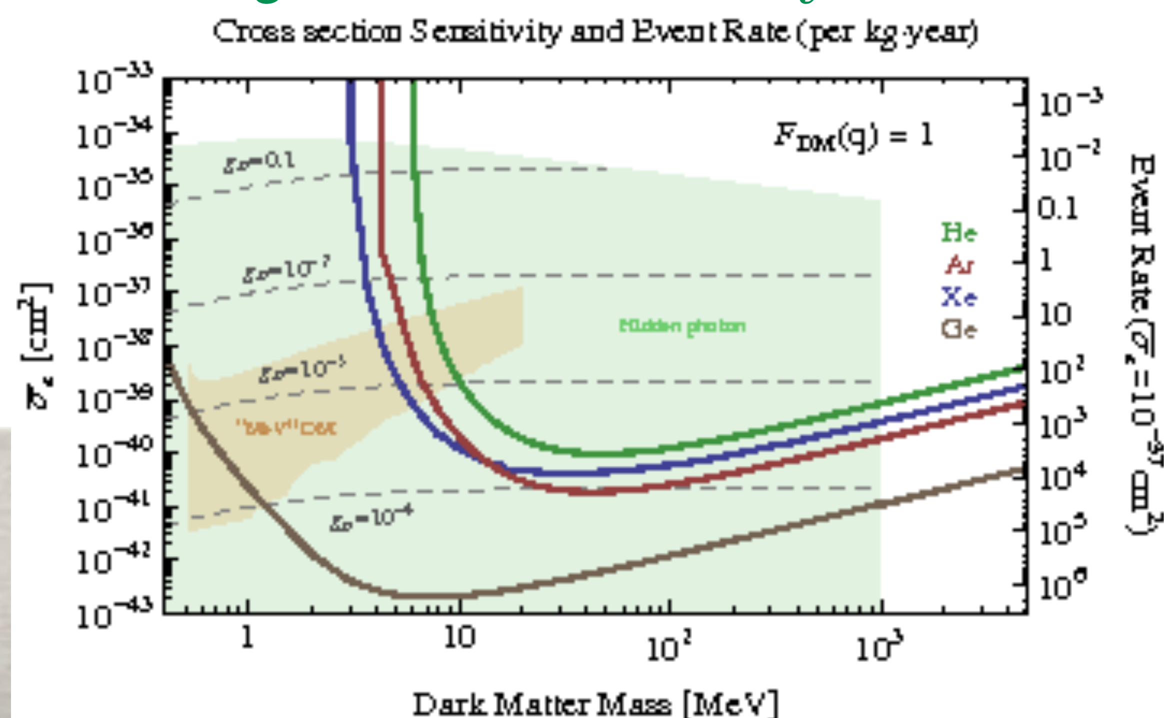


[R. Essig 2104.07634]

Warm DM

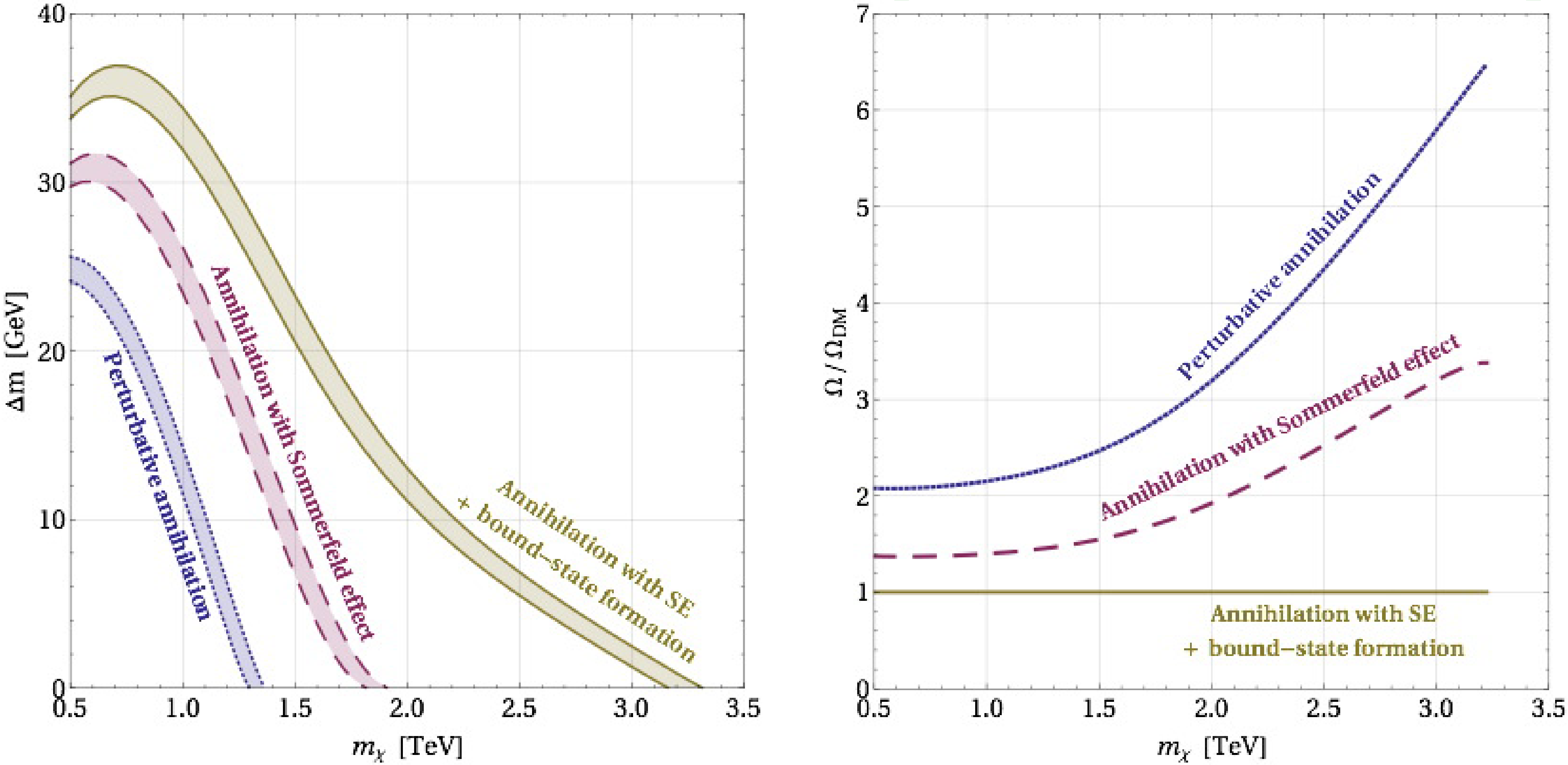
Cold Dark Matter

[Essig, Mardon & Volansky 1108.5383]



Sommerfeld Factor for coannihilation

[J. Harz & K. Petraki 2018]

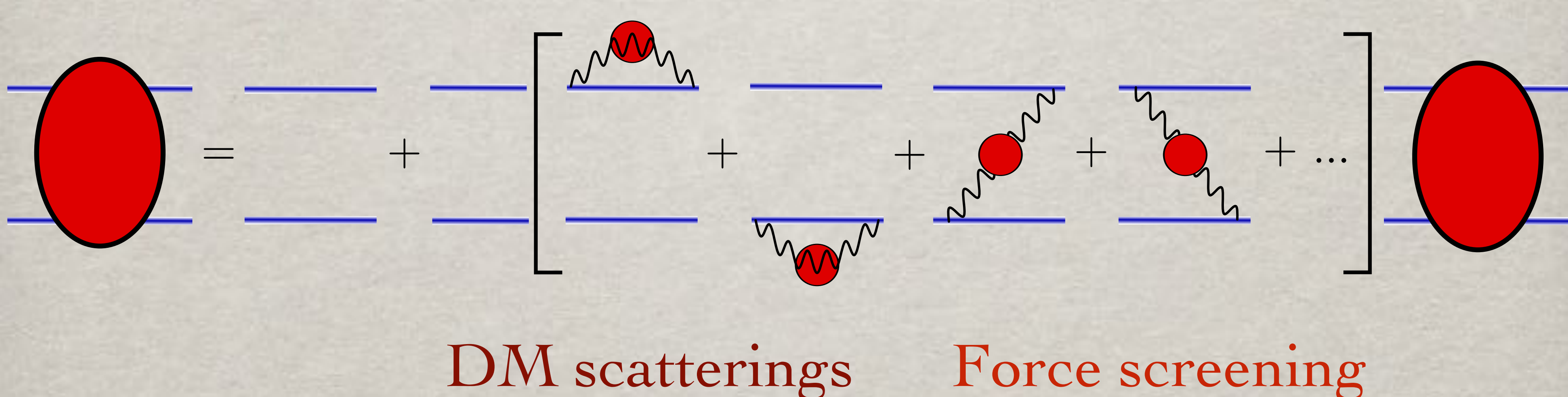


Coannihilation with a colored state:bound states are important !
The stronger annihilation makes higher masses preferred.

Bethe Salpeter equation

[T. Binder, LC, K. Mukaida '18]

We define a resummation procedure taking into account the self-energy corrections to the fermion propagator and to the gauge boson propagator to obtain an equation that respects thermal equilibrium properties:



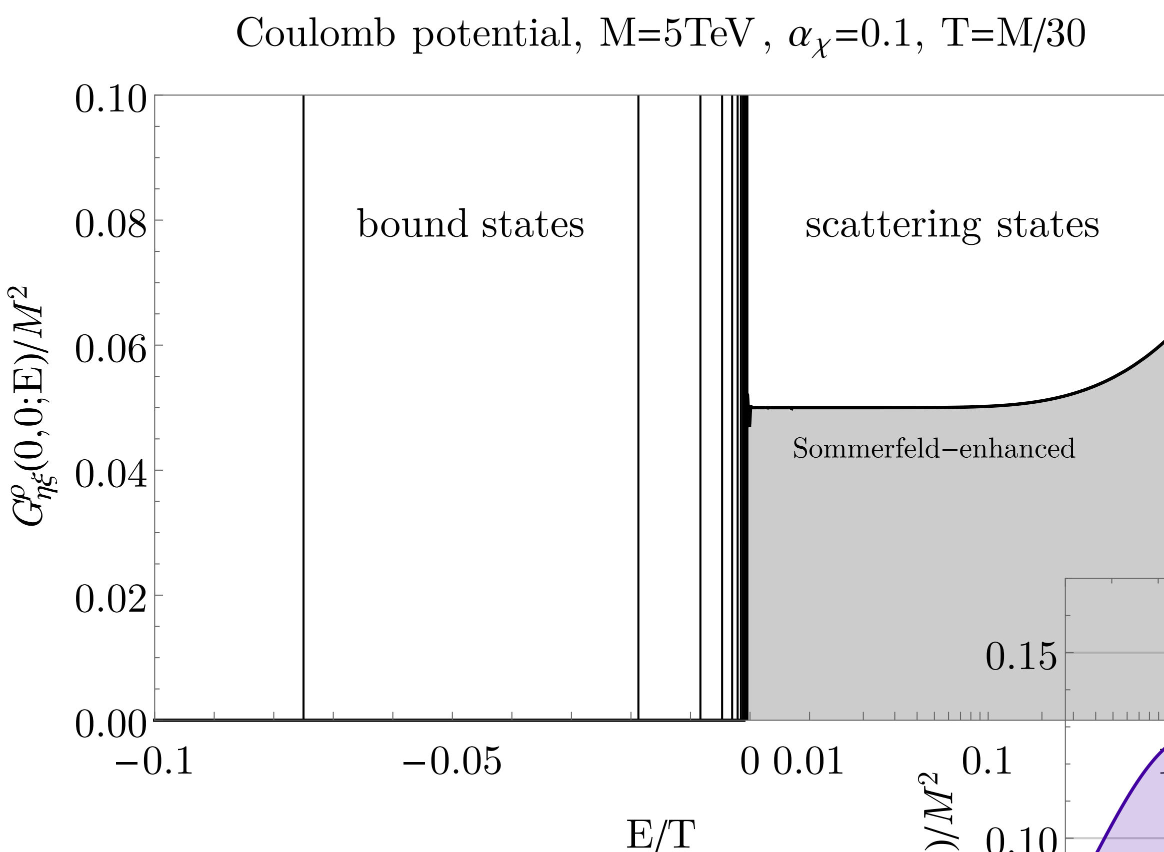
In the DM dilute limit, we obtain from this equation the modified Coulomb potential:

Yukawa-like ! Imaginary

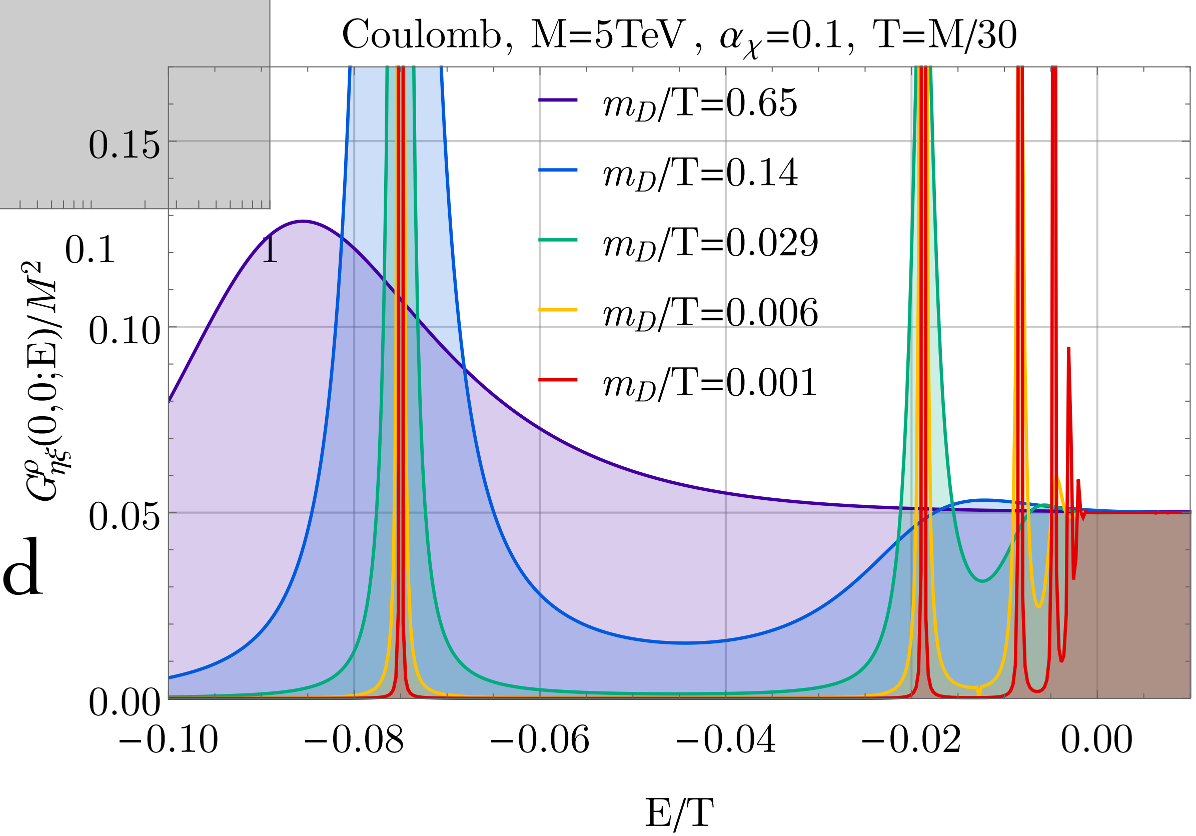
$$V_{eff}(\vec{r}) = -ig^2 \int_{-\infty}^{+\infty} d^3q(1 - e^{i\vec{q}\vec{r}})G^{++}(0,\vec{q}) = -\frac{\alpha}{r}e^{-m_D r} - i\alpha T\Phi(m_D r) + \dots$$

Temperature effects

[T. Binder, LC, K. Mukaida '18]



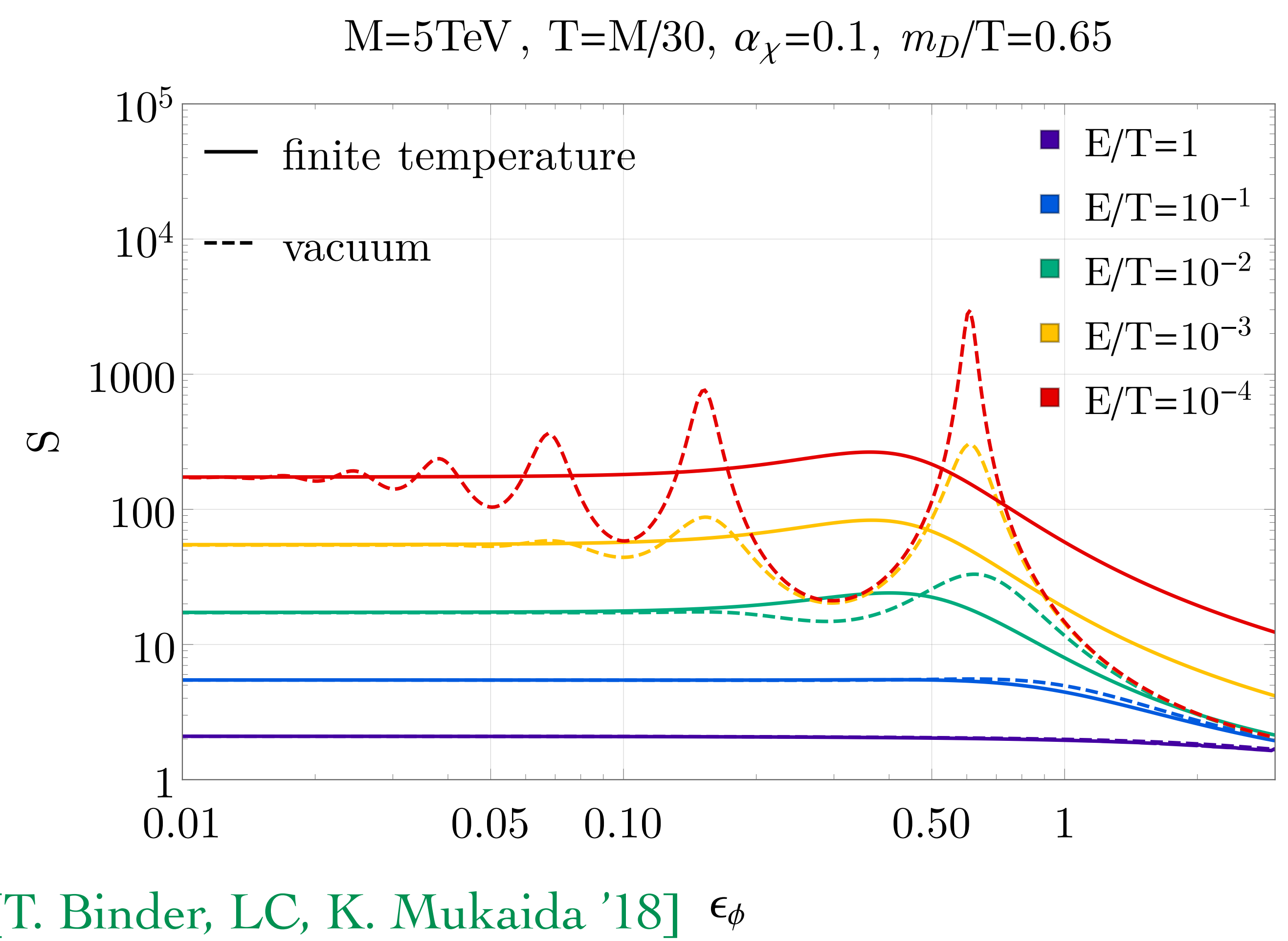
Without thermal corrections we recover the known results.



The presence of a plasma strongly modifies the bound states ! Even to the point of complete melting…

Sommerfeld enhancement

For the simpler Yukawa potential (but practically same as gauge theory at finite T): resonances are suppressed !



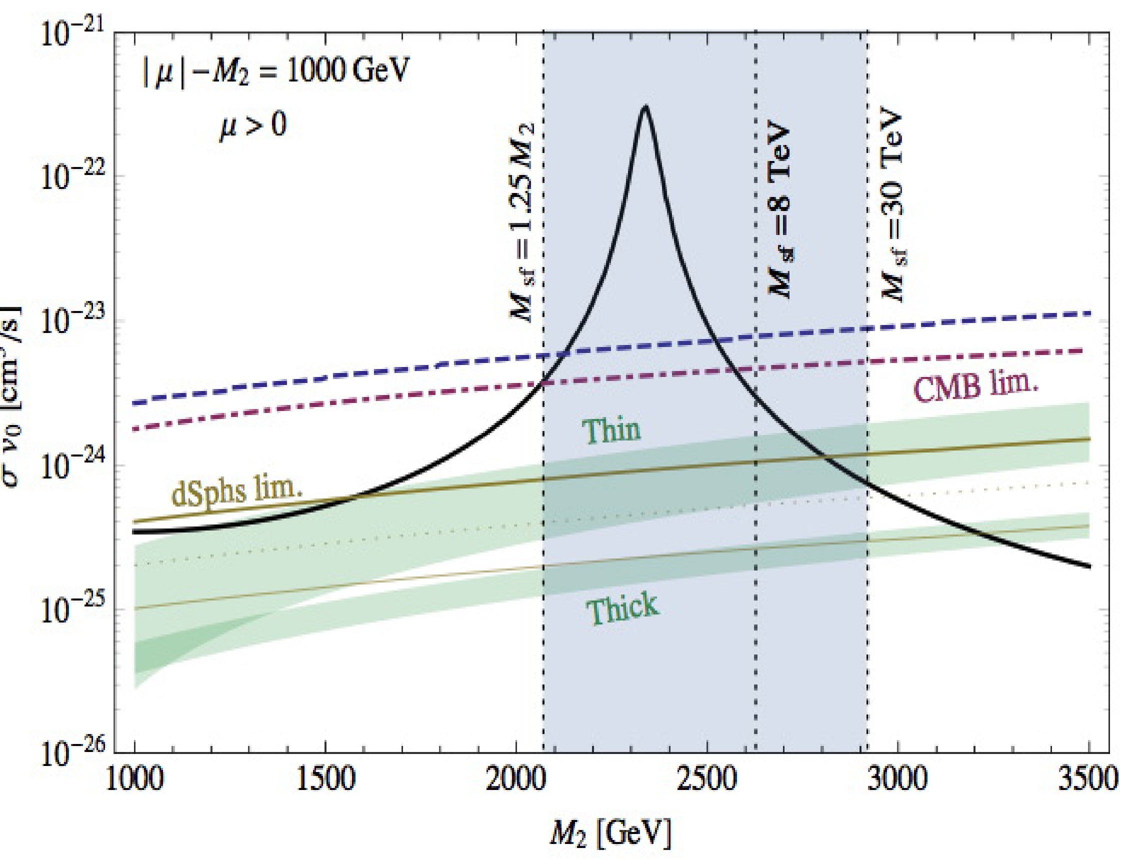
[T. Binder, LC, K. Mukaida '18]

We agree with results obtained in linear response and from coupled Boltzmann equations or Kadanoff-Baym eq. (up to ionization equilibrium) [S. Kim & M. Laine 16/17 , K. Petraki, M. Postma et al 14/15, M. Beneke, F. Dighera & A. Hryczuk 14]

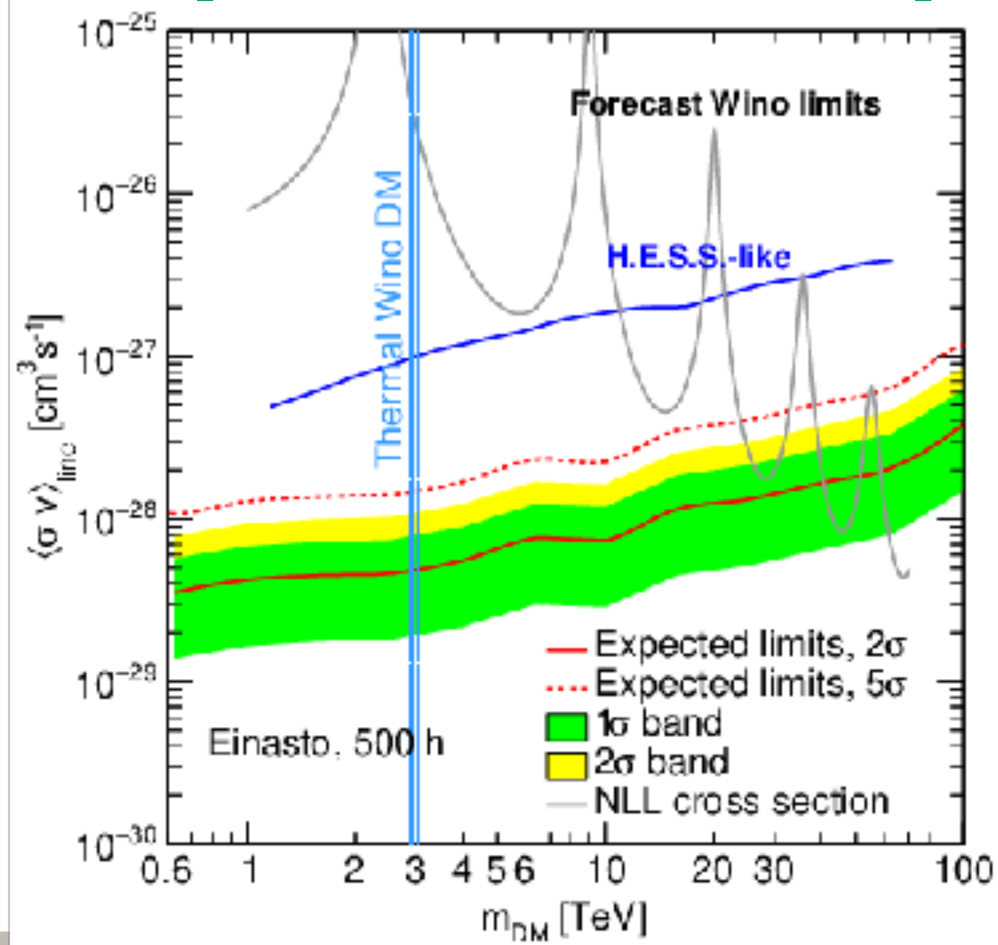
Wino Dark Matter

In the case of the Wino the Sommerfeld enhancement of the cross-section plays an important role !
Indirect detection can exclude pure Wino, also in the high mass region by CTA

[Beneke et al.1611.00804]



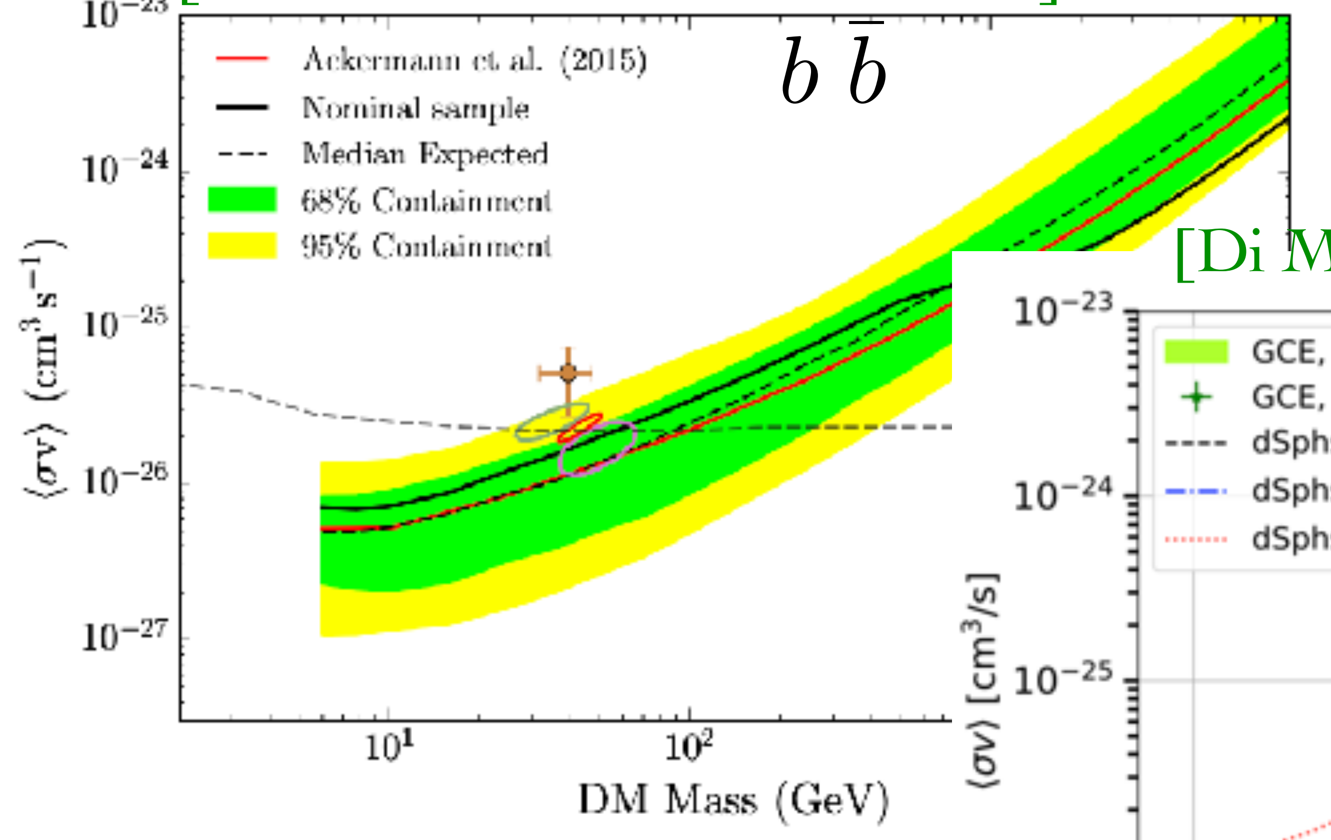
[Rinchiuso et al. 2008.00692]



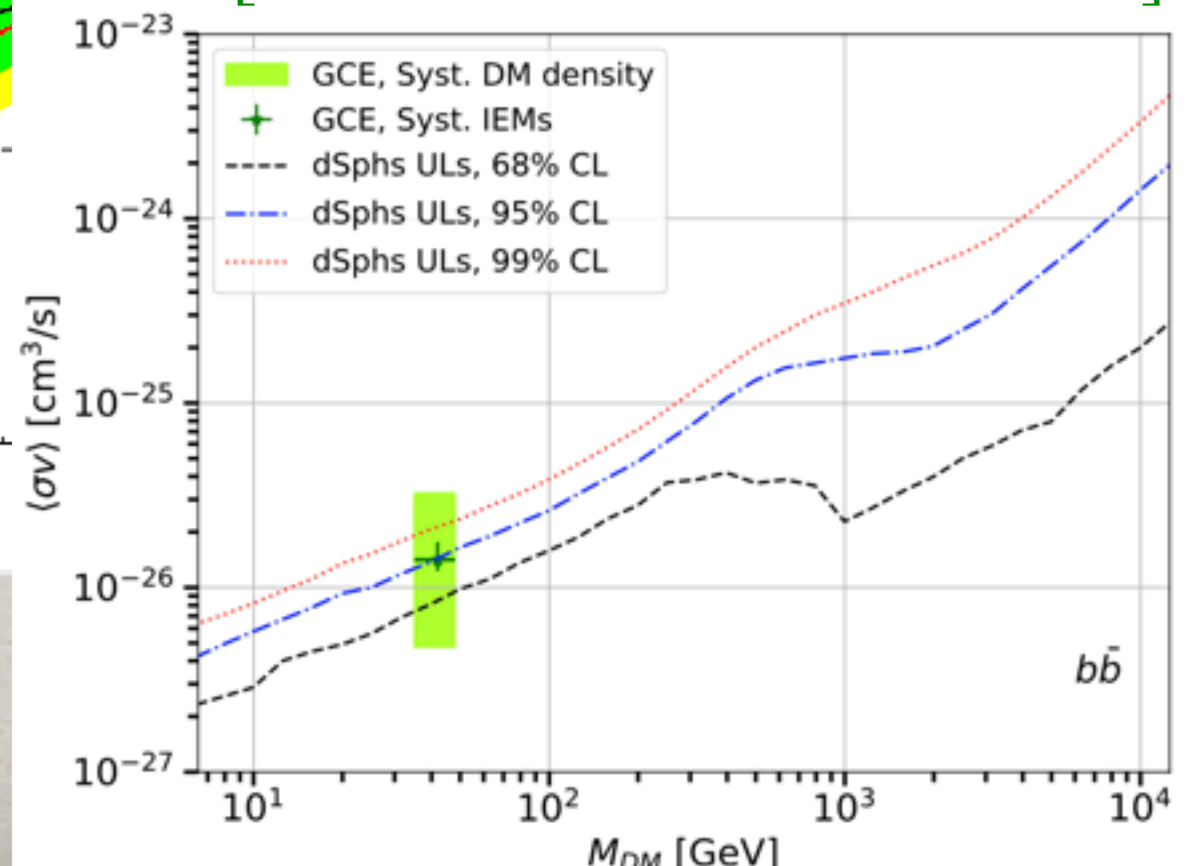
Bounds on WIMP DM

Strong limits are obtained from dwarf satellite galaxies, considering measured J-factors:

[Fermi-LAT & DES 1611.03184]



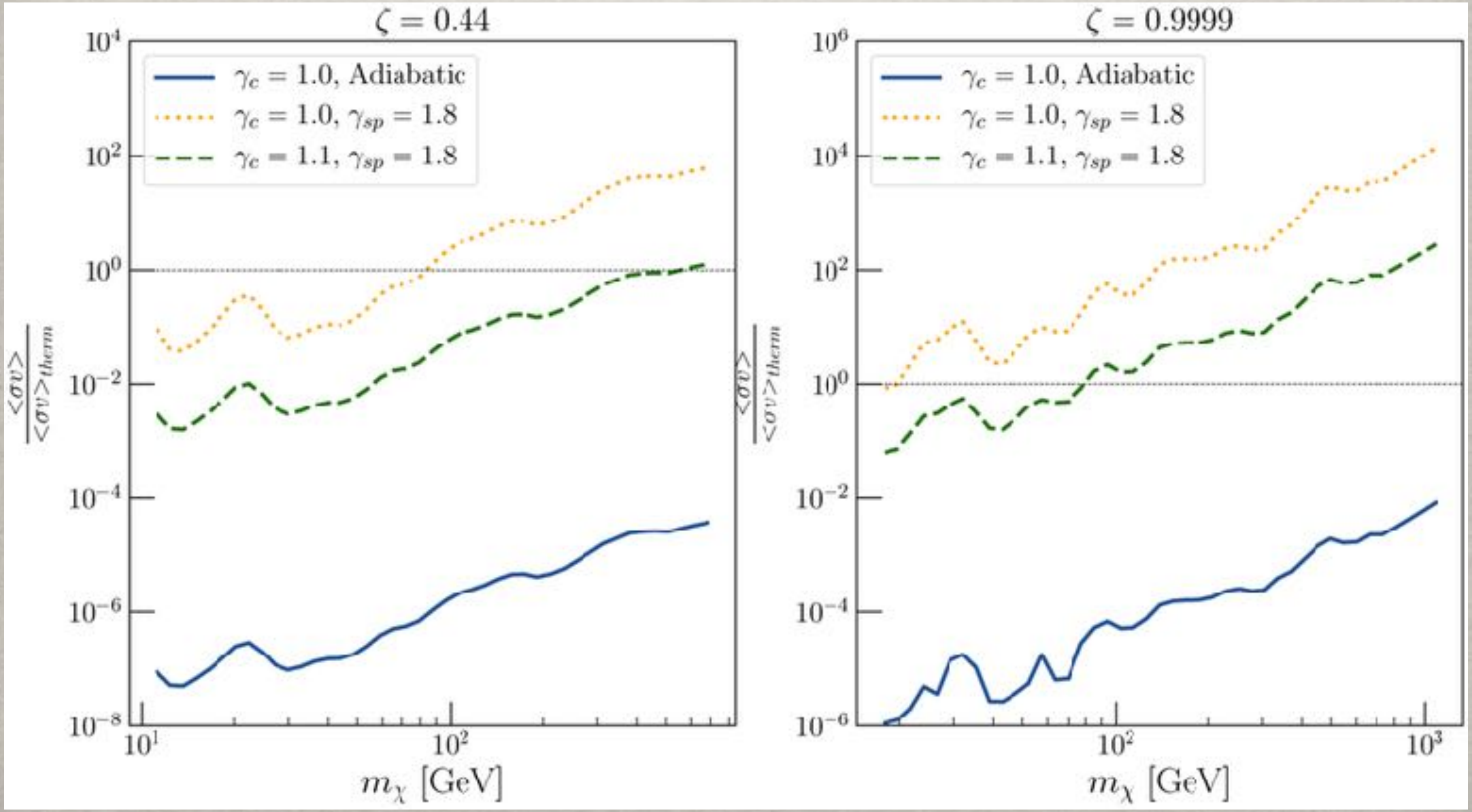
[Di Mauro & Winkler 2101.11027]



WIMP DM ID: p-wave

For a cuspy profile the centre of the galaxy can constrain also p-wave annihilation:

[FERMI-lat arXive:1904.06261]

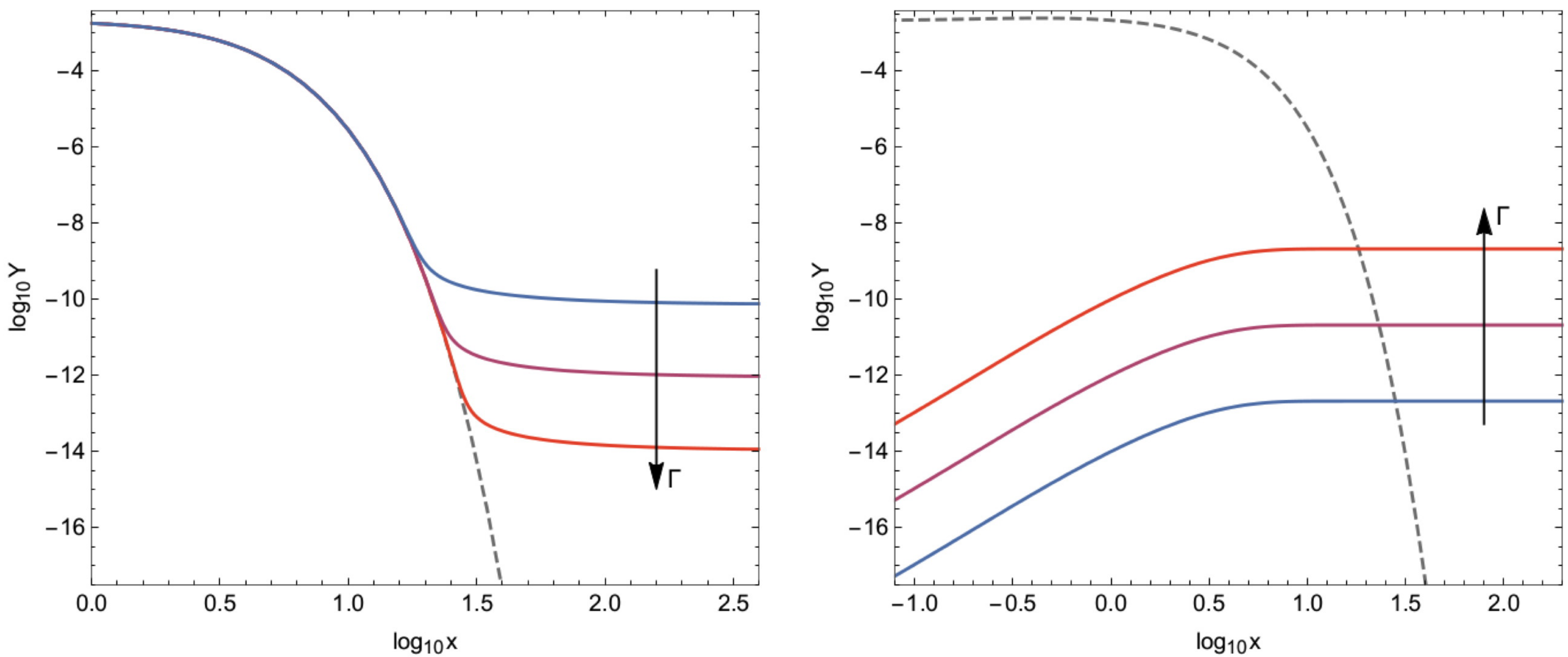


FIMP/SuperWIMP/ Decaying Dark Matter

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.

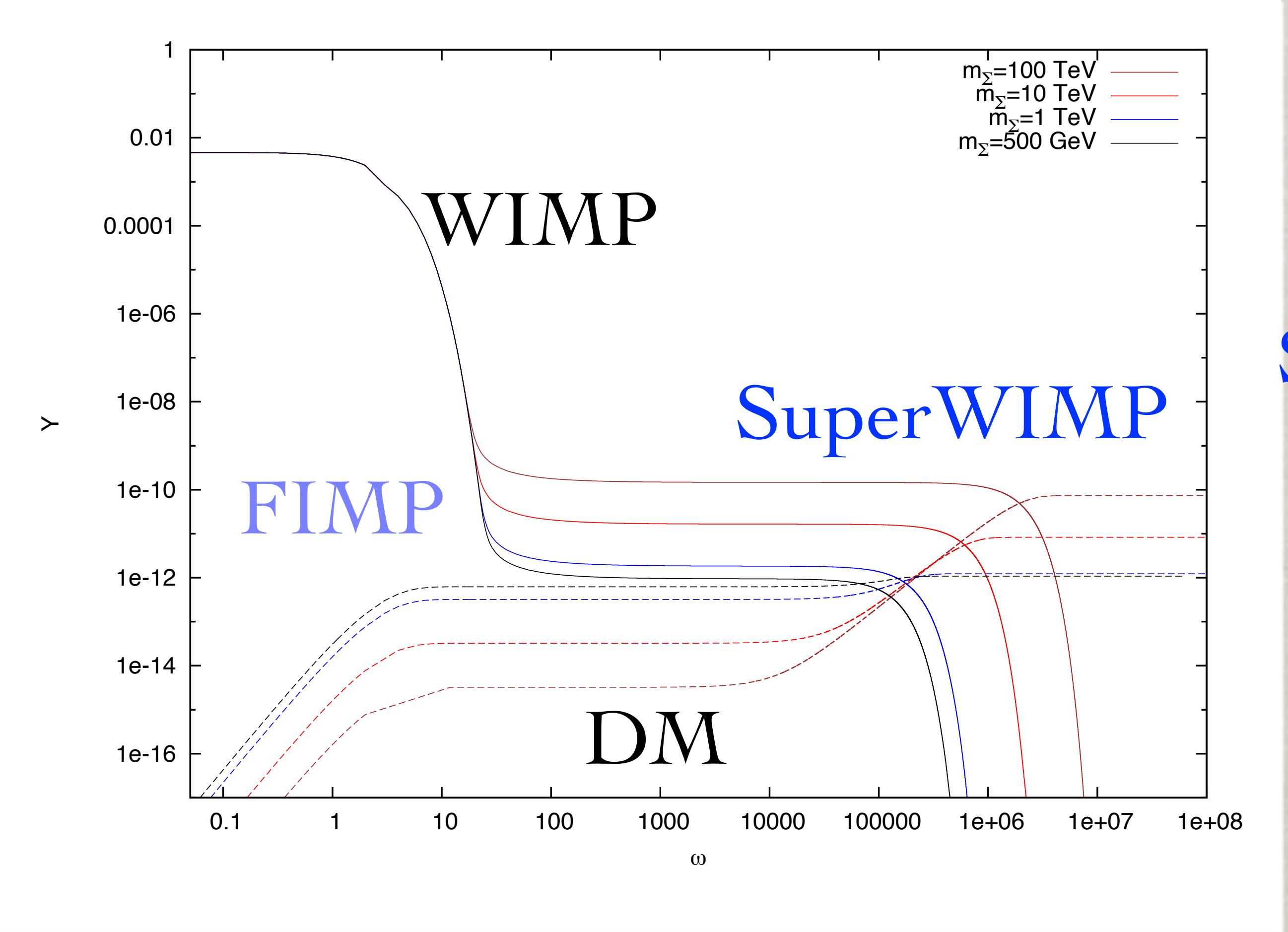
Same Boltzmann equation, but different dynamics !

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:

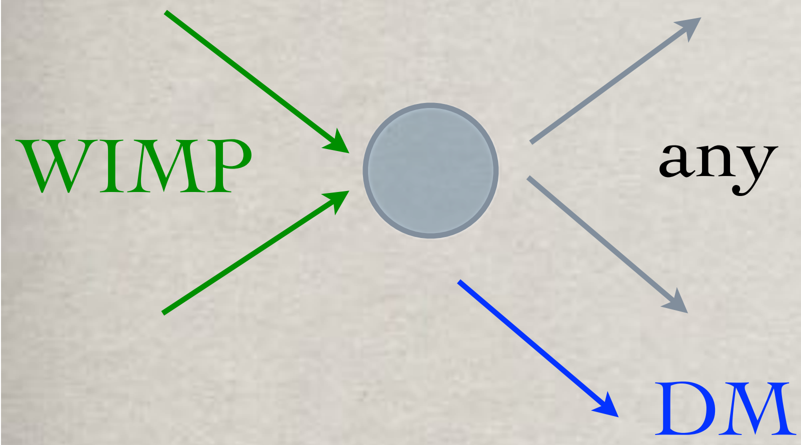
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} \, BR(\Sigma \to \psi) \, \Omega_\Sigma h^2$$

- Moreover 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

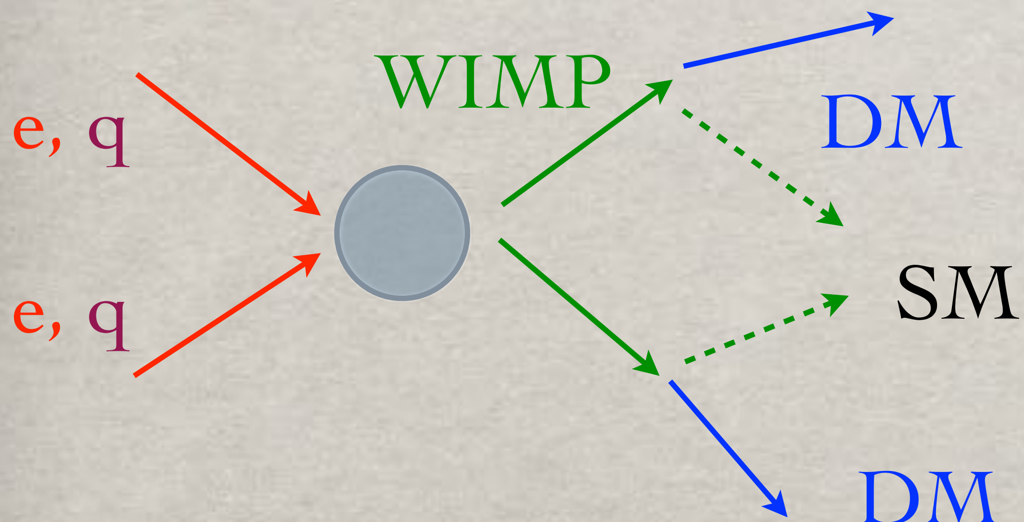
Early Universe: $\Omega_{CDM} h^2$



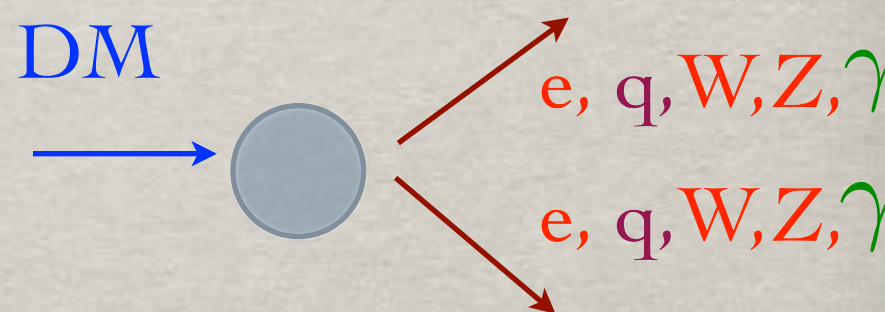
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:

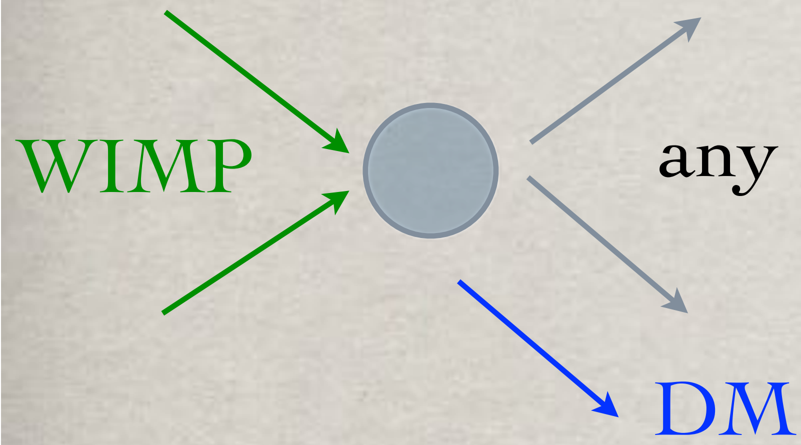


decaying DM !

3 different ways to check this hypothesis !!!

F/SWIMP CONNECTION

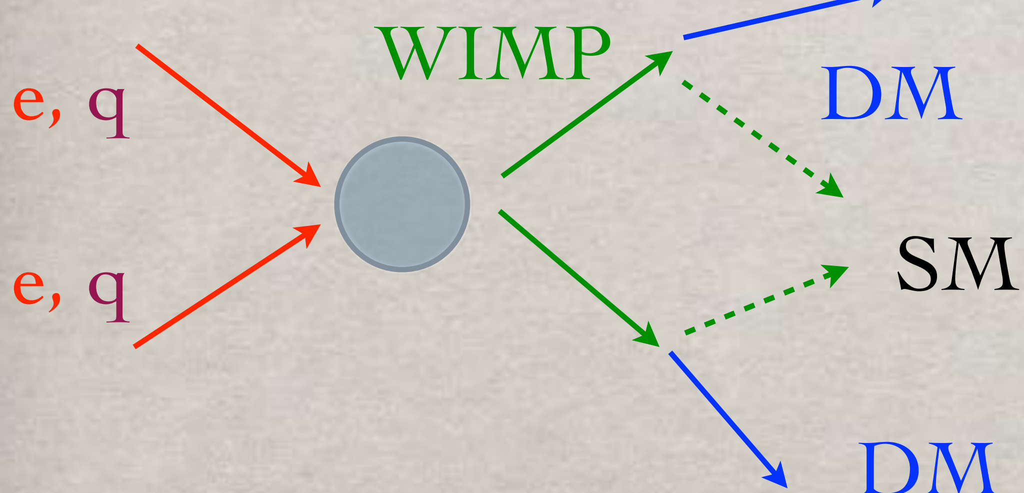
Early Universe: $\Omega_{CDM} h^2$



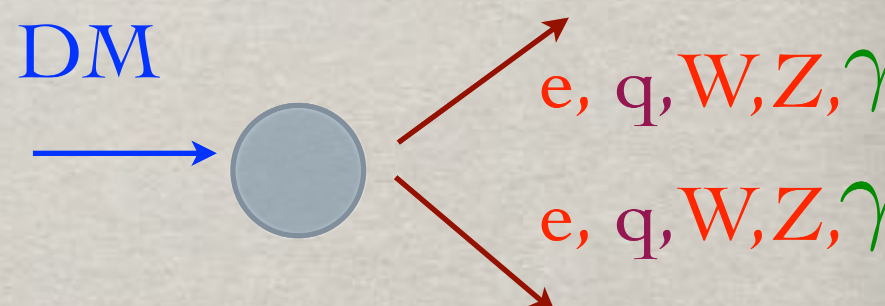
Direct Detection:

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

Colliders: LHC/ILC



Indirect Detection:



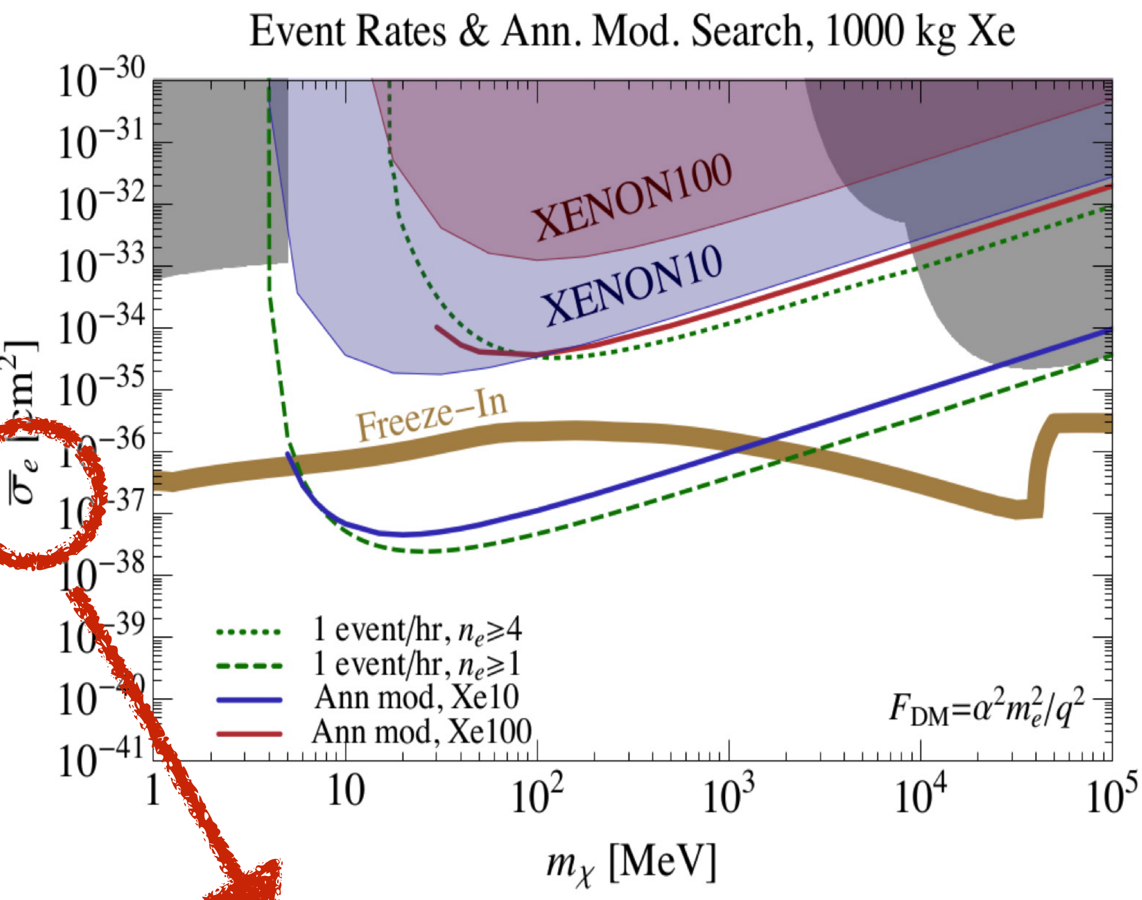
decaying DM !

3 different ways to check this hypothesis !!!

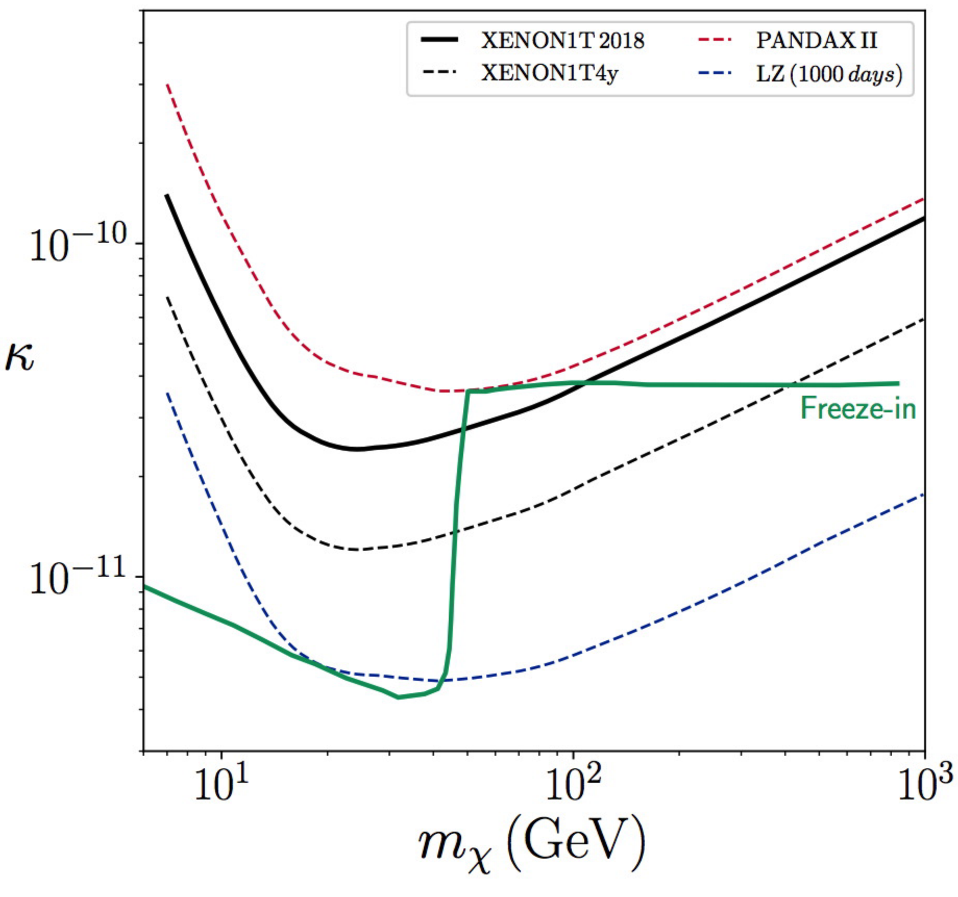
Direct detection of FIMPs

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 !!!

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 :

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

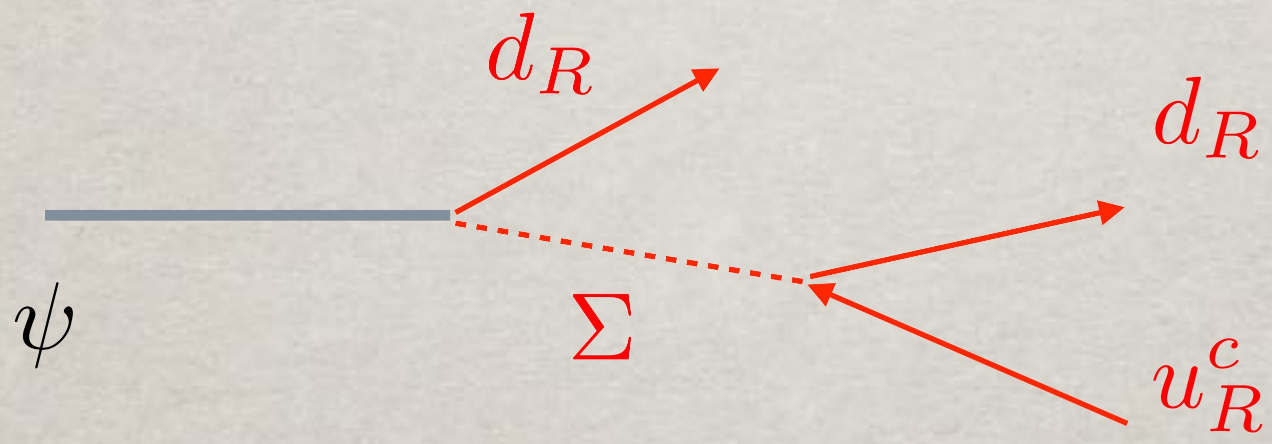
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection. Then the possibility would arise to measure the parameters of the model in two ways !

→ 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 $m_\Sigma \gg m_\psi$:

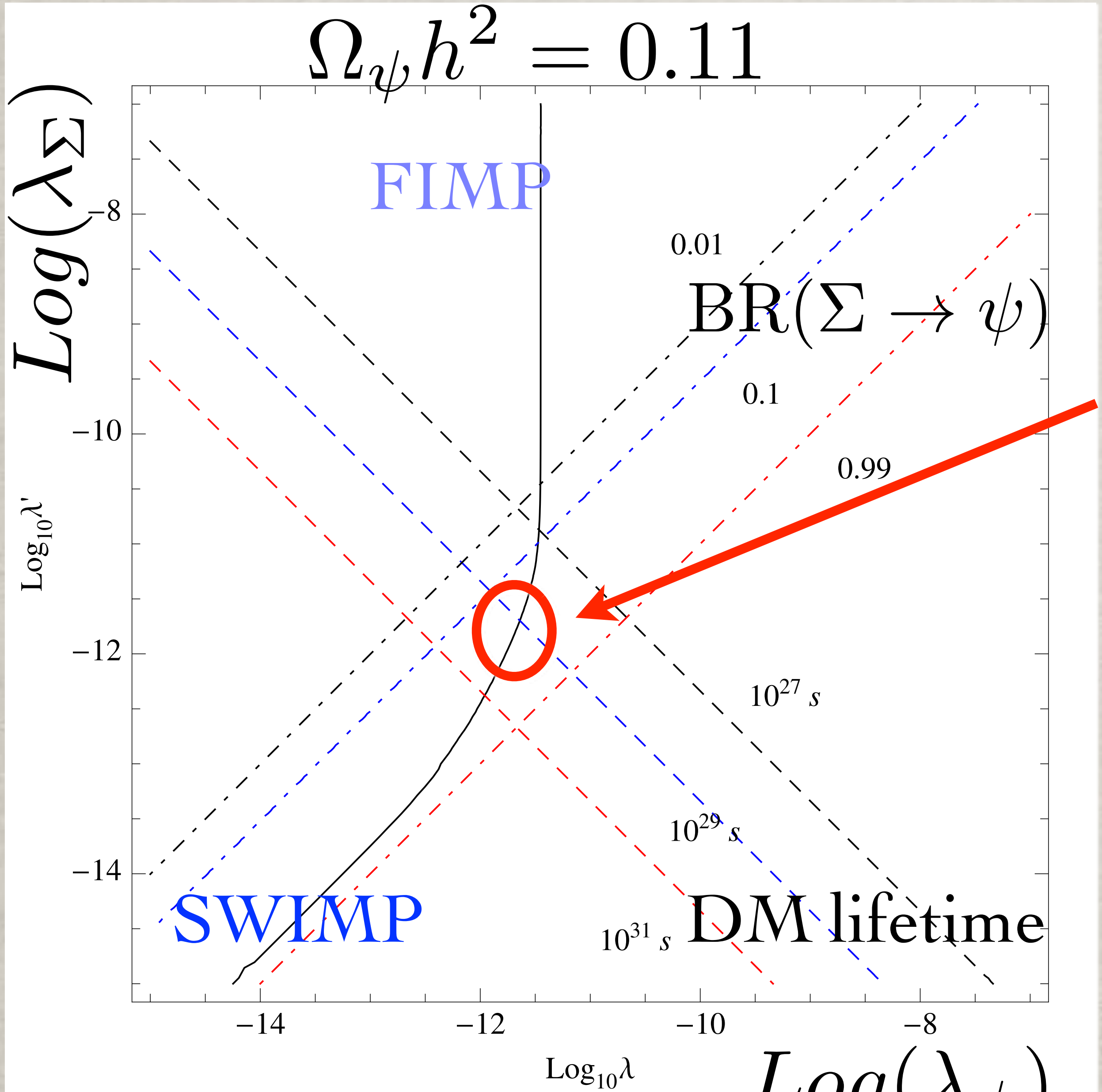


Decay into 3 quarks via both couplings !

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...

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

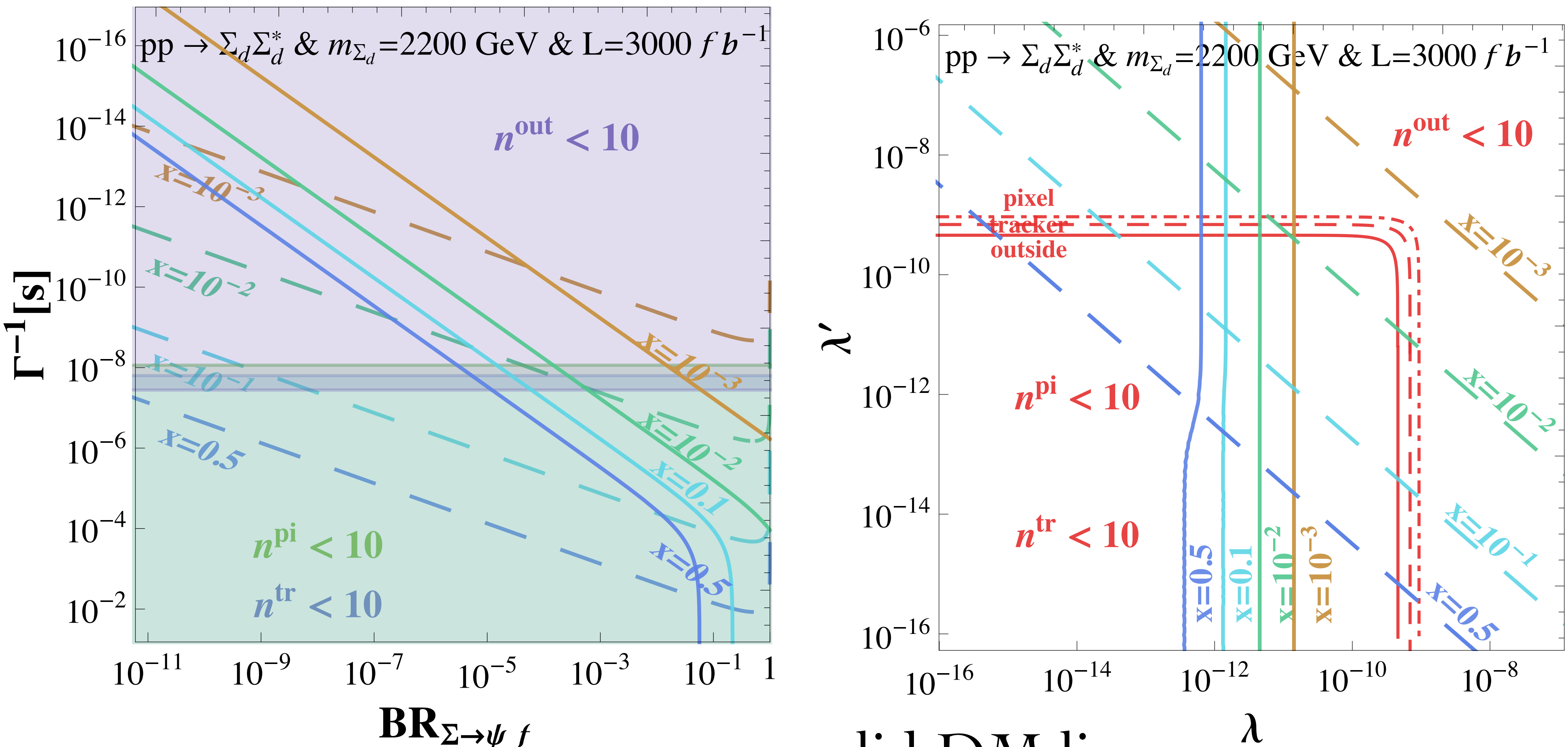
Moreover imposing ID "around the corner" gives

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

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...

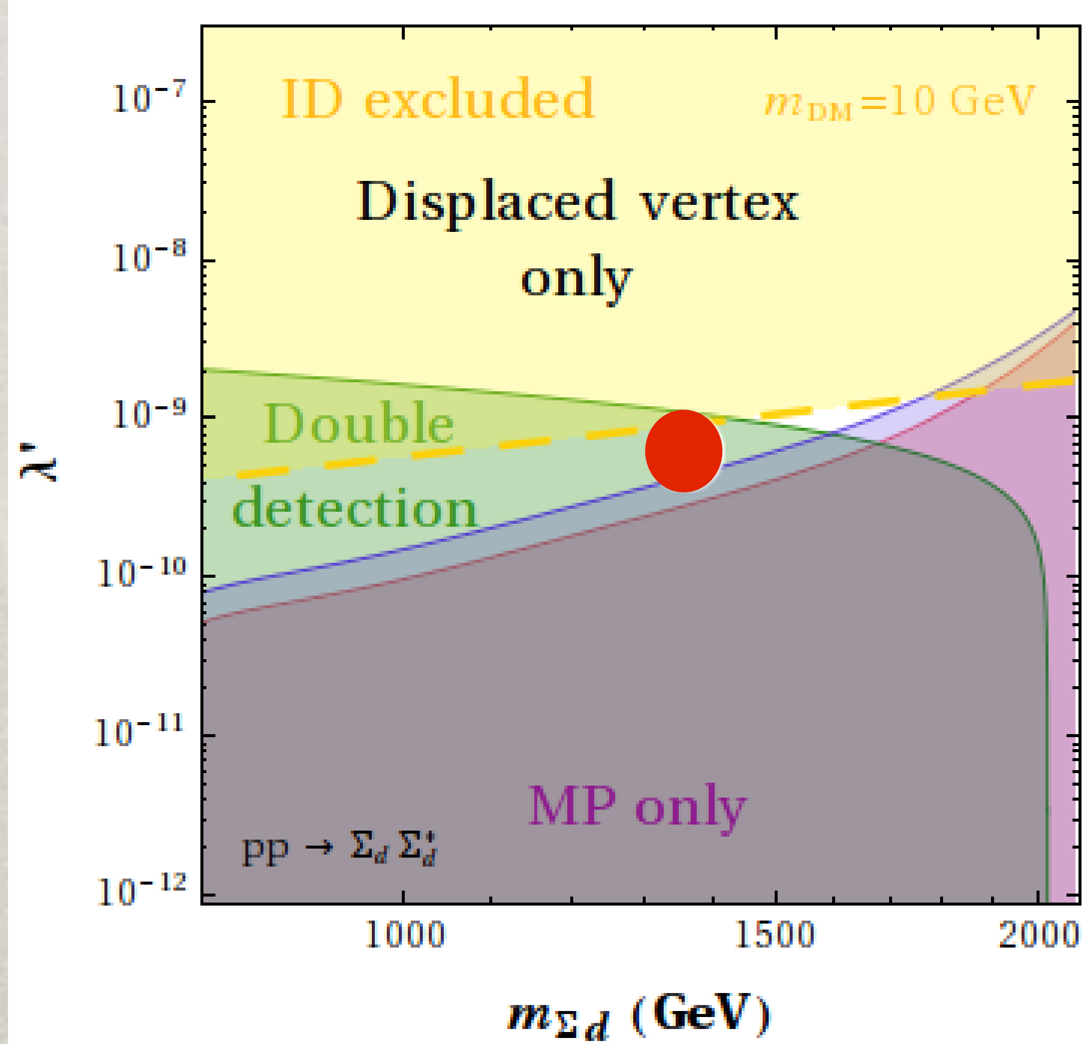
Σ Combined detection

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]



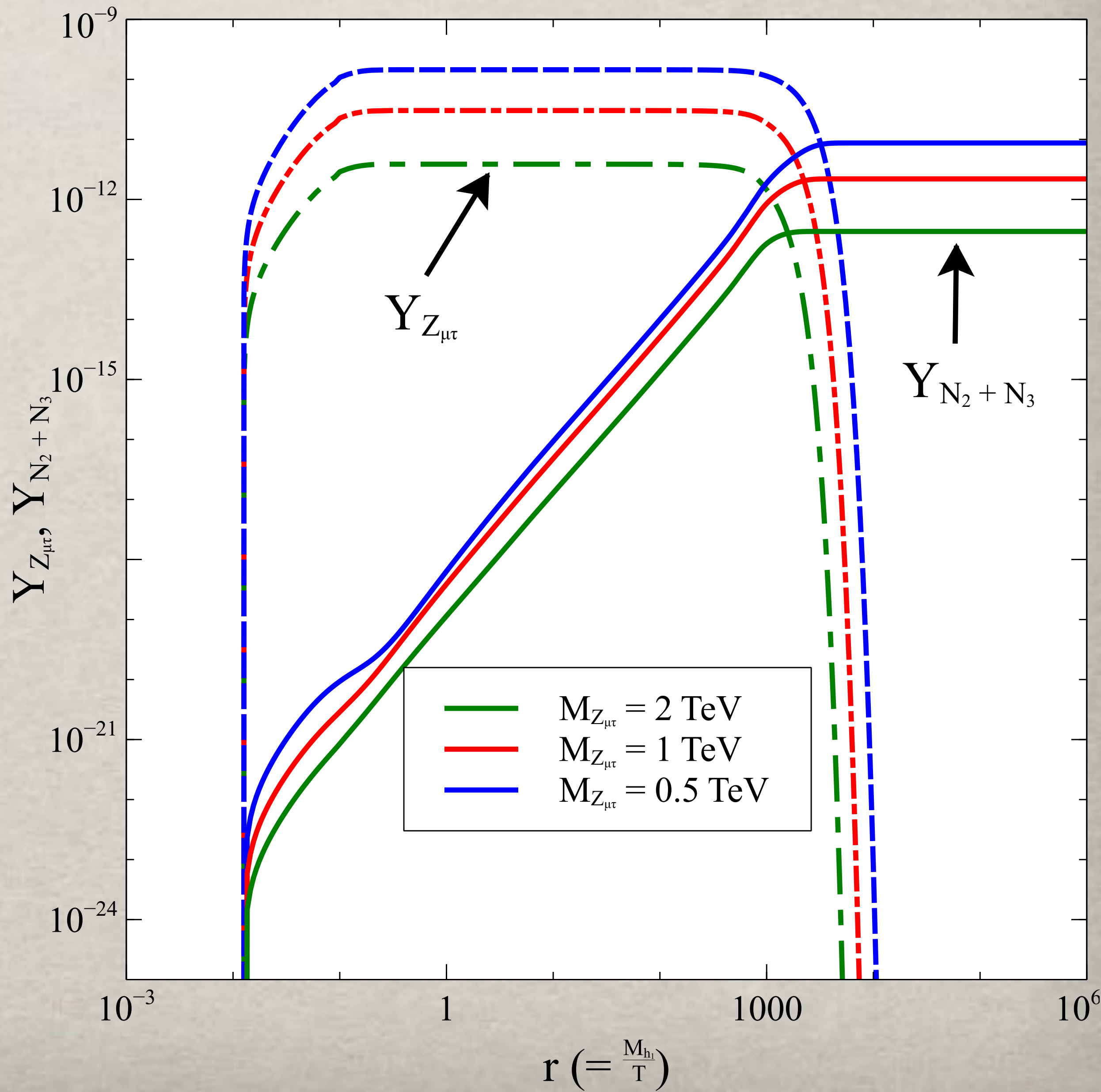
It is possible to over-constraint the model and check the hypothesis of FIMP production !

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:

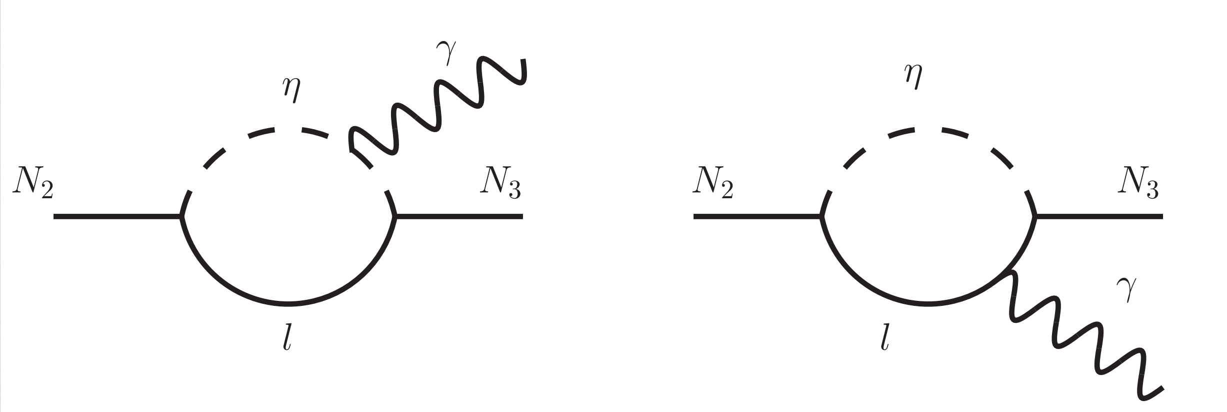
$$g_{\mu\tau} \sim 10^{-11}$$



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 & 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

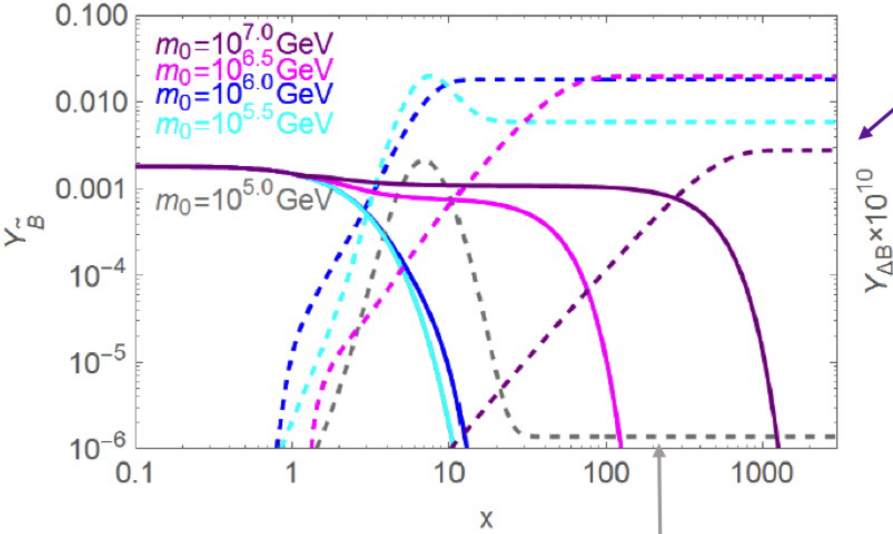
Gravitino DM: BR is naturally small and DM stable enough !

Baryogenesis in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]

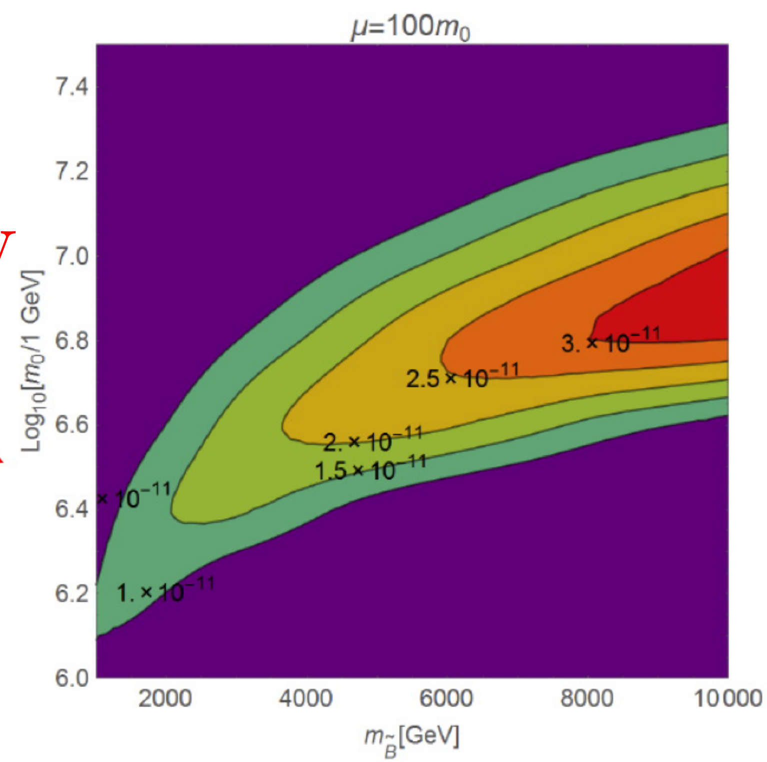
Unfortunately realistic models are more complicated than expected: wash-out effects play a very important role !!!

Asymmetry suppressed by the high scalars



Asymmetry suppressed by wash-out

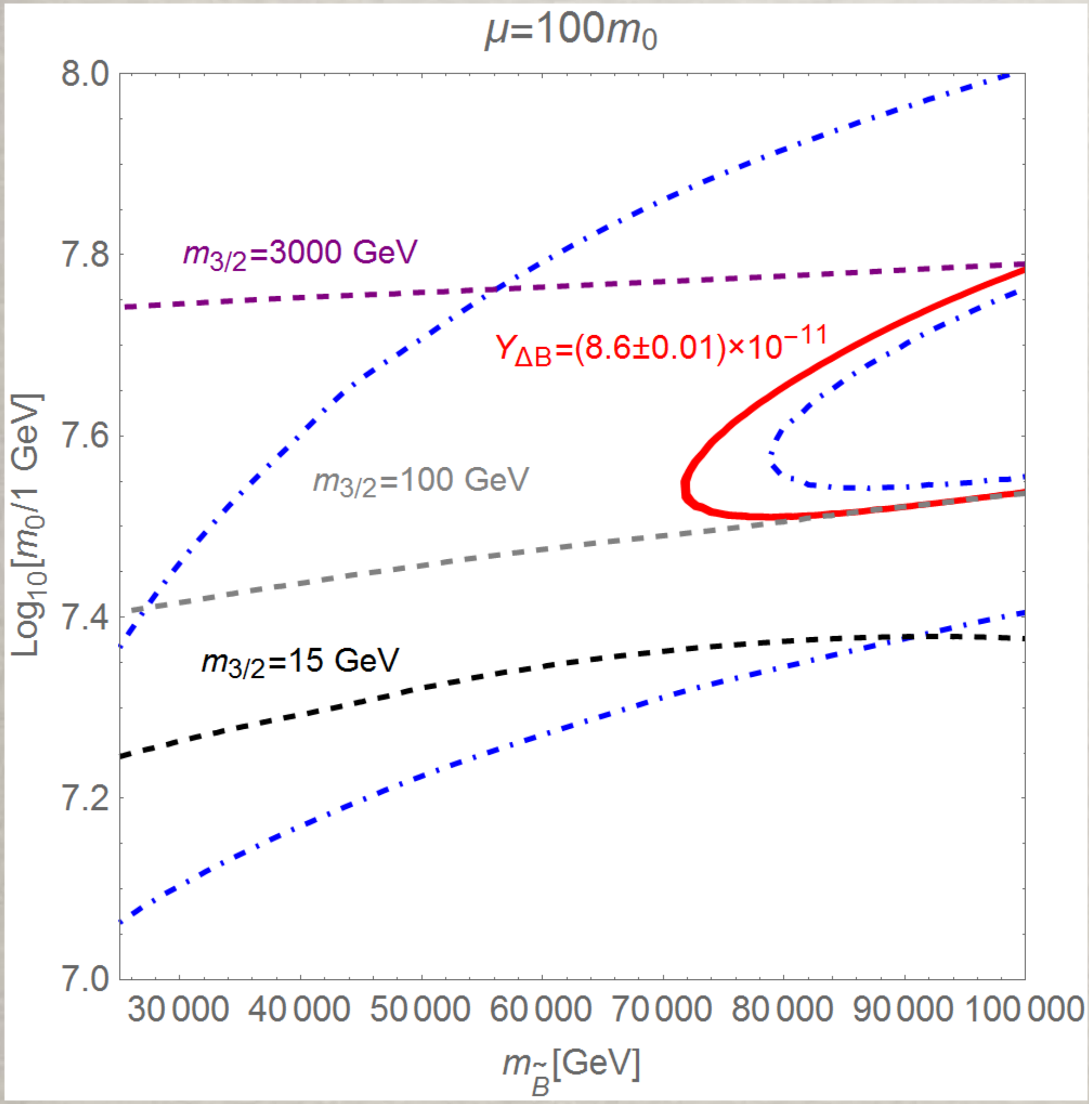
10^7GeV



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

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584]



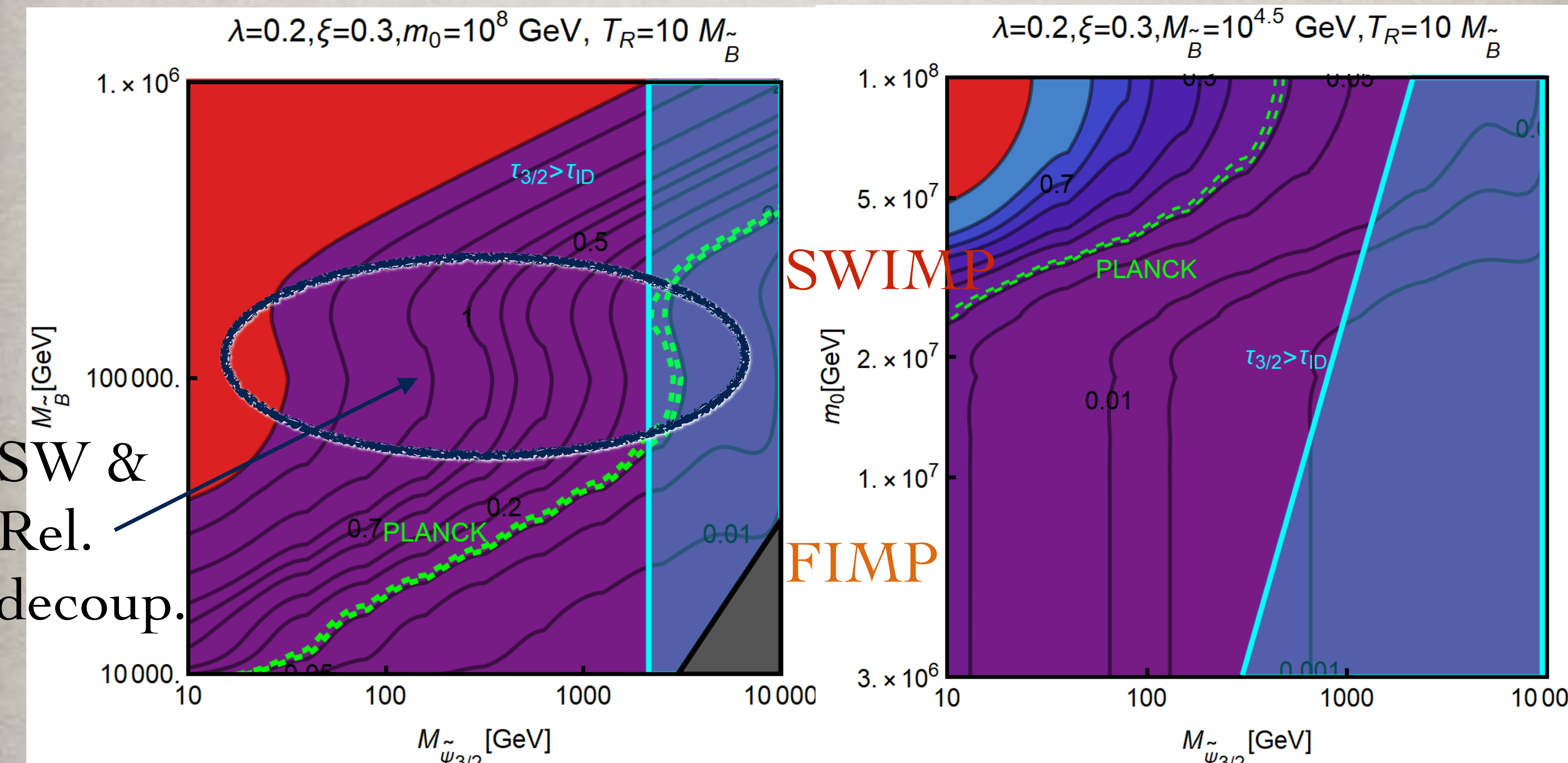
Moreover the large scalar mass suppresses the branching ratio into gravitinos too much...

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

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

Full numerical treatment with all contributions gives



Possible to obtain right abundance and long enough lifetime !

Gravitino DM in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC, Khan to appear]

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 and squark masses…

Gluino NLSP in RPV SUSY

[Arcadi, LC & Nardecchia 1507.05584, Arcadi, LC, Khan to appear]

The gluino is in this scenario the next-to-lightest SUSY particle and may be produced at colliders; we are still exploring how much lighter than the Bino it can be. For the range

$$m_{\tilde{g}} \sim 0.1 - 0.4\, m_{\tilde{B}} \sim 7 - 28 \text{ TeV}$$

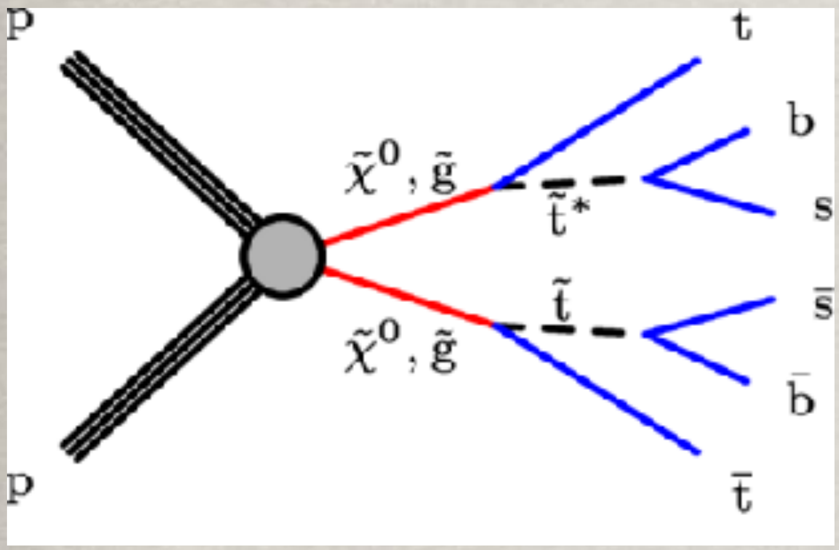
it could be in the reach of a 100 TeV collider.

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

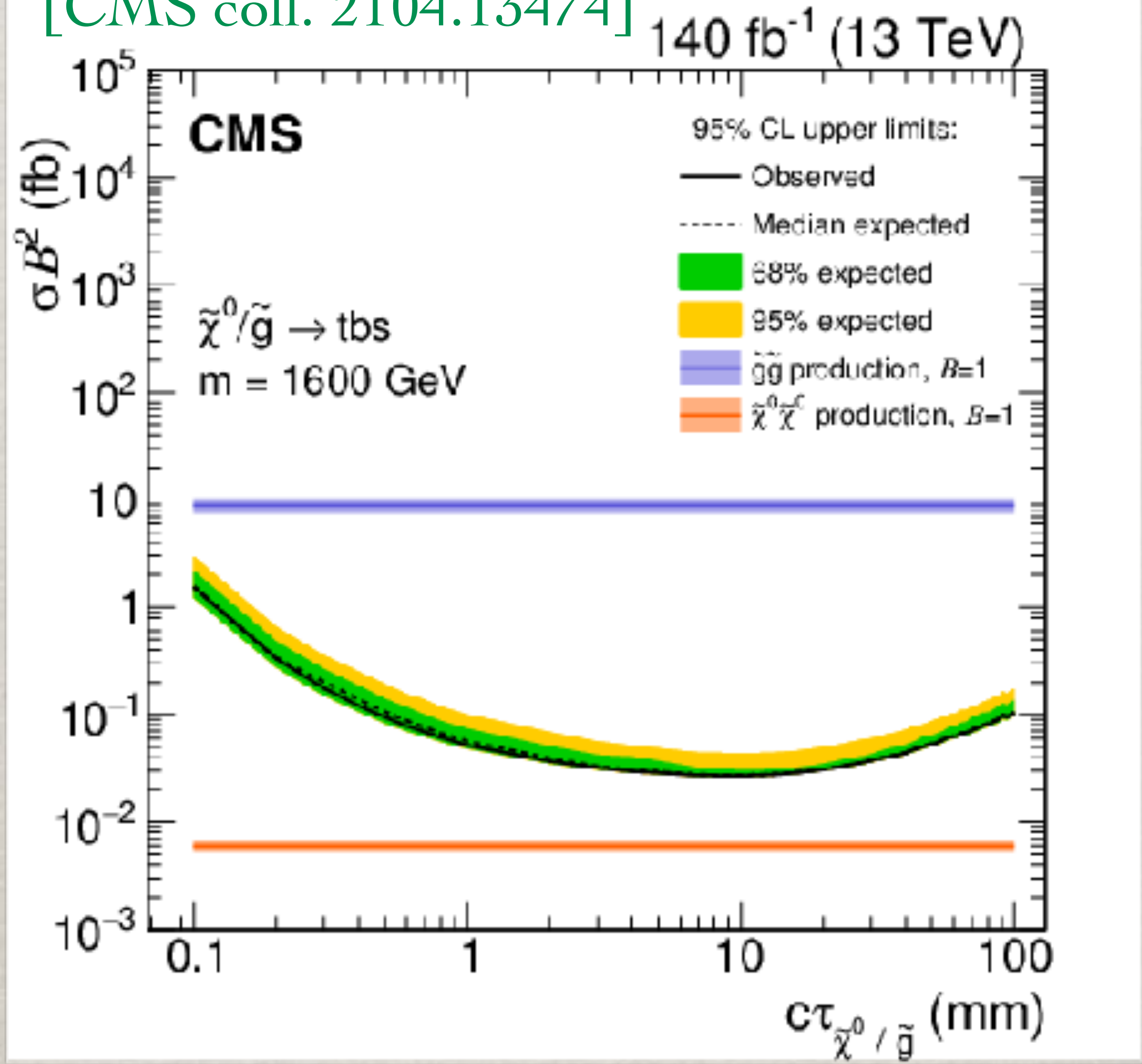
The heavy squarks give displaced vertices for the gluino decay via RPV, even for RPV coupling of order 1.

Gluino decay into gravitino DM is much too suppressed to be measured.

Displaced vertices at LHC

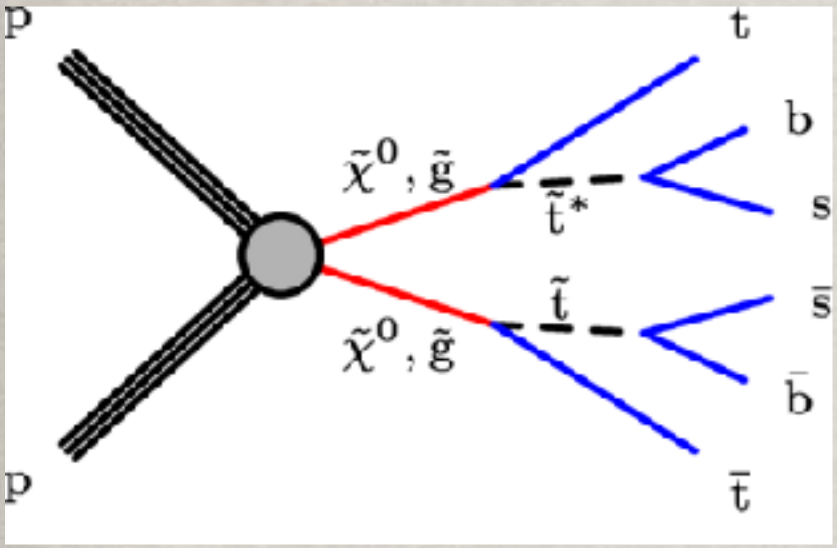


[CMS coll. 2104.13474]

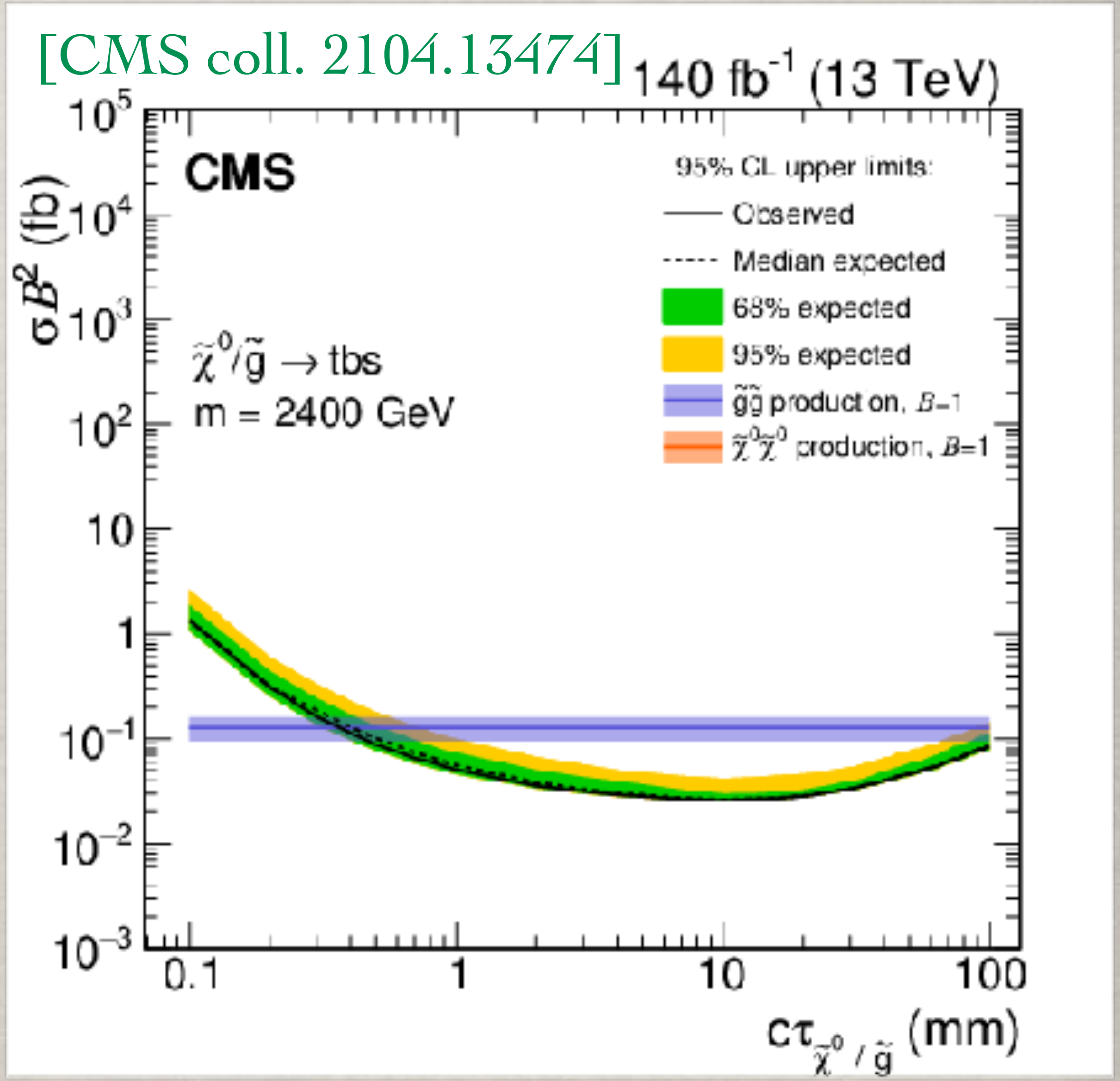


Also limits from ATLAS for gluino decay into neutralino

Displaced vertices at LHC



[CMS coll. 2104.13474]



Also limits from ATLAS for gluino decay into neutralino

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:

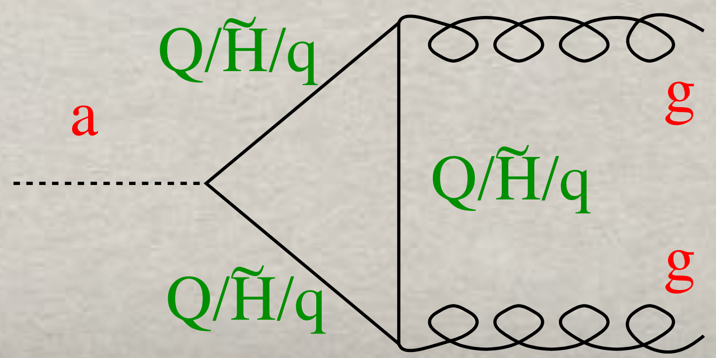
['t Hooft 76]

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

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

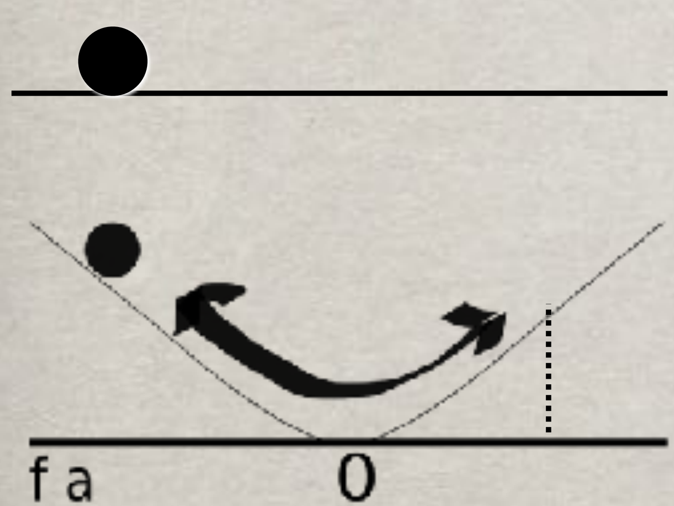
Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a , leaving the axion, a pseudo-Goldstone boson, interacting as

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



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

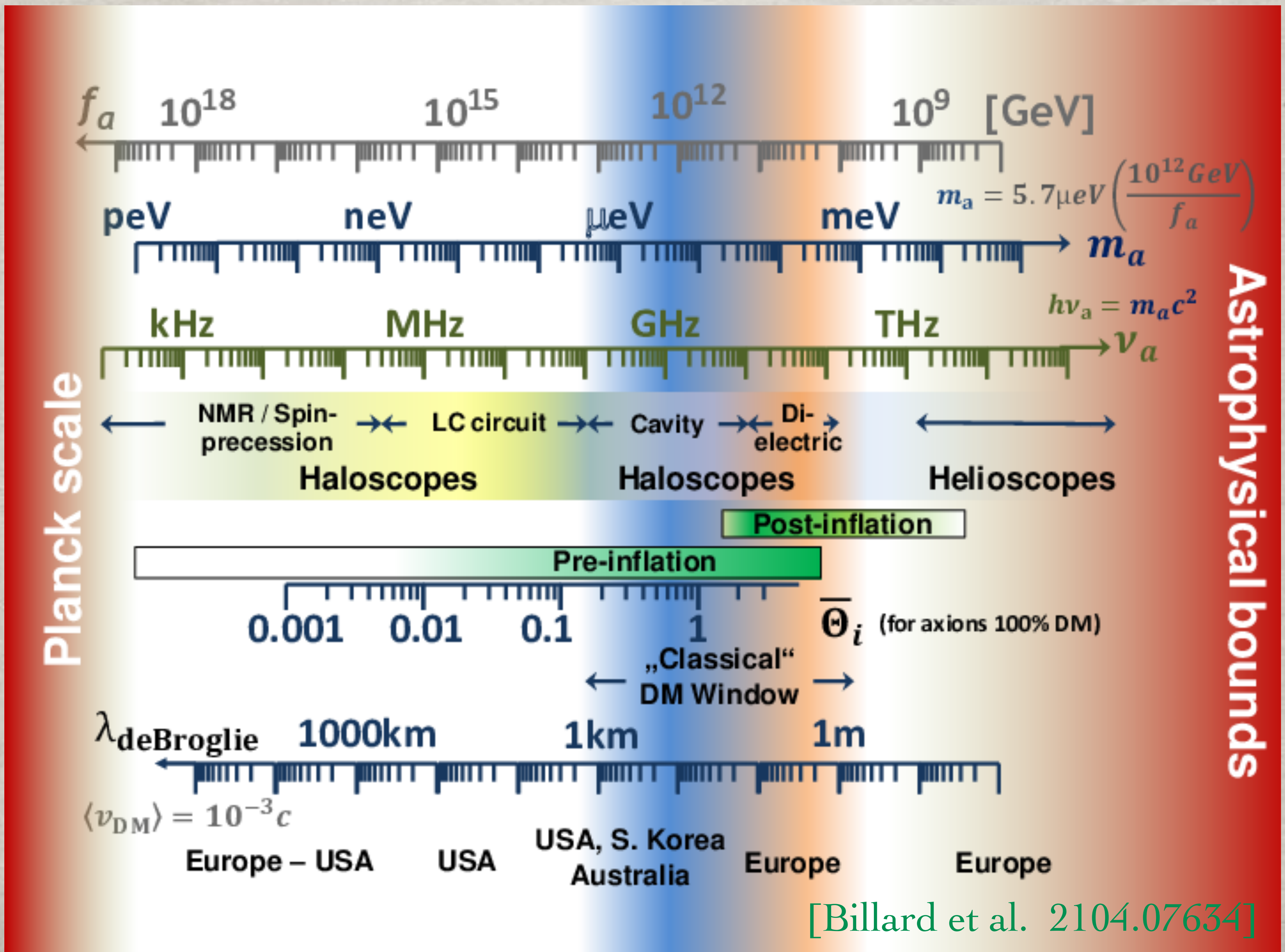
$$V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$

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

zero momentum particles >> CDM !

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

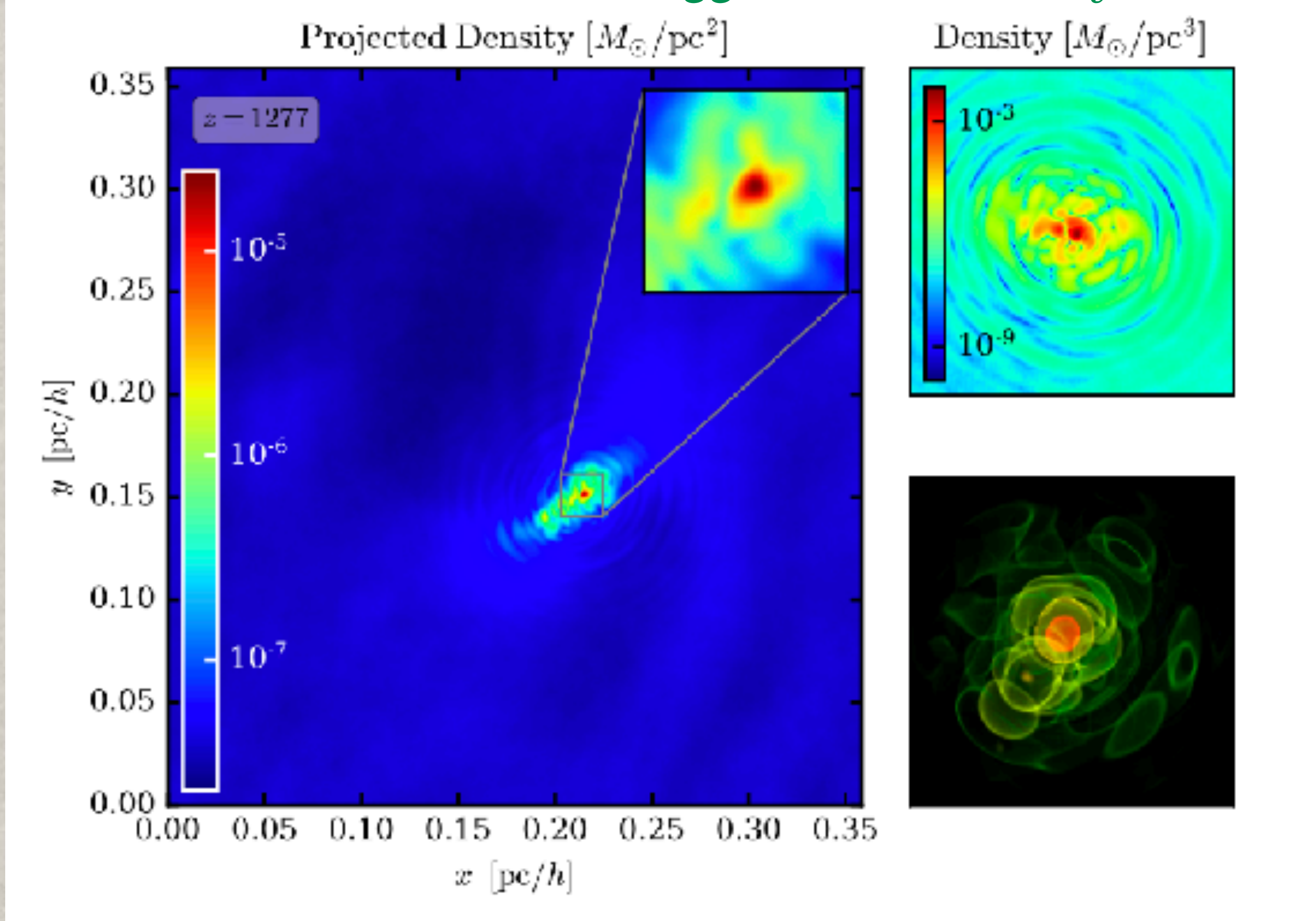
Axion's constraints



[Billard et al. 2104.07634]

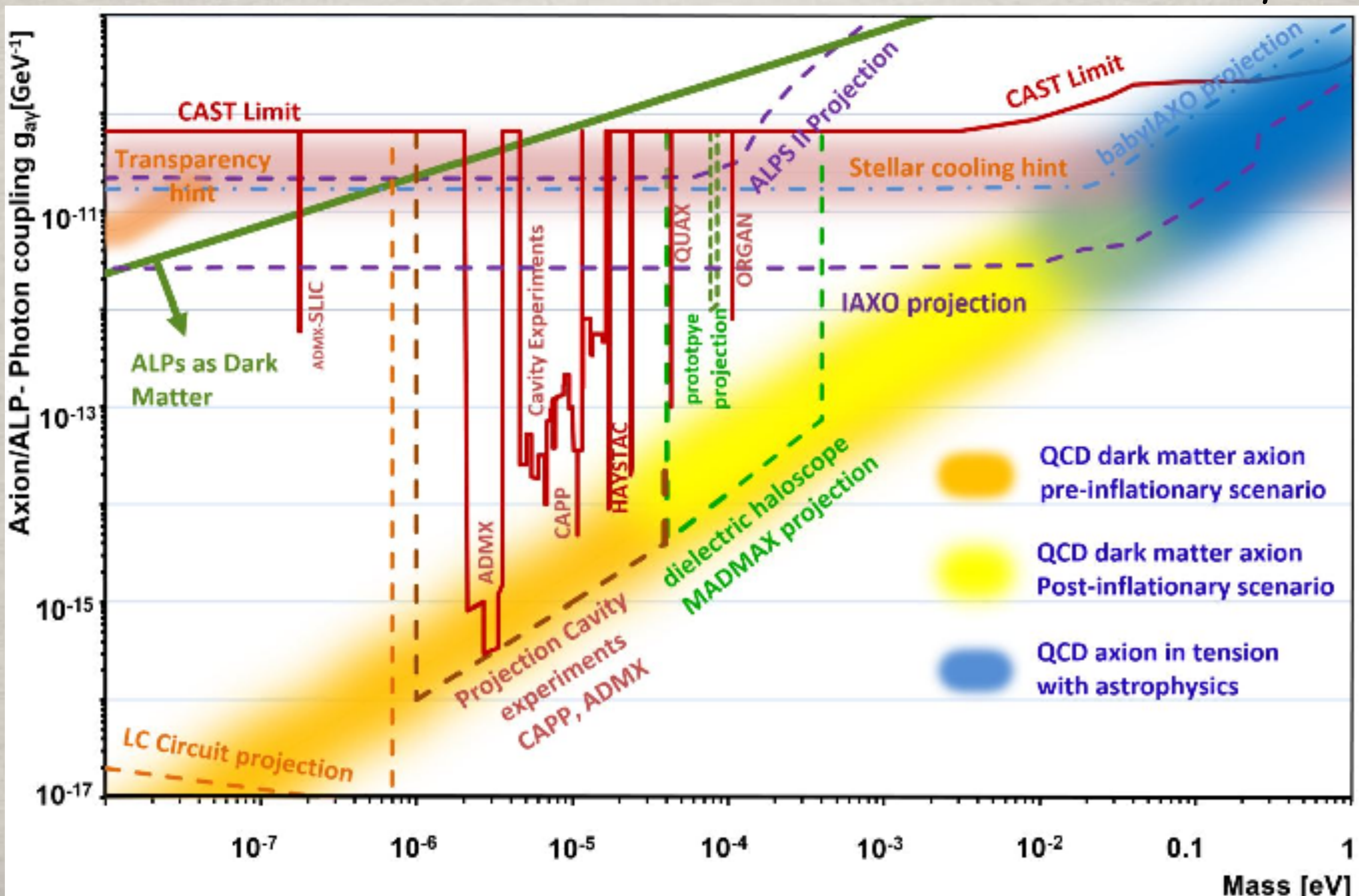
Axion miniclusters/stars

[Eggemeier & Niemeyer 2019]



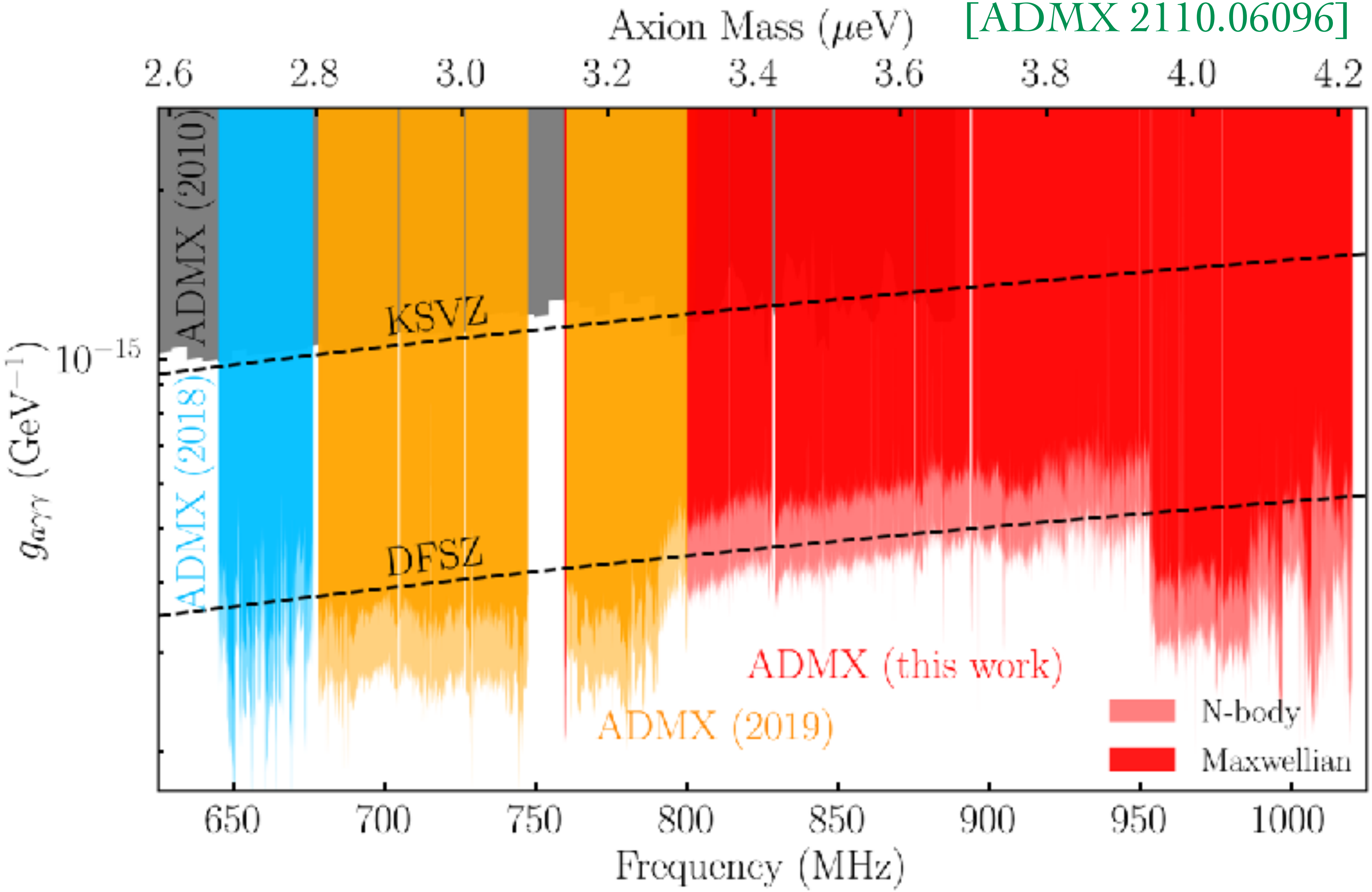
AXION DM SEARCHES

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 μeV.



AXION DM SEARCHES

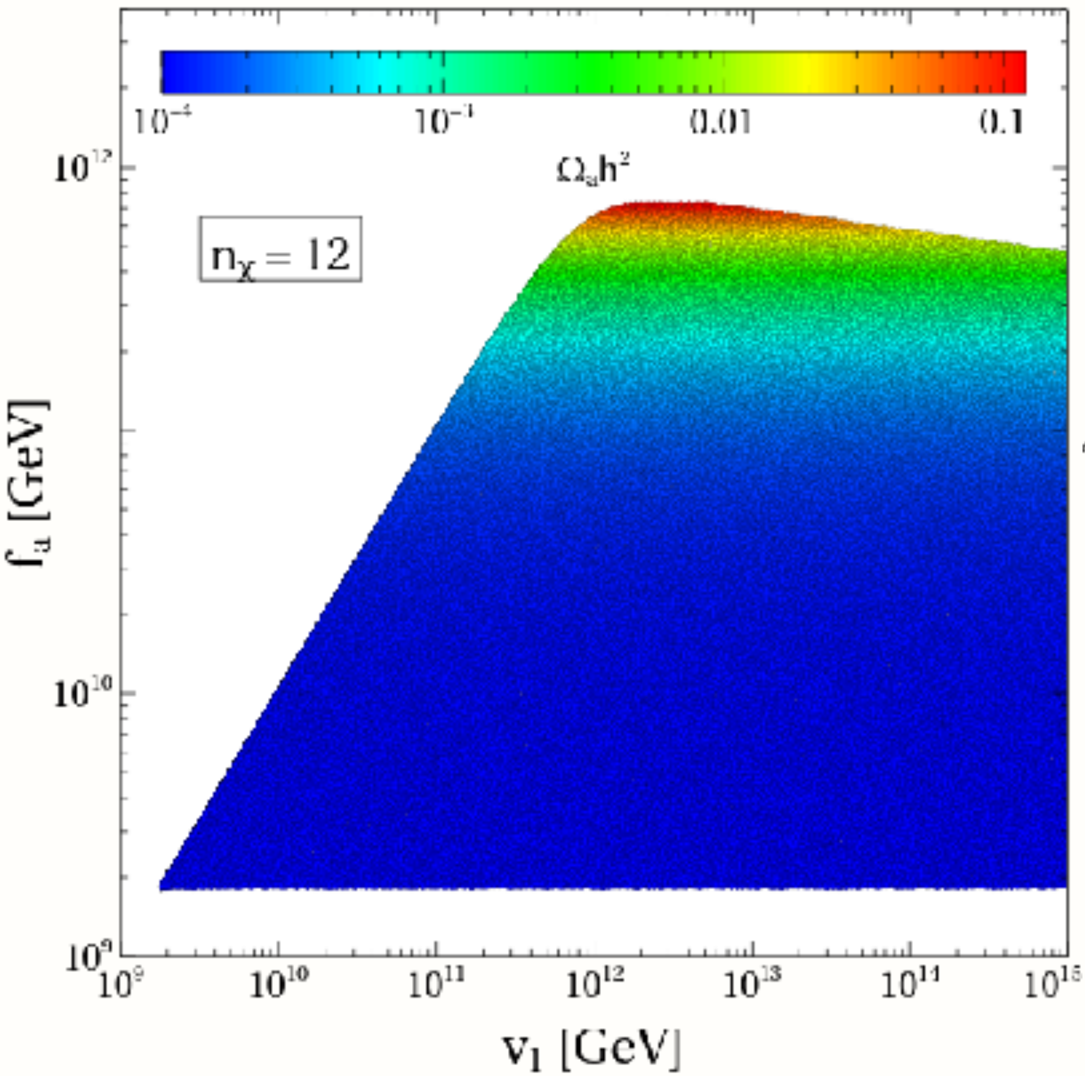
[ADMX 2110.06096]

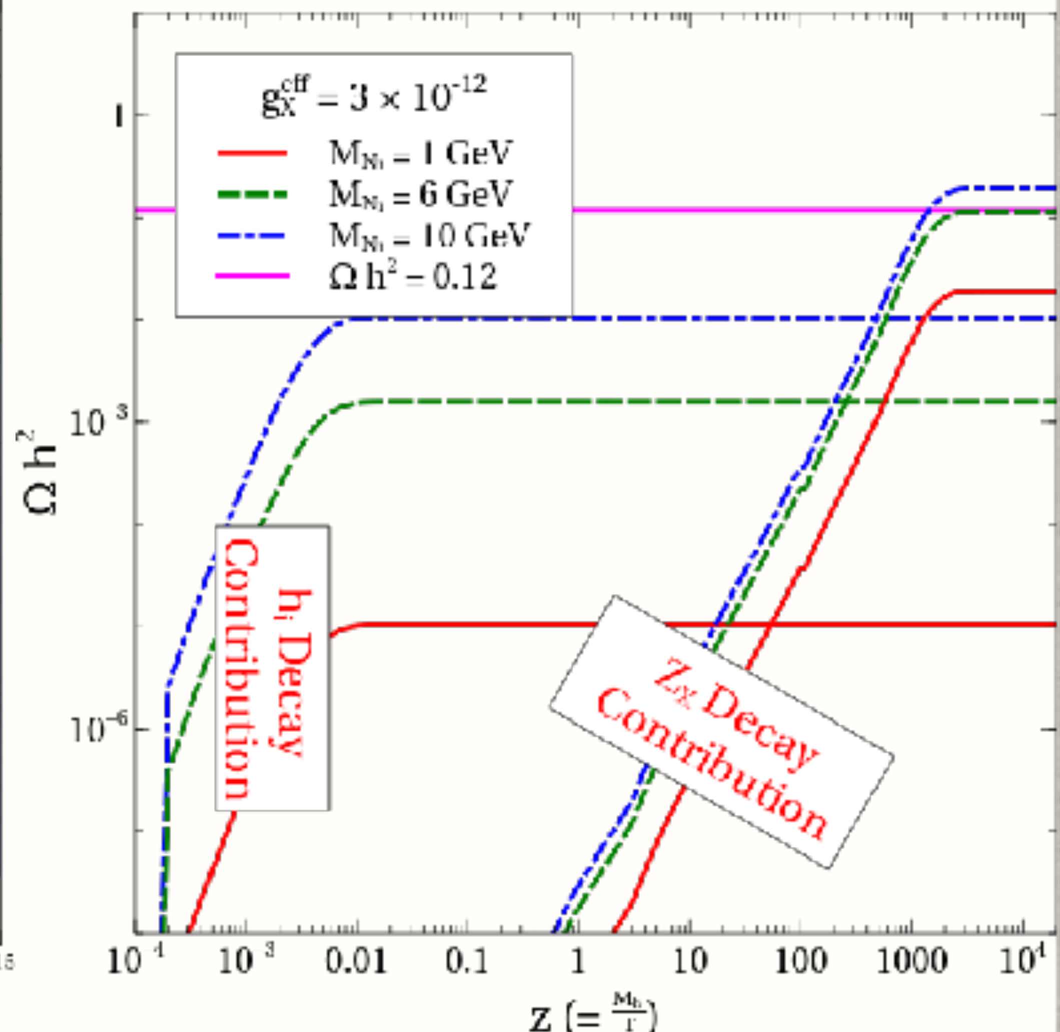


Axion & FIMP DM

Models with two DM candidates possible, e.g. axions and RH neutrinos FIMPs…

[LC & S. Khan 21xx.xxxx]





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.
- WIMPs are still a promising target, searches are being extended to low masses in DD and higher masses in ID. Improvement of relic density computations with thermal correction to Sommerfeld effect/bound states are in progress.
- The FIMP/SuperWIMP framework is quite general and could point to heavy metastable particles or displaced vertices at LHC with different decay channels.
- Finally axion experiments are finally reaching the predicted QCD axion band, more to come !

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